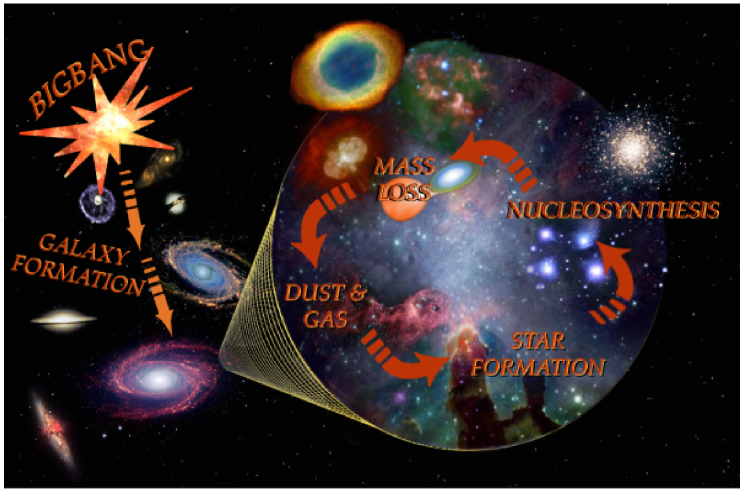
USRA NASA DLR SOFIA

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 available at http://www.sofia.usra.edu/Science/speakers/index.html

Outline

- *SOFIA's Heritage and Context*
- *Overview and Status of the SOFIA Mission*
- *SOFIA Instrumentation and Performance Specifications*
- *SOFIA Science Vision*
- *SOFIA Schedule and Opportunities for Collaboration*
- *Summary*

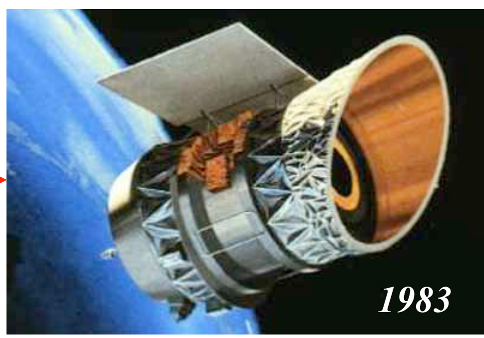
The History of Flying Infrared Observatories

NASA Lear Jet Observatory

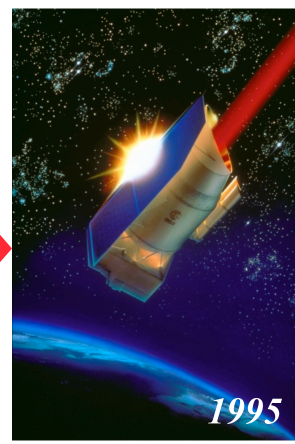
NASA Kuiper Airborne Observatory (KAO)

NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA)

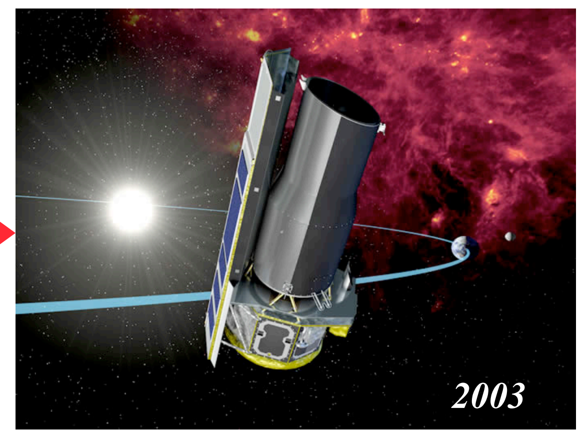
Air and Space



NASA Infrared Astronomical Satellite (IRAS)

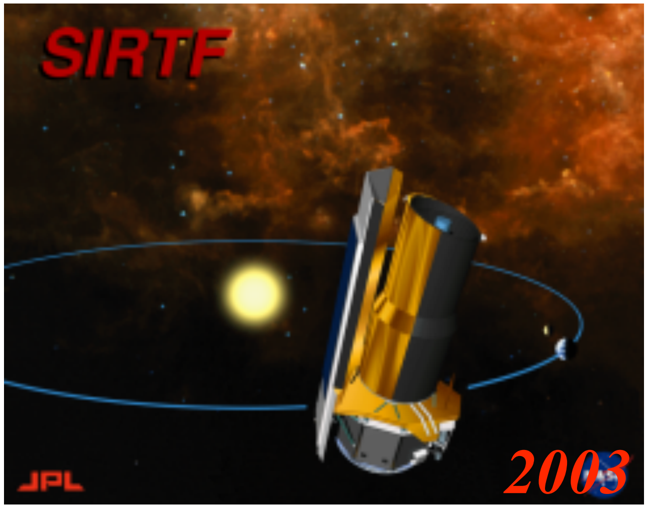


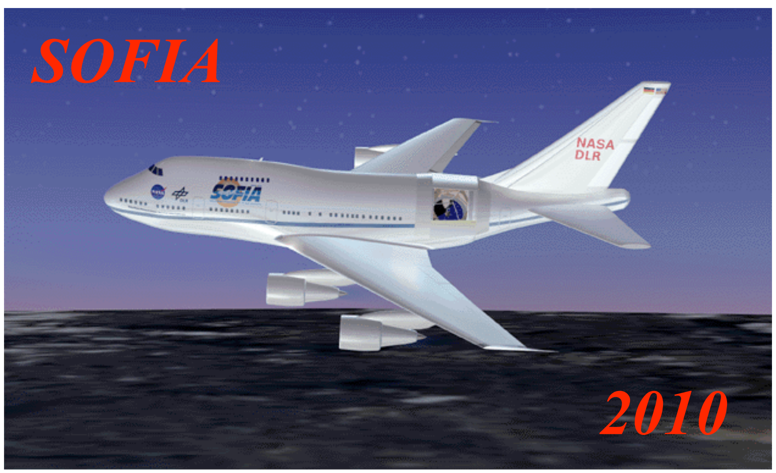
ESA Infrared Space Observatory (ISO)

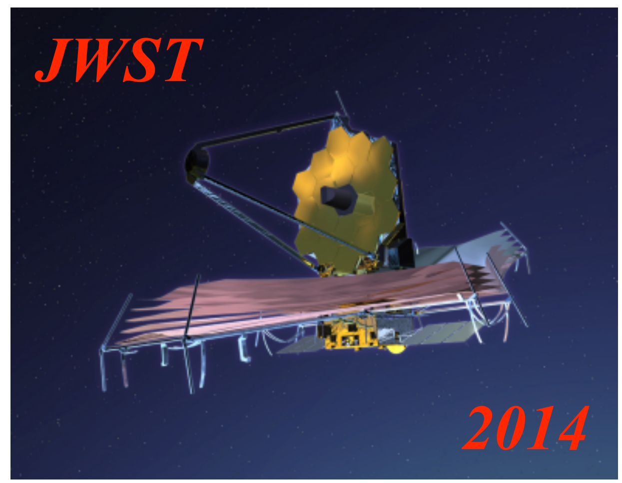


NASA Spitzer Space Telescope

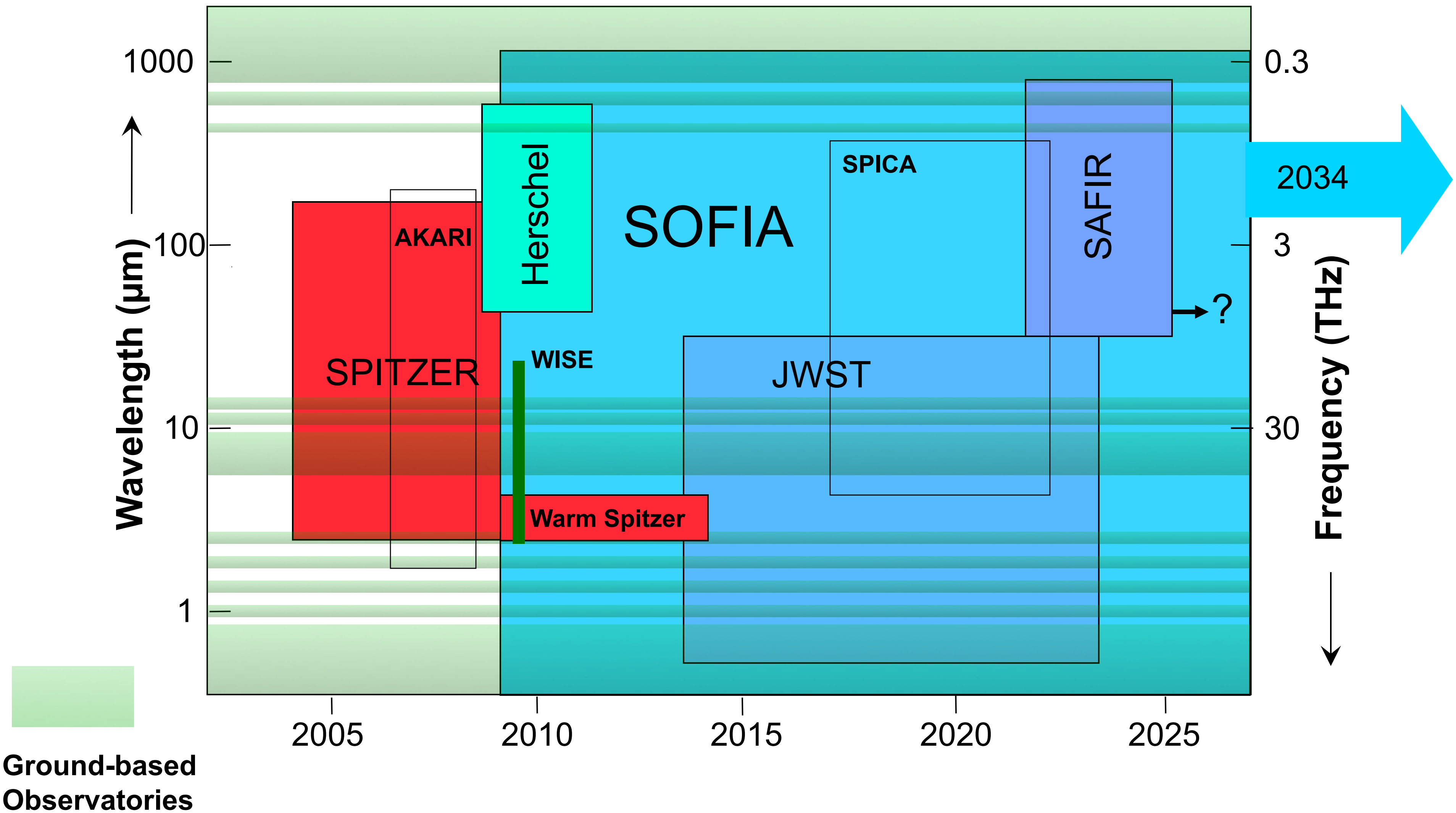
SOFIA and its Companions in Space







SOFIA and Major IR Imaging/Spectroscopic Space Observatories



SOFIA Mission Overview And Status

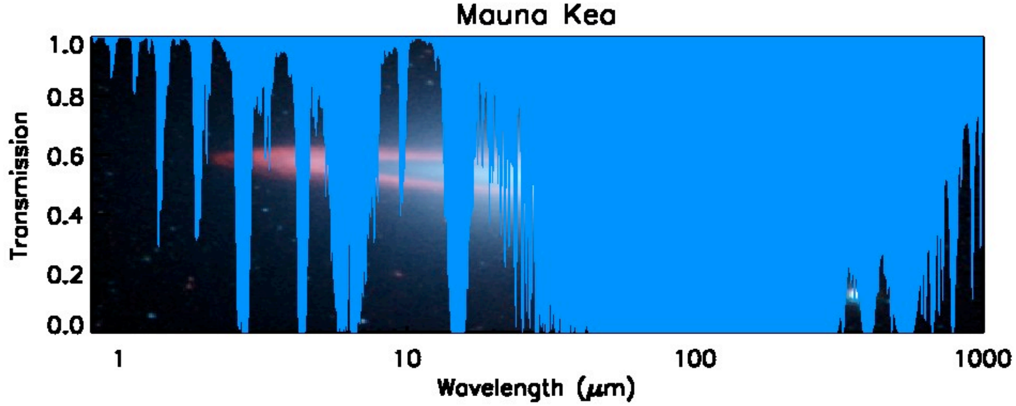
March 2010

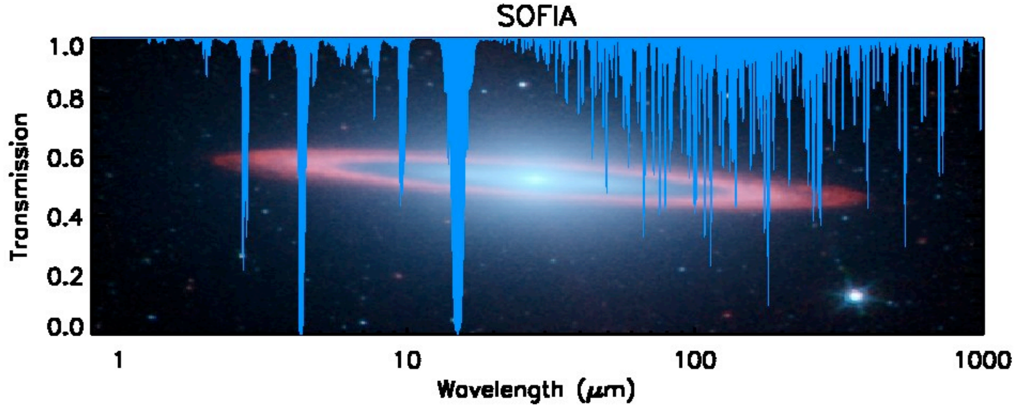
SOFIA Overview

- *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 in April 2010*
  - *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*

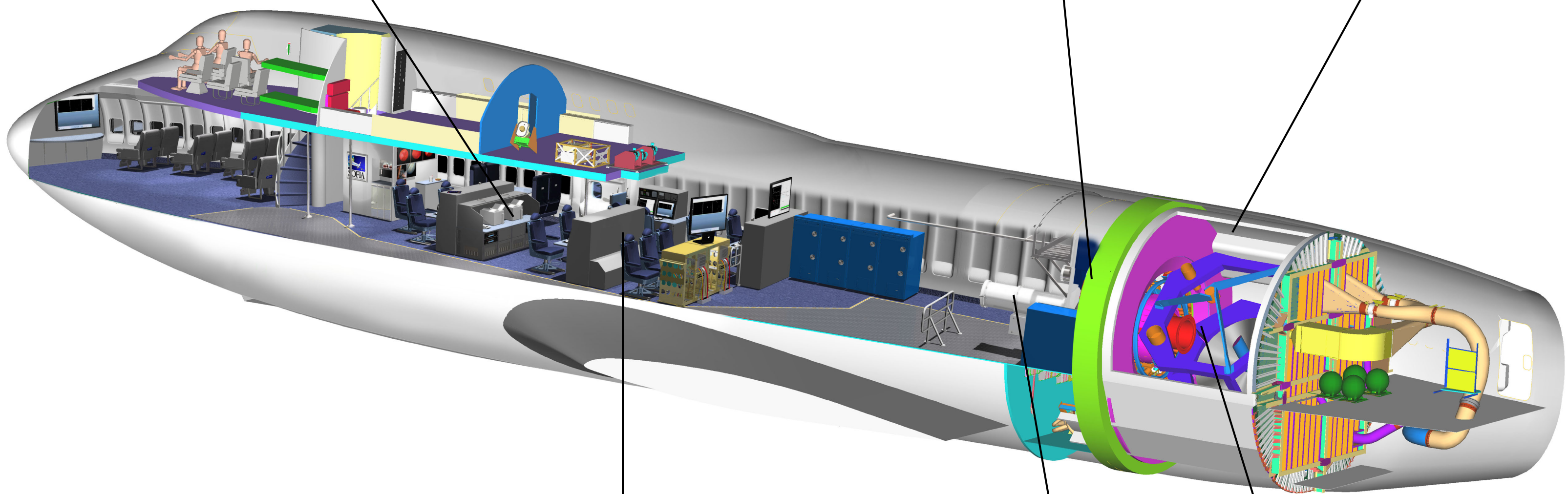
The Advantages of SOFIA

- *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*



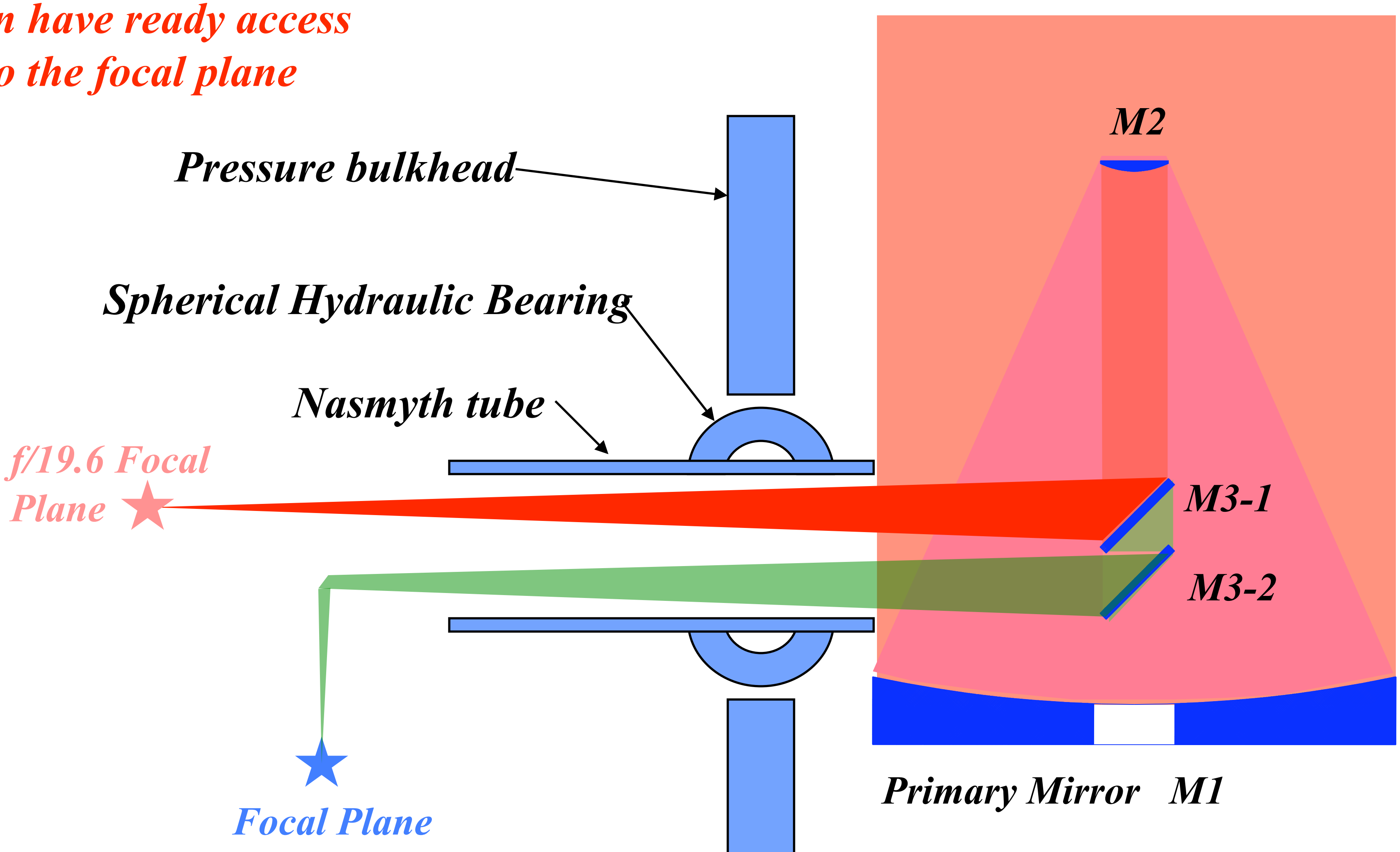


The SOFIA Observatory

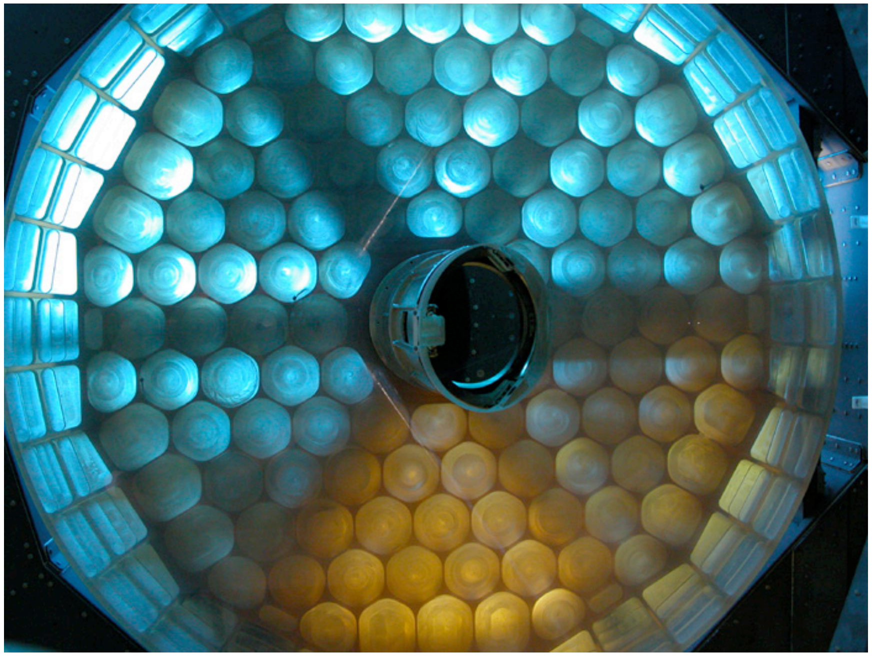


Nasmyth: Optical Layout

Observers in pressurized cabin have ready access to the focal plane



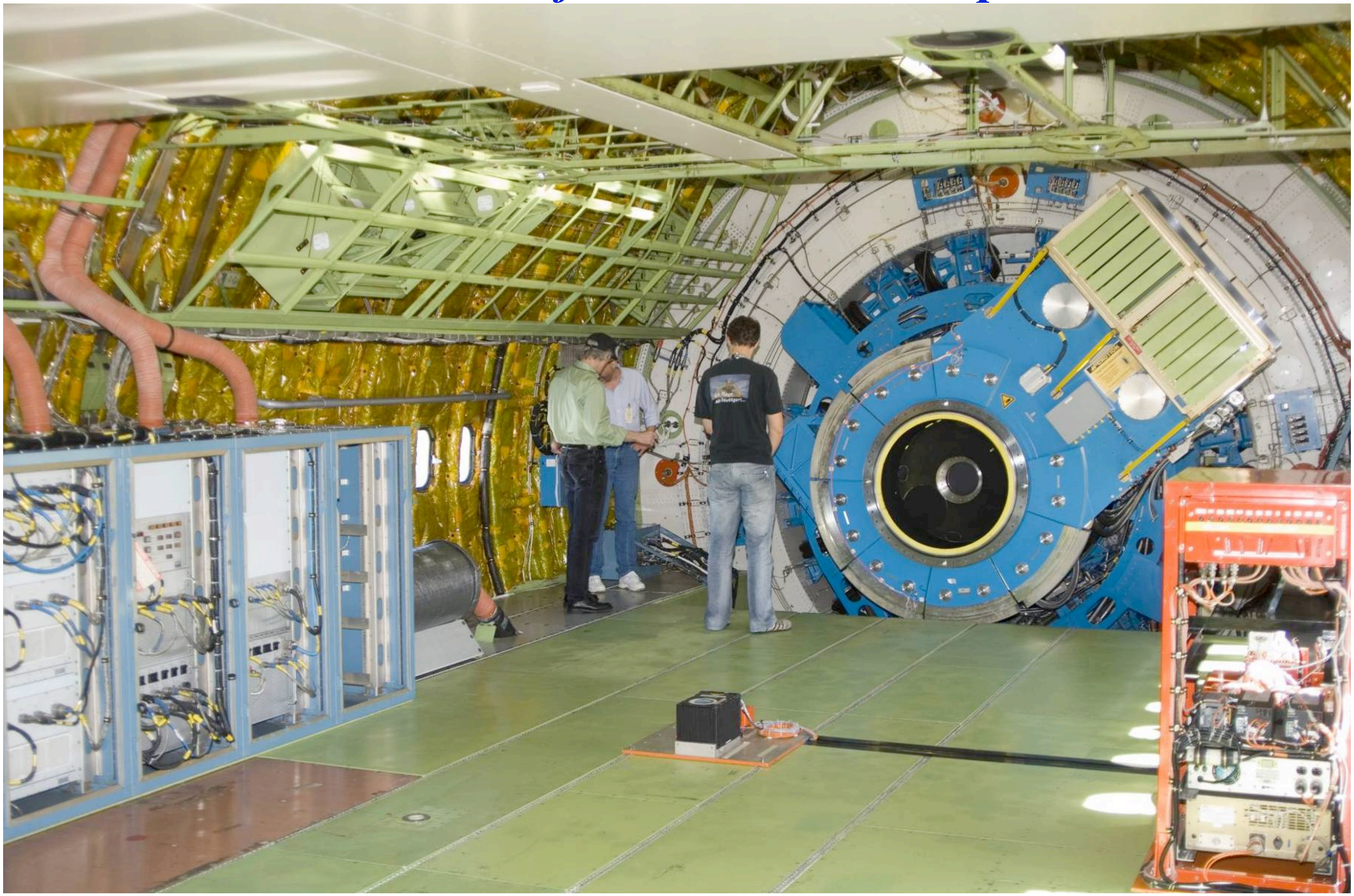
The Un-Aluminized Primary Mirror Installed



Primary Mirror Installed Oct. 8, 2008

hrz

Back End of the SOFIA Telescope



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

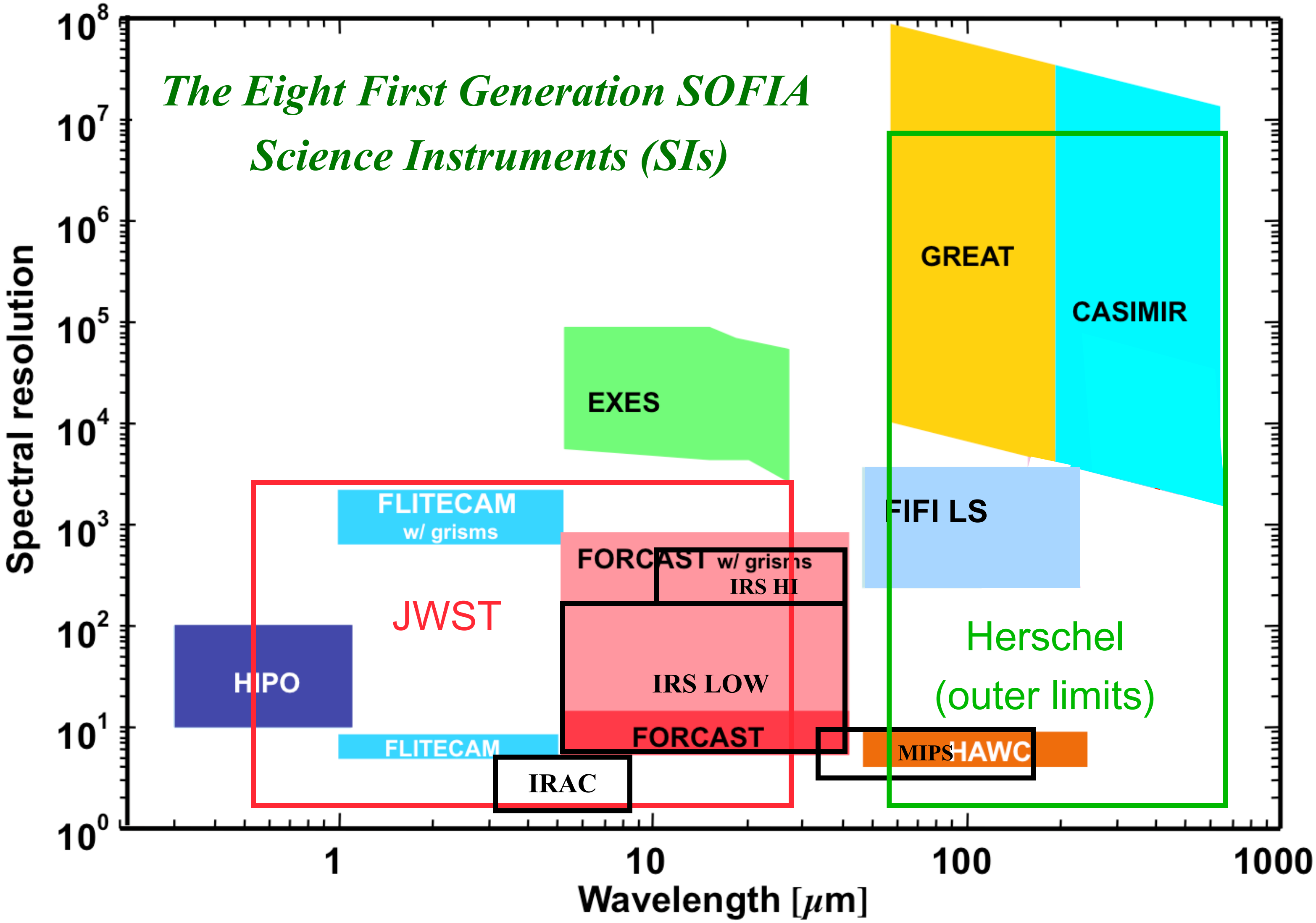
SOFIA's First-Generation Instruments

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
CASIMIR (Available 2011)	heterodyne receiver	250 -264, 508 -588	R ~ 10^4 -10^8	J. Zmuidzinas	Caltech
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.
EXES (Available 2011)	imaging echelle spectrograph	5 - 28.5	R ~ 3000 - 10^5	M. Richter	UC Davis

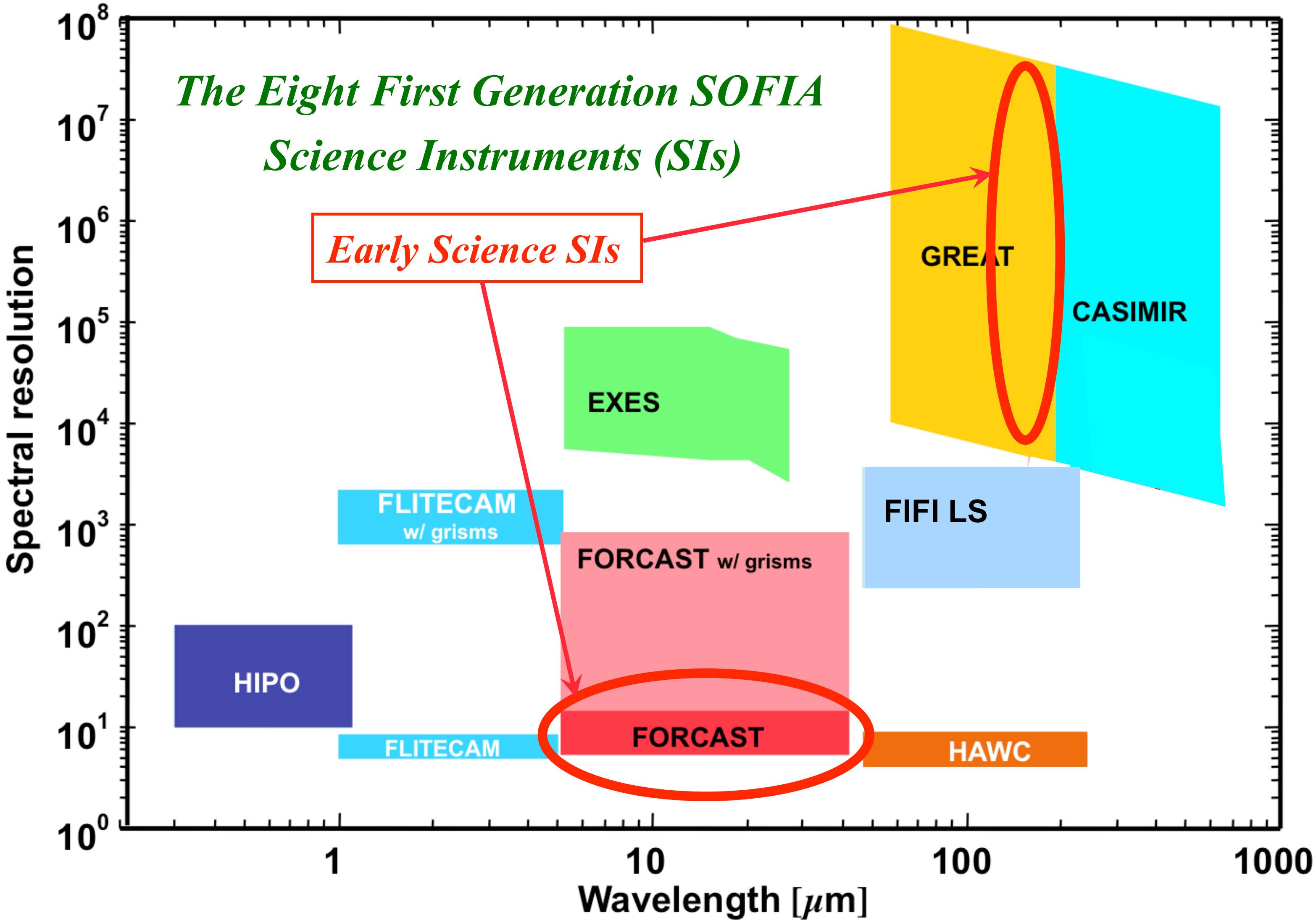
** Facility-class instrument*

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

SOFIA First Generation Spectroscopy



SOFIA First Generation Spectroscopy



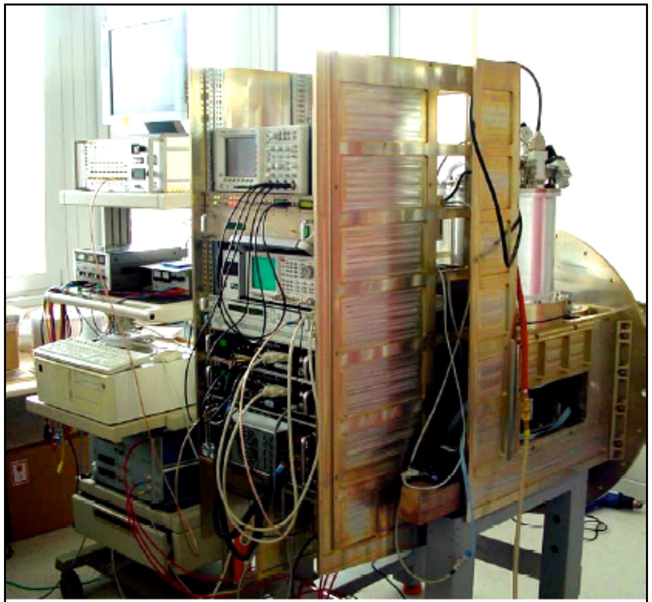
Early Science with FORCAST and GREAT

Faint Object infraRed Camera for the SOFIA Telescope (FORCAST)

- *Mid IR, two-channel camera*
- *0.75"/pixel 4-8 μm,16-40 μm*
- *R = 200 grisms in the (near?) future*

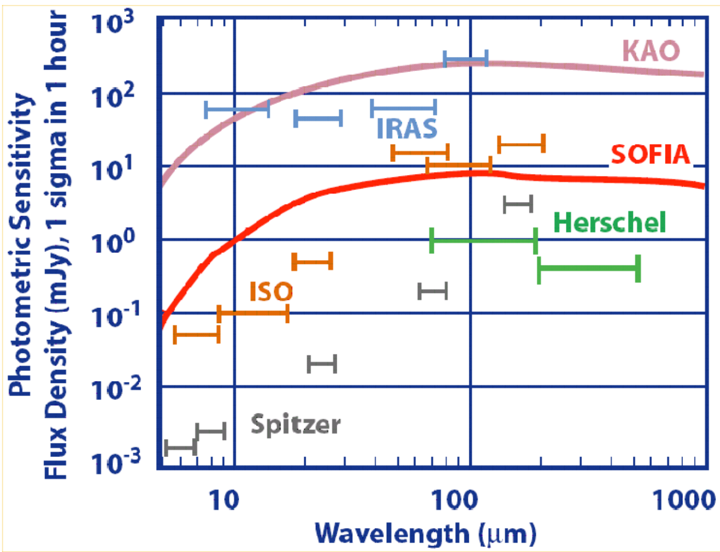
German REceiver for Astronomy at Terahertz frequencies (GREAT)

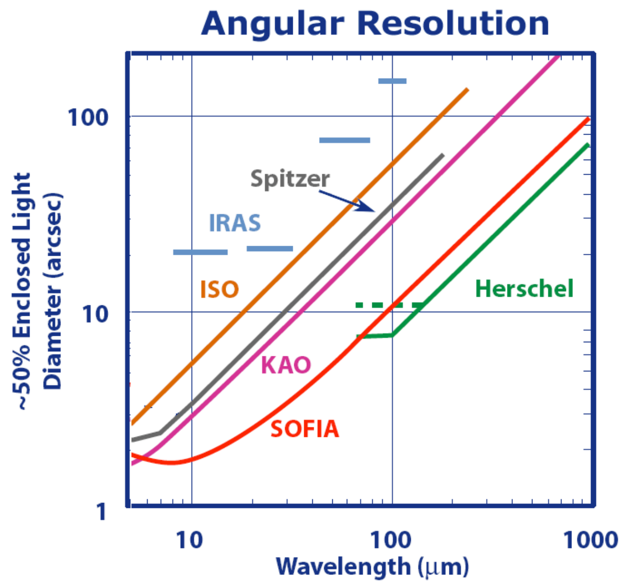
- *Heterodyne spectrometer*
- *Dual-channel 1.6-1.9 THz, 2.4-2.7 THZ (111-125 μm, 158-188 μm)*



Lab-picture of GREAT equipped with the KOSMA 1.9THz channel

Photometric Sensitivity and Angular resolution



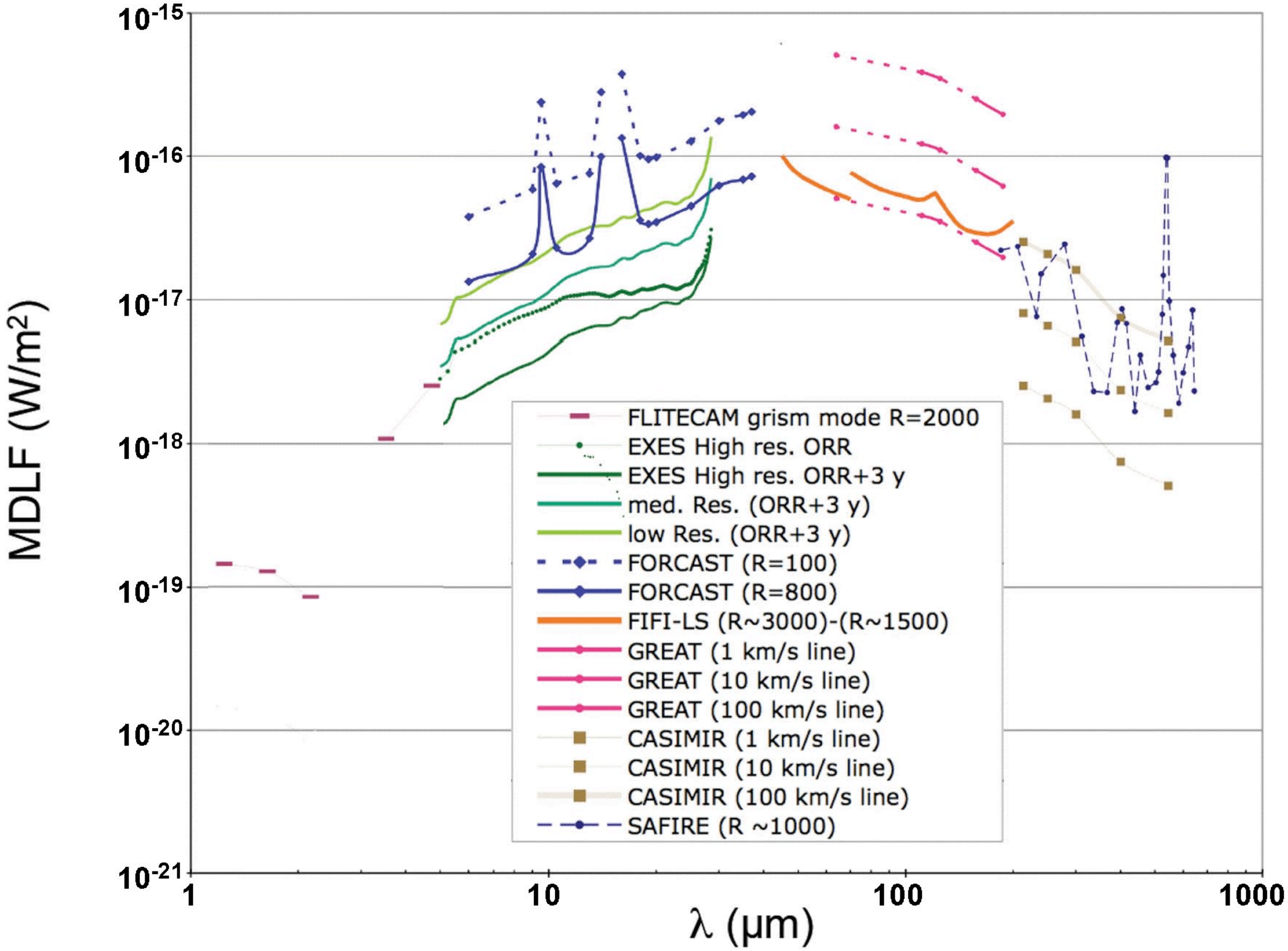


SOFIA is as sensitive as ISO

SOFIA is diffraction limited beyond 25 μm ($\theta_{min} \sim \lambda/10$ in arcseconds) and can produce images three times sharper than those made by Spitzer

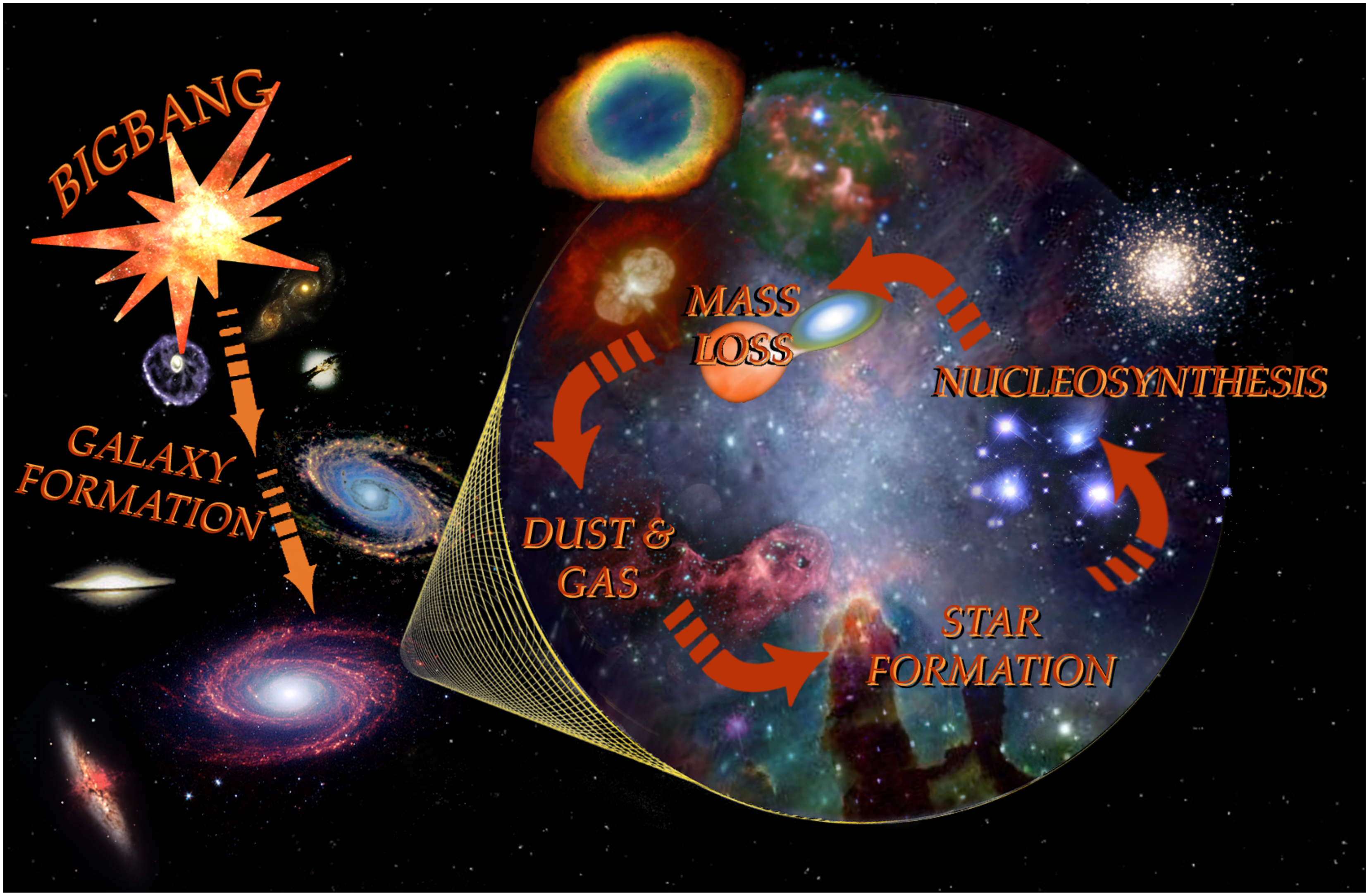
Line Sensitivities with Spectrometers

(4σ in 900 sec on source time)



SOFIA Science

The Physics and Chemistry of Stellar Evolution with SOFIA



SOFIA: Transient Events and Objects of Opportunity

Airborne astronomy has a heritage of prompt response to transient astronomical events (e.g. P/Halley, SN1987a)

- ***Many stages of stellar of the stellar evolution cycle are characterized by transient phenomena and involve studies of objects of opportunity. These include bright comets, eruptive variable stars, classical novae, supernovae, occultations, and transits of extra-solar planets.***
  - ***SOFIA can go where and when necessary to respond.***
  - ***The right instruments for the science can be mounted on short notice.***
  - ***SOFIA can fly above the clouds and most of the water.***
  - ***SOFIA operations permit in-flight observation planning.***

A Sampler of Key Science Goals for SOFIA

1. The ISM and the Formation of Stars and Planets
2. Stellar Astrophysics
3. Galaxies and the Galactic Center
4. Planetary Science: Transient Events and Objects of Opportunity

See "The Science Vision for SOFIA" at

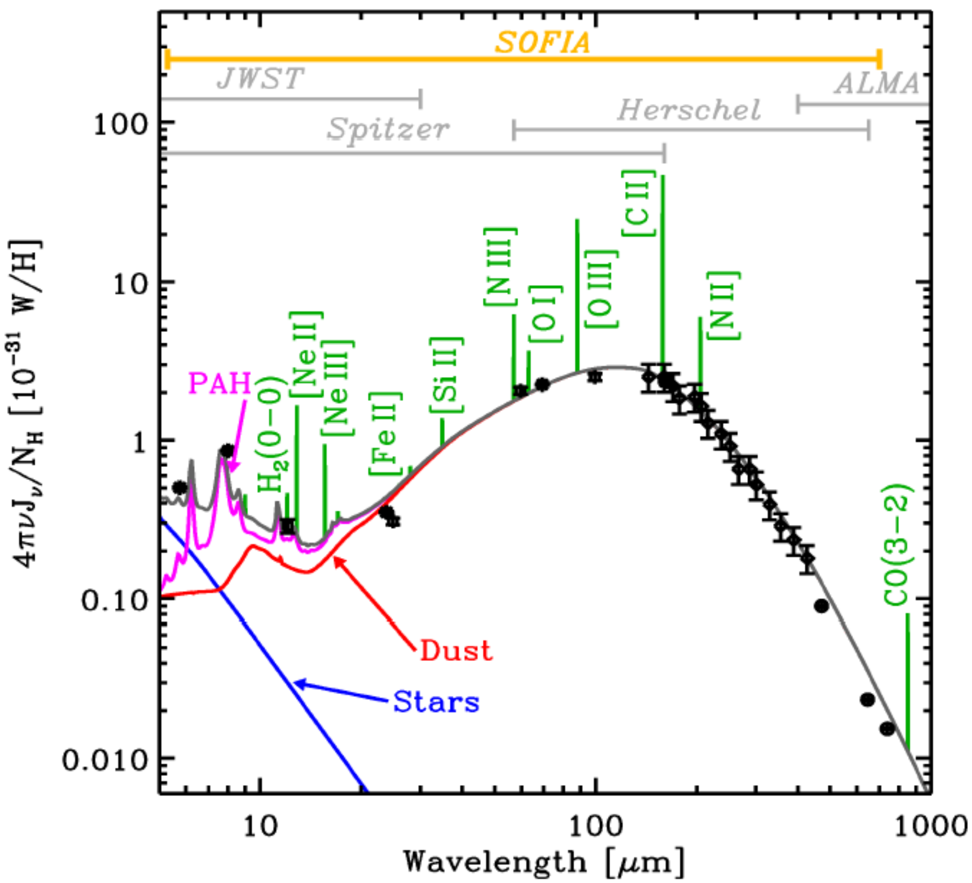
http://www.sofia.usra.edu/Science/docs/SofiaScienceVision051809-1.pdf

Key Science Goals for SOFIA

The ISM and the Formation of Stars and Planets

- *Physics and astrochemistry of star formation regions*
- *The formation of massive stars*
- *Understanding Proto-planetary Disks*

Thermal Emission from ISM Gas and Dust

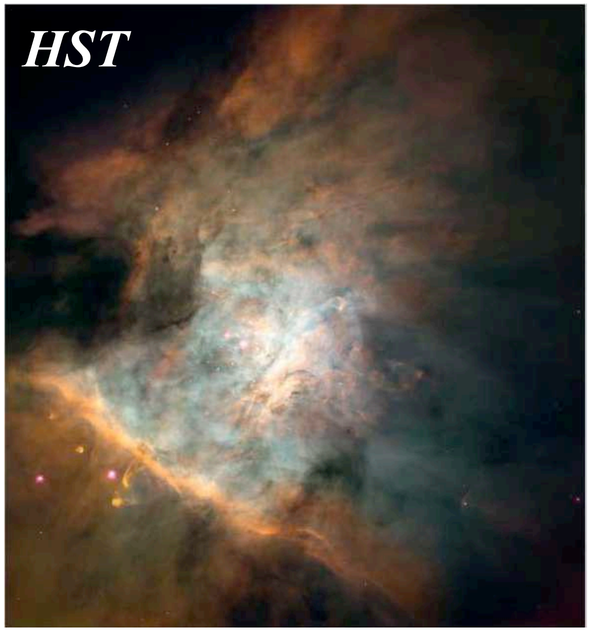


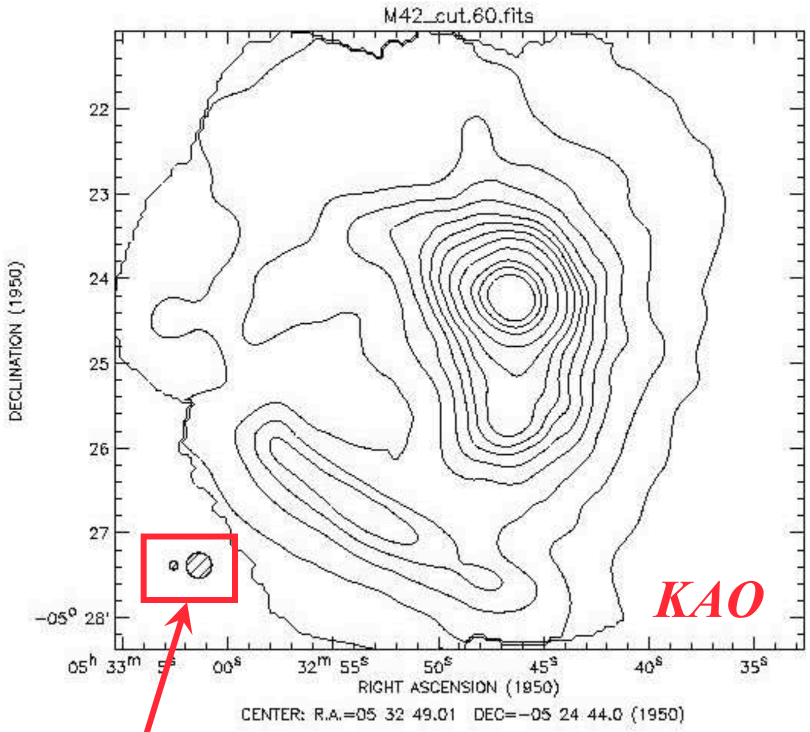
Spectral Energy Distribution (SED) of the entire LMC (courtesy of F. Galliano)

- ***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***

SOFIA and Regions of Star Formation

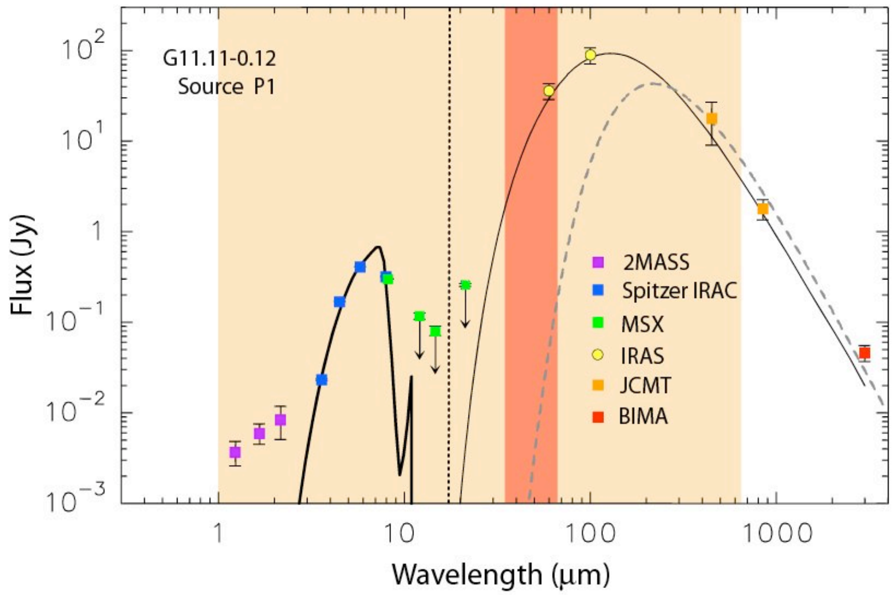
How will SOFIA shed light on the process of star formation in Giant Molecular Clouds like the Orion Nebula?





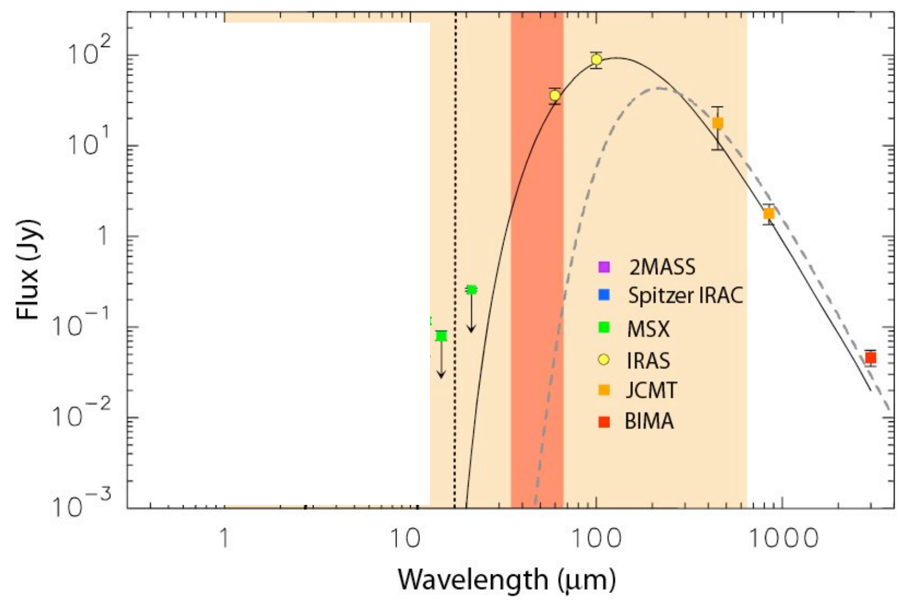
With 9 SOFIA beams for every 1 KAO beam, SOFIA imagers/HI-RES spectrometers can analyze the physics and chemistry of individual protostellar condensations where they emit most of their energy and can follow up on HERSCHEL discoveries.

Sources Embedded in Massive Cloud Cores

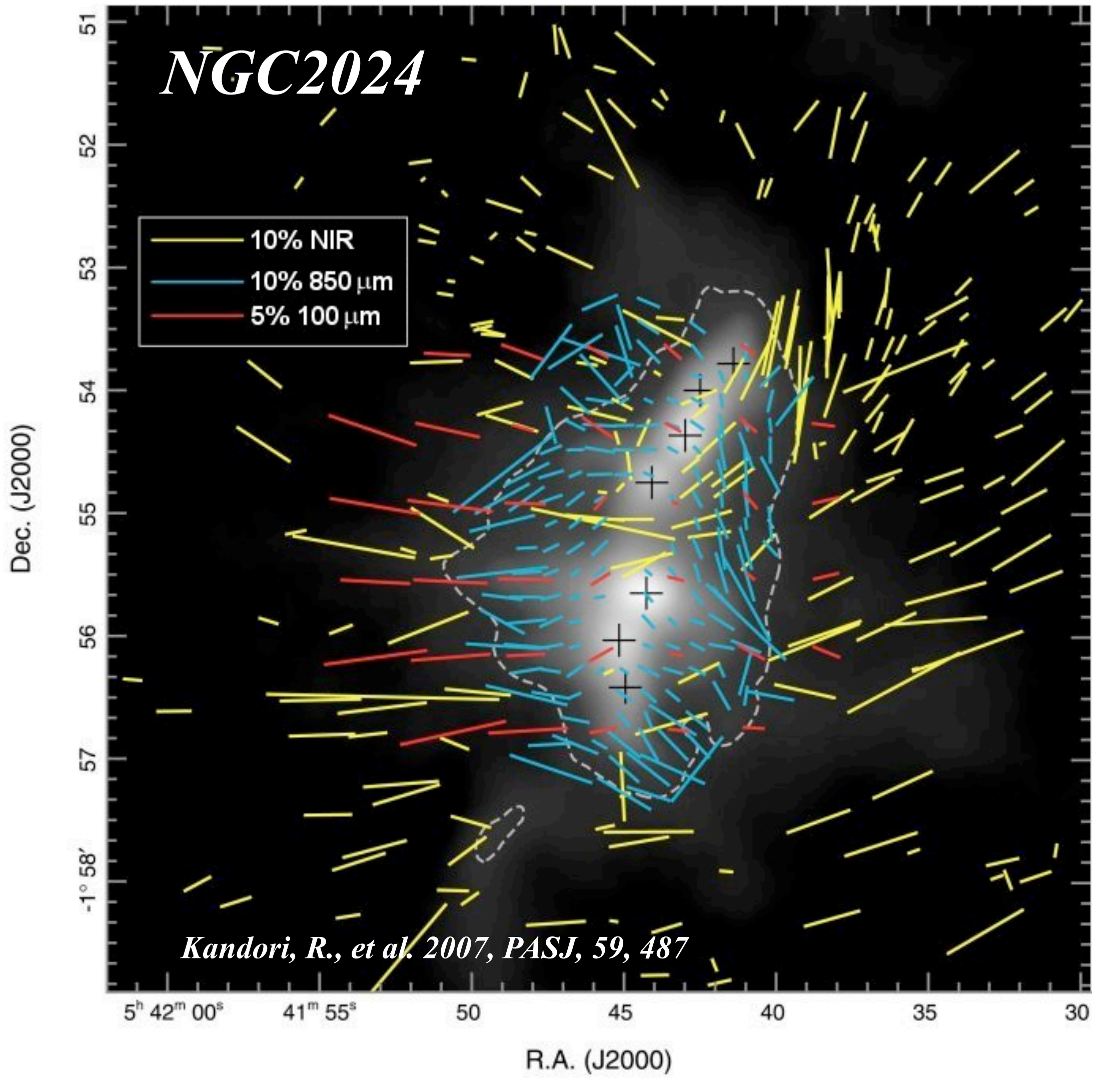


- 20 to 100 microns can provide a key link to shorter wavelengths

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



Magnetic Fields in Massive Star Forming Regions



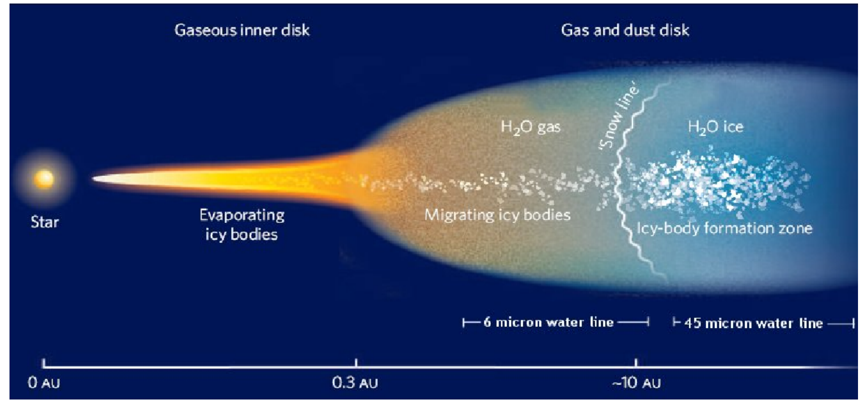
- *Within the dashed contour, NIR and sub-mm disagree on field direction. NIR probes outer low density material. FIR will probe warm, dense material*
- *A polarimetric capability for HAWC is being investigated*

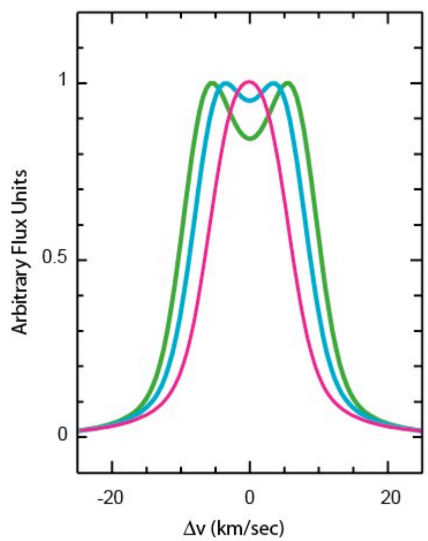
IRSF/SIRIUS and JCMT/SCUBA data

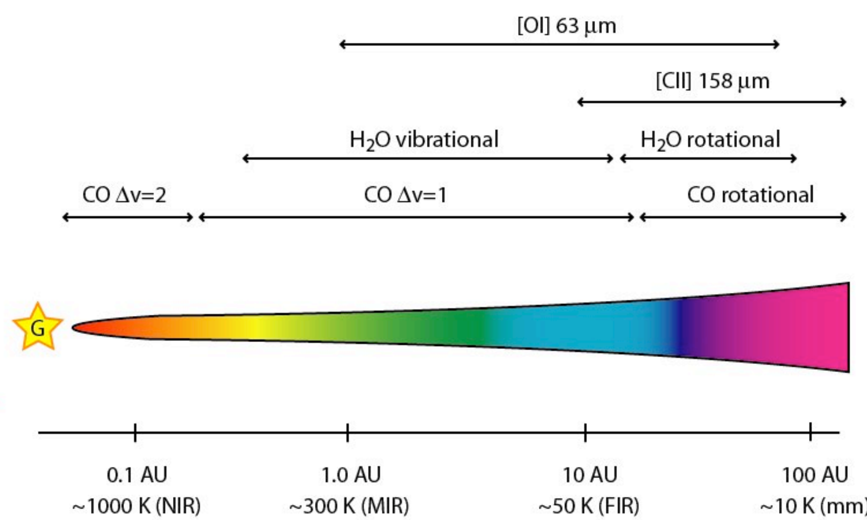
The Physics and Chemistry of Protoplanetary Disks

- *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

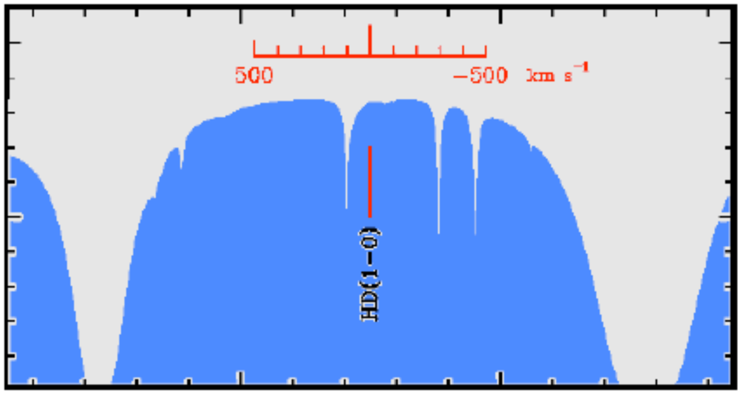






HD and Stellar Evolution

- The 112μm ground-state rotational line of HD is accessible to GREAT
- ISO detection of SGR B shows that HD column densities of ~ $10^{17} – 10^{18}$ cm^{-2} can be detected



Atmospheric transmission around the HD line at 40,000 feet

- All deuterium in the Universe was originally created in the Big Bang
- D is destroyed by astration in stars
- Therefore, D abundance probes the ISM that has never been cycled through stars and is an indicator of the star formation history of a region of star formation

Astrochemistry in Star Forming Regions

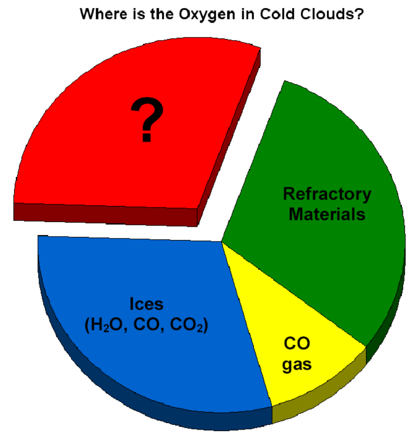
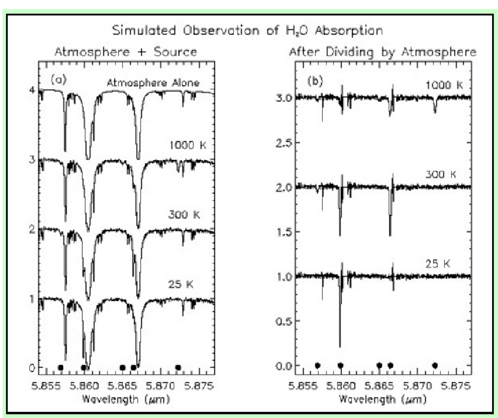


Figure 2-6. A pie chart showing the oxygen budget in cold clouds. Almost 1/3 of the oxygen is unaccounted for.



- *SOFIA is the only mission that can provide spectrally resolved data on the 63 and 145 μm [OI] lines to shed light on the oxygen deficit in circumstellar disks and star-forming clouds*

- *SOFIA has the unique ability to spectrally resolve Doppler shifted water vapor lines in the Mid-IR to probe and quantify the creation of water in disks and star forming environments*

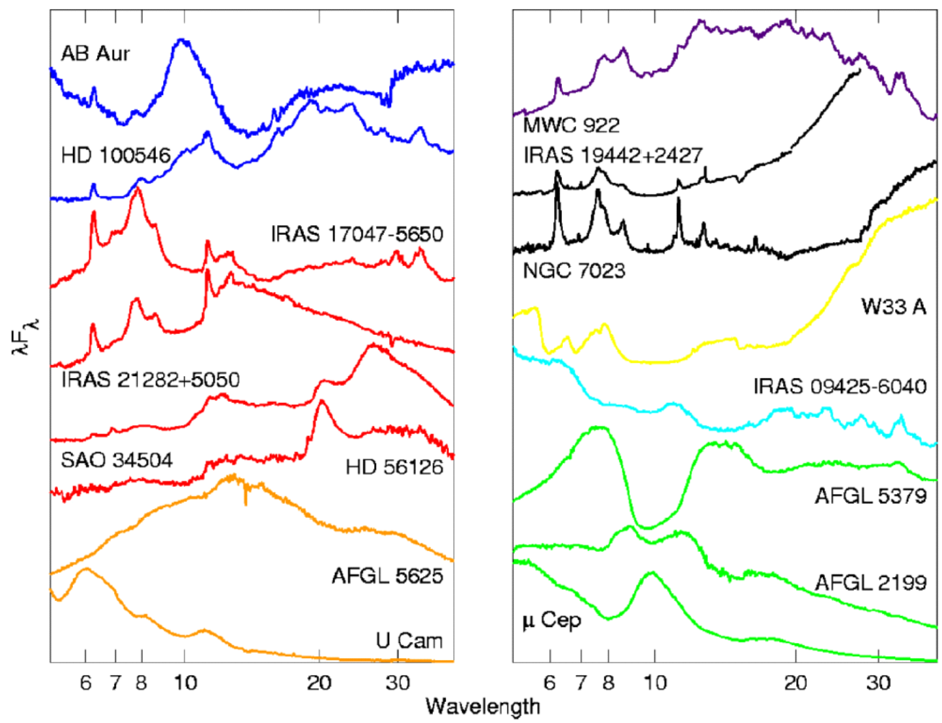
Key Science Goals for SOFIA

Stellar Astrophysics

- ***The diversity of dust and gas in circumstellar shells***
- ***Objects of opportunity and transient events such as eruptive variable stars, novae, and Supernovae,***

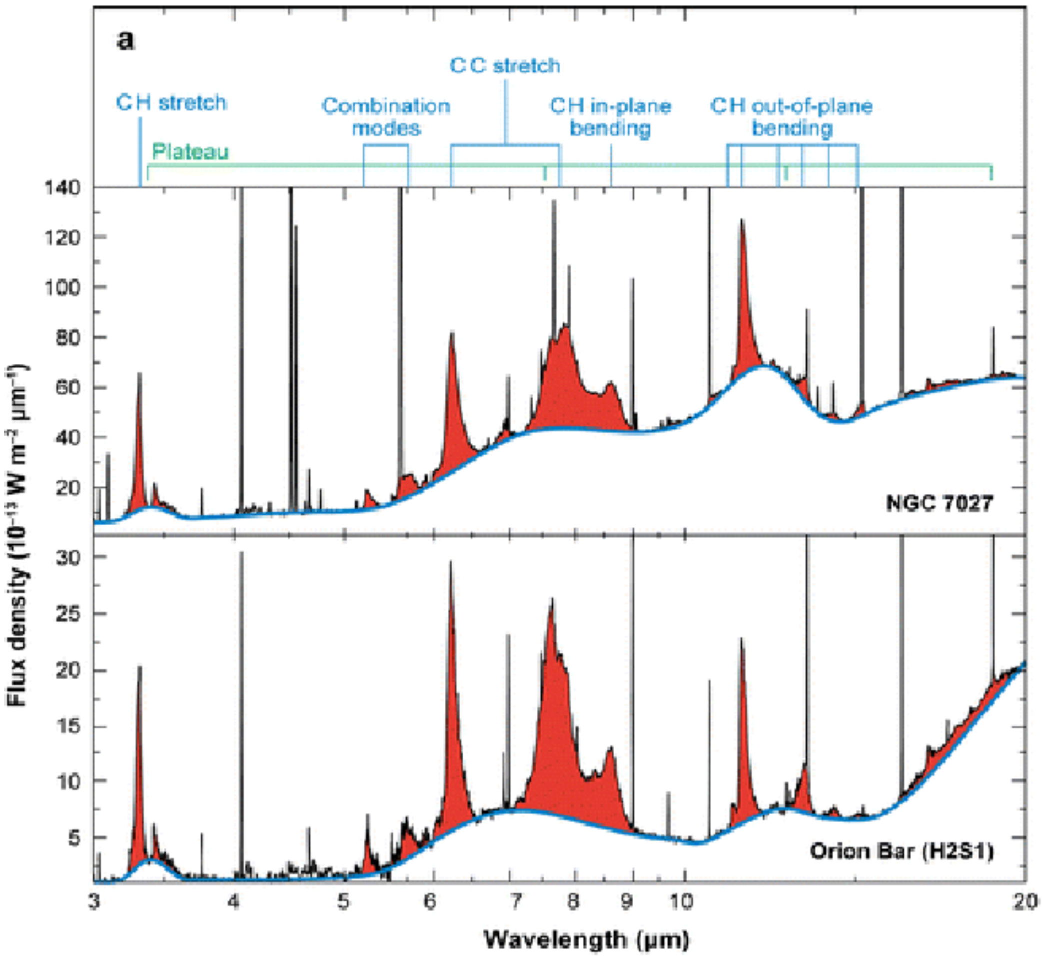
SOFIA Will Study the Diversity of Stardust

Herbig AeBe (blue)
Post-AGB and PNe (red)
Mixed chemistry post-AGB (purple)
C-rich AGB (orange)
O-rich AGB (green)
Mixed chemistry AGB (cyan)
Deeply embedded YSO (yellow)
HII region refection nebulae (black)



- *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*

Thermal Emission from PAH Rich Objects

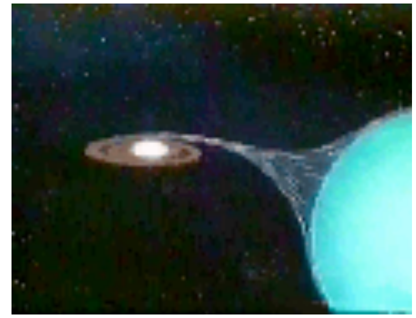


Vibrational modes of PAHs in a planetary nebula and the ISM (A. Tielens 2008)

- *A key question is whether portions of the aromatic population of PAHs are converted to species of biological significance*
- *Far-IR spectroscopy can constrain the size and shape of PAH molecules and clusters.*
- *The lowest lying vibrational modes ("drumhead" modes) will be observed by SOFIA's spectrometers*

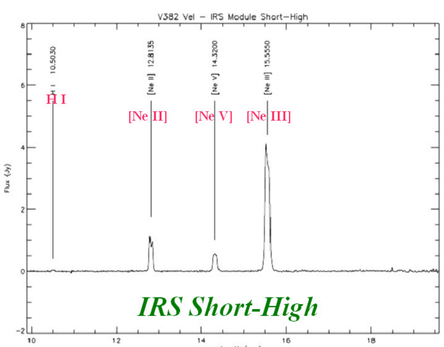
SOFIA and Classical Nova Explosions

What can SOFIA tell us about gas phase abundances and dust minerology in classical nova explosions?

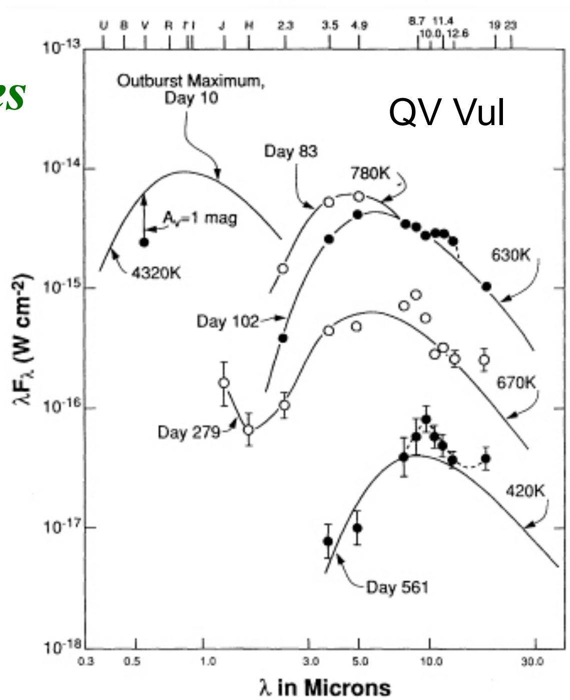


- ***Amorphous carbon***
- ***SiC***
- ***Amorphous silicates***
- ***Hydrocarbons***

Nova V382 Vul, *Spitzer*



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



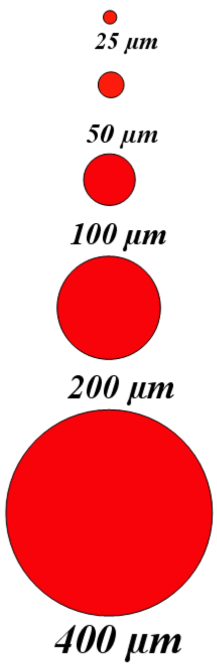
- ***Gas phase abundances of C, N, O, Mg, Ne, Al***
- ***SOFIA's wavelength and spectral range enables coverage of all forbidden lines and features of astrophysical dust components***
- ***Kinematics of the ejection***
- ***Contributions to ISM clouds and primitive solar system***

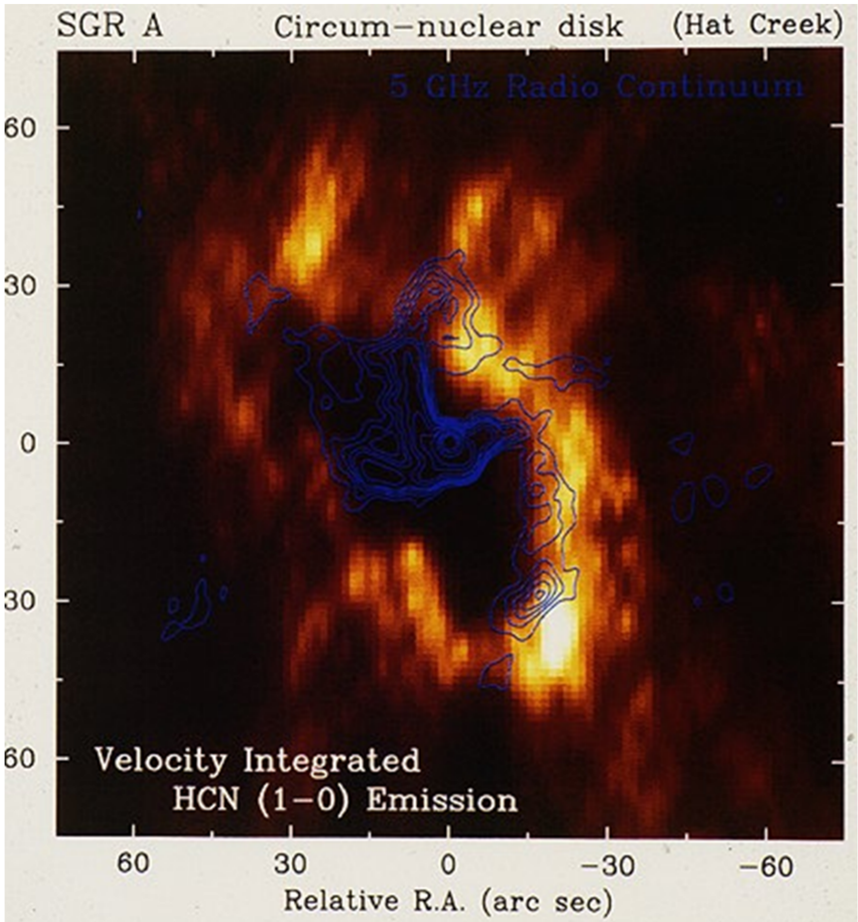
Key Science Goals for SOFIA

Galaxies and the Galactic Center

- *The Galactic Center*
- *The ISM and the Star Formation History of External Galaxies*

SOFIA and the Black Hole at the Galactic Center





SOFIA beams

- *SOFIA imagers and spectrometers can resolve detailed structures in the circum-nuclear disk at the center of the Galaxy*
- *An objective of SOFIA science is to understand the physical and dynamical properties of the material that feeds the massive black hole at the Galactic Center*

The ISM and Star Formation in External Galaxies

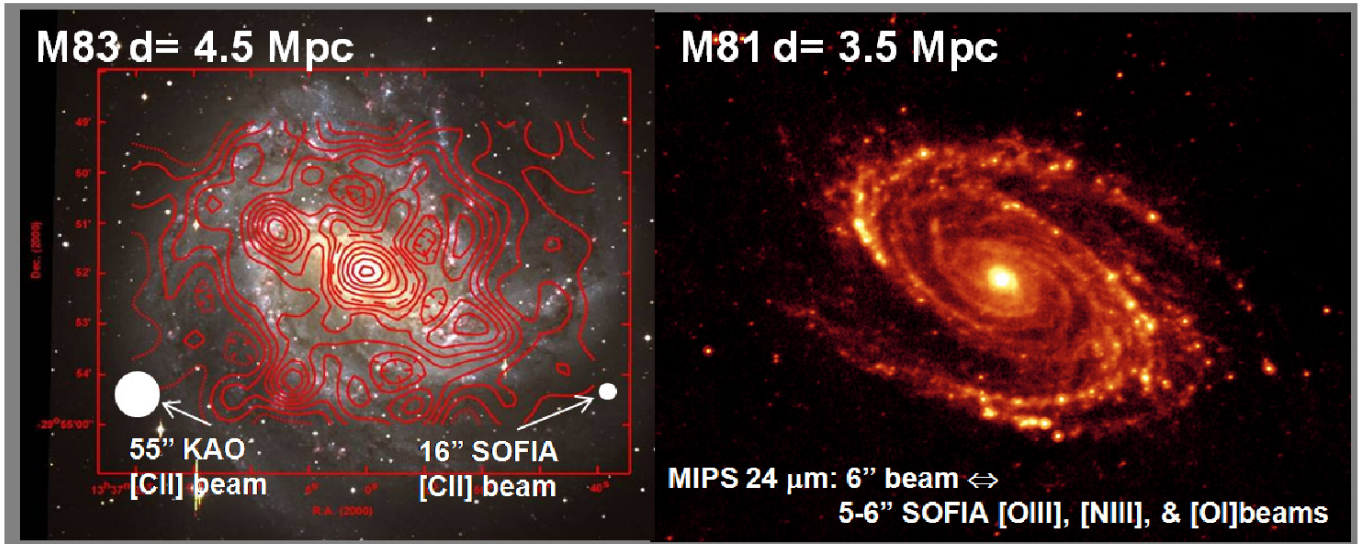


Figure 4-4. *(left) KAO [CII] map of M83 (d=4.5 Mpc) (contours, 55" beam) superposed on an optical image (Geis et al., in prep.). (right) MIPS 24 μm (6" beam) continuum image of M81 (d=3.5 Mpc). SOFIA can image nearby galaxies in the [OIII] 52 μm, [NIII] 57 μm, and [OI] 63 μm lines at a spatial resolution comparable to that of the Spitzer 24 μm image.*

- ***SOFIA observations of Far-IR lines can be conducted at unprecedented spatial resolution***
- ***ISM abundances and physical conditions can be studied as a function of location and nucleocentric distance***

Key Science Goals for SOFIA

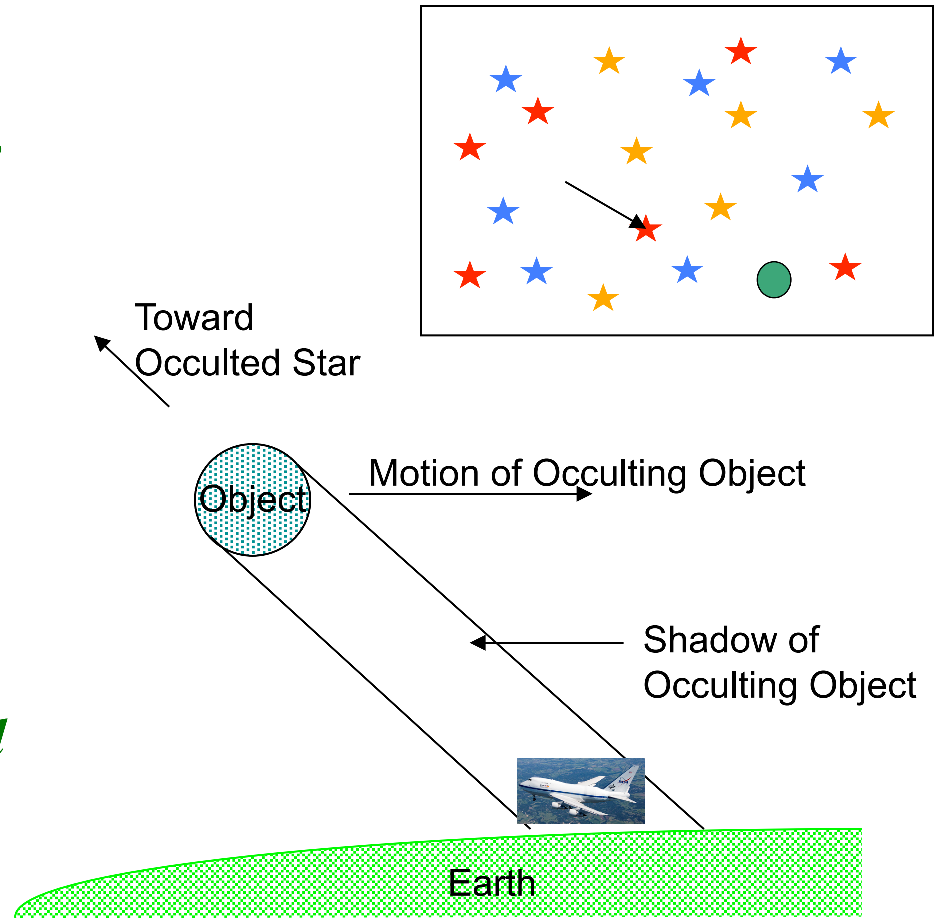
Planetary Science: Transient Events and Objects of Opportunity

- *Occultations by primitive Bodies*
- *Bright Comets, Occultations*
- *Transits of Extra-Solar Planets*

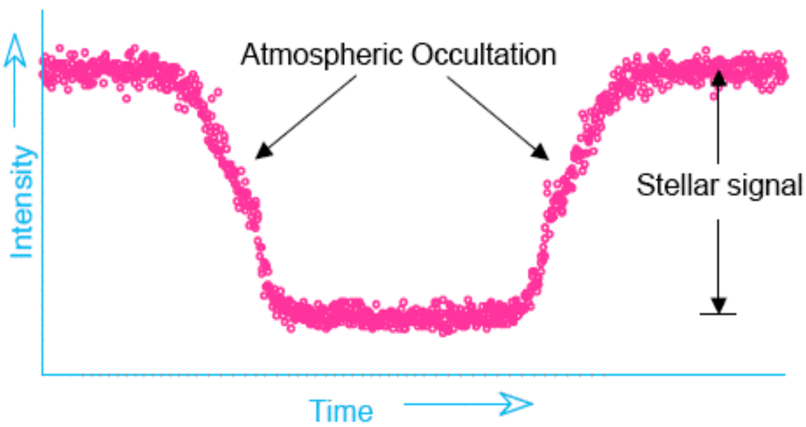
Occultation Astronomy with SOFIA

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.*

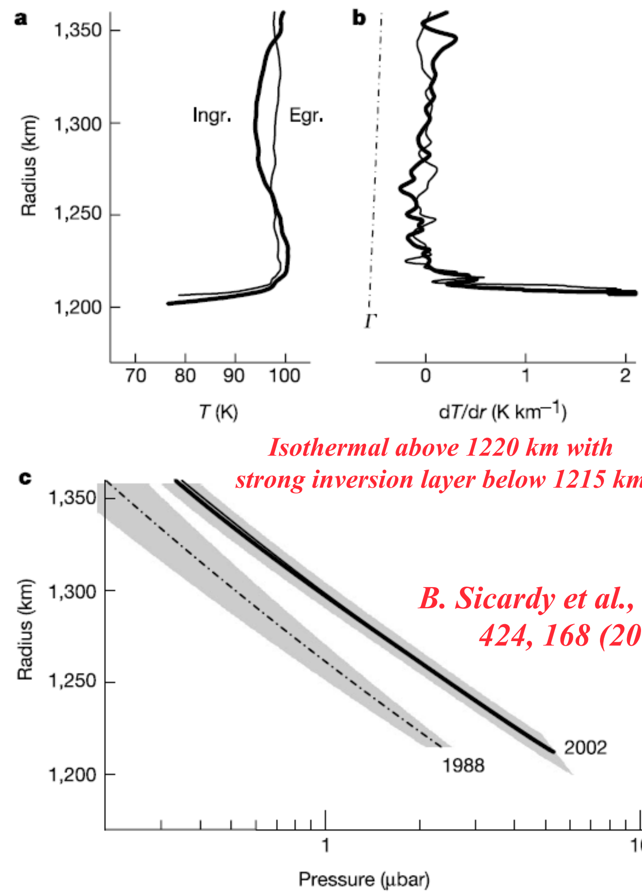


Occultations and Atmospheres



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

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

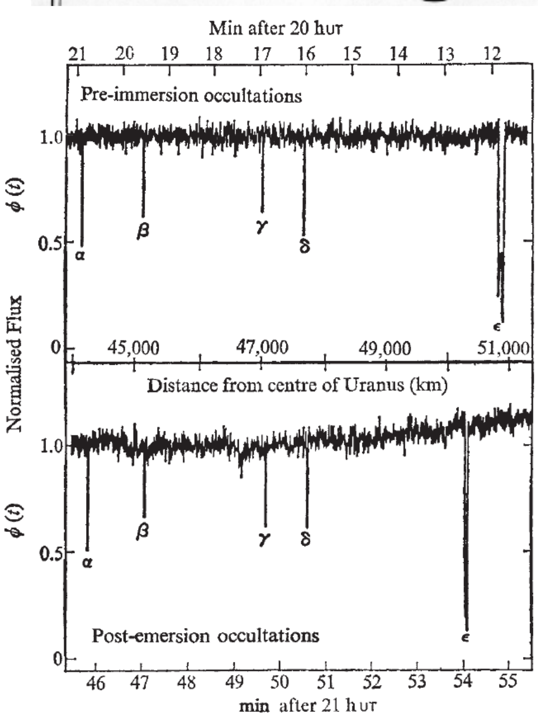


Isothermal above 1220 km with strong inversion layer below 1215 km

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

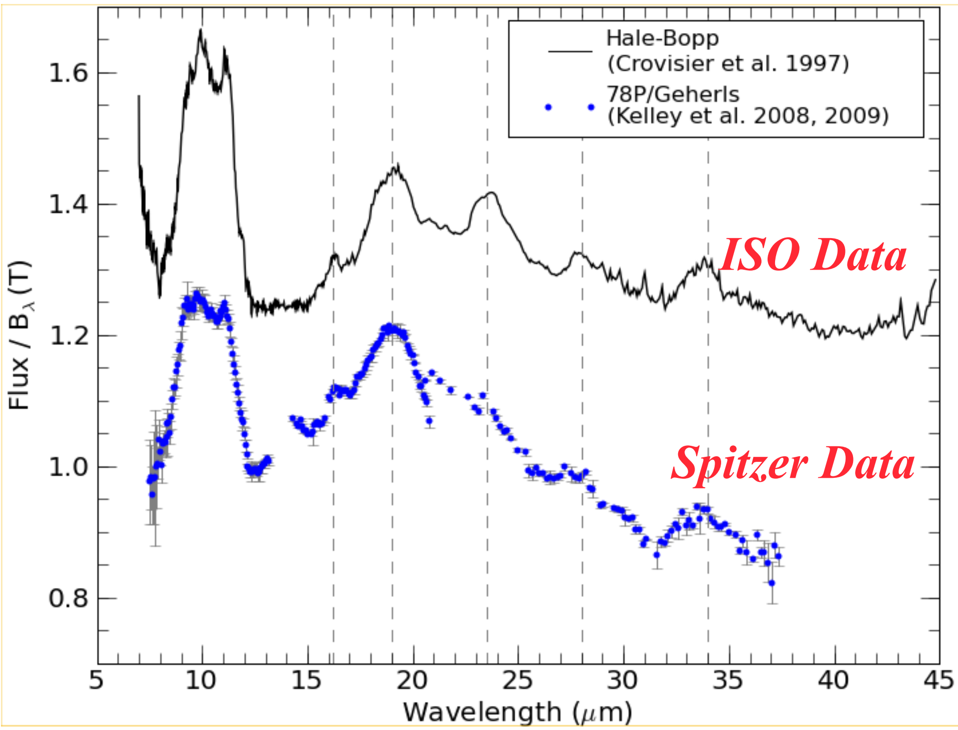
J. L. Elliot, E. Dunham, and D. Mink, Nature 267, 328-330 (1977)

Observing Comets with SOFIA

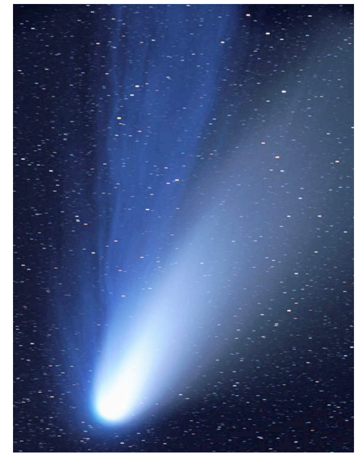
- *Comet nuclei are the Rosetta Stone of the Solar System and their ejecta reveal the contents and physical conditions of the primitive Solar Nebula when they are ablated during perihelion passage*
- *Comet nuclei, comae, tails, and trails emit primarily at the thermal IR wavelengths accessible with SOFIA*
- *Emission features from grains, ices, and molecular gases occur in the IR and are strongest when comets are near perihelion*
- *SOFIA has unique advantages: IR Space platforms like Spitzer, Herschel, and 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)

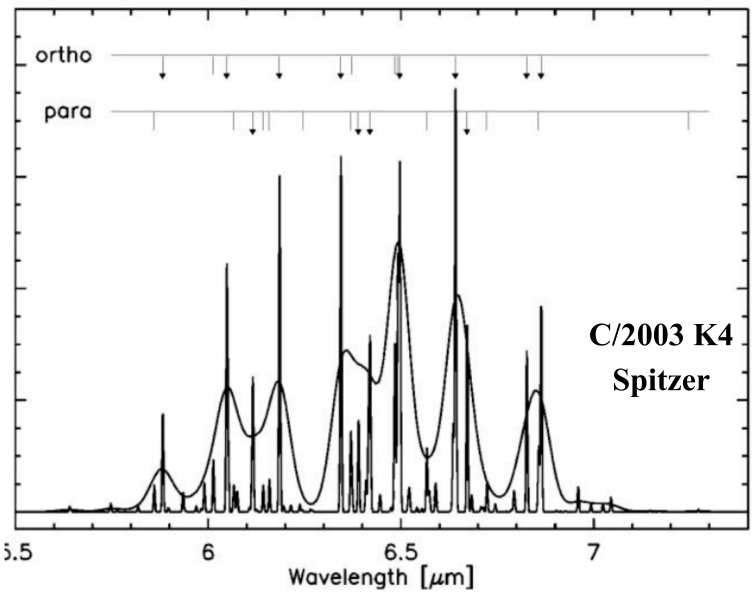


- ***Comet dust mineralogy: amorphous, crystalline, and organic constituents***
- ***Comparisons with IDPs and meteorites***
- ***Comparisons with Stardust***
- ***Only SOFIA can make these observations near perihelion***

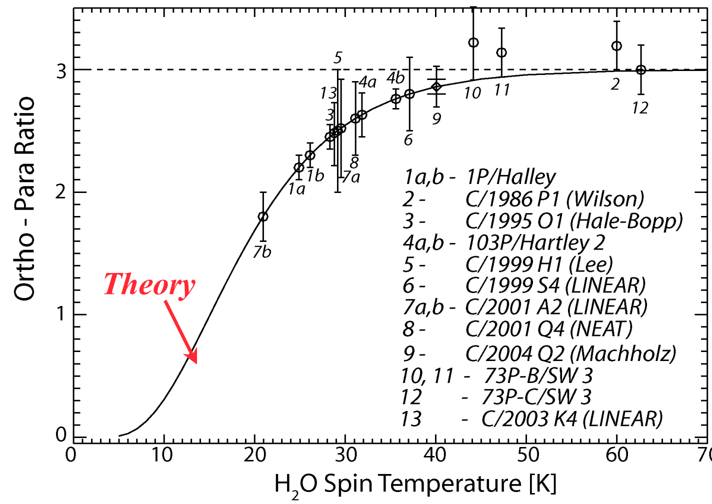
SOFIA and Comets: Gas Phase Constituents

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

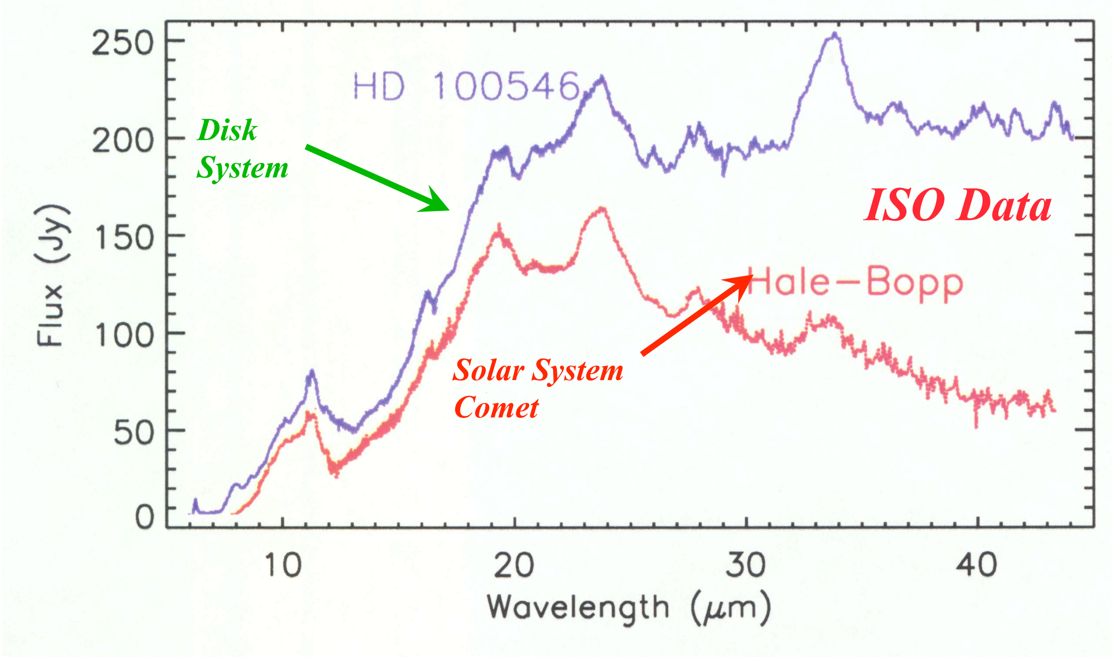
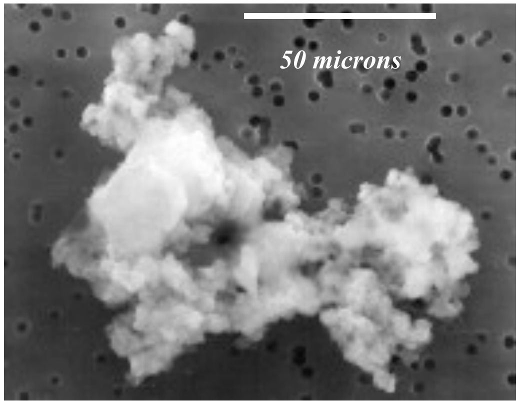


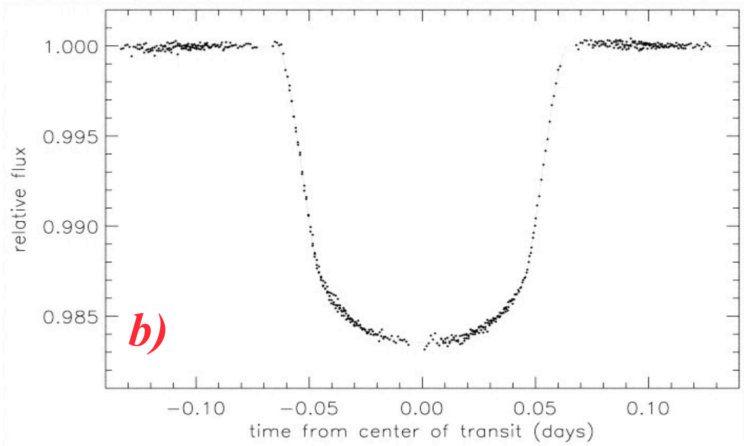
Image of Solar System IDP (Interplanetary Dust Particle)



- *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*

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 estimates for the mass, radius 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*

Using HIPO and FLITECAM for Observations of Exoplanet Transits

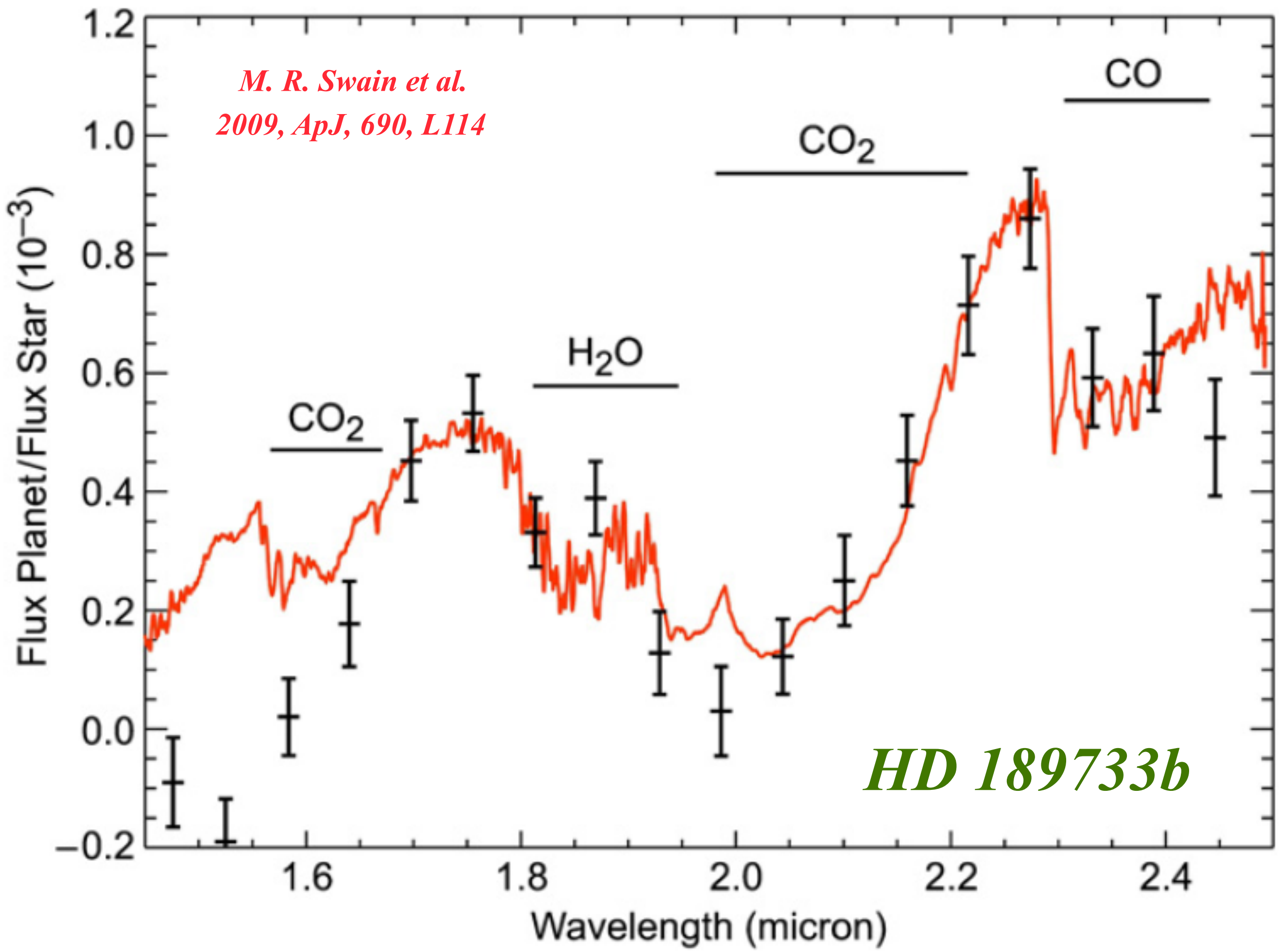
- *HIPO: Fast Imager; operates from 0.3 to 1.1 μm with interference filters*

- *FLITECAM: Imager; operates from 1.0 to 5.5 μm with interference filters and grisms; spectral resolutions as high as* $R = \lambda/\Delta\lambda = 2000$

- *HIPO and FLITECAM can observe simultaneously using a dichroic beam splitter*

We will also evaluate the FORECAST Imager for doing exoplanet transit observations: operates from 5.6 to 38 μm with interference filters and grisms; spectral resolutions as high as $R = \lambda/\Delta\lambda = 2000$

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



Early General Observer Opportunities

- ***First light images** will be obtained with FORCAST in late April 2010*
- ***Early Short Science** during 2010 with FORCAST and GREAT*
  - *Teams have been selected*
  - *Very limited number of flights (~3 per instrument)*
  - *GO's will not fly*
- ***Early Basic Science for General Investigators (GIs)** with FORCAST and GREAT*
  - *Longer period (~15 Flights) during early 2011*
  - *The SOFIA Basic Science Call will be released on April 19, 2010; Due date is July 2, 2010*
  - *http://www.sofia.usra.edu/Science/proposals/basic_science/index.html*
- ***General Investigator (GI) Science***
  - *Next call for proposals will be in 2011*
  - *Flights rate ramps up to over 100 per year by 2014*

SOFIA Instrumentation Development Program

- *The second call for instruments expected in 2011*
- *The instrumentation development program will include:*
  - *New Facility and PI Class science instruments*
  - *Upgrades to present instruments*
  - *New technology investigations*
- *There will be additional calls every 3 years*
- *There will be one new instrument or upgrade per year*
- *Funding for new instruments and technology is ~$10 M/yr*

SOFIA New Instrumentation Workshop

- *Asilomar Conference Center Monterey CA June 6-8, 2010*
- *A workshop to bring together theorists, observers, and instrument builders to identify key science investigations and the new instrumentation that enables them*
- *Deadline for registration is April 2, 2010*

http://www.sofia.usra.edu/Science/workshops/asilomar.html

Summary

- *The Program is making progress!*
  - *Aircraft structural modifications complete*
  - *Telescope installed, several instruments tested on ground observatories*
  - *Open door flight testing is continuing.*
  - *First light will be in April 2010*
  - *Early Science Programs will occur during 2010-2011*
- *SOFIA will be one of the primary observational facilities for far-IR and submillimeter astronomy for many years*

SOFIA we site: http://www.sofia.usra.edu/

This talk will be available at http://www.sofia.usra.edu/Science/speakers/index.html

Backup

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?*

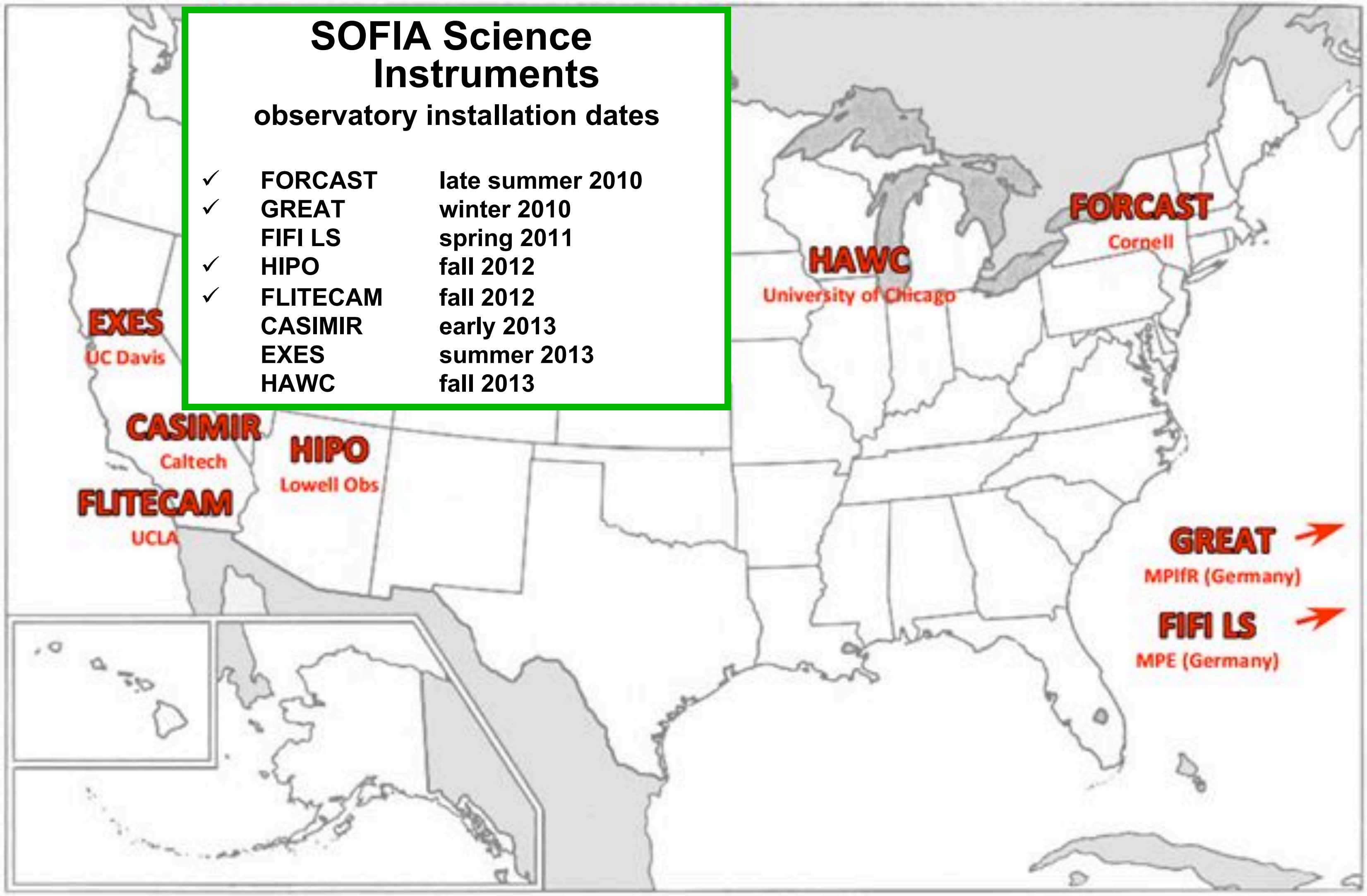
Extragalactic Astrophysics

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

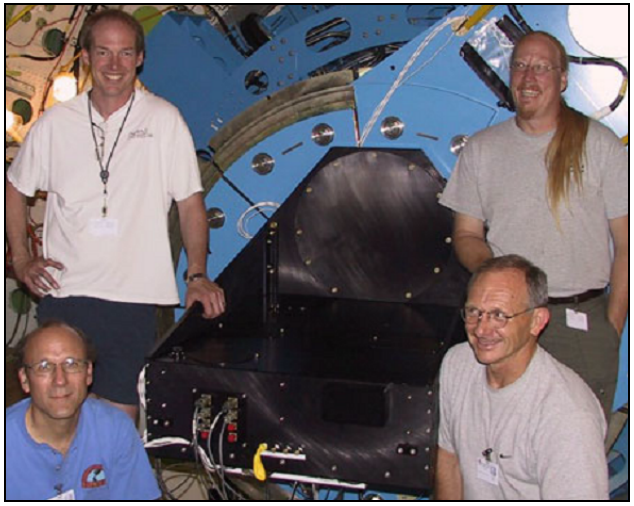
The Initial SOFIA Instrument Complement

- *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*
- *CASIMIR: CAltech Submillimeter Interstellar Medium Investigations Receiver*
- *FIFI-LS: Field Imaging Far-Infrared Line Spectrometer*
- *HAWC: High-resolution Airborne Wideband Camera*
- *EXES: Echelon-Cross -Echelle Spectrograph*
- *SAFIRE: Submillimeter And Far InfraRed Experiment*

Science Instruments – Key Activities

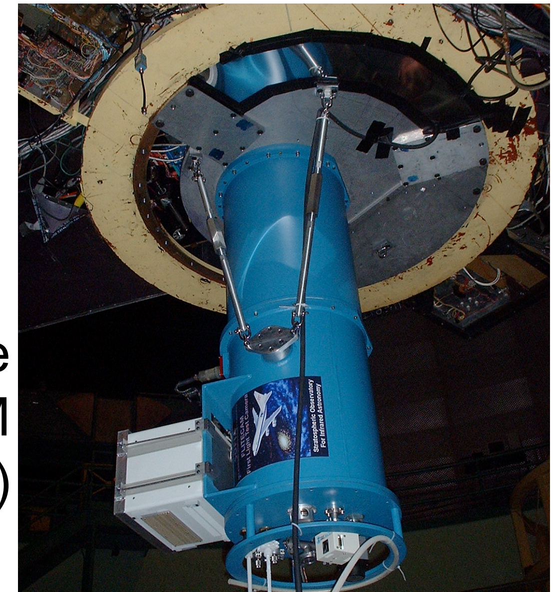


FOUR OF THE 1st GENERATION INSTRUMENTS



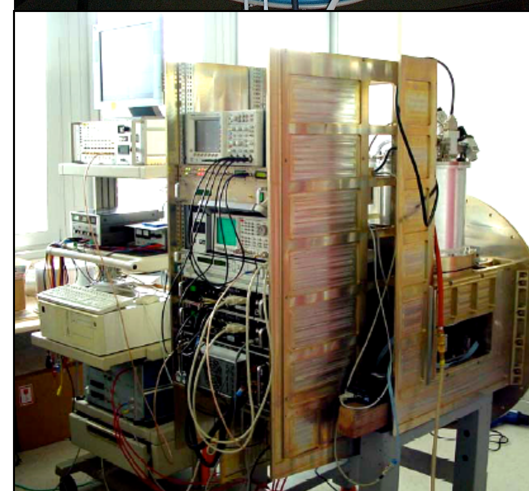
Working/complete
HIPO instrument
(on SOFIA)

Working/complete
FLITECAM
(Lick observatory)



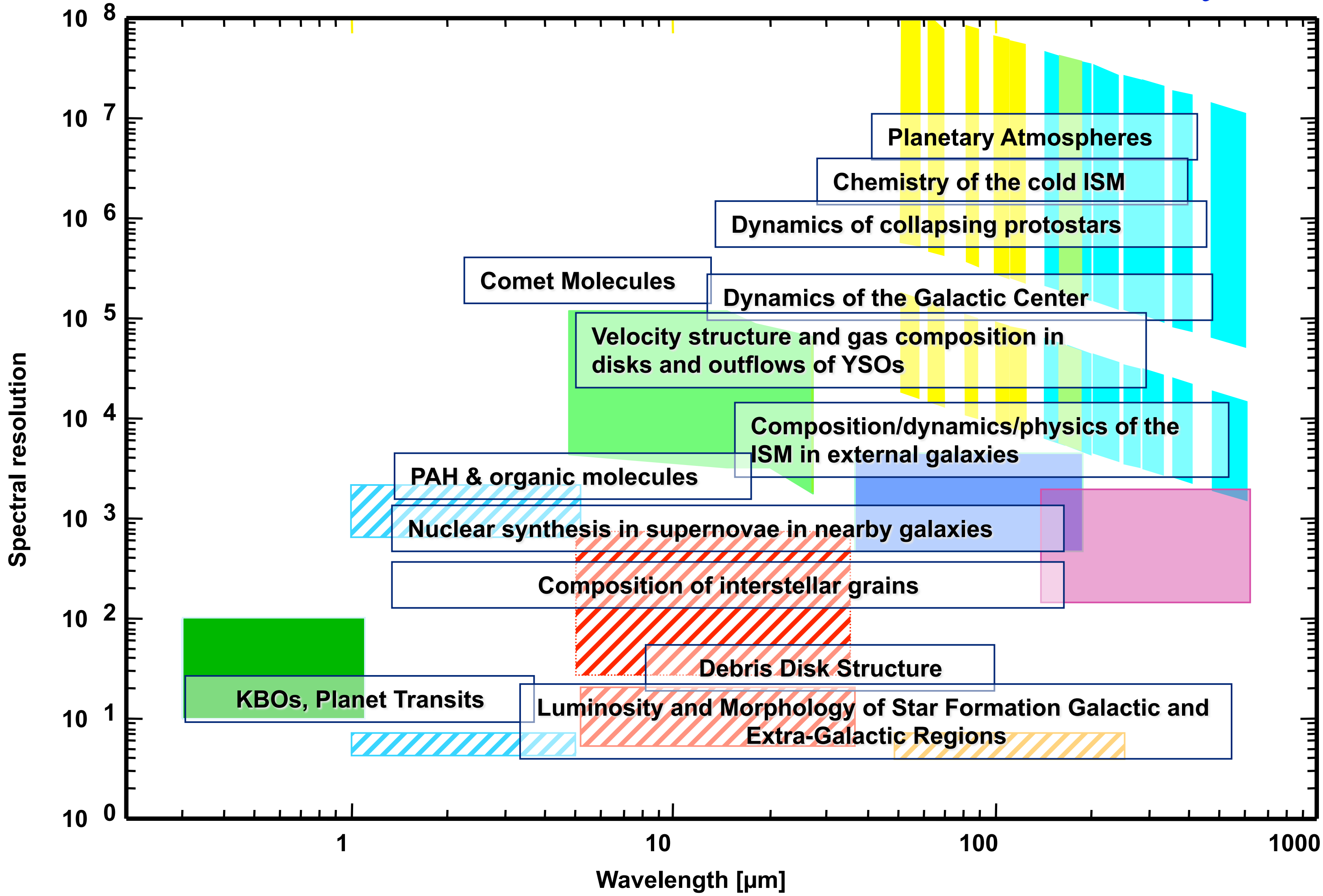
Working/complete
FORCAST
instrument
(Palomar)

Successful lab
demonstration
of GREAT



Lab-picture of GREAT equipped with the KOSMA 1.9THz channel

SOFIA: Science For the Whole Community

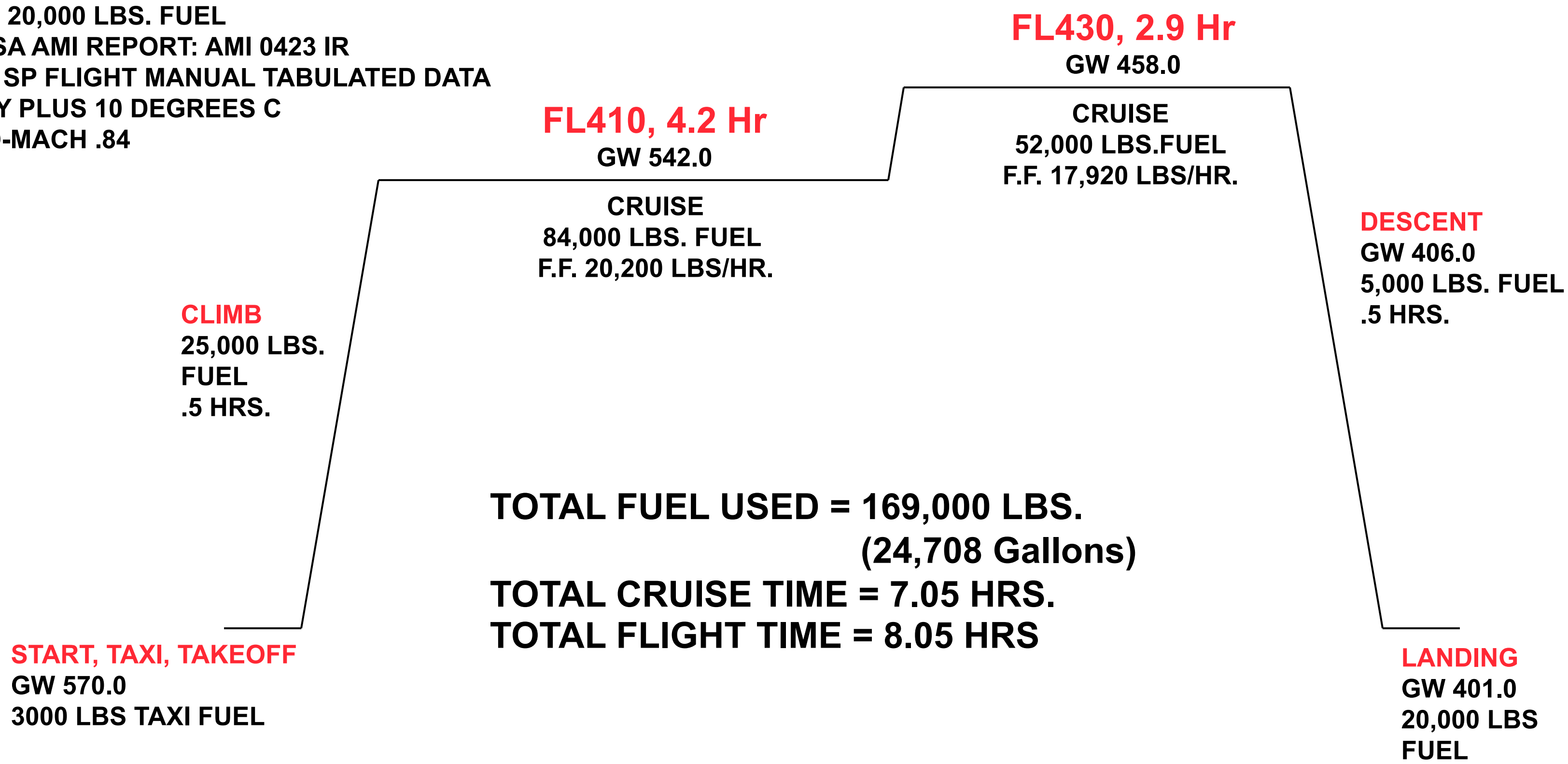


Flight Profile 1

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



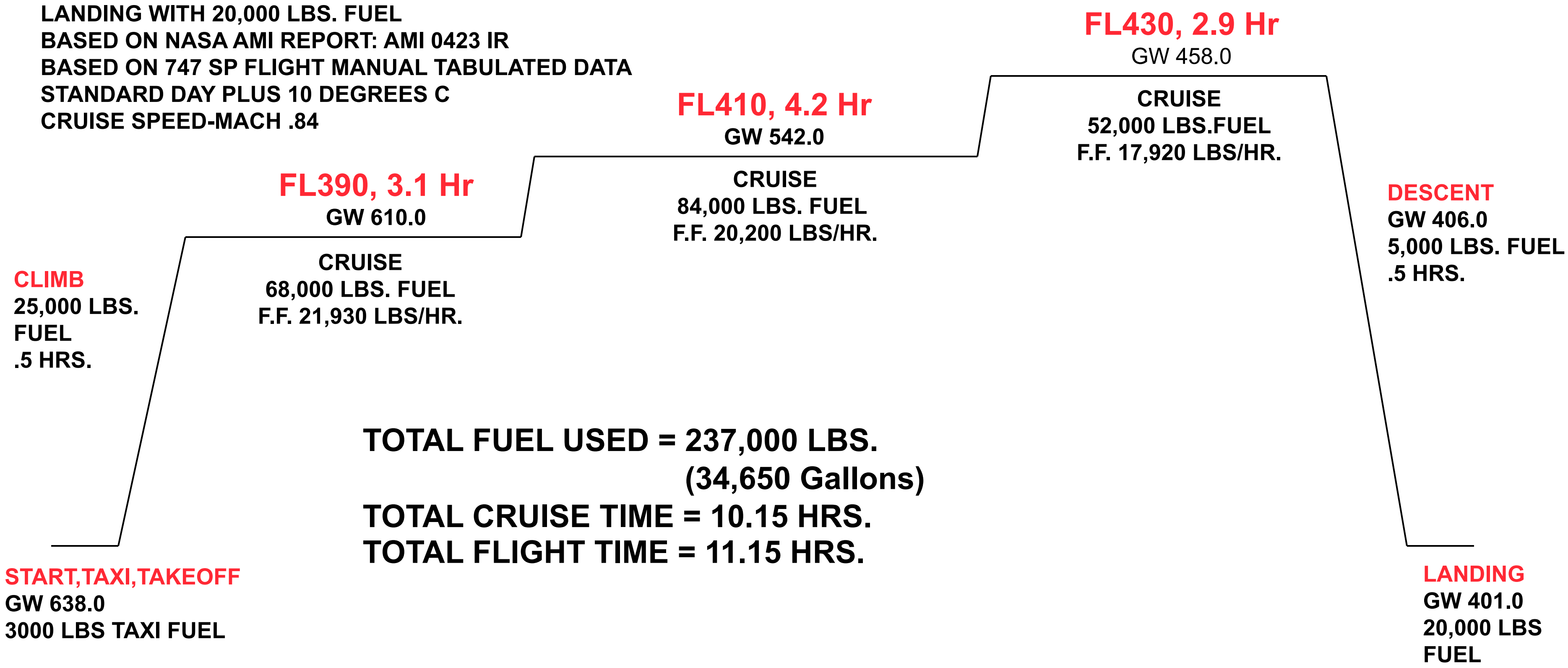
TOTAL FUEL USED = 169,000 LBS.
(24,708 Gallons)
TOTAL CRUISE TIME = 7.05 HRS.
TOTAL FLIGHT TIME = 8.05 HRS

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.