Optimization of Instrumentation for the Probe faR-Infrared Mission for Astrophysics (PRIMA)

Matt Bradford (JPL / Caltech -- PRIMA Project Scientist / DPI)

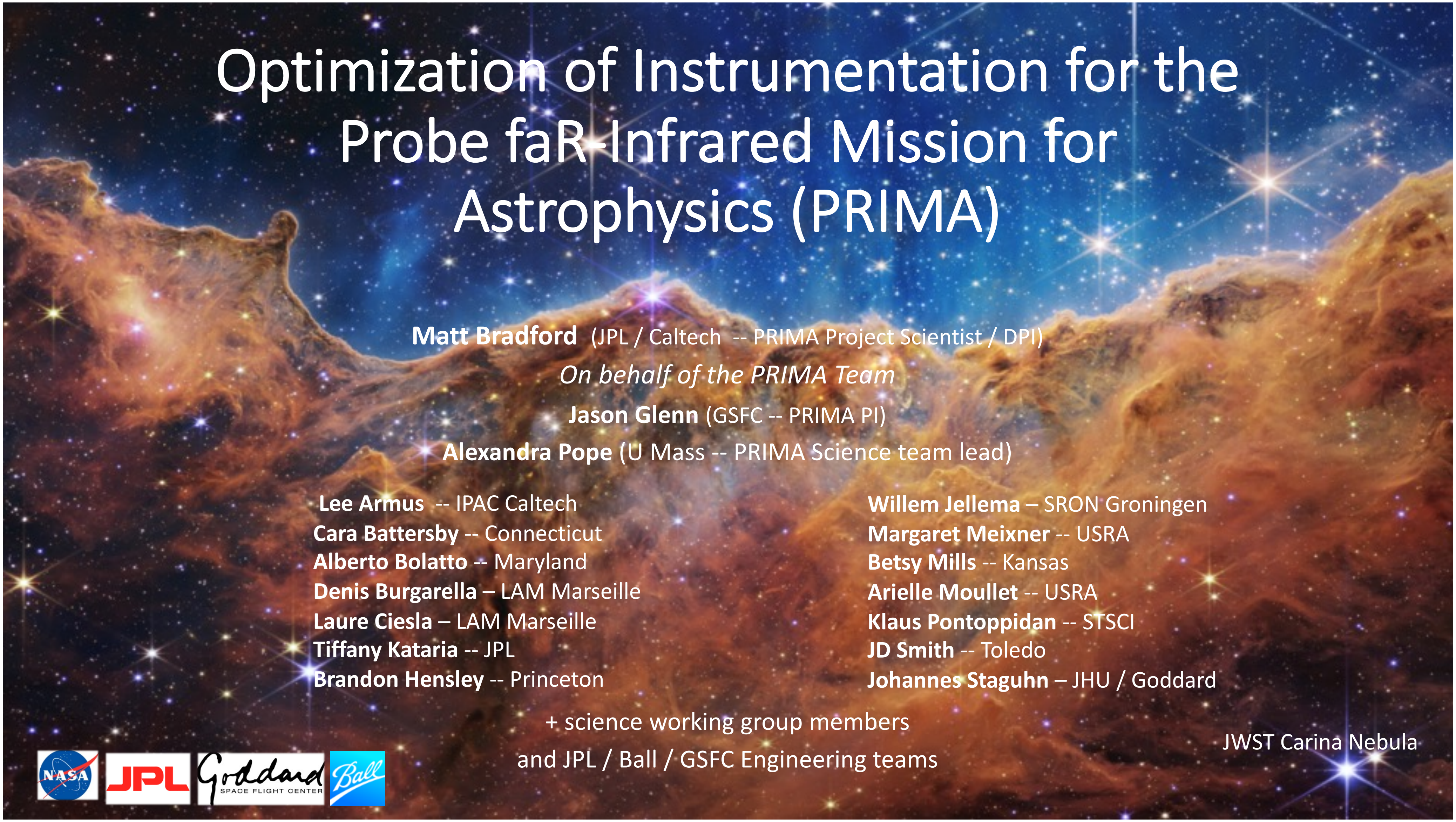
On behalf of the PRIMA Team

Jason Glenn (GSFC -- PRIMA PI)

Alexandra Pope (U Mass -- PRIMA Science team lead)

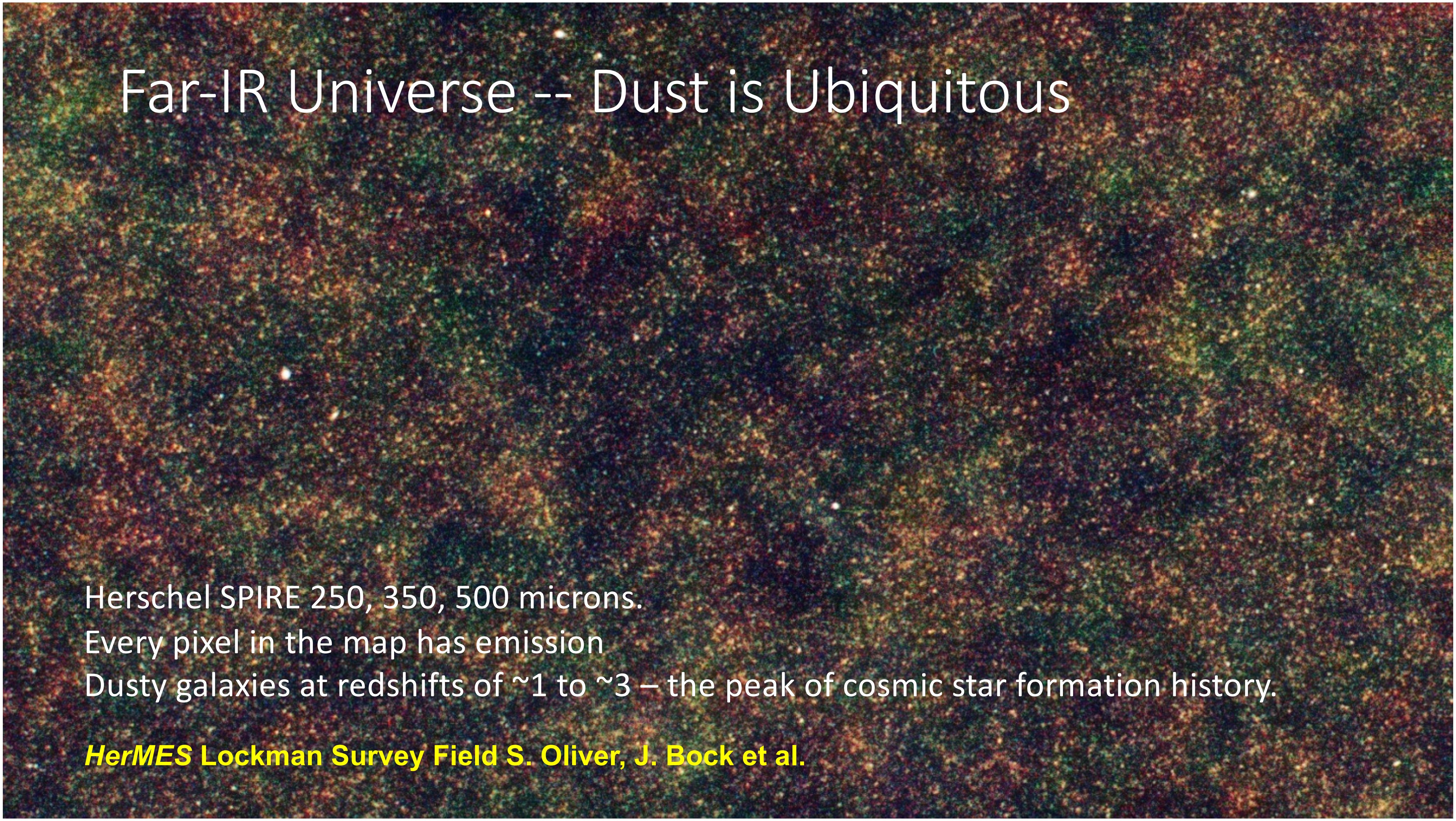
Lee Armus -- IPAC Caltech
Cara Battersby -- Connecticut
Alberto Bolatto -- Maryland
Denis Burgarella – LAM Marseille
Laure Ciesla – LAM Marseille
Tiffany Kataria -- JPL
Brandon Hensley -- Princeton
Willem Jellema – SRON Groningen
Margaret Meixner -- USRA
Betsy Mills -- Kansas
Arielle Moullet -- USRA
Klaus Pontoppidan -- STSCI
JD Smith -- Toledo
Johannes Staguhn – JHU / Goddard

+ science working group members
and JPL / Ball / GSFC Engineering teams



JWST Carina Nebula

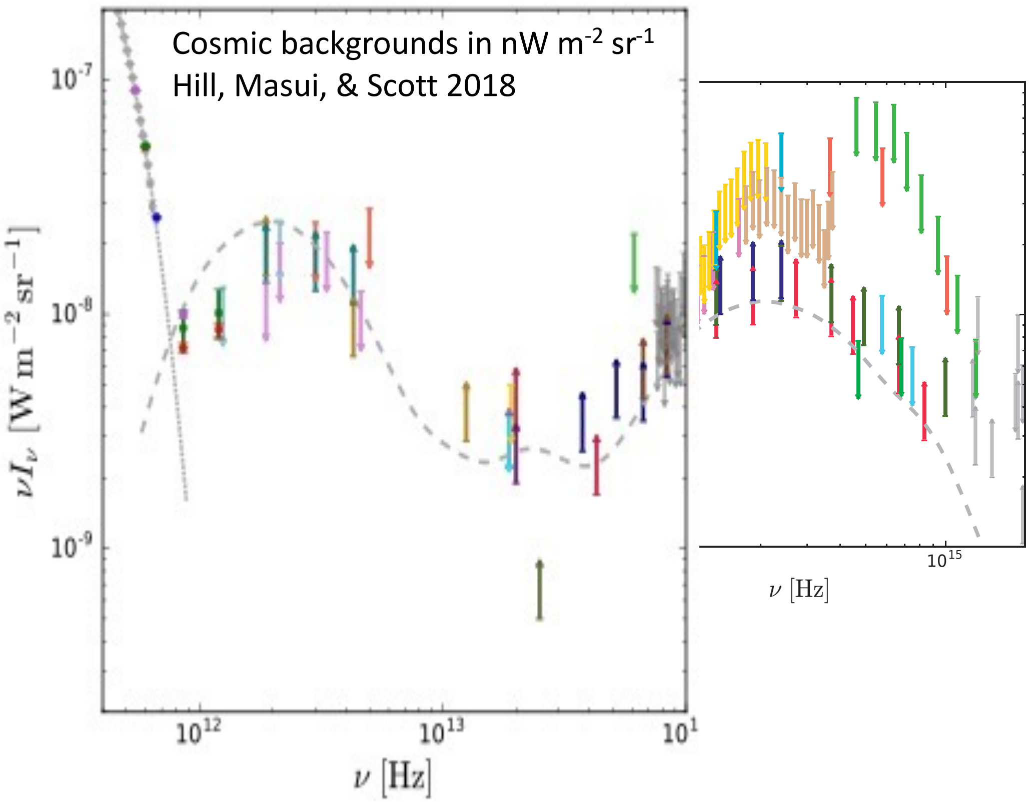
Far-IR Universe -- Dust is Ubiquitous



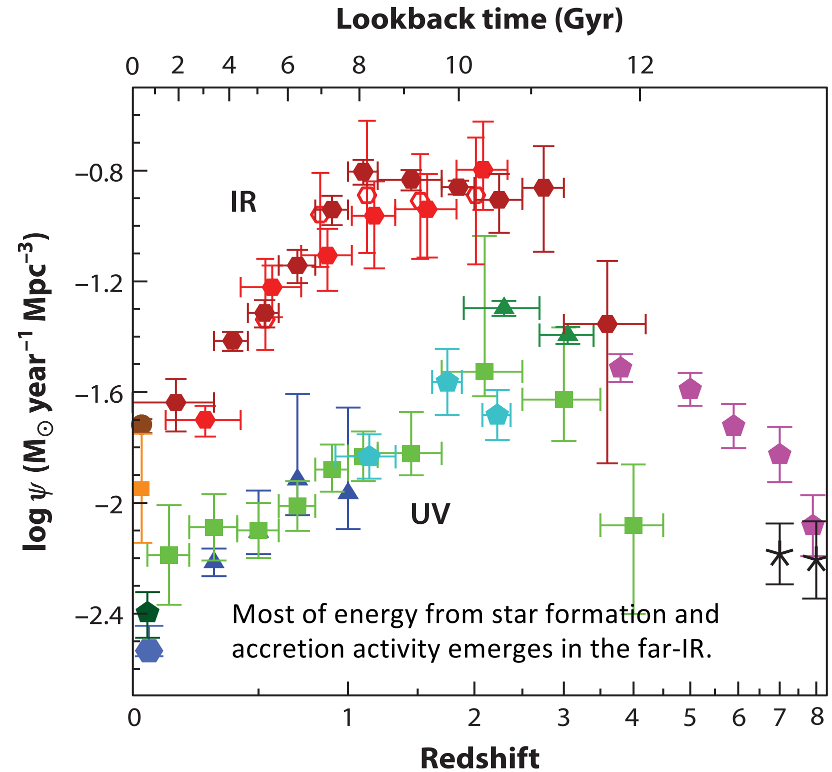
Herschel SPIRE 250, 350, 500 microns.
Every pixel in the map has emission
Dusty galaxies at redshifts of ~1 to ~3 – the peak of cosmic star formation history.

***HerMES* Lockman Survey Field S. Oliver, J. Bock et al.**

Far-IR Universe: Dust is Ubiquitous



Energy output from galaxies:

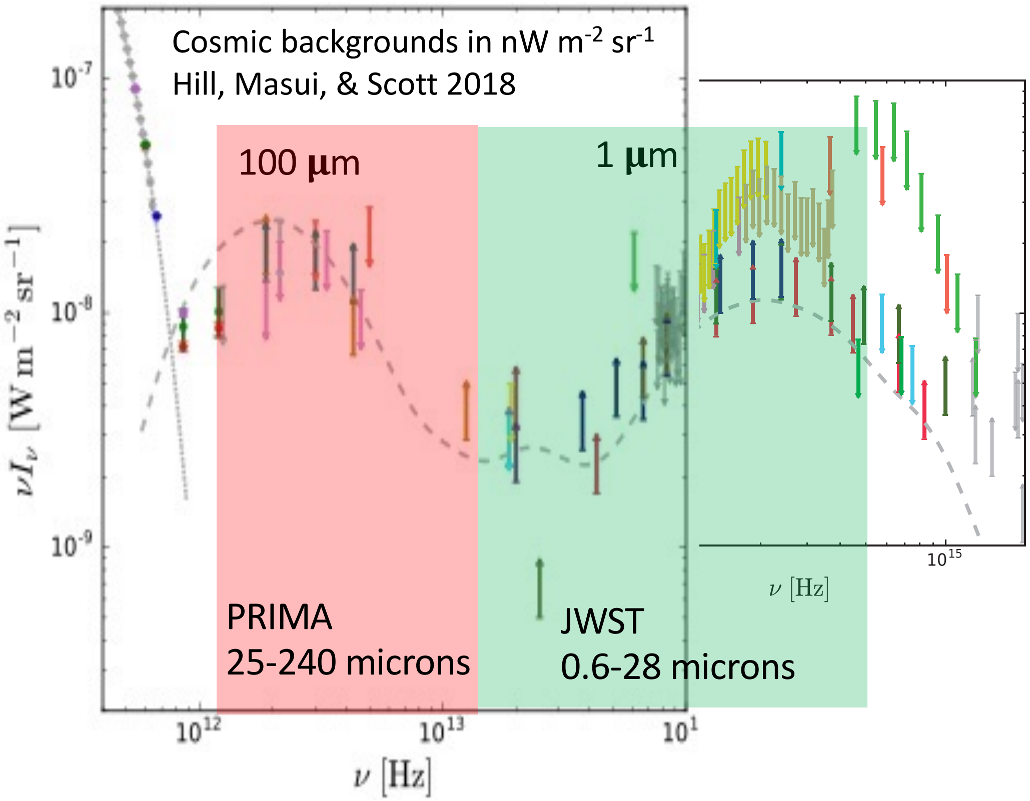


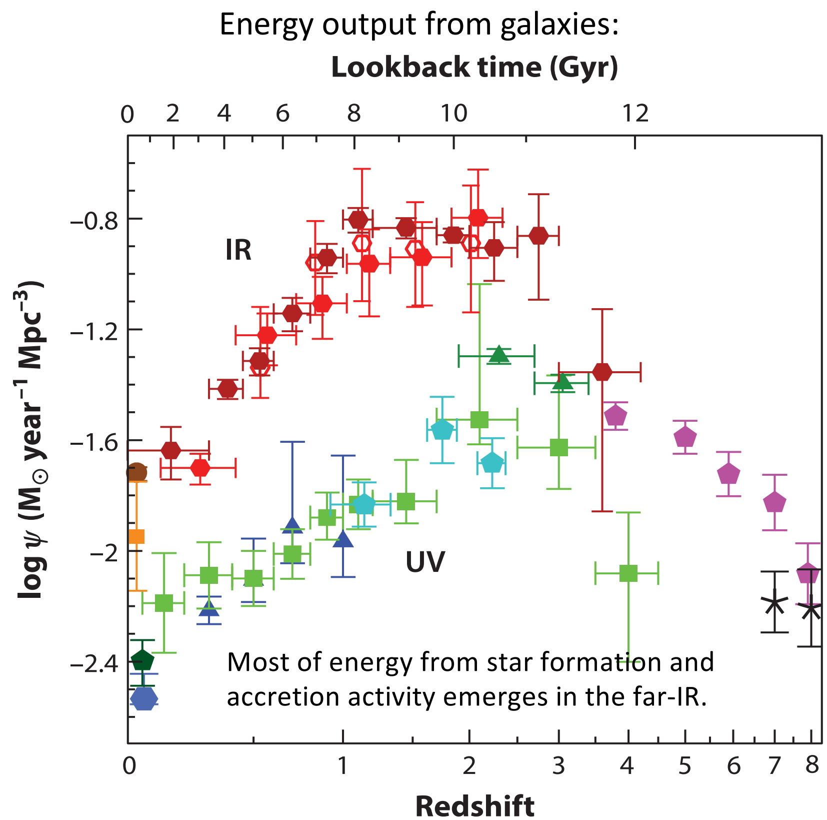
~Half of the remnant electromagnetic light from stars and galaxies is in the far-IR.

Far-IR background is a cosmological background, not a low-redshift phenomenon.

Star formation has been predominantly obscured.

Far-IR Universe: Dust is Ubiquitous





~Half of the remnant electromagnetic light from stars and galaxies is in the far-IR.

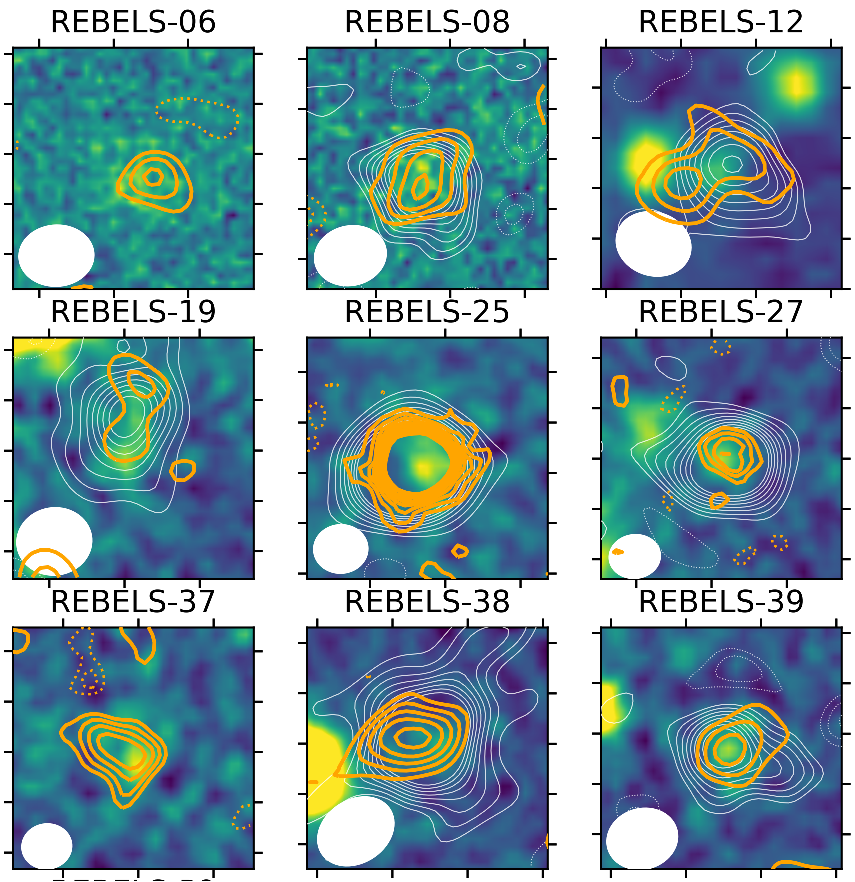
Far-IR background is a cosmological background, not a low-redshift phenomenon.

Star formation has been predominantly obscured.

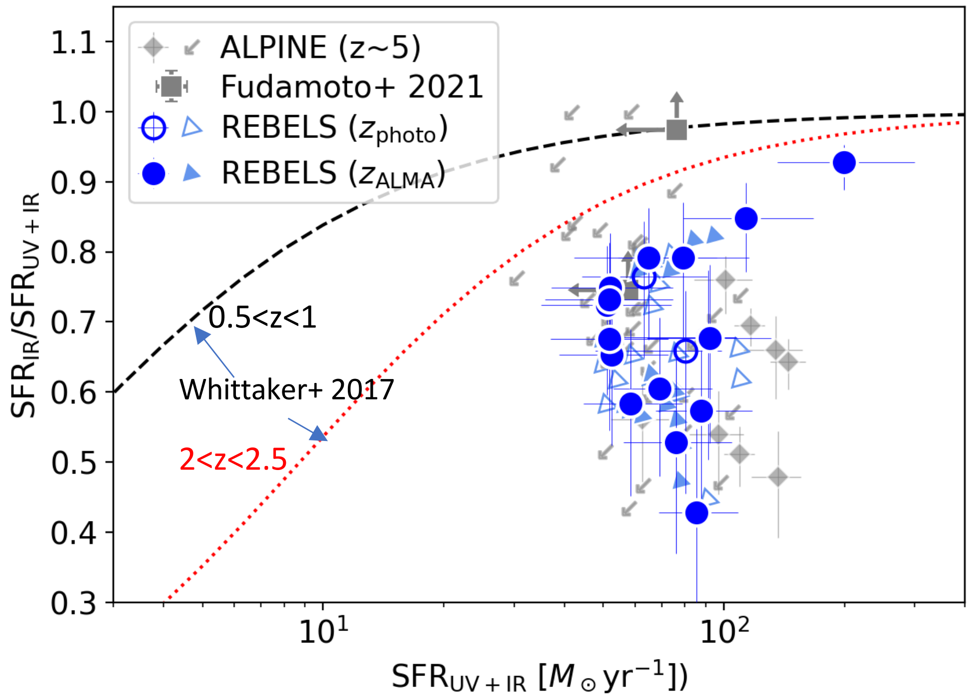
Dust present at very early times

ALMA detects dust in UV selected high-z galaxies

Example: REBELS survey z>6.5 Inami et al, 2022

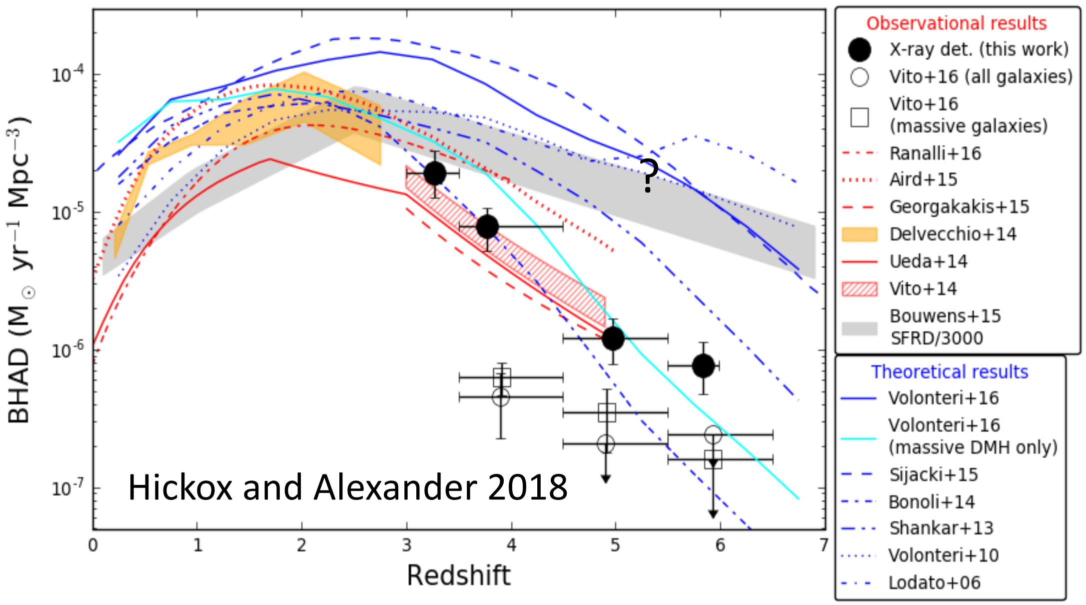


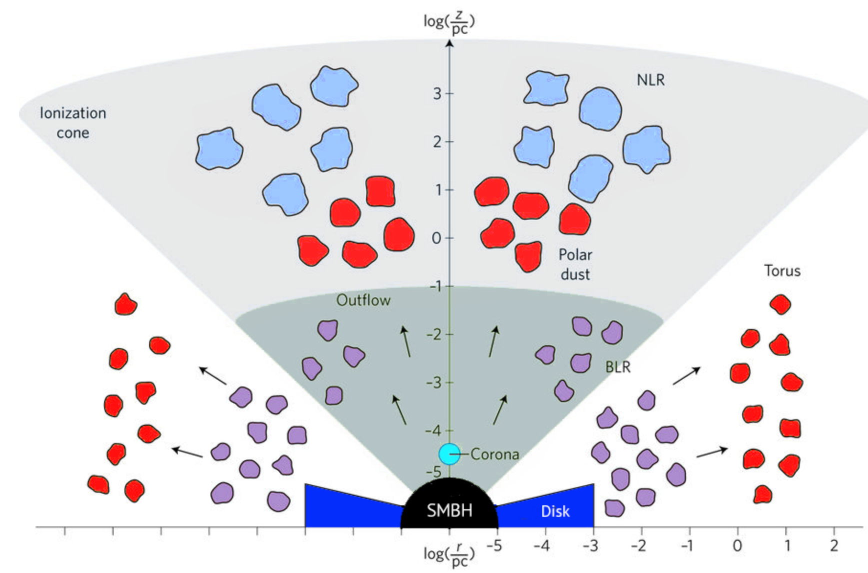
5 x 5 arcsec, JHK background, dust orange, CII white

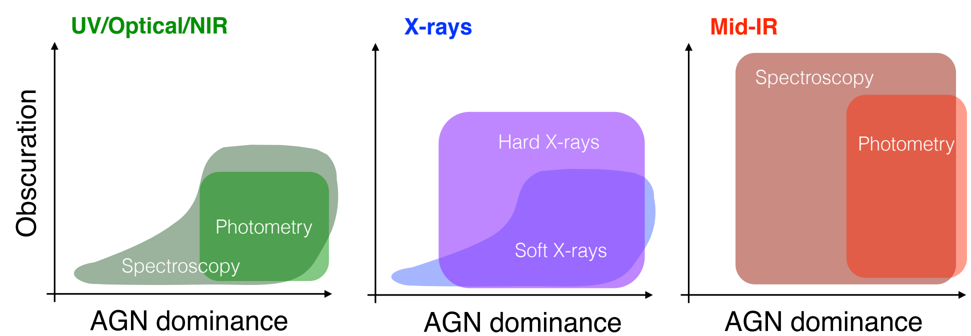


- UV selected galaxies -> 20/49 detected with ALMA. Expect more when pushed deeper.
- ***Those detected indicate that most of their star formation is obscured.***

Historical Role of Obscured AGN? Unknown

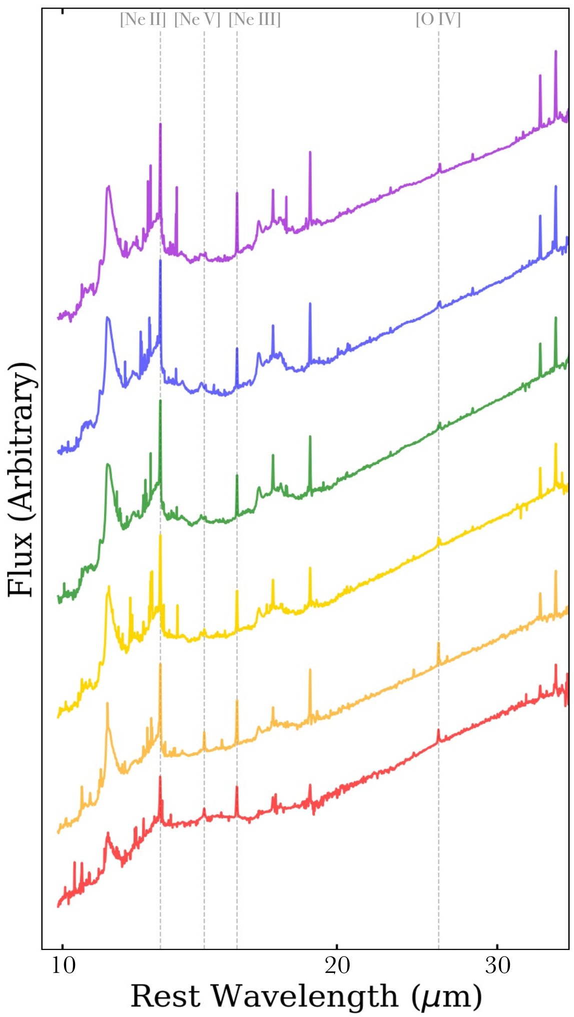






- Most models require AGN feedback at levels greater than observed.
- Typically attributed to obscured AGN – obscured AGN may well be the dominant mode.
- Obscuration can occur in the torus or in the host galaxy material – obscures optical, UV, and X-ray.

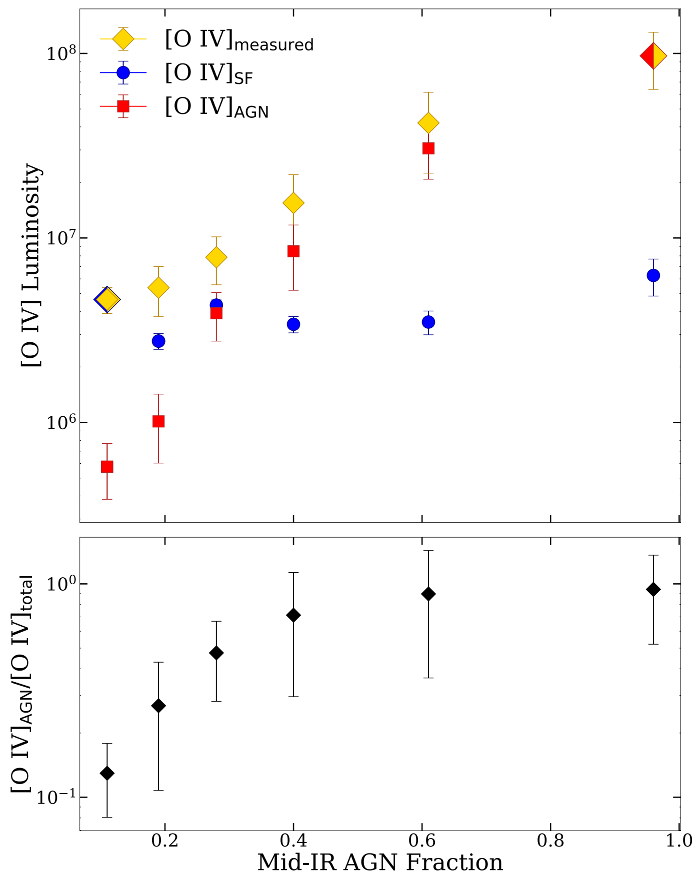
Historical role of Obscured AGN? Measure with far-IR



Rest-frame mid-IR spectroscopy is largely immune to dust obscuration, a powerful tool for assessing obscured AGN.

- [NeV] mid-IR transitions always an unambiguous probe, but a challenging measurement.
- [OIV] 26 microns emerging as a reliable tracer of embedded accretion, can be reliably corrected for (sub dominant) star formation contribution.

Meredith Stone et al, 2022
(using Gruppioni+ 2016 correlations which tie directly to X-rays.)



$$\dot{M}_{BH}(M_\odot/yr) = 6.44 \times 10^{-15}\,(L_{[\mathrm{OIV}]meas} - aL_{[\mathrm{NeII}]})^{1.69}$$

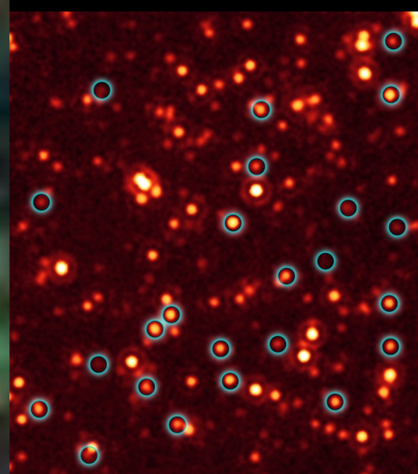
PRIMA Far-IR Spectroscopy Sees Through Dust, Overcomes Confusion

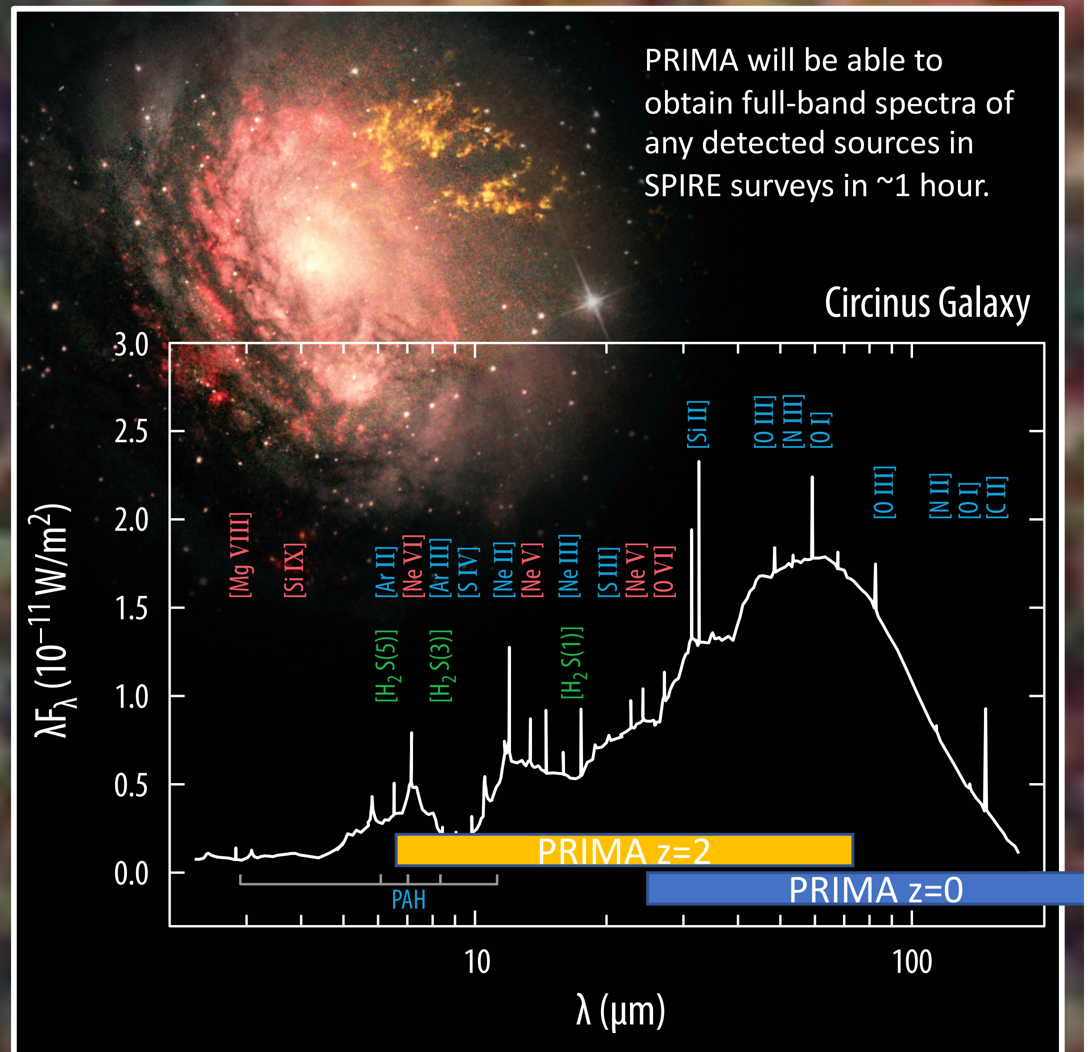
***HerMES* Lockman Survey Field with Herschel SPIRE:**
Broad Continuum Bands: 250, 350, 500 microns
=> Confusion Limited at long wavelengths in the continuum from galaxies at z=1-3.

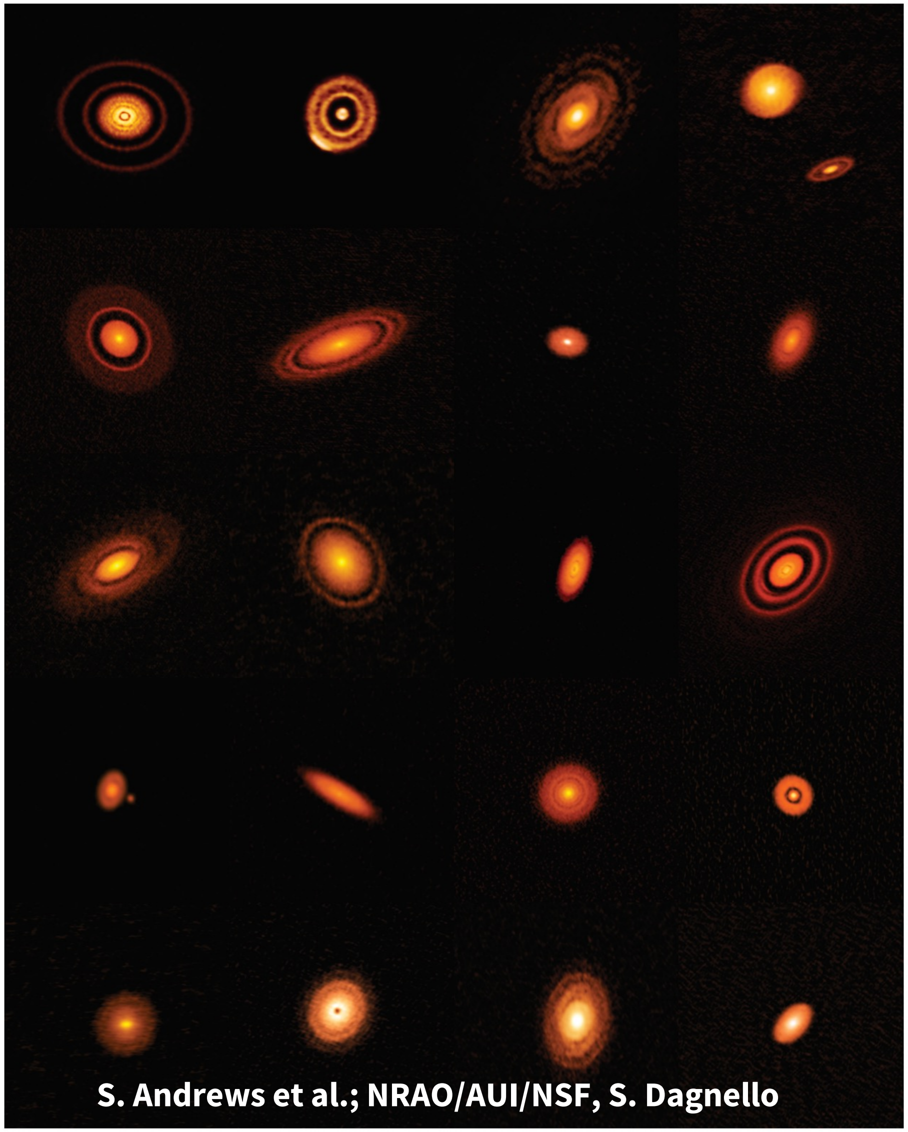
Beamsize with PRIMA at 55-60 microns will be comparable to Spitzer 24 microns. Unconfused and resolves most of the light.

Confusion mitigated with spectroscopy – unconfused in line counts.

Spitzer MIPS 24 micron

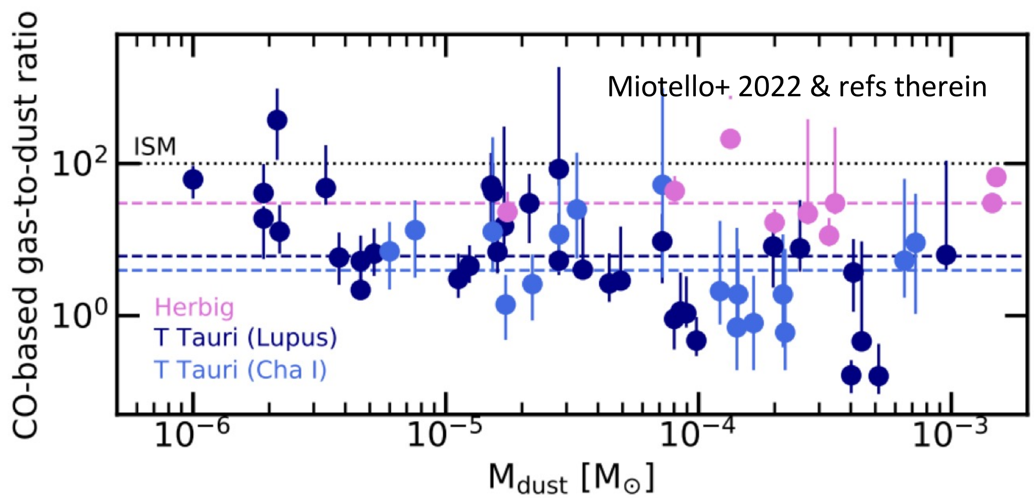




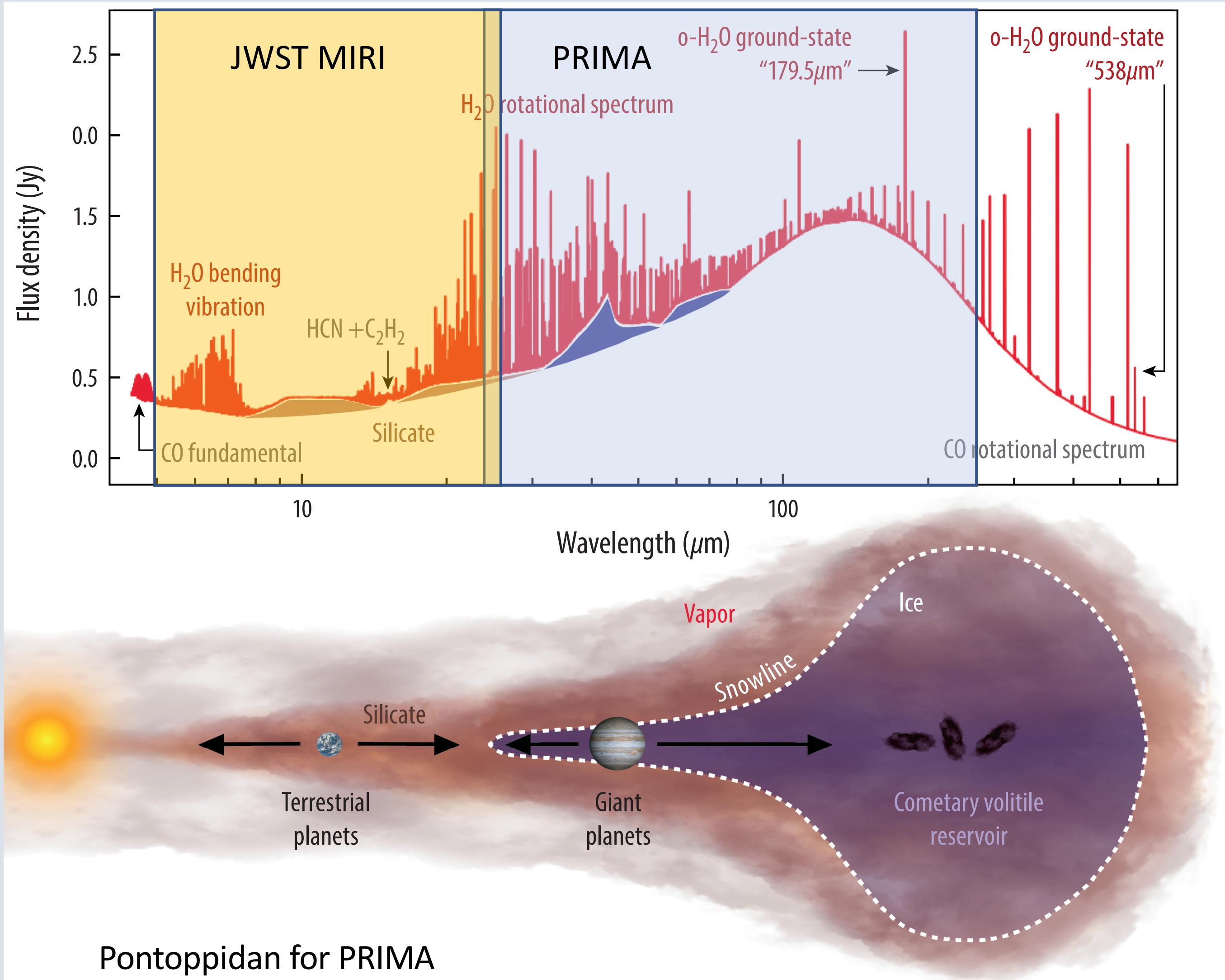


Planetary System Formation

- ALMA has provided beautiful images in millimeter continuum and CO.
- But disk mass remains a huge problem, massive uncertainties from unknown CO abundance and varying dust depletion.



- **HD rotational fundamental at 112 µm provide an excellent H_2 mass proxy measurement. PRIMA will measure HD in hundreds of disks.**



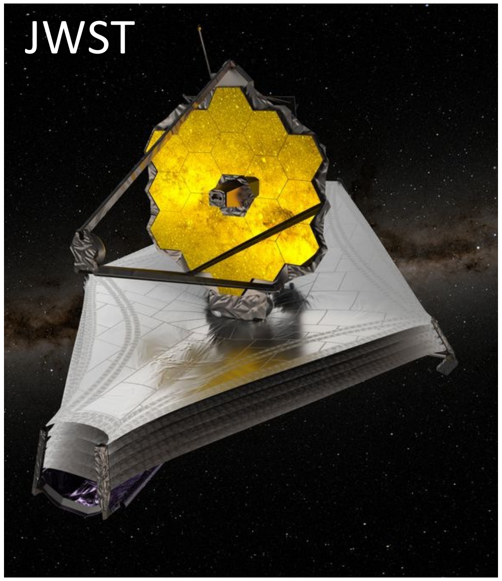
Pontoppidan for PRIMA

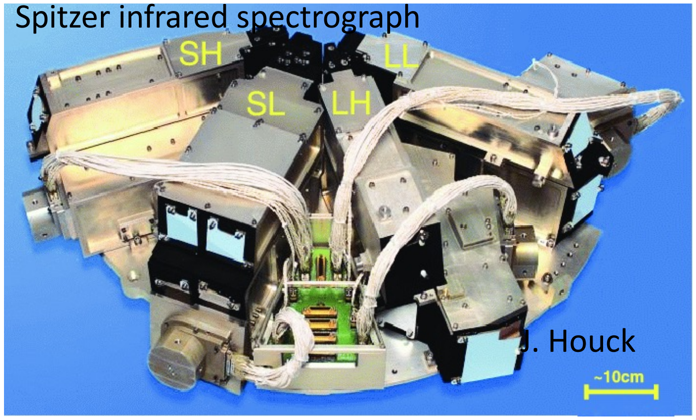
Water In Disks

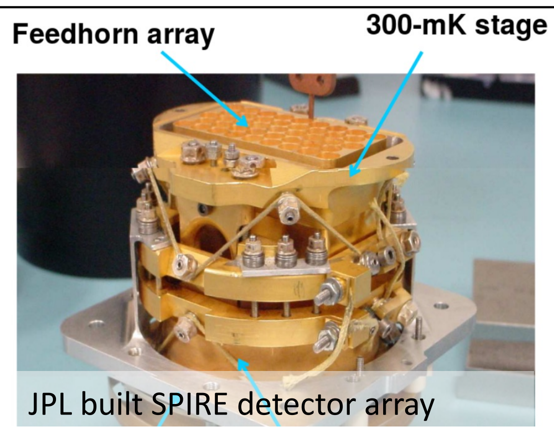
- Protoplanetary disks have rich spectra with a host of water transitions from a range of temperatures.
- JWST accesses warm inner disk, not carrying the bulk of the mass.
- **PRIMA measures the bulk of disk water with the full spectrum,** allowing models of the water distribution.
- Resolving power sufficient to detect 100s of lines including those of isotopes.
- Will survey hundreds of disks, spanning age, stellar mass, environment.

PRIMA Approach

- Cryogenic observatory at L2
  - Leverages experience with Spitzer and JWST
    - Planck, Herschel, ISO, others. Cryogenics work.
  - 2-meter telescope close to 4 K, focal planes below 1 K.
  - Passive design + mechanical coolers.
- Background-limited in the band from JWST to ALMA: 25 to ~300 μm.
  - Sensitive Long-slit spectroscopy with low (R~few x 100) and high (R~few x 1000) modes.
  - Spectrophotometric imaging and polarimetry.
  - 2-3 mechanisms at most
- Envision 5 years life, most of which is for community open time.
- JPL lead, with GSFC contributions, Ball spacecraft.

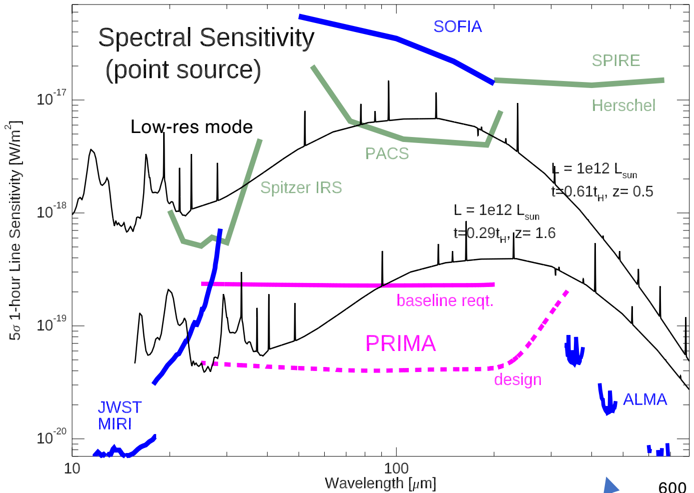




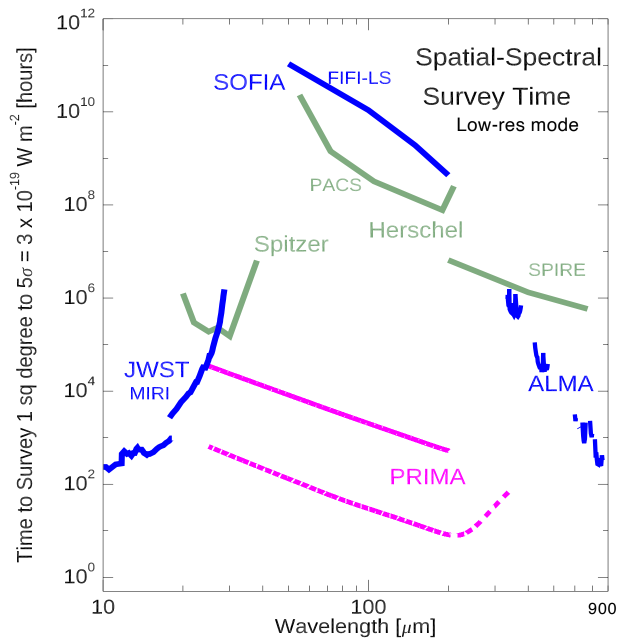


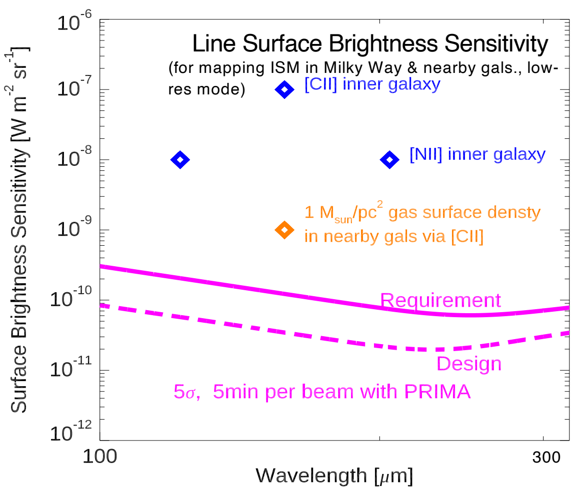
Instrumentation Optimizes Sensitivity (=speed) & Spectral Coverage

PRIMA-S Wideband Multi-Mode Spectrometer



Preliminary Performance Estimates





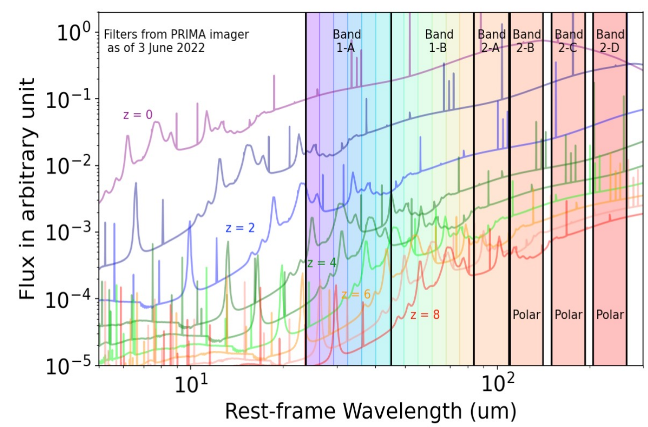
High-Res mode will have **comparable sensitivity** and **full spectral coverage** with R~3000-5000 at 100 microns

PRIMAGER: Multiband Spectro-photometric Imaging and Polarimetry

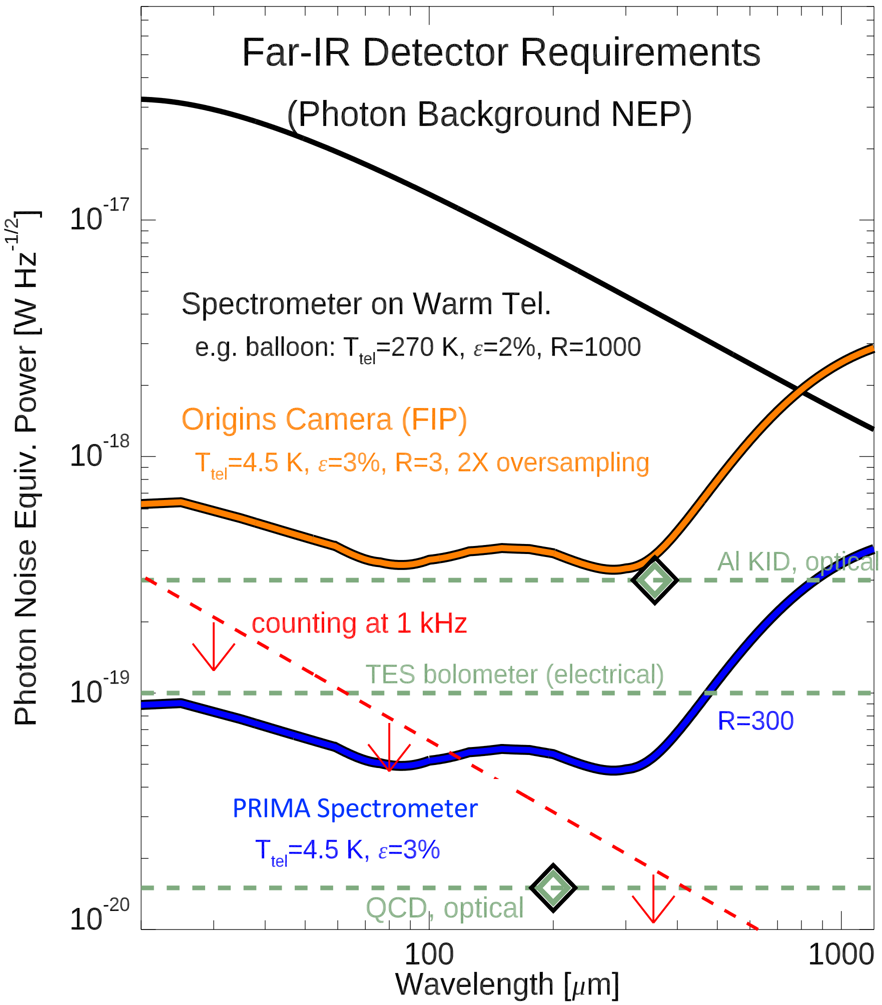
Imager provided by European consortium led by CNES and SRON.
D. Burgarella, L. Ciesla, W. Jellema leads

Preliminary Specifications

- R~10 at 25 to 80 microns in two 2x2 arcmin arrays. (12 filter bands)
- R~4 in four longer wavelength bands (each 2x2 arcmin), 3 w/ polarimetry.



Detectors for PRIMA



Far-IR detectors and readouts must be built by the science community. We have been working steadily for 2 decades.

Format

- Herschel – few hundred pixels in each of SPIRE and PACS (non multiplexed)
- Multiplexing has emerged in the last 2 decades, uses superconductivity
- We are targeting 2 to 4 thousand pixels for PRIMA.

-> Use Kinetic Inductance Detectors (KIDs)

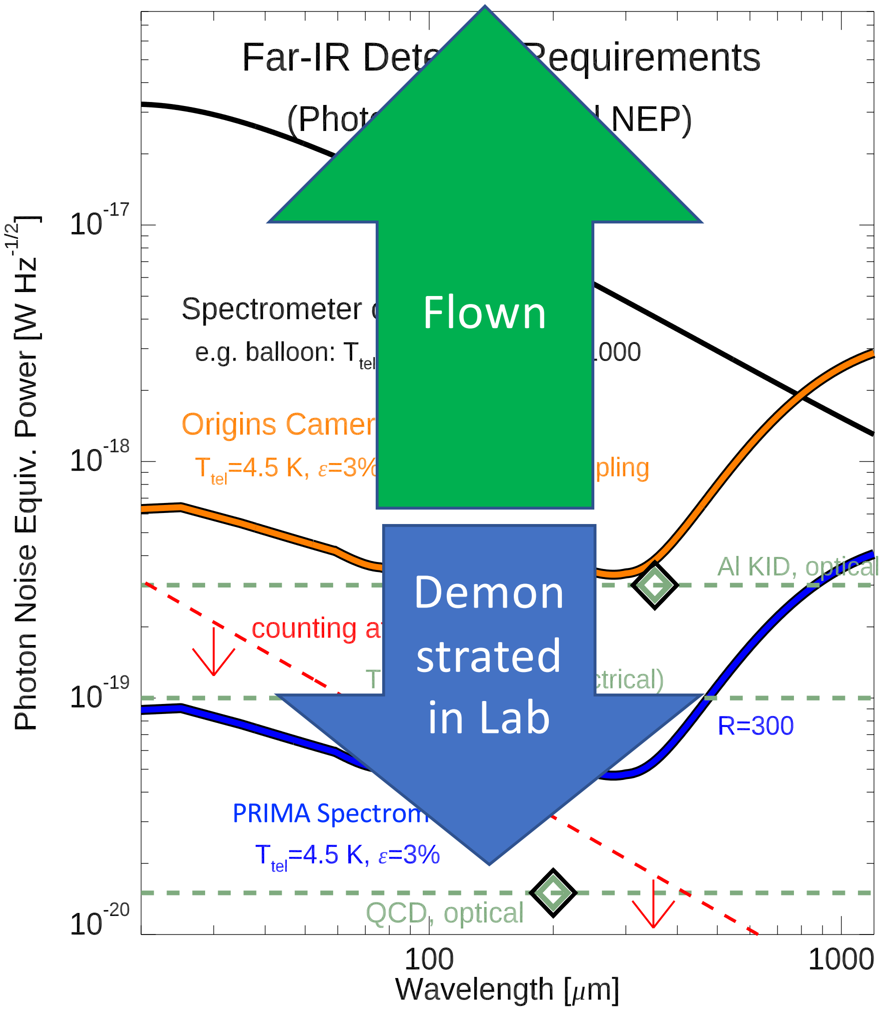
See FarIR / submm/ mm detectors conference (12190)
Especially R. Janssen Friday afternoon. PRIMA-like KID arrays

Sensitivity

- Required per-pixel detector sensitivity is determined by the backgrounds, not the aperture, so the same for all cold telescope.
- No sub-orbital or ground platform that can serve as sensitivity pathfinder for cold space telescope.

-> Demonstrations of basic performance now in hand.

See Baselmans et al (de Visser) Thursday 2:40 in 12190



Detectors for PRIMA

Far-IR detectors and readouts must be built by the science community. We have been working steadily for 2 decades.

Format

- Herschel – few hundred pixels in each of SPIRE and PACS (non multiplexed)
- Multiplexing has emerged in the last 2 decades, uses superconductivity
- We are targeting 2 to 4 thousand pixels for PRIMA.

-> Use Kinetic Inductance Detectors (KIDs)

See FarIR / submm/ mm detectors conference (12190)
Especially R. Janssen Friday afternoon. PRIMA-like KID arrays

Sensitivity

- Required per-pixel detector sensitivity is determined by the backgrounds, not the aperture, so the same for all cold telescope.
- No sub-orbital or ground platform that can serve as sensitivity pathfinder for cold space telescope.

-> Demonstrations of basic performance now in hand.

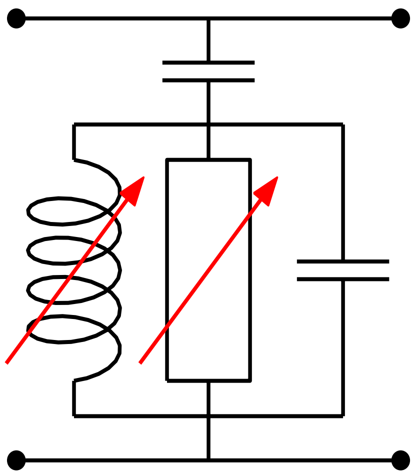
See Baselmans et al (de Visser) Thursday 2:40 in 12190

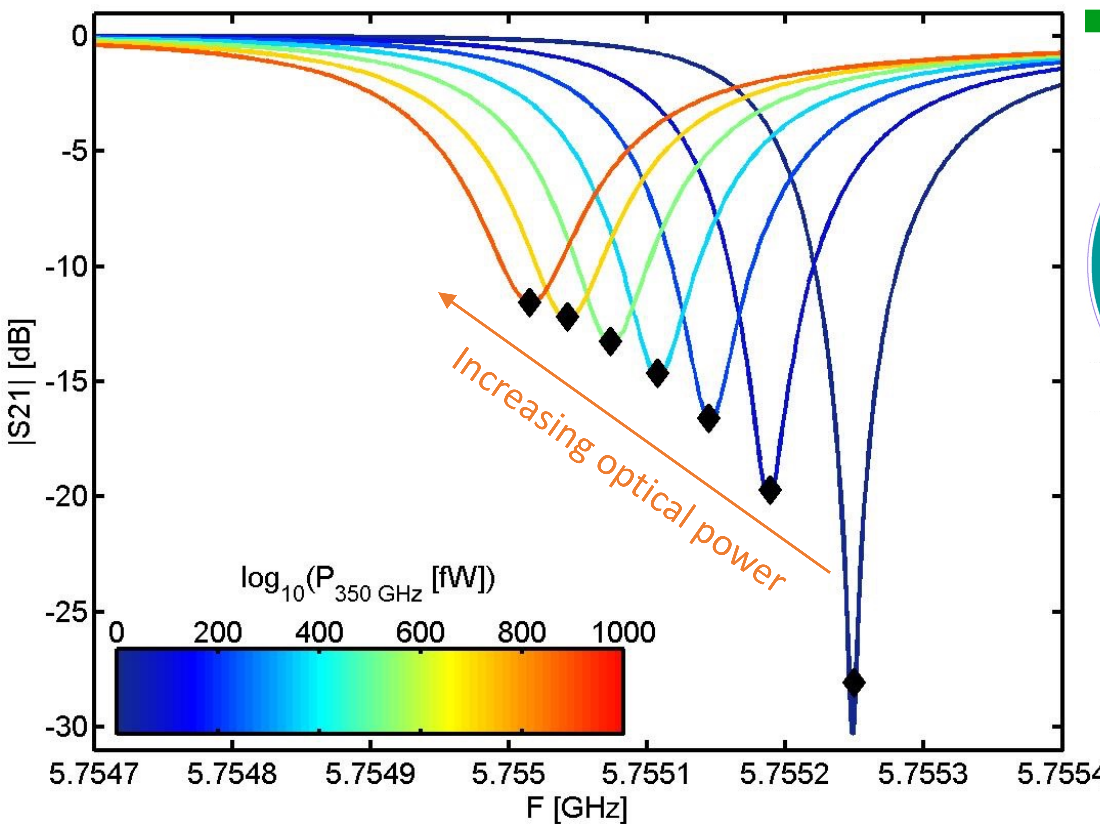
Kinetic Inductance Detector – Operational Principle

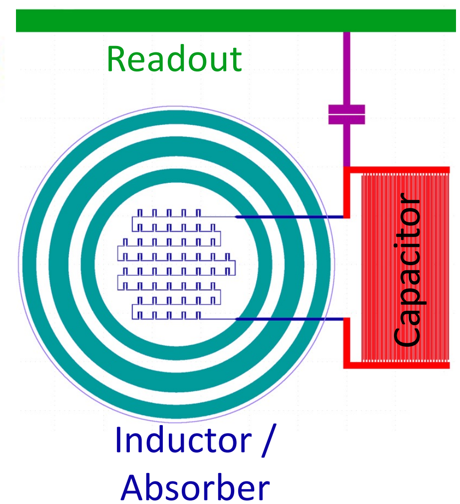
enables massive multiplexing

Superconducting resonator

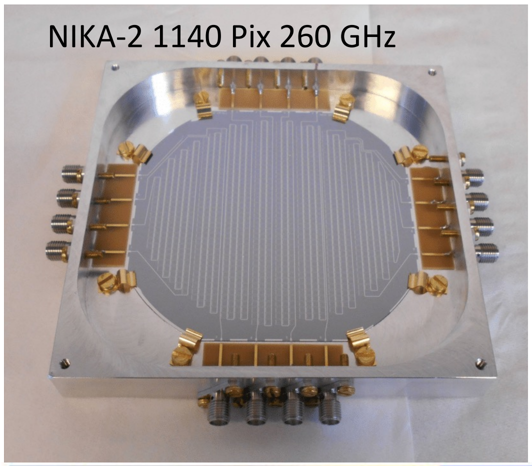
Q ~ $10^4 – 10^6$
Fres ~ 0.1 – 10 GHz

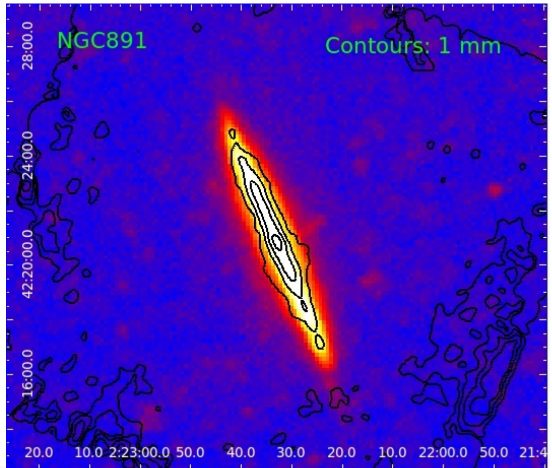


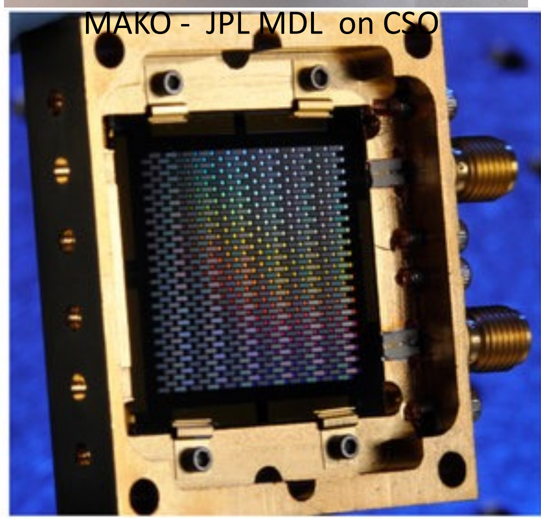


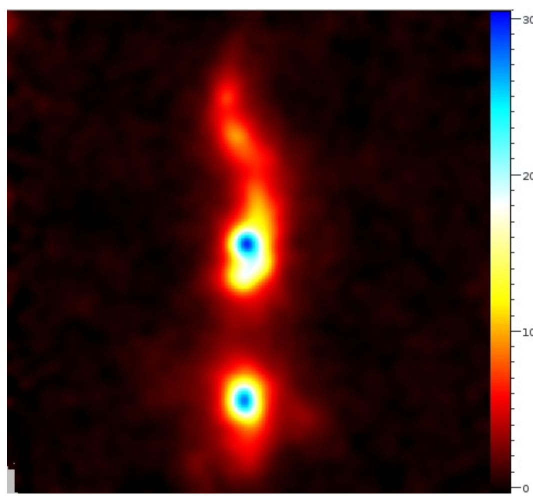


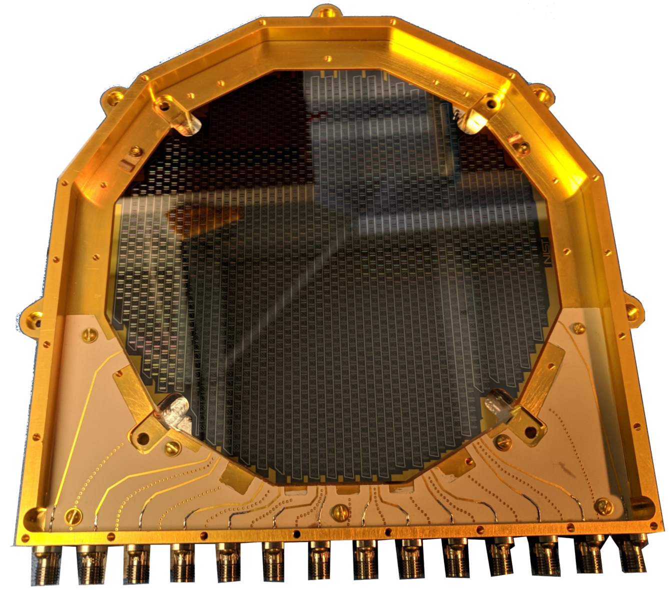
KID arrays fielded in many instruments





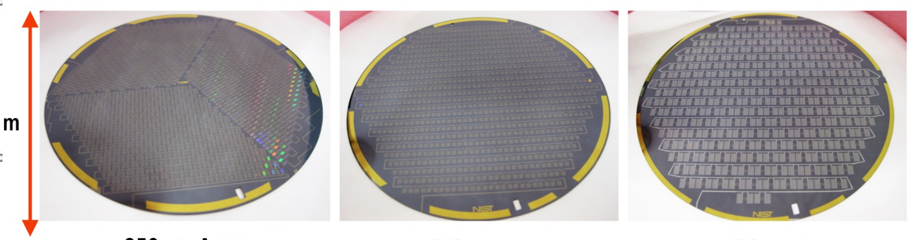






TolTEC on LMT 1.1 mm, 1.4 mm, 2 mm 7000 total pixels

BLAST – TNG far-IR balloon



250 μm Array
1836 Detectors

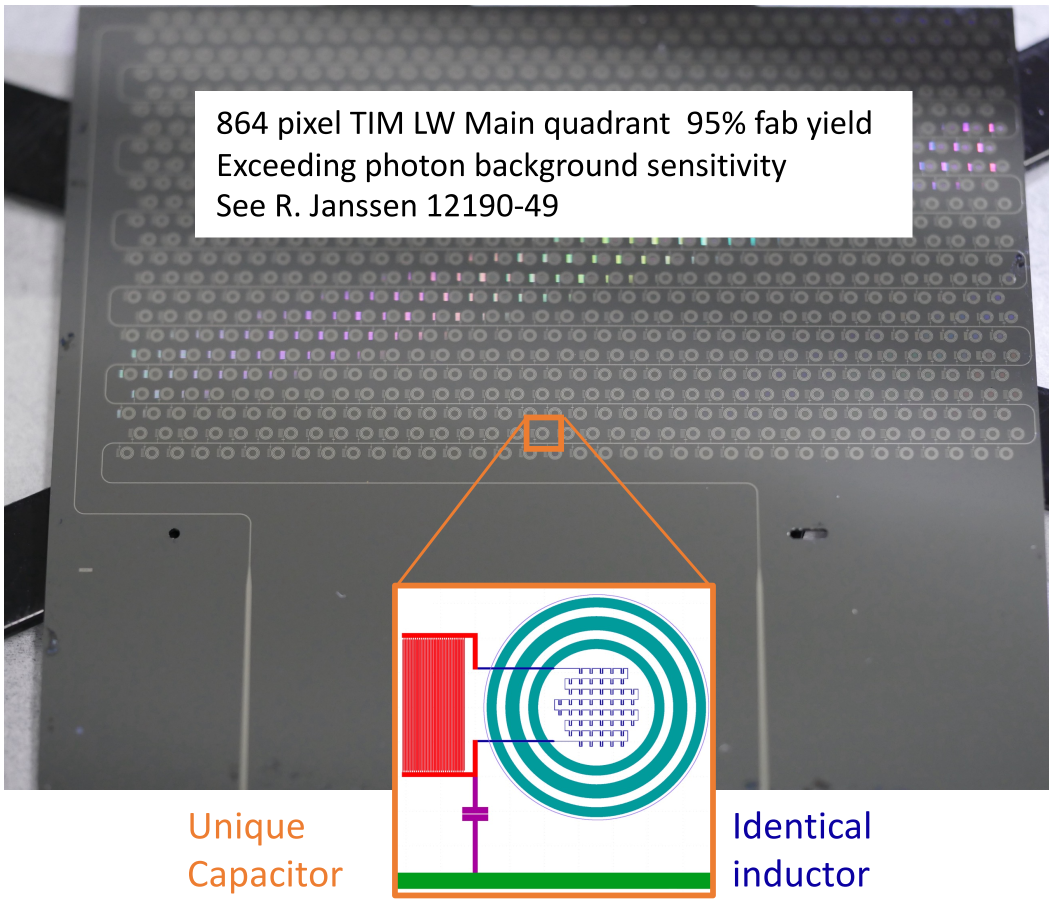
350 μm Array
938 Detectors

500 μm Array
544 Detectors

jpl.nasa.gov

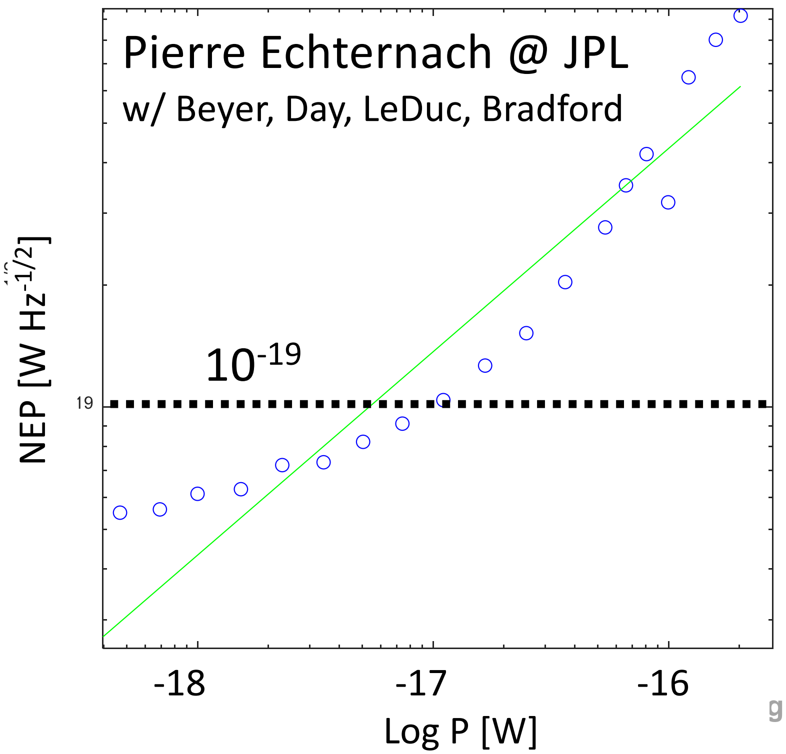
Terahertz Intensity Mapper (TIM) Balloon – a PRIMA Pathfinder

2 spectrometers covering 240 to 420 microns, 7000 pixels total. Marrone et al. this conference

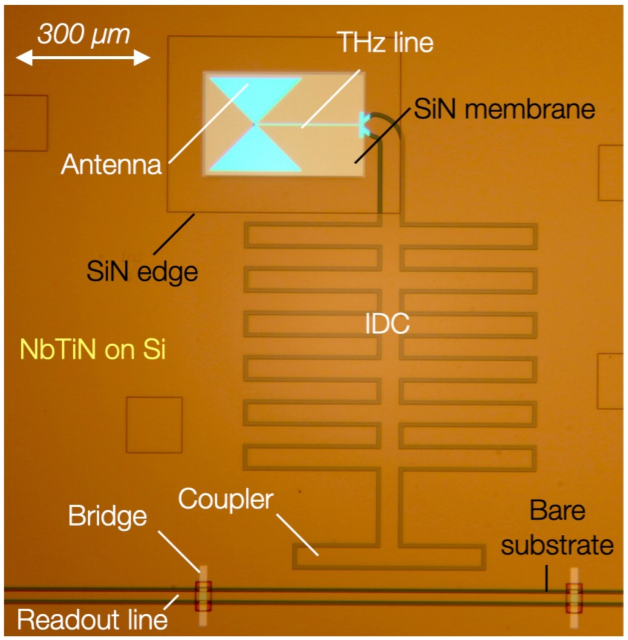


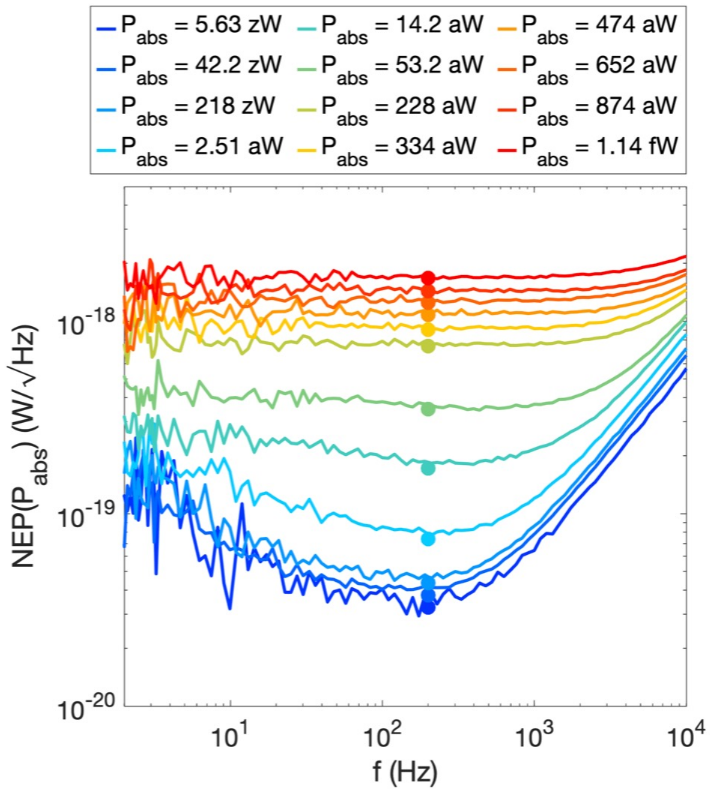
Adapting for PRIMA sensitivities:

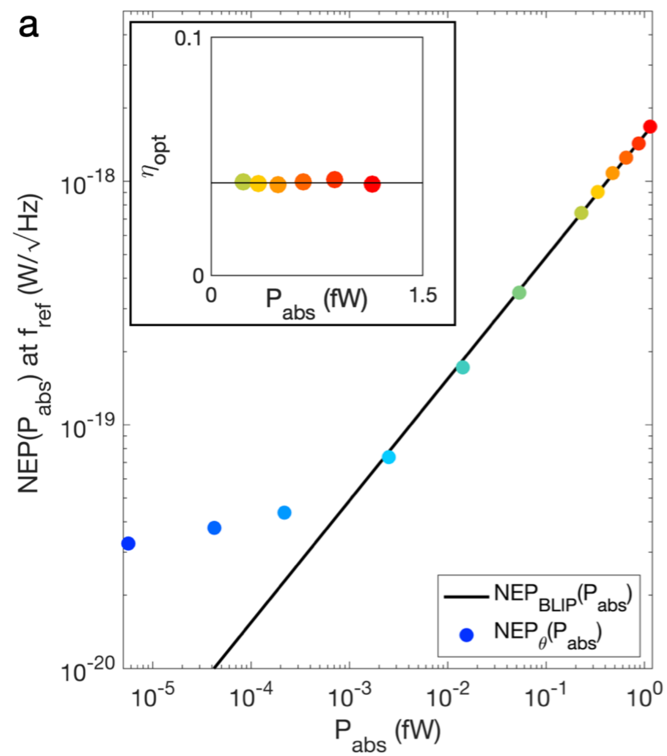
-> Smaller KID Inductor. Use electron beam patterning: 7 cubic micron device



TU Delft / SRON (Baselmans et al) Hitting Space NEP Goal







12190-32 tomorrow 2:40 PM 524A

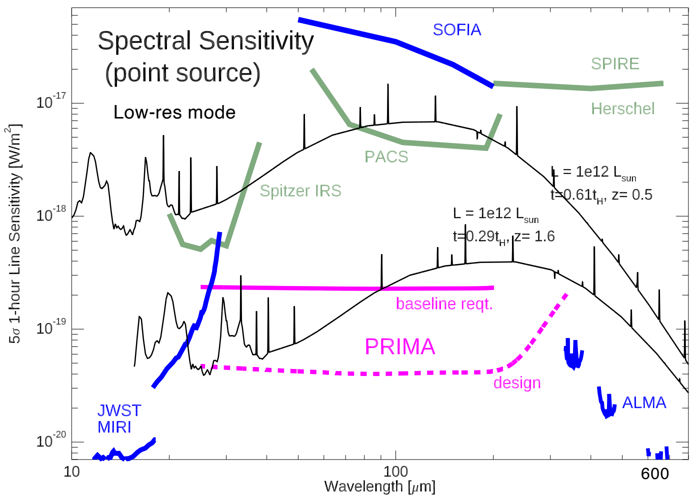
SRON Netherlands Institute for Space Research

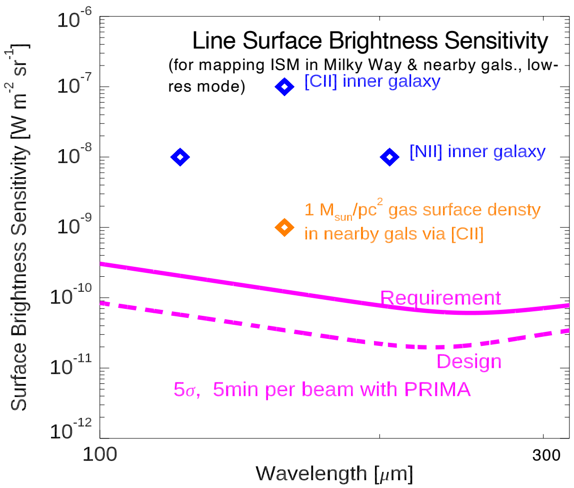
TU Delft

jpl.nasa.gov

PRIMA The PRobe far-Infrared Mission for Astrophysics

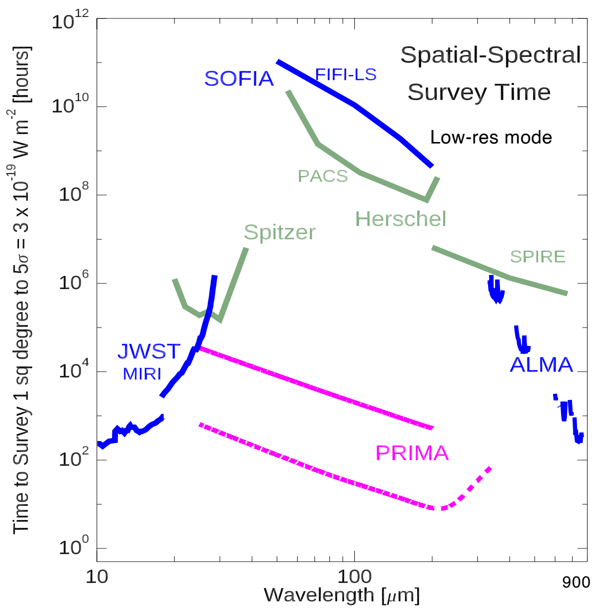
PRIMA-S Wideband Multi-Mode Spectrometer





Preliminary Performance Estimates

High-Res mode will have comparable sensitivity and full spectral coverage with R~3000-5000 at 100 microns

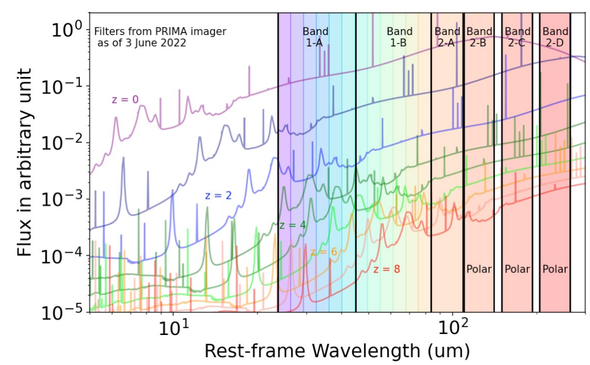


PRIMA-I: Multiband Spectro-photometric Imaging and Polarimetry

Imager provided by European consortium led by CNES and SRON.
D. Burgarella, L. Ciesla, W. Jellema leads

Preliminary Specifications

- R~10 at 25 to 80 microns in two 2x2 arcmin arrays. (12 filter bands)
- R~4 in four longer wavelength bands (each 2x2 arcmin), 3 w/ polarimetry.



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

Contact with questions:
Denis Burgarella (LAM Marseille) denis.burgarella@lam.fr
Laure Ciesla (LAM Marseille) laure.ciesla@lam.fr
Willem Jellema (SRON) W.Jellema@sron.nl

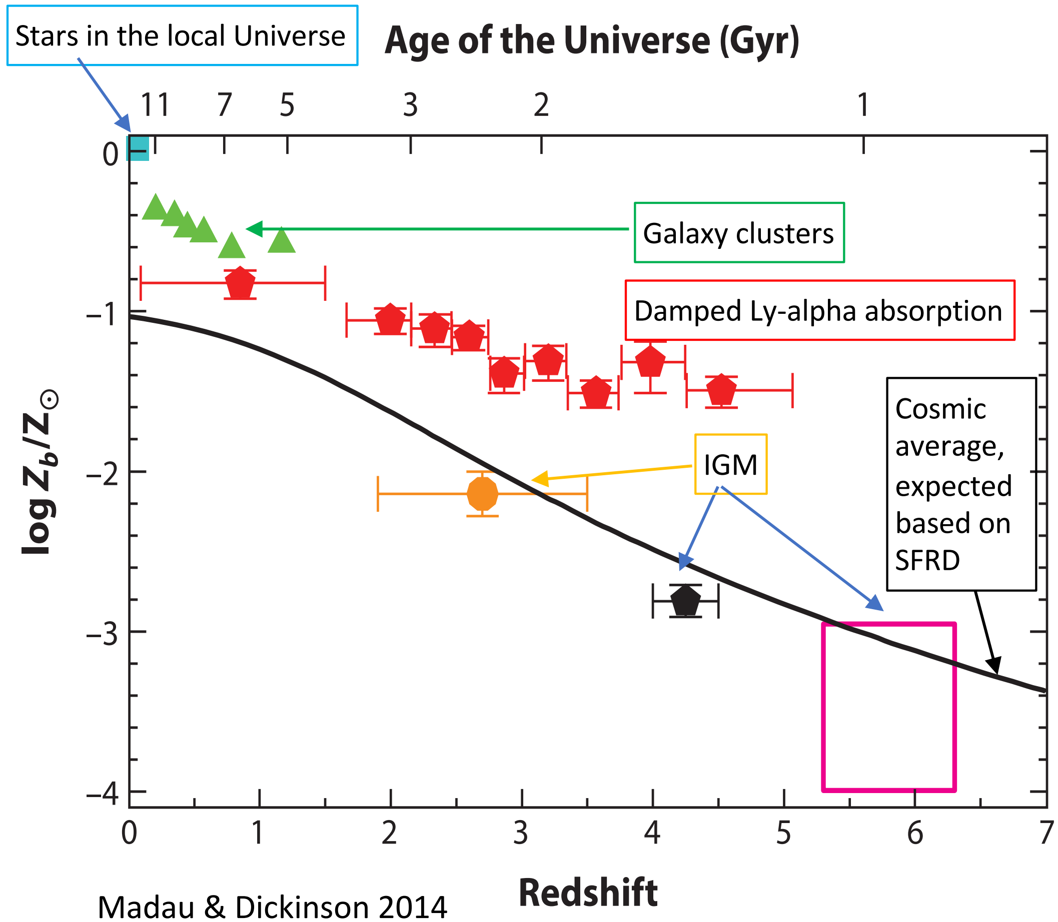
Complete Census of Heavy Elements in the Universe

Galaxies, though a small fraction of the 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, and regardless of dust, suffer from degeneracies with temperature (ionization state).

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



Madau & Dickinson 2014

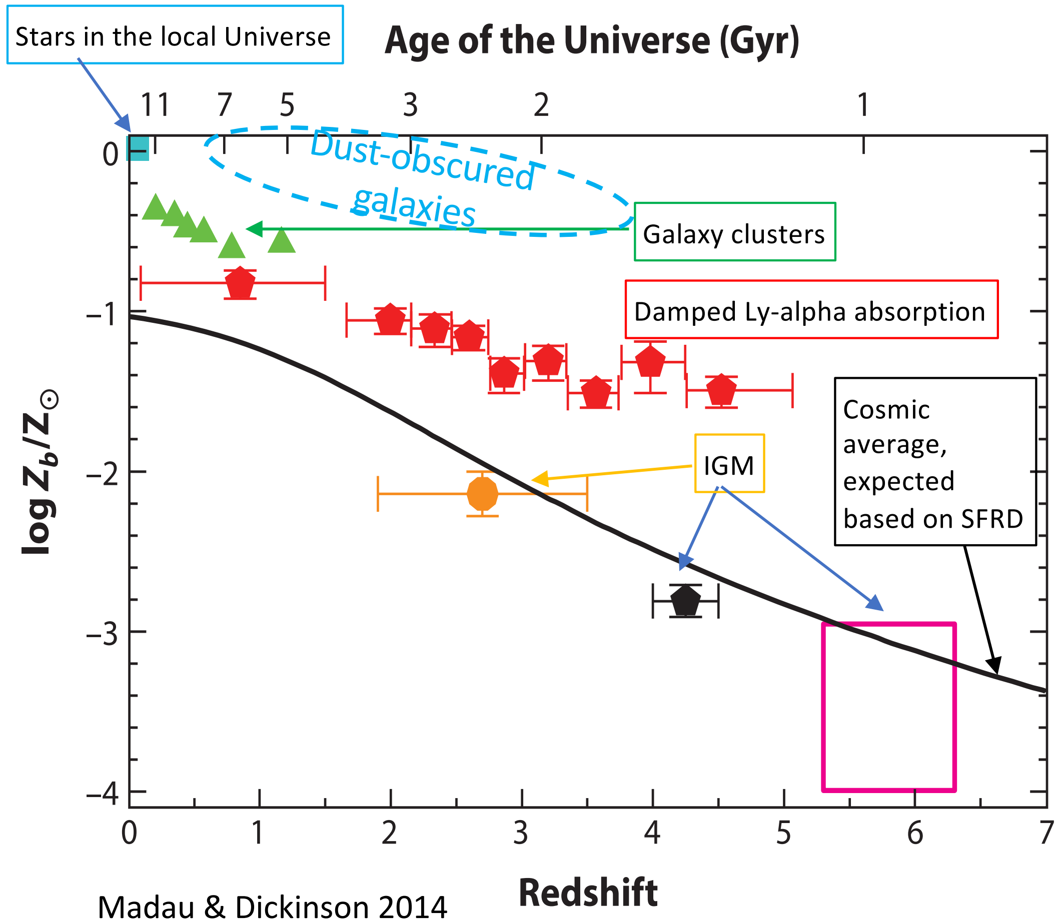
Complete Census of Heavy Elements in the Universe

Galaxies, though a small fraction of the 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, and regardless of dust, suffer from degeneracies with temperature (ionization state).

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

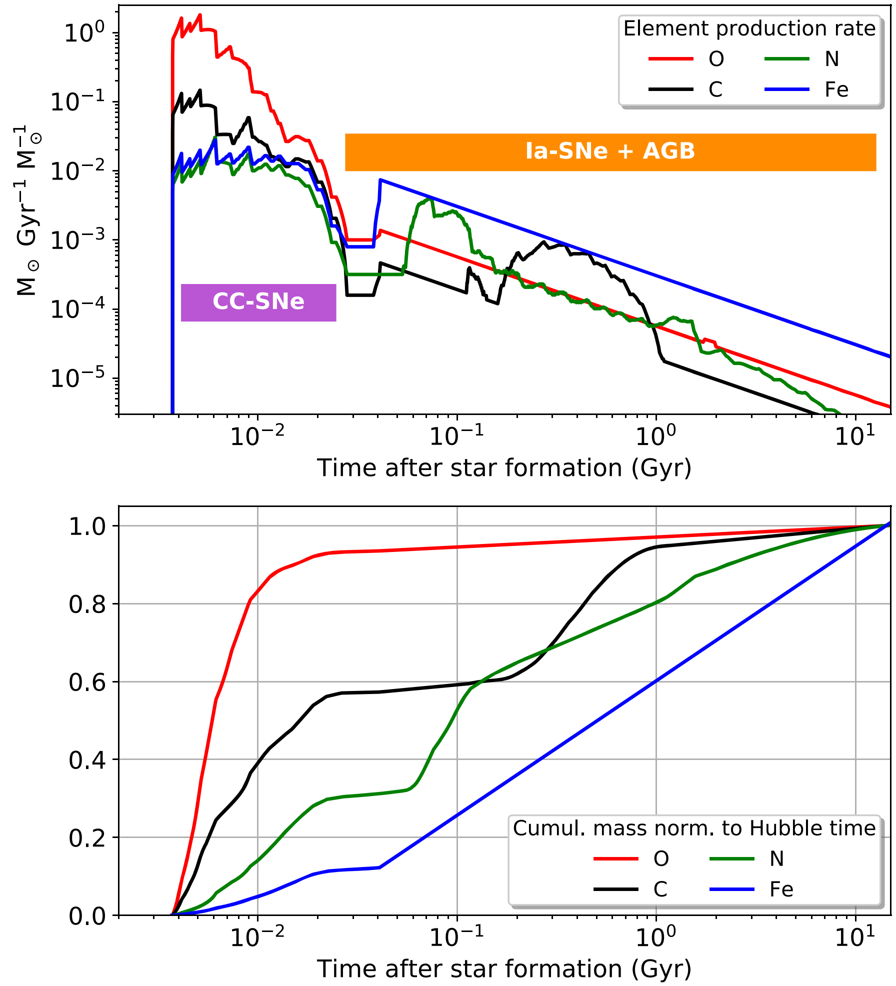


Madau & Dickinson 2014

Nucleosynthesis History via O, N Fine-Structure Transitions

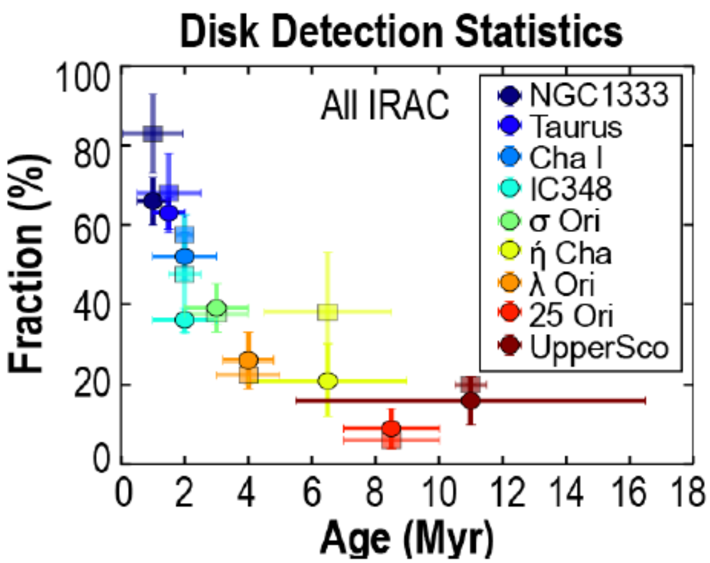
Absolute metallicities not well measured in dusty galaxies.   Use far-IR lines to access the bulk.

- Nitrogen is special as a secondary nucleosynthesis product. Comes on later in the arc of stellar processing.
- O/N ratio thus measures stellar processing, a proxy for metallicity. E.g. Pilyugin + 2014
- OIII and NIII fine-structure lines share ionization state dependence.
- Far-IR lines are both dust-immune and temperature insensitive.
- Form density independent O3N3 diagnostic with 2 OIII lines and one NIII line. Nagao+ '07, Periera-Santella+ 2013
- Added calibration of N/O ratio as a function of metallicity in local (relatively unextincted) galaxies with Sloan. Find 0.1 dex scatter. (JD Smith)

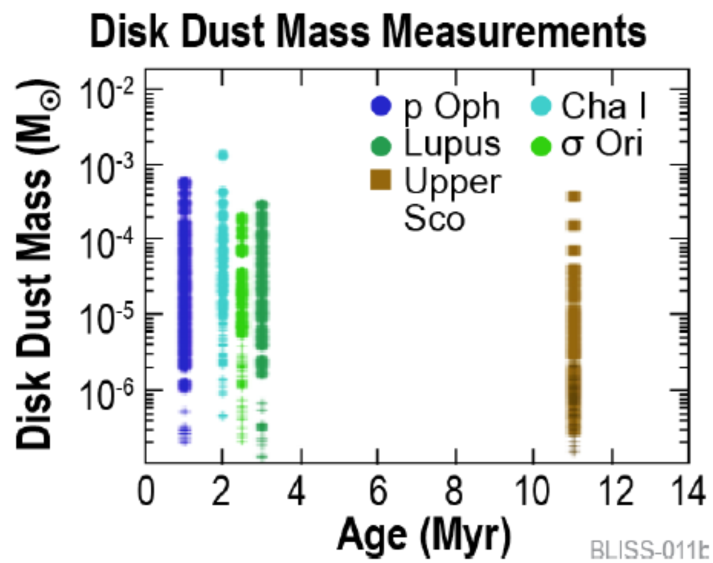


Model of elemental yields, Vincenzo et al., 2019

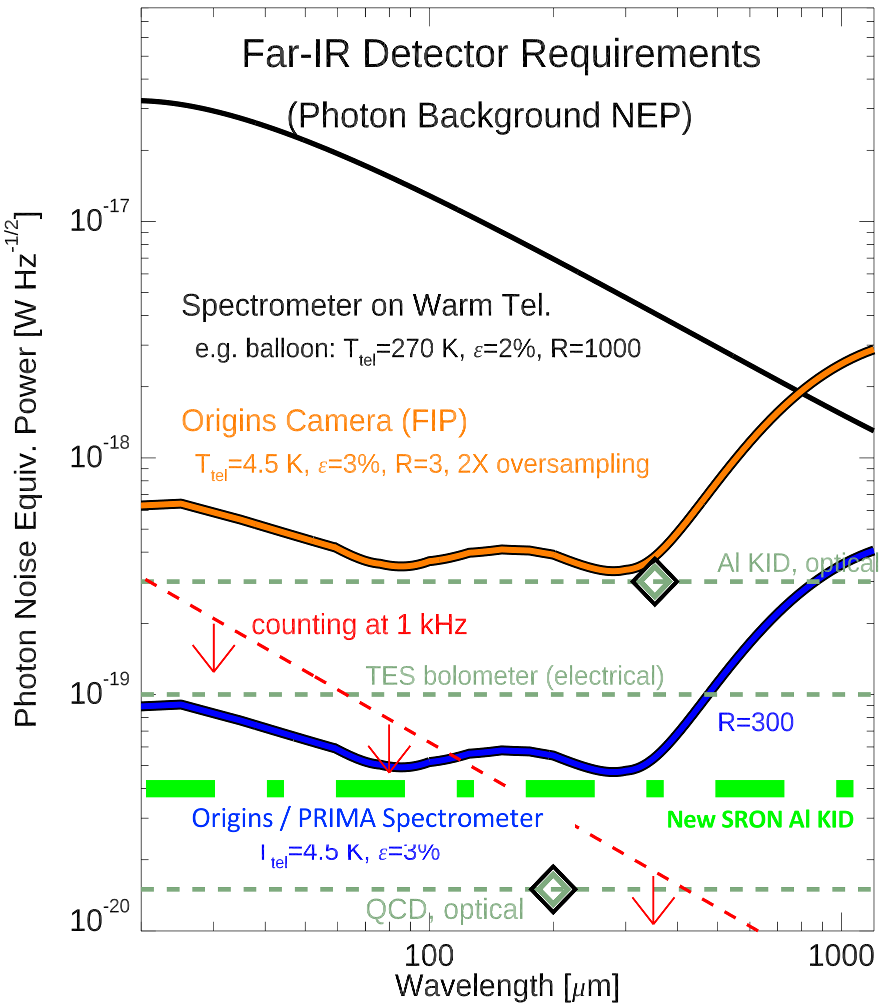
Origin of Planetary Systems and Water Transport to the Habitable Zone



Left: Fraction of stars with detected IR excesses in various star formation sites as a function of age. (Ribas et al. 2014).
Suggests some evolution / dispersal, but maybe just inner disk?



ALMA dust mass (compiled from archive by Ted Bergin). This serves as ballpark gas mass estimate when multiplied by the typical ISM gas to dust ratio of 100.
True gas mass unknown by orders of magnitude.



Detectors for the Far-IR

Far-IR detectors and readouts must be built by the science community. We have been working steadily for 2 decades.

Investment is paying off

Format

- KIDs now being fielded in arrays of several thousand in ground-based and balloon-borne missions.

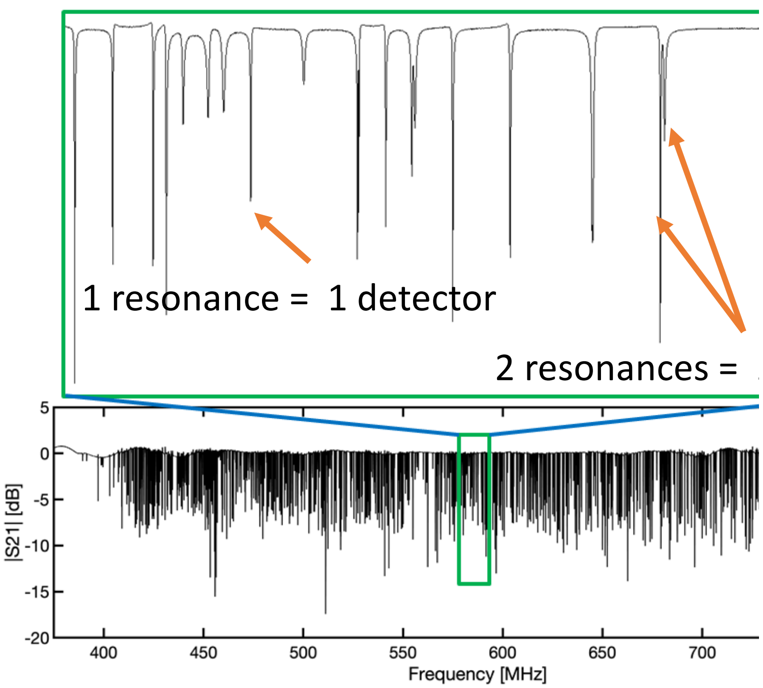
Sensitivity

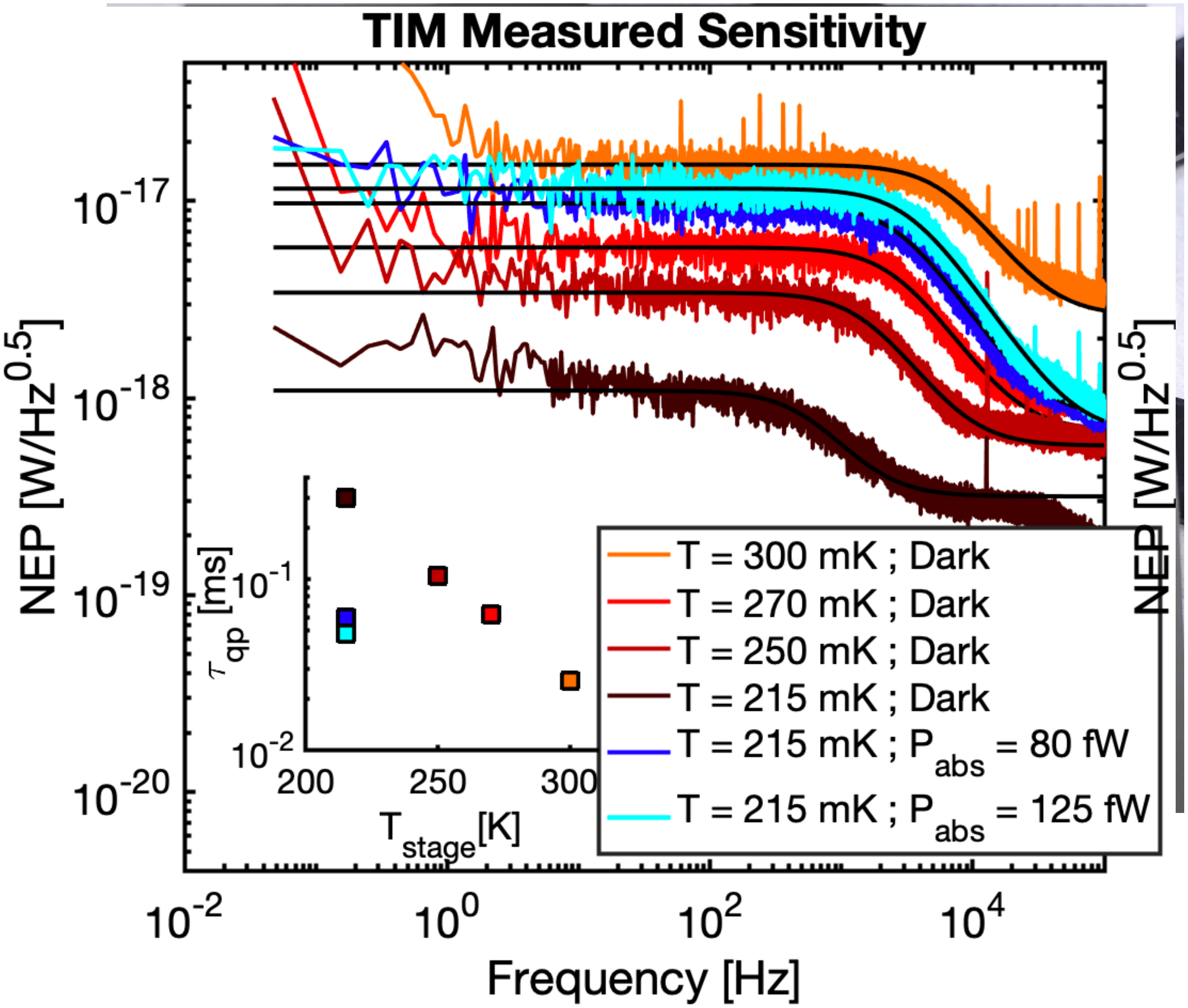
- Sensitivities for spectroscopy with Origins or PRIMA have now been demonstrated in multiple devices, compatible with the same readout / multiplexing as the ground/suborbital demonstrations.

We are ready to build our Probe.

TIM KID Array

Easily meets sensitivity needs of balloon platform.

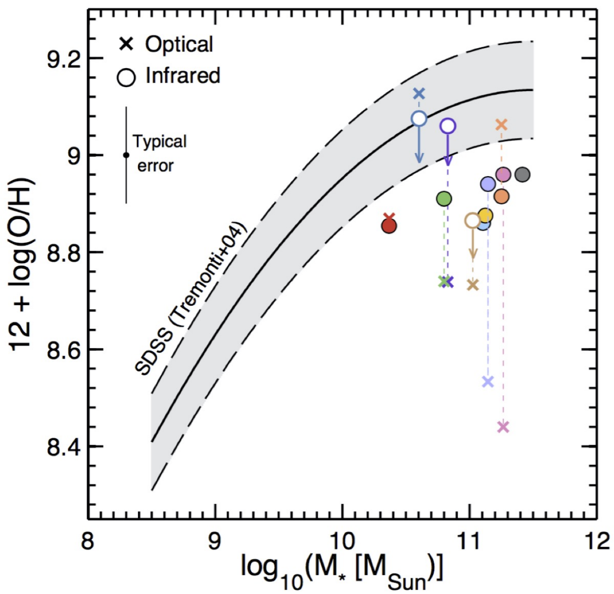




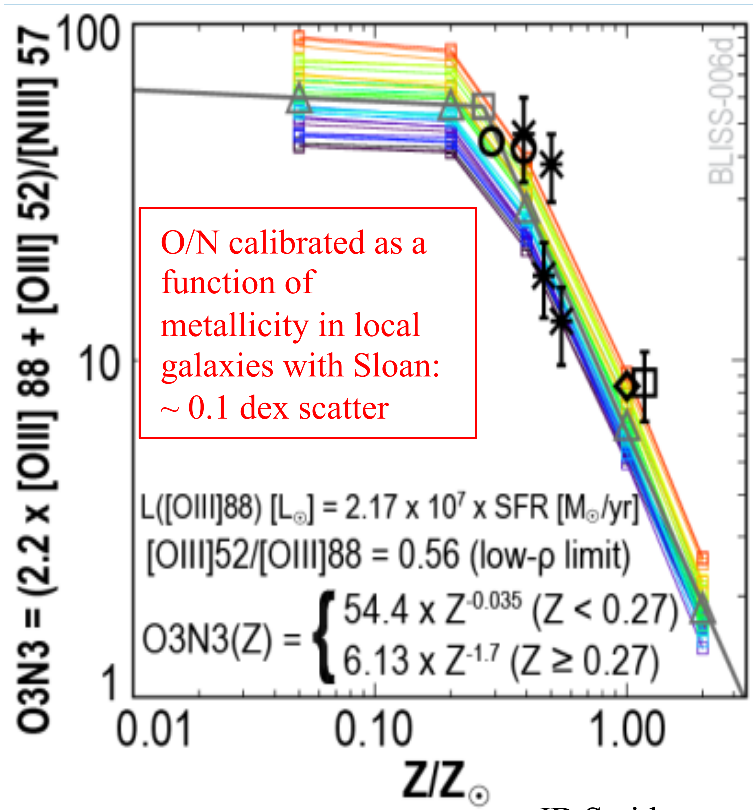
Reinier Janssen et al. @ JPL / Caltech

Charting Nucleosynthesis Where It Happens

Most SF at Cosmic Noon happens in high extinction regions → use extinction-free far-IR lines!



Herrera-Camus (2018) SHINING results



JD Smith

$0 \leq z \leq 1.2$

- 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

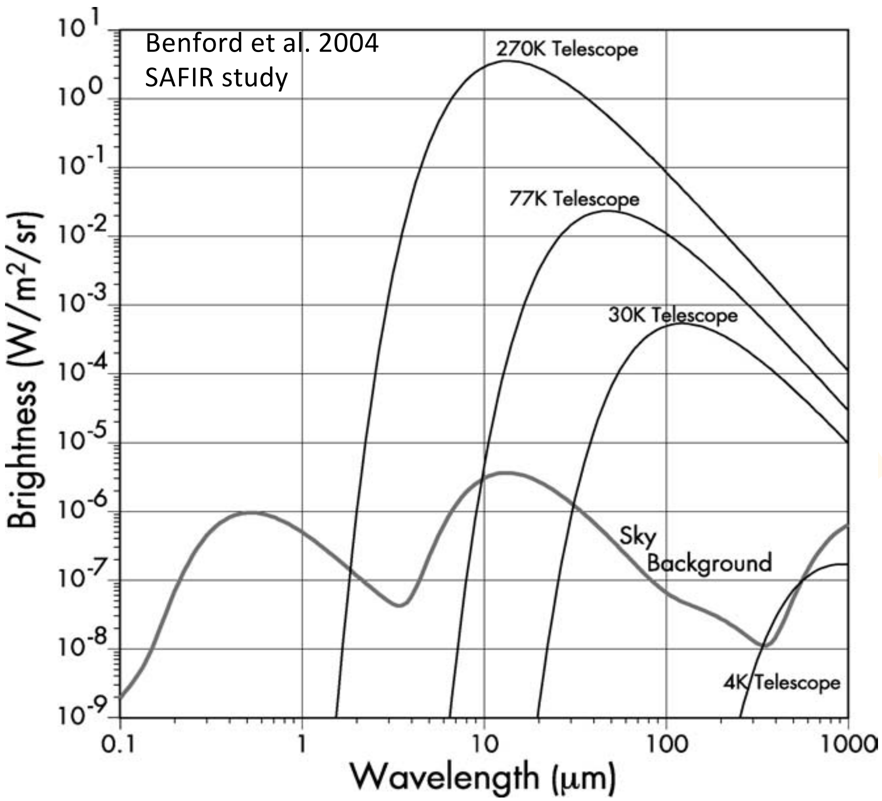
➢ Density-independent O3N3 diagnostic (2 OIII lines, 1 NIII line; Nagao et al. 07, Periera-Santella, et al. 2013)

$1.5 \leq z \leq 3$

- 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)

Cryogenic telescope is a powerful opportunity



Comparing low-emissivity 300 K system to zodiacal light background is about a factor of 1 million, e.g. at 60 microns. Sensitivity is the square root of brightness, speed is this ratio.

Daytime to darkest 20% at Mauna Kea: V-band brightness ratio is 30 million