SOFIA: Stratospheric Observatory for Infrared Astronomy

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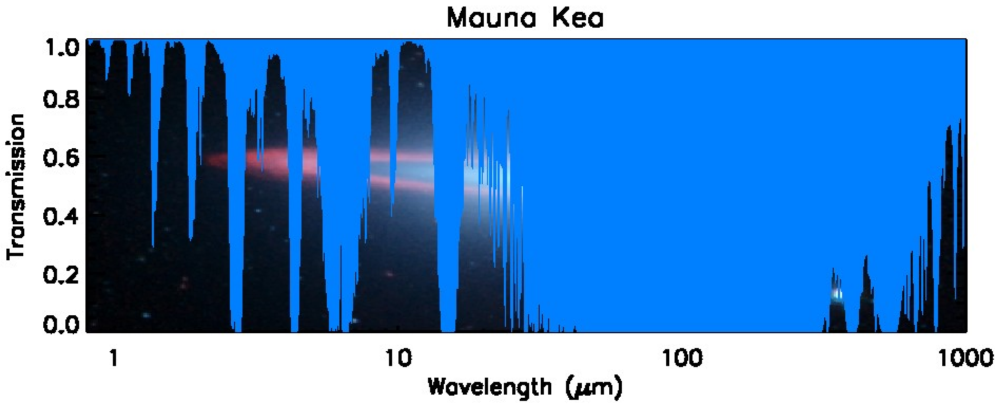
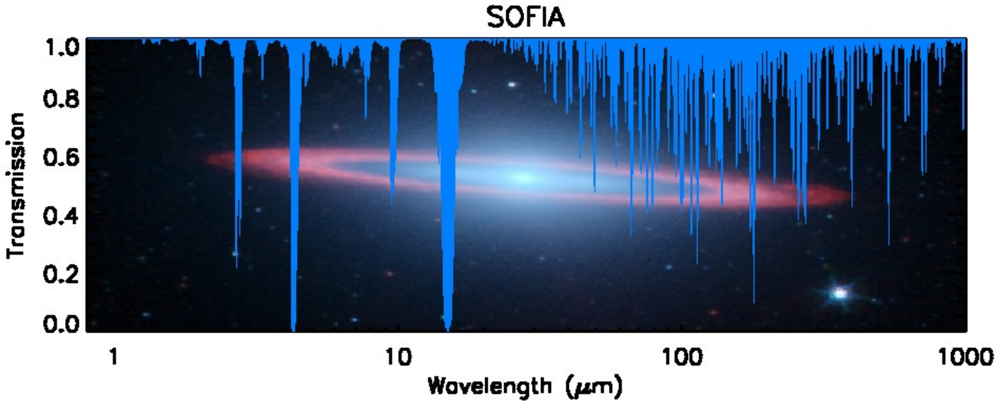
SOFIA Overview

- 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
  - Science Ops at NASA-Ames; Flight Ops at Dryden FRC (Palmdale-Site 9)
  - Deployments to the Southern Hemisphere and elsewhere
  - Goal is >120 8-10 hour flights per year

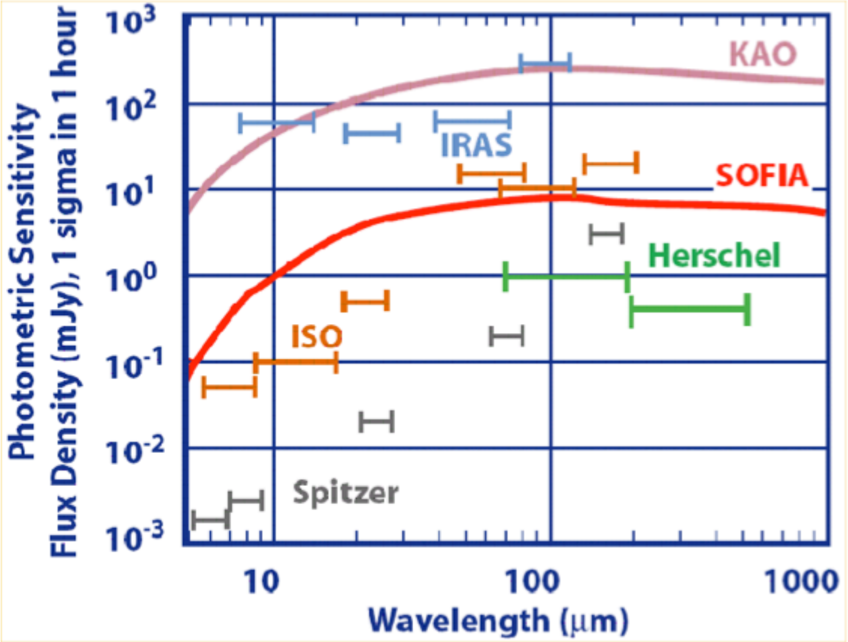
Why SOFIA?

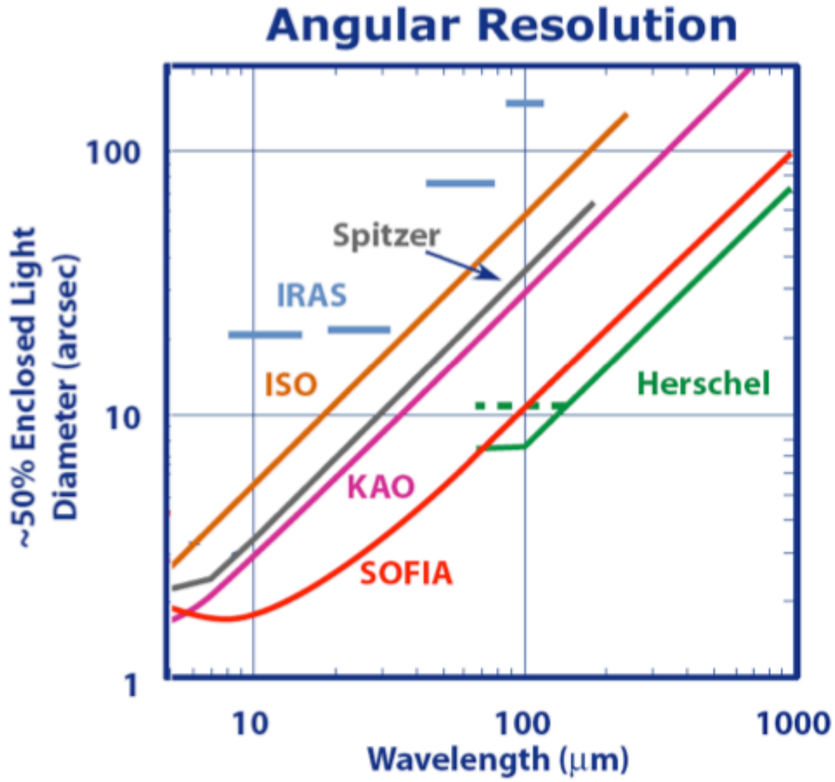
- Infrared transmission in the stratosphere very good because we fly above 99.8% of water in the Earth's atmosphere
- Transmission >80% from 1 to 1000 microns
- Instrumentation: wide complement, rapidly interchangeable, state-of-the art
- Mobility: anywhere, anytime
- Long lifetime
- Outstanding platform to train future Instrumentalists
- Comes home after every flight





Photometric Sensitivity and Angular resolution

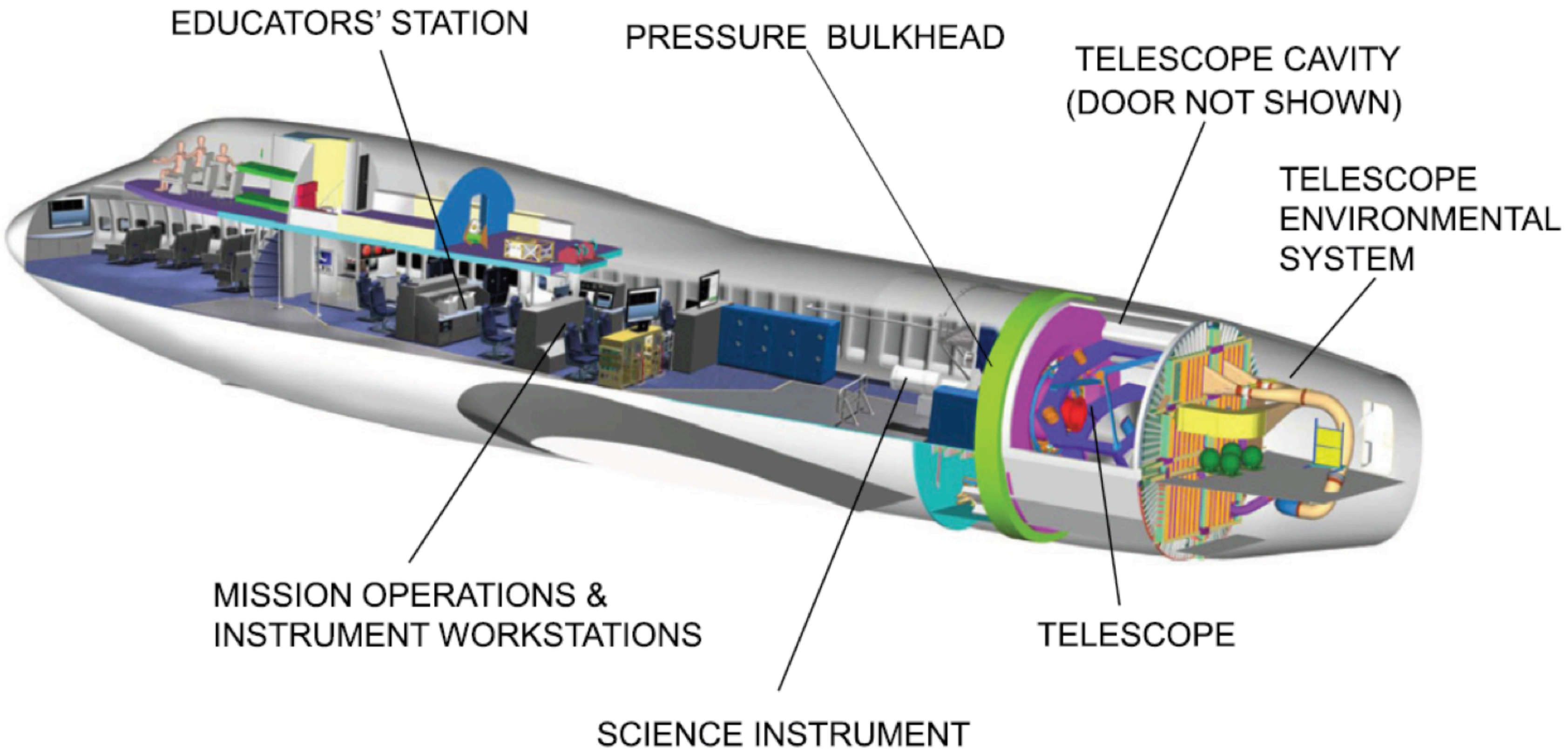




SOFIA is as sensitive as the Infrared Space Observatory

SOFIA is diffraction limited beyond 25 μm and can produce images three times sharper than those made by Spitzer

The SOFIA Observatory



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

SOFIA Airborne on July 13, 2010

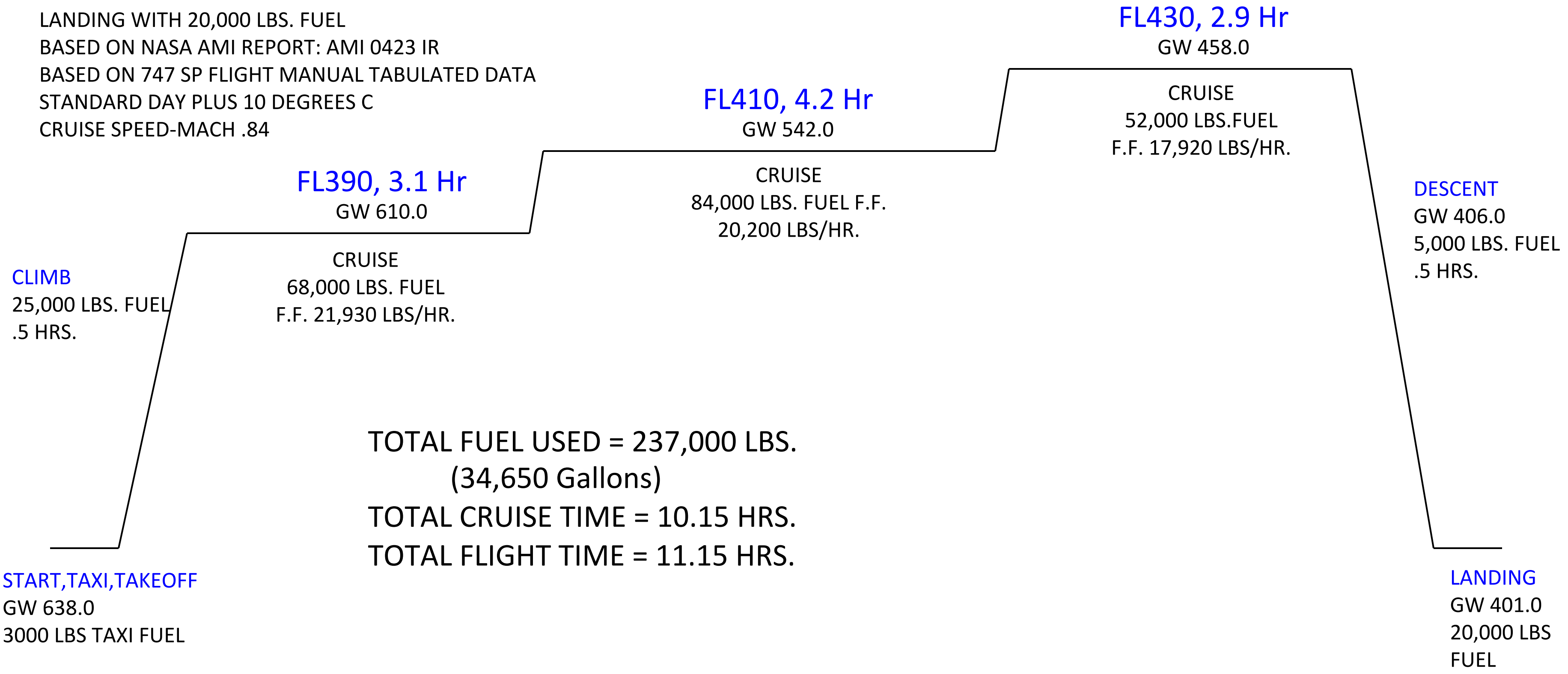
SOFIA at DAOF during Line Ops – Spring 2011

Flight Profile

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



START,TAXI,TAKEOFF
GW 638.0
3000 LBS TAXI FUEL

CLIMB
25,000 LBS. FUEL
.5 HRS.

FL390, 3.1 Hr
GW 610.0

CRUISE
68,000 LBS. FUEL
F.F. 21,930 LBS/HR.

FL410, 4.2 Hr
GW 542.0

CRUISE
84,000 LBS. FUEL F.F.
20,200 LBS/HR.

FL430, 2.9 Hr
GW 458.0

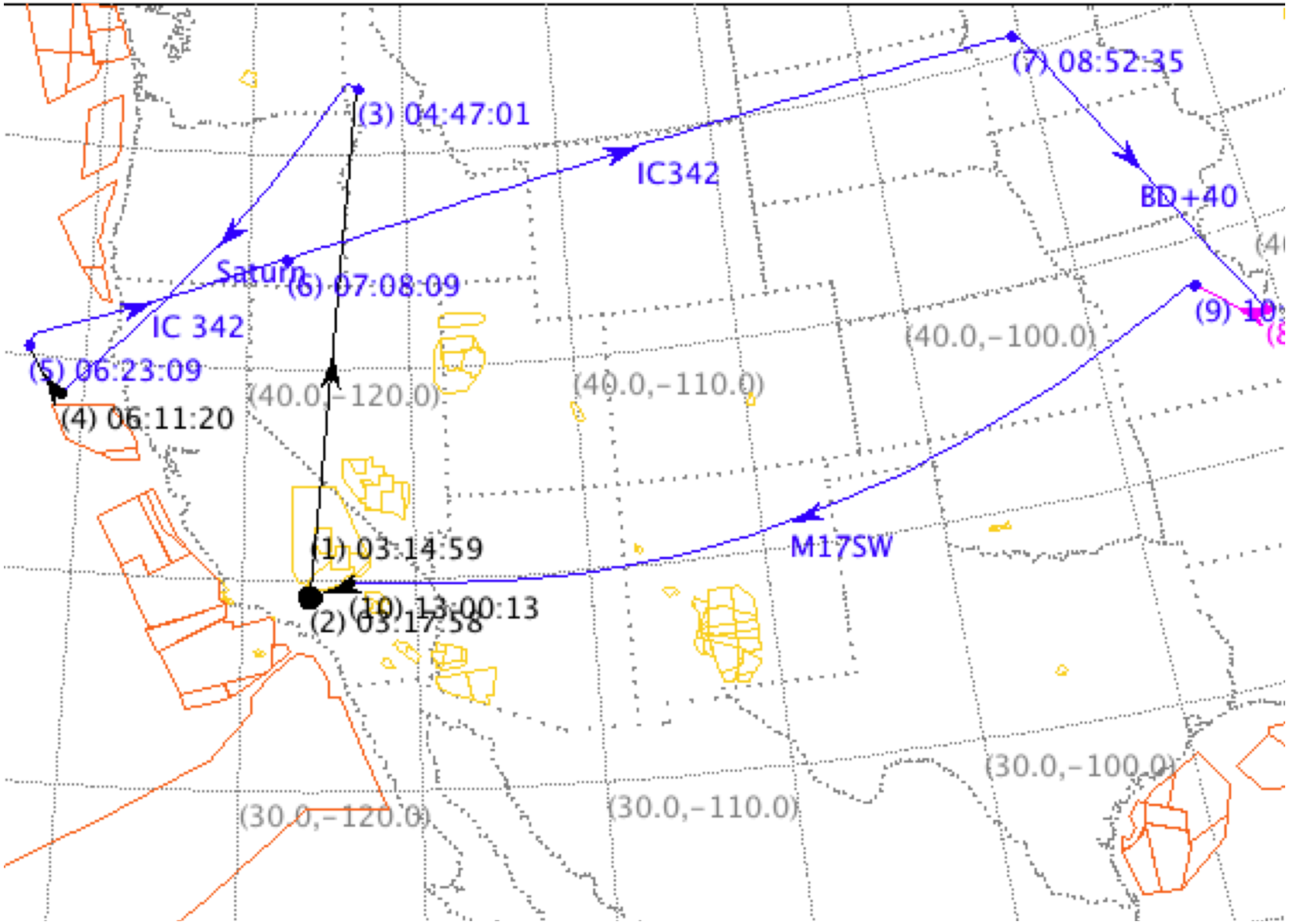
CRUISE
52,000 LBS.FUEL
F.F. 17,920 LBS/HR.

DESCENT
GW 406.0
5,000 LBS. FUEL
.5 HRS.

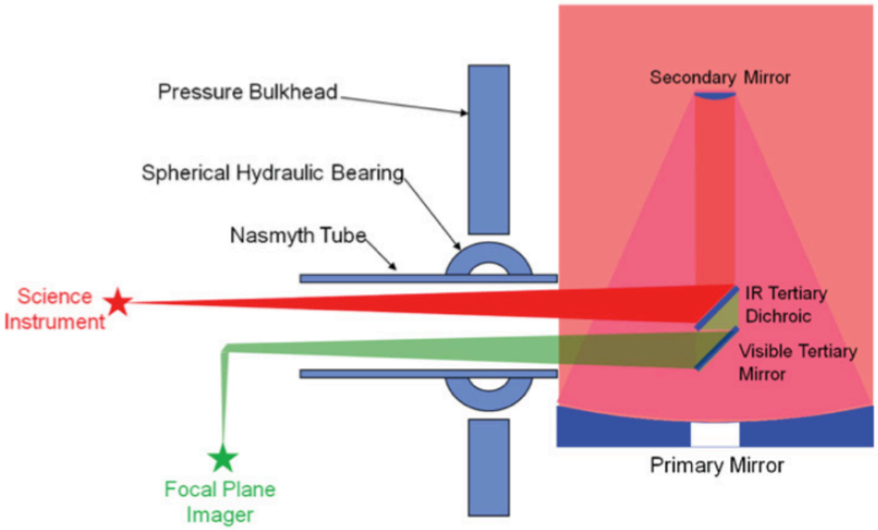
LANDING
GW 401.0
20,000 LBS
FUEL

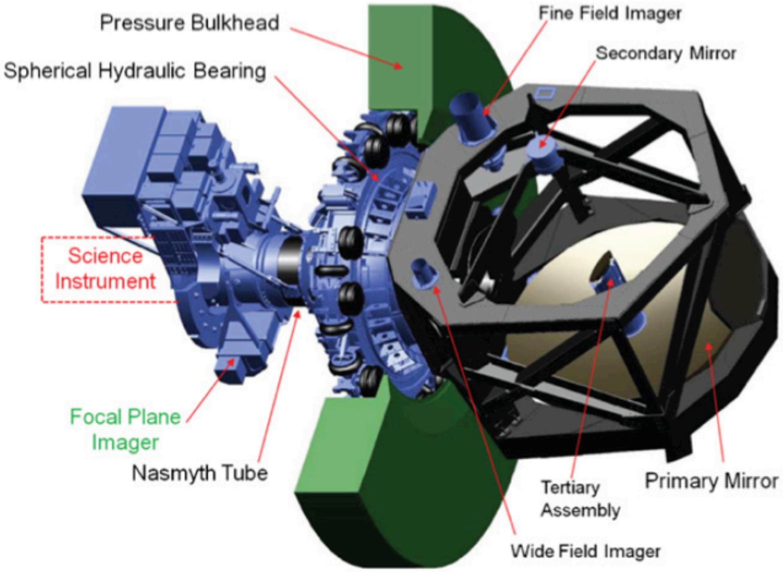
TOTAL FUEL USED = 237,000 LBS.
(34,650 Gallons)
TOTAL CRUISE TIME = 10.15 HRS.
TOTAL FLIGHT TIME = 11.15 HRS.

Flight Planning



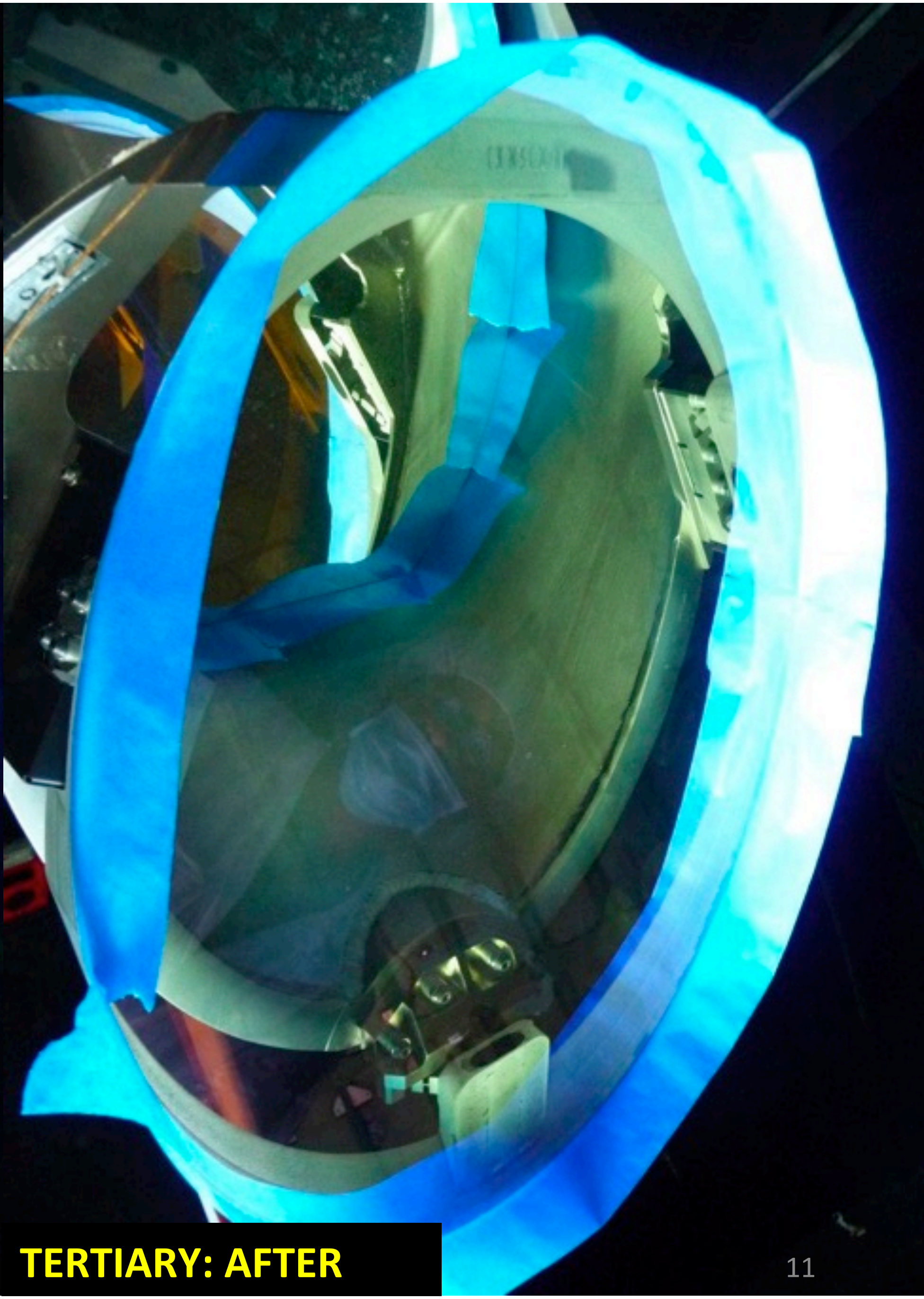
Telescope and Optical Layout





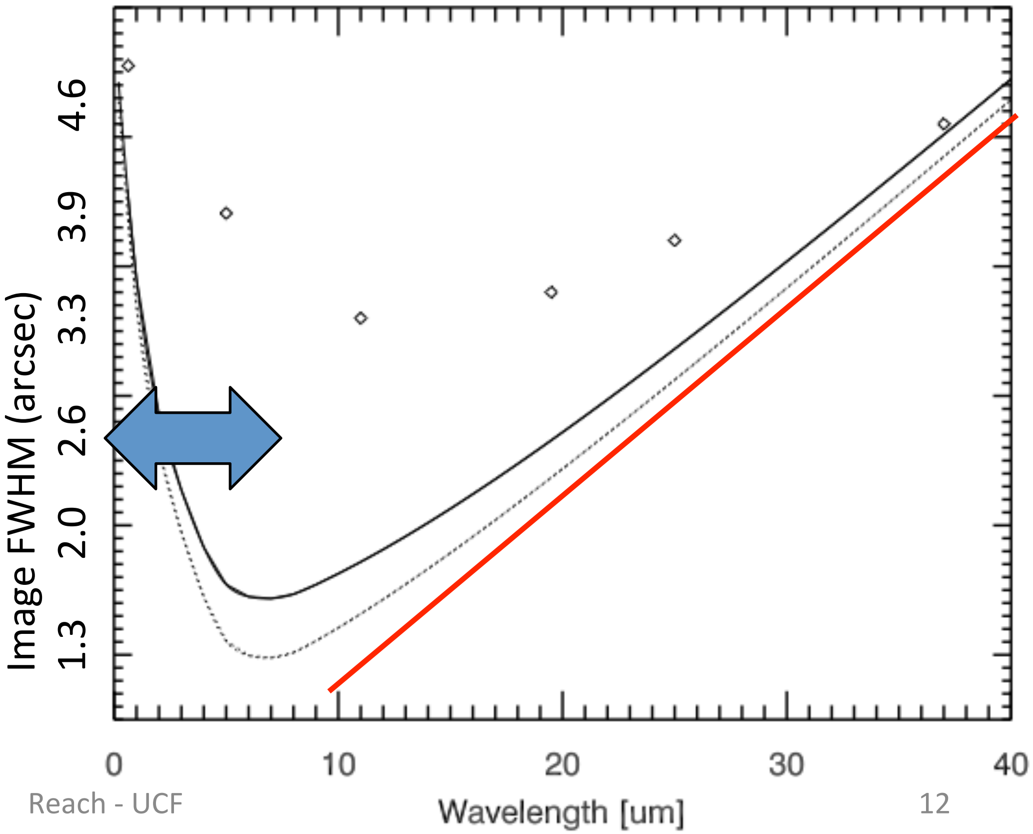
E.T Young et al. 2012, ApJ, 749, L17


TERTIARY: BEFORE

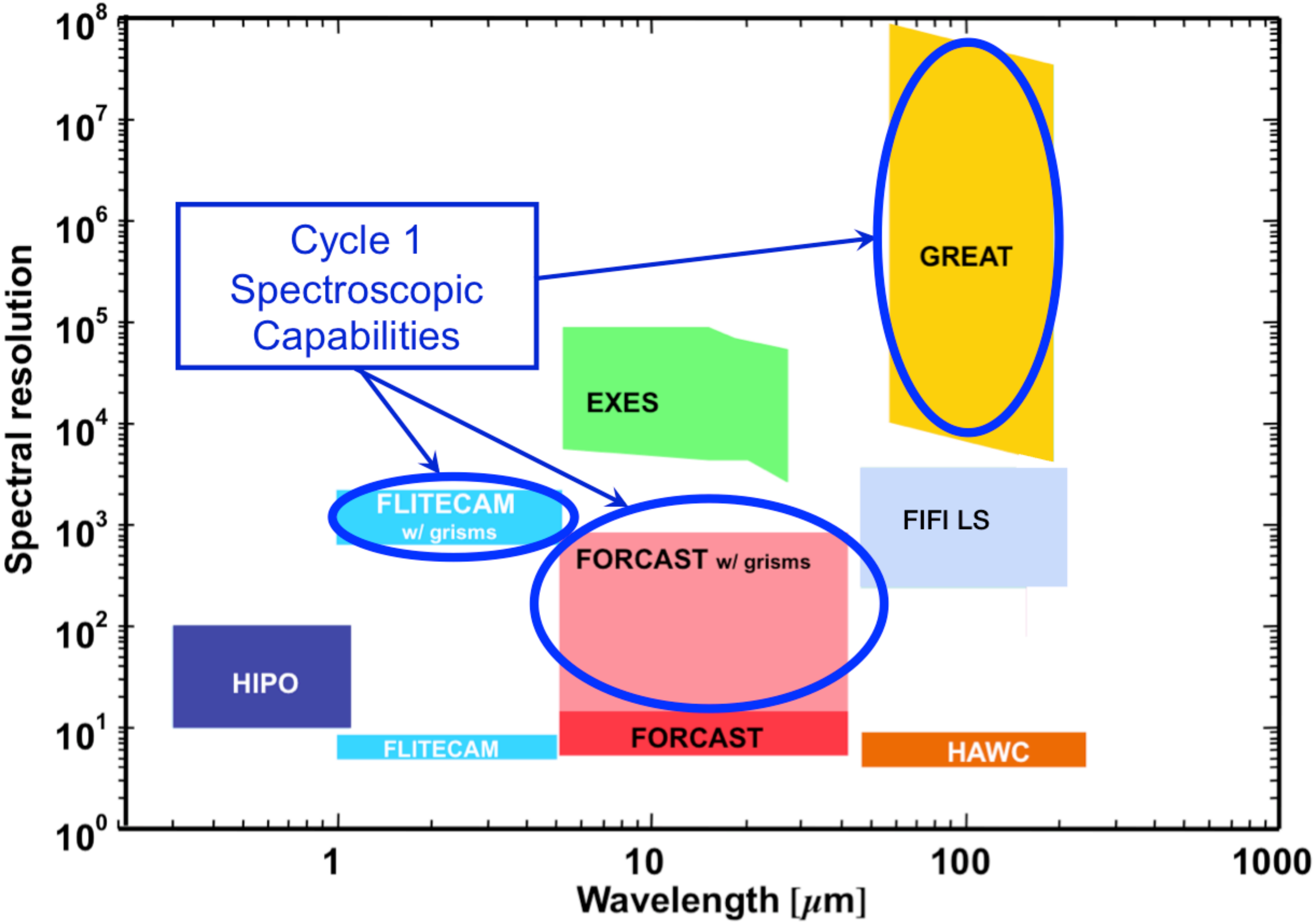

TERTIARY: AFTER

Telescope Performance

- SOFIA telescope was built in Germany and contributed by DLR
- Image quality depends on wavelength
  - Diffraction: λ(microns)/10 arcsec
  - Jitter of telescope
  - Shear layer turbulence
  - Other effects
- Measured performance
    - diamonds
- Expected performance
  - Active mass dampers
  - Goal
    - Solid line
- Ultimate goal
    - Dotted line



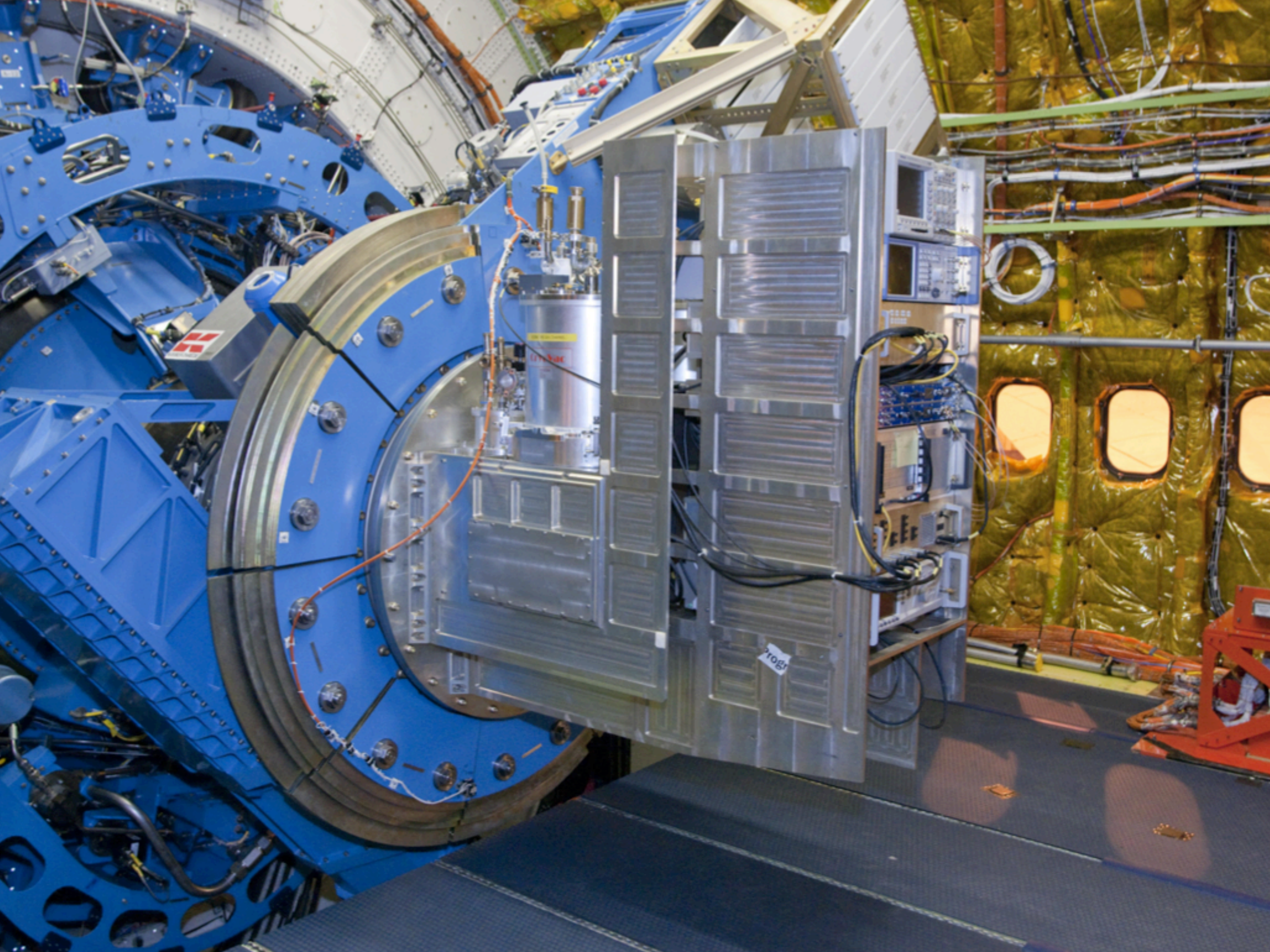
SOFIA First Generation Instruments



Cycle 1
Spectroscopic
Capabilities

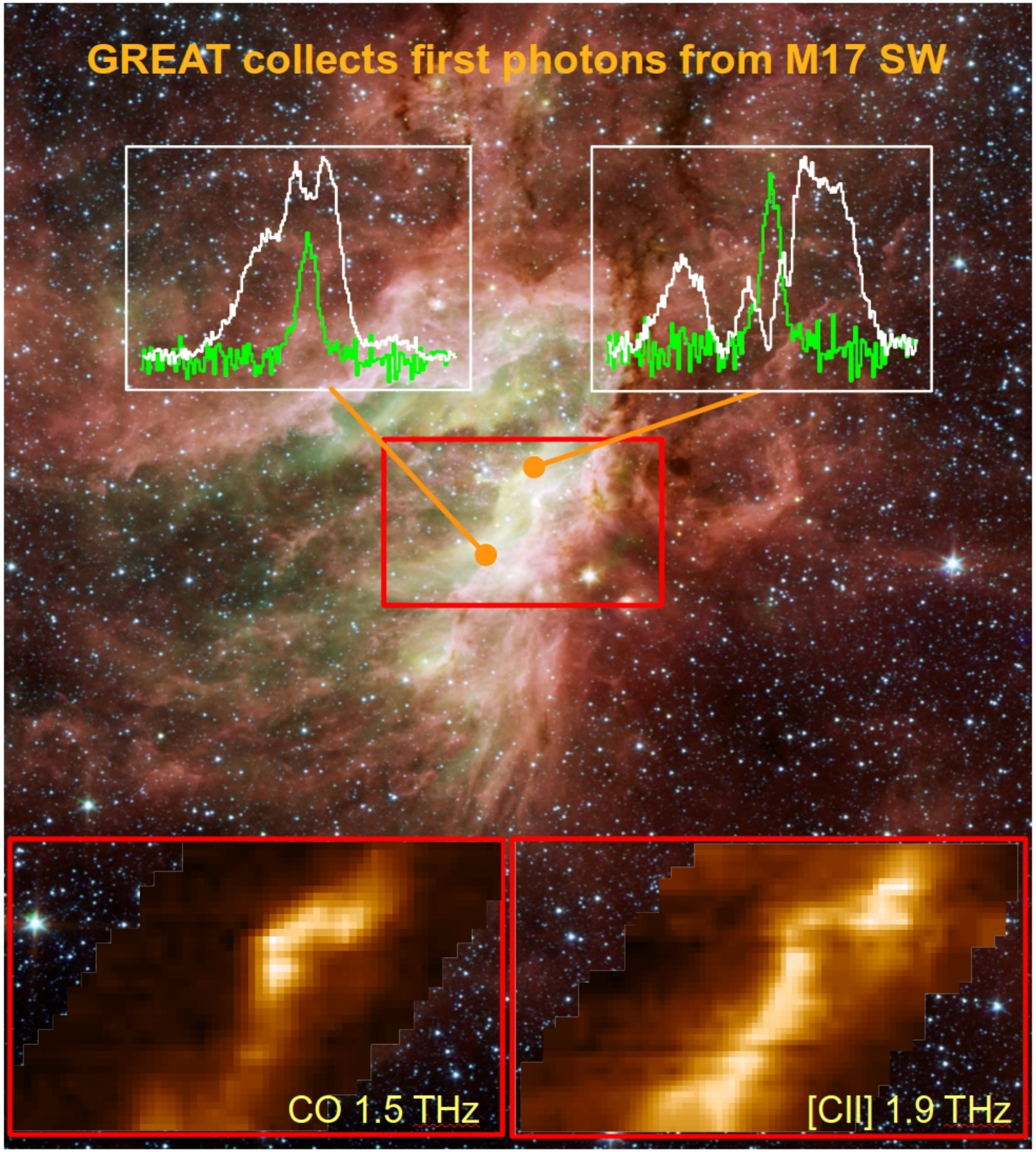
SOFIA Science Instruments

- Facility Science Instrument
  - Developed by contract and delivered to Project
  - Offered to all proposers
  - Operated by the science center
- Principal Investigator Science Instrument
  - Developed by contract and retained by contractor
  - Offered to all proposers
  - Operated by the PI team


Progr

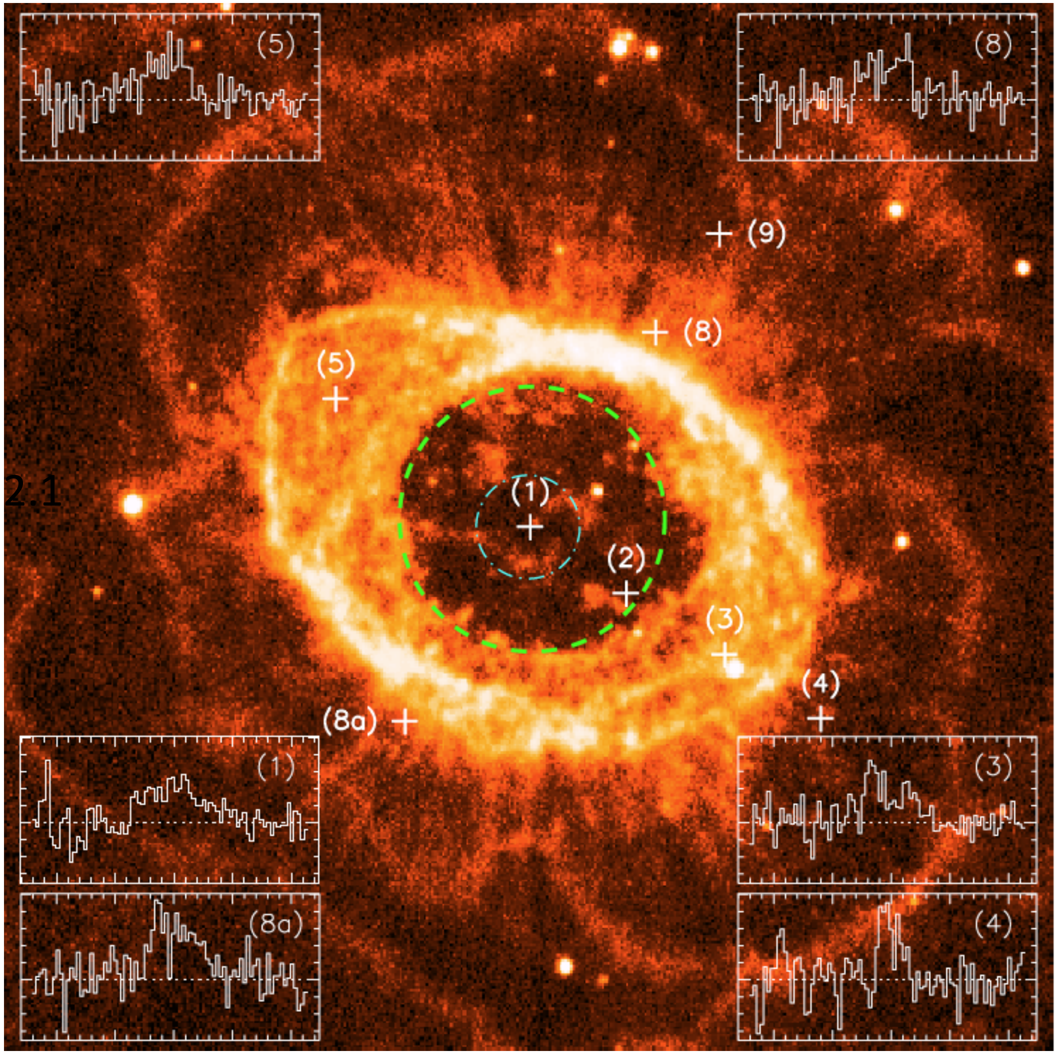
First Science with GREAT

White=ionized carbon,
Green=CO molecule



[CII] in the Ring nebula

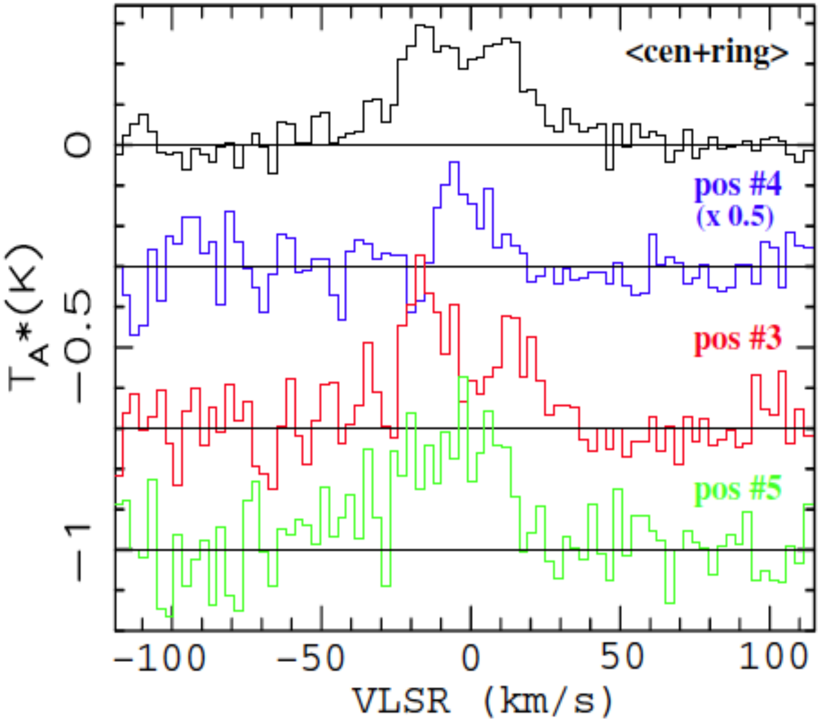
Background image 2.1 µm H_2 emission



Background image 2.1 µm H_2 emission in NGC6720

[CII] observations of the Ring nebula (NGC 6720)

- NGC6720 is one of the best studied planetary nebulae
- It was observed by ISO in [CII], but without spatial and spectral resolution to resolve where [CII] comes from
- GREAT observations (sparse map) show that the [CII] lines are broad (50 km/s), most of the carbon is in CI or [CII], the total [CII] mass ~ 0.11 M_{sun}
- [CII] emission strong in the PDR just outside the optical ring

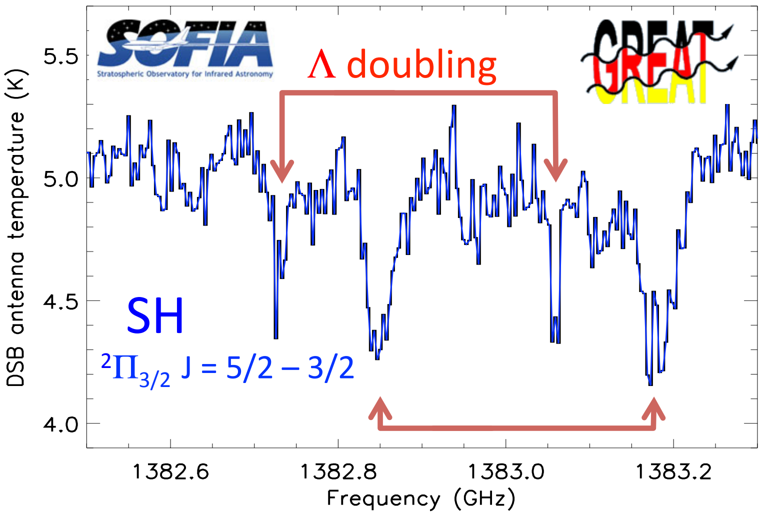


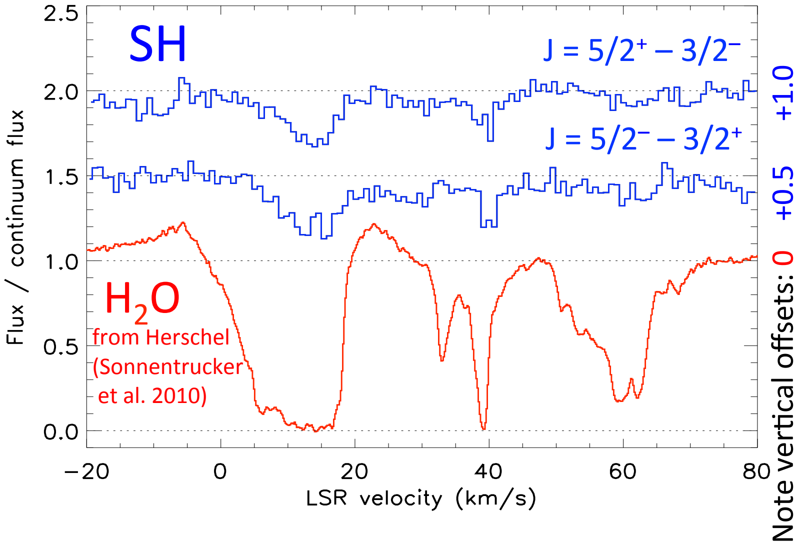
[CII] spectra at selected positions, see next slide. Top is average of center plus 3, 5 , 8, and 8a.

Sahai et al. 2012, A&A **542**, L20 (special GREAT issue)

SOFIA/GREAT discovery of interstellar mercapto radicals (SH)

W49N





Neufeld, Falgarone, Gerin, Godard, Herbst, Pineau des Forêts and the GREAT Team (2011)

QUICK-LOOK data reduction: not fully-calibrated

SH has been detected in absorption toward W49N and W31C (G10.62 – 0.4)

Its 1.383 THz ground state transition lies in the gap between Herschel/HIFI Bands 5 and 6.

SH is a key hydride, for which astronomical data was conspicuously missing until now.

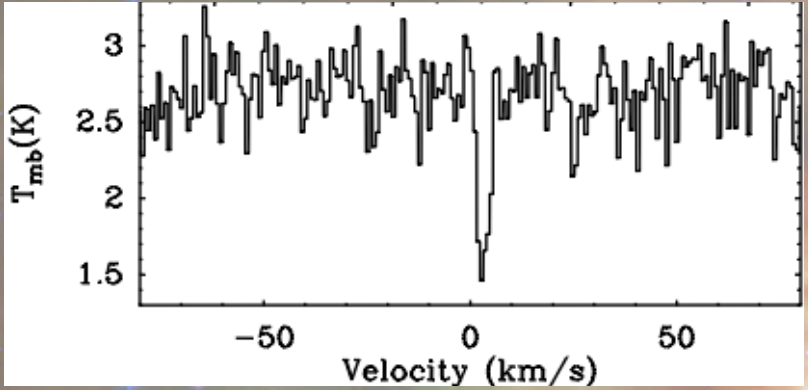
Its presence suggests a "warm chemistry", driven by shocks or turbulent dissipation, that can enable endothermic formation paths.

Eight neutral diatomic hydrides have now been detected in the ISM:

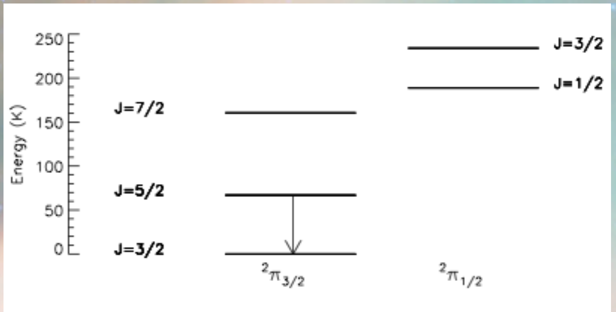
H_2 (Carruthers 1970)
CH (Swings & Rosenfeld 1937)
NH (Meyer & Roth 1991)
OH (Weinreb 1963)
HF (Neufeld et al. 1995)

SiH (tentative; Schilke et al. 2001)
SH (SOFIA/GREAT 2011)
HCl (Blake et al. 1985)

First Detection of OD outside the Solar System



OD J=5/2->3/1 transition observed toward protostar IRAS16293, smoothed to 0.79 km/s



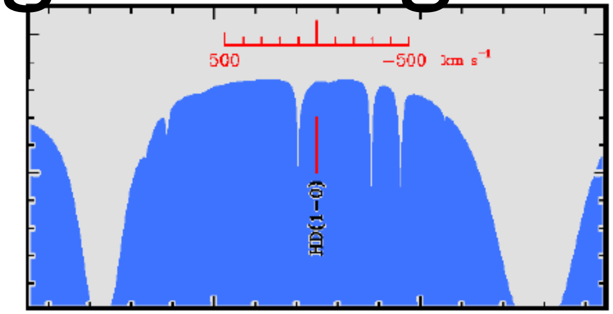
Parise et al. 2012, A&A

Ground state transition: Sensitive to cold gas

- In cold and dense clouds, chemical reactions forming molecules with Hydrogen prefer the isotope Deuterium. This process, called fractionation, leads to relatively high abundances of deuterated molecules.
  - Fractionation is driven by the fact that the heavier molecule (OD) has a lower energy ground state than the lighter one (OH)
- SOFIA/GREAT observations detected OD, the deuterated form of the hydroxyl radical, OH, which is important in the chemical pathway for forming water, in the protostar IRAS 16293-2422.

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.

Detections with ISO means a GREAT high resolution spectroscopic study possible.

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

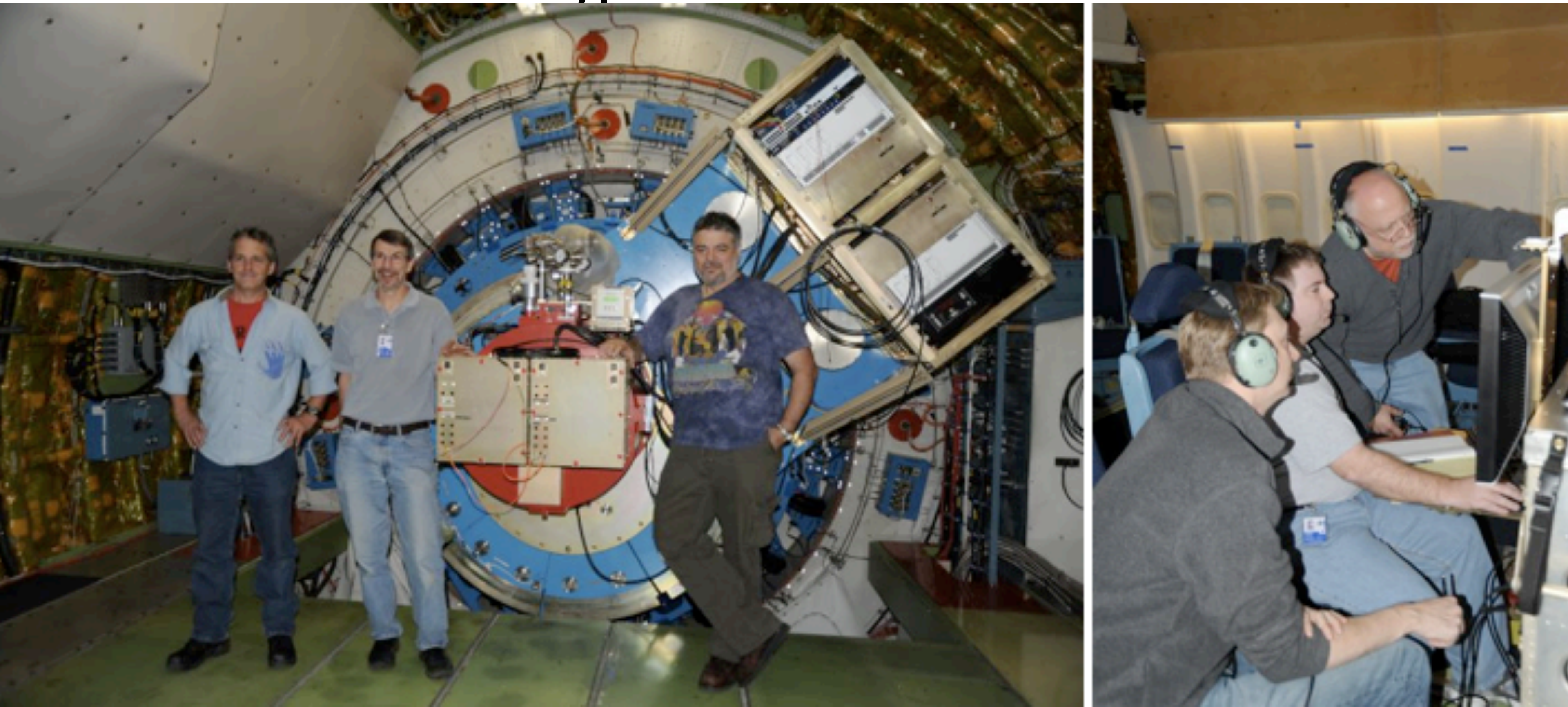
As pointed out by Bergin and Hollenbach, HD gives the cold molecular hydrogen

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

Faint Object infraRed CAmera for the Sofia Telescope: FORCAST

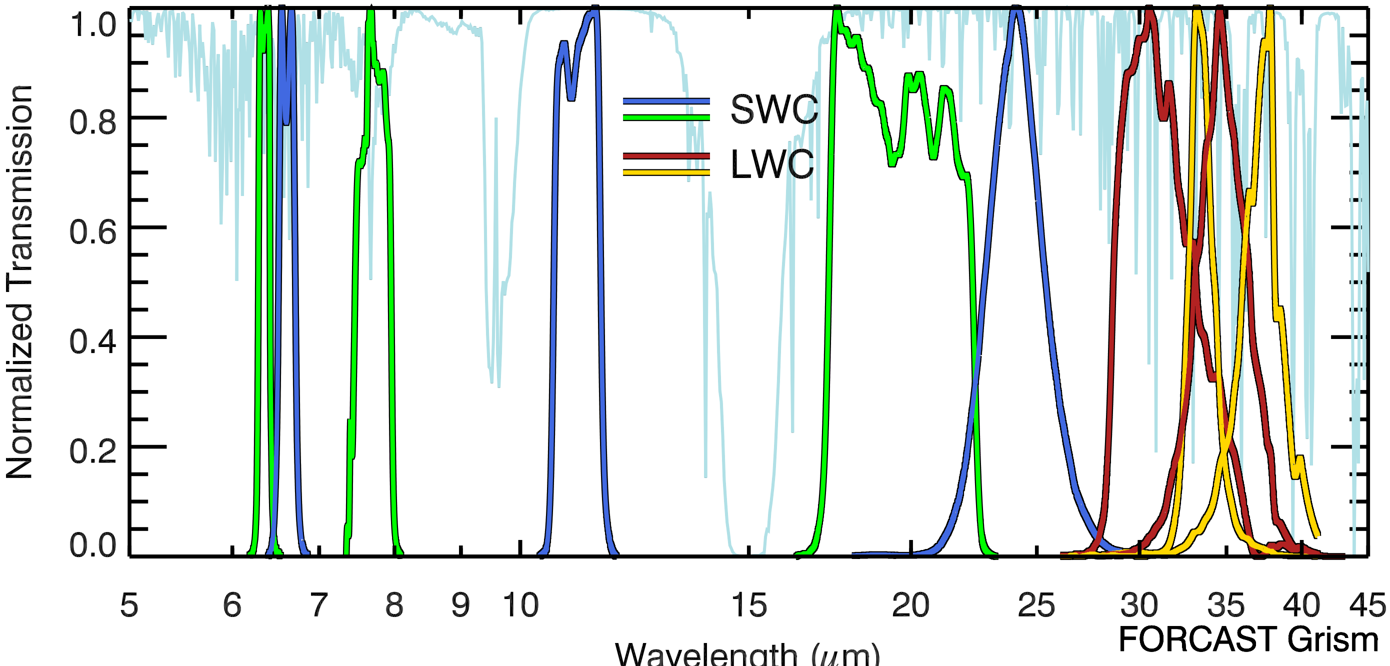
5 to 40 μm Facility Camera

- **Detector:** Si:As & Si:Sb BIB Arrays, 256 × 256 pixels
- **Plate Scale:** 0.75”/pixel ⇔ 3.2’ × 3.2’ FOV

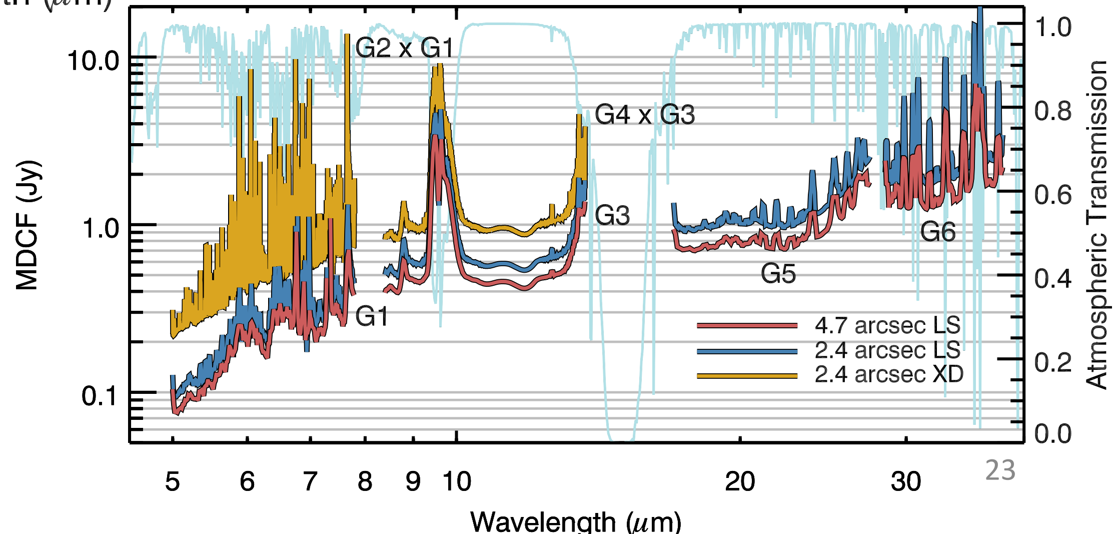


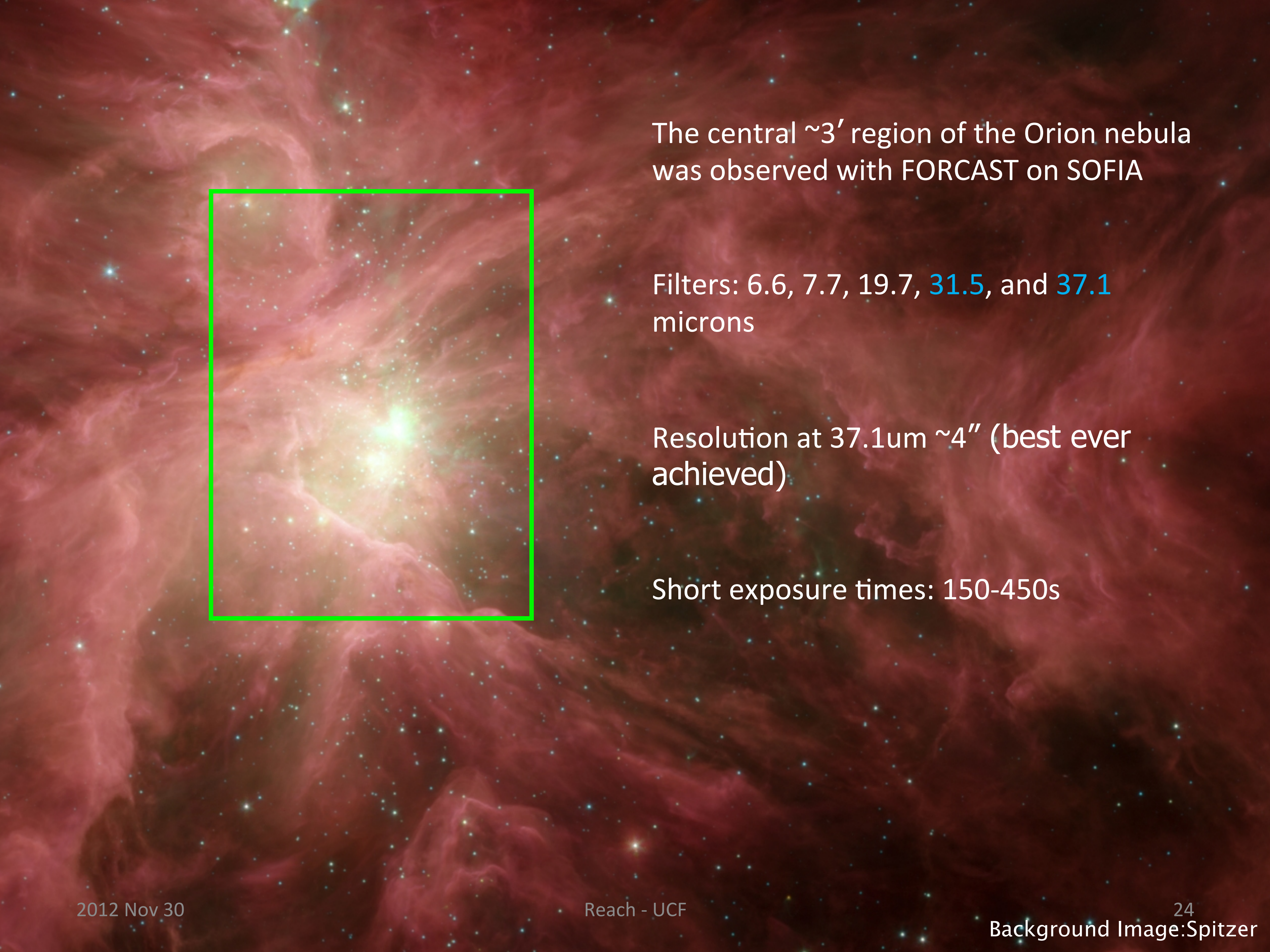
FORCAST Spectral Passbands

FORCAST Filter Transmission Profiles



FORCAST Grism Sensitivities





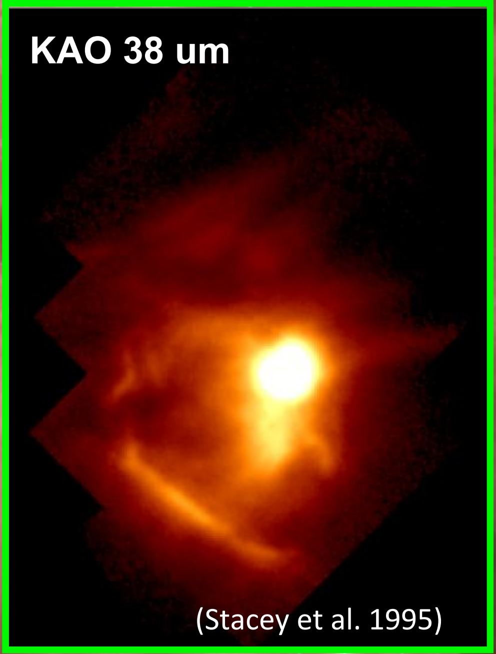
The central ~3′ region of the Orion nebula was observed with FORCAST on SOFIA

Filters: 6.6, 7.7, 19.7, 31.5, and 37.1 microns

Resolution at 37.1um ~4″ (best ever achieved)

Short exposure times: 150-450s

Background Image:Spitzer



(Stacey et al. 1995)

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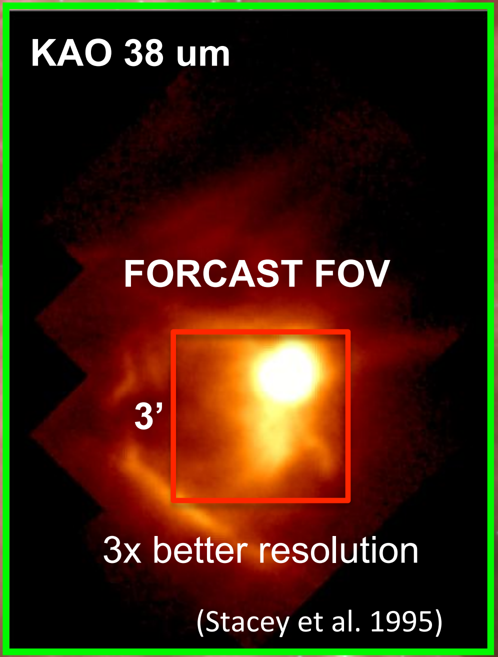

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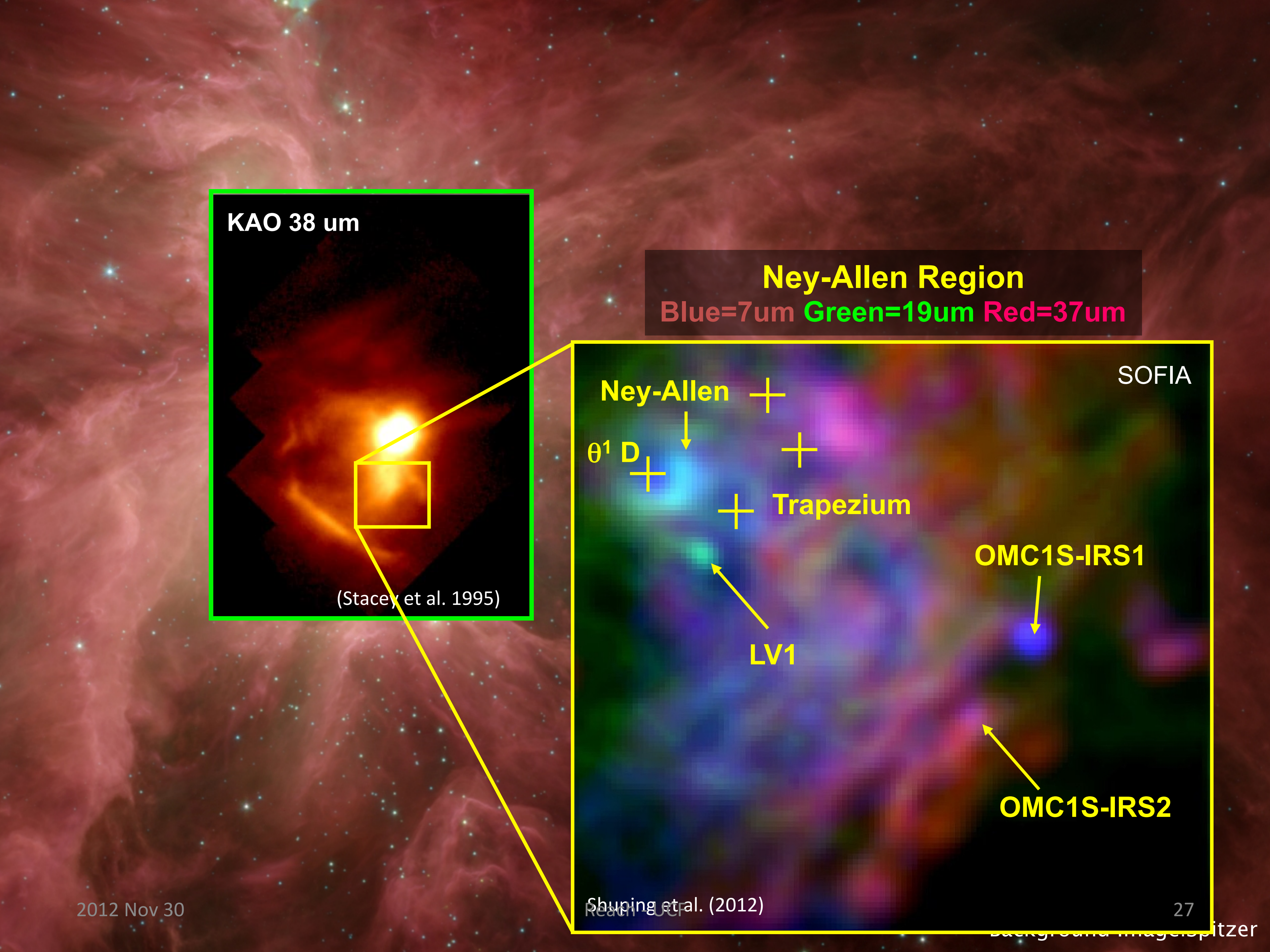
Ney-Allen Region

Blue=7um Green=19um Red=37um

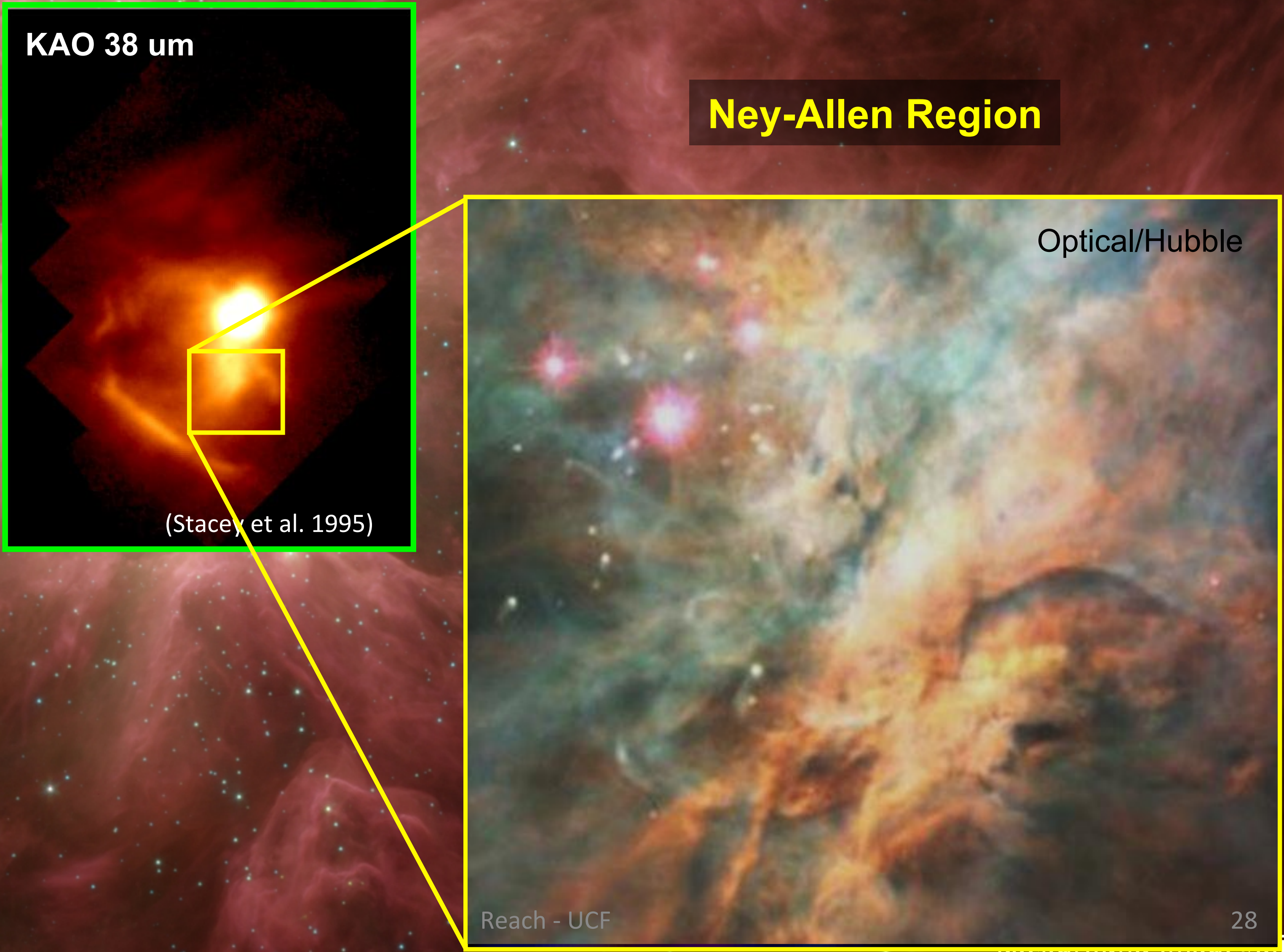


(Stacey et al. 1995)

Shuping et al. (2012)

Background image: Spitzer

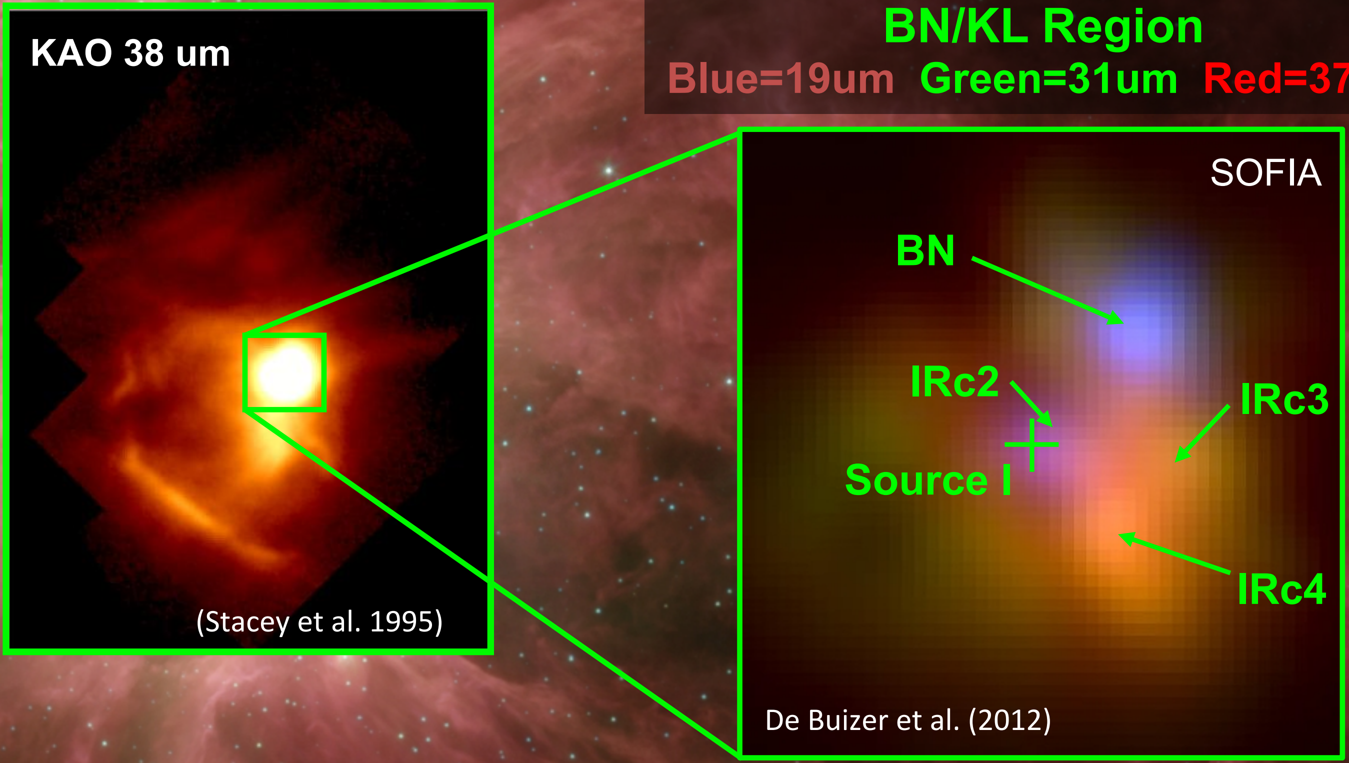
Ney-Allen Region



Background image: Spitzer

BN/KL Region

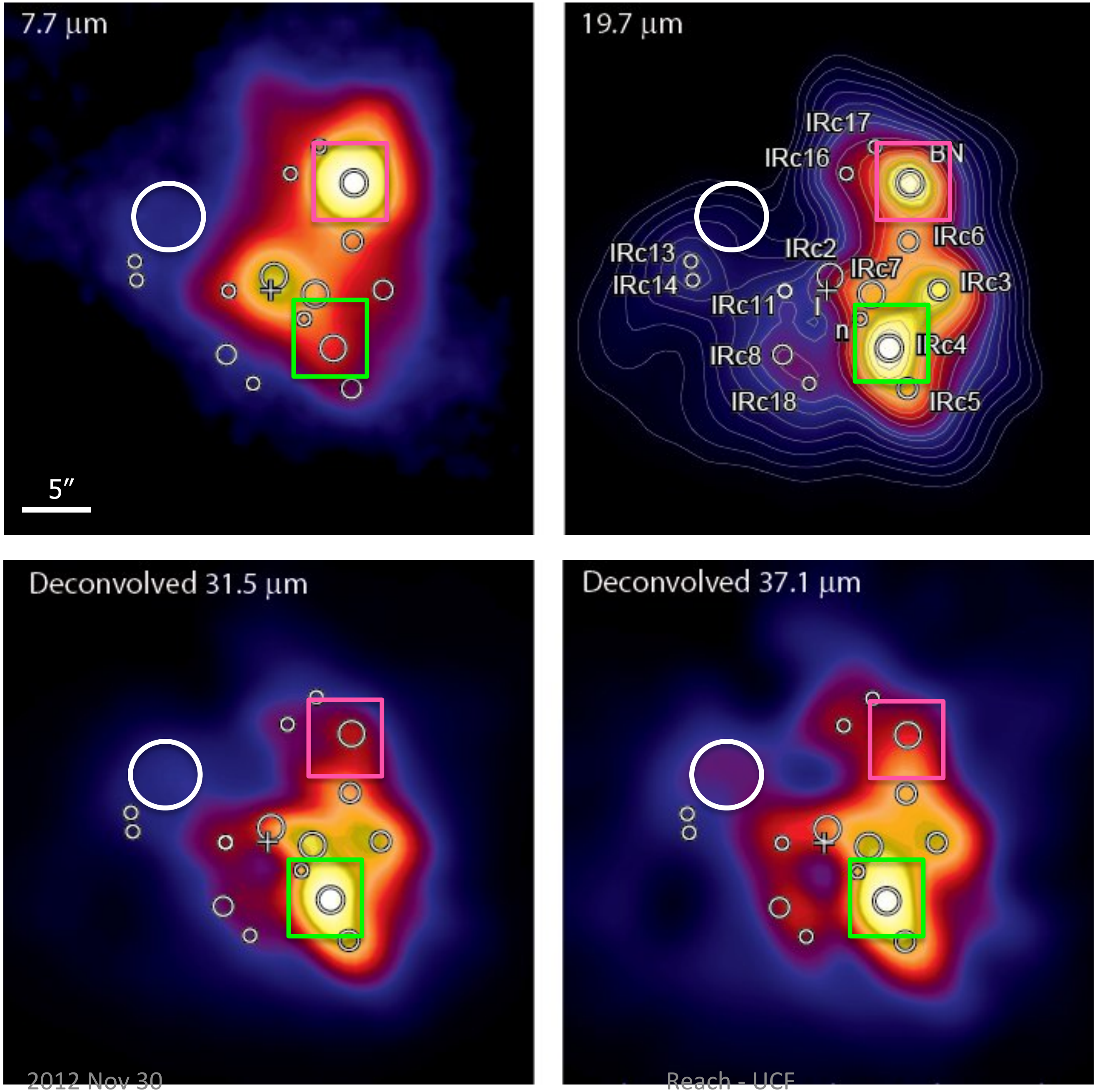
Blue=19um Green=31um Red=37um



(Stacey et al. 1995)

De Buizer et al. (2012)

Background Image:Spitzer



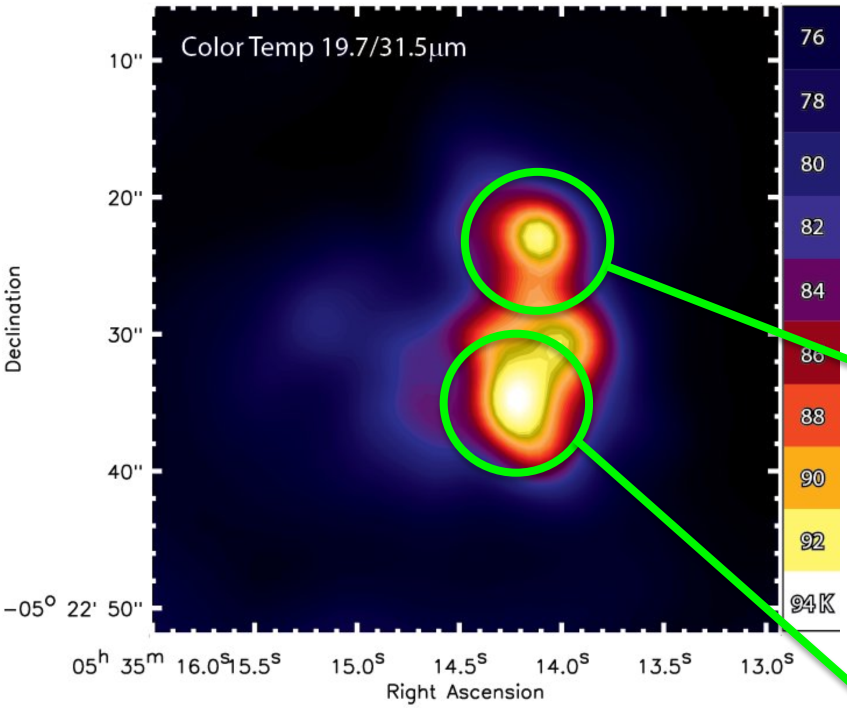
BN declines in prominence at longer λ's

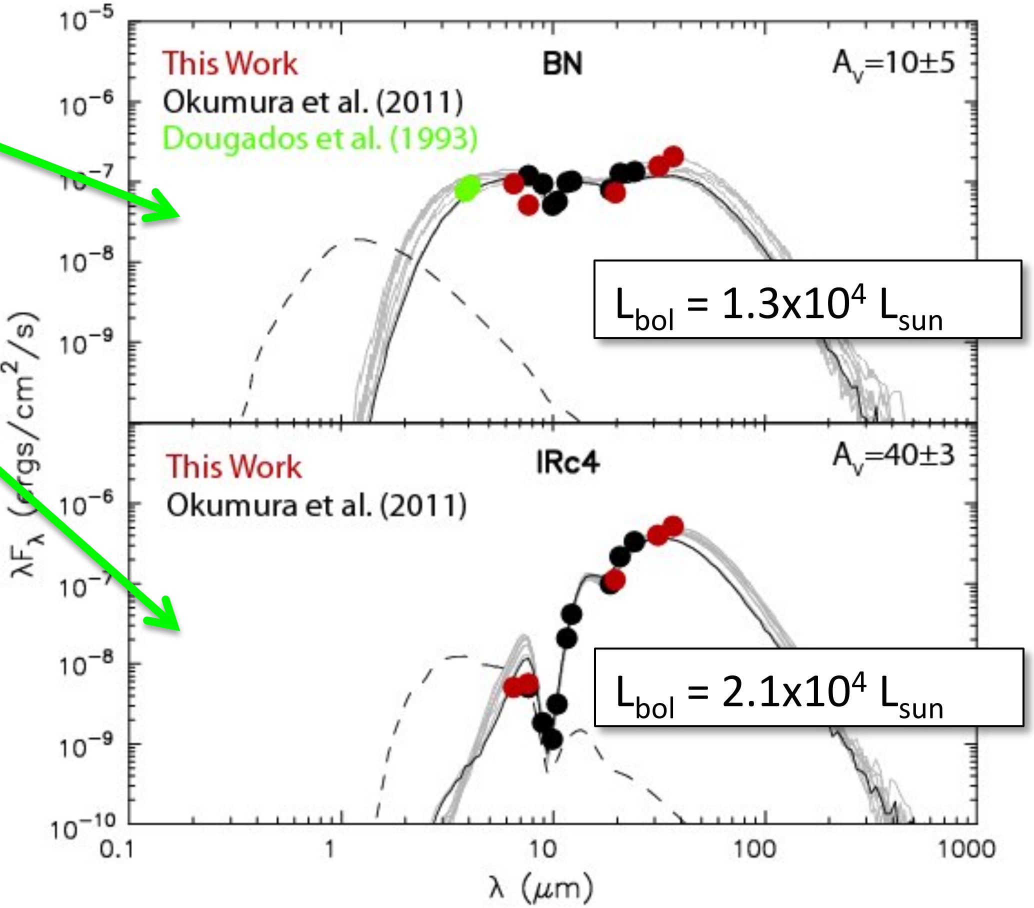
IRc4 dominates at λ >31um

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

De Buizer et al. (2012)

Like BN, IRc4 is a self-luminous source





L_{bol} = 1.3x10^4 L_{sun}

L_{bol} = 2.1x10^4 L_{sun}

IRc4 luminosity is too high to be caused by externally heating

BN+IRc4 account for ~50% of the ~10^5 L_{sun} of the BN/KL region

De Buizer et al. (2012)

FIRST LIGHT INFRARED TEST EXPERIMENT CAMERA: FLITECAM

Facility 1 to 5.5 μm imager/spectrometer

- Detector: InSb ALADDIN II, 1024 × 1024 pixels
- Seeing limited imaging: plate scale 0.47"/pixel, 8' FOV
  - **Continuum: J, H, K, K_{long},, L, L', M**
  - **Lines: e.g. Pa α (1.88 μm), Br β 2.63 μm imaging**
- Grism Spectroscopy: R~1300 with 2" wide slit (variable slit width from 1" → ≥ 15")
- **8' FOV efficient narrow-band imaging (Pa α, Br β, PAHs)**
- **Survey the stellar populations embedded in star forming regions (e. g. Orion or M 16).**

FLITECAM Spectral Passbands

Wavelength range: **1 - 5.5 µm**

Direct imaging mode, and grism spectroscopy mode.

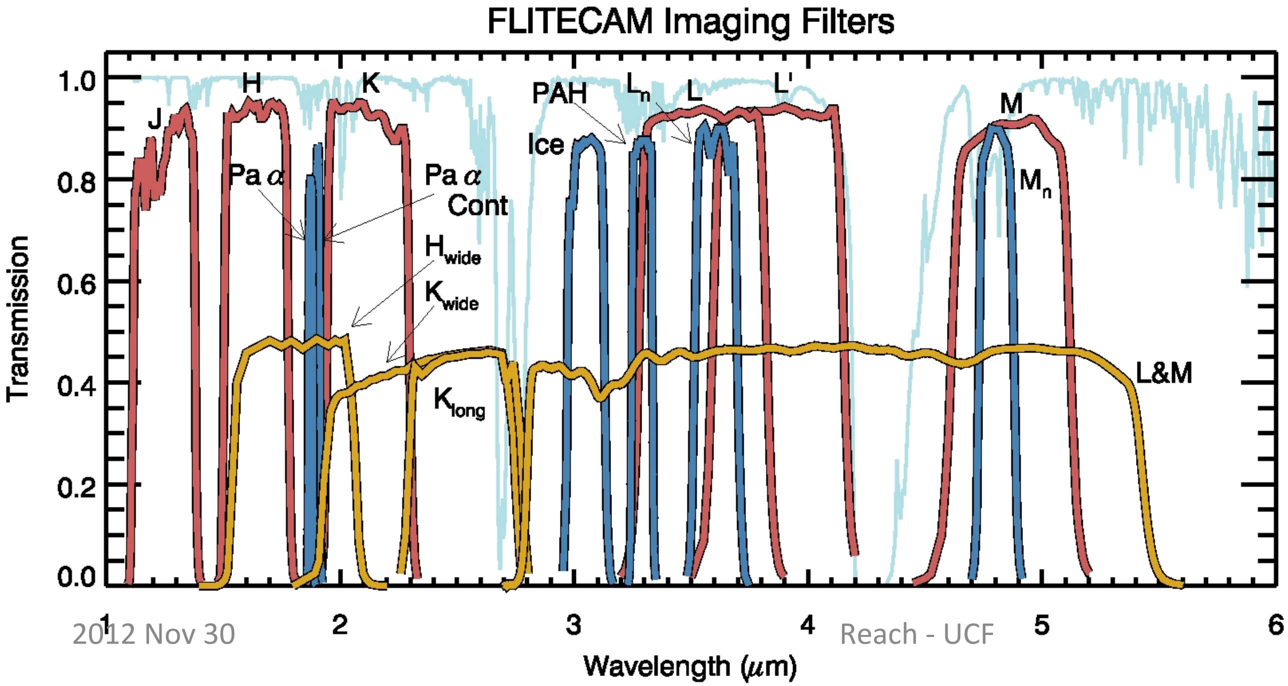
High-speed imaging at ~12 full frames per second, or 16x8 subframe at ~30 kHz.

Broadband imaging filters:

- Standard J, H, K, L', M passbands
- "KL" : 2.3 - 3.3 µm

Capability to use narrow-band filters e.g.:

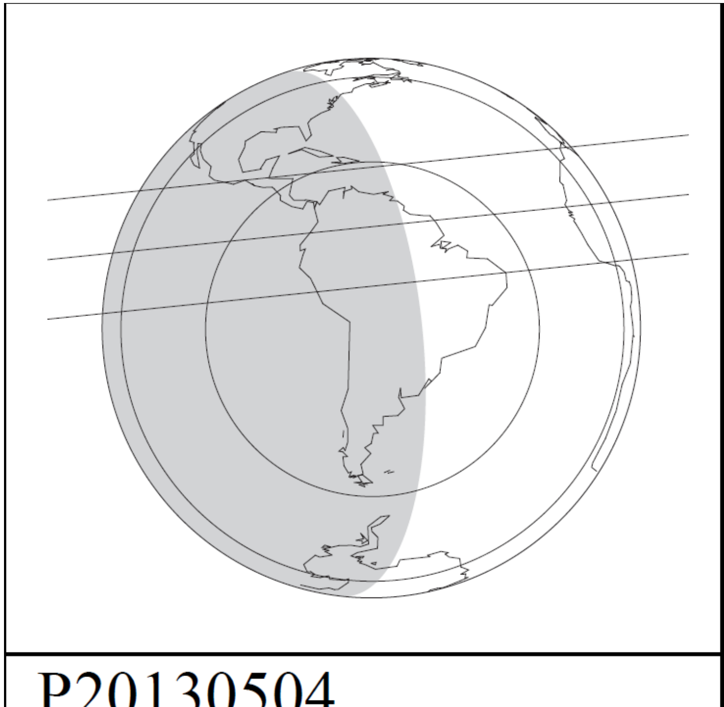
C_2 :	1.4, 1.8 µm
Paschen α :	1.88 µm
Brackett δ :	1.96 µm
C_2H_2 :	2.0, 2.4, 2.6, 3.0, 3.8 µm
Brackett β :	2.63 µm
PAH:	3.3, 5.2 µm
HCN:	3.5 µm



In-flight atmospheric transmission at grism resolution R = 2000, with planned broadband filter passbands, and grism orders indicated by labeled horizontal bars.

HIGH-SPEED IMAGING PHOTOMETER FOR OCCULTATIONS: HIPO

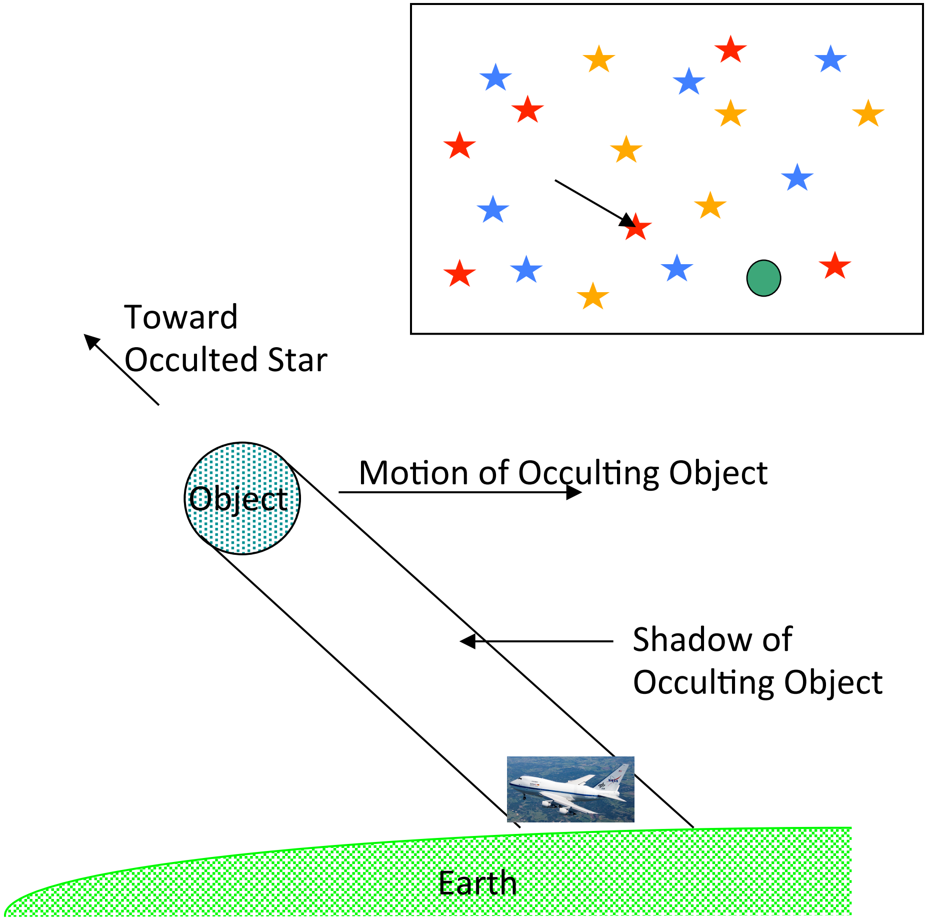
- **Dual-channel CCD Occultation photometer**
  - Detectors: Two Marconi CCD47-20, 1024 × 1024 pixels
  - Seeing limited imaging: plate scale 0.33"/pixel, 5.6' FOV
  - Precise Photometry: Very low scintillation noise, stable PSF
  - Mobility: SOFIA allows observations from almost anywhere
- **Can co-mount with FLITECAM**
  - **Visible + Near-infrared atmospheric profile**



Occultation Astronomy with SOFIA

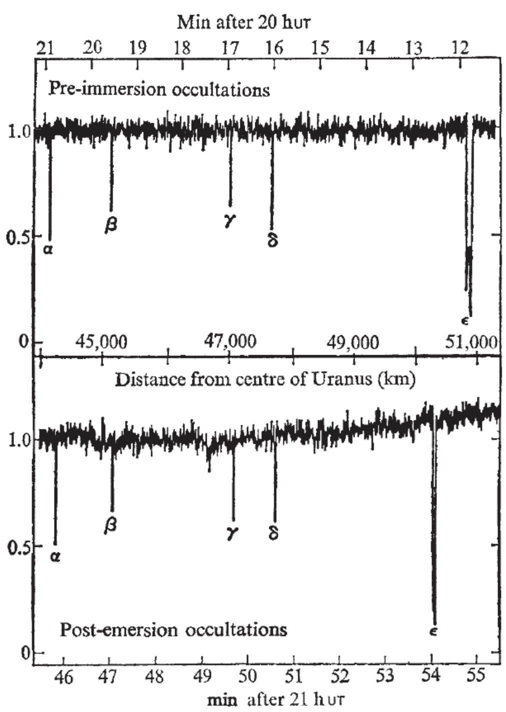
How will SOFIA help determine the properties of small Solar System bodies?

- 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: Rings and Moons

Uranus' Rings: The Story of a Discovery



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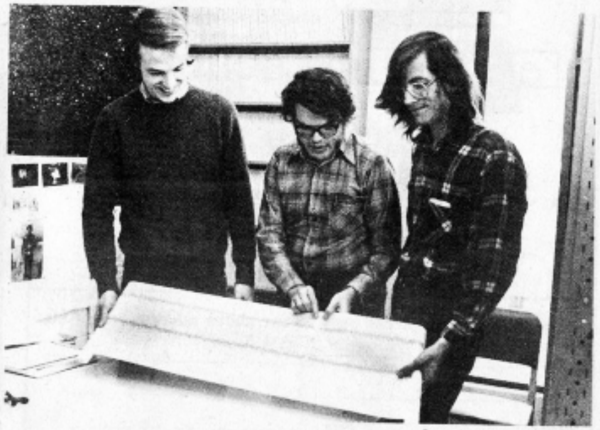
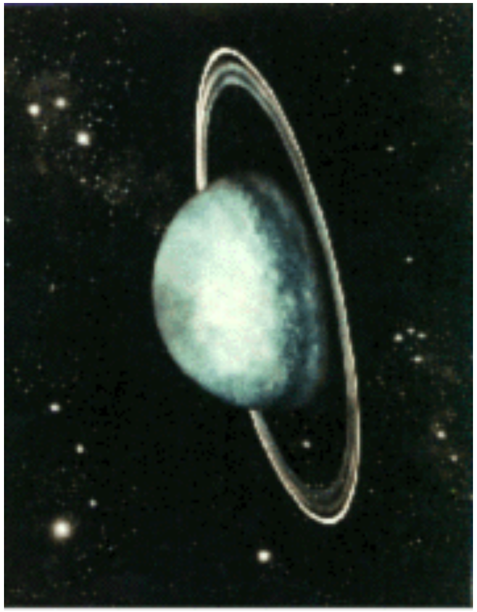


—Sun Photo by Liz Warner

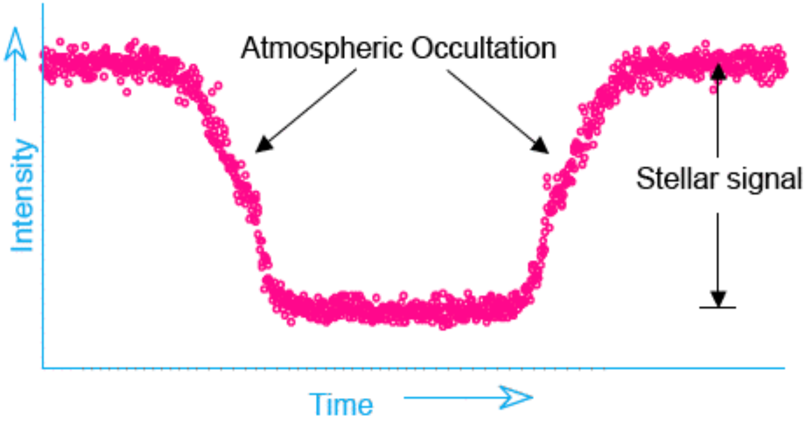
THE TEAM: Researchers Edward Dunham (l.), James Elliot, and Douglas Mink examine the unexpected signal pattern produced on the charter recorder by the outermost ring of Uranus.



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

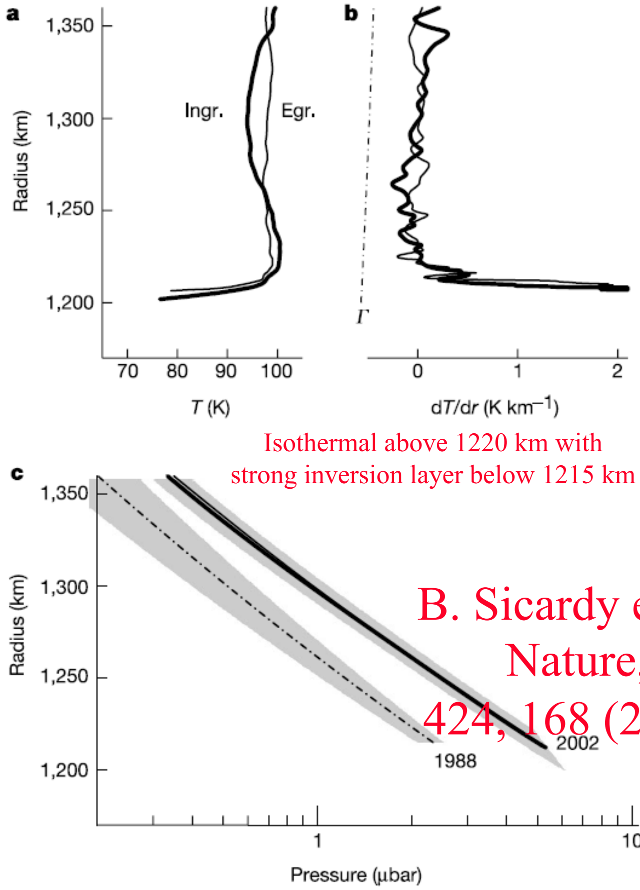
J. L. Elliot, E. Dunham, and D. Mink, Nature 267, 328-330 (1977)

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, and we take into account the curvature of Pluto’s limb as well as the variation

Echelon Cross-Echelle Spectrograph EXES

Wavelength range: **5 - 28 μm**

Three Resolving Powers:

High: ~ 10^5
Medium: ~ 10^4
Low: ~3000

The resolving power plotted corresponds to the FWHM of the instrument line spread function for a monochromatic line from a point source.

Wavelength changes require about 3 minutes.

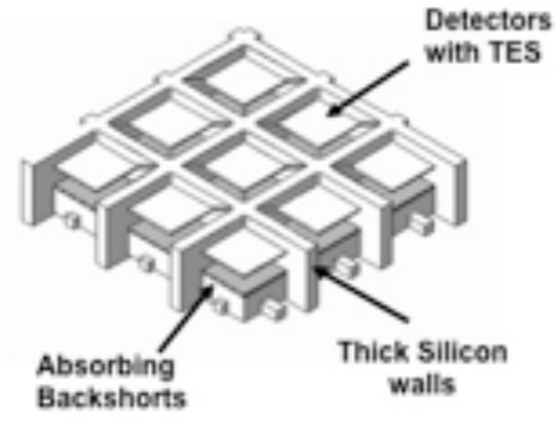
Resolution change requires about 3 minutes.

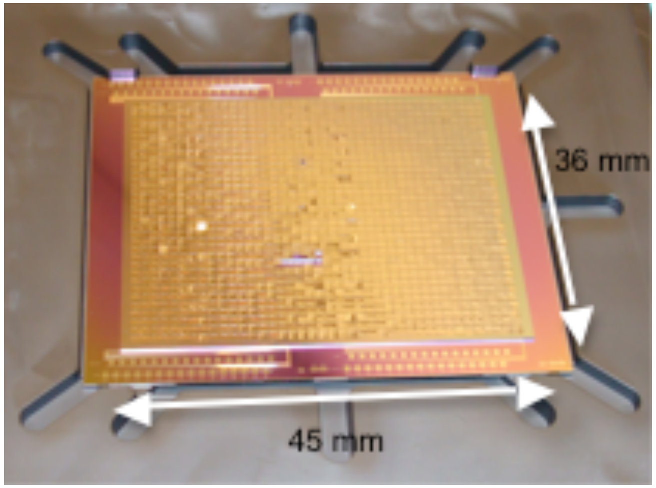
High-resolution Airborne Wideband Camera

HAWC+

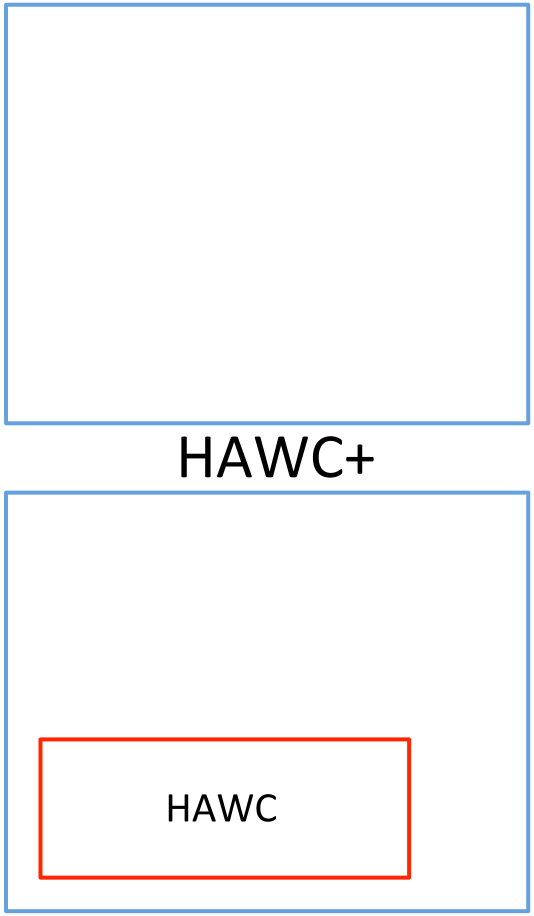
- HAWC was one of the 1st generation has been completed under leadershi (Yerkes Observatory, U. Chicago)
  - Far-infrared imaging 40-300 µm
  - Bolometer array
- As a result of a 2nd generation instrument announcement of opportunity, an upgrade to HAWC was selected with new leader Darren Dowell (JPL) with detector upgrade led by Johannes Staguhn (Johns Hopkins)
  - Polarization-sensitive imaging

BUGs for HAWC

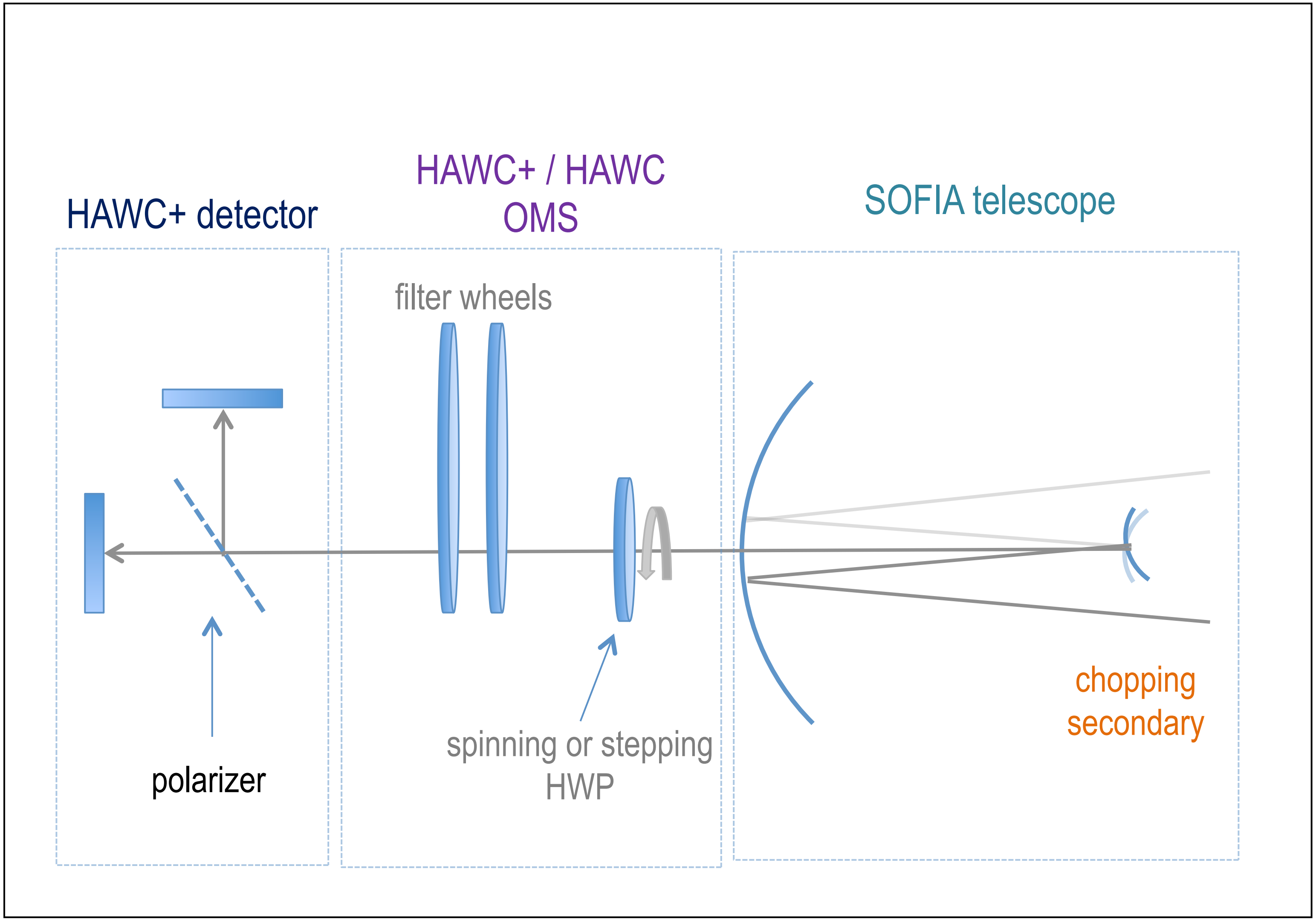




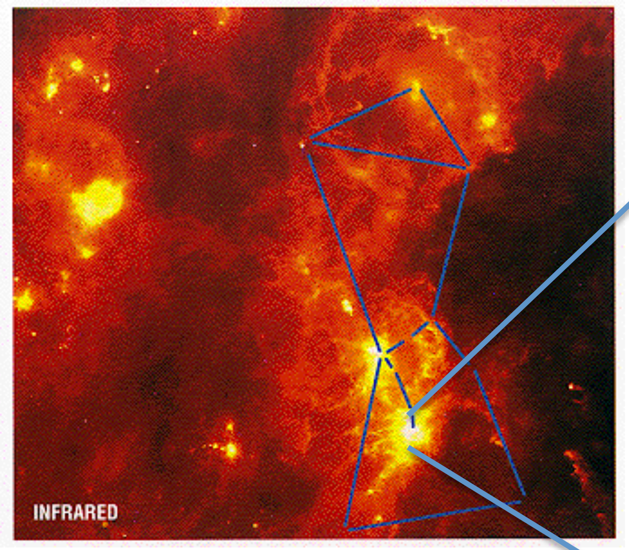
- Building on success with GISMO detector and instrument, Goddard detector group is making larger-format Backshort Under Grid detector arrays
  - Transition-Edge Sensors which hybridize with NIST SQUID multiplexers
  - 1.135 mm detector spacing
  - 32 × 40 detectors in each tile
- HAWC+: 2 tile field of view × 2 polarizations sampled



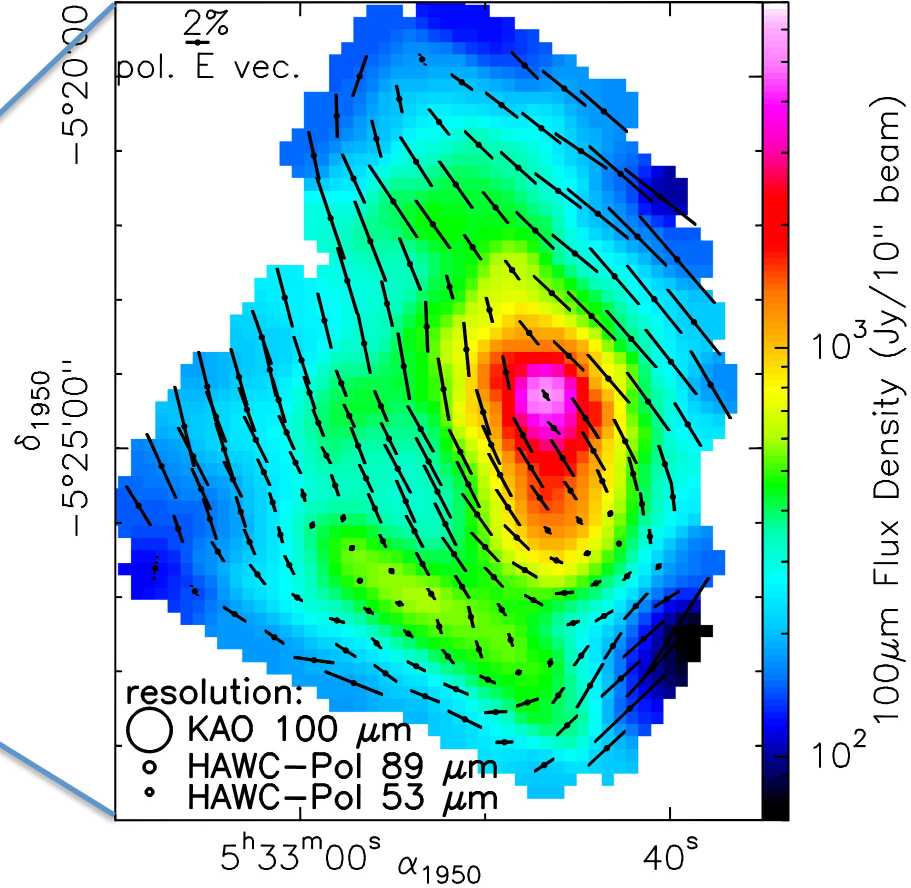
HAWC+ schematic optical path



HAWC+ Science Goals / Magnetic Fields in ISM



Orion Molecular Cloud, Kuiper Airborne Obs.

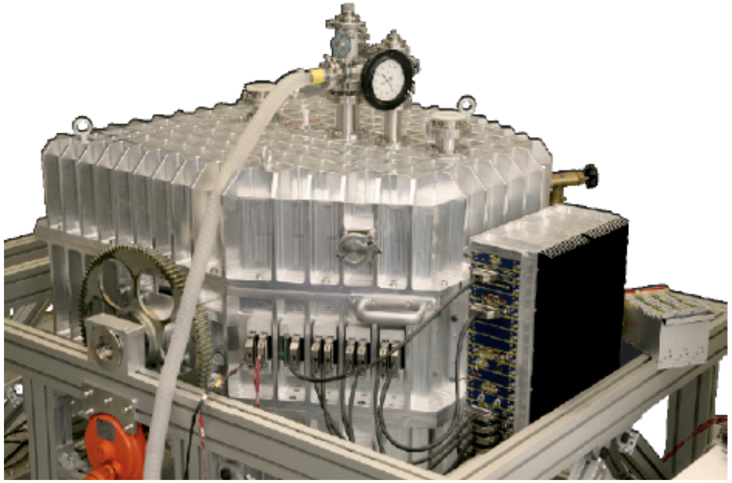


- Compared to previous facilities:
  - 7× more sensitive to extended emission (can reach $A_V \approx 1$)
  - 50× more sensitive to point sources
  - 10× better areal resolution
  - 20× as many imaging elements
  - 5 wavelength bands instead of 1

- tests of (ordered) magnetic field models
- statistical estimation of field strength (Chadrasekhar-Fermi)
- tests of grain alignment theory (Radiative Torque alignment)

FIFI-LS: Far-IR Spectrometer

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



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

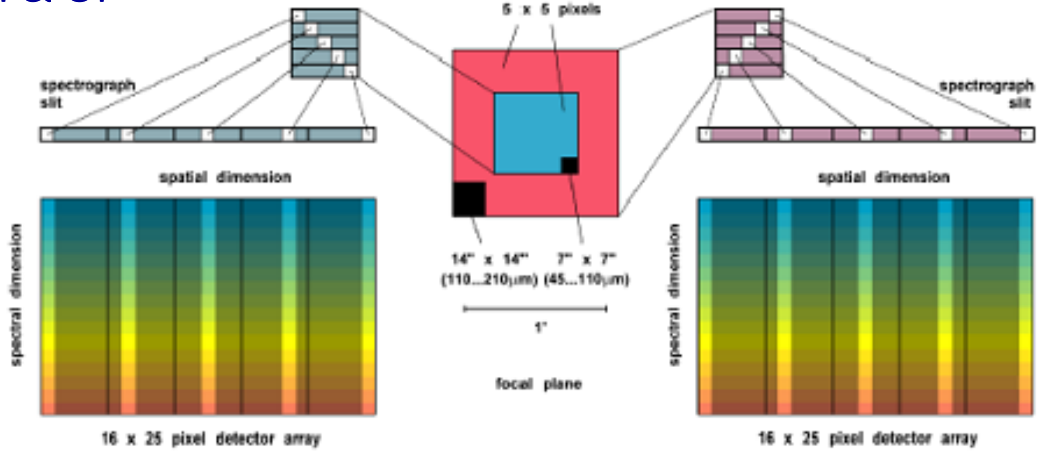
Field of View: 30” x 30” (blue), 60” x 60” (red)

R= 1500 - 6000

Science: Imaging of extragalactic CII & OI

Targets: Extragalactic imaging

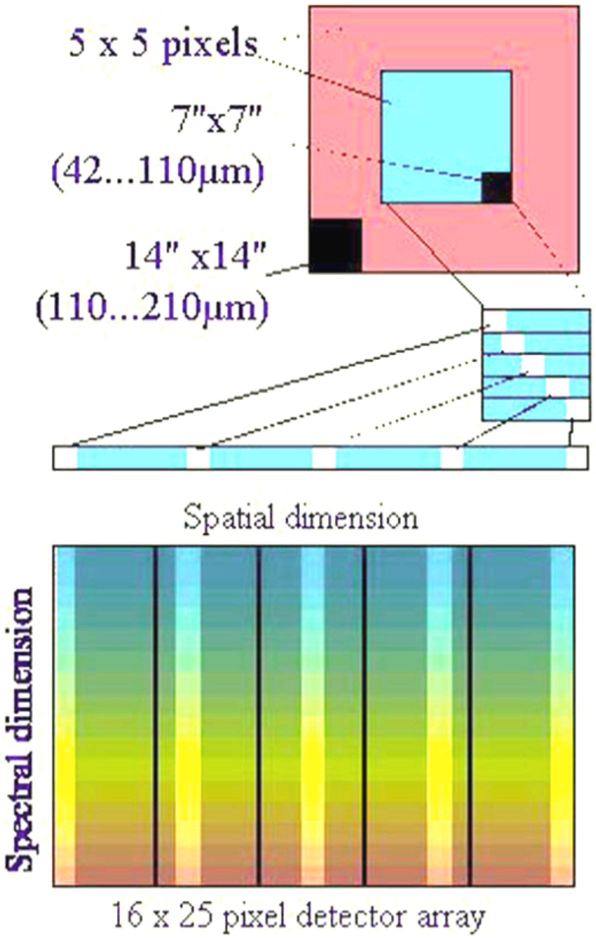
NB: Imaging array is
5 x 5 pixels

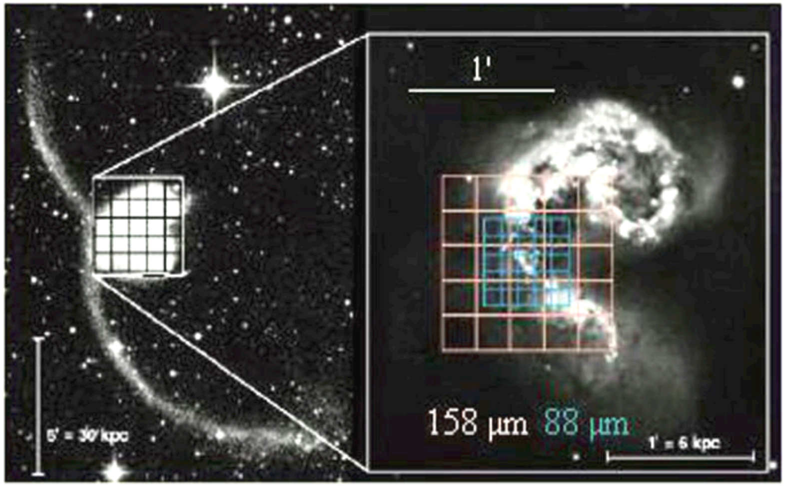


On sky orientation of ‘blue’ and ‘red’ channels

FIFI-LS Science Example:
C II Data Cube in Interacting Galaxies

NGC 4038/39 "Antennae": Star Formation Triggered in Interaction Zone

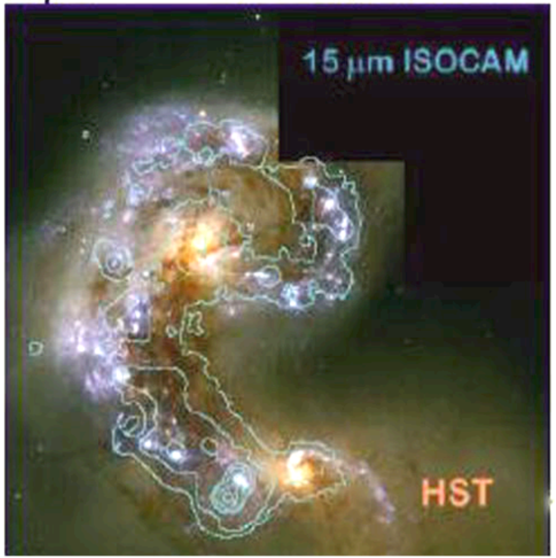




FIFI / KAO 158 µm

FIFI LS / SOFIA

FIFI LS: FIR spectral line imaging at a resolution comparable with ISOCAM in the MIR!



Involvement in SOFIA:
SOFIA was made for your discoveries!

- Observing proposals
  - Cycle N = Calendar 2012+N, due June 2011+N
  - Participate in the time allocation committee ☺
- Onboard observing
  - 1-2 guest investigators per flight
- SOFIA Users Group
  - Rotating committee of ~10 to advice Science Center
- SOFIA Community Task Force
  - Outreach telecons and biweekly "tele-talks"
- Town Hall, Splinter Sessions at AAS meetings
- First SOFIA Science Conference mid-2014