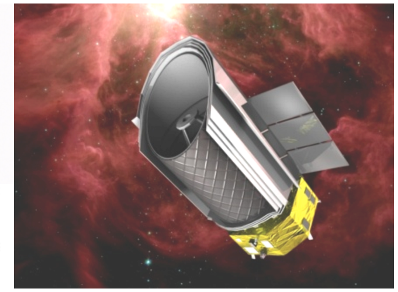


SPICA UPDATE AND BLISS

THE BACKGROUND-LIMITED INFRARED SUBMILLIMETER SPECTROGRAPH

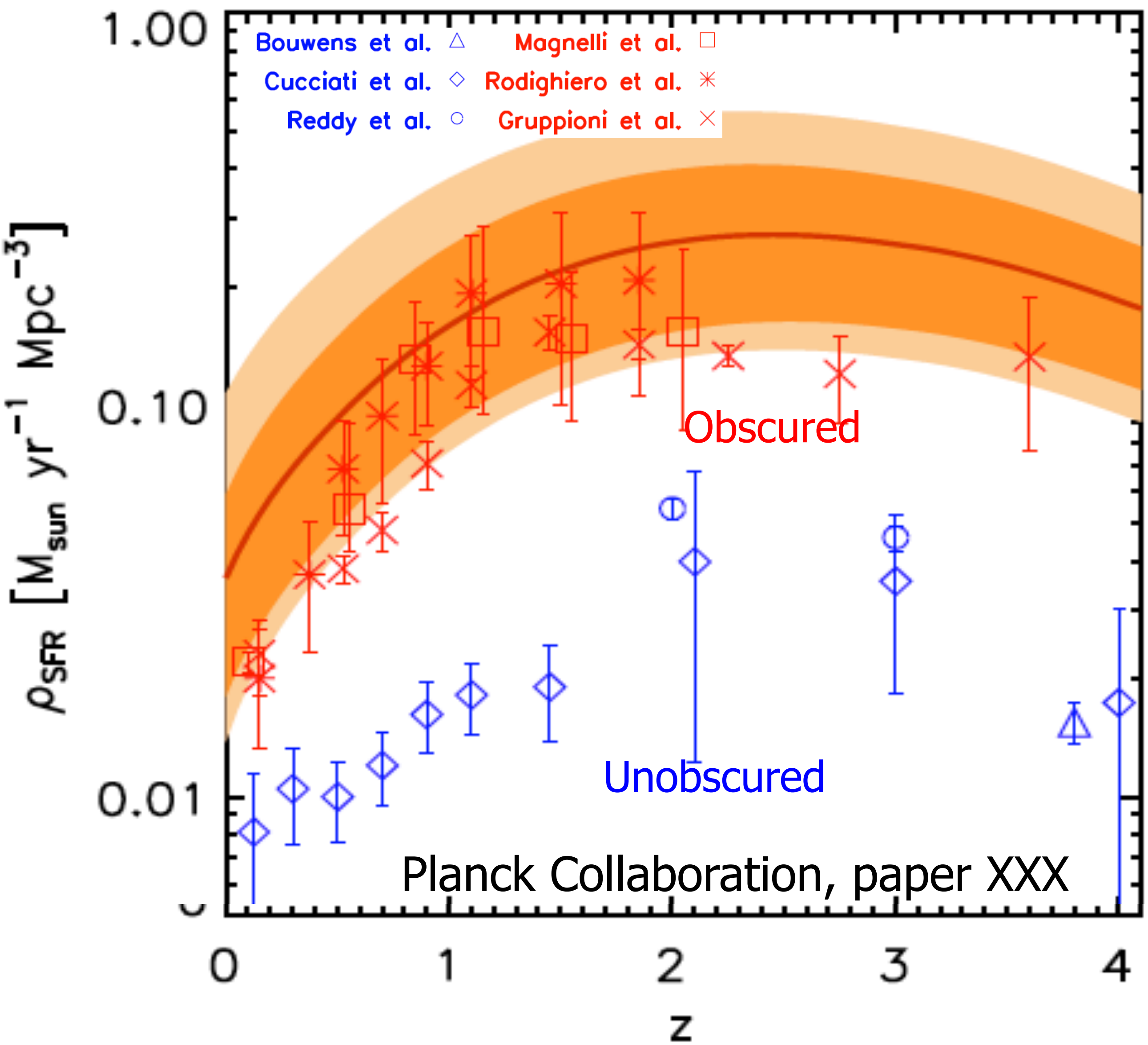
Matt Bradford (JPL / Caltech)

w/ Takao Nakagawa (ISAS JAXA)

Peter Roelfsema (SRON)

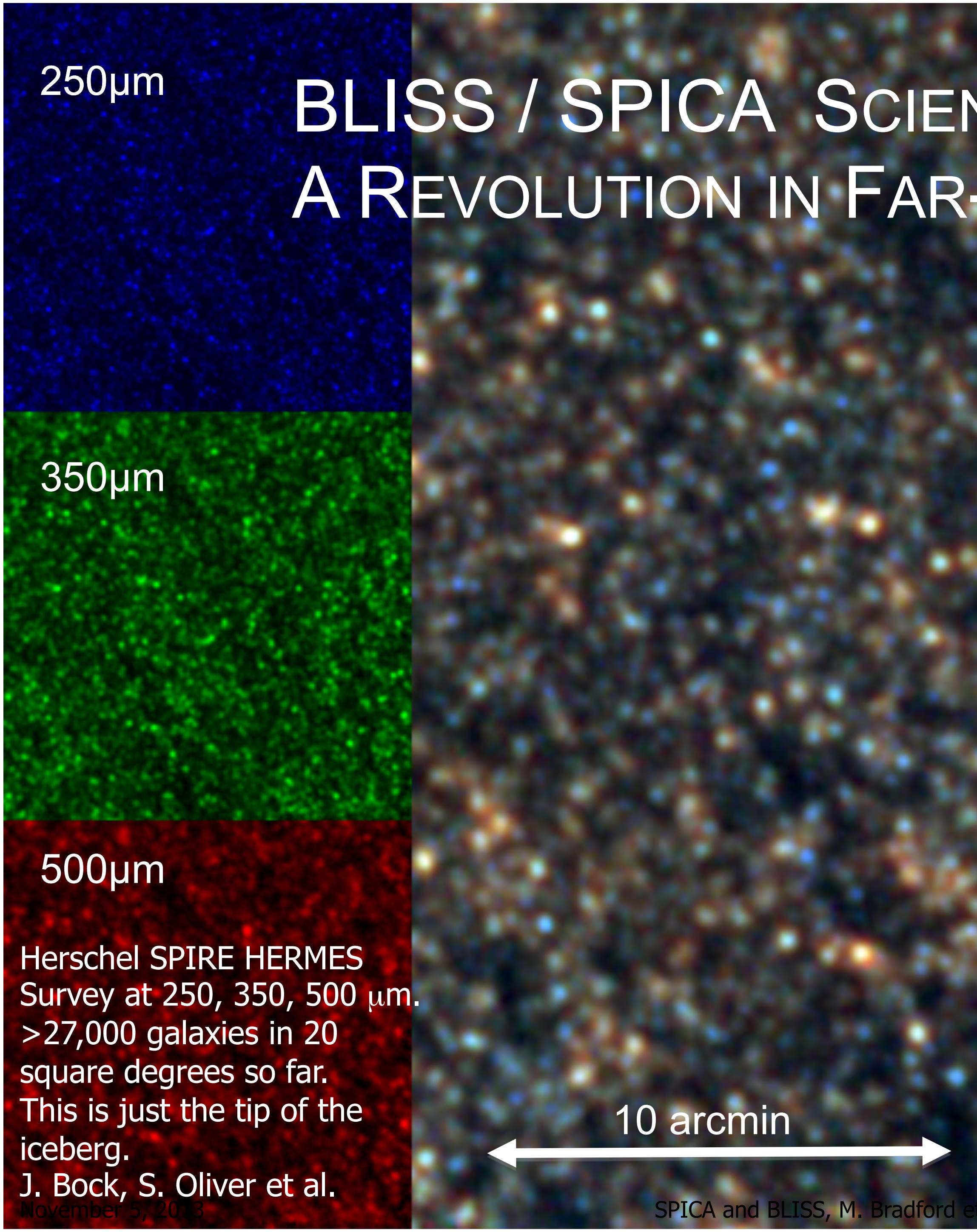
CAA Fall Meeting 2013

Most of the Cosmic Star Formation has been Obscured by dust



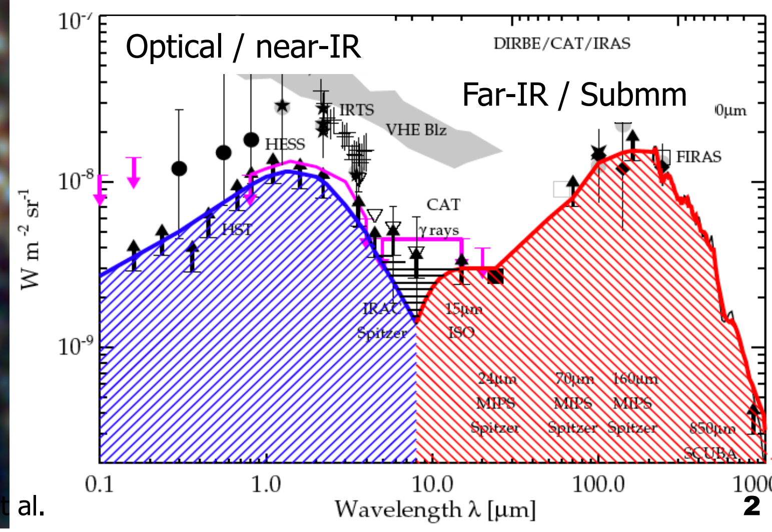
- Planck results constrain total star formation activity. Use correlations in all-sky far-IR / submm maps.
- On average 7-9 out of every 10 UV / optical photons is absorbed by dust.
- High-z dusty sources suggest that onset of dust appears very rapid.

BLISS / SPICA SCIENTIFIC MOTIVATION: A REVOLUTION IN FAR-IR ASTRONOMY



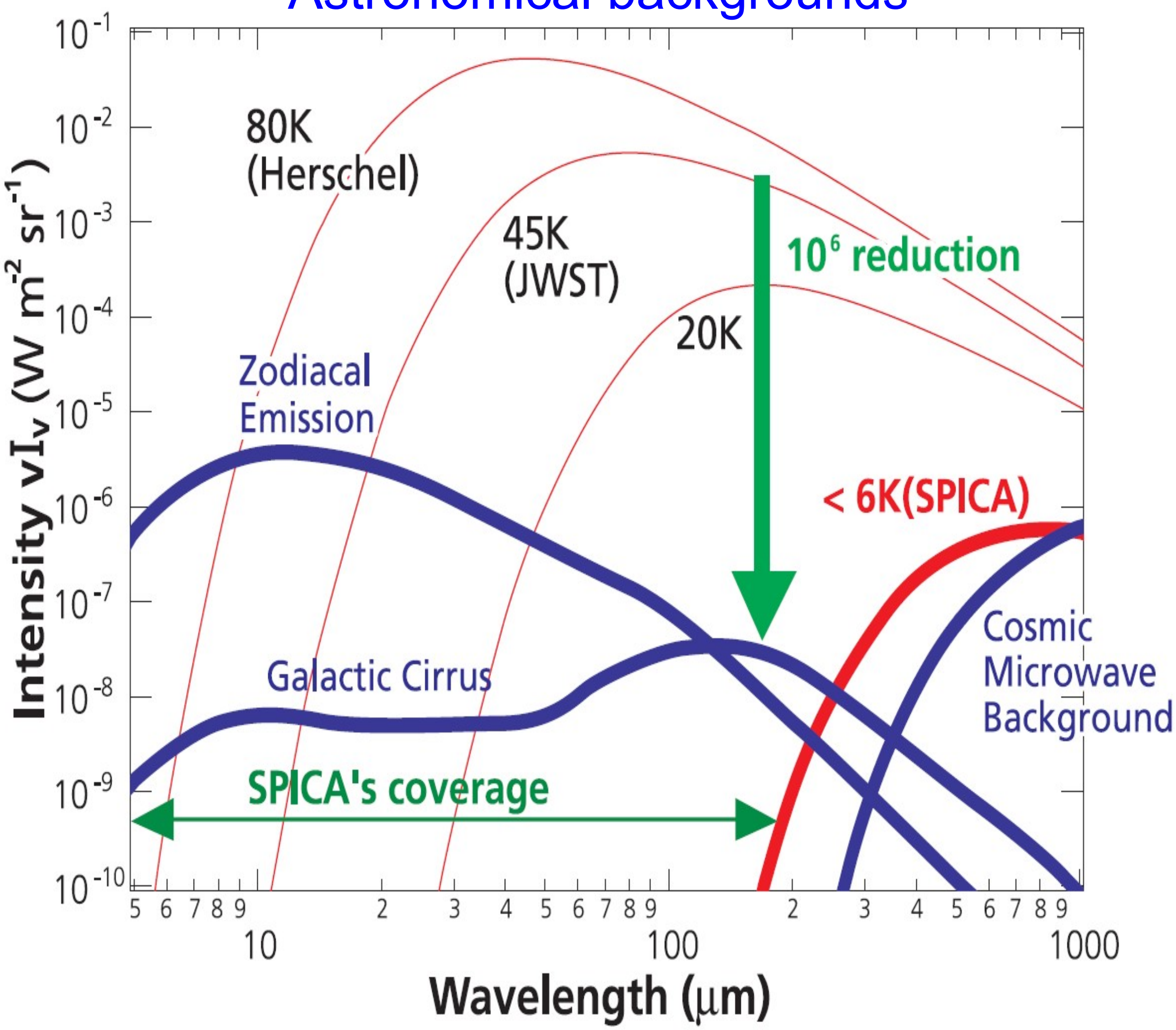
Herschel SPIRE HERMES Survey at 250, 350, 500 µm. >27,000 galaxies in 20 square degrees so far. This is just the tip of the iceberg.
J. Bock, S. Oliver et al.

Backgrounds including Spitzer stacking analyses at 70, 160 µm. *Dole et al. 2006.*



SPICA Concept:
6 K, 3-m Flagship-Class far-IR Observatory

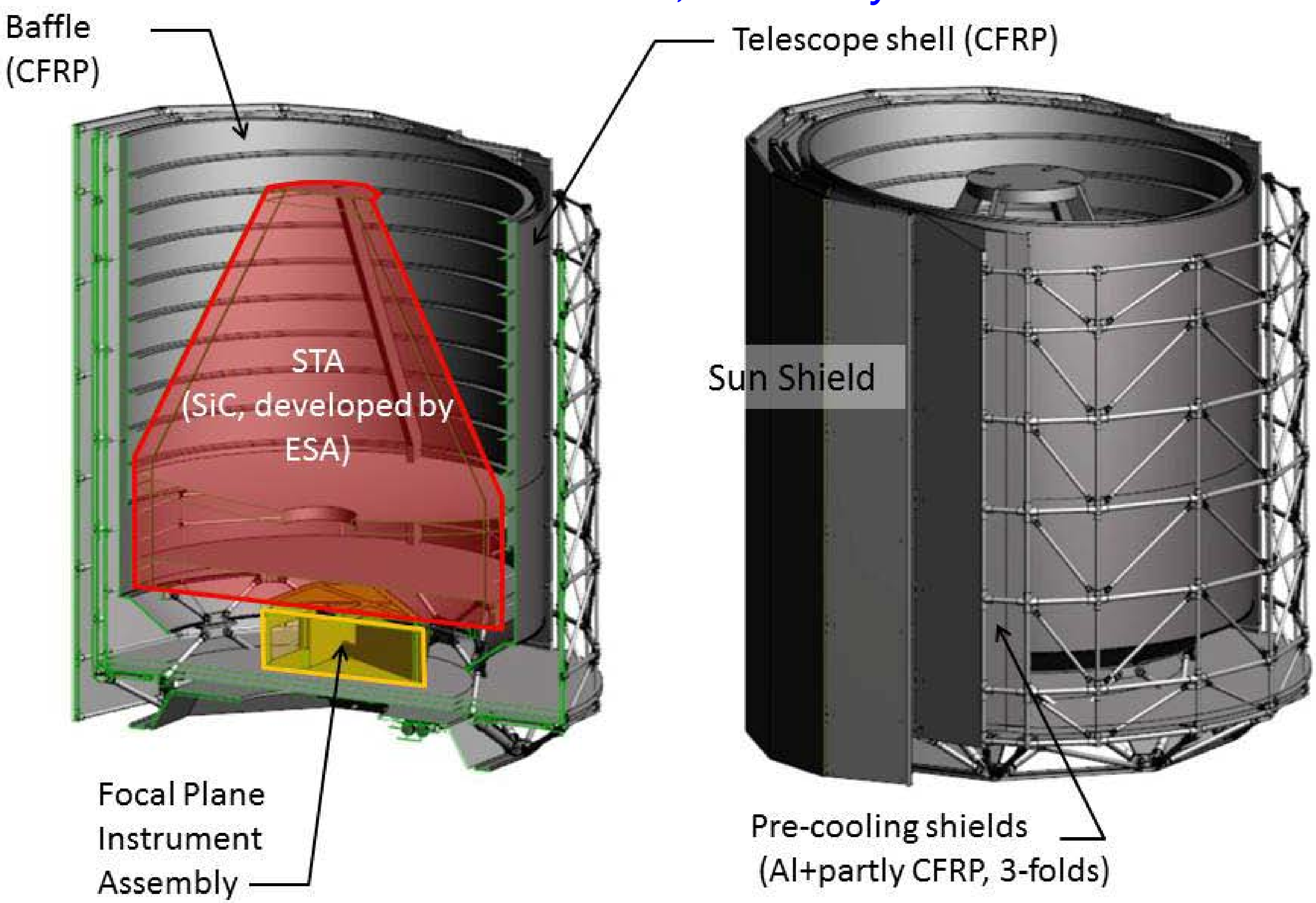
Astronomical backgrounds



Low temperature more important than large aperture

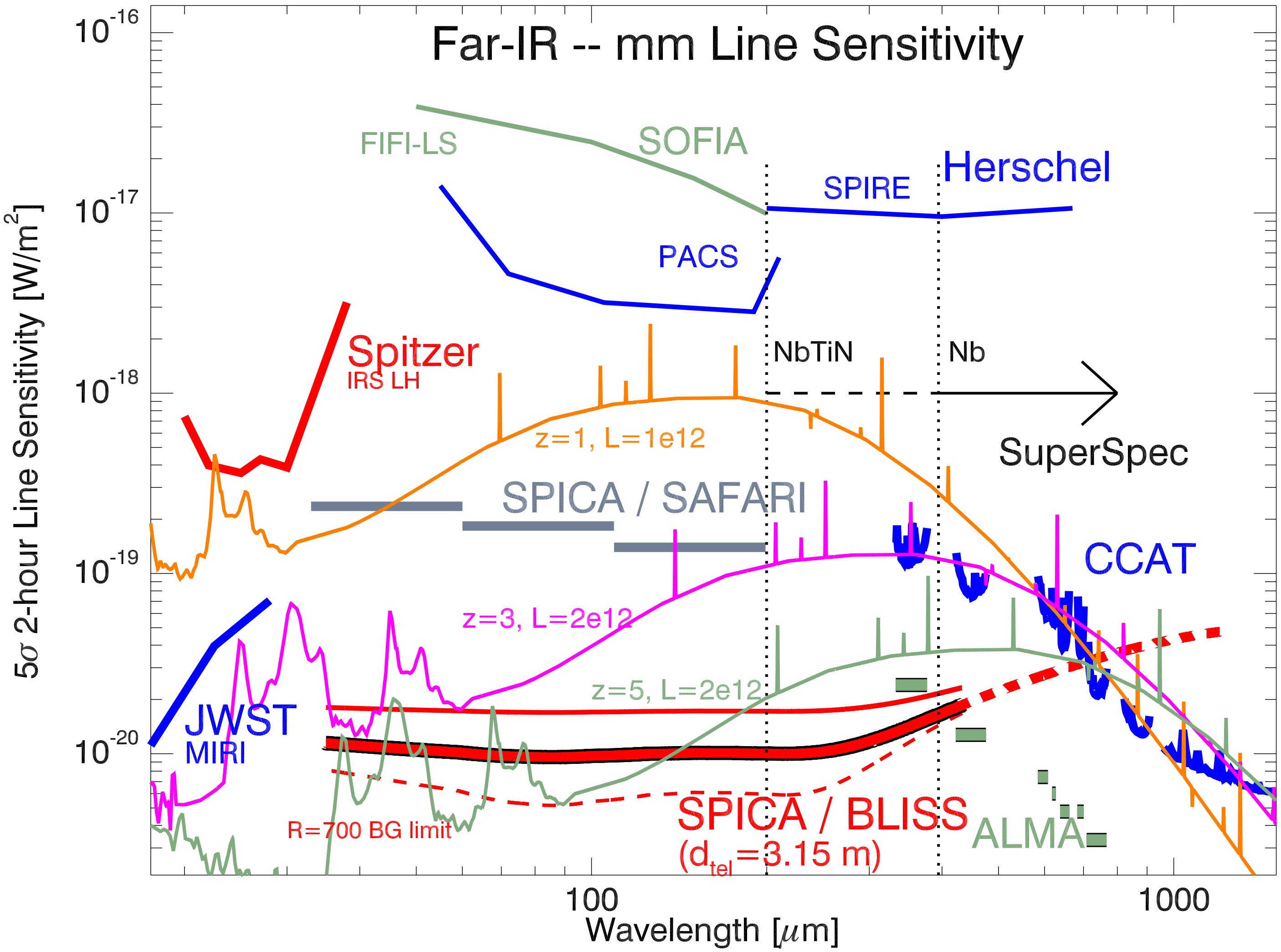
SPICA Concept:
6 K, 3-m Flagship-Class far-IR Observatory

warm launch to L2 orbit, closed cycle 4.5 K coolers



Low temperature more important than large aperture

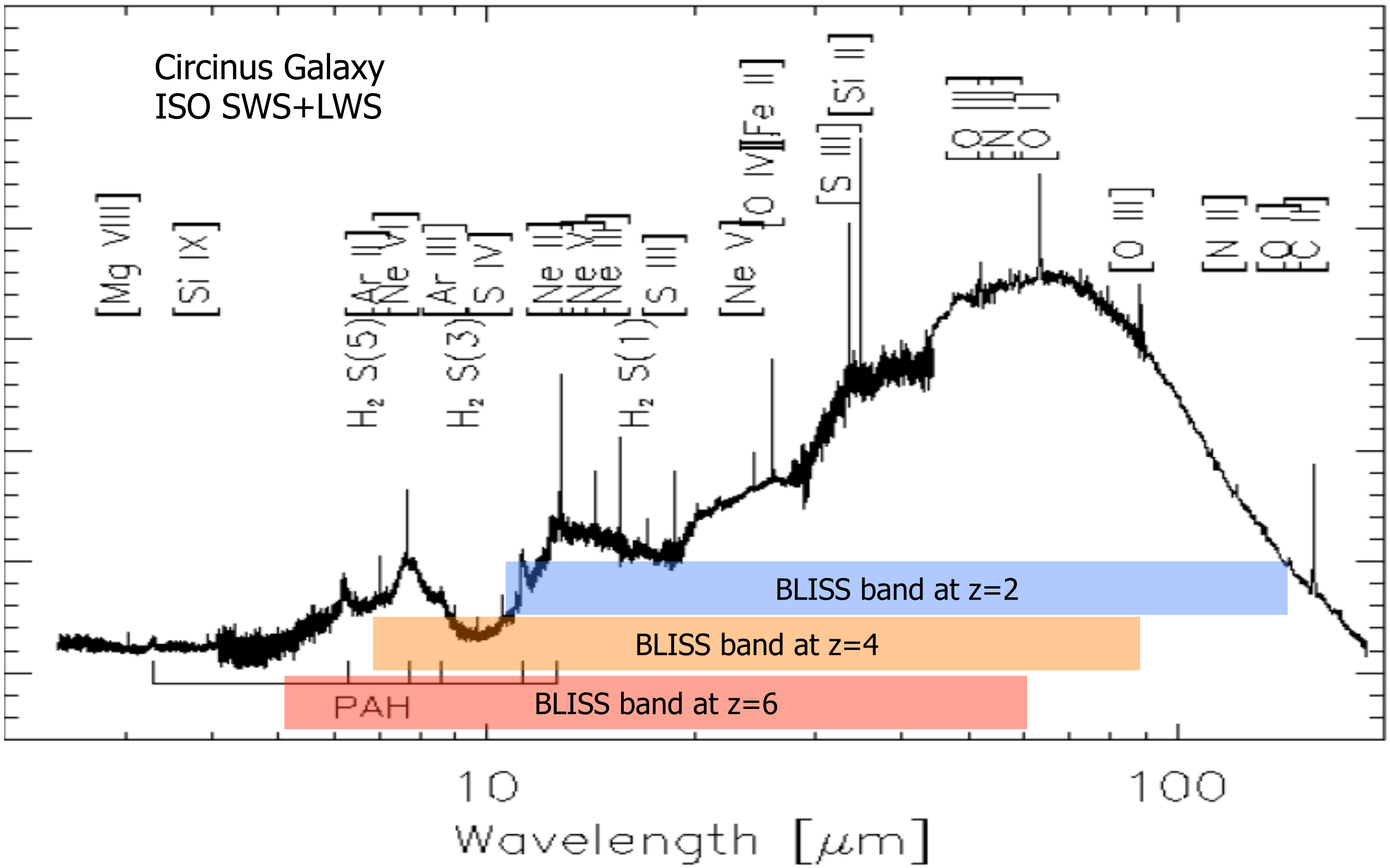
BLISS-SPICA ULTIMATE CAPABILITIES



- 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.

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

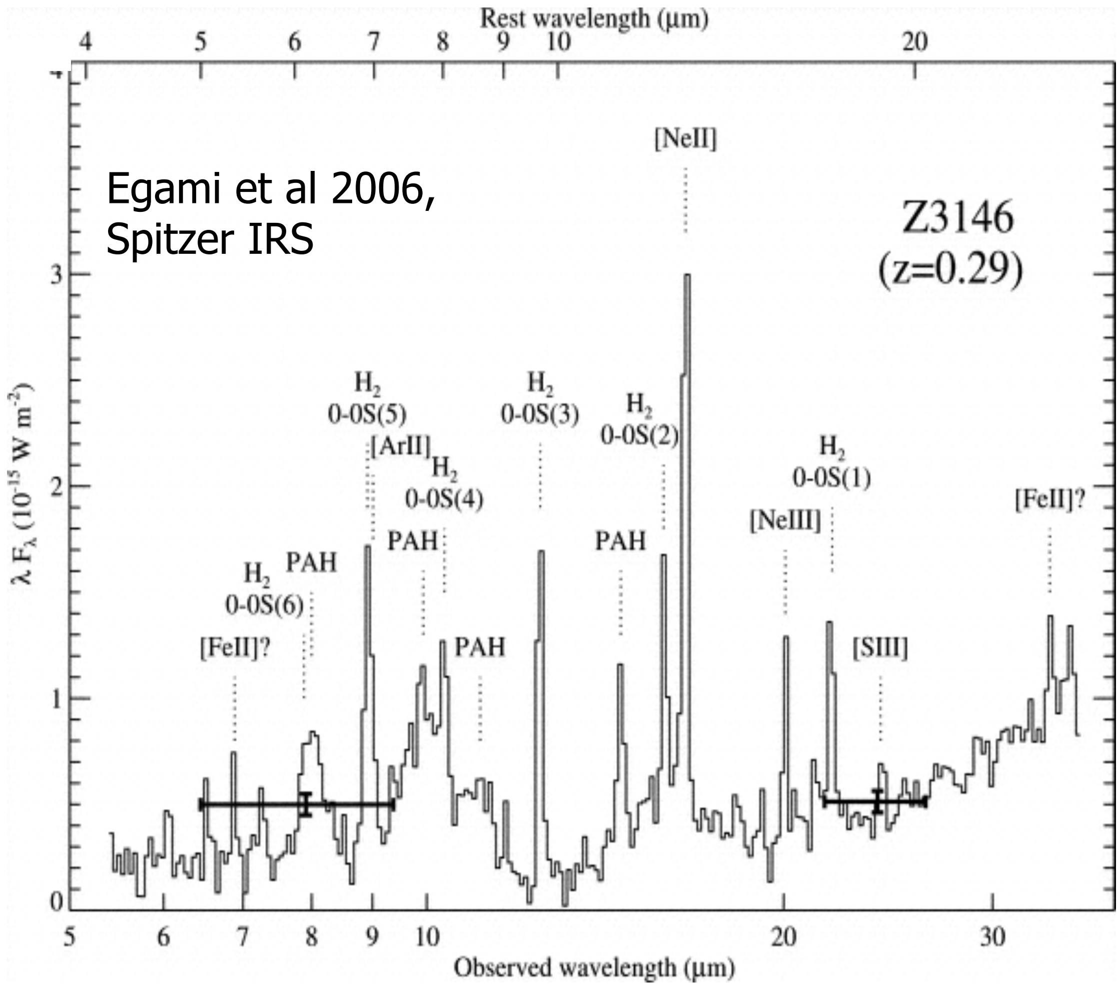
Far-IR Spectroscopy Probes the History of Star Formation



- Star formation rate, gas density and filling factor, and stellar effective temperature are measured with fine-structure lines of Ne^+ (13μm), Si^+ (34μm), C^+ (158μm), and O^0 (63μm, 145μm) together with the far-IR continuum.
- SPICA/BLISS + ALMA will measure the complete mid- far-IR suite in galaxies from z=6 (1 BY after the Big Bang) to the present.

The Cosmic Rise of Heavy Elements and 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.



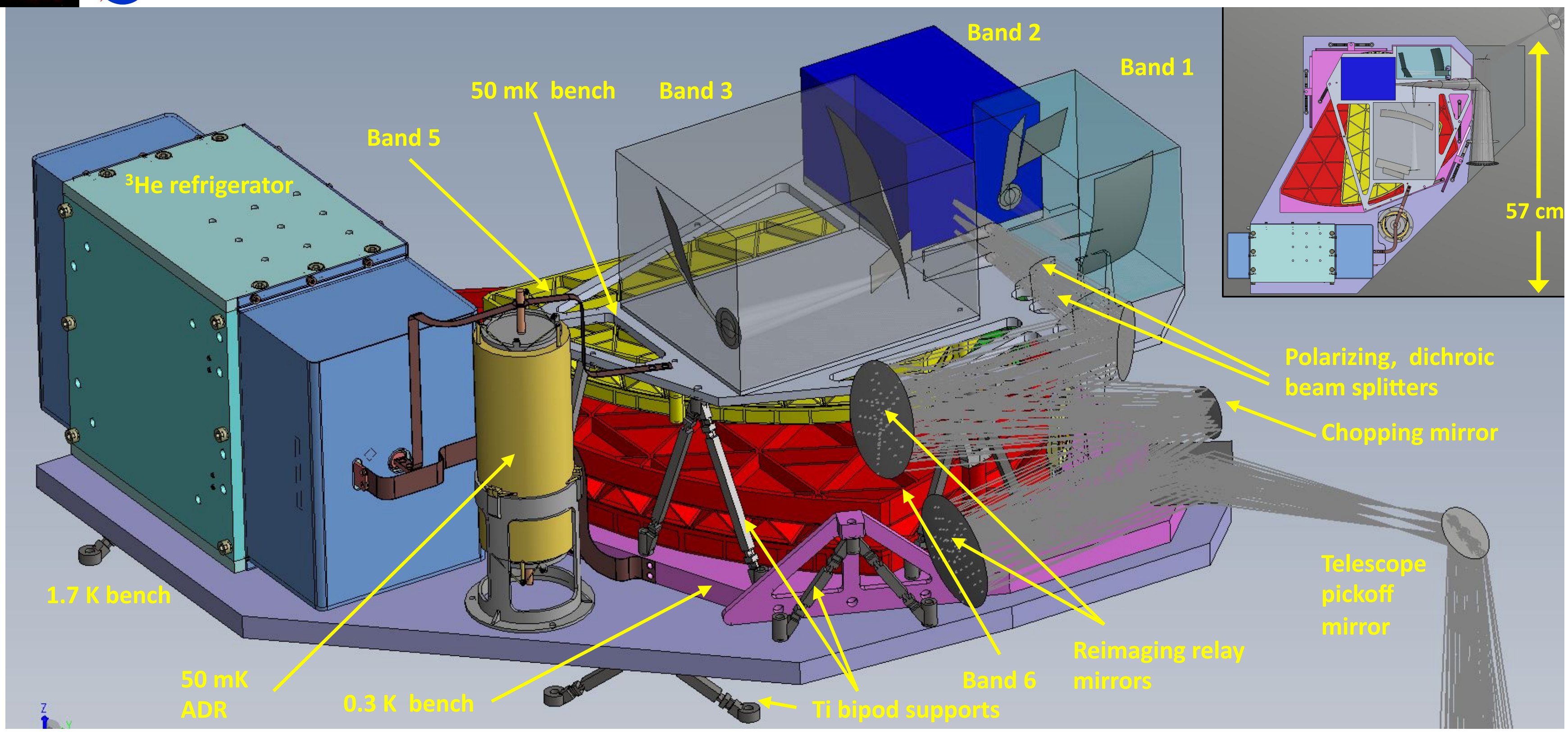
- Strong H_2 emitters found in the local-Universe may be analogs of early-Universe shocks produced in galaxy formation and AGN feedback.
- The Zw3146 spectrum at left would be detectable at z=8-10 with BLISS / SPICA!
- PAH features may offer the best probe of heavy metal abundance at early times.
- SPICA-BLISS can readily detect the PAH emission from galaxies systems at z~6, as they come to be (not accessible to JWST or ALMA.

ASTRO2010 PPP RECOMMENDATIONS

Table B.1 Summary of Priority Activities as Recommended by the Program Prioritization Panels.

EOS Project	Program Cost Appraisal (category)	PAG Project	Program Cost Appraisal (category)	RMS Project	Program Cost Appraisal (category)	OIR Project	Program Cost Appraisal (category)
(1) WFIRST	$1.5B (L)	(1) LISA	$1.5B (L)	(1) HERA-I and HERA-II	$25M + $85M (M)	(1) GSMT	≥$1B (L)
(2) IXO (project start)	$1.0B (L)	(2) ACTA (AGIS)	$0.2B (L)	(2) FASR (2) CCAT	$100M (M) $110M (M)	(2) LSST	$460M (L)
(3) Exoplanet Mission	$0.7B (L)	(1) Pulsar Timing Array for Gravitational Wave Detection	$70M (M)	ATA Enhancement	$44M (M)	(1) Mid-scale NSF program augmentation (OIR+PAG+RMS)	$200M
(1) BLISS	$0.2B (M)	(1) NASA Explorer Augmentation	$1B (M)	Enhancements to GBT, EVLA, VLBA, ALMA, Enhancements to CARMA, EHT	$120M $25M	(2) TSIP augmentation	$40M (M)
(2) Explorer	$0.5B (M)	(2) Technology development augmentation and ULDB R&D and augmentation	$550M NASA (M), $150M NSF+DOE (M)	---	---	(2) OIR System augmentation	$61M (M)
(3) R&A	$0.2B (M)	(3) Auger North	$60M (US portion) (M)	---	---	Small, unprioritized programs	$100M

BLISS OVERVIEW

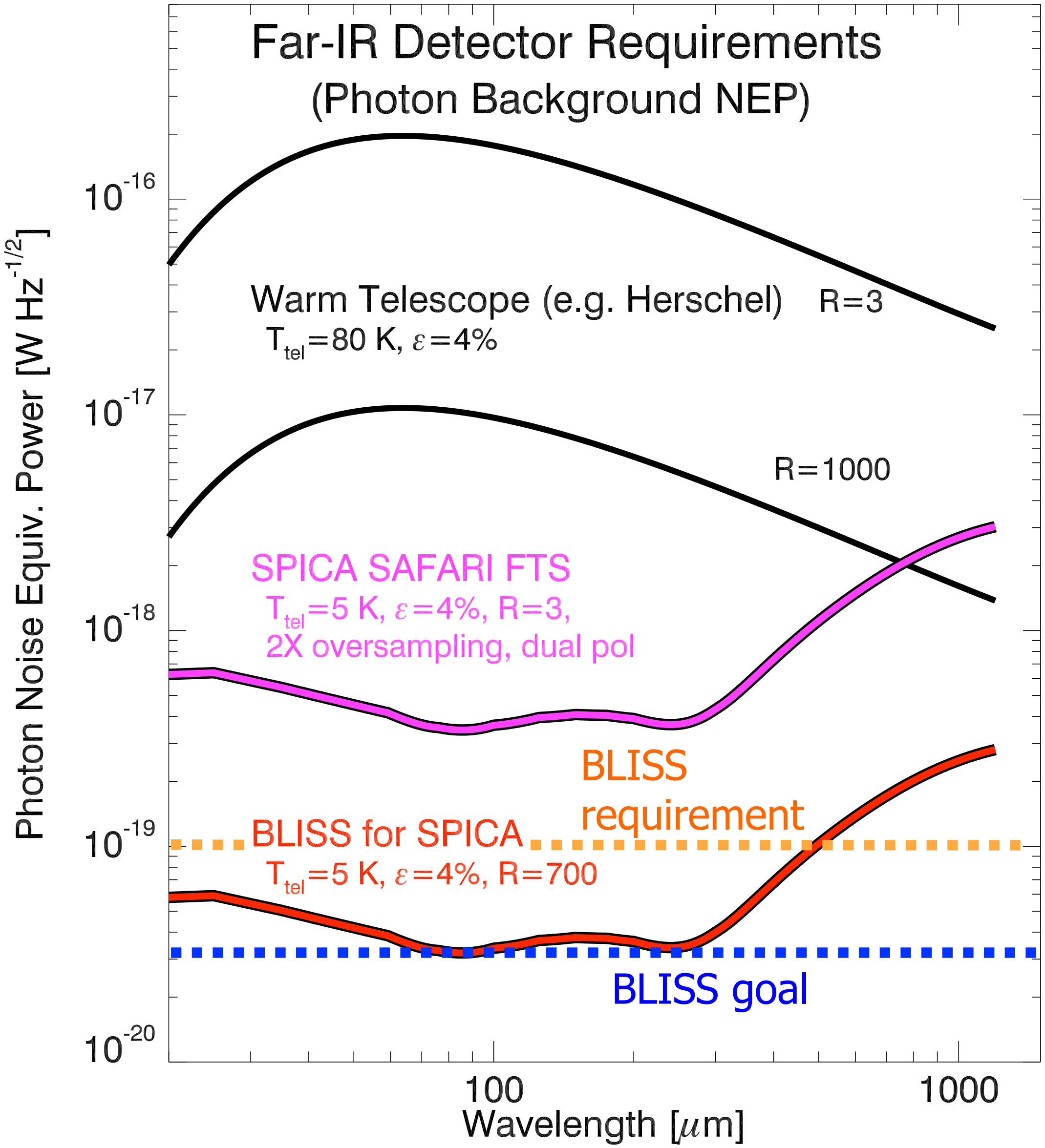


Approach: measure a galaxy's full spectrum from 35-433 μm simultaneously.

- 6 bands (shown B1-B6 in schematic) each coupling 2 sky positions at R~700.
- Use polarizer (P) then couple a single polarization in each spectrometer. Dichroic filters (FXX) separate the bands:
- Short-wavelength bands are echelle spectrometers (blue in schematic), long-wavelength bands are waveguide spectrometers (red in schematic).
- ~4000 superconducting bolometers with SQUID MUX, 700-800 detectors per band.
- Assembly cooled to 50 mK with a 2-stage refrigerator, supported with titanium suspension.
- Bolt and go, no moving parts except for chopping mirror in feed optics (not shown).
- **Specs**: 45x40x40 cm^3, 30 kg cold mass (w/ margin), Power ~100 W.

BLISS SENSITIVITY REQUIREMENTS

BLISS REQUIRES SENSITIVE DEVICES, PAVES THE WAY FOR FUTURE MISSIONS



- BLISS detectors must match the zodiacal+Galactic dust emission, and the telescope & CMB at 300 μm and longer. The BLISS requirement is set at 1x10^{-19} W Hz$^{-1/2}$.
- No suitable ground-or ballon-borne testbed. Even Herschel with its 80 K telescope has backgrounds 10,000 times too high.
- BLISS for SPICA NEP to astronomical sensitivity conversion:
- MDLF (3 sigma, 1 hour) [W m^{-2}] = 0.21 x NEP [W Hz$^{-1/2}$]

Including 3.15-m telescope @75%
chopping
single polarization @25%
extra factor of 3

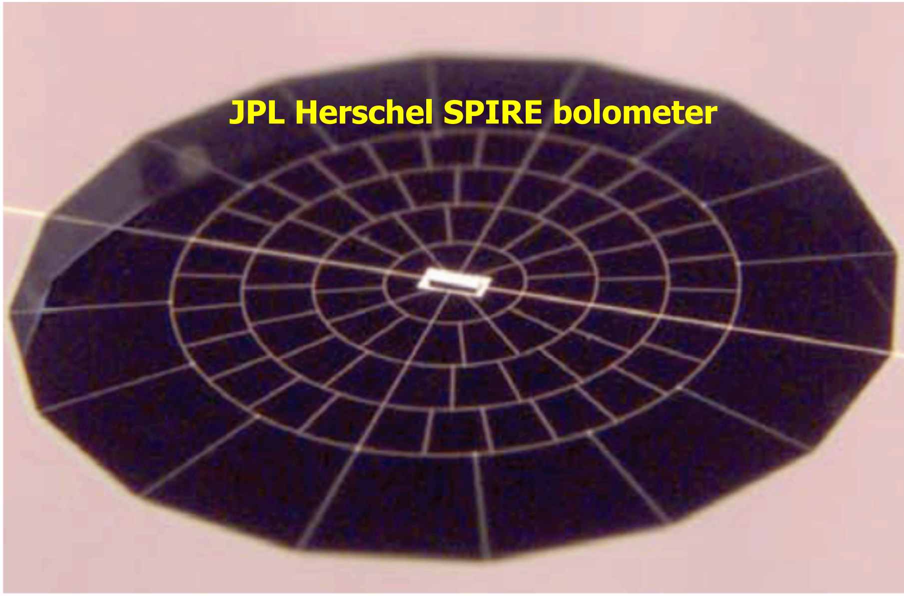
1e-19 W Hz$^{-1/2}$ -> 2e-20 W m^{-2} astronomical sensitivity

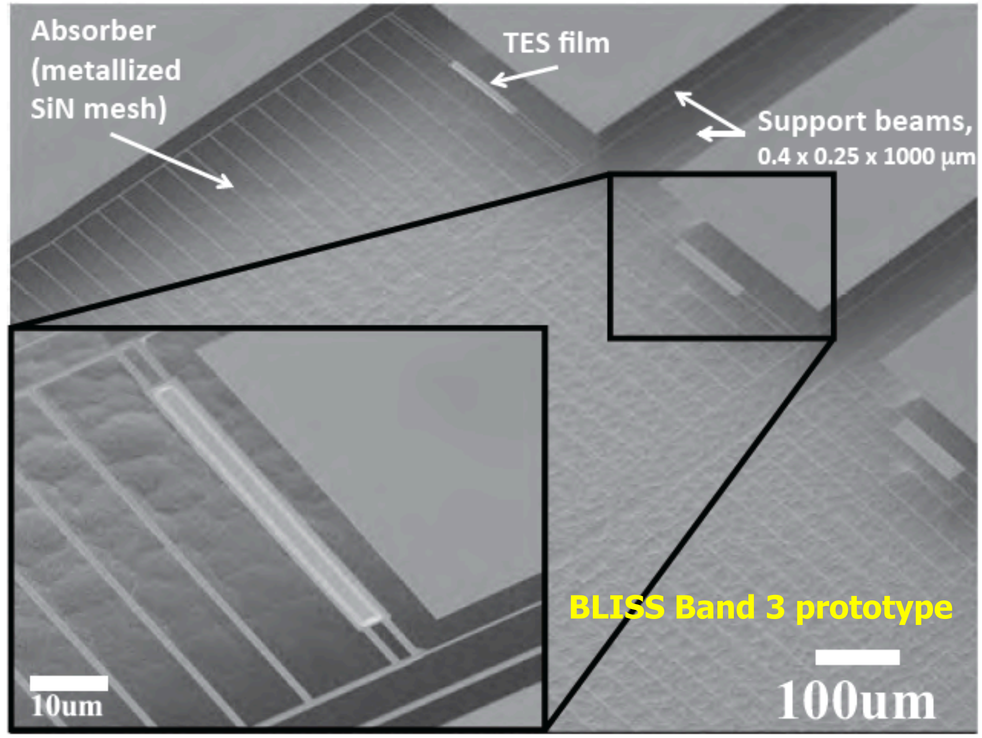
- BLISS detectors do not have demanding speed requirement. Need to modulate fast enough to beat telescope / observatory optical 1/f. Target 100 ms to comfortably allow 1 Hz modulation (additional chopped bias likely).

BLISS DETECTOR SUMMARY

- Sensitivity requirements for BLISS-type spectroscopy are unmatched with any suborbital or ground-based instrument.
  - Have to develop and demonstrate independently.
  - Cosmic-ray susceptibility will be an important design consideration.
- Baseline has been transition-edge sensed (TES) bolometers.
  - Mature cold multiplexing readout that has been demonstrated in ground-based and suborbital experiments.
  - Requires low noise-equivalent power which we have demonstrated.
  - Goal sensitivities still pending.
  - Could be used with SRON readout if necessary.
  - Number of individual pixels limited to a few thousand.
- More capable technologies are on the horizon which may enable larger formats (>10 k pixels).
  - Kinetic inductance detectors (KID): Reaching some level of maturity with ground-based instruments, but there are some challenges in achieving the very low noise-equivalent power (NEP).
  - Quantum capacitance detector (QCD): Demonstrated very low NEPs, but yet to be demonstrated in an instrument-type setting.

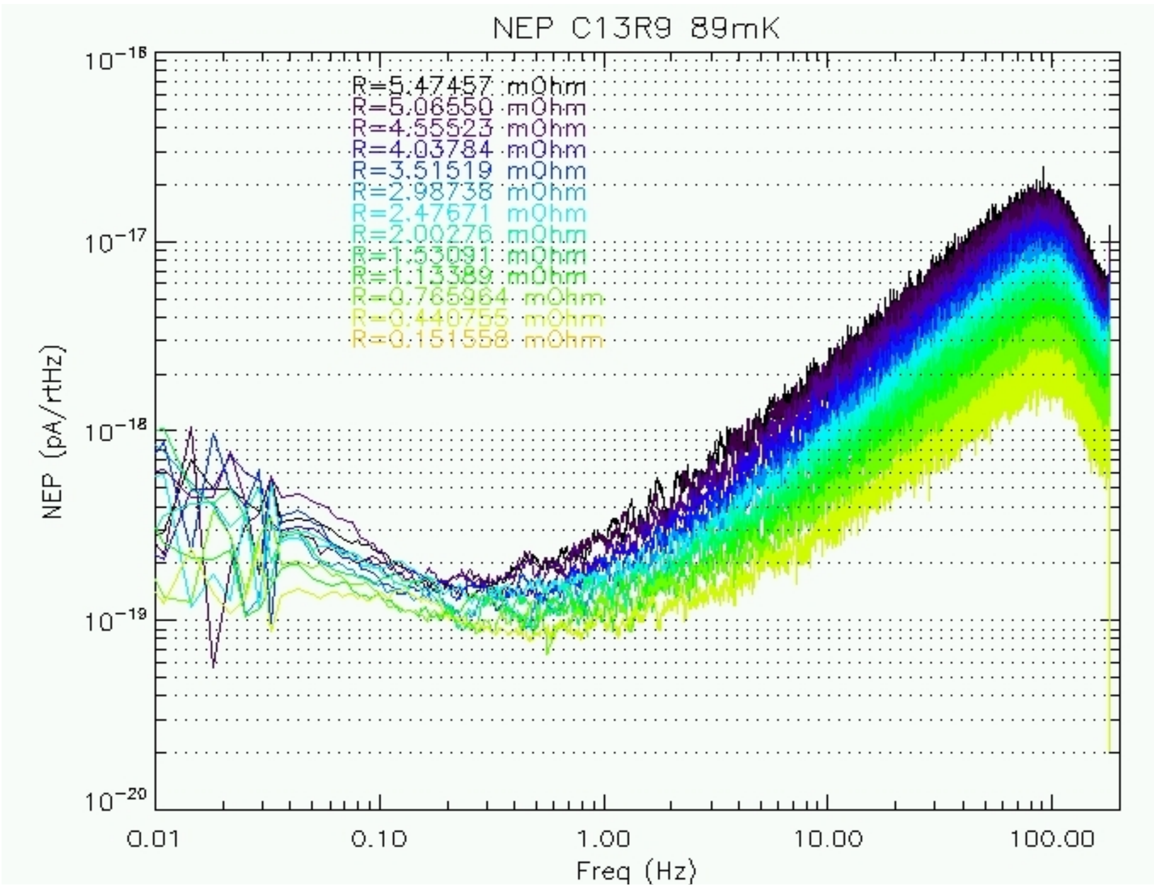
BLISS BOLOMETER APPROACH





- Silicon nitride micro-mesh approach with quarter-wave backshort.
- Absorber: 2 mm by 300 μm (for example). Gold bars thermalize along length.
- Isolation legs: e.g. 1 mm x 0.4 μm by 0.25 μm.
  - NEP = $(\gamma 4kT^2G)^{1/2}$, G meets BLISS requirement
- XF_2 etch undercuts front side on double SOI (silicon-on-insulator) wafer
  - Also investigating a wet-release process which reduces heat capacity.
- MoAu bi-layer TES (fraction of a square), TiN or niobium leads.
  - Operating impedance 3 milli-Ohms (R_N~7 mOhms).

BLISS TES BOLOMETERS -- PERFORMANCE

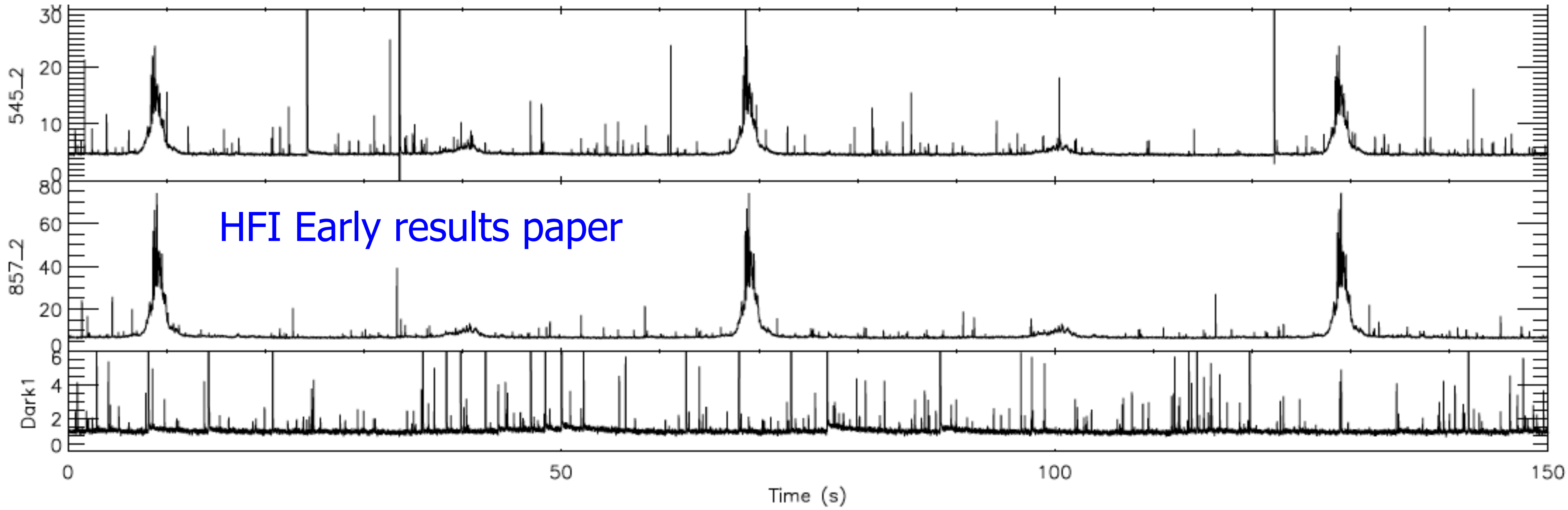


- Meeting NEP requirement w/ time-domain MUX
- Lower NEPs in reach, requires electrical improved filtration
- Have discovered anomalous excess heat capacity in ***mesh*** devices: ~10x relative to pure nitride
  - residue on edges related to our XeF_2 processing
  - solutions under study: etch nitride first, then clean (e.g. BOE) prior to metal layers.

BLISS operates with chop / nod so doesn’t need a lot of bandwidth

Cosmic Ray Susceptibility

Planck HFI cosmic ray experience informs design.

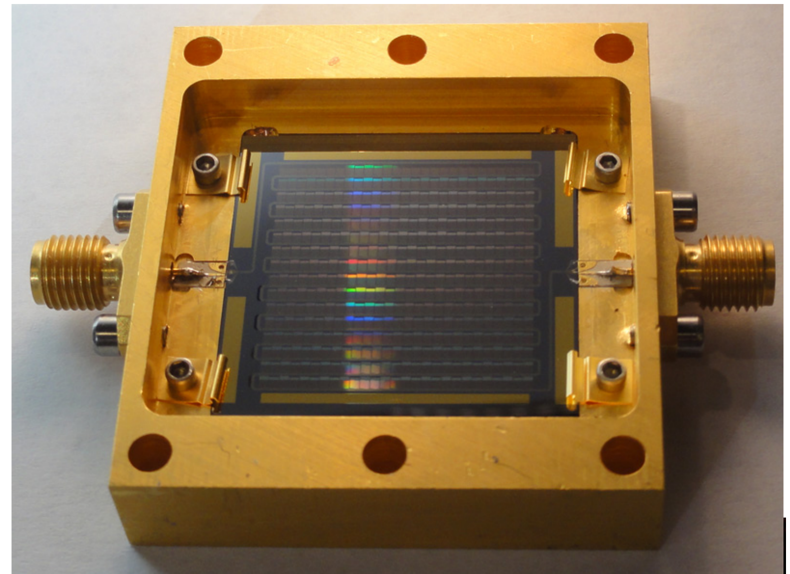


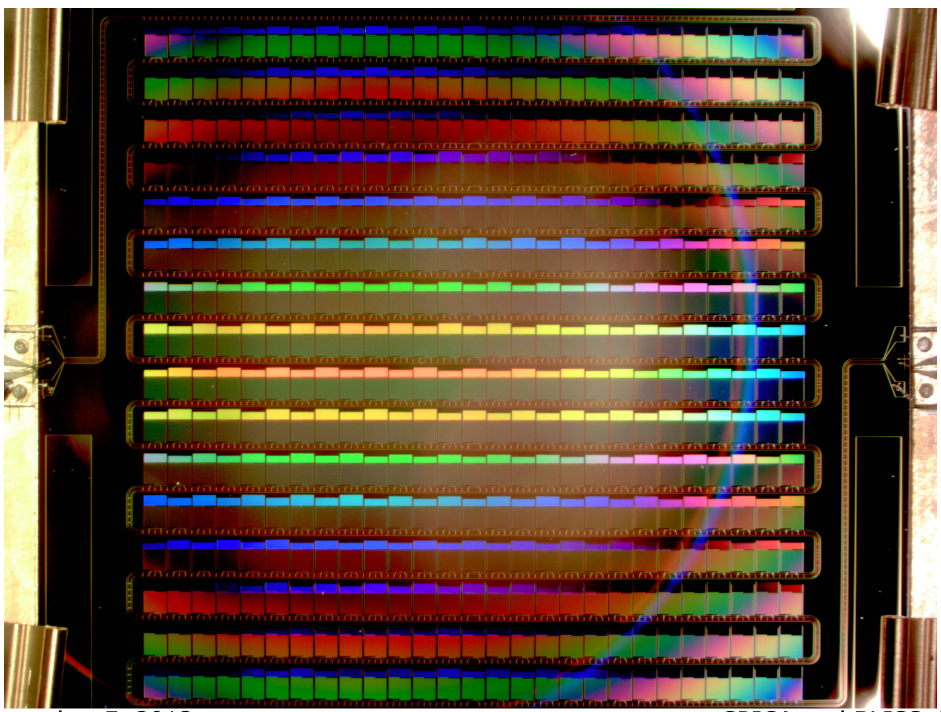
- Planck HFI detectors have ~80 events per minute, spectrum extends down to detection threshold.
- BLISS detectors ~100x lower NEP than Planck HFI, **but have ~500 times lower cross section than the HFI bolometers.**
  - Scales as mass x Z (atomic number), HFI dominated by chunk of Ge.
- Low energy events not fundamental. **Due to primary events in substrate generating athermal phonons which scatter into bolometers.**
  - Add heat capacity and phonon traps (embedded metal) to the frame. BLISS has 10s to 100s of detectors per frame

CALTECH / JPL KIDS:

350-MICRON TIN IMAGING DEMONSTRATED AT TELESCOPE

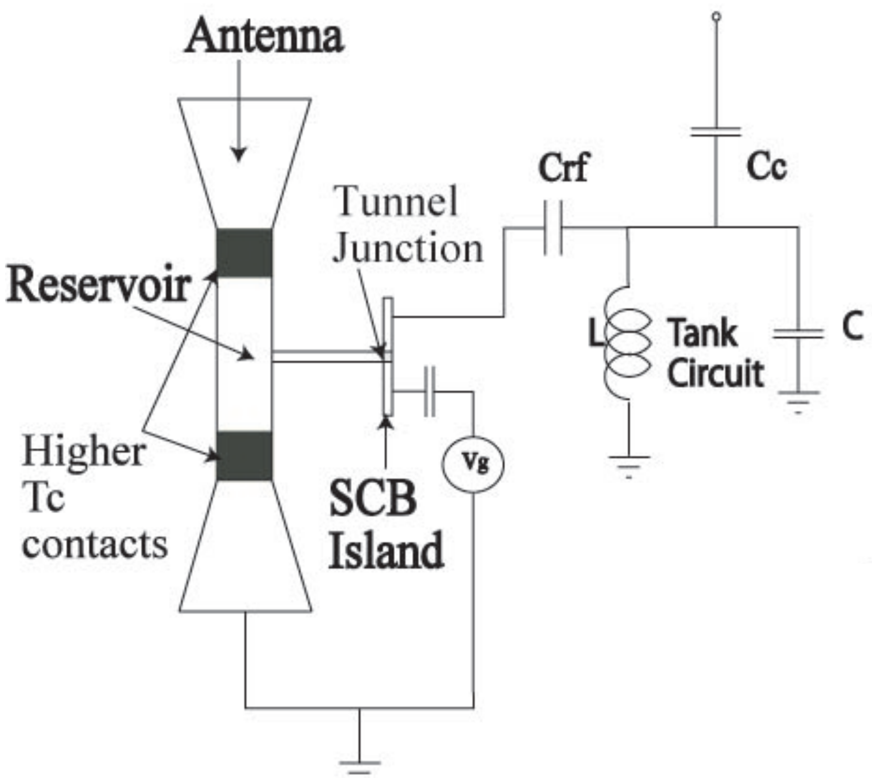
- 18 x 24 format, 1 mm^2 pixels
- Single readout line for frequency-multiplexed readout of entire array, 100-250 MHz
- Backside illumination, AR layer coming soon
- Typical pixel yield: 95%
- Fabrication time: 2-3 days
- Basic technology for all CCAT instruments, require design adjustments for cold telescope backgrounds

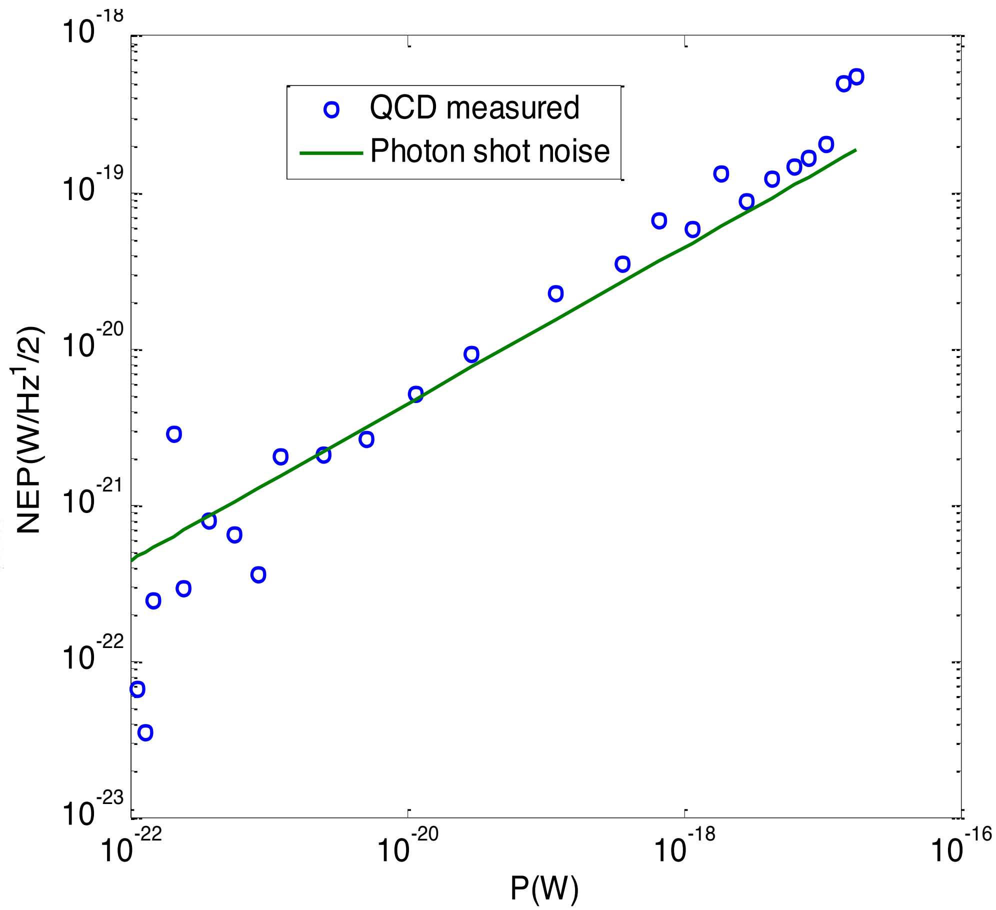




Quantum Capacitance Detector

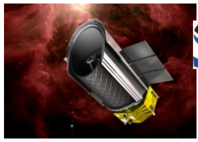
Pierre Echternach et al. (JPL)





- Photo-produced quasiparticles tunnel from reservoir to island, change capacitance of resonator tank circuit.
- Frequency multiplexed like KIDs.

Optical measured NEPs
Photon shot noise limited!



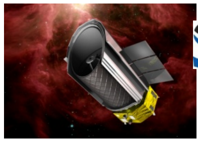
SPICA PROJECT STATUS

- Due to Japanese budgetary pressures in part due to Fukushima recovery, JAXA cannot afford all of the payload integration.
  - JAXA will remain as mission lead, will support launch spacecraft, operations and coolers.
- European + Japanese consortium would like ESA to take on payload integration.
- Intention is to propose as an M-class mission to Cosmic Visions in 2014.
  - Launch now envisioned for 2026.
- Looking to optimize scientific return for the mission, re-evaluating instrumentation priorities.
  - European leaders (Roelfsema at SRON) are soliciting a US instrument (like BLISS) to strengthen science case in preparation for CV proposal.

→ US scientists have an opportunity to participate with world-leading technology.

OPTIONS FOR NASA

- Science remains as compelling as identified by Astro2010 EOS Panel.
  - Sensitive far-IR measurements are a unique probe of planetary system formation, conditions in galaxies throughout cosmic time, and the EoR.
  - Can only made with a cold space telescope.
- Instrumental-level contribution remains an excellent value for NASA.
- Reconsider strategic investment for instrument-level contribution to SPICA.
  - The bulk of cost would come after JWST is launched
  - Optimal return for US $ requires early (but low level) involvement with European / Japanese team
- Suggest formal dialog with ESA & JAXA counterparts.
- Explore competed options
  - MoO frequency and cost cap a concern – can these be modified?
  - Can full Explorer budget be open to competition instead of distinguishing between MoO and full Explorer?
- Technology funds in the interim would greatly strengthen US position and help preserve a role for US in SPICA and future US-led missions



INTERNATIONAL SPICA TEAM

17 countries and one international org.


SPICA
Space Infrared Telescope for Cosmology and Astrophysics
Space Odyssey

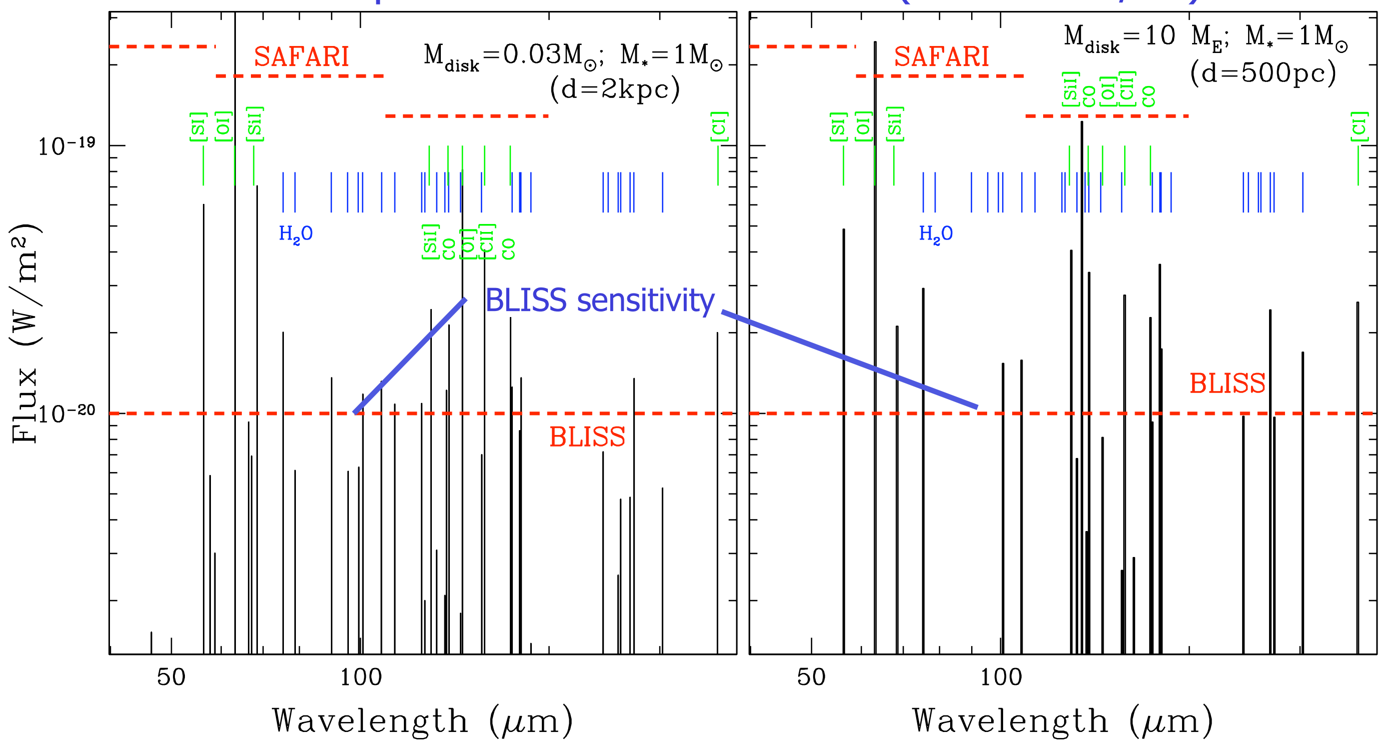
Thank you!

More information: `http://www.submm.caltech.edu/BLISS/`

BLISS / SPICA Probes the Birth of Planets and Planetary Systems

- Gas protoplanetary disks is essential for formation of gas giant planets
- Bulk of the mass in the disk is likely at r≥20 AU, cools through [OI], [CII] + rotational lines of CO and H_2O -> dominant coolants are in the far-IR regime.

Model spectra convolved to R=400 (fluxes in W/m²)



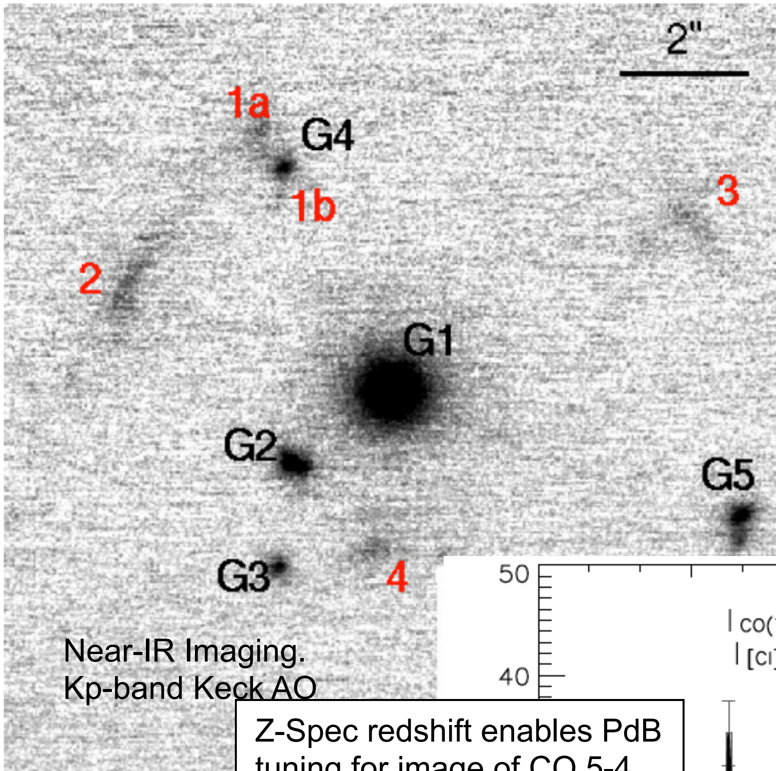
BLISS co-I Uma Gorti

- SPICA/BLISS covers the full evolutionary range, from primordial disks with 0.01 M_{sun} to evolved systems with only a few M_{Earth} of gas remaining.
- SPICA/BLISS allows observations at kpc-distances, accessing clusters with a wide range of ages, can measure the gas disk lifetimes directly for the first time.

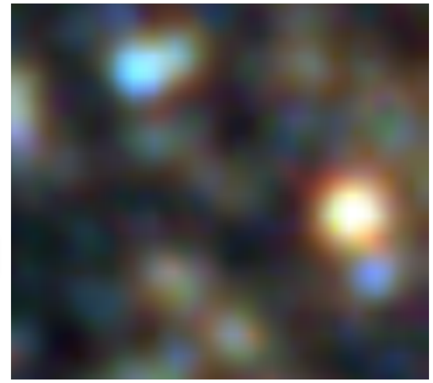
Example clusters for SPICA/ BLISS disk spectroscopy:

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

WIDEBAND SPECTROSCOPY PROBES THE COSMIC HISTORY OF STAR FORMATION



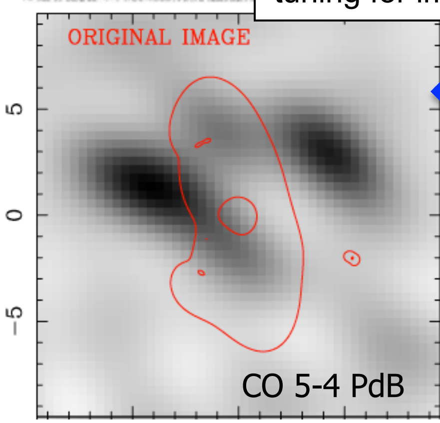
Near-IR Imaging.
Which / Where is counterpart ??

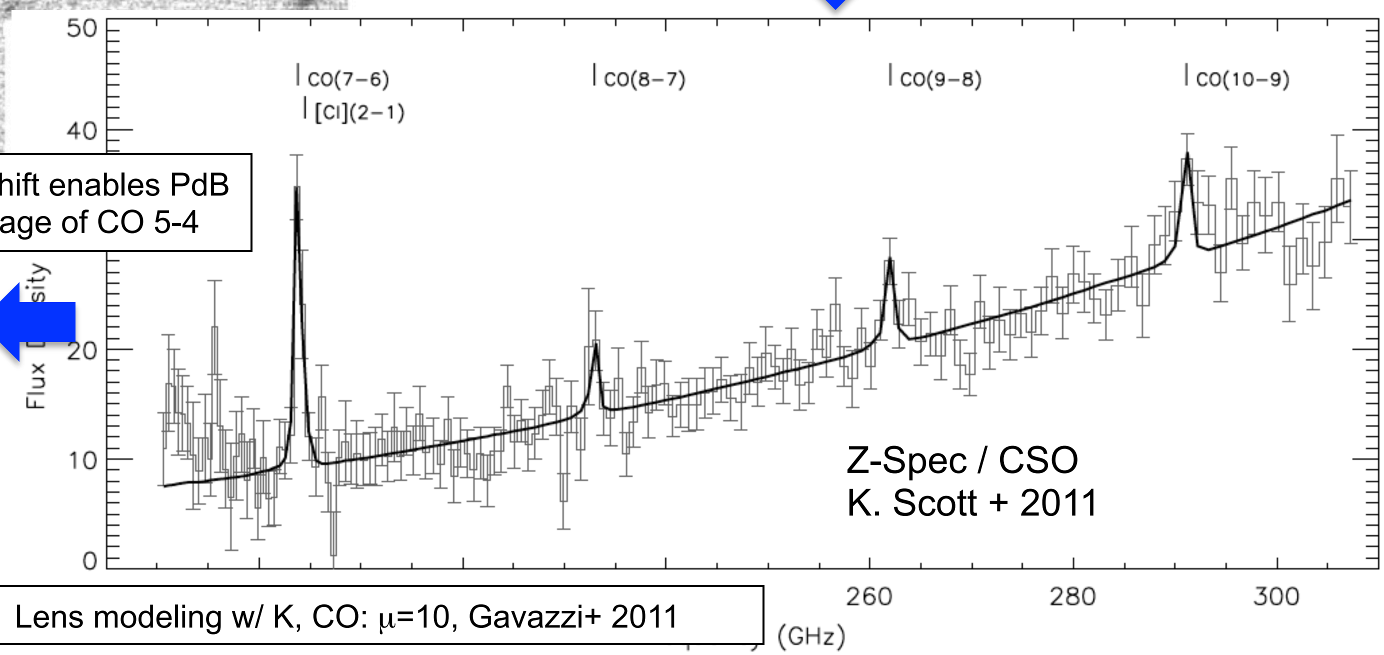


HeRMES Survey Bright (lensed) sources identified at 250, 350, 500 μm. HSLS 1

Direct Z-Spec redshift with CO lines in the mm: z=2.95

Z-Spec redshift enables PdB tuning for image of CO 5-4





Lens modeling w/ K, CO: μ=10, Gavazzi+ 2011

BLISS DETECTOR PARAMETERS

A detailed response and noise model, including all contributions from photons and bolometers + MUX.

Bd.	λ_{min} [μm]	λ_{max} [μm]	Det size [μm] spat	spec	Q [aW]	NEP [10^{-20}W/$\sqrt{\text{Hz}}$] Phot	Det	Mrgn	G [fW/K]	τ [ms]	Dyn range MoCu	Ti
Cross-Dispersed Echelle Modules												
1	34.5	52.6	1380	430	0.12	3.1	2.8	5.0	4	100	400	15000
2	52.6	80.2	1380	430	0.12	2.8	2.8	5.0	4	100	400	15000
3	80.2	122	2100	650	0.13	2.4	2.8	5.0	4	150	400	15000
Waveguide Far-IR Spectrometer (WaFIRS) Modules												
4	122	186	873	140	0.25	2.6	2.8	5.0	4	150	200	8000
5	186	284	1350	216	0.34	2.4	2.8	5.0	4	150	150	6000
6	284	433	2100	336	2.3	5.0	5.0	5.0	12	150	75	3000

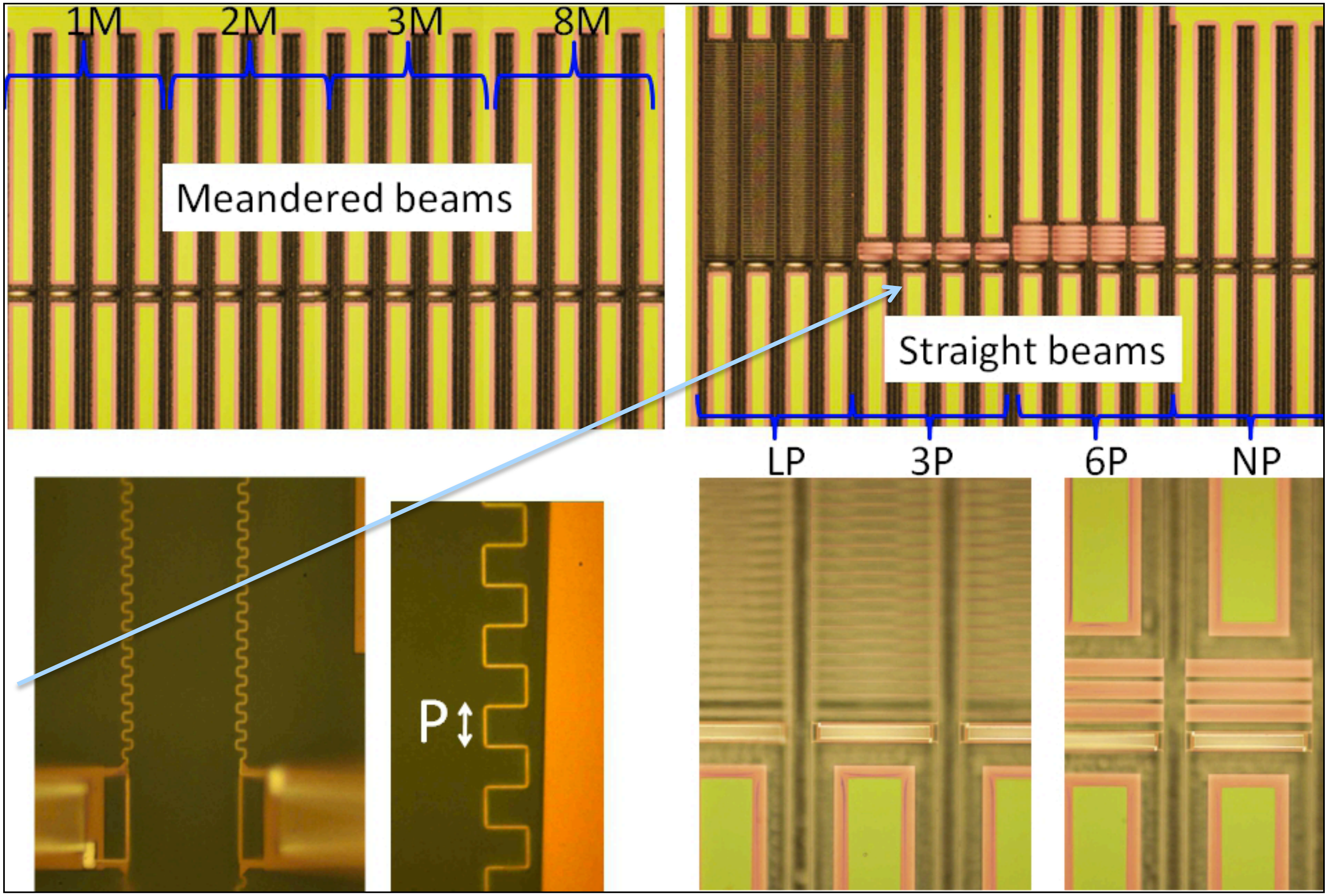
Notes: NEP columns are photon noise, design detector NEP, and detector NEP including margin. Detector noise includes all sources of detector and readout noise with an operating impedance of 10 mOhms with 2 pA/$\sqrt{\text{Hz}}$ unmultiplexed SQUID noise with TES transitions at 65 mK (MoCu) and 450 mK (Ti). Speed of response based on $\alpha = d\ln R/d\ln T = 100$ and a heat capacity of 10 fJ/K [3].

- Detectors for bands 1-5 are designed for 2.8e-20 W/Hz$^{1/2}$ intrinsic NEP, but we use 5e-20 for the (goal) sensitivity calculations as a way to carry margin.
- Multiplexing penalty is a negligible 3-5%.
- Table shows BLISS goal values, BLISS requirement is NEP=1e-19 W Hz$^{-1/2}$, requiring a G of 40 fW/K.

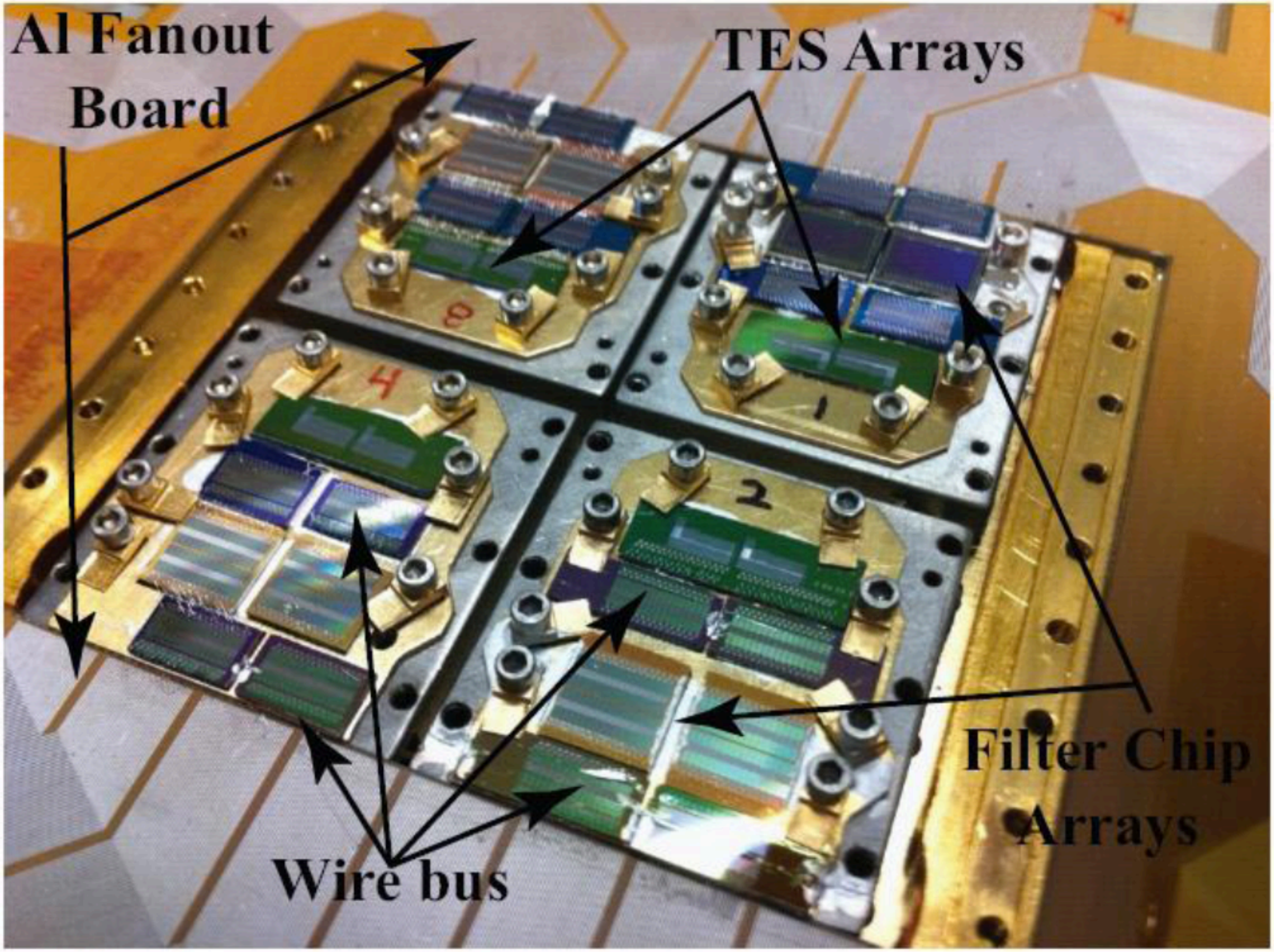
BLISS Prototype Arrays

Meanders: total length of 2 mm, cross section 0.4 by 0.25 micron

A variety of absorbers to enable high-speed and probe heat capacity



PROTOTYPE BOLOMETERS W/ MUX



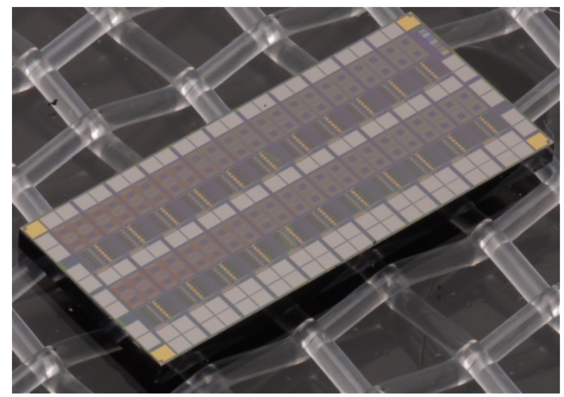
LOW-POWER TDM SQUID FOR BLISS

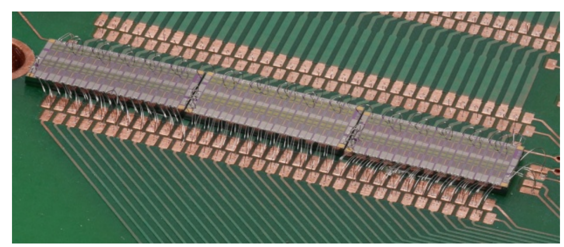
(K. IRWIN ET AL. @ NIST)

- An ultra-low-power TDM chip design has been developed for BLISS.
- Each 3 mm × 6 mm chip contains 11 TDM channels. The chips can be independently screened, and connected in a series configuration into one readout channel for larger multiplex factors.
- Each multiplexed set of chips is measured to dissipate only 0.25 nW of power at the cold stage.

(at JPL we baseline 0.5 nW as a way to include margin)

BLISS TDM chip with one cent coin for scale

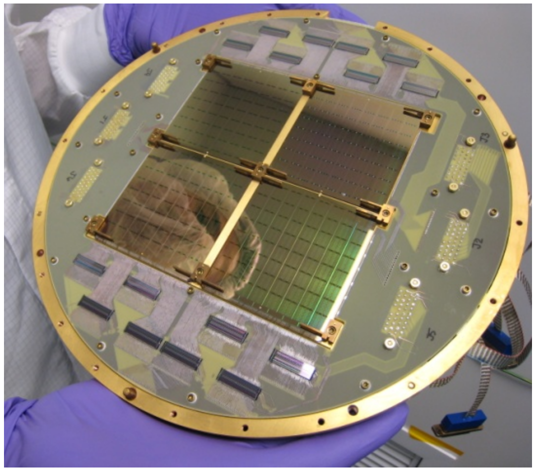

Close-up view of 3 mm × 6 mm BLISS TDM chip


Three BLISS TDM chips multiplexed in series for a MUX factor of 33

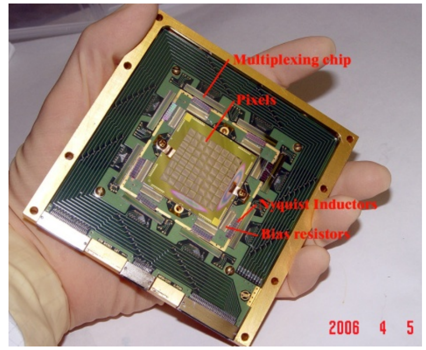
Time Domain SQUID MUX

Now the standard used in many ground-based and suborbital experiments

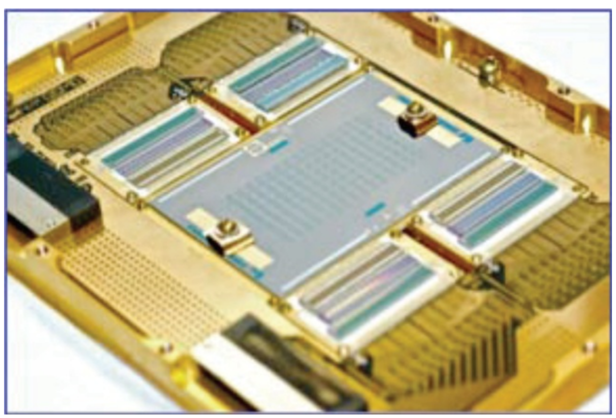
BICEP-2, 512



MUSTANG, 64

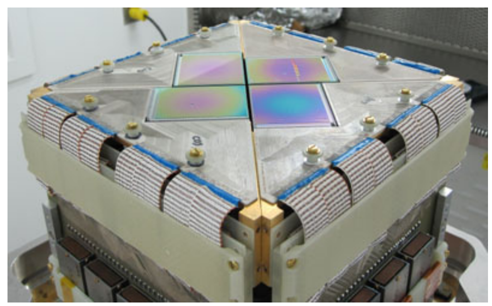


GISMO, 128

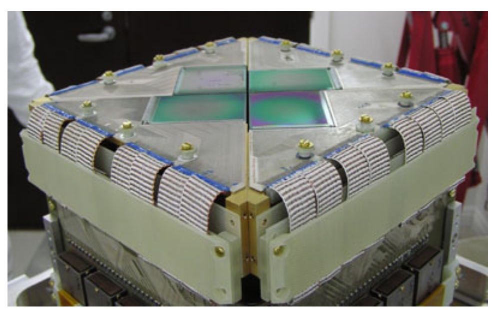


SCUBA-2, 10,000

450 um

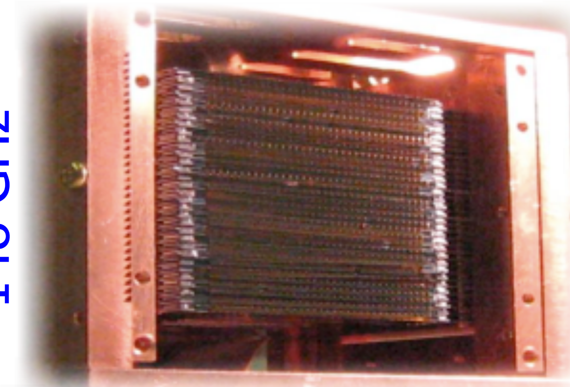


850 um

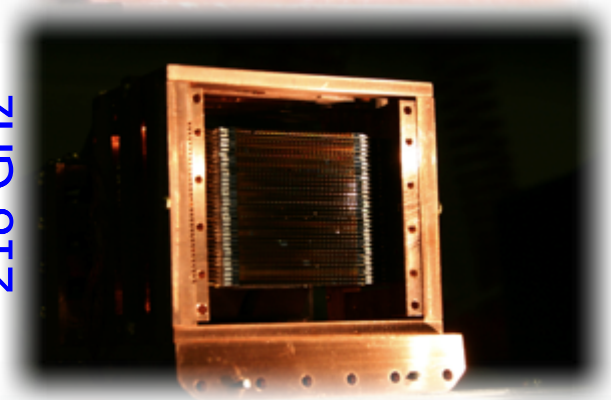


ACT-SZ, 3,000

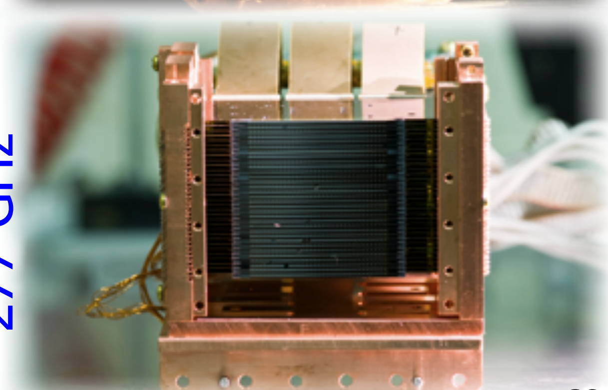
148 GHz



218 GHz

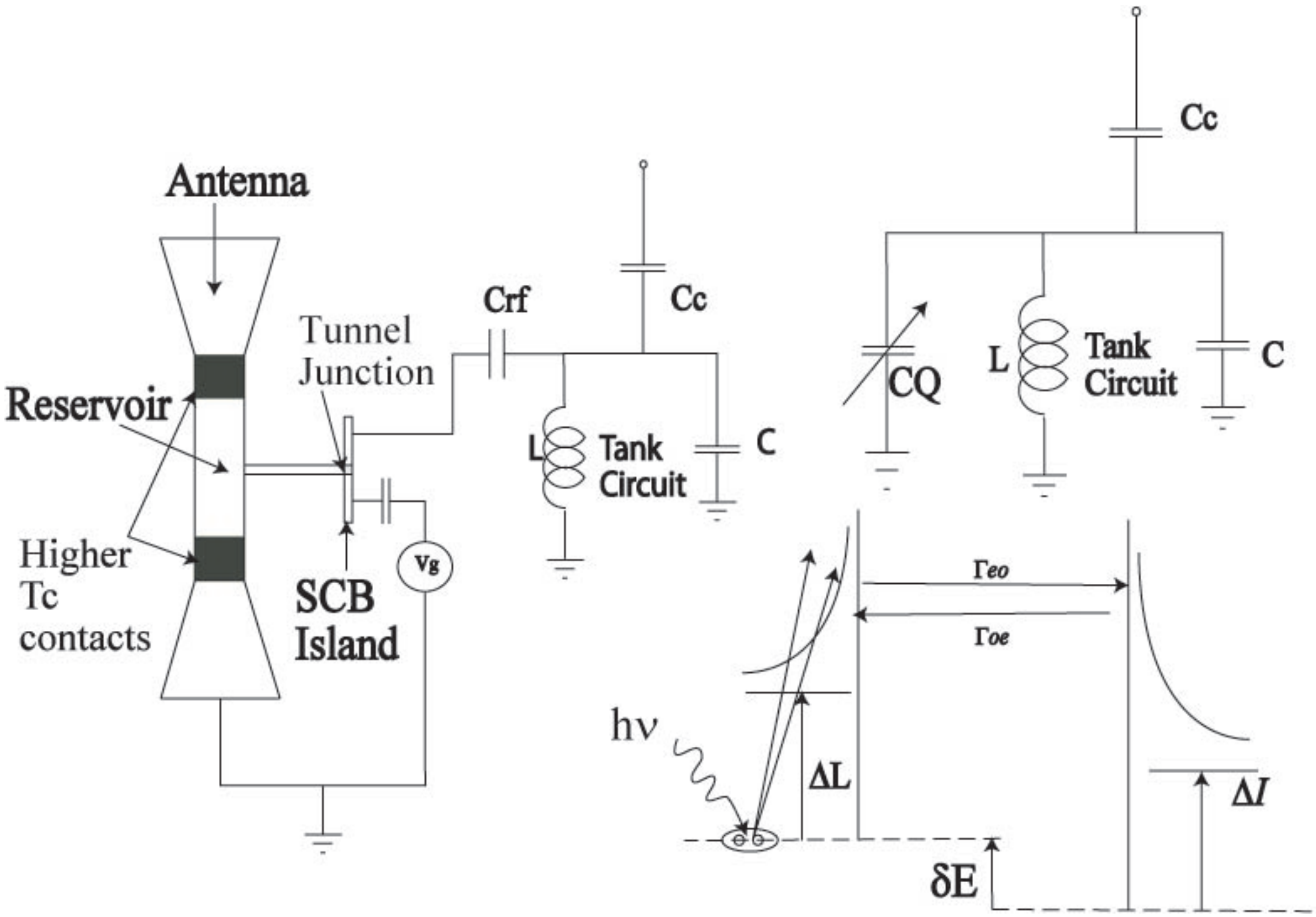


277 GHz



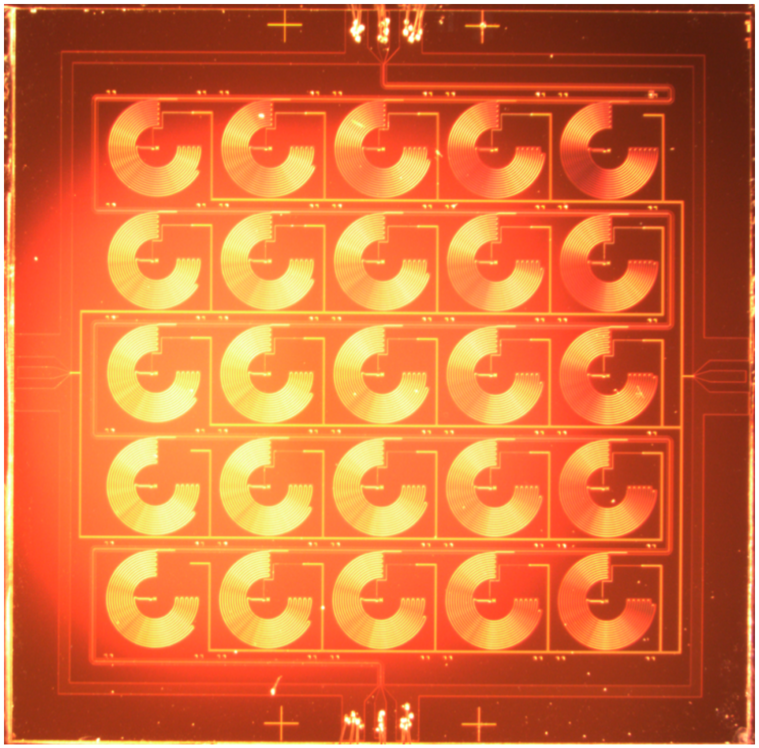
THE QUANTUM CAPACITANCE DETECTOR

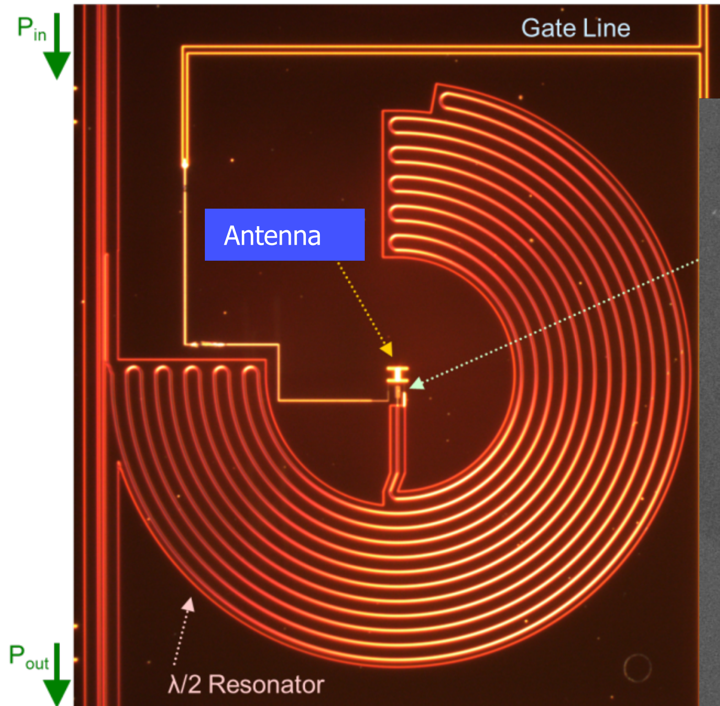
Pierre Echternach et al.

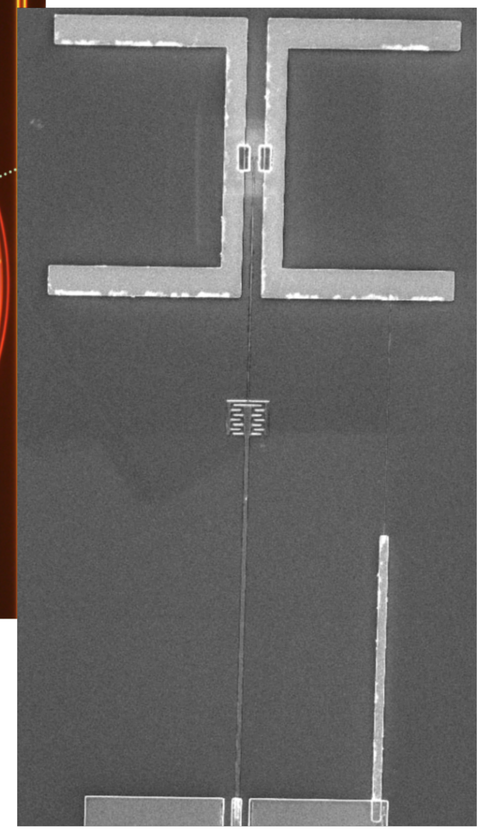


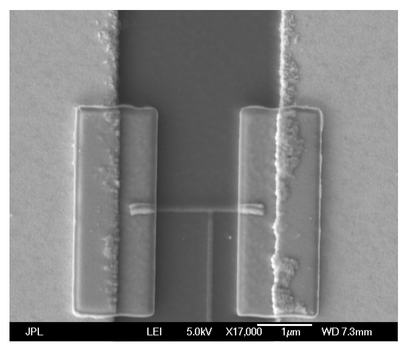
- Radiation coupled by an antenna breaks Cooper pairs in the reservoir (absorber)
- Quasiparticles tunnel onto the island with a rate Γ_{in} proportional to the quasiparticle density in the reservoir
- Quasiparticles tunnel out of the island with a rate Γ_{out} independent of the number of quasiparticles in the reservoir
- At steady state the probability of a quasiparticle being present in the island is given by *Po(Nqp)=Γin/(Γin+Γout,)*
- The resulting change in the average capacitance will be $C_Q = (4E_C/E_J)(C_g^2/C_\Sigma)Po(Nqp)$
- *This change in capacitance will produce a phase shift* $\delta\Phi \sim 2C_Q/(\omega_o Z_o C_C^2)$

The Quantum Capacitance Detector: 5x5 array





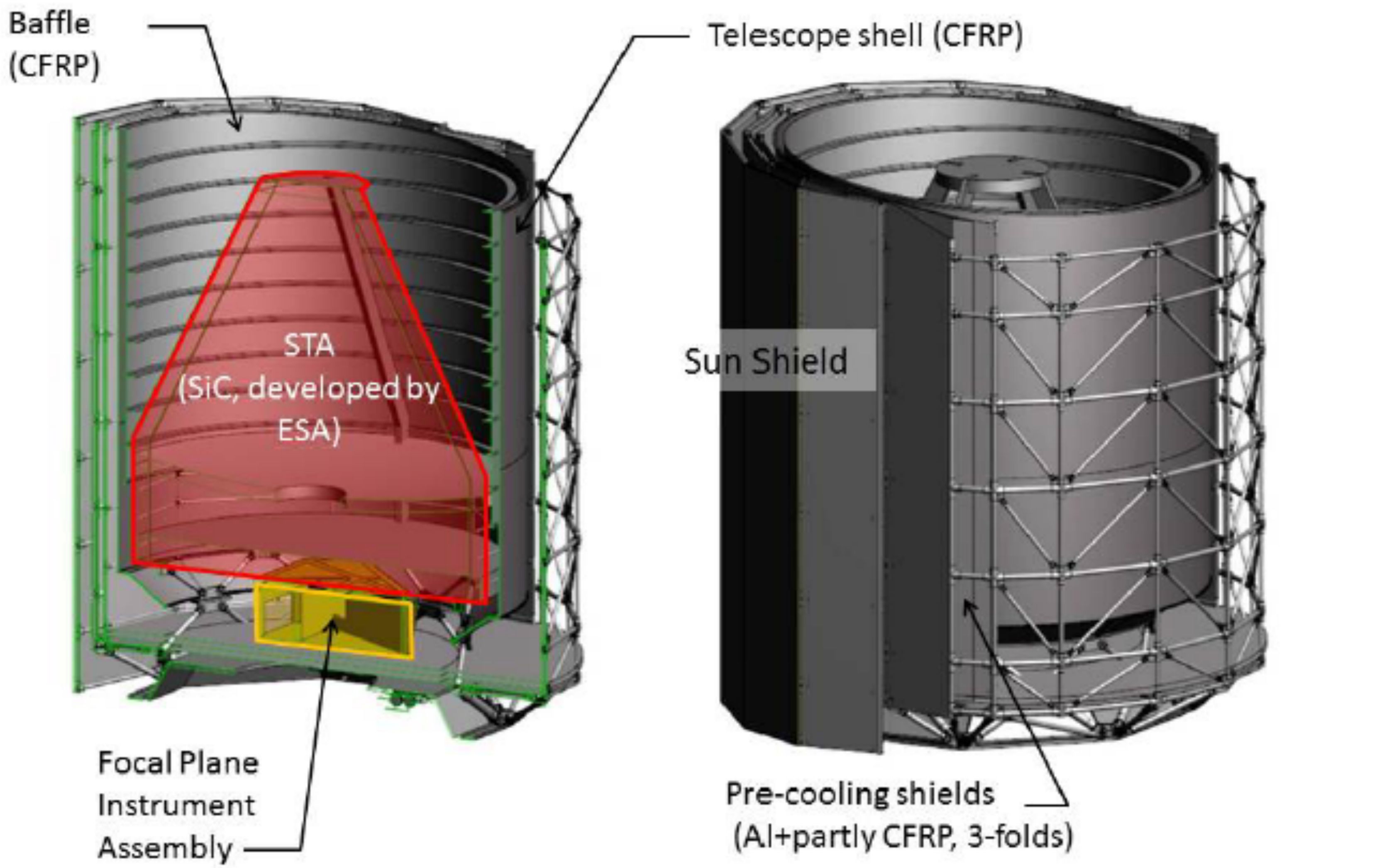




Only center device
Illuminated by lens.
Each device has a slightly
Different resonance frequency.

Nb plugs

SPICA PAYLOAD MODULE

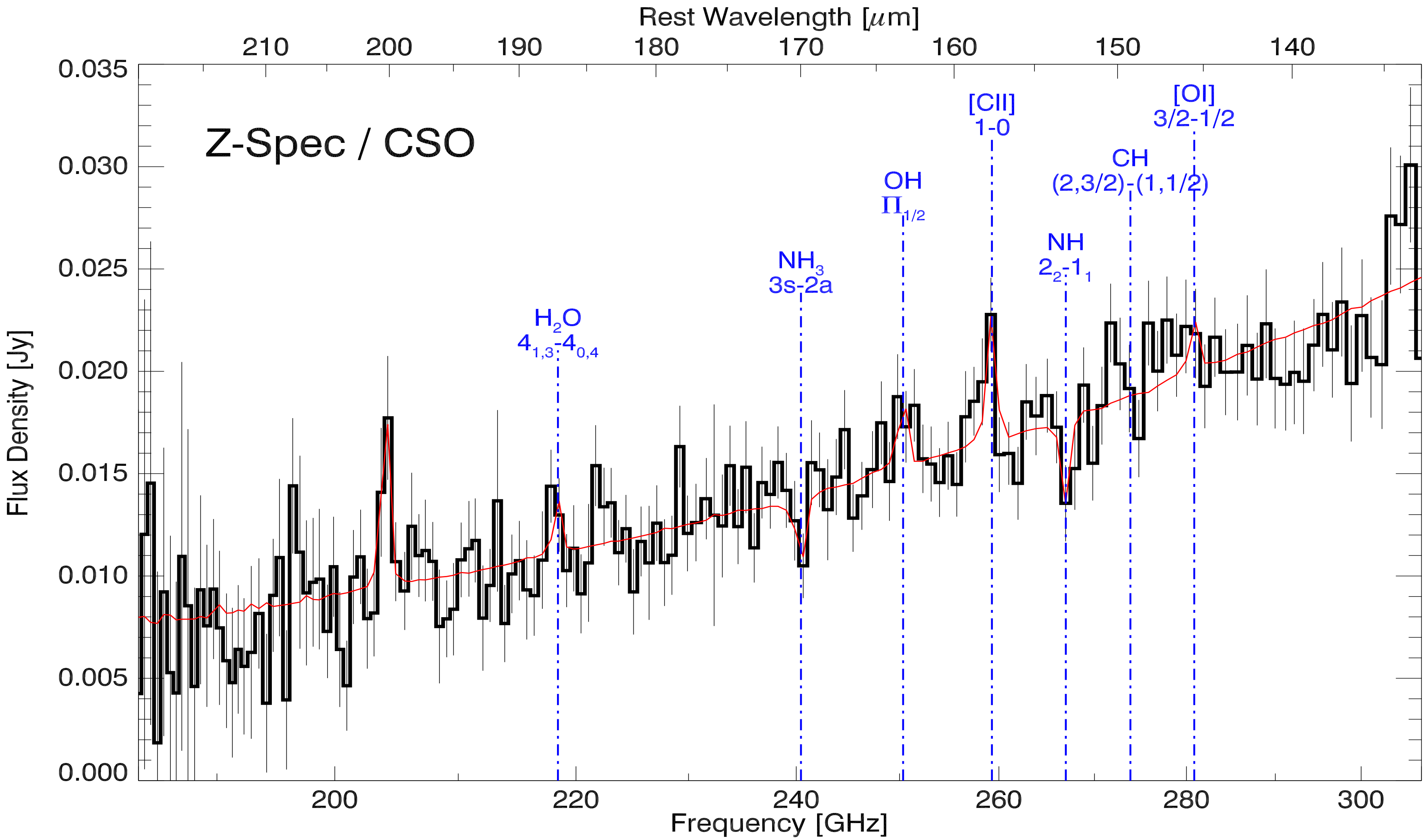


- Closed-cycle coolers with 20 K Stirling stages and JT stages at 4.5 K (40 mW EoL) and 1.7 K (^{3}He J-T, 10 mW EoL).
- Heat switches provide some redundancy against failure of a single cooler stage.

SPICA FOCAL PLANE INSTRUMENTS

- MCS (P.I. JAXA, Universities, and ASIAA (Taiwan))
  - Mid-infrared camera & spectrometer, including Si:As (2k x 2k) and Si:Sb arrays (1k x 1k)
- 5x5 arcmin FOV imaging
- LRS: R=100 long slit, 5-26 + 20-38 microns
- MRS: R=1000 image slicing IFU, 12-23 + 23-38 microns
- HRS: R=30,000 cross dispersed small slit, 4-8 microns, 12-18 microns
- FPC (focal plane camera)
  - Near-infrared camera and spectrometer
  - P.I. KASI (Korea)
  - SCI (SPICA coronagraphic instrument)
  - P.I. JAXA with Nagoya Univ.
- SAFARI
  - Far-infrared imaging spectrometer
  - P.I. SRON (Netherlands) with SAFARI Consortium
- US Instrument (e.g. BLISS)
  - Ultra-sensitive far-infrared, sub-mm spectrograph

z>6 survey spectroscopy

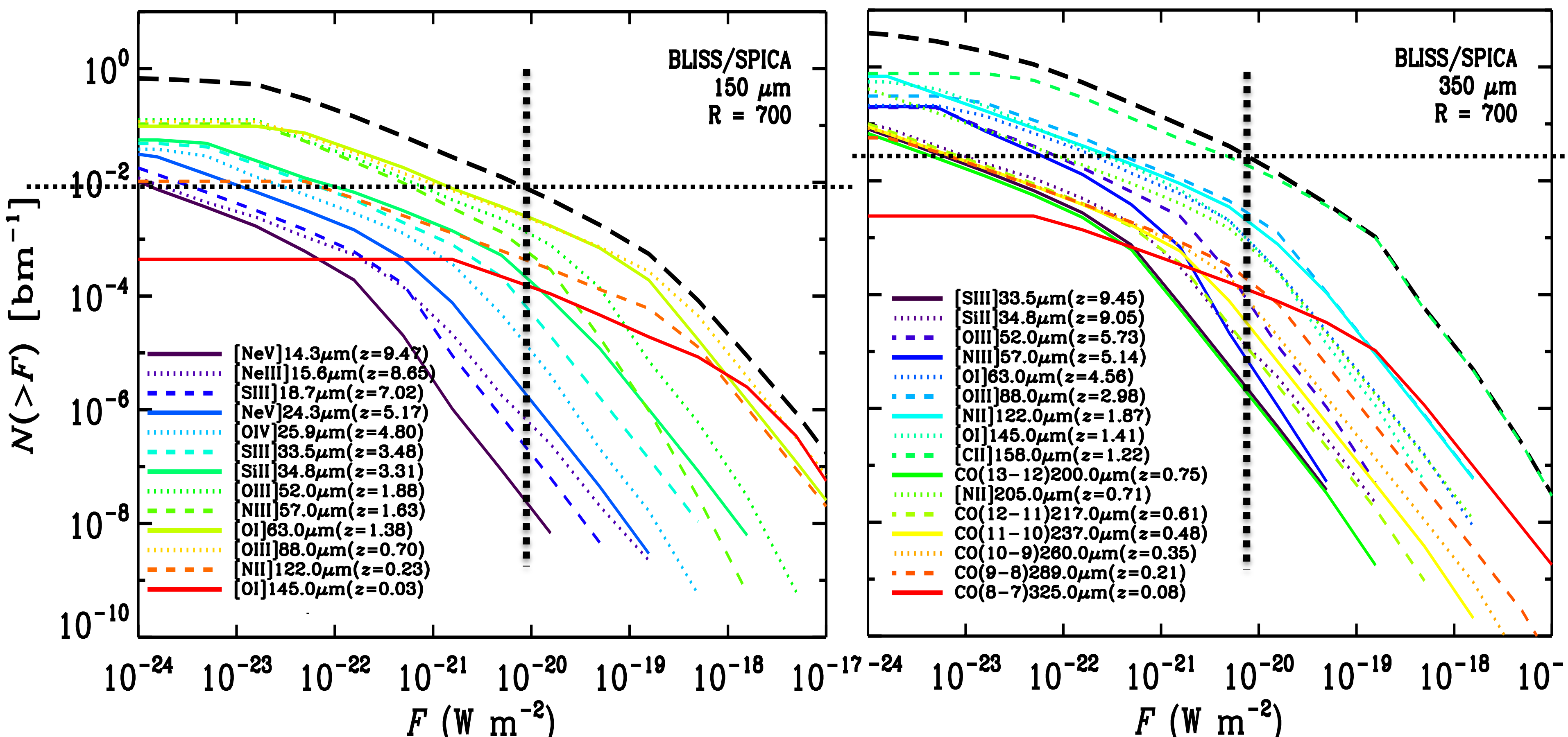


An Arp 220-like evolved starburst (weak C+) before t=1 By.

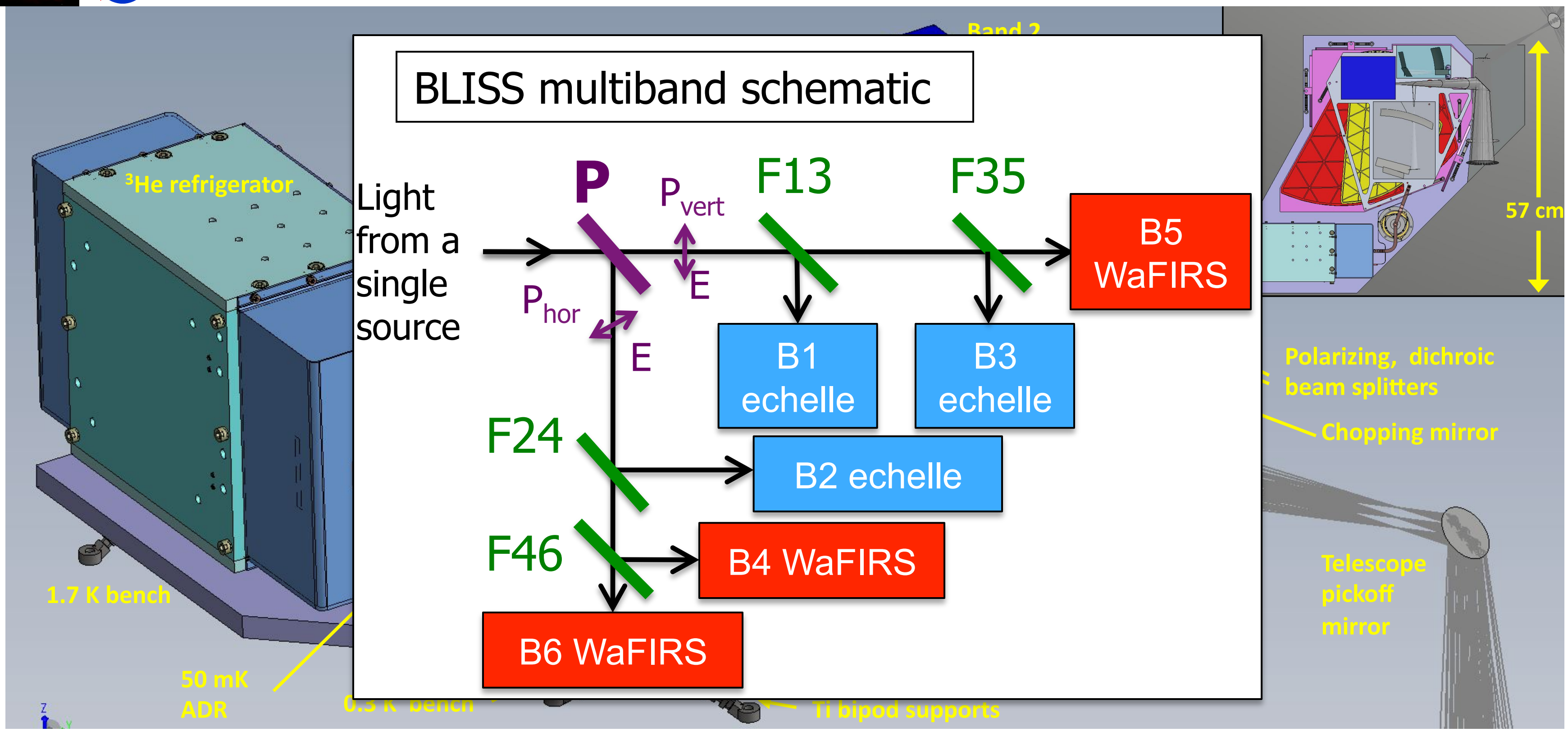
Line Confusion with BLISS / SPICA?

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 SPICA beam per R=700 bin



BLISS OVERVIEW

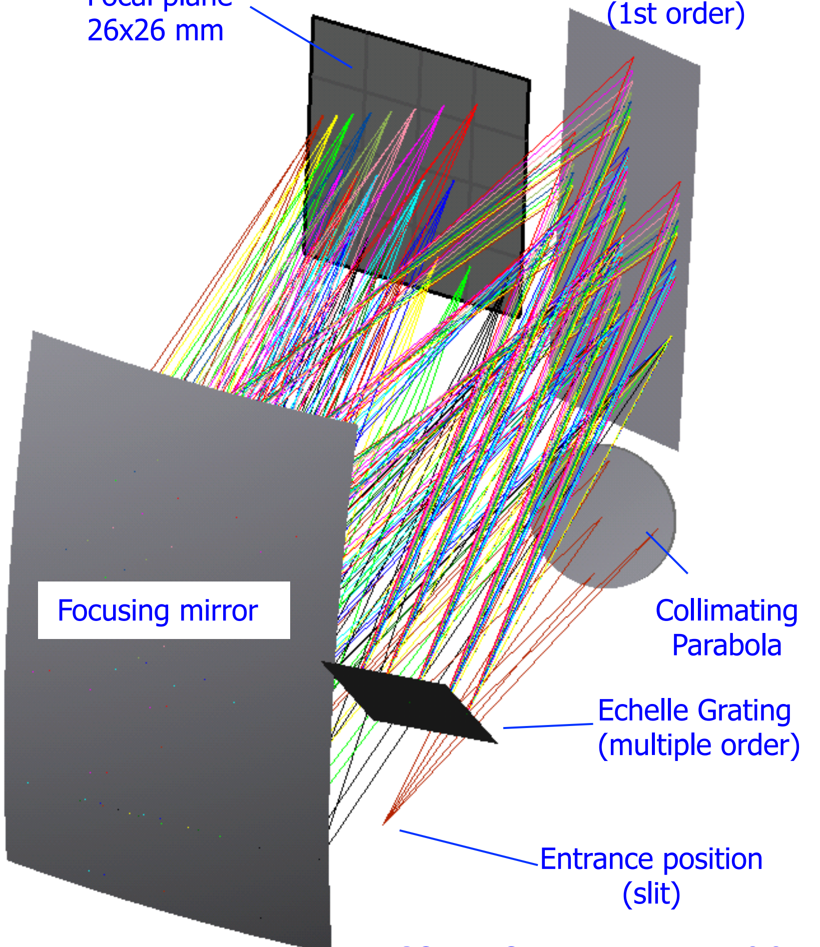


Approach: measure a galaxy's full spectrum from 35-433 μm simultaneously.

- 6 bands (shown B1-B6 in schematic) each coupling 2 sky positions at R~700.
- Use polarizer (P) then couple a single polarization in each spectrometer. Dichroic filters (FXX) separate the bands:
- Short-wavelength bands are echelle spectrometers (blue in schematic), long-wavelength bands are waveguide spectrometers (red in schematic).
- ~4000 superconducting bolometers with SQUID MUX, 700-800 detectors per band.
- Assembly cooled to 50 mK with a 2-stage refrigerator, supported with titanium suspension.
- Bolt and go, no moving parts except for chopping mirror in feed optics (not shown).
- **Specs**: 45x40x40 cm^3, 30 kg cold mass (w/ margin), Power ~100 W.

BLISS short-λ echelle spectrometers

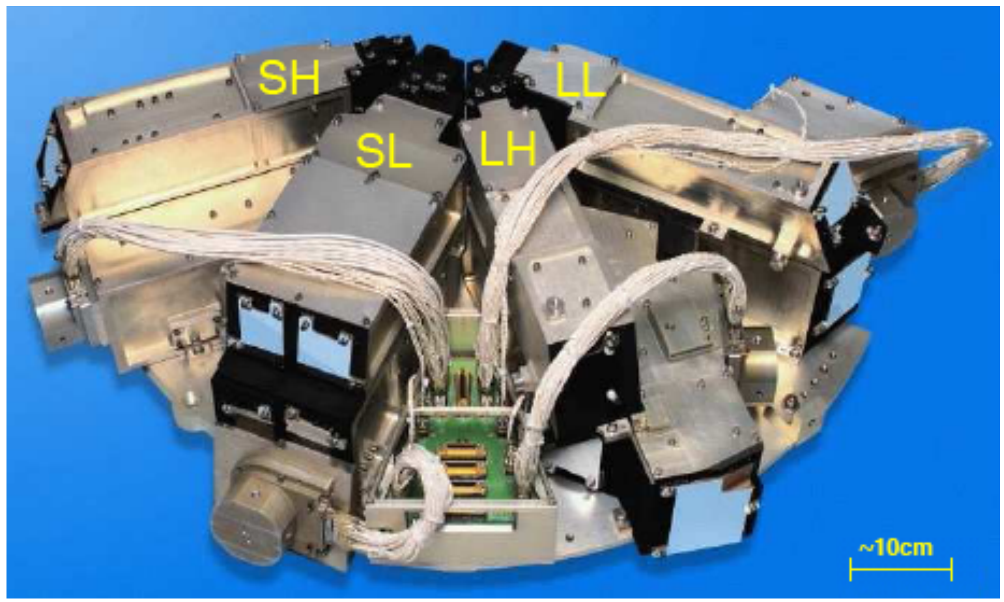
BLISS example echelle design



68-118 μm at R=700,
75 x 150 x 115 mm

BLISS requires a wide bandwidth and compact package; imaging not essential -> **Use cross-dispersed echelle grating spectrometers** (for short-wavelength bands).

- Uses Spitzer IRS concept, but we have developed an ultra-compact design for the BLISS wavelengths because package size scales with wavelength.
- Shown is λ=68-118 μm at R=700: 75x150x115 mm (shorter λ even smaller).
- Bolted aluminum construction, no moving parts.



Heritage: Spitzer infrared spectrograph (IRS)

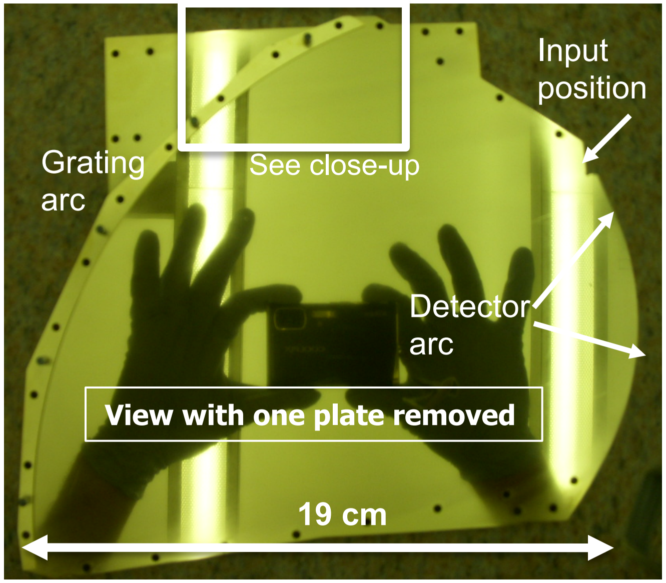
PROTOTYPING OF BLISS WAFIRS MODULES

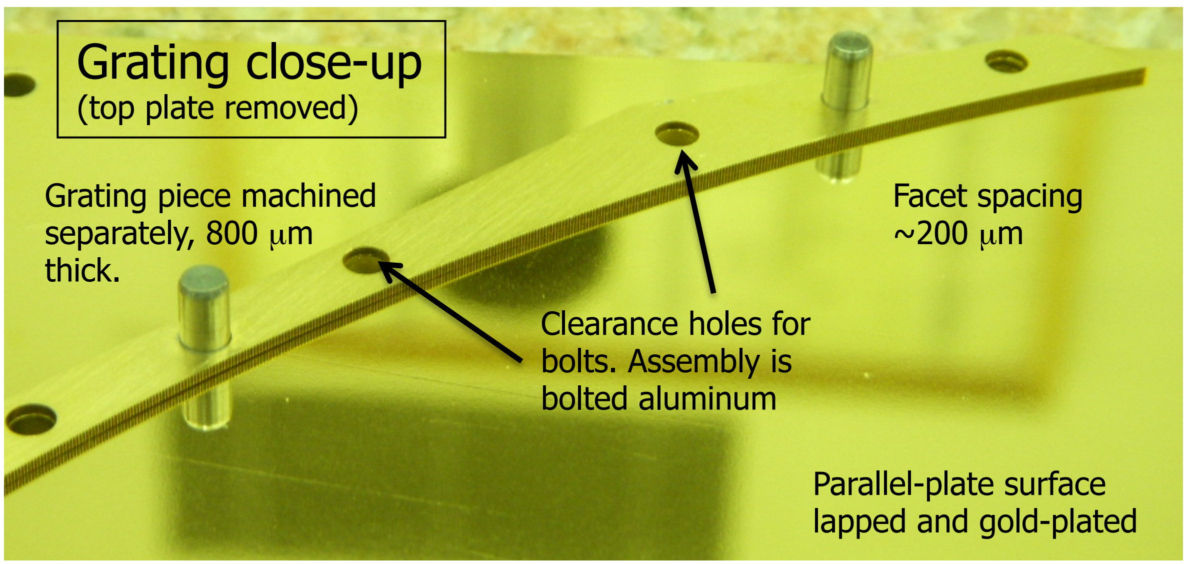
We have built a WaFIRS module for 180-300 μm designed to provide R=700.

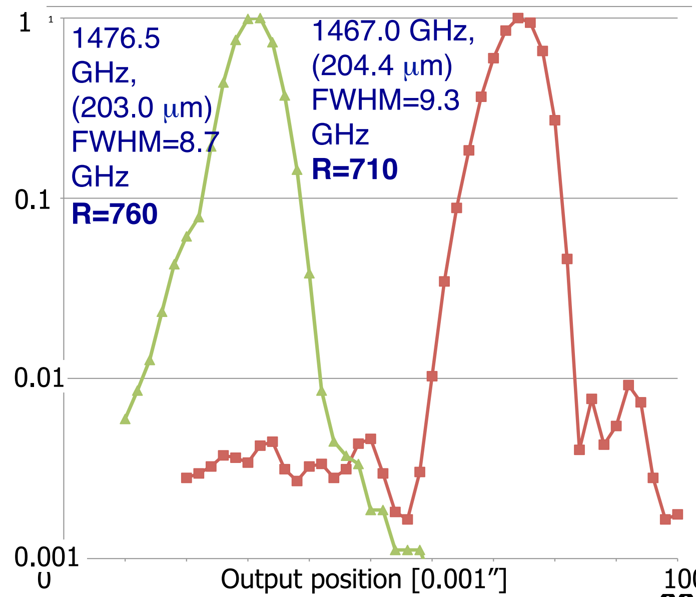
- 980 grating facets.
- Plate spacing 800 μm.
- 19 cm in size.

Initial testing with local-oscillator source & swept output feed demonstrates design resolving power! (below right).

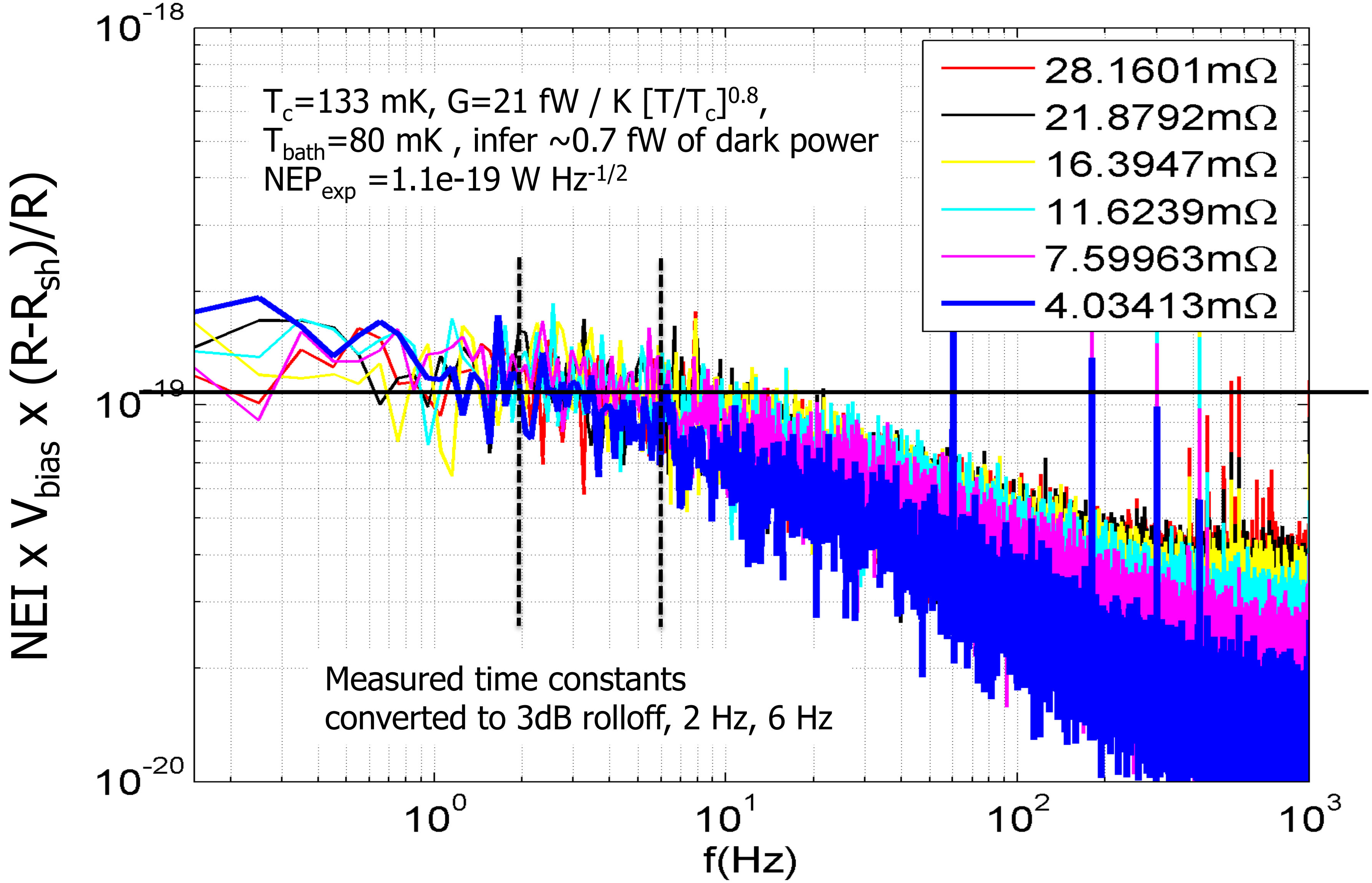
Further testing underway to measure system optical efficiency.







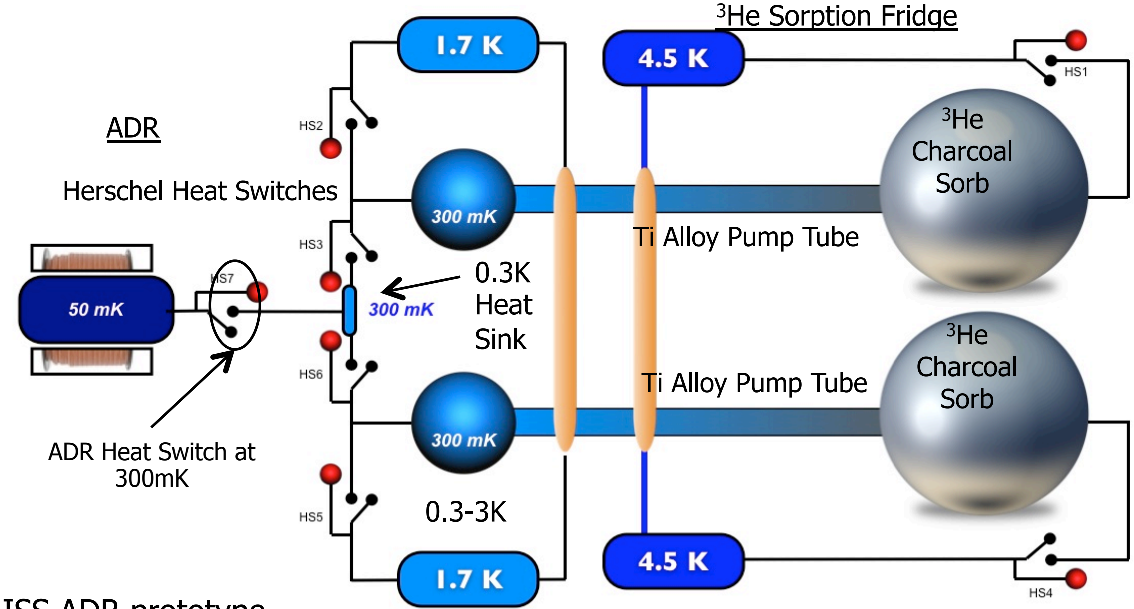
IR TEST DEVICE W/ COMMERCIAL SQUID



See A. Beyer talk, 8452-15, Wednesday 11:30 AM

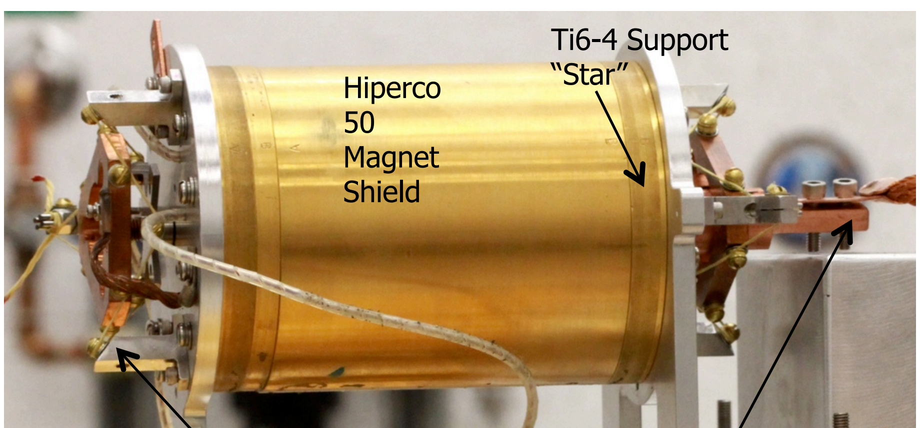
BLISS COOLING APPROACH:

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

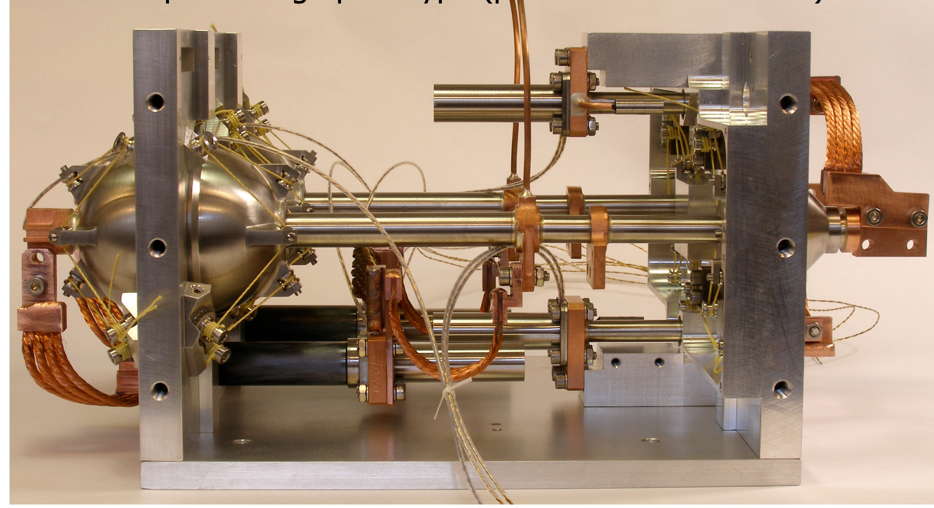
BLISS ADR prototype



Kevlar Suspension w/ 300 mK intercept

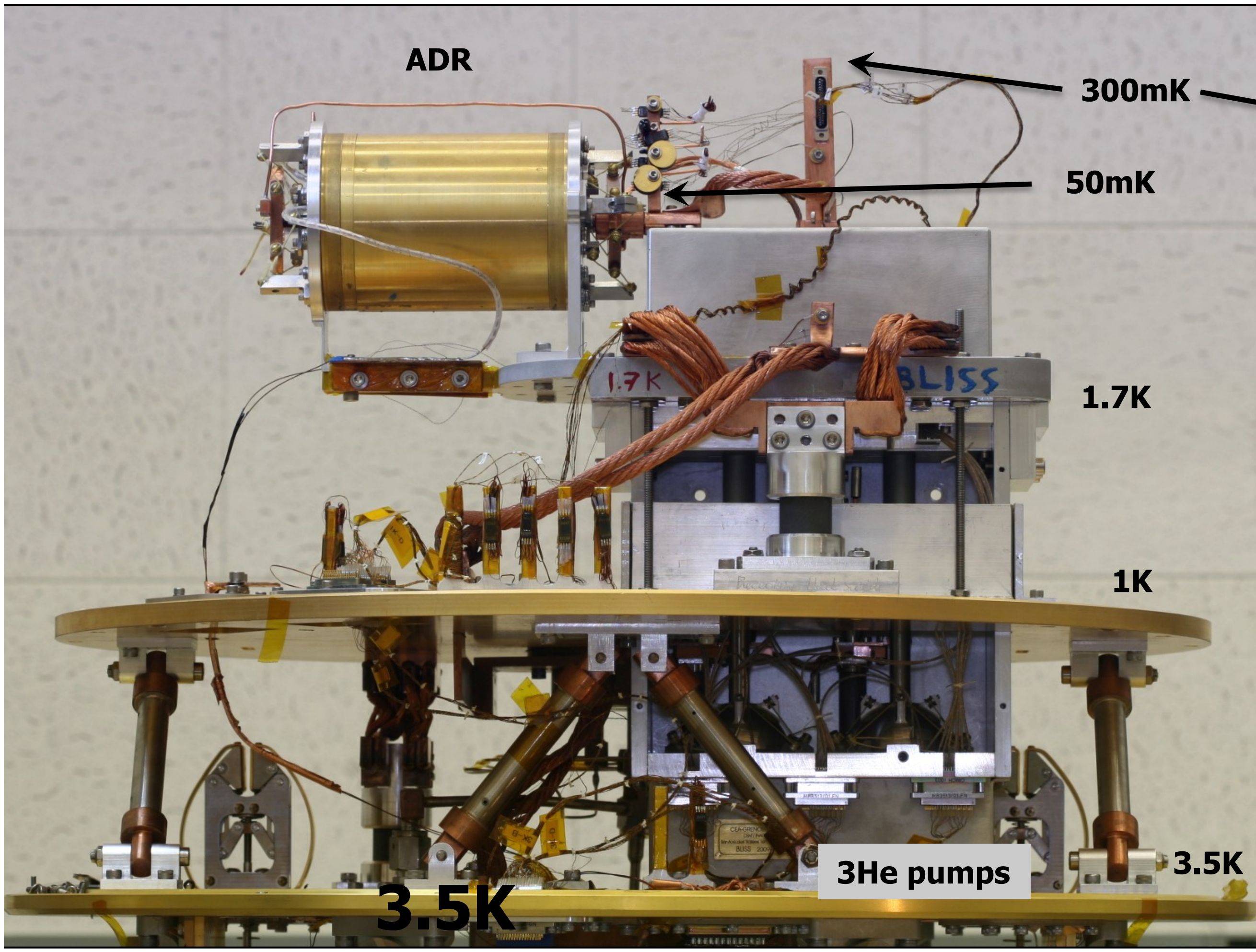
50mK Salt Pill Thermal Post

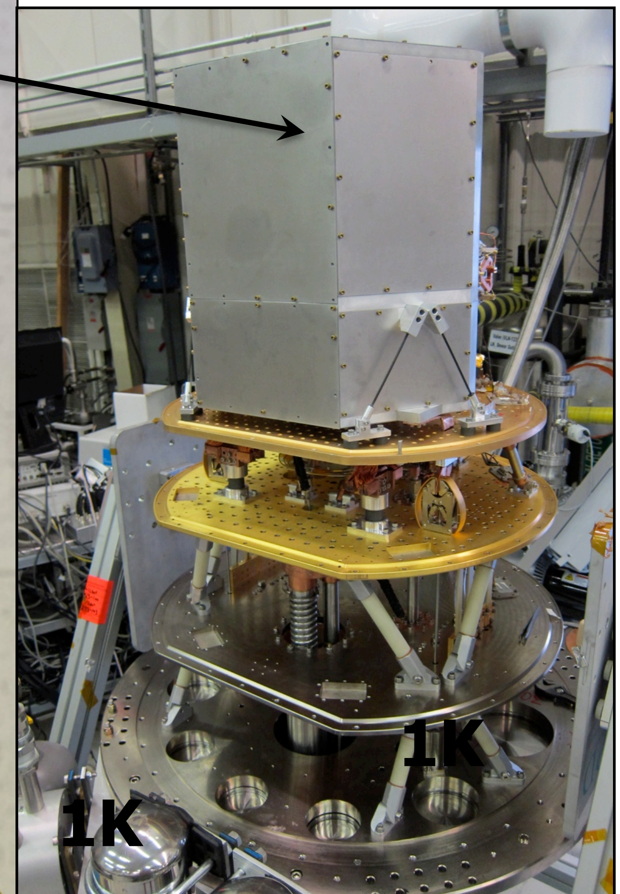
BLISS sorption fridge prototype (procured from Duband)



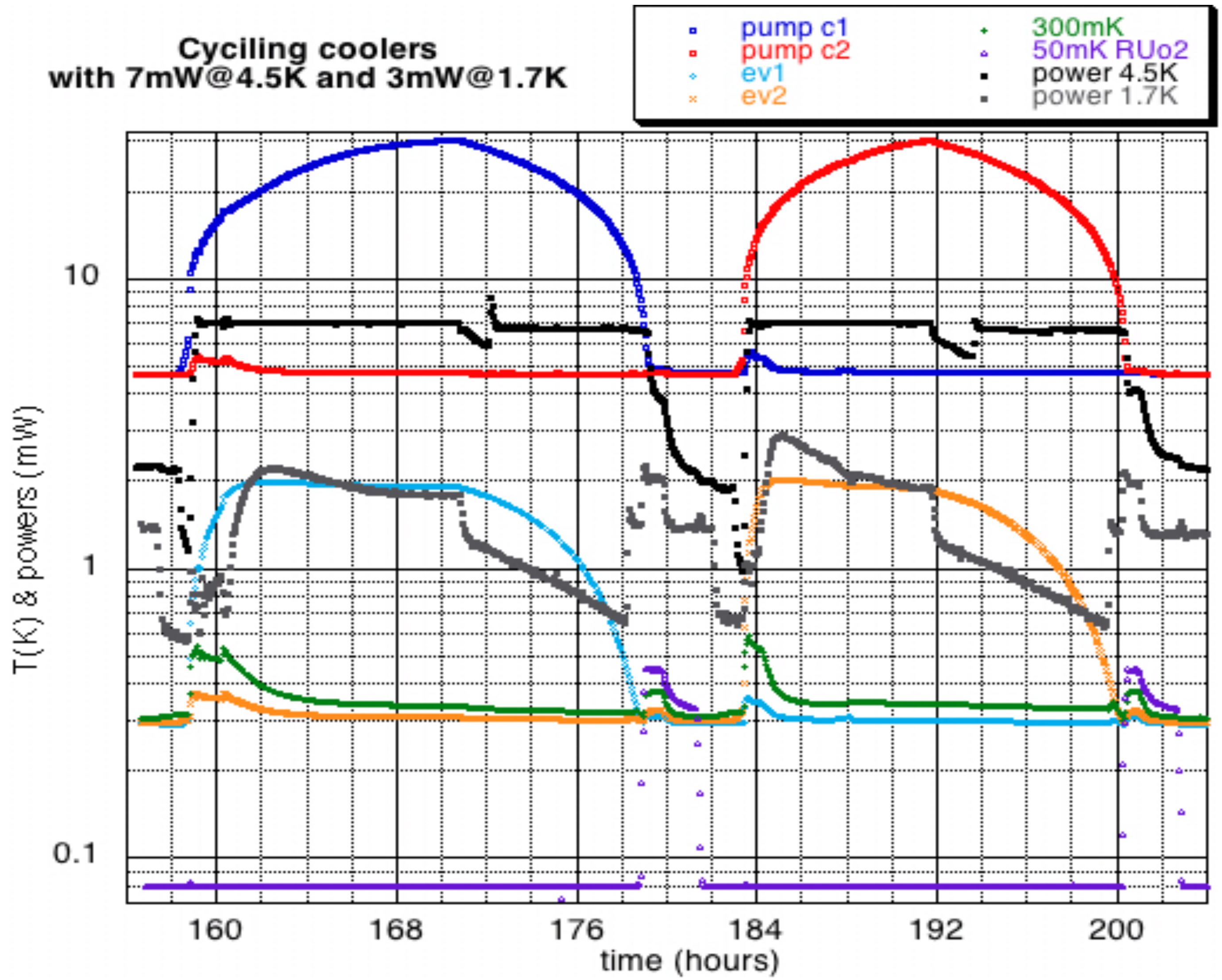
BLISS THERMAL TESTBED

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)

BLISS TES MEASURED SENSITIVITY

EXCEEDING BLISS REQUIREMENT