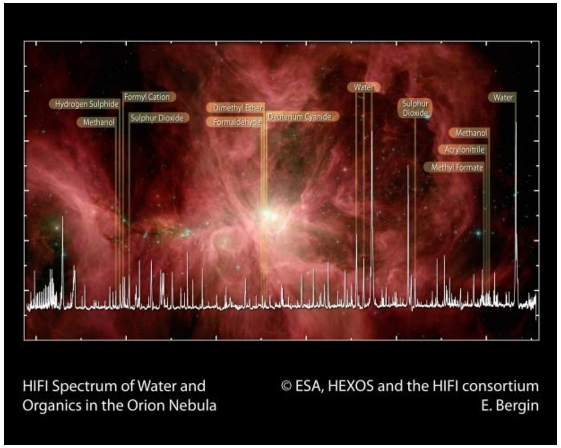
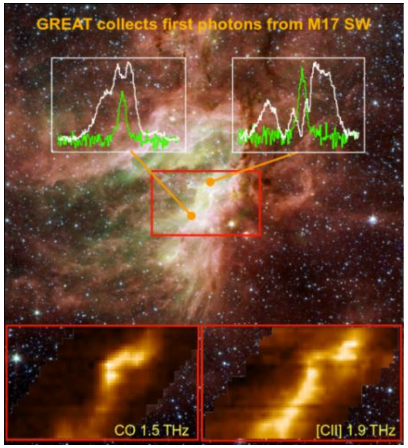
Recent Science Results from The Stratospheric Observatory for Infrared Astronomy (SOFIA)





R. D. Gehrz

Chair, SOFIA Users Group (SUG)

Minnesota Institute for Astrophysics, University of Minnesota

This talk is at: http://www.sofia.usra.edu/Science/speakers/index.html

University of Wyoming, Laramie, Wyoming, November 9, 2012

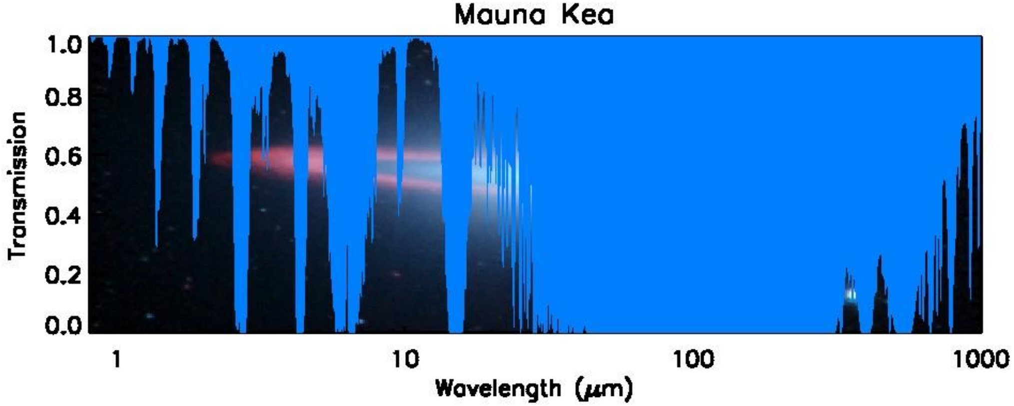
Outline

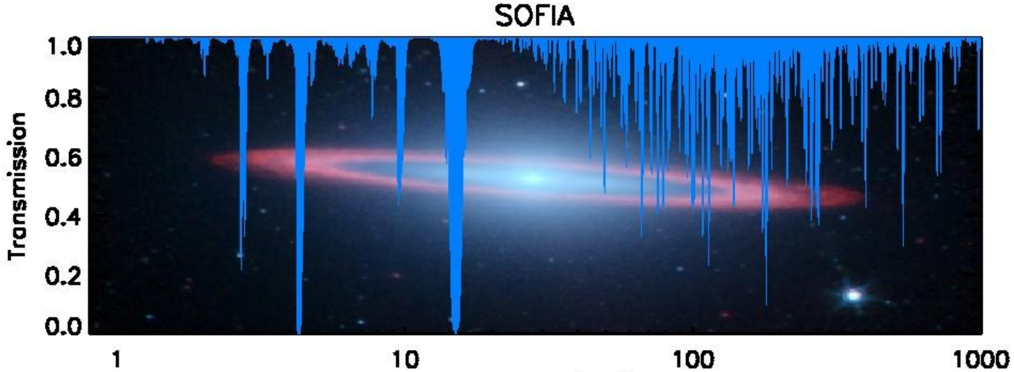
- *The SOFIA Facility and its Status*
- *SOFIA Science Instrumentation/Performance Specifications*
- *Early SOFIA Science Results*
- *SOFIA Schedule and General Investigator (GI) Opportunities*
- *Summary*

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)*
- *Operational Altitude*
  - *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 images were obtained on May 26, 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 SOFIA Observing Environment

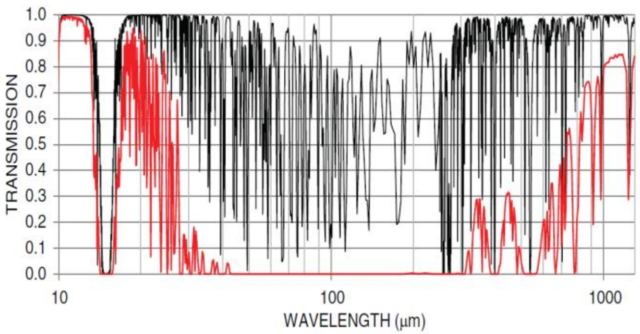




- *Above 99.8% of the water vapor*
- *Transmission at 14 km >80% from 1 to 800 μm*
- *Emphasis is on the obscured IR regions from 30 to 300 μm*

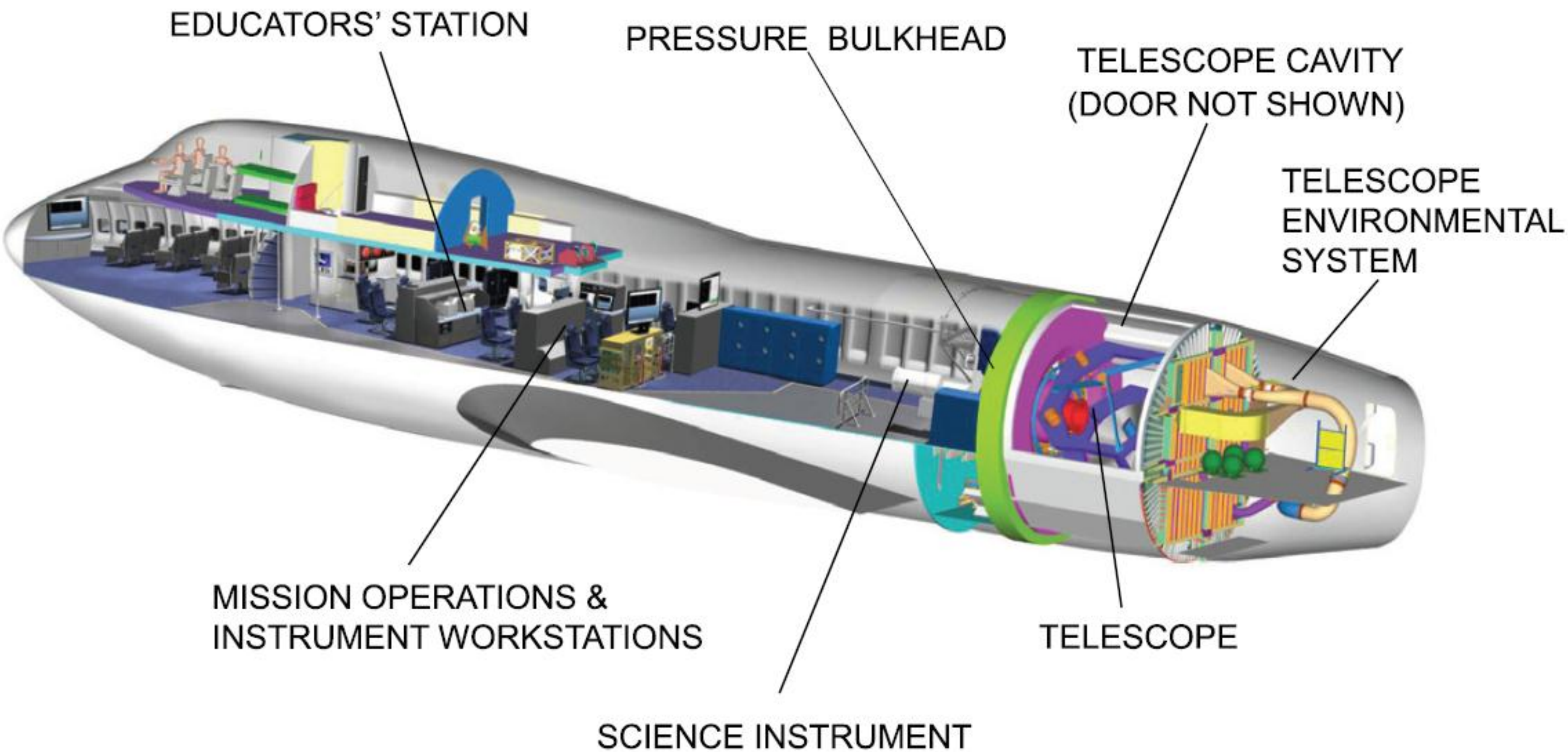
SOFIA , 10μm Precipitable Water Vapor

Cerro Chajnantor, 700μm Precipitable Water Vapor



E.T Young et al. 2012, ApJ, 749, L17

The SOFIA Observatory

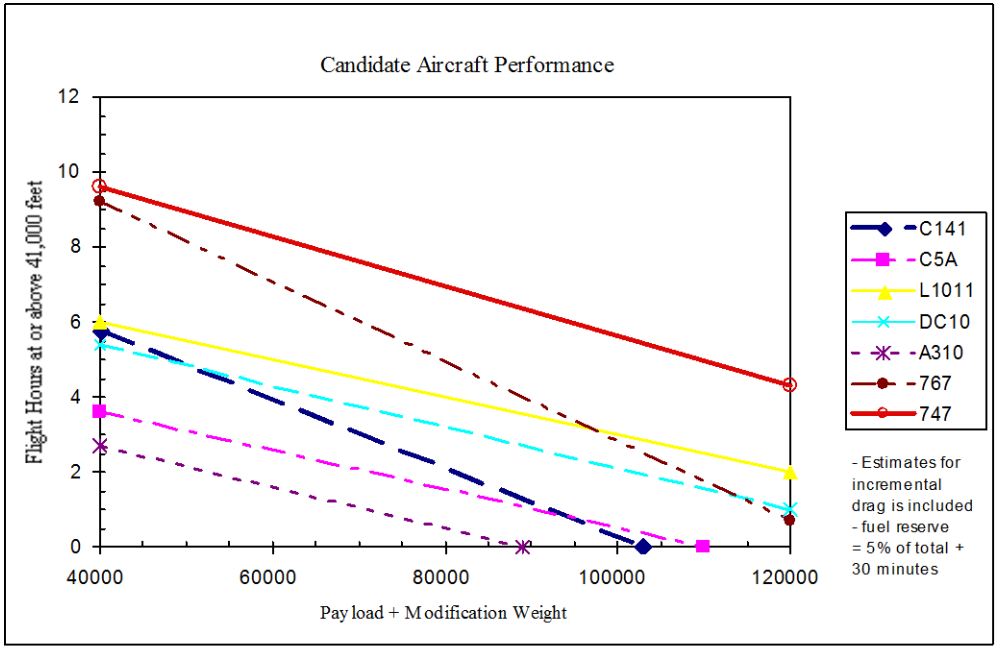


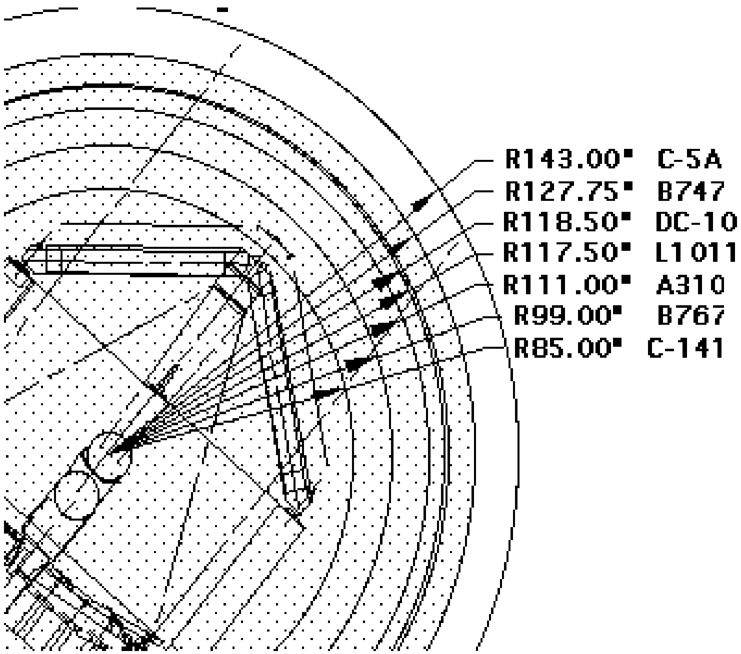
E.T Young et al. 2012, ApJ, 749, L17

Door

SOFIA: Selecting the Aircraft

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

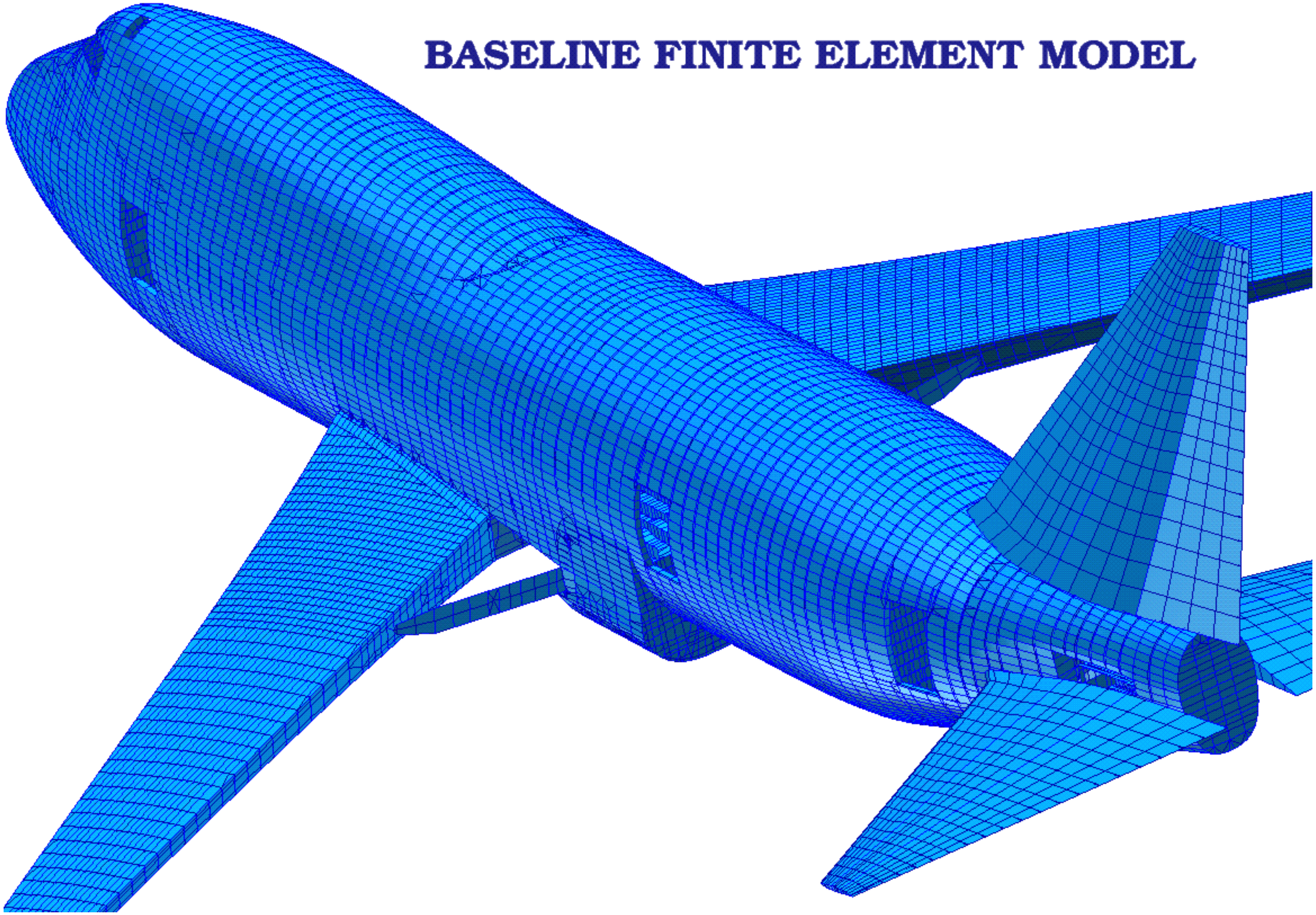




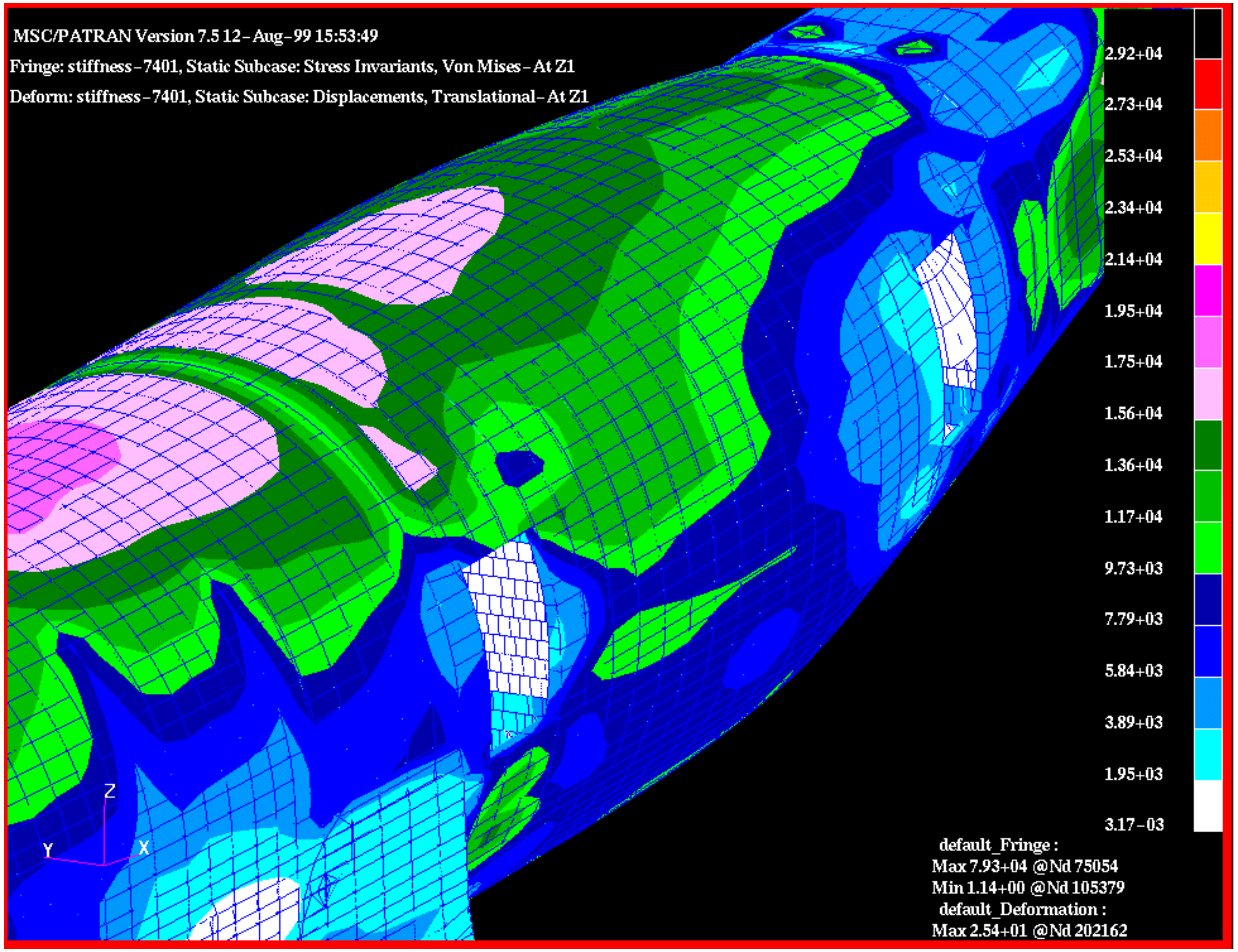
The winner: Boeing 747-SP

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

SOFIA: Modeling the Aircraft

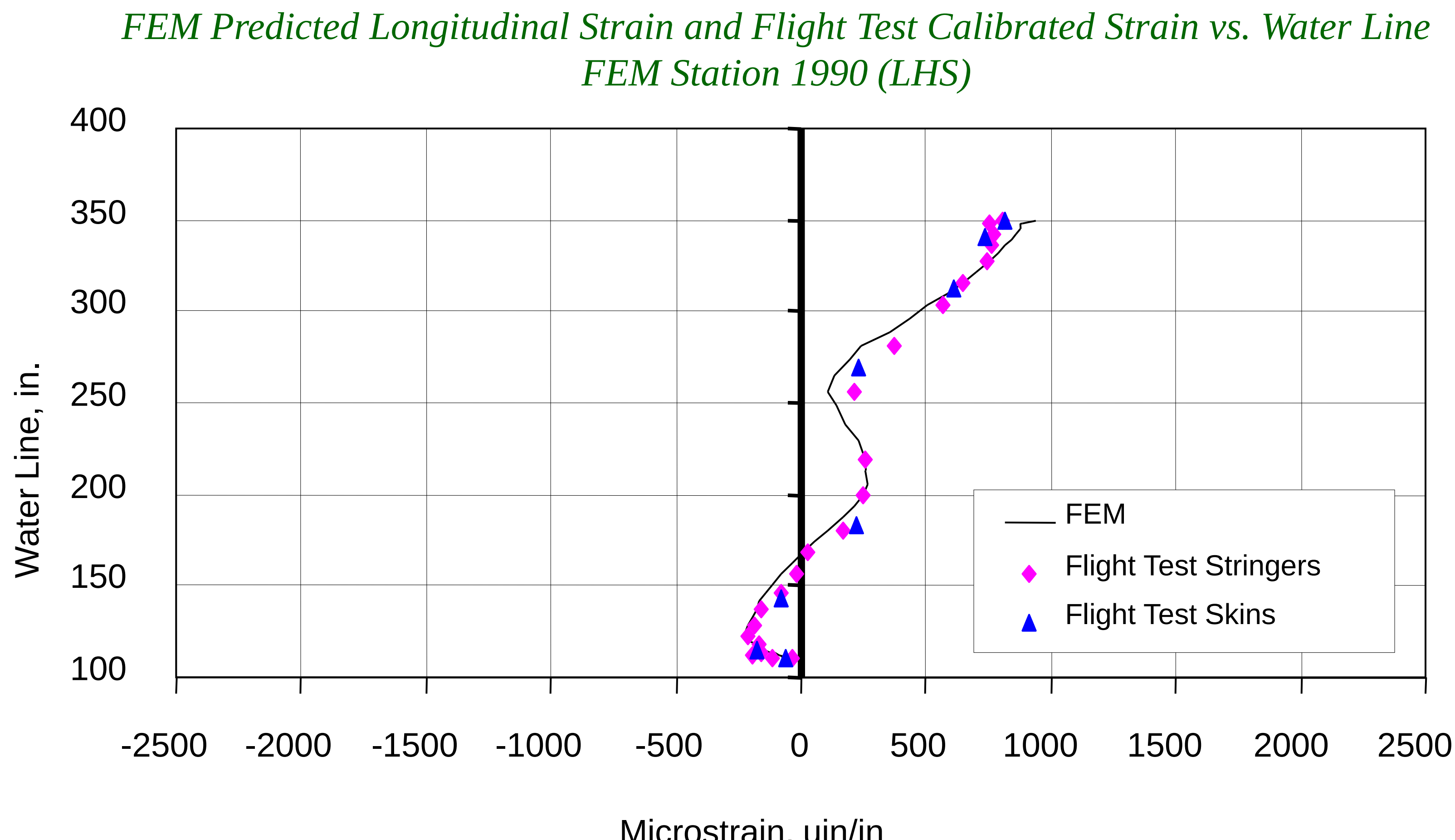


FEM Predictions for Unmodified Aircraft

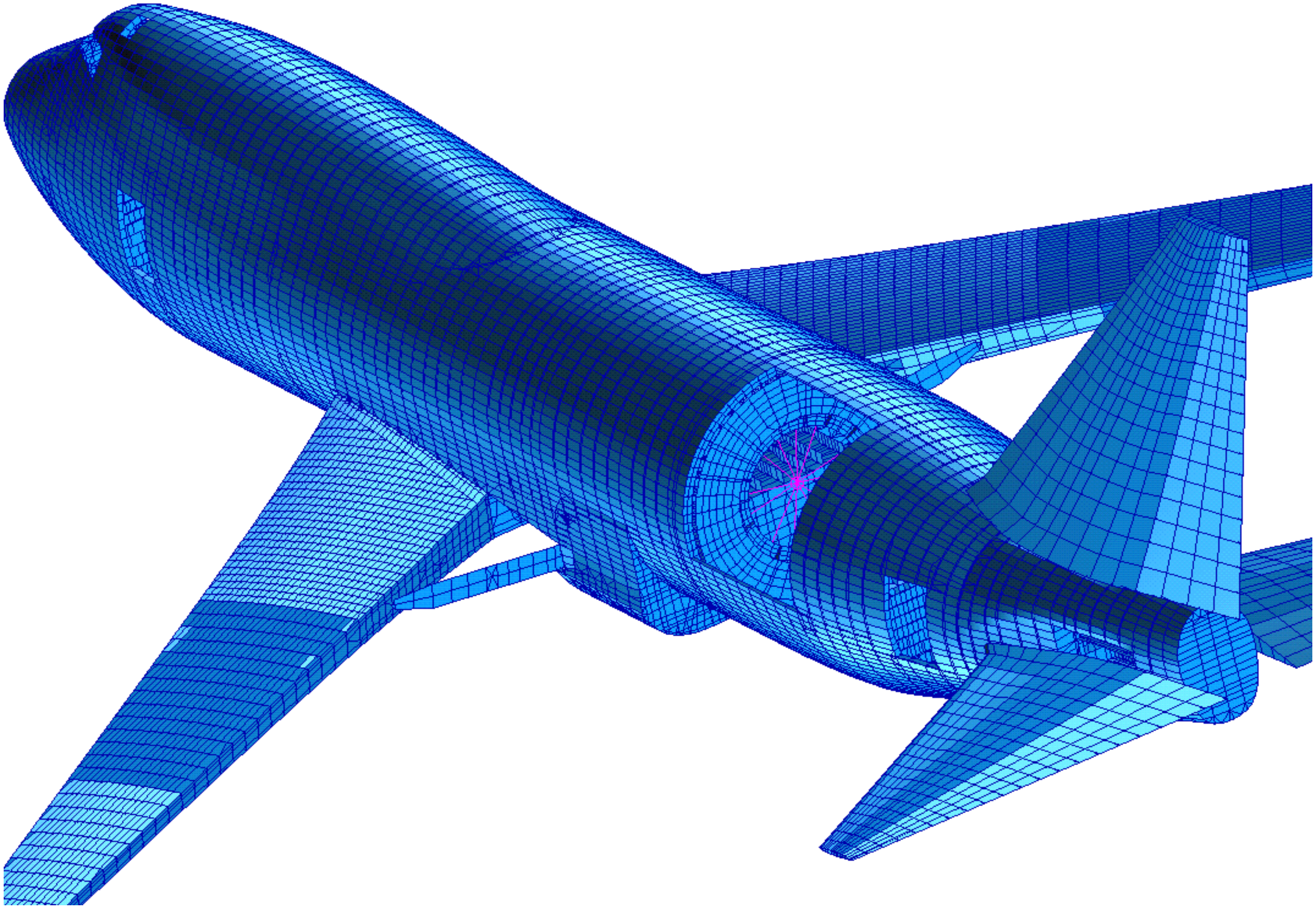


FEM Validation: Pre-Modification Flight Test Data

Sample Longitudinal Strain - Positive Vertical Acceleration

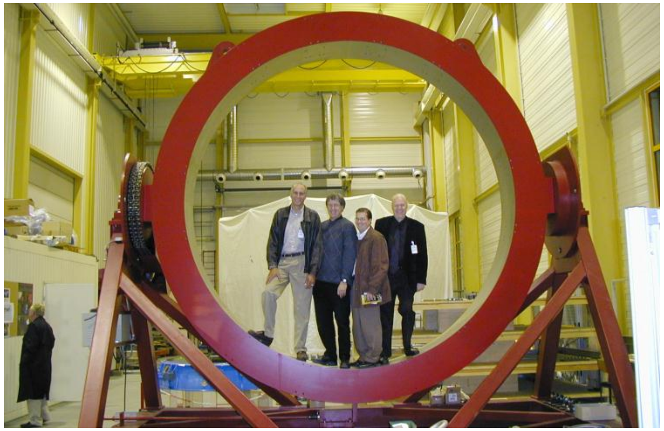


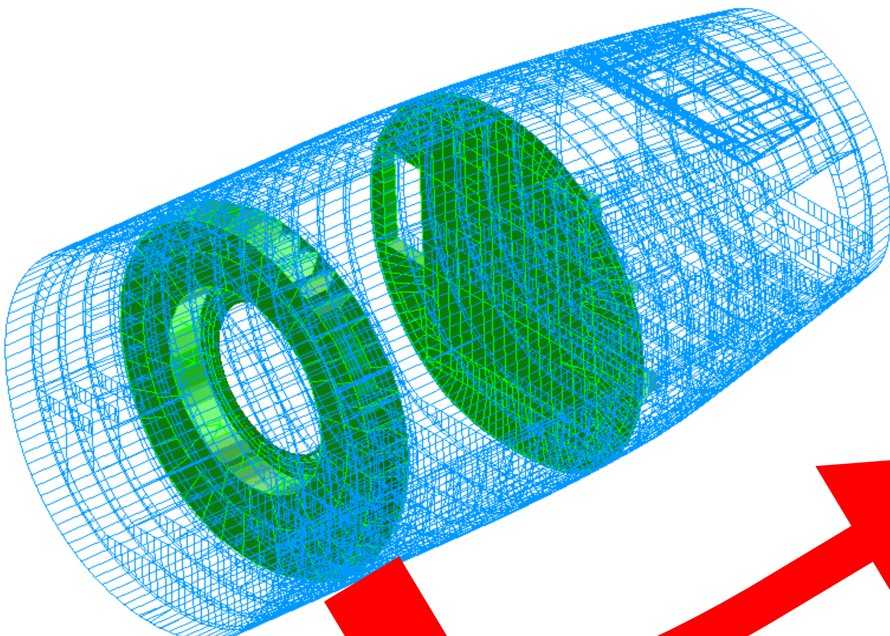
Modified Baseline Finite Element Model



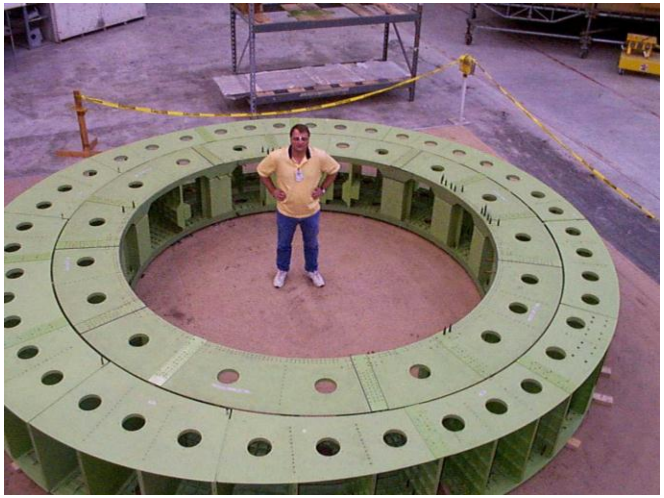
New 21.3 foot diameter Pressure Bulkhead

Bulkhead simulator used in Germany for Telescope Assembly buildup



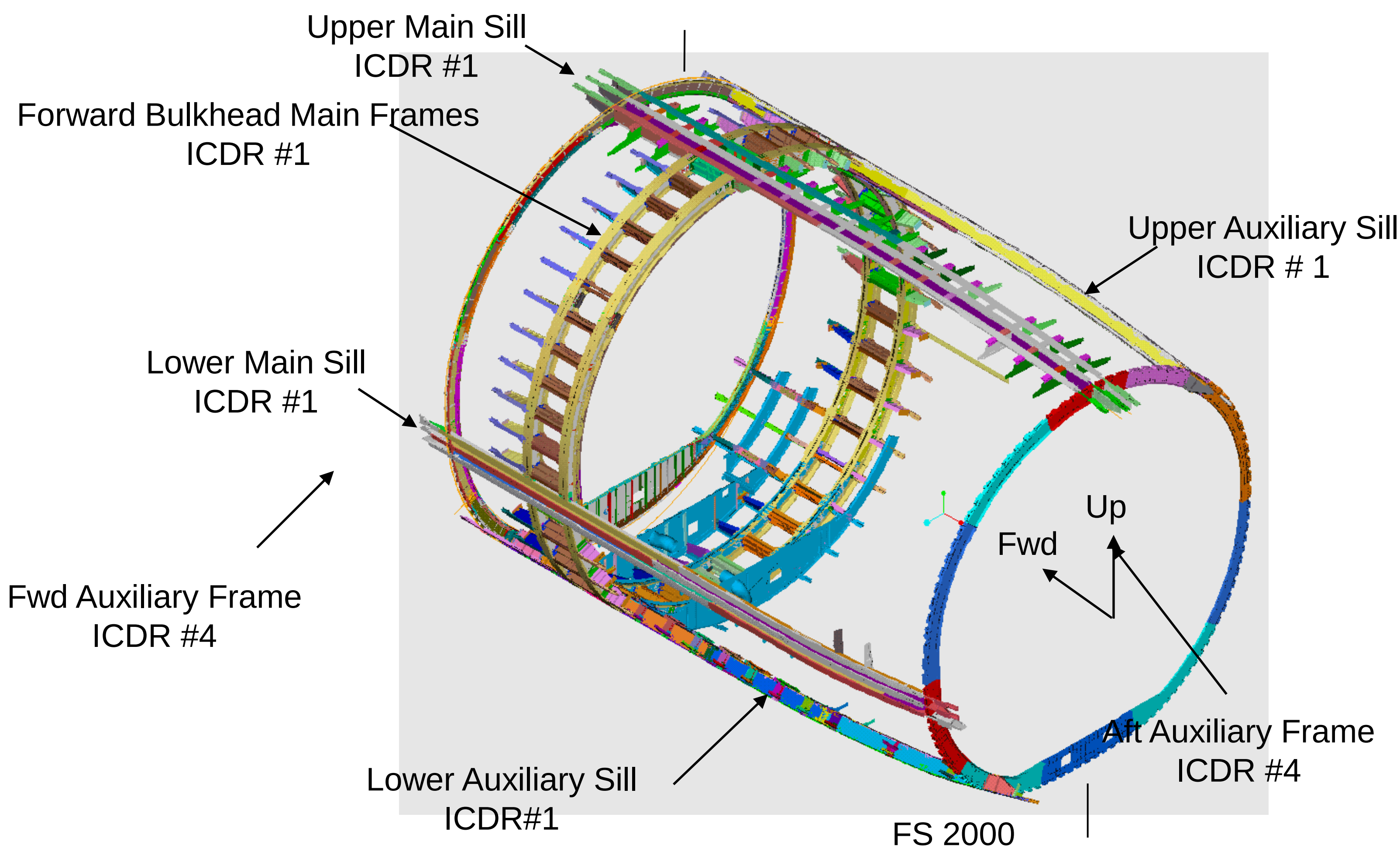


FEM

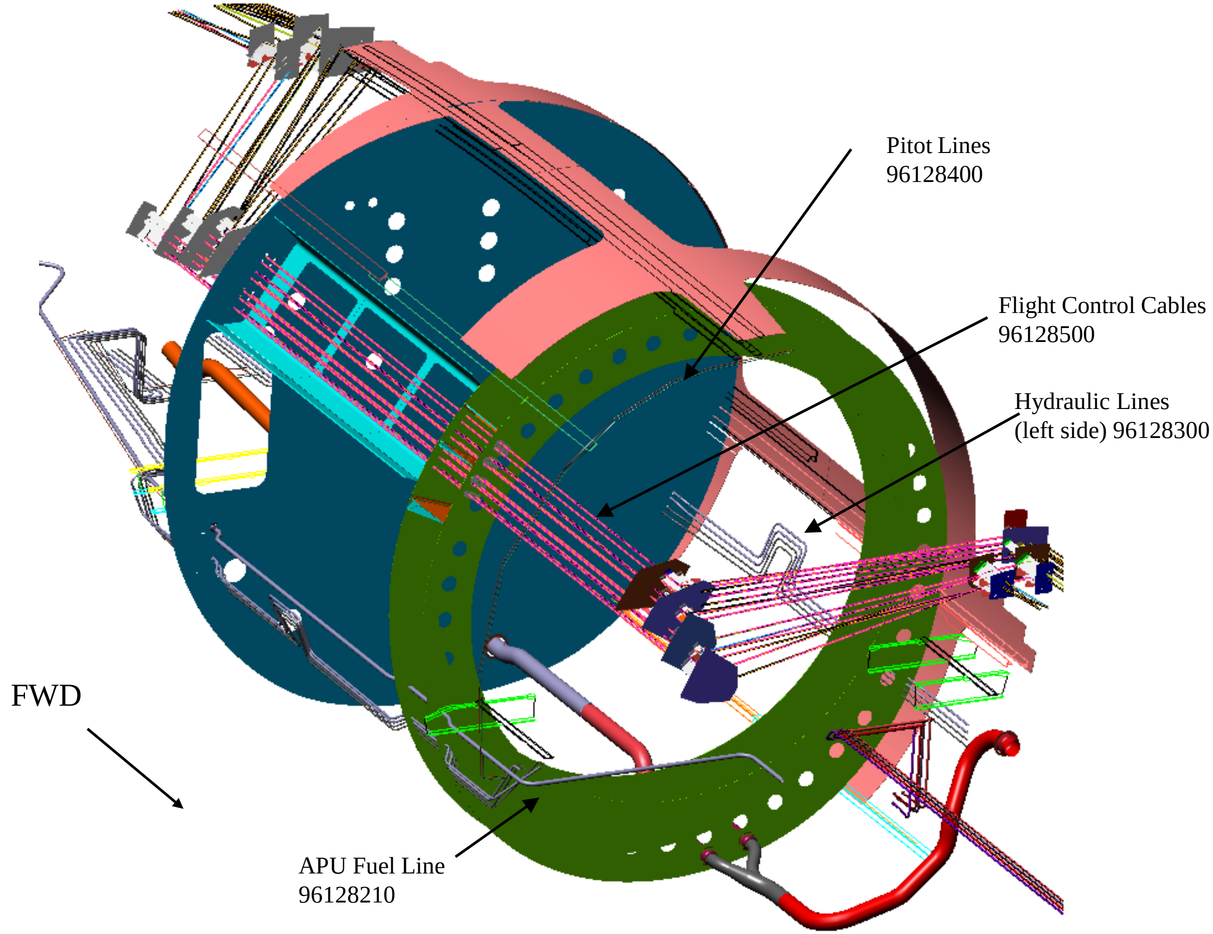


Bulkhead on Delivery

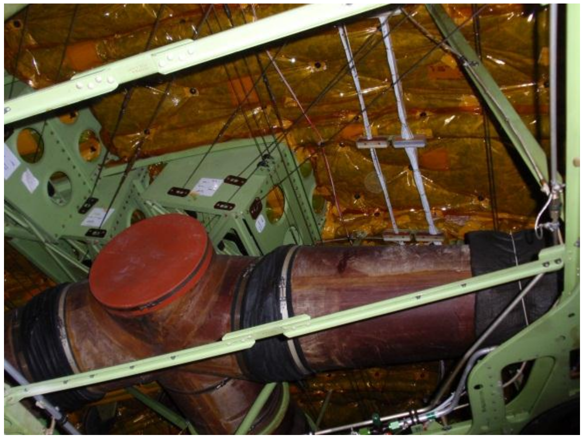
Frame Modifications and Sill Beams



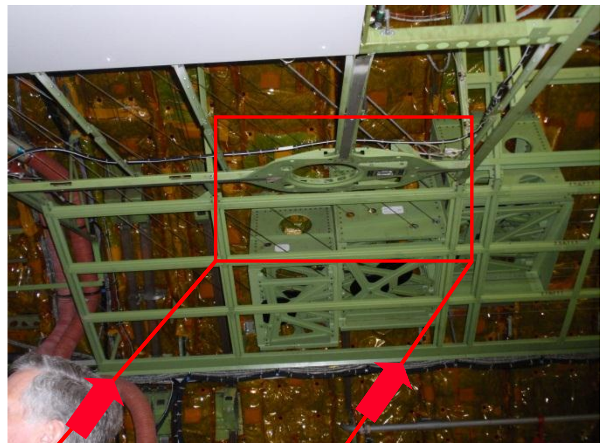
Control Cables - SOFIA Re-routing



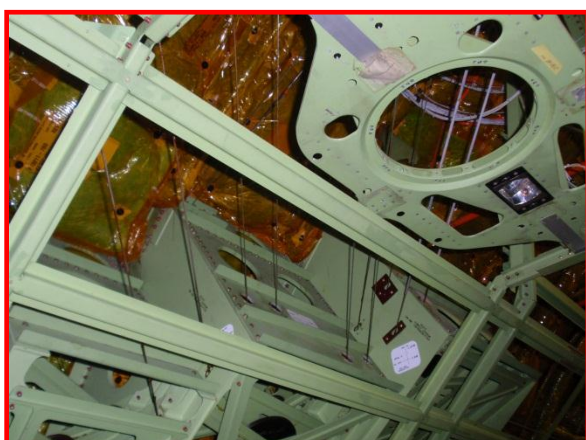
Control Cable Re-routing Details



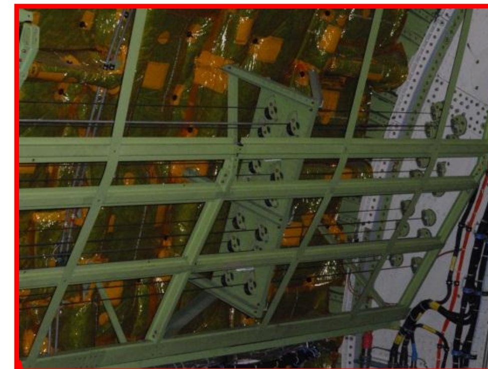
BP#1

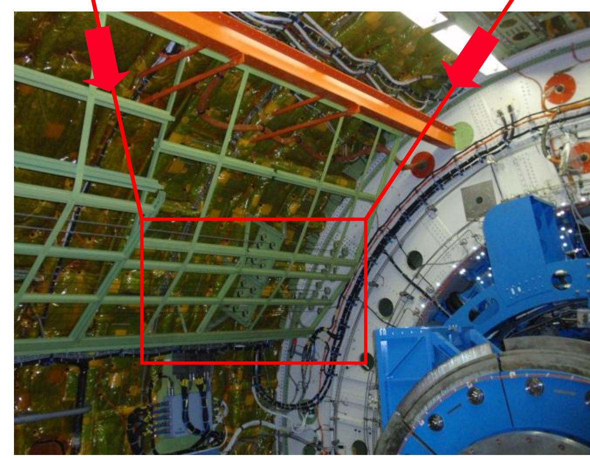


BP#2



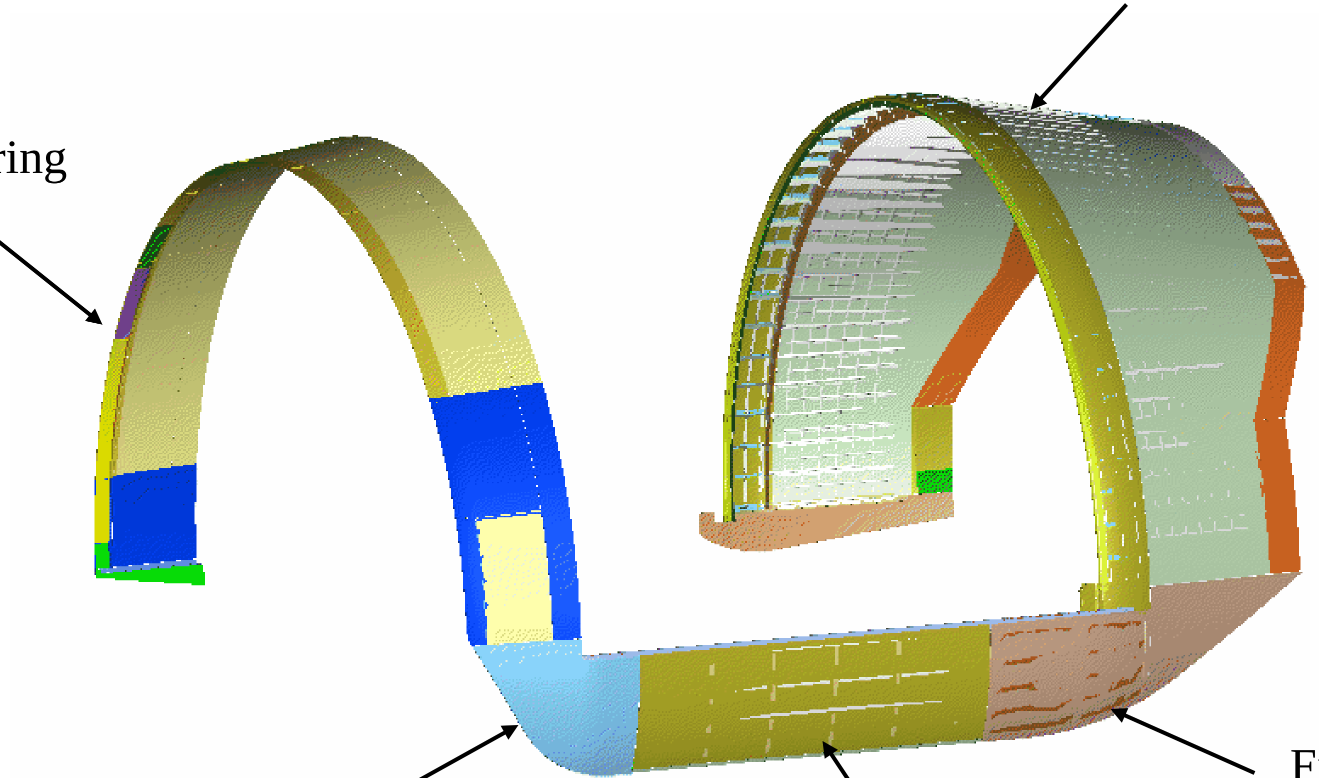
STA1394



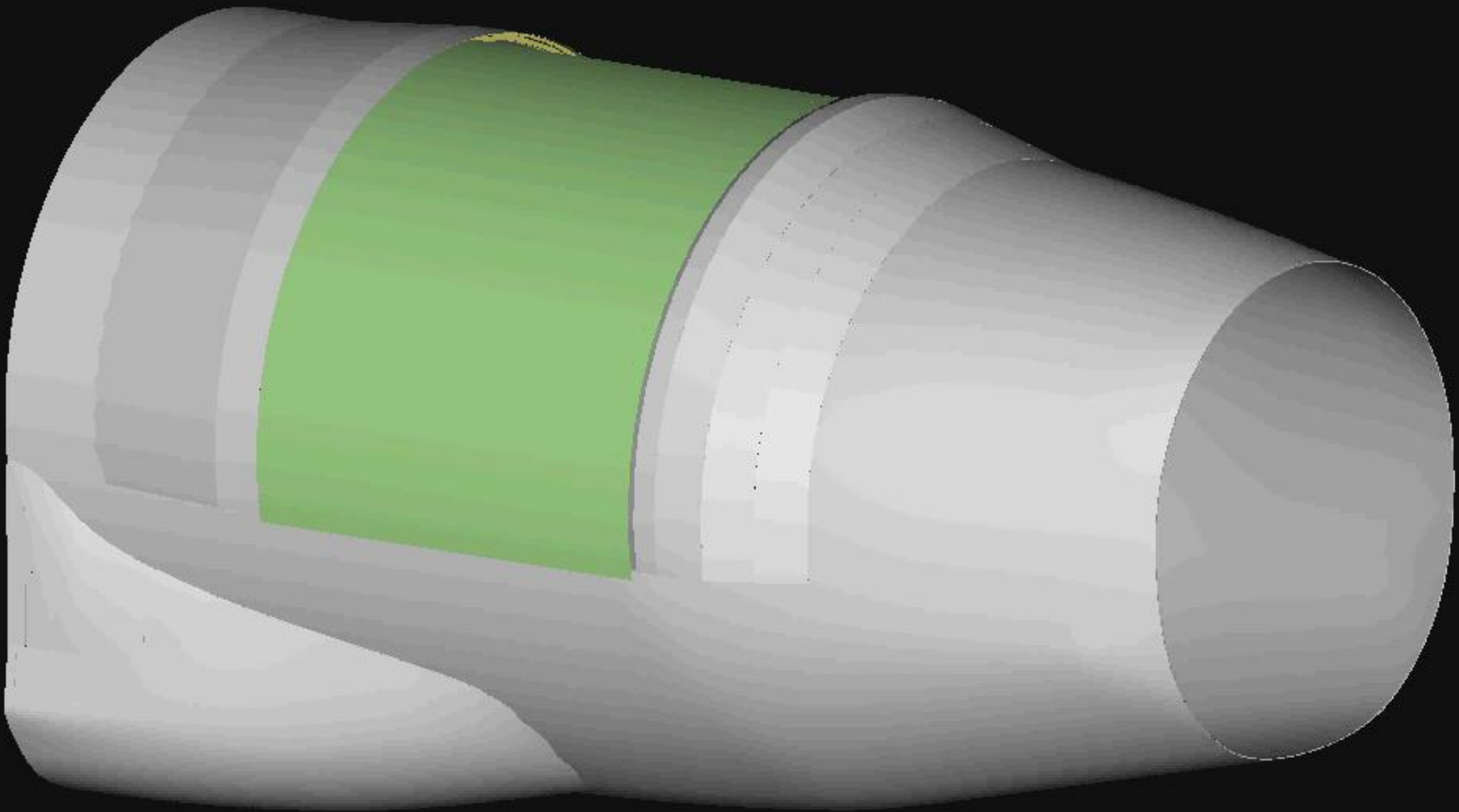


Forward Bulkhead Plate

Door System Fairings

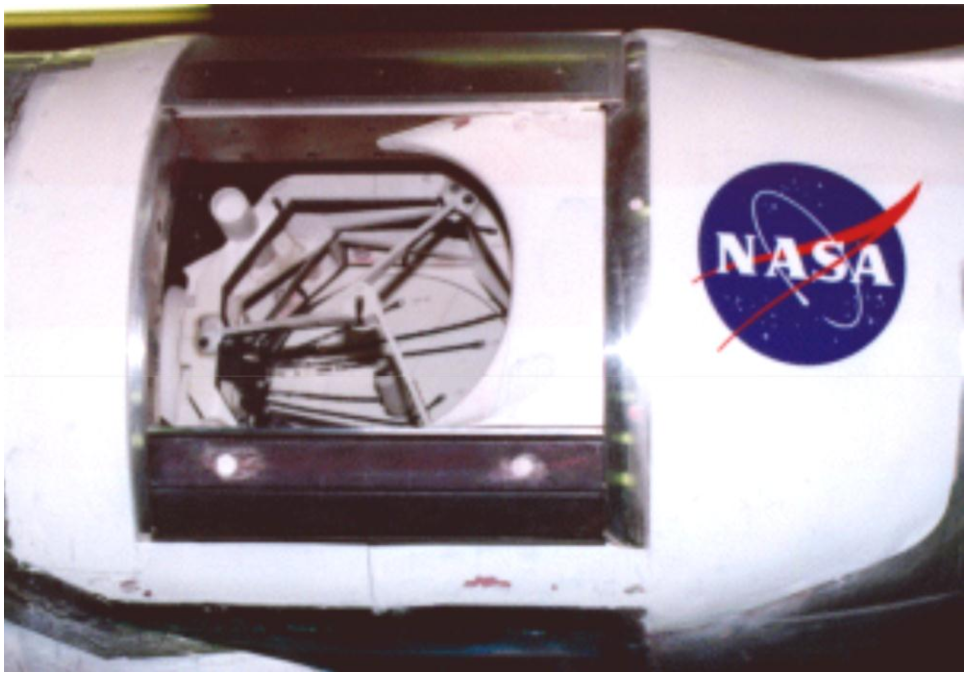


SOFIA Door System



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

7% Wind Tunnel Tests



Partial External Door

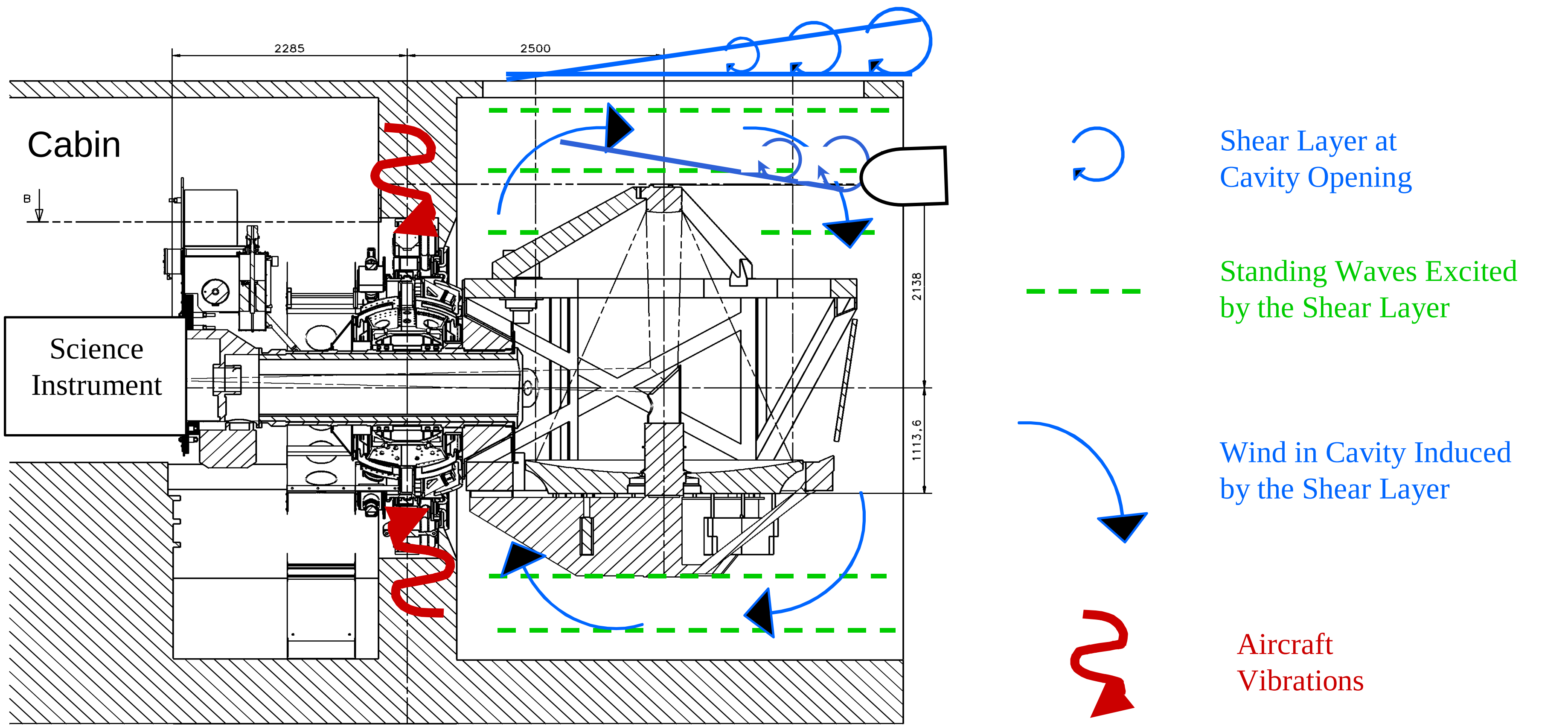
Test Description/Conditions

- 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

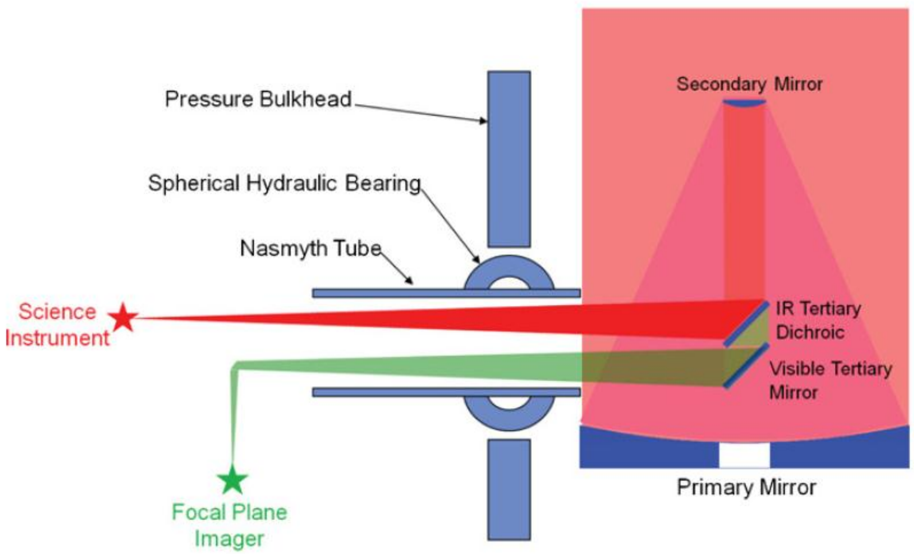
- Aero-acoustics
- Telescope torque
- Pressure loads
- Boundary layer characterization

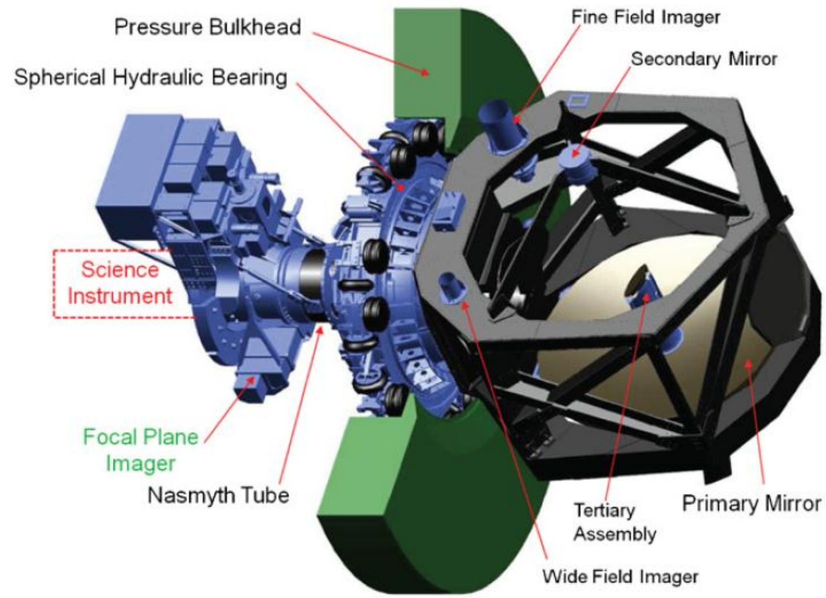
Dynamic Environment in the Cavity



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

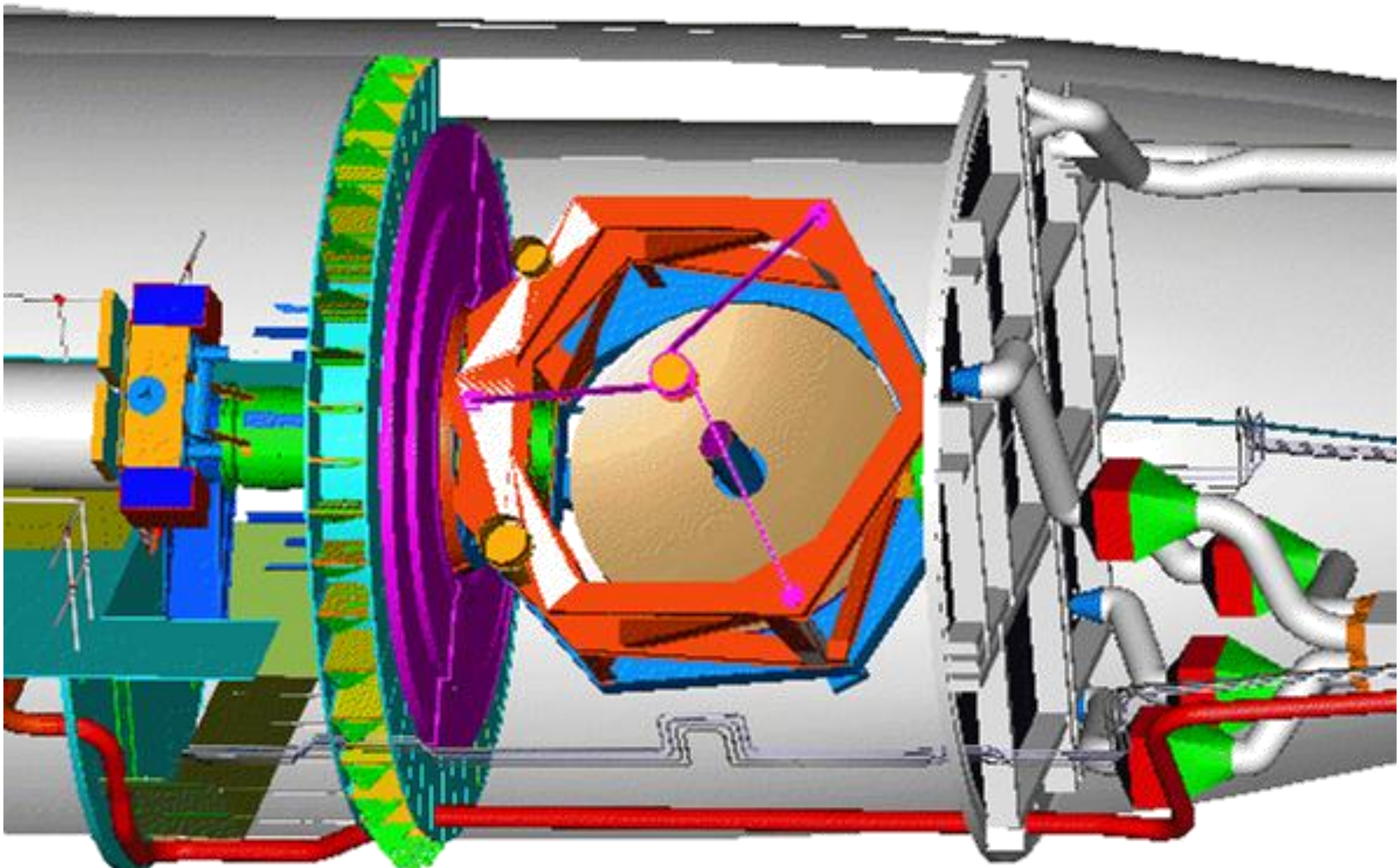
Telescope and Optical Layout



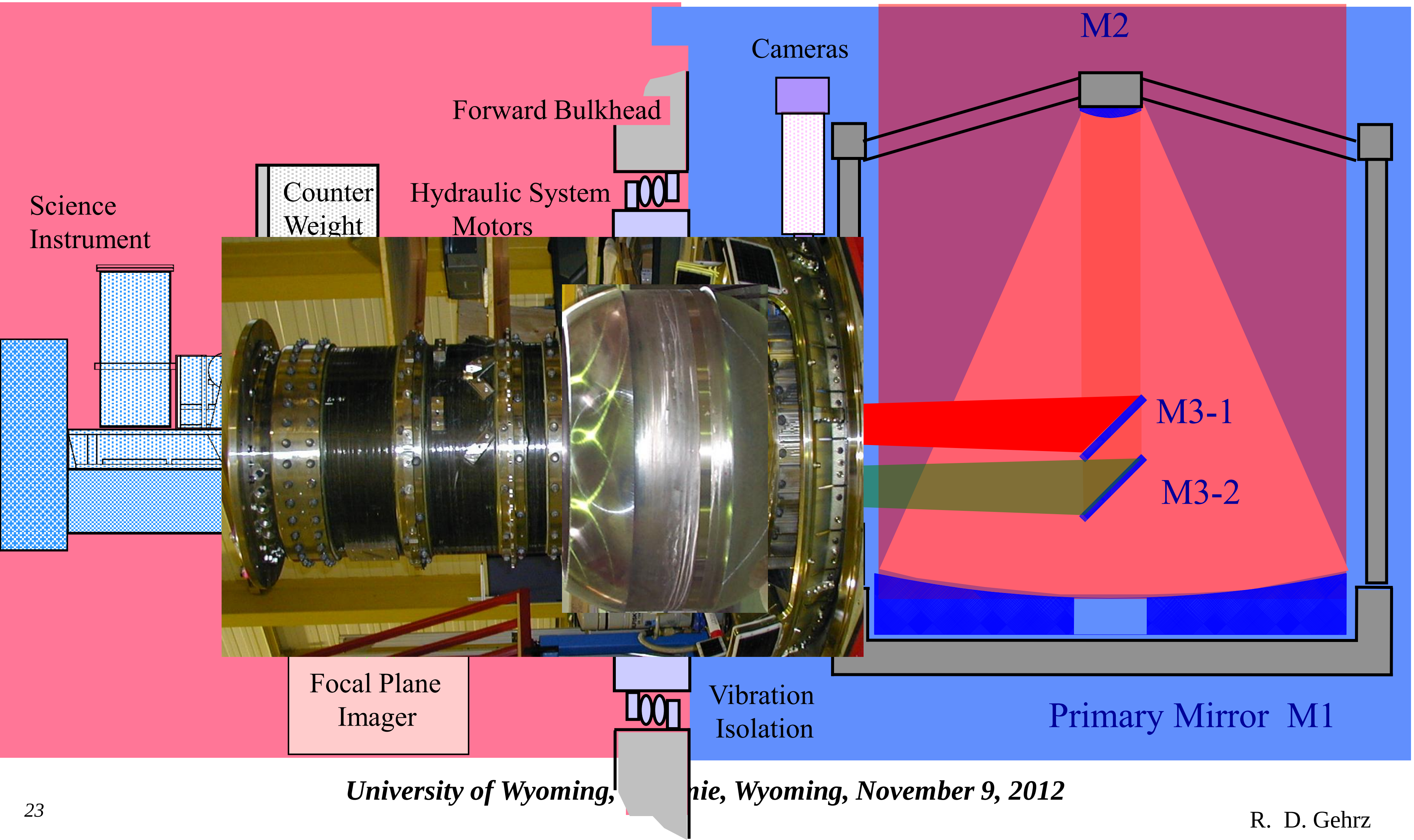


E.T Young et al. 2012, ApJ, 749, L17

Telescope Size is Maximum forAvailable Volume



Major Telescope Components



Back End of the SOFIA Telescope

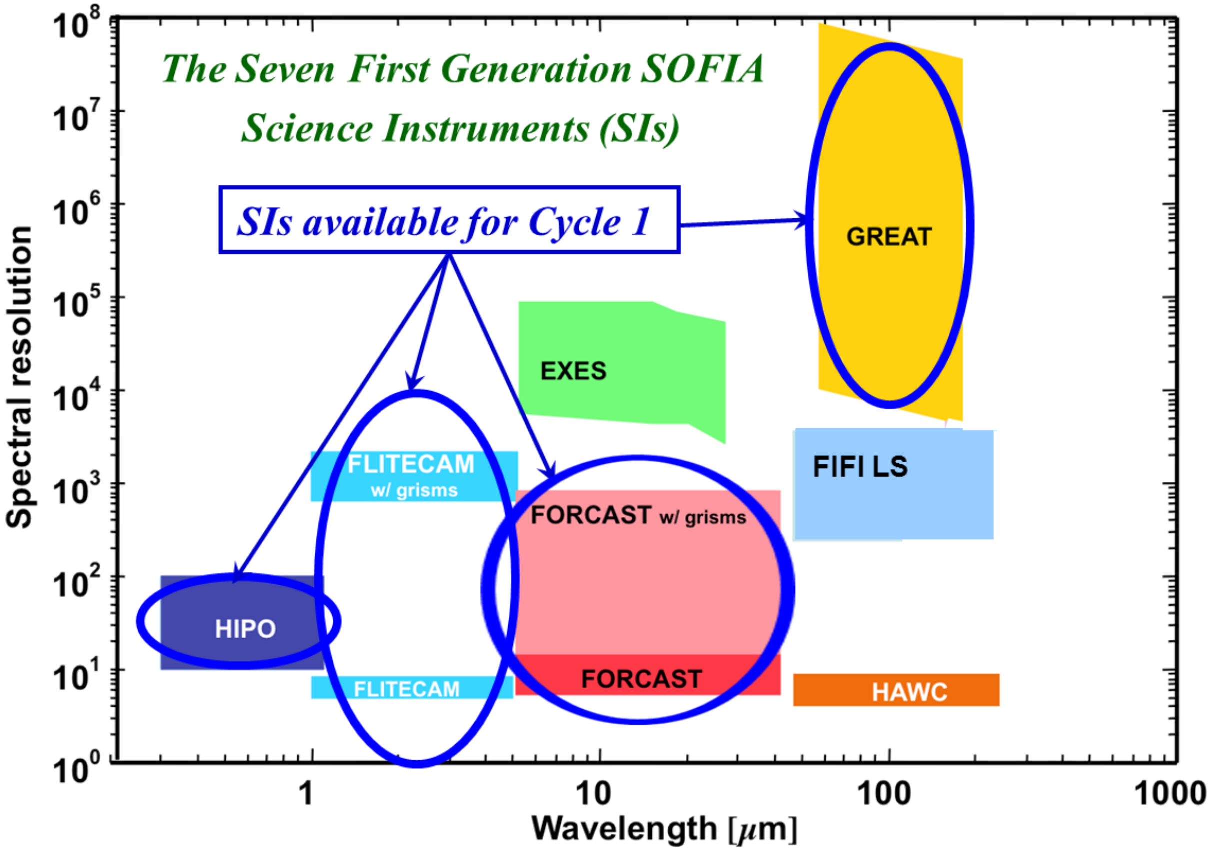
SOFIA Airborne on July 13, 2010

[*First Door Open Flight*]   [*Door Open 100*]

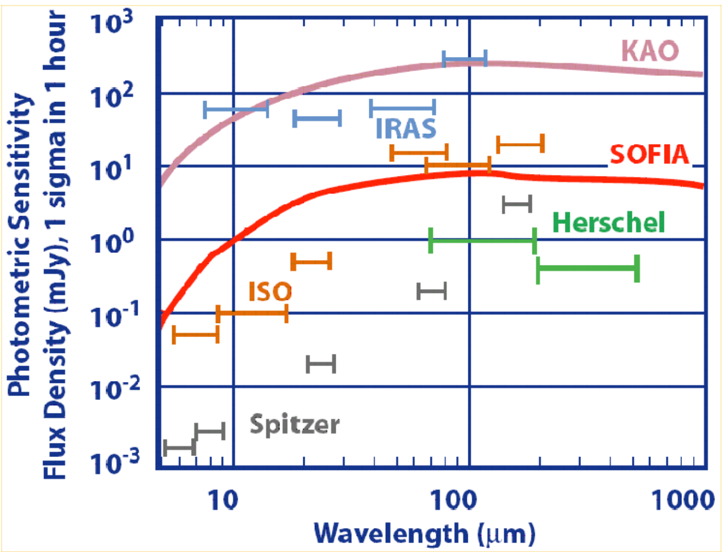
SOFIA Science Instruments

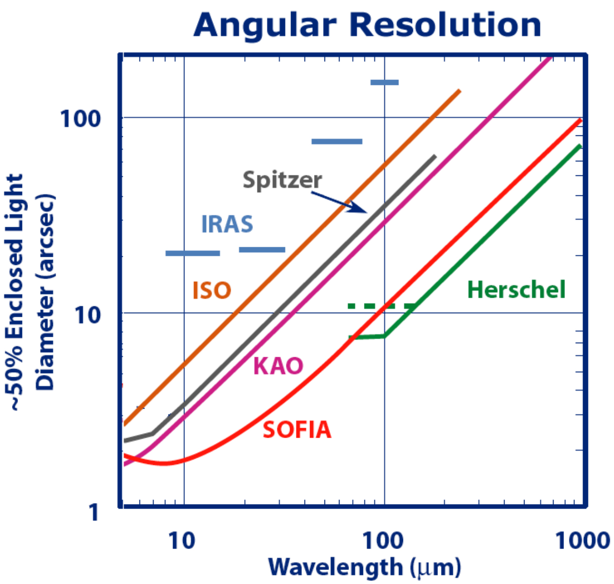
SOFIA supports a unique, expandable suite of Science Instruments (SIs)

- *SIs cover the full IR range with imagers and low to high resolution spectrographs*
- *4 SIs at Initial Operations; 7 SIs at Full Operations.*
- *SOFIA will take advantage of improvements in instrument technology.*
- *Will support both Facility Instruments and PI Class Instruments*



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

Results from the First Round of SOFIA Flights

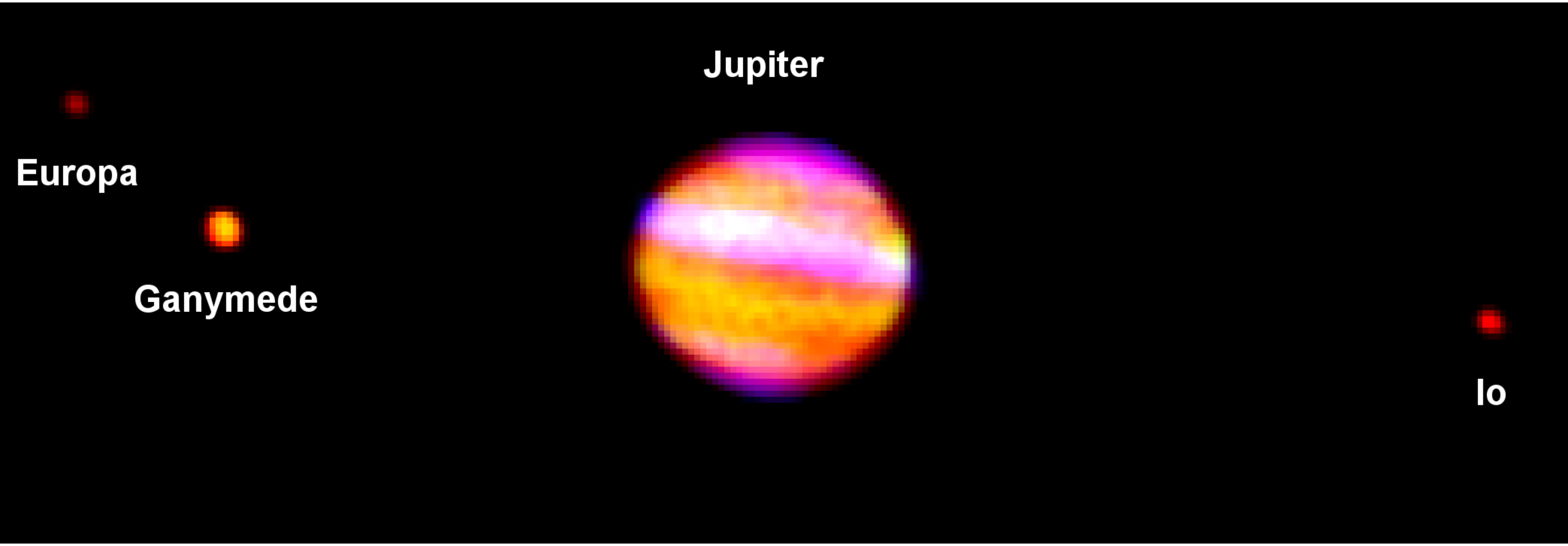
First Science Results with FORCAST

The FORCAST Team

The DSI Telescope Assembly and Mission Operations Team in action during the First Light Flight

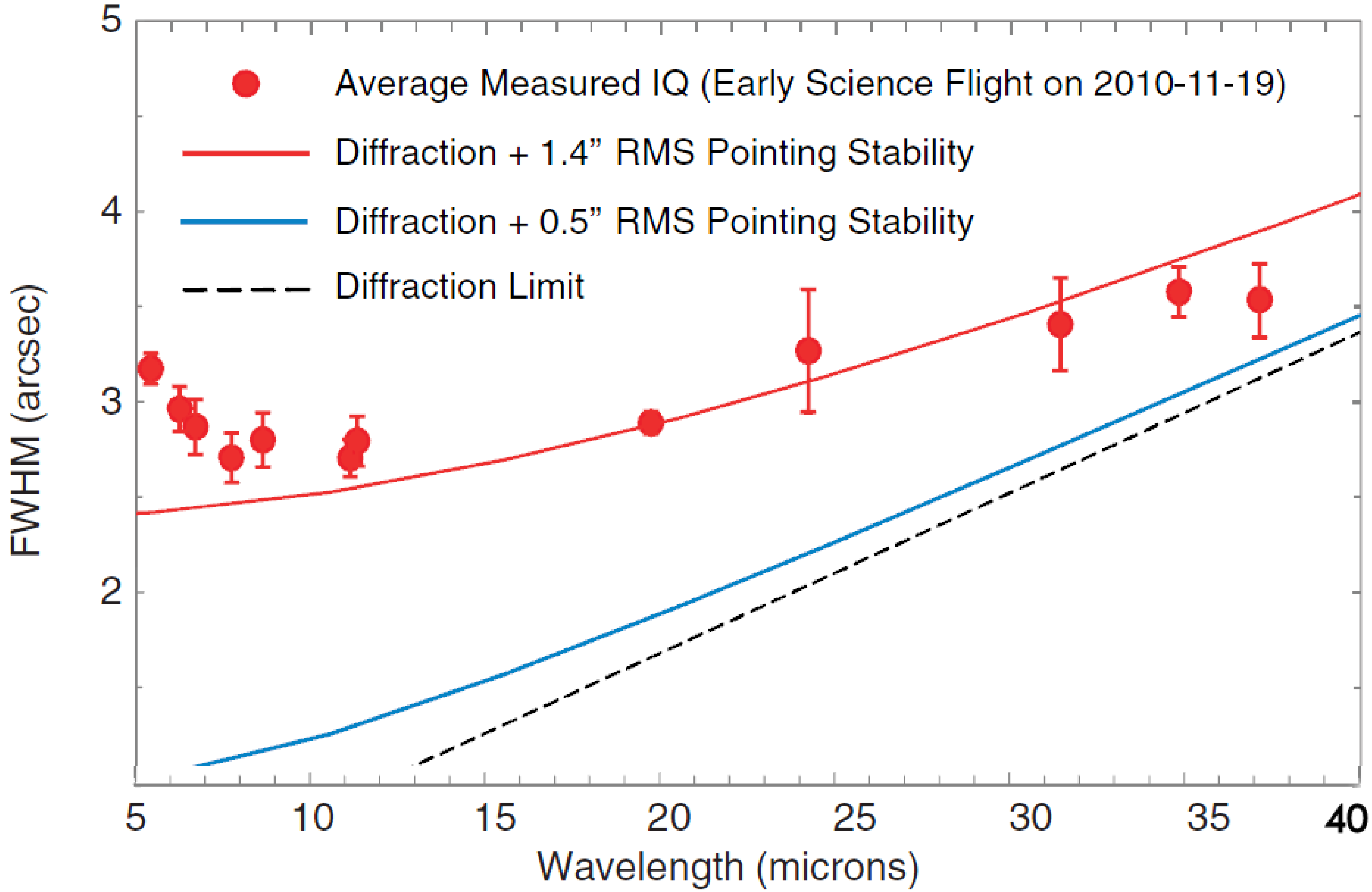
Eight papers have been published in ApJ Letters, 749, L17 (April 20 2012)

First Light on May 26, 2010 UT: We demonstrated diffraction limited imaging capability at 30 microns

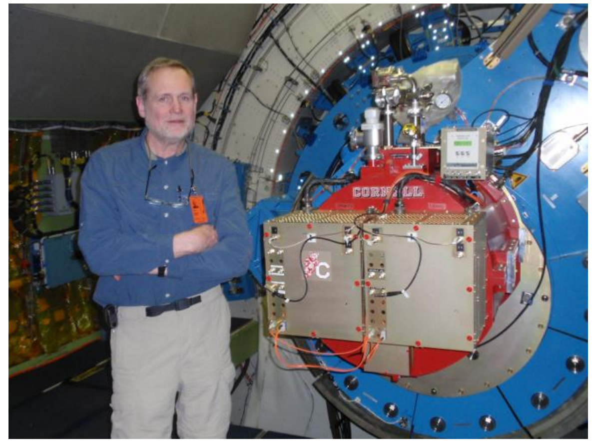


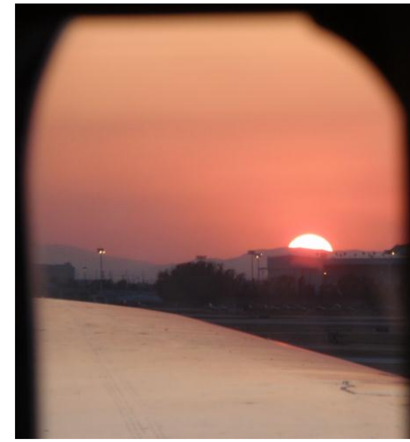
Red = 37.1 μm, Green = 24.2 μm, Blue = 5.4 μm

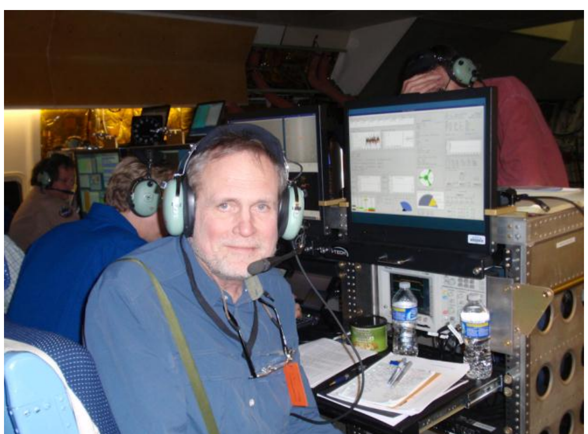
SOFIA Image Quality During Early Science

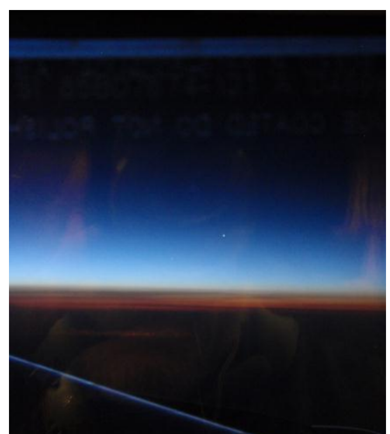


May 5, 2011: First Basic Science Flight









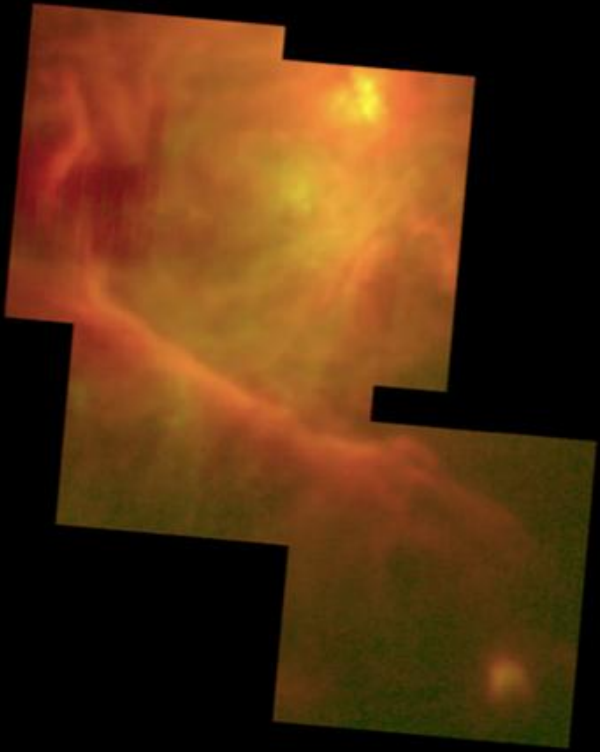
Inside the Observatory on the First Basic Science Flight

Telescope_Motion.wmv

20 (Green) and 37 (Red) Micron Data of Orion Nebula

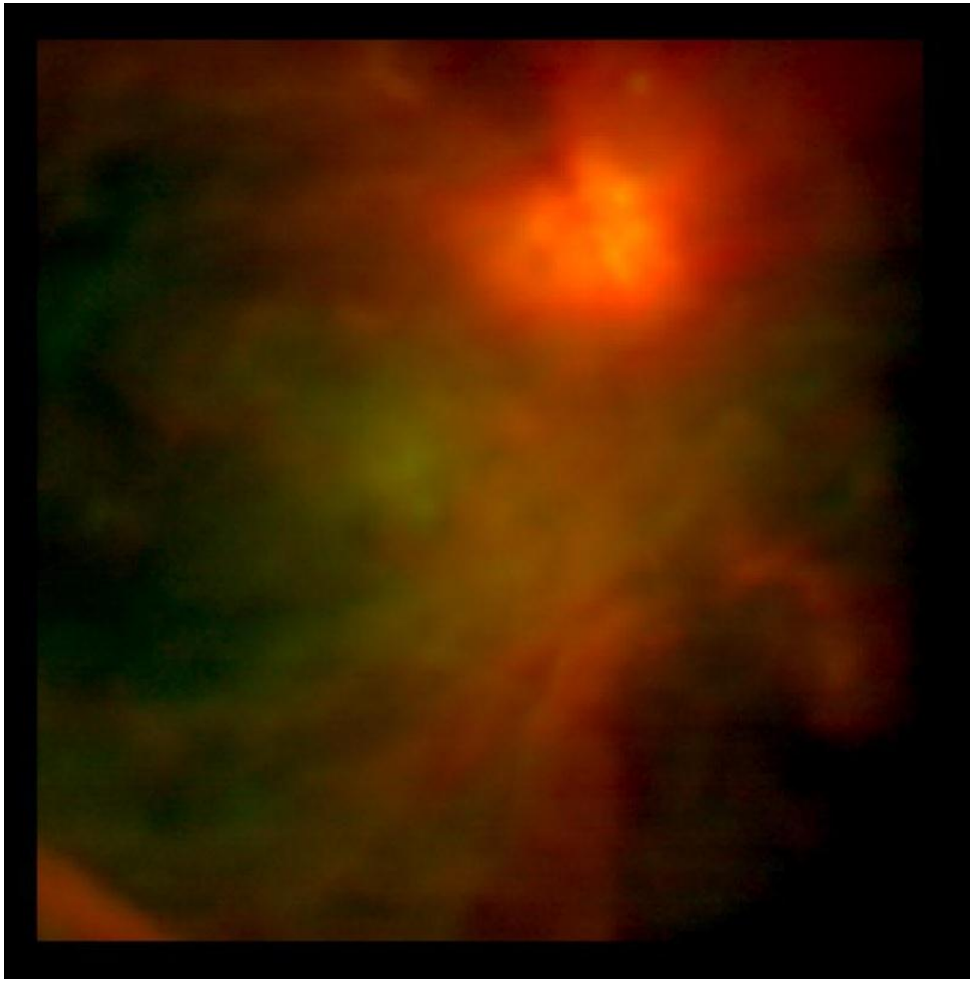
Visible light
(HST, C. O'Dell and S. Wong)

Near infrared
(ESO, M. McCaughrean)

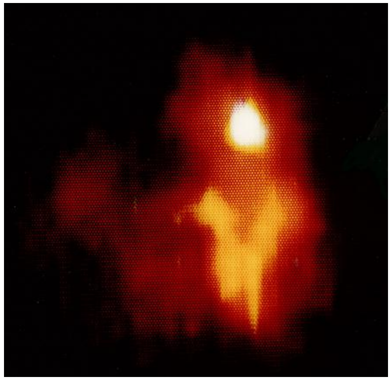


SOFIA mid infrared
(SS02)

SOFIA FORCAST Images of the Orion Nebula



Red = 37.1 μm, Green = 24.2 μm



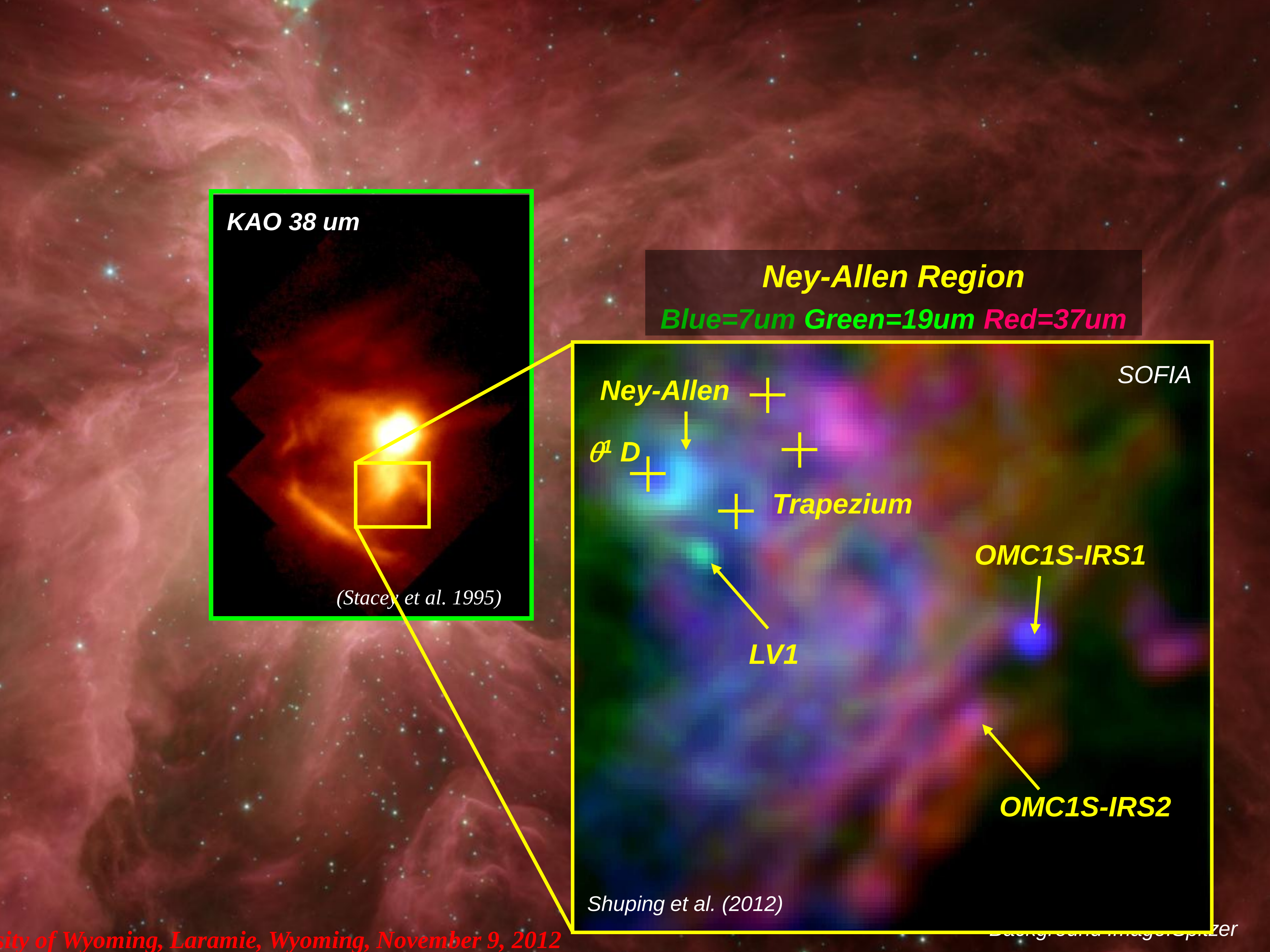
Wyoming Infrared Image from
Herzog et al., 1980, Sky and Telescope, 59, 18

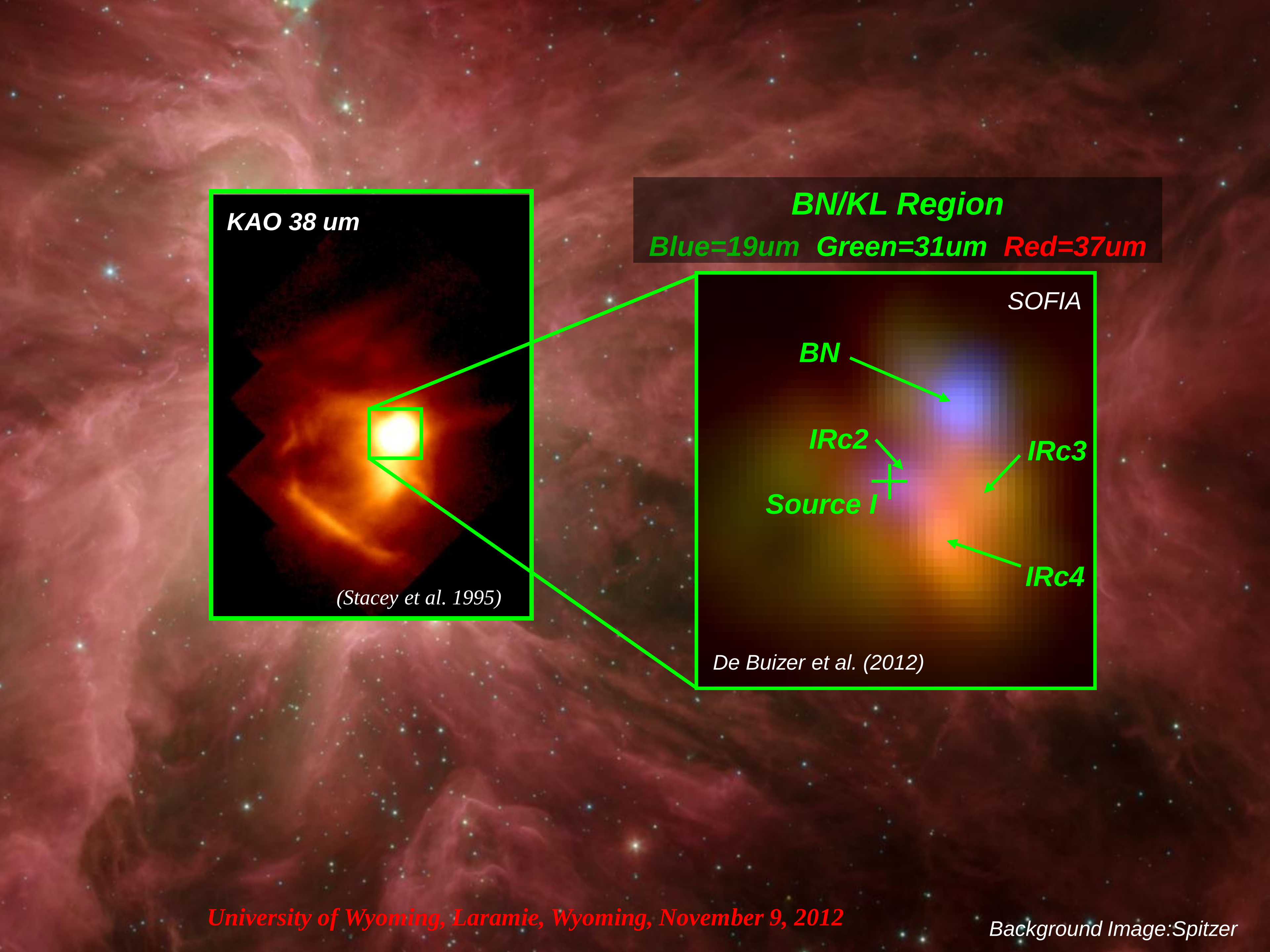
Red = 20 μm

Green = 12 μm

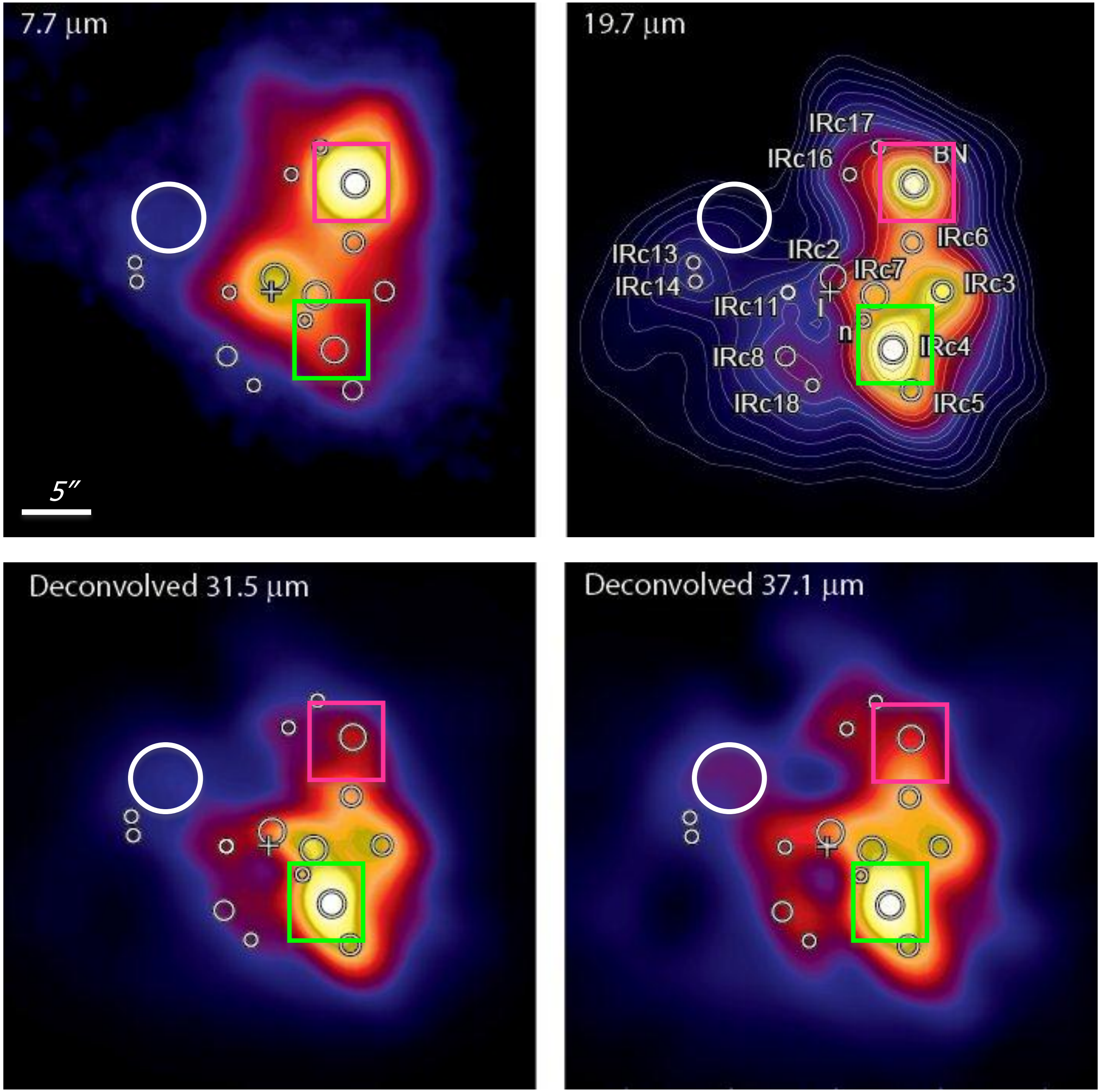
Blue = 11 μm

- *De Buizer etal ApJ Letters 2012 Vol 749 L23*
- *Shuping etal ApJ Letters 2012 Vol 749 L22*
- *Adams etal ApJ Letters 2012 Vol 749 L24 (OMC2)*


KAO 38 um
(Stacey et al. 1995)
Ney-Allen Region
Blue=7um Green=19um Red=37um
SOFIA
Ney-Allen
θ1 D
Trapezium
LV1
OMC1S-IRS1
OMC1S-IRS2
Shuping et al. (2012)
sity of Wyoming, Laramie, Wyoming, November 9, 2012



BN/KL Region
Blue=19um Green=31um Red=37um
KAO 38 um
(Stacey et al. 1995)
SOFIA
BN
IRc2
IRc3
Source I
IRc4
De Buizer et al. (2012)
University of Wyoming, Laramie, Wyoming, November 9, 2012
Background Image:Spitzer



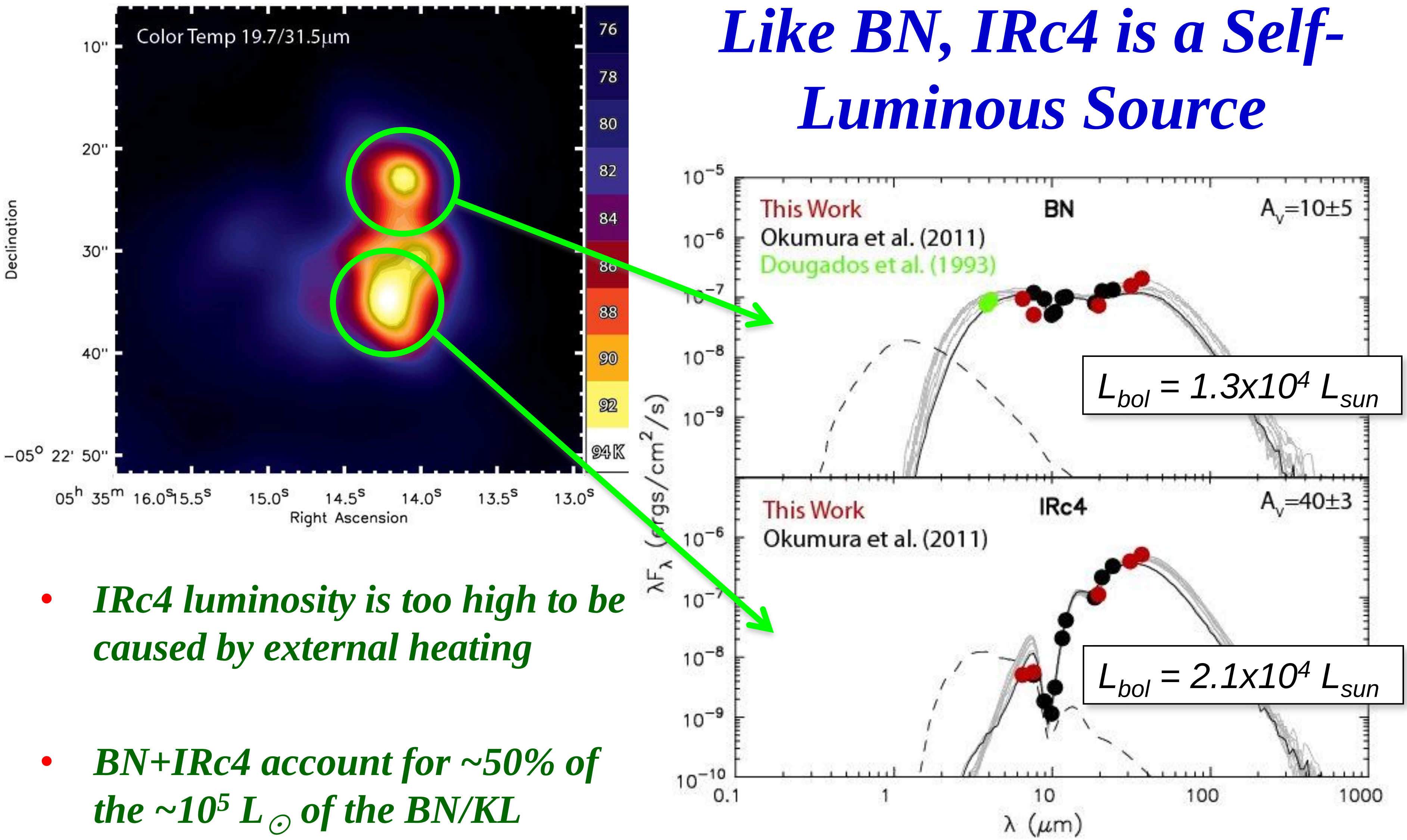
BN declines in prominence at longer l's

IRc4 dominates at l >31um

A previously unidentified area of emission is apparent at l >31um (SOF1)

De Buizer et al. (2012)

Like BN, IRc4 is a Self-Luminous Source

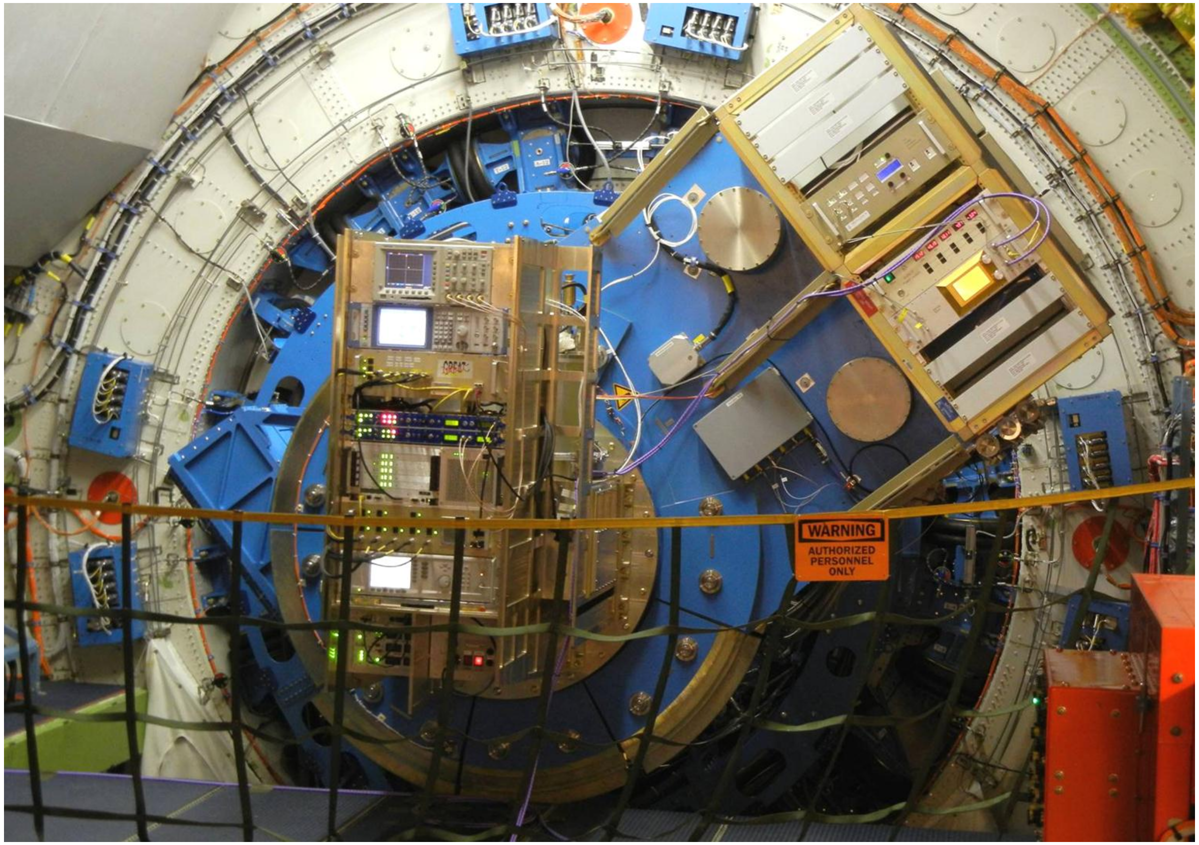


- *IRc4 luminosity is too high to be caused by external heating*
- *BN+IRc4 account for ~50% of the ~10^5 $L_\odot$ of the BN/KL region*

University of Wyoming, Laramie, Wyoming, November 9, 2012

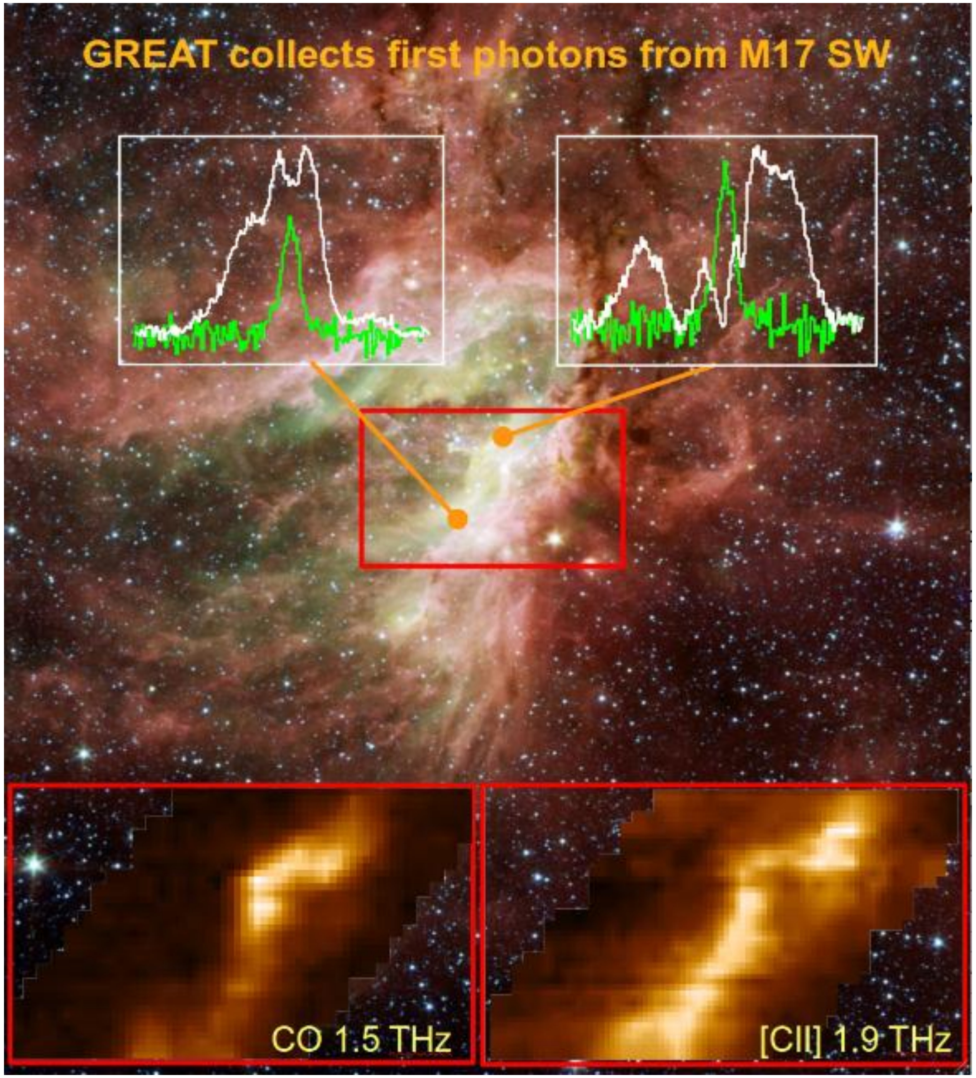
De Buizer et al. (2012)

First Science Results with GREAT on SOFIA



Twenty two papers on GREAT science have been published in a special edition of A & A Letters (2012, Volume 542)

Early Science with GREAT (White CII, Green CO)



- ***GREAT maps M17 SW molecular cloud***
- ***CII traces the photo-dissociation region created on the surface of the dark cloud by the ionizing radiation from the hot young stars***
- ***CO traces the warm cores where star formation may be occuring***

Studies of OH with GREAT on SOFIA

- *The OH (hydroxyl) was the first interstellar molecule detected in absorption at 18 cm radio wavelengths (Weinreb et al. 1963, Nature, Vol. 200, 829)*
- *The hyperfine Λ doublet at 18 cm wavelengths is well studied (both thermal and maser) from the ground, but this emission is dominated by relatively cool, diffuse gas ($N \sim 10^3$ cm^{-3})*
- *The FIR rotational lines of the OH $^2P_{1/2}$ and $^2P_{3/2}$ are observable with GREAT on SOFIA (the only facility that can do this) and probe denser, hotter gas than the 18 cm lines.*

OH level diagram

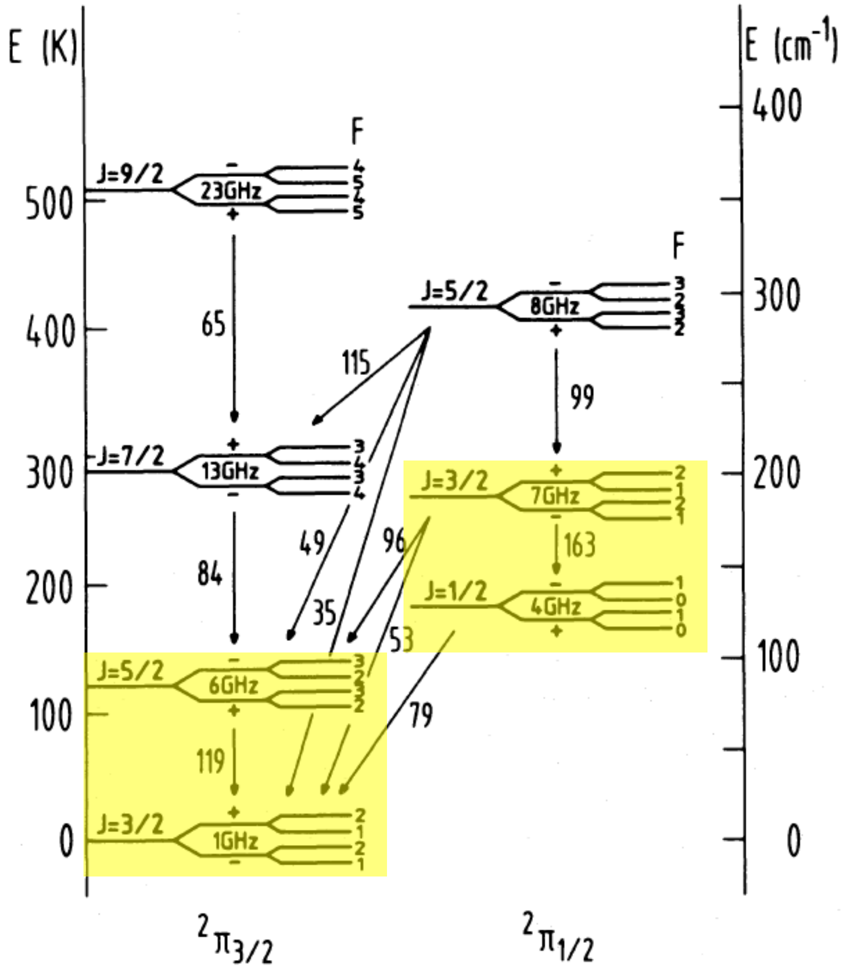
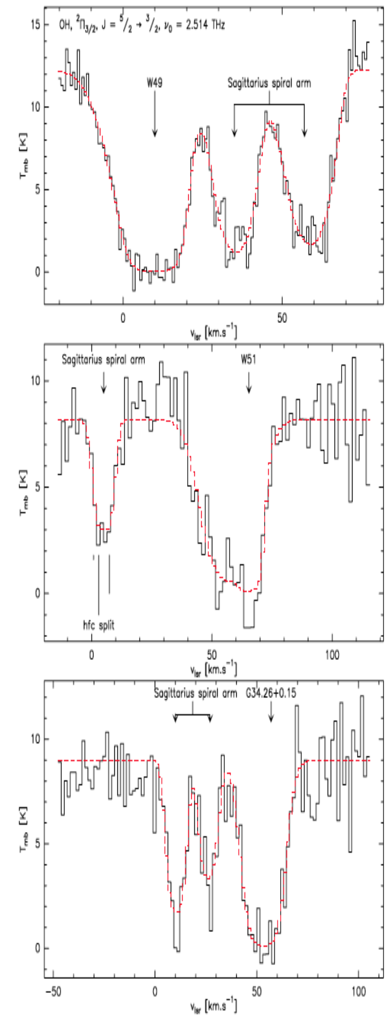


Fig. 1. Schematic representation of the lowest 28 energy levels of ^{16}OH. The Λ doubling and hyperfine splitting are not shown to scale.

- ***GREAT is tuned to observe the Λ doubling and hyperfine structure of the 163 μm (1.8378 THz and 1.8377 THz) and the 119 μm (2.514 THz) lines.***

$OH\ ^2\Pi_{3/2}\ J = 5/2 \leftarrow 3/2$ (119 μm)

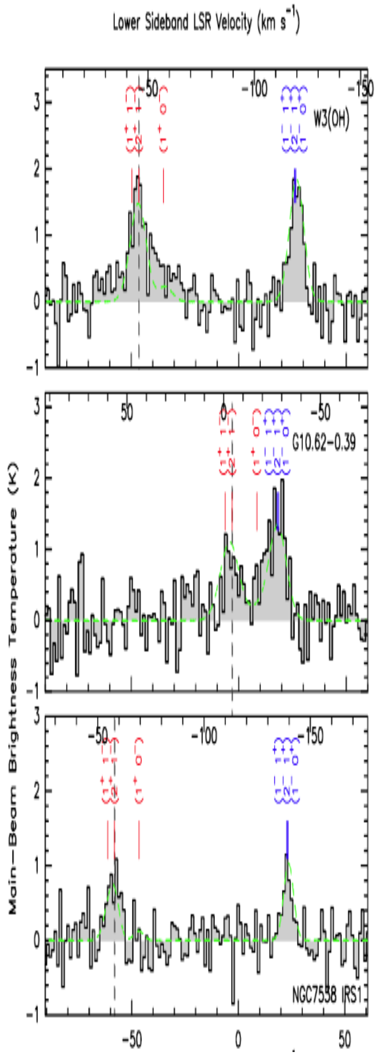
- *Wiesemeyer et al. (2012, A&A, 542, L7) observed the 119 μm OH ground state line in absorption towards several ultra compact HII regions.*
- *This is the first astrophysical velocity resolved spectrum ever observed of this transition*
- *The line traces molecular gas in the spiral arm clouds along the line of sight and near the HII regions.*
- *Using Herschel observations of H_2O, they find that the H_2O to OH abundances ranges from 0.3 – 1.0*



OH $^2\Pi_{1/2}$, $J = 3/2-1/2$ (163 μm)

- *Csengeri et al (2012, A&A, 542, L8) observed the J = 3/2 – 1/2 rotational OH transition in emission towards several ultra compact HII/OH maser sources. One pair (blue) in the signal band and the other fortuitously in the image side band (red)*

- *These observations show that the observed line intensities require a compact, high OH column density, warm gas component*



67th International Symposium on Molecular Spectroscopy , Columbus, OH, June 21, 2012

R. D. Gehrz

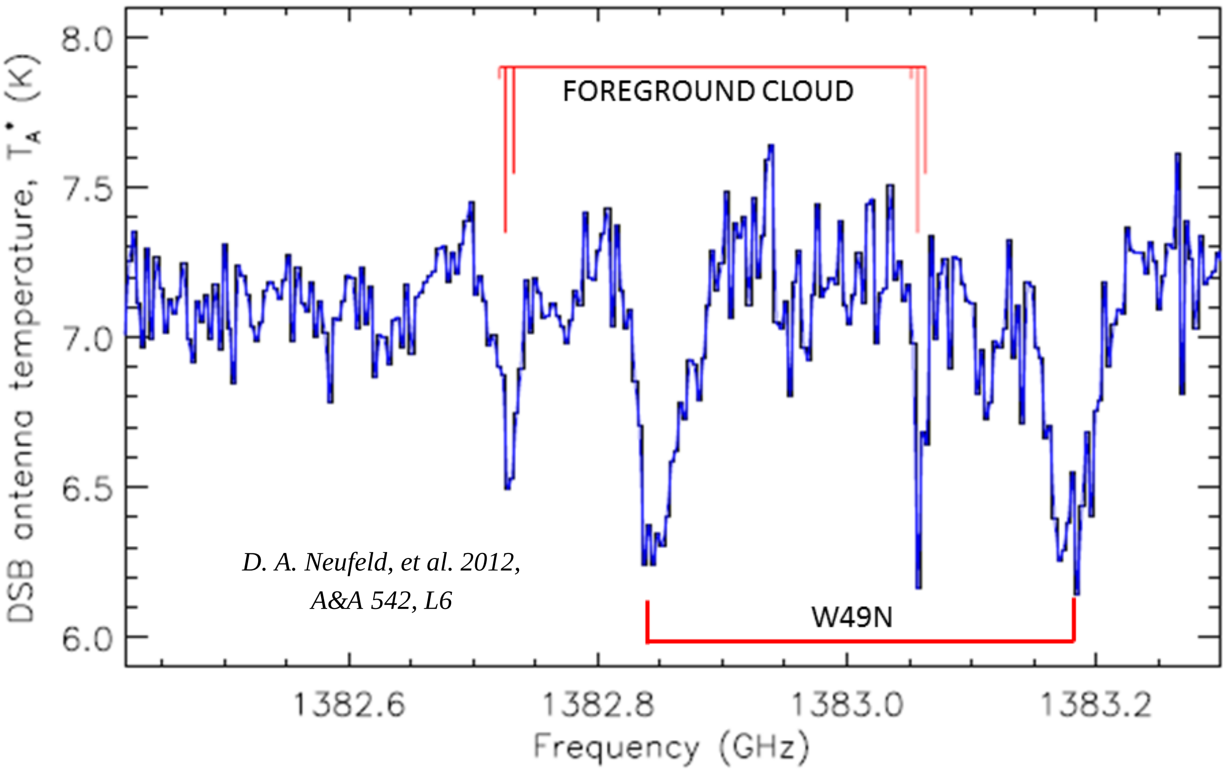
Discovery of SH (Mercapto radicals) in Interstellar Space

- ***SH is one of the simplest Hydrides previously undetected in the ISM***

- ***Its ground state rotation line at 1.383 THz (217 microns) shows Lambda-type doubling (nuclear rotation-electron spin interaction), so it is easy to identify***

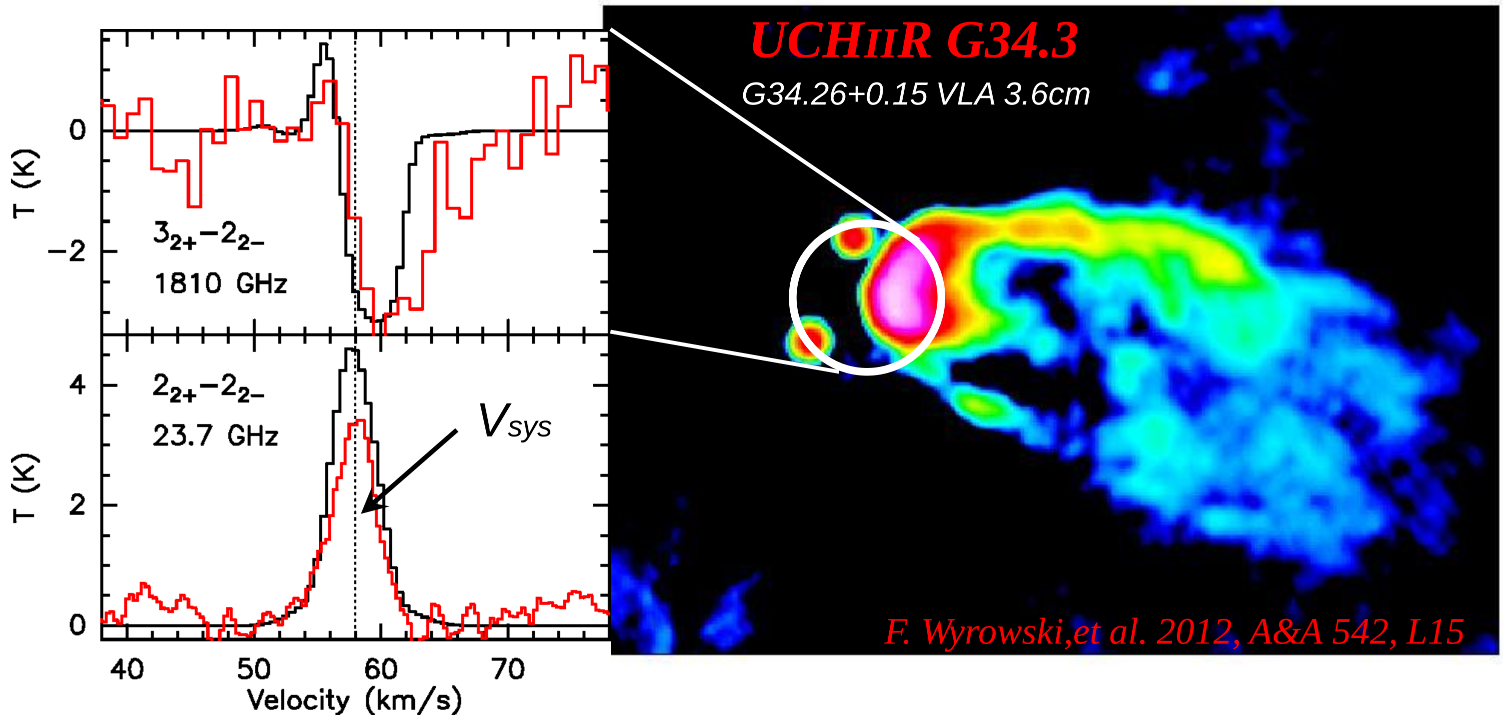
- ***W49N intersects several molecular clouds in it own and another spiral arm that cause absorption of the continuum.***

Mercapto Radicals in Absorption Toward W49N



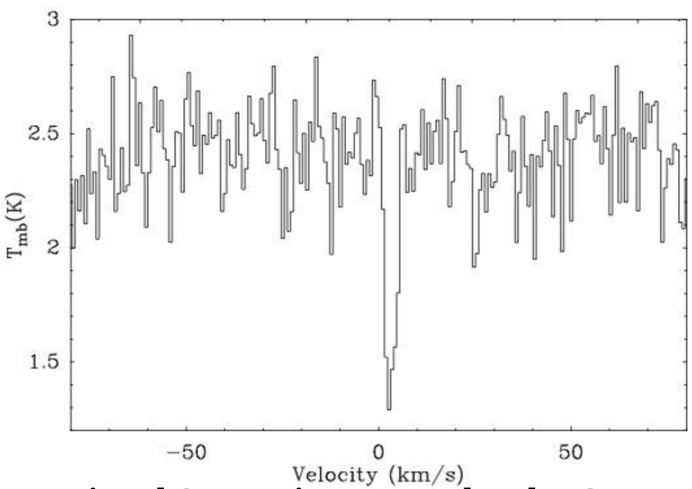
- *Hydrogen Sulfide (H_2S) is seen in absorption at the same velocities*
- *The implied diffuse cloud abundance ratio, $SH/H_2 \sim 10^{-8}$, suggests the presence of elevated gas temperatures (~1000K) within cloud cores*

Probing Protostellar In-Fall with Terahertz Ammonia Absorption in an Ultra Compact HII Region



- *Red-shifted ammonia (NH_3) absorption due to infall detected against the optically thick dust continuum*
- *Optically thin $C^{17}O$ at 1.27 cm (23.7 GHz) gives the systemic velocity*

Detection of OD Absorption towards the Low-mass Protostar IRAS 16293-2422



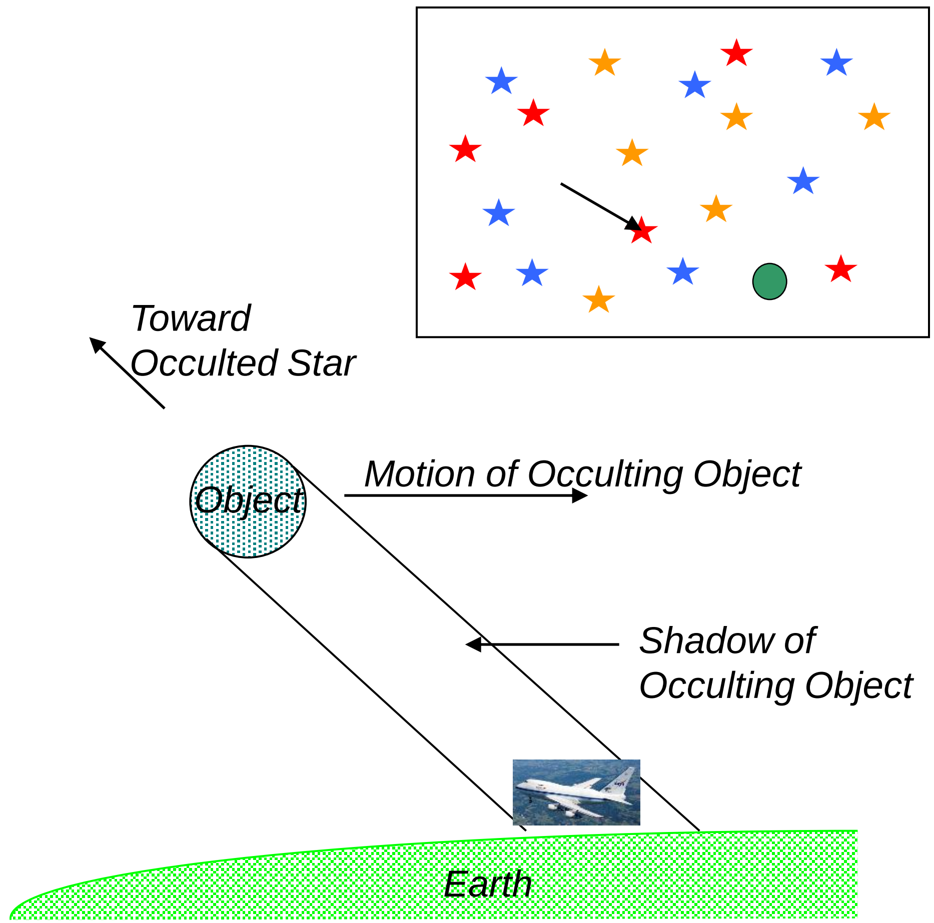
B. Parise - AAS SOFIA Splinter Session 09.01.2012

- Detection of the OD ground state line at 1.39 THz (216 μm) is detected in absorption
- First detection of OD outside of the solar system.
- The OD/HDO abundance of 17-90 where the absorption takes place is high compared to model values
- Dissociative recombination of H_2DO^+ into OH and H_2O may cause HDO depletion

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.*



HIPO/FDC Observation of Stellar Occultation by Pluto

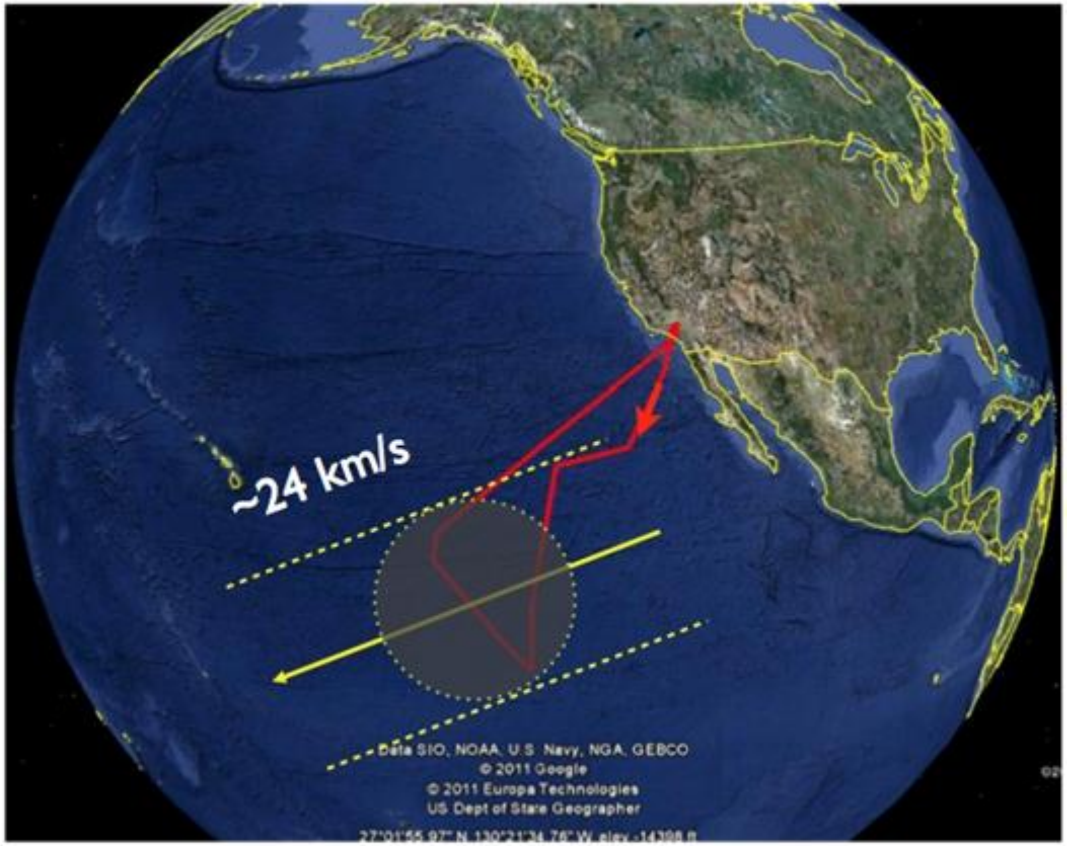
Scientific goals

- Measure temperature profile of Pluto's atmosphere
- Test atmospheric freeze-out models
- Target central flash – global atmospheric shape, possible extinction

Programmatic Goal

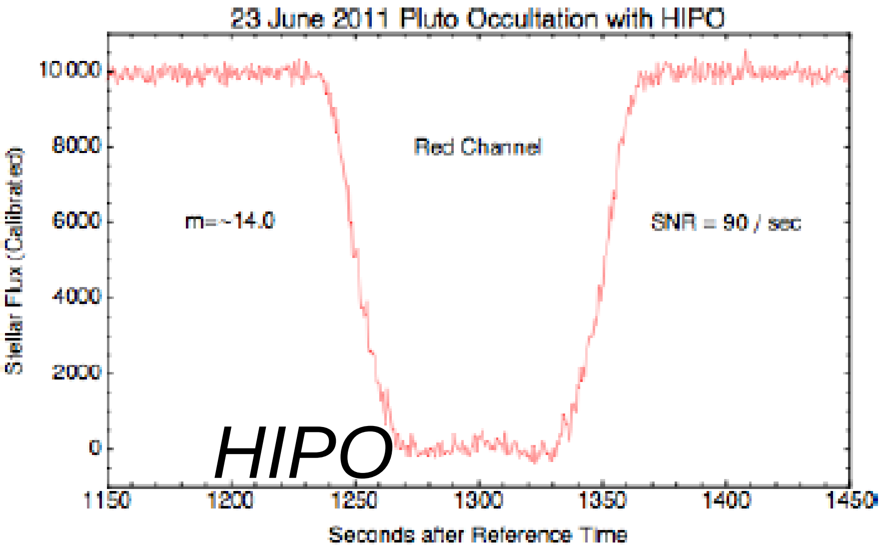
- Demonstrate successful in-flight prediction update and flight plan change to enable observation on the central chord

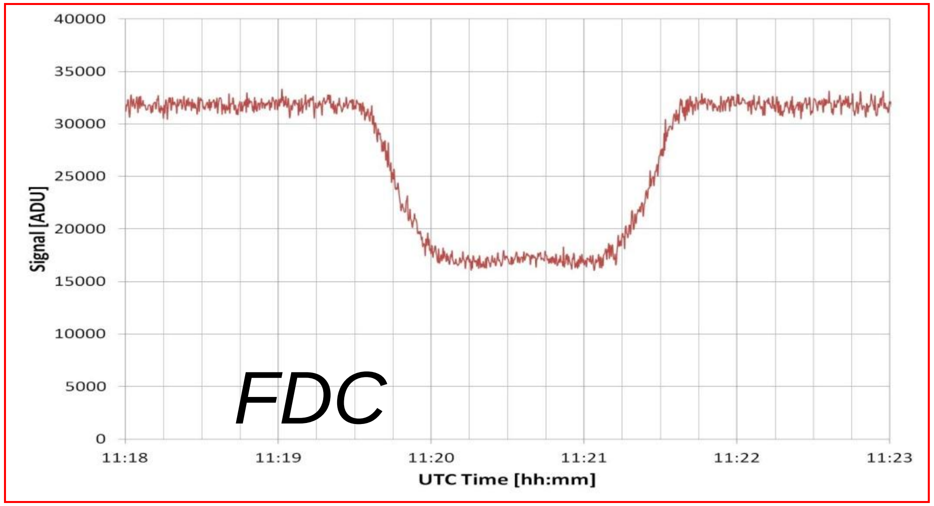
Ted Dunham et.al. (HIPO), Lowell Observatory, Jürgen Wolf (SOFIA DSI) & Mike Person et al., MIT



Pluto Occultation Results

- *Central brightening seen in HIPO blue and red channels and Fast Diagnostic Camera (FDC) visual channel*
- *Post-event data indicates impact parameter <100 km!*
- *The atmosphere of Pluto is still there contrary to predictions that it will frozen out as Pluto heads for aphelion*
- *Central brightening suggests the presence of a low-altitude haze layer*





Science Schedule

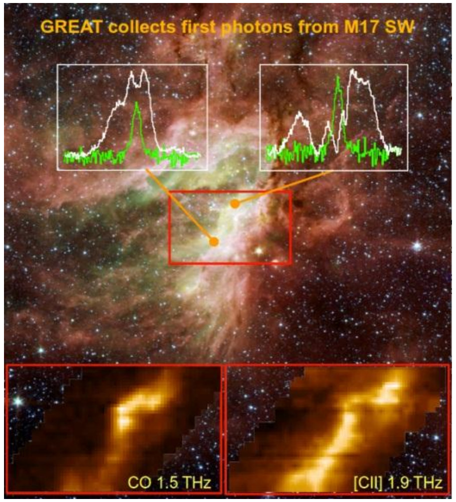
- *Aircraft and telescope control improvements are underway. Test flights will resume in November, 2012*
- *The Cycle 1 science call resulted in the award of about 200 hours of community science. There will be ~45 flights including ~8 Southern Hemisphere flights.*
- *Cycle 1 observations will begin with GREAT observations in November, 2012. New SIs are HIPO, FLITECAM, and FORCAST/FLITECAM GRISMs*
- *Cycle 2 proposals will be called for in Spring 2013 and due in June, 2013. EXES and FIFI-LS will be added as SIs*
- *There will be additional science calls annually*

Future Instrumentation Development

- ***A call for SOFIA second generations SIs was released on July 17, 2011***
- ***Eleven proposals were ingested on October 7, 2011***
- ***The selection of two proposals for upgrades to HAWC was announced on April 17, 2012.***
  - ***A new detector will increase the number of pixels from 380 to 2400***
  - ***A wide-field polarimetric capability will be added***
- ***NASA plans to issue another SI AO in 2014***

Summary

- *The Program is making progress!*
  - *Early and Basic Science flights have been concluded and have produced interesting results and 30 publications*
  - *Pluto occultation observation showcases SOFIA's potential*
  - *Performance expectations are being met*
  - *Cycle 1 observations will begin in 6 months*
- *SOFIA will be one of the primary observational facilities for far-IR and submillimeter astronomy for many years*



Our Web site: *http://www.sofia.usra.edu//*

This talk: *http://www.sofia.usra.edu/Science/speakers/index.html*

Backup

Future Molecular Spectroscopy with SOFIA

Name	Spectroscopic Capability	PI	Institution (Year of Commisioning)	Wave-lengths (μm)	Spectral Resolu-tion
FORCAST	Grism Spectrometer	T. Herter	Cornell (2013)	5-40	200
GREAT	Heterodyne Spectrometer	R. Güsten	MPIfR (2011-13)	60-240	10^6-10^8
FLITECAM	Grism Spectrometer	I. McLean	UCLA (2013)	1-5	2000
EXES	Mid-Infrared Spectrometer	M. Richter	UC Davis (2014)	5-28	3000, 10^4, 10^5
FIFI-LS	Integral Field Far-Infrared Spectrometer	A. Krabbe	U Stuttgart (2014)	42-210	1000-3750

SOFIA's First-Generation Instruments

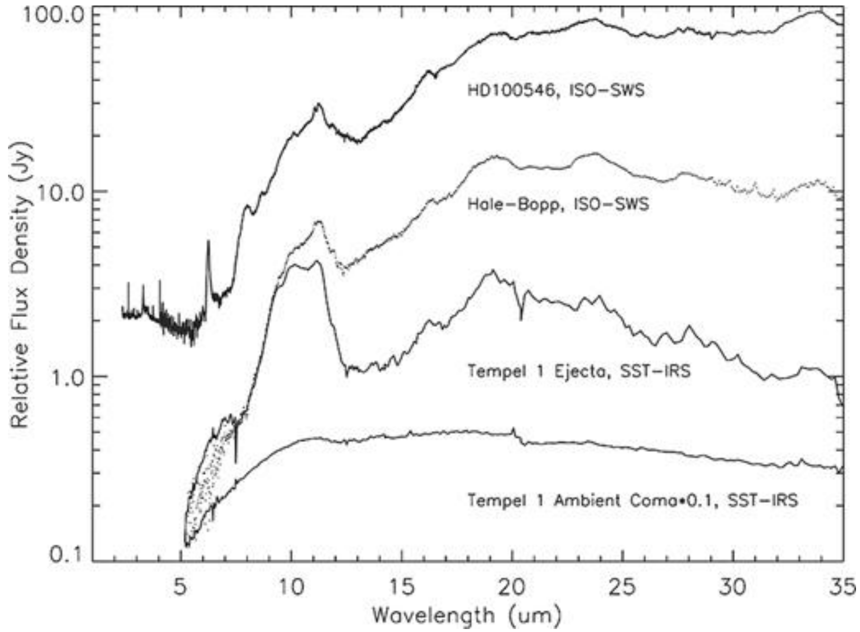
(http://www.sofia.usra.edu/Science/instruments/)

see also Gehrz et al. 2011 (arXiV:1102.1050)

Instrument	Type	λλ (μm)	νν (THz)	Resolution	PI
FORCAST (in operation)	imager / (grism)	5.4 - 37	8.1 - 56	filters / (R~2000)	T. Herter / Cornell U.
GREAT (H-Freq.) (M-freq. -- June 2011) (L-freq.'s -- operating)	heterodyne spectrometer	(62 - 65) (110 - 125) 156 - 165 200 - 240	(4.6 - 4.8) (2.4 - 2.7) 1.82 - 1.92 1.25 - 1.50	R ~ 10^4 - 10^8	R. Güsten / MPIfR
HIPO (summer 2011)	fast imager	0.3 - 1.1		filters	E. Dunham / Lowell Obs.
FLITECAM (summer 2011)	imager / (grism)	1.0 - 5.5		filters / (R~2000)	I. McLean / UCLA
FIFI-LS	imaging grating spectrograph	42 - 110 110 - 210	2.7 - 7.1 1.4 - 2.7	R ~1000 - 2000	Poglitsch,Krabbe /MPE,IRS
EXES	imaging echelle spectrograph	4.5 - 28.4	10.6 - 67	R ~ 3000 - 10^5	M. Richter / UC-Davis
HAWC	imager	45 - 270	1.1 - 6.6	filters	D. A. Harper / U. Chicago

SOFIA and Comets during Perihelion Passage

What can SOFIA tell us about The origin of the Solar System for studies of comets at perihelion passage?

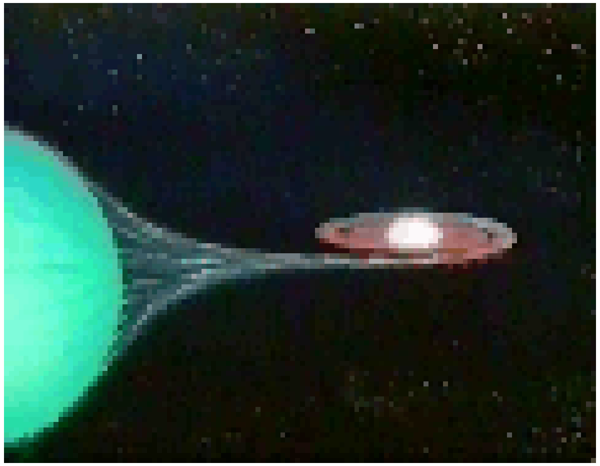


NASA/UM C. M. Lisse et al., Science 313, 635 (2006)

- *Comet dust mineralogy and physical properties*
- *Comparisons with IDPs*
- *Comparisons with meteorites*
- *Comparisons with Stardust*
- *Only SOFIA can get these observations*

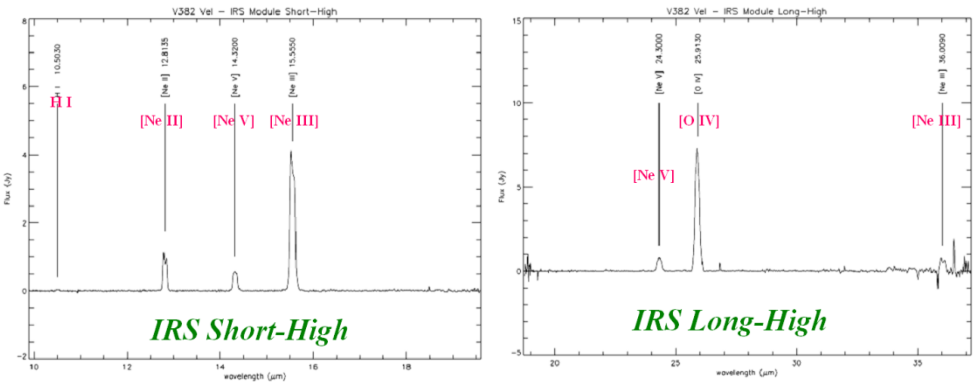
SOFIA and Classical Nova Explosions

What can SOFIA tell us about Classical Nova Explosions?



Spitzer Spectra of Nova V382 Vel

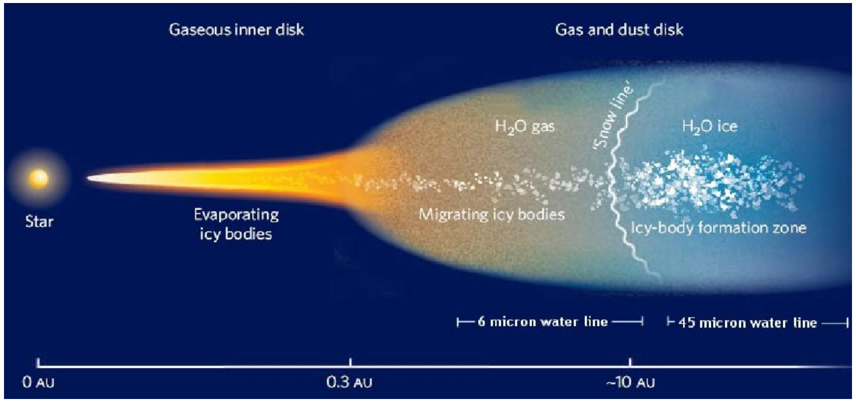
R. D. Gehrz, et al. 2005, ApJ, in preparation [PID 124]



- *Gas phase abundances*
- *Stardust formation and mineralogy, and abundances*
- *Contributions to ISM clouds*
- *Kinematics of the Ejection*

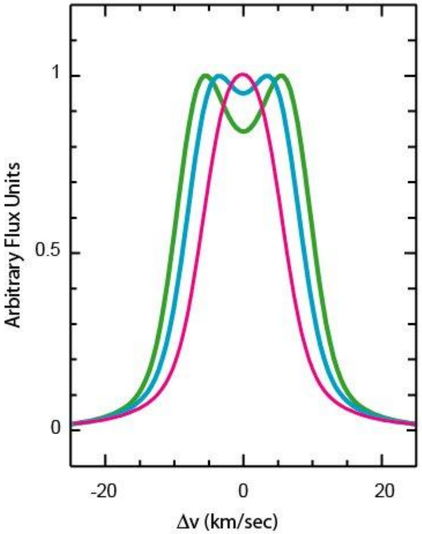
EXES: The chemistry of disks with radius and Age

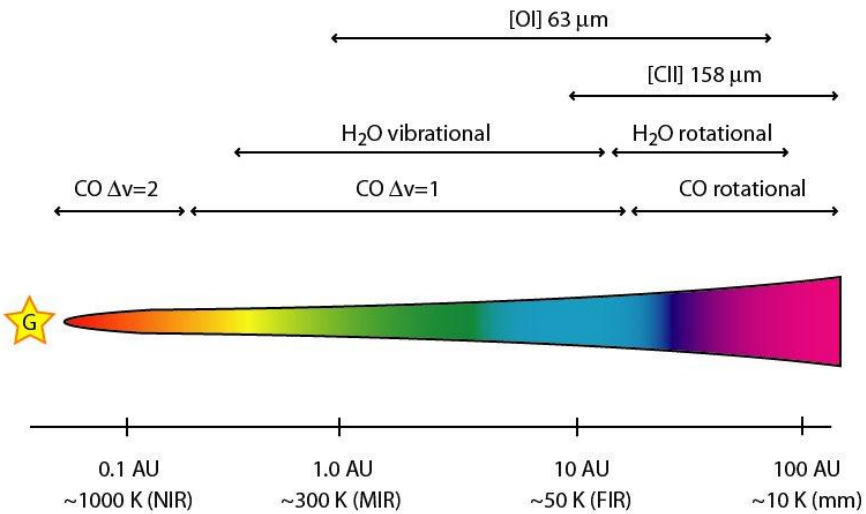
- *High spatial and spectral resolution can determine where different species reside in the disk*



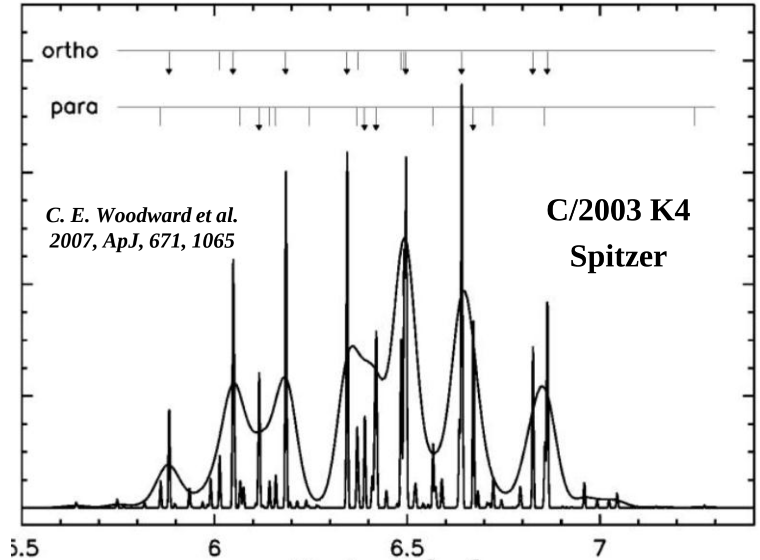
- *small radii produce double-peaked, wider lines.*

- *Observing many disks at different ages will trace disk chemical evolution*





EXES and Comets: Gas Phase Constituents



- Production rates of water and other volatiles
- Water (H_20) H_2 ortho/para (parallel – anti-parallel) hydrogen spin isomer ratio gives the water formation temperature; a similar analysis can done on the spin isomers of methane (CH_4)
- Only SOFIA can make these observations near perihelion