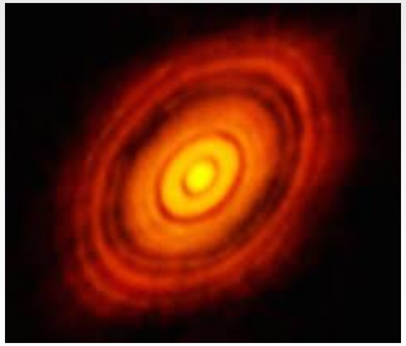
High-Resolution Direct-Detection Spectroscopy with SOFIA

Gordon J. Stacey
Cornell University

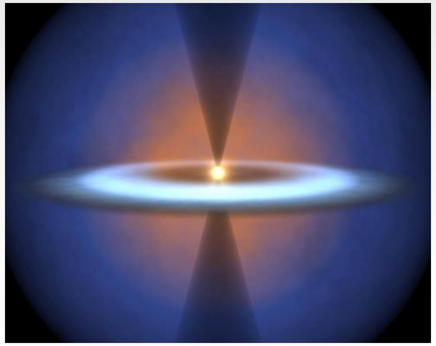
Overview

- ❑ Address the science applications of HIRMES (now cancelled) and why these capabilities should not be lost
  - ➢ Primary application is the investigation of protoplanetary disks
  - ➢ Other applications: YSO’s, debris disks, comets, gas giant planet atmospheres, fine-structure line imaging of galaxies, O/H, N/O abundances
- ❑ Why use direct detection spectrometers?
- ❑ HIRMES description

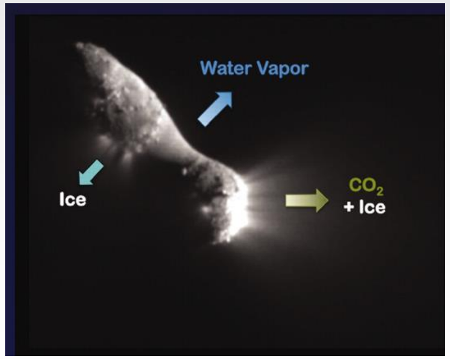
HL Tau



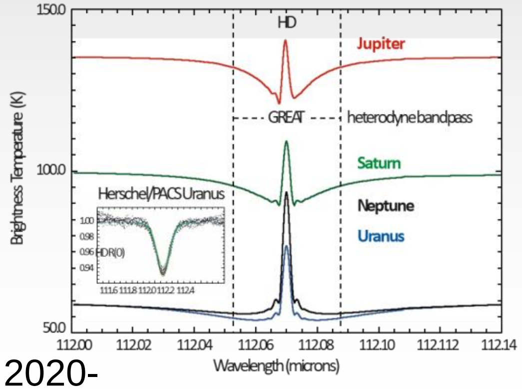
YSO



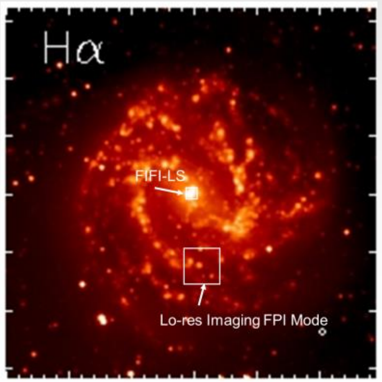
Comets



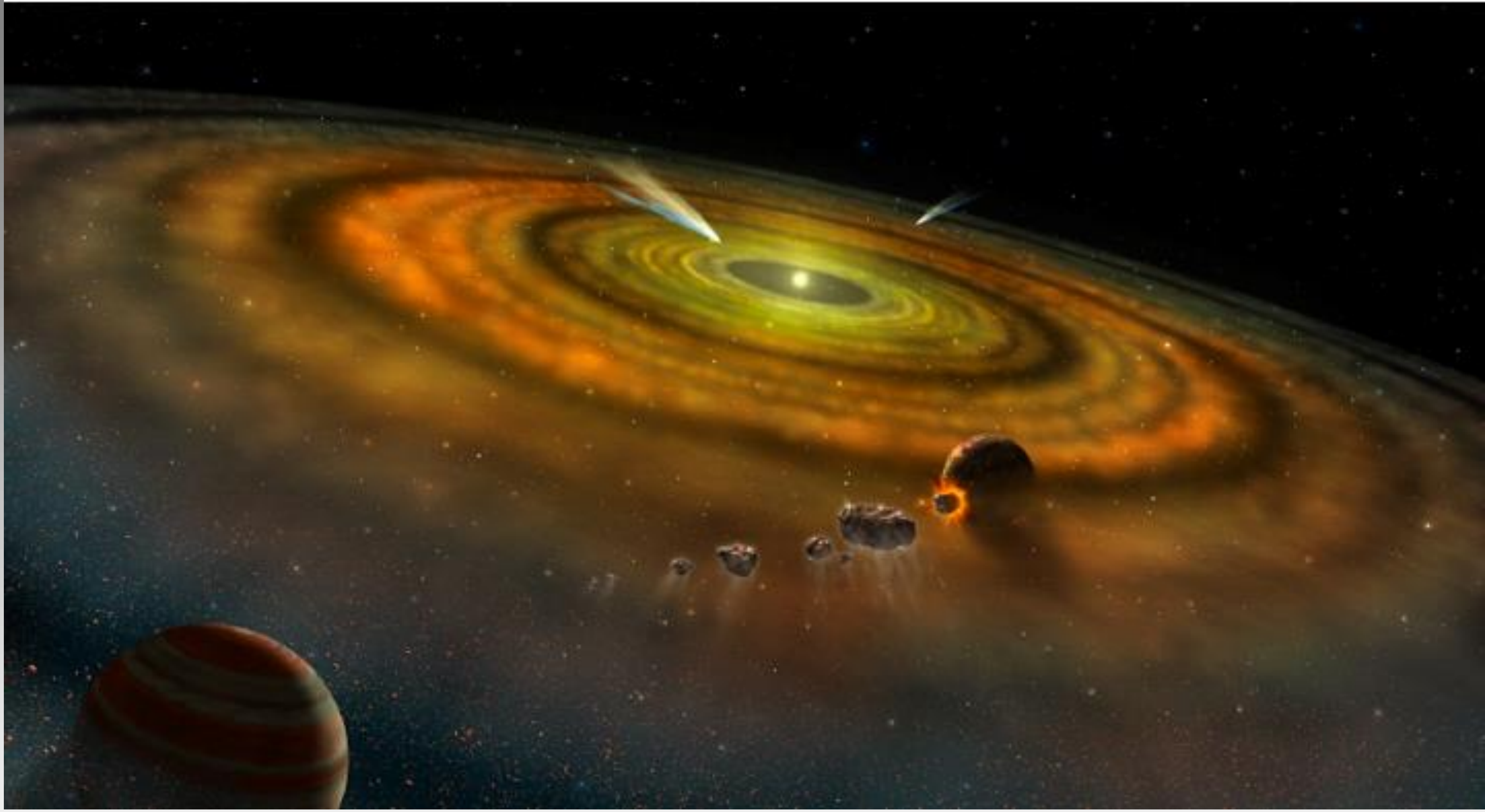
Gas Giants



Galaxies



Protoplanetary Disks



- ☐ Over ~ 10 million years, protoplanetary disks evolve into planetary systems
- ☐ Bulk of mass is H_2 gas (including H_2, O, H_2O), and ices – all critical to theories of planet formation, but challenging to observe.

Far-infrared spectroscopy is critical to our understanding of planet formation – and SOFIA holds the keys

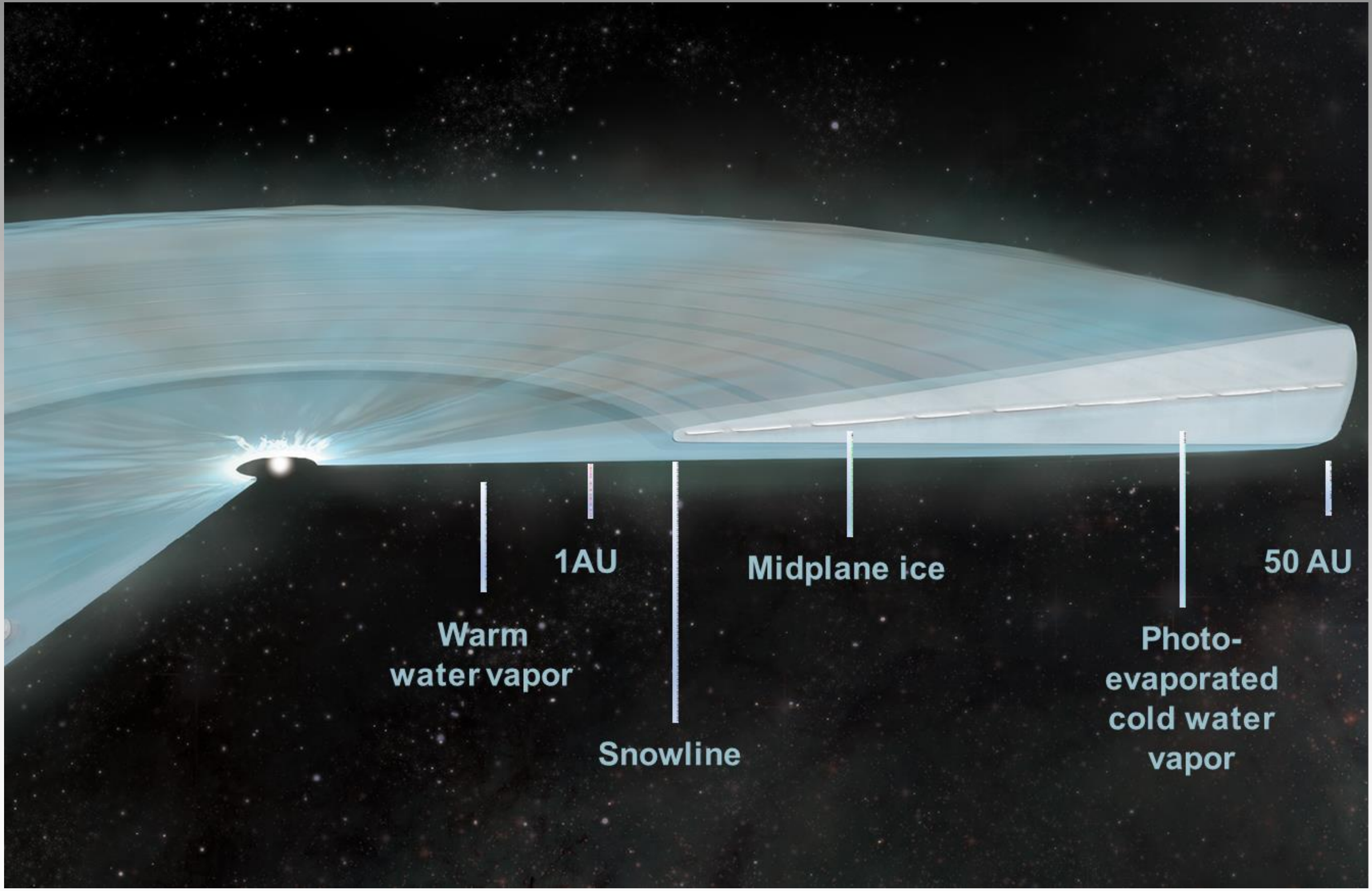
Far-infrared Lines Important

The critical building blocks for the formation of planets include water, oxygen, and molecular hydrogen

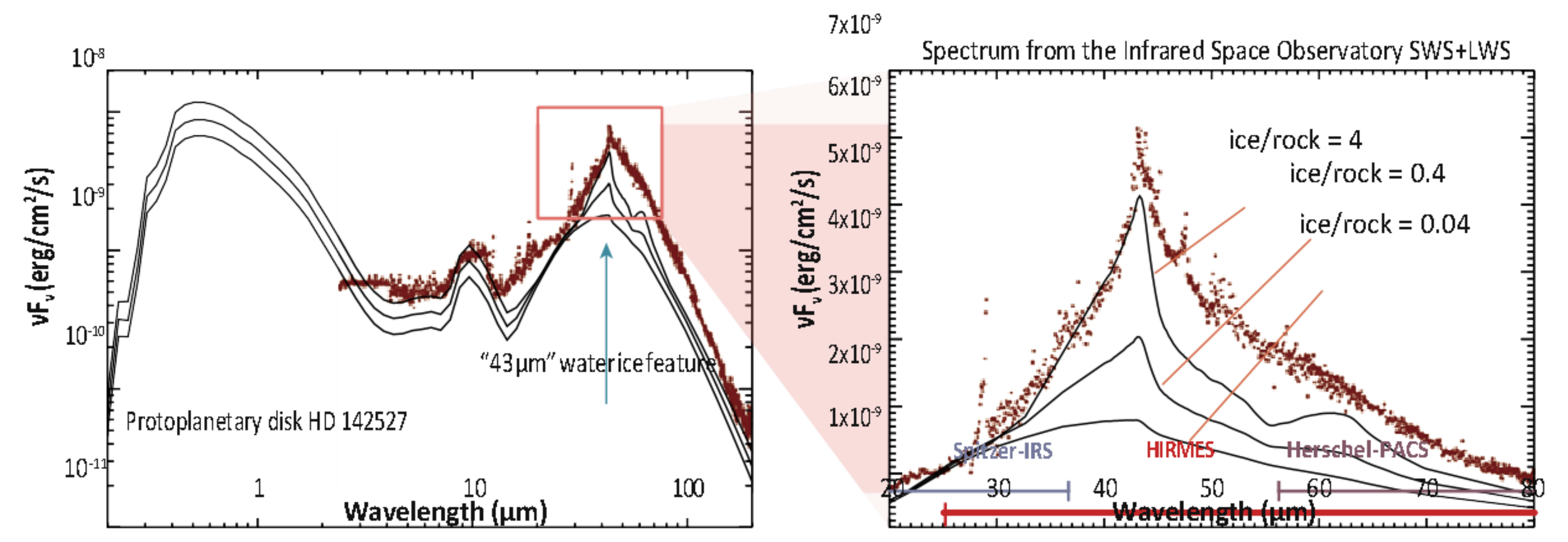
- Water is a key ingredient for life:
  - Emits strongly in its far-infrared rotational lines, but is nearly impossible to observe from the ground – because of the telluric lines, hence airborne astronomy…
- Oxygen is key ingredient for life:
  - Product of the photodissociation of H_2O, CO_2, and CO ices that are released during collisions between planetesimals.
  - Critical to understanding the formation of the gas and ice giants, and terrestrial planet atmospheres.
- Hydrogen is primary component of protostellar disks, since it carries most of the mass
  - But its role is poorly understood since it is so difficult to observe.

Water and Ice

- ❑ Water is central to our understanding of the formation of habitable worlds
- ❑ Beyond the “snow line” is it mostly ice
- ❑ Within the habitable zone water is gaseous
  - ➢ Terrestrial planets likely form “dry” since this water is photodissociated before incorporation
  - ➢ Water transported in from beyond snow line in later phases by icy bodies



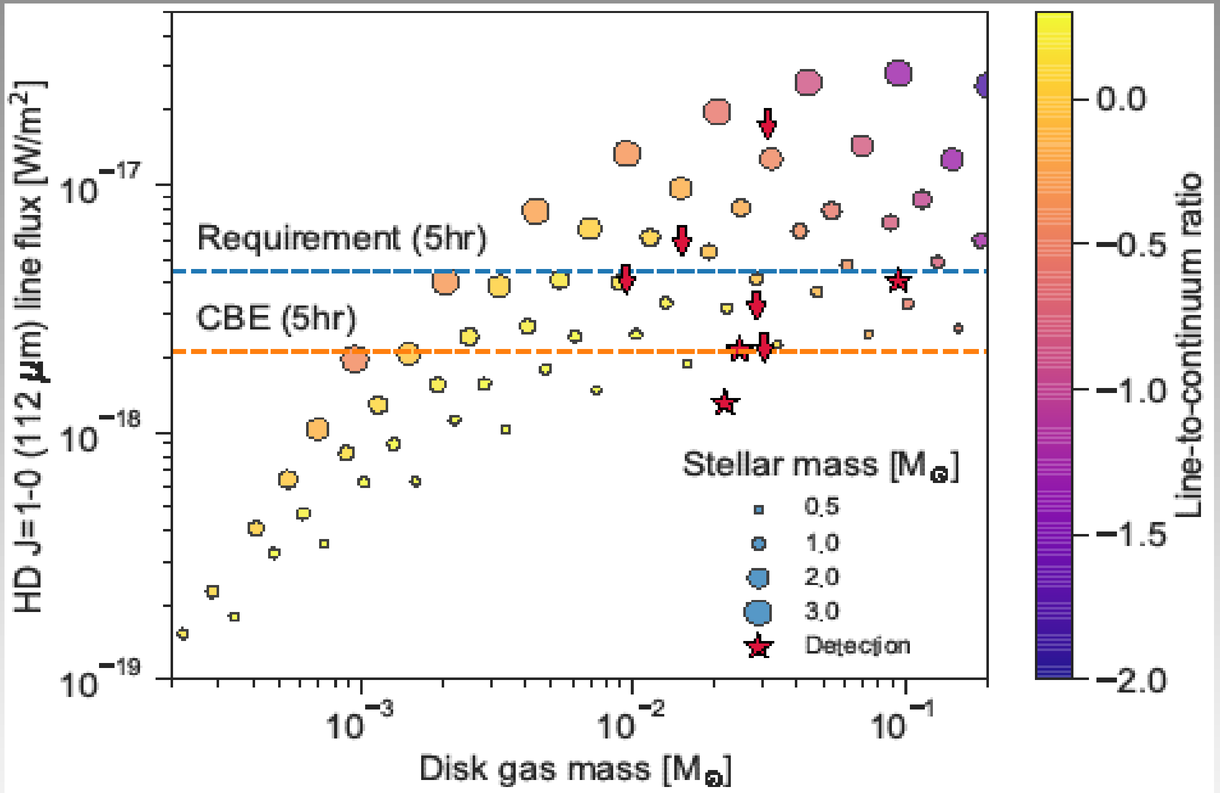
Ice Diagnostics



- Detect ice through its strongest features near 40 μm in emission
  - Shorter wavelength bands in absorption, since warm (emitting) ice would melt
- Emission arises from small icy grains above the colder disk
- Feature strength & shape yields mass, and ice/rock ratios critical for core-accretion formation models
- Ice features not available to other facilities so this is not well explored observationally

Molecular Hydrogen: Disk Mass

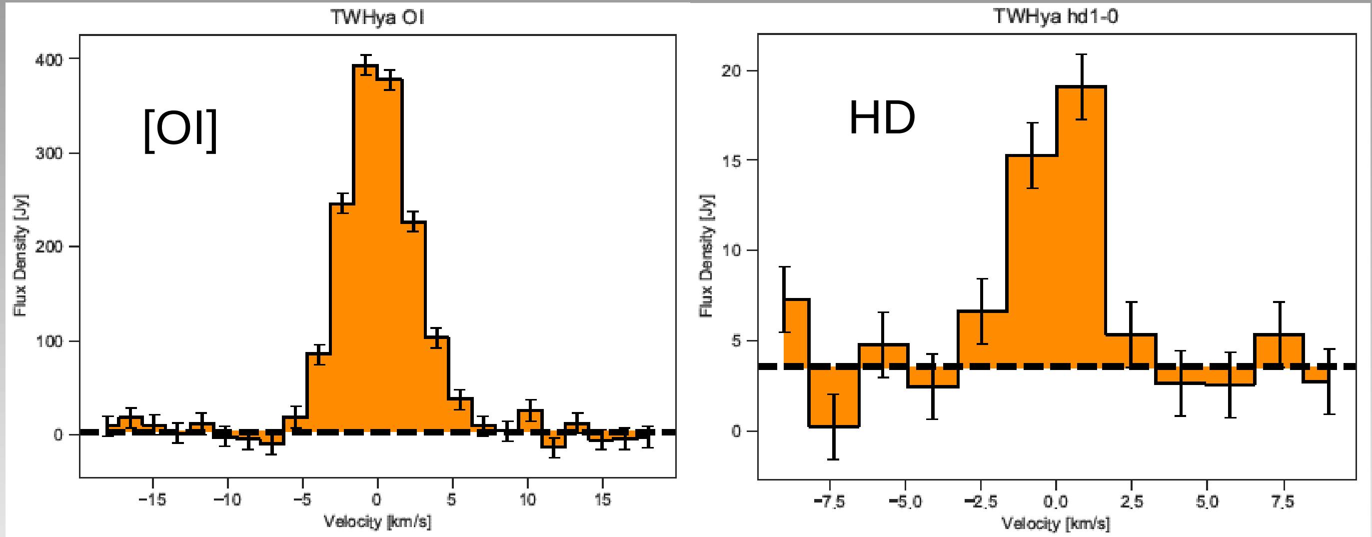
- Protoplanetary disks are mostly gaseous: Gas:Dust is 100:1 by mass
- Mostly, H_2 – a very weak emitter since first (quadrupole) emitting level is 550 K above ground, and the disk temperature is only a few 10’s of K
- CO proxy is not very good, since “conversion factor” varies by orders of magnitude ⇒ masses of PPD totally unconstrained
- HD is a good proxy: low-lying128 K, 385 K, ….) rotational lines
  - J= 1-0 112 μm
  - J= 2-1   56 μm



HIRMES could detect the HD 1 – 0 line at 112 μm in disks of masses $>10^3$ M $_\odot$ around stars of > 1 M $_\odot$. The figure shows model predictions for HD 1–0 line fluxes (circles), along with detections (stars) and upper limits from Herschel-PACS. All models and data are scaled to a distance of 125 pc.

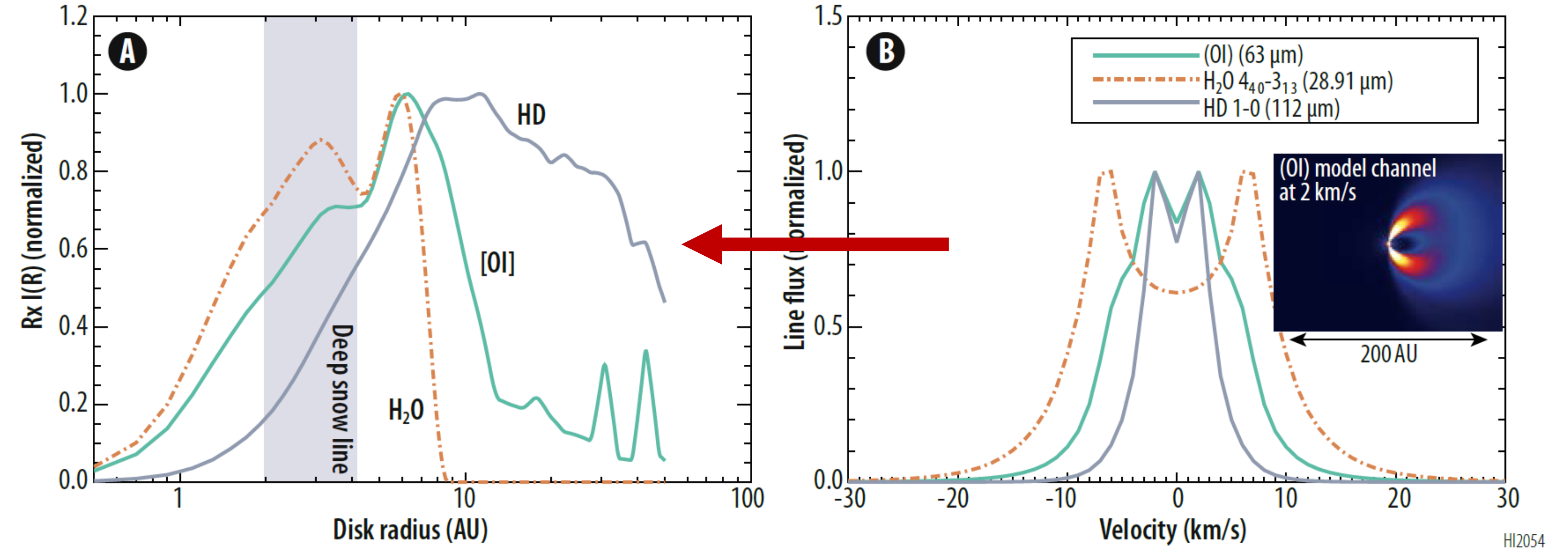
Neutral Oxygen: Disk energetics

- [OI] 63.2 μm is typically the most luminous emission line of protoplanetary disks
  - Most commonly detected line from disks by Hershel-PACS
    - Interpretation limited by lack of ability to distinguish ~10 km/s disk emission from 100 km/s outflows and shocks.
- HIRMES will produce velocity-resolved [OI] spectra of more than 30 protoplanetary disks
  - These data will determine the origins of emission disk/outflows
  - Radial surface energy and mass from 1-100 AU.



Simulated HIRMES spectra of TW Hya (a disk with typical line strengths). The signal-to-noise on [OI] 63.3 μm (left) and HD 1-0 (right) correspond to 1.5 and 10 hours of observing time with overheads

Far-IR Spectral Line Tomography



- Velocity resolve spectral lines
- Place radial distance in the emitting disk assuming Keplerian orbits.
- O and H_2O are likely in and around the snow line while HD is external ⇒ HD requires less velocity resolution than O and H_2O observations

Uniqueness

- Water, [OI], HD and H_2 detected by Hershel/Spitzer, but not with the resolving power necessary for tomography, and/or at the necessary sensitivity.
- JWST will detect some of these lines, but not at the required resolving power.
- ALMA has so far detected just one water line from PPD - many available to HIRMES to outline excitation as a function of distance from the central star.

Why not heterodyne spectroscopy?

Direct vs. Coherent Detection

- Direct detection refers to detectors that detect the energy of the photon
  - Photo-electrons in semi-conductor, or warming the crystal lattice in a silicon bolometer
  - For high resolving powers (10^5) at 112 μm, interference paths 5.6 m long are necessary (in free space)! – but a FPI folds the path….
- Coherent detection refers to detectors that detect the wave nature of the light
  - Typically coherent detectors measure the source signal that is in phase with a strong monochromatic local oscillator
  - Very high resolution spectroscopy can be performed at low radio frequencies, digitally.

Why Direct Detection?

- Direct detection is inherently more sensitive than coherent detection
  - Detection of phase leads to “quantum noise”: $T_{QN} = {}^{h\nu}/_{k}$

    $580 < T_{QN} < 130\ K$ as 25 μm < λ < 112 μm
  - Typical noise temperatures are: 5·T_{QN}(DSB) ⇒ 5800 to 1300 K
- Direct detection devices do not detect phase. In the best case they are “background limited”
  - One can show that for reasonably efficient systems ($\tau_{cold} \boxed{?}\ 20\%$):

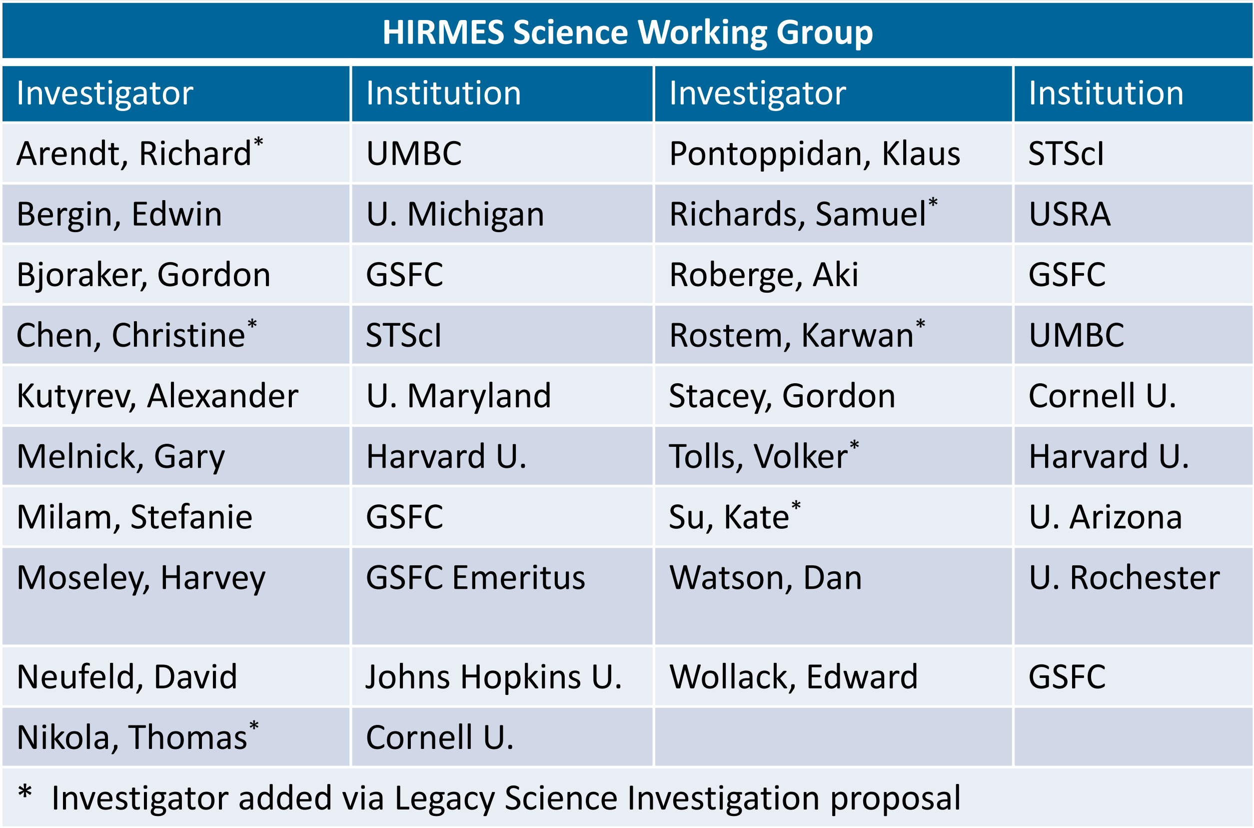
$$T_{BLIP,RJ,SSB} = \frac{T_{warm}}{\sqrt{\tau_{cold}}} \approx 150\ to\ 330\ K\ (25 - 122\quad m)$$

$$T_{BLIP,RJ,SSB} = 160\ K\ (SSB)\ @\ 112\ \mu m\ HD\ (J = 1 - 0)$$

HIRMES

- High resolution (RP ~ 10^5) far-IR spectrometer based on direct detection
- Selected as the 3rd generation SOFIA instrument
- Close to integration and test – cancelled on April 1, 2020 due to cost and schedule overruns – driven by challenges with detectors
- *Revival in the cards when these challenges are overcome*

PI: Matt Greenhouse (GSFC); FPI developed at Cornell; Science Team Lead (Gary Melnick)



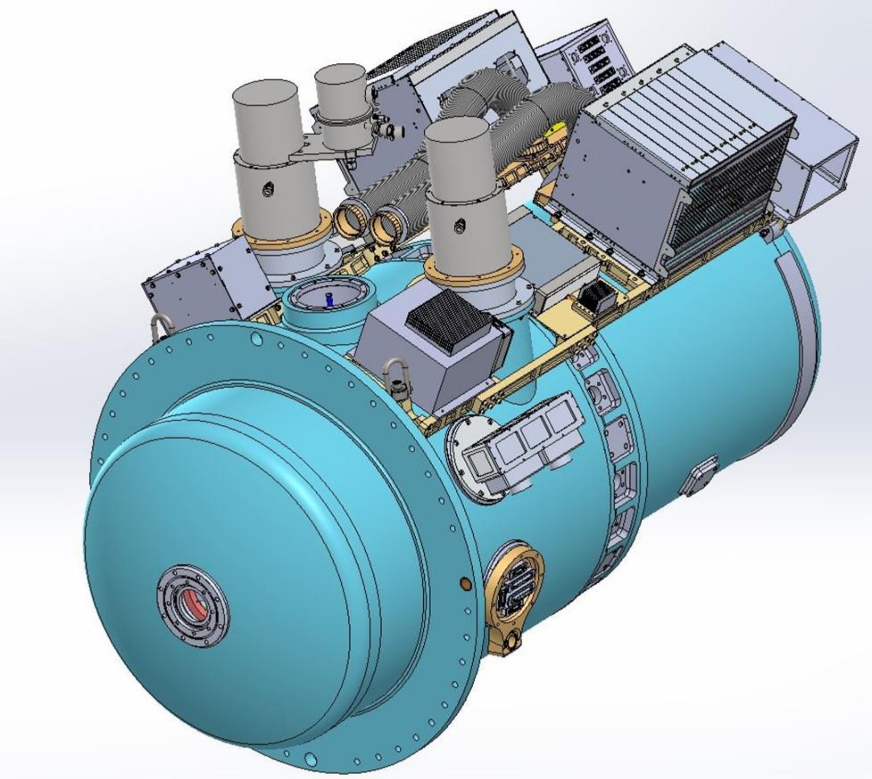
HIRMES Science Working Group

Investigator	Institution	Investigator	Institution
Arendt, Richard*	UMBC	Pontoppidan, Klaus	STScI
Bergin, Edwin	U. Michigan	Richards, Samuel*	USRA
Bjoraker, Gordon	GSFC	Roberge, Aki	GSFC
Chen, Christine*	STScI	Rostem, Karwan*	UMBC
Kutyrev, Alexander	U. Maryland	Stacey, Gordon	Cornell U.
Melnick, Gary	Harvard U.	Tolls, Volker*	Harvard U.
Milam, Stefanie	GSFC	Su, Kate*	U. Arizona
Moseley, Harvey	GSFC Emeritus	Watson, Dan	U. Rochester
Neufeld, David	Johns Hopkins U.	Wollack, Edward	GSFC
Nikola, Thomas*	Cornell U.		

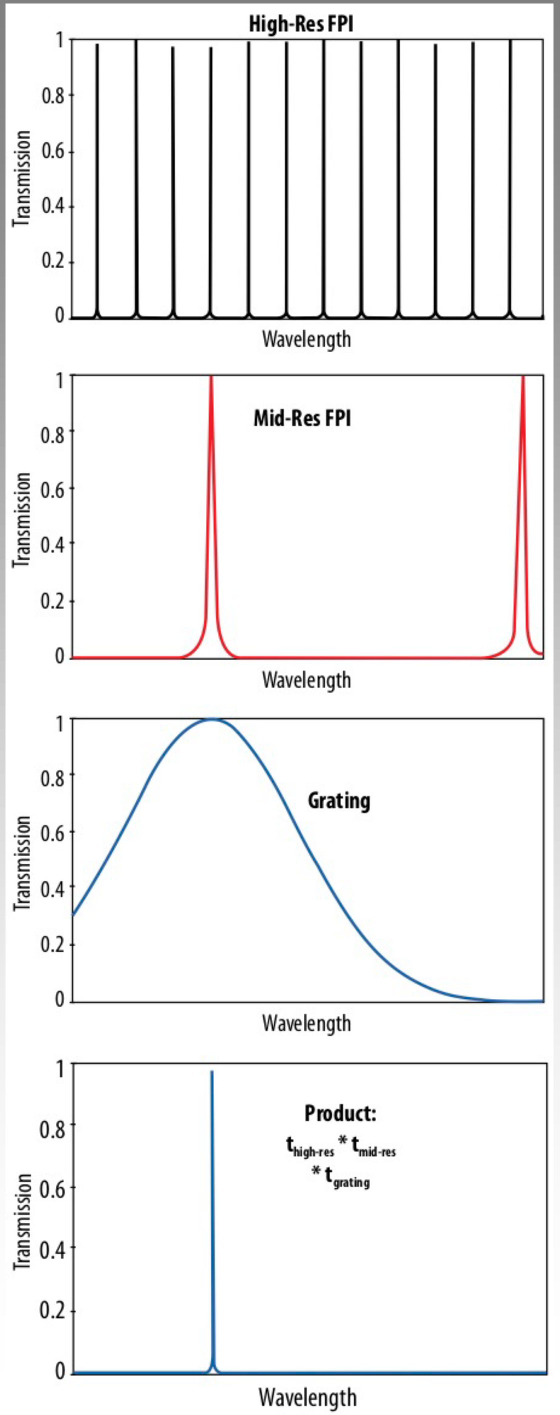
* Investigator added via Legacy Science Investigation proposal

HIRMES Fact Sheet

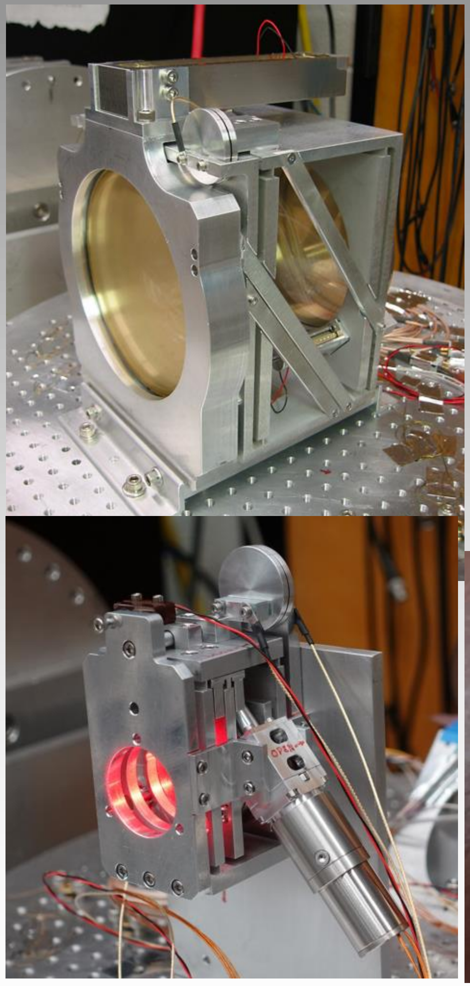
- A direct detection spectrometer covering the spectral range from 25 to 122 μm
- Four spectroscopic modes to HIRMES
  - High-res mode: RP ~ 50,000 → 100,000
  - Mid-res mode RP ~ 10,000
  - Low-res mode RP ~ 600
  - Imaging spectroscopy mode: RP ~ 2000
- Modes optimized for the science goals.
- HIRMES uses:
  - Background limited bolometers
  - Combination of Fabry-Perot Interferometers and gratings



Achieving High RP w/ Fabry-Perots

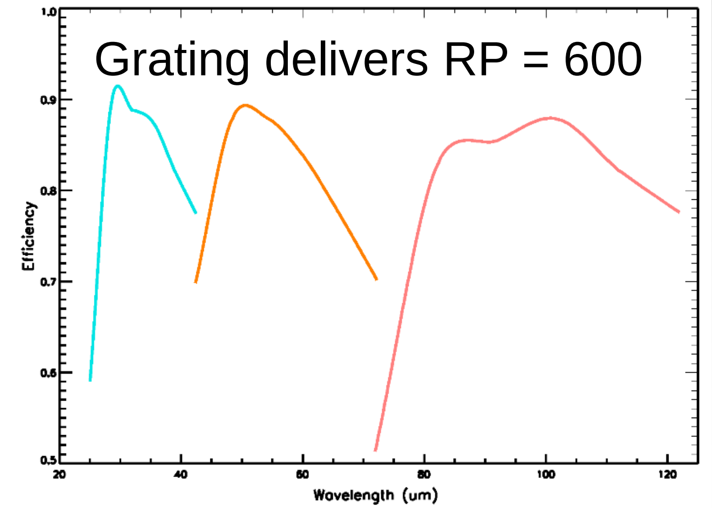


Mode	Scanning FPI	Central Wavelength	Wavelength Range	Resolving Power	Etalon Diameter
slit	high-R LW	112 μm	86-122 μm	100,000	100 mm
slit	high-R MW	63 μm	50-86 μm	100,000	90 mm
slit	high-R SW	35 μm	25-36 μm	50,000	90 mm
slit	mid-R LW	112 μm	86-122 μm	12,000	90 mm
slit	mid-R MW	63 μm	50-86 μm	12,000	90 mm
slit	mid-R SW	35 μm	25-36 μm	12,000	90 mm
imaging	low-R SW	57 μm	50-70 μm	2000	30 mm
imaging	Low-R LW	102 μm	80-125 μm	2000	30 mm



HIRMES high (top) and low (bottom) resolution scanning etalons

HIRMES fixed etalon imaging filters

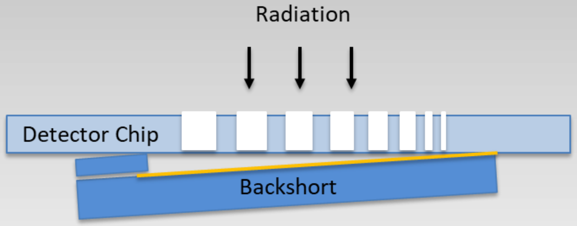


Grating delivers RP = 600

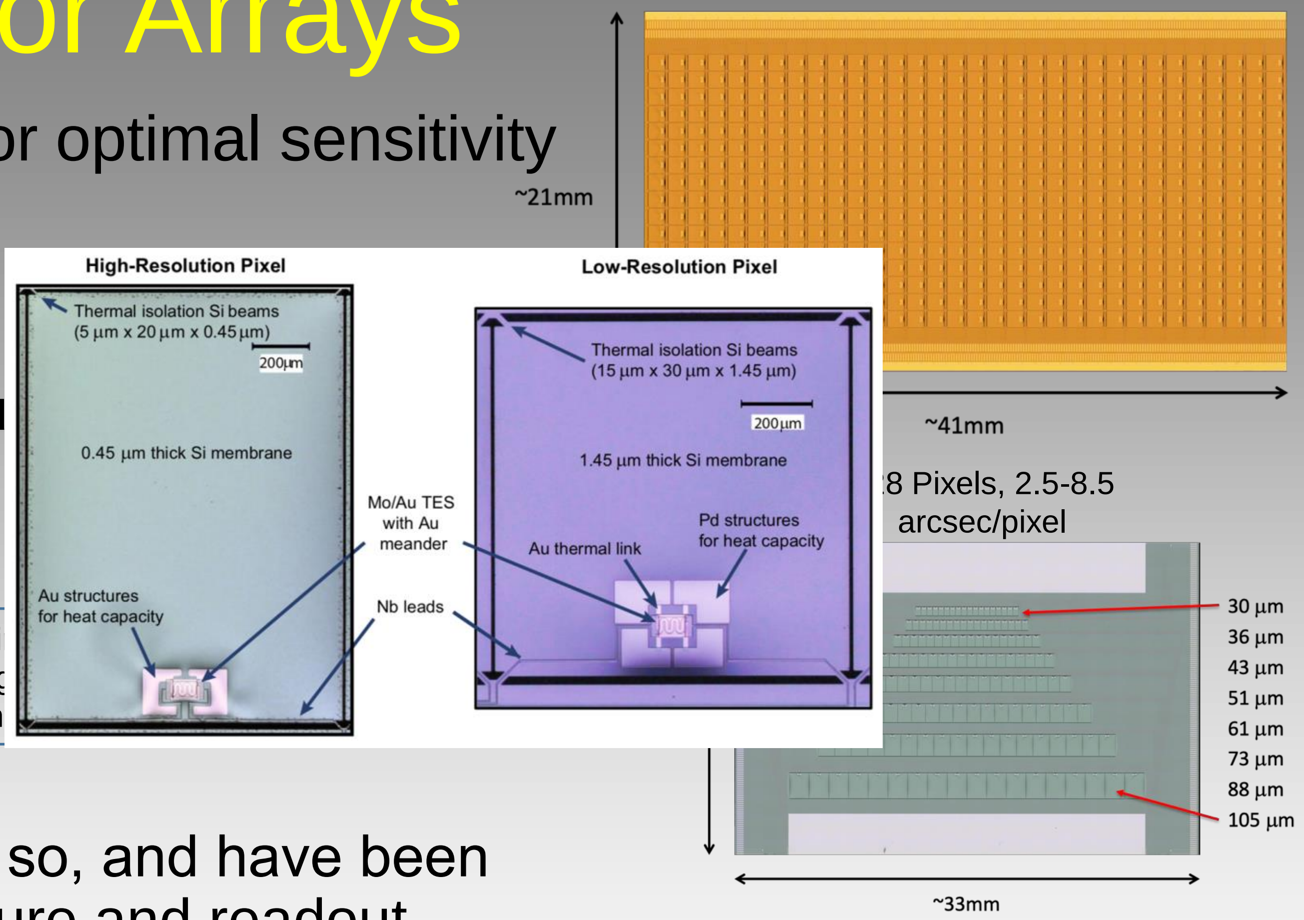
HIRMES diffraction gratings

Detector Arrays

- ❑ Membrane absorber, TES bolometers for optimal sensitivity
- ❑ Subarrays: imaging and long slits
- ❑ Challenges
  - ➢ Point source sensitivity optimization requ
    ⇒ need series of arrays 3.4 to 1 in scale
  - ➢ Maximizing DQE requires a back-short

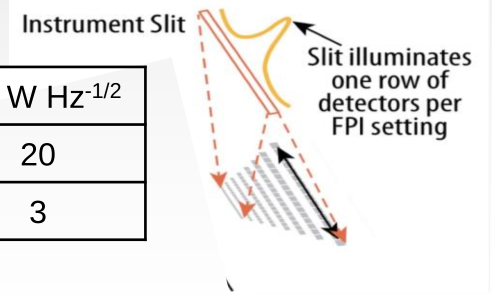


A tilted mi
integrating
at the cen



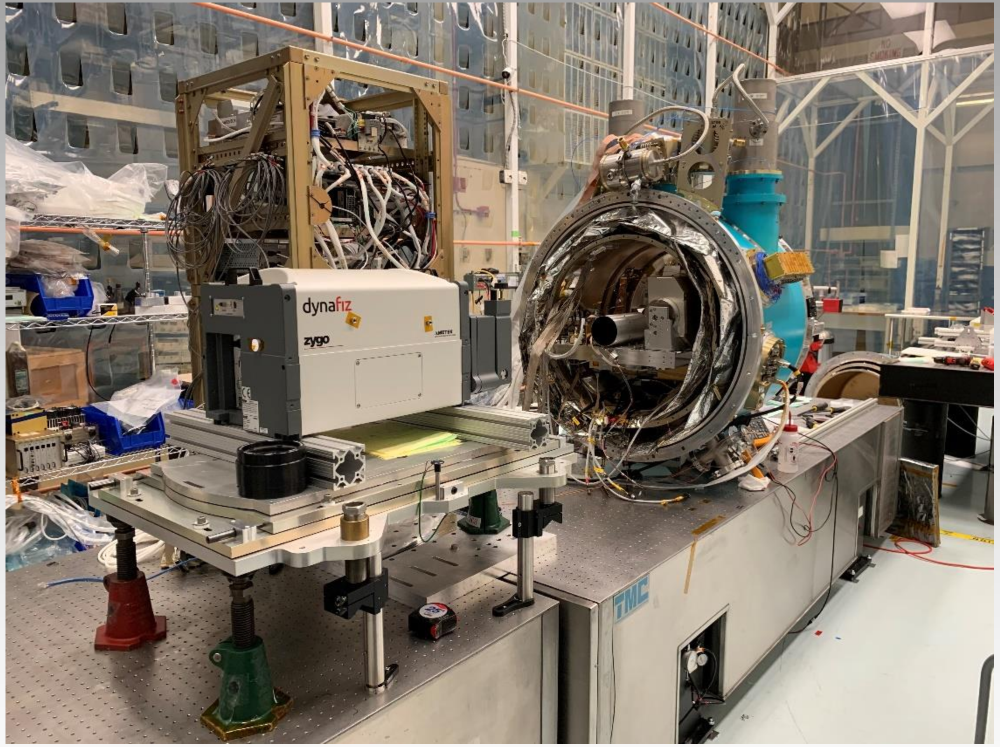
- ➢ NEP's challenging, but not exceptionally so, and have been demonstrated – challenges are architecture and readout
- ➢ Longest wavelength, largest pixels, and the most demanding NEP requirements ⇒ demands on architecture

Dark Detector NEP 10^{-18} W Hz$^{-1/2}$	
Low Resolution	20
High Resolution	3

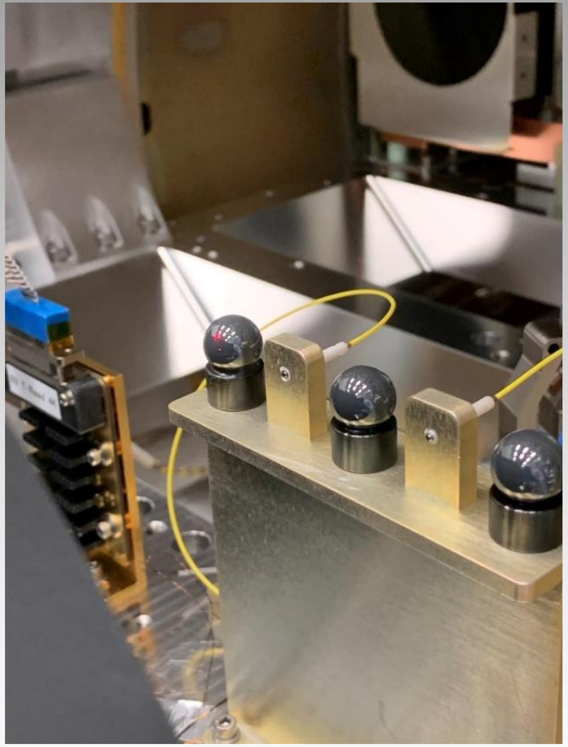


Steps toward Integration and Test

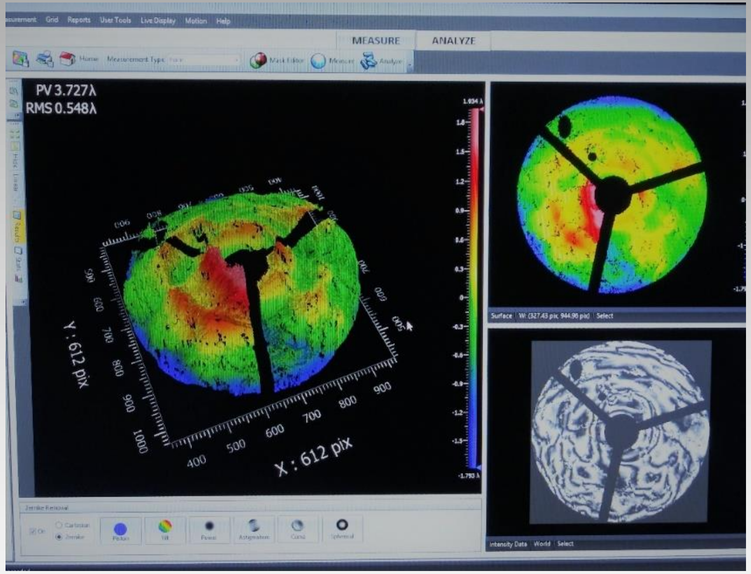
Cryogenic optics alignment verfication



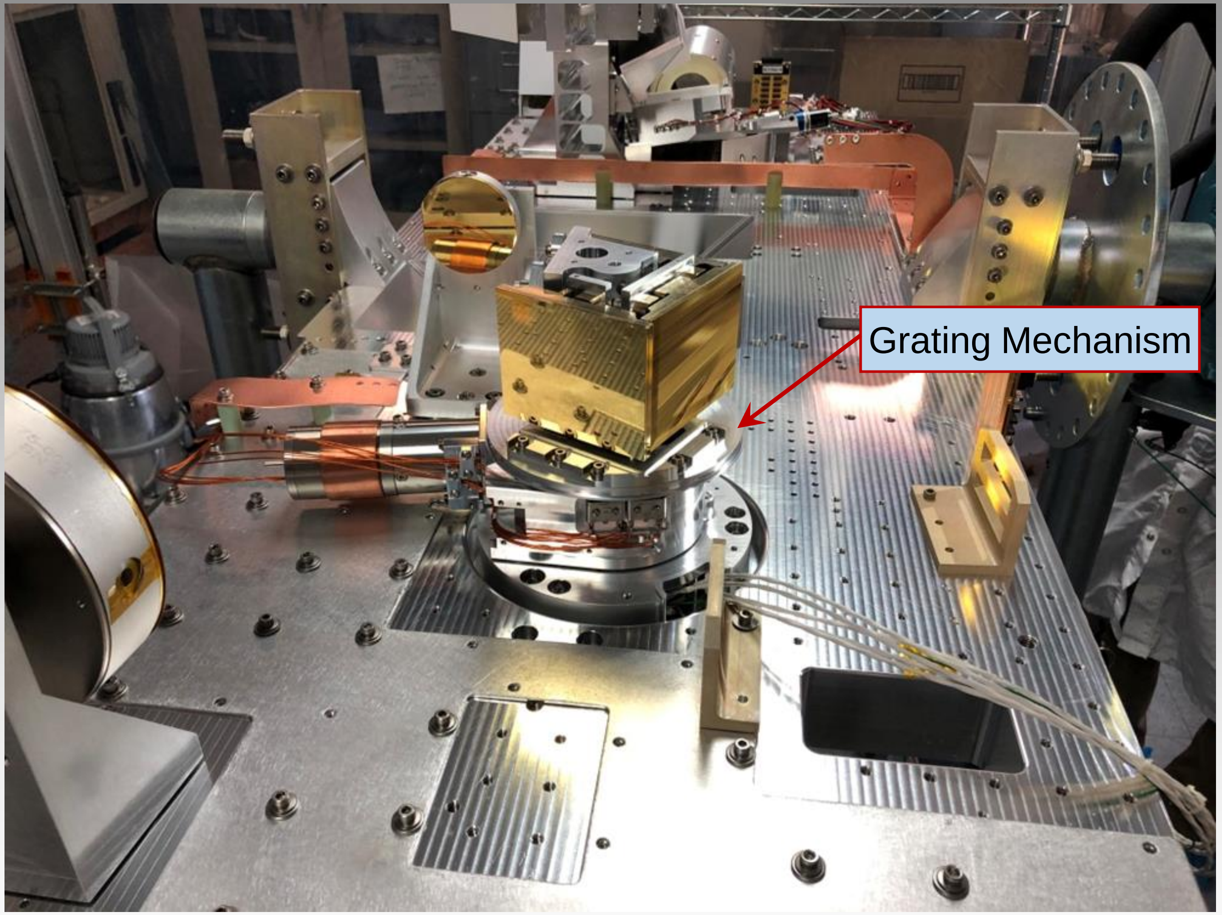
Warm test set-up. Cryogenic test is performed using a fused silica cryostat pressure window.



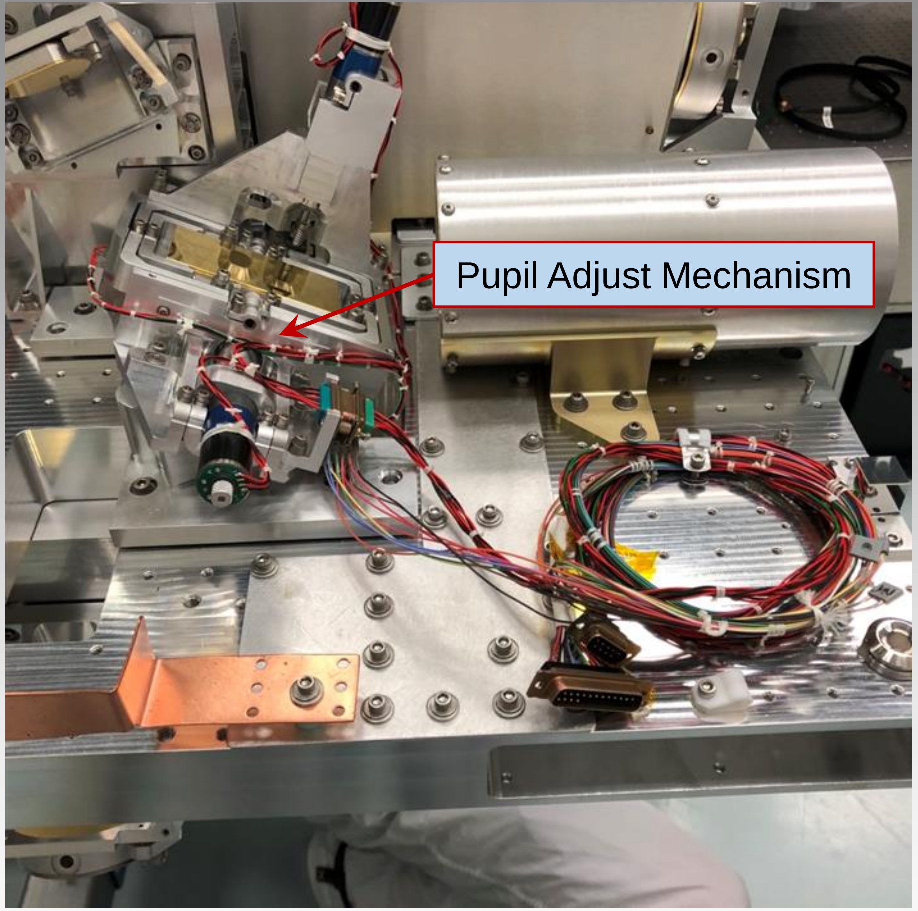
Cryogenic OGSE (tooling balls and fiber sources) is located in place of the FPA to support the double pass test



Double-pass alignment test

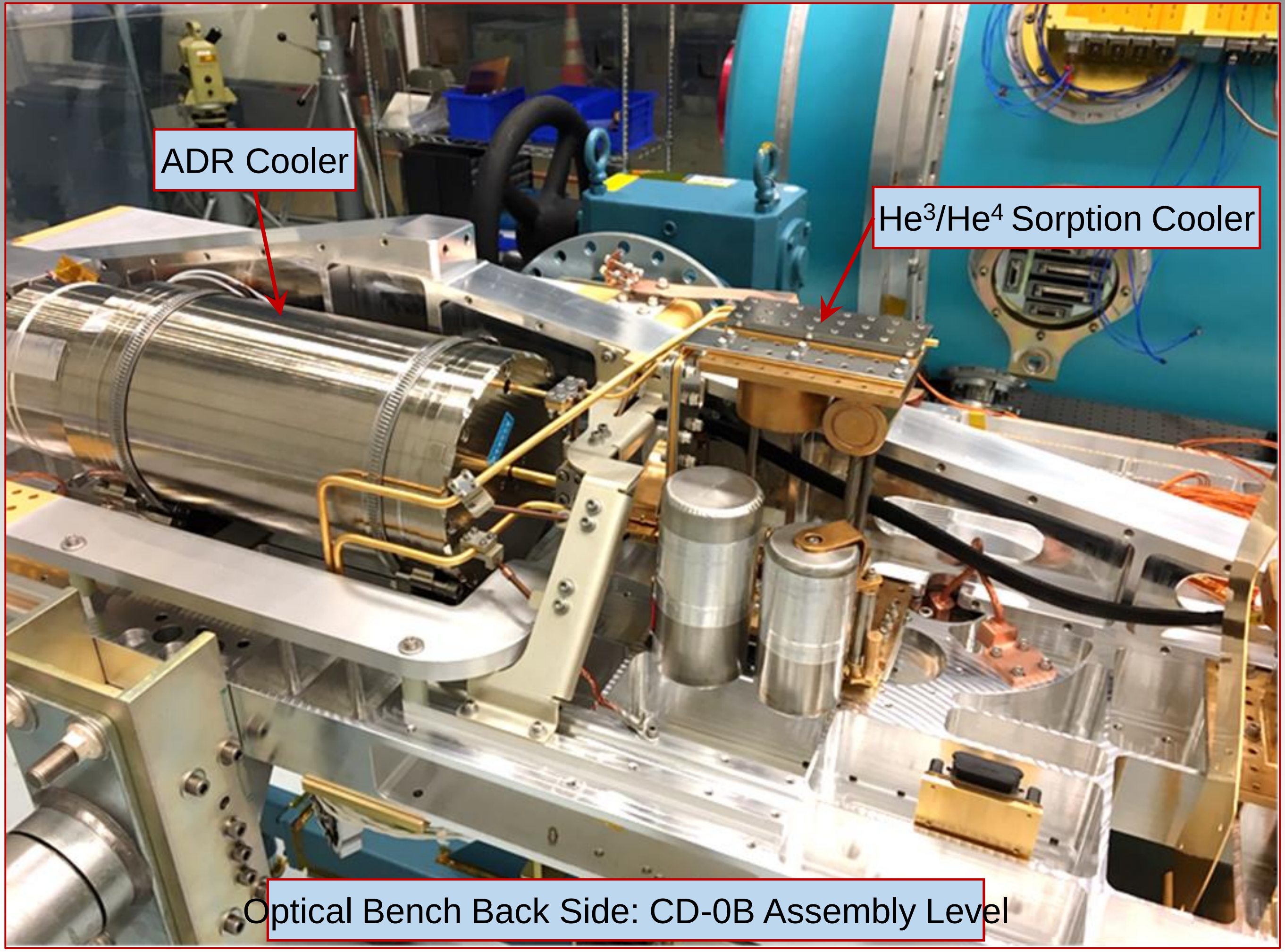


The grating mechanism carries 3 diffraction gratings and 1 mirror. It provides +/- 180 degree rotation with 8 arc-sec precision and stability



The pupil adjust mechanism enables alignment of the HIRMES entrance pupil with the telescope secondary mirror. It provides +/- 3 degrees tile in two axis with 1 arc-min precision and stability

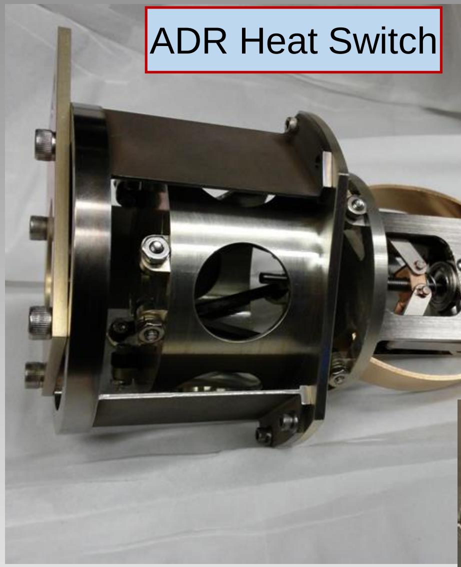
Key elements of the HIRMES mK cooling system



ADR Cooler

He^3/He^4 Sorption Cooler

Optical Bench Back Side: CD-0B Assembly Level

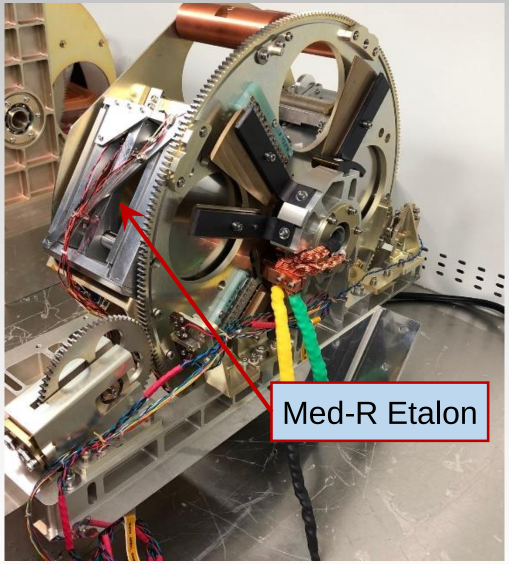


ADR Heat Switch

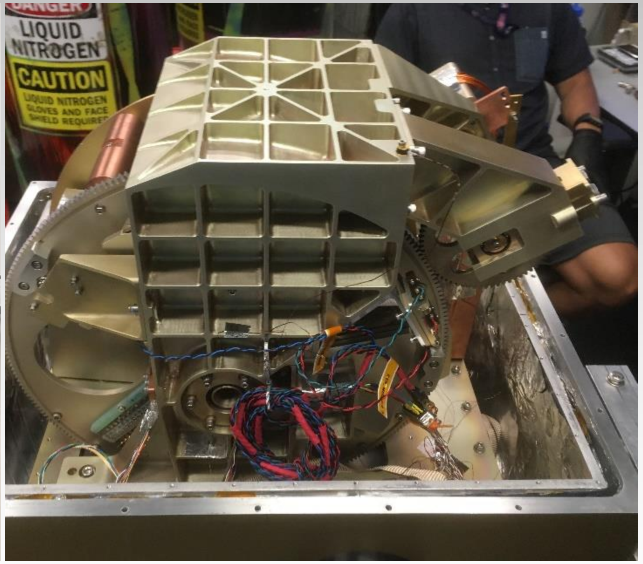
Heat Switch Thermal Interface

Each unique observation requires setting 6 mechanisms

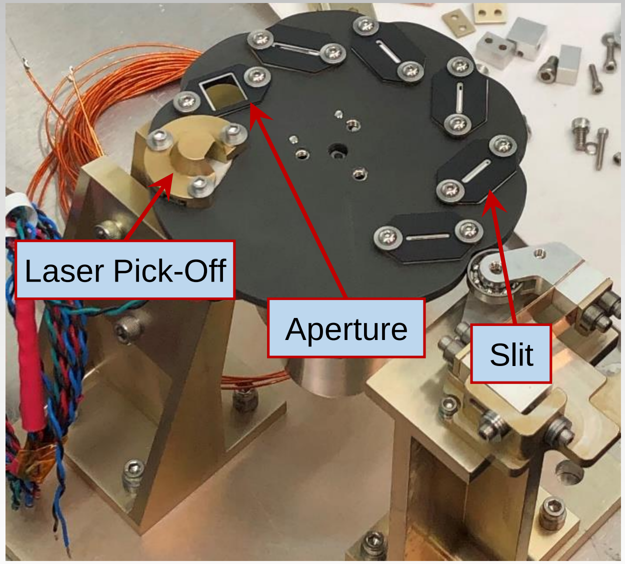
Spectroscopy Mode	X Denotes Element in Beam Line					
	HR Scanning FPI	MR Scanning FPI	LR Scanning FPI	Grating	Filters & Fixed FPI	Slit
High Resolution	X	X		X	X	X
Medium Resolution		X		X	X	X
Low Resolution				X	X	X
Imaging			X		X	



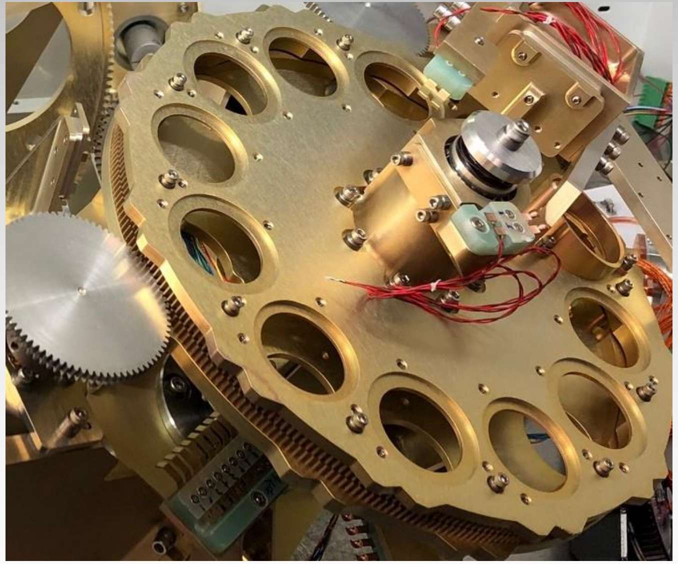
Medium-R FPI selection wheel



High-R FPI selection wheel in test



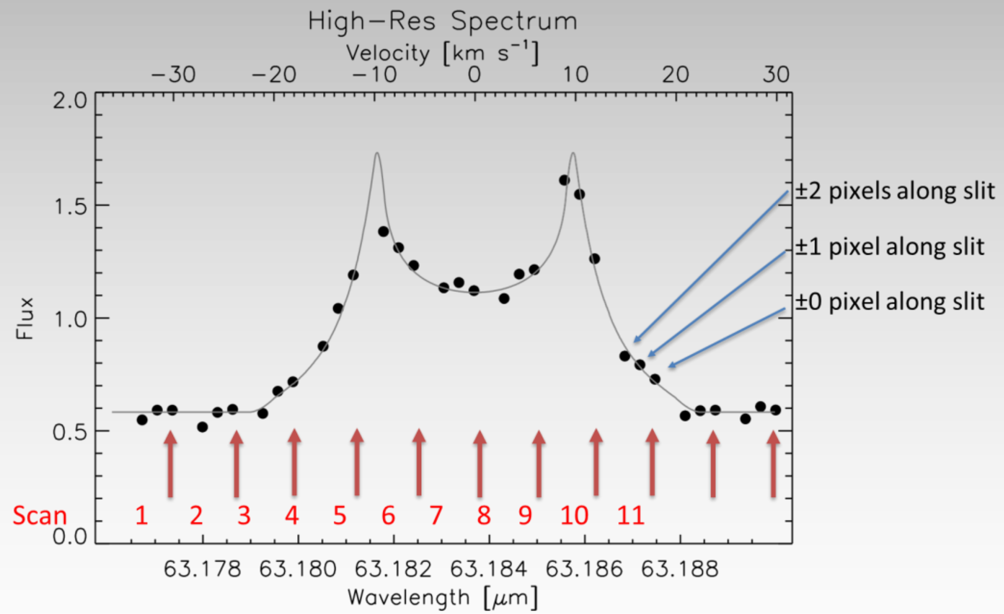
Slit selection wheel



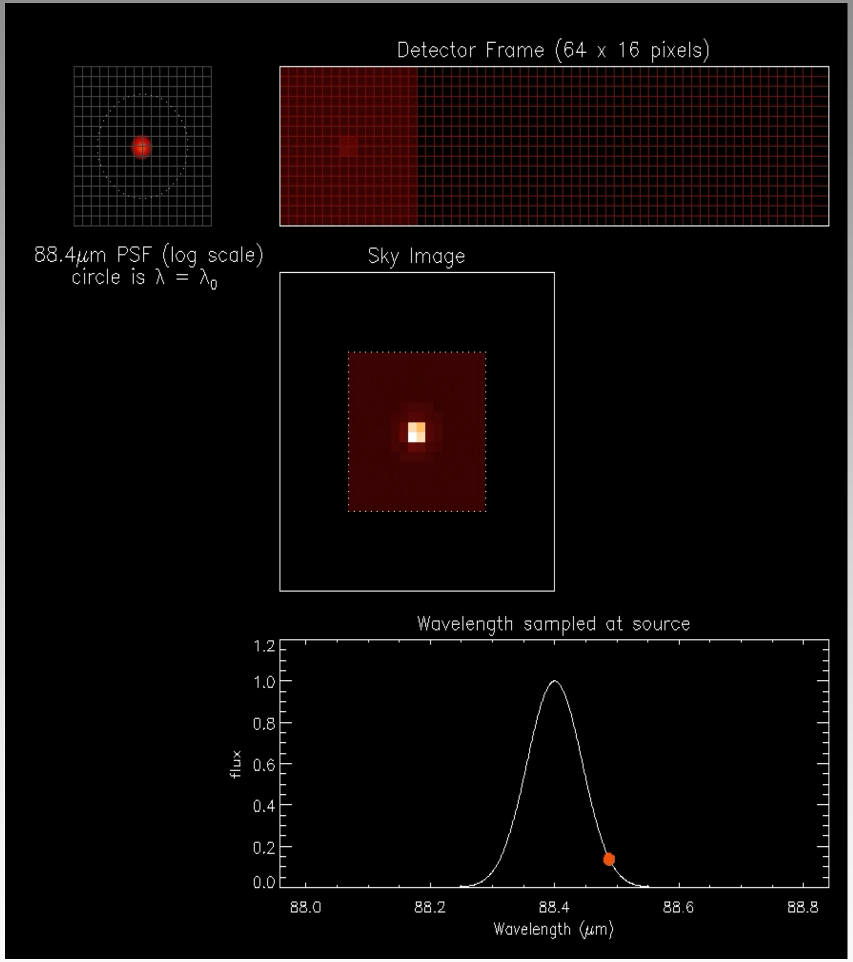
Filter selection wheel

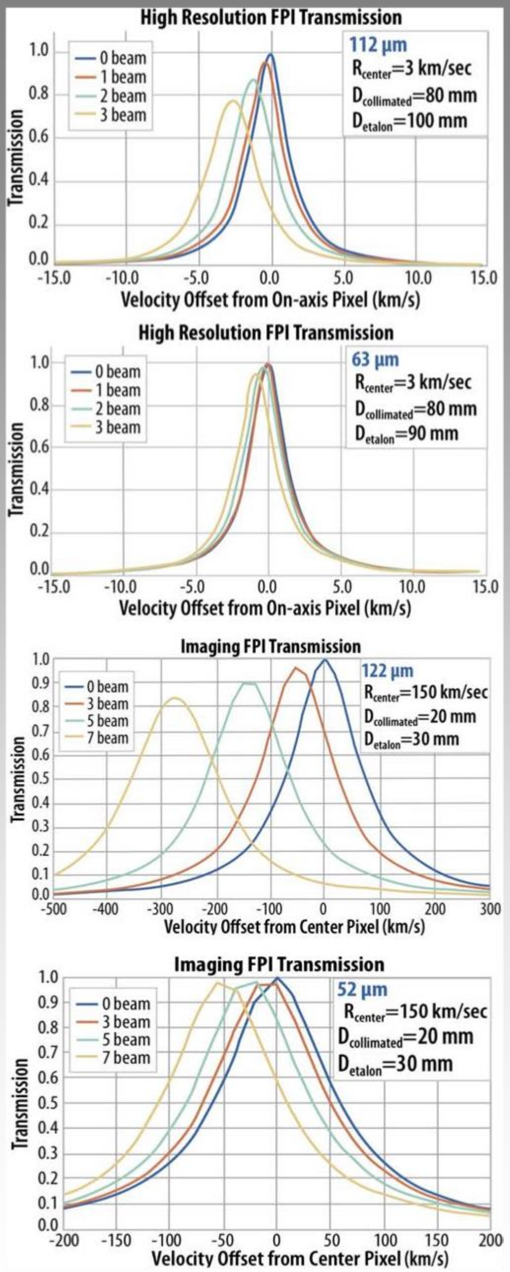
Spatial scanning

- Gets above 1/f noise and removes sky background, minimizes losses
- FPI transmits to blue off-axis
  - Lissajous or Box scan patterns for spectroscopy imaging
  - Scans along slit for high-res modes



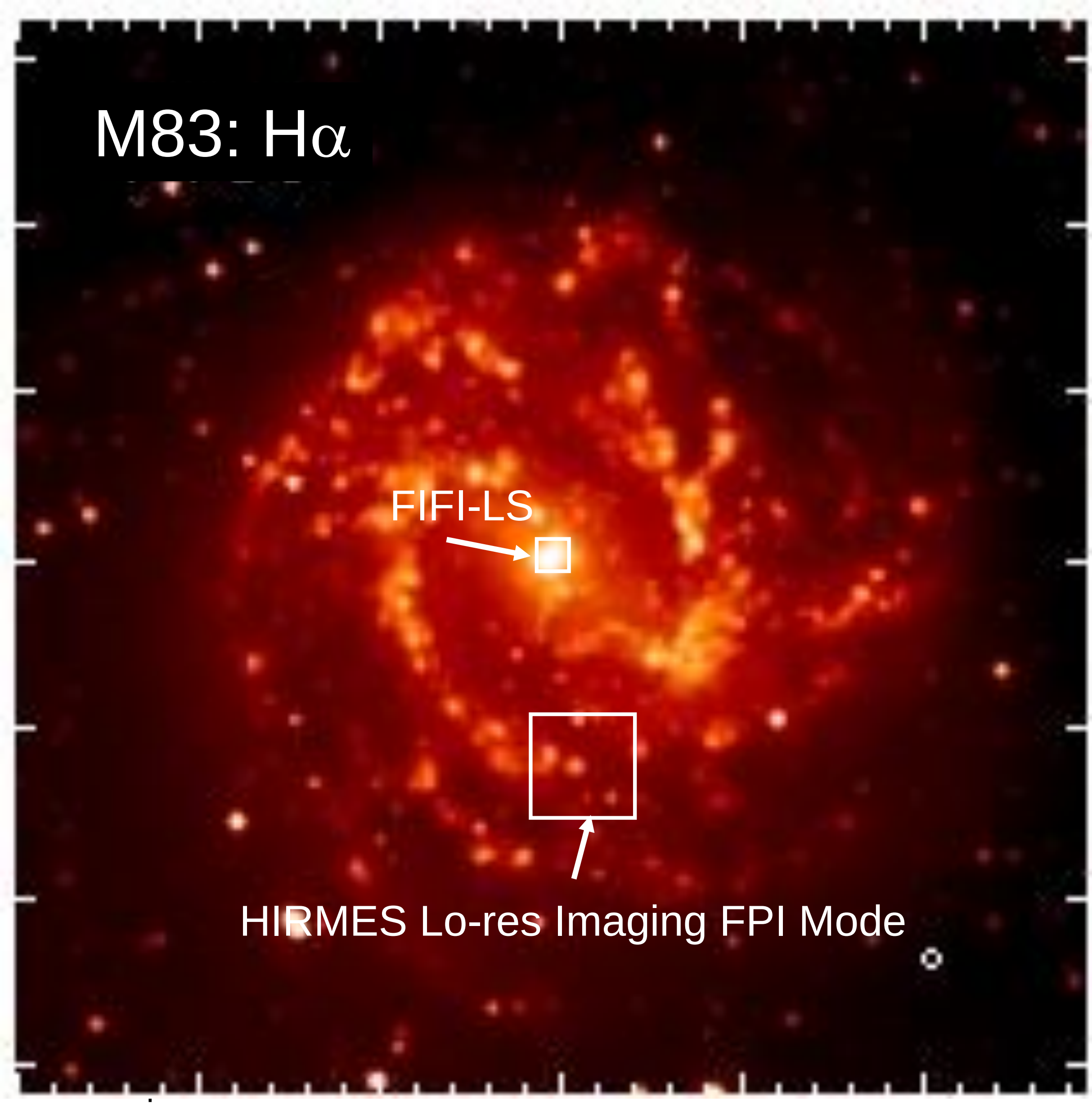
Simulated line profile of a rotating disk showing 11 scans at nominal wavelengths to sample the line profile. Additional sampling appears as the source is scanned up and down the slit by ±2 pixels.





Imaging Spectroscopy Mode example:

- M83: [OIII] × 2, [NIII], [NII]
  - Ionization/stellar populations
  - Obscured star formation
  - Metallicity O/H, N/O ⇒ SF history
- [OIII]: 52 μm
  - Line flux: 6 E-17 W/m^2
  - 12 σ in 15 minutes
  - 30 pointings ⇒7.5 hours
- All lines: additional 1 × 7.5, 2 × 3.0 hrs
  - *Total: 21 hours for complete [OIII] × 2, [NIII], [NII]*



Summary

- High resolution direct detection spectroscopy is a *unique and compelling* niche for SOFIA
  - Tomographic locations of the building blocks of planetary systems
  - YSO's, debris disks, comets, gas giant planet atmospheres
- The HIRMES spectrometer was funded and built to pursue this science and enabled much more such as:
  - Velocity resolved spectroscopy of galaxies
  - Efficient imaging of galaxies in fine-structure lines
- HIRMES encountered challenges with detector arrays
- Revival of HIRMES in the cards when these challenges are overcome

Thanks!