
SOFIA
NASA
DLR
N747NA
NASA
850

Hans Zinnecker

Deputy Director
SOFIA Science Mission Operations

Seminar at TU Berlin
November 4, 2011

First Science Results with SOFIA, the Stratospheric Observatory for Infrared Astronomy

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November 4, 2011

With Support from

- Jim DeBuizer
- Mark Morris (UCLA)
- Eric Becklin (SOFIA chief advisor)
- Ralph Shuping
- Bill Vacca
- Erick Young (SOFIA SMO director)
- Terry Herter and FORCAST team
- Rolf Guesten and the GREAT team
- Bob Meyer (NASA Program Manager)

WEBSITE: www.sofia.usra.edu (incl. science vision)

Recent review: Gehrz et al. 2011 (Adv. Space Res.)

Outline of Material

- Overview of SOFIA
- The SOFIA Observatory
- Science Capabilities and Instruments
- First Science with SOFIA
- Future Science
- Schedule and Future Opportunities
- Summary

OVERVIEW

Overview of SOFIA

- SOFIA is 2.5 meter telescope in a modified B747SP aircraft
  - Optical-mm performance
  - Obscured IR (30-300 microns) most important
- Joint Program between the US (80%) and Germany (20%)
- NASA/DLR, USRA/DSI partners
- First Early Science Flight Dec 1, 2010
- Designed for 20 year lifetime

- SOFIA is the successor of the Kuiper Airborne Obs. (KAO)

NASA's Kuiper Airborne Observatory, *(KAO) C-141 with a 36-inch telescope onboard, based at NASA-Ames near San Francisco, flew from 1975 - 1996*

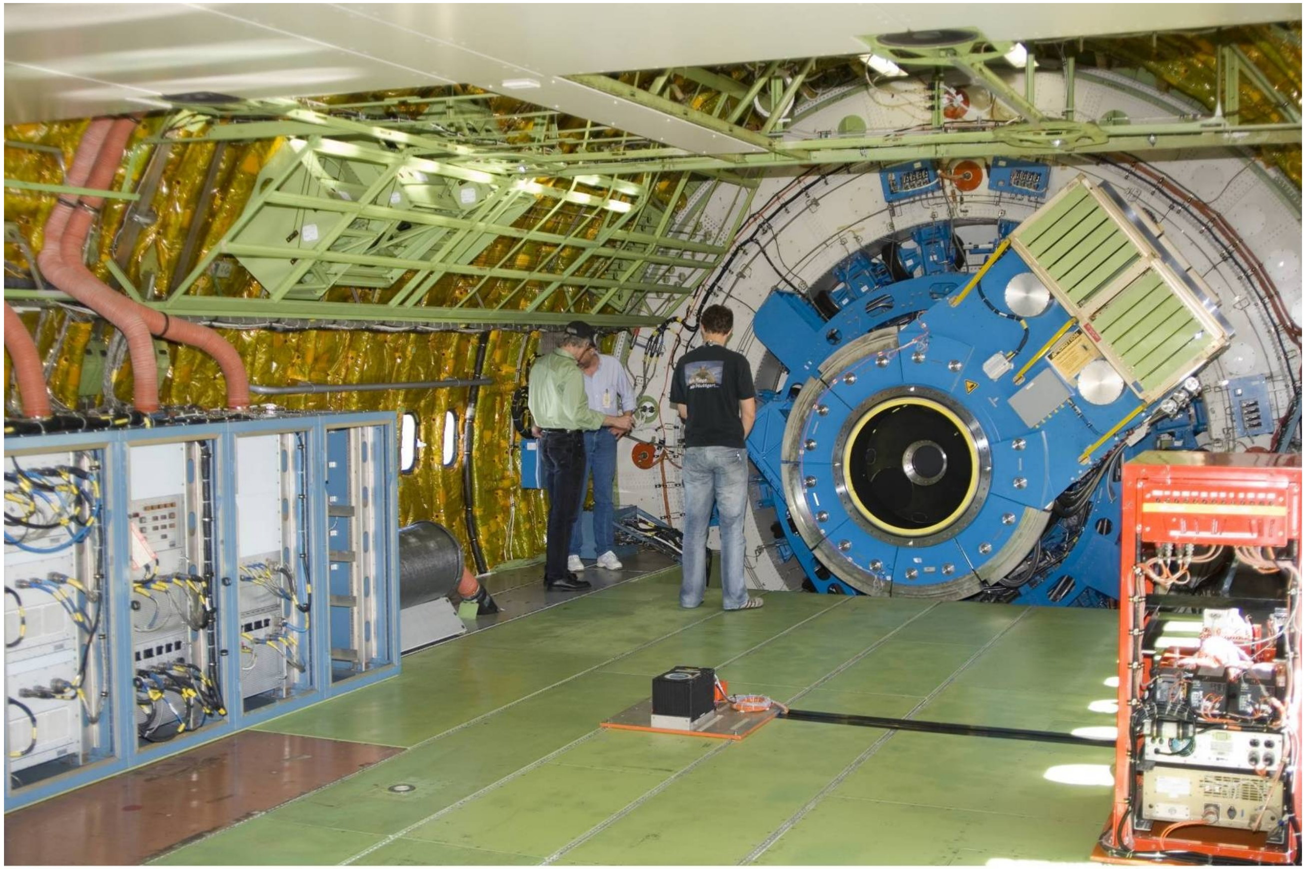
- High-flying aircraft -- above 40,000 ft -- can observe most of the infrared universe
- Airborne infrared telescopes can be more versatile -- and much less expensive -- than space infrared telescopes

Overview of SOFIA (Cont)

- Operating altitude
  - 39,000 to 45,000 feet (12 to 14 km)
  - Above > 99% of obscuring water vapor
- World Wide Deployments
- Ramp up to ~1000 science hours per year (12% of the time)
- Build on Kuiper Airborne Observatory (KAO) heritage with improvements (more and longer flights, facility instruments, science support)
- Science flights to originate from Palmdale, CA ….
  aircraft operation by NASA Dryden Research Center (DFRC)
- Science Center is located at NASA Ames Research Center in Mountain View, CA

Inside the Aircraft

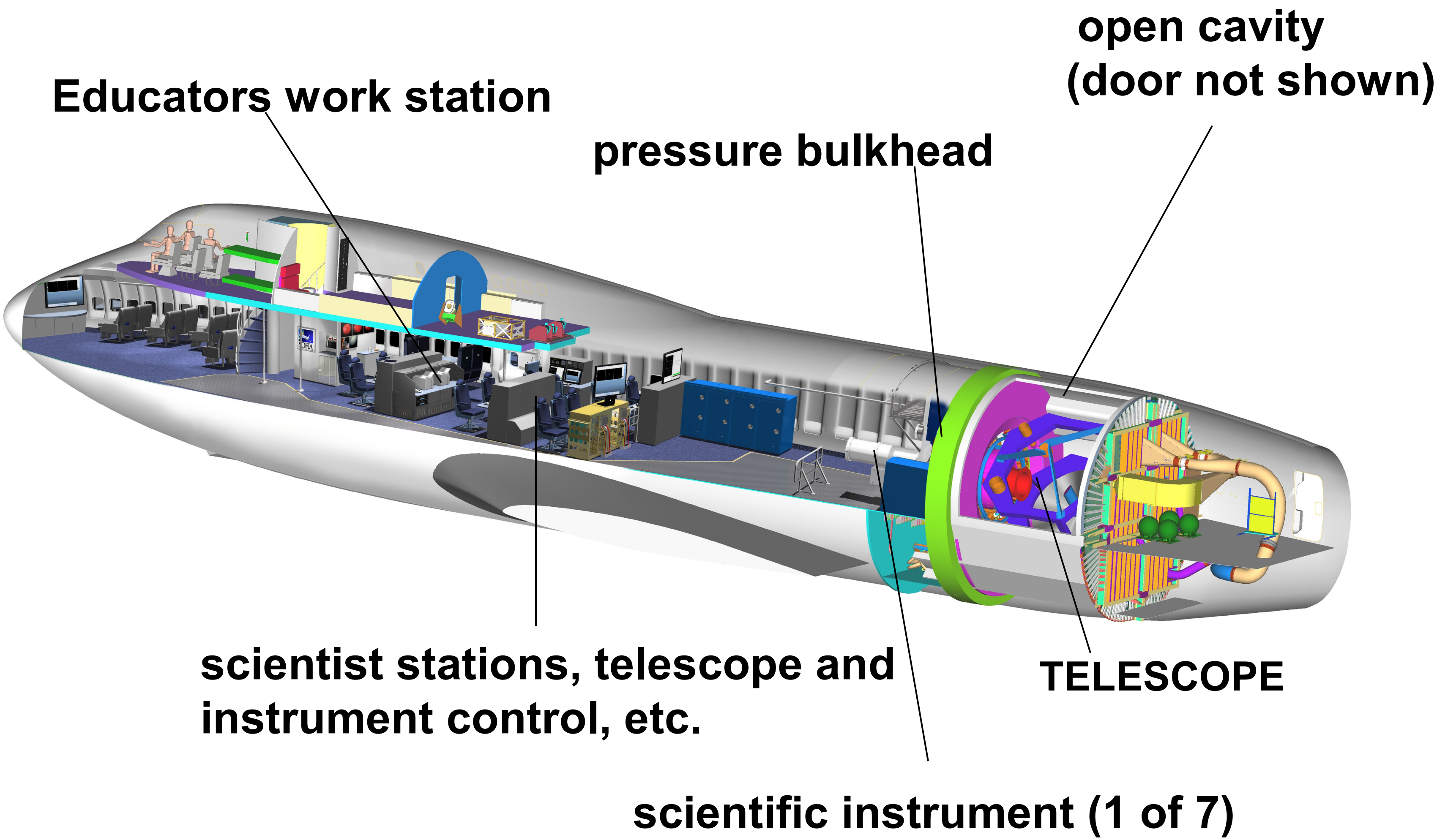
Main Deck, Looking Aft at Instrument Interface



NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED07-0078-033 Date: April 25, 2007 Photo By: Tony Landis

Technicians check out the mounting structure of the infrared telescope installed in NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA).

SOFIA — The Observatory



Why SOFIA?

- Infrared transmission in the Stratosphere very good:
- >80% from 1 to 1000 microns

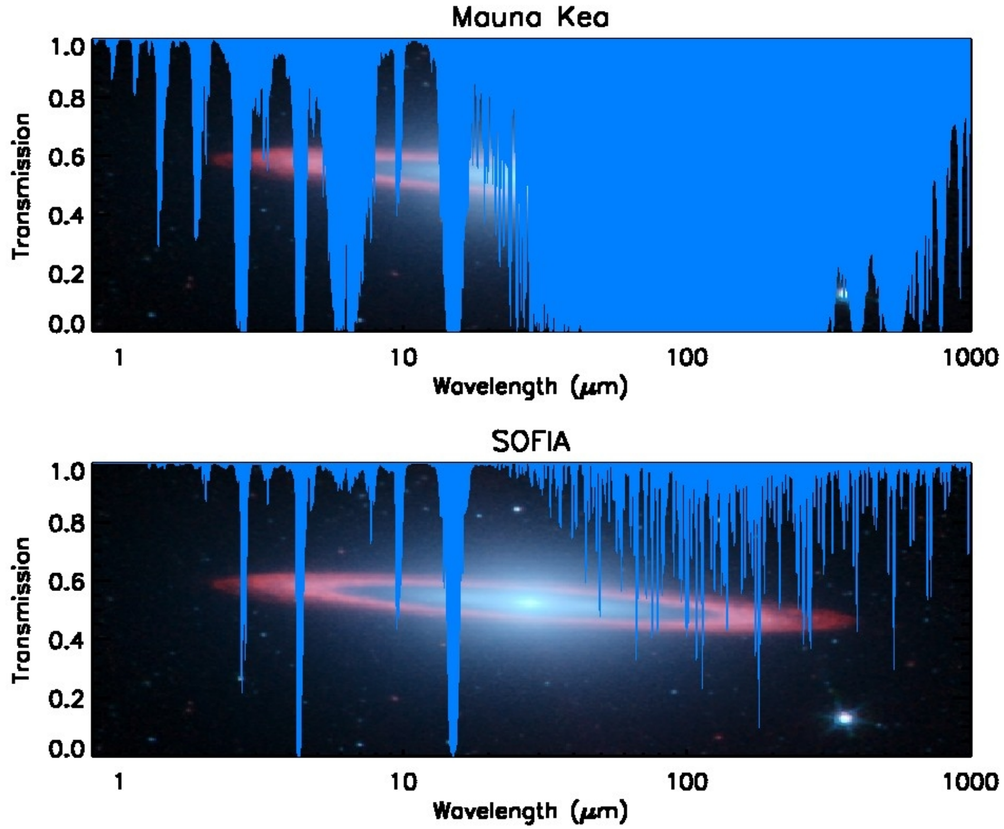
- Instrumentation: wide complement, rapidly interchangeable, state-of-the art

- Mobility: anywhere, anytime

- Long lifetime

- Outstanding platform to train future instrumentalists

- Near Space Observatory that comes home after every flight

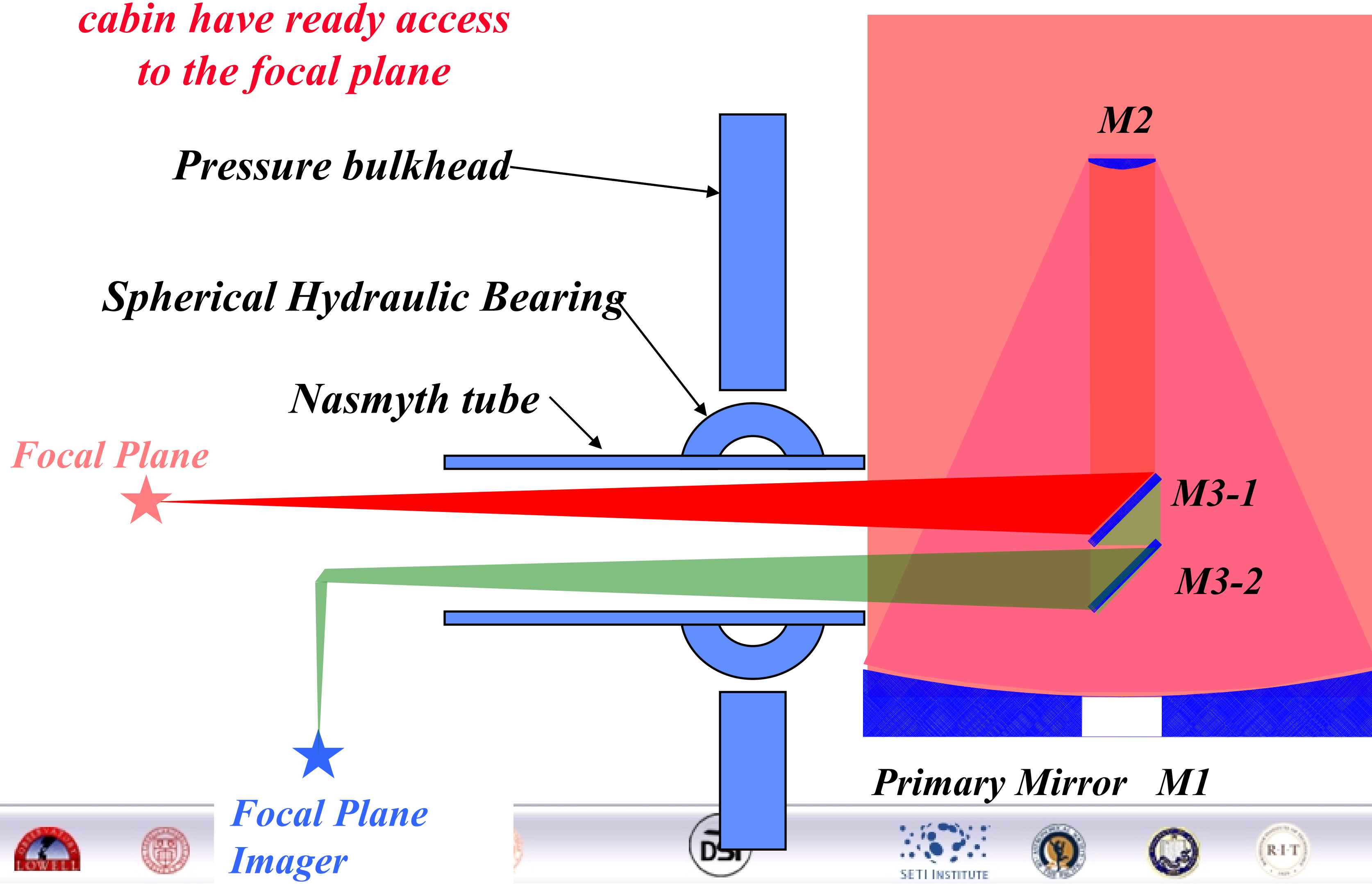


The SOFIA Observatory

SOFIA Open Door Tests 2009

Nasmyth: Optical Layout

Observers in pressurized cabin have ready access to the focal plane

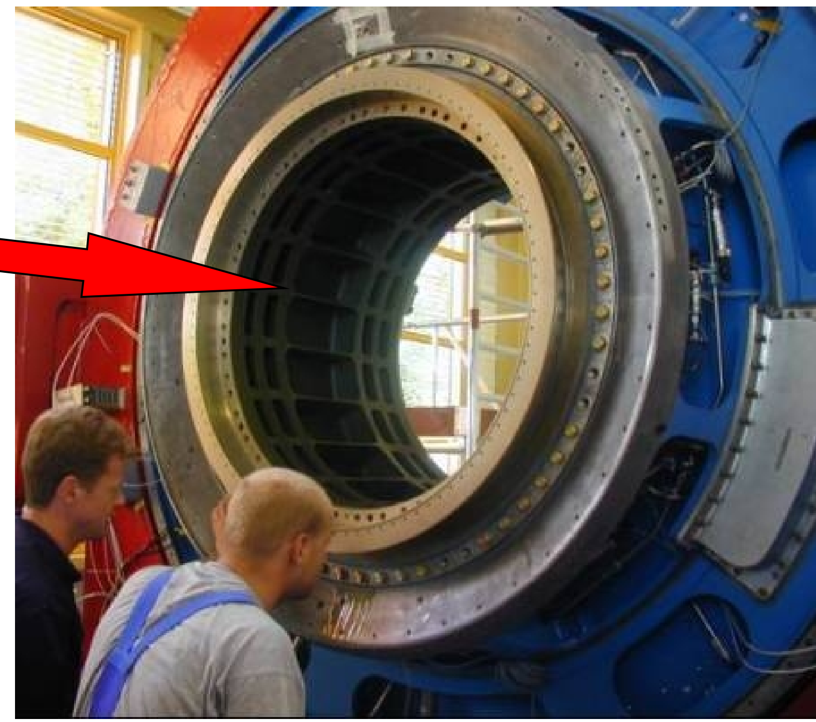


Rotation Isolation Subsystem

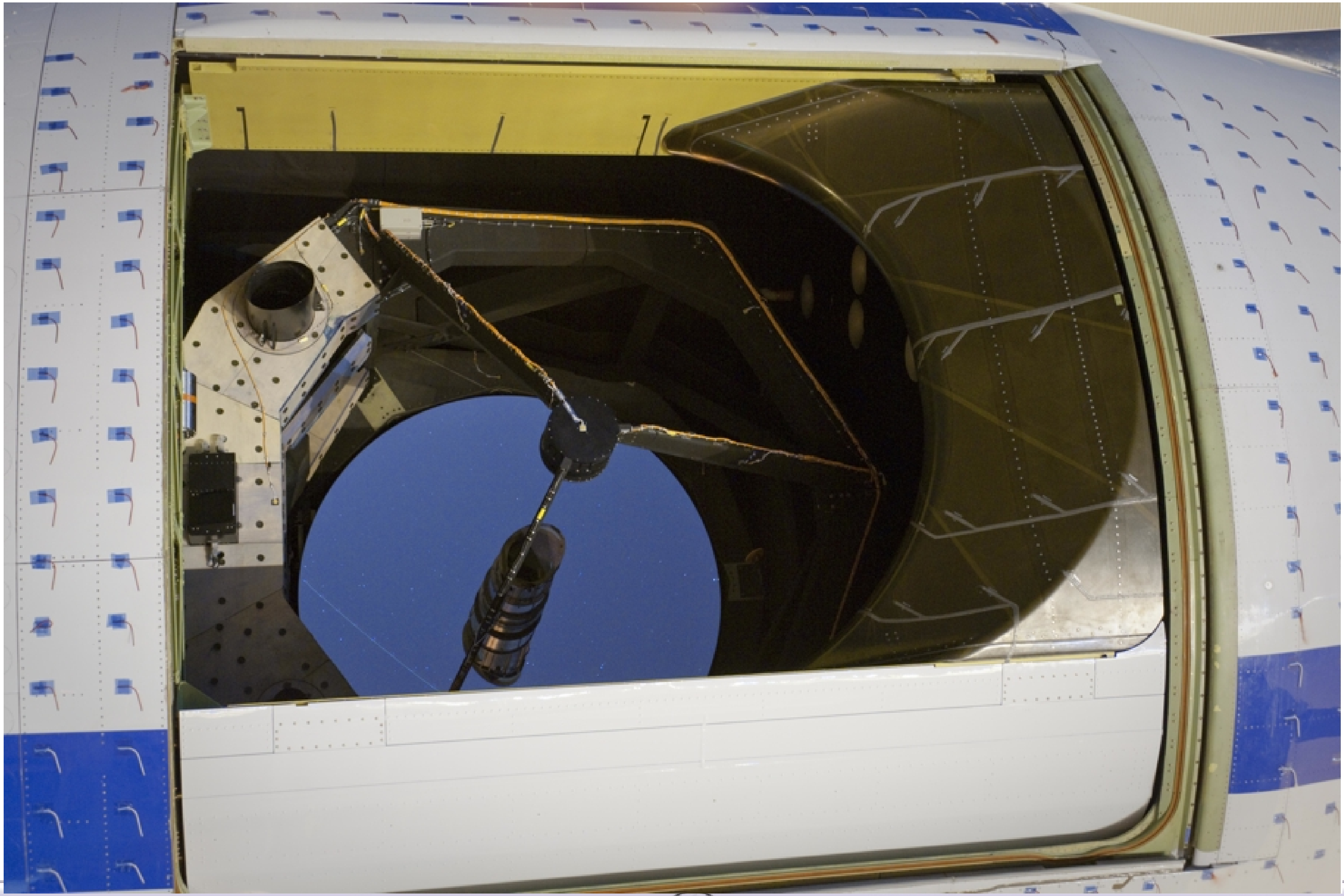
Spherical Bearing

The Bearing Sphere on the Nasmyth Tube

"First Oil"



Coated Mirror and Aperture on SOFIA



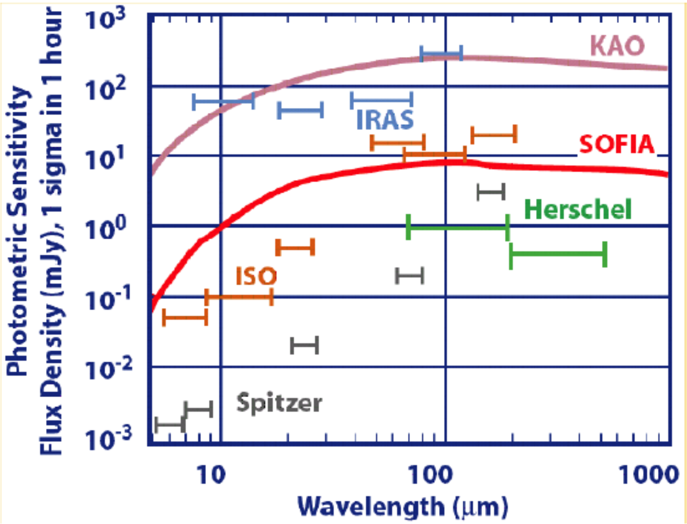
Uncoated Primary

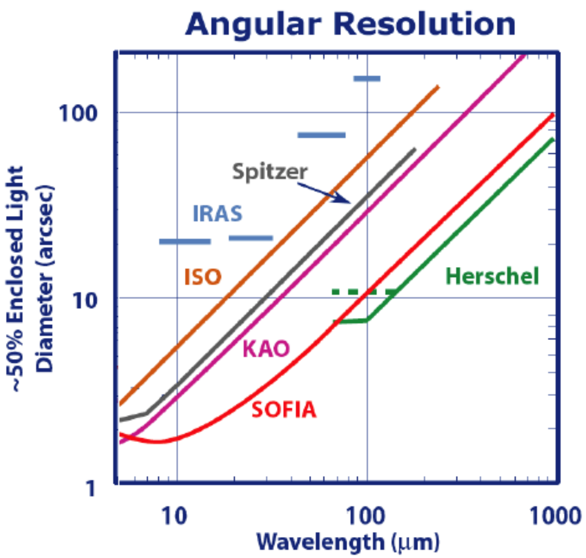
SCIENCE CAPABILITIES and INSTRUMENTS

Science Capabilities

- Because of large aperture and better detectors, sensitivity for imaging and spectroscopy are similar to that of ISO
- 8x8 arcmin field-of-view allows use of very large detector arrays
- Image size is diffraction-limited beyond 15-25 μm, making it 3 times sharper than Spitzer at these infrared wavelengths

Photometric Sensitivity and Angular resolution





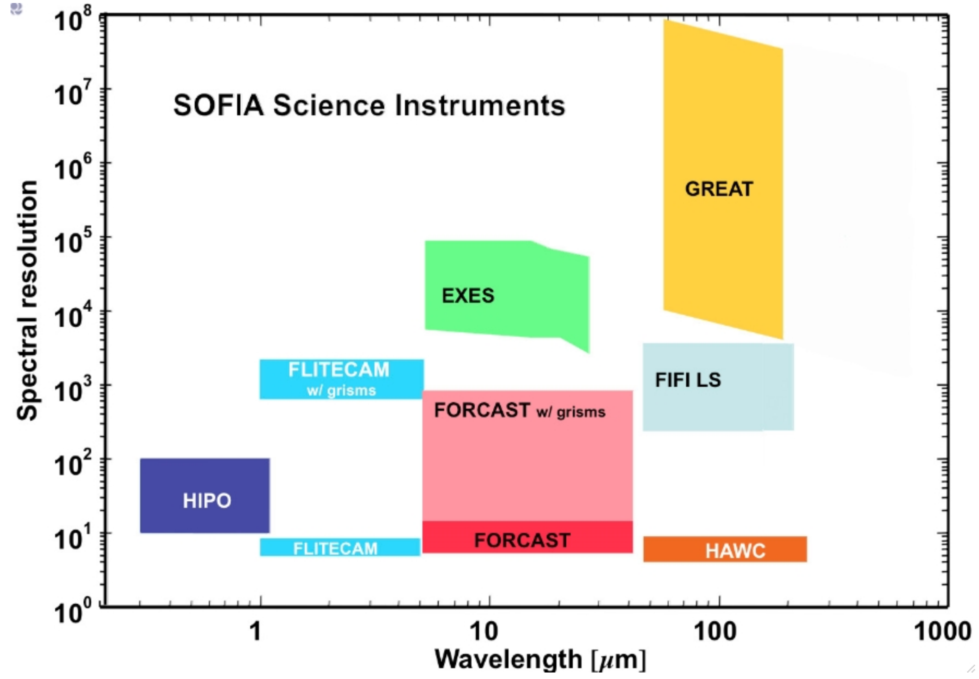
SOFIA is as sensitive as ISO

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

SOFIA's Instrument Complement

As an airborne mission, SOFIA supports a unique, expandable instrument suite

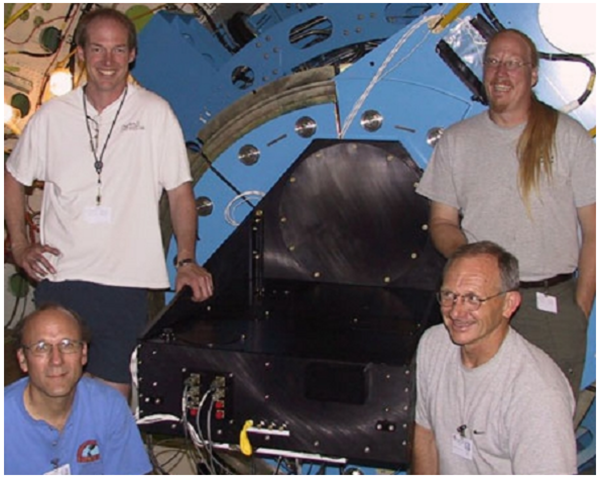
- SOFIA covers the full IR range with imagers and low- to high-resolution spectrographs
- 4 instruments at initial operations; and 7 instruments at full operations.
- SOFIA will take full advantage of improvements in instrument technology. There will be one new instrument or major upgrade each year.
- Will support both facility instruments and PI class instruments



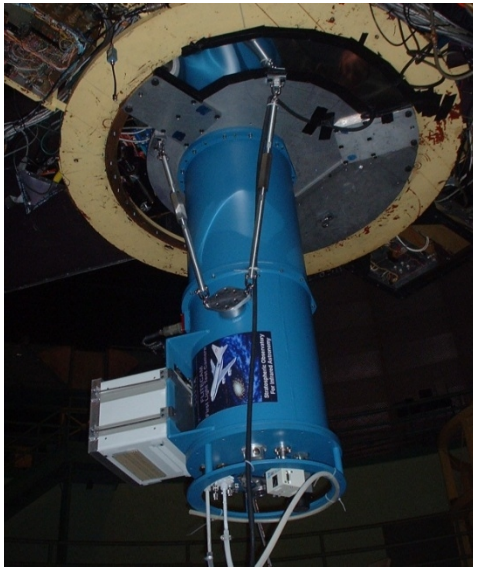
SOFIA instrument suite

- FORCAST
- GREAT
- HIPO
- FLITECAM
- FIFI-LS
- HAWC
- EXES

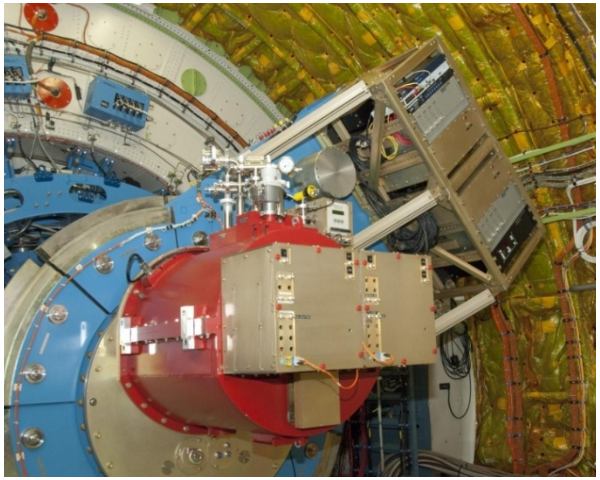
Four Completed 1st Generation Instruments



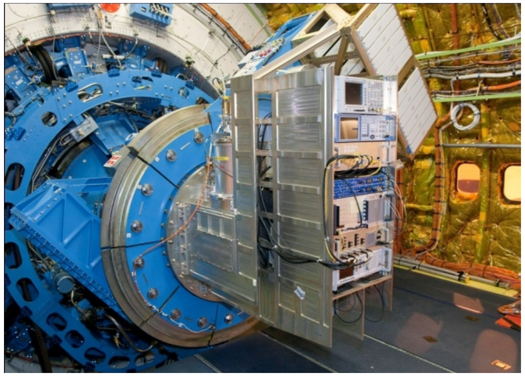
HIPO
High Speed Photometer
(on SOFIA)



FLITECAM
Near IR Camera
(at Lick observatory)



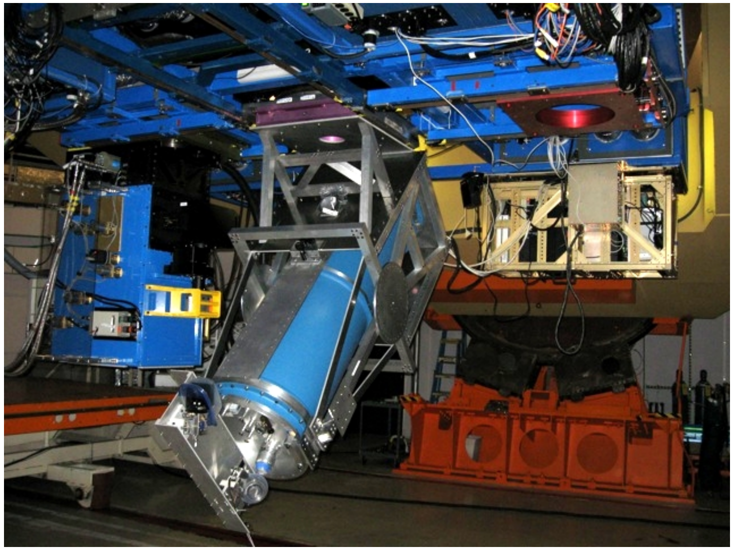
FORCAST
Mid-IR Camera
(on SOFIA)



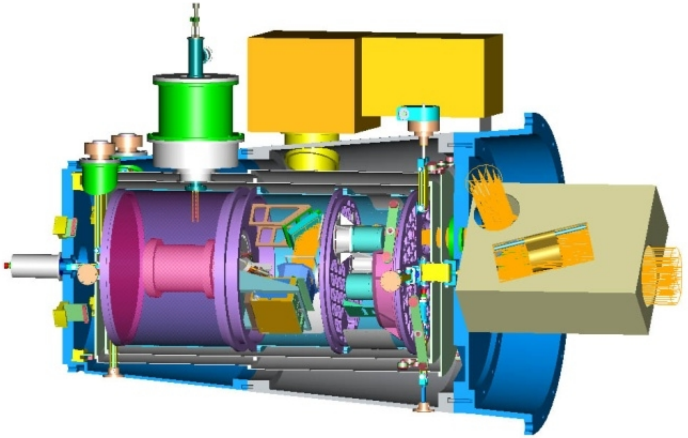
GREAT
Heterodyne spectrometer

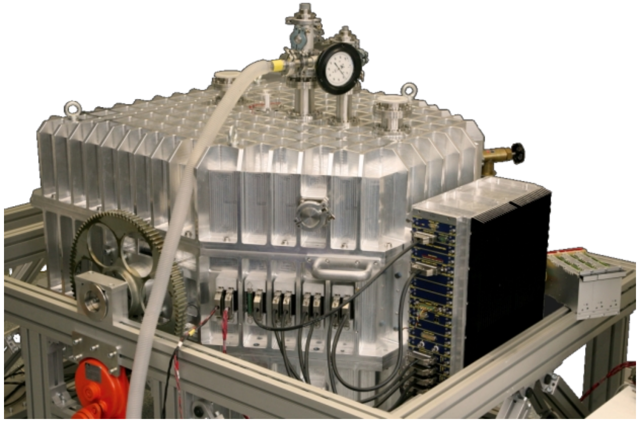
(on SOFIA)

Instruments in development



HAWC
Bolometer Camera





FIFI LS
Integral Field Spectrometer

EXES
Mid- IR Spectrometer

FORCAST: Mid-IR Imager

PI: T. Herter (Cornell Univ.)
herter@astrosun.tn.cornell.edu

Detectors: Dual channel
256 x 256 arrays;
5 – 25 μ m (Si:As)
20 – 40 μ m (Si:Sb)
Field of View: 3.2’ x 3.2’

Science: Thermal and narrow band imaging

Targets: Circumstellar disks, Galactic Center, Galactic and extragalactic star formation

NB: Diffraction Limited > 15 microns;
Grism upgrade funded (Ennico et al.)

GREAT: Heterodyne Spectrometer

PI: R. Guesten, Max-Planck Institut, Bonn

guesten@mpifr-bonn.mpg.de

Detector: dual channel mixer (HEB);
60 – 200 μm (1.5 – 5 THz)

Field of View: single element

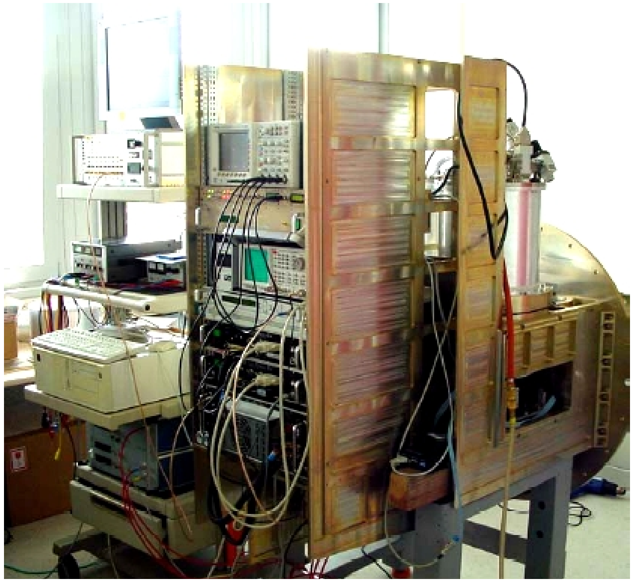
R= 10^6 -> 10^8

Science: Spectroscopy of CII (158 μm), and HD (112 μ m)

Targets: Galactic and extragalactic ISM, circumstellar shells

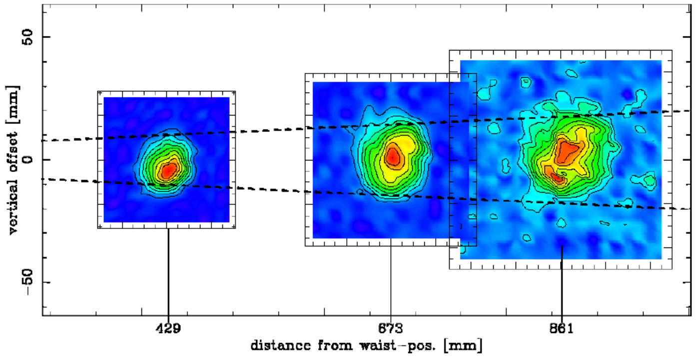
NB: T_S *~ 1500 K at 158 μm*

High frequency upgrade at 4.7 THz expected for OI (63 μm).



Theoretical beam-width @ focal plane: 2.55mm

Measured in x-direction : (2.2 ±0.2)mm
in y-direction : (2.5 ±0.2)mm



Successful lab demonstration of GREAT in Oct 2005

GREAT details

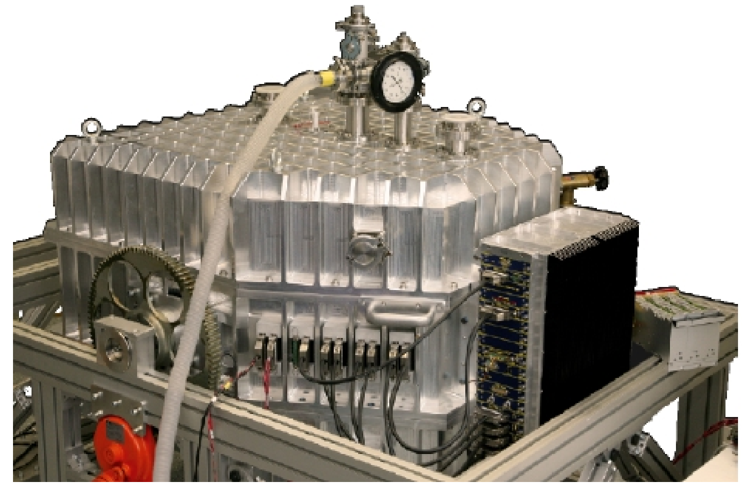
dual channel heterodyne spectrometer

L1 ab 1.25-1.50 THz: N+, CO, OD, H2O+, SH
L2 ab 1.81-1.91 THz: NH3, OH, CO 16-15, C+
M ab 2.5 THz, 2.7 THz: OH ground state, HD 1-0
H band 4.7 THz: [OI] 63 micron line (2013)

two out of 4 channels can be operated simultan.
Spectral resolution: sub km/s, IF bandwidth 1.2 GHz
beam=lambda/10 (16” for C+ 158 micron line)
upGREAT (funded): 2x7 pixel arrays

FIFI-LS: Far-IR Spectrometer

PI: A. Poglitsch, Max-Planck Institut, Garching
alpog@mpe.mpg.de → Krabbe@DSI



Detectors: Dual channel 16 x 25 arrays;
42 – 110 μ m (Ge:Ga)
120 - 210 μ m (Ge:Ga stressed)

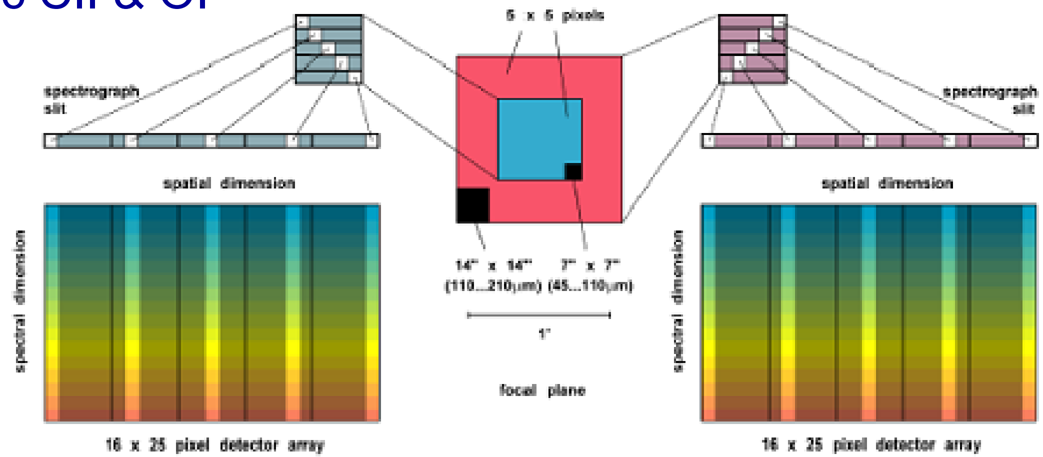
Field of View: 30” x 30” (blue), 60” x 60” (red)

R= 1500 - 6000

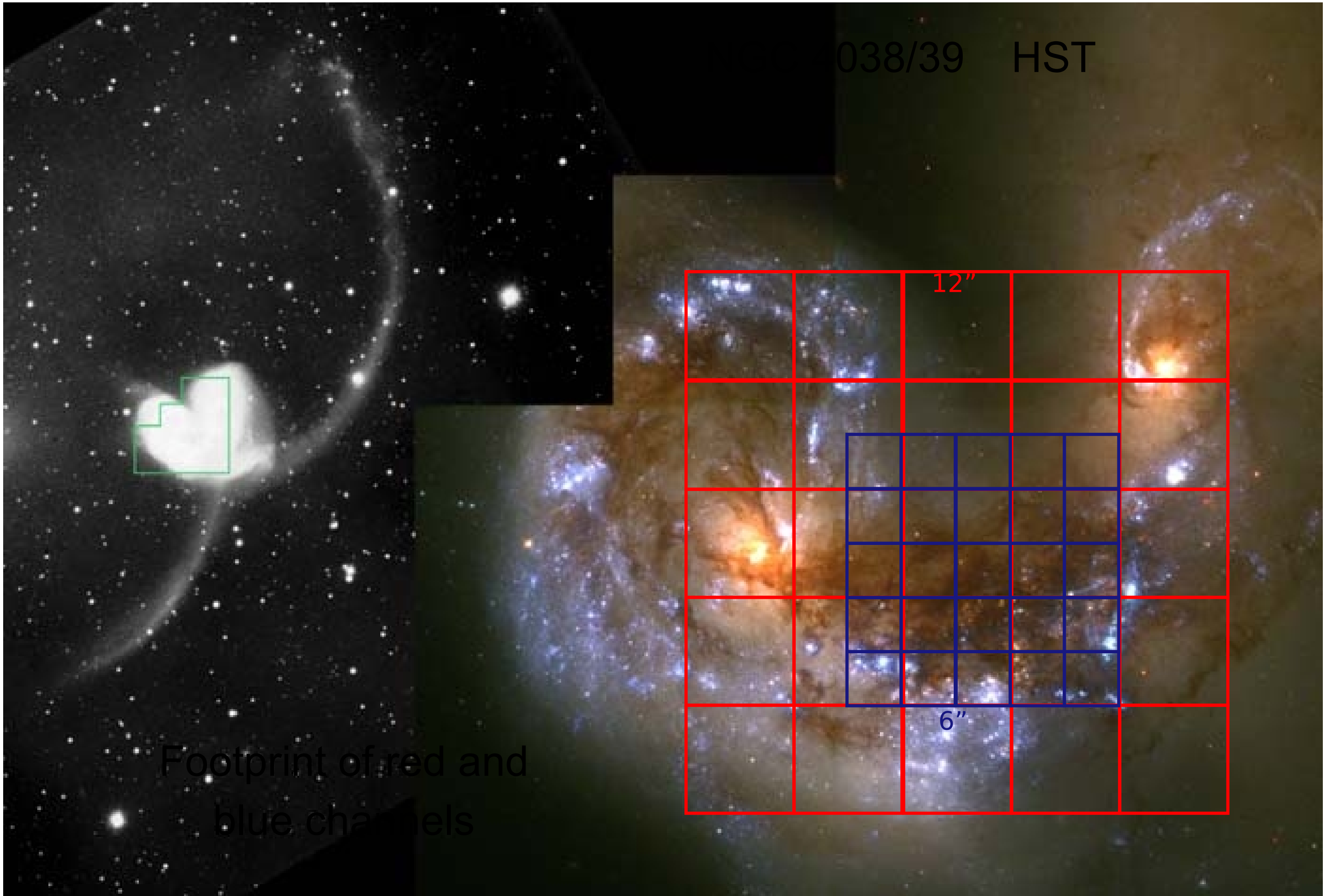
Science: Imaging of extragalactic CII & OI

Targets: Extragalactic imaging

NB: Imaging array is
5 x 5 pixels



On sky orientation of ‘blue’ and ‘red’ channels


038/39 HST
12”
6”
Footprint of red and
blue channels

FIRST SCIENCE WITH FORCAST, GREAT and HIPO on SOFIA

SOFIA First Light Flight

Science with FORCAST

- There was outstanding science from the FORCAST on three 10-hour science flights and an engineering flight in Nov/Dec.

- Observations included: several regions where massive stars are forming: Orion, W3, and S106 (6 to 37 microns)

- An Infrared Galaxy, M82 (6 to 37 microns)

- A comet, Hartley 2 (11, 20, 31, and 37 microns)

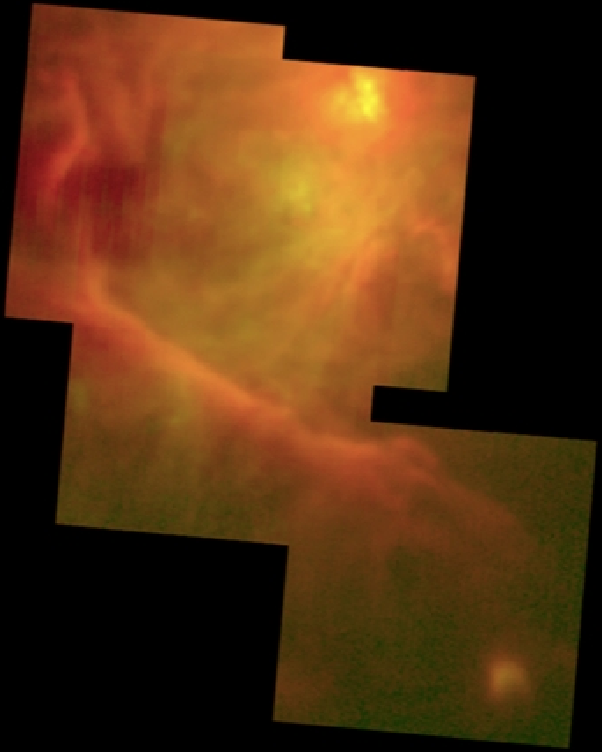
- Results were presented at the AAS 1st in Seattle and also a press release. At least eight papers are being worked on and expected to be published this year (aiming for Oct 1 deadline)

Looking at the Data

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)

KLEINMANN LOW INFRARED NEBULA

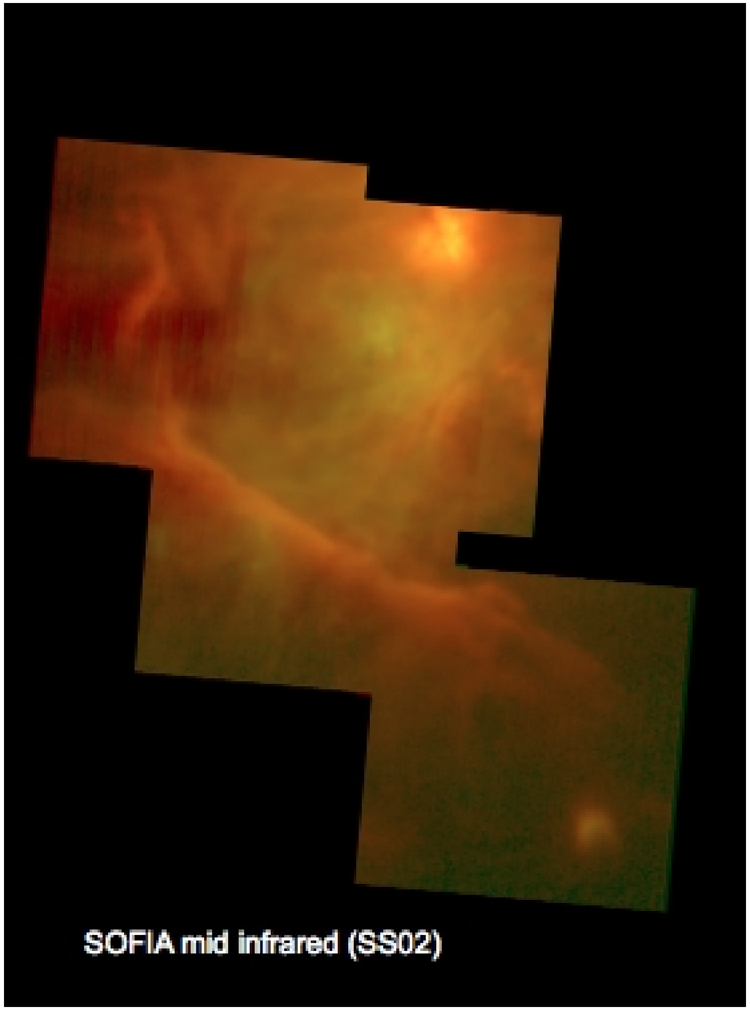
Orion Nebula at Mid IR with 3 arcsec Resolution

- Focus on the very bright and luminous BNKL region

- Total power output similar to the bright very young Trapezium stars L ~ 10(5) L(Sun)

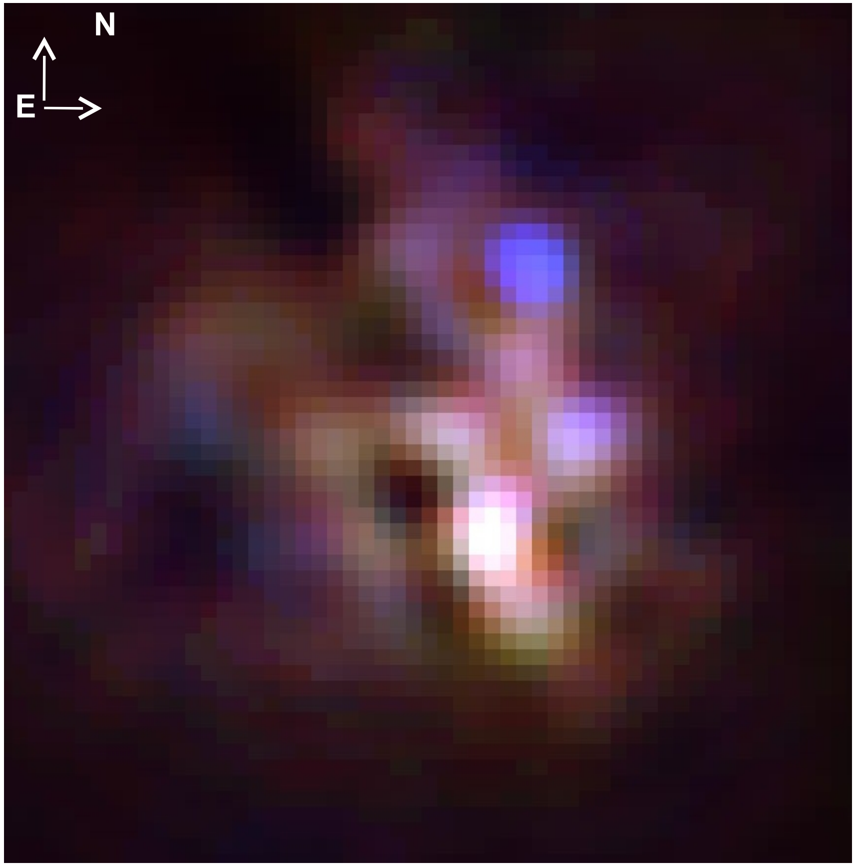
- But all of the radiation is in the IR. Also center of molecular activity and outflows

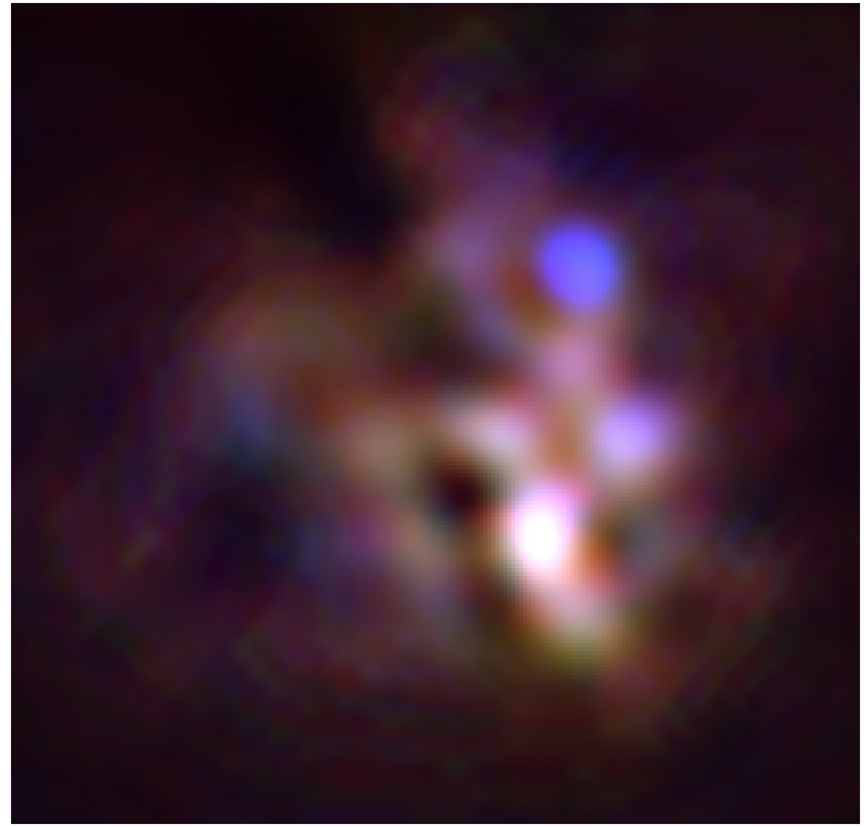
- Major questions:
  - What is causing all the radiation?
  - Still forming stars converting gravity to luminosity.
  - Very young stars just starting their nuclear burning.
  - An explosive type event 500 yrs ago.



3-color images of BNKL region

19um, 31um, 37 um





This is made with the two data pairs on the left of the last slide. The two 19um images were Used to bootstrap the registration of the 31 and 36um images. Array distortion could affect The relative appearance of the 37um image with respect to the 19/31um pair. The right image is with the natural pixel scale of FORCAST, the right is a reconstruction under the assumption that the data is Nyquist sampled.

What new do we find?

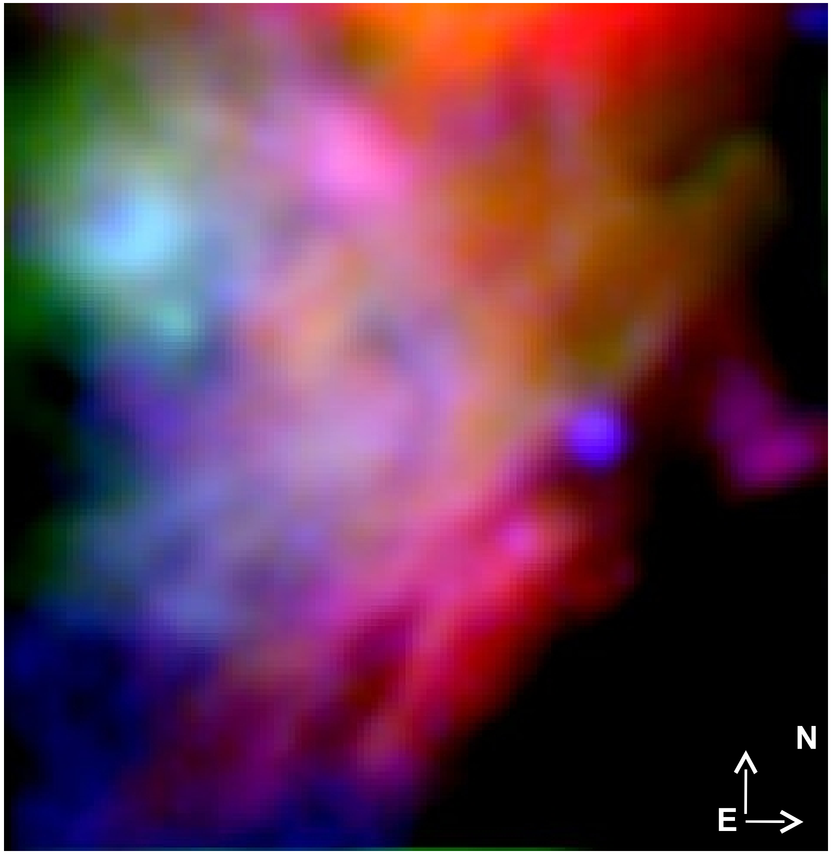
- BN is the hottest source and is not seen at 37 microns.
- The source IRc2 (bright at 12 microns) and radio source “I” are not seen at 37 microns.
- There is in fact a hole in the 37 micron emission at IRc2/“I”
- The brightest source at 37 microns is IRc4. Apparently heated from within (no color gradients). Also one of the coldest and most luminous sources (T~100K).
- Need more data. Results from Herschel or HAWC on SOFIA. Also spectra needed → EXES and ALMA obs.

TRAPEZIUM REGION AND A NEW SOURCE ?

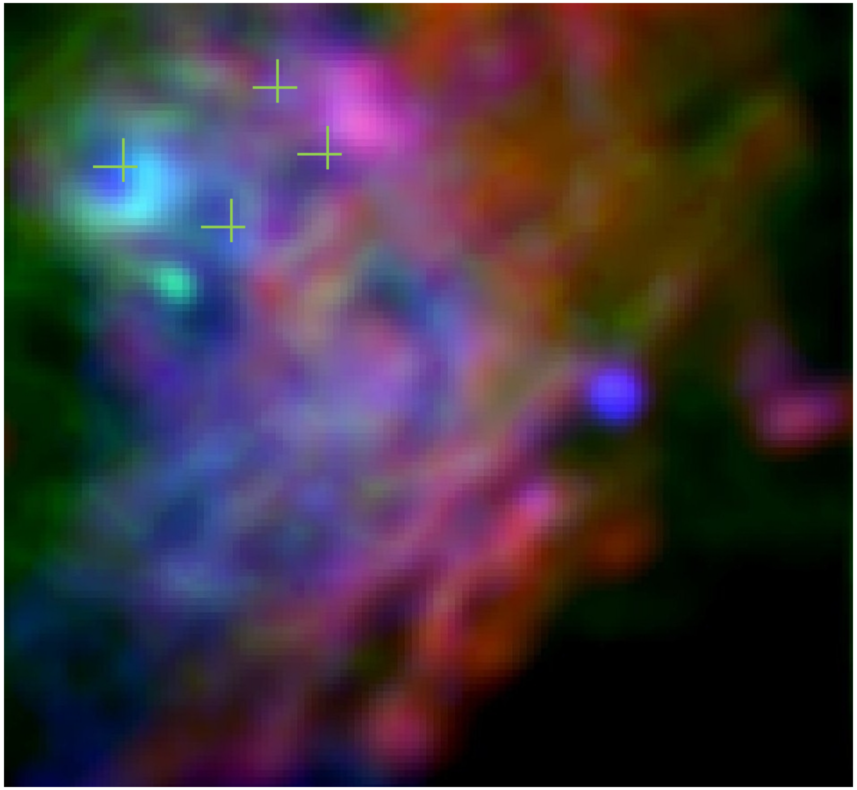
3-color images of Trapezium region

7um, 19um, 37 um

Natural Resolution



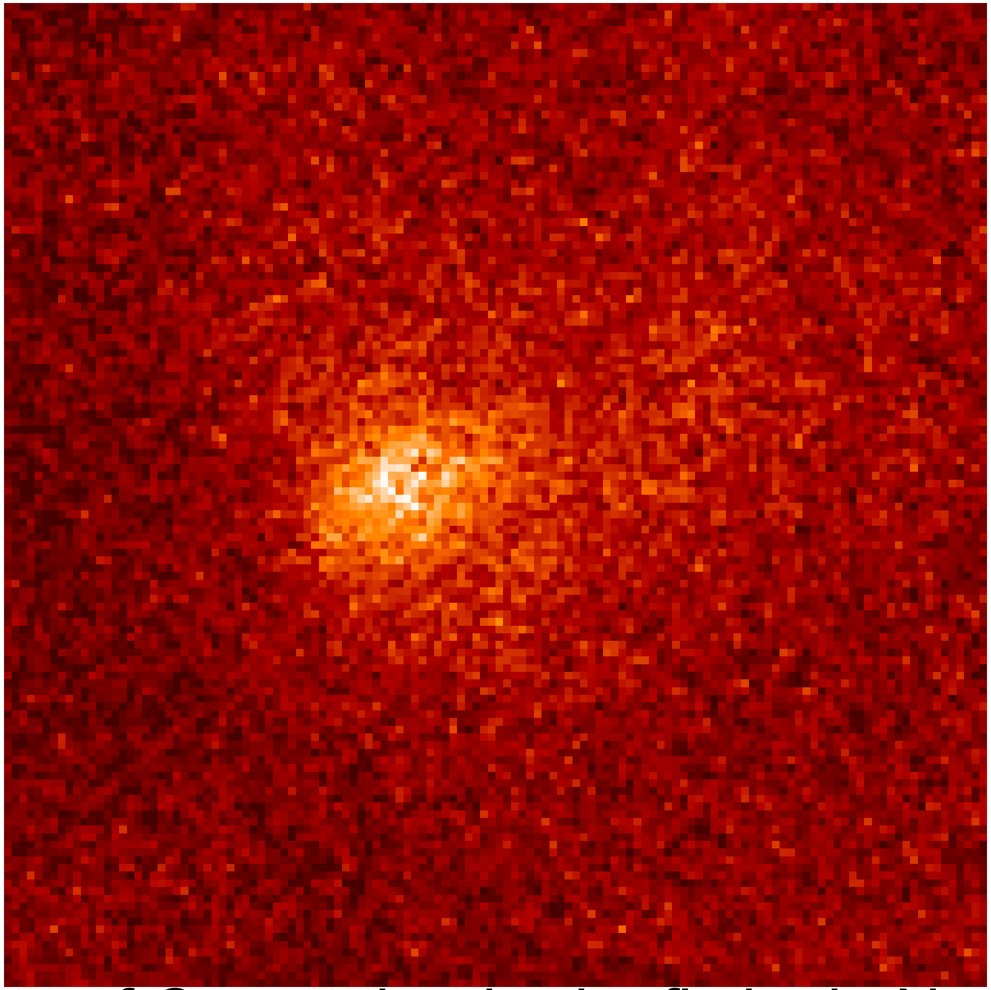
DMRM Deconvolution



We have two data pairs with 7/37um and 19/37um taken simultaneously with the dichroic so their ***relative*** source locations are well-registered. 37um image was used to bootstrap the offsets between 7 and 19um, but are subject to some changes when new distortion algorithm is finished. On the right, only the 19 and 37um images are deconvolved.
A new source is seen just west of the western-most trapezium star.

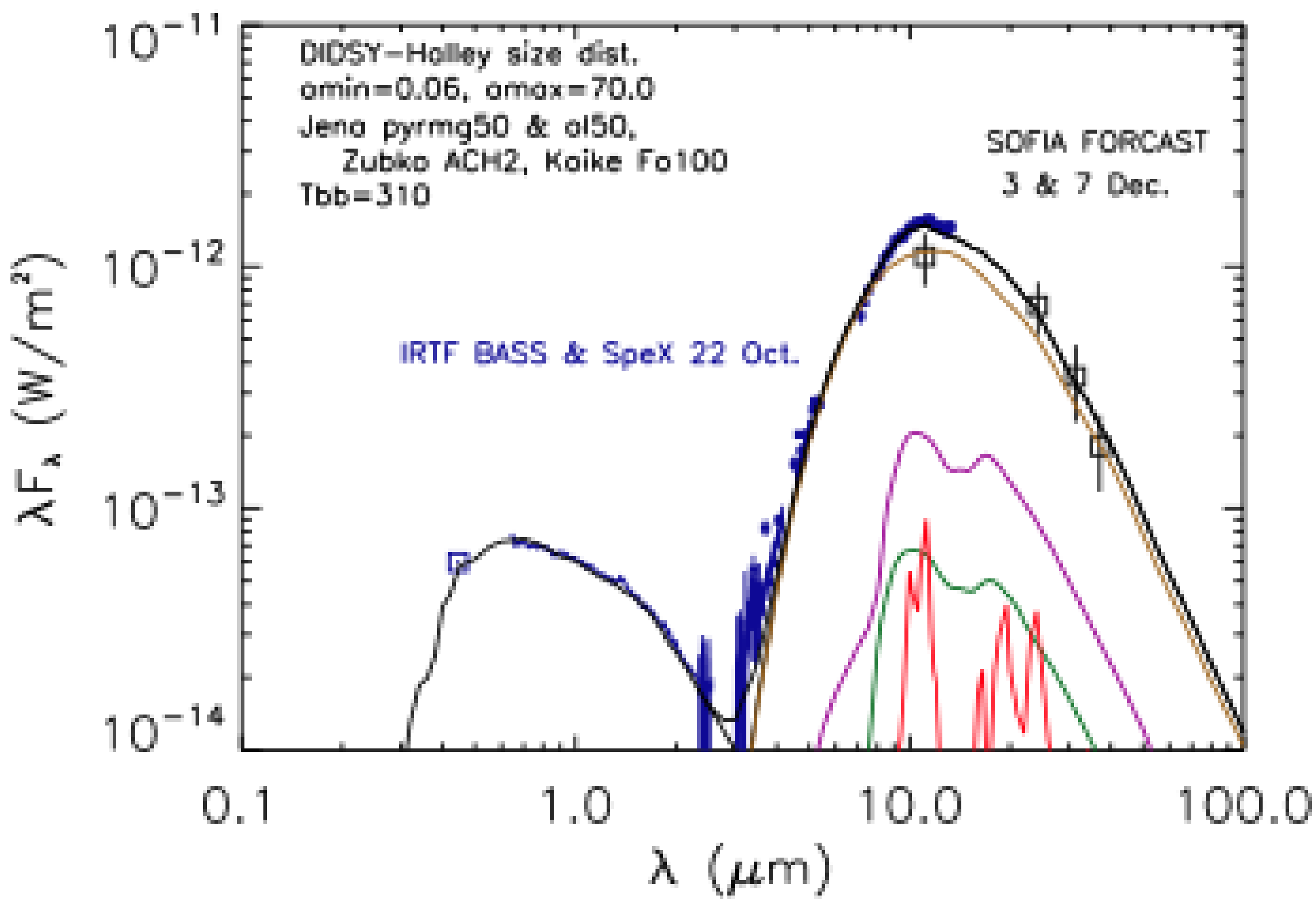
Comet Hartley 2

31.4 microns



- 31 and 37 Micron data of Comet that had a fly by in Nov.
- First Astro Results Publication of SOFIA 20 Jun ApJ2011

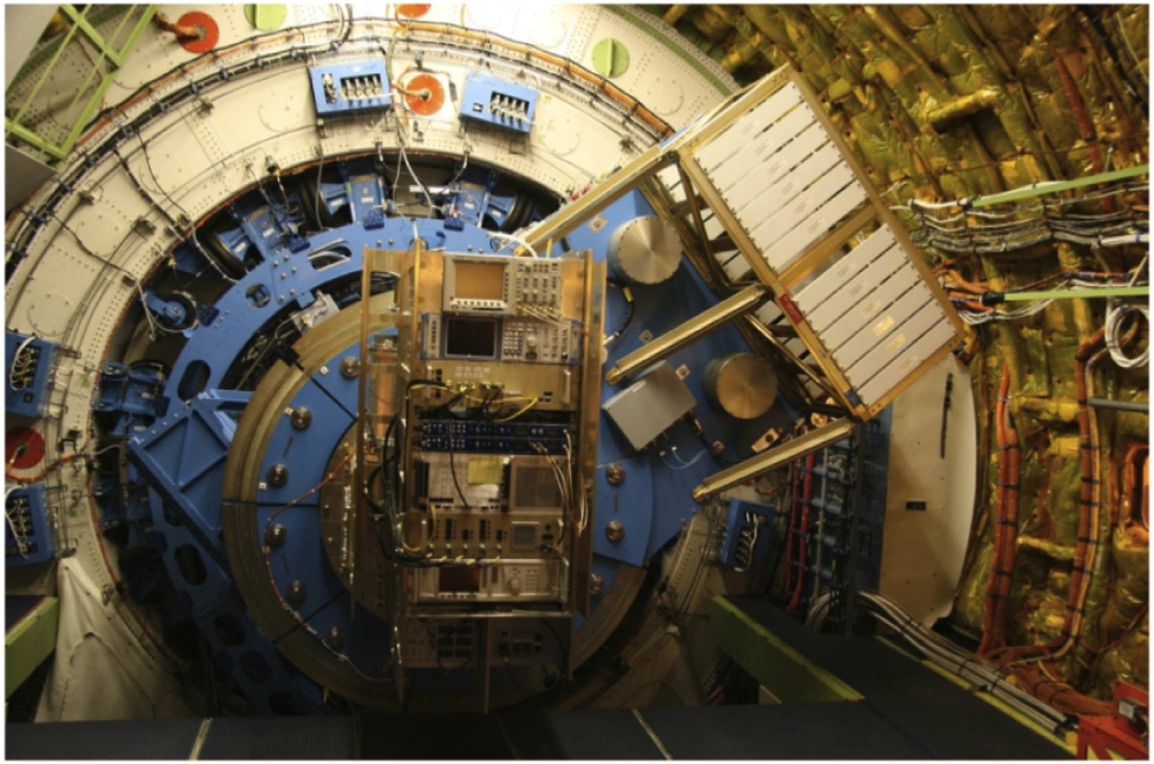
Energy Distribution of Hartley 2 (Meech etal)



FIRST SCIENCE WITH GREAT on SOFIA

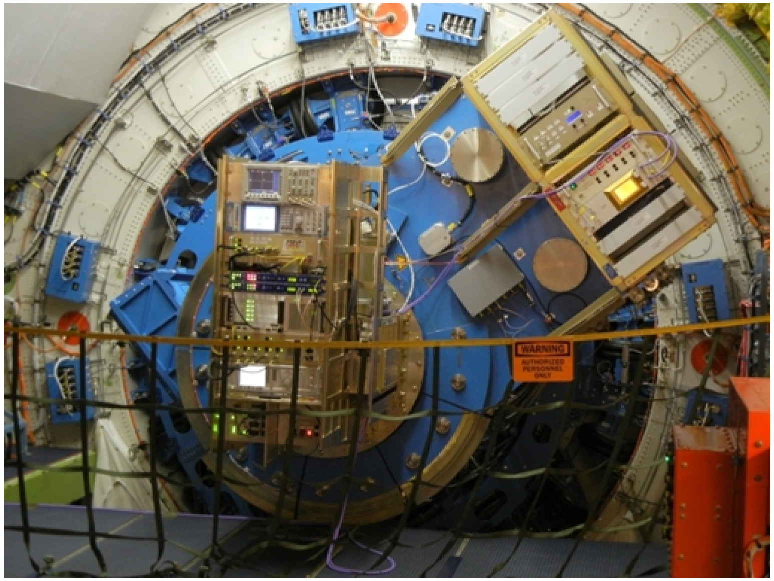
German REceiver for Astronomy at Terahertz frequencies

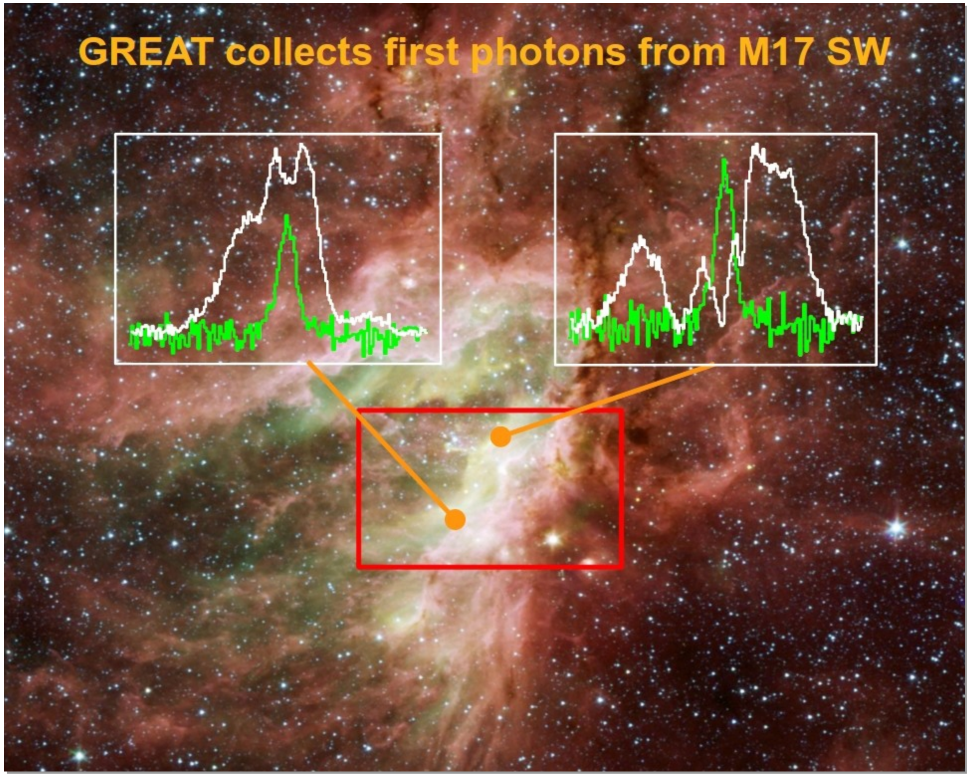
Channel	Frequencies [THz]	Astronomical lines of interest
low-frequency #1	1.25 – 1.50	[NII], CO(12-11), $^{(13)}$CO(13-12), HCN(17-16), H_2D^+
low-frequency #2	1.82 – 1.92	[CII], CO(16-15)
mid-frequency	2.4 – 2.7	HD, OH($^2\Pi_{3/2}$), CO(22-21), $^{(13)}$CO(23-22)
high-frequency	~ 4.7	[OI]



Our first science flight

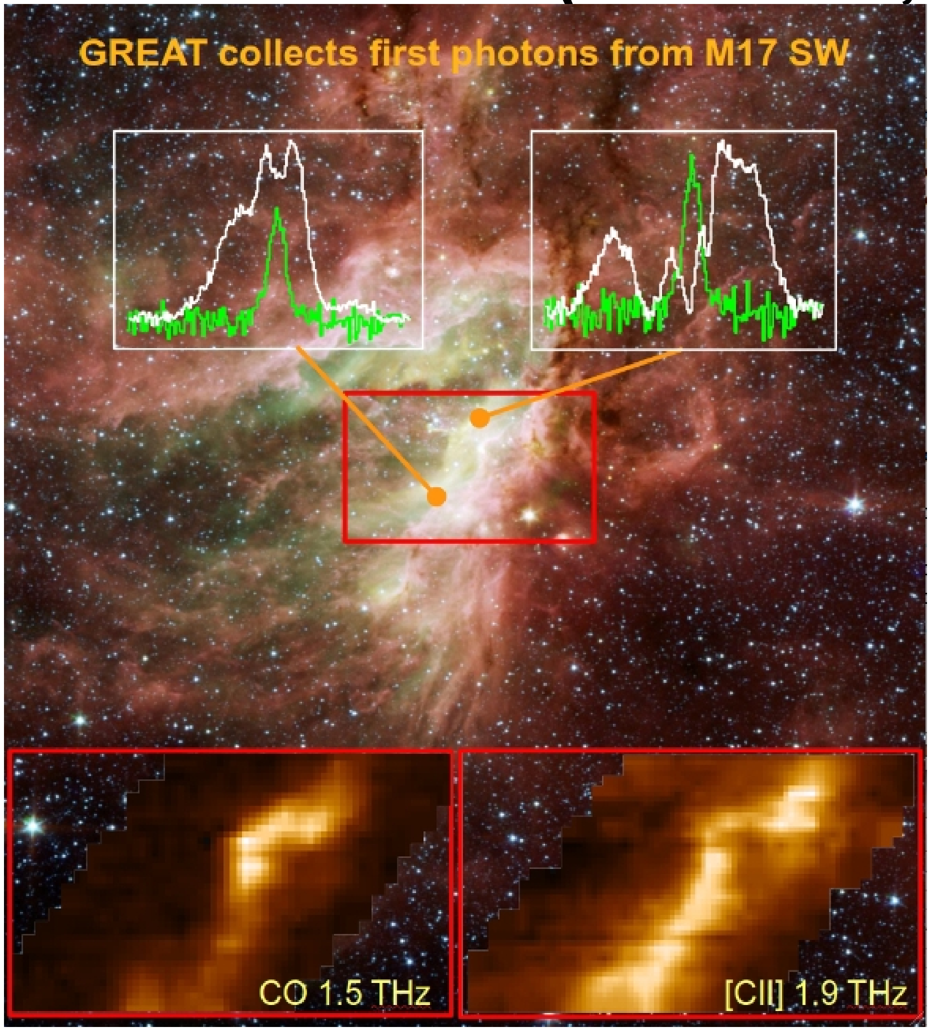
Press release 7 April 2011





GREAT observed the fine-structure line of ionized carbon iC+ at 1.9 THz and of warm carbon monoxid CO(13-12) at 1.5 THz towards M17SW, a molecular cloud near M17-cluster forming new massive stars (triggered).

First Science with GREAT (White CII, Green CO)



GREAT dips into cradle of star formation

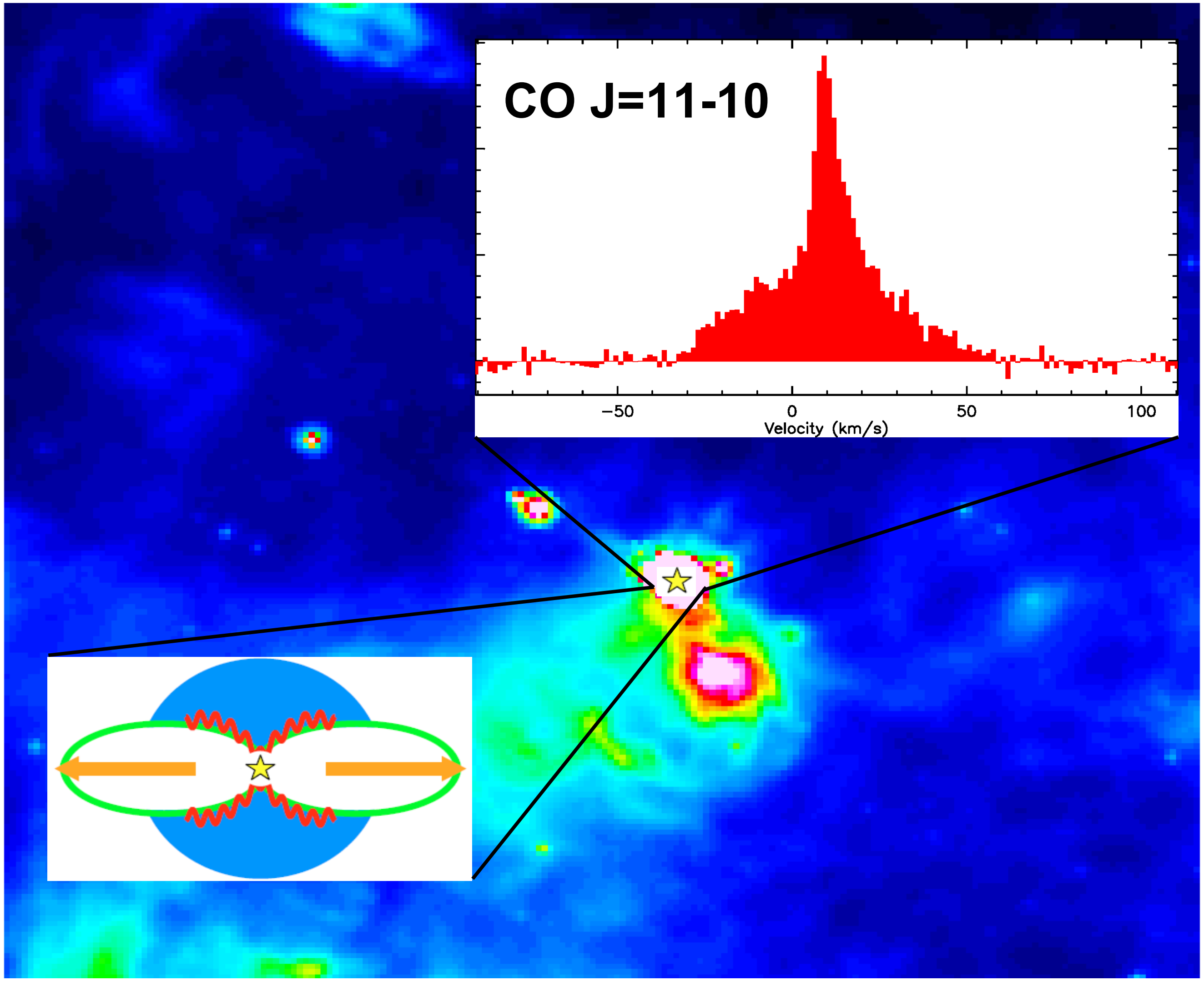


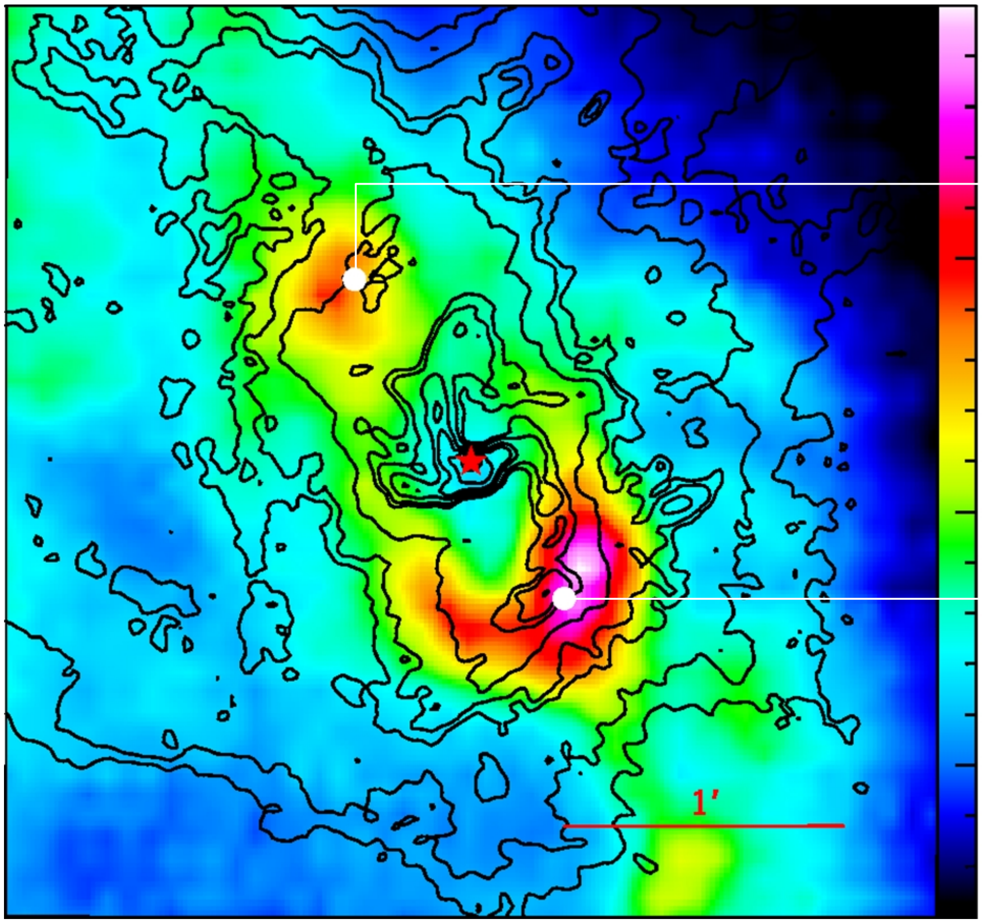
Image: Spitzer/GLIMPSE 8 μm

G5.89 :
a cluster of massive stars in the making

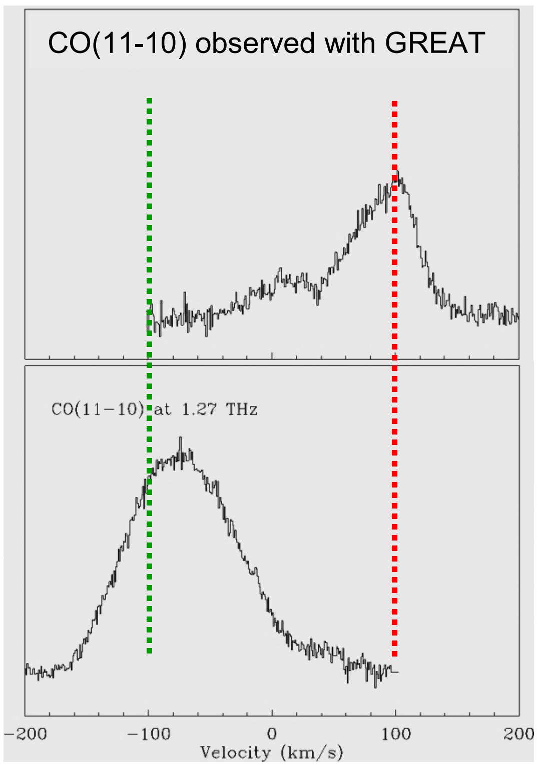
Cloud collapse is associated with energetic outflows that can be studied with GREAT/SOFIA

The circum-nuclear disk in the GC

a massive gas disk is rotating around & feeding the black hole in the Galactic center

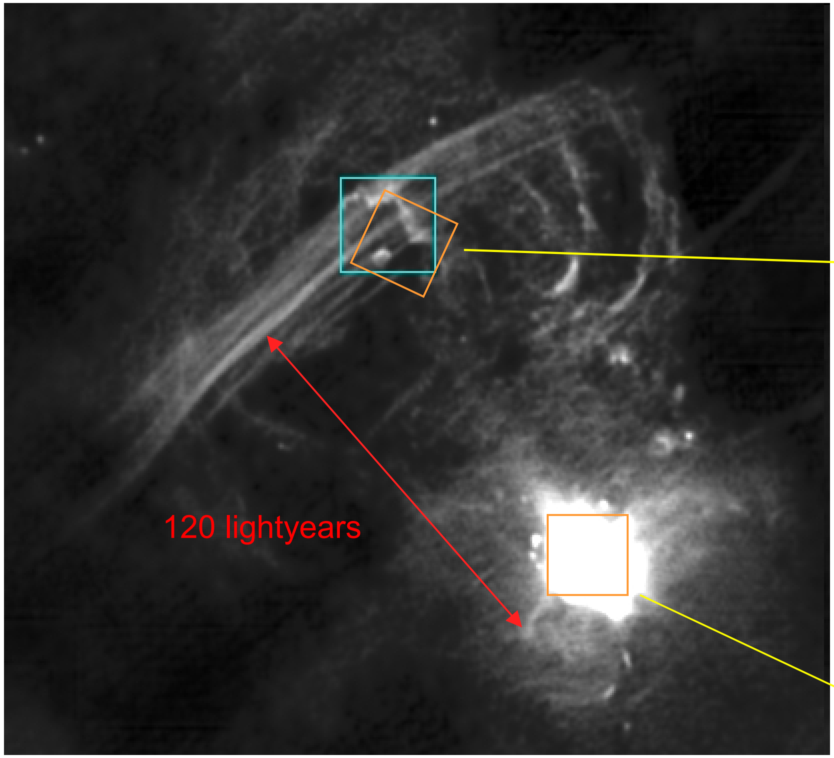


carbon monoxid (CO) in orbit around the central mass

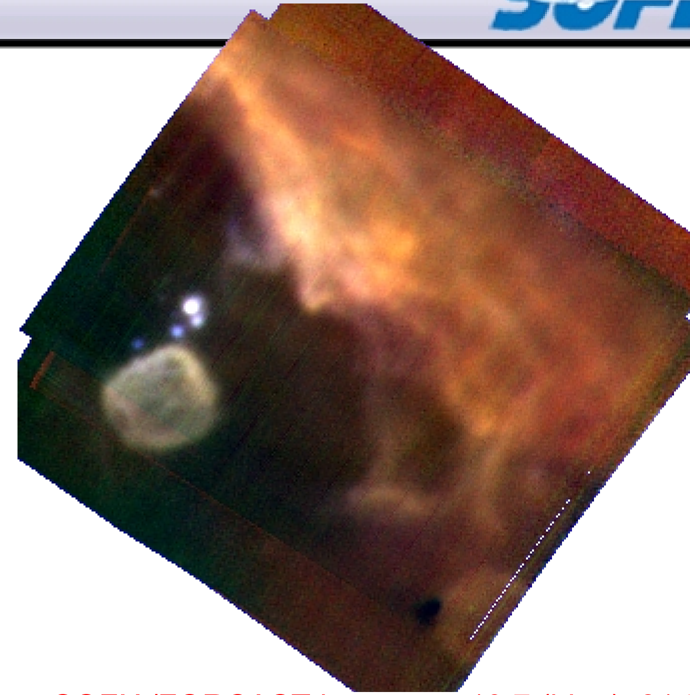


GREAT will help constraining the physical conditions of the gas reservoir, feeding the nucleus

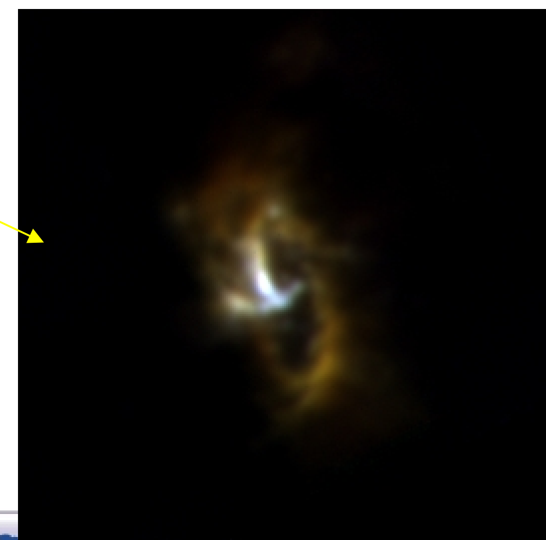
The Galactic Center



Radio image of Sgr A, pistol, sickle, filaments and arches

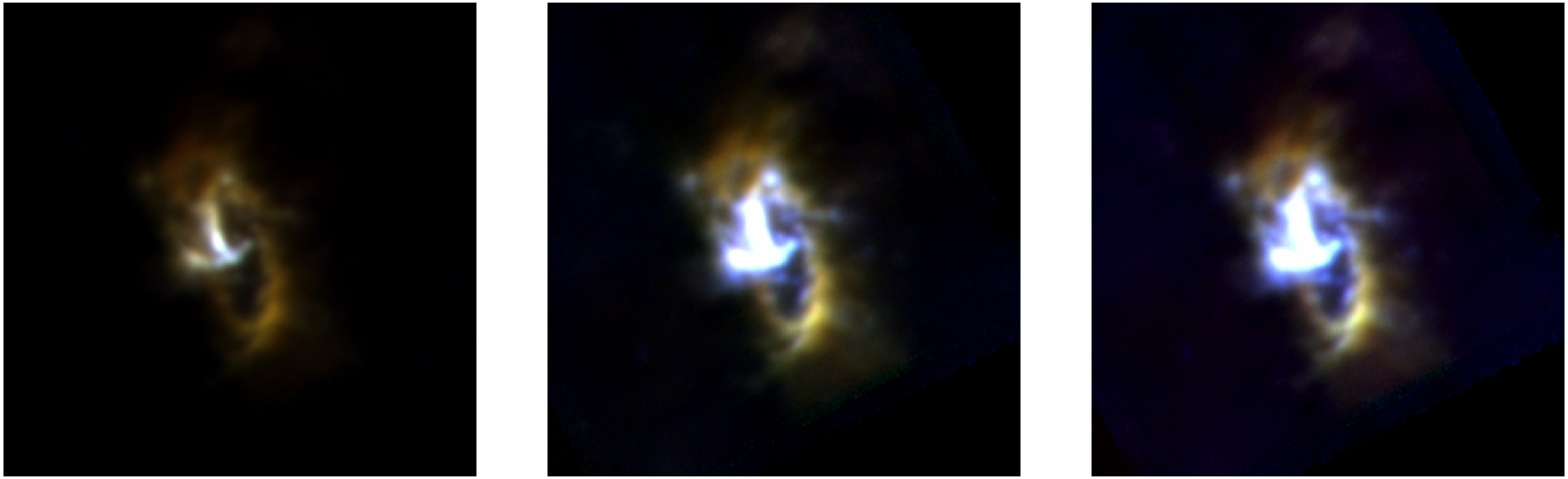


SOFIA/FORCAST images at 19.7 (blue), 31.5 (green), 37.1 (red) μ m



- At right are mulitcolor infrared images of two regions of the center of the Milky Way made with FORCAST SOFIA (courtesy of T. Herter)

Sgr A - CND



19.7 (blue), 31.5 (green), 37.1 (red)

- Multicolor image of circumnuclear disk (CND) in the Galactic Center (courtesy of T. Herter)
- Scaling varies from left (scaled to central brightness) to right (scaled to emphasize the ring)

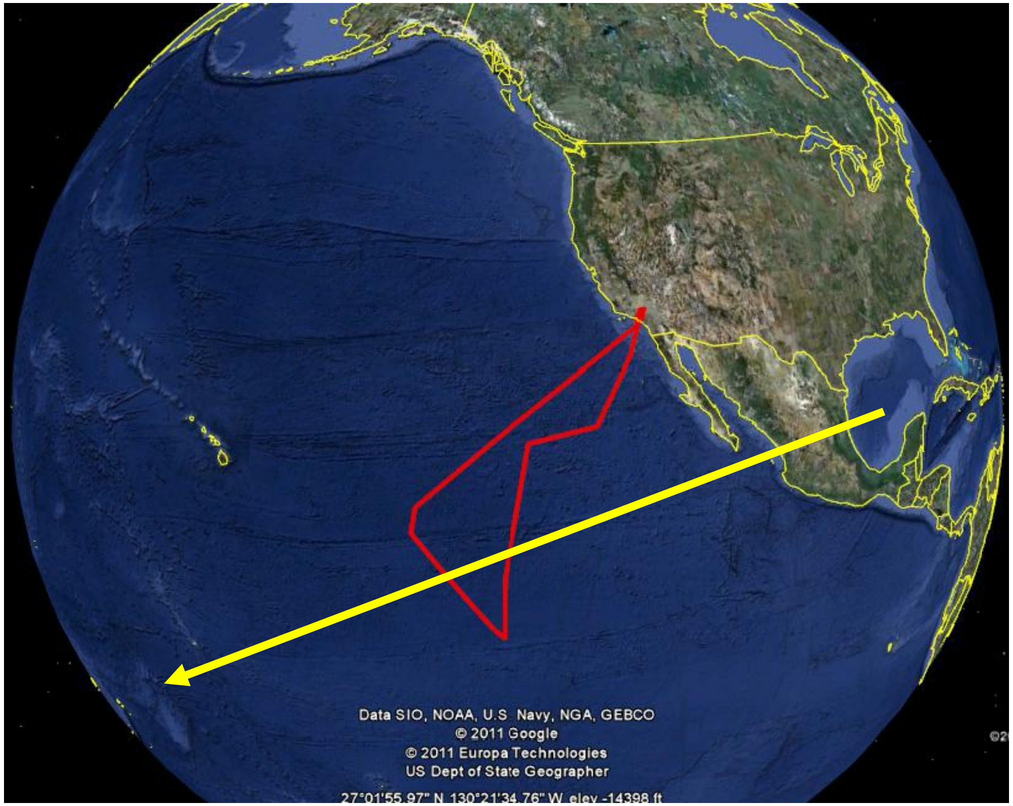
HIPO Occultation of Pluto

HIPO Occultation of Pluto

- On 23 June, Pluto occulted a 14 mag star over the Pacific
- HIPO was placed on the telescope to attempt to measure the occultation at two wavelengths, as close to the center line as possible. If Pluto's atmosphere is dense enough, a central brightening, due to refraction, should be seen.
- Positional updates 3 hours before the event allowed us to cross the central cord within ~ 100 km and see a central brightening. Central path occurred south of Hawaii.

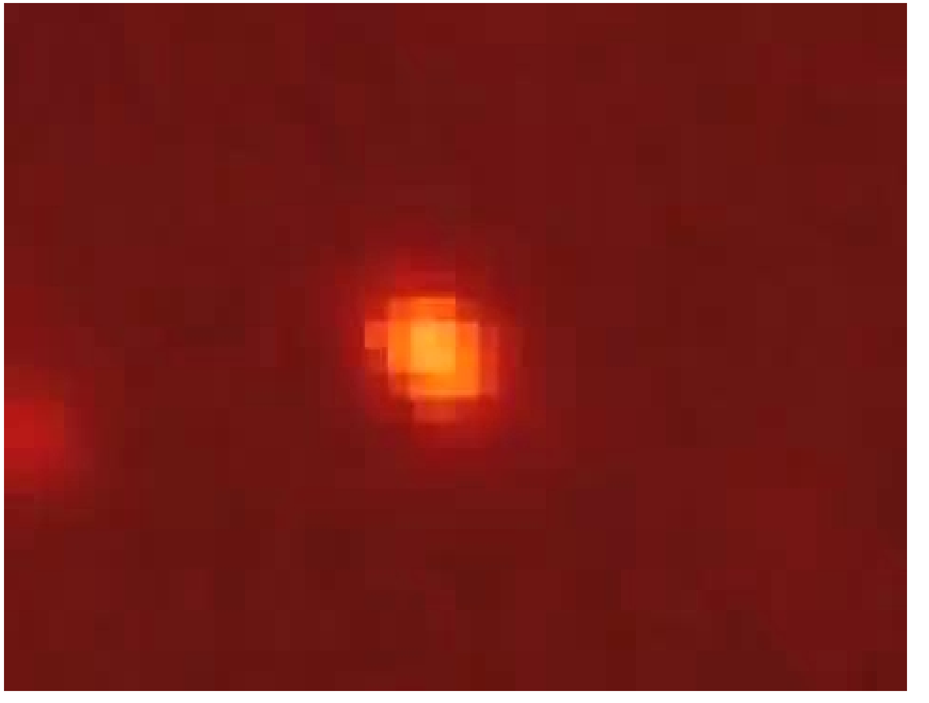
Occultation by Pluto 2011 June 23

- Observation of Pluto passing in front of a bright star is used to provide highly detailed information about the atmosphere
- Mobility of SOFIA is key to successful observations



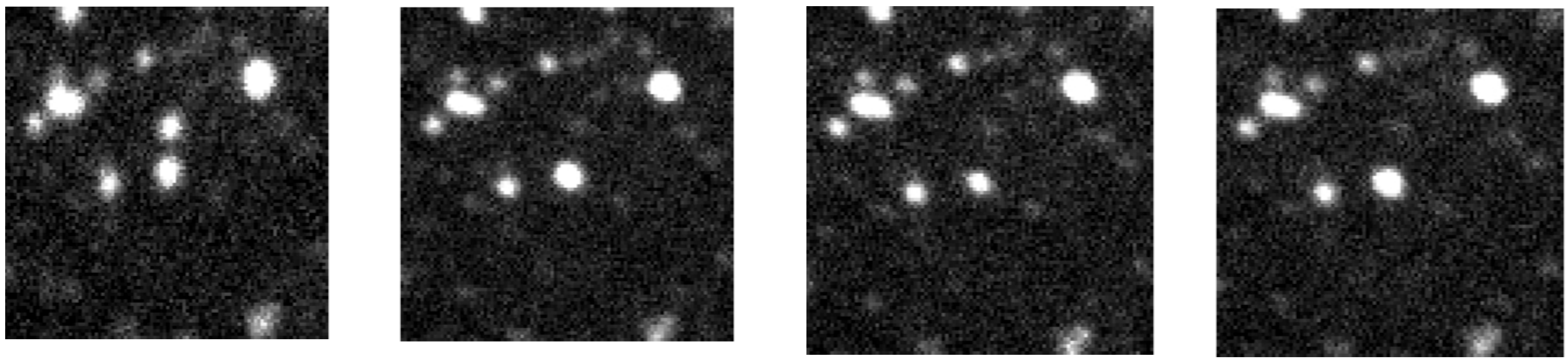
Occultation Results

- Goal of flight was to get as close as possible to center line of occultation
  - If close enough to center line, we can see brightening at mid-event due to atmospheric refraction in Pluto
- Required refinement of prediction as close to time of event as possible
  - Observations at US Naval Observatory, Flagstaff AZ
  - Reductions at MIT
  - Rerouting of SOFIA during flight
- Successful detection indicated SOFIA hit the mark within 100 km.



Ted Dunham, Lowell Observatory, HIPO instrument

Pluto Occultation: 3 hours before, just before, during and just after.



Technical Results from First Science

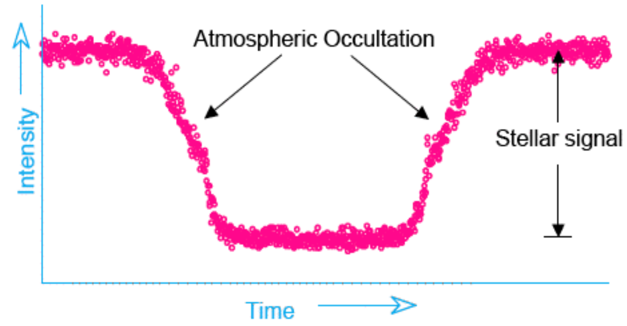
- Image Stability was very good. Allowed near diffraction limited imaging at 37 microns. FWHM images ~3 arcsec

- Infrared and sub-millimeter sensitivity is what was expected.

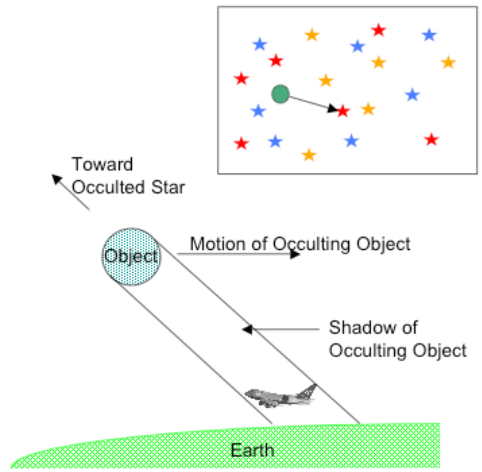
FUTURE SCIENCE

Occultation astronomy with SOFIA

SOFIA will determine the properties of Dwarf Planets in and beyond the Kuiper Belt



Pluto occultation lightcurve observed on the KAO (1988) probes the atmosphere



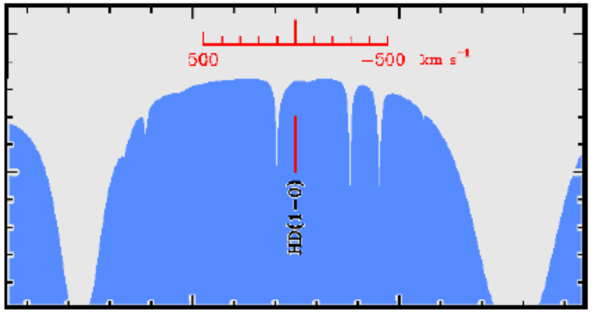
- SOFIA can fly anywhere on the Earth, allowing it to position itself under the shadow of an occulting object.

- Occultation studies with SOFIA will probe the sizes, atmospheres, and possible satellites of newly discovered planet-like objects in the outer Solar system.

- The unique mobility of SOFIA opens up some hundred events per year for study compared to a handful for fixed observatories.

Cold Molecular Hydrogen using HD

SOFIA will study deuterium in the galaxy using the ground state HD line at 112 microns. This will allow determination the cold molecular hydrogen abundance.



Atmospheric transmission around the HD line at 40,000 feet

Deuterium in the universe is created in the Big Bang.

Measuring the amount of cold HD (T<50K) can best be done with the ground state rotational line at 112 microns accessible with SOFIA (HD in emssion and in absorption).
.

Detections with ISO means that GREAT high resolution spectroscopic study is possible.

HD has a much lower excitation temperature and a dipole moment that almost compensates for the higher abundance of molecular hydrogen.

As pointed out by Bergin and Hollenbach, HD traces the cold molecular hydrogen

In the future HD could be used, much like the HI 21cm maps but for cold molecular gas.

Schedule & Future Opportunities

Observer Opportunities

- We had a call last year for first observing (~18 Flights) in "Basic Science" in CY 11 with FORCAST and GREAT. Proposals from US and Germany were selected and FORCAST observing has finished, GREAT flew in July and continued with 3 more flights Sept 2011.
- Future calls every year with additional 1st generation instruments. Next call in Fall 2011, observing proposals for FORCAST, GREAT, HIPO and FLITECAM due in Jan 2012
- Open Observatory with Facility Instruments

Next Call for New Instruments

- The next call for instruments is now out. Call and selection of instruments will be done by NASA Headquarters.
- We are considering:
  - New Science Instruments both FSI and PSI
  - Studies of instruments and technology
  - Upgrades to present instruments
- There will be additional calls every 3 years.
- There will be one new instrument or upgrade per year
- Approximate funding for new instruments and technology is ~$5 to10M/yr

SOFIA EP/O

- Airborne Astronomy Ambassadors Program Launched
  - All 6 US educators in the first AAA class flew on Basic Science 1 flights
  - Parallel German AAA program flew their first educators during Basic Science 2

- SOFIA will be deployed to Germany in mid-September to support the Cologne Air Show September 18, 2011

- NASA has approved SOFIA participation at an EP/O event in Washington to support the First Lady's "Joining Forces" initiative for military families

Educators from the first Airborne Astronomy Ambassadors flight. (l-r) Margaret Piper, Lincoln Way High School, Frankfort, Ill.; Theresa Paulsen, Mellen School District, Mellen, Wis.; and Kathleen Joanne Fredette, Desert Willow Intermediate School, Palmdale, Calif.

SOFIA Schedule (Major Milestones)

• First Re-Flight	April ’07
• First Open Door Flights	Dec 09
• First Light and Heat	May 10
• Full flight tests to 45000 ft	Sept 10
• First Science FORCAST	Dec 10
• First Science GREAT	April 11
• First Occultation with HIPO	June 11
• First Community Science	May-Sept 11
• Next call for new Instruments	July 2011

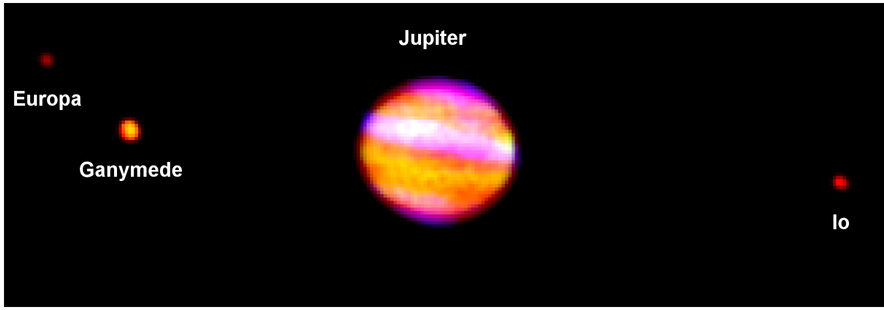
SOFIA Highlights 2011

- April 2011 — GREAT Early Science Flights
- May 2011 — FORCAST Basic Science Flights
- June 2011 — Pluto Occultation Flight
- July 2011 — Call for 2nd Generation Instruments
- July 2011 — GREAT Basic Science
- Sept 2011 — Deployment to Germany
- Sept 2011 — E/PO Event at Andrews AFB
- Sept 2011 — Completion of Basic Science (into Nov.)
- Oct 2011 — 2nd Generation Instrument Proposals Due
- Nov 2011 — Call for Cycle 1 observing proposals
- deadline Jan 27, 2012 (also for internat.)
- Dec 2011 — Begin Maintenance Downtime (Seg 3).

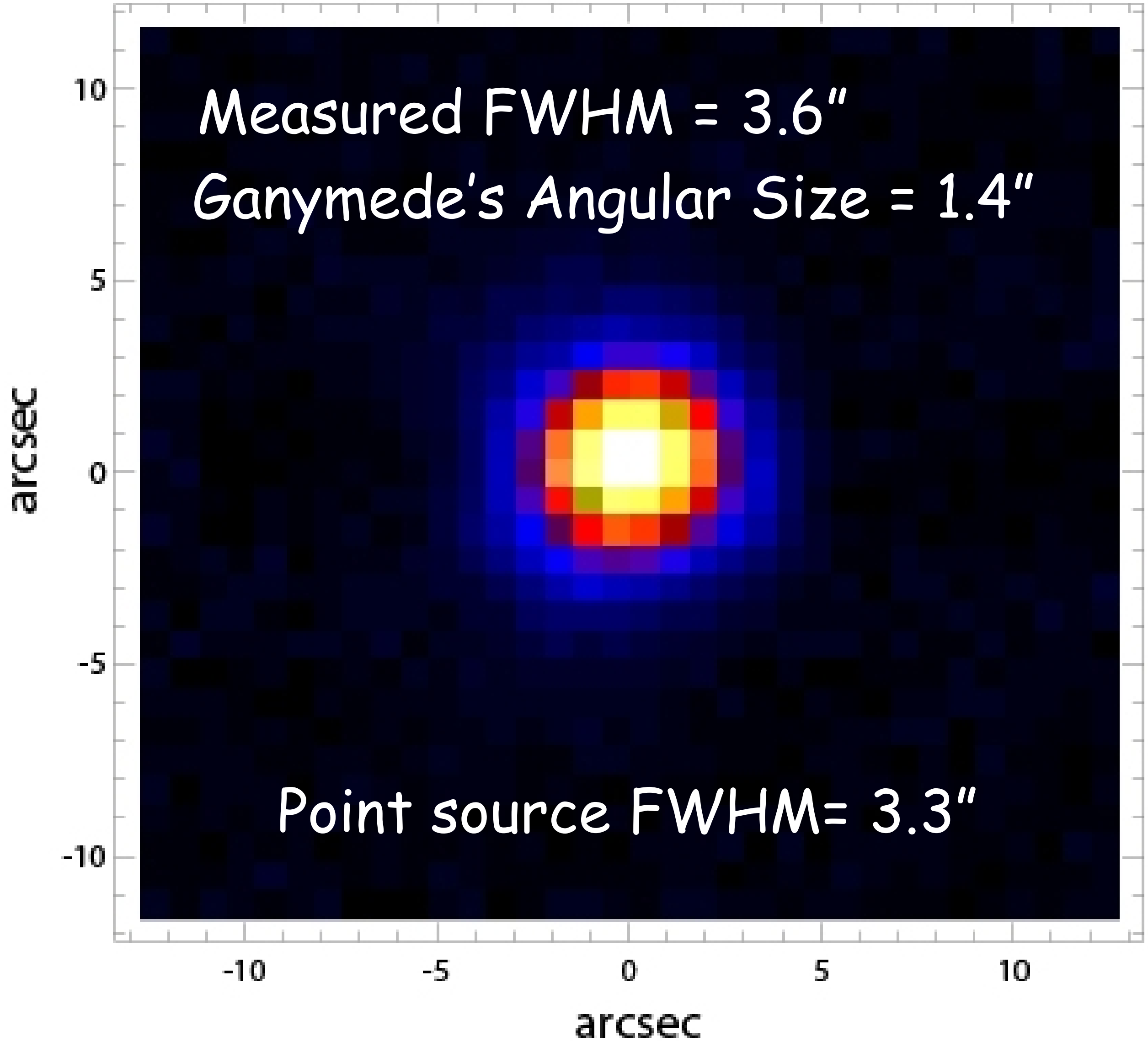
SOFIA in the Dryden Aircraft Operations Facility

Summary

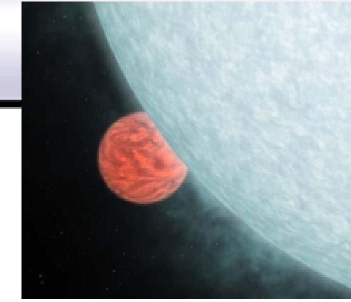
- SOFIA program getting into gear!
  - First Science with FORCAST and GREAT was a great success
  - Aircraft handles well, even with door open (unnoticable in flight)
  - Aircraft now cleared to 45,000ft
  - Community science has started with 15 of 18 flights.
  - Successful Occultation of Pluto in June over the Pacific
  - Deployment to Germany and to Washington DC in Sept
  - Call for 2nd instruments due today
- SOFIA will be one of the prime facilities for mid-IR and far-IR-astronomy for many years to come



Ganymede at 24.2 um from First Light flight

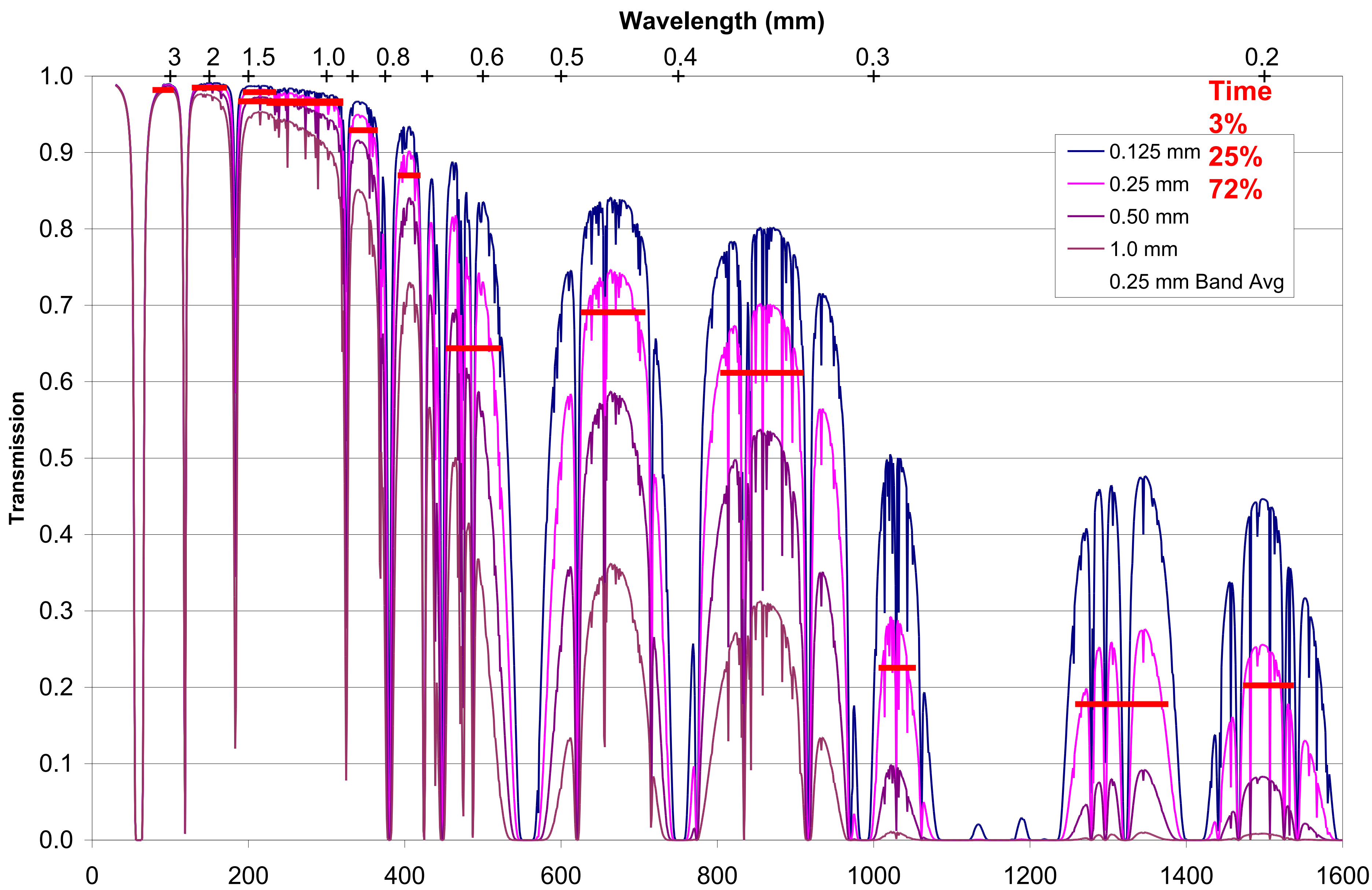


☑ Sensitivities in the 5-40um range as expected!



Ende

Atmospheric Transmission Cerro Chajnantor (5,600 m)



SOFIA Inauguration

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