Large Submillimeter Telescope as 3D Explorer of Universe

D=50 m at ALMA plateau
FOV > 0.5 deg diameter for 70-420 GHz
Capability of obs up to 1 THz with under-illumination
Active Surface control to achieve 45 micron (rms)
Developing new discovery space complementary to ALMA
- wide field imaging in line & continuum
- time-domain science

Ryohei Kawabe (NAOJ)
Kotaro Kohno (U. Tokyo)
Yoichi Tamura (Nagoya U)
and LST working group
Frontier of High-z Universe

"First Metal production" ➔ What is Origin?

[OIII] & Dust @ $z = 8.312$

Spectroscopic redshift

$z = 9.110$

Hashimoto, YT et al. (2018) Nature

LETTER First SF occurred @ $z = 15$

The onset of star formation 250 million years after the Big Bang

Kohno, Tamura, Inoue, RK + 2019
(white paper for ASTRO2020)
Galaxy Formation and Metal Production in Epoch of Re-ionization

- Still not well understood, sample for ALMA obs depends on candidates from HST
- Larger sample at $z = 10-15$ available with HST? => No because does not catch Lyα FOVs of JWST, ALMA are too small for survey

Census of extremely high-z galaxies needs $>1\ \text{deg}^2 \cdot$ peak flux $\sim1\text{mJy in [OIII]}$

\[0.5\text{ deg} = 50h^{-1}\ \text{cMpc}\]

[OIII]-emitters

$z=7$

\[\text{Inoue et al.}\]
**Light cone from the LST 2-deg$^2$ Survey**

*with imaging spectrograph*

“observations” of mock galaxies from S$^3$-SAX

**Assumptions**
- Spatial pix: 100
- Freq 70 – 370 GHz
- Survey Area 2 deg$^2$
- Obs timr 1,000 hours (on-source)

Tamura, Y., + in prep.

Kawabe, R., + 2016, SPIE

10$^5$ galaxies across the cosmic time
10$^3$ galaxies in the epoch of reionization
LST $z = 8 - 15$ galaxy survey

- 2 deg$^2$, but deeper $t_{\text{obs}} = 9,000$ hrs with LST 50m
  - Larger sample of $z = 8 - 10$ galaxies,
  - accessible to $z = 12 - 15$ galaxies
- Larger imaging spectrograph (spatial pix $> 1000$)
  - galaxy clustering/dark haro & luminosity function at $z > 10$

![Graph showing log-sigma noise level vs. frequency with ALMA 1 hr and LST 2 deg$^2$ survey]
SKA Design Studies – Virtual Hydrogen Cone

[Diagram of molecular/atomic hydrogen distribution across different redshifts (z), ranging from 0 to 10 Gpc.]

Yoichi Tamura / Large Aperture Sub/mm Single Dish Telescopes in the ALMA Era

CO/[CII] Tomography

+ [OIII] emitter

RSD Redshift Space Distortion
Verify GR by estimating the growth rate of structure, dark energy problem

LSS Cosmic Large-Scale Structure
Investigate the correlation between dark and baryonic matters from clustering analysis, dark matter problem

EoR Epoch of Reionization
Search for earliest “hidden” galaxies, first generation galaxies

Tamura, Y., + in prep.

CSFH Cosmic Star-formation History
Investigate mass/luminosity function of molecular gas as a function of redshift, “hidden” history of baryonic matter

Evolution of Galaxies
Cosmic evolution of galaxies proved through properties of interstellar medium

Kawabe, R., + 2016, SPIE

... and serendipitous discoveries
Line emitters, transient and variables, ...
AzTEC/ASTE 1.1mm **confusion limited** deep survey

<table>
<thead>
<tr>
<th>Field</th>
<th>ADF-S</th>
<th>SXDF</th>
<th>SSA22</th>
<th>COSMOS</th>
<th>GOODS-S</th>
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<tbody>
<tr>
<td>Coverage (arcmin^2)</td>
<td>909</td>
<td>954</td>
<td>973</td>
<td>2967</td>
<td>270</td>
</tr>
<tr>
<td>Depth (1σ, mJy)</td>
<td>0.4-0.80</td>
<td>0.5-0.9</td>
<td>0.7-1.3</td>
<td>1.2-2.2</td>
<td>0.5-0.7</td>
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<tr>
<td>N sources (&gt;3.5σ)</td>
<td>233</td>
<td>215</td>
<td>125</td>
<td>205</td>
<td>48</td>
</tr>
</tbody>
</table>

references

AKARI Deep Field South (ADF-S)
“Submm galaxies” are bright, but...


Bright SMGs > a few mJy @1mm are ubiquitous, but their contribution to CIB is just ~10-20%

θ ~28” @1.1mm

233 sources
0.4 - 0.8 mJy (1σ)
area ~0.25 deg²

ASTE10m

Bolometer camera
AzTEC (UMASS/INAOE..collaborat.ion)
50m LST allows 100% resolving CIB

- Complete Understanding of CIB, i.e., obscured star formation in the universe.
ALMA Deep Fields

Survey area [arcmin$^2$] vs Survey depth (1σ) [μJy/beam]

- SXDF-ALMA (cy1, Kohno)
- ADF22 (cy2, Umehata)
- GOODS-S/HUDF (cy3, Elbaz)
- HFFs (cy1+, Bauer)
- ASAGAO (cy3, Kohno)
- ALCS (cy6 Large, Kohno)
- ASPECS (cy2, Aravena)
- ASPECS-large (cy5 large, Walter)

1.1 mm
1.2 mm
1.3 mm

- 80 μJy (1σ)
- 33 clusters
- ALCS PI: K. Kohno
- ALMA Cy6 Large Program
- z>7のダストを持つ銀河は稀 ➔ 大規模探査
Mapping Speed in Continuum Survey

単位時間あたり、ある深さで掃くことのできる面積

![Graph showing mapping speed](image-url)
Open up Time-domain Science: Detection reverse shock from Long-GRB@z=5-30

- high-z long-GRBs host reverse shock for several hours to 1 days
- Reverse shock has a SED with peak at submm – to FIR
- Peak ~ mJy
- Possible Sign Post of EoR, most distant objects, first stars etc

LST Science; Galactic case

1. Continuum (+pol) / Spectral Line Mapping survey
   - IMF vs CMF for various Star forming regions
   - Origin of Brown Dwarfs and Planetary mass objects
2. Spectral Line Mapping survey from starless cores to PPDs
   - Study of chemical evolution and chemical diversity; 
     e.g., formation of COMs and CCMs.


Herschel
LST

0.6 pc
1 arcmin

1 arcmin.
Wide-Field Spectroscopic Imaging

Time-domain Science

High-cadence submm VLBI

Distant Galaxies and Clusters

Wide-Field multi-color Imaging

Galactic Plane

Spectral-line mapping survey

Nearby Galaxies

Magellanic Clouds

Submm Transients

Planetary atmospheres

LST

LARGE SUBMILLIMETER TELESCOPE
Superconducting On-chip filterbank Spectrometer DESHIMA

- One of keys technologies for 3D exploration/Tomography; other are SperSpec, MicroSpec
- Demonstrated for the first time on ASTE (Nov., 2017)
Wave-front Sensor for Large Submillimeter Telescopes
- Transmitters on Dish (ToD) to measure **short-timescale deformation of surface**
- Correlation with reference signal provides phase change, converted to deformation correction with adaptive primary surface or other optics

**Demonstration on NRO 45m planned**
Timeline of LST (+AtLAST)

- **2008**: NRO/NAOJ Started Study on Future Large mm/submm Telescope
- **2013**: ESO Started Study
- **2014**: LST concept proposed to SCJ for MP2017
- **2015**: LST International Workshop, Mitaka
- **2016**: AtLAST Plan
- **2017**: MP2017
- **2018**: LST (50m) SPIE paper (Kawabe, Kohno, Tamura et al. 2018)
- **2019**: AtLAST WSs - discussion on LST/AtLAST common goals
- **2020**: MP2020
- **2025**: Start Construction (Goal)
- **2031**: Start Early Science (Goal)
International Collaboration: Support Letter from AtLAST

9th January 2019

Ryohei Kawabe
National Astronomical Observatory of Japan
Mitaka, Tokyo 181-8588, Japan

Kotaro Kohno
Institute of Astronomy, School of Science, The University of Tokyo, Mitaka, Tokyo, 181-0015, Japan

Dear Dr. Kawabe and Dr. Kohno,

We write in strong support of your initiative to merge the Large Submillimeter Telescope (LST) and the Atacama Large Aperture Submm/mm Telescope (AtLAST) into one unified project. The participation of the LST experts such as yourselves during the AtLAST workshops in 2018 showed a large overlap in the science goals of the two projects, and has already influenced our design. As a result, we are strongly convinced that the only way forward is to join forces as an ambitious multinational project. We understand this aligns directly with your proposal to the Science Council of Japan for the Master Plan 2020.

Many members of the submillimeter and millimeter community worldwide recognize the unique value that a 50-meter class single dish with a large (> 1 square degree) field of view would bring. The mapping speed attainable with a fully-instrumented large single dish would be over 1 million times that of the full ALMA observatory, and even since the beginnings of ALMA many have argued for the inclusion of a widefield, large single dish. This facility would give us unprecedented access to large-scale, low surface brightness structures, and so would place AtLAST (and the overall mm/submm community) in a privileged position to complement future astronomical facilities working in different wavelength ranges (the SKA, Athena, Lynx, DES, LSST, SDSS V, JWST, LiteBIRD, SPICA, OST, etc.) and multi-messenger astronomy.

As we look forward to the 2020’s, and having seen the progress of mm/submm instrumentation over the last decade, it is clear now is the optimal time to move forward, and that the best and only way to succeed is through a multinational partnership.

Our recent workshops at the European Southern Observatory (ESO) and the Royal Observatory Edinburgh (ROE) have shown there is much enthusiasm for the AtLAST project not only inside Europe and the United Kingdom, but worldwide, including members of the Chilean, East Asian, and North American communities.

We thank you very much for leading this crucial effort of proposing to the Science Council of Japan to unify the LST and AtLAST projects, and we look forward to a strong partnership.

Sincerely, on behalf of the AtLAST community,

Frank Bertoldi (Bonn), Claudia Cicone (INAF), Carlos De Breuck (ESO), Simon Dicker (U. Pennsylvania), James Geach (Hertfordshire), Diah Gunawan (U. Valparaiso), Eduardo Ibar (U. Valparaiso), Rob Ivison (ESO), Pamela Klaassen (UK Astronomy Technology Centre), Tony Mroczkowski (ESO), Omid Noroozian (NRAO), Leonardo Testi (ESO), Alwyn Wootten (NRAO)

Strong Support form EU, NA ALMA Community

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Astronomy and Astrophysics Panel in SCJ (Science Council of Japan) reviewed LST together with other large scale future projects, and finally recommended LST for MS2020 (Master Plan 2020) this year.
Chinese (PMO) 60-m submm Telescope at Tibet?
- up to 500 GHz?
- covered by Astro-dome for wind
- site testing at Ali (5800m, 北緯32°)

China-JP collaboration on R&D planned (btw. PMO/CAS & NAOJ/JSPS)
LMT collaboration

**B4R (2mm)**: NAOJ/Japanese Univ. collaboration (Installation and commissioning last year)

**FINER (2mm-800um)**: Nagoya-U led Japanese Univ/NAOJ collaboration
- R&D of new spectrometer funded
- preparing a proposal to JSPS (Japan Society of Promotion of Science)

**B1R (40 GHz)** for LMT: AISAA-NAOJ collaboration for Zeeman etc.
- plan to install on the 45m telescope and test this winter
- move to LMT two or three years later

**MOSAIC**: SRON/Delft-UTokyo/NAOJ/NagoyaU collaboration (fully funded and under development)
- 5 x 5 spatial array of upgraded-DESHIMA
- covering 185 to 365 GHz in one shot, ~ 500 MHz freq resolution.
- Beam-steering mechanism is optional
LMT collaboration: Band-4 Receiver (B4R)

- Single beam, dual-polarization, side-band-separating mixer receiver for 2-mm and + spectrometer system for redshift determination via CO detection, CO-SLED study
- Frequency (RF) range: 125 – 163 GHz
- Instantaneous bandwidth for spectrometer: 10 GHz in total ➔ 15 GHz ➔ 20 GHz ? (depending on funding..)
- Spectral resolution: \( df = 88.5 \text{ kHz} \) or \( dv = 0.18 \text{ km/s} \) @2mm
FINER for LMT

Far-Infrared Nebular Emission Receiver

PI: Yoichi Tamura

- 125-365 GHz Heterodyne receiver (B4 - B7) for LMT: combination of two new SIS mixers, B4+5, B6+7
- Aiming at pioneering EoR (z~10) with [OIII] 88 µm and [CII] 158 µm in the northern sky with many candidates
- LMT (~ 40% of ALMA in correcting area) can compete with NOEMA (also ~40% of ALMA)
  - the LMT site is better than the NOEMA site
  - Correcting area are comparable, but LMT surface worse a bit: achieving ≤ 75 µm (rms) in LMT is desired
- (Optional) Millimetric Adaptive Optics is needed for the LMT together with Active Surface?
Ultra-Wideband Spectrometer for FINER: OCTAD-S

Hittite ADC
- > 16 Gsps, 3 bits
- FFT with FPGAs
- 4 ADCs, 32k-point FFT outputs for each ADC (> 8 GHz Bandwidth and 16 k freq. channels)
- Flexible spectral data outputs with FPGAs
- (digital or LO offset) sideband separation capability will be implemented for IRR < - 30 dB
- R&D funded recently
Atmospheric Transmission: Mauna Kea

PWV: 1.00 mm

16*4 = 64 GHz/2 beams/pol
32k chx8 = 0.256 M ch
MOSAIC on LMT proposed

• Proposing to the on-chip imaging-spectrograph MOSAIC on LMT 50m.
• Instantaneous frequency coverage: 185 – 365 GHz (covering 180 GHz width in one shot!)
• With a coarse resolution $R = \frac{f}{df} \approx 500$ (dv $\approx 600$ km/s)
• $5 \times 5 = 25$ spatial pixels (350 detectors per pixel, 8,750 detectors in total)
• The proposed target year of installation: 2021/22
• Suited for follow-up of AzTEC & Toltec (and other bright submm) sources Note: beam steering will be in the 2nd generation MOSAIC
• 25-beam DESHIMA/MOSAIC on LMT is >10 times more efficient than ALMA in blind search for line emitters
• Fully funded by Dutch & Japanese grants (ERC and JSPS grants, > 1 M Euro each)
MOSAIC cryostat@TU Delft

Akira Endo (DESHIMA-PI)  
Oct. 2018

Jochem Baselmans (MOSAIC-PI)
Multi color camera
3 color multichroic x 2 focal planes ➔ 6 colors

- SZE of groups, clusters, WHIM, +...

<table>
<thead>
<tr>
<th>Band (GHz)</th>
<th>FWHM @10mφ (&quot;)</th>
<th>N_{beam}</th>
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<tbody>
<tr>
<td>135-160</td>
<td>51</td>
<td>91</td>
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<tr>
<td>180-245</td>
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<td>390-420</td>
<td>19</td>
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</tr>
<tr>
<td>630-700</td>
<td>11</td>
<td>271</td>
</tr>
</tbody>
</table>
Development items for Broader & Multi bands

2019 • Vacuum window (NAOJ)
  • Horn array (NAOJ)
  • Planar OMT (NAOJ)
  • On-chip filters (NAOJ)
  • MKID Detector (RIKEN/NAOJ)

2020 • Test of Integrated OMT + on-chip filters + MKIDs (NAOJ)

Design of On-chip filters

OMT design

150GHz: 80µm x 374µm

270GHz: 80µm x 510µm

Read-out Test of MKIDs
• Future large submillimeter telescopes very much desired in the mm/submm community worldwide

• Integrated efforts in Asian regions necessary to realize one or two large telescopes as well as world wide collaboration
  - developing science cases; i.e., key science
  - developing key technologies, 3D-cam, MAO, etc

• JCMT/ASTE and LMT/45m can enhance single dish science and keep our community active, and would lead us to the future