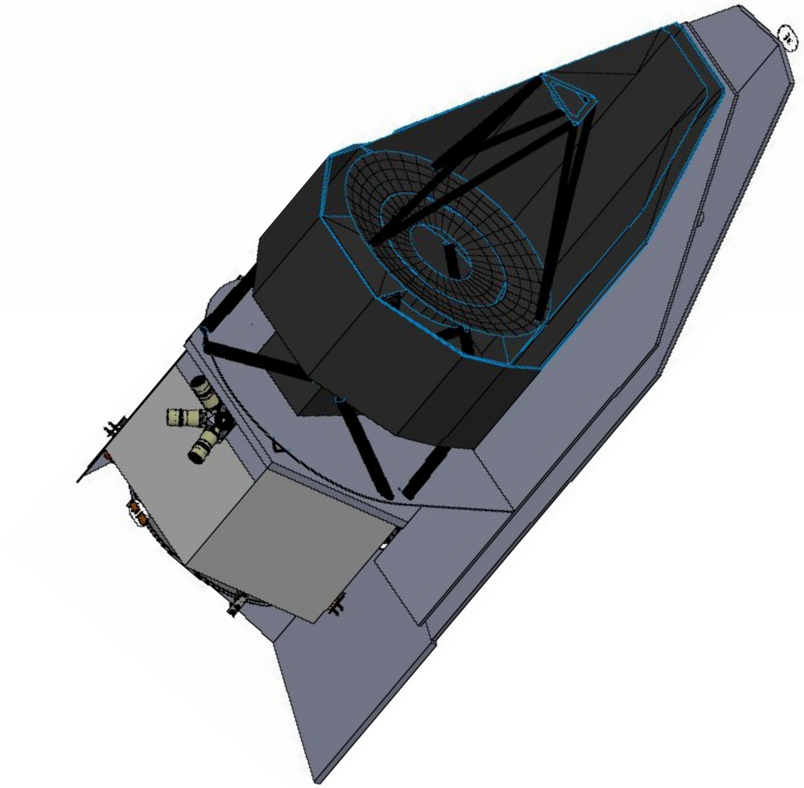
PRIMA: the Probe far-Infrared Mission for Astrophysics

Jason Glenn, Principal Investigator, GSFC

On behalf of the amazing PRIMA team

November 16, 2022



University of Maryland Astronomy
Department colloquium

PRIMA Core Science Leadership Team

Who to talk to if you want to get involved

PI: Jason Glenn, Goddard
Acting Deputy PI and PS: Matt Bradford, JPL
Science Lead: Alexandra Pope, UMass

Cycling Through Cosmic Ecosystems

Lee Armus	IPAC
Alberto Bolatto	UMD
Betsy Mills	KU

How Stars and Planets Get Their Mass

Cara Battersby	Uconn
Klaus Pontopiddan	STScI

Guest Observer Science & Community Engagement

Tiffany Kataria	JPL
Margaret Meixner	USRA Arielle
Moullet	USRA

Rise of Dust and Metals in Galaxies

JD Smith	U Toledo
Brandon Hensley	Princeton

Other Co-Is

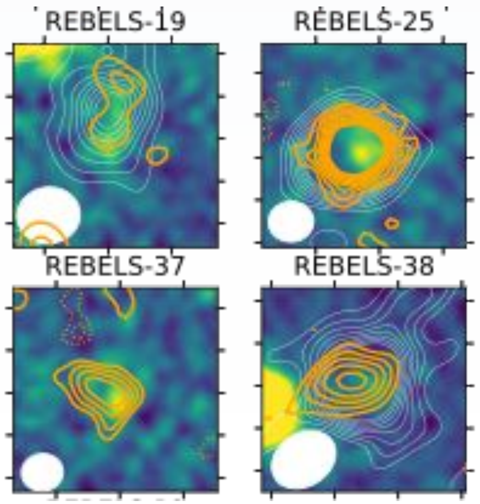
Jochem Baselmans	SRON
Denis Burgarella	LAM
Laure Ciesla	LAM
Willem Jellema	SRON
Rachel Somerville	Flatiron Inst.
Johannes Staguhn	JHU & GSFC

+ strong formulation and engineering support at JPL and Goddard

The origins of the rich universe we see today

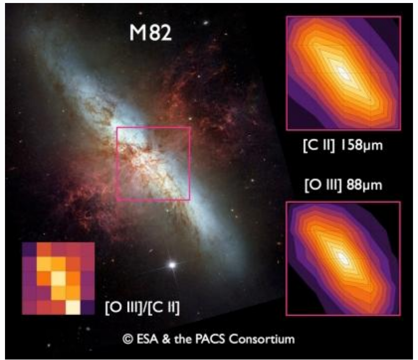
Stars, planets, and galaxies filled with metals, molecules, and dust

Galaxies formed early and began making stars and dust, obscuring their own origins



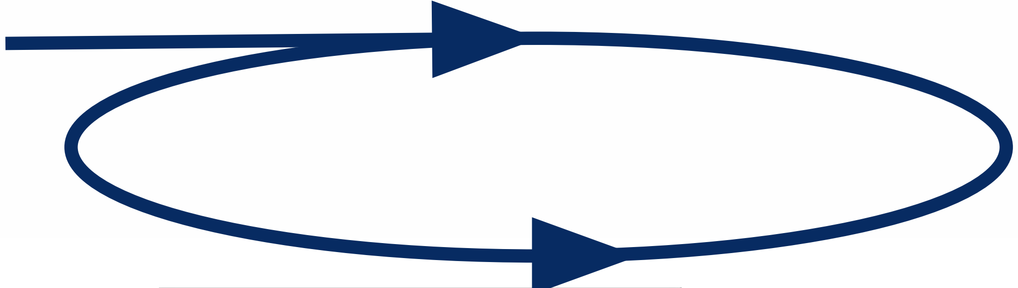
Inami et al. 2022

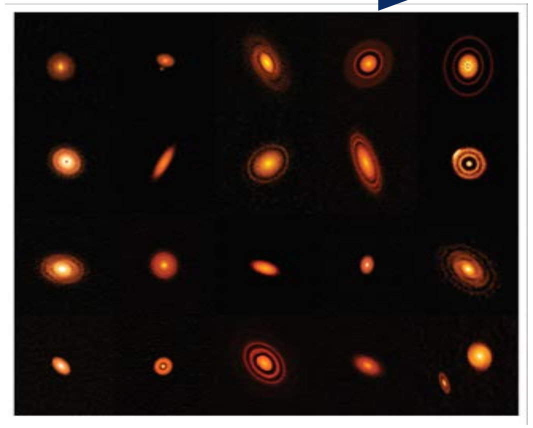
Gas cycled into, through, and out of galaxies that regulated their own masses



Cloud collapse and star formation were fueled by infall and mergers, further enriching ISM

ESA/SPIRE/PACS
P. Andre





S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello

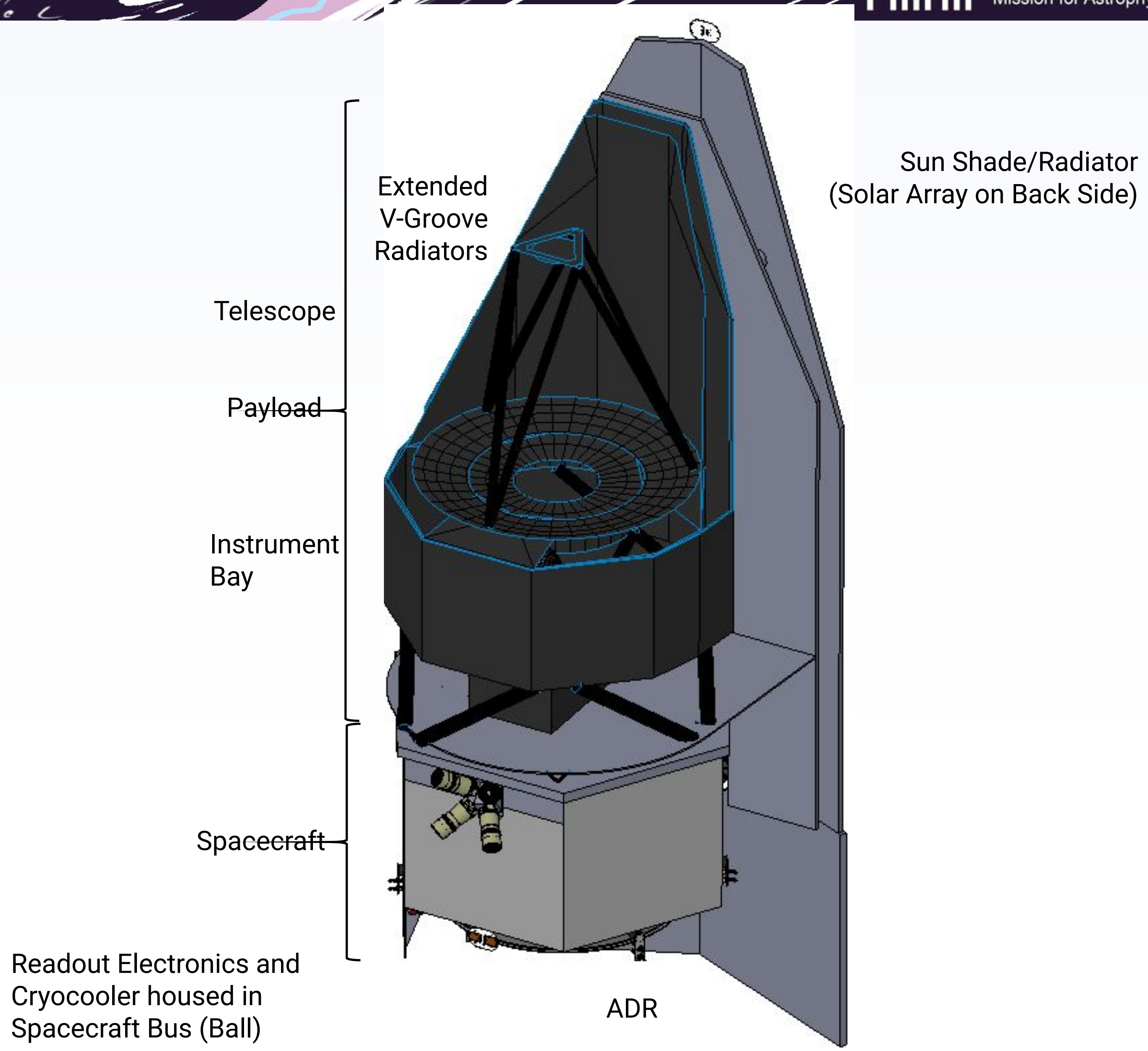
Planets formed in disks with gas, dust, minerals, and water that are the seeds of planets and their atmospheres

> *We are made of star stuff.*
> – Carl Sagan

What Is PRIMA?

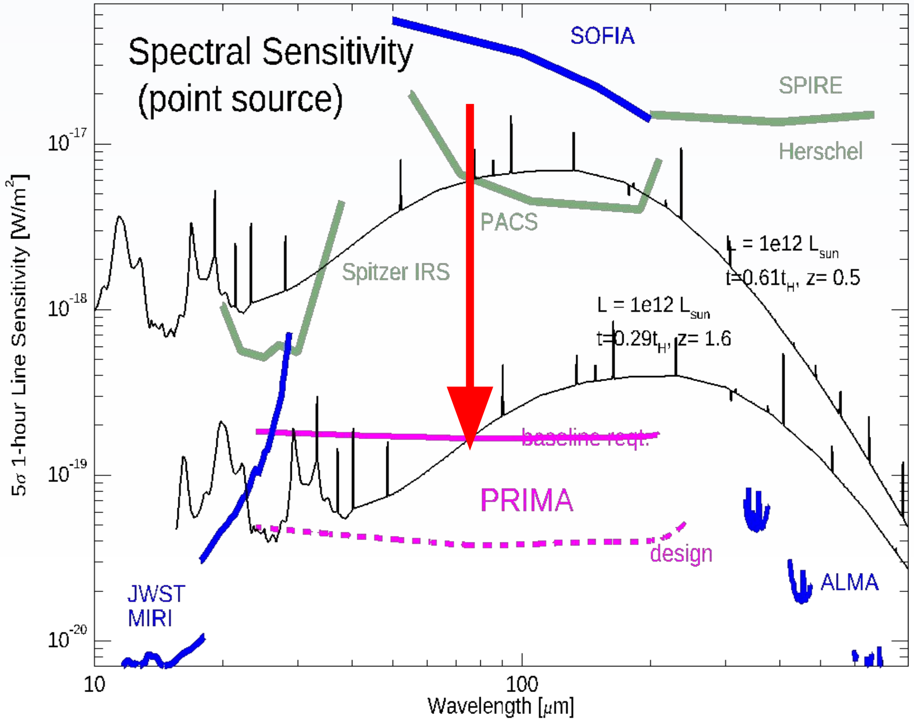
Payload		
Instruments		
	Telescope	2.0 m all-aluminum on-axis telescope, cooled to 4.5 K
	Spectrometer	4 gratings, small-volume KIDs, 100 mK, 24-230 µm, R = 170
	Imager	Foreign-contributed PRIMAGER - 100mK, 25-264 µm, narrow short-wave bands
	FTS	High resolution mode: R = 4,400 @ 112 µm
Active / Passive Thermal		
	Active	Cryocooler & ADR for the focal planes
	Passive	V-groove radiators & sun-shade

≥ 70% of PRIMA observing time will for Guest Observers over planned 5 year lifetime



Filling a wavelength gap with major sensitivity gain

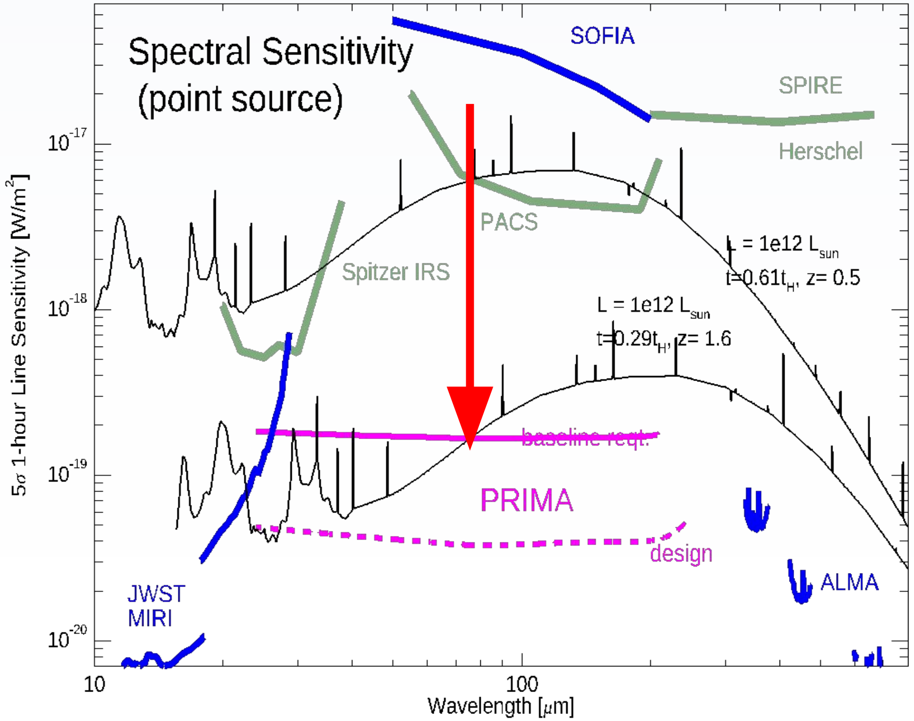
Pointed observations, low-res mode



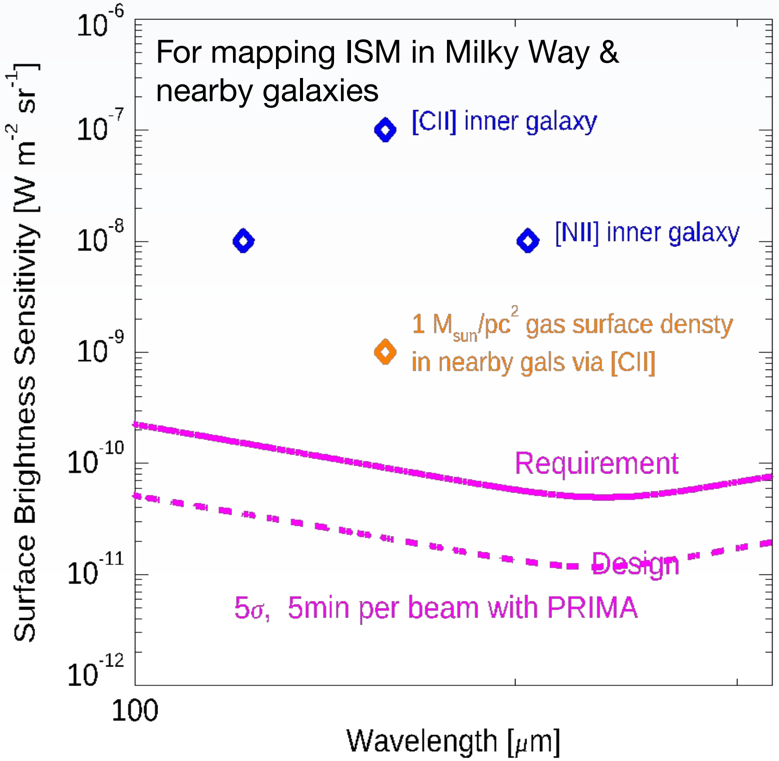
High-Res mode (FTS) will have comparable sensitivity and full spectral coverage with R ~ 4,400 at 112 μm

Filling a wavelength gap with major sensitivity gain

Pointed observations, low-res mode



Surface brightness sensitivity



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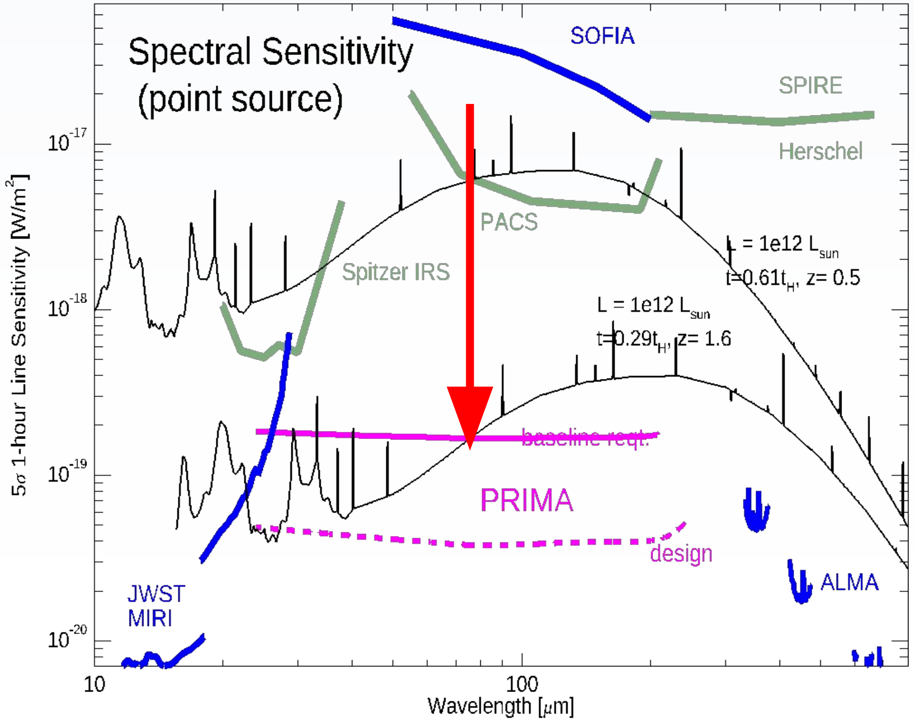

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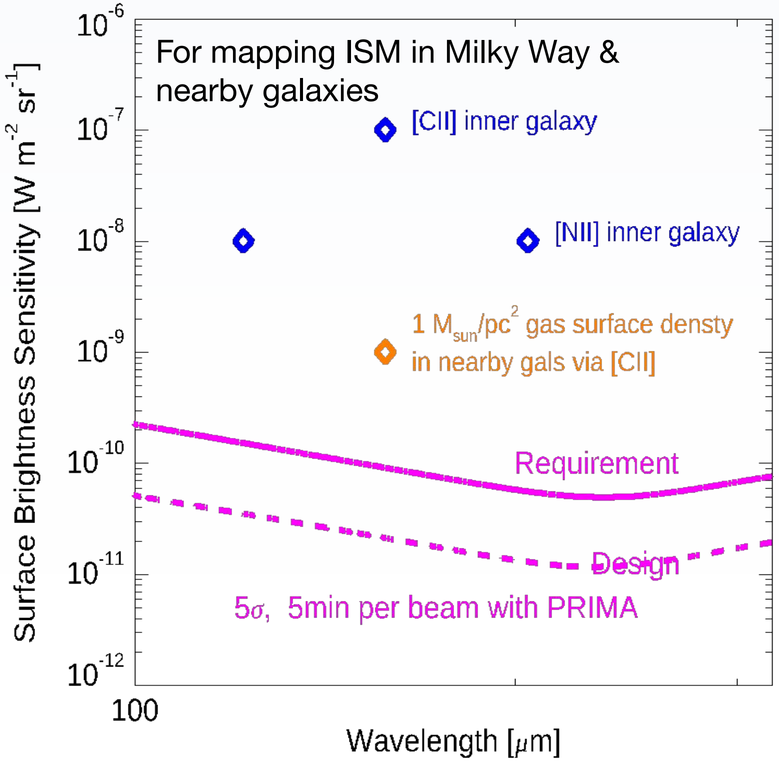
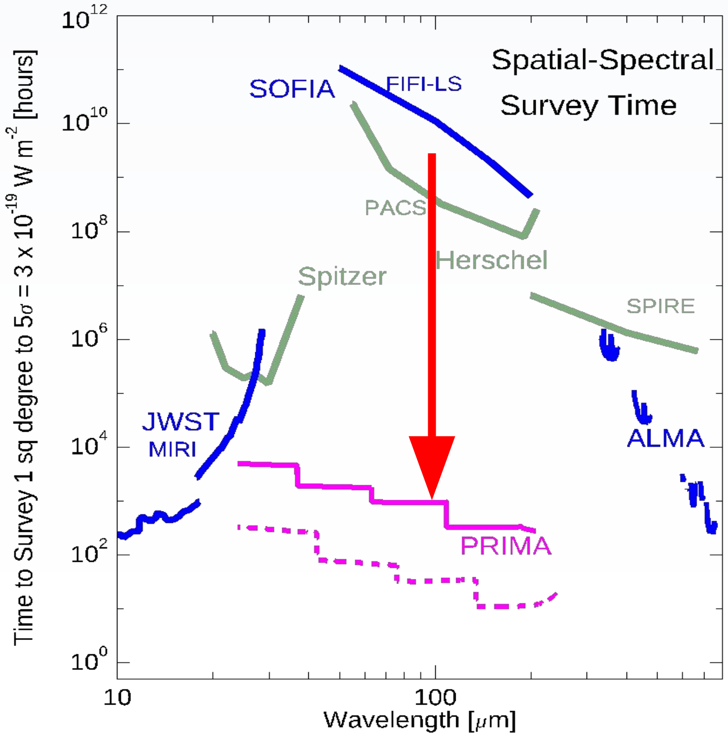


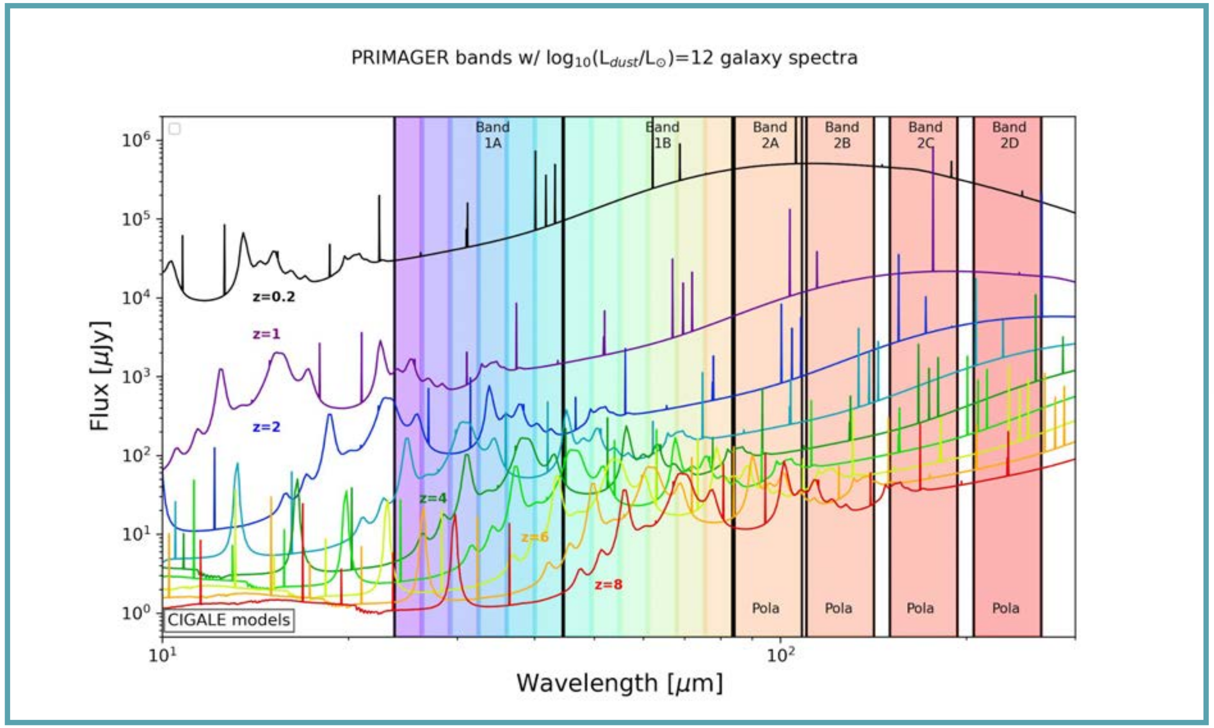
Spectral Mapping Speed



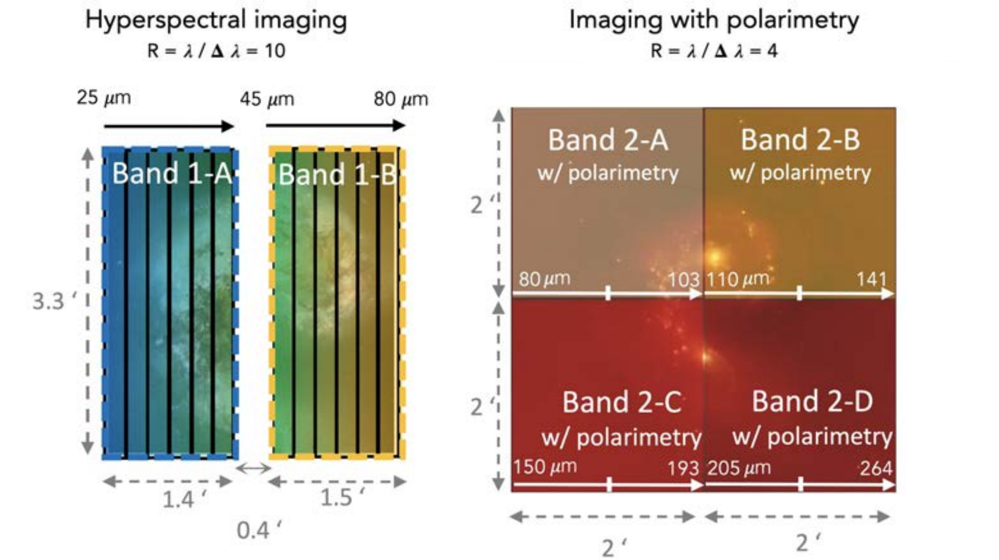
High-Res mode (FTS) will have comparable sensitivity and full spectral coverage with R ~ 4,400 at 112 μm

PRIMAger

Parameters	Hyperspectral - Band 1 (A, B)	Polarimeter - Band 2 (A, B, C, D)
Wavelength range	**25-80 microns** in 2 bands of 6 filters	**80-264 microns** in 4 broad band filters
Polarization	No	Yes (bands 2A, 2B, 2C, 2D)
Resolution	R=10	R=4



Bands definition

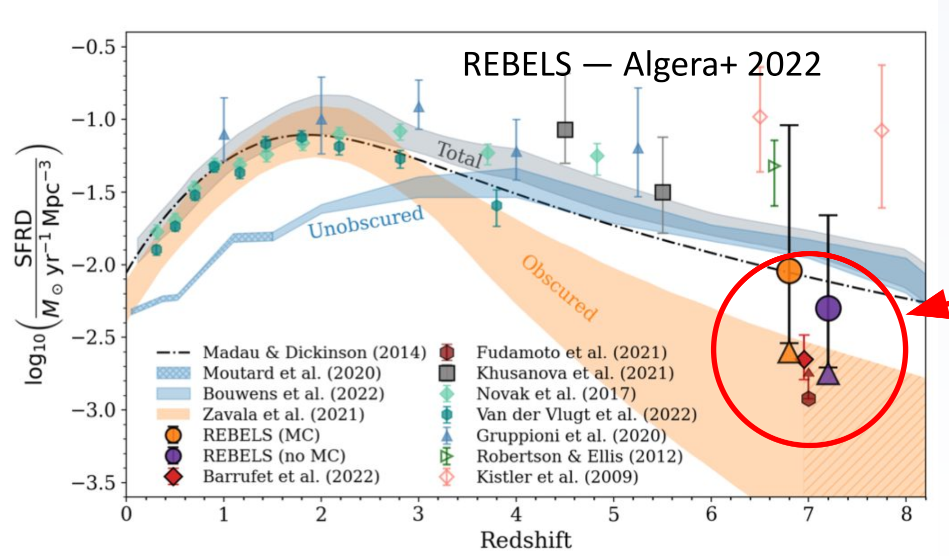


- Band 1A: 6 contiguous filters 25-45 microns
- Band 2A: 6 contiguous filters 45-80 microns
- Band 2: 4 broad band filters with polarimetry

Rise of Dust and Metals in Galaxies

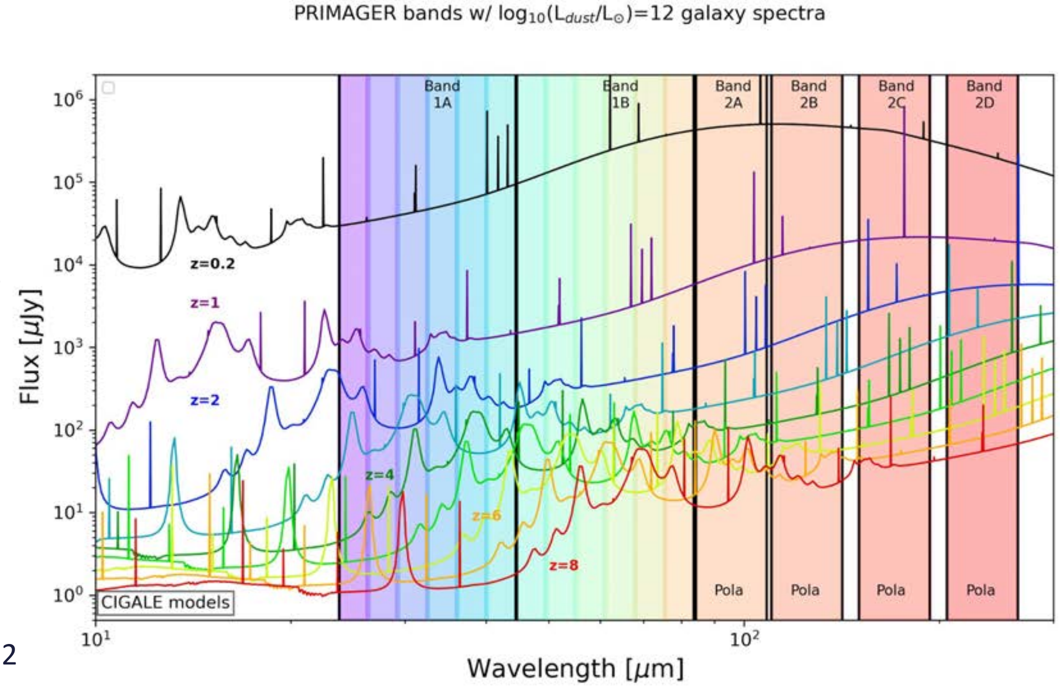
When did dust build up in galaxies?

- Heavy elements in the solid phase:
    - Control molecule formation
    - Mediate energy transport through the ISM and the star formation process
    - Trace metal content in galaxies
    - PRIMA will measure dust content, conditions and composition + solid metal content galaxies and reveal the emergence of the first small grains and organic hydrocarbons in the Universe

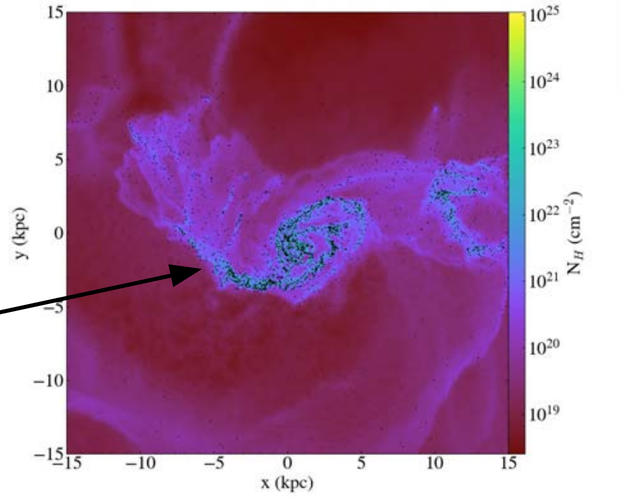


ALMA: dust-obscured star formation by z = 7!

Hyperspectral imaging and moderate-R spectroscopy: well matched to PAH emission for z = 1 – 7


PRIMAGER bands w/ $\log_{10}(L_{dust}/L_\odot)$=12 galaxy spectra

Small grain evolution: a key new development area in cosmological simulations



PAH Strength

Rise of Dust and Metals in Galaxies

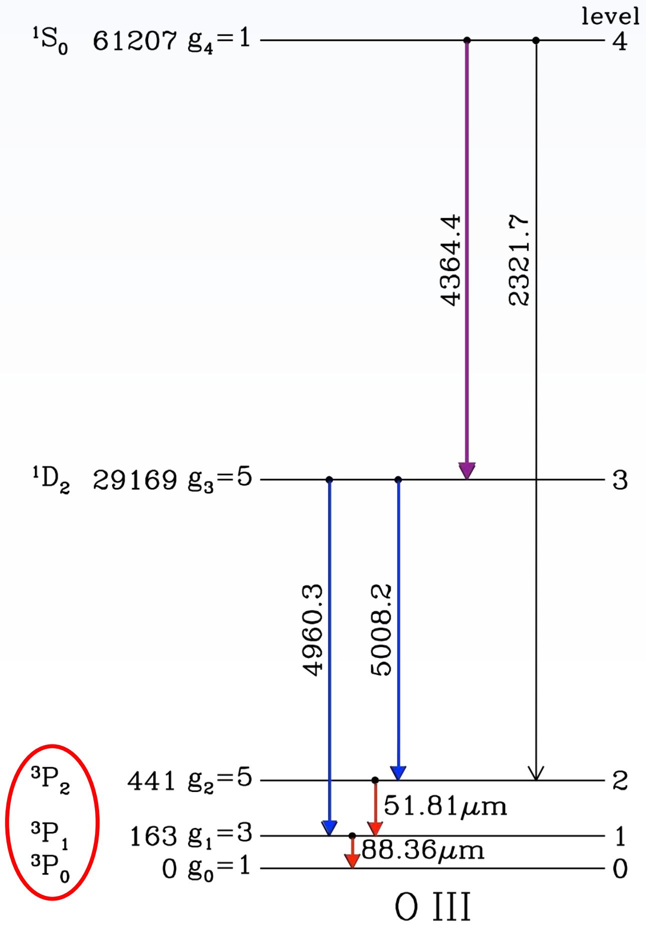
Beyond stellar mass and black hole assembly, the *chemical enrichment history of the Universe* is the next great challenge

Optical abundance issues

- Strong temperature sensitivity
- Bias from heavy extinction in obscured sources at cosmic noon that host most star formation

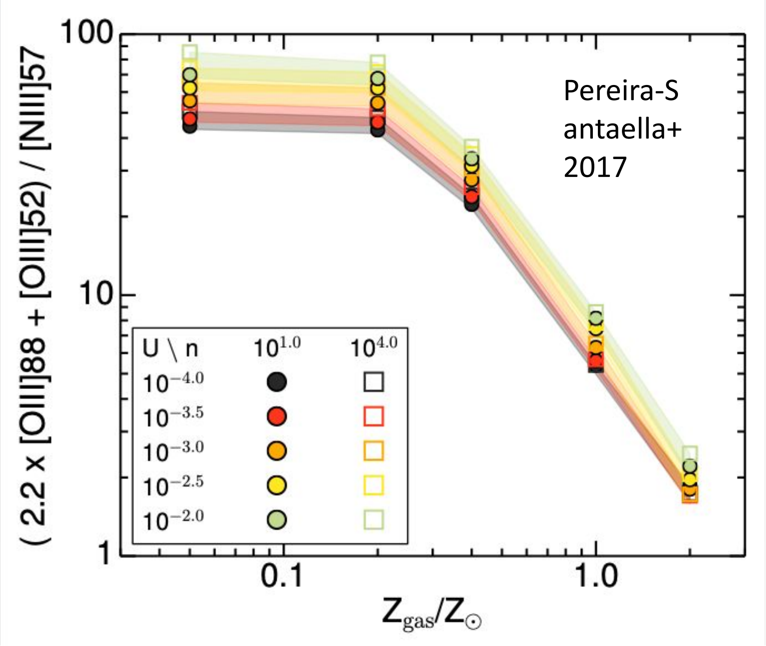
PRIMA far-IR abundances: temperature insensitive and low extinction

- [O III] in thousands of galaxies z = 0 – 3.5
- [Ne III] / [Ne II] ionization tracers and NGVLA free-free continuum for direct O abundances
- [N III] / [O III] relative abundances as a measure of stellar processing
- Temperature-corrected hybrid optical/far-IR abundances in thousands of Roman / JWST galaxies



Temperature insensitive

Metallicity relation calibrated locally with *Spitzer*



Rise of Dust and Metals in Galaxies

How does dust evolve in the ISM?
Do All Dust Grains Look the Same?

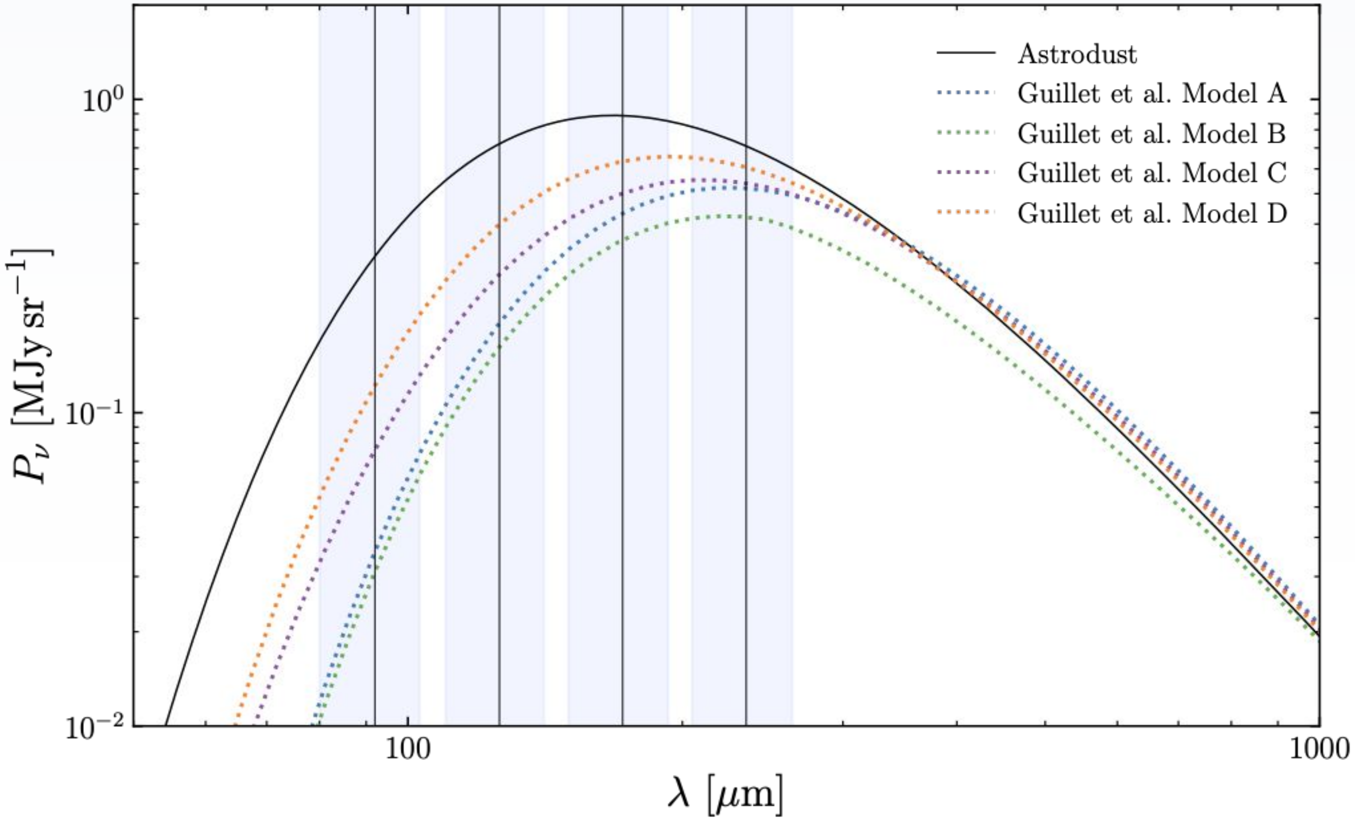
How does the composition of dust change with metallicity, star formation history, galactocentric radius…?

- **Weak polarization near SED peak** if there are carbonaceous and silicate dust populations; the polarized intensity will have a different SED than total intensity
- **Strong polarization near SED peak** and same P_ν and T SEDs for single composition models
- Measurements near SED peak where temperature effects are non-linear – separate components by different temperatures

Survey of LMC

- Range of environments
- Access scales down to 5 pc
- Compare to Galactic regions

PRIMA Polarimetry Bands

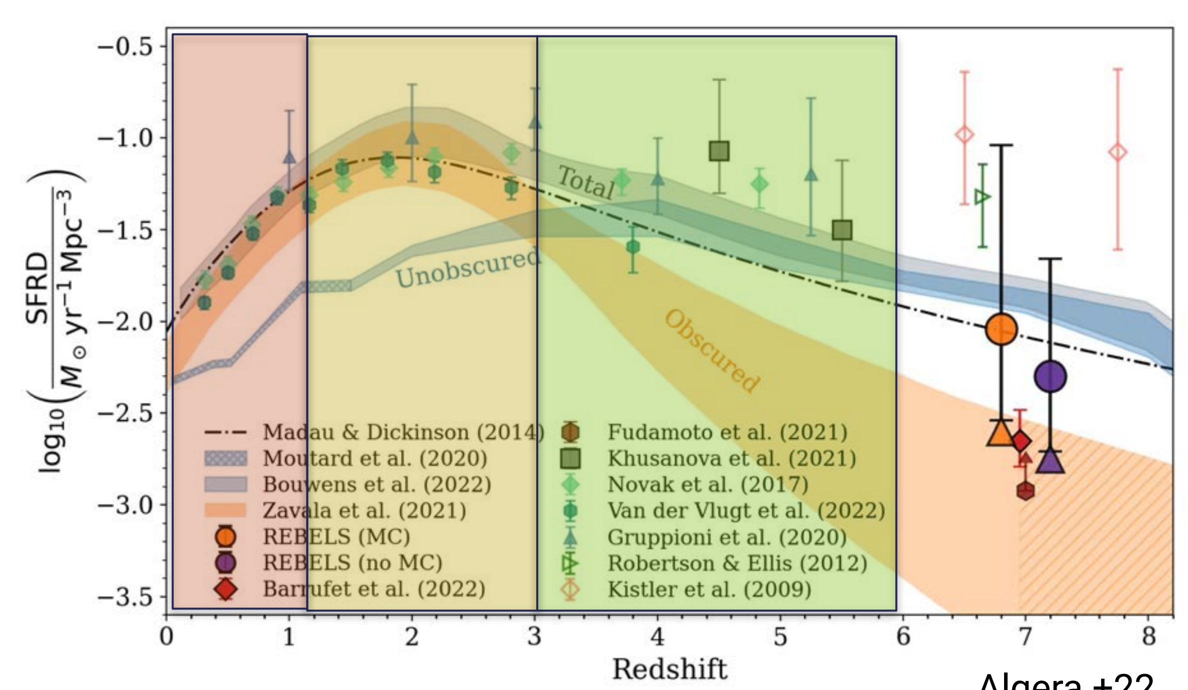


Comparison of some one-component (solid) vs two-component (dotted) models of dust that agree in the mm but diverge sharply in the far-IR

Cycling Through Cosmic Ecosystems

Some context: What we know about the star formation history of the Universe

- From EoR to Cosmic noon - the rise to the peak in the average SFRD and BHARD
- Rapid SF and BH Growth @ Cosmic Noon – starbursts, accretion, rise of metals
- Galactic sunset - the last 10 billion years –quenching star formation and establishment of key local scaling relations (e.g., mass-metallicity, SMBH-bulge mass)

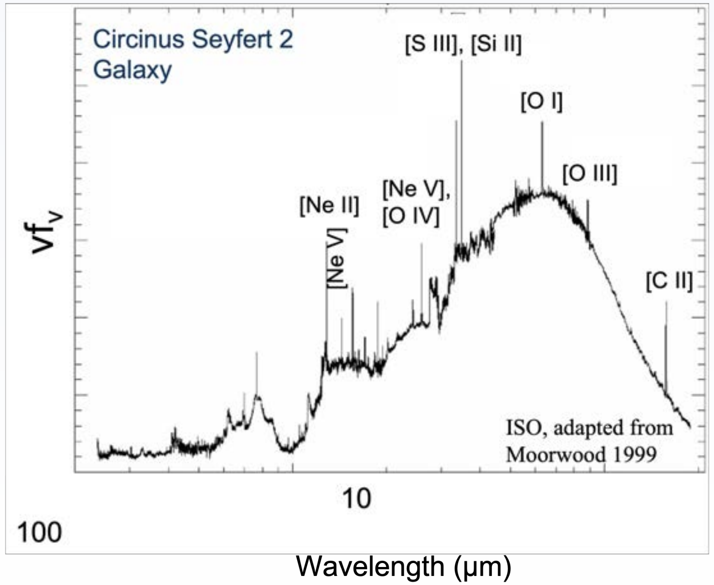


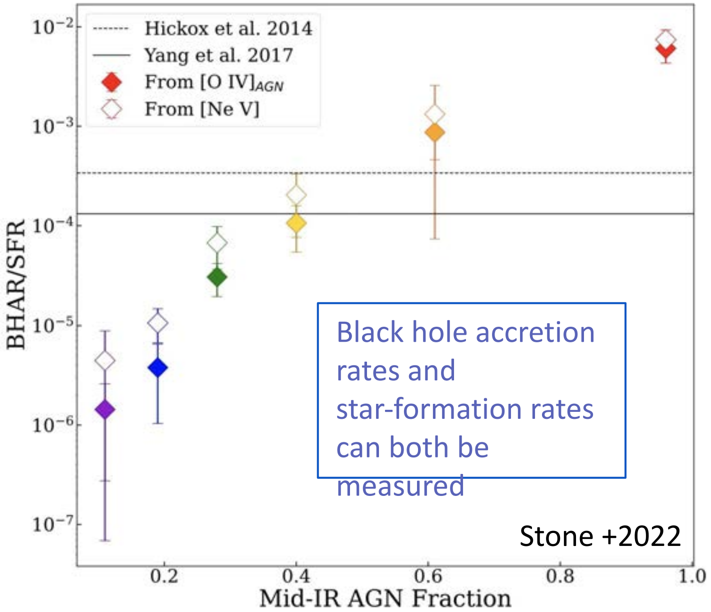
Algera +22

Cycling Through Cosmic Ecosystems

How did supermassive black holes form and how is their growth coupled to the evolution of their galaxies?

- Most galaxies contain highly obscured starbursts at z ~ 1 - 3
    - Establish the BH accretion rate (BHAR) in the presence of abundant star formation
- Rest-frame mid-IR and far-IR provide direct tracers of SFR: accurate map of the co-evolution of galaxies and SMBH – unique to IR
    - IR transitions are robust to extinction and can directly trace SMBH accretion rates (Gruppioni +16)
    - [Ne V] is only produced in AGN
    - [OIV] is much brighter but has a contribution from SF at low AGN fractions. This has been calibrated through observation of low-ionization [Ne II] and [Ne III] lines (Stone +22).





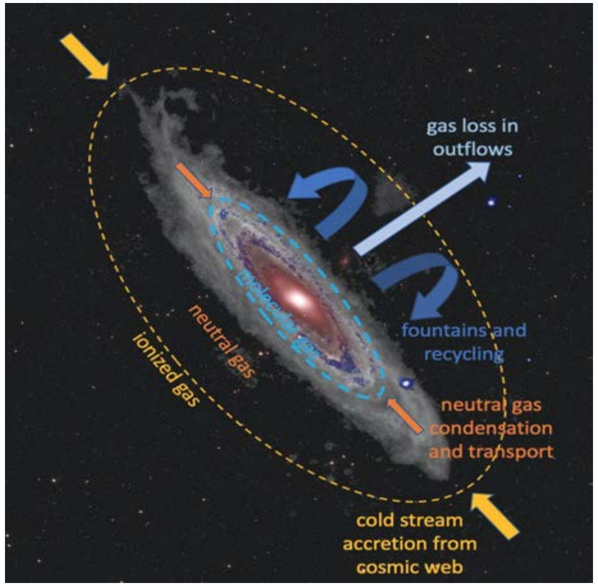
Black hole accretion rates and star-formation rates can both be measured

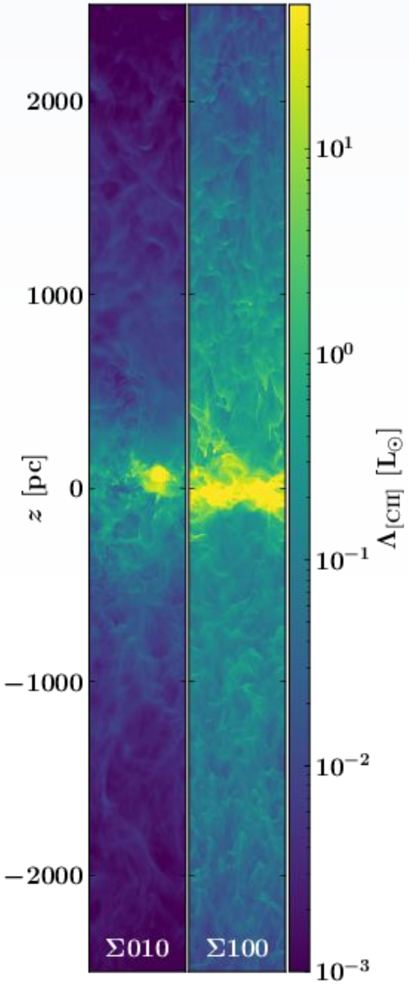
Stone +2022

Cycling Through Cosmic Ecosystems

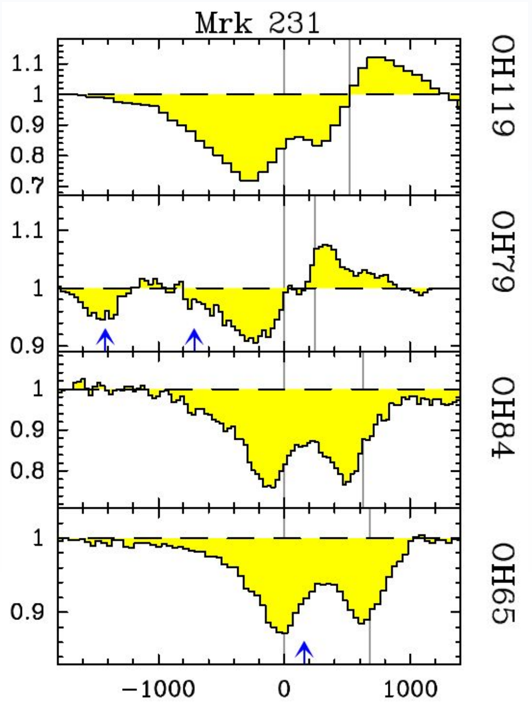
How does gas flow into, through, and out of galaxies?

- Map in-plane and extraplanar gas distribution
  - [CII] in emission – best sensitivity to surface brightness
- Evaluate mass and kinematics of the cool ($T<10^4$ K) phase of galaxy outflows, which dominates the mass budget
  - OH in absorption – unambiguous outflows against bright FIR nucleus
  - Unique to the FIR
  - Only possible before PRIMA for a handful of nearby galaxies





SILCC-zoom [CII] in starburst Ebagezio +2022



Gonzalez-Alfonso +2017

FTS: R = 4,400 ->
Δv = 70 km/s

How Stars and Planets Get Their Mass

How do star-forming structures arise from and interact with the diffuse ISM? What regulates the structure and motions within molecular clouds?

- Extragalactic B-field science has been limited to bright star-forming regions
- With PRIMA sensitivity, can connect magnetic fields in individual molecular clouds to large-scale Galactic fields, bridging the angular scales of CMB experiments and ALMA
- Are GMC magnetic fields aligned with the large-scale field?
- Test roles of magnetic fields in both star formation and galaxy evolution

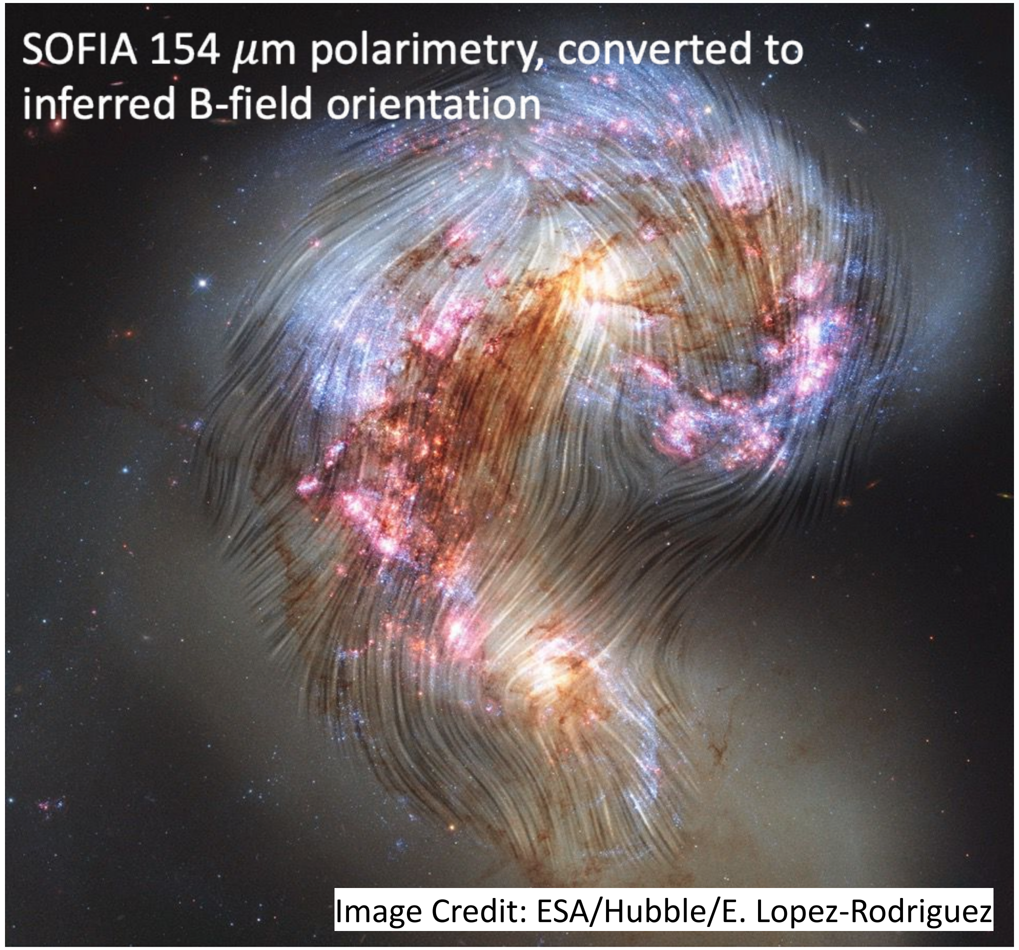
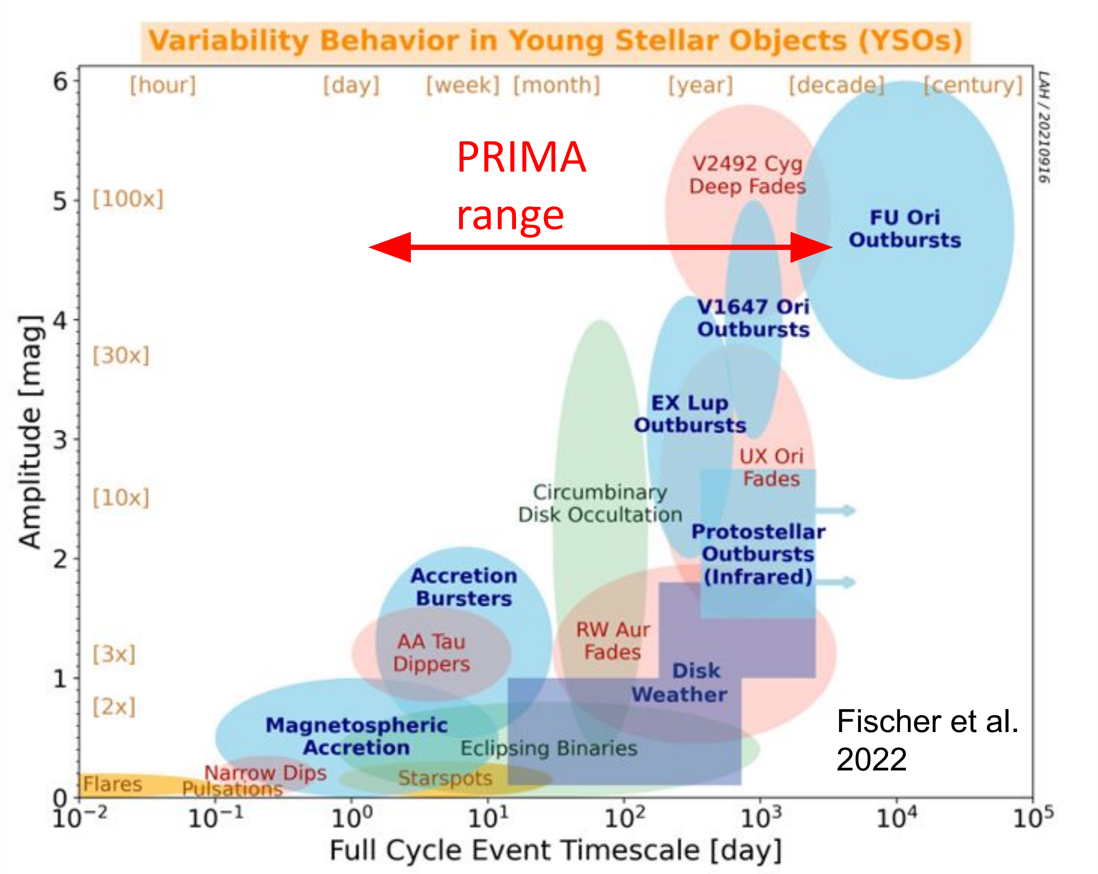


Image Credit: ESA/Hubble/E. Lopez-Rodriguez

How Stars and Planets Get Their Mass

How do protostars accrete from envelopes and disks? What does this imply for protoplanetary disk transport and structure?

- Protostars exhibit a broad range of variability
- The steady-state vs. stochastic mass accretion rates have not been established
- Consequences for growth rate and disk physics
- Requires $\lambda \sim 100\ \mu m$ observations
  - ➢ Optically thin
  - ➢ Probe disks, not predominantly envelopes
- Rare events require many protostars and frequent revisits

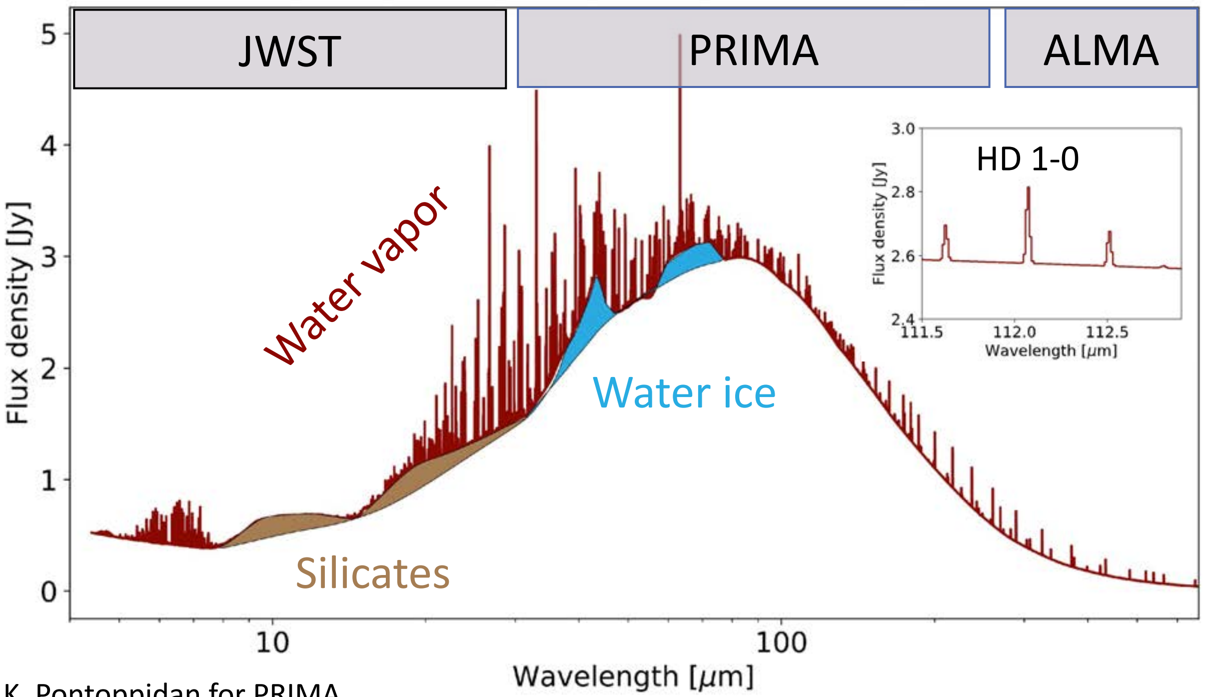


Fischer et al. 2022

How Stars and Planets Get Their Mass

Origins of Planetary Systems and Water Transport to the Habitable Zone

Protoplanetary disk around solar-mass star, rendered at R=5,000



K. Pontoppidan for PRIMA

*A probe can balance resolving power and sensitivity for transformative **surveys** of protoplanetary and debris disks*

Water transport

- Spatial water distribution can be retrieved using many lines across many temperatures.
- Measure both **vapor AND ice**
- Studied as a function of evolution

Planet-forming gas mass

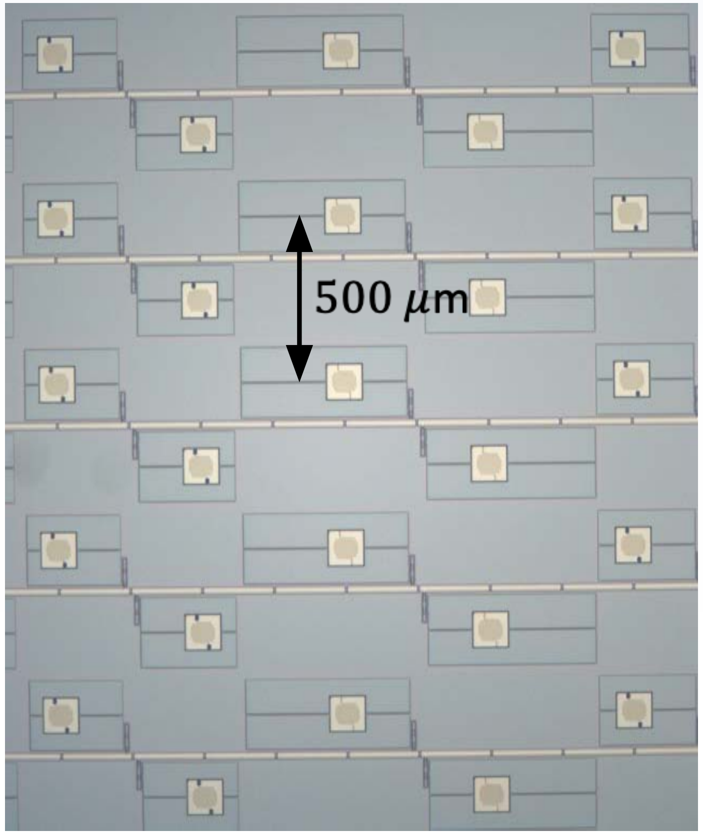
- Large uncertainties from unknown CO abundance and dust depletion
- Precise measurements from optically thin HD 1-0 (112 micron)

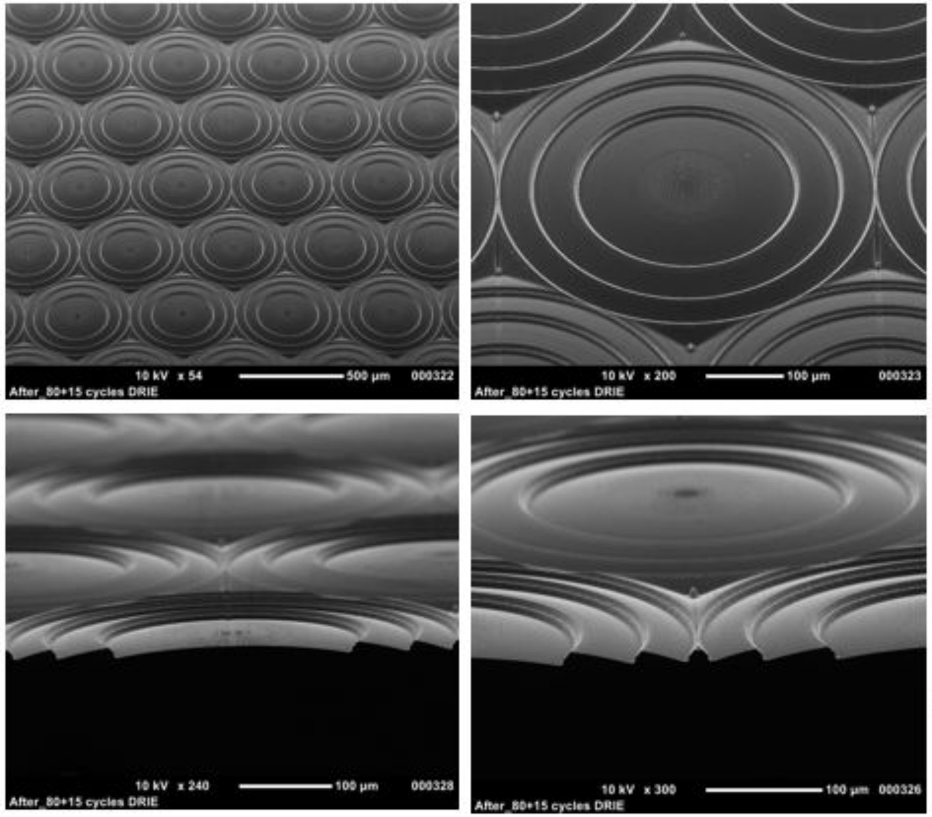
Optimize for spectral sensitivity

- @ R~3,000-5,000, a ~2m cold telescope can reach many disks.
- Large surveys of **hundreds of disks** across range of stellar masses and ages

Hundreds of disks will be detected in HD and H_2O

Kinetic Inductance Detectors – the miracle making this possible!



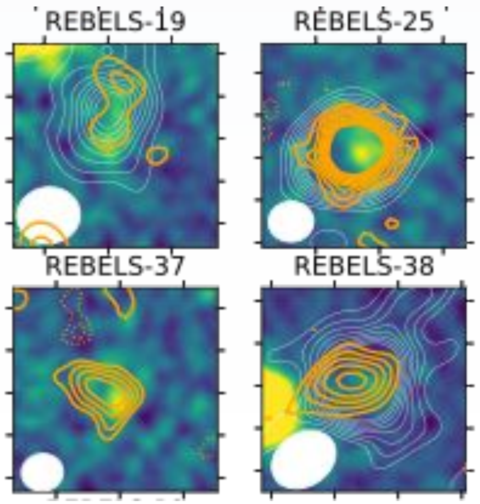


Peter Day, Nick Cothard, Pierre Echternach, Jason Glenn,
Rick Leduc, Joanna Perido, Thomas Stevenson…

PRIMA: The origins of the rich universe we see today

Stars, planets, and galaxies filled with metals, molecules, and dust

Galaxies formed early and began making stars and dust, obscuring their own origins



Inami et al. 2022

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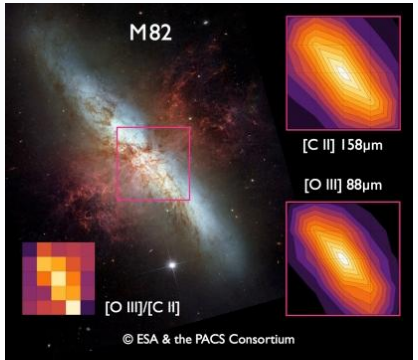

© ESA & the PACS Consortium

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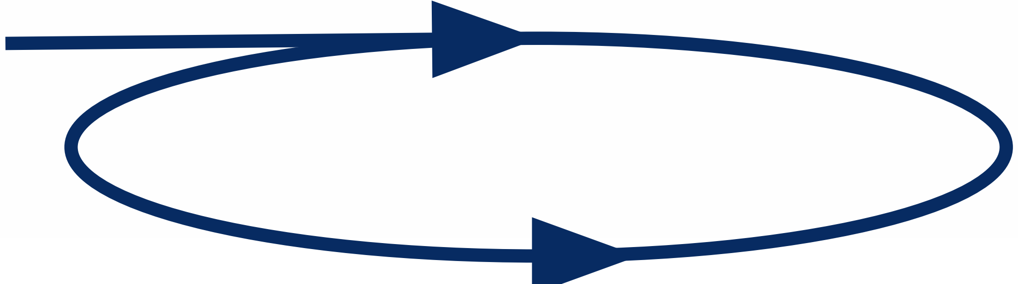

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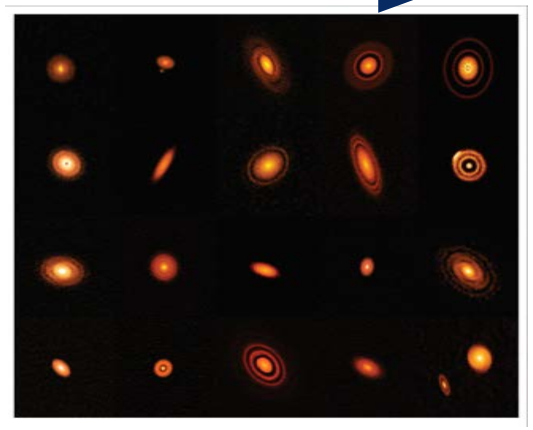

S. Andrews et al.;
NRAO/AUI/NSF,
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Planets formed in disks with gas, dust, minerals, and water that are the seeds of planets and their atmospheres

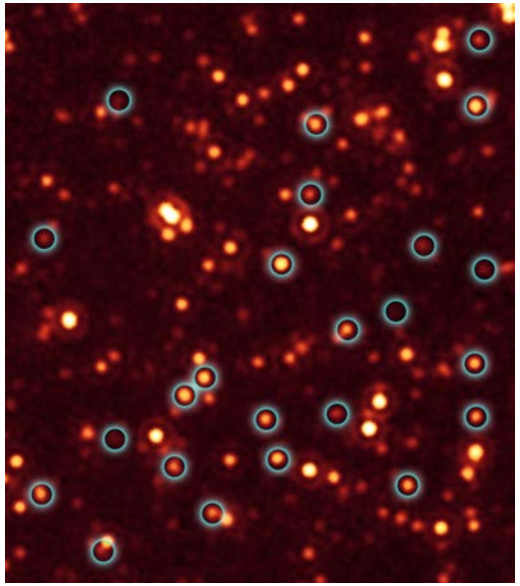
We are made of star stuff.
– *Carl Sagan*

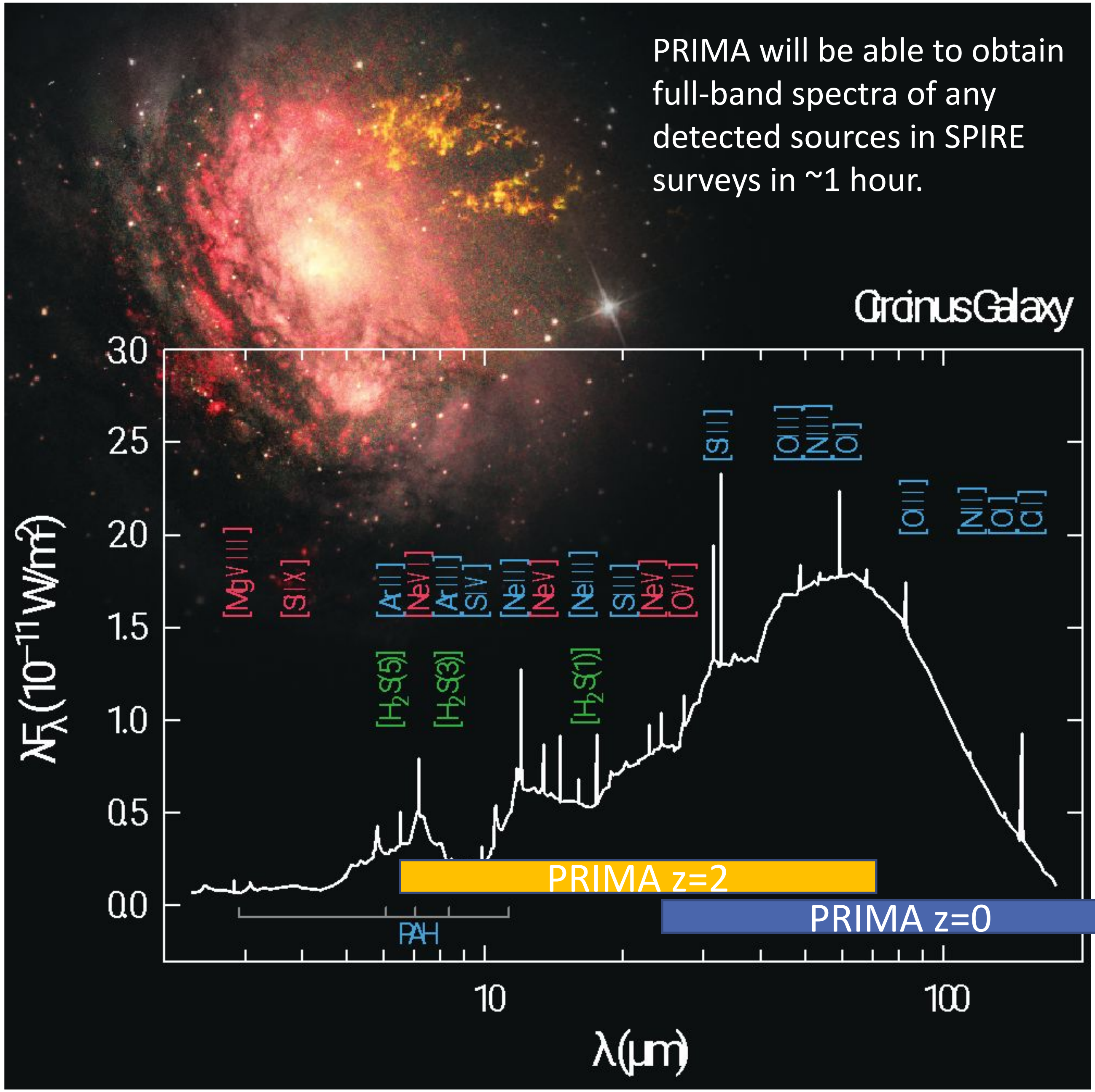
Extra Slides

Extragalactic Source Confusion

- **Spectral lines will not be confused**
- **PRIMA will not be confused for $\lambda \leq 70\ \mu m$:**
    - ➢ Number counts analysis (Glenn et al. 2021)
    - ➢ *Spitzer* was not significantly confused at 24 μm and resolved most of the light
    - ➢ PRIMA will have the same beamsize at 60 μm: (6’’)
- **Flux densities can be reliably extracted down to θ_{FWHM}**: excellent positional priors from short PRIMA wavelengths and Roman with XID+ (Hurley et al. 2017)
- *Herschel* flux densities can be used for $\lambda > 100\ \mu m$, but retain PRIMA long- λ for photometric cross-calibration and polarimetry

Spitzer MIPS 24 μm




PRIMA will be able to obtain full-band spectra of any detected sources in SPIRE surveys in ~1 hour.

Extragalactic Source Confusion

PRIMA will have similar lack of spectral confusion as Origins: PRIMA will have larger spatial-spectral bands than Origins but will not observe as deep.

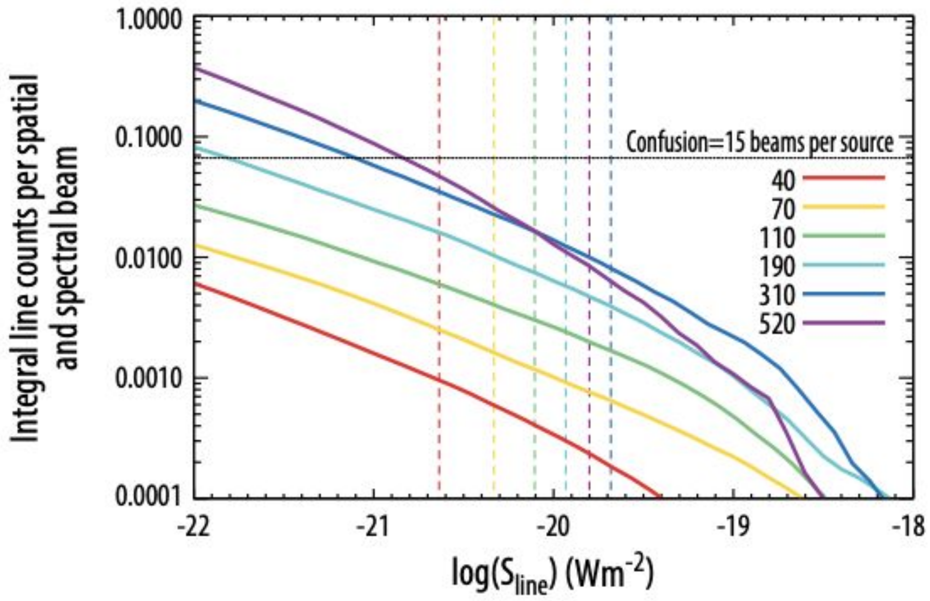


Figure 1-21: The Integral Line Counts per spatial beam and spectral resolution element (R=300) show that spectroscopic confusion is not a problem. The integral line counts are shown for each *Origins*/OSS band in μm (see legend). The detection limit of the deep survey in each band is shown by the vertical dashed lines. The nominal 2D confusion limit of 15 beams per source is shown as the dotted horizontal line. In all bands, the counts for the deep survey are well below the confusion limit.

Origins study report

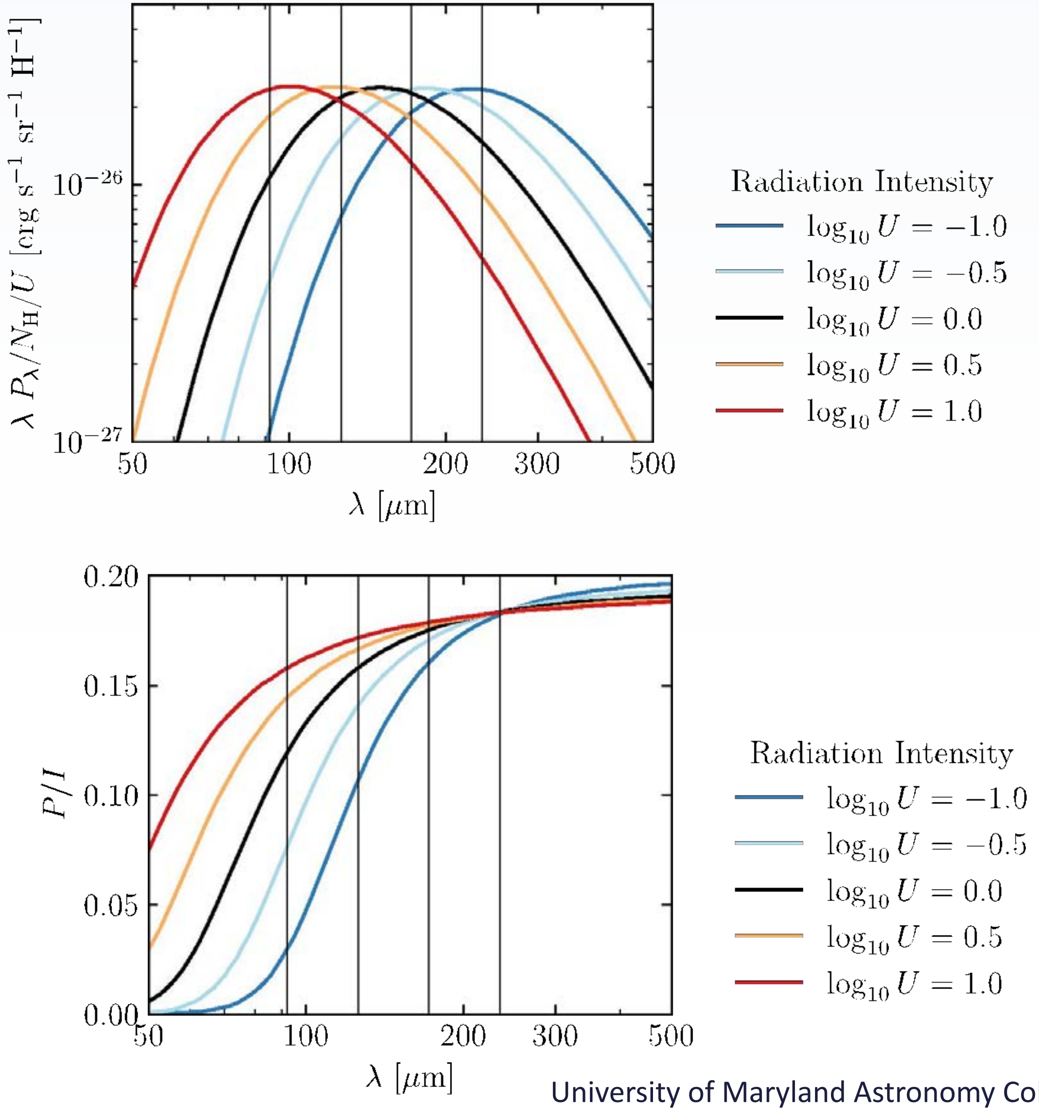
Rise of Dust and Metals in Galaxies

How does dust evolve in the ISM?
Do All Dust Grains Look the Same?

A key (and under-appreciated) benefit of polarization

- Measuring are emission from the large, aligned, steady-state temperature grains only.
  - Their emission is much easier to model than the stochastically heated grains!
  - There be dragons in total intensity that we avoid entirely in polarization, yielding a cleaner measurement of dust temperature and the far-IR opacity law (and thus dust composition).
  - 3D polarization maps will disambiguate dust properties, radiation fields and dust composition.

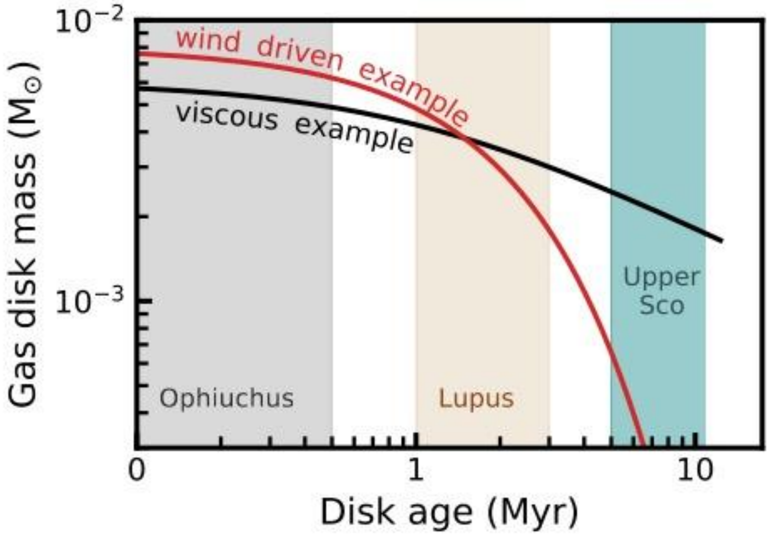
PRIMA Polarimetry Bands



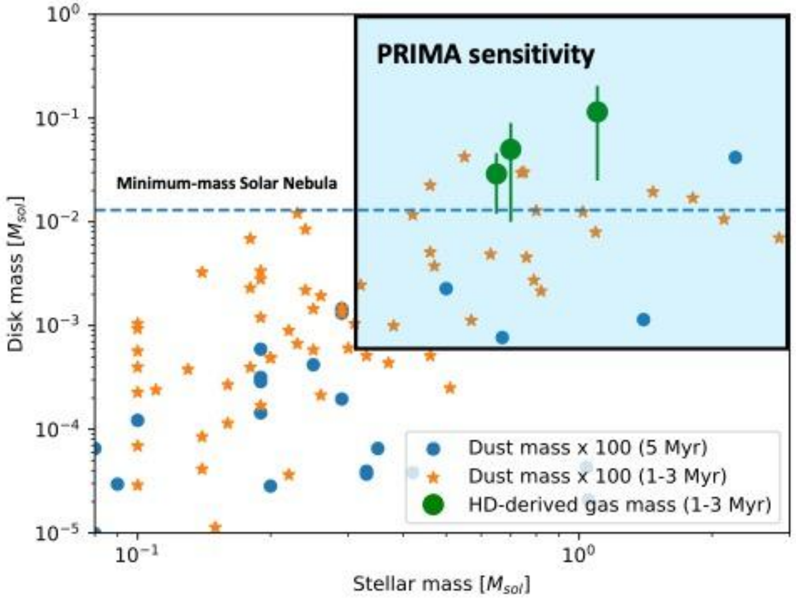
How Stars and Planets Get Their Mass

Origins of Planetary Systems and Water Transport to the Habitable Zone

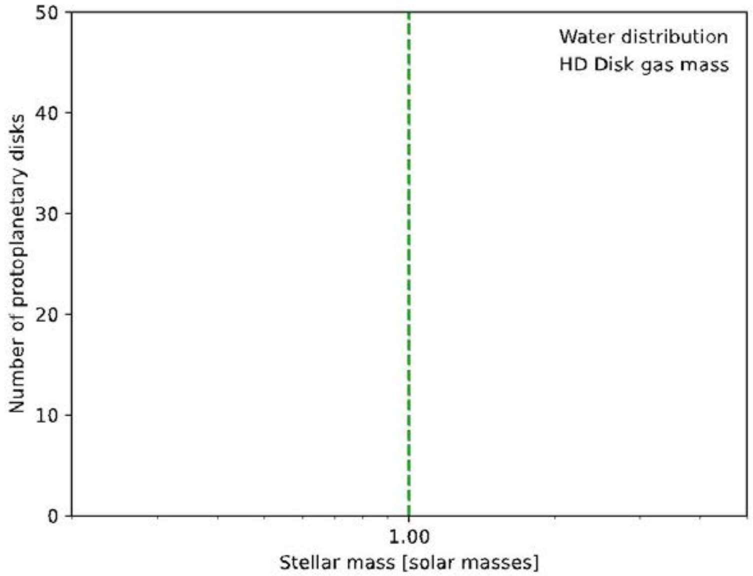
Detection Statistics



Disk ages from tenths of Myr to 10 Myr are available in nearby clouds



PRIMA will be able to measure well below the minimum-mass solar nebula



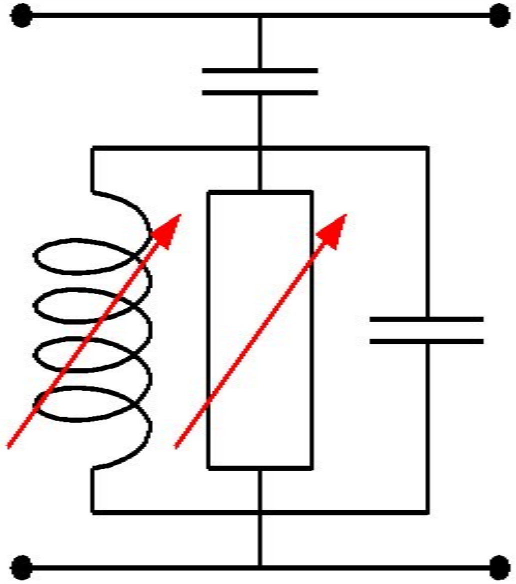
100s of disk will be detectable

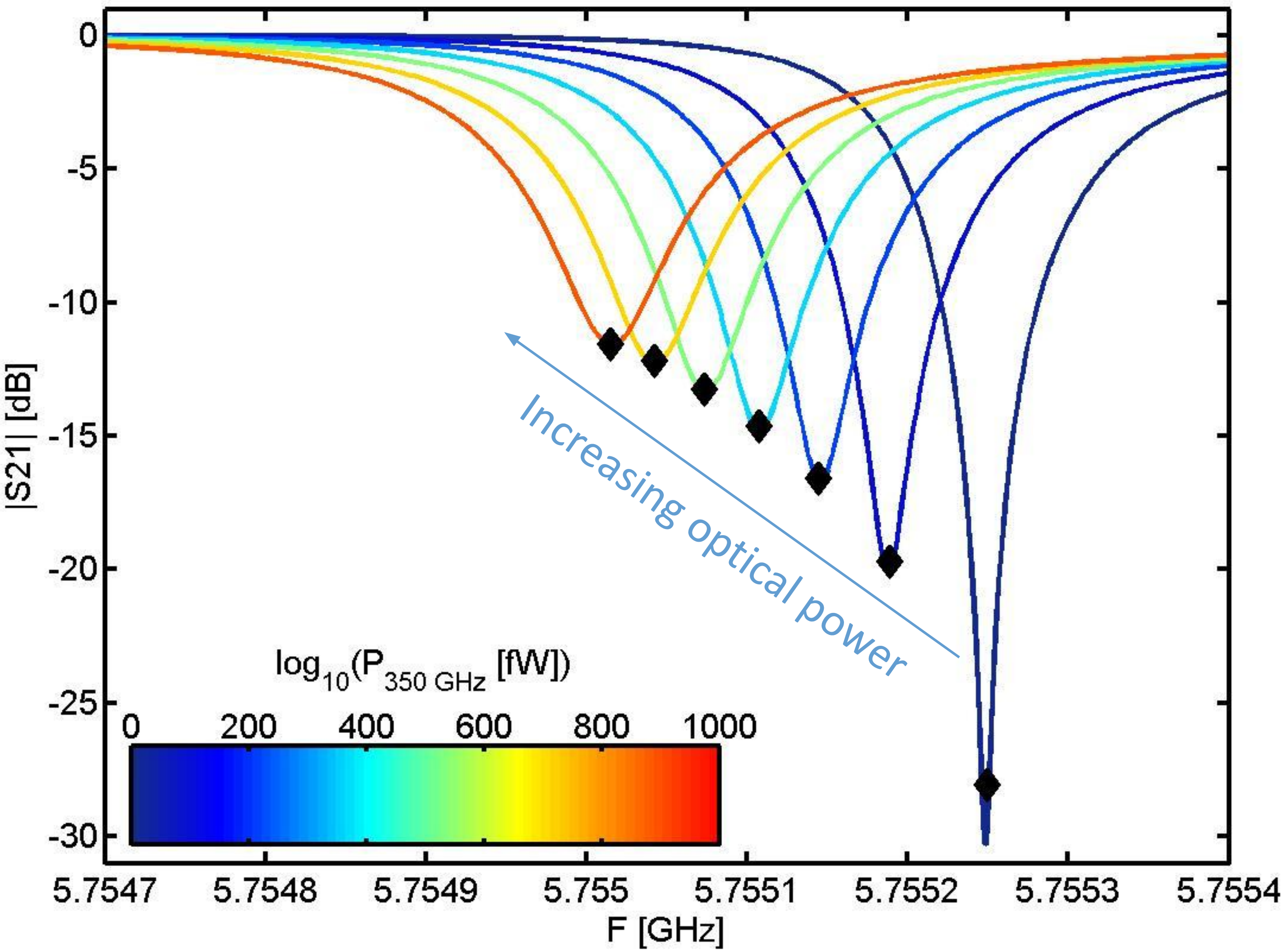
Kinetic Inductance Detectors – the miracle making this possible!

Superconducting resonator

$Q \sim 10^4 - 10^6$

Fres ~ 0.1 – 10 GHz

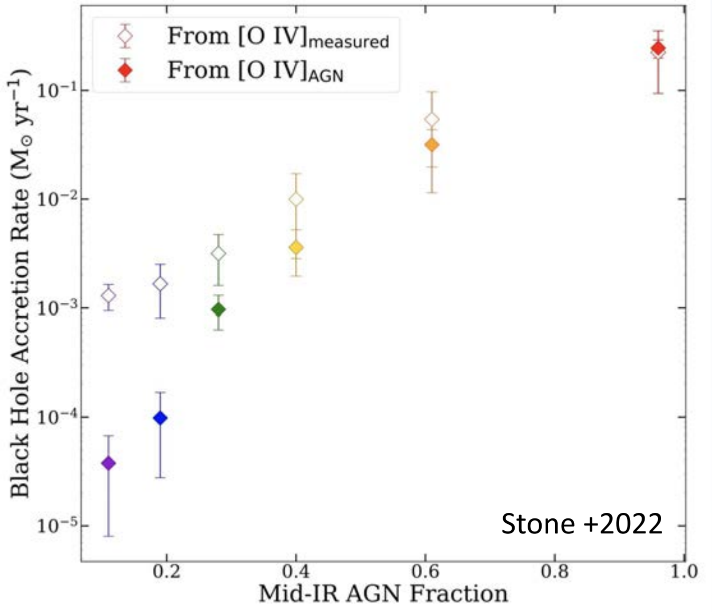




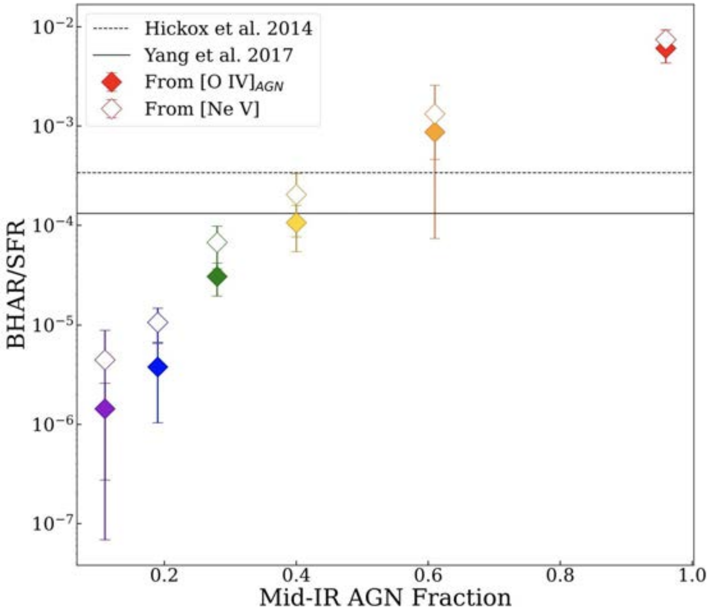
Cycling Through Cosmic Ecosystems

How did supermassive black holes form and how is their growth coupled to the evolution of their galaxies?

- Most galaxies contain highly obscured starbursts at z ~ 1 - 3
  - Establish the BH accretion rate (BHAR) in the presence of abundant star formation
- Rest-frame mid-IR and far-IR provide direct tracers of SFR: accurate map of the co-evolution of galaxies and SMBH – unique to IR.
  - IR transitions are robust to extinction, and can directly trace SMBH accretion rates (Gruppioni +16), even in galaxies with powerful starbursts.
  - [Ne V] is only produced in AGN
  - [OIV] is much brighter but has a contribution from SF at low AGN fractions. This has been calibrated through observation of low-ionization [Ne II] and [Ne III] lines (Stone +22).



Stone +2022



Lee Armus &
Alex Pope

Sample PRIMA Guest Observer Science (≥ 70% of observing time)

Planetary Systems and disks

- Cometary water (D/H ratio)
- Kuiper Belt Objects – sizes/composition
- Atmospheric composition in exoplanets and brown dwarfs
- Ices in protoplanetary disks
- Hydrides chemistry in protoplanetary disks
- Gas in debris disks

Galactic science: ISM and stars

- The ISM in the Central Molecular Zone
- Magnetic fields in molecular clouds
- The Dense Warm Interstellar Medium
- Magnetic Field in the Galactic Center
- Young stars in the Milky Way: an inventory
- Population study of evolved massive stars

Dust mineralogy

- In nearby galaxies
- In stellar environments
- The evolution of metallicity in dust

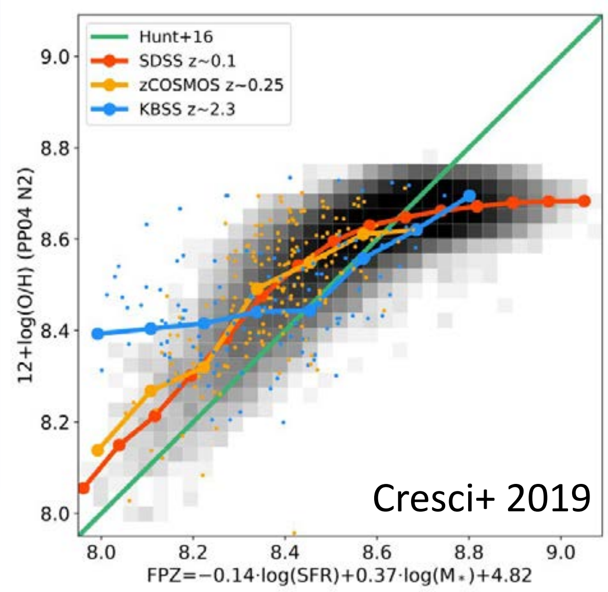
Time Domain

- Gamma-Ray Bursts
- Neutron Stars mergers
- Novae
- Supernovae

Rise of Dust and Metals in Galaxies

Beyond stellar mass and black hole assembly, the *chemical enrichment history of the Universe* is the next great challenge

- Metals provide a ***unique and direct tracer*** of baryon cycling processes.
- Heavy elements are a highly ***biased*** by-product of galaxy assembly.
- Optical metal abundance tracers suffer from two main is

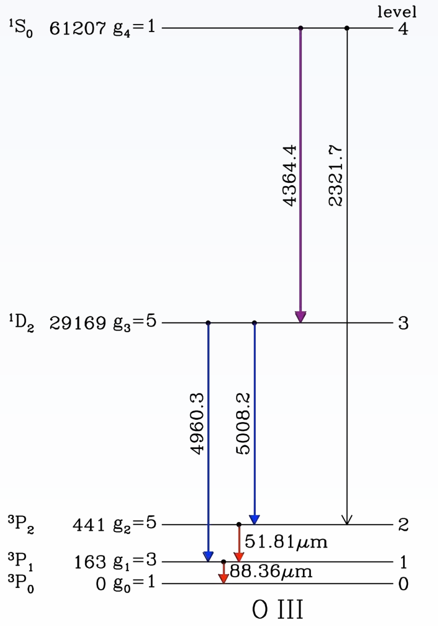


Cresci+ 2019

Fundamental

Metallicity

Plane

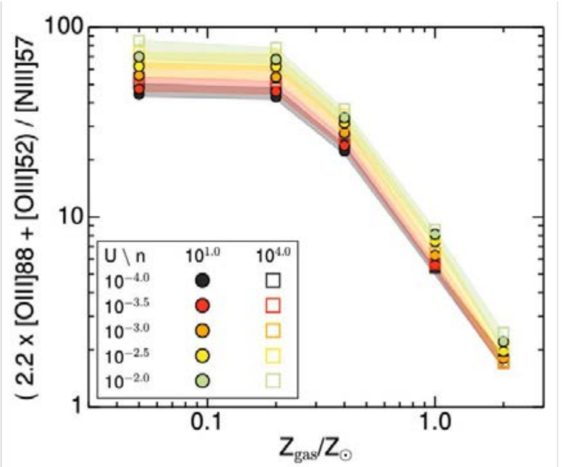


1. Strong **temperature sensitivity**, and
2. Bias from **heavy extinction** in the obscured sources which host the majority of star formation at cosmic noon.

- PRIMA's **far-Infrared metal abundances toolset** penetrates high dust columns and provides **temperature-agnostic** heavy element abundances in the hearts of galaxies.
- PRIMA will:

1. Measure the dominant coolant of ionized gas ([OIII] 52/88) in >1,000 sources from **z = 0-3.5**.
2. Use low-extinction NGVLA free-free continuum and [NeIII]/[NeII] ionization tracers to measure **direct IR oxygen abundance**.
3. Recover [NIII]/[OIII] ***relative abundances*** in dozens of sources

Pereira-Santaella+ 2017



PRIMA Science Overview

Ultrasensitive observations of dust and gas to reveal how stars, planets, and galaxies grow and interact with their environments.

Cycling Through Cosmic Ecosystems

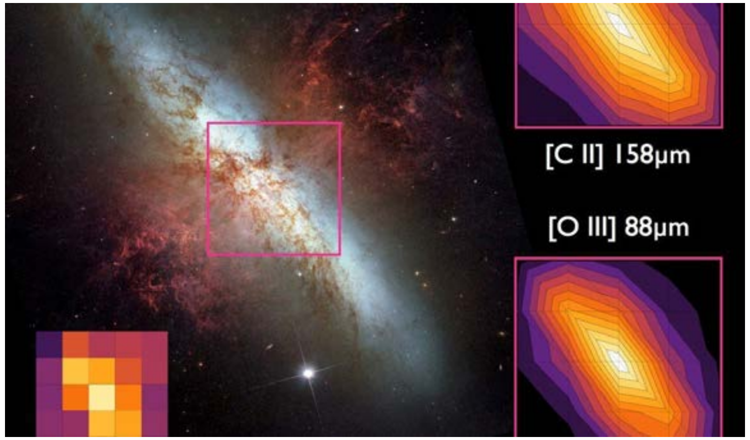
- *Cool gas flow into, through, and out of galaxies*
- *Assembly of stars and supermassive black holes and ISM conditions conducive to their growth*

Rise of Dust and Metals in Galaxies

- *Build-up of dust and metals in galaxies over cosmic time*
- *Grain sizes and heating as a function of environment*

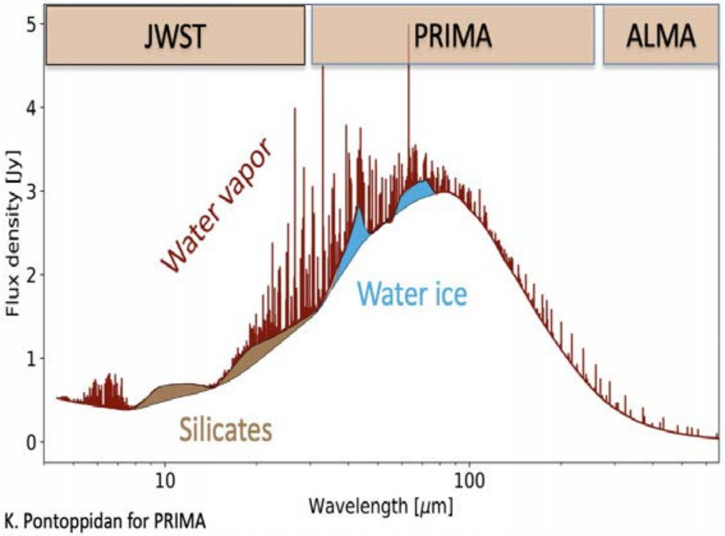
How Stars and Planets Get Their Mass

- *Protoplanetary disk gas masses, water vapor, ice, and mineral contents*
- *Protostar accretion rates*
- *Influence of magnetic fields*



ESA, NASA, JPL-Caltech

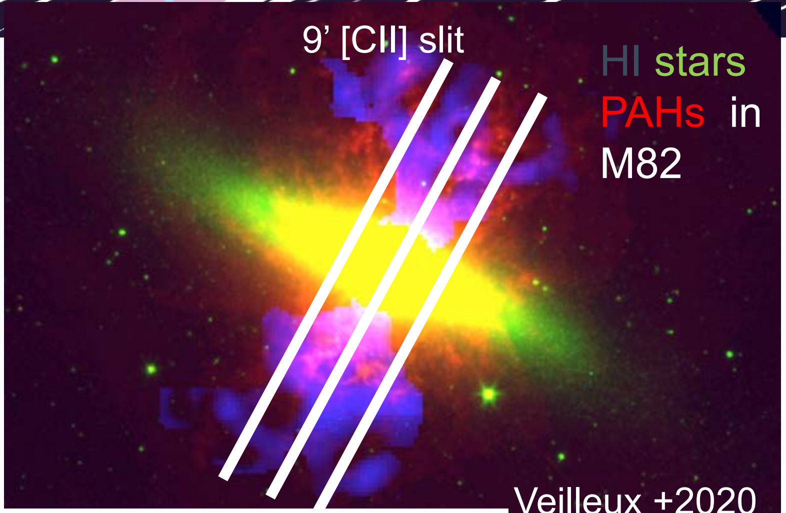
ESA/Herschel/PACS/SPIRE/J. Fritz, U. Gent; X-ray: ESA/XMM Newton/EPIC/W. Pietsch, MPE



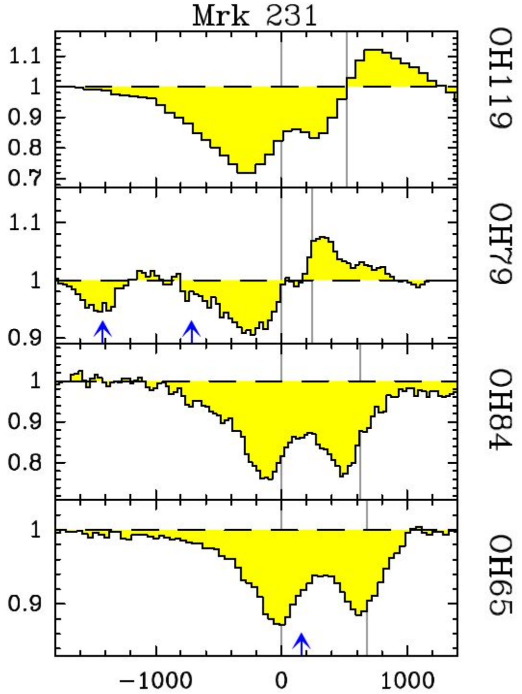
K. Pontoppidan for PRIMA

Cycling Through Cosmic Ecosystems

- **Objective:** Evaluate mass and kinematics of the cool ($T<10^4$ K) phase of galaxy outflows, which dominates the mass budget, using FIR transitions
  - [CII] in emission – best sensitivity to surface brightness,
  - OH in absorption – unambiguous outflows against bright FIR nucleus)
  - Unique to the FIR – A probe of all cool neutral gas, less dependent on chemistry, good constraints on geometry (extent of outflow)
  - Only possible before PRIMA in a handful of nearby galaxies

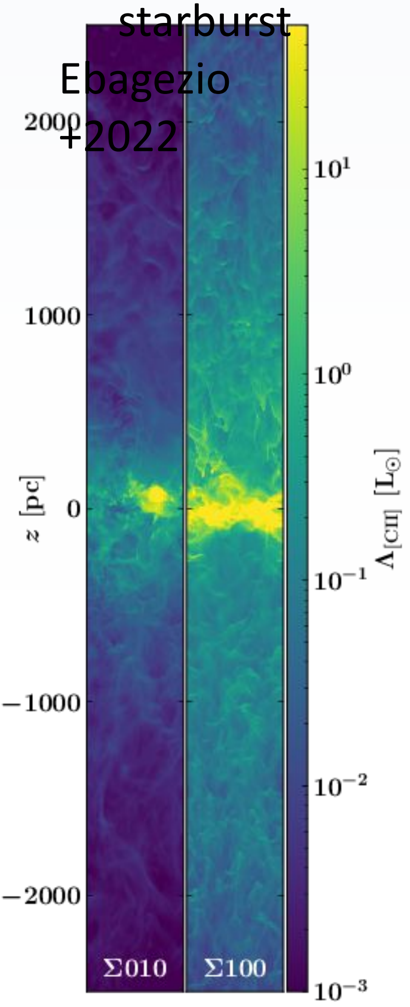


Veilleux +2020



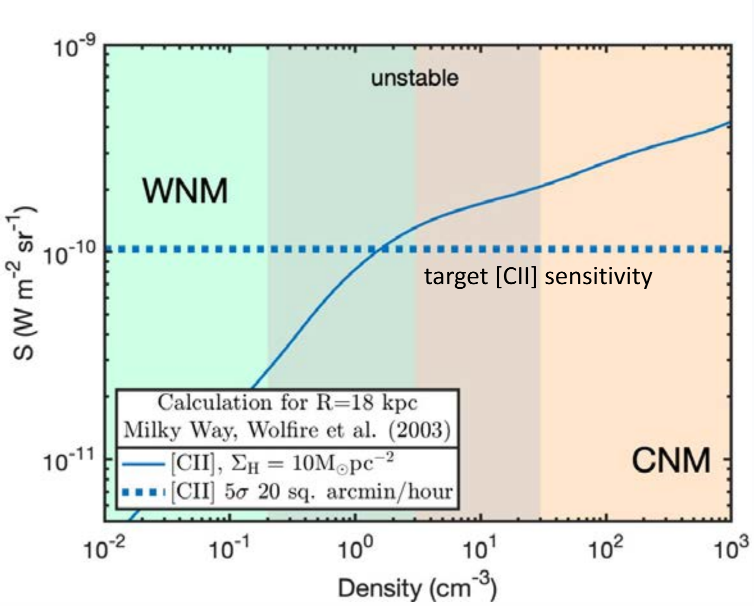
Gonzalez-Alfonso +2017

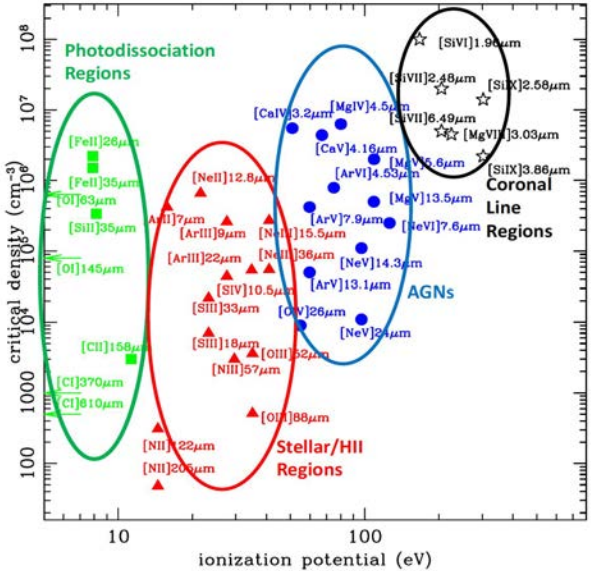
SILCC-zoom [CII] in starburst Ebagezio +2022



Cycling Through Cosmic Ecosystems

- **Objective:** Establish the physical conditions in the ISM as a function of activity & galaxy mass
  - total cooling rates, feedback indicators, radiation field hardness, molecular column densities, etc
  - establish local [NIII]/[OIII] metallicity calibration
  - Unique to the FIR – No other wavelength regime (JWST included) has access to dominant cooling transitions or HD, is robust to extinction
  - H_2 S(0) (28 um), HD, [CII], [OI], [NII], [NIII], [NeIII],[SIII], [OIII], [SiII], [OIV], [NeV] + dust
  - Very limited access before PRIMA – Lack of sensitivity and mostly "single line" measurements

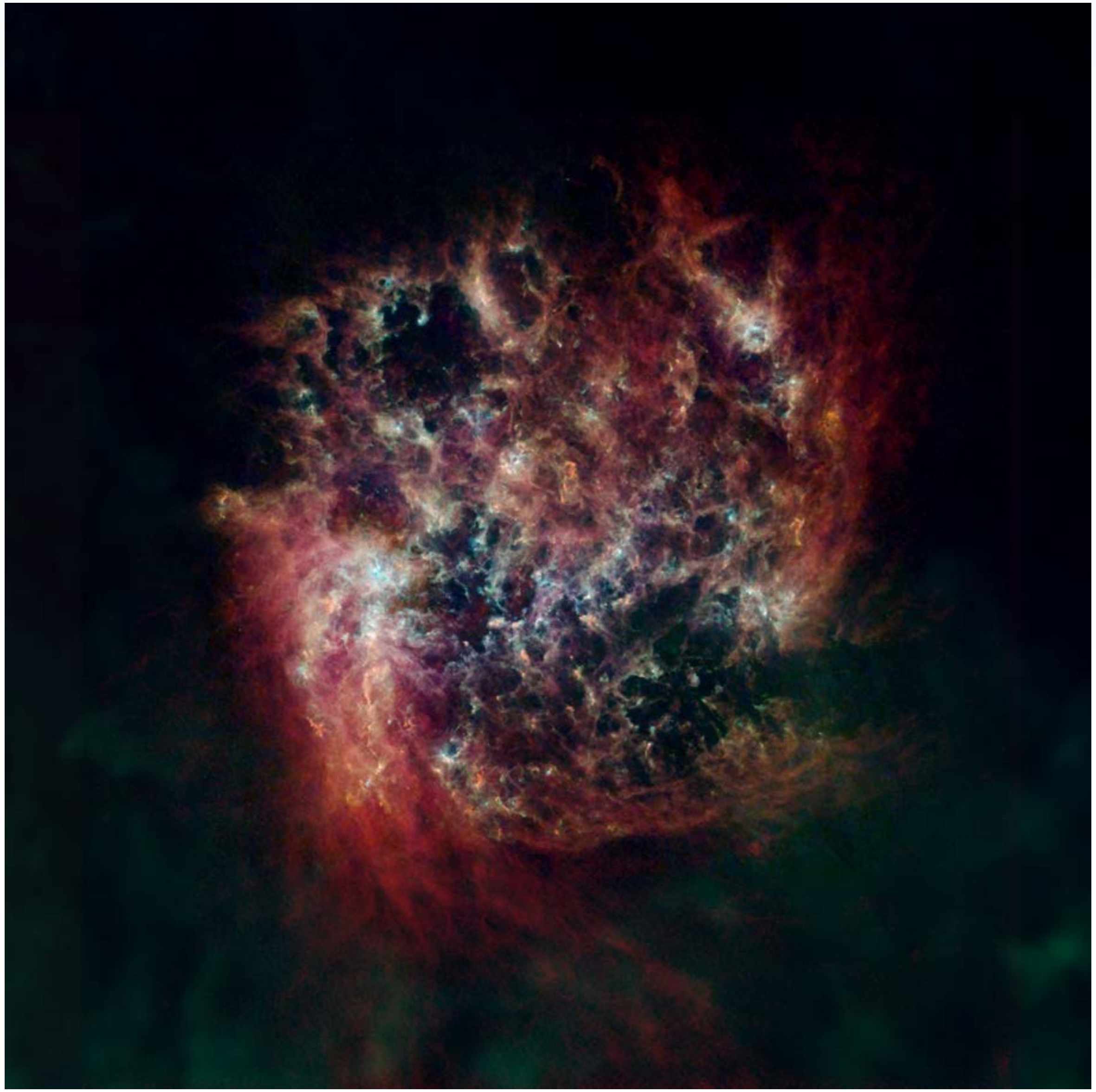




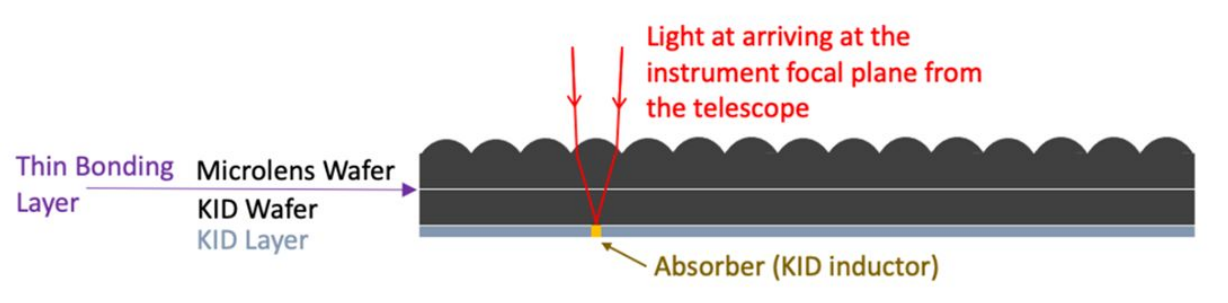
PRIMA LMC Survey

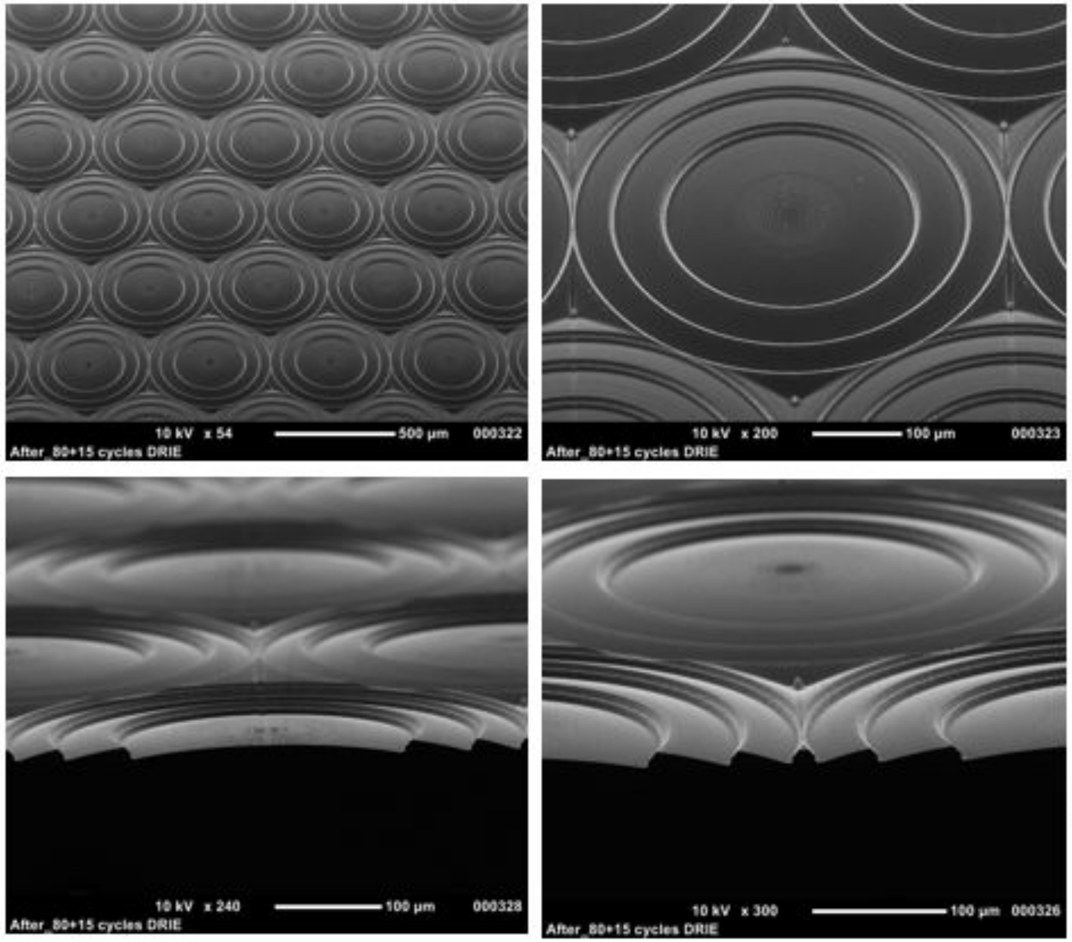
- Flagship survey showcasing PRIMA polarization science:
  - Access a range of physical scales from kpc to ~5 pc
  - Wealth of ancillary data constraining dust and gas properties
  - B-fields at full resolution over the entire galaxy
- Can be complemented with:
  - Sample of nearby galaxies where B-fields can be resolved
  - Selected Galactic regions (Galactic Center, molecular clouds…)

Credit: ESA/NASA/JPL-Caltech/CSIRO/C. Clark (STScI)



Fresnel Microlens Arrays for Optical Coupling



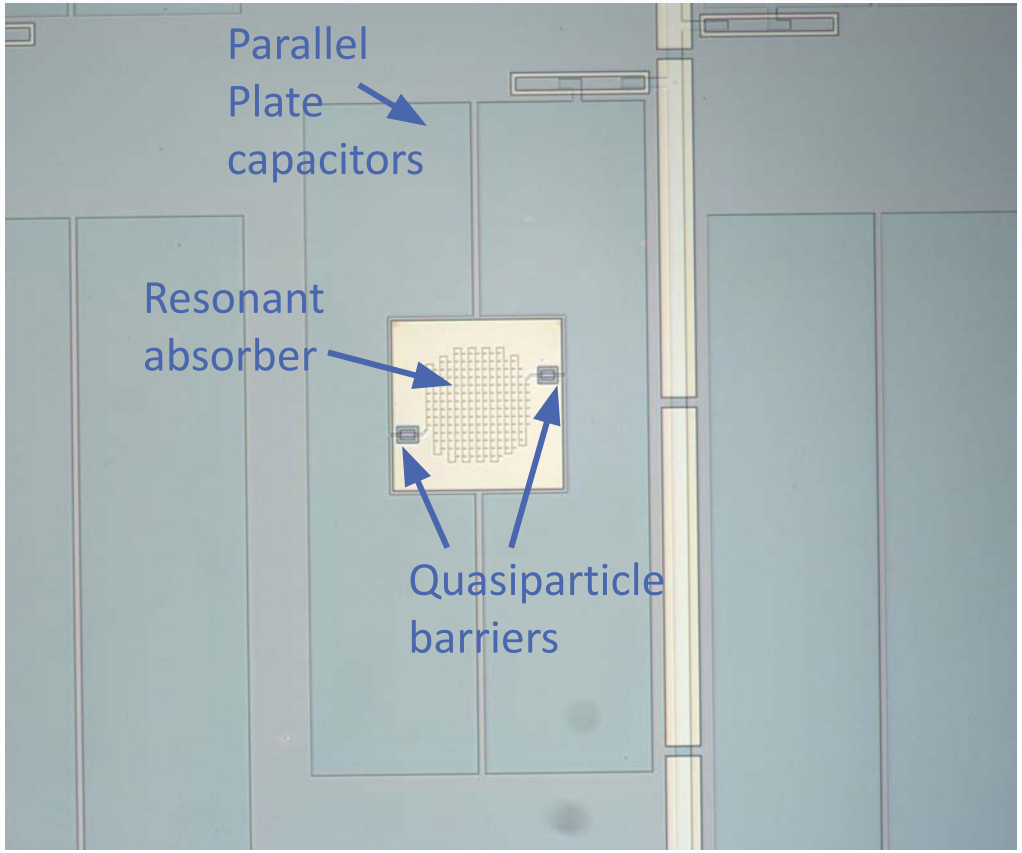


- From profilometer measurements, first prototypes expected to have 90% efficiency compared to perfect lenses; improvement with smaller write-head
- Alignment and bonding process demonstrated with ~1 μm gap – insignificant losses
- 4 μm Parylene coating deposited and thermally cycled 10x with no delamination
- Next steps
  - Bond to KID wafer & measure optical NEPs
  - Attempt smooth lenses (larger sag)
  - Attempt larger pitches

Detector Design

Parallel-plate capacitor KIDs

- Larger capacitance per area decreases detector size
  - 500 µm pixel pitch
  - Keeps resonance frequency low for greater fractional bandwidth
- Use of aSi dielectric reduces TLS noise to level similar to IDC
- 1/f noise $S_{\delta f/f} \sim 1\text{x}10^{-16}$ @ 150 mK consistent with NEP target

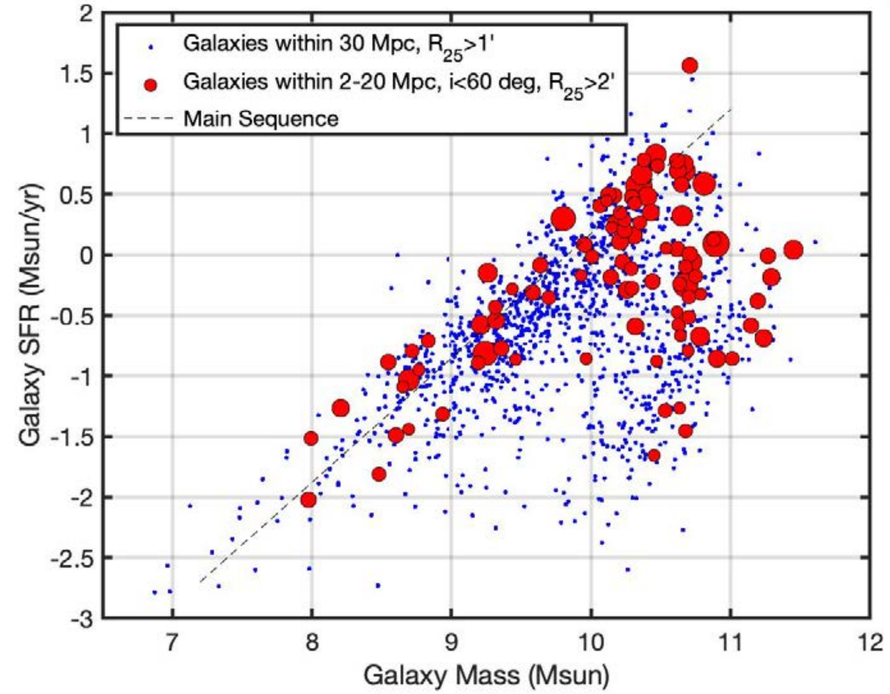


Day & Leduc – JPL

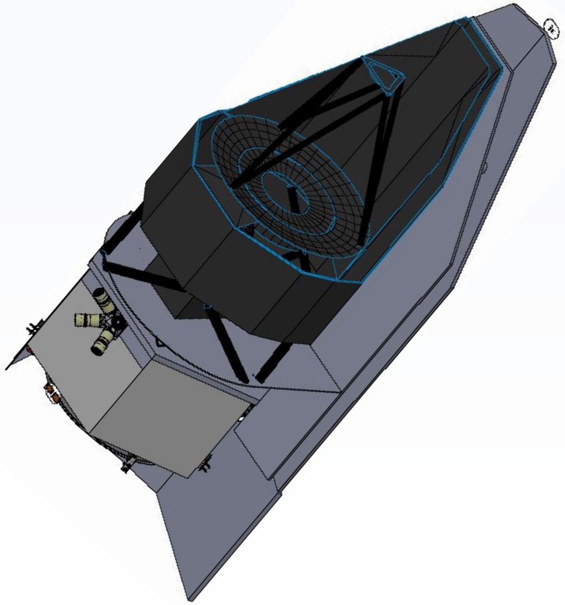
IMPLEMENTATION

- GOAL 2a
  - Spectral mapping of galaxy sample – binning on SFR-M* plane, maintain good representation of AGN, consider distance, metallicity, and inclination distributions, mapping out to R_{25}, 500 objects
  - Mapping speed to target sensitivity of 10^{-10} $\mathrm{Wm^{-2}sr^{-1}}$ is ~20 $\mathrm{arcmin^2/hr}$.
  - Example: Mapping all red symbols (100), ~350 hrs

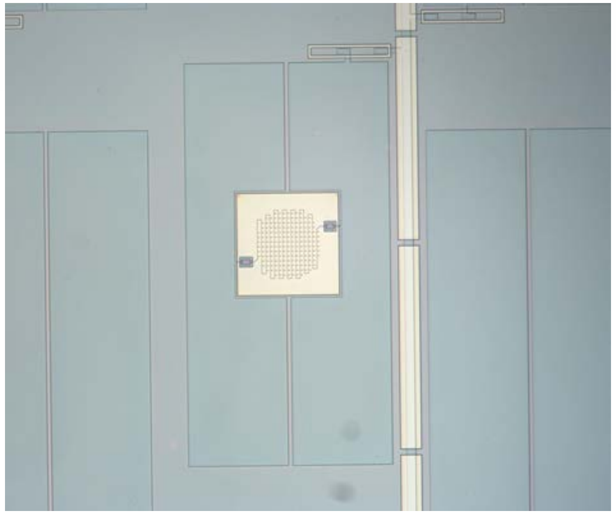
- GOAL 2b
  - Pointed galaxy sample – based on SDSS selection, will have continuity with high-z
  - Fast per object (~10 min), a few to several hundreds of objects.



Why PRIMA and why now?



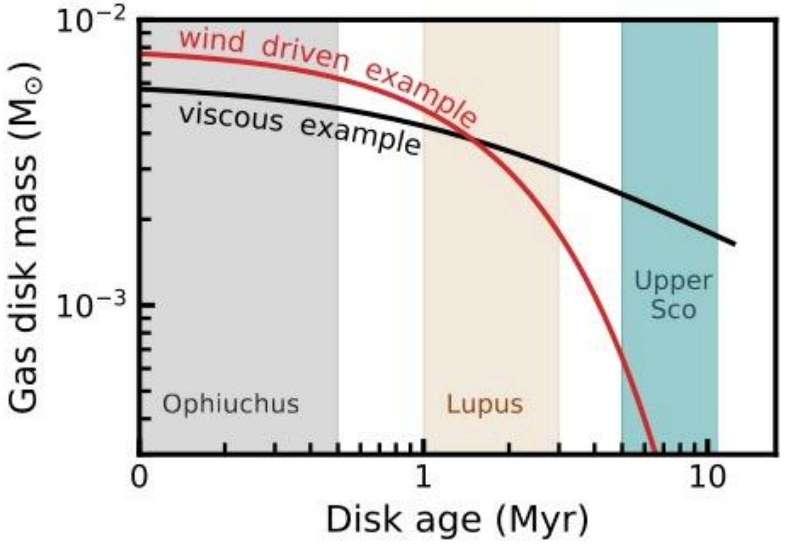
2020 Decadal Survey Recommended a Far-IR or X-ray Probe

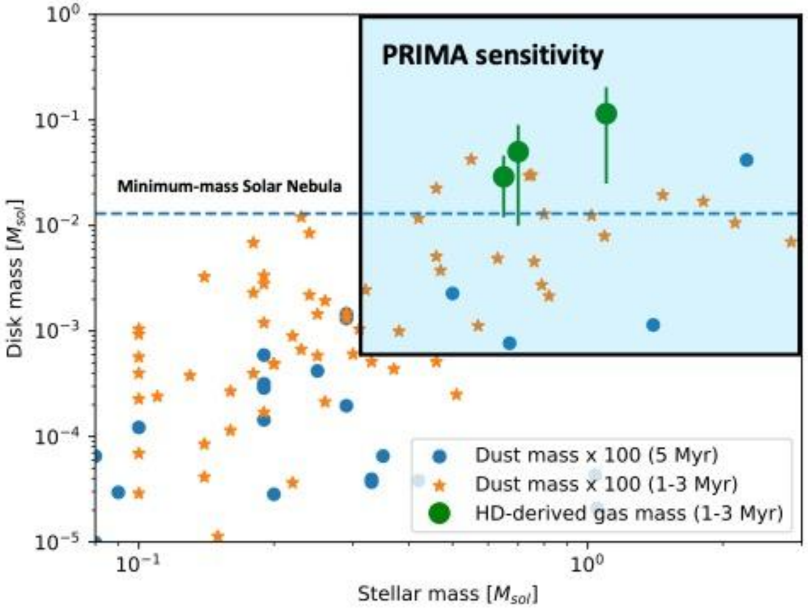


Decades-long investment in detector technology paying off, enabling astrophysical photon-limited far-IR sensitivity with a 4 Kelvin telescope

How Stars and Planets Get Their Mass

Mass Comparison





PRIMA GO program:

- The PI-led program defines capabilities of PRIMA.
- The GO community science will extend and exceed the PI-led science because of the substantial discovery space in PRIMA.
- The GO programming on PRIMA will comprise 75% +/- 5% of the mission observing time.
- The PRIMA GO program will be the most important science coming out of the mission.

GO science programs: community examples

Planetary systems and disks

- Comets: water deuterium abundance (Lis)
- Atmospheric composition of planets and brown dwarfs (Ciardi/Kataria)

Galactic ISM

- Magnetic field mapping of Galactic Center (Pare)
- Dense Warm Interstellar Medium (Goldsmith)
- Galactic Star formation processes (Battersby)

Stellar populations: Massive evolved stars, e.g. LBVs (Morris)

Dust mineralology:

- Nearby galaxies (Kemper)
- Stellar environments (Bowey)

Time Domain

- Neutron star mergers (Andreoni)
- Gamma Ray bursts (Anna Ho)

High-z galaxies

- Lensed galaxies (Egami)
- Intensity mapping (Switzer)

PRIMA community engagement efforts

Focused on generating excitement for far-IR science in the astronomical community

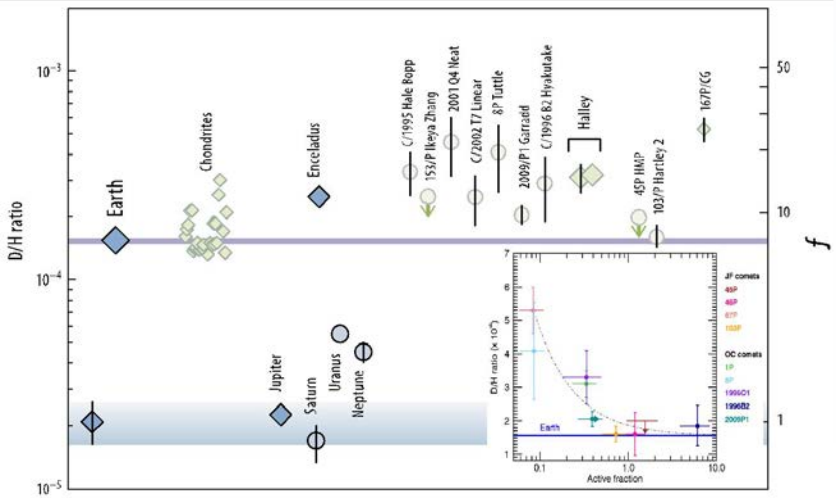
March 2022 virtual community science workshop

Website: https://prima.ipac.caltech.edu

Newsletters: One in August, one coming soon

AAS special session: Beyond JWST and ALMA: Far-infrared Spectroscopy of Cosmic Ecosystems

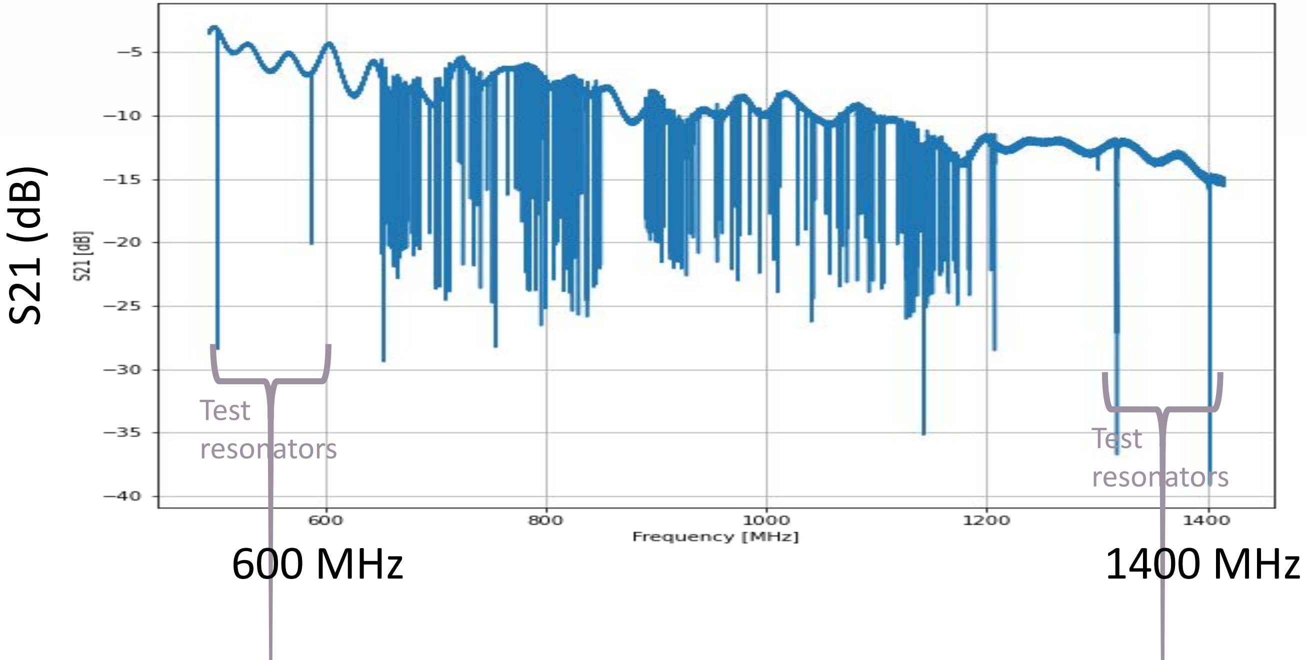
Comets

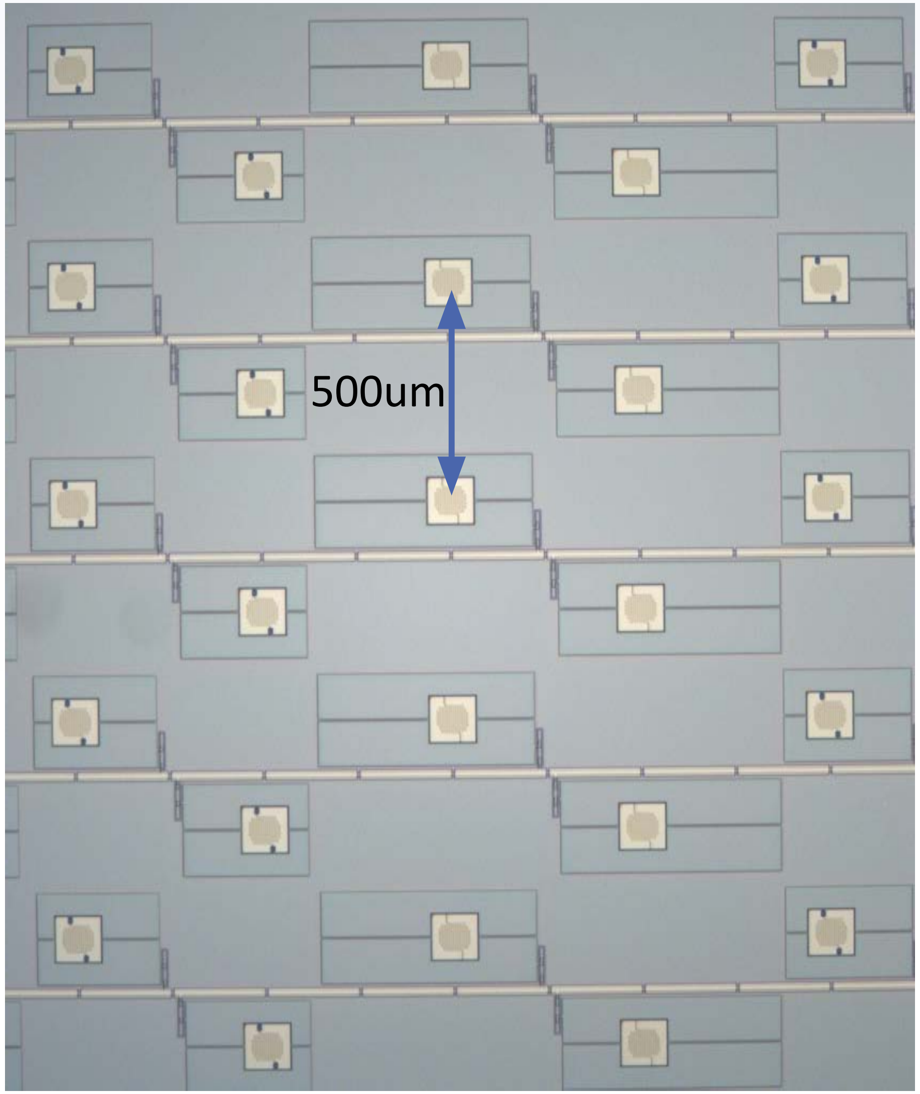

D/H ratio
10^{-3}
10^{-4}
10^{-5}
Earth
Chondrites
Enceladus
Jupiter
Saturn
Uranus
Neptune
C/1995 Hale Bopp
153/P Ikeya Zhang
2001 Q4 Neat
C/2002 T7 Linear
8P Tuttle
2009/P1 Garradd
C/1996 B2 Hyakutake
Halley
45P HMP
103/P Hartley 2
167P/CG
50
10
1
f
D/H ratio (× 10^{-4})
Active fraction
0.1
1.0
10.0
Earth
JF comets
45P
46P
67P
103P
OC comets
1P
8P
1995O1
1996B2
2009P1

Prototype Arrays

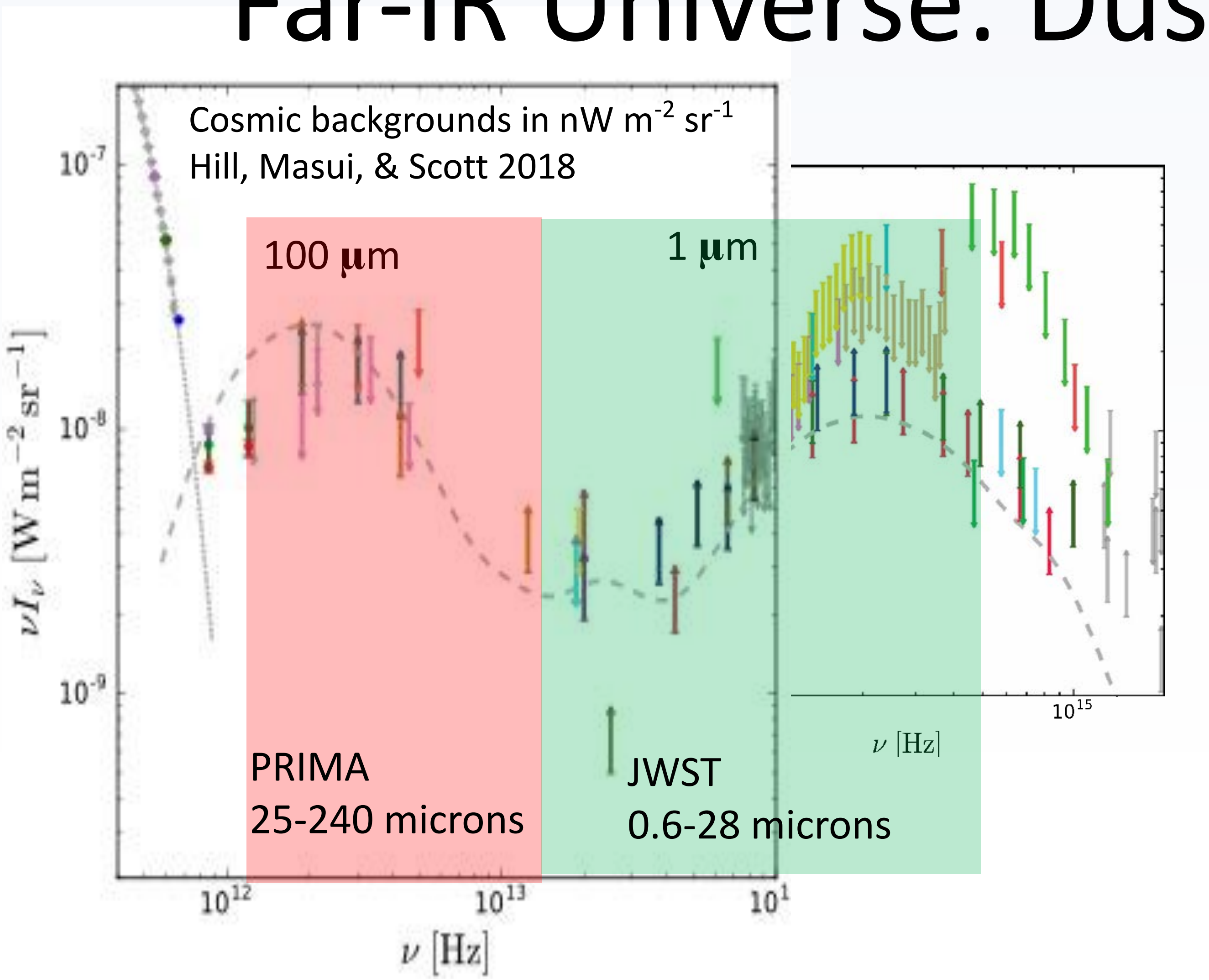
244-pixel arrays with backside alignment structures delivered to GSFC for lenslet array bonding

- High yield of identified resonances typically ~240/244
- Pixel-mapping / capacitor-trimming cycle planned for reducing frequency collisions

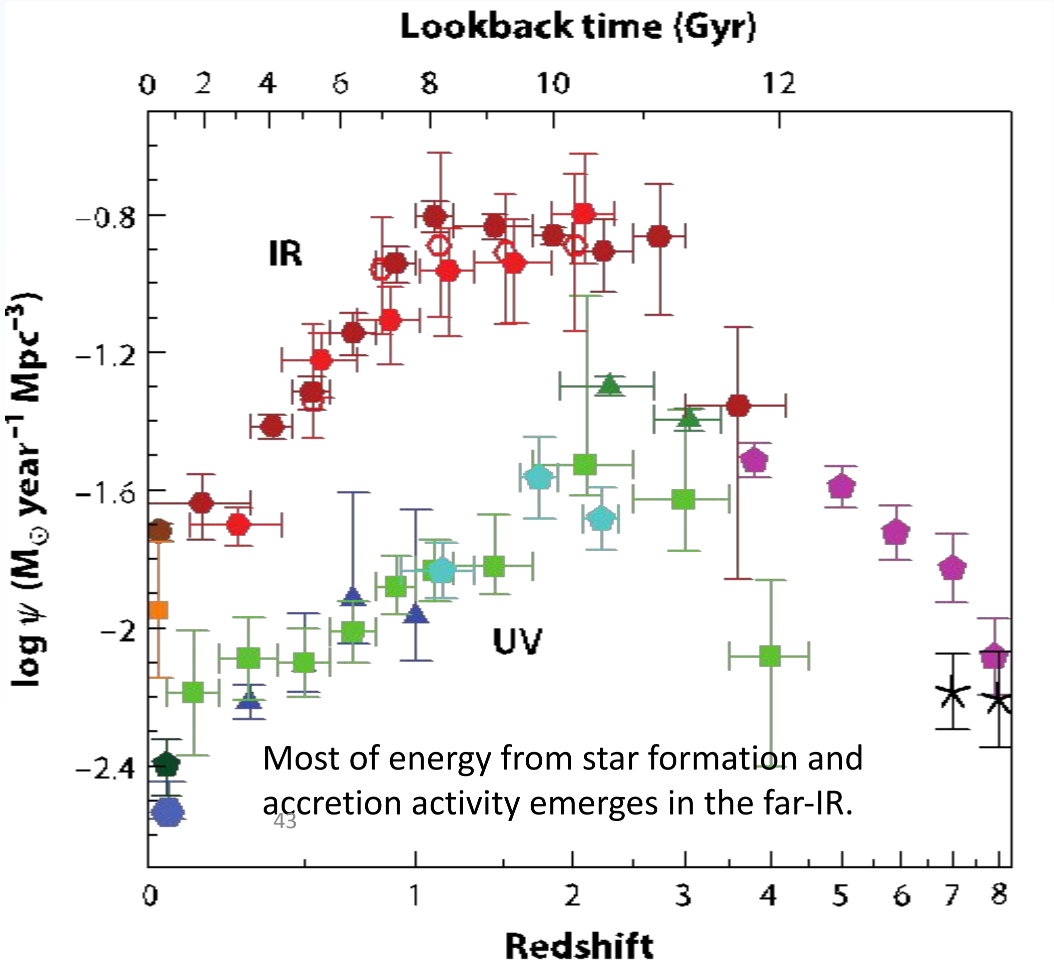




Far-IR Universe: Dust is Ubiquitous


Cosmic backgrounds in nW m^{-2} sr^{-1}
Hill, Masui, & Scott 2018

Energy output from galaxies:



Most of energy from star formation and accretion activity emerges in the far-IR.

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

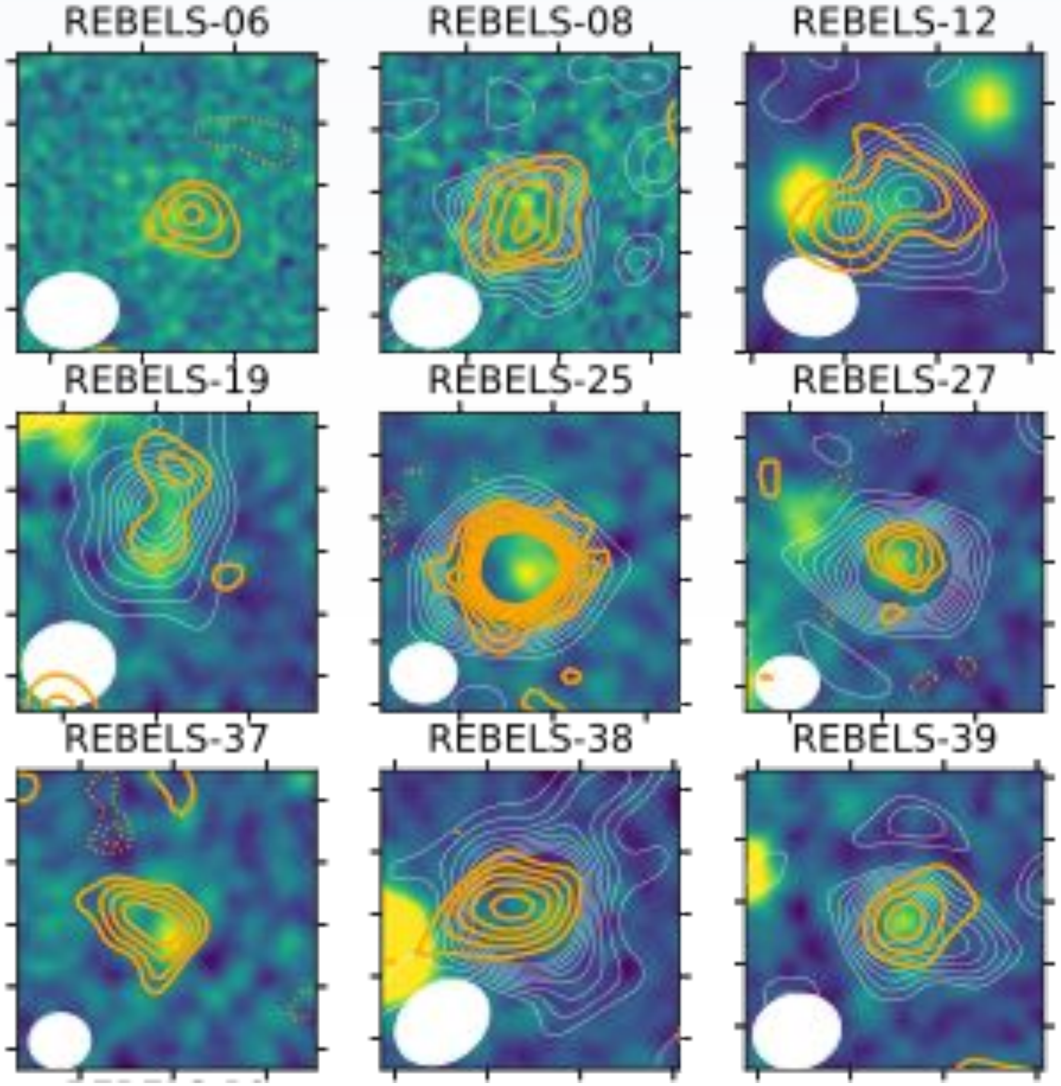
Far-IR background is a cosmological background, not a low-redshift phenomenon.

Star formation has been predominantly obscured.

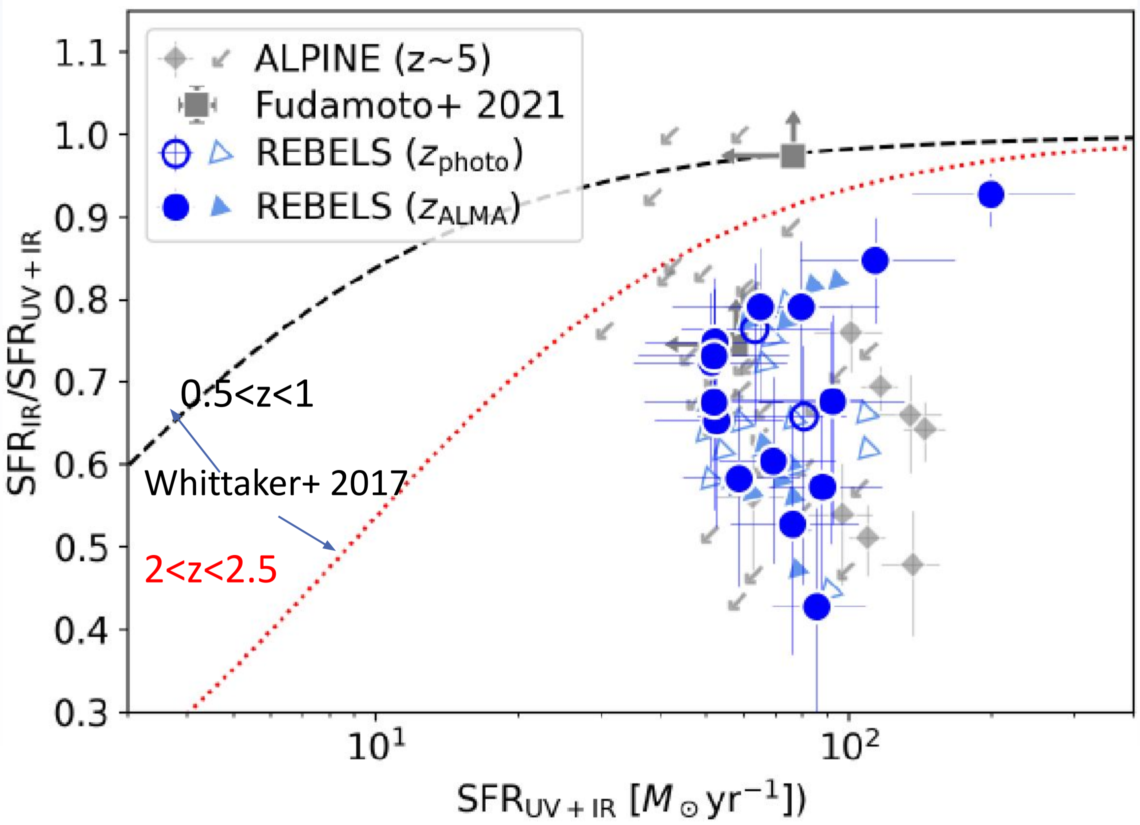
Dust present at very early times

REBELS ALMA survey z>6.5

Inami et al, 2022

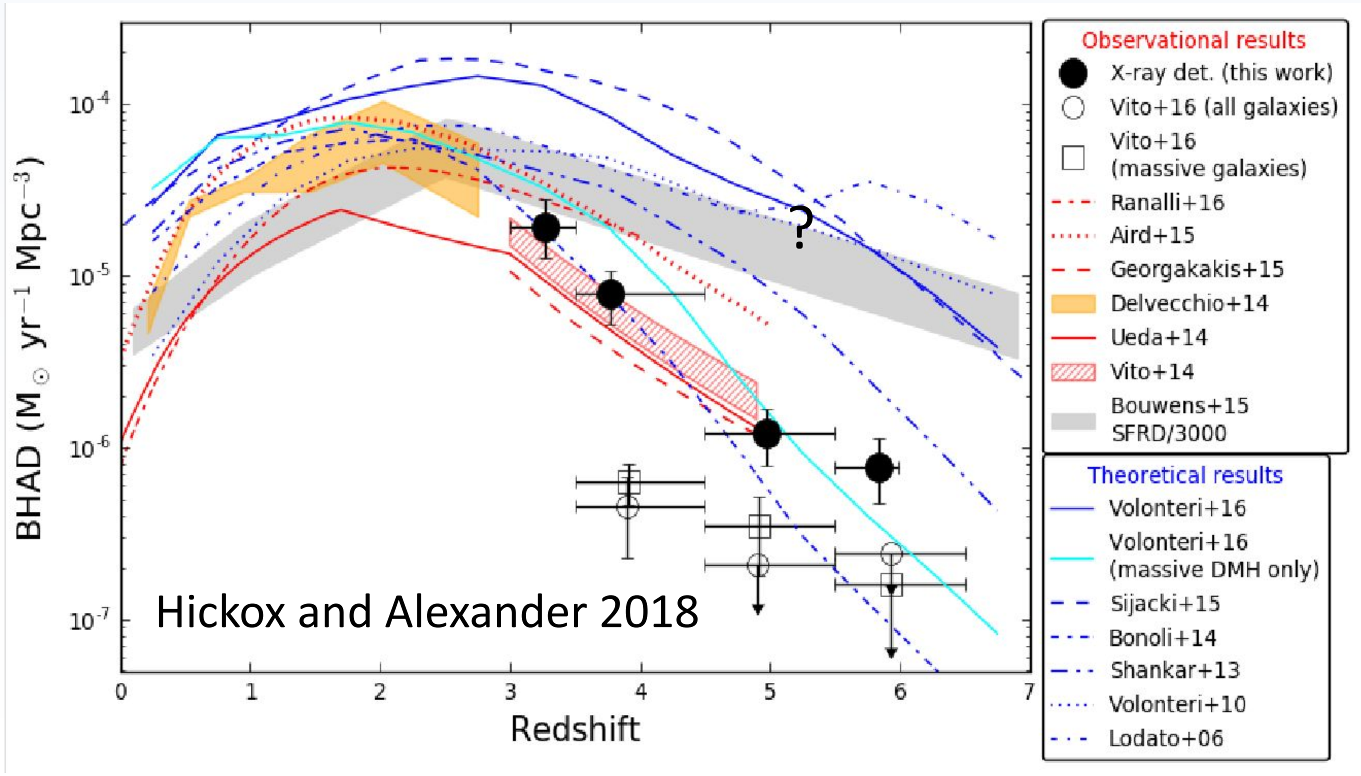


5 x 5 arcsec, JHK background, dust orange, CII white

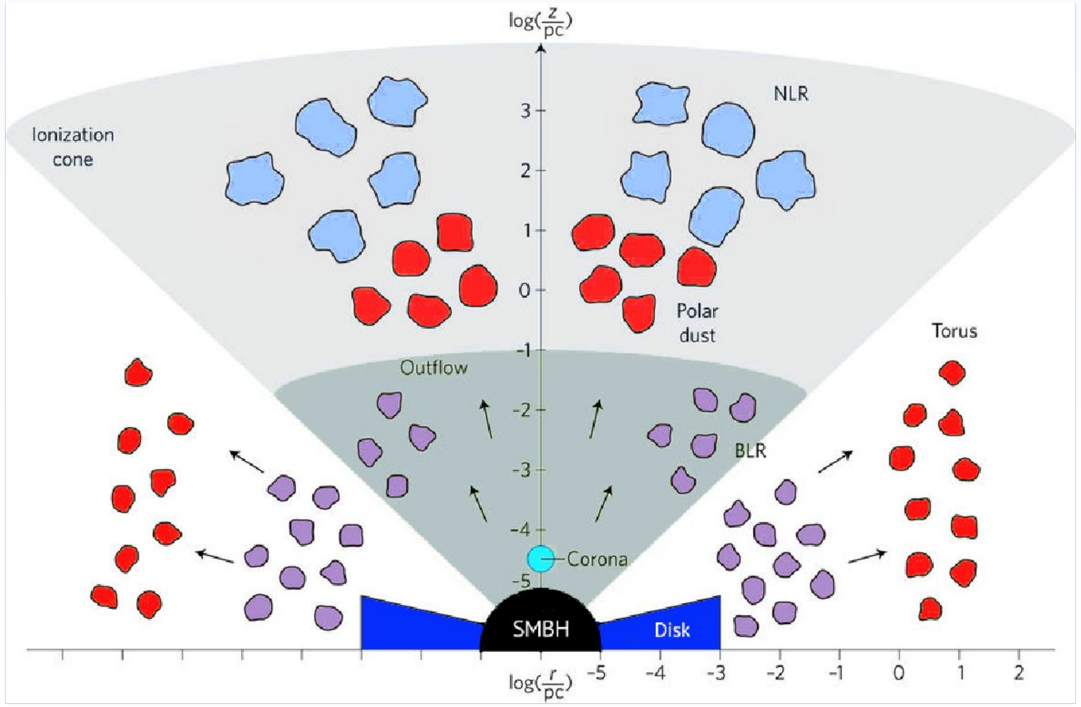


- UV selected galaxies -> 20/49 detected with ALMA.   Expect more when pushed deeper.
- Those detected indicate that most of their star formation obscured.
- Dust emission is often spatially separated from UV emission – further evidence of distinct modes.
- Detections will advance rapidly with blind mm-wave surveys coming from TolTEC / LMT

Historical Role of Obscured AGN? Unknown

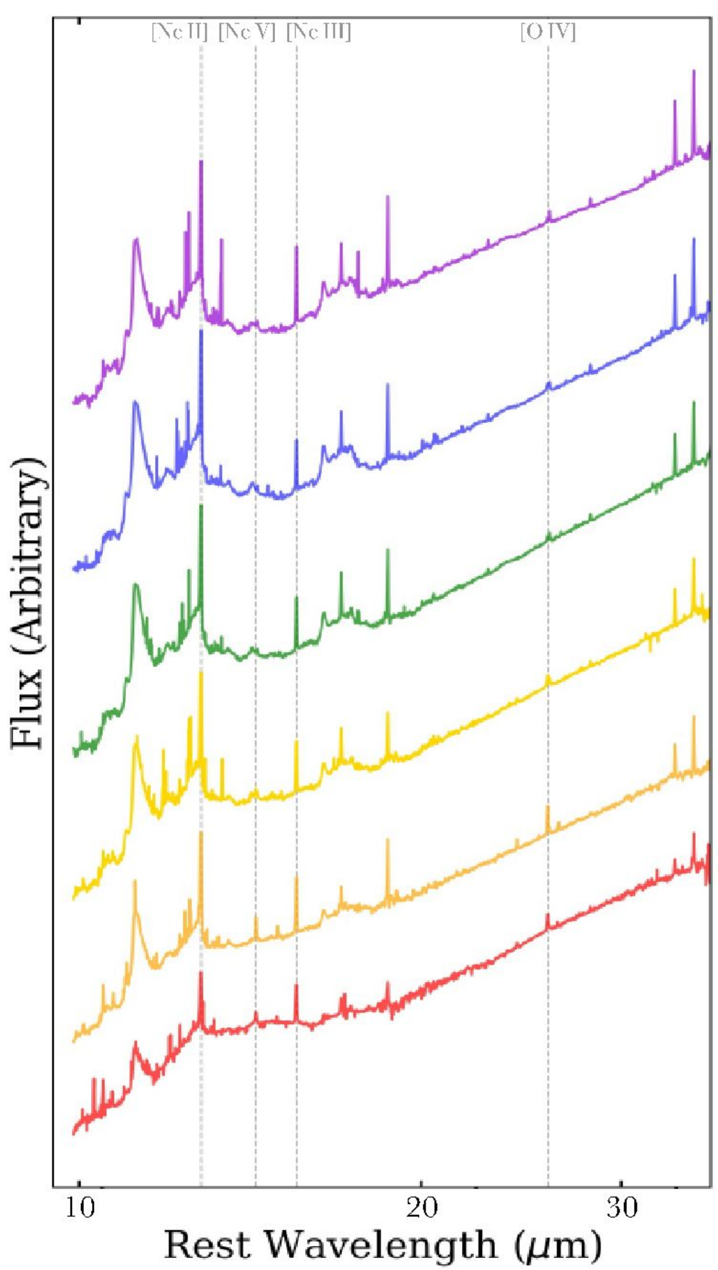


Hickox and Alexander 2018



- 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.

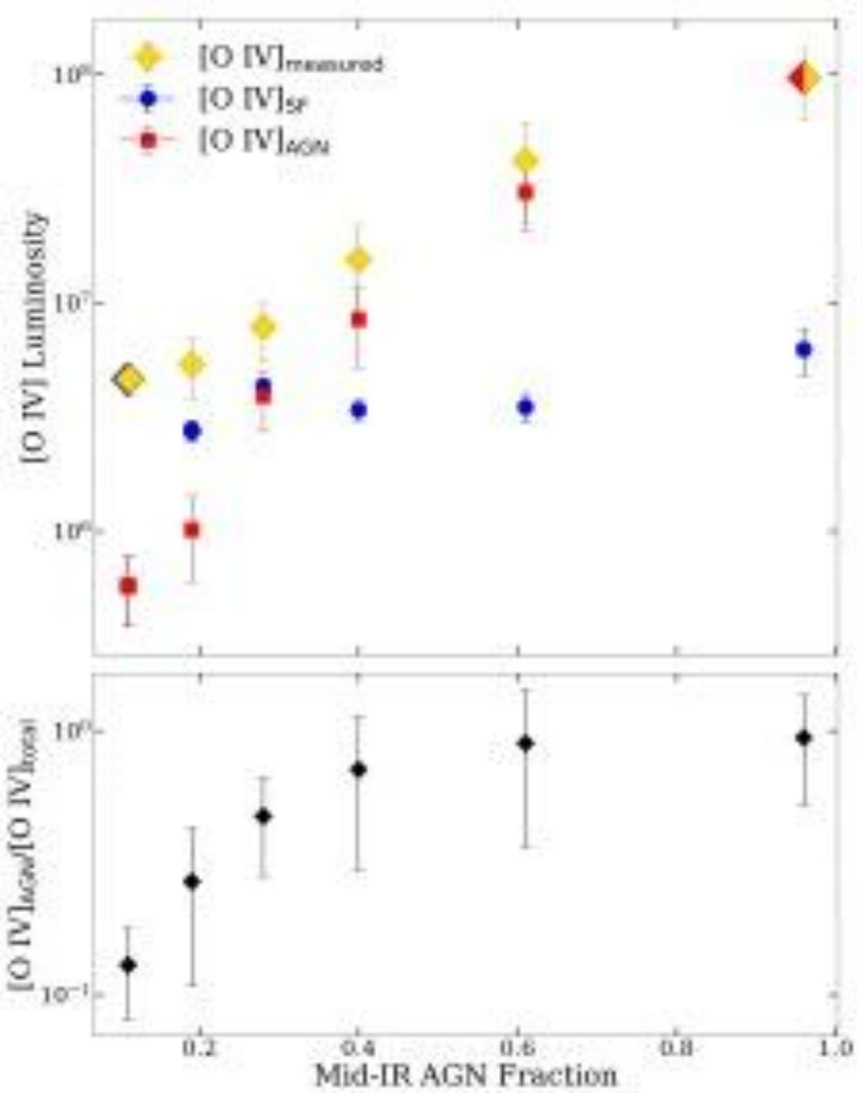
Historical role of Obscured AGN? Measure with far-IR



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

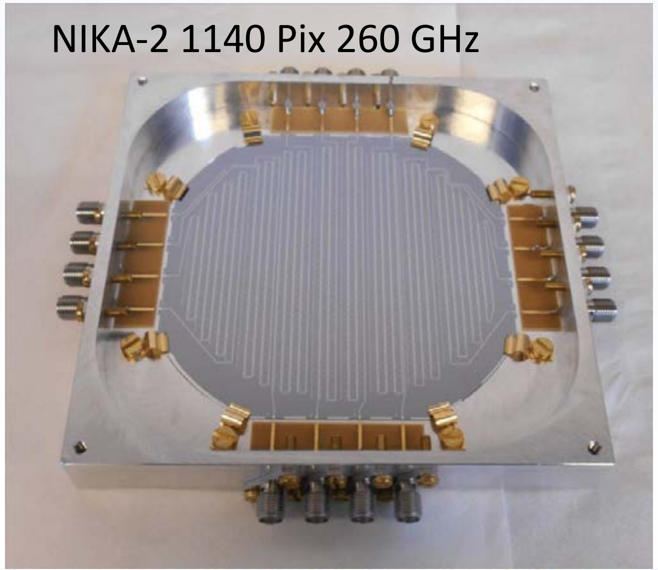
- [NeV] mid-IR transitions always an unambiguous probe, but a challenging measurement.
- [OIV] 26 microns emerging as a reliable tracer of embedded accretion, can be reliably corrected for (sub dominant) star formation contribution.

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

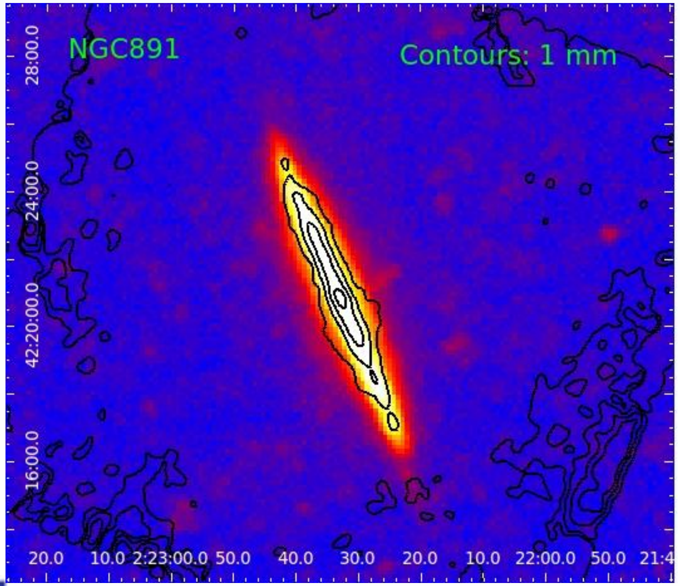


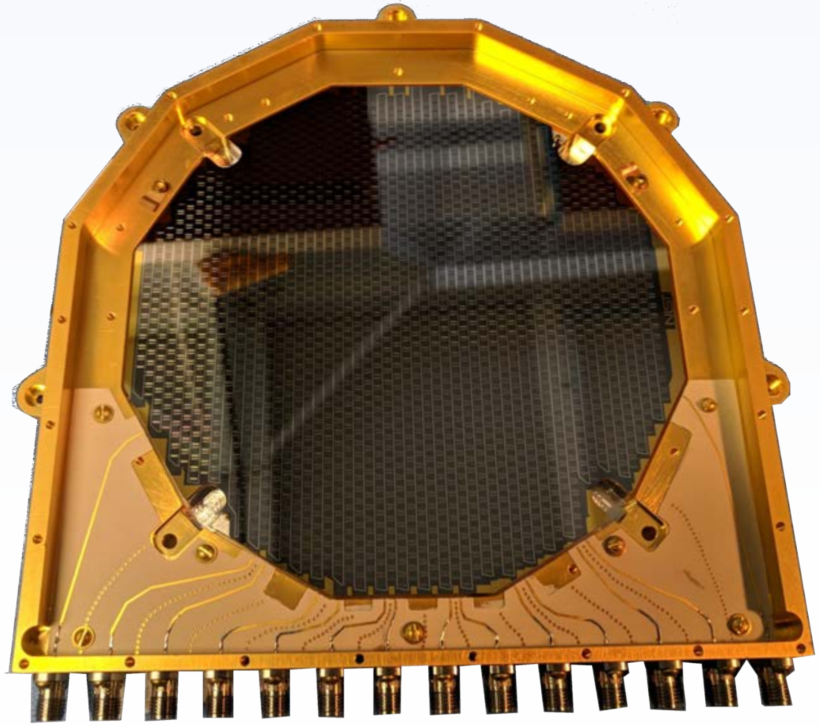
$$\dot{M}_{BH}(M_\odot/yr) = 6.44\times 10^{-15}\,(L_{[\mathrm{OIV}]meas} - aL_{[\mathrm{NeII}]})^{1.69}$$

KID arrays fielded in many instruments



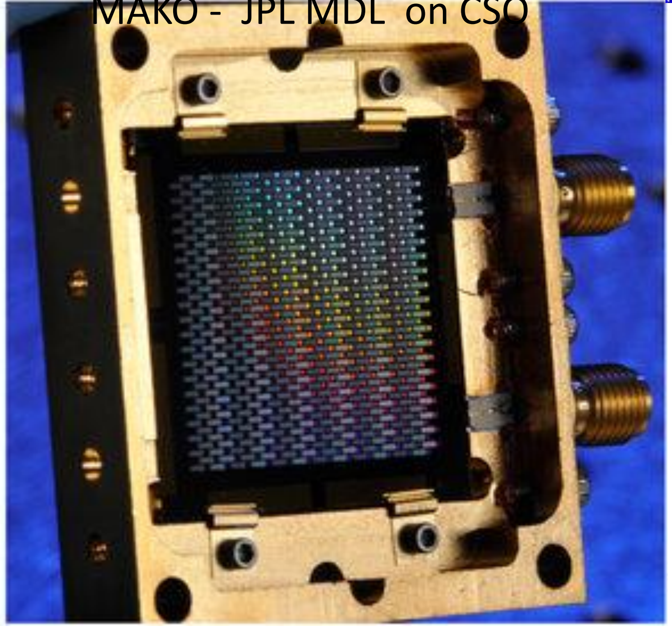
NIKA-2 1140 Pix 260 GHz

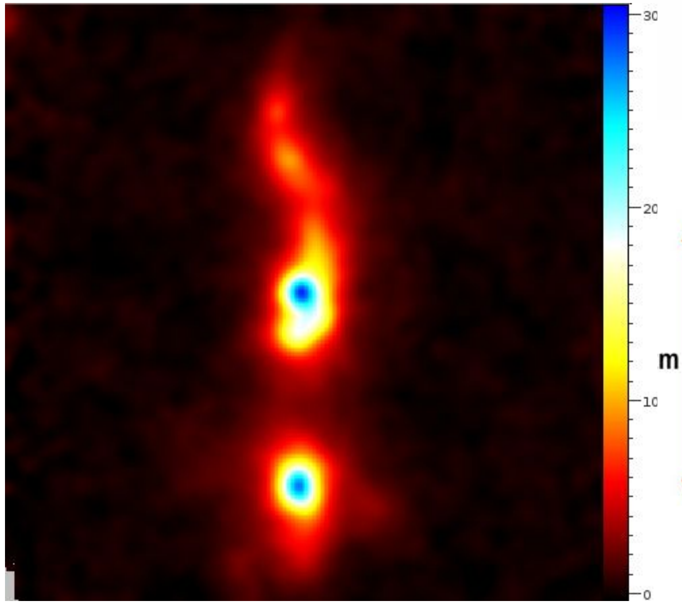




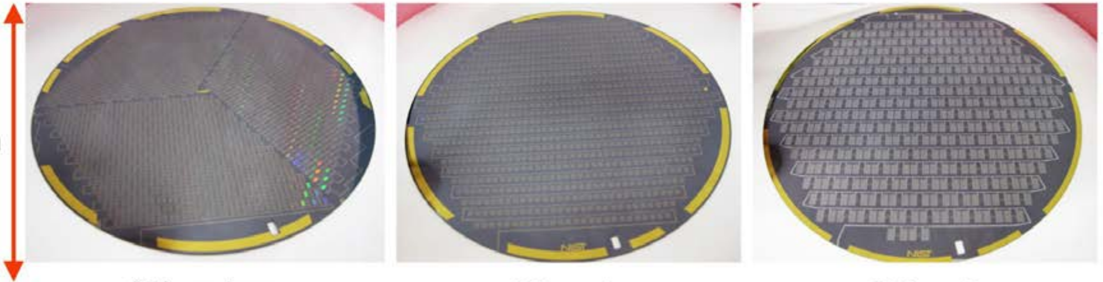
TolTEC on LMT 1.1 mm, 1.4 mm, 2 mm 7000 total pixels

MAKO - JPL MDL on CSO





BLAST – TNG far-IR balloon

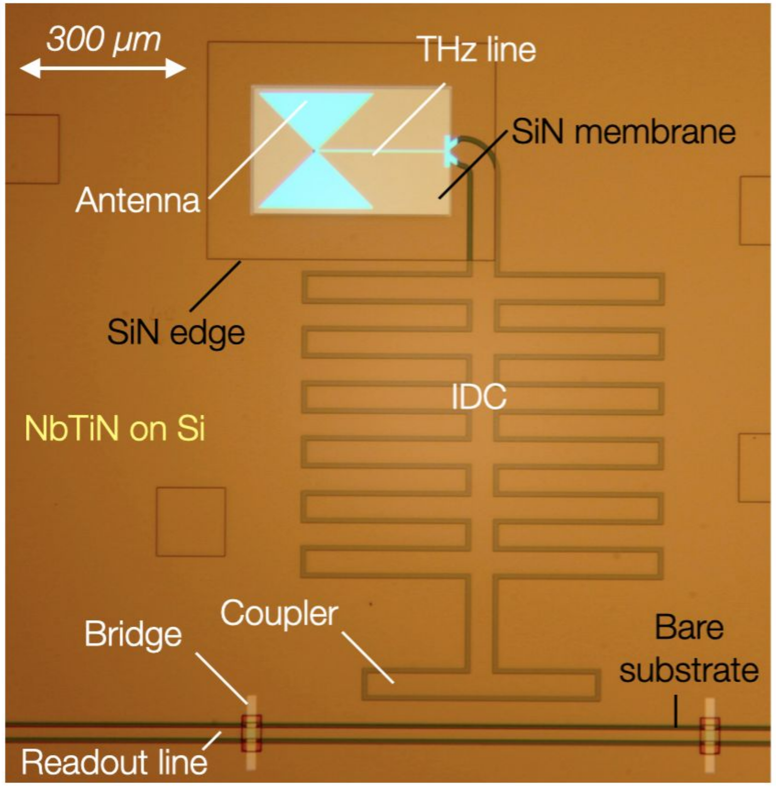


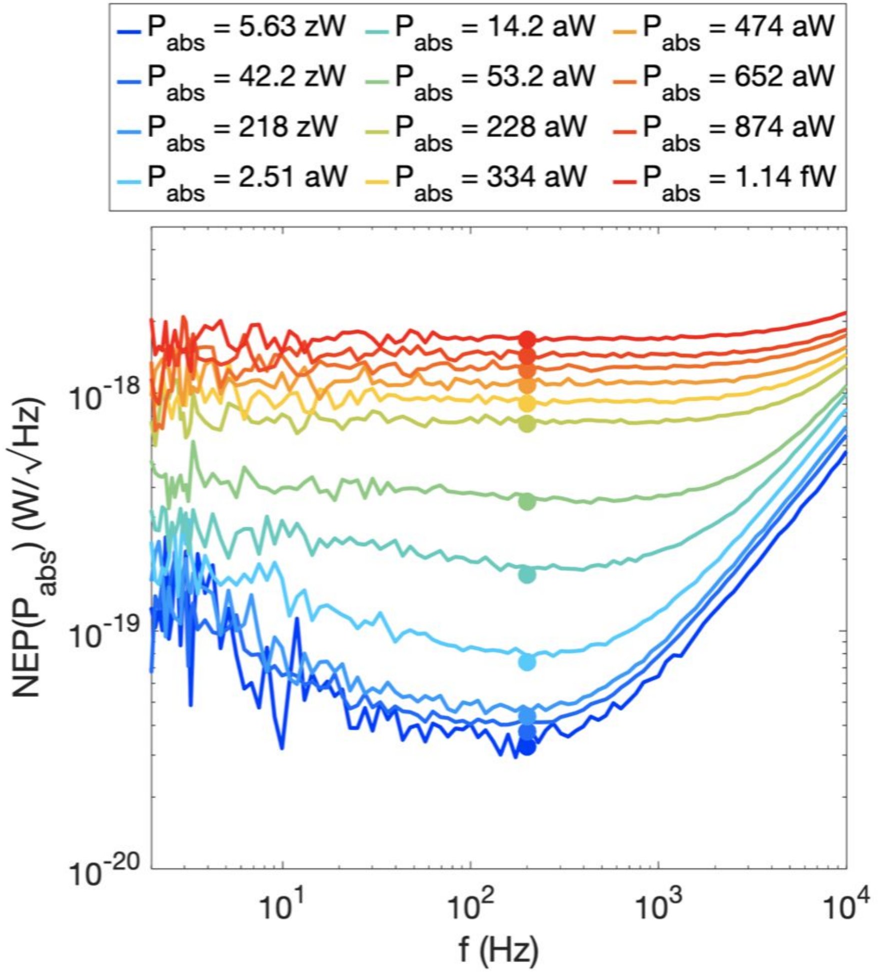
250 μm Array
1836 Detectors

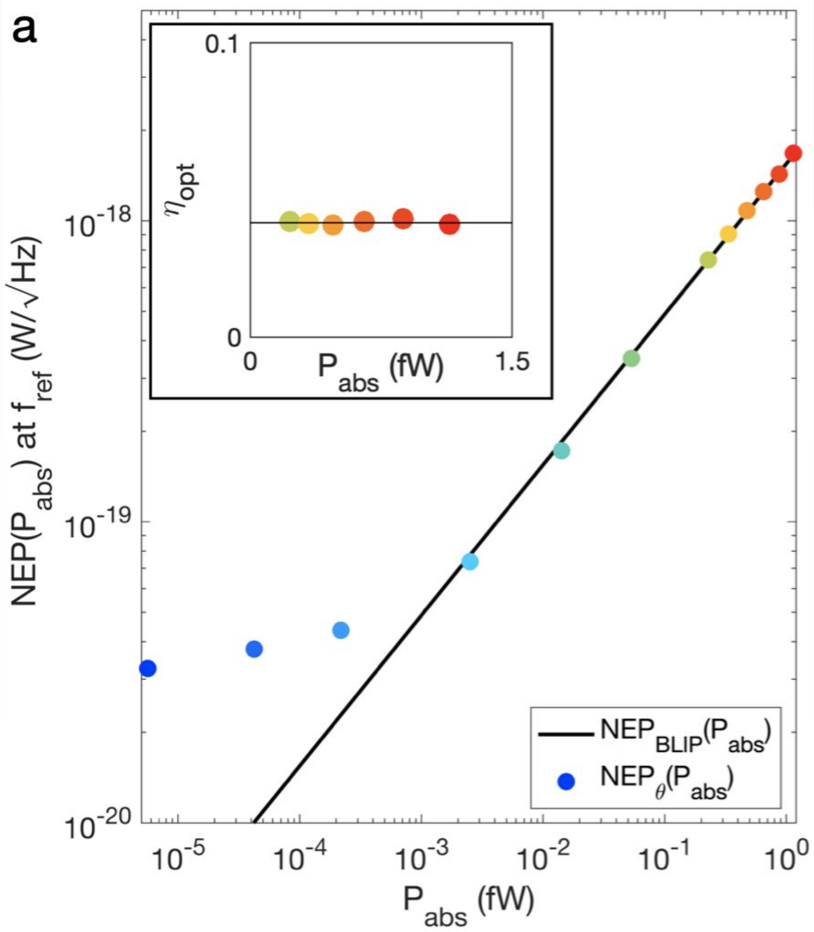
350 μm Array
938 Detectors

500 μm Array
544 Detectors

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



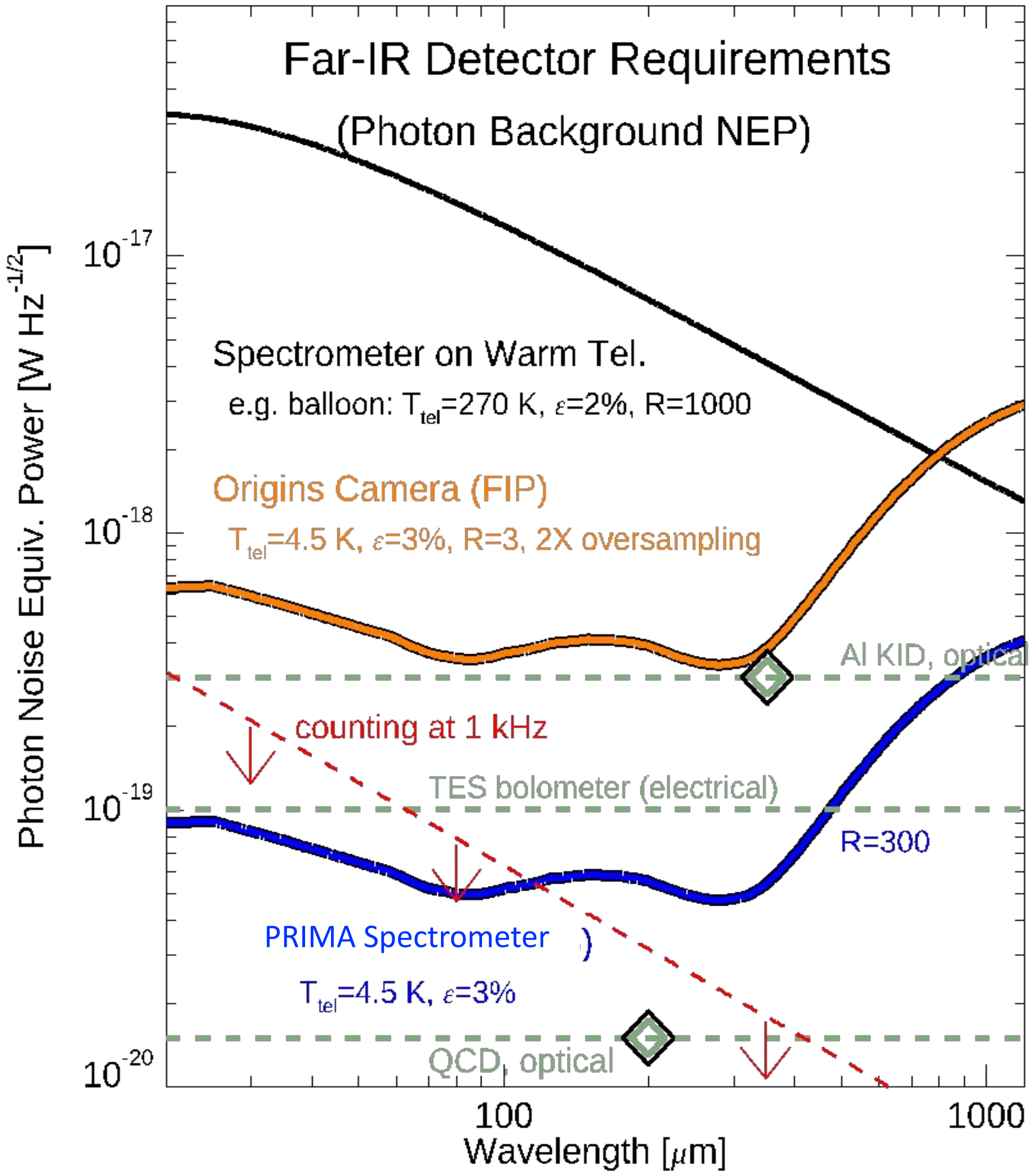




12190-32 tomorrow 2:40 PM 524A

SRON Netherlands Institute for Space Research

TU Delft



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

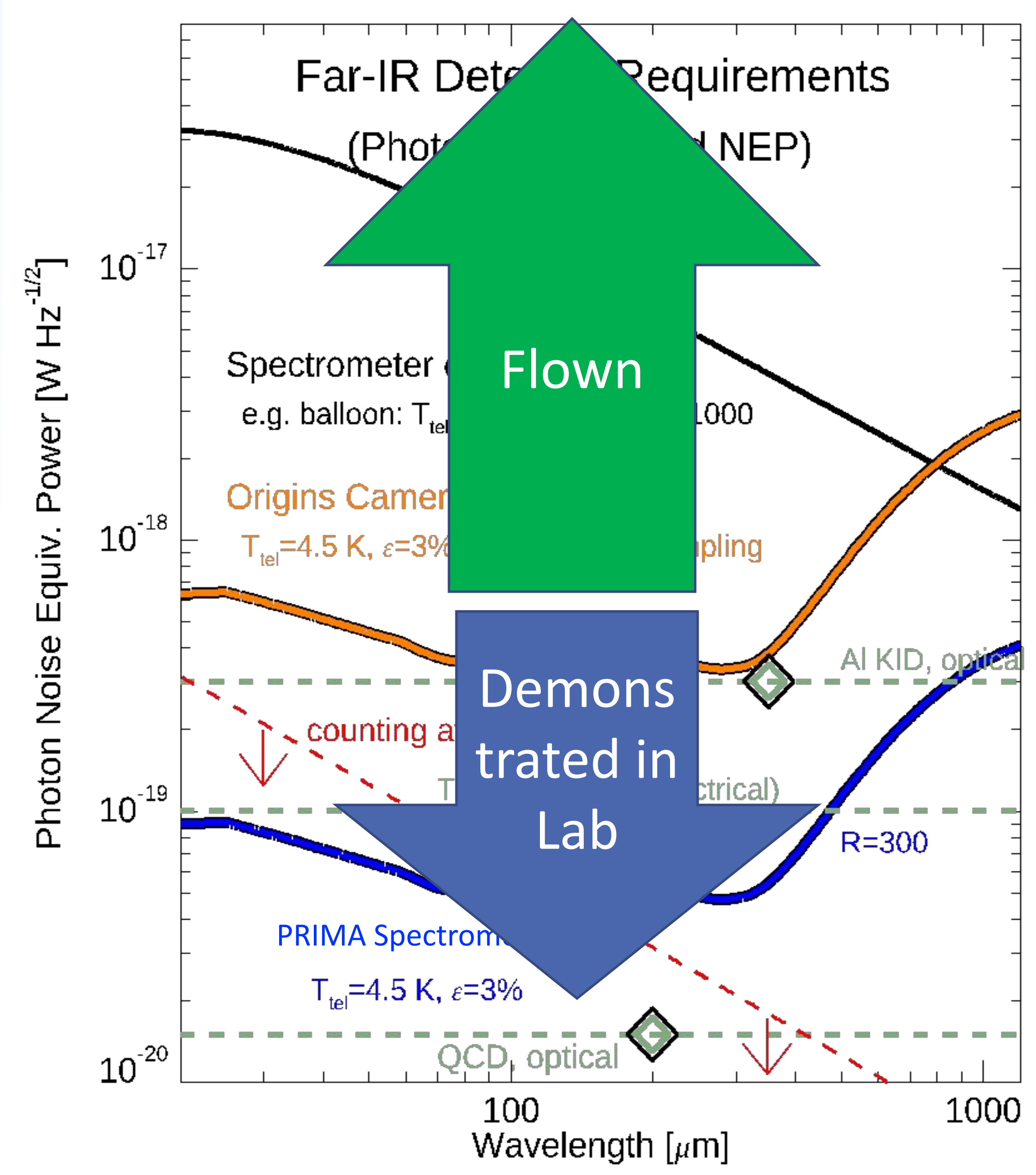
Sensitivity

- 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

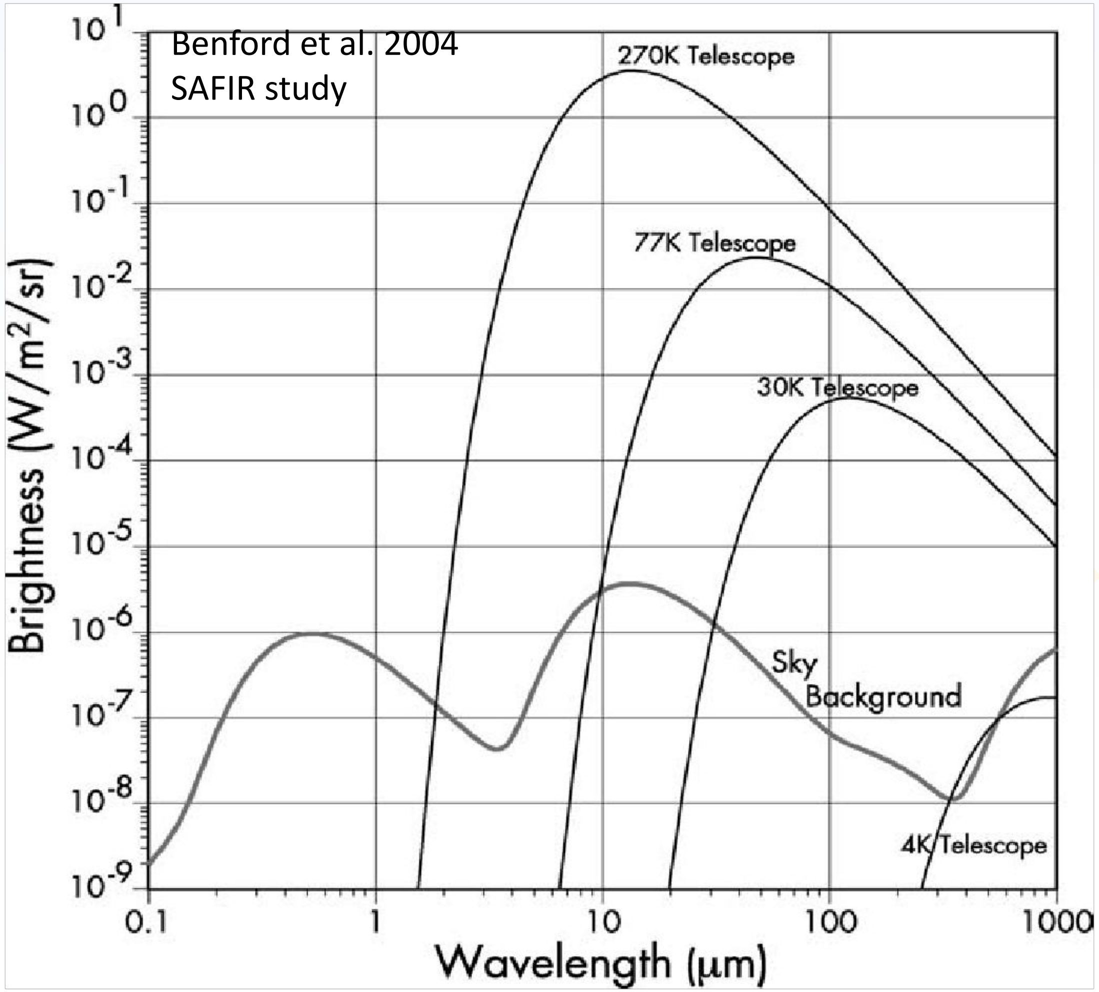
Sensitivity

- 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

Cryogenic telescope is a powerful opportunity


Benford et al. 2004
SAFIR study

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

IMPLEMENTATION

- Unbiased spectroscopic and photometric surveys
  - wide tier (base layer): hyperspectral and broad band imaging to net rare, luminous objects and sample cosmic variance (~2-10 sq. deg)
  - middle tier: moderated depth, unbiased spectroscopic survey (~1-2 sq. deg), plus a 2nd imaging tier to reach confusion limit and select more sources for spec follow-up
  - Possible top tier (0.1 sq. deg.) for a deep, spectroscopic survey
  - All tiers will be placed in Roman High Latitude Wide Area Survey field: 1700 sq. deg., 4-band optical imaging and slitless grism spectroscopy: H-alpha redshifts and stellar masses of 1E7 galaxies from 1 < z < 4
- Spectroscopic follow-up
  - high res (R~1000-2000) for outflow measurements. Can target specific bands (using low-res redshifts or phot-z's) if needed. Initial estimates suggest targeting ~300-500 sources for ~500hrs, selected to have feedback tracers in the blind survey.
  - Possible ultra-deep (5-10hr) low-res spectra of ~20-50 high-z targets for PAH detection/analysis.

Some IR Lines Accessed by PRIMA

Species	Rest λ (μm)	Redshift Range	Ionization Energy (eV)	Typical Line Luminosity × 10^{-4} L_{FIR}
PAHs	3 – 13.5	> 0.8	N/A	100
[Ne II]	12.8	> 0.9	21.6	3
[Ne V]	14.3	> 0.7	97.1	2
[Ne V]	24.3	< 7	97.1	2
[O IV]	25.9	< 6.5	54.9	5
[S III]	33.5	< 4.7	23.3	3
[Si II]	34.8	< 4.5	8.2	4
[O III]	51.8	< 2.7	35.1	20
[O I]	63.2	< 2.0	N/A	10
[O III]	88.4	< 1.1	35.1	8
[N II]	122	< 0.6	14.5	2
[O I]	146	< 0.3	N/A	3
[C II]	158	< 0.2	11.3	20

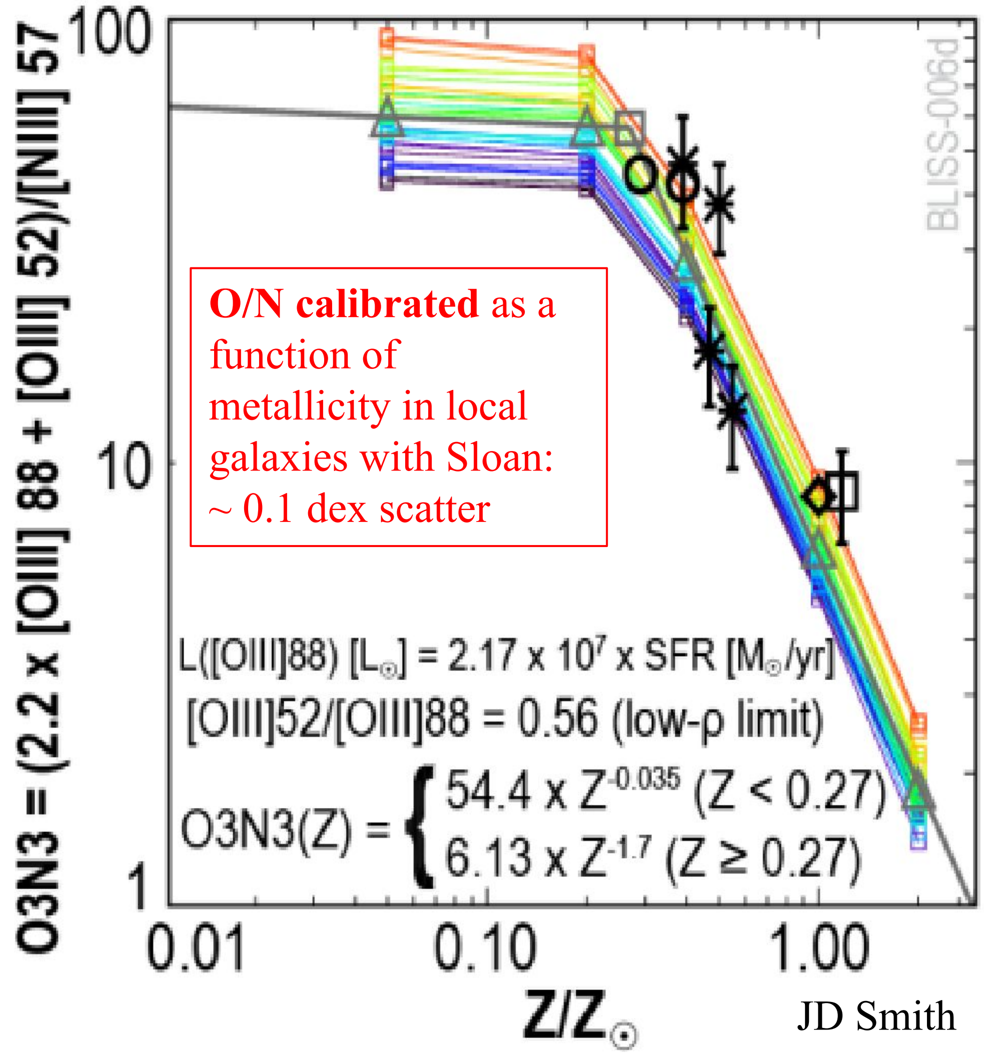
Table assumes 24 – 193 μm coverage; range to be optimized.

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

Nucleosynthesis History

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



O/N calibrated as a function of metallicity in local galaxies with Sloan: ~ 0.1 dex scatter

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)