Science and Vision for a Far-Infrared Probe to Address Decadal Science Priorities

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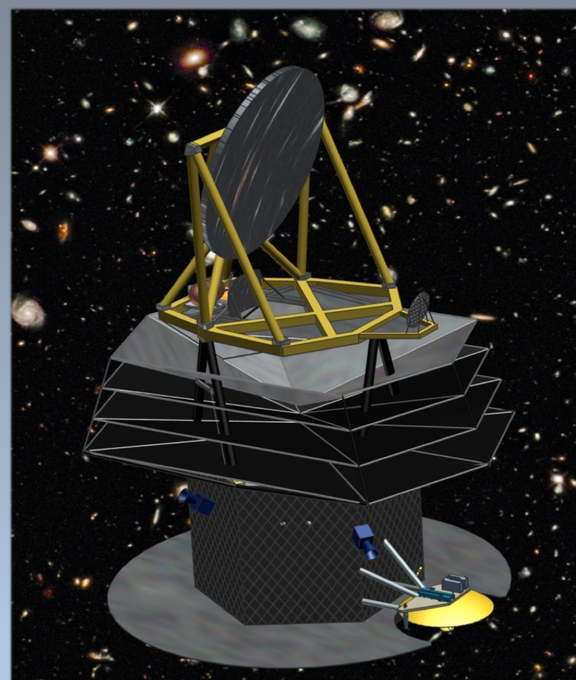
NASA Goddard Space Flight Center

IR STIG
31 March 2022



Basics

- 2 meter, 4 – 6 Kelvin telescope
- Spectroscopy and imaging
- Precursor GEP design study closed under $1B

➢ Glenn, J., et al., *JATIS*, 7(3), 034004 (2021).

Who is PRIMA?

A JPL Probe with Goddard participation and a community-based science team.

<u>The science leadership team is partially assembled</u>:

Lee Armus	IPAC
Cara Battersby	UConn
Alberto Bolatto	UMaryland
Brandon Hensley	Princeton
Tiffany Kataria	JPL
Margaret Meixner	USRA
Betsy Mills	KU
Arielle Moullet	USRA
Klaus Pontoppidan	STScI
JD Smith	UToledo
Rachel Somerville	Flatiron Inst.
Johannes Staguhn	GSFC

PI: Jason Glenn GSFC
Deputy PI / Acting PS:
Matt Bradford JPL
Science Lead:
Alex Pope UMass
+ likely international partners

We are still building the working groups. Contact us if you're interested!

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NASA Astrophysics Probe Basics

A rare opportunity for transformational far-IR science!

Scope

- $1B cost cap (exclusive of launch vehicle & Guest Observer programs)
- International contributions welcome, ≤1/3 of cost

Important Dates	
Draft Announcement of Opportunity	June 2022
Announcement of Opportunity	January 2023
Proposals Due	≤ 90 days post-AO
Downselect	Mid 2025
Launch	~ 2030!

The 'delay' in Origins and 'cancellation' of SPICA let a gap in the future of far-IR astronomy that we must fill.

Meeting the Decadal Challenge

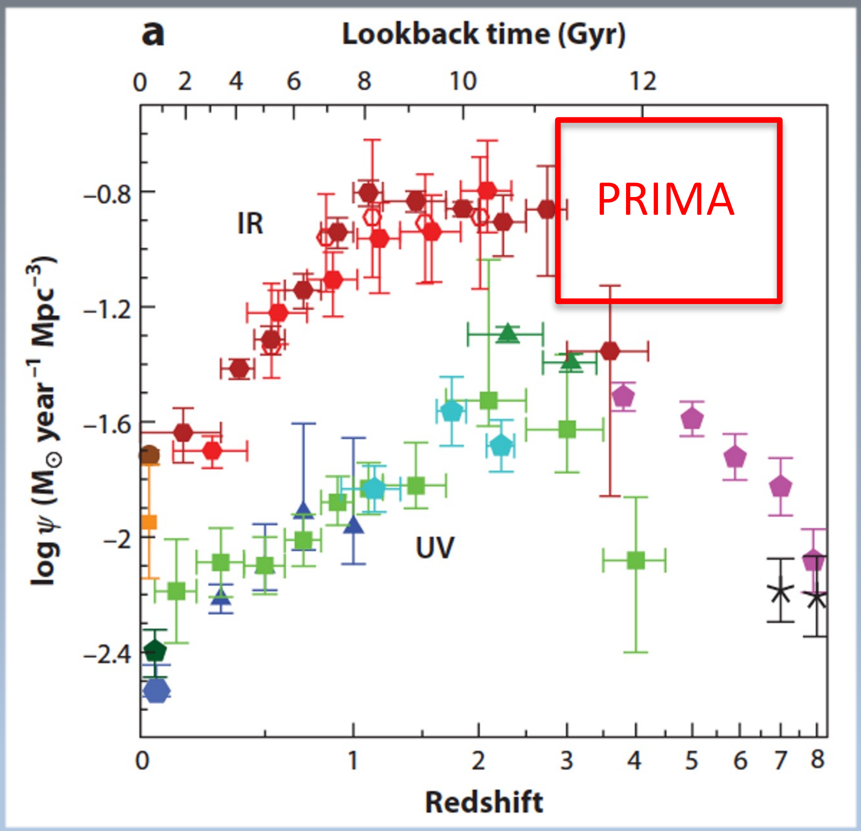
From *Pathways to Discovery in Astronomy and Astrophysics for the 2020s, a Far-IR Probe should address one or all of:*

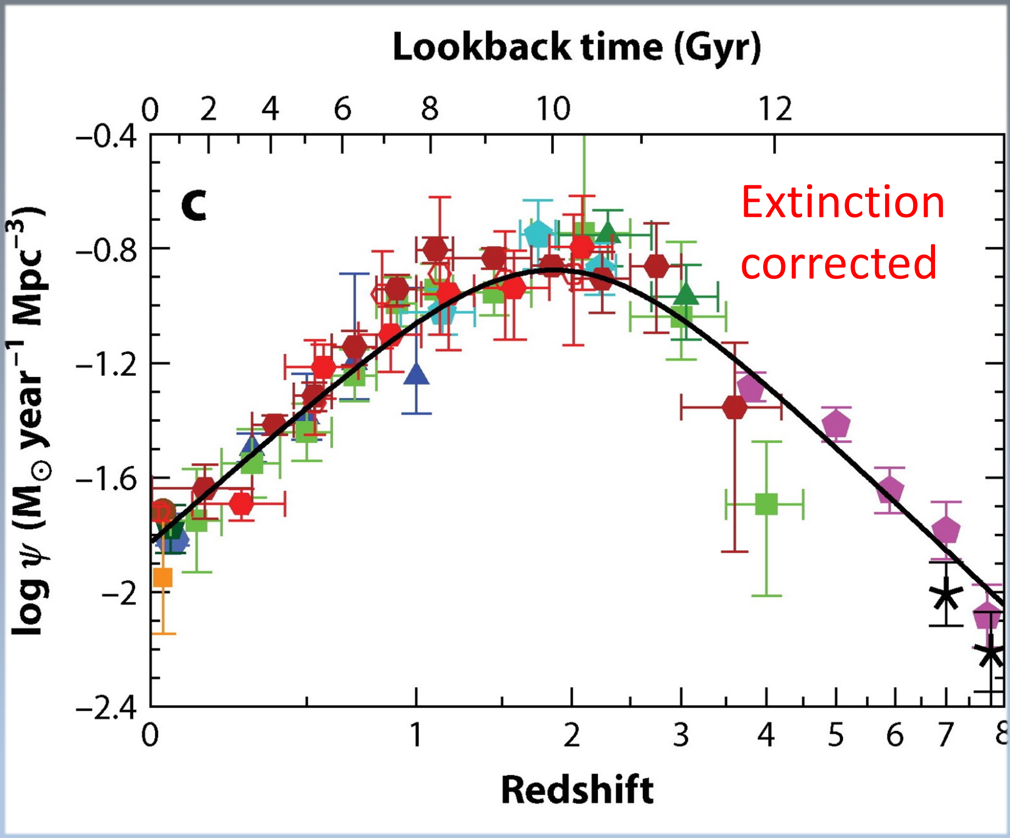
- Measure the building up of galaxies, heavy elements, and interstellar dust from the first galaxies to today
- Probe the co-evolution of galaxies and their supermassive black holes across cosmic time
- Trace the astrochemical signatures of planet formation (within and outside our own Solar System)

GEP's science case was narrowly focused on the first two ($100k design study).
PRIMA's science case substantially broadens that science case and brings a strong GO program.

The Buildup of Galaxies

The cosmic star-formation history is characterized to z ~ 2

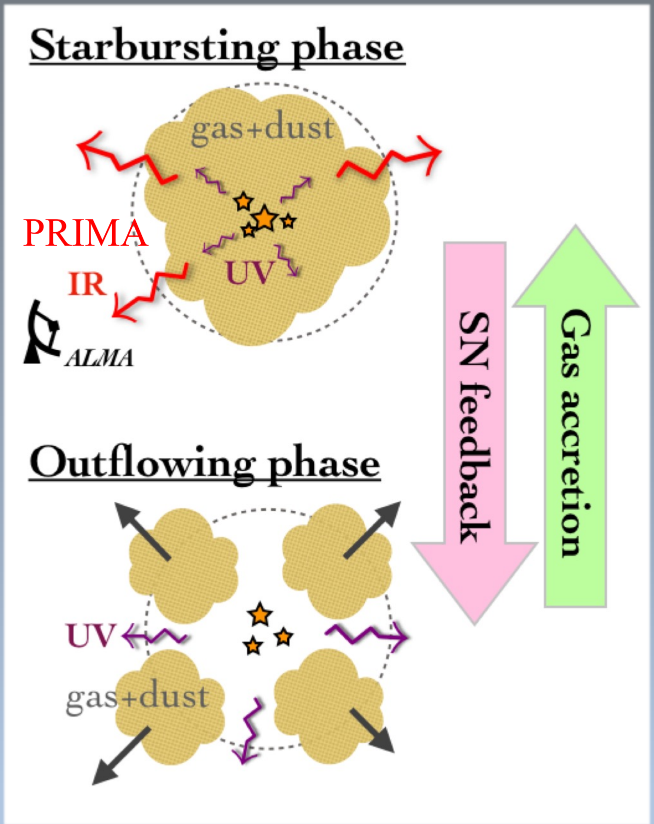


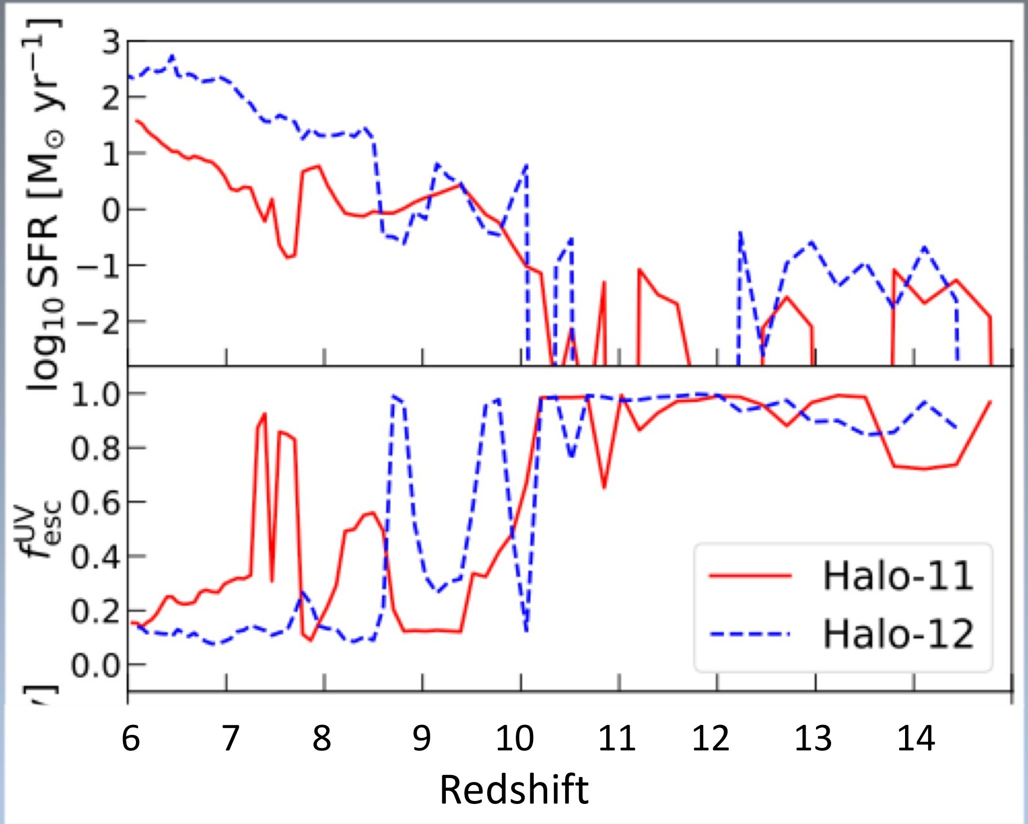


Madau & Dickinson 2014 ARAA

Far-IR observations will be needed to measure star-formation rates (even with JWST).

Why the IR Perspective is Needed

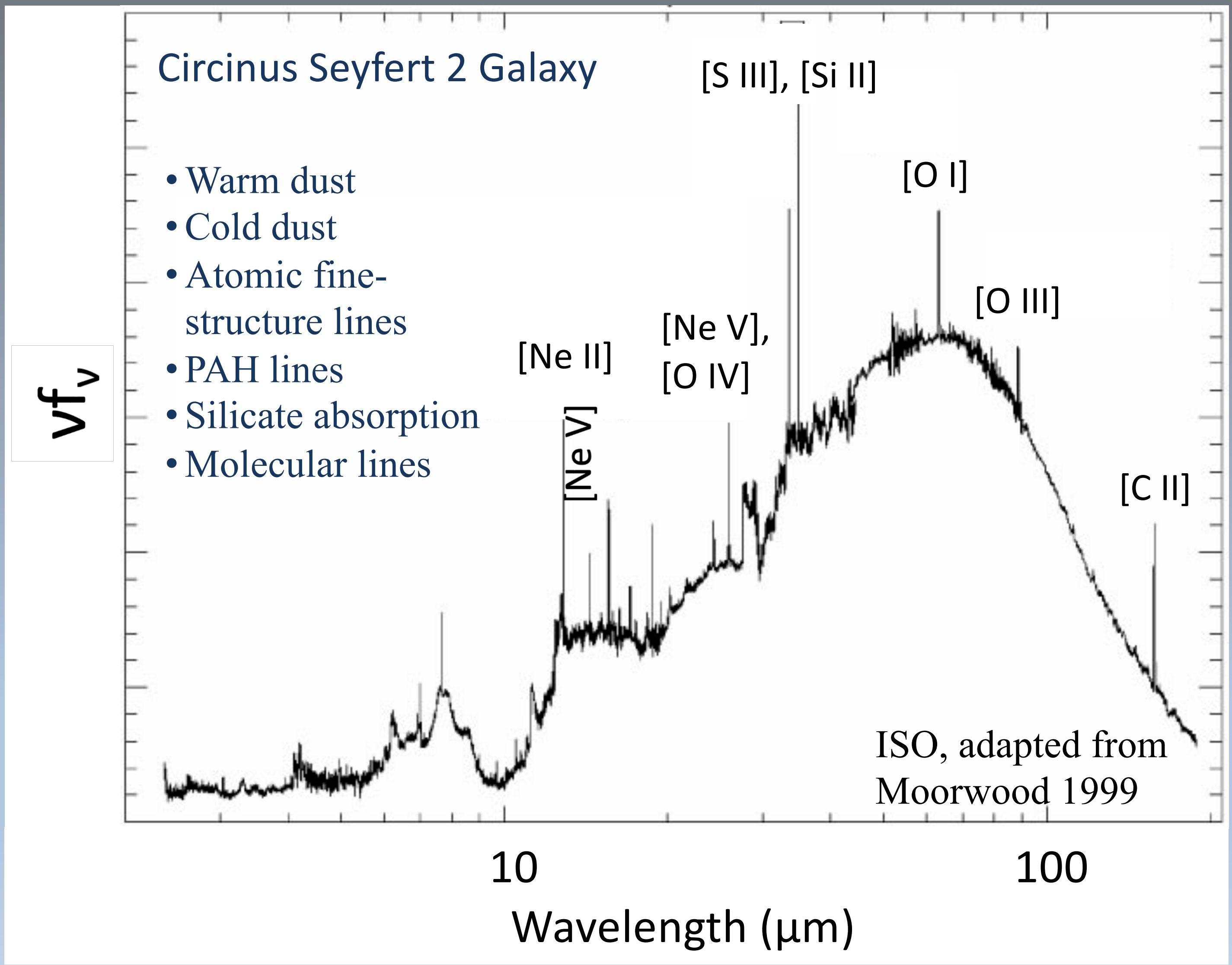




Arata et al. (2019): The escape fraction of UV photons varies dramatically on 100 Myr timescales (halo free-fall timescale).

Mid- and Far-IR Spectra of Galaxies

What are the constituents?



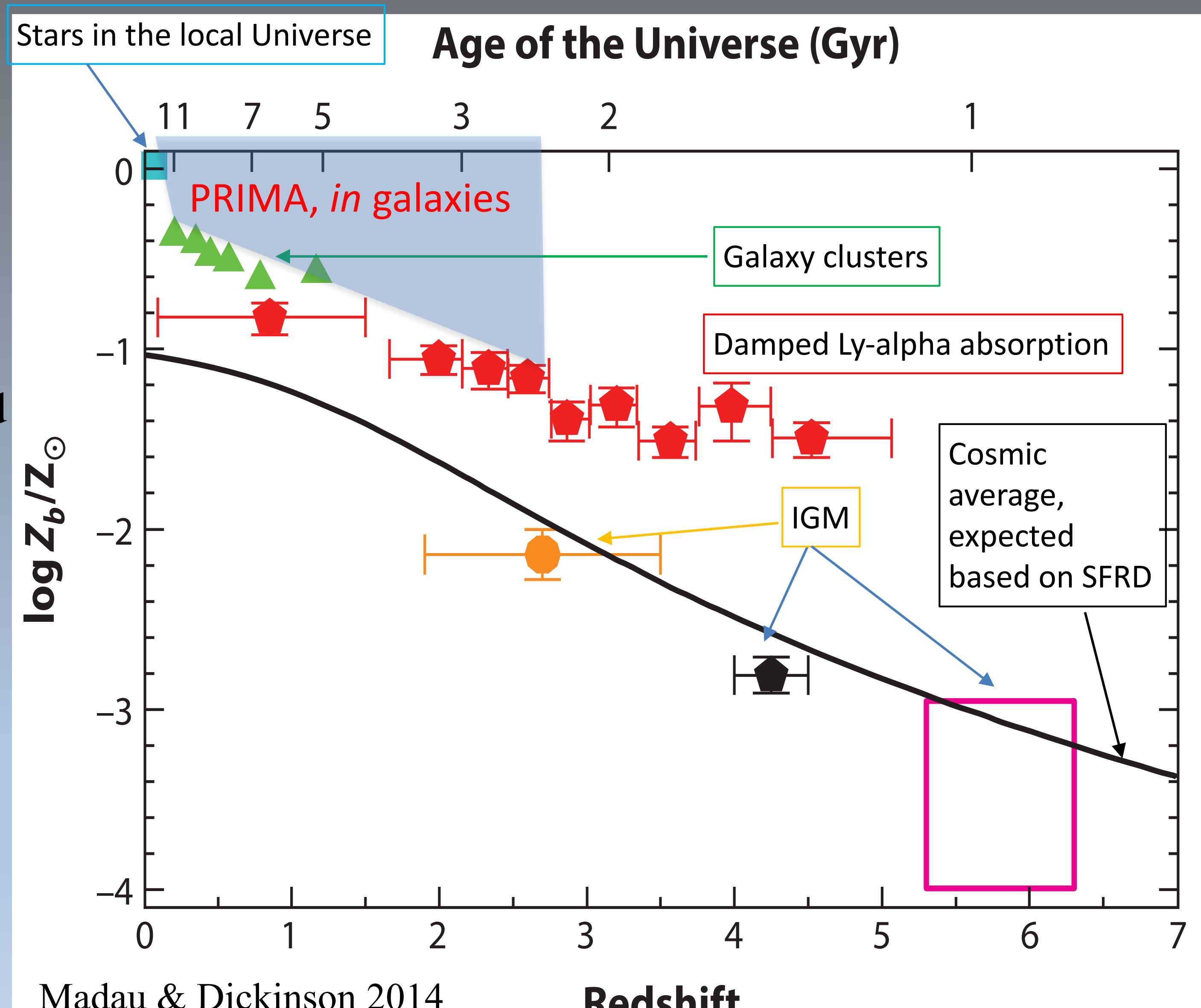
Complete Census of Heavy Elements in the Universe

Galaxies, though a small fraction of baryons, are an important part of Universe's metal budget.

Heavy element contents typically measured with nebular spectroscopy in the optical.

But optical measurements are limited by dust to unobscured regions; suffer from degeneracies with temperature (ionization state).

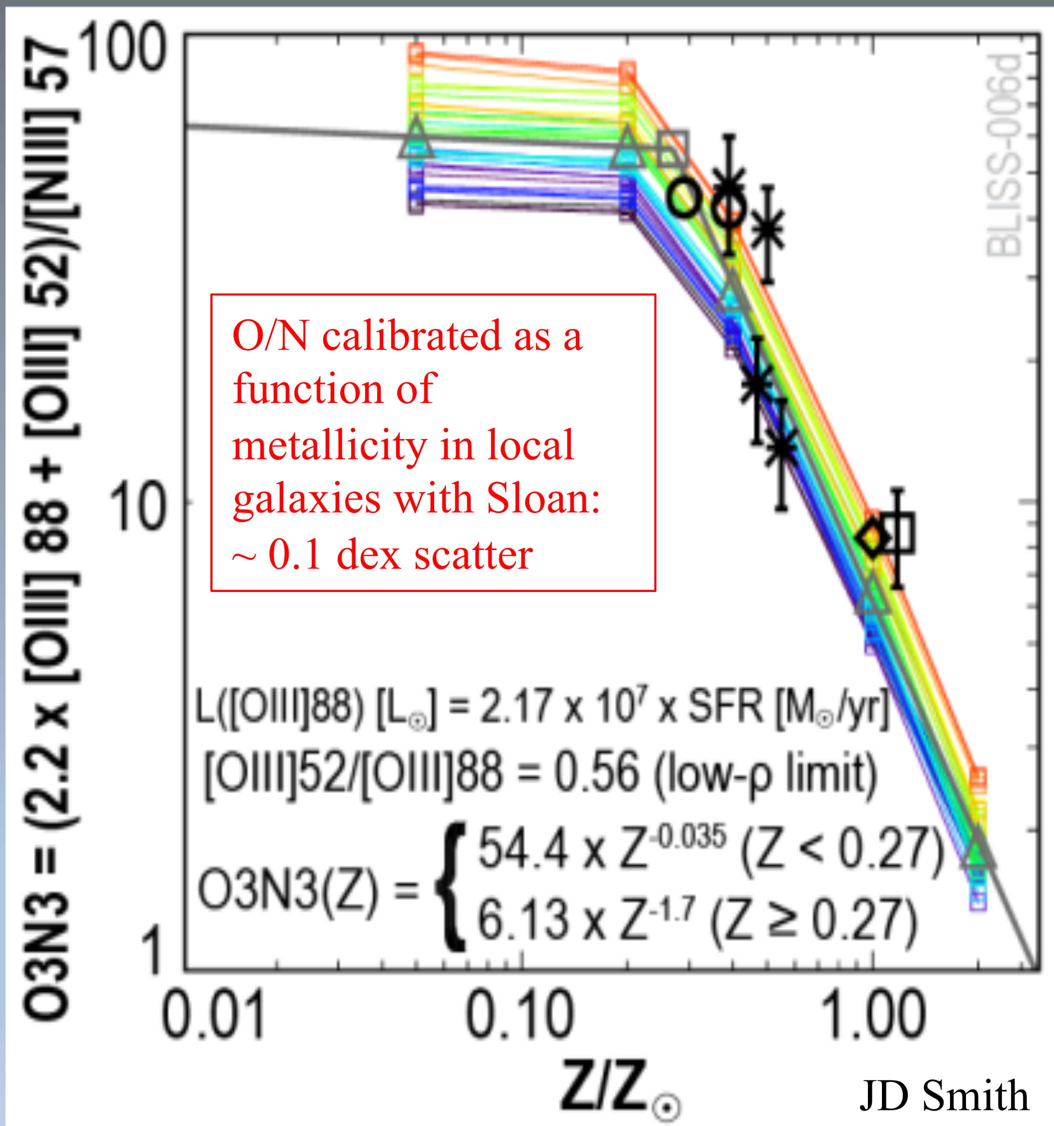
Far-IR measurements are not susceptible to these effects and complement other measures.



Madau & Dickinson 2014

Nucleosynthesis History

Absolute metallicities not well measured in dusty galaxies → use extinction-free far-IR lines!



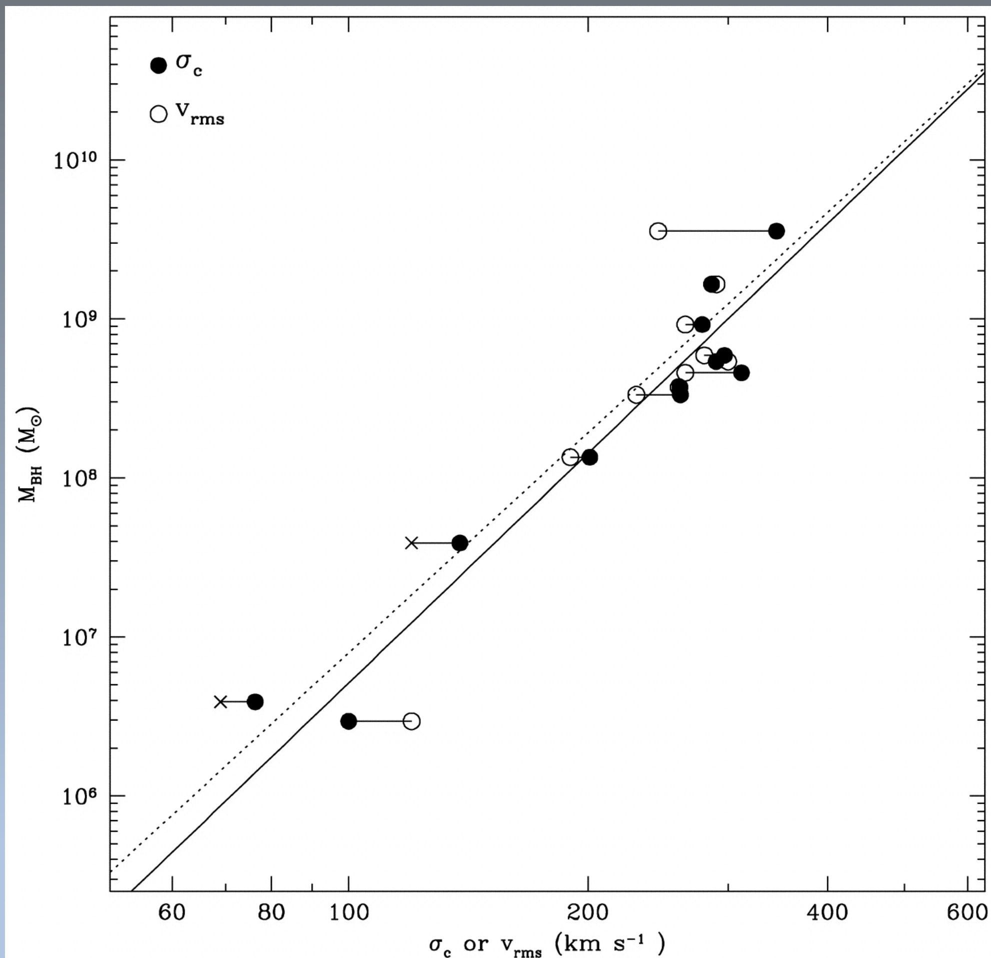
$0 \leq z \leq 1.2$

- Nitrogen is special as a secondary nucleosynthesis product – comes on later in stellar processing.
- O/N ratio measures stellar processing → 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)

$1.5 \leq z \leq 3$

- Ne inert, abundance tracks metallicity
- S partially depleted onto dust grains; tracks < linearly with metallicity
- ➢ [Ne II]+[Ne III] / [S III]+[S IV] (e.g., Fernández-Ontiveros et al. 2021)

Unfinished Business: The M-σ_c Relationship

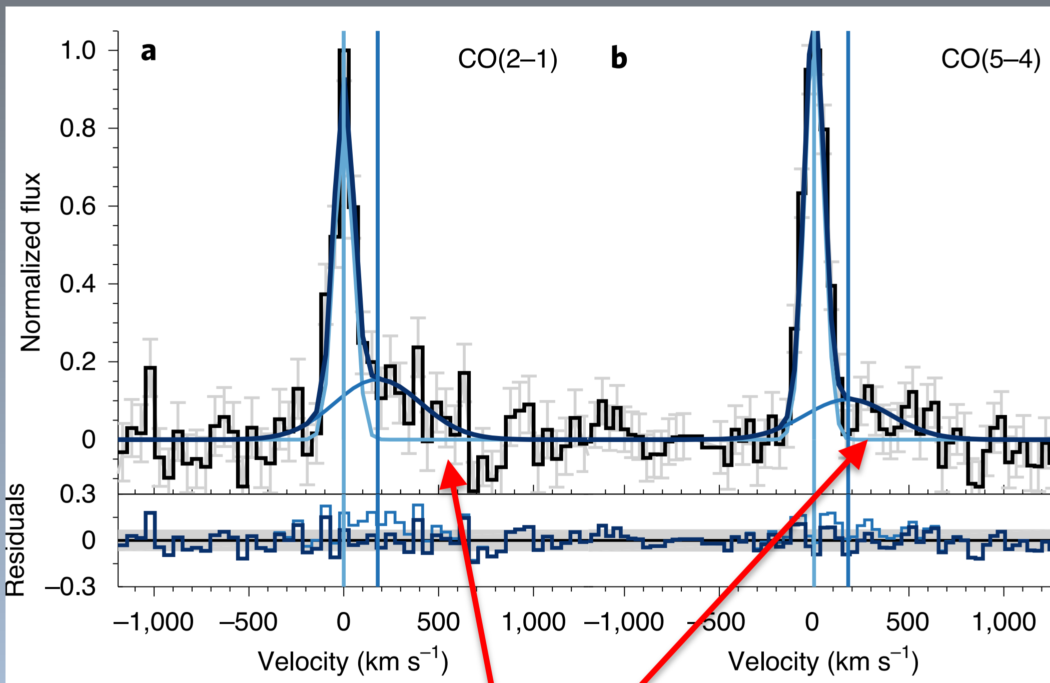


From the Ferrarese & Merritt 2000 paper

While the mechanism of the relationship between bulge stellar mass and SMBH mass remain uncertain, it is clear that stellar and AGN feedback likely play important roles.

→ What are the energetics of feedback and how to they regulate the growth of stellar mass and supermassive black holes?

Observing Feedback with Outflows



Massive starburst at z=1.4
Puglisi et al. 2021.

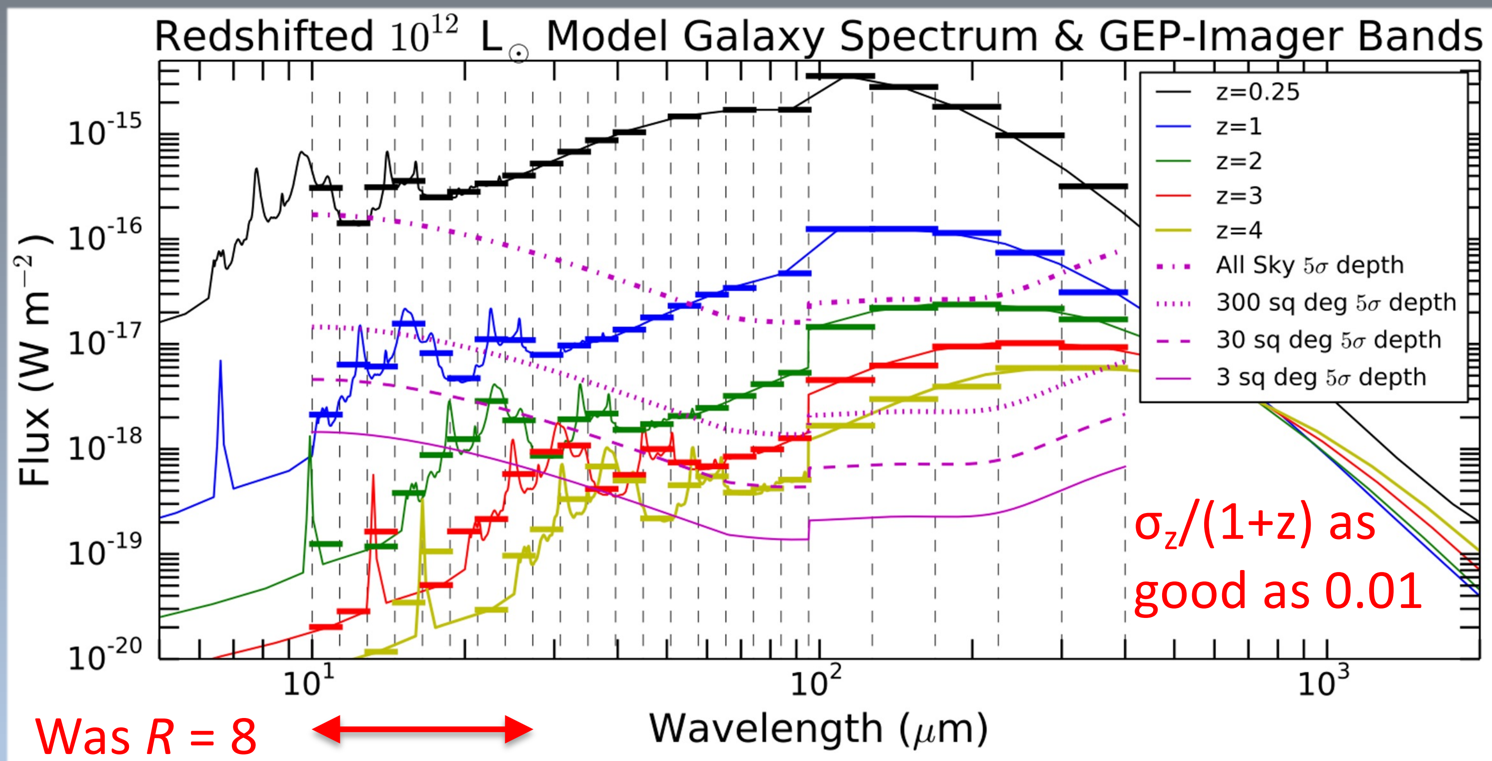
Evidently ejecting 46% of is molecular gas mass, rate of >10,000 $M_\odot$ / year!

(Suggests that merger-driven episodic events may be more important than more steady-state feedback-driven winds in quenching star formation.)

$R \geq 10^3$ enables galactic outflows to be characterized (mass, energy) with far-IR fine-structure lines and molecular lines.

Original GEP Imager Vision

Co-evolution of galaxies and their SMBHs: measure star-formation & AGN accretion rates for many galaxies.

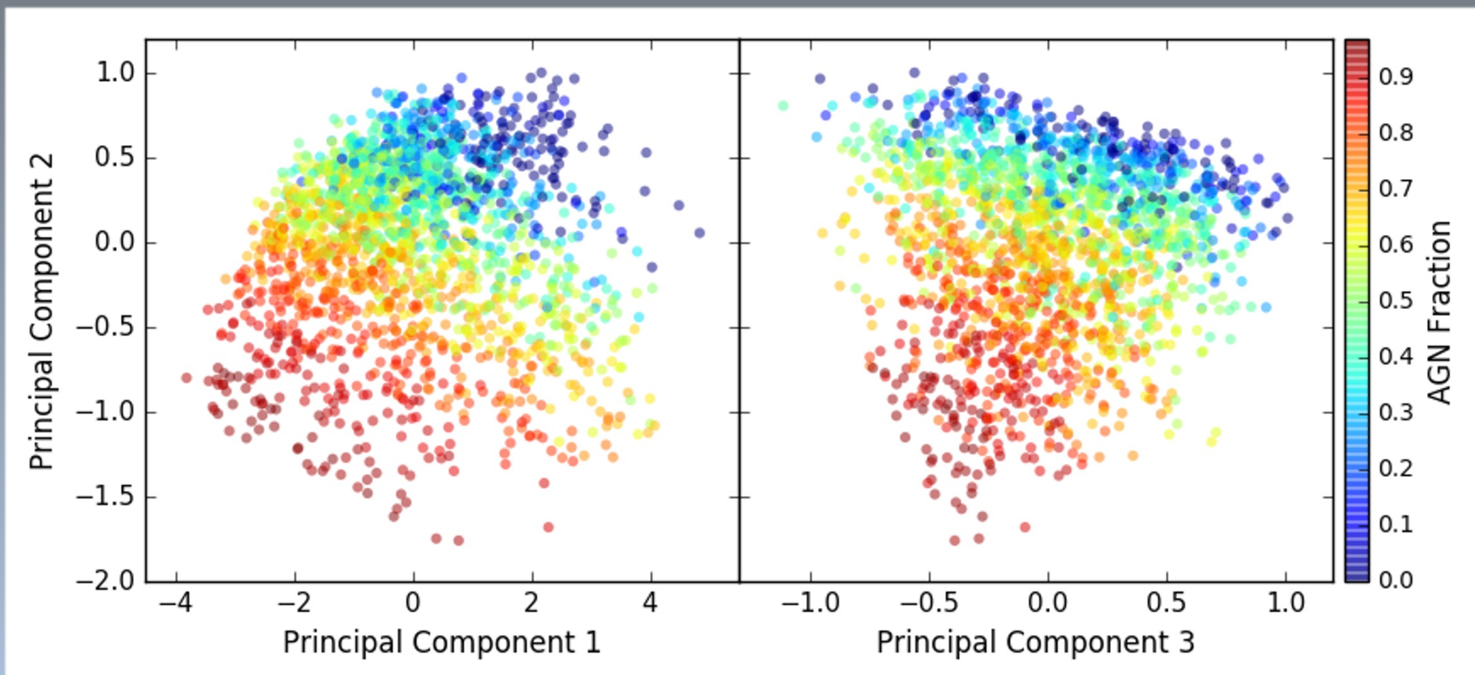


Rebaselined to R = 20

'Hyperspectral' imager would detect millions of galaxies and measure redshifts using the prominent PAH emission lines (and silicate absorption).

Coevolution of Star Formation and SMBH

The incidence of deeply embedded AGN and their contributions to bolometric luminosities is still not well known.



Jeremy Darling, z = 1.0 – 1.2 galaxies

Star formation & AGN separated with mid-IR spectra.

AGN indicators:

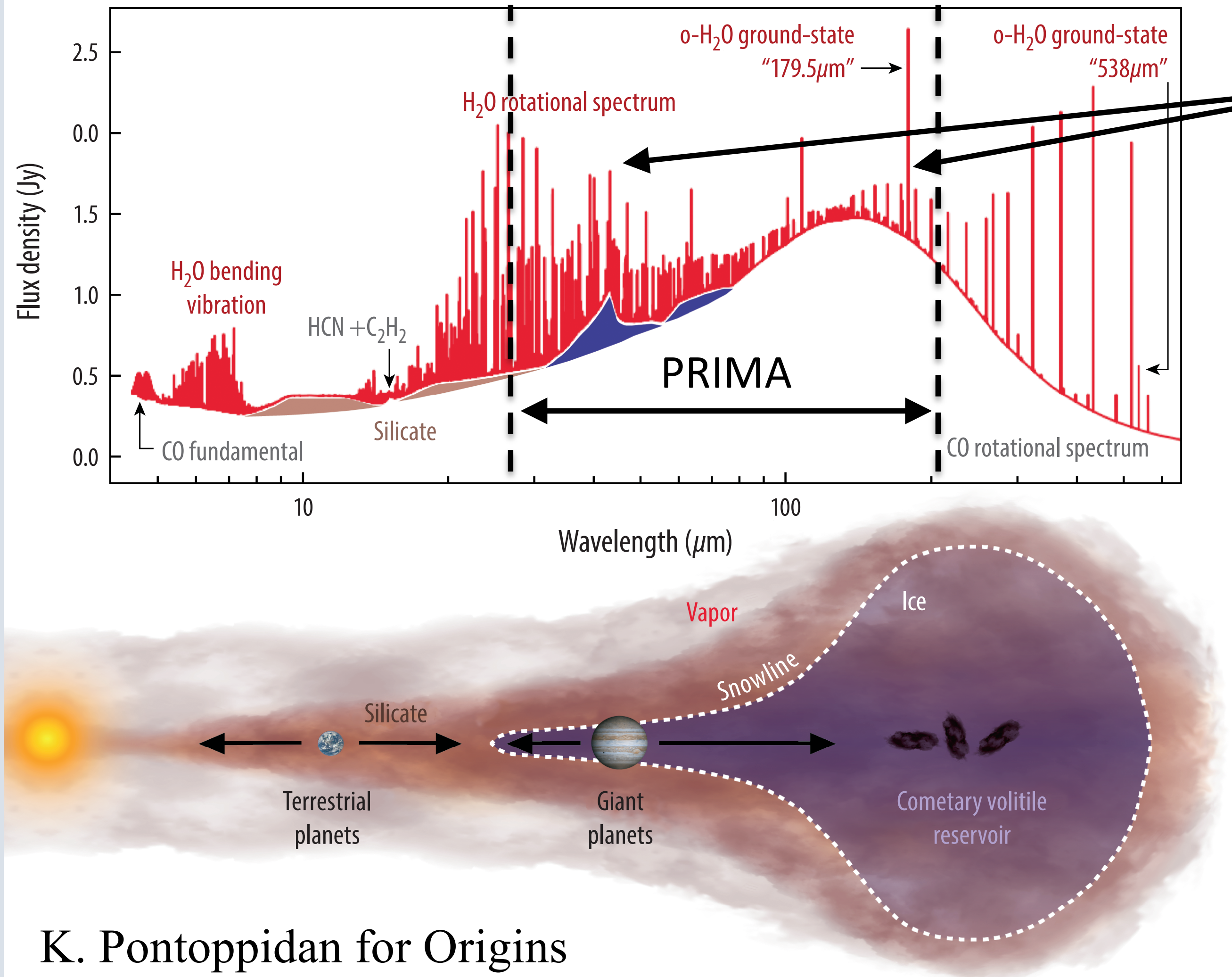
- Warm dust dominant ('blue' mid-IR spectrum)
- Low PAH-to-continuum ratio

This can be done with spectroscopy too, which also obtains the far-IR fine-structure lines.

Figure out what to say about polarimetry

Probably not space for another slide

Origin of Planetary Systems and Water Transport to the Habitable Zone



K. Pontoppidan for Origins

- **Water distribution** can be modeled from the suite of lines and studied as a function of disk age.

M_{disk}: orders of magnitude uncertainty from unknown CO abundance and dust depletion.

- 112 μm HD fundamental optically thin, but weak.

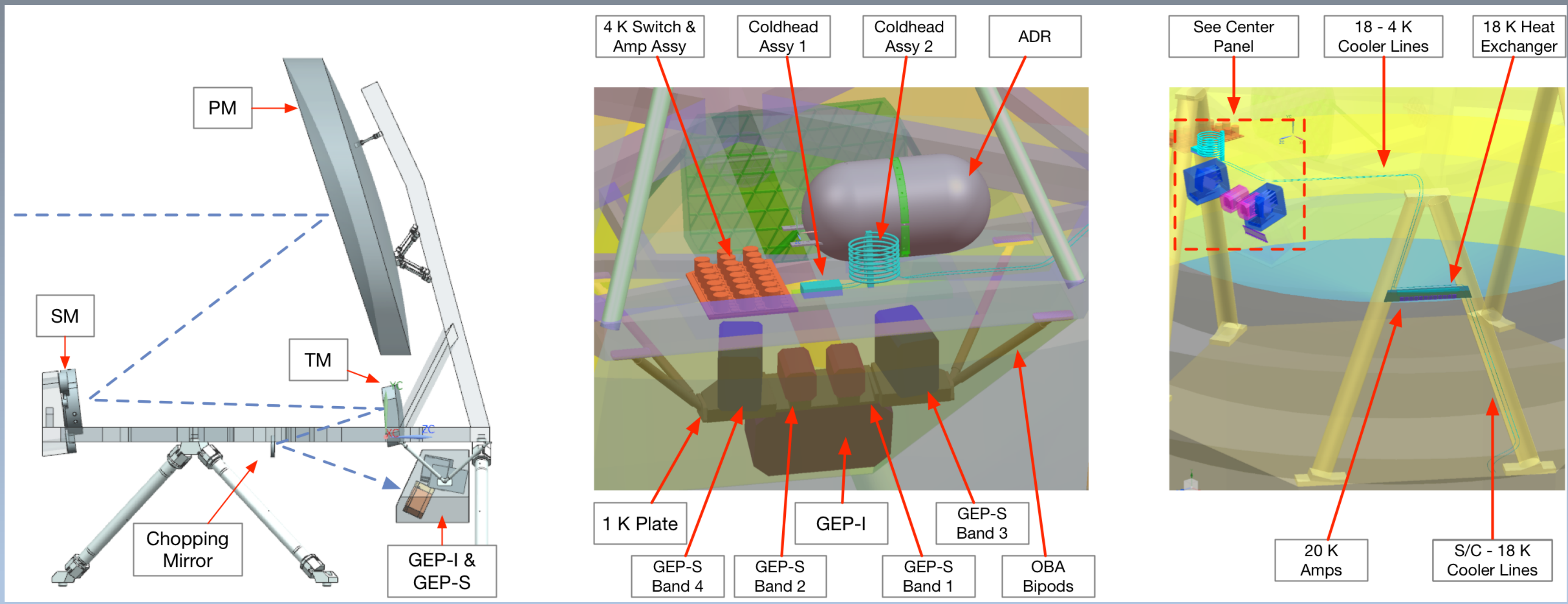
➢ $R \geq 3x10^3$?

Q. How much resolving power do we need for this science?

What Can You Build with $1B?

We are informed by the GEP concept study

- *~2 m, 4 – 6 K telescope*
- *1 – 2 ambitious cryogenic instruments (arrays of 10^4 detectors)*



We are reprioritizing the science and the instrument requirements will follow.

We are specifically investigating $R = \frac{\lambda}{\Delta\lambda} = 10^3 - 10^4$ spectrometer options.

Where to from here?

Community Survey

- 121 responses so far – broad representation across areas of astrophysics

Workshops

- 22 March: 173 participants
- Early career workshop 25 March: 20 participants

Contact us if you want to learn more or get involved!

PRIMA

The PRobe far-Infrared Mission for Astrophysics

A community-driven general-observer-accessible far-IR-optimized observatory for 2030.

- JPL implementation lead, GSFC key contributions.
- International partnerships in development.
- A cryogenic telescope with a target aperture of 2-3 meters.

Science and hardware formulation underway – inputs welcome.

Potential instrumentation capabilities:

Imaging / Polarimetry: ~10 to 300 μm

- Mapping speed: $\sim 10 \left(\frac{\text{deg}^2}{\text{hour}}\right)\left(\frac{F}{1\ \text{mJy}}\right)^2\left(\frac{1}{\text{SNR}}\right)^2$ (Extragalactic confusion limited for λ>70 μm).

Base low-resolution spectroscopy w/ wideband gratings: ~25 to 330 μm.

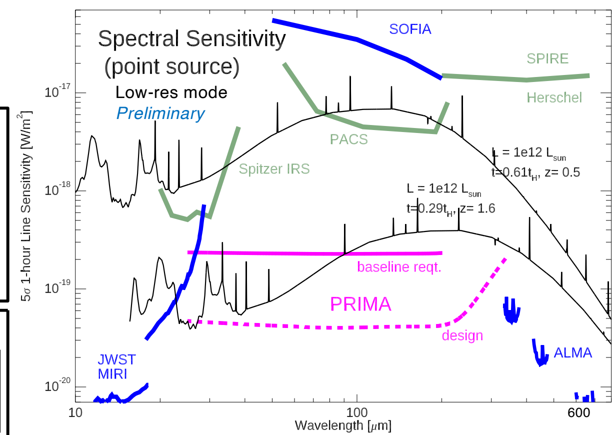
- Resolving power 60 to 250.
- Unprecedented line surface brightness sensitivity (bottom center figure).
- Spectral-line sensitivity when pointed: 5σ, 1 hour of 5×10^{-20} to 2×10^{-19} W/m² (top right).
- Full instantaneous coverage of at least one ~octave bandwidth spectrometer band at a time, multiple bands simultaneously on source is a goal.
- Mapping speed: 10^{-1} to 10^{-4} sq degrees per hour to 3×10^{-19} W/m² (bottom right figure).

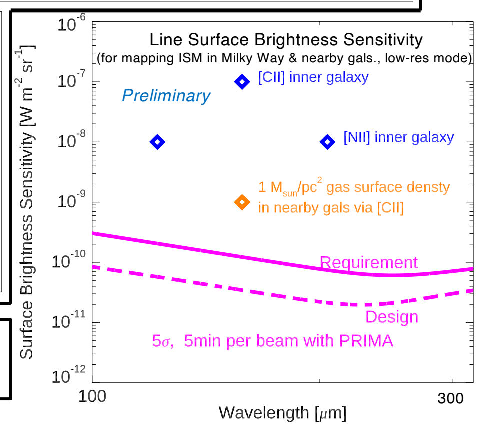
Medium-resolution capability using addition to low-resolution gratings: same 25-330 μm band.

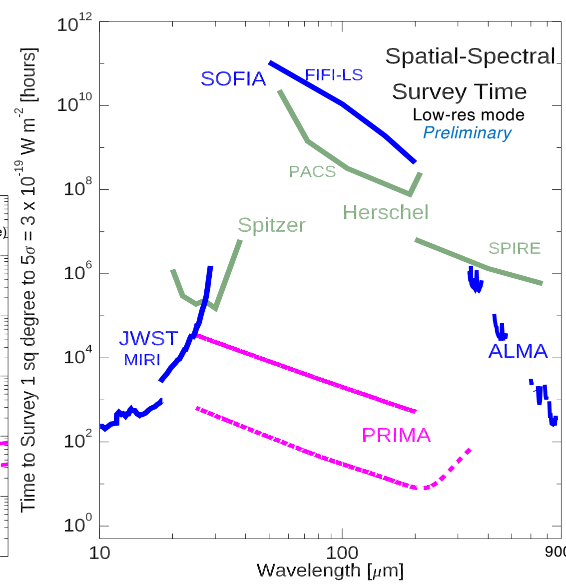
- Available resolving power: up to 5000-8000.
- Sensitivity range: 5σ, 1 hour of 10^{-19} to 2×10^{-18} W/m² per spectral resolution element (or unresolved line).
- Mapping speed in medium-res mode: modest, to be determined, depends on R desired.

Contact with questions:
Jason Glenn (jason.glenn@nasa.gov),
Matt Bradford (matt.bradford@jpl.nasa.gov)

PRIMA factsheet version 1.1, 22 Feb 2022







https://docs.google.com/forms/d/e/1FAIpQLSdM1J_4hrgqEL0l0knG1vpS_083wPYbHIbclySmkkjtt5VIJQ/viewform

PRIMA
The PRobe far-Infrared Mission for Astrophysics

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Matt Bradford	JPL
Science Lead:	
Alex Pope	UMass

+ likely international partners

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matt.Bradford@jpl.nasa.gov

Extras

Some IR Lines Accessed by PRIMA

Species	Rest λ (μm)	Ionization Energy (eV)	Traces	Typical Line Luminosity × 10^{-4} L_{FIR}
[Ne II]	12.8	21.6	SF	3
[Ne V]	14.3	97.1	AGN	2
[Ne V]	24.3	97.1	AGN	2
[O IV]	25.9	54.9	AGN (& SF)	5
[S III]	33.5	23.3	SF	3
[Si II]	34.8	8.2	SF	4
[O III]	51.8	35.1	SF (& AGN)	20
[O I]	63.2	N/A	SF	10
[O III]	88.4	35.1	SF (& AGN)	8
[N II]	122	14.5	SF	2
[O I]	146	N/A	SF	3
[C II]	158	11.3	SF	20

GEP-S:

24 μm ≤ λ ≤ 193 μm

Line carrying 10^{-3} L_{FIR} for 10^{12} $L_{\odot}$ galaxy detectable at z = 2, 5σ, in ~1 hour

(similar in class to SPICA)

Adapted from Spinoglio 2013

GEP-S Spectroscopic Surveys

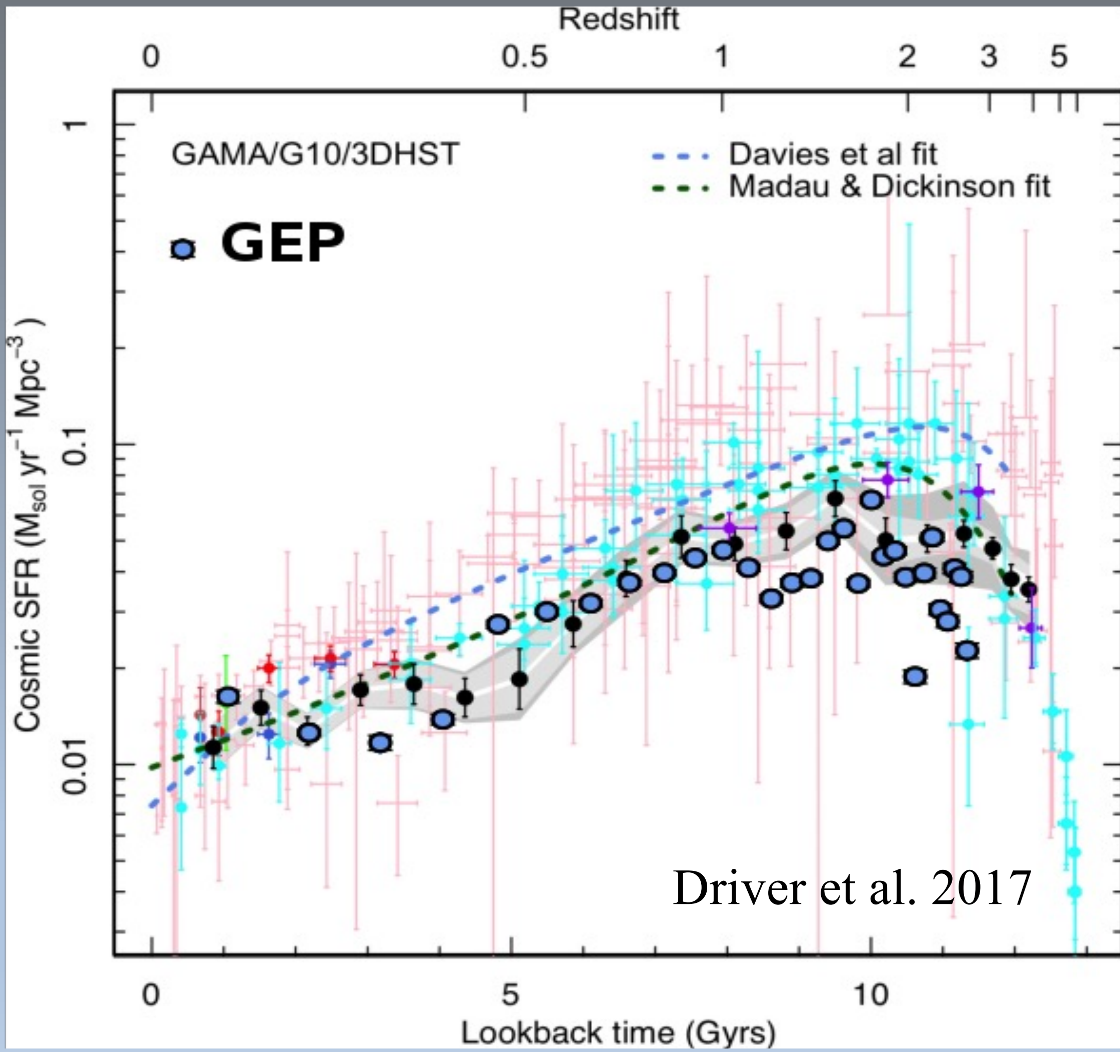
The physical conditions of gas in z > 0 galaxies and the role of gas in galaxy evolution are generally poorly known.

1. **Precise redshifts, AGN markers**
2. **ISM physical conditions:** Stacking on ~10^6 NGRST or Euclid galaxies detected in Hα to correlate with mid- / far-IR tracers
   - Feedback: High-velocity outflows
   - Stellar T_{eff} and densities around young stars:

     [N III] / [N II] and [O III] 52 μm / 88 μm
3. **Metallicities in galaxy disks:** Extinction-free tracers,

   e.g. [Ne II]+[Ne III] / [S III]+[S IV] and [O III] / [NIII]
4. **Integrated luminosity density and clustering:** Intensity mapping of source-removed residual data cubes to assess low-luminosity sources in aggregate.

Cosmic Star Formation History



- Accurate and precise star formation rates across broad ranges of redshift and environment
- Deep surveys and brightening by gravitational lensing will probe to z ~ 7.

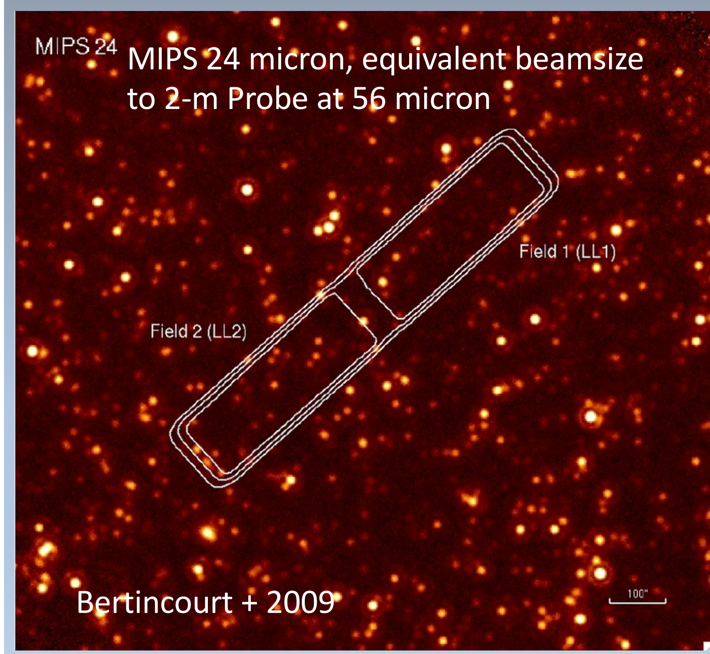
These GEP simulations only sample $0 < z \leq 3$ (Galacticus + Dale et al. spectra).

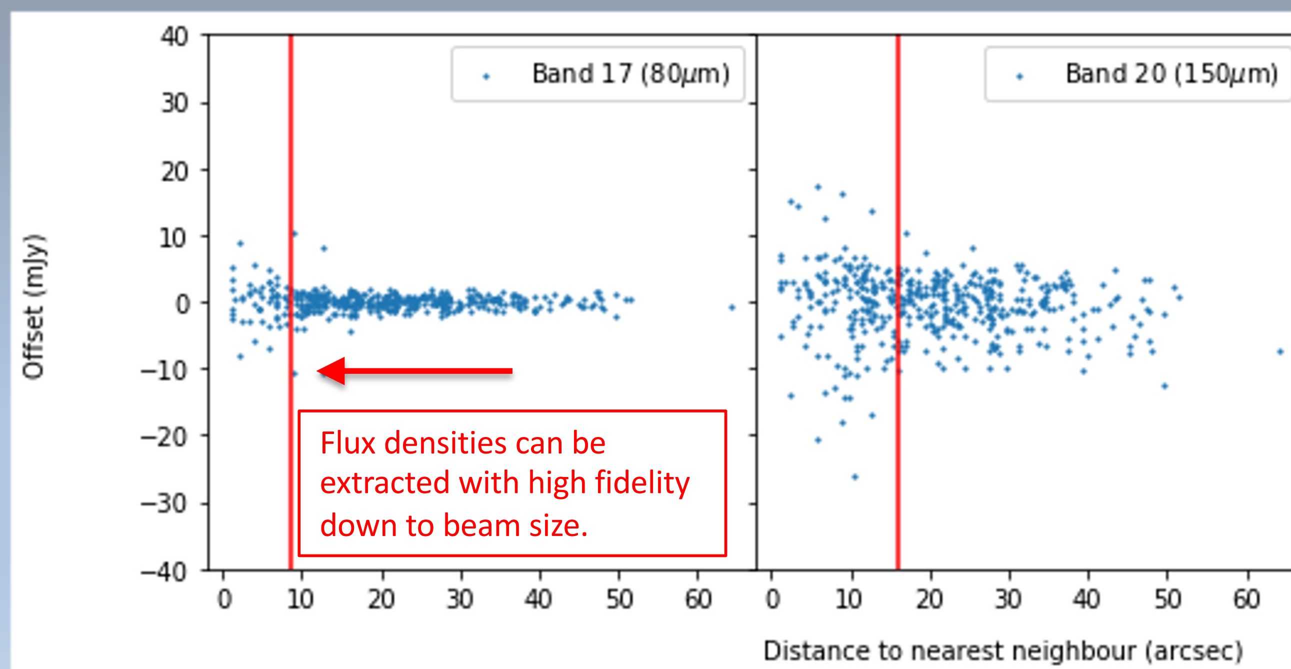
Andrew Benson

Extragalactic Source Confusion

- Spectroscopy: Fine-structure line emission will not be confused
- Imaging:
  - Angular resolution 3”x ($\lambda/25\mu$m)
  - Issue primarily for $\lambda \geq 70$ μm
  - To be mitigated with, e.g., XID+ (Oliver et al.)

FIR flux densities can be extracted with high fidelity down to the beam FWHM using strong GEP mid-IR positional priors with XID+ (Raphael Shirley).

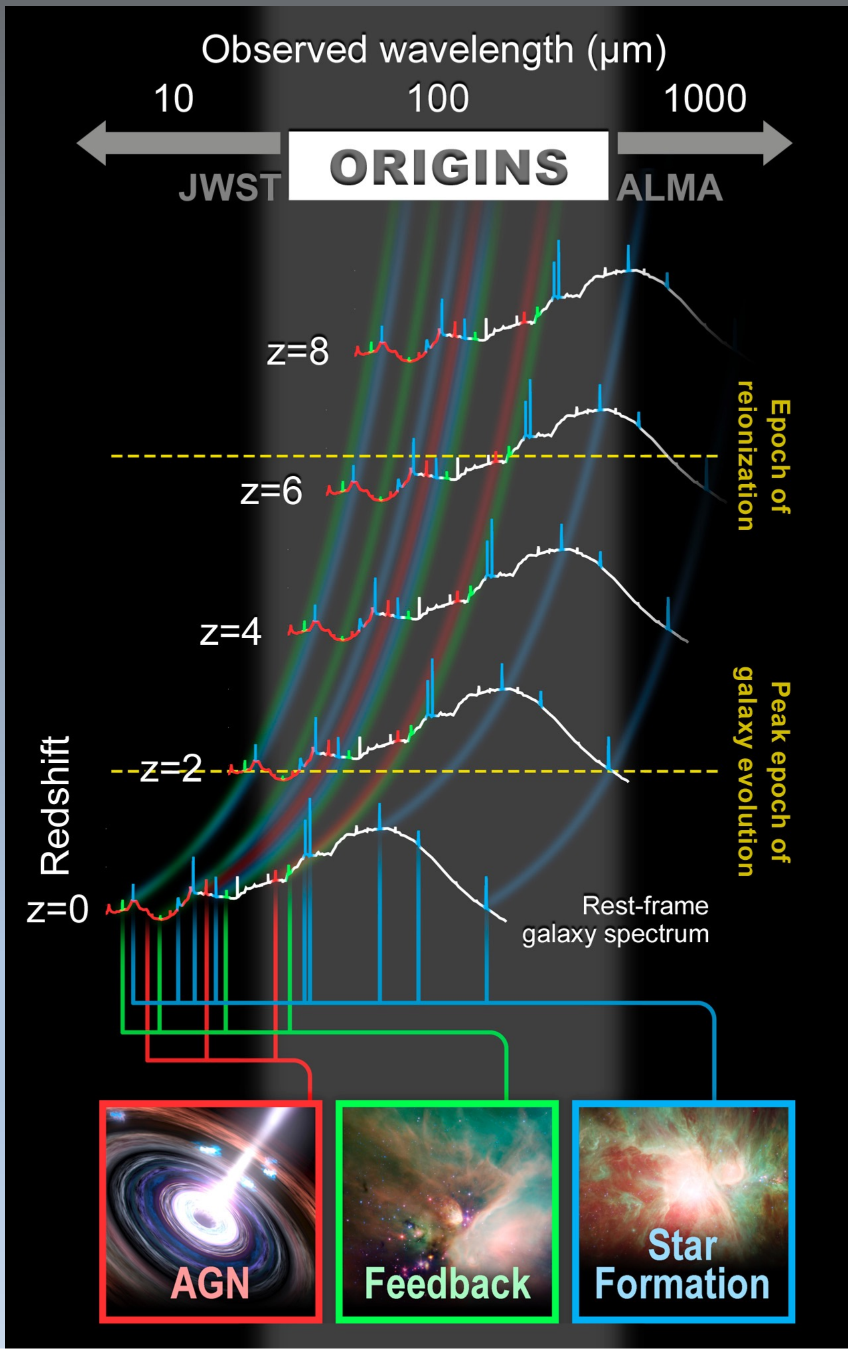




Driver et al. 2017

Extragalactic Survey Spectroscopy with the Probe

Survey the Universe in 3 dimensions, reveal heavy elements, SF, AGN, feedback



Key requirements

- Push toward background-limited sensitivity
- Modest resolving power. Most important attribute is detecting lines, so looking at integrated line sensitivity. Sensitivity dependence on resolving power is modest, but resolving power drives mass and pixel count.
- Large spatial coverage (limited by practicalities such as mass / size and array format)
- **Also require ability to go deep on single objects when necessary.**
- **→ Drives us to wideband, R~200 long-slit grating modules.**
- Wavelength coverage under study. Origins went to 588 microns, where ground-based windows open up. Longer is larger.

Origins figure from Alex Pope, same idea for Probe!