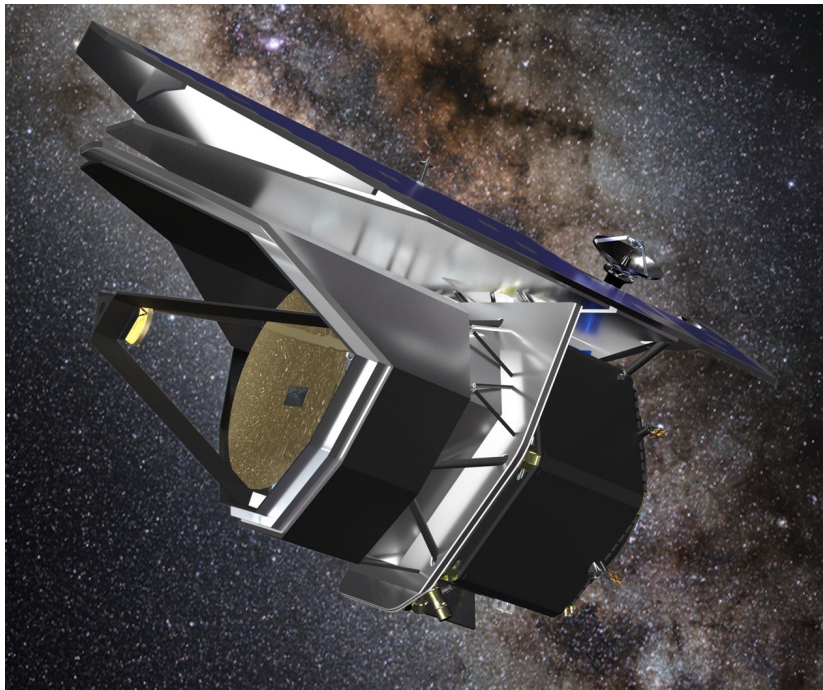




New Astrophysics of Galaxies, Protoplanets, and the ISM Enabled by Transformative Detector Technology



Jason Glenn, Principal Investigator
Margaret Meixner, Deputy PI, JPL
Matt Bradford, Project Scientist, JPL
Klaus Pontoppidan, Deputy PI, JPL
Alexandra Pope, Science Lead, UMass
Tiffany Kataria, Deputy SL, JPL
Jenn Rocca, Proposal Capture Lead, JPL

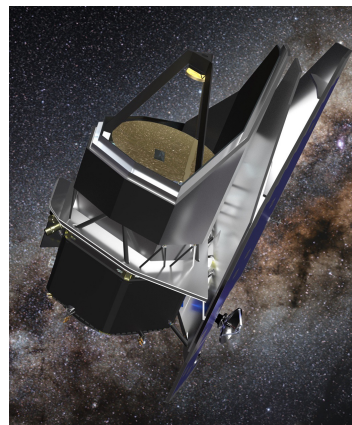
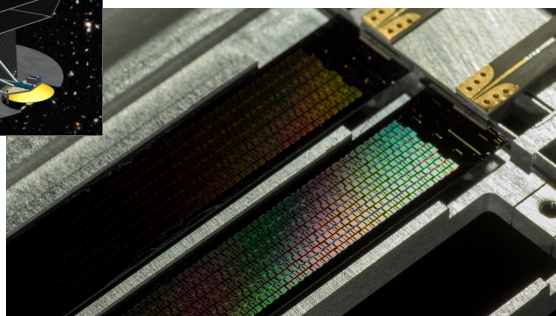
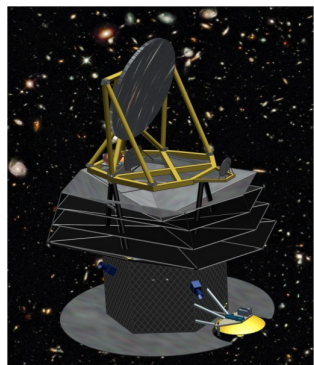
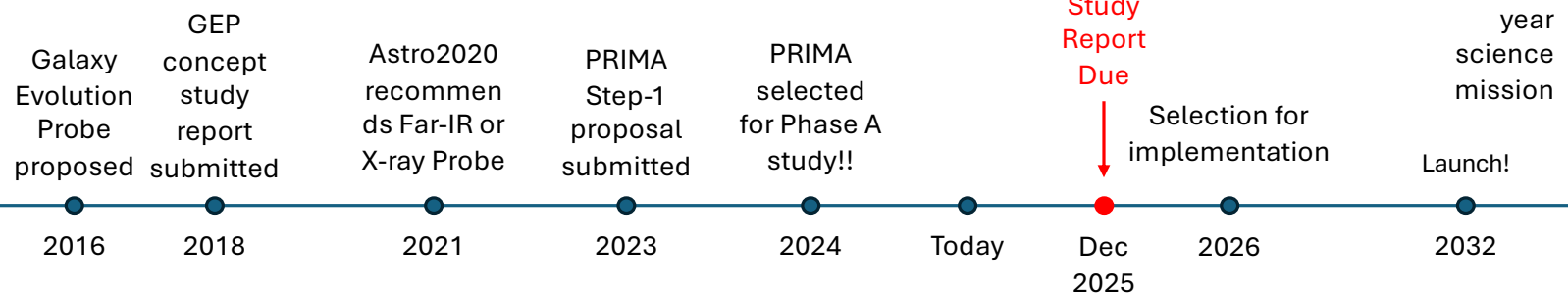
Please see our website:



PRIMA Timeline

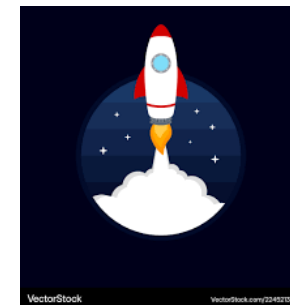
Foundation:

>20 yrs NASA
investment in
detector and
cryocooler technology
– KIDs, MIRI
cryocooler, CADR



Why now?

1. Detector & cryocooler technology mature
2. Excellent complementarity to JWST & ALMA
3. Unprecedented sensitivity → vast discovery potential
4. Implementation feasible in 5 years





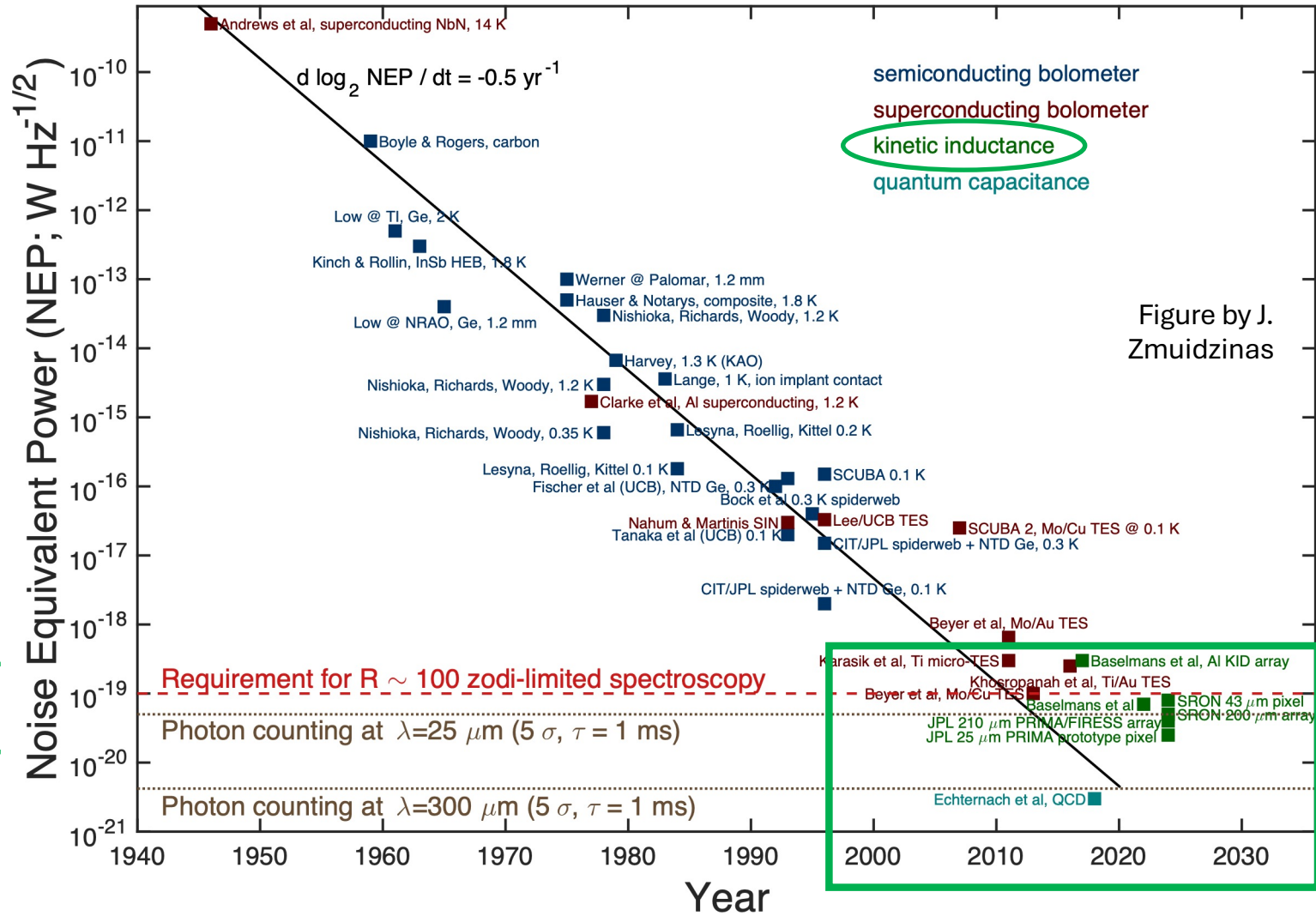
PRIMA

The PRobe far-Infrared
Mission for Astrophysics

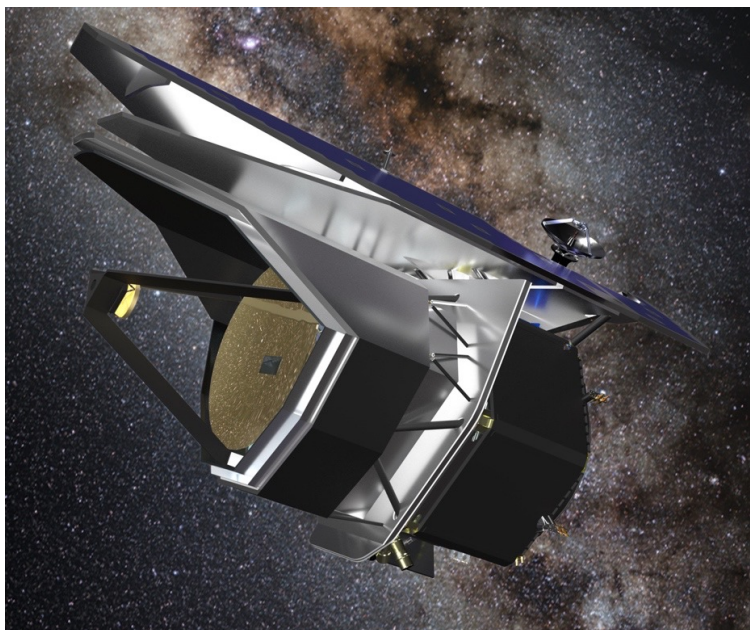
Why Now? → Far-IR Detector Technological Readiness

*Sensitivities of far-IR
detectors have doubled
approx. every two years
for 75 years!*

Far-IR Probe
region of
interest



PRIMA Basics

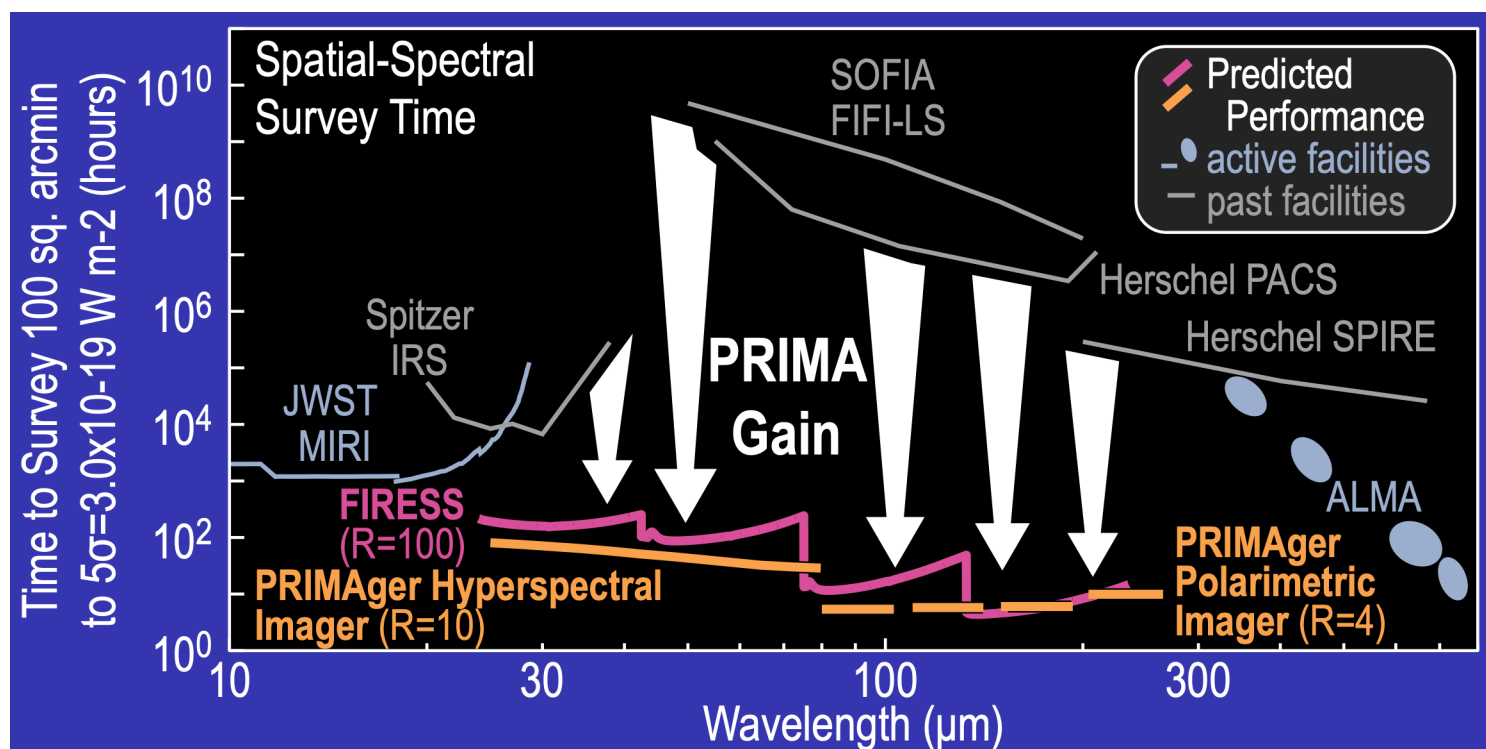


Observing Time

- 25% or Principal Investigator science
- 75% for NASA-managed Guest Observers
- PI data will be available quickly for Guest Investigator science

Telescope	1.8-m, aluminum, 4.5 Kelvin
PRIMAger Imager & polarimeter	R = 8 hyperspectral imaging 25-80 μm R = 4 imaging & polarimetry 91-261 μm
FIRESS Spectrometer	R > 85 spectroscopy 24-235 μm High-resolution mode: R = 4,400 $\times$ ($112\mu\text{m}/\lambda$)
Detectors	100 mK KID arrays (11k total)
Orbit	Earth-Sun L2
Launch	2032

Large Gains and New Capabilities from Coupling Sensitive KID Arrays To a Cold (4.5 K) Telescope (and Dispersive Spectroscopy)



Newly enabled:

- Extended-source and line intensity spectral mapping
- Extensive polarimetric mapping
- Deep all-sky far-IR GO-proposed survey

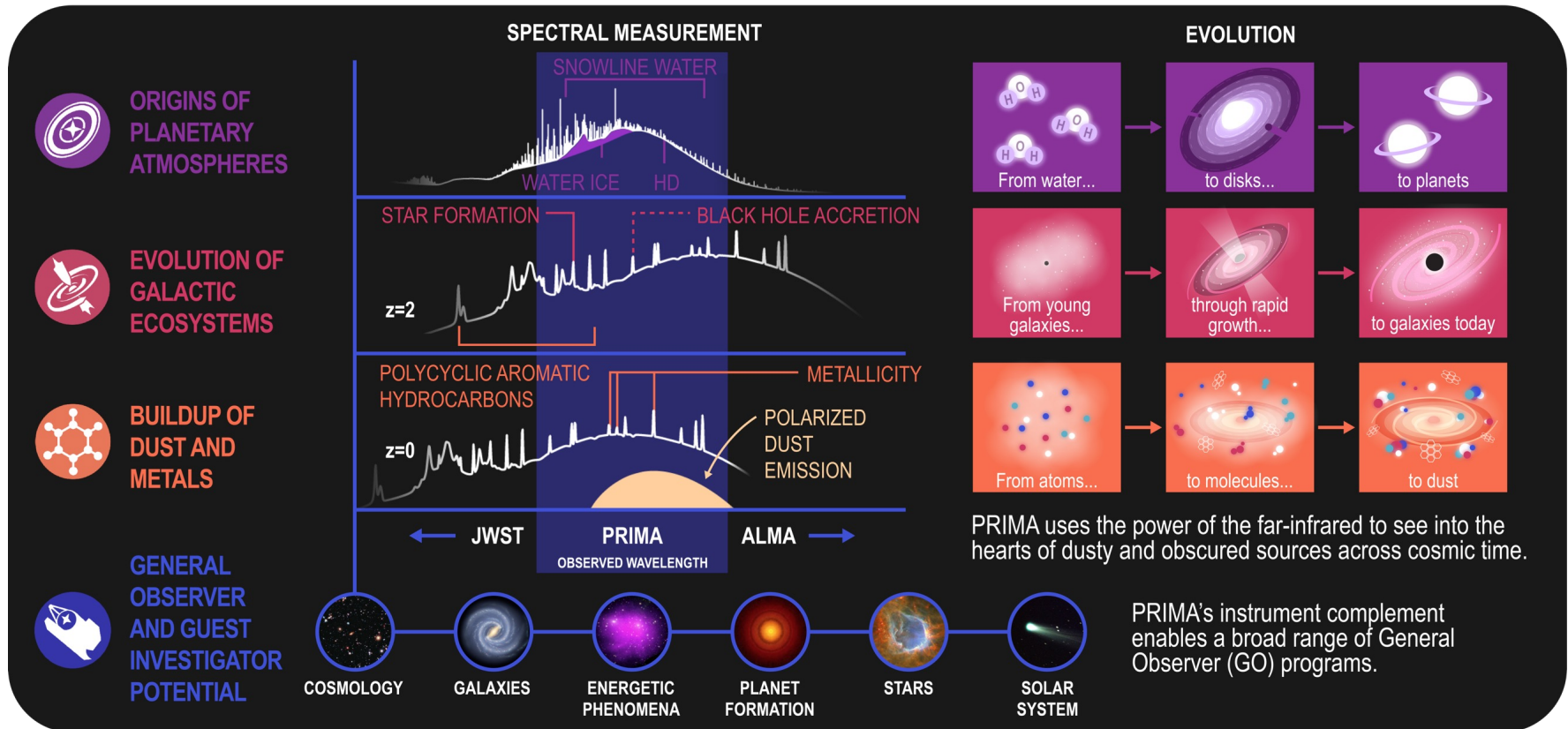


PRIMA

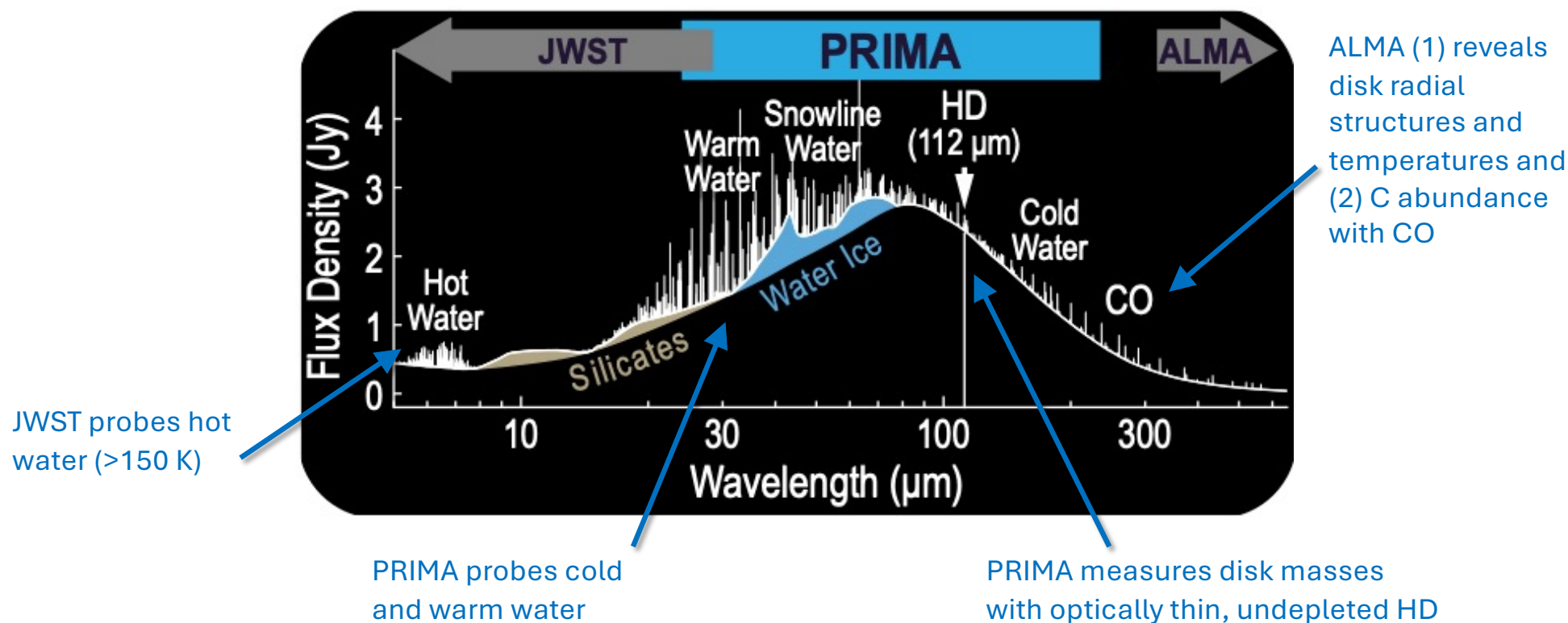
The P*RO*b*ER* far-Infrared
Mission for Astrophysics



PRIMA Science Themes



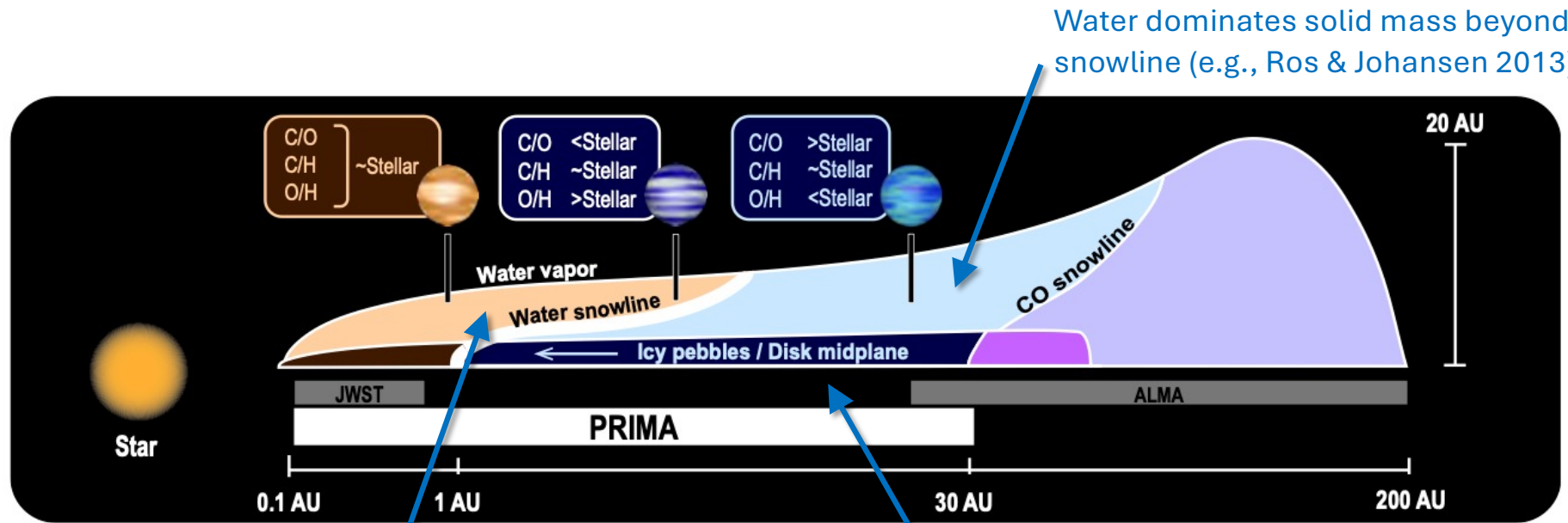
Protoplanetary Disks: Context with a Model Spectrum



Pontoppidan, Cleeves, Bergin, MacGregor

Protoplanetary Disks

Is there sufficient water mass to drive the formation of planetesimals and giant planet cores near the water snow line?

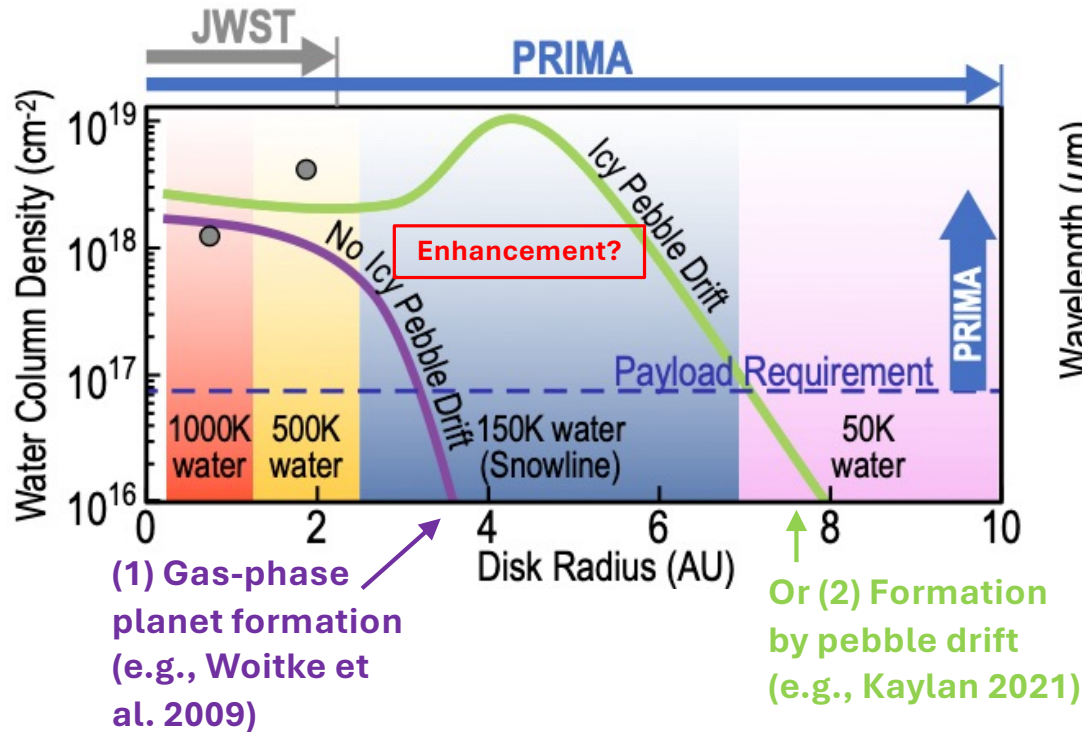


PRIMA measures relative water vapor column density in the disk surface inside, near, and outside the snow line to establish if icy pebble drift can catalyze formation

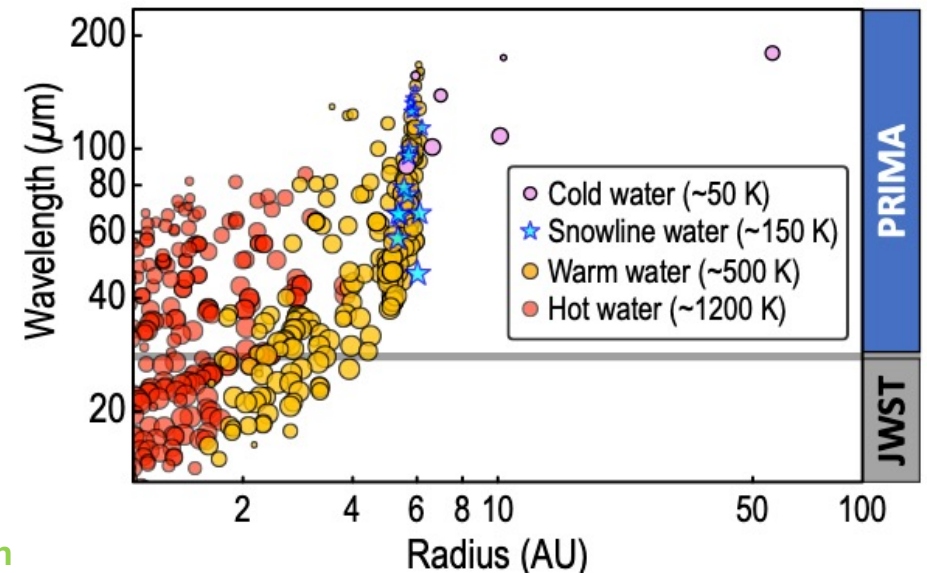
Does icy pebble drift transfer enough mass in to 10-20 AU where most planets likely form?

Is there enough water mass to drive the formation of planetesimals near the water snowline?

Do giant planets form by gas phase accretion in the outer disk or by inward icy pebble drift seeding? Which model is correct?



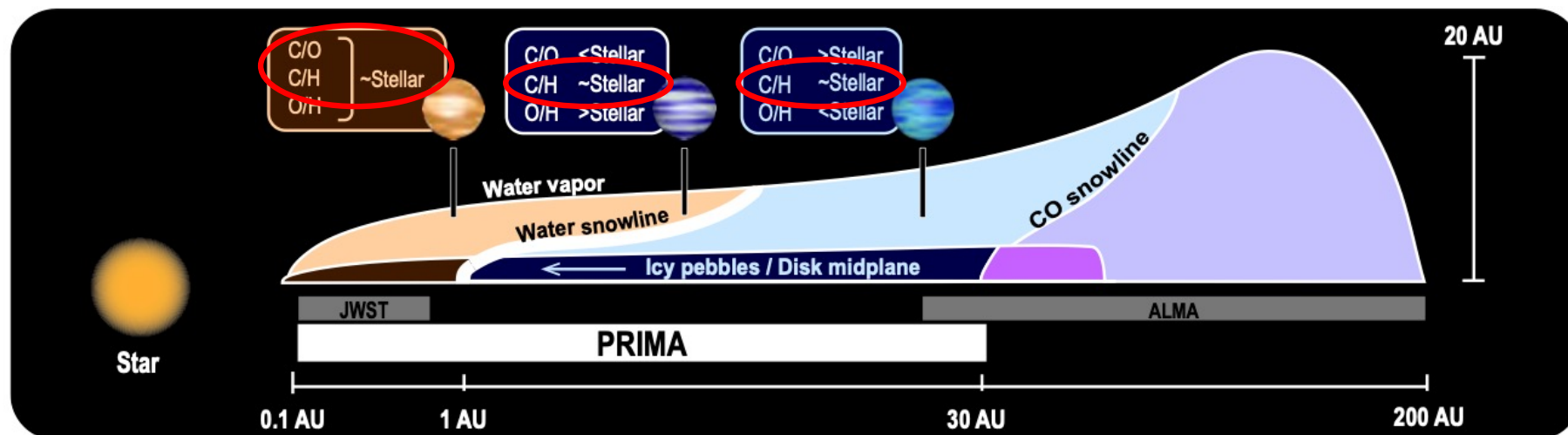
PRIMA FIRESS FTM will measure the level of inner-disk water enhancement in 200 disks (one simulation shown) of various ages and masses (point size $\propto$ line flux).



Protoplanetary Disks

Do protoplanetary disks have non-solar C and O abundances in the 10-20 AU regions where most planets form?

- While planetary cores likely form from the reservoir of solids, atmospheres accrete from the gas reservoir (e.g., Mordasini et al. 2016).
- Hypothesis: Measured transiting exoplanet [C/H] and [O/H] derive from disk abundances (e.g., Öberg et al. 2011).
- Due to uncertain CO depletion, disk masses are uncertain to an order of magnitude.
 - PRIMA derives H from HD (112 μm) and hence [C/H] and [O/H].

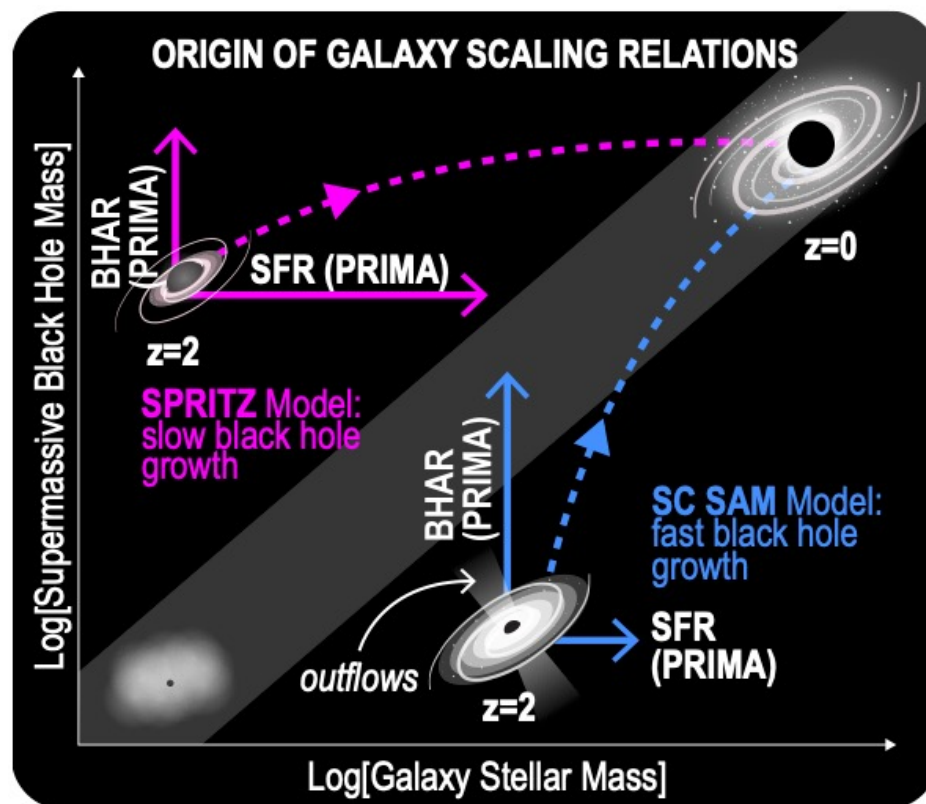


Galaxy Evolution

What is the relation between black-hole accretion rate and star-formation rate in luminous galaxies since the peak epoch ($z \sim 2$)?

SPRITZ – star-formation based model linked to Spitzer, Herschel datasets (Bisigello et al. 2021).

Observed relation between black hole mass and stellar mass (Reines & Volonteri 2015).



Santa Cruz Semi-analytic model: more black hole growth at cosmic noon (Somerville et al. 2021).

Pope, Bolatto, Gruppioni, Somerville

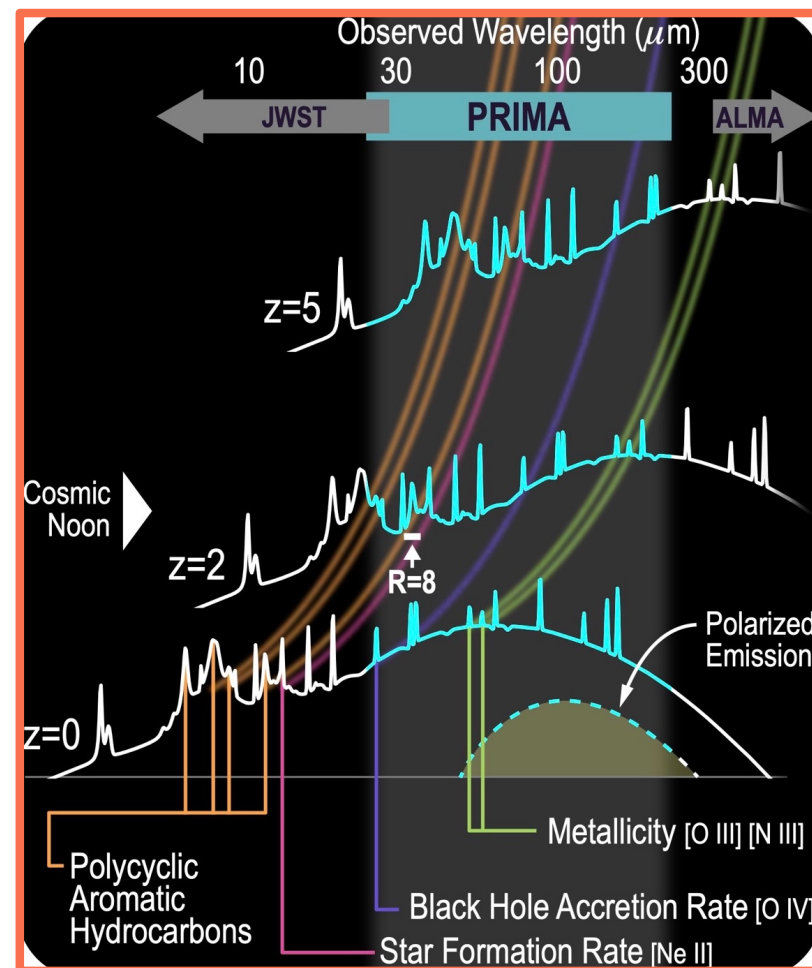
Background: (Rest-Frame) Mid- and Far-IR Galaxy Spectra

Simultaneous black
hole accretion rates
and star formation
rates

- Spectral energy distributions
- Relative PAH-to-continuum ratios
- [O IV] vs [Ne II] strengths

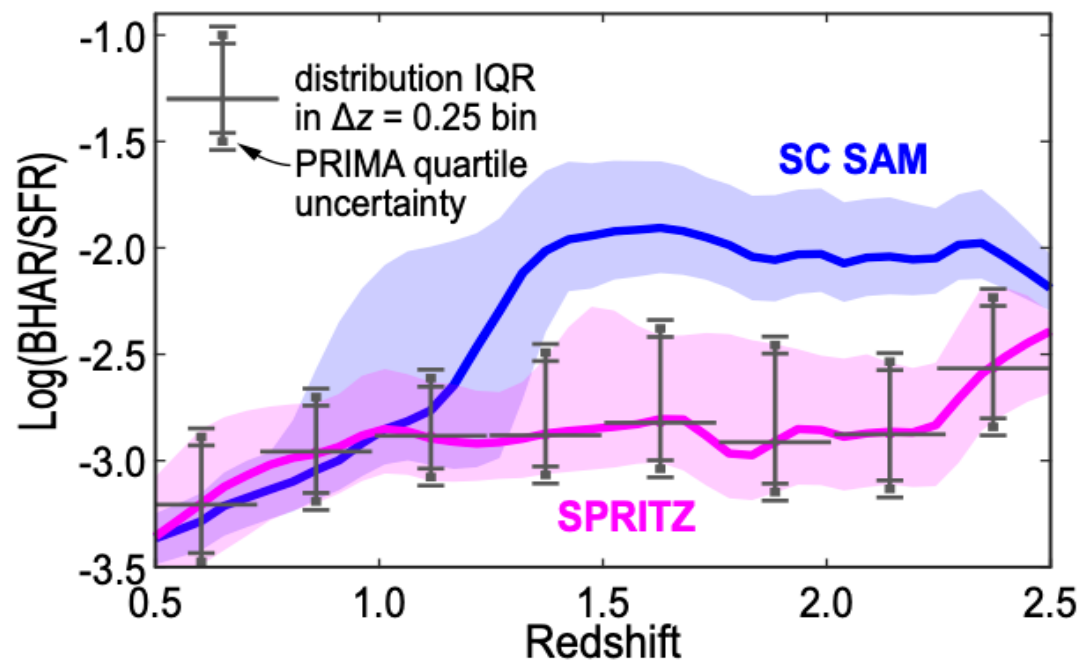
Other objectives

- Metallicities from [O III]/[N III]
- PAHs (to high z)



Galaxy Evolution

What is the relation between black-hole accretion rate and star-formation rate in luminous galaxies since the peak epoch ($z \sim 2$)?



- PRIMA one square degree survey: 42k galaxies (Donnellan+ 2024)
- Spectroscopic validation and refinement:
Spectroscopic sub-samples of 160 $z = 1.0$ -2.5 galaxies using [O IV] and [Ne II] (rest frame 26 & 12.8 μm)

Galaxy Evolution

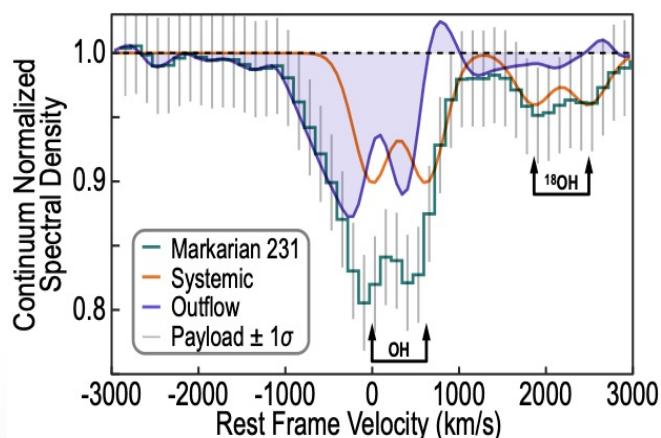
Do winds in luminous $z = 1 - 2$ galaxies quench star formation?

Models



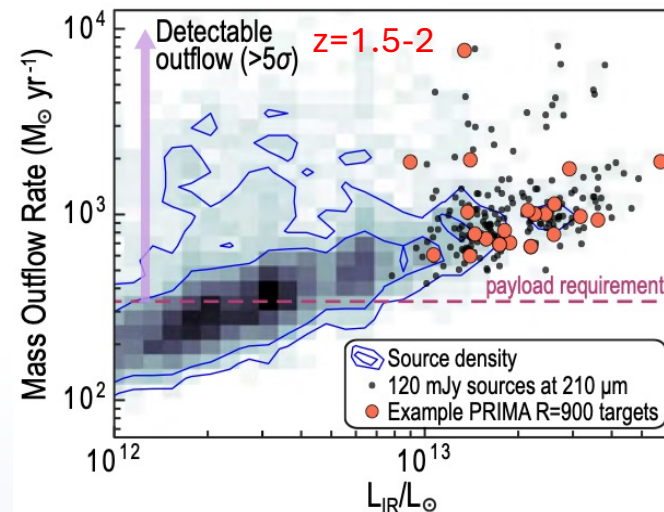
- Models require winds ejecting gas to quench star formation in massive galaxies
- Need velocities and mass outflow rates to test models
- Cool component ($T < 10,000\text{K}$) dominates the mass

Method



- OH doublet absorption features (here $84\ \mu\text{m}$ @ $z=1.5$; also $61, 71, 79\ \mu\text{m}$) with the FIRESS FTM tuned to $R=900$
- Fit components to measure outflow velocity and mass
- Shown: $850\ M_{\text{sun}} / \text{yr}$ @ 13σ

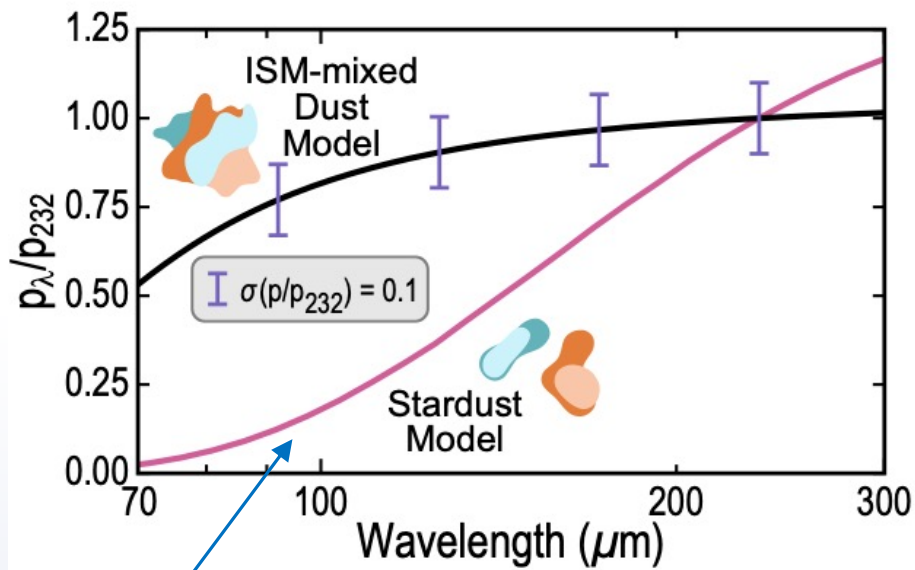
Survey



- Contours: Illustris TNG outflow model on PRIMA SPRITZ populations
- Requirement: detect $340\ M_{\odot} / \text{yr}$ (all HLIRGs should have this)
- Survey: 25 galaxies each in redshift bins $z = 1-1.5$ and $z = 1.5-2.0$

Interstellar Dust Grain Structure and Composition

How does the structure of interstellar dust change across environments in the local universe?



Warm, C-rich grains
unpolarized

Hensley, Dowell, Sauvage, Essinger-Hileman

- **Polarization:**
 - Pristine stardust from C-rich AGB stars does not produce polarized emission.
 - Composite grains aggregating stardust with ISM-grown grains does.
 - Albedo difference leads to strong polarization wavelength dependence.
- **Test:** Are ISM grain growth rates suppressed in low-metallicity galaxies/environments?
- **Survey:** 91-232 μm polarization imaging of 31 local galaxies

PRIMA Guest Observer Program and Community Outreach



**PRIMA General Observer
Science Book**

Editors: A. Mouillet (National Radio Astronomy Observatory), T. Kataria, D. Li, S. Usvi, & Y. Hasegawa (Jet Propulsion Laboratory, California Institute of Technology), E. Mills (University of Kansas), C. Battersby (University of Connecticut), A. Roc (Pomona College), M. Meixner (Jet Propulsion Laboratory, California Institute of Technology)

1st ed.: 76 papers

2nd ed.: 38 revisions
and 91 new!

**Special Section on the
PRIMA Probe-Class
Mission Concept**

Guest Editors: Naseem Rangwala and Matt Griffin

[Read the articles](#)

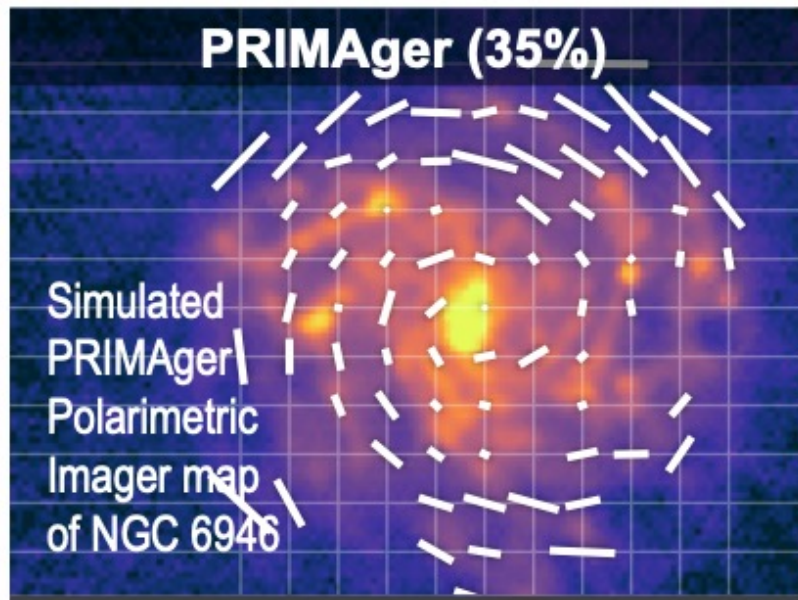
JATIS special issue:
33 submissions!

PRIMA Internship Program
PI: Meredith MacGregor



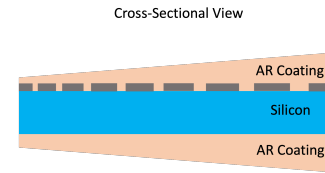
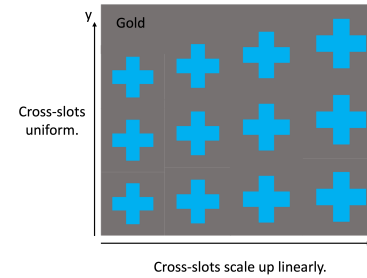
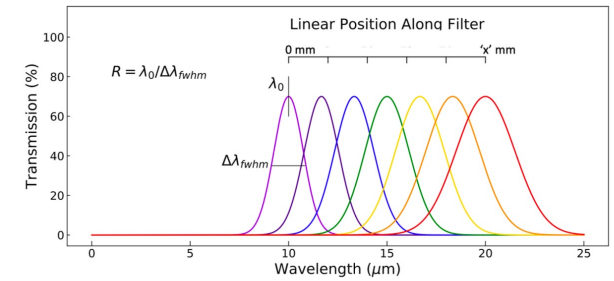
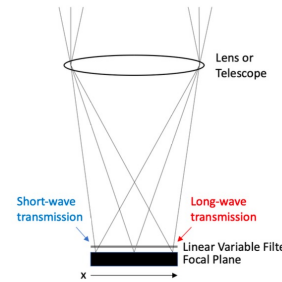
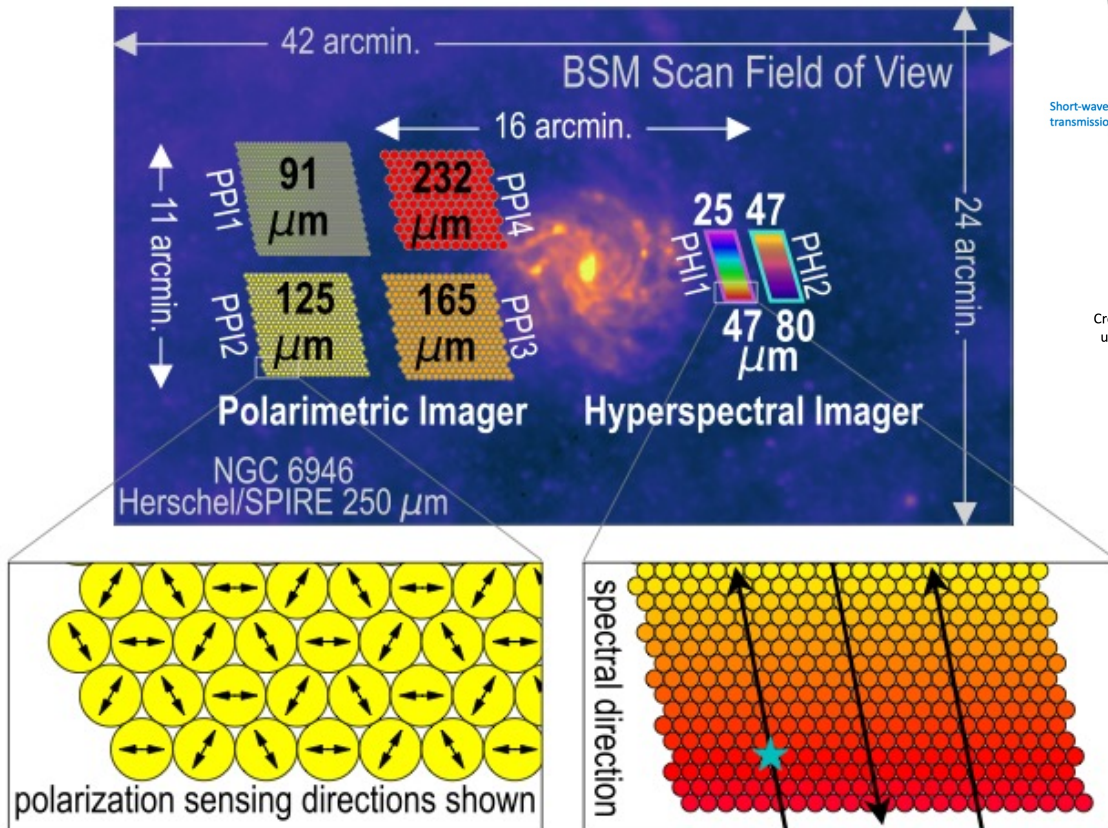
Engaging graduate and upper-
division undergraduate students in
hands-on mission development at
JPL and GSFC

GO Science: Polarimetry and Magnetic Fields in Galaxies



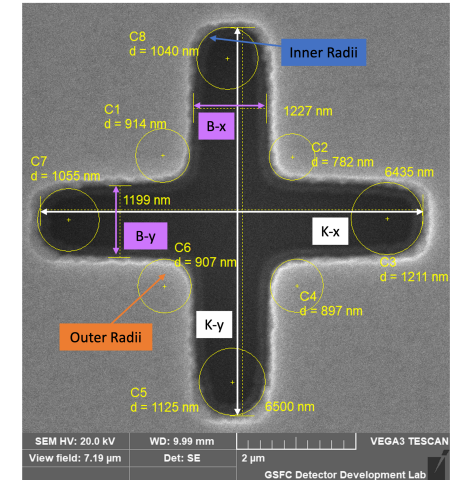
- Simulations of polarimetric capability: Dowell+ 2024
- GO: Magnetic fields (Lopez-Rodriguez; Louvet; Paré; Pattle)
 - Galactic clouds: The role of magnetic fields in cloud dynamics
 - Nearby, resolved galaxies: Do molecular cloud fields generally align with and reflect radio (cosmic ray) derived fields on larger scales?

PRIMAger (LAM)



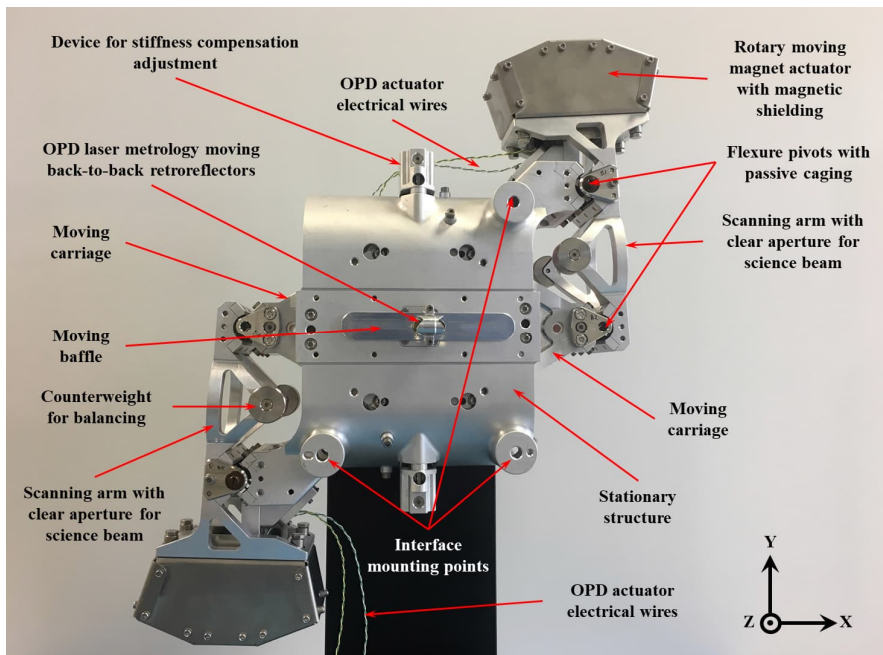
Logarithmically Variable Filters

Perido et al. (2024),
SRON

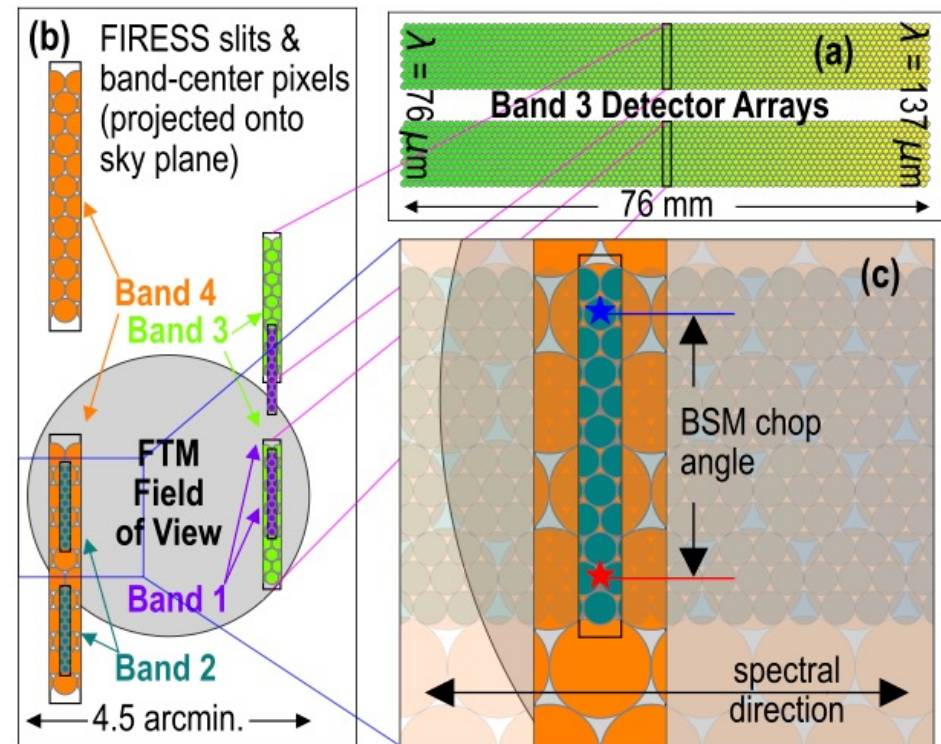


FIRESS (JPL & GSFC)

- 4 dispersive diffraction gratings
- Fourier Transform Spectrometer with ABB / University of Lethbridge SPICA-type phase-delay mechanism (with post dispersion)



Cournouyer et al. (2023)



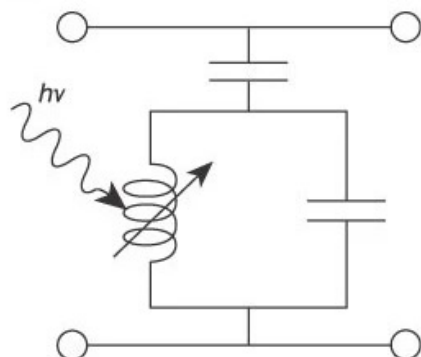
- 4 slit-fed grating modules, each 24 x 84 pixels
- Bands 1 and 3 overlap, Bands 2 and 4 overlap.
- High-res mode with FTM couples all bands when engaged.

KID Principle of Operation

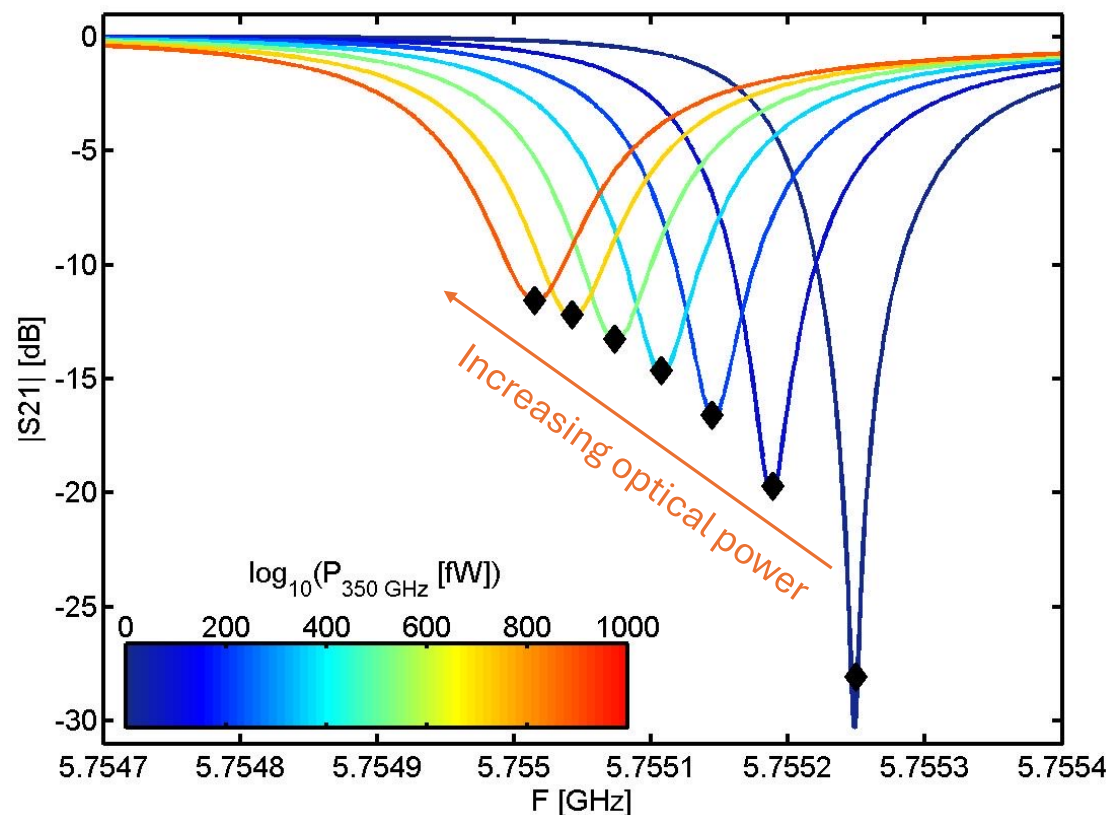
Superconducting resonator

$$Q = \frac{f_0}{\Delta f} 10^4 \text{ to } 10^6$$

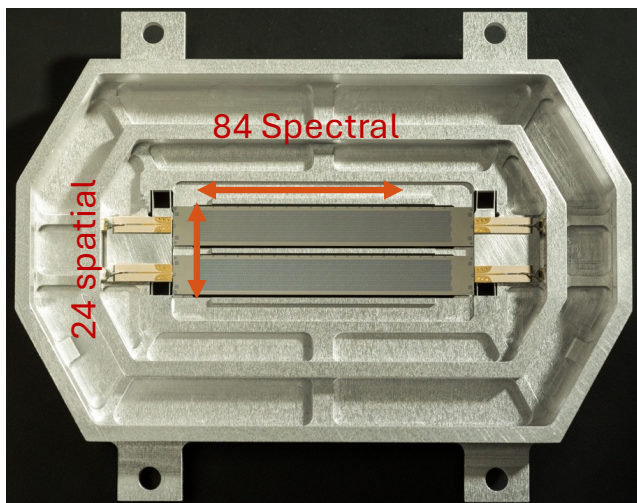
$$f_0 = 0.1 - 10 \text{ GHz}$$



Day et al. 2003

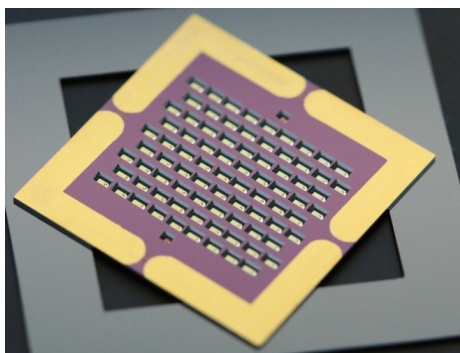


KIDs: Culmination of 2 Decades of Technology Investment

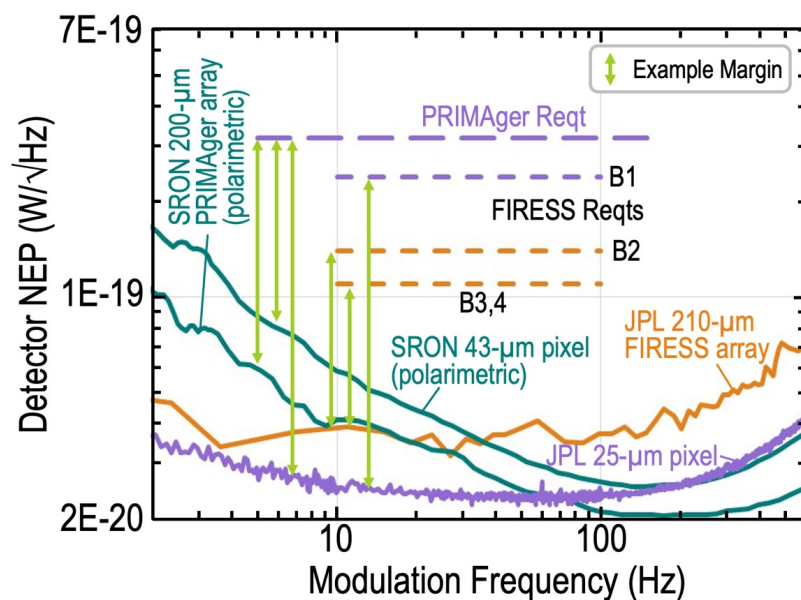


JPL FIRESS
prototype KID arrays
with GSFC
microlenses

SRON polarimetric
KIDs (derived from
SPACEKIDs effort for
SPICA)

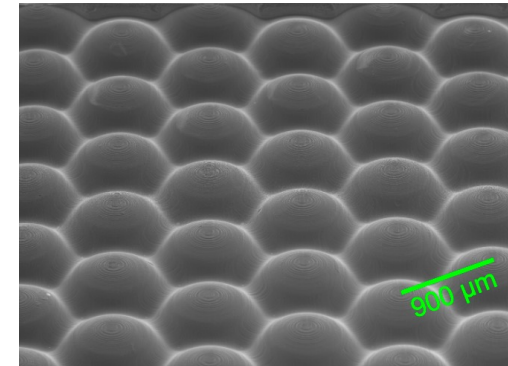
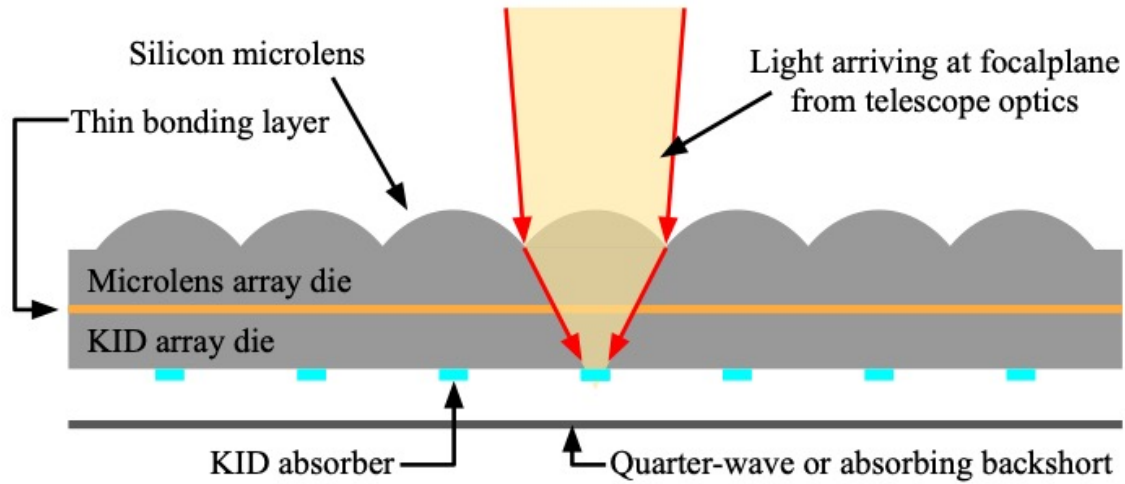


Prototype KIDs meet PRIMA requirements



25 μm result: Day+ 2024, Phys Rev X

Microlens Arrays & Hybridization



GSFC greyscale-etched microlens arrays & hybridization technique.

Accuracy across the bulk of each lens is $\sim 2 \mu\text{m}$!

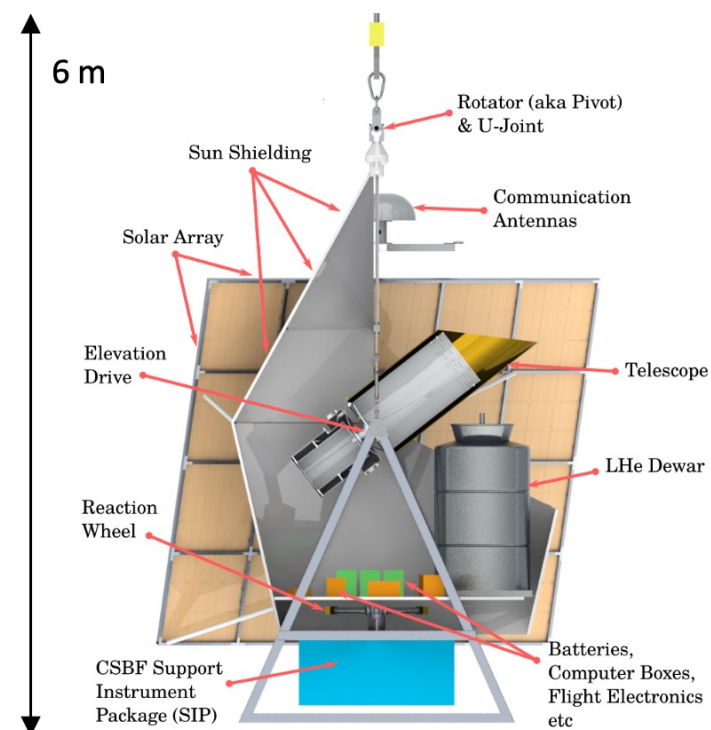


Stevenson, Cothard et al. (2024), Dahal et al. (2025)

Beyond PRIMA: Science Opportunities with PRIMA Technology

- **Balloon** using high-background PRIMA-type KIDs and logarithmically variable filter technology
 - Radiative ISM feedback from massive stars: Measure heating (single- and multi-photon) and size distributions of small dust grains near hot, young stars
- **MIDEX** far-IR all-sky polarimetric mapper using PRIMA's ultrasensitive KIDs and readout:
 - Measure dust composition and B-fields throughout the Milky Way
- **Asteroid finding with concurrent surface temperatures** using PRIMA's KIDs and logarithmically variable filters
 - Significantly reduced mass uncertainties
- **Origins Space Telescope**

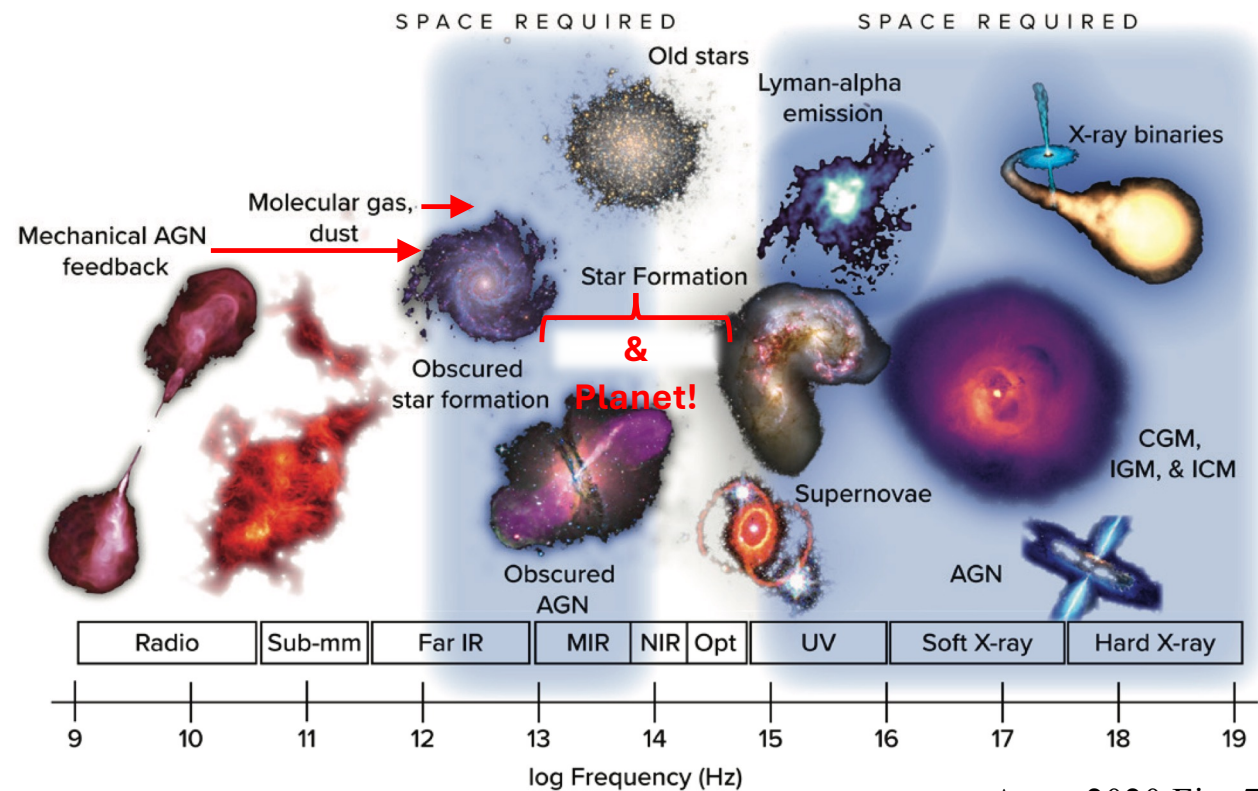
Balloon Experiment for Galactic Infrared Science



Extra slide follows

Astrophysics Probed with Far-IR Observations

- Uniqueness: Dust-obscured star formation and AGN; protoplanetary disk masses & chemical abundances
- Complementarity: Cooler gas than JWST can access (e.g., < 150 K H_2O in protoplanetary disks)



Astro 2020 Fig. 7.1

Protoplanetary Disk Masses from HD

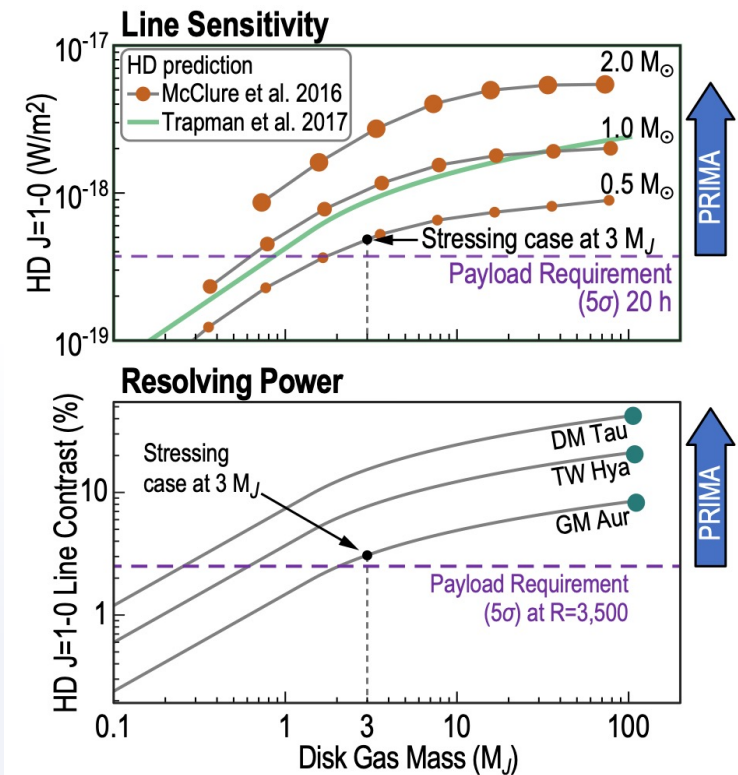
CO-derived disk masses are currently uncertain to a factor of 10 due to depletion

- Mass retrieval accurate to 2x when combining unresolved lines with far-IR SED (e.g., Seo+ 2024)
- Consistent with previous Herschel-PACS HD-based masses (e.g., Trapman+ 2017, Kama+ 2020)
- Seo+ show that $R > 1.5 \times 10^6$ required to fully resolve the line at high S/N to significantly improve uncertainty.

PRIMA

- H_2 mass derived from HD 112 μm (using temperatures from existing ALMA CO or CI observations)
- 200 disks of various ages

HD line flux vs. disk mass for two model and 3 stellar masses (luminosities).

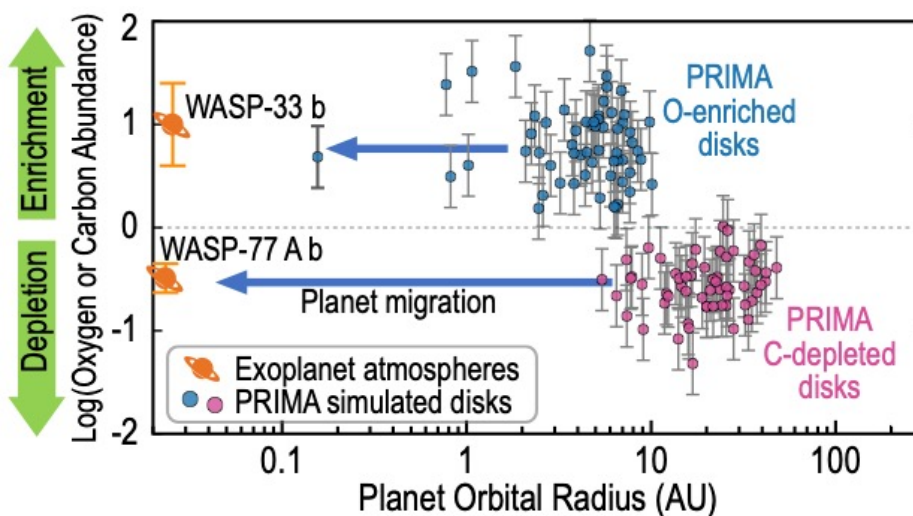


Protoplanetary Disk C and O Abundances

JWST transit observations of exoplanet atmospheres are yielding C and O abundances different from their stars.

- Departures can be due to disk chemical evolution, planetary migration, and accretion (e.g., Mordasini & Burn 2024).
- There is a paucity of disk C and O abundance measurements (a few disks with ± 1 dex uncertainty; e.g., Grant+ 2023) to compare to exoplanet abundances and test models.

PRIMA's disk survey simulated as two sub-samples with expected error bars (200 disks of various ages will be observed).



Oxygen derived from water and (gas-phase, which drives gas-giant formation) carbon from existing CO ALMA observation



Protoplanetary Disk Water Vapor Column Density Measurements

Retrievals via slab models with unresolved lines

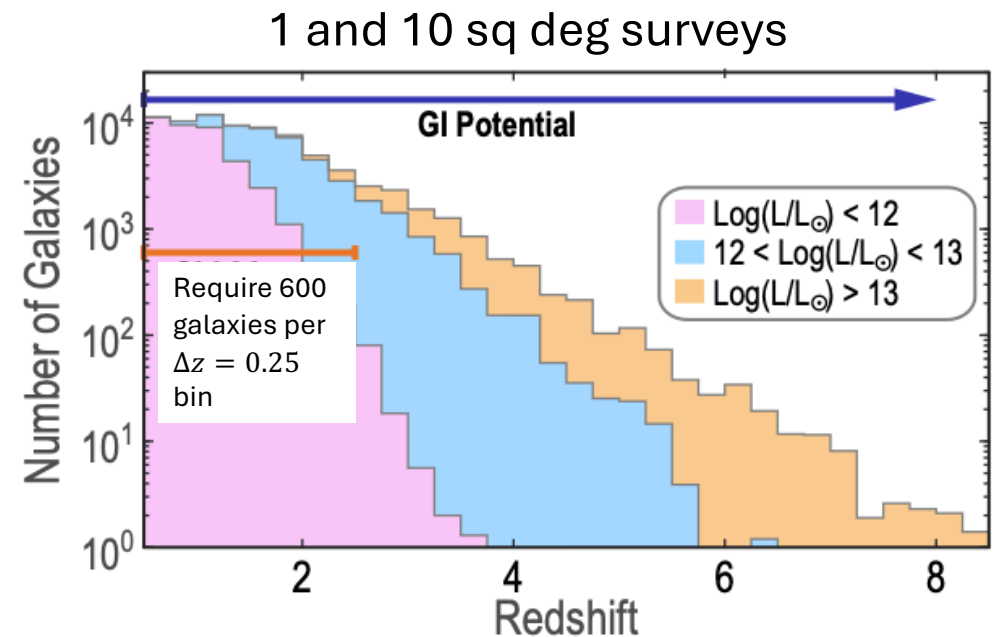
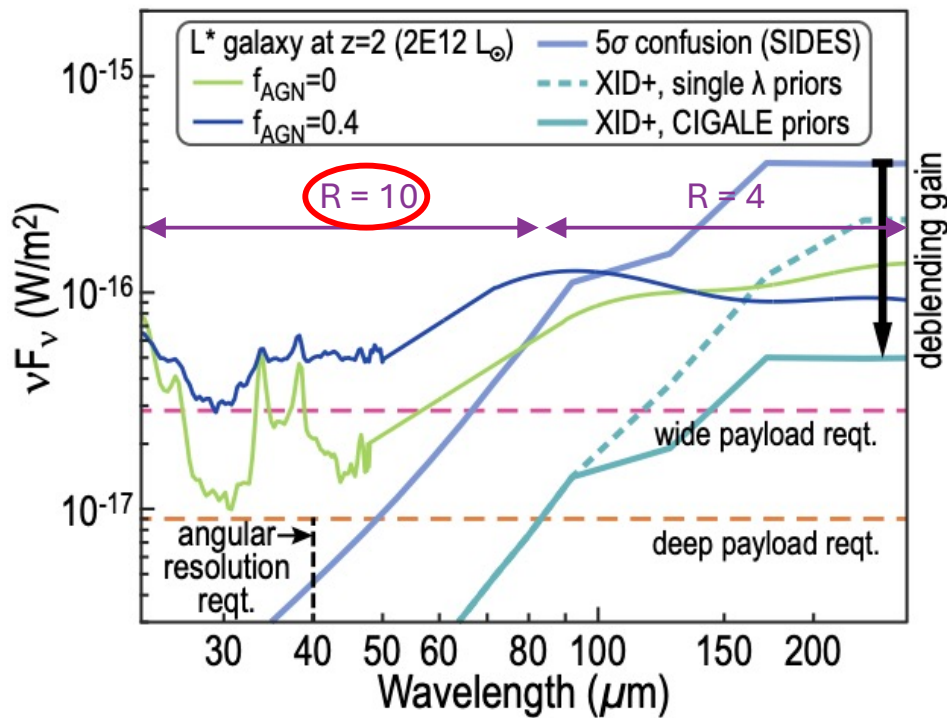
- Previously: Spitzer (Zhang+ 2013) and Herschel (Blevins+ 2016)
- Recently: Unresolved R = 3000 JWST MIRI spectroscopy (Pontoppidan+ 2024, Munoz-Romero+ 2024).

Parameter	Uncertainty
Water column density	2x
Temperature	10%
Emitting area / radius	20%

- Consistent with predicted disk-surface dust-temperature profiles

PRIMA will have ~100 lines per spectrum in 200 disks.

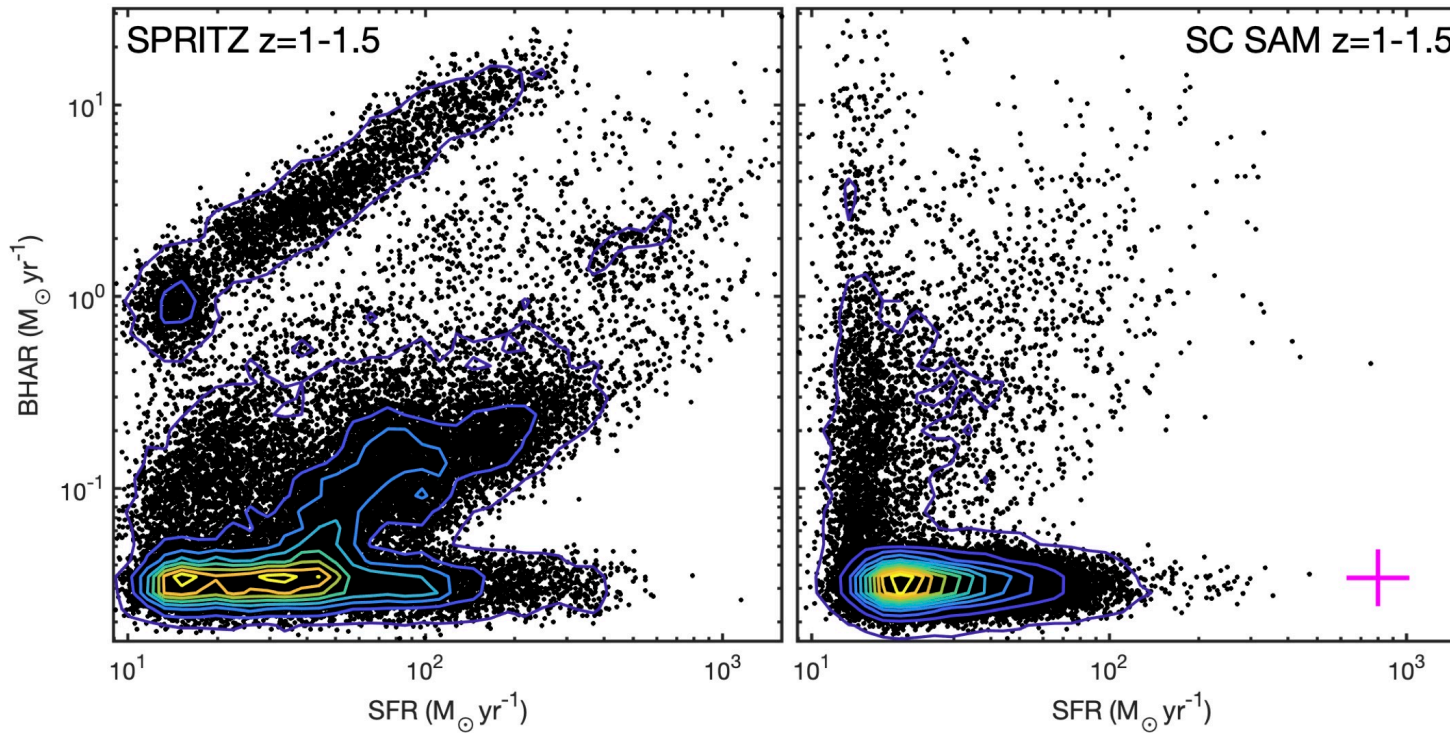
Mitigation of Confusion: Spectrally densely sampled, $R = 10$ rest-frame mid-IR spectra – excellent short-wave positional priors



Bethermin+ 2024
Donnellan+ 2024

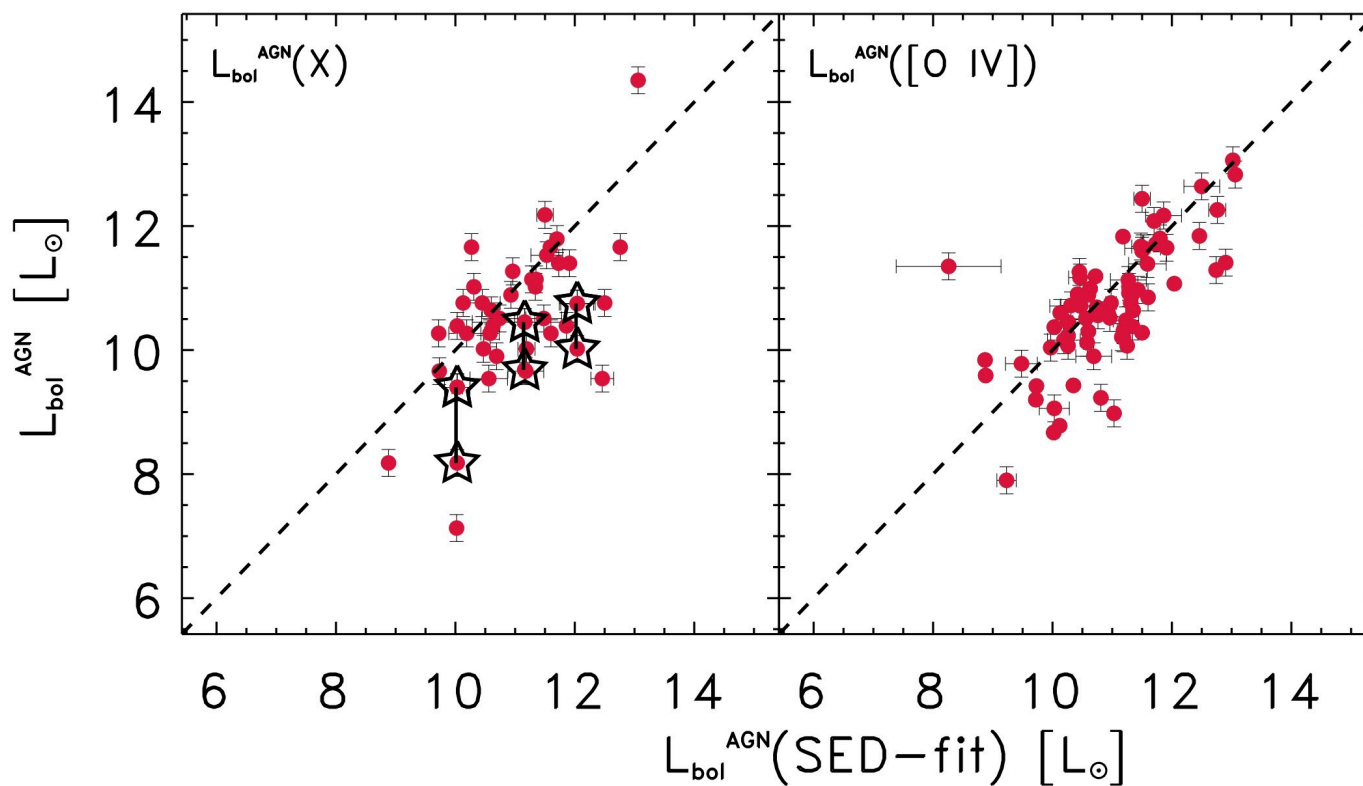
BHAR and SFR for Two Models

Model predictions vary considerably and new data are needed to test them.



- 10 sq deg, 1500 hrs
 - SPRITZ models are empirical and have a large number of coevolving galaxies
 - SC models are semi-analytical, black holes form early and quench star formation
 - Cross denotes typical error bars
- From Bisigello+ 2024

AGN Tracers

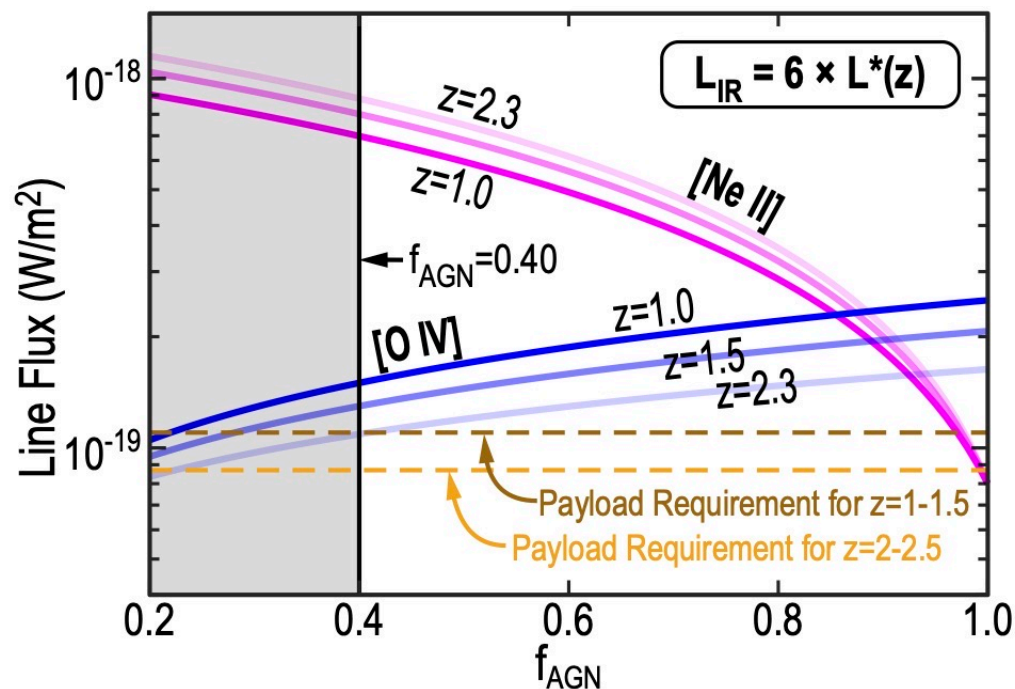


- X-rays are 2-10 keV
- 3 points with stars denote corrections from hard X-rays for known Compton-thick sources
- Other X-ray points may lie below 1:1 line due to obscuration
- From Bisigello+ 2024

Galaxy Evolution: Star-Formation Rate and AGN Luminosity from Atomic Fine-Structure Lines

How to measure the SFRs and obscured SMBH luminosities simultaneously in galaxies?

⇒ Redshifted mid-IR and far-IR spectral energy distributions (SEDs) and **atomic fine-structure lines**.



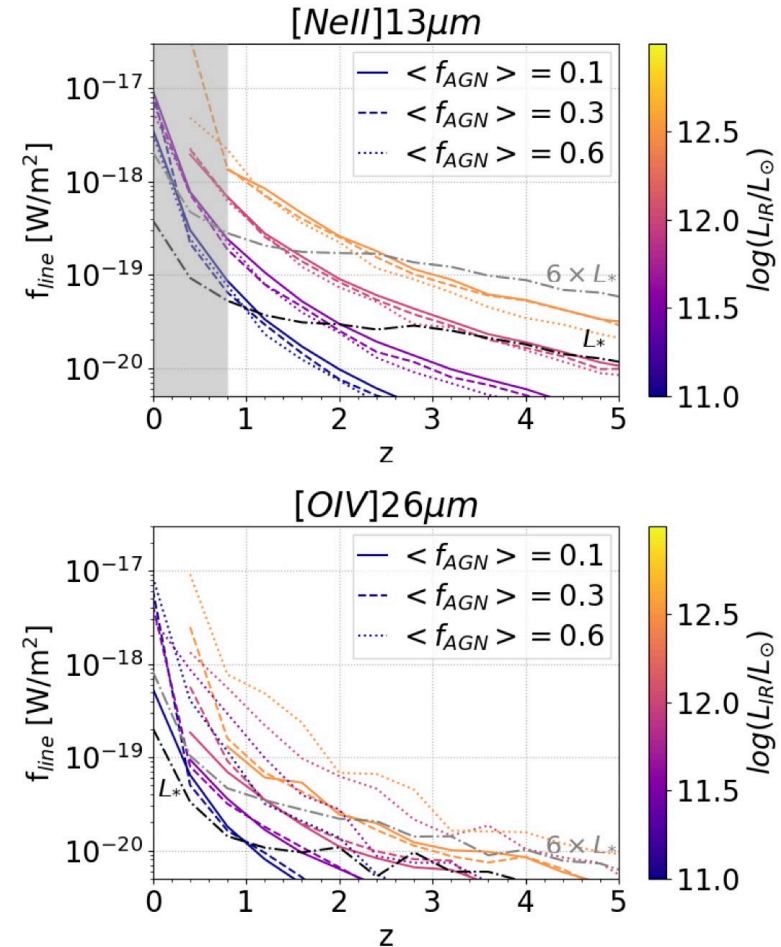
Spectroscopic sub-samples of 160 $z = 1.0-2.5$ galaxies using [O IV] and [Ne II] (rest frame 26 & 12.8 μm)

Models based on Bonato+ 2019 (also Gruppioni+ 2016 and Stone+ 2022)

[Ne II] and [O IV] Detectability

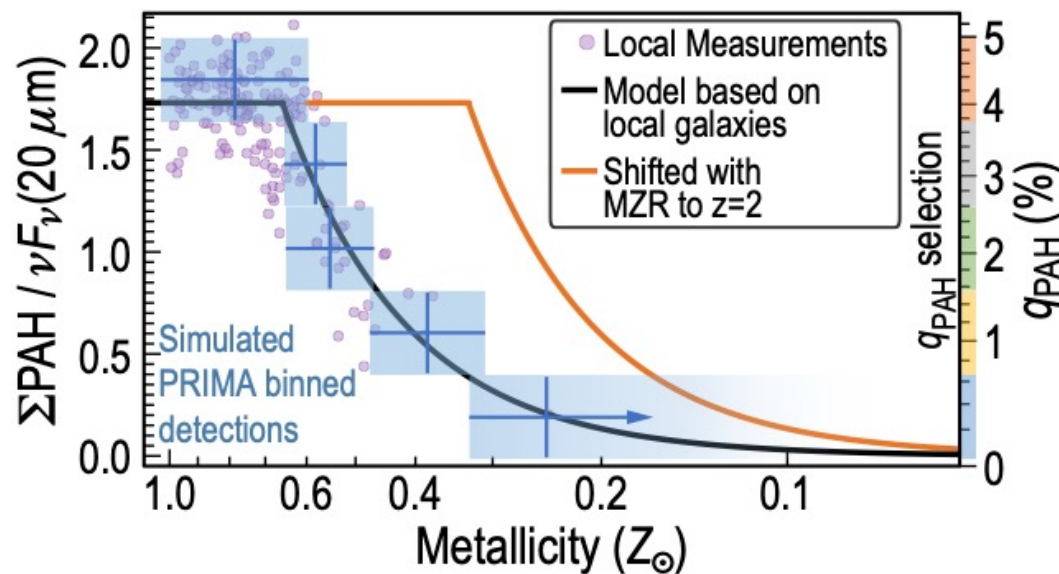
- PRIMA wavelength coverage starts where JWST stops
- Dashed lines show L^* and $6 \times L^*$
- L^* galaxies with significant AGN will be detectable up to cosmic noon, above L^* to high redshifts

From Bisigello+ 2024



The Rise of Dust and Metals: Has the relationship between PAHs and metals evolved since cosmic noon?

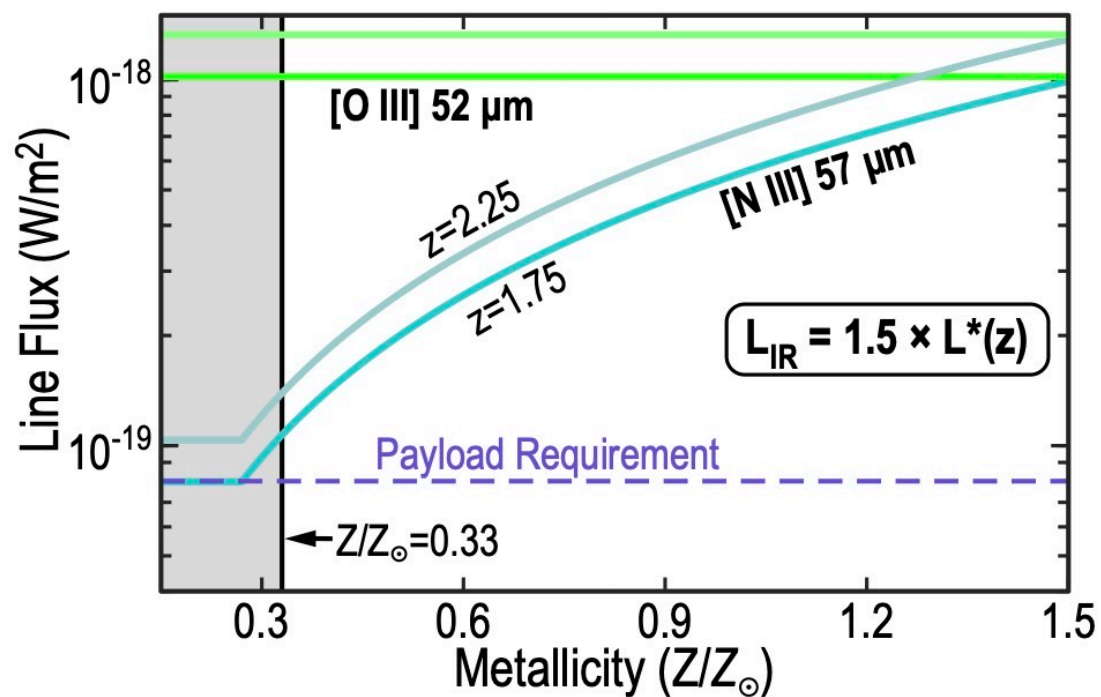
In the local universe, there a reduction in PAH emission with reduced metallicity.



For 100 $1.75 \leq z \leq 2.25$ galaxies in 5 q_{PAH} bins, PRIMA will measure

- Gas-phase abundances of O and N via [O III], [NIII]
- q_{PAH} from rest-frame 11.3 and 12.7 μm bands

Metallicities from [N III] / [O III]

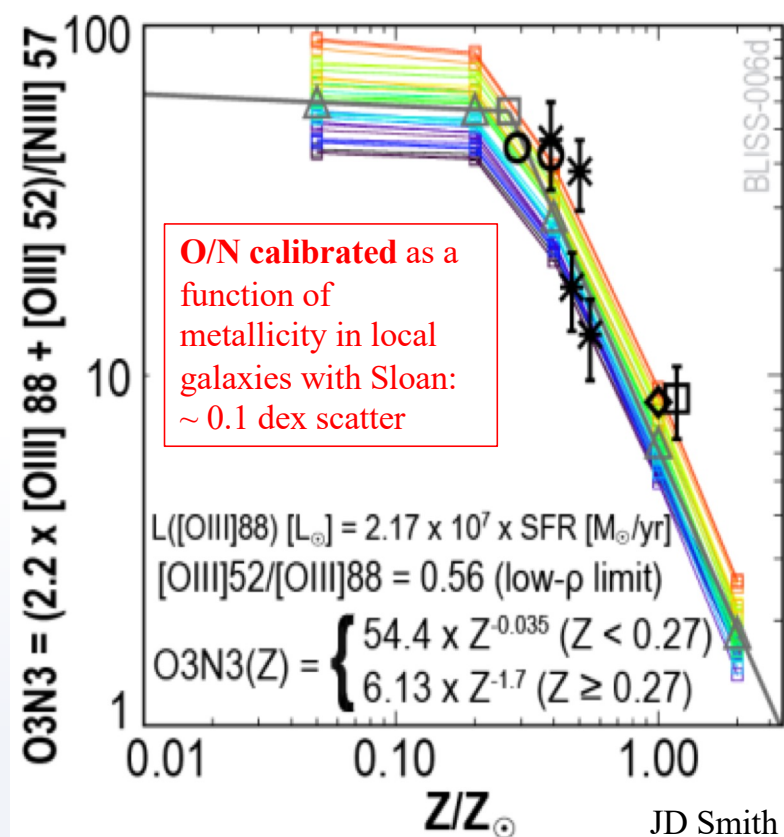


Sample of 100
galaxies $z = 1.75\text{-}2.25$

Calibrate [N III] / O [III]
with local galaxies

Models shown based
on Peng+2021

Extinction and Temperature Independent Metallicities

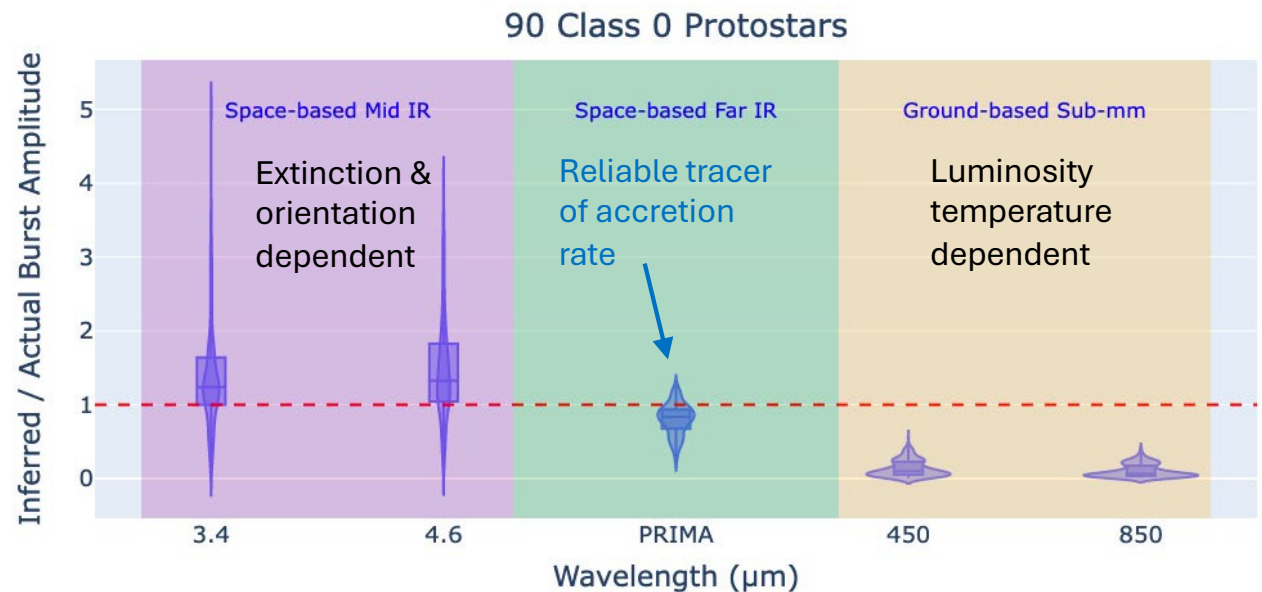


- Nitrogen is a secondary nucleosynthesis product – comes on later in stellar processing.
- O/N ratio measures stellar processing $\rightarrow$ proxy for metallicity (e.g. Pilyugin, et al. 2014)
- OIII and NIII: same ionization state, dust-immune, T insensitive
- Density-independent O3N3 diagnostic (2 OIII lines, 1 NIII line; Nagao et al. 07, Periera-Santella, et al. 2013)



GO Science: How do stars get their mass?

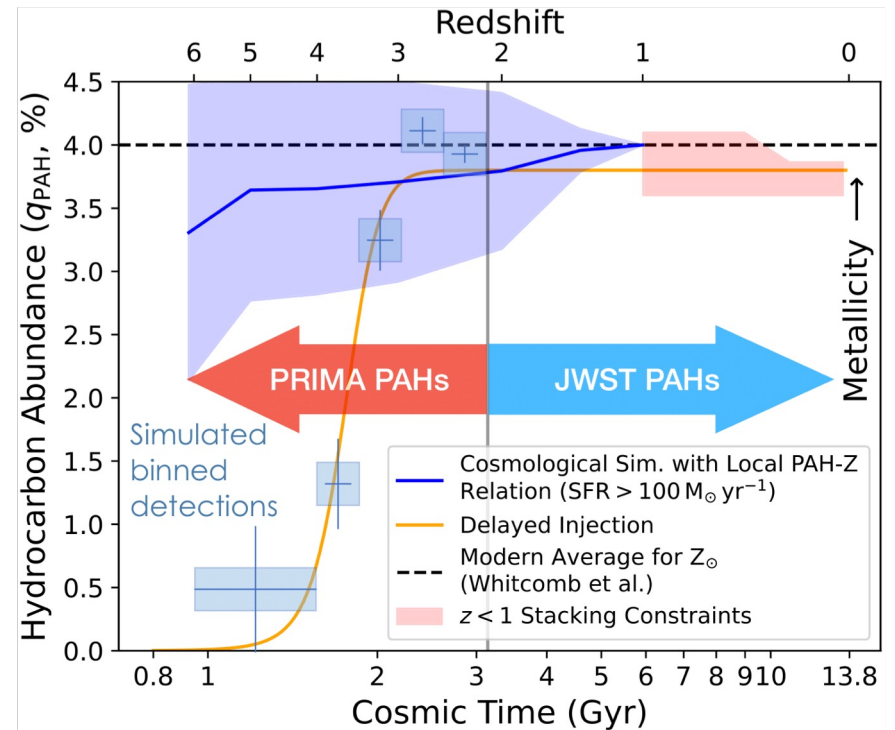
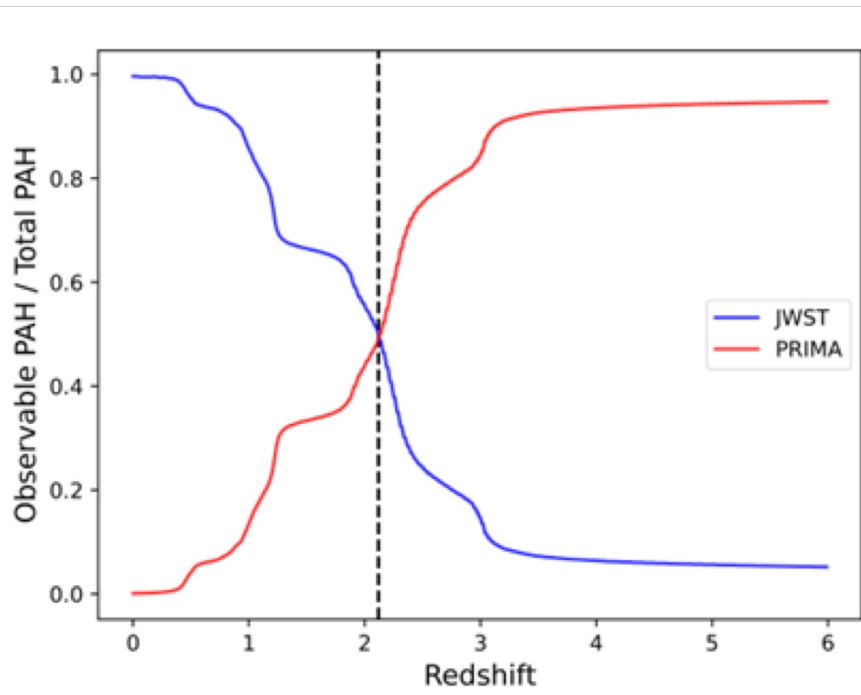
- Mass: The fundamental property of stars, but we do not know how they accrete their mass. Quiescent or episodic?
- Far-IR: Only wavelength for which luminosity correlates tightly with accretion rate.
- Test: >50% of mass is derived from rare events?
- Survey: 2000 protostars with cadences of 2 wks to 5 yrs (& back to Herschel)
- Archival value: Huge, plus polarimetry!



Battersby, et al., (2023,
PRIMA GO Science Book)

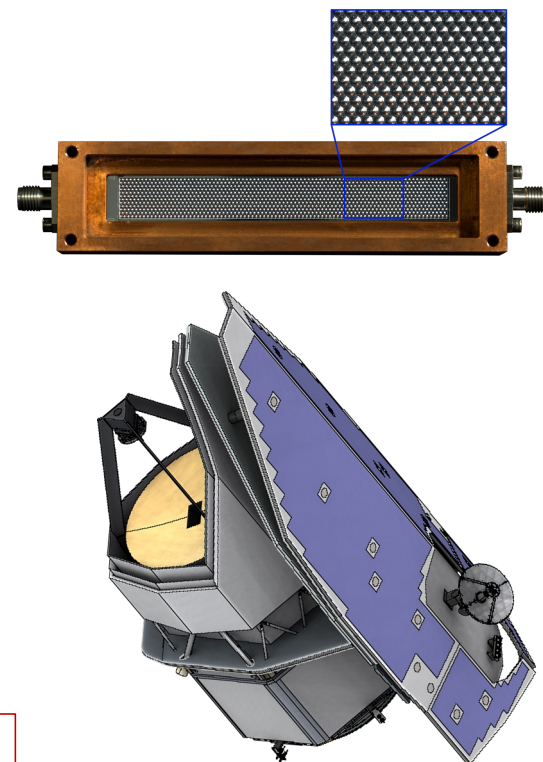
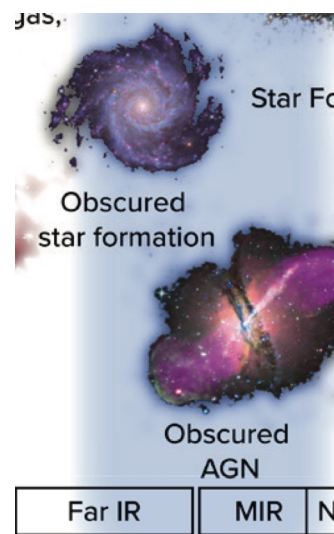
GO Science: High-z PAHs

An exciting and unique opportunity to observe hydrocarbons in the early universe, complementary to JWST (Donnelly et al., PRIMA GO Science Book)



Simple Take-Away Points

- The Far-IR provides unique probes of the cool ISM.
- PRIMA is poised to measure the coevolution of galaxies and their black holes, the buildup of dust and metals in the universe, and abundances in protoplanetary disks (PI science) and provide a broadly capable observatory for exciting GO science (*75% of the observing time*).
- With exciting results over the last several years, the detector technology is in hand!



Please consider how far-IR observations can address *your* science and talk to the PRIMA team!

<https://prima.ipac.caltech.edu>

The timing is perfect for a background-limited Far-IR Observatory

Our JPL / Goddard / SRON collaboration has demonstrated kinetic inductance detector (KID) sensitivities exceeding PRIMA's requirements spanning PRIMA's wavelengths

PRIMA R = 10 imaging requirement

PRIMA R = 100

spectroscopy requirement

Demonstrated performance
(lower on this plot is better!)

