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DOI

[10.1117/12.2561238](https://doi.org/10.1117/12.2561238)

Publication date

2020

Document Version

Final published version

Published in

Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy X

Citation (APA)

Kohno, K., Kawabe, R., Tamura, Y., Endo, A., Baselmans, J. J. A., Karatsu, K., Inoue, A. K., Moriwaki, K., Hayatsu, N. H., & More Authors (2020). Large format imaging spectrograph for the Large Submillimeter Telescope (LST). In J. Zmuidzinas, & J.-R. Gao (Eds.), *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy X* (Vol. 11453, pp. 128 - 138). Article 114530N (Proceedings of SPIE - The International Society for Optical Engineering; Vol. 11453). SPIE. <https://doi.org/10.1117/12.2561238>

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SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2020, Online Only

Large format imaging spectrograph for the Large Submillimeter Telescope (LST)

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ABSTRACT

We present a conceptual study of a large format imaging spectrograph for the Large Submillimeter Telescope (LST) and the Atacama Large Aperture Submillimeter Telescope (AtLAST). Recent observations of high-redshift galaxies indicate the onset of earliest star formation just a few 100 million years after the Big Bang (i.e., $z = 12\text{--}15$), and LST/AtLAST will provide a unique pathway to uncover spectroscopically-identified “first forming galaxies” in the pre-reionization era, once it will be equipped with a large format imaging spectrograph. We propose a 3-band (200, 255, and 350 GHz), medium resolution ($R = 2,000$) imaging spectrograph with ~ 1.5 M detectors in total based on the KATANA concept (Karatsu et al. 2019), which exploits technologies of the integrated superconducting spectrometer (ISS) and a large-format imaging array. A 1-deg 2 drilling survey (3,500 hr) will capture a large number of [O III] 88 μm (and [C II] 158 μm) emitters at $z = 8\text{--}9$, and constrain [O III] luminosity functions at $z > 12$.

Keywords: galaxy formation and evolution, fine structure lines ([O III], [C II]), kinetic inductance detectors (KIDs), integrated superconducting spectrometer (ISS), DESHIMA/MOSAIC/KATANA, imaging spectrograph, The Large Submillimeter Telescope (LST), The Atacama Large Aperture Submillimeter Telescope (AtLAST)

1. INTRODUCTION

Recent multi-wavelength surveys of distant galaxies have revealed that the majority of the star-forming activities at a redshift $z = 1\text{--}3$, where the cosmic star formation rate densities peak, is obscured by dust, emphasizing importance of the study of dust-obscured activities in the universe. However, the roles of the dust-obscured star-formation beyond the redshift of $z > 4\text{--}8$ remain unclear, because different measurement techniques result in different indications, as shown in Figure 1. For instance, ALMA observations of Lyman break galaxies in *Hubble* Ultra Deep Field suggest that the dust obscured star formation plays rather minor roles among such star-forming galaxies selected by rest-frame ultraviolet (UV) radiation.^{1,2} On the other hand, *Herschel* observations of “red” SPIRE sources suggest elevated star-formation rate densities up to $z \sim 6$,³ which is also supported by recent ALMA observations.⁴ Latest ALMA studies also demonstrate the presence of sub/millimeter-selected galaxies without any significant counterpart seen in the optical and near-infrared: *HST*-dark galaxies.^{5–9} Although such a class of galaxies has been known from the beginning of the discovery of the submillimeter galaxies (SMGs), recent ALMA observations unveil much fainter sub/millimeter sources ($S_{1\text{mm}} \sim$ a few 10–100 μJy), which were unable to isolate before due to the source confusion limit of submillimeter-wave survey facilities like SCUBA/SCUBA2 on JCMT 15-m telescope and AzTEC on ASTE 10-m telescope. And more importantly, such faint sub/millimeter galaxies are much more ubiquitous⁶ and therefore responsible for the bulk of the cosmic infrared background-light (CIB).^{5,10,11} The importance of *HST*-dark but IRAC-detected (a.k.a. *H*-dropout) galaxies as a key tracer of the early phases of massive galaxy formation at $z \sim 4\text{--}6$ has been discussed,^{6,12} but the difficulty of obtaining spectroscopic redshifts for such *HST*-dark galaxies hampers the physical characterization of these sources. After pioneering spectral scan observations of the *Hubble* Deep Field North using IRAM Plateau de Bure Interferometer,¹³ ALMA and NOEMA have been used to search for millimeter-wave line emitters^{14–20} without any priors in the optical/near-infrared bands, but the total surveyed area has been (and will be) limited to tiny patches of the sky because of the narrowness of the ALMA/NOEMA field-of-view. All of this progress motivates us to design a wide-area spectroscopic survey of dust-enshrouded galaxies in a more systematic way.²¹

Recent discoveries of star-forming galaxies at $z = 8\text{--}11$ ^{22–24} and candidate passive galaxies at $z \sim 6$ ²⁵ indicate the onset of the earliest star formation just a few 100 million years after the Big Bang, i.e., $z \sim 12\text{--}15$. This prompts us to establish a methodology to uncover a statistically large number of spectroscopically-identified, “first forming galaxies” during the epoch of reionization (EoR) and beyond, i.e., the pre-reionization era/cosmic

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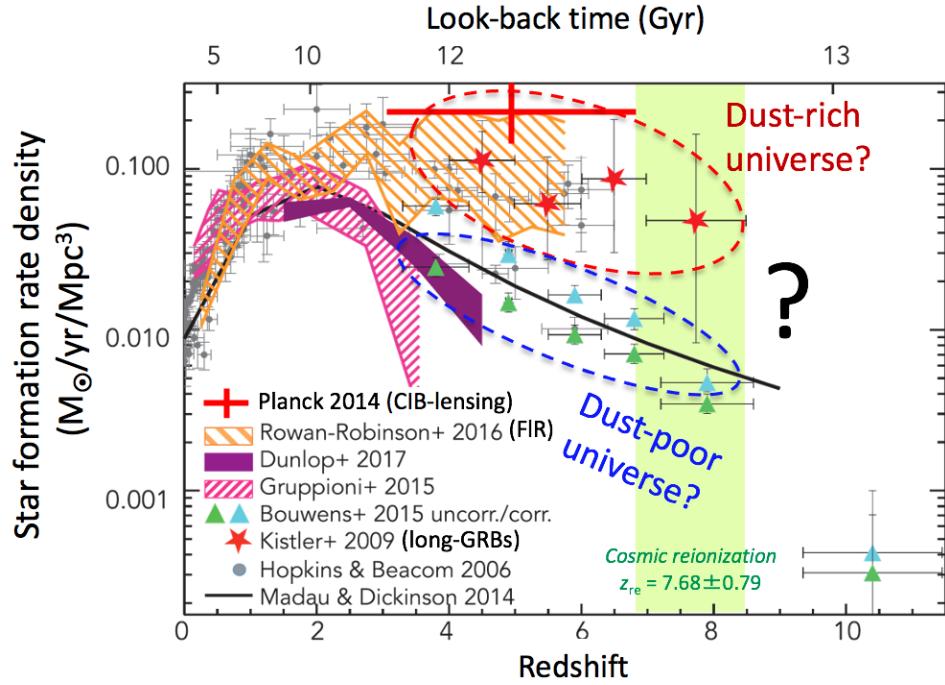


Figure 1. The redshift evolution of the cosmic star-formation rate density, illustrating two inconsistent trends of measurements at $z = 4 - 8$, i.e., “dust-rich, actively star-forming universe” (suggested by *Herschel* - FIR, long- γ -ray bursts, and cosmic infrared background-light (CIB) lensing analysis with *Planck*) and “dust-poor, calm early universe” (suggested by observations of Lyman break galaxies with dust-extinction corrections).

dawn. Although both ALMA and *JWST*/NIRSpec can detect [O III] 88 μm and [C III] 1907Å + C III] 1909Å lines, respectively, at $z > 10-15$ with a reasonable observing time, they are not optimized for a wide-area survey to uncover such candidate sources. A $>100 \text{ deg}^2$ near-infrared imaging survey at $\lambda = 2-5 \mu\text{m}$ with a modest depth ($\sim 27 m_{AB}$) would be the optimum option to find spectroscopic follow-up targets at $z \sim 15$ (Inoue et al.) but the Roman Space Telescope will have no survey capability at $\lambda > 2 \mu\text{m}$.

Here we argue that next-generation large submillimeter single-dish telescopes optimized for wide-area, broad-band spectral coverage surveys, such as the Large Submillimeter Telescope (LST)^{26*} and the Atacama Large Aperture Submillimeter Telescope (AtLAST)^{27†}, will provide a unique pathway for that purpose once these telescopes are equipped with a large format imaging spectrograph.²⁸ In this paper, we present a conceptual study of a 3-band imaging spectrograph, which specifically aims for the [O III] 88 μm and the [C II] 158 μm tomography at $z = 4-8$ (with [C II]) and $z = 8-16$ (with [O III]), based on the KATANA concept (Karatsu et al. 2019)[‡] using the technologies of the integrated superconducting spectrometer (ISS)^{29,30} and a large-format imaging array like A-MKID.³¹ Our goal here is not to propose a very detailed specification of the observing instrument, but to provide a conceivable observing instrument case based on a set of science requirements; it will give some insights and implications for further investigations of the observing instrument and technologies for LST/AtLAST. A brief overview and updates of the LST project are also given.

2. THE LARGE SUBMILLIMETER TELESCOPE

The LST project was originally discussed as the planning of a next-generation telescope for sub/millimeter-wavelengths that could inherit both the large collecting area of the Nobeyama Radio Observatory (NRO) 45-m telescope³² and the submillimeter capabilities of Atacama Submillimeter Telescope Experiment (ASTE) 10-m

*<https://www.lstobservatory.org>

†<https://atlast-telescope.org>

‡<https://agenda.infn.it/event/15448/contributions/95630/>

telescope.³³ The current major specifications of the LST, along with the conceptual design and key science behind have been summarized in Kawabe et al. (2016).²⁶ In brief, the LST will be a 50-m diameter high-precision (45 μm rms) telescope for wide-area imaging and spectroscopic surveys with a field-of-view of $>0.5 \deg \phi$ primarily focusing on the 70–420 GHz frequency range, with a capability for high frequencies up to 1 THz using an inner high-precision surface. A novel concept of a millimeter wavefront sensor that allows real-time sensing of the surface, which will be a key to establish “millimetric adaptive optics (MAO)”, has been proposed by Tamura, Y., et al.³⁴ Statistical approaches to efficient atmospheric noise removal for submillimeter-wave spectroscopy have been proposed and implemented by Taniguchi, A., et al. for e.g., NRO 45-m telescope³⁵ and DESHIMA on ASTE.³⁶

One of the recent major milestones of the LST project is the master plan 2020 (MP2020) led by the Science Council of Japan (SCJ), which aims to set the list of high priority large academic research projects in Japan. The LST project was invited to give a presentation at two MP2020 symposia in September 2018 and January 2019, which were organized by the astronomy and astrophysics sub-committee of SCJ, to discuss the progress of the project since the previous master plan activity (MP2017) and the status of the international collaboration including the EU-led AtLAST project. A support letter from the AtLAST community was highly appreciated. Now the LST is formally listed as one of the large academic projects in the astronomy and astrophysics field in MP2020, which was announced in January 2020. During these activities, a merger between the AtLAST and LST projects has been intensively discussed. After the success of the 3.5 M Euro ERC program for the AtLAST design study in 2021–2024,²⁷ we anticipate the merger in 2024 where the design study will end. There are some apparent inconsistencies of telescope specifications such as the target surface accuracy and the field of view, which are expected to be discussed further during the AtLAST design study in coming years. A next step forward in the LST would be a proposal to National Astronomical Observatory of Japan (NAOJ) to launch a study group of the LST under a support from the community in Japan. Figure 2 displays the LST timelines and milestones, along with those of the AtLAST.

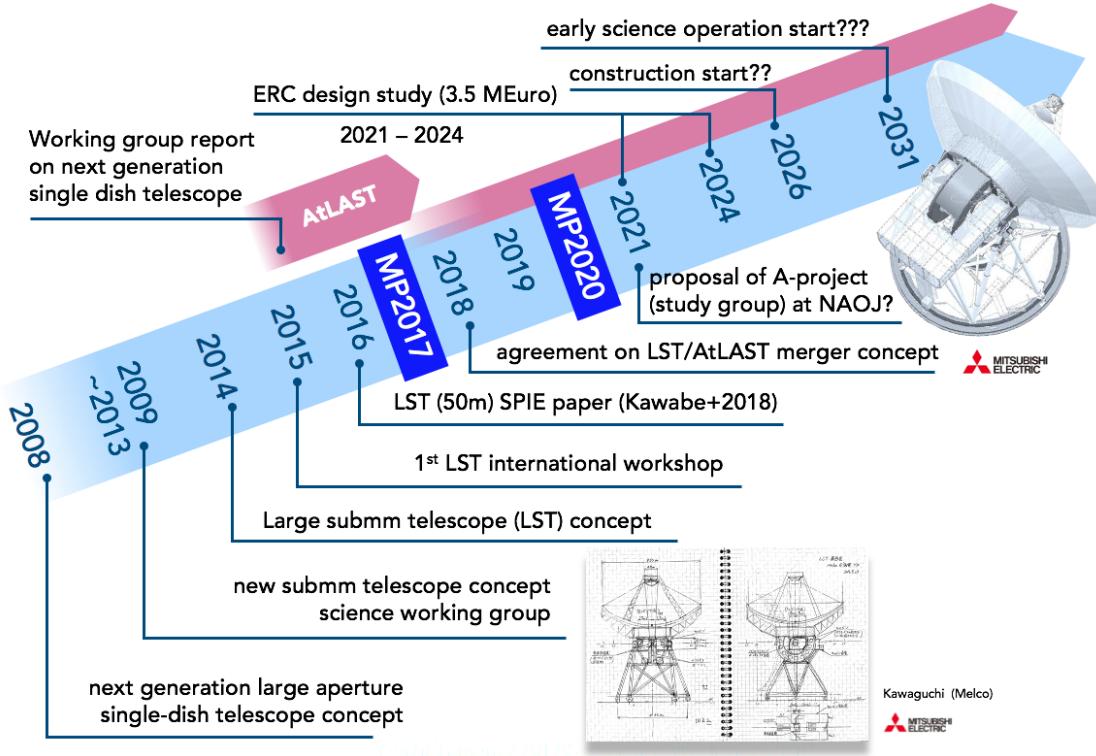


Figure 2. LST project timeline and milestones.

	DESHIMA 1.0	DESHIMA 2.0	MOSAIC	KATANA			KATANA 2.0		
Frequency range	332 – 377 GHz	220 – 440 GHz	185 – 365 GHz	197 GHz (1.5 mm) 190 - 204 GHz	255 GHz (1.2 mm) 246 - 265 GHz	352 GHz (0.85 mm) 339 - 365 GHz	197 GHz (1.5 mm) 190 - 204 GHz	255 GHz (1.2 mm) 246 - 265 GHz	352 GHz (0.85 mm) 339 - 365 GHz
Frequency coverage	45 GHz	220 GHz	180 GHz	14 GHz	19 GHz	26 GHz	14 GHz	19 GHz	26 GHz
Number of spatial pixels	1	1	25	100	100	100	1,000	1,000	3,000
Spectral resolution (R)	380	500	500	500	500	500	2,000	2,000	2,000
Number of KIDs	49 x 1 x 1 pol	347 x 1 x 1 pol	350 x 25 x 1 pol	35 x 100 x 2 pol	37 x 100 x 2 pol	37 x 100 x 2 pol	140 x 1,000 x 2 pol = 280 k	148 x 1,000 x 2 pol = 296 k	148 x 3,000 x 2 pol = 888 k
Telescope (year)	ASTE (2017)	ASTE (2021-)	LMT ?	LMT ?			LST/AtLAST ??		
Line mapping speed	-	-	-	15 arcmin ² mJy ⁻² hr ⁻¹	7 arcmin ² mJy ⁻² hr ⁻¹	0.4 arcmin ² mJy ⁻² hr ⁻¹	110 arcmin ² mJy ⁻² hr ⁻¹	60 arcmin ² mJy ⁻² hr ⁻¹	26 arcmin ² mJy ⁻² hr ⁻¹



Figure 3. Summary of the major specifications of DESHIMA, MOSAIC, and the proposed 3-band imaging spectrograph based on the KATANA concept, which will exploit technologies of the integrated superconducting spectrometer (DESHIMA) and a large-format imaging array (like A-MKID). Pictures of DESHIMA and A-MKID, along with the proposed array configuration of MOSAIC, are inserted.

3. FROM DESHIMA TO KATANA: 3-BAND IMAGING SPECTROGRAPH

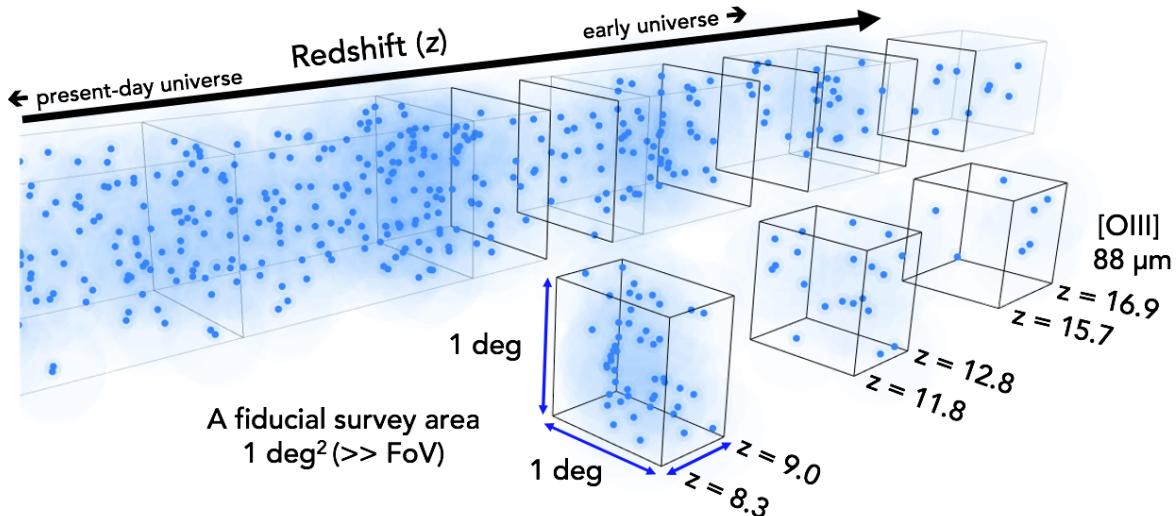
We propose a 3-band (200, 255, and 350 GHz), medium resolution ($R=2,000$) imaging spectrograph with ~ 1.5 M detectors in total, which is anticipated to become available in the early 2030s. The key technologies of the KATANA concept (Karatsu et al. 2019) are a dual-polarization sensitive broadband antenna, an on-chip filter-bank spectrometer, and NbTiN-Al hybrid microwave kinetic inductance detectors (MKIDs) to readout the spectral channels, which have been successfully demonstrated by the recent DESHIMA 1.0 on ASTE campaign.^{29,37,38} DESHIMA 2.0, which will have a much wider frequency coverage with a better optical efficiency, will be deployed in ASTE for full science operation in mid-2021. MOSAIC, a multi-pixel version of DESHIMA, has been proposed for the Large Millimeter Telescope Alfonso Serrano (LMT)[§] and discussed during the Guillermo Haro 2018 Workshop. Figure 3 presents a summary of major specifications of DESHIMA, MOSAIC, and the proposed 3-band imaging spectrograph with the KATANA concept. Here “KATANA” is for the existing facilities like ASTE and LMT, whereas KATANA 2.0 is for the future survey telescopes in the early 2030s, i.e., the LST/AtLAST. Figure 4 summarizes the frequency ranges and corresponding redshifts of [O III] and [C II], along with the conceptual view of a fiducial 1-deg² drilling survey.

One of the key requirements for the instrument is a spectral resolution R of 2,000 (a velocity resolution dv of 150 km s⁻¹), because the target sources at $z > 8$ are expected to be less massive and therefore have a narrow line width of ~ 100 km s⁻¹, as demonstrated by reported [O III] 88 μm line emitters at $z = 7\text{--}9$ ($dv = \text{a few } 10\text{--}150$ km s⁻¹).^{23,24,39} This is currently the limiting factor of the spatial pixels because we need >100 spectral channels to have a redshift width dz of around unity for each band (Figure 4). The line mapping speed of the proposed configurations was computed based on the achievements with the DESHIMA 1.0 along with the reasonable assumptions of the telescope surface accuracy (45 μm rms) and a precipitable water vapor (0.5 mm). We set a 5 σ line sensitivity of 1 mJy (peak flux) or 0.15 Jy km s⁻¹ at Band-3, which corresponds to a [O III] 88 μm line luminosity of $4 \times 10^8 L_\odot$ at $z \sim 8\text{--}9$, based on the estimation of the [O III] 88 μm line luminosity functions from the UV luminosity functions^{40,41} and their extrapolation (Inoue et al.). Theoretical simulations⁴² also support the validity of the target line sensitivity.

We find that a 1-deg² survey spending 3,500 hrs with the proposed 3-band configuration will uncover a

[§]<http://lmtgtm.org>

statistically large number of [O III] 88 μm line emitters at $z = 8$ –9. A fraction of them will be [O III]-[C II] dual line emitters because [C II] can also be bright at $z \sim 8$ galaxies.⁴³ Furthermore, Band-2 is designed to cover the same redshift range in the [N II] 122 μm line. Although the nitrogen line must be significantly weaker than [O III] and [C II], stacking may work to assess the average ISM properties, such as metallicity, radiation field, and gas density.⁴⁴ The expected number of sources for the redshift bins of ~ 12 and 16 is highly uncertain at this stage, but we will be able to put a meaningful observational constraint on the [O III] 88 μm luminosity functions at $z \sim 12$ and 16. A wider survey with this depth will be necessary for better statistics in any case, implying for the necessity for more detectors to provide a higher line mapping speed.



Band	Center frequency (wavelength)	Frequency range	Redshift range		Line sensitivity (5σ)	[OIII] 88 μm line luminosity (5σ)	Expected number of [OIII] 88 μm emitters
			[OIII] 88 μm	[CII] 158 μm	(mJy)	(L_\odot)	
Band1	197 GHz (1.5 mm)	190 – 204 GHz	15.7 – 16.9	8.32 – 9.00	0.49	5.0×10^8	< 1 ???
Band2	255 GHz (1.2 mm)	246 – 265 GHz	11.8 – 12.8	6.17 – 6.73	0.66	4.6×10^8	~1 – 10 ???
Band3	352 GHz (0.85 mm)	339 – 365 GHz	8.31 – 9.00	4.21 – 4.60	1.0	4.3×10^8	~100 ?

Figure 4. The proposed 1 deg^2 drilling survey using the KATANA 3-band imaging spectrograph, which is designed to blindly uncover [O III] 88 μm line emitters at 3 specific redshift ranges. The lowest frequency band also corresponds to a [C II] 158 μm redshift range of $z = 8.3$ –9.0, allowing to detect [O III]-[C II] dual line emitters at this redshift range. With the observing time of 3,500 hrs, we will reach a 5σ line sensitivity of 0.5–1.0 mJy (peak flux) or 0.074–0.15 Jy km s^{-1} , which are translated into a [O III] 88 μm line luminosity of $\sim (4 - 5) \times 10^8 L_\odot$. Note that with this line sensitivity we can detect both [O III] and [C II] lines of MACS0416_Y1 at $z = 8.31$.^{24,43}

4. TECHNICAL CONSIDERATIONS

4.1 ISS option

One of the technical issues is how to realize $R = 2,000$ with the ISS technology. DESHIMA1.0 has a coplanar waveguide (CPW) signal line coupled to planar filters, but suffers from large radiation losses. Microstrip filters will eliminate such losses, but then we need transparent deposited dielectrics. The development will require a better understanding of the noise behavior of a deposited dielectric, which has two level systems (TLS) noise.⁴⁵

Another challenge is how to implement $>1,000$ spatial pixels which are coupled with a broad-band antenna. Further investigations on the quasi-optics as well as the chip structure will be necessary to have a better design for very large arrays.

The line mapping speed with the proposed 3-band configuration, which requires ~ 1.5 M detectors in total, seems to be minimal to achieve the science goal with a reasonable observing time (for $z = 12$ and 16 , we need an even wider surveys with this depth). It implies that the cost of the proposed imaging spectrograph can be comparable to the telescope itself. What is the anticipated cost per channel in 2030s?

4.2 Heterodyne option

High spectral resolution ($R \sim 10^7$ or $dv \sim 0.03$ km s $^{-1}$) is available, but such high R may not be mandatory for the proposed high-redshift galaxy survey using emission lines; a moderate R (a few 1,000) can work. Nevertheless, the heterodyne receivers are indeed an attractive option as demonstrated by a 275–500 GHz heterodyne receiver with an instantaneous IF bandwidth of 4–21 GHz,⁴⁶ which exploits the high-current-density superconductor-insulator-superconductor (SIS) junctions and related technologies. It is therefore conceivable to develop a dedicated moderate-resolution digital spectrometer system to be connected to such a novel wide-band heterodyne receiver.

Another technical challenge is implementation of $\sim 10^3$ pixel heterodyne receiver array, where power consumption of a large number of cryogenic low-noise amplifiers and complexity of the structure can be an issue, although possible solutions have been proposed and investigated.^{47,48} A heterodyne receiver array with $\sim 1,000$ pixels per band has been considered for the AtLAST, and the primary limiting factor is likely to be cost.⁴⁹

5. SUMMARY AND OUTLOOK

Successive detection of the [O III] 88 μ m line in $z = 7$ –9 galaxies along with the mounting evidence for the earliest star formation at $z \sim 12$ –15 galaxies motivate us to establish a pathway to find suitable targets for ALMA spectroscopy at these redshift range. We propose and discuss a 3-band imaging spectroscopy survey with the KATANA concept (Karatsu et al. 2019) for LST/AtLAST by exploiting the technologies of the integrated superconducting spectrometer (ISS) and a large-format imaging array. A 1-deg 2 drilling survey (3,500 hrs) with the proposed 3-band configuration (covering 200, 255, and 350 GHz band, 1,000–3,000 spatial pixels per band, $R = 2,000$ spectroscopy, yielding ~ 1.5 M detectors in total) will capture a statistically large number of [O III] line emitters at $z \sim 8$ –9 (with some [O III]-[C II] dual line detection along with [N II] 122 μ m constraint by stacking), and a significant chance of uncovering [O III] emitter candidates up to at $z \sim 12$ and ~ 16 . Development of low-loss films, which requires better understanding of noise behavior of dielectrics, is necessary for realizing $R = 2,000$ with ISS. How to implement $>1,000$ spatial pixels with a broad-band antenna is another challenge. A large format heterodyne array may also become an option given the rapid progress of SIS receiver technologies, but the cost remains a big issue.

ACKNOWLEDGMENTS

This research was supported by the Netherlands Organization for Scientific Research NWO (Vidi grant no. 639.042.423, NWO Medium Investment grant no. 614.061.611 DESHIMA), the European Research Council ERC (ERC-CoG-2014 - Proposal no. 648135 MOSAIC), the Japan Society for the Promotion of Science JSPS (KAKENHI grant nos. JP25247019 and JP17H06130), NAOJ ALMA Scientific Research grant no. 2018-09B, and the Grant for Joint Research Program of the Institute of Low Temperature Science, Hokkaido University.

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