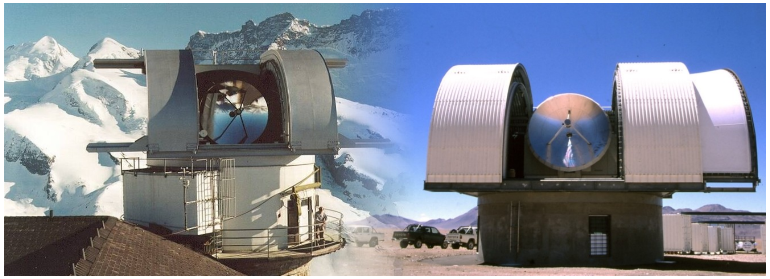
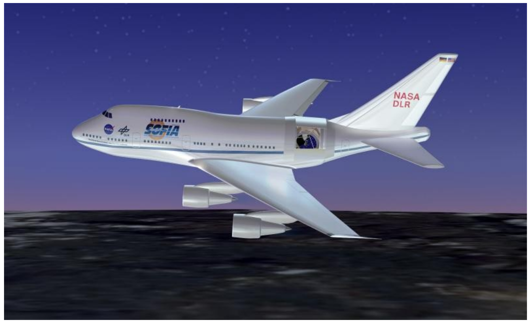
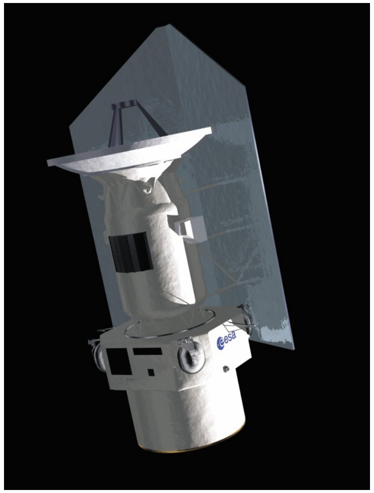
FIR/submm astronomy: science, observatories, and perspectives for lunar observatory



Prof. Jürgen Stutzki

I. Physikalisches Institut der Universität zu Köln
Kölner Observatorium für Submm-Astronomie
(KOSMA)





Co-PI Heterodyne Instrument for the Far-Infrared (HIFI)/
ESA cornerstone mission Herschel

Co-PI German Receiver for Astronomy at Terahertz frequencies (GREAT),
SOFIA Terahertz Array Receiver (STAR)
Stratospheric Observatory for Infrared Astronomy (SOFIA)

PI NANTEN2/KOSMA Submm Observatory, Pampa la Bola, Chile

FIR/submm astronomy: science, observatories, and perspectives

the electromagnetic spectrum: the Far-IR spectral range

- science topics
- astronomy and instrumentation

present missions: operational and/or implemented

- ground: APEX, NANTEN2, ALMA
- airborne: SOFIA
- spaceborne: Herschel

perspectives and limitations

- the angular resolution gap -> interferometry
- mission studies:
  - Dome C/A Antarctica
  - FIRI/ESPRIT

Summary

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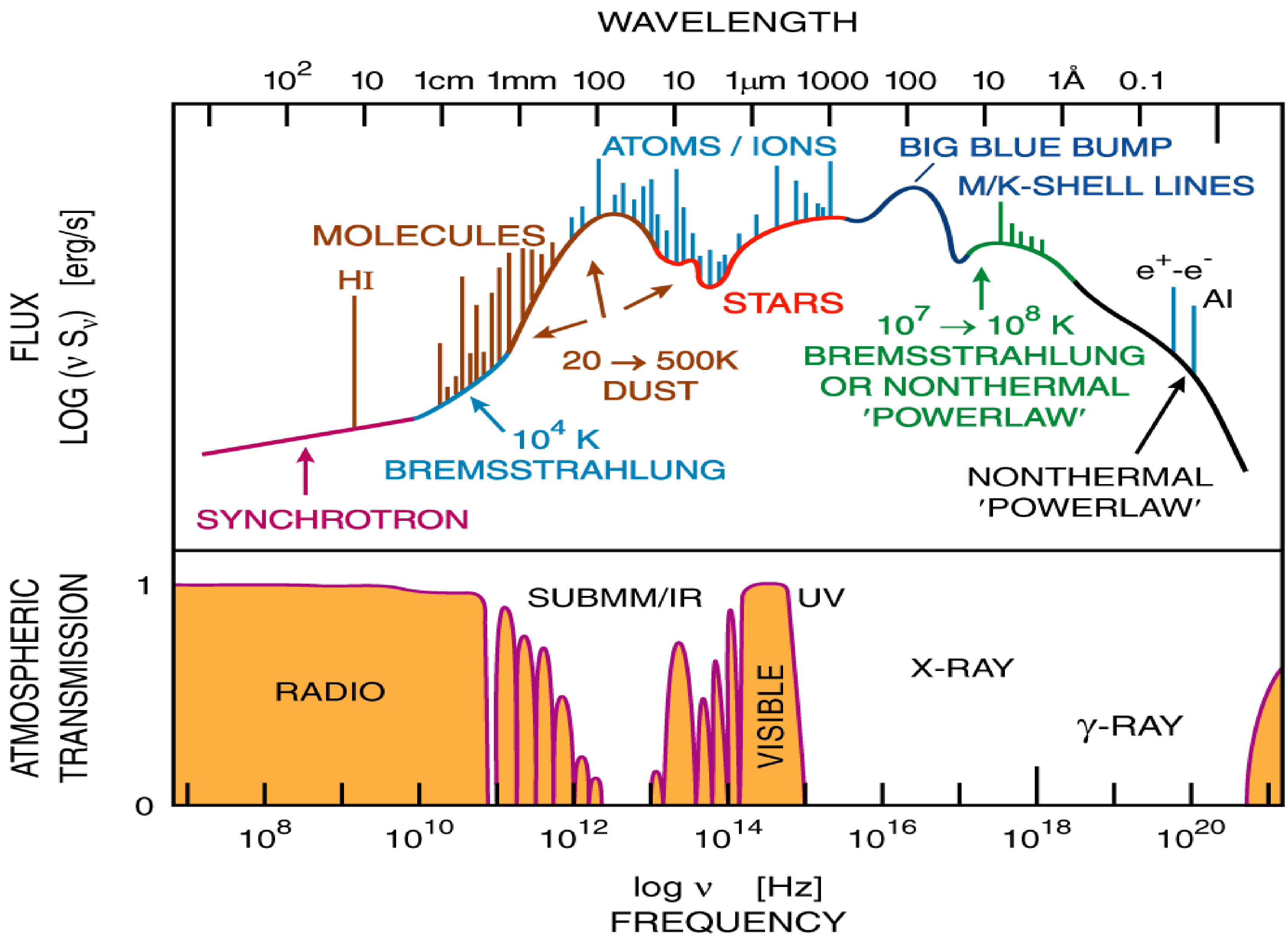
Summary

Astrophysics across the electromagnetic spectrum



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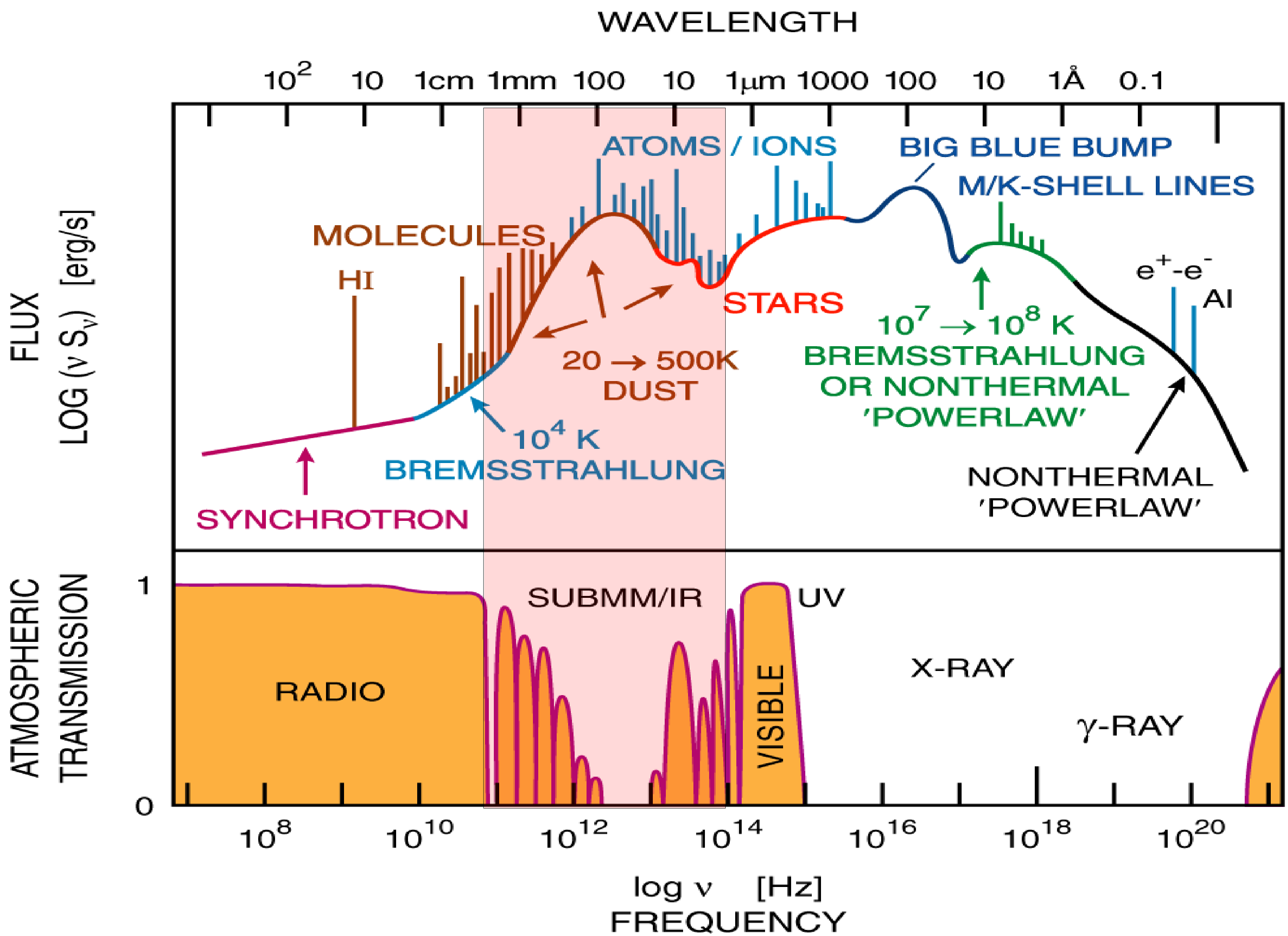


submm- and far-IR spectral range

astrophysical motivation:

- **the cosmos is cold:** emission peaks in the submm/FIR
  - *local/Galaxy: molecular clouds, star formation, dusty disks, planets, stellar envelopes,*
  - *global: active galaxies, galaxy evolution, cosmology (high-z gala-xies, cosmic background)*
- the submm/IR has a **high density in spectral characteristics**
  - *atoms (neutral and ions): fine-structure lines,*
    molecules: rotational and ro-vibrational lines,
    solid state: broad spectral features (silicates, ices), dust emission
- submm- and FIR-radiation **penetrates clouds** throughout a galaxy, offers view into galactic nuclei
- **redshift:** emission of distant, i.e. cosmologically young, objects shifted into submm-/FIR

submm/Far-IR: top science goals

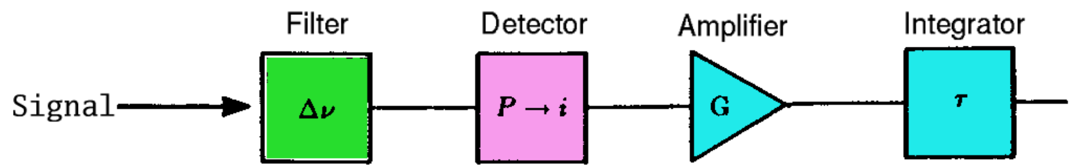
- **census of early, i.e. distant, galaxies**
  - broad band flux, spectral energy distribution
    - high angular resolving power with bolometer detectors
  - follow up line observations (strongest cooling lines)
    - line fluxes: imaging spectroscopy at moderate spectral resolution
- **galaxy evolution**: tracing the physical and chemical conditions of the interstellar medium
  - multi-line studies, kinematic and dynamic information
    - high sensitivity and moderate to high spectral resolution
- **formation of stars and planetary systems**
  - physical and chemical status of proto-planetary disks (dust and gas)
    - ultimate angular resolving power and sensitivity
- **instrument/telescope boundary conditions:**
  - **direct detection: large and cold telescopes**
  - **incoherent detection: multi-element interferometer with large collection area**

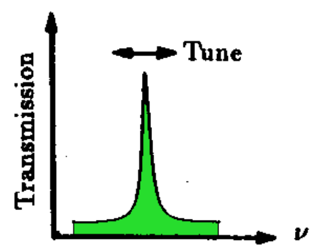
submm- und far-IR spectral range/ detectors and instruments

two fundamental detection methods:

- **incoherent**

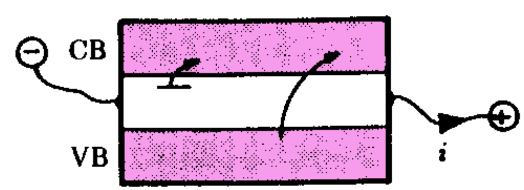
incoherent (direct) detection



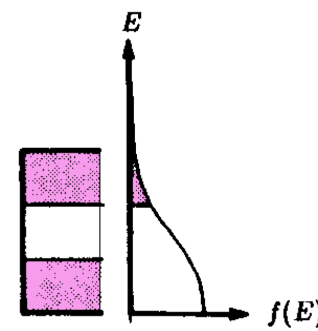


Filter

Detectors:



Photoconductor



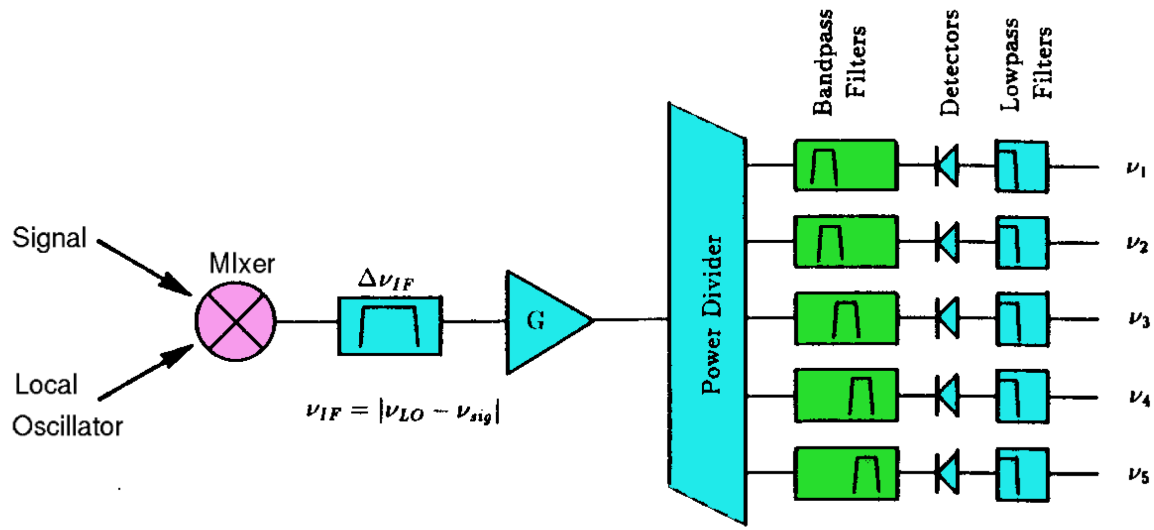
Semiconductor Bolometer

Filter: pre-detection
- Fabry-Perot
- Grating, etc.

Detector:
- intrinsic or extrinsic photoconductor
- bolometer

submmm- und far-IR spectral range/ detectors and instruments

and
- **coherent (heterodyne) detection**



Local Oscillator:
- FIR-Laser
- Carcinotron,BWO
- solid-state multiplier chain
- Quantum Cascade Laser

Mixer: (non-linear element)
- quantum mixer: SIS-junction
- quantum mixer: Hot Electron Bolometer

$$V_{non-lin} \ll \frac{h\nu}{e} = \frac{\nu_{GHz}}{242.83} mV$$

Backend: (Filter, post-detection)
- digital correlator
- acousto-optical spectrometer
- digital Fourier transform spectrometer

direct vs. heterodyne detection

- **direct detection**: photon shot noise (background limited)
  - background limited: requires cold telescope
  - multi element interferometry challenging: pre-detection interference
- **heterodyne detection**: quantum limit (phase coherence)
  - close to fundamental limit of sensitivity (quantum limit)
  - multi-element interferometry with large collection area feasible (post detection interference)

fundamental physics and state-of-the-art-detector performance give:

- crossover resolution (break-even in sensitivity)
- in the far-IR: at about 30 km/s line width

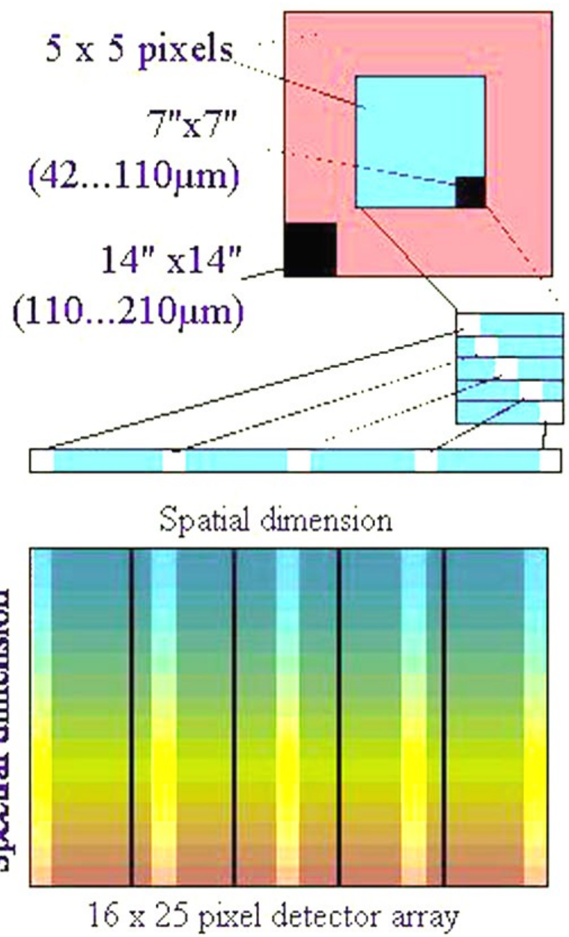
Both technologies by now can do **spectral imaging** (3D data cubes)

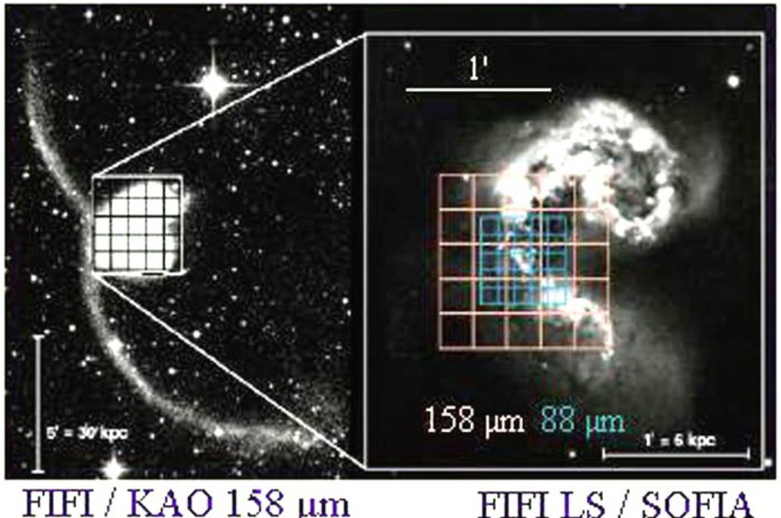
Science areas:

- global emission from galaxies (continuum and line):
  - direct detection
- galaxy dynamics and structure; interstellalr medium; star formation
  - heterodyne detectiond

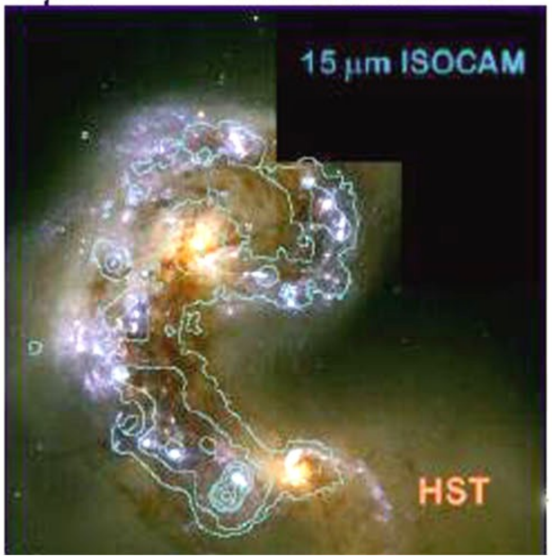
FIFI-LS Science: C II Data Cube in Interacting Galaxies

NGC 4038/39 "Antennae": Star Formation Triggered in Interaction Zone



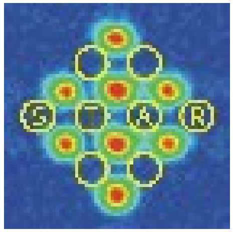


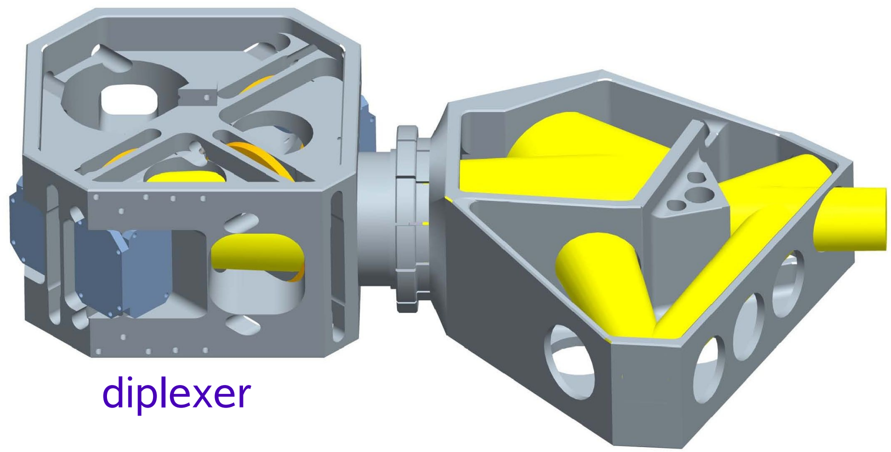
FIFI LS: FIR spectral line imaging at a resolution comparable with ISOCAM in the MIR!



CII and OI lines

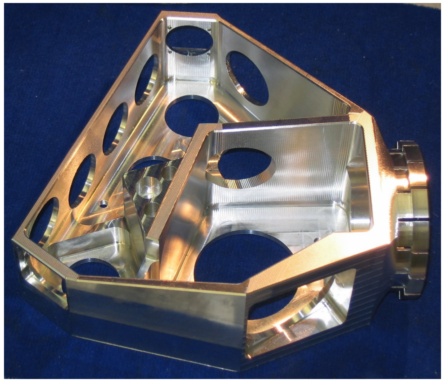
SOFIA THz Array Receiver: STAR (Graf et al.)
16 pixel (receivers) integrated optics concept





diplexer

beam rotator



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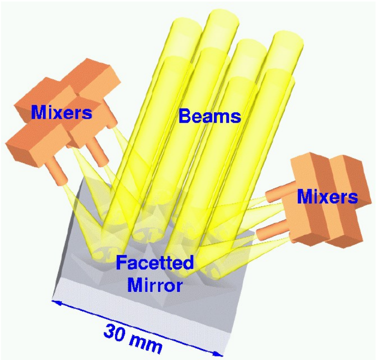
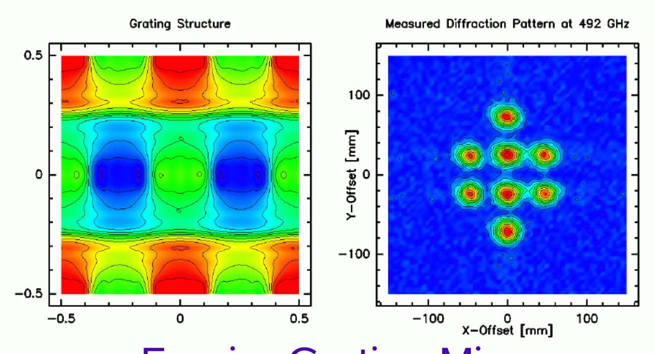


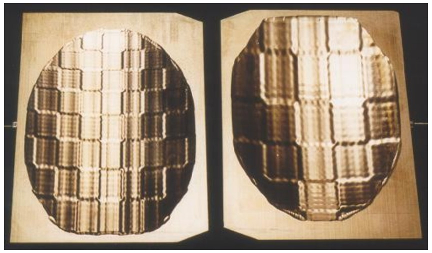
mixer unit (8x)

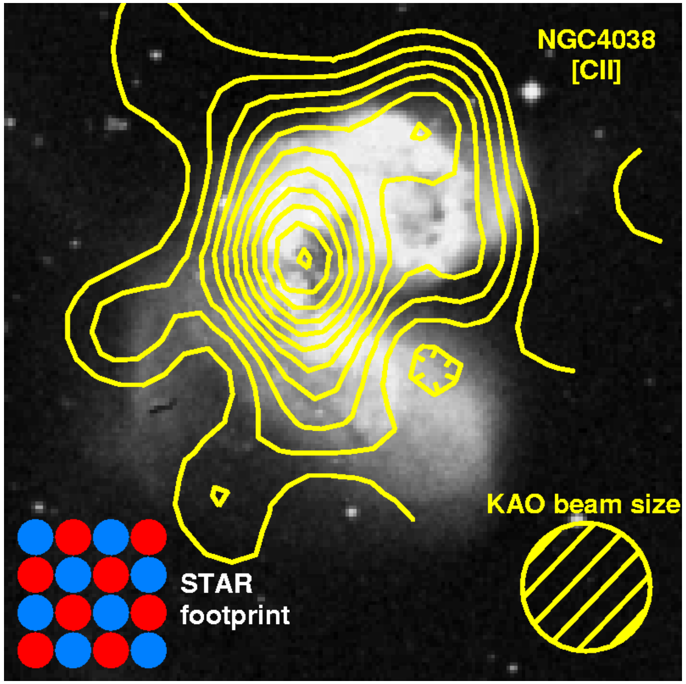
second generation SOFIA instrument

- **[CII] 158 µm 1.9 THz**
- **SMART & CHAMP heritage**
- **solid state LO chain (VDI)**
- **Fourier Grating Optics for LO mulitplexing**

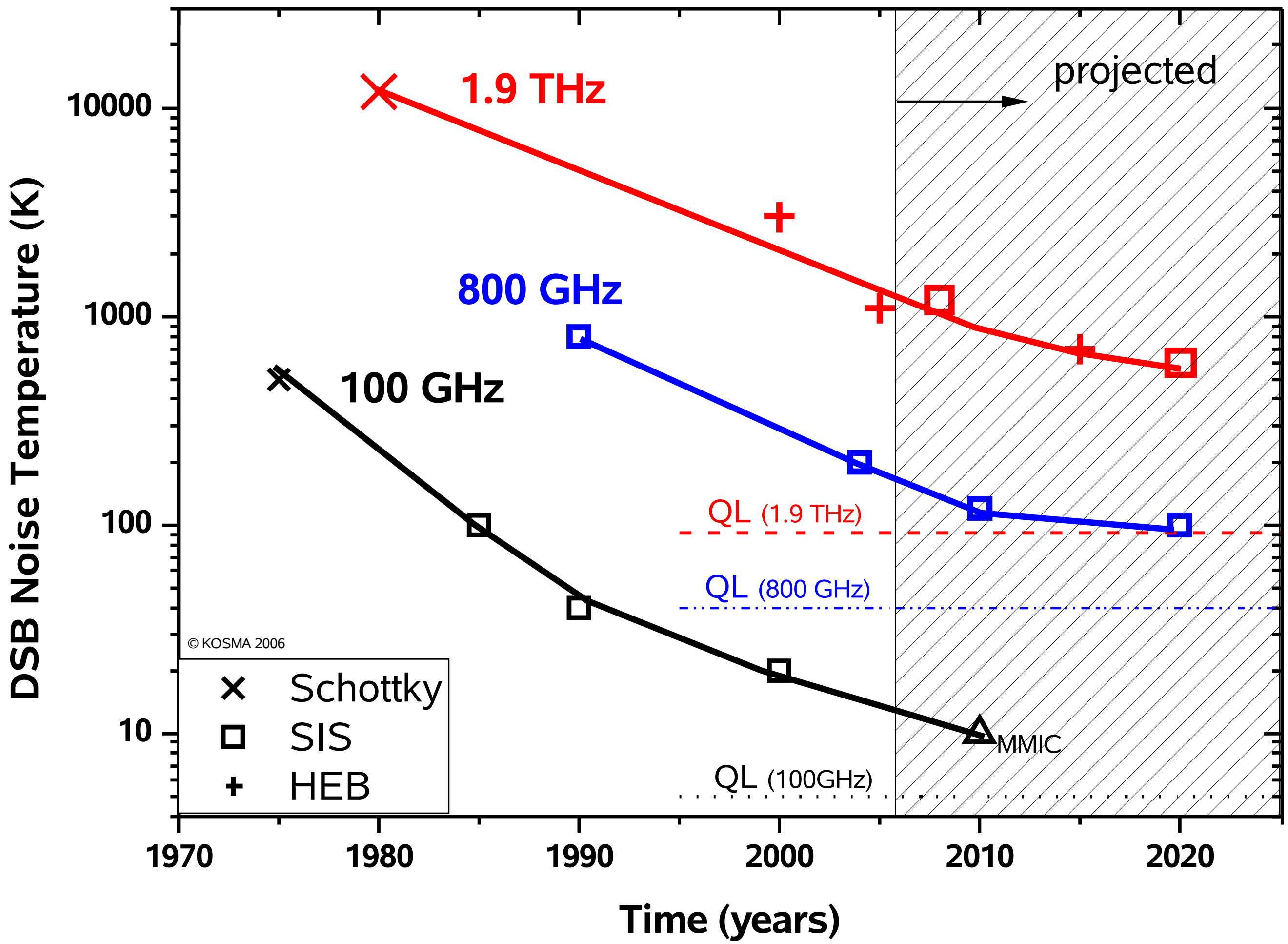


Fourier Grating Mirror





technological progress: heterodyne sensitivities



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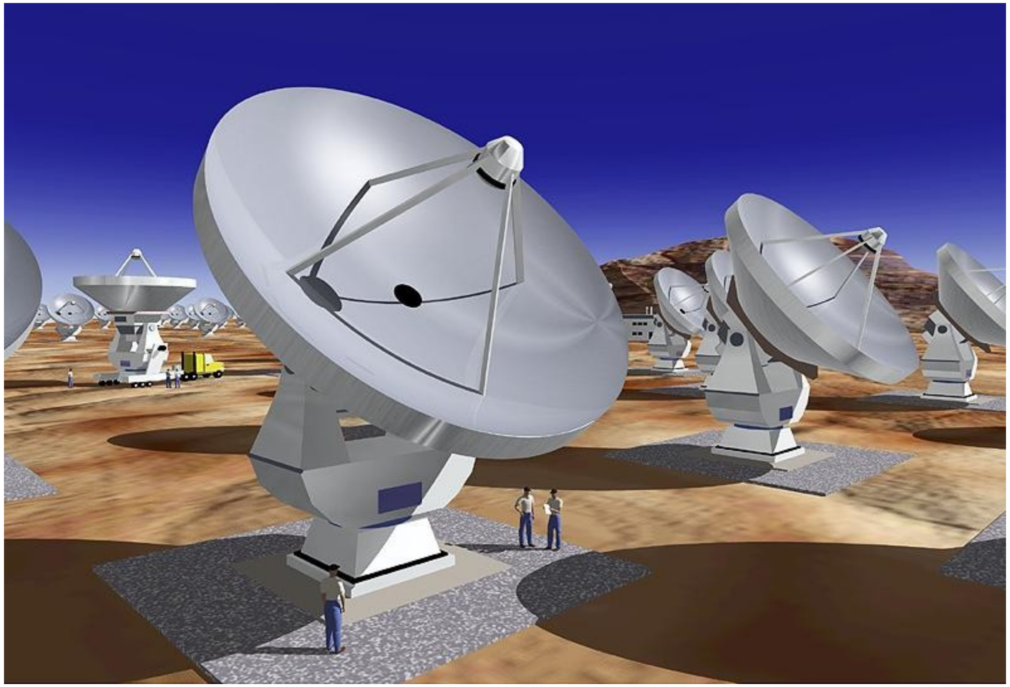
Summary

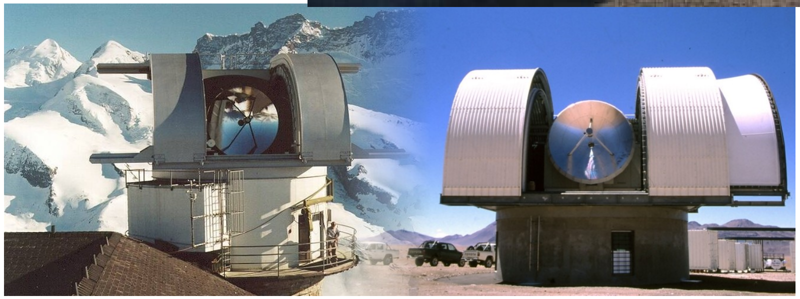
Ground Based submm/FIR

best ground based site (beyond Antartica):
Chile: Atacama:
Chajnantor Plateau &
Pampa la Bola
Future: Chajnantor Summit

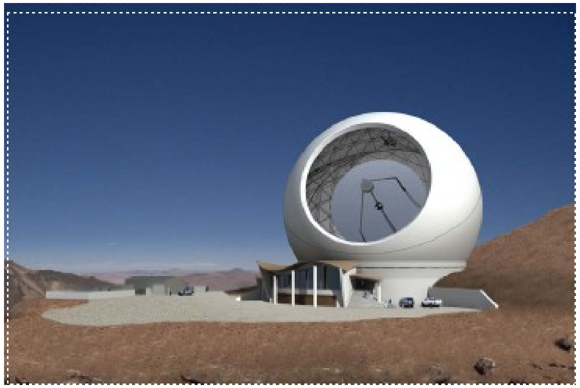
APEX
12 m telescope

ALMA 64 element submm interferometer





KOSMA/
NANTEN

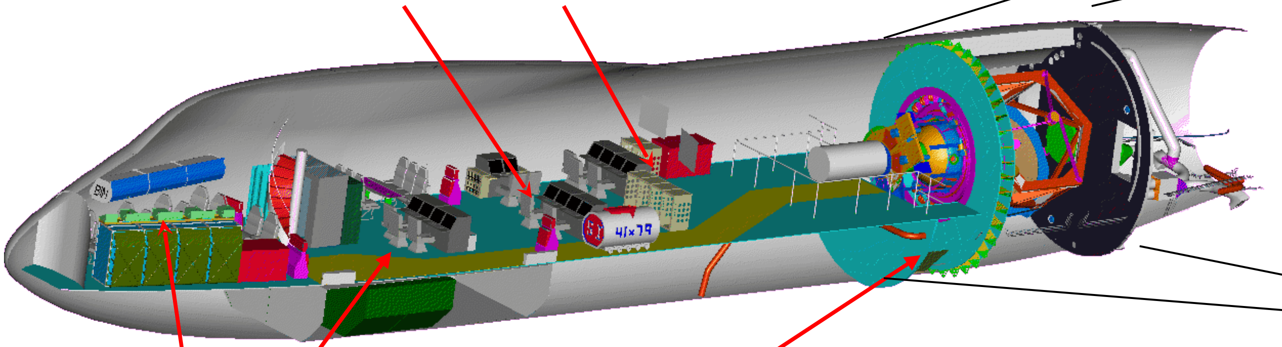


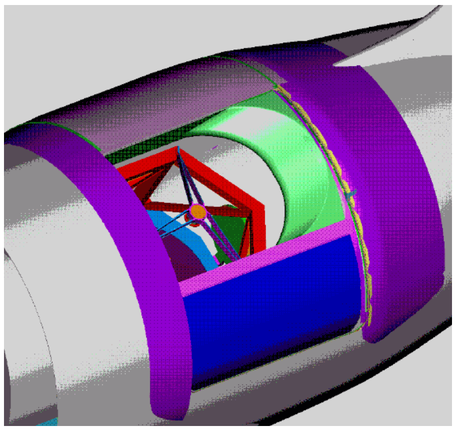
CCAT
25 m telescope
on Chajnantor summit

SOFIA

Mission Control & Science Operation Section

Open Port Cavity





Telescope Cavity Door

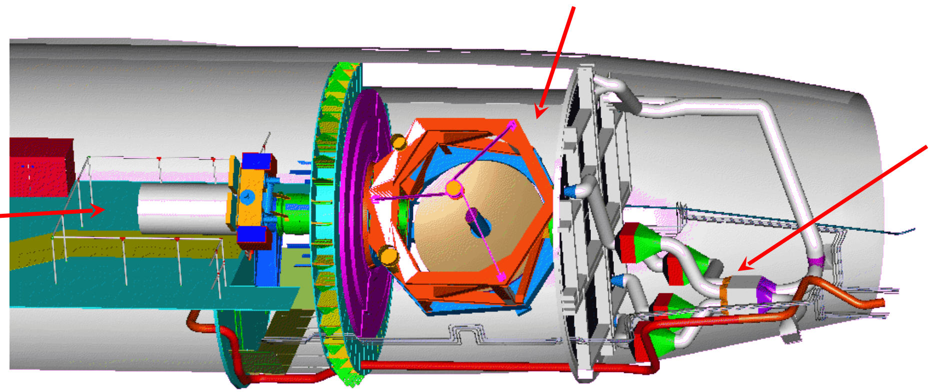
Education & Public Outreach Section

Pressure Bulkhead

Telescope 2.7m

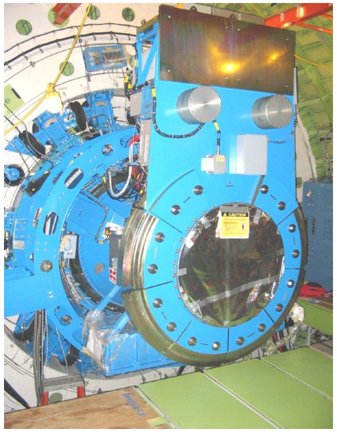
Cavity Environmental Control System

Science Instrument



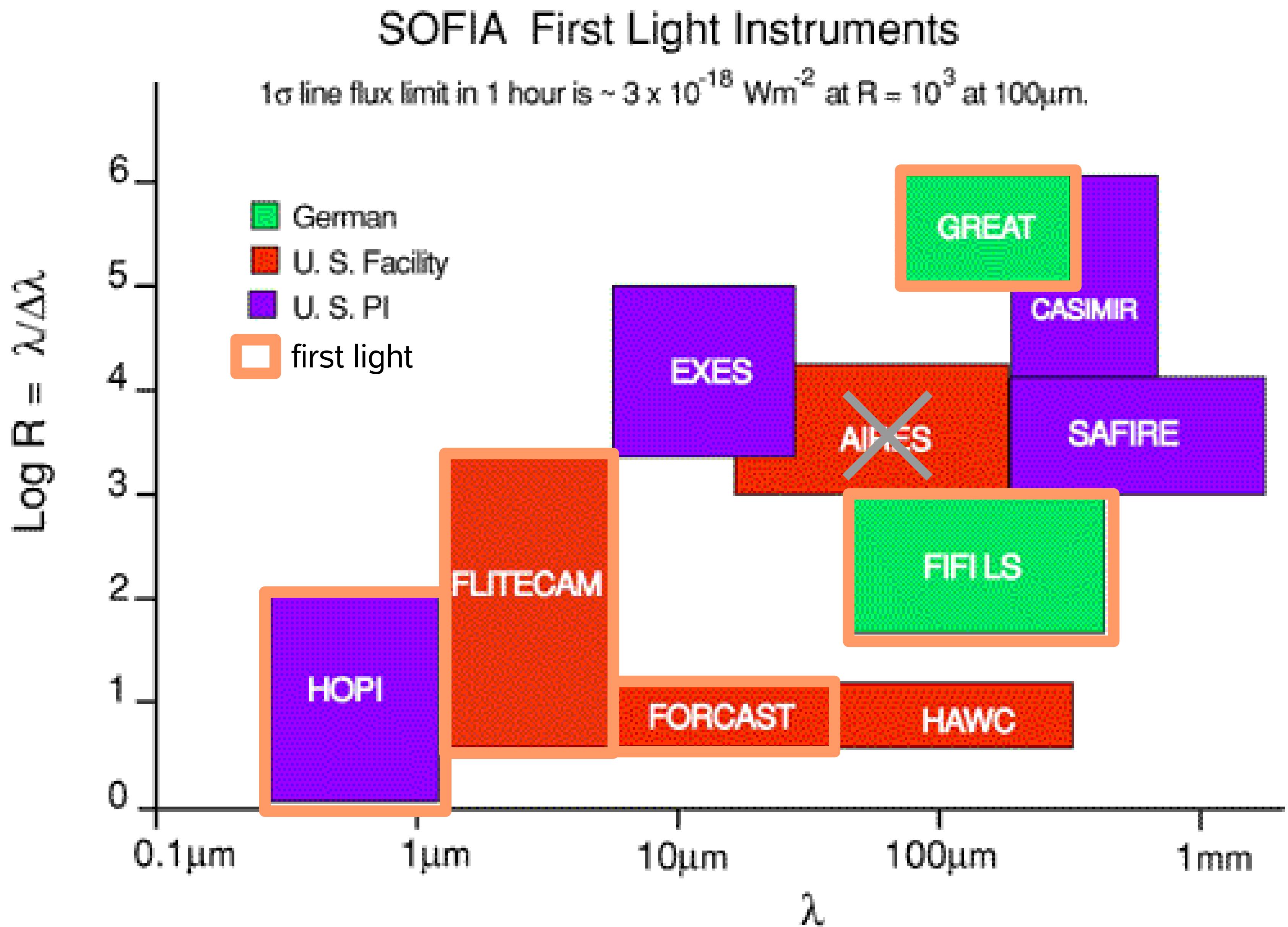
SOFIA
Stratospheric Observatory For Infrared Astronomy

SOFIA: roll-out after painting (Waco: Oct. 2006)



SOFIA is alive again, pending final budget decision by Congress end of November

SOFIA:
Stratospheric Observatory for Infrared Astronomy



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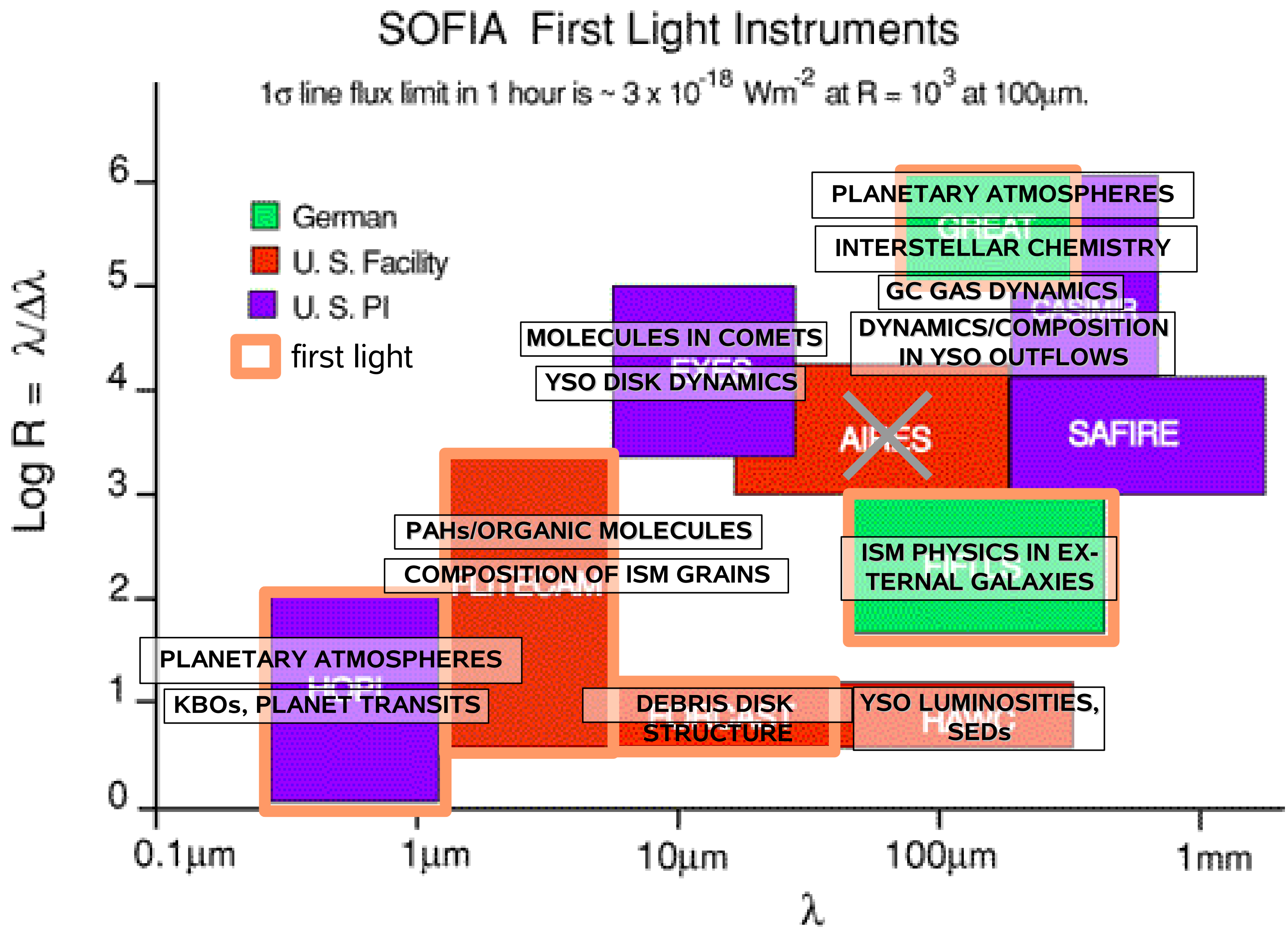
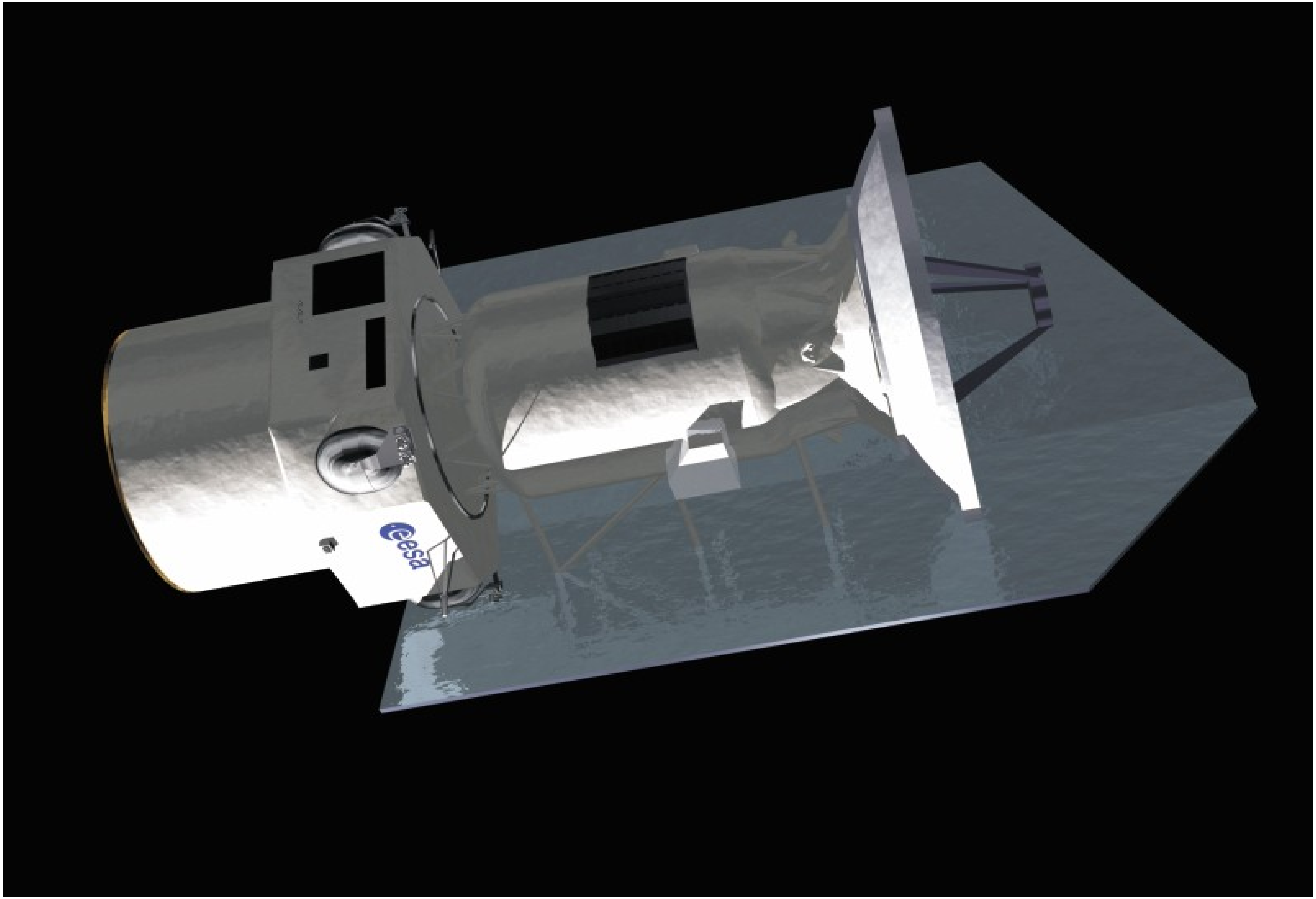
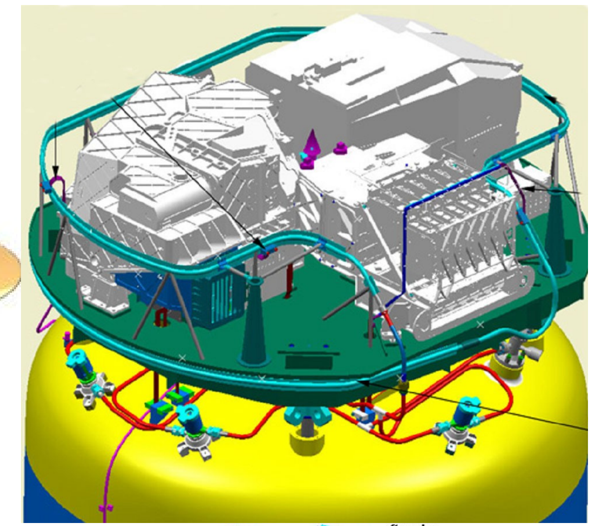


Herschel: ESA cornerstone no. 4: FIR-astronomy space mission

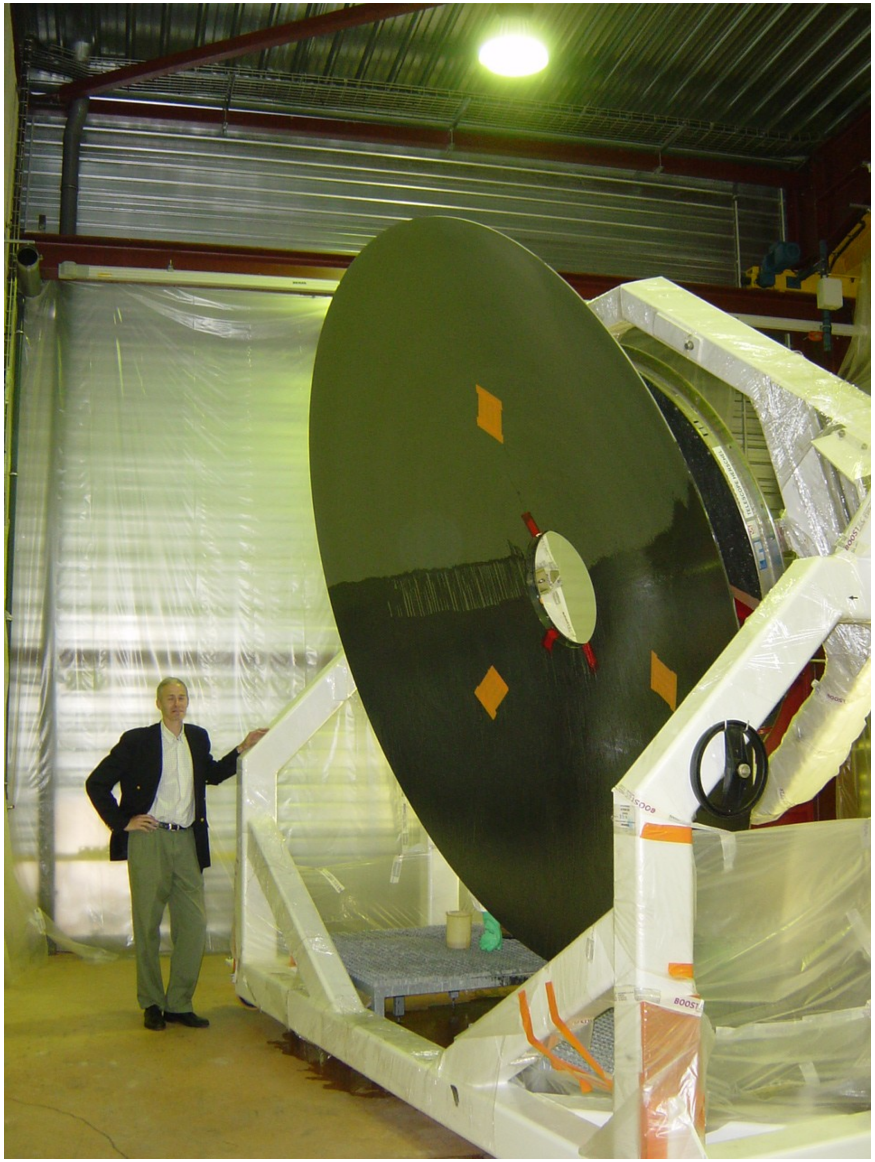


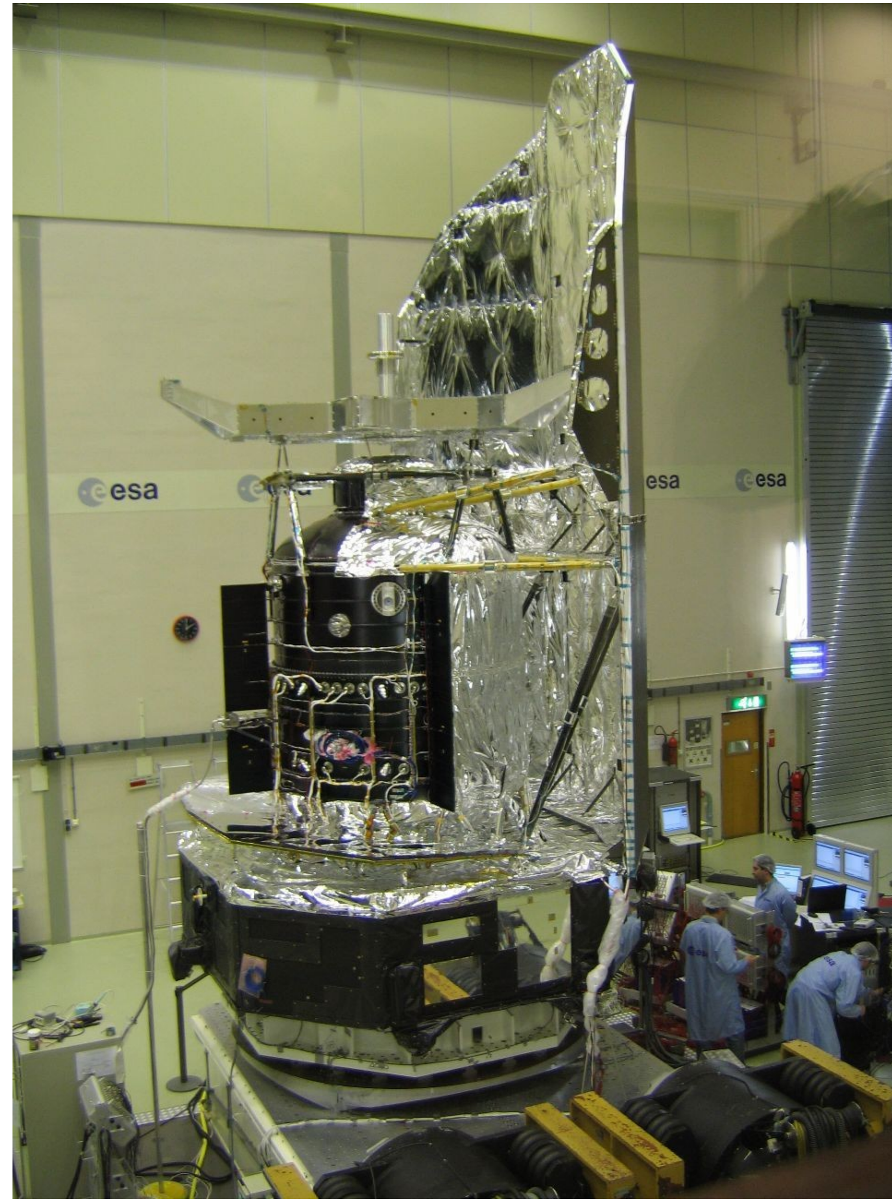
Herschel spacecraft

- telescope diameter 3.5 m
- telescope WFE < 6 μm
- telescope temp < 90 K
- telescope emissivity < 4%
- abs/rel pointg (68%) < 3.7” / 0.3”
- science instruments 3
- science data rate 130 kbps
- cryostat lifetime 4.0±0.4 years
- height / width ~ 7.5 / 4 m
- launch mass ~ 3200 kg
- power ~ 1500 W
- orbit ‘large’ Lissajous around L2
- solar aspect angle 60-120 deg
- launcher (w Planck) Ariane 5 ECA

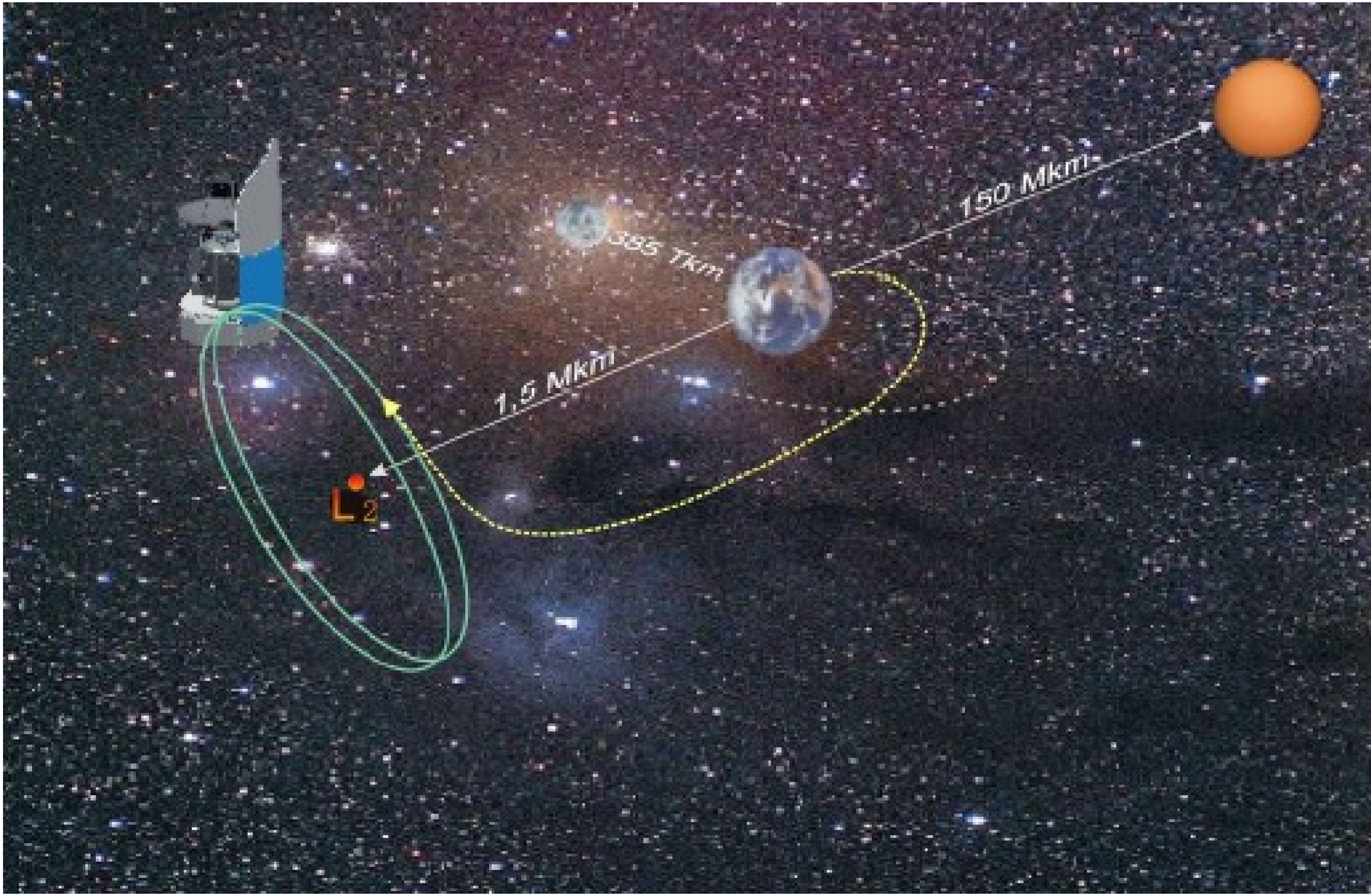


Herschel hardware





Herschel: Launch and orbit



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  - science topics
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- present missions: operational and/or implemented
  - ground: APEX, NANTEN2, ALMA
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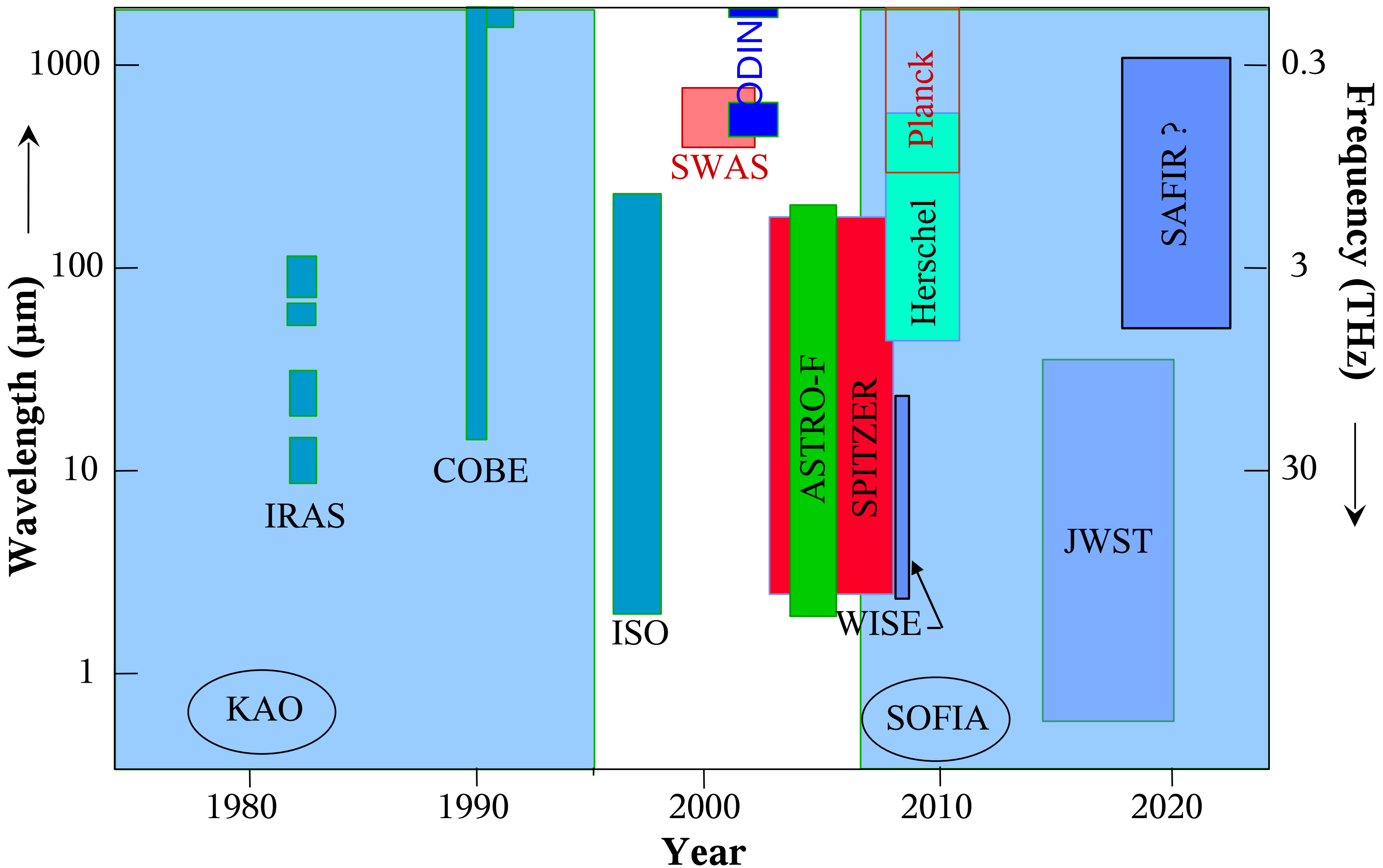
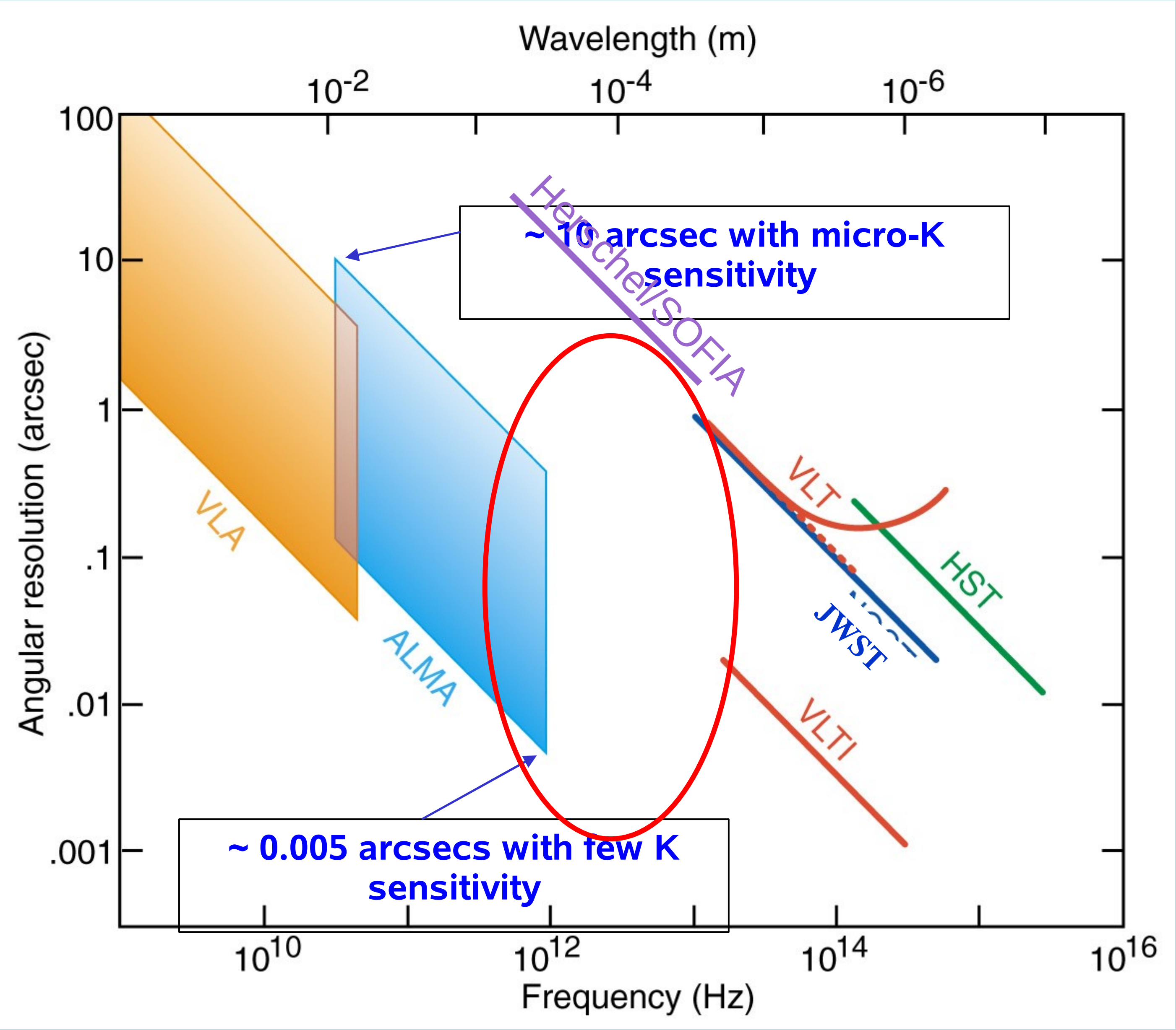
  - spaceborne: Herschel
- **perspectives and limitations**
  - the angular resolution gap -> interferometry
  - mission studies:
    - Dome C/A Antarctica
    - FIRI/ESPRIT
- Summary

Timeline of IR - FIR - Submm Missions



Airborne observatories provide temporal continuity and wide spectral coverage, complementing other facilities.

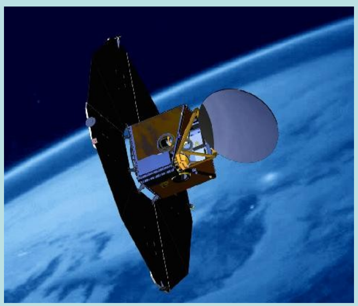
The Far-IR Spatial Resolution Gap: Interferometry

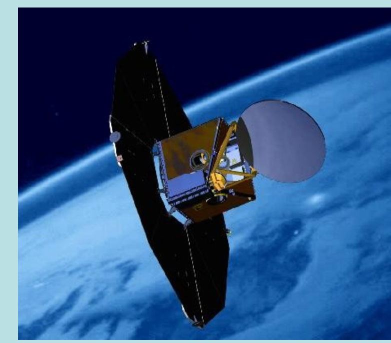


FIRI/ESPRIT:
Far-IR Imager Mission study

ESPRIT = mission concept for a free-flying sub-millimetre and far-infrared heterodyne space interferometer

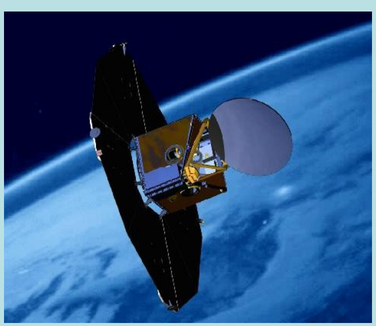
"Exploratory Space Submm Radio Interferometric Telescope"

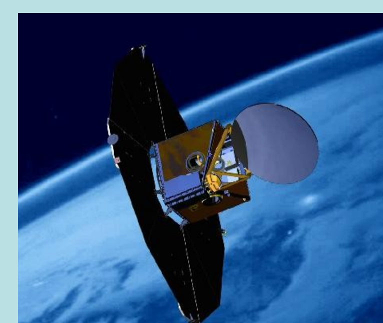


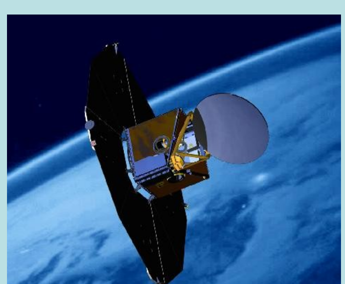


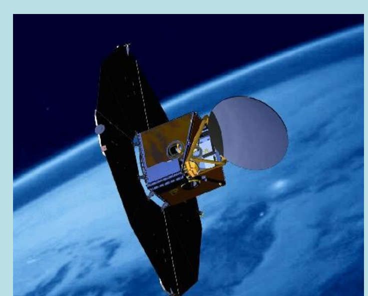
Telescopes: N ~ 6 ; free-flying

Telescope size	: ~ >3.5 m
Temperature	: ambient (90K)
Proj. Baselines	: ~ 7- 200 - 1000 m
Freq. range in	: 0.5–6 THz (600–50 μm)
Inst. Bandw.	: ~ >4 GHz
Angular Res.	: 0.02 arcsec (@100 μm)
Spectr. Res.	: 1 Km/s (@100 μm)

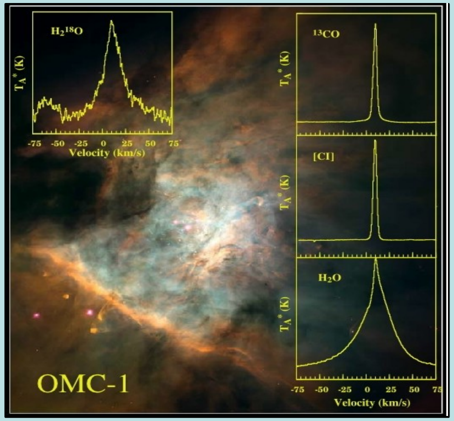


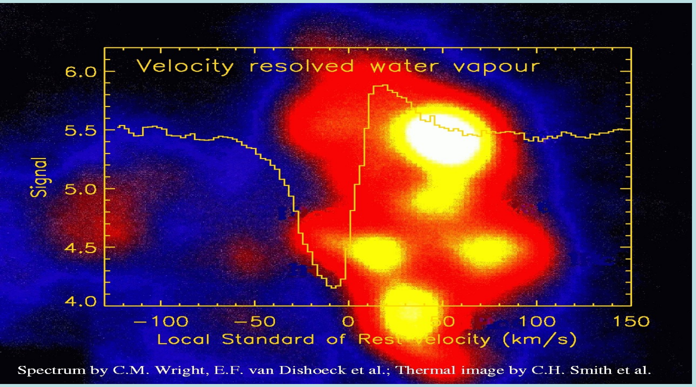


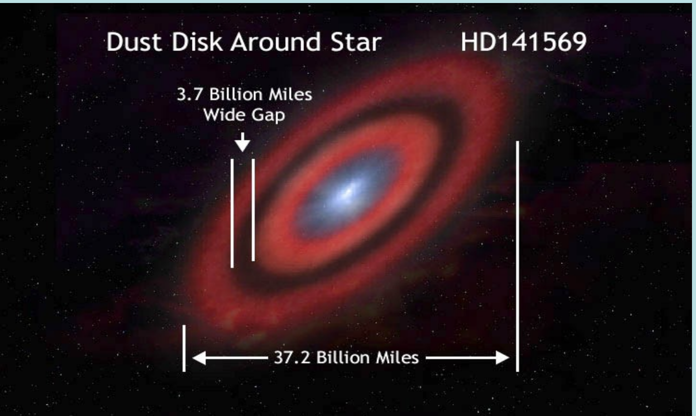




FIRI/ESPRIT Science objectives







A. Complementary to ALMA:
  - Different frequency range > 950 GHz (ALMA)
  - No atmosphere hindering in phase and transmission

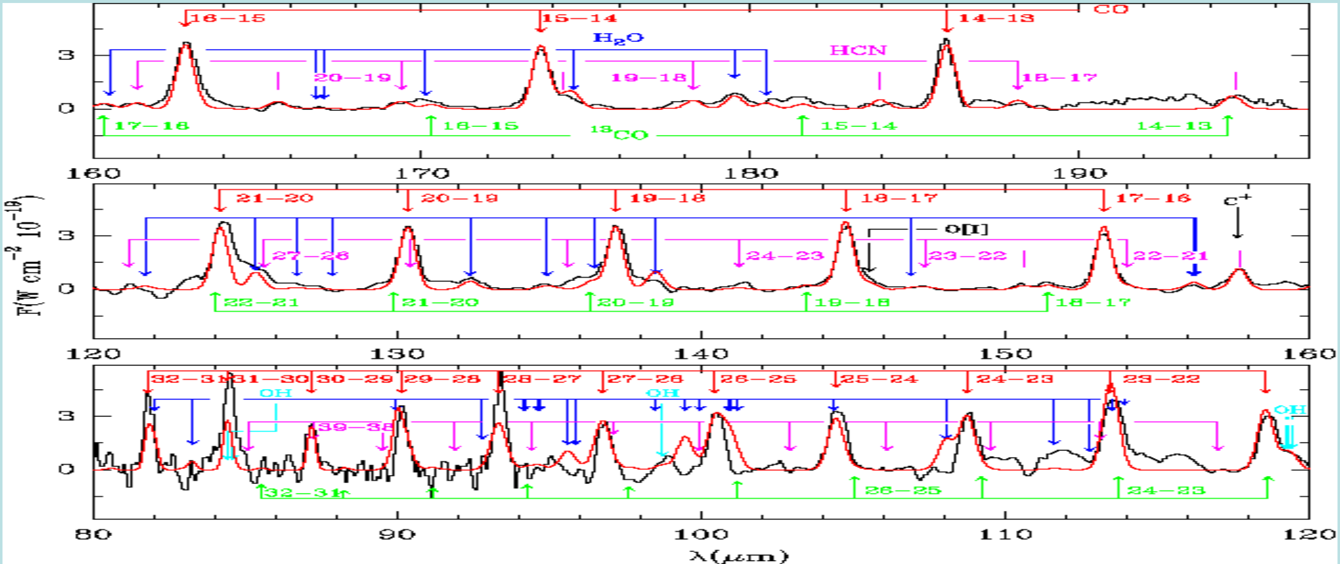
B. Imaging **water** and molecular ions in star forming regions and **proto-stellar/proto-planetary disks:** H2O, OH, OH+, CH, CH+, CH2+, CH3+,

C. Imaging in important atomic fine-structure lines:

CII, NII, OI, OIII,

Imaging in high excitation lines of CO, HCN, HCO^+, etc

D. Follow-up on ISO-LWS, SWAS, ODIN, Herschel,…

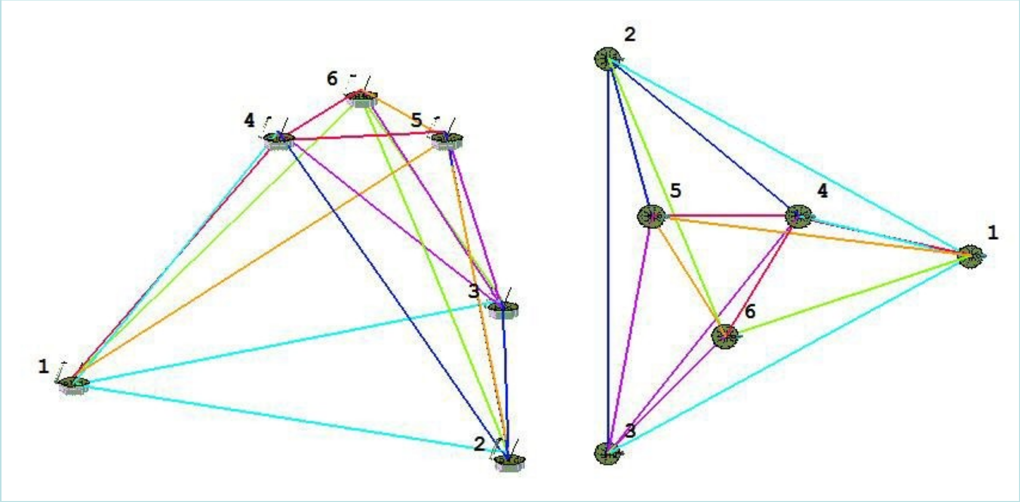


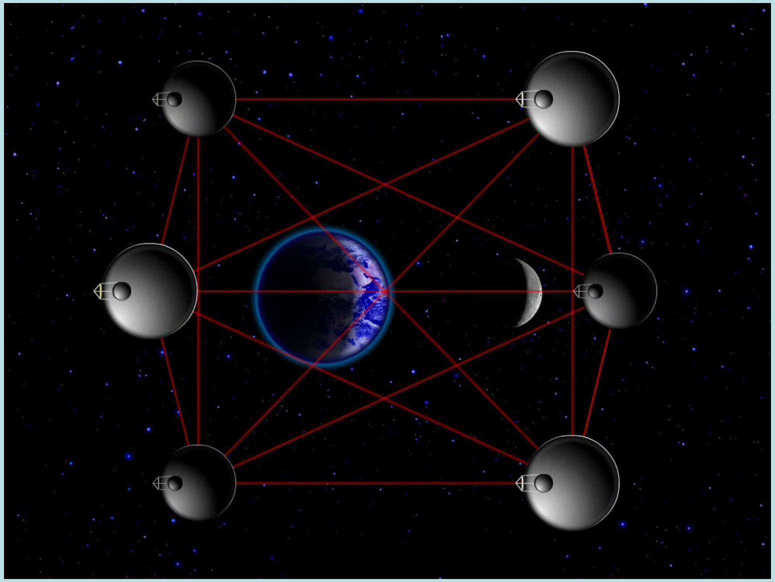
Interferometer element linking

Free flying Interferometer-elements linking requirements:

1. Optical metrology for position determination
2. Signal transport between elements for correlation
3. Locking of all the LOs (reference distribution)

Design goal is to have all three functions carried out by optical means, using same optical components.





Antartic: Dome C Exploration

pro:
excellent atmosphere
low ambient temperature

but:
challenging logistics

SUMMARY (1)

- **FIR astronomy:**
  - unique and competitive science goals
  - detector, instrument and telescope technologies make rapid progress
  - next step: interferometry (incoherent/coherent)
- **broad band/incoherent:**
  - very low thermal background: spaceborne
  - need for new generation of ultra-sensitive detectors
- **high resolution spectroscopy:**
  - close to fundamental sensitivity limit
  - multi-element interferometry routinely performed
- **spatial resolution**: long wavelength (λ/D):
  - either **large single dish** telescopes needed and/or
  - **multi element interferometry** needed

SUMMARY (2)

- **a lunar-based FIR-observatory?**
  - low gravity allows for larger telescopes ADVANTAGE
  - solid foundation allows for “easy” interferometry implementation
  - thermal environment : uncritical for high spectral resolution, difficult for direct detection systems
  - moderate effort in cryo-/vacuum technology
  - science use case discussion shows: useful minimum configuration is
    - **6 plus interferometer elements, possibly with larger central dish.**
    - **each greater 6 m diameter,**
  - is this feasible?
- competing with opportunities in **Antartic program** (Dome C/A)
- competing with **formation free flying** space interferometer
- possible **technology demonstration:**
  submm/THz monochromatic source installed on the moon
  as phase reference for ALMA ????