Far-IR Surveyor Concept

Matt Bradford
on behalf of far-IR community

June 8, 2015

Outline

Why far-IR space astrophysics?

- Cosmic history of star formation and black-hole growth.
- H_2 and rise of organic molecules in the first billion years.
- From gas to planetary systems and habitable planets.

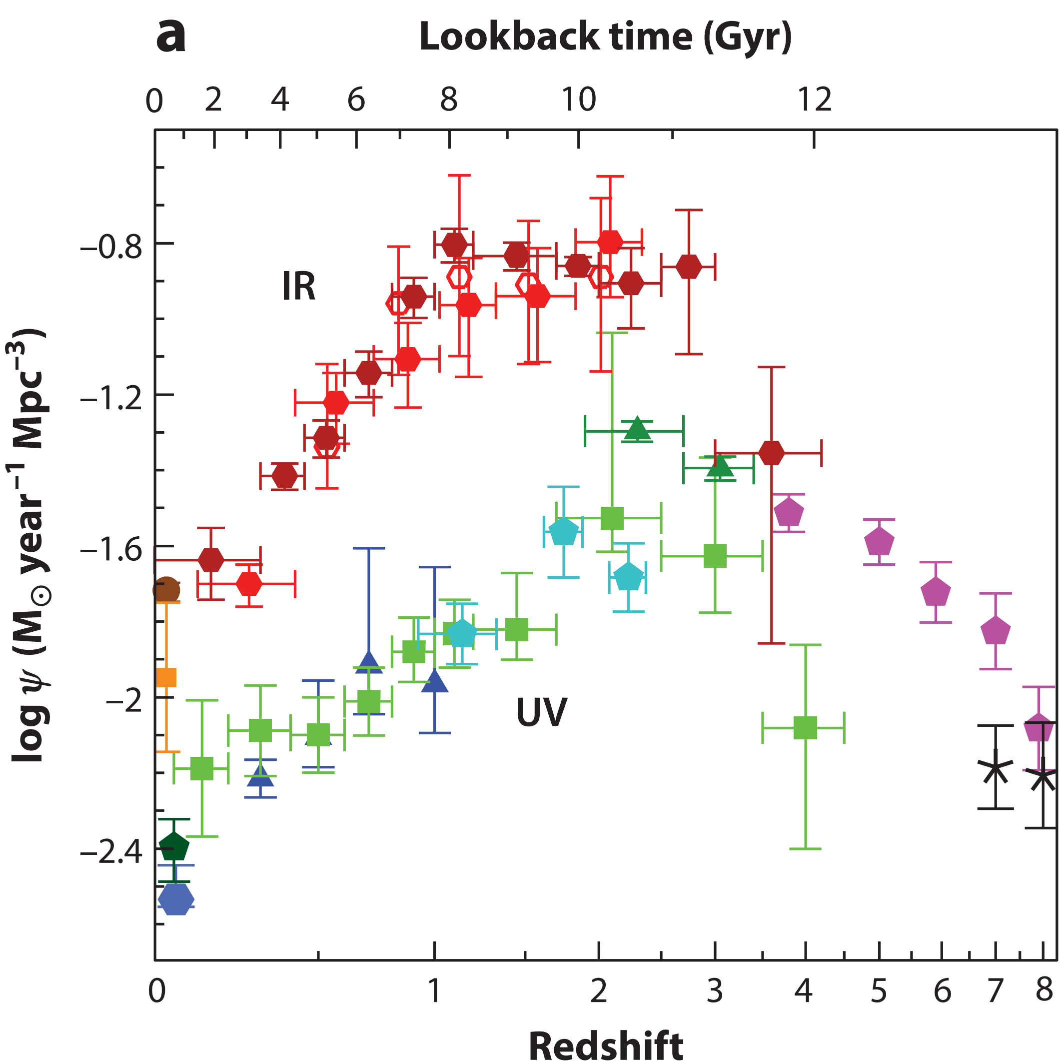
Recap of 3-5 June Far-IR Workshop

- http://conference.ipac.caltech.edu/firsurveyor/

Cryogenic-Aperture Large Infrared-Submillimeter Telescope Observatory (CALISTO) concept.

- Sensitivity, confusion
- Direct-detection spectrometer ideas, example campaigns
- Heterodyne instrumentation
- Thermal strawman, data rates, cost estimate

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?

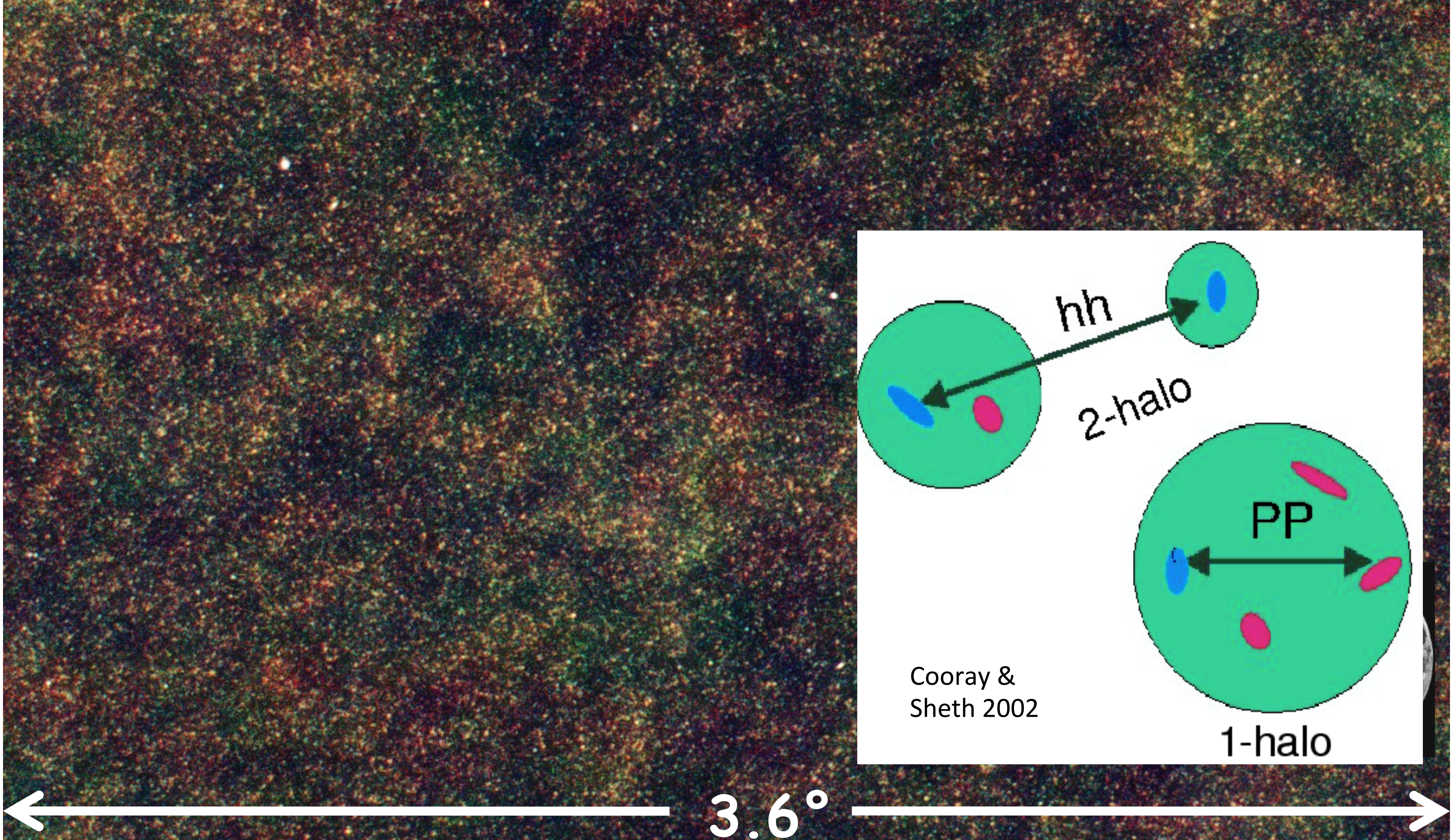
Why does BH growth track star formation?

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.

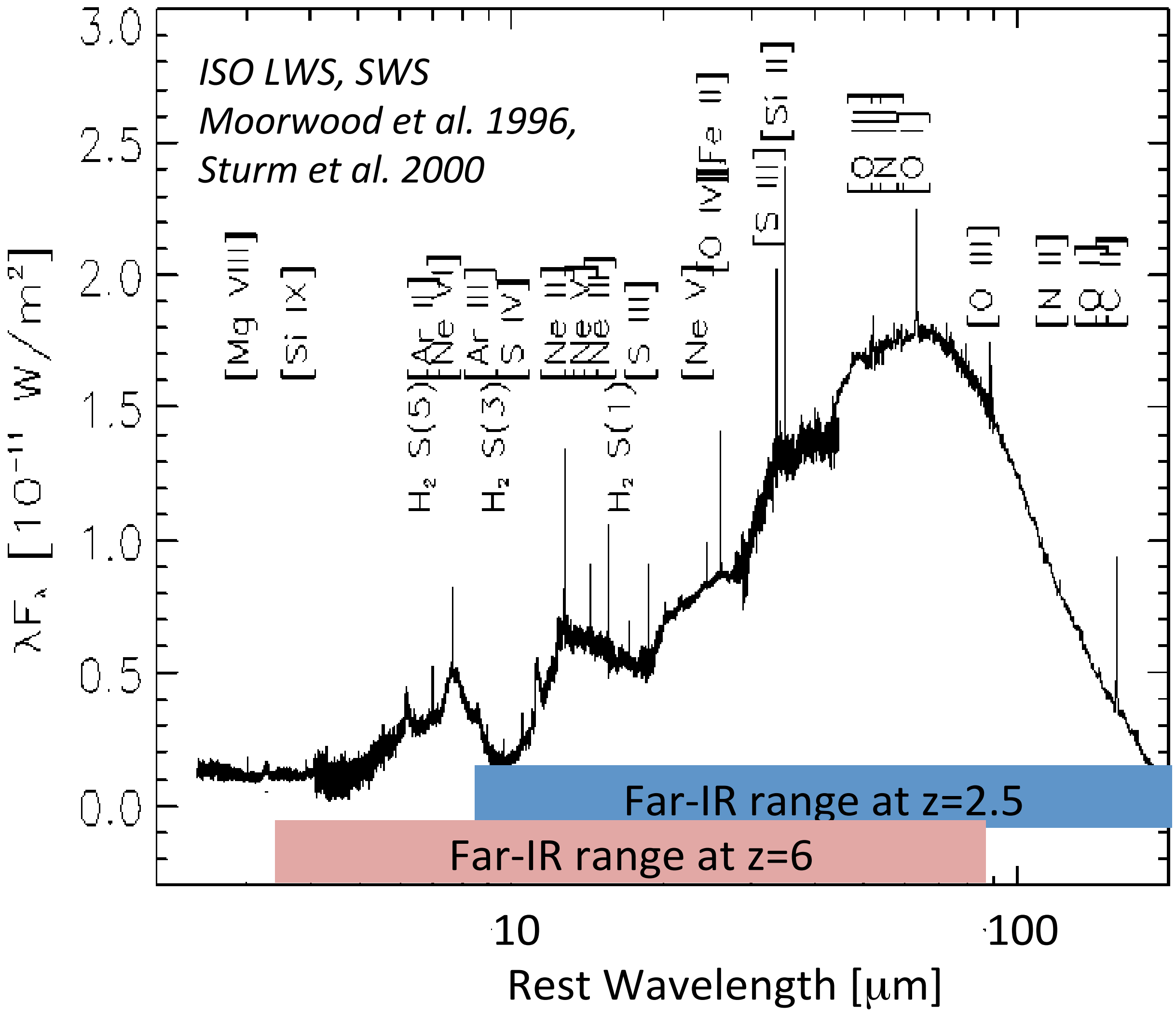
The Far-IR SKY

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)

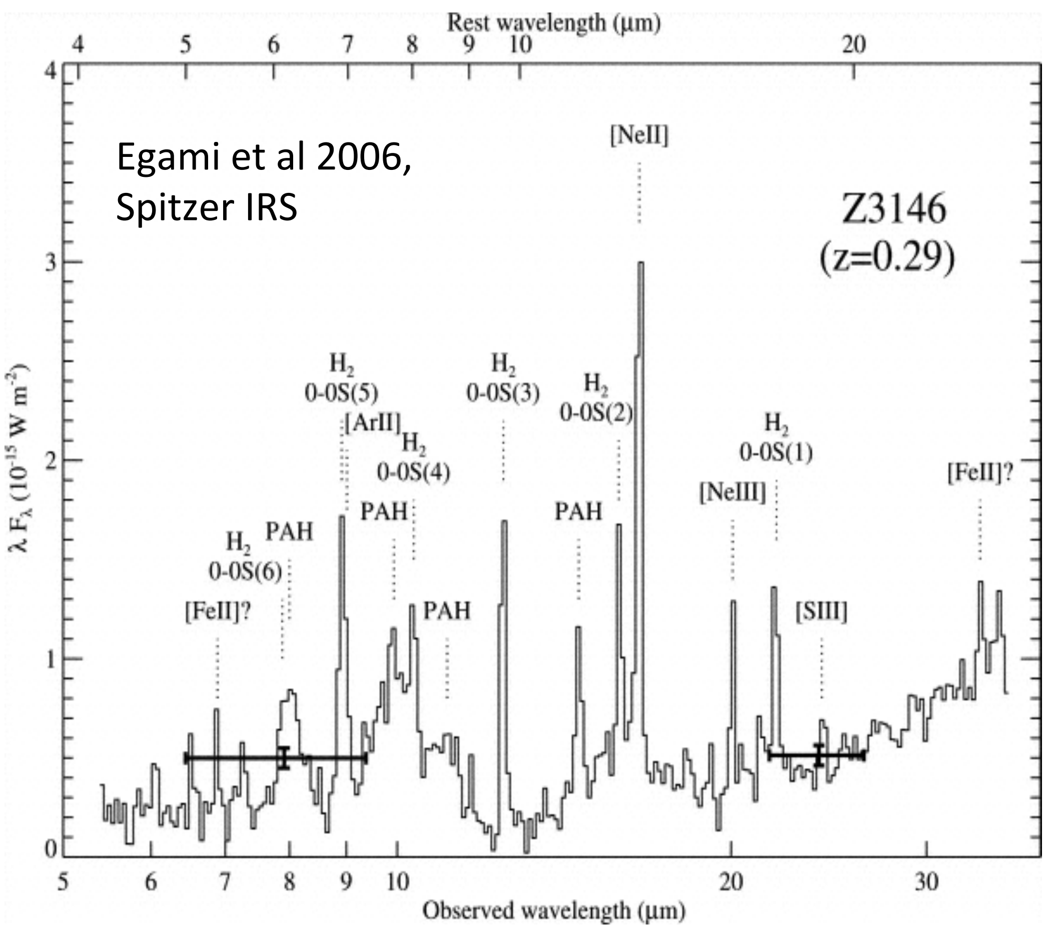
Measures mass and density of interstellar gas – the fuel for star formation.

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

Armus whitepaper

Cosmic Dawn, Rise of Organic Molecules

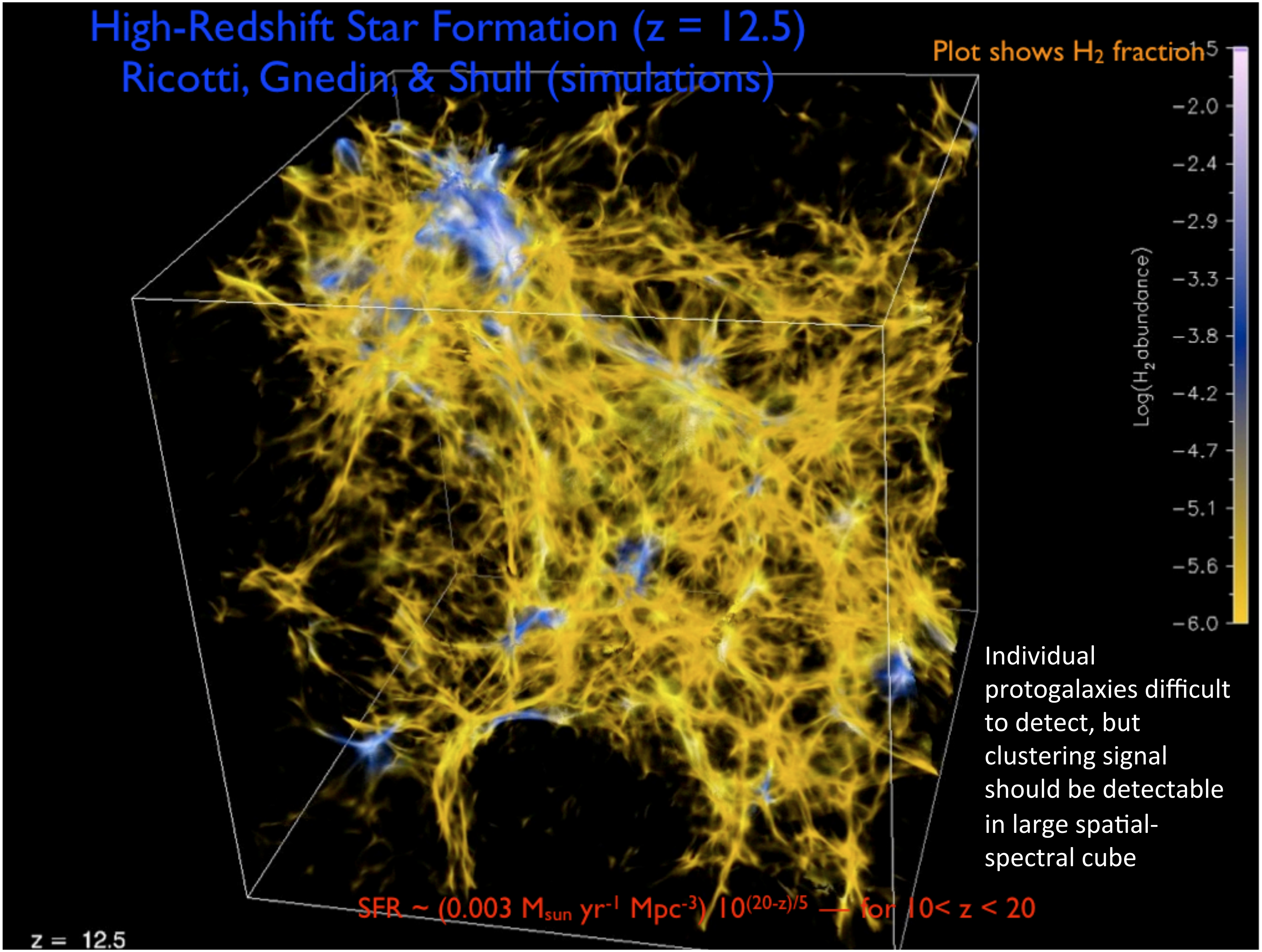
As primordial gas is enriched with metals from the first stars, the dominant cooling pathways shift from pure H_2 to fine-structure lines and dust features.

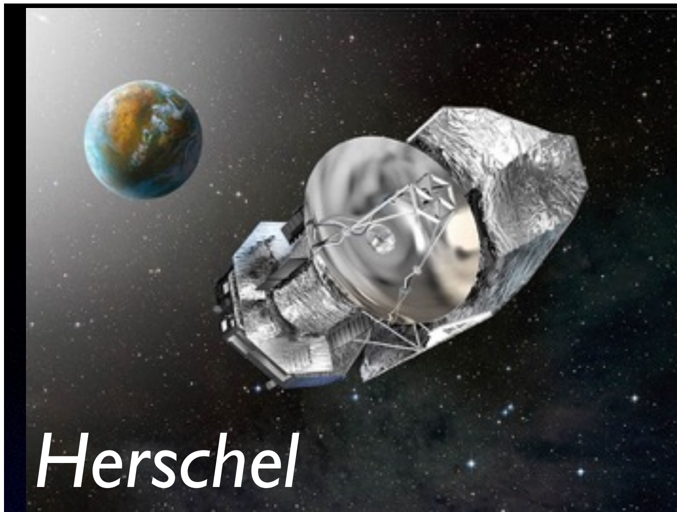


- Strong H2 emitters found in the local-Universe may be analogs of early-Universe shocks produced in galaxy formation and AGN feedback, perhaps as element enrichment is taking place. The Zw3146 spectrum at left would be detectable at z=8-10 with CALISTO.

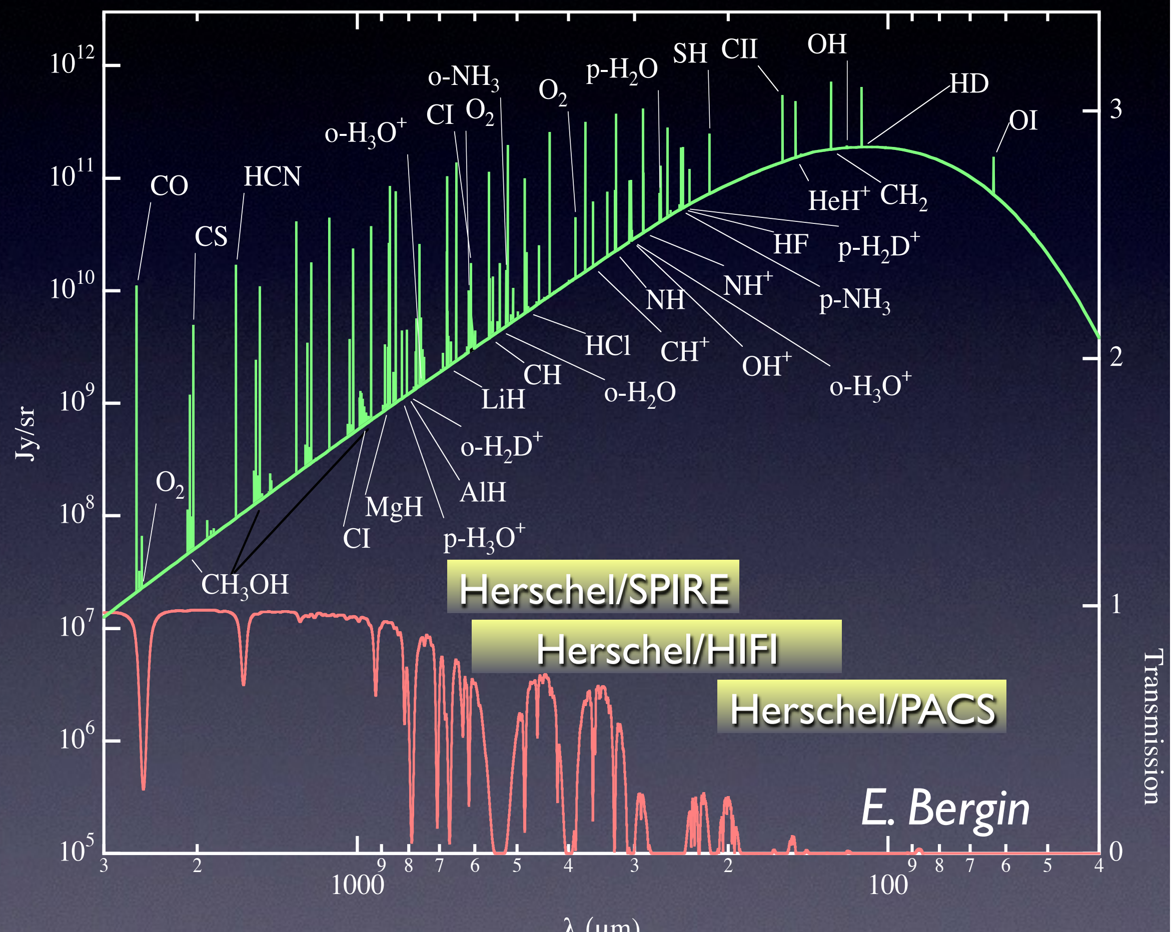
(See Appleton, Cooray talks, white papers for more on H_2)

- 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.


High-Redshift Star Formation (z = 12.5)
Ricotti, Gnedin, & Shull (simulations)
Plot shows H₂ fraction
-1.5
-2.0
-2.4
-2.9
-3.3
-3.8
-4.2
-4.7
-5.1
-5.6
-6.0
Log(H₂ abundance)
Individual protogalaxies difficult to detect, but clustering signal should be detectable in large spatial-spectral cube
SFR ~ (0.003 Msun yr-1 Mpc-3) 10(20-z)/5 — for 10< z < 20
z = 12.5

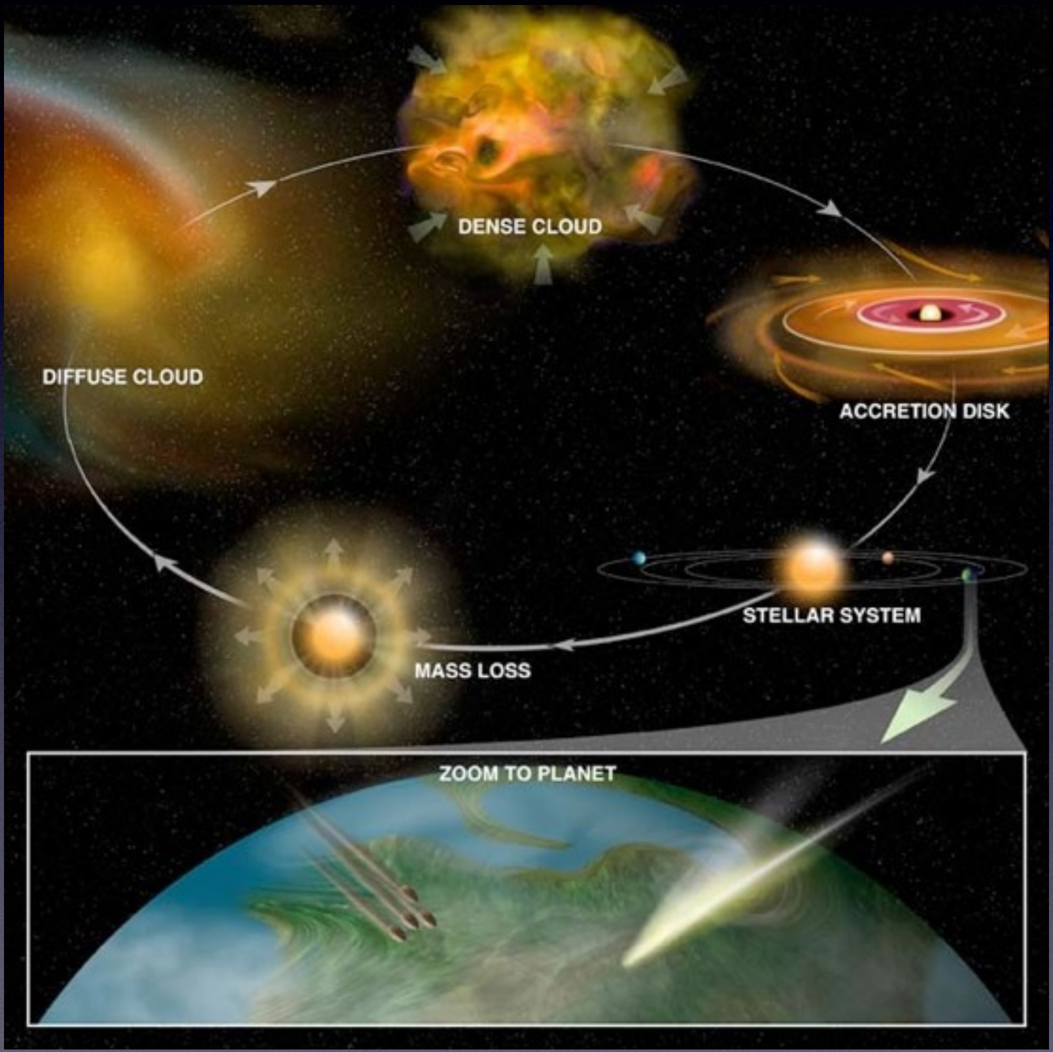


Submillimeter/FIR Astrophysics



- Inability to view the entire spectrum of star forming gas — water, key coolants (e.g., [CII], [OI], high-J CO ladder)

Astrochemistry and Planet Formation



http://www.space.com

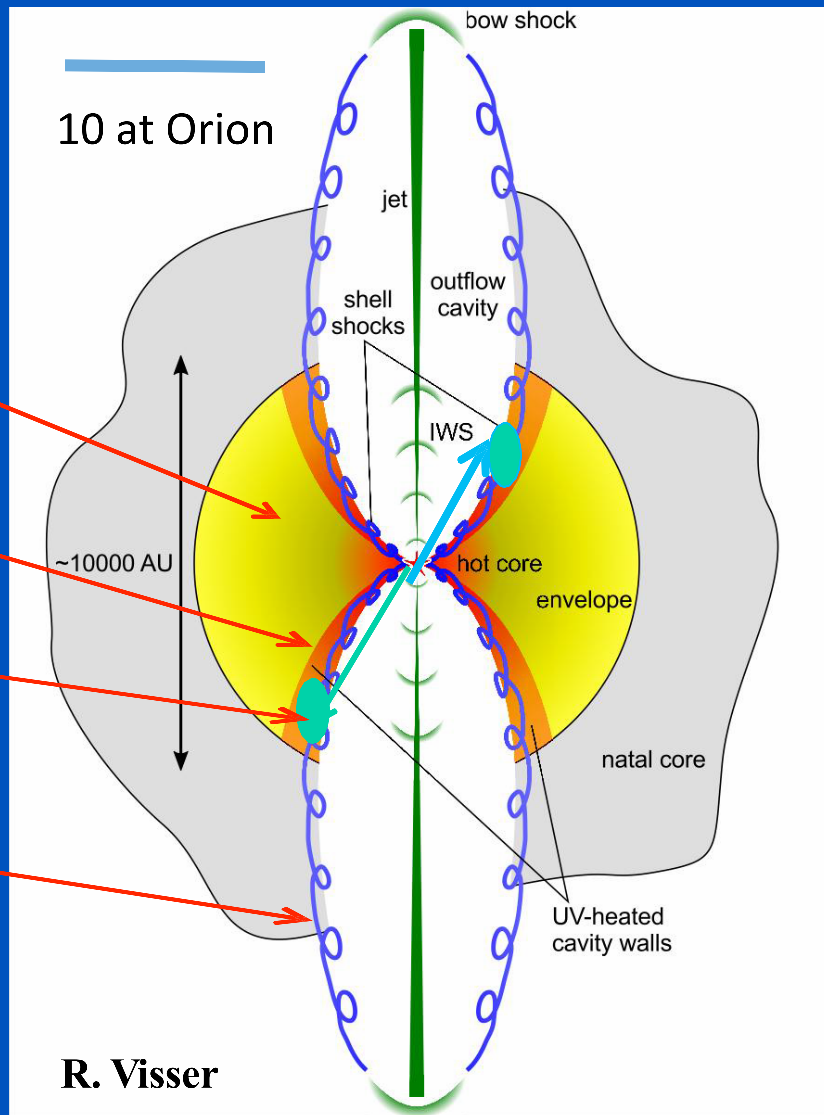
- Molecular clouds exhibit a high degree of chemical complexity — water, carbon monoxide, carbon dioxide, organics
- Gas phase chemistry, catalytic chemistry on grain surfaces, gas-grain interactions
- Delivery to the planet-forming disks and to young planets
- Molecules as tracers of *physical conditions* in the ISM and star-forming regions (e.g., density, temperature, UV field, ionization fraction…)

Conditions and Cooling in Galactic Star Formation Sites

example: water

Warm and hot water emission has many components

- Quiescent envelope
  - Narrow absorption/emission
- UV-heated cavity walls
  - Narrow emission CO mid-J
- Currently shocked gas
  - H_2O broad, CO high-J
- Entrained outflow gas
  - CO low-J



Very High-Resolution Spectroscopy

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.

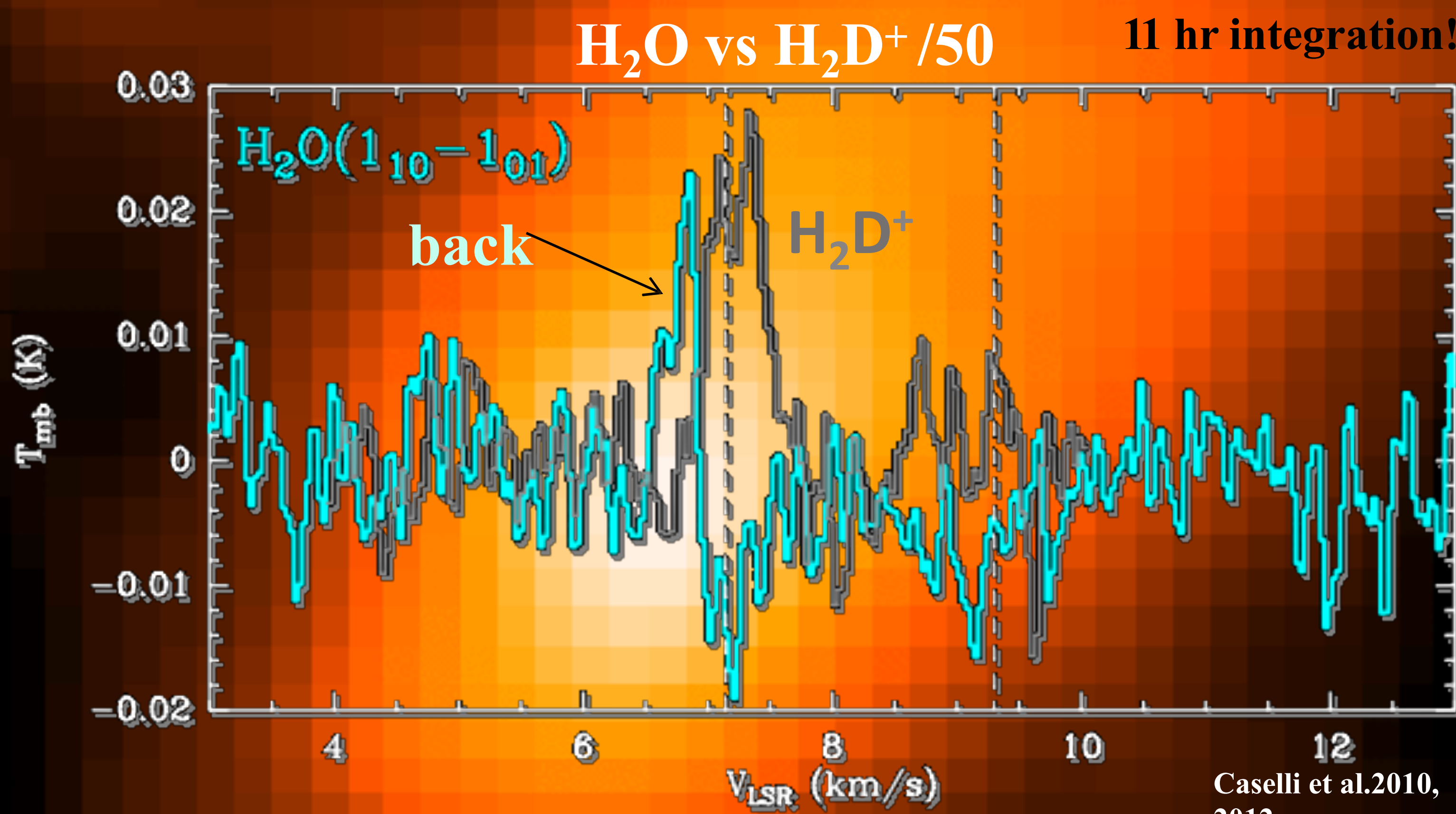
This applies to objects including comets, asteroids, planetary atmospheres, protostellar disks, cloud cores, YSO dark clouds, YSO outflows, shocks, GMCs, the Galactic ISM, and nearby Galaxies.

Herschel HIFI, and SOFIA GREAT have shown potential for submillimeter velocity-resolved spectroscopy but there is enormous potential just now starting to be available.

Key aspects

- Receiver sensitivity comparable to that on Herschel, so only modest per-pixel gain.
- But now can field focal plane arrays with sizeable pixel count (~100).
  - More powerful and flexible LO sources
- Greater instantaneous bandwidth
- Mixer operation at higher temperatures
- Low power, broadband digital signal processing
- Multi-frequency receivers

The prestellar core L1544



Caselli et al.2010, 2012

- Emission requires high central density ~10^7 cm^{-3}
- Profile indicates infall of 0.1 km/s at 1000 AU

1.3 mm continuum map from Ward-Thompson et al. (1999)

Workshop Recap

http://conference.ipac.caltech.edu/firsurveyor/

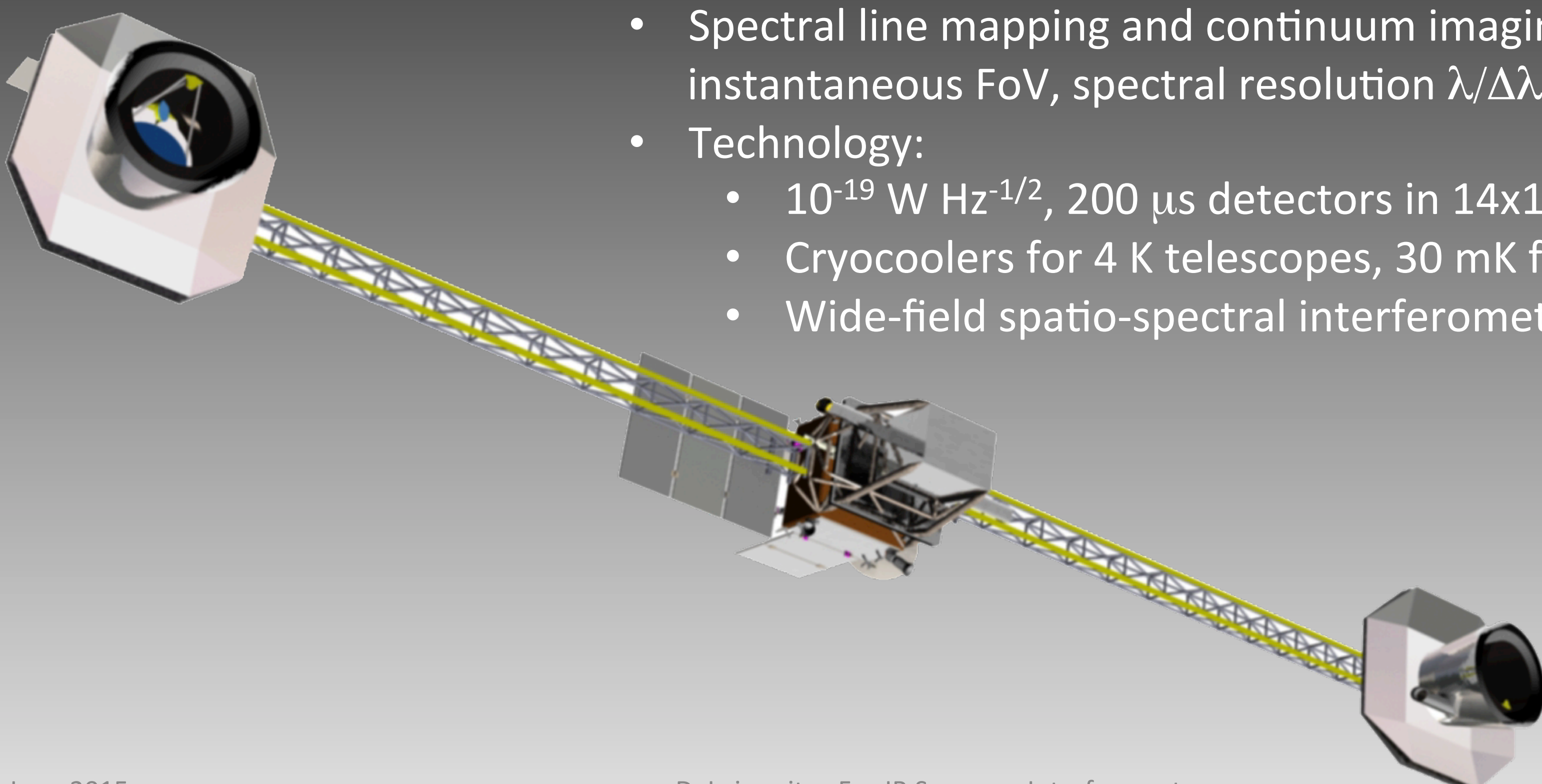
- Pasadena June 3-5, 2015
- Science presentations ranging from solar system to distant Universe
  - Conference talks as well as white papers submitted to COPAG posted on conference web site.
- Goal to decide which of 2 concepts to bring forward to PAGs as the Far-IR Surveyor.
  - 2-element interferometer (SPIRIT)
  - single-dish telescope (CALISTO)
- Single-dish telescope selected at 70:30 ratio in anonymous poll
  - 101 voters (restricted to US astronomers who attended in person or virtually).
- Currently preparing document outlining the vision to be provided to PAGs.
  - Expect to have in ~2-3 weeks, ~15-20 pages?
  - Suggestions from PhysPAG on format?

Goddard Space Flight Center

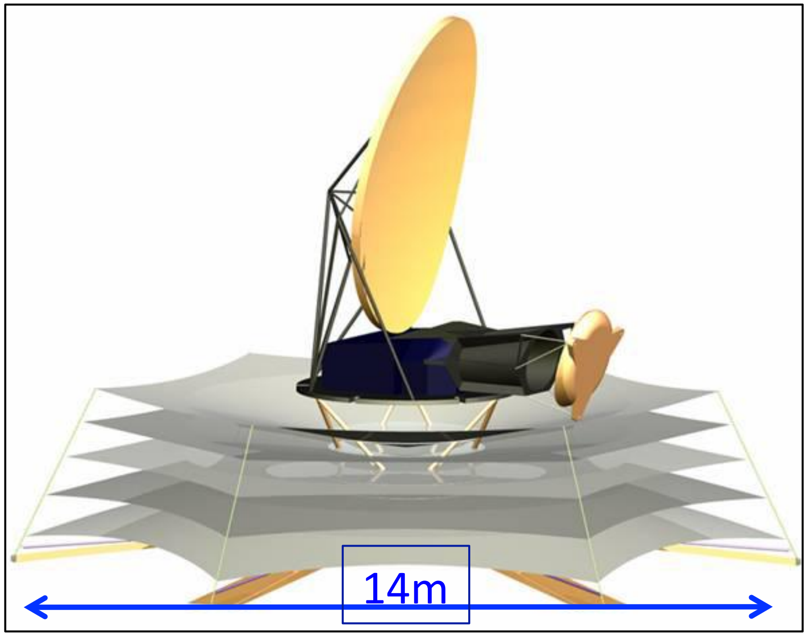
SPIRIT "C" mission concept

Space Infrared Interferometric Telescope

- Structurally-connected λ25 – 400 μm interferometer
- Two 1-m afocal off-axis telescopes
- Telescopes move radially, and structure rotates to provide dense *u-v* plane coverage with maximum baseline ~36 m, θ = 0.3 arcsec (λ/100 μm) imaging
- Spectral line mapping and continuum imaging in 1 arcmin instantaneous FoV, spectral resolution $\lambda/\Delta\lambda > 10^3$
- Technology:
  - 10^{-19} W $Hz^{-1/2}$, 200 μs detectors in 14x14 pixel arrays
  - Cryocoolers for 4 K telescopes, 30 mK focal planes
  - Wide-field spatio-spectral interferometry



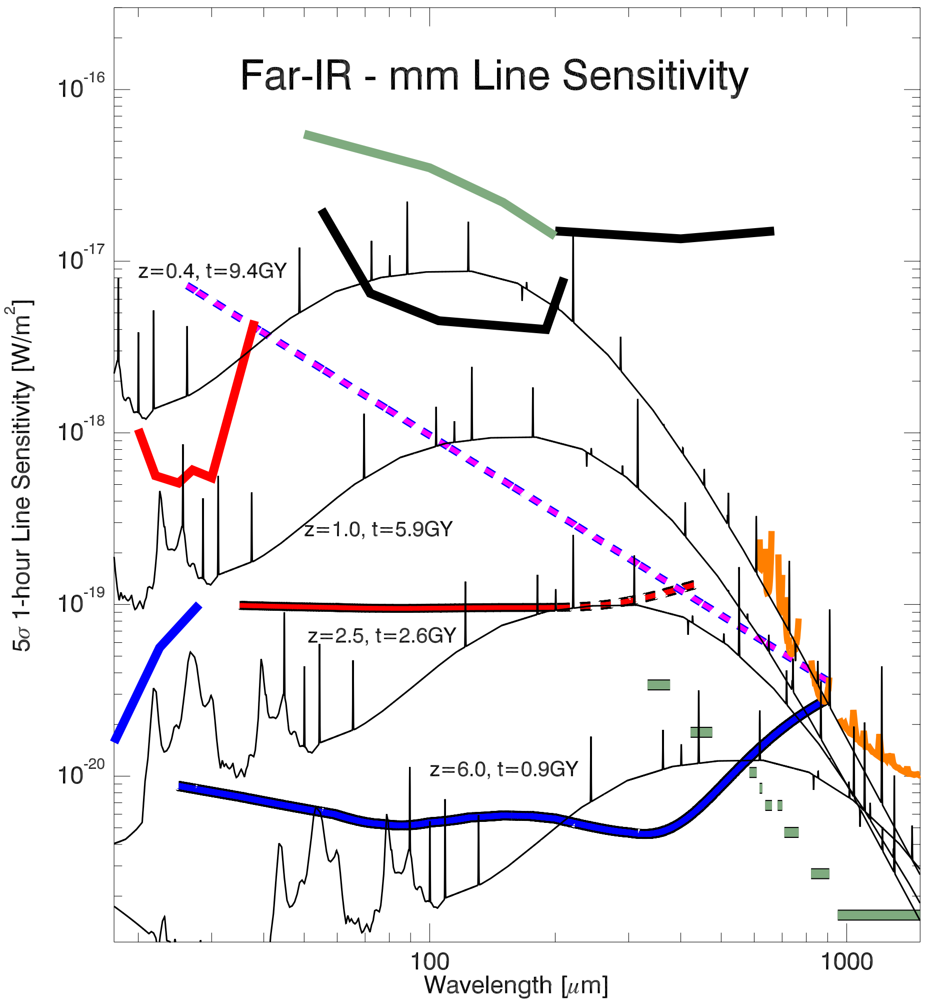
CALISTO Concept

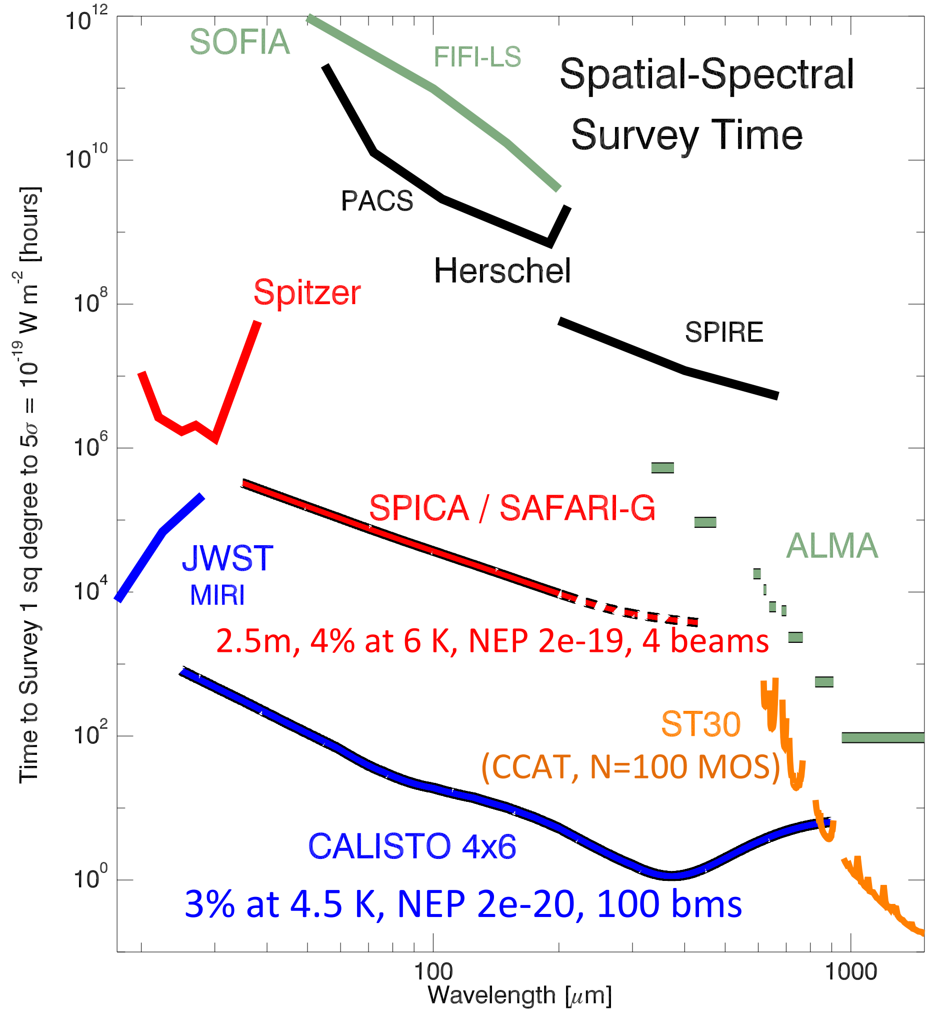


Parameter	Value
Telescope Temperature	<4 K
Telescope Diameter	~ 5 m
Telescope Surface Accuracy	1 μm
Telescope Field of View	1 deg at 500 μm
Instrument Temperature	50–100 mK
Total Number of Detectors	$1\text{–}5 \times 10^5$
Heat Lift at 4 K	~ 150 mW
Heat Lift at 20 K	~ 2 W
Data Rate	~Gbit / sec

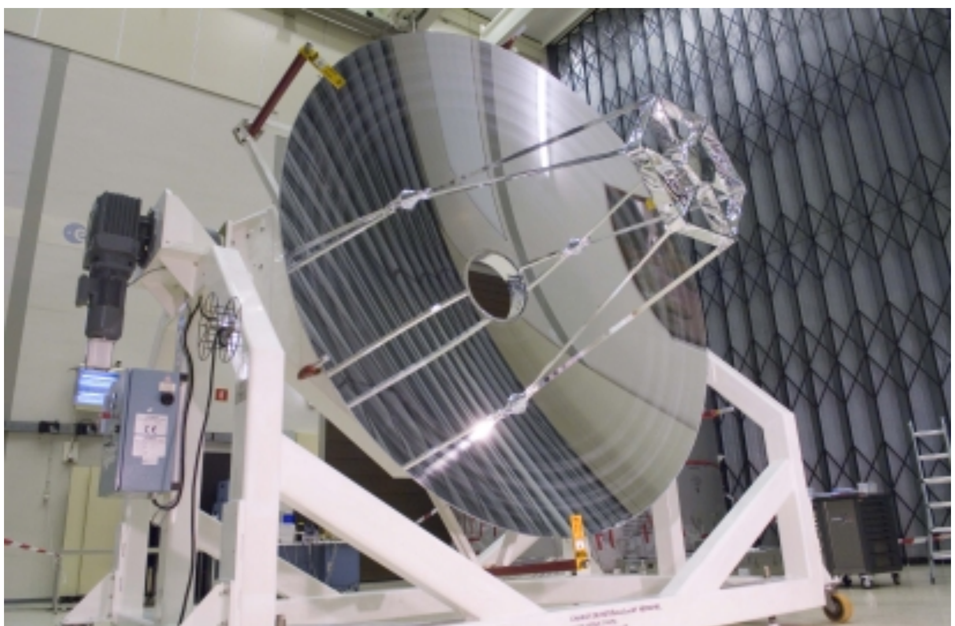
- Cryogenic wide-field surveyor with imaging spectroscopy as its thrust.
- L2 orbit, careful thermal design including passive (V-groove radiators) and closed-cycle active cooling.
- Example concept: 4x6 meter off-axis telescope with hinge-deployed secondary
  - Efficient use of 5-meter fairing.
  - 1 degree FOV possible with no corrector.
- On axis also possible, if strut blockage (=loading) can be kept to ~1-2%.
- Instrument suite at T< 100 mK. Few hundred thousand individual detectors, each coupling a spatial mode at R~500 photon background limit.

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.

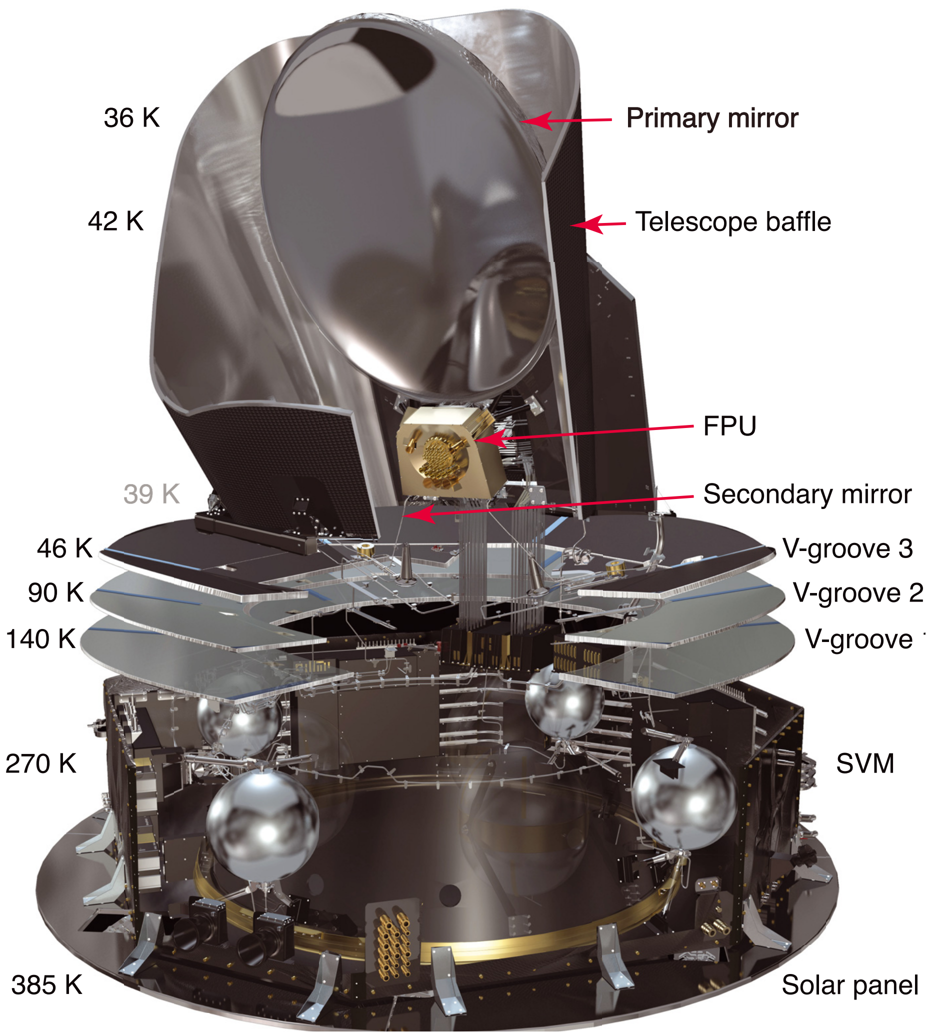


Telescope Concept

- 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?

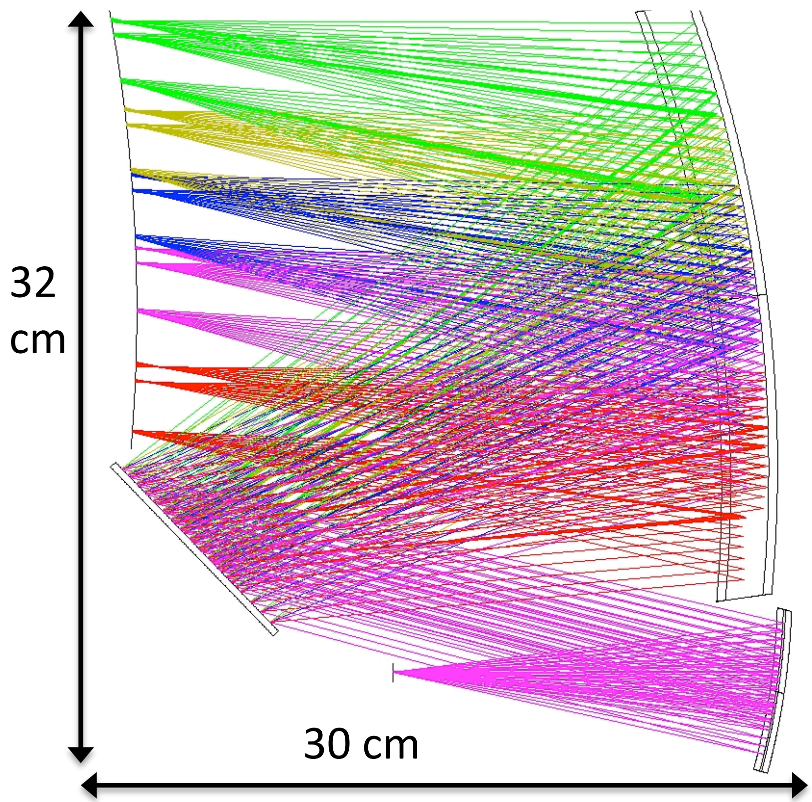
Thermal Design Strawman

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

Instrumentation Strawman



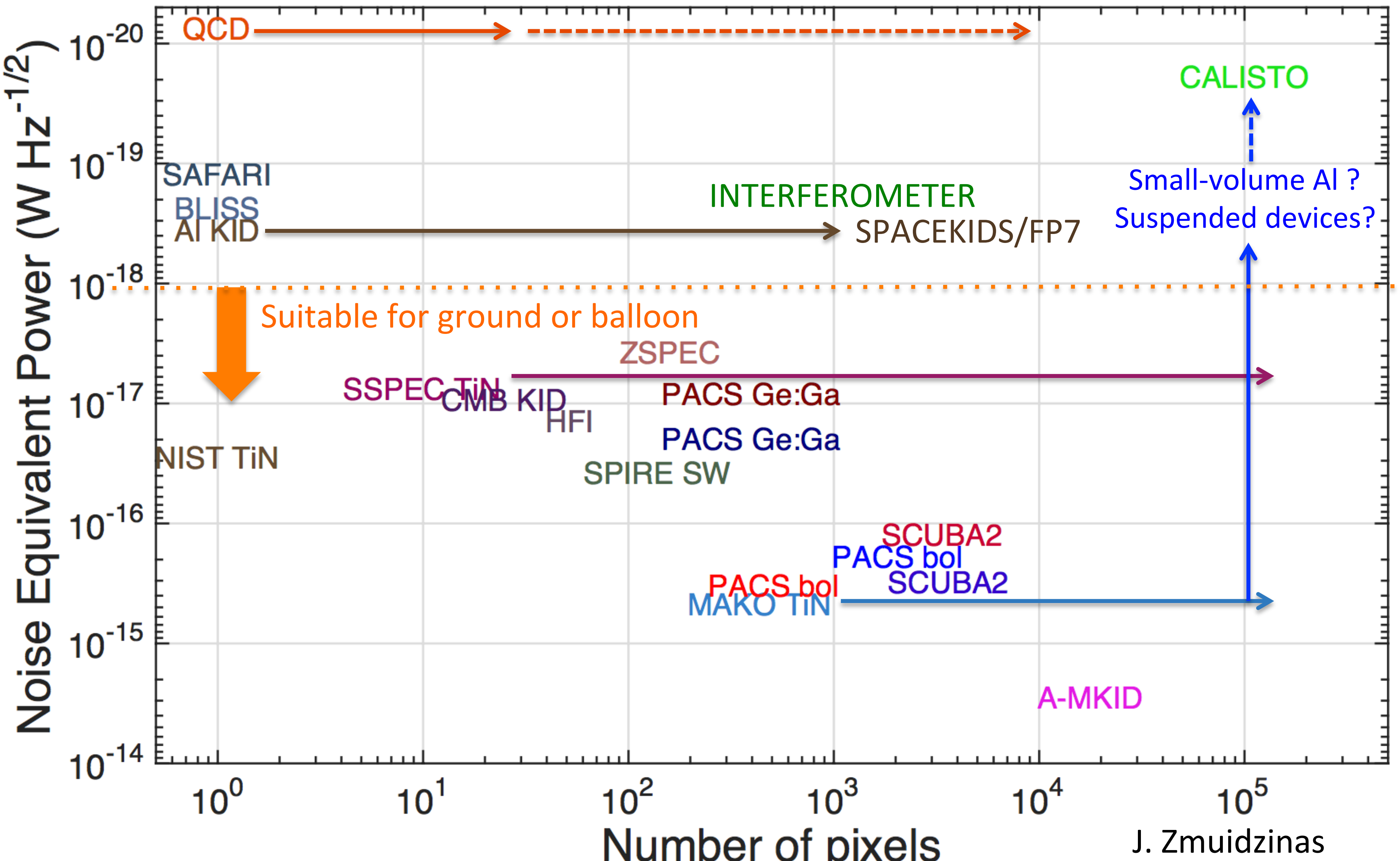
Example wide-field echelle grating module

- 165-beam long slit.
- 1:1.5 bandwidth, all diffraction limited.
- Dimensions for 100 micron central wavelength, R=400.

- 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.
- 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.

Far-IR spectroscopy requires high sensitivity detectors

and we need large format



Example Programs

- Individual galaxies – pointed follow up spectroscopy. **(6k hours)**
  - 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). (**3k 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.
- 3,000 proto-planetary disks candidates, average time: 1 hour. **(3k hours)**
  - Fully evolutionary range. Distances ranging to few kpc, gas masses down to 0.03 solar.
- Mapping of Galactic plane in [CII] with 16 pixel heterodyne array: 60 square degrees at 8 arcsec resolution, $\Delta T = 0.1$ K rms: **(2k hours)**
  - **Heterodyne spectroscopy under consideration for post-cryo warm mission / cooldown phase**
- Continuum imaging – all sky at 100 microns in **(4k hours)** (4000-beam camera)
- **Adds up to 18 k hours** (5 yrs @75% efficiency = 33k)**. Much more to do as well.**

CALISTO Cost Estimate

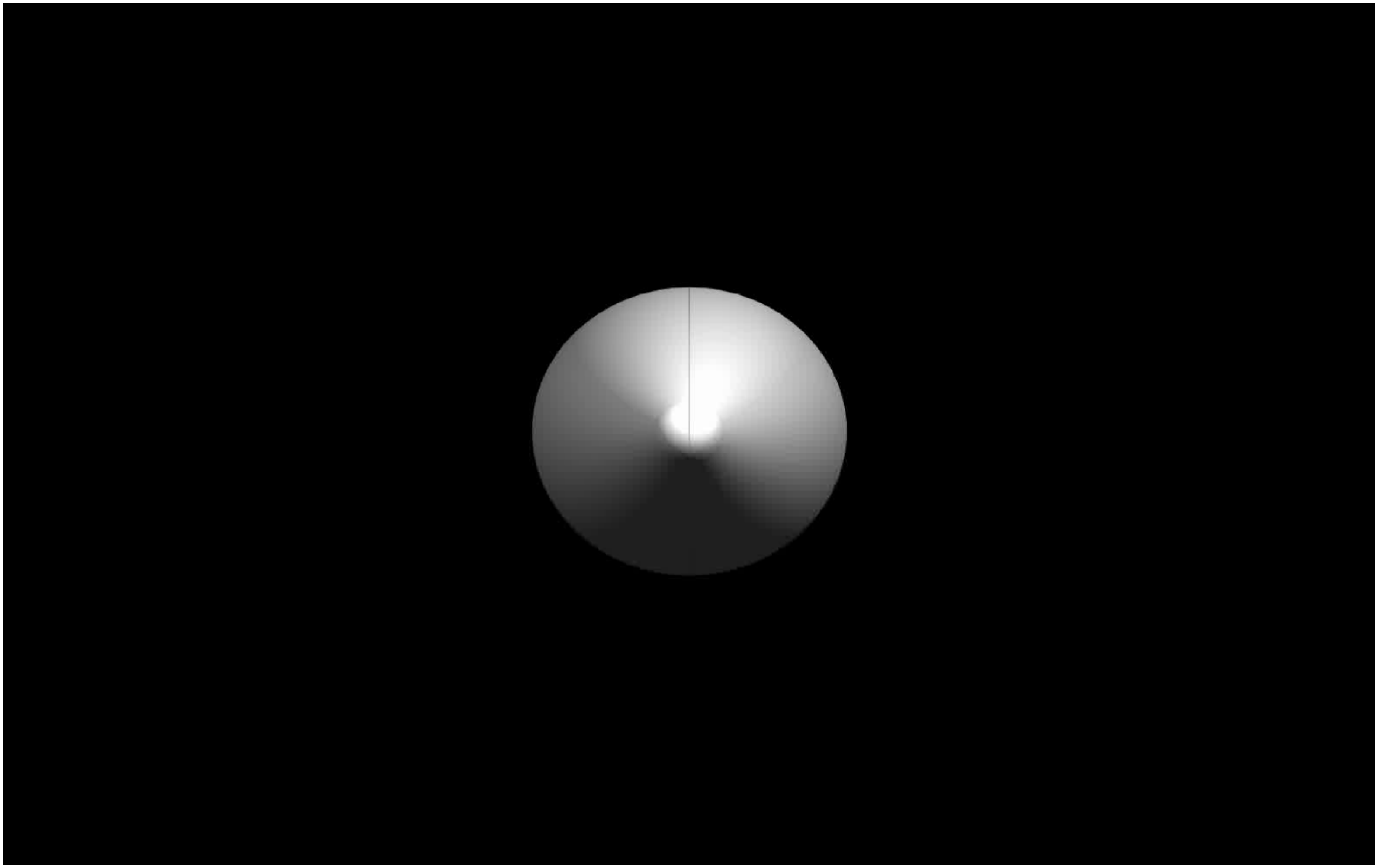
JPL Team-X 2008

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, but multiplexing easier.
- Analogy: Herschel, $1.1 B, Planck $700 M per ESA.

EXTRAS

Telescope Concept



CALISTO Parameters

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 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 W m^{-2}, 5σ, 1h	4.2e-21	3.3e-21	3.2e-21	$\propto D^{-2}$
Pt. sce. mapping speed [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	$\propto D^0$

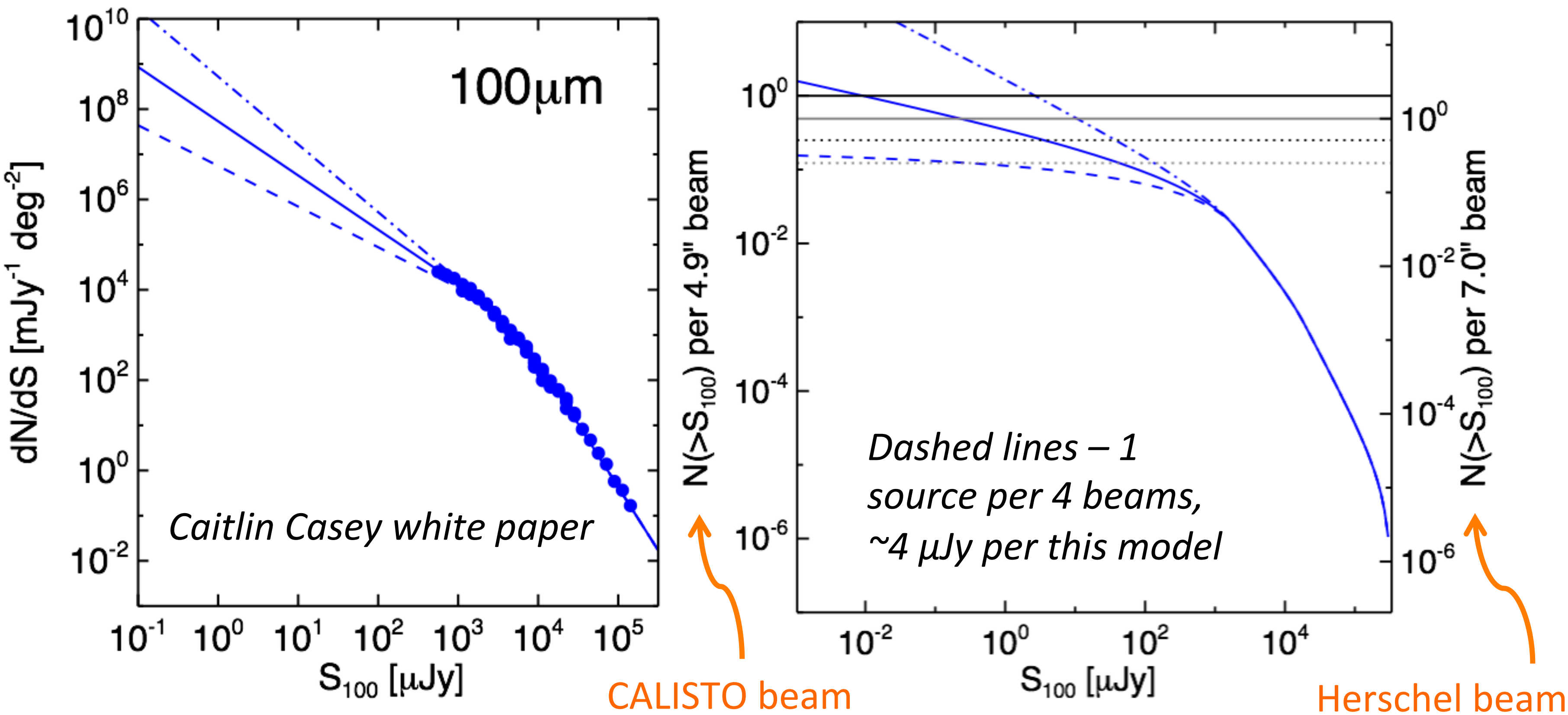
Notes: Sensitivities assume single-polarization instruments with a product of cold transmission and detector efficiency of 0.25 in a single polarization, and an aperture efficiency of 0.75. FOV estimate assume slit widths of 165 λ/D for the 40 and 120 μm examples, and 100 individual single-beam spectrometer 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$_\nu$ z=2 L$_\odot$	νL$_\nu$ z=5 L$_\odot$	NEF$_{\rm inst}$ 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. NEF$_{\rm inst}$ 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.

Broadband Imaging and Confusion for CALISTO

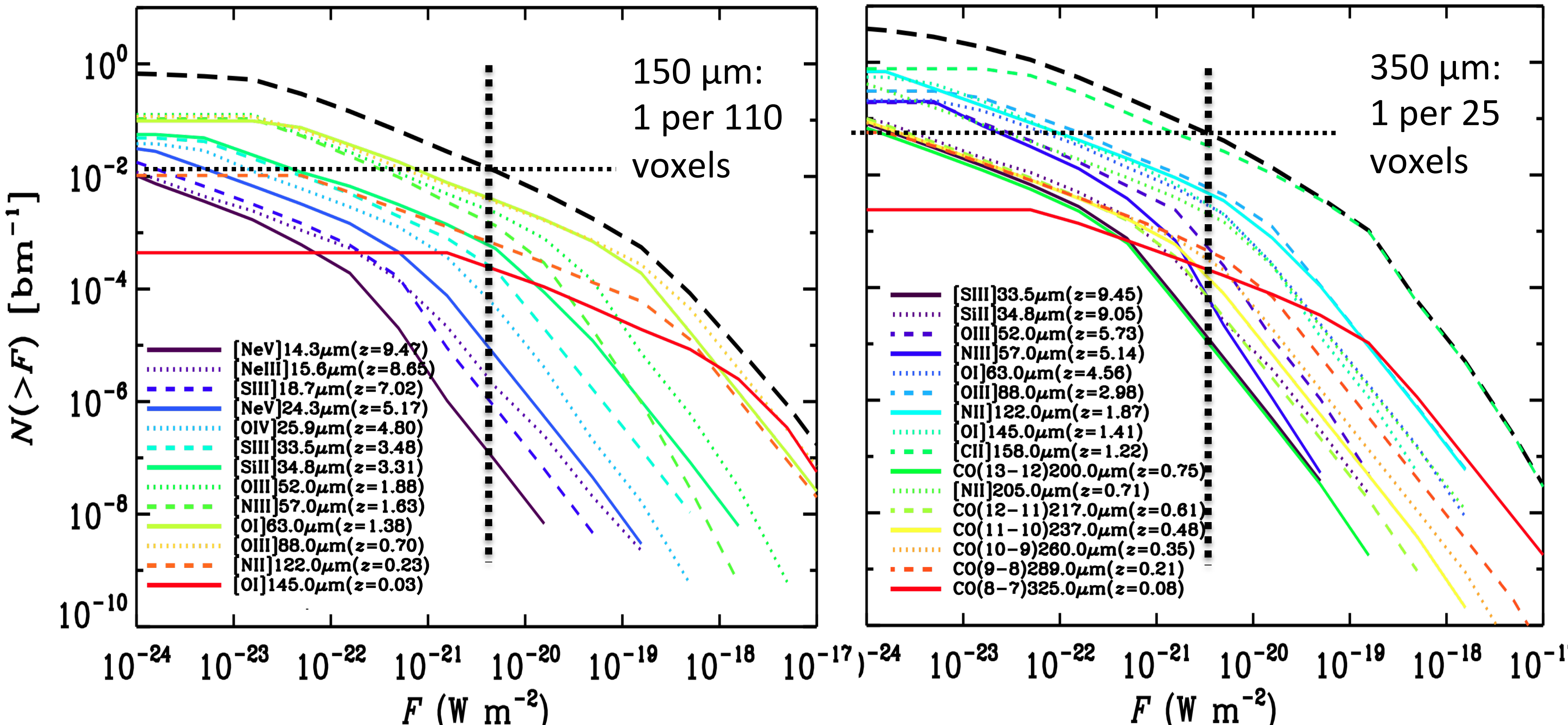


- The 2x reduction in beam solid angle (vs Herschel) translates to a 10x improvement in depth at 100 μm due to the shallow slope of the luminosity function. Further improvements may be possible via removal of bright sources, combining datasets with the 2 telescope orientations.
- **Imaging at 50 - 100 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.**

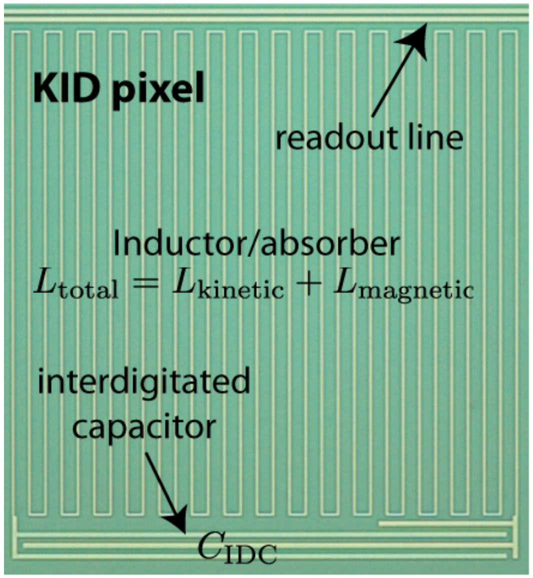
CALISTO Unconfused in 3 Dimensions

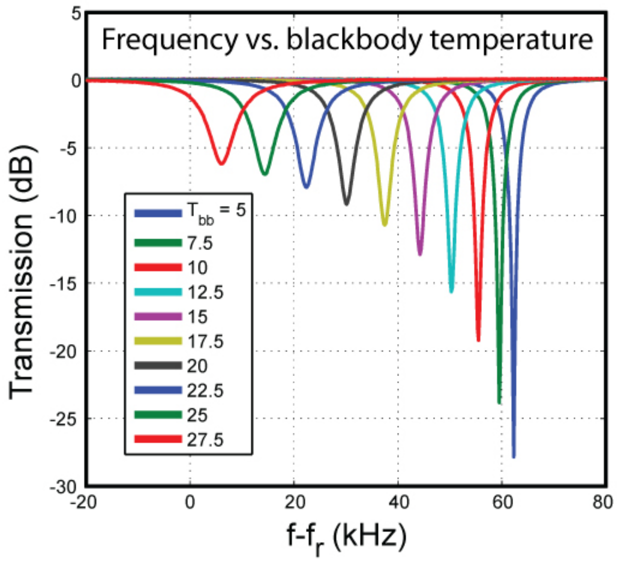
Fine-structure 'line counts' E.J. Murphy et al.

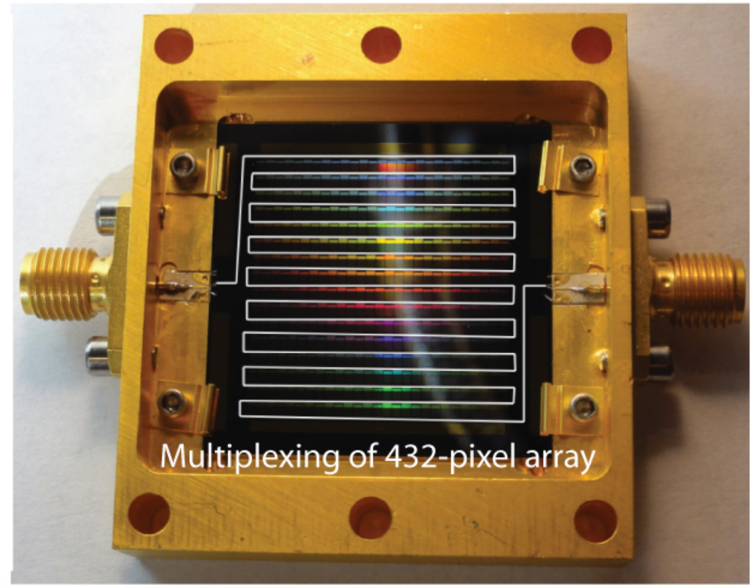
- Based galaxy models from Chary & Pope 2010,
  (backward evolving from Chary & Elbaz 2001, L* evolution with z)
- Lines from galaxy luminosity from Spinoglio 2011 compilation of Spitzer, ISO LWS.
- Cumulative counts per spectral spectral bin (here numbers for 3.15-meter telescope, R=700, numbers corrected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

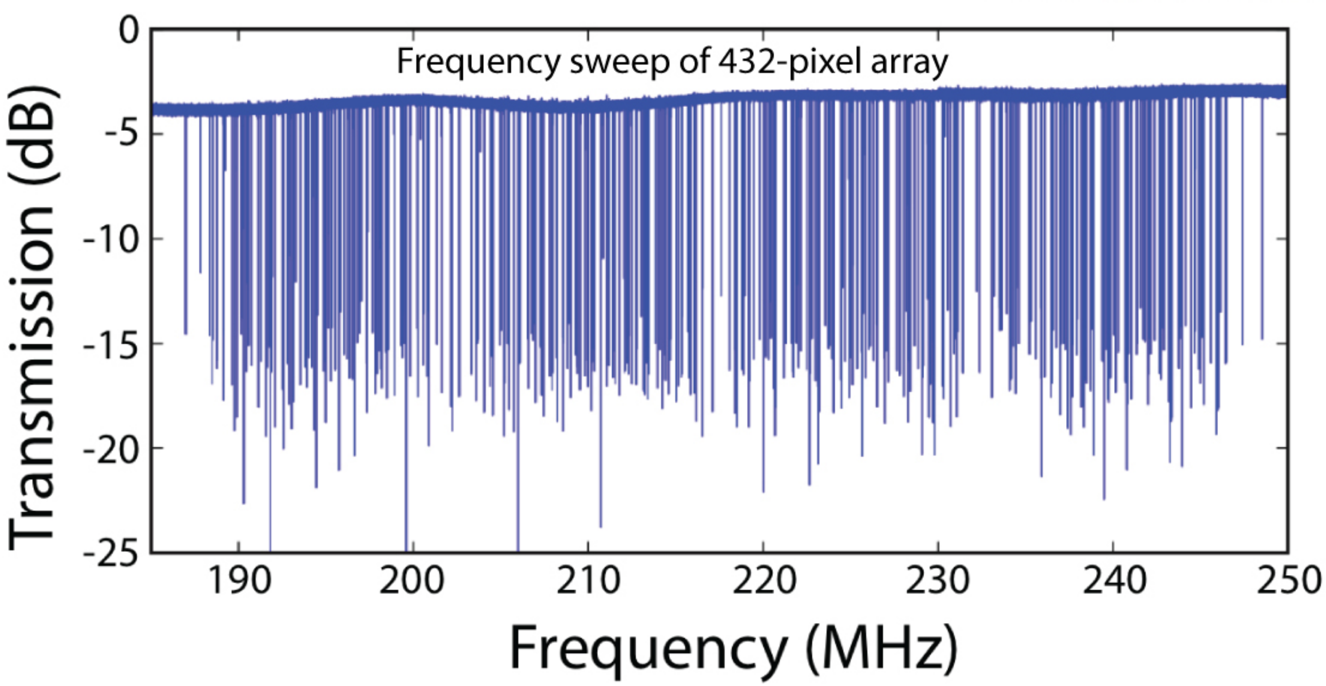


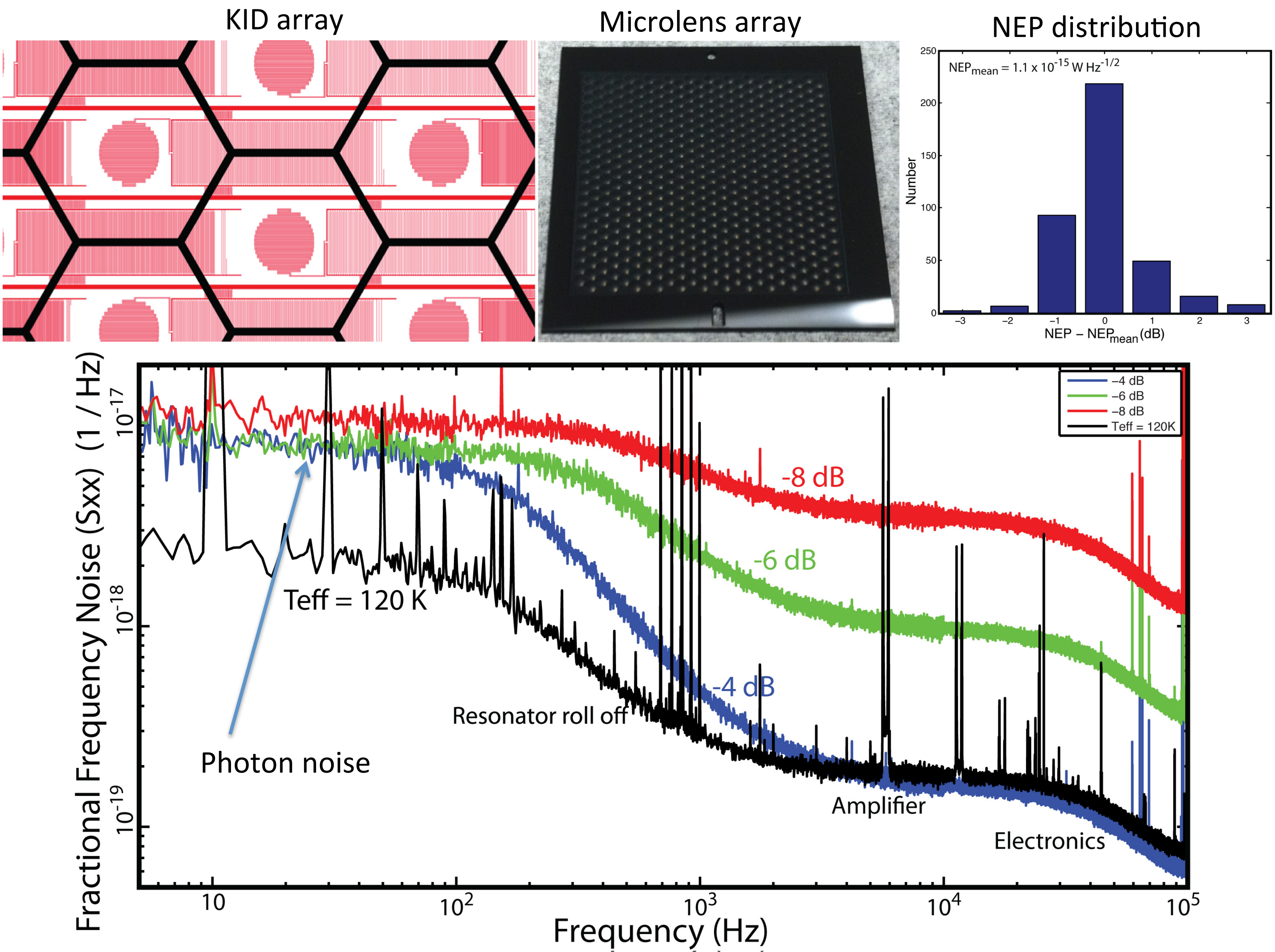
KIDS: basic concept



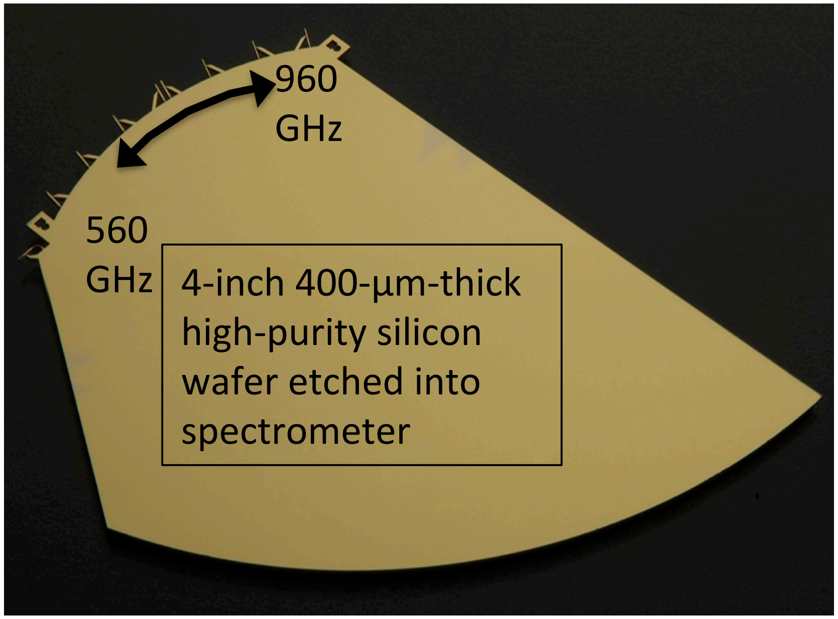


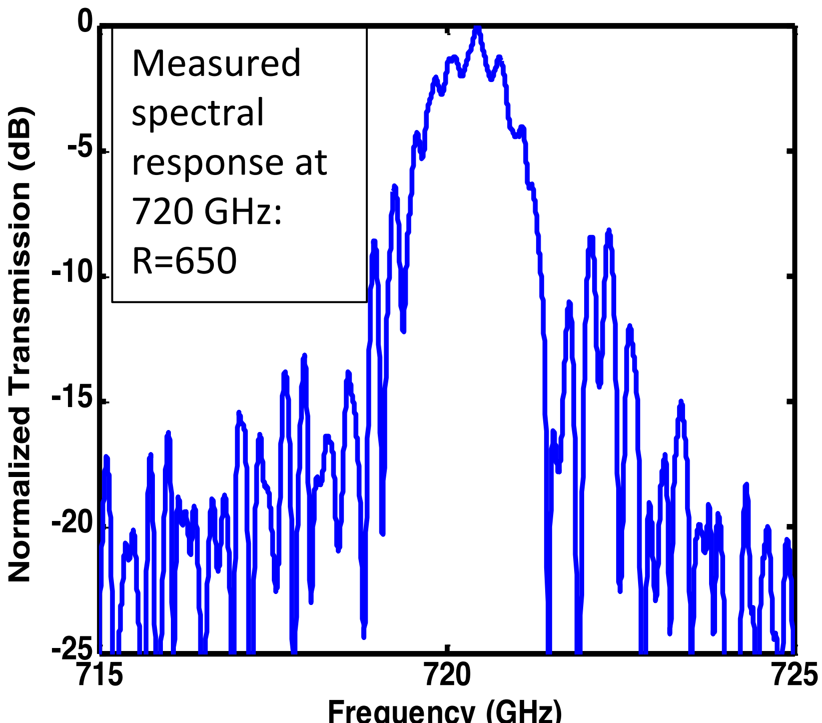





KID array
Microlens array
NEP distribution
NEP$_{mean}$ = 1.1 x 10^{-15} W Hz$^{-1/2}$
Number
NEP − NEP$_{mean}$ (dB)
−4 dB
−6 dB
−8 dB
Teff = 120K
-8 dB
-6 dB
-4 dB
Teff = 120 K
Photon noise
Resonator roll off
Amplifier
Electronics
Fractional Frequency Noise (Sxx) (1 / Hz)
Frequency (Hz)

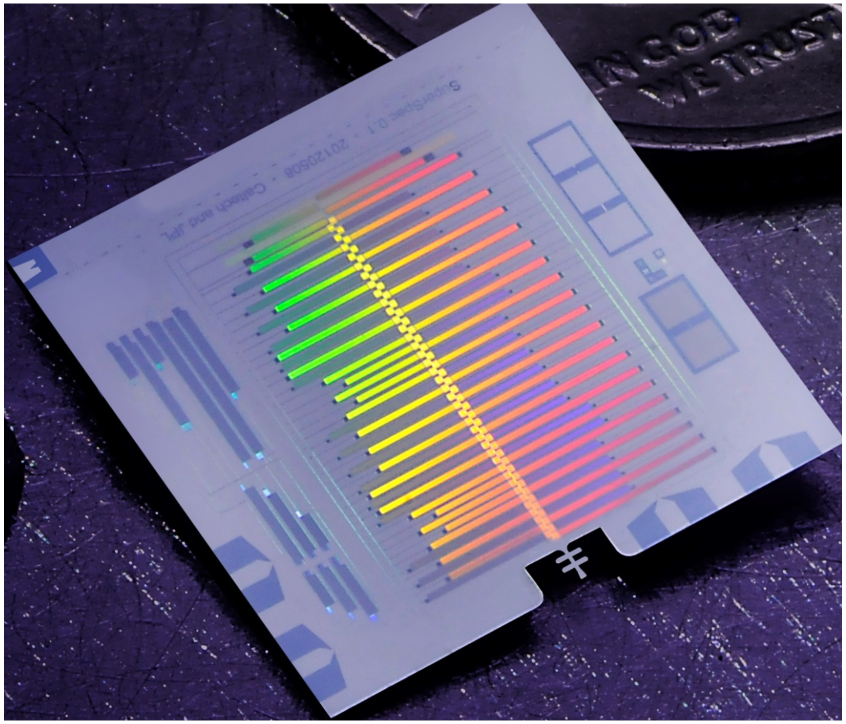
Spectrometer Concepts (2): Silicon-Immersed Waveguide Grating





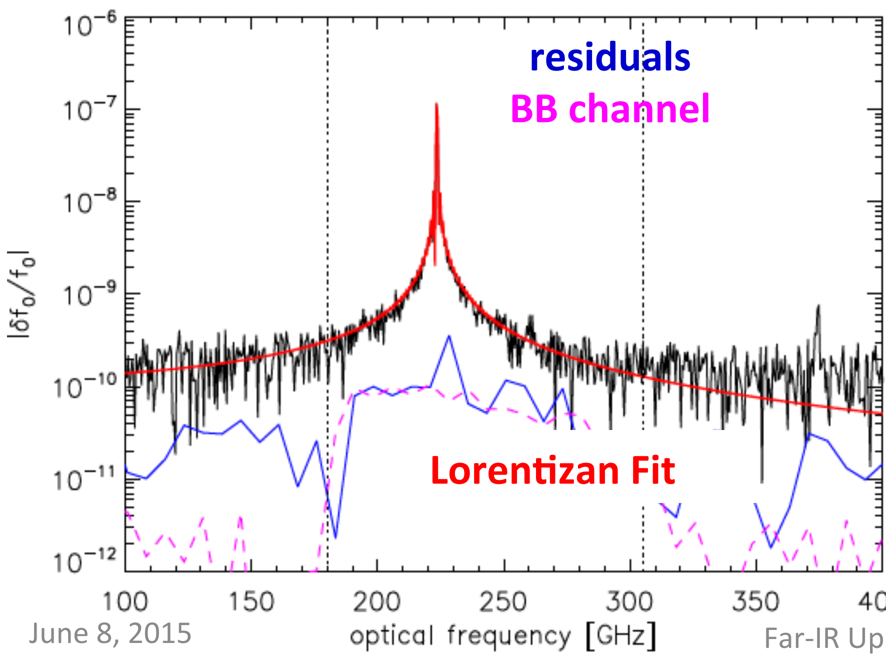
- Curved grating in parallel plate waveguide. Single polarization, good efficiency over 1:1.6 bandwith.
- Demonstrated at λ=1.3 mm, R=300 in Z-Spec at CSO (free-space propagation medium).
- Now demonstrated R=700 device in float-zone silicon wafer with warm test.
- End-to-end efficiency test and integration 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



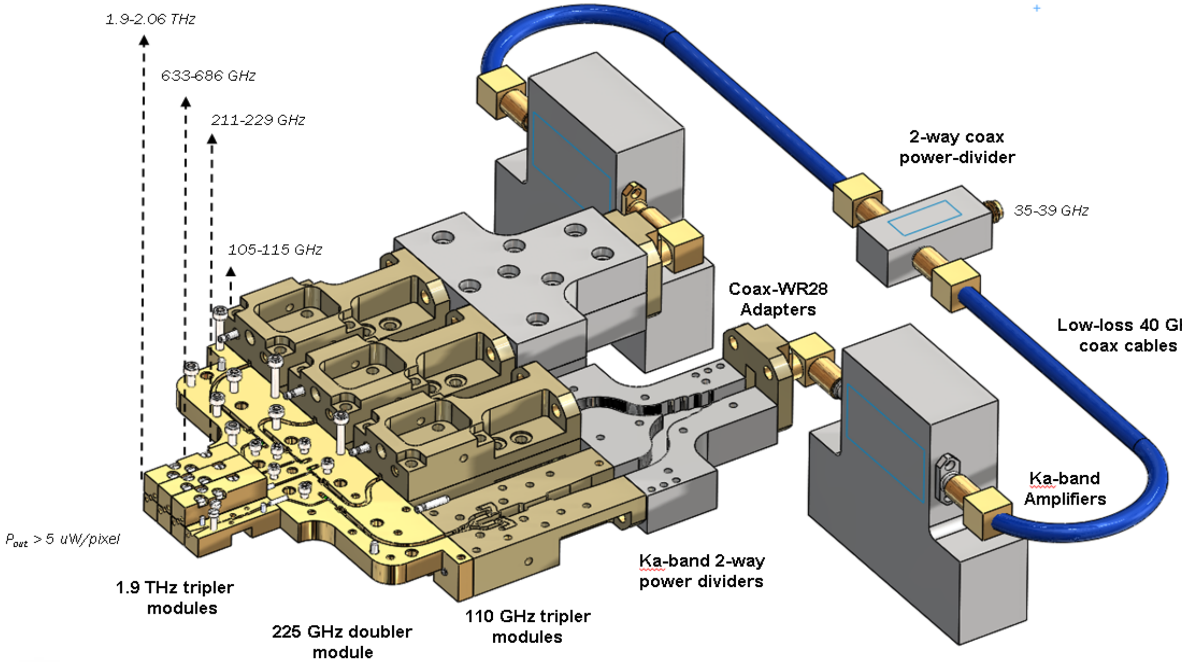
Spectrometer Concepts (3): SuperSpec on-chip spectrometer

- 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

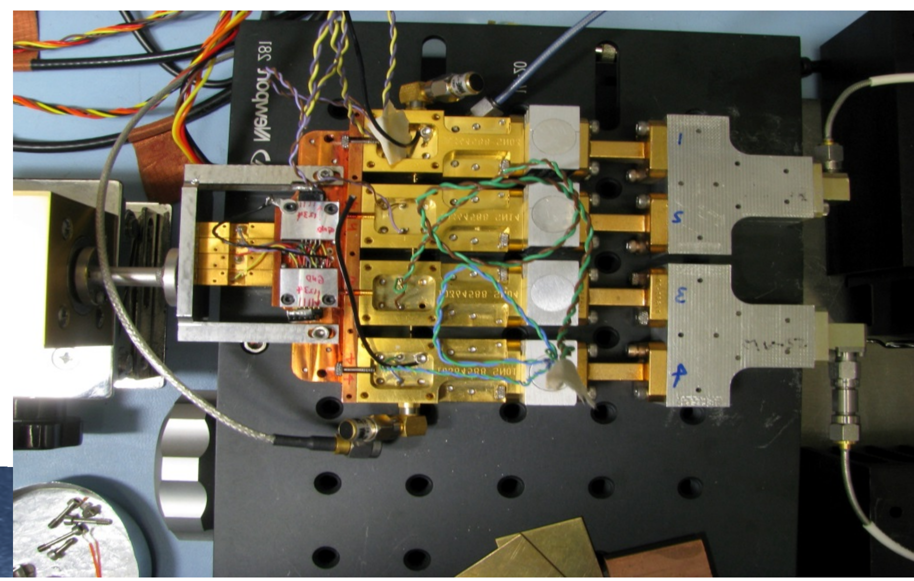
4-Pixel 1.9 THz Local Oscillator Subsystem



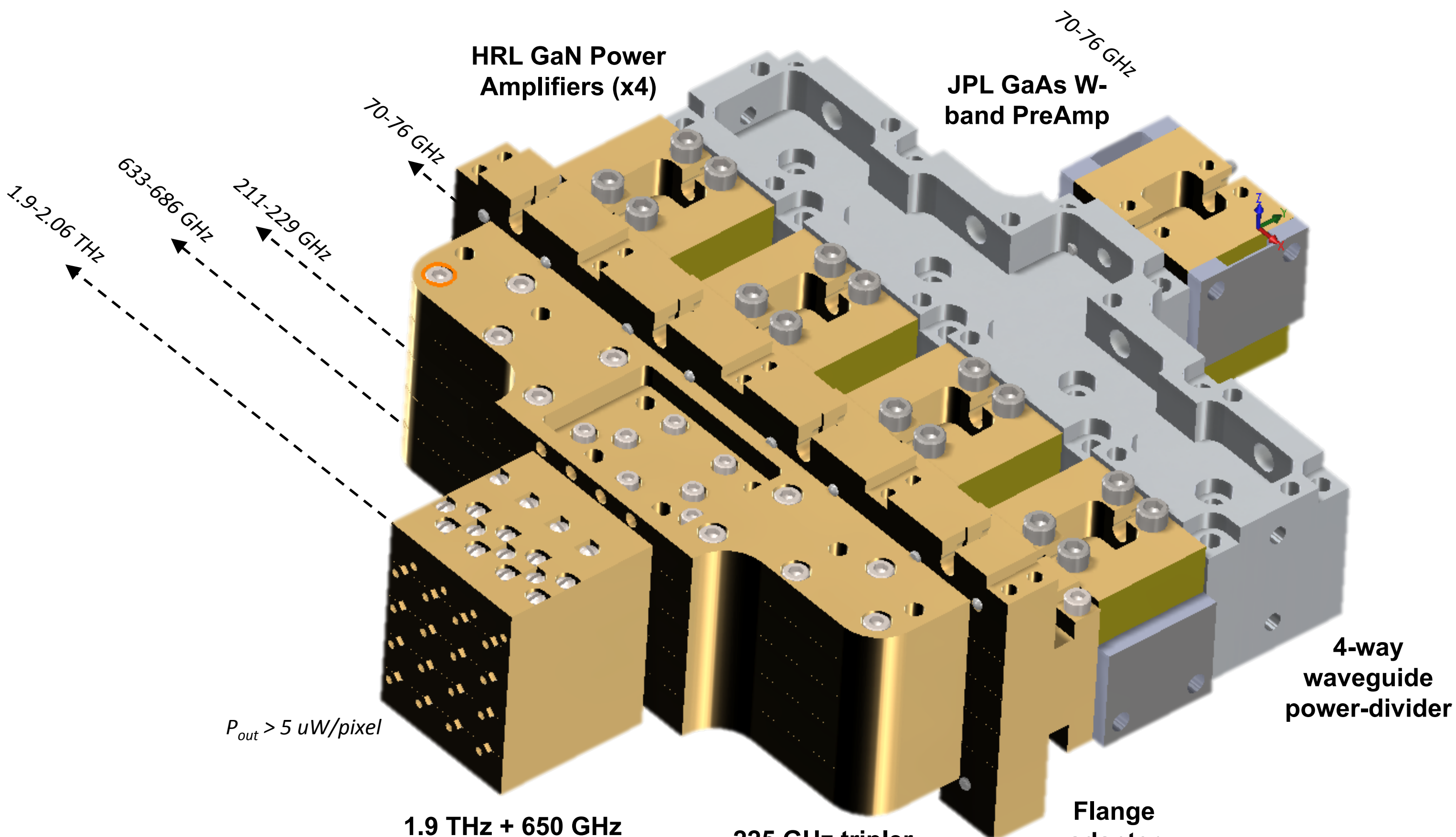
More than 10 uW per pixel measured

J. Siles

20 cm x 20 cm x 10 cm



Extending Heterodyne Array Architecture to 16 pixels

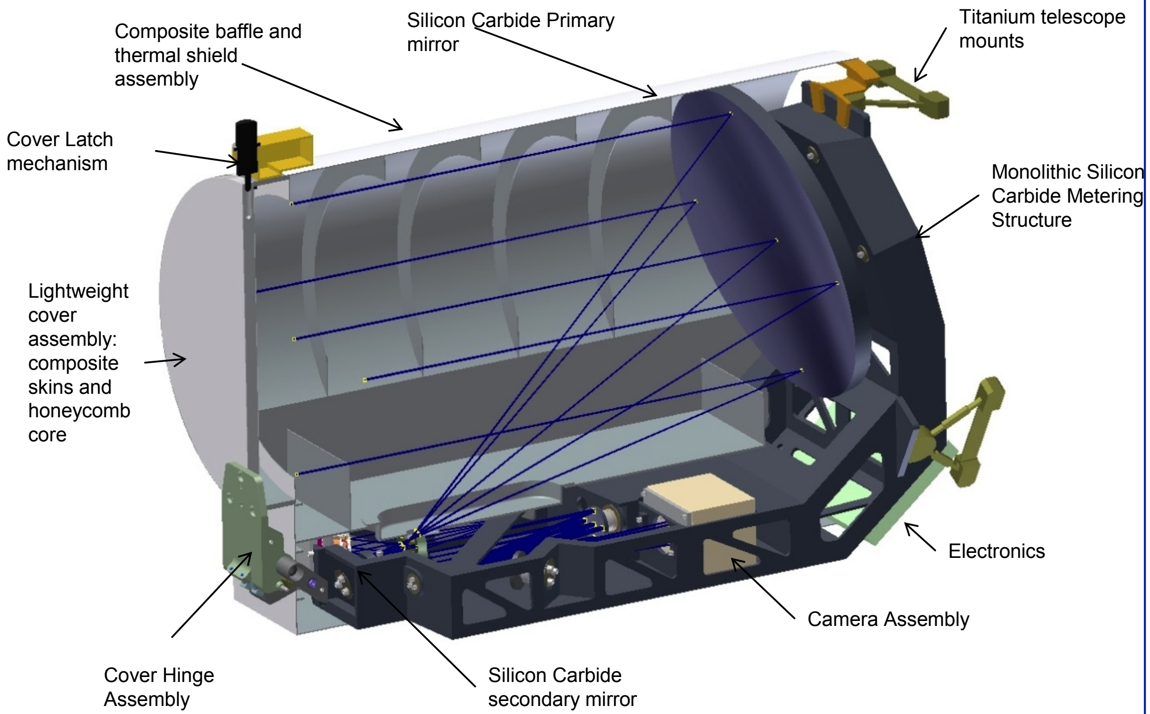


J. Siles & Imran Mehdi

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)*