Enabling Technologies for the Origins Space telescope (OST)

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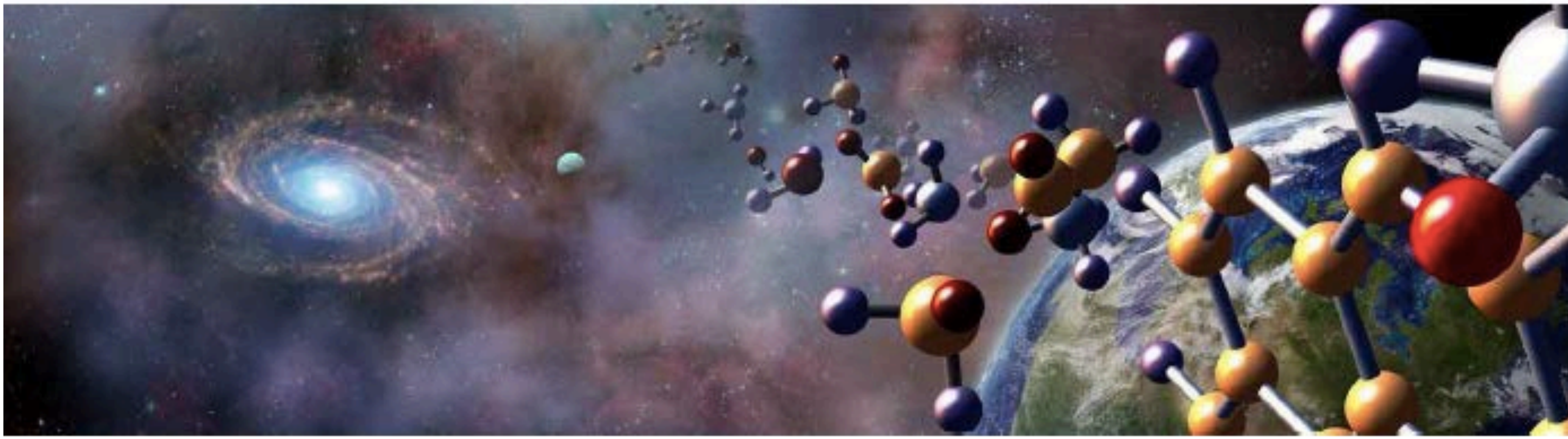
ORIGINS Space Telescope

Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.

NASA



NASA Mission concept for 2020 Decadal review; launch 2030s

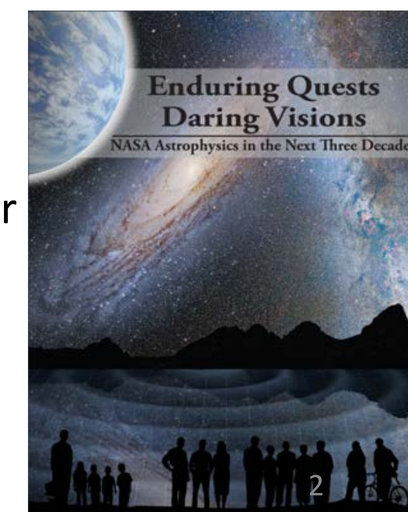
Large, cold (5 K) telescope 8-15 m, 5 instruments covering 6 μm – 800 μm

Study Chairs: Margaret Meixner & Asantha Cooray

Study at NASA/GSFC, Study Scientist: David Leisawitz, Mangr.: Ruth Carter

Comes from the NASA Astrophysics Roadmap, Enduring Quests, Daring Visions: Improvements from *Herschel, Spitzer & JWSTs MIR capabilities*

- large gain in sensitivity and spectroscopic capabilities
- angular resolution sufficient for deep cosmic surveys
- MIR Choronography, imaging, and spectroscopy



ORIGINS
Space Telescope

Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.

NASA

Tracing the signatures of life and the ingredients of habitable worlds

Origins will trace the trail of water from interstellar clouds, to proto-planetary disks, to Earth itself facilitating understanding of the abundance and availability of water for habitable planets.

Unveiling the Growth of Black Holes and Galaxies over Cosmic Time

Origins will reveal the co-evolution of super-massive black holes and galaxies, energetic feedback, and the dynamic interstellar medium from which stars are born.

Origins will trace the metal enrichment history of the Universe, probe the first cosmic sources of dust, the earliest star formation, and the birth of galaxies.

Charting the Rise of Metals, Dust, and the First Galaxies

Origins will chart the role of comets in delivering water to the early Earth, and conduct a survey of thousands of ancient Trans Neptunian Objects (TNOs) in the outer reaches of the Solar System.

Characterizing Small Bodies in the Solar System

- For the Scavenger Hunters among you:

The secret word is *Superconductor*

Major Technologies needed for OST

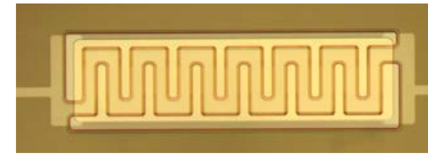
- Large Format, High Sensitivity Far IR Direct Detectors
- Wide-band medium R and high-R Far IR Spectrometers using direct detectors
- Low Noise Imaging Heterodyne Spectrometers for very large R
- High-power 4.5 K Cryocoolers
- Sub-Kelvin Cooling (50 mK)
- Large Cryogenic Optics
- High contrast Mid IR Coronagraphy

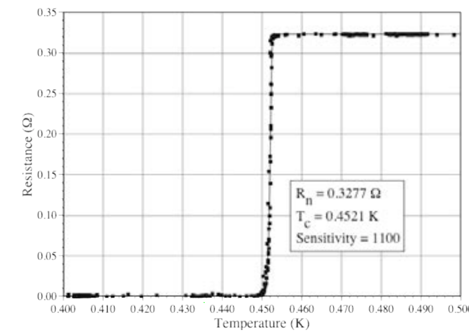
FIR Direct Detectors

- State of the Art
  - 325 bolometers with $4x10^{-17}$ W/√Hz NEP (TRL9 Herschel/SPIRE)
  - 3,840 pixels with 1×10^{-16} W/√Hz NEP (TRL 5 HAWC+ camera) (next slide)

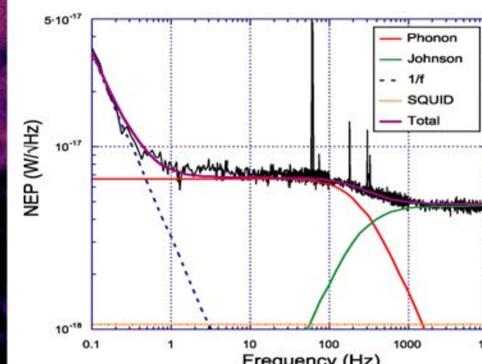
Form more on detectors see presentation by M. Bradford

HAWC+: FIR Imager and Polarimeter for SOFIA

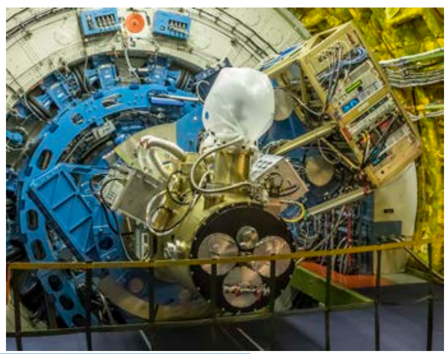


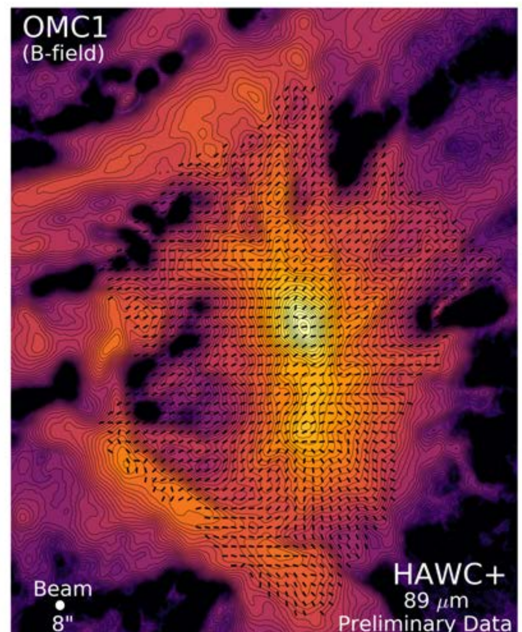


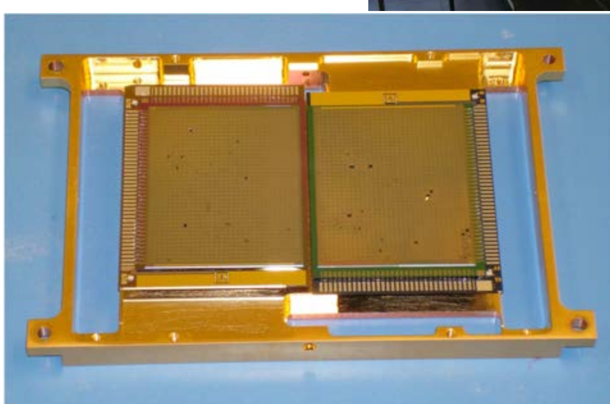
HAWC + uses Transition Edge Sensors (TES)
And conventional halfwave plates



HAWC+
on SOFIA







FIR Imager and Polarimeter

- OST Needs
  - $10^5 - 10^6$ pixels with < $3x10^{-19}$ W/√Hz NEP (imaging)
    - Reduce readout frequencies and/or develop hybrid readout systems (e.g. CDM plus frequency domain,…) / reduction in electronics power dissipation
    - Wideband Polarimeter technologies (e.g. novel embedded reflective half-wave plates (ER-HWP))

Form more on detectors see presentation by M. Bradford

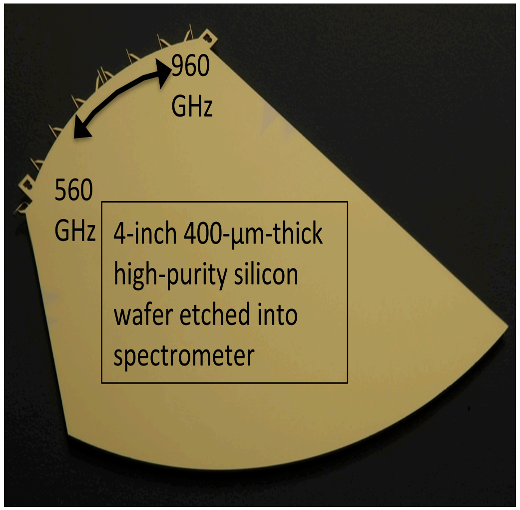
ORIGINS Space Telescope

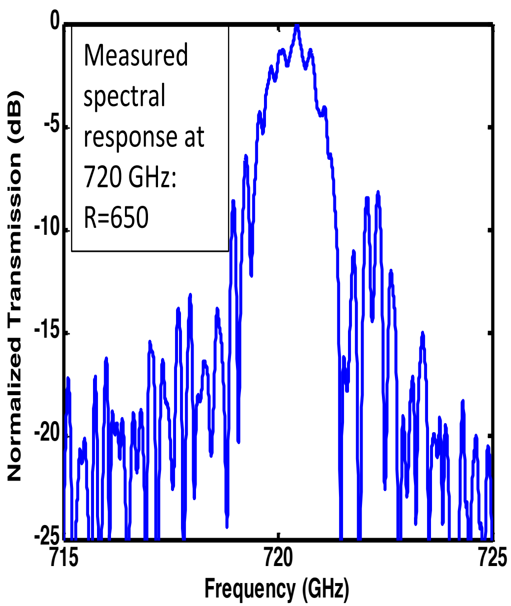
Compact low/medium R Integrated FIR-Spectrometer

- OST Needs:
  - Continuous coverage from 30 to 800 μm (current technology is adequate for < 100 μm)
  - High Sensitivity/Efficiency
  - Resolving Power, R > 500
  - 3×10^{-20} W/√Hz NEP (spectroscopy)
    - Antenna vs. absorber coupling
    - Low heat capacity/high isolation
- Development Needs:
  - Stack spectrometers for large bandwidth, combine with high sensitivity direct detector arrays
- State of the Art:
  - See following slide for example technologies

Compact Spectrometers

Waveguide Gratings



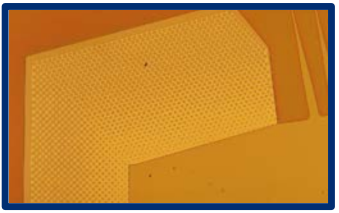


- Curved grating in parallel plate waveguide. Single polarization, good efficiency over 1:1.6 bandwith.
- Demonstrated at λ=1.3 mm, R=300 in Z-Spec at CSO + Apex (free-space propagation medium).
- Now demonstrated R=700 device in float-zone silicon wafer with warm test.
- End-to-end efficiency test and integration with detectors coming.
- Stack these into quasi-slit-spectrometer with line of 2 fλ feeds.
- **Stack lots, 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).

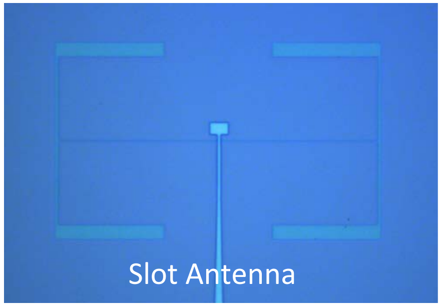
Echternach, Reck, Pepper, Bradford, Hodis @ JPL

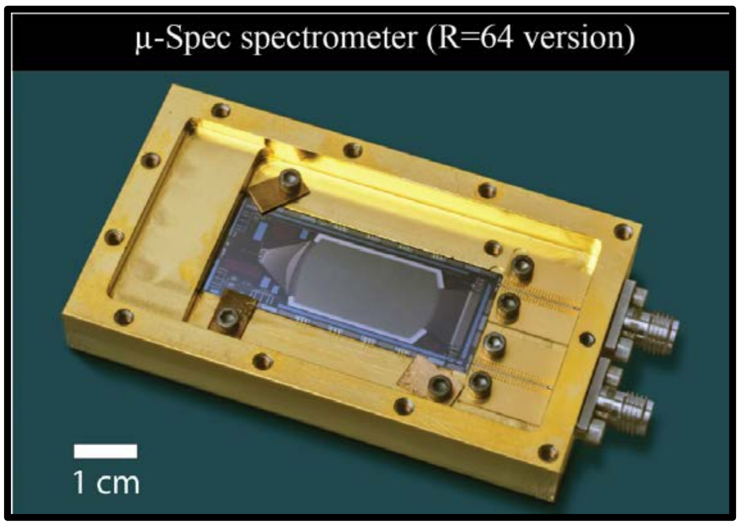
Compact Spectrometers

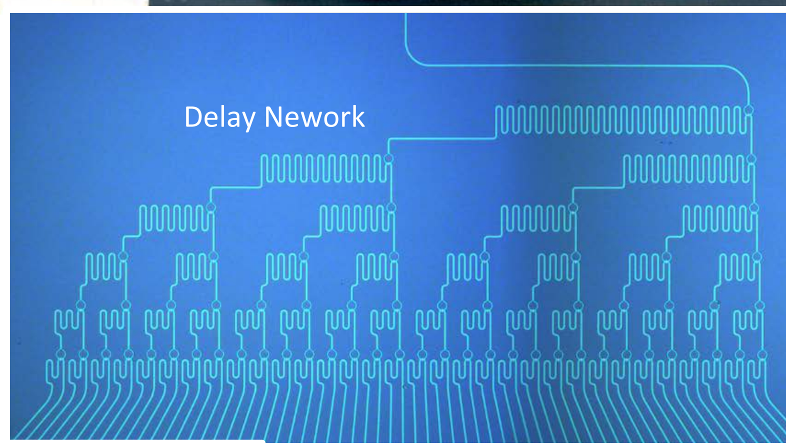
Ultracompact, transmission line spectrometers on silicon dielectric



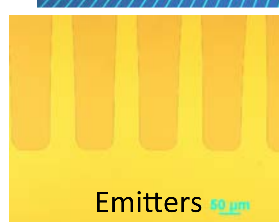
Absorbing sidewall



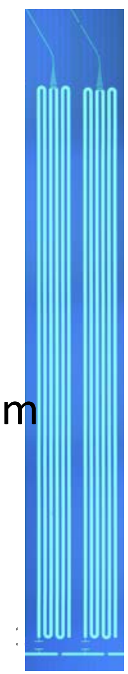




μ-Spec is a compact submillimeter (~100 GHz – 1 THz) spectrometer which uses low loss superconducting microstrip transmission lines and a single-crystal silicon dielectric.
A R=512 μ-Spec version is currently being built.



Aluminum KIDs

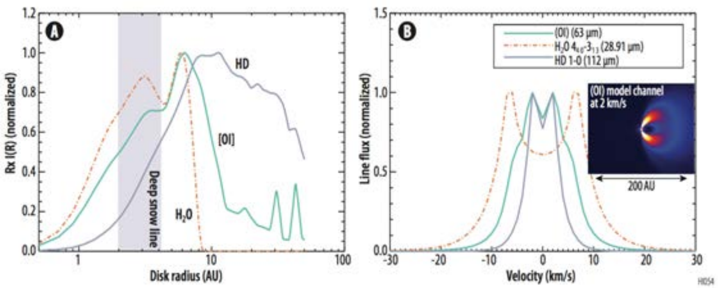


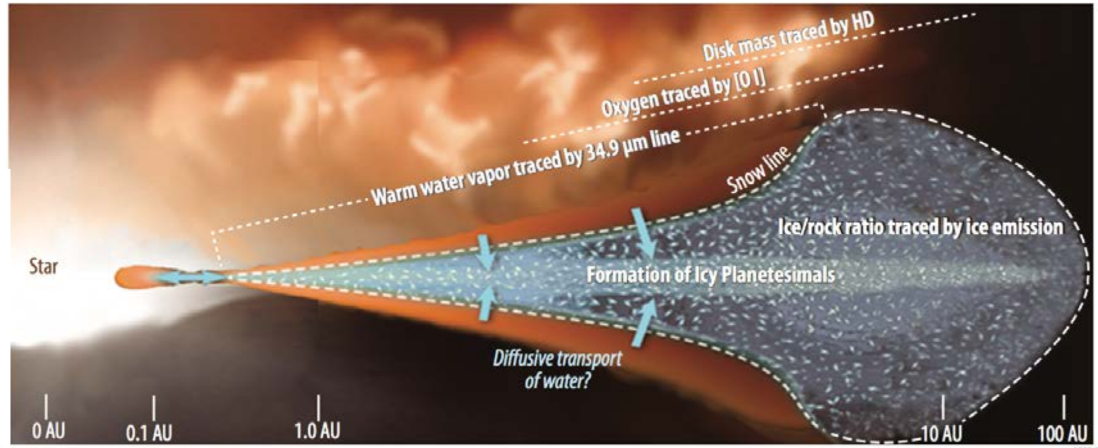
PI: S. Harvey Moseley
Team: Emily M. Barrentine, Giuseppe Cataldo, Ari D. Brown, Negar Ehsan, Omid Noroozian, Thomas R. Stevenson, Kongpop U-Yen, Edward J. Wollack

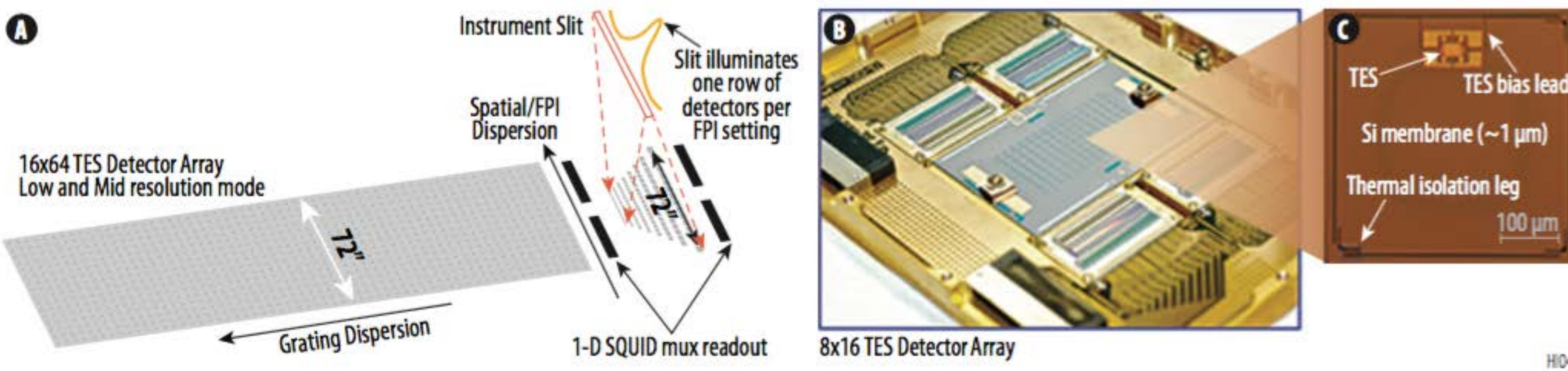
High-Spectral Resolution Spectrometer

- OST Needs:
  - High Sensitivity/Efficiency
  - Resolving Power up to R ~ 500,000
- Development Needs:
  - Tile-able gratings followed by Fabry-Perot Interferometer (FPI)
  - direct detectors with NEP~1×10^{-20}W $Hz^{-1/2}$/ photon counting detectors
- State of the Art:
  - See following slide for example technologies

HIRMES: High-R Spectrometer for SOFIA

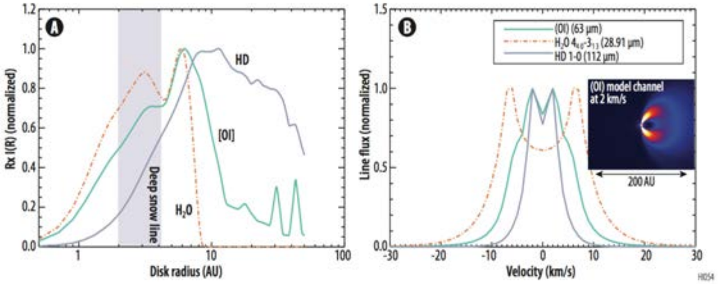


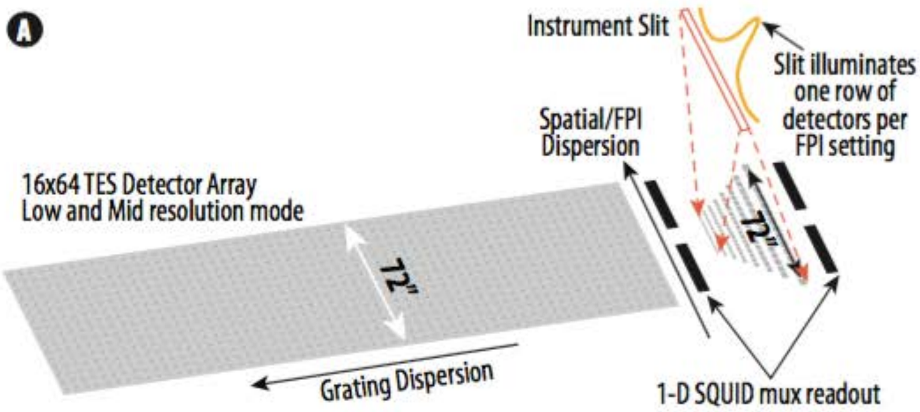




PI: S. Harvey Moseley

HIRMES: High-R Spectrometer for SOFIA



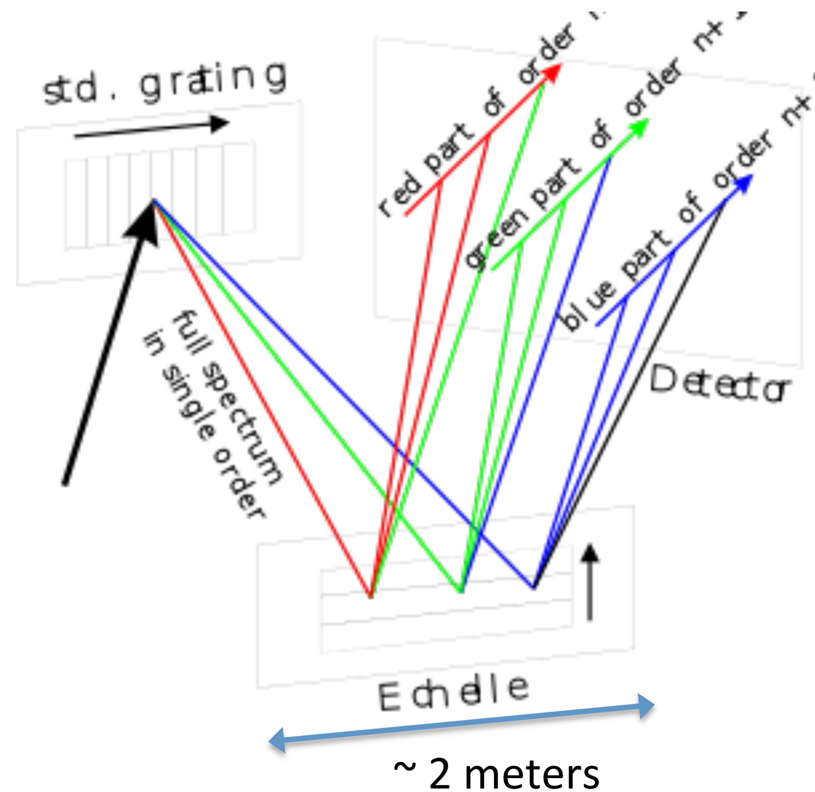


- spectral range: 25-122 µm
- R ~ 600 grating
- a mid-resolution R ~ 12,000 FPI as order sorter for
- high resolution FPI operating in high order R~ 100,000

PI: S. Harvey Moseley

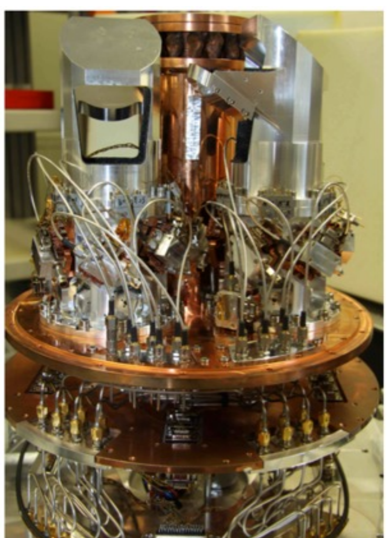
High-R Spectrometer Study for OST

- Echelle grating from 10 tiled gratings. Those (individual tiles) will be phased grating sections-> equivalent of phasing a big mirror
- 2m grating R=80,000 @ 50 μm
- Fabry-Perot R ~1/2 million
- With photon counting detectors (background limited) spectrometer will be ~10^4 faster than heterodyne spectrometer

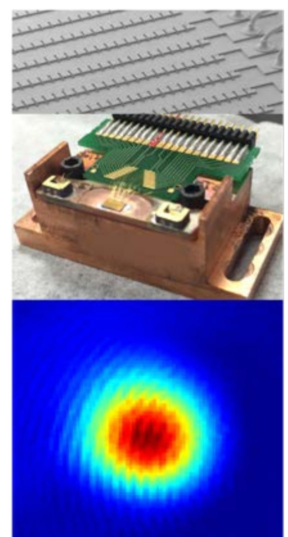


Heterodyne Spectrometers

- State of the Art
  - Up to 2 THz (150 µm), single pixel (TRL 9 Herschel/HIFI)
  - 4.7 THz 14 pixel (TRL5 SOFIA/upGREAT)
  - **Advances since HIFI:**
    - Frequency range extended to 4.7 THz using QCL for Local Oscillator (LO)
    - T_{sys} ~ 800 K
    - Focal plane array technology for increased imaging speed



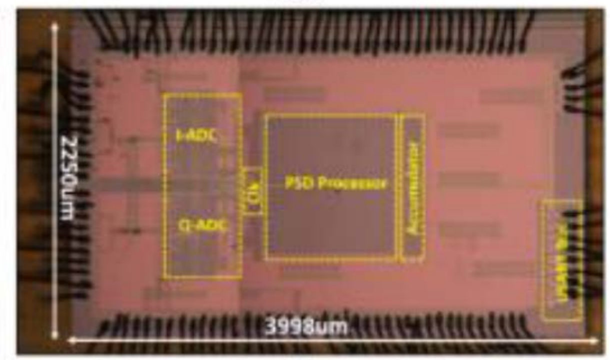
upGREAT 14-pixel 2 THz RX on SOFIA (Univ. Köln; Risacher+ 2016)



Quantum Cascade Laser (QCL) – multiple units for different frequencies

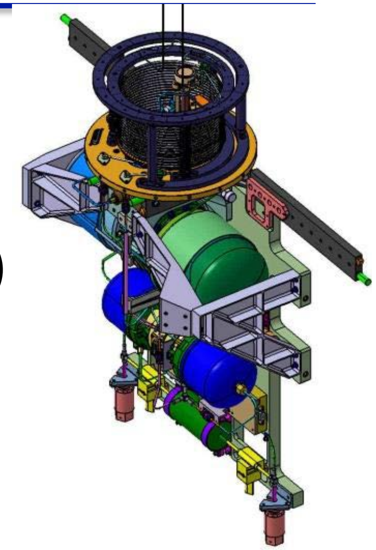
Heterodyne Spectrometers

- OST Needs
  - Increase pixel count to > 128
  - Decrease Receiver temperature
- Development Topics
  - Demonstrate LO sources covering 2 THz – 3.5 THz with > 10 μW power output
  - Demonstrate broadband balanced and dual-polarization submillimeter receivers
  - Demonstrate 16 pixel LO system for 63 μm (4.7 THz)
  - Develop next-generation large pixel count system (N > 128) for 2 THz range
  - Develop and demonstrate 4 GHz-bandwidth digital ASIC spectrometer
  - Demonstrate complete HEB mixer spectrometer system with ASIC spectrometer in 100 μm (3 THz) range



Prototype CMOS ASIC VLSI chip
Digital FFT spectrometer
750 MHz bandwidth; 256 channels
Includes ADC, processor, memory, USB interface
1.5 GHz version with 1024 channels in process
A. Tang JPL/UCLA/Broadcom

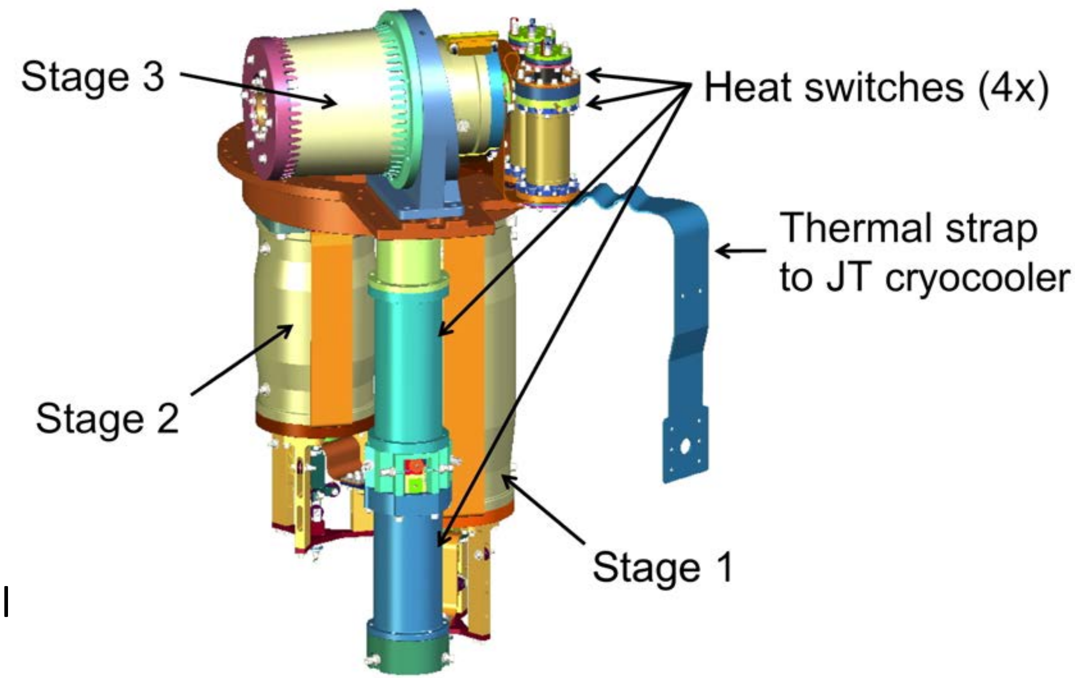
4.5 K Cryocoolers



- OST Needs
  - Sub-Kelvin precooler for detectors (~40 mW at 4.5 K)
  - Telescope cooling (~250 mW at 4.5 K)
    - Higher cooling power is easier than lower T!
- State of the Art
  - SHI 40 mW at 4.5 K (TRL 9-Hitomi)
  - NGAS 70 mW at 5.7 K (TRL7-JWST/MIRI)
    - Extension to 4.5 K is straightforward
  - Creare 230 mW at 10K (TRL 4)
    - Practically speaking, no vibration
    - Extension to 4.5 K using Adiabatic Demagnetization
- Development Needs:
  - Demonstrate higher cooling power and lower temperature, push TRL level

Sub-Kelvin Cooling

- State of the Art
  - Single shot dilution refrigerator 100 nW @ 100 mK (TRL9-Planck)
  - 3 stage ADR 500 nW @ 50 mK and 1.5 mW at 1.5 K (TRL9-Hitomi)
  - Continuous ADR (CADR) 6 µW @ 50 mK (TRL4)



- OST Needs
  - 1-5 µW @50 mK and 1 mW at 1.2 K
- Development Requirements:
  - Raise CADR to TRL 6
    - Expand the temperature range to < 50 mK and > 4.5 K
    - Improve temperature control and magnetic field shielding
    - Vibration Isolation

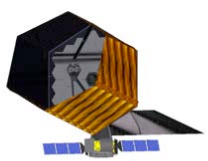
Large Cryogenic Optics

- Low dissipation actuators
  - State of the Art:
    - 1.35 m demo at room T (see next slide)
    - some testing at cryogenic temperatures
  - OST Needs:
    - Cryogenic actuators with high resolution and dynamic range to enable cost effective ground tests of a large cryogenic telescope in existing facilities
  - Development Requirements:
    - Raise TRL to 6 for 4K actuators
- Material properties
  - Examples: Damping of structures, emissivity of MLI at low T
  - OST Needs:
    - Large, thermally isolating, quiet structures
  - Development Requirements:
    - Enable use of new composites for optics support and thermal isolation

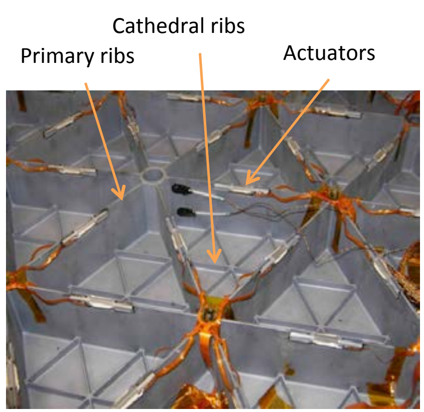
Cryogenic Active Mirror Heritage

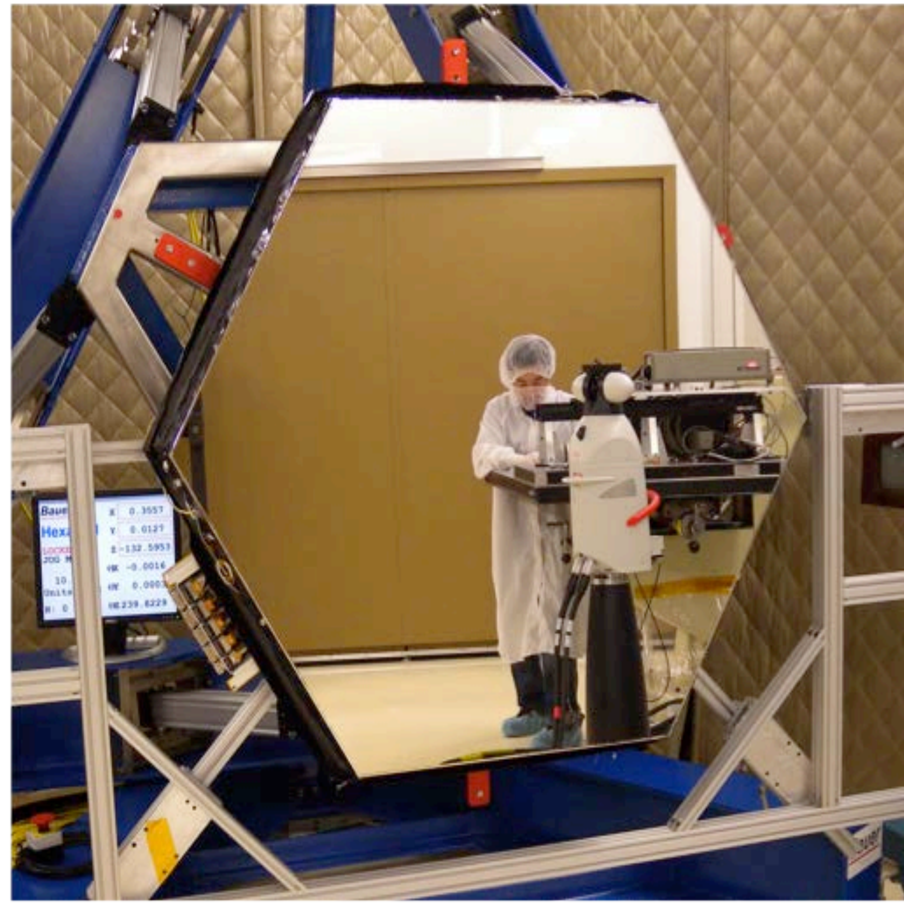
Actuated Hybrid Mirrors (AHMs) demonstrate active mirror architecture

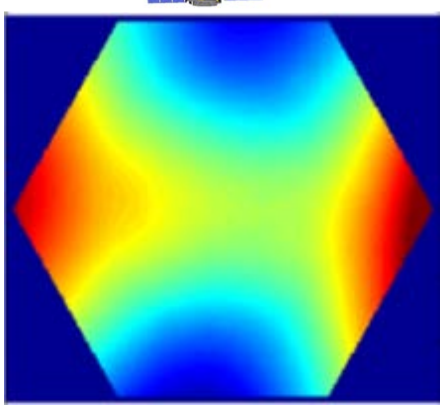
- Active mirror segments
  - 37 to 414 actuators
- 0.5 to 1.35 m size demonstrated
- <14 nm rms SFE demonstrated
- 10-15 kg/m^2 substrate
- <25 kg/m^2 total
- Tested in 1G to 0G specs



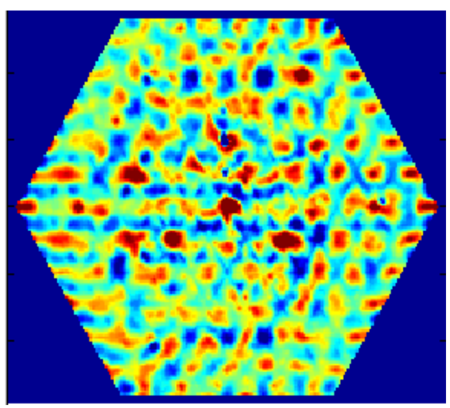
SiC Mirror Back Structure







EM-4a Uncorrected
SFE = 1.88 µm RMS



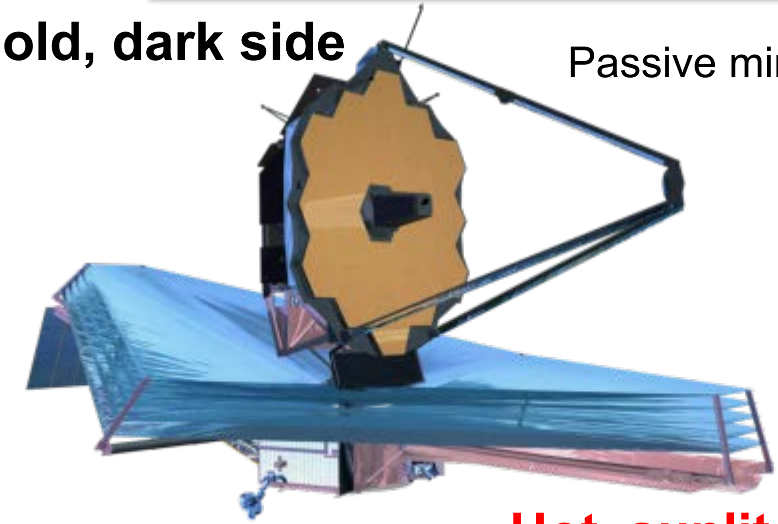
EM-4a Corrected
SFE = 0.014 µm RMS
(colors scale with RMS)

ORIGINS Space Telescope

Lessons from Webb

Cold, dark side

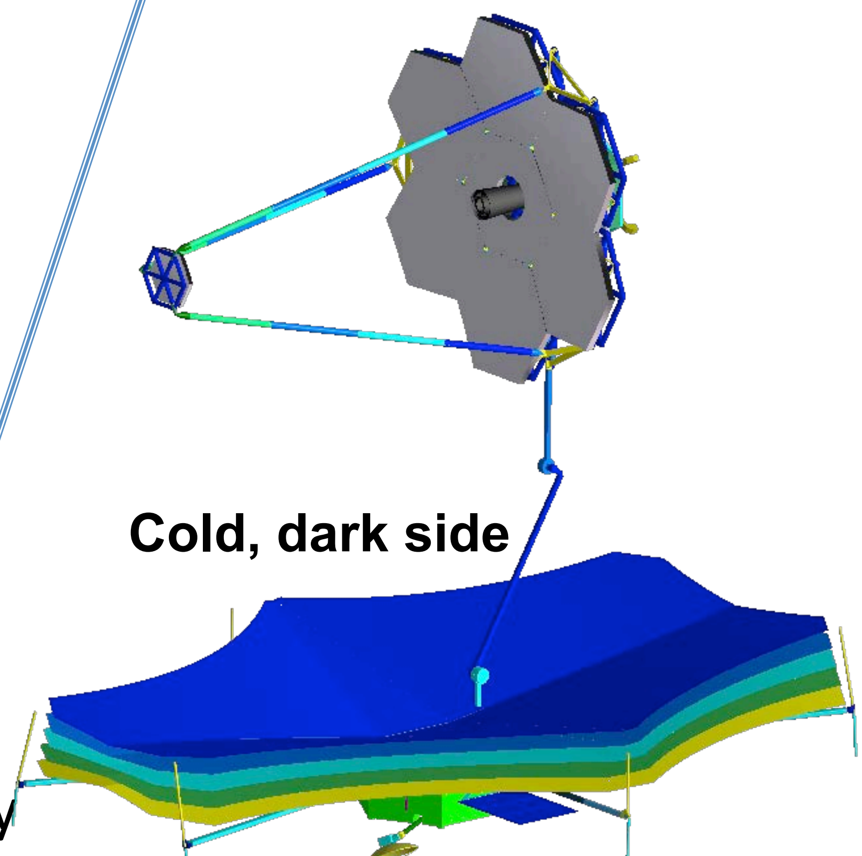
Passive mirror cooling



Hot, sunlit side

- Separate hot from cold
  - Get electronics (IEC) off cold side
- Minimize sunshield penetration
- Increased core view to space
- Intercept heat
- Utilize the passive cooling capability of coldest layer

Active cryo-cooled mirrors



Cold, dark side

Hot, sunlit side

SAFIR ca. 2004

Mid IR Instrument w/ Coronagraph

- Primary objective: detect and *characterize* analogs of the solar system giant planets.
- State of the Art (Coronography)
  - 10^{-3} to 10^{-4} contrast at 11 to 23 µm (TRL7 JWST/MIRI)
  - Inner working angle (IWA) of ~0.33-2.16”, at 10.65 and 23 micron, respectively (TRL 7 JWST/MIRI)
- OST Needs
  - Contrast better 10^{-6}
  - Wavelength range 6-40 µm
  - IWA 0.25” at 15 µm for warm Neptunes at 10 parsec
  - High sensitivity (few µJy).
  - Spectrometer with R ~ 500

    (goal: spectrally resolve CH_4, CO_2, CO, N_2O, O_3, NH_3, SO_2, and H_2O absorption features in emission spectrum)
- Development needed:
  - Increase the contrast and wavelength range of existing and new technologies

Conclusion

- Major Technology Developments required for OST, most already at relatively high TRL levels (in particular cryo coolers, cold optics,…)
- Well established path forward for spectrometer technologies (excl. detectors)
- Lowest TRL -> urgent need for development funding: *low noise detectors + large format superconducting arrays*