Submillimeter Spectroscopic Science from Space

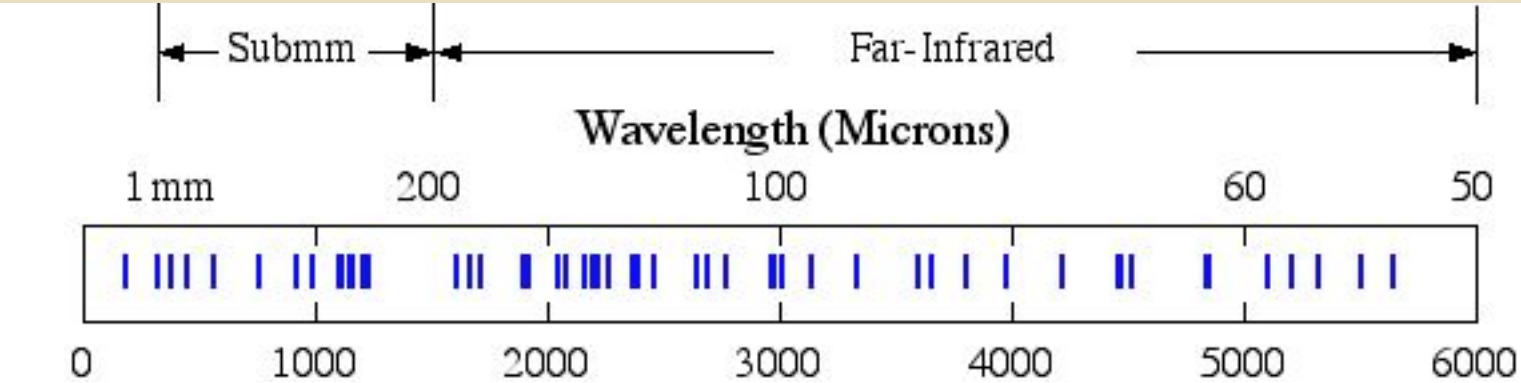
The Big, the Small, and where Harold Yorke has contributed to advancing the field

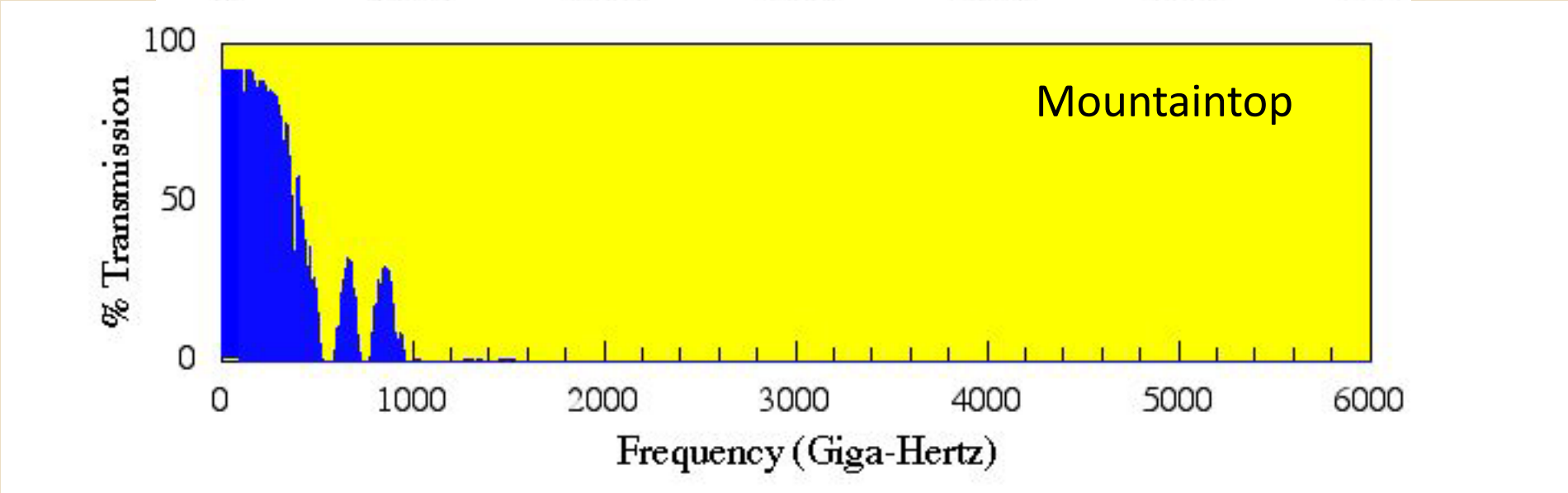
Paul Goldsmith

Jet Propulsion Laboratory, California Institute of Technology

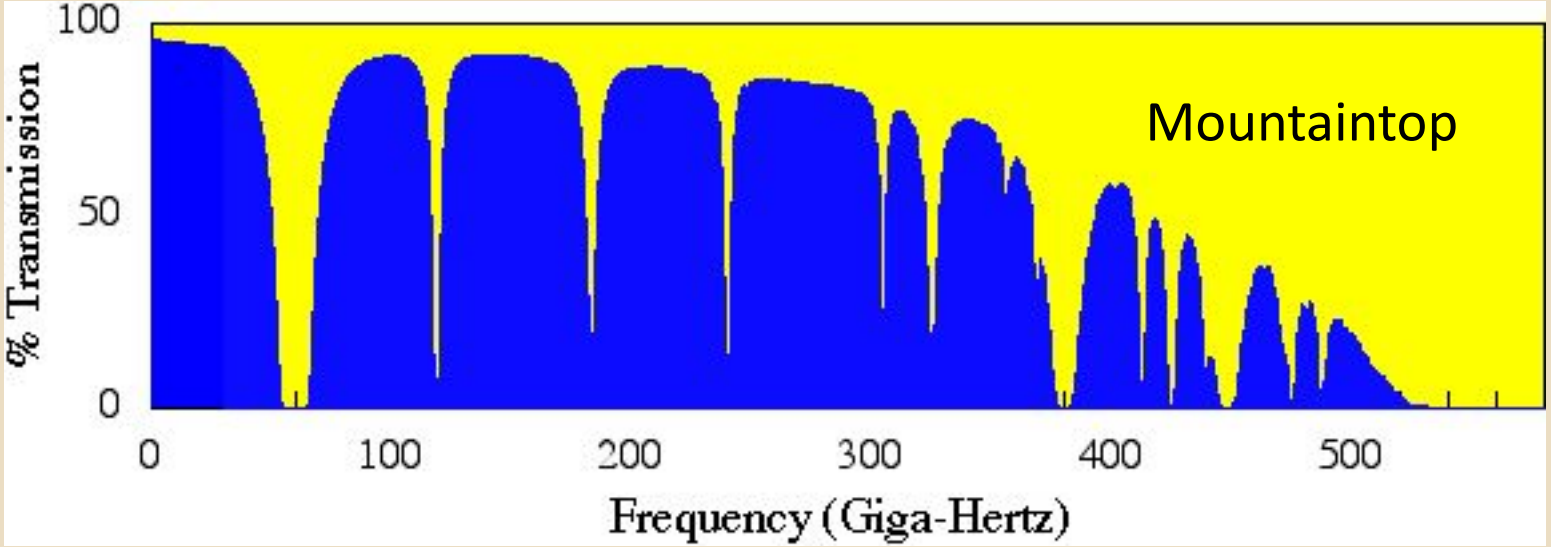
Why Submillimeter Astronomy from Space?

Wavelengths of lowest-lying (T < 500 K) water transitions

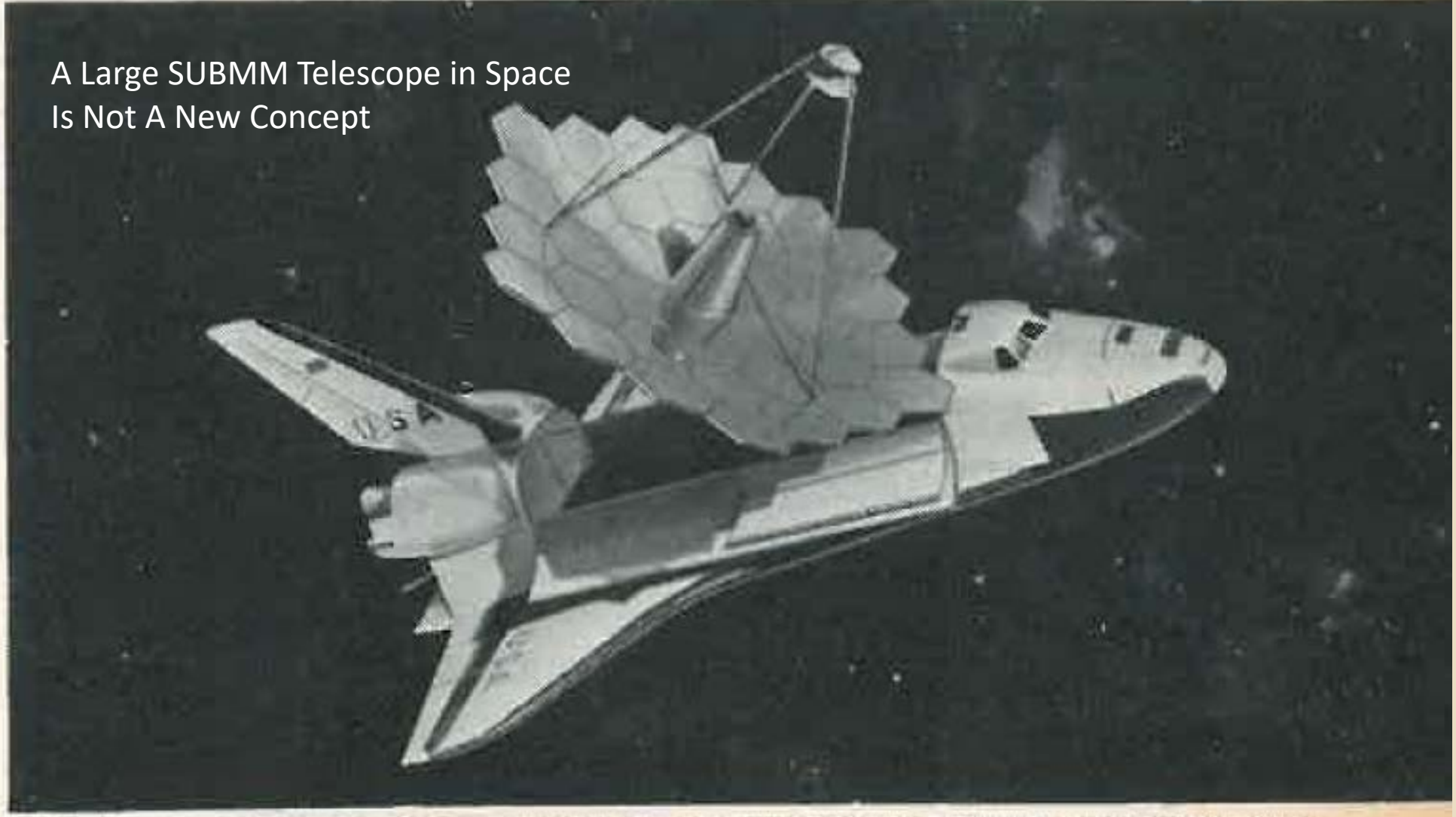




Water Lines Remain Opaque from Mountaintop and Even Airplane



We must go to space to study water and O_2 as well as many other "blocked" species. You can do continuum from mountaintops and SOFIA in "windows"



F-5 Large space antennas would open a dramatic vista to submillimeter radio astronomy. Illustration depicts a 10-m precision deployable antenna with a surface accuracy on the order of 50 μm being evaluated.

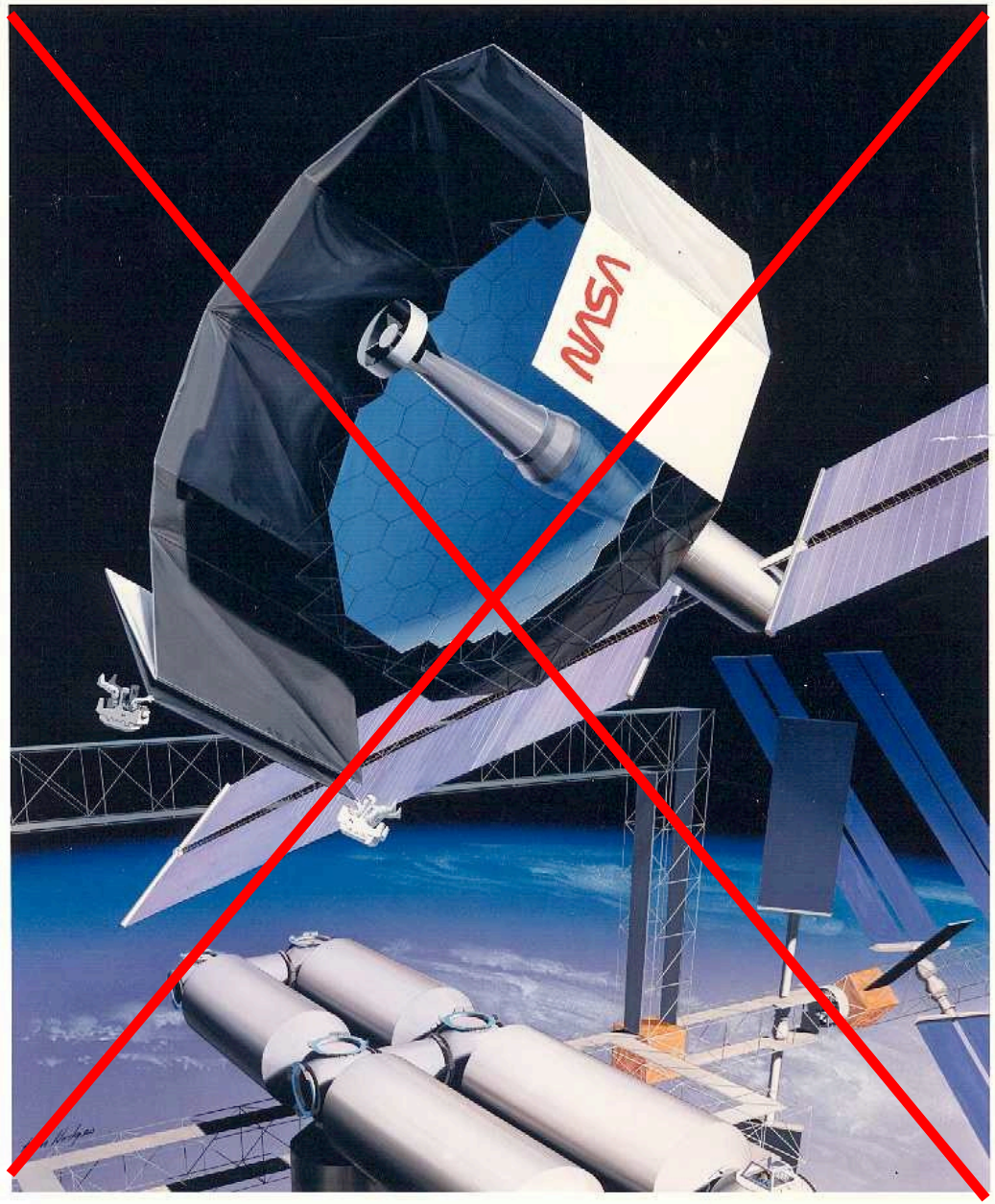
Powell & Hibbs, Astronautics & Aeronautics 1977, vol. 15, 58

Large Deployable Reflector (LDR) NASA Project circa 1985

20m diameter
30 µm – 1 mm wavelength

Passively cooled to ~150K
Low earth orbit
Astronaut assembly

Heterodyne RX for high-resolution spectroscopy (Schottky & SIS)
Grating Spectrometer for low resolution
FPI for moderate resolution



Submillimeter Wave Astronomy Satellite (SWAS): Spectral Lines Targeted

Two important "blocked" species for the first time

- **Ortho-H_2O** 1(1,0) - 1(0,1) at 556.9 GHz (E_u/k = 61.0 K)
- **$H_2{}^{18}O$**
- **O_2** at 487.25 GHz (E_u/k = 26.4 K)

Two other important ISM tracers that are difficult to observe even from mountaintop locations

- **CI** $^3P_1$ - $^3P_0$ at 492 GHz (E_u/k = 23.6 K)
- **^{13}CO** J = 5-4 at 551 GHz (E_u/k = 79.3 K

Four lines observed simultaneously with velocity resolution < 1 km/s

SWAS is a Complete Radio Observatory in Space

1) Off-Axis Cassegrain Telescope

- 68 x 54-cm aperture
- 3.3 x 4.5 arcmin. beam (553 GHz)
- 3.5 x 5.0 arcmin. beam (490 GHz)

2) Submillimeter Heterodyne Receivers

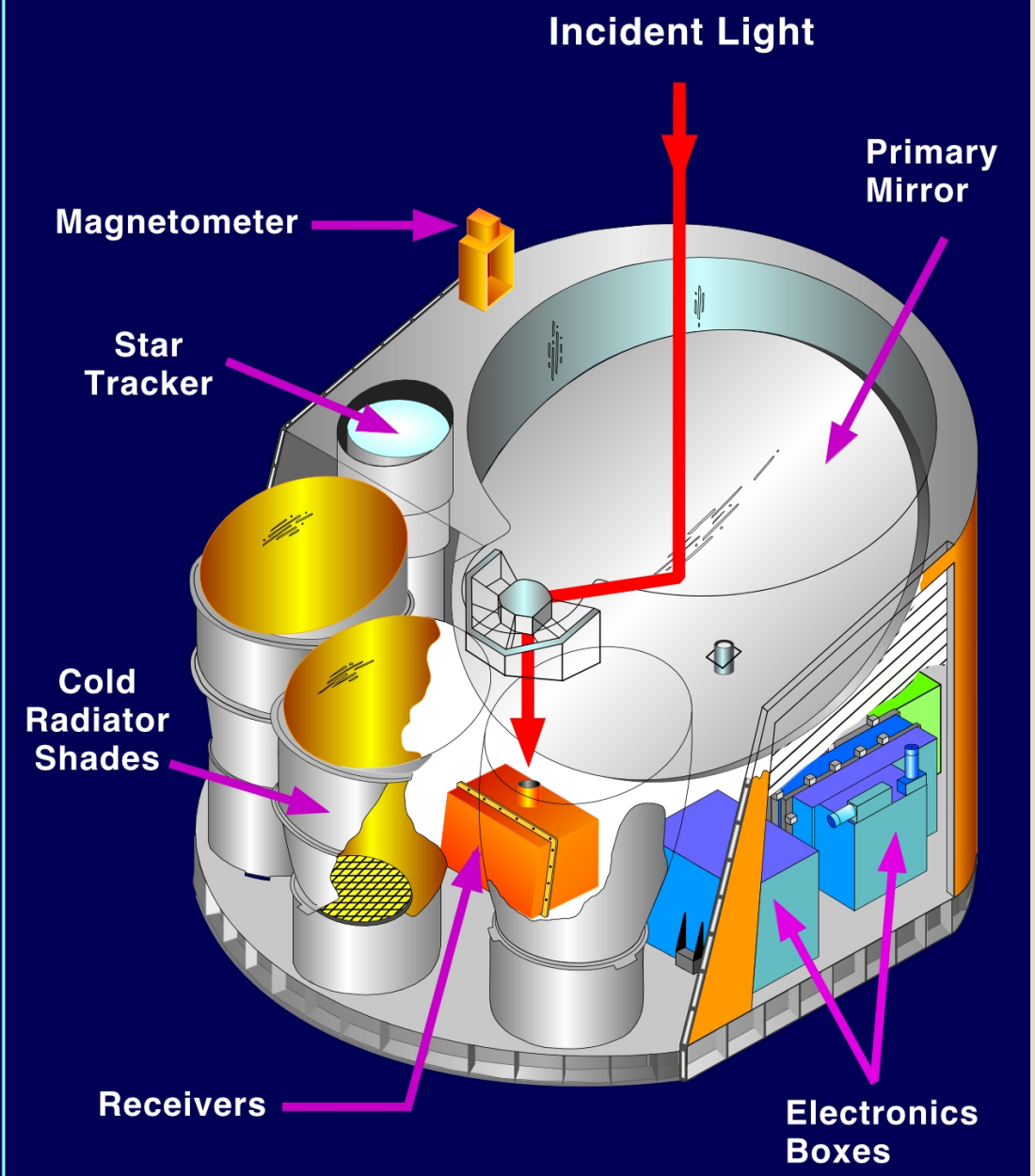
- Two receivers: 490 & 553 GHz
- Passively-cooled to 175 K

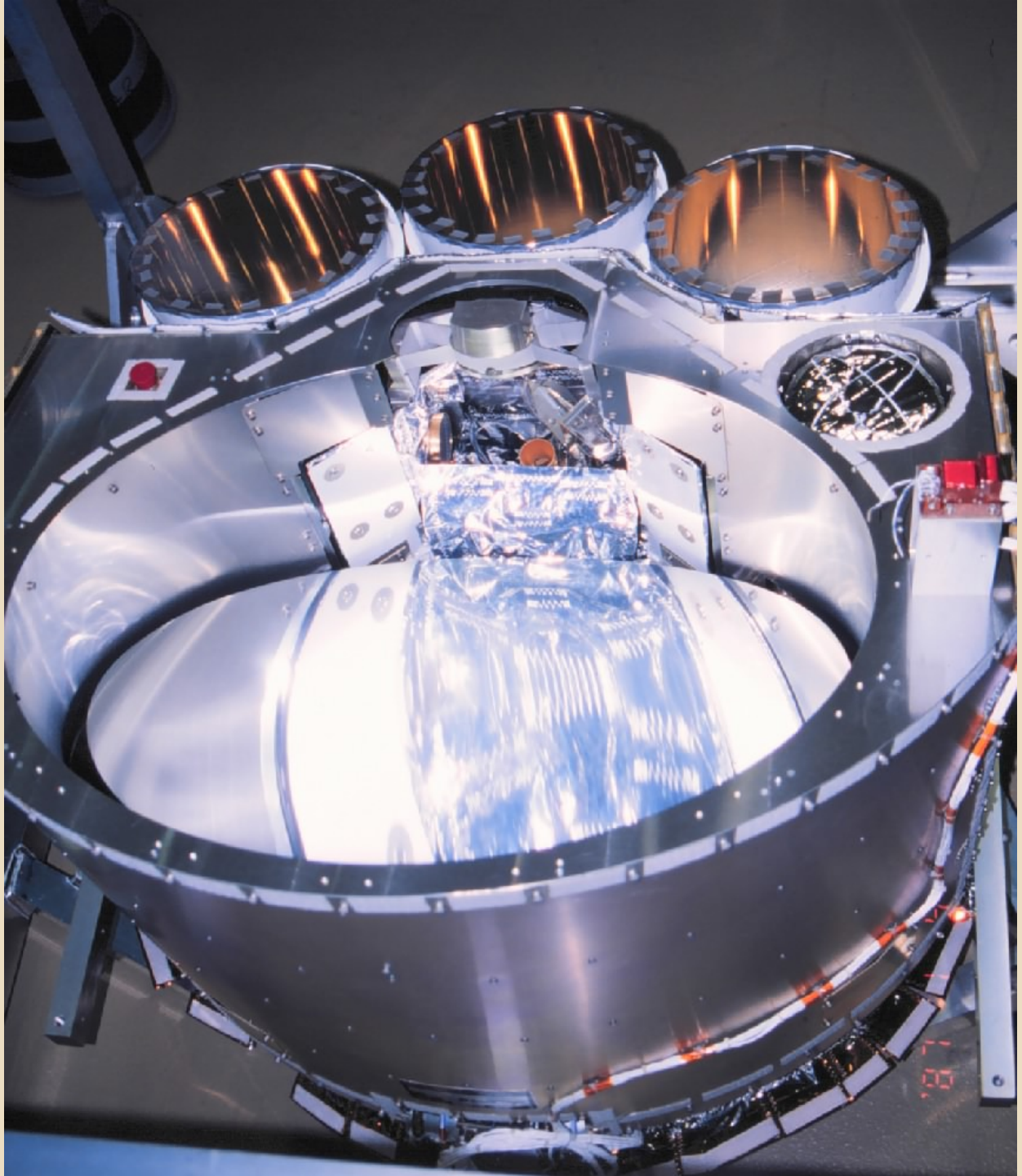
3) Backend Spectrometer (AOS)

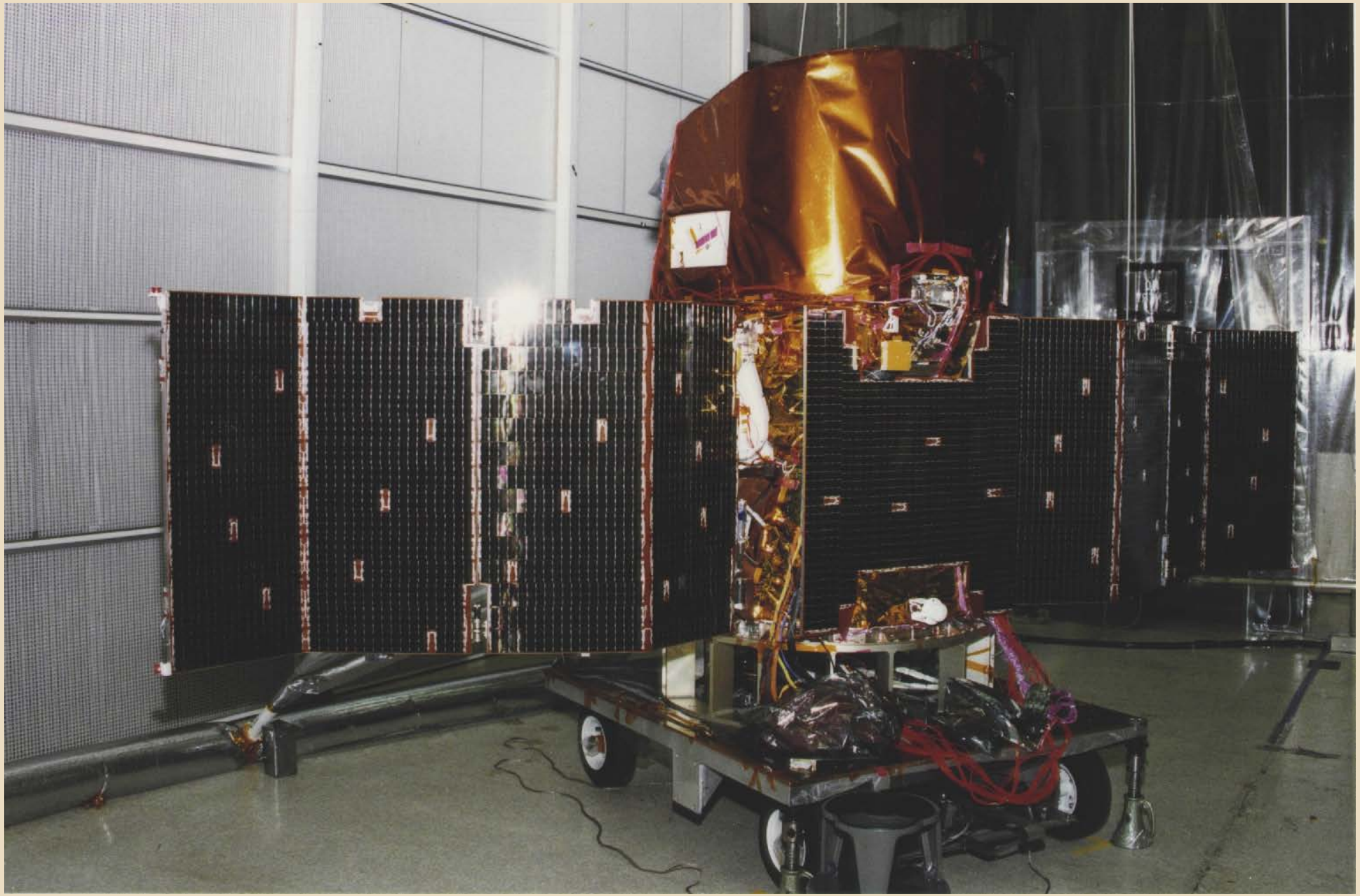
- Observe all lines simultaneously
- Velocity resolution of 1 km/s

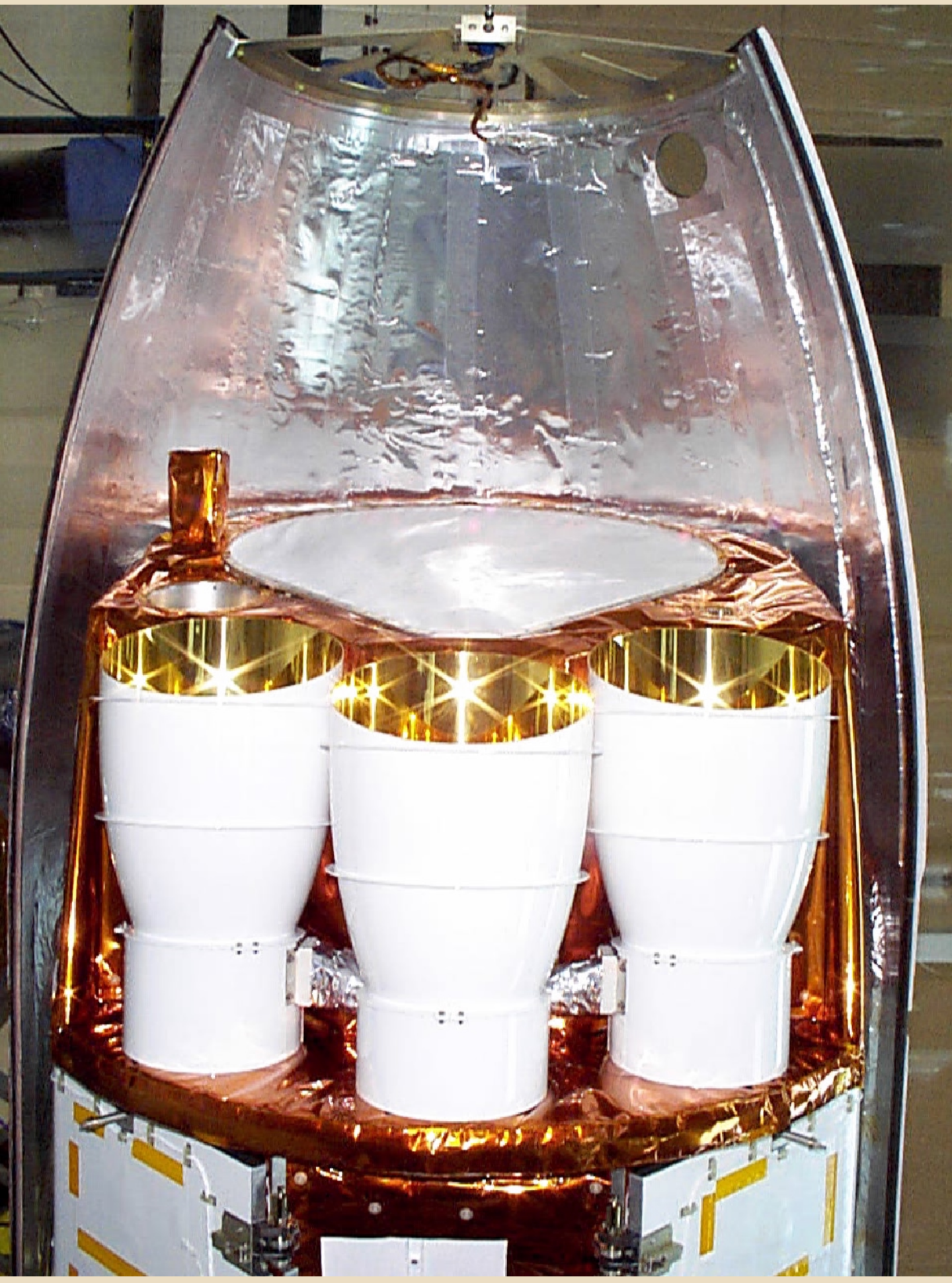
4) Pointing

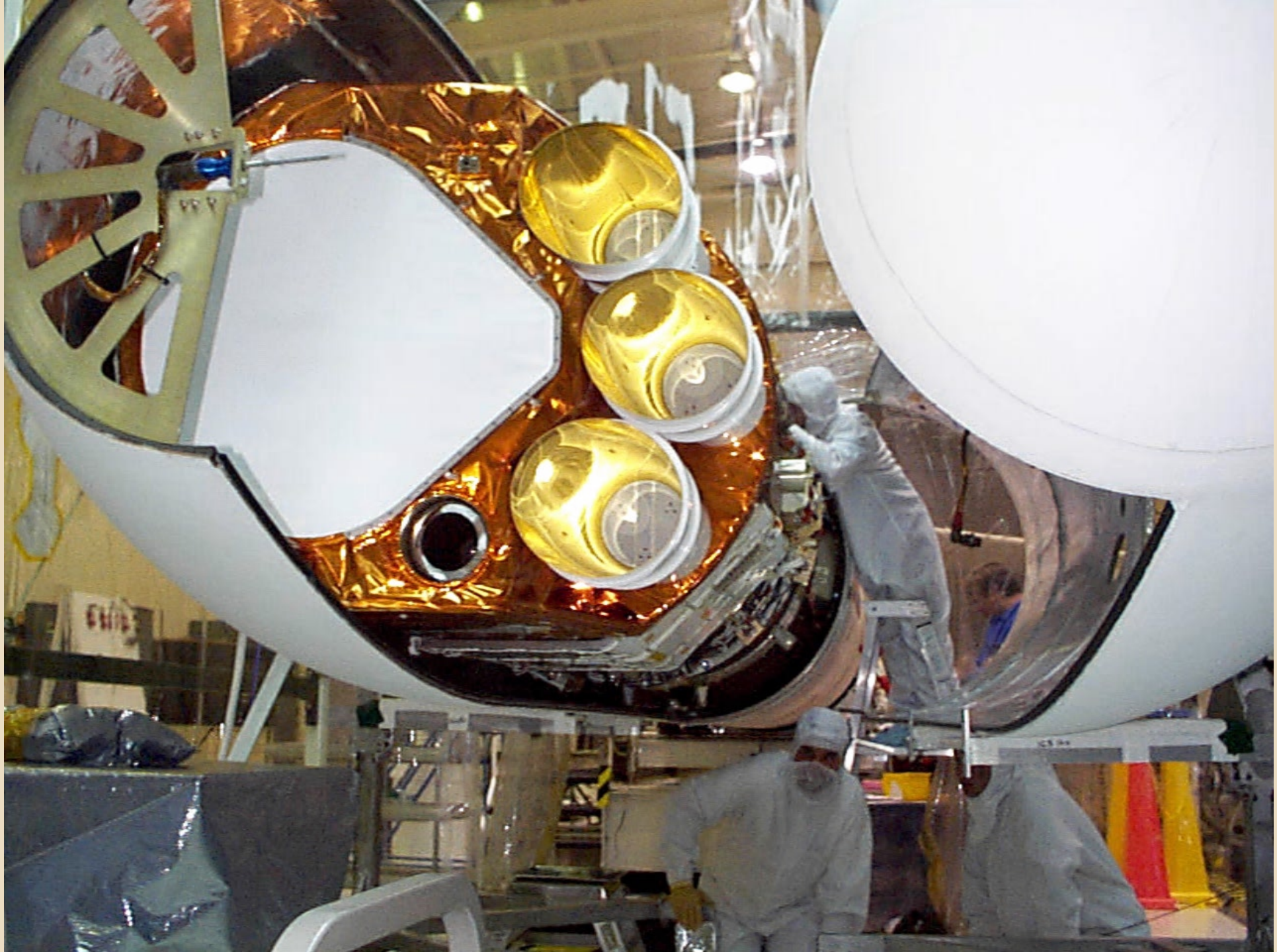
- 3-axis stabilized
- 5'' absolute pointing
- 3-5'' pointing stability





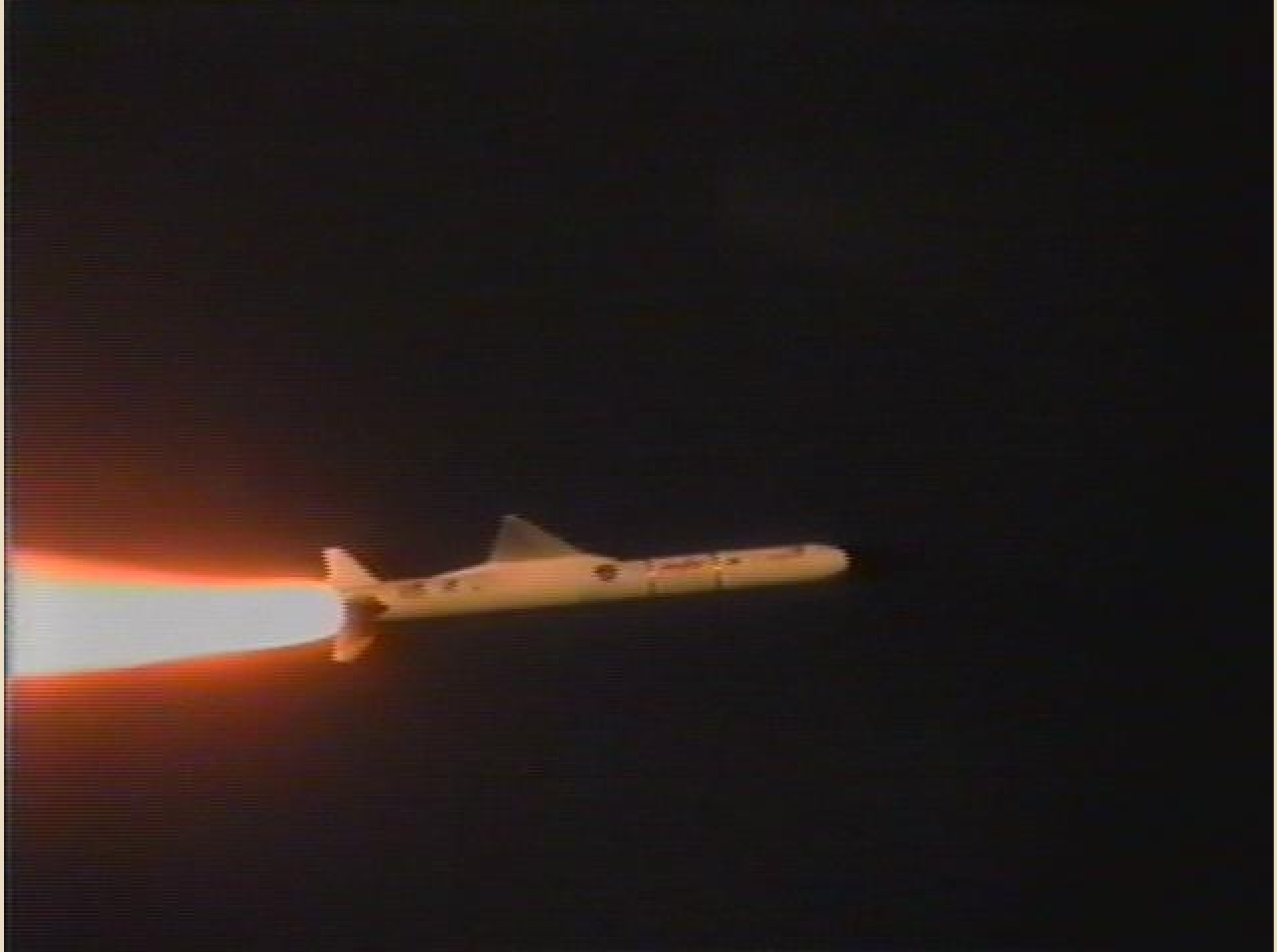






December 5, 1998
Vandenberg AFB

Airbrasil

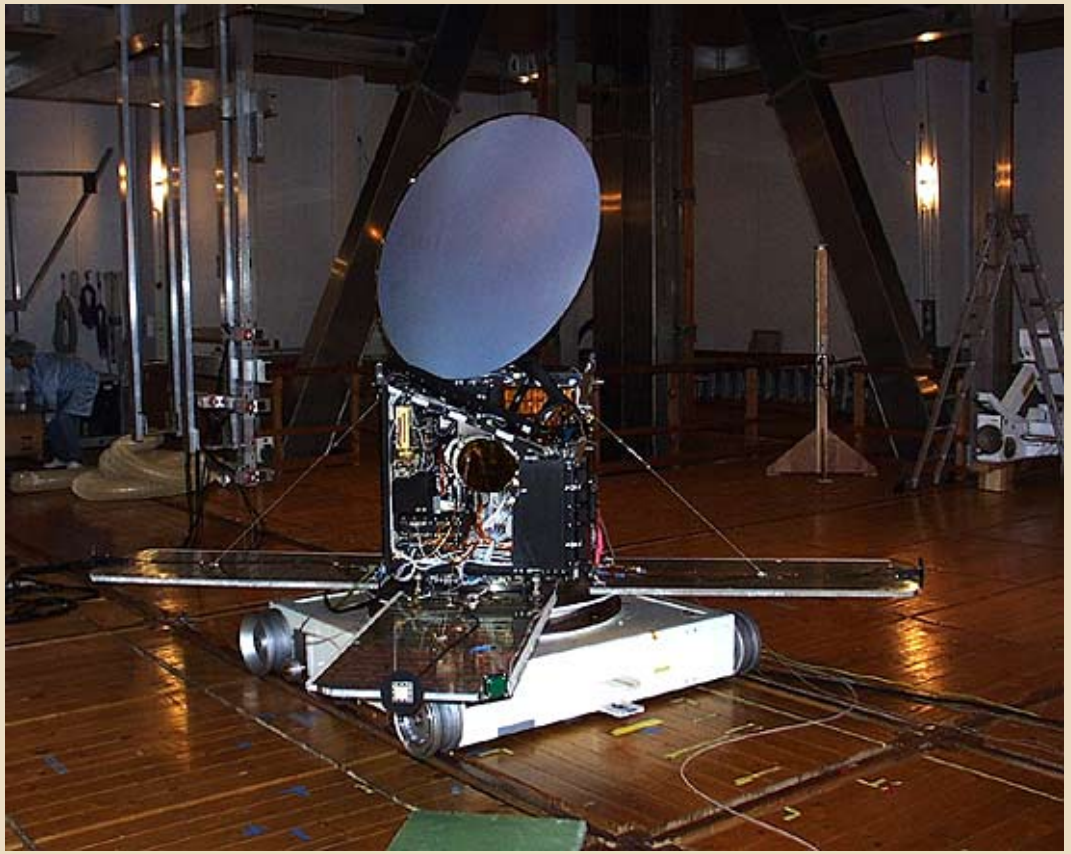


Odin

1.1 m offset Gregorian antenna
Beam size 10' (118 GHz);
2.4'→ 2.1' in submm range
242 kg

Launched 20 February 2001

Multiple receivers:
118 GHz HEMT (O_2)
486- 504 GHz tunable Schottky
541- 581 GHz tunable Schottky
Stirling cycle cooler to 140 K
AOS and digital autocorrelation spectrometers



Sweden + European collaboration

Herschel – an ESA Cornerstone Submm Space Mission

3.5m diameter SiC Cass telescope – largest monolithic astronomical space telescope

3 L-He cooled instruments

670 μm → 60 μm range

Wavefront error < 6μm rms

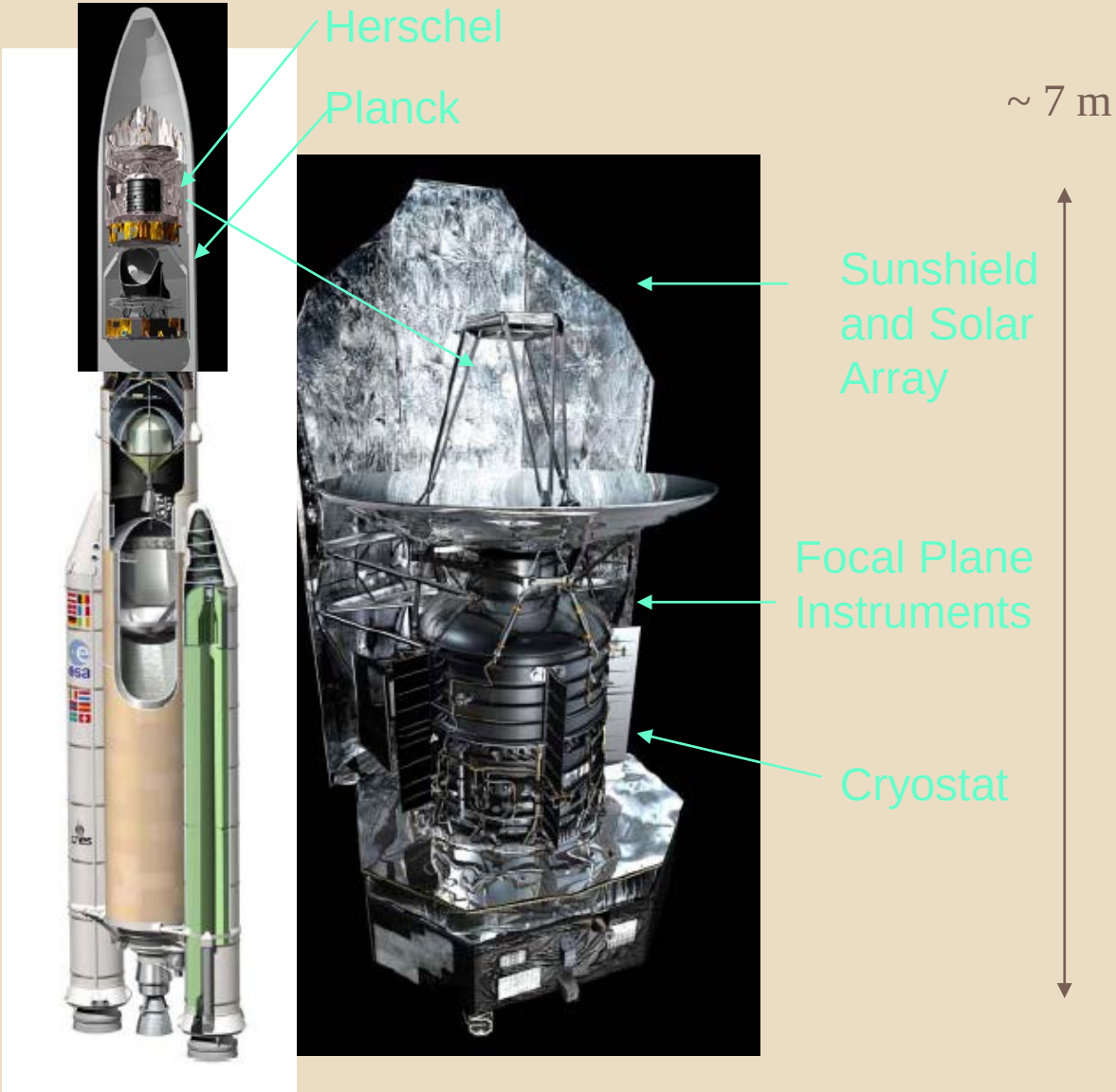
$\Delta\theta = 50'' \rightarrow 9''$

L2 halo orbit

Minimum 3.5 yr mission lifetime

Ariane 5 ECA Launch

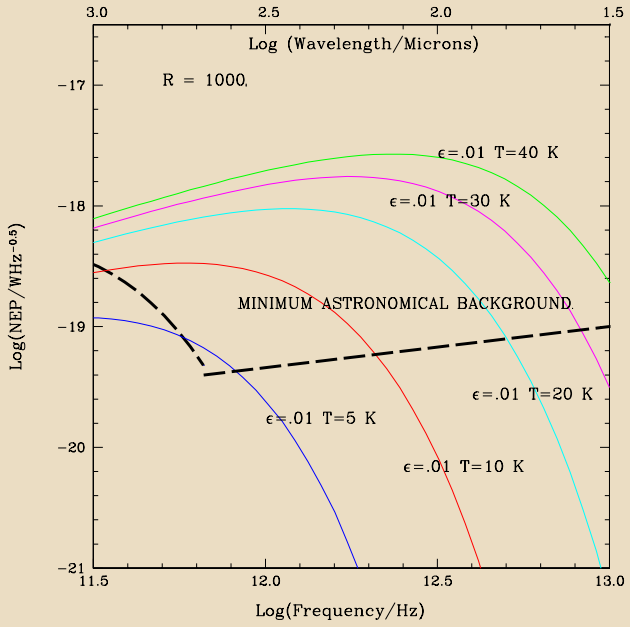
Harold Yorke was NASA Herschel Project Scientist 2001-2006



NASA Made Major Investments in Herschel Satellite and Operations

- Provided mission-enabling technology for two of three Herschel instruments
  - Spiderweb bolometer detectors and readouts for SPIRE photometer and spectrometer
  - Submillimeter local oscillator system and front-end for one band for HIFI instrument
- For U.S. Scientific community, the NASA Herschel Science Center is a major resource
  - NHSC provides data reduction training, computer resources, and is conduit for NASA funding to Herschel investigators
- NHSC has provided to Herschel mission as a whole
  - observation planning, proposal submission, and other software used by HSC
  - Personnel embedded at HSC and ICCs during pre-launch and performance verification periods

Beyond Herschel – SAFIR
Single Aperture Far Infrared Mission



Some Science Themes:

Observe fine structure lines at high redshift (z < 10)

Detect H_2 rotation lines to z = 20

Detect Kuiper Belt objects; measure albedo and temperature

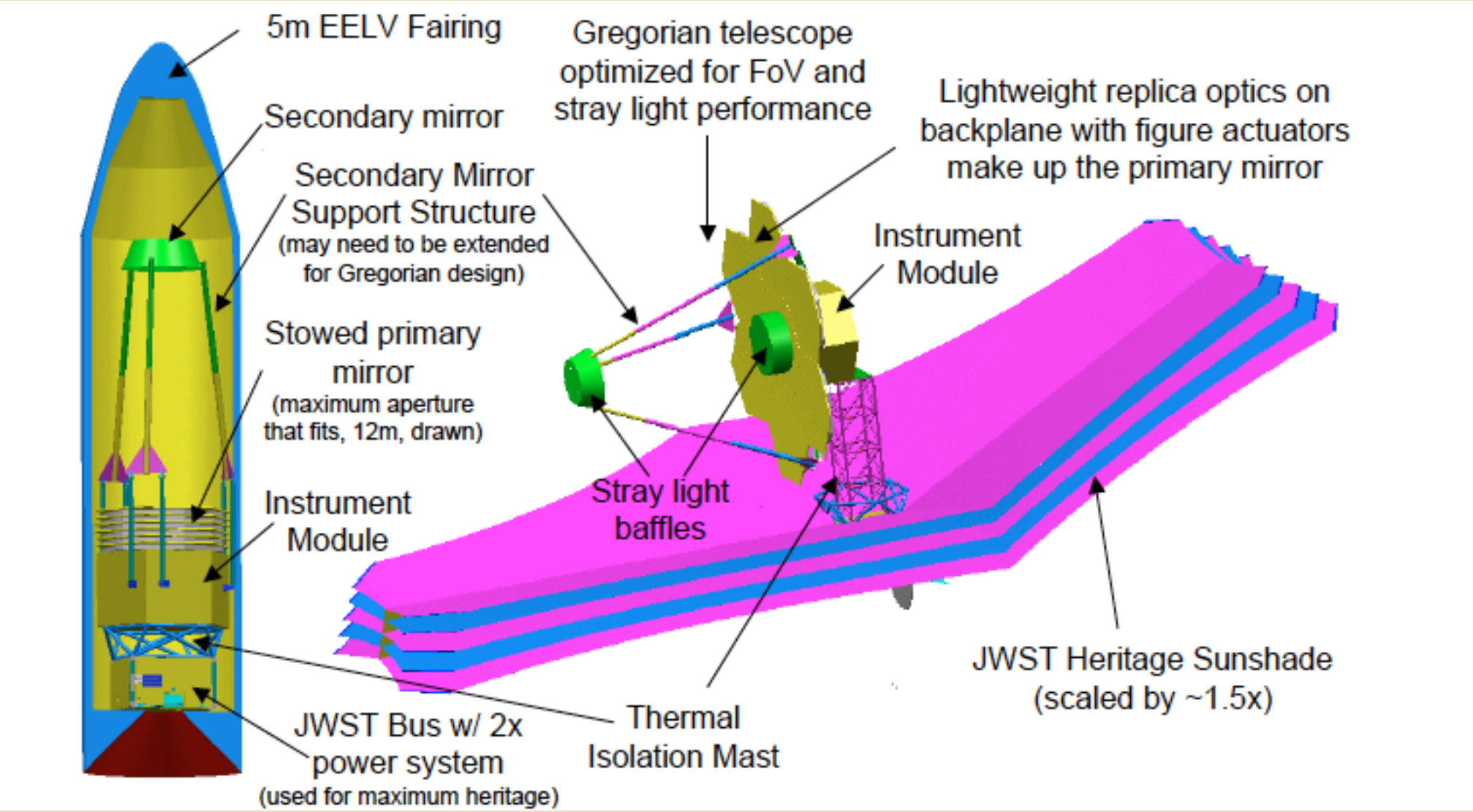
~10m dia. aperture for required sensitivity and reduced confusion limit for photometry

Cooling aperture to ~4 K results in being limited by photon noise from astronomical background assuming detector noise can be appropriately low

Recommended for study by 2000 Decadal survey

H.Y. had major involvement in science planning, conferences, and design studies

SAFIR Conceptual Design Derived Significantly from JWST

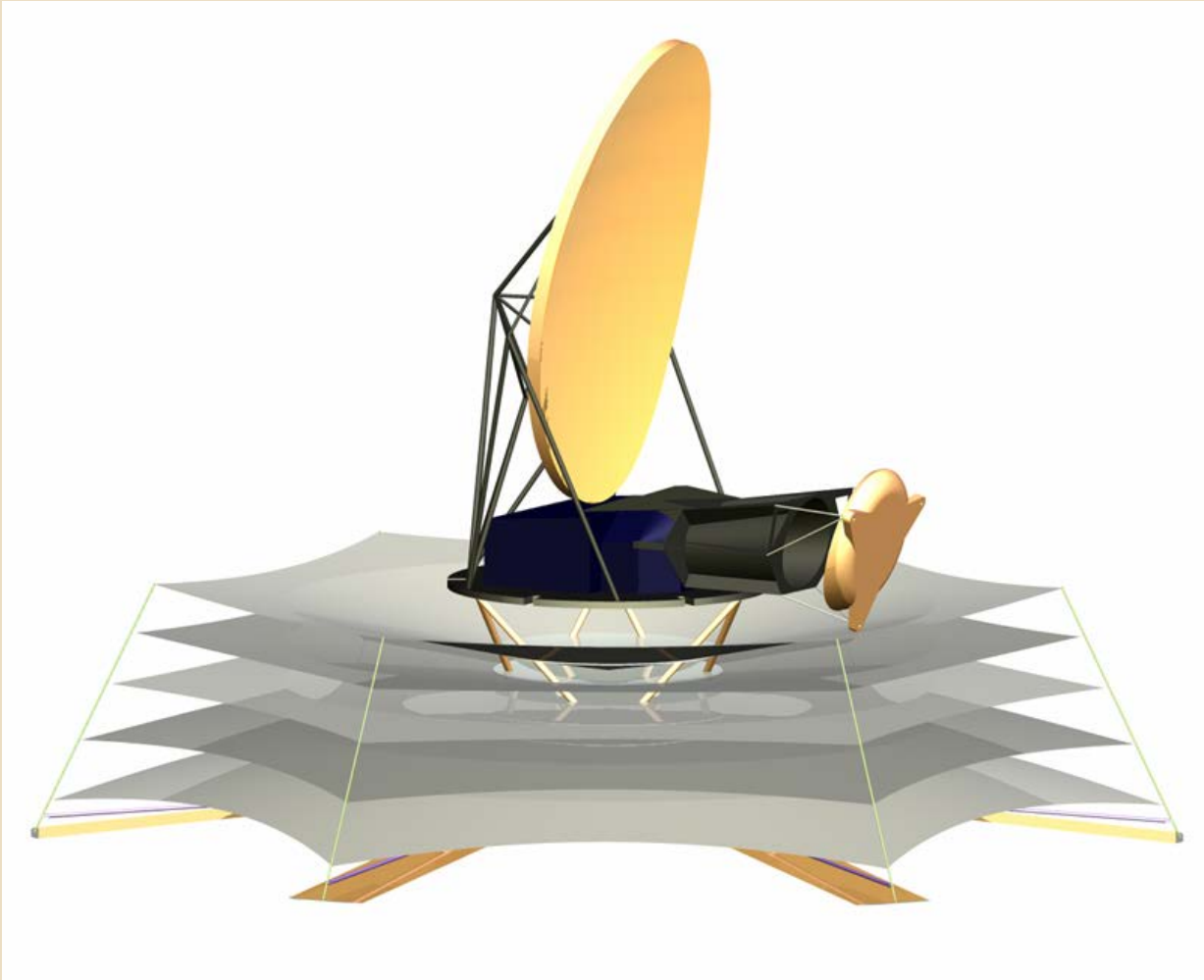


Cryogenic Aperture Large Infrared Space Telescope

CALISTO

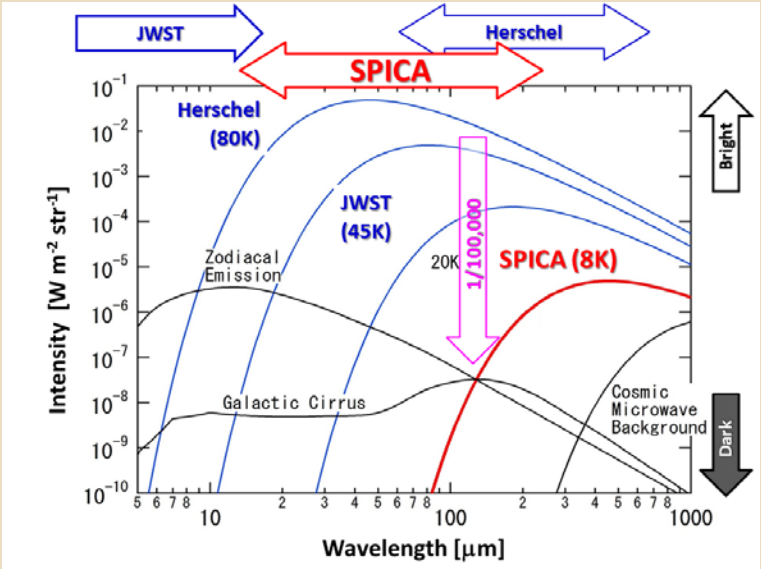
Studied at JPL 2005-2008
Key realization was that to achieve
ASTRONOMICAL LIMITED BACKGROUND (ABG)
over much of the sky is impossible when spillover and scattering from conventional (symmetric) telescope feedlegs and subreflector are included
Solution: use off-axis (unblocked) design (as recognized by CMB community)

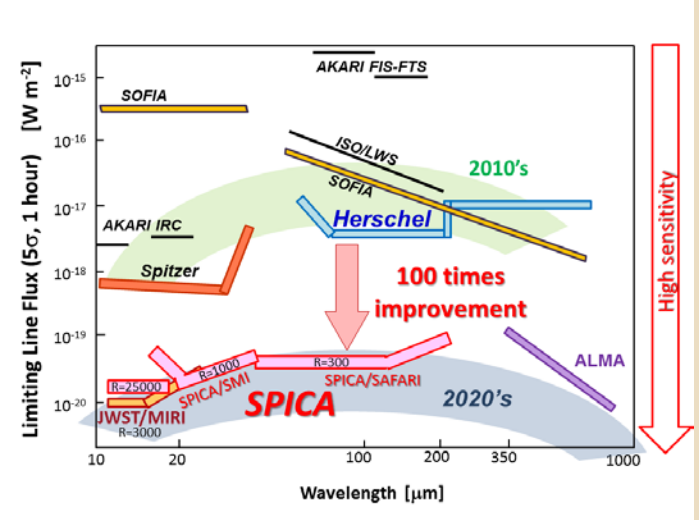
Concept has 4m x6 m off—axis Gregorian
Planck-like multilayer sunshields
General science and instruments follow SAFIR heritage
Harold Yorke was involved in science and mission design
Presented to 2010 Decadal Survey for Technology Development

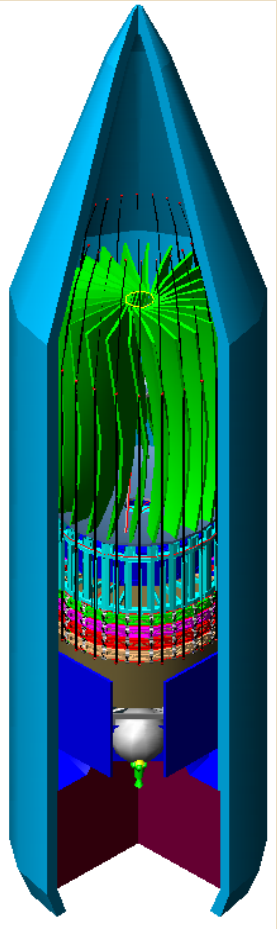


SPICA – ESA-JAXA Joint Mission (with possible US/JPL involvement)

2.5 m diameter SiC telescope
Cooled to 8 K
Instrument complement being refined
Mid-infrared instrument (SMI; 12 - 36 µm)
Far -infrared instrument (SAFARI; 34 - 230 µm)
Set of BLISS grating spectrometers (M.Bradford & NASA MOO)
Submitted to ESA M5 Call in October
ESA must approve for mission to proceed







MILLIMETRON

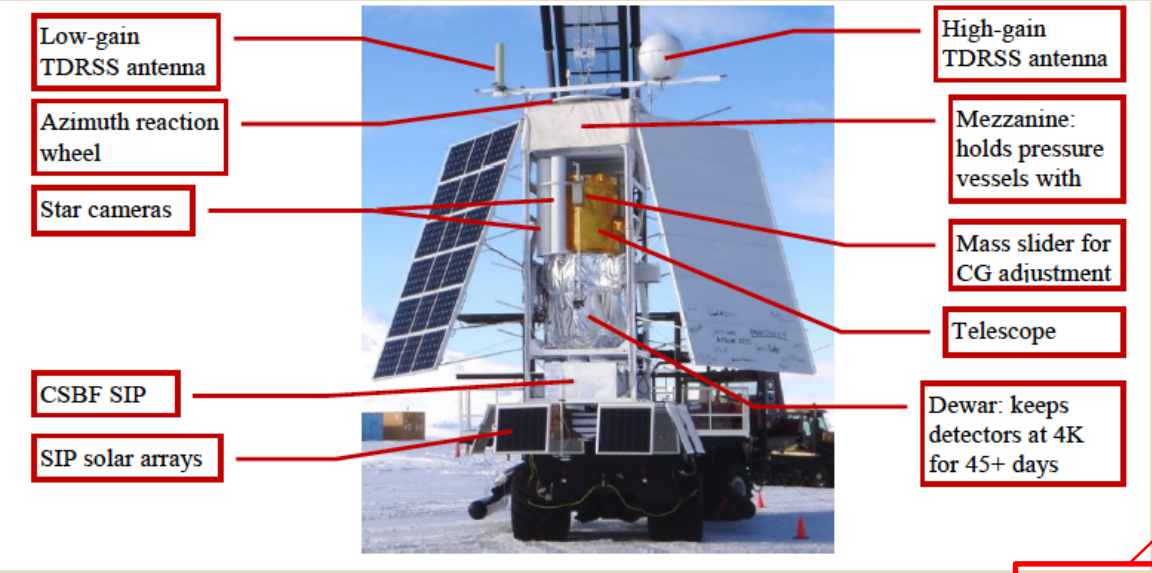
Space mission in Russian Federation Space Budget through 2020

Key Elements of Capability

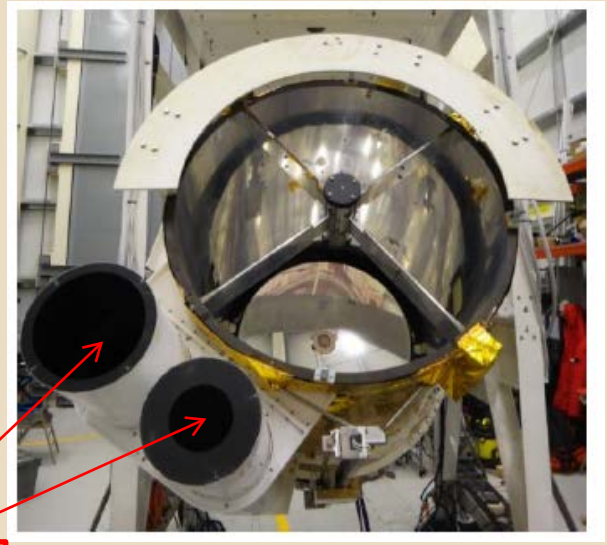
- Earth-Space VLBI (with ALMA)
- **S**hort-wave **A**rray **C**amera **S**pectrometer **(SACS)** Camera: 4 bands: **70, 125, 230, 375 µm**
- Spectrometer: long slit grating spectrometers: **50-450 µm**
- **L**ong wave-**A**rray **C**amera **S**pectrometer **(LACS)**
  FTS : **0.3-3 mm**
- High resolution (heterodyne) spectrometer w/ 3-7 pixels 60-600 µm

RUSSIA *MILLIMETRON* D = 10m

What's Coming?
STO-2 Mission (C.Walker U of A PI)
NASA ADAP Antarctic U/LDB – Dec. 2016 launch



STO-1 before launch

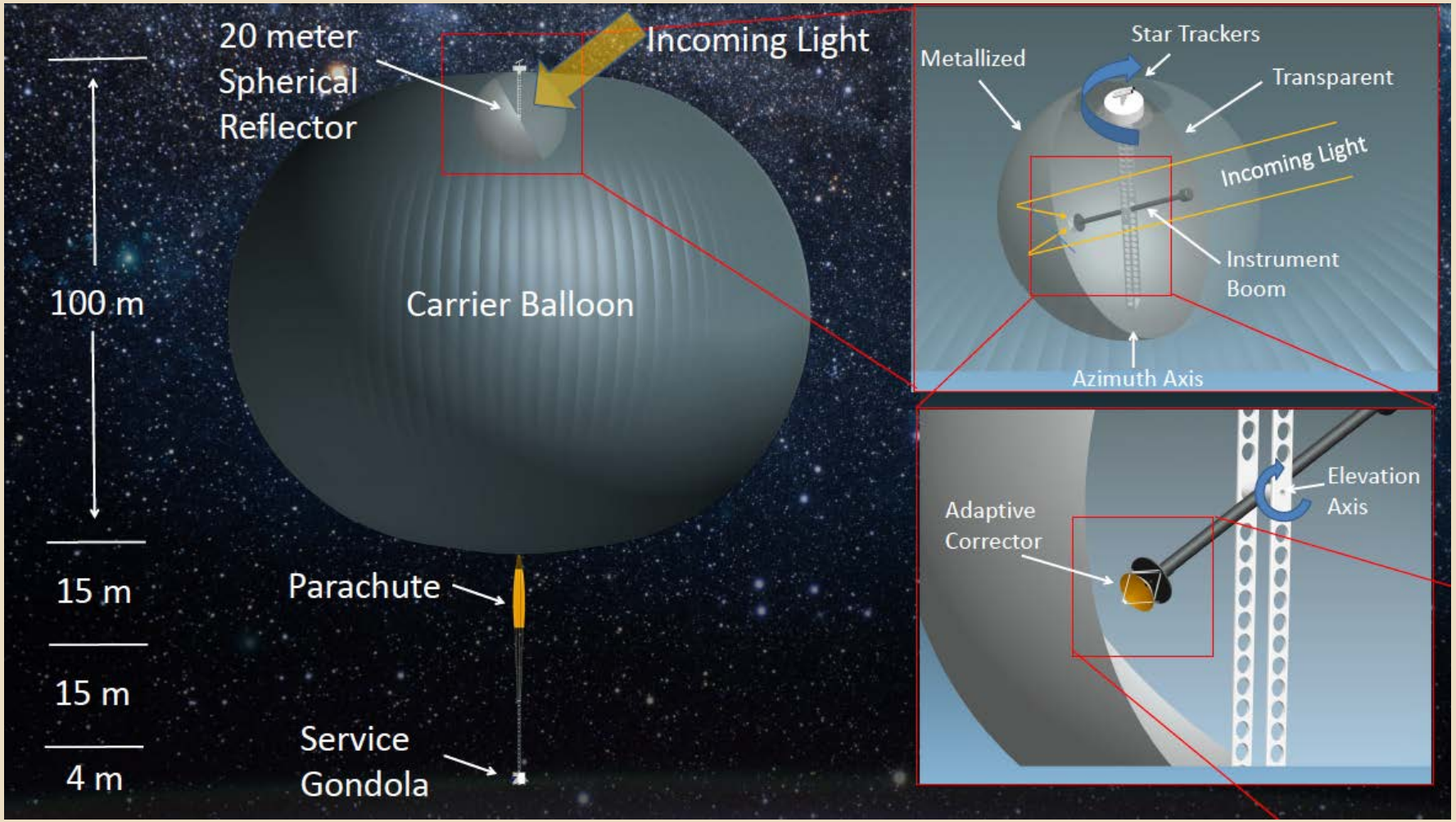


Star Trackers

80cm dia telescope; 1' resolution

Focal Plane Includes 5 HEB mixers:
2 pixels @ 1.46 THz for **[NII]** $^3P_1$- $^3P_0$ frequency-multiplied LO (JPL)
1 pixels @ 1.90 THz for **[CII]** $^2P_{3/2}$- $^2P_{1/2}$ frequency-multiplied LO (JPL)
1 pixel @ 4.75 THz for **[OI]** $^3P_1$- $^3P_2$ QCL LO (SRON)
Goal: Image 10^ox2^o region of inner galaxy in 3 key fine structure line tracers of molecular cloud evolution and star formation; 4^{o2} region of Large Magellanic Cloud

Large Balloon Reflector (LBR) – 10m dia submm Telescope for λ > 500μm



Provide ~ 3x angular resolution and ~6x point source sensitivity compared to Herschel at longer submm wavelengths – completed Phase II NIAC Project

U of A, SWIRI, JPL, Cornell Univ.