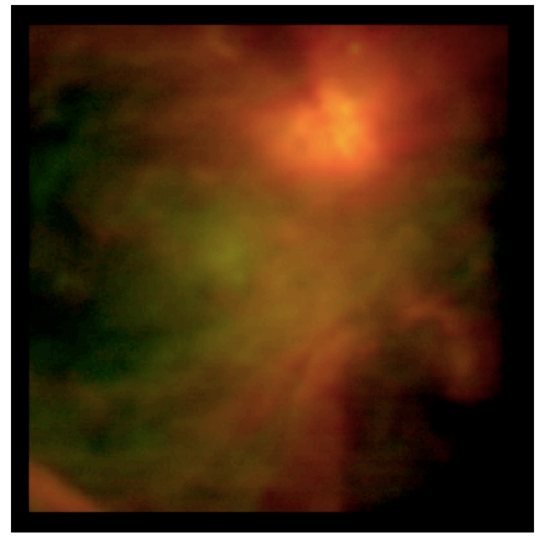
The Stratospheric Observatory for Infrared Astronomy (SOFIA)



R. D. Gehrz

Lead, SOFIA Community Task Force

Department of Astronomy, University of Minnesota

This talk will be posted at [*http://www.sofia.usra.edu/*](http://www.sofia.usra.edu/)

Outline

- *SOFIA Heritage and Context*
- *SOFIA Aircraft and Observatory Development Program*
- *SOFIA Performance Specifications*
- *SOFIA Science*
- *SOFIA Science and Instrumentation Schedule*
- *Summary*

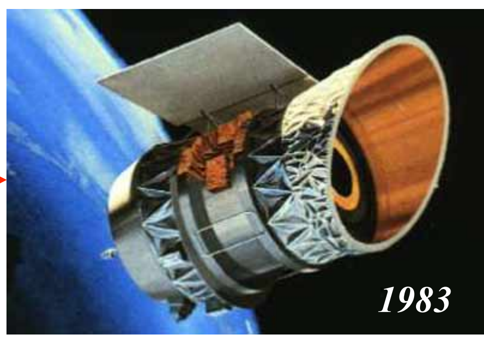
The History of Flying Infrared Observatories

NASA Lear Jet Observatory

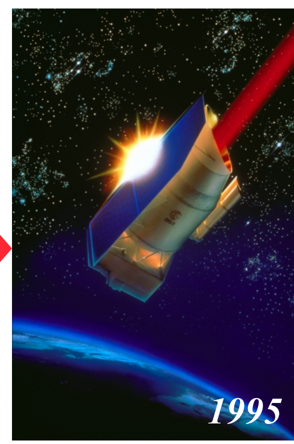
NASA Kuiper Airborne Observatory (KAO)

NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA)

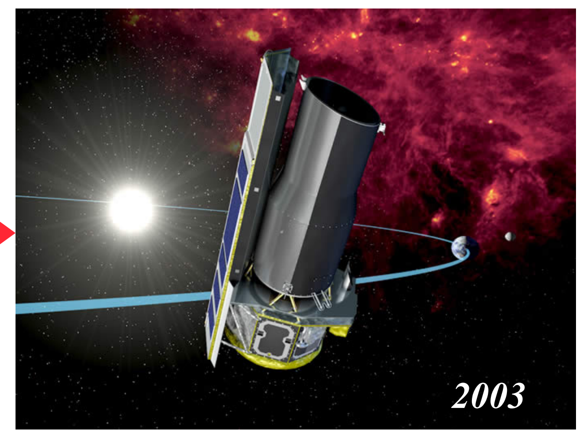
Science objectives



NASA Infrared Astronomical Satellite (IRAS)



ESA Infrared Space Observatory (ISO)



NASA Spitzer Space Telescope

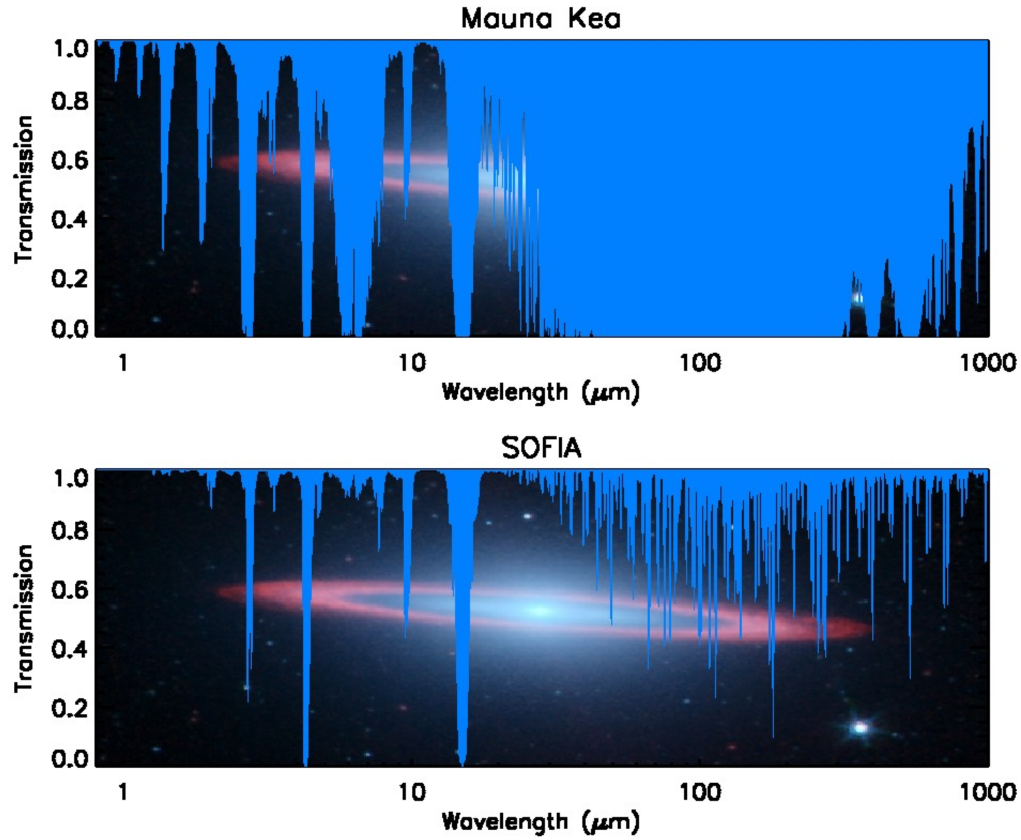
SOFIA Mission Overview, Aircraft Modification, and Status as of February 25, 2011

SOFIA Overview

- *2.5 m telescope in a modified Boeing 747SP aircraft*
  - *Imaging and spectroscopy from 0.3 μm to 1.6 mm*
  - *Emphasizes the obscured IR (30-300 μm)*
- *Service Ceiling*
  - *39,000 to 45,000 feet (12 to 14 km)*
  - *Above > 99.8% of obscuring water vapor*
- *Joint Program between the US (80%) and Germany (20%)*
  - *First Light Science in 2009*
  - *20 year design lifetime –can respond to changing technology*
  - *Ops: Science at NASA-Ames; Flight at Dryden FRC (Palmdale- Site 9)*
  - *Deployments to the Southern Hemisphere and elsewhere*
  - *>120 8-10 hour flights per year*

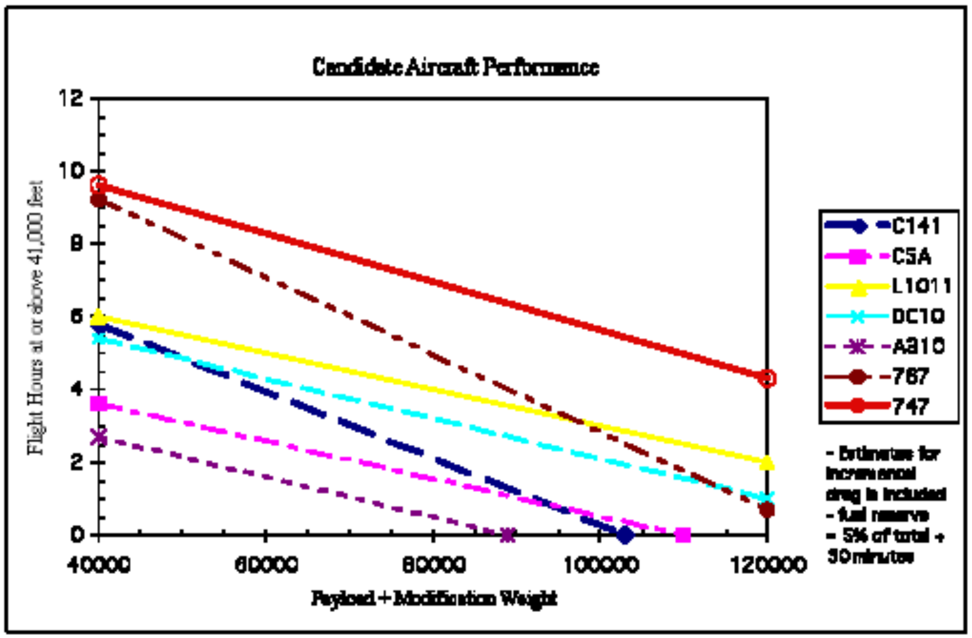
The Advantages of SOFIA

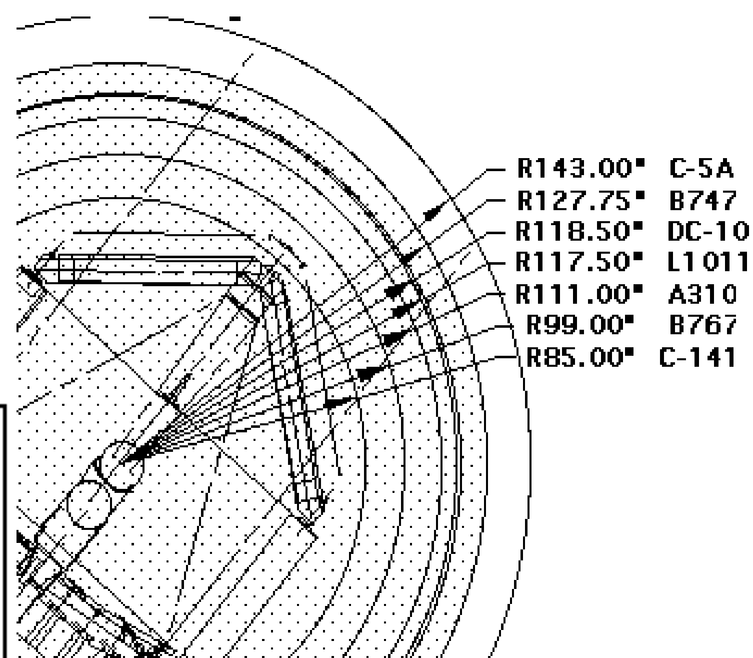
- Above 99.8% of the water vapor
- Transmission at 14 km >80% from 1 to 800 µm; emphasis on the obscured IR regions from 30 to 300 µm
- Instrumentation: wide variety, rapidly interchangeable, state-of-the art – SOFIA is a new observatory every few years!
- Mobility: anywhere, anytime
- Twenty year design lifetime
- A near-space observatory that comes home after every flight



SOFIA: Selecting the Aircraft

- *Fuselage diameter (length not an issue)*
- *Payload and loiter time at FL >410*
- *Cost ($13M in 1995 dollars)*

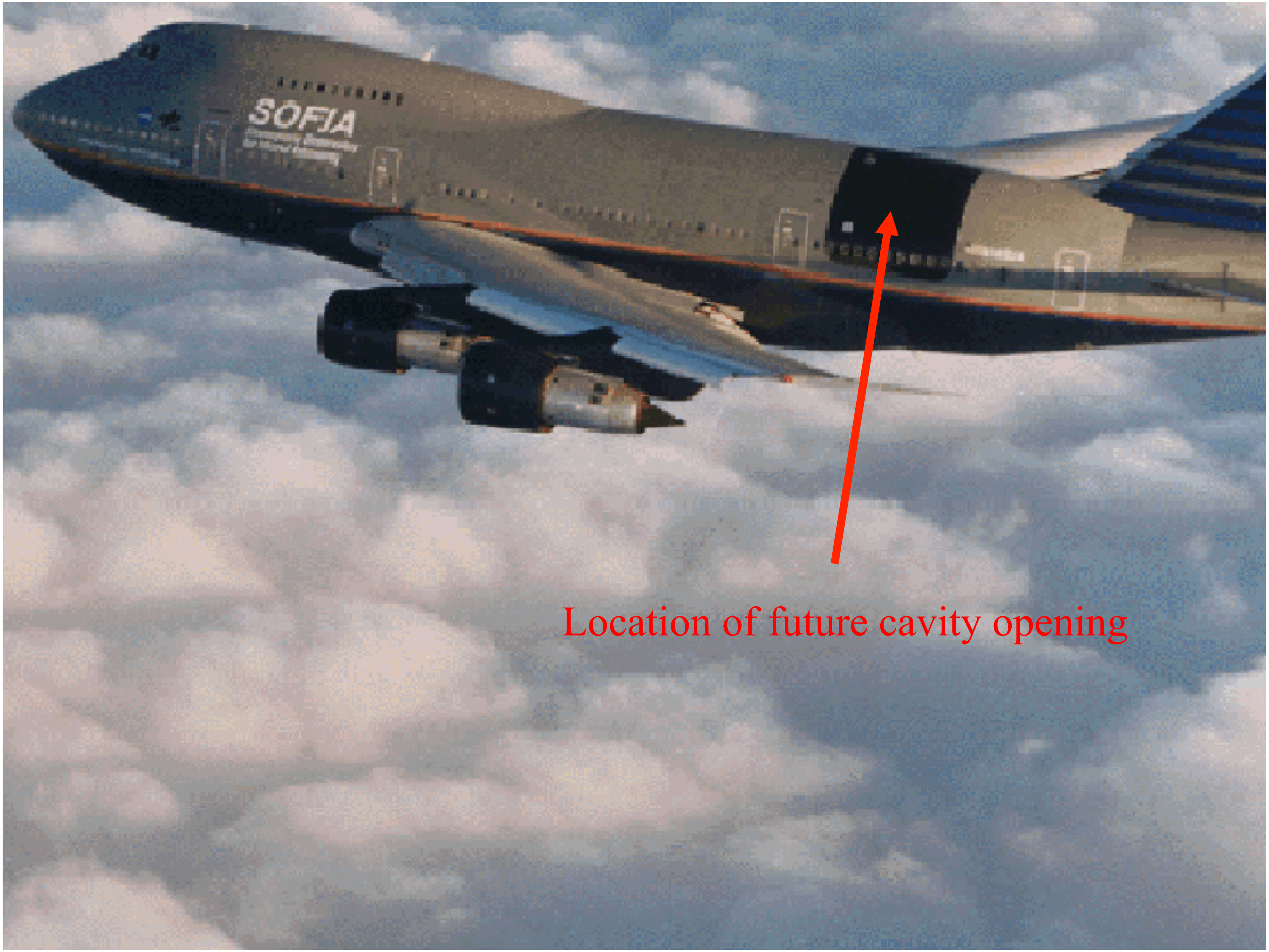


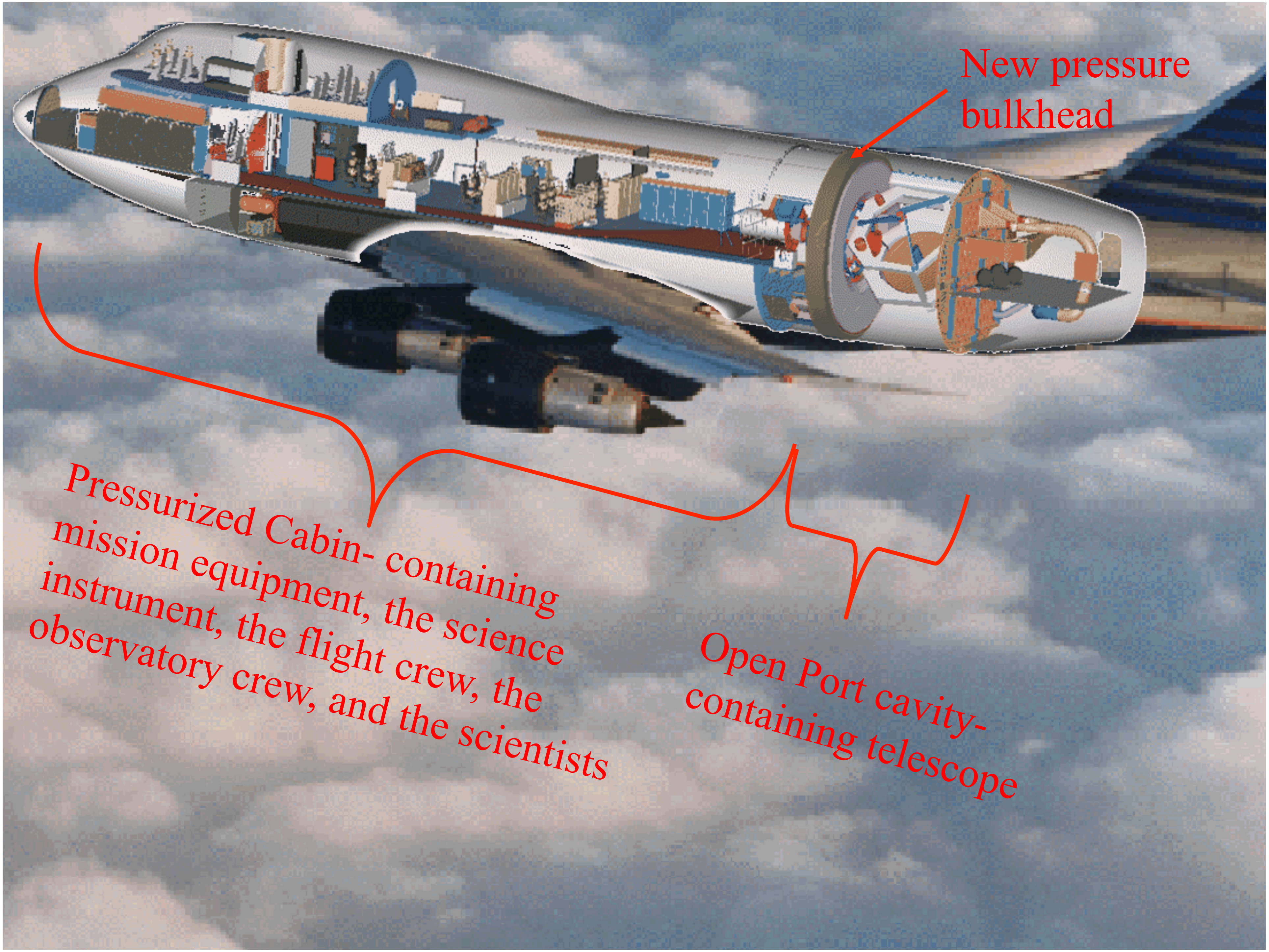


The winner:

Boeing 747-SP

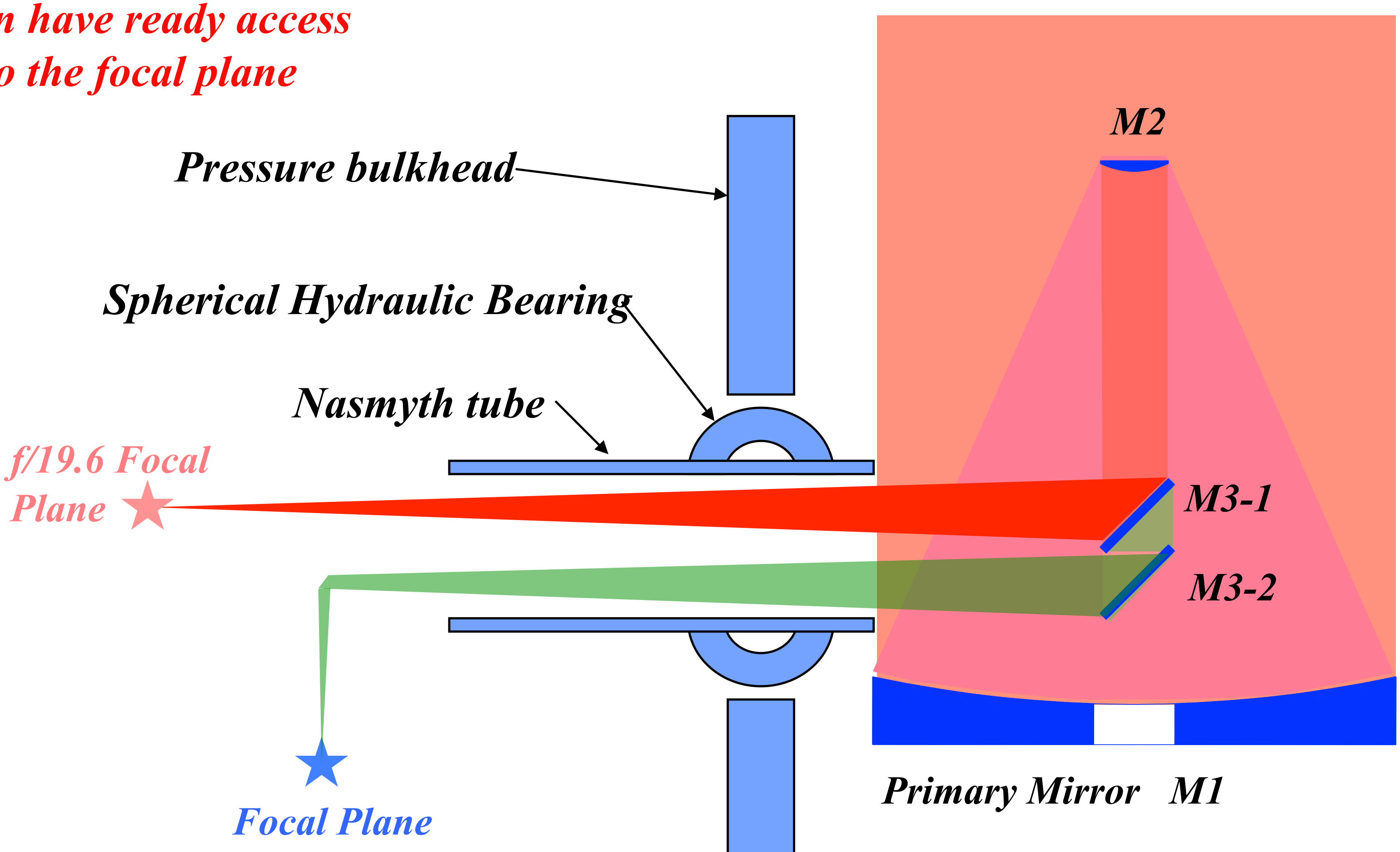
Retrofitted with P&W JT9D-7J engines to provide operational margin


SOFIA
Location of future cavity opening

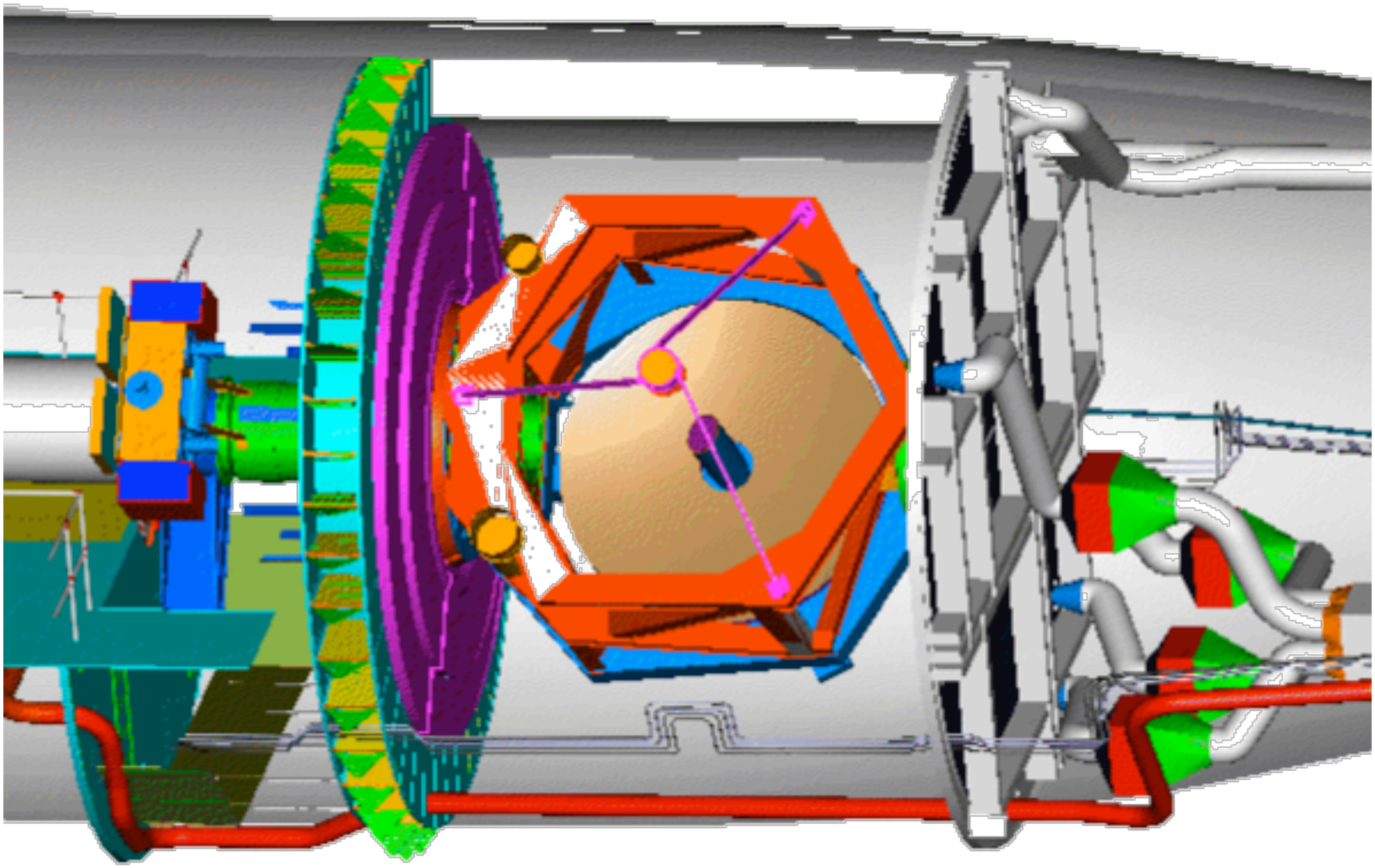

New pressure bulkhead
Pressurized Cabin- containing mission equipment, the science instrument, the flight crew, the observatory crew, and the scientists
Open Port cavity- containing telescope

Nasmyth: Optical Layout

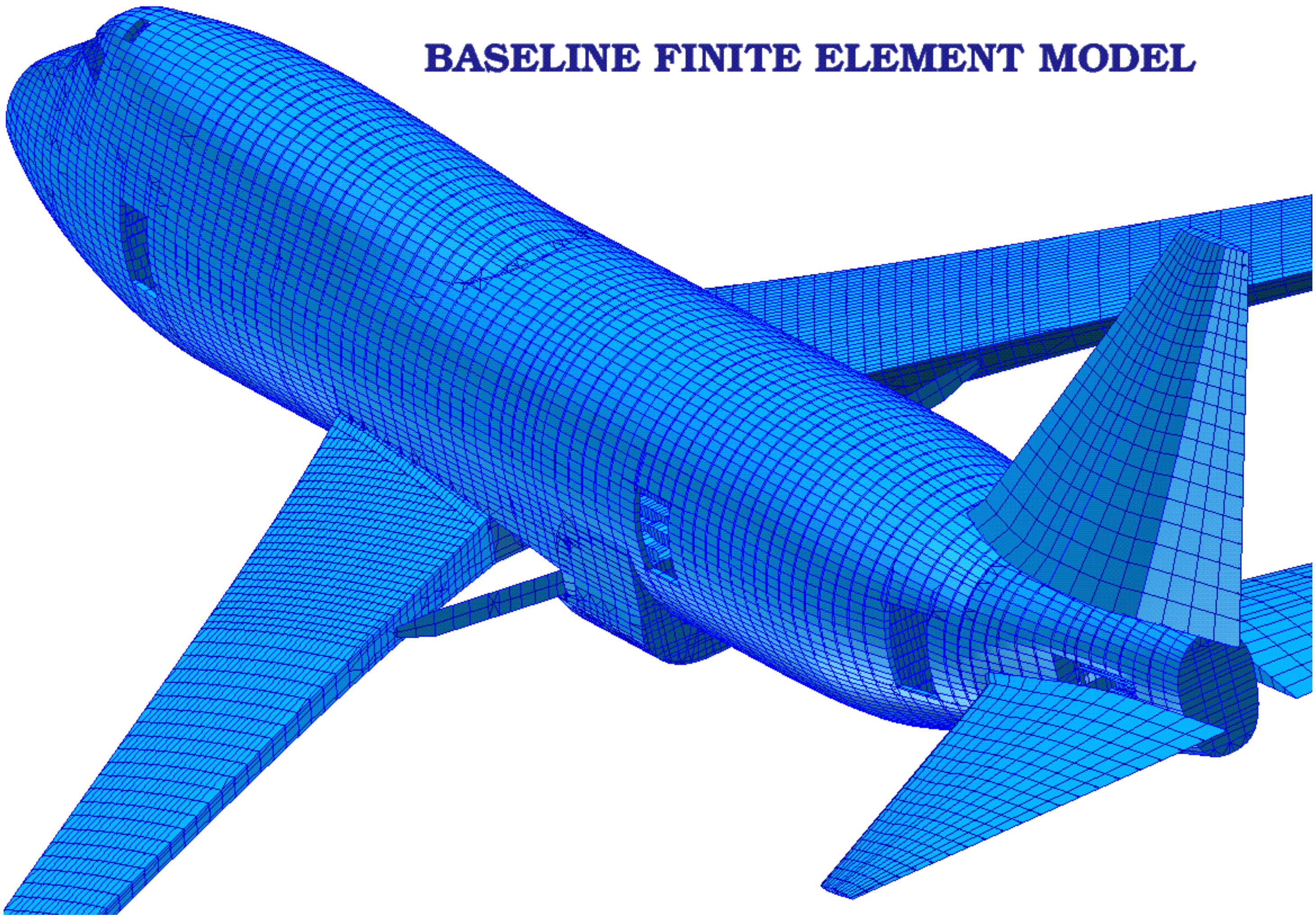
Observers in pressurized cabin have ready access to the focal plane



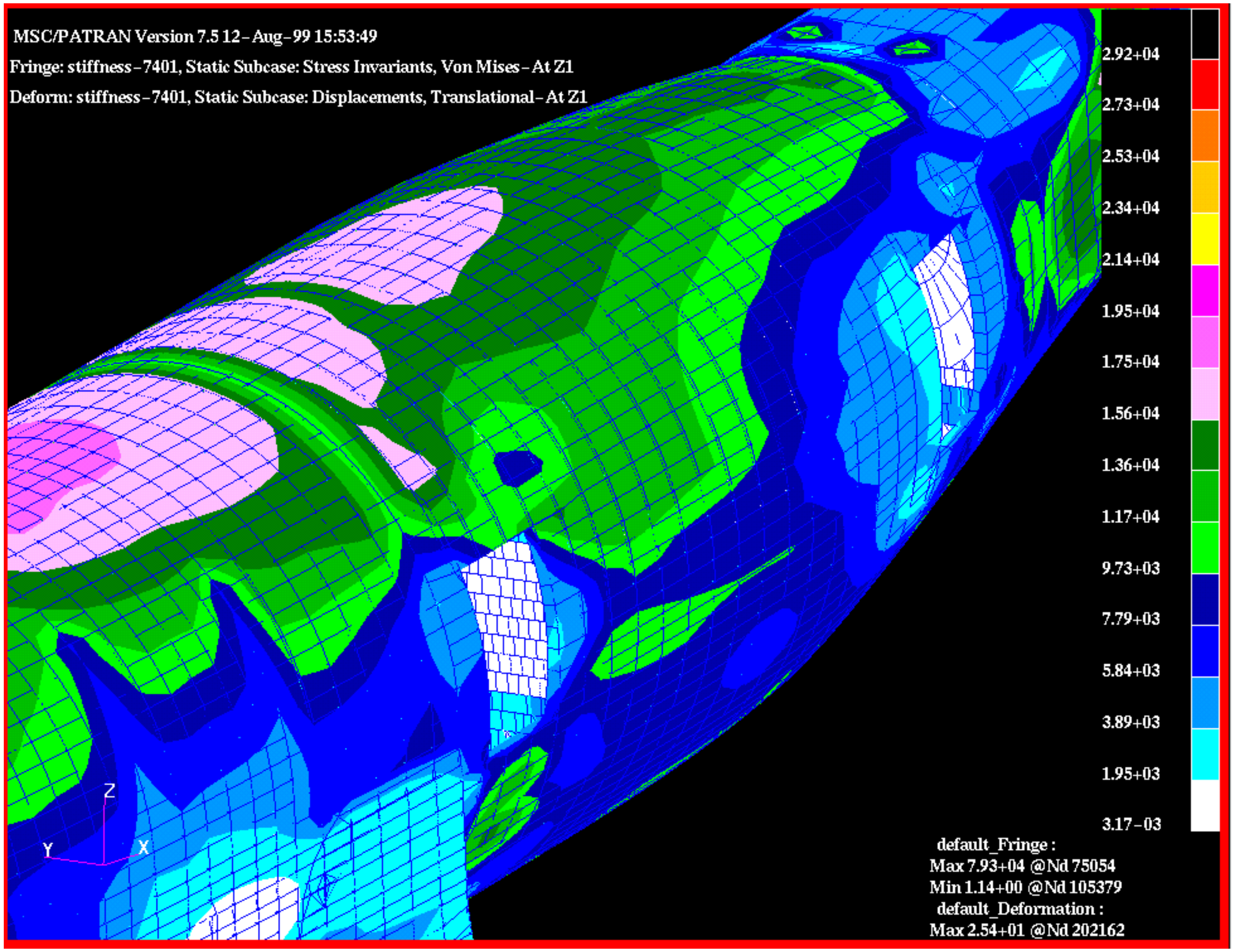
Telescope Size is Maximum that can fit Available Volume



BASELINE FINITE ELEMENT MODEL



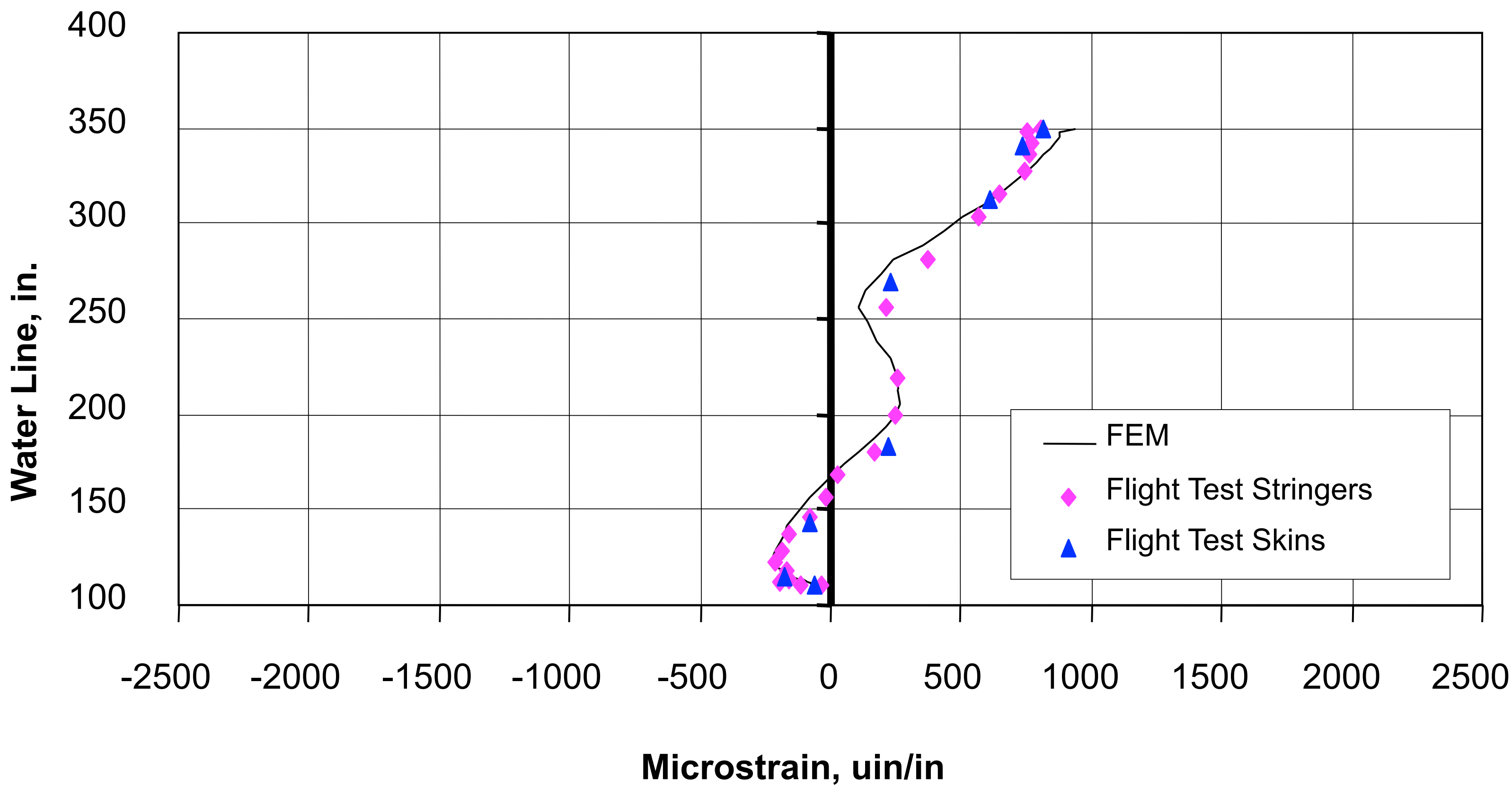
FEM Predictions for Unmodified Aircraft



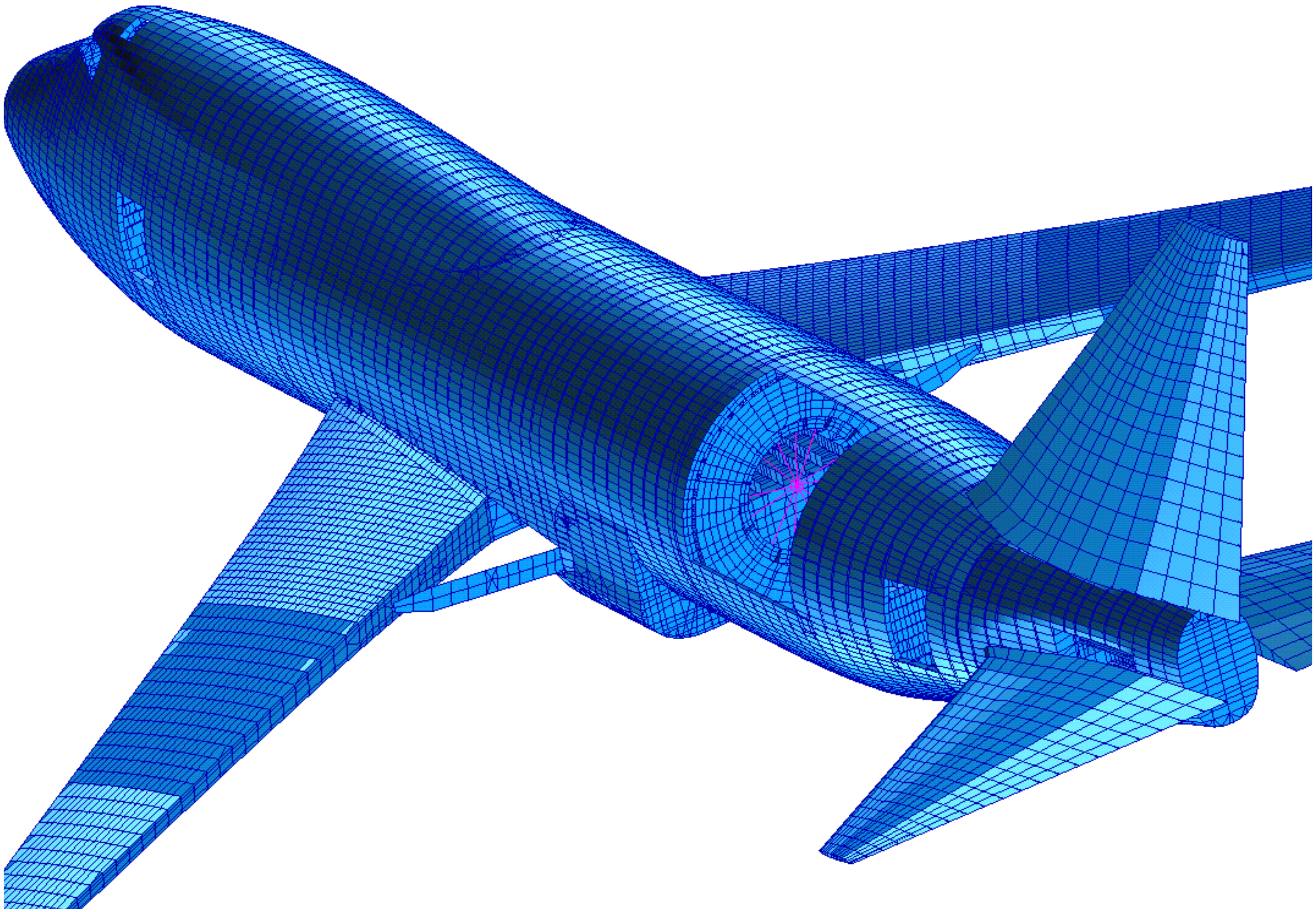
FEM Validation: Pre-Modification Flight Test Data

Sample Longitudinal Strain - Positive Vertical Acceleration

FEM Predicted Longitudinal Strain and Flight Test Calibrated Strain vs. Water Line
FEM Station 1990 (LHS)

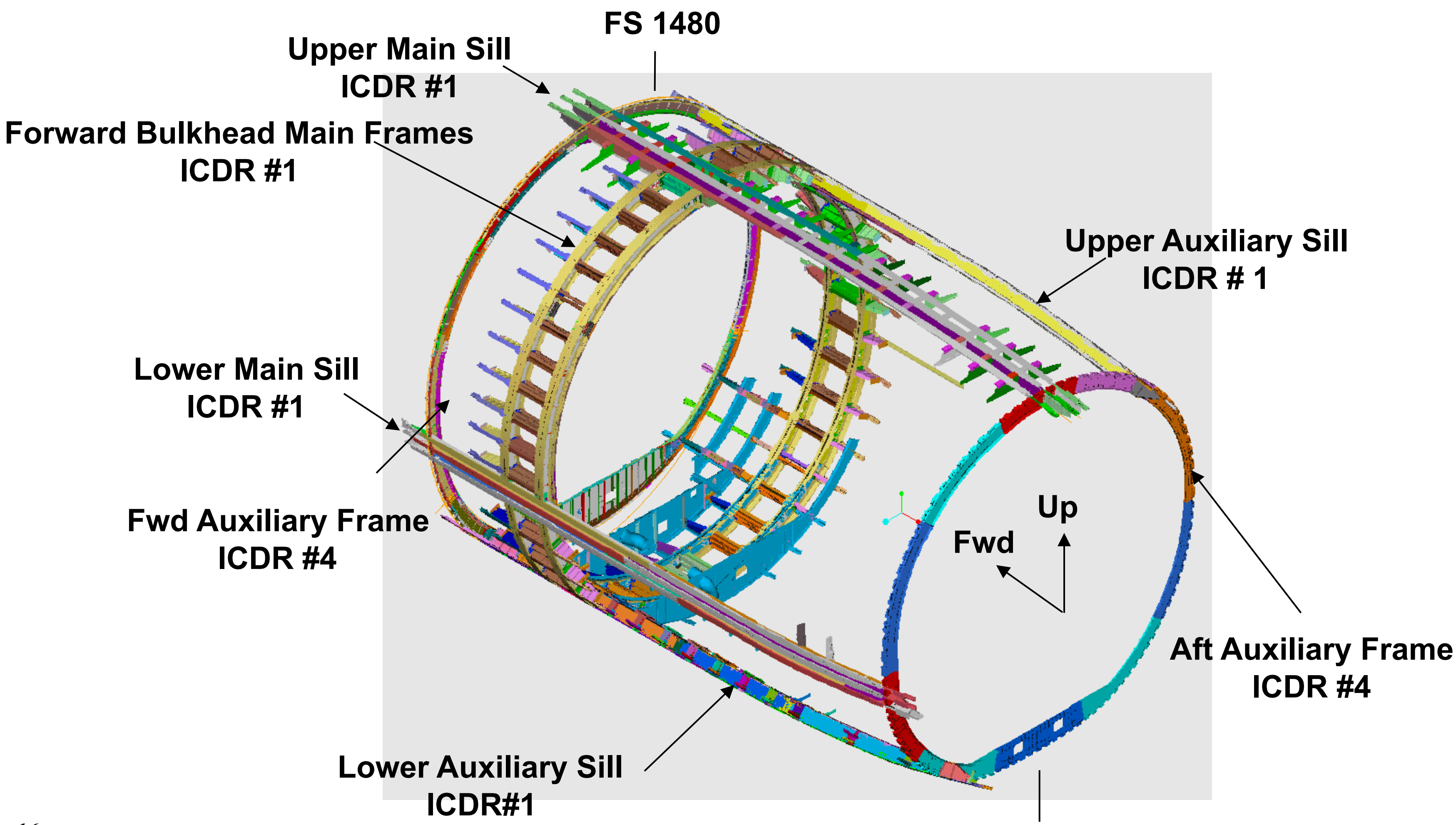


Modified Baseline Finite Element Model

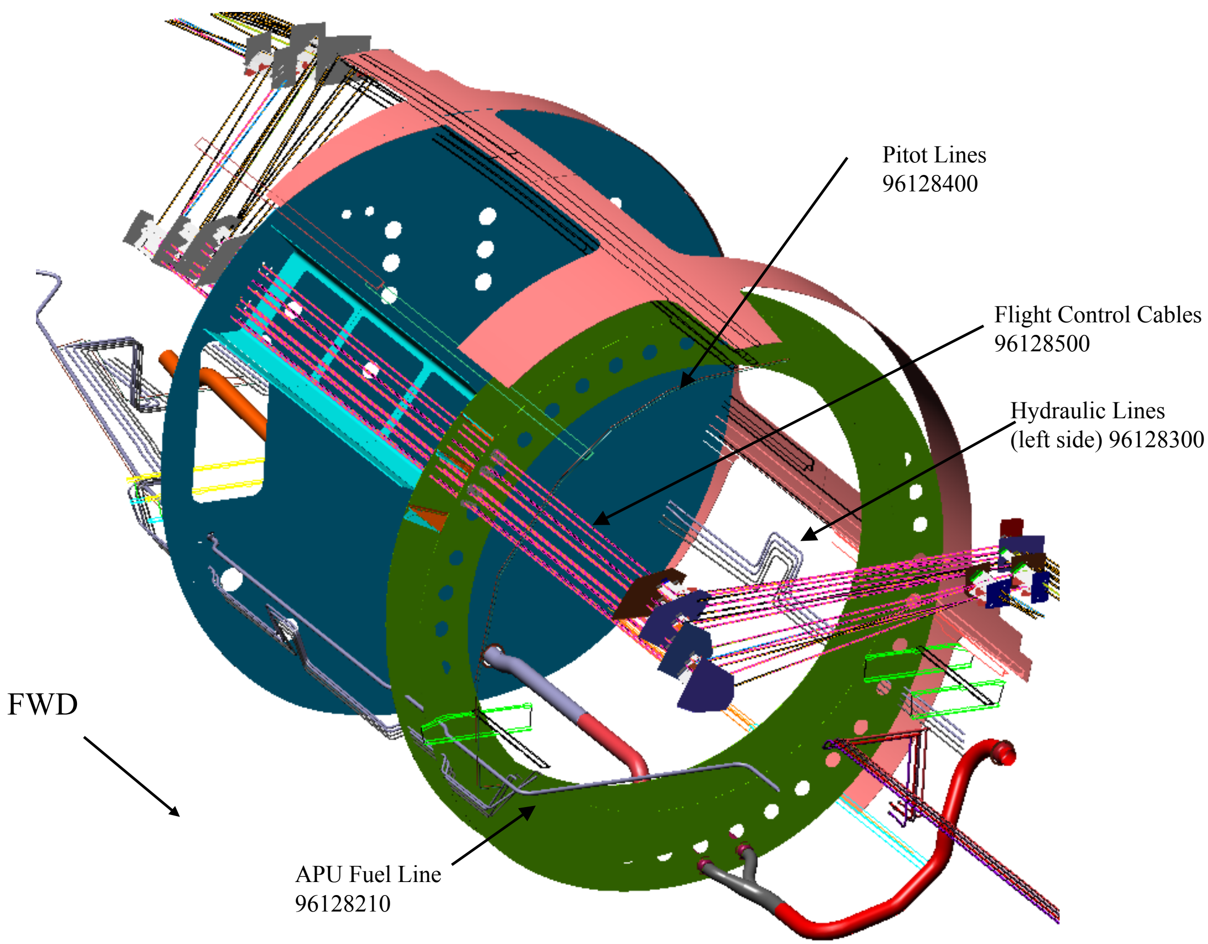


Incremental Critical Design Review = ICDR

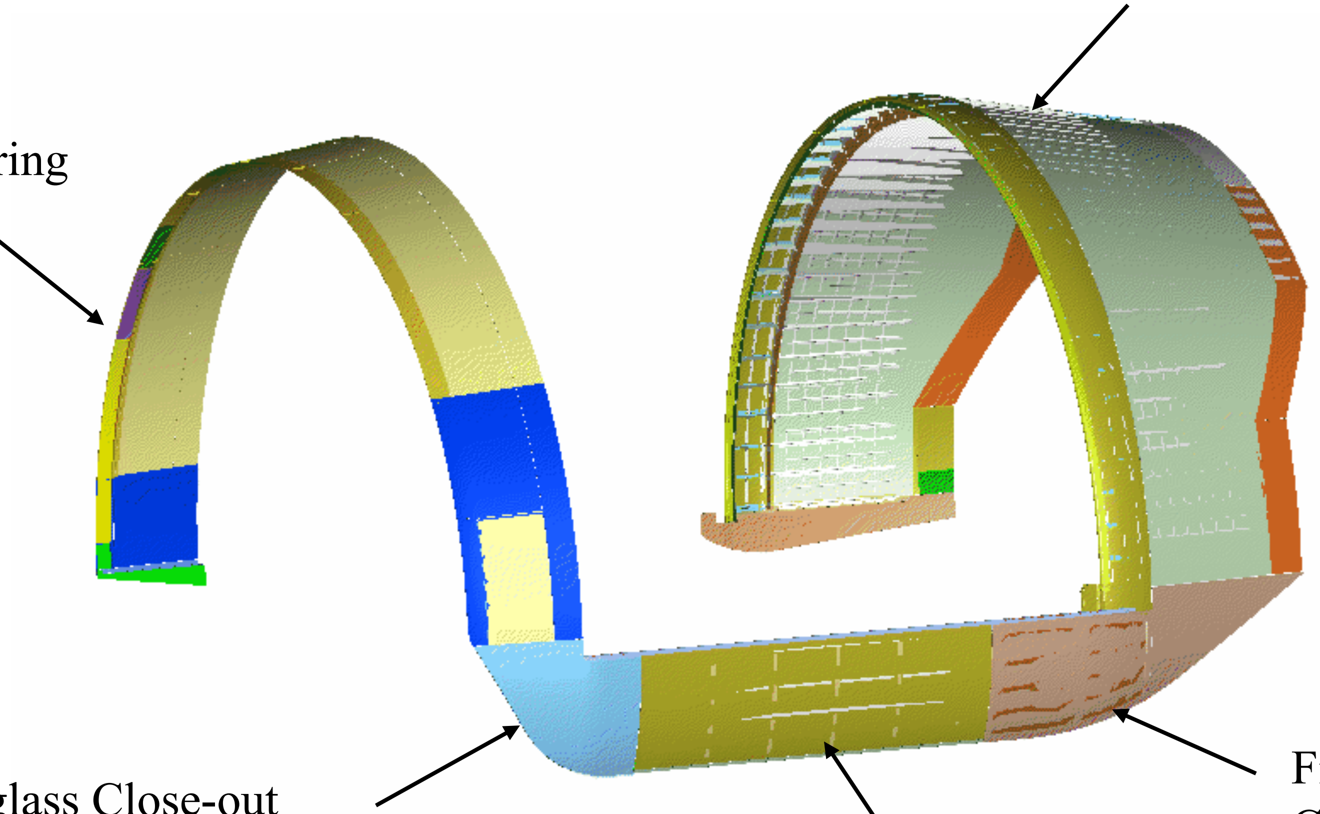
Frame Modifications and Sill Beams

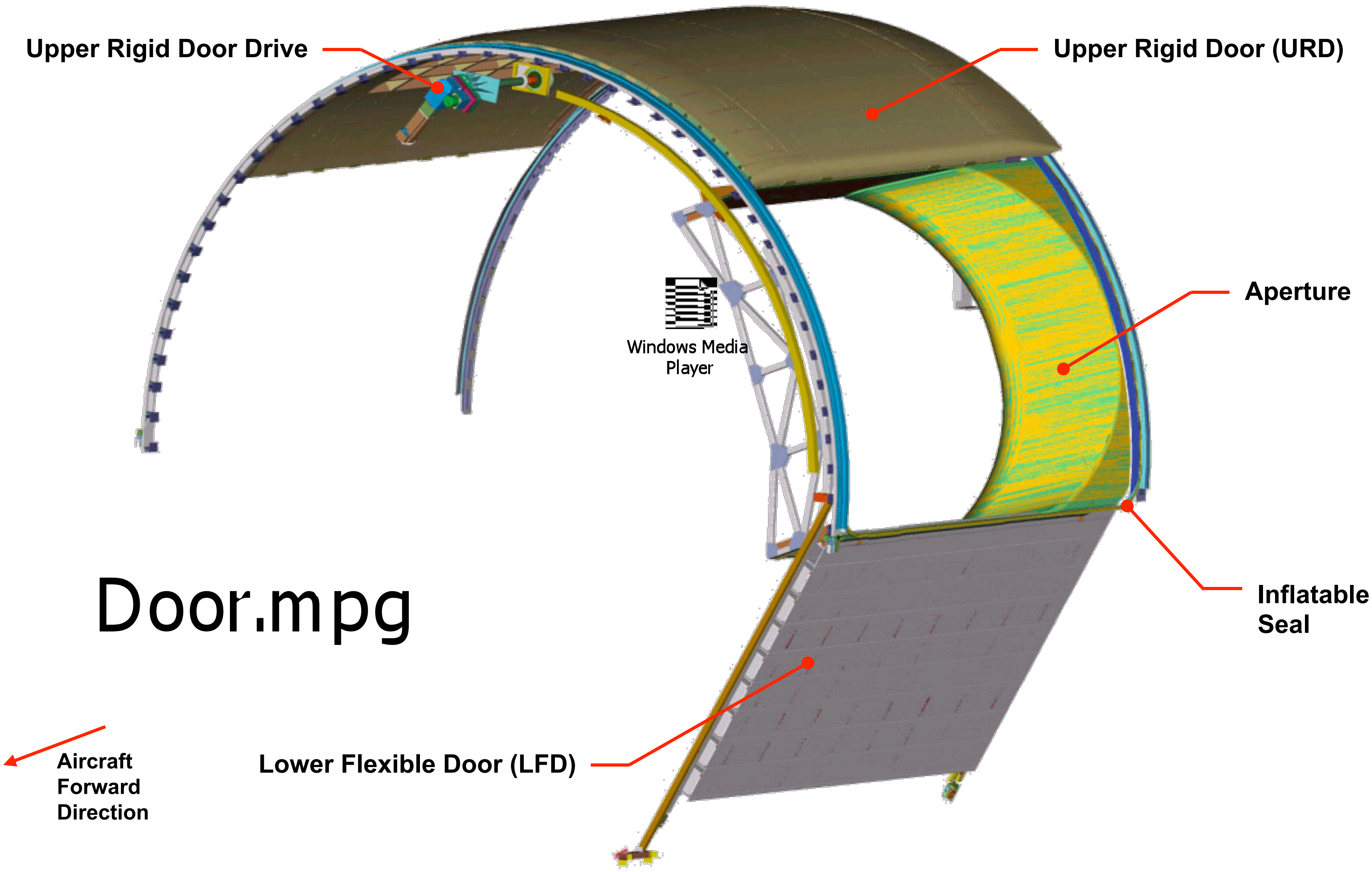


Control Cables - SOFIA Routing



Door System Fairings

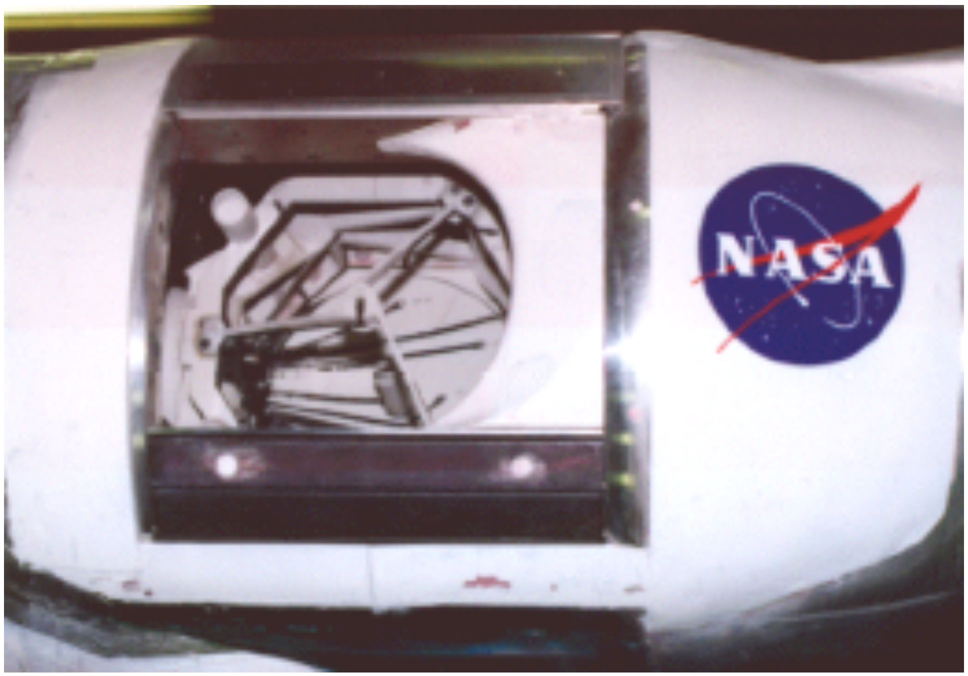



Upper Rigid Door Drive
Upper Rigid Door (URD)
Aperture
Windows Media Player
Inflatable Seal
Lower Flexible Door (LFD)
Aircraft Forward Direction

Door.mpg

Studies of Cavity Acoustics: SOFIA 7% model in Ames 14 foot Transonic Wind Tunnel

7% Wind Tunnel Tests



Partial External Door

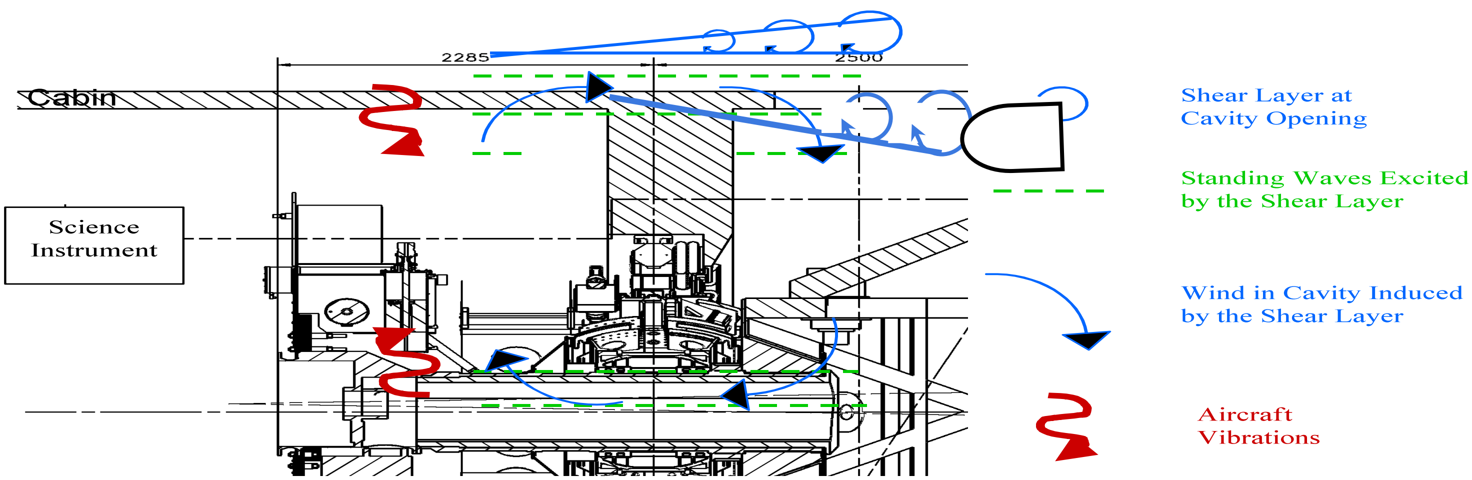
Test Description/Conditions

- Boeing 747-SP 7% Model
- NASA ARC 14-Foot Tunnel
- Mach: $0.3 \leq M \leq 0.92$
- Yaw: $-4.5 \leq b \leq 4.5^o$
- Angle of attack: $2^o \leq a \leq 5^o$
- TA Elevation: $25^o \leq g \leq 60^o$

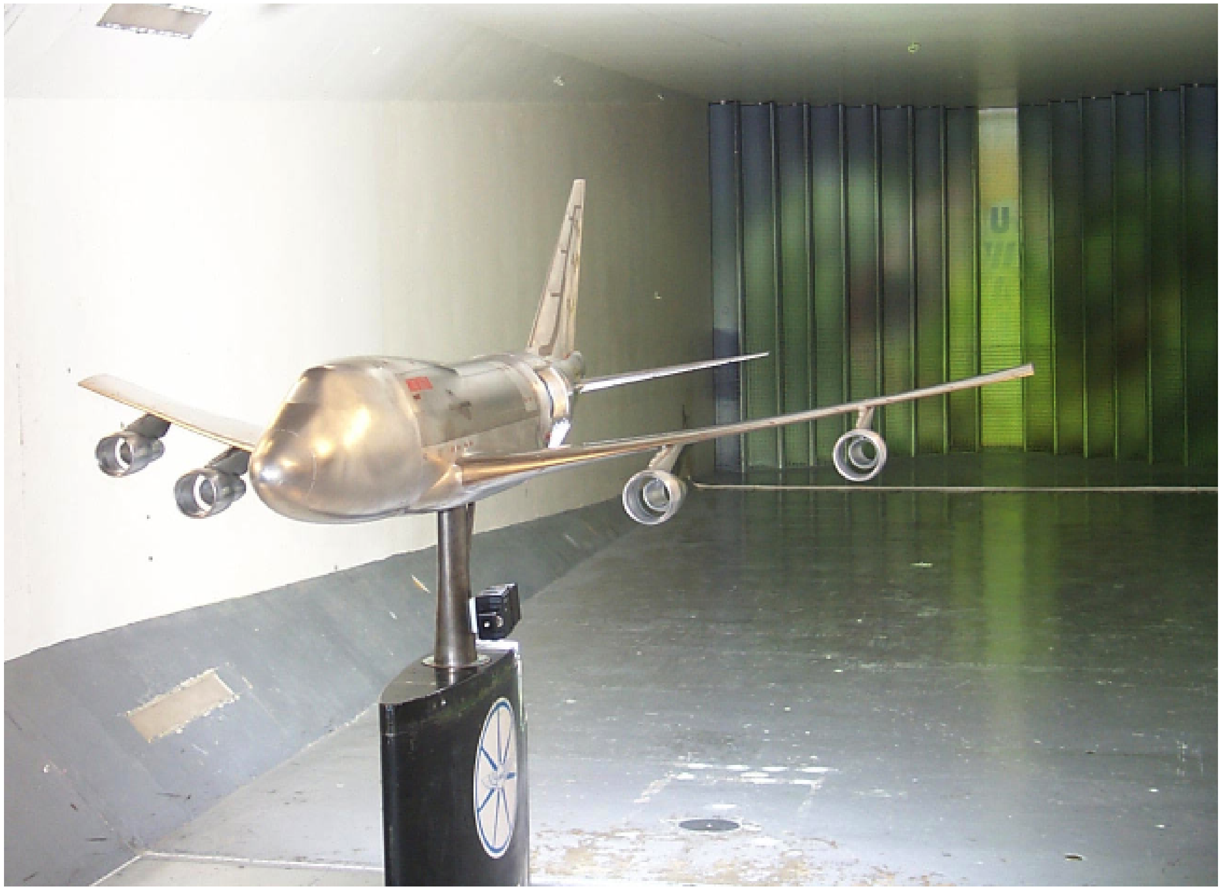
Data Acquired /Design validation

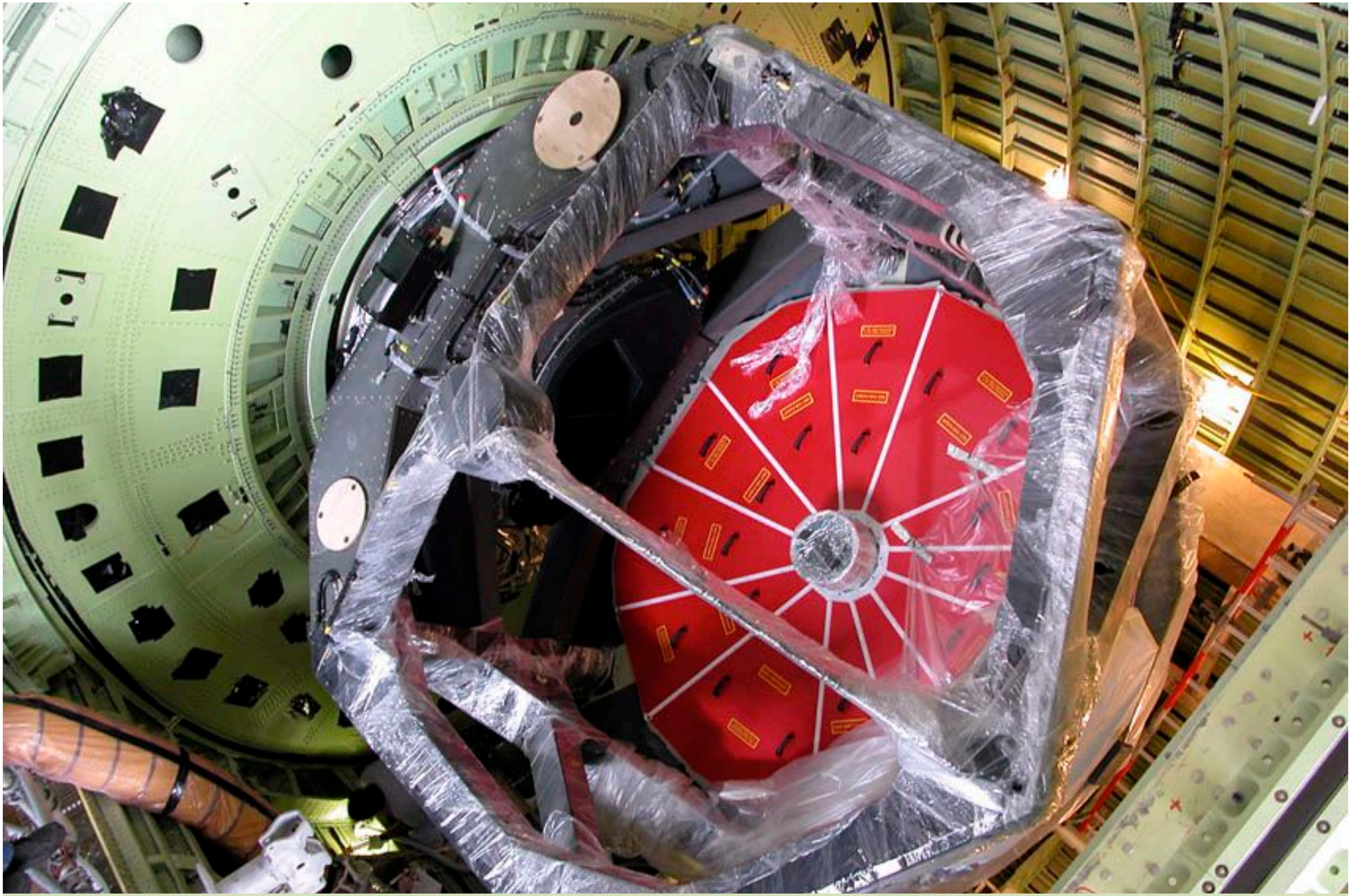
- Aero-acoustics
- Telescope torque
- Pressure loads
- Boundary layer characterization

Dynamic Environment in the Cavity

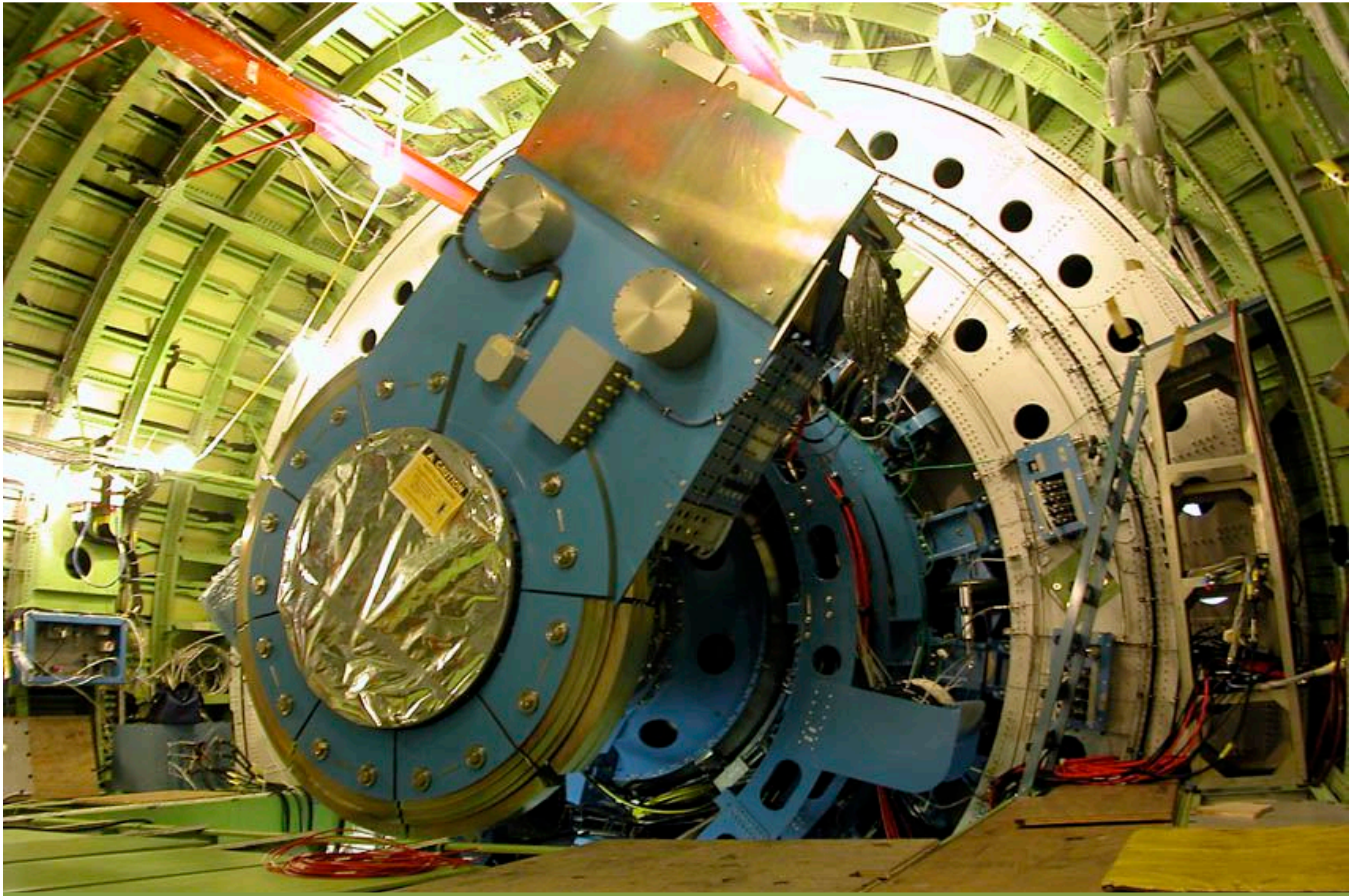


Stability and Control Studies: SOFIA Model in U of W Kirsten Wind Tunnel





Telescope inside Aircraft Cavity



Inside the aircraft - Fall 2003

Primary Mirror Installed Oct. 8, 2008

hrz

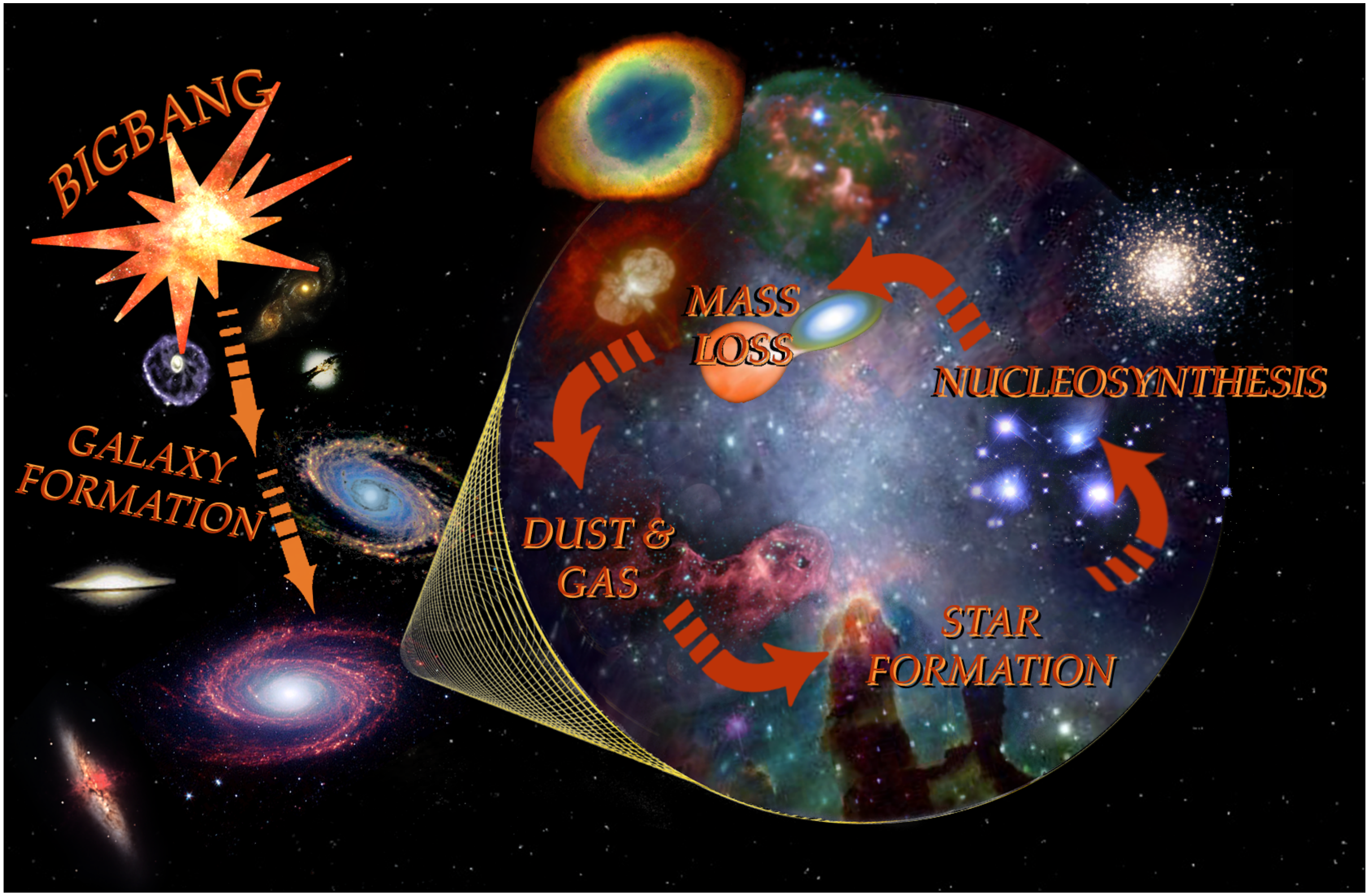
SOFIA Airborne with Door Open!

NASA's Stratospheric Observatory for Infrared Astronomy 747SP on Dec. 18, 2009. (NASA Photo / Carla Thomas)

Flight.wmv Flight.wmv

SOFIA Science

SOFIA Science: Studying the Chemical Evolution of the Universe



SOFIA Addresses Key Science Questions

Stellar Astrophysics

- *How does the ISM turn into stars and planets?*
- *How do dying stars enrich the ISM? What becomes of their ashes?*

Planetary Science

- *What are dwarf planets? How do they relate to solar system formation?*
- *Are biogenic molecules made in space? Are they in other solar systems?*

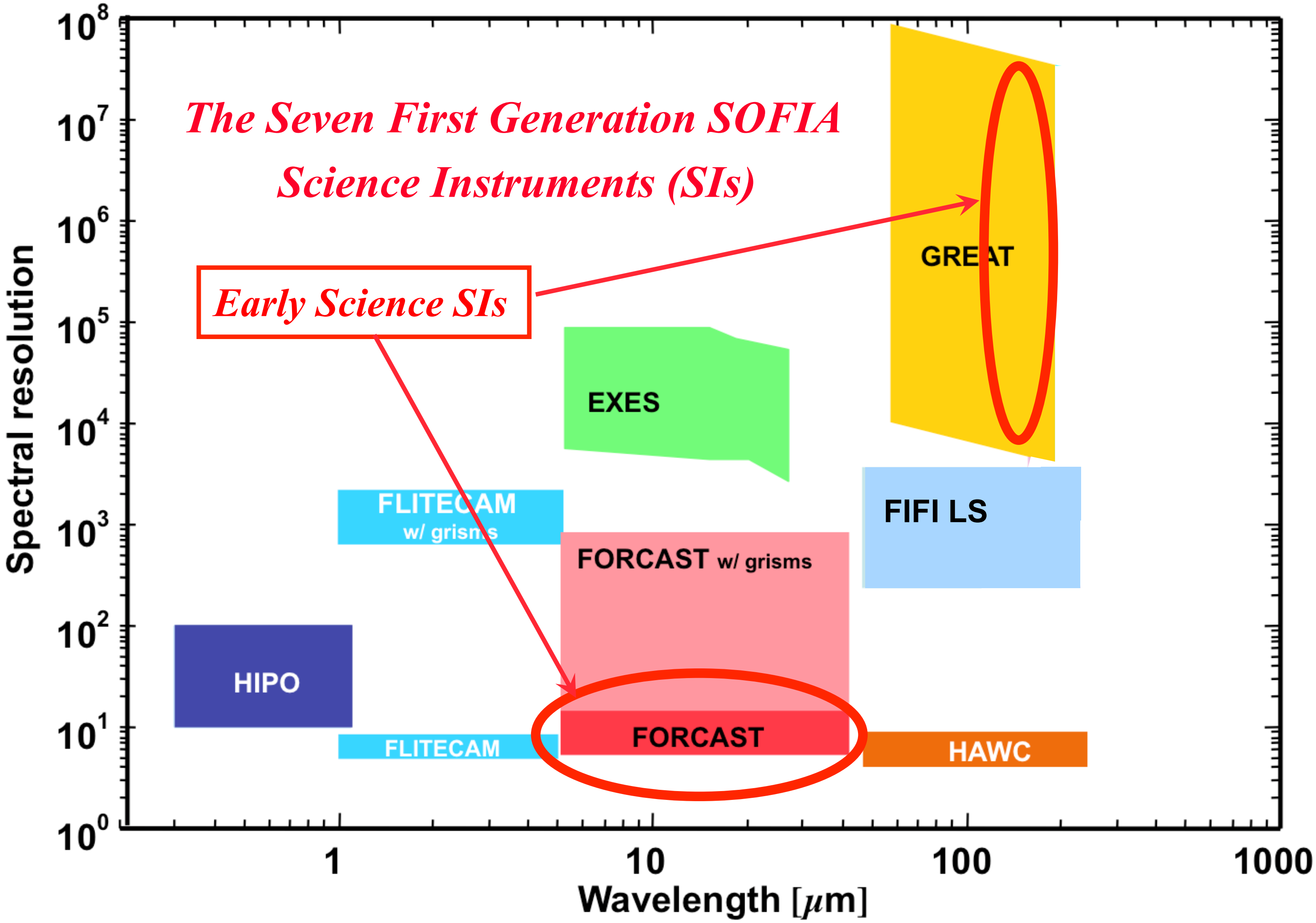
Extragalactic Astrophysics

- *What powers the most luminous galaxies? How do they evolve?*
- *What is a massive black hole doing at the center of our Galaxy?*

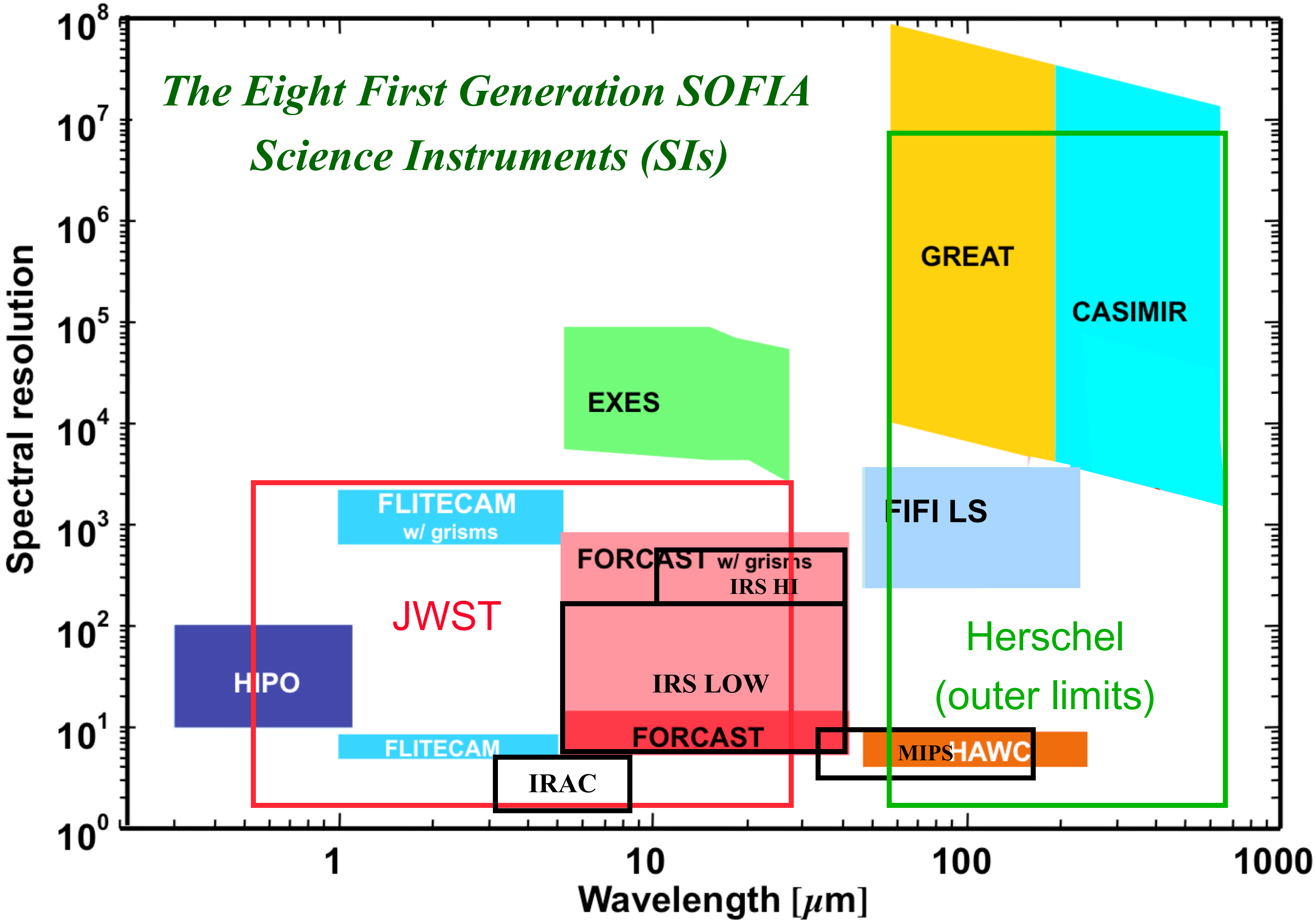
Objects of Opportunity

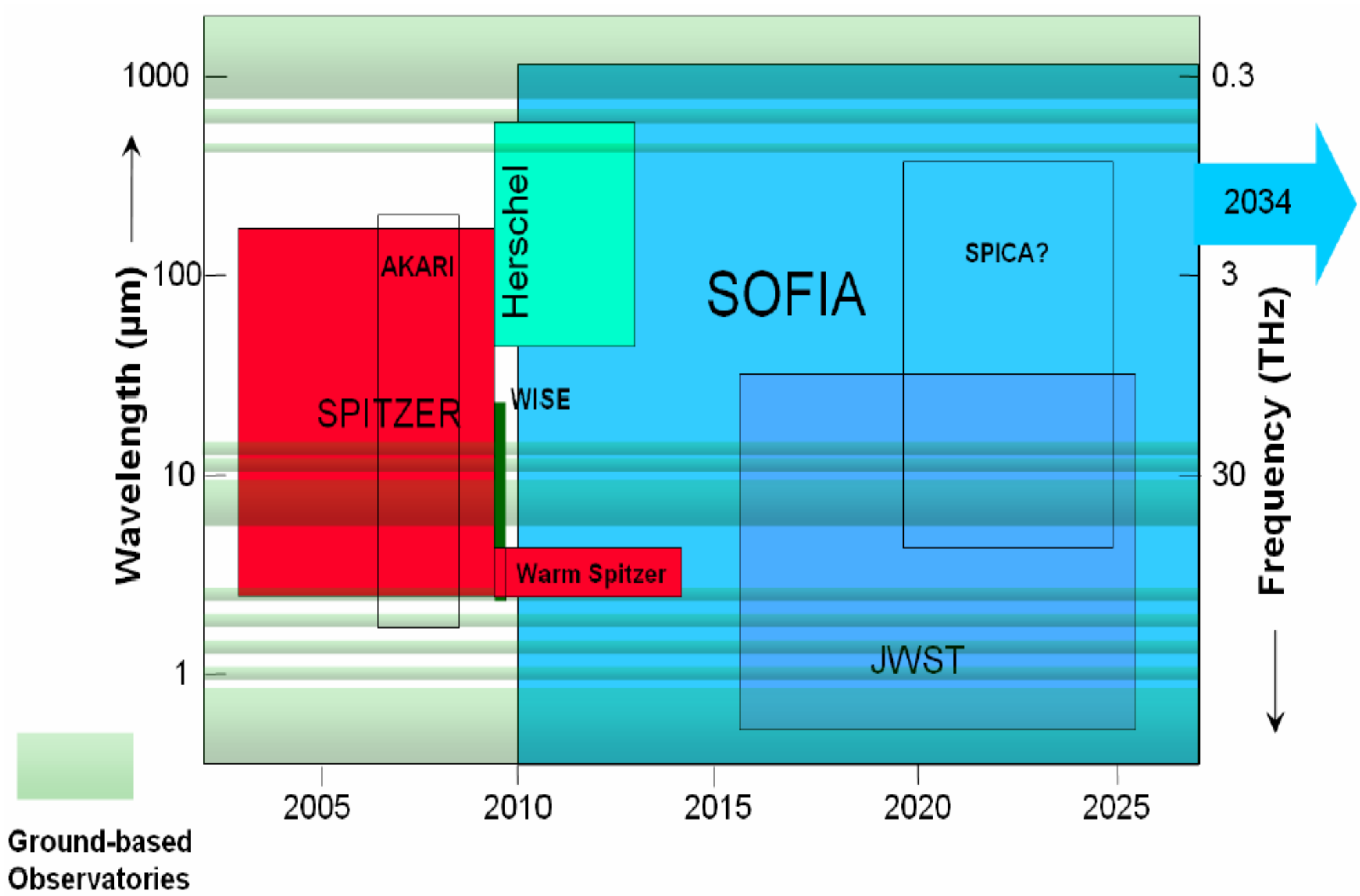
- *Bright comets, eruptive variable stars, classical novae, supernovae, occultations, transits of extra-solar planets*

SOFIA First Generation Spectroscopy

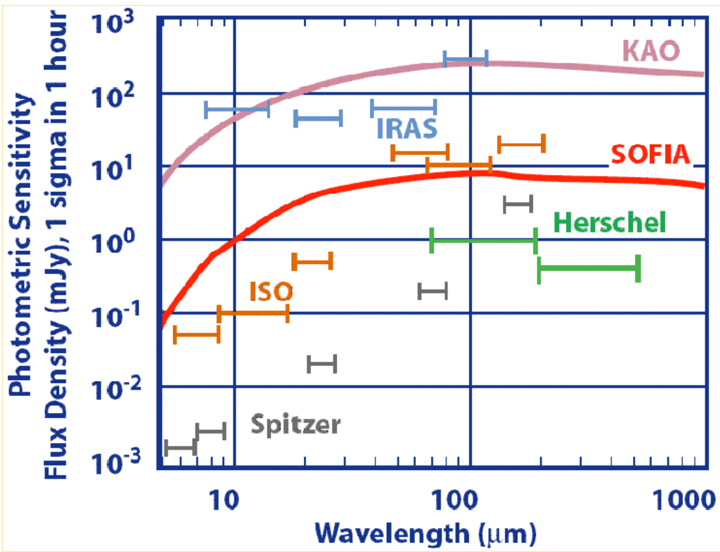


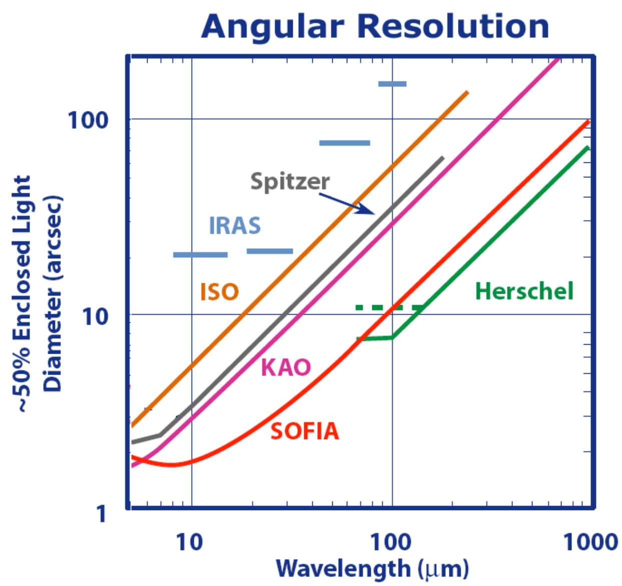
SOFIA First Generation Spectroscopy




1000
100
10
1
Wavelength (μm)
0.3
3
30
Frequency (THz)
2034
SOFIA
SPICA?
Herschel
AKARI
SPITZER
WISE
Warm Spitzer
JWST
2005
2010
2015
2020
2025
Ground-based Observatories

Photometric Sensitivity and Angular resolution





SOFIA is as sensitive as ISO

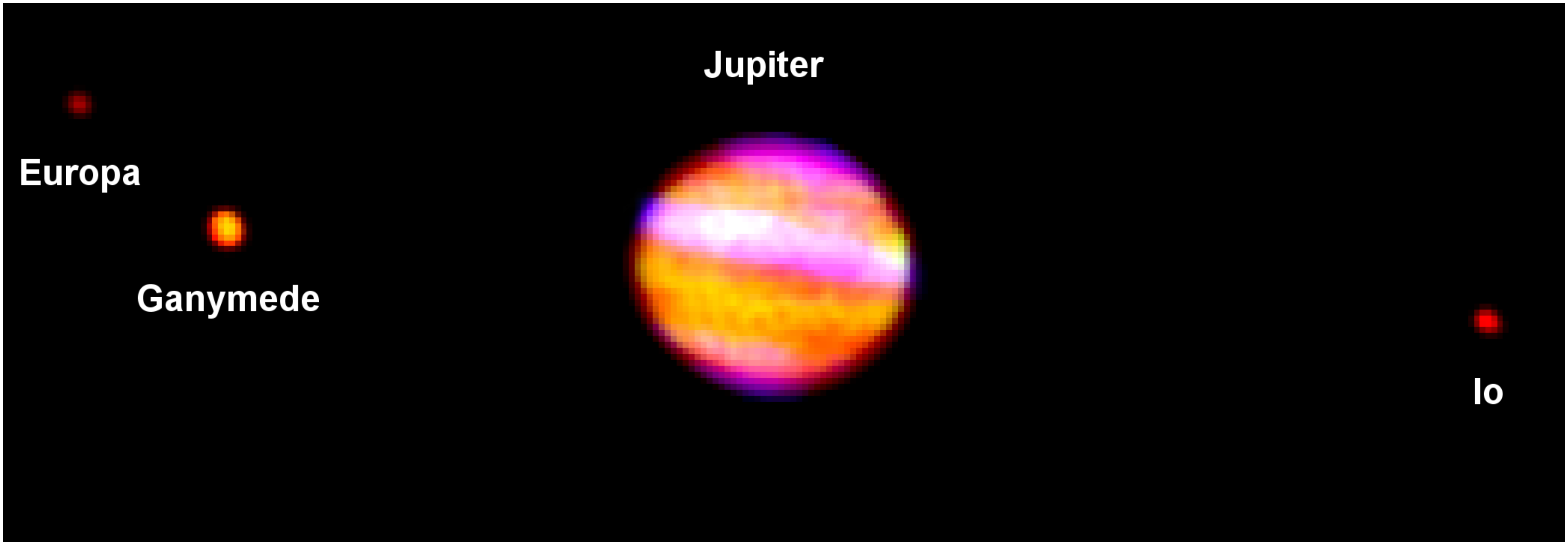
SOFIA is diffraction limited beyond 25 µm (θmin ~ λ/10 in arcseconds) and can produce images three times sharper than those made by Spitzer

The First Light and Early Science with FORCAST

The FORCAST Team

The FORCAST Team in action during the First Light Flight

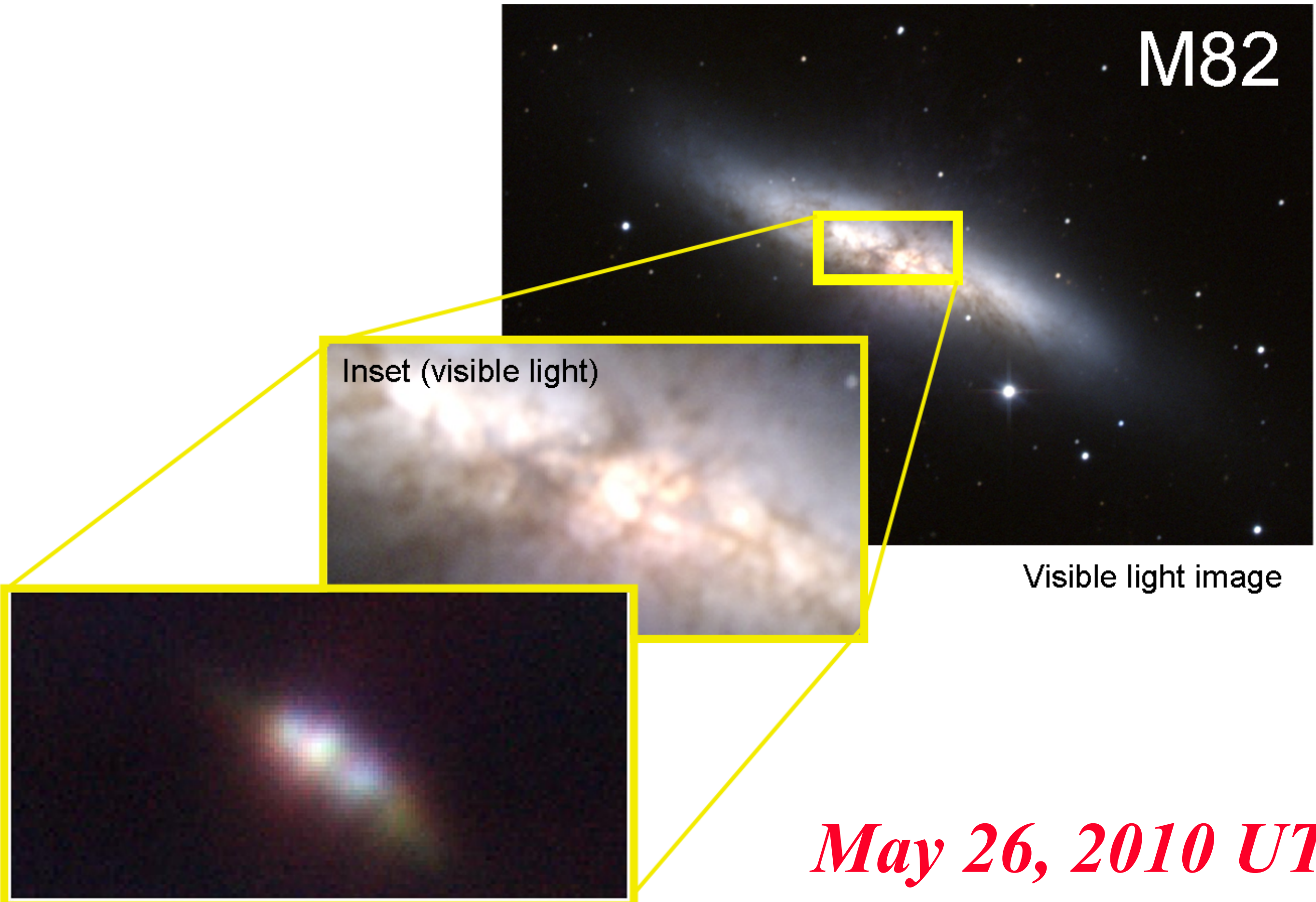
First Light on May 26, 2011 UT: We demonstrated imaging capability from 5 to 37 microns with 3-4 arcsecond FWHM



Red = 37.1 µm, Green = 24.2 µm, Blue = 5.4 µm

Red = 37.1um, Green = 24.2um, Blue = 5.4um

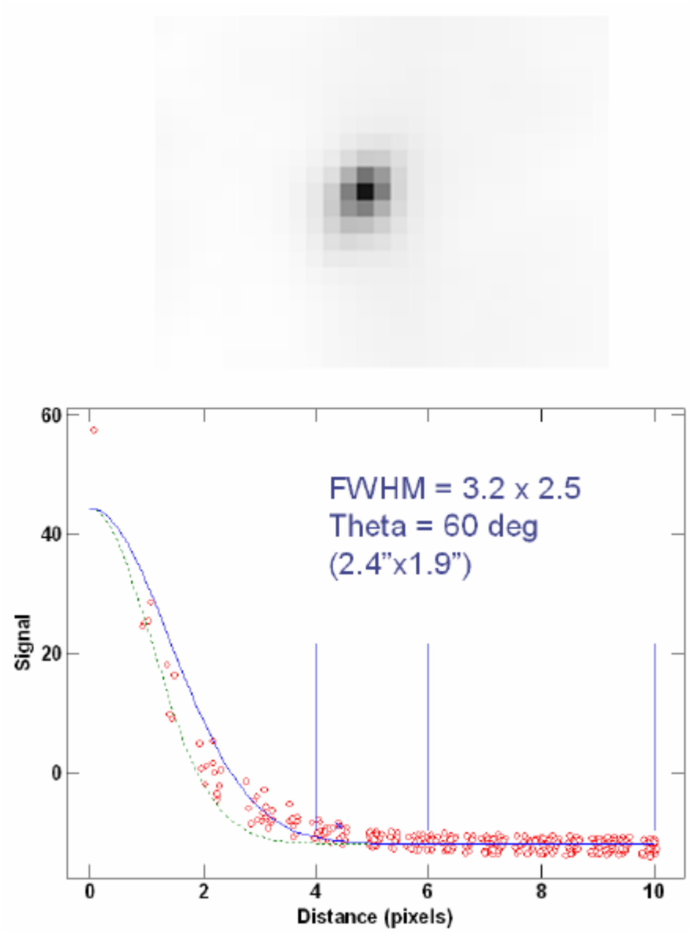
SOFIA's FORCAST First-Light Images: M82



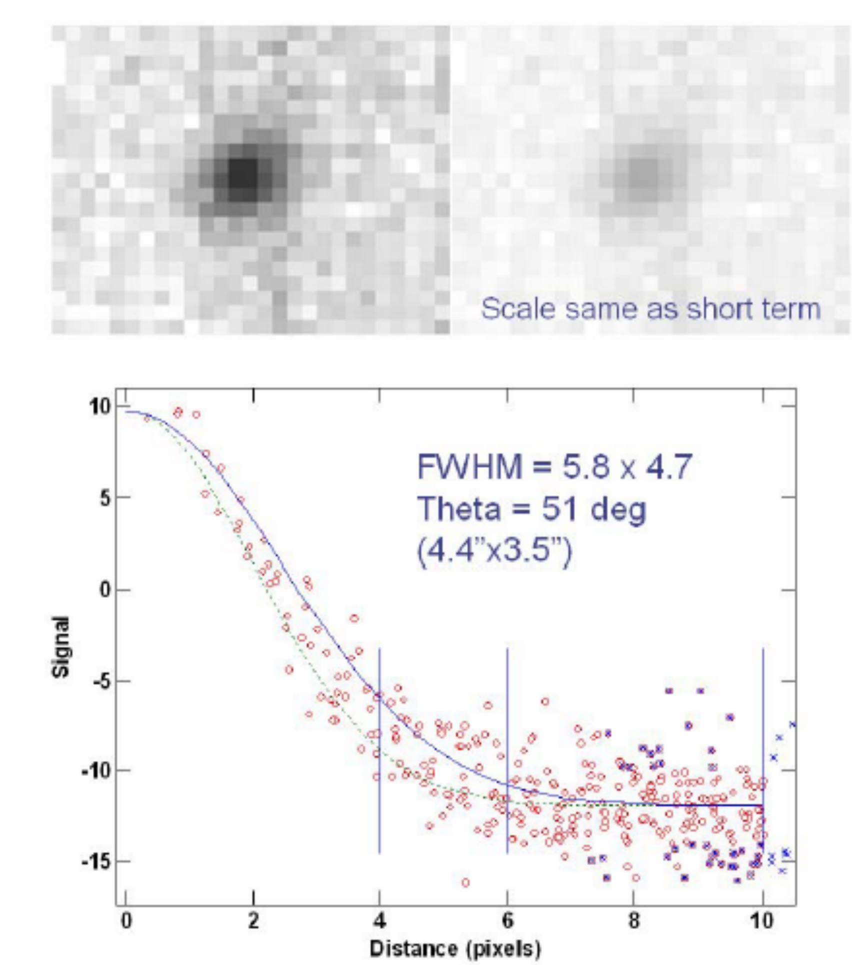
SOFIA infrared image (19.7, 31.5, and 37.1 μm)

May 26, 2010 UT

PSF and Jitter from Images of γ Cygni



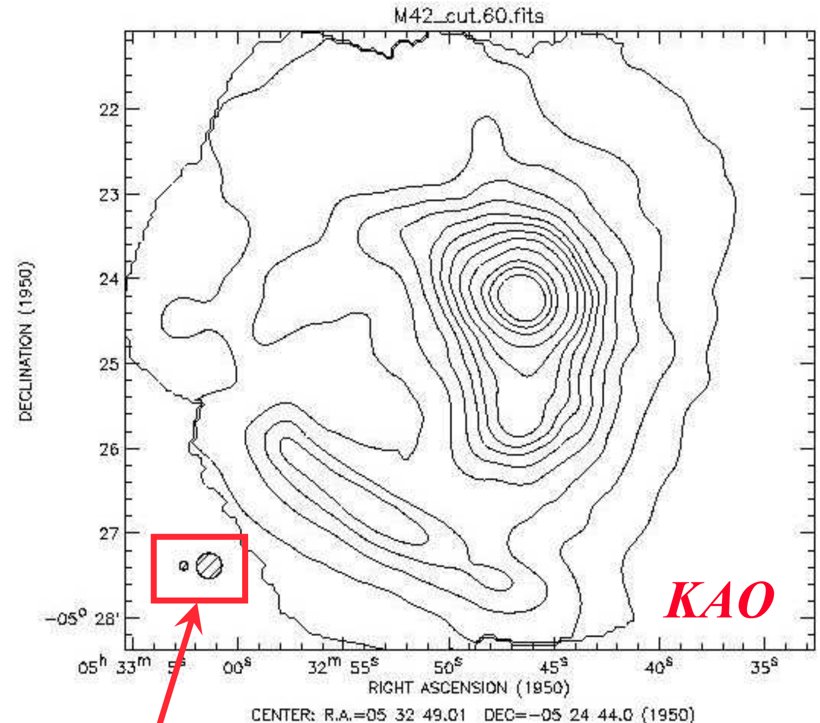
2,800 2.5 ms images shifted and co-added



Same data w/o shift and add

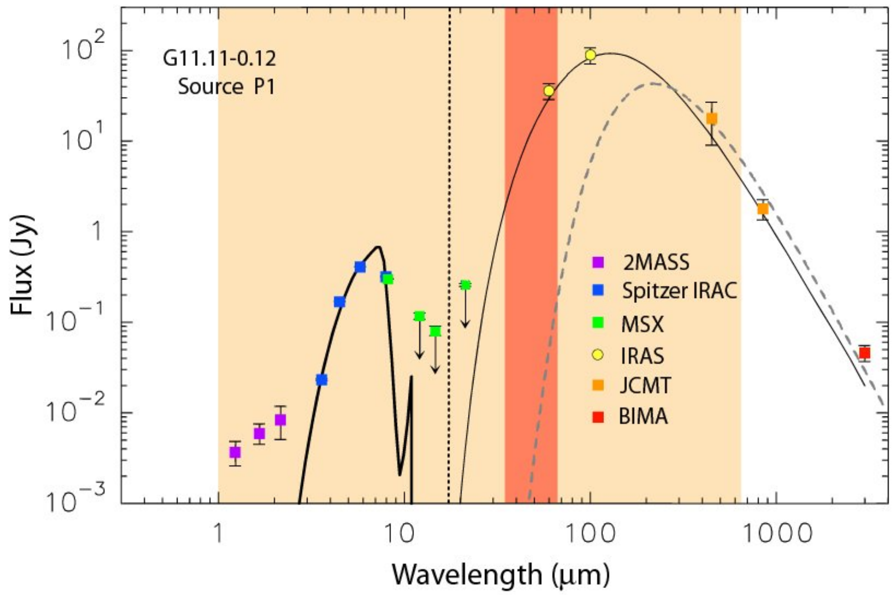
SOFIA and Regions of Star Formation

How will SOFIA shed light on the process of star formation in Giant Molecular Clouds like the Orion Nebula?



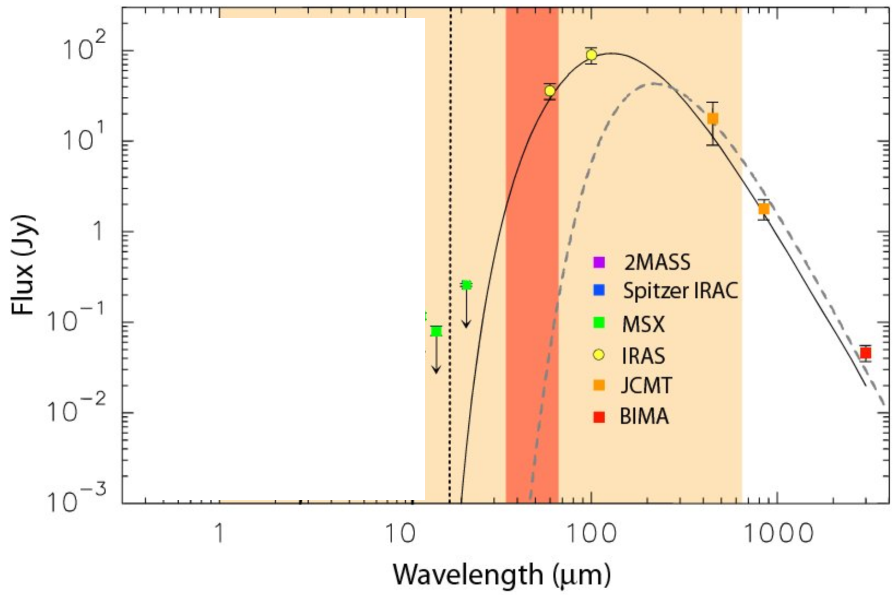
With 9 SOFIA beams for every 1 KAO beam, SOFIA imagers/HI-RES spectrometers can analyze the physics and chemistry of individual protostellar condensations where they emit most of their energy and can follow up on HERSCHEL discoveries.

Sources Embedded in Massive Cloud Cores

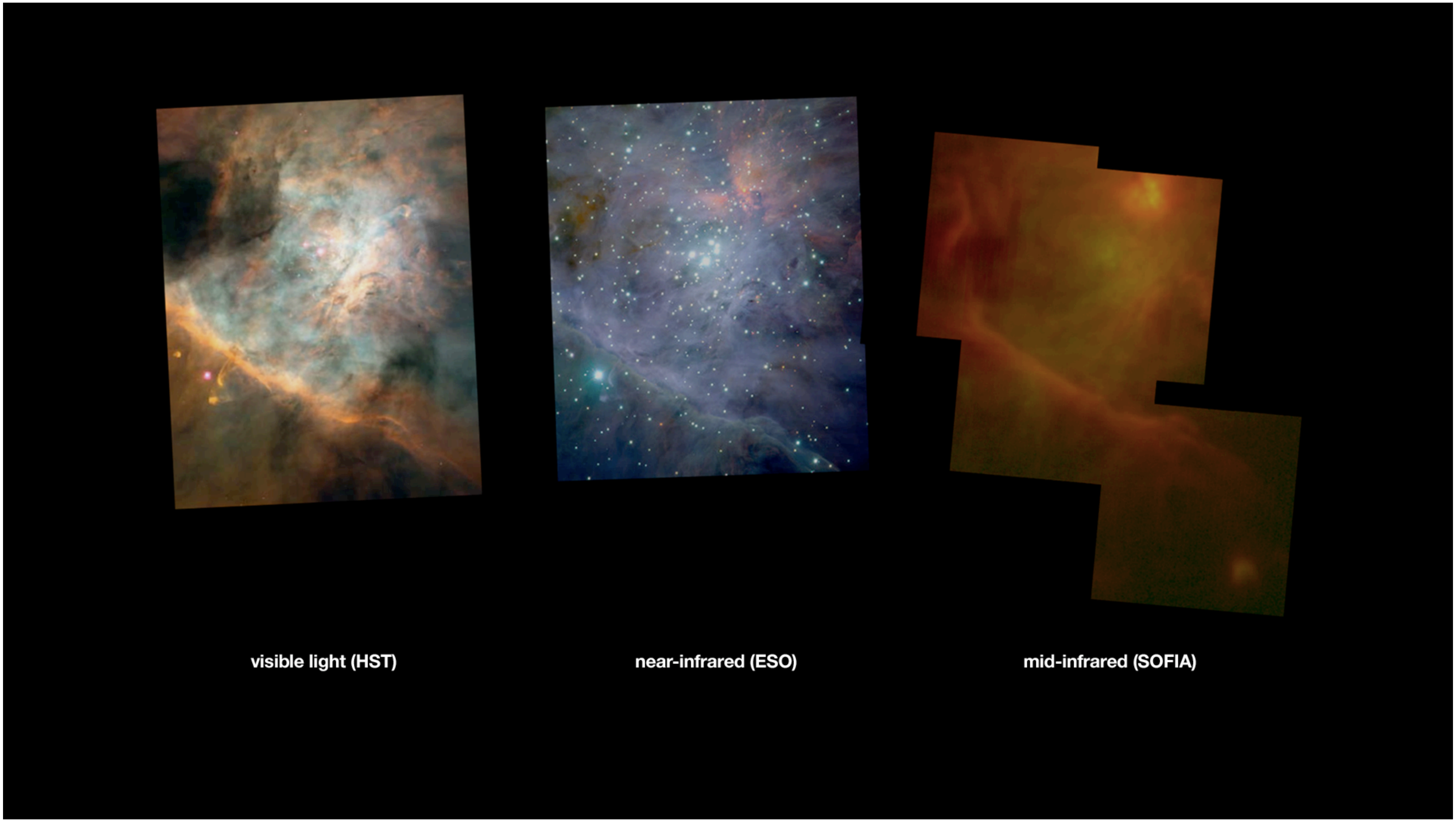


- ***20 to 100 microns can provide a key link to shorter wavelengths***

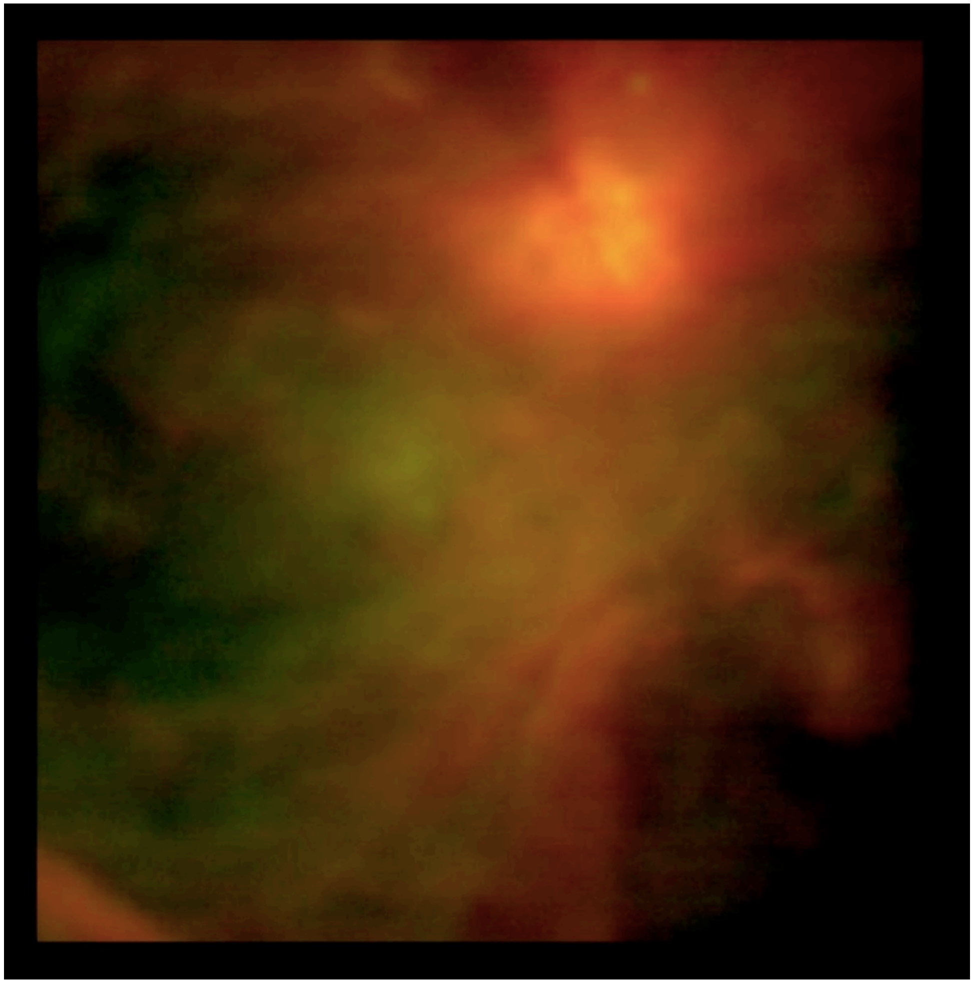
- ***In highly obscured objects, no mid-IR source may be detectable***



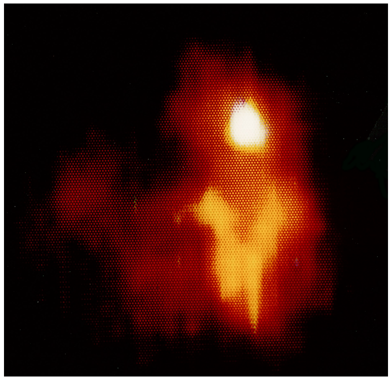
SOFIA Early Science Images



SOFIA Early Science Images



Red = 37.1 µm, Green = 24.2 µm



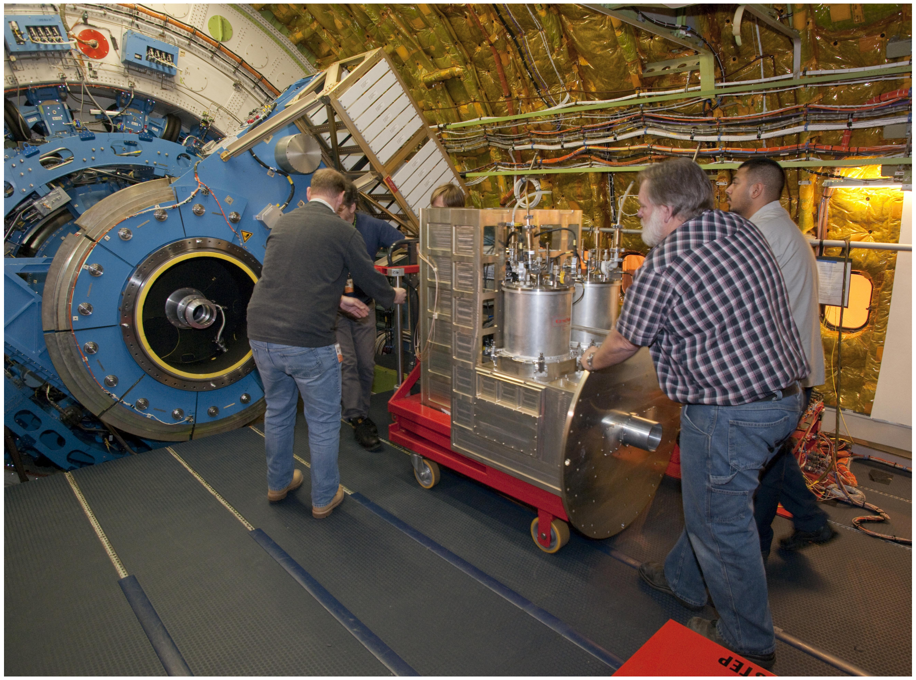
Red = 20 µm

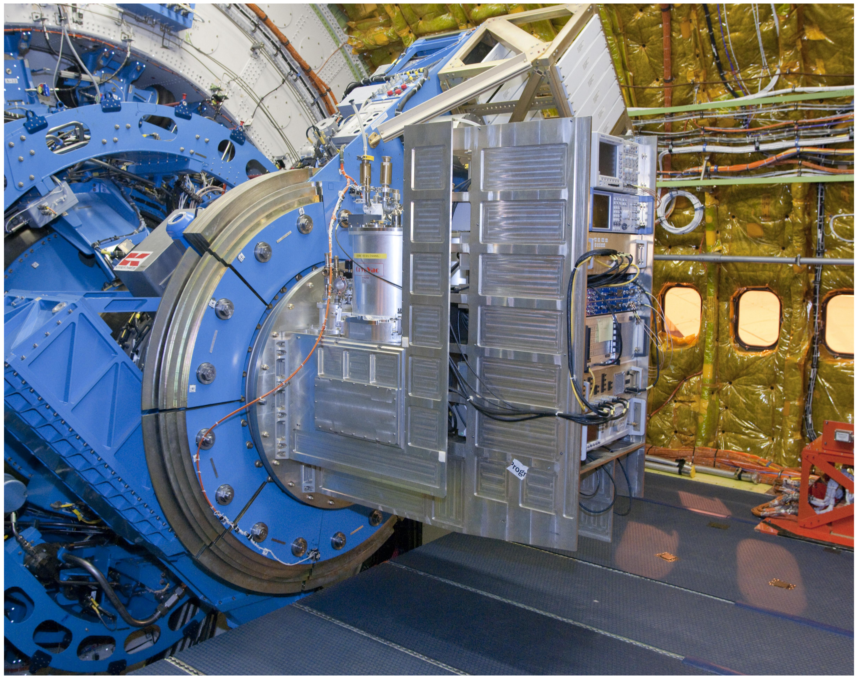
Green = 12 µm

Blue = 11 µm

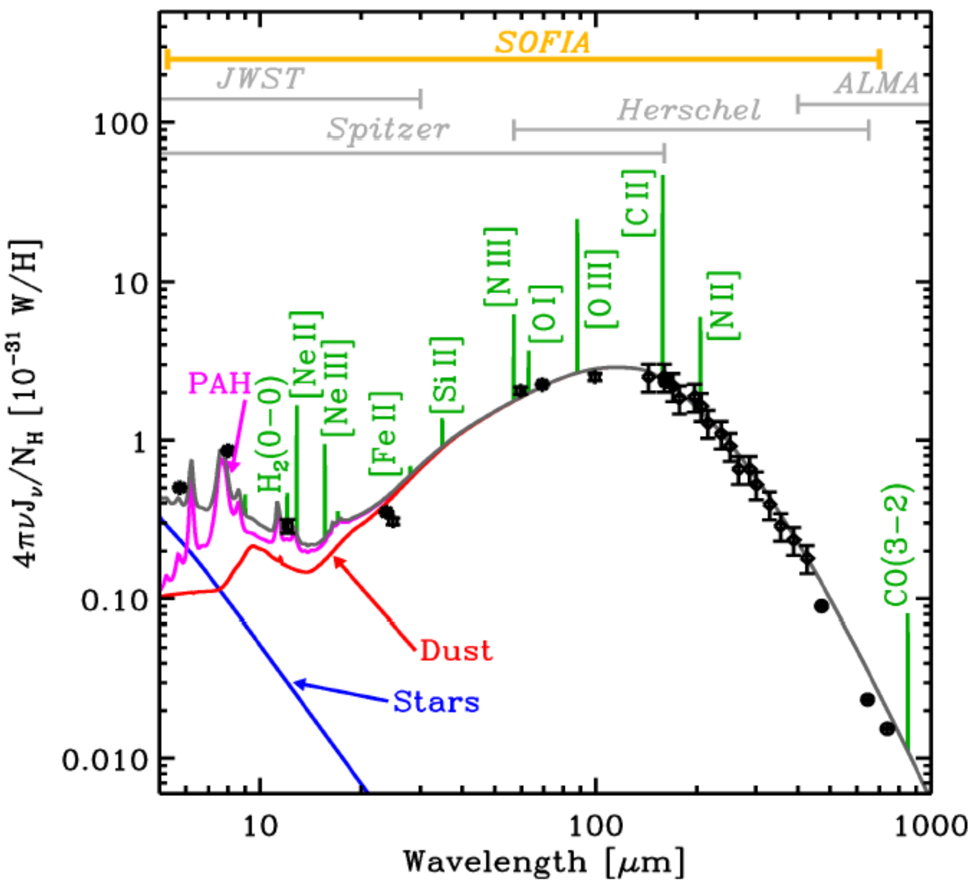
Wyoming Infrared Image from
Herzog et al., 1980, Sky and Telescope, 59, 18

GREAT Early Science in April 2011





Thermal Emission from ISM Gas and Dust



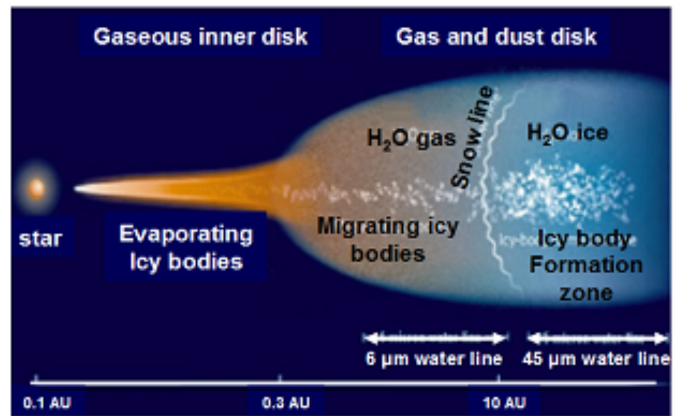
Spectral Energy Distribution (SED) of the entire LMC (courtesy of F. Galliano)

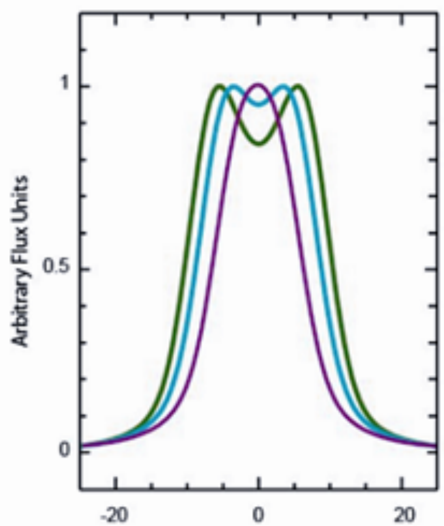
- ***SOFIA is the only mission in the next decade that is sensitive to the entire Far-IR SED of a galaxy that is dominated by emission from the ISM excited by radiation from massive stars and supernova shock waves***
- ***The SED is dominated by PAH emission, thermal emission from dust grains, and by the main cooling lines of the neutral and ionized ISM***

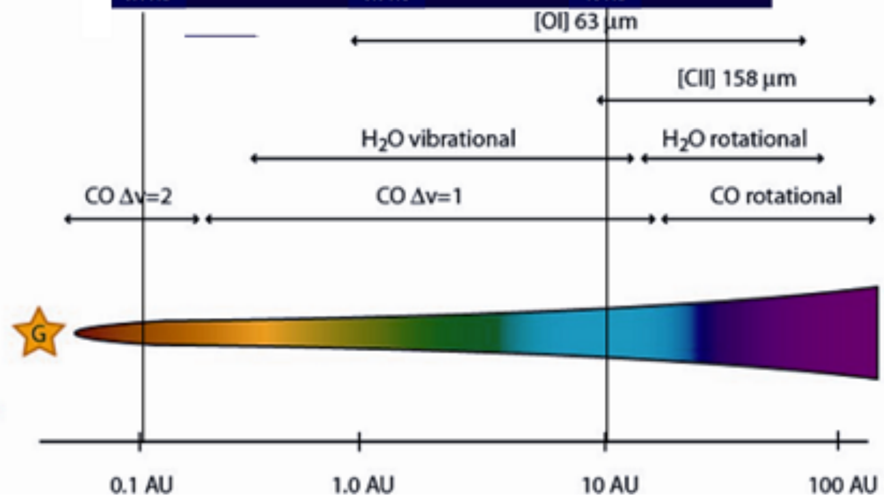
The Physics and Chemistry of Protoplanetary Disks

- ***High spectral resolution enables dynamical studies and can establish where different atomic, molecular, and solid state species reside in the disk***
- ***small stellar-centric radii are associated with wide, double-peaked line profiles; large radii with narrow line profiles***
- ***Observing many disks of different ages will trace the temporal evolution of disk dynamics and chemistry***

Simulations from N. J. Evans et al. 2009





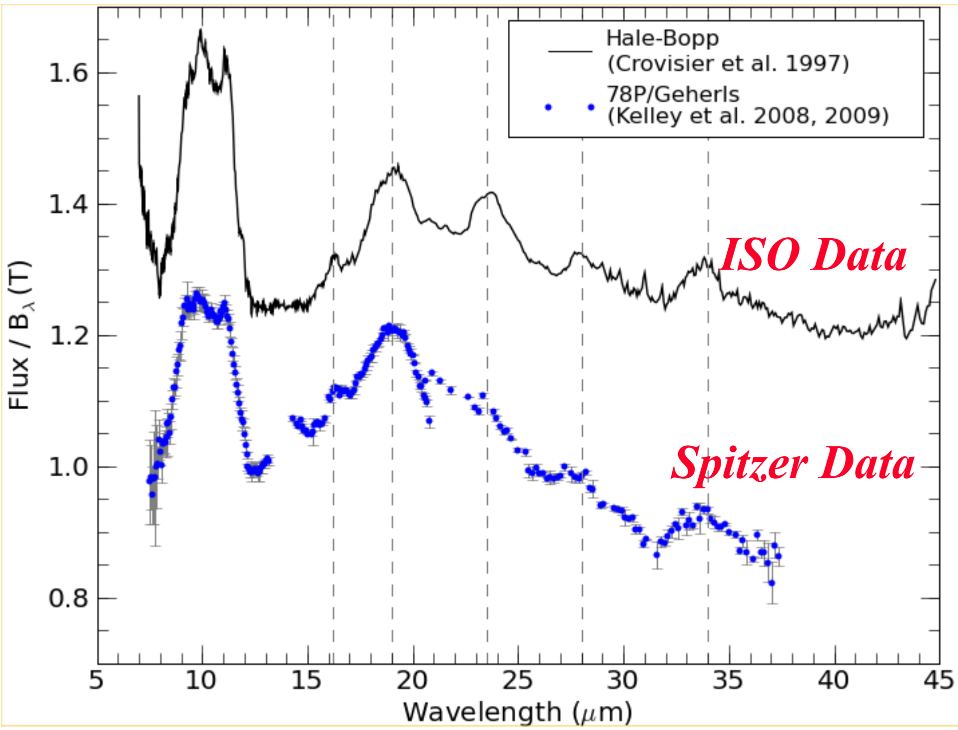


Observing Comets in the IR with SOFIA

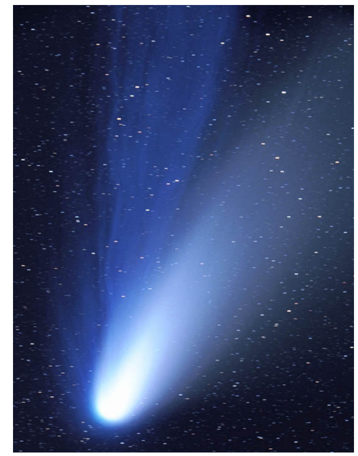
- *Comet nuclei are the "Rosetta Stone" of the Solar System*
- *Comet nuclei, comae, tails, and trails emit primarily at the thermal IR wavelengths accessible with Spitzer (3-180 μm)*
- *Emission features from grains, ices, and molecular gases occur in the thermal IR*
- *IR Space platforms (Spitzer, Herschel, JWST) cannot view comets during perihelion passage due to pointing constraints*

SOFIA and Comets: Mineral Grains

What can SOFIA observations of comets tell us about the origin of the Solar System?



The vertical lines mark features of crystalline Mg-rich crystalline olivine (forsterite)

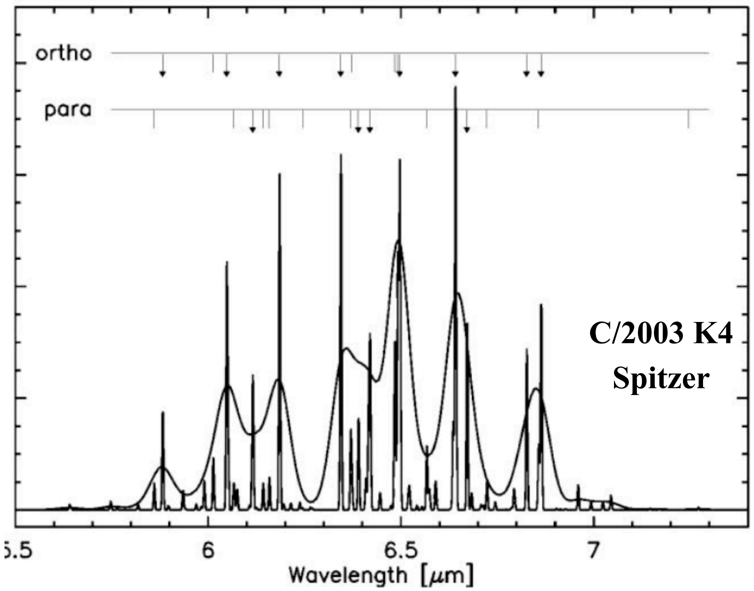


- ***Comet dust mineralogy: amorphous, crystalline, and organic constituents***
- ***Comparisons with IDPs and meteorites***
- ***Comparisons with Stardust***
- ***Only SOFIA can make these observations near perihelion***

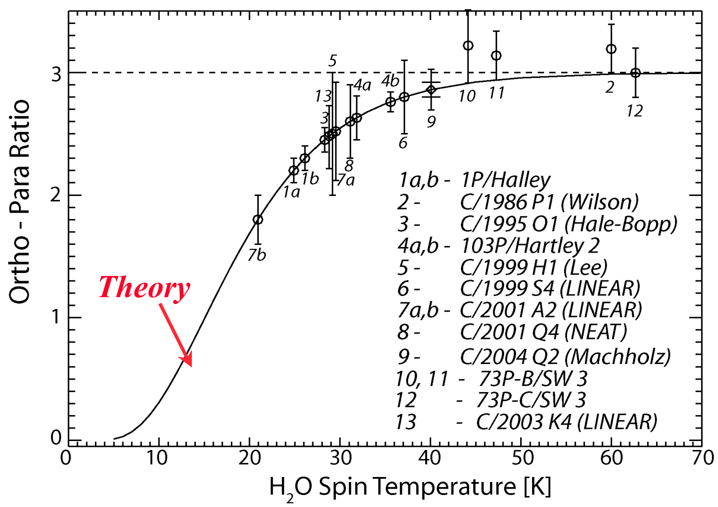
SOFIA and Comets: Gas Phase Constituents

What can SOFIA observations of comets tell us about the origin of the Solar System?

C. E. Woodward et al. 2007, ApJ, 671, 1065



B. P. Bonev et al. 2007, ApJ, 661, L97



- *Production rates of water and other volatiles*
- *Water H_2 ortho/para (parallel/antiparallel) hydrogen spin isomer ratio gives the water formation temperature; a similar analysis can done on ortho/para/meta spin isomers of CH_4*
- *Only SOFIA can make these observations near perihelion*

SOFIA and Comets: Protoplanetary Disks

What can SOFIA observations of comets tell us about the origins of our Solar System and other solar systems?

ISO Observations — Adapted from Crovisier et al. 1996, Science 275, 1904 and Malfait et al. 1998, A&A 332, 25

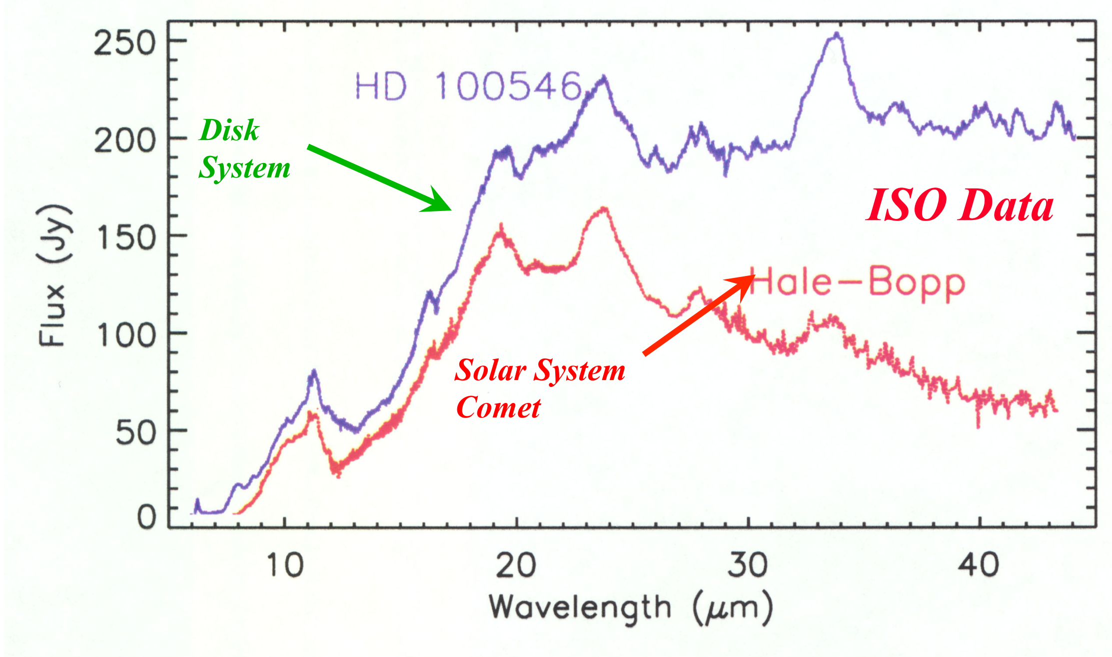
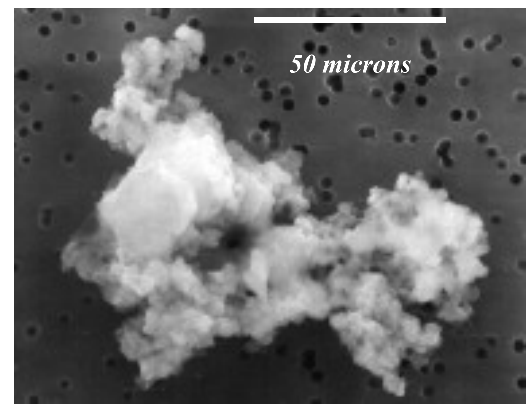


Image of Solar System IDP (Interplanetary Dust Particle)



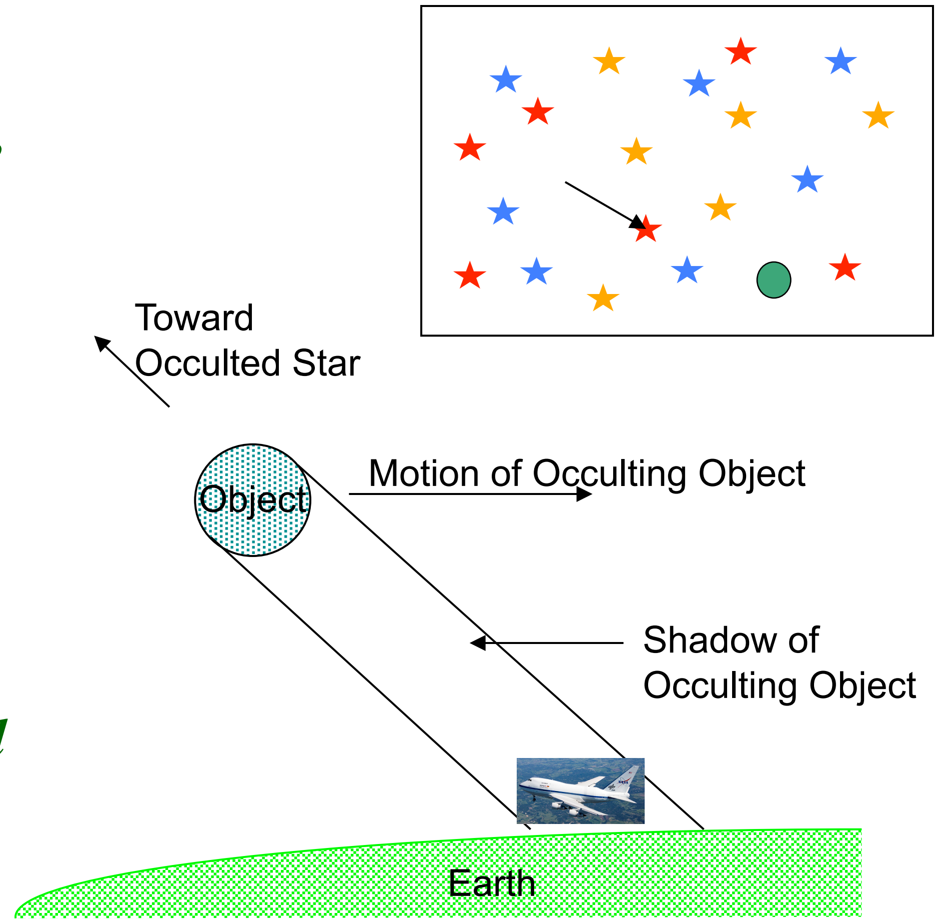
- *The similarities in the silicate emission features in HD 100546 and C/1995 O1 Hale-Bopp suggest that the grains in the stellar disk system and the small grains released from the comet nucleus were processed in similar ways*

Occultation Astronomy with SOFIA

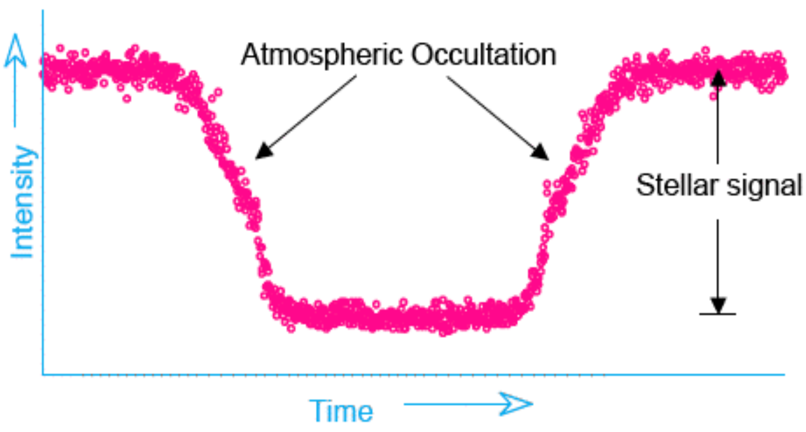
How will SOFIA help determine the properties of small Solar System bodies?

- ***Occultation studies probe sizes, atmospheres, satellites, and rings of small bodies in the outer Solar system.***

- ***SOFIA can fly anywhere on Earth to position itself in the occultation shadow. Hundreds of events are available per year compared to a handful for fixed ground and space-base observatories.***

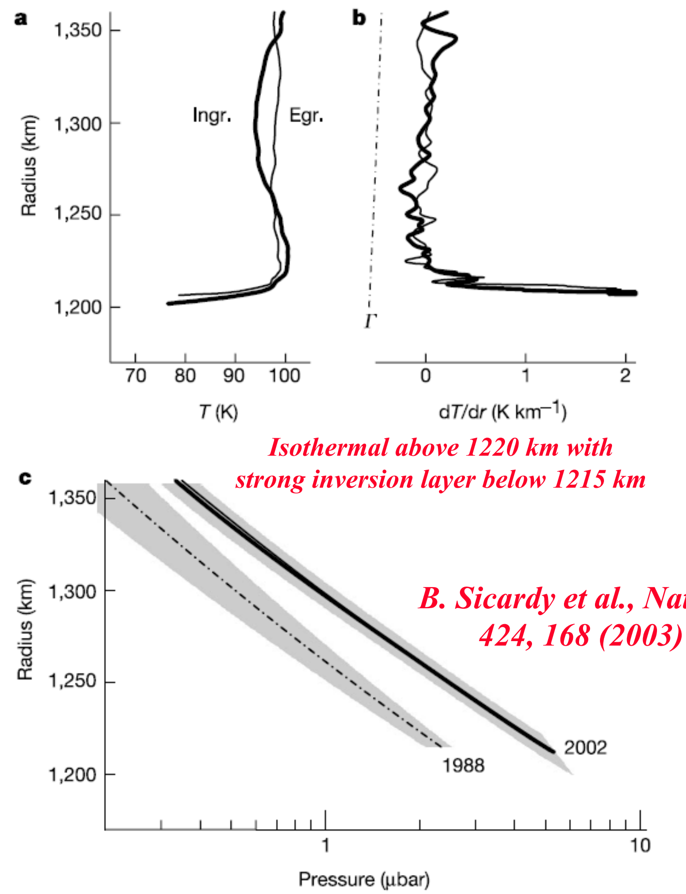


Occultations and Atmospheres



This occultation light curve observed on the KAO (1988) probed Pluto's atmosphere

J. L. Elliot et al., Icarus 77, 148-170 (1989)

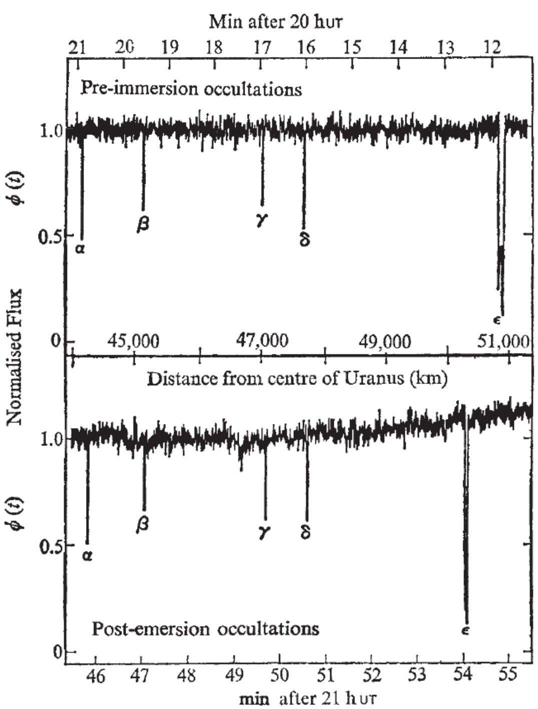


Isothermal above 1220 km with strong inversion layer below 1215 km

B. Sicardy et al., Nature, 424, 168 (2003)

Figure 2 Temperature and pressure profiles of Pluto's atmosphere derived from the inversion of the P131.1 light curve. This inversion[17] assumes a spherically symmetric and transparent atmosphere. It first provides the atmospheric refractivity profile, then the density profile for a given gas composition, and finally the temperature profile, assuming an ideal gas in hydrostatic equilibrium. We assume for Pluto a pure molecular nitrogen[6] atmosphere,

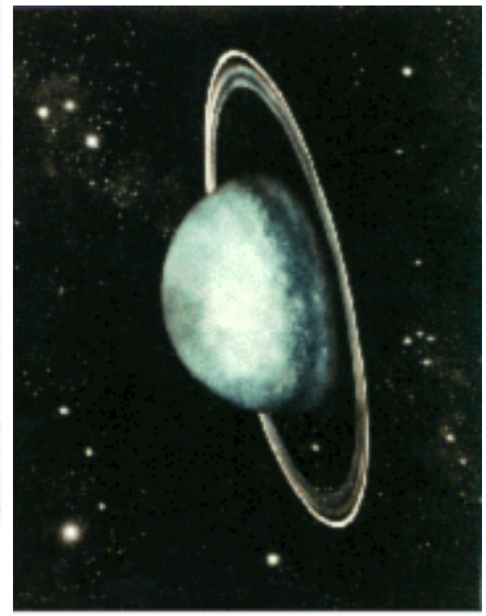
Occultations: Rings and Moons



Uranus' Rings: The Story of a Discovery

—Sun Photo by Liz Werner

THE TEAM: Researchers Edward Dunham (l.), James Elliot, and Douglas Mink examine the unexpected signal pattern produced on the charter recorder by the outermost ring of Uranus.

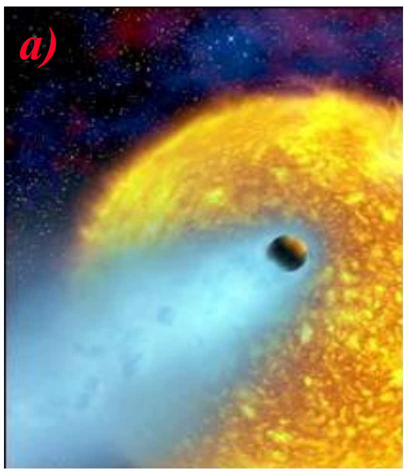


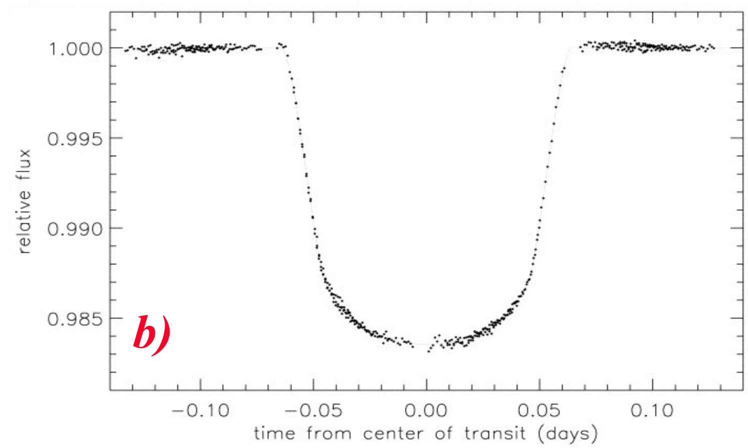
This occultation light curve observed on the KAO in 1977 shows the discovery of a five ring system around Uranus

J. L. Elliot, E. Dunham, and D. Mink, Nature 267, 328-330 (1977)

SOFIA and Extra-solar Planet Transits

- *There are 358 extra-solar planets; more than 59 transit their primary star*
- *SOFIA flies above the scintillating component of the atmosphere where it can detect transits of planets across bright stars at high signal to noise*





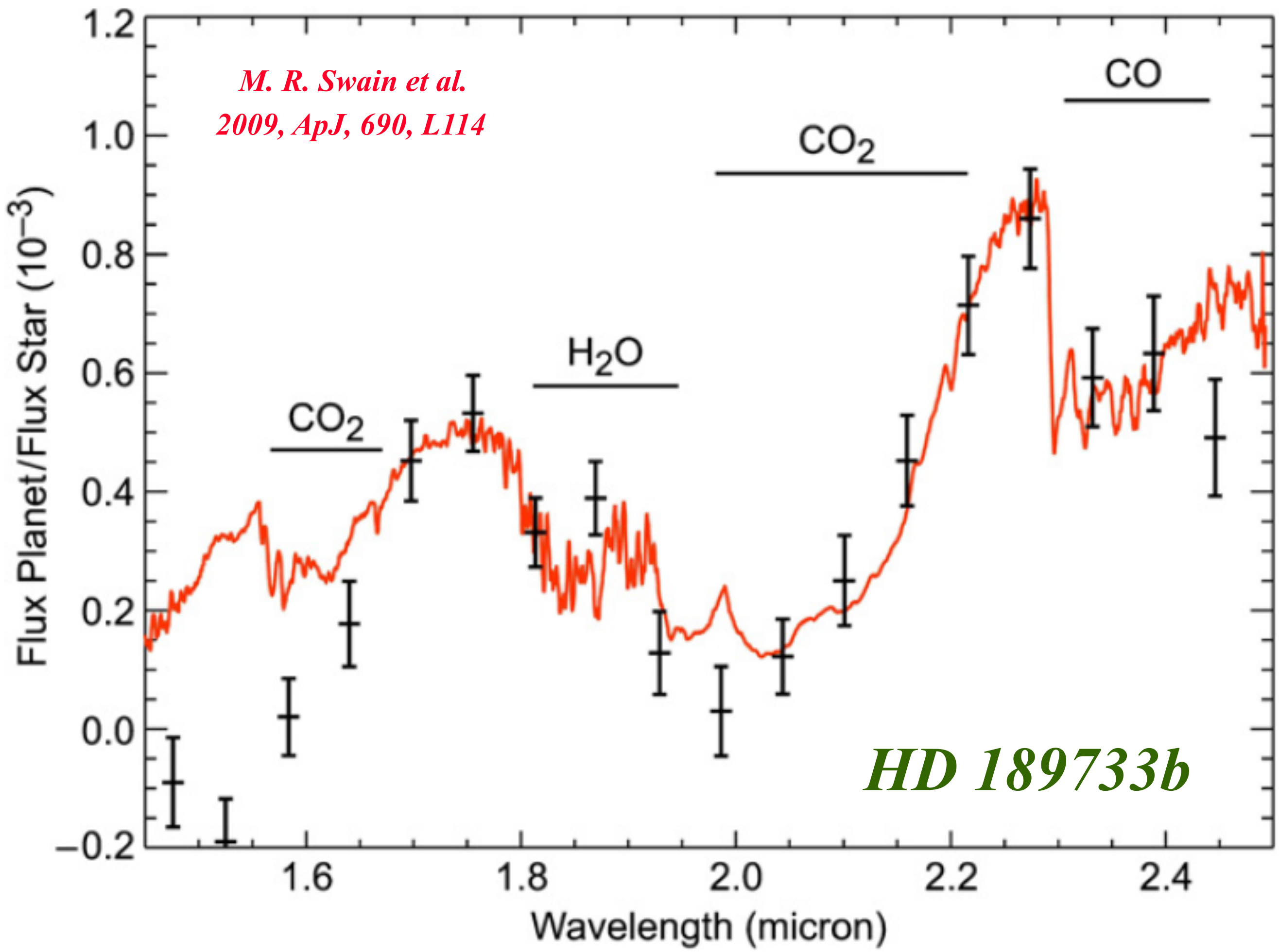
HD 209458b transit:

a) artist's concept and

b) HST STIS data

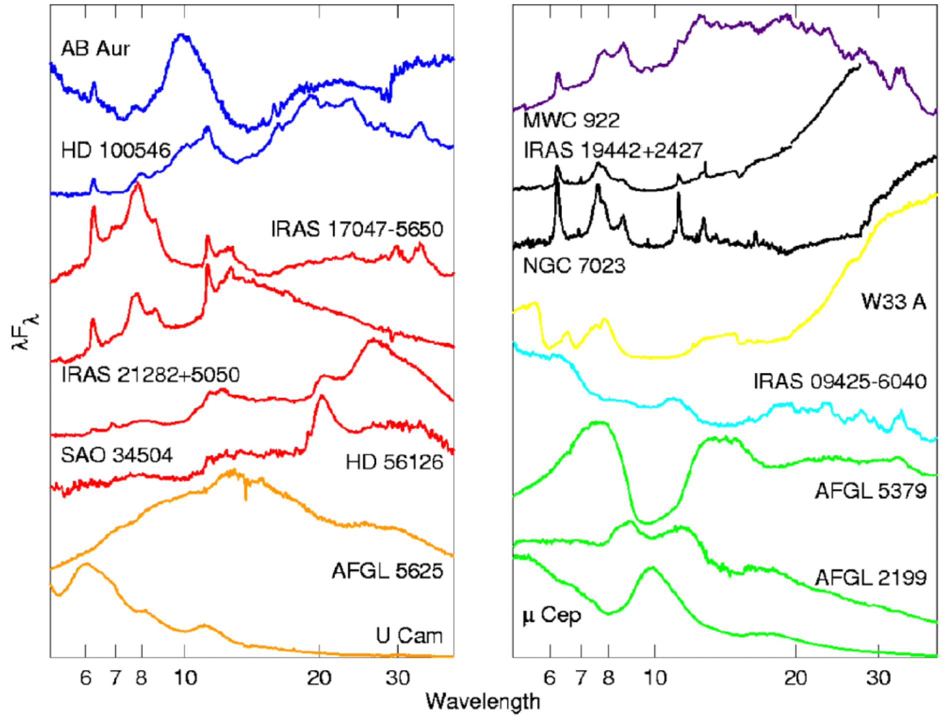
- *Transits provide good estimates for the mass, size and density of the planet*
- *Transits can reveal the presence of, satellites, and/or planetary rings*
- *Spectroscopic observations can reveal the presence and composition of an atmosphere*

Detection of Biogenic Molecules in Extrasolar Planetary Atmospheres by the transit Method



SOFIA Will Study the Diversity of Stardust

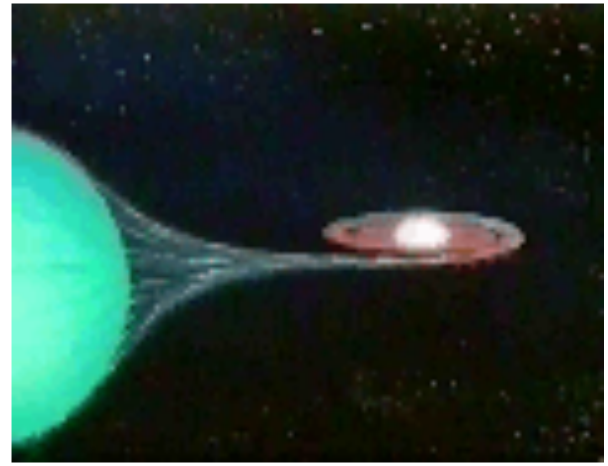
- *Herbig AeBe*
- *Post-AGB and PNe*
- *Mixed chemistry post-AGB*
- *C-rich AGB*
- *O-rich AGB*
- *Mixed chemistry AGB*
- *Deeply embedded YSO*
- *HII region refection nebulae*



- *ISO SWS Spectra: stardust is spectrally diverse in the regime covered by SOFIA*
- *Studies of stardust mineralogy*
- *Evaluation of stardust contributions from various stellar populations*
- *Implications for the lifecycle of gas and dust in galaxies*

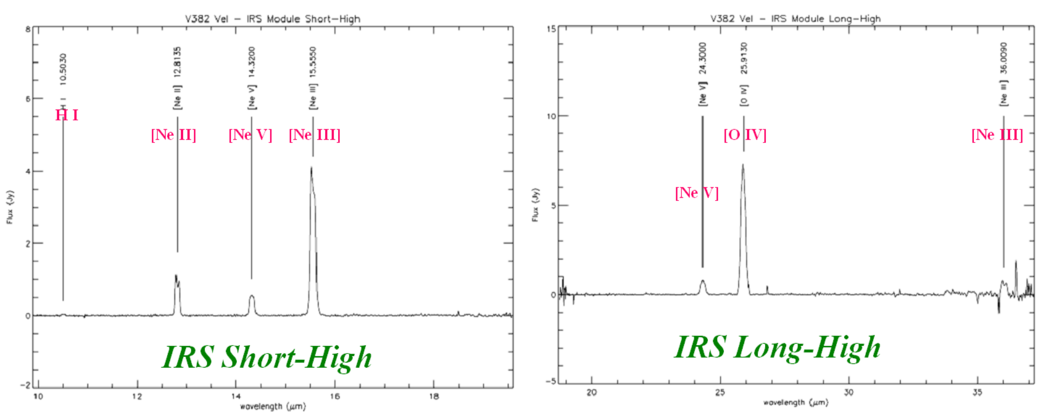
SOFIA and Classical Nova Explosions

What can SOFIA tell us about gas phase abundances in Classical Nova Explosions?



Spitzer Spectra of Nova V382 Vel

R. D. Gehrz, et al. 2005, ApJ, in preparation [PID 124]

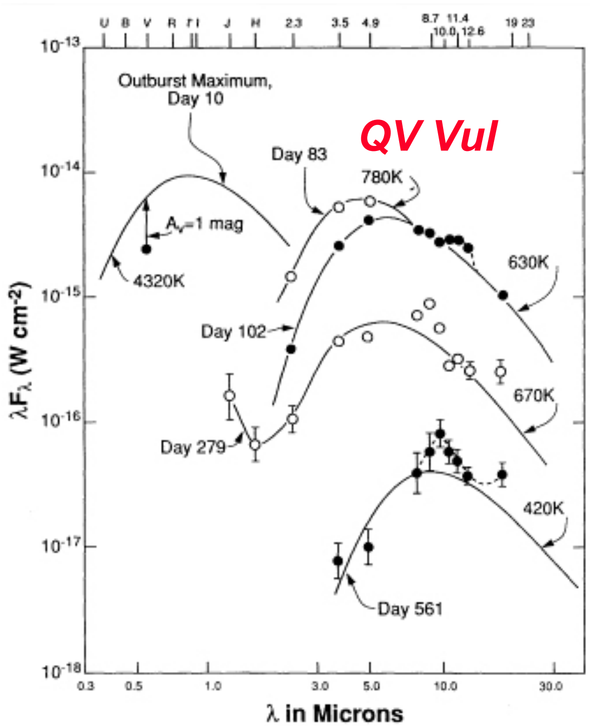


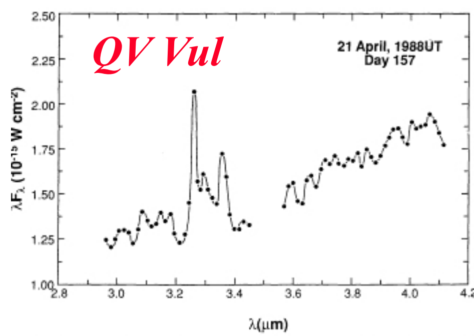
- *Gas phase abundances of CNOMgNeAl*
- *Contributions to ISM clouds and the primitive Solar System*
- *Kinematics of the Ejection*

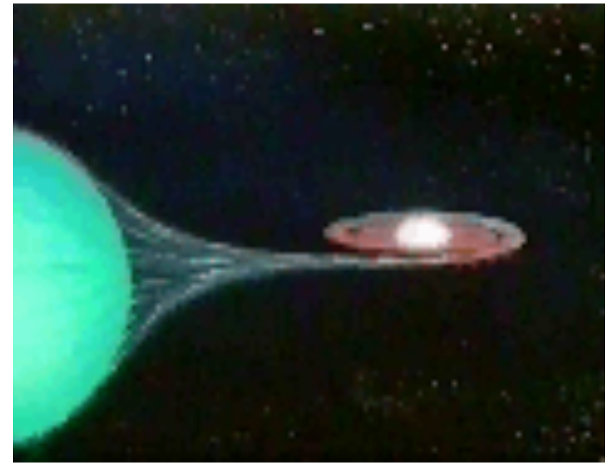
SOFIA and Classical Nova Explosions

What can SOFIA tell us about the mineralogy of dust produced in Classical Nova Explosions?

Gehrz et al. 1992 (Ap. J., 40, 671)







- *Stardust formation, mineralogy, and abundances*
- *SOFIA's spectral resolution and wavelength coverage is required to study amorphous, crystalline, and hydrocarbon components*
- *Contributions to ISM clouds and the Primitive Solar System*

US Basic Science Program

12 Flights available (3 additional flights being negotiated)

- *Call for Proposals released April 2010*
- *60 unique proposals were received*
  - *53 with US PIs (26 Institutions)*
  - *7 with International PIs (5 Institutions)*
- *49 FORCAST Proposals and 11 GREAT Proposals*
- *Requested Time*
  - *234 hours requested for FORCAST*
  - *42 hours requested for GREAT*

FORCAST US Basic Science Awards

PI	Institution	Title	Country	Hours
Tan	U Florida	Peering to the Heart of Massive Star Birth	US	4.5
Rubin	NASA/ARC	SOFIA's Opportunity to Solve the Nebular Abundance Problem	US	2.3
Rebull	JPL	SOFIA Observations of the Gulf of Mexico Cluster	US	2.5
Werner	JPL	FORCAST Imaging of Planetary Nebulae	US	4.0
Shuping	USRA	Mid-Infrared imaging of the W40 Star Forming Region using SOFIA-FORCAST.	US	1.5
Looney	U. Illinois	Resolving Class 0 Binaries in the Mid-Infrared	US	4.0
Grady	Eureka Scientific	Spatially-Resolved Far-Infared Imaging of Bright Debris Disks	US	2.7
Sarre	U. Nottingham	FORCAST Study of 21 Micron Sources	UK	0.6
Harvey	U Texas	Far-IR Interferometry With SOFIA: A Test of Lunar Occultation Observations	US	0.4
Bally	U. Colorado	FORCAST imaging of the mini-starburst in W43	US	5.0
Armus	IPAC	Observations of the Nearby Starburst Galaxy NGC 2146 with FORCAST on SOFIA	US	2.8
Hill	CEA Saclay	SOFIA 24 and 35um imaging of the OB young stellar objects in Cygnus-X	France	2.8
Vacca	USRA	Uncovering Buried Star Clusters in Nearby Starburst Galaxies	US	3.0
Huard	UMD College Park	Resolving Protostars in the Serpens South Protocluster	US	2.1
Kobulnicky	U Wyoming	Intermediate-Mass Star Formation Regions: Defining a High-Latitude Sample	US	1.3
Nikola	Cornell	Probing The AGN-Starburst Connection	US	2.0
Sandell	USRA	The nature of Young High-mass (proto)stars in NGC7538	US	3.4
Rushton	U Central Lancashire	SOFIA observations of recurrent novae	UK	2.0
Meixner	STScI	FORCASTing Evolved Star Mass Loss in the Galactic Bulge	US	2.0
Humphreys	U. Minnesota	Cool Dust and the Mass Loss Histories of Cool Hypergiants	US	2.0
Orton	JPL	19-37 Micron Photometry of Outer Planets	US	1.2
				52.1

http:// sofia.usra.edu/Science/

GREAT US Basic Science Awards

PI	Institution	Title	Country	Hours
Sahai	JPL	Using GREAT to Probe [CII] emission in the Ring Nebula	US	3.2
Neufeld	JHU	Search for interstellar mercapto radicals (SH) with SOFIA	US	3.0
Kaufman	CalState SJ	High frequency water masers with SOFIA/GREAT	US	3.0
Schneider	CEA Saclay	Pillars of Creation: physical origin and connection to star formation	France	2.4
Hewitt	GSFC	GREAT Diagnostics of Molecular Shocks in Interacting Supernova Remnants	US	1.0
Li	JPL	Mapping "Dark Gas" in Rho Ophiuchus A	US	4.8
				17.4

http:// sofia.usra.edu/Science/

Anticipated Science Schedule

• *April 2011*	*GREAT Early Science Flights*
• *May – June 2011*	*FORCAST Basic Science Flights*
• *June 2011*	*Observatory Engineering Flights*
• *July – September 2011*	*GREAT Early Science*
• *Late 2011*	*Next Call for GI Science Proposals*

Future Instrumentation Development

- *Draft solicitation released on December 15, 2010*
- *First Solicitation release: Mid 2011 (target)*
- *Proposals due 90 days later*
- *Selections announced: Late 2011*
- *Contracts initiated: Early 2012*
- *There will be additional calls every three years*
- *$5-$10 million/year for life of the program*

Summary

- *The Program is making progress!*
  - *Flight envelope testing is completed*
  - *Science flights have begun*
- *SOFIA will be one of the primary observational facilities for far-IR and submillimeter astronomy for many years*

http://www.sofia.usra.edu/

Backup

The Initial SOFIA Instrument Complement

- *HIPO: High-speed Imaging Photometer for Occultation*
- *FLITECAM: First Light Infrared Test Experiment CAMera*
- *FORCAST: Faint Object InfraRed CAmera for the SOFIA Telescope*
- *GREAT: German Receiver for Astronomy at Terahetz Frequencies*
- *FIFI-LS: Field Imaging Far-Infrared Line Spectrometer*
- *HAWC: High-resolution Airborne Wideband Camera*
- *EXES: Echelon-Cross -Echelle Spectrograph*

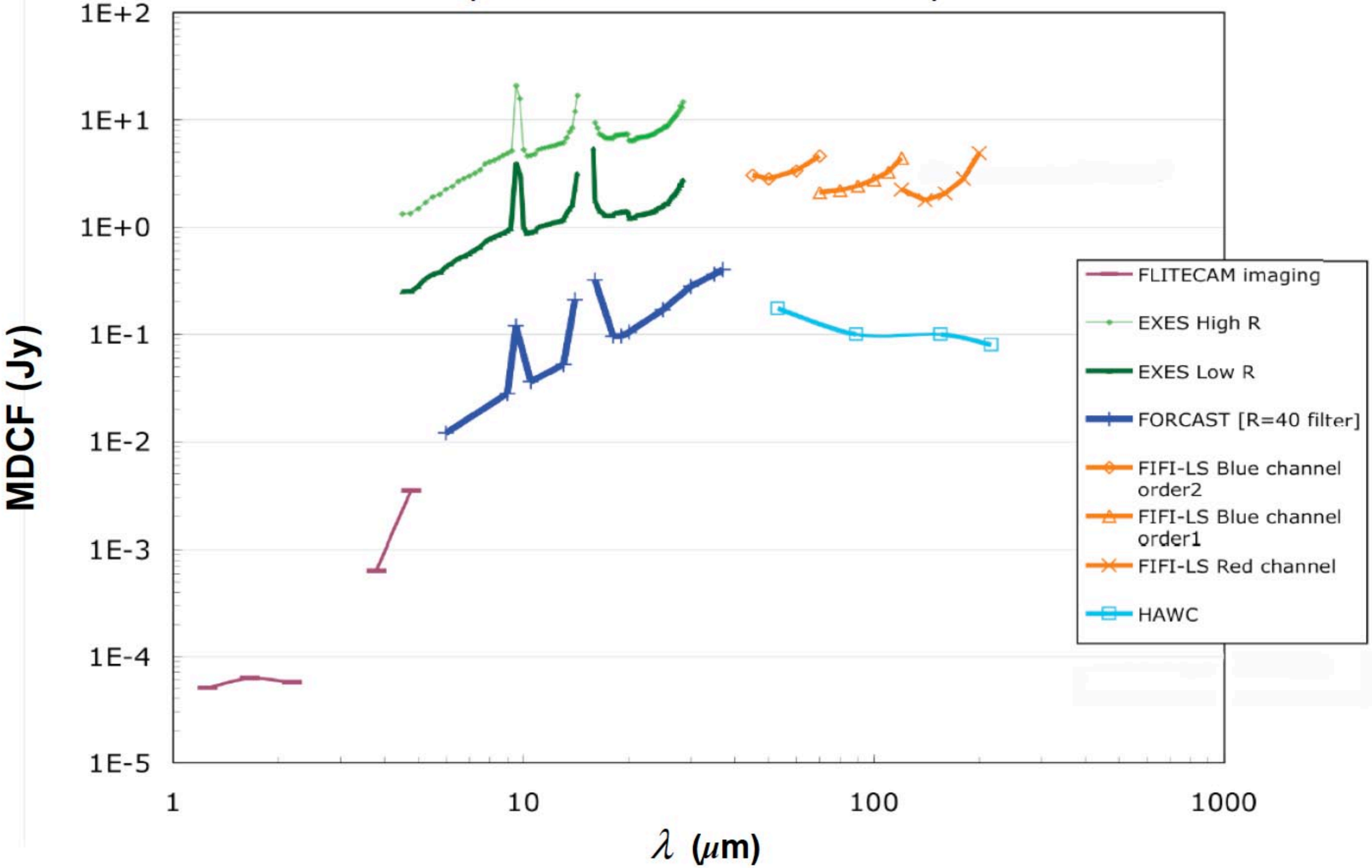
SOFIA's First-Generation Instruments

Instrument	Type	λλ (μm)	Resolution	PI	Institution
HIPO (Available 2010)	fast imager	0.3 - 1.1	filters	E. Dunham	Lowell Obs.
FLITECAM * (Available 2010)	imager/grism	1.0 - 5.5	filters/R~2000	I. McLean	UCLA
FORCAST * (Available 2009)	imager/(grism?)	5.6 - 38	filters/(R~2000)	T. Herter	Cornell U.
GREAT (Available 2009)	heterodyne receiver	62 - 65 111 - 12 158 - 187 200 - 240	R ~ 10^4 - 10^8	R. Güsten	MPIfR
FIFI LS ** (Available 2009)	imaging grating spectrograph	42 - 110, 110 - 210	R ~1000 - 2000	A. Poglitsch	MPE
HAWC * (Available 2011)	imager	40 - 300	filters	D. A. Harper	Yerkes Obs.
SAFIRE (Available 2012)	F-P imaging spectrometer	150 - 650	R ~ 1000 - 2000	H. Moseley	NASA GSFC

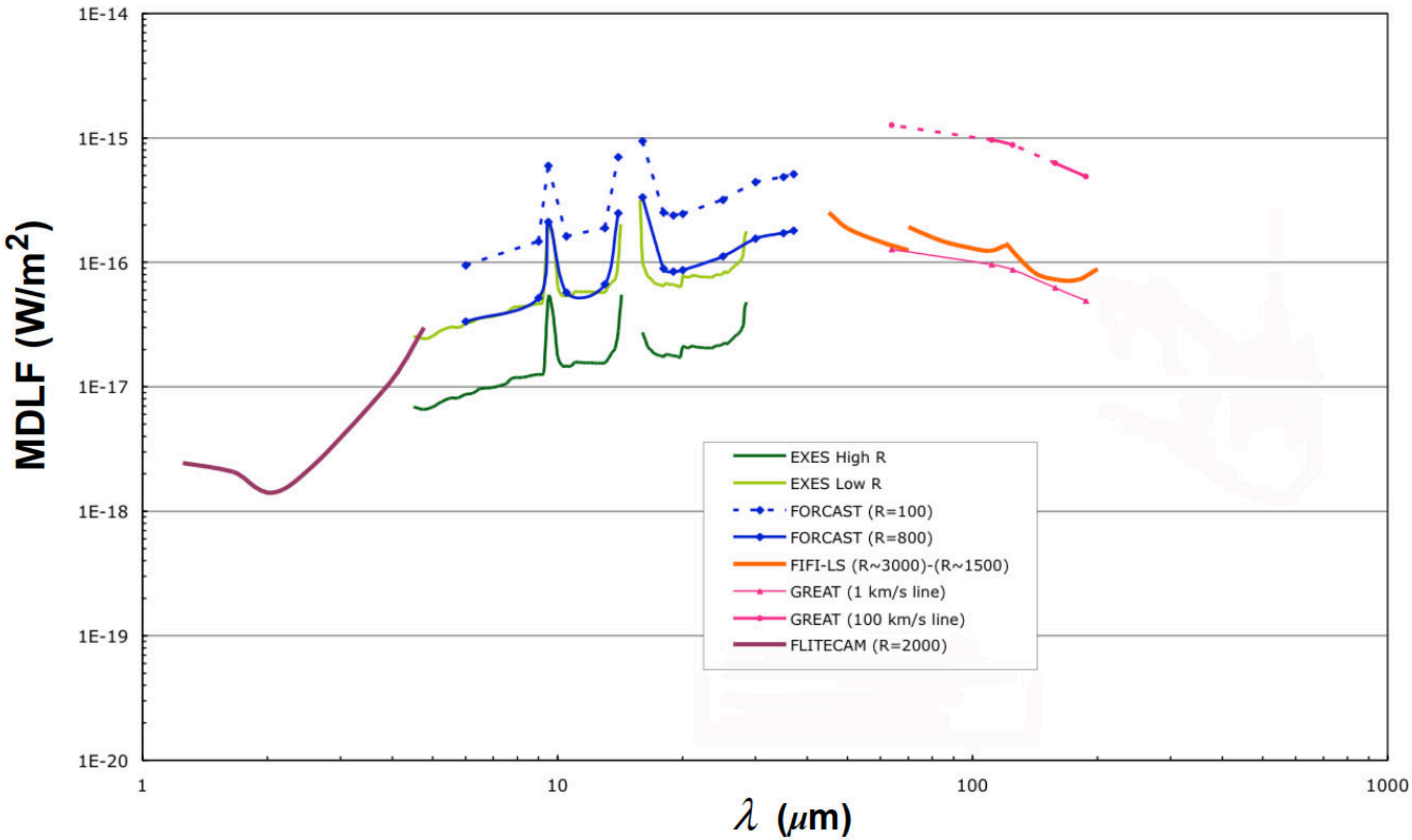
**** Facility-class instrument***

***** Developed as a PI-class instrument, but will be converted to Facility-class during operations***

Continuum Sensitivities
(10 σ in 900 sec on source time)



Line Sensitivities with Spectrometers
(10 σ in 900 sec on source time)

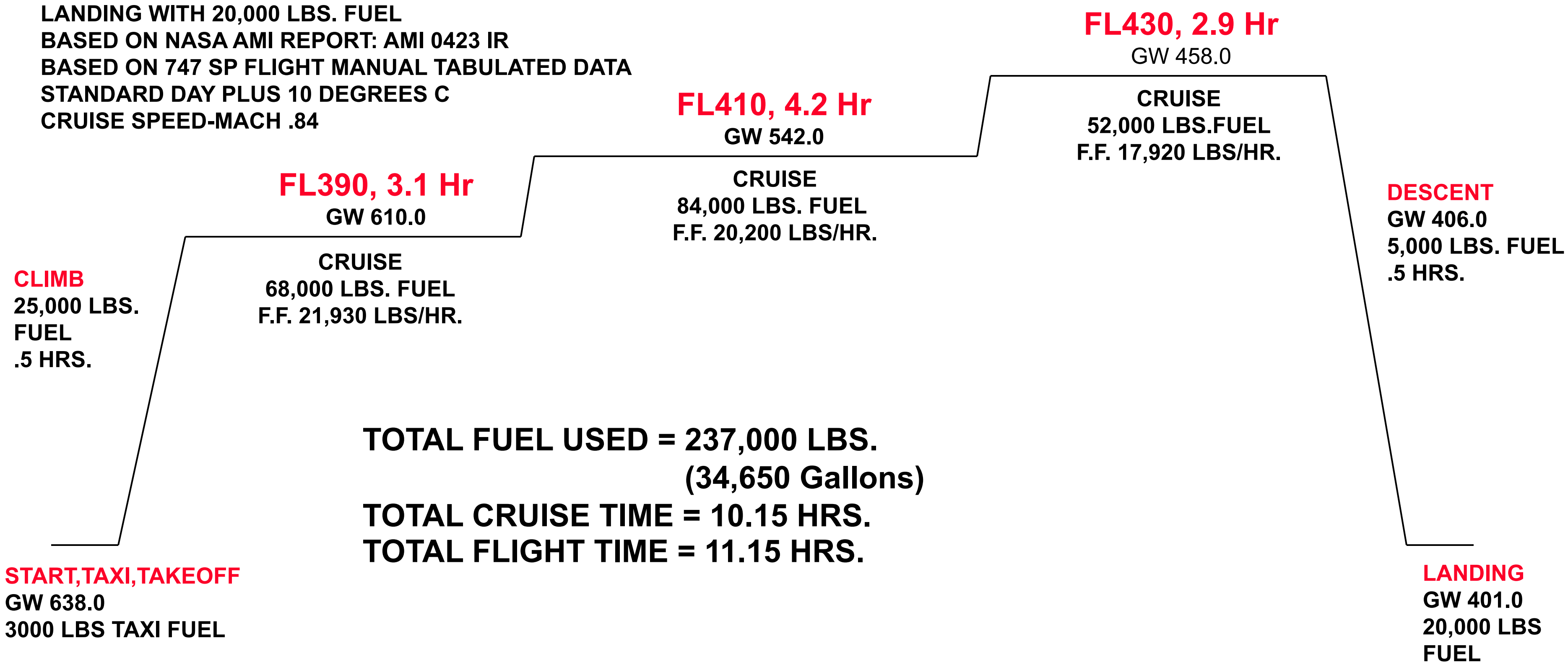


Flight Profile 2

Performance with P&W JT9D-7J Engines:
Observations - start FL390, duration 10.2 Hr

ASSUMPTIONS

ZFW 381,000 LBS.
ENGINES OPERATE AT 95% MAX CONT THRUST AT CRUISE
25,000 LBS. FUEL TO FIRST LEVEL OFF
CLIMB TO FIRST LEVEL-OFF AT MAX CRUISE WT
LANDING WITH 20,000 LBS. FUEL
BASED ON NASA AMI REPORT: AMI 0423 IR
BASED ON 747 SP FLIGHT MANUAL TABULATED DATA
STANDARD DAY PLUS 10 DEGREES C
CRUISE SPEED-MACH .84



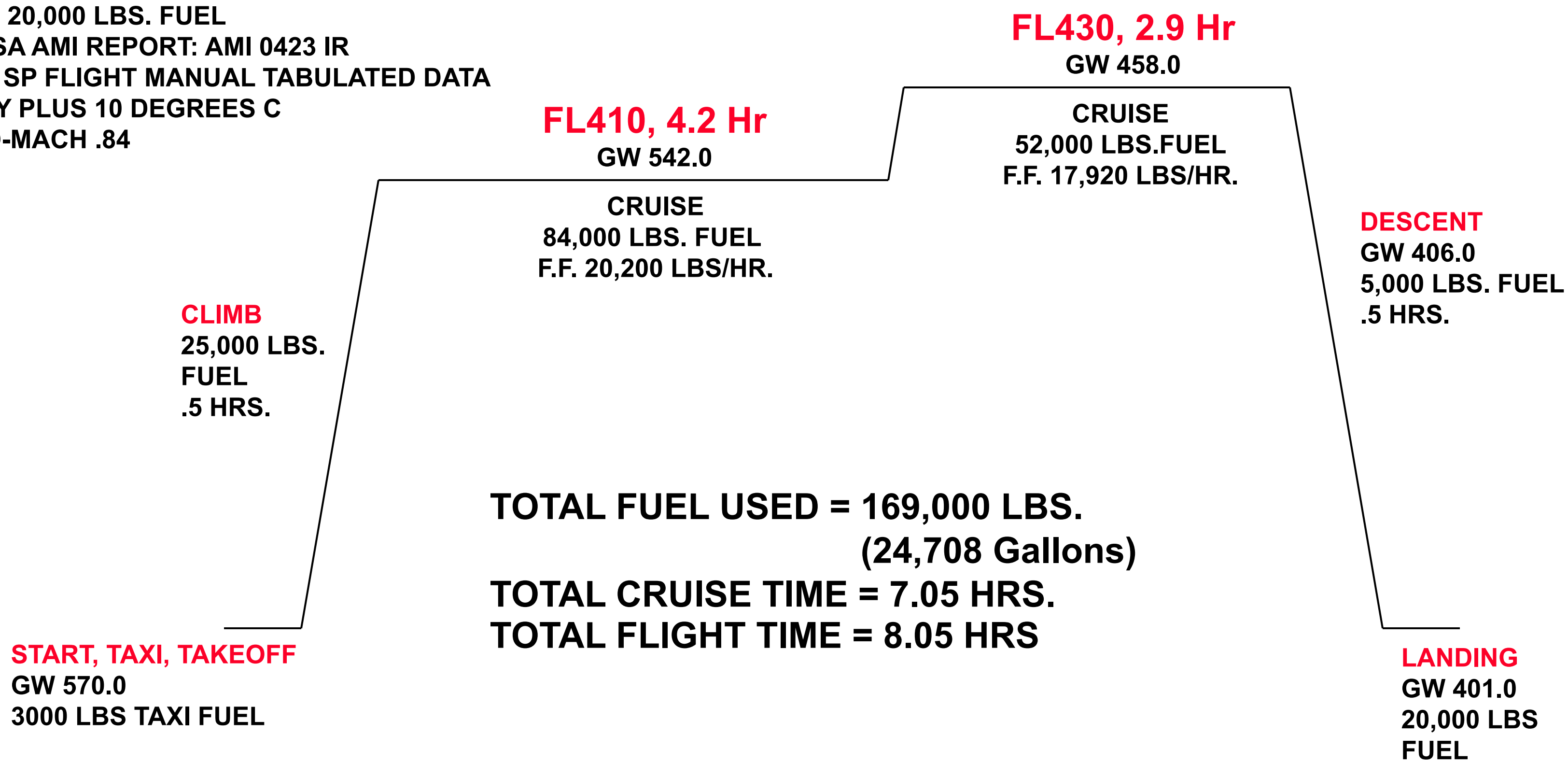
TOTAL FUEL USED = 237,000 LBS.
(34,650 Gallons)
TOTAL CRUISE TIME = 10.15 HRS.
TOTAL FLIGHT TIME = 11.15 HRS.

Flight Profile 1

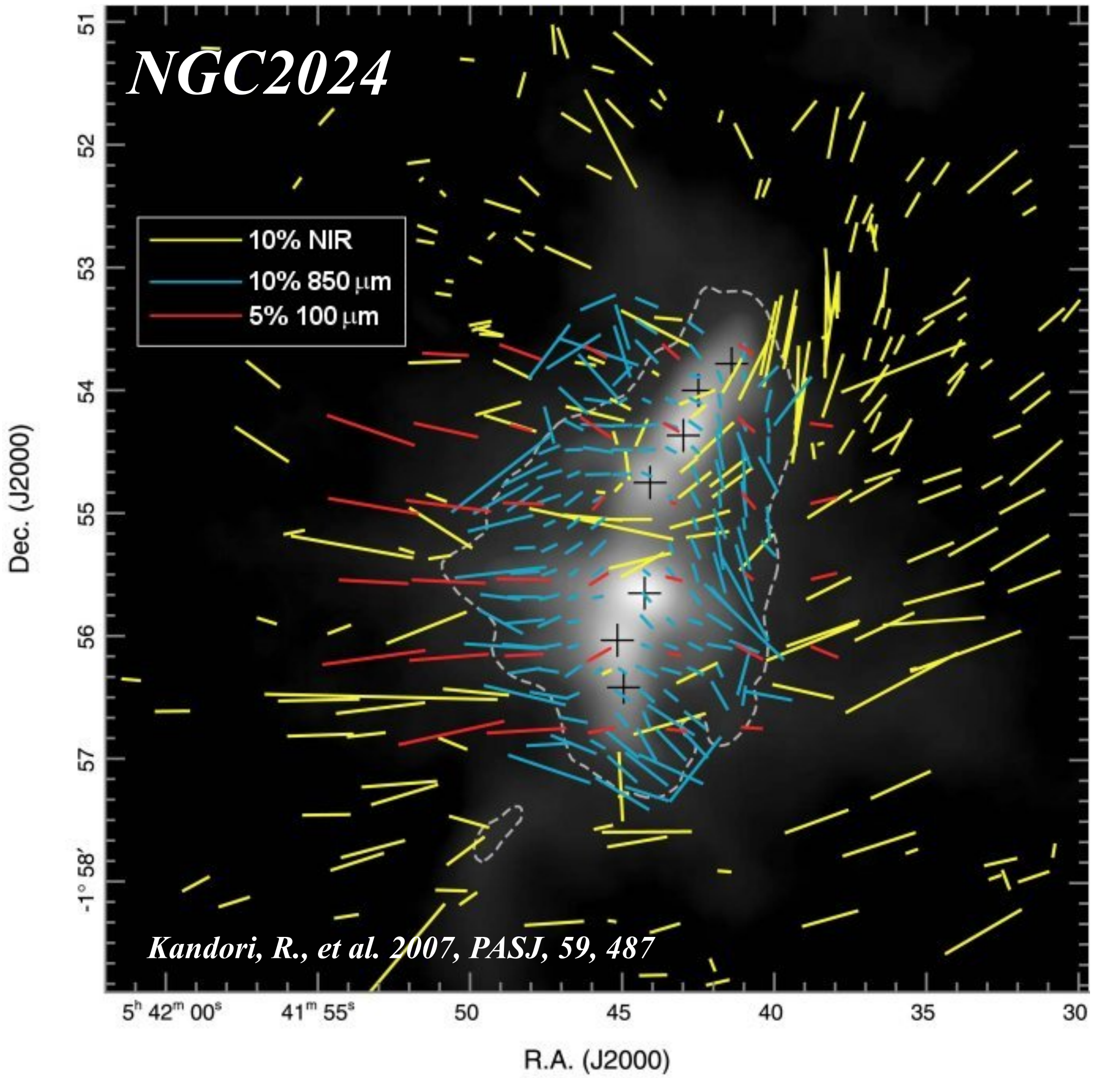
Performance with P&W JT9D-7J Engines: Observations - start FL410, duration 7.1 Hr

ASSUMPTIONS

ZFW 381,000 LBS.
ENGINES OPERATE AT 95% MAX CONT THRUST AT CRUISE
25,000 LBS. FUEL TO FIRST LEVEL OFF
CLIMB TO FIRST LEVEL-OFF AT MAX CRUISE WT
LANDING WITH 20,000 LBS. FUEL
BASED ON NASA AMI REPORT: AMI 0423 IR
BASED ON 747 SP FLIGHT MANUAL TABULATED DATA
STANDARD DAY PLUS 10 DEGREES C
CRUISE SPEED-MACH .84

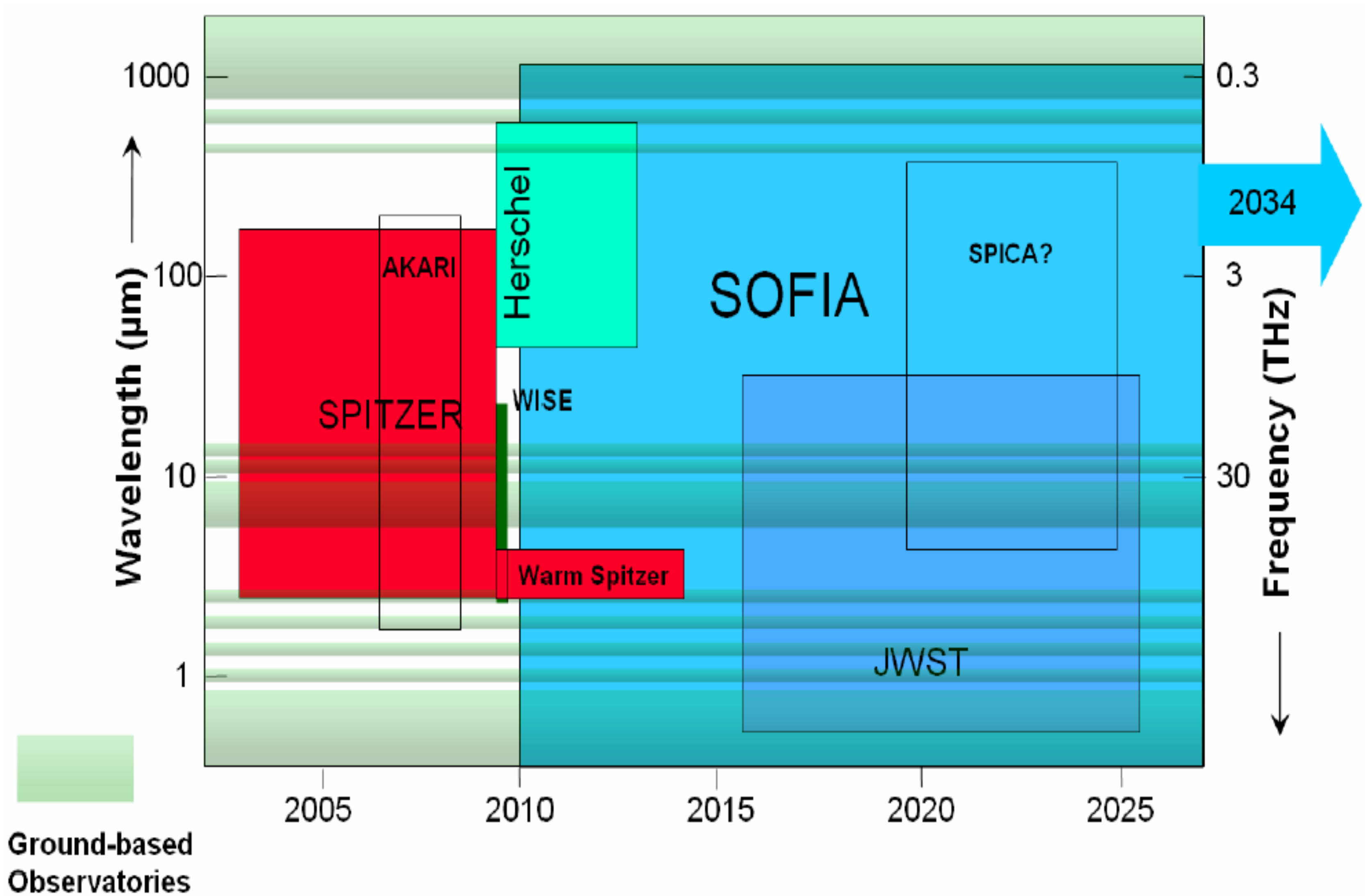


Magnetic Fields in Massive Star Forming Regions



Within the dashed contour, NIR and submm disagree on field direction. NIR does not probe the dense material. FIR will probe warm, dense material.

IRSF/SIRIUS and JCMT/SCUBA data


1000
100
10
1
Wavelength (μm)
0.3
3
30
Frequency (THz)
2034
SPITZER
AKARI
Herschel
WISE
Warm Spitzer
SOFIA
SPICA?
JWST
2005
2010
2015
2020
2025
Ground-based
Observatories