SOFIA – project overview and potential for magn. field measurements in star forming regions

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STARS2015 conference, Cuba
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OUTLINE

What is SOFIA?
Motivation for SOFIA
The SOFIA Instrument Suite
Science Vision

Potential for Far-IR Polarimetry
HAWC-pol instrument (5 bands)
polarisation spectrum, power spectrum
grain alignment mechanism, B-strength

What is SOFIA?

SOFIA = Stratospheric Observatory for Infrared Astronomy

flying at ~12-14km

- 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, international Observatory

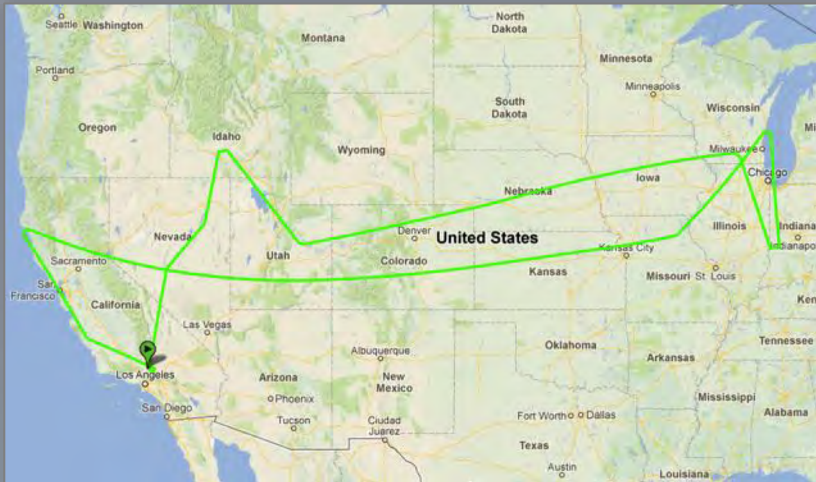
The SOFIA Aircraft

SOFIA is a highly modified Boeing 747SP

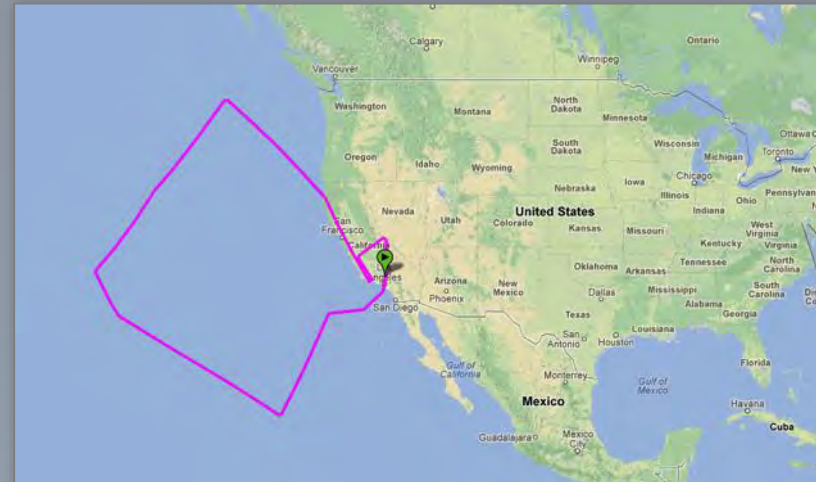
- Length: 177 feet
- Wingspan: 196 feet
- Service ceiling: 45,000 feet (13.7 km)
- Airspeed at 41,000 feet: 450 knots (Mach 0.8 or 520 mph)
- Range: 6,625 nautical miles
- Mission duration: 8 to 10 hours (standard); 12.2 hours (maximum)
- Cavity door (18 feet by 14.3 feet)
- Fuel usage: 150,000 to 250,000 pounds (standard duration mission)

SOFIA Science and Operations Centers

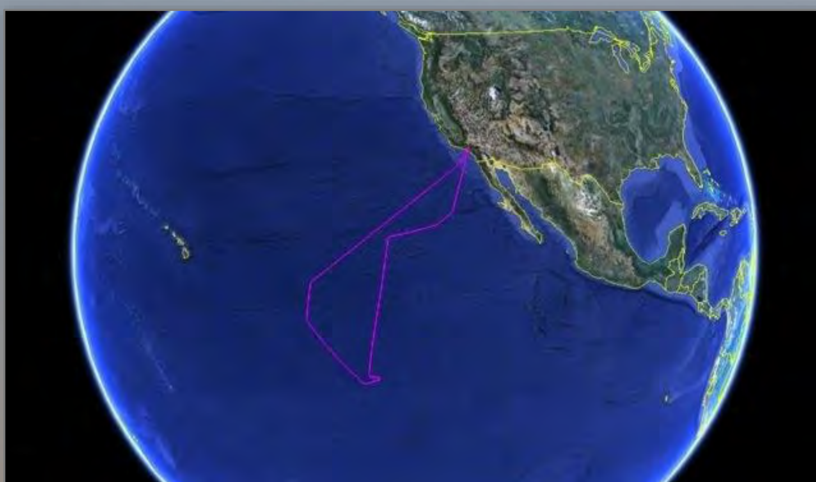
Sample Flight Plans (Palmdale and New Zealand)



May 24, 2011: Basic Science 1 Flight (FORCAST)



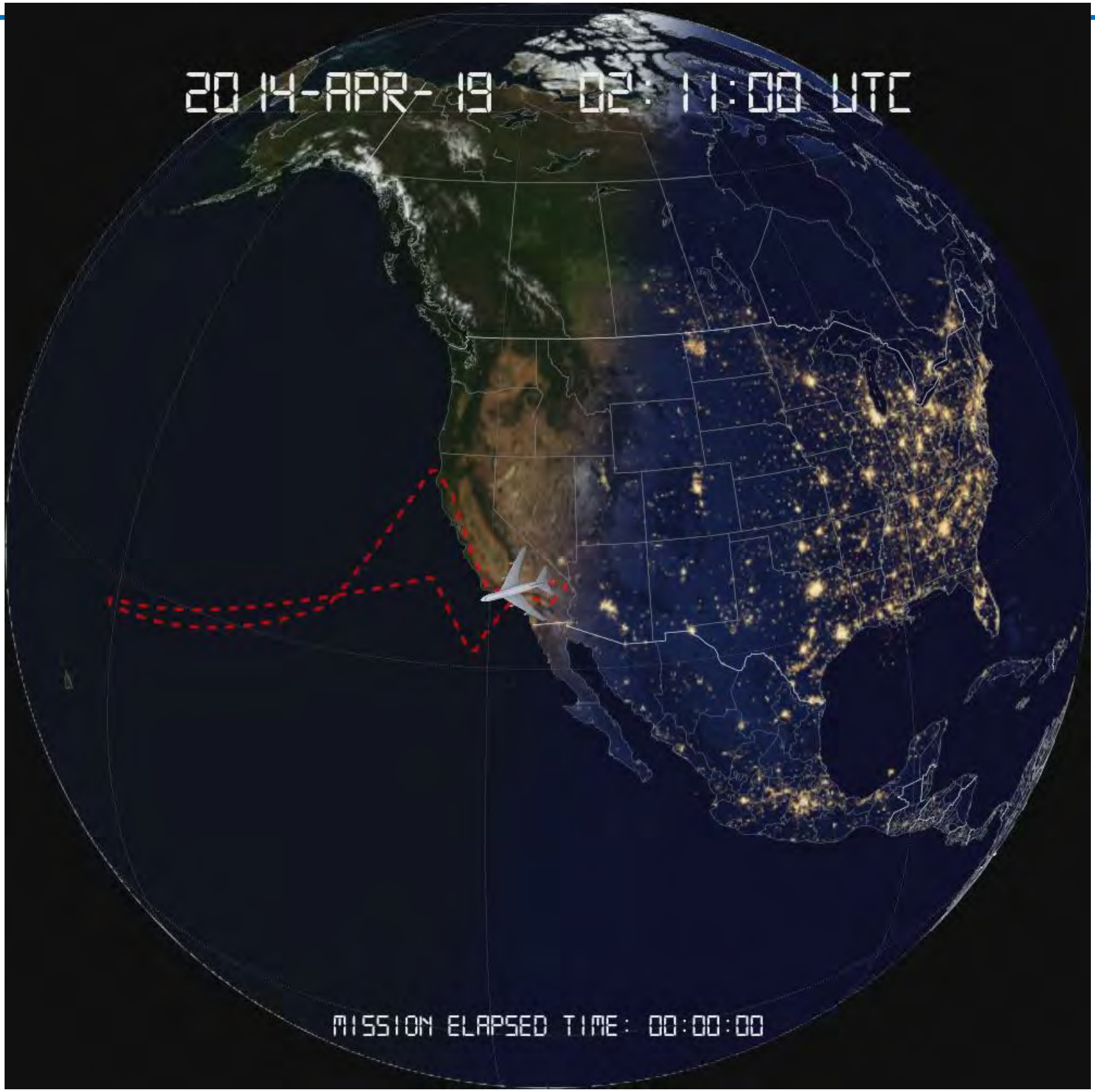
May 21, 2011: Basic Science 2 Flight (GREAT)



June 22, 2011: Pluto Occultation Flight (HIPO)

July 17, 2013: New Zealand Science Deployment Flight (GREAT)

SOFIA Flight 161 with FIFI-LS

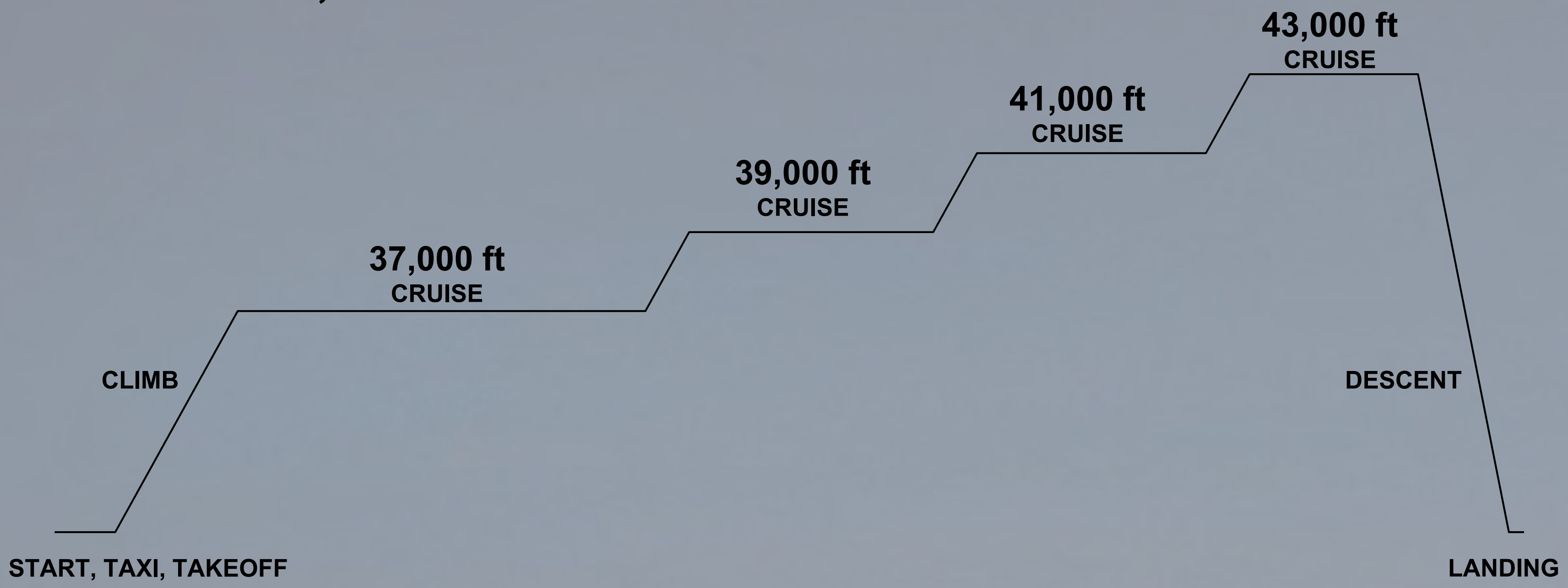


Flight Paths

Geographic Distribution of SOFIA Science Flights (2010-2011)

Observing Flight Profile

Starts at ~37,000 feet



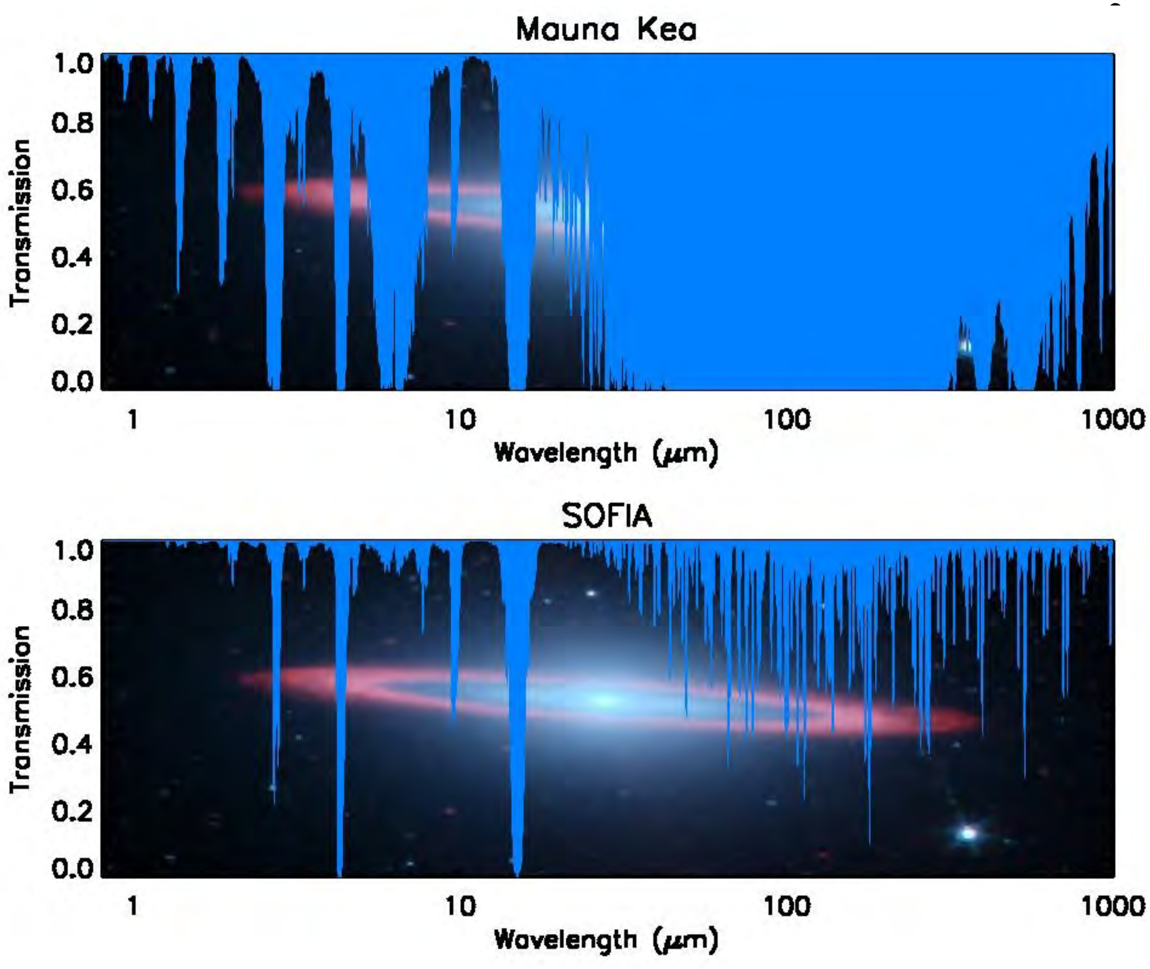
Total cruise time – 9 hours

Total flight time – 10 hours

Motivation for SOFIA

- Infrared transmission in the stratosphere very good: >80% from 1 to 1000 μm
- Resolution and sensitivity is set by the size of the telescope
- Instrumentation: wide complement, rapidly interchangeable, state-of-the art
- Mobility: anywhere, anytime
- Long lifetime
- Outstanding platform to train future Instrumentalists
- SOFIA will have an important role in education and public outreach

Motivation for Airborne Astronomy



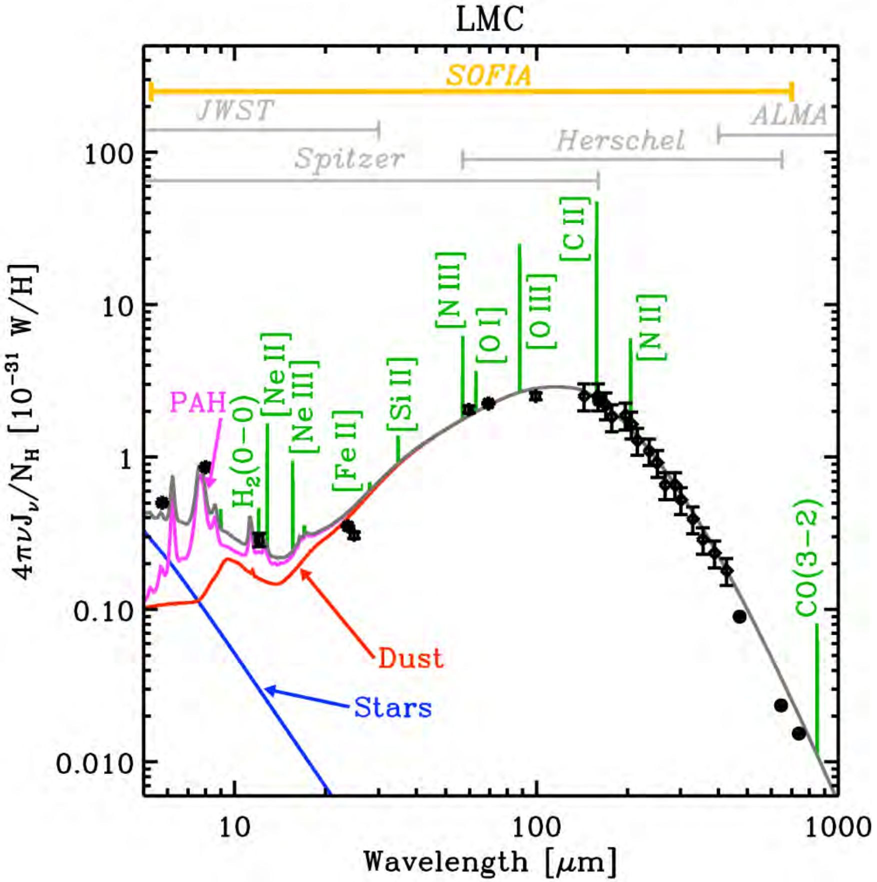
- For much of the infrared, the Earth's atmosphere blocks all transmission.
  - The problem is water vapor

If we can get above this water vapor, much more can be observed (average PWV is 10-20 mu, < 0.2%)

50x better than Mauna Kea
20x better thanAPEX/ALMA

Importance of Far IR / Sub-mm

- Most of the energy of star formation regions, external galaxies, and cooler objects in the universe is in the far-IR and Sub-mm
- The most important cooling lines in the ISM fall in this spectral region

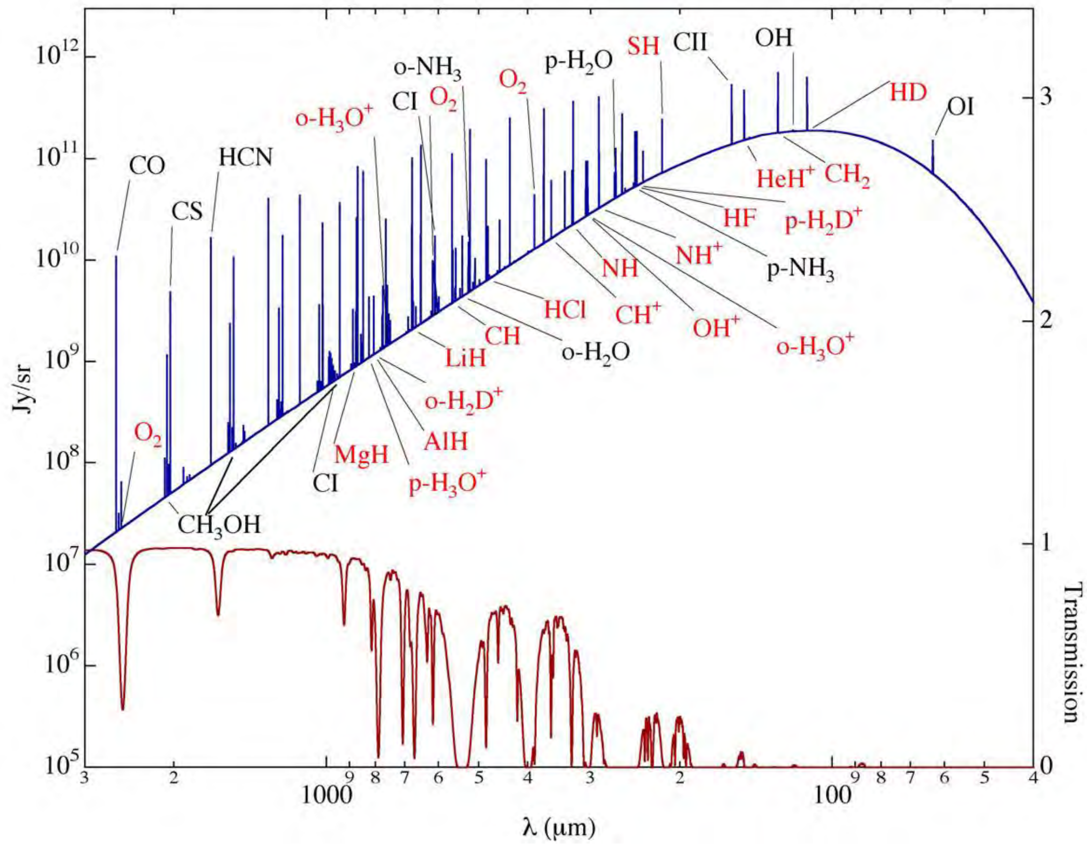


The spectral energy distribution of the entire LMC, based on data from Spitzer, IRAS and FIRAS (Bernard et al. 2008). SEDS are fitted with the dusty PDR model of Galliano et al. (2008). Figure courtesy of Galliano.

Importance of Far IR / Sub-mm -2

- Most of the key atomic and molecular tracers of the Interstellar Medium are in the Far Infrared and Sub-mm

Molecular Cloud Spectrum



Ted Bergin, 2008

SOFIA science vision (excerpt)

SOFIA is a long-term ISM Observatory for studying the interstellar matter cycle + feedback processes:

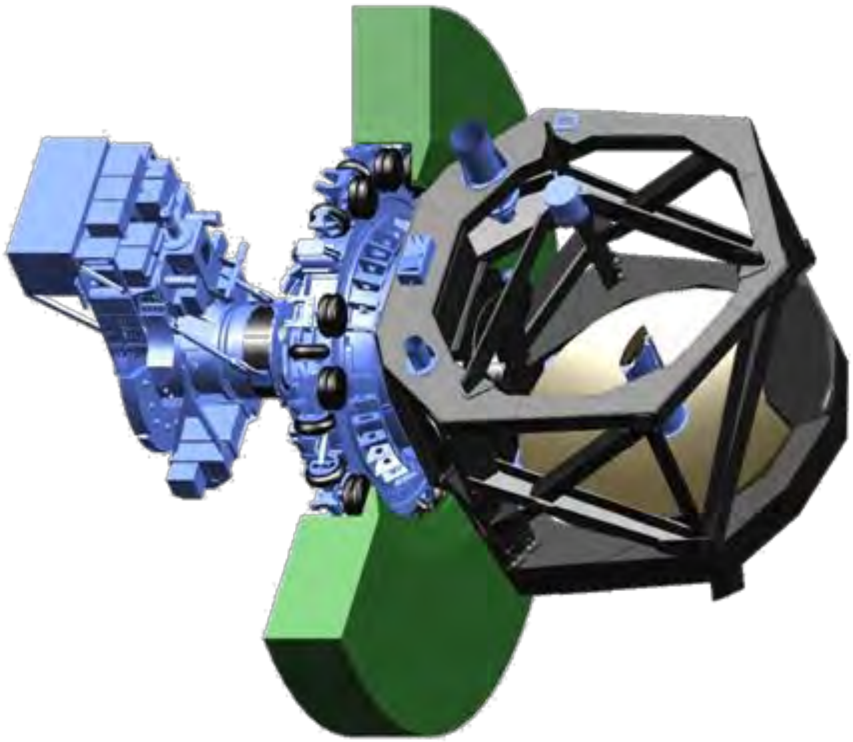
-molecular gas spectroscopy: collapse, outflows, turb.

-dust emission broad-band, narrow-band, pol. imaging

SOFIA's suite of instruments comprehensively covers the wide range of wavelengths and spectral resolution (1 -250 microns, spectral resolution up to 10,000,000)

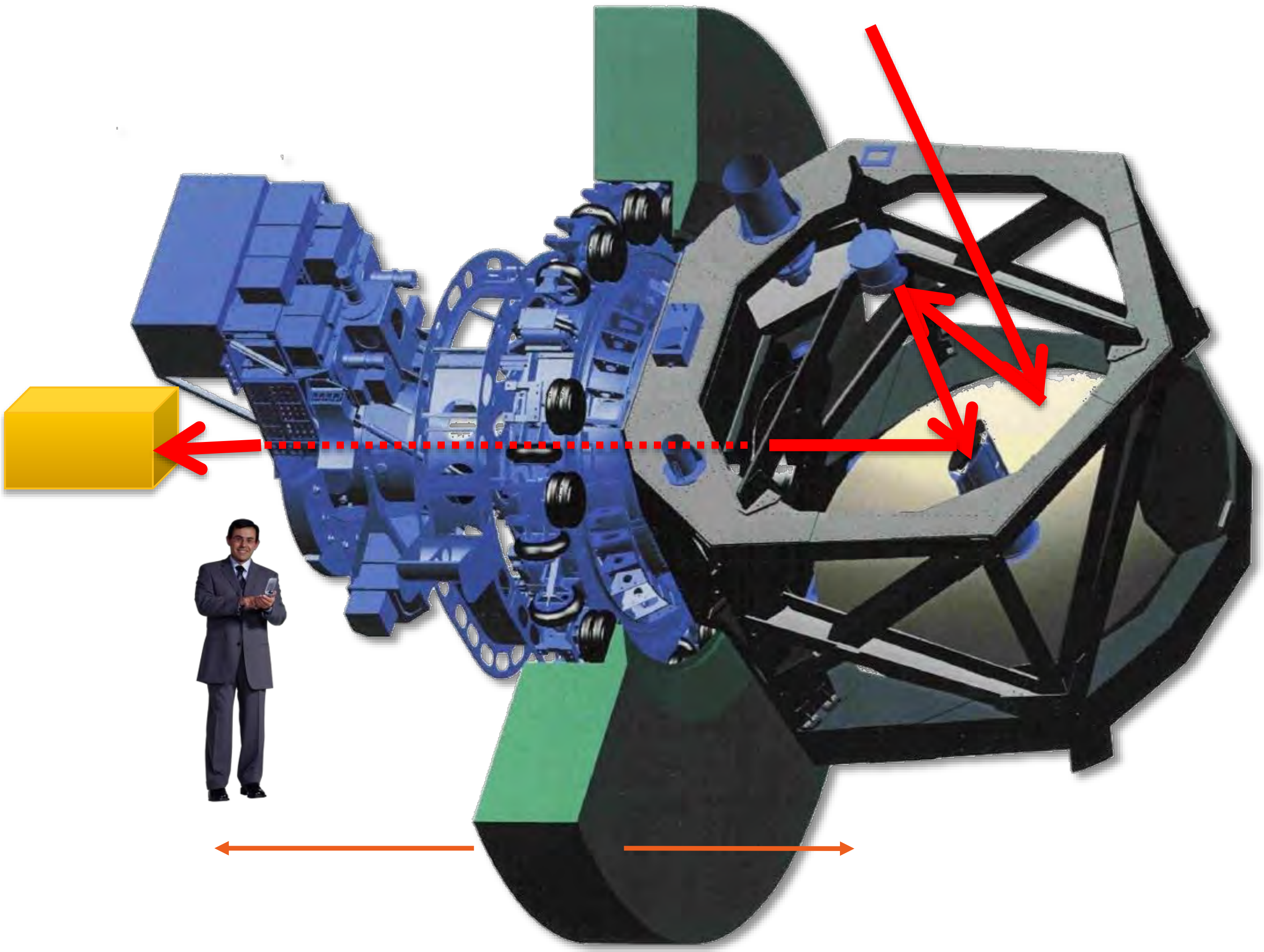
Follow-on IRAS, ISO, Spitzer and Herschel IR satellites

The Telescope Assembly – A Major German Contribution

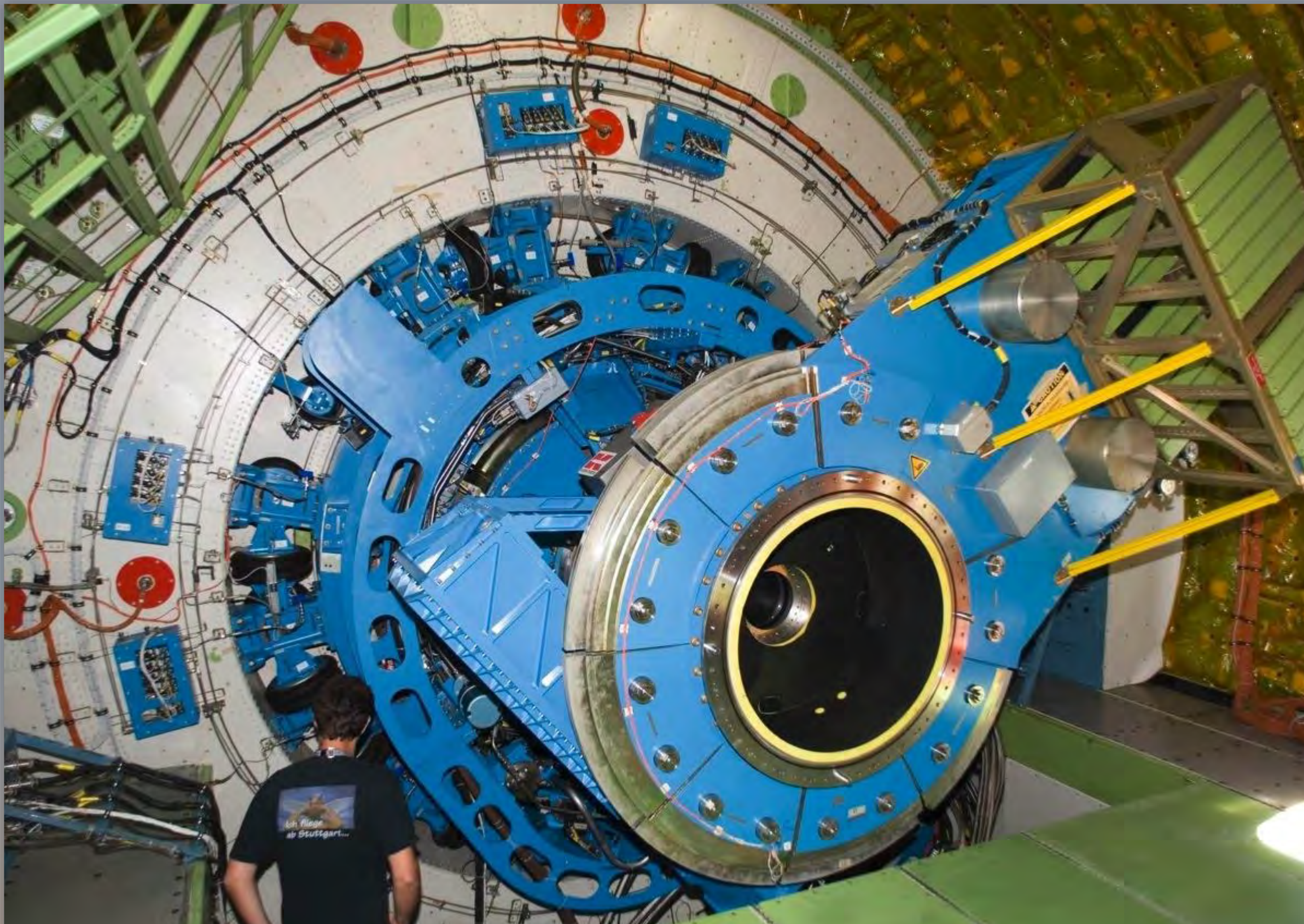


THE SOFIA TELESCOPE

- The telescope is a major contribution from Germany
- 2.7 meter diameter mirror
- Wavelength: 0.3 to 1,600 microns
- Installed weight: 17 metric tons



Interior (Main Cabin) View of Telescope Assembly



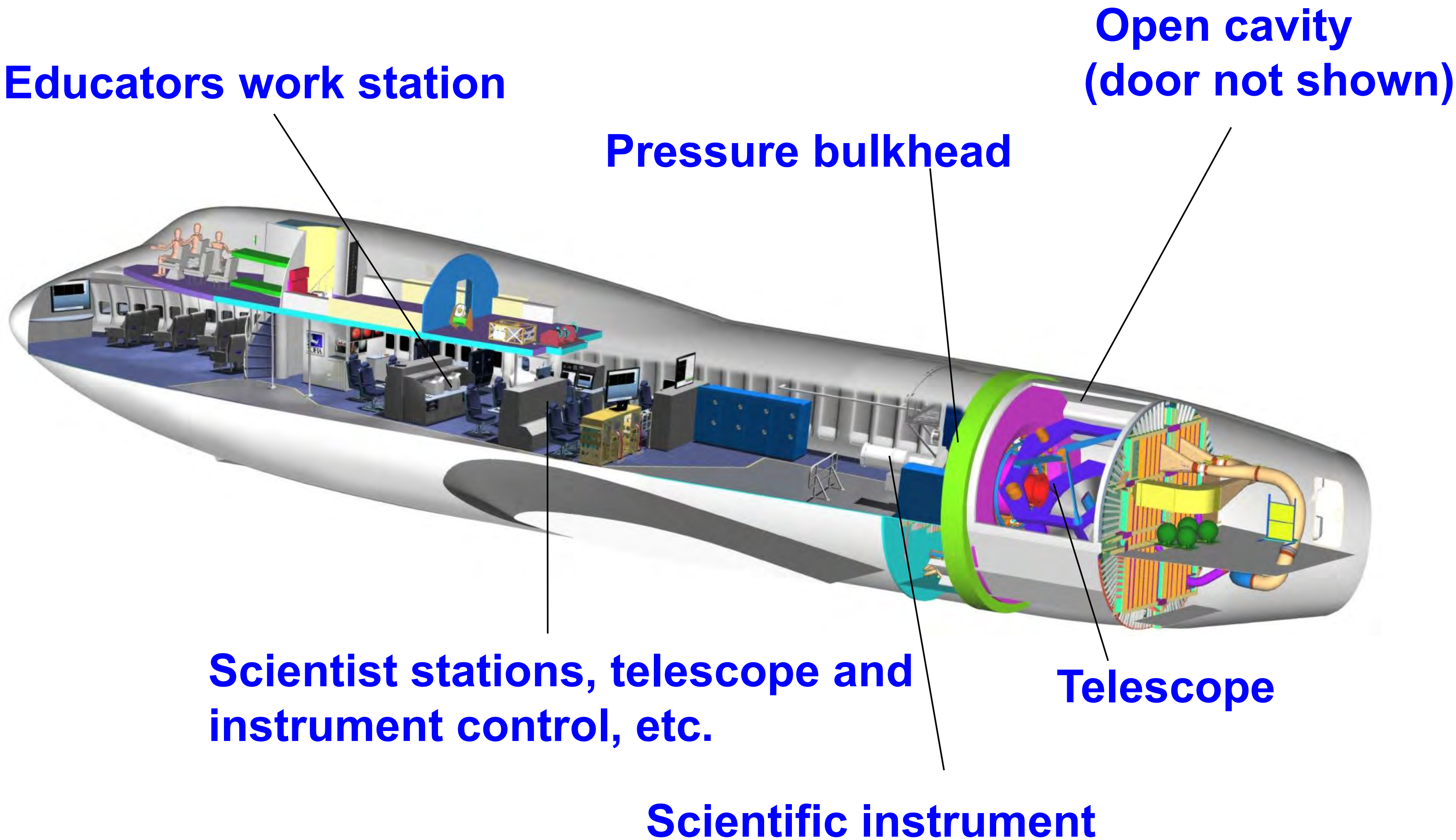
White is pressure bulkhead

Blue is DLR-supplied telescope

USRA NASA DLR SOFIA

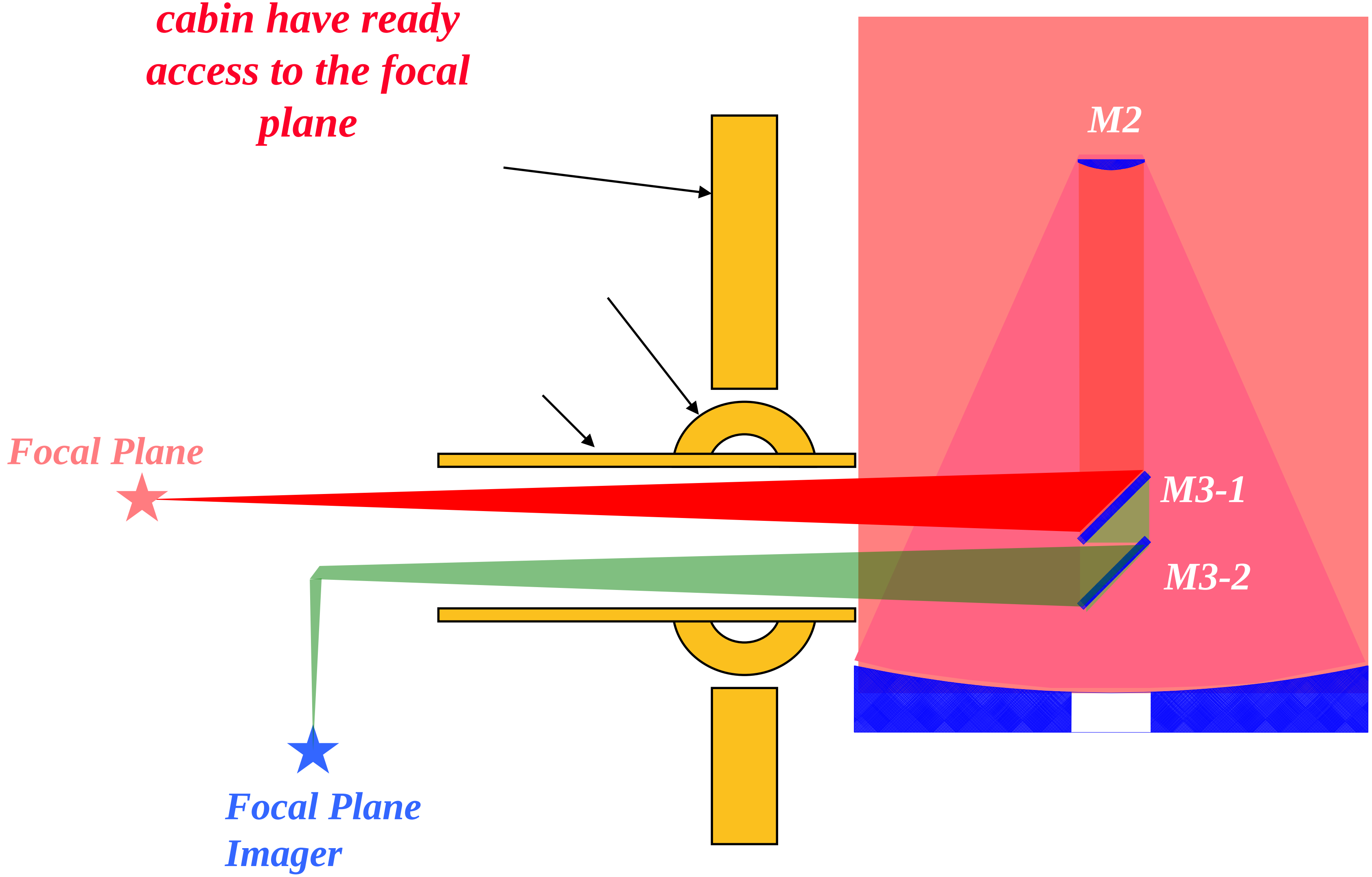
SOFIA First Science Flight (FORCAST, Dec 2010)

SOFIA – The Observatory



Nasmyth: Optical Layout

Observers in pressurized cabin have ready access to the focal plane



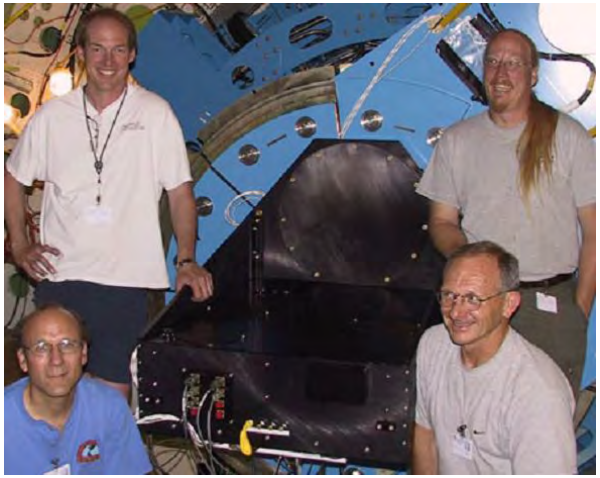
SOFIA instrument suite

- FORCAST
- GREAT
- HIPO
- FLITECAM

- FIFI-LS
- EXES

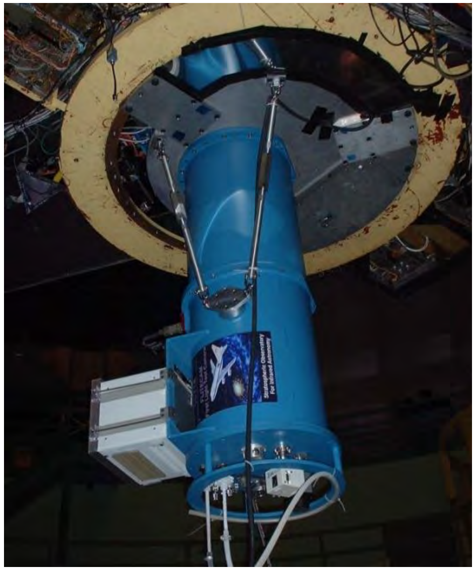
- HAWC +, HAWC ++ (pol)
- upGREAT

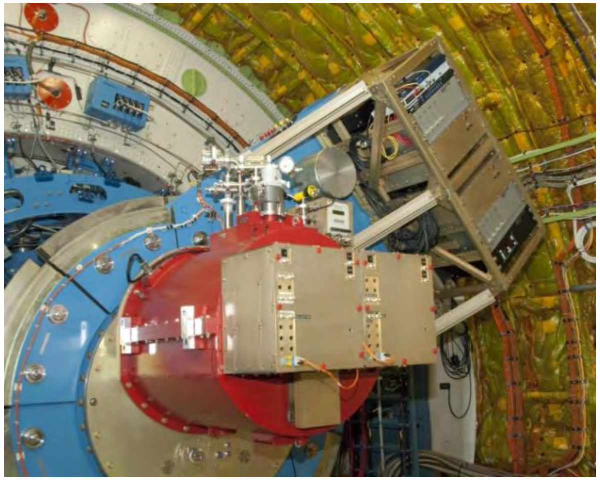
Four Completed 1st Generation Instruments



HIPO
High Speed Photometer

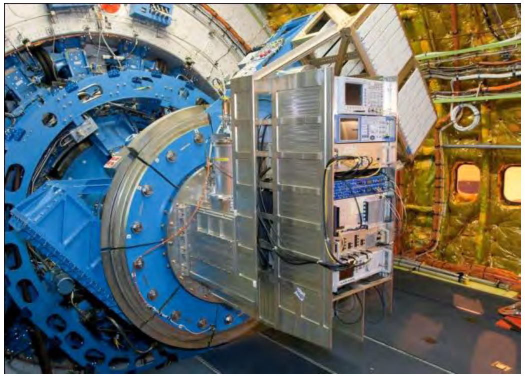
FLITECAM
Near IR Camera
(at Lick)





FORCAST
Mid-IR Camera

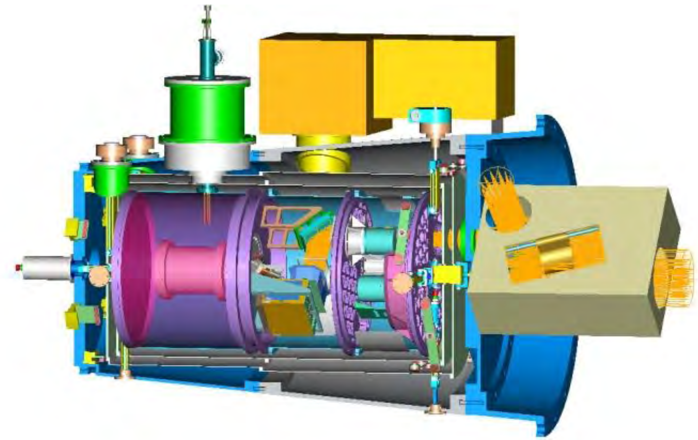
GREAT
Heterodyne spectrometer



Instruments in development

HAWC

Bolometer Camera

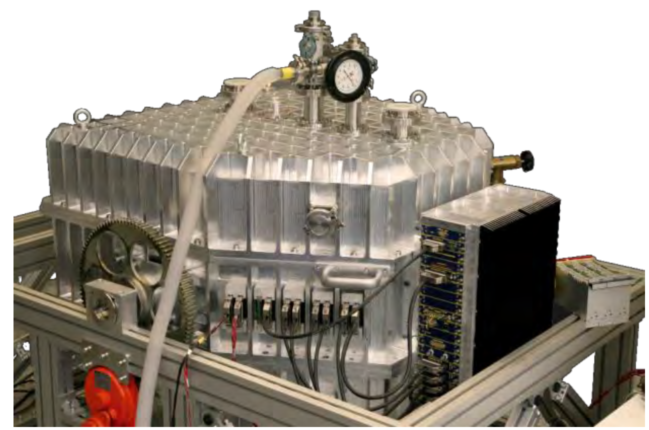


EXES

Mid- IR Spectrometer

FIFI LS

Integral Field Spectrometer



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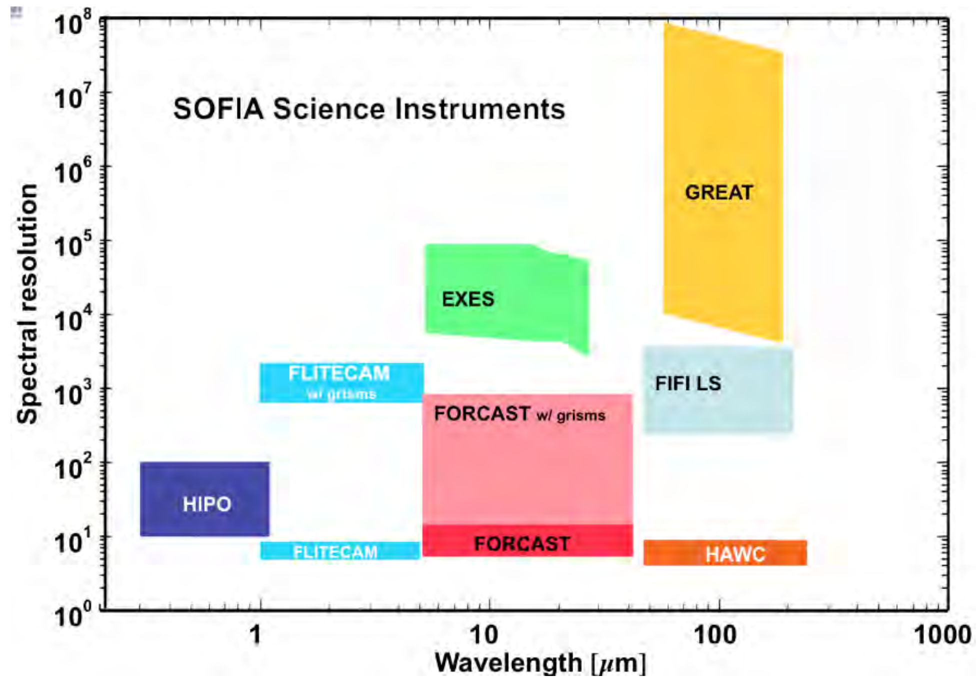
SOFIA's Instrument Complement

- FORCAST
- GREAT, upGREAT
- HIPO
- FLITECAM

- FIFI-LS
- EXES
- HAWC-POL (2nd gen)



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 scale: 0.75 arcsec/pix

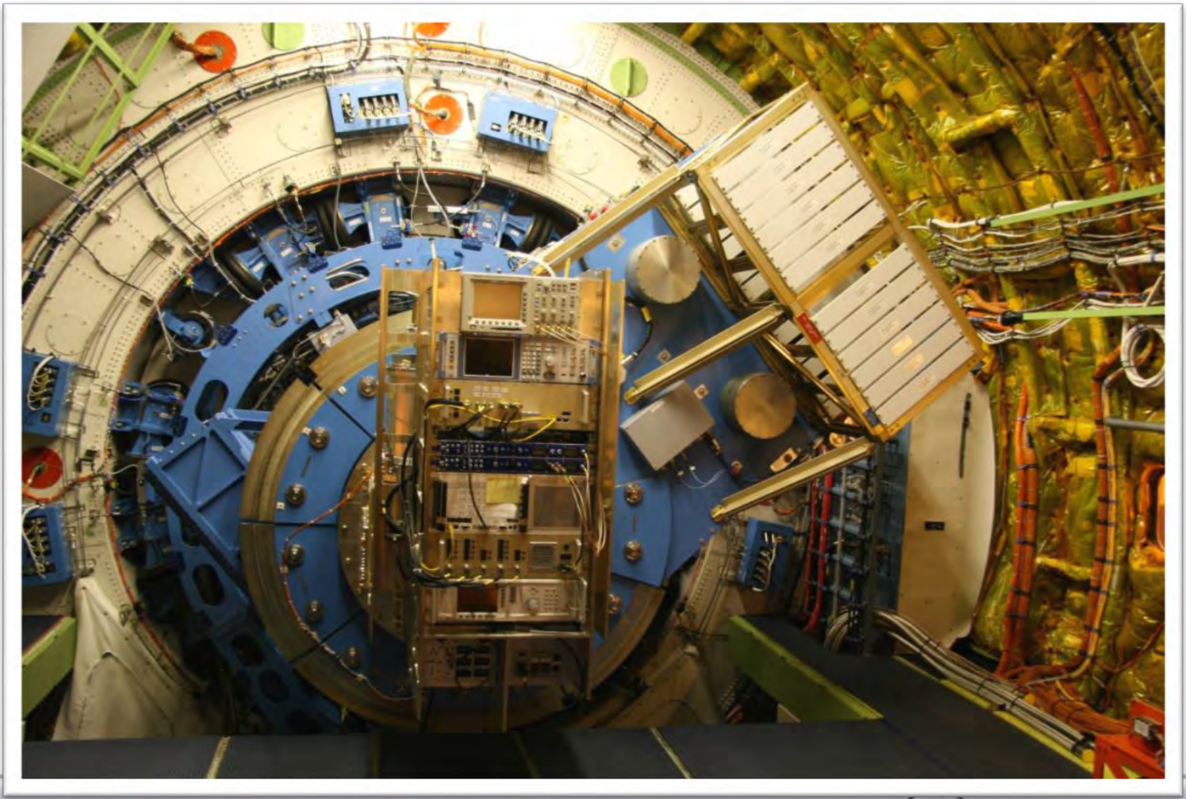
Science: Thermal and narrow band imaging

Targets: Circumstellar disks, Galactic Center,
Galactic star formation regions (Spitzer sat.)

NB:
at present Diffraction Limited > ca. 30 microns;
There are various low-res grism modes (→PAH)

German REceiver for Astronomy at Terahertz frequ. (PI: R. Guesten, MPIfR/Bonn)

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]



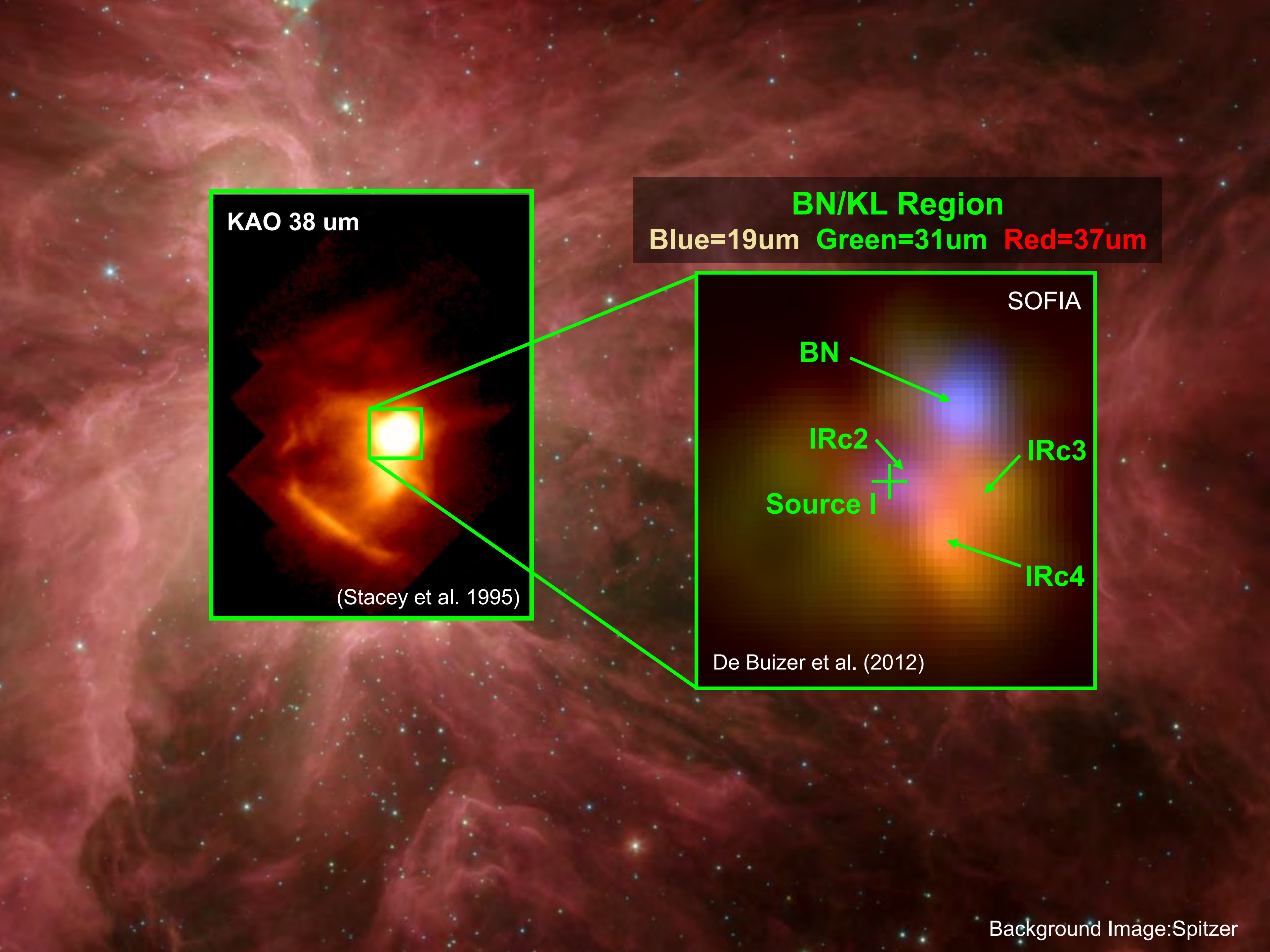
USRA NASA DLR SOFIA

Early Science Highlights

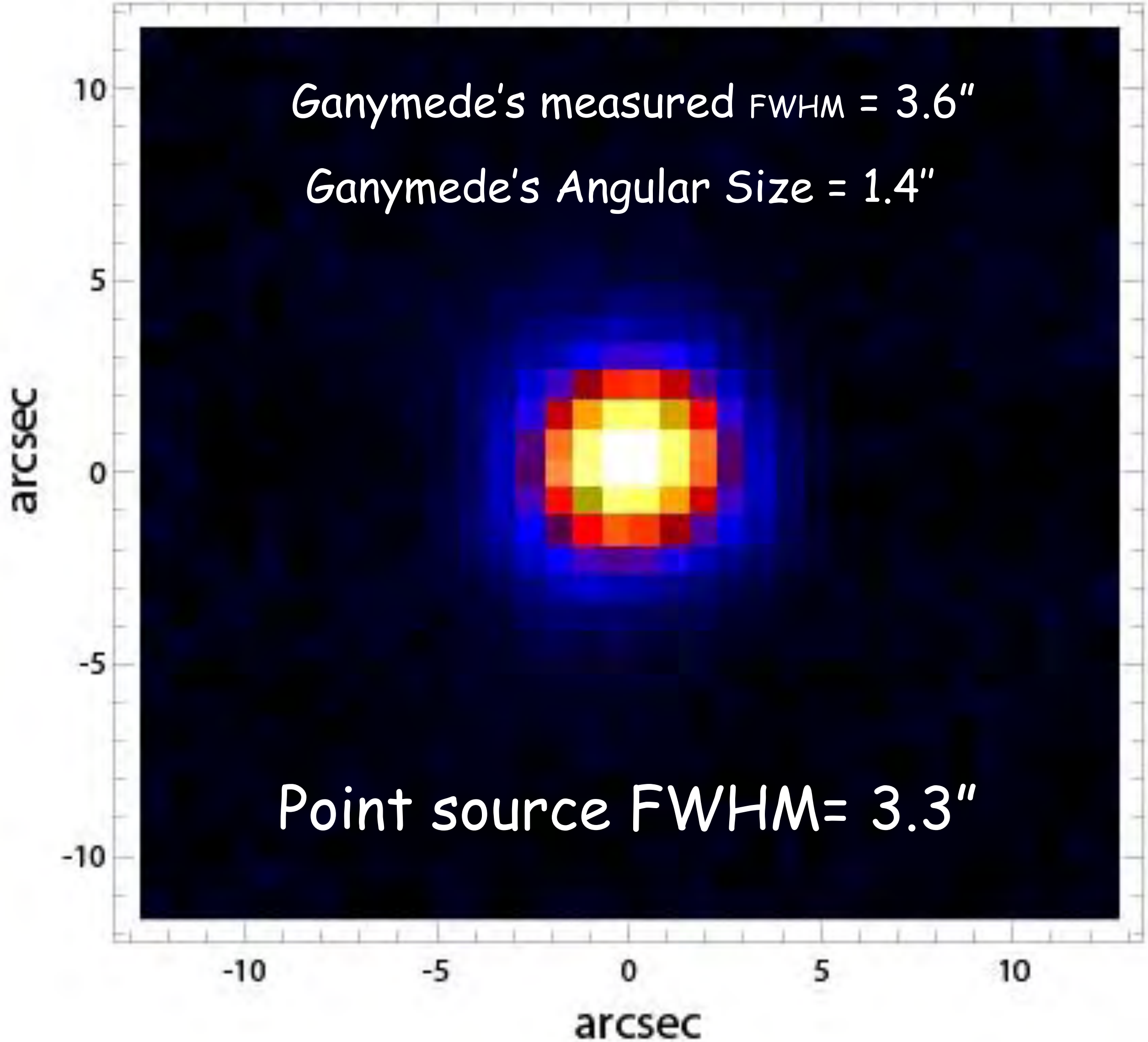
FORCAST: Orion Trapezium region warm dust clouds
BN/KL-Nebula energy sources (SEDs),
Galactic Center circumnuclear dust disk/ring

GREAT: M17 photodissociation region (C+/CO map)
G34.3 accreting massive star (NH3 inflow)
W49N: new molecules SH, OH/OD (in abs.)

Pluto occultation of a star (out over Pacific) successful !


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

SOFIA image quality at 24 microns



Close to the diffraction limit (ca. 2.4")

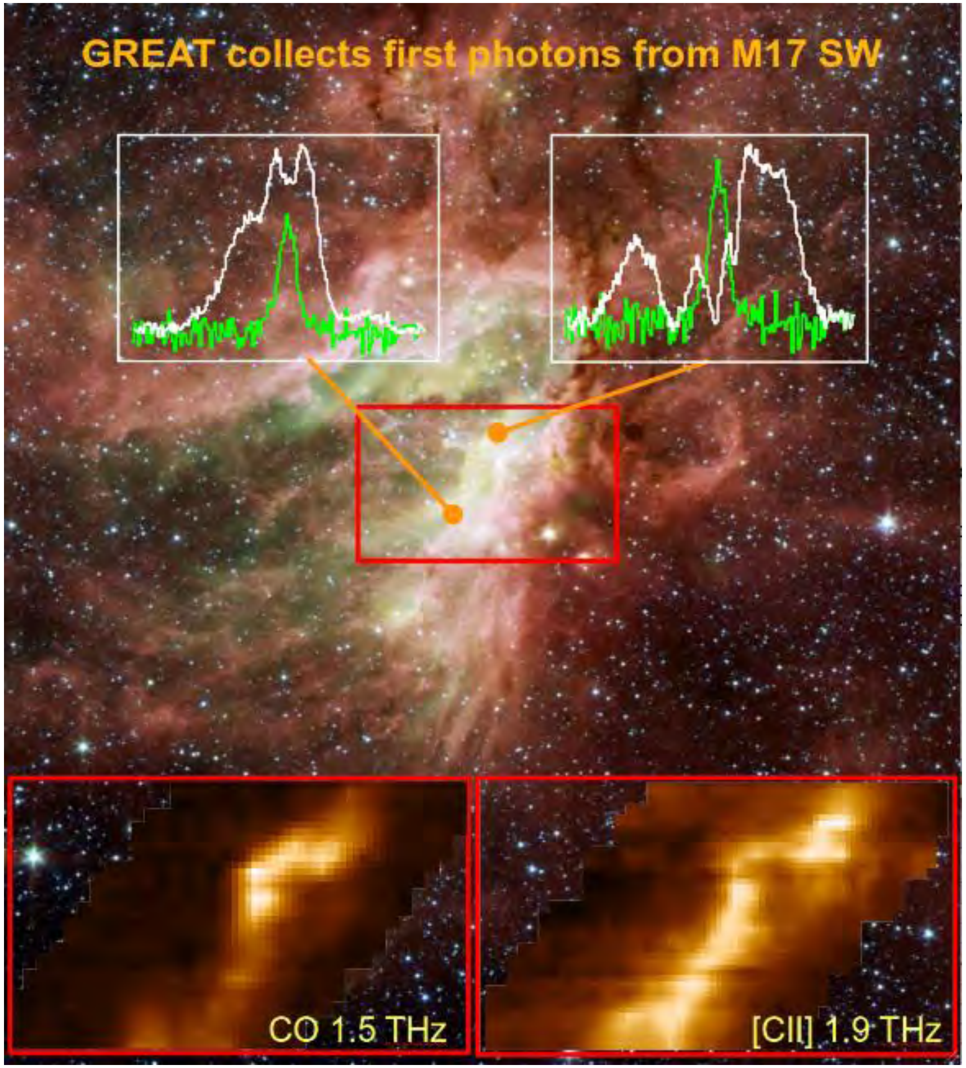
GC-CNR at 19(blue), 31(green) and 37(red) microns

This is the highest resolution image of the CircumNuclear Ring ever obtained with ~3 arcsec FWHM (R. Lau et al. 2013, ApJ)

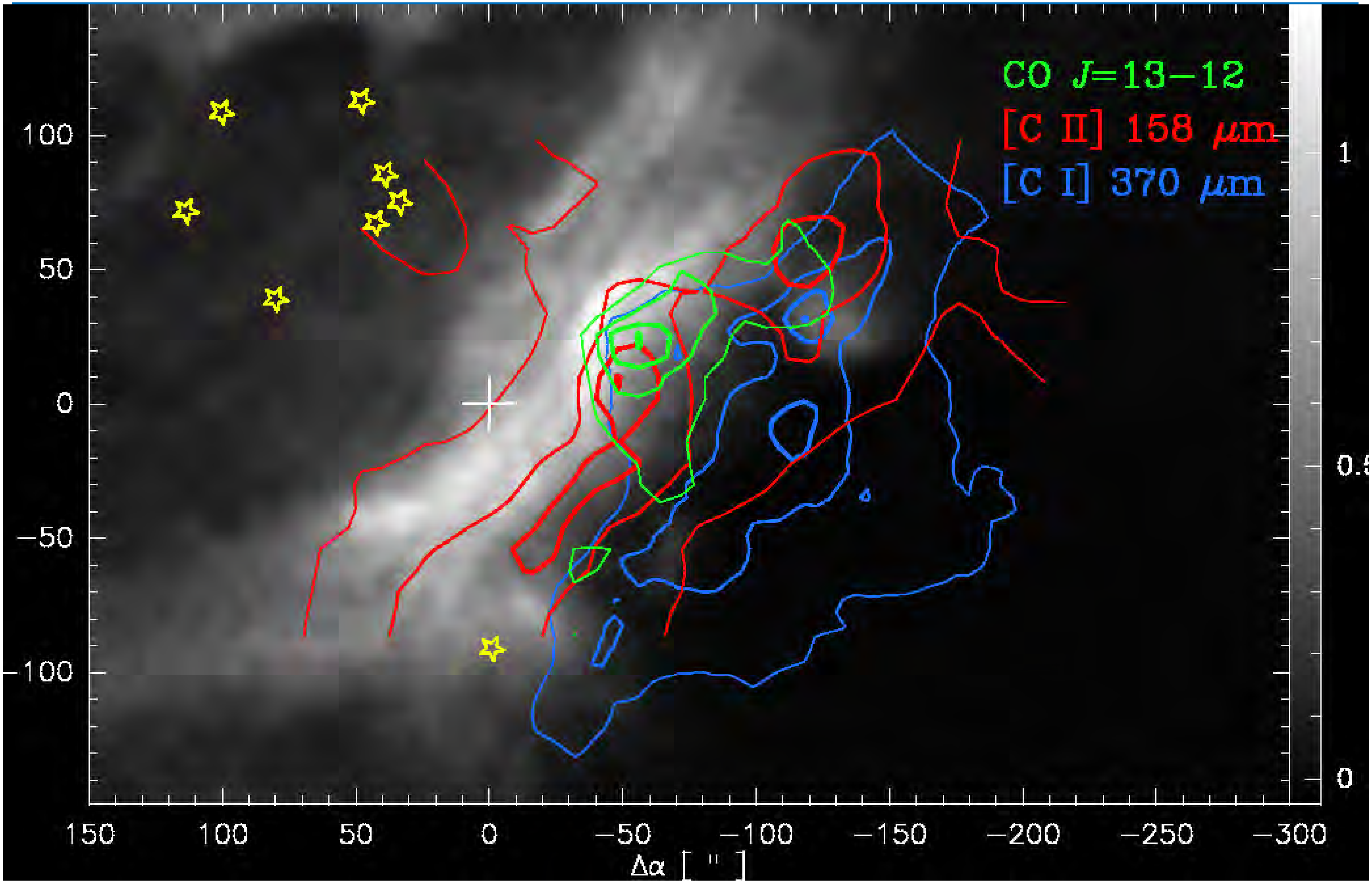
- White central emission is from the hot dust heated by ionized gas of the northern and eastern arms
- Almost perfect 1.5 pc radius ring is seen in cooler dust (T~100K) centered on the Massive Black Hole and tilted about 18 degrees to the LOS and The Galaxy
- The ring is resolved with a width of about 0.3 pc (no star formation along the ring)
- There is interesting small structures along the ring, almost periodic in nature.

USRA NASA DLR SOFIA

First Science with GREAT (white [CII], green CO)
M17 photodissociation region

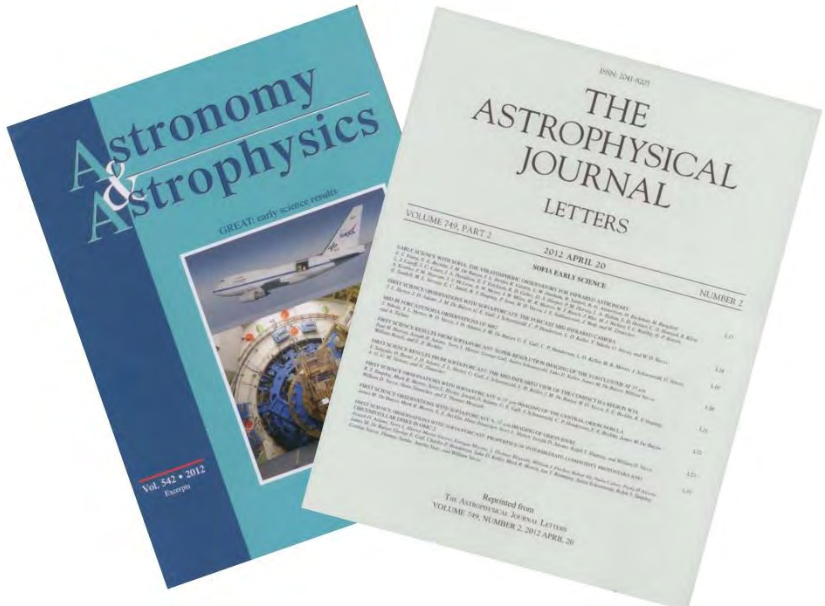


M17SW photo-dissociation region (GREAT/APEX)



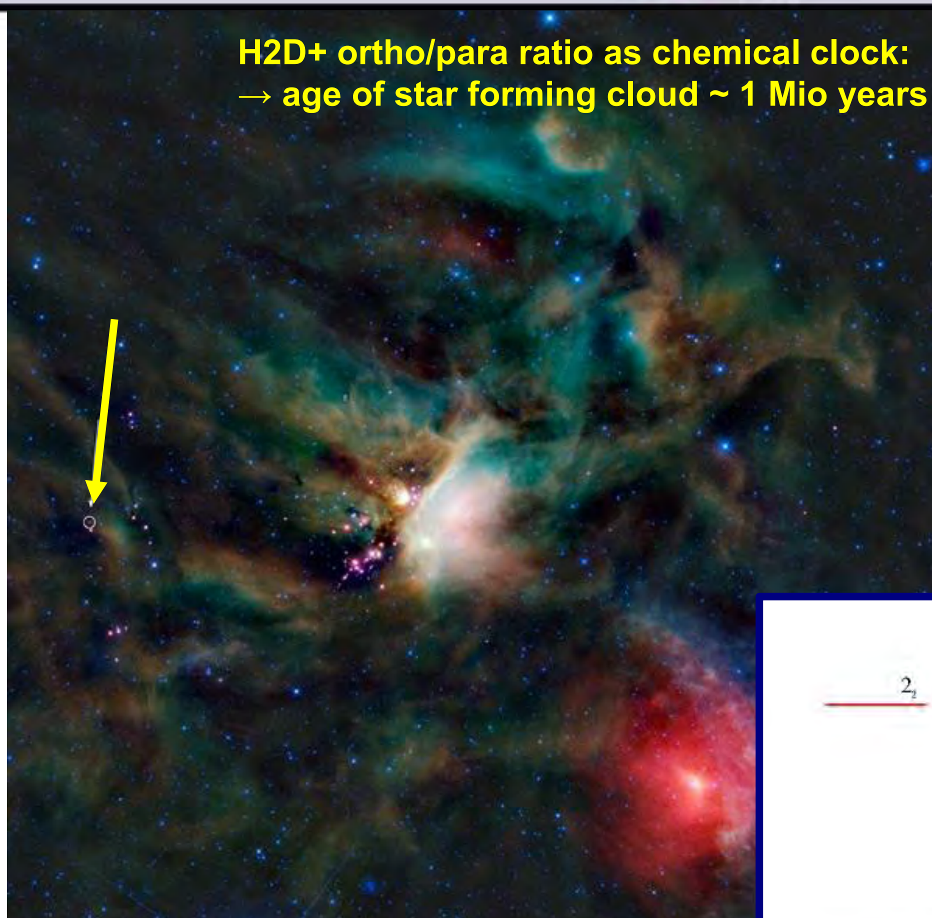
Recent Results

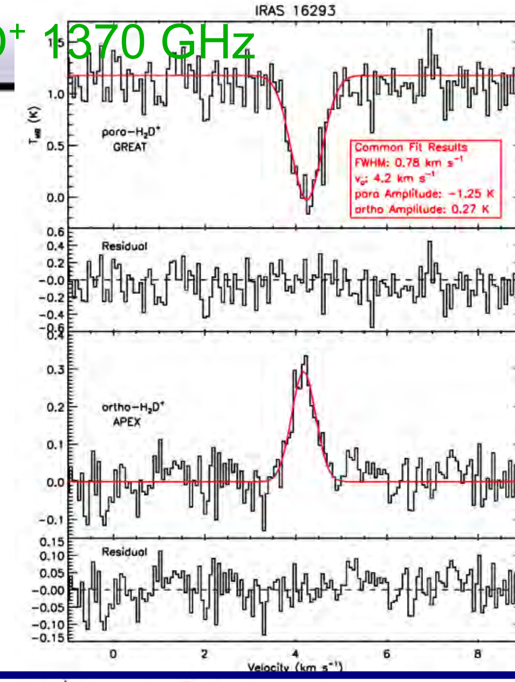
- SOFIA has published two special issues that highlight the science accomplished during the Early Science period
- HZ SOFIA review in Proc. Hamburg AG (AN 334, 558, 2013)



GREAT: first firm detection of para H_2D^+ 1370 GHz

H2D+ ortho/para ratio as chemical clock:
→ age of star forming cloud ~ 1 Mio years

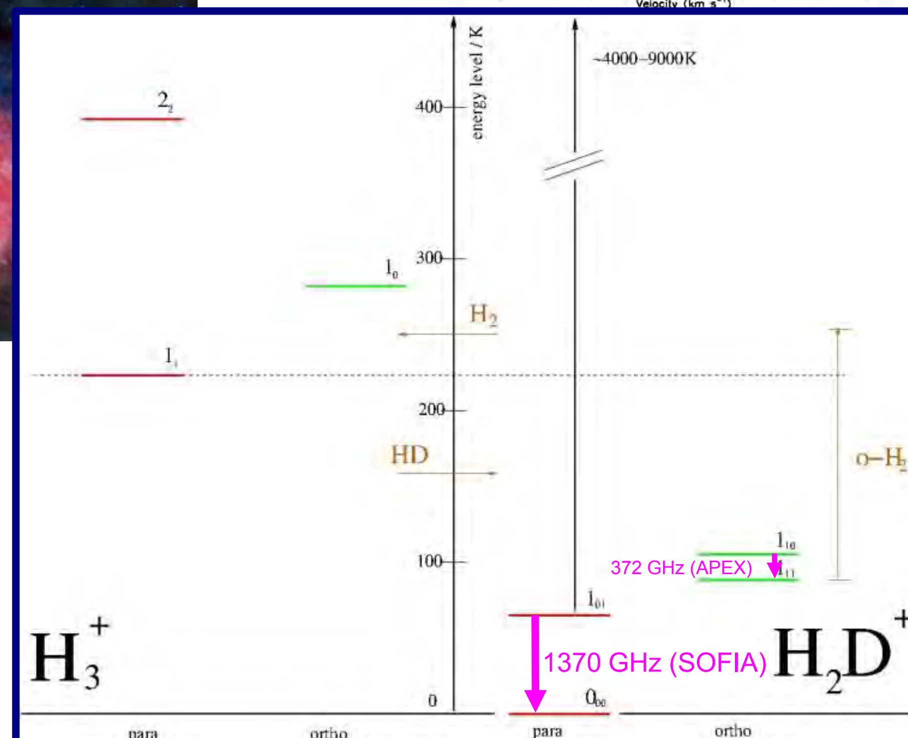




$$
\begin{array}{lcl}
H + H & \xrightarrow{\text{dust}} & H_2 \\
H + \mathrm{cr}/\gamma & \longrightarrow & H^+ + e \\
C + \mathrm{cr}/\gamma & \longrightarrow & C^+ + e \\
 & & \\
H_2 + H^+ & \longrightarrow & H_3^+ \\
 & \longrightarrow & H + H + H^+ \\
H_3^+ + HD & \longrightarrow & H_2D^+ + H_2 \\
 & & \\
H_2 + C^+ & \longrightarrow & CH^+ + H \\
CH^+ + O & \longrightarrow & CO + H^+ \\
OH + C & \longrightarrow & CO + H
\end{array}
$$

Nature paper:
Brünken et al, 2014

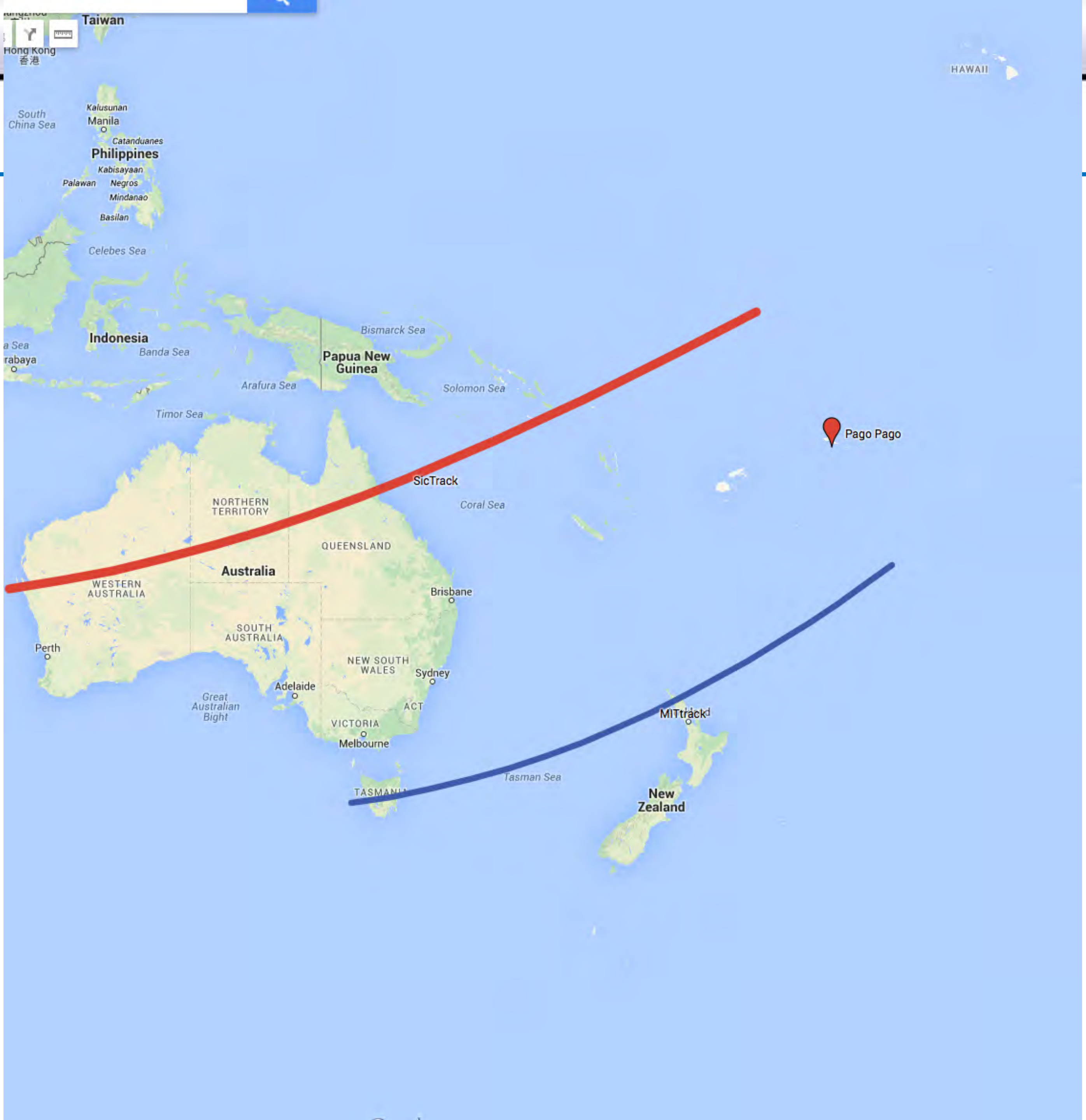
NOTE:
KAO Betz et al.
tentative detection Orion
T_{rec}=30000 K



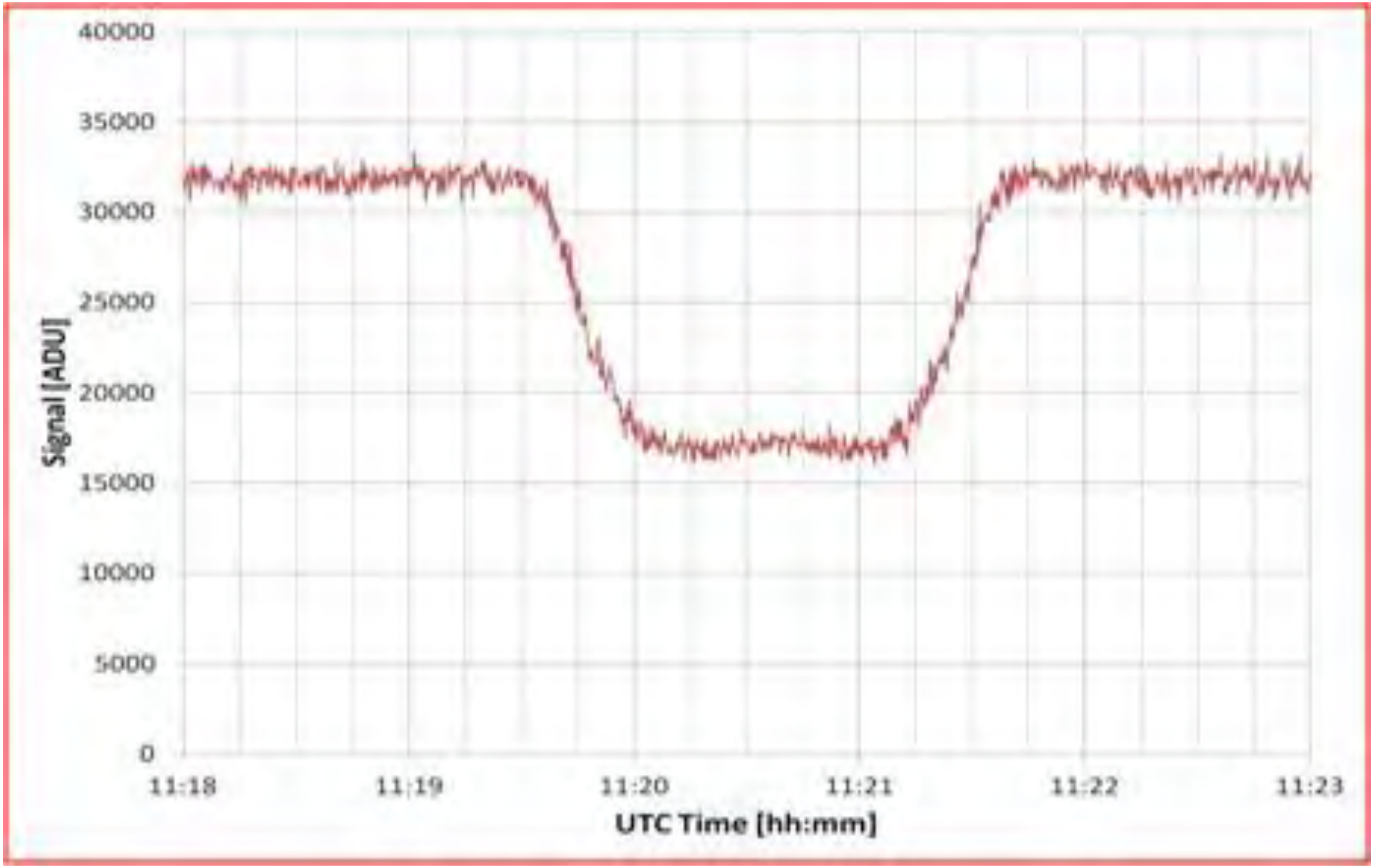
NZ Deployment

Pluto with SOFIA

A case for a dedicated observation to support the *New Horizons* mission


Taiwan
Hong Kong
香港
HAWAII
South China Sea
Kalusunan
Manila
Catanduanes
Philippines
Kabisayaan
Palawan
Negros
Mindanao
Basilan
Celebes Sea
Indonesia
Banda Sea
Bismarck Sea
Papua New Guinea
Arafura Sea
Solomon Sea
Timor Sea
Pago Pago
SicTrack
Coral Sea
NORTHERN TERRITORY
QUEENSLAND
Australia
WESTERN AUSTRALIA
Brisbane
SOUTH AUSTRALIA
Perth
NEW SOUTH WALES
Sydney
Adelaide
Great Australian Bight
ACT
MITtrack
VICTORIA
Melbourne
Tasman Sea
New Zealand

SOFIA/Pluto occultation lightcurve



Education and Public Outreach

Cycle 0 Airborne Astronomy Ambassadors "Pilot" Program

May 26-July 15, 2011

Mary Blessing, Herndon, Va.; Cris DeWolf, Remus, Mich.; and Dana Backman (SETI)

Cecilia Scorza (DSI); Wolfgang Vieser, Munich, Germany; and Jörg Trebs, Berlin, Germany

Terry Herter (Cornell); Jim De Buizer (USRA); Theresa Paulsen, Mellen, Wis.; and Marita Beard, San Jose, Calif.

Pamela Harman (SETI); Margaret Piper, Frankfort, Ill.; and Kathleen Fredette, Palmdale, Calif.

FIR Dust Continuum Emission Polarimetry

- Far Infrared polarimetry will help elucidate the role of magnetic fields in the energetics of the interstellar medium
- SOFIA will have a unique polarimetric capability that was recently selected for the Second Generation Instruments NASA AO

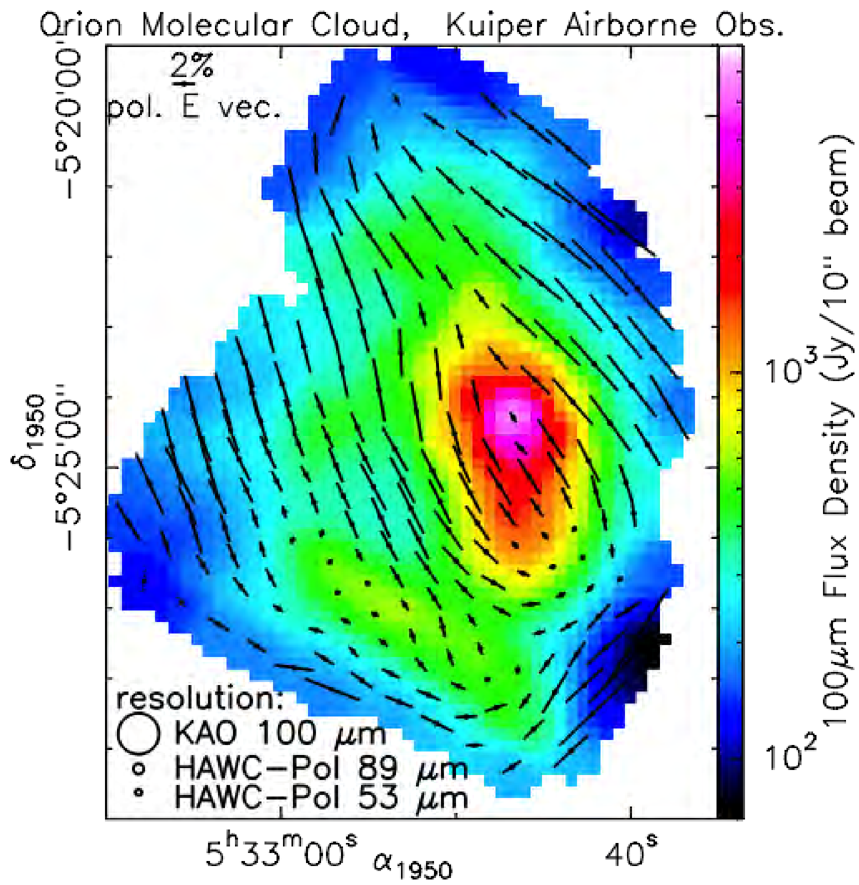


Figure 5. Linear polarization of the Orion Nebula at 100 μm measured with the KAO by Schleuning (1998) . Shown are the beam sizes of the KAO polarimeter and HAWC upgrade. (Dowell et al. 2007)

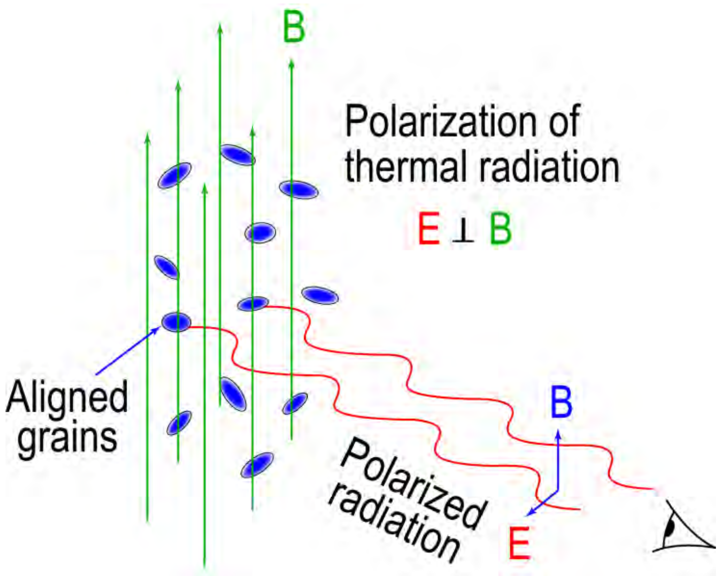
FIR/MM Polarimetry of the ISM

- Polarized FIR/MM emission is dominated by thermal dust
  - non-spherical cross sections
  - spin- (smallest) axes are aligned with local magnetic fields.

* goals of FIR/MM polarisation:

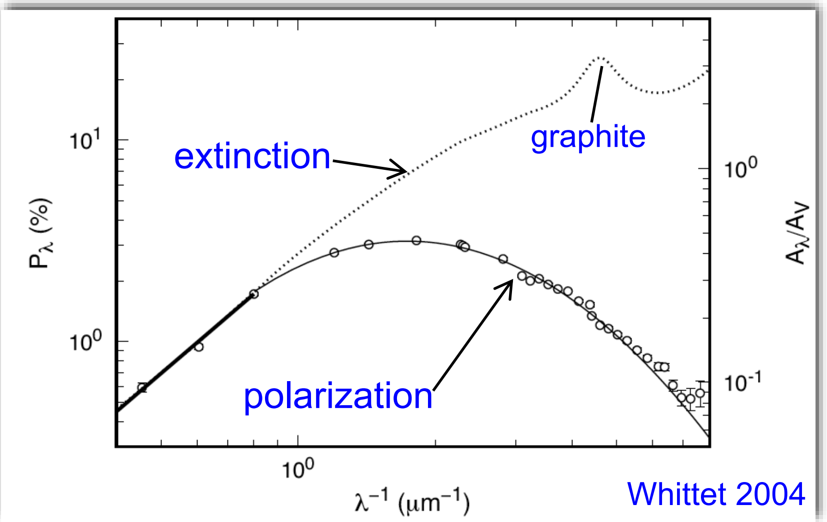
- study magn field orientation
- study dust grain alignment

  (RAT mechanism predict.)



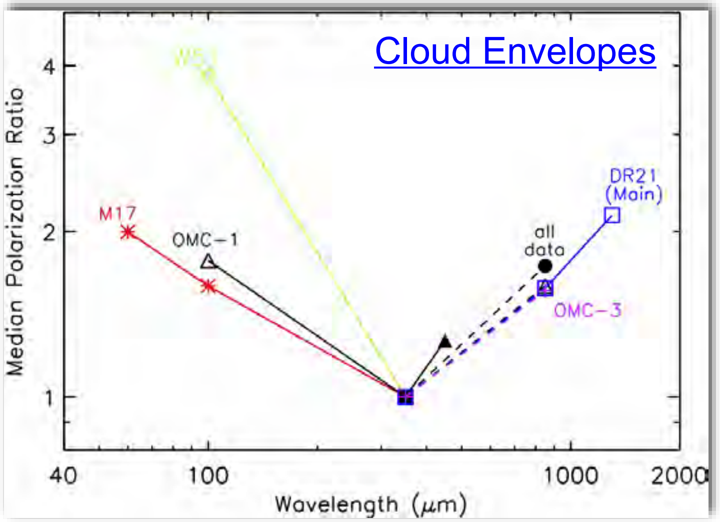
Polarization Spectra

Near-optical wavelengths (λ~a)



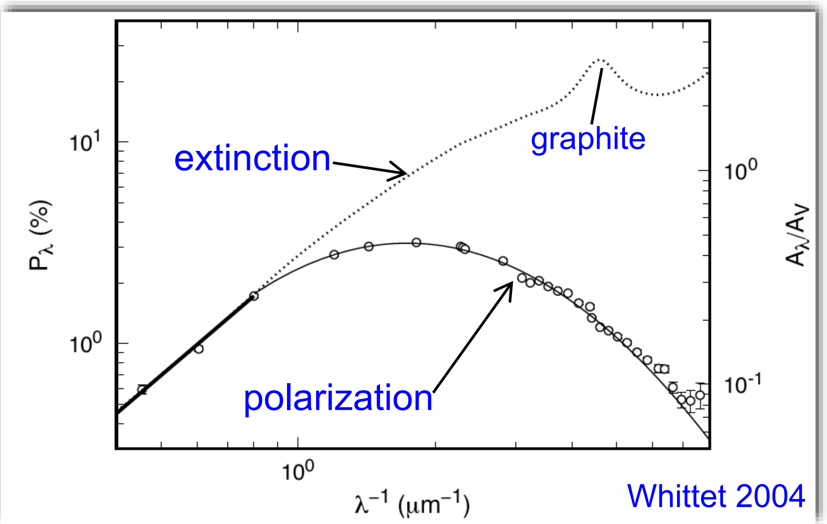
- large grains (traced by NIR) better aligned than small grains (traced by UV); e.g. Kim & Martin 1995
- "Serkowski curve" (1975)

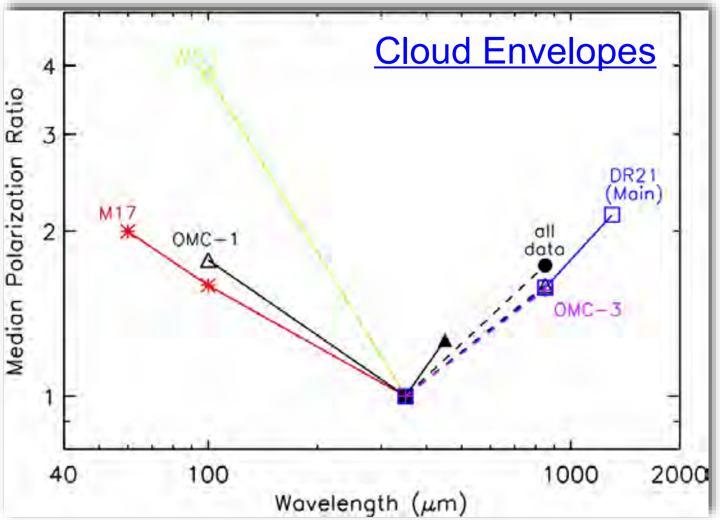
FIR–MM wavelengths (λ>>a)



- multiple domains of grain temperature/emissivity and polarization/alignment; e.g., Hildebrandt 1999 and Vaillancourt & Matthews 2012

Polarization Spectra





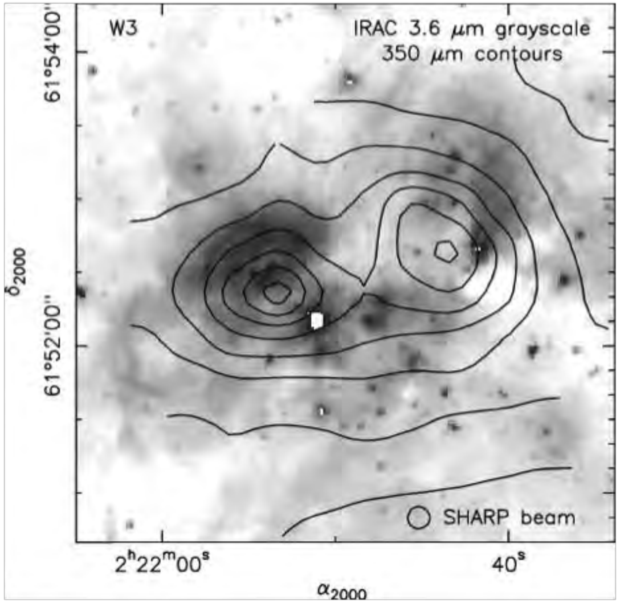
Grain Size ⟷ Grain Temperature

Obs. Tests – Stars

Key Prediction of RAT: grain *alignment efficiency* depends on both *intensity* and *color* of incident radiation field.

- How to measure radiation intensity?
  - Stellar Location

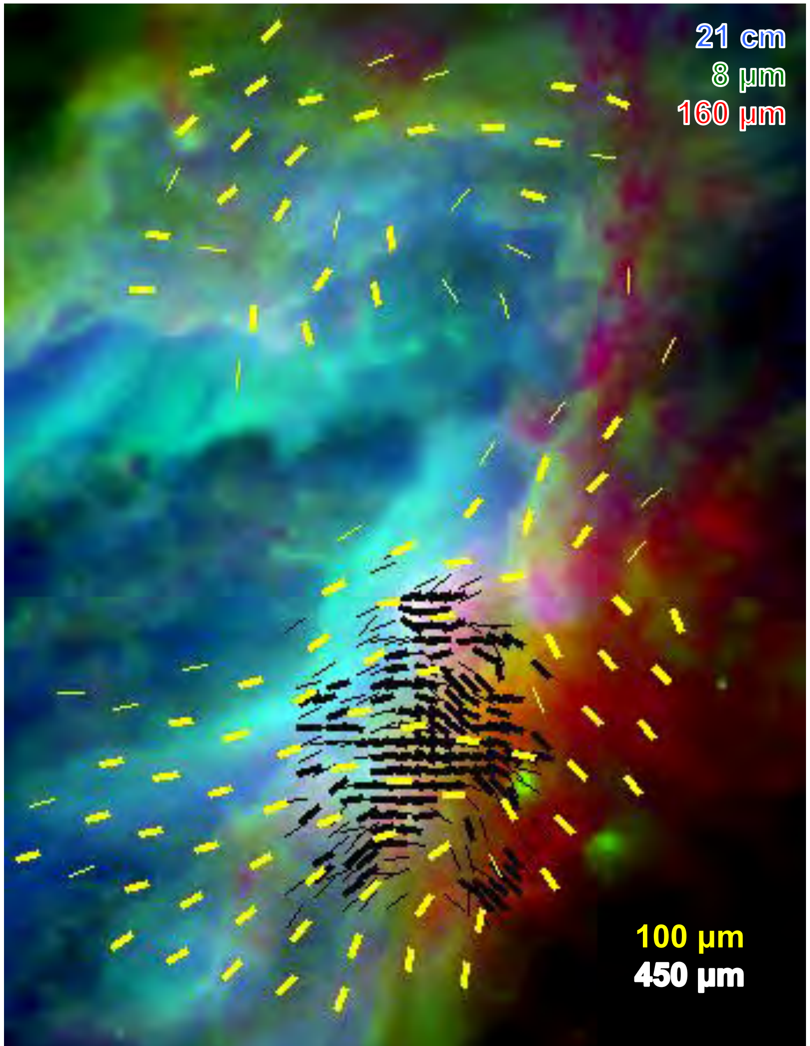
- FIR/MM: Is polarization enhanced towards embedded stars?



- Existing sub-mm polarization observations (20 arcsec) insufficient to resolve stars

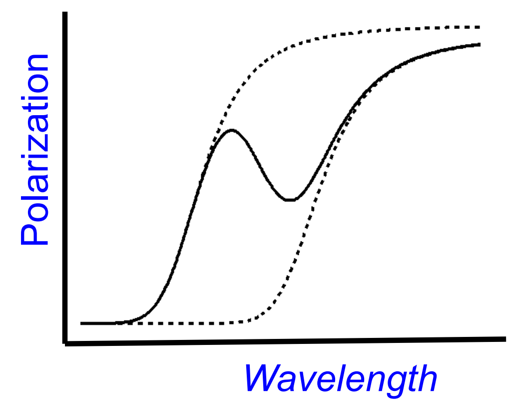
- SOFIA / HAWC (see talk by C. D. Dowell)
  - 5” - 10” @ 50 - 100 μm
  - more sensitive to warm dust near stars

M17: an edge-on PDR (courtesy J. Vaillancourt, Ames)



Goals:

1) Use geometry of HII region and PDR as a proxy for radiation intensity
2) Use P-spectrum shape to trace alignment



Intensity

Blue = 21 cm, atomic gas; Green = 8 μm, excited PAH (*Spitzer*/GLIMPSE); **Red = 160 μm, dust, molecular gas** *(Herschel)*

Polarization "vectors"

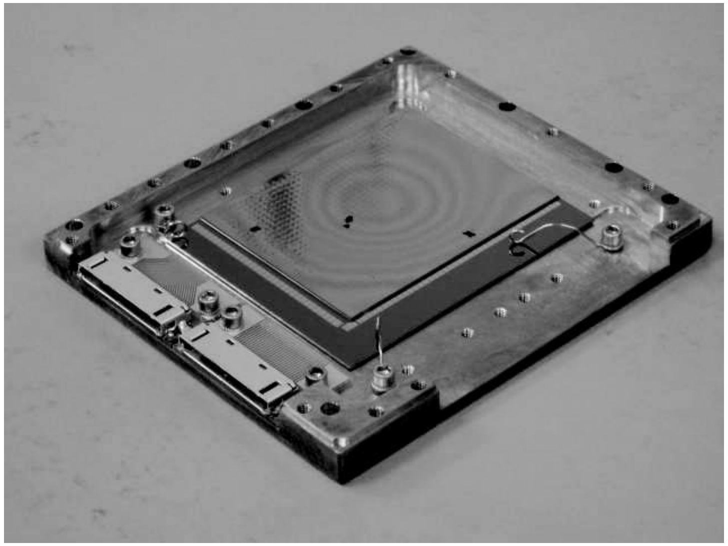
Yellow = 100 μm polarization; black = 450 polarisation

HAWC Upgrades

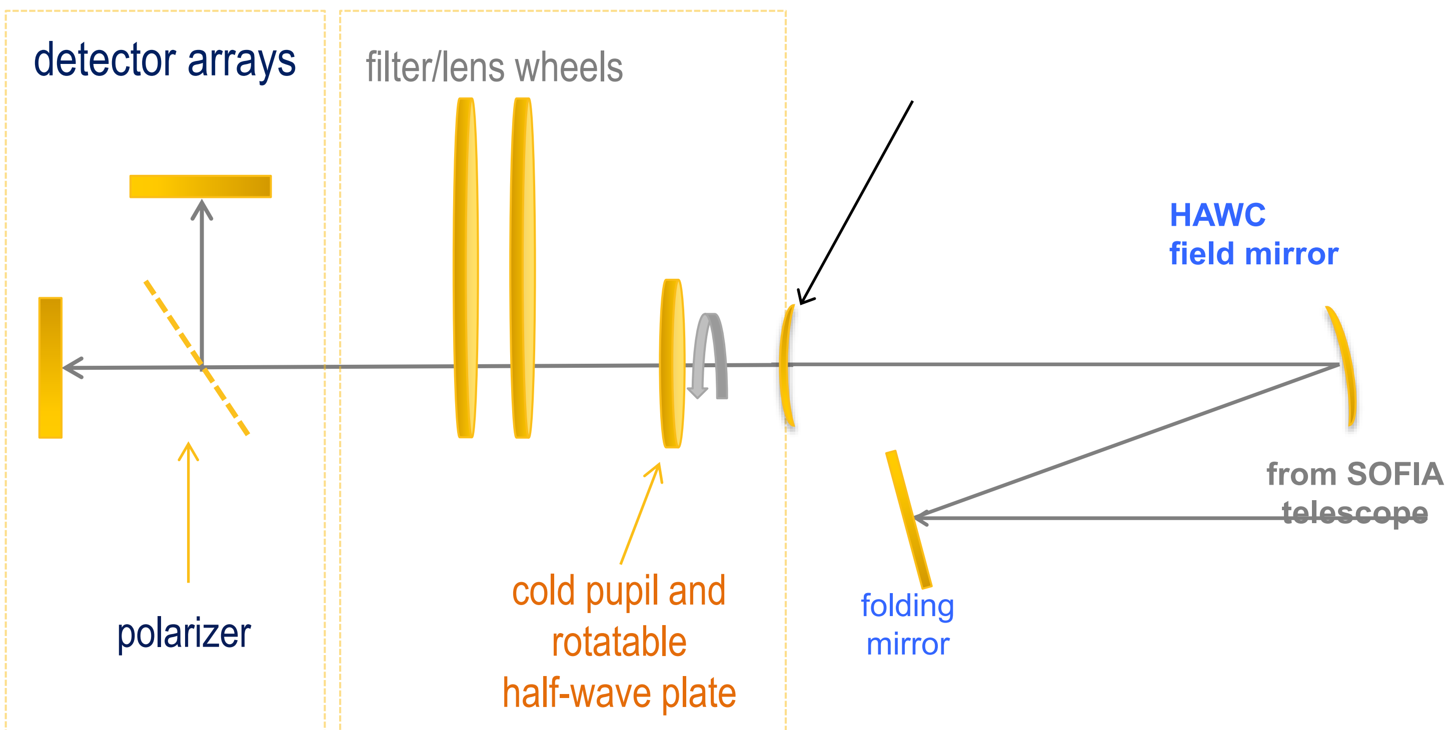
- HAWC-POL
- PI- Darren Dowell (JPL)
- Polarizer mechanism replaces existing pupil wheel on HAWC

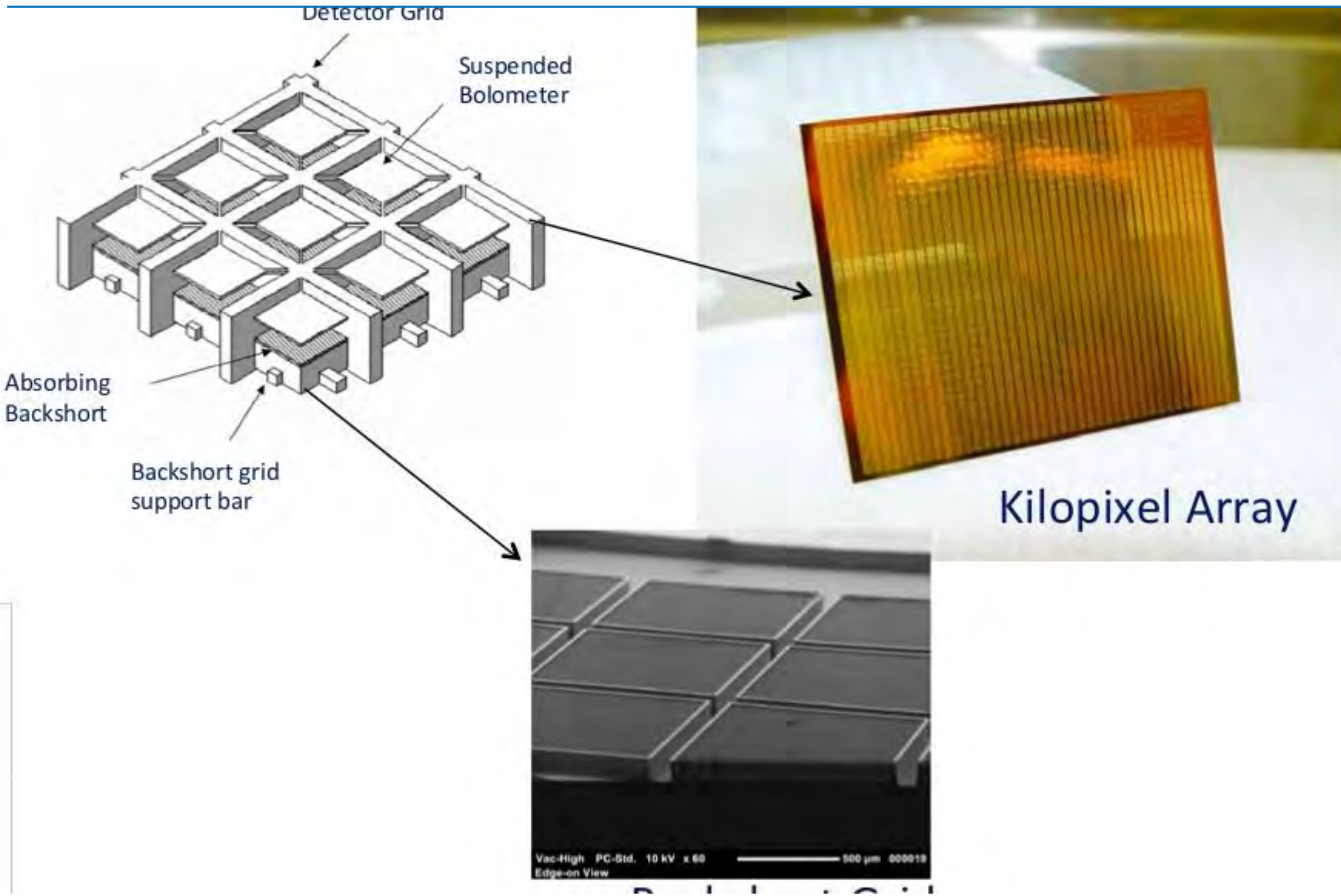
HAWC-POL Mechanism
Novak & Dowell (2009)

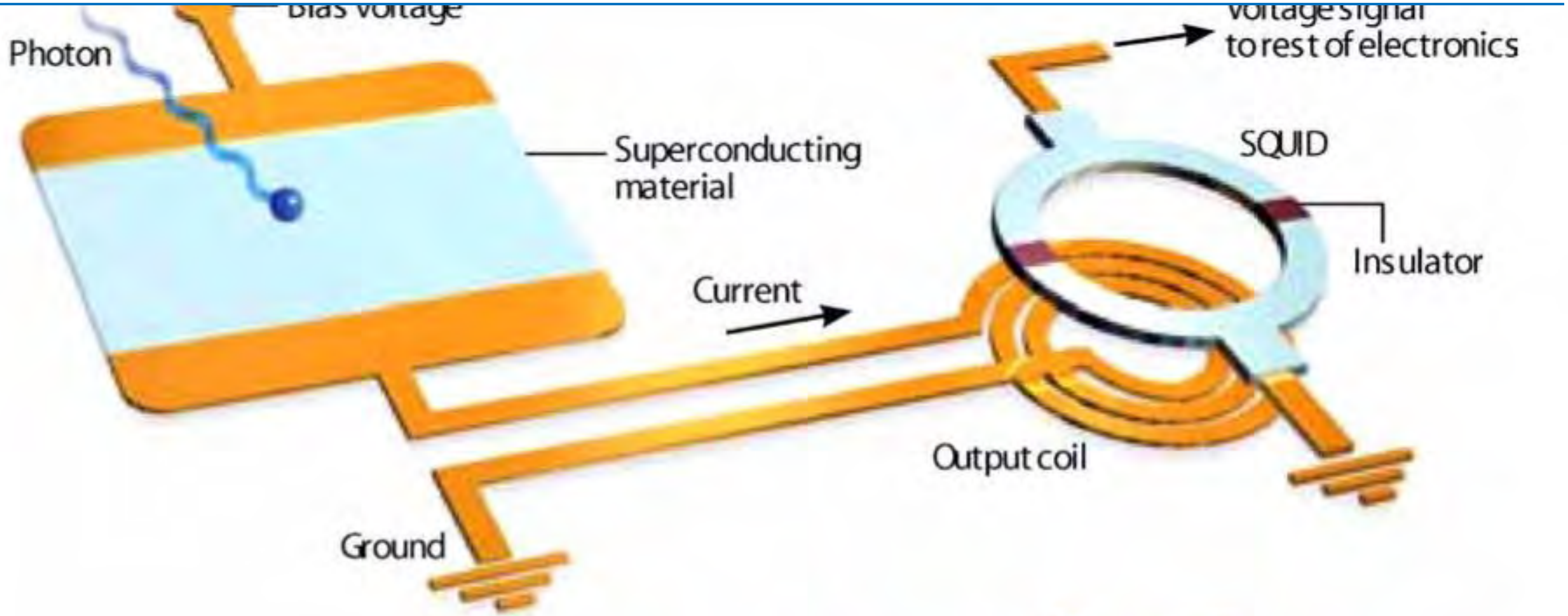
- HAWC++
- PI Johannes Staguhn (Johns Hopkins)
- Increases detector format on HAWC from 384 to 2560 pixels per polarization



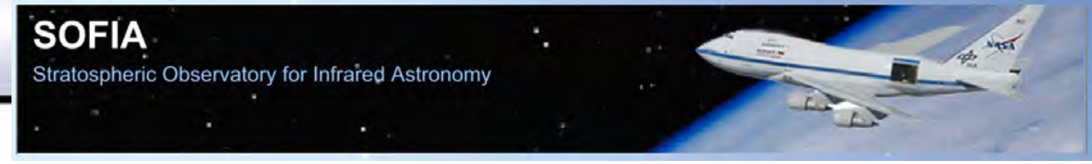
PIPER 32x40 Prototype detector
Chuss et al. (2010)

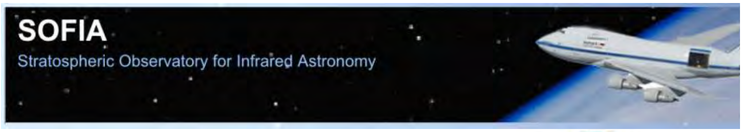

detector arrays
filter/lens wheels
HAWC
field mirror
from SOFIA
telescope
folding
mirror
polarizer
cold pupil and
rotatable
half-wave plate


Detector Grid
Suspended Bolometer
Absorbing Backshort
Backshort grid support bar
Kilopixel Array


Photon
Superconducting
material
to rest of electronics
SQUID
Insulator
Current
Output coil
Ground

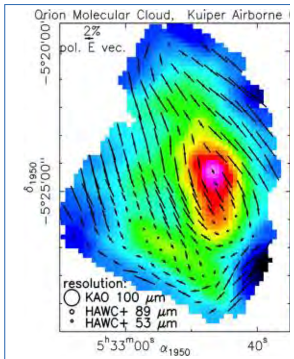
USRA



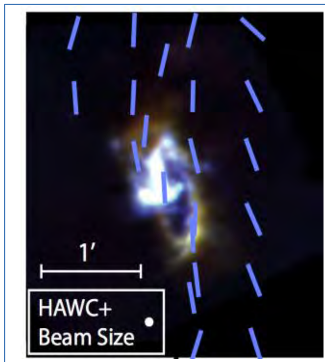


High-resolution **A**irborne **W**ideband **C**amera

HAWC is a Facility-class, far-infrared camera and polarimeter for SOFIA. It is scheduled for commissioning in early 2016. HAWC's optics, state-of-the art detector arrays, and upgradability will permit a broad range of important astrophysical investigations. The ongoing HAWC+ upgrade adds capability to measure linear polarization, providing the unique and powerful ability to map magnetic fields in molecular clouds.



HAWC+ will produce maps of linear pola akin to the Kuiper Airborne Observatory Orion (*above*; D. A. Schleuning 1998, ApJ 4 SOFIA/HAWC+ has much better sensitivity better areal resolution, and multiple wa bands. The polarization is due to dus aligned with respect to the interstellar r field. Polarization mapping reveals the stru magnetic fields and estimates their strengt



Magnetic field vectors (100 µm) overlaid on a SOFIA/FORCAST 3-color image (20, 32, 37 µm) of the circumnuclear disk in the Galactic center (Hildebrand+ 1993, ApJ 417:565, Lau+ 2013, ApJ 775:L37). The angular resolution of SOFIA/HAWC+ will allow for a more detailed mapping of this and many other regions.

HAWC+ will investigate many topics, including:

- Estimates of magnetic field strength and turb power spectrum in nearby molecular clouds
- Efficiency of dust grain alignment
- Magnetic field configuration of the Galactic C
- Polarization and (potentially) the primary ma field orientation of T Tauri star disks and env
- Magnetic structure in the dense interstellar r of nearby bright galaxies

HAWC+ will obtain useful polarization maps and with thousands of vectors in part of a single SOF

SOFIA NASA DLR USRA DSI SETI INSTITUTE Jet P

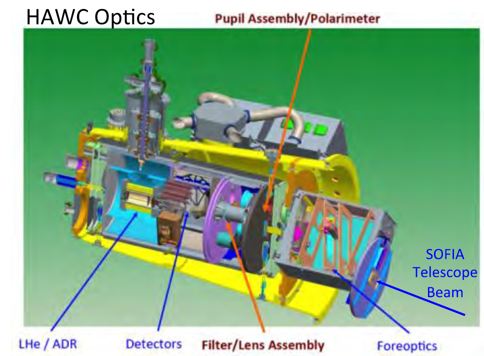
HAWC Specifications

Principal Investigator: Dr. Darren Dowell,
Jet Propulsion Laboratory

SOFIA Instrument pages - http://www.sofia.usra.edu/Science/instruments

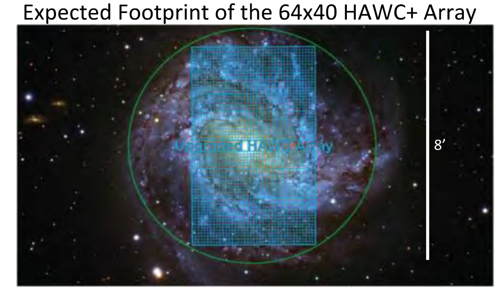
HAWC+ is designed to offer imaging and polarimetry in each of five bands from λ = 53 to 216 µm. NASA/Goddard and NIST are producing the two bolometer detector arrays for HAWC+. For SOFIA far-IR continuum bands, the detectors will deliver background-limited performance with high quantum efficiency. The baseline format of each array is 32×40, and the system is designed to support up to 64×40. HAWC+ uses standard chopped-nodded SOFIA observing patterns for polarimetry and will optimally use cross-linked scans for imaging.

HAWC Optics



Band / Wavelength	Δλ/λ	Diffraction Limit	Polarimetry Mode (chop-nod)
A / 53 µm	0.17	5.4" FWHM	58 µm HWP
B / 62 µm	0.12	6.4" FWHM	58 µm HWP
C / 89 µm	0.19	9.0" FWHM	89 µm HWP
D / 155 µm	0.22	16" FWHM	155 µm HWP
E / 216 µm	0.20	22" FWHM	216 µm HWP

Expected Footprint of the 64x40 HAWC+ Array



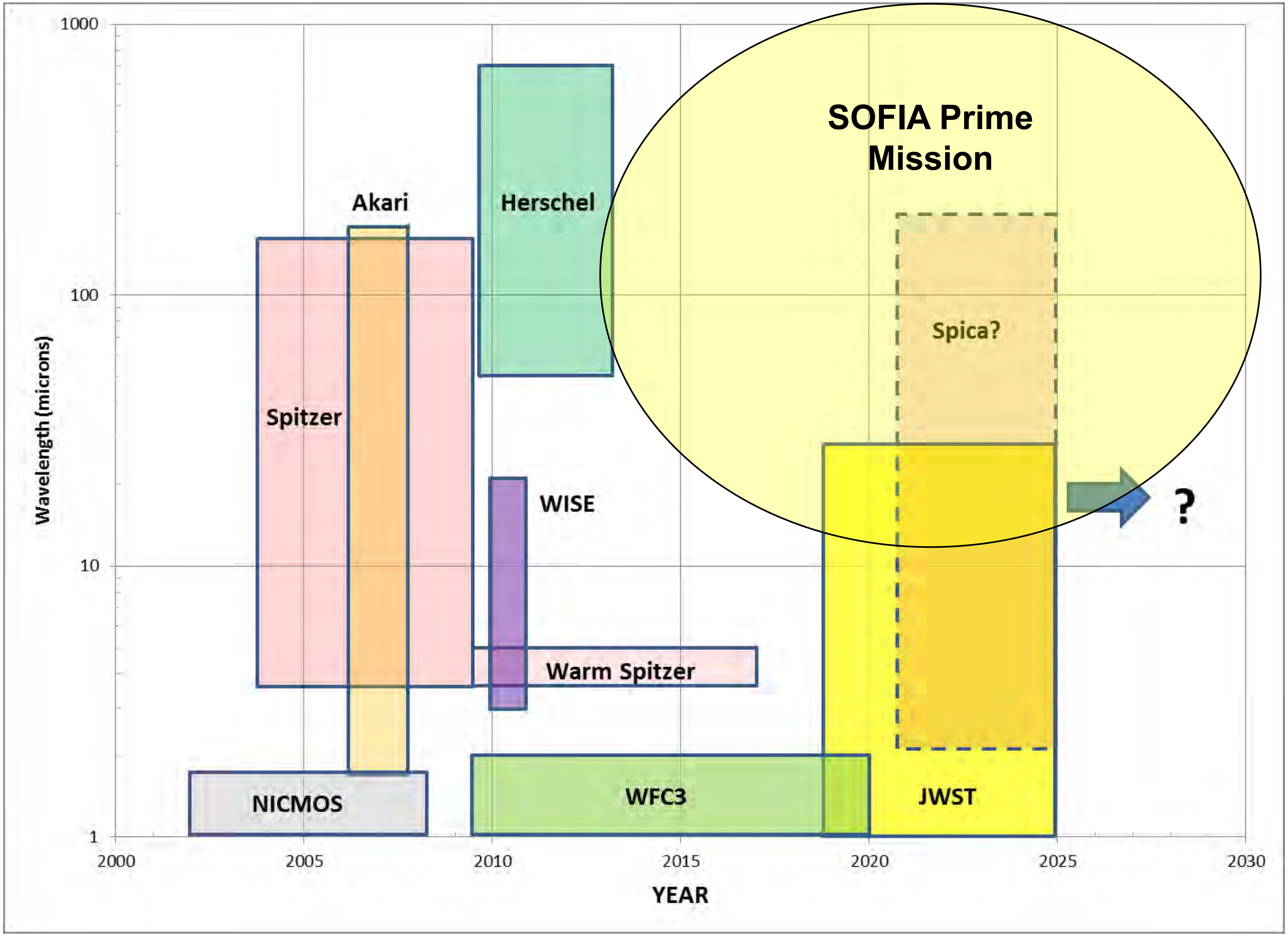
Predicted performance for continuum imaging and polarimetry

Instrument Parameter	Band A	Band B	Band C	Band D	Band E
Wavelength (mm)	53	62	89	155	216
Imaging NEFD[a] (Jy/beam $s^{1/2}$)	0.93	0.80	0.79	0.64	0.55
Field of view (square arcmin)	2.3	5.5	5.5	17	30
Min. flux density[b] for s(P) < 0.3% in 1 hr (Jy/beam)	10.7	9.2	9.1	7.3	6.3
Min. surface brightness[b] in 1 beam for s(P) < 0.3% in 1 hr (MJy/sr)	13,500	8200	4100	1090	480
Min. column density in 1 beam for s(P) < 0.3% in 1 hr (A_V)	0.9	1.2	2.5	5	5

[a]Noise Equivalent Flux Density detectable with S/N=1 in a 1 s integration. S/N scales as (flux/NEFD) × $(\text{time})^{1/2}$.

[b]Assumes 60% observing efficiency. s(P) refers to the percent uncertainty in the measured degree of polarization.

Courtesy: Erick Young Mind the Gap



SOFIA Context with Other Observatories

- Far-IR ESA Satellite Herschel ran out of cryogens inSpring 2013 after 4 years of operation: SOFIA is natural successor, Herschel community using SOFIA note: Herschel Obs. had no polarimetric capability

- Because of lack of funding for SPICA and Mmtron(?), SOFIA will provide the only access to the far-infrared and sub-sub-millimeter for the better part of a decade
- Synergy with ALMA and APEX (submm spectroscopy), CCAT (25m single dish submm) and JWST (5-28 mu)

2014: SOFIA development phase → operations phase

http://www.sofia.usra.edu

http://www.dfrc.nasa.gov/Gallery/Movie/SOFIA/index.h

Cycle 4 call for obs. proposals: released 8 May 201


THANK YOU