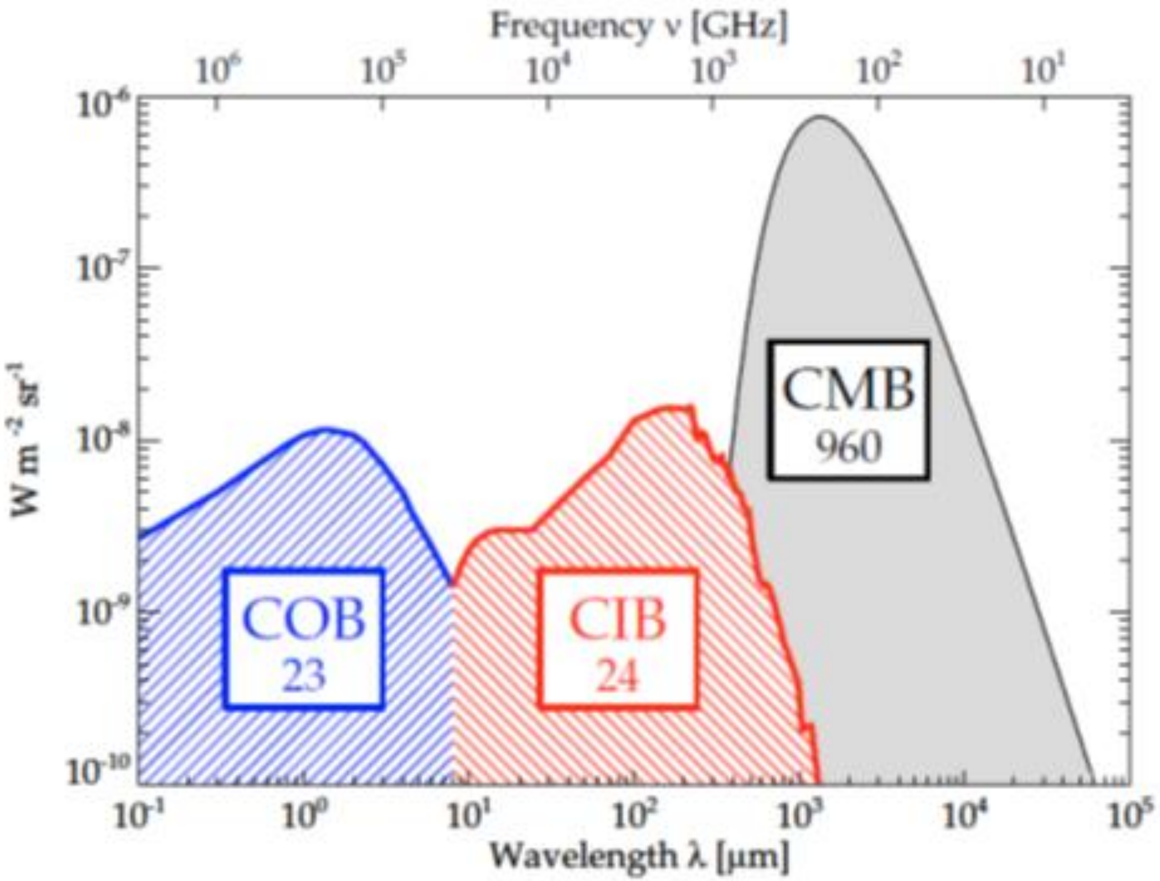
Elucidating formation and evolution of celestial bodies using far-infrared and terahertz interferometers

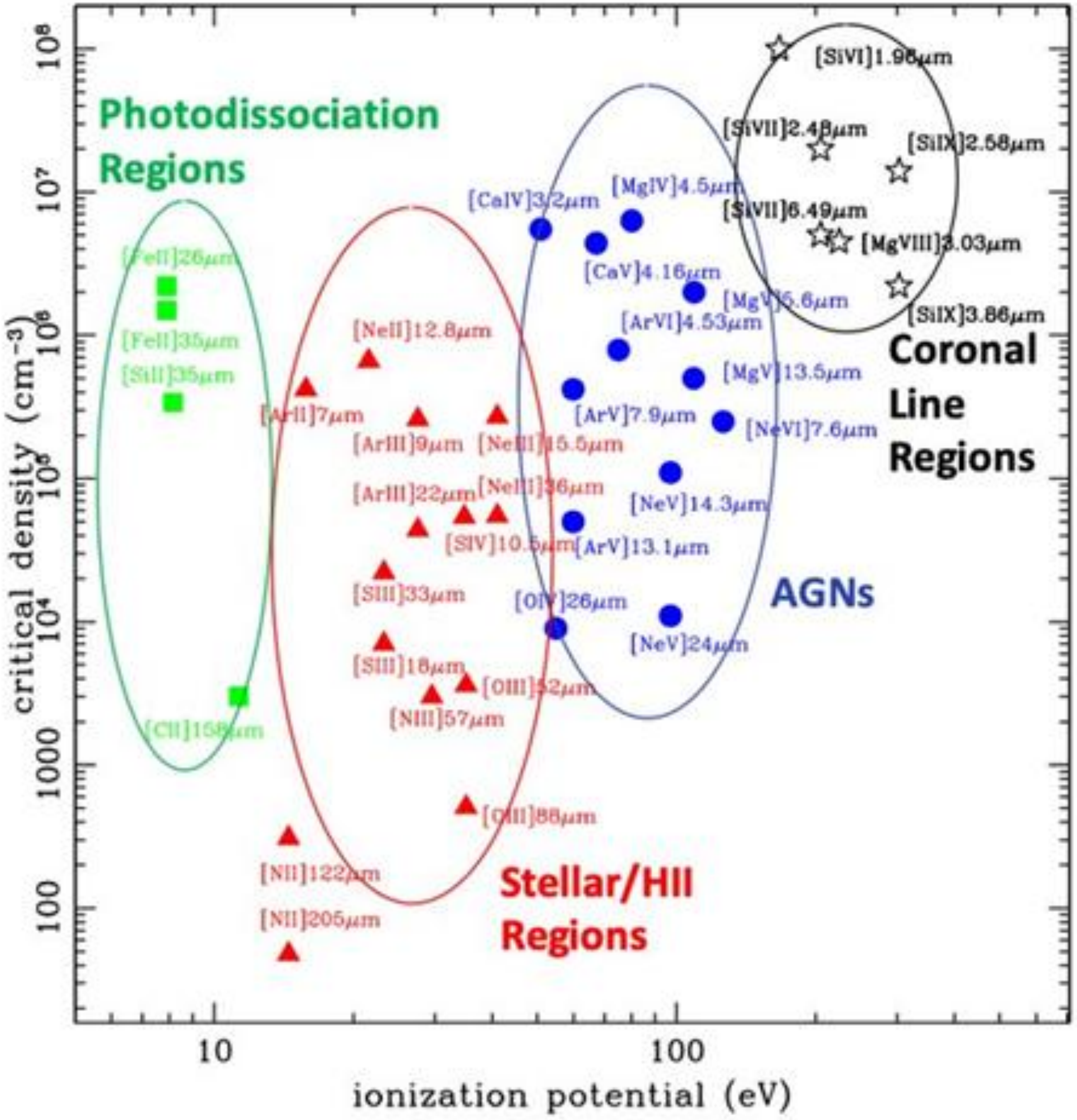
遠赤外線テラヘルツ干渉計による天体の形成と進化の解明

Hiroshi Matsuo (ATC/NAOJ)

Astronomical Background Radiation（Dole et al. 2006）



FIR atomic lines (Spinoglio et al. 2021)

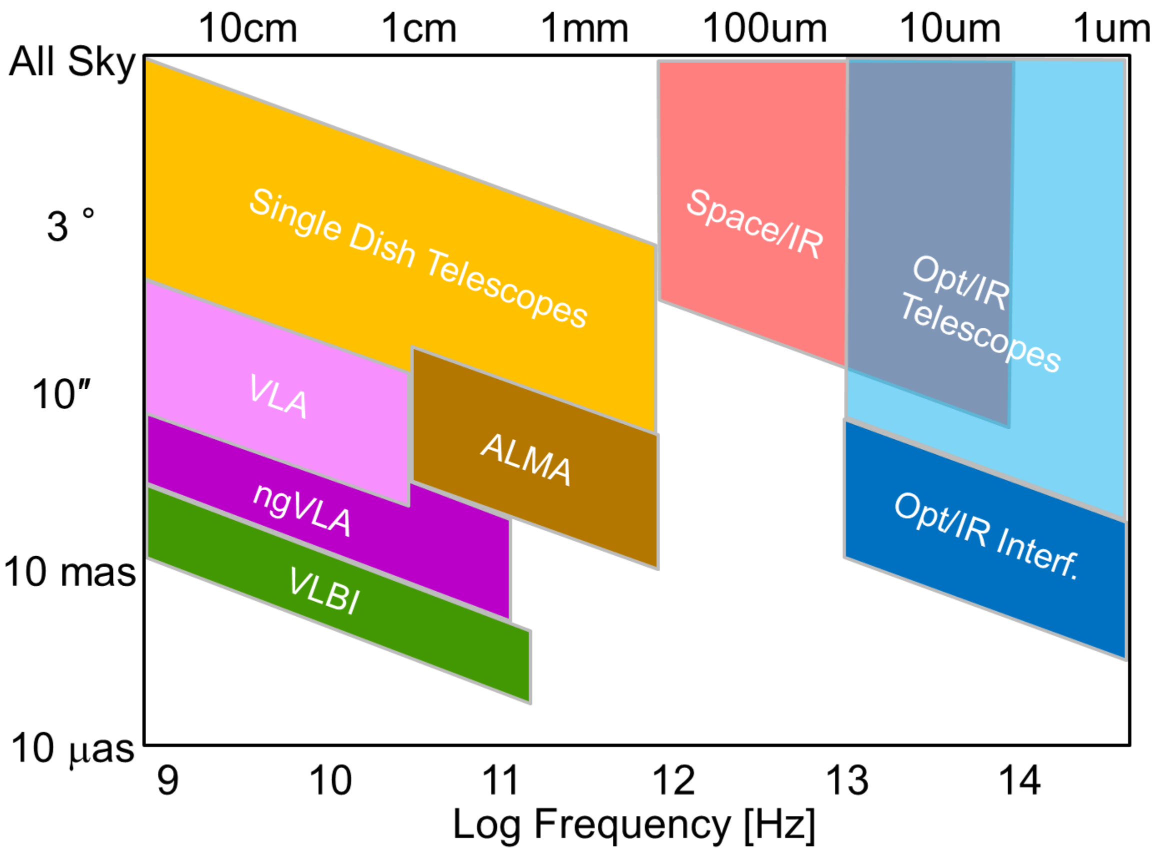


2. Science goals

- Identifying existence and form of heavy elements in our universe, whose emission can be observed in far-infrared and terahertz frequencies (FIR/THz) elucidating emission from astronomical sources under formation and evolution.
- High angular resolution in FIR/THz is the key to study physical/chemical structure together with other facilities like ALMA, JWST etc.

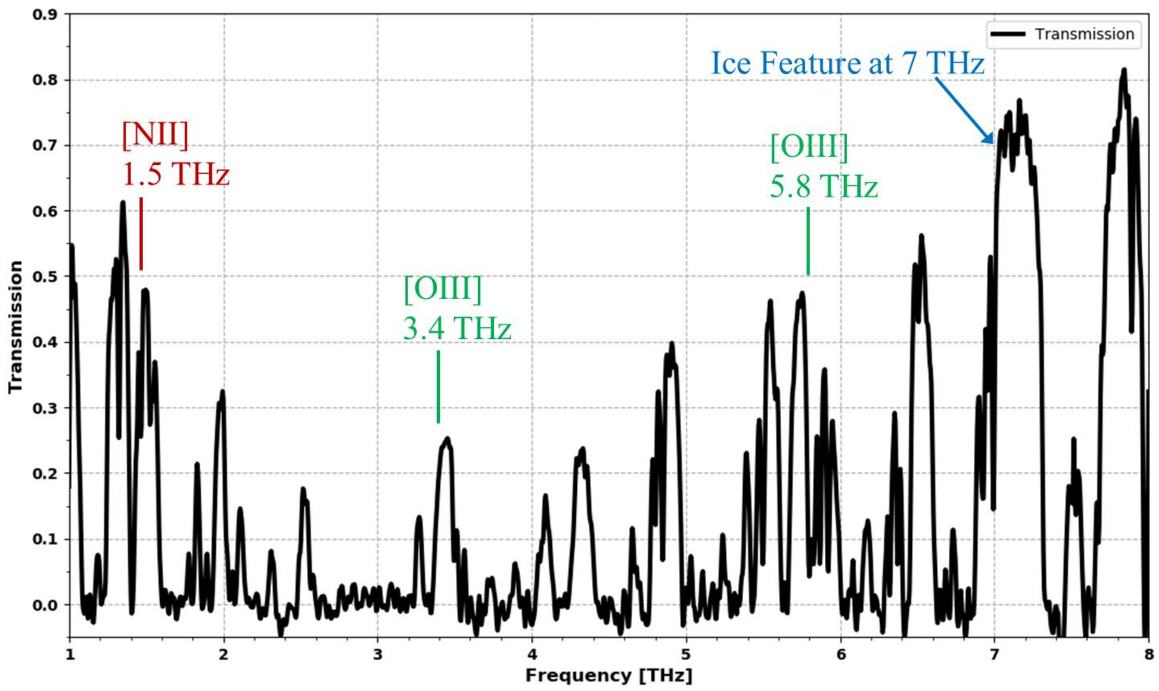
Also, Hydrogen Molecules (H_2, HD) and Water Ice Feature !

Angular Scale of Observations



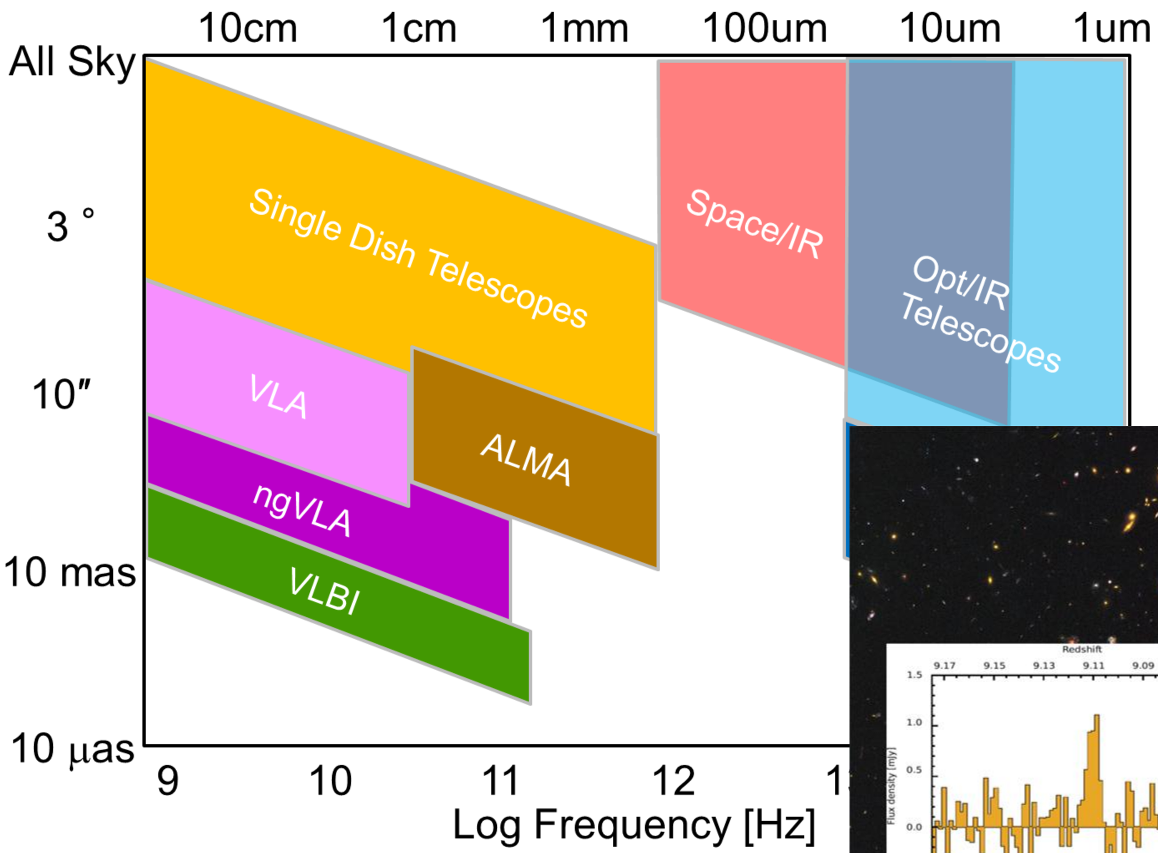
THz Atmospheric Windows

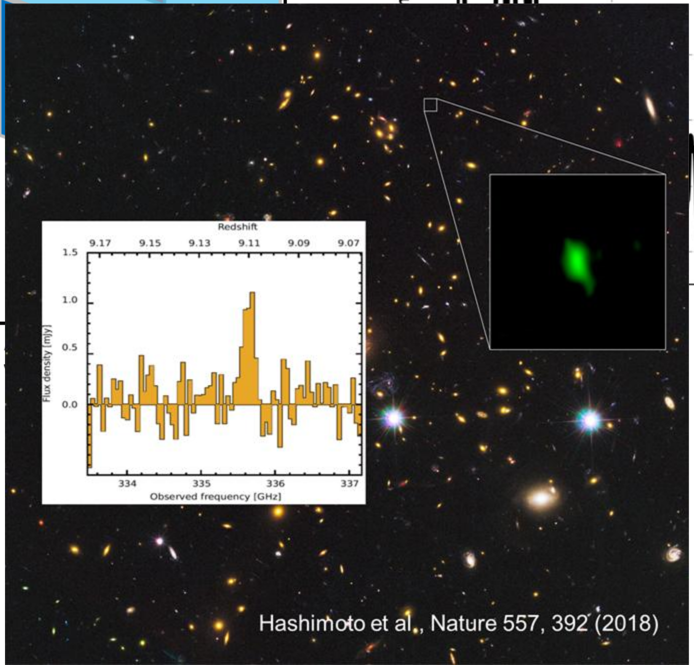
Dome-A. August 9th 12–18h UTC. 2010



Matsuo et al. Advances in Polar Science (2019)

Angular Scale of Observations





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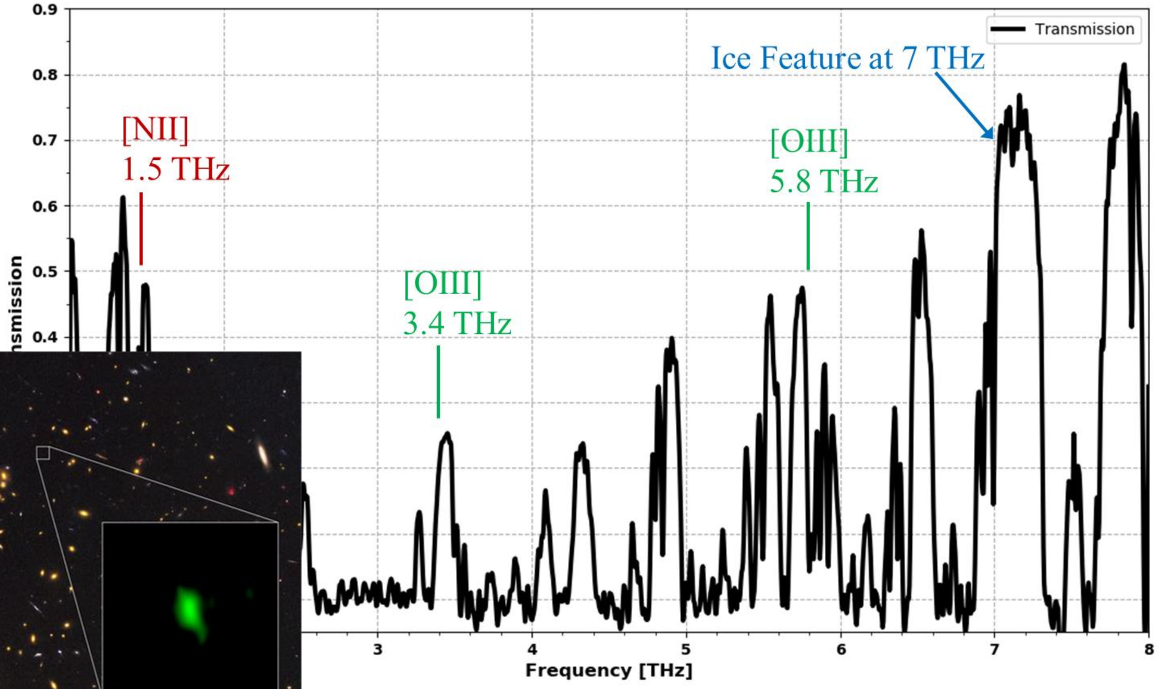


Matsuo et al. Advances in Polar Science (2019)

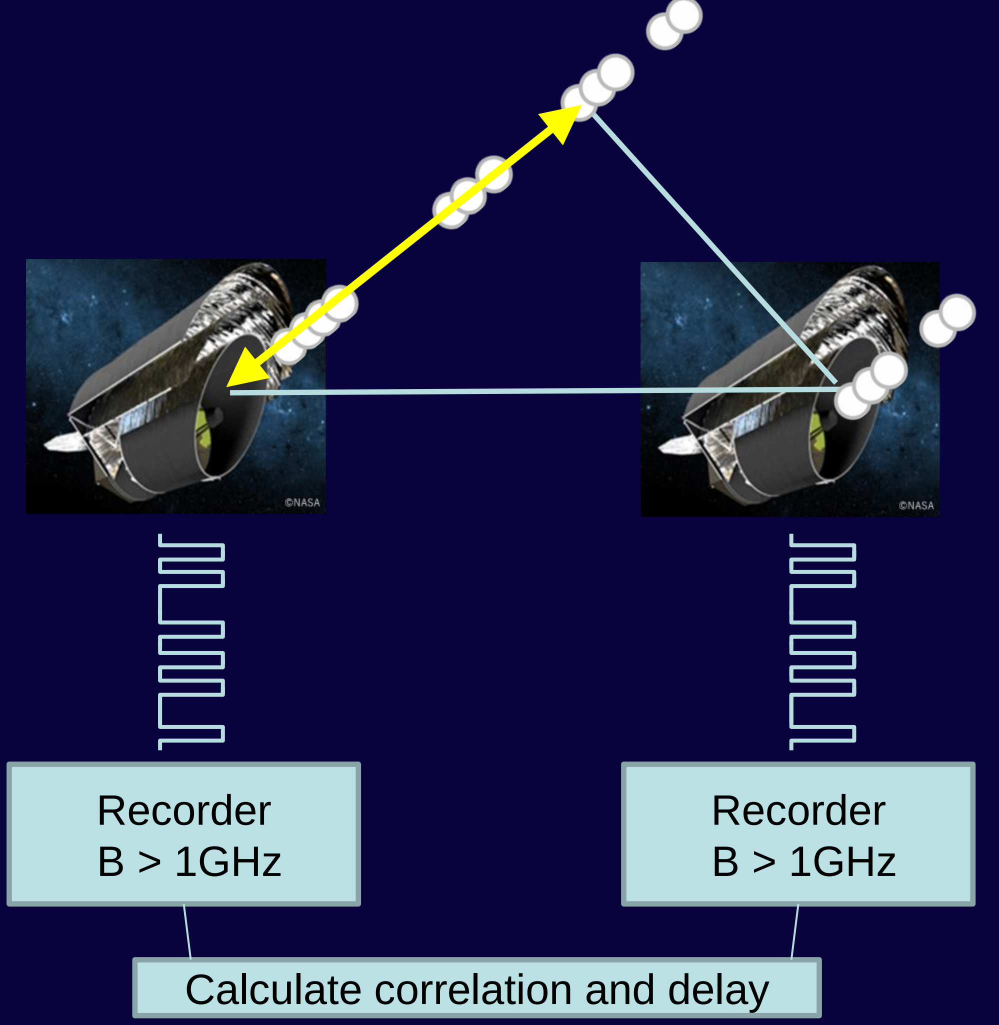
3. Scientific objectives

H_2 17/28
HD 56/112
Ice feature 42/63
PAH features

[CII]158, [OI]63 PDR
[NII]122/205 gas density
[OIII]88/52 gas density
[NIII]15.6/36 gas density
[OIII]52/[NIII]57 metallicity
[OIV]26 AGN
[NeII]12.8 SFR

- High angular resolution (~1 milli-arcsec) and background limited observations (NEP~10^{-19} W/Hz$^{0.5}$) in FIR/THz will reveal formation and evolution of astronomical sources from the Big Bang to the nearby universe.
- Identifying dust and atomic/molecular emission lines to study their physical/chemical and kinematic structures revealing the phase of heavy elements in formation and evolution of stars, planets, galaxies, AGNs, galaxy clusters.

Space Far-Infrared Intensity Interferometry



Photon Bunches

from thermal sources

Beyond Quantum Limit with photon counting detectors

NEP = 10^{-19} W/Hz$^{0.5}$ B=100GHz

T_{RX} = NEP / (2k B$^{0.5}$) = 10 mK

Background vs. Quantum limit ~ 4 orders

Bandwidth (100 GHz /1 GHz)$^{0.5}$ ~ 1 order

4. Science Investigations

- Installing FIR/THz intensity interferometers in Antarctic plateau and in space. Antarctic plateau such as Dome-Fuji and Dome-A are ideal sites for THz astronomy for long baseline interferometers from ground. Ultimate sensitivity could be achieved with space-borne intensity interferometers with cryogenic FIR telescopes.

  4.1. Science Investigations until 2033

  Deployment of Antarctic THz interferometry in Dome-Fuji.

  Concept study on space-borne FIR interferometers.

  4.2. Science Investigations beyond 2034

  Long baseline THz interferometry in Antarctic Dome-Fuji and Dome-A.

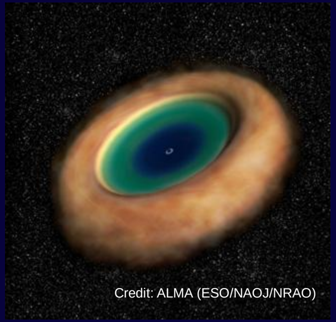
  Realization of space-borne FIR interferometers.

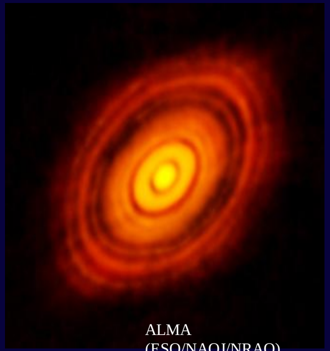
  4.3. Threshold Science

  Achieve less than 10 milli-arcsec resolution for catalogued FIR sources.

5. Instruments and data to be returned

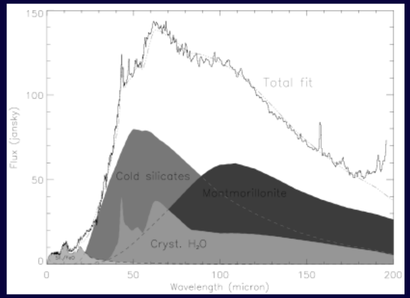
- THz intensity interferometer composed of large telescopes; ATT12, ATT30 & Dome-A Telescopes.
- FIR intensity interferometer composed of 1-m class telescopes in sun-synchronous polar orbit.
- FIR intensity interferometer composed of 10-m class telescopes in S-E L2 halo orbit.
- After real-time correlation analysis, intensity correlation data will be recorded.



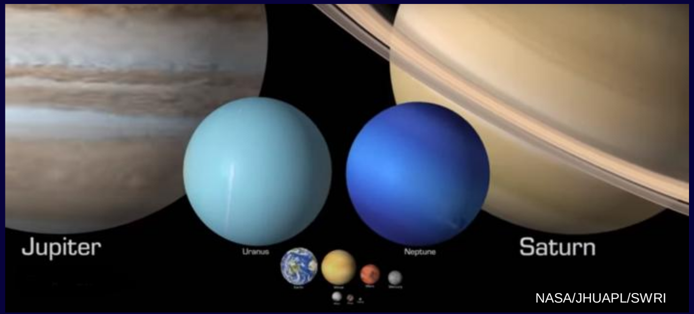


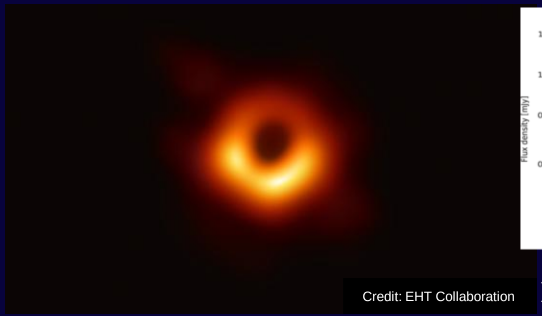
ALMA
(ESO/NAOJ/NRAO)

Water ice feature

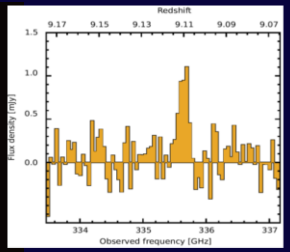


HD142527
Malfait et al. (1999)





[OIII] 88μm



Hashimoto et al. (2018)

6. Originality and international competitiveness

- ALMA and JWST are observing high redshift galaxies, but wavelength coverage is limited. Only in FIR/THz, all atomic species and dust emission can be observed to obtain the physical/chemical condition of dust and gas.
- Antarctic Dome-Fuji and Dome-A sites are the best THz observing sites with stable atmospheric conditions.
- FIR telescopes SPICA and OST were proposed, followed by the FIR probe mission. FIR interferometer is the next step, but technologies are not identified. Intensity interferometer can be a solution for long baseline and background limited sensitivity.

6. Originality and international competitiveness

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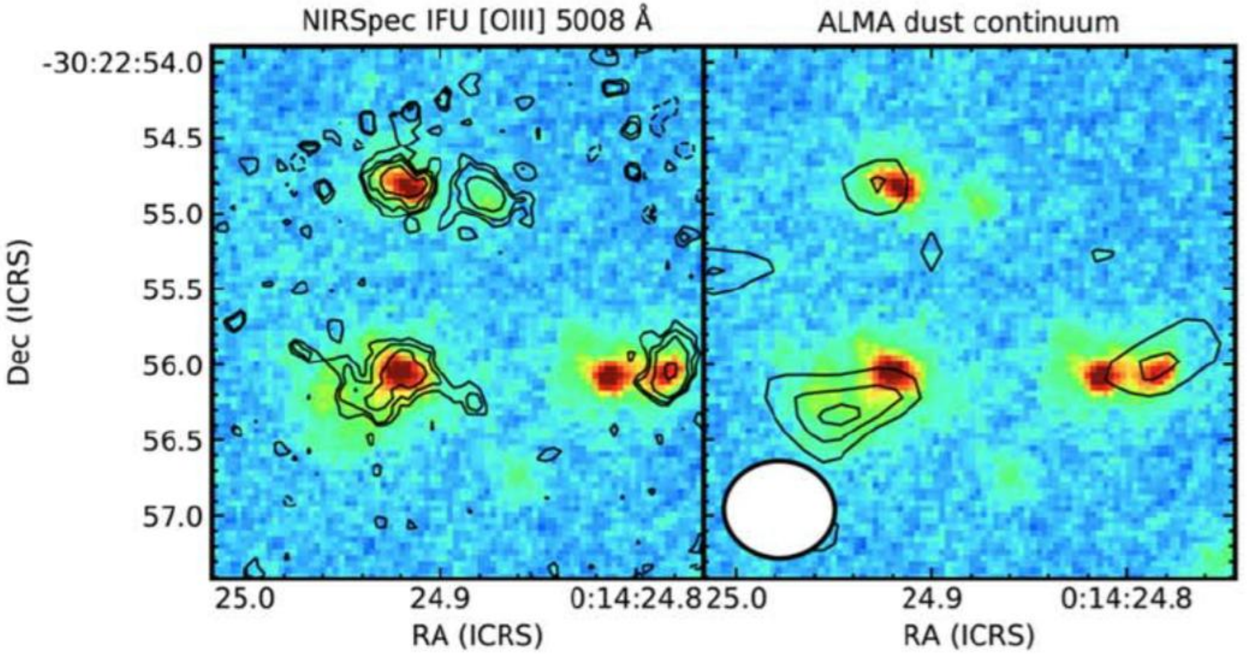
RIOJA (Reionization and the ISM/Stellar Origins with JWST and ALMA)

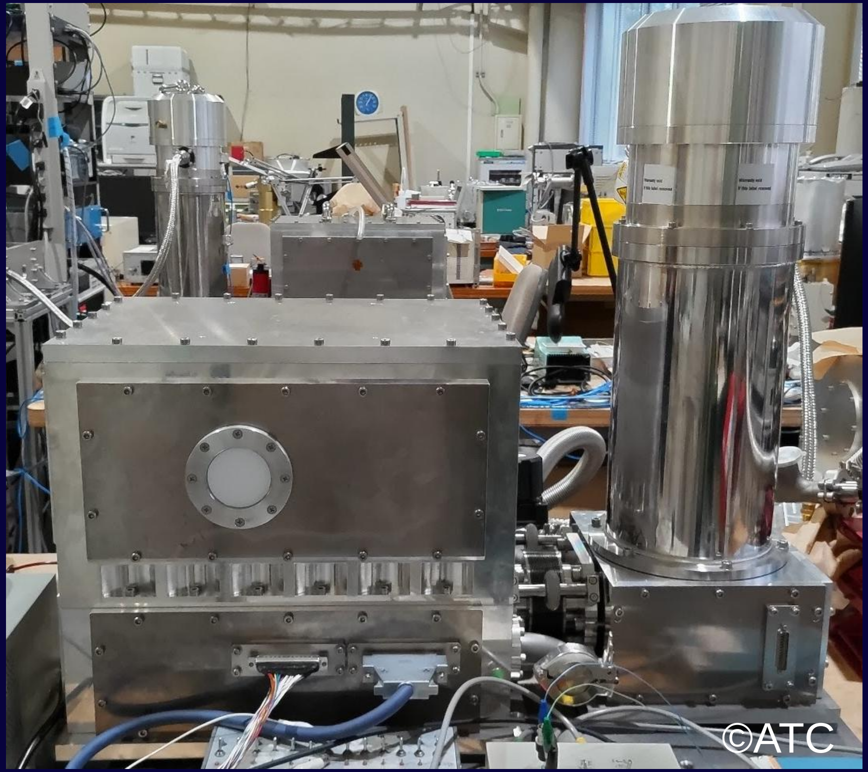
Hashimoto et al. (2023)



7. Current Status

- Now preparing laboratory demonstration of aperture synthesis imaging using a new cryostat.
- SIS photon detectors at 660 GHz and 530 GHz were developed and optical evaluations were made.
- Fast readout electronics are now under development.
- Simulations on aperture synthesis imaging was started.
- 30-cm Antarctic THz interferometer is proposed.
- Discussing formation flying for space-borne FIR interferometry

Supported by JSPS Grants for Challenging Research (20K20346, 20K20345), ISAS Basic R&D and Matsuo Foundation.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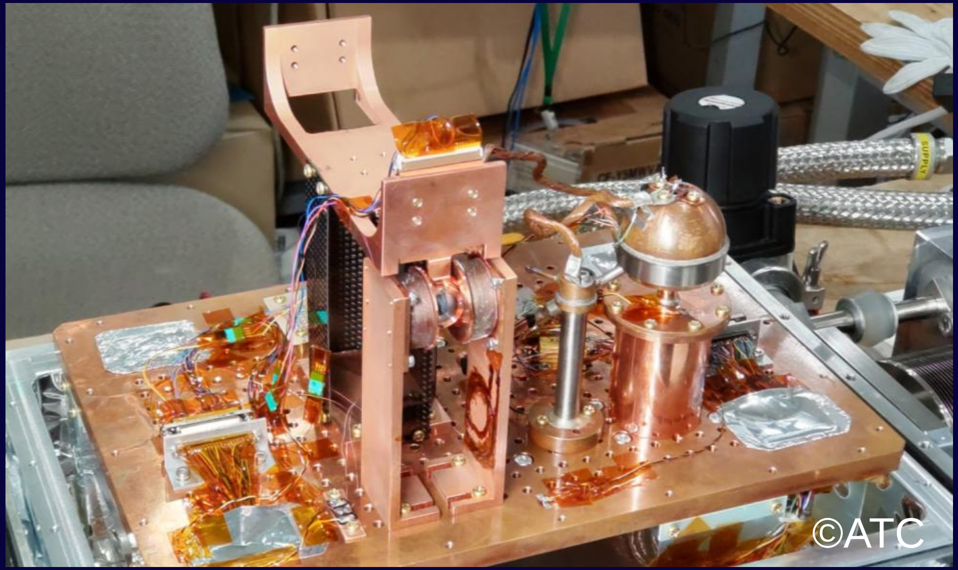
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8. Cost assessments, budget line and status

- NAOJ hire young researchers and engineers to develop detectors, electronics and interferometer technologies. (100 Myen/yr)
- Cost of Antarctic telescope should be covered separately, except for interferometer facilities.
- Cost of space-borne telescope should be covered separately, except for interferometer facilities.
- Budget for interferometer facilities is not estimated yet, which will be based on laboratory demonstration.
- The project continues until large space-borne interferometer terminate operation.

9. Project Organization

- NAOJ work for the interferometer technologies and data analysis.
- Antarctic group (universities, NIPR, PMO & NAOJ) work for Antarctic telescope operations.
- ISAS/JAXA work for the cryogenic space telescopes, formation flying (SILVIA), data acquisition etc.
- NAOJ work for organizing international partnerships.
- Current members in NAOJ
  - Matsuo, Ezawa, Oshima, Kamazaki, Wada
- Ground-based telescopes
  - Kuno, Honda, Hashimoto (U Tsukuba), Seta, Nakai (Kwansei U), Kamizuka (U Tokyo)
- Space-borne telescopes
  - Inami (Hiroshima U), Nagao (Ehime U), Izumi, Nakagawa (ISAS/JAXA), Matsuo (Nagoya U)

10. Why NAOJ ?

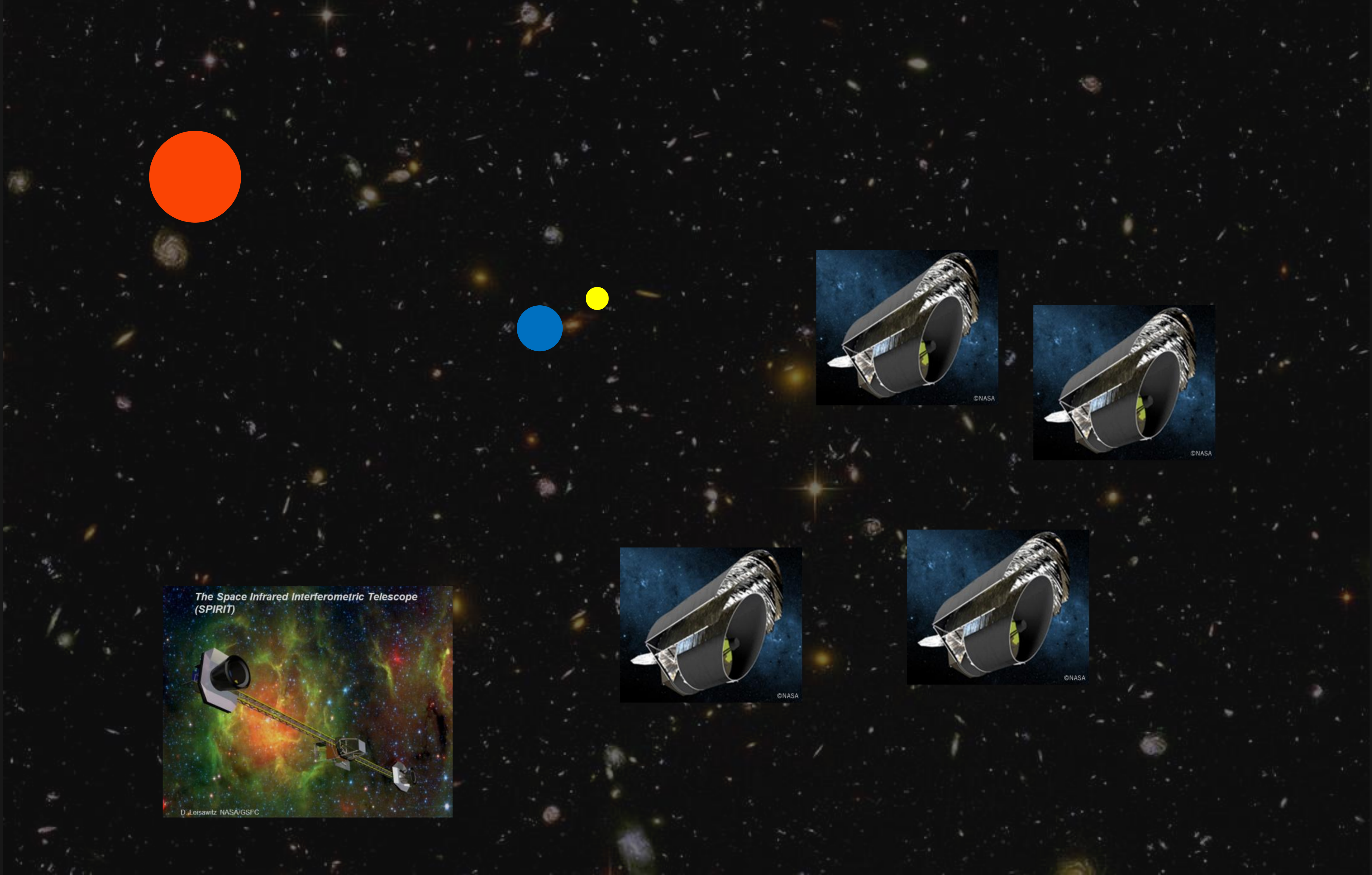
- Half of astronomical emission is emitted in FIR/THz. Utilizing high frequency radio technologies, NAOJ should be responsible to observe such astronomical targets in collaboration with universities, ISAS/JAXA and international partners.
- ATC/NAOJ can work on development of intensity interferometer technologies. NAOJ can contribute to Antarctic telescopes (with Japanese universities) and the FIR probe mission (main contribution by ISAS/JAXA), based on past activities in high radio frequencies.

11. Collaboration and spillover effects outside astronomy

- In FIR/THz duality of wave and particle can play role, intensity interferometry is one of such applications.
- Photon statistics can be a new tool for astronomy
- Quantum measurements utilizing THz photons with photonic technology and superconducting/microwave technologies for compact system at moderate temperature (~1 K).
- THz applications have been limited due to detector sensitivities. Fast photon detector will revolutionize such applications as material characterization and imaging.

1. Summary of the proposal

- Science goals and objectives
  - Identify heavy elements in our universe by FIR/THz emission with high angular resolution and high sensitivity observations to study formation and evolution of astronomical sources.
- Science investigations, instrumentation and data
  - Install FIR/THz intensity interferometers in Antarctic plateau and in space.
- Threshold science
  - Realize at least 10 milli-arcsec angular resolution images for cataloged FIR sources.
- Cost estimation
  - Development of interferometer system should be covered by NAOJ.
- Project Organization
  - Antarctic interferometers need collaboration with NIPR and PMO.
  - Space-borne interferometer need collaboration with ISAS/JAXA and international partners.


The Space Infrared Interferometric Telescope (SPIRIT)
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