SOFIA (EXES/GREAT) observations of the Herbig Ae/Be stars

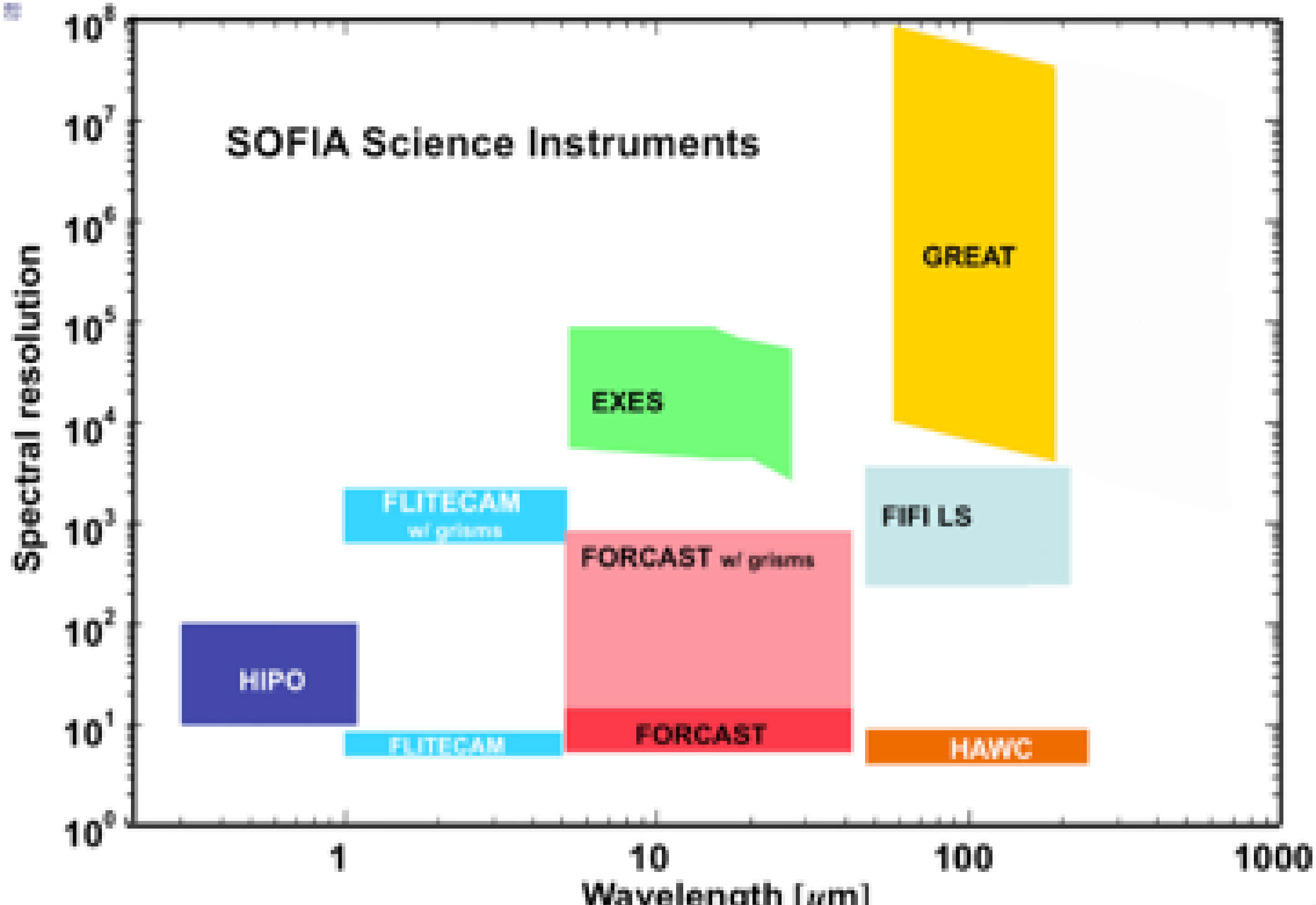
Hans Zinnecker
SOFIA Science Mission Operations
NASA-Ames/Univ. Stuttgart

Herbig Ae/Be star Workshop
ESO Santiago
10 April 2014

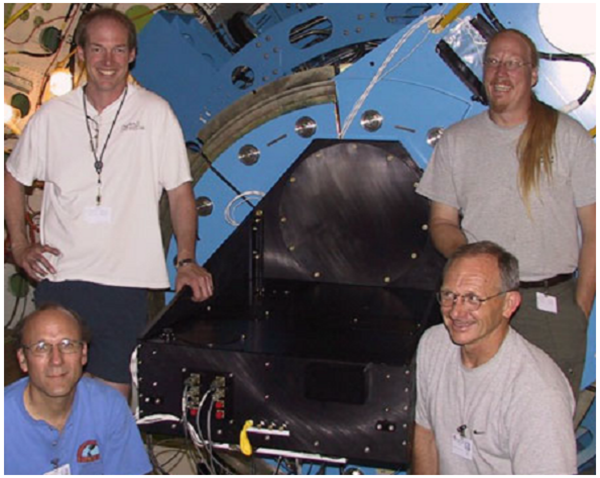
George Herbig in 1993 at Galaxy Hotel Amsterdam

http://www.sofia.usra.edu

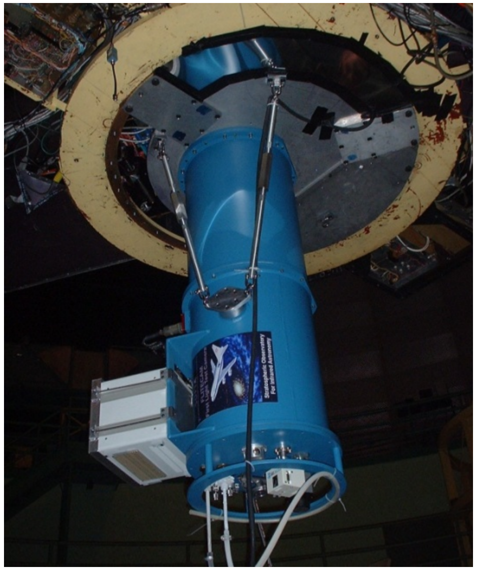
EXES niche within SOFIA



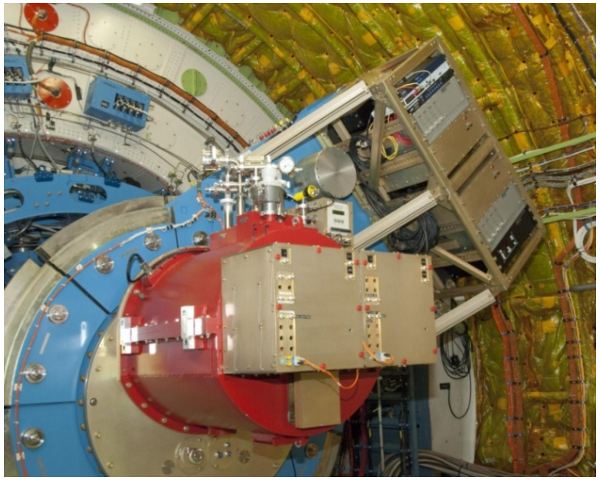
Four Completed 1st Generation Instruments



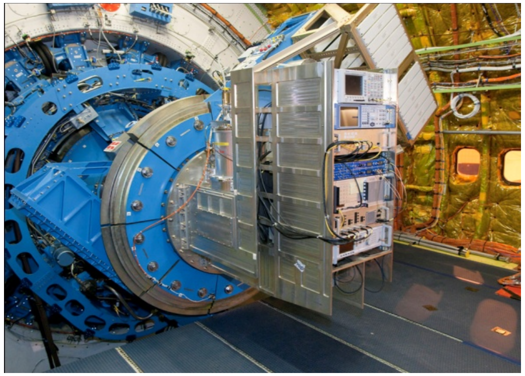
HIPO
High Speed Photometer
(on SOFIA)



FLITECAM
Near IR Camera
(at Lick observatory)



FORCAST
Mid-IR Camera
(on SOFIA)

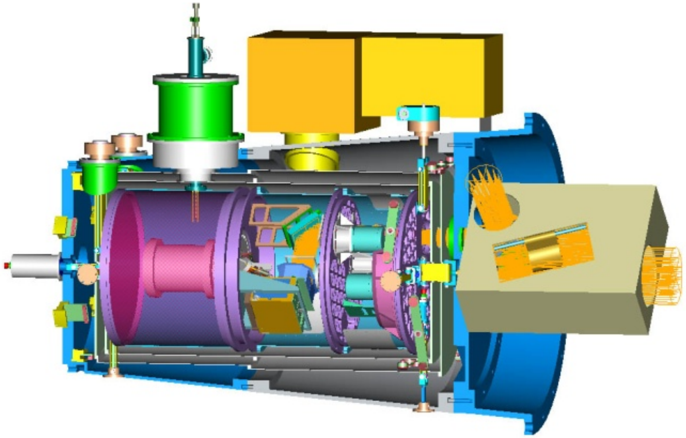


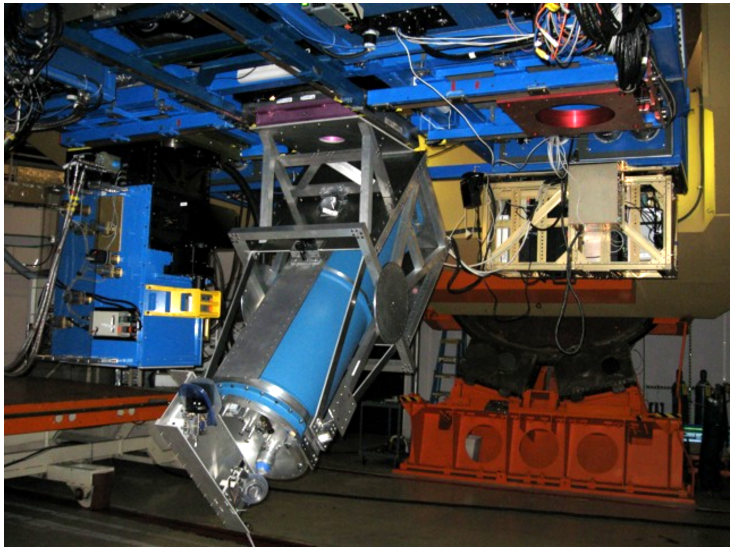
GREAT
Heterodyne spectrometer
(on SOFIA)

Instruments in development

HAWC

Bolometer Camera



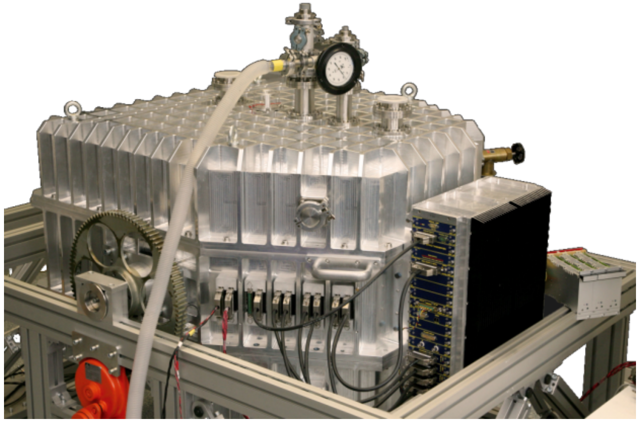


EXES

Mid- IR Spectrometer

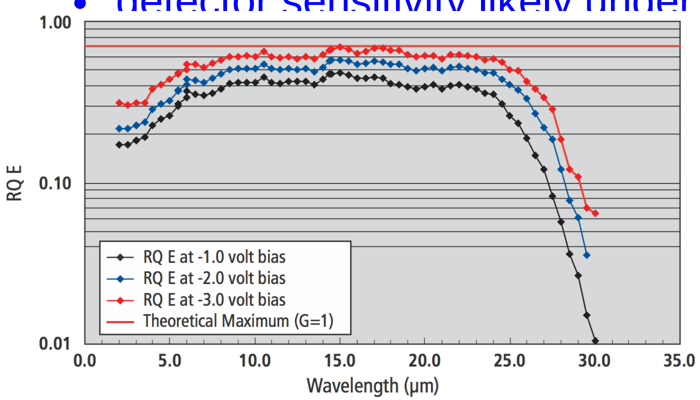
FIFI LS

Integral Field Spectrometer

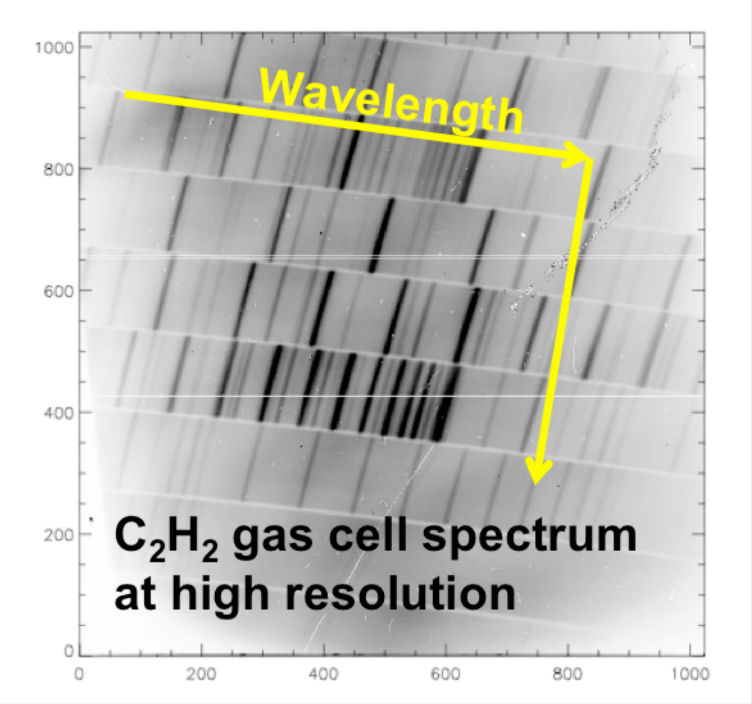


About EXES

- EXES is a PI instrument optimized for high spectral resolution in mid-IR
  - High resolution mode:
    - cross-dispersed with R = 50,000 to 110,000 depending on slit width
    - single setting coverage of ~1% with 4-40” long slit or ~4% with 2-3” long slit
  - Other spectral modes
    - R ~ 5,000 to 20,000
    - R ~ 1000 to 3000
  - imaging for slit-positioning and pupil
- Wavelength range set by detector and science
  - shortest wavelength (~4.5 μm): CO Δv=1
  - longest wavelength (~28.3 μm): H_2 J=2-0
    - detector sensitivity likely under 10% for H_2

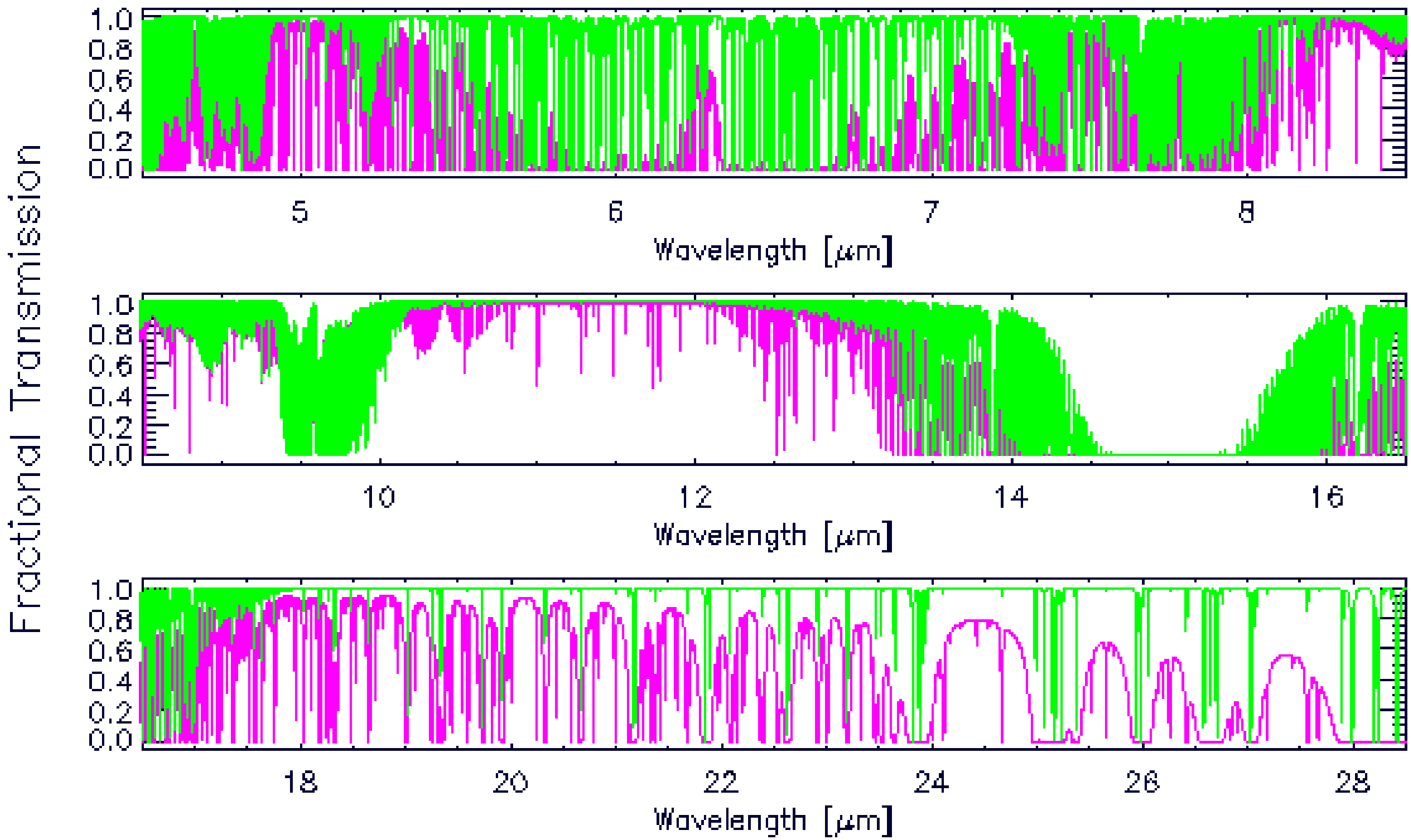


Spectral response of a device similar to EXES’s detector



Atmospheric comparison (EXES 5-28mu)

SOFIA vs Mauna Kea



SOFIA/EXES and molecules

Low lying pure rotational transitions of H_2

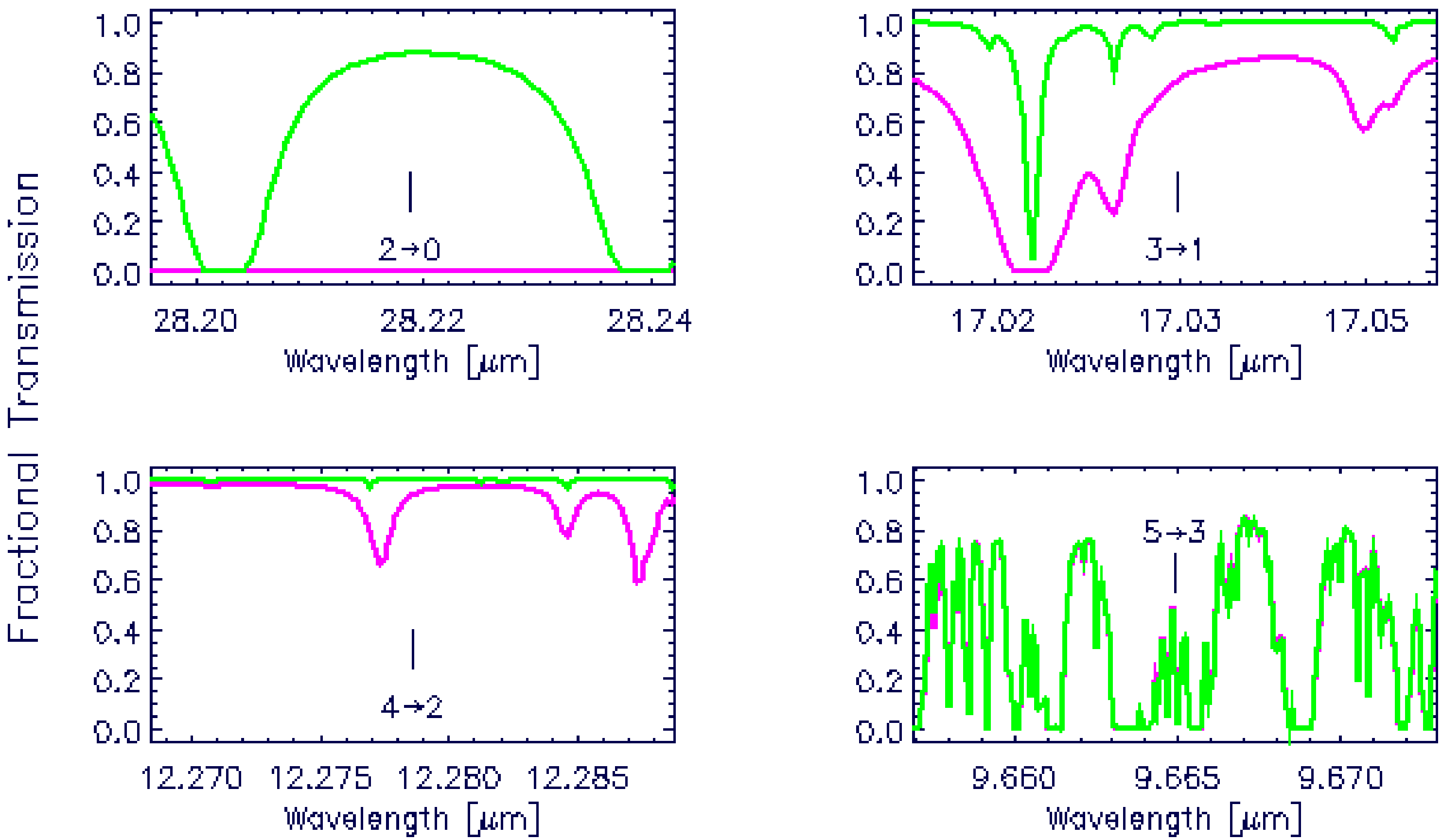
- S(1), S(2), S(4) observable from the ground (TEXES)
  - SOFIA makes these better
  - AB Aurigae TEXES observations (Bitner et al. 2007)
- S(0), S(5), S(6) only observable from SOFIA
- S(3) very difficult anywhere

Other important molecules such as H_2O, CH_4, CH_3, C_2H_2, HCN, and SO_2 are much better from SOFIA (if ~10 Jy)

- C_2H_2 Q-branch observed from ground
- Might try CH_3 ("Mrs. Angela Merkel's molecule")
  Q-branch (16.5mu) in commissioning TONIGHT

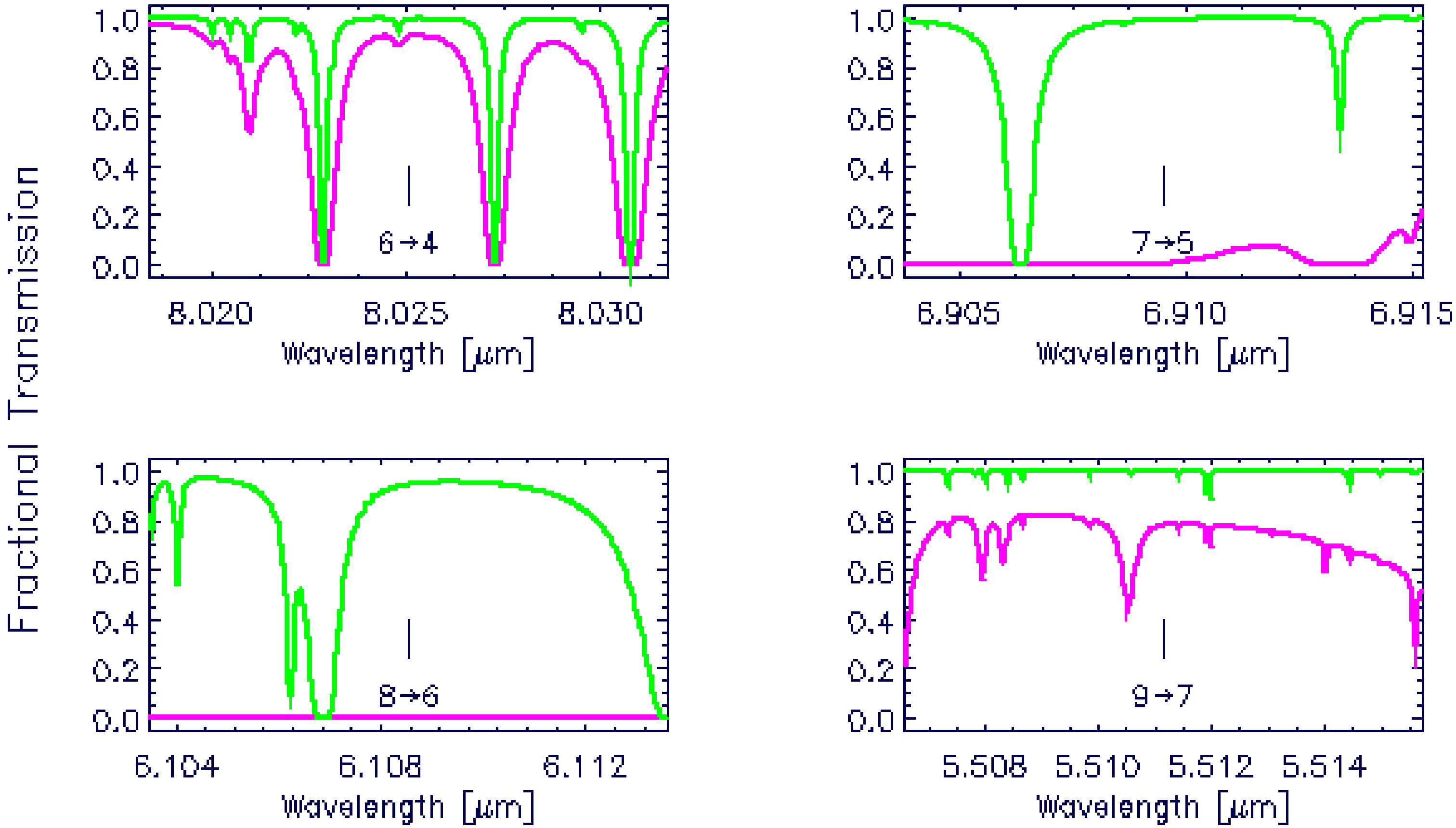
H_2 observations: atmospheric comparison

SOFIA vs Mauna Kea

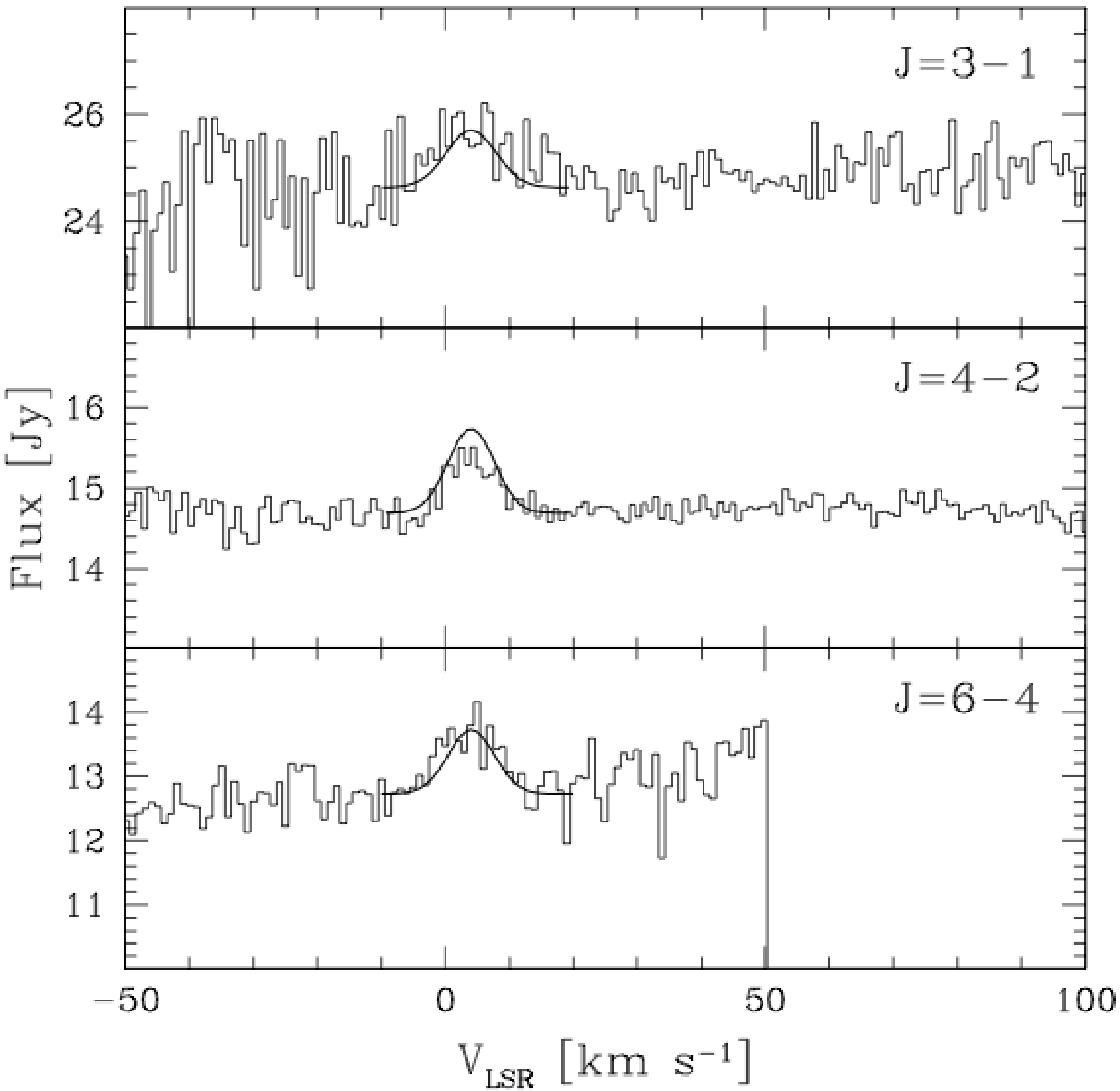


H_2 observations: atmospheric comparison

SOFIA vs Mauna Kea



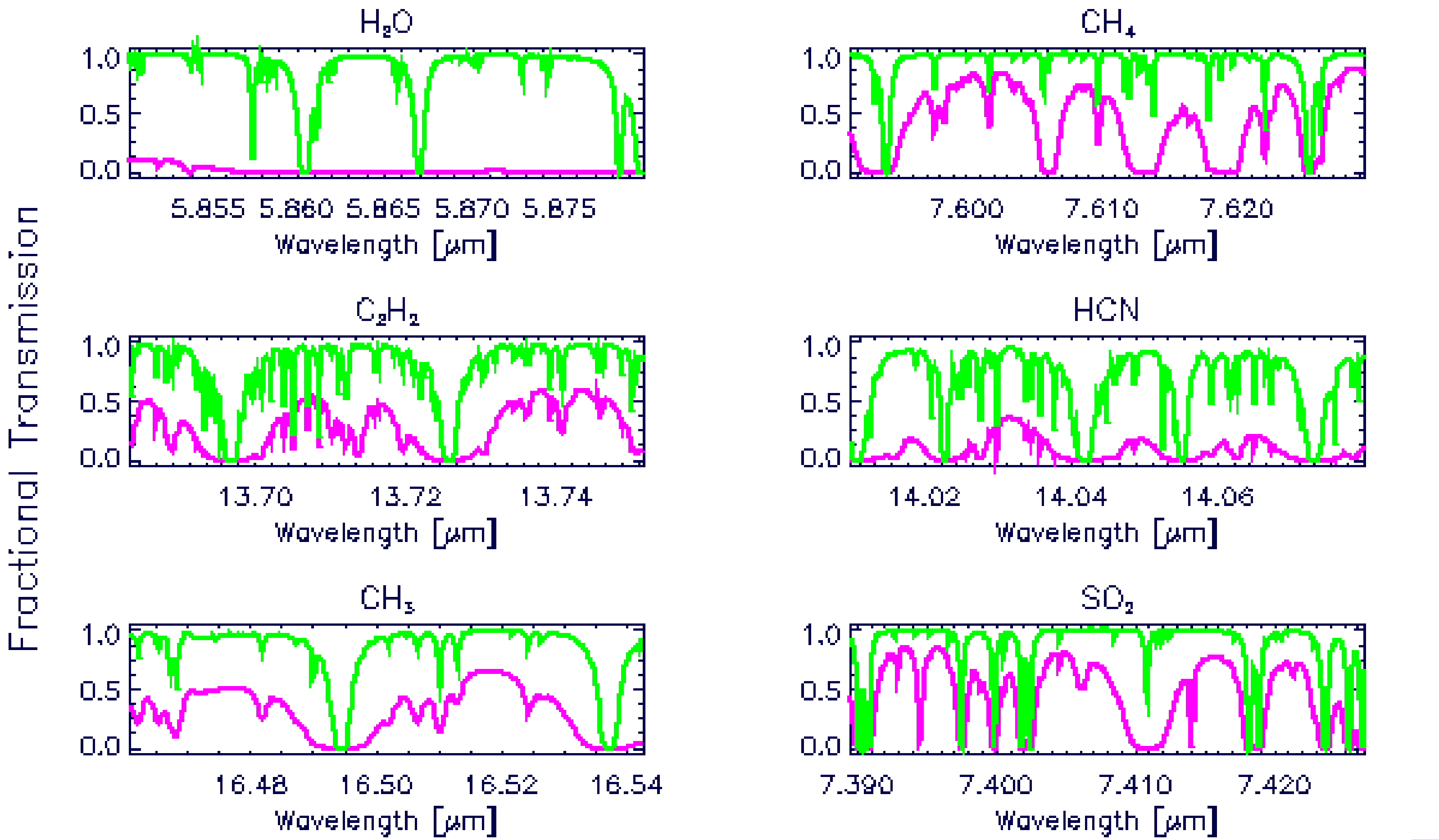
OBSERVATIONS OF H_2 EMISSION FROM AB AURIGAE



Bitner et al. (2007)

Other molecules

SOFIA vs Mauna Kea



EXES Science: circumstellar disk chemistry

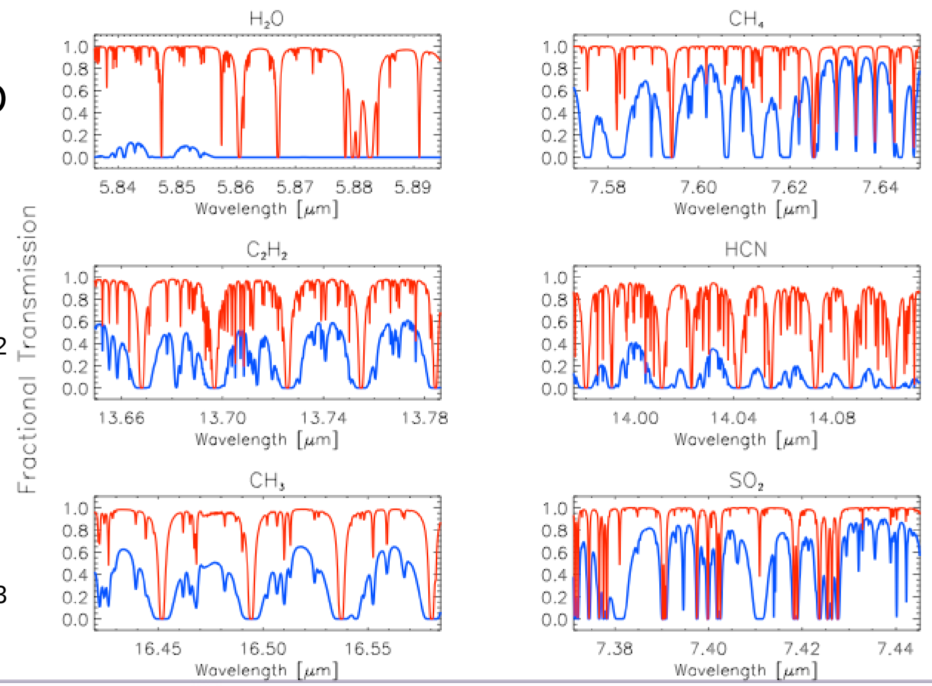
- high-spectral resolution obs. in mid-IR inaccessible from ground
- capabilities not available with Spitzer, JWST or Herschel
- complements ALMA through molecules with no dipole moment (H_2, CH_4, C_2H_2, CH_3)

WATER in HAeBe disks?

Comparison of transmission from **SOFIA** and **Mauna Kea** for some important molecules

EXES velocity-resolved line profiles pinpoint origin of molecular emission/abs. (aka disk chemistry, Lacy).

H_2O C_2H_2 CH_3

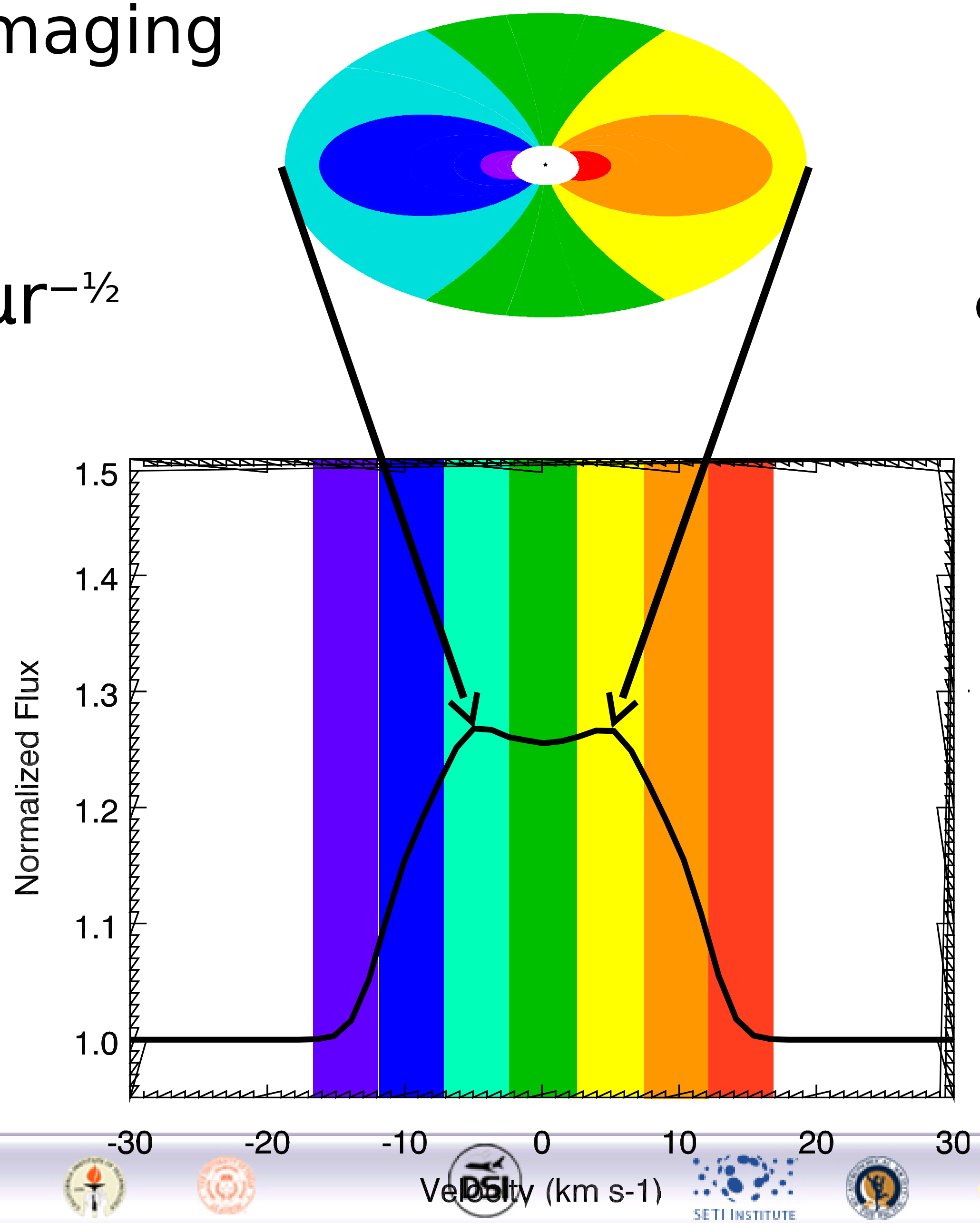


CH_4 HCN SO_2

Spectrally Resolved Lines as Surrogates for High Resolution Imaging

$v(M_*, i, r) \propto r^{-1/2}$

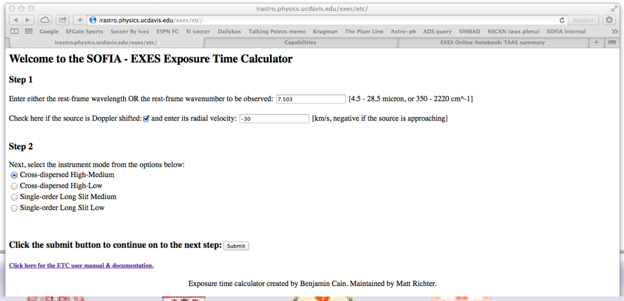
Courtesy Sean Brittain



(See Smak 1981)

EXES Exposure Time Calculator

- Have functional EXES Exposure Time Calculator for planning observations.
  - *http://irastro.physics.ucdavis.edu/exes/etc/*
- User steps through three pages
  - observing wavelength and instrument configuration
  - grating order, slit width, aircraft altitude, observing mode, desired S/N, source brightness
  - summary of input with calculated integration time, clock time, and electron rates. Downloadable text file.



irastro.physics.ucdavis.edu/exes/etc/

Welcome to the SOFIA - EXES Exposure Time Calculator

Step 1

Enter either the rest-frame wavelength OR the rest-frame wavenumber to be observed: 7.503 [4.5 - 28.5 micron, or 350 - 2220 cm^-1]

Check here if the source is Doppler shifted: ☑ and enter its radial velocity: -30 [km/s, negative if the source is approaching]

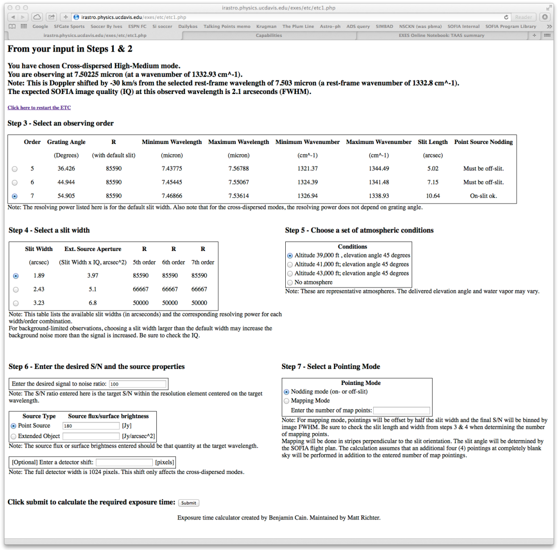
Step 2

Next, select the instrument mode from the options below:
- (•) Cross-dispersed High-Medium
- ( ) Cross-dispersed High-Low
- ( ) Single-order Long Slit Medium
- ( ) Single-order Long Slit Low

Click the submit button to continue on to the next step: Submit

Click here for the ETC user manual & documentation.

Exposure time calculator created by Benjamin Cain. Maintained by Matt Richter.



irastro.physics.ucdavis.edu/exes/etc/etc1.php

From your input in Steps 1 & 2

You have chosen Cross-dispersed High-Medium mode.
You are observing at 7.50225 micron (at a wavenumber of 1332.93 cm^-1).
Note: This is Doppler shifted by -30 km/s from the selected rest-frame wavelength of 7.503 micron (a rest-frame wavenumber of 1332.8 cm^-1).
The expected SOFIA image quality (IQ) at this observed wavelength is 2.1 arcseconds (FWHM).

Click here to restart the ETC

Step 3 - Select an observing order

	Order	Grating Angle	R	Minimum Wavelength	Maximum Wavelength	Minimum Wavenumber	Maximum Wavenumber	Slit Length	Point Source Nodding
		(Degrees)	(with default slit)	(micron)	(micron)	(cm^-1)	(cm^-1)	(arcsec)	
( )	5	36.426	85590	7.43775	7.56788	1321.37	1344.49	5.02	Must be off-slit.
( )	6	44.944	85590	7.45445	7.55067	1324.39	1341.48	7.15	Must be off-slit.
(•)	7	54.905	85590	7.46866	7.53614	1326.94	1338.93	10.64	On-slit ok.

Note: The resolving power listed here is for the default slit width. Also note that for the cross-dispersed modes, the resolving power does not depend on grating angle.

Step 4 - Select a slit width

	Slit Width	Ext. Source Aperture	R	R	R
	(arcsec)	(Slit Width x IQ, arcsec^2)	5th order	6th order	7th order
(•)	1.89	3.97	85590	85590	85590
( )	2.43	5.1	66667	66667	66667
( )	3.23	6.8	50000	50000	50000

Note: This table lists the available slit widths (in arcseconds) and the corresponding resolving power for each width/order combination.
For background-limited observations, choosing a slit width larger than the default width may increase the background noise more than the signal is increased. Be sure to check the IQ.

Step 5 - Choose a set of atmospheric conditions

Conditions
- (•) Altitude 39,000 ft , elevation angle 45 degrees
- ( ) Altitude 41,000 ft; elevation angle 45 degrees
- ( ) Altitude 43,000 ft; elevation angle 45 degrees
- ( ) No atmosphere

Note: These are representative atmospheres. The delivered elevation angle and water vapor may vary.

Step 6 - Enter the desired S/N and the source properties

Enter the desired signal to noise ratio: 100

Note: The S/N ratio entered here is the target S/N within the resolution element centered on the target wavelength.

Source Type	Source flux/surface brightness	
(•) Point Source	180	[Jy]
( ) Extended Object		[Jy/arcsec^2]

Note: The source flux or surface brightness entered should be that quantity at the target wavelength.

[Optional] Enter a detector shift: [pixels]

Note: The full detector width is 1024 pixels. This shift only affects the cross-dispersed modes.

Step 7 - Select a Pointing Mode

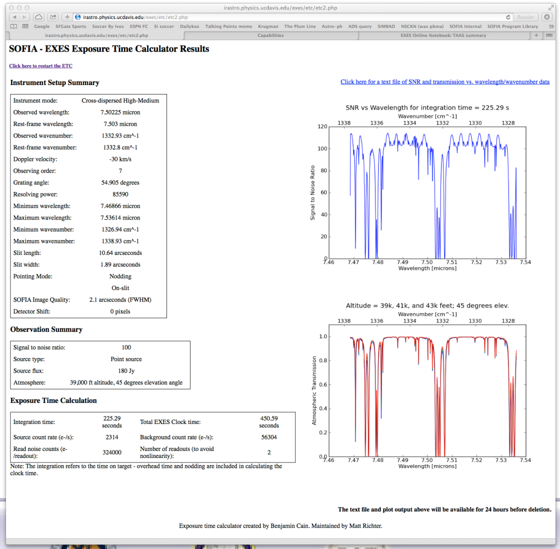
Pointing Mode
- (•) Nodding mode (on- or off-slit)
- ( ) Mapping Mode

Enter the number of map points:

Note: For mapping mode, pointings will be offset by half the slit width and the final S/N will be binned by image FWHM. Be sure to check the slit length and width from steps 3 & 4 when determining the number of mapping points.
Mapping will be done in stripes perpendicular to the slit orientation. The slit angle will be determined by the SOFIA flight plan. The calculation assumes that an additional four (4) pointings at completely blank sky will be performed in addition to the entered number of map pointings.

Click submit to calculate the required exposure time: Submit

Exposure time calculator created by Benjamin Cain. Maintained by Matt Richter.



irastro.physics.ucdavis.edu/exes/etc/etc2.php

SOFIA - EXES Exposure Time Calculator Results

Click here to restart the ETC

Instrument Setup Summary

Click here for a text file of SNR and transmission vs. wavelength/wavenumber data

Instrument mode:	Cross-dispersed High-Medium
Observed wavelength:	7.50225 micron
Rest-frame wavelength:	7.503 micron
Observed wavenumber:	1332.93 cm^-1
Rest-frame wavenumber:	1332.8 cm^-1
Doppler velocity:	-30 km/s
Observing order:	7
Grating angle:	54.905 degrees
Resolving power:	85590
Minimum wavelength:	7.46866 micron
Maximum wavelength:	7.53614 micron
Minimum wavenumber:	1326.94 cm^-1
Maximum wavenumber:	1338.93 cm^-1
Slit length:	10.64 arcseconds
Slit width:	1.89 arcseconds
Pointing Mode:	Nodding On-slit
SOFIA Image Quality:	2.1 arcseconds (FWHM)
Detector Shift:	0 pixels

Observation Summary

Signal to noise ratio:	100
Source type:	Point source
Source flux:	180 Jy
Atmosphere:	39,000 ft altitude, 45 degrees elevation angle

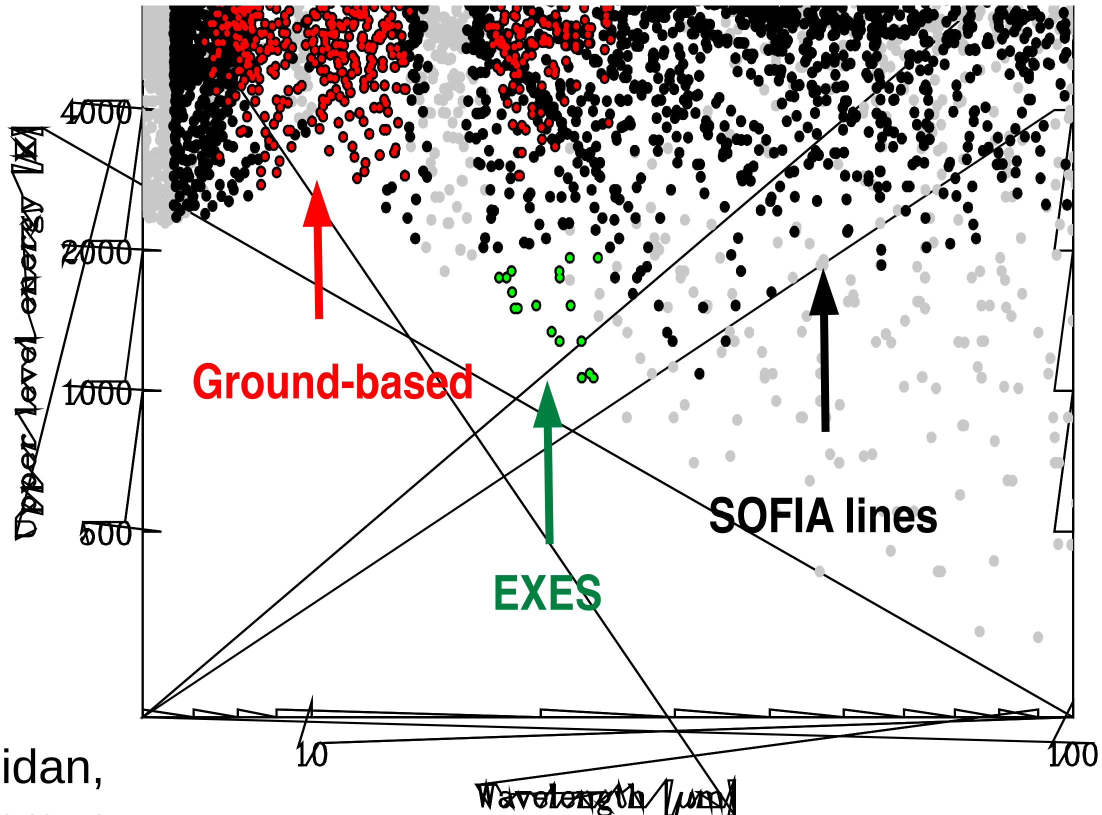
Exposure Time Calculation

Integration time:	225.29 seconds	Total EXES Clock time:	450.59 seconds
Source count rate (e-/s):	2314	Background count rate (e-/s):	56304
Read noise counts (e-/readout):	324000	Number of readouts (to avoid nonlinearity):	2

Note: The integration refers to the time on target - overhead time and nodding are included in calculating the clock time.

The text file and plot output above will be available for 24 hours before deletion.

Exposure time calculator created by Benjamin Cain. Maintained by Matt Richter.



Pontoppidan,
priv. commun.

Figure 1: Plot of all the strong ($A_{ul} > 10^{-2}\,\mathrm{s}^{-1}$) water lines in the mid-infrared in GREY. The BLACK points are the lines that get > 75% transmission at the line center at the SOFIA altitude of 40 000 feet, assuming a Doppler reflex motion of 30 $\mathrm{km\,s^{-1}}$. The RED points are the lines that can be reached from Mauna Kea. It is among the red points that we have selected our typical ground-based settings, including the TEXES observations. The GREEN points are those that can be targeted with EXES. It is seen that it

GREAT details

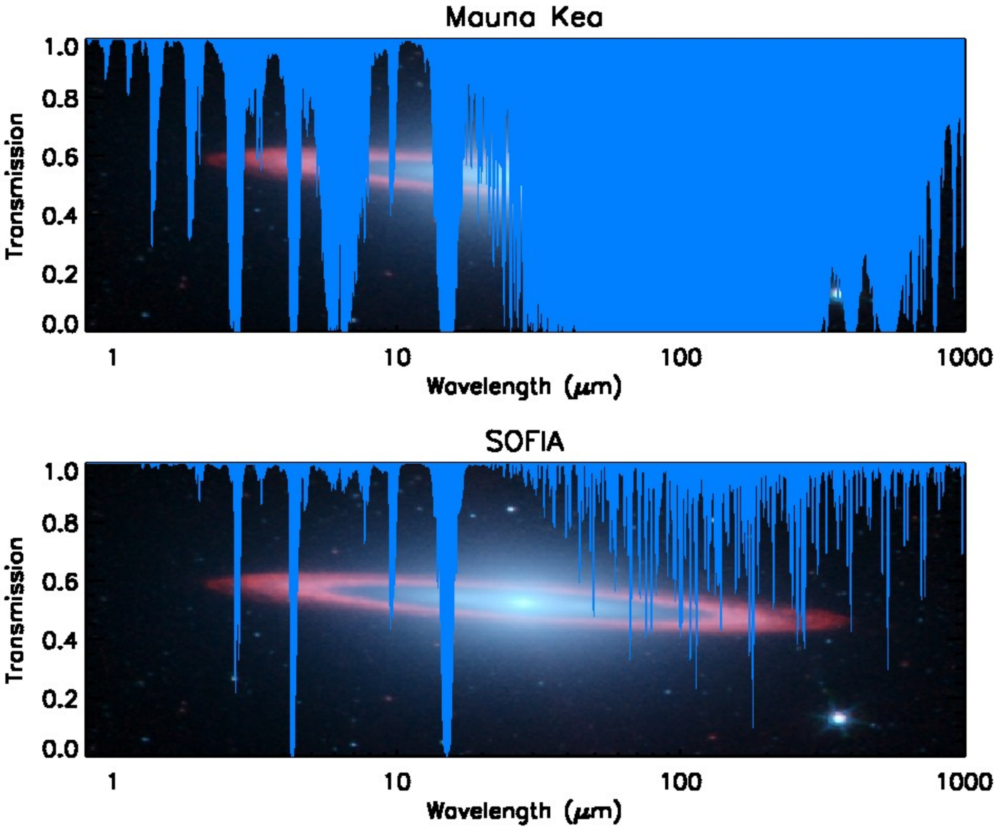
dual channel heterodyne spectrometer

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)

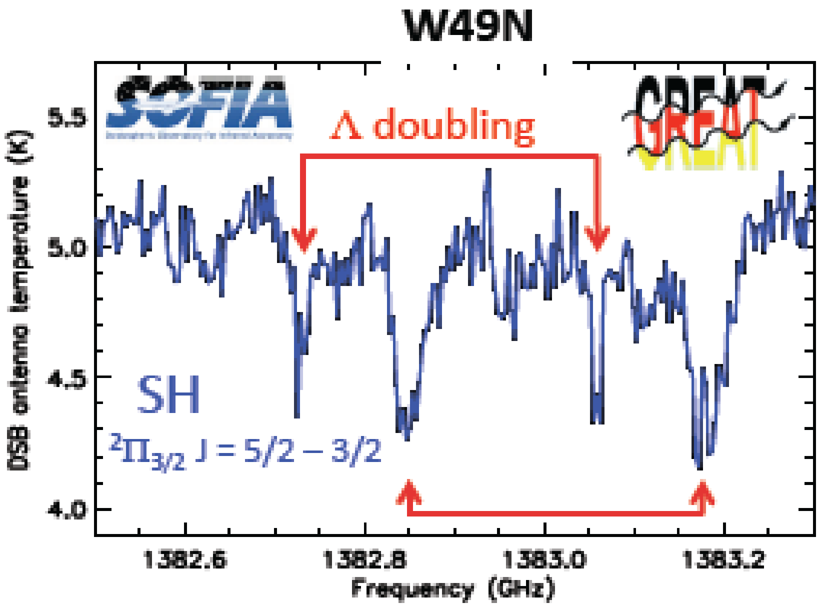
two out of 4 channels can be operated simultan.
Spectral resolution: sub km/s, IF bandwidth 1.2 GHz
beam=lambda/10 (16" for C+ 158 micron line)
upGREAT (funded): 2x7 pixel arrays

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



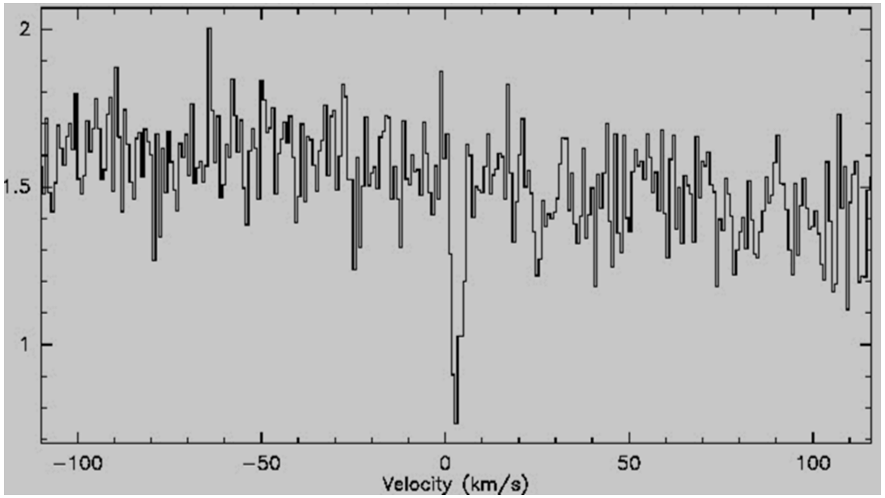
GREAT science examples



D. Neufeld: discovery of interstellar mercapto radical SH in absorption against W49N.

Wiesemeyer: OH rot. ground-state also detected in absorption(2.5THz)

(unaccessible to Herschel HIFI)



B. Parise: most beautiful detection of deuterated hydroxyl OD towards the protostar IRAS16293A

(might try OD/OH in Herbig stars)

SOFIA First Light Flight (Dec 1, 2010)

Thanks and Acknowledgements

Matt Richter (EXES PI)

Goeran Sandell (Ames)

Adwin Boogert (Ames)

Andres Carmona (LAOG)

Klaus Pontoppidan (JHU)

Mario Perez (NASA-HQ)

THANK YOU

for your interest in

and support of the

SOFIA OBSERVATORY

Stay tuned for CfP3 …

References (MIR/FIR spectroscopy, disks)

Bitner et al. 2007, ApJ Lett. 661, L69 (H_2)

Boogert & Blake 2004, ApJ Lett. 606, L73 (CO)

Boonman et al. 2003, A & A 399, 1047 (CO_2, C_2H_2, HCN)

Carmona et al. 2008, A & A 477, 839 (H_2)

Feuchtgruber et al. 2000, ApJ Lett. (CH_3)

Knez, Lacy et al. 2009, ApJ 696, 471 (CH_3, CH_4, etc)

Jacquemart et al. 2003 JQSRT 82, 363 (C_2H_2)

Lacy 2013, Review on mid-IR spectroscopy …

Meeus et al. 2013 (Herschel PACS, [OI]...)

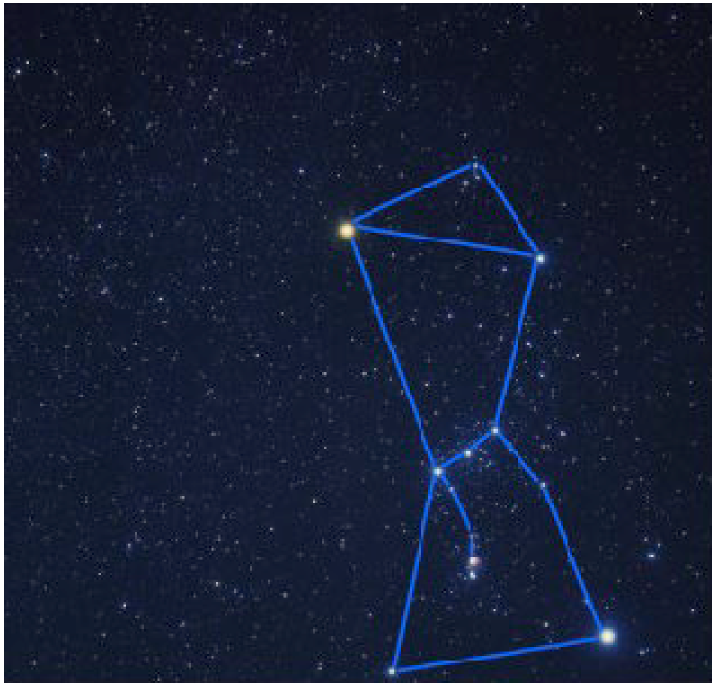
Pontoppidan et al. 2010, ApJ Lett 722, L173 (H_2O)

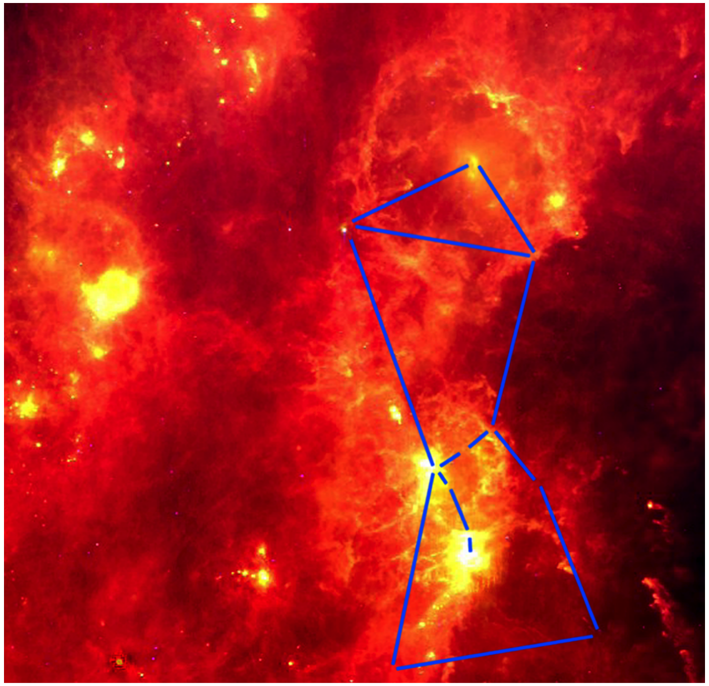
Salyk et al. 2009, ApJ 699, 330 (H_2O)

Sandell et al. 2011, ApJ 727, 26 (submm survey of HAeBe stars)

Getting the WHOLE picture

An object can look radically different depending on the type of light collected from it:





Constellation Orion visual wavelengths

interstellar matter far-infrared image

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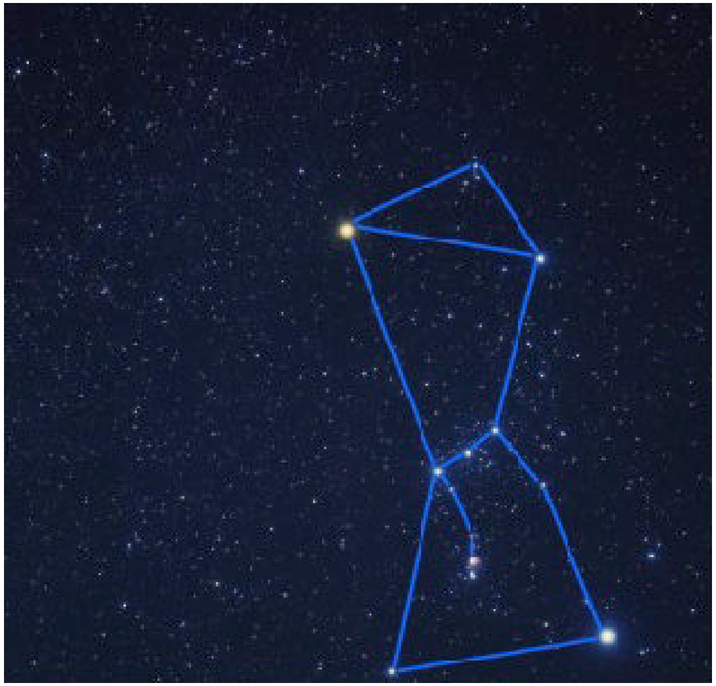

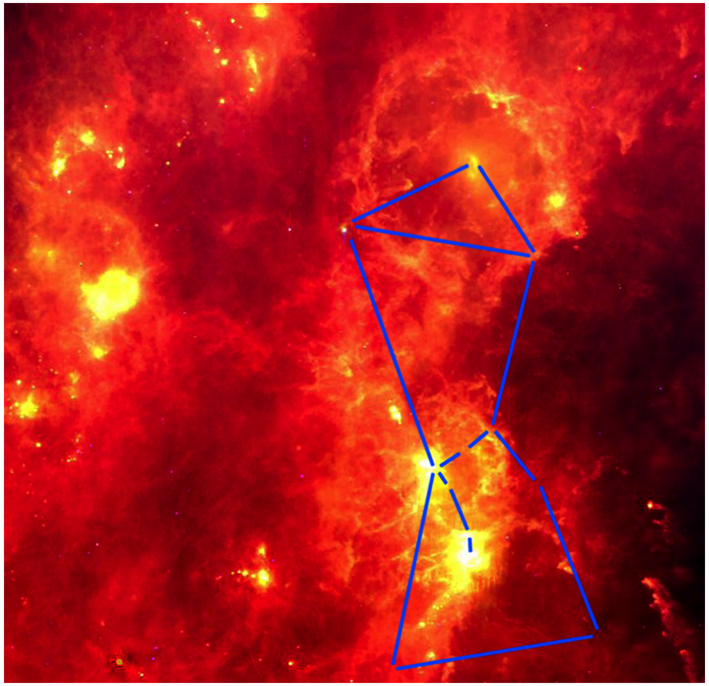

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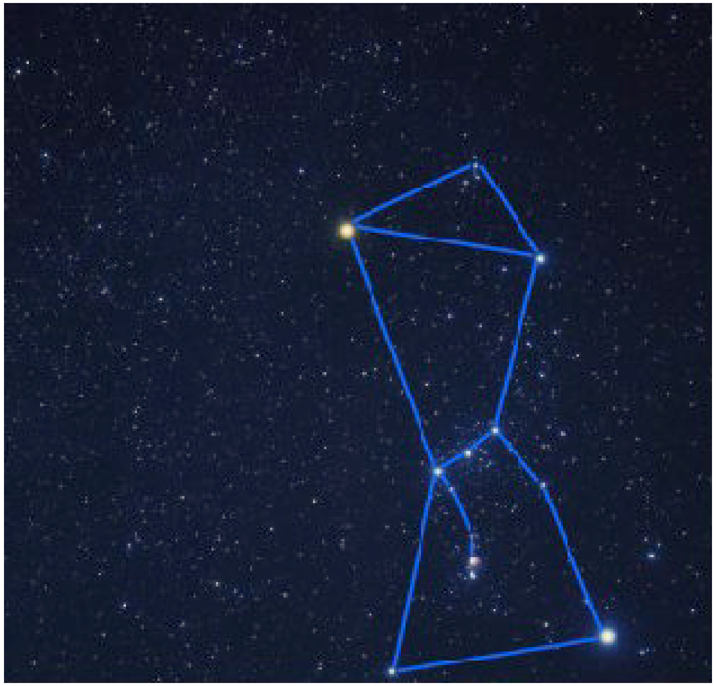
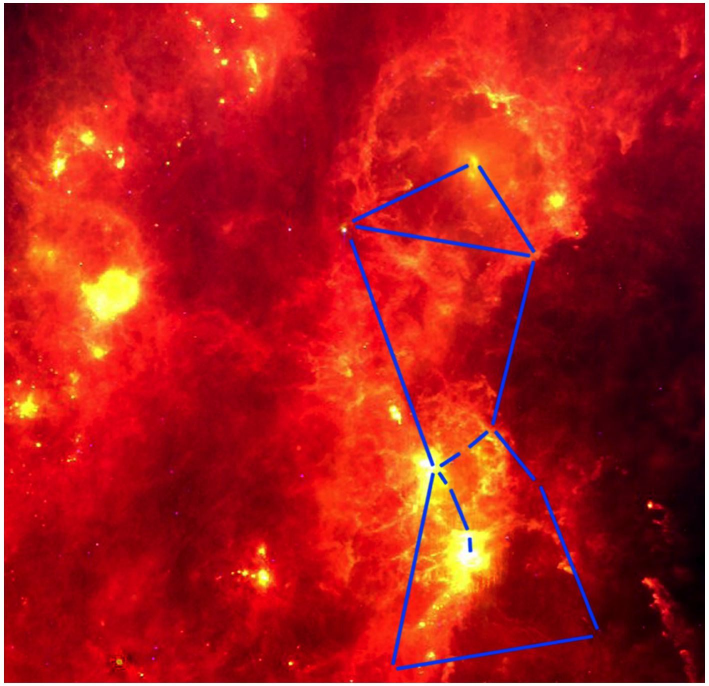




Constellation Orion visual wavelengths

interstellar matter far-infrared image

OUTLINE of the talk

Introduction to Orion
Introduction to SOFIA
SOFIA mid-IR results

Why observe Orion?

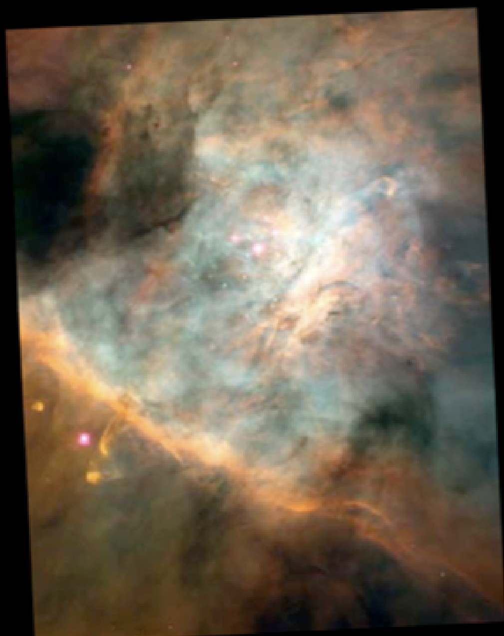
•"Obligation"

•To determine which sources are internally heated and contribute to the luminosity of BN/KL (motivation)

The mid-infrrared wavelengths of FORCAST offer more dust penetrating power than near-infrared and optical obs.

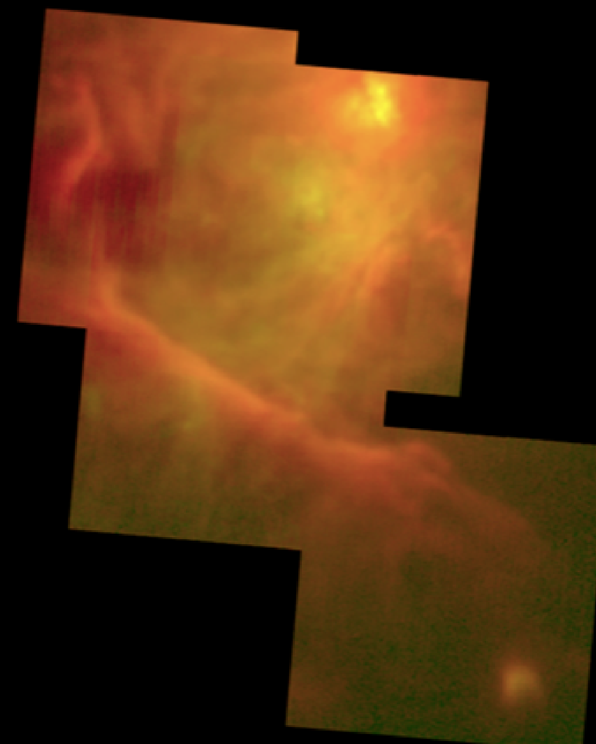
Background Image:Spitzer

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



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

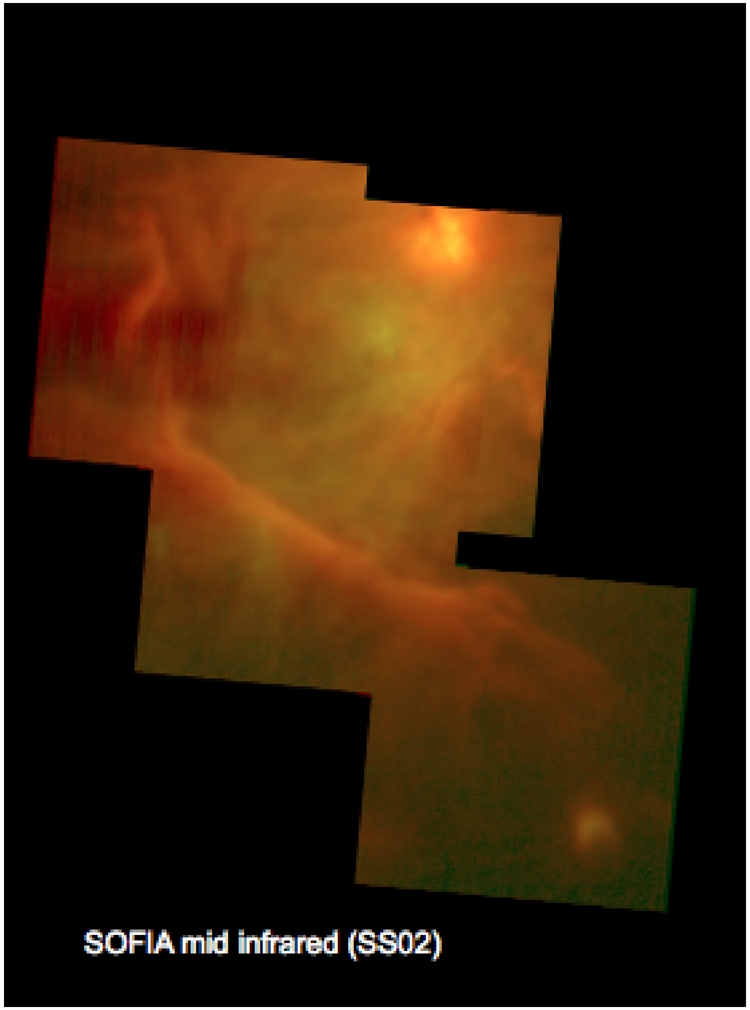
Near infrared
(ESO, M. McCaughrean)



SOFIA mid infrared
(SS02)

Orion Nebula at Mid IR with 3 arcsec Resolution

- Focus on the very bright and infrared-luminous BN/KL region (all radiation is in the infrared)
- Total power output similar to the opt. bright young Trapezium stars Luminosity L ~ 100,000 L(Sun)
- center of molecular activity (outflows, SiO masers, H2 fingers)
- Major questions:
  - What is causing all the radiation? Which energy sources?
  - Still forming stars converting gravity to accretion luminosity?
  - Very young massive stars just starting their nuclear burning?
  - An "explosive" type event 500 yrs ago (due to a stellar merger)?



With Support from

- Jim DeBuizer (FORCAST instrument scientist)
- Eric Becklin (SOFIA chief advisor, Orion master-mind)
- Ralph Shuping (Data Cycle System specialist)
- Bill Vacca (FORCAST calibration specialist)

- Erick Young (SOFIA SMO director, ApJL overview paper)
- Terry Herter (PI of FORCAST facility instrument, Cornell)

de Buizer et al. (2012), ApJL (Orion BN/KL SOFIA paper)
Shuping et al. (2012), ApJL (Orion Trapezium SOFIA paper)

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 41,000 ft -- can observe most of the infrared universe (above water vapor)**
- **Airborne infrared telescopes can be more versatile -- and longer lasting than space infrared telescopes (3-5 yr)**

SOFIA

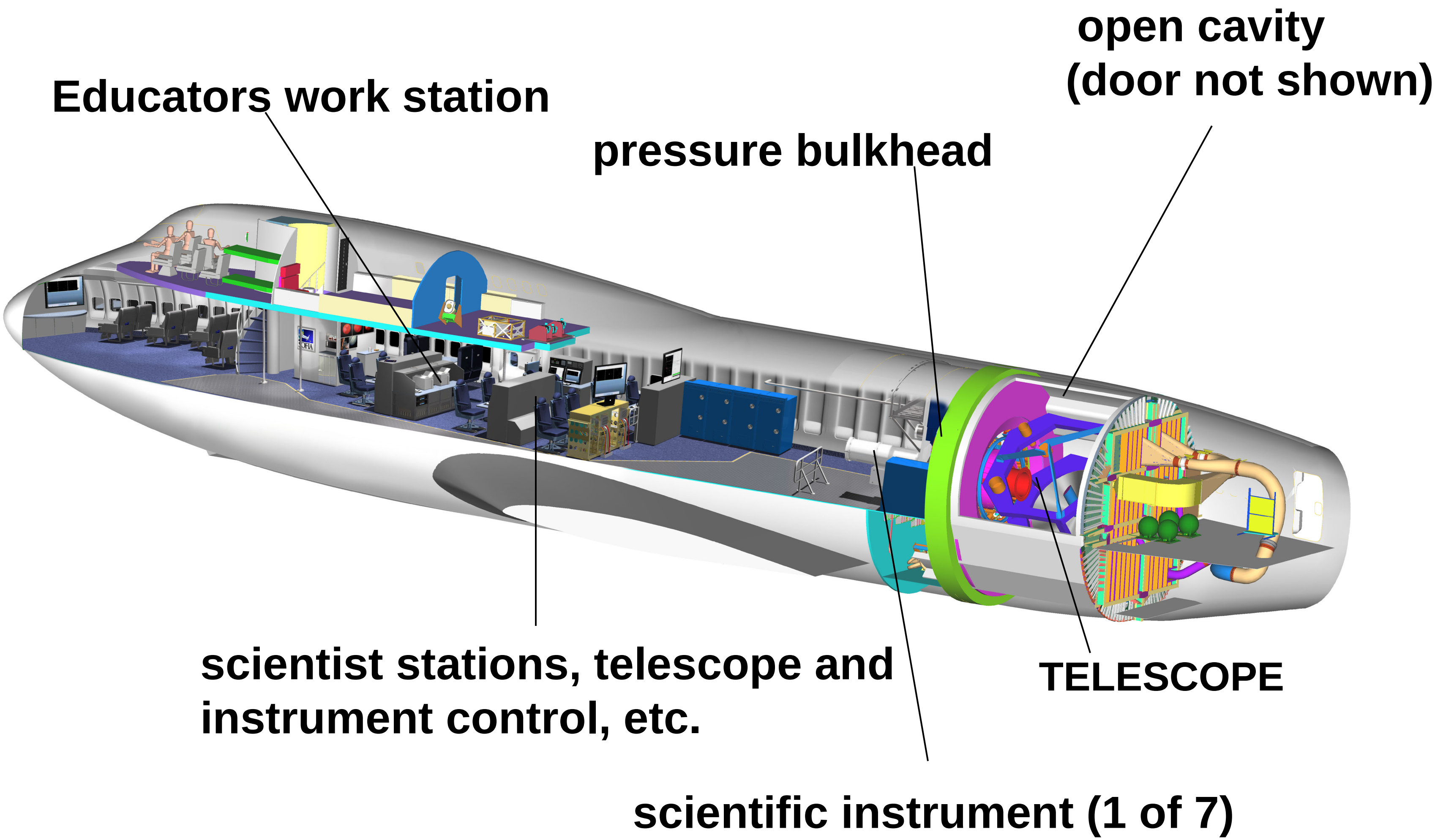
Stratospheric Observatory for Infrared Astronomy

Boeing 747SP

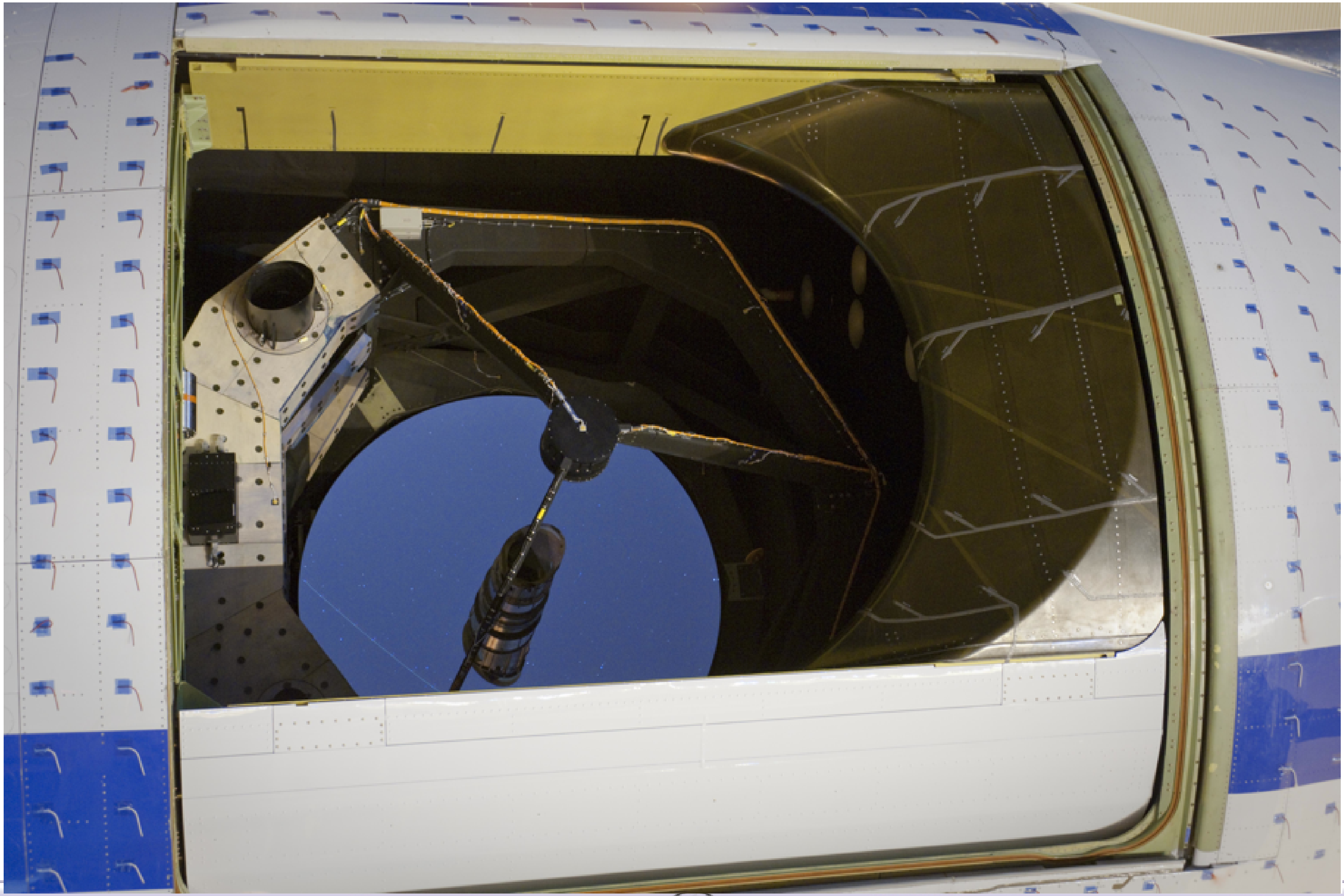
2.7-meter

- International partnership:
  - 80% -- NASA (US)
  - 20% -- DLR (Germany)
- Global deployments, incl. southern hemisphere
- ~1000 research hours per year in full operation (2015)
- ~ 20 year projected lifetime

SOFIA — The Observatory



Coated Mirror and Aperture on SOFIA



FORCAST: Mid-IR Imager

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

Detectors: Dual channel
256 x 256 arrays;
5 – 25 μm (Si:As)
20 – 40 μm (Si:Sb)

Field of View: 3.2' x 3.2'
Pixel size: 0.75" (~4 pixels per PSF)

Science: broad/narrow-band imaging
low-res grism spectroscopy

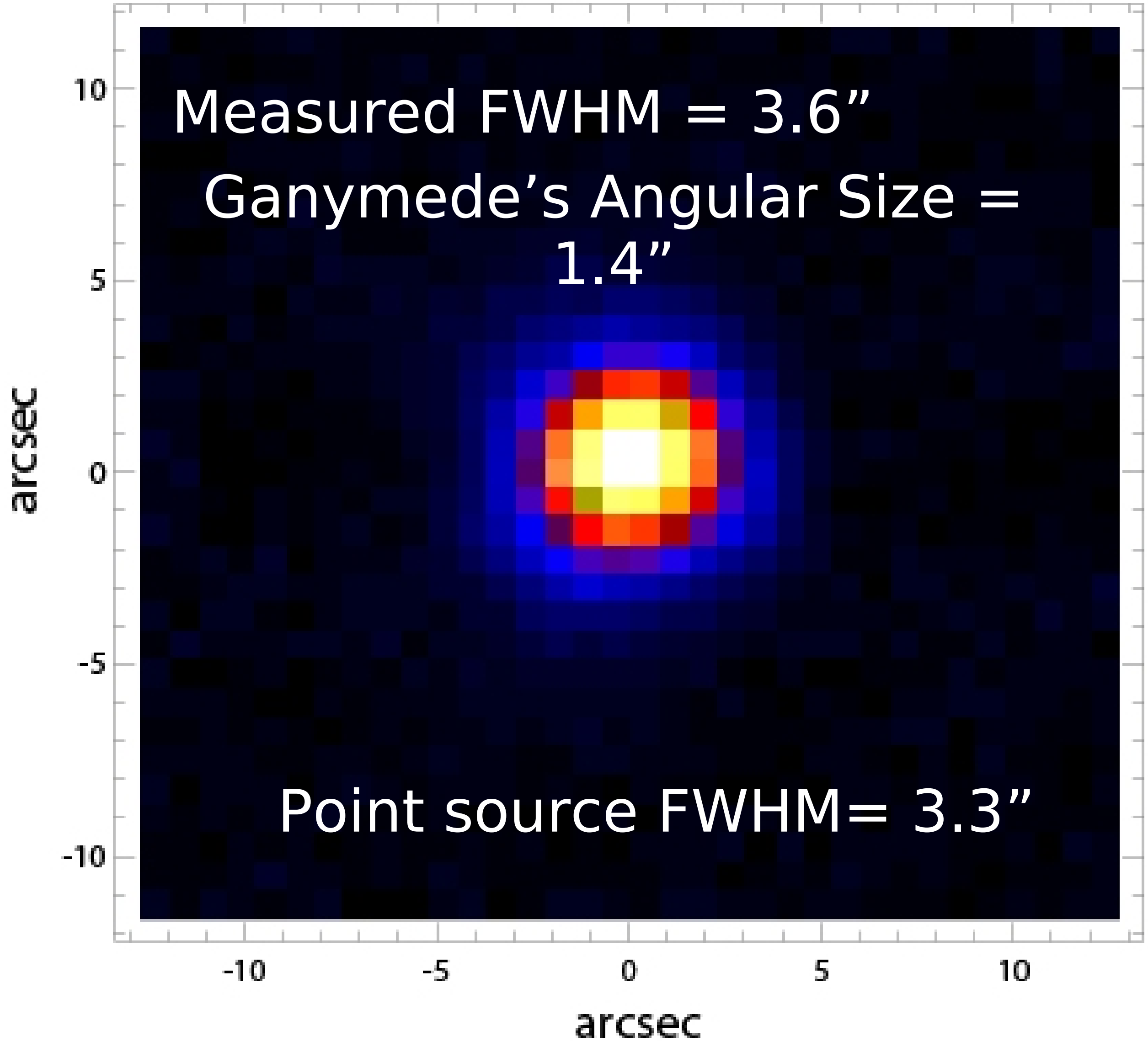
Galactic Star Forming Clouds, HII Regions
Galactic Center Environs, Starburst
Galaxies

NB: FORCST diffraction-limited at lambda> 30 microns; PSF ~ 3 arcsec

SOFIA First Light Flight (Dec 1, 2010)

Looking at the Data

Ganymede at 24.2 um from First Light flight



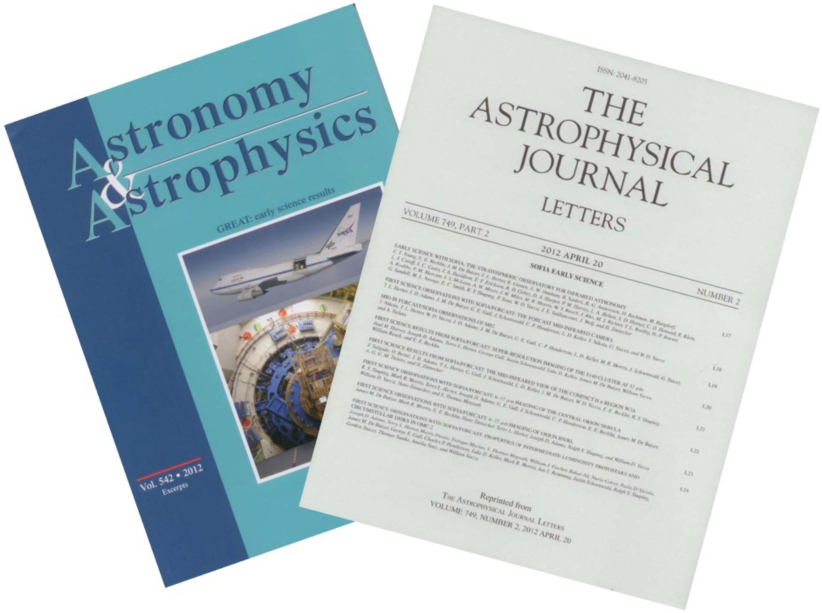
☑ Sensitivities in the 5-40um range as expected!

Science with FORCAST

- There was outstanding science from the FORCAST on three 10-hour science flights and an engineering flight (Dec 2010)
- Observations included: several regions where massive stars are forming: Orion Nebula, 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 first presented at AAS in Seattle and Austin. Eight papers have been submitted to ApJL 471 special issue (published in print April 20, 2012)

Recent Results

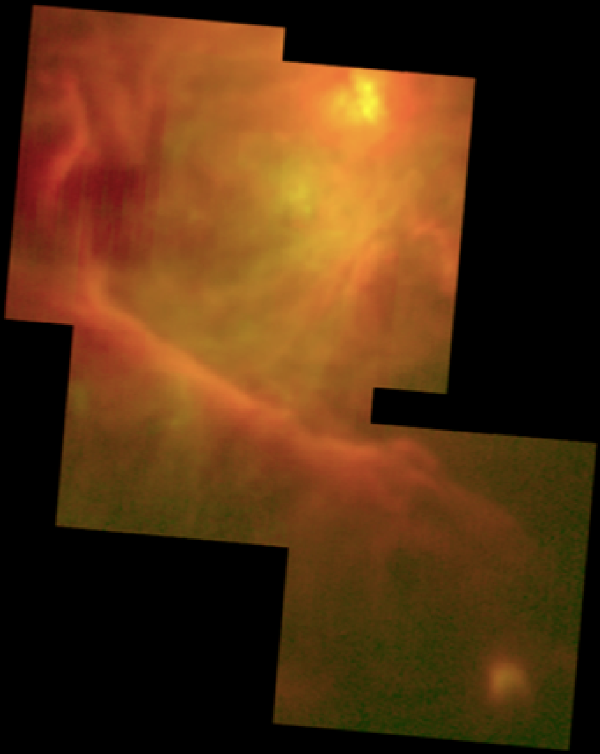
- SOFIA has published two special issues that highlight the science accomplished during the Early Science period



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

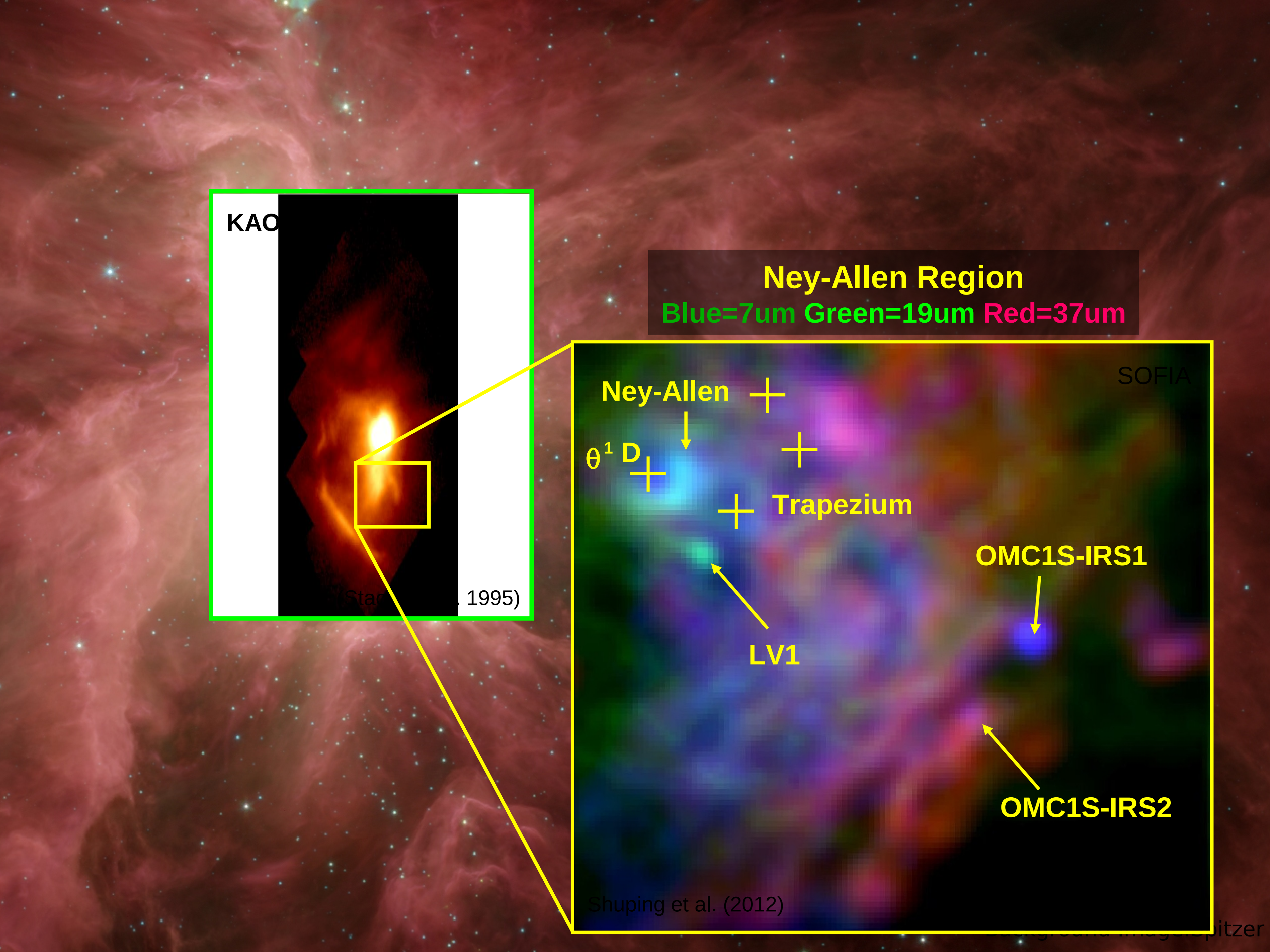
Visible light
(HST, C. O'Dell and S. Wong)

Near infrared
(ESO, M. McCaughrean)

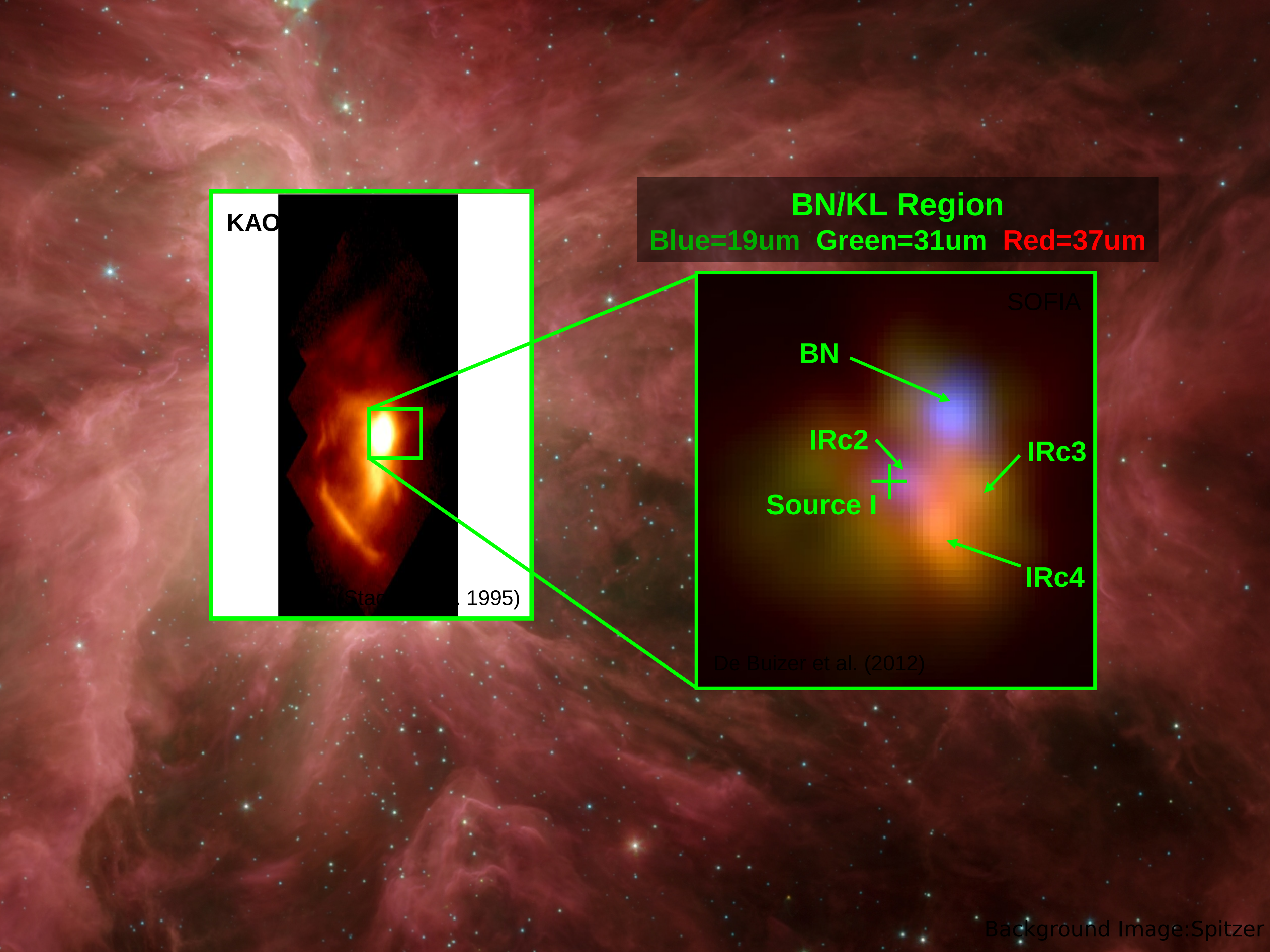


SOFIA mid infrared
(SS02)

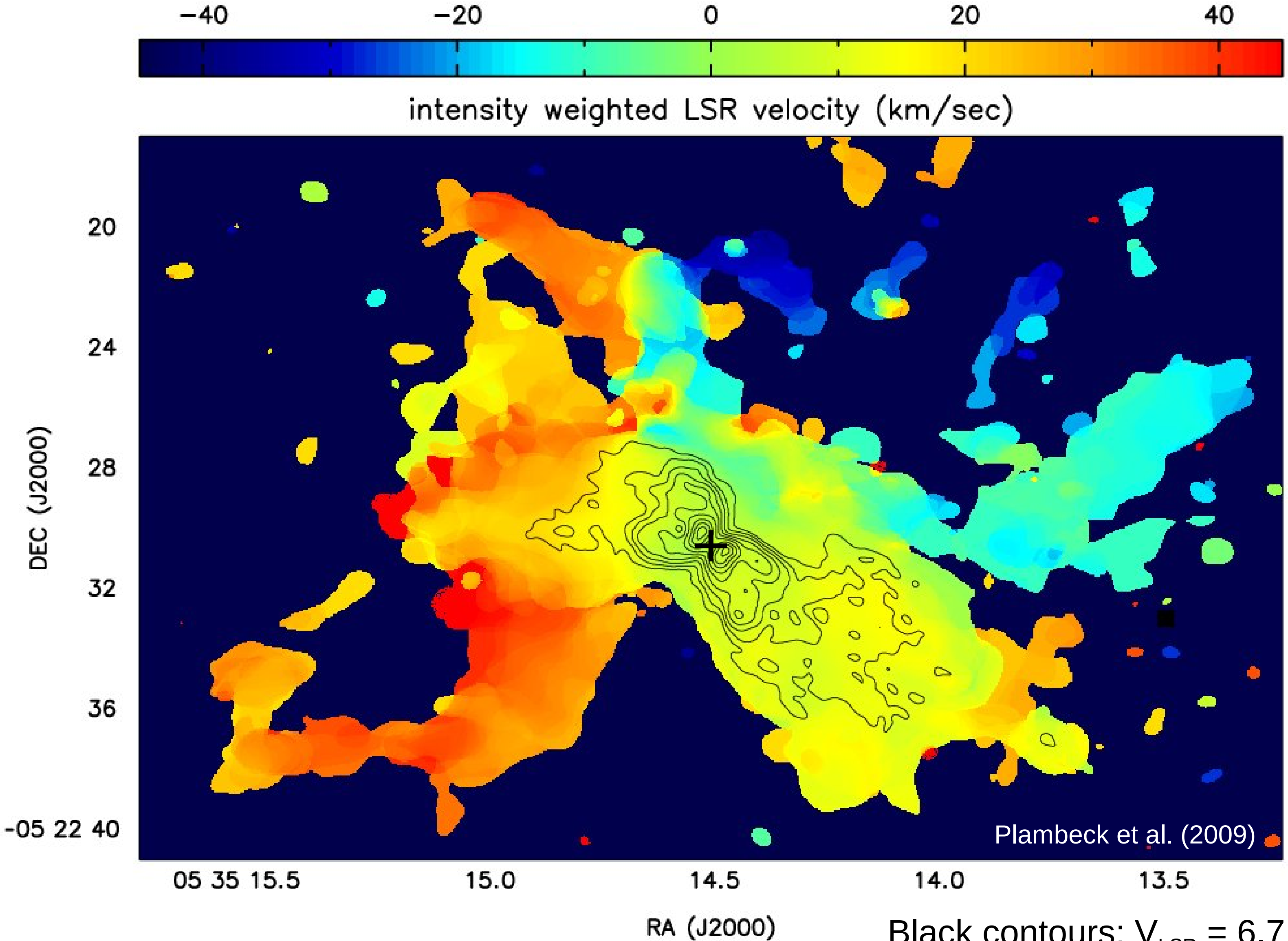
TRAPEZIUM
STARS REGION


KAO
Ney-Allen Region
Blue=7um Green=19um Red=37um
SOFIA
Ney-Allen
θ¹ D
Trapezium
OMC1S-IRS1
LV1
OMC1S-IRS2
Shuping et al. (2012)

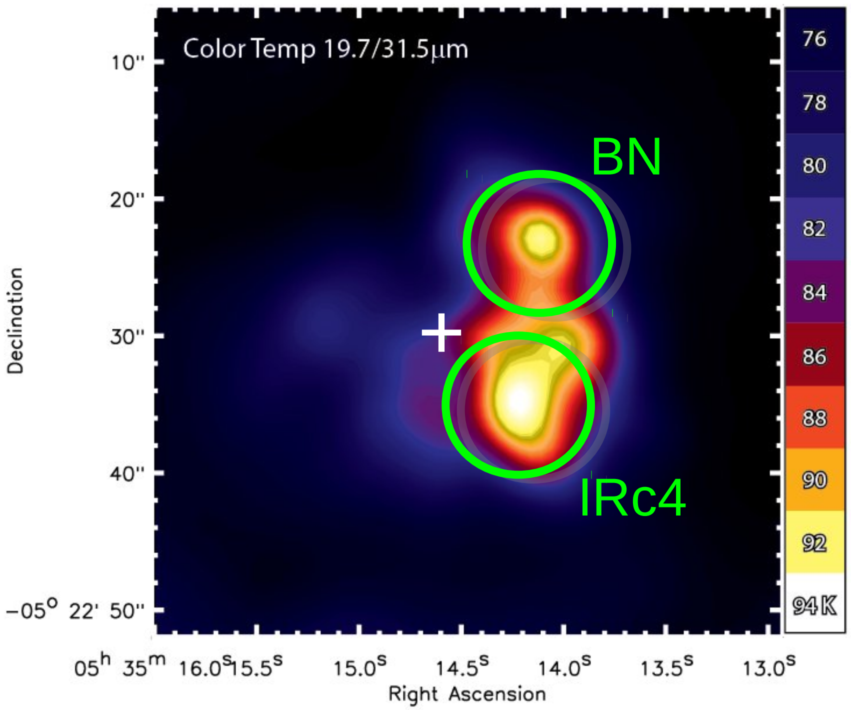
KLEINMANN LOW INFRARED NEBULA


KAO
BN/KL Region
Blue=19um Green=31um Red=37um
SOFIA
BN
IRc2
IRc3
Source I
IRc4
De Buizer et al. (2012)
Background Image:Spitzer

There is an SiO outflow centered near Source I



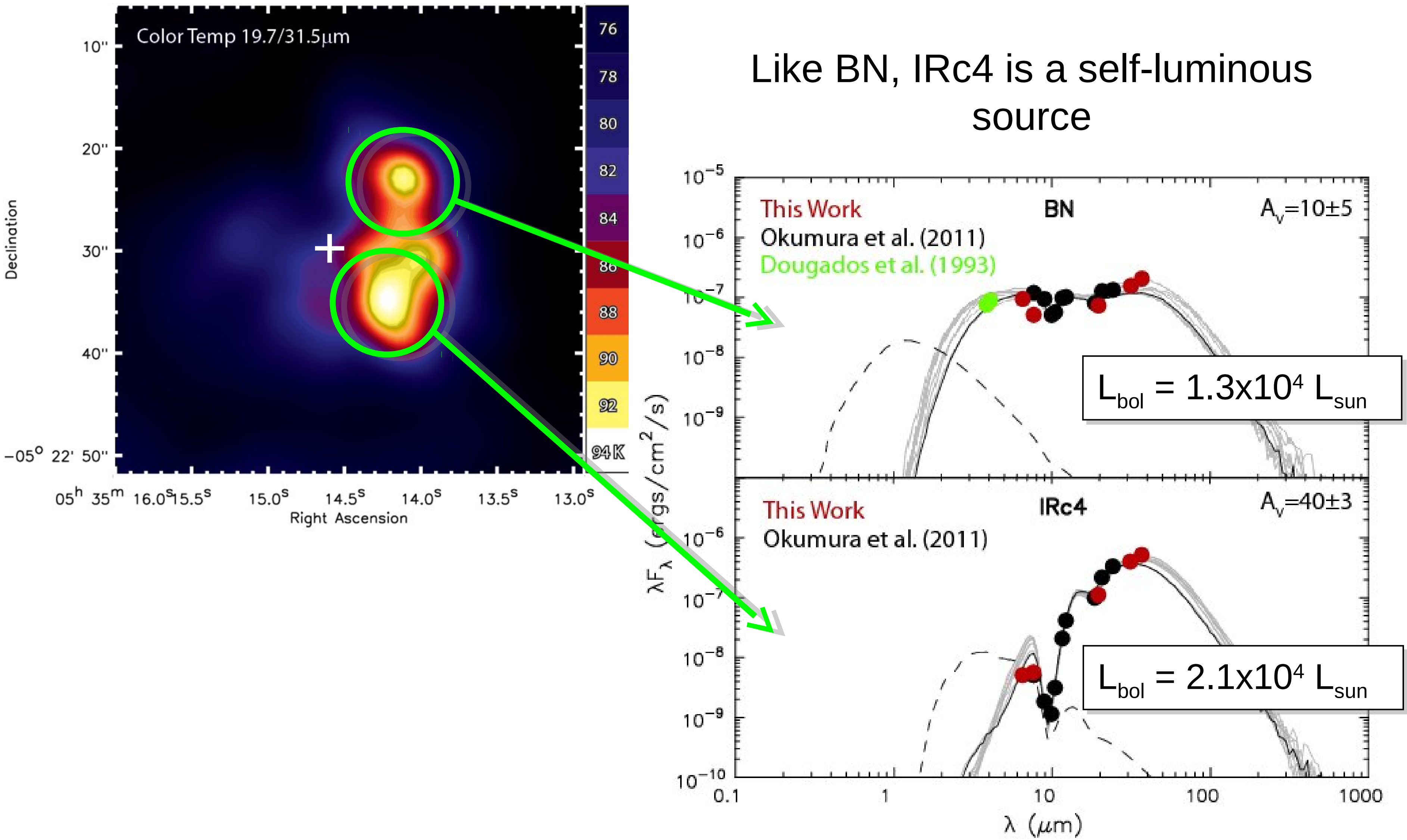
Black contours: V_{LSR} = 6.7 km s^{-1}



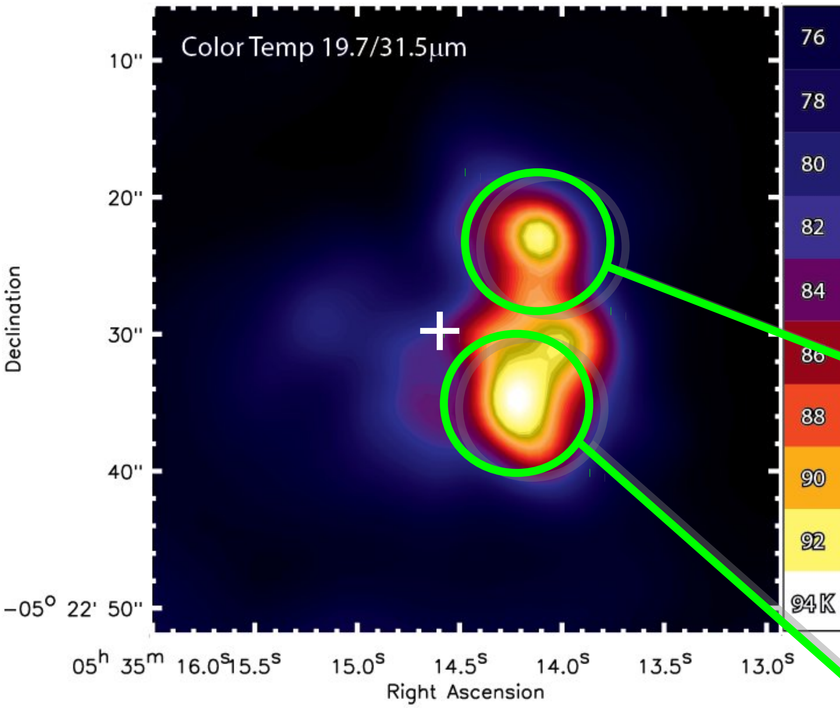
Like BN, IRc4 is a self-luminous source

De Buizer et al. (2012)

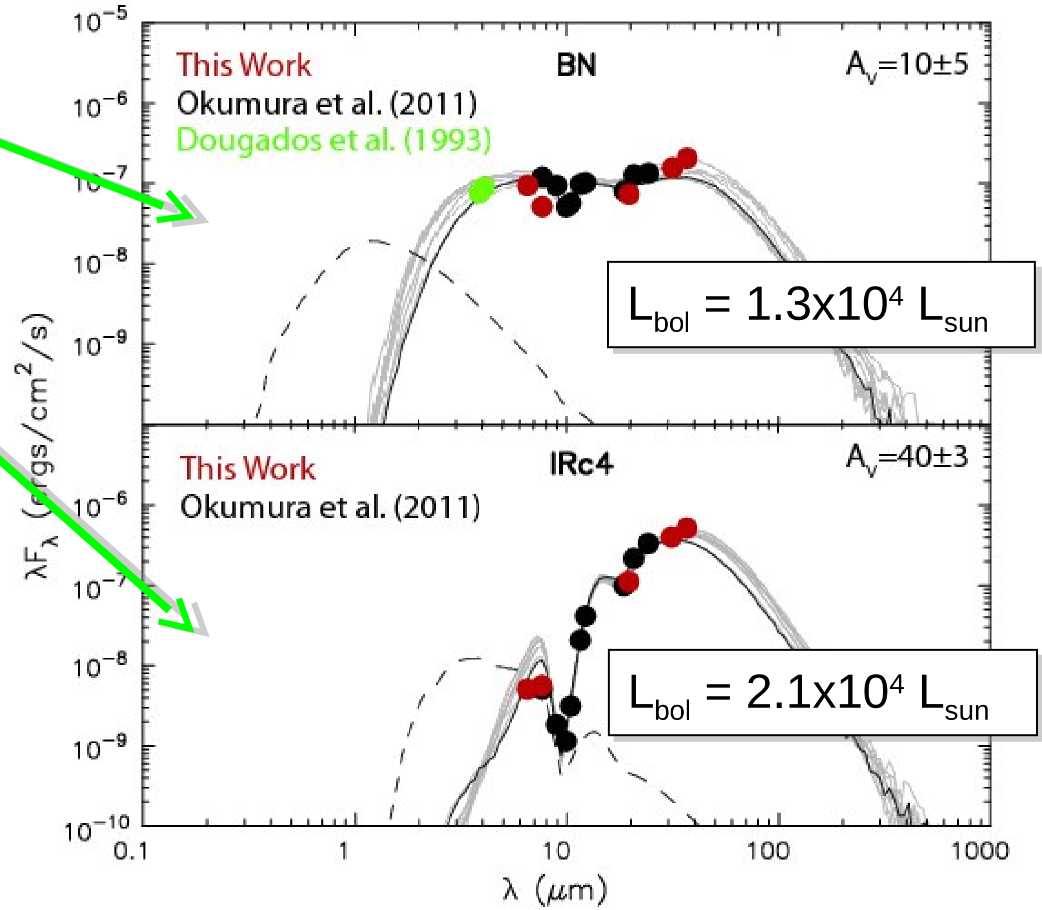
Like BN, IRc4 is a self-luminous source



De Buizer et al. (2012)



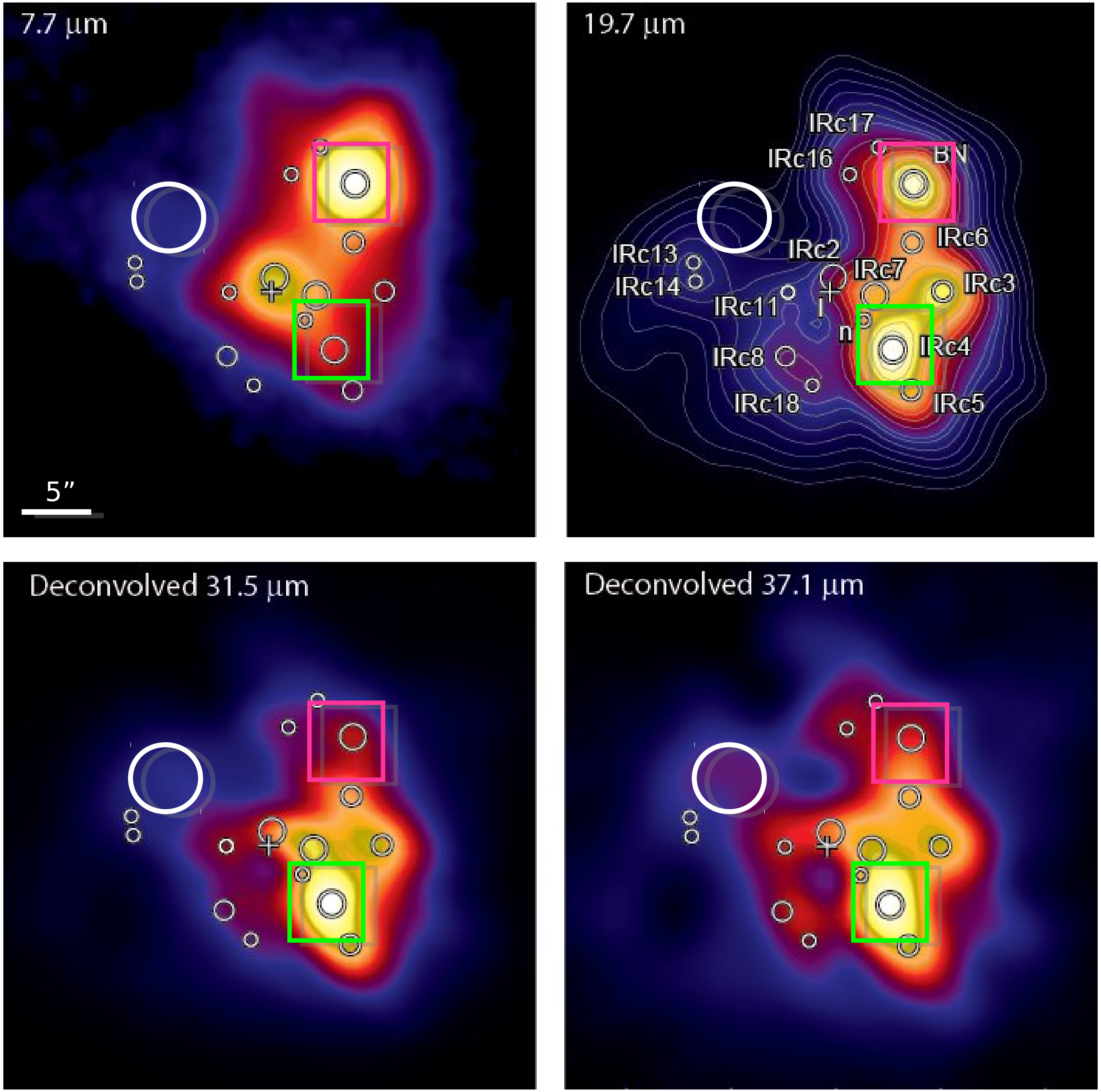
Like BN, IRc4 is a self-luminous source



IRc4 luminosity is too high to be caused by externally heating

BN+IRc4 account for ~40% of the ~10^5 L_{sun} of the BN/KL region

De Buizer et al. (2012)



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)

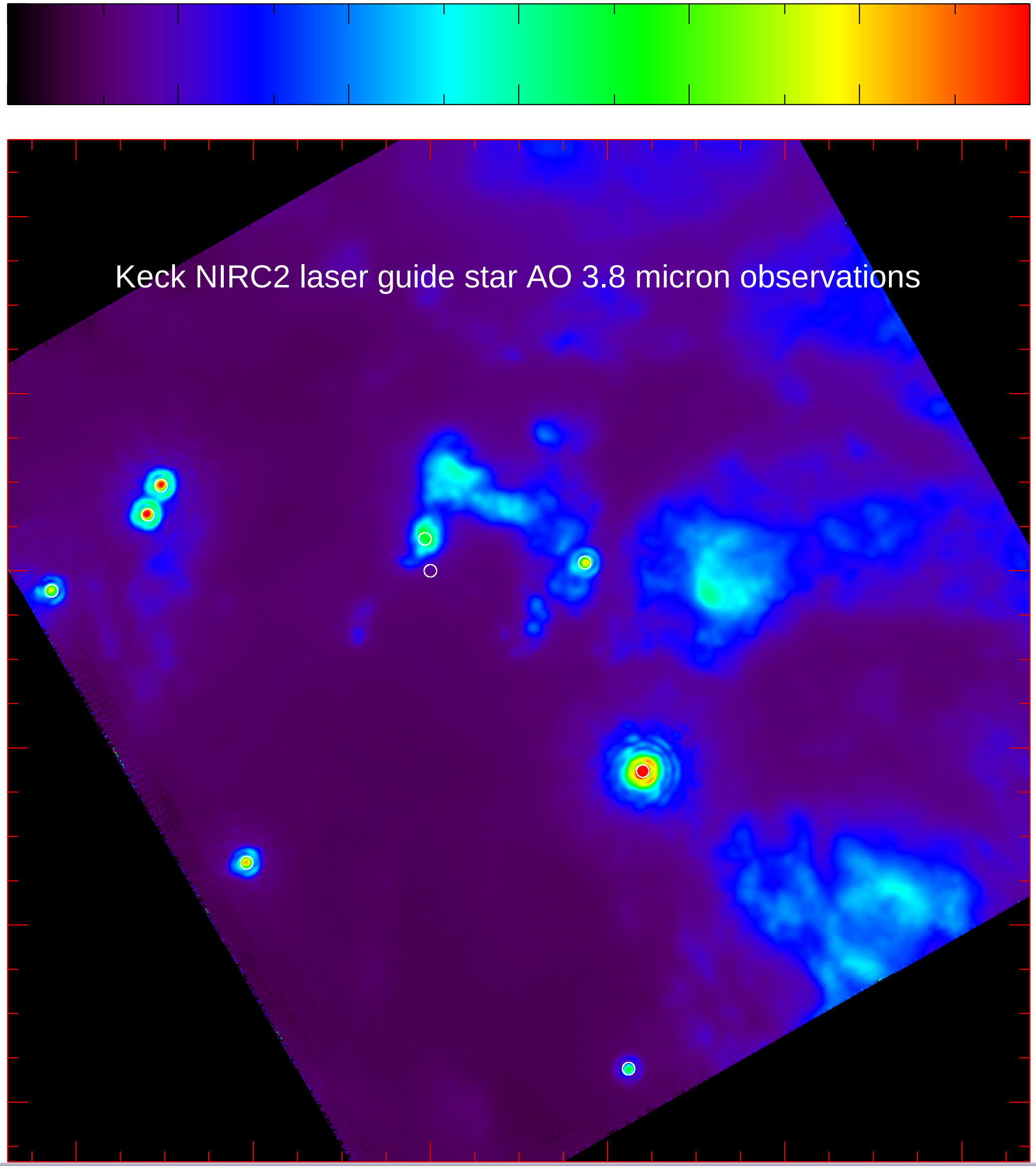
De Buizer et al. (2012)

What new did we find?

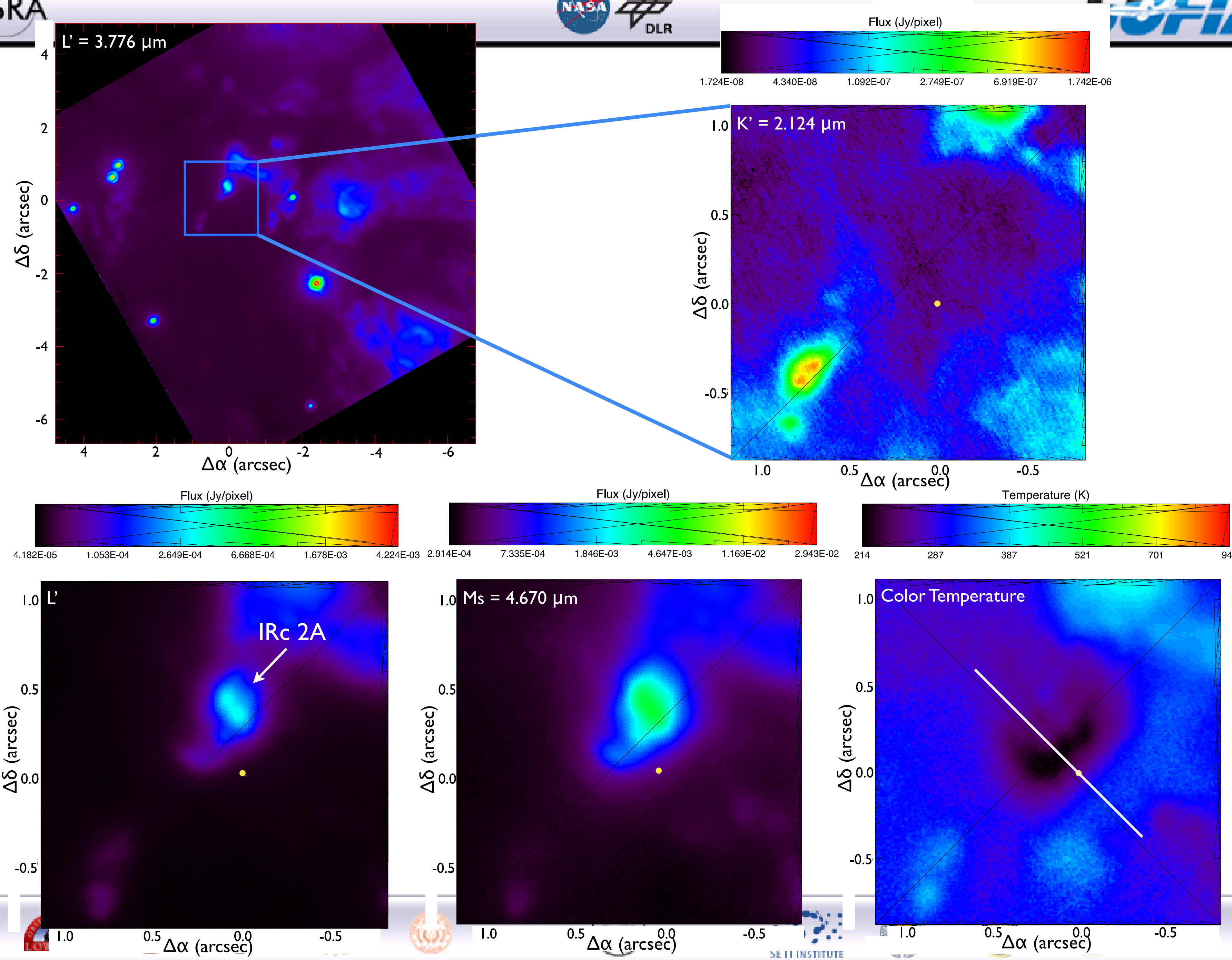
- BN is the hottest source and is not seen at 37 microns.

  The source IRc2 (bright at 12 microns) and radio source “I” are not seen at 37 microns (longer wavelengths needed).
- 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). Protostar!

- Need more data. We got Keck AO 0.1’’ obs (2-5 micron) !
- Herschel or HAWC on SOFIA needed to detect source “I”.
- Also infrared/submm spectra needed EXES and ALMA

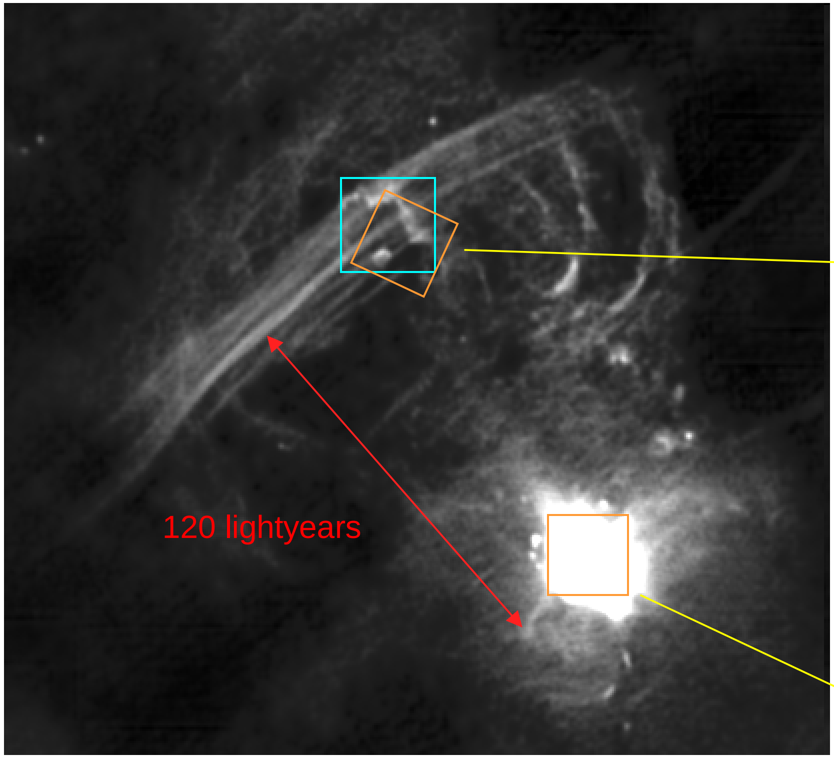

Keck NIRC2 laser guide star AO 3.8 micron observations

ESO/VLT AND KECK NIR OBSERVATIONS

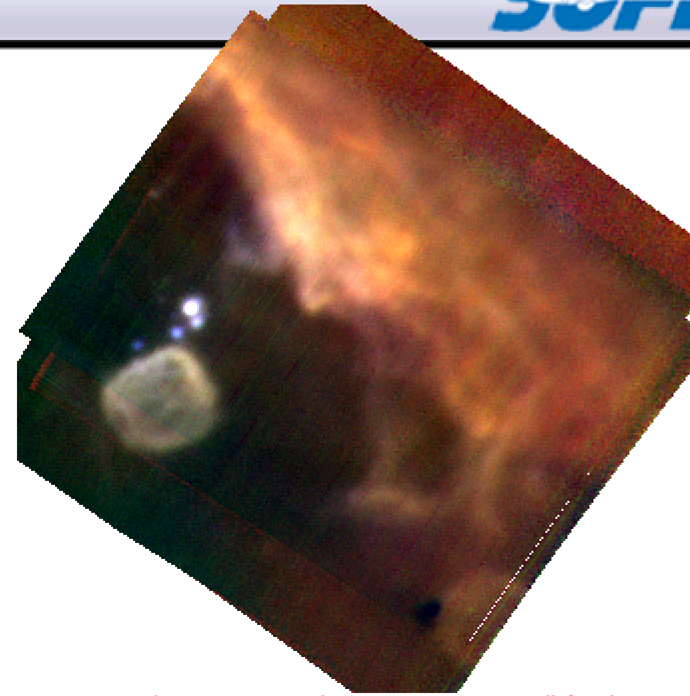


L' = 3.776 μm
Δδ (arcsec)
Δα (arcsec)
Flux (Jy/pixel)
1.724E-08
4.340E-08
1.092E-07
2.749E-07
6.919E-07
1.742E-06
K' = 2.124 μm
Flux (Jy/pixel)
4.182E-05
1.053E-04
2.649E-04
6.668E-04
1.678E-03
4.224E-03
Flux (Jy/pixel)
2.914E-04
7.335E-04
1.846E-03
4.647E-03
1.169E-02
2.943E-02
Temperature (K)
214
287
387
521
701
943
L'
IRc 2A
Ms = 4.670 μm
Color Temperature

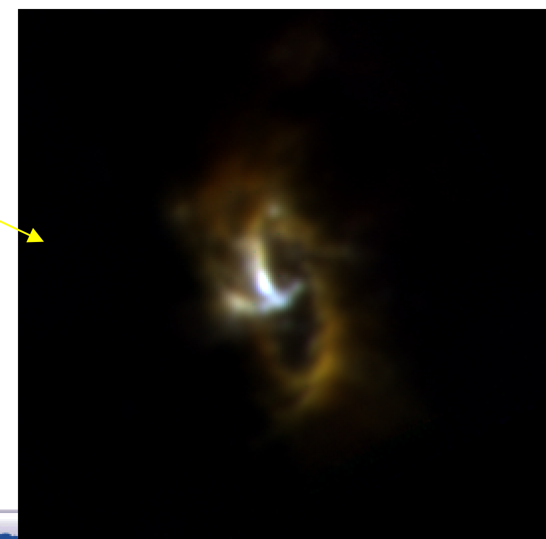
The Galactic Center



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



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



- At right are multicolor infrared images of two regions of the center of the Milky Way made with FORCAST SOFIA (courtesy of T. Herter)
- Released at the Jan 2013 AAS in Long Beach

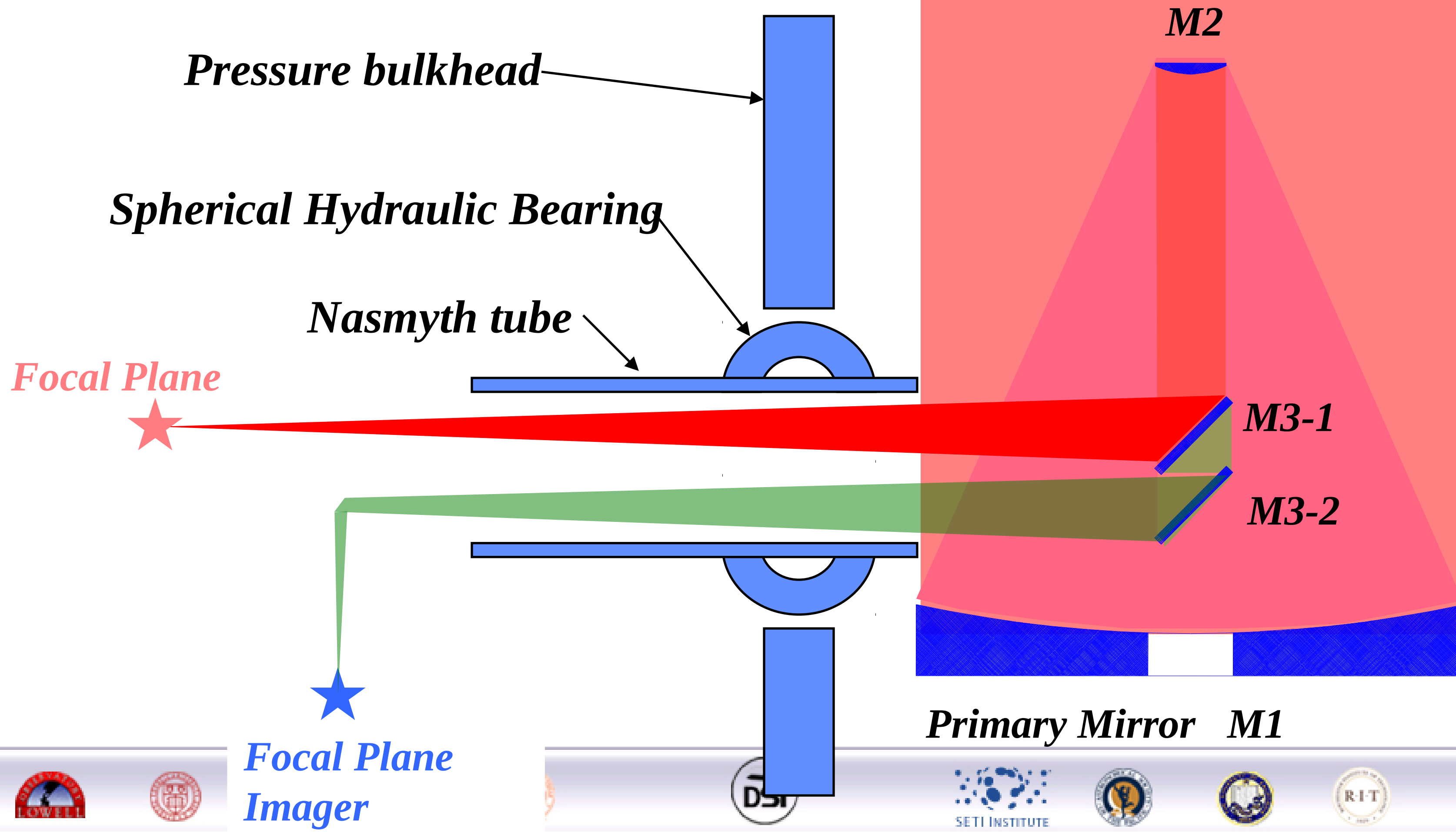
http://www.sofia.usra.edu

deployment to the Southern Hemisphere:
9 flights out of Christchurch/NZ
July 15 to Aug 1

targets are Galactic Center
and the Magellanic Clouds

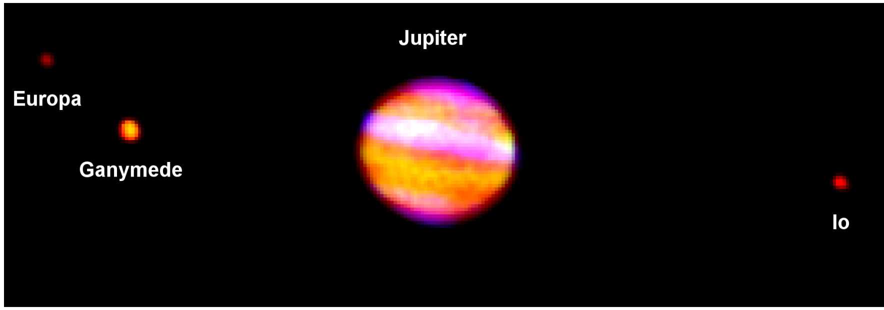
Nasmyth: Optical Layout

Observers in pressurized cabin have ready access to the focal plane



Summary

- SOFIA program getting into gear!
  - Early Science with FORCAST and GREAT was a great success
  - Some 30 science flights in 2011
  - 30 papers subm. to ApJL + A&A
  - Discoveries: BNKL; OH, OD, SH
  - Aircraft handles well, even with door open (unnoticable in flight)
  - Aircraft now cleared to 45,000ft
  - Successful Occultation of Pluto in June 2011 over the Pacific
  - Deployment to Germany and to Washington DC in Sept 2011
  - Cycle 1 Call for US/German Open Time Proposals (133 US, 39 GER) successful proposals flying in 2013
  - Premier facility for mid-IR and far-IR-astronomy for many years to come (post Herschel)



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
  - 26 new US ambassadors selected
- SOFIA has been deployed to Germany in mid-September to support the Cologne Air Show September 18, 2011
- SOFIA stopped over at Andrews Airforce Base in Washington/DC to Sept 25, 2011 on the way back from Stuttgart/Germany to Calif.

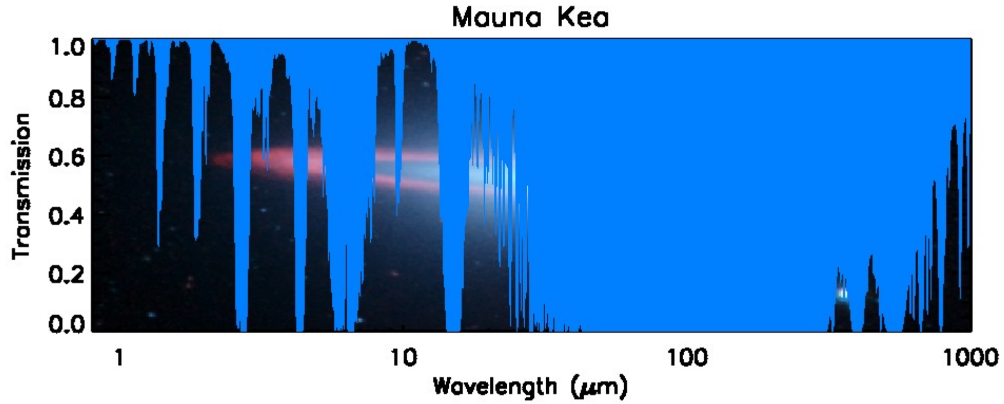
Educators from the first Airborne Astronomy Ambassadors flight. (l-r) Margaret Piper, Lincoln Way High School, Frankfort, Ill.; Theresa Paulsen, Mellen School District, Mellen, Wis.; and Kathleen Joanne Fredette, Desert Willow Intermediate School, Palmdale, Calif.

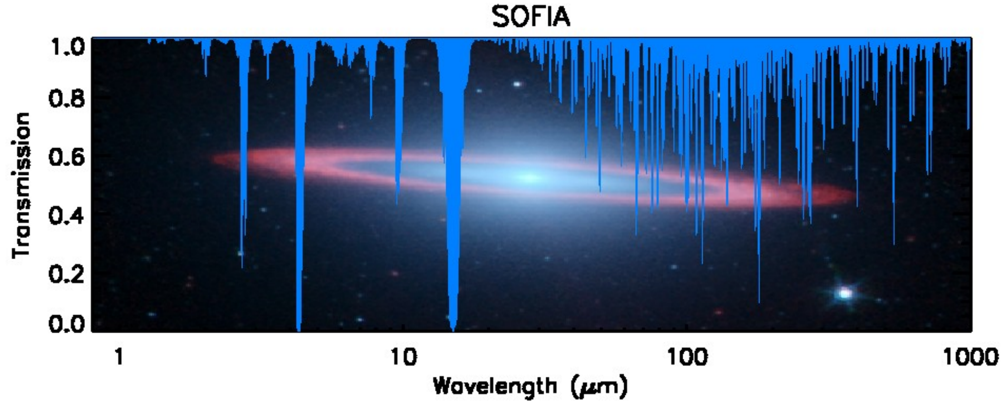
Overview of SOFIA (Young et al. 2012 ApJL)

- 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

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

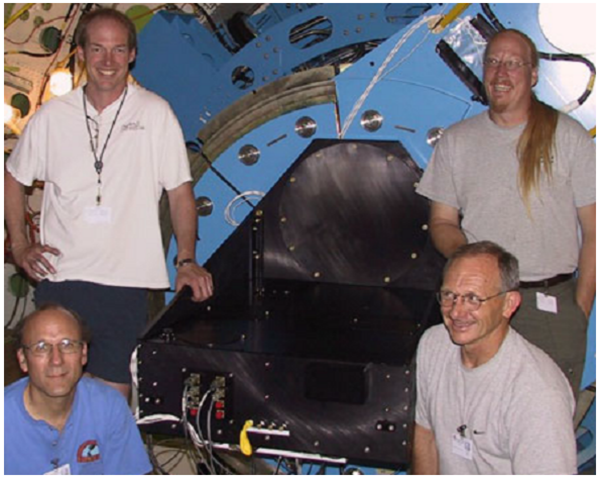




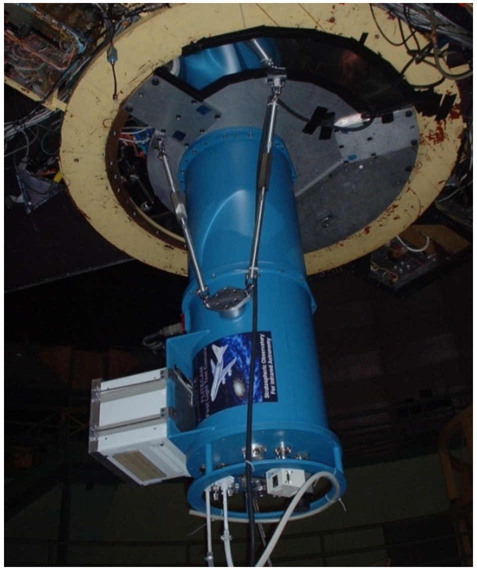
SOFIA instrument suite

- FORCAST
- GREAT (upGREAT)
- HIPO
- FLITECAM
- FIFI-LS
- HAWC (HAWC-Pol)
- EXES

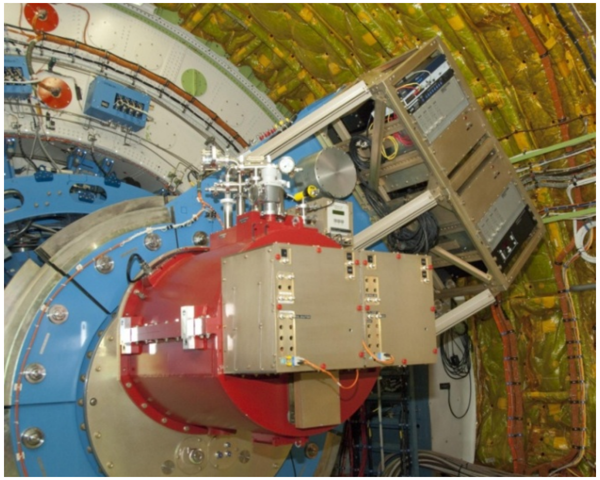
Four Completed 1st Generation Instruments



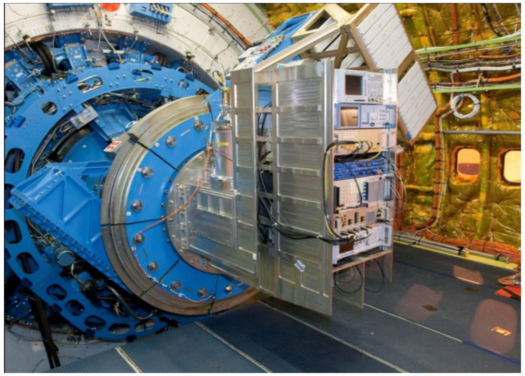
HIPO
High Speed Photometer
(on SOFIA)



FLITECAM
Near IR Camera
(at Lick observatory)



FORCAST
Mid-IR Camera
(on SOFIA)

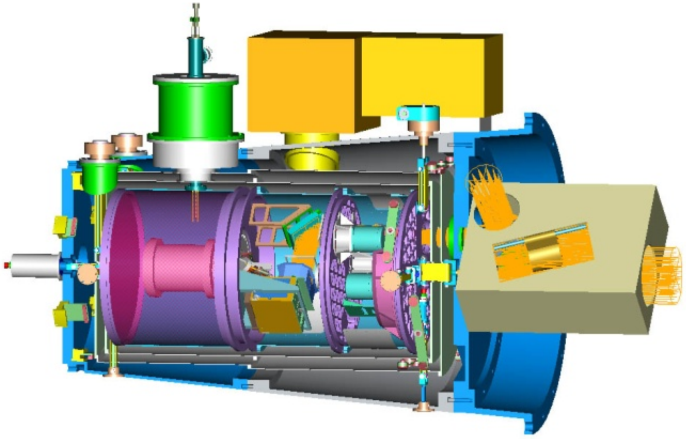


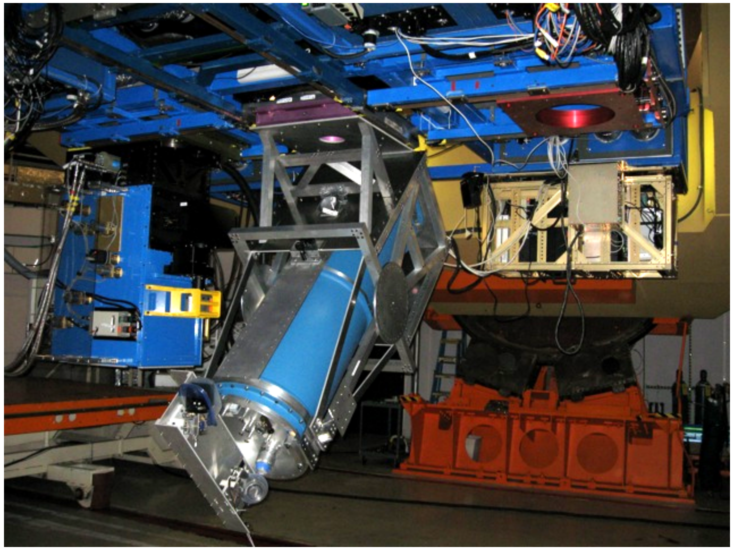
GREAT
Heterodyne spectrometer
(on SOFIA)

Instruments in development

HAWC

Bolometer Camera



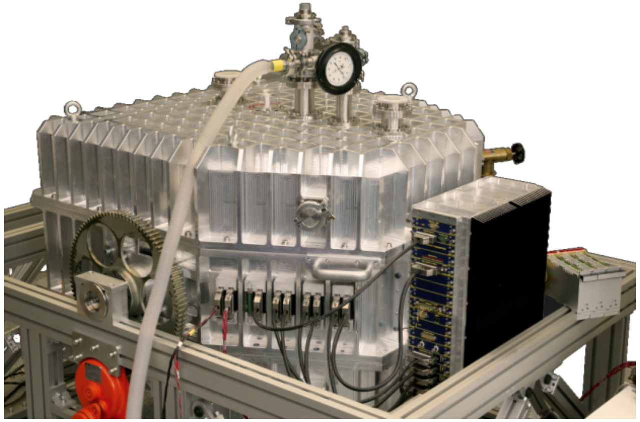


EXES

Mid- IR Spectrometer

FIFI LS

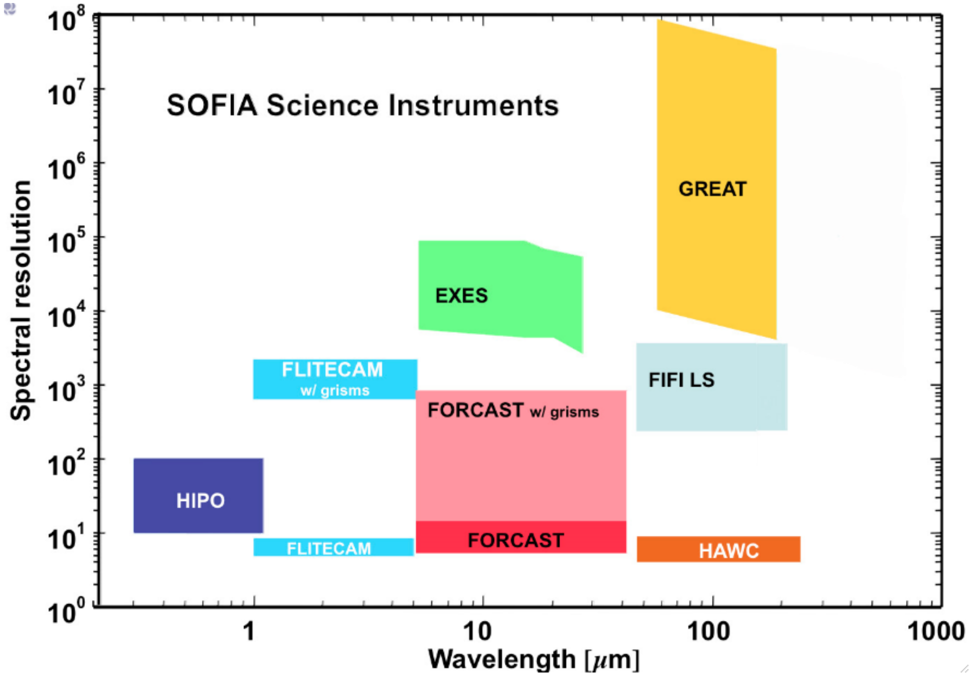
Integral Field Spectrometer



SOFIA's Instrument Complement

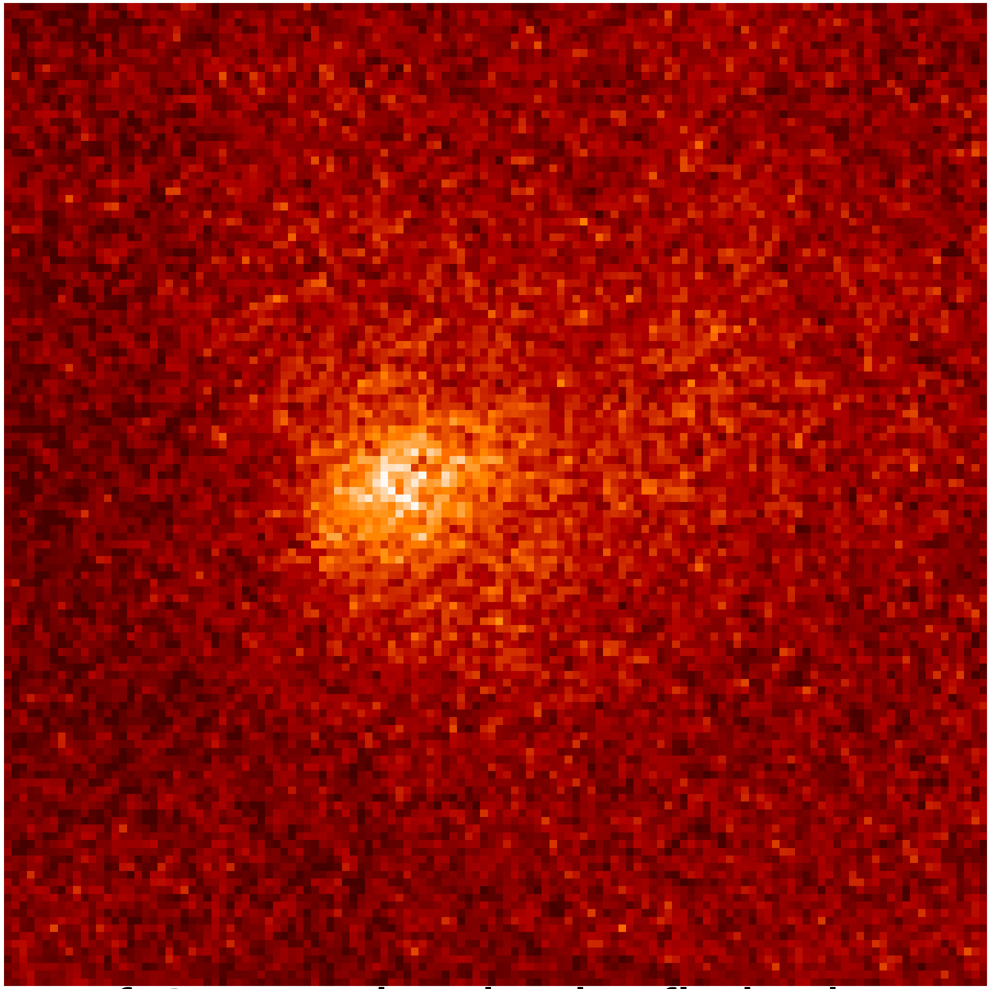
As an airborne mission, SOFIA supports a unique, expandable instrument suite

- SOFIA covers the full IR range with imagers and low- to high-resolution spectrographs (30-60 mu missing)
- 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 every other year.
- Will support both facility instruments and PI class instruments
- 2nd gen instrument selected (April 2012) (HAWC upgrade: HAWC-Pol, HAWC++)



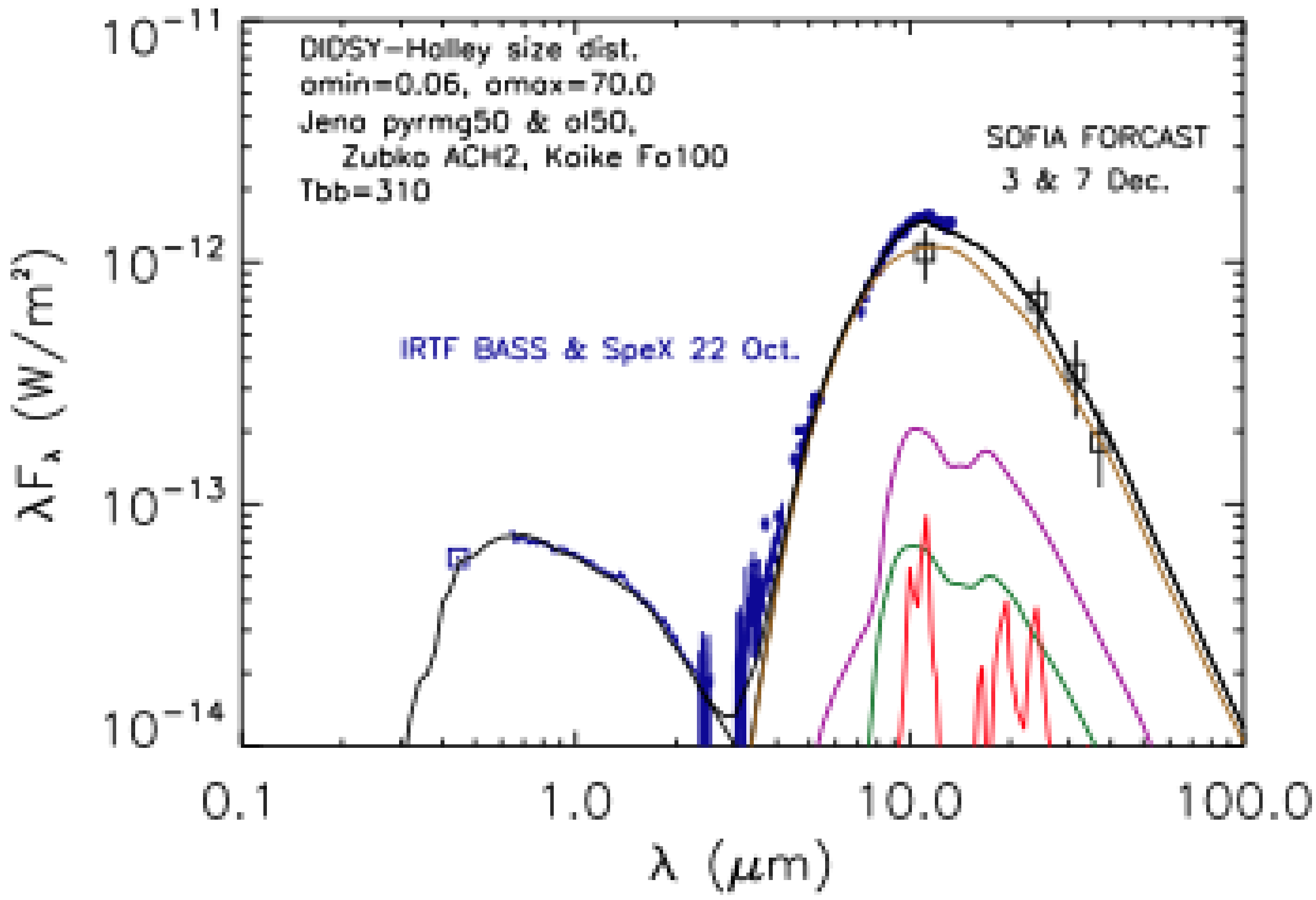
Comet Hartley 2

31.4 microns

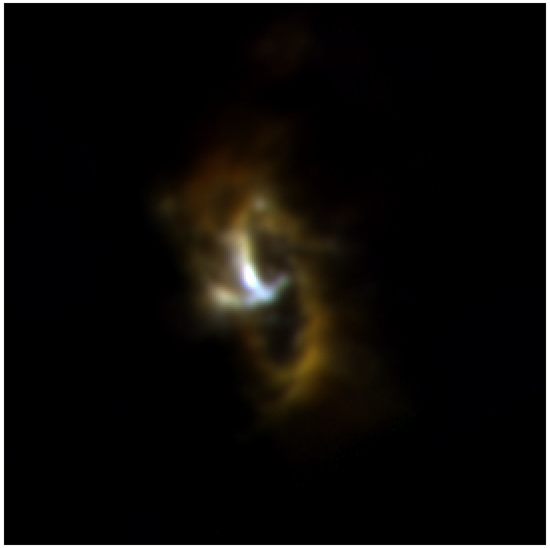


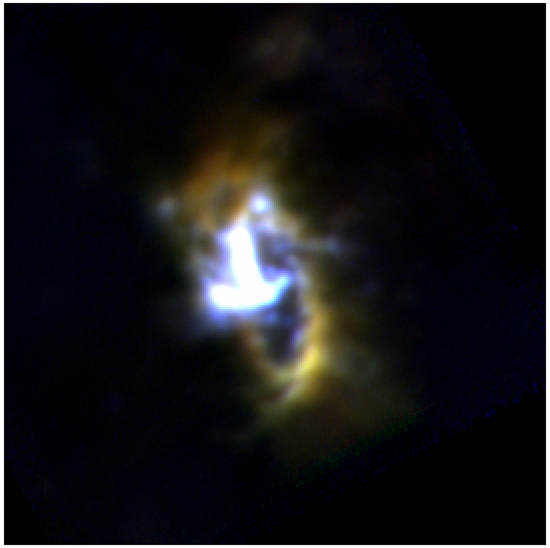
- 31 and 37 Micron data of Comet that had a fly by in Nov.
- First Astro Results Publication of SOFIA 20 Jun ApJ2011

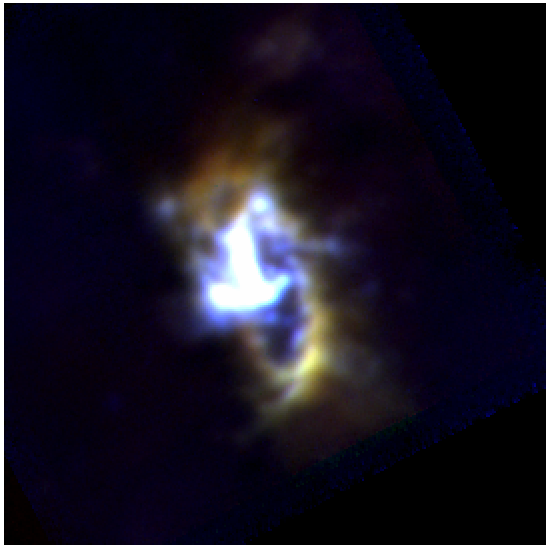
Energy Distribution of Hartley 2 (Meech etal)



Sgr A - CND





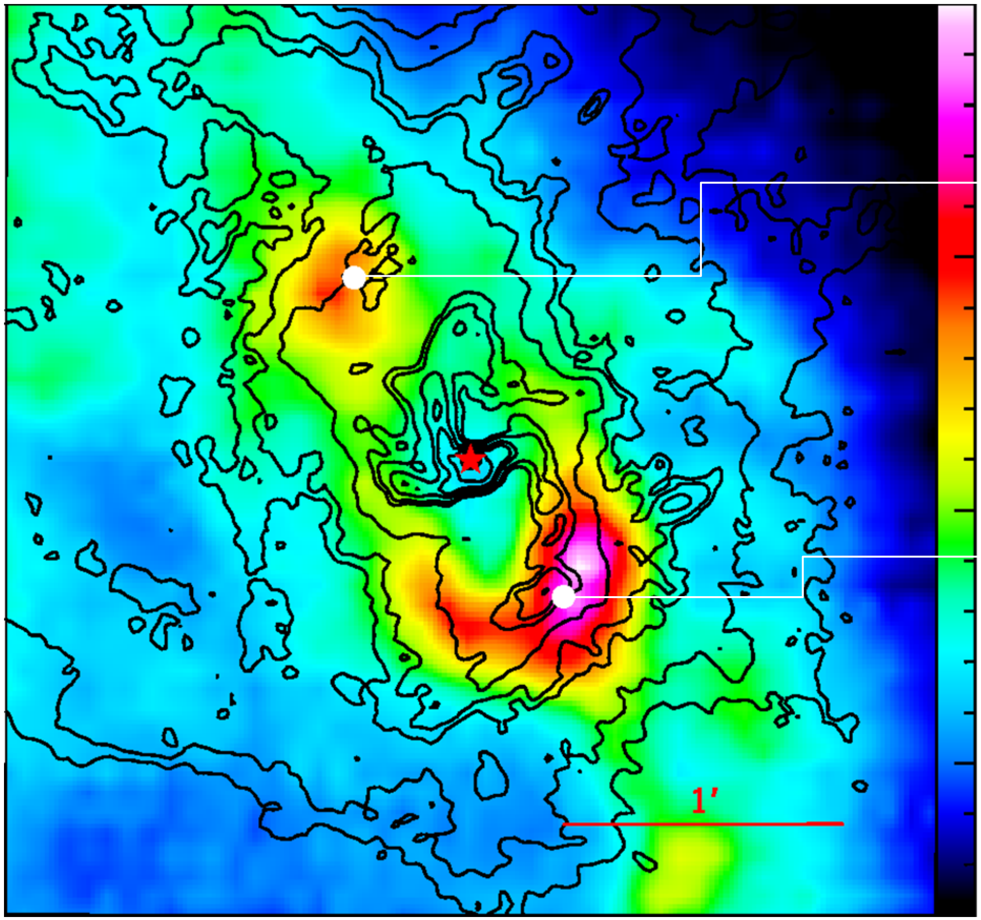


19.7 (blue), 31.5 (green), 37.1 (red)

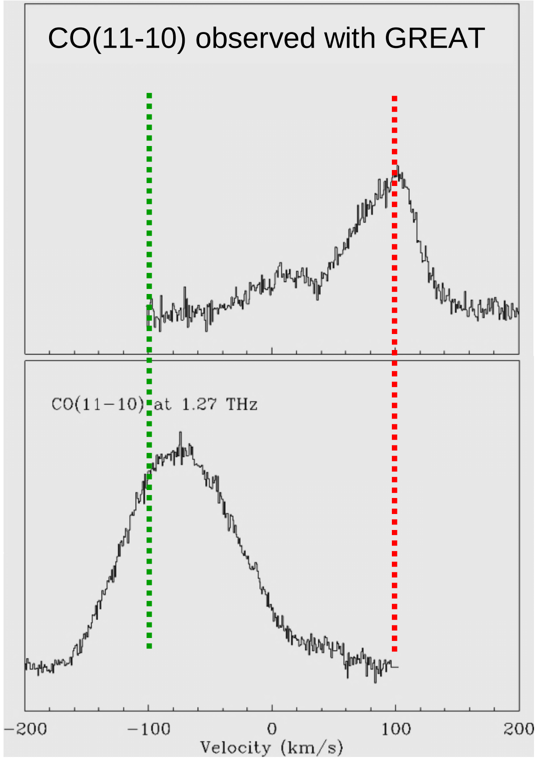
- Multicolor image of circumnuclear disk (CND) in the Galactic Center (courtesy of T. Herter)
- Scaling varies from left (scaled to central brightness) to right (scaled to emphasize the ring)

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

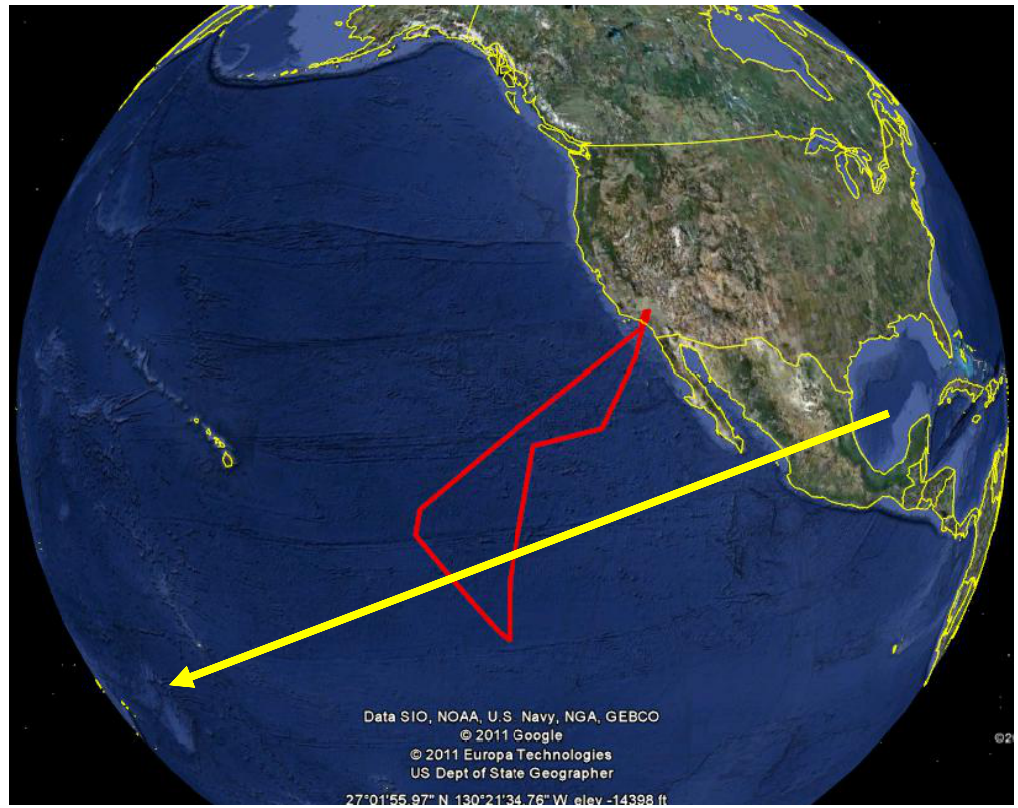
HIPO Occultation of Pluto

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.

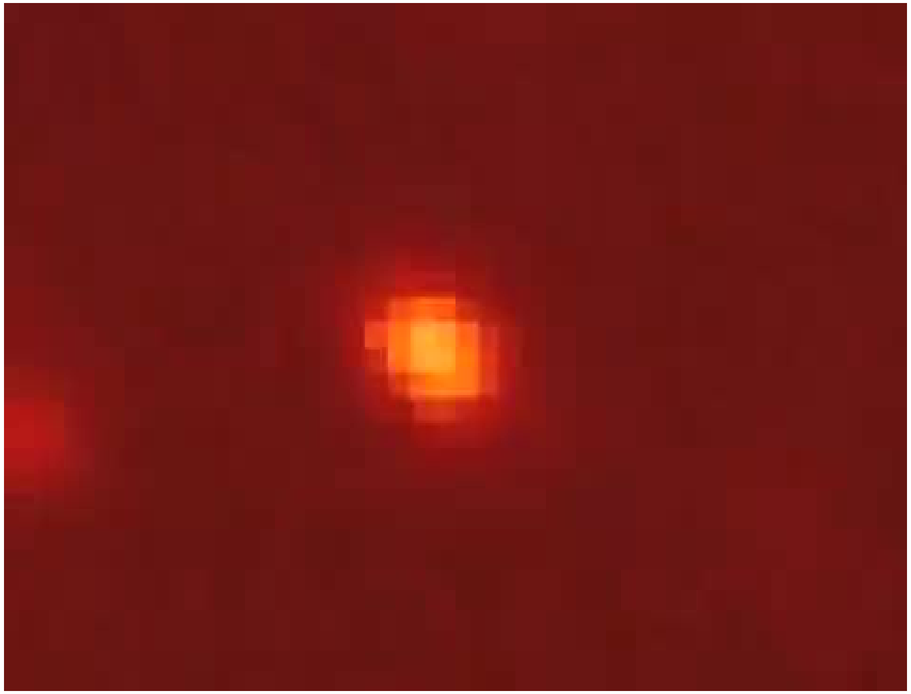
Occultation by Pluto 2011 June 23

- 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



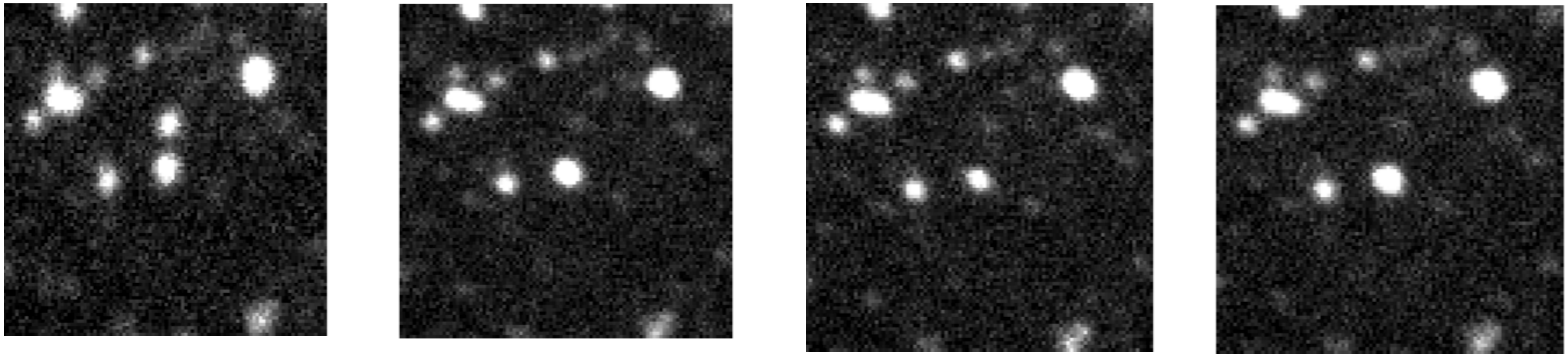
Occultation Results

- 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.



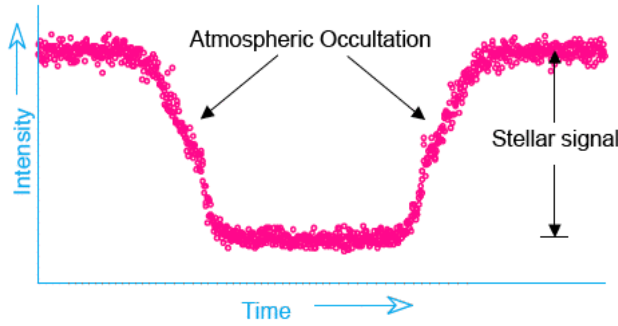
Ted Dunham, Lowell Observatory, HIPO instrument

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

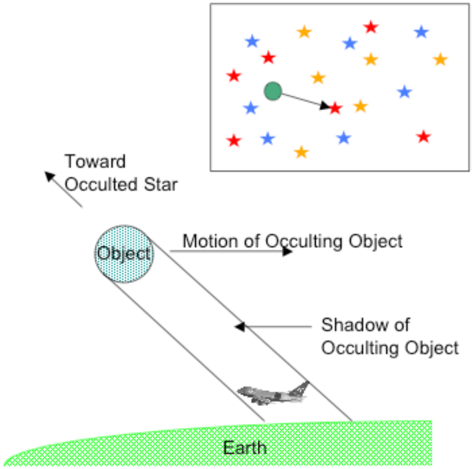


Occultation astronomy with SOFIA

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



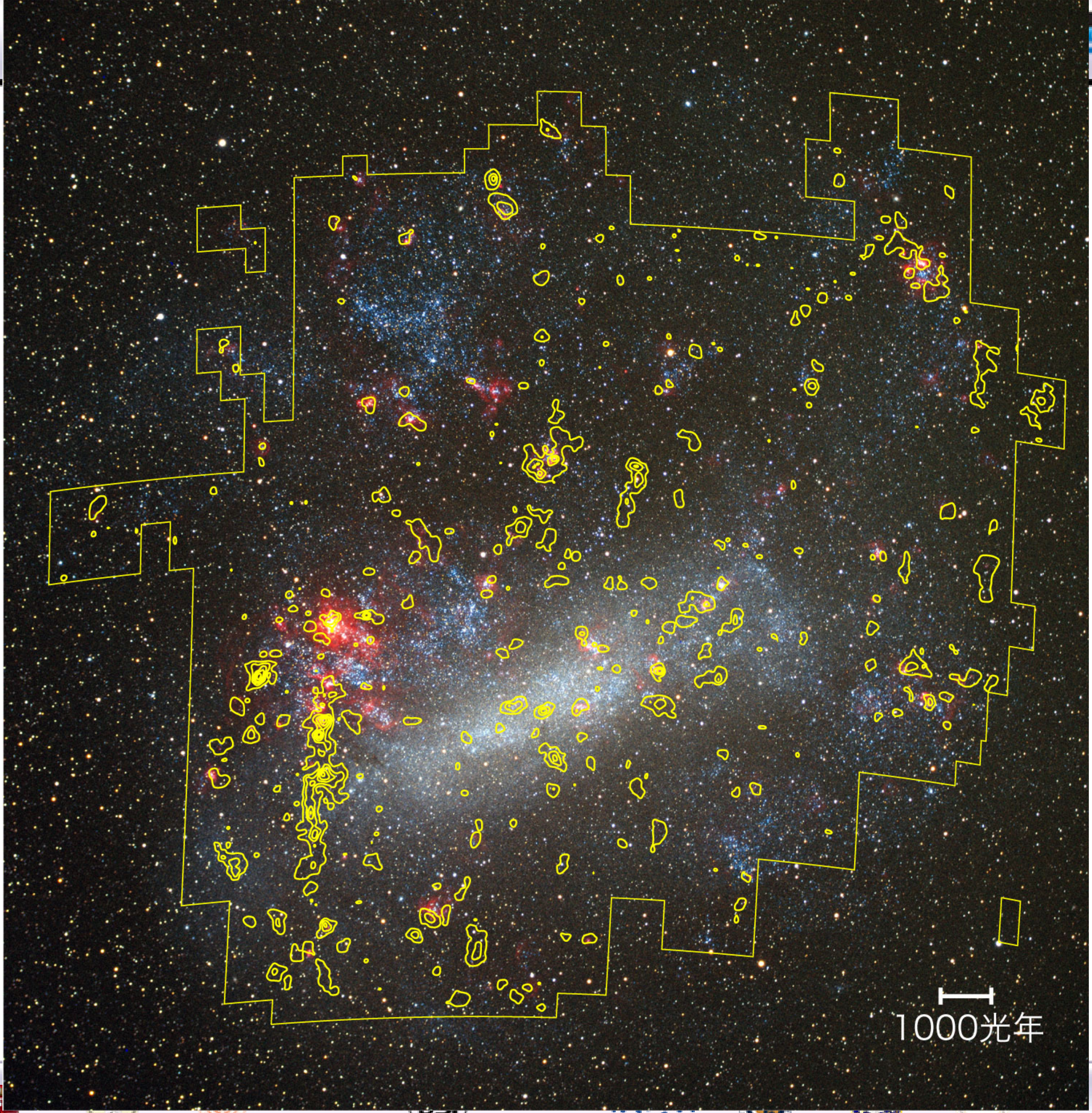
- SOFIA can fly anywhere on the Earth, allowing it to position itself under the shadow of an occulting object.

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

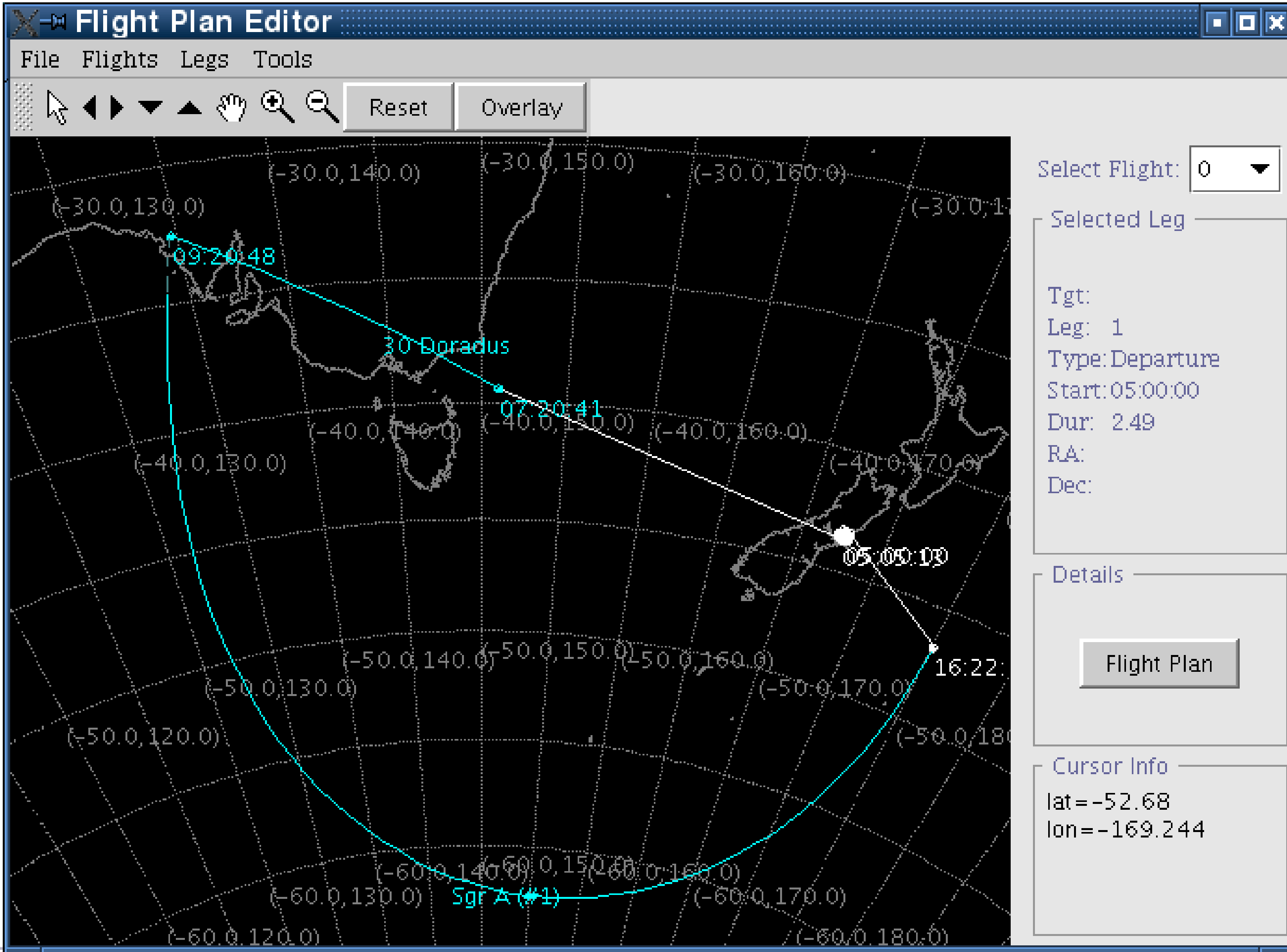
- The unique mobility of SOFIA opens up some hundred events per year for study compared to a handful for fixed observatories.

LMC
GMCs (CO 1-0)

Fukui et al. 2008
NANTEN 4m tel.

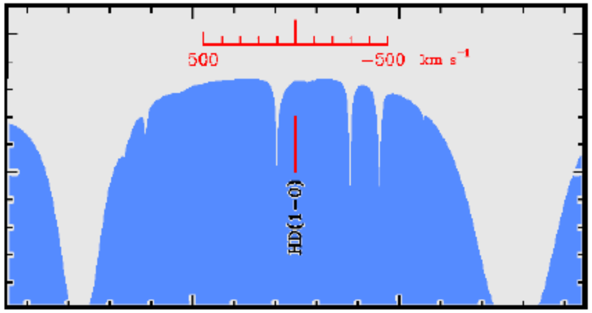


12.3h flight, 7h on Sgr A*



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.

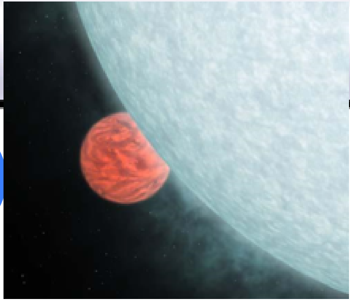
Schedule & Future Opportunities

next call for proposals (Cycle 2): April 2013
next deadline (Cycle 2): 28 June 2013
4+2 instruments on offer for 2014 obs.
(two on shared risk basis)

FORCAST, GREAT, FLITECAM, HIPO
(FIFI-LS, EXES on shared risk)

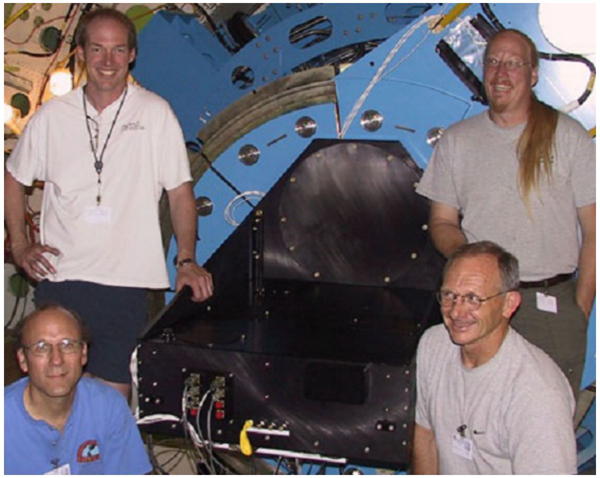
We expect an oversubscription of factor 5

SOFIA in the Dryden Aircraft Operations Facility



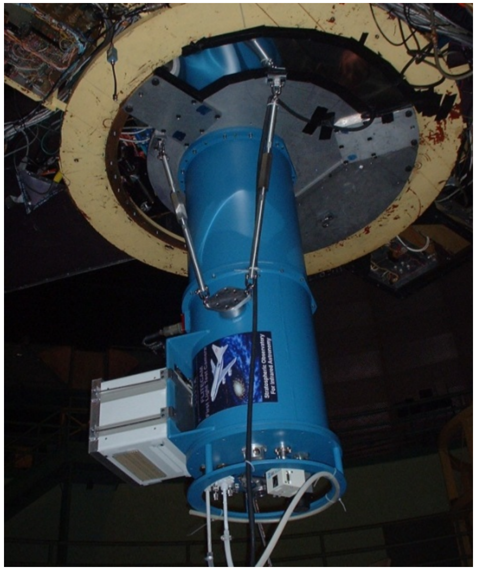
SOFIA movie (take-off and landing)

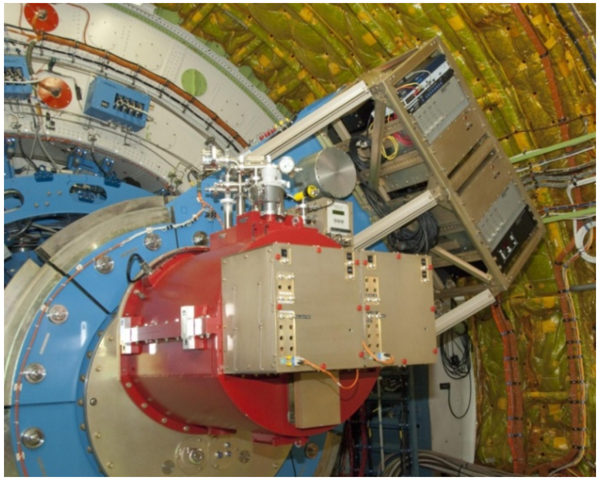
Four Completed 1st Generation Instruments



HIPO
High Speed Photometer
(on SOFIA)

FLITECAM
Near IR Camera
(at Lick observatory)





FORCAST
Mid-IR Camera
(on SOFIA)

GREAT
Heterodyne spectrometer
(on SOFIA)