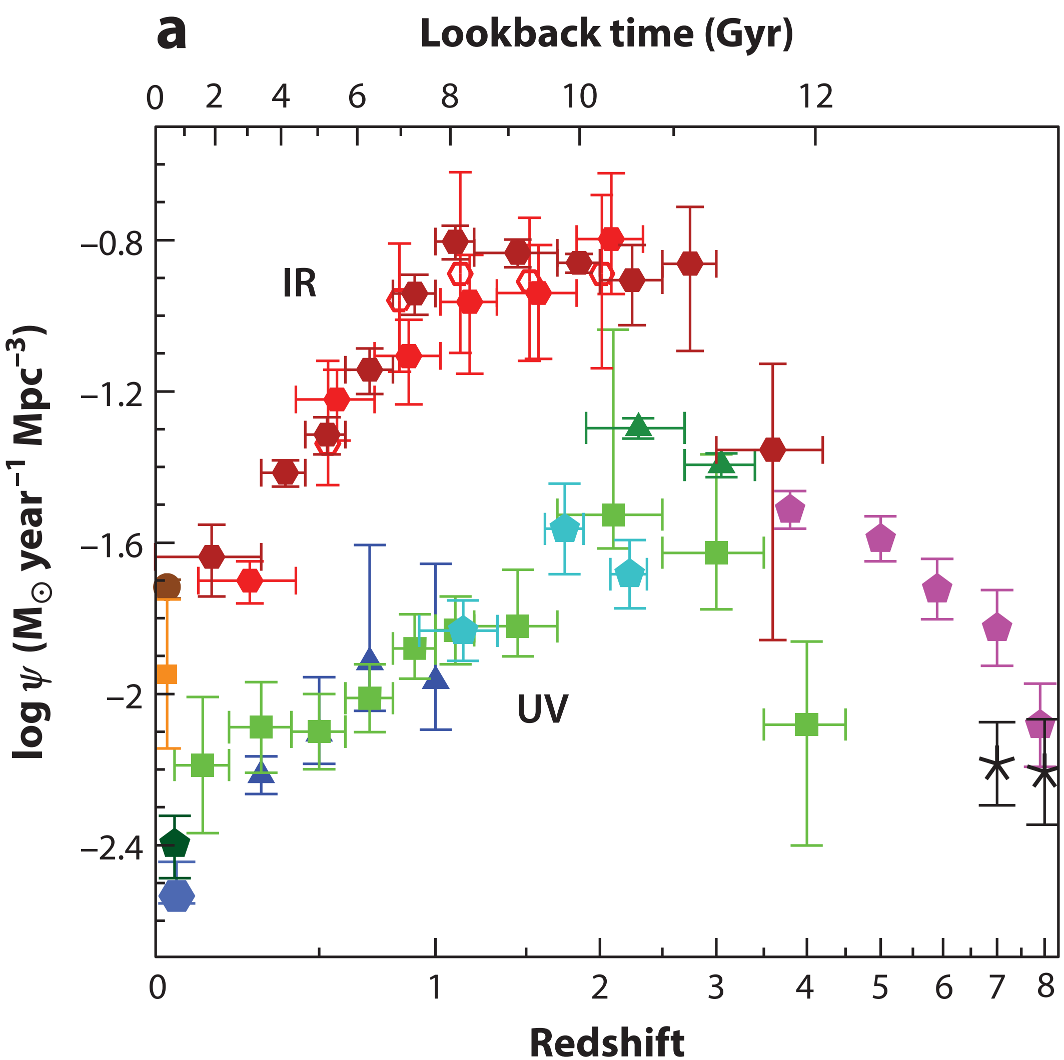
A Single-Aperture Telescope for Far-IR Space Astrophysics

Matt Bradford
Paul Goldsmith
+ others

Outline

- Why far-IR space astrophysics? (Bradford ideas)
  - Cosmic history of star formation and black-hole growth.
  - Rise of organic molecules in the first billion years.
  - From gas to planetary systems.
- CALISTO Concept
  - Sensitivity, confusion
  - Spectrometer Ideas, example campaigns
  - Thermal strawman, data rates, cost estimate
- Heterodyne Spectroscopy (Goldsmith)
  - Motivation
  - Technology for heterodyne arrays
  - Example observing programs

Studying Cosmic Star Formation is a Far-IR Question



Madau & Dickinson ARAA '14, Integrating down to 0.03 L_*.
Far-IR SFR from Spitzer 70, 24 (Magnelli + 09, 11), Herschel (Gruppioni +13). GOODS, COSMOS.

Most of the star formation activity has been obscured by dust: e.g. 80% at redshift 1.8.

Far-IR sensitivities for faint end lacking beyond redshift 2.5, though we know of powerful dusty systems in this epoch.

What sets the shape of this curve?

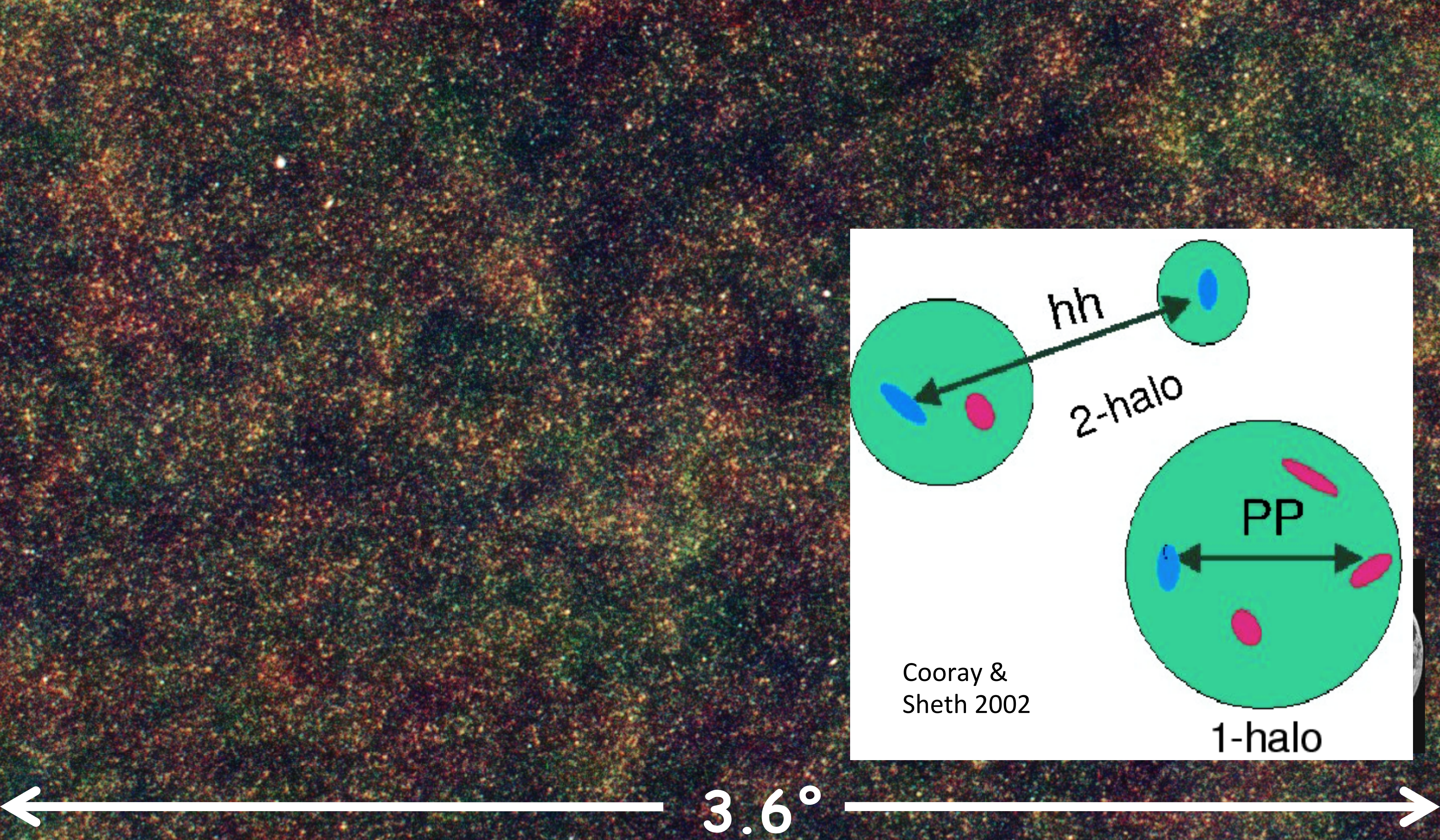
Why does BH growth track star formation?

Star formation seems to be driven by 'main sequence' galaxies, not mergers.

-> Balance of accretion rate with feedback processes. Interaction with stars / BH and the gas which is their raw material.

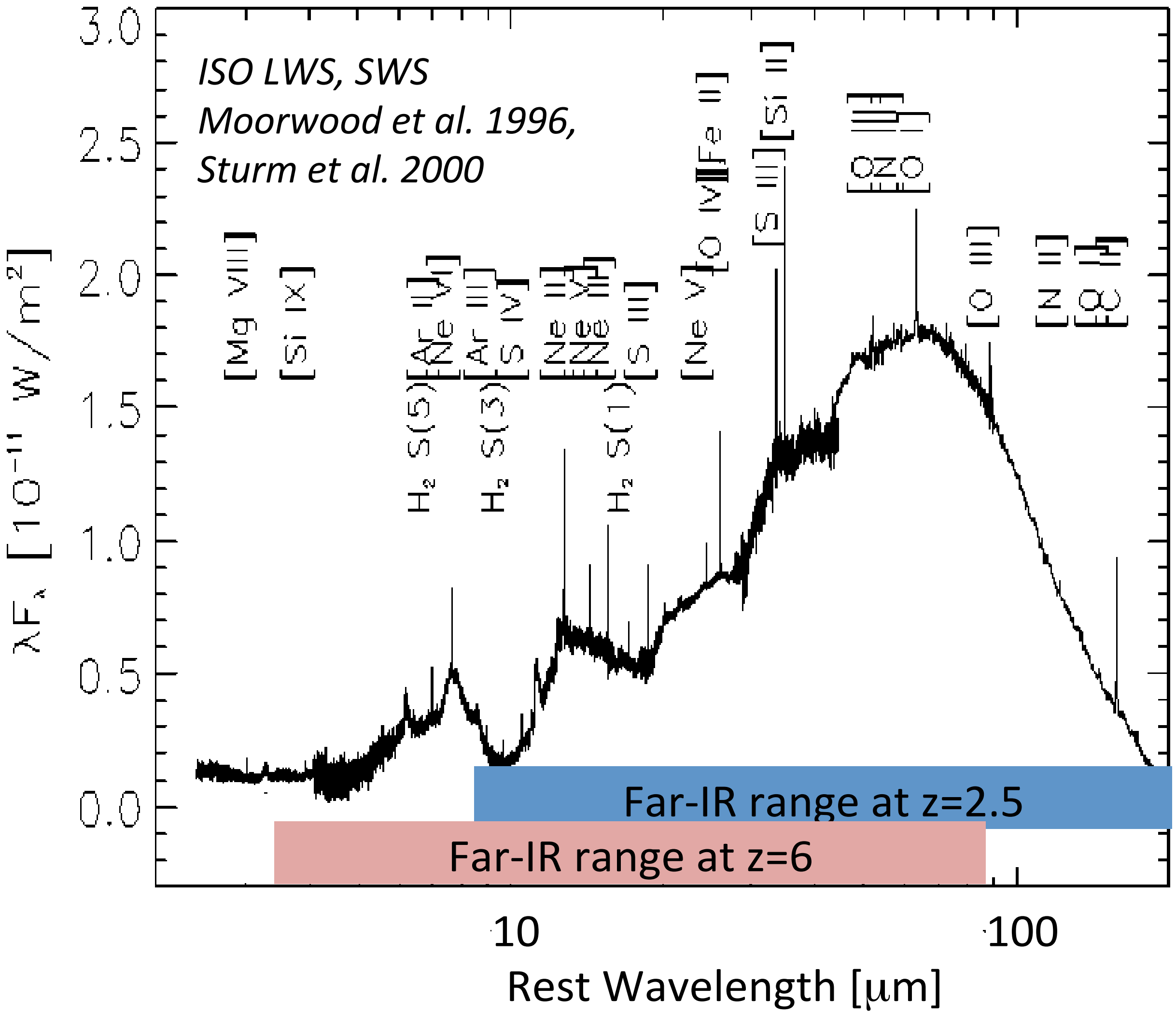
The Far-IR SKY

HerMES Lockman Survey Field with Herschel SPIRE: 250, 350, 500 microns



Spectroscopy Decodes the Far-IR Universe

Circinus galaxy – a nearby AGN-dominated system



Provides redshifts -- **3-D view of the far-IR Universe**

Measures cooling of the ionized, neutral atomic, and molecular gas, the primary ISM cooling channels.

Reveals UV field intensity and hardness – constrains ionizing source: accretion or massive stars. (e.g. [OIV] / [OIII], Ne sequence)

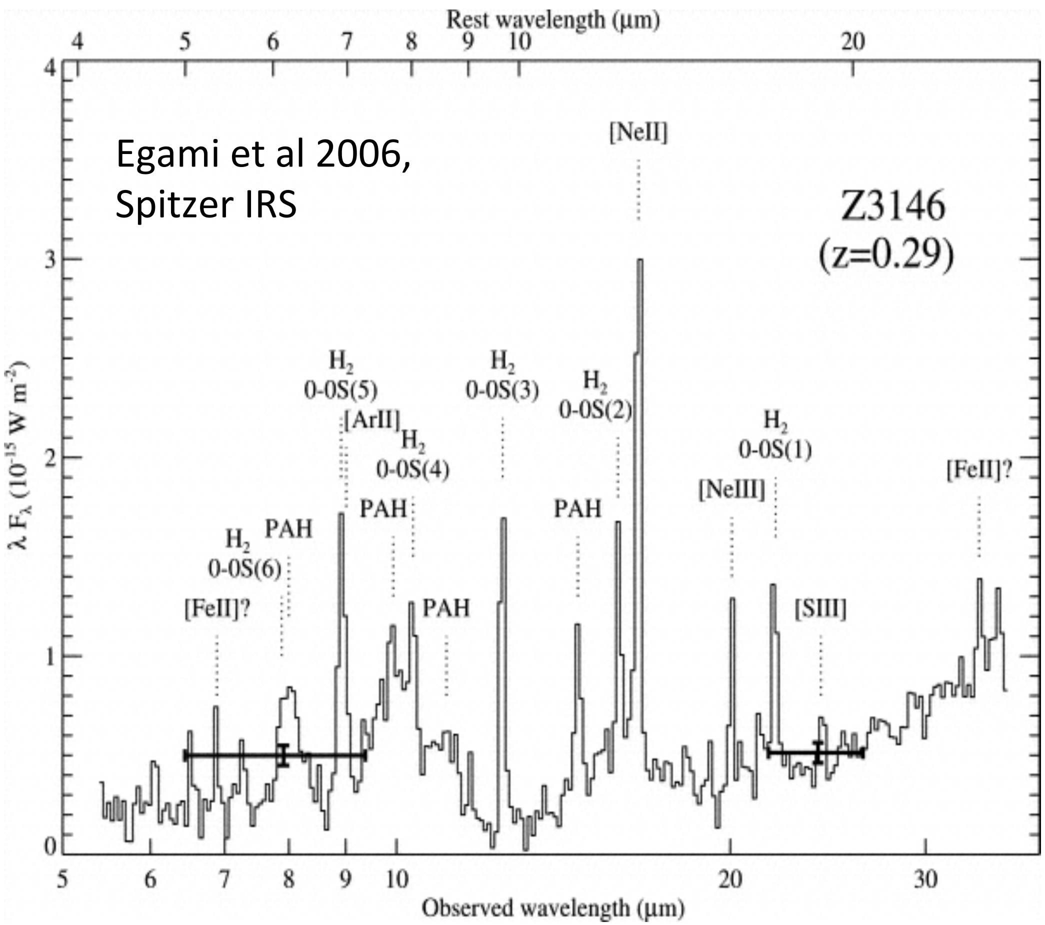
Measures mass and density of interstellar gas – the fuel for star formation.

N/O ratio a measure of metallicity and stellar processing history.

Armus whitepaper

Cosmic Dawn, Rise of Organic Molecules

As primordial gas is enriched with metals from the first stars, the dominant cooling pathways shift from pure H_2 to fine-structure lines and dust features.



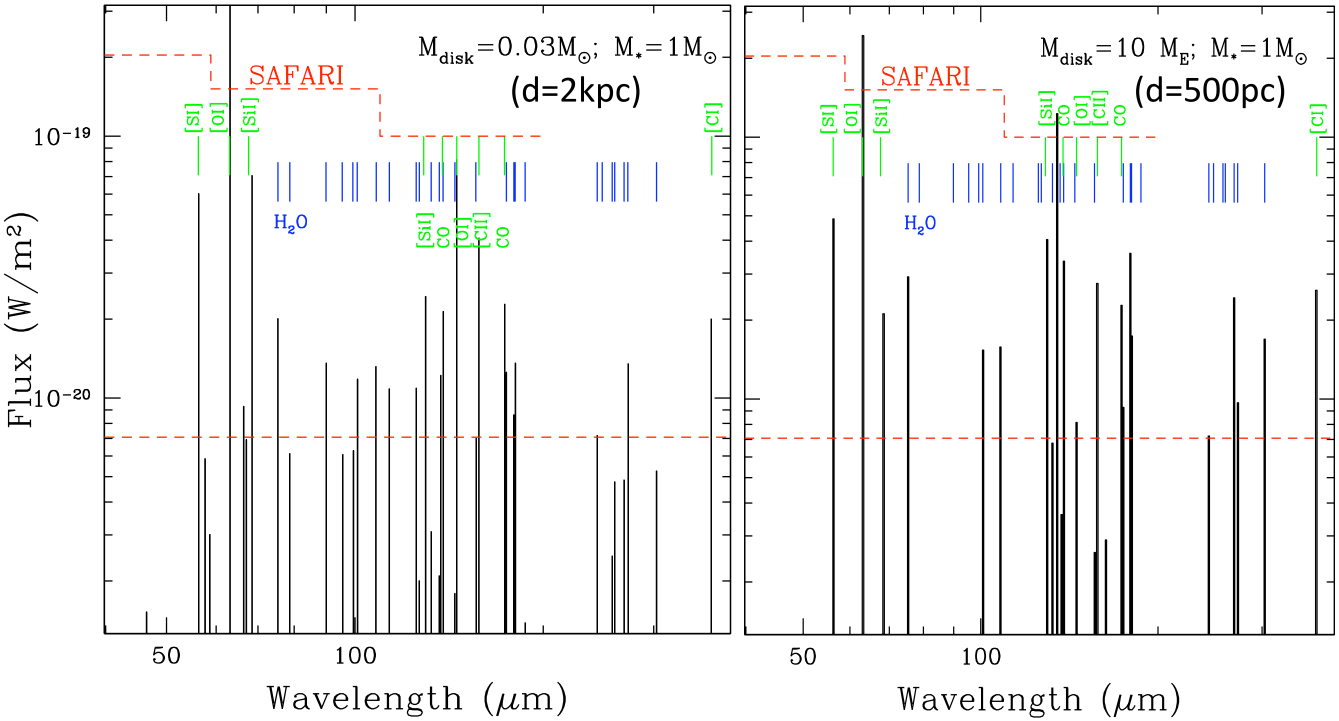
- Strong H2 emitters found in the local-Universe may be analogs of early-Universe shocks produced in galaxy formation and AGN feedback, perhaps as element enrichment is taking place. The Zw3146 spectrum at left would be detectable at z=8-10 with CALISTO.

(See Appleton, Cooray talks, white papers for more on H_2)

- As they arise, PAH features become important ISM coolants. With their large equivalent widths and unambiguous template for redshift identification, they may offer the best probe of heavy metal abundance at early times. While not accessible to JWST or ALMA, CALISTO can readily detect the PAH emission from galaxies systems at z~6, as they come to be.

Gas in Forming Planetary Systems

Model spectra convolved to R=400 (fluxes in W/m^2)
(credit Uma Gorti)



The full suite of spectral lines in the modeled objects above are readily detected with the raw sensitivity of the grating (but very difficult with an FTS-based instrument). A key aspect to consider is line-to-continuum ratio for the fainter lines.

See also talks by Bergin, Pontoppidan

Grating spectrometer enables census of the full evolutionary range, from massive primordial disks with 0.01 M_{Sun} of gas to older, evolved systems with only a few M_{Earth} of gas remaining.

Allows observations at kpc-distances, accessing clusters with range of ages. By surveying many, CALISTO can measure the gas disk lifetimes directly.

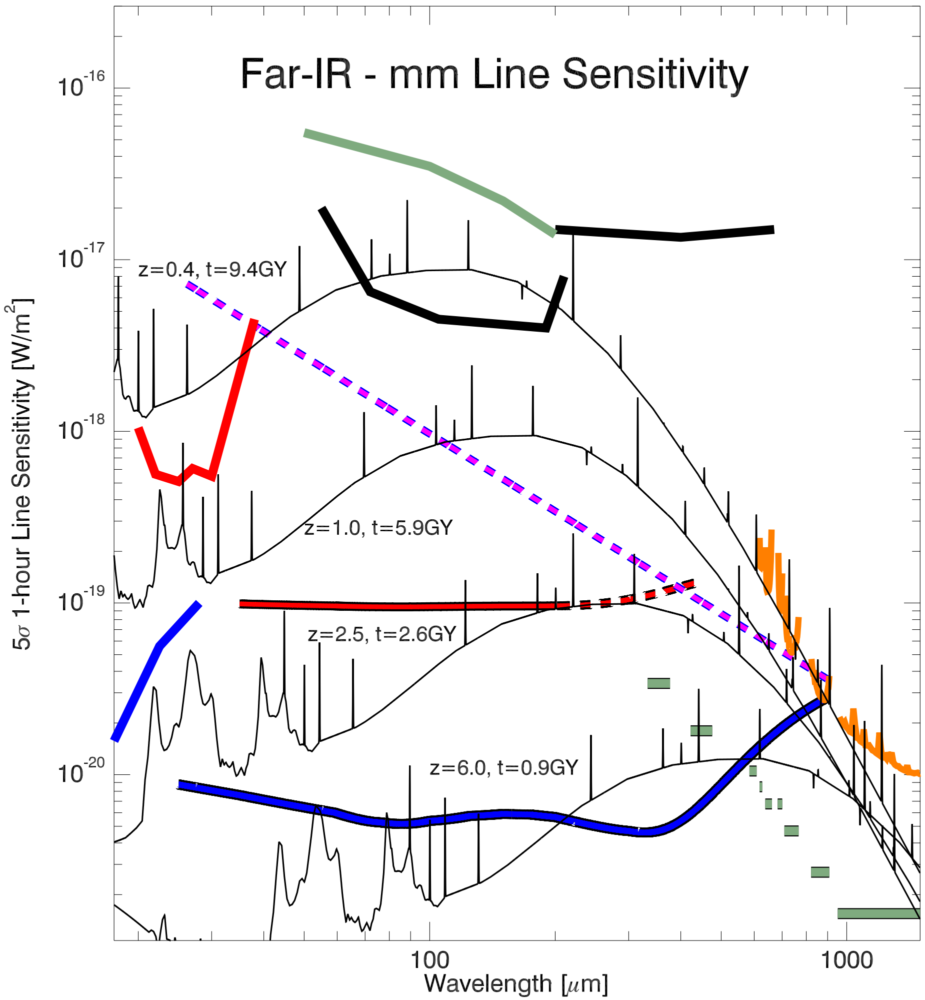
Example clusters for disk spectroscopy: NGC 2362 (5Myr, d=1.5 kpc), NGC 6871 (10Myr,d=1.7 kpc), h-&χ-Per (13Myr, d=2.3kpc), and many more.

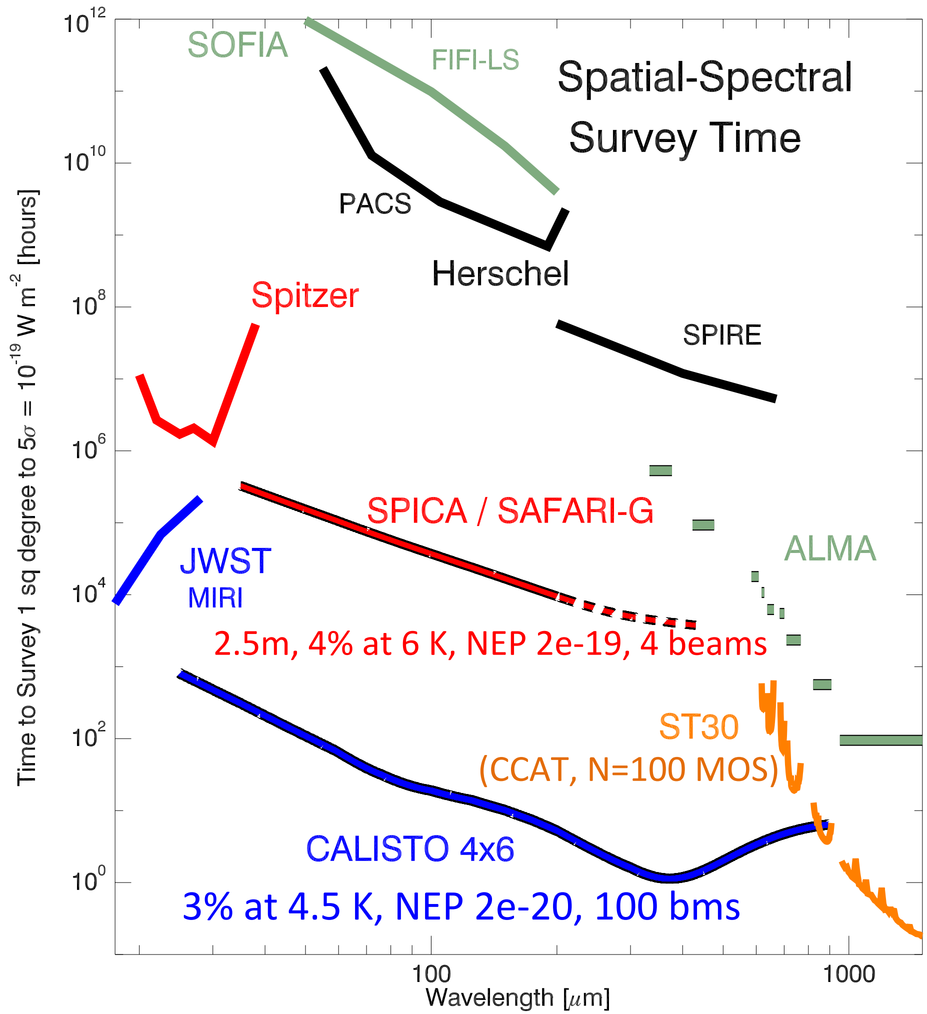
CALISTO Concept

Parameter	Value
Telescope Temperature	<4 K
Telescope Diameter	$\sim$5 m
Telescope Surface Accuracy	1 μm
Telescope Field of View	1 deg at 500 μm
Instrument Temperature	50–100 mK
Total Number of Detectors	1–5$\times 10^5$
Heat Lift at 4 K	$\sim$150 mW
Heat Lift at 20 K	$\sim$2 W
Data Rate	~Gbit / sec

- Cryogenic wide-field surveyor with imaging spectroscopy as its thrust.
- L2 orbit, careful thermal design including passive and closed-cycle active cooling.
- Instrument suite at T< 100 mK. Few hundred thousand individual detectors, each coupling a spatial mode at R~500 background limit.
- Other instruments possible.

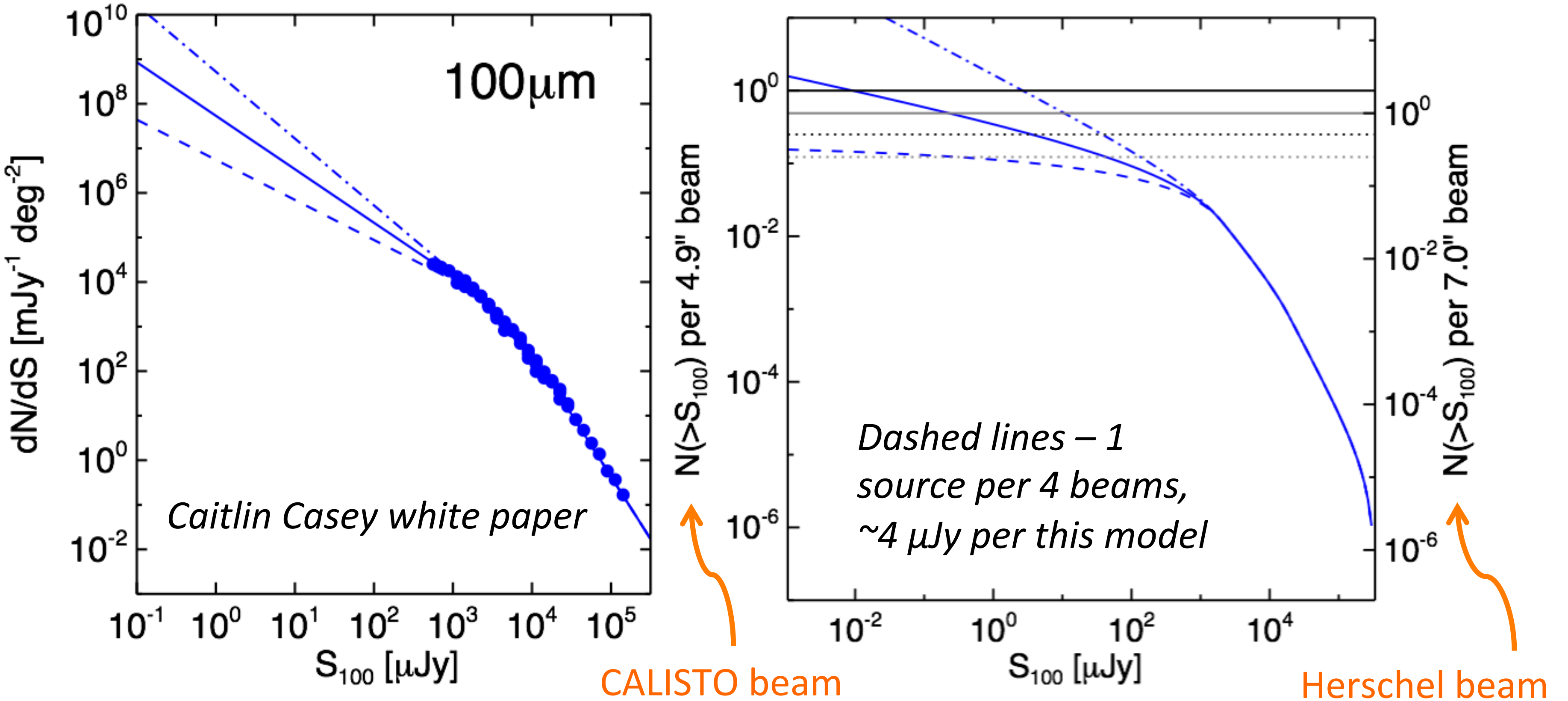
CALISTO Sensitivity





- CALISTO reaches 0.1 L_* at z=2.5, ULIRG at z=6.
- Discovery potential or discovery speed: N_{det} x (A / NEP)^2.

Broadband Imaging and Confusion for CALISTO

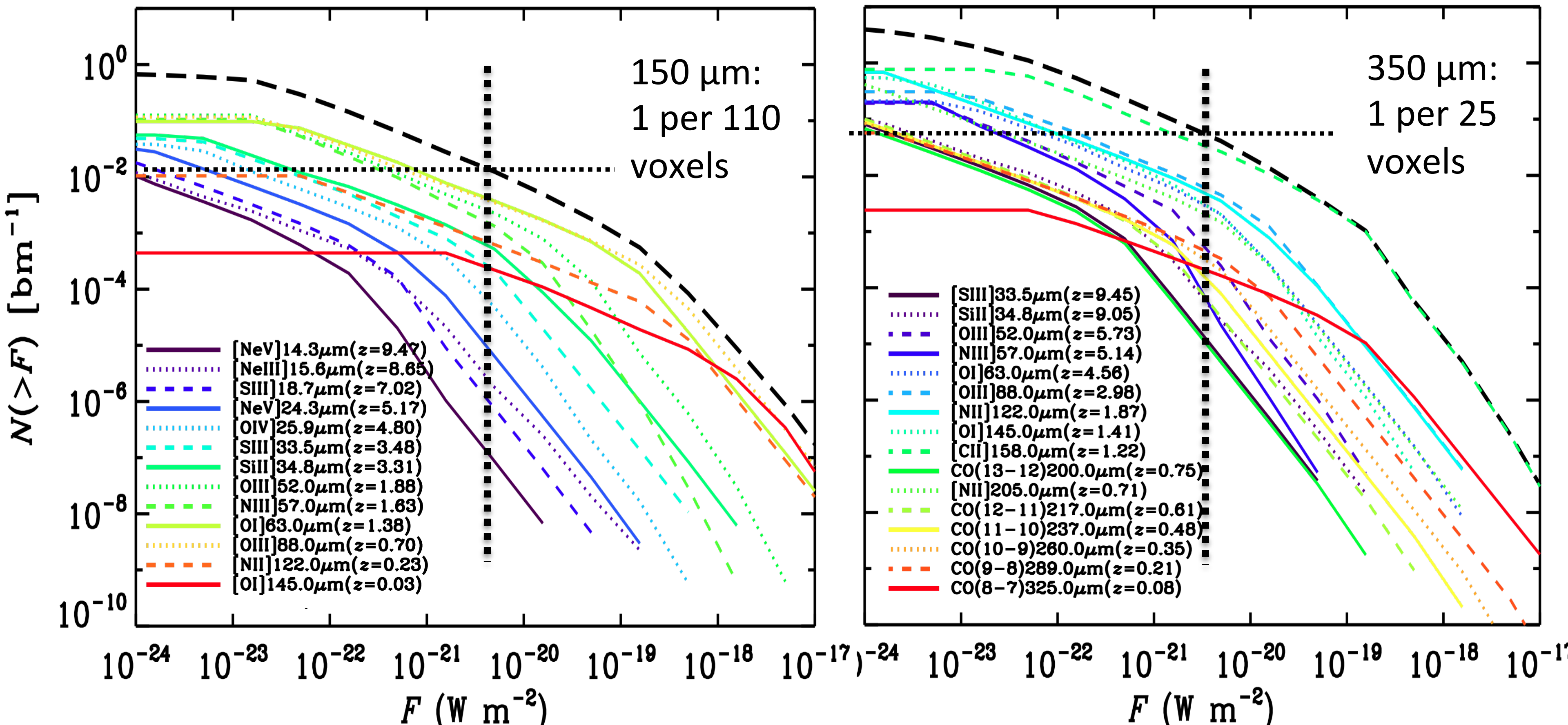


- The 2x reduction in beam solid angle (vs Herschel) translates to a 10x improvement in depth at 100 µm due to the shallow slope of the luminosity function. Further improvements may be possible via removal of bright sources, combining datasets with the 2 telescope orientations.
- **Imaging at 50 - 100 µm will be very powerful for CALISTO.**
- Adopting 38 uJy for the confusion limit (at 100µm), the luminosity at 5 × this depth is 1.3e10 L_{sun} at z=2, 1.2e11 L_{sun} at z=5. (See Table 2 in CALISTO white paper). Can cover a square degree to this depth in 0.1 hour with a 4000-beam camera. **So full sky in 4100 hours.**

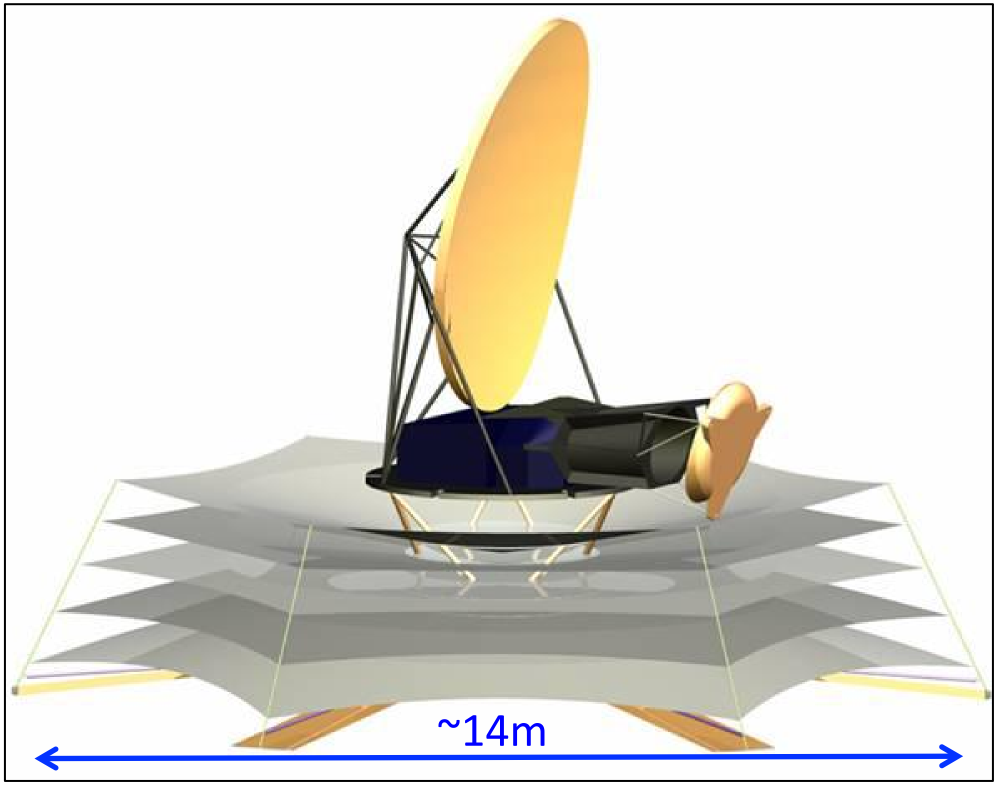
CALISTO Unconfused in 3 Dimensions

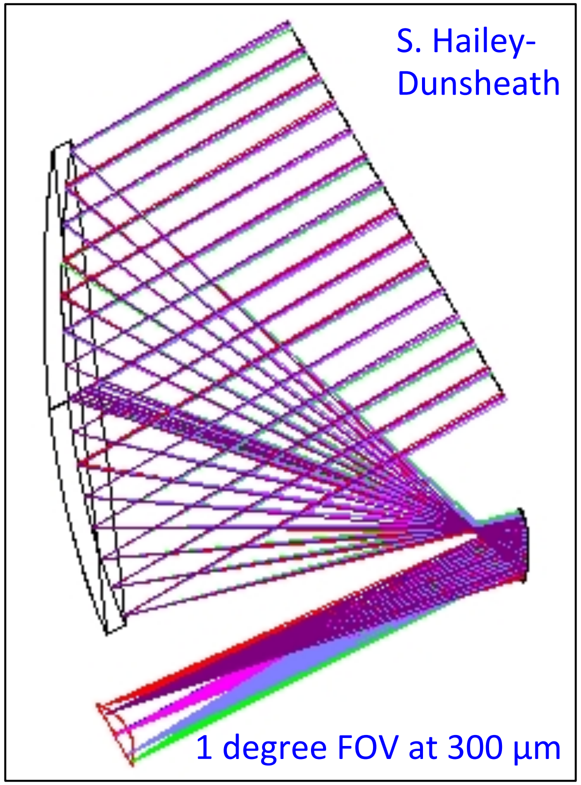
Fine-structure 'line counts' E.J. Murphy et al.

- Based galaxy models from Chary & Pope 2010,
  (backward evolving from Chary & Elbaz 2001, L* evolution with z)
- Lines from galaxy luminosity from Spinoglio 2011 compilation of Spitzer, ISO LWS.
- Cumulative counts per spectral spectral bin (here numbers for 3.15-meter telescope, R=700, numbers corrected by 1 / 1.8 for CALISTO.

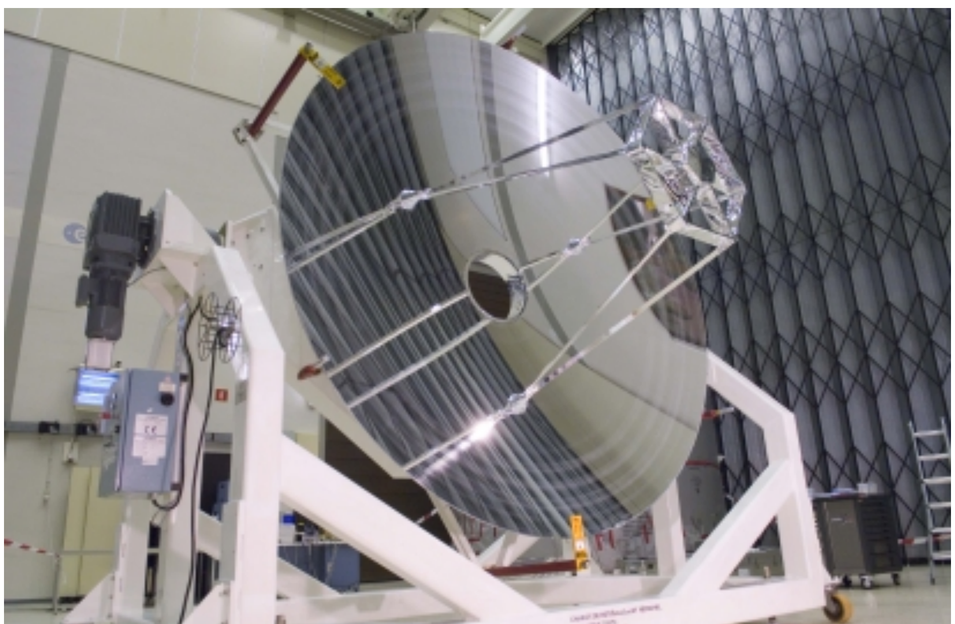


Telescope Concept





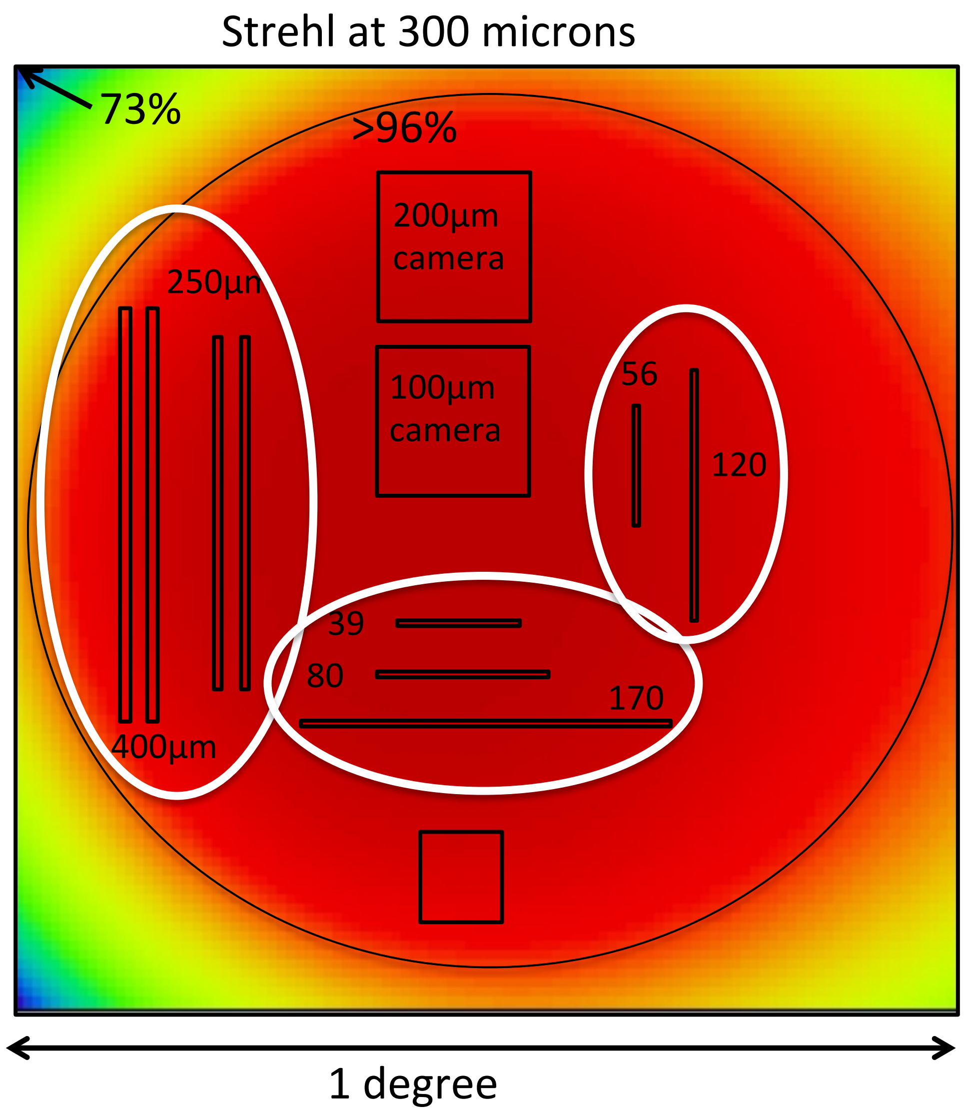
- Cryogenic operation (<5K) a key requirement.
- Drives to an L2 mission with deployed multi-stage V-groove sunshade.
- Breakaway struts to support payload during launch.
- Example concept: 4x6 meter off-axis with secondary deployed on hinge.
  - Efficient use of 5-meter fairing.
  - 1 degree FOV possible with no corrector.
- On axis also possible, if strut blockage (=loading) can be kept to ~1-2%.



Telescope Concept

- Material TBD, but sintered silicon carbide a good candidate. Can be assembled in pieces.
- Surface accuracy requirement order 1 micron, comparable to what was achieved with Herschel.
- Adaptive vs passive telescope to be studied.
  - Cryogenic figuring costs might be saved with an low-bandwidth adaptive system with sufficient authority to overcome thermal deformations.
  - At primary or pupil image mirror?
- Dave Redding, Thursday afternoon.

Instrumentation Strawman



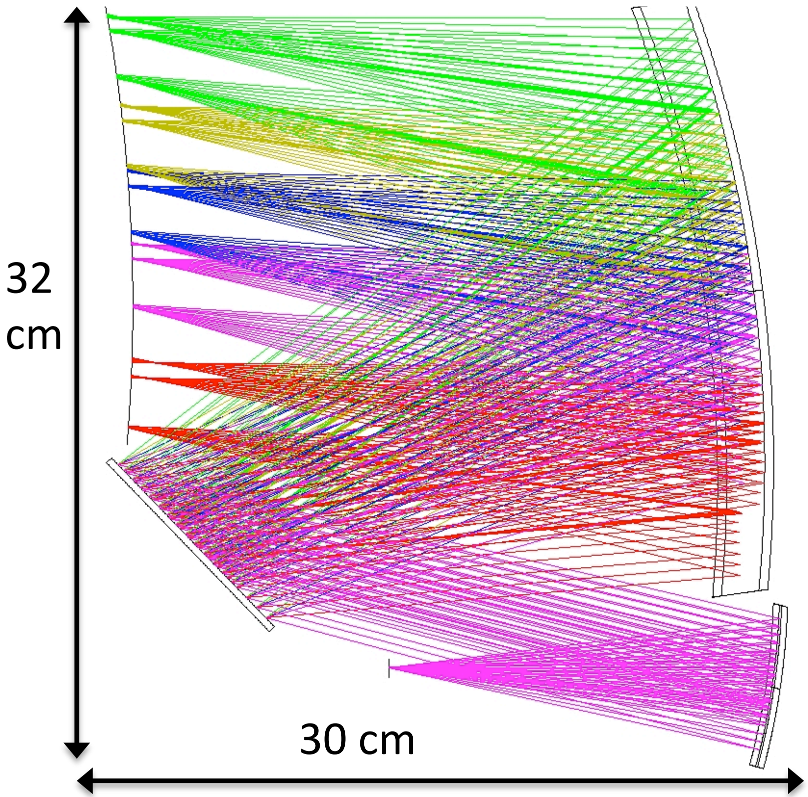
- 6-8 log-spaced bands covering 25 to 500 µm.
- Each covers 1:1.5 band at R~500, so 200 spectral resolution elements, not oversampled.
- Each has ~100-150 beams on the sky, so 20k-30k detector pixels per module.
  - Naturally easier to have more beams at the higher frequencies, can do it if we can carry the detector count.
- Detectors at the photon background limit, 3e-20 W $Hz^{-1/2}$.
  - Need not be fast – tens of Hz OK.
  - Frequency domain MUXed in groups few 1000.
  - Zmuidzinas presentation Thursday.
- Configuration in the telescope focal plane TBD. Multi-color observations of a given field possible with dichroic and/or polarization beamsplitters (white ovals show slits which could be co-pointed on the sky).
- Spectrometers will require modulation, perhaps chopping mirror at cold pupil, needs study.
- Etalon in advance of grating backends a possibility for R~3000-5000 mode.
- Camera modules: 2 or 3 at 50 to 200 µm. Sizes show 4000 beams at 200 µm, 16,000 at 100 µm. Polarimetry a possibility, best with on-axis telescope.
- Heterodyne spectrometer arrays – discussed independently, but have plenty of AΩ.

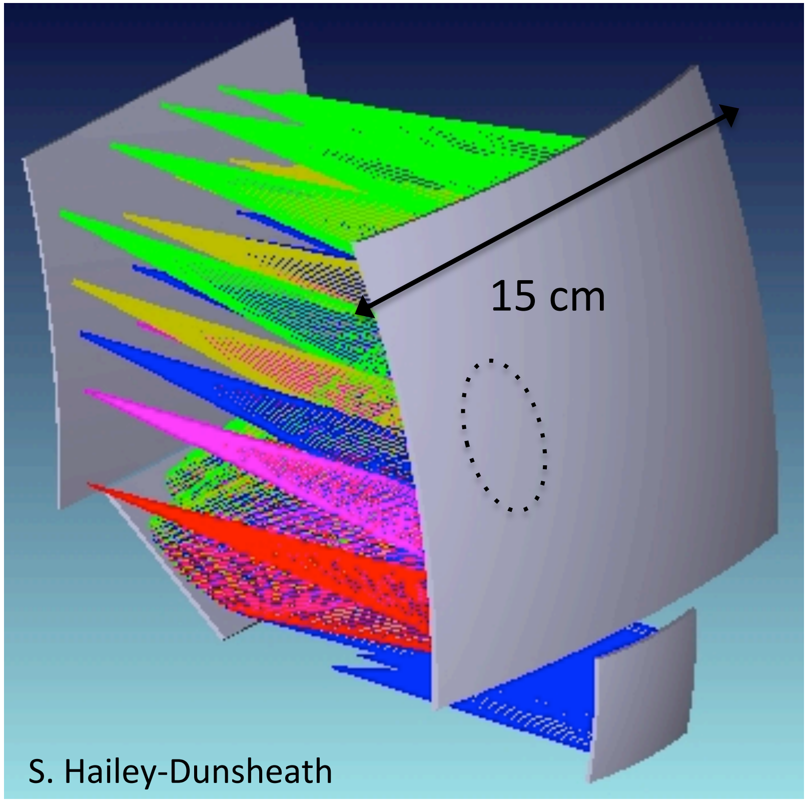
Example Programs

5 years at 75% efficiency = 33,000 hours

- Individual Galaxies – pointed follow up spectroscopy.
  - 3,000 galaxies at an average of 1 hour each (e.g. z=6)
    - Automatically surveys 0.12 to 7 deg^2 (39…400 microns) (to the 4e-21 depth)
  - 10,000 galaxies at 0.3 hours each (z=2)
    - Automatically surveys 0.4 to 23 deg^2
  - Efficiency for full-band spectra depends on band-to-band multiplexing.
- Blind spectral survey of 10 square degrees (e.g. 2 fields at ecliptic poles). 3000 hours gives 7e-21 W m^{-2} survey RMS at 40 μm (7e-22 W m^{-2} at 400 μm).
  - Many galaxies detected individually.
    - E.g. 70e6 voxels at 300-450 microns, ~2e6 have detectable CII, LIRG depth.
  - Tomography shows clustering in the residual signal, absolute line luminosities and line ratios for everything, including the faint end of the luminosity function.
  - For wide fields, not dependent on details of band / band multiplexing.
- 5,000 protoplanetary disks candidates, average time: 1 hour.
  - Fully evolutionary range. Distances ranging to few kpc, gas masses down to 0.03 solar.
- Imaging – all sky at 100 microns in 4000 hours (4000-beam camera)
- Adds up to 18 k hours.

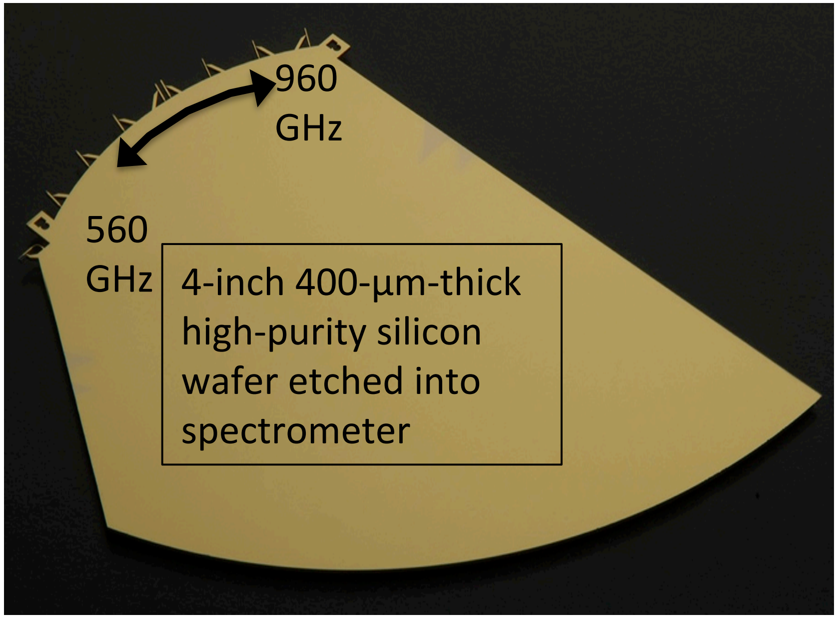
Spectrometer Concepts – 1) Slit Fed Echelle Grating

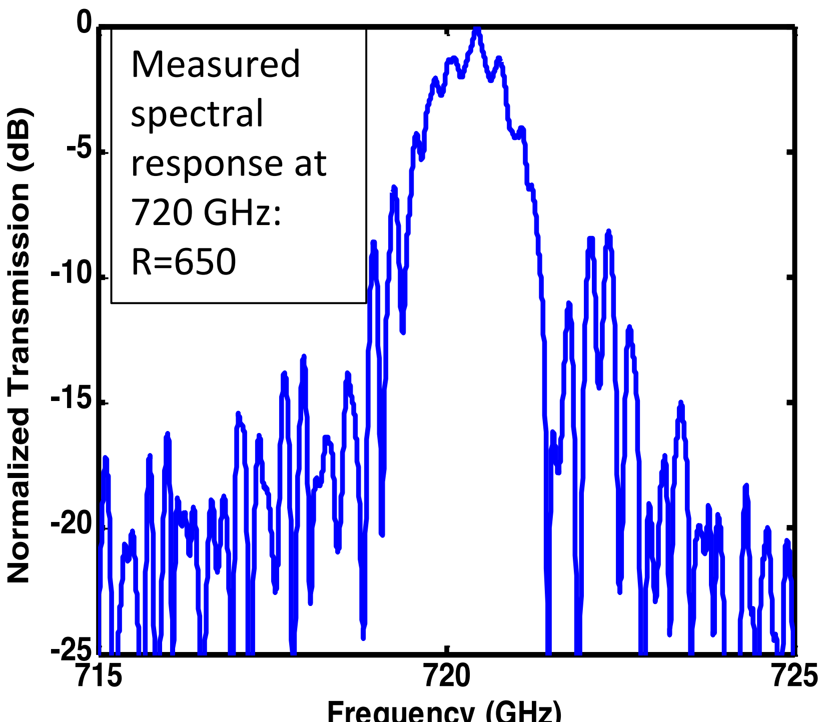




- 165-beam long slit.
- 1:1.5 bandwidth, all diffraction limited.
- Dimensions for 100 micron central wavelength, R=400.
- Estimated masses scaled from this to our bands & R=500: range from 3.5 kg (38 μm) to 27 kg (170 μm).

Spectrometer Concepts (2): Silicon-Immersed Waveguide Grating

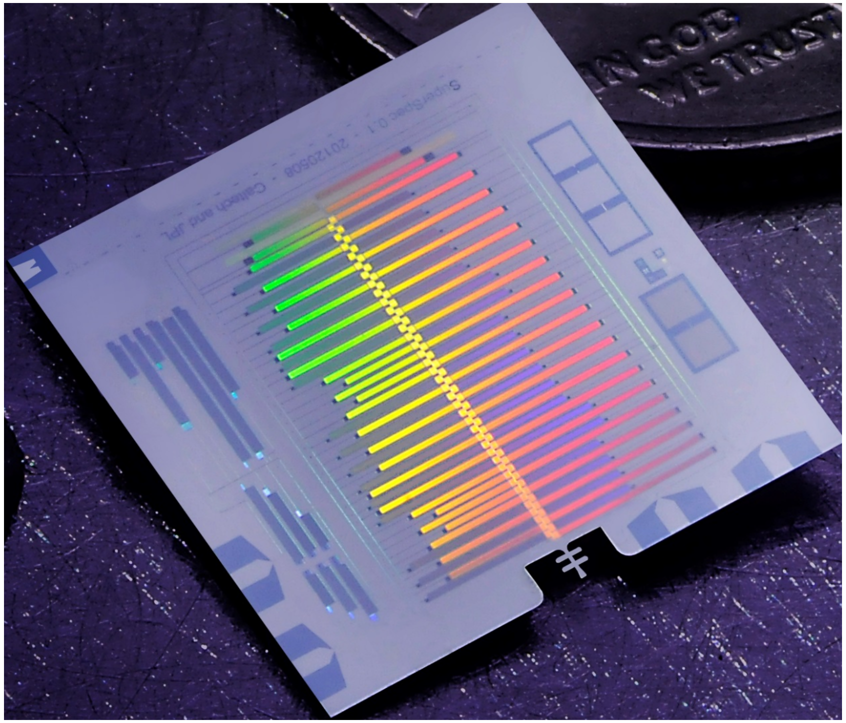


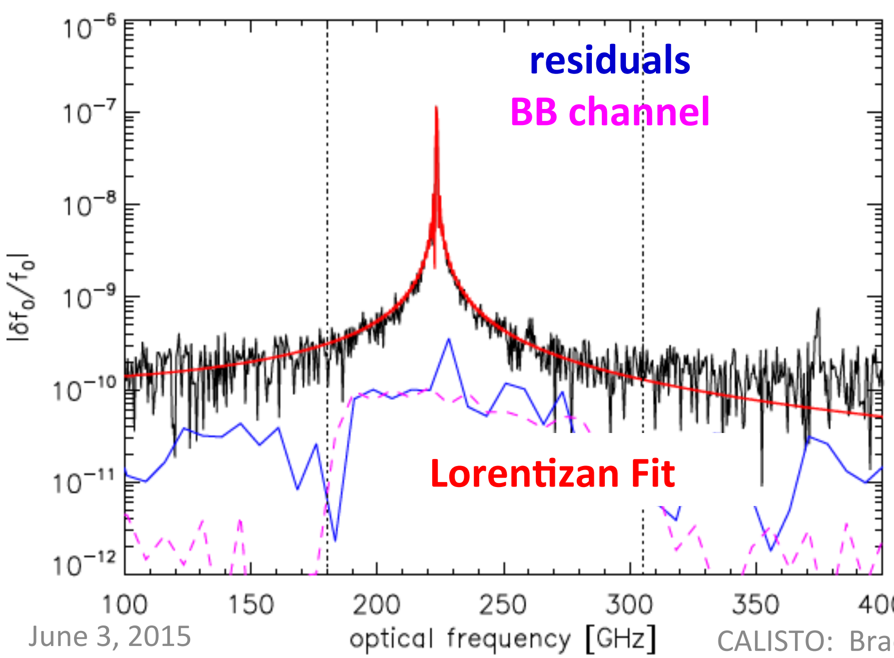


- Curved grating in parallel plate waveguide. Single polarization, good efficiency over 1:1.6 bandwith.
- Demonstrated at λ=1.3 mm, R=300 in Z-Spec at CSO (free-space propagation medium).
- Now demonstrated R=700 device in float-zone silicon wafer with warm test.
- End-to-end efficiency test and integration with detectors coming.
- Stack these into quasi-slit-spectrometer with line of 2 fλ feeds.
- **Stack of 100, with detectors in 2-D sub-arrays on planar facets on the back of the stack:**
- Wafer size ranging from 31 mm to 71 mm (λ=165 to 400 µm).
- Mass estimate: ranging from 5 to 13 kg (λ=165 to 400 µm).

Echternach, Reck, Pepper, Bradford, Hodis @ JPL

Spectrometer Concepts (3): SuperSpec on-chip spectrometer





- Filterbank patterned in Nb / SiN / Nb microstrip.
  - Suitable for ν<700 GHz
  - NbTiN, could extend to 1.5 THz.
- Integrated array of TiN KIDs
- Demonstrated R=700 spectrometer, so dielectric loss bounded (Q_{loss} ~ 1400)
- Detector NEP below 1e-17
- End-to-end system sensitivity demo underway.
- Full chip size on order 10 cm^2 for a single 200-channel spectrometer.
- Can be arrayed in 2-D.

Shirokoff (Caltech -> U. Chicago), Hailey-Dunsheath, LeDuc, Bradford, Zmuidzinas (Caltech / JPL) + others

µ-Spec: An Ultraminiature Broadband Submillimeter Spectrometer for Space Astrophysics

PI: S. Harvey Moseley/NASA-GSFC

GSFC Team Members: Emily Barrentine, Ari Brown, Giuseppe Cataldo, Negar Ehsan, Wen-Ting Hsieh, Omid Noroozian, Thomas Stevenson, Kongpop U-yen, and Edward Wollack

The high-efficiency µ-Spec instrument works as an analog to a grating spectrometer at 300-750 GHz, in which phase delay is introduced on superconducting microstrip transmission lines on a low-loss single-crystal Si substrate.

This instrument would enable a wide range of spectroscopy missions, which have been impossible due to the challenges of meter-scale cryogenic spectrometers in space

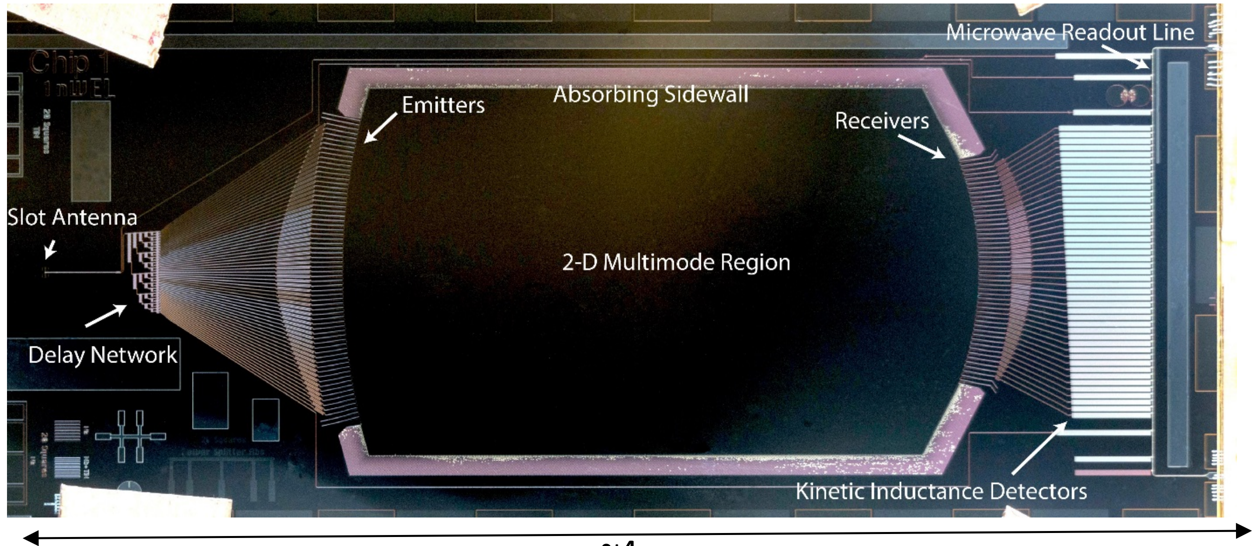
Current Status:

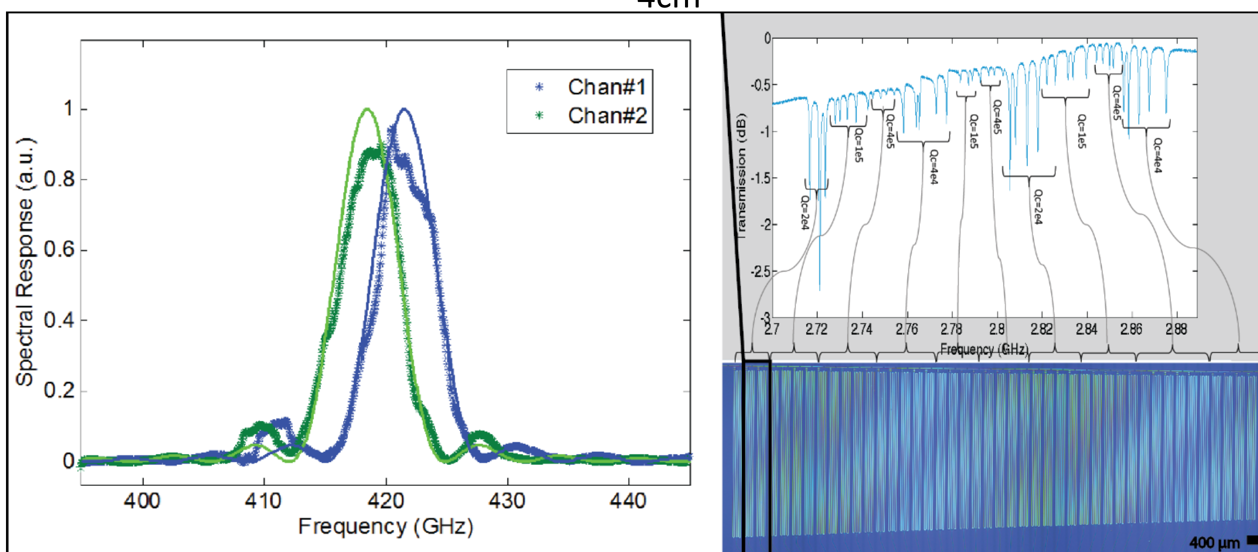
- A µ-Spec prototype with R=64, including all the spectrometer components, has been demonstrated with design resolution and absolute frequency in the laboratory environment.

Future plans (1-3 Years):

- Develop R=256/512 prototypes with balloon-borne sensitivities
- Determine the path to developing up a resolution of R~1500, for space applications (300-1 THz).

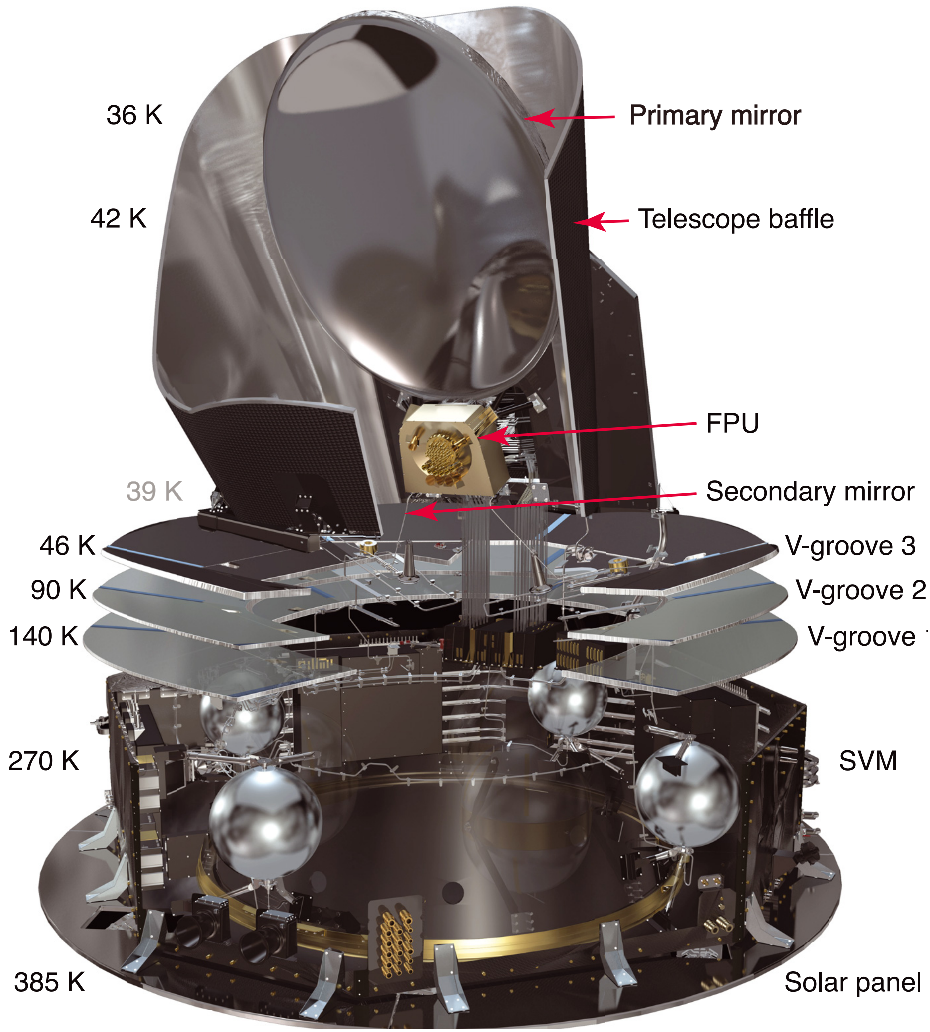
R=64 Prototype demonstration:





Thermal Design Strawman

Planck: heritage for passive design

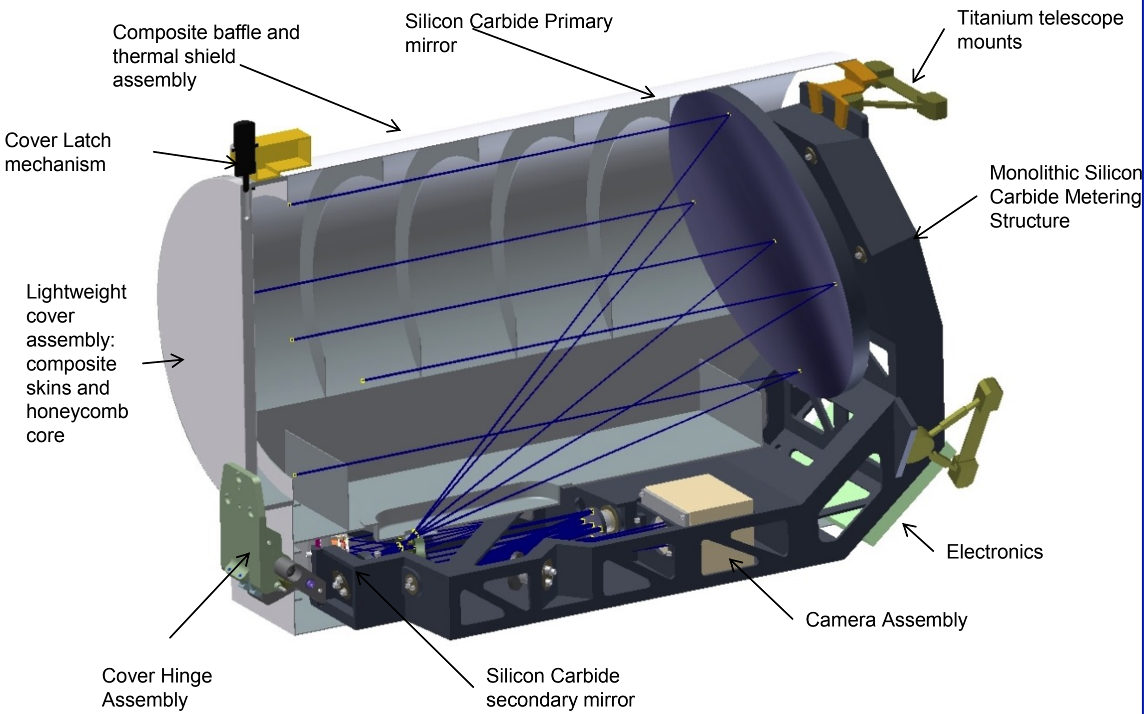


- Closed cycle coolers integrated with passive V-groove system, including breakaway struts.
- Sumitomo and US coolers, lift at 4.5-6 K and 20 K.
  - Sumitomo: 2500:1 at 4 K, 450:1, 18 K
- Estimated requirements:
  - 4.5 K: 150 mW, 100 mW parasitics , 50 mW support for sub-K coolers.
  - 18 K: 1.5 W, parasitics plus amplifiers
- Requires 2000 W including 2x margin.
- Entire 100 kg instrument cooled to 50-100 mK.
  - Multiple options exist, both ADRs, dilution systems demonstrated in space.
  - BLISS continuous sorption + ADR demonstration: 5 mW at 4.5 K, 2 mW at 1.7 K per 10 K of cooled mass.
- DiPirro presentation Thursday

Downlinking CALISTO Data

- Total power detectors sampled continuously.
- 16 bits at 100 Hz, 0.25M pixels = 0.5 Gbit / sec, 35 Tbits / day
  (Compare: Euclid 0.85 Tbits / day, WFIRST baseline raw: 52 Tbits / day)
- Will need some on-board processing and/or compression

Deep space optical transceiver (33 kg, 110W)



- Optical communications promising
  - 622 Mbits / sec demonstrated from the moon with LADEE.
  - Pushed by Planetary programs, featured in Discovery call
  - L2 a good optical comm (always night)
- Strawman based on these experiences: 1.6 W transmit power in 22-cm telescope linked to 3-meter receiver on Earth: 1 Gbit / sec at L2. *(Bill Farr, JPL)*

CALISTO Cost Estimate

JPL Team-X 2008

Item	Cost [$M '08]
Management, Systems Eng., Mission Assurance	101
Payload System (primarily science instruments)	196
Flight System (incl. sunshield, telescope, coolers)	608
Operations and Ground Data System	132
Launch Vehicle	156
Assembly, Test and Launch Operations	53
Science	114
Education, Public Outreach	6
Mission Design	10
Reserves	330
Total Estimated Project Cost	1,706

- Should be revisited, but clearly less than competing flagship-class facilities (JWST, LUVOIR)
- Now advocating more capable instrumentation than '08.
- Analogy: Herschel, $1.1 B, Planck $700 M per ESA.

Why a Heterodyne Instrument?

The only way to get sufficient frequency resolution to spectrally resolve line emission from sources in the Milky Way & nearby galaxies is to use heterodyne (mixing) systems

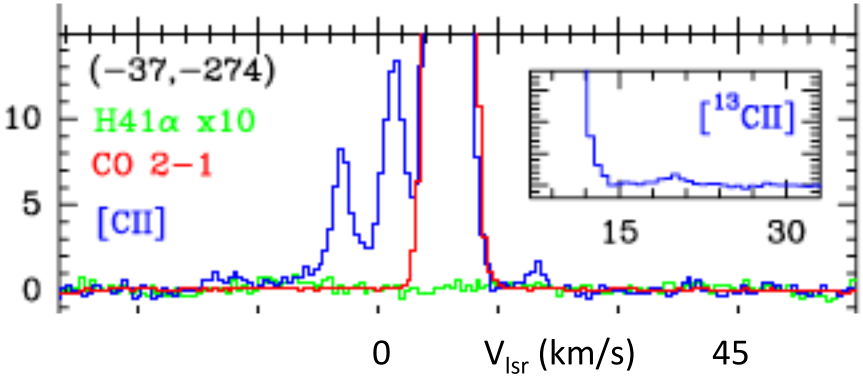
This applies to objects including comets, asteroids, planetary atmospheres, protostellar disks, cloud cores, YSO dark clouds, YSO outflows, shocks, GMCs, the Galactic ISM, and nearby Galaxies

Herschel HIFI, and SOFIA GREAT have shown potential for submillimeter velocity-resolved spectroscopy but there is enormous potential just now starting to be available. This should be factored into consideration of any beyond-2020 mission, such as a FIR Surveyor

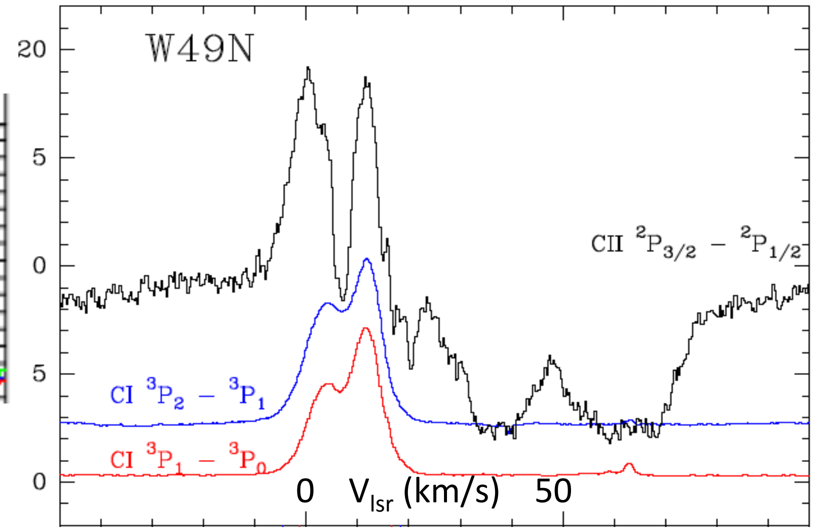
Key aspects

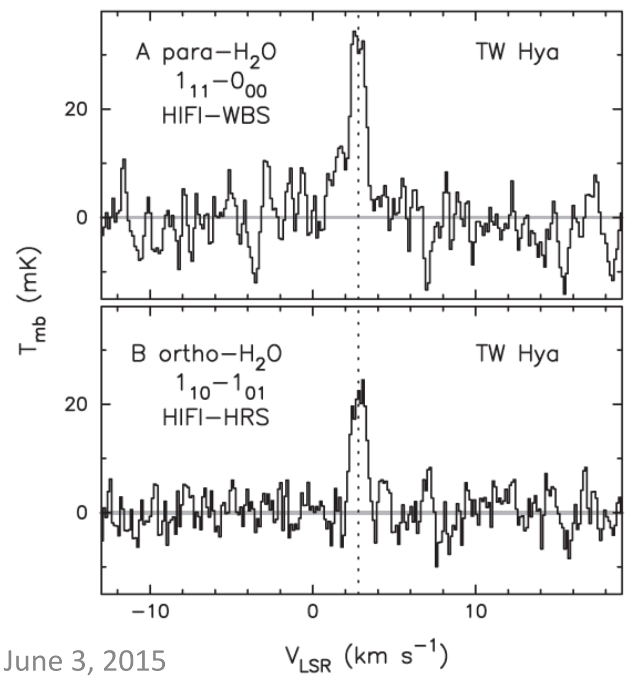
- More powerful and flexible LO sources
- Greater instantaneous bandwidth
- Focal plane arrays with sizeable pixel count
- Mixer operation at higher temperatures
- Low power, broadband digital signal processing
- Multi-frequency receivers

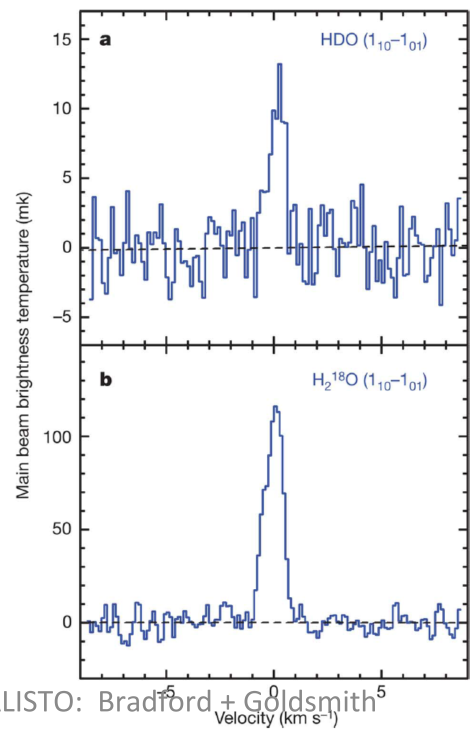
Some Examples of Resolved Spectral Lines

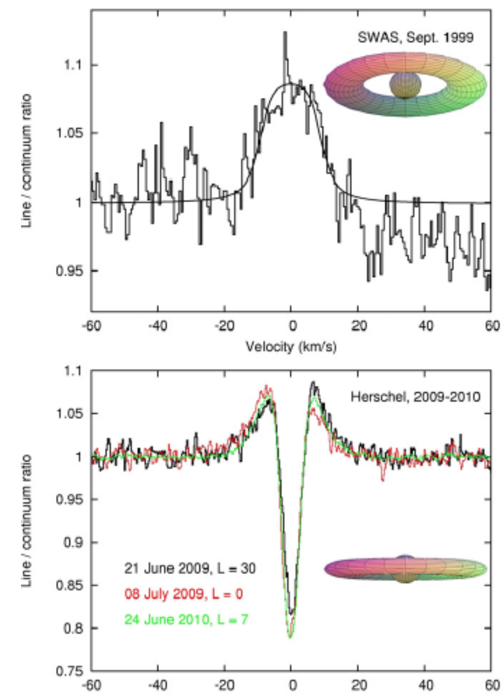


[CII] in Orion



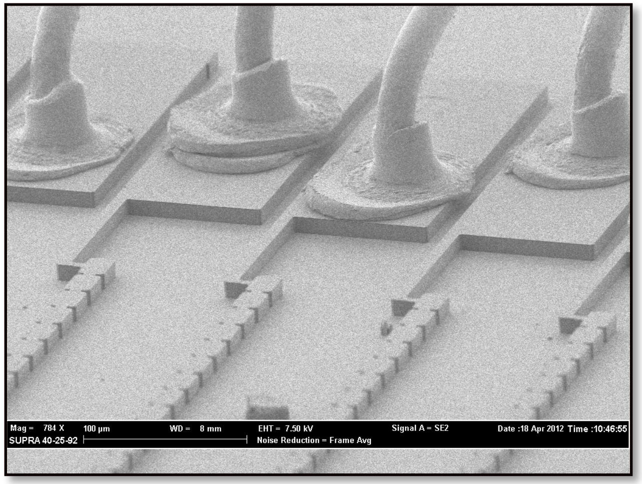


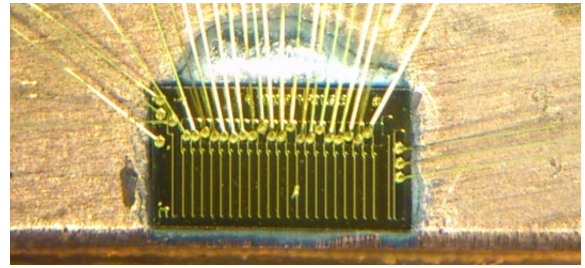




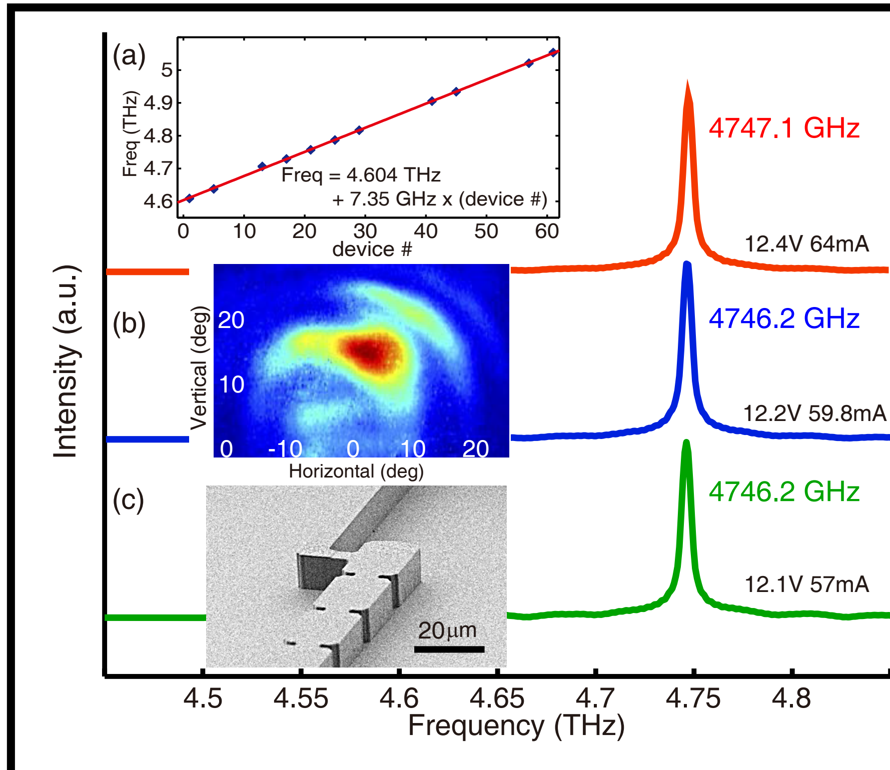
Quantum Cascade Laser (QCL)

Rapidly-developing technology for local oscillator at "short" submm wavelengths





J.R. Gao TNW



Kloosterman et al. APPLIED PHYSICS LETTERS (2013)

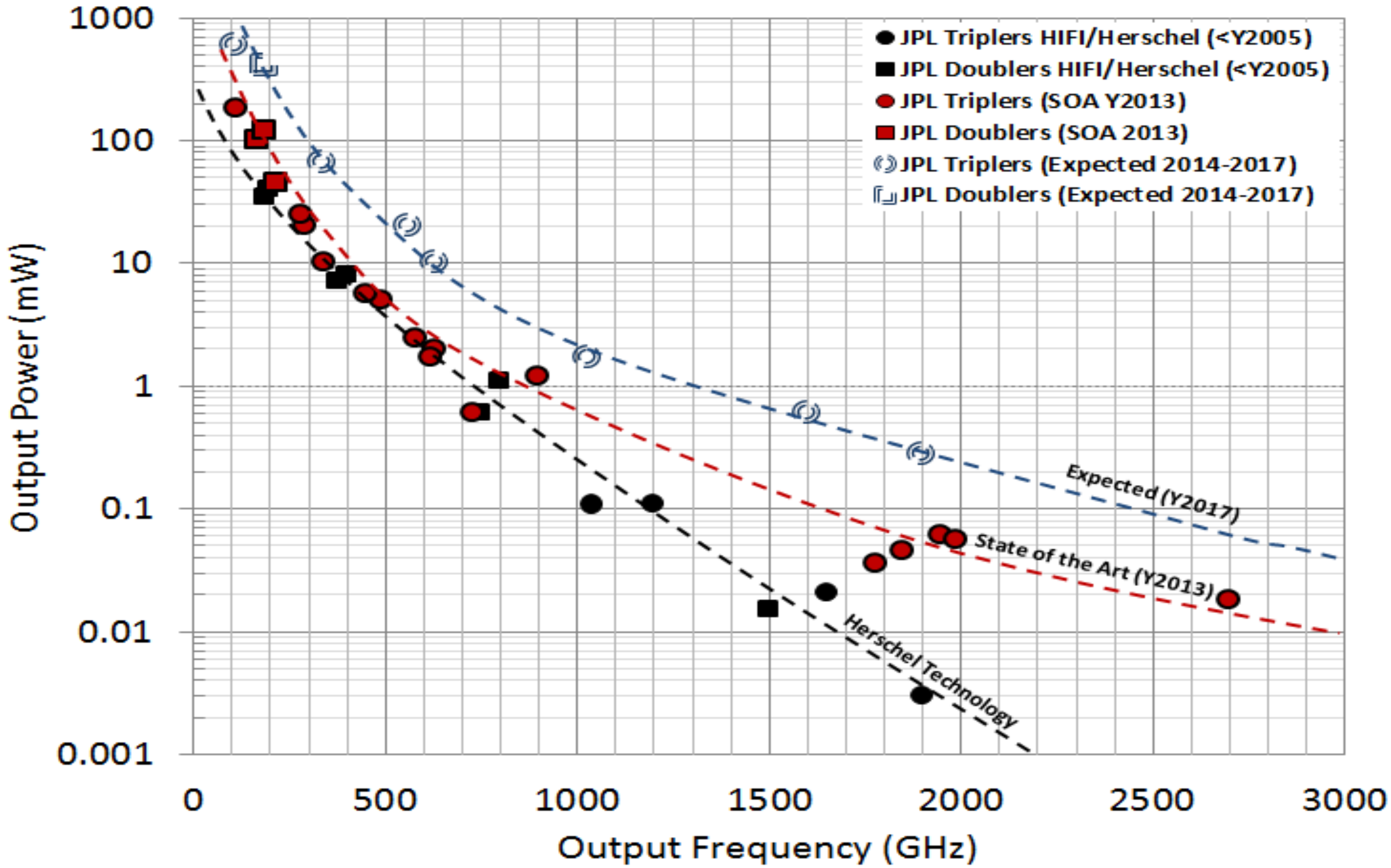
4.7 THz QCL from SRON used as LO with HEB mixer

- Tuning range: 1.5 GHz
- Tuning coefficient: 2.4 GHz/V
- THz pwr output: 0.25 mW
- DC power requirement: 0.8 W @ 15 K
- Operating Temp.: up to 77 K

QCL used in 4.7 THz channel for upGREAT instrument on SOFIA

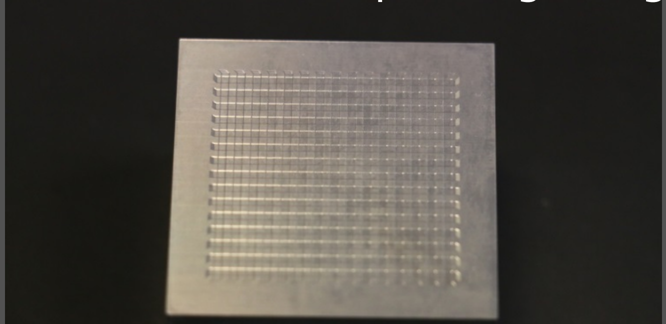
GaAs Terahertz Frequency-Multiplied Sources

Room-temperature Schottky diode based multiplied sources

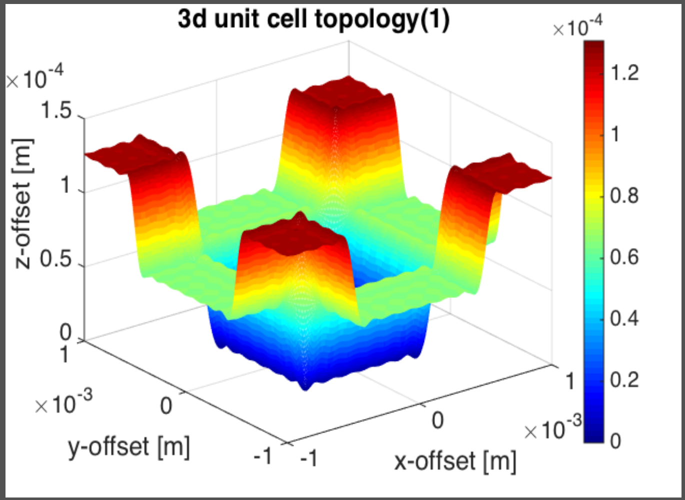


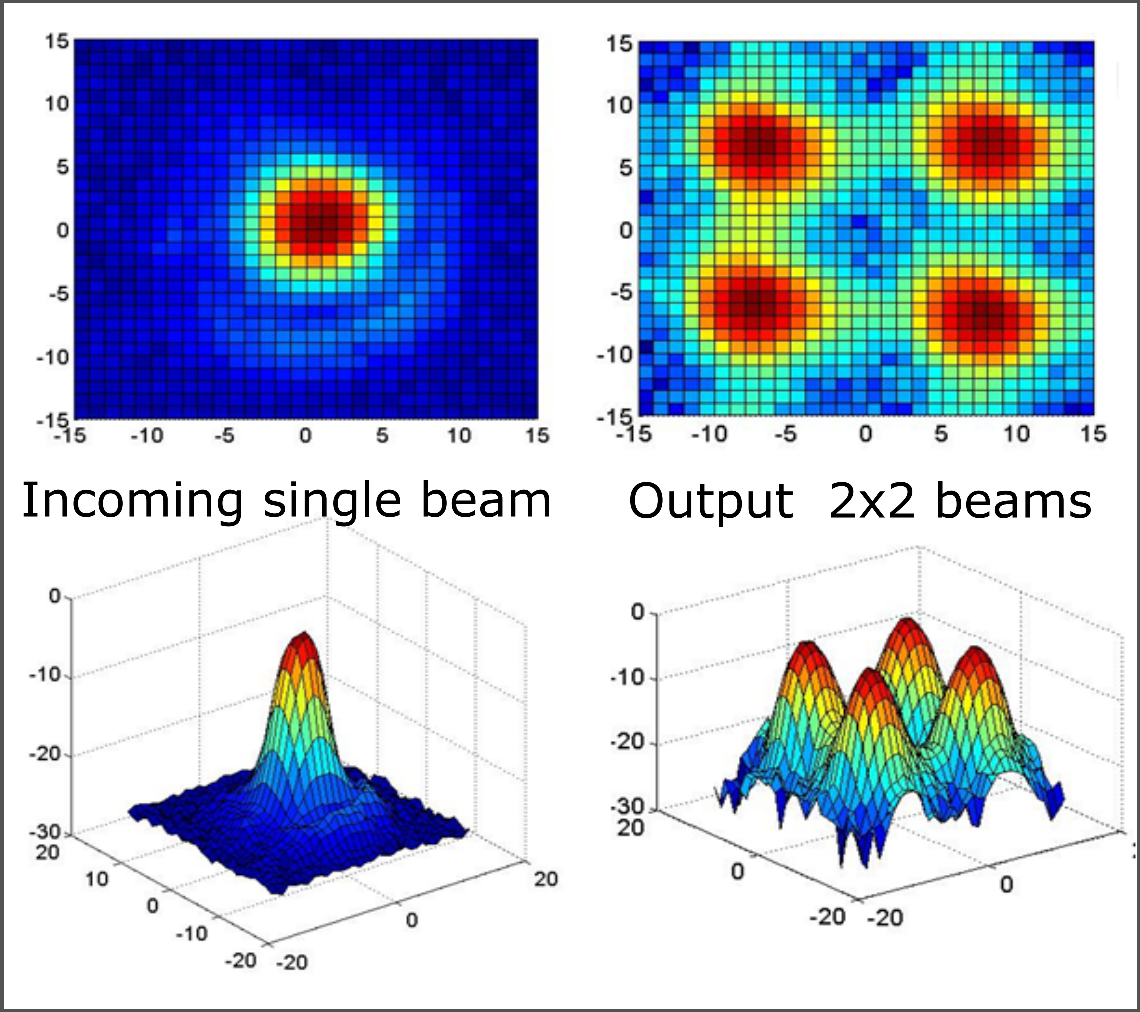
Fourier Phase grating to generate 2x2 LO beams

Reflective Fourier phase grating



Material: Al



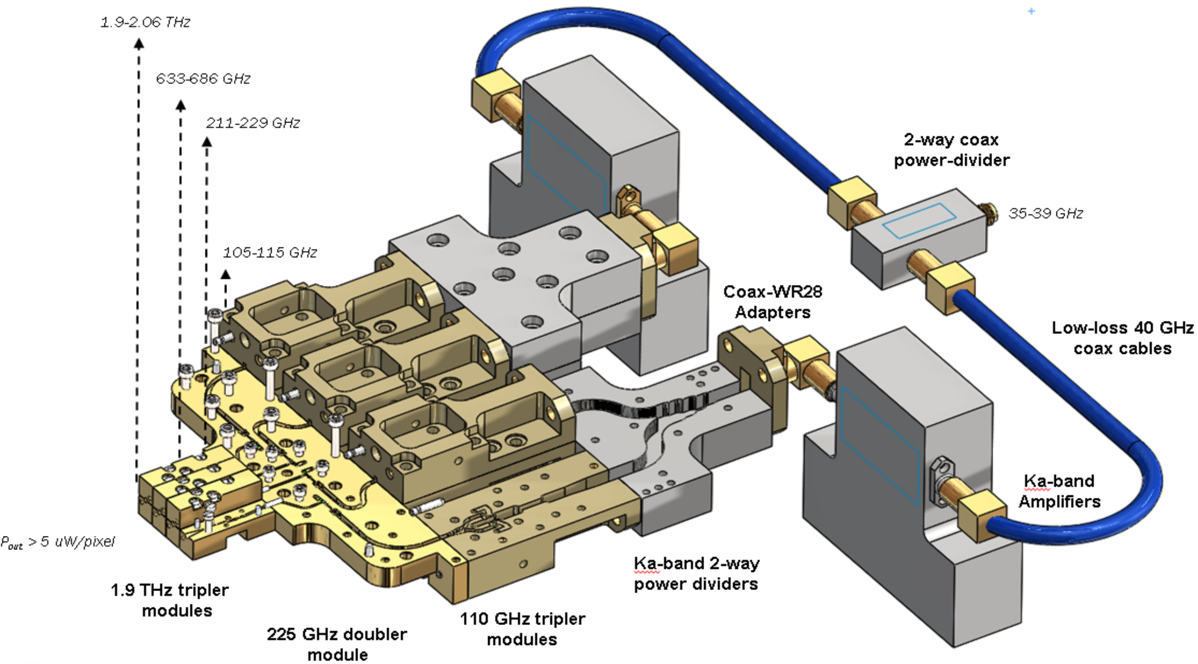


Incoming single beam

Output 2x2 beams

Demonstrated experimentally at 1.4 and 5.3 THz at SRON/TU Delft

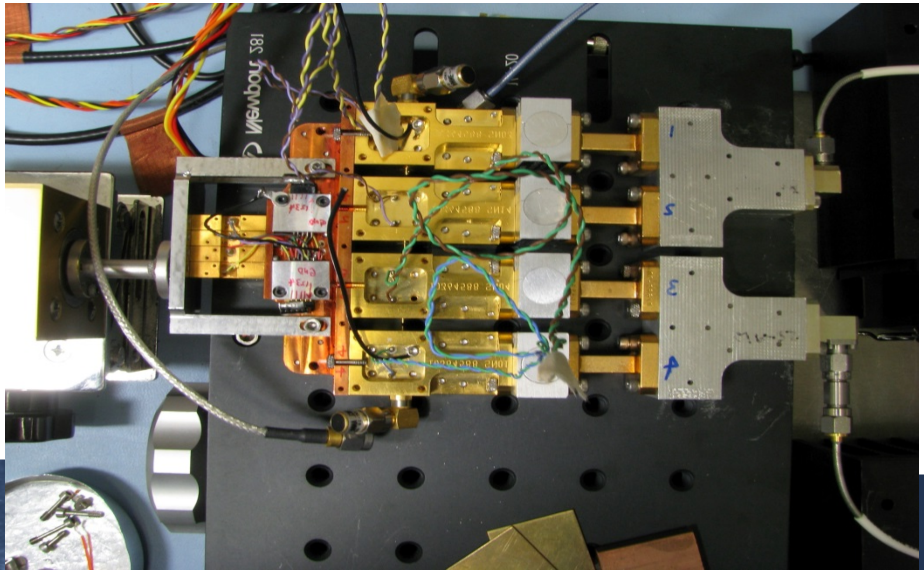
4-Pixel 1.9 THz Local Oscillator Subsystem



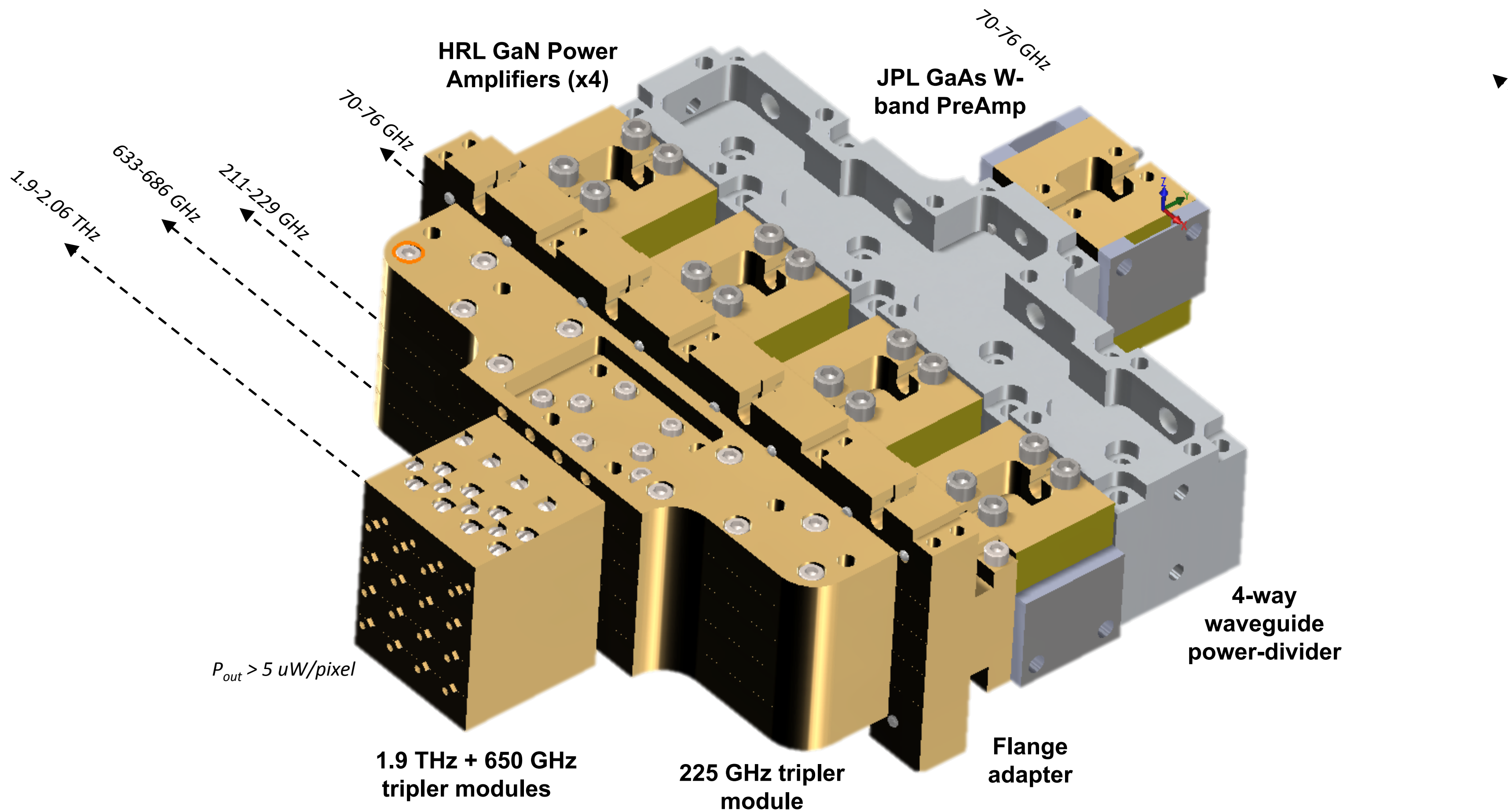
More than 10 uW per pixel measured

J. Siles

20 cm x 20 cm x 10 cm



Extending Array Architecture to 16 pixels



J. Siles & Imran Mehdi

Mapping Speed with Heterodyne Array

Assume equivalent 5m dia telescope
Main beam solid angle = 9e-10 sr +. 3.3e5 beams/sq. deg.

Assume T_{sys} = 2000 K(SSB)
Δv = 2.4 km/s (16 MHz)
t = 25 s (no overhead and OTF with shared longer REF pos)

ΔT = 0.1 K rms (good for Galactic survey)

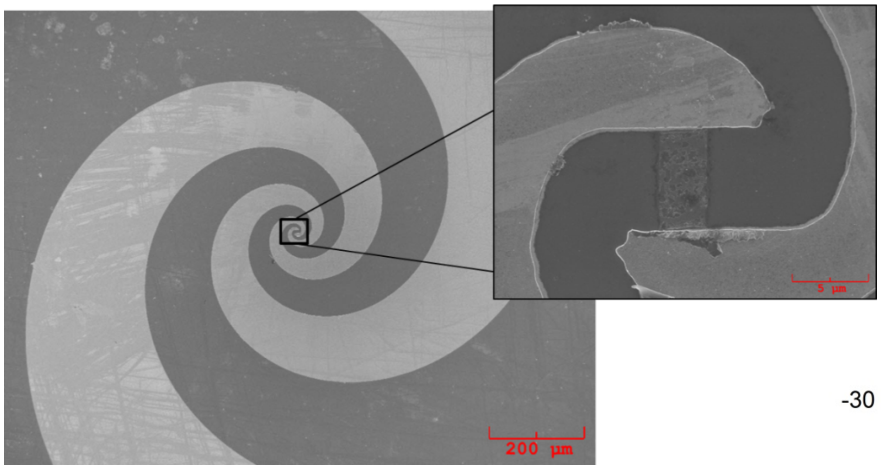
TIME = 2292 hr/Npix per square degree

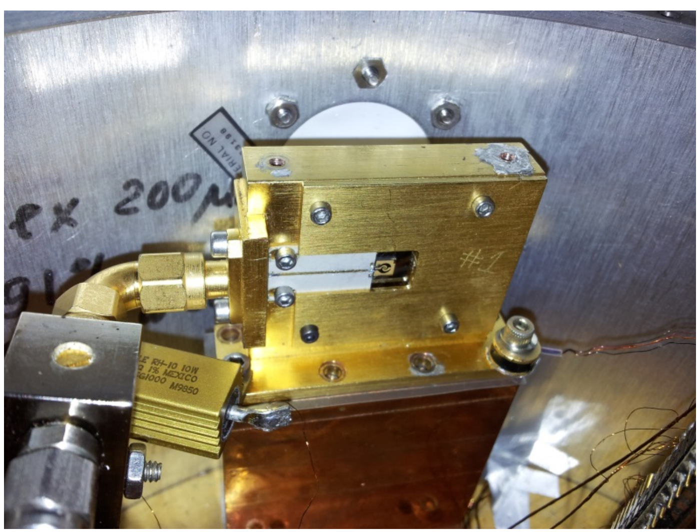
= 143 hr/sq. deg. for 16 pixels
= 36 hr/sq. deg. for 64 pixels

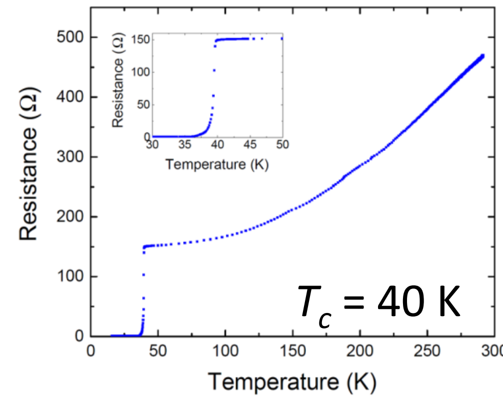
With 64 pixel array for [CII]
2000 hr: 60° x 1° map of Galactic plane with 8" resolution
~30 hr: map of LMC (2 pc resolution)
~9 hr: full map of M51 (30 pc resolution)

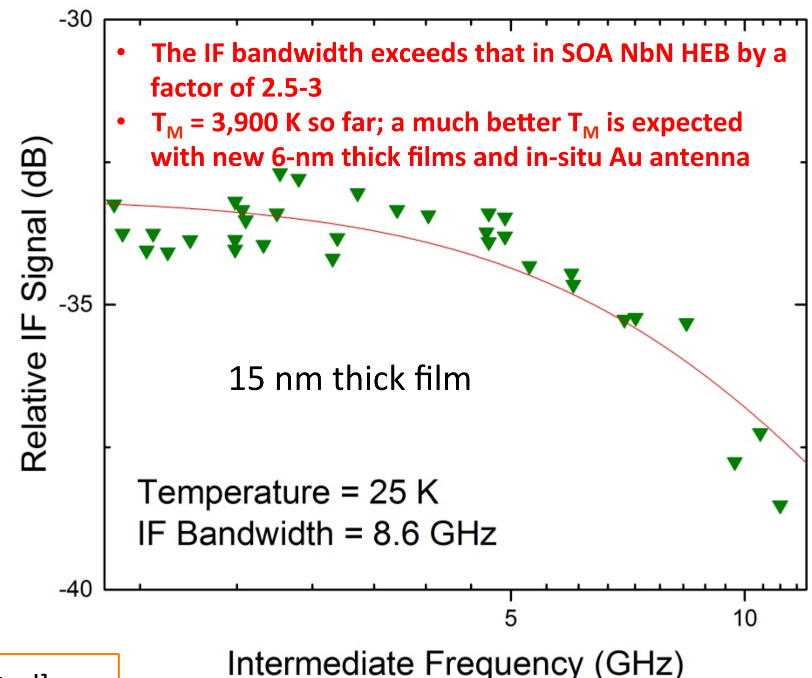
MgB_2 Hot Electron Bolometer Mixer for High Resolution THz Spectroscopy

D. Cunnane, J. Kawamura, and B. Karasik (JPL)
M. Wolak, N. Acharya, T. Tan, and X.X. Xi (Temple Uni.)









Proc. SPIE, Vol. 9153, 91531Q (2014) ASC2014, 1EOr1C-02. [Invited]

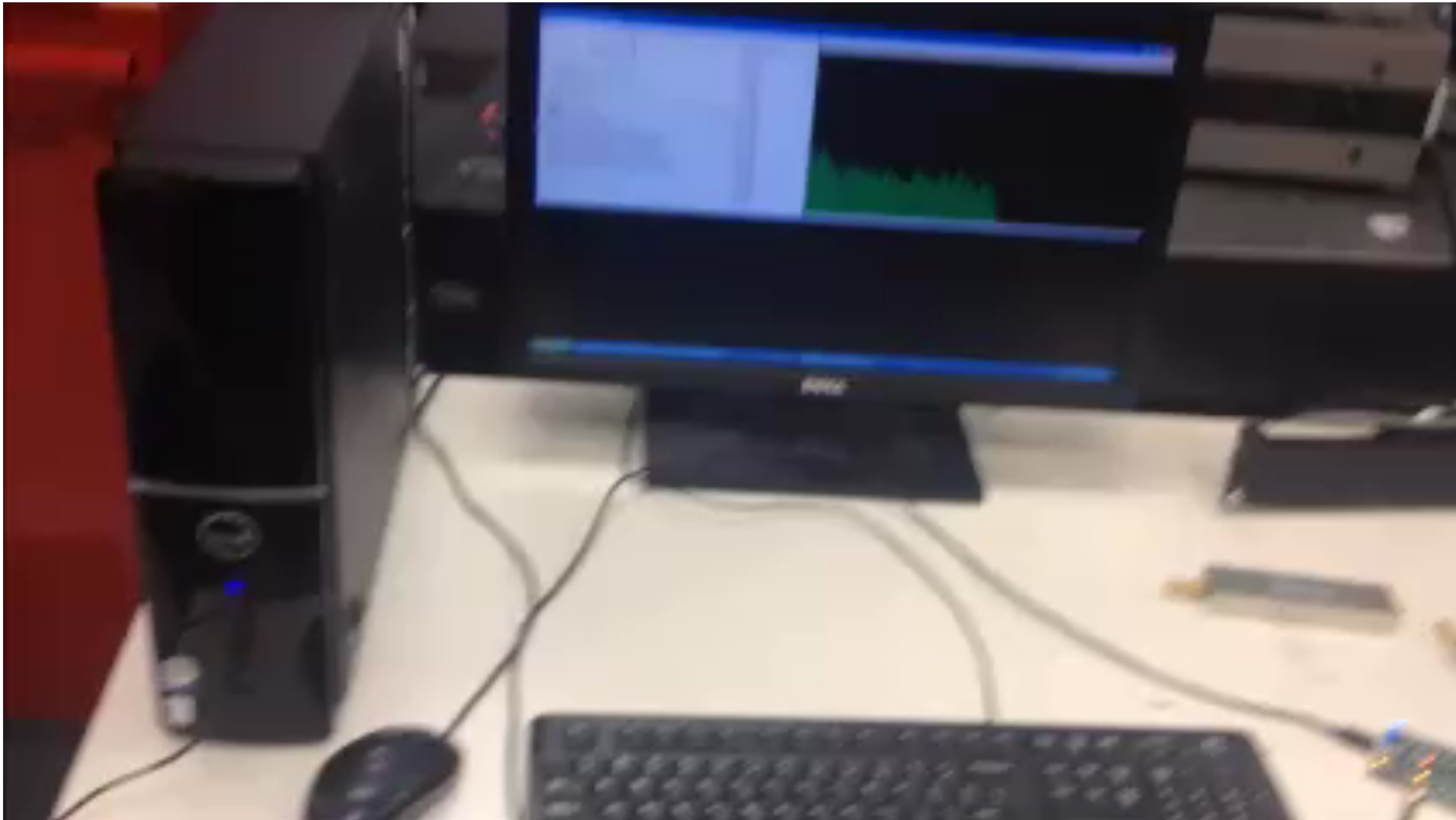
Spectrometer for Heterodyne Receivers

This has been an issue at mm/submm wavelengths because **of required large bandwidth** and multiplicity of lines

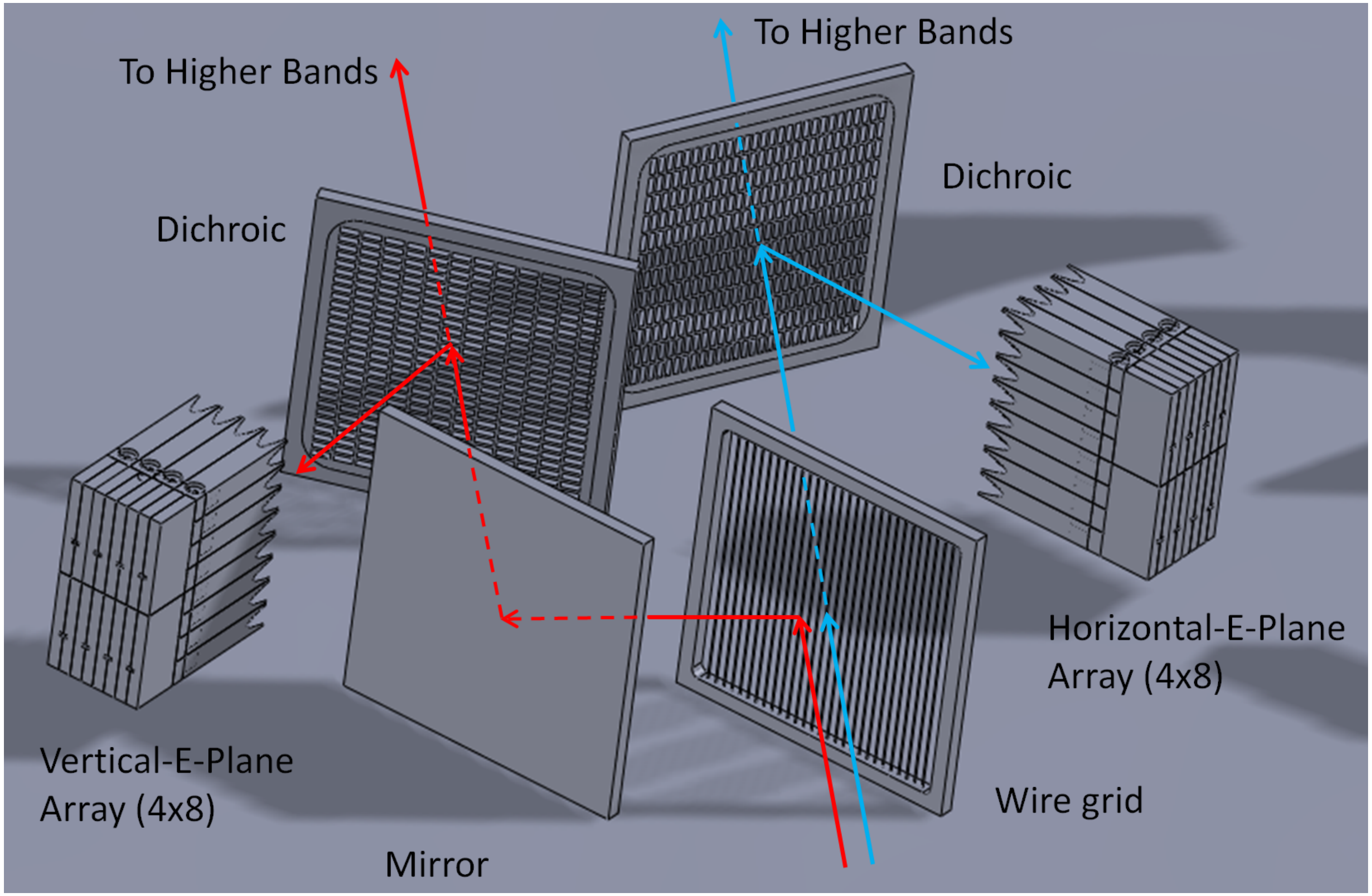
Solutions have included filterbanks (typically used on atmospheric sounders), chirp spectrometers (low power; used on planetary missions), and acousto-optical spectrometers (complex, heavy; used on SWAS (SMEX) and Herschel/HIFI)
Digital signal processing, offering many advantages, is now feasible but FPGA approach is relatively power hungry (~4W/GHz BW)
Ideal technology is custom VLSI using technology developed for cell phones and other communications systems
Dr. Adrian Tang at JPL has unique partnership with UCLA team and Qualcomm for development of CMOS VLSI chips for NASA applications

"SPECTROCHIP II" has 1000 MHz bandwidth, 512 spectral channels, includes digitizer, data accumulator, and USB output interface
5x10cm size on board with support circuitry; 200mW DC power

Next generation (Dec 2015) will have ≥ 2 GHz bandwidth, 8K channels



Dichroic Plates Enable a Multi-Frequency Receiver



Schematic showing how wire grid polarizer & dichroic plates could be used in a multi-frequency dual-polarization focal plane array receiver.

Summary

Recent technological development make possible multipixel high-bandwidth heterodyne receivers with tunable LO's and low-power digital spectrometers

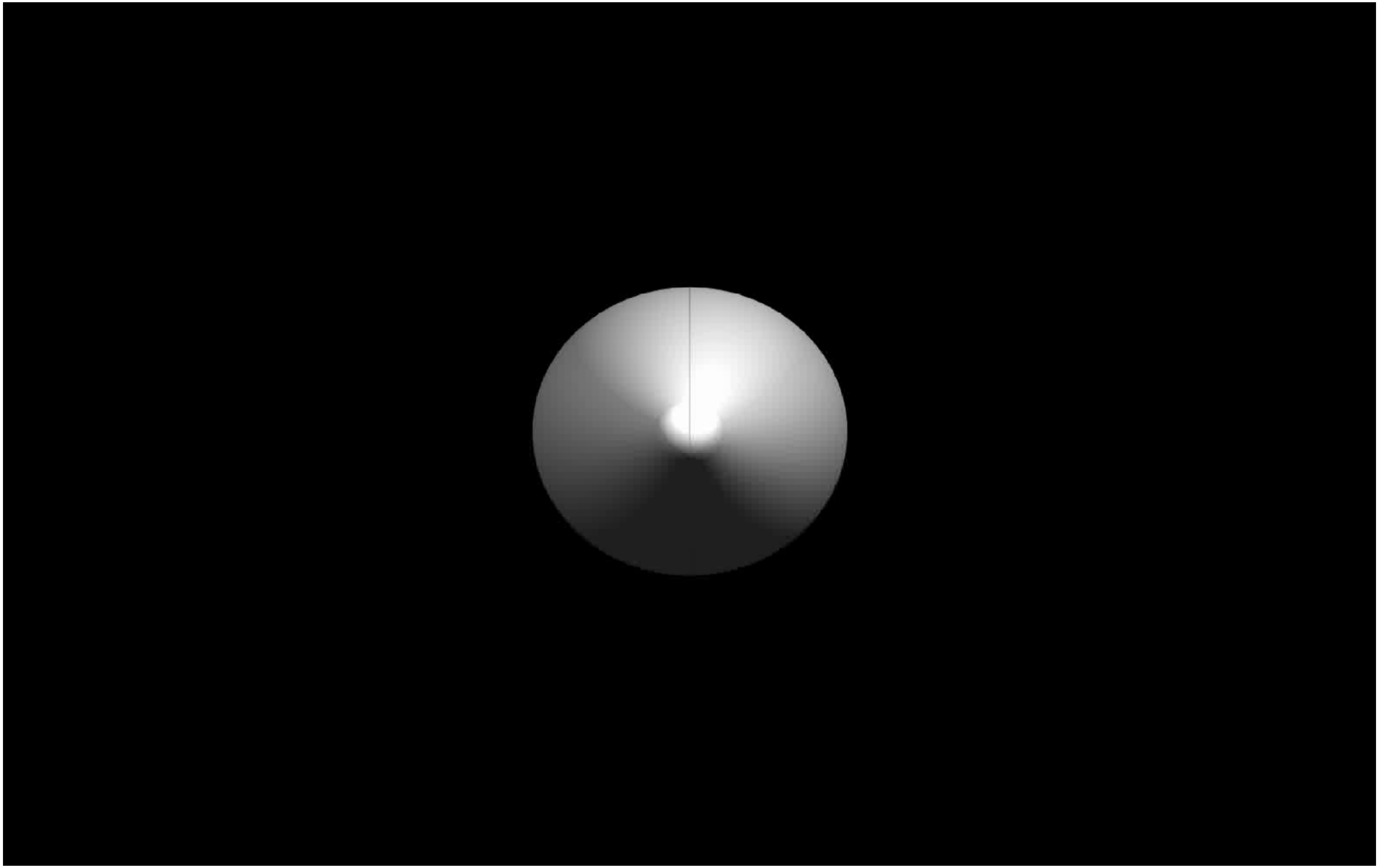
These can be most effectively deployed for spectral imaging of astronomical sources where velocity resolution of 1 km/s to few km/s is justified

A plausible heterodyne instrument for FIR Surveyor could have 16 to 64 pixel arrays for H_2O, [CII], HD, [OI]…

A key question is which lines with what priority, and how many pixels vs. how much frequency coverage

Multi-frequency (simultaneous) operation offers many advantages including faster mapping speed & improved ability to study variable sources

Telescope Concept



CALISTO Tables

1 σ

Table 1: CALISTO Spectrometer Backends: R=500 Strawman Design

Parameter	40 μm	120 μm	400 μm	Scaling w/ $D_{\rm eff}$
Dominant background	zodi dust	zodi. + gal. dust	tel. + CMB	...
Photon-noise limited NEP [W $\rm Hz^{-1/2}$]	3e-20	3e-20	4e-20	...
Beam size	$1.9''$	$5.9''$	$19''$	$\propto D^{-1}$
Instantaneous FOV [sq deg]	4.0e-5	3.8e-4	2.3e-3	$\propto D^{-2}$
Line sensitivity $\rm W\,m^{-2}$, 5σ, 1h	4.2e-21	3.3e-21	3.2e-21	$\propto D^{-2}$
Pt. sce. mapping speed $[\rm deg^2/(10^{-19} W\,m^{-2})^2/sec]$	1.6e-4	2.4e-3	1.6e-2	$\propto D^2$
Surface bright. sens. per pix [MJy/sr $\sqrt{\rm sec}$]	4.2	1.1	0.33	$\propto D^0$

Notes: Sensitivities assume single-polarization instruments with a product of cold transmission and detector efficiency of 0.25 in a single polarization, and an aperture efficiency of 0.75. FOV estimate assume slit widths of 165 λ/D for the 40 and 120 μm examples, and 100 individual single-beam spectrometer backends for the 400 μm case.

Table 2: CALISTO Approximate Confusion Limits and Mapping Speeds

λ μm	Herschel σ_C mJy	estimated σ_C mJy	νL_ν z=2 $L_\odot$	νL_ν z=5 $L_\odot$	$\rm NEF_{inst}$ mJy$\sqrt{s}$	5×time s	5×time per sq deg h
50 μm	0.016	0.004	2.9e9	2.6e10	0.015	70	15
100 μm	0.15	0.038	1.3e10	1.2e11	0.024	2.1	0.11
200 μm	1.39	0.35	6.1e10	5.5e11	0.051	0.11	1.4e-3

Notes: Herschel σ_C values are based on a power law implied by the 100 and 160 μm map RMS values in PACS deep fields (Magnelli et al., 2013 [46]). We simply reduce this by a factor of 4 to obtain an estimated σ_C for CALISTO. Luminosity densities are then provided for 5× this depth, for z=2 and z=5. $\rm NEF_{inst}$ is the raw instrument sensitivity. Times to confusion limit are conservatively estimated at 5× the time required for the instrument per-beam RMS to equal σ_C. The time to a square degree assumes a 4000-beam camera.

Co-Eval SF history and BH growth

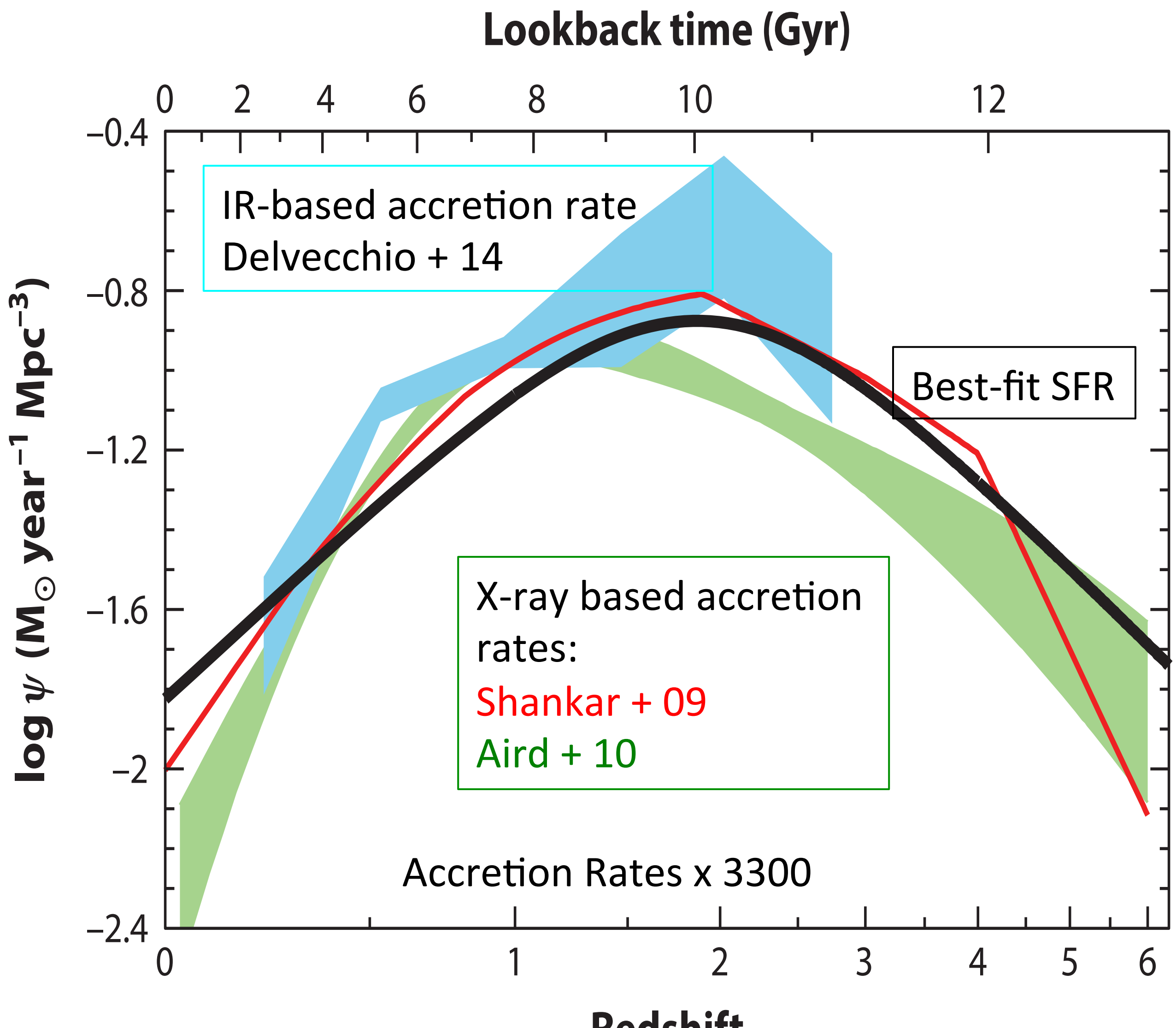
What is the real answer at z>4?

What sets the shape of this curve?

Why does BH growth track star formation?

Star formation seems to be driven by 'main sequence' galaxies, not mergers.

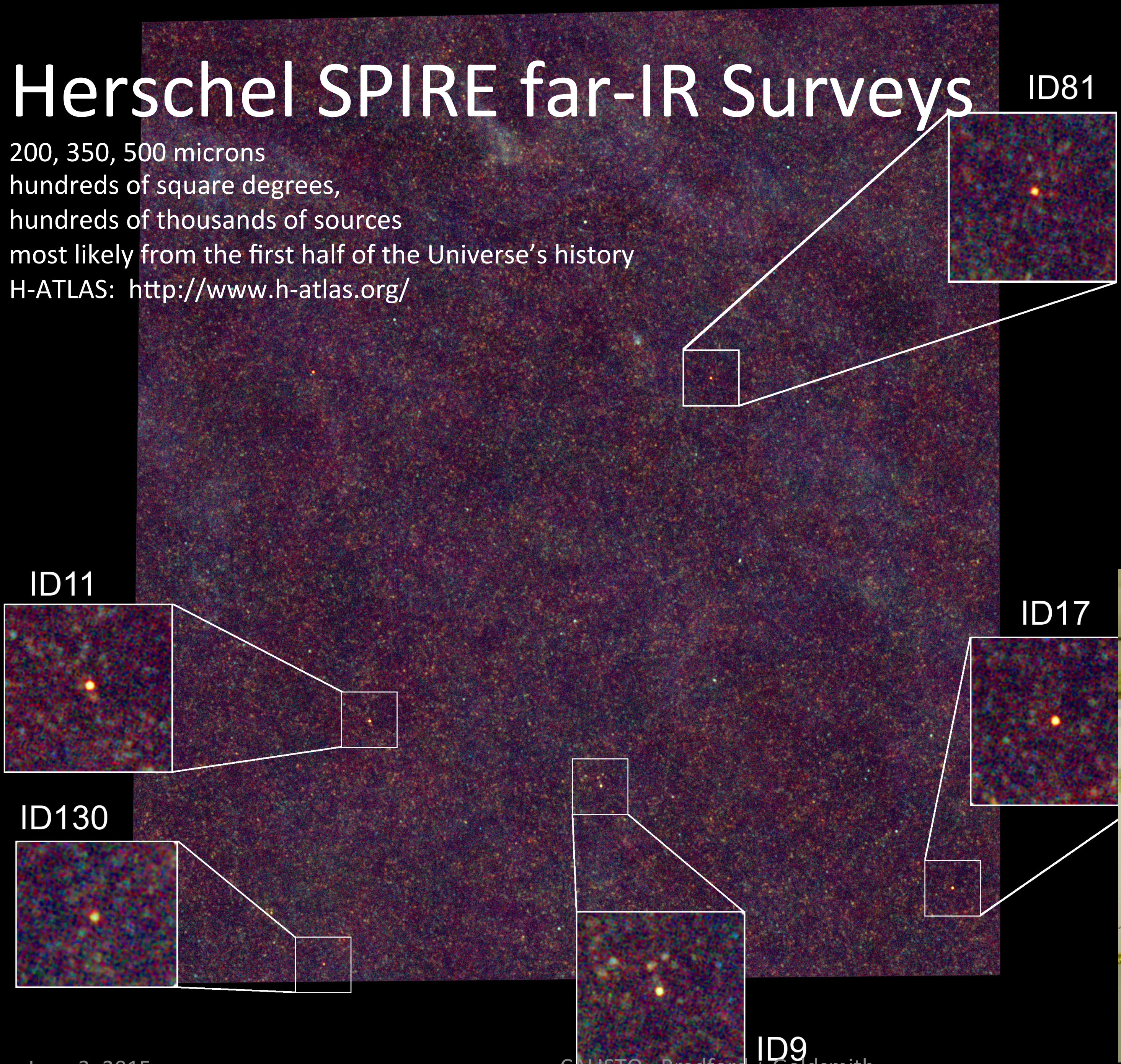
-> Balance of accretion rate with feedback processes. Interaction with stars / BH and the gas which forms them raw materials.

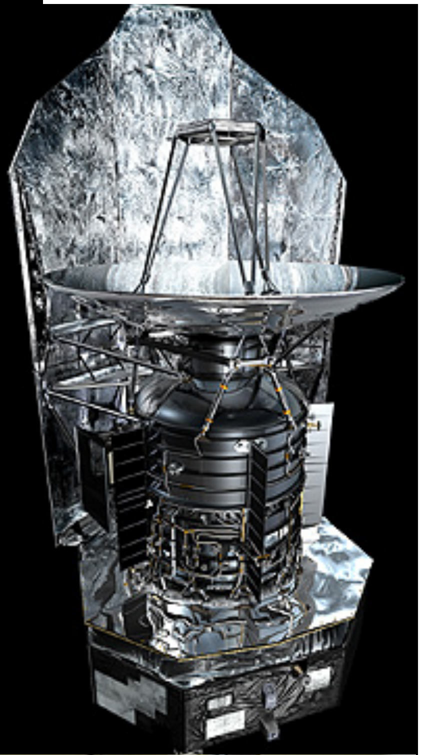


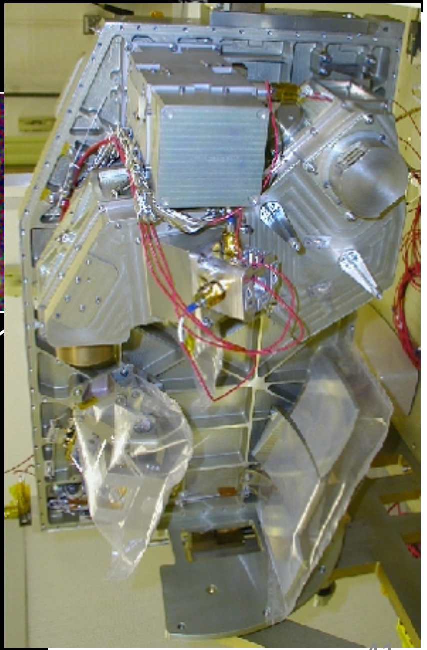
Madau and Dickinson ARAA 2014

Herschel SPIRE far-IR Surveys

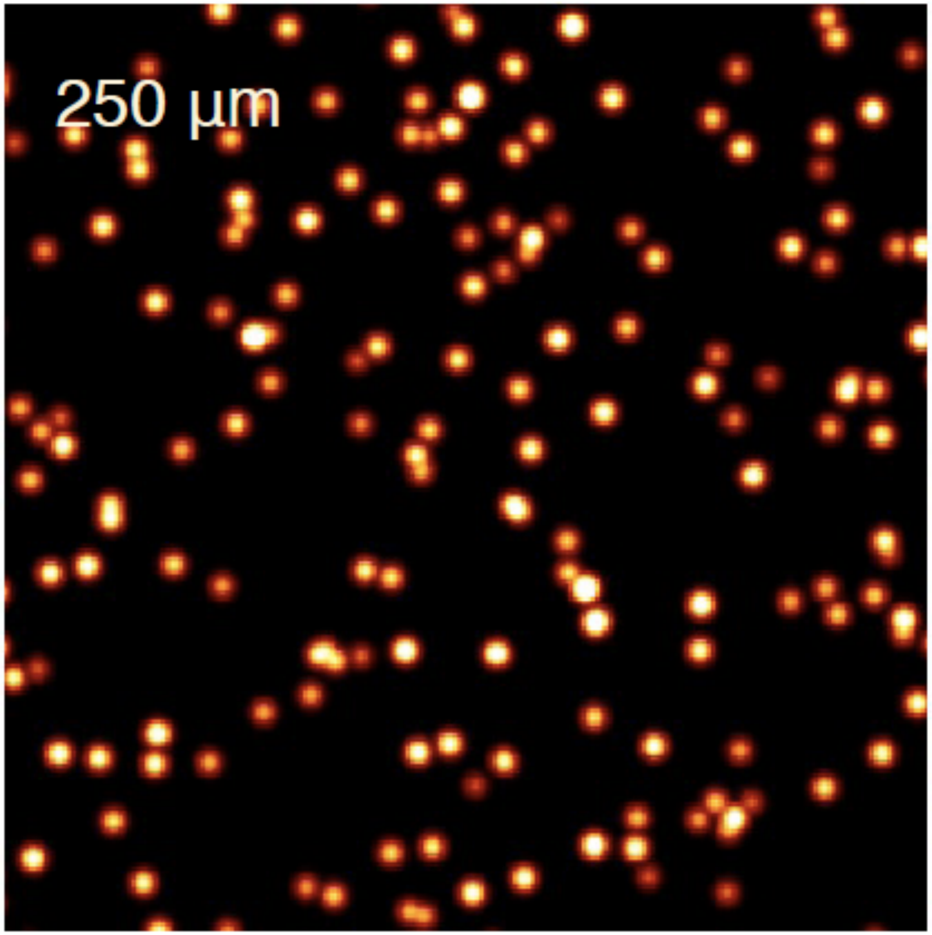
200, 350, 500 microns
hundreds of square degrees,
hundreds of thousands of sources
most likely from the first half of the Universe's history
H-ATLAS: http://www.h-atlas.org/



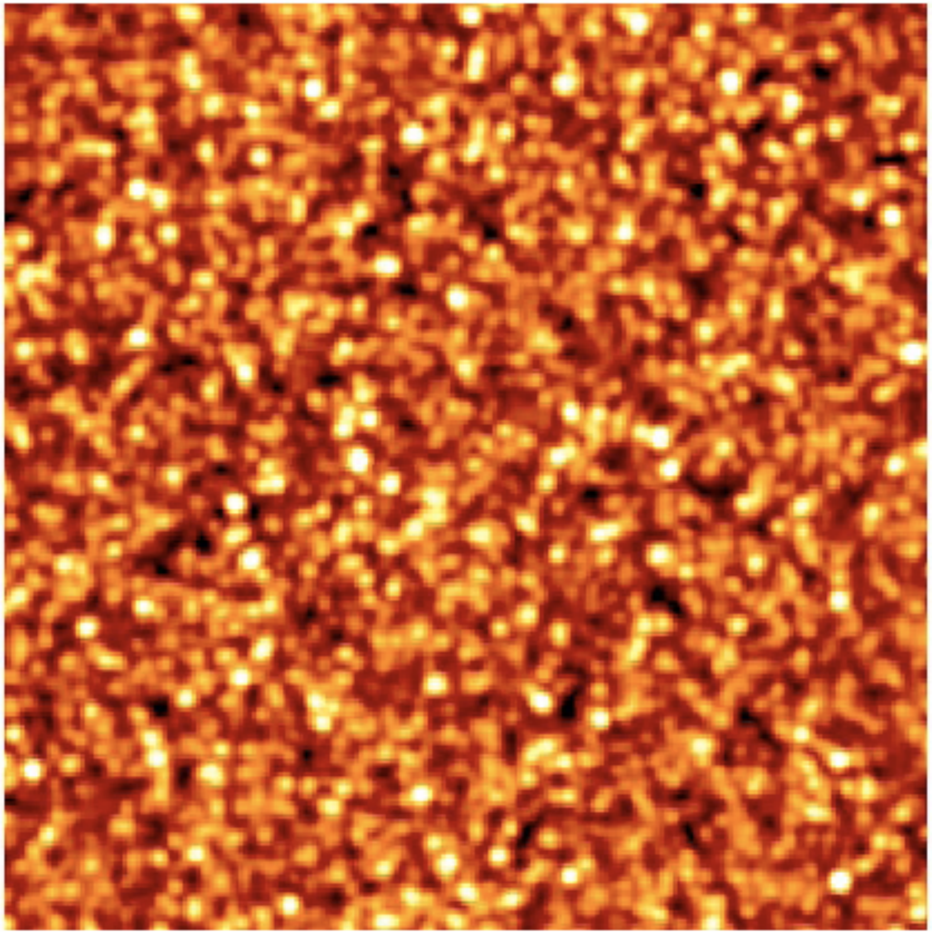




Use maps to measure clustering,
Instead of discrete sources.

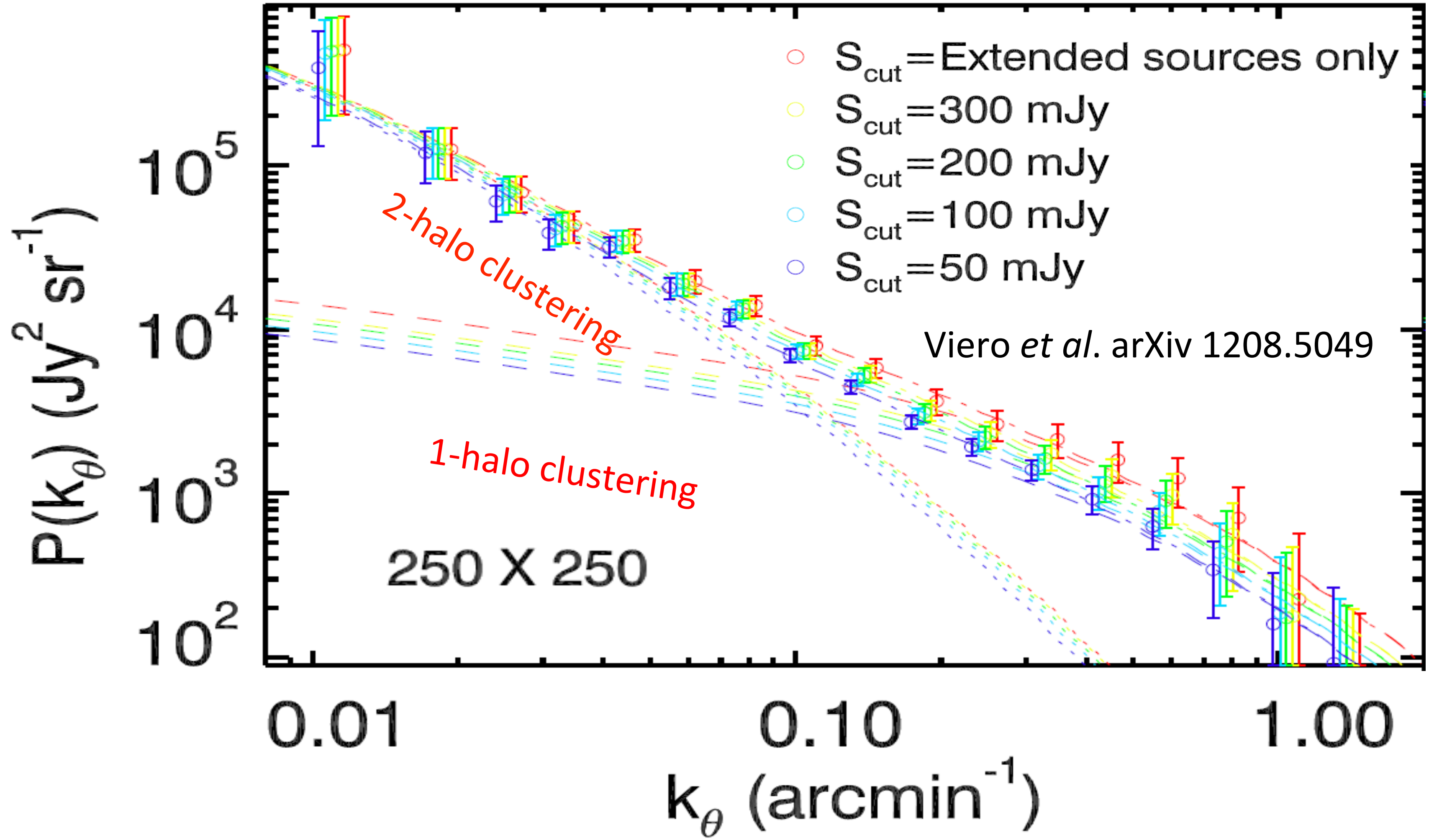


S > 20 mJy : 1,200/deg^2



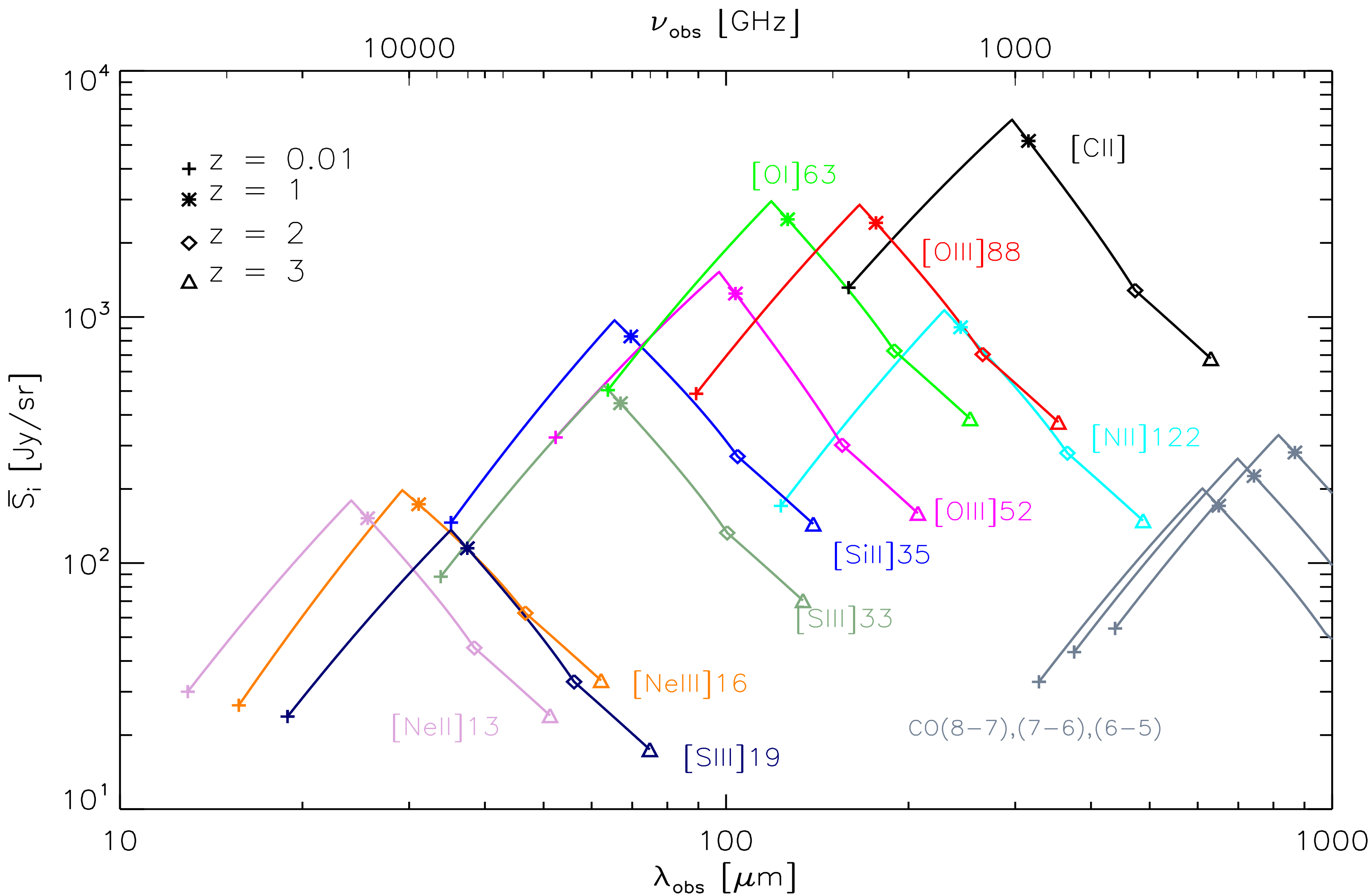
S < 20 mJy : 480,000/deg^2

Spatial Power Spectrum of SPIRE Maps



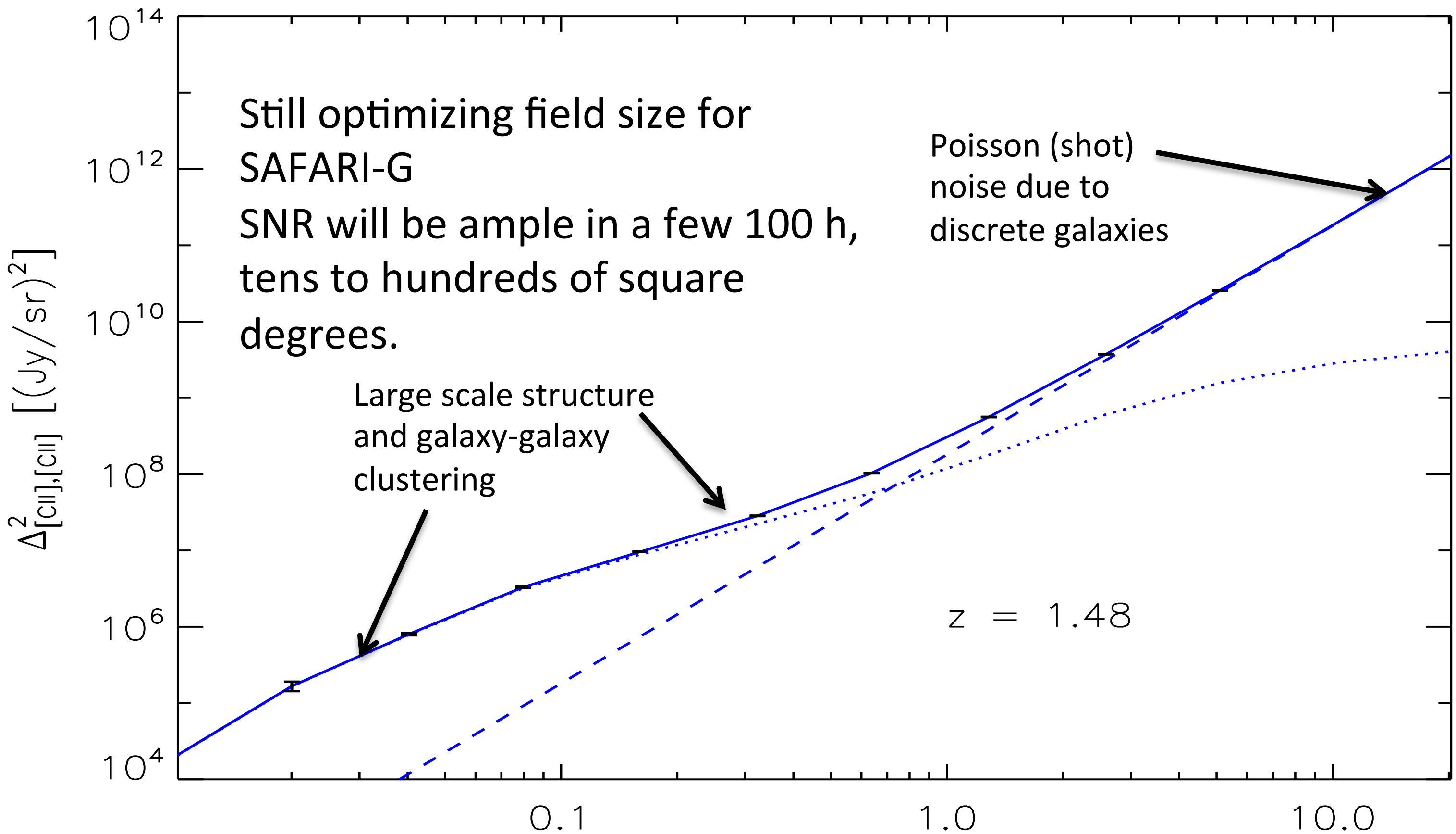
- But this is only 2 dimensions – projects over all emitting sources along the line of sight.
- Dominated by $z < 4$ – can't readily extract high-z component.
- **Need a narrow-band spectral feature to break this degeneracy.**

Mean Intensities of Key Interstellar Coolants



Spinoglio et al. lines bolted onto Bethermin luminosity function.

Example power spectrum calculation



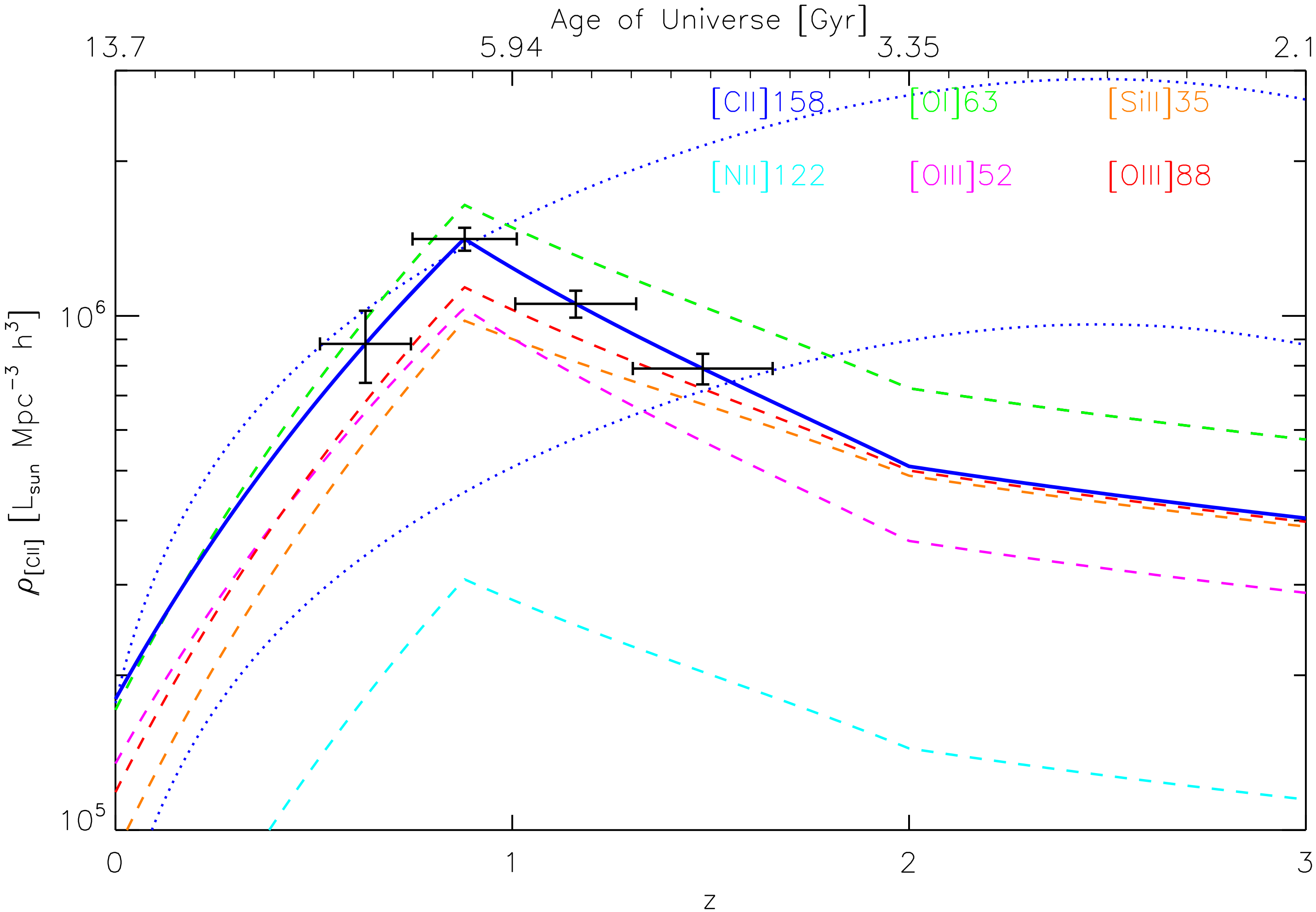
- Example calculation from Uzgil et al
- Halo-halo clustering term encodes mean intensity (w/ galaxy bias), see Uzgil+ 2014

$$P^{clust}_{i,i}(k,z) = \bar{S}^2_i(z)\bar{b}_i^2(z)P_{\delta\delta}(k,z).$$

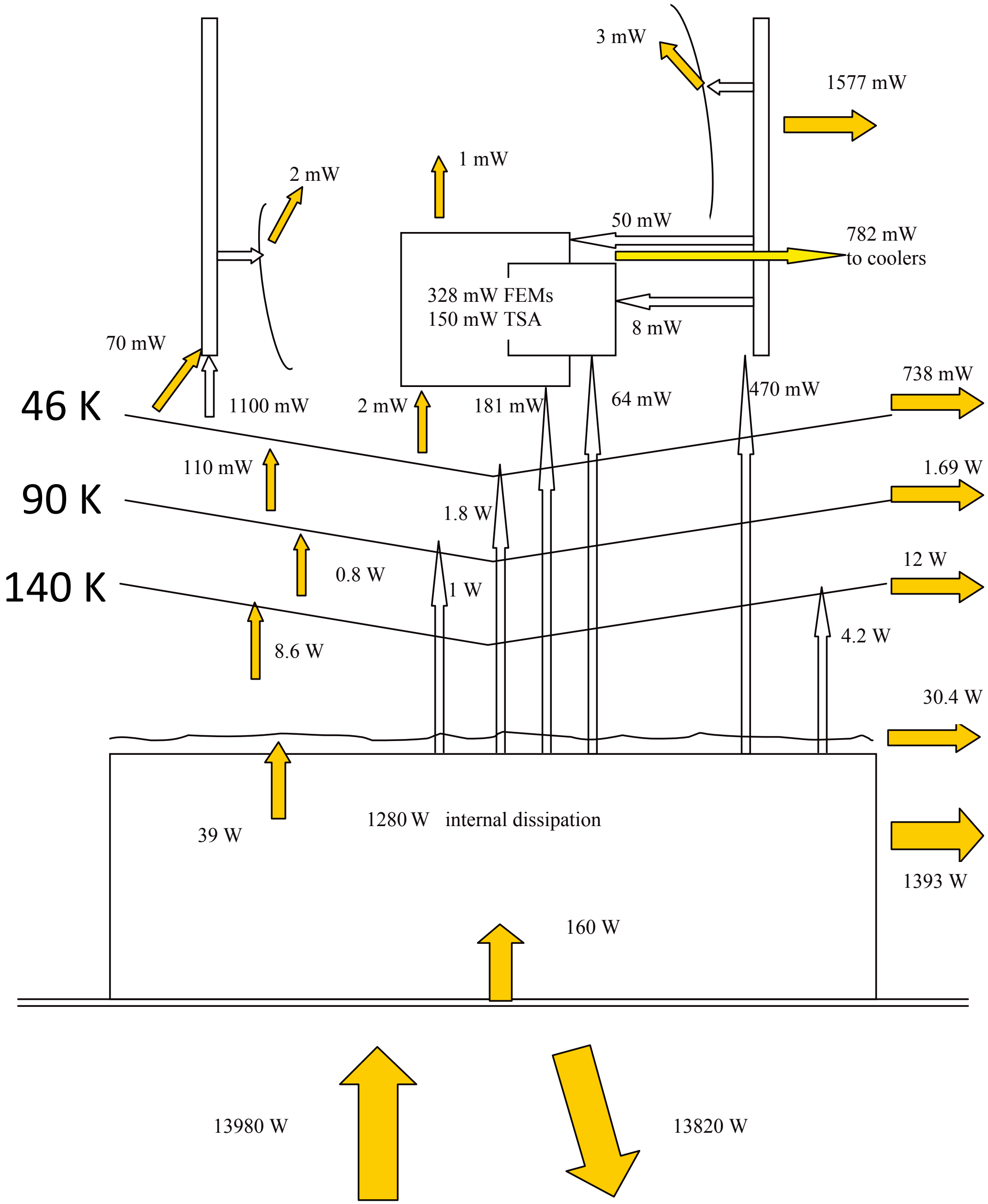
$$\text{SNR on } \bar{S}_{[\text{CII}]} = 2 \times \sqrt{\sum_{\text{linear k-bins only}} \left(\frac{P^{clust}_{i,i}(k)}{\sigma_{clust}(k)}\right)^2}$$

- Grating or FTS approximately equally capable for this experiment.

Measuring cosmic line intensities



These error bars for a balloon experiment targeting CII – SPICA SAFARI will be much better
Can also do multiple lines and cross correlations among the lines.



Planck Thermal Architecture

Planck: 3 independent coolers + careful system design.

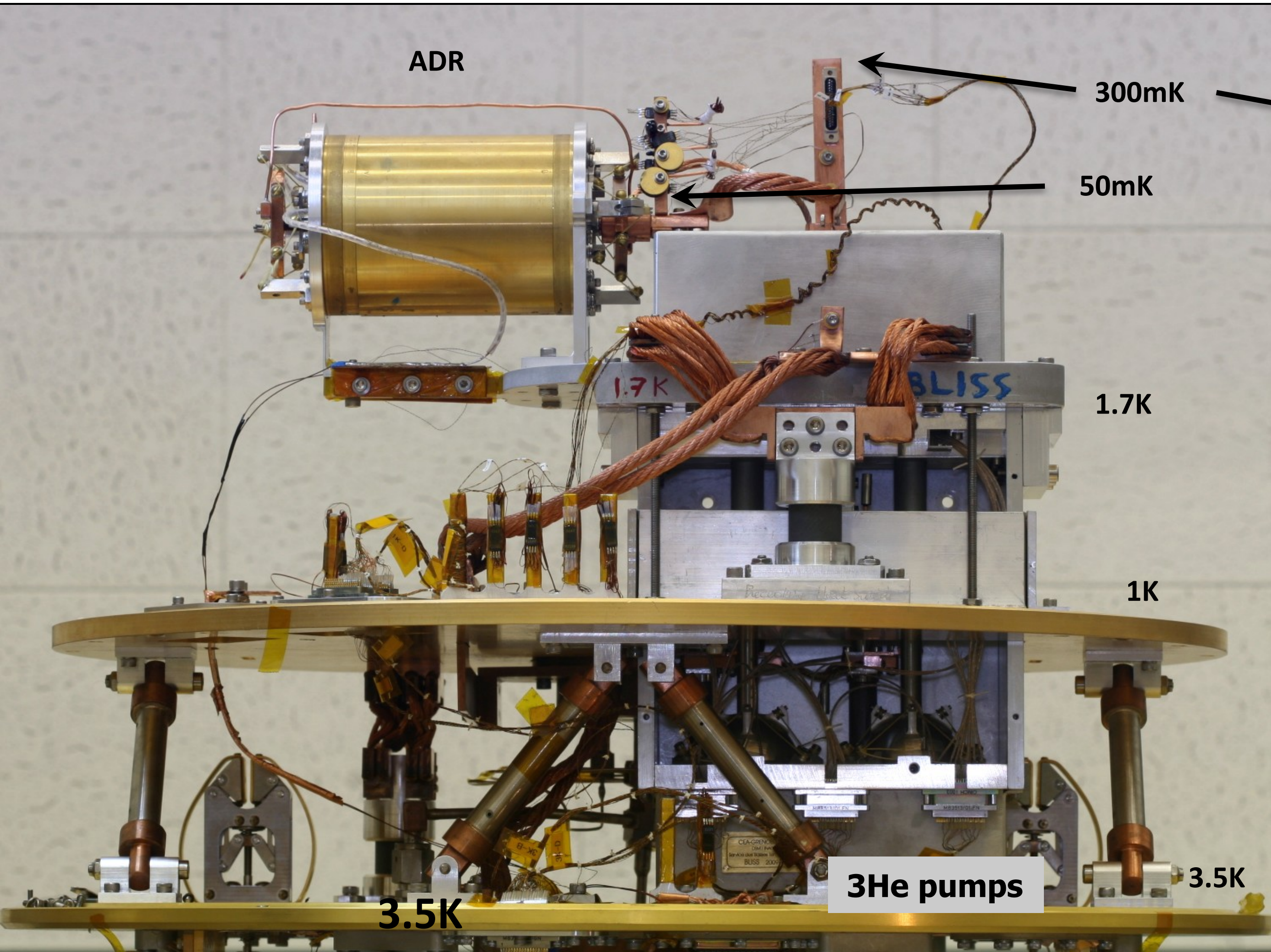
- Hydrogen sorption cooler: 1 W at 20 K for 400 W in (JPL). (unusually high 2.5% Carnot efficiency)
- Helium mechanical cryocooler: 15 mW at 4.5 K for 120 W in (RAL / EADs Astrium).
- Dilution system with expendable 3He: 0.6 uW at 0.1 K + lift at 1.4 K (Benoit et al.)

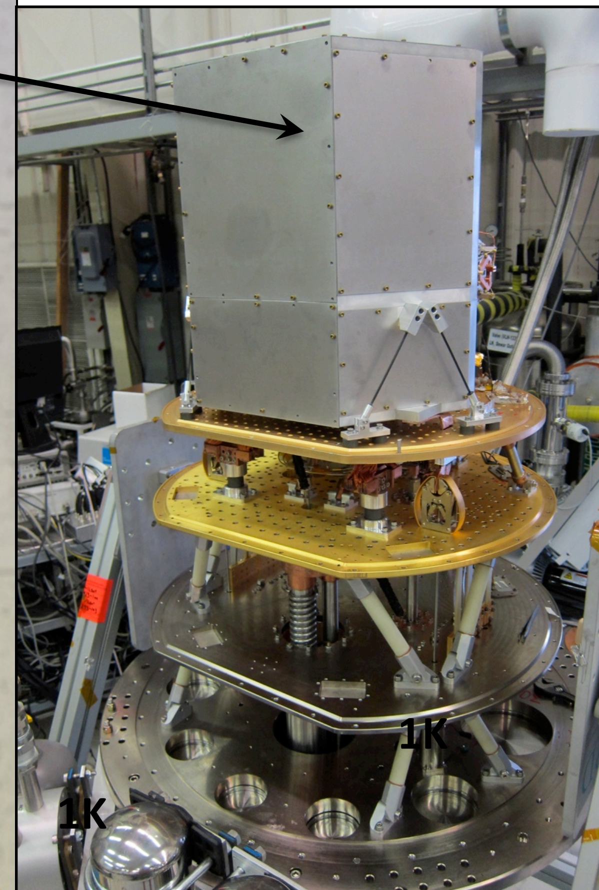
Below V-grooves, loads are conductive. Should scale with mass.

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

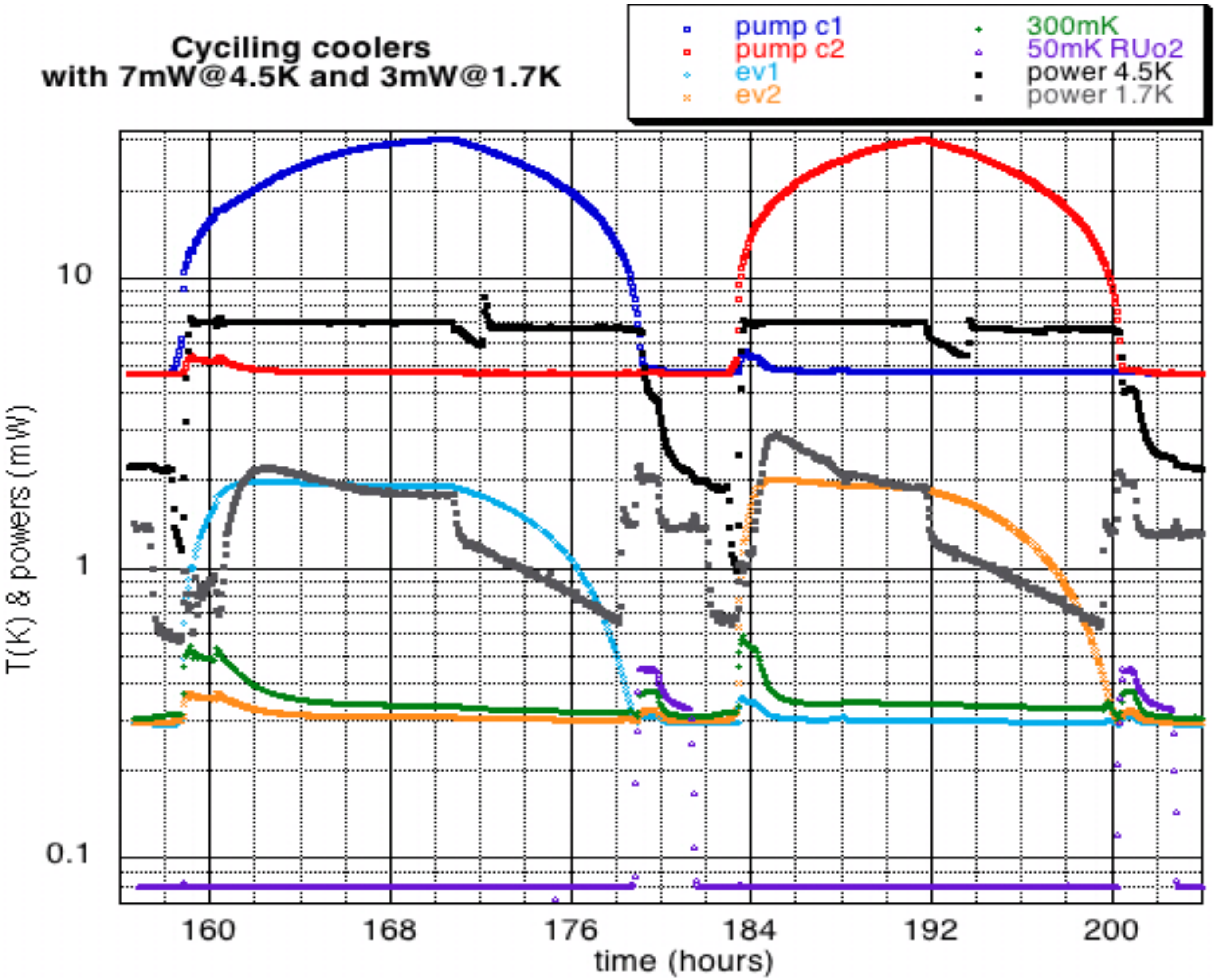
BLISS Thermal Testbed

5Kg of Al
Cooled by ADR inside





Continuous System 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.

Thomas Prouve (JPL)