HIRMES – HIgh Resolution Mid-infrarEd Spectrometer

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What is HIRMES?

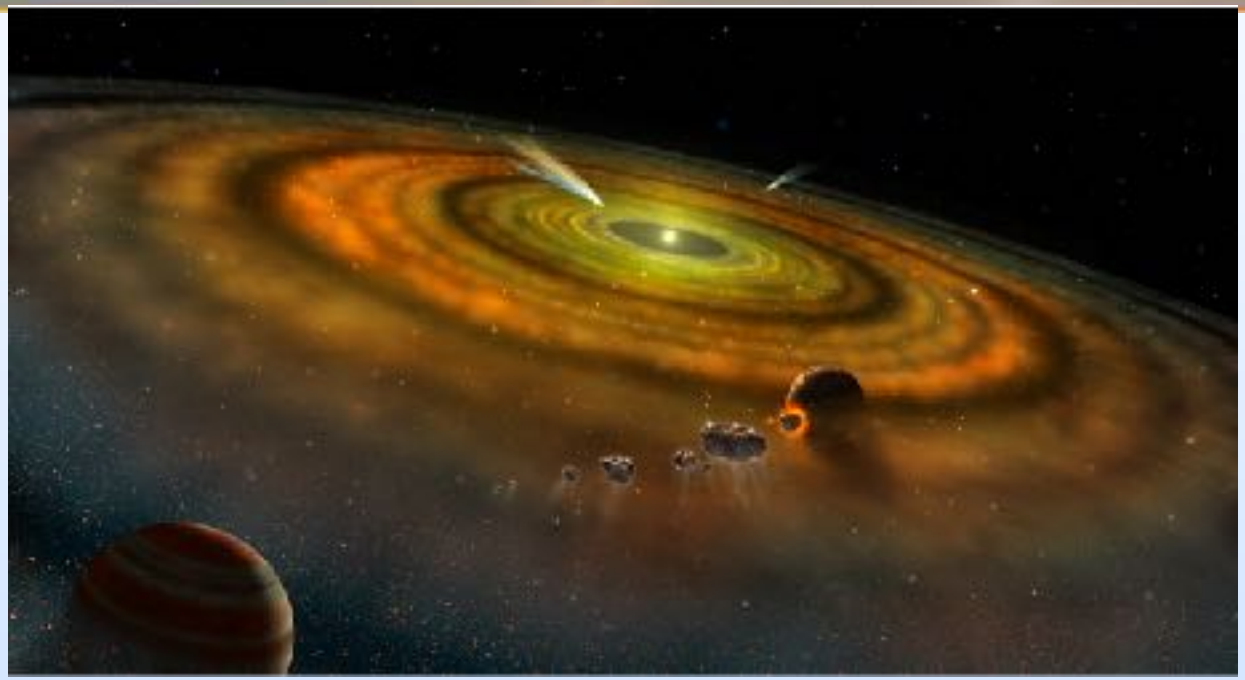
- HIRMES is the recently selected 3rd generation instrument that will fly on SOFIA in early 2019
- HIRMES primary science is to investigate protoplanetary disk physics and addresses the questions:
  - How does the disk mass evolve during planetary formation?
  - What is the distribution of oxygen, water 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 R ~ 100,000
  - Mid-res mode R ~ 10,000
  - Low-res mode R ~ 600
  - Imaging spectroscopy mode: R ~ 2000
- The modes are optimized to deliver the maximum sensitivity achievable with SOFIA. HIRMES uses:
  - Background limited bolometers
  - Combination of Fabry-Perot Interferometers and gratings

Primary Science

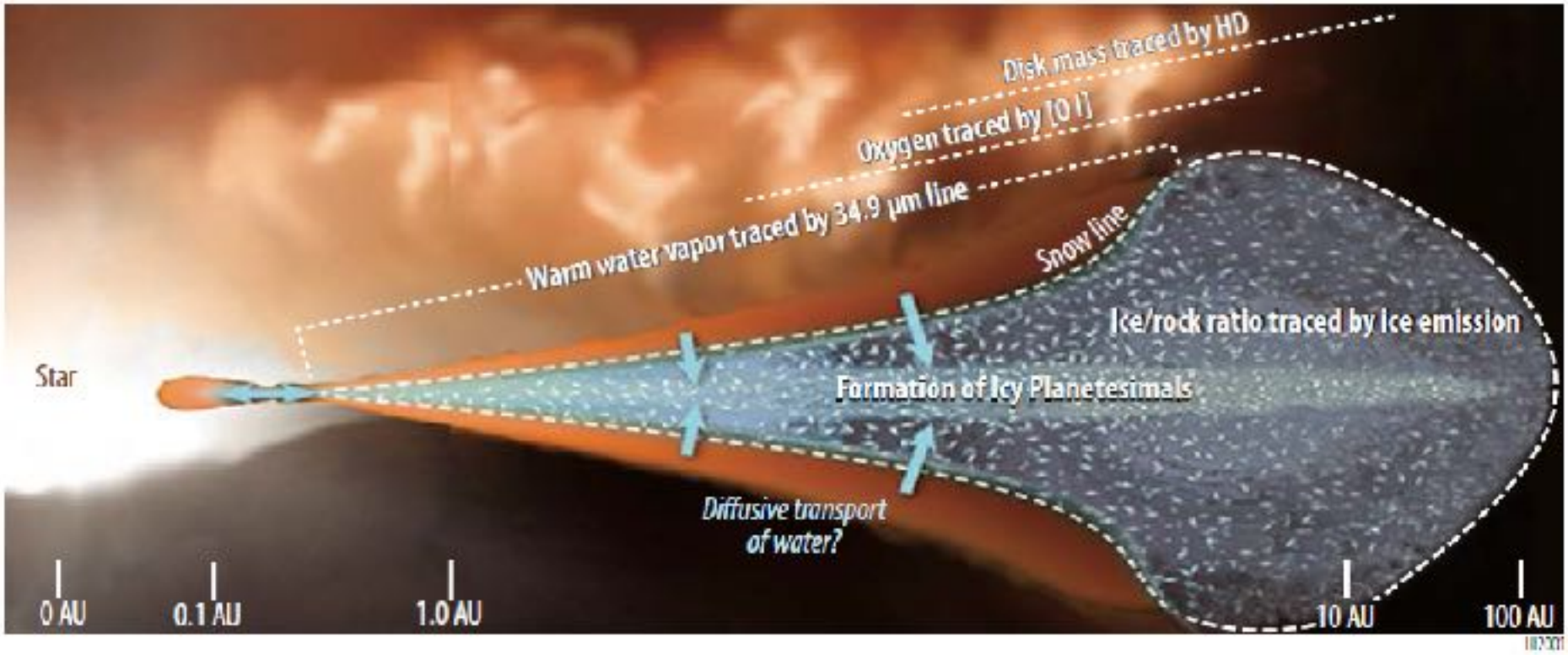


- Over ~ 10 million years, protoplanetary disks evolve into young planetary systems
- Bulk of mass is gas and ice – both hard to observe
- Hinders testing & development of planet formation theories

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
- **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

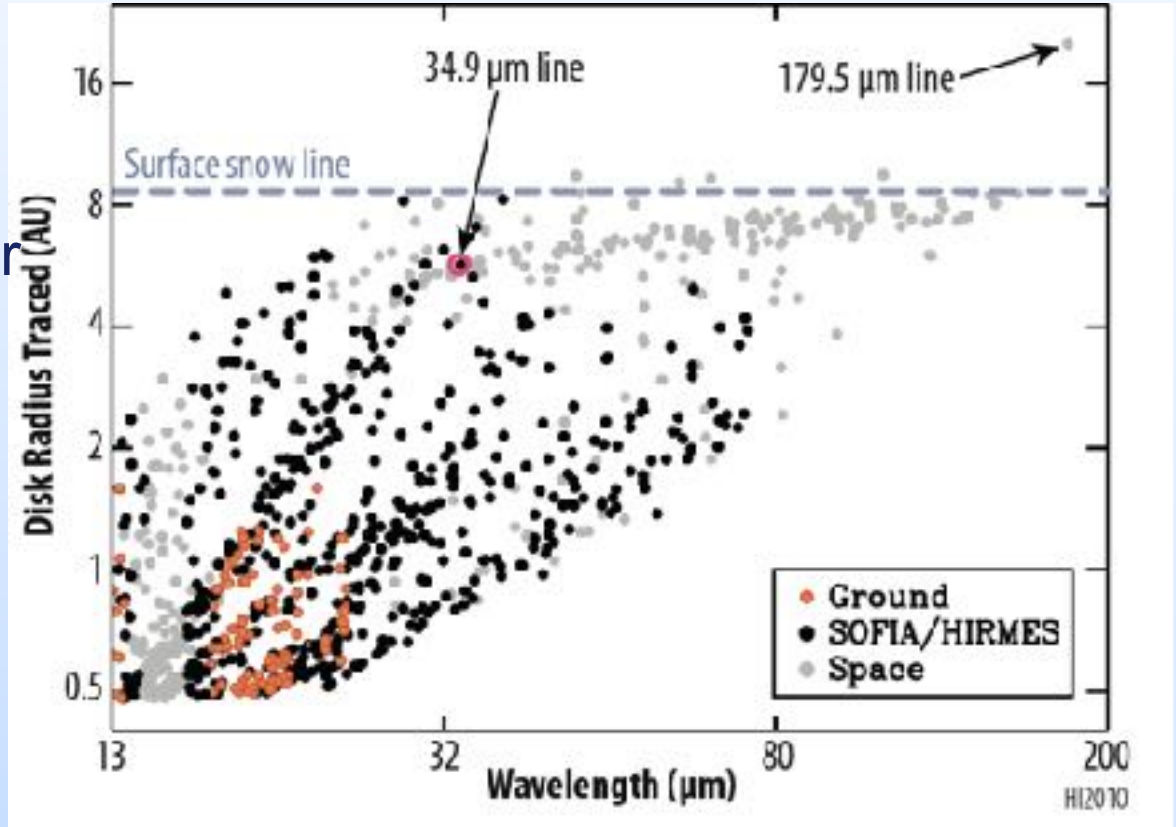
Water and Ice



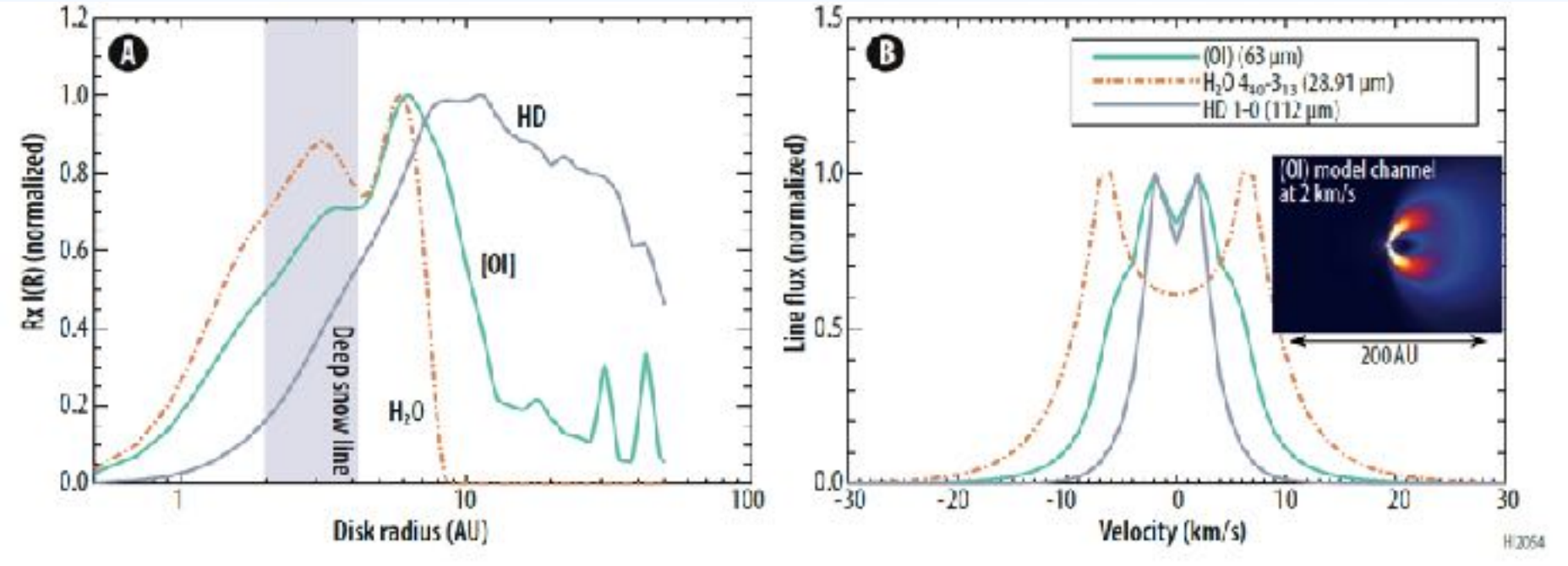
Water line measurements locate the transition region between warm water vapor and ice through velocity resolved spectroscopy

HIRMES Traces Water at the Snow Line

- Ground based lines probe very inner regions
- Space based can probe entire disk, but will not have the resolving power
- HIRMES probes out to the snow line regions at ~ 10 AU with sufficient velocity resolution and sensitivity to constrain models



Distributions of O, H_2O and HD



- Measuring the line profiles determines the radial distributions of O, H_2O and HD in the disk
- O and H_2O are expected to be in and around the snow line while HD is external ⇒ HD requires less RP than O and H_2O observations

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

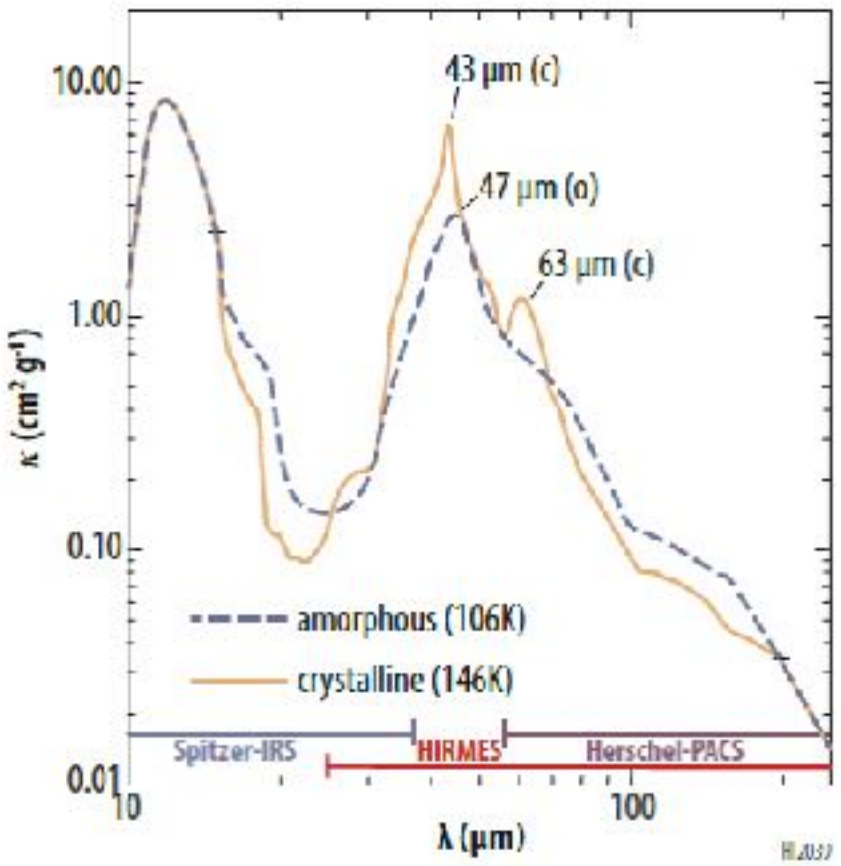


Figure D-4: HIRMES can infer the thermal history of grain mantles by observation of the 43, 47 and 63 μm water-ice features. The plot shows the emission/absorption coefficients (McClure et al. 2015).

The Impact of Star Formation

- The process of mass accretion leading to star and planet formation involves shocks that release refractories and can result in ionized gas emission lines
- [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 μm, [NIII] 57.30 μm, [OI] 63.18 μm, [OIII] 88.35 μm
- Lines and ratios reveal gas abundances, ionization state, and density testing shock models and mass flow models
- The velocity resolved line profiles reveal the shocked gas kinematics
- Herschel and Spitzer did trace intensity and spatial profiles, but the spectral profiles are key components of shock models

Further Shopping List

High velocity resolution and high sensitivity of HIRMES enables much new science

- Outflows from massive protostars traced with CO
- HD as a probe of D abundance
- Resolved HD rotational lines from giant planets
- Titan chemistry
- ...
- Imaging spectroscopy mode with its wide field of view enables large-scale mapping of nearby galaxies in fine-structure line emission

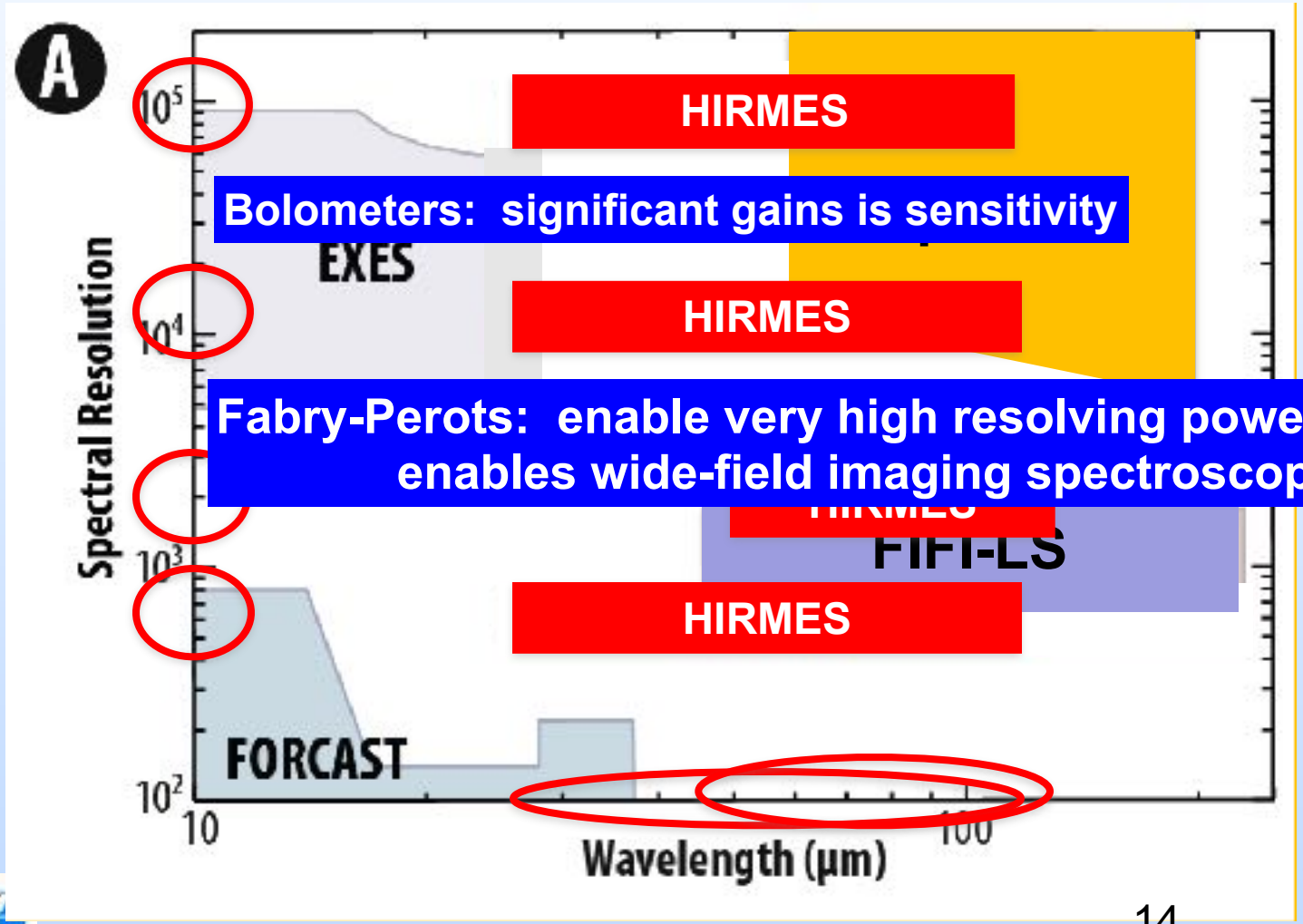
Sensitivity Estimates in Hi-Res Mode

Line/λ (μm)	V_{obs} (km/s)	Pixel	η_{atm}	NEP (W/Hz$^{1/2}$)	η_{pix}	NEF (W/m^2/Hz$^{1/2}$)	MDLF (W/m^2, 5σ/hr)
H_2O 34.9823 μm	-40	2.9”	94%	1.35E-17	60%	2.4E-17	1.4E-18
	+20		84%	2.24E-17		4.4E-17	2.6E-18
	+40		93%	1.35E-17		2.4E-17	1.4E-18
[OI] 63.1837μm	-40	5.2”	65%	1.37E-17	60%	3.6E-17	2.1E-18
	0		62%	1.45E-17		4.2E-17	2.3E-18
	+40		59%	1.45E-17		4.2E-17	2.5E-18
HD 112.0725 μm	-40	9.2”	58%	9.47E-18	60%	2.9E-17	1.7E-18
	0		58%	9.49E-18		2.9E-17	1.7E-18
	+40		56%	9.67E-18		3.1E-17	1.8E-18

SNR Estimates: HD163296

Line	Flux	MDLF	SNR if line width is:			
Line	Flux	MDLF	0 km/s	3 km/s	6 km/s	15 km/s 0.5 hours/samp.
H_2O	3.1E-17	1.97E-18 RP = 50,000	75 (1 hr)		75 (5 hrs)	50 (5 hours)
		1.40E-18 RP =100,000	110 (1 hr)	114 (3 hrs)	100 (5 hrs)	50 (5.5 hours)
[OI]	2.1E-16	3.50E-18 RP = 50,000	300 (1 hr)		220 (1 hrs)	90 (1 hours)
		2.49E-18 RP =100,000	420 (1 hr)	260 (1 hrs)	175 (1 hr)	85 (1 hours)
HD	1.0E-17	2.55E-18 RP = 50,000	20 (1 hr)		21 (3 hrs)	16 (5 hours)
		1.82E-18 RP =100,000	27 (1 hr)	29 (3 hrs)	25 (5 hrs)	15 (5 hours)

HIRMES in SOFIA Context



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Comparision with upGreat

- Coherent detection fundamentally limited in sensitivity by the quantum noise limit inherent in the detection of phase and manifest as: $T_{QN} = \frac{h\nu}{k}$

Sensitivity ratio estimates based on public upGREAT sensitivities:

[OI] 63 μm 10:1 HD 112 μm 10:1

T_{rec}~590 K @ 122 μm ⇢ 2770 @ 26 μm single side band

- The sky plus telescope emissivity is ~ 20% so the fundamental limits are T_{rec}~$0.2 \cdot 240 = 48\ K$
- Direct detection in principle wins by factors of 12 (122 μm) to 58 (26 μm) over coherent detection

Comparisons with FIFI-LS

- Both are direct detection spectrometers, so they do not suffer from quantum noise limit
- However, bolometers have two advantages over photoconductors
  - Bolometers can have >90% quantum efficiency over reasonably broad bands
  - Bolometers do not have generation recombination noise

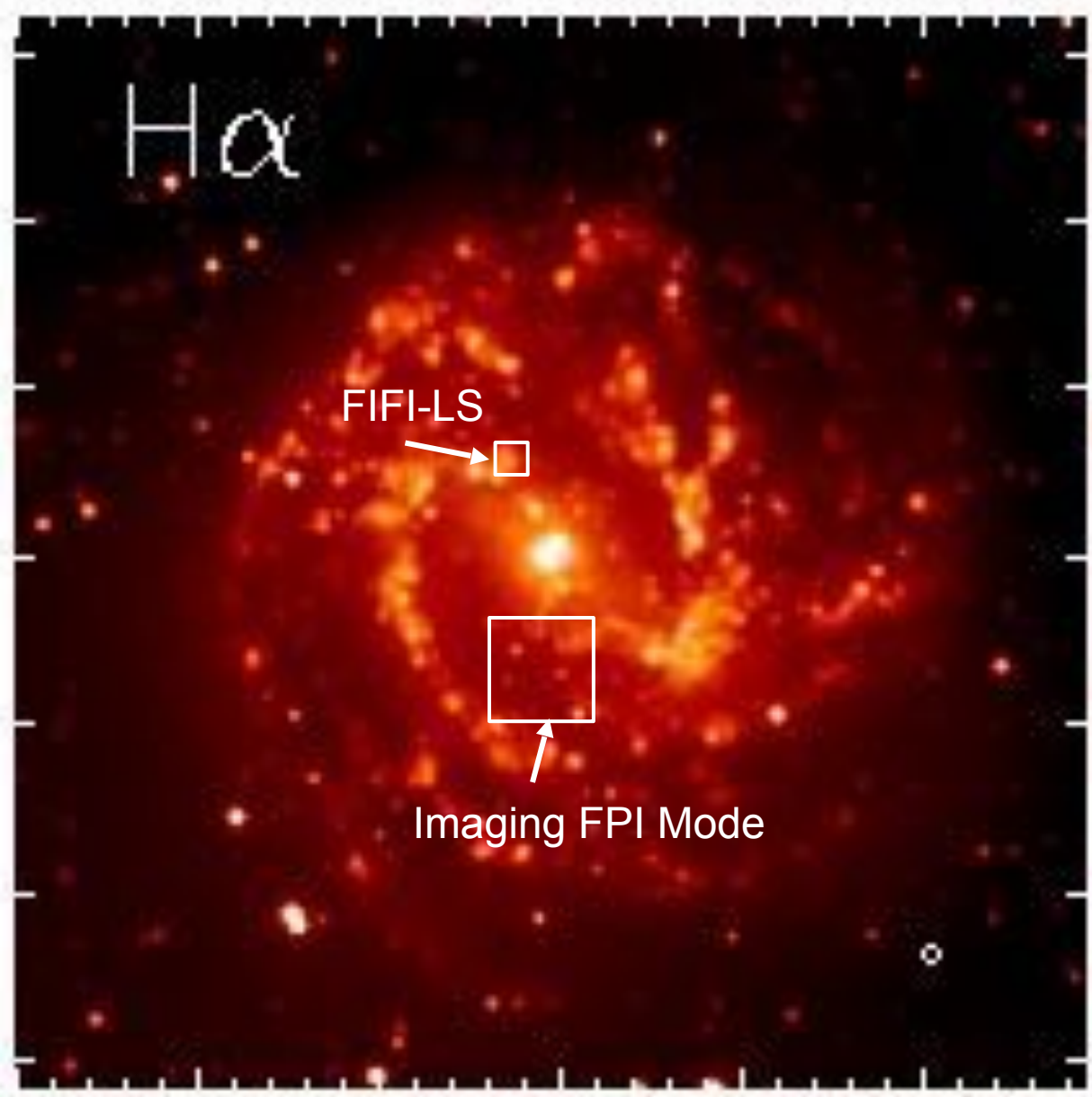
  Penalty for FIFI-LS is ~ $\sqrt{(0.95/0.5)} \times \sqrt{2}$ ~ 2 in sensitivity
- FIFI-LS is a spectral multiplexer, but HIRMES is not

  Penalty for HIRMES = $\sqrt{5}$ ~ 2.23 (res. el.) in sensitivity

Imaging Mode Mapping Speed

Line	FIFI-LS	HIRMES	Sens. Ratio	Sky Sub.	FPI Scan	Net Sens	Areal Cover.	Mapping Speed
[OIII] 51.8 μm	5.4E-17	2.0E-17	0.36	0.84	2.23	0.69	10.6	22
[NIII] 57.3 μm	5.1E-17	2.1E-17	0.41	0.84	2.23	0.77	10.6	18
[OI] 63.2 μm	6.4E-17	3.3E-17	0.52	0.84	2.23	0.98	10.6	11
[OIII] 88.4 μm	4.3E-17	0.76E-17	0.18	0.84	2.23	0.33	10.6	95
[NII] 122 μm	6.9E-17	1.2E-17	0.18	0.84	2.23	0.34	2.6	23

NOTES: FL = 41,000', v = 0 km/s except for [NII] @ 43,000', v = 520 km/s; source el. = 45°; MDLF = 4σ, 15 minutes; sky sub. = 1.7 (FIFI), 1.1 (HIRMES)


Hα
FIFI-LS
Imaging FPI Mode

HIRMES on the Outside

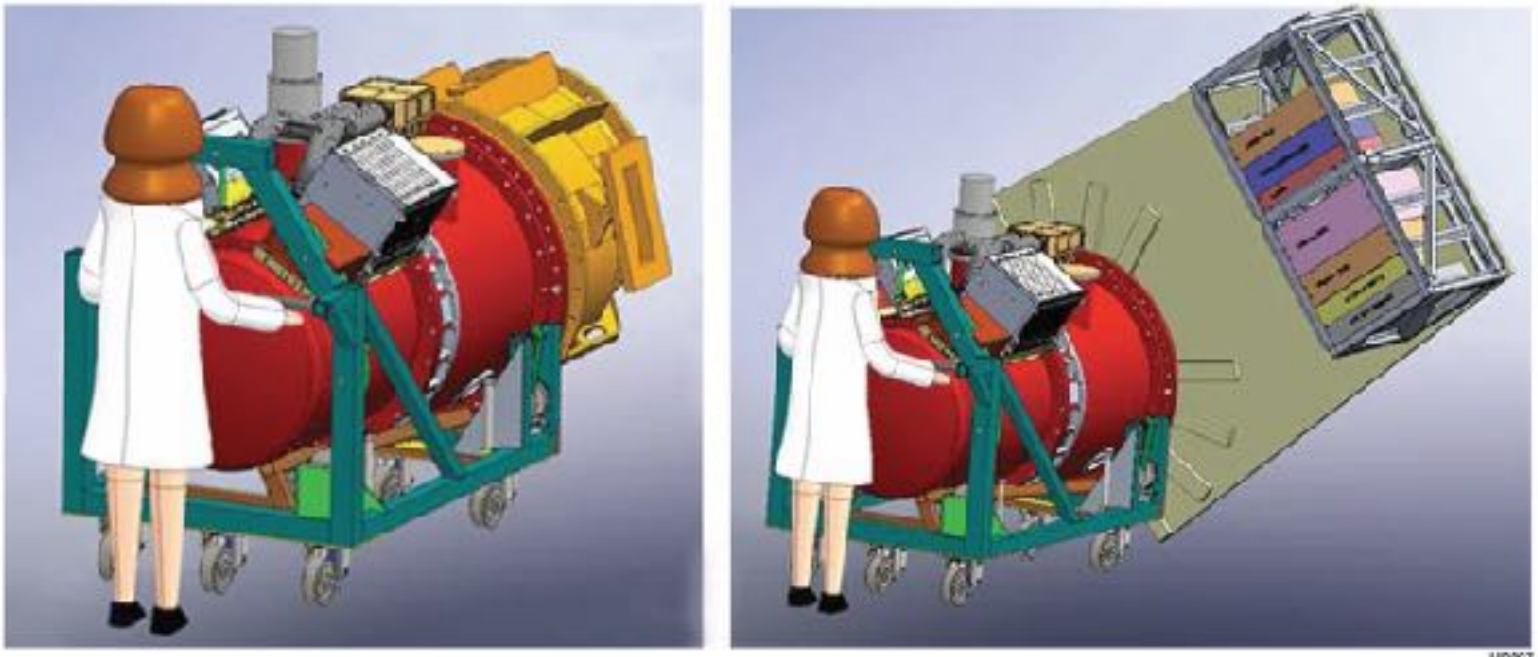
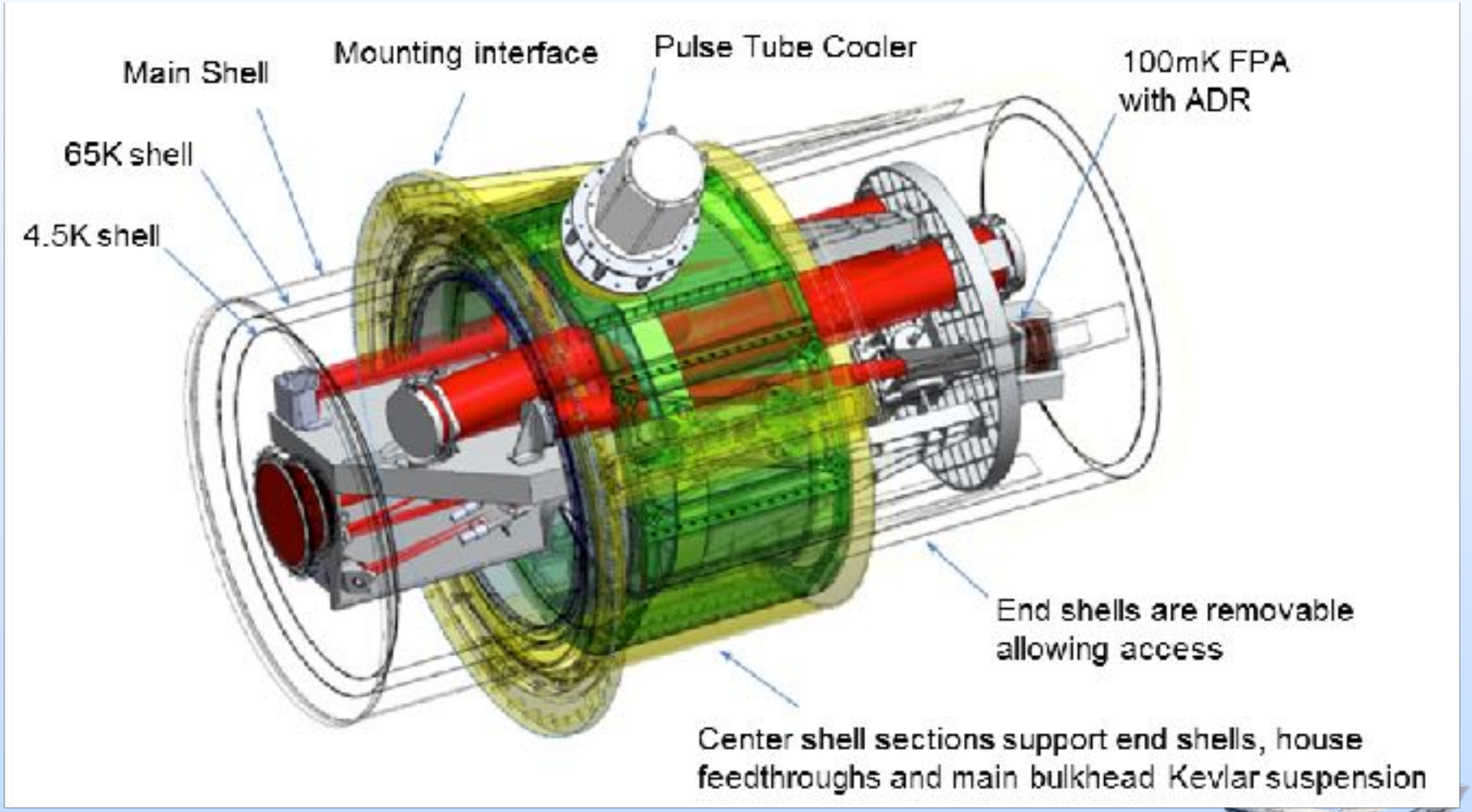
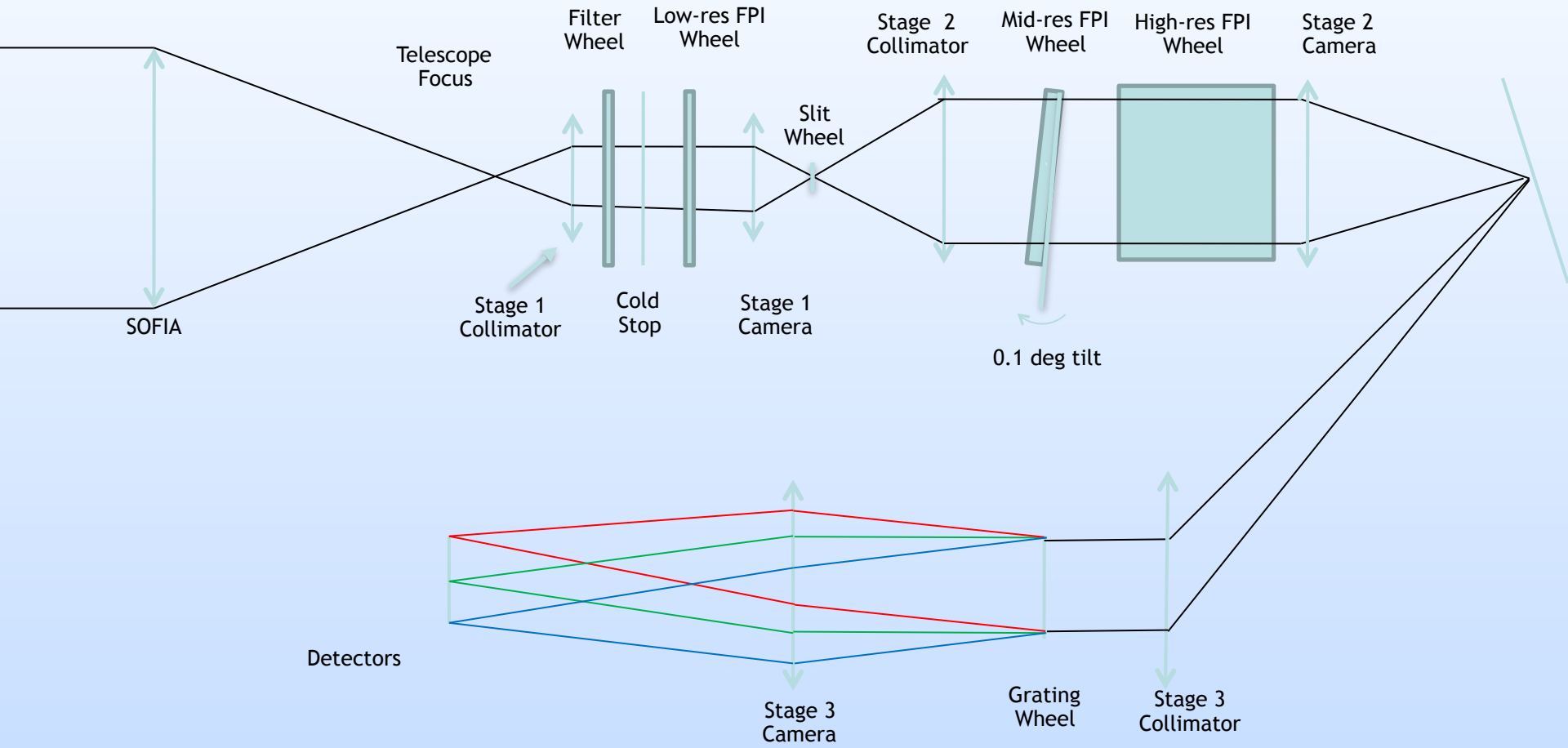


Figure E-4: Left: HIRMES on installation cart; Right: HIRMES and CWR installed on TA.

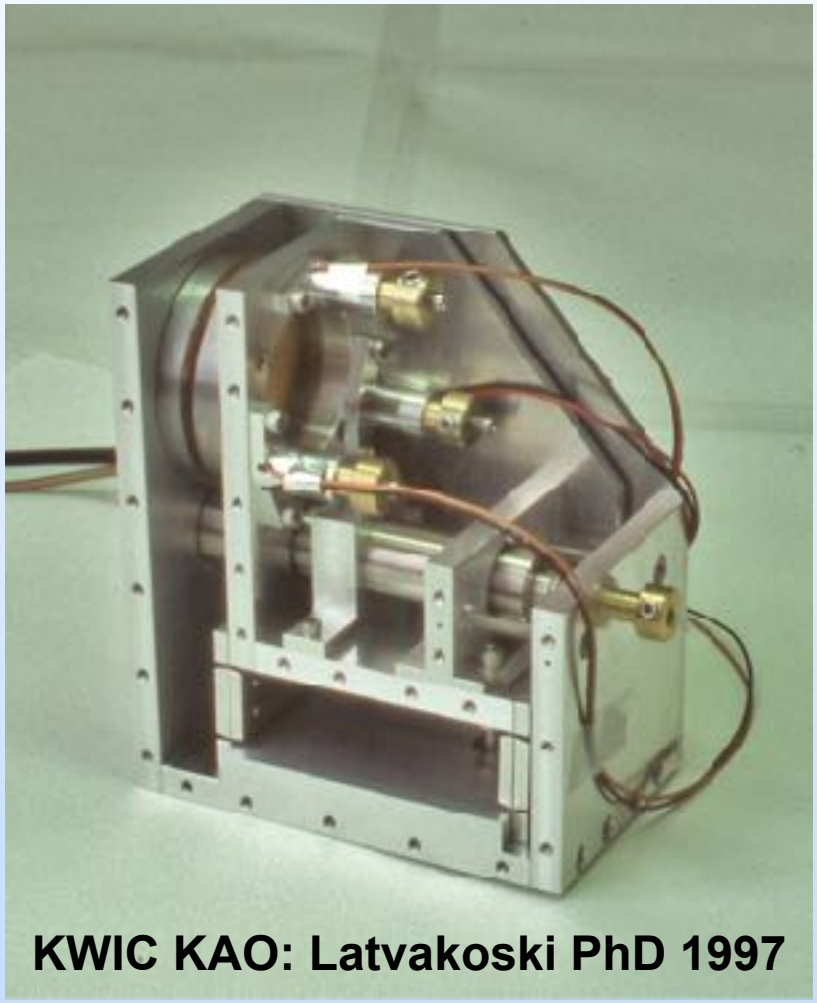
HIRMES Interior



Schematic Optical Path



Scanning FPI Examples



KWIC KAO: Latvakoski PhD 1997

SPIFI JCMT: Bradford PhD 2000

Scanning FPI Designs

- Wire EDM manufacture
- Fixed order, PZT drive
- Capacitive bridge control
- Metal mesh mirrors
- 3 Hi-res; 3 Mid-res

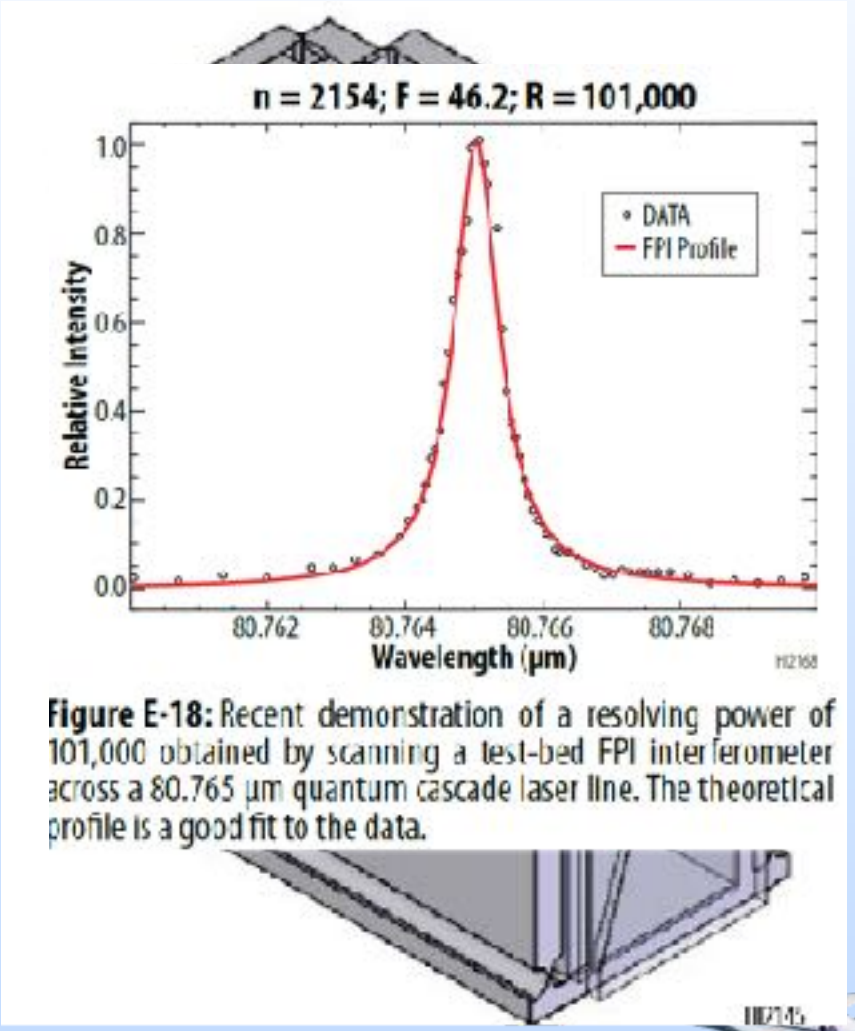
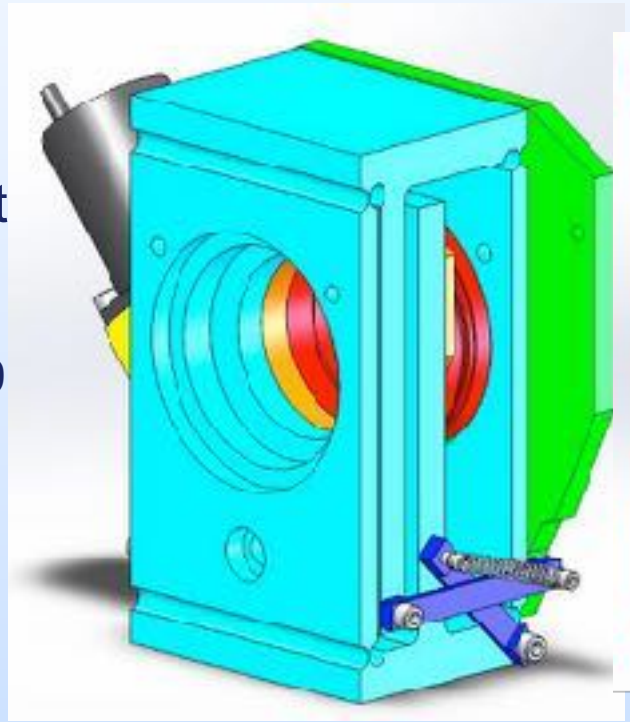


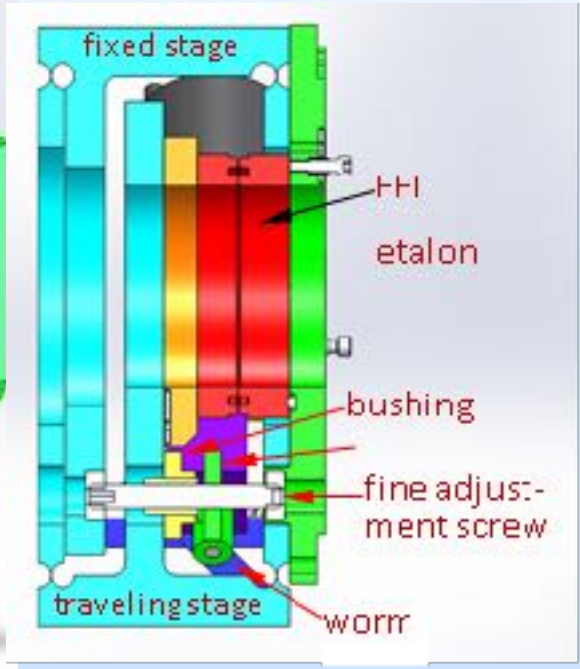
Figure E-18: Recent demonstration of a resolving power of 101,000 obtained by scanning a test-bed FPI interferometer across a 80.765 μm quantum cascade laser line. The theoretical profile is a good fit to the data.

Low-Res Imaging FPI

Based on Miniature Cryogenic Scanning FPI Design

- Two Imaging FPI required
- Fix order for R.P. = 2000 at band center
- Imaging FPI -1
  - F = 41 @ 57 μm ⇒ m = 49
  - F = 50 @ 63 μm ⇒ RP = 2200
  - F = 34 @ 52 μm ⇒ RP = 1810
- Imaging FPI -2
  - F = 60 @ 122 μm ⇒ R.P. = 2260
  - F = 31 @ 88 μm ⇒ R.P. = 1630





Wire EDM eliminates need for tilt PZTs

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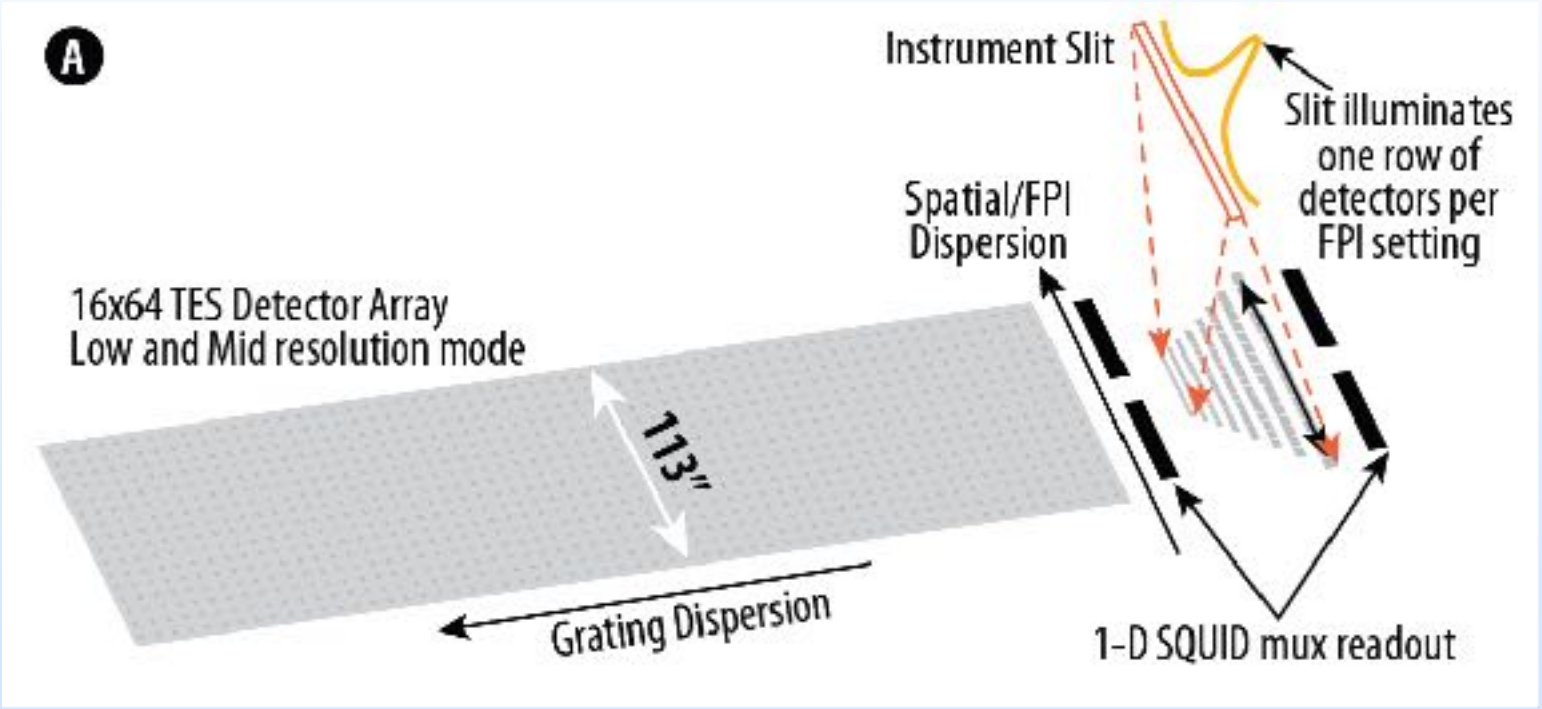
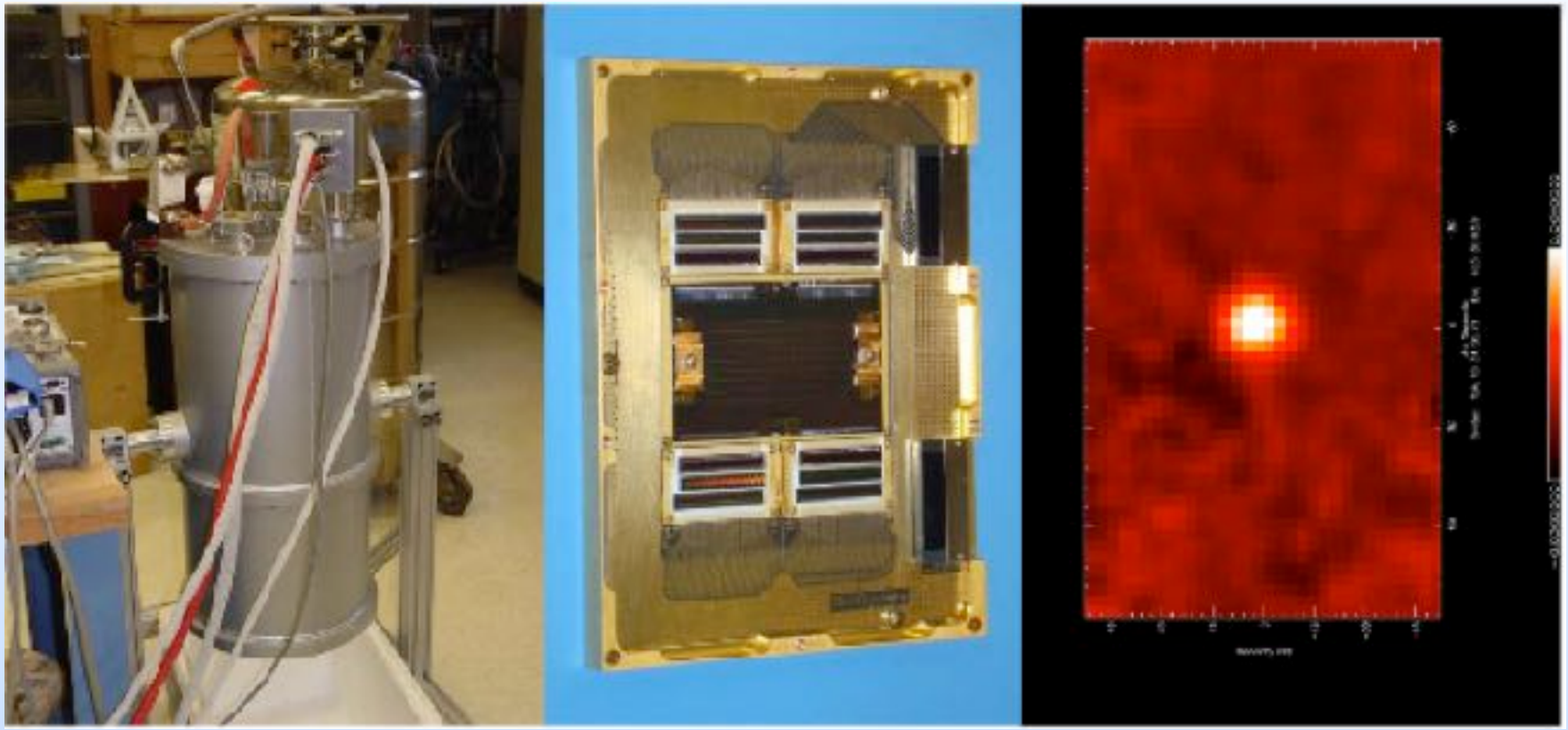
Bolometer Arrays



Pixel scales
Array 1:
6.1×6.1”
No back short ⇒ very broad band response
Array 2:
2.5 to 8.5”
Back short tuned

- Two MoAu TES bolometer arrays are used within HIRMES
  - 16 × 64 pixel array used for low-res (grating) mode, mid-res mode, and imaging spectroscopy mode
  - 8 × 16 pixel array used for high-res mode

Heritage: GISMO (J. Staguhn)

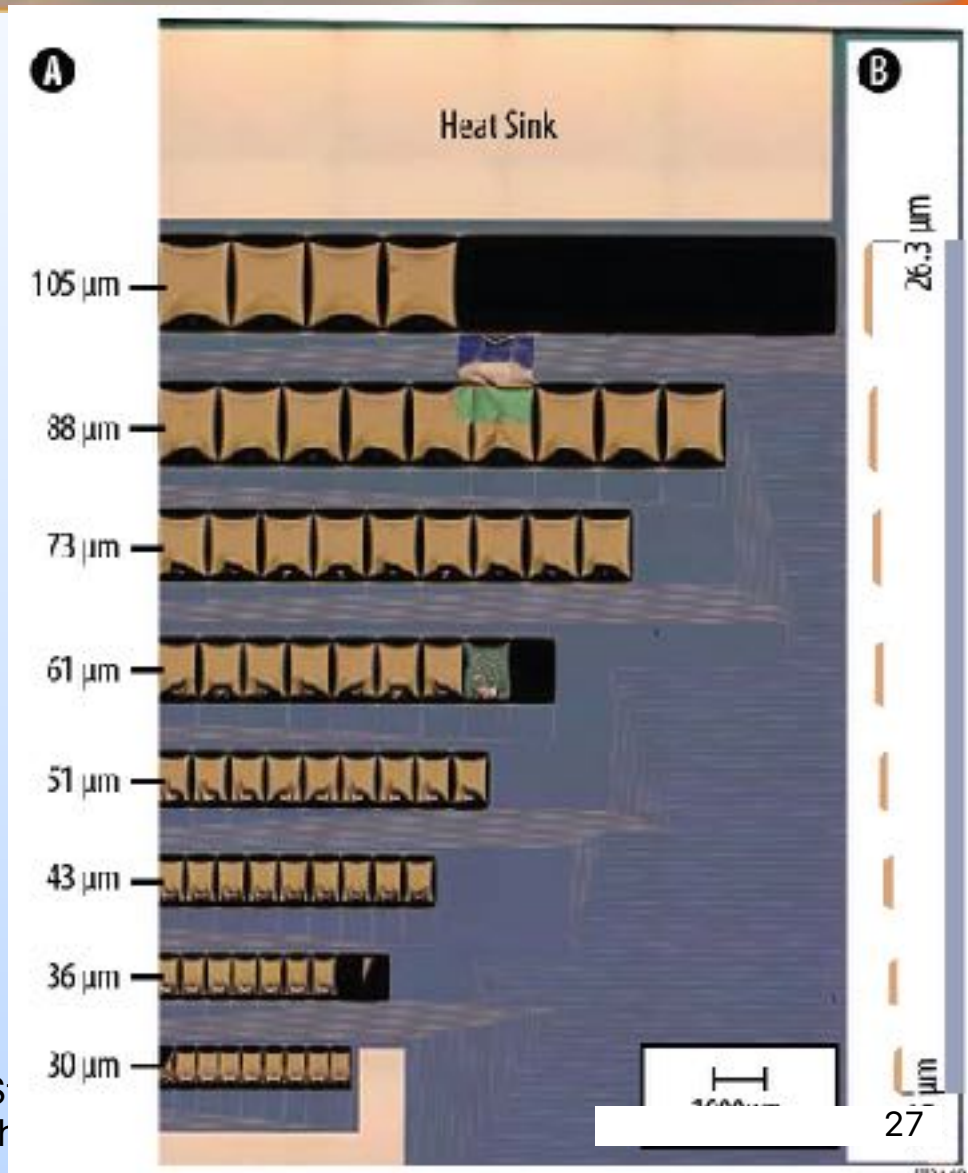


GISMO instrument (left), center – detector assembly, right - image of Arp 220 - ULIRG. GISMO is being operated at IRAM 30m sub-mm telescope for a number of years.

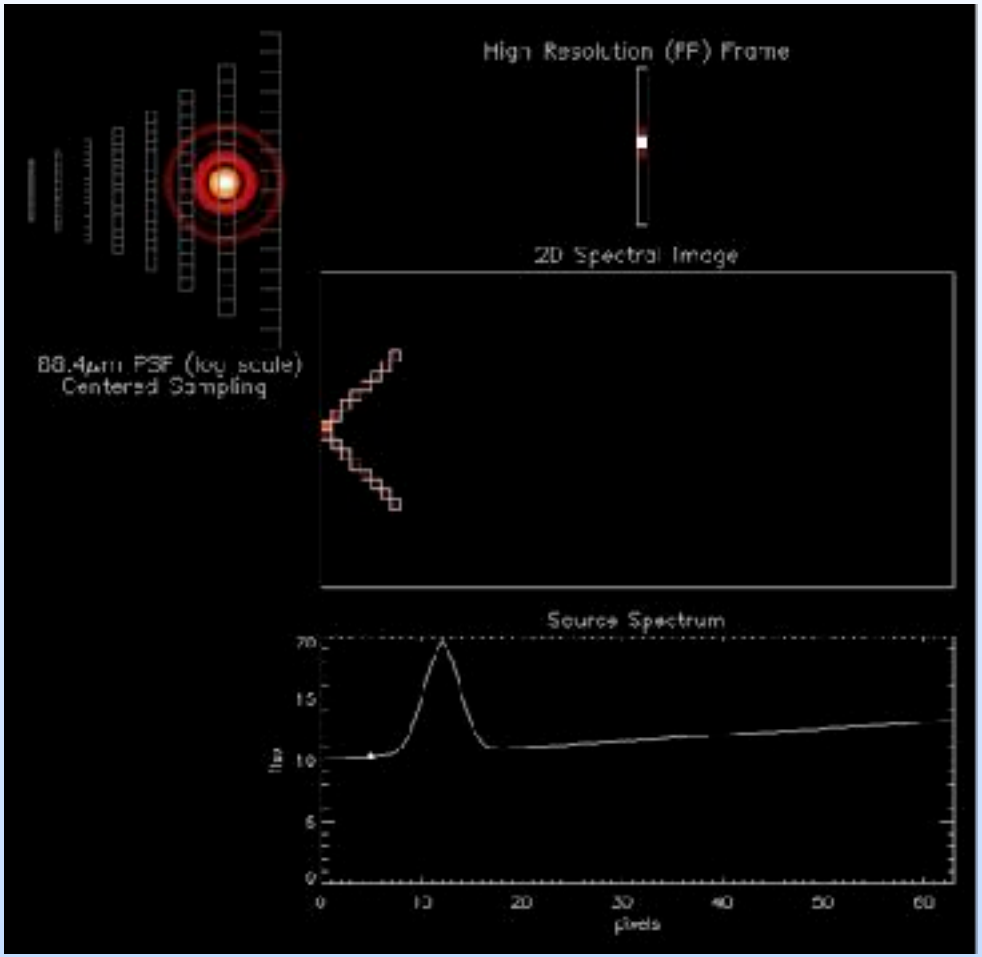
Array Development

8 × 16 array

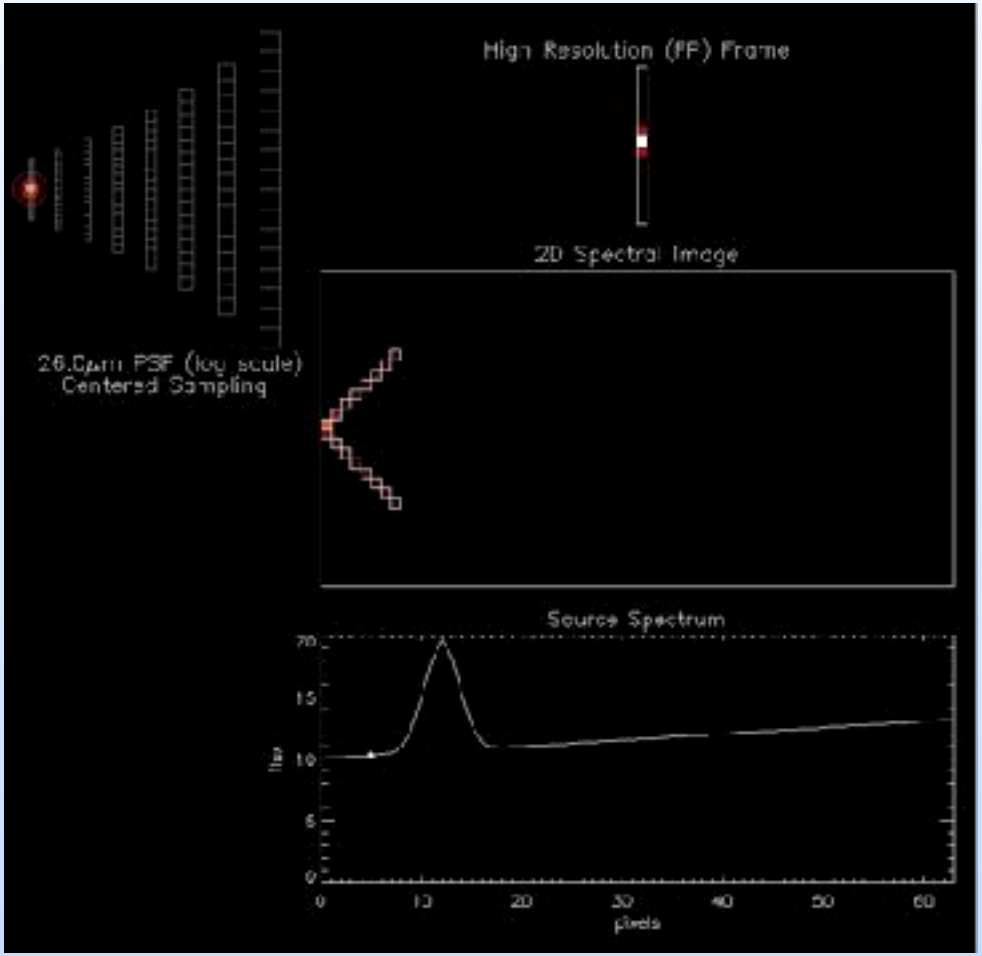
- Pixel scale always λ/D for optimal sensitivity
  - Optimal signal/pixel vs noise/ pixel extraction for point sources
  - Minimizes aberrations and spectral shifts for high-res spectra
- Each array tuned with back short at center of band ⇒ DQE > 90%
- Requisite sensitivity demonstrated at GSFC



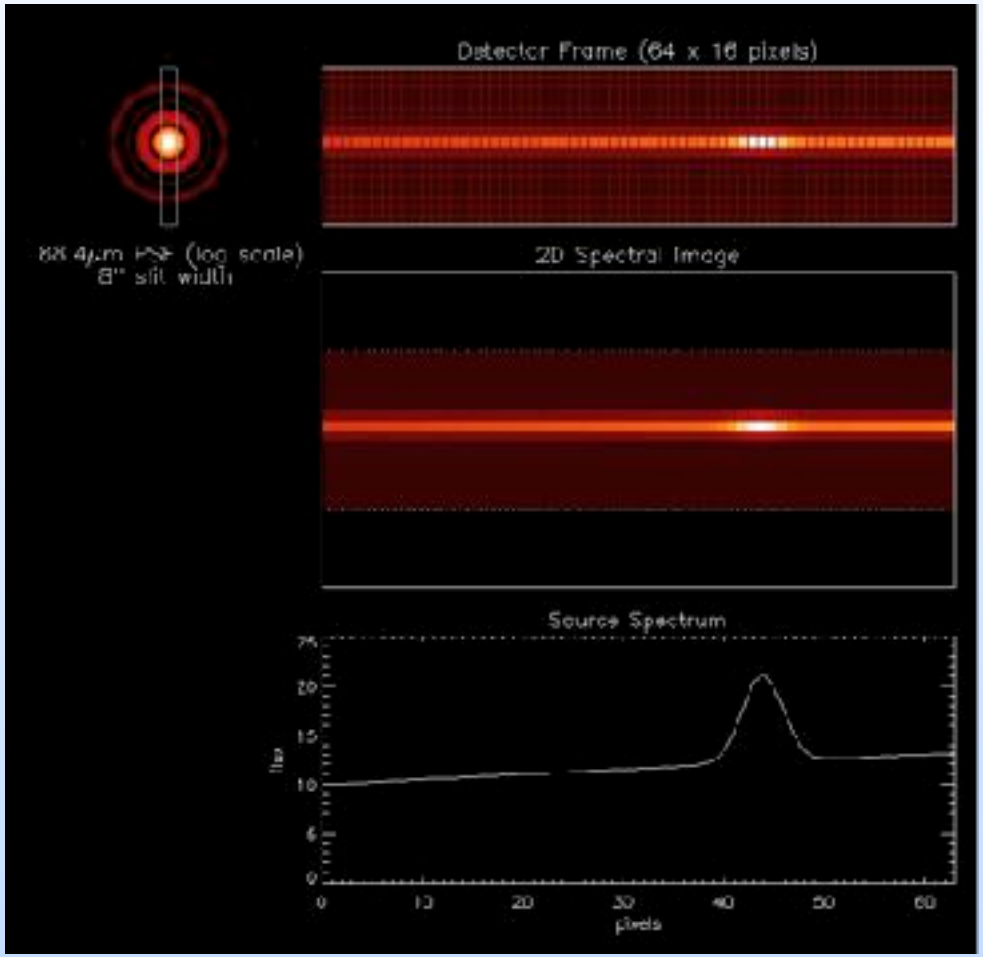
Building the Hi-Res Spectrum



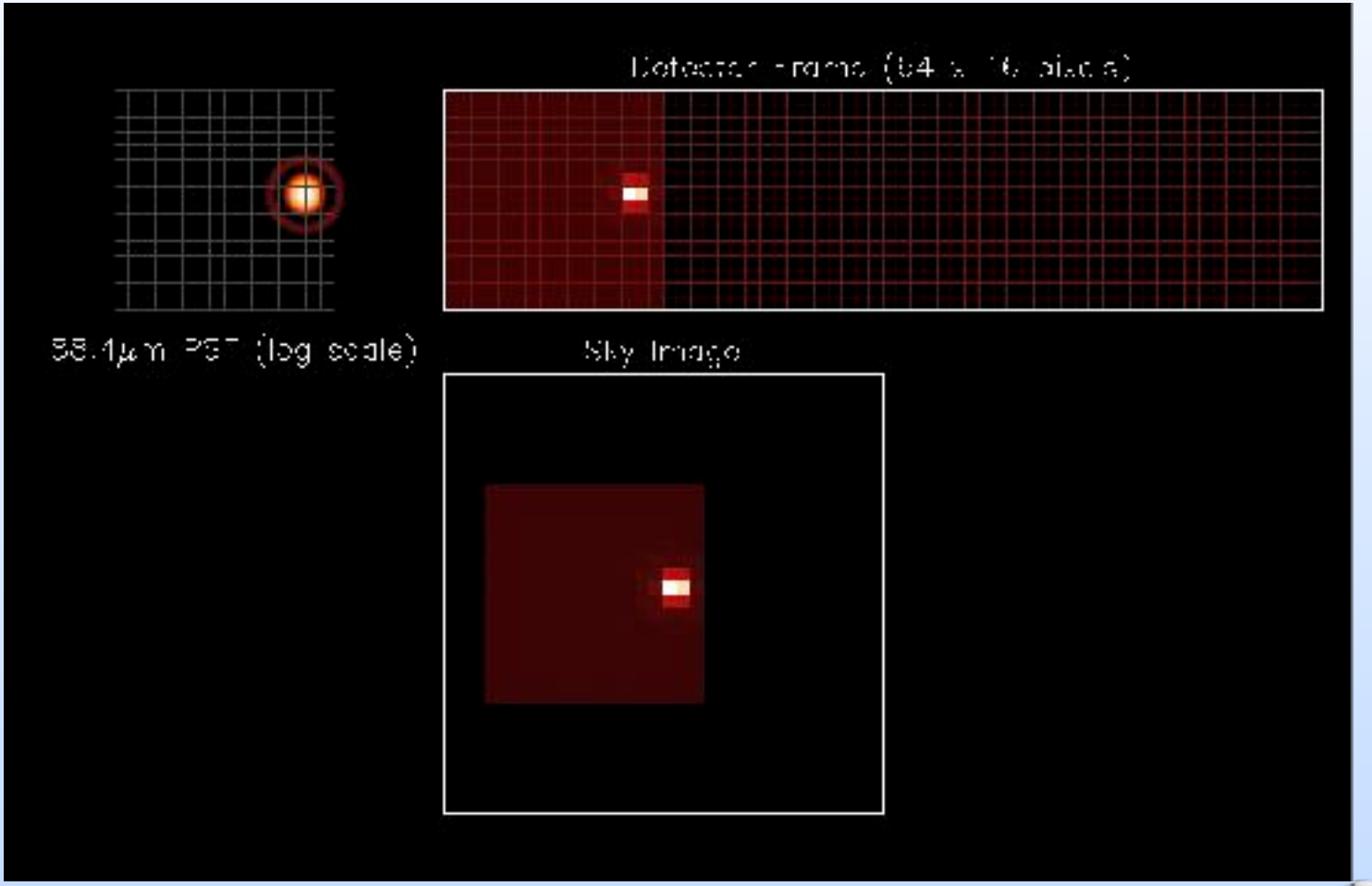
26 μm High-Res



Grating Mode Spectroscopy



Building the Imaging Mode Spectrum

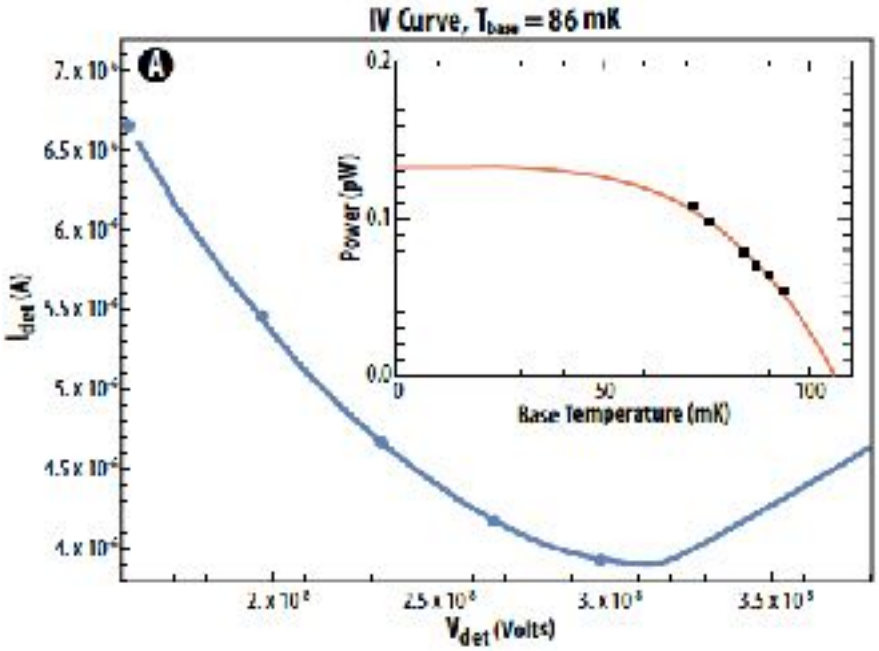


Technical Developments

- Detectors
  - Demonstration of required NEP, plans for flight parts
- Vibrational Heating
  - Approach and design development for a vibration-tolerant system

IV Curve Analysis

- A measured IV curve is shown on the right. The points on the graph indicate bias points where noise measurements were made
- The sweep begins in the linear normal range and proceeds along the hyperbolic path expected in the transition. This is a measured curve, not a fit
- The inset shows the determination of the saturation power, made by taking IV curves at a series of base temperatures.



P_{sat}: 0.13 pW
$G(T) = G_0 T^N$
G_0: 4.3 x 10^{-9} W/K^4
N: 3 (constrained)
T_c: 106 mK
$G(T_c)$: 5x10^{-12} W/K
R_N: 9.0 mΩ
NEP_{phonon}: 1.8-10 ^{18} W/√Hz

- The responsivity of the detector at a given bias point can be accurately derived from the IV curve. This responsivity, combined with the noise spectrum, provides an accurate measure of the detector NEP.

Major Risk in Vibration Immunity

- Based on measured results from the Wisconsin XQC cryostat, we have a design approach and all the tools to design to an operating vibration level
- Our demonstrated dampers provide up to a factor of 100 extra margin
- **Our largest remaining risk is in the definition of the maximum operating vibration level for SOFIA. We must develop this requirement early in the instrument development with the SOFIA program.**

Why Vibrational Heating Now?

- Vibrational heating was not a dominant issue on the Kuiper Airborne Observatory (KAO)
  - Some trouble with microphonic noise pickup
  - No significant effect on cryogenic performance
- The HAWC instrument was designed and built largely by analogy with the KAO instruments, using best practices developed, but not to an operational vibration specification.
  - The user's manual includes a typical vibration spectrum, but there is no "maximum operating environment" and mechanical transfer function for its interpretation.

How is HAWC different?

- HAWC differs from earlier KAO instruments in three ways:
  - It uses an ADR to operate at 200 mK, while the KAO instrument operated at 340 mK using a 3He evaporation refrigerator
  - The suspended mass of the ADR and detector assembly are significantly higher than those of KAO low temperature instruments.
  - HAWC operates on SOFIA, so the vibration environment may be different.

Vibration Control

- HIRMES will be designed to function at full sensitivity at the vibration level measured in flight on the SOFIA telescope
  - The SOFIA operators manual shows a typical spectrum measured on the FORCAST. In the absence of a formal requirement, we will adopt a provisional requirement of 3 dB higher than the FORCAST in flight measurement. We will work with the SOFIA project to acquire sufficient data to generate a formal requirement which we shall meet prior to delivery
  - Final design must be based on a vibration spec representative of the full range of flight conditions, and thus will depend on the cooperation and participation of the SOFIA project in generating such a spec.
    - We requested a maximum operating vibration spec from the project during the study phase, but it was not available

The HIRMES Approach

- The HIRMES team will design the system *ab initio* to have immunity to vibrational input, and will include eddy current dampers to provide significant additional margin against it.
  - Our development program includes FEM analysis and vibrational tests at the instrument level to assure compliance. We will use small inertial drivers for subsystem tests to minimize risk prior to system integration. The drivers and accelerometers will remain on the instrument and their data logged during the full life of the instrument.

Solving the Problem

- Limiting the coupling to environmental vibration is a well understood engineering problem, and there are examples of its solution.
  - I will focus on a closely related system, the XQC (the X-ray Quantum Calorimeter), a cryogenic rocket instrument operating at 0.050K. It has flown 7 times, and has routinely achieved precision control at 0.05 K within 30 s of launch.
  - The HIRMES PI is a coauthor on the paper describing the vibration mitigation

The Mechanical System

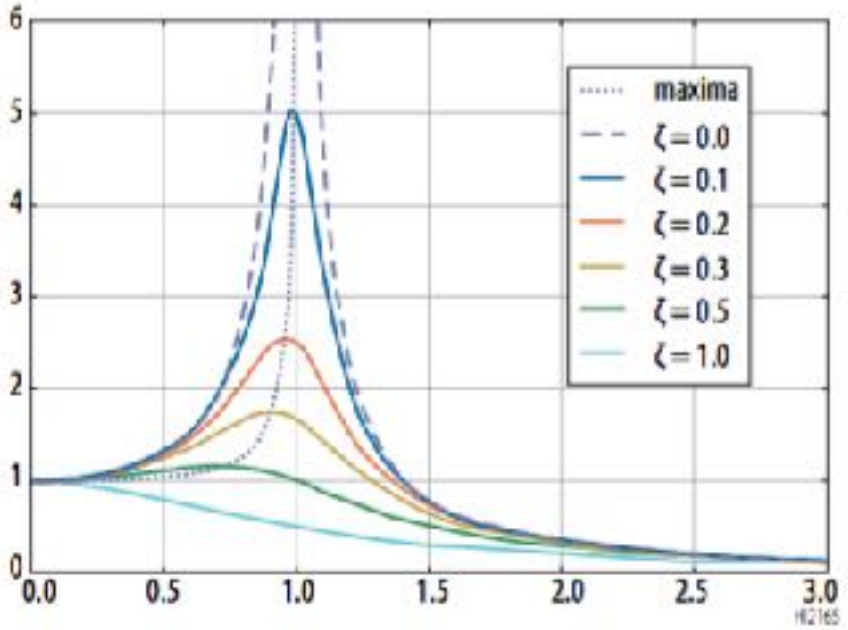
- The detector system is modeled as a harmonic oscillator with damping in its support structure.
- When its base is vibrated, the system oscillates. It reaches equilibrium when the input power to the system is balanced by the dissipation in the structure. The amplitude of oscillation will generally increase until this condition obtains.

Energy Transferred to a Resonator

- When the base of a damped harmonic oscillator is excited by a white noise spectrum, its ultimate dissipation is independent of the Q of the oscillator, and depends only on mass.
- One cannot reduce the coupled power by increasing damping of the support structure, but only by filtering the input spectrum to limit the signal amplitude at the resonant frequency.

Damped Oscillator

- One cannot reduce the coupled power by increasing damping of the resonator, but only by filtering the input spectrum to limit the signal amplitude at the resonant frequency.
- The coupled power is proportional to the suspended mass
  - The HIRMES ADR salt pill is 300g compared to 1.7 kg for HAWC



Design Concept

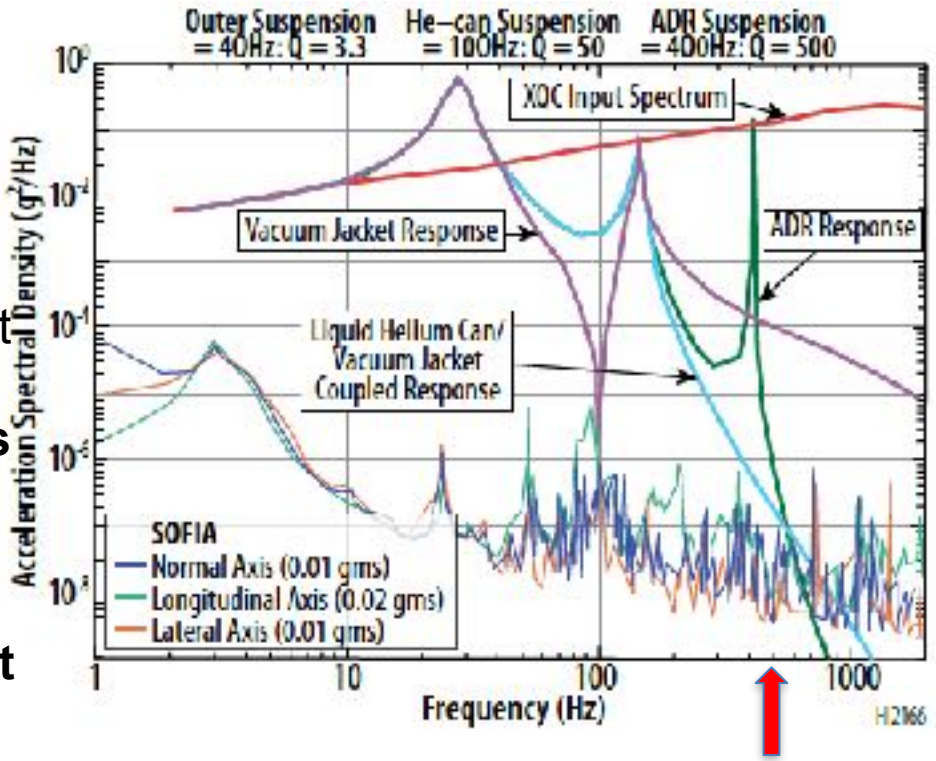
- To reduce the amplitude of vibrational input power at the input to ADR and detector assembly, one must:
  - Place fundamental resonances of cryostat structure at low frequencies (~30 Hz)
  - Put the ADR/detector frequency at the highest practical frequency (~400 Hz)
  - Put intermediate stages at optimized intermediate frequencies.

Detailed Design Process

- One must carry out a coupled modes analysis to measure the transmission of input vibrational power from the instrument mounting ring to the ADR/Detector mounts
- The parameters that are free for optimization are the frequencies of the optical bench, the 1 K isolation stage, and the 0.05 K detector system

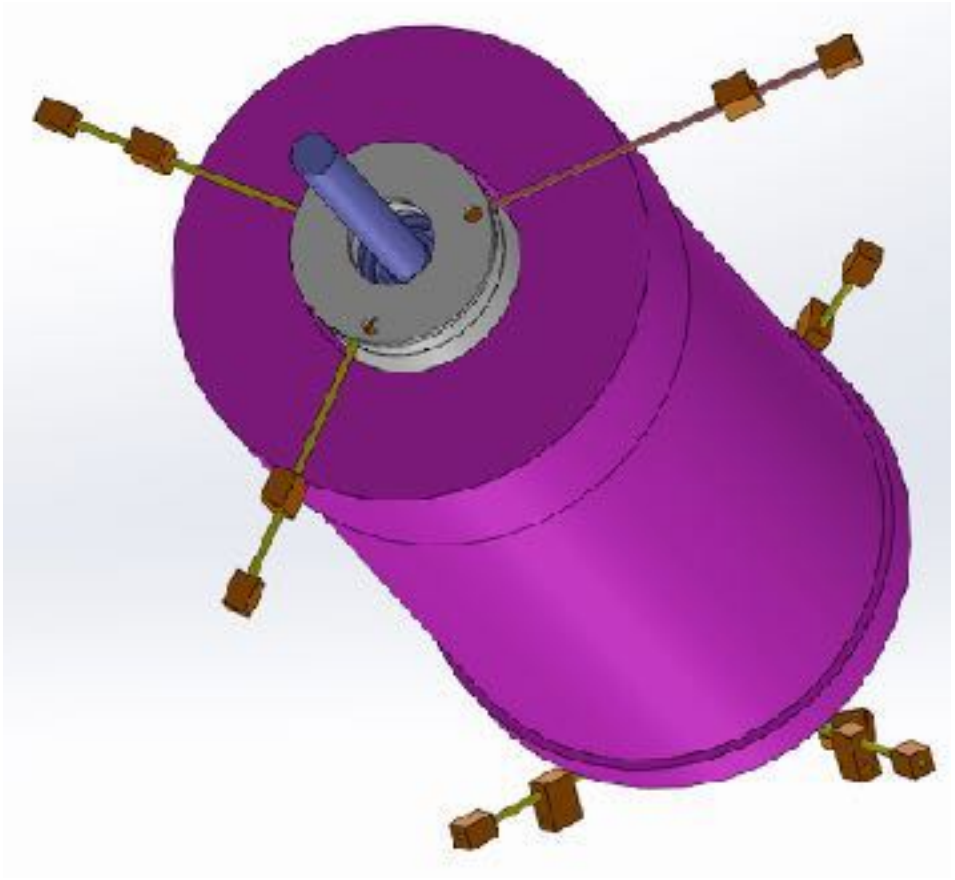
ADR Vibrational Heating

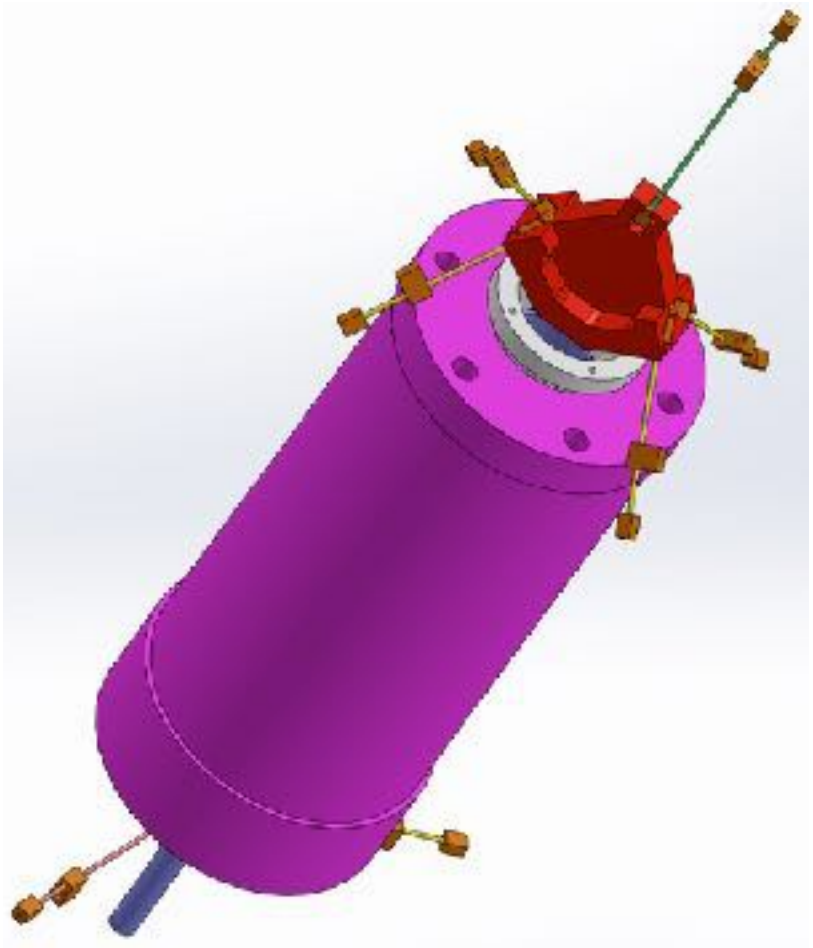
- The cryostat and its support structure can act as a mechanical filter to limit coupling to the low temperature stage
- Vibrational amplitude of ADR was within a factor of two of the model prediction
- Several additional orders of magnitude reduction can be achieved with eddy current damping, described below
- **Based on instrument level vibration tests at Wallops, the Wisconsin ADR would have a factor of ~10^3 less heating than HAWC+ (scaled to the HAWC+ low temperature mass) given the SOFIA input spectrum (240 μW for HAWC+, 26 nW predicted for scaled XQC)**
- **Damping will provide at least a factor of 10 extra margin, probably more with design work**



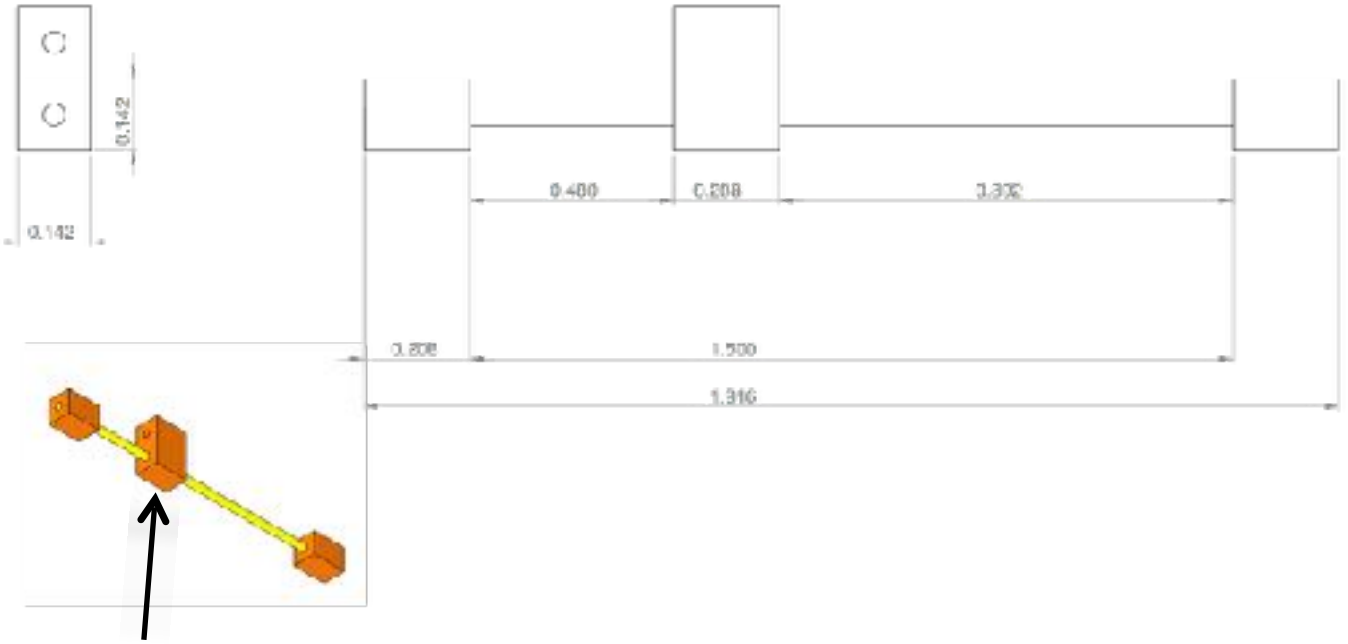
Cui, W., Almy, R., Deiker, S., McCammon, D., Morgenthaler, J., Sanders, W. T., Kelley, R. K., Marshall, F. J., Moseley, S. H., Stahle, C. K., and Szymkowiak, A. E., 1994, SPIE, 2280/363, doi: 10.1117/12.186824.

ADR Magnet, Salt Pill, Inconel Tube, and Inner Kevlar Attachment



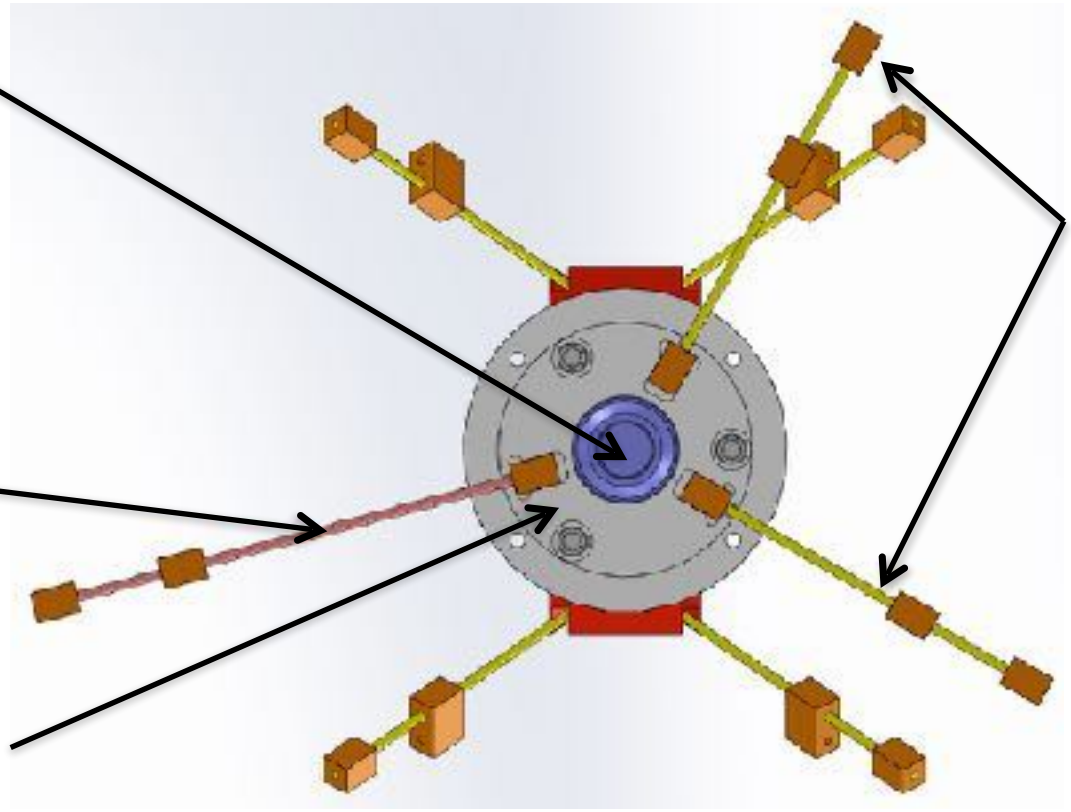


Rigid Kevlar Element



Intermediate Heat Sink. Copper heat strap wire will be inserted into extra hole and crimped at assembly.

2 Degree Of Constraint (DOC) End Detail

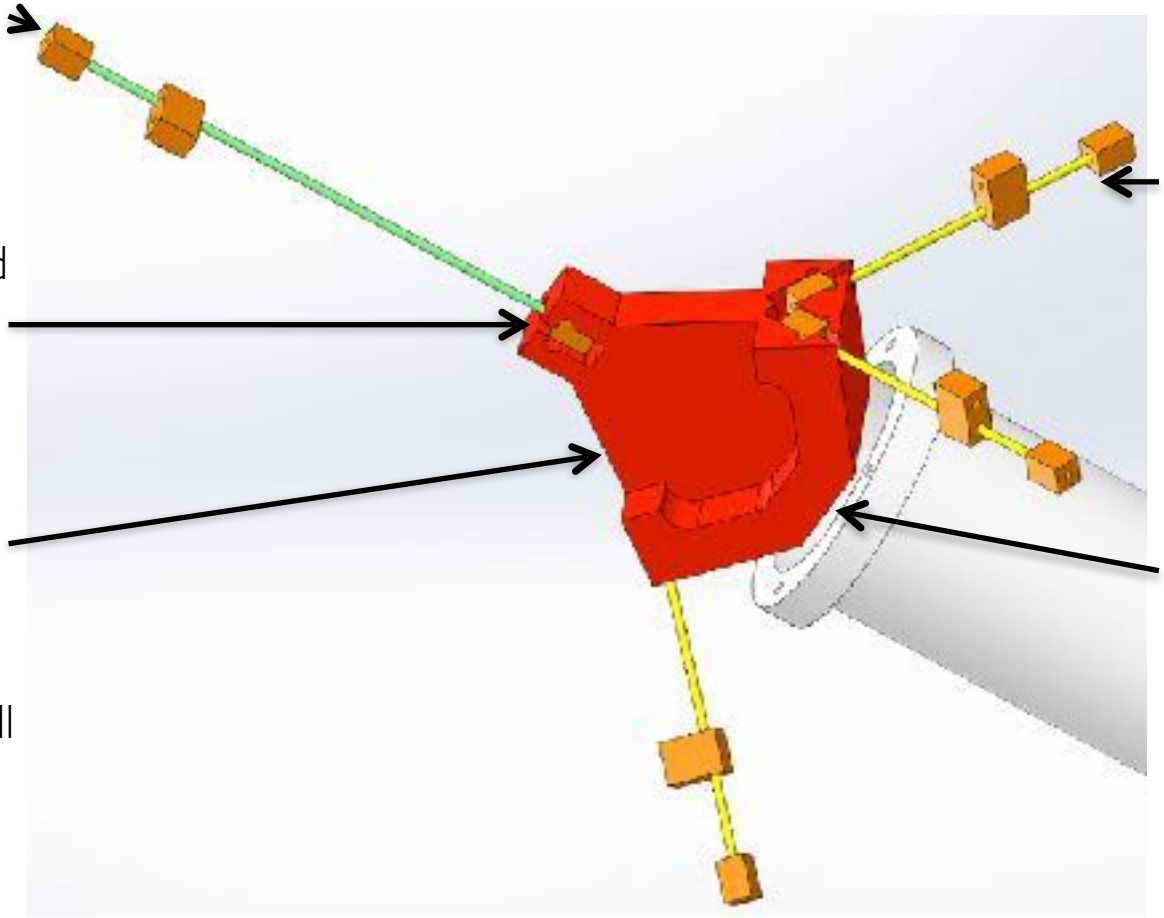


4 DOC End

Axial preload Kevlar is "longer"

Kevlar swages will be retained by caps screwed in place.

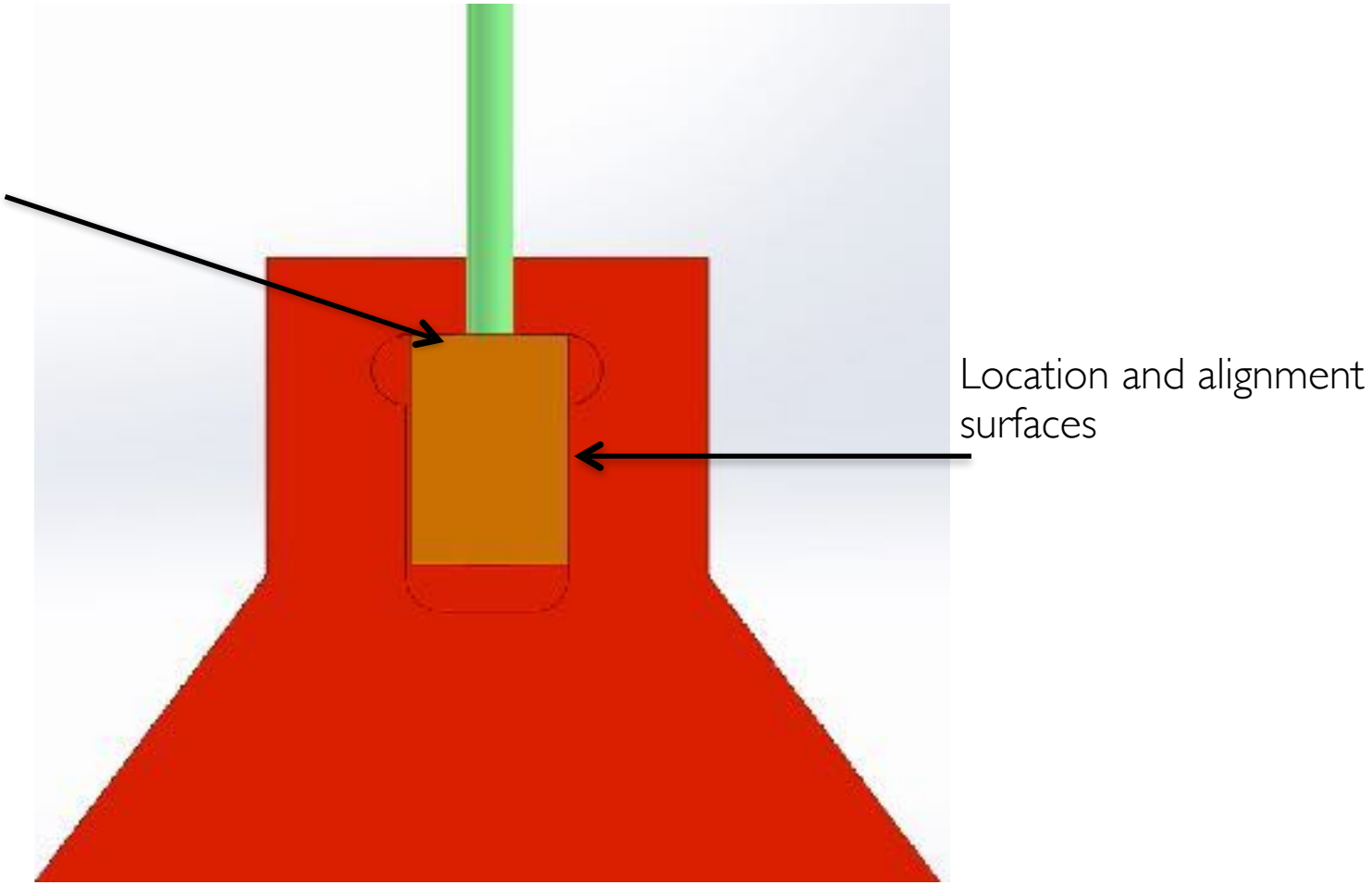
4 DOC fitting is "relatively" easy to machine, compound Kevlar angles will be straightforward to measure.



Kevlar element length (and thus salt pill position) adjustment will be by means of shims at the outboard ends.

Not attached to Inconel tube yet, awaiting feedback on concept.

Detail of Kevlar Swage Fitting



XQC Thermal Performance

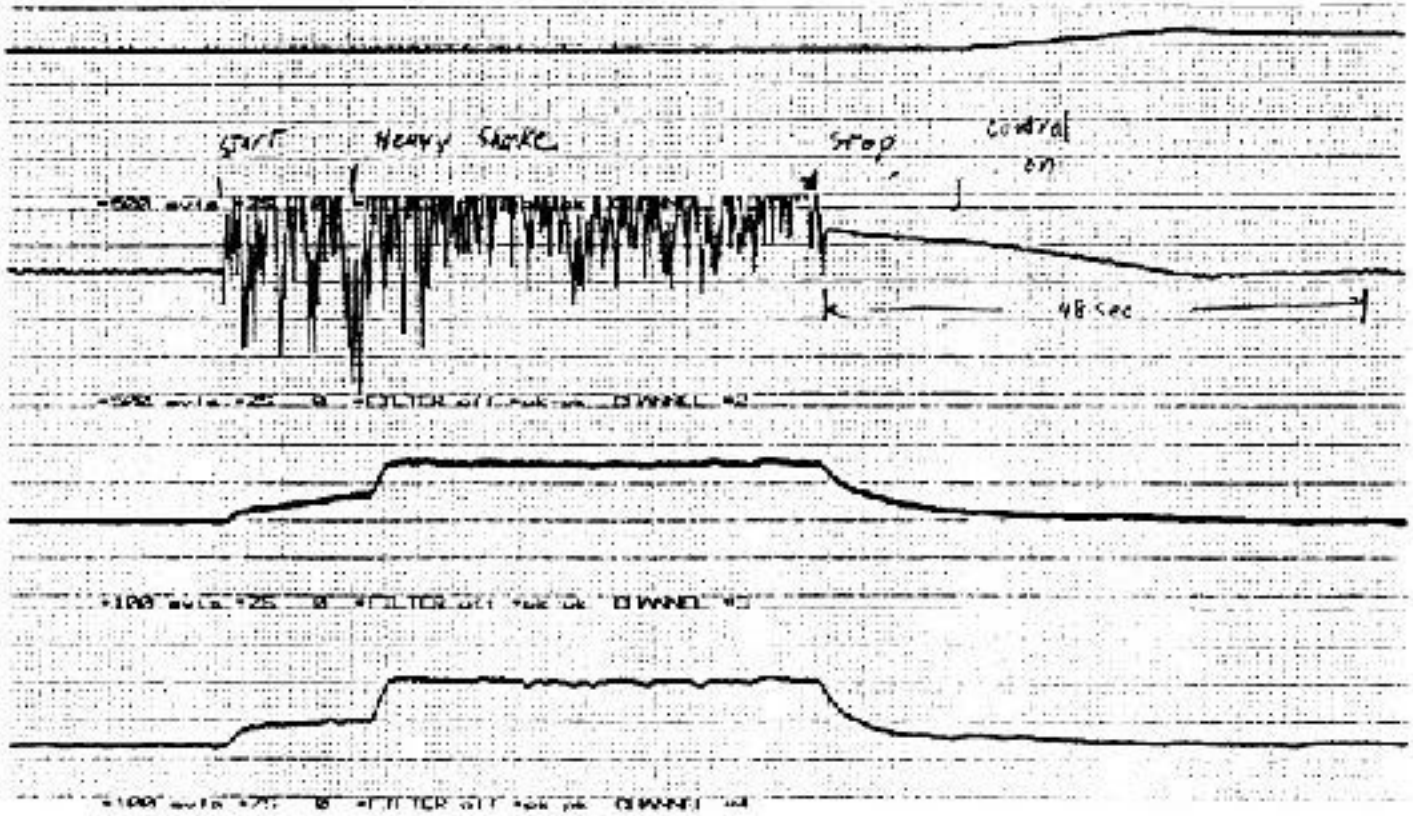


Figure 5: Chart record of coldplate temperature during "simulated flight" vibration test at Wallops Flight Facility. Temperature returns to within 5 μK of the 65 mK setpoint about 48 seconds after end of powered flight.

Vibrational Heating Mitigation on Astro-H

- The Astro-H detectors had significant additional noise due to heating from the cryocooler compressor vibration
  - They were bolted to the dewar shell
- This was mitigated by designing external damping systems for the compressors. The mitigation completely eliminated the problem
- The HIRMES PI was involved in the analysis of the heating problem and in developing mitigation approaches
- **Vibration isolation is a solvable engineering problem given the input spectrum and the allowable response.**

Damping

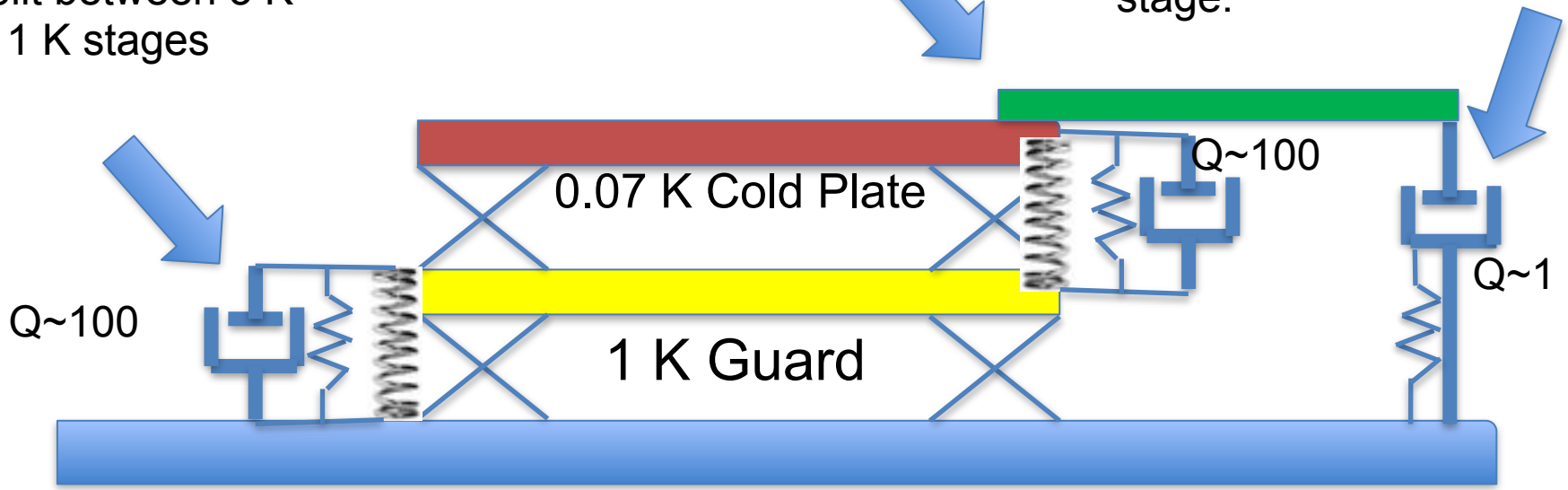
- The mechanical loss (damping) of typical cryogenic structures is small, with tensile Kevlar cryogenic suspensions providing quality factors (Q) ranging from 50 – 400.
- Application of damping can greatly reduce the amplitude of the vibrations
  - If the damped power is dissipated on the ADR/ Detector stage, there is no reduction in heating
  - If the power can be dissipated on another stage with more cooling power, this eliminates much of the heating on the low temperature stage.

Damping in Cryogenic Systems

Support dissipation is split between 3 K and 1 K stages

Support Dissipation is split between 1 K and 0.07 K stages

Power dissipated in eddy current damper is all deposited on the 1 K stage.

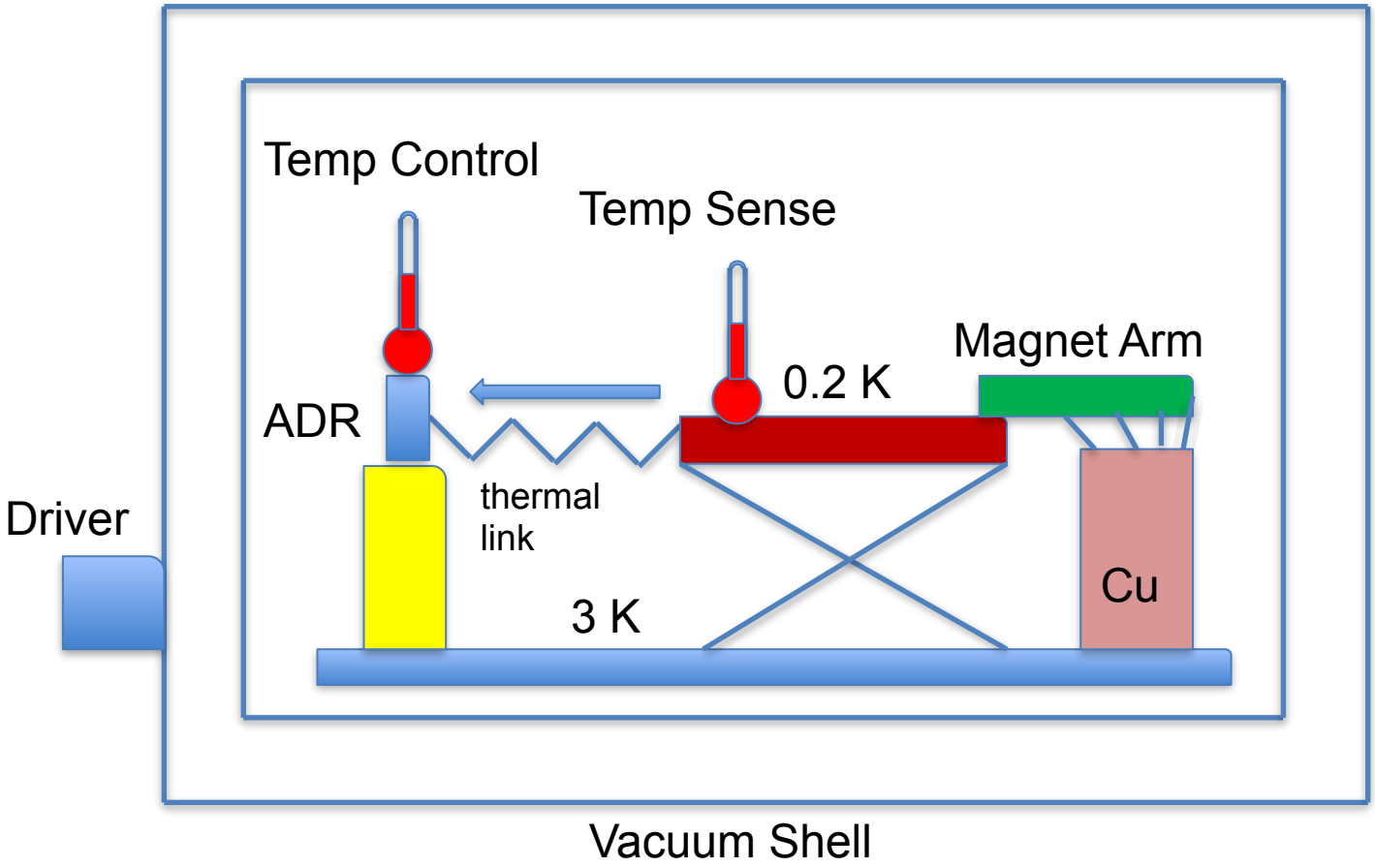


The eddy current damping constant dominates that of the support structure, so most (>99%) of the dissipated power can be directed to the 3 K plate.

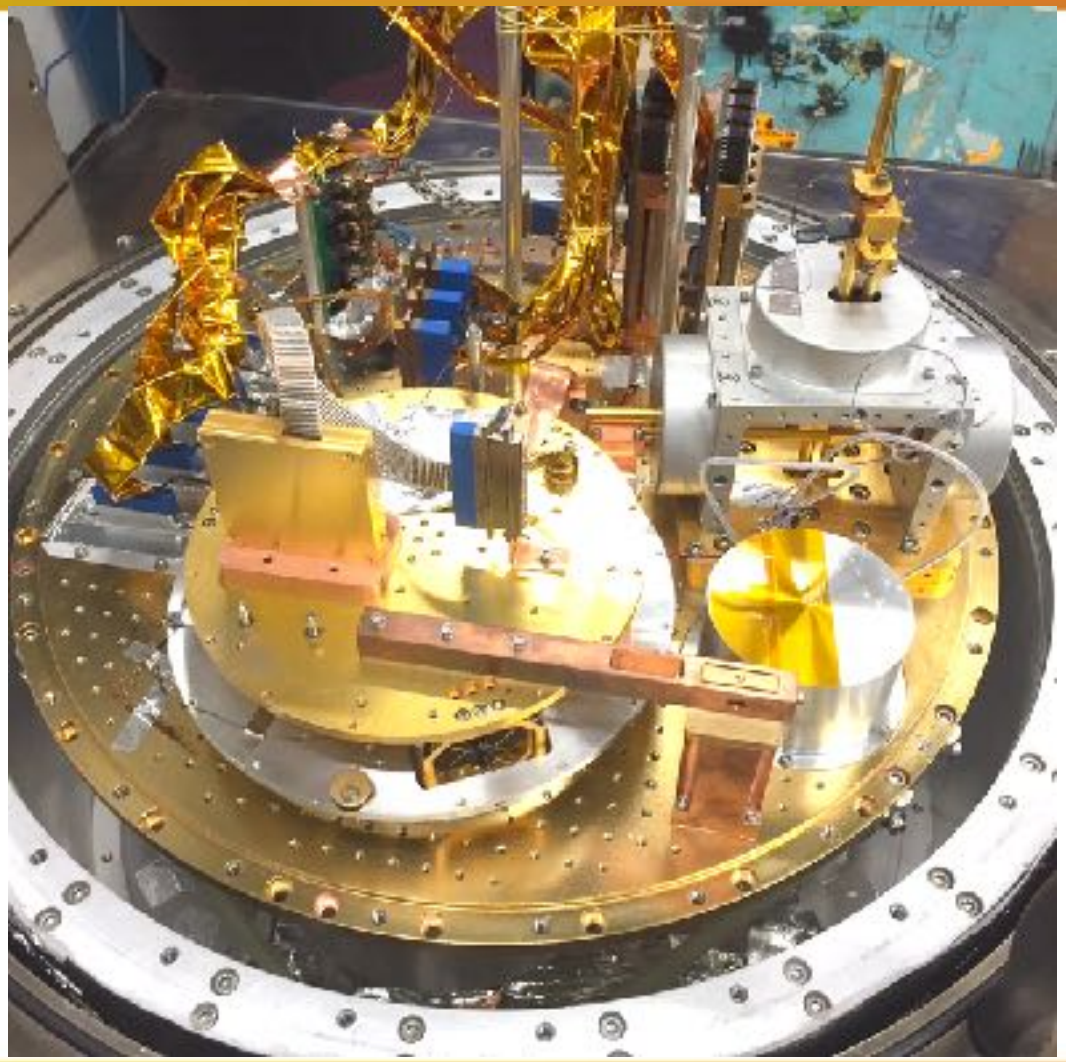
Magnetic Damping

- Eddy current damping is an excellent mechanism for low temperature damping.
  - Passive
  - Improves linearly with metallic conductivity
- We have developed a design using multipole magnets that provide excellent damping.
  - The high order multipole field decays rapidly
  - Residual field can be eliminated using Cryoperm or other low temperature permeable shield materials

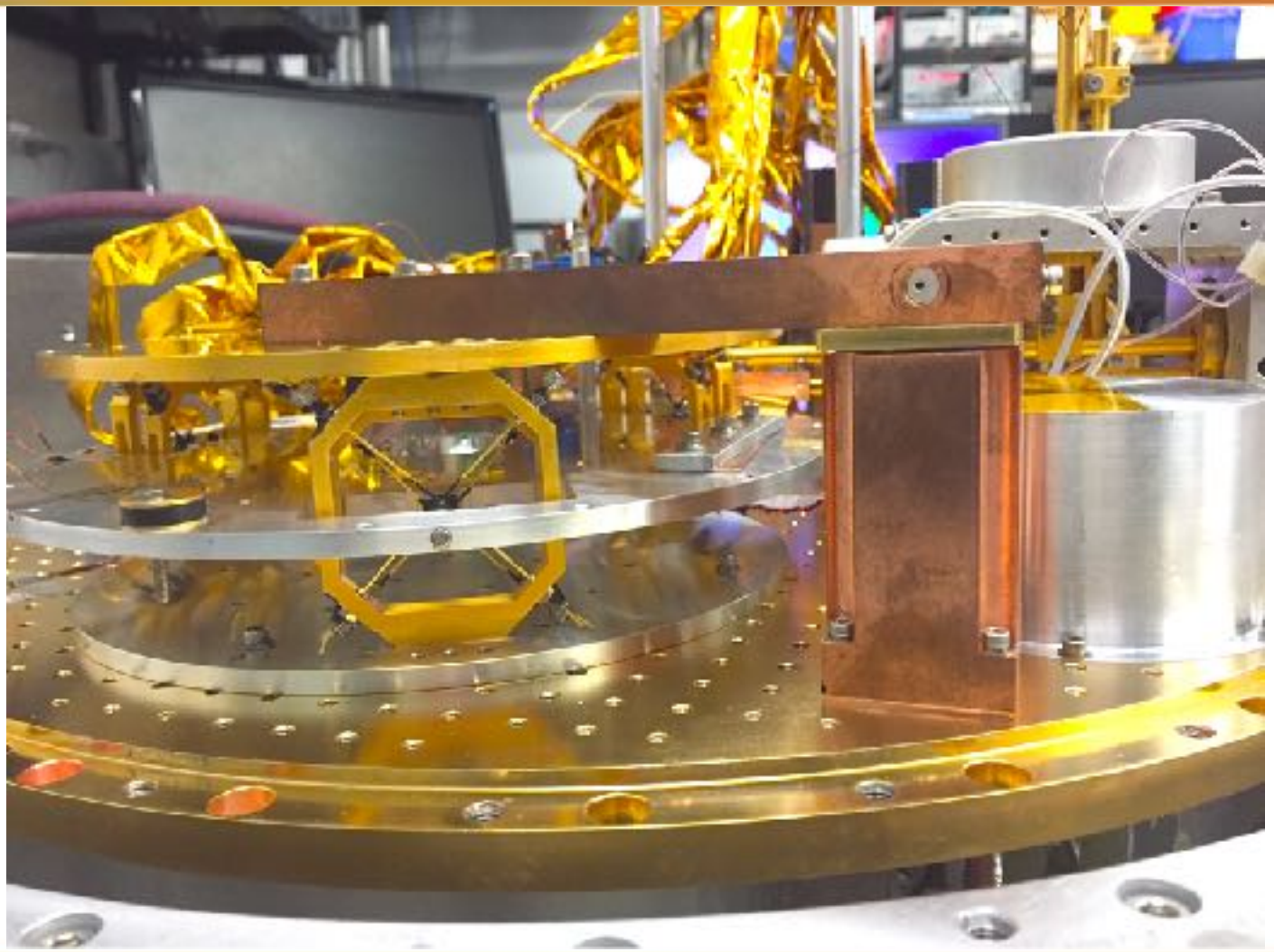
Experimental Setup



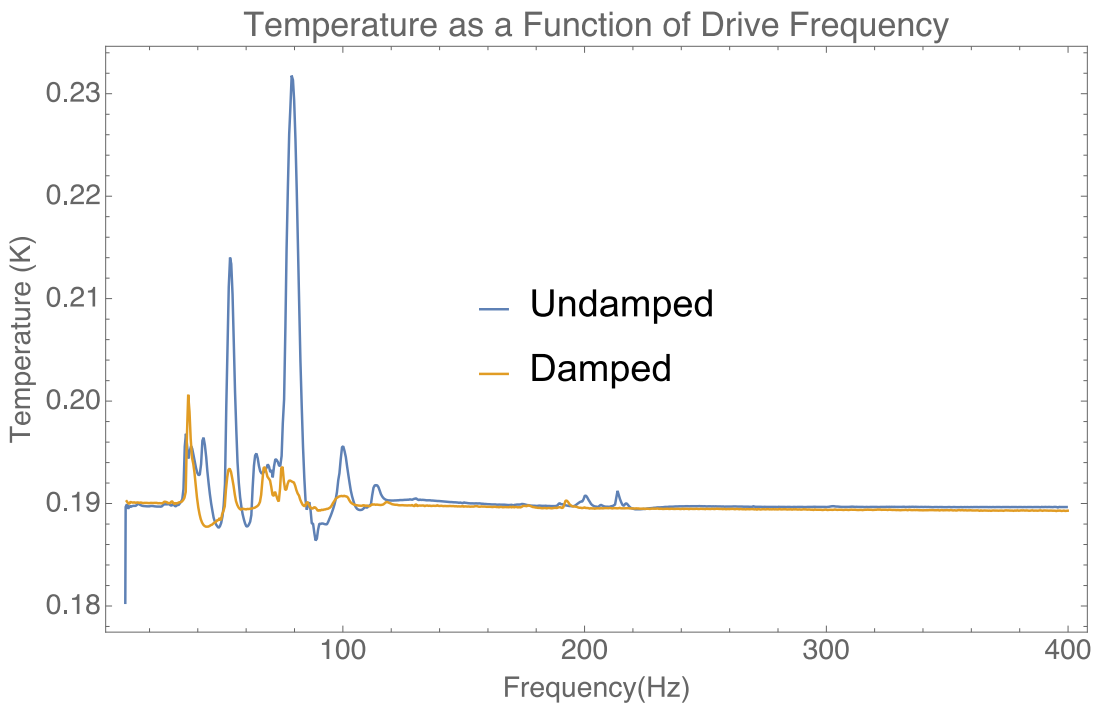
Heating Test Configuration



Heating Test Configuration



Magnetic Damping Greatly Reduces Vibrational Heating



- Initial test of partially damped system
- No damper on 1 K stage

ADR Vibration Summary

- We are including vibration control in the design from the beginning. Proper design, demonstrated on XQC, will provide a robust design for SOFIA operation.
- GSFC has the experience and expertise from XQC and Astro-H to address this problem.
- Given the SOFIA vibration level in the Vibration and Dynamic Environment section in the SI Developers Handbook (measured with FORCAST mounted), our design will provide significant margin.

Schedule

- PDR: Documents — November 2016
  - Technical — Jan 2017
- CDR: — May 2017
- I&T at GSFC: — November 2017
- Delivery to Armstrong: — December 2018
- First Flights: — Spring 2019
- Re-introduce selves to families: — Summer 2019

Thanks!

GTO Observing Program

Table D-1: GTO Observing Program Targets (observing times are calculated based on 1×10^{-17} W m^{-2} 5σ in 1 hour)*.

Program	Intensity (W/m²)	SNR	Total time with overhead (hours)
Optimal $H_2{}^{16}O$ water lines for Protoplanetary disks with HIRMES (transition/wavelength μm)			
4 4 0 -> 3 1 3 (28.914)	3.10E-17	27.00	4.5
6 4 3 -> 6 1 6 (32.313)	3.30E-17	29.00	4.5
6 5 1 -> 6 2 4 (34.987)	2.20E-17	19.00	4.5
Subtotal			**13.5**
H_2O vapor targets			
RNO 90	3.10E-17	26.85	4.5
AS 205	4.96E-17	35.07	3
HD 163296	3.10E-17	31.00	6
Subtotal			13.5
Targets (HD (1-0) transition)			
HD 163296	1.00E-17	21.7	5
TW Hya	5.00E-18	17.5	10
Subtotal			**15**
[OI] 63 μm targets			
RNO 90	1.29E-16	45.61	0.75
AS 205	2.15E-16	76.01	0.75
HD 163296	2.08E-16	73.68	0.75
TW Hya	3.65E-17	12.90	1.5
Subtotal			**3.75**
H_2O ice targets **	**Flux density (Jy)**		
RNO 90	3.2	64.0	0.75
AS 205	15.5	310.0	0.75
HD 163296	17	340.0	0.75
TW Hya	2.5	50.0	0.75
Subtotal			3
Total Time			**48.75**

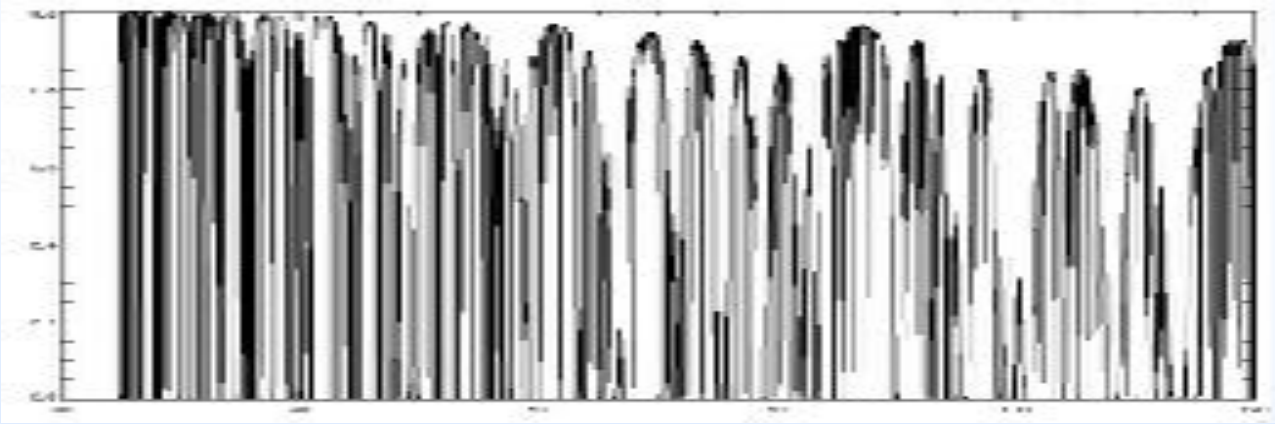
*The expected performance is significantly better (depending on the line), e.g., the observing time gain margin for HD, H_2O and [OI] lines are 7.3, 16.0 and 2.5, respectively.

** Smoothed down to 1 μm resolution.

HIRMES Instrument Specification

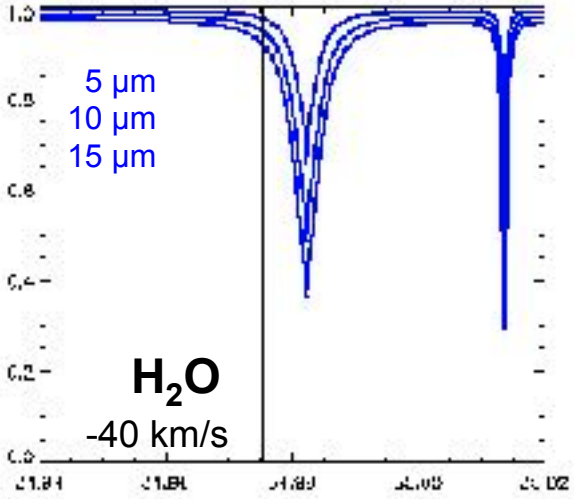
Parameters	Note
Sensitivity (5σ, 1 hour)	3 x 10^{-18} W/m^2
Resolving power	λ/Δλ ~ 100,000(high) ; 19,000 (mid); 600(low)
Angular resolution	Diffraction limited @ λ=45 μm
Spectral range	25-122 μm
Number of det. modules	2
Detector format	16 x 64 mid/low-res, 8x16 high-res
Detector technology & operating temperature	TES bolometers @ 0.1 K
Detector sensitivity	NEP ~ 1 x 10^{-18} W/√Hz including photon noise
Detector cold readout	SQUID
Detector warm readout	UBC Multichannel Electronics (MCE)
Cooler	Pulse tube cooler and adiabatic demagnetization refrigerator (ADR)

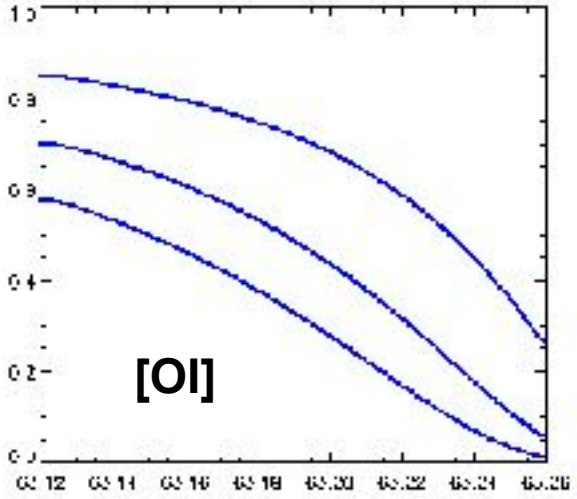
Atmospheric transmission

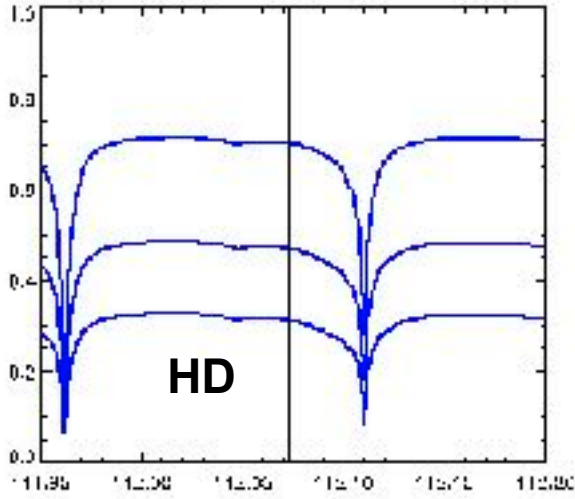


ATRAN Model Input Parameters

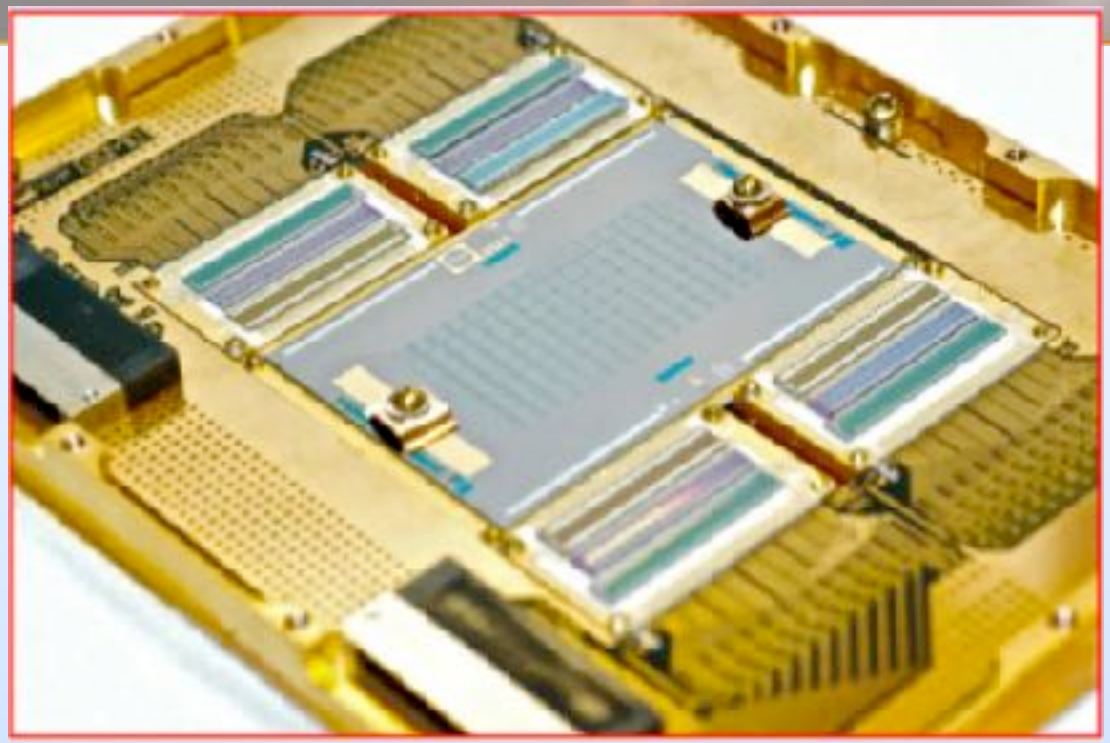
Observatory Altitude:	41000 feet
Observatory Latitude:	30 degrees
Water Vapor Overburden:	10 microns
Std Atmosphere with :	2 Layers
Zenith Angle:	45 degrees







HIRMES detector assembly



Shown is an 8x16 array of 2-mm pixels. HIRMES will have 8x16 and 16x64 arrays of 1-mm pixels in a similar design modular package.