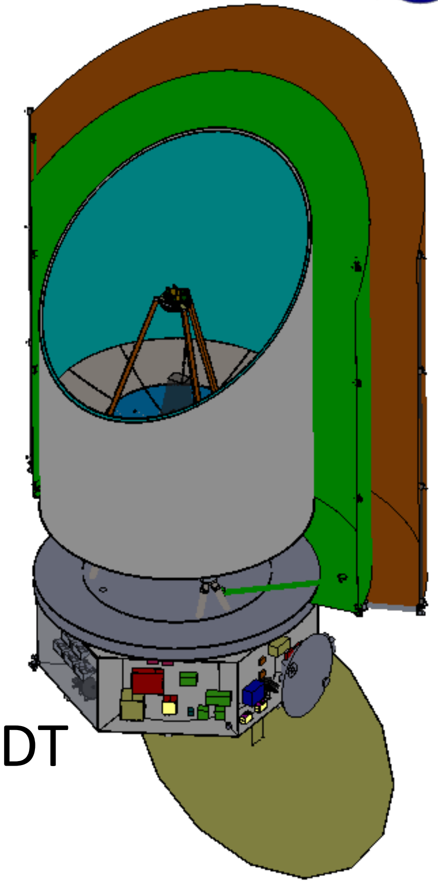
ORIGINS Space Telescope

Cryosystem Design for the Origins Astrophysics Flagship Mission

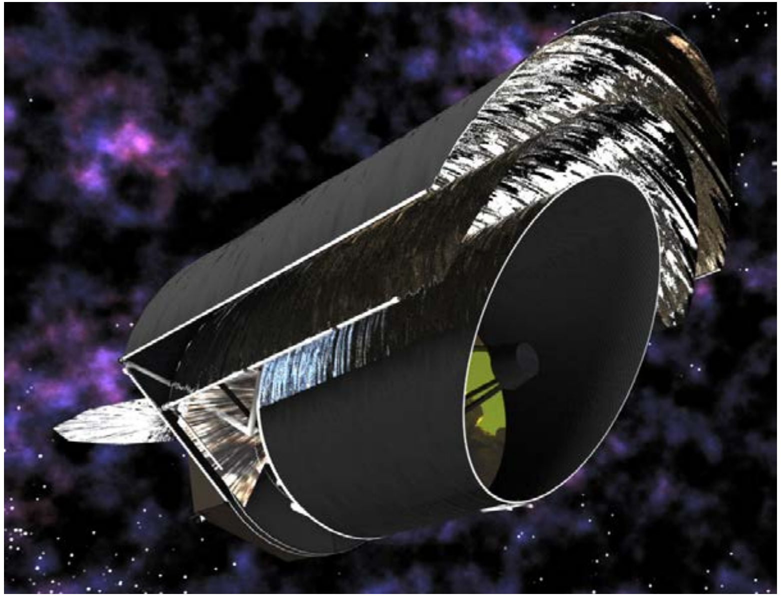


Mike DiPirro/NASA-GSFC

For the Origins Study Center and the Origins STDT

Outline

- Introduction to OST
- Predecessors
- Editorial: Cryogenic Engineering is not the same as Low Temperature Thermal Engineering
- The OST Challenges and Trades
- Technology Development
- Summary



Intro to OST

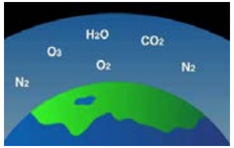
- Originally the Far-InfraRed Surveyor
- => Origins Space Telescope when Mid-Infrared Instrument Added
  - Key to biosignatures in transiting exoplanets
- Follows Spitzer (0.85 m diameter, cold for 5.5 years) and Herschel (3.5 m diameter, but warm 80 K)
  - OST has a 5.9 m primary with 25 m^2 of collecting area (same as JWST)
- General Observatory with 5 Year nominal mission duration with 10 years of consumables, designed for servicing
- Covers wavelengths from 3 microns to 600 microns

Top three themes

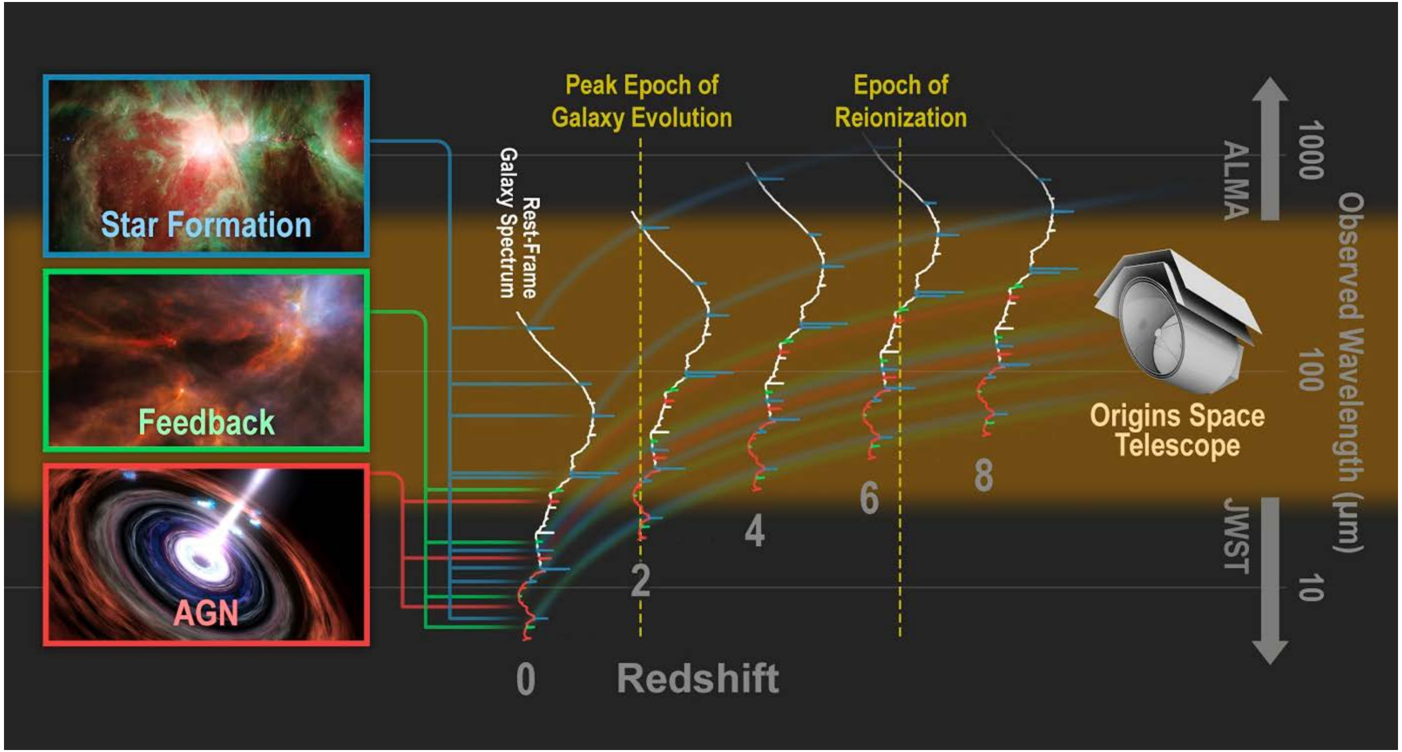
(I) How does the Universe work? OST question: How do galaxies form stars, make metals, and grow their central supermassive blackholes from reionization to today? *OST will spectroscopically 3D map wide extragalactic fields to measure simultaneously properties of growing super-massive blackholes and their galaxy hosts across cosmic time.*

(II) How did we get here? OST question: How do the conditions for habitability develop during the process of planet formation? *With the sensitive and high-resolution far-IR spectroscopy OST will map the water trail in our Galaxy.*

(III) Are we alone? OST question: How common are life bearing planets around M dwarf stars? *With sensitive mid-infrared transit spectroscopy, OST will measure biosignatures, including ozone, carbon-dioxide, water, and methane in the atmospheres of Earth-sized habitable exoplanets.*

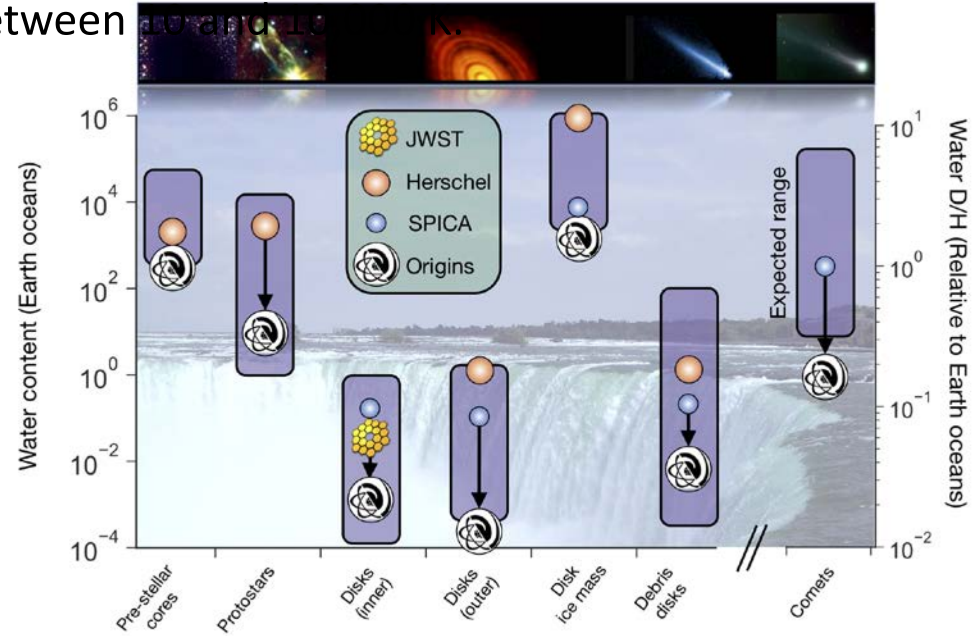


How do galaxies form stars, make metals, and grow their central supermassive blackholes from reionization to today?

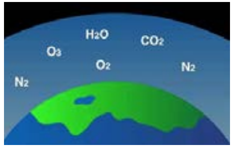


How do the conditions for habitability develop during the process of planet formation?

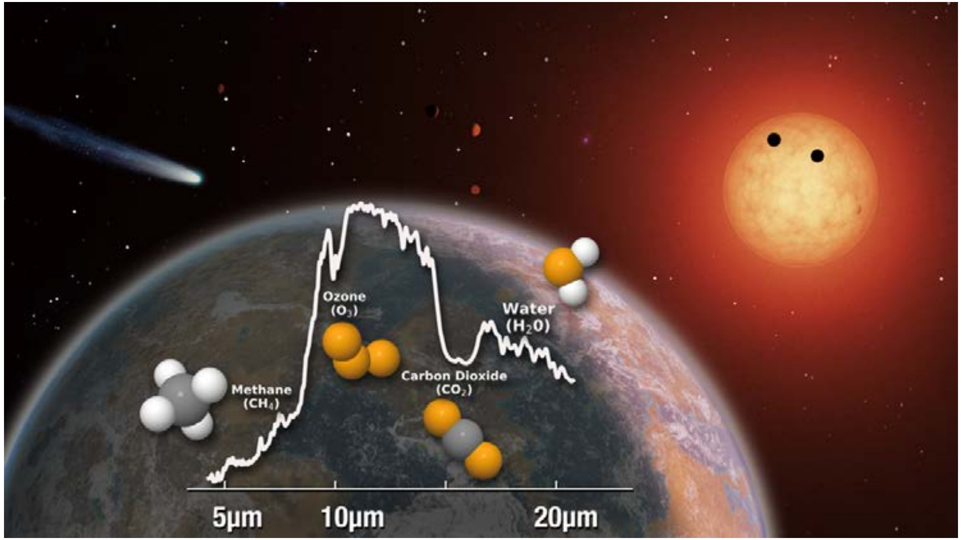
Science Objective 1: Measure the water mass at all evolutionary stages and across the range of stellar mass tracing water vapor and ice at all temperatures between 10 and 10[illegible] K.



OST will make the definitive statement on
the disposition of water as stars and planets are assembled.



How common are life bearing planets around dwarf stars?



Advantages to characterizing habitable zone transiting planets in the mid-IR

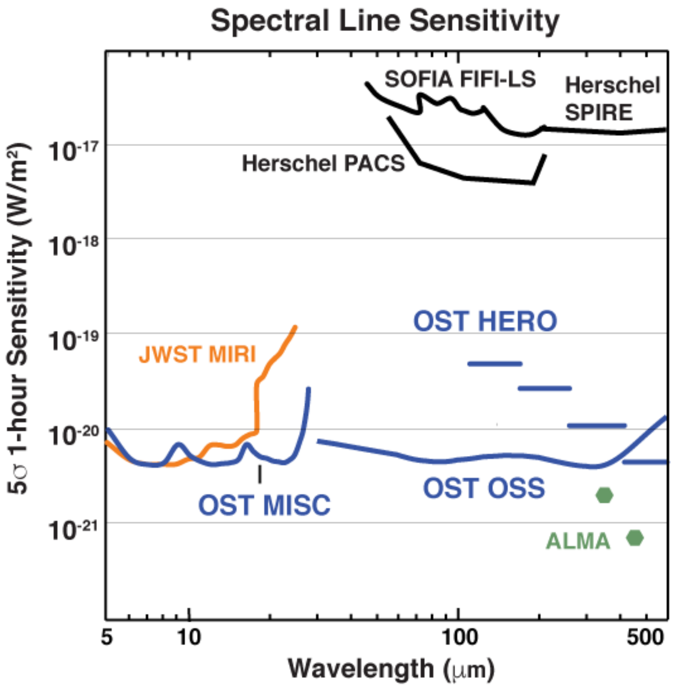
Precisely determined masses and radii -> bulk densities

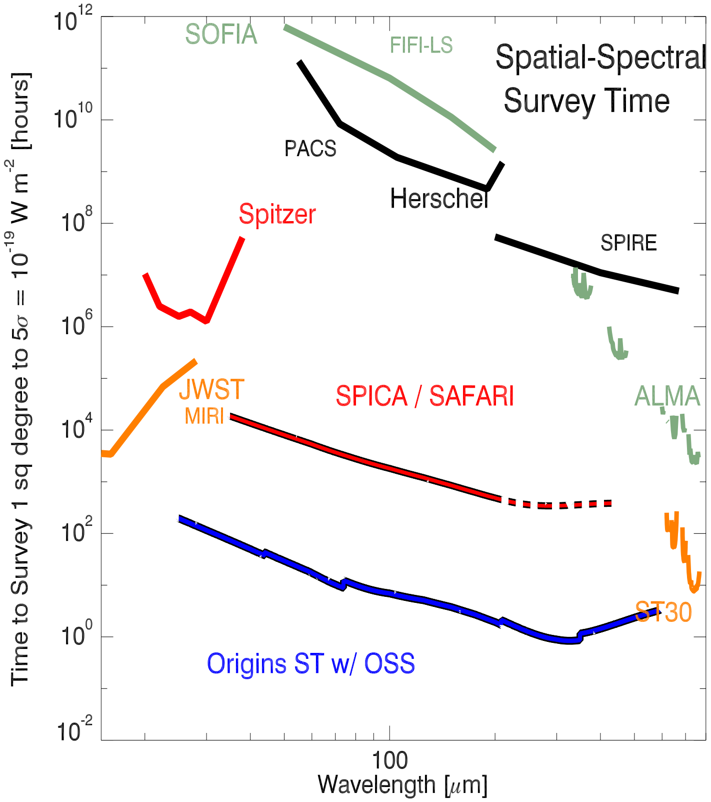
Favorable planet-star flux & size contrasts

Mid-IR be sensitive to key spectral signatures (H_2O, CO_2, O_3, CH_4, N_2O) for HZ planets with Earth-like atmospheres transiting mid-to-late M dwarfs

Temperature constraint at apparent surface

Sensitivity Improvement



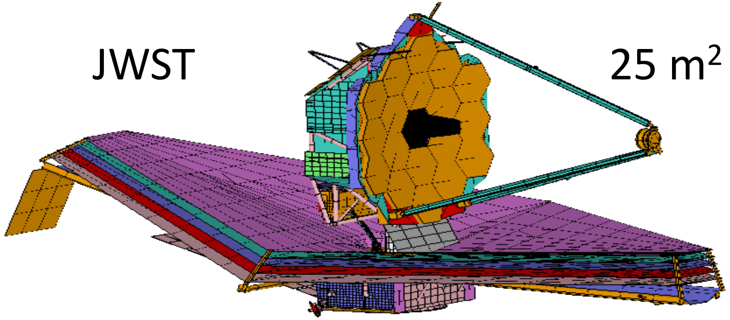


Architecture Features

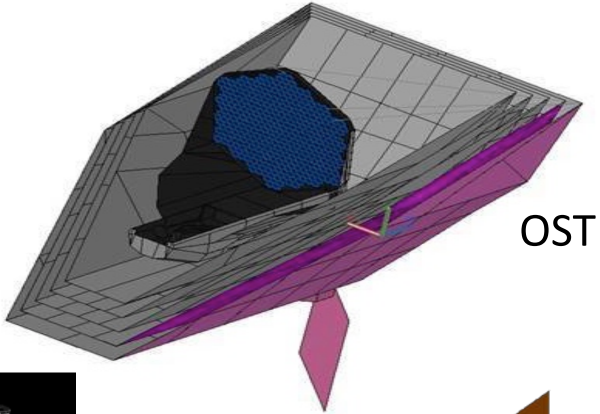
- Concept 1 (Open, JWST-like)
  - Pros: Easier to fold to stow for launch
  - Cons: stray light suppression is more difficult, Larger sunshield is more difficult to deploy and demonstrate on the ground
- Concept 2 (Closed, Spitzer-like)
  - Pros: suppression of stray light, ground demonstration of thermal performance, can be fully deployed at launch
  - Cons: limits the primary size to the fairing diameter
- Operating Temperature
  - 4.5 K, allows sky background-limited performance
  - Compatible with mechanical cryocooler and sub-Kelvin cooler technology

Overall Architecture

JWST



25 m^2



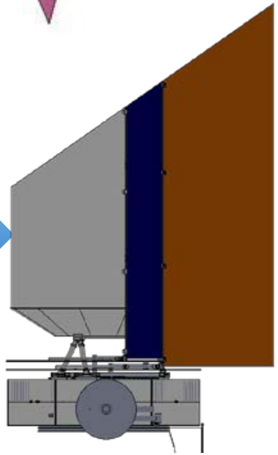
OST Concept 1

52 m^2

- Spitzer-like rather than JWST-like
- Cold Baffle is more forgiving for stray light
- Cold radiator gives extra 35 K cooling
- Simple shield deployment that can be demonstrated on the ground

Spitzer

0.5 m^2



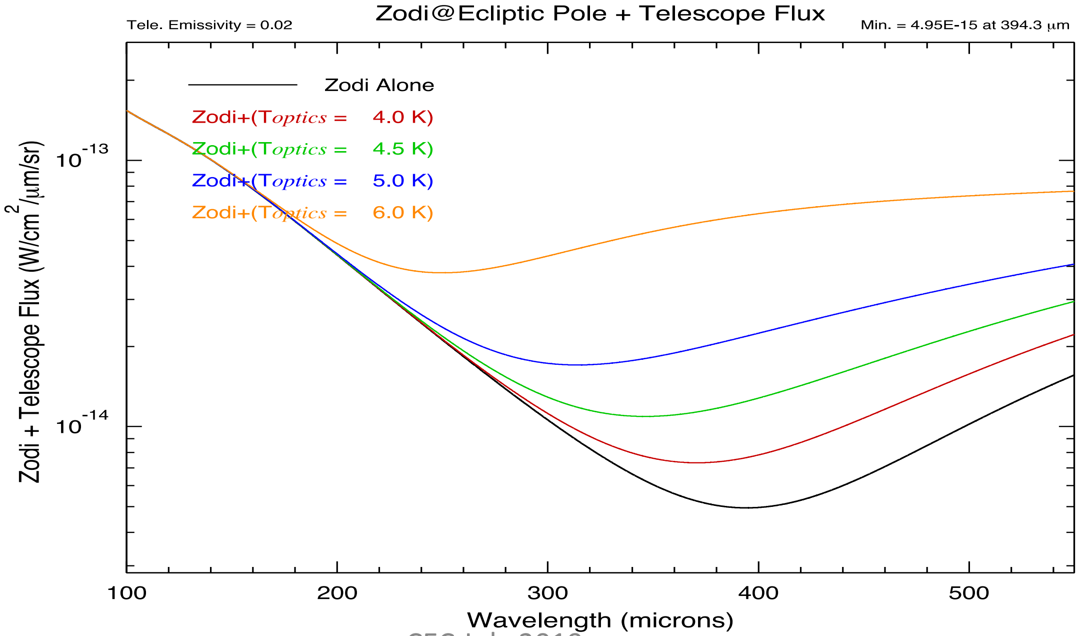
OST Concept 2

25 m^2

Why Do We Need a 4.5 K Telescope?

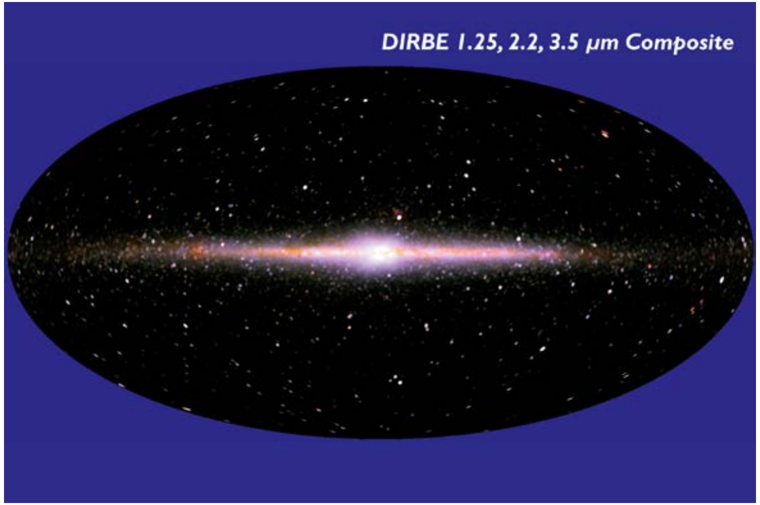
OST will cover the wavelength range from 5 µm to 600 µm

The goal is to be background limited – limited by the cosmos rather than self emission from the telescope

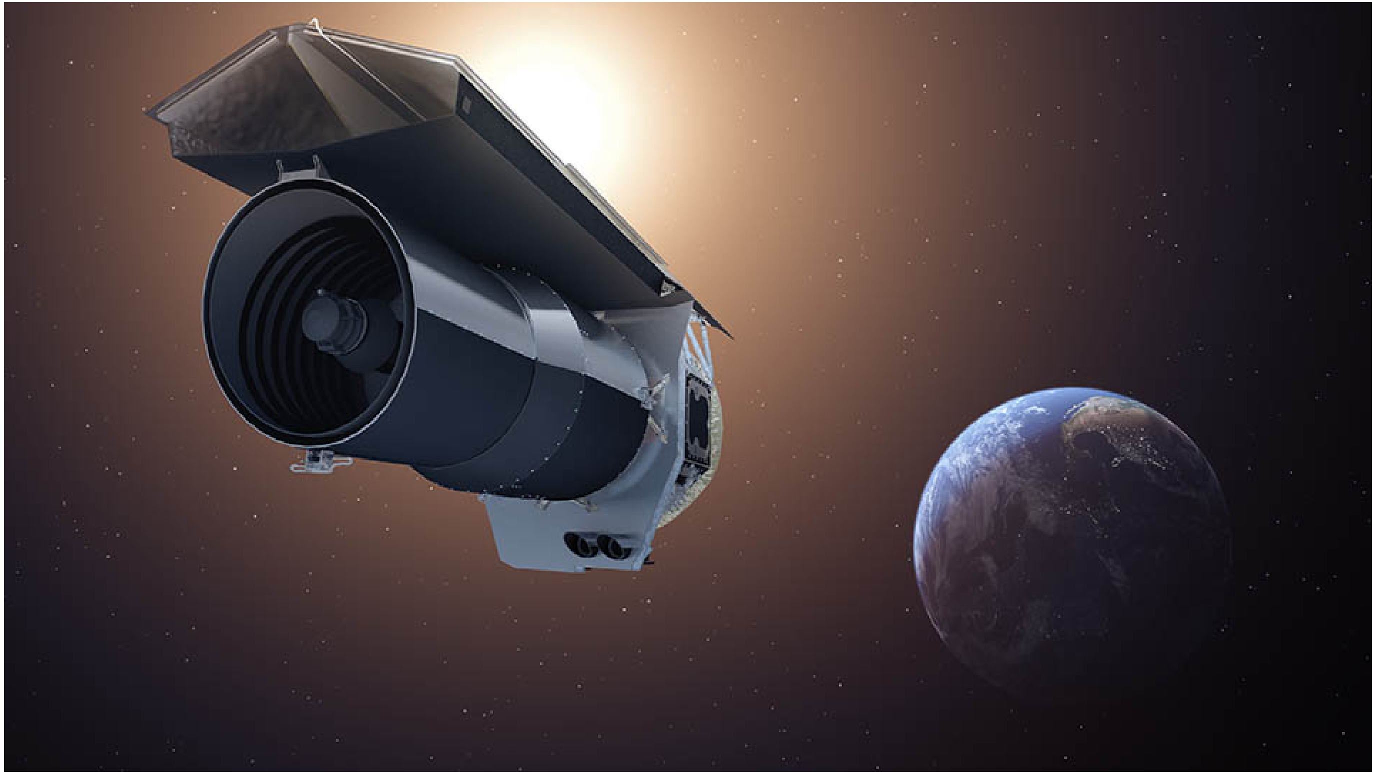


Predecessors

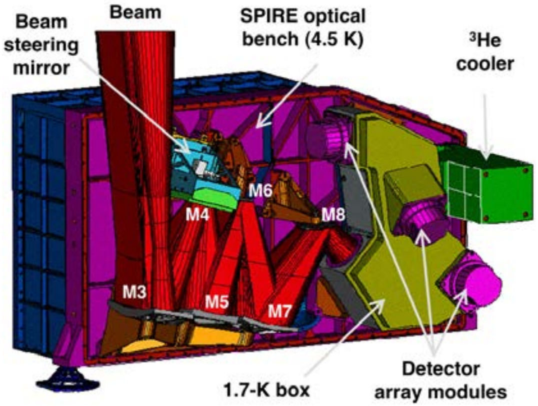
- IRAS
  - 57 cm dia primary
  - Liquid helium cooled
  - Launched 1983, duration 10 months
- COBE
  - DIRBE has 19 cm primary
  - Liquid helium cooled
  - Launched 1989, duration 10.5 months

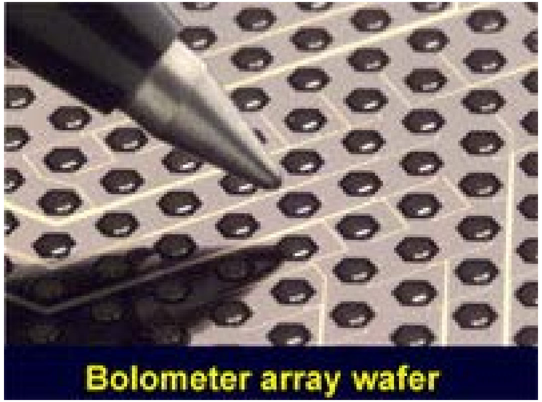


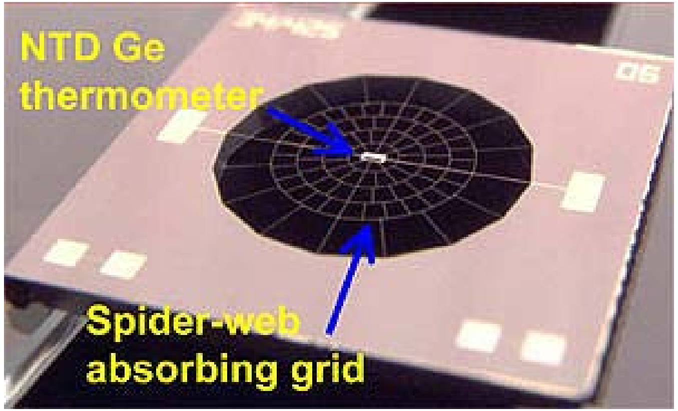
Spitzer



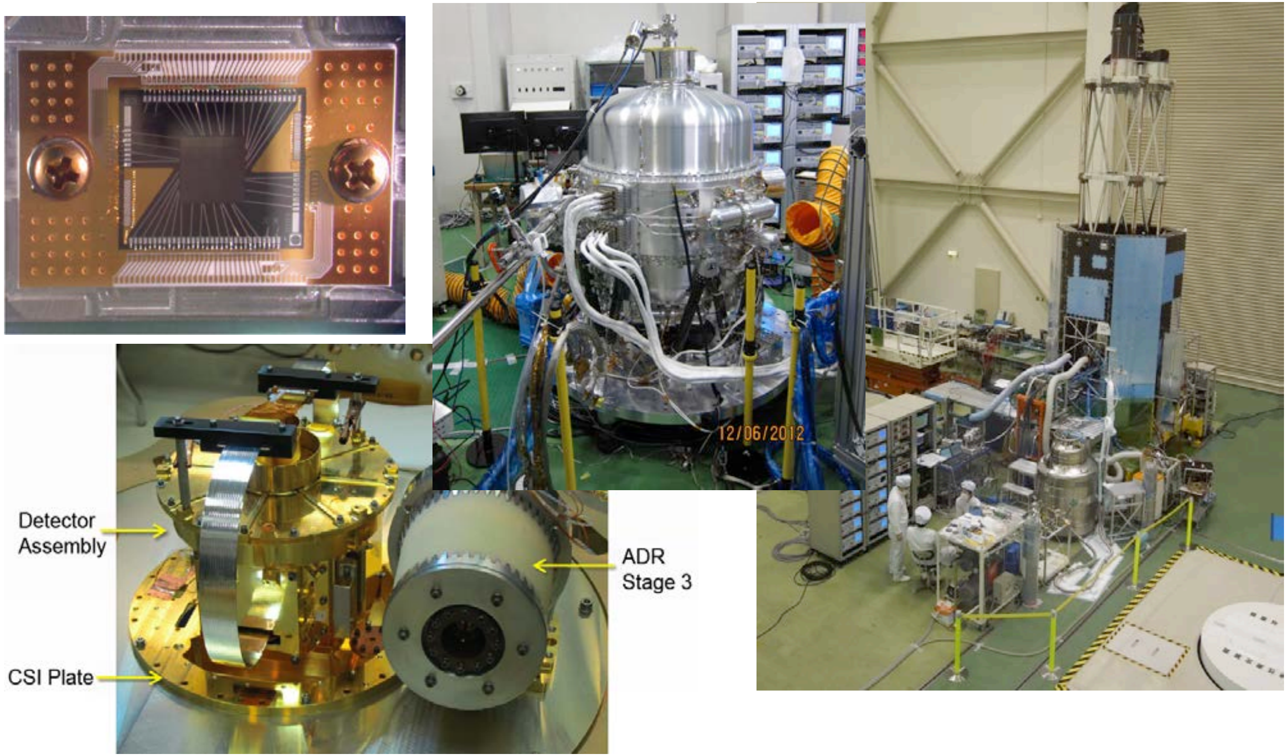
Herschel-SPIRE







Hitomi Cryogenic System



Mid-Far IR Predecessors

Name	Effective Aperture Meters	Wavelength Coverage µm	Temp. (K)	Year
Human Eye	~0.01	0.39-0.75		
IRAS	0.57	5-100	1.6	1983
COBE-DIRBE	0.19	1.7-118	1.5	1985
MSX	0.33	4.3-21	6	1996
ISO	0.60	2.5-240	2.2	1996
Spitzer	0.85	3-180	5.5	2003
Akari	0.68	2-200	1.6	2006
Herschel	3.5	60-672	80	2009
WISE	0.40	3-25	12	2010
JWST	6.5	0.6-28.5	40	2021

How Does OST Differ from JWST?

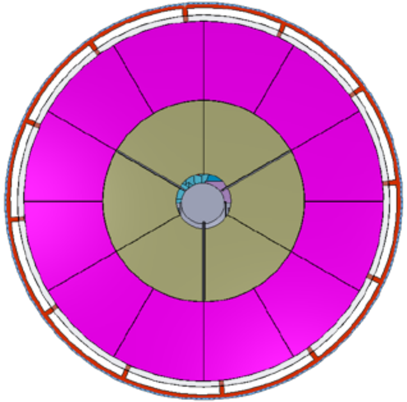
- Wavelength
  - 3-600 μm vs. 0.6-28 μm
  - Temperature of telescope (4.5 vs. 40 K) enables sky-limited performance
- Wide Field of View
- Closed vs. Open Geometry
  - Better at suppressing stray light
  - No optics deployment
- Fast detectors and nimble spacecraft enable mapping of relatively large areas
- Instrument designed specifically for transiting exoplanets
- OST comes later so makes use of potential targets in mid-IR discovered by JWST

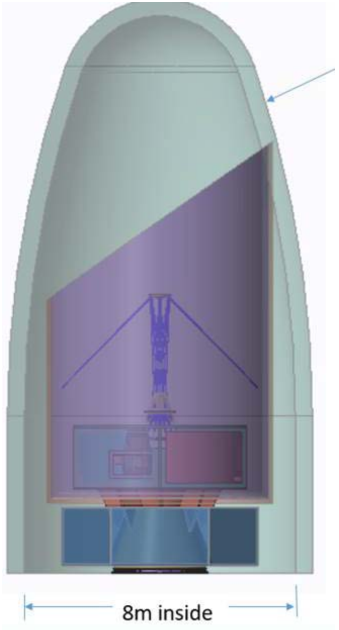
Cryogenic Engineering is Not the Same as Low Temperature Thermal Engineering!

- Properties of materials change
- Be aware of approach to absolute zero
  - Everything (almost!) goes to zero there
- The physics changes
  - Gases condense and freeze, superconductivity appears
- Low temperature physicists make use of these changes
  - Getters for gases, use of superconductivity for sensors, motors, and magnetic shields, etc.

Major Architecture Trades-1

- Telescope size
  - JWST collecting area to capture transit spectroscopy from enough Earth-like planets
- Deployed vs. Non-deployed
  - Non-deployed optics for simplicity
  - SLS (or BFR) required but viewed as less risky than deployment
- On- vs. off-axis
  - On axis for ease of packaging
- Size of primary mirror segments
  - JWST size, but forming circular aperture
    - 18 segment with only two prescriptions
    - Manufacturing facilities exist





Major Architecture Trades-2

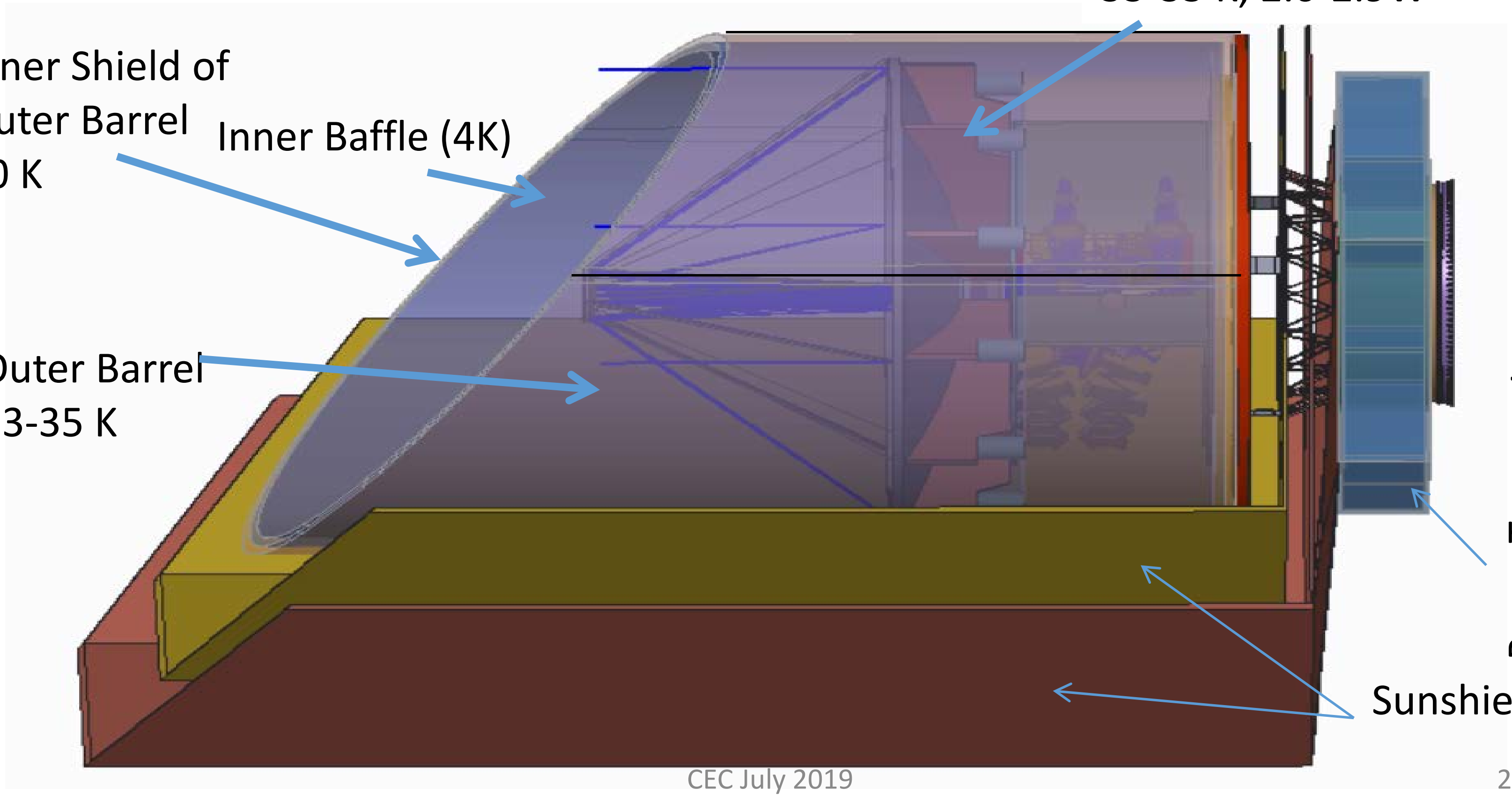
- 3-mirror vs. 2-mirror design
  - 3 mirror allows use of Field Steering Mirror
- Beryllium vs. Silicon Carbide and other materials
  - Beryllium chosen over silicon carbide for mass savings and higher thermal conductivity (isothermal structure and mirrors)
- Instrument Complement
  - OSS (Far IR Spectrometer)
  - MISC (Mid Infrared Transit Spectrometer)
  - FIP (Far-IR Imager and Polarimeter)

Cryogenic Design

- Staged cryogenic system provides immunity to external disturbances
  - 2 layer sunshield (~140 K)
  - Deep space radiator (35 K)
  - 3 stage cryocooler (70 K, 20 K, 4.5 K)
    - Four TRL4-5 cryocoolers in parallel gives 100% margin over current heat loads
    - Higher TRL chosen over larger, somewhat more efficient cryocoolers
      - NASA has 20 years of technology development in this kind of cryocooler
      - Jitter requirement is met with standard soft-mount techniques
  - Nothing warmer on the colder side of a shield
    - Thermal analysis is simpler and more amenable to back-of-the-envelope calculations
  - Use cold amplifiers to bring low level signals to room temperature

Thermal analysis shows > factor of 2 margin at each cooling stage

Thermal Zones



ORIGINS Space Telescope

ACS Driving Requirements

- Absolute Pointing: 0.15 arcsec (OSS, Inertial Point)
- Onboard Pointing Knowledge: 0.15 arcsec (OSS, Inertial Point)
- Jitter: 6 mas RMS > 1 Hz (MISC Transit Spectrometer)
  - MISC will further stabilize using Field Steering Mirror
- Scanning Rate: 60 arcsec/sec (OSS and FIP Large Survey)
  - Definitive (i.e. after ground processing) Attitude Knowledge: 150 mas
  - Onboard pointing knowledge driven by absolute pointing accuracy of 2 arcsec
    - Achievable using only star tracker and gyro

Momentum and Torque Requirements

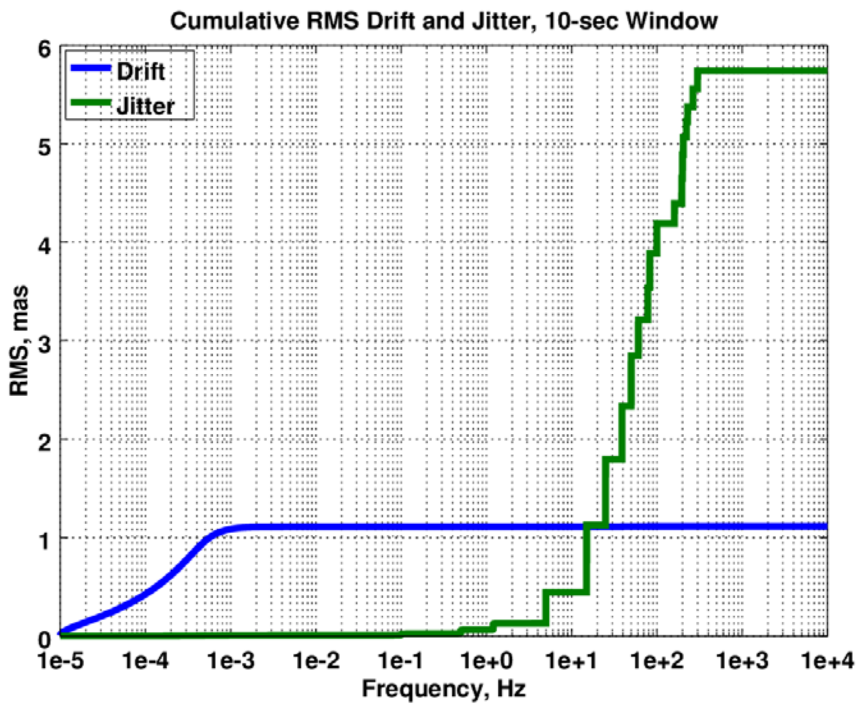
- 13 Nms Storage for Survey
  - 60 arcsec/sec, 45,000 kg-m^2
- 170 Nms Storage for SRP Torque
  - Assuming unload once/day
  - ~14 minutes required to unload 170 Nms at 0.2 Nm
- 0.5 Nm Torque Capability for Survey
  - Allows reversal of raster direction in ~60 sec (for 60 arcsec/sec rate)
- These requirements may be met by a set of 6 HR18-250 reaction wheels
  - 0.2 Nm, 250 Nms each, arranged in "pyramid"
  - Variant models trade momentum for torque capability
  - No CMGs needed

Slew Rates

- Mass properties and wheel complement are comparable to WFIRST
- Max slew rate ~0.12 deg/sec
- 90 deg slew in < 15 minutes
- Assume settle times ~30 sec
  - Solar array flexibility

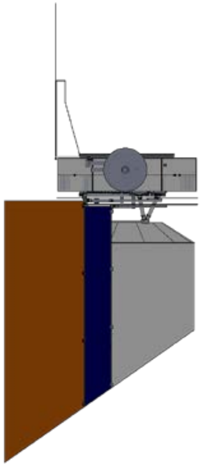
Drift and Jitter for Inertial Pointing

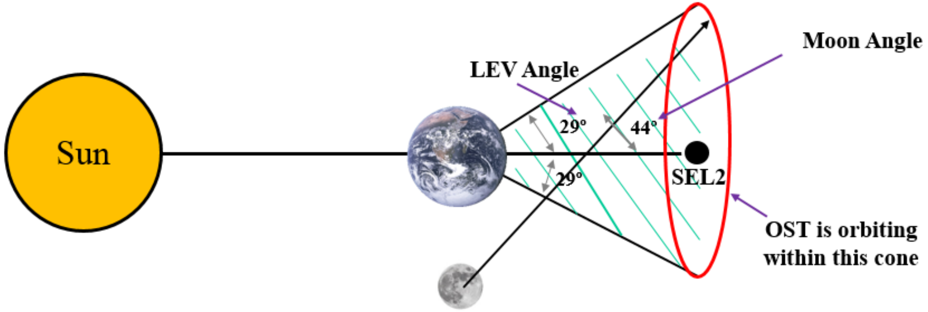
- Assumptions
  - Star Tracker NEA 2.0 arcsec
  - Field steering mirror
  - Some arbitrary structural modes
- Star tracker noise is largest contributor
- Cryocoolers at 50 Hz are isolated to 0.1 N each
- Other step increases are reaction wheels hitting structural resonances



Field of View and Orbit

- +5/-45° pitch, +/- 5° roll, +/-180° yaw
  - Same as JWST
- Quasi halo orbit at L2
  - Similar to JWST
  - Orbit dimensions chosen to optimize
    - Fuel use to mission operability
  - 20% of time Moon will rise over sunshield in extreme pointing directions





ORIGINS Space Telescope

Sunshield

- Very simple deployment with 4 actuators and spring-loaded mechanisms similar to those used in other deployments on many missions
- Sunshield design minimizes distance between center of pressure and observatory center of mass
  - Decrease fuel and overhead required for momentum unloading
- Deployment can be demonstrated on the ground
  - Test-as-you-fly

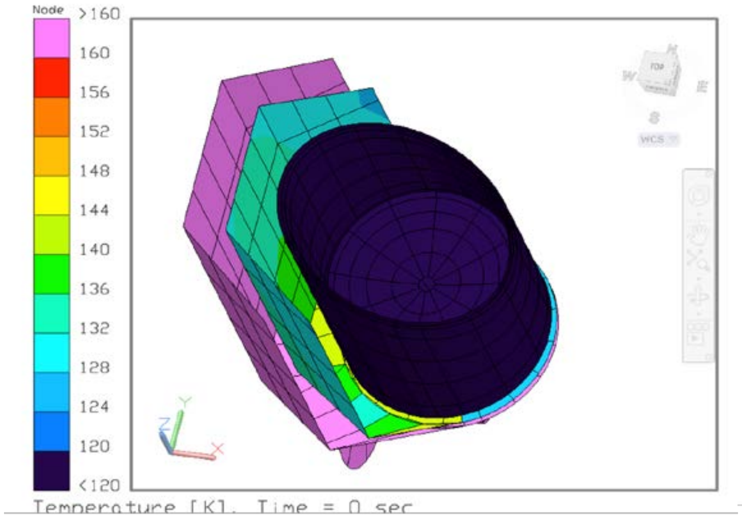
Power, Propulsion, Comm and Data Storage

- 5000 W for Baseline fully margined
  - Requires 20 m^2 solar array
  - Of this 1800 W for cryocoolers
- Biprop maximizes propulsion force per mass and uses high TRL
- Allows mid-course correction pointing toward sun
  - Reflective cover on aperture protects until ejection at ~L+24 hours
- Data rate: ~20 Tb per day
  - Optical comm chosen

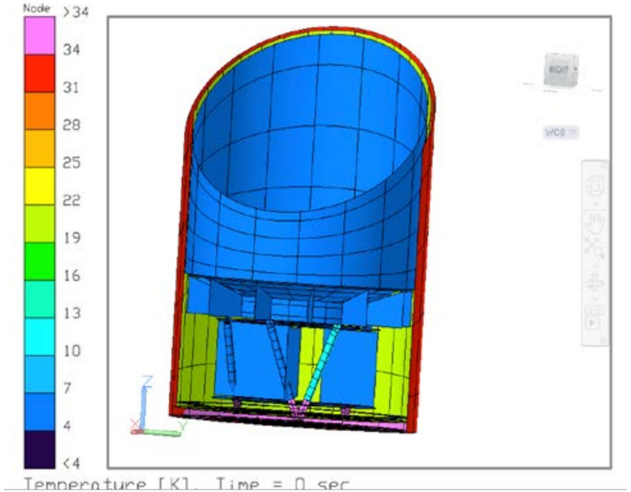
Spacecraft Thermal Analysis

- Power is dissipated by body mounted radiators connected by heat pipes to high power sources
  - Cryocoolers (450 W each x 4)
  - Instrument electronics (OSS ~ 1000 W)
  - However, fixed radiators can handle the full 7654W before descope

Cryo/Thermal Radiation Analysis

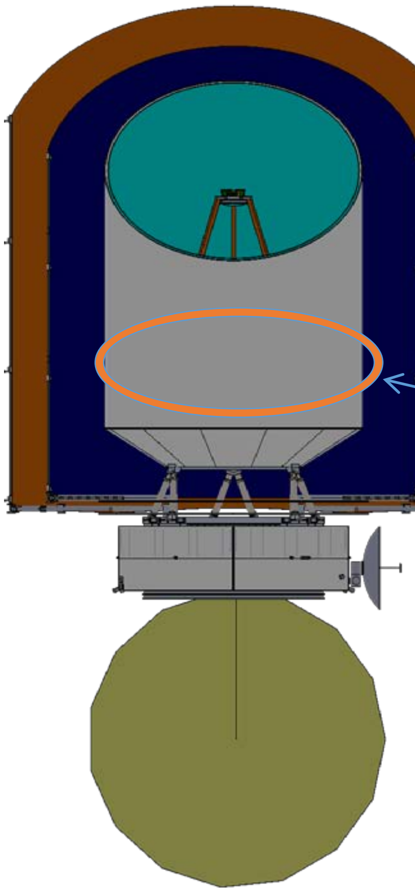


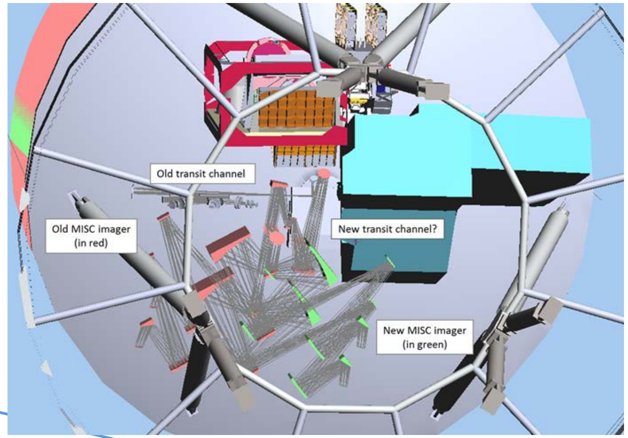
Only two sunshields needed

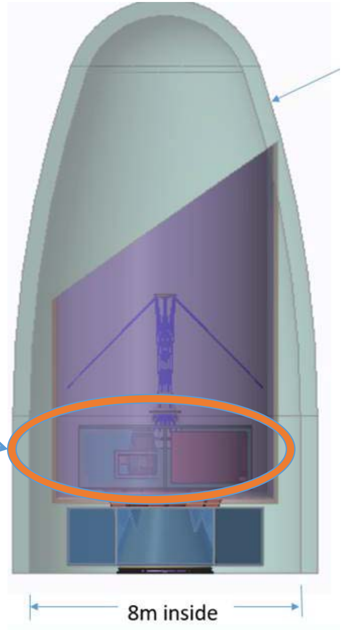


Inside of Barrel lined with Al "sandwich" held at 20 K by cryocooler upper stage

Instruments



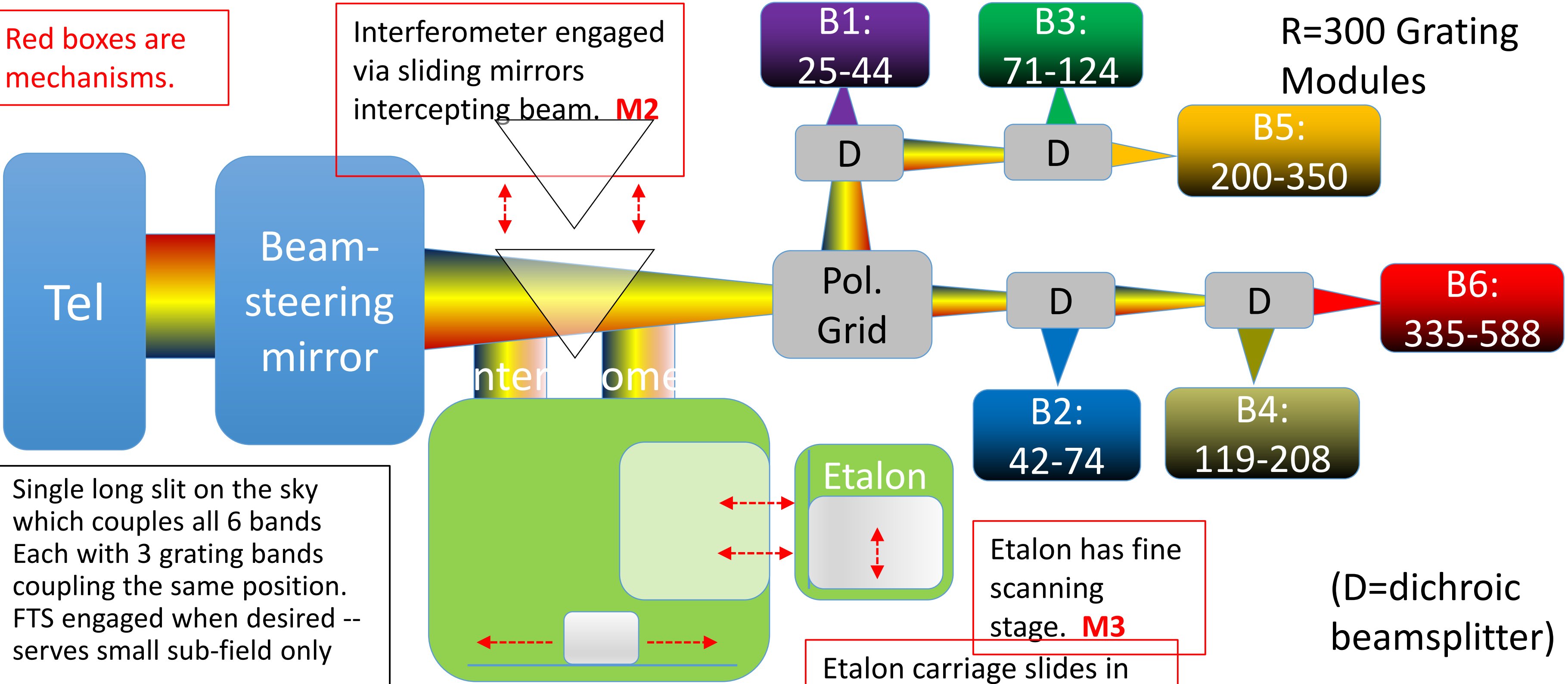




OSS Optical / Functional Block Diagram

Red boxes are mechanisms.

Interferometer engaged via sliding mirrors intercepting beam. **M2**



R=300 Grating Modules

(D=dichroic beamsplitter)

- Single long slit on the sky which couples all 6 bands
- Each with 3 grating bands coupling the same position.
- FTS engaged when desired -- serves small sub-field only

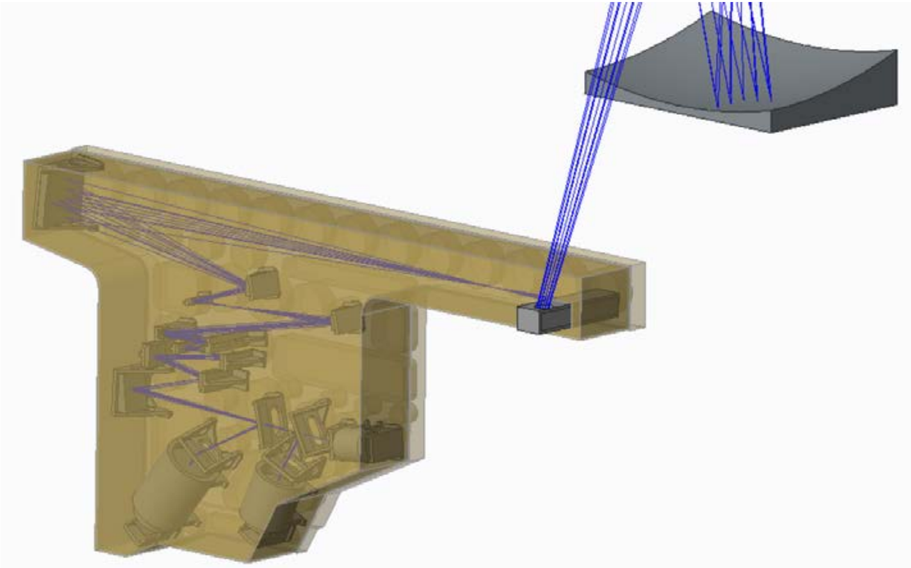
Etalon has fine scanning stage. **M3**

Etalon carriage slides in and out of interferometer beam. **M4**

Interferometer has long scanning stage. **M1**

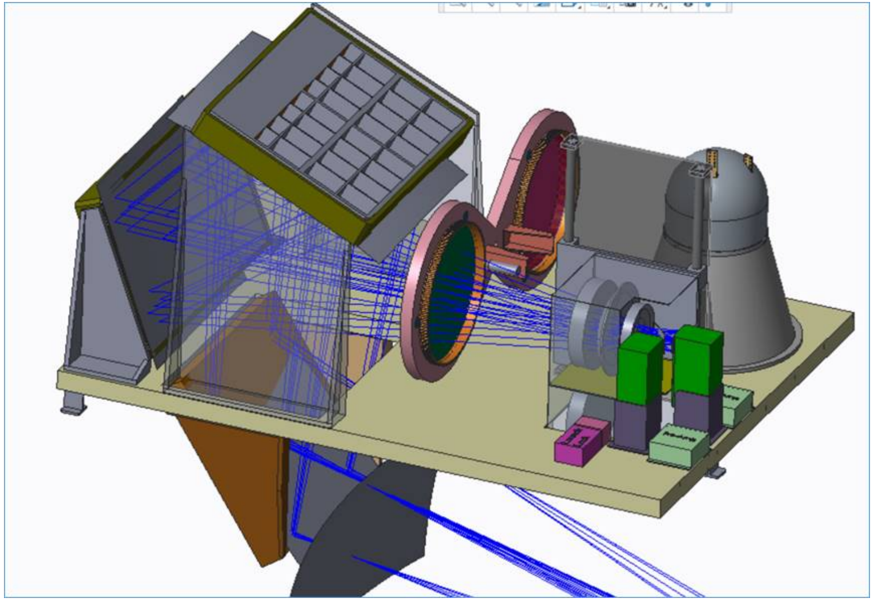
Instrument Description - MISC

- Designed to measure the spectra of transiting exoplanets from 3-28 μm
- Potential up-scope to camera and spectrograph



Instrument Description - FIP

- 12’ x 5’ field of view
- 50 and 250 µm bands
- Can map at speeds up to 60 arc sec/sec
- Can dwell to obtain deep field
- Arrays of 120 x 120 pixels
- Pixel NEP 3 x 10^{-19} W/√Hz



Testing/Verification

- JSC Chamber A, which was used for JWST, is large enough and cold enough to thoroughly test OST
  - 13 m inner diameter
  - Tested to 11 K
  - With software change capable of 10 K
- Full sunshield deployment will also be tested on ground
- Full end-to-end test of entire observatory in thermal/vac is planned – “test-as-you-fly”
- Shorter I&T overall than JWST because intermediate ISIM step is not needed and Infrastructure at Chamber A already exists

Origins Space Telescope

Enabling Technologies for OST

- Far IR Detectors -- FIP, OSS
- Mid IR Detectors -- MISC transit channel
- 4.5 K Cryocoolers -- FIP, OSS, telescope
  - Several qualified vendors (NGAS, Ball, Lockheed,and Creare)
  - SHI 4.5 K cryocooler with required specs has flown on Hitomi
- SubKelvin Coolers -- FIP, OSS
  - Ongoing SAT to develop continuous ADR from TRL 4->6

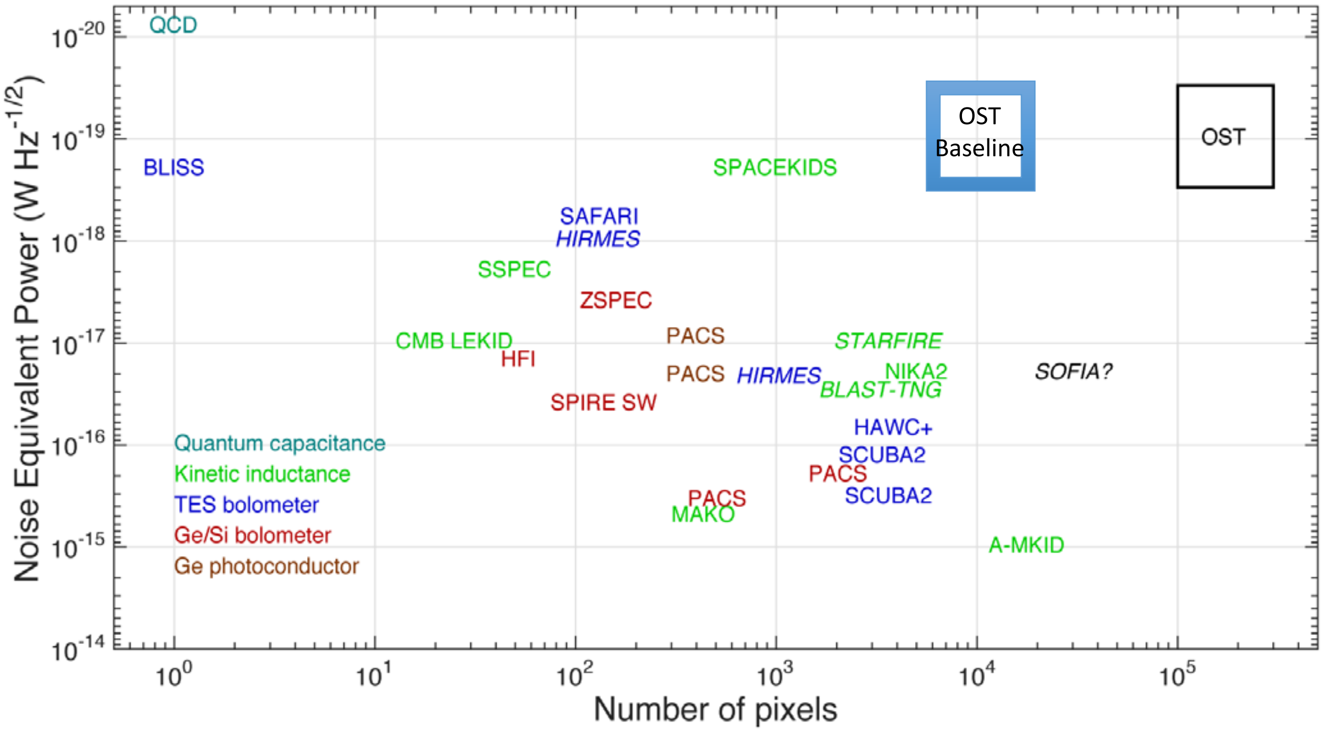
Far IR Detectors

Focal Plane Array

- Require
  - 10^4 scalable to 10^6 pixels with $<3 \times 10^{-19}$ W/√Hz NEP (imaging) (10^4 pixels is enabling)
    - Reduce readout frequencies / electronics power dissipation
  - $<3 \times 10^{-20}$ W/√Hz NEP (spectroscopy) (enabling, OSS) with 3×10^{-21} background limited detection (enhancing)
  - Reaching enabling numbers decreases the observing time by factor of ~100 and increases areal coverage by 10-100 times
- SOA
  - 325 bolometers with 4×10^{-17} W/√Hz NEP (TRL9 Herschel/SPIRE)
  - 5120 pixels with low $x10^{-16}$ W/√Hz NEP (TRL 5 SCUBA 2)
  - Sensitive (NEP low 10^{-19} W/√Hz), fast detectors (TES bolometers, and MKIDs in kilo pixel arrays) are at TRL 3.
- Path to get there: Develop MKID, TES, and QCD detector technologies in parallel

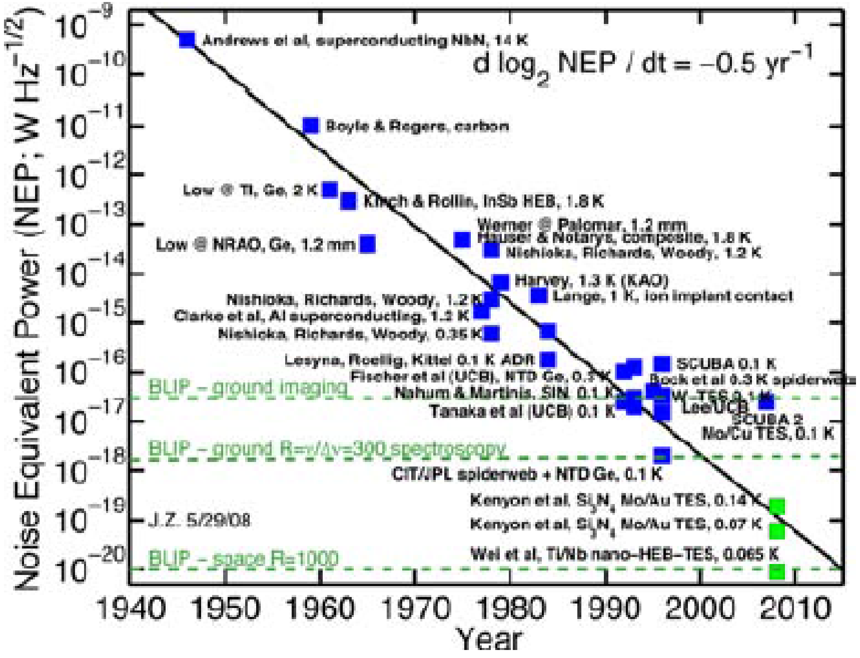
Three technologies offer multiple paths to required resolution and array size.

State-of-the-art NEP and Array Size



Far IR Detector Heritage

COBE FIRAS Bolometer



Far IR Detectors

Multiplexing and Amplification

- Require
  - 4 GHz Bandwidth per 2000 pixels
    - Microwave SQUIDs and/or discreet resonators for frequency domain multiplexing
  - Low dissipation at 4 K (0.3 mW per 2000 pixel amplifier)
- SOA
  - LNF HEMT is commercial part
  - SQUIDs under development at NIST and SRON have demonstrated necessary resonator spacing but for smaller total numbers (<200)
  - LNF HEMT shows proper noise and gain for 0.3 mW/channel
- Path to get there
  - Continue testing SQUID multiplexers and LNF HEMTs
  - X-ray microcalorimeters for Athena and Lynx require similar technology advances

Follow x-ray microcalorimeter SQUID developments and test LNF HEMTs

Far IR Detectors

Room Temperature Readout

- Require
  - Low dissipation at per readout channel
- SOA
  - FPGA requires 40 W per channel
  - Emerging RFSoCs (specialized FPGAs) need ~10 W (mobile phone 5G technology)
- Path to get there
  - Hardware RFSoC codes adapted for our use
  - Follow with ASICs to lower power by another >factor of 4

Leverage 5G technology to lower input power required

Mid IR Detectors

- Require: 5 ppm stability over 1-2 hours
- SOA: 30 ppm (JWST/MIRI), HgCdTe tests
- Path to get there: More HgCdTe testing, develop calibration sources with required stability

Excellent background stability measured in HgCdTe

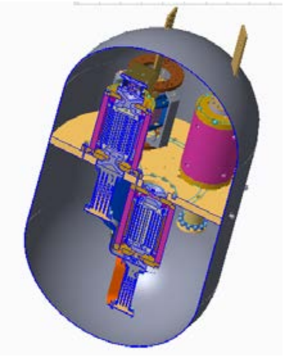
4.5 K Cryocoolers

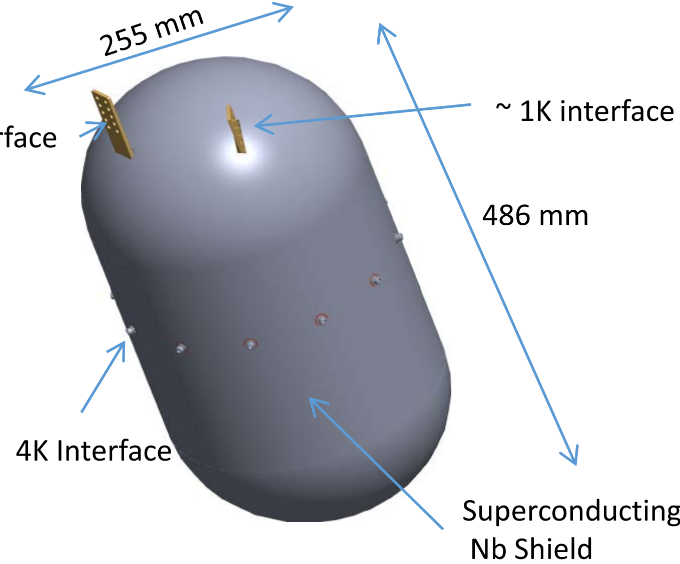
- Require: 200 mW cooling at 4.5 K + 400 mW cooling at 20 K + 20 W cooling at 70 K with input power of 2250 W
  - Includes 100% margin
  - Note that expected cryocooler-induced jitter has been shown to be not an issue even for the most sensitive instrument, MISC
- SOA: MIRI cooler has 65 mW cooling at 6 K + 203 mW cooling at 18 K 425 W input power
- Sumitomo cryocooler provided 50 mW of 4.5 K cooling on Hitomi
- Path to Get There: use 4 MIRI coolers with ^3He as working fluid (to reach 4.5 K) or use Ball, Lockheed, or Creare coolers

Multiple manufacturers with TRL 4+ technology offer multiple paths to success

Sub-Kelvin Coolers

- Require: 6 µW of cooling power at 50 mK
- SOA: 0.4 µW@ 50 mK demonstrated on orbit by Hitomi. Lab demo 6 µW@50 mK of cooling power at TRL4. Electronics at TRL 6 (same cards have flown)
- Path to Get There: SAT-funded development to achieve TRL 6 for a continuous ADR cooling to 50 mK with 6 µW of cooling power. Use same electronics as Hitomi.





TRL 4 demonstrated, TRL 6 funded for 2019 demonstration. High cooling power at lower T also provides another path for meeting Far IR NEP resolution in TES.

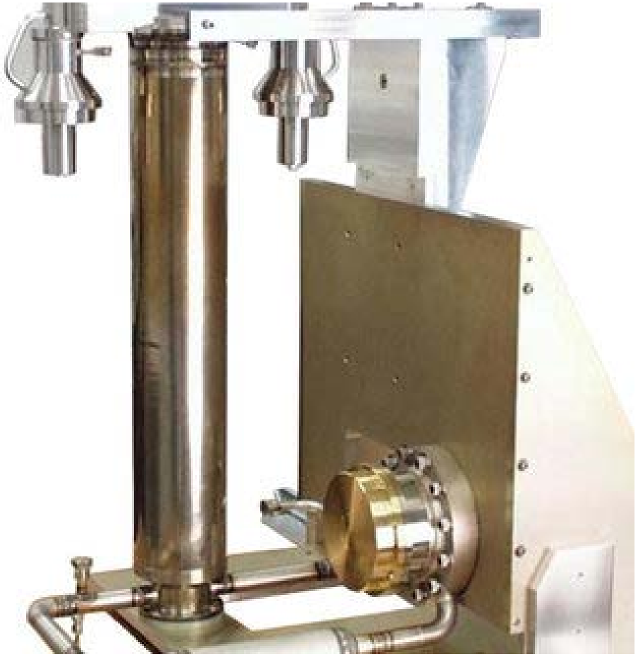
Summary

- OST addresses three astrophysics themes:
  - How does the universe work? (“the rise of metals”)
  - How did conditions for life develop? (“follow the water”)
  - Are we alone? (biosignatures in transiting exoplanets)
- OST’s architecture is simple, and is “test-as-you-fly”
- Cooling technology has rapidly evolved
  - Sub Kelvin cooler will be TRL 6 by 2020
  - 4.5 K cryocooler will be TRL 5-6 by 2025
- Detector technology has a clear path to be ready by 2025 (Start of Phase A)

Back Up

NICMOS and MIRI Coolers

HST/NICMOS Cryocooler



JWST/MIRI Cryocooler

JT Stage Heat Exchanger

Compressors