The HIRMES Spectrometer: Science and Technical Details

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What is HIRMES?

- HIRMES is the 3rd generation instrument that will fly on SOFIA in the winter of 2020-2021
- HIRMES primary science is to investigate protoplanetary disk physics and addresses the questions:
  - How does the disk mass evolve during planetary formation?
  - What is the distribution of oxygen, water ice, and water vapor in different phases of planet formation?
  - What are the kinematics of water vapor and oxygen in protoplanetary disks?

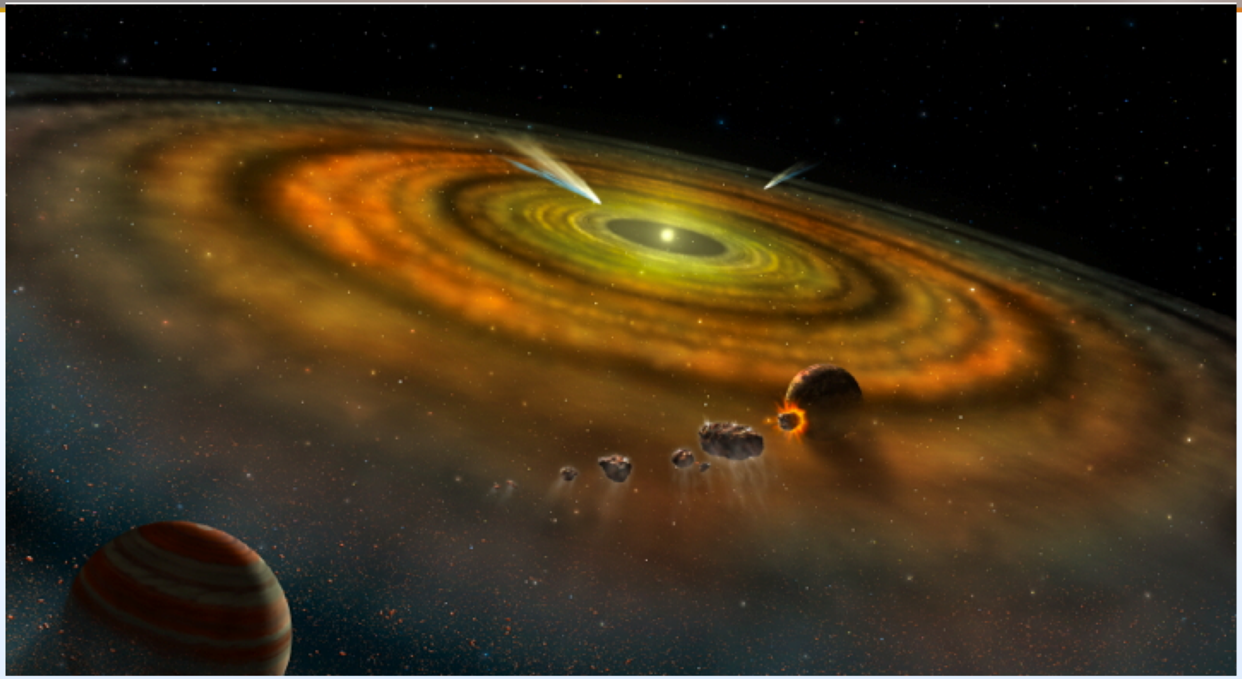
Over riding theme is discover how protoplanetary systems evolve

How is the Science Achieved

- HIRMES is a direct detection spectrometer covering the spectral range from 25 to 122 μm
- There are four spectroscopic modes to HIRMES:
  - High-res mode – 1-3 positions — R ~ 50,000 to 100,000
  - Mid-res mode – long slit 16 spatial pos. — R ~ 10,000
  - Low-res mode – long slit 16 spatial pos. — R ~ 600
  - Imaging spectroscopy mode: 256 spatial pos. — R ~ 2000 – 5 selected regions
- For high sensitivity and resolving power with direct detection HIRMES uses:
  - Background limited bolometers
  - Combination of Fabry-Perot Interferometers and gratings

HIRMES

Primary Science

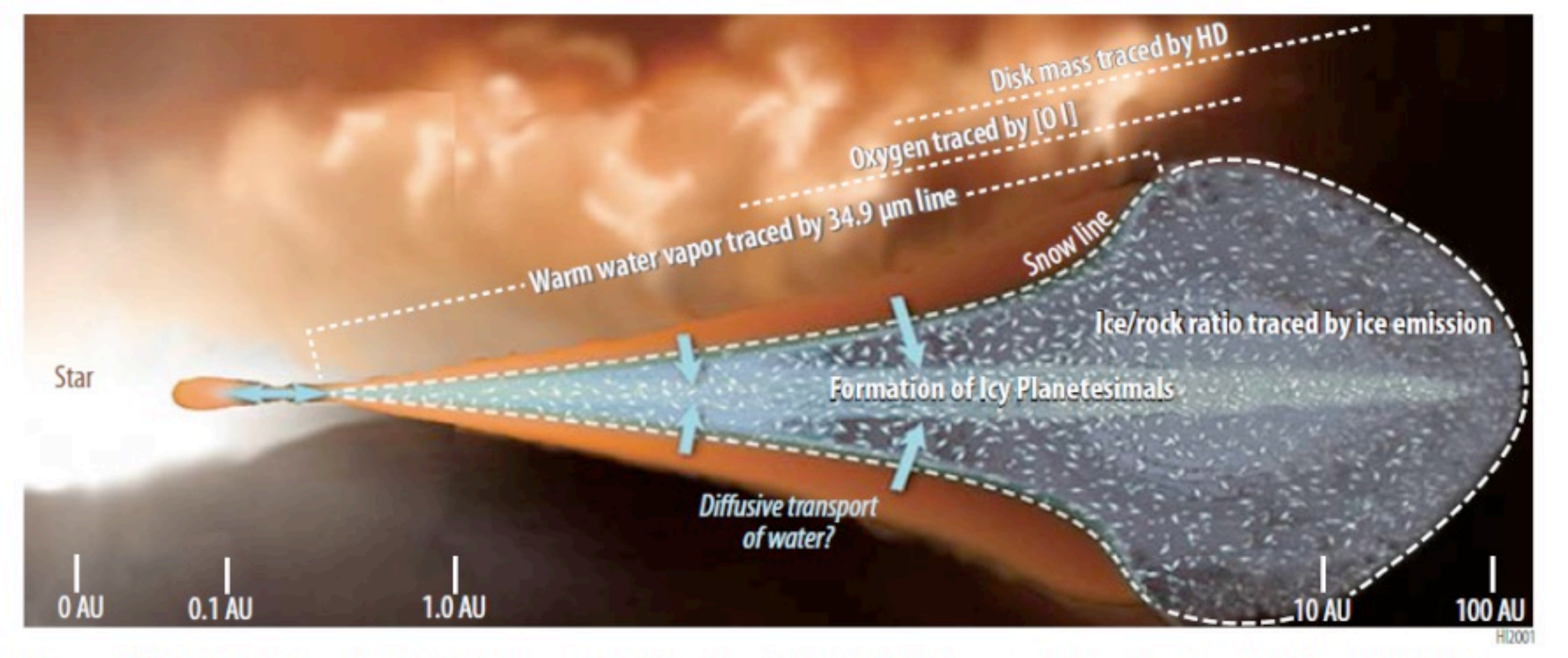


- Over ~ 10 million years, protoplanetary disks evolve into young planetary systems
- Bulk of mass is gas and ice – both difficult to observe
- Hinders testing & development of planet formation theories

HIRMES and Protoplanetary Disks

- **Water and ice:** water and ice play a critical role in the formation of giant planet cores and, producing habitable conditions in terrestrial planets
  - H_2O 34.9823 μm 651-624 rotational line
  - Ice 43, 47, 63 μm solid state feature
- **Neutral Oxygen:** a tracer of disk chemistry and radial structure
  - [OI] 63.1837 μm $^2P_1$-$^3P_2$ fine-structure line
- **Deuterated hydrogen:** a tracer of disk mass
  - HD 112.0725 μm J = 2-0 rotational line
  - HIRMES resolves these narrow lines and determines their origins from velocity profiles

Water and Ice



Water line measurements locate the transition region between warm water vapor and ice through velocity resolved spectroscopy

Ice Diagnostics

- Detect ice through its **crystalline** (43 and 63 μm) and **amorphous** (47 μm) ice features
- The far-IR has unique tracers of ice, since ice warm enough to emit in its **shorter wavelength bands will melt**
- Emission arises from small icy grains **above the colder disk**
- Strength of features yields **mass** of ice
- Ice features not available to other facilities so this is not well explored observationally

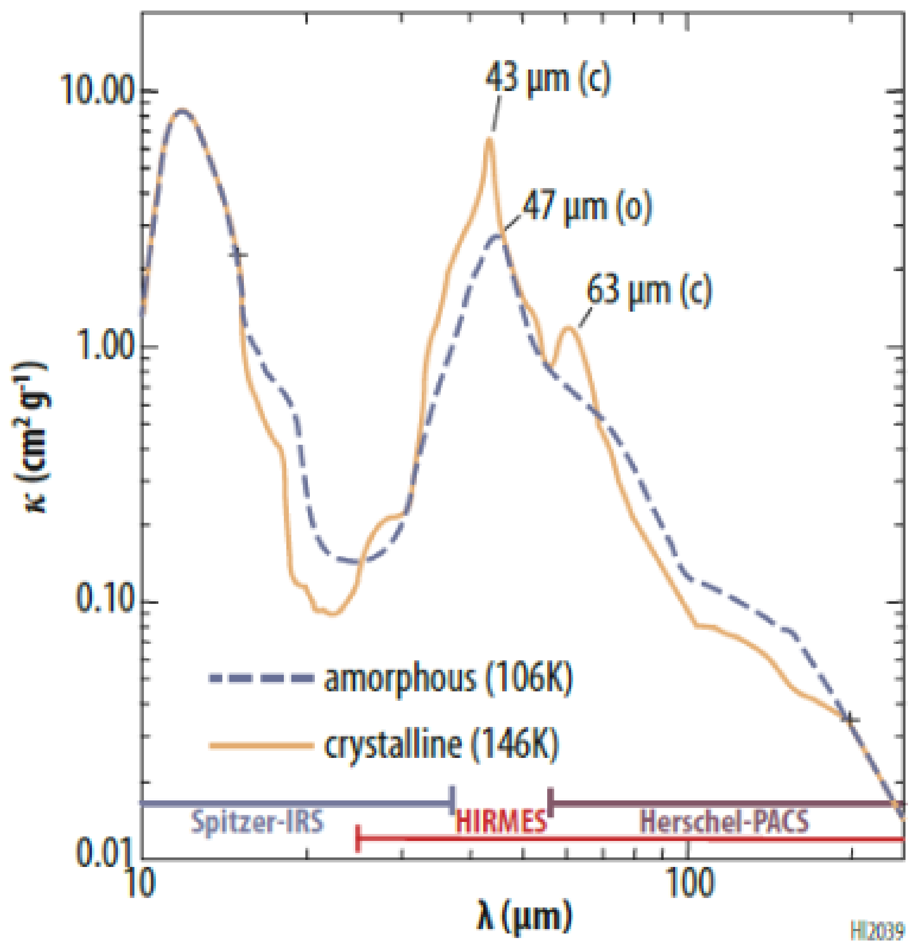


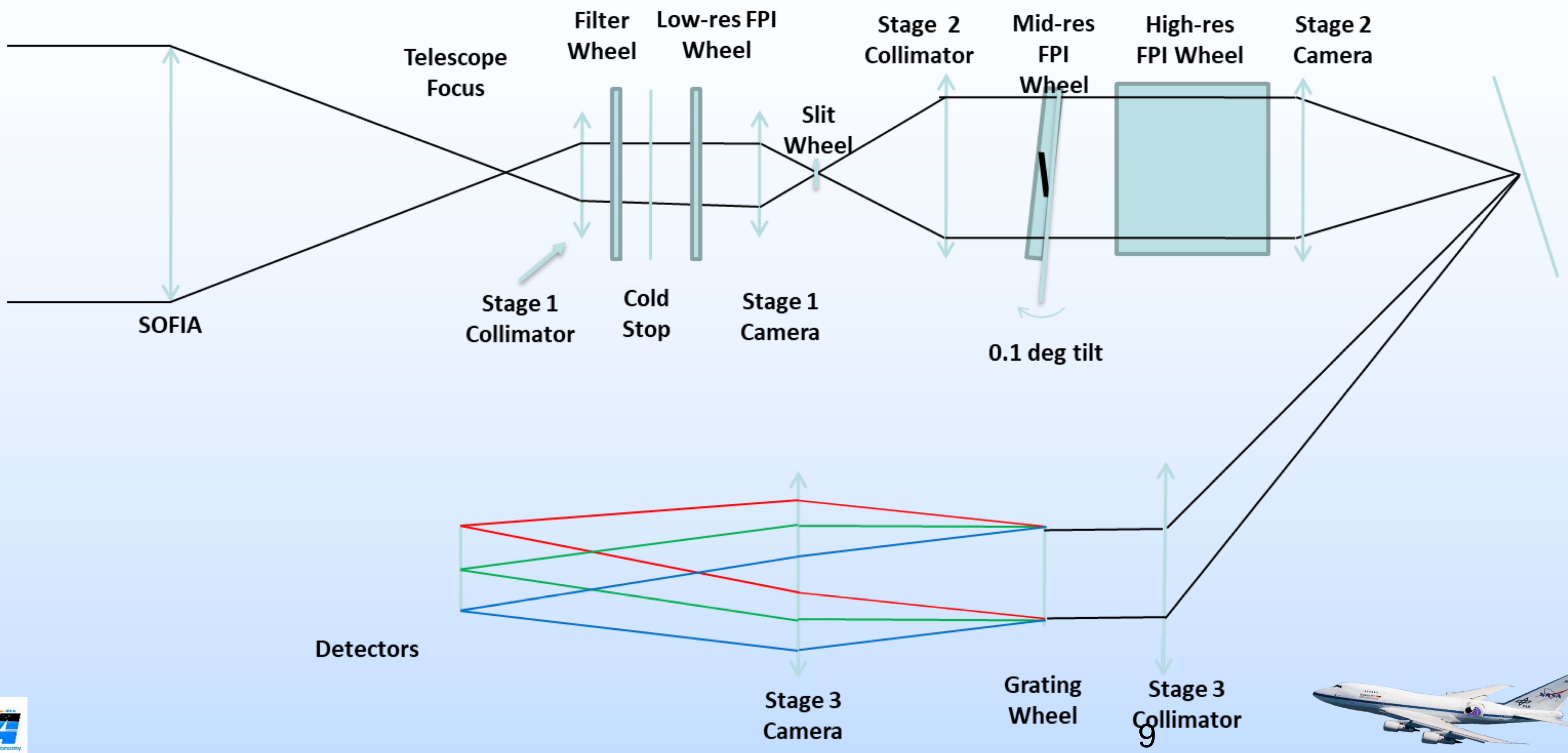
Figure D-4: HIRMES can infer the thermal history of grain mantles by observation of the 43, 47 and 63 μm water-ice features. The plot shows the emission/absorption coefficients (McClure et al. 2015).

Lots of other science

- **Galactic chemistry, radiation fields, shocks:** [SI] 25.25 μm; [FeII] 25.99, 35.35 μm, [SIII] 33.48 μm, [SiII] 34.81 μm; [NeIII] 36.0 μm, [OIII] 51.81, 88.36 μm, [NIII] 57.30 μm, [OI] 63.18 μm
- **Outflows:** OH, CO
- **Extragalactic lines** resolved with mid-res, imaged with low res
- **SEDs** with grating mode

HIRMES

Schematic Optical Path

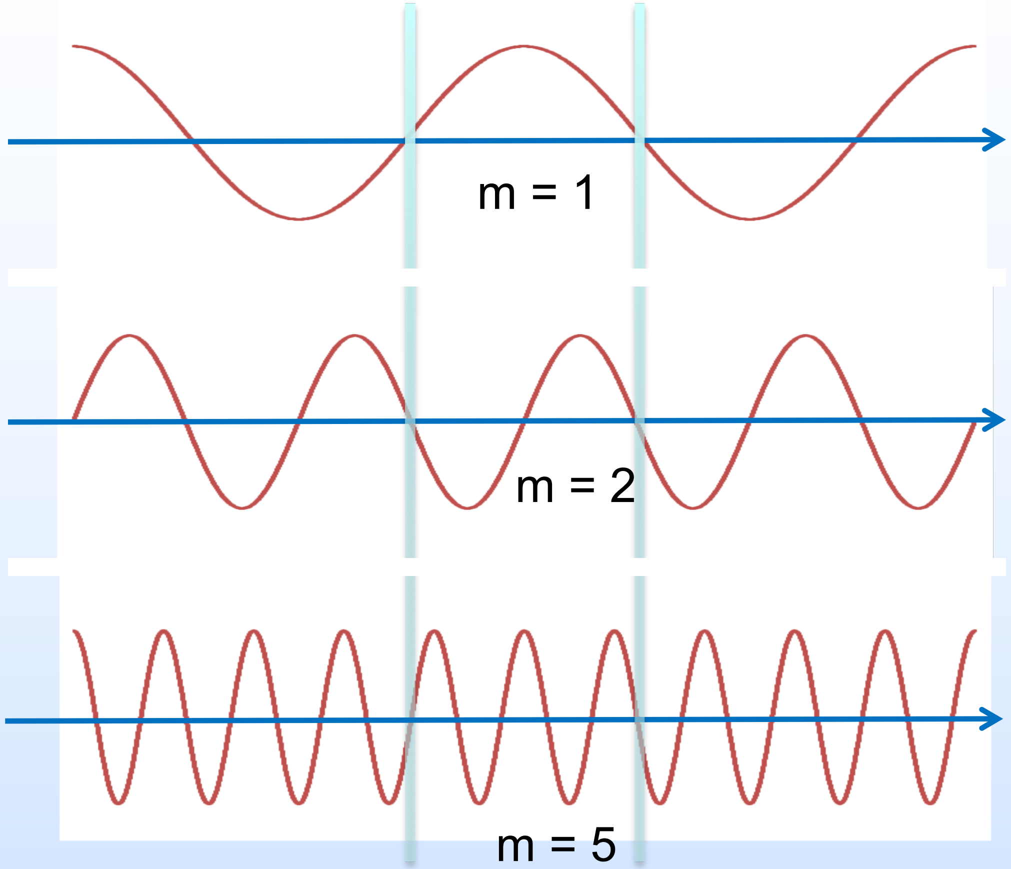


FPI in a Nutshell

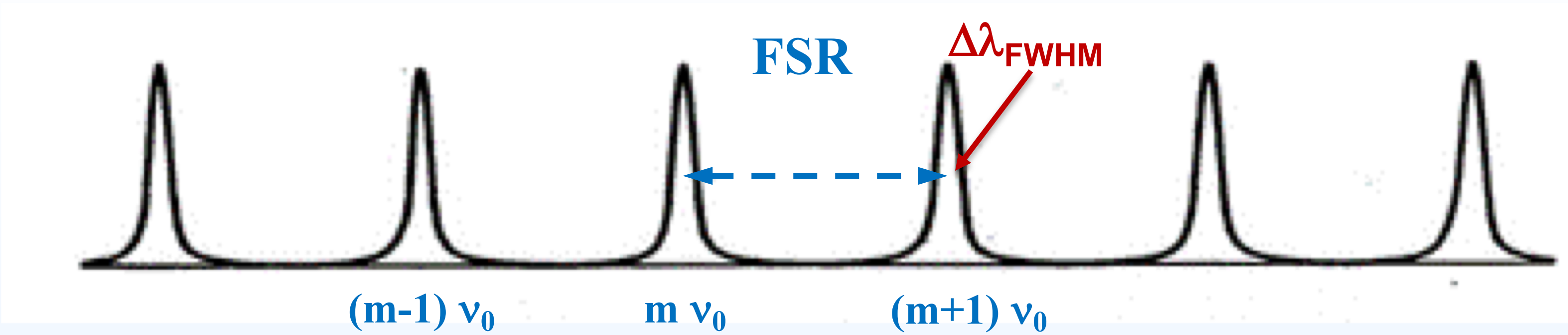
- Highly reflective mirrors form resonant cavity
- Resonances at: $m\lambda_m/2 = d$

  $\Rightarrow \nu_m = c/\lambda_m = m*(c/2d) = m\cdot\nu_0$
- Series of transmissive spikes at:

  $\nu_m = m\cdot\nu_0$



FPI Basics

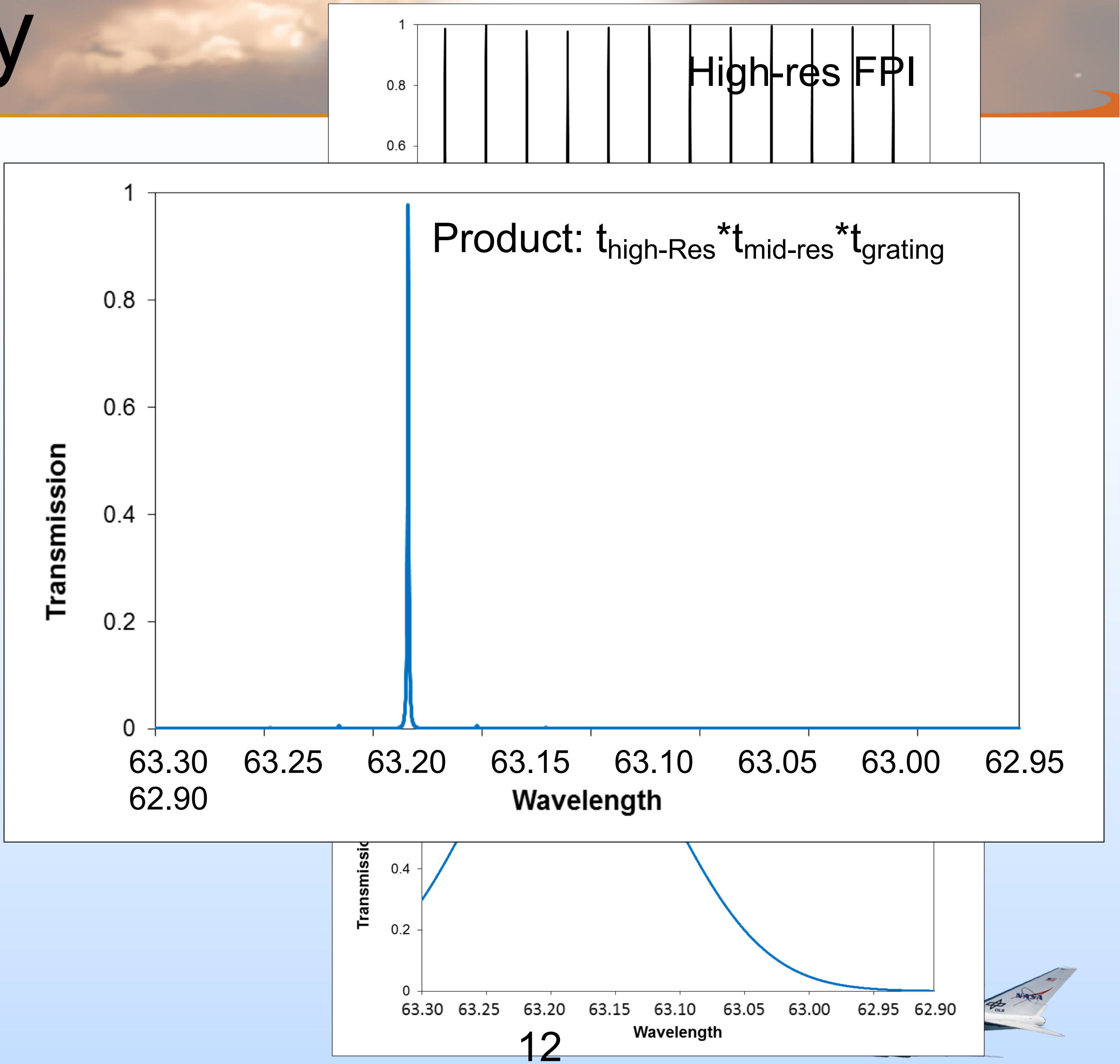


- **Finesse:** the "quality factor" of the resonance ~ numbers of bounces before transmission. Finesse depends on **r**: $F \approx \pi\sqrt{r}/(1 - r)$
- **Resolving power:** the RP depends on F and m: $R_{FPI} \equiv \lambda/\Delta\lambda_{FWHM} = m \cdot F$
- **Free Spectral Range:** the distance between resonant peaks at a given frequency – if you scan a free spectral range at ν_0 then all frequencies higher than ν_0 will be addressed
- The RP is $\propto$ spacing, d and the free spectral range is $\propto$ 1/d, so when RP $\uparrow$, FSR $\downarrow$ $\Rightarrow$ at high orders, the orders begin to overlap

Need to select orders of operation

Spectral Purity

- Sorting High-Res Orders
  - $F_{High\text{-}Res} \sim 30\text{-}60 \Rightarrow n_{HOFPI} \sim 3333\text{-}1667$
  - Need order sorting at the level of $R_{Mid\text{-}Res} \sim 3/2\ n_{High\text{-}Res} = 5000\text{-}2500$
  - Mid-Res has $R_{Mid\text{-}Res} \sim 10{,}000$
- Sorting Mid-Res Orders
  - $F_{mid\text{-}Res} \sim 30\text{-}50 \Rightarrow n_{Mid\text{-}Res} \sim 333\text{-}200$
  - Need order sorting at the level of $R_{Grating} \sim 3/2\ n_{mid\text{-}Res} = 600\text{-}360$
  - Grating has $R_{grating} \sim 600$
- Out of band then protected with reststrahlen salt filters, etc…



Limits to Performance: Aperture Effects

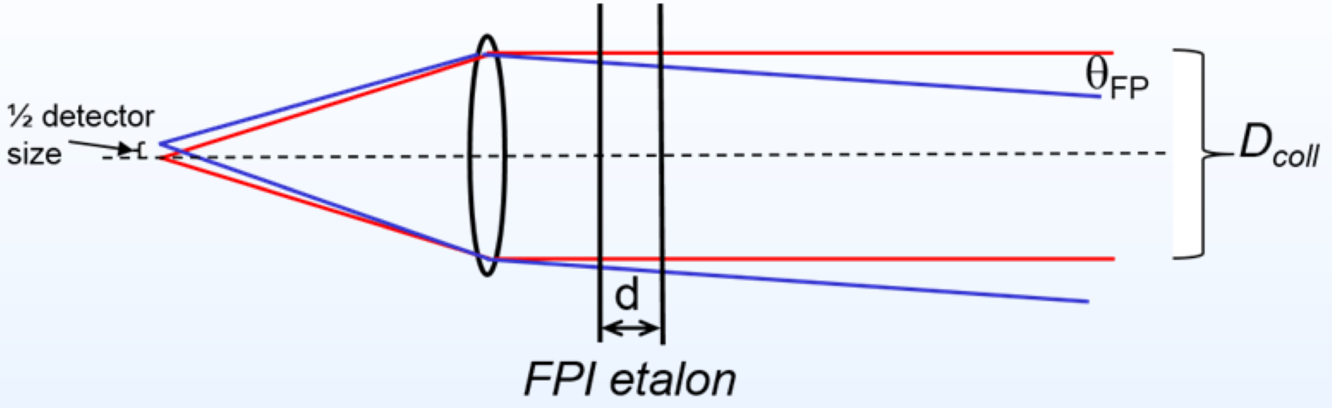
- Off-axis rays resonant at a different frequency than the on-axis ray:

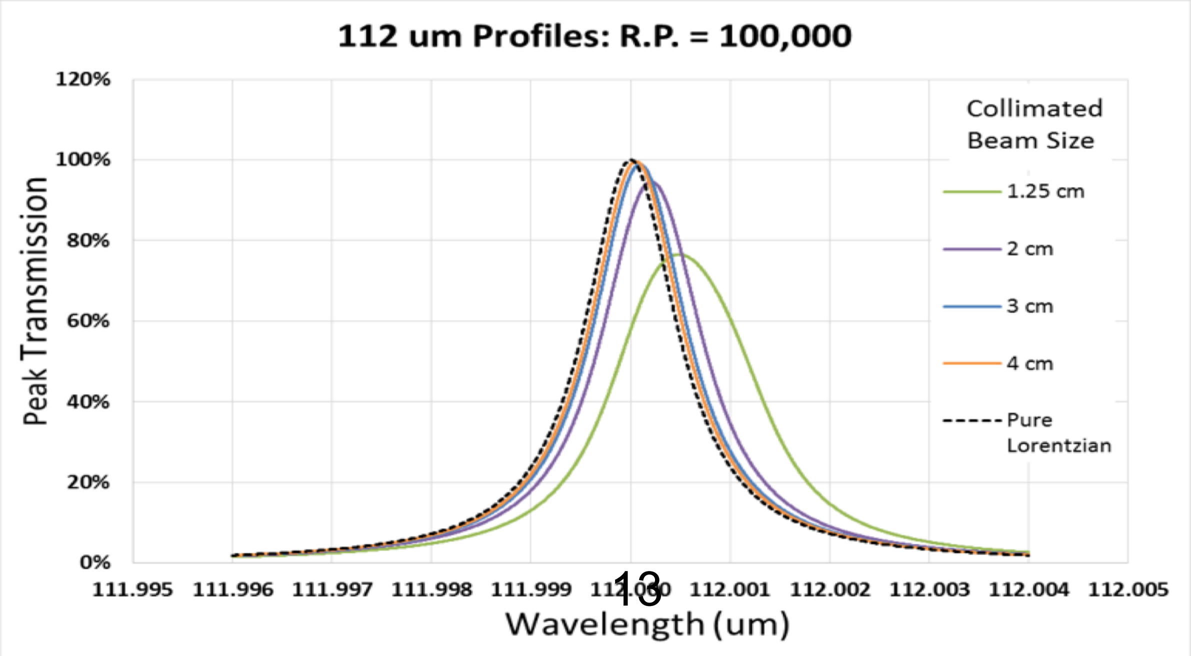
$$R_{max} = 2\pi\{A_{FP}/A_{Primary}\}/\Omega_{Primary}$$

- Minimum Ω set by diffraction:

$$R_{max} = 8\cdot(D_{FP}/\lambda)^2$$

- Determines a minimum size of collimated beam
- If beam is too small, both spectral profile and peak transmission suffer

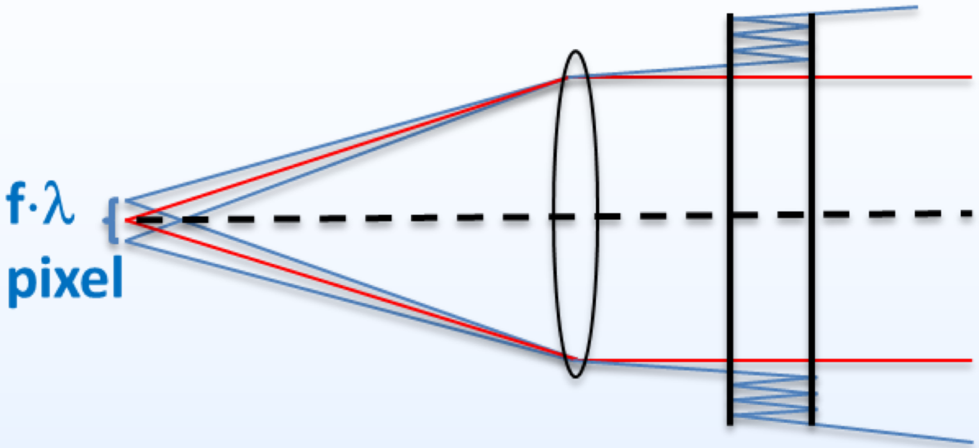




Limits to Performance: Walk-off

Walk-off: Fundamental

- Rays from outer regions of f·λ beam "walk-off" etalon through multiple bounces off mirrors
- Need to oversize etalons to capture these off-axis rays

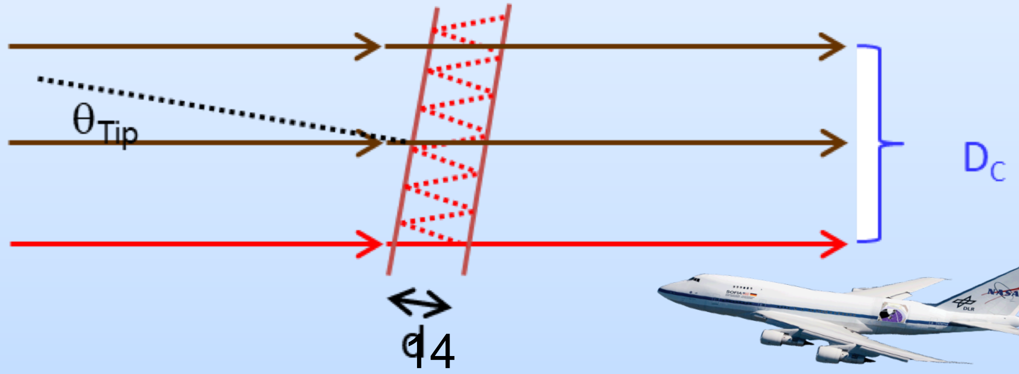


Walk-off: Etalon Tilt

- Rays "walk-off" etalon limiting transmission and finesse

$$F_{Tip} \approx D_C/(2d \cdot \theta_{Tip})$$

- Tilting the etalon also moves the transmission peak to the blue



Limits : Parallelism and Surface Defects

Parallelism

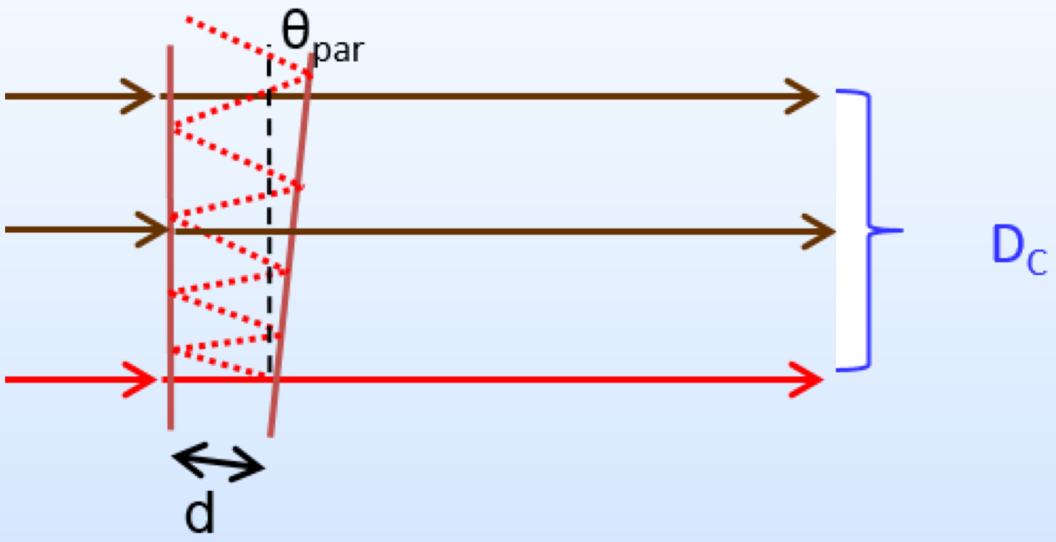
- Lack of parallelism creates a multiplying walk-off effect
  - Loss of transmission
  - Degradation of resolving power

$$F_{Par} = \lambda/(2\Delta)$$

If the mirrors are parallel to λ/n, then

$$F_{Par} = n/2$$

$\Rightarrow$ we need parallelism to better than $\lambda/200$

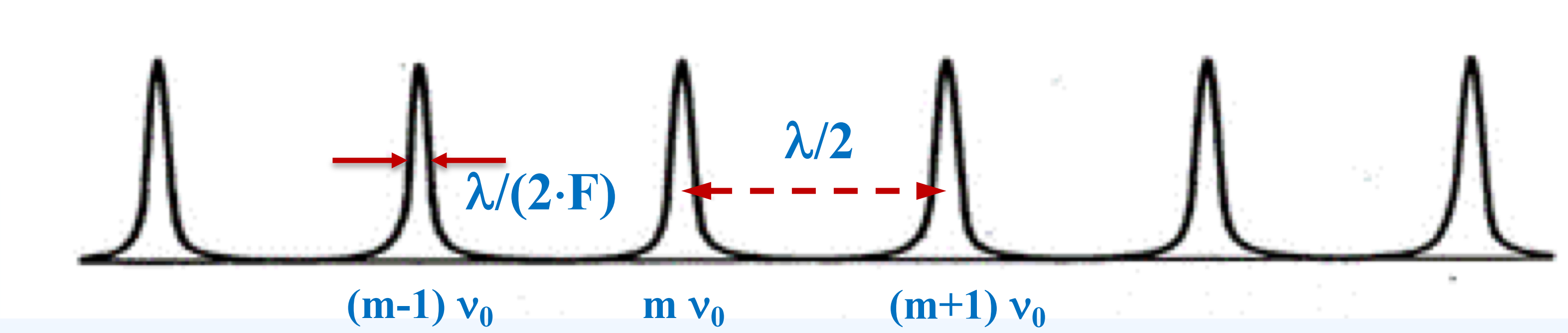


Surface Defects

- Could be due to errors in mounting or structures on mirror surfaces:

$$F_{surf} = \lambda/\{(32(\ln 2))^{1/2}\Delta s\} \approx \lambda/(4.7\Delta s)$$

Is it difficult to achieve R = 10^5?



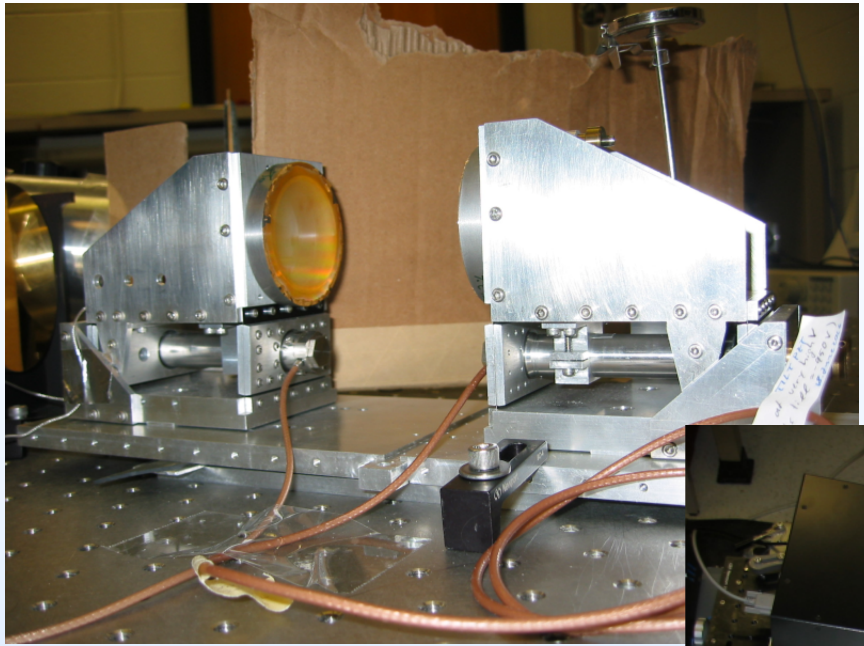
- Resolving power of a FPI is given by: **RP = *F*·m**
  - Distance between orders is constant = **λ/2** in lab space
  - The fringe width is the resolution element = **λ/(2·*F*)** in lab space
- So the metrology/required mirror stability for a resolution element is equally difficult in 20th order (R.P. ~ 10^3) as it is in 2000th order (R.P. ~ 10^5)

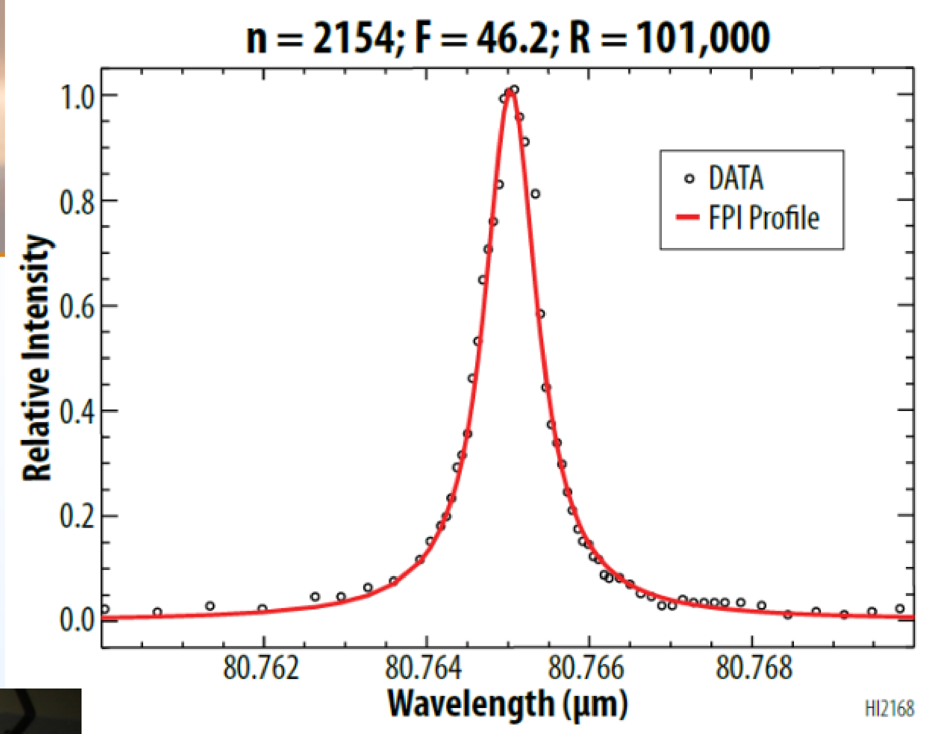
To measure/maintain to 1/10th resolution element we need to measure/maintain to λ/(2·*F*·10)

Or ~ 30 to 70 nm

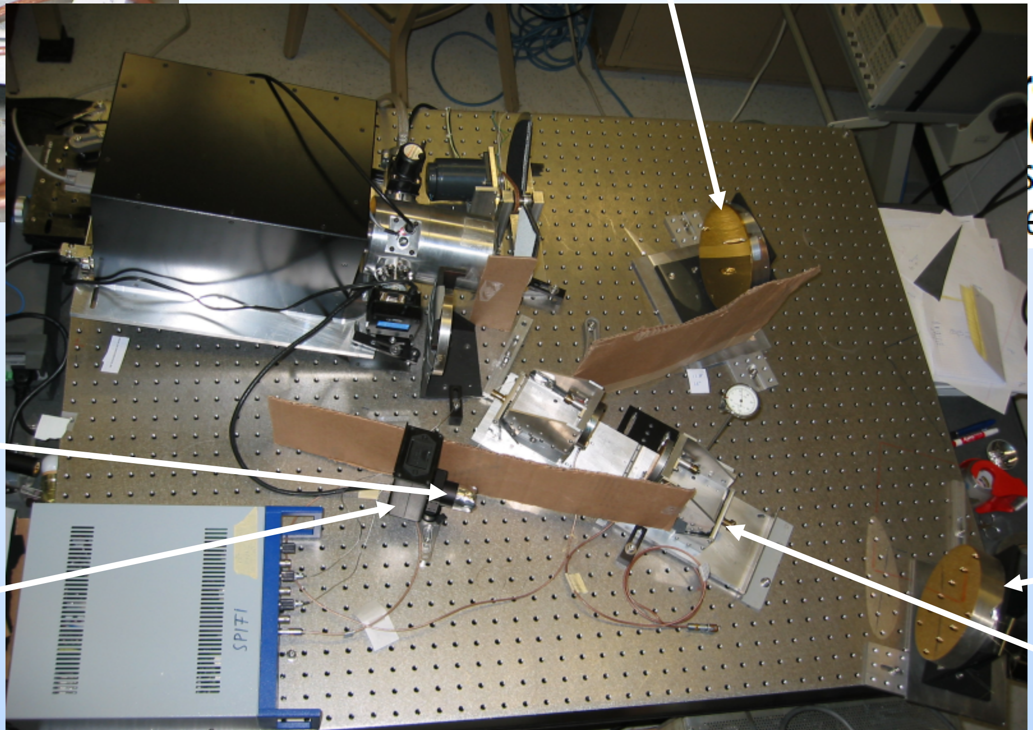
HIRMES

Achieved RP = 101,000





re E-18: Recent demonstration of a resolving power o
00 obtained by scanning a test-bed FPI interferomete
s a 80.765 μm quantum cascade laser line. The theoretica
e is a good fit to the data.



Off-axis parabola mirror from KEGS

Fixed filter low-resolution FPI (from KWIC)

Pyroelectric detector

OAP mirror from SPIFI

HiRes FPI

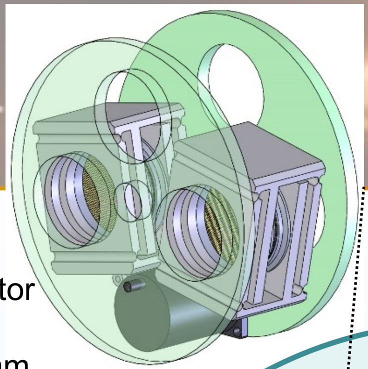
HIRMES

FPI Etalons

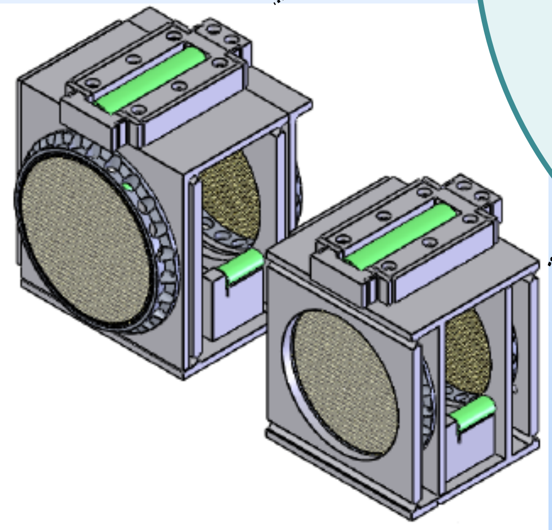
Free standing metal mesh have R that is a strong f(λ)

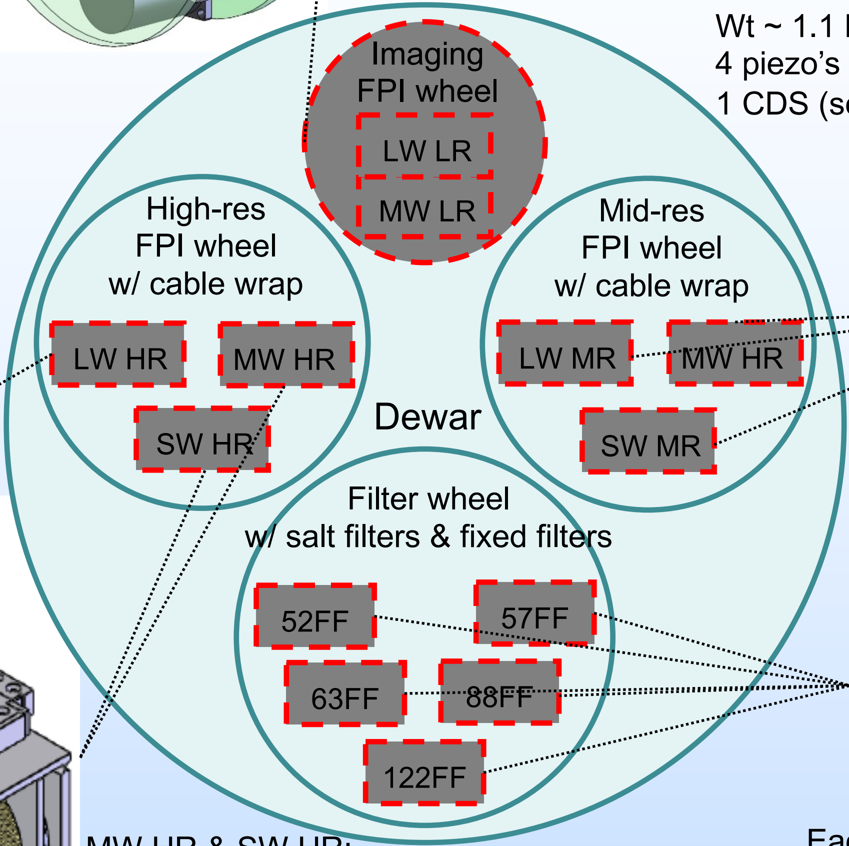
- ⇒ F ~ $\lambda^{2.5-3}$!
- ⇒ Limits their utility to factor of ~ 1.5 in BW
- ⇒ If F is too low (<20) spectral purity suffers
- ⇒ If F is too high (>70) transmission will suffer
- ⇒ We need 3 FPI for the full 25 to 112 um BW

LW LR & SW LR:
Dual flexures driven by cryo motor
Clear aperture = 30 mm
Etalon wheel = 105 OD x ~52 mm
Wt ~ 0.8 kg (0.5 kg Al, 0.3 kg SS)
1 cryogenic stepper motor
2 cap. disp. sensors (CDS, scan)



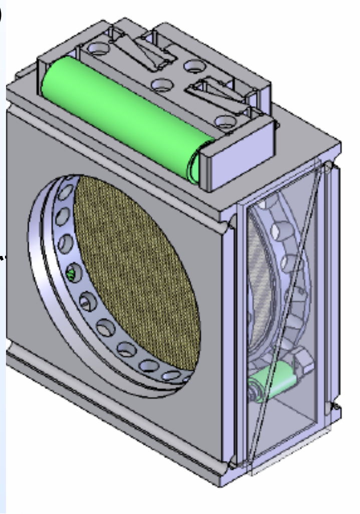
LW HR:
Clear aperture = 100 mm
HxWxD = 154x131x112 mm
Wt ~ 1.4 kg (1.0 kg Al, 0.4 kg SS)
4 piezo's (1 scan, 3 tilt)
1 capacitive disp. sensor

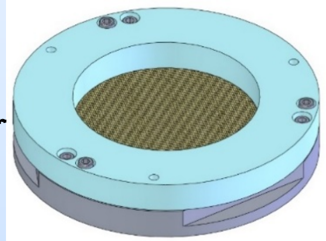




MW HR & SW HR:
Clear aperture = 90 mm
HxWxD = 141x119x112 mm
Wt ~ 1.2 kg (0.9 kg Al, 0.3 kg SS)
4 piezo's (1 scan, 3 tilt), 1 CDS (scan)

Each mid-res FPI:
Clear aperture = 90 mm
HxWxD = 141x119x63 mm
Wt ~ 1.1 kg (0.8 kg Al, 0.3 kg SS)
4 piezo's (1 scan, 3 tilt)
1 CDS (scan)

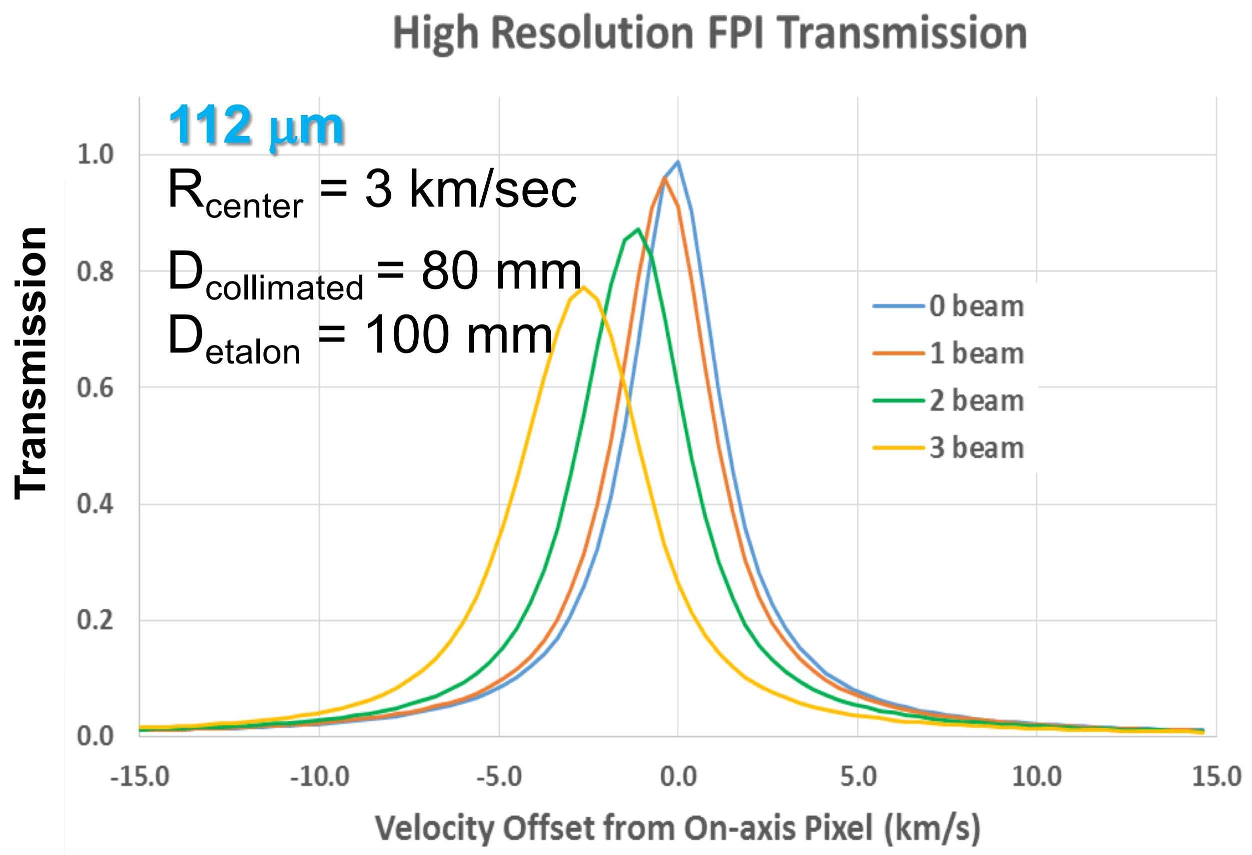




Each fixed order filter:
Clear aperture = 30 mm, OD = 49 mm
Ht ~ 10 mm, Wt ~ 0.085 kg (SS)

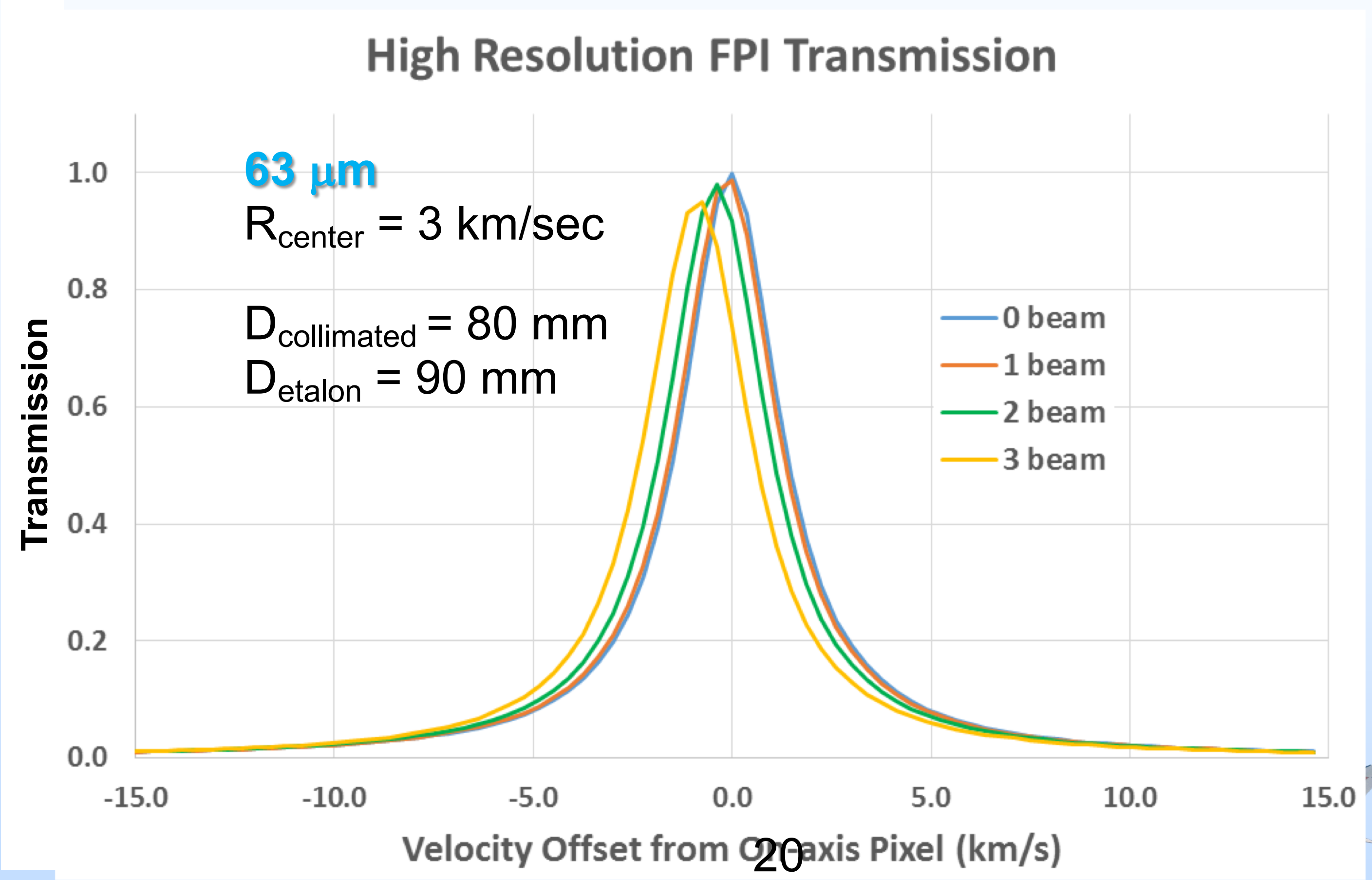
Optical Design: High-res Path

- For optimal sensitivity – we don't plan to chop: we scan point sources ± 2-3 (λ/D) beams across the slit
- The need for high sensitivity at ± 2-3 beams drives the etalon parameters: D_{coll} = 80 mm; $D_{aperture}$ = 100 mm @ 112 μm
  - Large pupil ensures that the spectral profile is not significantly degraded
  - Oversize aperture ensures transmission is not significantly degraded by walk-off



Optical Design: High-res Path

- Since angles are smaller for λ/D beams at shorter wavelengths, we reduce the aperture to 90 mm for 63 μm and 35 μm etalons, reducing filter wheel (hence) instrument size



Optical Design: Mid-res Path

- The resolving power of the Mid-res FPI is 10 times less than that of the High-res etalons
- Therefore, the walk-off path becomes 10 times less and walk-off loses become negligible
- All beams are successfully captured with high efficiency with:
  - $D_{collimated}$ = 80 mm
  - D_{etalon} = 90 mm
- All three (35, 63, and 112 μm) Mid-res FPI have the same design, but with different mirror gaps appropriate for the desired resolving power at the three wavelengths

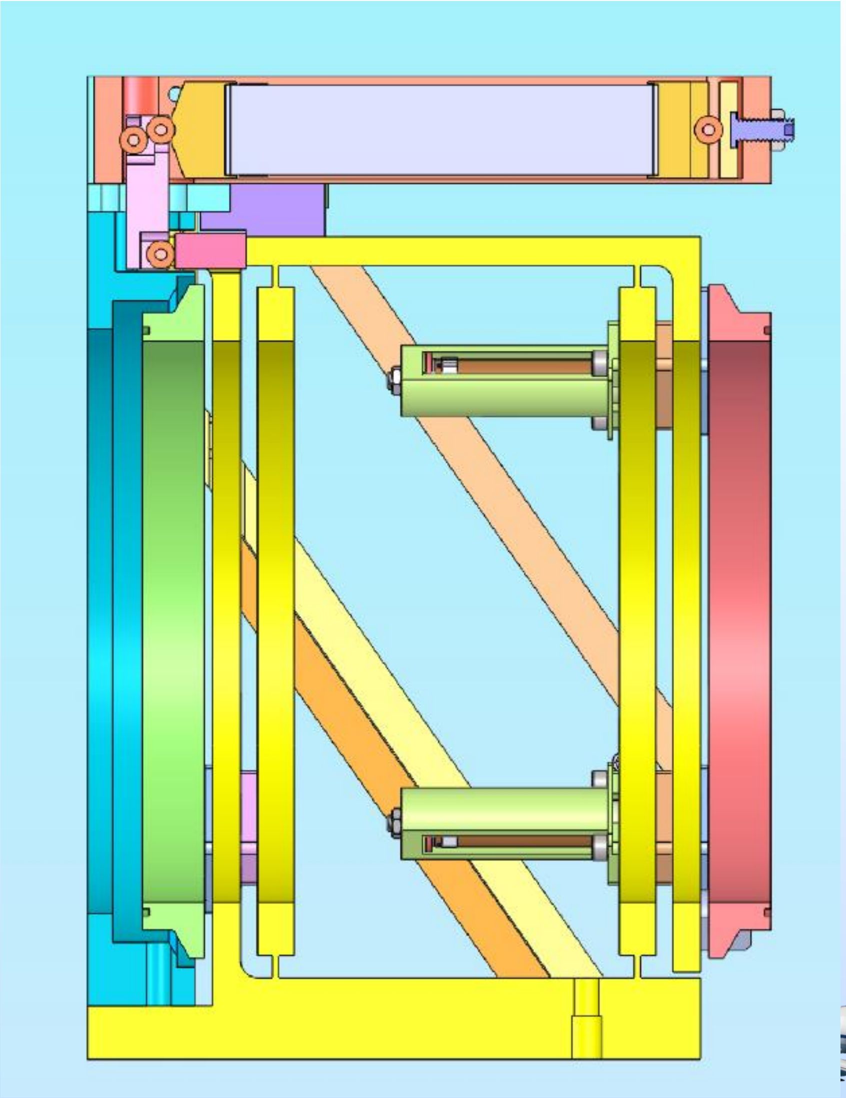
Design Details, Long Wavelength High-Res

Translation Stage

- Flex-vane based stage with long heritage
- Wire EDM stage for accuracy of travel
- SS rings with Au coated Ni mesh
- Tilt PZTs for capturing small deflections on cooling or rotations

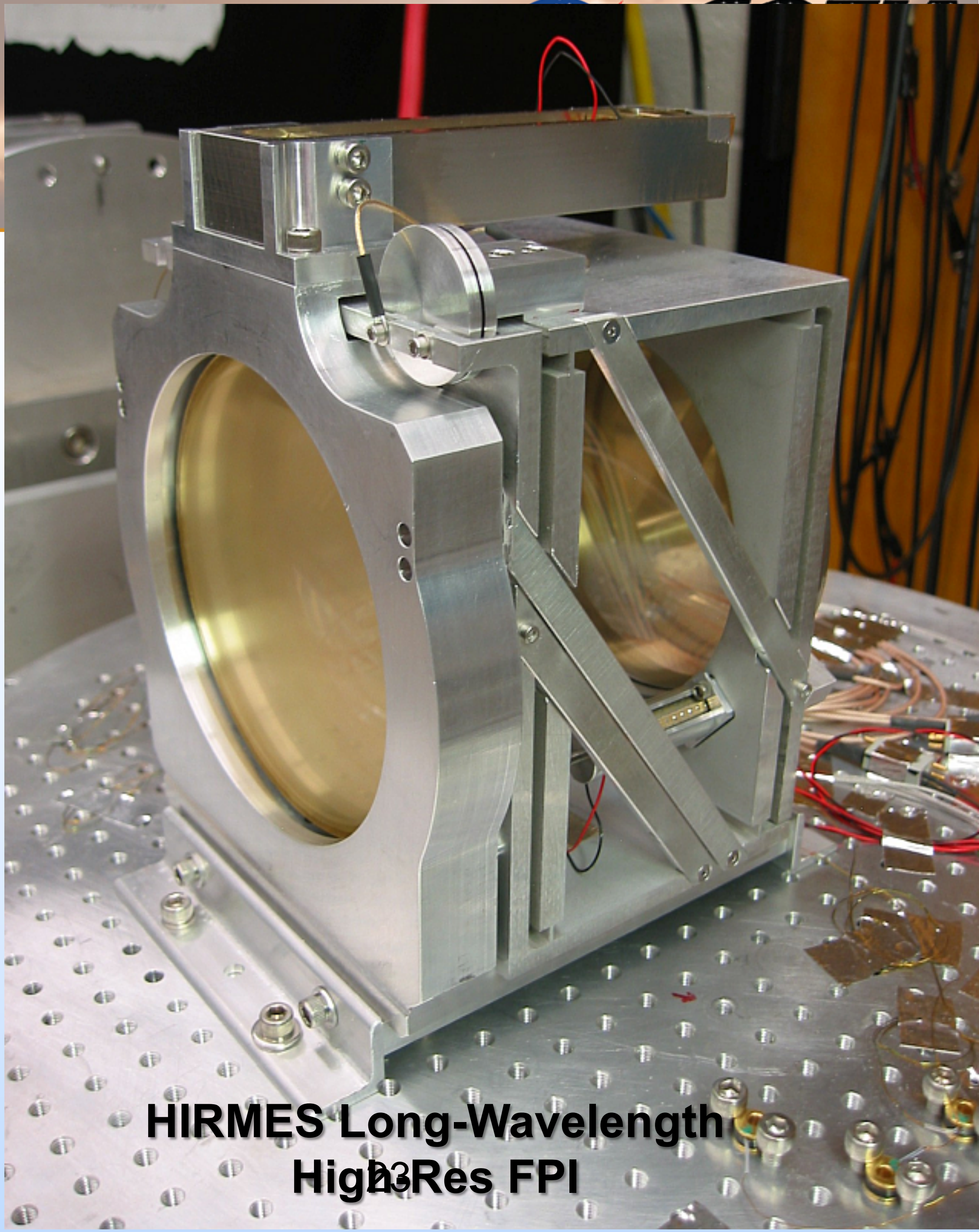
Motion multiplier

- Need to travel a FSR: but LVZTs only travel ~ 17 μm
- Designed a motion multiplier capable of delivering the × 5 we require at 112 μm with stiffness and accuracy
- Key element is near neutral contraction from room T to 4 K.



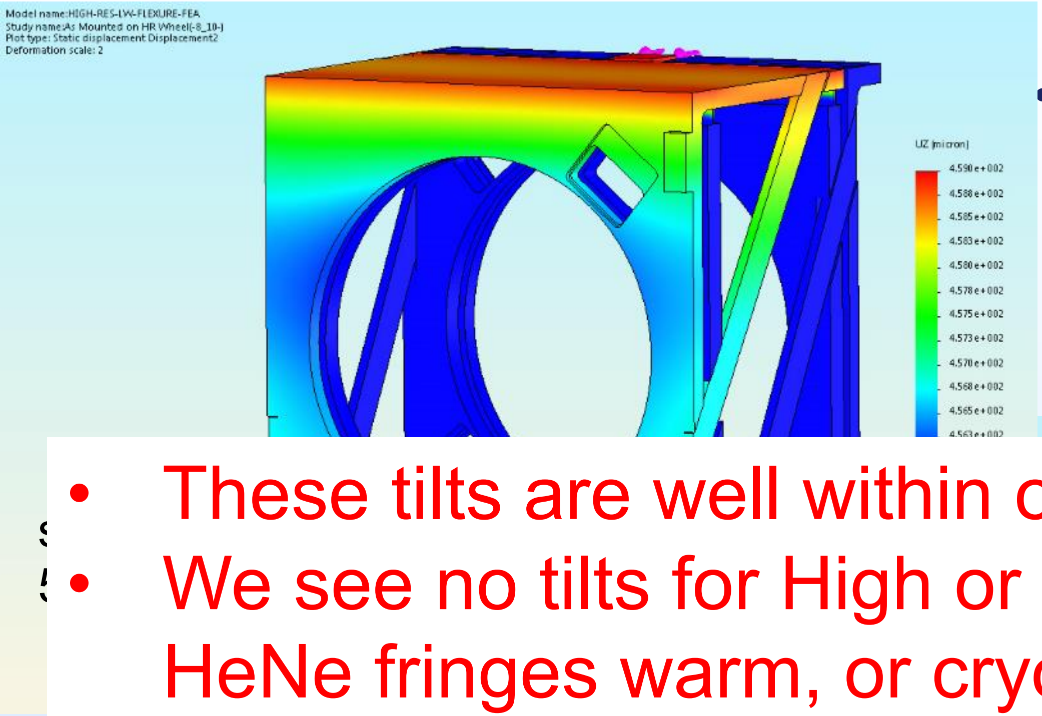
Scanning FPI Designs

- Capacitive bridge control to 10 nm resolution
- Short-wavelength (λ_{cen} ~ 35 μm) , mid-wavelength (63 μm), and long wavelength (112 μm) versions centered on H_2O, [OI] and HD observations
- 3 Hi-Res R ~ 10^5
- 3 Mid-Res R ~ 10^4
- 2 Low-Res R ~ 2000 FPI



HIRMES Long-Wavelength High-Res FPI

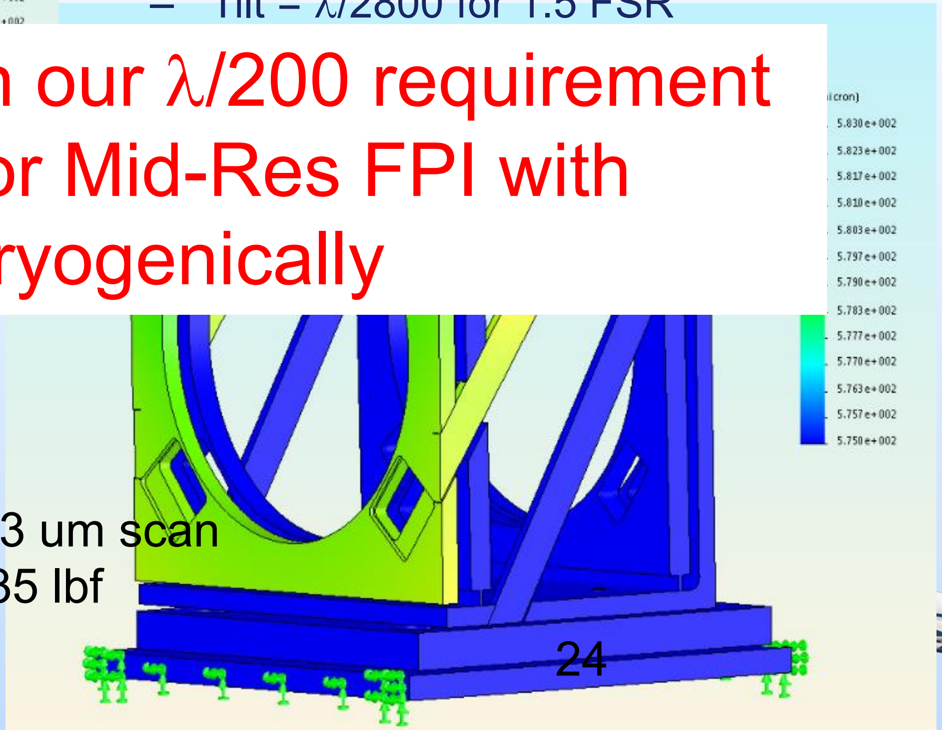
Stress Analysis: Hi-Res, Long λ



- Tilt change between scan start position (with preload) and the end of a 123 μm (2.2 FSR) scan is 0.058 μm
  - Tilt = λ/1900 for 2.20 FSR
  - Tilt = λ/2800 for 1.5 FSR

- These tilts are well within our λ/200 requirement
- We see no tilts for High or Mid-Res FPI with HeNe fringes warm, or cryogenically

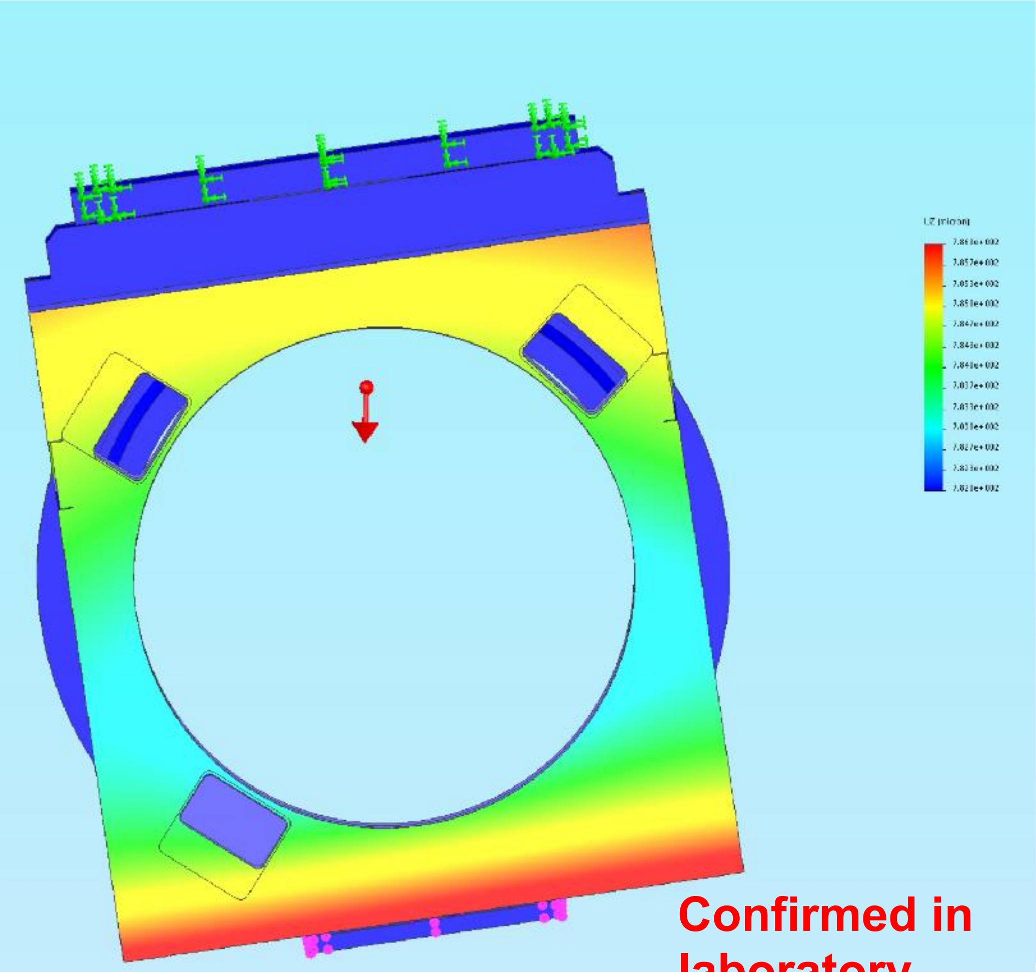
- Things scale with wavelength – both tilt and scan length
- At 25 μm we scan 16.6 μm for 1.5 FSR so that:
- Delta tip/tilt = 0.0078 μm
  - Tilt = λ/2800 for 1.5 FSR



123 um scan
6.35 lbf

Statics: Rotation of Hi- Res Long λ FPI

- HIRMES mounted on SOFIA will rotate $\pm$ 20° from the mount angle
- Most observations will rotate less than 20° in an hour
- Re-alignment of FPI will generally not be necessary but is expected to take 5 minutes
  - Will use internal 63 and/or 78 μm QCD lasers
- Overall tilts are ~ 0.2 μm
- Look-up table for quick compensation



Confirmed in laboratory measurements

Accomplishments

Full set of three Hi-Res FPI delivered to GSFC on July 19, 2018

HIRMES

Mid-Res Deliveries

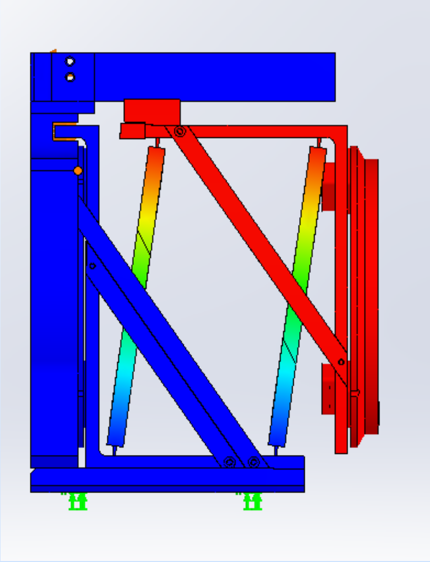
Pictures show FPIs on the optical bench in the HIRMES lab at GSFC.

- Short and Long Wavelength Mid-Res FPI delivered to GSFC on October 12, 2018

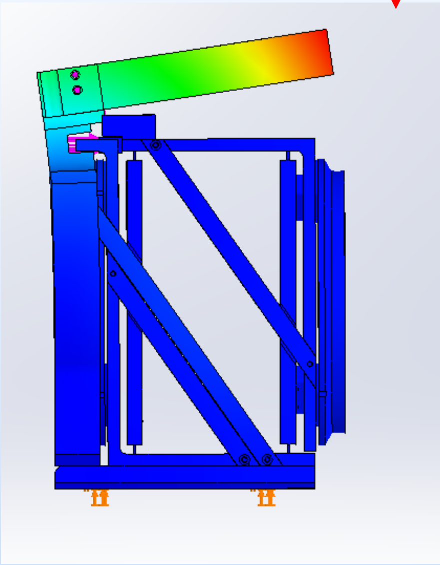
Modal Analysis: HR-LW FPI

- Long wavelength as analyzed in SolidWorks
- Fixed at bottom of FPI and 8 lbs force applied to lever arm

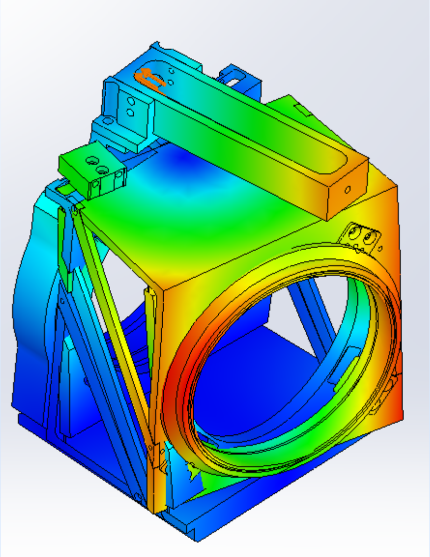
Natural frequency #1
50.4 Hz



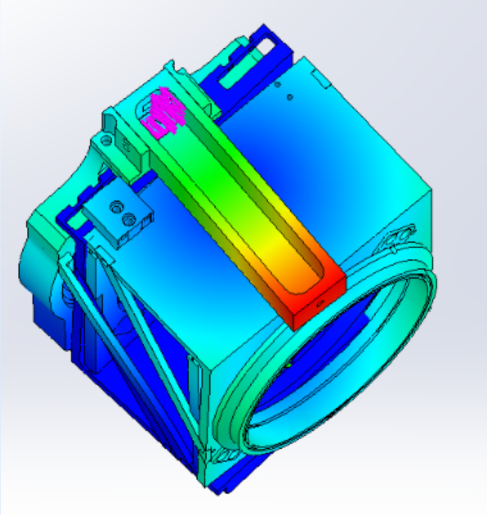
Natural frequency #2
240.9 Hz



Natural frequency #3
277.9 Hz



Natural frequency #4
333.3 Hz



Carriage swing mode

Drive arm mode

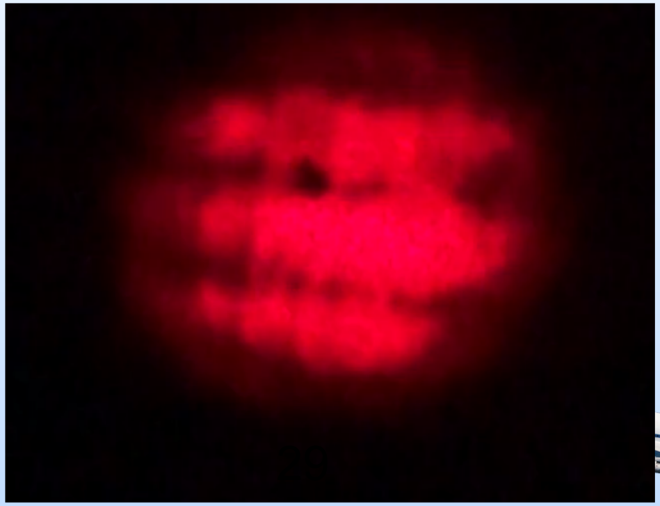
Drive swing modes

Vibration Tests

Vibration Sensor Sentry RT128 (screwed to cryostat handle)

Shaker LDS Model V203

Observed HeNe laser beam fringes from the FPI meshes, measuring the vibration of the FPI meshes.

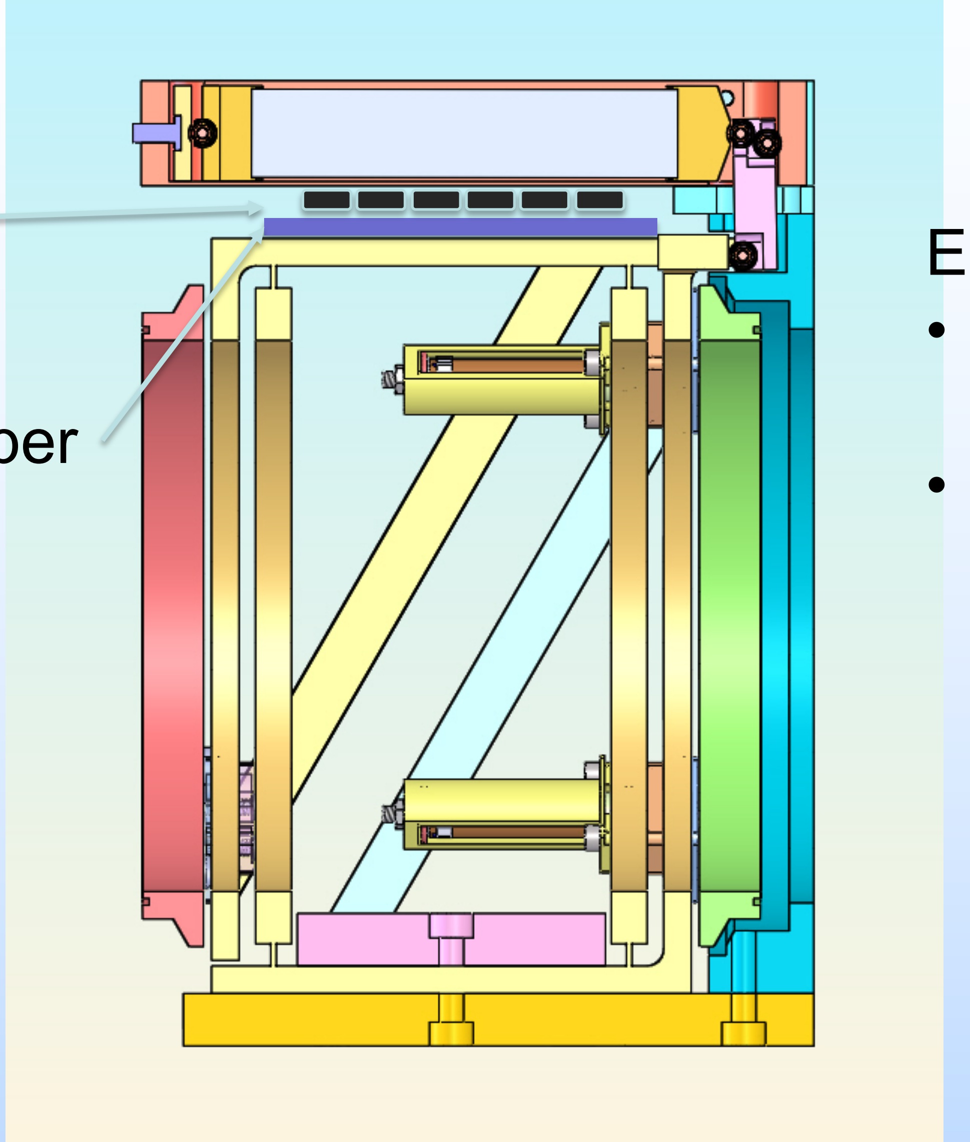


Mid-Res. Mid-λ FPI inside cryostat (not visible from this viewing angle)

Mitigation: Eddy Current Damping

neodymium iron boron magnets

high purity copper

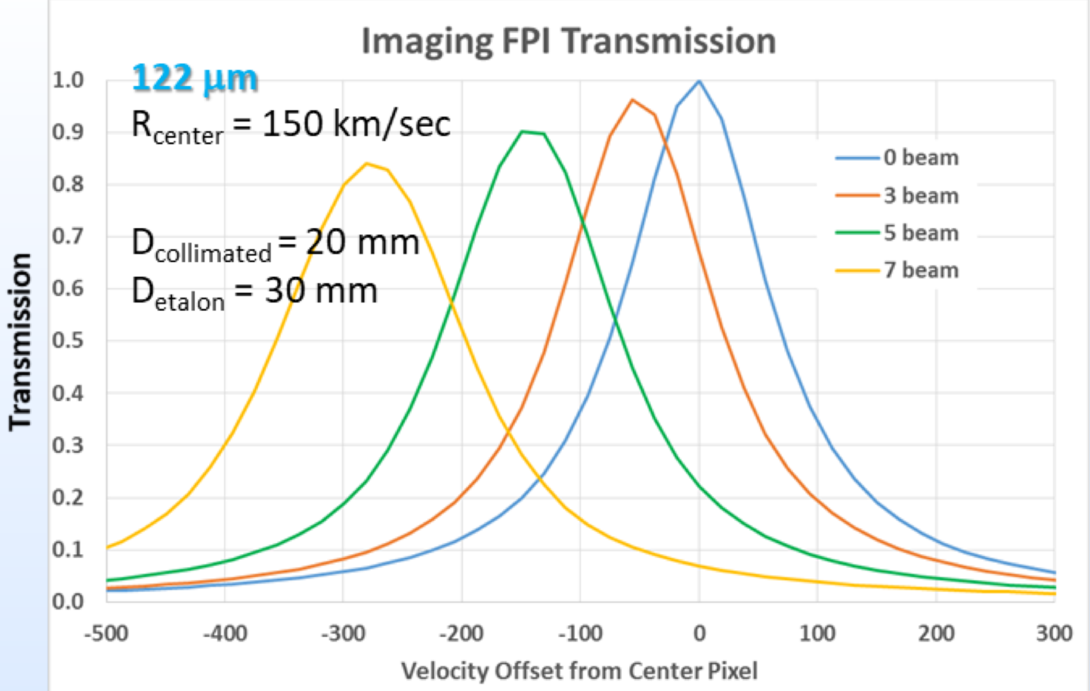


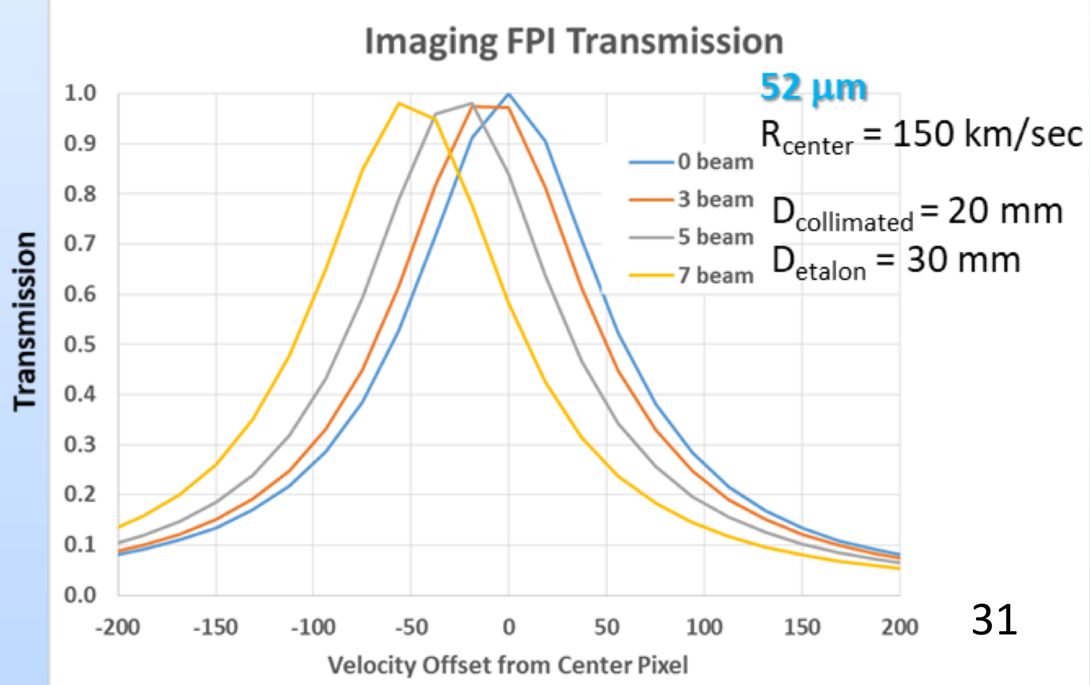
Easy installation:

- spot Stycast Cu sleeve
- Magnetically attach magnets to INVAR

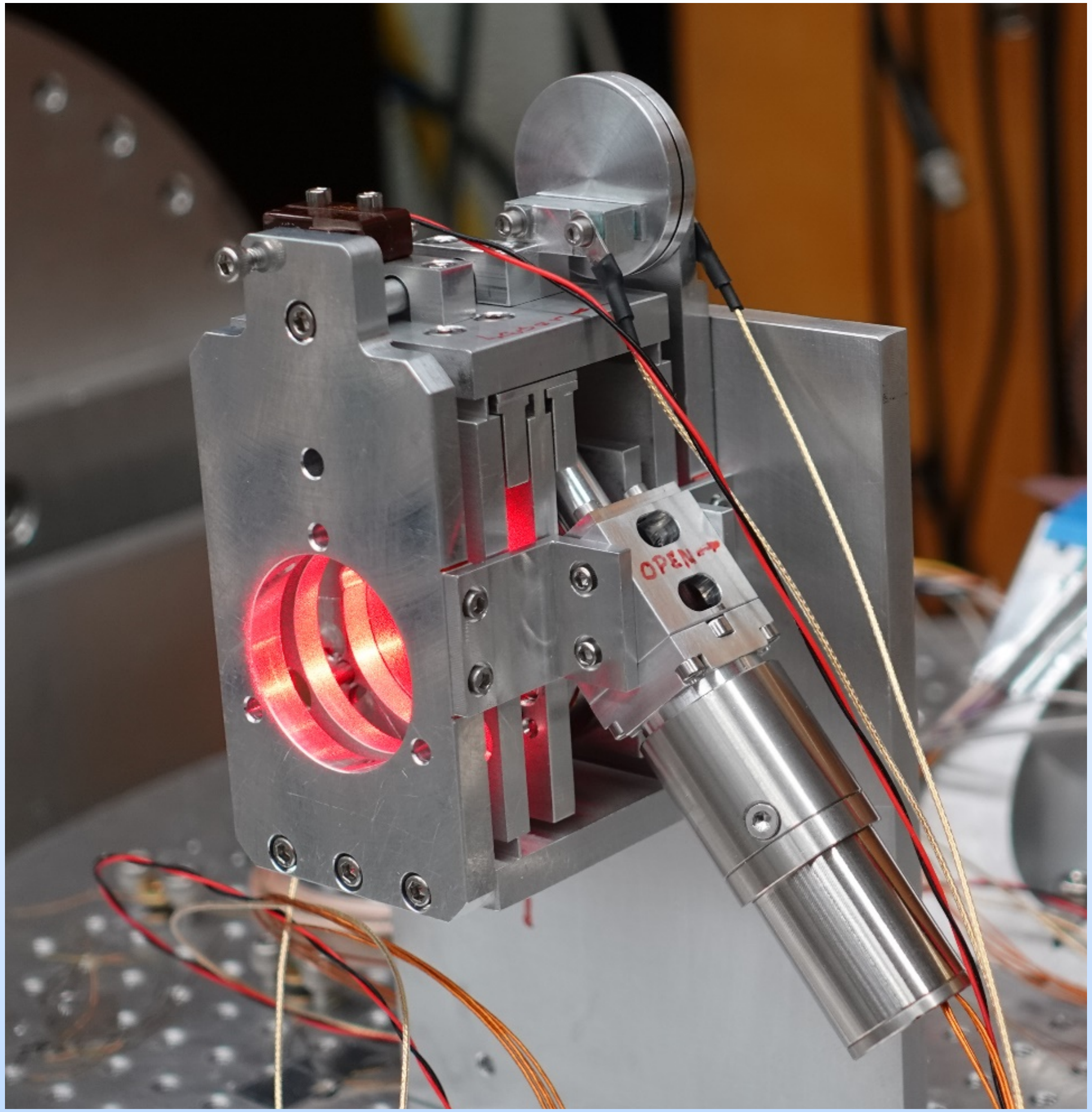
Optical Design: Imaging Path

- The imaging FPI need to properly feed a 16 × 16 pixel (λ/D) array for imaging spectroscopy
- With a modest (20 mm) pupil, the outlying beams will be shifted in velocity space
- However, there is only a modest loss in resolving power, even at 122 μm
- Only 2 imaging FPI are required:
  - [OIII] 51.8, [NIII] 57.3 & [OI] 63.2 μm
    - F ~ 33 to 50
  - [OIII] 88.4 & [NII] 121.9 μm
    - F ~ 32 to 60



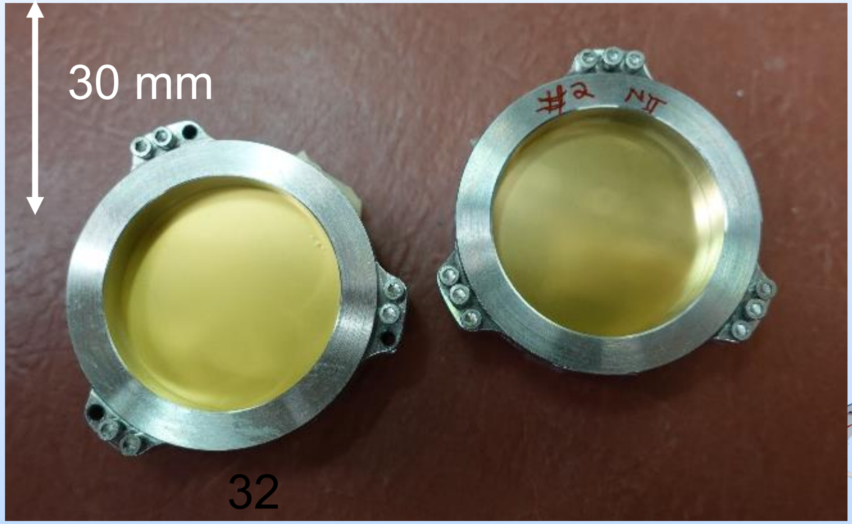


Imaging (Low-Res) and Fixed FPI



Stepper motor driven to enable gross translations

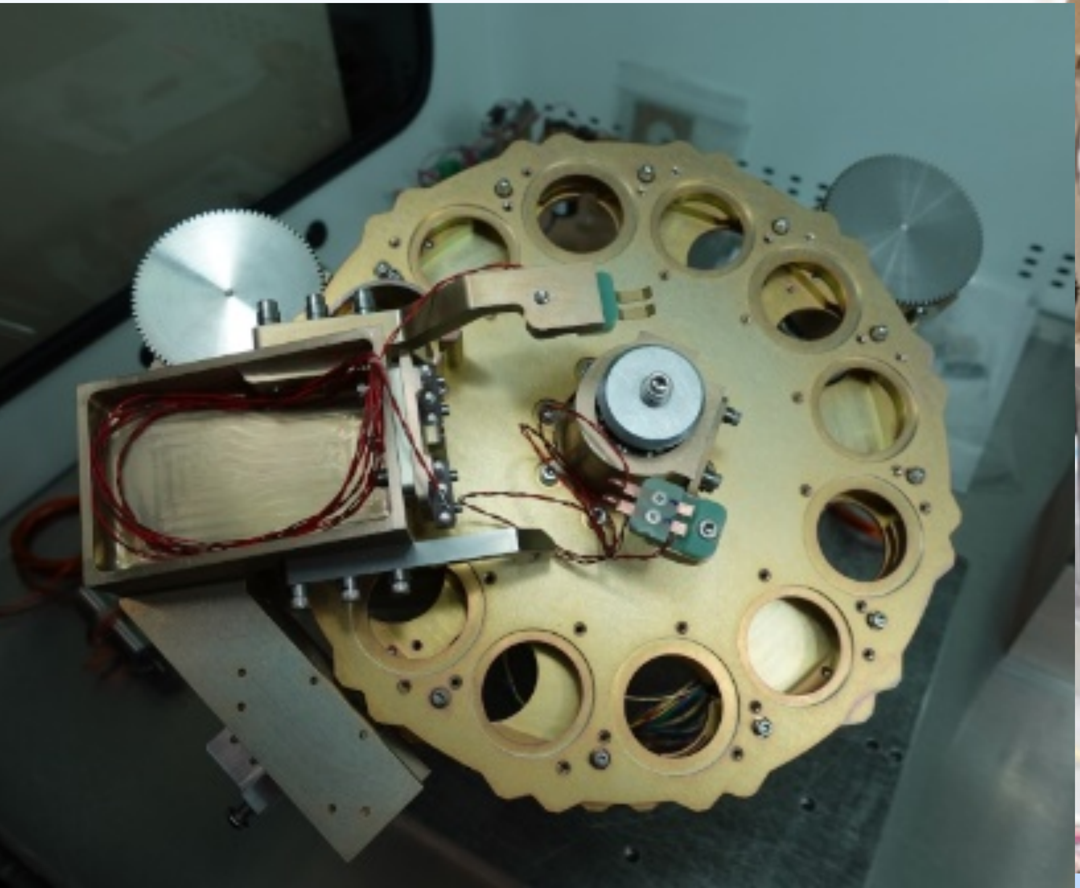
- Long λ from 88 to 122 μm
- Short λ from 52 to 63 μm
- Primary mode is mapping [OIII], [NIII], [OI] and [NII] FS lines.

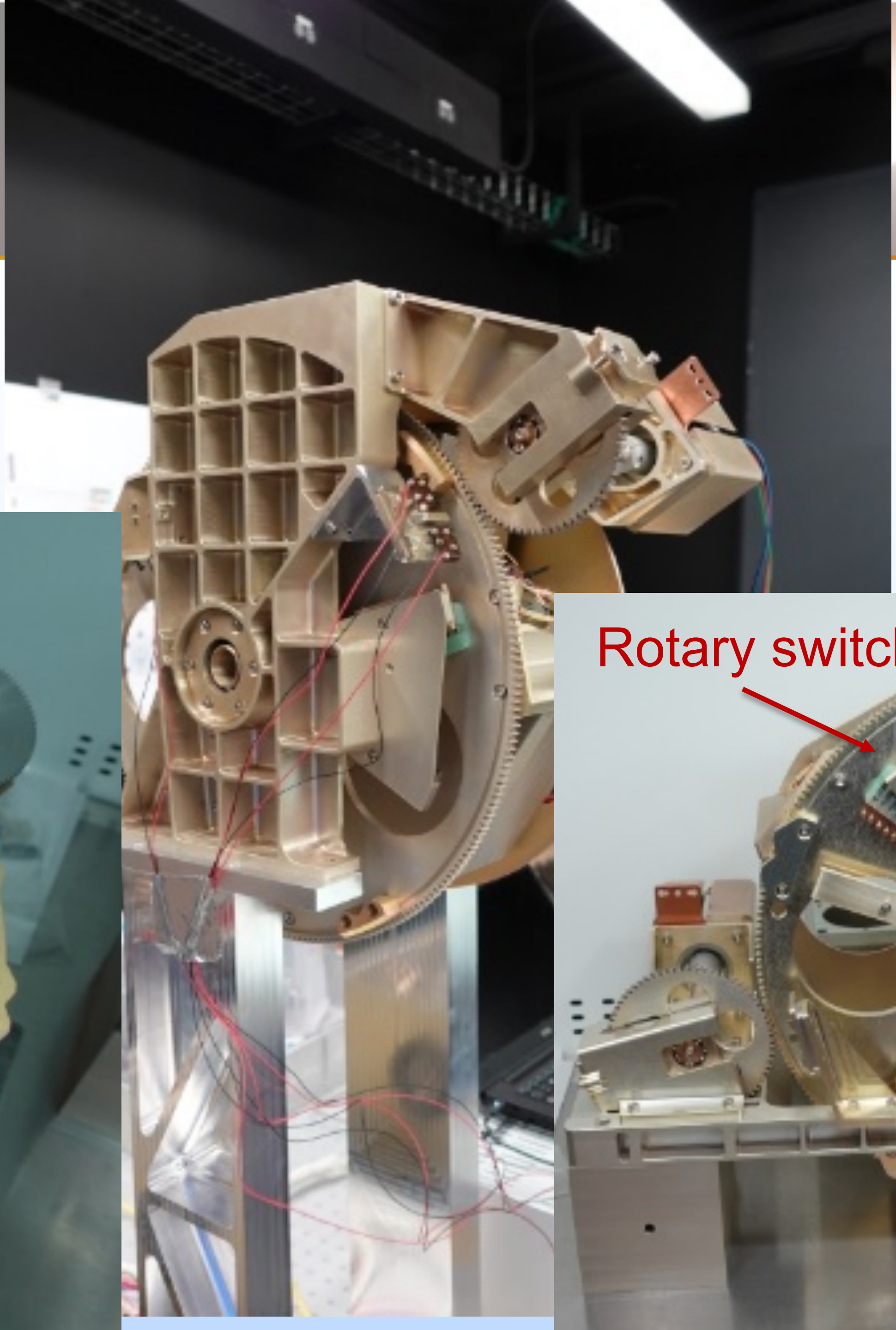


HIRMES

The Wheels..

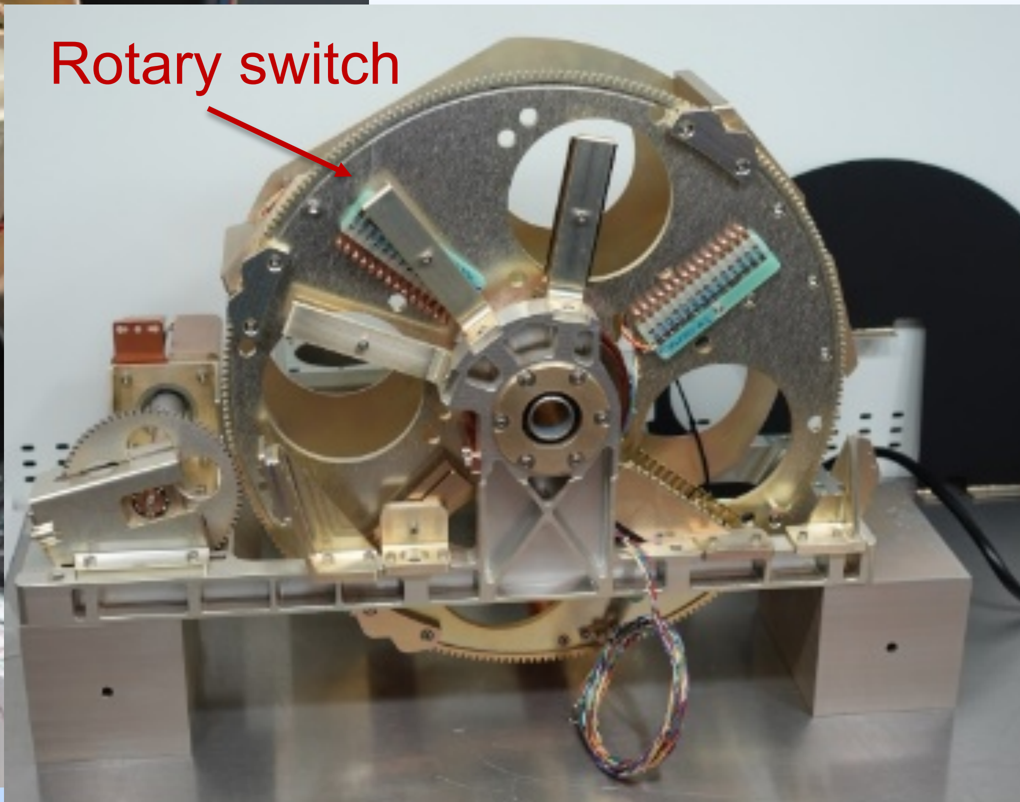
Lo-Res and filter wheel



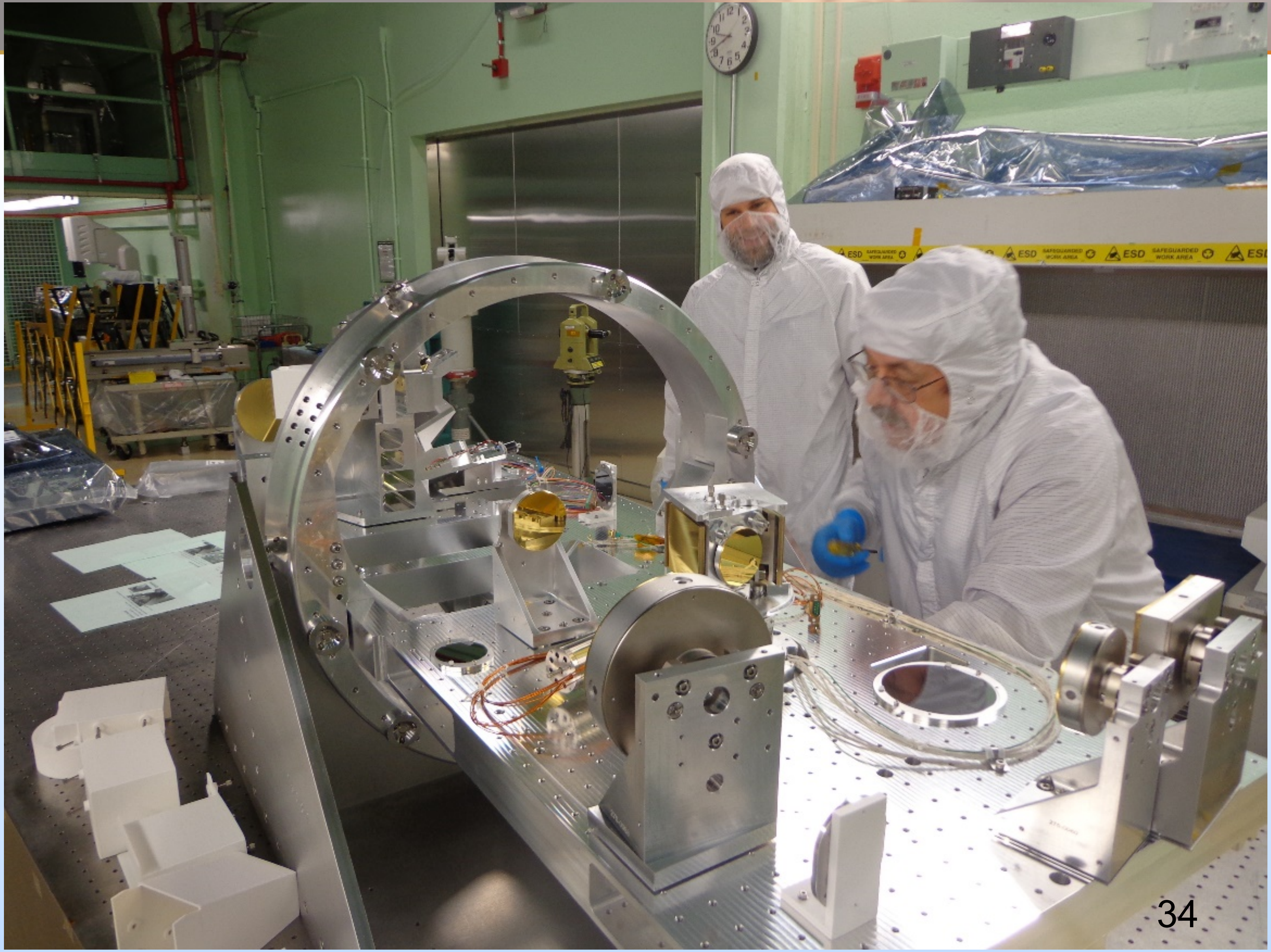


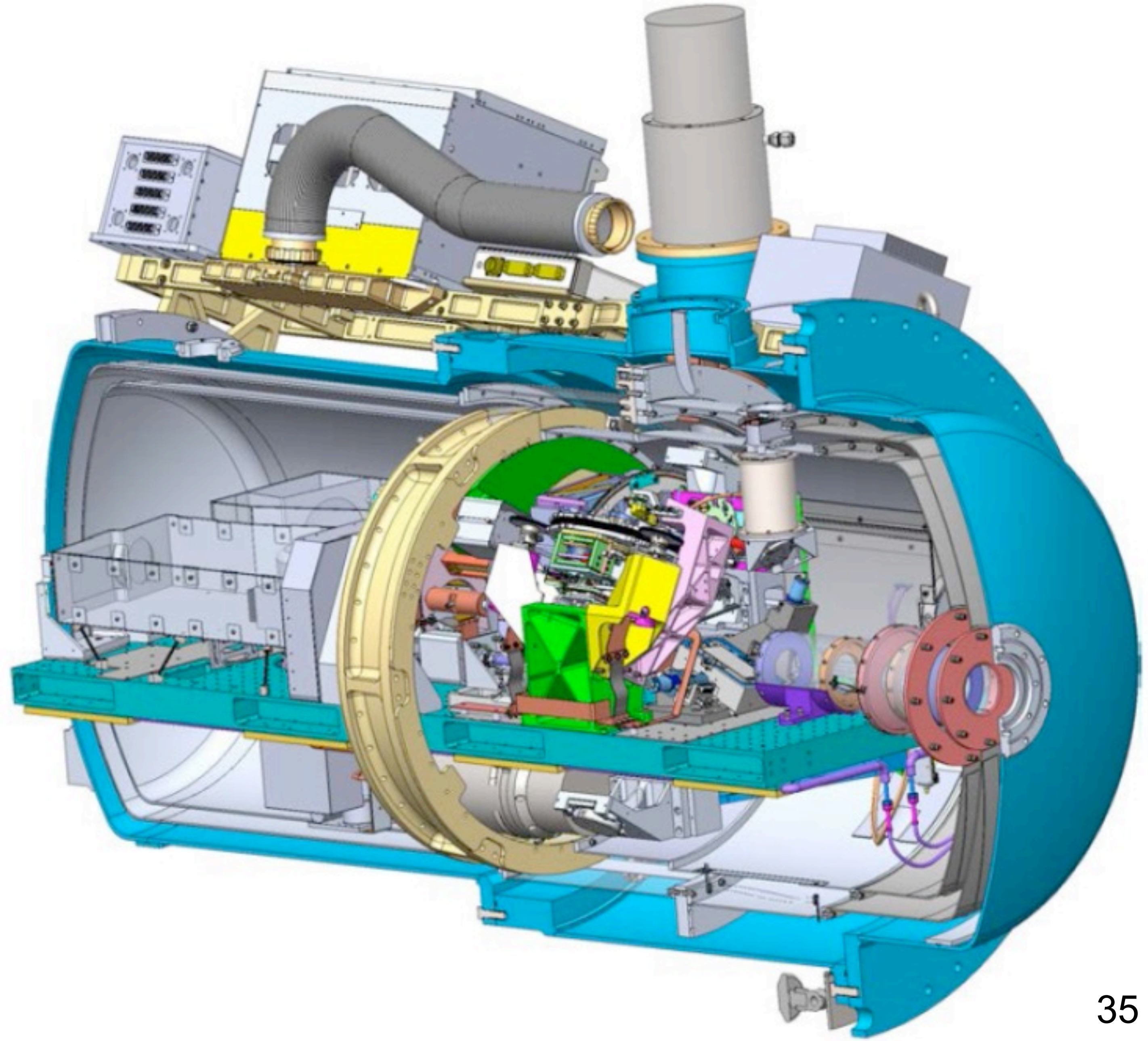
Hi-Res

Mid-Res

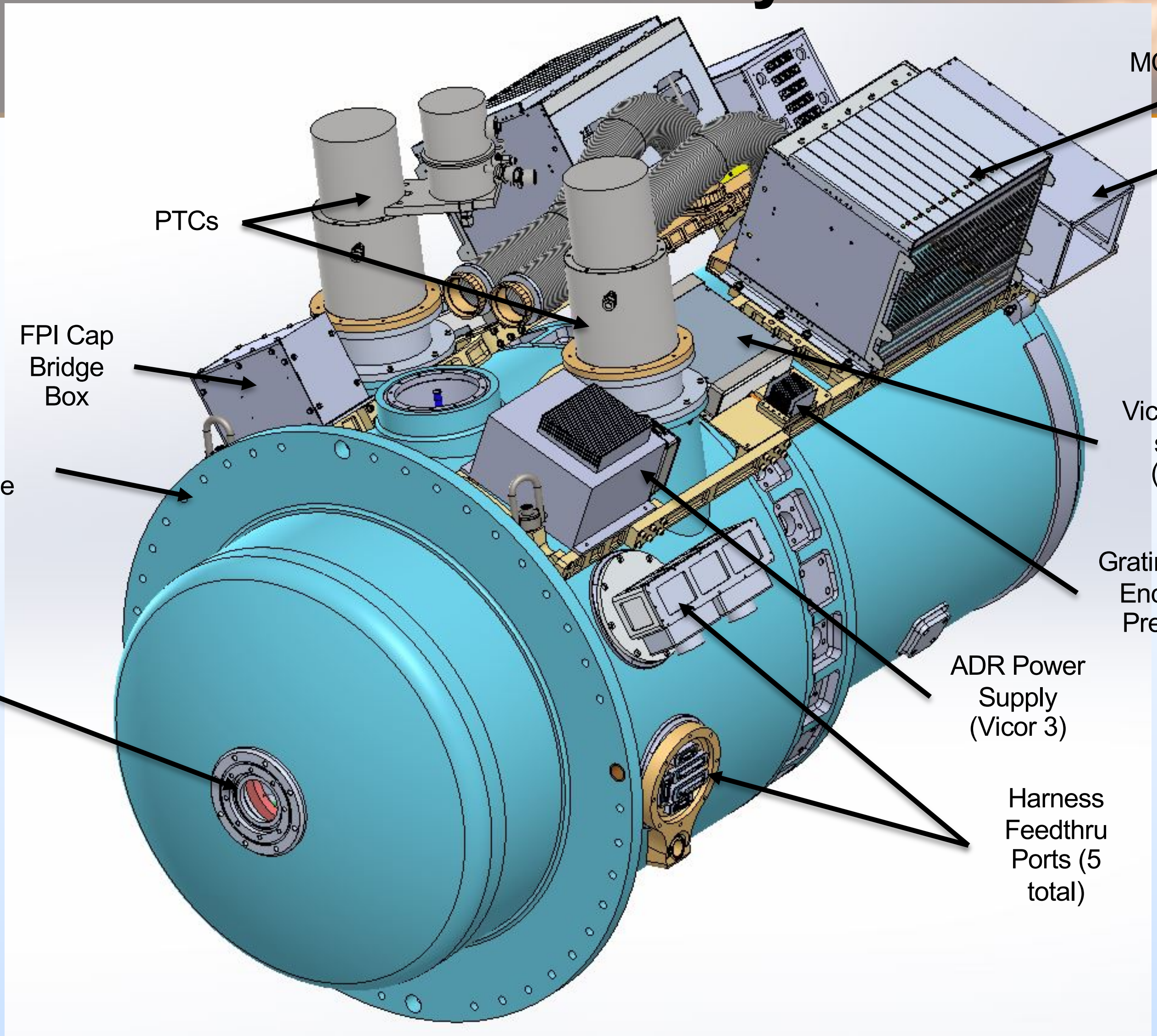


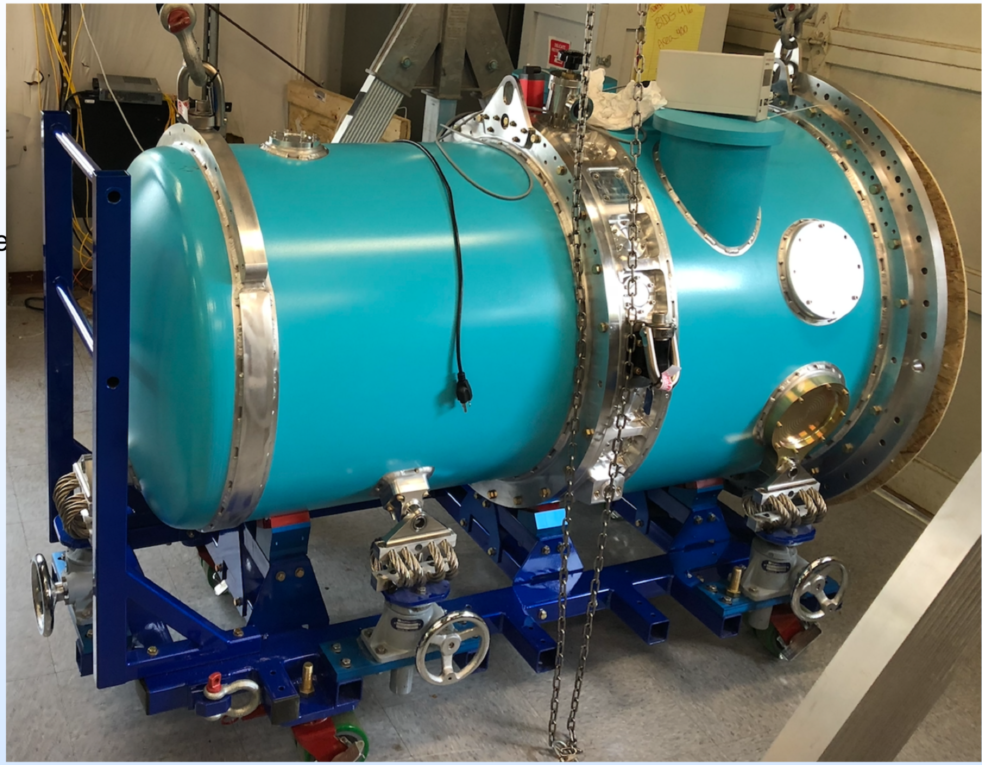
Optical Bench





HIRMES Cryostat Assembly





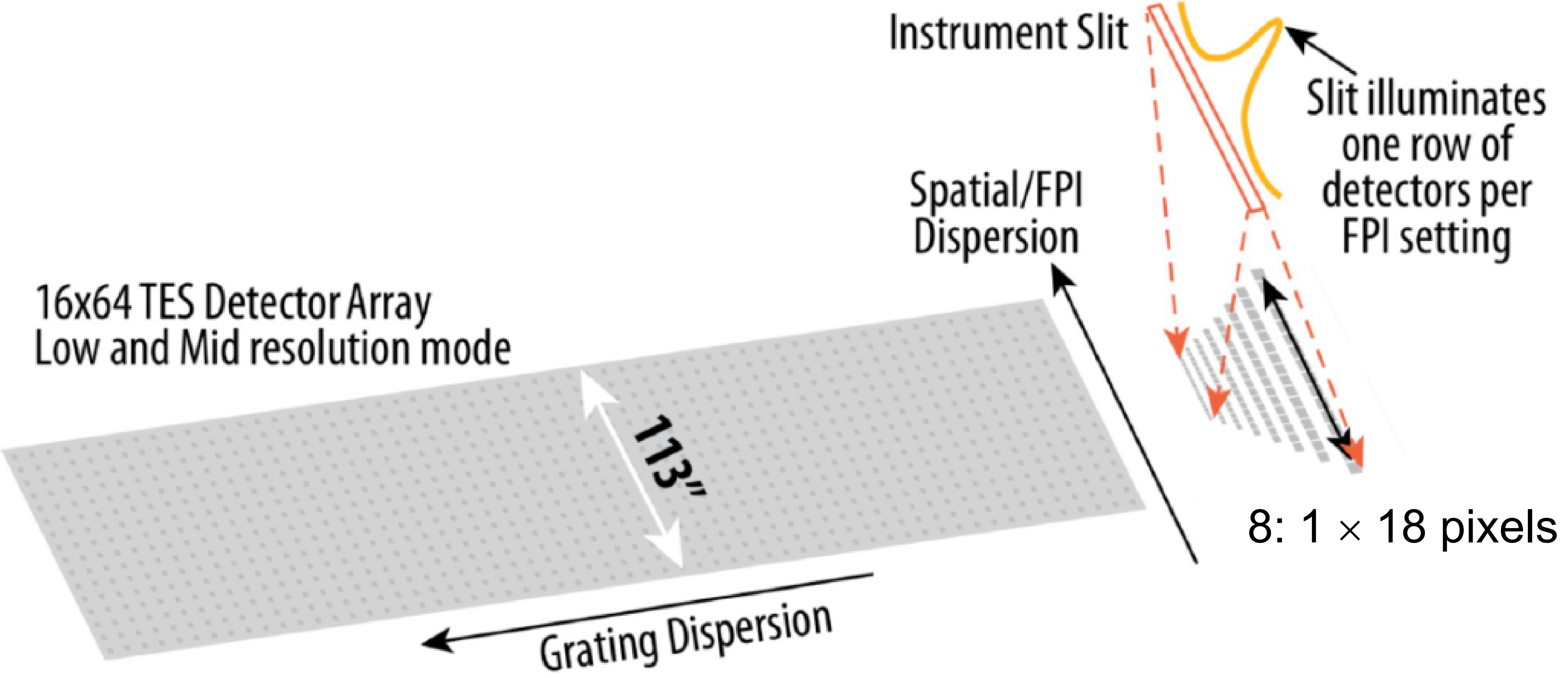
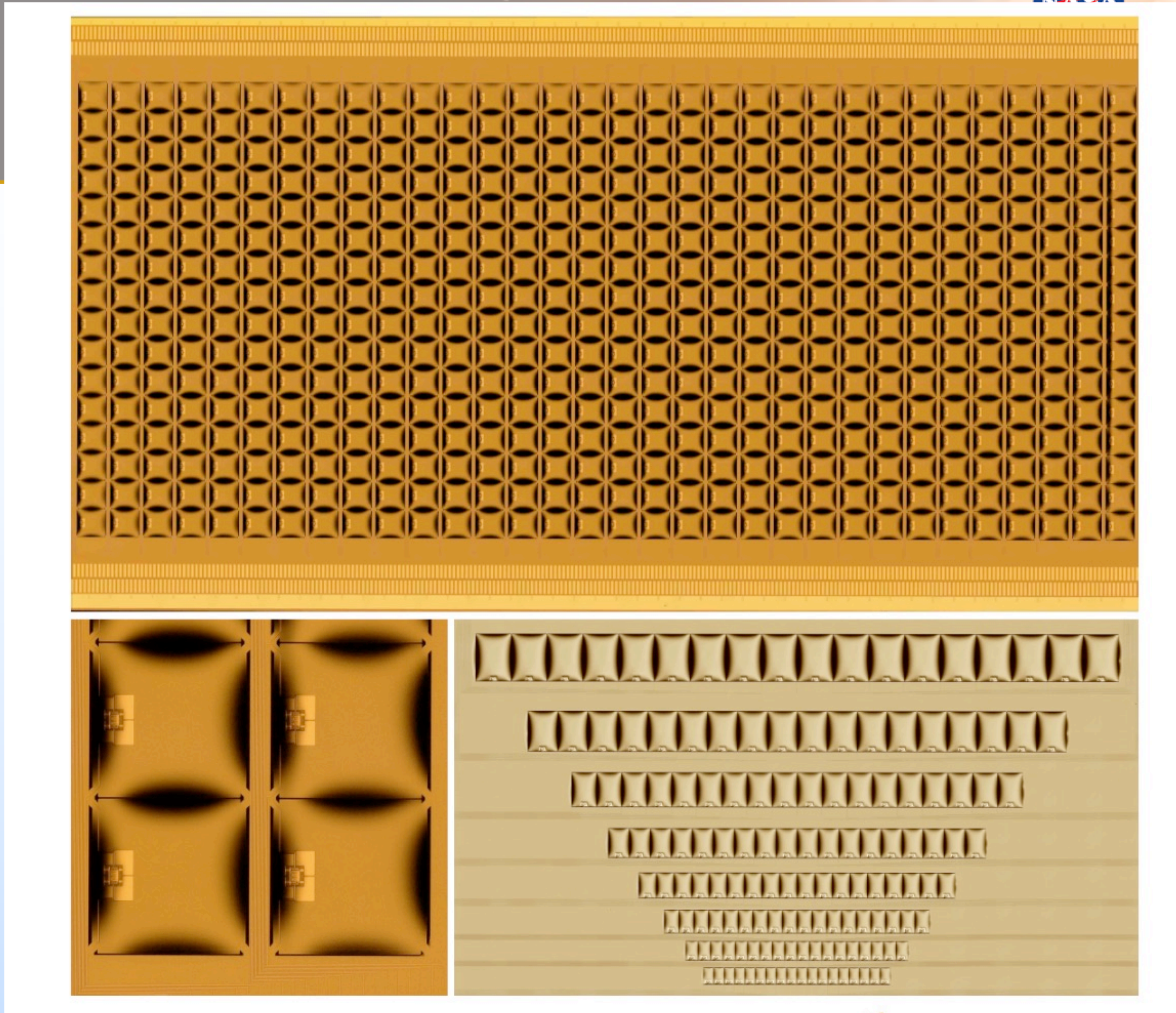


Fig. 8. (Top) One half of the 64×16 pixel Low-Resolution detector. (Middle-Left) A zoom in of the 4 most lower-right pixels of the Top image. (Middle-right) The eight, 1×18 pixel subarrays of the High-Resolution detector, in which the pixels located at the edges of each subarray are not read out, resulting in 1×16 active pixel subarrays. (Bottom) A schematic of the layout of both detectors on the Focal Plane.

- GSFC TES Bolometers
- Backshorts for High and Mid-res modes



Sensitivity Calculation 1/2

$$NEP = h\nu\{2 \cdot \Delta\nu \cdot N \cdot p \cdot \varepsilon_{warm}\,\eta_{det}\eta_{cold}\tilde{n}(1 + N \cdot \varepsilon_{warm}\eta_{det}\eta_{cold}\tilde{n}\}^{1/2}$$

NEP is referred to the detector

- Where
  - h is Planck's constant, ν is frequency, $\Delta\nu$ is bandwidth
  - $N \equiv A\Omega/\lambda^2$ is the number of spatial modes = 0.8 for λ/D pixels
  - p (= 2) is the number of polarization modes accepted by the detector
  - $\tilde{n} = 1/\left(e^{h\nu/kT} - 1\right)$ is the mode occupation number
  - The factor of 2 arises from expressing the NEP in $Hz^{-1/2}$
  - η_{cold} is the product of all the cold blocking filters, cold optics, FPI, and grating
  - η_{det} is the detector quantum efficiency
  - ε_{warm} is the warm emissivity which includes the sky emissivity, the telescope emissivity and the window emissivity: $\varepsilon_{warm} = ((1-\eta_{sky})\cdot\eta_{tel}+(1-\eta_{tel}))\cdot\eta_{window}+(\varepsilon_{window})$

Sensitivity Calculation 2/2

$$NEF = NEP/\left(A_{tel}\Delta\nu \cdot \eta_{det}\eta_{cold}\eta_{warm}\eta_{sky}\right)$$

- Where
  - $\eta_{warm} = \eta_{window}\eta_{tel}\eta_{spill-over}$
  - $\eta_{sky} = f(\lambda)$ is from ATRAN
  - We take $\eta_{spill-over} = 1$

MDLF is referred back to the sky and includes a sky subtraction efficiency of 90%

$$MDLF = 5 \cdot NEF/\sqrt{2 \cdot 3600}$$

- Assumptions
  - $T_{tel} = T_{sky}$ =240 K
  - Zenith PWV = 7.3 um
  - Elevation = 45
  - FL = 41,000 feet
  - Latitude = 39°
  - η_{det} = 90%
  - η_{pixel} = 60%
  - η_{cold} = 30%
  - η_{tel} = 80%
  - η_{window} = 93%
  - ε_{window} = 1%
  - η_{FPI} = 75%
  - $\eta_{grating} = f(\lambda)$
  - η_{filter} = 70%
  - η_{mirror} = 99.5%

SNR Including Spectral Scanning

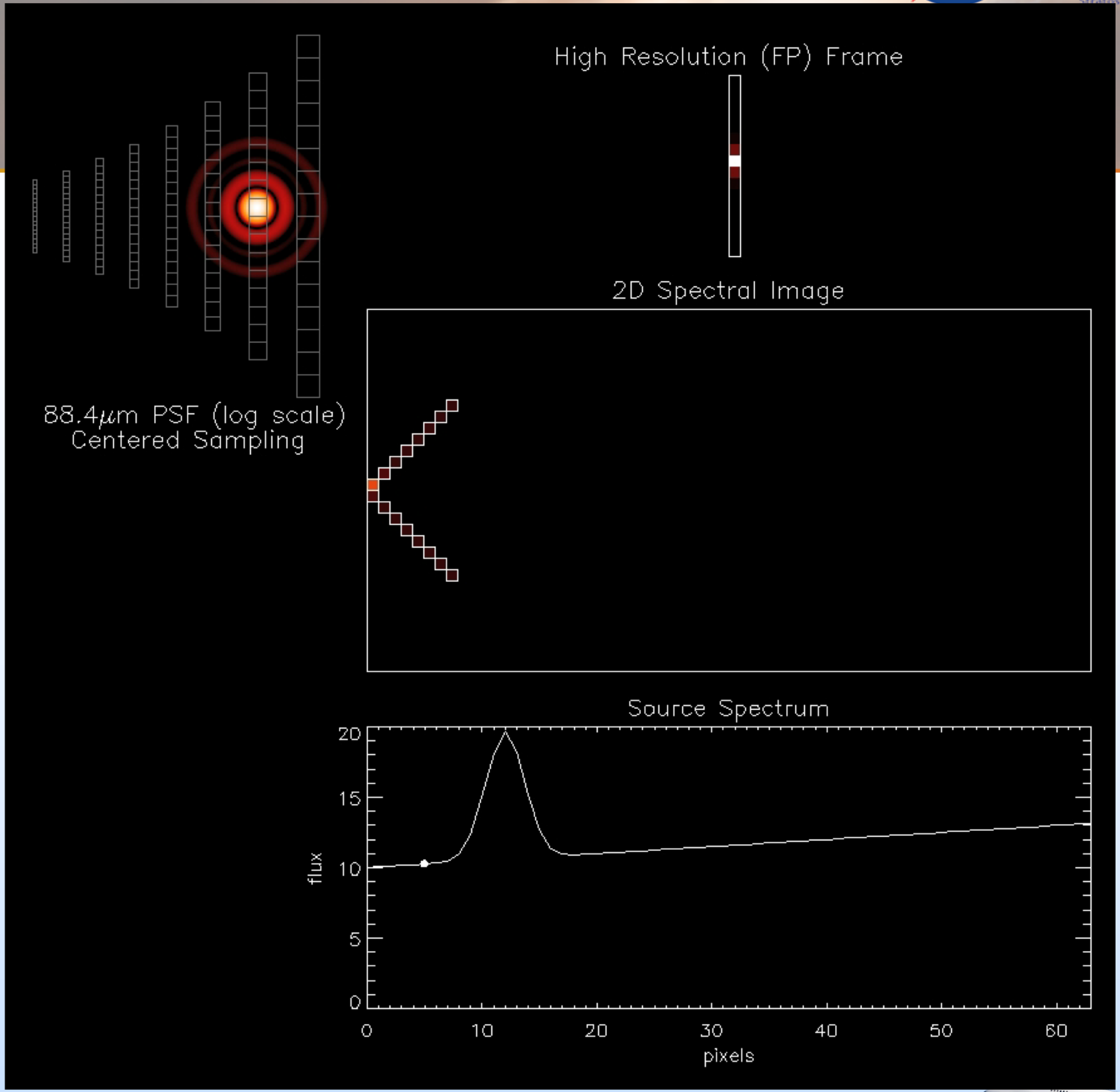
- The FPI is not a spectral multiplexer
- HIRMES always gets off-line baselines, but need to scan the FPI to obtain spectral profiles
- Number of spectral samples required is a function of resolving power and astrophysical lines widths

Sensitivity Estimates in Hi-Res Mode

Species/ wavelength (µm)	V_{obs} (km/s)	Pixel (arcsec)	η_{atm} (%)	NEF ($W/m^2/Hz^{1/2}$)	MDLF per res. el. (5σ 1 hr) (W/m^2)	MDLF – spectral scan (W/m^2)	
						5 el. scan	10 el. scan
H_2O 34.9823	-40	2.9	94	3.3E-17	2.0E-18	4.4E-18	6.2E-18
RP = 50,000	+20		84	4.4E-17	2.6E-18	5.8E-18	8.2E-18
	+40		93	3.3E-17	2.0E-18	4.4E-18	6.2E-18
[OI] 63.1837	-40	5.2	65	3.6E-17	2.1E-18	4.7E-18	6.7E-18
RP = 100,000	0		62	3.9E-17	2.3E-18	5.1E-18	7.2E-18
	+40		59	4.2E-17	2.5E-18	5.6E-18	7.9E-18
HD 112.0725	-40	9.2	58	2.9E-17	1.7E-18	3.8E-18	5.4E-18
RP = 100,000	0		58	2.9E-17	1.7E-18	3.9E-18	5.4E-18
	+40		56	3.1E-17	1.8E-18	4.1E-18	5.8E-18

45° elevation

Building the Hi-Res Spectrum



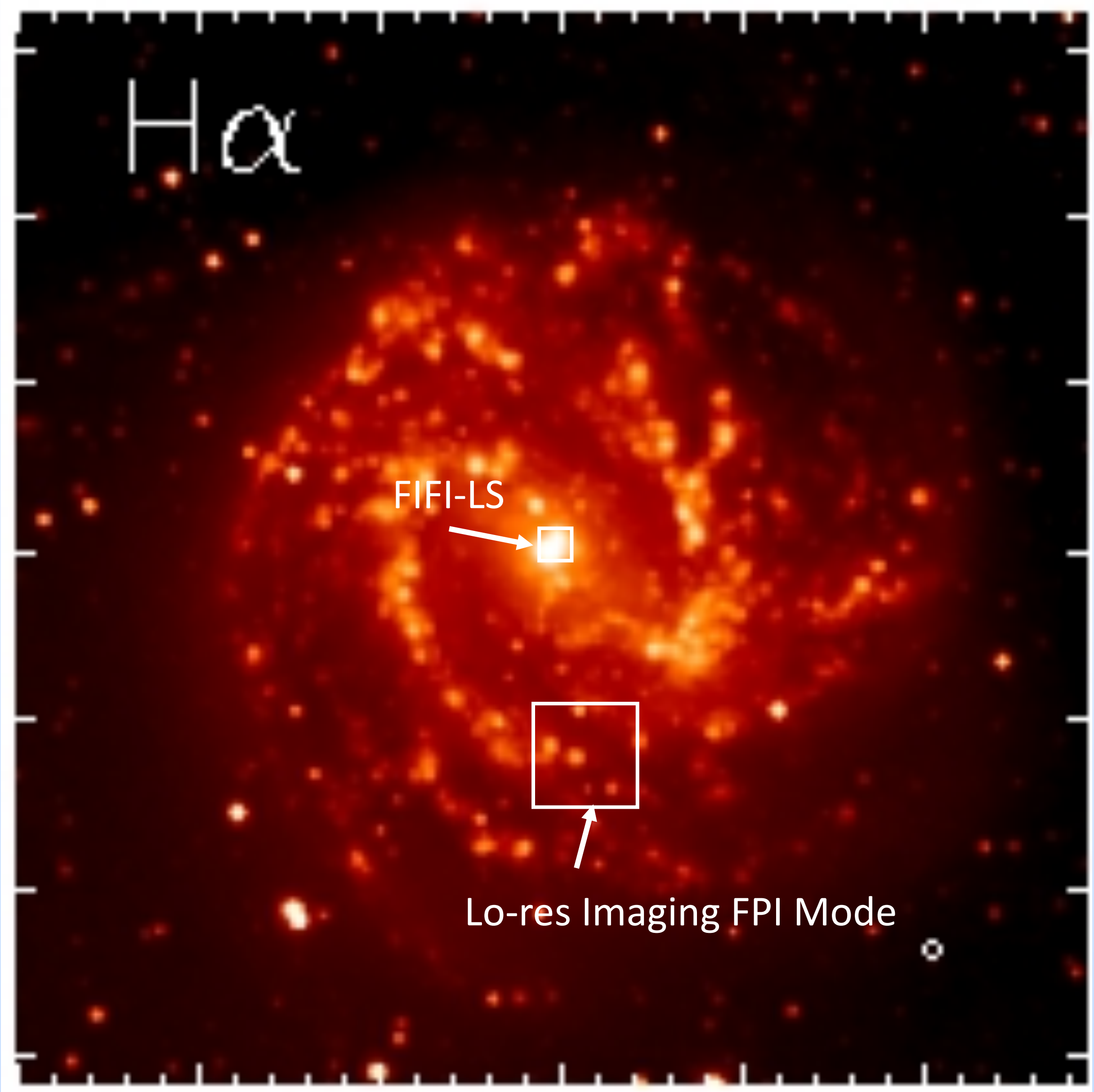
Imaging Spectroscopy Mode example: M83

[OIII]: 52 μm

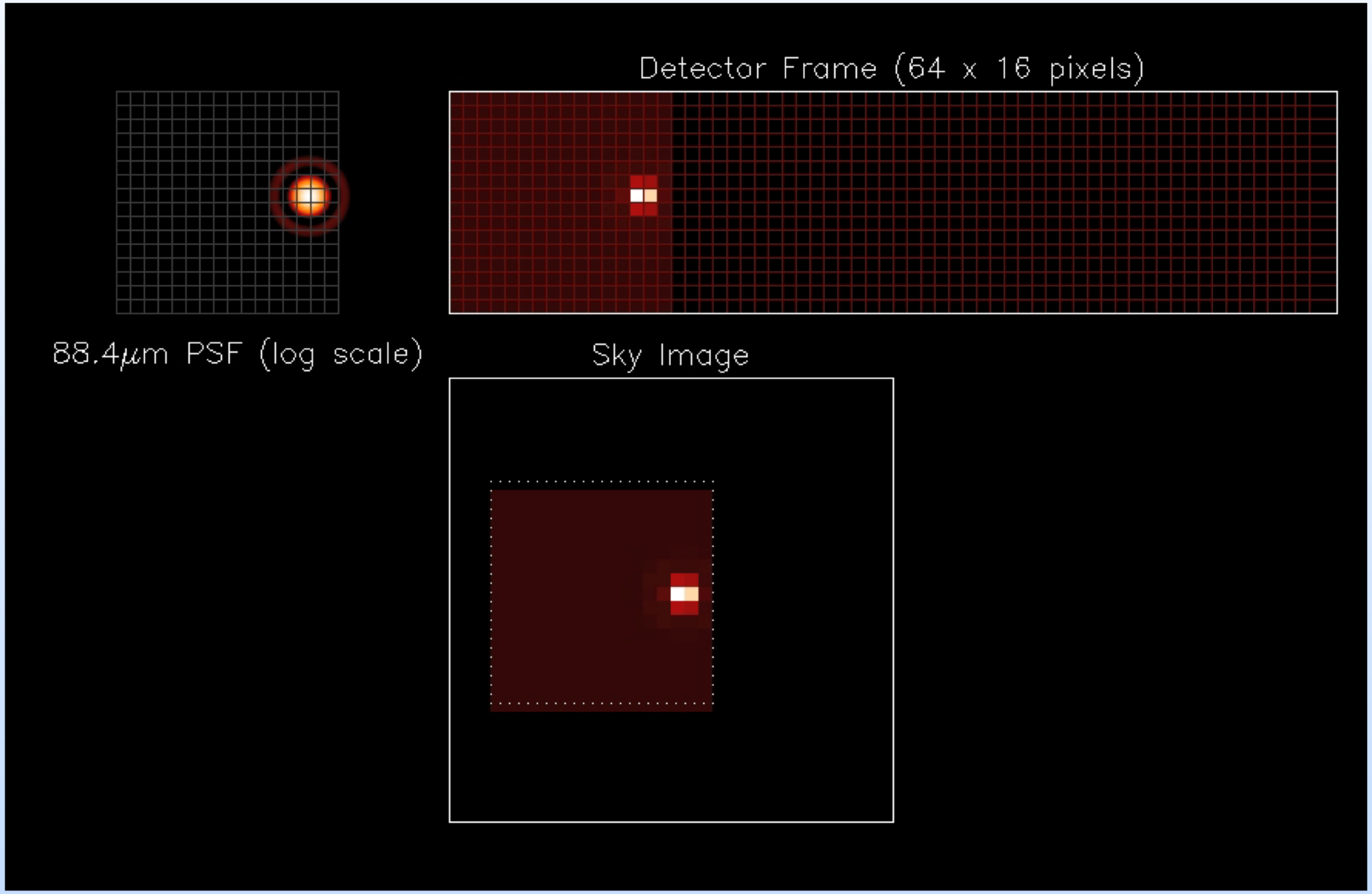
- Line flux: 6 E -17 W/m^2
- 12 σ in 15 minutes
- 30 pointings $\Rightarrow$7.5 hours

All lines: additional 1 $\times$ 7.5, 2 $\times$ 3.0

Total: 21 hours for complete [OIII] $\times$ 2, [NIII], [NII]



Observing Strategies: Imaging FPI



FPI Summary

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

8 total FPI: 6 are essentially the same PZT driven design but with different etalon gaps, and the remaining two are identical cryomotor driven designs

HIRMES Instrument Paper Available

- “SOFIA-HIRMES: Looking Forward to the HIgh-Resolution Mid-infrarEd Spectrometer” Samuel N. Richards et al. 2019 Journal of Astronomical Instrumentation, Vol. 7, No. 4

https://www.worldscientific.com/doi/abs/10.1142/S2251171718400159