SINGLE-APERTURE FAR-INFRARED SPACE TELESCOPES

CONCEPTS for MAJOR FIR SPACE MISSIONS

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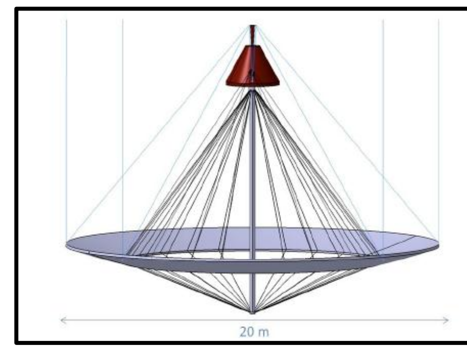
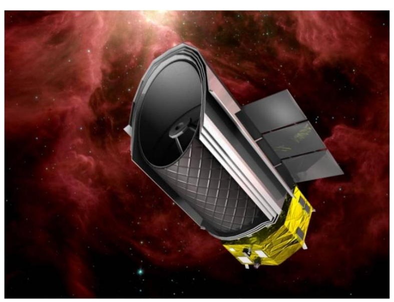
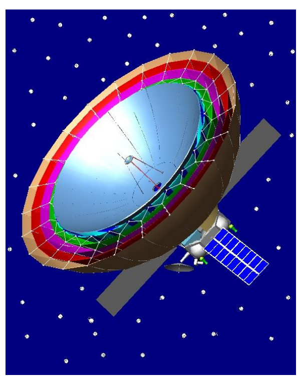
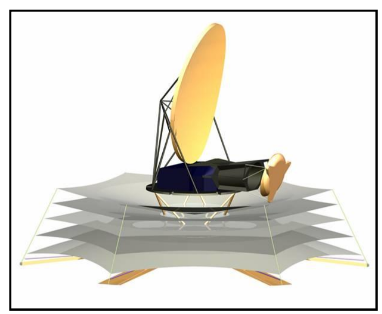
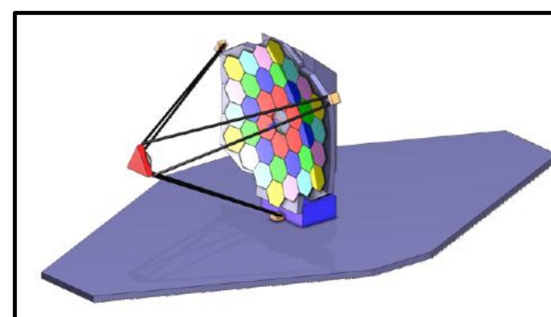








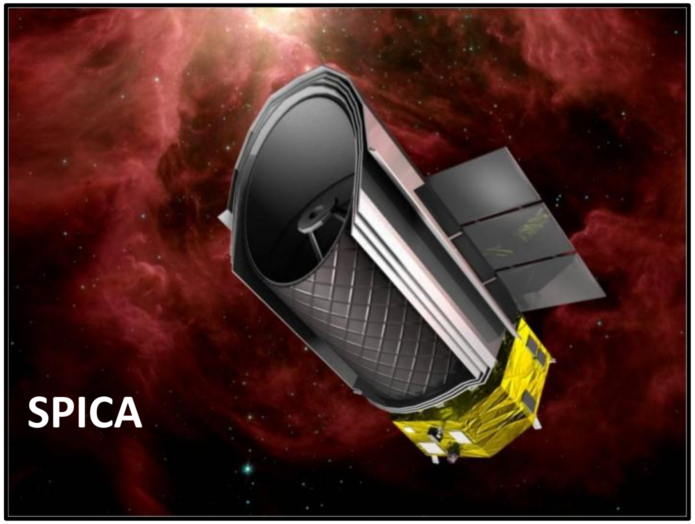


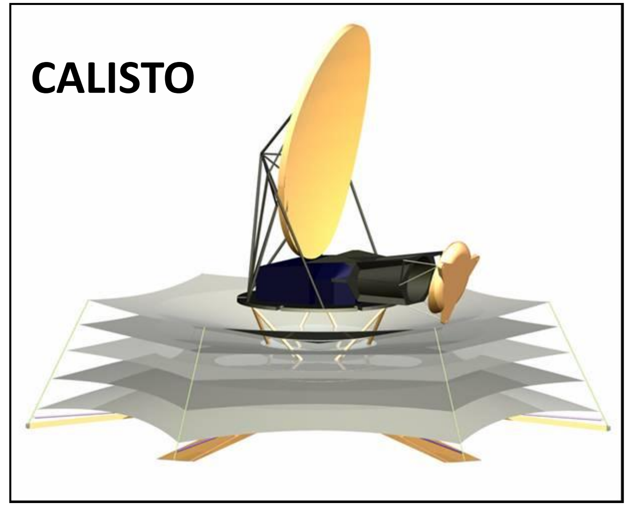
Question: What is the justification for a major far-infrared space mission?

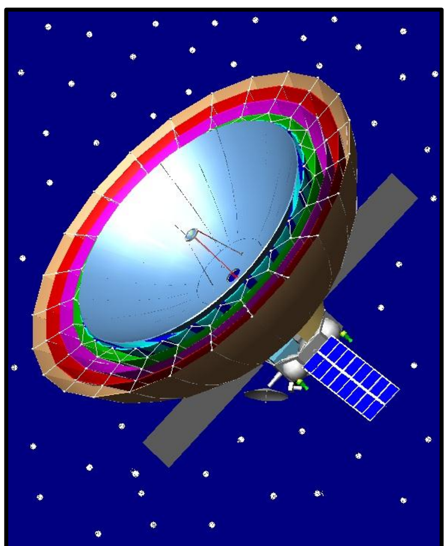
Answer: Address a significant scientific question that can *only* be answered with data from an instrument in space

- Observing at a frequency that is blocked by the atmosphere
- Carrying out a survey that can only be done from space
- Utilizing unique capability of location of space observing platform

These 3 Concepts for Single-Aperture Far-Infrared Space Missions With Low-T (< 6 K) Optics are Being Developed

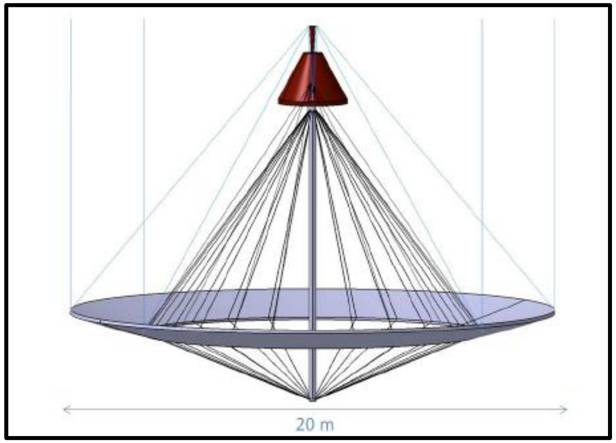






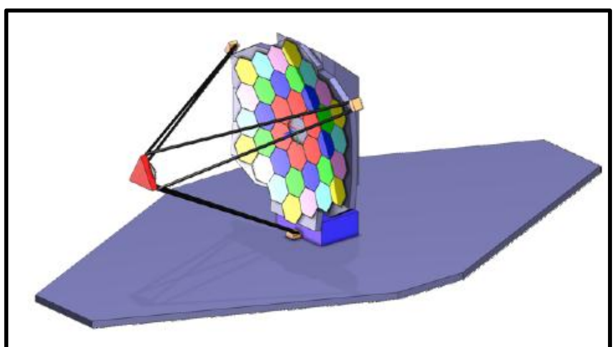
MILLIMETRON (MMSO)

Concepts for Large Aperture/Specialized FIR Missions



TALC

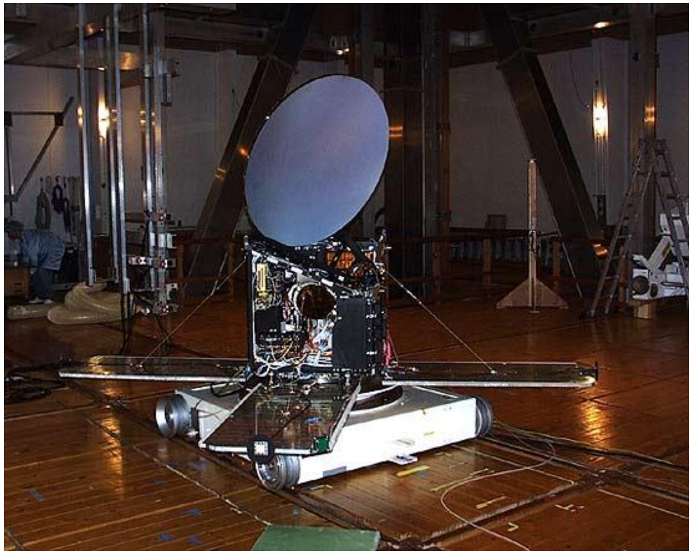
Thinned Aperture Light Collector



OSSO

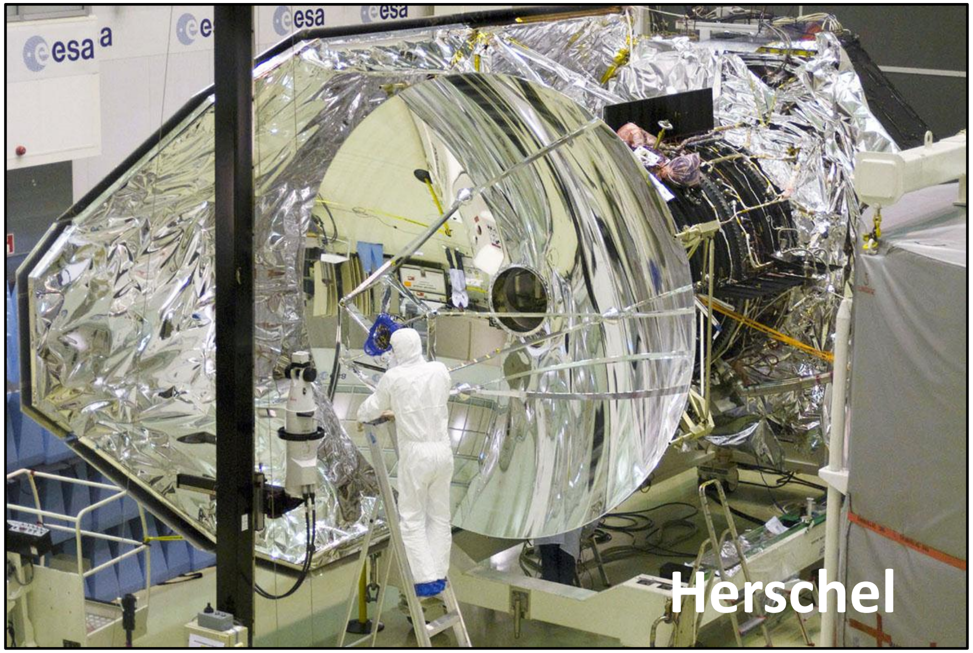
Orbiting Submillimeter Spectroscopic Observatory

Context (1): Small Satellites for Far-Infrared (Spectroscopy)

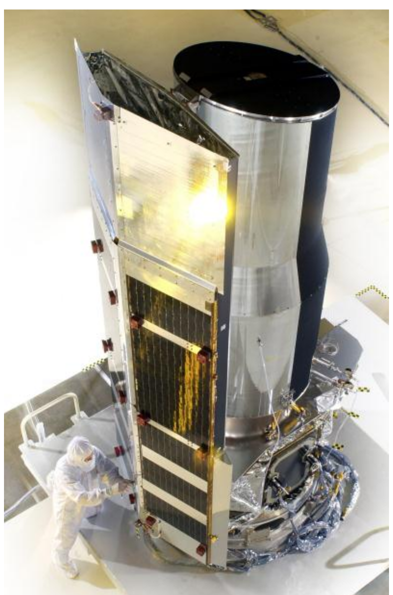


SWAS **Odin**

Context (2): Observatories with Major Impact on FIR Astronomy



Spitzer



Planck

Context (3): Suborbital FIR Facilities

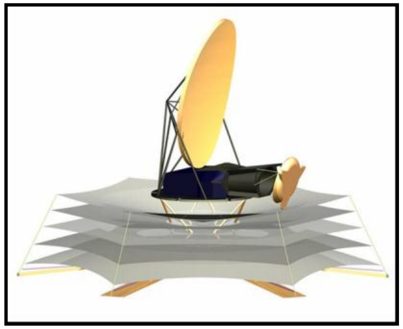
Kuiper Airborne Observatory (KAO)
91.5cm telescope
1974-1995

Stratospheric Observatory for Infrared Astronomy (SOFIA)
NASA/DLR
2.5m telescope

More information on SOFIA in talk by E. Young

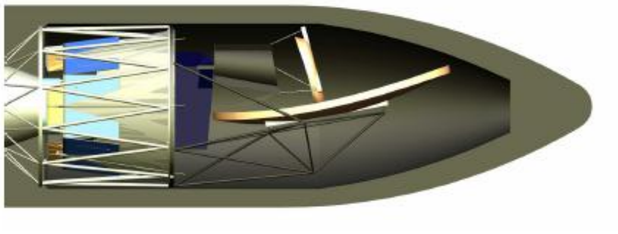
Information on balloons in talk by C. Walker

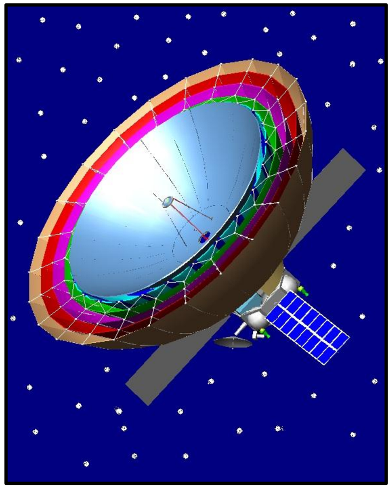
Three Concepts for Cold Single Aperture Far-Infrared Space Missions



CALISTO

NASA concept deriving from 2005 SAFIR study 4m x 6m to 30 μm

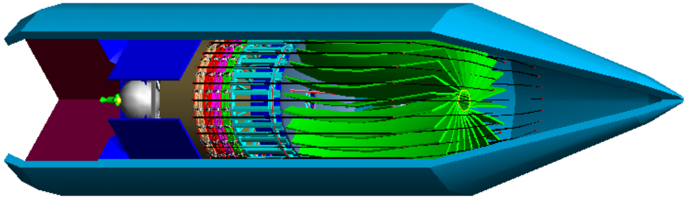


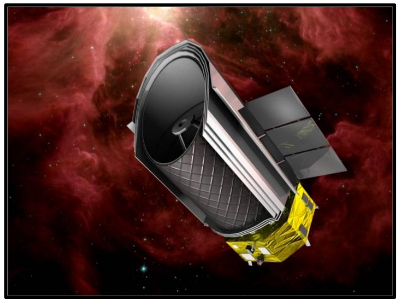


MILLIMETRON (MMSO)

Astro-Space Center of Lebedev Physical Institute (Moscow) with involvement of SRON and Italy (Space Agency & Univ. Sapienza, Rome). Launch 2019+ 10m to 50 μm

MM & SubMM VLBI with ALMA & other ground-based telescopes





SPICA

JAXA Mission with major ESA involvement (telescope; SAFARI instrument). Additional information in talk by M. Bradford

All of above have optics cooled to < 6 K, use cryocoolers, and operate at L2

CALISTO INSTRUMENTATION

- **CAMERA: 4 sub bands covering 30 µm to 251 µm**
– 4096 pixels each

- **MED-RES SPECTROMETER: 4 sub bands**
– **grating or WaFIRS technique with 4 spectrometers per sub band**

Wavelength	Resolution	N_{pix}	Slit (“)
30 – 51	2000	12,000	1.4
51 – 87	2000	12,000	2.3
87 – 147	2000	12,000	4.0
147 – 251	1500	9,000	6.7

(Also considering having many more spatial pixels with lower resolution; ~ same total # of detectors;; M. Bradford’s talk)

- **HIGH-RES (Heterodyne) SPECTROMETER**
  - Focus on key transitions of H_2O and fine structure lines of C+, N+, OI with 16-pixel arrays
  - 557 GHz, 1126 GHz, 1460 GHz, 2000 GHz, 4700 GHz with ±10% tunability

MMSO INSTRUMENATION

- Short-wave Array Camera Spectrometer (SACS)
  - 4 camera bands: 70, 125, 230, 372 μm
  - long-slit grating spectrometers 50 – 450 μm; R = 500-1000
- Long-wave Array Camera Spectrometer (LACS)
  - 4-band FTS optimized for S-Z observations R ~ 500

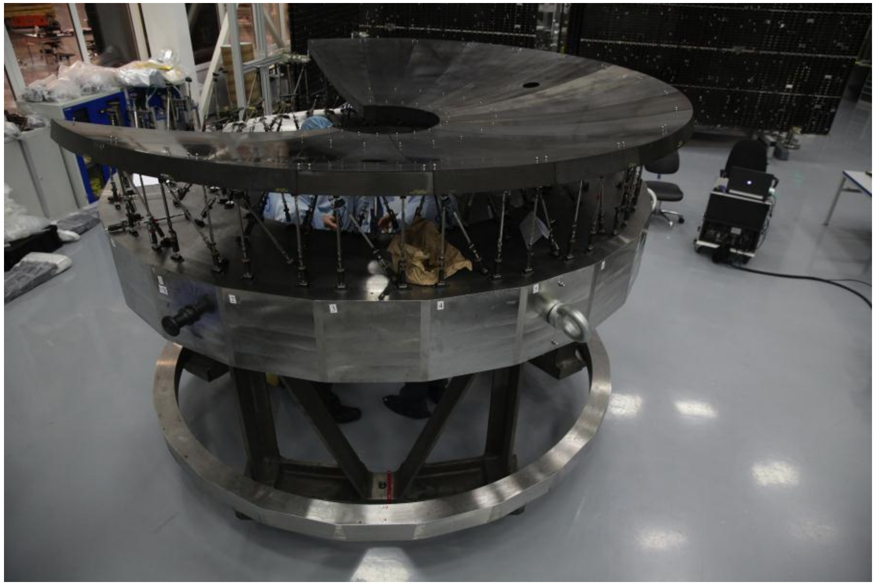
λ-range(μm)	3000-1500	1500-850	840-450	450-300
FWHM (")	42	22	12	7.5
# pixels	6	9	25	36

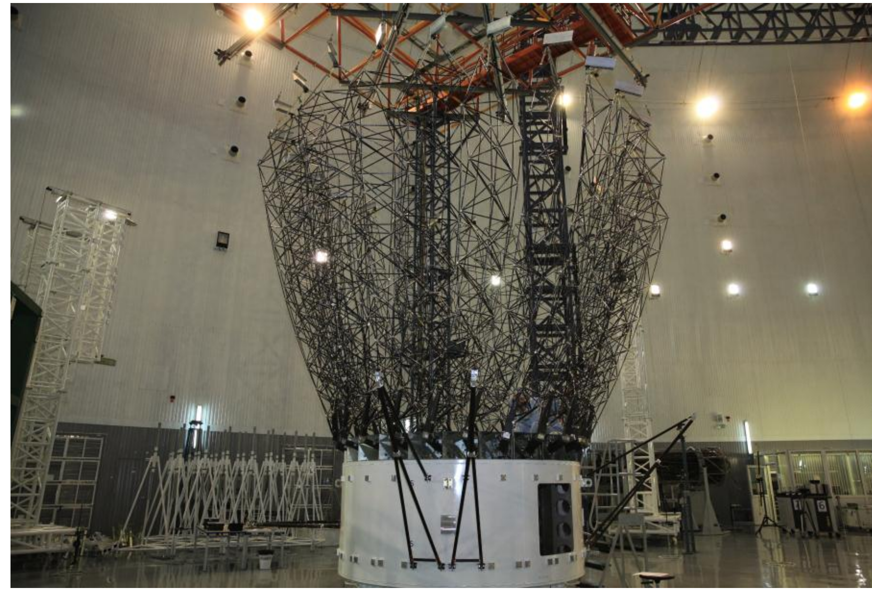
- Millimetron Heterodyne Instrument for the Far-IR (MHIFI)

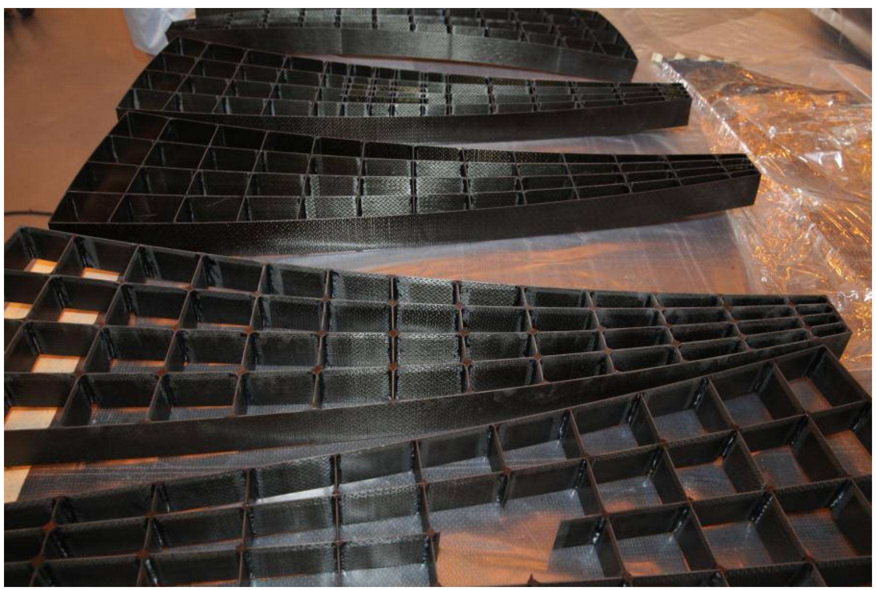
  550- 650 GHz (3 pixels)   950-2100 GHz (7 pixels)

  2450-3000 GHz (7 pixels)   4760-5360 GHz (7 pixels)
- Space VLBI; single pixel dual polarization HEMT/MMIC & SIS
  - 18-26; 33-50; 84-116; 211-275; 275-355; 602-720 GHz

Millimetron Development







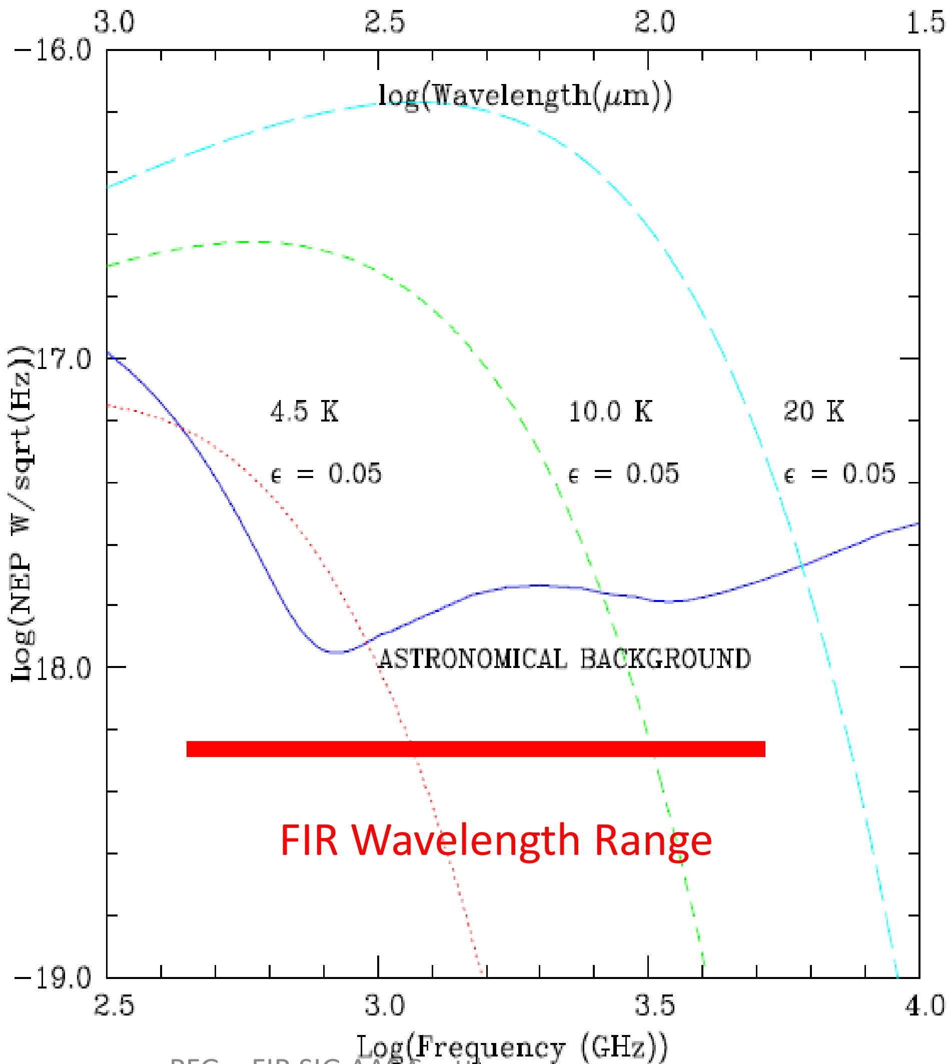
Astronomical Background Limited Observations

Requirement #1 : cool optical system to reduce contribution to NEP below that from the background

Astronomical background at North Ecliptic Pole (minimum)

Noise Equivalent Power (NEP) in δν/ν = 1 fractional bandwidth

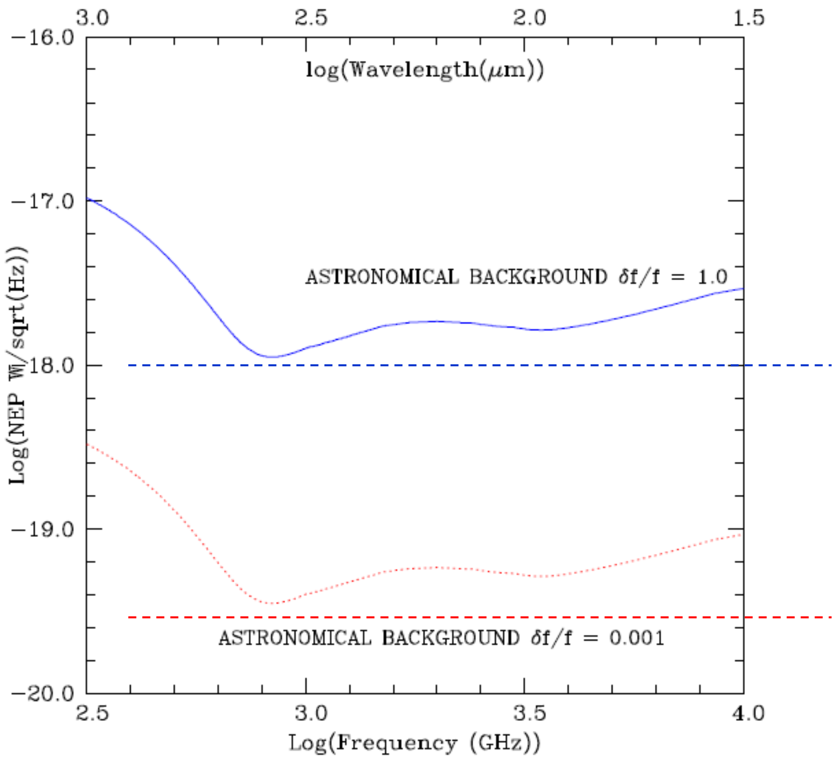
T < 4.5 K ε = 0.05 (total) optics required to have astronomical background determine system NEP for λ ≤ 300 μm



Astronomical Background Limited Observations

Requirement #2: Reduce detector NEP to less than astronomical background NEP (or at least get close)

This is difficult for broadband detectors and very challenging for spectrometers ($\delta v/v = 0.001$) since NEP varies as $\delta v^{0.5}$

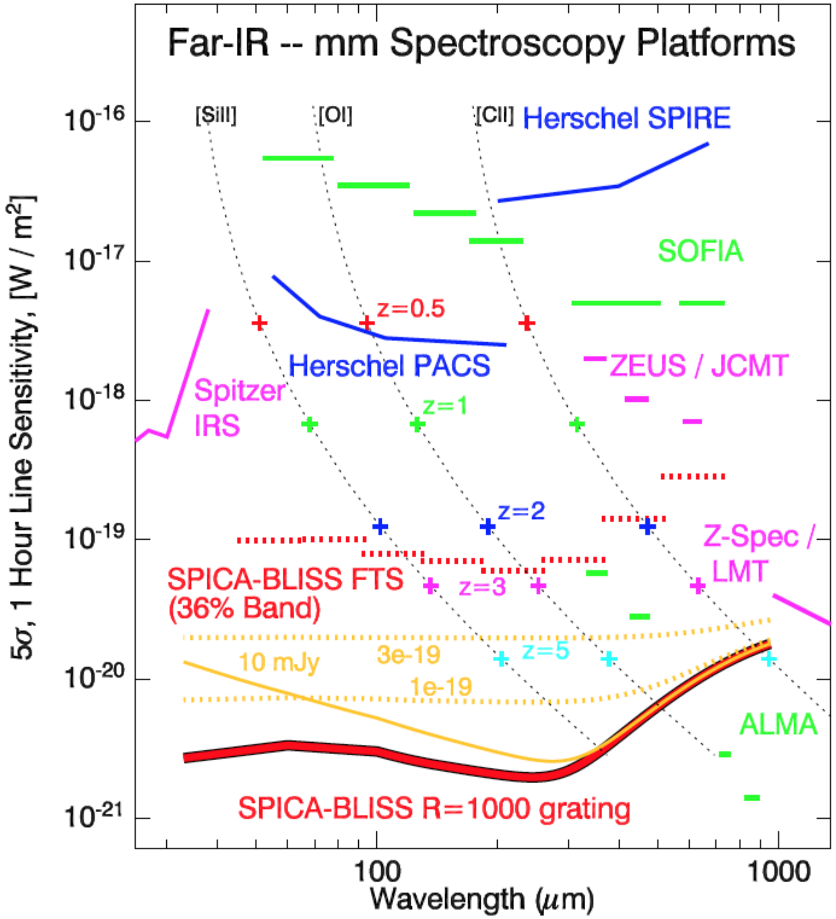


Astronomical background NEP levels for different fractional bandwidths

1×10^{-18} W/√Hz

3×10^{-20} W/√Hz

With sufficiently low noise detectors and a cold telescope you are in great shape for photometry and low/med resolution spectroscopy



From Bradford SPIE 2006

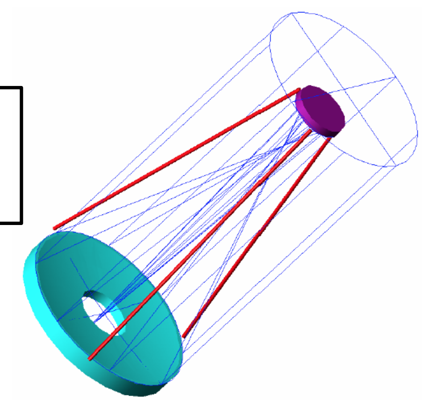
Every major FIR mission presentation has a figure like this one!

CAVEAT EMPTOR!!

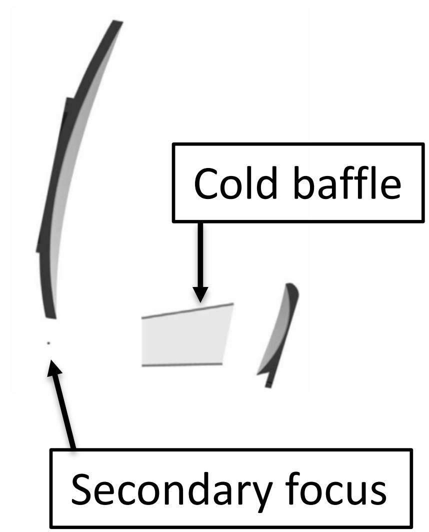
Generally assume cold telescope with negligible emission
"Goal" sensitivity or noiseless detectors
Minimum (or no) astronomical background

Achieving Astronomical Background Limit Operation – Impact on Telescope Design

Typical symmetric telescope SAFIR geometry

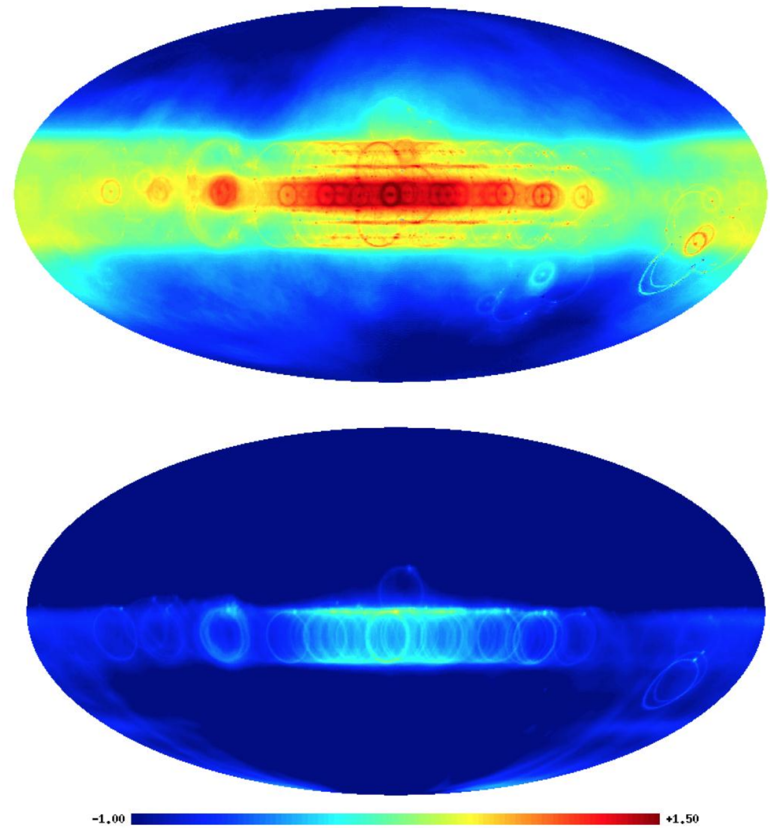


Unblocked (off axis) CALISTO design with cold baffle at image of primary



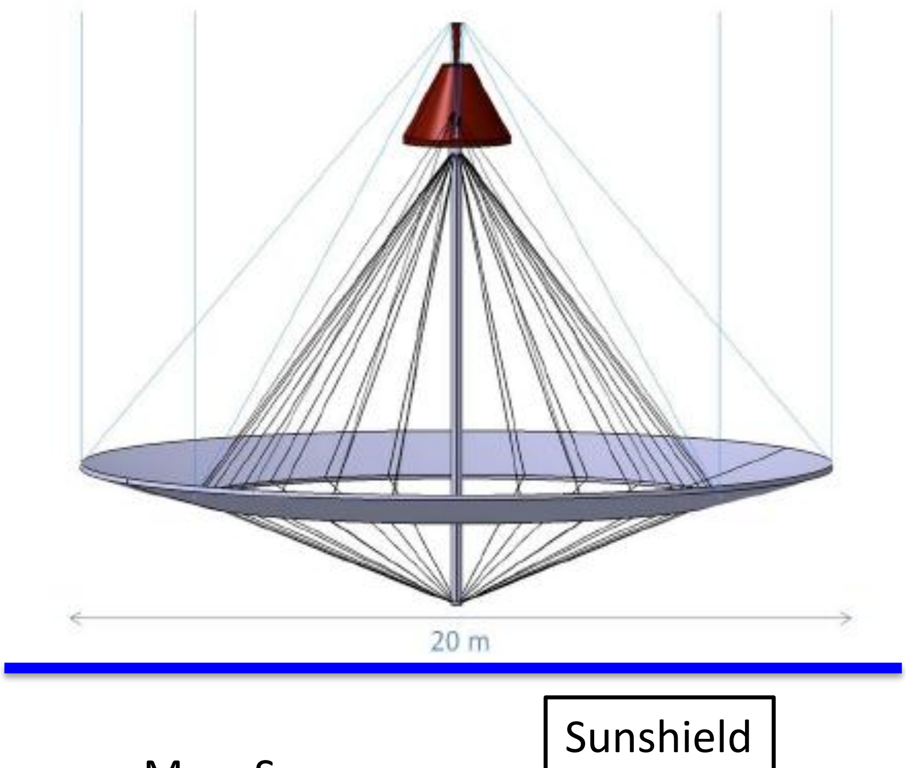
Limiting NEP α [power collected]$^{0.5}$

Dramatic reduction of pickup from Galactic plane – **most of the sky is DARK**



Log(I_{100}μm/MJysr^{-1})

TALC - *T*hinned *A*perture *L*ight *C*ollector



Marc Sauvage
CEA Saclay (France)

Key Features:

20 m diameter "thinned" aperture
Operate to 100 µm wavelength
Collecting area = 20x Herschel
Beam size equal to that of 27m filled aperture
$\Delta\theta = 0.9''$ @ 100 µm
Elegant deployment scenario
Ariane 5 launch vehicle

Significant Open Questions:
Impact of PSF
Thermal behavior of telescope
 V-grove sunshade; 80 K temperature
 at L2 (similar to Herschel)
 uniformity?
Instrumentation
Illumination of thinned aperture

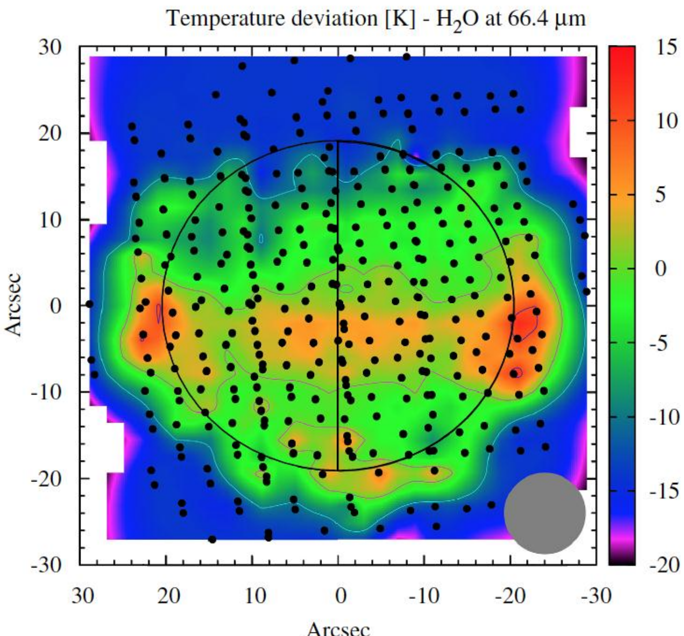
Considerations for FIR Spectroscopic Observatory

There is a major divergence in technology for a space observatory making continuum/low resolution observations and one doing FIR high-resolution spectroscopy

- For the former, as discussed above, a cold (< 6 K) telescope allows enormous improvement (compared to e.g. *Herschel*) and background-limited performance is within reach. This approach is adopted for 3 missions discussed
- For the latter, optics temperature is not important since emissivity is only few % adding only few to 10's of K to system noise temperatures of 100's – 1000 K. The only way to significantly improve sensitivity is to have (1) larger telescope and (2) array receivers (for extended sources)

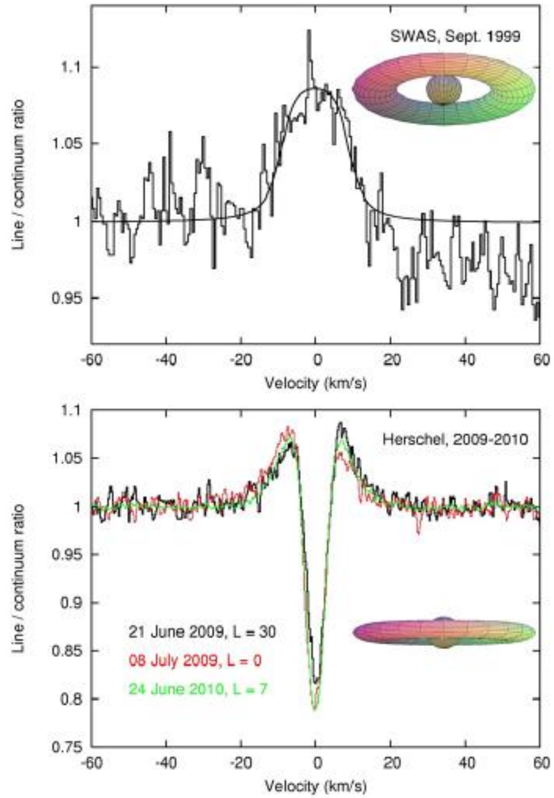
An uncooled (or passively cooled) LARGE telescope for high resolution (heterodyne) observation deserves consideration as it may not be overly expensive. Heterodyne detector systems are also much less demanding in terms of cooling (15 K or 6 K adequate, compared to sub-K for direct detectors)

Water Throughout the Solar System

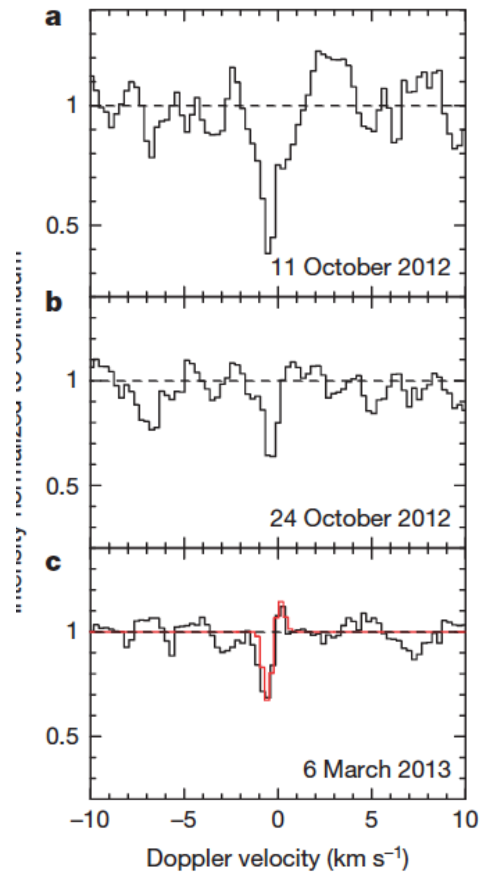


In Jupiter's atmosphere
Cavalié et al. (2010)
Herschel/PACS

Comet Shoemaker
Levy impact July



In **Saturn's moon Enceladus**
Hartogh et al. (2011)
557 GHz 1_{10}-1_{01}

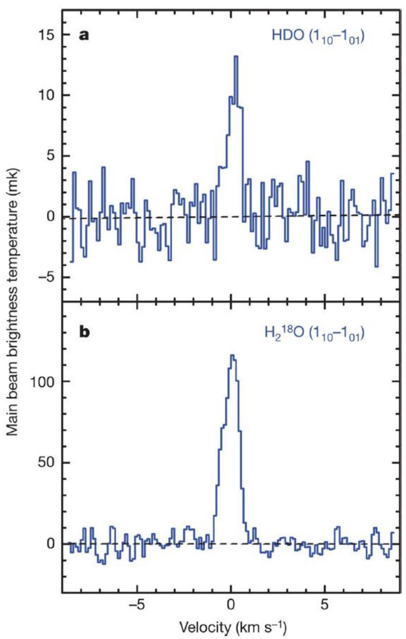


In **dwarf planet Ceres**
Küppers et al. (2014)
Herschel/HIFI 557 Ghz

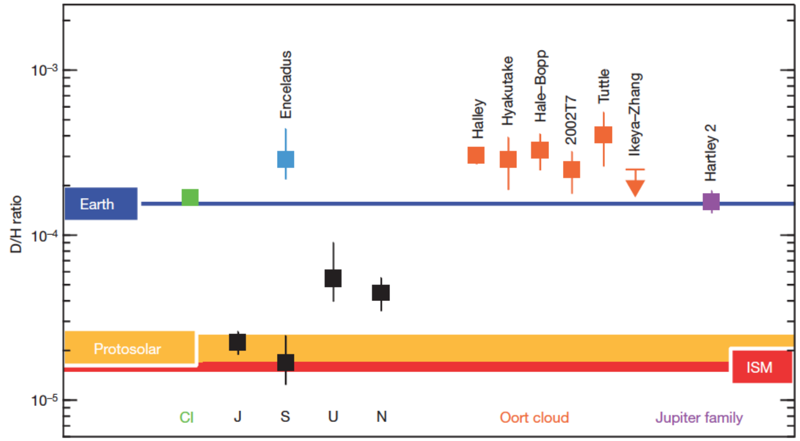
Water and Heavy Water in Comets: Origin of the Earth's Oceans (?)

Narrow lines require high spectral resolution

Deuterated Water
Comet 103P/Hartley 2

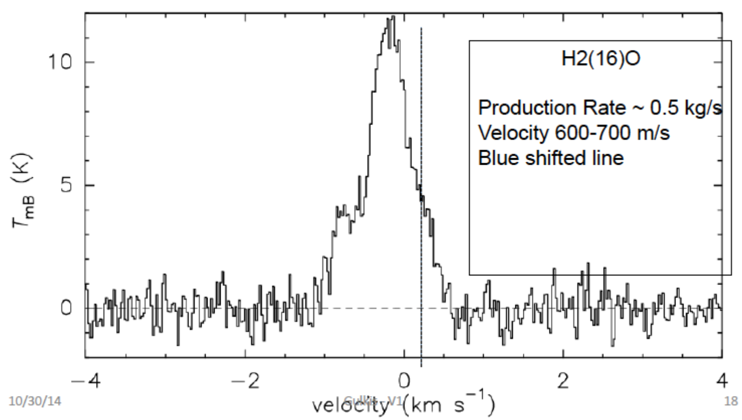


Hartogh et al. (2011)



>10,000 AU
P ~ 10,000 yr

Kuiper Belt
P<20yr



D/H ratio varies significantly within the solar system
Earth's D/H ratio does NOT match that of Oort Cloud (very distant) comets

D/H ratio **DID** match that of first Jupiter-Family Comet observed in water

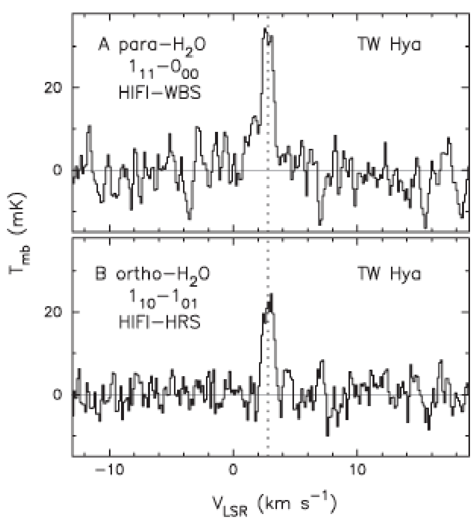
Ground state (557 GHz) water line in comet C.-G. measured by ROSETTA spacecraft on 6 July 2014
Different D/H ratio!

Hartogh et al. (2011)

Water is a Key Molecule Throughout Critical Regions of ISM

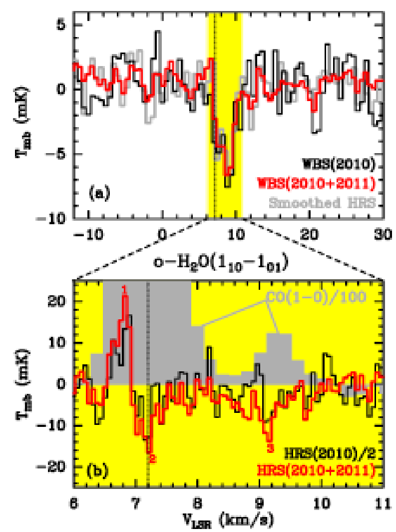
- Diffuse Clouds – unravel gas-grain chemistry
- Shocks and Photon Dominated Regions (PDRs)
- Collapsing cores forming New Stars – major coolant and tracer of central velocity field
- Protostellar Disks – The ``snow line'' and water in forming planets

Protostellar Disk TW Hya



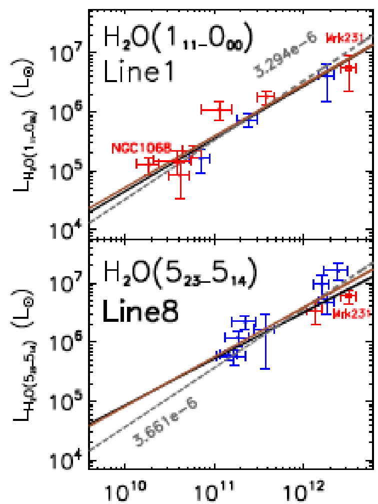
Hogerheijde et al. 2011

Protostellar Core L1544



Caselli et al. 2012

Nearby IR Galaxies



Yang et al. 2013

OSSO

Orbital Submillimeter Spectroscopic Observatory

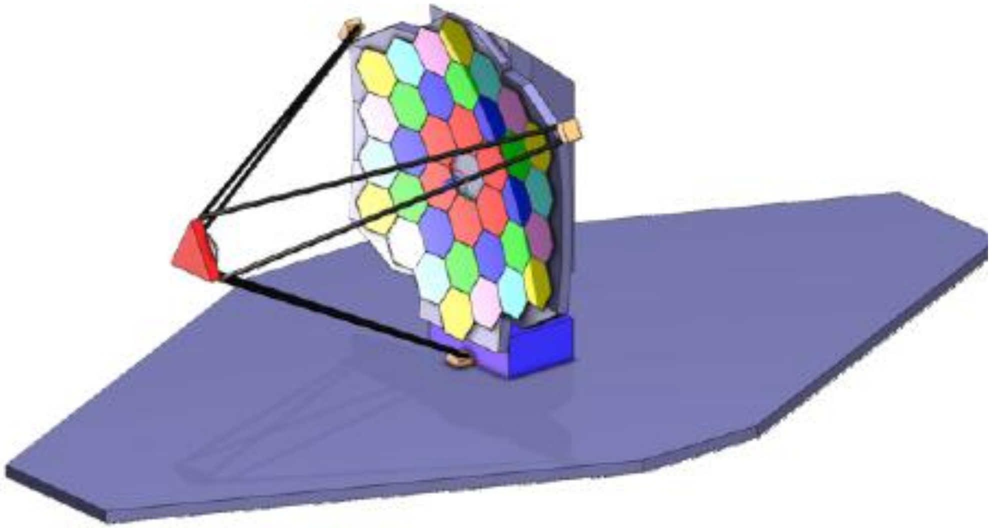
- Observe lowest water transitions between 500 GHz and 1100 GHz (650 µm – 270 µm) with heterodyne system offering better than 1 km/s velocity resolution
- **Collecting area an order of magnitude greater than that of Herschel**, allowing study of representative sample of asteroids, comets, cloud cores, outflow regions, and protostellar disks
- Include broadband **focal plane array receivers** to accelerate imaging of extended sources

KEY QUESTION: How do you get habitable planets?

KEY SCIENCE GOAL: Trace water from the solar system to distant star-forming regions

- Possibly include selected other lines of critical importance for which high spectral resolution is also required – [CII] 158 µm, HD 112 µm
- Possibly include higher water lines for study of more active regions

Orbiting Submillimeter Spectroscopic Observatory (OSSO)



SPACECRAFT & TELESCOPE DESIGN

1000x Longer wavelength than JWST
Optics temperature NOT critical

36 ~1.2m hexagonal panels
    Composite aluminum / CFRP construction (LDR heritage)
    CFRP space frame

Folds with two hinges and fits into FALCON 9 LV (5.2m dia)
Mass estimate: 7000 kg (comparable to JWST)

Considerable JWST heritage in (simpler) sunshade and
    secondary deployment

Under study: orbit; panel alignment and control; instrument
    complement; upper frequency limit vs. cost