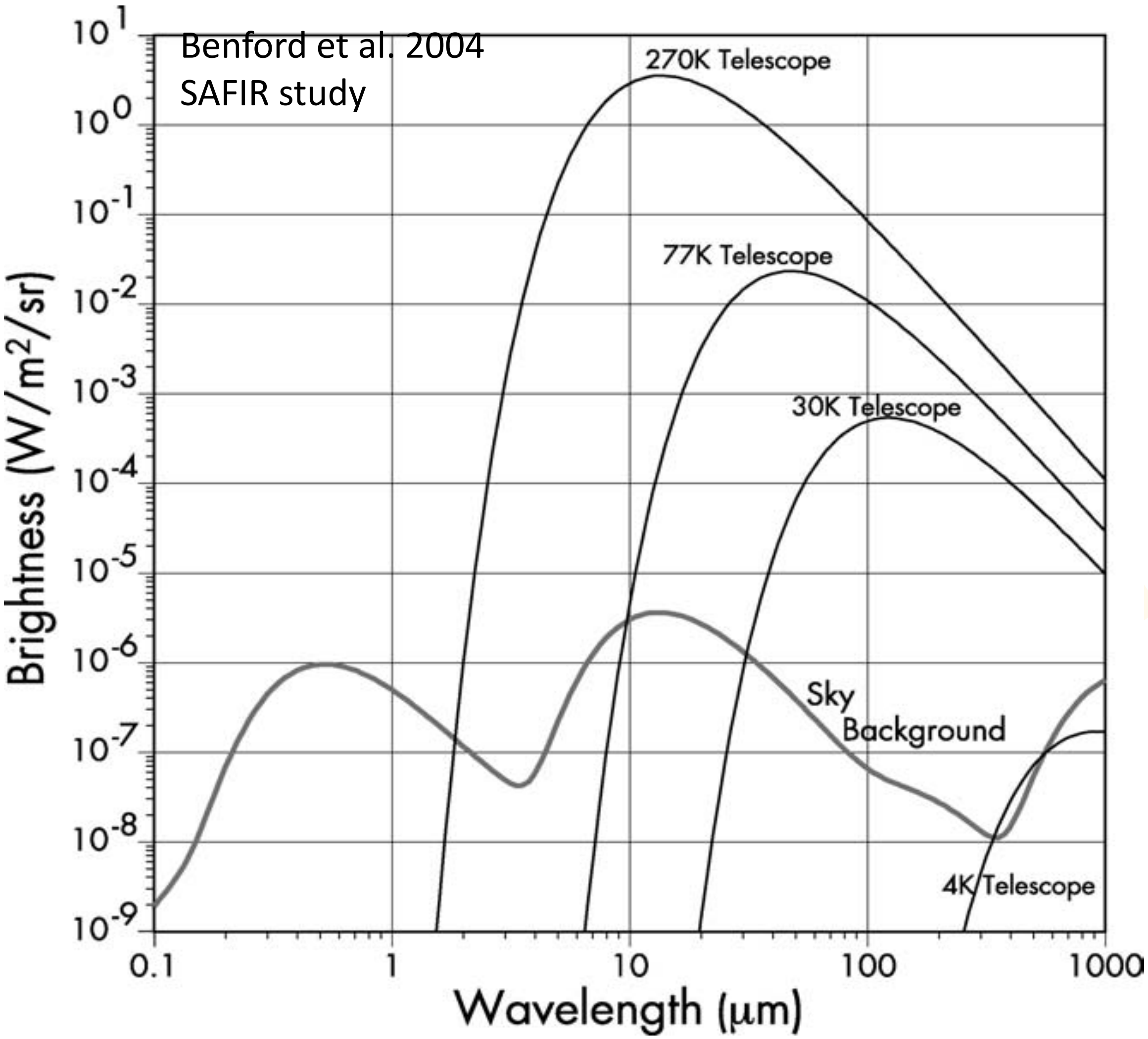
PRIMA (and general far-IR) Probe Instrumentation

Matt Bradford

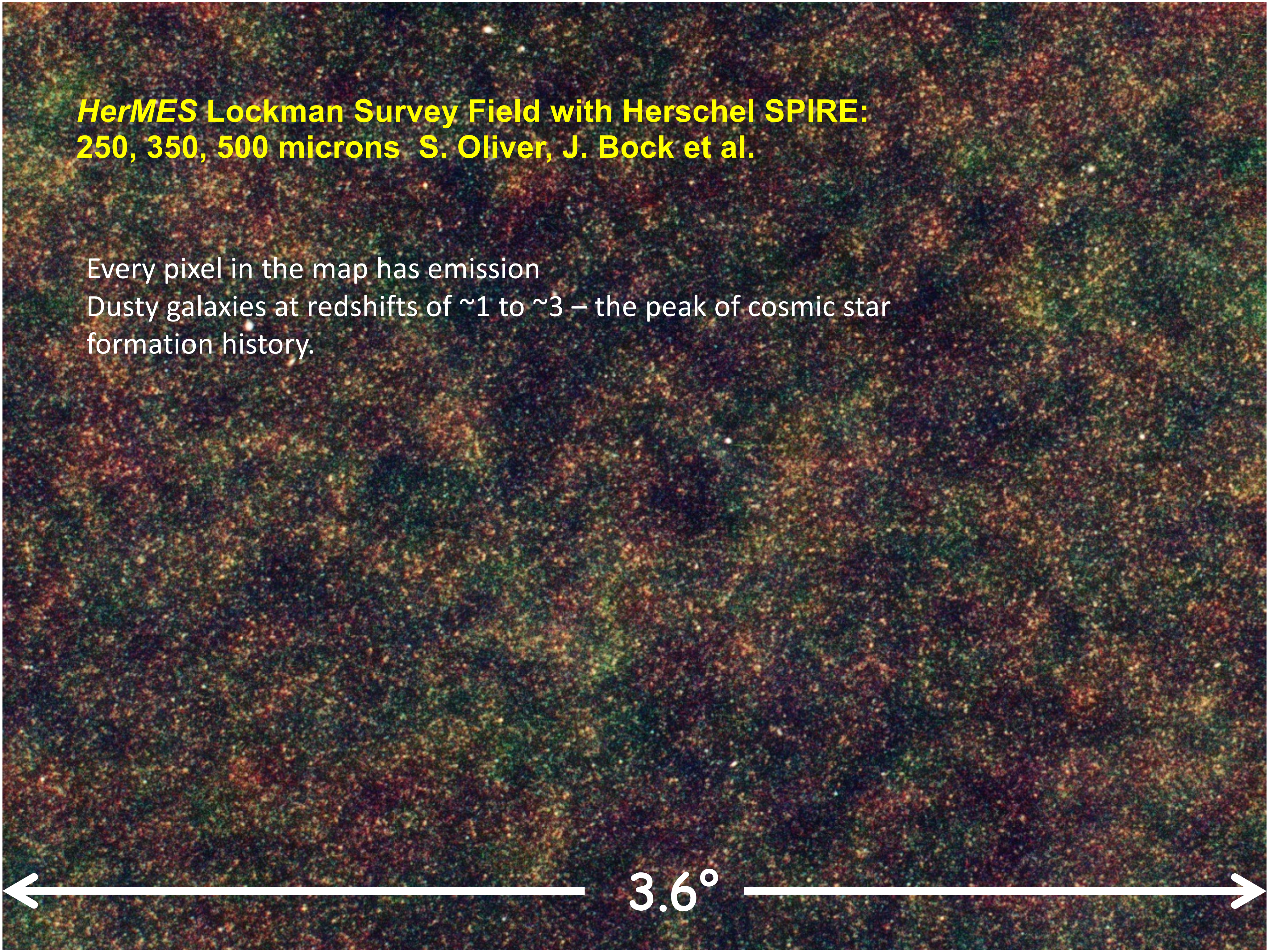
March 31, 2022

Cryogenic telescope is a powerful opportunity

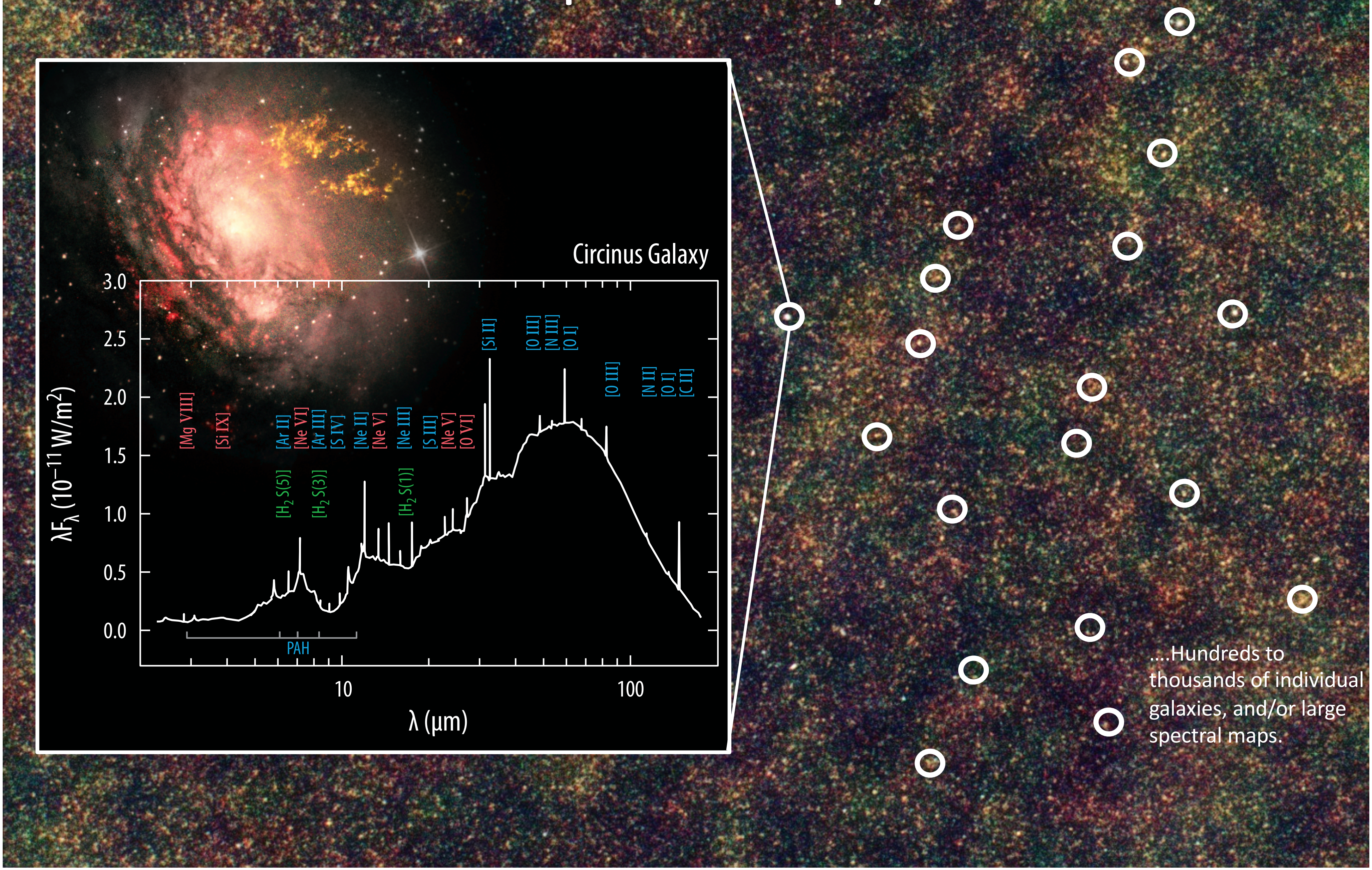


Comparing low-emissivity 300 K system to zodiacal light background is about a factor of 1 million, e.g. at 60 microns. Sensitivity is the square root of brightness, speed is this ratio.

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


HerMES Lockman Survey Field with Herschel SPIRE:
250, 350, 500 microns S. Oliver, J. Bock et al.
Every pixel in the map has emission
Dusty galaxies at redshifts of ~1 to ~3 – the peak of cosmic star formation history.
3.6°

Low-resolution spectroscopy with PRIMA



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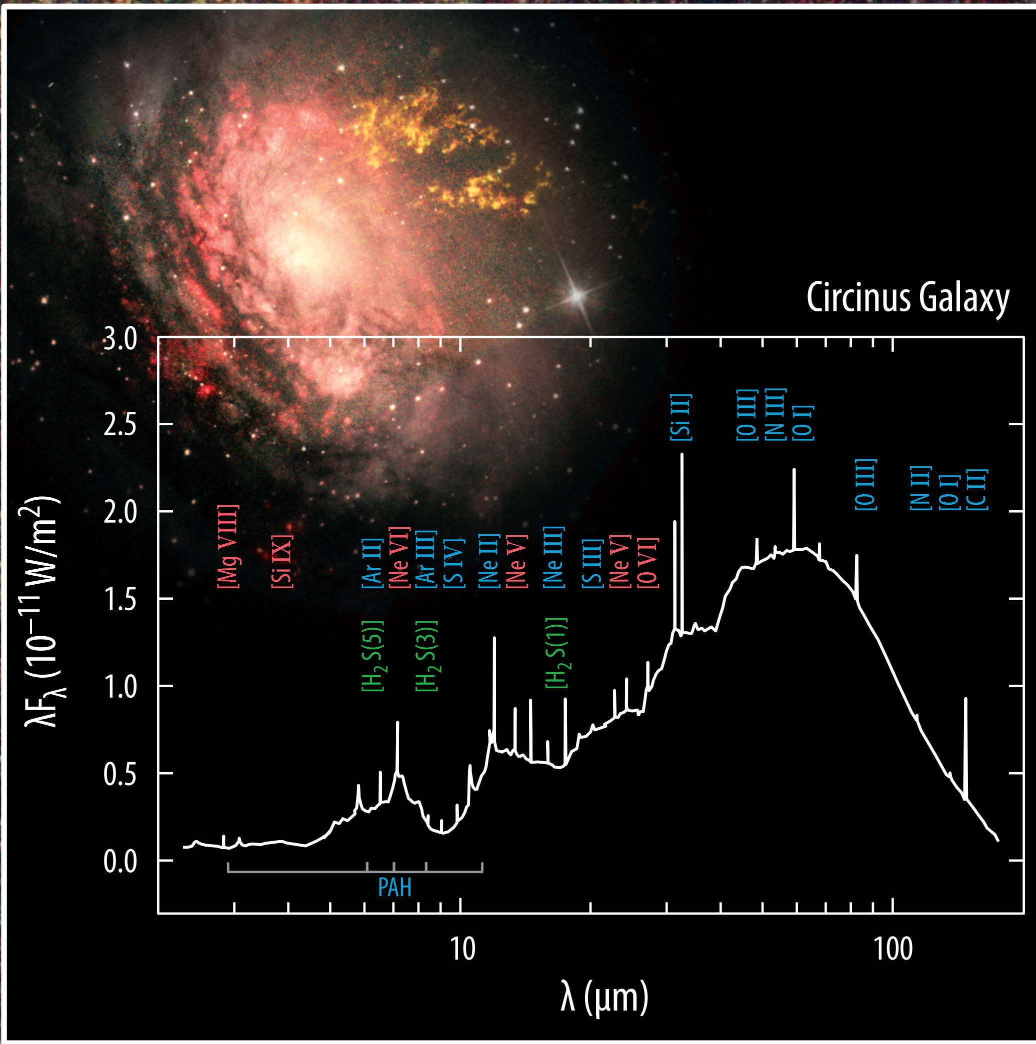

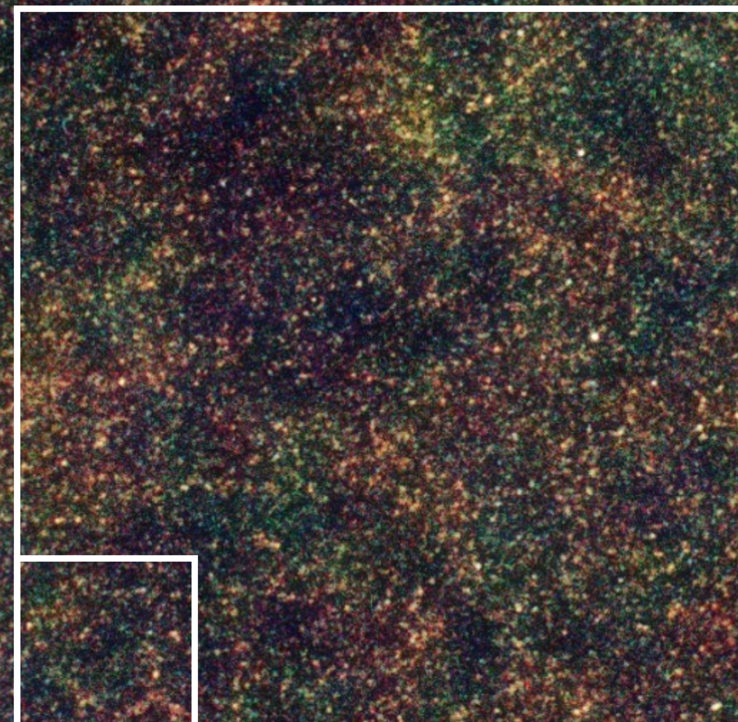

Example Field-Filling Spatial / Spectral Surveys: Deep, Medium

A data cube with every pixel having a spectrum

Source confusion not an issue for spectral lines. E.g. M. Bonato+ 2019

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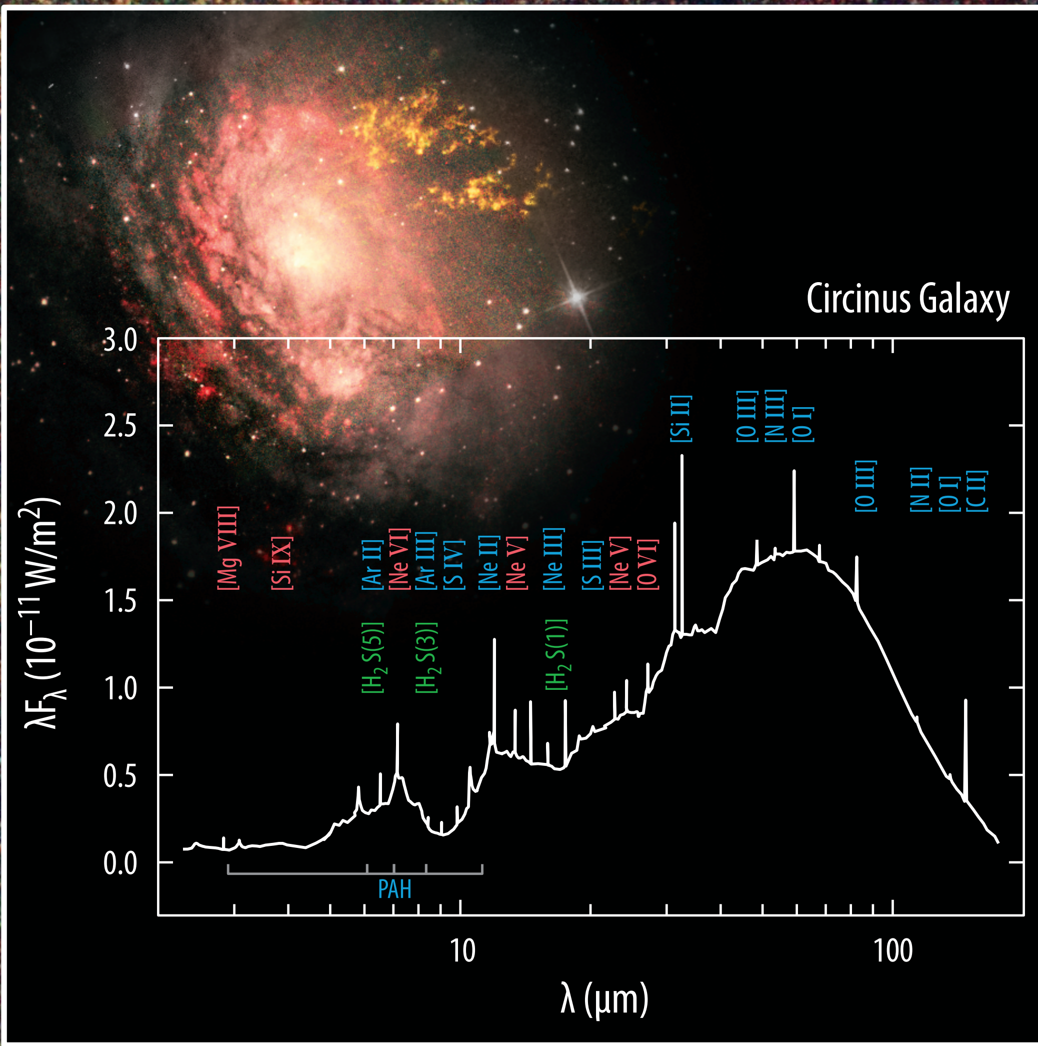

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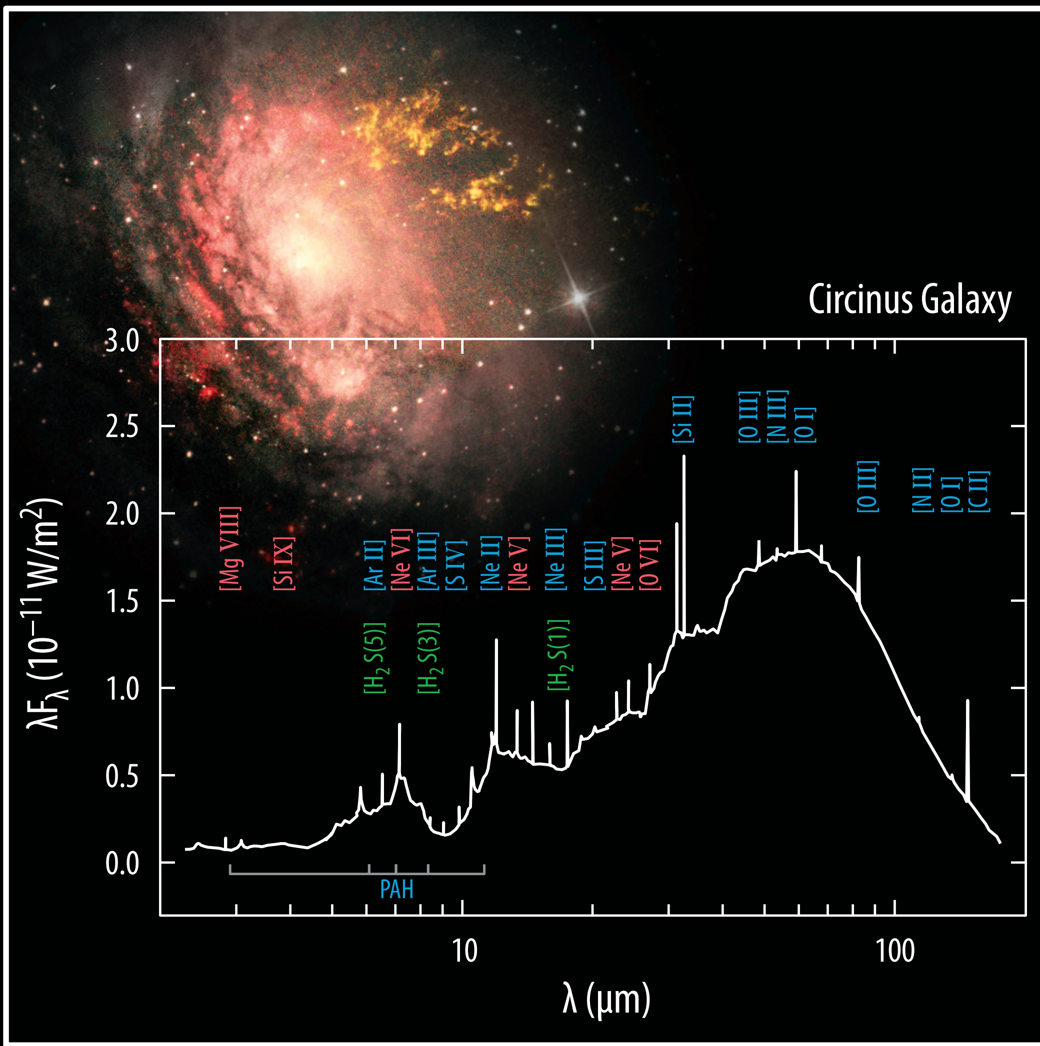

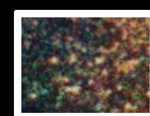

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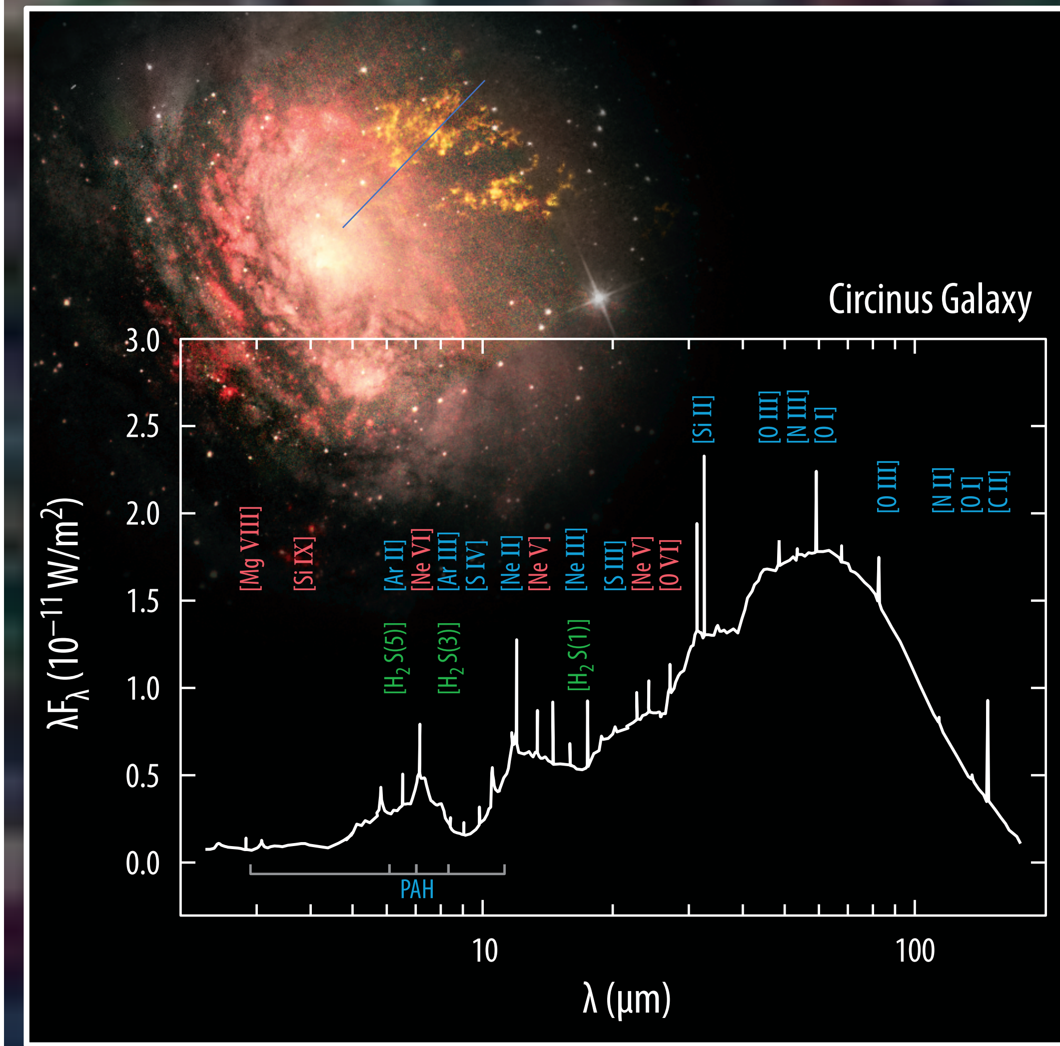
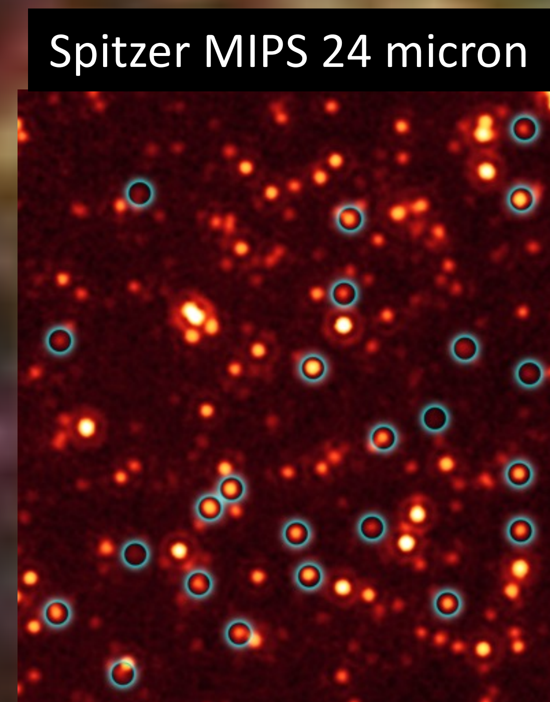
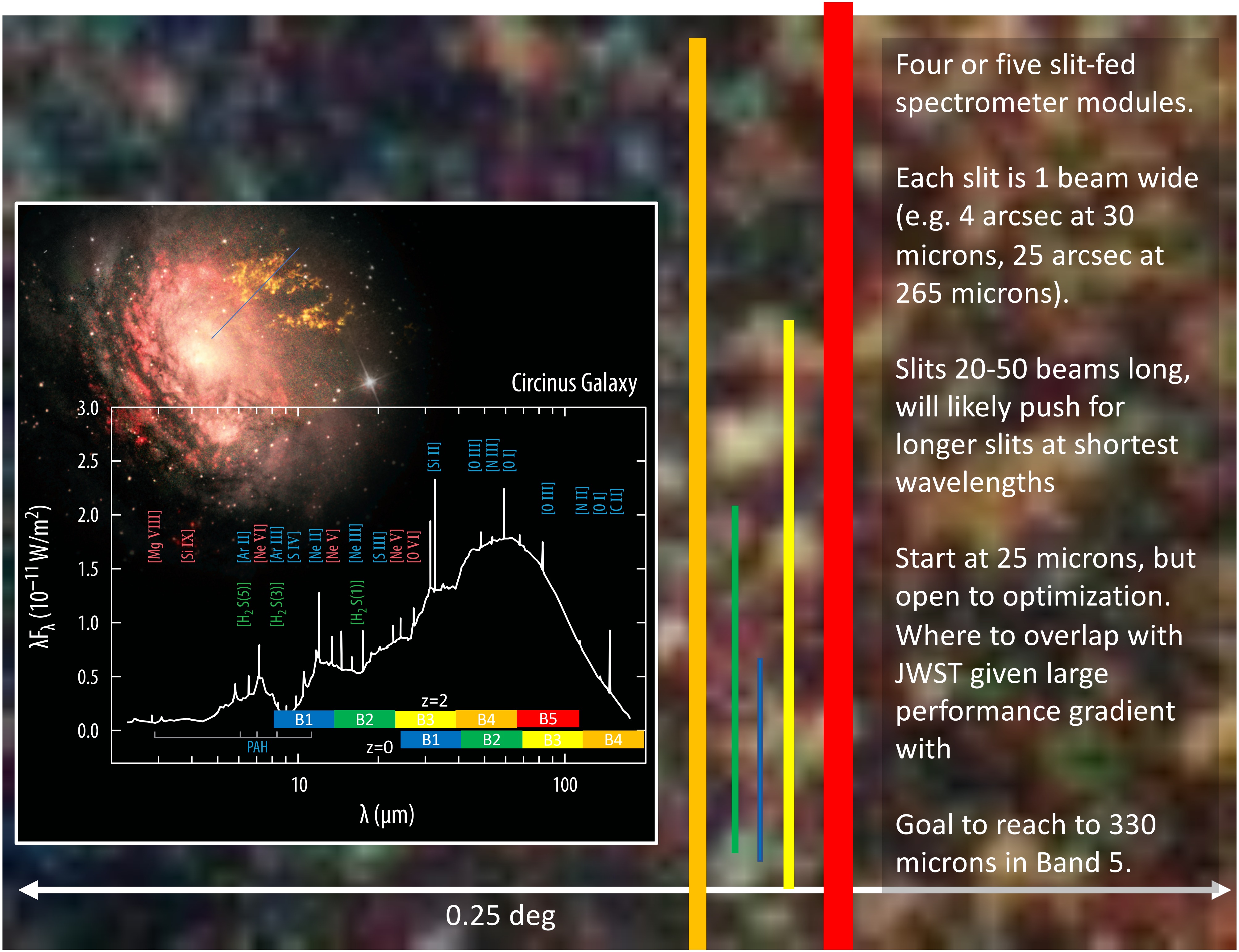
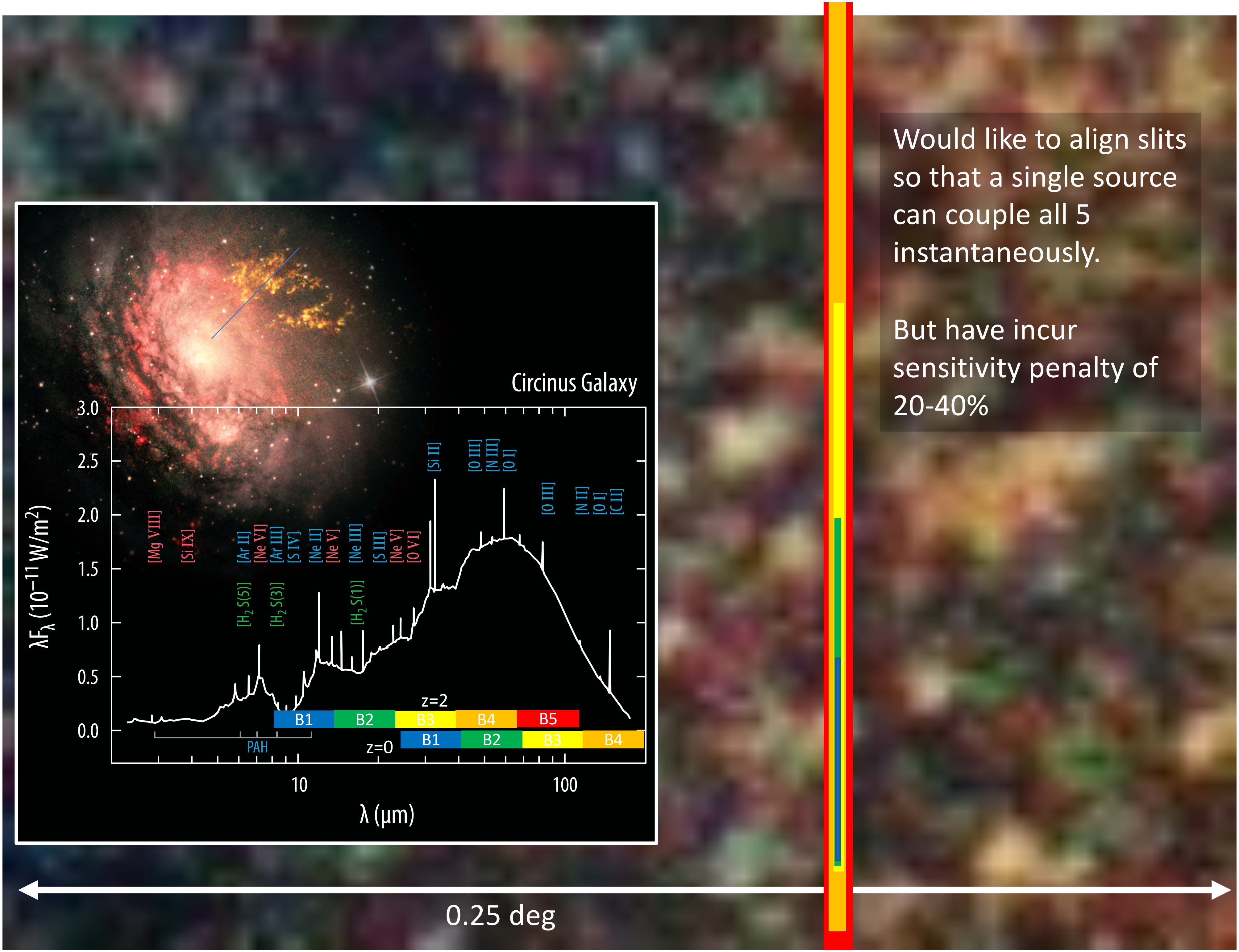




0.25 deg


Circinus Galaxy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
λF_λ (10^−11 W/m^2)
[Mg VIII]
[Si IX]
[Ar II]
[Ne VI]
[Ar III]
[S IV]
[Ne II]
[Ne V]
[Ne III]
[S III]
[Ne V]
[O VI]
[Si II]
[O III]
[N III]
[O I]
[O III]
[N II]
[O I]
[C II]
[H2 S(5)]
[H2 S(3)]
[H2 S(1)]
PAH
z=2
B1 B2 B3 B4 B5
z=0
B1 B2 B3 B4
10
100
λ (μm)
0.25 deg
Four or five slit-fed spectrometer modules.
Each slit is 1 beam wide (e.g. 4 arcsec at 30 microns, 25 arcsec at 265 microns).
Slits 20-50 beams long, will likely push for longer slits at shortest wavelengths
Start at 25 microns, but open to optimization. Where to overlap with JWST given large performance gradient with
Goal to reach to 330 microns in Band 5.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PAH
z=2
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B4
B5
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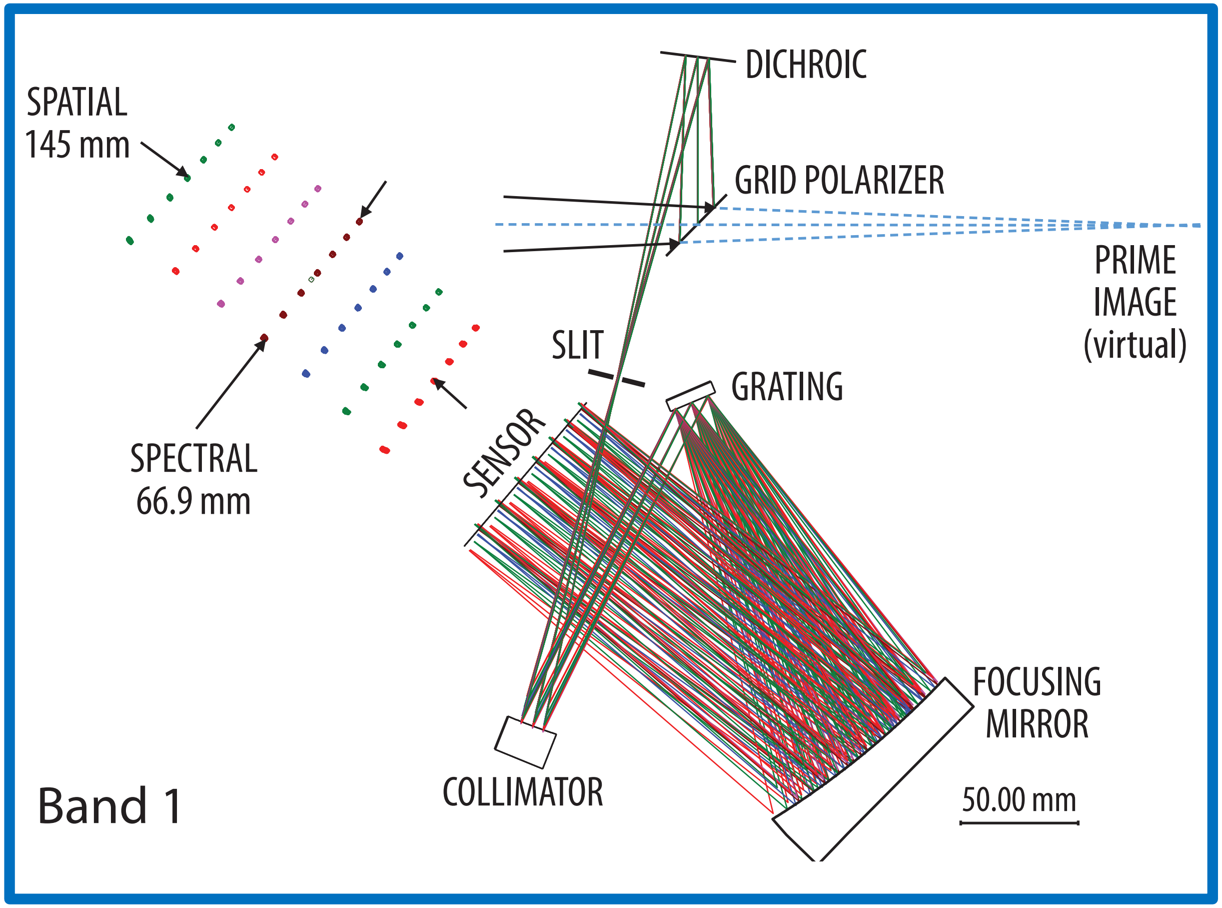
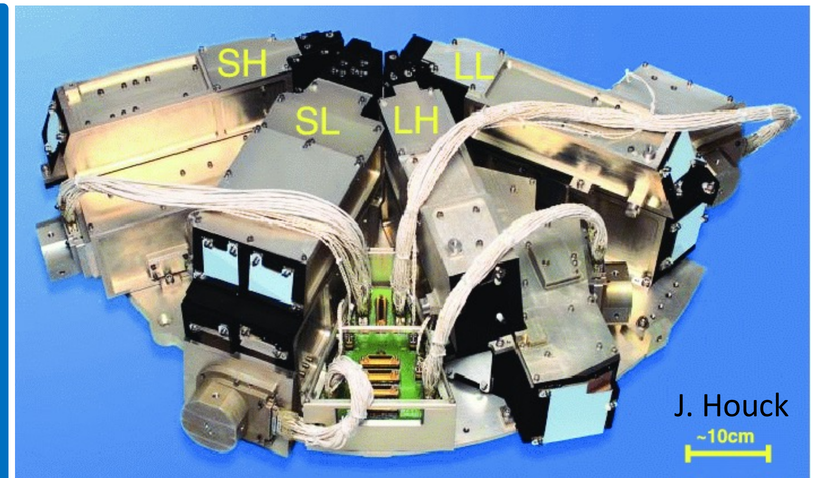
B1
B2
B3
B4
10
100
λ (μm)
Would like to align slits so that a single source can couple all 5 instantaneously.
But have incur sensitivity penalty of 20-40%
0.25 deg

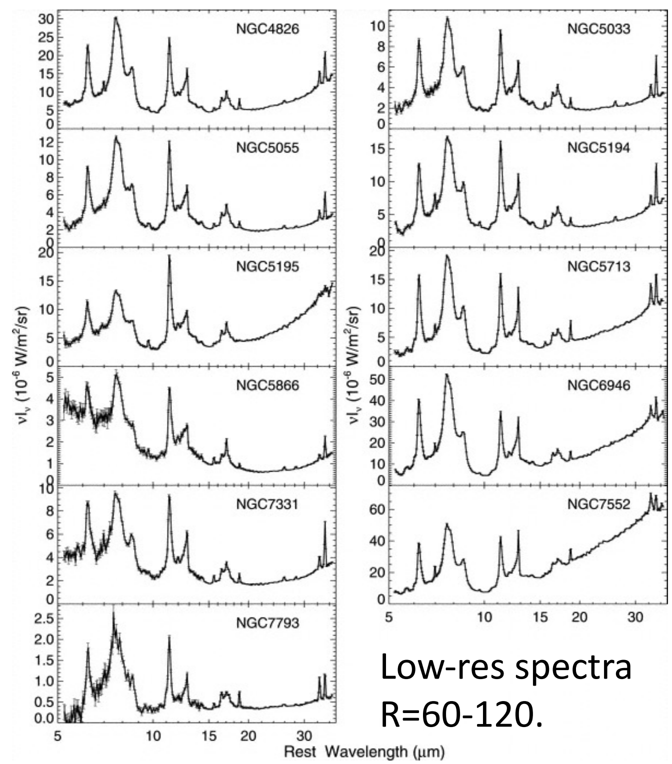
PRIMA: Simple all-aluminum spectrometers



Example design for Band 1, in progress.
(MB, Bruce Cameron @ JPL)
Enclosure cooled to ~1K.
Array will be cooled to 50 to 100 mK.



Spitzer infrared spectrograph



Low-res spectra
R=60-120.

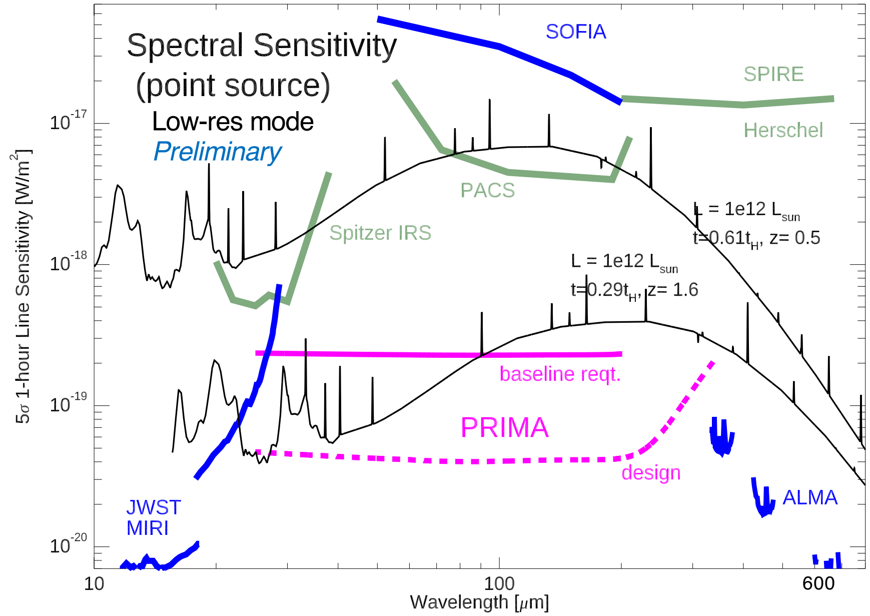
PRIMA

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: ~10 $\left(\frac{\text{deg}^2}{\text{hour}}\right)\left(\frac{\text{F}}{1\ \text{mJy}}\right)^2\left(\frac{1}{\text{SNR}}\right)^2$ (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/m^2 (top right).
- Full instantaneous coverage of at least one ~octave bandwidth spectrometer band at a time, multiple bands simultaneously on source is a goal.
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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/m^2 per spectral resolution element (or unresolved line).
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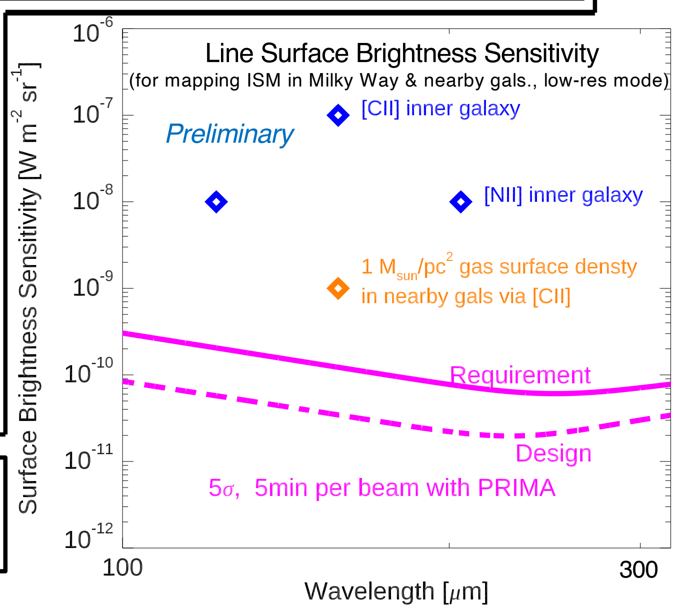
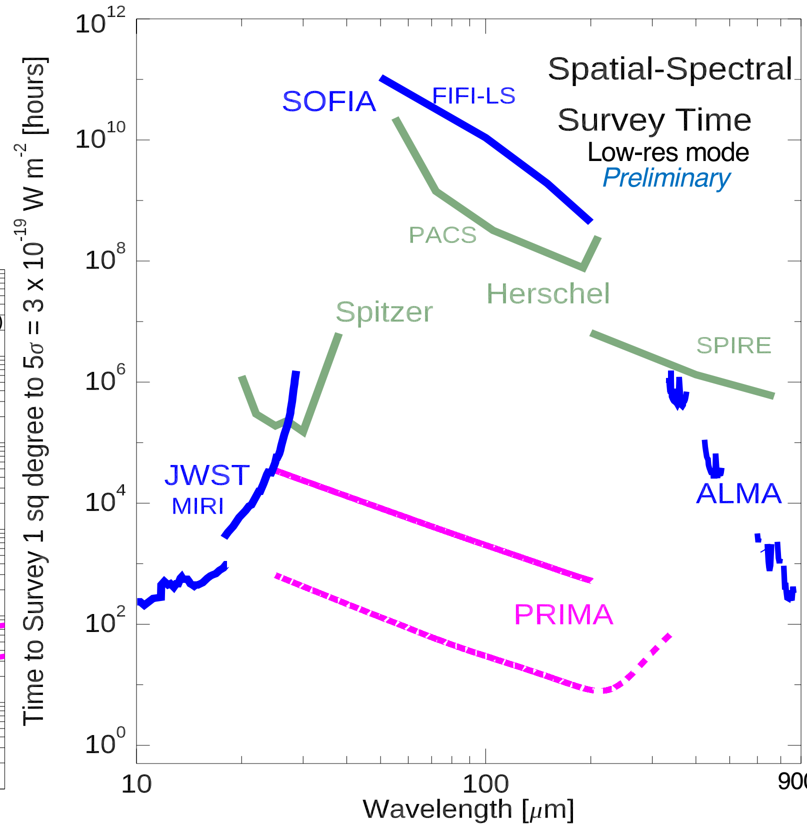


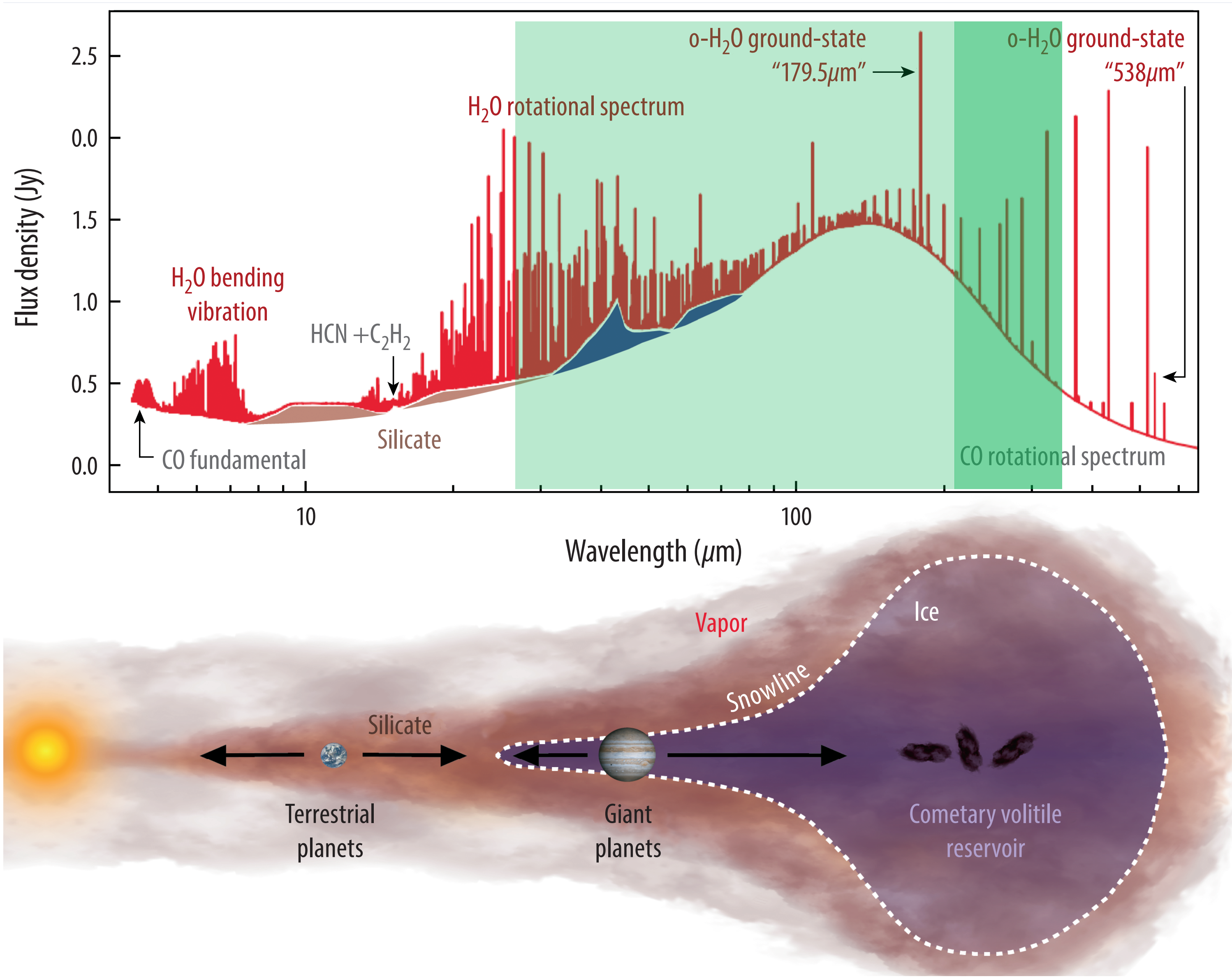


Contact with questions:

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

PRIMA factsheet version 1.1, 22 Feb 2022

High Resolution Spectroscopy with PRIMA



Targeting R of a few thousand across the band.

R value to be determined. Larger R increases instrument volume, mass

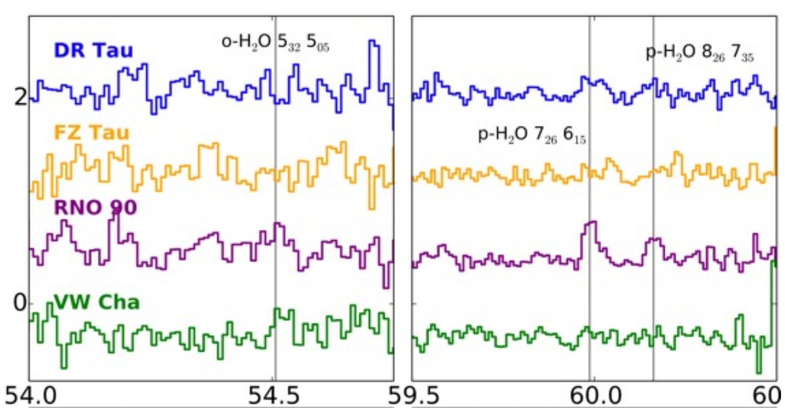
Water spectrum and HD (mass tracer) unique to far-IR

Question for PRIMA: how does this science scales with spectral resolving power.

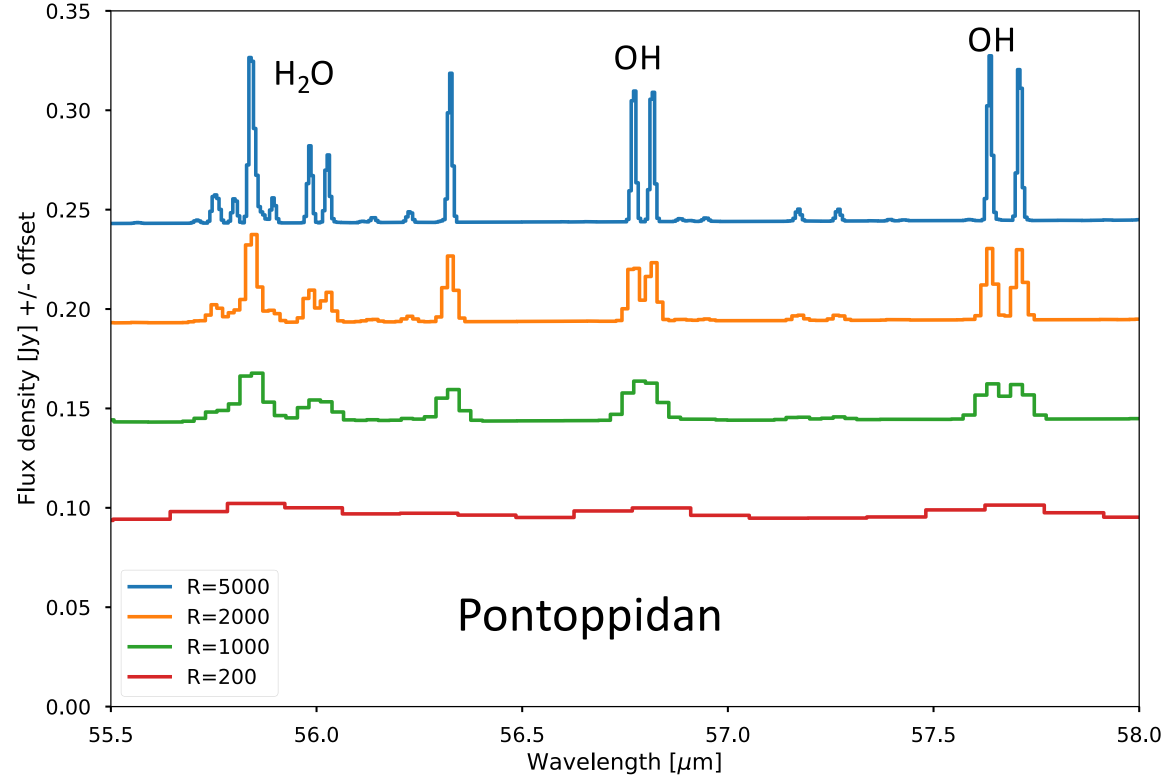
What Drives R?

Line confusion and continuum calibration

- 1000s of water lines in the FIR spectrum
- Potentially blended with other species (OH, CO, HD, hydrides)
- Physical/chemical information tends to be in weaker lines (optically thin, rare species, isotopologues, etc.)
- **→ Cleanly separating individual, diagnostic molecular lines requires R>2000, ideally at least R~5000 at all relevant wavelengths.**

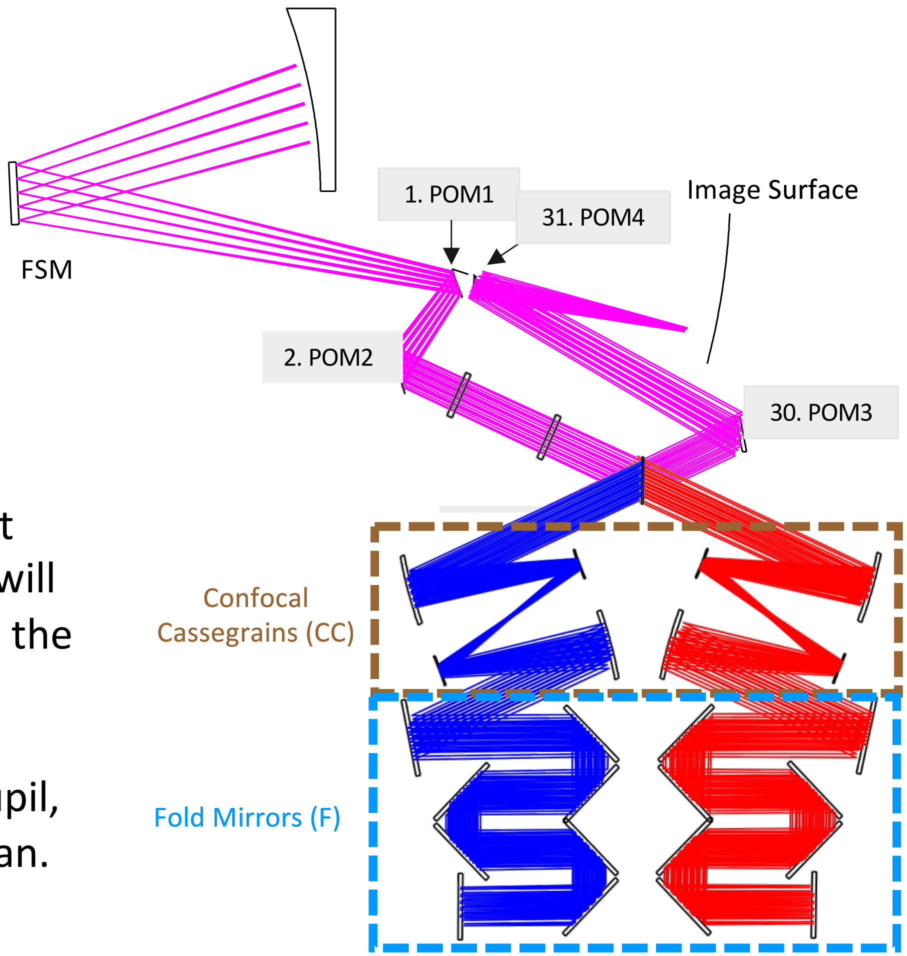


Herschel-PACS for ~1 Msol stars (R~3000, Blevins et al. 2016)



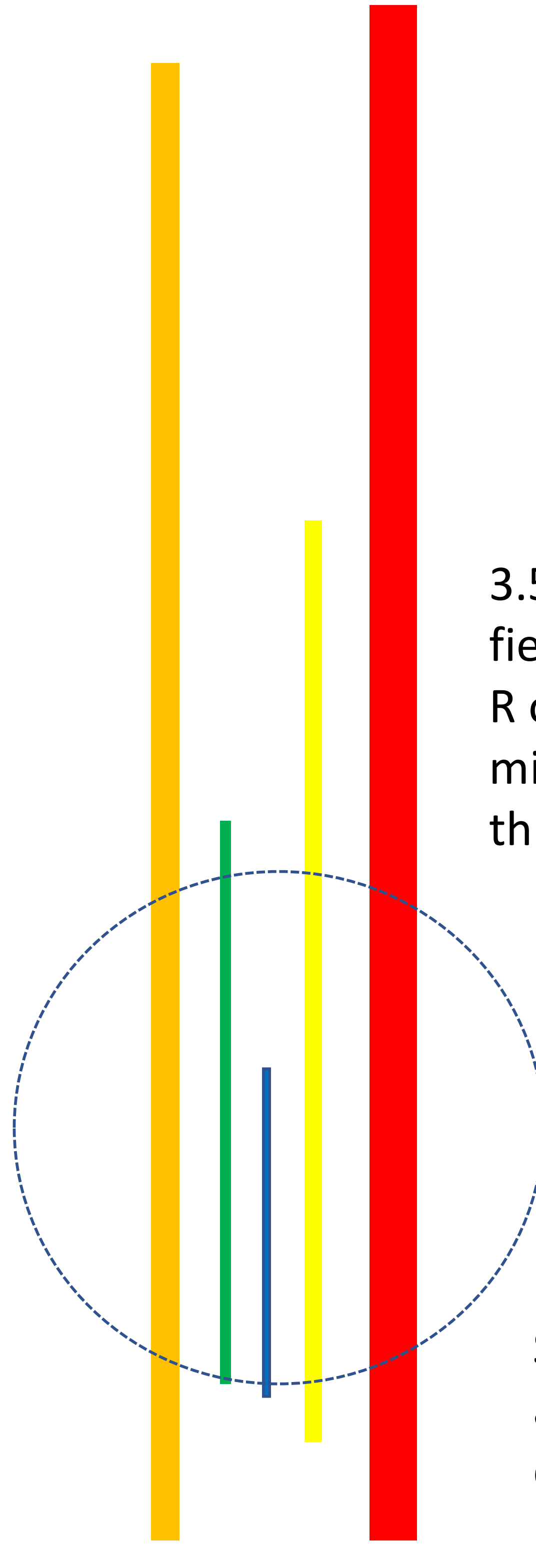
Representative spectral range for protoplanetary disk around 0.3 Msol star at 160 pc.
2D RT model, noiseless, Gaussian line profile (not realistic for FTS)

One Approach: Process light with FTS then detect with Gratings.



Origins OSS, but PRIMA will be 1/10 the mass.

4 cm pupil, 4 cm scan.



3.5 arcminute field.
R of 6k at 112 microns over this field.

Slit alignment a separate question.

FTS advantage: all the light on the detector, good for faint sources. FTS also calibrates well.

Other approach: Etalon (Fabry-Perot) inserted inside each grating module. G. Stacey talk Friday.

Benefits:

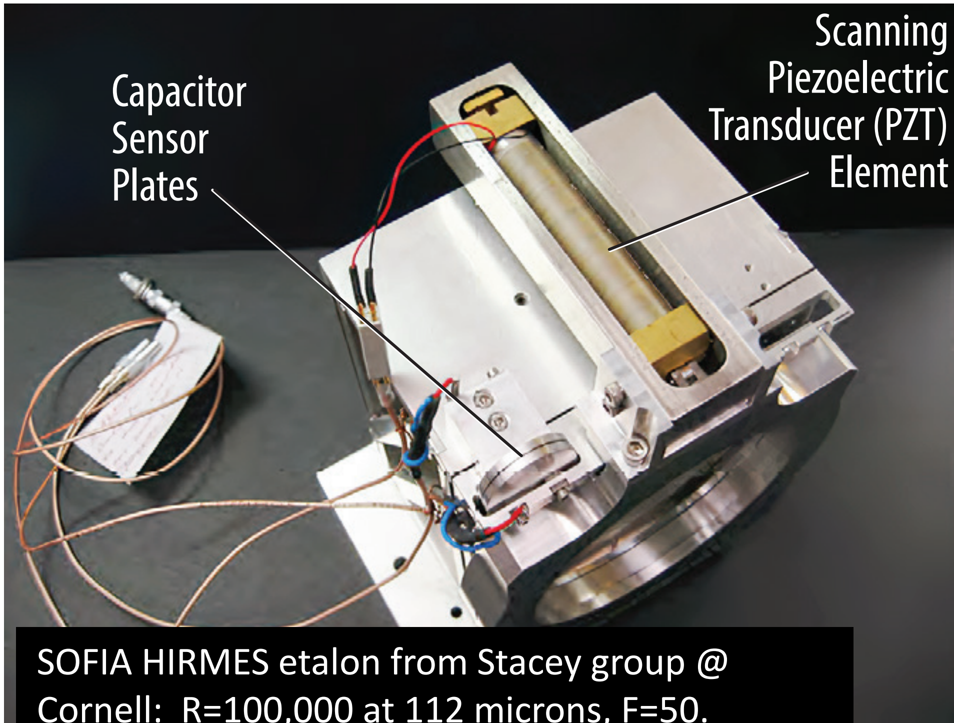
Uniform R,

More compact each one since path folding.

Drawbacks:

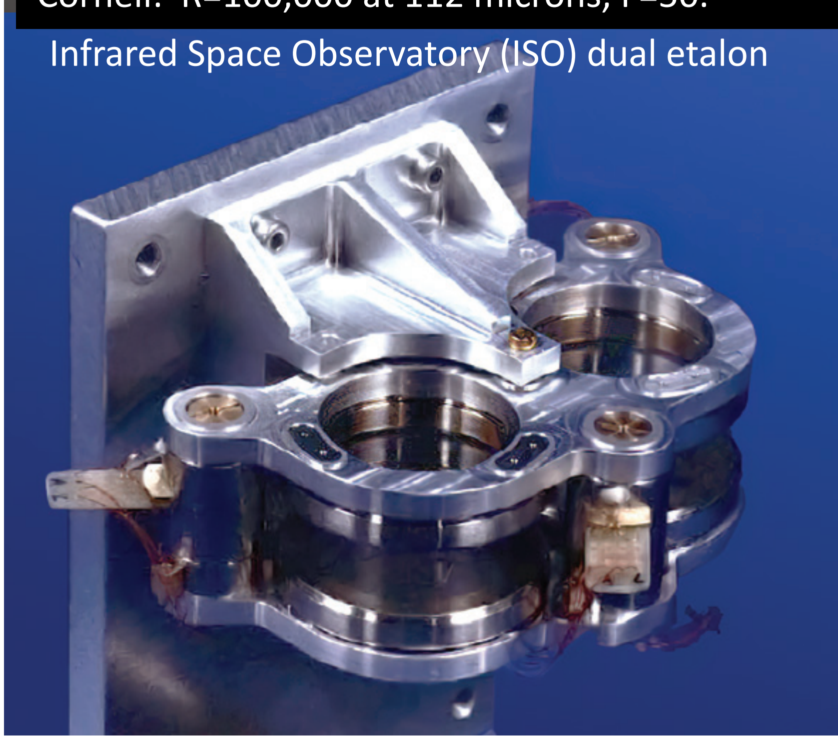
Requires one per module, so 4 or 5.

Requires scanning to get full spectrum.

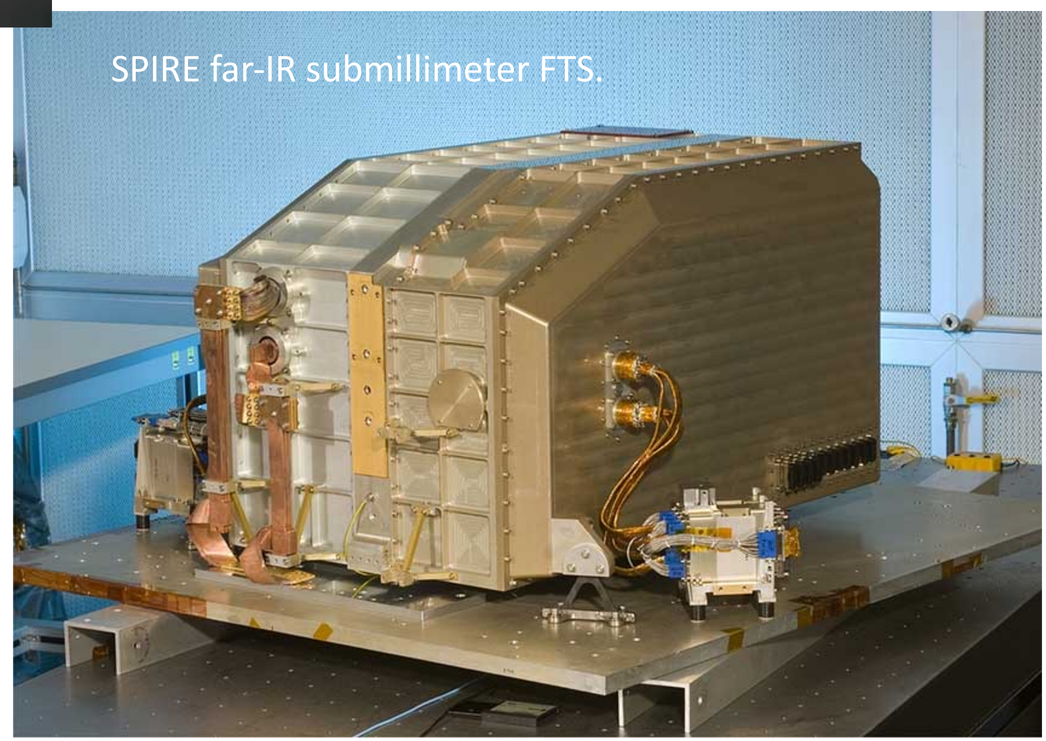


SOFIA HIRMES etalon from Stacey group @ Cornell: R=100,000 at 112 microns, F=50.

Flight Heritage for both

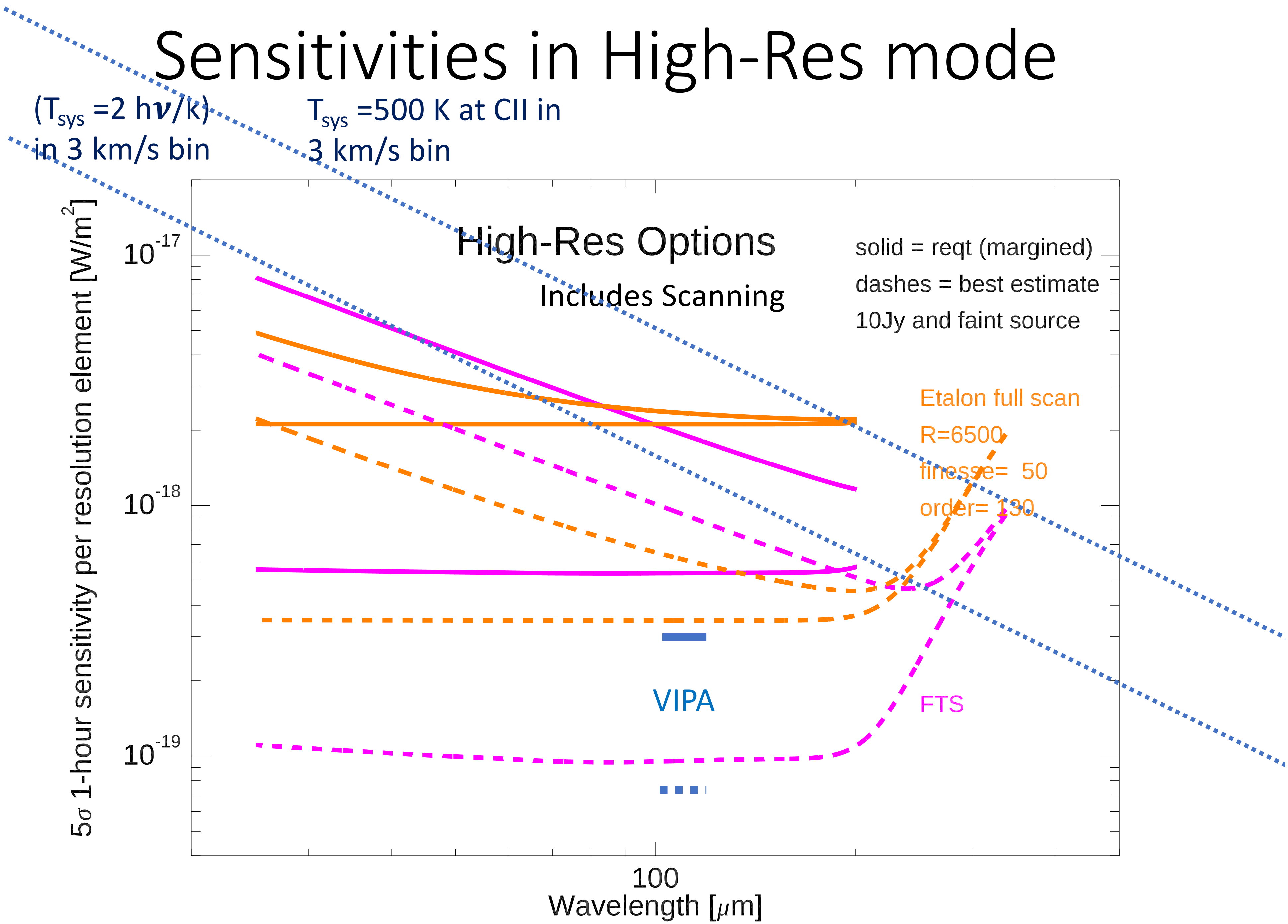


Infrared Space Observatory (ISO) dual etalon



SPIRE far-IR submillimeter FTS.

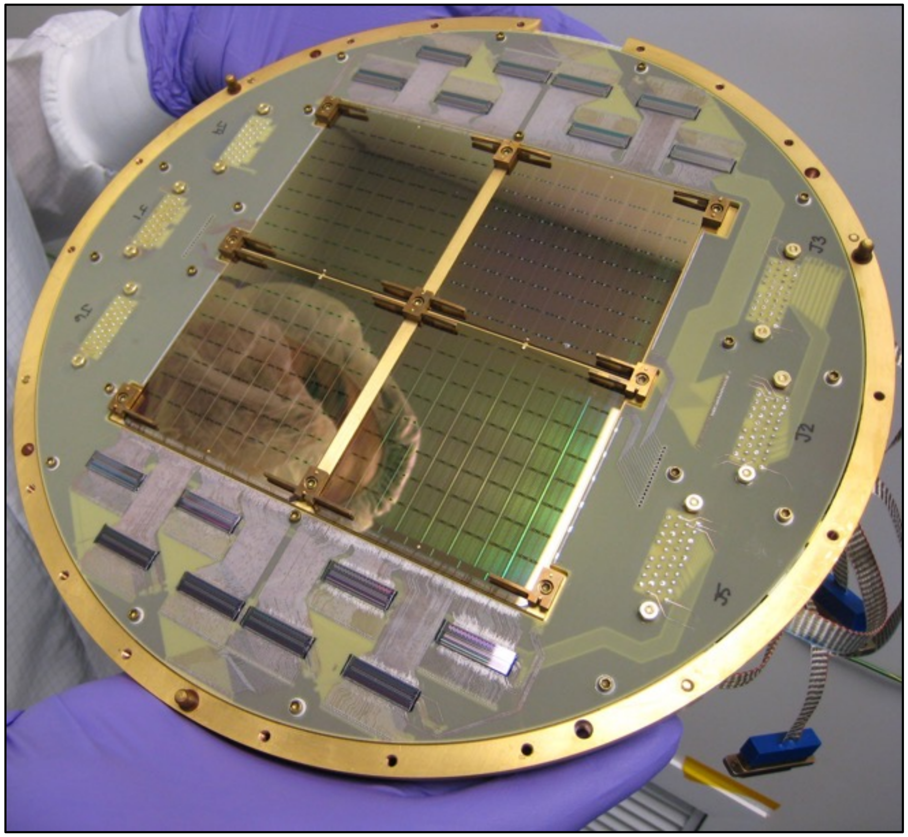
Sensitivities in High-Res mode



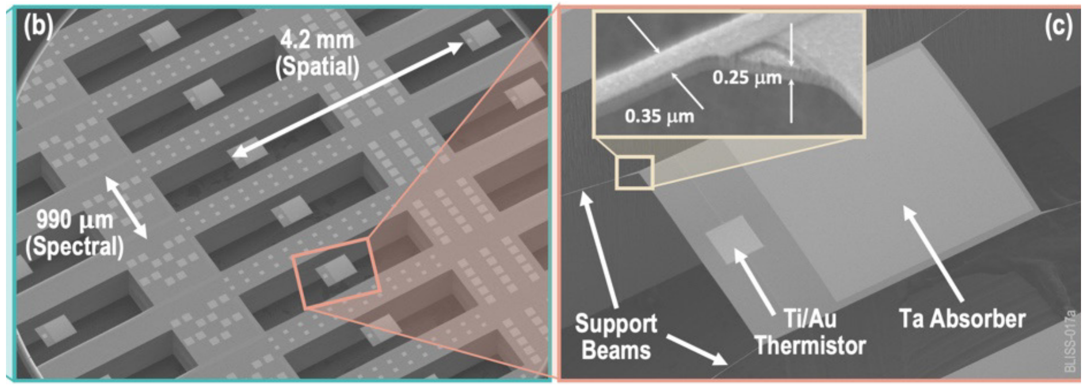
Key Enabling Technology is Detector Arrays

Sensitive detectors for the far-IR have no commercial providers – must be build by science / technology community.

JPL and NASA, NIST have invested over the last 2 decades – now paying dividends.



Bolometer arrays for the microwave background work. Fielded on the ground and in balloons. Here 512 total pixels
Works great, but PRIMA requires greater sensitivity & number.

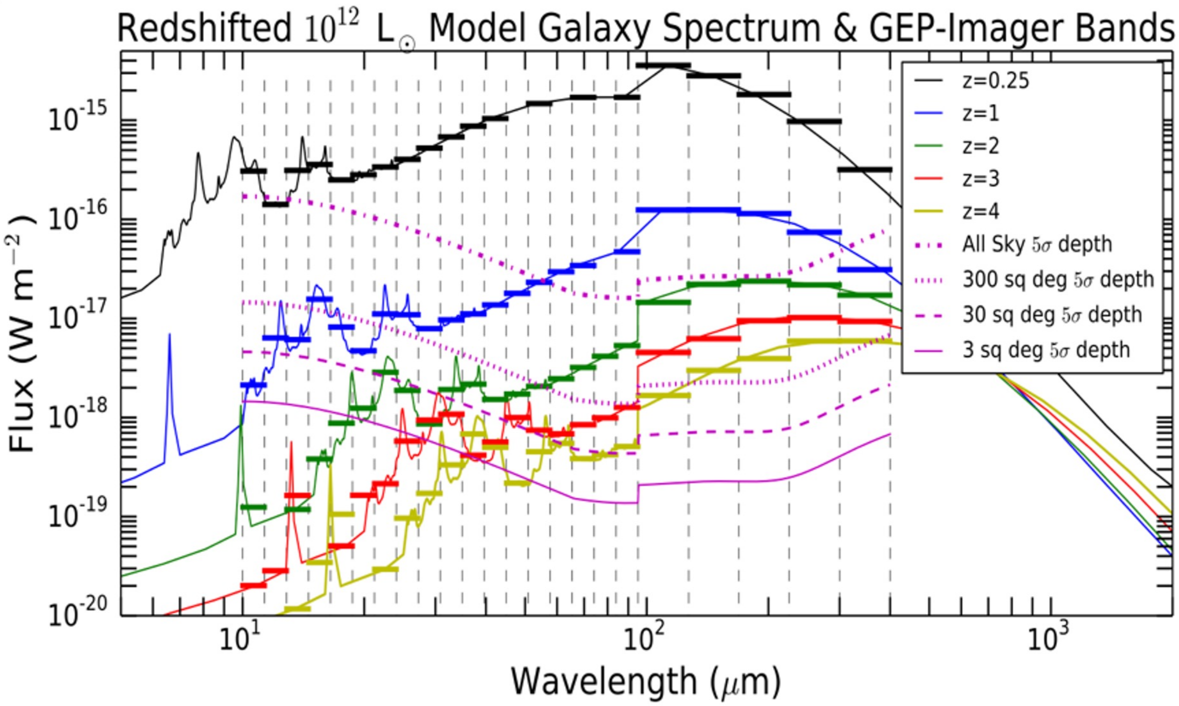


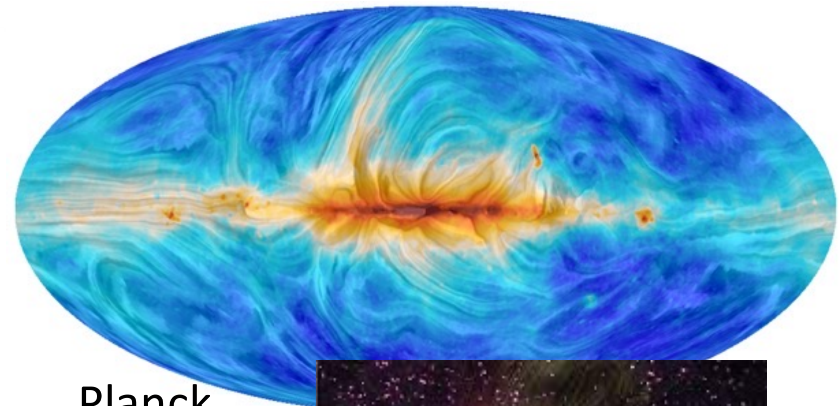
Example devices built for far-IR space sensitivities.

<u>Sensitive Far-IR Detectors:</u>

- Use superconductivity in one form or another
- Operate at temperatures of 50-100 mK
- Require microdevices fabrication professionals and low-temperature physics expertise.

Imaging with PRIMA





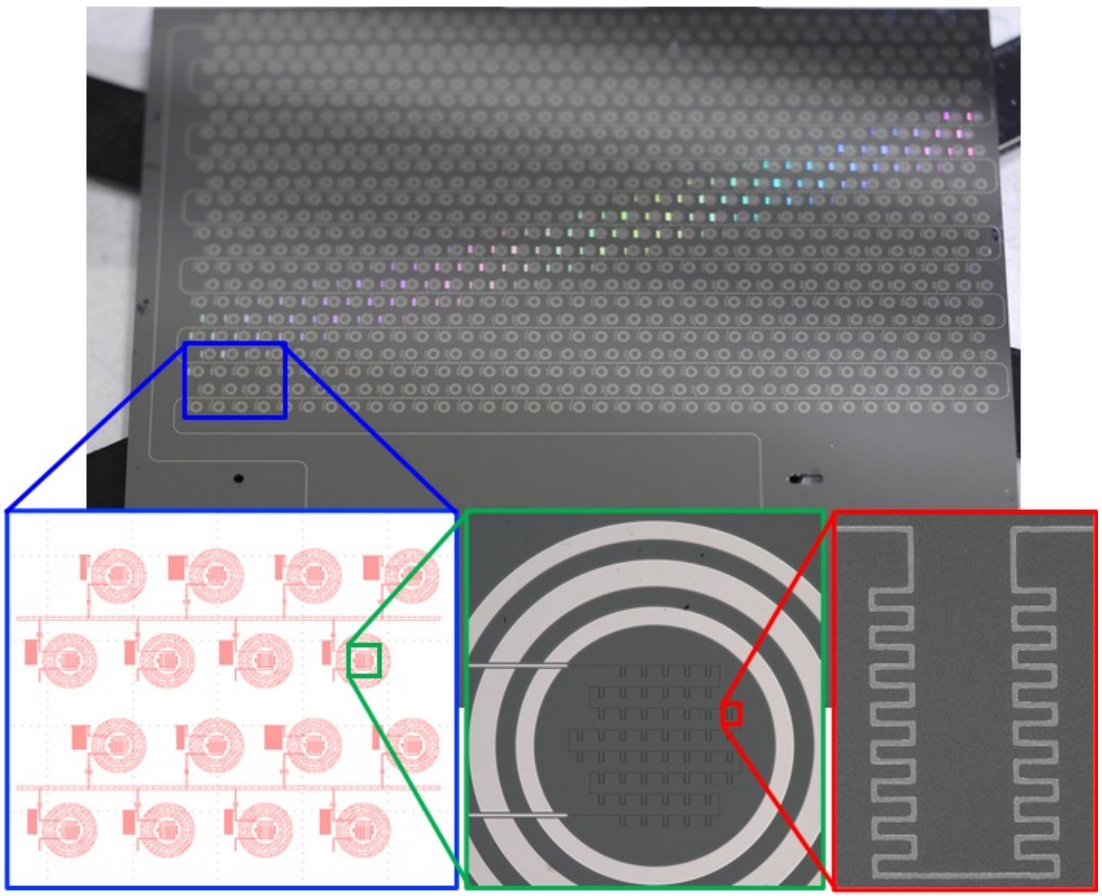
Planck

HAWC+
SOFIA

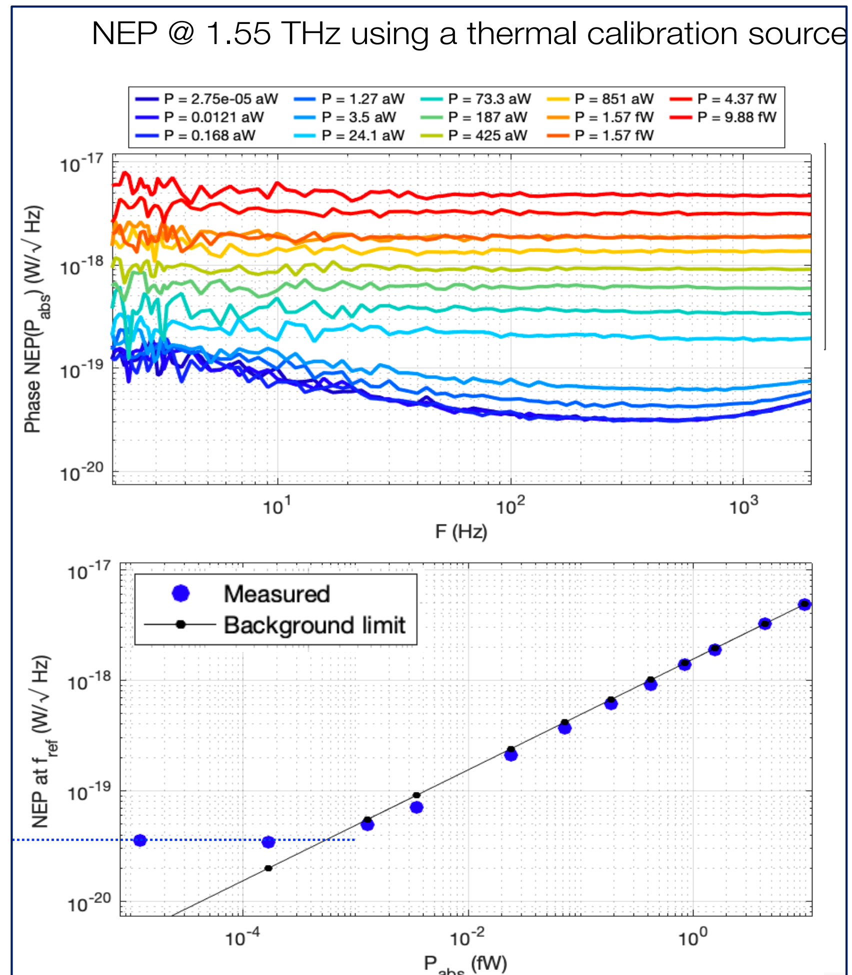
- Powerful opportunity for:
  - Wide-field coverage: tens to hundreds of square degrees.
  - Excellent depth, can resolve the CIB at ~50-100 microns.
  - Narrow-band spectrophotometry (figure), can provide PAH redshifts.
  - Multi-band dust polarimetry.
- Collaborating with French (D. Burgarella / L. Ciesla, et al.) / Dutch (W. Jellema / P. Roelfsema) / European consortium that is working to develop PRIMA imager.

Key Enabling Technology is Detector Arrays

KIDs are baseline for PRIMA.
Enables the large mapping speeds and simplifies observatory cryo design.
See **Reinier Janssen** talk on Friday to learn more about our balloon-borne KIDs, approaches to PRIMA KIDs, and some recent results from SRON.



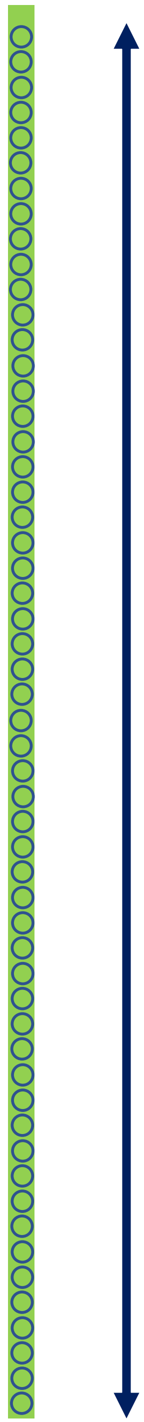
TIM KIDs



SRON latest results – exceeds requirements

Thank you!

Slit spectrometer maps to 2-D array with spatial & spectral dimensions



Slit: 1 x N beams on the sky. N > 30.
Circles indicate individual detector power patterns on the sky

Spatial direction e.g. 10 arcminutes at 100 microns

Spectral direction: e.g. 70-120 microns in 100 bins

PRIMA mapping (like submillimeter

Lissajous Scan

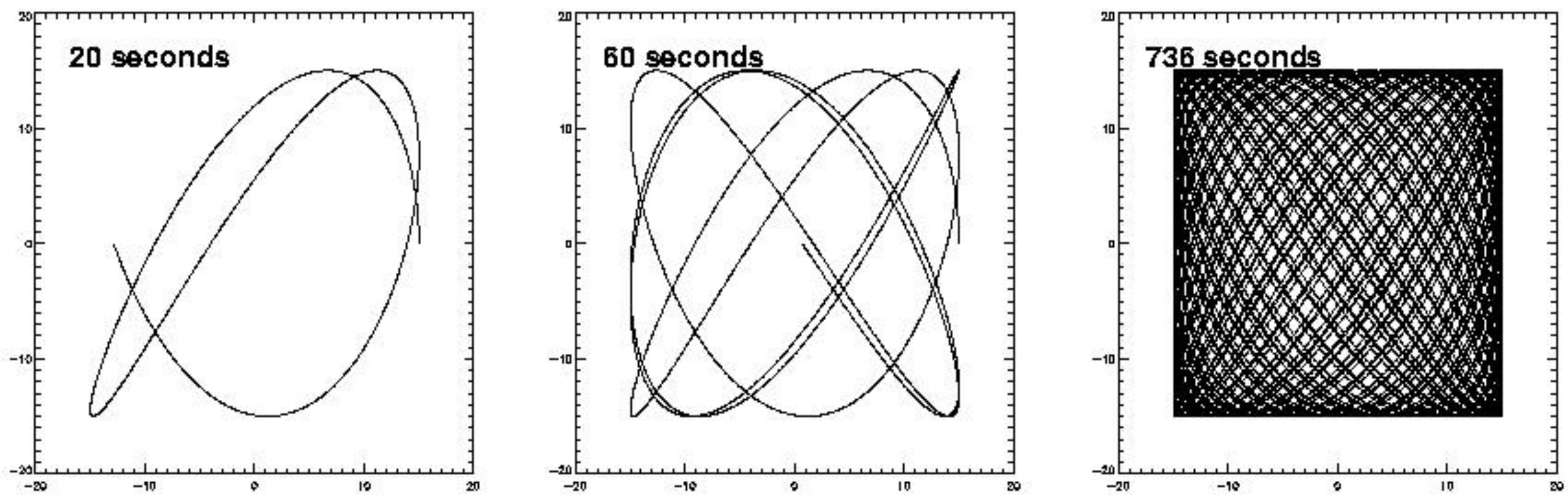
For mapping areas of size on order the SHARC-II array field of view (2'x1'), or for observing point sources, we use a lissajous pattern. Starting from the center of the map, the telescope modulates it's X and Y position with a different sine wave for each. X and Y are either azimuthal, equatorial, or galactic coordinates, and the user is also free to choose the amplitudes and periods of the sine waves in each direction. The offsets, dx, and dy are given by:

```
dx(t) = AX cos(2*pi*t/TX)

dy(t) = AY sin(2*pi*t/TY)


where:
AX,AY = amplitude in arcseconds
TX,TY = period in seconds
```

As it turns out, if the ratio of the periods can be expressed as a rational number, then the scan will be cyclical and repeatable. Because we would like to prevent any periodic motion (we become unable to separate sky noise at those frequencies with true astronomical signal), we use ratios that are irrational.



Here we show the progress of the scan at 3 different times.

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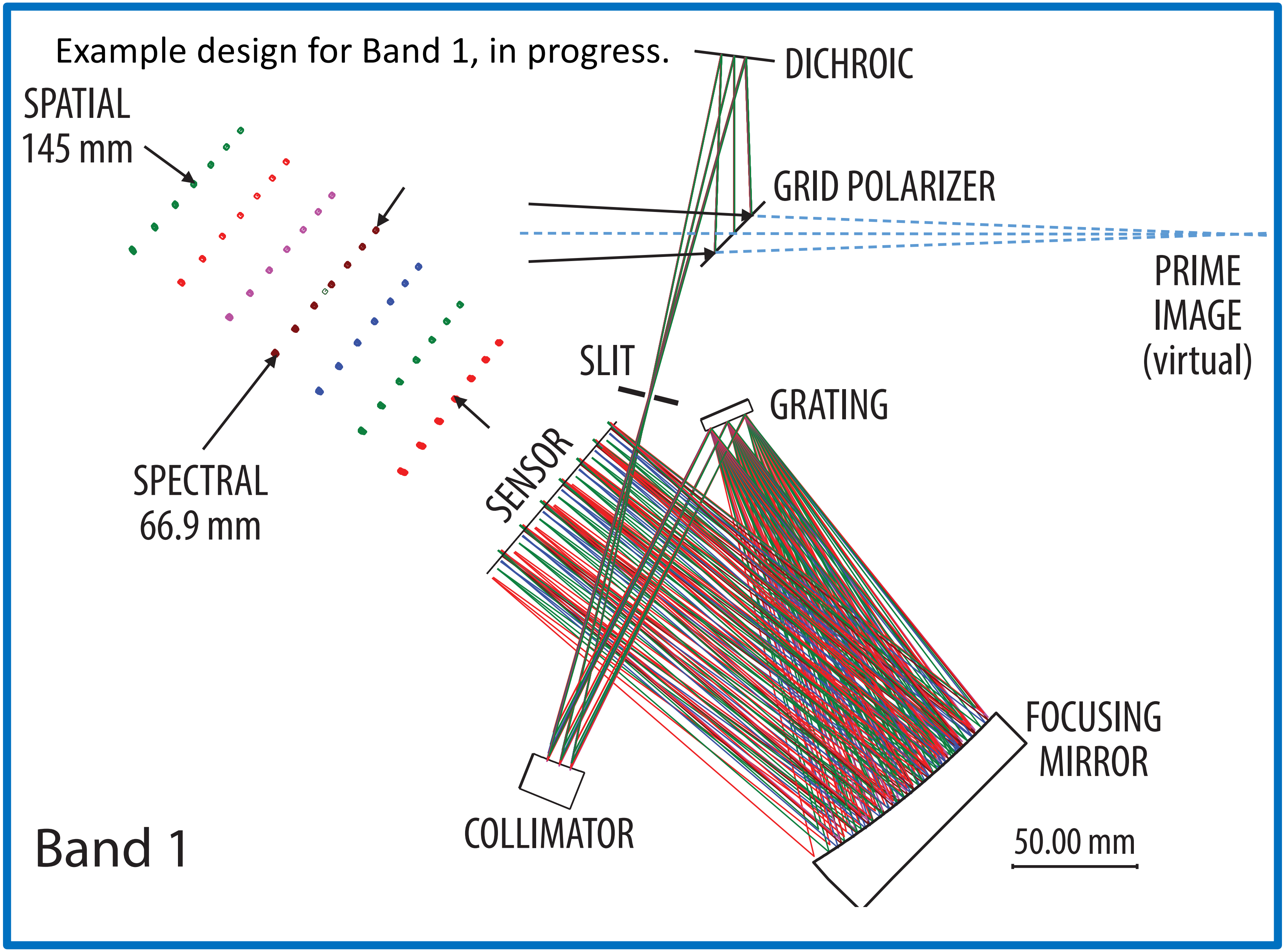

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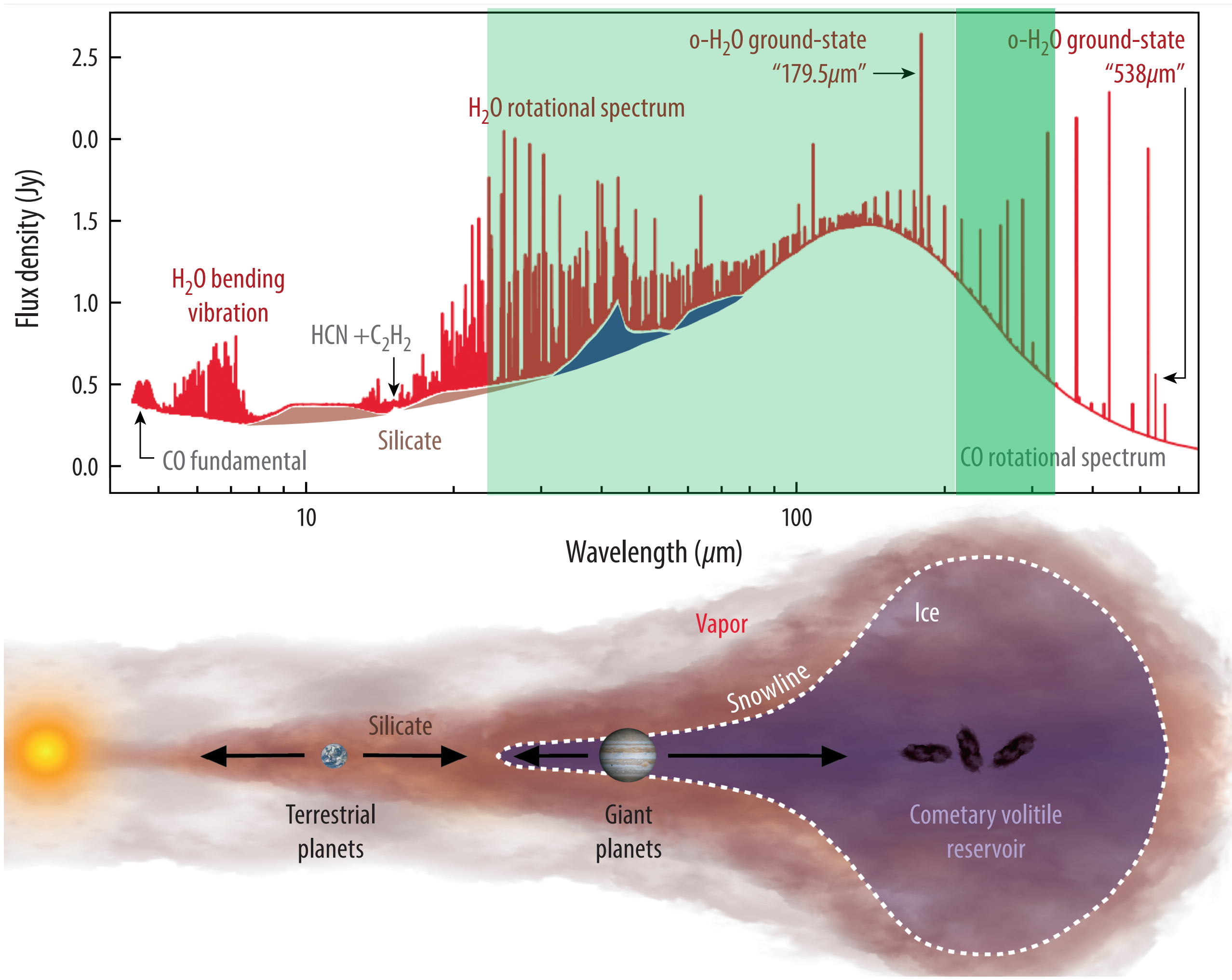
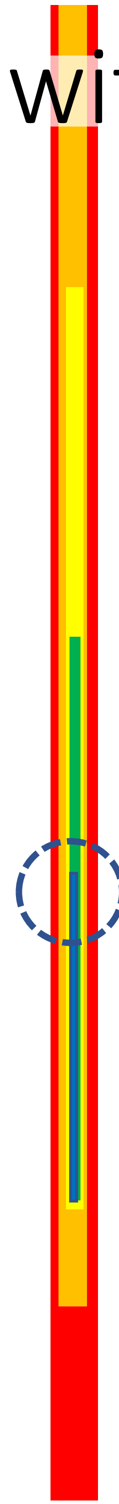


Water spectrum and HD (mass tracer) unique to far-IR
Question for PRIMA: how does this science scales with spectral resolving power. Integrate with observatory in optimized manner.



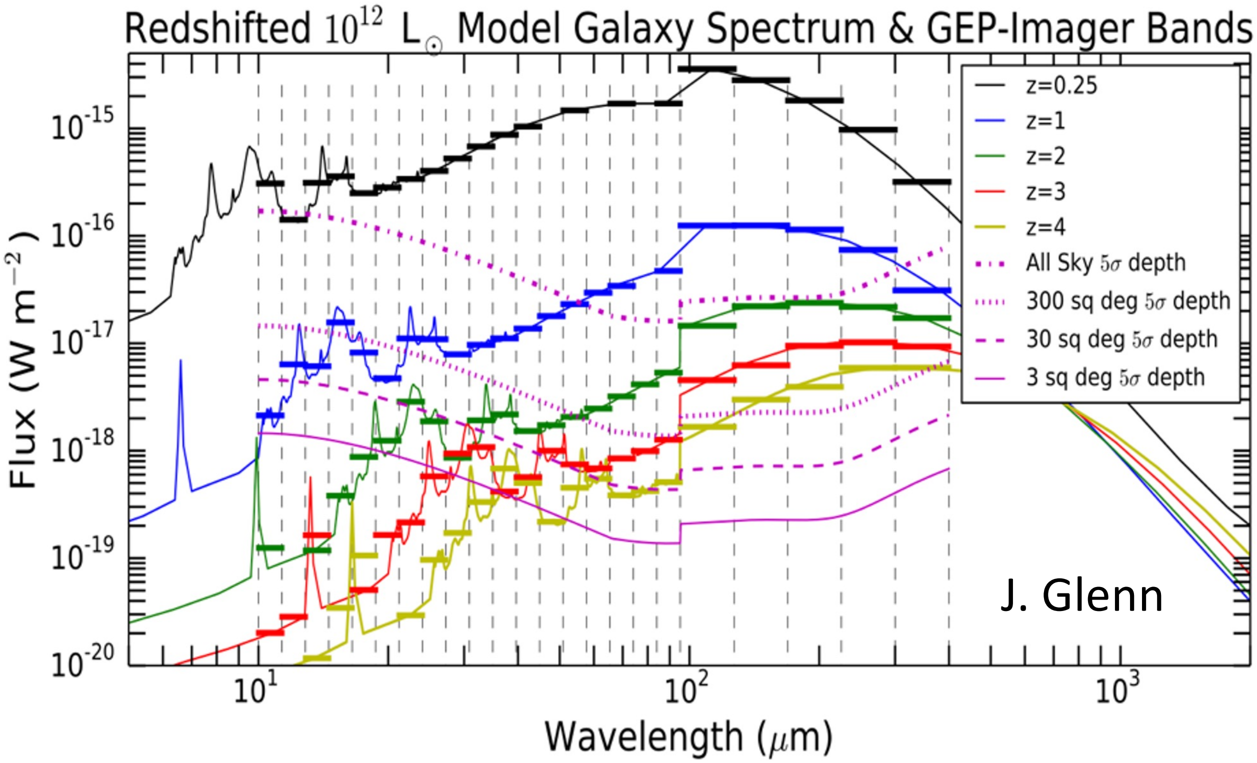
One approach: Pick off small field common to all slits. Process through FTS and re-insert into beam to be detected by grating spectrometers.

Targeting R of a few thousand across the band.

Line sensitivity will be degraded somewhat relative to grating: e.g. 2x

R value to be determined. Larger R increases instrument volume, mass

Imaging with PRIMA



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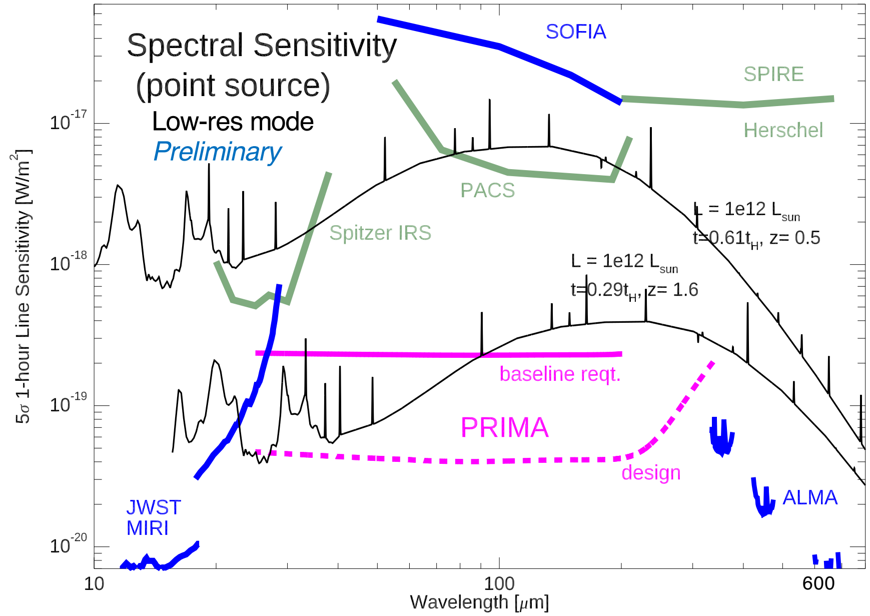

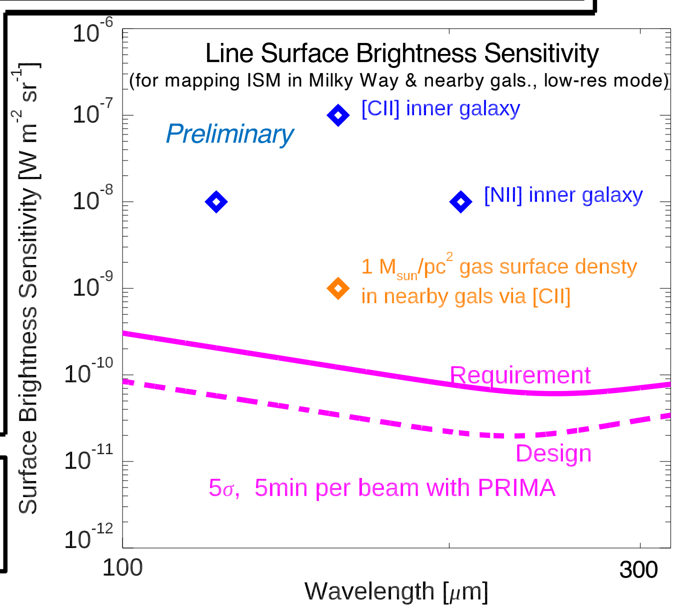

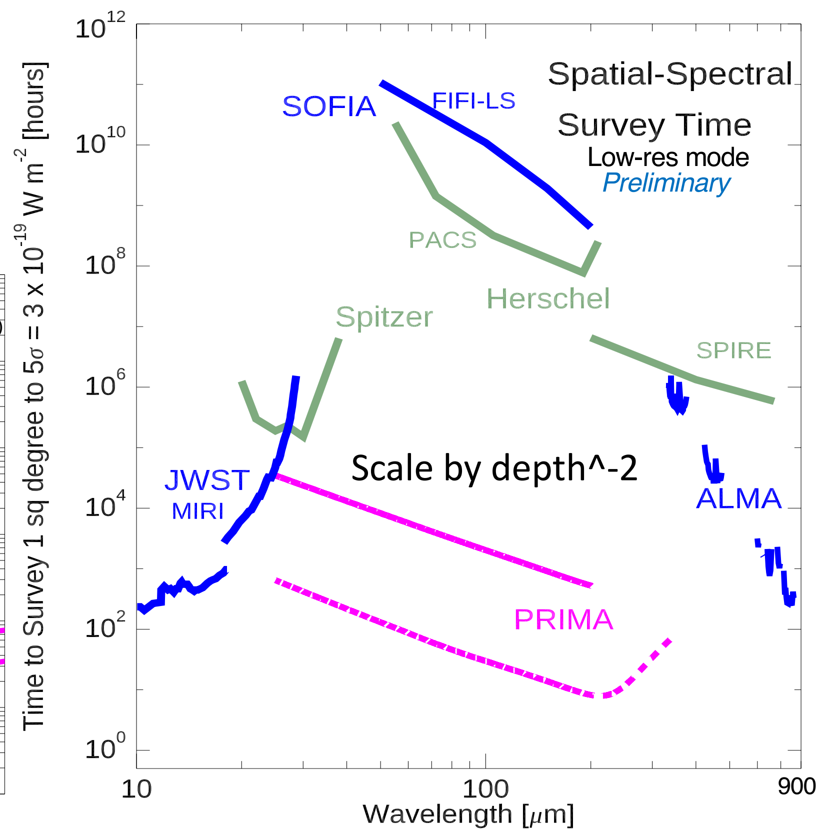

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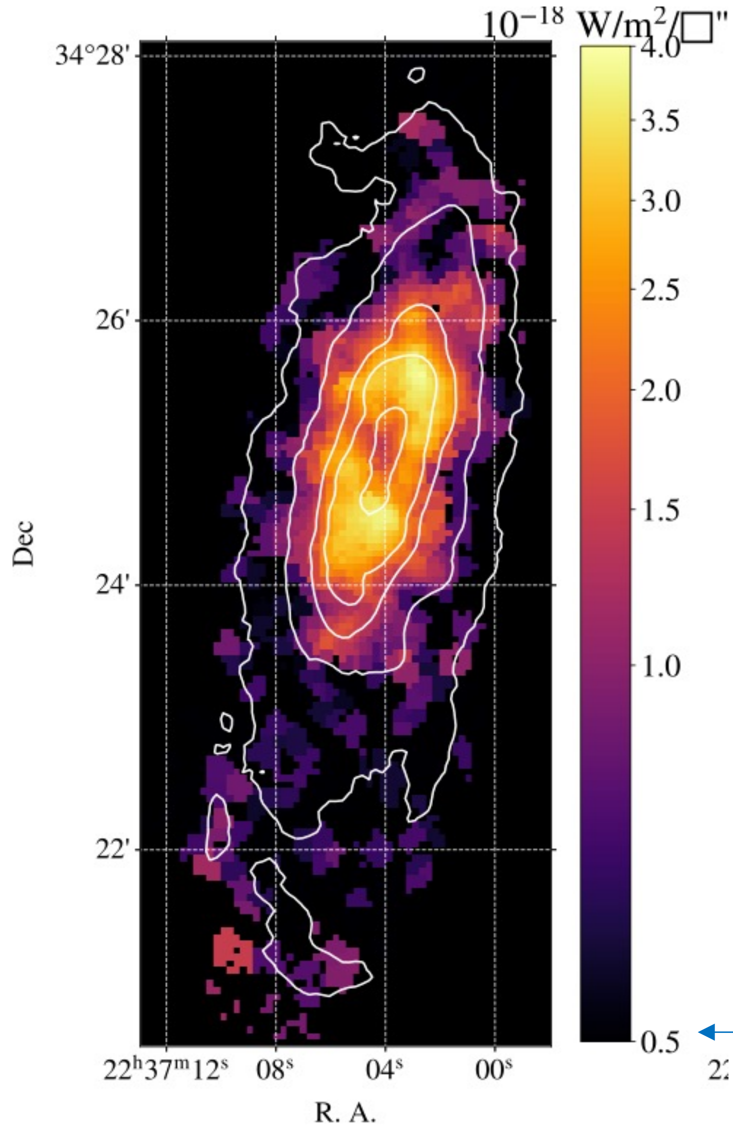
Low-surface brightness Line mapping.



NGC 7331
[CII] map from SOFIA FIFI-LS. Sutter & Fadda 2022
4.5 hours flight time.

Single line, Limited to bright, dense gas.

PRIMA will be thousands of times faster, measuring CII cooling in galaxy halos and outer disks. Comparison with HI provides cooling per baryon. Other lines also measured at the same time.

10 sigma, 1 second, PRIMA, per beam!