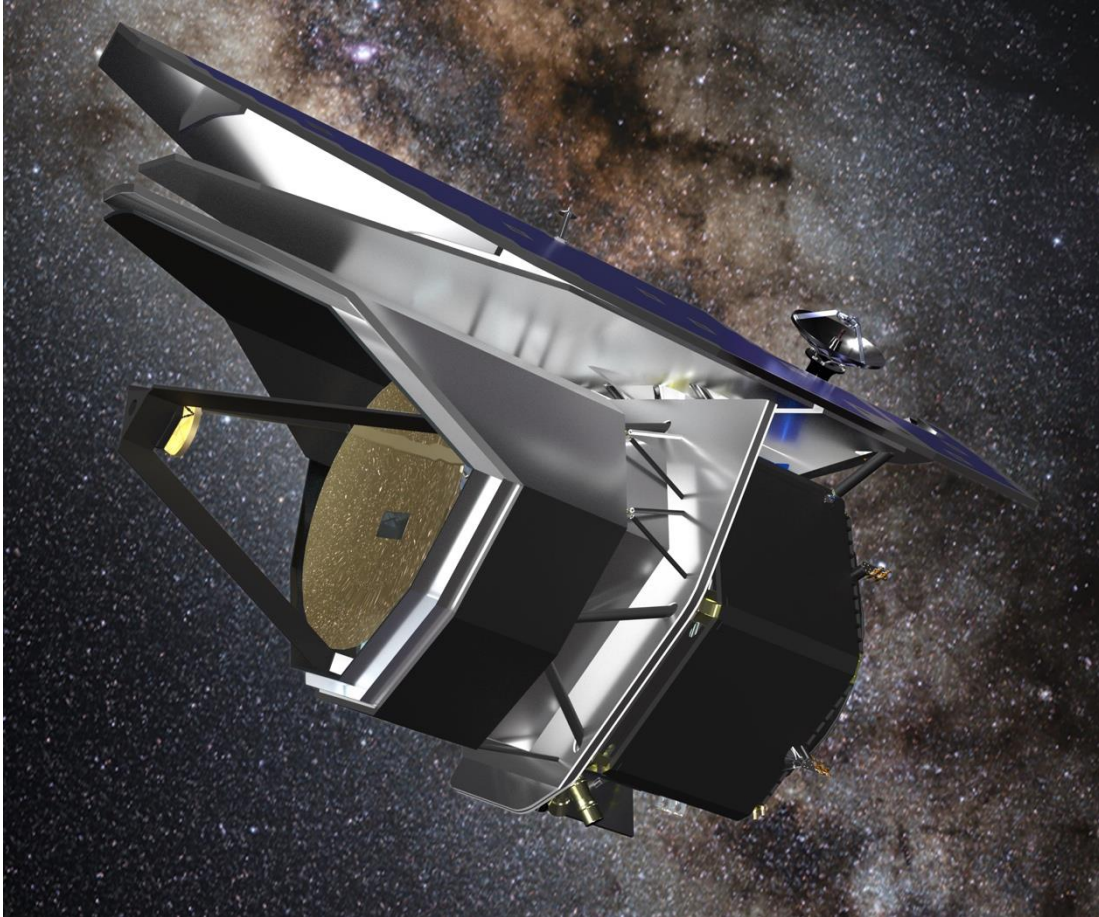




The PProbe far-Infrared Mission for Astrophysics



Jason Glenn, Principal Investigator, Goddard Space Flight Center
Margaret Meixner, Deputy PI, Jet Propulsion Laboratory
Matt Bradford, Project Scientist, Jet Propulsion Laboratory
Klaus Pontoppidan, Deputy PI, Jet Propulsion Laboratory
Alexandra Pope, Science Lead, University of Massachusetts Amherst
Tiffany Kataria, Deputy SL, Jet Propulsion Laboratory
Jenn Rocca, Proposal Capture Lead, Jet Propulsion Laboratory

Please see our website
for a list of Co-Is:





PRIMA Timeline

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

Galaxy
Evolution
Probe
proposed

2016

GEP
concept
study report
submitted

2018

Astro2020
recommends
Far-IR or X-
ray Probe

2021

PRIMA Step-1
proposal
submitted

2023

*PRIMA
selected for
Phase A
study!!*

2024

Today

CSR due

Dec
2025

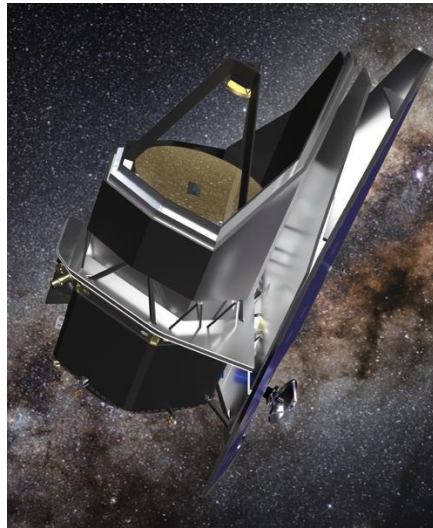
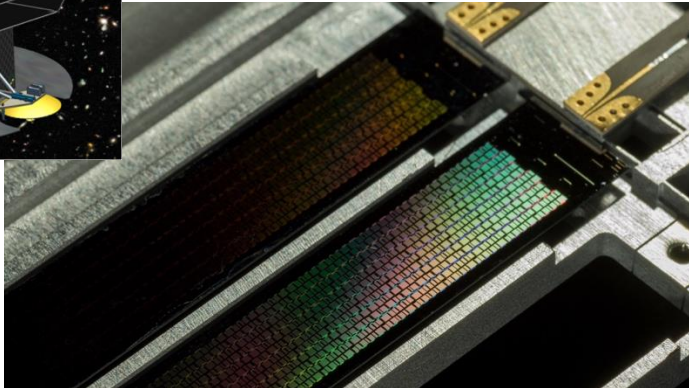
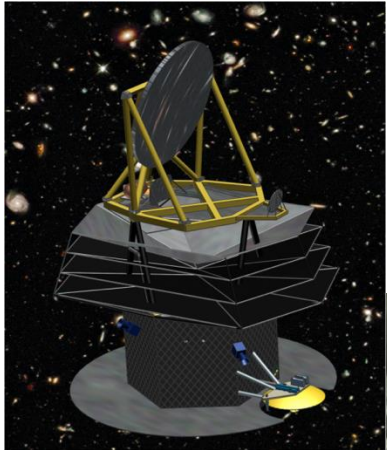
Selection for
implementation

2026

Launch!

2031

Nominal 5-
year science
mission



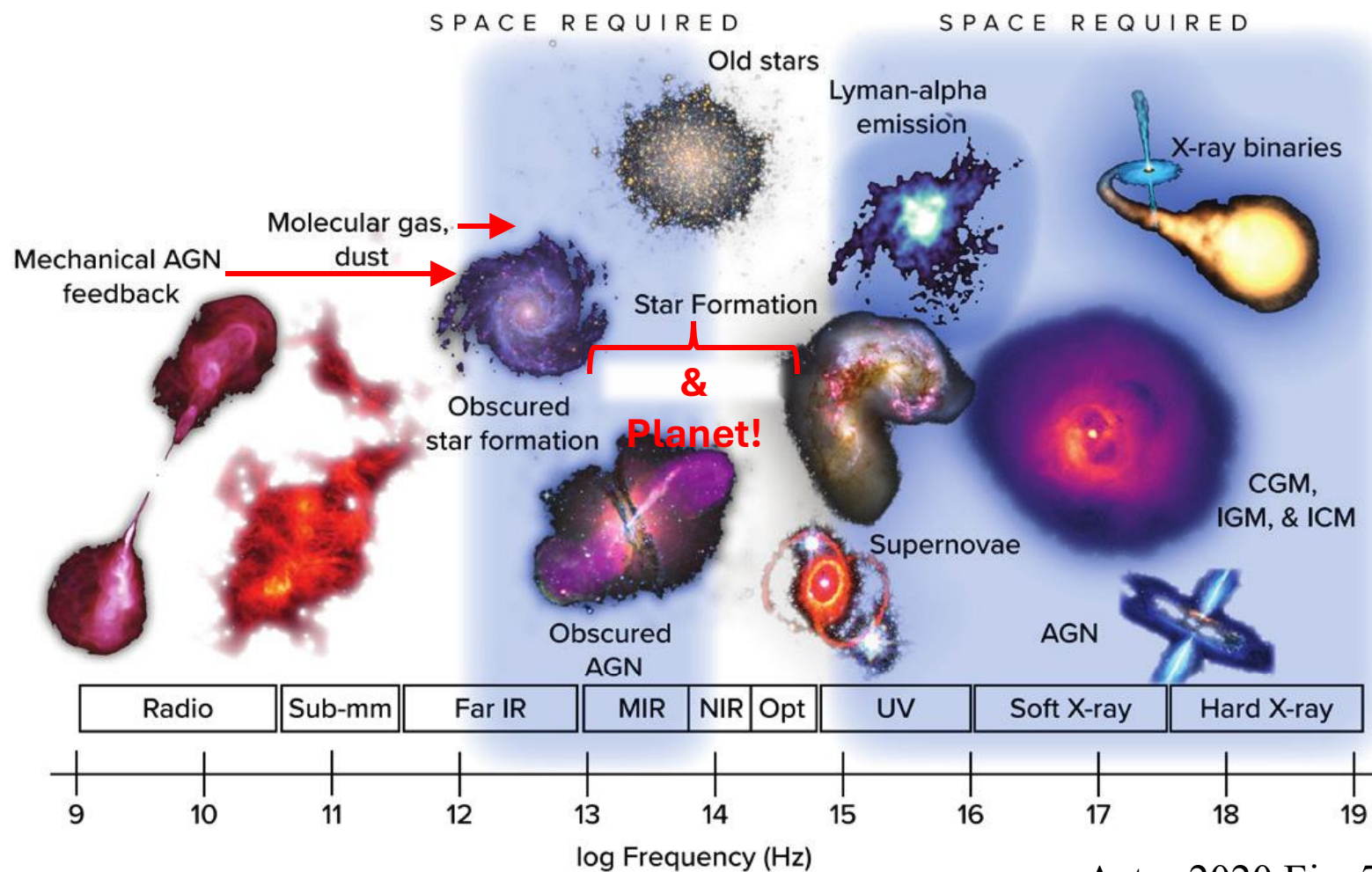
Why now?

Detector and
cryocooler technology
are mature, excellent
complementarity to
JWST and ALMA,
sensitivity → vast
discovery potential,
implementation
feasible in 5 years



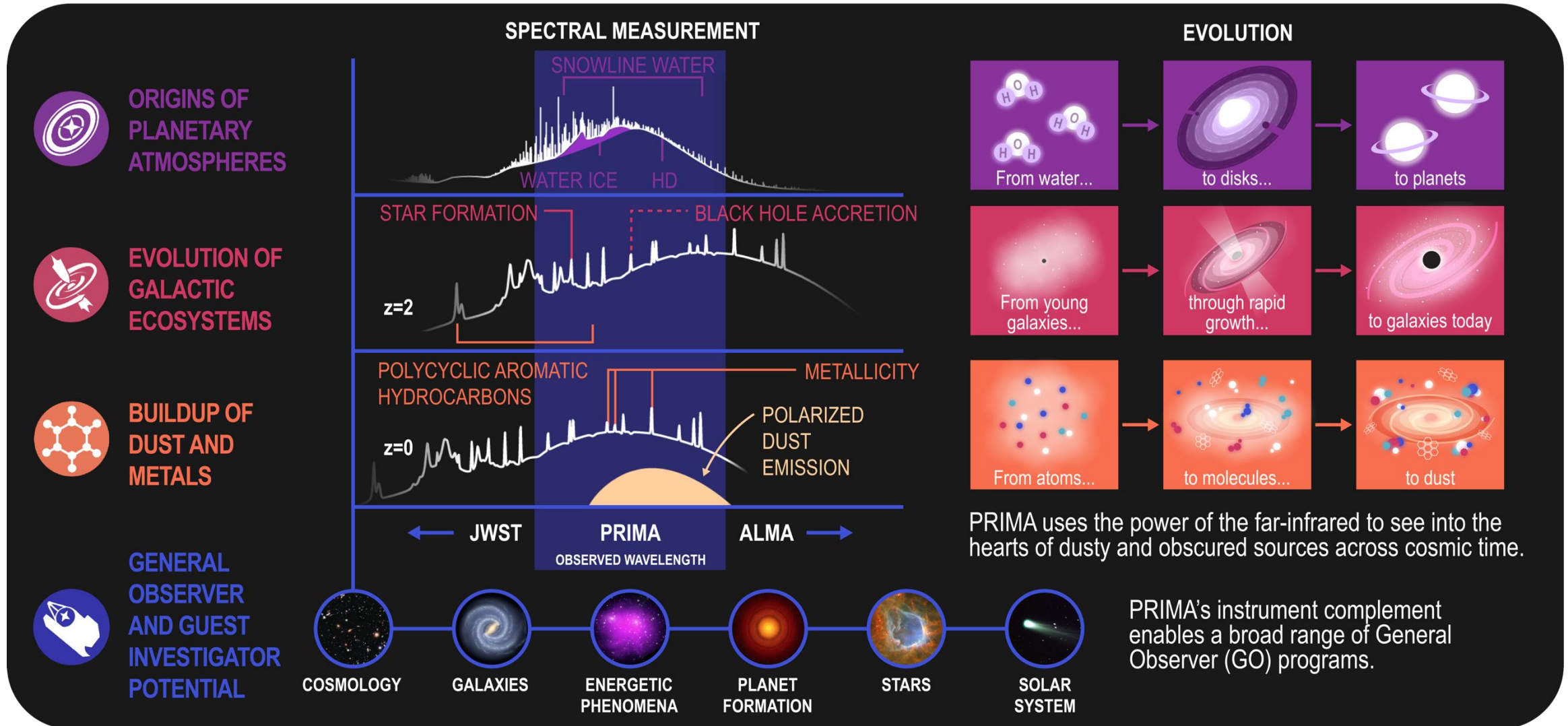
Astrophysics Probed with Far-IR Observations

- 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

Discovering how black holes & galaxies evolved together and how planet got their atmospheres

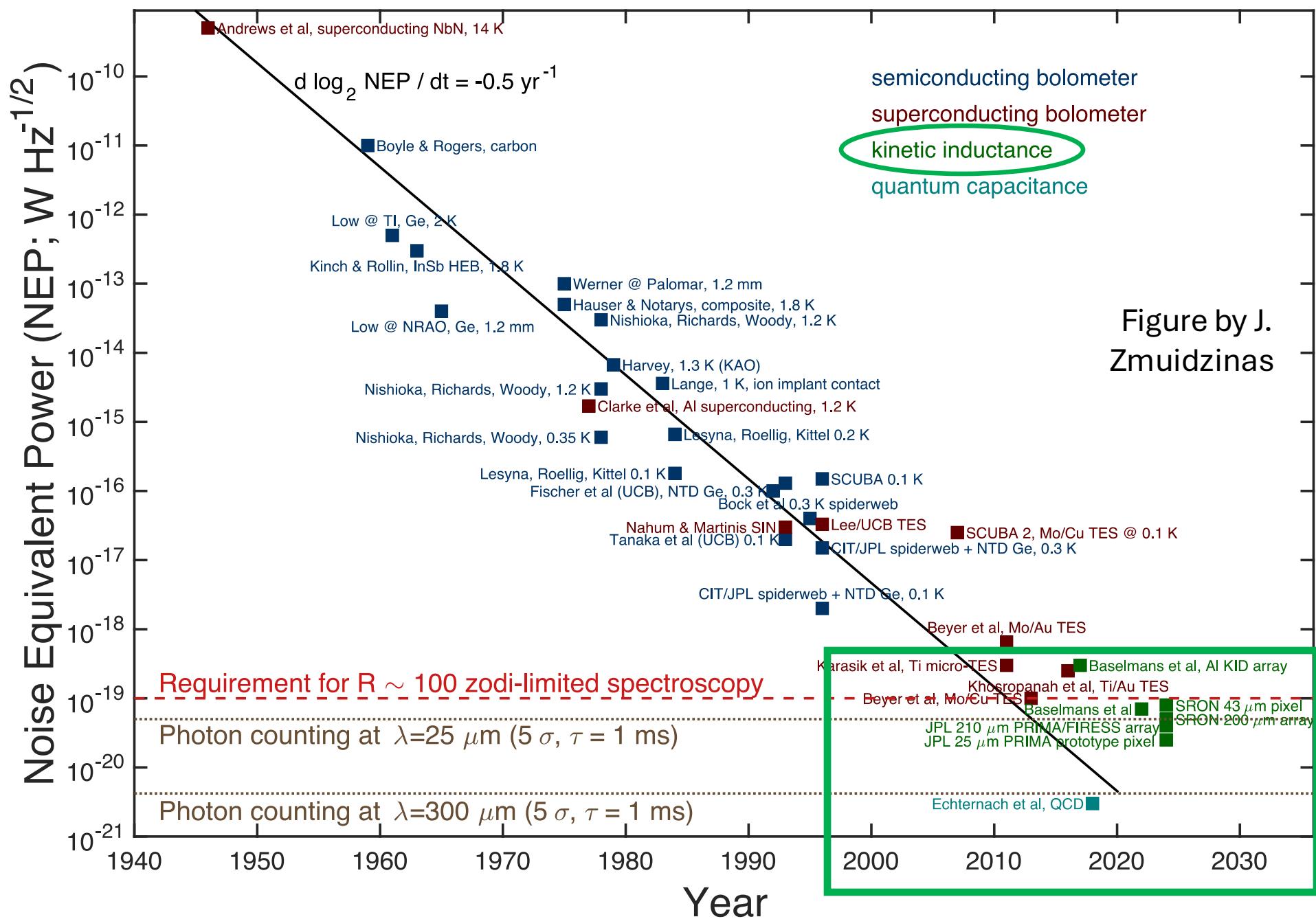


Why Now?

→ Far-IR Detector
Technological
Readiness

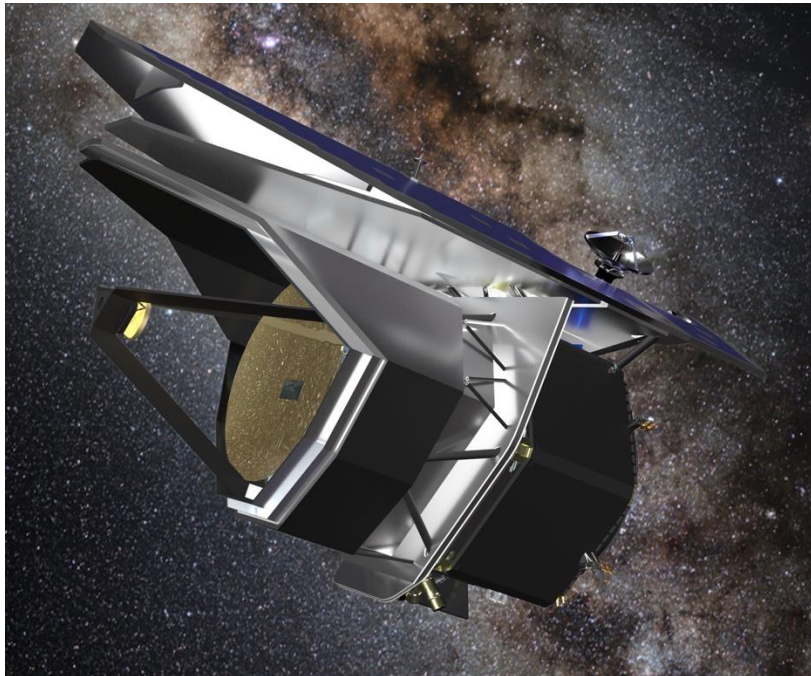
*Sensitivities of far-IR
detectors have doubled
approx. every two years
for 75 years!*

Probe region
of interest



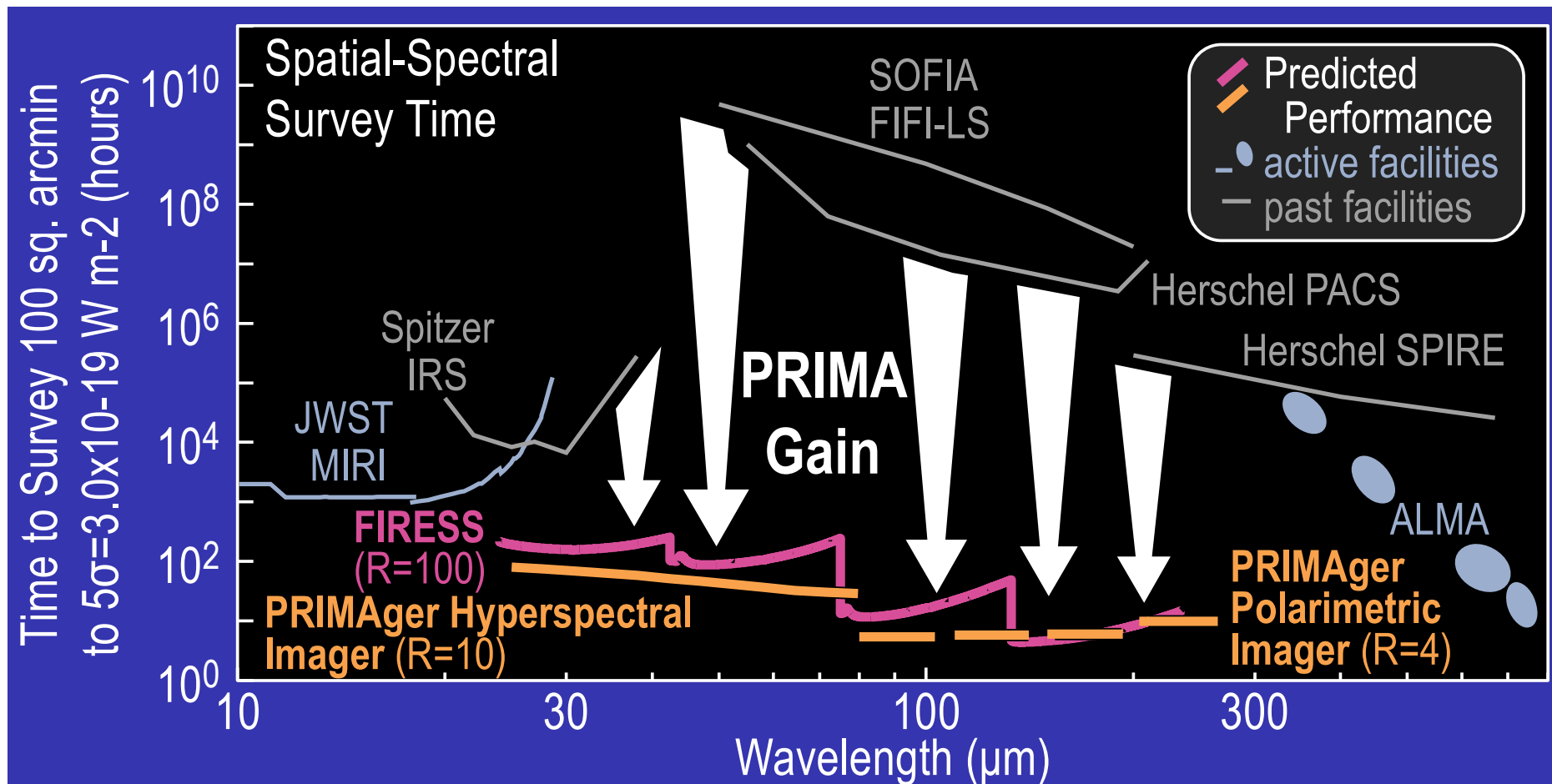
PRIMA

- 25% is for *Principal Investigator science*
- 75% of observing time is for *Guest Observers*
- *PI data will be available quickly for Guest Investigator science*



Telescope	1.8-m, all 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-Res mode R = 4,400 $\times$ ($112\mu\text{m}/\lambda$)
Detectors	100 mK KID arrays (~11k total)
Data	IPAC
Orbit	Earth-Sun L2
Launch	2032
Observations	75% GO, 25% PI ($\rightarrow$ GI)

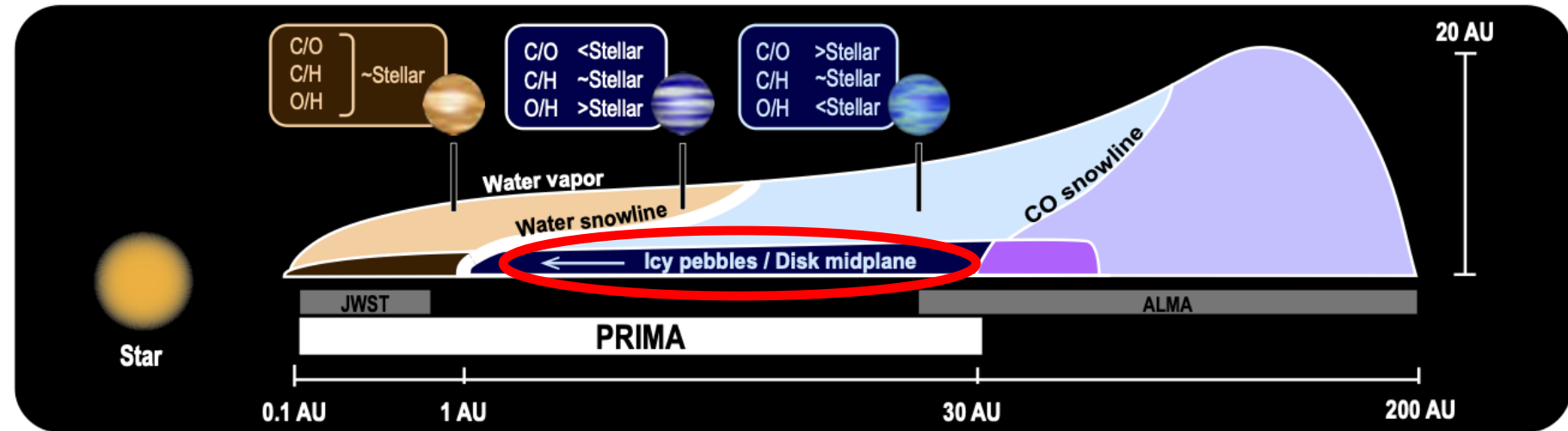
Large Gains and New Capabilities from Sensitive KID Arrays



Newly enabled

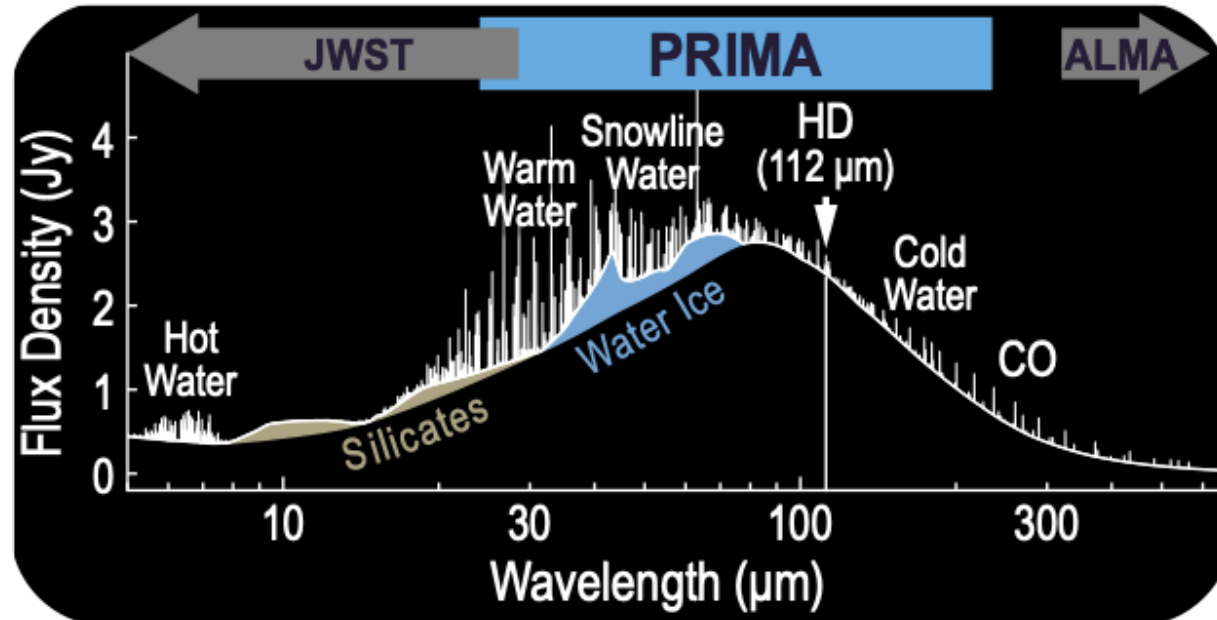
- Extended-source and line intensity spectral mapping
- Extensive polarimetric mapping
- Deep all-sky far-IR survey

Planet Growth in Disks



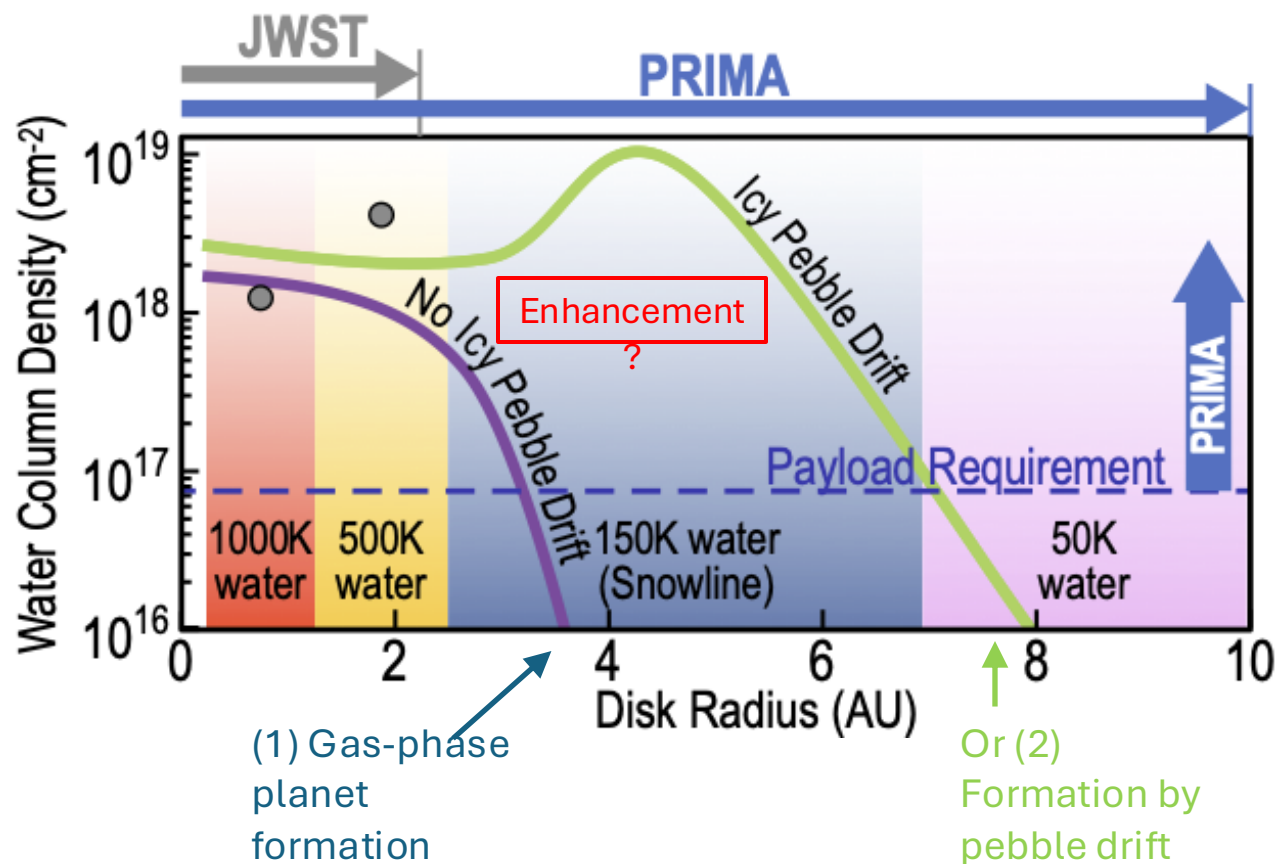
Unknowns and uncertainties

- Disk masses uncertain to an order of magnitude due to CO depletion → HD
- Disk C and O abundances – do they map to stellar metallicities?
- Icy pebbles probably drives planetesimal accretion → water vapor content and distribution

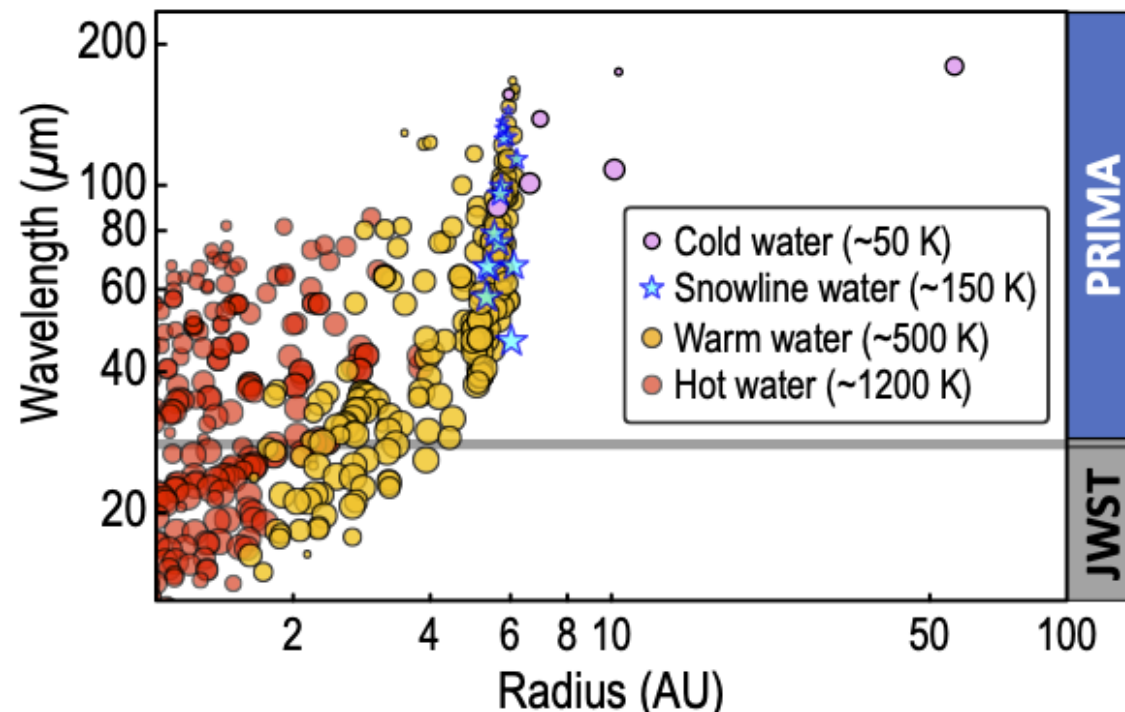


Is there enough water mass to drive the formation of planetesimals near the water snowline?

Water likely dominates the solid disk mass outside the snow line and coagulates via ice pebble drift to form planetesimals. PRIMA measures $N_{\text{H}_2\text{O}}(T)$ to test models.



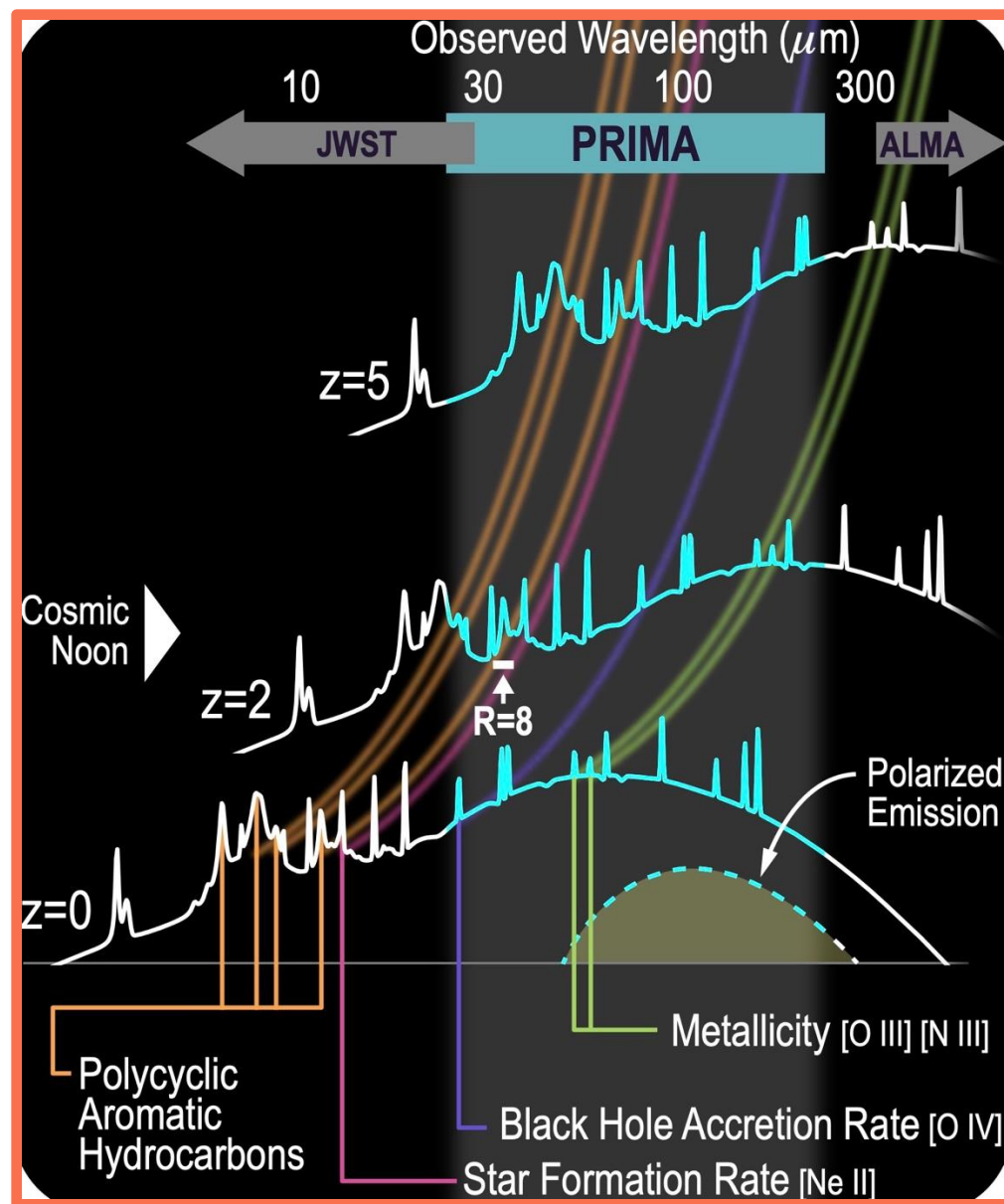
PRIMA FIRES FTM will measure the level of water enhancement in 200 disks of various ages and masses (point size $\propto$ line flux).



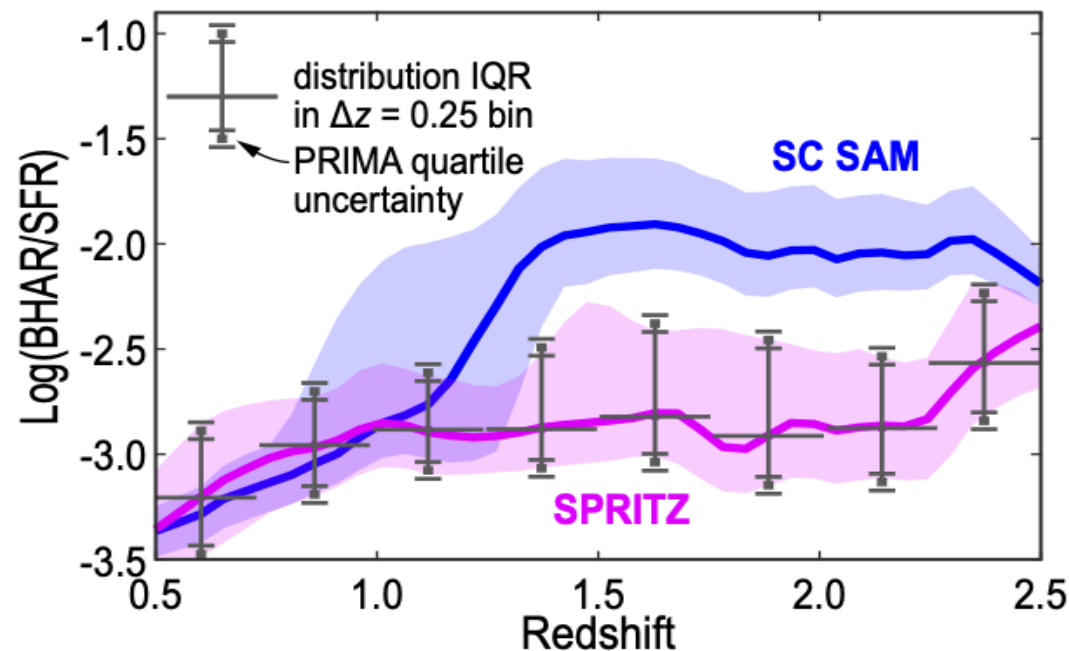
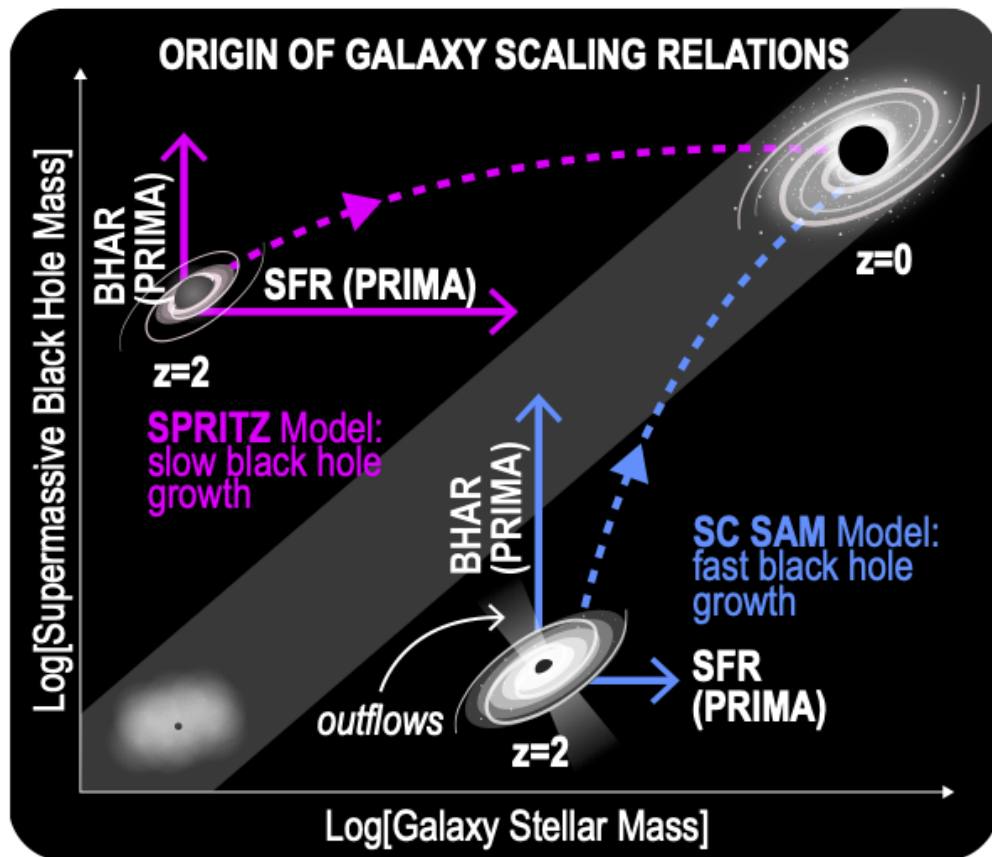


Background: Mid- and Far-IR Galaxy Spectra

- Simultaneous black hole accretion rates and star formation rates
- Metallicities
- PAHs



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



2 example histories

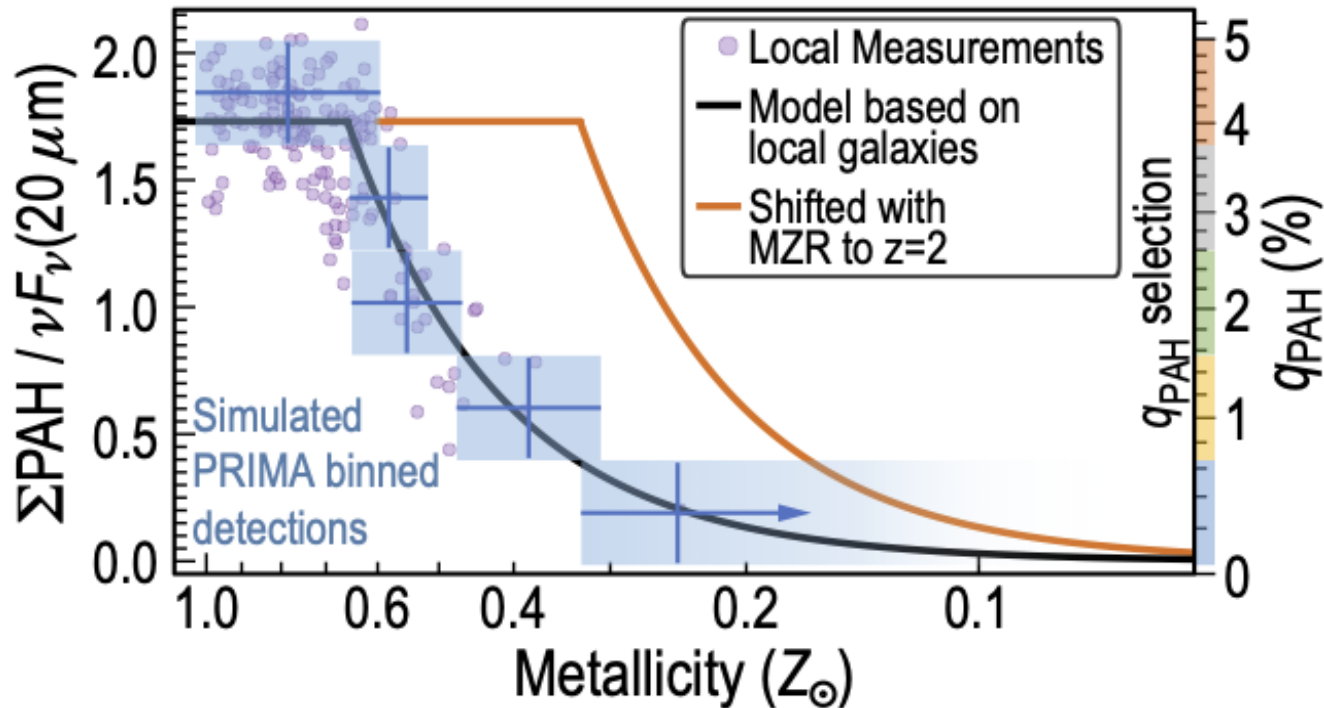
Santa Cruz Semi-analytic model: more black hole growth at cosmic noon.

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

- 42k galaxies in 1 sq deg (Donnellan+ 2024)
- Spectroscopic sub-samples of 160 $z = 1.0$ -2.5 galaxies using [O IV] and [Ne II] (rest frame 26 & 12.8 μm)
- Measure cool mass outflow rates of 50 $z = 1$ -2 galaxies with OH ($R = 900$ @ 84 μm) absorption to test if they are consistent with quenching

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.

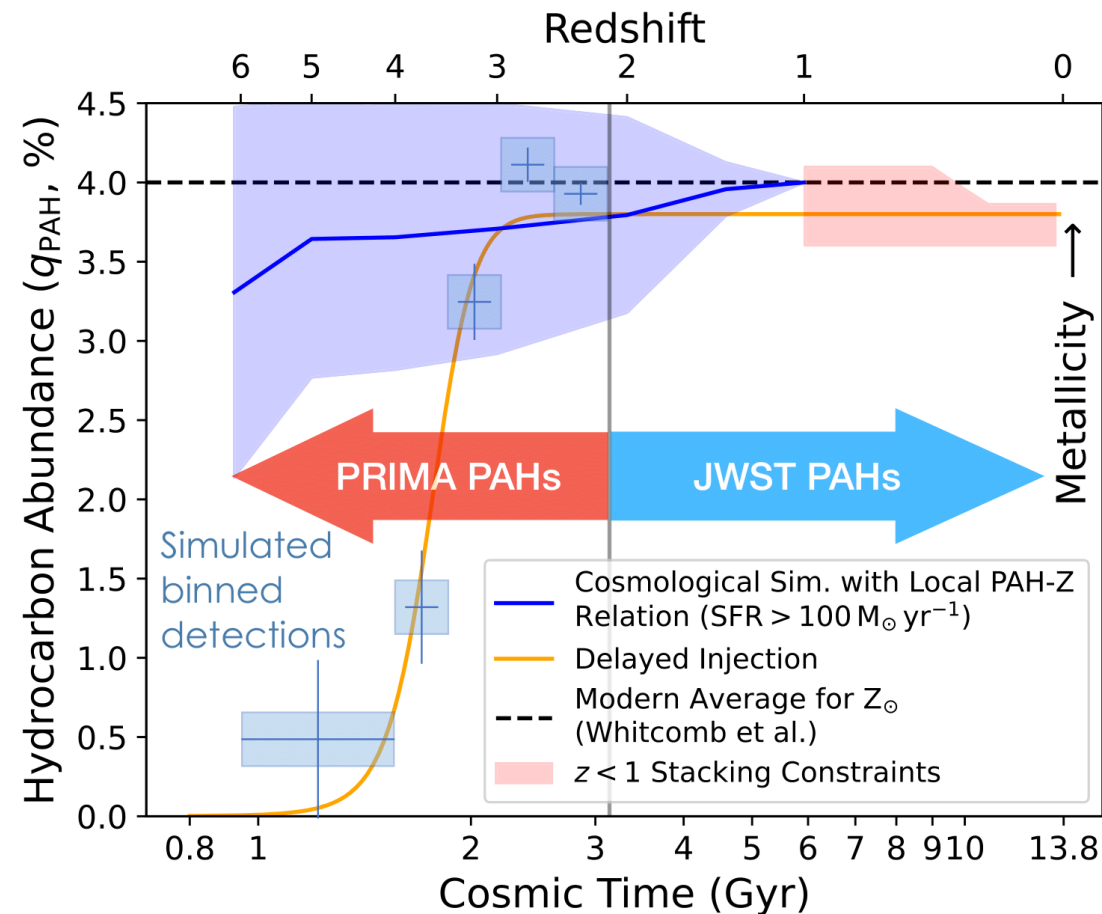
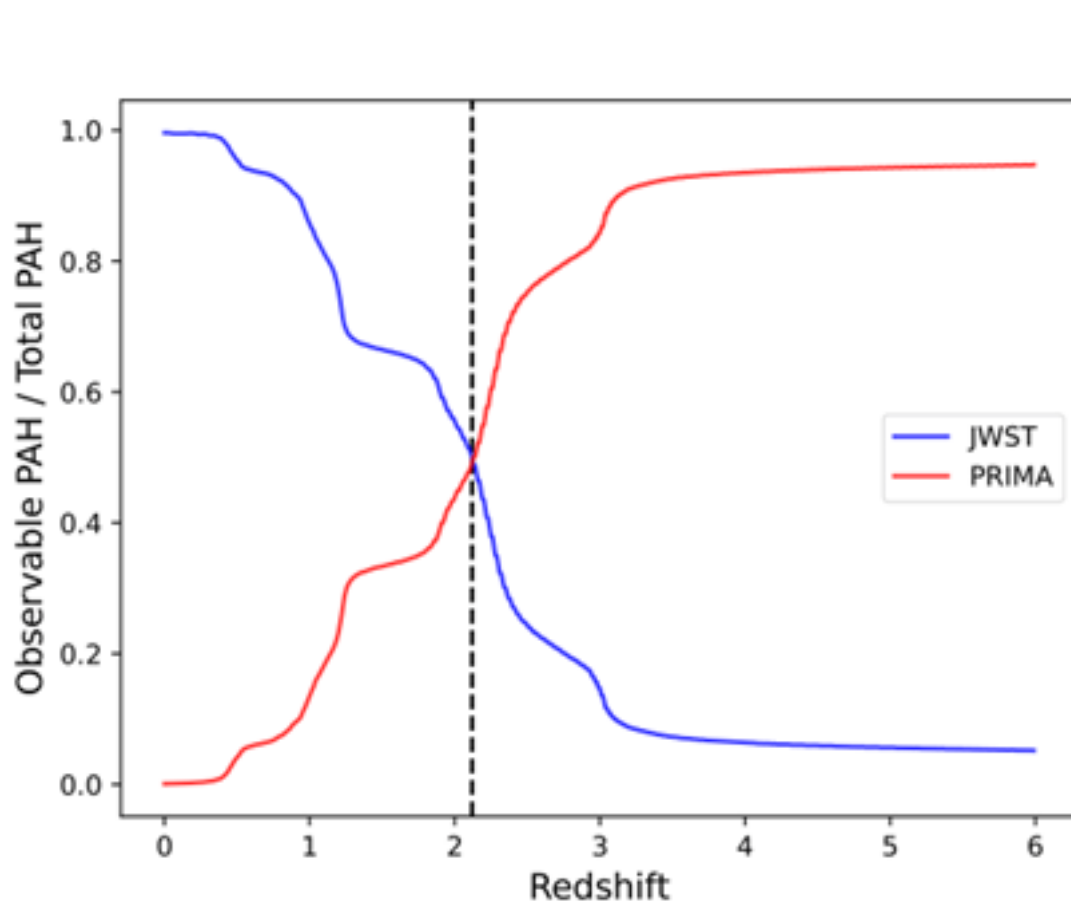


For 100 $1.75 \leq z \leq 2.25$ galaxies in 5 q_{PAH} bins, PRIMA will measure

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

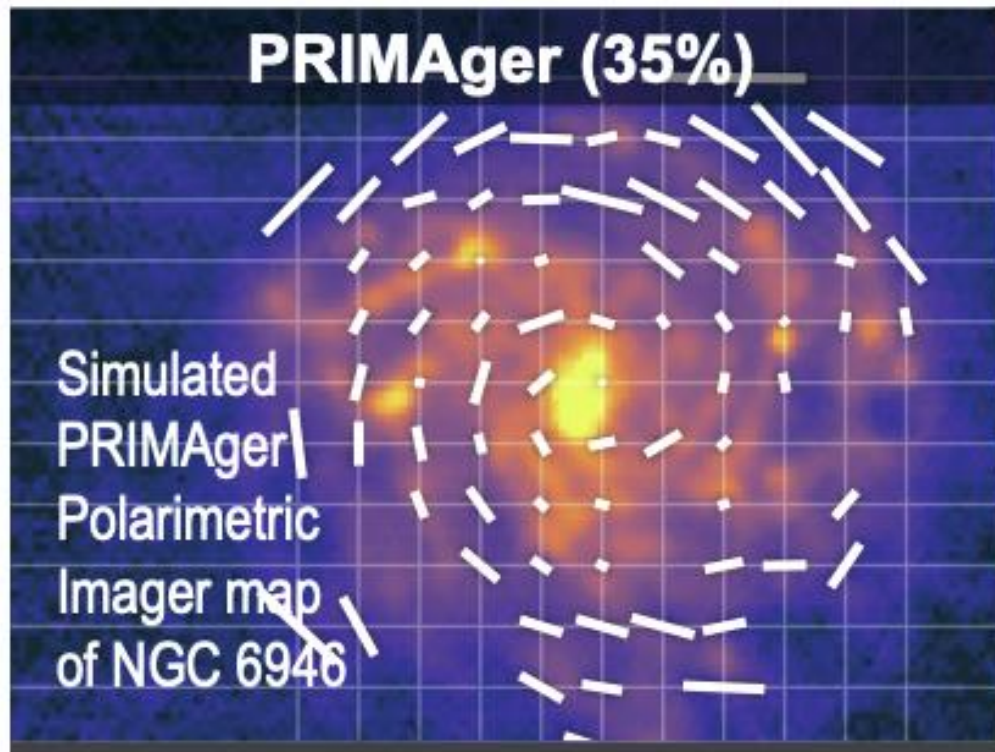
GO Science: High-z PAHs

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



GO Science: Polarimetry and Magnetic Fields in Galaxies

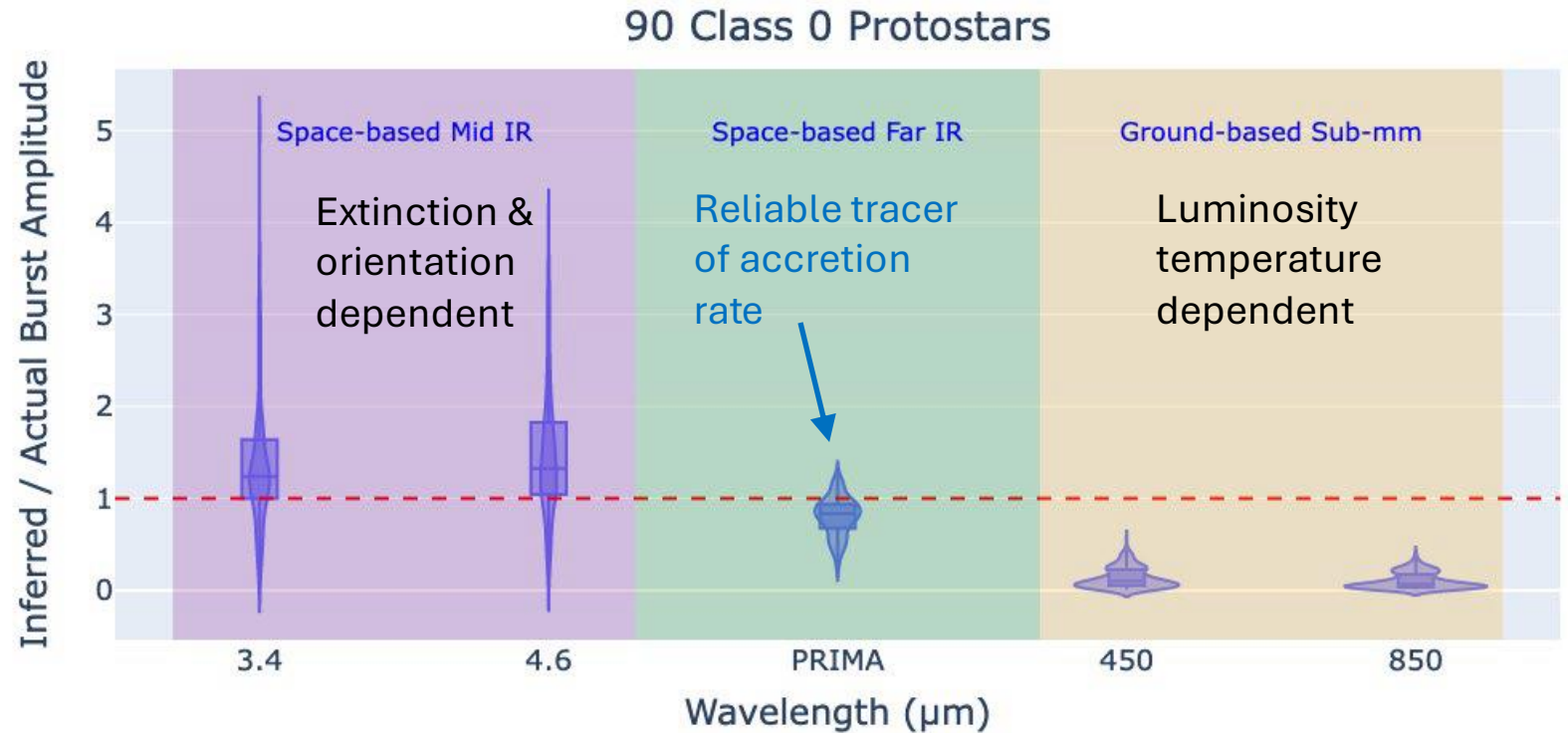
(In PI science, PRIMA will test dust models with far-IR polarimetry.)



- Simulations of polarimetric capability: Dowell+ 2024
- 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?

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!



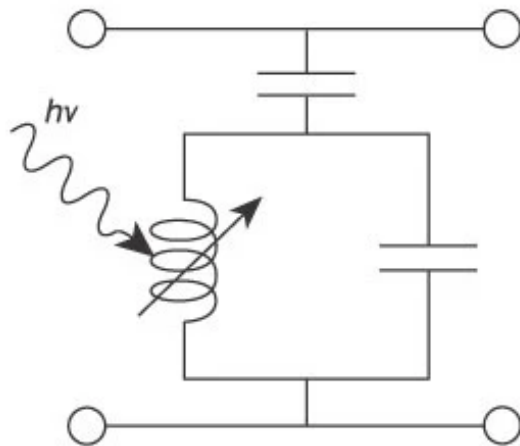
Battersby, et al., (2023, PRIMA GO Science Book)

KID Principle of Operation

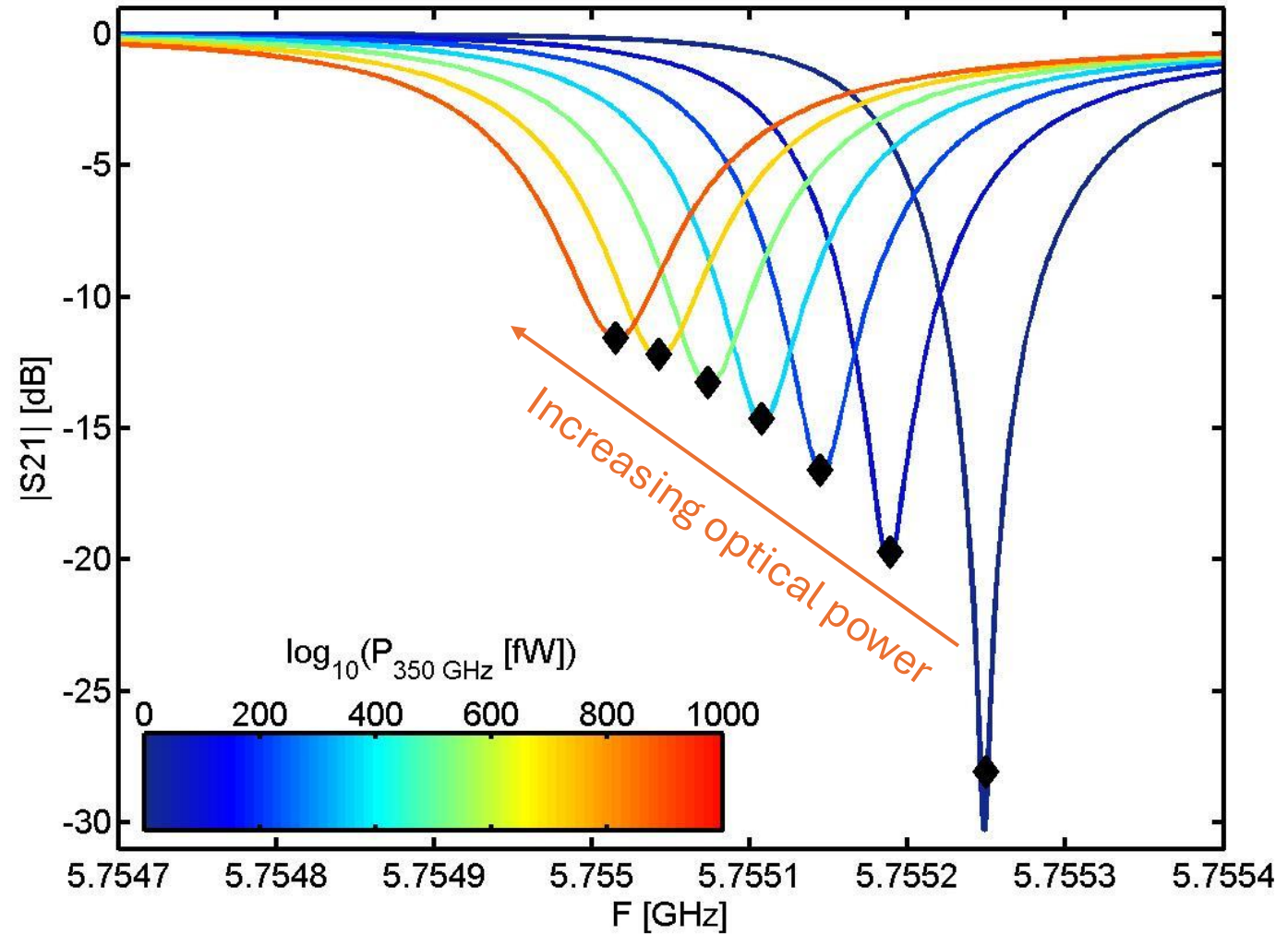
Superconducting resonator

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

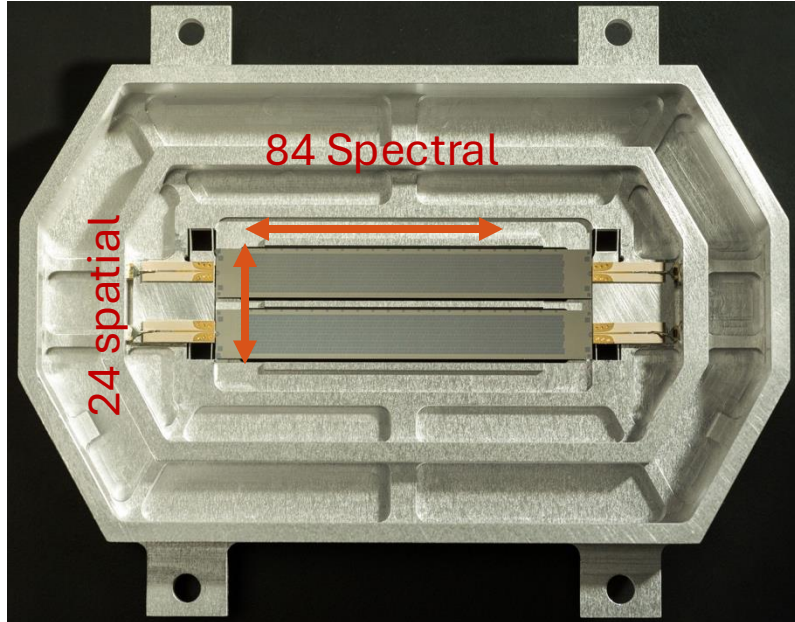
$$f_0 = 0.1 - 10 \text{ GHz}$$



Day et al. 2003

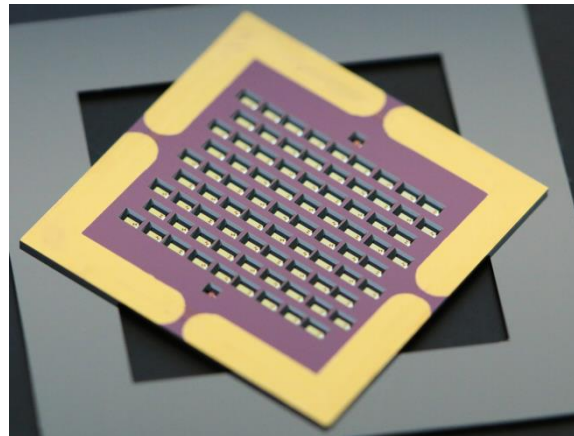


KIDs: Culmination of 2 Decades of Technology Investment

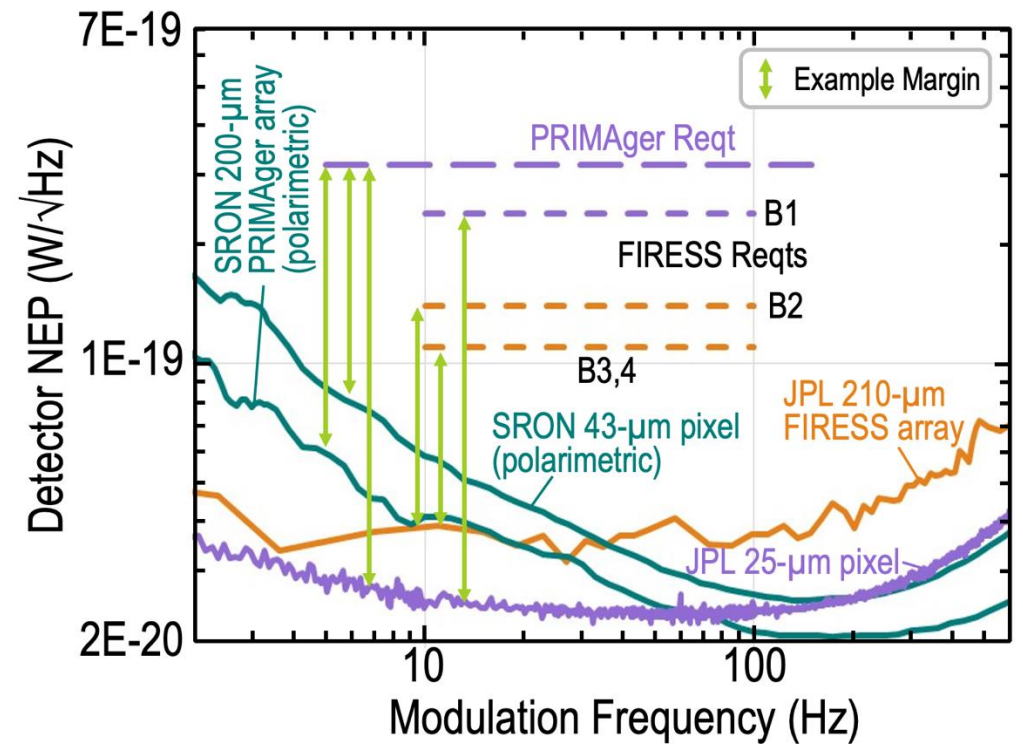


JPL FIRESS prototype KID arrays with GSFC microlenses

SRON polarimetric KIDs (derived from SPACEKIDs effort for SPICA)



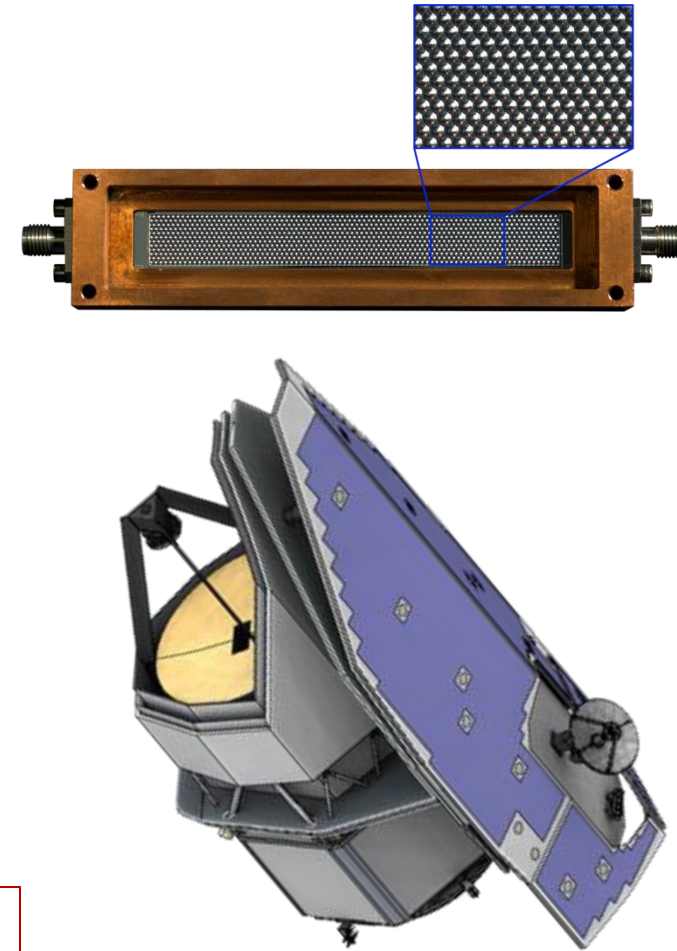
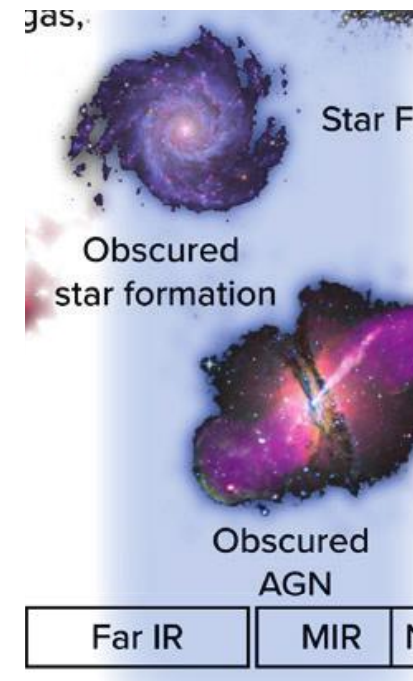
Prototype KIDs meet PRIMA requirements



25 μm result: Day+ 2024, Phys Rev X

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>



Extra slide follows

Getting Involved

- See website for news, events, papers, etc.
- Join the mailing list
- Submit an application to join a working group
- Next scientific conference in Marseille
March 31 – April 2 *Dusting Off the Secrets of the Cosmos with PRIMA*

<https://primaconf.sciencesconf.org/>

Website



GO book v1



Screenshot from a breakout session of the March 2022 GO science white paper early career scientist mentoring workshop.



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.

Protoplanetary Disk Masses from HD

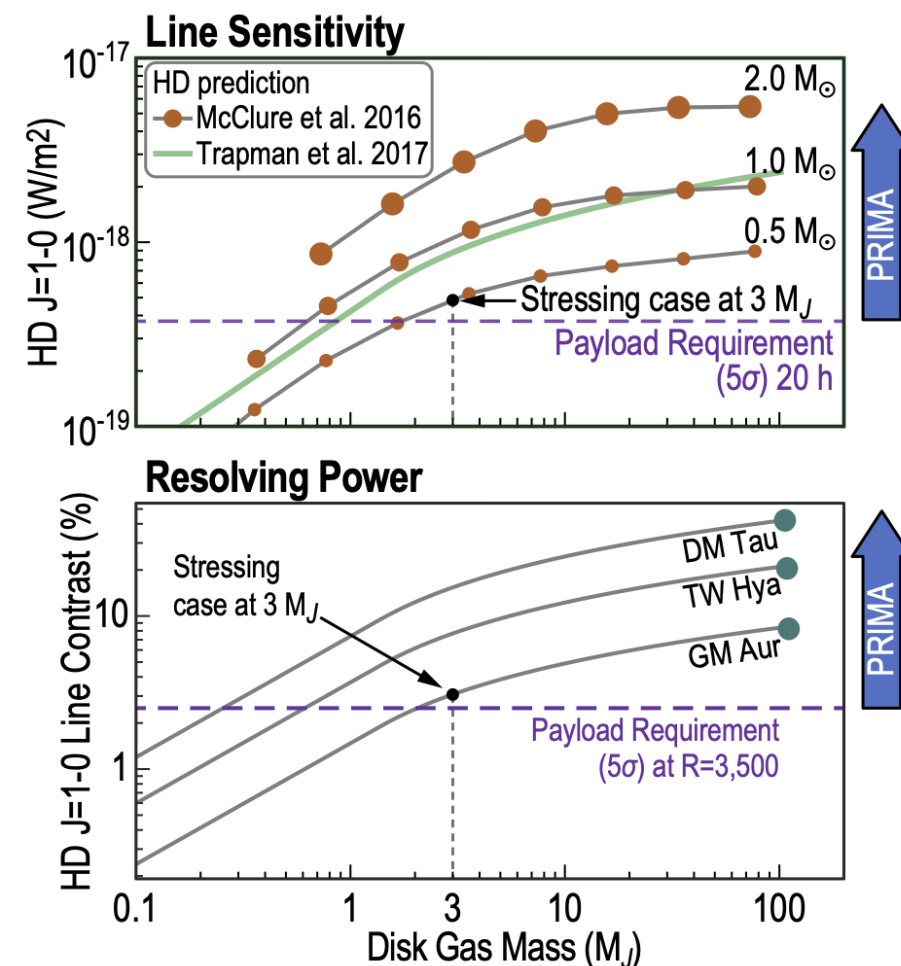
CO-derived disk masses are currently uncertain to a factor of 10 due to depletion

- 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).

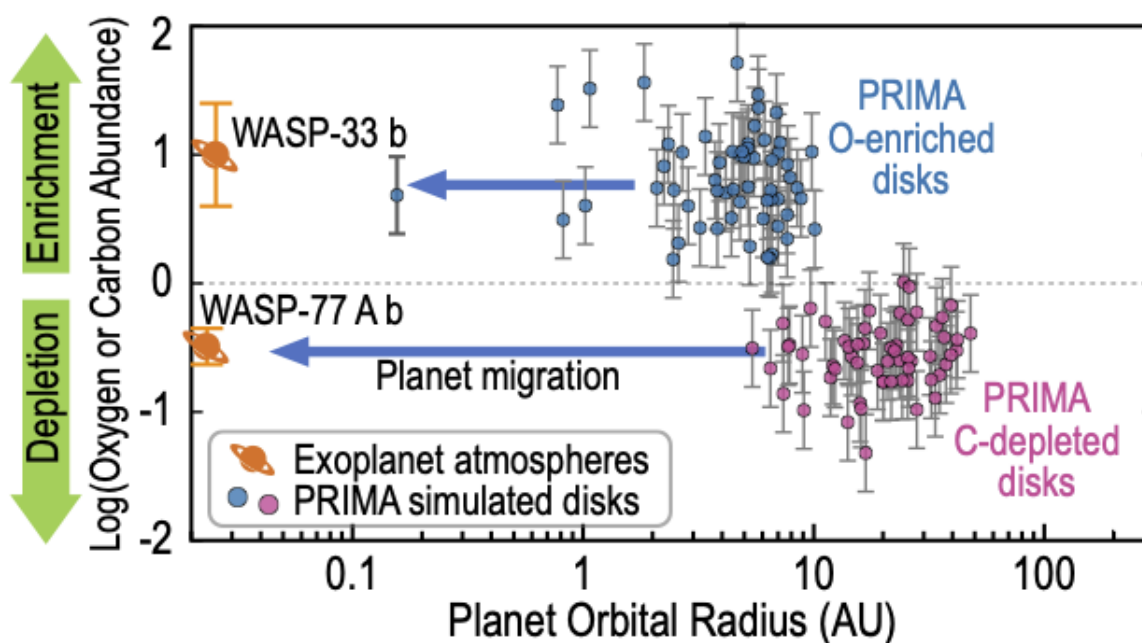


Protoplanetary Disk C and O Abundances

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).

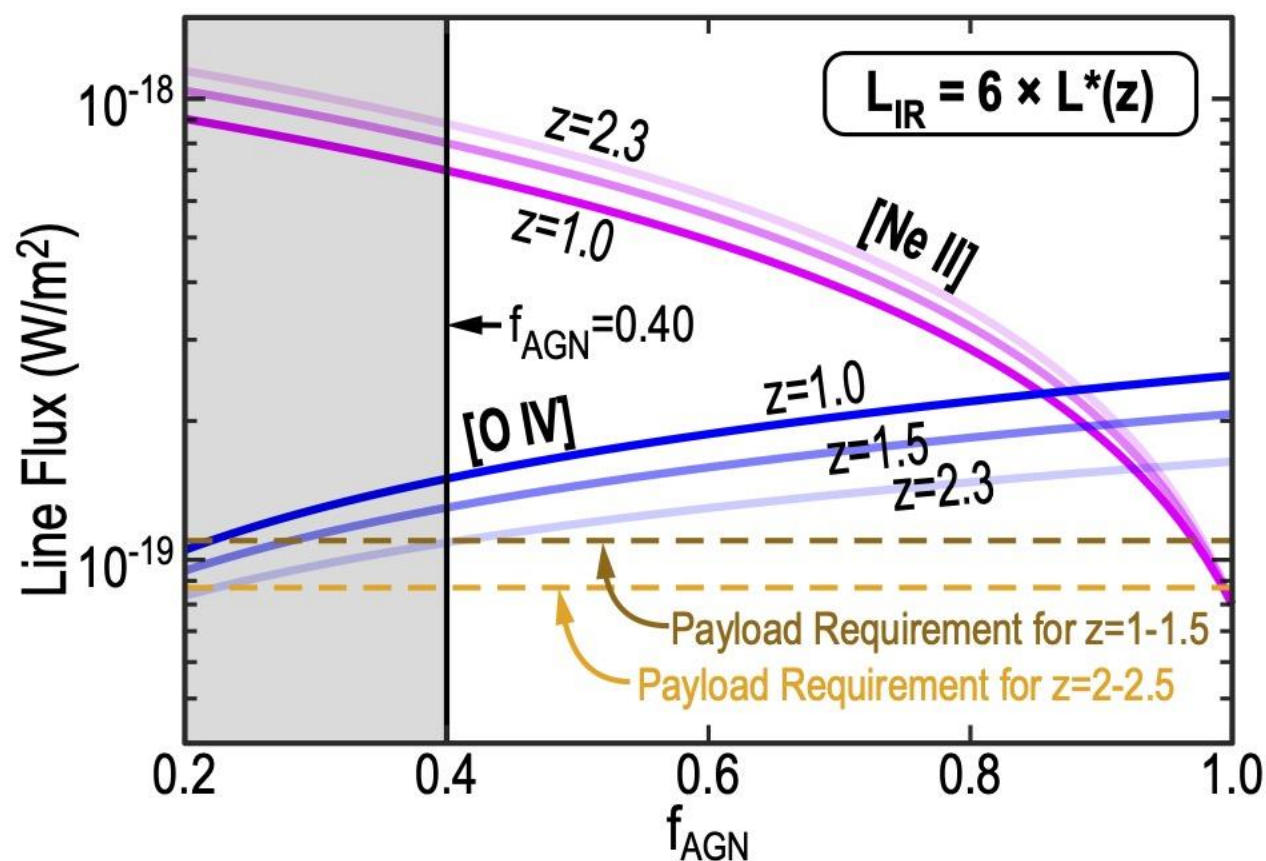


Oxygen derived from water and (gas-phase, which drives gas-giant formation) carbon from existing CO ALMA observation

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?

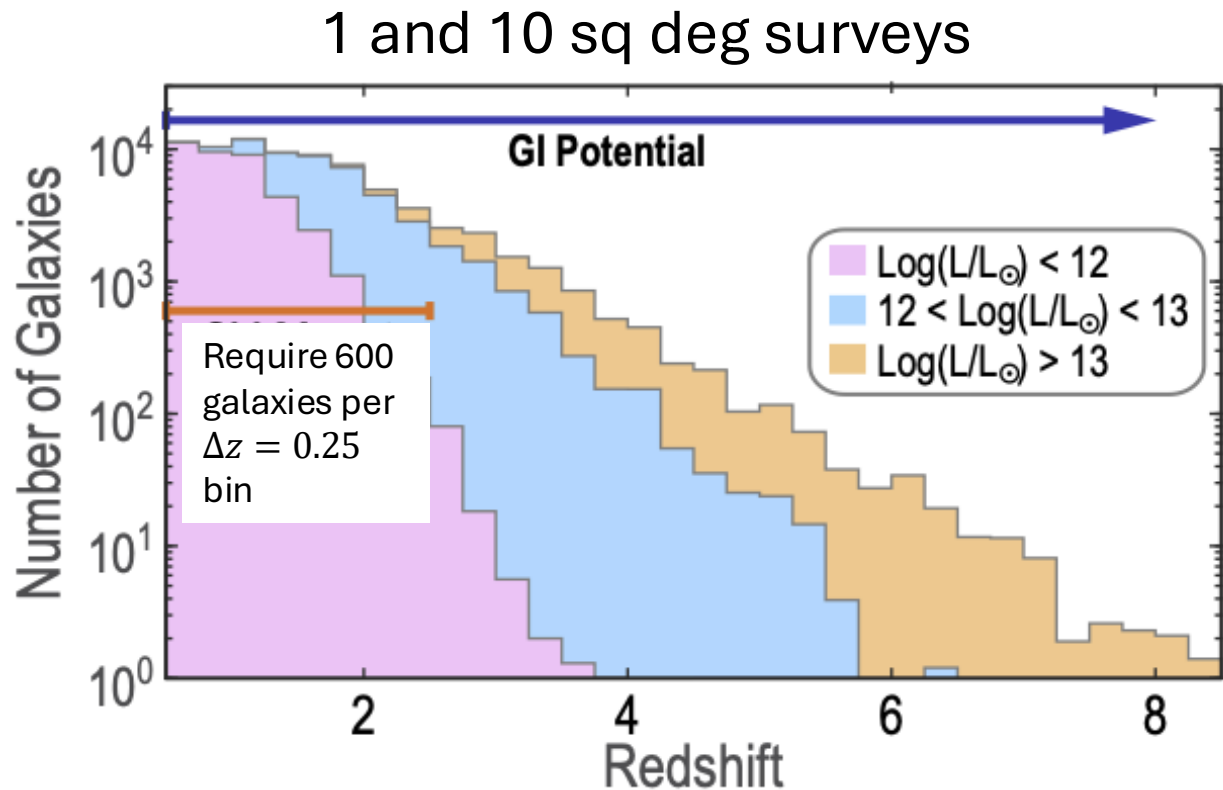
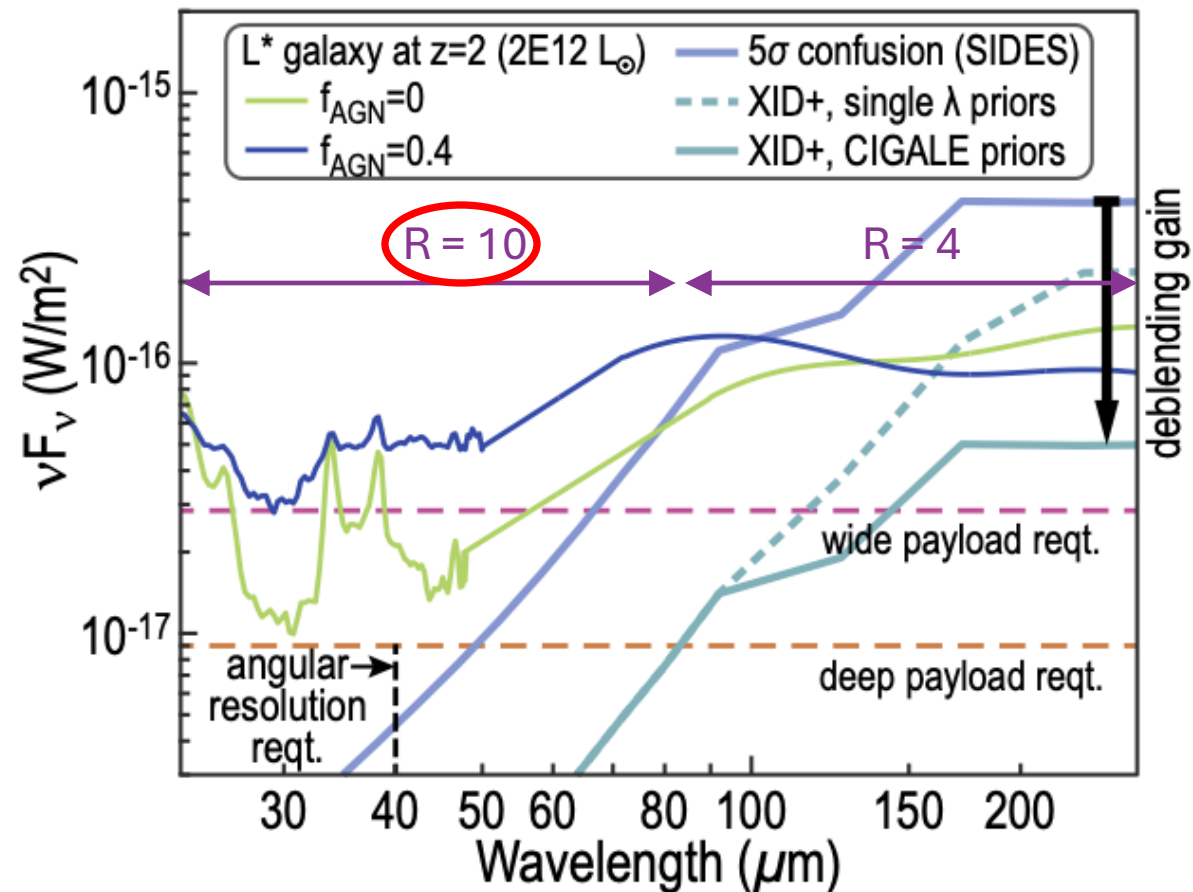
⇒ Redshifted mid-IR and far-IR spectral energy distributions (SEDs) and **atomic fine-structure lines**.



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

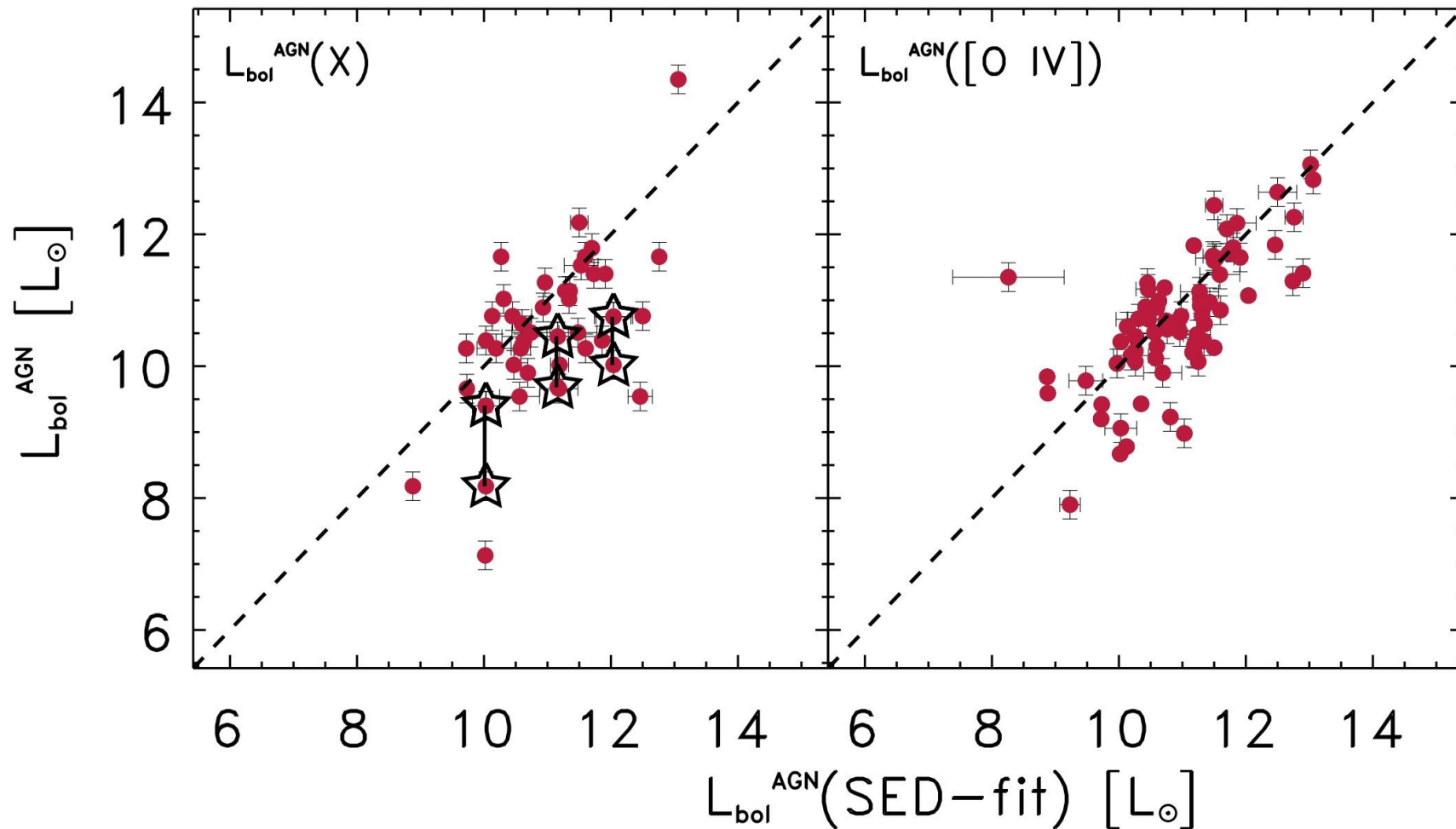
Models based on Bonato+ 2019 (also Gruppioni+ 2016 and Stone+ 2022)

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



Bethermin+ 2024
Donnellan+ 2024

AGN Tracers

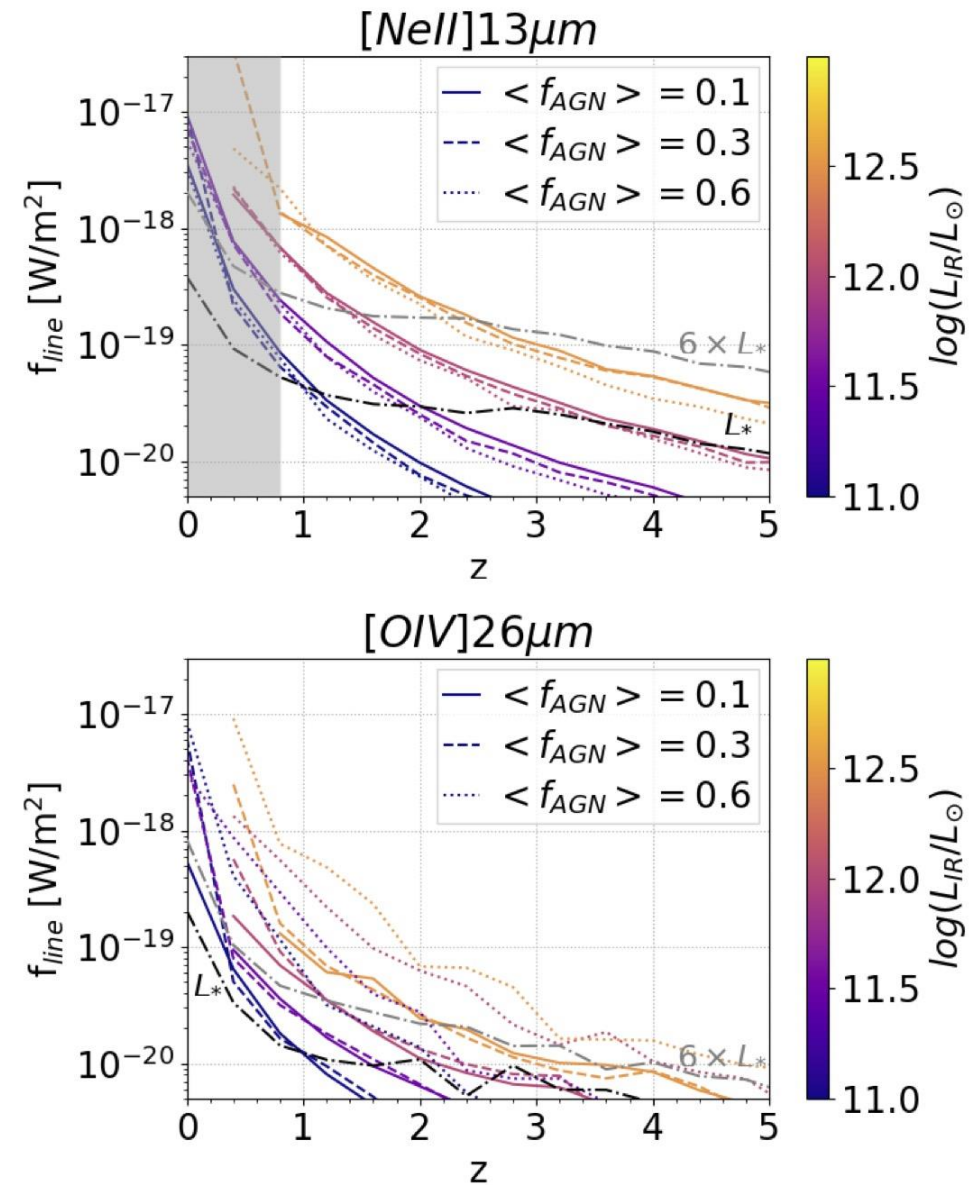


- X-rays are 2-10 keV
- 3 points with stars denote corrections from hard X-rays for known Compton-thick sources
- Other X-ray points may lie below 1:1 line due to obscuration
- From Bisigello+ 2024

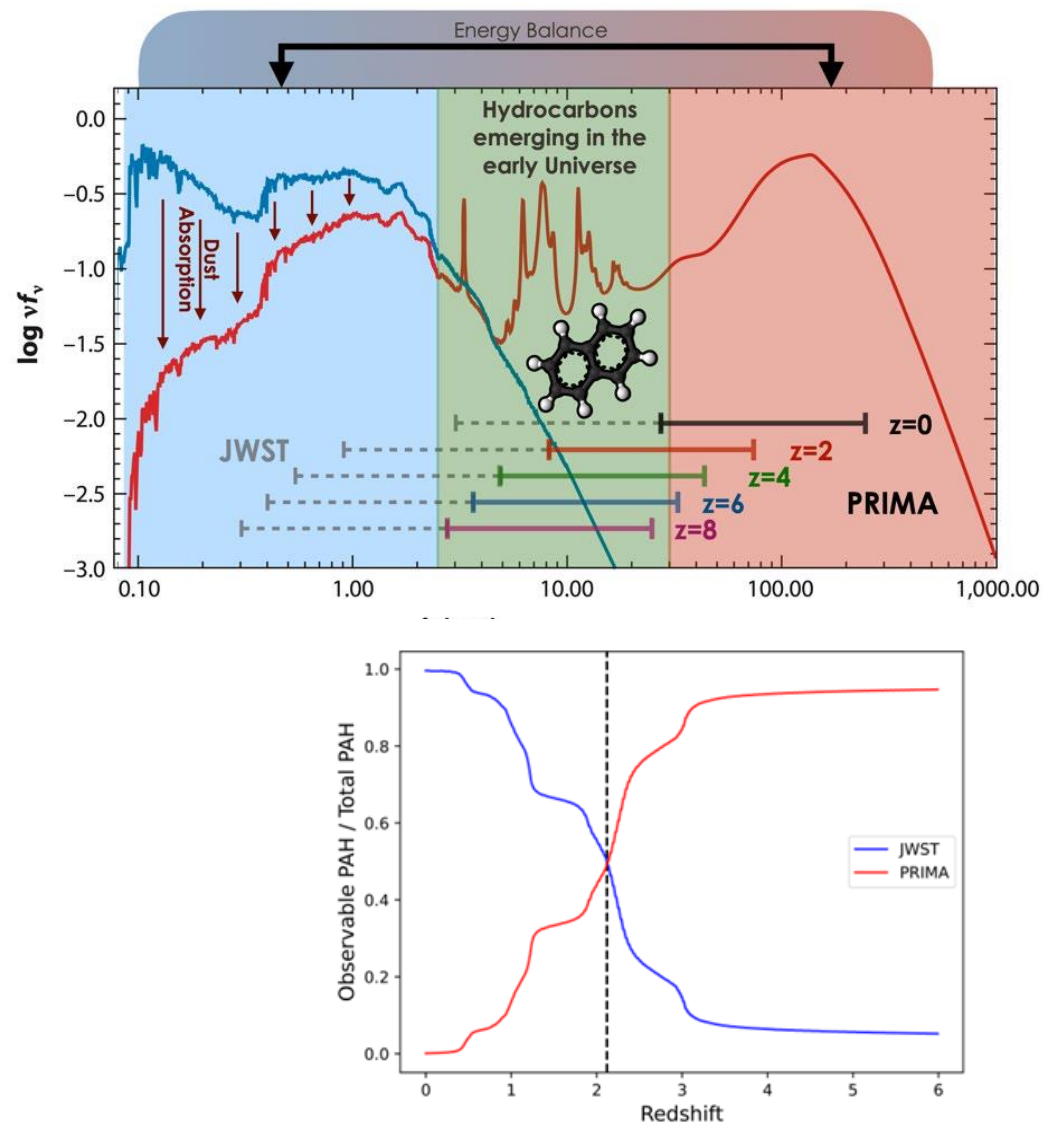
[Ne II] and [O IV] Detectability

- 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

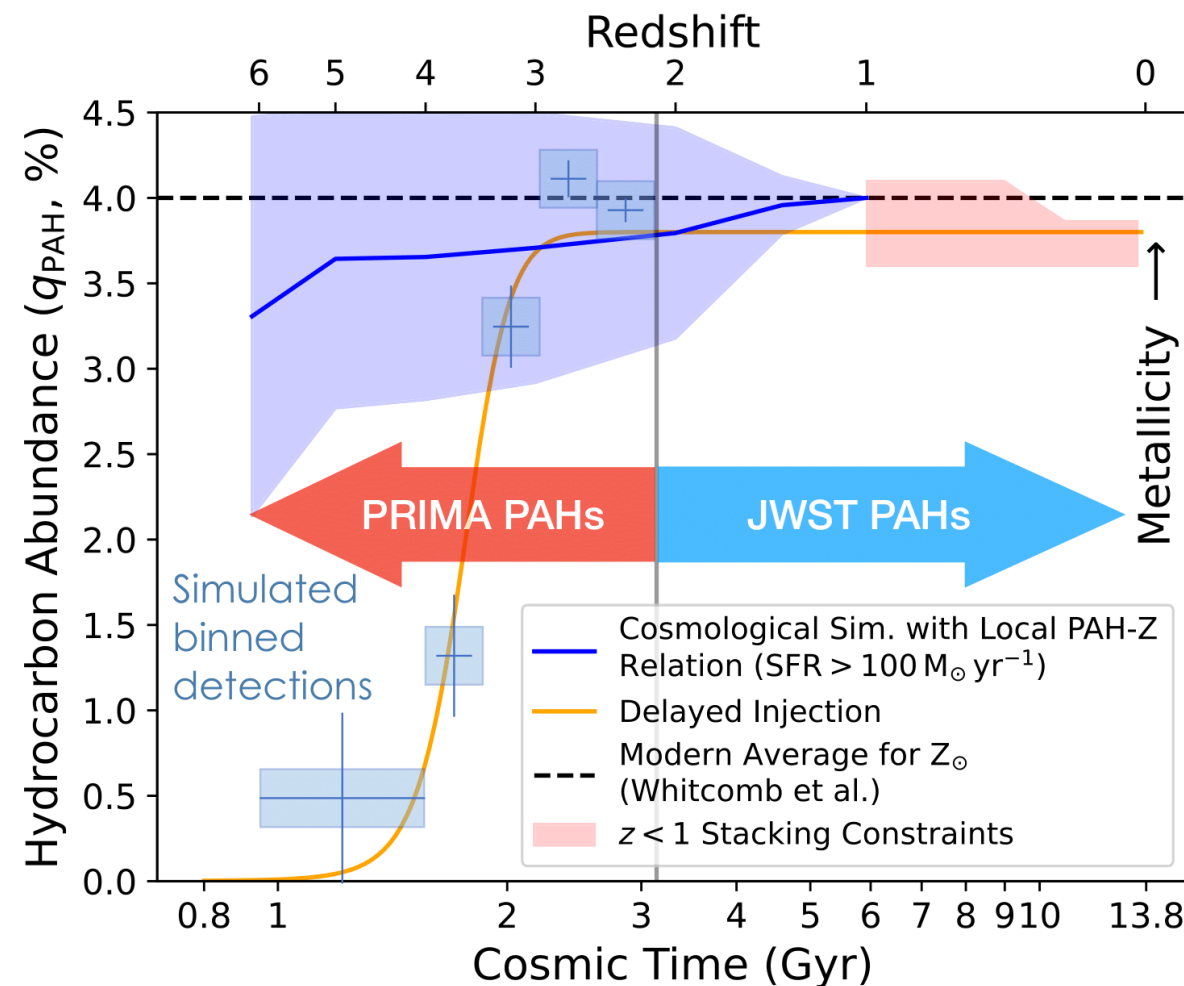
From Bisigello+ 2024



GO Science: High-z PAHs

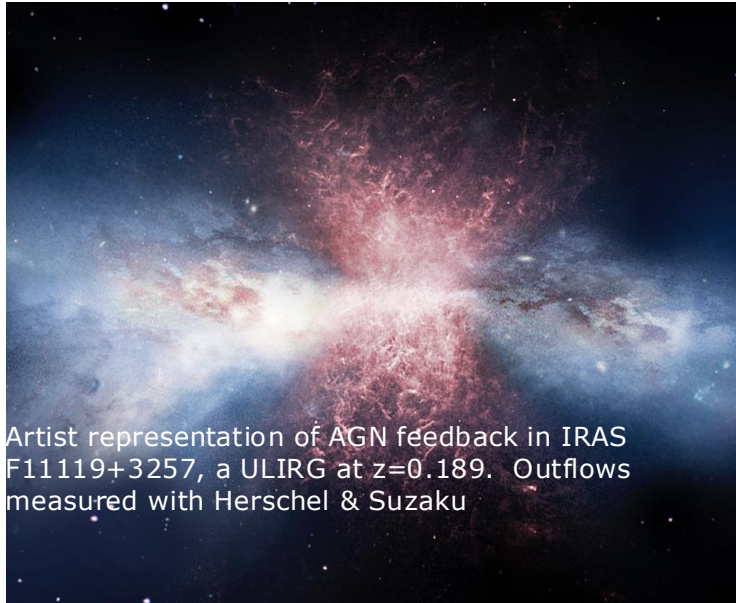


An exciting and unique opportunity to observe hydrocarbons in the early universe, complementary to JWST (Donnelly et al., PRIMA GO Science Book)

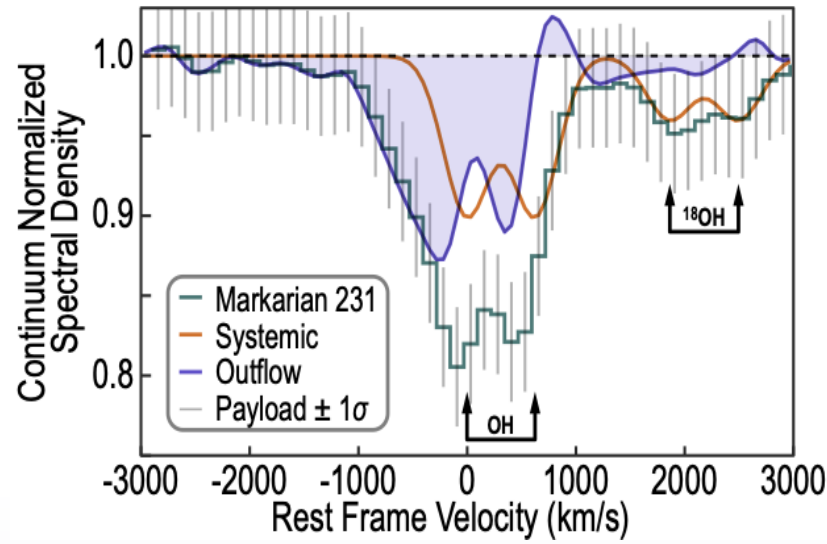


Evolution of Galactic Ecosystems: Can outflows quench $z = 1-2$ star formation?

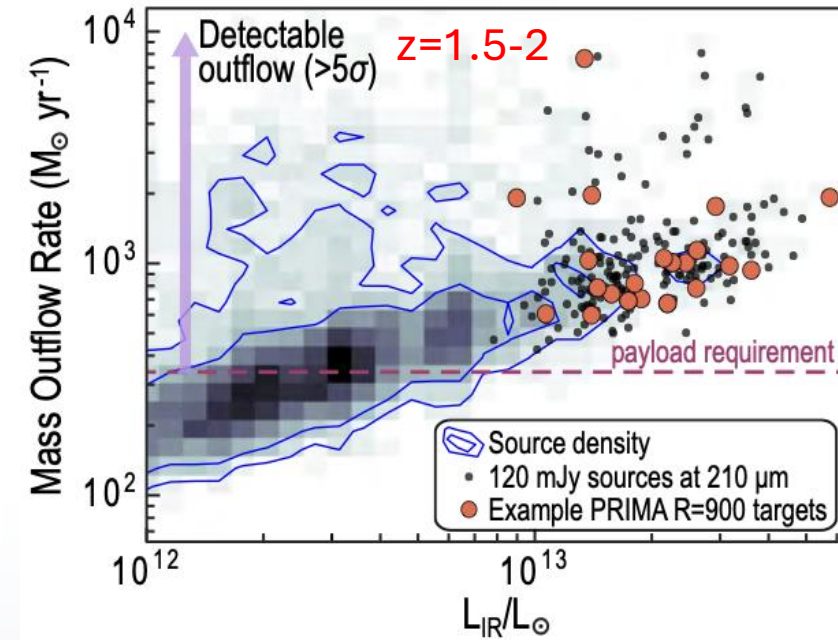
Models



Method



Survey



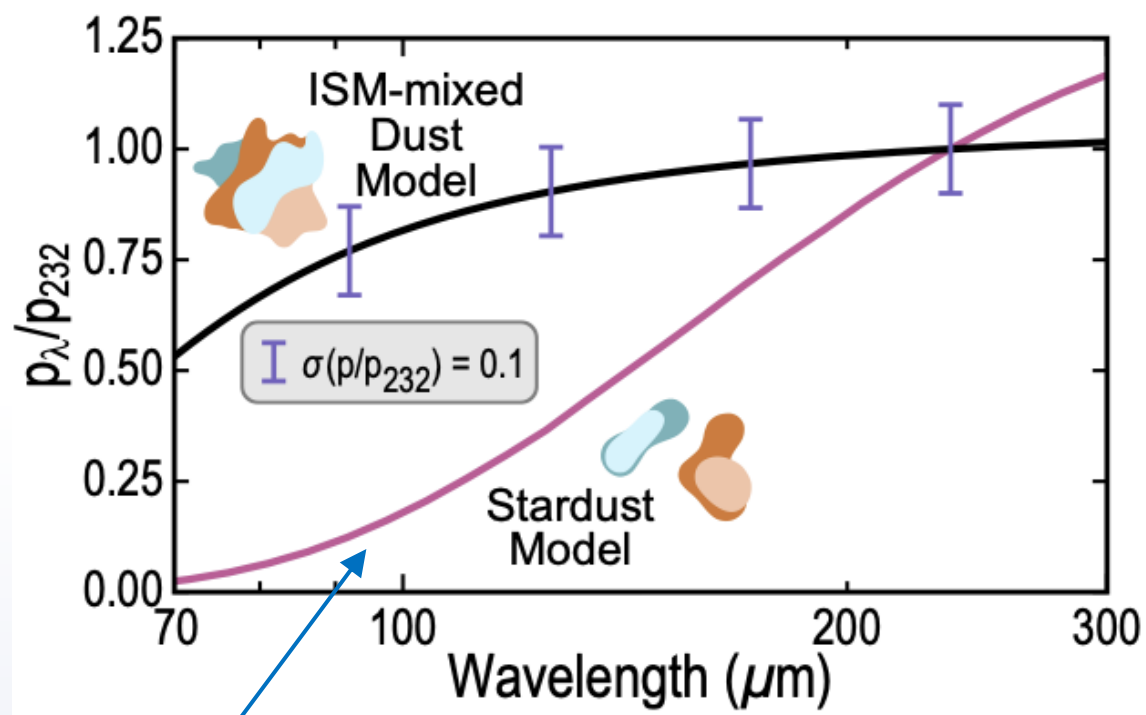
- Models require winds ejecting gas to quench star formation in massive galaxies
- Need velocities and mass outflow rates to test models
- Cool component ($T < 10,000\text{K}$) dominates the mass

- 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

- 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

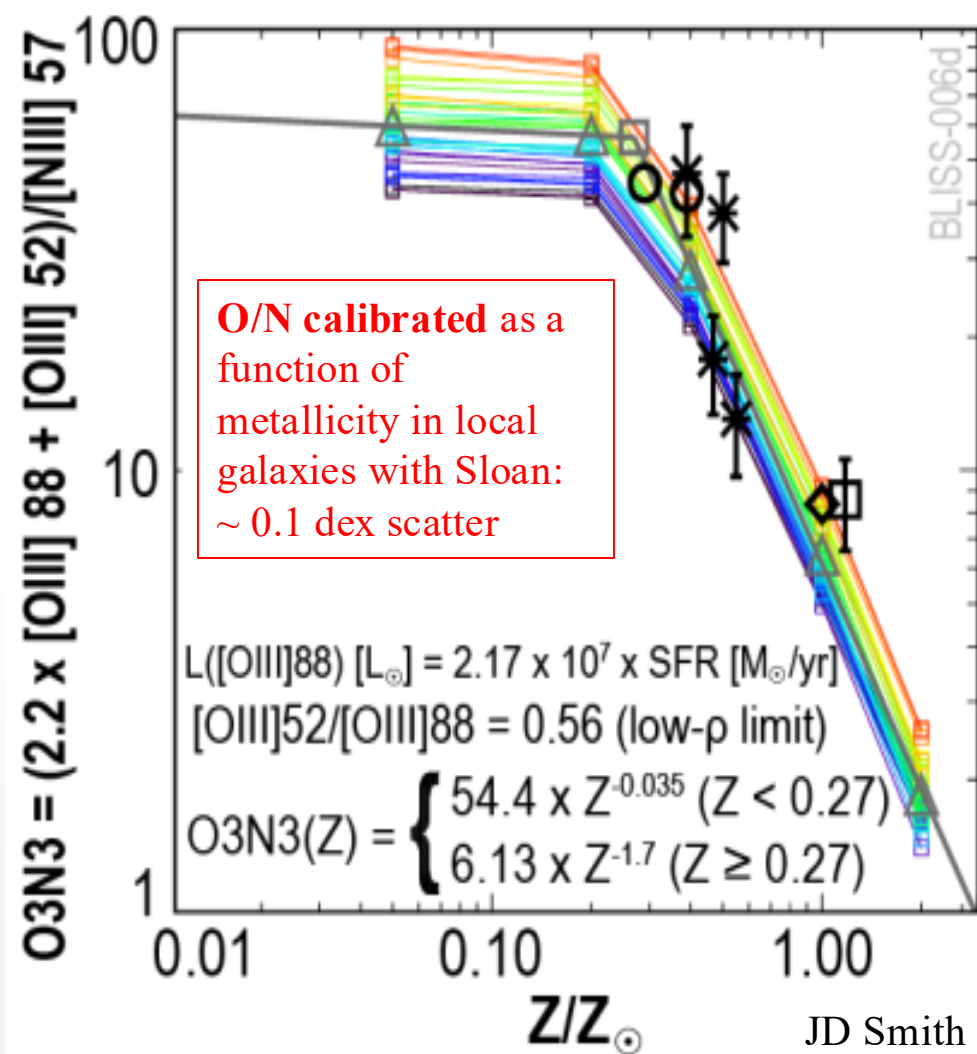
How does the structure of interstellar dust change across environments in the local universe?



Warm, C-rich grains
unpolarized

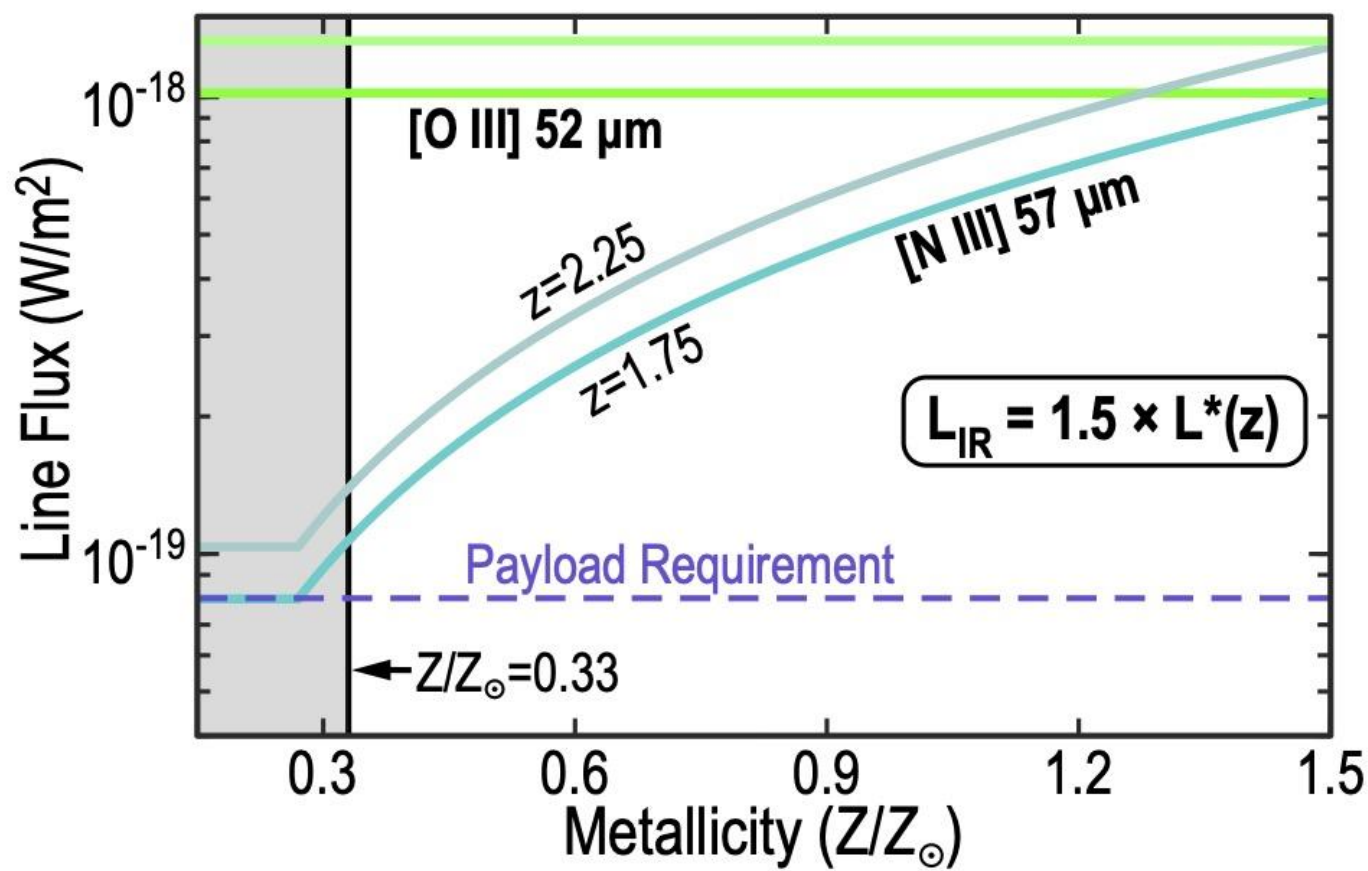
- Polarization:
 - Pristine stardust from C-rich AGB stars does not produce polarized emission.
 - Composite grains aggregating stardust with ISM-grown grains does.
- Test: Are ISM grain growth rates suppressed in low-metallicity galaxies/environments?
- Survey: 91-232 μm polarization imaging of 31 local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

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)

Metallicities from [N III] / [O III]



Sample of 100
galaxies $z = 1.75-2.25$

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

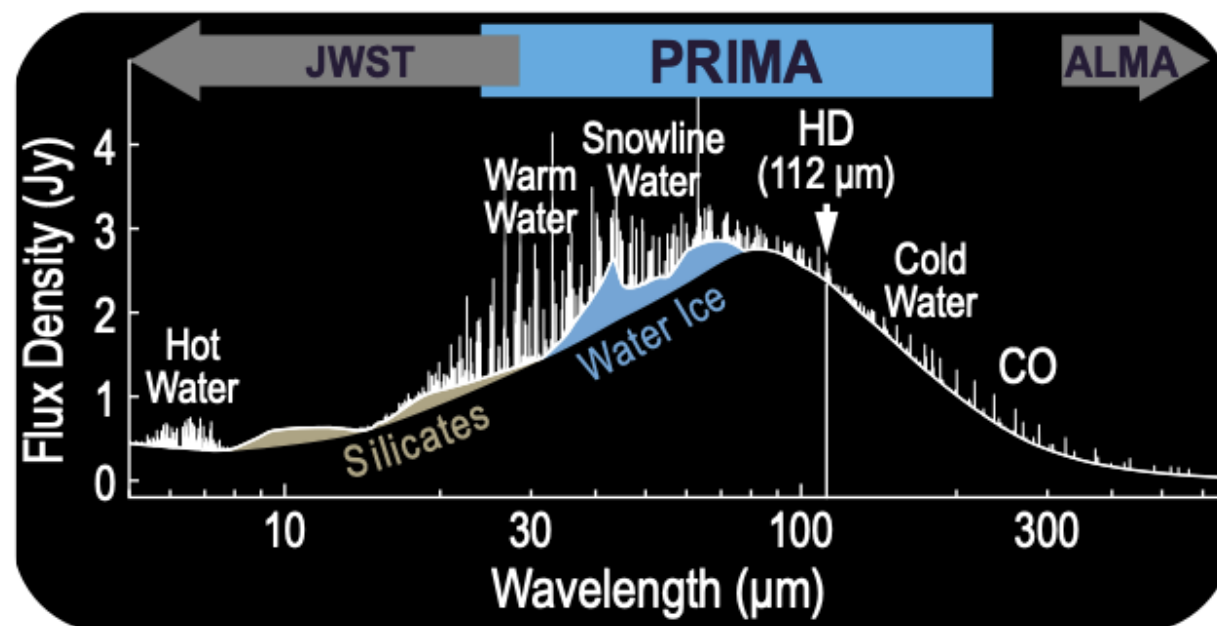
Models shown based
on Peng+2021

GO Science – 75% of observing time

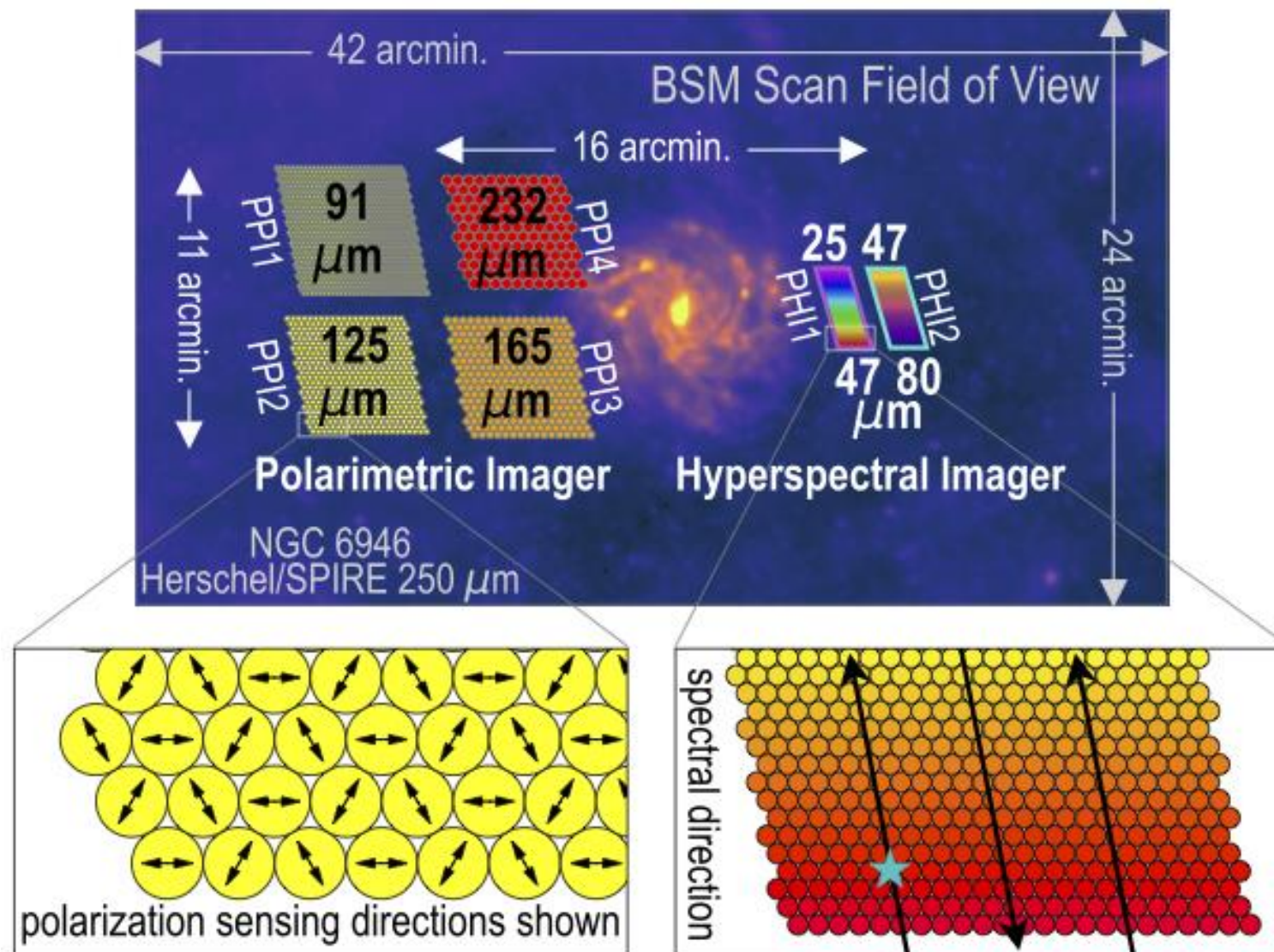
See the inspiring GO Science Book at <https://arxiv.org/abs/2310.20572>

76 cases ranging from comets to cosmology!

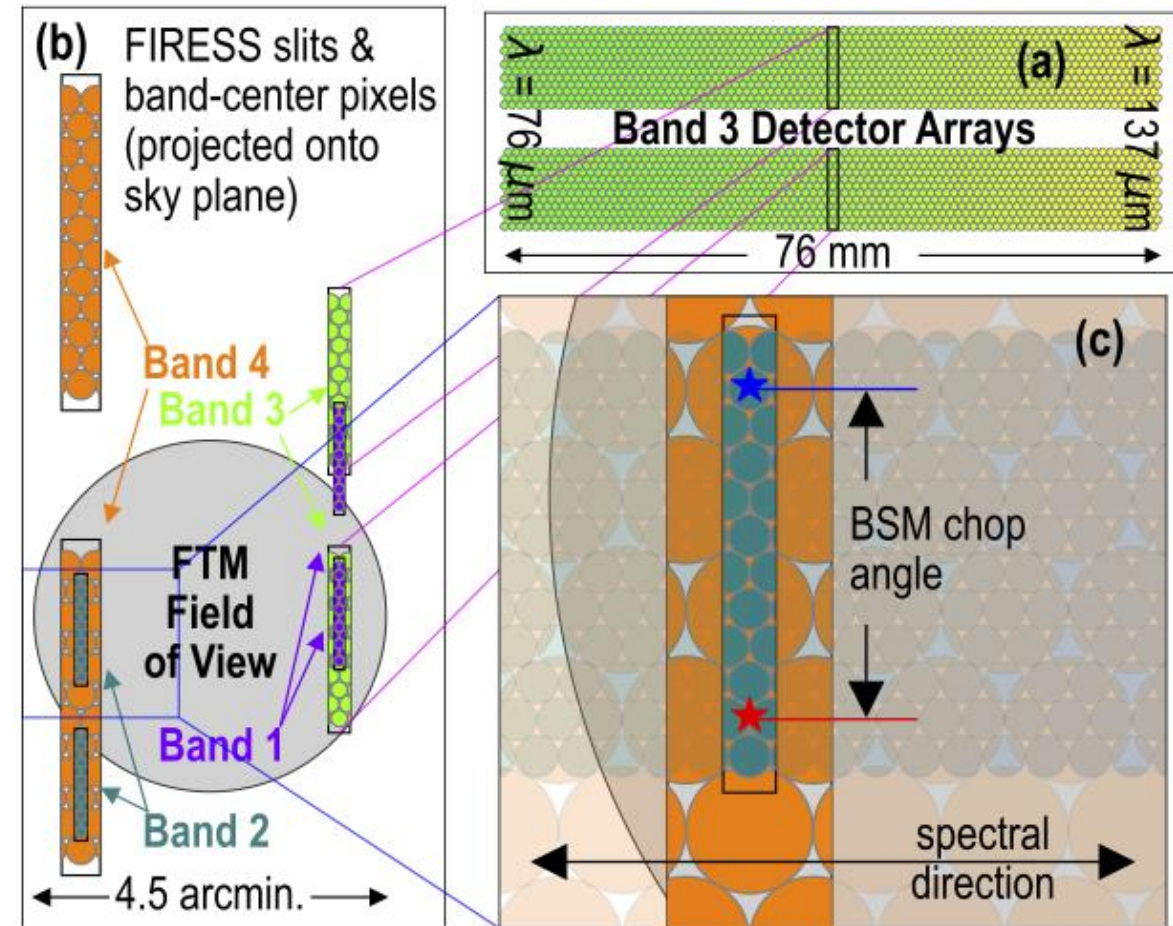
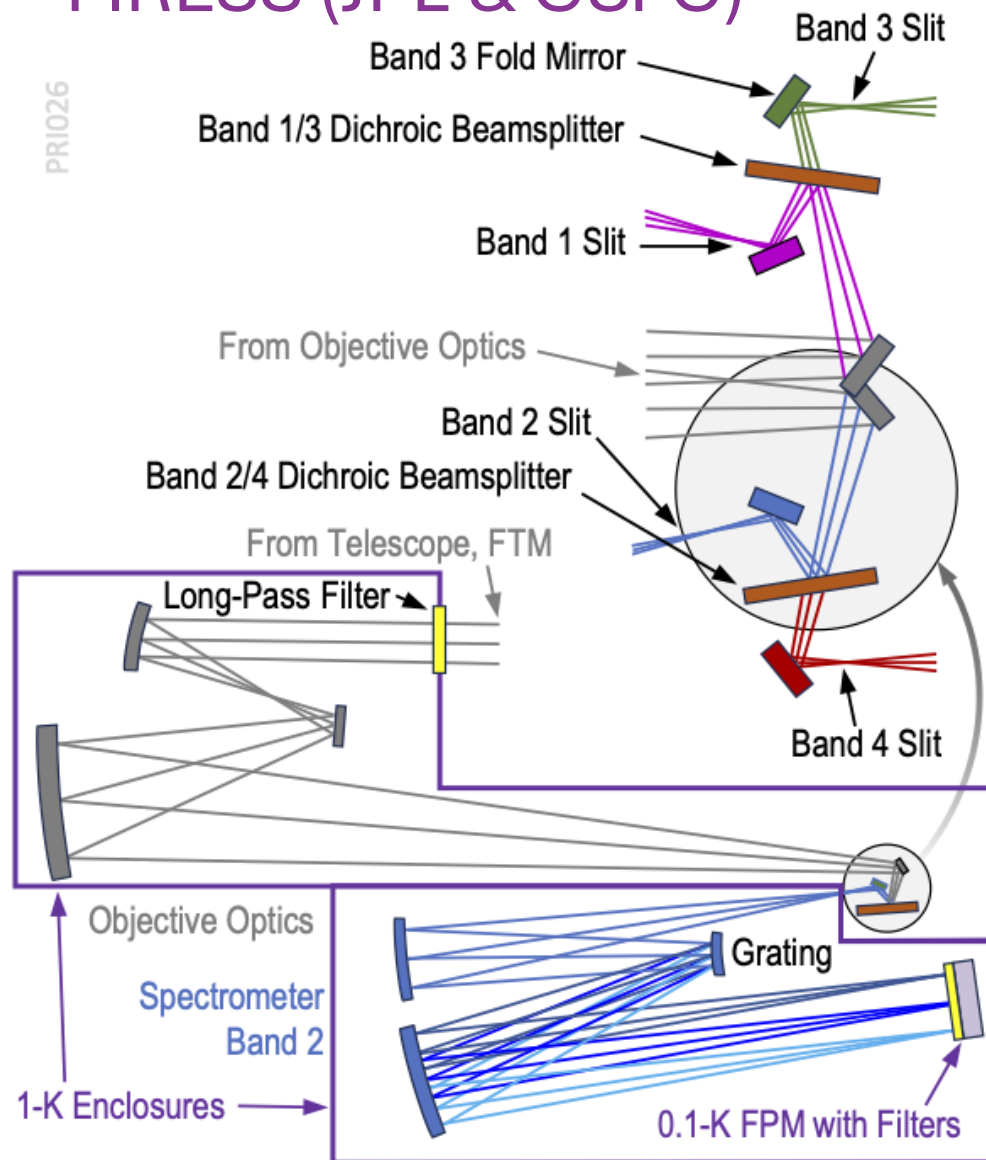
- Ices and minerals in protoplanetary disks – total disk ice mass and new solid-state studies (Seo)
 - Comes free as GI science!
- Solid-state in the ISM (Galliano)
- All-sky survey (Wright)
 - All-sky survey 100x deeper than IRAS and Akari in 5000 hours
- Comets: Measure D/H to understand the origins of the Earth's oceans (Lis)



PRIMAger (LAM)

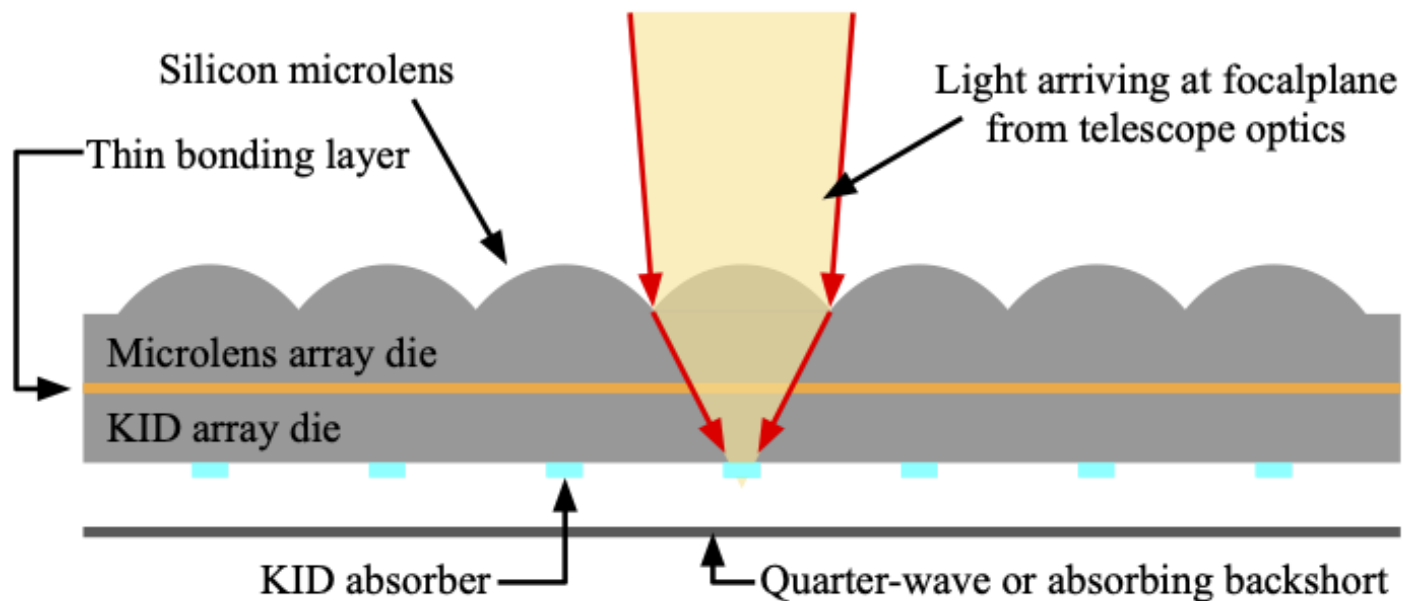


FIRESS (JPL & GSFC)

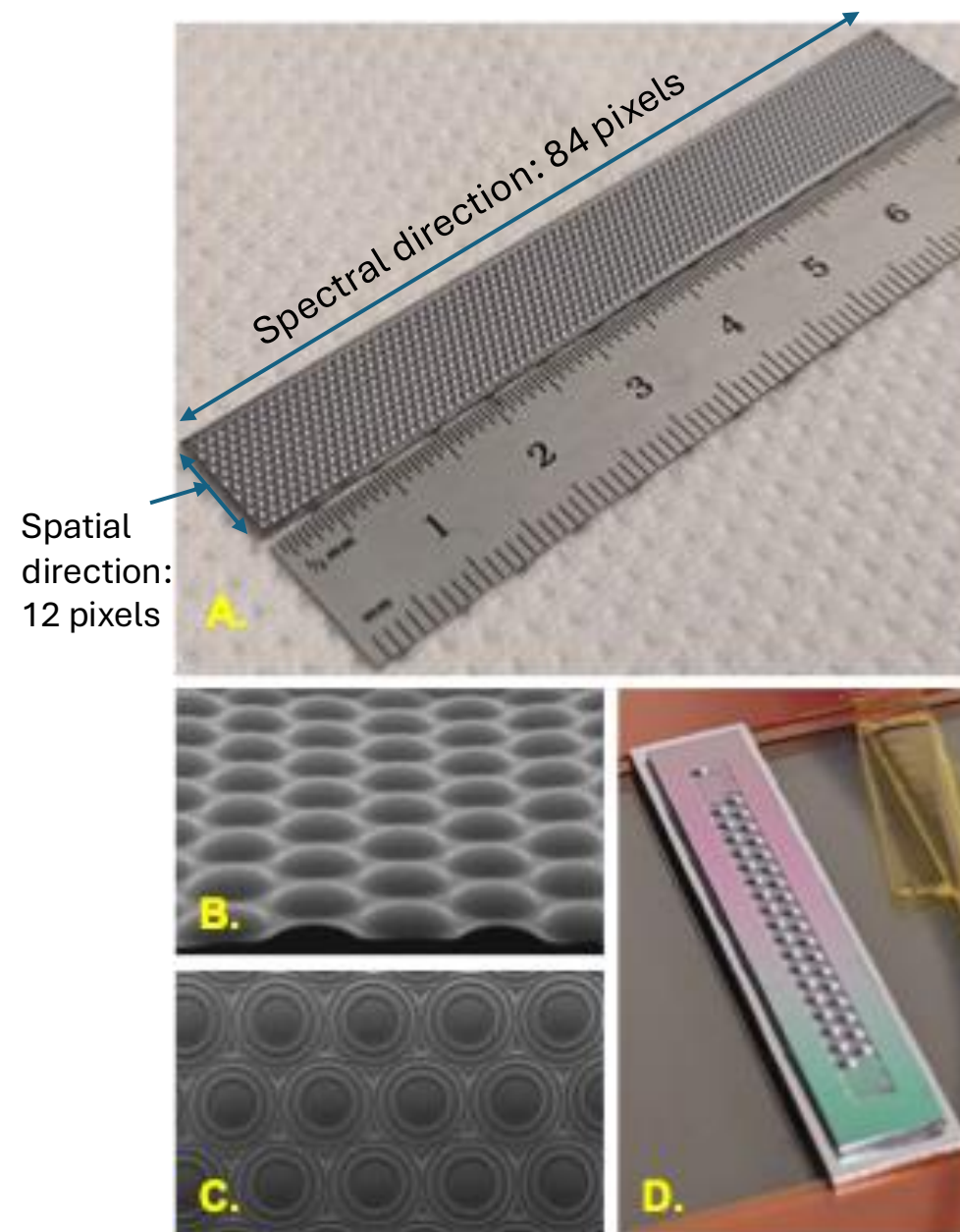


- 4 slit-fed grating modules, each 24 x 84 pixels
- Bands 1 and 3 overlap, Bands 2 and 4 overlap.
- High-res mode with FTM couples all bands when engaged.

Microlens Arrays & Hybridization



GSFC greyscale-etched microlens arrays & hybridization technique.
 Accuracy across the bulk of each lens is $\sim 2 \mu\text{m}$!
 Cothard et al. (2024)



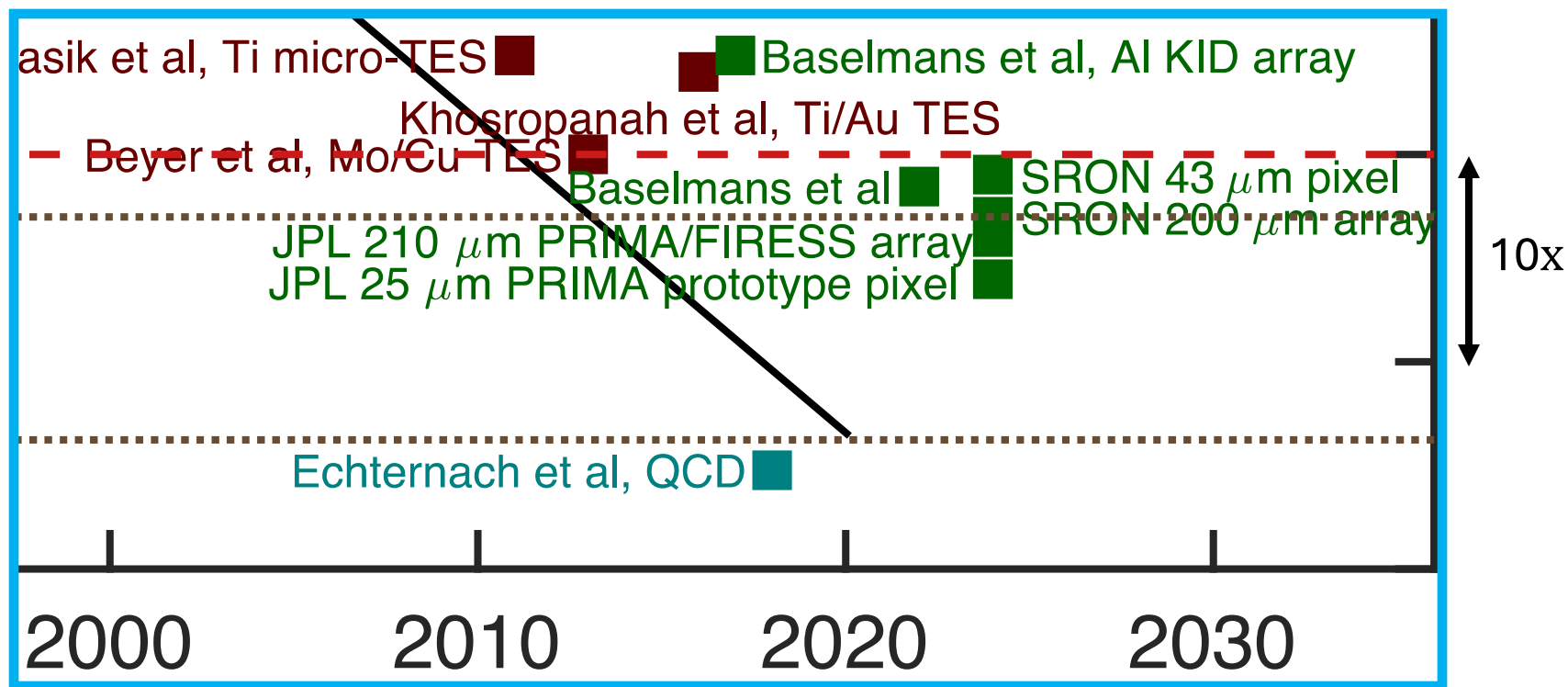
The timing is perfect for a background-limited Far-IR Observatory

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

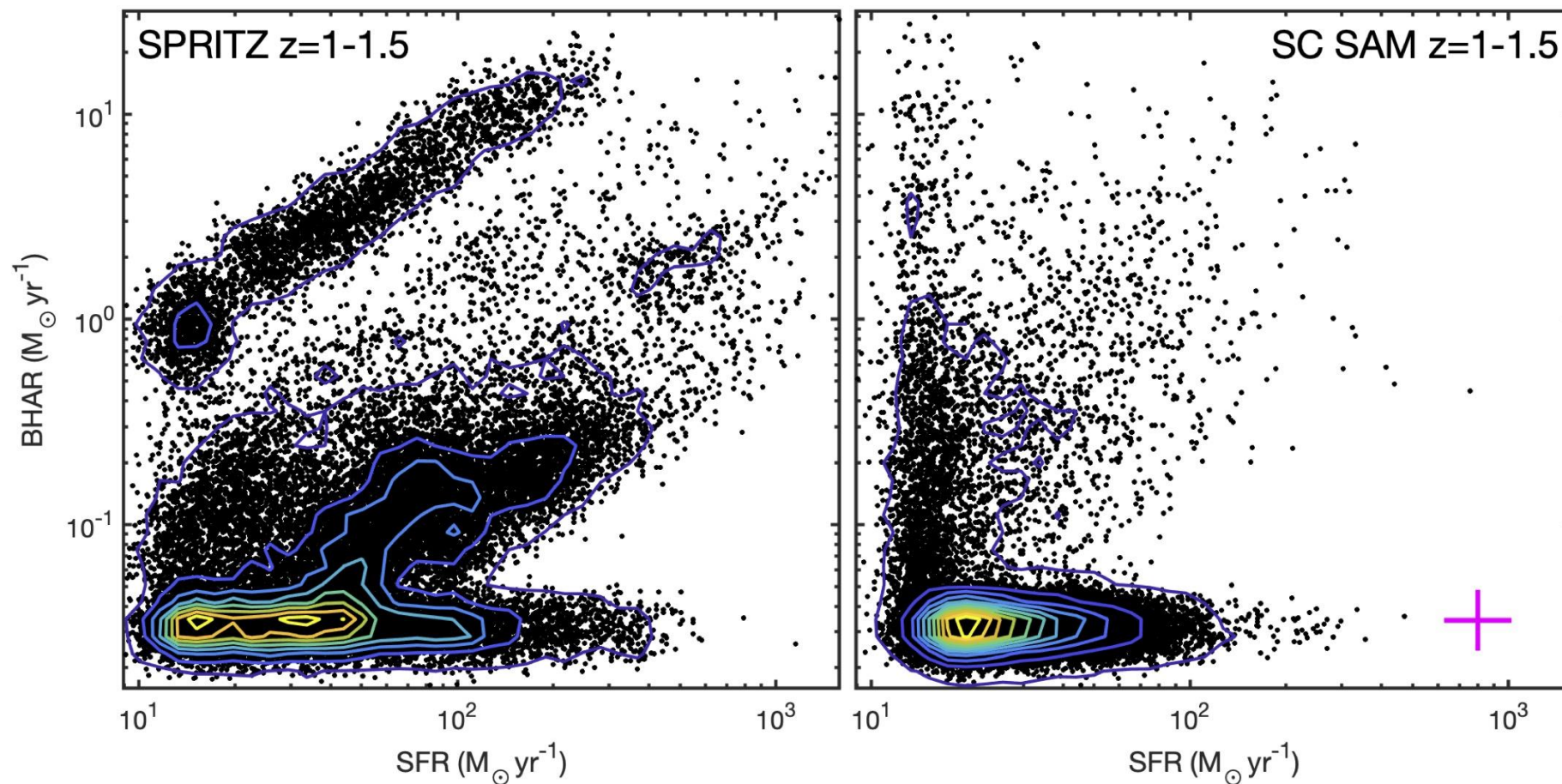
PRIMA R = 100 spectroscopy requirement

Demonstrated performance (lower on this plot is better!)



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

KID Detectors: JPL / GSFC / SRON Collaboration for PRIMA

- Sensitivity exceeds performance requirements over full wavelength range.
- Demonstrated detector/lenslet hybridized arrays with full FIRESS format (84x12, 900- μm pixel pitch). PRIMAgar prototypes in place from SRON.

