Developing Far-Infrared Astronomy with PRIMA

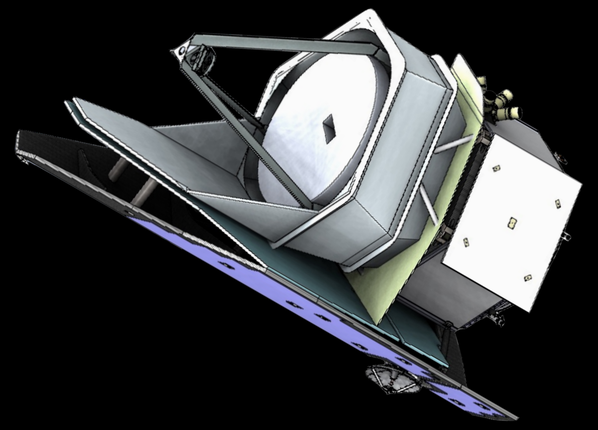
Hanae Inami
(Hiroshima University)

Hideko Nomura, Shinobu Ozaki, Ryuji Suzuki, Yoshiki Toba, Ayaka Okuya (NAOJ)
Tohru Nagao (Ehime U), Shuji Matsuura (Kwansei Gakuin U)
Hidehiro Kaneda, Takuma Kokusho (Nagoya U)
Issei Yamamura, Takao Nakagawa (ISAS/JAXA)

2024/12/04

NASA FIR-Probe PRIMA

PRobe far-Infrared Mission for Astrophysics



- Cryogenically cooled far-infrared observatory (D=1.8m)
- Wavelength coverage: 24—250μm
  - Imaging, Polarimetry, Spectroscopy
- Planned launch: June 2031 (NASA’s requirement no later than July 2032)
- Sun-Earth L2, 5 years on orbit
- Observing time: 25% PI science + 75% Guest Observer (GO) science
  - Guest Investigator (GI) science: science that uses PI science data

Science Goals

- **What are the chemical processes in protoplanetary disks and star formation?**
  - How much H_2O and hydrogen is there? What are the elemental abundances?
- **How did galaxies and massive black holes build up?**
  - What is the origin of the co-evolution of blackholes and star formation?
- **How did heavy elements form and evolve to create the current world?**
  - What are the metallicity and dust properties and their relationship?

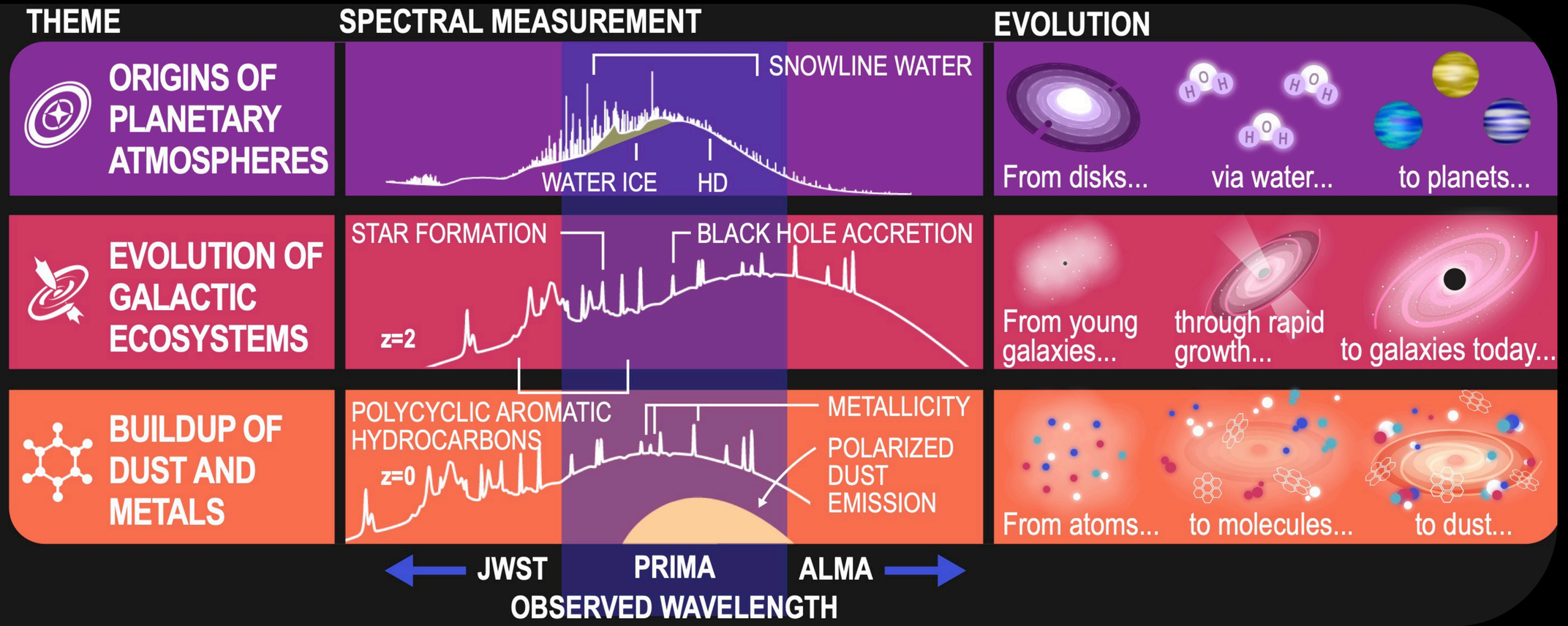
Astro2020 Sec 7.5.3.3

and a probe scale mission is an extremely timely and compelling opportunity to do so. These scientific areas include tracing the astrochemical signatures of planet formation (within and outside of our own Solar System), measuring the formation and buildup of galaxies, heavy elements, and interstellar dust from the first galaxies to today, and probing the co-evolution of galaxies and their supermassive black holes across cosmic time. These goals are all central to the broader scientific themes of the survey. The

Scientific Objectives

Far-Infrared Observations

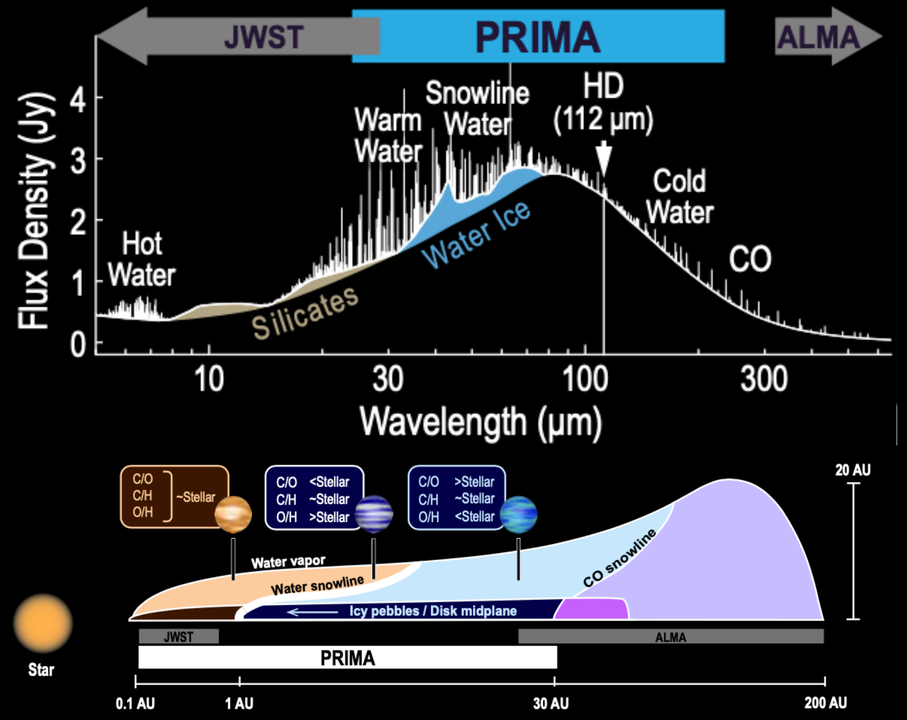
PRIMA uses the power of the far-infrared to see into the hearts of dusty and obscured sources across cosmic time.

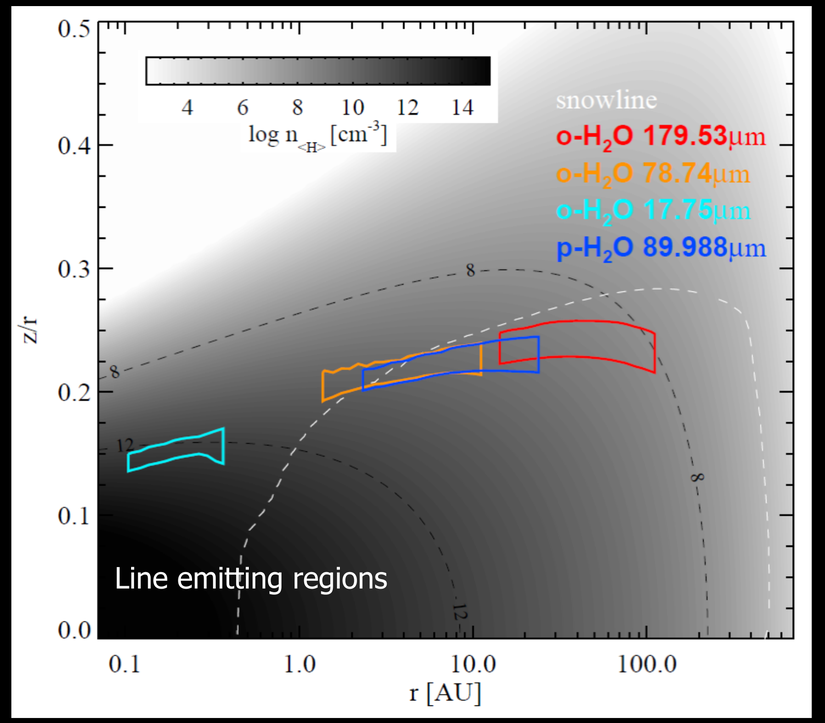


Science Investigations

Science Investigations until 2033 and beyond 2034, synergy with NAOJ

ALMA: Molecular lines
Subaru/TMT: H_2O ice
PRIMA: Thermal processes and history traced by H_2O water and ice





Kamp et al. 2021

Contributed by Hideko Nomura (NAOJ)

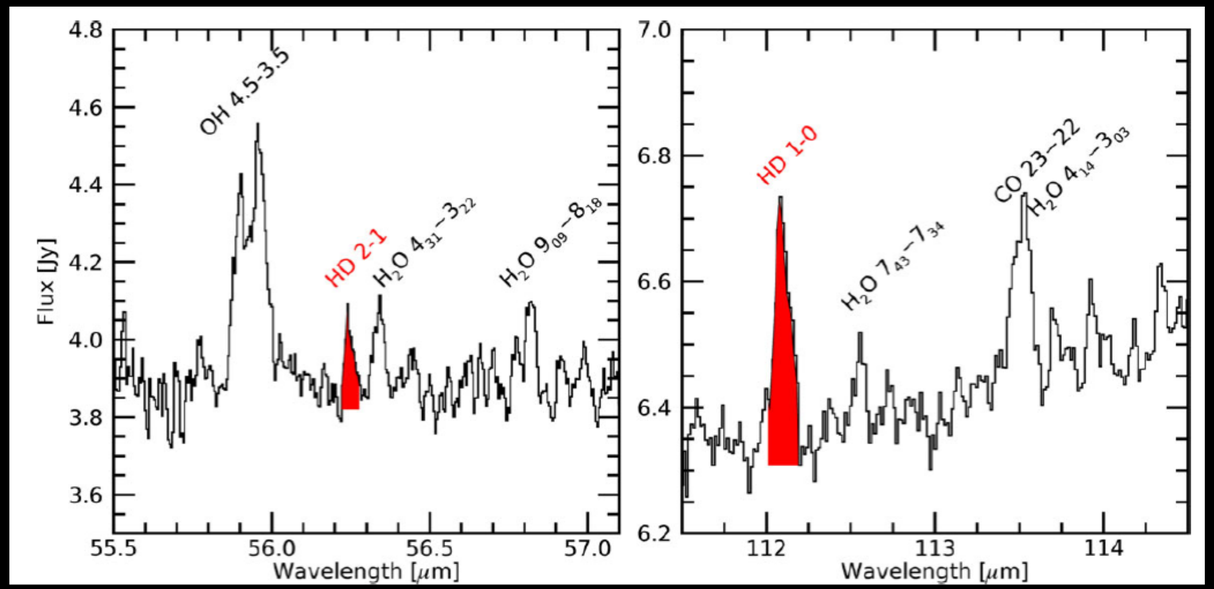
Science Investigations

Science Investigations until 2033 and beyond 2034, synergy with NAOJ

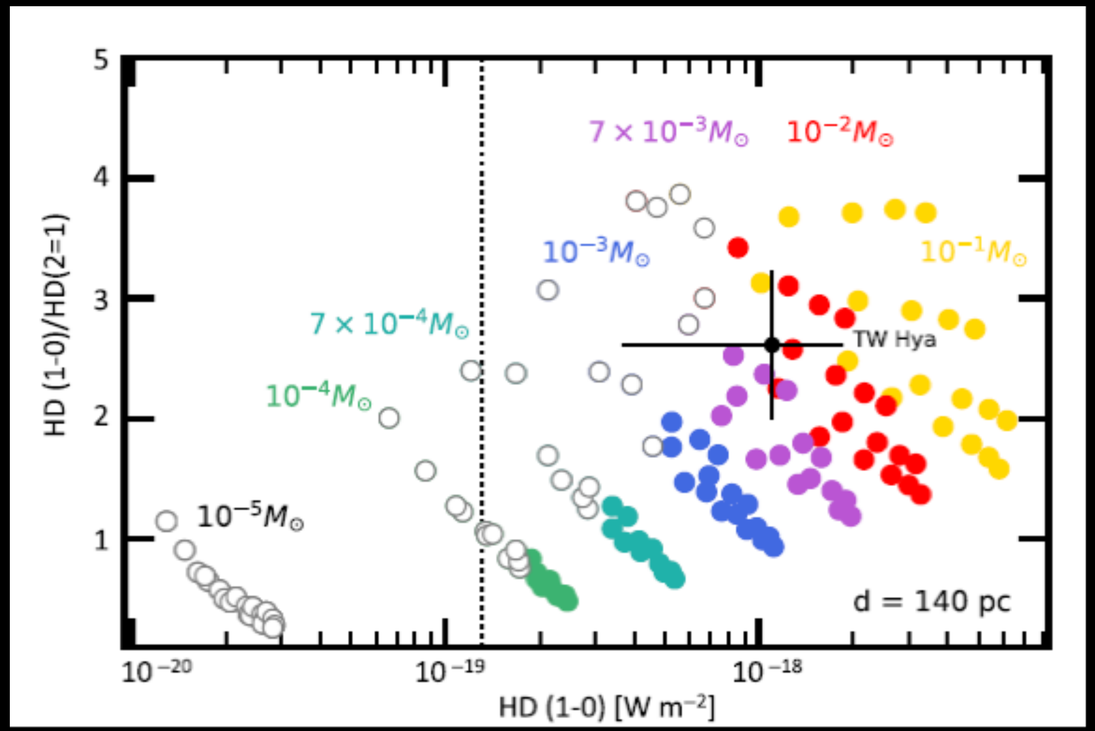
ALMA: has played an important role in detecting dust and CO gas

PRIMA: H_2 gas mass in disks can be traced by HD lines in the far-IR

TW Hya observed by Herschel



HD lines were only observed in a few protoplanetary disks



Bergin et al. 2013, Kamp et al. 2021

Contributed by Hideko Nomura (NAOJ)

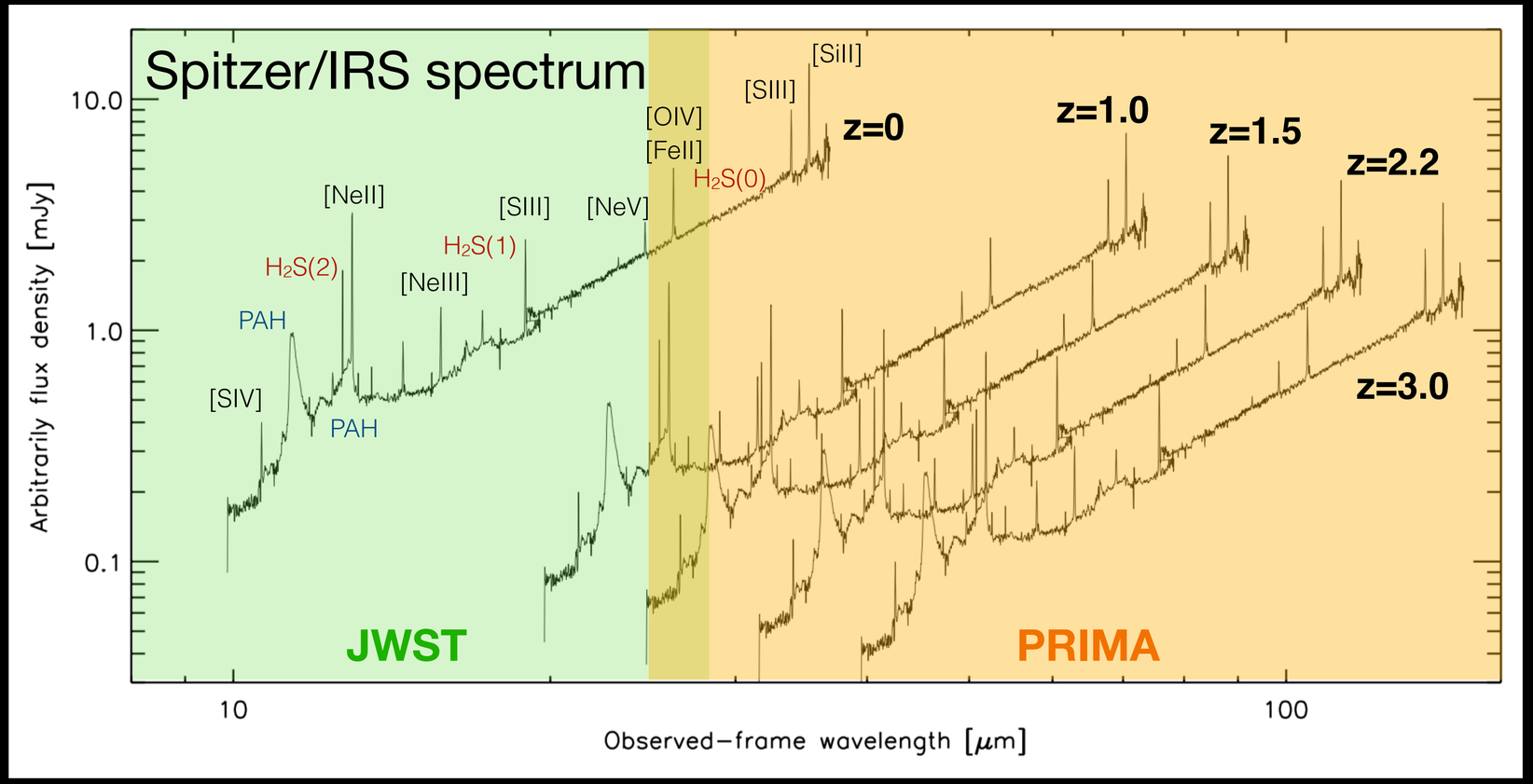
EVOLUTION OF GALACTIC ECOSYSTEMS

BUILDUP OF DUST AND METALS

Science Investigations

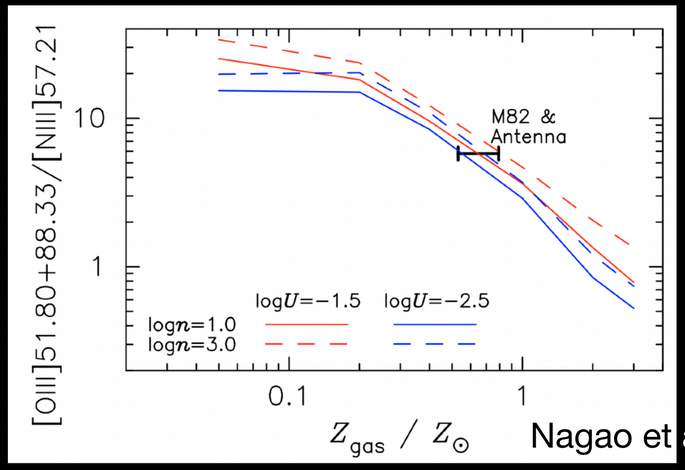
Science Investigations until 2033 and beyond 2034, synergy with NAOJ

Mid- to far-IR spectral coverage

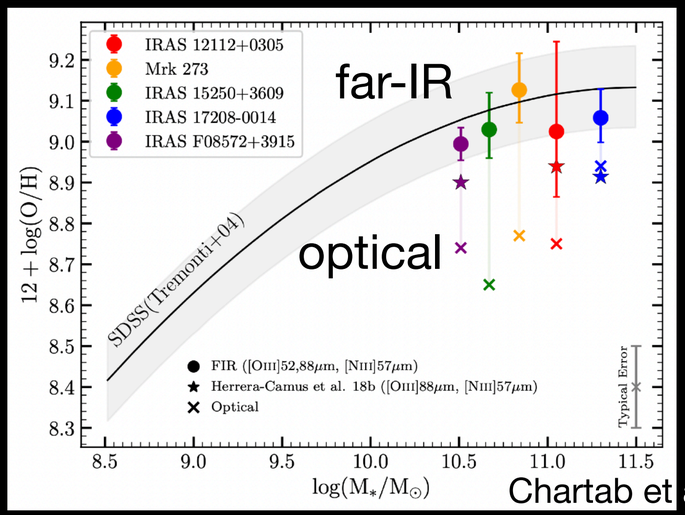


A local LIRG spectrum

Dust-free metallicity measurements



Nagao et al. 2011



Chartab et al. 2022

EVOLUTION OF GALACTIC ECOSYSTEMS

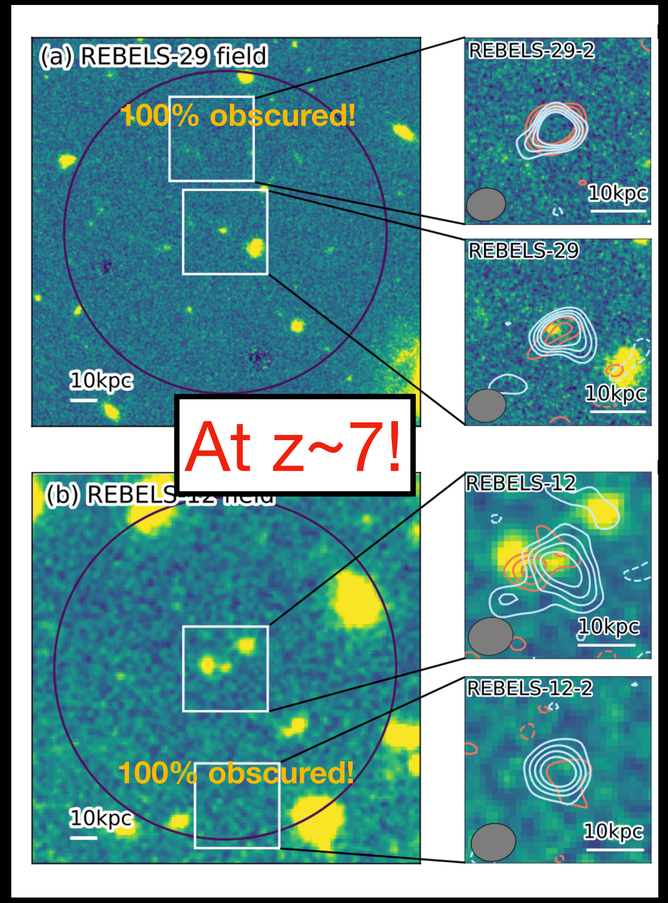
BUILDUP OF DUST AND METALS

Science Investigations

Science Investigations until 2033 and beyond 2034, synergy with NAOJ

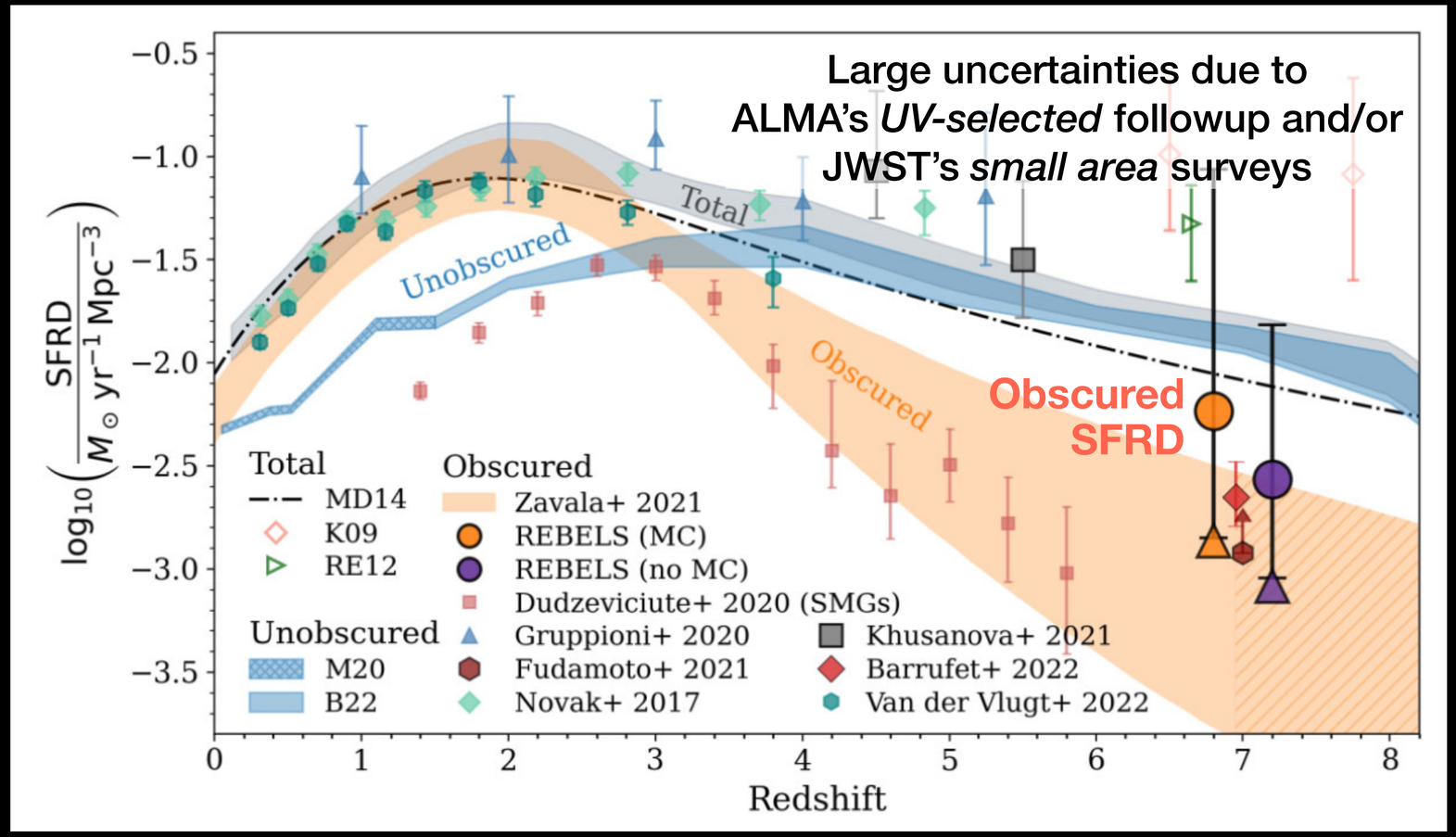
ALMA discovered that the distant Universe is dusty!

Unbiased large surveys by PRIMA



Fudamoto et al. 2021

Red: dust, White: [CII]



Algera et al. 2023

EVOLUTION OF GALACTIC ECOSYSTEMS

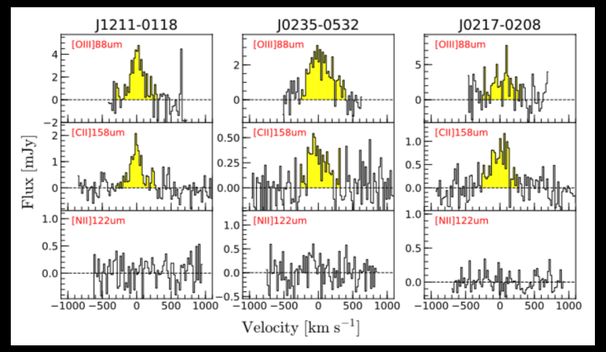
BUILDUP OF DUST AND METALS

Science Investigations

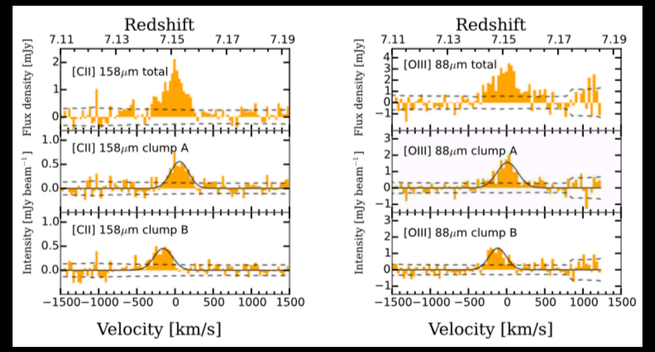
Science Investigations until 2033 and beyond 2034, synergy with NAOJ

ALMA
[OIII]88, [CII]158, [NII]122,205

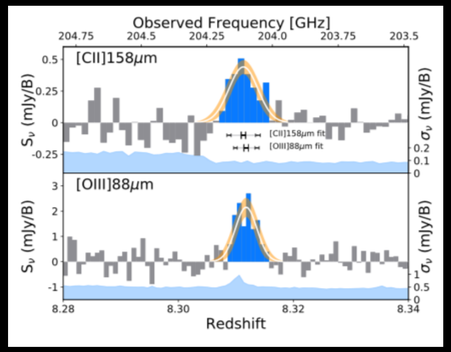
PRIMA will
add [O III]52, [N III]57, [O I]63,145
offer a wider redshift coverage



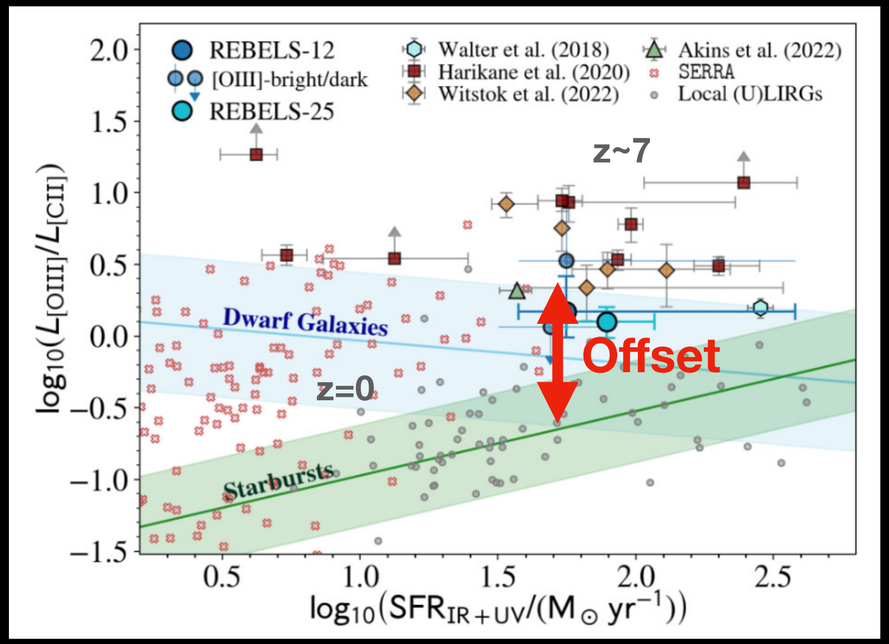
Harikane et al. 2020

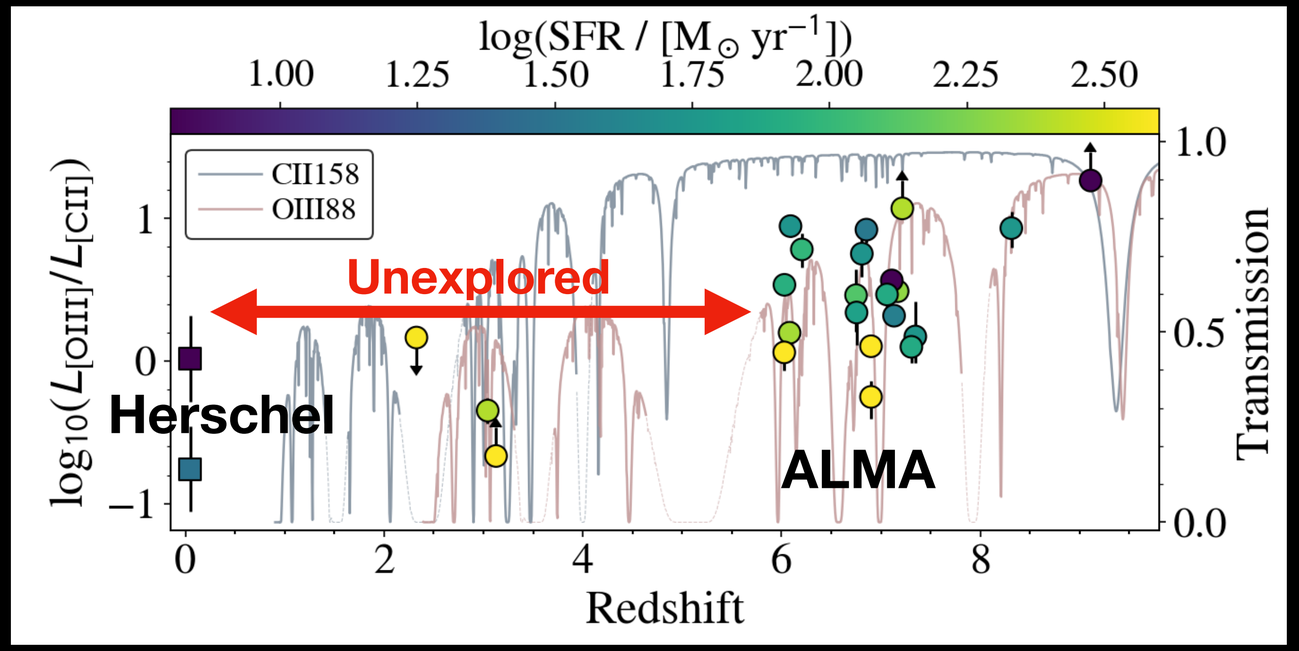


Hashimoto et al. 2019, Sugahara et al. 2021



Tamura et al. 2019, Bakx et al. 2020





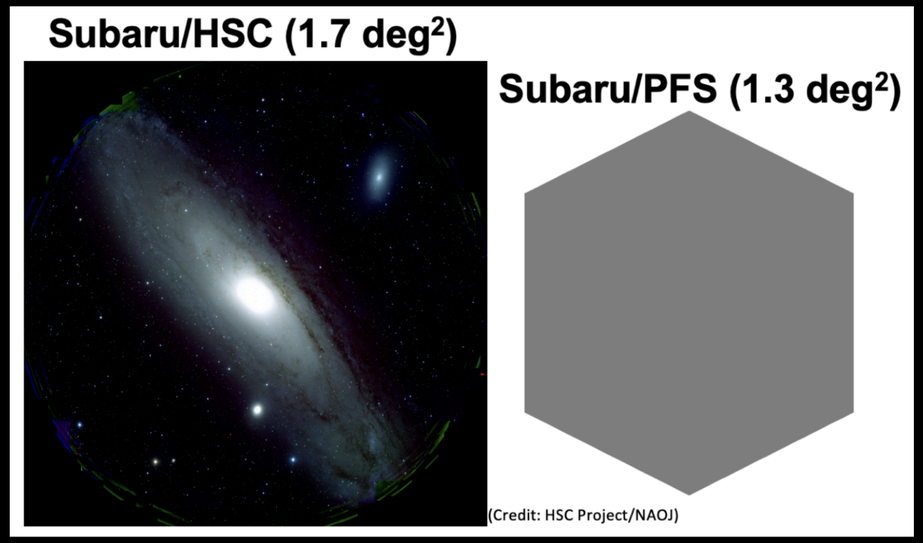
Algera et al. 2023

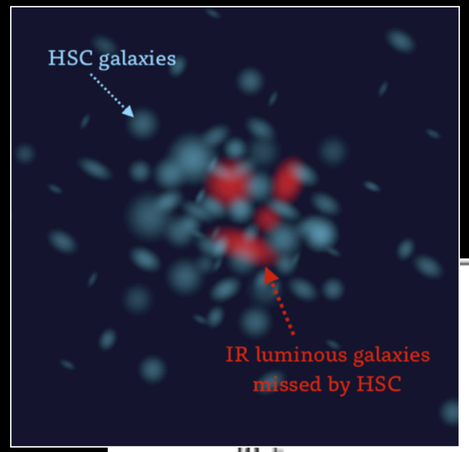
EVOLUTION OF GALACTIC ECOSYSTEMS

BUILDUP OF DUST AND METALS

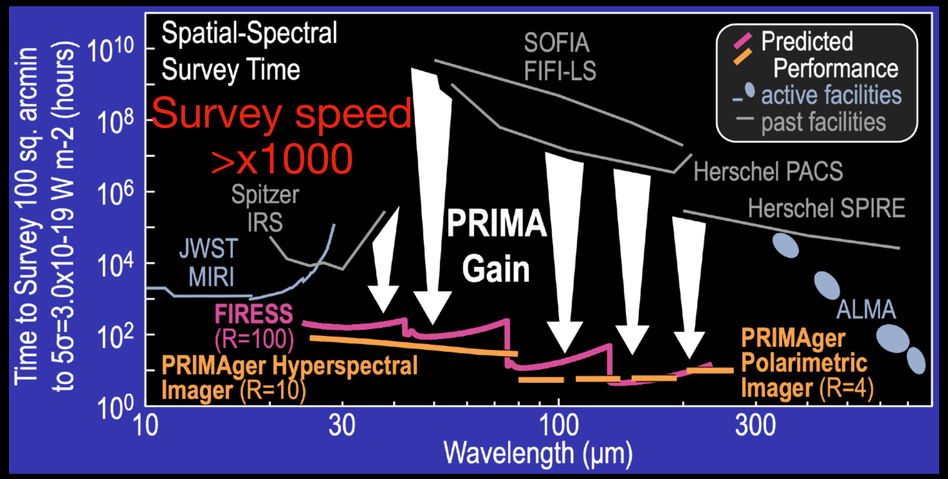
Science Investigations

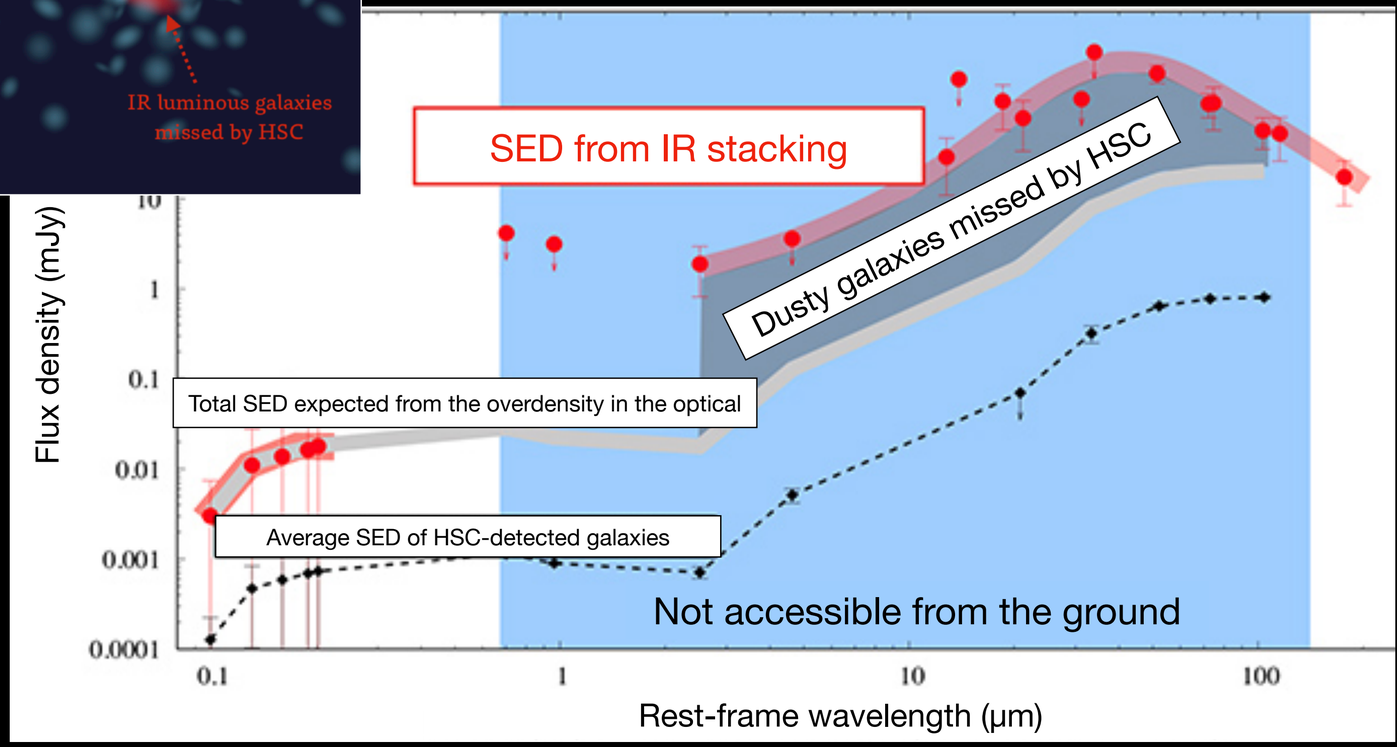
Science Investigations until 2033 and beyond 2034, synergy with NAOJ





Excellent synergies with Subaru
HSC, PFS, ULTIMATE





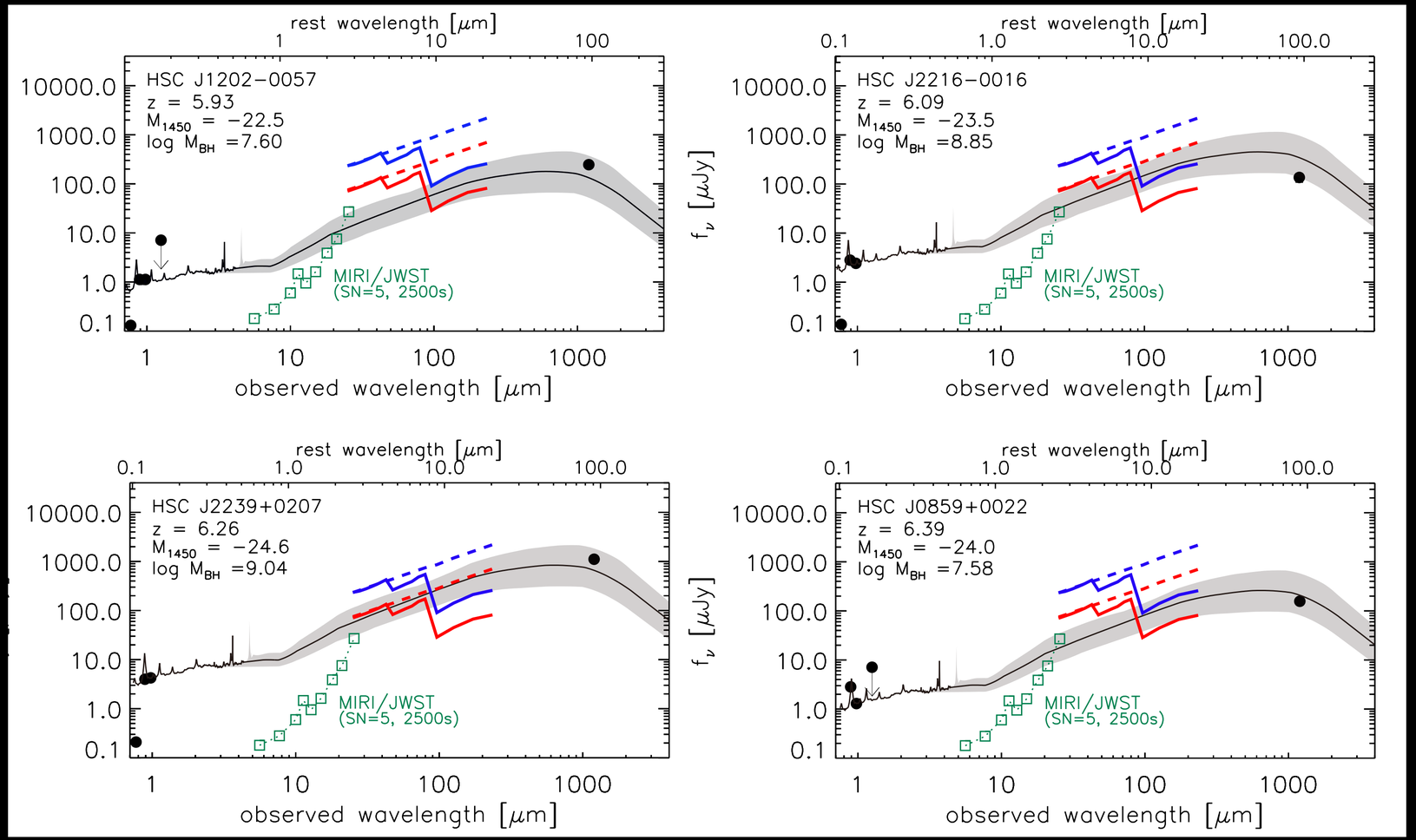
Kubo et al. 2019 / NAOJ

EVOLUTION OF GALACTIC ECOSYSTEMS

BUILDUP OF DUST AND METALS

Science Investigations

Science Investigations until 2033 and beyond 2034, synergy with NAOJ

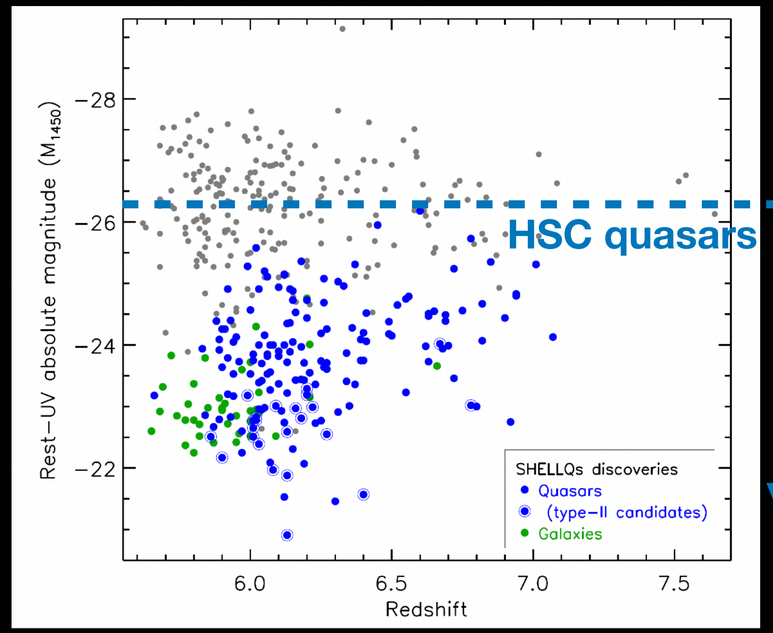


Deep (conservative)

Deep (payload)

Wide (conservative)

Wide (payload)



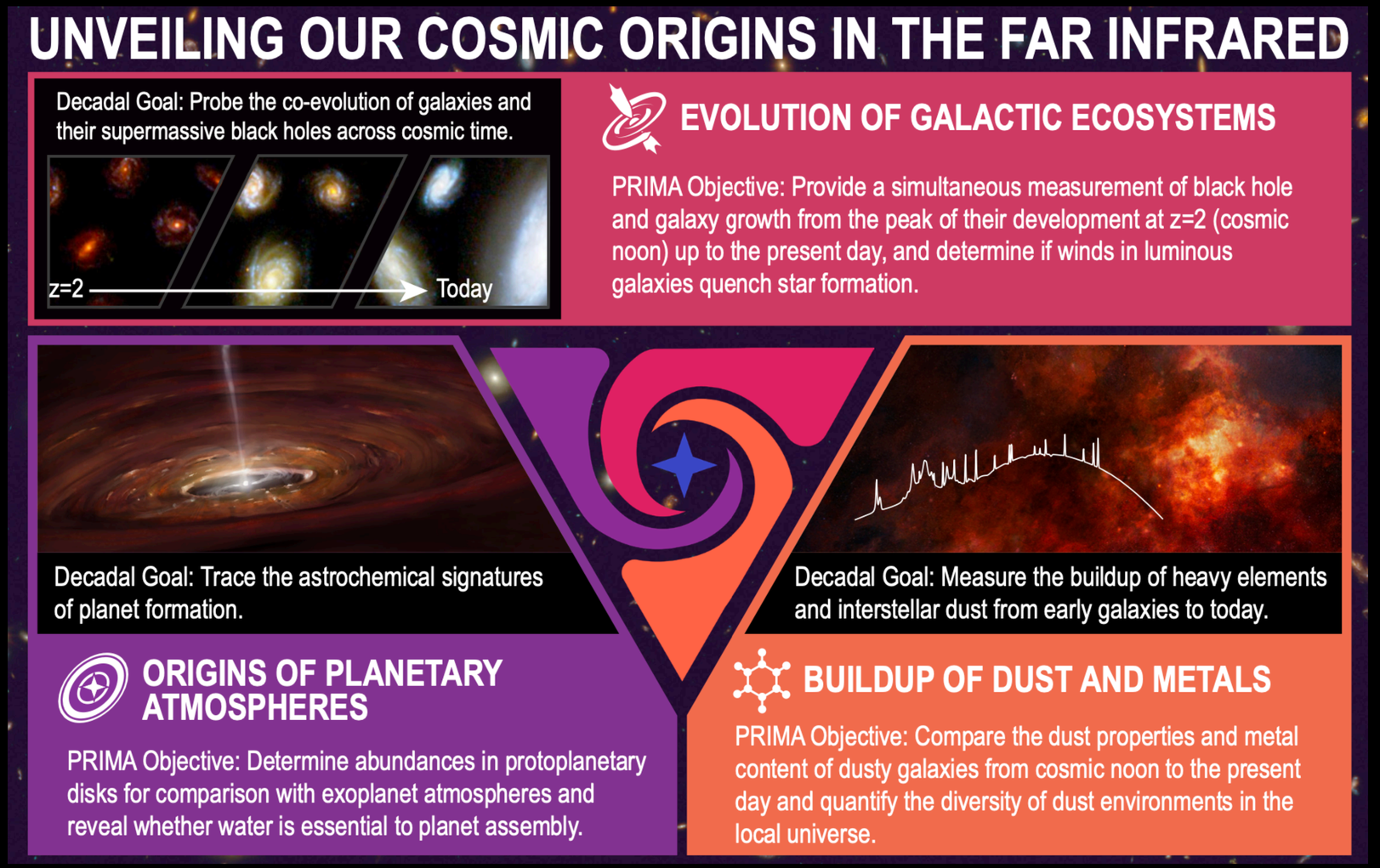
Contributed by Toba Yoshiki (NAOJ)

Matsuoka et al. 2022

Science Investigations

Threshold Science

PI Science



Infrared SED
PAH
[Ne II], [O IV]

H_2O and HD lines

[O III], [N III]
PAH
Polarization

Instruments and Data to be Returned

Japanese contributions to PRIMA science +

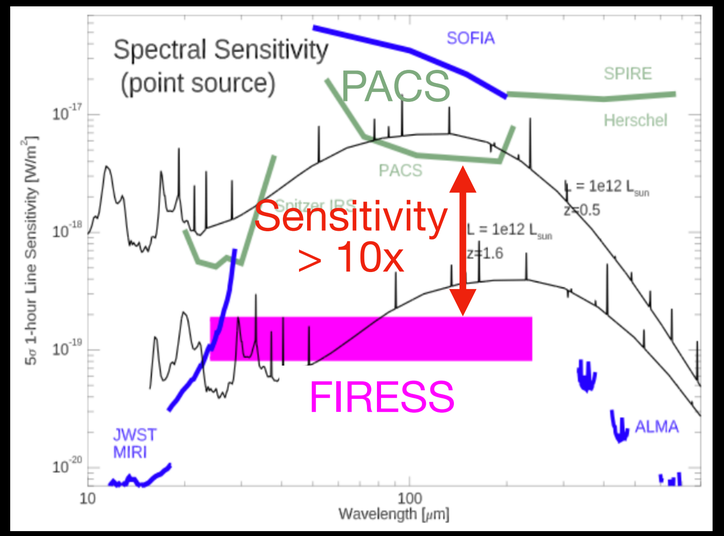
Spectroscopy: FIRESS (24-235μm) [US]

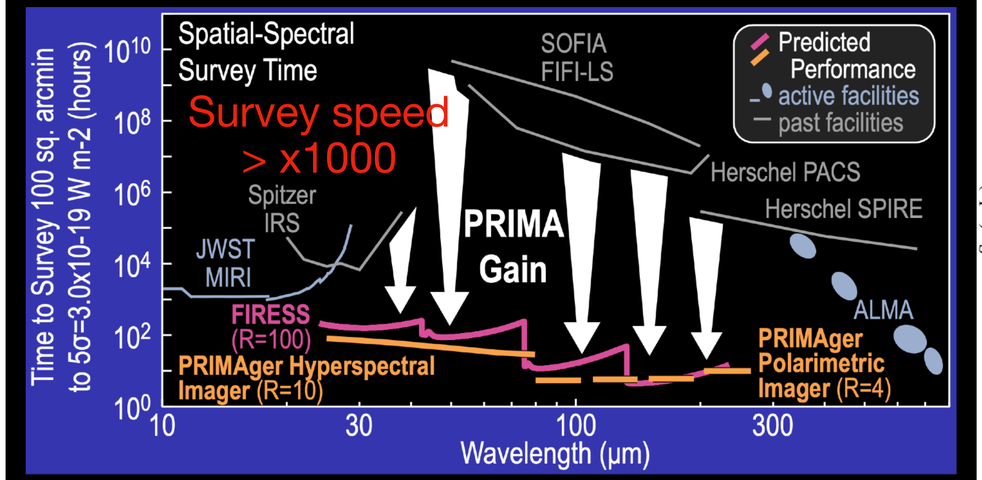
- Low-resolution mode (R > 85)
  - 4 bands, 2-band simultaneous obs.
- High-resolution mode (Fourier spec.)
  - Max R = 4,400 x (112μm / λ)

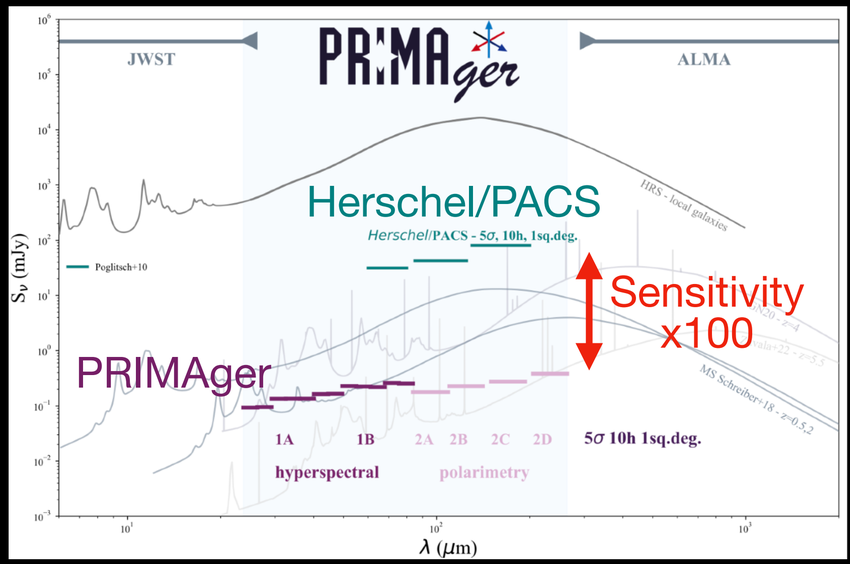
Imaging: PRIMAger (24-261μm) [France]

- Imaging: 24-84μm
  (R=10, the first in the FIR)
- Imaging + polarimetry: 80-261μm
  (4 bands, R=4)

+others



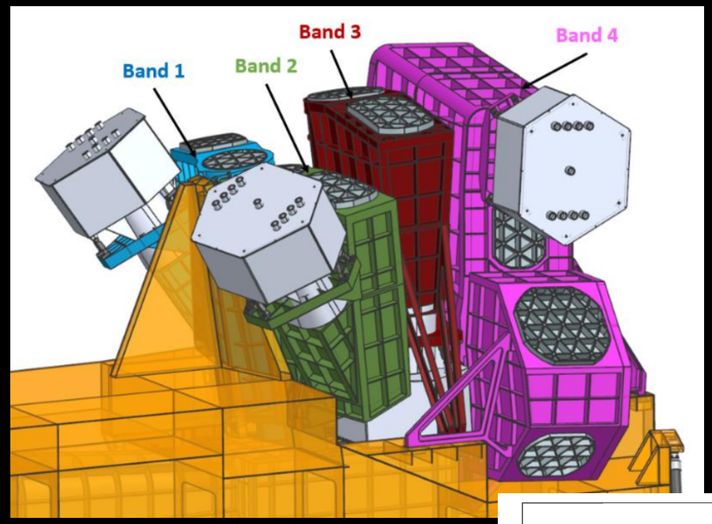




Instruments and Data to be Returned

Candidates for Japanese contributions

- **PI Science**
  - Target selections, software/simulators, etc
- **Cryo-optics with freeform mirrors**
  - Bands 1 and 2 or
    All optical elements for all 4 Bands
  - Demonstrating a single mirror with NINS/Open Mix Lab
- **Data downlink**
  - JAXA's Misasa Deep Space Station
  - Roman's heritage
- **Cryogenics**
  - 18K shield for the payload
- **Spacecraft components**



Rodgers et al. 2023

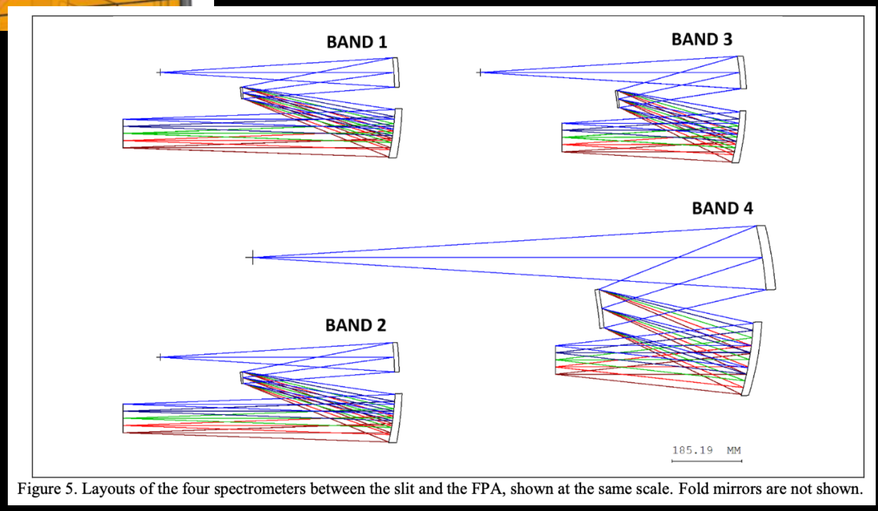
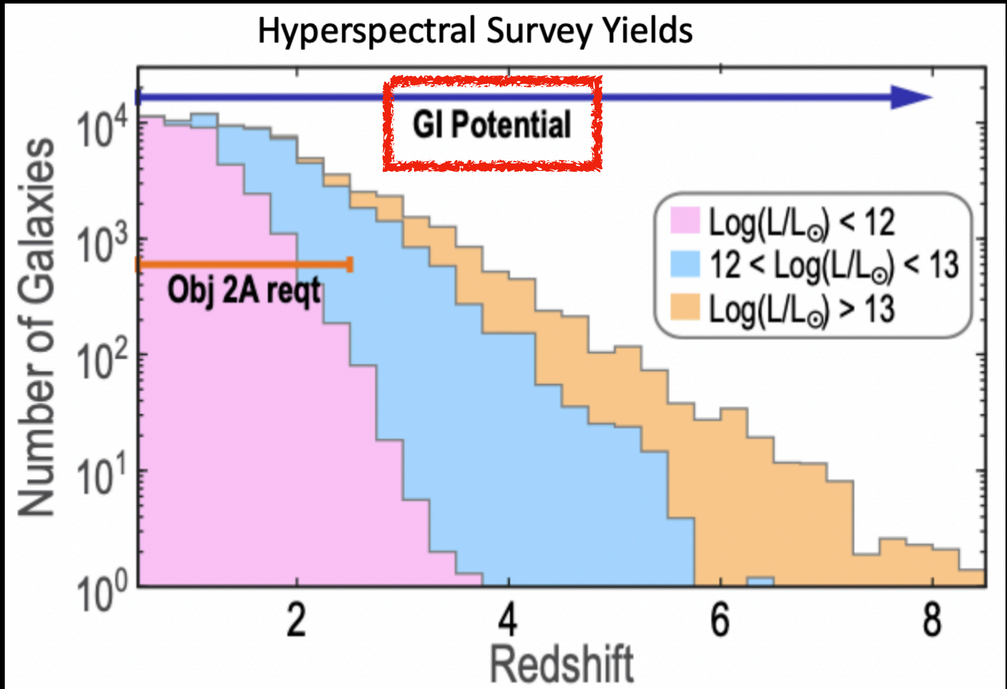


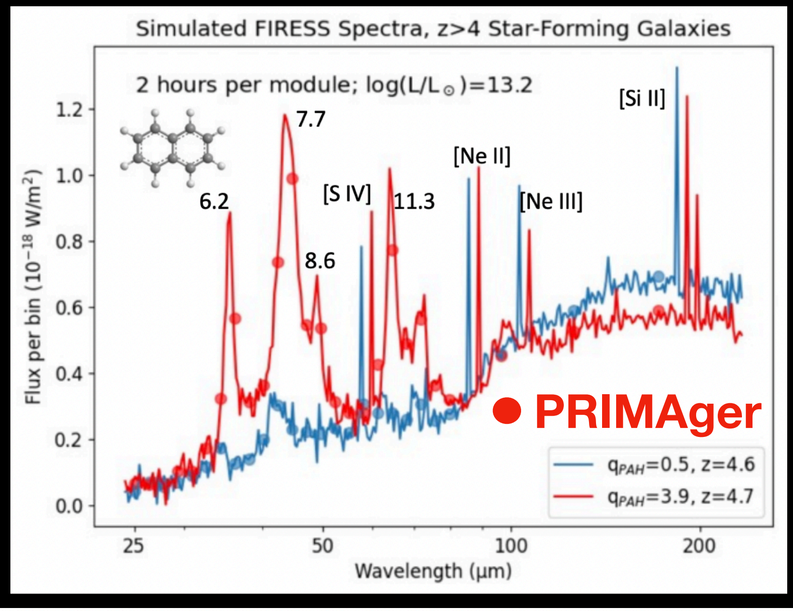
Figure 5. Layouts of the four spectrometers between the slit and the FPA, shown at the same scale. Fold mirrors are not shown.

Data to be Returned

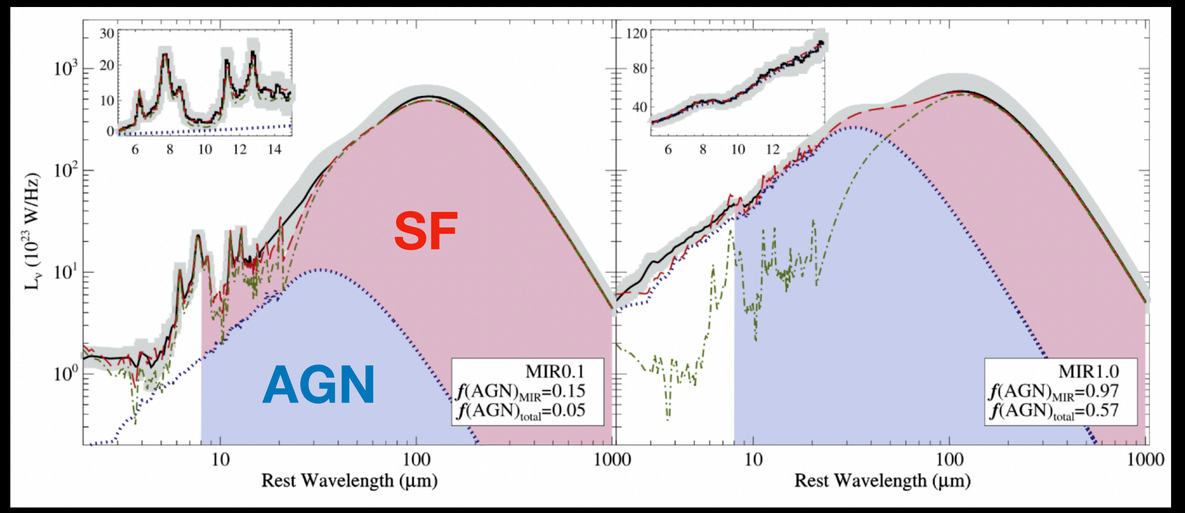
PI Science Data



- 2 tiered survey with 1 square degree and 10 square degree tiers. GO could do additional tiers.
- Expect ~ 10,000 galaxies per delta z = 0.25 bin. A rich archival dataset.



PRIMA GO science book
Donnely et al.



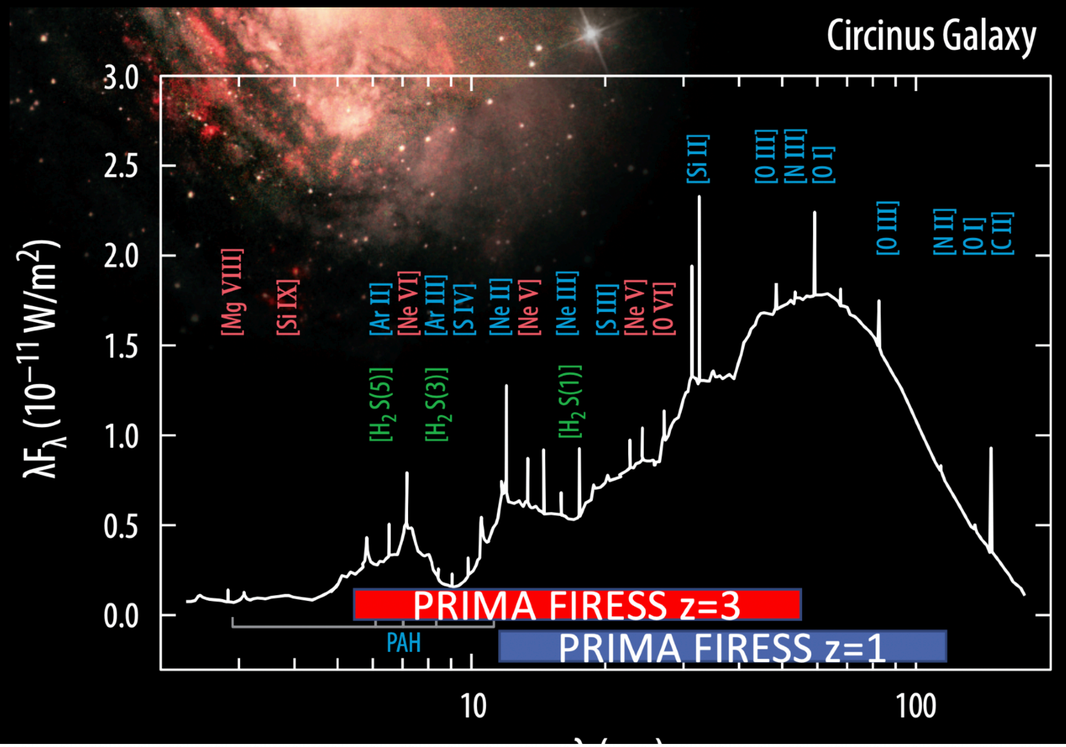
Kirkpatrick et al. 2015

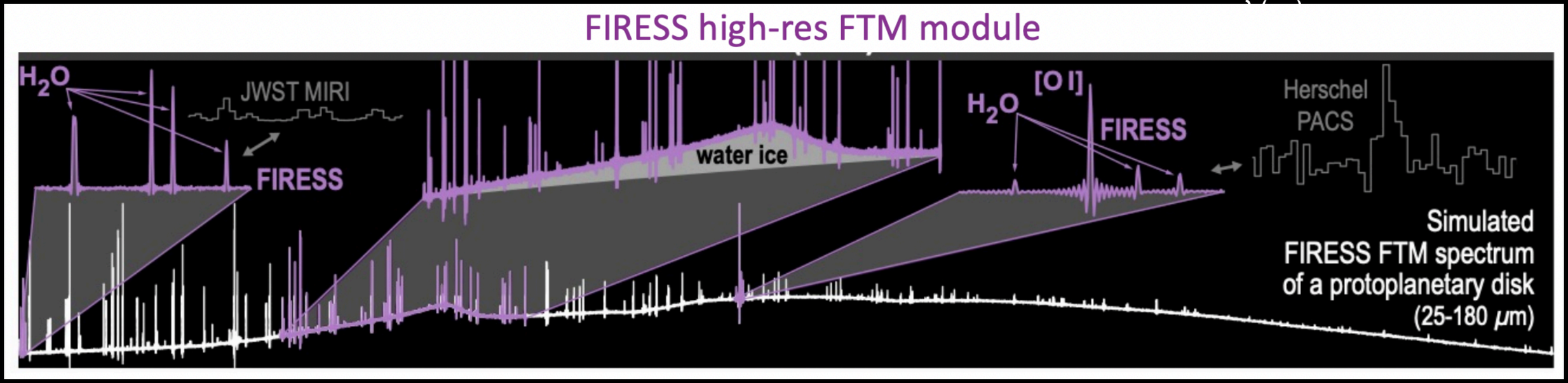
Data to be Returned

PI Science Data

Systematically-selected target observations

Follow up observations





More to be Returned

- **Science (not limited to the data)**
  - Participate in high-impact research that is difficult to conduct with GO proposals
  - Early access to PI science data
  - Early preparation of GI science
  - Official PRIMA workshops in Japan
  - Early start of GO proposal preparation

PRIMA is an observatory for the community
Participation in PRIMA will significantly reduce the hurdle to obtaining cutting-edge data and observation time for both individuals and groups

- **Technology (future applications)**
  - Free-form mirror optics
    - Important technology for next-generation telescopes, both in space and on the ground
  - Further development of cryogenic technology

- **Long-term perspective (beyond PRIMA)**
  - Pathway to GREX-PLUS and Habitable Worlds Observatory (HWO).

Originality and International Competitiveness

- **The only far-IR observatory in the coming decade**
  - The previous FIR observatory, Herschel, ended 10 years ago
- **PRIMA will address all the scientific themes identified by Astro2020 for a far-IR mission**
  - SPICA was expected to “make significant progress in a number of the science areas highlighted by Astro2010”
- **Recommendation of a space-based FIR observatory by the Kavli-IAU Workshop on Global Coordination**
  - Presented at the IAU 2024 General Assembly and submitted to the IAU Executive Committee

The EOS-2 panel considered the landscape for a future far-IR mission prior to ESA discontinuing its consideration of SPICA. The survey committee believes that considering this change in landscape there are many unique opportunities for a properly scoped far-IR probe to advance high priority science, and a probe scale mission is an extremely timely and compelling opportunity to do so. These scientific

Astro2020 Sec 7.5.3.3

Major Recommendations

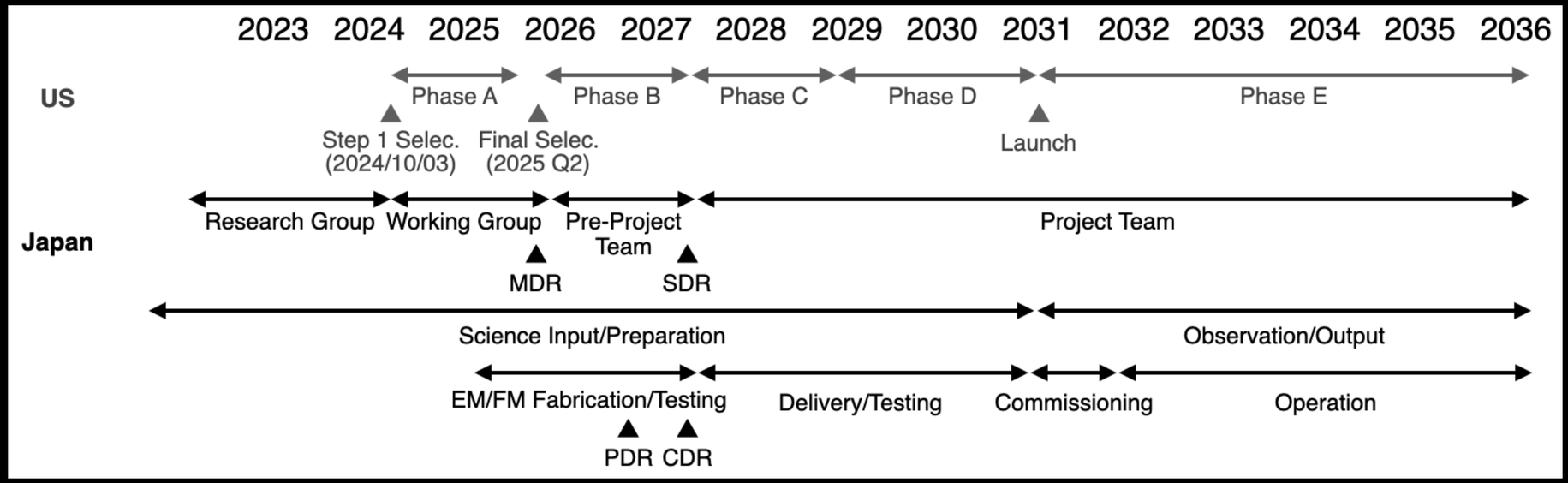
3. A space-based FIR observatory should be pursued with urgency to avoid losing critical scientific, technical and industrial expertise, and to fully exploit synergies with JWST and ALMA. The international community should remain engaged in the APEX process so their participation results in a more powerful mission.

Report of the Kavli-IAU Workshop on Global Coordination (page 3; arXiv:2409.07570)

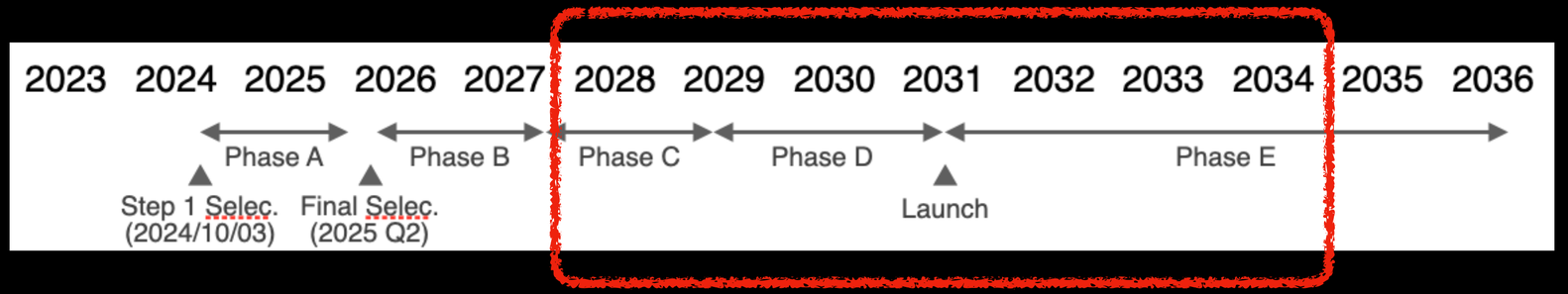
Current Status

PRIMA has been selected for the Phase A study
(Along with the X-Ray Probe, AXIS)

- Phase A study duration: Nov 14, 2024 — Nov 14, 2025 (report due)
- The final selection: Apr — June, 2026
- Currently:
  - **Finalizing the design, including Japanese contributions**
  - Demonstrations of technology with the NINS/Open Mix Lab program



Expectations for NAOJ



- 2028-2031: Pre-launch contributions
  - Data and science organizations
  - Ancillary data organizations/observations
  - Software/simulator/science case developments
- 2031-2034: Generation of scientific outputs
  - Multi-wavelength database taken with NAOJ's facilities
  - Domestic data release and user support for related matters
  - software/simulator/science case updates

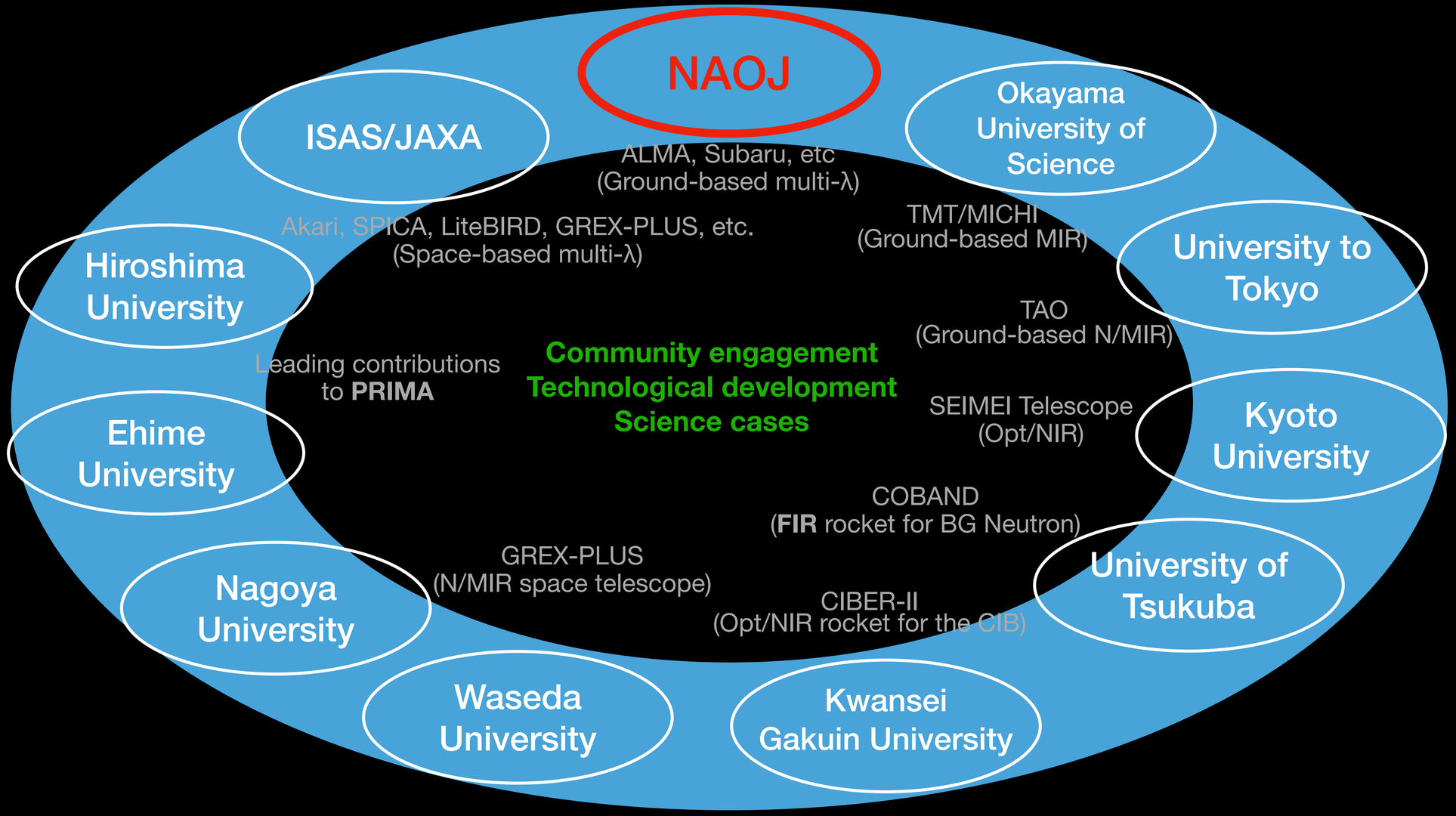
- Related NAOJ Departments
  - Scientific and Technological contributions from NAOJ employees
  - Support from the NAOJ Astronomy Data Center (ADC)
  - Partial developments at the NAOJ Advanced Technology Center (ATC)

Cost Assessments, Budget Line, and Status

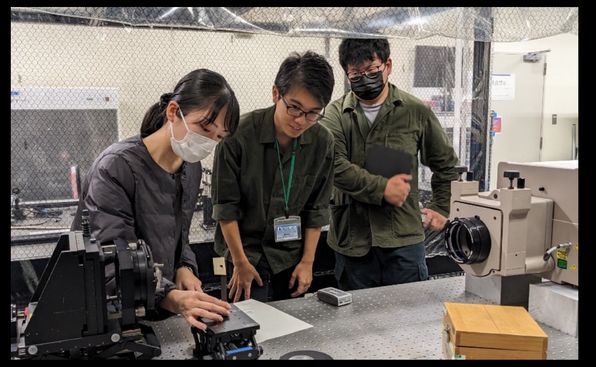
- PRIMA: 1B USD excluding the launch
  - Up to 1/3 from international collaborators
- Japanese contribution to PRIMA
  - ~2-3B JPY
  - Scheme: JAXA’s International Strategic Collaboration (under negotiation)
- Expectations for NAOJ
  - 63M JPY (2028-2034)
  - 9M JPY x 7 years (personnel cost, individuals’ effort control)
  - A scheme to collaborate with ISAS/JAXA
- Current status related to NAOJ
  - NINS/Open Mix Lab (OML):
    - “Development of an Infrared Astronomy Platform Based on Cryogenic Freeform Optics”
  - Visiting Researcher FY2024: Hanae Inami
    - “Enhancing Cryogenic Optics with Freeform Mirrors and Fostering Domestic Collaboration in Infrared Astronomy"

Space-Ground Collaborations via NINS/OML

Removing boundaries of ground/space and universities/institutes

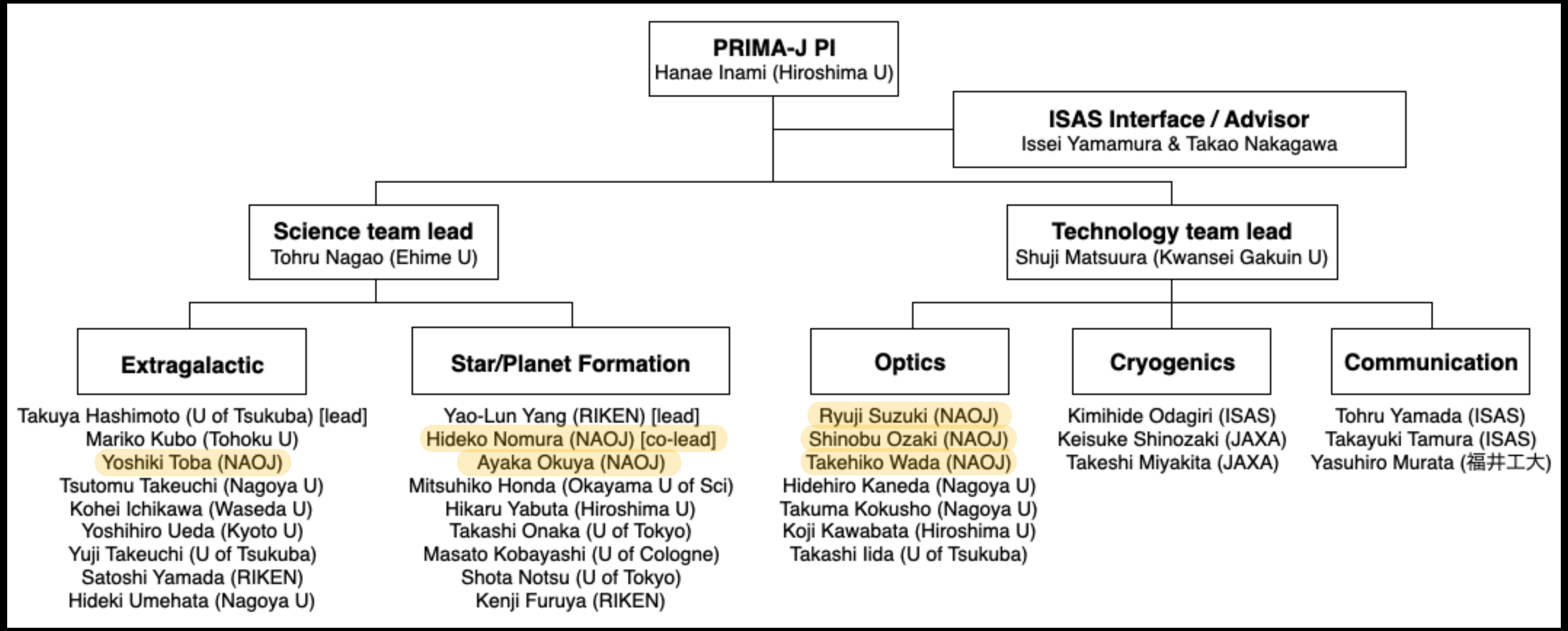


Career Development of Young Scientists



Diverse Feedback

Project Organization



Everybody is welcome to join!

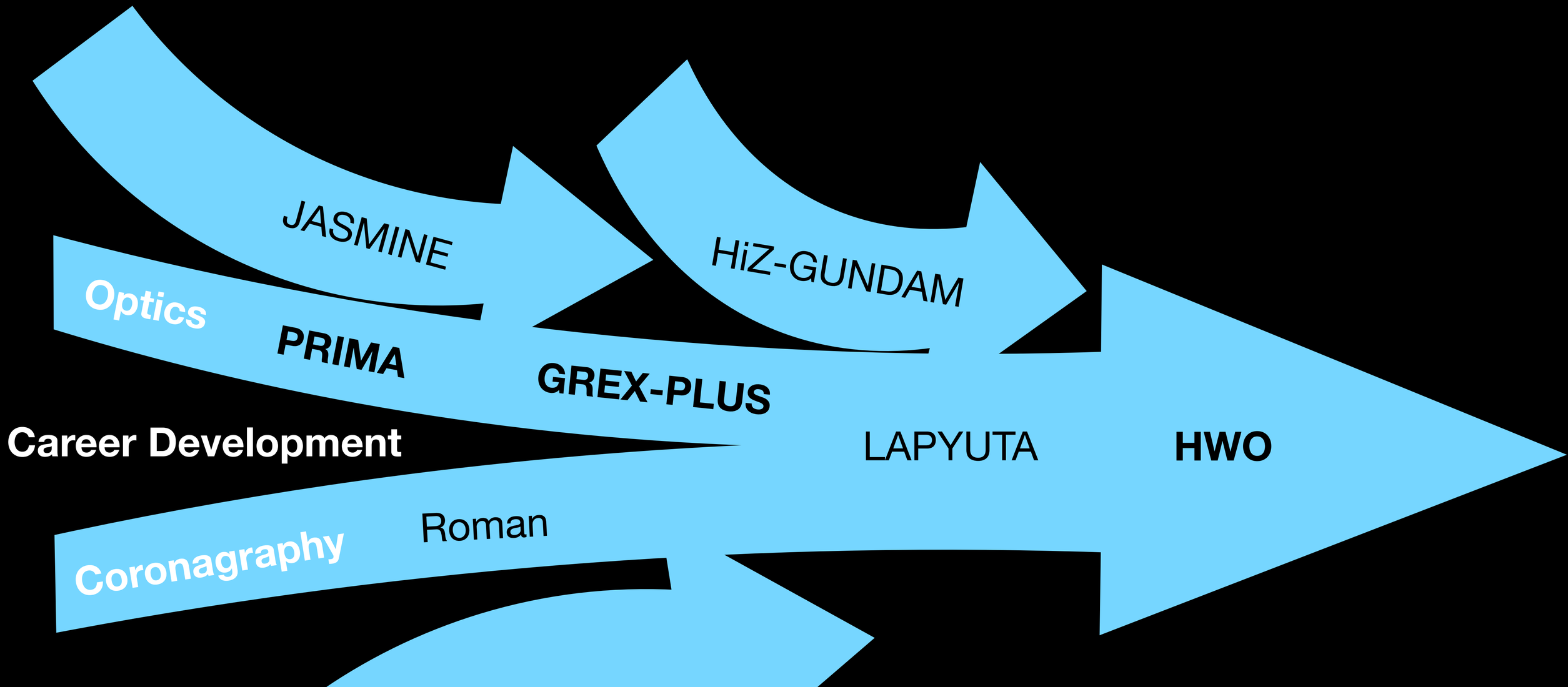
Why NAOJ ?

- Domestic science development and data center
  - Maximizing efficient and effective scientific outcomes of PRIMA
  - Enhancing NAOJ’s facilities and multi-wavelength science

- Joint technological development related to PRIMA
  - Joint research with NAOJ has been cultivated through NINS/OML
  - The seed of NAOJ's participation in space and space observations
  - Diverse career paths for young scientists and engineers

Why NAOJ ?

PRIMA as the “seed” for NAOJ Space Mission Developments



Summary

- PRIMA is the only FIR observatory to address the central science objectives by Astro2020
  - What are the chemical processes in protoplanetary disks and star formation?
  - How did galaxies and massive black holes build up?
  - How did heavy elements form and evolve to create the current world?

Excellent synergy with NAOJ's ALMA and Subaru

- Science investigations
  - H_2O lines, HD line, dust emission and polarization, fine structure lines, H_2 molecular lines

Only accessible in far-IR

- Contributions
  - Science development via science ideas and data center
  - Technological instrumentation and data
  - 63M JPY over 7 years (2028-2034) for NAOJ

Transformative multi-wavelength science

The seed for NAOJ space missions