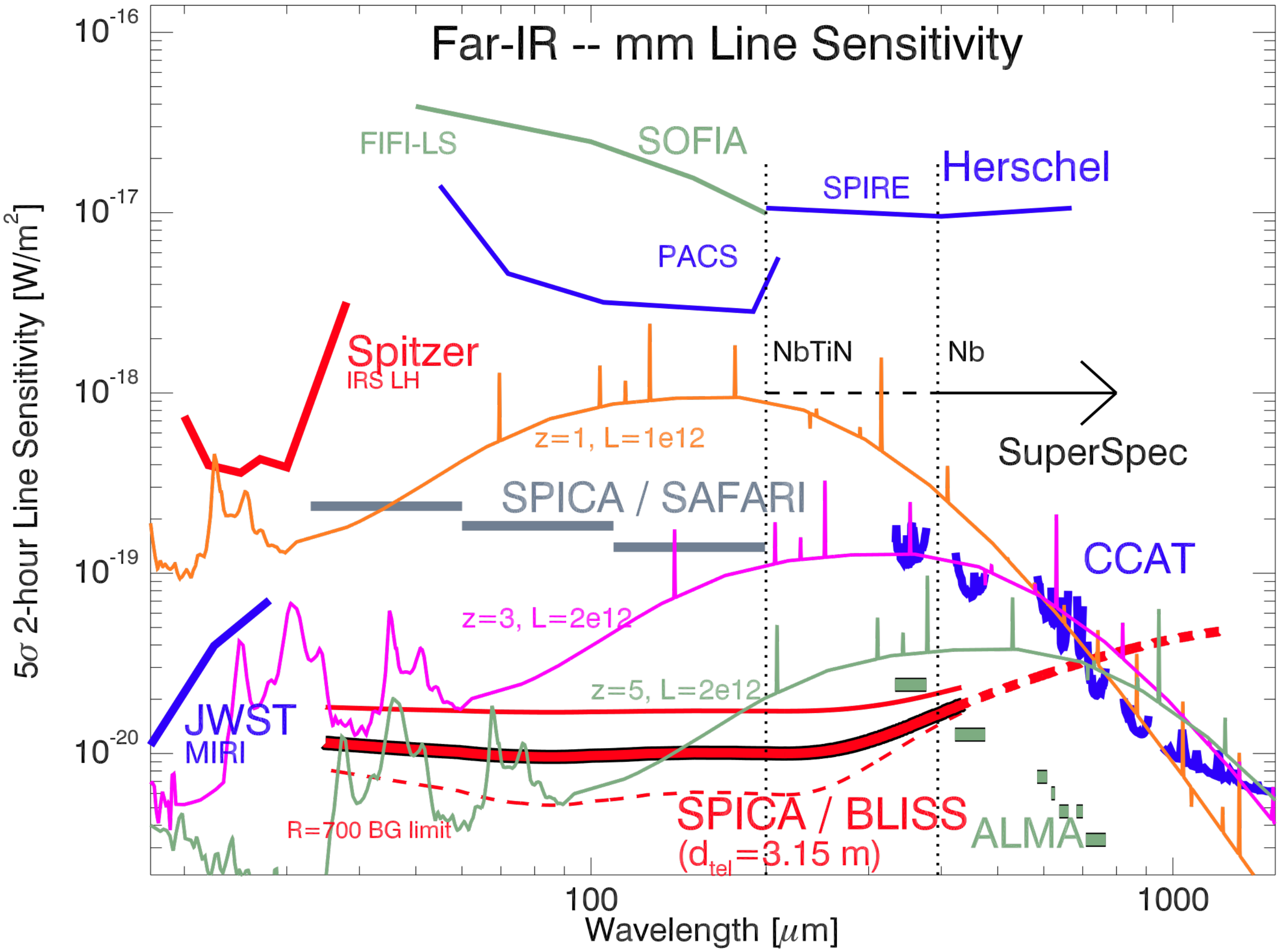
System-level Approaches and Technologies for Far-Infrared Astrophysics

Matt Bradford (JPL / Caltech)

May 12, 2014

Far-IR Community Workshop

Cold Telescope Offers Ultimate Capabilities



SPICA: 3.15 m, 5.5 K with 4% emissivity and 75% aperture efficiency

- BLISS-SPICA can obtain spectra of galaxies in the Universe's first billion years as they are borne, comparable to JWST and ALMA in sensitivity.
- Observing speed scales as the inverse square of the sensitivity, factor of 1e6 beyond existing facilities (for point sources).
- Source confusion is not a problem for R~700 spectroscopy.

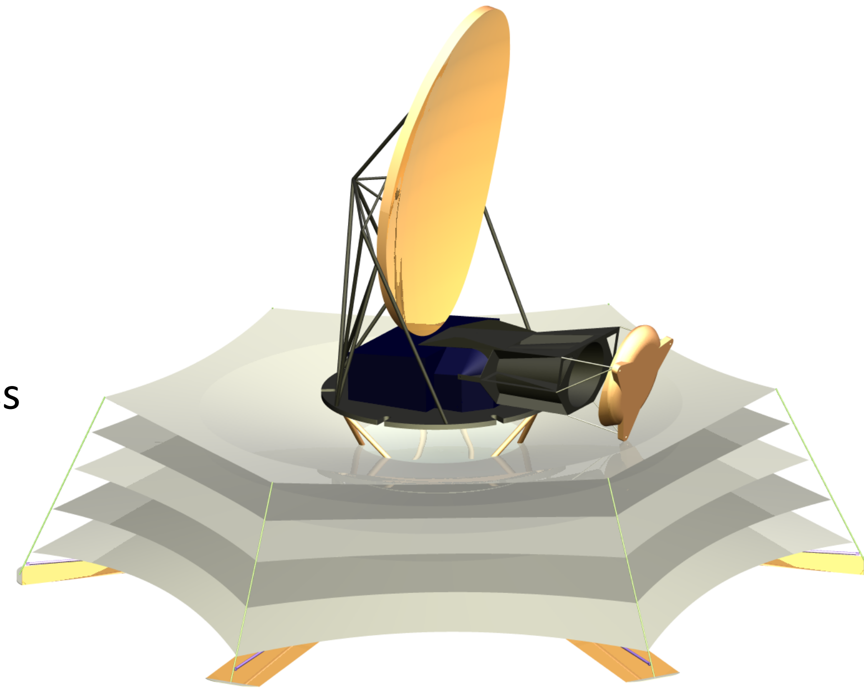
Cryogenic Far-IR Space Telescope

Field of View:

- Not a strong driver since spectroscopy will be the emphasis.
- 10,000 spatial modes is 0.75 square degrees (400 µm, D= 3m)
- -> 2500 spectrometer pixels at the longest wavelength.
- => 1 square degree a good goal, somewhat less is acceptable.

On-axis vs off-axis for cold telescope:

- Off-axis system preferred.
- CALISTO study indicates cold stop can eliminate most of the ~6% which could be scattered to large angles in an on-axis system, but this may be able to be de-convolved, or blocked with absorbing coatings on struts
- For point sources, on-axis may be OK.
- Requires further study for deep intensity mapping experiments aiming to faint recover large-scale structure.
  - Herschel SPIRE worked OK, but at the peak of the CFIRB, not probing into lines.



CALISTO 4x6 meter off-axis

- RMS ~ 1 micron goal.
- Efficient use of 5-meter fairing without deployment
- Deployed secondary on hinge
- Deployed v-groove thermal system.

Cryogenic Far-IR Space Interferometer

SPIRIT concept: a double-Fourier Interferometer.

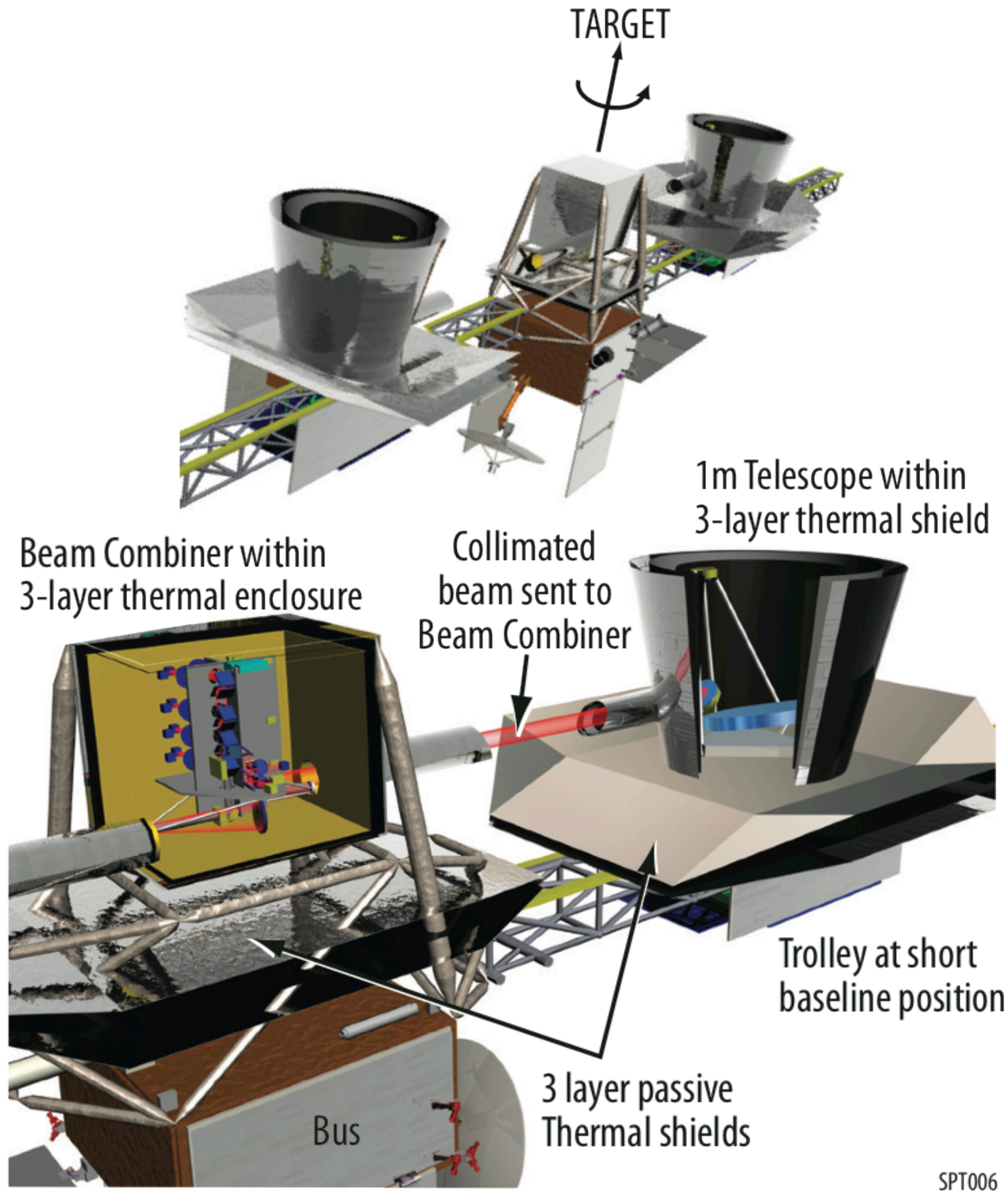
Shares basic cooling requirement with telescope, but multiplied 3x

Backend instrument TBD, similar to that single-dish telescope.

Moving delay lines consist of cryogenic mechanisms, extensions of e.g. Herschel SPIRE FTS mechanism.

Boom extensions similar

Engineering problems (=cost) not fundamental technology concerns.

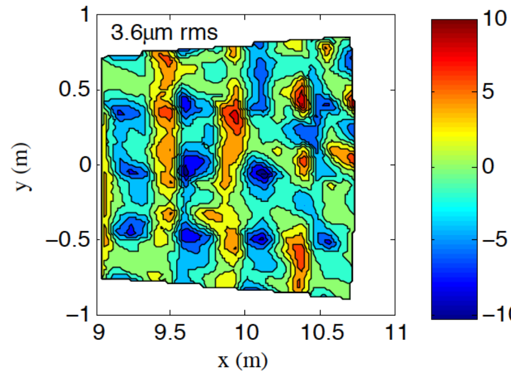


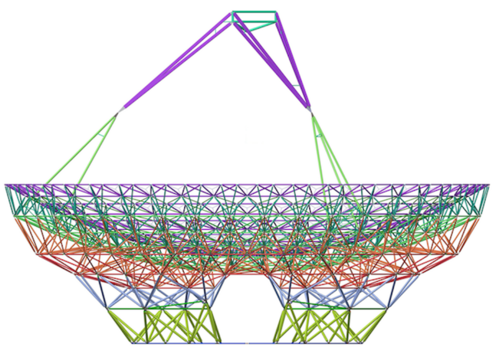
Mirror will be blanked in pieces

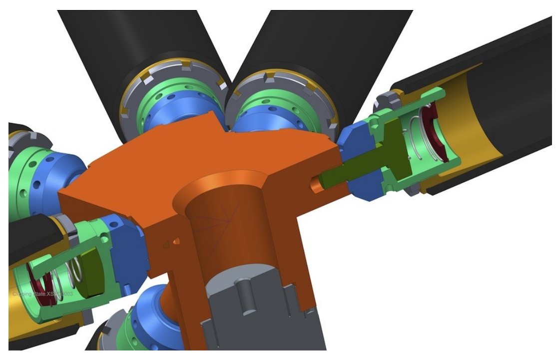
Herschel sintered silicon carbide.
-> 12 'petals' braised into full 3.5 meter monolithic mirror.

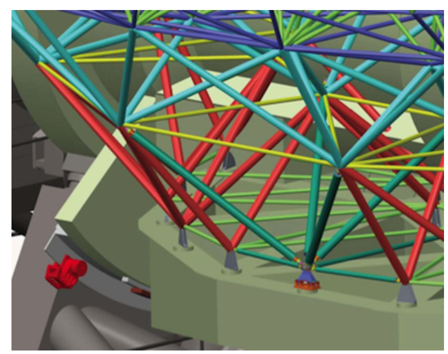
CCAT segmented telescope approach:

- Carbon-fiber spaceframe truss with tuned CTE.
- 2-meter compound panels, Al on CFRP.





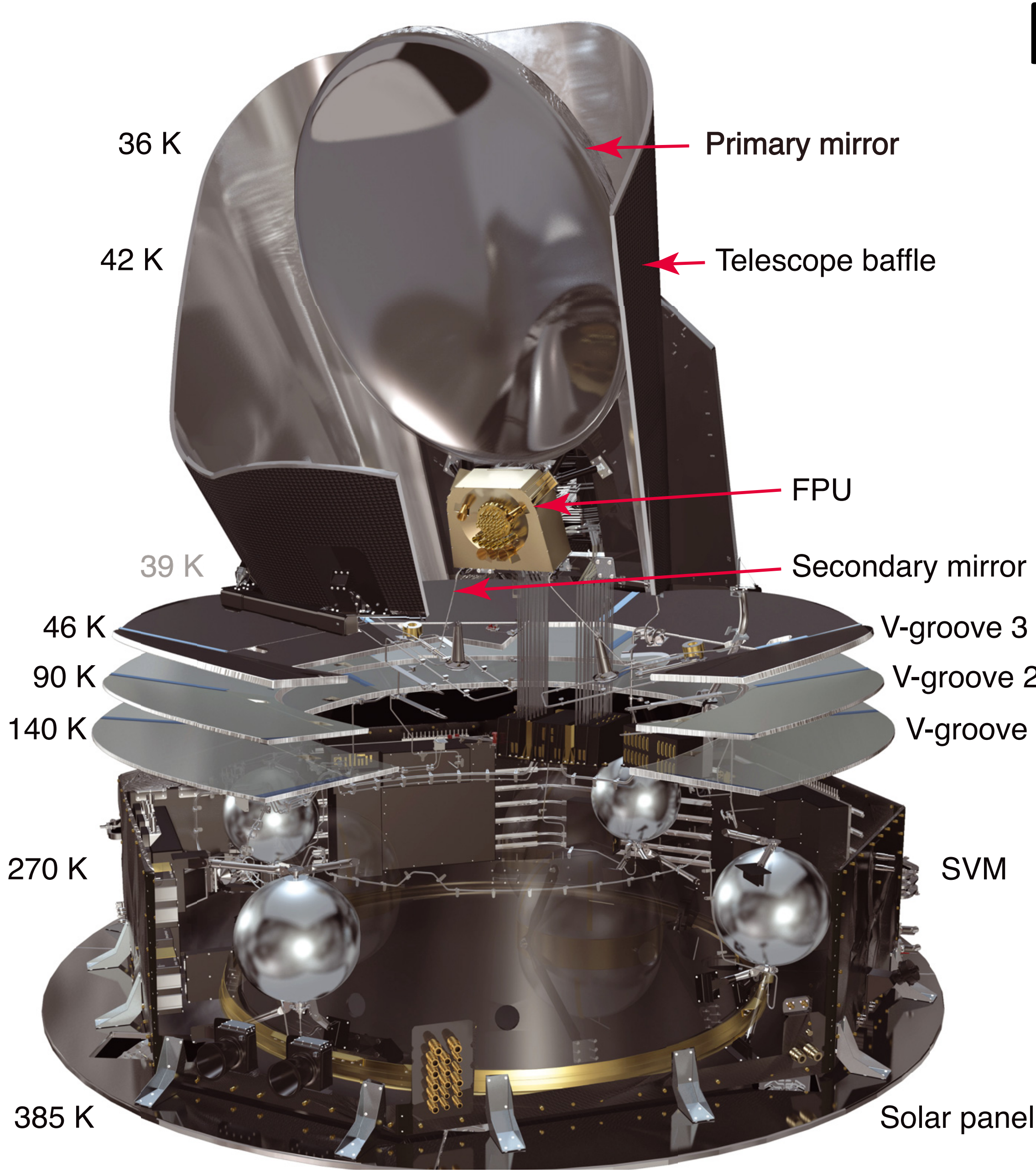




How to cool observatory

- Temperature ~ few Kelvin is required for both minimizing loading from the telescope / optics and for backing sub-K coolers.
  - Passive cooling can reach ~30-40 K, so active cooling is required.
  - 6 K acceptable for optics, but need 4 K or below to back coolers.
- Liquid helium bath presents challenges for both lifetime and agility (e.g. spinning or fast slewing).
- State of the art is warm launch with active closed-cycle coolers.
- Coolers must be integrated with a careful system-level design
  - Staged passive cooling is critical
- L2 much better than earth orbit or even earth-trailing orbit.
  - Earthshine in LEO is ~1/3 of the solar flux, and distributed over 2π steradians, orthogonal to sun direction.
  - L2 point has common earth-sun line and is 235 earth radii away.

Planck Thermal Architecture



Planck: 3 independent coolers + careful system design.

- Hydrogen sorption cooler:
  1 W at 20 K for 400 W in (JPL).
  (unusually high 2.5% Carnot efficiency)
- Helium mechanical cryocooler: 15 mW at 4.5 K for 120 W in (RAL / EADs Astrium).
- Dilution system with expendable 3He: 0.6 uW at 0.1 K + lift at 1.4 K (Benoit et al.)

Below V-grooves, loads are conductive. Should scale with mass.

e.g. at 4.5 K. 10 mW, including some dilution precooling. 4 K mass < 10 kg

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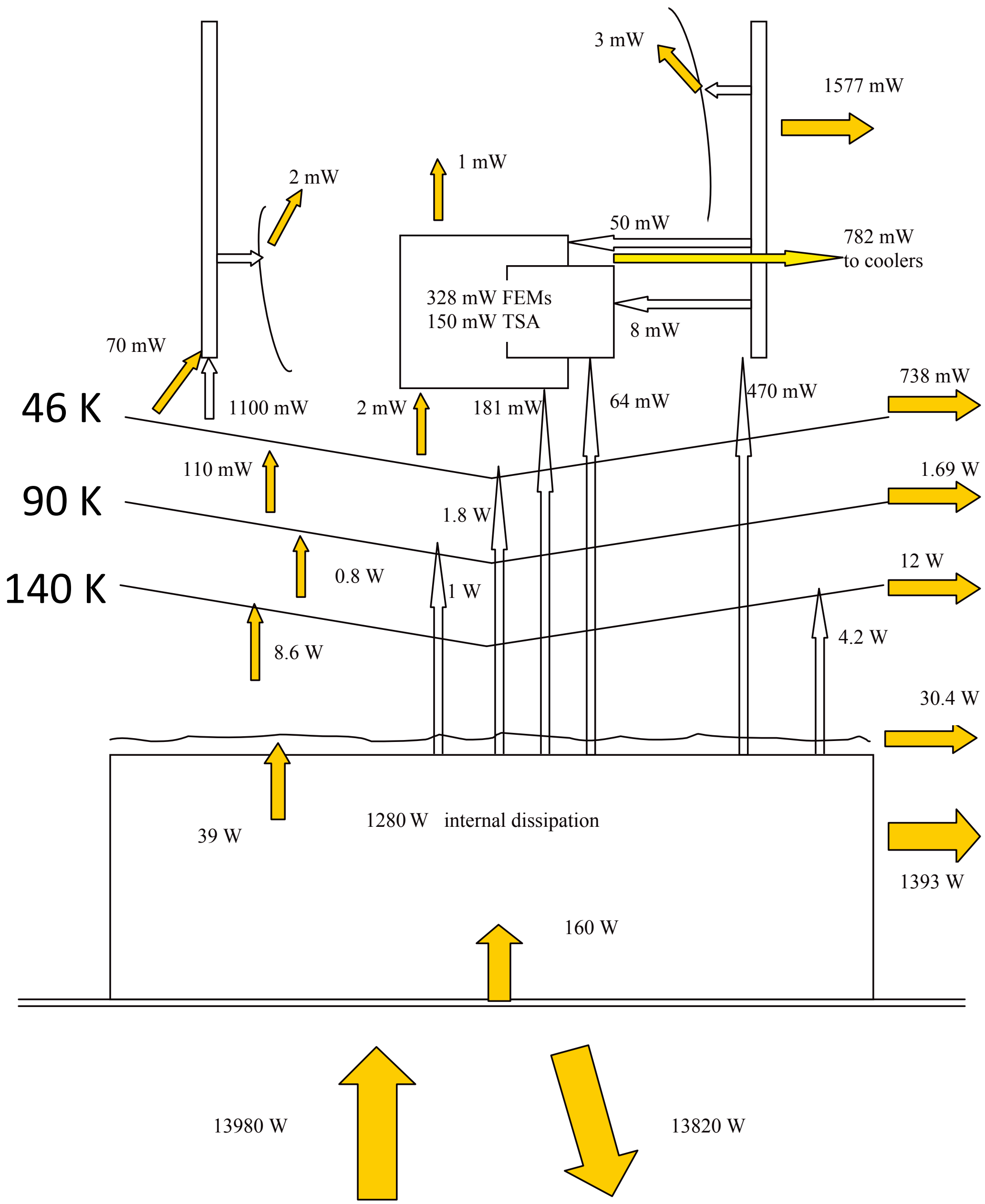

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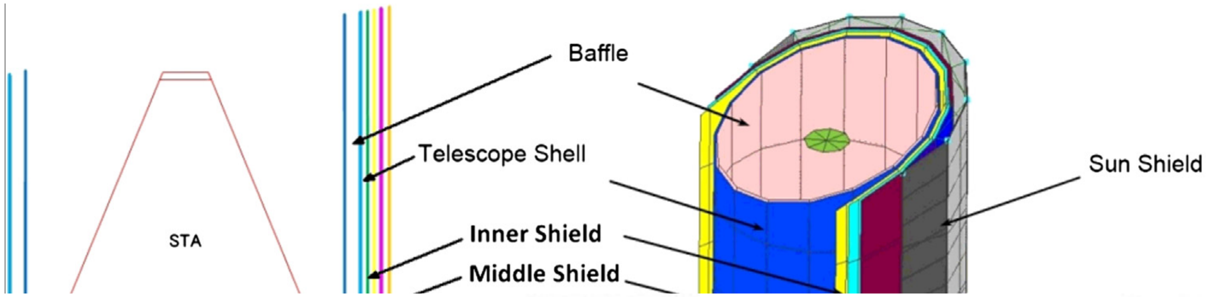
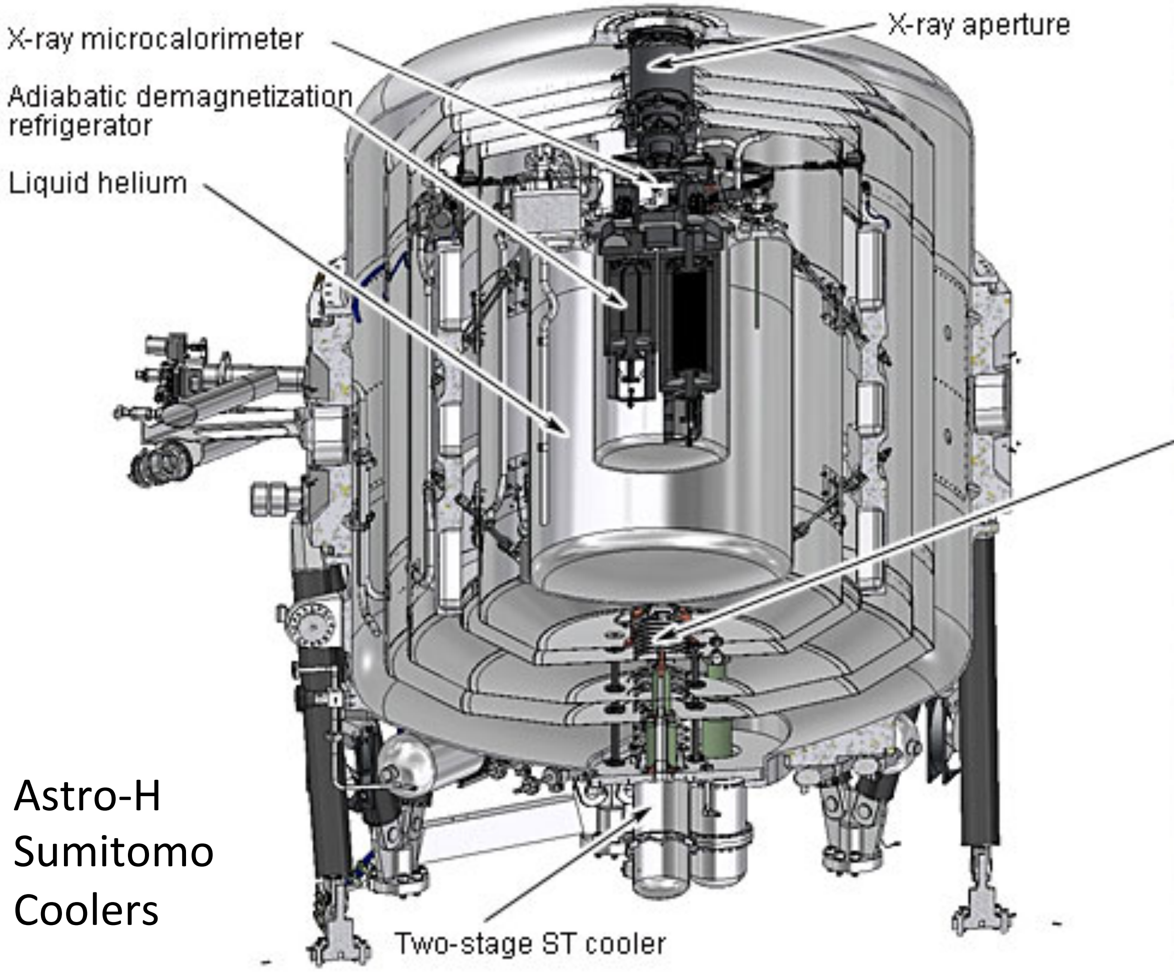
From Planck to a large cold telescope?

Must increase 4 K cooling to:

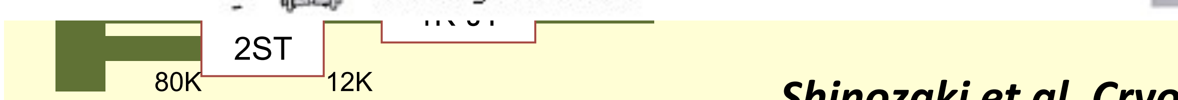
- Cool large telescope
  - E.g. 3 m telescope, loading scales with mass for optimized structure. E.g. 10 kg / m^2 for silicon carbide -> at least 100 kg.
  - Planck < 10 kg for 15 mW
  - Not possible to scale from Planck. Need to support launch loads with separate break-away structure, leaving lightweight optimized truss.
- Support recycling of sub-K coolers for instruments. Open cycle dilution not an option for a long-life mission.
- Will want 50-100 mW of cooling at 4 K for a large telescope.

SPICA Approach



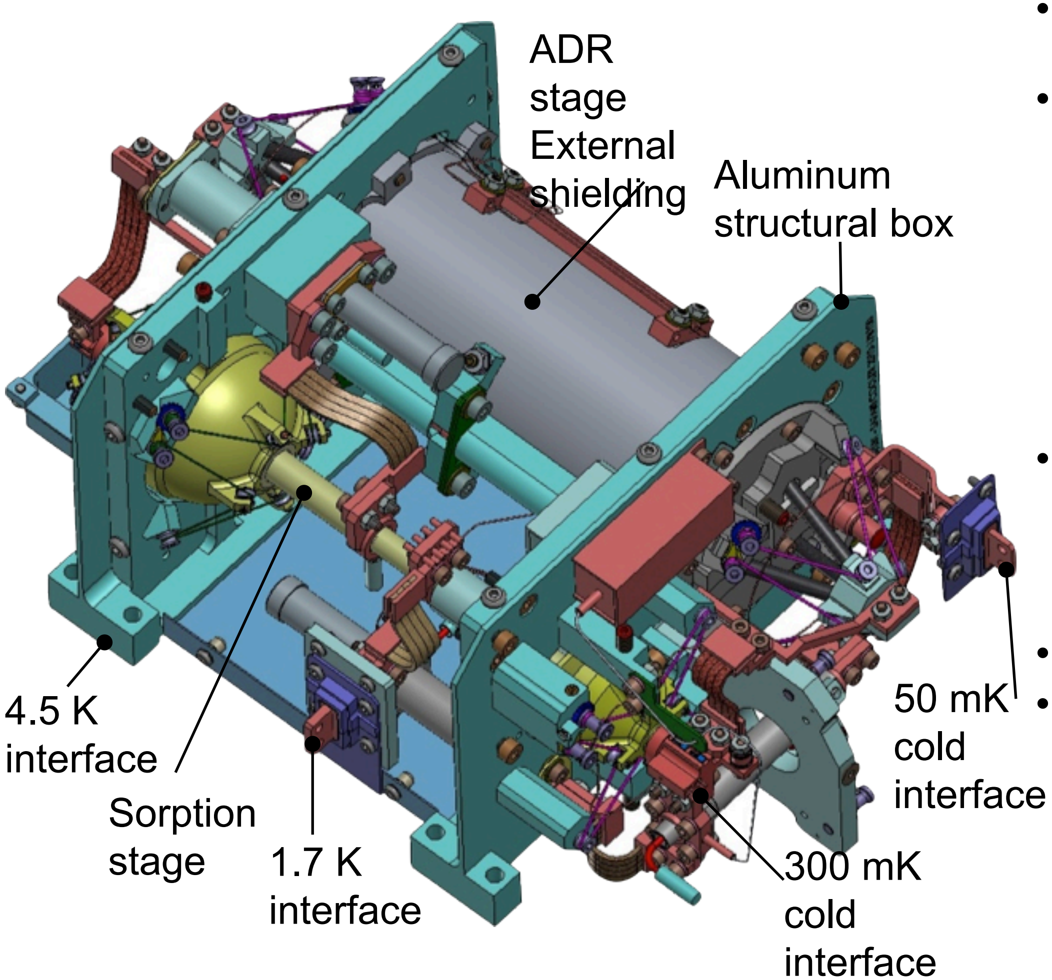


Astro-H
Sumitomo
Coolers



Shinozaki et al, Cryogenics in press

Cooling a Sub-K Instrument Payload

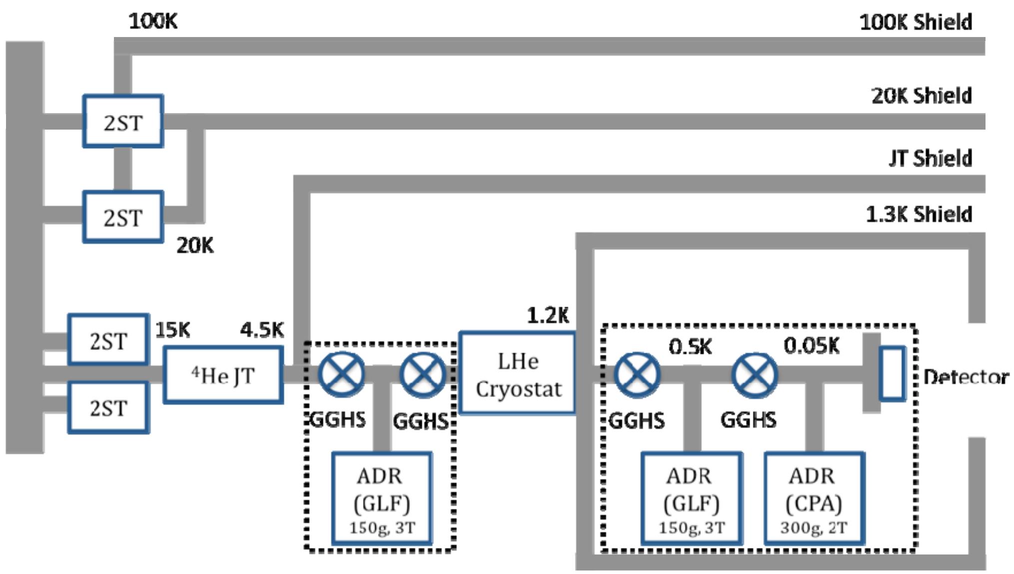


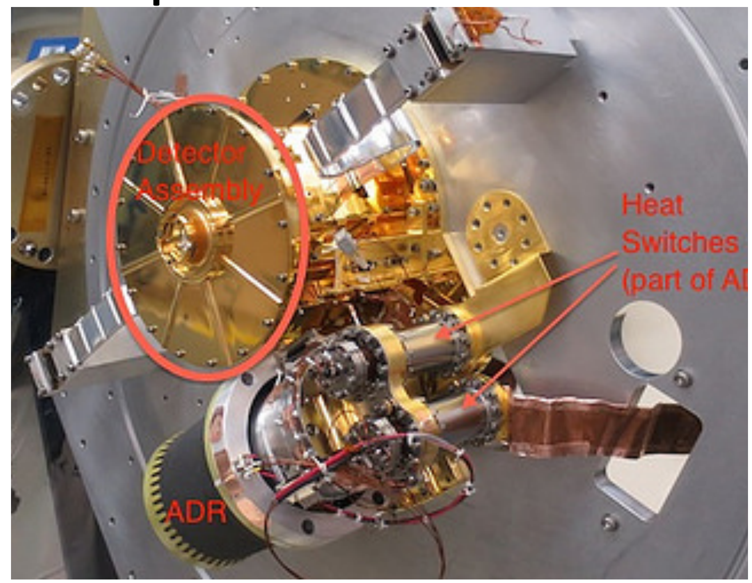
SAFARI cooler (Duband)

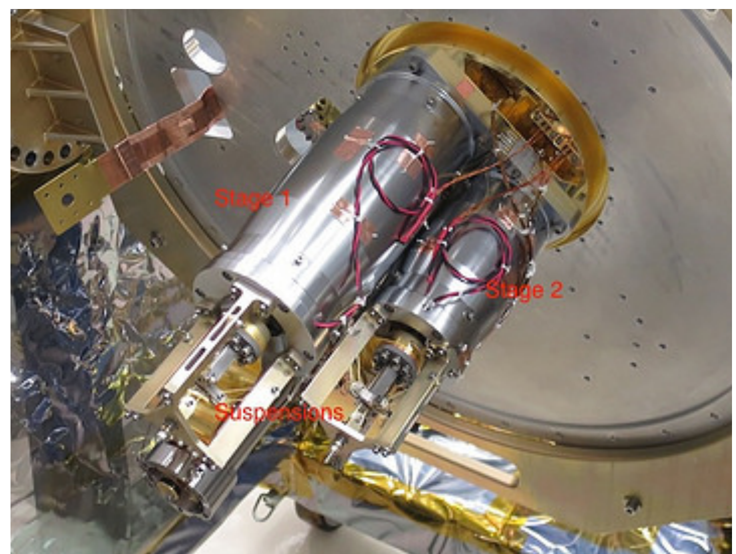
- We require 50-100 mK (below what is accessible with simple sorption systems).
- Step 1: want some kind of 1-2 K intercept. SPICA ^{3}He JT works well.
  - Alternative is a dilution system which naturally provides 1 K pot. Benoit et al have continuous dilution system, still requires 2 K lift and external compressor.
  - 4He sorption a possibility as well.
- Then, use additional intercept at 0.3-0.5 K
  - Dilution system is again `self-intercepting,'
  - 3He sorption a possibility
- Assume 20 kg cooled to 50 mK,
- Support with `magic' Ti (Ti 15-3-3-3) struts sized to survive launch
  - Parasitic loads are ~0.4-0.8 uW, depending on intercept temperature.
  - (Kevlar ~2 x lower load, but harder to implement)

3-Stage ADR

Shirron et al., GSFC for Astro-H spectrometer





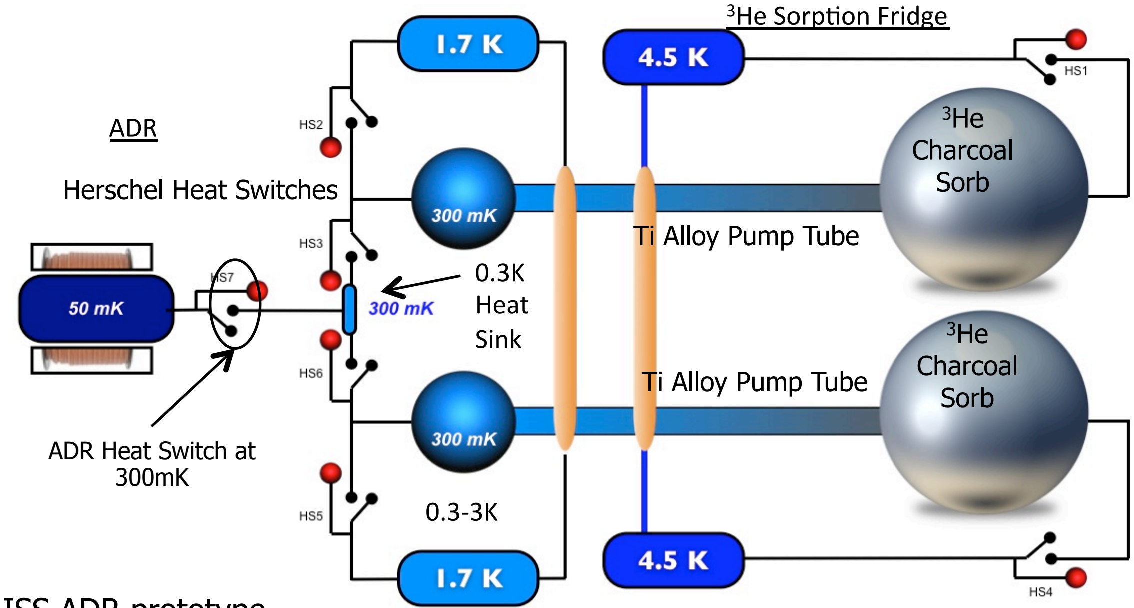


Astro-H

He dewar and JT cooler provide redundant cooling path.
Top ADR stage can help cool He dewar.
When helium is exhausted, top stage provides 1.2 K.
Bottom 2 stages cool intercept and 50 mK calorimeter
 single shot with 100 h lifetime (1-2 h recycle).
 0.5 uW lift at 50 mK
 0.2 mW to 1.2 K but higher peak loads

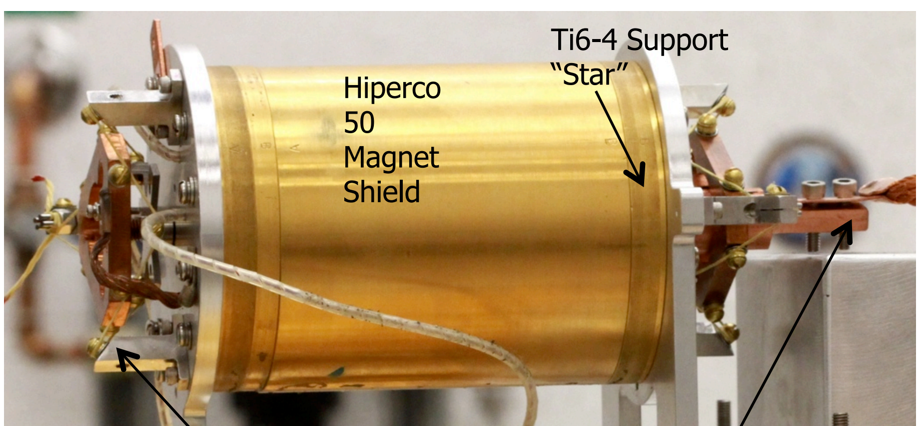
BLISS Sub-K Cooling Appraoch:

A HIGH-HERITAGE DUAL-STAGE SUB-K COOLER

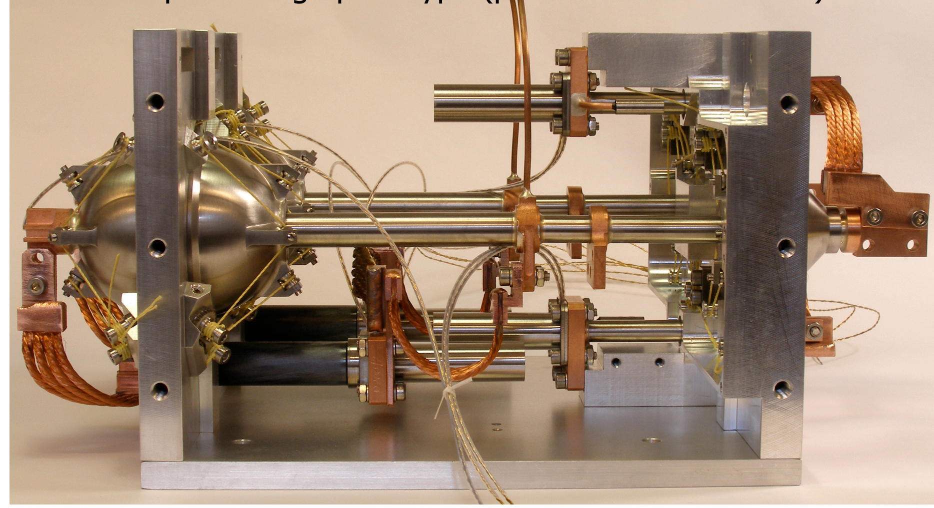


- Use two ‘Herschel’ coolers at 300 mK to provide a continuously-cooled intercept stage.
- Use a single-shot ADR to cool the spectrometers and detectors to 50 mK.
- 24-hour hold time and >90% duty cycle.
- Heat rejection requirements to 4.5 K, 1.7 K consistent with SPICA allocations

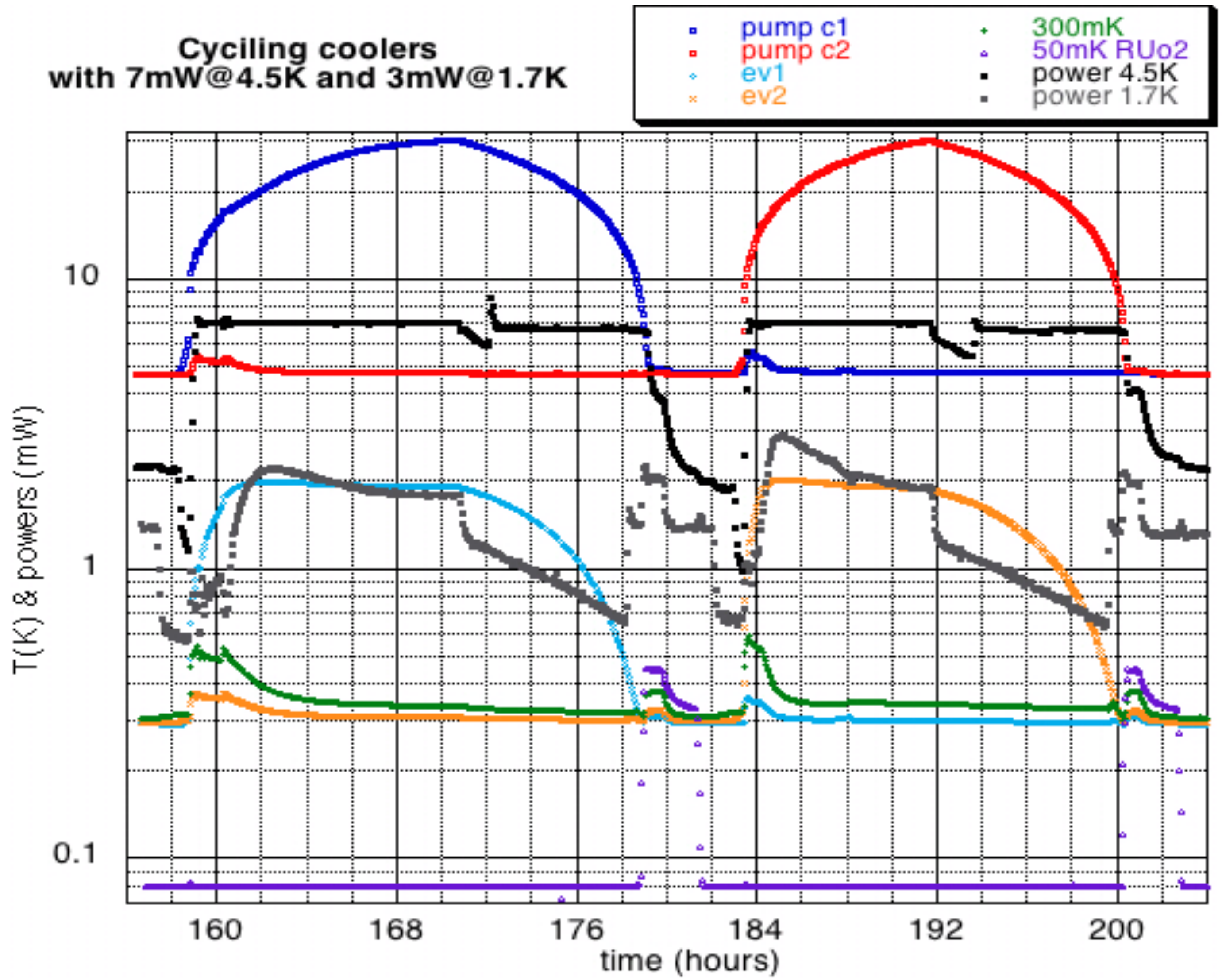
BLISS ADR prototype



BLISS sorption fridge prototype (procured from Duband)



Continuous Sorption Intercept in Operation

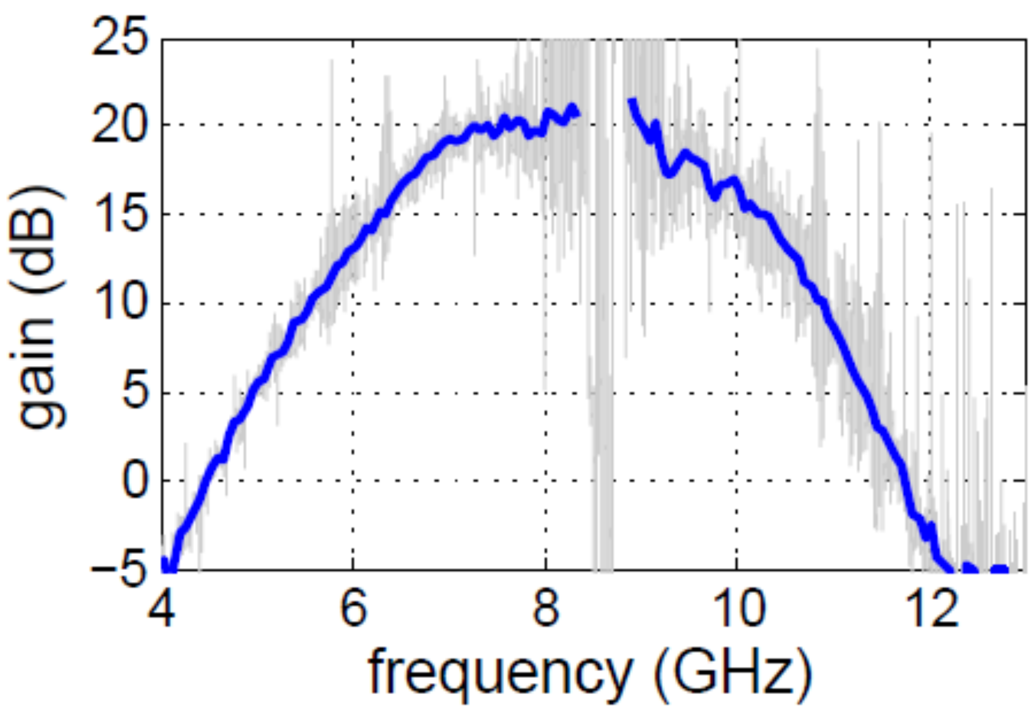


- Regulated stages at 1.7, 4.5 K allow measurement of rejected power
- Can tune to fit SPICA allocations (e.g. 7mW, 3 mW + parasitics)
- 50 mK prototype pill under construction. Likely CCA.
- With the right pill, system can support 1 uW lift.

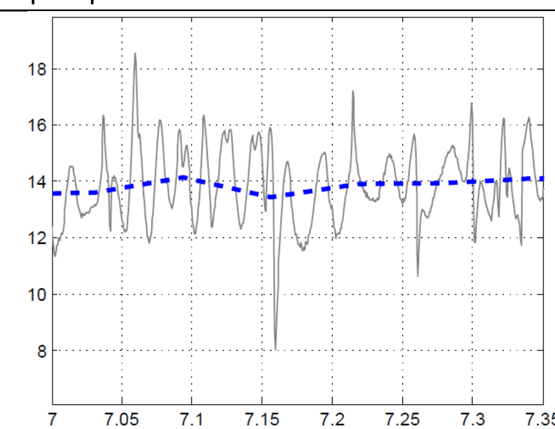
Thomas Prouve + others (JPL)

Parametric amplifier for RF-multiplexed systems.

- Microwave / RF multiplexed arrays require cold amplifier.
- Current SiGe amps if pushed to lower power (single stage) dissipate ~3 mW. Quickly becomes a problem for 4 K as instrument scales to several kpixels (several readout lines). (Might be possible at 20 K on Stirling cycle.)
- New superconducting parametric amplifier (para-amp) uses non-linearity of kinetic inductance to provide gain. Low noise because mechanism is reactive, not resistive. **2 photons of noise = e.g. 1 K at 10 GHz.**



- Measured gain ~ 20 dB, 1-2 GHz BW
- 0.8 m long, NbTiN CPW
- 35 nm thick, 1μm wide
- f_{pump} = 8.5 GHz, **~100 μW**

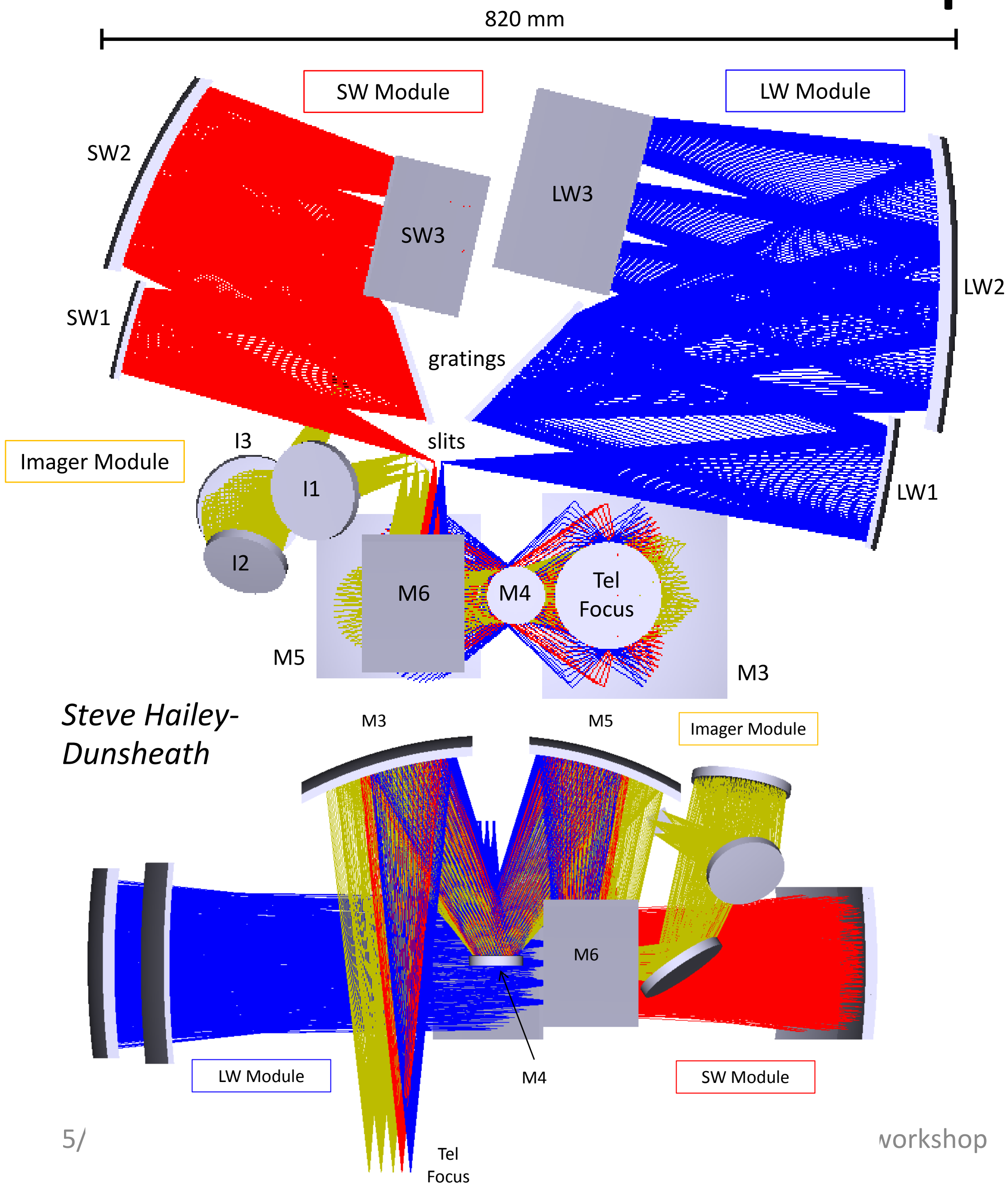


Peter Day, Rick Leduc, Byeong Ho Eom, Saptarshi Chaudhuri, Seth Meeker, Emma Wollman, Jonas Zmuidzinas

Spectrometer Approaches

- Future science requiring dispersive instrument which multiplexes in both frequency and spatial position.
- We have multiple detector options which are sufficiently sensitive for dispersive spectroscopy.
- Double-Fourier interferometer backend can also benefit substantially from dispersion at the image plane.
- Target e.g. R=200-500, from 40-400 microns with ~20-50 beams. $N_{det} = N_{beams} \times R \ln(10)$ = 23kpix minimum (~ 5x larger than SAFARI or BLISS).
  - Can trade R and N_beams.
- Dispersive spectrometer works best over a single octave. Processing a larger bandwidth tends to not couple optimally to telescope.
  - Wide-band antenna coupling a possible exception to this for low frequencies

Slit-fed wideband spectrometers



Steve Hailey-Dunsheath

This for STARFIRE:
2 arrays, each 32 (spatial) by 50 (spectral) KID pixels (3200 total)

SW: 240-317 microns
LW: 317-420 microns
R=450, 2 grating setting each.

Offner relay with pupil in front.

Telecentric focal plane for horn-coupled TiN KIDs

Wideband spectrometer must process large angles from the grating.

Slit-fed spectrometers typically have sizes many times R x λ.

See Aguirre et al. poster.

WaFIRS: a more compact grating spectrometer

RS module for

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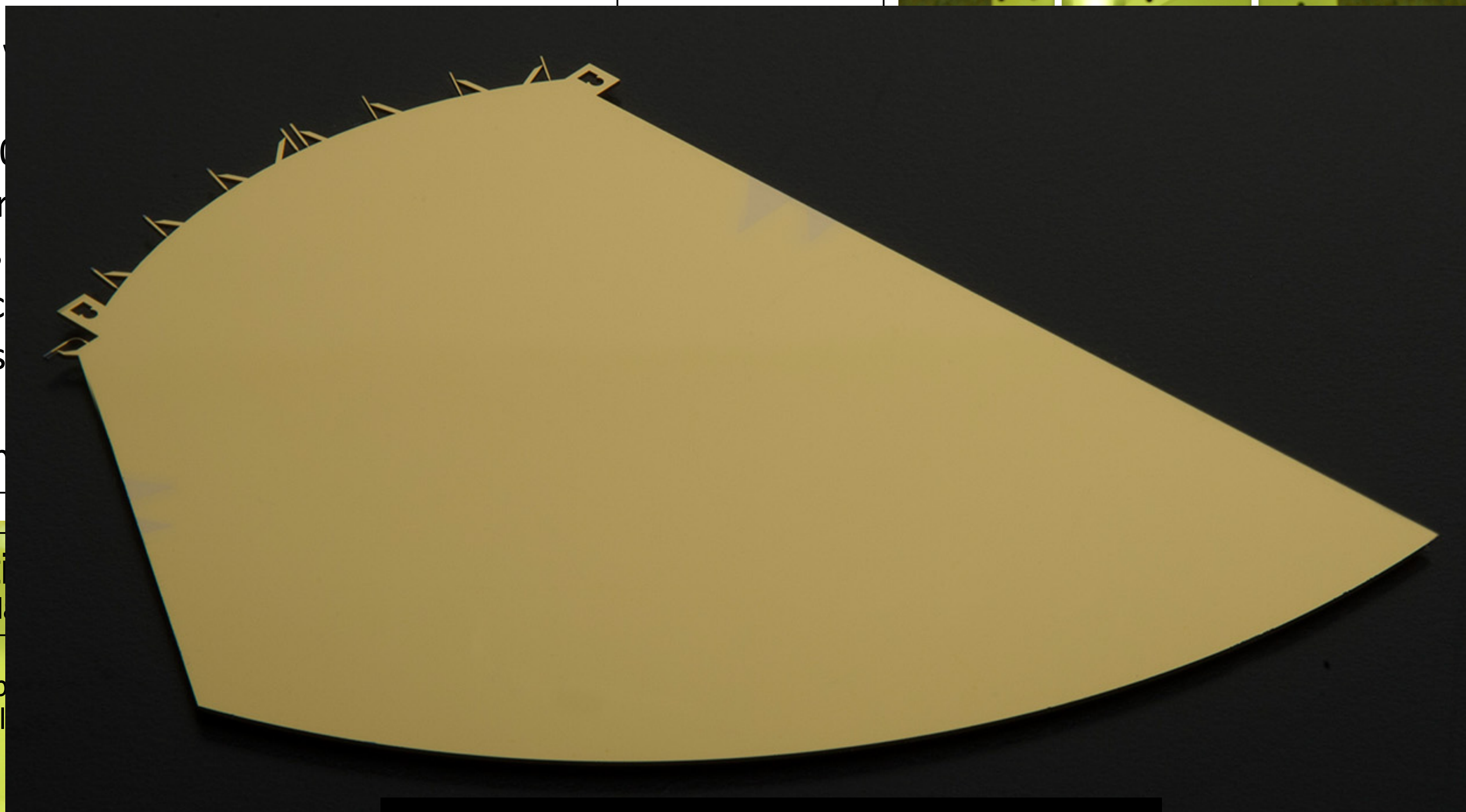


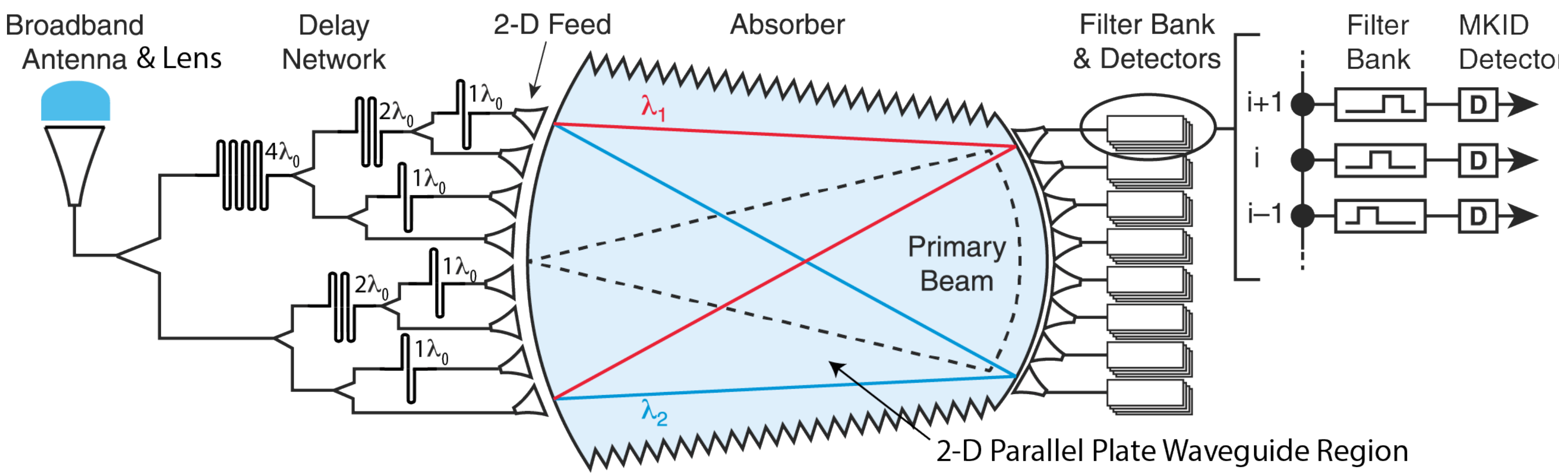
bolts
bolte

position [0.001″]
100

WaFIRS spectrometer on a 4” wafer
Design R=450 over 310-510 microns
Next: integrate detectors on output
Echternach, Reck, Bradford

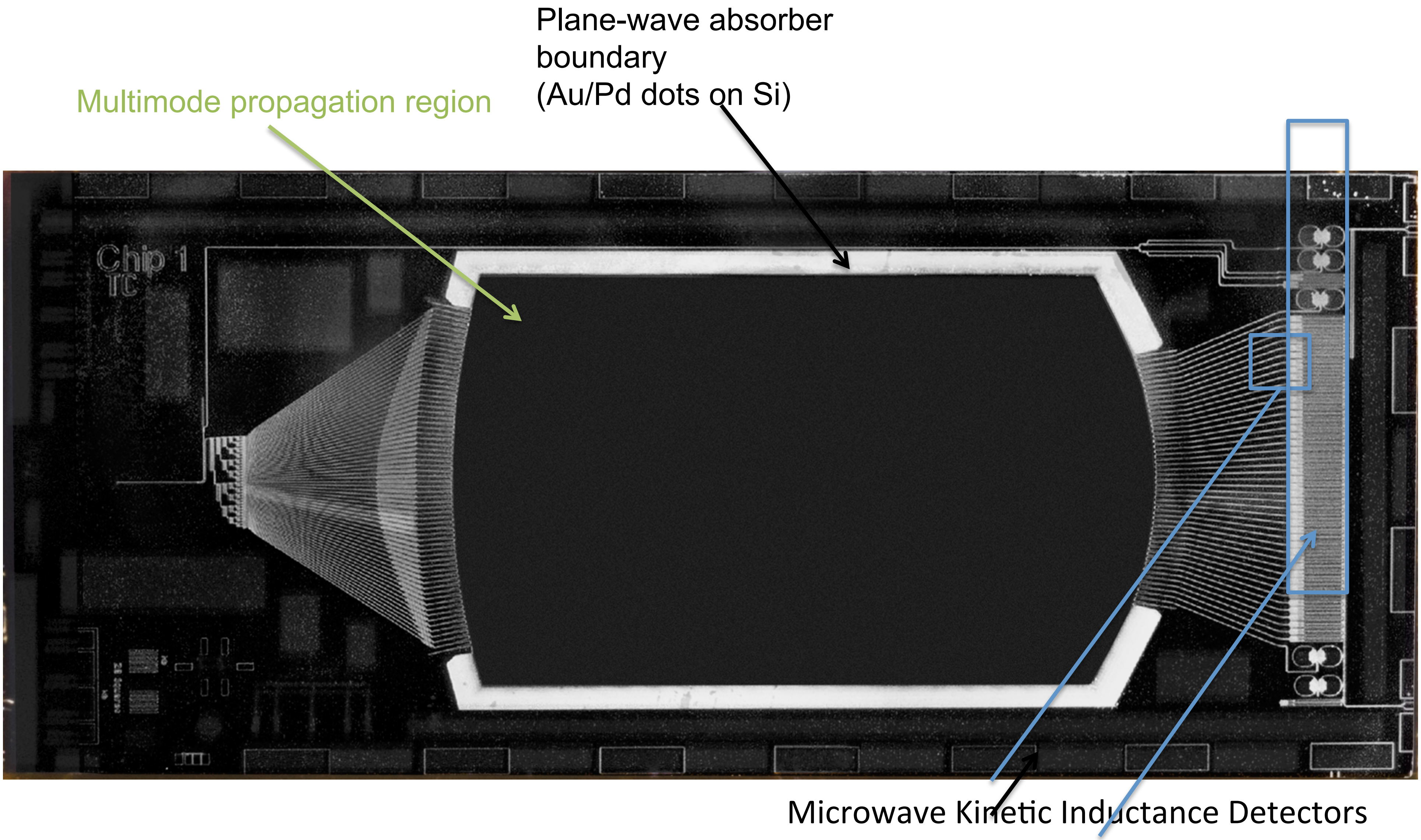
μ-Spec concept: a compact integrated on-chip spectrometer

Moseley et al. GSFC



The μ-Spec design uses delay lines to create the phase delay for R~1500 spectroscopy, and can be fabricated on a single 10 cm wafer in a volume 10^4 times smaller than conventional designs. It can produce diffraction-limited line images across the focal surface. The synthetic grating operates in high order (~10), and compact filter banks (right) separate the orders and direct them to individual MKID detectors.

µ-Spec: a compact integrated on-chip spectrometer



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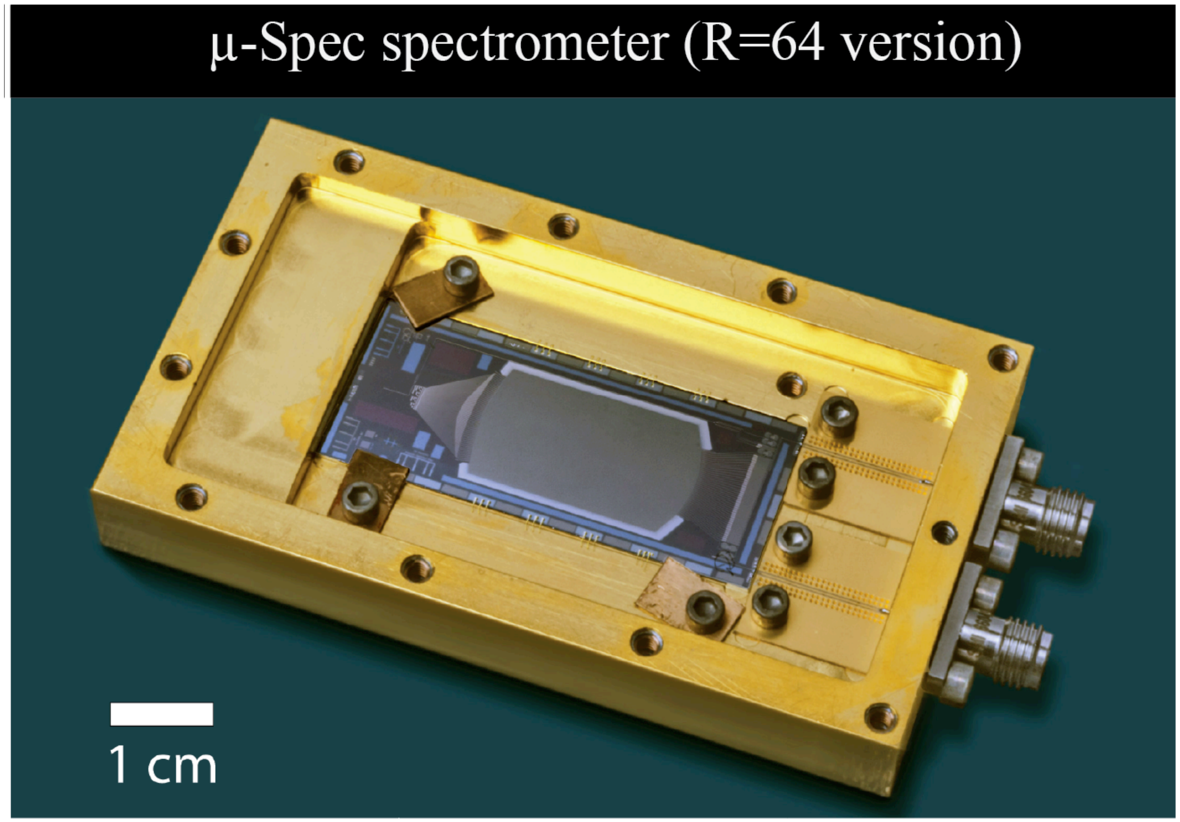
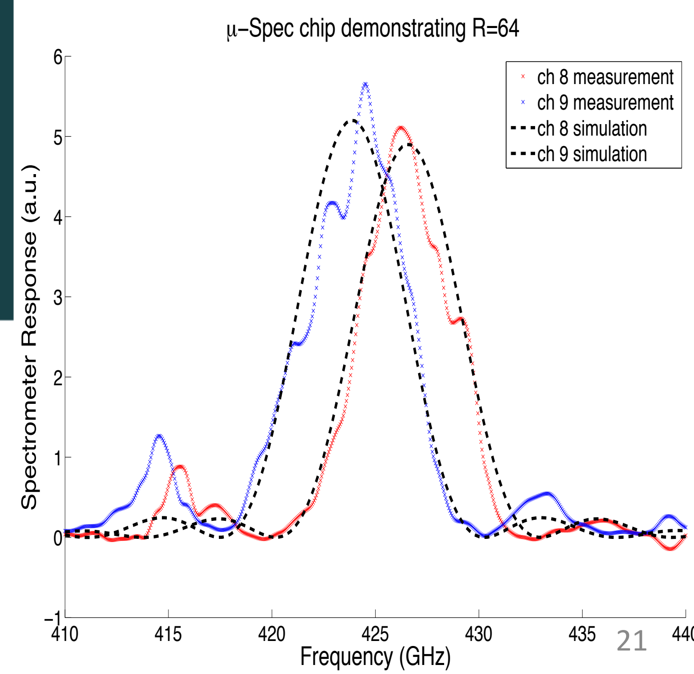


- Frequency within 1 GHz of design value by fab tolerances
- Channel width and spacing is consistent with design within measurement error

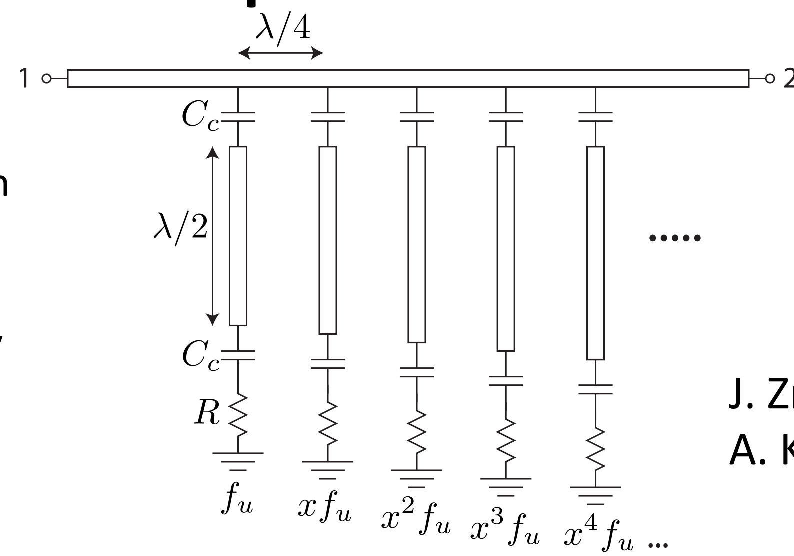


λ > 400 μm (due to Nb gap)
$\lambda < \lambda_{MKID}$ (~ 700 μm for MoN trilayer MKID)
48 actual spectral channels

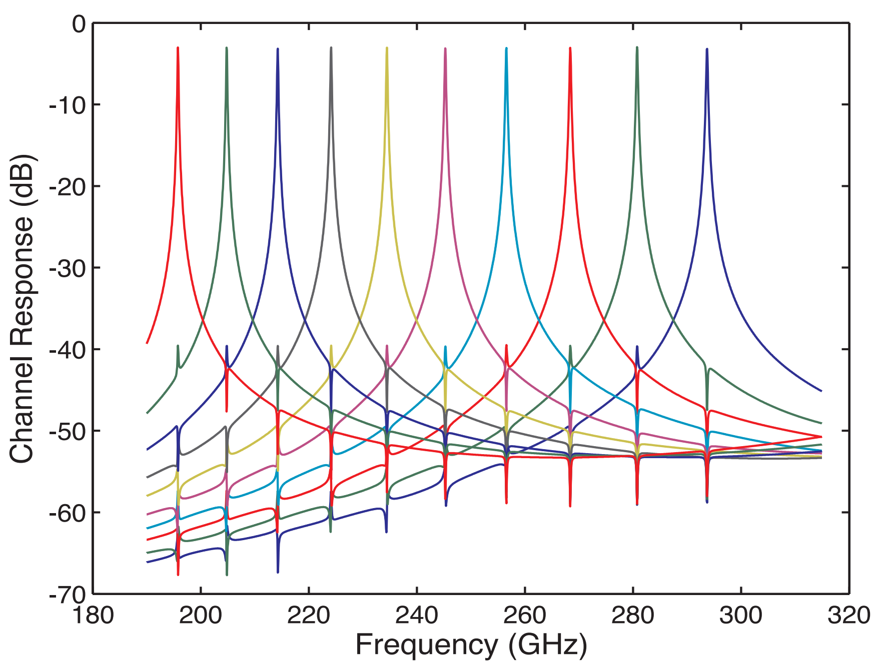
Moseley et al. **See Noorozian et al. poster**

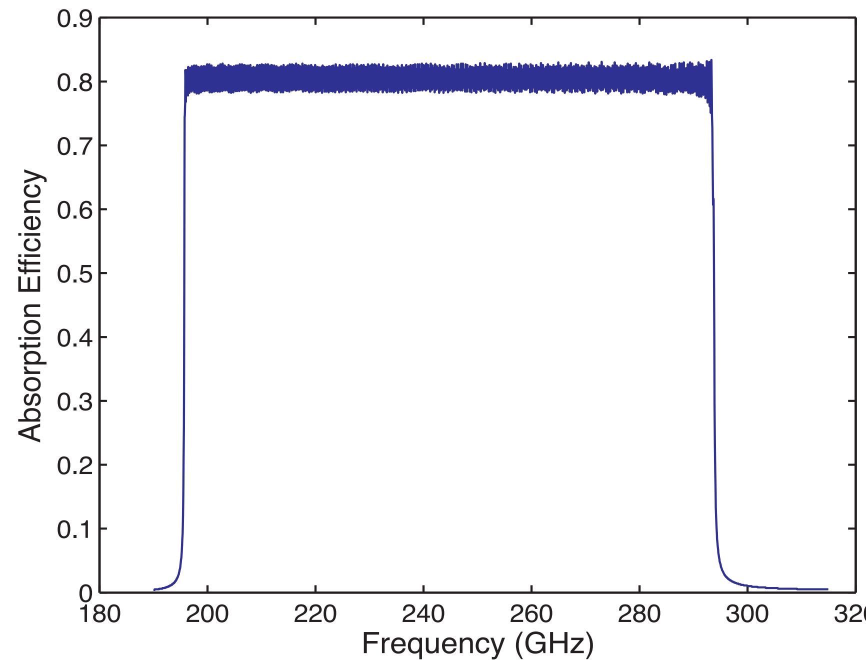
On-Chip Filterbank Spectrometer

- Incoming radiation sorted by narrowband filters.
- Filter is a half-wave section of transmission line, Q is set by coupling in and out.
- Each channel couples to a single KID.
- Channel width and spacing are individually tuned.
- Single channel absorbs 50%, multiple channels combine to couple up to ~80%

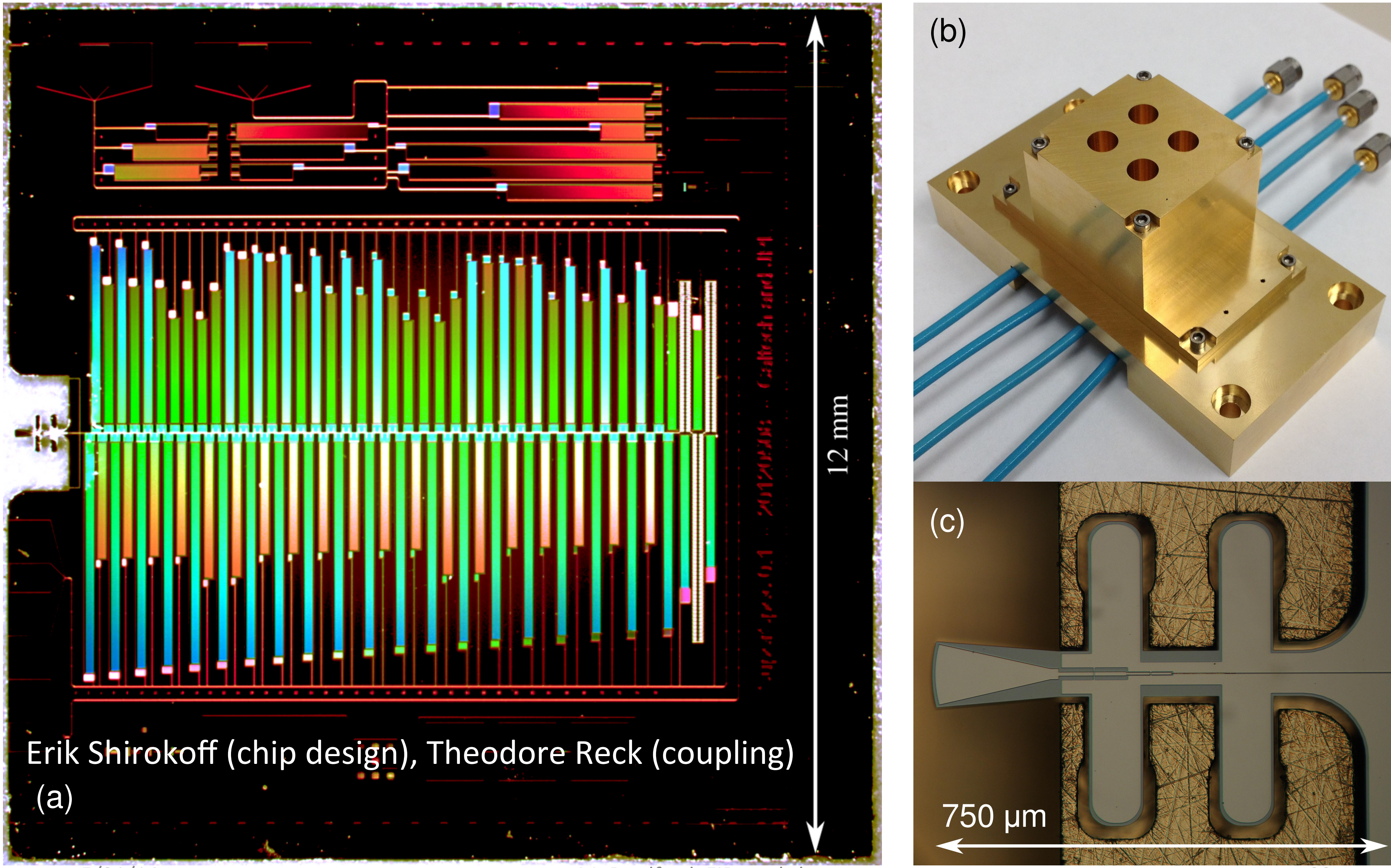


J. Zmuidzinas,
A. Kovacs





SuperSpec first 80-channel test device



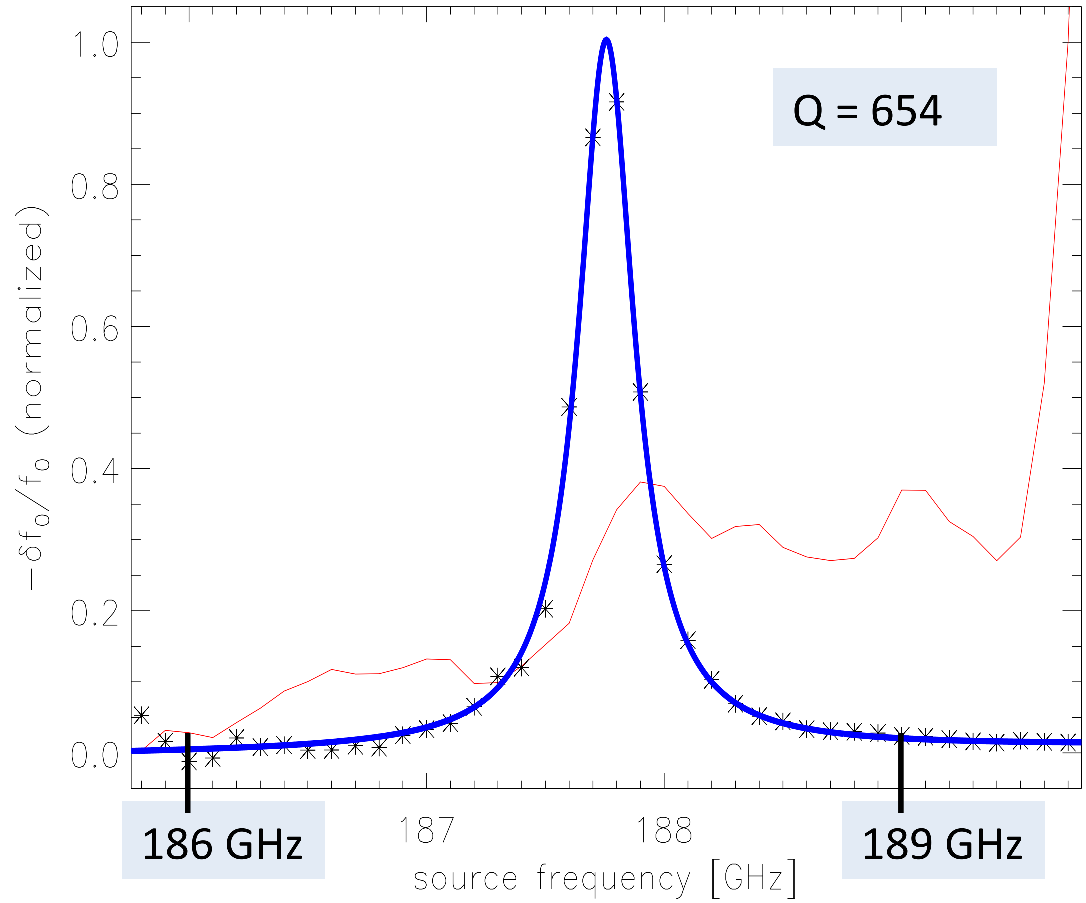
Optical Characterization: Swept Source

Chip has 3 different kinds of detectors:

- Spectral channels
- Broad-band ~1% absorbers
- Terminators (at end of line (4 sequential)

Characterization of chip through a combination of:

- Swept source (aka local-oscillator) measurements -- high-power tunable source provides detailed profile
- Blackbody response measurements -- provides radiometric response and noise.
- Fourier-Transform measurements – measures channel centers and constrains out-of band response



Example channel profile measured with swept source. Red is broadband response used to normalize the channel response. Blue is the Lorentzian fit.
Steve Hailey-Dunsheath, chip characterization

Conclusions

- Large-format spectroscopic back-end on a large cryogenic space telescope is a compelling future for far-IR space astrophysics.
- Participation in SPICA remains an near-term opportunity with excellent value and demonstrates techniques for the future pathfinders.
- RF / microwave frequency-multiplexed detector systems are coming close, consider at least 20 kpixel for next generation mission.
- Telescopes must be cooled to a few K. Mature technology exist, but careful thermal design of the full observatory is required.
  - With intercepts, 1 mW at 4.5 K for 8-10 W warm
  - Full large system: e.g. 50-100 mW at 4.5 K: up to 1 kW of power -> 10 m^2
  - Launch-locks will be required for next-generation cryogenic telescopes.
- Direct-detection systems have to be cooled to below 1K, so mass and volume are important.
  - Compact spectrometer technologies exist and are advancing.
  - 1 uW of lift at 50 mK should support 20 kg.
  - Can be lifted to ~15 mW at 4 K + 5 mW at 1.7 K.
- Balloon pathfinders are possible, but
  - Sensitivity-wise it is difficult to overcome atmosphere and warm telescope.
  - Operationally, gravitational and thermal deformations are also important
  - 3-meter class CFRP systems can be passive to gravity and thermal deformations, larger telescope may require active control.