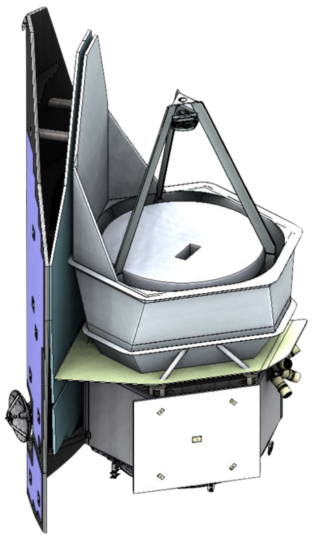
Japanese Contribution to the Science Preparation for NASA FIR-Probe Mission PRIMA

T. Nagao (Ehime U.), H. Inami (Hiroshima U.), T. Onaka (U. of Tokyo), T. Hashimoto, Y. Takeuchi (U. of Tsukuba), T. Nakagawa (ISAS), S. Matsuura (Kwansei Gakuin U.), and "PRIMA Science Book" Co-authors



PRIMA: The PRobe far-Infrared Mission for Astrophysics
- Cooled 1.8m-aperture Infrared Space Telescope
- PI: Jason Glenn (GSFC) / Science Lead: Alexandra Pope (UMass)
- One of the candidates for the NASA probe mission

Instruments
- FIRESS (PRIMA Far-IR Enhanced Survey Spectrometer)
  - 24-235 μm, R=130 (FTS R=4,400 @ 112 μm)
- PRIMAger
  - 24-84 μm (12 filters), R=10
  - 80-261 μm (4 filters), R=4, with Polarimeter

Key Sciences (c.f. PRIMA Science Book: arXiv:2310.20527)
- Growth of Galaxies and Black Holes
- The Rise of Metals and Dust
- Cosmic Ecosystem
- Star and Planet Formation

FIR-Probe/PRIMA Milestones

12 Jun. 2023: Research Group (RG) established in ISAS
Nov. 2023: NASA Step1 proposal submitted
Q4 in 2024: Release of the Step1 selection result
Working Group (WG) will be established in ISAS
Q2 in 2026: Release of the NASA final selection result
June 2031: Launch

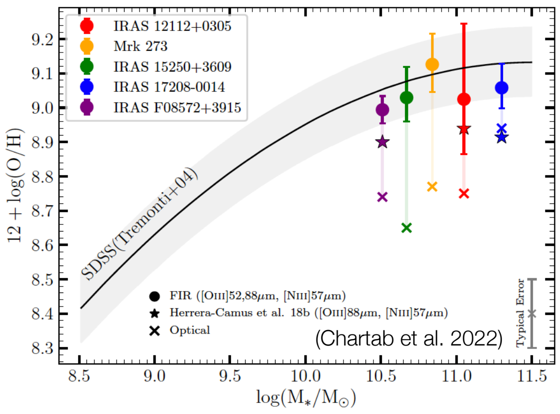
Any science inputs from Japanese community are highly welcome !!

FIR science workshop at ISAS: 19-20 Feb
(Please contact Nagao/Inami if you are interested in)

Metallicity of dusty galaxies in the cosmic noon

T. Nagao, J. A. Fernández-Ontiveros, T. Hashimoto, K. Ichikawa, H. Inami, T. Izumi, B. Pérez-Díaz, E. Pérez-Montero, L. Spinoglio, T. T. Takeuchi, Y. Tamura, H. Umehata, J. Vílchez, T. Wada

Optical spectroscopic observations of dusty star-forming galaxies (such as LIRGs/ULIRGs) in low-z Universe tend to show significantly lower metallicity than optically-thin galaxies with a similar stellar mass (e.g., Rupke et al. 2008; Caputi et al. 2008). However, this result is largely affected by the extinction effect and thus the inferred metallicity is significantly underestimated, revealed by FIR spectroscopy (e.g., Chartab et al. 2022).



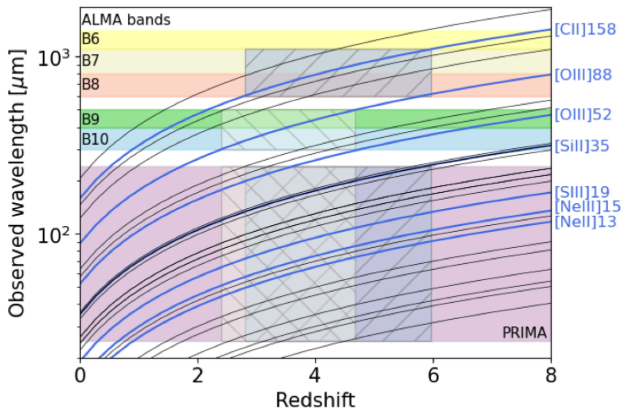
(Chartab et al. 2022)

Then, how about the metallicity of dusty star-forming galaxies in the cosmic noon (z~2) where the cosmic star-formation and metal enrichment show their peaks? To explore their metallicity without suffering the extinction effect, PRIMA's superb sensitivity in the FIR spectroscopy is crucial.

Complete view of the ISM at the era of peak galaxy growth

H. Inami, A. Vishwas, L. Spinoglio., J. A. Fernández-Ontiveros, T. Nagao, H. Umehata, J. Surace

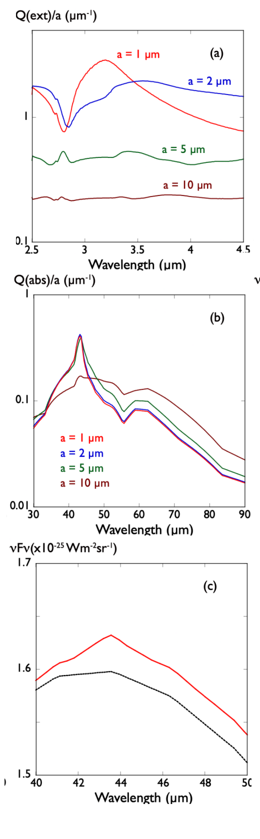
During the peak of galaxy evolution, a majority of galaxies are obscured by interstellar dust, making infrared observations indispensable. By comparing galaxies identified at optical and near-infrared with the Subaru Telescope, we will be able to finally reveal a more complete picture of galaxy properties and their evolution.



Subaru's expertise in wide-area surveys aligns particularly well with PRIMA, which has an aptitude for large-scale surveys. PRIMA covers 25-260um, including emission lines that directly trace the physical and chemical properties of the ISM (see the figure below). PRIMA will probe ISM conditions behind the dust, from cosmic noon to today. Exploring regimes uncharted due to insufficient sensitivity in previous infrared observations, PRIMA aims to uncover how the Universe evolved into a world rich in heavy elements.

Search for missing oxygen in the interstellar medium

T. Onaka[1], I. Sakon[1], T. Shimonishi[2], M. Honda[3]
(1: U. Of Tokyo, 2: Niigata U., 3: Okayama U. of Sci.)



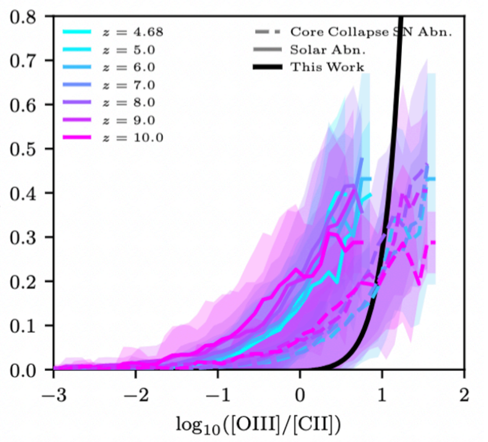
The recent study of interstellar elemental depletion poses an important problem in the interstellar matter that at least a quarter of the total oxygen (~160 ppm relative to hydrogen) is not accounted for in any known form in the translucent or dense interstellar medium (ISM). The study of the 3 μm absorption feature of water ice suggests that one fifth of the missing oxygen may reside in 3 μm-size water ice grains. Recent near-infrared (NIR) spectroscopy indicates the ubiquitous presence of water ice in star-forming regions, further supporting a possibility that a significant fraction of oxygen may hide in even larger water ice grains in the dense ISM. However, the 3 μm feature becomes complex and weak for grains larger than 3 μm, and thus the NIR spectroscopy is not the best means to study large ice grains reliably. Here we show that sensitive observations of the far-infrared (FIR) features of water ice at 44 and 62 μm enable us to constrain the amount of crystalline water ice grains up to 5 μm or even larger accurately. Oxygen is one of the key elements of the ISM chemistry, and [O I] 63 μm is a dominant cooling line in the neutral ISM. The understanding of the actual form of the missing oxygen in the ISM is crucial for the study of the ISM and star-formation. To detect the FIR features of the crystalline water ice over the expected strong continuum, a sensitive FIR spectrograph represented by PRIMA/FIRESS is indispensable for this study. Since the feature is broad, the low resolution of R~130 is sufficient, but accurate relative calibration better than 1% is required.

FIR spectroscopy of low-z ionizing-photon leakers

T. Hashimoto (U. of Tsukuba), et al.

Understanding the process and drivers of cosmic reionization, the final phase transition in the universe that occurred between redshifts of ~ 6 and 20 (the cosmic age of around 200 Myr and 1 Gyr), is one of the most important issues in modern astronomy. One of the key parameters is the escape fraction (f_{esc}) of ionizing photons (LyC), however, direct observation of LyC is impossible in the early universe due to absorption by neutral hydrogen atoms in the intergalactic medium.

Theoretical studies show that the luminosity ratio of the far-infrared (FIR) fine structure lines, [OIII] 88 μm/[CII] 158 μm, can correlate with fesc (figure). Our



pilot study with NASA/SOFIA (Ura & Hashimoto et al. 2023, ApJ) indeed demonstrated the potential of the line ratios to obtain f_{esc}, although the sample is small. Here we propose to use PRIMA to observe FIR lines in a statistical number of local analogues of high-z galaxies. With PRIMA, we can simultaneously target [OIII] 52/88 μm, [CII] 158 μm, as well as other FIR lines, that are essential to break the degeneracy of the dependence of [OIII] 88 μm/[CII] 158 μm. We calibrate the technique and apply to high-z galaxies observed with ALMA.

Search for the radiative decay of the cosmic neutrino background by CIB spectral measurements

Y. Takeuchi[1], S. Matsuura[2], S. H. Kim[1], T. Iida[1] (1: U. of Tsukuba, 2: Kwansei Gakuin U.)

We propose an unprecedented and unique search for the distinctive FIR spectrum contributed from radiative neutrino decay ($\nu_3 \rightarrow \nu_{1,2}+\gamma$) of the cosmic background neutrino (CνB) through the precise measurement of in the Cosmic Infrared Background (CIB) spectrum.

The heaviest (third-generation) neutrino (ν_3) has:
- An expected lifetime of ν_3 of $O(10^{43})$ years in the Standard Model of particle physics.
- The possibility of shorter lifetimes ranging from $O(10^{14})$ years to $O(10^{17})$ years in non-standard models.
- Only a lower limit of $O(10^{12})$ years based on previous observations in terms of lifetime.

The photons generated from CνB decay, originating from the two-body decay of neutrinos uniformly distributed throughout the universe, yield a spectrum characterized by a sigmoidal-like function with a sharp rise at a wavelength of 50 μm, assuming a mass (m_3) for ν_3 to be 50 meV (Fig.1). On the other hand, when integrating over a sufficiently wide field of view (~1° sq.), the cumulative light from distant galaxies, unidentifiable as point sources, is expected to approach a continuous distribution. Consequently, it becomes feasible to search for the sharp rising edge of CνB decay contribution.

For 100 hours of observations in PRIMA's mapping mode, it is possible to explore lifetimes in $O(10^{15})$ years for ν_3 (Fig. 2). If neutrino radiative decay were observed at these sensitivities, it would not only serve as compelling evidence for non-standard model contributions to neutrino decay but also represent a direct detection of CνB. Furthermore, information on the neutrino absolute masses and cosmological parameters can be obtained from the spectrum.

Since excluding emission lines from distant galaxies is crucial for sensitivity improvement, information on more distant galaxy maps obtained by Subaru/PFS will be of significant assistance to this observation.