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CASE STUDY

REVISED Atacama Large Aperture Submillimeter Telescope (AtLAST) science: Gas and dust in nearby galaxies

[version 2; peer review: 2 approved, 1 approved with reservations]

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Abstract

Understanding the physical processes that regulate star formation and galaxy evolution are major areas of activity in modern astrophysics. Nearby galaxies offer unique opportunities to inspect interstellar medium (ISM), star formation (SF), radiative, dynamic and magnetic ($B \rightarrow$) physics in great detail from sub-galactic (kpc) scales to sub-cloud (sub-pc) scales, from quiescent galaxies to starbursts, and from field galaxies to overdensities. In this case study, we discuss the major breakthroughs in this area of research that will be enabled by the Atacama Large Aperture Submillimeter Telescope (AtLAST), a proposed 50-m single-dish submillimeter telescope. The new discovery space of AtLAST comes from its exceptional sensitivity, in particular to extended low surface brightness emission, a very large 2° field of view, and correspondingly high mapping efficiency. This paper focuses on four themes which will particularly benefit from AtLAST: 1) the LMC and SMC, 2) extragalactic magnetic fields, 3) the physics and chemistry of the interstellar medium, and 4) star formation and galaxy evolution. With ~ 1000 — 2000 hour surveys each, AtLAST could deliver deep dust continuum maps of the entire LMC and SMC fields at parsec-scale resolution, high-resolution maps of the magnetic field structure, gas density, temperature and composition of the dense and diffuse ISM in ~ 100 nearby galaxies, as well as the first large-scale blind CO survey in the nearby Universe, delivering molecular gas masses for up to 10^6 galaxies (3 orders of magnitude more than current samples). Through such observing campaigns, AtLAST will have a profound impact on our understanding of the baryon cycle and star formation across a wide range of environments.

Plain language summary

The interstellar medium (ISM) – the gas and dust that permeates galaxies – governs the evolution of galaxies. Stars form from the coldest regions of the interstellar gas in a complicated process that we still only understand partially. At the same time, the ISM is replenished by material shed by stars and fresh gas accreted from the outside environment. Building a complete model of star formation requires the study of a wide range of ISM processes on scales ranging from that of an entire galaxy (several kiloparsecs) to that of a small cloud core (below 0.1 parsec).

With current telescopes, we can however only observe the full details of star formation in our own galaxy. Nearby galaxies offer a chance to get detailed observations of a more diverse galaxy population, but observing them requires more advanced facilities. The Atacama Large Aperture Sub-millimeter Telescope (AtLAST [1]) is a 50-m single dish

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sub-millimeter telescope designed to take on this important challenge. Compared to the current generation of telescopes, AtLAST will be extremely sensitive to faint and extended emission, and able to efficiently map large areas of the sky. This paper describes four key areas in Nearby Universe research where AtLAST will be particularly impactful. They are: (1) the study of the dense and diffuse ISM in two of the Milky Way's satellite galaxies, (2) the origin, structure, and physical importance of magnetic fields, (3) the physics and chemistry of the ISM and how it regulates star formation, and (4) the demographics of dust and molecular gas across the galaxy population, from dwarf to giant galaxies.

Keywords
Interstellar medium, Interstellar dust, Magellanic Clouds, Magnetic fields, Astrochemistry, Star formation, Galaxy evolution



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REVISED **Amendments from Version 1**

The new manuscript has a new Figure 1 and Table 1, in corresponding to the referees' comments about adding more quantitative comparison to current facilities. Minor changes were made to Table 2/Table 3/Table 4/Table 5 and to Figure 3 for better readability and clarity according to the referees' comments. The changes includes adding information about the sensitivity of the LMC/SMC observations collected in Table 2/Table 3, a better explanation of the over-massive dust masses and (sub)millimeter excess, a better description of the the field of view (1–2 deg) and assumed IFU instrument, etc. The overall contents and main ideas are unchanged. We thank the two referees, and also Dr. Francisco M. Montenegro-Montes, who all provided helpful comments to the initial manuscript.

Any further responses from the reviewers can be found at the end of the article

1 Introduction

Of all the important unsolved problems in modern astrophysics, the development of a general and complete theory of star formation, applicable in all environments and at all cosmic times, would arguably have the greatest impact on our understanding of the universe. The challenge lies in the vast range of scales and processes involved, with gravity, turbulence and magnetic fields being the lead actors (e.g. McKee & Ostriker, 2007). While modern star formation theories can successfully explain the star formation efficiency of molecular clouds in environments similar to the solar neighbourhood, they fail to accurately describe star formation in more extreme environments, such as the high-pressure central regions of galaxies or the low metallicity gas that must have permeated primordial galaxies.

The reason for this predicament is that our understanding of the physics of star formation is currently vastly based on observations of the Milky Way. These observations have the highest physical resolutions possible (e.g., the Atacama Large Millimeter/submillimeter Array, ALMA, resolves ~0.1–0.2″ or ~1000 AU scales in the Galactic central molecular zone or complex substructures of Galactic clouds), but they are limited in the range of environments they can probe (in terms of density, metallicity, UV and X-ray radiation fields, cosmic rays, magnetic fields, etc), not to mention difficulties with distance estimation and confusion along the line of sight. Nearby galaxies (within ∼ 100 Mpc) are therefore of crucial importance, as they alleviate these issues while still being observable at resolution of tens of parsecs, or even better in the case of Local Group galaxies such as the Small and Large Magellanic Clouds (SMC and LMC, respectively[2]).

[1] http://atlast-telescope.org/

[2] The SMC and LMC are the two brightest Milky Way satellite galaxies, and can be seen with the naked eye in the southern sky. They are historically called the Small and the Large Magellanic Clouds, but the usage of the Portuguese explorer's name has a triggering impact on part of the astronomical community and a call has been issued to rename these galaxies as the Small and the Large Milky Cloud. While this matter pends, in this paper we will use their three letters acronyms (SMC and LMC) throughout rather than the full names.

Indeed, significant progress has been made over the past decade thanks to new and upgraded (sub)millimeter facilities such as ALMA and the IRAM 30m/NOEMA starting to enable "Galactic-like" science in extragalactic environments, while also enabling observations of the ISM in large, representative galaxy samples. From such observations, a picture is emerging where both large-scale environment and local conditions impact the structure and properties of molecular clouds and their star formation outputs: we observe variations from galaxy to galaxy (e.g. Saintonge & Catinella, 2022), with environment within nearby galaxies (e.g. Leroy *et al.*, 2021b), and even between the inner and outer regions of the Milky Way (e.g. Schruba *et al.*, 2019). In parallel, sensitive dust polarimetry measurements with instruments such as POL2 on the JCMT and HAWC+ on SOFIA have proved beyond doubt the crucial role of magnetic fields in regulating star formation (e.g. Chuss *et al.*, 2019; Pattle & Fissel, 2019; Pattle *et al.*, 2023; Pillai *et al.*, 2020). These studies show that magnetic fields channel gas flows along galactic filaments, thus affecting the structure and history of star formation history on galactic scales.

To achieve another step change in our understanding of ISM physics/chemistry and star formation, we need yet another significant increase in our observing capabilities. The Atacama Large Aperture Submillimeter Telescope (AtLAST) is a concept for a next generation 50-meter class single-dish submm telescope that would offer such opportunities (Klaassen *et al.*, 2020; Mroczkowski *et al.*, 2023; Mroczkowski *et al.*, 2024). AtLAST is designed to offer very high sensitivity and exceptional mapping speeds through both its large aperture, extended 1–2 degree field of view, and the excellent atmospheric conditions of the Chilean Chajnantor plateau. With its unique combination of spatial coverage, angular resolution and sensitivity (in particular to extended, low surface brightness emission), AtLAST will enable the study of the ISM in nearby galaxies as has never been possible before.

In this case study, we explore four prominent nearby galaxies science areas where AtLAST will be transformational:

1. ISM physics and star formation in the LMC and SMC, with a focus on the important yet poorly studied diffuse gas (e.g., atomic gas, low surface density gas in the outer part of galaxies) and dust;

2. the origin and structure of magnetic fields, from tens of kpc down to sub-kpc scales, and their impact on star formation;

3. the physics and chemistry of the ISM as probed by multiple dust and gas tracers;

4. ISM properties and star formation across the full range of environments of the local Universe through large statistical surveys.

The background and key science questions are presented in Section 2, highlighting those that AtLAST will be uniquely positioned to address, with a description of possible survey strategies. The technical requirements for AtLAST to reach

these science goals are summarised in Section 3. Finally, we summarize the key science goals and technical requirements for AtLAST in Section 4.

This paper is one of the series AtLAST Science Case papers that highlight the unique role of AtLAST in all the relevant astrophysics aspects, including science questions relating to Milky Way ecology, the sun, high-redshift galaxies, large-scale structure and the early Universe. We provide a comparison of AtLAST's proposed capabilities to that of other current facilities in Table 1, and highlight the irreplaceable place of AtLAST in the collecting area --- mapping speed parameter space in Figure 1.

2 AtLAST nearby galaxies science case highlights

2.1 Dust and gas in the LMC and SMC

2.1.1 Context and open questions. The LMC and SMC are the most massive satellites of our Milky Way Galaxy. Together with Andromeda (M 31), M 33, as well as other smaller galaxies out to $D \sim 1.5$Mpc, they form our Local Group. The LMC and SMC are strongly bound to the Milky Way and on a collision course, with the LMC expected to merge with our

Table 1. Comparing AtLAST with current millimeter and submillimeter telescopes.

(1)	IRAM (2)	LMT (3)	NOEMA (4)	CSO (5)	JCMT (6)	ASTE (7)	APEX (8)	GLT (9)	CCAT-p (10)	ALMA 12m array (11)	AtLAST (12)
Antenna diameter [m]	30	50	(12×)15	10.4	15	10	12	12	6	(54×)12	50
Surface Accuracy R.M.S. [μm]	66	75	50	15	23	20	17	17	10.7	16	≤20
Line Frequency Range [GHz]	72–350	88–350	70–276	150–850	77–375	270–500	159–738	86–345	460, 830	(35) 84–950	84–950(?)
Continuum Camera	NIKA2	TolTEC	...	MUSIC; SHARC II	SCUBA2	TES Camera	LABOCA; ArTéMiS	...	PrimeCam	...	TBD
Continuum Frequency Range [GHz]	230, 345	150, 210, 270	...	270; 666, 850	350, 666	270, 350	345; 850	...	850	...	TBD
Field of View (FoV) [arcmin][(a)]	6.5	4	0.28	14	6.7	7.5	11	0.35	**78**	0.35	**≥60**
Angular Resolution, ν_{ref}	11″, 260GHz	5.0″, 300GHz	**0.2–3.9″**	8″, 850GHz	14″, 350GHz	11″, 450GHz	21″, 300GHz	21″, 300GHz	15″, 850GHz	0.005–12″	1.7–15″
Continuum noise-equivalent flux density (NEFD) [mJy $s^{1/2}$] , ν_{ref}	33, 260GHz	**1.5, 280GHz**	4.11, 260GHz[(b)]	55, 270GHz	90, 350GHz	10, 270GHz	110, 345GHz; 600, 850GHz	...	21, 280GHz; 400, 850GHz[(c)]	**1.37, 280GHz[(b)]**	**1.05, 280GHz[(d)]**
Mapping Speed[(e)] [deg^2 mJy^{-2} hr^{-1}]	0.0219	5.4	0.00335	0.0646	0.109	0.277	0.0078	...	10.5	0.0465	**2.48×10^3**

[(a)] FoV is roughly the size of the continuum camera assuming a square shape when available, otherwise the equivalent primary beam FWHM of the antenna at 1 mm.

[(b)] For the continuum NEFD of the NOEMA and ALMA interferometers, we use the RMS of 1-second integration with typical conditions at the reference frequency using the telescope's sensivity calculators. For ALMA continuum observation, we use the current bandwidth of 8 GHz and dual polarization. For NOEMA continuum, we use the current bandwidth of 16 GHz and dual polarization.

[(c)] We adopt the continuum NEFD of CCAT-p (FYST) from CCAT-Prime Collaboration *et al.* (2023), which assumed a bandwidth of 60 GHz at 280 GHz and the second quartile of PWV (~0.85mm).

[(d)] We use the AtLAST sensitivity calculator to estimate the NEFD at 280 GHz, assuming a continuum bandwidth of 20 GHz.

[(e)] Mapping Speed = FoV × $NEFD^{-2}$, in units of [deg^2 mJy^{-2} hr^{-1}].

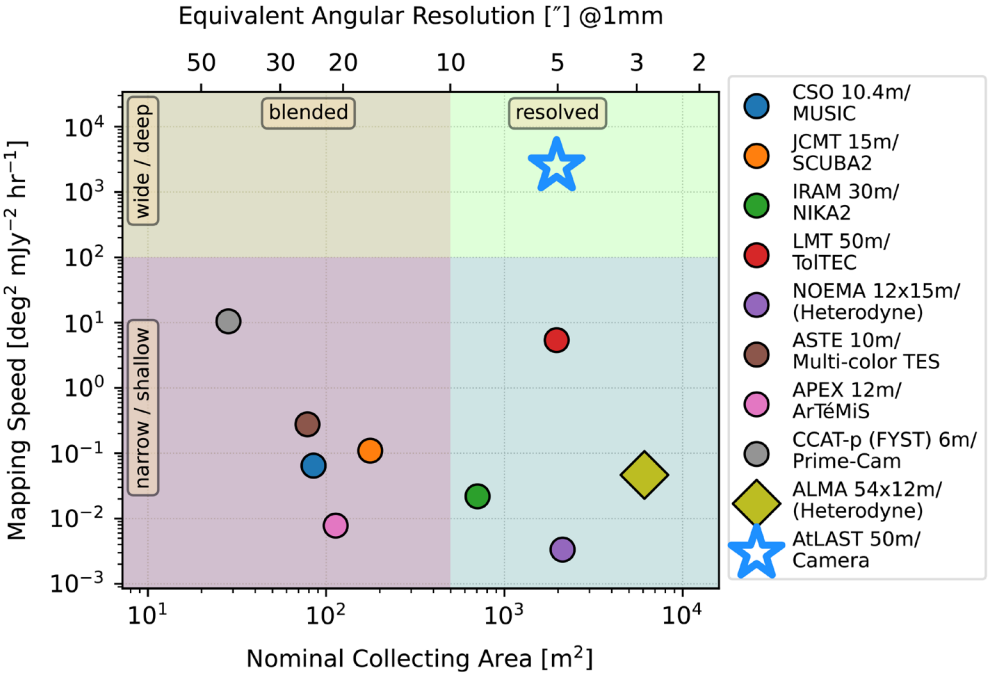

Figure 1. Comparison of nominal collecting area and mapping speed of AtLAST and other current millimeter/submillimeter facilities. Nominal collecting area is simply the antenna dish area. Mapping speed is computed as the field of view divided by the square of the noise-equivalent flux density (NEFD). See Table 1 for the detailed telescope parameters.

Galaxy in ∼ 2.5 Gyr (Cautun *et al.*, 2019). The intensity of the gravitational interaction between the SMC, LMC and Milky Way is pulling significant amounts of the interstellar gas away from the galaxies, which can be observed across the sky as large HI streams (Mathewson *et al.*, 1974; Wannier & Wrixon, 1972; see Figure 2).

With gas-phase metallicities of only 20–50% of the solar abundance, the SMC and LMC are the nearest laboratories to study star formation in low-metallicity environments (Russell & Dopita, 1992). This is important, because metallicity is a key parameter regulating the ISM: metals influence the efficiency of gas cooling, the shielding of molecules from the harsh UV radiation field, the production of dust grains, which in turn are the formation sites of molecules.

At a distance of ∼50 kpc (de Grijs *et al.*, 2014) and aided by the LMC's low inclination (i ∼ 38°, Balbinot *et al.*, 2015) we can spatially resolve the finest details of typical less metal abundant interstellar environments present. We can thus unveil physical processes at sub-parsec scales, and quantify the relative contribution of the various ISM components/tracers to the integrated, unresolved ISM observations which are available for distant galaxies. For example, determining locally (in the Milky Way and other very nearby galaxies such as the SMC and LMC) which tracers best measure the amount of high density gas is crucial in estimating the star formation efficiency of any dense gas in large extragalactic samples (see also Section 2.3).

The hot and cold ISM of the LMC, both gas and dust, have been extensively observed with radio and (sub)mm facilities such as ASKAP, MeerKAT, ALMA, APEX, and SOFIA (see details in Table 2 and Table 3). In addition, both the LMC and SMC have been observed in the mid- and far-infrared by the *Spitzer* SAGE and *Herschel* HERITAGE surveys (Gordon *et al.*, 2011; Meixner *et al.*, 2006; Meixner *et al.*, 2013). The currently most powerful near-infrared space telescope, JWST, observed warm, shocked, and/or ionized gas in a tiny part of the Large Magellanic Cloud. In the future, the Roman Space Telescope will be able to map the Magellanic Clouds with its much wider field of view. These near-infrared imagers and spectrographs will provide additional information on warm, shocked, and/or ionized gas. Combined, the synergy of these observations have led or will lead to significant new insights, but important questions about the diffuse and dense ISM remain open due to lacking a large-aperture single-dish in the (sub)mm wavelength regime.

How much molecular gas is there? These existing observing campaigns yield important constraints on the properties of the ISM in the LMC and SMC (see Figure 3). For example, Fukui *et al.* (2008) show that most of the molecular gas in the LMC is contained in over a hundred individual giant molecular clouds (GMCs; Hughes *et al.*, 2010), with a mean molecular mass surface density ∼ 50$M_\odot$ pc^{-2}, making those clouds only half as dense as those in the inner Milky Way. At the distance of LMC, resolving a few to tens of parsec-scale GMCs would need an angular resolution ≲4″. On the other hand, observations

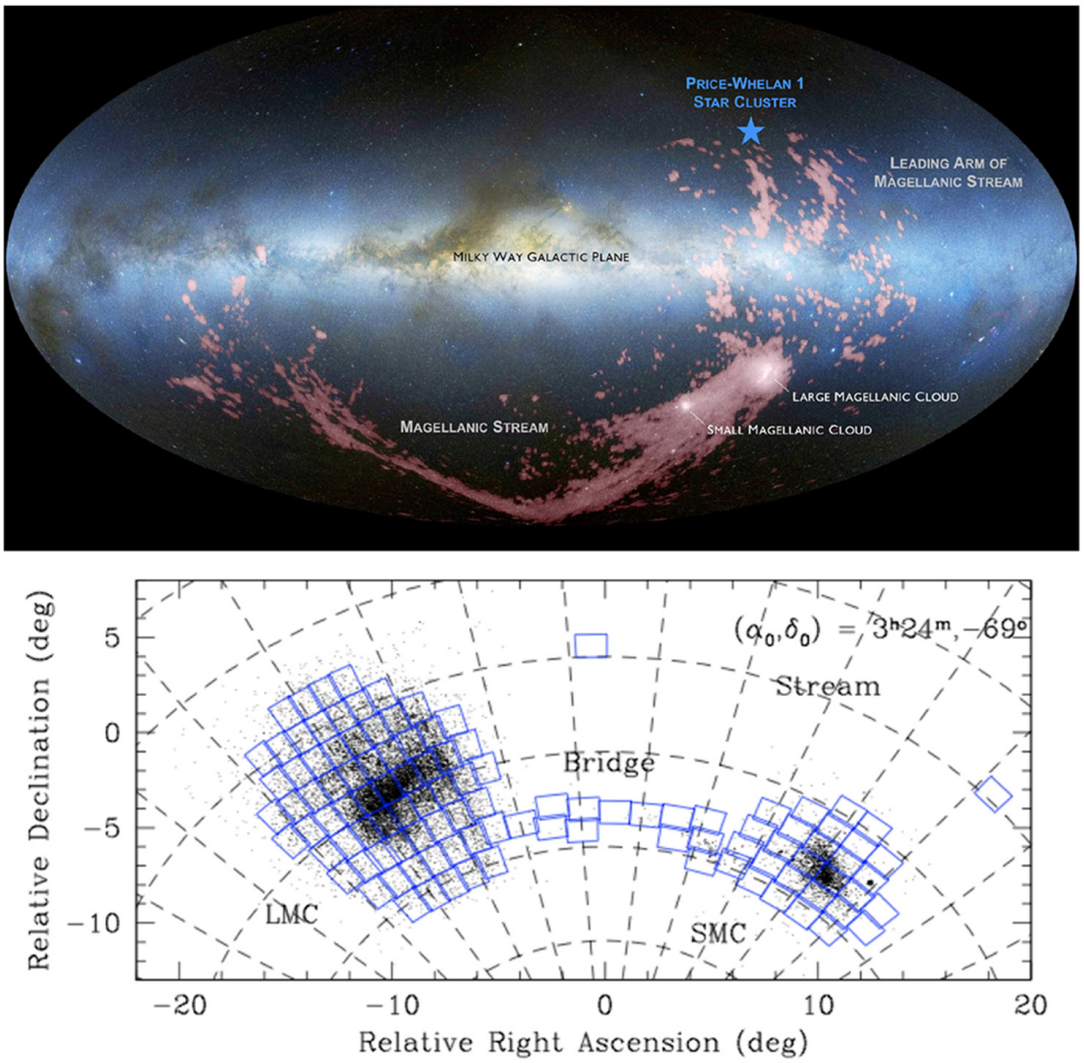

Figure 2. Full sky view of the LMC, SMC and the associated Stream system. Left: LMC, SMC, the Stream between the LMC/SMC and the Milky Way, and the leading arm of Stream in HI (red), on top of the optical all-sky image in Aitoff projection (West to the left and North up), adapted from Nidever *et al.* (2010). (Credit: D. Nidever/ NASA/ Simons Foundation URL.) **Right:** LMC and SMC in sky R.A. and Dec. coordinates (East to the left and North up), adapted from the ESO VISTA survey of the Magellanic Clouds system (VMC; Cioni *et al.*, 2011; see also https://www.eso.org/sci/publications/announcements/sciann17518.html, with blue squares showing the footprints of the VISTA survey covering ~110 deg^2 in the LMC, ~40 deg^2 in the SMC, ~20 deg^2 in the Bridge and ~3 deg^2 in the Stream.

of the [CII] line emission in the LMC with SOFIA/GREAT suggest that ≳ 75% of the cold gas may be "CO-dark", that is, missed from observing the tranditional tracer CO lines (Chevance *et al.*, 2020a). Accurately quantifying the molecular gas contents is of foremost importance, as a significant open question in the field is whether the ability of an individual GMC to form stars (i.e. its star formation efficiency) is determined by the intrinsic properties of the cloud, or dependent on interstellar environments (e.g. Chevance *et al.*, 2020b; Girichidis *et al.*, 2020; Krumholz & McKee, 2005). The first step to answer this fundamental question is therefore to characterise the molecular gas content (both CO-dark and CO-bright) of GMCs of various properties in a broad range of environments characterised by different levels of large-scale turbulence, pressure, external shear, and magnetic field strengths (e.g. André, 2017; Pattle *et al.*, 2023).

How much dust is there? Using common methods and calibrations, it can be demonstrated that the interstellar dust masses calculated for the SMC are too large to be explained by the dust production from evolved stars The infrared to submm emission of Magellanic Clouds have been observed either globally or point by point and modelled with simple phenomenological (Gordon *et al.*, 2014; Leroy *et al.*, 2007) or full state of the art dust models (Bot *et al.*, 2010; Chastenet *et al.*, 2017). These studies have inferred quite large dust masses of ~ 2×10^4 –10^5 $M_\odot$ for the SMC and ~ 4×10^5 –3×10^6 $M_\odot$ for the LMC, compared to the known dust production from

Table 2. Observations of ISM tracers in the LMC (an incomplete collection).

ISM phase	LMC
Atomic gas (HI)	ATCA+Parkes HI survey, beam~ 1′, area~10°×10°, RMS~2.4 K (Kim *et al.*, 2003; Staveley-Smith *et al.*, 2003)
	GASKAP: an HI survey with the ASKAP telescope, beam~30″, area~250 deg^2, RMS~2 K (Dempsey *et al.*, 2022; Dickey *et al.*, 2013; Pingel *et al.*, 2022)
	MagiKAT: a MeerKAT large survey of HI and OH, beam~20″, RMS~0.49 K per 1 km s^{-1} (van Loon *et al.*, 2010)
Molecular gas (CO)	CO(1–0) at beam~ 8.8′ over 6° ×6° with Columbia 1.2-m Millimeter-Wave Telescope, RMS~0.06 K per 1.3 km s^{-1} (Cohen *et al.*, 1988)
	Various CO(1–0) observations in selected regions with the SEST 15-m, with beam~45″ at 115 GHz and typical RMS~0.1–0.5 K per 0.1 km s^{-1} (Caldwell & Kutner, 1996; Israel *et al.*, 1986; Israel *et al.*, 2003; Johansson *et al.*, 1994; Johansson *et al.*, 1998; Kutner *et al.*, 1997)
	NANTEN complete survey of CO(1–0) at beam~ 2.6′ with NANTEN 4-m, covering ~ 30 deg^2, RMS~0.07 K per 0.65 km s^{-1} (Fukui *et al.*, 1999; Fukui *et al.*, 2008; Mizuno *et al.*, 2001)
	MAGMA survey of CO(1–0) at beam~ 33″ with Mopra 22-m, covering 3.6 deg^2 RMS~0.24 K per 0.53 km s^{-1} (Hughes *et al.*, 2010; Pineda *et al.*, 2009; Wong *et al.*, 2011; see Data Release URL)
	APEX CO(2–1) at beam~27″, CO(3-2) at ~18″, CO(6-5) at ~9″, and isotopologue lines in 3–13 arcmin^2 areas (Okada *et al.*, 2019)
	APEX CO(3–2) at beam~ 20″ (~ 5 pc) over 13.8 deg^2 RMS~150 mK per 0.5 km s^{-1} (Grishunin *et al.*, 2024)
	Herschel SPIRE high-J CO at beam~17–42″ over ~5′×5′ (Lee *et al.*, 2016)
Radio continuum	ASKAP 888 MHz survey, beam~ 13′, area~ 120 deg^2, RMS~ 58 μ Jy beam^{-1} (ASKAP-EMU; Pennock *et al.*, 2021)
PDR tracers ([CI])	AST/RO in N159/N160 H II regions at beam~ 3.8′, line RMS ~0.1 K km s^{-1} (Bolatto *et al.*, 2000a)
	APEX [CI](1–0) at beam~13″ and [CI](2–1) at ~8″ in 3–13 arcmin^2 areas (Okada *et al.*, 2019)
	Herschel/HIFI at ~ 44″ for [CI](1–0) and ~ 26.6″ for [CI](2–1) along 36 lines of sight (Pineda *et al.*, 2017)
Ionized gas & PDR ([CII])	Herschel/HIFI at ~ 12″ along 36 lines of sight (Pineda *et al.*, 2017)
	SOFIA/GREAT at ~ 16″ in 3–13 arcmin^2 areas (Okada *et al.*, 2019)
	SOFIA observations over ~40′ × 20′ (60 pc × 30 pc) area (Madden & LMC+ Consortium, 2023)
Ionized gas & H II regions (Hα)	Hα maps with $\lesssim$ 5″ resolution covering 8° × 8° in the LMC (MCELS; Smith & MCELS Team, 1998; Smith & MCELS Team, 1999; Winkler *et al.*, 2015)
	Hα maps with 1° resolution covering ~25° × 25° area centered at the LMC (Wisconsin Hα Mapper, WHAM; Smart *et al.*, 2023)
	SDSS-V Local Volume Mapper (LVM) survey of optical emission lines, area~78.5 deg^2, spatial resolution~10 pc (fiber diameter 0.5°) (Drory *et al.*, 2024)
Dust (IR/submm)	Spitzer SAGE (Meixner *et al.*, 2006): all 7 IRAC and MIPS bands
	Herschel HERITAGE (Meixner *et al.*, 2013): beam~ 7″–36″, area~ 7° × 7°, RMS~0.2–9 MJy sr^{-1} (see Data Release URL)
	QUEST maps from Clark *et al.* (2021) that includes the diffuse dust from a combination with Planck
	high resolution dust reddening at 25″ resolution from Chen *et al.*, 2022
	South Pole Telescope (and Planck) at 1.4, 2.1, and 3.0 mm, beam~ 1.0–1.7′, (5–10′ for Planck data), area~ 7.5° × 7.5° (Crawford *et al.*, 2016)
	SOFIA/HAWC+ dust continuum and polarization at 53–214 μm with beam =5–18″ (Tram *et al.*, 2021; Tram *et al.*, 2023)

Table 3. Observations of ISM tracers in the SMC (an incomplete collection).

ISM phase	SMC
Atomic gas (HI)	ATCA+Parkes HI survey, beam~ 1.6′ (30 pc), RMS~2 K (Stanimirovic *et al.*, 1999)
	GASKAP: an HI survey with the ASKAP telescope, beam~30″, area~250 deg^2, RMS~2 K (Dickey *et al.*, 2013; Dempsey *et al.*, 2022; Pingel *et al.*, 2022)
	MagiKAT: a MeerKAT large survey of HI and OH, beam~20″, RMS~0.49 K per 1 km s^{-1} (van Loon *et al.*, 2010)
	HI outflows with ASKAP at ~ 30″ (Dempsey *et al.*, 2020; McClure-Griffiths *et al.*, 2018)
Molecular gas (CO)	CO(1–0) at ~ 8.8′ (~ 160 pc) with Columbia 1.2-m Millimeter-Wave Telescope covering 2°×2°, RMS~0.012 K per 1.3 km s^{-1} (Rubio *et al.*, 1991)
	Various CO(1–0) and (2–1) observations in selected regions with the SEST 15-m, with beam~45″/22″ at 115/230 GHz and typical RMS~ 0.1–0.2K per ~ 0.1kms^{-1} (Israel *et al.*, 1986; Israel *et al.*, 1993; Rubio *et al.*, 1993; Rubio *et al.*, 1996)
	CO(1–0) at ~ 42″ with the Mopra 22-m, RMS~210 mK per 0.9 km s^{-1} (Muller *et al.*, 2010)
	CO(1–0), ^{13}CO(1–0) and C^{18}O(1–0) at ~ 33″ with Mopra 22-m along 18 lines of sight, plus CO(3–2) and ^{13}CO(3–2) at ~ 17.5″ with APEX 12-m (Pineda *et al.*, 2017)
	CO(2–1) at ~ 27″ (~ 9 pc) in two regions (10′×10′ and 7′×10′) with APEX, RMS~ 32–37 mK per 0.25 km s^{-1} (Di Teodoro *et al.*, 2019)
	CO(2–1) at ~ 27″ (~ 9 pc) in discrete regions totaling ~ 0.4 deg^2 (0.47 kpc^2) region with APEX, RMS~ 0.1–0.7 K per 0.25 km s^{-1} (Saldaño *et al.*, 2023a)
	CO(3–2) at ~ 20″ (~ 6 pc) in ~ 2.5 deg^2 region with APEX, RMS~1 K per 0.4 km s^{-1} (Saldaño *et al.*, 2023b)
Radio	ASKAP 960/1320 MHz survey, beam~30″/16″, area~30 deg^2, RMS~186/165 μJy beam^{-1} (ASKAP-EMU; Joseph *et al.*, 2019)
	MeerKAT 1.3 GHz survey, beam~ 13″, area~ 7°×7°, RMS~ 11 μJy beam^{-1} (Cotton *et al.*, 2024)
PDR tracers ([CI])	ISO satellite at 3.8′ (Bolatto *et al.*, 2000b)
	Herschel/HIFI at 44″ for [CI](1–0) and 26.6″ for [CI](2–1) along 18 lines of sight (Pineda *et al.*, 2017)
Ionized gas & PDR ([CII])	Herschel/HIFI at 12″ along 18 lines of sight (Pineda *et al.*, 2017)
Ionized gas & H II regions (Hα)	Hα maps with $\lesssim$ 5″ resolution covering 4.5° × 3.5° in the SMC maps (MCELS; Smith & MCELS Team, 1998; Smith & MCELS Team, 1999; Winkler *et al.*, 2015)
	Hα maps with 1° resolution covering ~20° × 20° area centered at the SMC (Wisconsin Hα Mapper, WHAM; Smart *et al.*, 2019)
	SDSS-V Local Volume Mapper (LVM) survey of optical emission lines, area~16.4 deg^2, spatial resolution~10 pc (fiber diameter 0.5°) (Drory *et al.*, 2024)
	MUSE observation of optical emission lines, area~ 1′ × 1′ , resolution~ 1.3″ (Bodensteiner *et al.*, 2020)
Dust (IR/submm)	Spitzer SAGE (Meixner *et al.*, 2006): all 7 IRAC and MIPS bands
	Herschel HERITAGE (Meixner *et al.*, 2013): beam~ 7″–36″, area~ 7° × 7°, RMS~0.2–9 MJy sr^{-1} (see Data Release URL)
	South Pole Telescope (and Planck) at 1.4, 2.1, and 3.0 mm, beam~ 1.0–1.7′, (5–10′ for Planck data), area~ 5° × 5° (Crawford *et al.*, 2016)
	QUEST maps from Clark *et al.* (2021)
	AzTEC 1.1 mm continuum over 4.5 deg^2 with ASTE 10-m (Takekoshi *et al.*, 2017)

evolved stars (1.3×10^{-6} $M_\odot yr^{-1}$; Schneider *et al.*, 2014; Srinivasan *et al.*, 2016), assuming that dust destruction and star formation are non-negligible sinks of interstellar dust in the ISM. Similarly, excessively large dust masses are also observed in high redshift (and therefore relatively low metallicity) galaxies (e.g., Dwek & Cherchneff, 2011; Donevski *et al.*, 2020; Rowlands *et al.*, 2014), with these observations particularly hard to explain at $z \gtrsim 6$ (e.g., Witstok *et al.*, 2023),

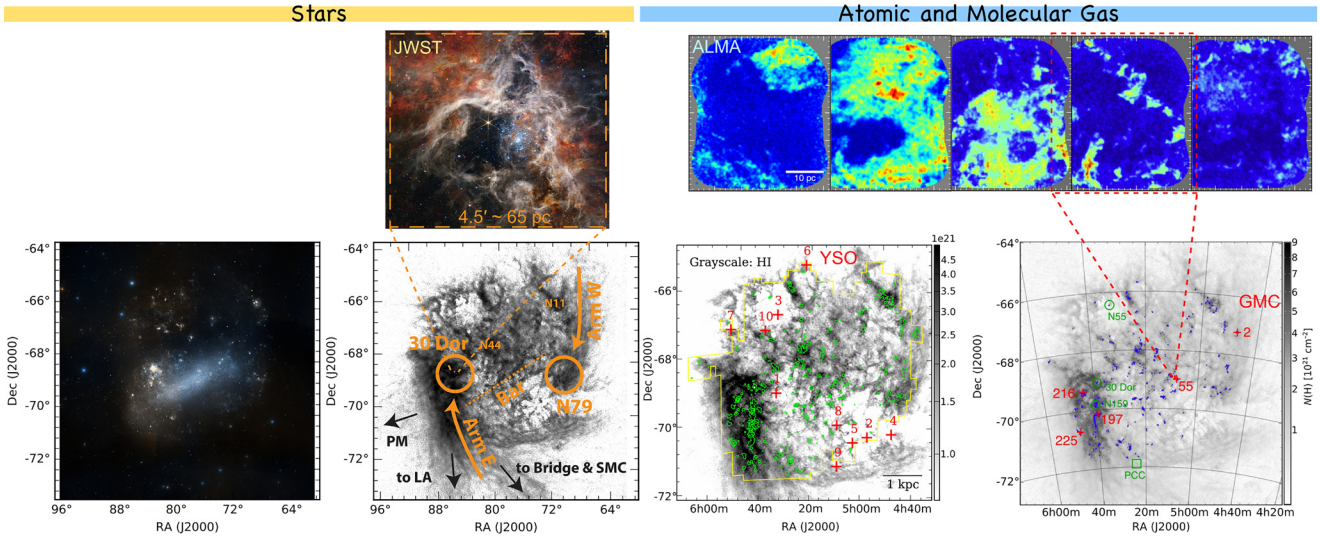

Figure 3. Bottom four panels: Stellar light, HI, and CO emission in the LMC. Panels from left to right show the optical RGB image from the ESA Sky; HI emission in gray with labels of regions from Ochsendorf *et al.* (2017); CO(1–0) emission (green) from the NANTEN telescope (at 2.6′ ~ 40 pc resolution; Fukui *et al.*, 2008) on top of HI column density gray image (at ~ 14′ ~ 200 pc resolution; Kim *et al.*, 2003) adapted from Harada *et al.* (2019); and the ALMA small mosaic observations at a few locations highlighted in green and red, adapted from Sawada *et al.* (2018). **Top-left panel** shows the JWST NIRCam RGB image of the Tarantula Nebula star-forming region at ultra-high resolution (0.06″ ~ 3000 AU), adapted from NASA website. **Top-right five panels** show the ALMA observations of the ^{12}CO(1–0) emission in five GMCs in the LMC (field of view 2.5′ × 2.5′ each) at sub-parsec scales (at 3″ ~ 0.7pc resolution) from Sawada *et al.* (2018).

when the Universe is too young for Asymptotic Giant Branch stars to have evolved to the dust forming stage.

However, recent work on dust in the LMC, SMC and other nearby resolved galaxies suggests that this "dust budget crisis" might be attributed to our lack of understanding of cosmic dust in low density, low metallicity environments and wrongly applying assumptions based on observations of dust in high metallicity environments. Indeed, submm and mm emission excesses have been observed in nearby galaxies, especially mm excesses are found at low metallicities and/or in diffuse environments such as the ISM of the LMC (Galliano *et al.*, 2011), and even more prominently in the SMC (Bot *et al.*, 2010; Gordon *et al.*, 2014; Planck Collaboration *et al.*, 2011). The excess refers to the emission observed in the (sub)mm regime that is higher than what is extrapolated by single modified black-body emission or full dust models fitted on the far-infrared peak (Bot *et al.*, 2010; Galliano *et al.*, 2011; Gordon *et al.*, 2011). It can be either due to an excess above standard emissivity index (β = [1.5–2]) in the shorter wavelengths, or a flattening (decreasing β index) or break in the spectral energy distribution toward longer wavelengths. The excess is also often associated to a lower dust mass surface density, and low metallicities or dwarf galaxies (Galametz *et al.*, 2014; Galliano *et al.*, 2018; Kirkpatrick *et al.*, 2013). In the Magellanic Clouds, an excess has been observed at even longer wavelengths in the mm to centimeter range, above the expected dust emission fitted to the far-infrared to submm energy range (Bot *et al.*, 2010; Israel *et al.*, 2010; Planck Collaboration *et al.*, 2011).

This (sub)mm dust emission excess can be interpreted as an indication of a different dust composition, grain properties or emissivity at longer wavelengths in low metallicity environments (Galliano *et al.*, 2018), or the emission from magnetic nanoparticles (Draine & Hensley, 2013). Furthermore, Clark *et al.* (2021) have shown that in such large galaxies, *Herschel* observations suffered from spatial filtering on large scales, compounding the problem. After correcting for this missing large scale, diffuse emission by adding data from the *Planck* satellite, part of the tensions between observations and models however appear to be resolved (Clark *et al.*, 2023). This highlights the vital importance of getting submm and mm observations at an angular resolution (of a few arcseconds) that resolves individual environments and that also account for diffuse, large-scale dust emission, if we are to characterise the properties of interstellar dust in low metallicity environments.

2.1.2 The role of AtLAST in the study of the LMC and SMC. Interferometers like ALMA and current single dish submillimeter telescopes like APEX are very inefficient at mapping large-scale, low-density interstellar medium at multiple bands, either due to filtering of flux on large scales, poor sensitivity, poor spatial resolution, or low mapping efficiency[3].

[3] For instance, the ALMA 12-m antenna array's Maximum Recoverable Scale (MRS) is about 8″ to 28″ in its commonly used Band 3 to Band 7; the ALMA 7-m antenna array's MRS is approximately 1 arcmin in Band 3. The MRS is also approximately the FWHM of the ALMA single pointing field of view, thus ALMA cannot map diffuse, large-scale emission over a few degree scales like in the Magellanic Clouds.

The characterization of the diffuse molecular and atomic ISM, where GMCs are born and remain embedded, is therefore impossible without a next-generation (sub)millimeter single dish telescope such as AtLAST. We give an overview here of how AtLAST will tackle the core questions raised above regarding the ISM in the LMC/SMC, together with a description of the corresponding technical requirements in Section 2.1.3.

What are the properties of interstellar dust in the diffuse and dense ISM? So far, studies of the distribution and properties of dust in the LMC/SMC have relied heavily on the full maps observed with *Herschel* at wavelengths of ~ 70–500 μm (spatial resolution ~ 7–36″; see summary in Table 2 and Table 3). To expand on these results, higher spatial resolution (e.g., tens of parsecs cloud-scale) measurements are required to trace spatial variations in dust properties, being sensitive to large scale emission is required to properly trace the very diffuse dust component, and longer wavelength data are required to increase the precision to which we can measure the dust emissivity index (and as a consequence dust temperature) and the dust surface density. The advantages of such an approach are demonstrated for instance for M 31, which was targeted by the HASHTAG programme with SCUBA-2 on the JCMT at 450 and 850 μm (Smith *et al.*, 2021). Unfortunately, it is currently not possible to make large scale continuum maps (7° × 7° for the LMC and 3° × 5° for the SMC) at submm or mm wavelengths. The exception is the survey performed with the South Pole Telescope, which was expanded to include the LMC and SMC at 1.4, 2.1 and 3 mm (Crawford *et al.*, 2016). However, this survey has a spatial resolution of only 1.0′ to 1.7′ (~ 400–800 pc), and contains contributions from free-free and synchrotron radiation complicating the measurement of thermal dust emission at these wavelengths.

With AtLAST, we will characterise the shape of the dust spectral energy distribution from the far-infrared to the millimeter in several bands (e.g., with enerby-balancing code like MAGPHYS (da Cunha *et al.*, 2008), CIGALE (Boquien *et al.*, 2019), and many others), from dense regions to diffuse environments. This will make it possible to separate the cold dust component from free-free emission, but also from background emission from distant galaxies or CMB fluctuations. Studying this emission in the two different metallicity regimes offered by the LMC and SMC will enable us to understand how dust varies with environment and hence to model it precisely and ultimately get better dust properties (including the most precise dust temperature, emissivity index β, and dust masses in LMC/SMC-like enviornments). The significantly (up to ~ 15×) higher spatial resolution compared to *Herschel* will make it possible to trace substructures, and characterise the multi-temperature dusty medium, in principle in any nearby galaxies.

How can we trace dark molecular gas, and what is its importance? As metallicity decreases, CO is restricted to the highest density parts of the molecular clouds, leaving a substantial molecular layer of H_2 without CO that has been dubbed "CO-dark" (e.g. Wolfire *et al.*, 2010). This CO dark component is often conceptualised as the outer layer of giant molecular complexes, but in reality the geometry of the ISM is much more complicated. Given the filamentary structure of the ISM, only small CO-emitting clumps survive the photoionisation, making the whole CO-dark/CO-emitting components very difficult to detect without sensitive, high resolution and large field-of-view observations (as observed for example with ALMA in the low metallicity dwarf galaxy WLM, Rubio *et al.*, 2015). Observations of the [CII] line emission in the LMC with SOFIA/GREAT suggest that $\gtrsim$ 75% of the cold gas may be CO-dark (Chevance *et al.*, 2020a). To reach our goal of understanding how star formation proceeds in low density, low metallicity environments, it is vital that we accurately resolve the molecular gas reservoirs of galaxies such as the SMC and LMC, and therefore we must look beyond CO for molecular ISM tracers.

The neutral carbon's [CI](1–0) and (2–1) fine structure lines are popular tracers of CO-dark gas, proposed to be very promising for tracing the CO dissociation layer of PDRs and the low-metallicity gas without much CO (Glover & Clark, 2016; Ramambason *et al.*, 2024). By observing both [CI] lines, it is furthermore possible to measure the temperature, density and optical depth of the gas. Significant mapping of the [CI] in the LMC and SMC is currently impossible: ALMA's field of view is far too small[4], and a 12m single dish like APEX does not offer enough sensitivity and resolution[5]. A survey of the LMC and SMCs with AtLAST in Bands 8 and 9[6] would therefore allow us to map not just the distribution of the diffuse molecular gas, but its physical conditions as well, at unprecedented sensitivity and resolution. This would be a game-changer in our understanding of the ISM and of star formation in diffuse, low metallicity extragalactic environments. For example, accurate mapping of the full molecular gas reservoir (CO *and* CO-dark) will allow us to answer the very important question of the extent to which star formation can occur in diffuse ISM environments.

How does metallicity drive the gas-to-dust ratio? Given the low metallicity ISM of especially the SMC, key physical and chemical processes that regulate cooling, heating, dust and molecule formation are different than in the Milky Way. Studies of nearby galaxies have shown that such processes do not scale linearly with the amount of metals available. For example, the gas-to-dust ratio is observed to evolve linearly as expected only at high metallicities. Below a critical metallicity threshold, the amount of dust per gas unit breaks down from the expected relationship (e.g. Galliano *et al.*, 2018; Rémy-Ruyer *et al.*, 2014; Roman-Duval *et al.*, 2017). This

[4] ALMA 12-m atennna array's field of view FWHM is about 6″ and ALMA 7-m antenna array's field of view FWHM is about 14″ at the [CI](1–0) frequency.

[5] An APEX-like 12-m single dish has a factor of 4.2 worse spatial resolution and a factor of 17 smaller collecting area than a 50-m single dish like AtLAST.

[6] Throughout this review, we adopt the ALMA definition of observing frequency bands, see https://www.eso.org/public/teles-instr/alma/receiver-bands/

critical metallicity of $\sim 0.2Z_{\odot}$ is usually interpreted as the threshold above which grain growth becomes efficient (Zhukovska *et al.*, 2016). An alternative interpretation is that the break corresponds to a regime change where diffuse gas becomes more important (Clark *et al.*, 2023). Straddling this metallicity transition region, the LMC/SMC and lower-metallicity, fainter dwarf galaxies will offer us a unique opportunity to accurately measure both dust and gas abundances to significantly improve our understanding of how these two components of the ISM interrelate. AtLAST will be essential in achieving these goals, as they can only be achieved through a complete census of the metals (e.g., with the optical integral-field Local Volume Mapper survey; Kollmeier *et al.*, 2019), dust and gas (with AtLAST).

2.1.3 AtLAST surveys of the LMC and SMC. At declinations of ~ -70 degrees, the LMC and SMC are only observable from the Southern hemisphere (see Figure 2). They have already been mapped by a wide range of radio and (sub)mm telescopes, as summarised in Table 2 and Table 3, but suffer from lack of resolution, confusion, and/or lack of sensitivity to large-scale flux. AtLAST will be transformational, by allowing full mapping of the LMC and SMC over nearly a hundred square degrees in continuum emission and moderately bright lines, scanning through the electromagnetic spectrum from Band 3 ($\sim$ 100 GHz) to Band 10 ($\sim$ 850 GHz) to determine accurate dust and gas properties. The best spatial resolution can be achieved in the highest-frequency Band 10, about 1.5–2 arcsec (0.4–0.6 pc).

Continuum observations With AtLAST we will be able to obtain multi-band submillimeter continuum maps with sufficient sensitivity and area coverage to trace emission from bright star forming regions to the faint, diffuse ISM. Coverage in multiple bands will be crucial: it is needed in the first place to derive the spectral shape of the dust emission to constrain the dust composition and grain sizes, and to discriminate between dust and free-free emission in regions where ionized gas is important. Due to the sensitivity and large field of view of AtLAST, "contamination" by Cosmic Microwave Background (CMB) fluctuations will be an issue, but with multi-band observations we will be able to disentangle them, given the well characterised spatial and spectral characteristics of the CMB. Similarly, we can expect to be affected by confusion with more distant sub-millimeter/millimeter galaxies, resolved or unresolved (Cosmic Infrared Background), which will create correlated noise that will have to be estimated, but can be separated from dust emission using its spatial scale properties and wavelet phase harmonics (Auclair *et al.*, 2024).

Figure 4 and Figure 5 show the footprint of a proposed mapping survey of the LMC and SMC with AtLAST. Assuming a field of view of 1 deg^2 for the first-generation AtLAST continuum camera, we will need $\sim$ 40 pointings to cover the LMC ($\sim 7° \times 7°$) and $\sim$ 8 pointings to cover the SMC ($\sim 4° \times 2°$). For each pointing, the integration time depends on the bandwidth and depth. Here we adopt a high-spatial-resolution multi-wavelength SMC dust simulation by C. Bot *et al.* (in prep.) to estimate the expected observing time. The simulation

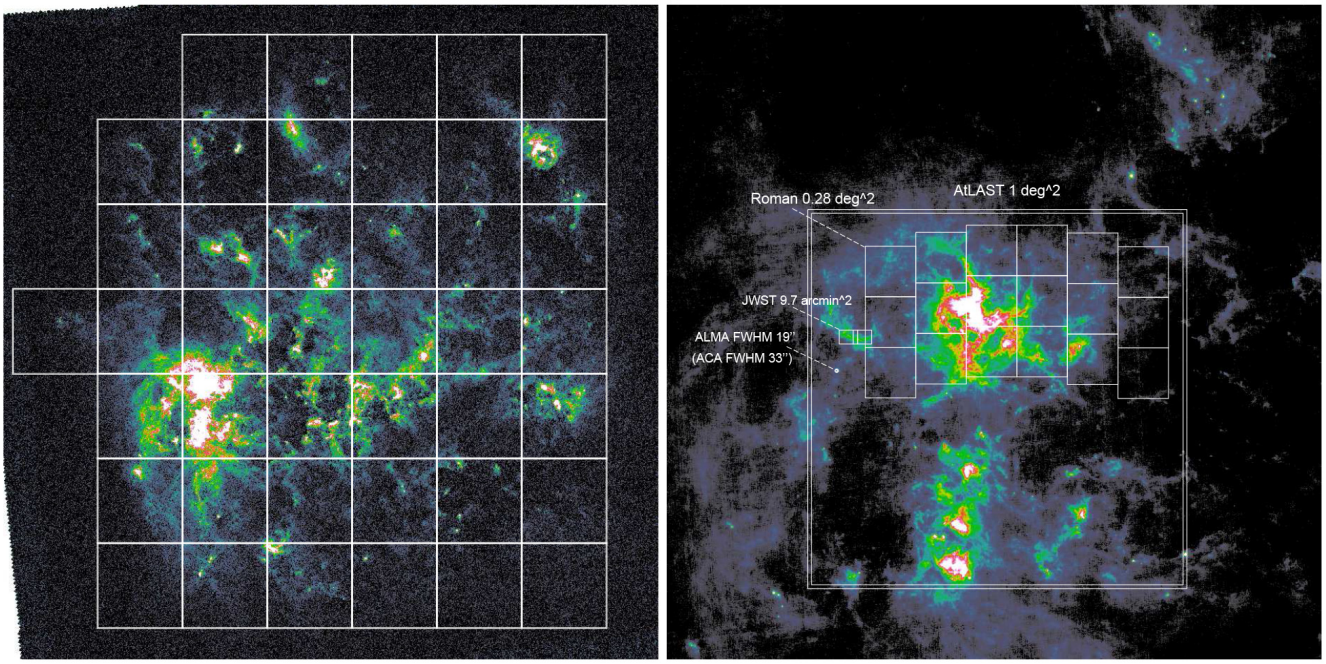

Figure 4. Dust emission at 100 μm in the LMC from the *Herschel* space observatory (Meixner *et al.*, 2013) The left panel shows the full ~ 7° × 7° area of LMC. Grids are 1° × 1° fields of view of AtLAST continuum camera. The right panel shows the zoom-in 30′ view around the 30 Doradus HII region. The fields of view of AtLAST, ALMA (12-m array and 7-m array), *JWST* NIRCam and *Roman* Space Telescope WFI are shown for comparison. Only the future-generation AtLAST and *Roman* are able to map the full near to far-infrared and sub-millimeter dust emission in the LMC.

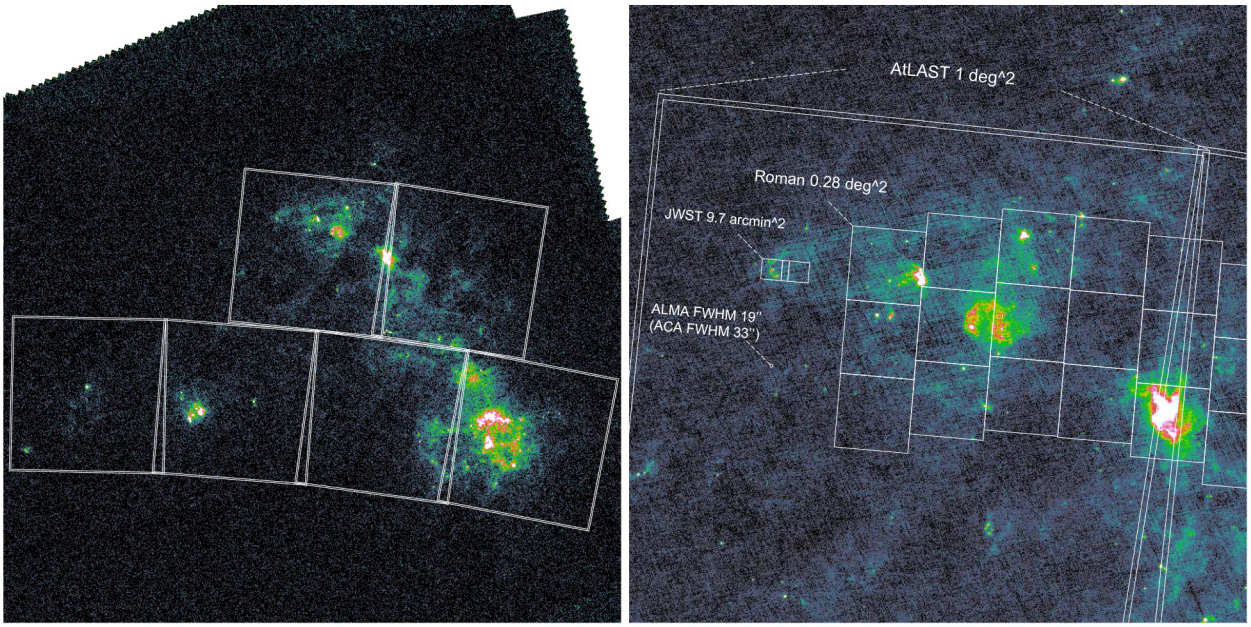

Figure 5. Similar to Figure 4 but for the SMC.

uses the dust parameters from Clark *et al.* (2023) to extrapolate the observed dust spectral energy from the *Herschel* HERITAGE survey (Meixner *et al.*, 2013) combined with Planck on large scales (Clark *et al.*, 2021) to AtLAST wavelengths and sampled at the AtLAST angular resolutions (Table 4). CMB fluctuations contributing on large scales were also added using the SMICA map from Planck data (Planck Collaboration *et al.*, 2020). From these maps, we find that the detection limit can be set by the faintest dust structures in the SMC bar region, which has flux densities of the order of 0.01 MJy/sr at 100 GHz (Band 3), to 0.25 MJy/sr at 400 GHz (Band 8) and 0.5 MJy/sr at 680 GHz (Band 9). Given the angular resolution of AtLAST at these bands, we can derive the RMS to achieve at least 3σ per angular resolution unit: which is 1.5 μJy/beam, 22 μJy/beam and 19 μJy/beam at 100 GHz, 400 GHz and 680 GHz, respectively.

Using the AtLAST sensitivity calculator, with a bandwidth of 32 GHz, elevation 45 deg, and H_2O percentiles of 70, 40 and 10 for the aforementioned bands, we obtain an on-source integration time of 27.0 h, 5.2 h, 28.5 h, respectively, for one pointing. The Band 8 observation (calculated at 400 GHz) has the best observing efficiency in terms of the significantly shorter integration time to achieve the detection limit. This is set by both the dust SED shape and the angular resolution at that frequency. Other bands are more time-consuming, but are still crucial to constrain the shape of dust SED at each position. To map the whole LMC and SMC, we need to multiply the above times by the number of pointings. Thus the total amount of on-source time will be about $\sim$ 2900 h. Spreading the observing time into multiple years, and in each year to obtain a full mapping of LMC and SMC, will be a wise option to ease the scheduling pressure and also to allow for transient studies (see companion case study by Orlowski-Scherer *et al.*, 2024).

This AtLAST LMC/SMC survey will eventually provide multi-band (e.g., 3 bands, from Band 3 $\sim$ 100 GHz to Band 9 $\sim$ 700 GHz) deep dust continuum mapping, with angular resolutions $\gtrsim$ 10× better than *Herschel* and $\gtrsim$ 4× better than APEX, with unprecedented sensitivity to diffuse emission that ALMA will completely miss, and with important frequency and spatial coverages not covered by *Herschel*, ALMA, APEX, LMT, etc.

Line observations The molecular gas in the LMC has (in an area-covering way) so far only been observed in CO main isotopologue lines, e.g., in the CO(1-0) line by Fukui *et al.* (1999, 2008) and Kawamura *et al.* (2009) with the NANTEN 4-m telescope at 40 pc (2.6′), and further at 11 pc (30″) by Wong *et al.* (2011) with the Mopra 22-m telescope for selected small regions (3.6 deg^2 in total). An on-going large survey with the APEX 12-m telescope targets the ^{12}CO(3–2) and ^{13}CO(3–2) lines at 5 pc resolution, aiming to cover 17.4 deg^2 or 13.3 kpc^2 (Grishunin *et al.*, 2024; Weiß *et al.*, 2023). Deeper and/or higher spatial resolution observations of CO and other tracers remain limited to individual pointings or small specific regions (e.g., Sawada *et al.*, 2018; Wong *et al.*, 2017; Wong *et al.*, 2022). The lack of contiguous, sensitive, high-resolution multi-line coverage of at least significant portions of the LMC and SMC, in order to sample the full range of environments they contain, is still a very important obstacle preventing us from understanding the physical and chemical structure of our neighbour low-metallicity galaxies.

Table 4. Angular resolution (AR) and maximum recoverable scale (MRS).

frequency	Band	AtLAST 50m	ALMA 43×12m AR/MRS		
		AR	C1	C3	C5
(GHz)		(arcsec)	(arcsec)	(arcsec)	(arcsec)
100	3 (84–116)	15.088	3.38/28.5	1.42/16.2	0.55/6.70
200	5 (163–211)	7.544	1.69/14.3	0.71/8.10	0.28/3.35
300	7 (275–373)	5.029	1.13/9.50	0.47/5.40	0.18/2.23
400	8 (385–500)	3.772	0.84/7.12	0.35/4.05	0.14/1.68
500	8 (385–500)	3.018	0.68/5.70	0.28/3.24	0.11/1.34
600	9 (602–720)	2.515	0.56/4.75	0.24/2.70	0.092/1.12
700	9 (602–720)	2.155	0.48/4.07	0.20/2.31	0.079/0.96
800	10 (787–950)	1.886	0.42/3.56	0.18/2.02	0.069/0.84
900	10 (787–950)	1.676	0.38/3.17	0.16/1.80	0.061/0.74

Notes: AR is naively calculated as 1.22 λ/D, which may slightly deviate from the AtLAST 50-m angular resolution in reality. ALMA (ACA) field of view: $\lesssim$ 0.08 ($\lesssim$ 0.24) arcmin^2 (single-beam receiver) vs. AtLAST field of view 1–2 deg^2 (large-format continuum camera or multi-beam receiver) at 300 GHz. ALMA collecting area: 43 × π × 6^2 ~ 4863 m^2 vs. ACA collecting area: 12 × π × 3.5^2 ~ 462m^2 vs. AtLAST collecting area: π × 25^2 ~ 1963 m^2. ALMA available time in the most-compact C1–C2 configurations for faint, diffuse emission: ~ 50 days vs. AtLAST available time: ~ 330 days. To recover the zeroth-*uv* data, namely "total power", the ALMA total power antenna 12m dish is 17× less sensitive than the AtLAST 50m dish when only considering the area difference.

We here outline prospects (and limitations) for possible line mapping surveys of the LMC and SMC with AtLAST. First, we describe a CO(3–2) survey that would correspond to the APEX ^{12}CO(3–2)/^{13}CO(3–2) survey of Weiß *et al.* (2023) and Grishunin *et al.* (2024), but 4× higher spatial resolution and an order of magnitude higher sensitivity. Such a survey would reveal CO-bright molecular gas in a much more complete way (including intrinsically faint structures as well as small features suffering from beam dilution if observed with poorer spatial resolution). It also serves as an illustration as to which extent extensive mapping of correspondingly fainter lines from other tracers will be possible. Second, we describe a survey in the neutral carbon [CI] lines at 492 and 809 GHz, which will be key in understanding the contribution of "CO-dark" molecular gas and atomic gas at the transition between the diffuse ionized ISM and molecular clouds. For the [CI] surveys we set the target sensitivity to be able to achieve 4-5 σ detections of a 0.1 K line brightness, as the [CI] lines detected by Pineda *et al.* (2017) and Bolatto *et al.* (2000a) are at levels of a few times 0.1 K (with line-widths of typically a few km/s).

Table 5 summarizes our example LMC/SMC line surveys in terms of the time that would be required to cover one square degree. For the "APEX-like" CO(3–2) survey, AtLAST (if equipped with a large multi-pixel heterodyne array) will provide mapping speeds comparable with contemporary facilities due to the combined effect of spatial resolution and field of view, but the resulting data will have an order of magnitude improvement in sensitivity and a factor of several in spatial resolution. Full cloud scale maps in a number of lines significantly fainter than the main CO lines will be possible, on scales ranging from the full galaxies down to about one parsec, i.e., the scales of clumps within clouds that are thought to form clusters or groups of stars.

At higher frequencies, aiming for lines such as the [CI] lines or higher-*J* CO lines, the situation is more challenging. It will still be possible to cover significant area at sufficient sensitivity in the brightest lines (particularly if observations can be spread over several observing periods) at moderately high frequencies (e.g., [CI] $^3P_1$–$^3P_0$ in ALMA Band 8). At even higher frequencies (ALMA Bands 9 and 10) observations will be restricted to partial coverage. In terms of [CI] $^3P_2$–$^3P_1$ observations (required to constrain the excitation conditions of the gas), we will likely need to adopt the observing strategy of targeting only regions where the $^3P_1$–$^3P_0$ line has been detected.

Table 5 also shows the time estimate for the [CI] $^3P_1$–$^3P_0$ 492 GHz line for three different values of the H_2O pwv percentile. While at the 10 and 20 percentile (corresponding to about 0.5 and 0.8 mm pwv, respectively, according to the documentation of the ETC) significant (multisquare degree) coverage is still feasible, this clearly becomes prohibitive at the 40 percentile level (corresponding to about 1.5 mm pwv). Going

Table 5. Telescope time needed to cover one square degree for the APEX CO(3-2) survey of Weiß *et al.*, (2023) (Weiß2023) using the 7-pixel LASMA receiver array, a corresponding deeper AtLAST survey at similar frequencies (AtLAST ^{13}CO), and higher frequency AtLAST [CI] surveys (assuming 1000 pixel heterodyne arrays on a 50 m diameter AtLAST). AtLAST telescope times were estimated using the AtLAST sensitivity calculator, assuming an elevation of 40° (accounting for the low declination of the LMC/SMC).

Survey	frequency (GHz)	resolution spatial/velocity	sensitivity 1 σ	pwv H_2O percentile	time/ square degree[a]
Weiß2023	345.8, 330.6	19″/0.5 km/s	200 mK		36.7 h
AtLAST ^{13}CO	330.6	4.6″/0.5 km/s	20 mK/38 mJy	40	~ 40 h
AtLAST [CI] $^3P_1$–$^3P_0$	492.16	3″/1.0 km/s	22 mK/40 mJy	20	~260 h
				10	~150 h
				40	~1000 h
AtLAST [CI] $^3P_2$–$^3P_1$	809.34	1.8″/1.0 km/s	22 mK/40 mJy	10	~1500 h

[a] All times are without any observational overheads

to a high and dry site, as AtLAST will, is absolutely mandatory if any significant sensitive coverage at these frequencies is to be achieved.

2.2 Extragalactic magnetic fields

2.2.1 Context and open questions. Cosmic magnetic fields are one of the most elusive forces in our Universe, even though their importance has become increasingly clear in all areas of astrophysics. Magnetic fields are one of the main regulators of local star formation efficiency (Krumholz & Federrath, 2019) and play a crucial role in the ISM dynamics in galaxies (Beck, 2015). They affect the transport of ionized gas, dust, and metals outward to the circumgalactic medium (CGM) via galactic outflows (Lopez-Rodriguez, 2023; Lopez-Rodriguez *et al.*, 2021a; Lopez-Rodriguez *et al.*, 2023; Thompson *et al.*, 2006), and they are central to the dynamics of cosmic rays (Rodríguez Montero *et al.*, 2023). B-fields are a crucial component in theoretical galaxy formation (e.g., Hennebelle & Iffrig, 2014; Hopkins *et al.*, 2023; Martin-Alvarez *et al.*, 2020; Moss *et al.*, 2000), with the new generation of numerical magnetohydrodynamical (MHD) simulations (e.g. Wissing *et al.* (2022)) posing magnetic fields and cosmic rays as alleviating forces for challenges such as matching the halo mass-stellar mass or mass-metallicity relations.

Magnetic fields in galaxies are thought to have originated as a weak seed during the early stages of the Universe (Subramanian, 2019; Widrow, 2002). These magnetic fields have to be amplified during galaxy formation to explain the observed $\sim \mu$G strengths in present-day galaxies (Beck *et al.*, 2020). Turbulence-driven dynamos are expected to be responsible for the generation of most of the magnetic energy required to reach these magnetic field strengths (Subramanian, 2019). Dynamos convert kinetic energy into magnetic energy. Mergers within the cosmic web trigger considerable star formation activity through starbursts. During these starburst phases, the magnetic fields of galaxies can be further enhanced via turbulent dynamos driven by stellar feedback such as supernova (SN) explosions. This generates tangled B-fields at and below the turbulent scale of approximately $< 50 - 100$ pc for SN feedback (Brandenburg & Subramanian, 2005; Haverkorn *et al.*, 2008). All of this leads to a theoretical scaling of $B_{\rm tot} \propto SFR^{1/3}$ in models of a galaxy dominated by SN-driven turbulence (Schober *et al.*, 2013). Thus, an amplification of the B-fields from the early universe to present-day galaxies is expected to be driven by star formation activity.

Most of our knowledge about magnetic fields in galaxies has been established using radio polarimetric observations in the 3–20 cm wavelength range (Beck, 2013). These observations trace the magnetic fields via synchrotron emission and Faraday rotation measurement arising from high-energy particles passing through a magneto-ionic ISM in the warm and diffuse phase of the ISM (Martin-Alvarez *et al.*, 2023). This method is widely used to measure the magnetic field strengths and directions in our Milky Way as well as nearby galaxies. Magnetic field strengths are estimated assuming equipartition between magnetic energy and cosmic ray electrons. Measuring the Rotation Measure (RM) requires at least three frequency bands with large frequency separations to accurately estimate the magnetic field direction along the line-of-sight (LOS). These remarkable efforts have shown that all spiral galaxies have kpc-scale ordered magnetic fields with an average strength of 5 ± 2 μG (Beck *et al.*, 2020). The total magnetic field strength, measured by synchrotron total intensity and assuming equipartition between the total B-field and total cosmic-ray electron density, is estimated to be $\sim 17\pm14$ μG (Beck *et al.*, 2020; Fletcher, 2010). However, these measurements have been performed at low resolution (>15″), which corresponds to a spatial scale of $\sim$ 300 pc at 20 Mpc, and tracing the warm ISM at vertical heights > 200 pc from the galaxy's

midplane, missing the information about the small-scale magnetic field closely related to the star formation activity. The SKAO will provide sub-arcsecond resolutions, thus enabling complementary high-resolution L-/C-band radio polarization studies, although the small-scale Faraday-rotation and Faraday-depolarization due to foreground clouds of diffuse thermal gas and magnetic fields can be very challenging to account for, for instance, the so-called "canals" in the maps of polarized intensity (e.g., Haverkorn & Heitsch, 2004; Haverkorn *et al.*, 2004).

Far-infrared/submillimeter polarimetry, on the other hand, observes the polarized thermal emission from magnetically aligned dust grains associated with the cold and dense phase of the ISM in galaxies. Elongated dust grains irradiated by starlight spin along the axis of their greatest moment of of inertia (i.e., the minor axis of the dust grain) producing a magnetic moment that aligns with the local magnetic field in the ISM. Thus, polarized thermal emission produce a measurable polarization with their position angle perpendicular to the local B-field. This technique has successfully traced the magnetic fields in more than a dozen nearby (<20 Mpc) galaxies (i.e., spirals, starbursts, dwarfs, mergers, active galactic nuclei) in the 53–250 μm using SOFIA/HAWC+ at resolutions of 4.8-18″ (90 pc - 1 kpc) (see most of the latest results from the SOFIA SALSA large survey; Borlaff *et al.*, 2023; Lopez-Rodriguez *et al.*, 2022b), as well as in starburst galaxies, M82 at 850 μm with the JCMT at a resolution of 15″ (277 pc) (Pattle *et al.*, 2021) and NGC 253 at 860 μm with ALMA at a resolution of ~ 0.3″ (5 pc) (Lopez-Rodriguez, 2023). FIR polarimetric observations of galaxies trace the magnetic fields as a density-weighted average within the beam size sensitive to the densest gas in the cold neutral phase of the ISM (Martin-Alvarez *et al.*, 2023). Specifically, SOFIA/HAWC+ observations trace FIR magnetic fields associated with dense, $\log_{10}(N_H[\mathrm{cm}^{-2}])$ = 19 – 23, and cold, T_d = 19 – 48 K, dusty, turbulent star-forming regions (those traced at FIR) and these are less ordered than those in the warmer, less dense interstellar medium (those traced at radio) (Borlaff *et al.*, 2023; Lopez-Rodriguez *et al.*, 2022b).

FIR polarimetric observations show that all spiral galaxies have kpc-scale magnetic fields spatially correlated with the molecular gas and with large angular dispersion (i.e., turbulent magnetic field) arising from the star-forming regions in the spiral arms (Borlaff *et al.*, 2021; Lopez-Rodriguez, 2021; Lopez-Rodriguez *et al.*, 2023; see examples in Figure 6). SOFIA/HAWC+ 154 μm observations of the Antennae, a merger system of two spiral galaxies, showed a circumgalactic medium permeated with a 9 kpc scale ordered magnetic field connecting both pair members (Lopez-Rodriguez *et al.*, 2023). This large-scale ordered magnetic field is not detected at radio wavelengths due to Faraday depolarization and the star formation activity in this region. In addition, FIR polarimetric observations are sensitive to the magnetic fields in the cold phase of the galactic outflows in starburst galaxies (Lopez-Rodriguez *et al.*, 2021a; Lopez-Rodriguez, 2023). Note that radio polarimetric observations suffer from the short lifetime of CR and Faraday rotation in the galactic outflows challenging the characterization

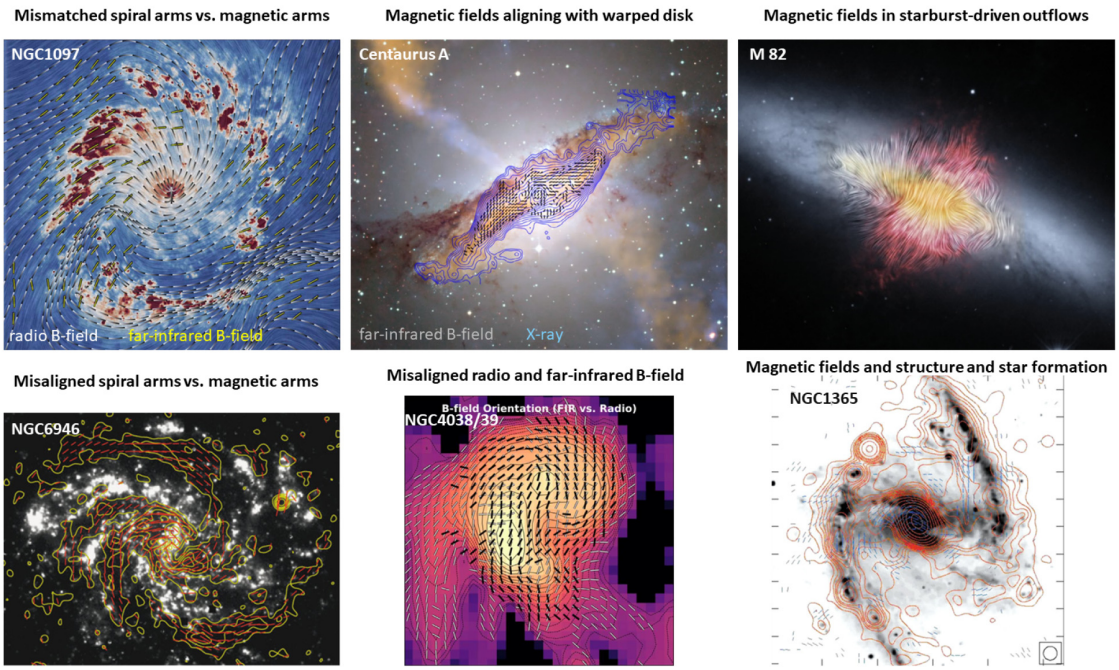

Figure 6. Magnetic fields in nearby galaxies and puzzling questions at a glance. Figures in the six panels from left to right and top to bottom are adapted from the following references: Lopez-Rodriguez *et al.* (2021b), Lopez-Rodriguez (2021), Lopez-Rodriguez (2023), Beck (2013), Lopez-Rodriguez *et al.* (2023) and Beck (2013), respectively.

of magnetic fields in starburst galaxies (Adebahr *et al.*, 2017). For M82, the magnetic field strength in the cold phase of the galactic outflow was estimated to be 305 ± 15 μG at a resolution of 90 pc (4.8") at 53 μm. This magnetic field was estimated to be 'open' into the CGM enriching it with dust metals and astrophysical magnetic fields amplified by supernovae explosions. The magnetic field strength was estimated using a modified version of the Davis-Chandrasekhar-Fermi (DCF) method (Chandrasekhar & Fermi, 1953; Davis & Greenstein, 1951). The original DCF was developed to measure the magnetic field strength for a steady state and uncompressible medium using the measurements of the gas velocity dispersion and the dispersion of the polarization angles. The modified DCF method includes large-scale flows and shearing to account of the several components in the galactic disk and galactic outflow (Guerra *et al.*, 2023; Lopez-Rodriguez *et al.*, 2021a). However, the low resolution observations achieved by SOFIA and JCMT impede the quantification of the magnetic energy in galaxies because the turbulent coherence length of the magnetic field is not resolved. Therefore, the energy budget in the ISM of host galaxies responsible for the gas dynamics and star formation history is still unknown, and the theoretical scaling of $B_{\rm tot} \propto SFR^{1/3}$ is still unconfirmed.

The FIR/submm polarized spectrum provides unique information about the properties of dust and physical conditions of the star-forming regions. In the Milky Way, the polarization spectrum of star forming regions has been observed to be wavelength dependent in the FIR/submm regime (e.g., Hildebrand *et al.*, 1999; Michail *et al.*, 2021; Vaillancourt *et al.*, 2008). This dependency is thought to arise from temperature gradients where only the warm silicate dust grains with high emissivity index embedded in the star-forming regions are aligned, while a colder component mainly following a black body emission is not aligned. Although dust models (e.g., Guillet *et al.*, 2018; Hensley & Draine, 2023) have been able to explain the polarized spectrum in the diffuse ISM of the Milky Way, these models do not reproduce the wavelength dependence of the polarized spectrum in regions of strong radiation fields in the Milky Way or nearby starburst galaxies. The diffuse ISM is characterized by a roughly flat polarized spectrum with a homogeneous mix of dust components. However, the strong radiation fields in star-forming regions can change the dust composition, dust grain sizes, and dust temperatures. In nearby starbursts, the unresolved gradient of temperatures and tangled magnetic field along the LOS makes the interpretation of the polarized spectrum very complex (Lopez-Rodriguez, 2023). However, the shape of the polarized spectrum has been shown useful to distinguish between disk- and starburst-dominated galaxies for unresolved polarimetric observations, and to characterize the dust composition on the cold phase of the galactic outflows. Multi-wavelength polarimetric observations are required to characterize the dust composition in the ISM of galaxies.

Thus, despite all these efforts so-far, we still do not fully understand how the measured B-fields in galaxies originated, are amplified, or are affected by star formation activity in galaxies. This is mainly due to the fact that radio wavelengths trace the warm ISM in a volume-filling medium and suffer from Faraday rotation and short lifetimes of cosmic rays in dense regions. The B-fields in the cold and dense ISM, where most of the mass and star formation reside, have been overlooked.

Even when SKA becomes available to map a large number of nearby galaxies' B-fields at (sub)arcsecond scales, we will still lack the crucial high-resolution far-infrared/submillimeter view of the magnetic fields. The ALMA interferometer can help us to achieve subarcsecond-resolution dust polarization imaging over square-arcminute scales, however, it is very inefficient in surveying a large number of galaxies, and more importantly, missing substantial diffuse ISM where magnetic fields play a crucial role. A complete view of magnetic fields in nearby galaxies, as a benchmark to understand distant Universe as well as ISM and MHD physics, is something AtLAST can uniquely deliver.

2.2.2 The role of AtLAST in the study of extragalactic magnetic fields. The concept for the AtLAST 50-m single dish submillimeter telescope (Mroczkowski *et al.*, 2024) has transformational capabilities for characterizing and understanding magnetic fields in our local Universe. First is its unprecedented survey speed for a large number (~ hundreds) of galaxies thanks to the large field of view. Nearby (< 20 Mpc) galaxies are typically tens of arcmin in diameter (except for the LMC/SMC and M31), which can be rapidly covered by AtLAST using a single pointing (~ 1 deg^2). Note that ALMA requires multiple pointings to cover a single galaxy making it very inefficient and even for the brightest galaxies, unfeasible (see Table 6). Second is its superb antenna collecting area and sensitivity to map the faint, diffuse dust emission in nearby galaxies and their circumgalactic media. This extended and diffuse emission is filtered out by interferometers. Third is its capability of observing the high-frequency multi-bands achieving

Table 6. Common extragalactic molecular/atomic lines.

Band	species & transition	rest-frame frequency	resolution
Band 3	HCN J = 1–0	88.632	17.0″
	HCO^+ J = 1–0	89.189	16.9″
	HNC J = 1–0	90.664	16.6″
	N_2H^+ J = 1–0	93.174	16.2″
	CS J = 2–1	97.981	15.4″
	$C^{18}O$ J = 1–0	109.782	13.7″
	^{13}CO J = 1–0	110.201	13.7″
	$C^{17}O$ J = 1–0	112.359	13.4″
	CN J = 3/2–1/2	113.491	13.3″
	CO J = 1–0	115.271	13.1″

Band	species & transition	rest-frame frequency	resolution
Band 4	$H_2CO\ 2_{1,2}–1_{1,1}$	140.840	10.7″
	CS J = 3–2	146.969	10.3″
Band 5	HCN J = 2–1	177.261	8.5″
	HCO^+ J = 2–1	178.375	8.5″
	HNC J = 2–1	181.325	8.3″
	N_2H^+ J = 2–1	186.345	8.1″
	CS J = 4–3	195.954	7.7″
Band 6	$C^{18}O$ J = 2–1	219.560	6.9″
	^{13}CO J = 2–1	220.399	6.8″
	$C^{17}O$ J = 2–1	224.714	6.7″
	CO J = 2–1	230.538	6.5″
	CS J = 5–4	244.935	6.2″
	HCN J = 3–2	265.886	5.7″
	HCO^+ J = 3–2	267.558	5.6″
	HNC J = 3–2	271.981	5.5″
	N_2H^+ J = 3–2	279.512	5.4″
Band 7	CS J = 6–5	293.912	5.1″
	$C^{18}O$ J = 3–2	329.331	4.6″
	^{13}CO J = 3–2	330.588	4.6″
	$C^{17}O$ J = 3–2	337.061	4.5″
	CS J = 7–6	342.883	4.4″
	CO J = 3–2	345.796	4.4″
	HCN J = 4–3	354.505	4.3″
	HCO^+ J = 4–3	356.734	4.2″
	HNC J = 4–3	362.630	4.2″
	N_2H^+ J = 4–3	372.673	4.0″
Band 8	CO J = 4–3	461.041	3.3″
	[CI] $^3P_1–^3P_0$	492.161	3.1″
(fainter lines omitted hereafter)			
Band 9	CO J = 6–5	691.473	2.2″
Band 10	CO J = 7–6	806.652	1.9″
	[CI] $^3P_2–^3P_1$	809.342	1.9″

Notes: Line frequencies are based on NRAO Splatalogue database. Angular resolution with AtLAST 50-m is naively calculated as 1.22 λ/D.

1.5–3″ resolution to resolve nearby (<20 Mpc) galaxies at giant molecular cloud scales (20–300 pc). These resolutions perfectly match existing and future large surveys of nearby galaxies at cloud scales (e.g., the PHANGS large program; Leroy *et al.*, 2021a; the EDGE-CALIFA survey; Bolatto *et al.*, 2017, etc.), which allows a comprehensive study of the multi-phase ISM and correlates the magnetic field with the gas flows in galaxies[7].

Taking full advantage of AtLAST in observing nearby galaxies at a few arcsecond resolution, the following key science questions will be eventually addressed (to name a few):

- How do magnetic fields affect star formation at cloud scales?
- Does the star formation efficiency correlate with the magnetic field strength?
- Is the magnetic field the support of supersonic turbulence in the ISM?
- What determines the diversity and evolution of magnetic field strengths among galaxies?

2.2.3 AtLAST surveys to map magnetic fields in nearby galaxies. In addition to their immediate scientific objectives, polarization studies will simultaneously provide very deep and multi-wavelength dust continuum observations. For example, to achieve an uncertainty of 0.3% in the degree of polarization a signal-to-noise ratio of ~ 500 in the total intensity is required. Therefore through polarimetric observations, deep dust continuum maps will be provided to the community to perform more general studies of dust emission and dust grain properties.

To enable significant statistics, a survey of dust polarization in over a hundred nearby galaxies with AtLAST 50m is needed. Note that each galaxy will be resolved at scales of 20 – 300 pc providing thousands of statistically independent polarization measurements that will be used to study trends between the magnetic field structure and strength with the star formation activity and gas kinematics in the disk of galaxies.

We assume a conservative polarization of 1% by means of magnetically aligned dust grains in resolved polarimetric observations of nearby galaxies, based on the thermal dust polarization in spiral galaxies at 53–220 μm (Lopez-Rodriguez *et al.*, 2022a) and that the polarization is roughly constant in the disk of galaxies in the 50–800 μm wavelength range (Lopez-Rodriguez, 2023). Star-forming regions show a wavelength dependence in the polarized spectrum in the FIR/submm regime with a minimum polarization of 1% in the 100 – 200μm range and increasing to ~ 4% at shorter and longer wavelengths. The shape of the polarized spectrum is still under active study as it provides unique information about dust properties and composition. Thus, in the following, we estimate the required observing time to map ~ 100 nearby

[7] We note that such a magnetic field study in nearby galaxies cannot be achieved with current ground-based mm and submm facilities. For instance, the JCMT SCUBA-2 DOWSING large program uses 240 hours to map the total unpolarized dust continuum in 21 nearby bright galaxies. To map the ~ 1% polarized dust, the observing time would be naively increased by a factor of 100^2 (see Section 2.2.3), but the spatial resolution cannot match that of AtLAST. The decommissioned SOFIA observatory was able to achieve a comparable spatial resolution at 1–2 THz but with much less sensitivity due to its limited antenna size.

galaxies at the fiducial frequencies of 230 GHz (Band 6), 345 GHz (Band 7), 460 GHz (Band 8), 690 GHz (Band 9) and 806 GHz (Band 10) with AtLAST 50-m.

To estimate the sensitivity requirements, we use as a reference the JCMT SCUBA-2 HASHTAG/DOWSING large programs which reach a rms noise level of ∼ 2.0 mJy/beam (0.41 MJy/sr) with a 13.5″ beam at 850 μm (Smith *et al.*, 2021). Given the large SCUBA-2 beam,it is expected that the dust emission filling factor is ≪ 1, resulting into a flux density that would be much higher when measured with the smaller AtLAST beam. We use the PHANGS-ALMA CO(2–1) 1″ imaging data (Leroy *et al.*, 2021b) of a typical spiral galaxy NGC 4321 (M 100) to estimate the beam filling factor. We smooth the CO moment-0 image to the 3.3″ AtLAST beam and to the 13.5″ SCUBA-2 beam, respectively, then examine the emission at the outer disk and find a beam filling factor of 0.2. Furthermore, considering a greybody dust spectral energy distribution of $S/S_{850\mu m} \propto \nu/\nu_{850\mu m}^{3.8}$, we can estimate an SCUBA-2-equivalent RMS 5.7 MJy/sr (∼ 4.5 mJy/beam) with the AtLAST beam at 460 GHz. In order to detect the 1% polarized dust emission, we need to go 100× deeper than the SCUBA-2 surveys with AtLAST. Thus an RMS of ∼ 16 μJy/beam is needed.

We use the AtLAST sensitivity calculator to estimate the required on-source integration time. Assuming a source elevation of 45 deg, observing frequency 460 GHz, bandwidth 32 GHz, single polarization sensitivity, and H_2O profile percentile of 20 (30), we need 28.6 h (47.3 h) onsource integration time per galaxy. Similarly, at 345 GHz and 660 GHz (RMS ∼ 10 μJy/beam and ∼ 31 μJy/beam), with 50-th and 20-th H_2O percentile, we need 18 h and 36 h on-source integration time, respectively. This sets the condition to detect the polarized dust emission across extragalactic disks like the HASHTAG/DOWSING sample, but is 100× deeper than JCMT. Luminous and ultra-luminous infrared galaxies ((U)LIRGs) are brighter than the HASHTAG/DOWSING spiral galaxies, and thus they require shorter observing times (integration time ∝ flux^{-2}) of order of a few hours. For a survey of roughly a hundred nearby galaxies including ∼10–20 spirals and ∼50–100 (U)LIRGs, the total on-source integration time will be about one to two thousand hours. A wider bandwidth and/or a multiband continuum camera will reduce the required observing time correspondingly.

2.3 Physics and chemistry of the interstellar medium

2.3.1 Context and open questions. The relationship between the cold ISM of galaxies and their star formation output is commonly studied and parametrised as the Kennicutt-Schmidt relation (KS relation; Kennicutt, 1989; Schmidt, 1959). This empirical relation links the star formation rate (surface) density to the total HI and H_2 gas (surface) density, through a power law with a measured index of $N_{KS,HI+H2} \sim 1.4$ across large samples of nearby galaxies (de los Reyes & Kennicutt, 2019; Kennicutt & De Los Reyes, 2021). This power index, however, is found to be about unity in tens of nearby spiral galaxies on resolved kpc-scales (Bigiel *et al.*, 2008; Leroy *et al.*, 2008; Leroy *et al.*, 2013; Schruba *et al.*, 2011; Wong & Blitz, 2002), with significant variations in both slope and normalisation of the relation at GMC scales and from galaxy to galaxy (Pessa *et al.*, 2021; Pessa *et al.*, 2022; Sánchez *et al.*, 2021). At high enough sub-kpc scales, the KS relation eventually breaks down, a feature that can be exploited to place constraints on important timescales in the star formation process (e.g. Chevance *et al.*, 2020b; Kruijssen & Longmore, 2014).

In addition to this range of physical scales, the KS relation can be studied in multiple gas tracers, each sensitive to a different phase of the ISM. For example, it is found that it is the H_2 (molecular) gas rather than the HI (atomic) gas that determines the linear KS relation, even in atomic gas-dominated regions (e.g. Schruba *et al.*, 2011). However, when considering the flaring disk scale heights, the volumetric gas density and star formation rate density are more strongly correlated in both atomic and molecular phases (e.g. Bacchini *et al.*, 2019). Furthermore, Gao & Solomon (2004) first found that the dense gas, as traced by high-dipole-moment molecules like HCN, linearly traces the star formation rate ($N_{KS,dense} \sim 1.0$), with fewer galaxy-to-galaxy variations. This may indicate that the denser phase traced by HCN is the fundamental unit where H_2 gas is turning into stars at a constant efficiency (Gao & Solomon, 2004; Gao *et al.*, 2007; Greve *et al.*, 2014; Lada *et al.*, 2010; Lada *et al.*, 2012; Liu *et al.*, 2015; Wu *et al.*, 2005; Zhang *et al.*, 2014).

Despite these breakthroughs, we are far from having a full picture yet. In the past ten years, Galactic observations of an even higher-critical-density molecule, N_2H^+, and observations of HCN and HCO^+ in our galaxy as well as in central regions of nearby galaxies have brought into question whether some of the most popular extragalactic dense gas tracers, HCN and HCO^+, are indeed tracing the highest-density gas as commonly assumed (e.g. Kauffmann *et al.*, 2017; Pety *et al.*, 2017; Tafalla *et al.*, 2023). Differences between the spatial distributions of N_2H^+ and HCN in individual galactic giant molecular clouds (GMCs), and the abnormally enhanced HCN in nearby galaxy centers (Bigiel *et al.*, 2016; Gallagher *et al.*, 2018a; Gallagher *et al.*, 2018b; Jiang *et al.*, 2020; Jiménez-Donaire *et al.*, 2017; Jiménez-Donaire *et al.*, 2019; Usero *et al.*, 2015) all suggest that the chemical abundances and excitation conditions are playing crucial roles.

Such results make it obvious that further progress requires moving away from single-line observations, in favor of deep, high resolution, multi-tracer and multi-transition observations, alongside sophisticated non-local-thermaldynamic-equilibrium (non-LTE) excitation and radiative transfer modeling (Leroy *et al.*, 2017; Leroy *et al.*, 2022; Liu *et al.*, 2021; Neumann *et al.*, 2023; Priestley *et al.*, 2023; Teng *et al.*, 2022; Teng *et al.*, 2023).

2.3.2 The role of AtLAST in probing the physics and chemistry of the ISM. Sensitive, large-area and high-resolution multi-species, multi-transition line observations of nearby galaxies are a critical resource for obtaining an accurate understanding of the ISM and star formation physics in nearby galaxies. What is also needed are large surveys that provide significant statistics over a broad range of galactic environments (see example in Figure 7), from low-density regions

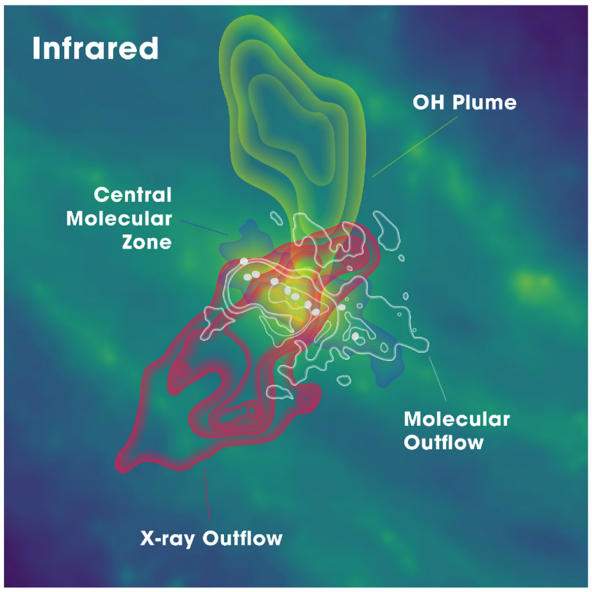

Figure 7. Artistic rendering (informed by real observations) of the key physical environments in the central kiloparsec of the nearest starburst galaxy NGC 0253 from Martín *et al.* (2021).

at the transition between the atomic and molecular phases, to giant star-forming complexes, and up to extreme environments such as circumnuclear regions, including gas exposed to radiative and mechanical feedback from starbursts and active galactic nuclei, and material affected by galaxy mergers.

Such a goal is impossible to reach with current facilities. First, spatially resolving multiple lines at physical scales of hundreds of pc or better is required to clearly distinguish physical processes that operate on a large range of spatial scales, from a hundredparsec cloud scales to kilo-parcsec sub-galactic scales (Schinnerer & Leroy, 2024). In the submillimeter wavelengths ($\nu \gtrsim 300$ GHz), where critical high-energy-level transitions of important molecules are found (see Table 6), the resolution from current submm single-dish telescopes (all ≤ 15 m in size) is insufficient[8]. Even the largest current millimeter telescope, the Large Millimeter Telescope (LMT), with an aperture of 50-m cannot come close to achieving the desired observations due to a lack of frequency coverage in the submm.

Secondly, the largest submillimeter interferometer, ALMA, has the sensitivity to achieve incredible multi-species, multi-transition observations, however, it has two severe limitations that will not be resolved even by planned upgrades: (1) extended emission is filtered out, and (2) ALMA has a very small field of view compared to the angular sizes of nearby galaxies (see Table 6). For example, the ALMA Cycle 5 large program ALCHEMI has conducted a comprehensive survey of spectral lines in Bands 3, 4, 6, and 7 at 1″ resolution in the nearest starburst galaxy, NGC 0253 (Martín *et al.*, 2021). Figure 8 shows how these observations reveal an astonishing number of spectral lines, from simple species all the way to complex organic molecules, but only within its central molecular zone (850 × 340 pc, see Figure 7), leaving a vast range of other galactic environments unexplored at such depth. Another important issue is the missing flux. Despite the large collecting area and sensitivity of ALMA's main array, the total power (TP) antennas with a diameter of 15m is less than one-tenth as efficient as a 50m antenna for scanning faint lines in a large sample of galaxies. Without adequate single-dish data, it has been demonstrated that missing flux can be severe for faint lines (e.g., Leroy *et al.*, 2021b; Liu *et al.*, 2023a), especially missing line flux at GMC edges and in inter-arm regions by more than 50% thus propagating to a huge error in line ratios. Figure 9 shows an example of missing extended flux when mapping a nearby galaxy with ALMA. In conclusion, because of the limitations listed above, ALMA is not the right instrument to expand a survey like ALCHEMI to many more galaxies (to reveal galaxy-galaxy variations), as it cannot recover the multi-line physics accurately at large scales.

AtLAST will uniquely enable such surveys of the multi-species, multi-transition molecular/atomic lines in hundreds of nearby galaxies, representing all kinds of galactic environments and thus physical mechanisms, at GMC/star-forming complex scales. ALMA will be highly complementary to achieving sub-cloud resolution in a limited number of targeted regions of interest. We summarize below some of the key science questions that can only be answered with AtLAST.

Is the gas-star formation relation universal? This question is fundamental in our understanding of star formation. The HERACLES (Leroy *et al.*, 2009), PHANGS (Leroy *et al.*, 2021a) and EDGE-CALIFA (Bolatto *et al.*, 2017; Sánchez *et al.*, 2021) surveys have achieved sub-kpc scale studies of the

[8] For instance, APEX 12-m and JCMT 15-m would only achieve ~ 250–300 pc resolution in the nearest starburst galaxy NGC 0253 at D ~ 3 Mpc at ν ~ 300 GHz.

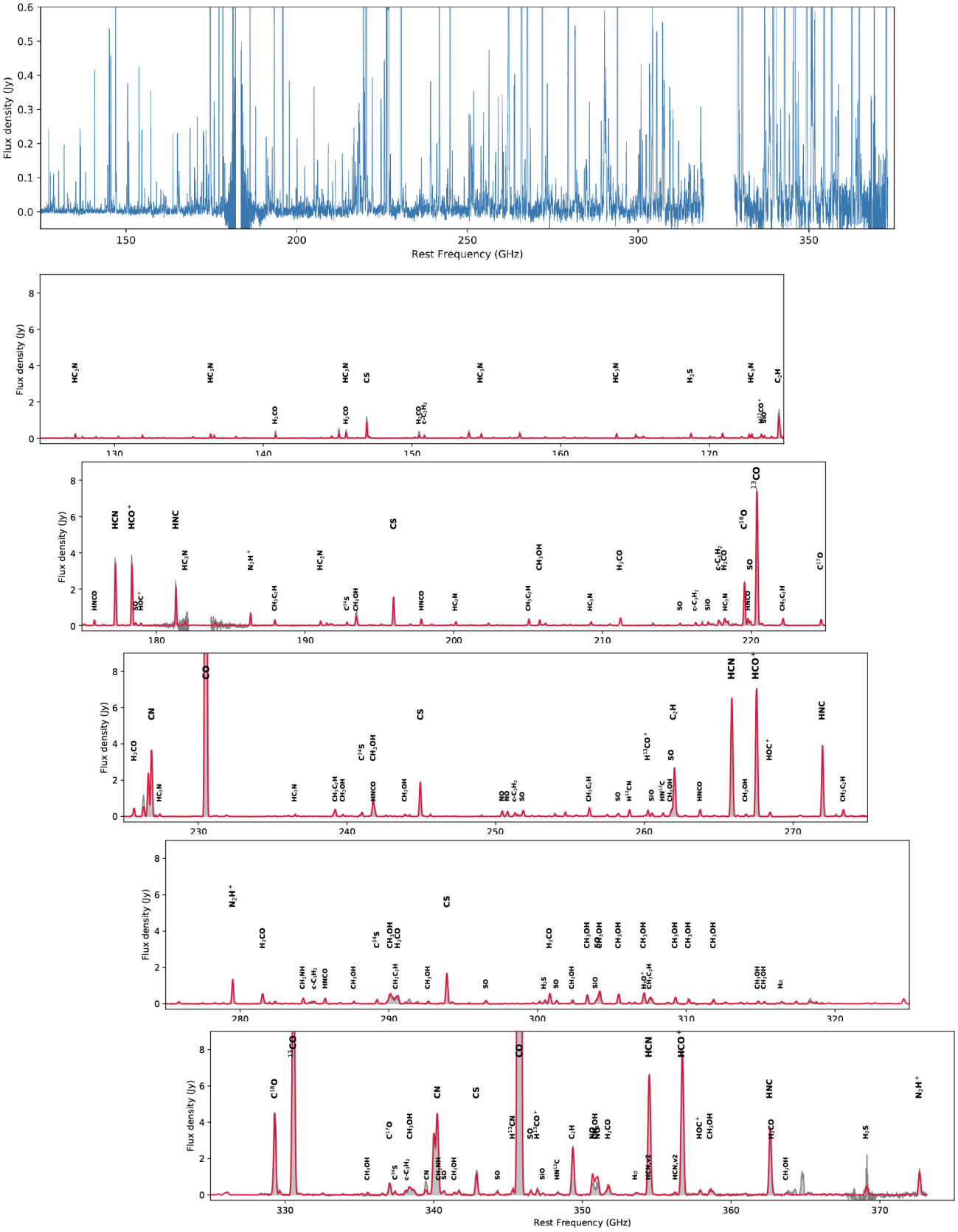

Figure 8. Spectrum of the central kiloparsec of the nearest starburst galaxy NGC 0253 from the ALCHEMI survey using the ALMA ACA 7-m array (Martín *et al.*, 2021).

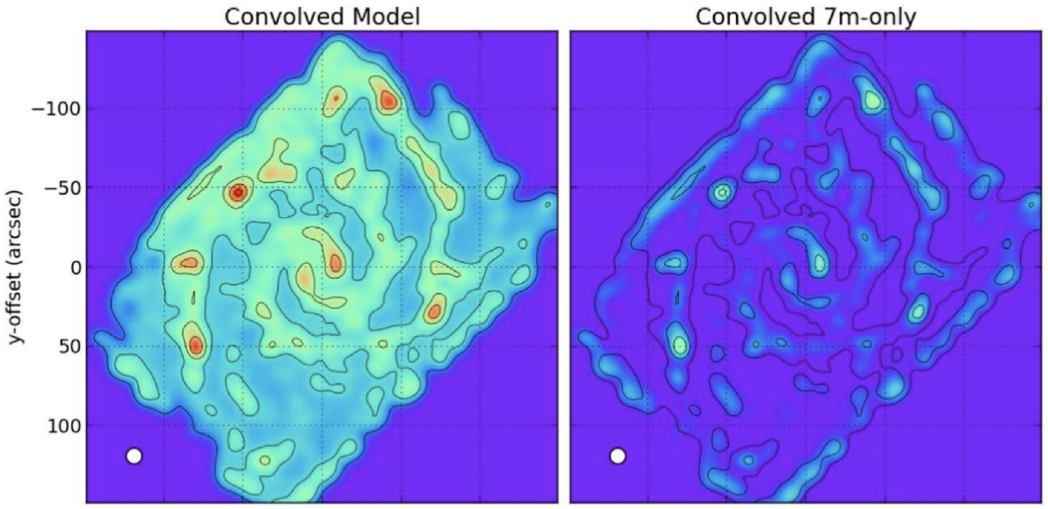

Figure 9. Figure from Leroy *et al.* (2021b) showing the effect of missing flux. The left panel shows a short-spacing corrected image of NGC 0628 in the CO(2-1) line, and the right panel shows a 7-m only cleaned image (i.e., without short-spacing correction using any TP data).

KS relation in a single $^{12}C^{16}O$ line in about a hundred nearby star-forming galaxies representing the local star-forming main sequence. The EMPIRE (Jiménez-Donaire *et al.*, 2019) and MALATANG (Jiang *et al.*, 2020; Tan *et al.*, 2018) surveys have achieved ≥ kpc-scale dense-gas KS relation studies in about ten IR-bright galaxies. However, the debate about the emissivity of dense gas tracers and the scatter in star formation efficiency at low densities are strongly limiting our theoretical understanding of the star formation processes. Is there a density threshold? Is local gas pressure playing a role? What drives the star formation efficiency / timescale variations? How well can we trust the surface mass densities from CO or HCN, using conversion factors? These are all related questions that need AtLAST's sensitivity, GMC-scale resolution, mapping speed and large field of view.

What are the gas densities and temperatures? Multi-transition non-LTE modeling of molecular/atomic lines is the most powerful tool to measure gas densities, temperatures and line excitation conditions for the multiphase gas in galaxies. Fifteen years ago, only very few galaxies had ground-based (sub)millimeter observations of the CO spectral line energy distribution (SLED) up to J = 6–5. The *Herschel* space observatory opened a new window to studying the CO SLEDs in over 160+ nearby galaxies (Greve *et al.* (2014); Kamenetzky *et al.* (2014); Kamenetzky *et al.* (2018); Kamenetzky *et al.* (2016); Kamenetzky *et al.* (2017); Liu *et al.* (2015); Lu *et al.* (2017); Rosenberg *et al.* (2015)), however, with ∼ 30–40″ resolution these observations do not resolve external GMCs. Moreover, the limited spectral resolution of the instruments on board the *Herschel* satellite prevents us from using these data to study spectral line profile variations in different H_2 tracers and CO transitions. The latter is a promising avenue for understanding the relation between extreme H_2 gas excitation and feedback mechanisms at play in galaxies, as shown by Montoya Arroyave *et al.* (2023) and Montoya Arroyave *et al.* (2024) using sensitive multi-J CO and [CI] APEX observations of tens of local (U)LIRGs.

High-resolution, multi-transition, multi-species non-LTE studies have only been made very recently in a few IR-bright galaxies using ALMA (e.g., CO isotopologues J = 1–0 to 3–2 Teng *et al.* (2022, 2023); CO J = 1–0 to 4–3 + [CI] $^3P_1$–$^3P_0$ Liu *et al.* (2023a, 2023b)). Also with ALMA, the PHANGS survey has mapped of order one hundred nearby galaxies in CO J = 2–1, but obtaining similar coverage of additional lines, e.g., CO J = 3–2, is still very time consuming given the small field of view and reduced atmospheric transmission at high frequencies. The ALMA studies are limited to a few galaxy centers, or a few off-center regions (e.g., like the GMC study in M83's XUV disk; Koda *et al.*, 2022), which do not probe the variety of galactic environments. Simulations and theory have shown that the emissivity of different species can vary significant with galactic environments, thus the conversion factors do vary accordingly. The gap from single-line conversion factor-based studies to multi-line non-LTE studies has to be filled in order to understand how gas density and temperature play a role across the star-forming disks/environments, and to anchor simulations and theories (e.g., photodissociation region, cosmic ray dominated region, X-ray dominated region and shock physics (Bisbas *et al.*, 2015; Bisbas *et al.*, 2017; Kaufman *et al.*, 1999; Kaufman *et al.*, 2006; Meijerink & Spaans, 2005; Meijerink *et al.*, 2007; Papadopoulos, 2010; Papadopoulos *et al.*, 2011; Wolfire *et al.*, 2022).

2.3.3 AtLAST surveys of multiple gas/dust tracers in the nearby Universe. A complete survey of multiple (sub)millimetre lines in a large number of galaxies at hundreds of parsec scales will enable unique studies of gas and chemistry in galaxies. The brightest (sub)millimetre lines are listed in Table 6, but

many fainter lines from species like HC_3N, HC_3HO, HOCN, $HOCO^+$ (Martín *et al.*, 2021) are also expected. The sample of nearby galaxies should include a variety of southern nearby galaxies. For main-sequence types, there are ~ 100 galaxies from the PHANGS-ALMA large program which have full-disk CO(2–1) line mapping at ~ 1″ (about 30–300 pc). This survey (the large program and a few pilot programs) used about a hundred hours of the ALMA main array and 600+ hours of ALMA ACA including the total power observations. The ^{13}CO(2–1) isotopologue line is observed simultaneously, but due to the limited sensitivity to the extended emission, only brightest clouds are imaged in high quality. AtLAST multi-line mapping of these galaxies will be an unprecedented legacy survey at moderately high resolution (~ 2–4″) starting from Band 7, or the CO(3–2) transition. The 3–2 transitions of CO isotopologues have been found crucially useful in determining the CO-to-H_2 conversion factors (Teng *et al.*, 2022; Teng *et al.*, 2023). The Band 8 CO(4–3) and [C I] lines are of great importance in constraining gas density and even possibly stellar and AGN feedback at resolved scales (Liu *et al.*, 2023a; Liu *et al.*, 2023b; Saito *et al.*, 2020). An ALMA ACA survey of the CO(4–3) and [C I](1–0) lines was conducted in 36 (ultra-)luminous galaxies at ~ 3″ (Michiyama *et al.*, 2021), leading to the finding of unusually low-[C I] galaxies which are still puzzling. However, the deep, multi-tracer single-dish APEX observations of local (U)LIRGs presented by Montoya Arroyave *et al.* (2023) include [CI](1-0) coverage for 17 sources (some of which in common with the ACA sample of Michiyama *et al.* (2021)) and show a significantly higher [CI] flux recovered by APEX, resulting in an average [CI](1-0)/CO(1-0) luminosity ratio as high as 0.210 ± 0.009 in local (U)LIRGs. The AtLAST survey of lines will be highly complementary to ALMA main array and ACA surveys which either have much higher resolution (and usually missing fluxes or would require hundreds of hours total power observing time) or only have the sensitivity to observe the most infrared-luminous starbursts.

We can consider a sample of 100 nearby galaxies with a variety of types:

- main-sequence spirals
- starbursts
- AGNs/composite galaxies
- dwarfs

and we observe the Band 6 (CO 2–1 isotopologue), Band 7 (CO 3–2), Band 8 (CO 4–3 and [C I] 1–0), Band 9 (CO 6–5), and Band 10 (CO 7–6 and [C I] 2–1) lines. In each Band, we assume that the receiver has sufficient bandwidth to cover all the key lines simultaneously, that is, ~ 16–20 GHz per sideband for a double-sideband receiver. We also require a multi-beam receiver or integral field unit (IFU) to efficiently map the galaxies. While both multi-beam receiver and IFU achieve a high mapping efficiency thanks to focal-plane multiplexing, multi-beam receiver uses superconducting heterodyne technique thus usually has a much higher spectral resolution than an IFU using superconducting kinetic induced detectors (KIDs). This spectral resolution capability is essential to spectral line science. In comparison, the large-format camera proposed for previous science cases has no spectral resolution thus is only for dust continuum science (but is sensitive to faint polarized signal). In the case of a multi-beam heterodyne receiver, assuming a 919-beam (18-layer) array, as shown in Figure 10, a galaxy like NGC 3627 at a

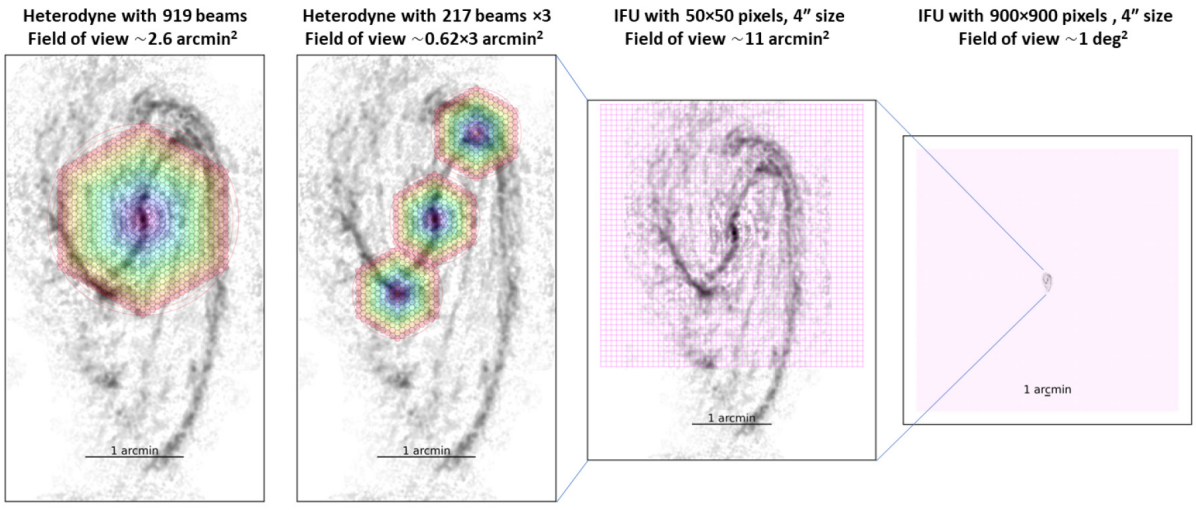

Figure 10. Footprints of various assumed instruments (from left to right): a 919-beam (18-layer) heterodyne receiver, a 217-beam (9-layer) heterodyne receiver, an IFU with 50 × 50 pixels, and an IFU with 900 × 900 pixels, on top of the nearby galaxy NGC 3627's CO(2–1) emission (Leroy *et al.*, 2021a). The heterodyne receiver's hexagon units and the IFU pixels are assumed to have a spacing/size of 4″, which is about the AtLAST 50-m angular resolutions at Band 7–10, and is about half of the angular resolutions at Band 4–5. A large-format IFU as shown in the last panel can most efficiently observe multiple galaxies, with each galaxy fully sampled at resolutions as shown in the first three panels.

distance of ~ 11 Mpc will be covered by roughly ten pointings. For slightly more distant local galaxies like those in the EDGE-CALIFA or MaNGA samples, fewer pointings are needed. In the case of an IFU, the field of view is much larger, allowing for these nearby galaxies to be covered in one pointing, but the spectral resolution is much lower, of only ~ 300–3000 km/s (R ~ 100–1000). Our survey of line ISM physics do not strongly require resolving the lines, but require accurate integrated line fluxes and ratios, therefore an IFU with a spectral resolution $R \gtrsim 1000$ will be more efficient than a multi-beam receiver (although a multi-beam receiver will enable kinematic studies that would add additional value).

Then, we estimate the line fluxes and sensitivity requirements. Taking NGC 3627 as an example (Figure 10), its CO(2–1) surface brightness ranges from $\gtrsim$ 1000 K km s^{-1} to ~ 30 K km s^{-1} at ~ 8 kpc away from the center along the spiral arm. The peak temperature ranges from ~ 8 K to ~ 1 K from the center to the ~ 8 kpc arm. The ^{13}CO lines are in general ~ 10× fainter than the ^{12}CO lines (e.g., Cao *et al.*, 2023; Cormier *et al.*, 2018; Henkel *et al.*, 2014; Jiménez-Donaire *et al.*, 2017; Taniguchi & Ohyama, 1998; Wilson & Rood, 1994), and the [C I](1–0) lines are generally ~ 5–10× fainter than ^{12}CO(2–1) (Liu *et al.*, 2023a). The ratios of CO(1–0) line fluxes to those of HCN and HCO$^+$ 1–0 are typically ~ 30–100 at resolved kpc scales (Bigiel *et al.*, 2016; Gallagher *et al.*, 2018a; Gallagher *et al.*, 2018b; Jiménez-Donaire *et al.*, 2019; Neumann *et al.*, 2023). Thus, in general we will need to reach an RMS of ~ 0.1 K km s^{-1} to achieve S/N $\gtrsim$ 3 detections for all the aforementioned lines. Given a line width of ~ 30 km s^{-1} and the AtLAST beam of 2″–7″ from Band 10 to Band 6 (Jy/K ~ 1.5–2), this RMS corresponds to ~ 5–7 mJy at these bands.

Using the AtLAST sensitivity calculator, we compute that at an elevation of 45 deg, an observing frequency 230/345/461/492/691/809 GHz, with a bandwidth of 0.023/0.035/0.05/0.05/0.07/0.08 GHz (~ 30 km s^{-1}), and an H_2O profile percentile 80/80/50/50/20/20, the on-source integration time will be ~ 1/10/24/84/25/60 minutes. Thus the expected typical on-source observing time is only ~ 3.5 hours for all the major Band 6–10 lines in one pointing in a galaxy like NGC 3627. The full survey of ~ 100 nearby galaxies with one IFU pointing (or multiple pointings with multi-beam heterodyne receiver) for each galaxy will be at scales of hundreds to a thousand hour.

2.4 An "SDSS-like" submillimeter survey for galaxy evolution studies in the nearby Universe

2.4.1 Context and open questions. The evolution of galaxies is a fundamental question and a complex process in astrophysics. The amount of cold gas, the rate of star formation, and the environment of galaxies all play a critical role in shaping galaxy evolution. How the cold gas is accreted into galaxy systems, how the star formation is set by the turbulent ISM properties, and how the gas and dust are influenced by the external gravitational forces in dense environments are all key processes demanding detailed understanding with large-sample surveys. While millions of galaxies have been observed in optical spectroscopic surveys such as SDSS and more recently DESI, only hundreds of them have constraints on the molecular gas reservoir — thus leading to a giant gap in our knowledge of galaxy evolution (Liu *et al.*, 2019; Saintonge *et al.*, 2011; Saintonge *et al.*, 2017; Saintonge & Catinella, 2022; Tacconi *et al.*, 2018; Tacconi *et al.*, 2020). An extra-large submillimeter survey in the local Universe will be a substantial breakthrough. It will help bridge the gap with optical, near-infrared (e.g., *Euclid*, LSST, *Roman*), and radio (e.g., with the SKA) surveys, which would otherwise become even greater. Extending galaxy samples with molecular gas measurements by orders of magnitude will lead to the most important statistical understanding of cold gas and star formation, and environments and galaxy quenching. Possibly tens of thousands of molecular line detections could be achieved with an "SDSS-like" survey with AtLAST, highly complementary to the atomic gas surveys with the future SKA.

The statistical properties of the molecular ISM gas in low-mass ($M_\star \lesssim 10^9$ M$_\odot$) galaxies is one of the major unknowns in galaxy surveys. Low-mass galaxies have sub-solar metallicities and correspondingly low CO abundance compared to the H_2. With less dust shielding, radiation fields created by the young massive stars are in general stronger and harder. Many low-mass galaxies are also satellites of massive galaxies, e.g., the LMC and SMC as described in Section 2.1. The xCOLDGASS survey (Saintonge *et al.*, 2011; Saintonge *et al.*, 2017) is the largest millimetre CO survey of local galaxies with the IRAM 30 m telescope. This survey has been able to constrain the local-Universe CO luminosity distribution down to $10^{7.5}$ K km s^{-1} pc^2 (or a stellar mass limit of $10^{9.0}$M$_\odot$). The CO luminosity function (and the consequent H_2 mass function) in the local universe is a important tool in constraining models (e.g. Vallini *et al.*, 2016) and anchoring studies of the redshift evolution of gas reservoirs (e.g., Dessauges-Zavadsky *et al.*, 2020; Liu *et al.*, 2019; Walter *et al.*, 2020). The scaling relations between molecular gas mass and other global galaxy properties (stellar mass, SFR, morphology,...) are also proving to be very constraining for hydrodynamical simulations (e.g. Davé *et al.*, 2020). Despite all these successes, with only ~ 1000 galaxies, combining xCOLDGASS and other similar surveys (Boselli *et al.*, 2014a; Cicone *et al.*, 2017; Colombo *et al.*, 2020; Wylezalek *et al.*, 2022), we can only scratch the surface, as significantly more statistics are required to disentangle the competing effects of different evolutionary mechanisms. It is particularly crucial to improve statistical constraints of the H_2 content of low-M_* galaxies, not only because these are the most common galaxies in the Universe, but also because including these sources allows us to expand the dynamic range of current scaling relations and so as to provide more reliable constraints for theoretical models, as shown by pilot studies using ~ 330 hours of APEX observations (ALLSMOG survey: Cicone *et al.*, 2017; Hagedorn *et al.*, 2024).

Due to these sample size limitations, current surveys are unable to accurately quantify the impact of large-scale environment and the position of a galaxy with respect to the cosmic web on the molecular ISM. In addition, compared to low-mass galaxies in the field, those in dense regions are experiencing both secular evolution and environmental processes which are not

fully understood. We know from HI observations that galaxies in dense regions (such as clusters) generally have a reduced atomic gas content and star formation activity, compared to their counterparts in low density environments (e.g. Haynes & Giovanelli, 1986). For example, Figure 11 shows an example of stripping of HI gas in a galaxy infalling into the Virgo cluster. A range of mechanisms, from gravitational interactions to hydrodynamic processes, can explain the impact of the dense cluster environment on the HI contents of galaxies. What is still not totally understood is their effect on the molecular gas component, as molecular gas is much more embedded into the gravitational potential of the disc and mainly located within giant molecular clouds, which means it is much less sensitive to external perturbations than the atomic phase (e.g., Boselli *et al.*, 2014b; Boselli *et al.*, 2022; see also recent APEX and ALMA studies from the GASP survey; Bacchini *et al.*, 2023; Moretti *et al.*, 2020).

An extra-large survey of > 10,000 local galaxies to measure accurate molecular gas masses, especially if extending the coverage of current surveys into the dwarf galaxy regime ($M_* < 10^{9.0}\,M_\odot$) and covering the full range of extragalactic environments, from field to clusters, is the only approach to achieve the statistics required to address several important questions in galaxy evolution, such as those described below.

2.4.2 The role of AtLAST in the study of the local galaxy population. AtLAST is ideally suited to shed light on these important topics. Thanks to its high sensitivity and large field of view, it can be used to map in a blind survey a sufficiently large fraction of the nearby sky to measure with unprecedented sensitivity and statistics the molecular gas mass function of galaxies in the local Universe for objects located in different density regions, from voids and filaments to groups and massive clusters.

What is the abundance of molecular gas in the local Universe and its distribution? The molecular gas mass function is a very useful constraint to semi-analytic models and cosmological simulations (e.g. Davé *et al.*, 2020; Diemer *et al.*, 2019; Lagos *et al.*, 2015). Like for atomic gas, where large blind HI surveys have allowed for accurate measurement of the HI mass function in the local Universe (Jones *et al.*, 2018), we can eventually have a deep and complete census of molecular gas in the nearby Universe with AtLAST. Therefore, a key next step is largely improving the constraints on the $z = 0$ molecular gas mass functions which have been exclusively based on optically- or IR-selected samples (e.g. Andreani *et al.*, 2020; Fletcher *et al.*, 2021; Keres *et al.*, 2003). AtLAST is the only facility which would enable a blind survey for molecular gas in the nearby Universe, which

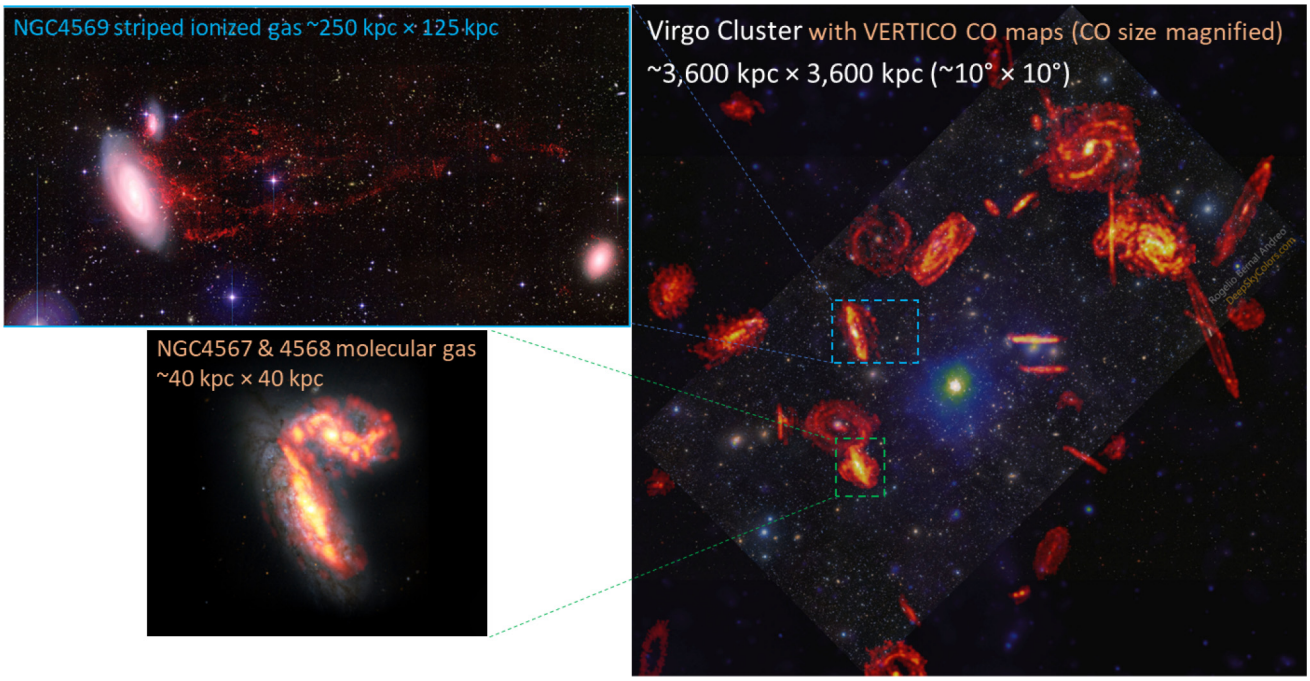

Figure 11. The right panel shows the Virgo cluster's optical and CO images from the VERTICO ALMA large program (Brown *et al.*, 2021, see the website) and the Astronomy Picture of the Day. The CO maps of each individual member galaxies are scaled up for visualization. The top left panel is adapted from Boselli *et al.* (2016) and Boselli *et al.* (2022), showing the very extended stripped materials from the Virgo cluster member galaxy NGC 4569. The image size is 50′ ×25′ or 250kpc×125kpc. The red image shows the stripped ionised gas extending up to 150 kpc. The bottom left panel is adapted from Brown *et al.* (2021), showing the cluster members NGC 4567 and NGC 4568. The Virgo cluster extends at least 10° × 10° in the sky.

is essential to anchor the all important studies of the redshift evolution of the baryonic mass of galaxies and their star formation output (e.g. Walter *et al.*, 2020).

Molecular gas scaling relations in the dwarf galaxy regime The first large systematic molecular gas surveys of the past 15 years, both at low and high redshifts, have been transformational in our understanding of the central roles of the baryon cycle and star formation efficiency in the galaxy evolution process (e.g., Carilli & Walter, 2013; Gao & Solomon, 2004; Kennicutt, 1998; Leroy *et al.*, 2008; Leroy *et al.*, 2021a; Saintonge *et al.*, 2011; Saintonge *et al.*, 2017; Tacconi *et al.*, 2018). With these surveys, we now have a good overview of the basic scaling relations between total molecular gas mass and other galaxy observables (e.g., de los Reyes & Kennicutt, 2019; Kennicutt & De Los Reyes, 2021; Tacconi *et al.*, 2020), but only in relatively massive galaxies ($M_* > 10^{9.5}$M$_\odot$). A key next step is systematically surveying CO and other species in lower mass galaxies (e.g. ALLSMOG, Cicone *et al.*, 2017). With the increased sensitivity of AtLAST and improved survey strategies enabled by its very large field of view (see Section 2.4.3), it will be possible to expand molecular gas scaling relations well into the regime of dwarf galaxies ($M_* < 10^9$M$_\odot$), either through direct line detection or stacking of the many undetected objects that would be covered by a blind CO line survey.

Why do galaxies stop forming stars? This question, often referred to as "star formation quenching", is central to our understanding of galaxy growth, and as of yet remains unanswered. A galaxy can stop forming stars if it runs out of cold gas, or if any cold gas it has is some-how prevented from forming stars. All the physical mechanisms that are invoked to explain quenching work by either affecting the gas contents of the galaxies, or the star formation efficiency out of any available gas. Therefore, only by having direct information about the cold atomic and molecular gas mass of galaxies can we accurately pinpoint the mechanisms that are causing star formation activity to shut down. Current evidence suggests that both a reduction of gas reservoirs and a decrease in star formation efficiency are at play (e.g. Colombo *et al.*, 2020; Saintonge & Catinella, 2022), but the sample size limitations are currently preventing us from understanding why these changes are happening. AtLAST will enable the assembly of a sample of $\sim 10^5$ galaxies with CO detections (two orders of magnitude more than current samples, see Section 2.4.3) which will finally allow us to disentangle the complex physical processes behind star formation quenching.

2.4.3 AtLAST surveys to probe star formation and galaxy evolution in the nearby Universe. The primary goal of this survey is to detect CO lines in a significantly large sample that is a factor of > 10–100 × larger than any existing survey in the local Universe. This consists of two types of targets: a mass-complete sample of field galaxies in the local Universe (e.g., redshift $z \sim 0.01$–0.38, or distances $\lesssim 2,000$ Mpc, and a stellar mass limit $\sim 10^{8-9}$ M$_\odot$);); and a sample of (super)clusters for the dense environments.

The field targets will naturally be drawn from on-going and future large optical/near-infrared and radio H I surveys, for example, the Dark Energy Survey (DES) and the LSST in the southern hemisphere. The sample selection will follow the COLDGASS and xCOLDGASS strategy but have great improvements in the volume completeness. As mentioned in Section 2.4.1, the COLDGASS and xCOLDGASS IRAM 30-m large programs randomly trim a large, mass-complete, H I-detected sample from the GALEX Arecibo SDSS Survey (GASS; Catinella *et al.*, 2010; Catinella *et al.*, 2013) down to a few hundred galaxies for the CO observations. The final combined sample is 532 galaxies with a total of ∼ 950 hr of IRAM 30-m observing time. The receiver has a single beam thus the field of view of each IRAM 30-m observation is limited to ∼ 22″ at 115 GHz and ∼ 11″ at 230 GHz. With a large-format submillimeter IFU taking advantage of AtLAST's very large field of view, surveys on unprecedented scales will become possible. We boldly assume that an expensive, large-format IFU can be build to fill about 1 deg^2 field of view on AtLAST, with a bandwidth of 32 GHz and a spectral resolution of R~1000 (~40 km/s at 230 GHz). This requires a spaxel unit separation of 4″ to achieve a Nyquist sampling of the ~7″ beam at 230 GHz, that is, a KID pixel array of 900 × 900 and channel number ~1000 along the third dimension. The cost scales up quickly with the number of KIDs, that is, 3D spaxel units. Under this assumption, each targeted observation at a selected galaxy will have an 1 deg^2 field of view to allow for detections of CO line emitters in the vicinity. According to our best constraint of the CO luminosity function so far (Fletcher *et al.*, 2021; Saintonge *et al.*, 2017), we predict that with 30 min on-source integration of the IFU, the number of CO line emitters will be as large as ∼ 150 in a single 1 deg^2 field of view as shown in Figure 12 (this estimate assumed metallicity-dependent conversion factors, see Figure 12 caption). Observing the CO(2–1) line will achieve more galaxies per redshift bin and a much lower M_{H_2} mass limit. Therefore, it is better than observing the CO(1–0) line for studying the faintest galaxies. If we observe a southern xCOLDGASS-like mass-complete sample of ∼ 500 primary targets, each with 30 min on-source integration with the IFU, then we will eventually obtain a combined sample of 500 × 150 ∼ 75, 000 galaxies at $0 < z < 0.16$ (i.e., out to a distance of 200 Mpc) with > 5σ CO(2–1) detections. The exact number depends on the actual CO luminosity distribution to be measured and may vary by a factor of a few, but this is truly transformational compared to any existing CO surveys.

In the dense environments, our (super)cluster targets should contain a statistically significant number of galaxies in the densest parts of our local Universe such as those located in the Coma/A1367 supercluster (e.g. Gavazzi *et al.*, 2010). This particular region of the sky includes ∼ 4000 objects down to the SDSS *r*-band mag 17.7 at a typical distance of 70–100 Mpc over ∼ 400 square degrees, with galaxies located in two rich clusters (Coma and A1367), in several groups and filaments, and in voids. It is in the northern hemisphere though (Dec ∼ +19). Another widely-studied cluster, the Virgo cluster, is also in the north (Dec ∼ +12), spreading over 100–200 deg^2

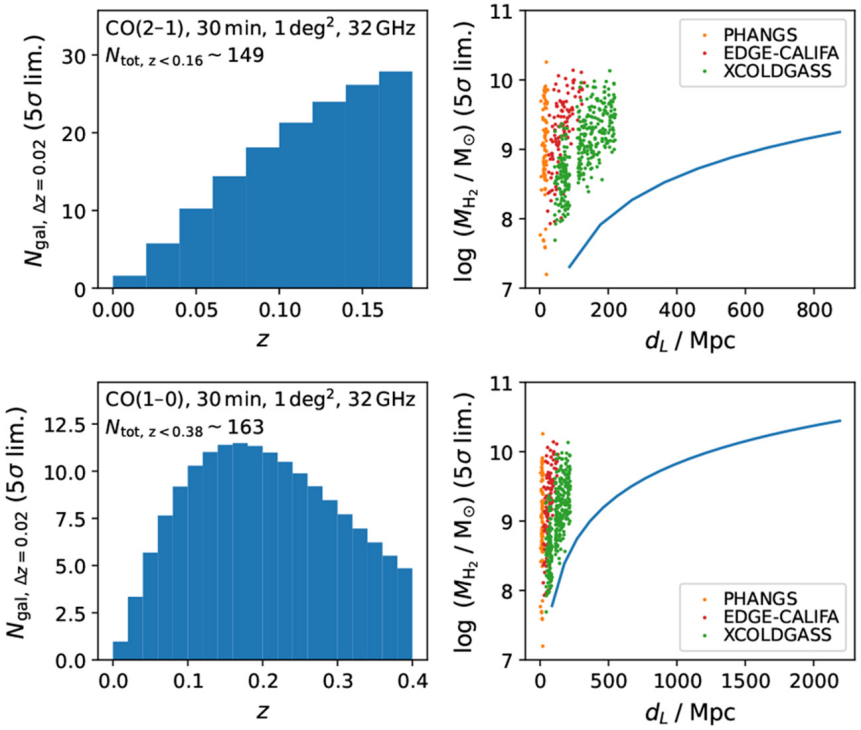

Figure 12. Predicted numbers of CO emitters in an 1 deg² field of view for 30 min on-source integration with the Band 3 CO(1–0) line (lower panels) and with the Band 6 CO(2–1) line (upper panels). With a bandwidth of 32 GHz, the CO(1–0) line frequencies are ~ 115–83 GHz, corresponding to $z \sim 0$–0.38, Similarly, for the CO(2–1) line the frequencies are~ 230–198 GHz, corresponding to $z \sim 0$–0.16. The numbers of CO emitters are calculated by integrating the CO luminosity distribution in (Saintonge *et al.*, 2017, see their Figure 6) from the 5σ detection limit L'_{CO} to 10^{11} K km s^{-1} pc^2. **Left panels** are the predicted numbers of CO emitters per redshift bin of $\Delta z = 0.02$ for CO(2– 1) and $\Delta z = 0.01$ for CO(1–0). The total predicted CO detections above 5σ are ~ 150–160 for the CO(2–1) and CO(1–0) lines. **Right panels** are the molecular hydrogen mass M_{H_2} detection limit computed from the 5σ L'_{CO} detection limit using a metallicity-dependent α_{CO} conversion factor following Bolatto *et al.* (2013). A half-solar metallicity is assumed for the M_{H_2} limits, and a CO(2– 1)/(1–0) brightness temperature ratio of 0.8 is assumed for the excitation.

in the sky with over 1300 member galaxies. To facilitate the observation at the AtLAST site, southern (super)clusters can be selected from the Abell *et al.* (1989) catalog, where over 4000 clusters are listed and each has at least 30 member galaxies. The AtLAST's unprecedented sensitivity to the extended emission will make the survey of nearby galaxy clusters not only for counting galaxies number densities and luminosity function, but also for mapping any possible stripped gas at tens of kpc scales (Figure 11). If a gas-rich satellite galaxy has 50% of its gas stripped, then an extended gas structure of a mass $M_{gas} \sim 10^8 M_\odot$ will be spread over tens of beams. Our detection limit of 30 min on-source integration is already $\sim 2 \times 10^7$ $M_\odot$ (for CO-traced H_2 gas at 0.5 $Z_\odot$) out to ~ 100 Mpc, thus it is very promising for AtLAST to open a new era for studying the extended stripped gas structures in clusters. These cluster observations can be much deeper than the field galaxy observations, as they require fewer pointings.

Combining the field and cluster CO surveys, this will provide us with an unrivaled sample of 10^5 CO emitters in the local Universe, enabling the transformative science depicted above. Such a survey will require 500 hours for the field galaxies and another 500 hours for the clusters, including calibration and telescope overheads, covering ~ 500–1000 deg² areas. Since the observations are done in Band 6, the observing time is not very sensitive to weather conditions and therefore such a survey could make good use of time in poor weather conditions. In the calculation for this survey, we assumed a water vapour percentile of 85 and 95 for the Band 6 and Band 3 sensitivity estimates using the AtLAST sensitivity calculator. We also assumed line widths of 200 km/s, which is 0.16 GHz and 0.073 GHz at Band 6 and Band 3, respectively.

3 Technical requirements for AtLAST

3.1 Multi-band dust continuum with polarimeter

A continuum camera with polarimeter is a key requirement to achieve the science objectives. While not essential, a multi-chroic camera would significantly increase the efficiency of observations and therefore is favored by the science users who want to increase the sample sizes in a fixed survey time.

The bandwidth of the continuum camera is a key parameter for determining the sensitivity of an observation, with wider bandwidths preferred. For the calculations in this white paper

we have assumed a conservative 32 GHz bandwidth, but larger bandwidths will likely be technically possible across most bands (for example, SCUBA-2 bandwidths are ~40–50 GHz, as limited by the atmospheric transmission windows available and filter transmission curves)[9].

A large field of view is needed for the continuum camera to facilitate our science cases. It is anticipated that the first-generation continuum camera can have a 1 deg^2 field of view, significantly larger than current instruments (e.g., ~ 13 arcmin^2 for TolTEC or ~8 arcmin^2 for SCUBA-2). With an angular resolution of 15″ to 1.6″ from Band 3 to Band 10 (Table 6), this means a camera would require at least a 2000 × 2000 pixels to sample the point spread function by a factor of $\gtrsim$ 1–8. Alternatively, the mapping needs could be met with a sparser array with ~ 10^6 pixels that undersamples the point spread function and a scanning or 'jiggle' observing strategy. A large field of view will also be crucial for observing emission on large spatial scales. Filtering of the variable sky-background emission will restrict the sensitivity to scales at most as large as the field of view (while not requiring fully sampled arrays).

3.2 Submillimeter integral field spectrograph

A submillimeter IFU will be a remarkable game-changer for large-area surveys. A high spectral resolution of $R \gtrsim 1000$ is needed in order to separate lines. A field of view of 1 deg^2 with a spaxel spacing of about 4″ will be critical for the mapping speed and Nyquist sampling of the beams. This means an IFU pixel array of ~ 900×900, and a channel number of 1000. A bandwidth of at least 32 GHz is required for the aforementioned surveys. Equipping AtLAST with IFUs at each of Band 6 (198–230 GHz) and Band 3 (83–115 GHz) will be complementary and give maximum flexibility to accommodate varying weather conditions.

3.3 Multi-beam heterodyne spectrometer

For the nearby galaxy spectral line survey (Section 2.3), in the case where a high spectral resolution ($R \gtrsim 1000$) IFU is unavailable, a multi-beam heterodyne will be critical to achieve the goal of submillimeter line survey in nearby galaxies. As shown in Figure 10, the number of beam units is important to reduce the required observing time to cover the whole galaxies. The spectral resolution requirement for most extragalactic targets is modest (compared to the needs for Galactic science), but the AtLAST heterodyne array should ideally have $\lesssim$ 0.5 km/s resolution, to enable additional kinematic studies in the LMC, SMC and other very nearby galaxies.

4 Summary and conclusions

In this paper, we have explored the potential of AtLAST, a future 50-m single dish submm telescope, to significantly increase our understanding of the physics and chemistry of interstellar gas and dust, star formation and galaxy evolution through large-scale surveys of galaxies in the nearby Universe. This should be viewed in the context of the overall "scientific portfolio" of AtLAST; nearby galaxies allow us to extend to a broader range of environments the detailed analyses of the ISM in our own Galaxy (Klaassen *et al.,* 2024) while at the same time informing the study of galaxies in the distant universe (Lee *et al.,* 2024; van Kampen *et al.* in prep.). Taken together, all these lines of investigations enabled by AtLAST will provide the solid observational framework required to make profound advances in our understanding of star formation and ISM physics across the Universe.

The two main features of AtLAST that will enable breakthrough advances in our understanding of nearby galaxies are its the sensitivity to extended, low surface brightness emission, and its large field of view allowing for efficient surveying or large areas at unprecedented resolution and depth. For the purposes of this overview paper, we have focused on four nearby Universe science areas where AtLAST will be particularly impactful, and in each case discussed possible surveys and the instrumentation required to achieve transformational outcomes.

Our first science case looks at two of the nearest neighbours of the Milky Way, the LMC and the SMC. An AtLAST continuum camera with a field of view of ~ 1 deg^2 could map the two galaxies fully in three bands (selected in the frequency range 100–680 GHz) with ~ 2900 h on-source integration; this observing time would be significantly reduced with a multi-band camera. The uniqueness of these observations would be the sensitivity to the diffuse, low surface brightness ISM, which is completely missed in current observations with both interferometers and 10–15m class single dish telescopes. This will allow us to answer crucial questions about the early stages of cloud formation, for example.

We then identified the study of magnetic fields on galactic scales as another area where AtLAST can make a unique contribution. With AtLAST, we will be able to map the magnetic fields ($\vec{B}$) from dust polarization in possibly a hundred nearby galaxies, when currently only a handful of nearby galaxies have dust polarization observations (from the decommissioned SOFIA observatory and the 15-meter JCMT). Complementary to, but different from, the radio (L-/C-band) polarization, the submillimeter polarization uniquely probes the thermal emission of dust grains, and thus opens an extra dimension in understanding the complexity of the interplay between the $\vec{B}$ fields and star formation. AtLAST will achieve the largest sample of this kind at giant molecular cloud scales (tens to a hundred parsec) while also tracing the link between galactic- and cloud-scale magnetic fields.

Our third and fourth science cases take advantage of the expected extremely large bandwidth and mapping speed of the AtLAST instruments to achieve the largest-ever samples for submillimeter spectral line and molecular gas surveys. Whereas the current largest submillimeter interferometer, ALMA, is

[9] See SCUBA-2 filter instrumental description where they show the filter transmission curves on top of the atmospheric transmission windows: https://www.eaobservatory.org/jcmt/instrumentation/

capable of detecting hundreds of lines (e.g., the ALCHEMI survey) or observing the most important CO lines in slightly over a hundred nearby galaxies (e.g., the PHANGS survey), AtLAST will enable unprecedented statistical astrochemistry and CO luminosity/gas mass function studies by increasing the sample sizes by several orders of magnitude. With such surveys, we will be able to answer fundamental questions regarding the impact of large scale environment on star formation efficiency and gas availability in galaxies, the shut-down of star formation during the quenching process, and the nature of the star formation efficiency variations across the local galaxy population, to name just a few.

Ethics and consent

Ethical approval and consent were not required.

Data availability

No data are associated with this article.

Software availability

The calculations used to derive integration times for this paper were done using the AtLAST sensitivity calculator, a deliverable of Horizon 2020 research project 'Towards AtLAST', and available from this link.

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Open Peer Review

Current Peer Review Status: ? ✓ ✓

Version 2

Reviewer Report 23 July 2025

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✓ **Yogesh Wadadekar**
NCRA, Tata Institute of Fundamental Research, Ganeshkhind, Maharashtra, India

This paper presents a compelling and comprehensive science case for the Atacama Large Aperture Submillimeter Telescope (AtLAST), focusing on its potential to revolutionize our understanding of gas and dust in nearby galaxies. The authors have done an excellent job of outlining the key scientific questions that AtLAST will be uniquely positioned to address and have provided a clear and well-structured overview of the proposed surveys and technical requirements. The paper is well-written, thoroughly researched, and makes a strong case for the transformational capabilities of AtLAST.

Overall, AtLAST is positioned as something that improves on both ALMA and APEX. Good sensitivity (particularly for large angular scale features which ALMA resolves out), better resolution than APEX, large field of view (much larger than ALMA). This makes it a unique instrument for nearby galaxy studies. This aspect has been brought out in bits and pieces. Would suggest to consolidate these points in one place, perhaps in the introduction or conclusion? Figure 1 is important to highlight this, but it is not adequately discussed in the text.

Multiwavelength complementarity with Roman/Euclid/LSST and SKA surveys have been mentioned, but that discussion could be expanded to describe what new science could be enabled by this.

Minor comments:

The terms "diffuse" and "dense" gas are used throughout the paper, but their definitions are not explicitly stated. Providing a clear definition of these terms, perhaps in terms of gas density, would be

beneficial for the reader.

The paper mentions different values for AtLAST's FoV (2 degrees in the abstract, 1-2 square degrees in the Introduction, and >=60 arcmin in Table 1). This should be clarified for consistency.

Caption of Figure 1 should be expanded to highlight the exceptional capabilities of AtLAST in this parameter space.

"The currently most powerful near-infrared space telescope, JWST, observed warm, shocked, and/or ionized gas in a tiny part of the Large Magellanic Cloud" Provide a citation to support this claim.

In the introduction or the conclusions, authors may consider presenting the present status of the proposal, and if possible, rough timelines and cost.

In section 2.1.2, it might be useful to state explicitly how the 15x improvement in resolution wrt Herschel translates to spatial resolution at tens of parsec cloud scale, up to what distance.

It would be good to state how many hours of observing time will be available per year. This will place the ~2900 hours required for LMC/SMC survey in context.

It is clear that for the LMC/SMC continuum survey, AtLAST will be in a class of its own. Radio/submm surveys with current instruments cannot compete. However, complementary Roman surveys will be important. If there are any relevant surveys planned with Roman, these can be mentioned.

I am not well qualified to comment on Section 2.2 on magnetic fields.

Is the background of the case's history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Not applicable

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Galaxy formation and evolution, Star-formation in and around galaxies, Radio AGN, Astronomical Software development, SKAO Monitoring and Control Software.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 04 October 2024

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Pastrav Bogdan Adrian
Institute of Space Science, Bucharest-Măgurele, Romania

The authors present the science case for a concept - a proposed, largest (to date) aperture, 50-m single dish, multi-beam sub-millimeter telescope. The uniqueness of AtLAST comes from its high-resolution, high sensitivity, mapping speeds, very large field of view and large frequency coverage. The need for such an instrument and for an extra-large sub-millimeter survey in the local Universe is clearly emphasized multiple times throughout the paper. The authors focus on four main science areas where AtLAST will be a game-changer for studies of nearby galaxies and not only. All these main science areas are well put into context, with the main questions that exist at present and the technical limitations of current similar surveys (e.g. ALMA, APEX or others) clearly underlined and well documented. The proposed role of AtLAST in shading light in each of these science areas and on the main scientific questions is afterwards described at length.
The paper is surely worth indexing and will be of interest for the relevant scientific community.
My comments below are rather minor, with a few points that I would recommend the authors to address (marked with an "*" below).

Section 1
1st paragraph: "...applicable in all environments and cosmic times, would arguably have..." -> "...applicable in all environments and at all cosmic times, would arguably have..."
3rd paragraph - comma after "NOEMA" and "is emerging"
4th paragraph - "...through both its large aperture, extended 2 degree field of view,..." Here and in the abstract the expected FOV of AtLAST is mentioned to be 2 degrees, in the notes of Table 3 it

appears as "1-2 square degrees", while in Section 2 an expected 1 deg FOV is mentioned throughout the various subsections. Could you please clarify
this for consistency throughout the paper?

Section 2
2.1
2.1.1 Caption of Fig. 1: Instead of left/right -> up /down
(*) 3rd paragraph, first two sentences - The full range of environments within LMC may very well not span the full range of environments encountered in distant galaxies, for which observations are currently available. Therefore, a quantification of the relative contribution of the various ISM components/tracers to the integrated, unresolved ISM observations, based solely on LMC observations (or even including the SMC and Milky Way) may not offer an accurate enough quantification to be further extrapolated and used uniformly on large scale studies of more distant galaxies.
I would rephrase a bit these sentences or at least comment upon this issue (or give references if indeed the LMC, SMC & MW present the full range of ISM environments).
Figure 2 - the last two bottom plots have very blurry axis labels and info, that cannot be distinguished clearly. Maybe you could please fix this minor issue.

2.1.2 Page 9, last paragraph -> how will the shape of the dust spectral energy distribution from FIR to sub-mm be characterized (e.g. SED model/fitting routine, algorithm or such) to extract the desired parameters? Maybe you can mention this here or in another relevant place;
(*) Same paragraph: my concern is that studying thoroughly the dust emission only in the LMC and SMC, even though the metallicity regimes are quite different in these two galaxies, will not be enough/sufficient for an accurate understanding of the variation of dust properties with environment and for obtaining better dust properties. Thus, I seriously doubt that "the most precise dust temperature, emissivity index β, and dust masses" will be derived as the authors affirm in this paragraph, based solely on the LMC and SMC study. As the degeneracy between dust temperature and dust emissivity index β is well known, how will this be overcome?
Shouldn't more nearby galaxies also be included for this purpose (from the Local Group or other nearby ones), that will span a larger range of environments and properties? A few phrases could be added here to strengthen this affirmation and motivate this choice.

2.2
2.2.1 3rd paragraph (page 14), "...to accurately estimate the magnetic field direction along the LOS." -> please expand LOS (line-of-sight) as here it is the first time that it is used in the paper
page 15, end of 1st paragraph: "Multi-wavelength polarimetric observations is required..." -> "Multi-wavelength polarimetric observations are required..."
2.2.3 1st paragraph , "polarization studies simultaneously will provide very..."-> "polarization studies will simultaneously provide very..."
2nd paragraph, "each galaxy will be resolved at scales 20 — 300 pc..."-> "each galaxy will be resolved at scales of 20 — 300 pc..."
3rd paragraph, "Starforming"-> "Star-forming"; last sentence - The information about the required time is missing here "Thus, we estimate the required observing time to map...". Please add this information here. If the estimated observing time(s) is(are) the one(s) from paragraph 5 (the last of this subsection), then this sentence should be removed from this paragraph, as it is not really connected with the previous one(s).
4th paragraph: "...then examine the emission at the outer disk..." -> "...then examine the

emission in the outer disk..."
2.3
2.3.2 page 16, 3rd paragraph. The sentence "The Herschel space observatory opened ... should end after the enumeration of references. Then the next one can follow: "However, with 30-40" resolution..."
last paragraph, page 17 (before section 2.3.3) "Simulations and theory...can vary significant with galactic environments..." ->"...can vary significantly with galactic environments..."
2.3.3 2nd paragraph, the sentence "In the case of an IFU... " Please delete "thus" from the middle of the sentence and rephrase a bit, e.g. "In the case of an IFU the field of view is much larger, allowing for these nearby galaxies to be covered in one pointing ...."
Same paragraph, last sentence, in brackets "...(although a multi-beam receiver will enable kinematic studies thus can add additional value)" - > "thus" is also inappropriately used here, as in a few other places in the paper. -> maybe rephrase as "...(although a multi-beam receiver would enable kinematic studies that would add additional value)".

2.4
2.4.1 1st paragraph: "...and how the gas and dust is influenced by..." -> "...and how the gas and dust are influenced by..." ; other references could also be added, from other groups of research (not mainly the ones of some of the authors of the present paper)
End of 2nd paragraph, page 23: "...of current scaling relations and so provide more reliable constraints..." -> "...of current scaling relations and to provide more reliable constraints..."
End of 3rd paragraph (page 24), last sentence: "...and mainly located within giant molecular clouds thus much less sensitive to external..." -> "...and mainly located within giant molecular clouds, being much less sensitive to external..."

2.4.2 3rd paragraph (page 25), first two phrases -> some references seem to be missing here for "large systematic molecular gas surveys of the past 15 years" and for the studies giving an "overview of the basic scaling relations" between the mass of H2 and other galaxy properties. Please add these references.
2.4.3 1st paragraph - "This consists of two types of targets: a mass-complete sample of field galaxies..." What would be the desired / expected stellar mass range for the sample of field galaxies? It would be worth mentioning this detail here.
2nd paragraph The phrase "Assuming that the IFU..." is full of information but a bit unclear in its abrupt ending and could also be connected with the following one (but that would create an extremely large sentence). Therefore, please rephrase it so that its ending to have meaning.
(*) Same paragraph. From previous sections it follows that AtLAST will surely have an 1deg^2 FOV. Here it looks like this an assumption rather than just something very probable. Is the ~1deg^2 field of view achievable and therefore a certainty? Maybe you could clarify this.
"Observing...thus is better than observing"-> "Observing...therefore being better than observing"

Section 3
3.1 - Maybe comment upon why a multi-chroic camera would increase the efficiency of observations; couldn't such a camera be incorporated from the very beginning if this would ensure an increase in sample sizes?
"larger bandwidths will likely be technically possible across..." - up to which values (taking into account the limitations due to atmospheric transmission)?

Section 4, 2nd paragraph.
"...in our understanding of nearby galaxies are its the sensitivity to extended, low surface brightness emission..." -> "...in our understanding of nearby galaxies are its sensitivity to extended, low surface brightness emission..."
"...and in each case discuss possible surveys..." -> ...and in each case discussed possible surveys...

Is the background of the case's history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Not applicable

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Galaxy structure and morphology, Dust and ISM Physics, Galaxy scaling relations, Galaxy Evolution

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 23 September 2024

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?

Matilde Mingozzi
Space Telescope Science Institute, Baltimore,, MD, USA

I reviewed the manuscript "Atacama Large Aperture Submillimeter Telescope (AtLAST) science: Gas and dust in nearby galaxies'' by D. Liu and collaborators. This work presents a very detailed review

of gas and dust in nearby galaxies and discusses multiple interesting science cases for the new facility AtLAST, a concept for the next generation of 50-m class single-dish observatories. The science background and science cases are clearly presented and it is clearly explained how sub-mm and mm facilitates are crucial to understanding star formation and ISM physics. The paper reads well and is very informative, providing a great overview of how AtLAST could impact galaxy evolution and star formation studies. However, the uniqueness of AtLAST could be better highlighted, as well as its synergy with state-of-the-art and future facilities. Overall, the paper surely deserves to be accepted in Open Research Europe 2024, but I would have some comments, listed below, that I would advise to (partly) incorporate in the final version of the paper. Comments refer to the section numbers and pages of the submitted version of the paper.

MAIN GENERAL COMMENTS

1. In many parts of the paper, some gas/galaxy properties are described qualitatively with “generic” adjectives. In this kind of paper, that aims at proving that current facilities are not sensitive enough/do not have enough spatial/spectral resolution and sky coverage, it is particularly important to clarify quantitively properties and instrument characteristics. I have highlighted examples of where the information given could be more quantitative in the minor comments section below. The text should be checked carefully to see where it is more appropriate to implement these comments. An alternative solution would be to move Section 3 (technical requirements) before Section 2 and explain there in detail AtLAST modes (i.e., IFU, multi-beam receiver, etc) and properties (i.e., sensitivity, FOV, spectral resolution, spatial resolution, ..), showing also how they compare with similar current facilities. Then, in the following sections, all the technical details would not need to be repeated because citing this technical section would be enough.
2. Following up on point 1, in order to maximize the importance of the role of AtLAST, a summary table collecting AtLAST characteristics and how they compare to current facilities such as ALMA (possibly also to past facilities) related to the proposed science cases could be added at the beginning/end of a proposed science case section. For instance, for the SMC/LMC science case, this could be done by adding information in Tables 1, 2 and 4, highlighting what is still missing and the level of sensitivity/resolution etc that AtLAST could provide. In this case, the improvement of AtLAST with respect to previous facilities becomes more clear only at the beginning of Section 2.1.3, where for the first time AtLAST capabilities for this science case are specified quantitatively, but this should be better highlighted, given all the already available data discussed in 2.1.1 and 2.1.2.
3. A thing that is currently missing from the paper is a discussion about synergy with state-of-the-art and future facilities. For instance, JWST and Roman are mentioned in figure captions, but never in the text, while SKA and Euclid are mentioned few times. JWST/MIRI (despite the small FOV) can be used to study CO-dark gas using H2 rotation lines in the MIR (e.g., Hernandez+23), but also to study dust with MIR features in the nearby universe. Roman will also be an IR mission, similar to Euclid. Moreover, the paper focuses on science cases mostly related to the local universe, but studying metal-poor environments and low-mass galaxies can be useful to understand properties of high-z systems, mainly studied with HST, ALMA and currently with JWST. Overall, discussing (e.g., in a dedicated section before the conclusions) the synergy between AtLAST and these important current and future missions, and discussing how the presented science cases can be linked to the high-z Universe would help to link even better AtLAST to the big picture.

MINOR COMMENTS

Introduction:

1. Paragraph 2, page 5 (see also main point n.1): the meaning of “highest physical resolution possible” referred to the Milky Way could be clarified.
2. Paragraph 2, page 5: It is written that “... JCMT and SOFIA are proving ...”. However, SOFIA was dismissed so this should be clarified. This is mentioned only later in the paper, so perhaps here “are proving” could just be changed to “proved”. Similar changes could be applied in other parts of the text where SOFIA is mentioned.
3. Paragraph 4, page 5 (see also main point n.1): “unique resolution” is mentioned among the characteristics of AtLAST, but it could be clarified if the term resolution refers to spatial, spectral or both.

Section 2:

1. Some concepts are either briefly mentioned and then explained only much later in the paper or not fully explained, but should be clarified. For instance, the concept of CO-dark gas is first mentioned when describing LMC and SMC in Section 2.1.1, page 7, but it is explained only at the beginning of page 10, in Section 2.1.2. Giant molecular clouds are also mentioned on page 7 for the first time, but it is not mentioned which spatial scales they have, and thus which spatial resolution is needed to study them. Gas and dust tracers are presented in Tables 1 and 2, but it is explained only later in Sec. 2.1.2 why these are good tracers and in which conditions. A possible solution could be to revise the structure of Sections 2.1.1 and 2.1.2, starting by presenting the general background first (integrating parts of Section 2.1.2 in Section 2.1.1) and moving all the details about SMC and LMC after what is written in the current Section 2.1.3, that starts highlighting why AtLAST is really important to study them.
2. Other things mentioned but not well defined are “diffuse” and “dense” gas (e.g., which density and spatial extension?).

Section 2.1.1:

1. Paragraph 1, page 5: a reference could be added where Figure 1 is mentioned.
2. Paragraph 2, page 5: a reference for 20-50% Zsun for SMC and LMC could be added.
3. Figure 1 caption: “top” and “bottom” panels instead of left and right. Also, the VISTA survey is shown in the bottom panel, as mentioned in the caption, but never in the text. Thus, it is not clear the purpose of the bottom panel of Figure 1.
4. Figure 2 is a bit small and difficult to read.
5. Tables 1 and 2 present an overview of observations of LCM and SMC “hot” and “cold” ISM. However, this is just a sub-selection of information, since LCM and SMC have also been observed with other facilities (e.g., HST, JWST, ESO facilities like MUSE). Here, the reasons for this selection could be clarified (e.g., are these observations mapping entirely LMC and SMC, while others mapped only part of them?). Also, the spatial resolution as well as sensitivity information could be added to these tables for all the listed observations (at the moment spatial resolution in arcsec and pc is specified only for a few of them), to better highlight what is still missing that AtLAST could do. Finally, it could be specified which tracers were used to observe dust in the works listed (e.g., ~70-500 micron with Herschel; dust emissivity index; etc).
6. Paragraph 5, page 7 (see also main point n.1): the meaning of “too large” dust mass and “excessively large dust masses are also observed in high redshift” could be clarified, also

specifying which facilities were used at high-z. Also, Rowlands+14 study galaxies at z~1-5, while here z~>6 galaxies are mentioned.

7. Paragraph 6, page 8 (see also main point n.1): the meaning of "sub-mm and mm emission excesses" could be clarified as well as in which nearby galaxies these excesses have been found, apart from SMC and LMC.
8. Paragraph 6, page 9 (see also main point n.1): the resolution needed to "resolve individual environments and account for diffuse dust emission" could be specified, as well as how it is defined the "diffuse gas emission".

Section 2.1.2:

1. Paragraph 1, page 9 (see also main point n.1): ALMA Largest Angular Structure (LAS), ALMA and APEX, sensitivity, spatial resolution and mapping efficiency could be clarified and compared to the values expected from AtLAST, to let the reader understand the meaning of "poor" and the problem of filtering. In this paragraph, the spatial resolution needed to best study GMCs in SMC and LMC could be specified.
2. Paragraph 2, page 9 (see also main point n.1): the required "higher spatial resolution measurements" could be specified.
3. Paragraph 4, page 10 (see also main point n.1): when discussing CO-dark gas, it is written that CO clumps are "very difficult to detect without sensitive, high resolution and large field-of-view observations", but this could be explained quantitatively. Also, there have been works studying metal-poor local dwarfs with ALMA, IRAM and NOEMA (e.g., Hunt+14, Hunt+15, Amorin+16, Shi+16, Hunt+17, Cormier+17, Zhou+21) – these works definitely have limitations due to the sensitivity, but it would be interesting to see how AtLAST would improve this.
4. Paragraph 4, page 10 (see also main point n.1): instead of "ALMA's field of view is too small" and "APEX does not offer enough sensitivity and resolution", it could be specified what are ALMA FOV and APEX sensitivity and resolution at [CI] frequencies.
5. Paragraph 5, page 10: "While we could hope that such processes scale linearly with the amount of metals available, studies of nearby galaxies have shown that reality is more complex." This could be rephrased in "Studies of nearby galaxies have shown that such processes do not scale linearly with the amount of metals available."
6. Paragraph 5, page 10: it is mentioned a critical metallicity threshold of 0.2 Zsun and then it is suggested that studying LMC and SMC could help to better understand the relation between physical properties and metals. However, LMC and SMC have 0.2-0.5 Zsun, so this point is not very clear.

Section 2.1.3:

1. Paragraph 2, page 10: CMB acronym is defined after mentioning CMB.
2. Paragraph 4, page 12: it is mentioned that ~2900 hours of AtLAST would be needed to map SMC and LMC. Would it be realistic to have ~121 days dedicated to this science case? It would also be interesting to understand how long would it take for current facilities to complete one AtLAST pointing. Also, it is written that "... H2O percentiles of 70, 40 and 10 for the aforementioned bands, we obtain an on-source integration time of 27.0 h, 5.2 h, 28.5 h, respectively" – is there a typo or at 400 GHz only 1/5th of the time is needed?

Section 2.2.1:

1. Last paragraph, page 15 (see also main point n.1): "ALMA can help to some extent in those efforts" could be presented more quantitatively. ALMA is mentioned only once in the

previous paragraphs.

Section 2.2.2:

1. Paragraph 1, page 16 (see also main point n.1): Table 3 could be cited when mentioning that the ALMA field of view is not sufficient. Also, AtLAST "super sensitivity" could be expressed quantitatively. Which value is needed for this kind of observations?
2. Paragraph 5, page 16: as commented for section 2.1.3, it would be interesting to read how much would it take for current facilities to do a similar study.

Section 2.3.1:

1. Paragraph 2, page 17: Concerning the KS relation, it has been shown that the law works also for atomic gas, but taking into account the volume density instead of the surface density, suggesting that the atomic gas can be a good tracer of the cold star-forming gas, especially in low-density HI-dominated environments (see e.g., Bacchini+2019).

Section 2.3.2:

1. Paragraph 2, page 18 (see also main point n.1): It is written that "high spatial resolution" means hundreds of pc, while in the previous sections (but also on page 20 when referring to AtLAST's spatial resolution) the term "high spatial resolution" refers to GMC-scale resolution, so tens of pc or lower. Also, it is written that the resolution of a sub-mm 15-m single dish is insufficient, but this could be defined quantitively (e.g., give an example of resolution in arcsec and in pc for a nearby object, e.g., NGC253 shown in Fig.6, of AtLAST versus current facilities). Also, there are larger single-dishes than 15-m apart from LMT (e.g., IRAM), as written in other parts of the paper.
2. Table 5 (see also main point n.1): There is a "resolution" column, but it is not specified which instrument. The caption could be more specific. Also, it could be useful to specify the typical luminosity of the listed denser gas tracers with respect to CO. Definitely a higher sensitivity is needed to detect them, which could be another aspect in favour of AtLAST.
3. Paragraph 3, page 18 (see also main point n.1): the sentences "extended emission is filtered out" and "ALMA has a very small field of view" could be more specific, for instance giving a range of ALMA LAS and FOV.
4. Paragraph 3, page 18 (see also main point n.1): in the sentence "TP antennas are far from being sensitive enough" the sensitivity of the TP could be specified.
5. Paragraph 5, page 20: on page 13 it is written that AtLAST mapping speed is "comparable with contemporary facilities", while from here it seems that it is better, so this should be clarified.
6. Paragraph 7, page 20: mapping higher J CO transitions with ALMA is "very difficult" also due to the reduced transmissivity of the atmosphere at higher frequencies, which is true also for future sub-mm facilities, so a further sentence to clarify why things for AtLAST will be easier could be added here.

Section 2.3.2:

1. Paragraph 2, page 21: here it is mentioned for the first time a multi-beam receiver or integral field unit (IFU). It could be clarified why these types of instruments were not needed for the two previous science cases. Also, there are currently no sub-mm IFU, so it would be interesting to know more about this mode (e.g., feasibility, spatial resolution – the spectral resolution and FOV are mentioned/shown). If there are technical AtLAST papers about this topic, they should be cited here. Finally, it is not explained why the spectral resolution of the

IFU would be much lower than the one of the multi-beam receiver (for which the spectral resolution is not specified). The IFU is mentioned again in section 2.4.3 on page 24, where it is assumed that the spectral resolution can be higher than what is stated here, so this should be clarified.
2. Last paragraph, page 22: here it is explained how long it would take to observe 100 galaxies with AtLAST for all the transitions, taking as a reference a galaxy like NGC3627. Is the so large difference between this case (~3.5 hr for all the transitions) and the LMC/SMC (>20 hrs) due uniquely to the difference in gas-phase metallicity?

Section 2.4.1:
1. Paragraph 3, page 23: here the topic discussed is the few molecular gas studies of low-mass galaxies (<10^9 Msun), where CO-dark gas can be dominant. It is not clear the link between the first two paragraphs and the third one, which instead discusses cluster environment (and cluster galaxies generally have larger masses and metallicity with respect to less dense environments). Concerning the study of molecular gas in cluster galaxies affected by ram-pressure stripping there are some recent APEX and ALMA studies from the GASP survey (e.g., Moretti+2020, Bacchini+2023).

Section 2.4.2
1. The paragraphs “Molecular gas scaling relations in the dwarf galaxy regime” and “Why do galaxies stop forming stars?” repeat concepts already discussed in 2.4.1 and could be removed/integrated with the text in the previous section.

Section 2.4.3
1. Also in this section, there are repetitions of concepts discussed in 2.4.1 (e.g., 950 hrs of IRAM).
2. Paragraph 2, page 24: Concerning the use of AtLAST for blind surveys including low-metallicity galaxies, it is not clear if it would be feasible to easily detect molecular gas in metal-poor environments. It is not clear if the dependence of CO flux as a function of metallicity (as well as SFR; see e.g., Hunt+2020, MAGMA survey) is taken into account in the calculations presented here, where only 30 mins per source are considered, given the large amount of time needed for one pointing on the SMC/LMC (>20 hrs). Also, here is mentioned a range in redshift of z~0-0.16, while in the previous paragraph, there is written z~0.01-0.38.

Is the background of the case’s history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?

Partly

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My area of research is focused on galaxy evolution and interstellar medium studies in the nearby universe. In particular, I am an expert in spectroscopy studies of the ionized gas in different types of galaxies, from massive galaxies with/without AGN activity to metal-poor nearby dwarfs, considered high-z analogs. I have been also involved in studies on the cold molecular reservoirs in nearby luminous IR galaxies and objects affected by ram-pressure stripping, and I am currently carrying out IR and subm-mm studies on metal-poor nearby dwarfs, using JWST/MIRI, IRAM and ALMA observatories.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.