SOFIA Science Capabilities and Instrument Overview

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with lots of help from

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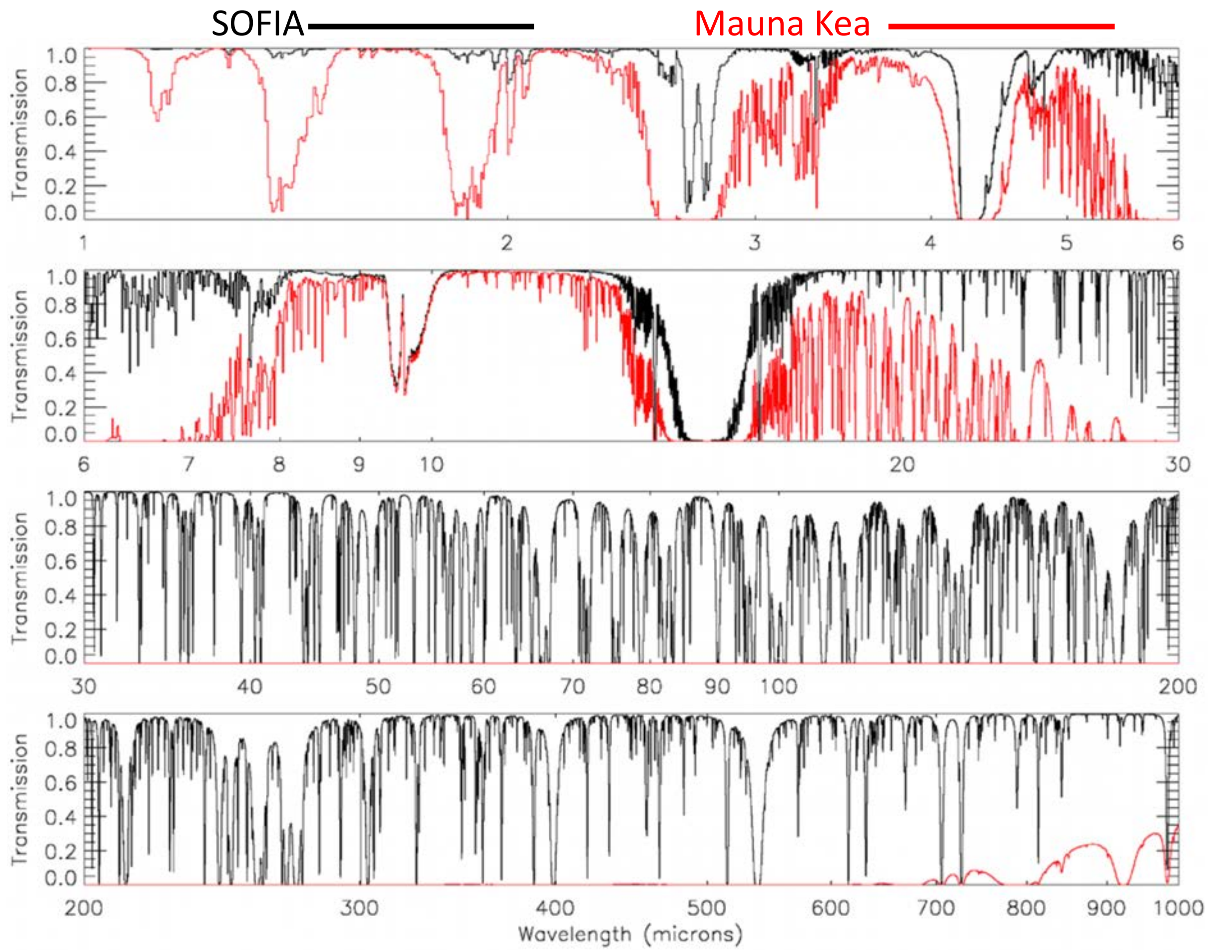
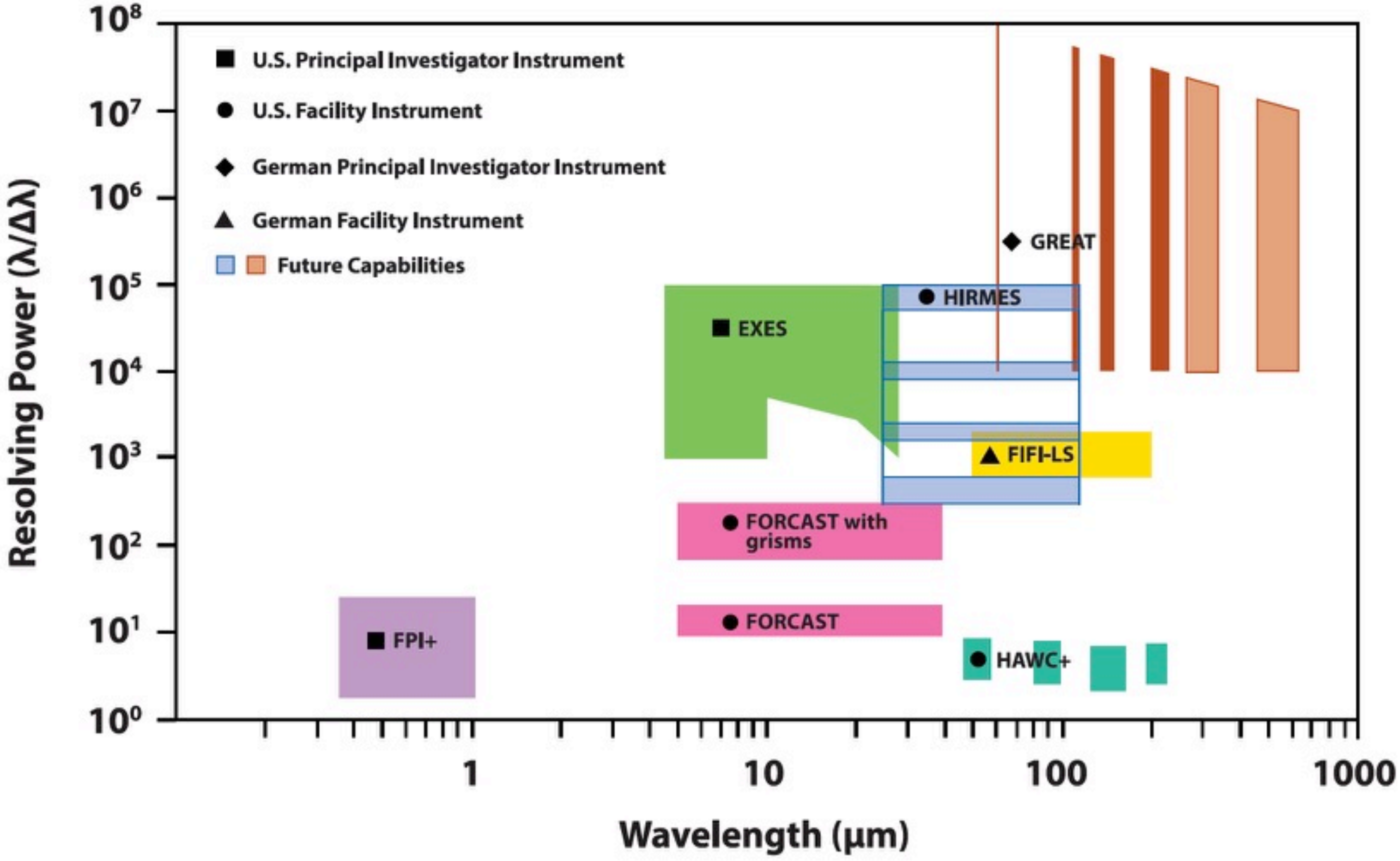
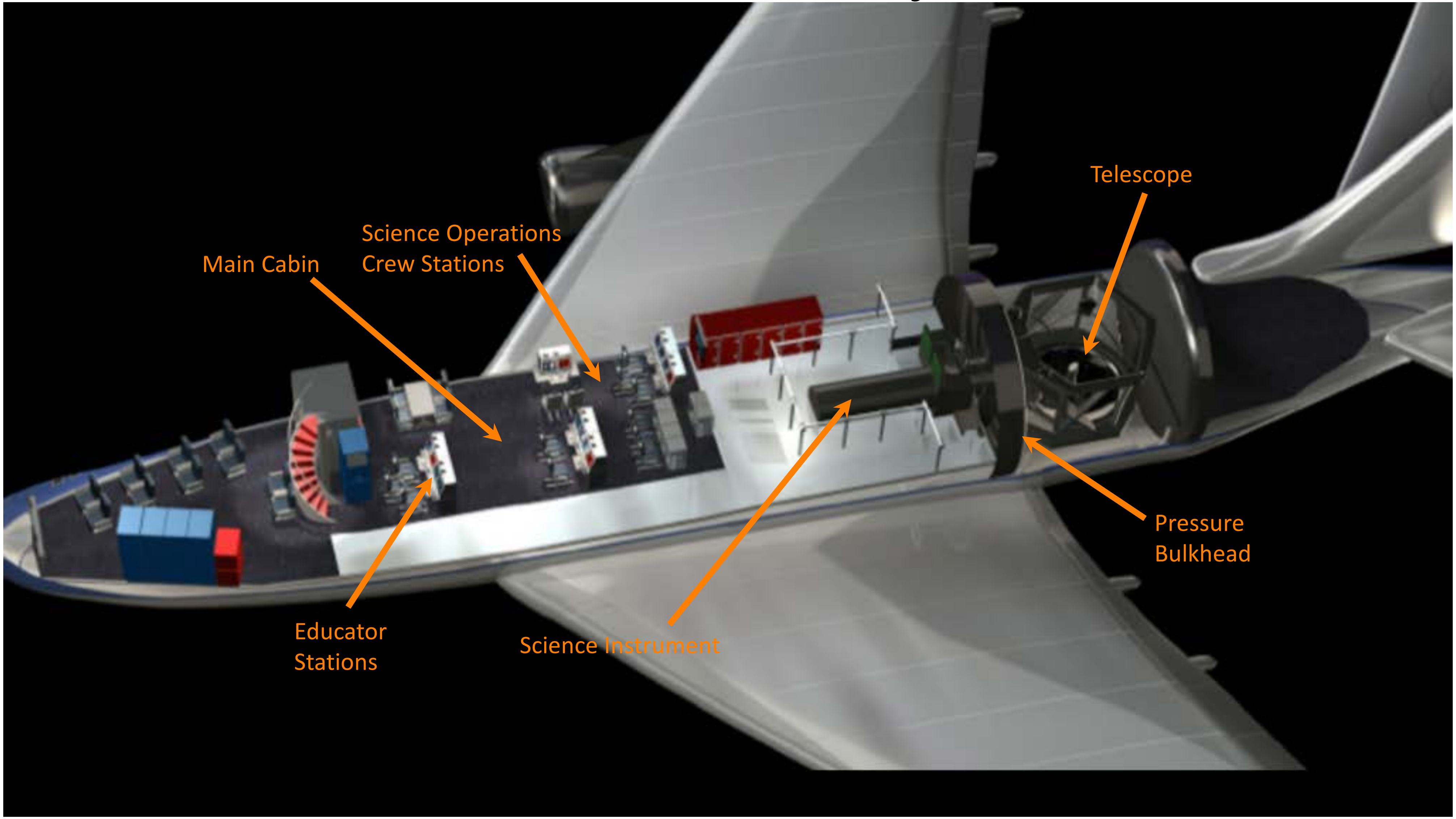
Atmospheric Transparency



Instrumentation

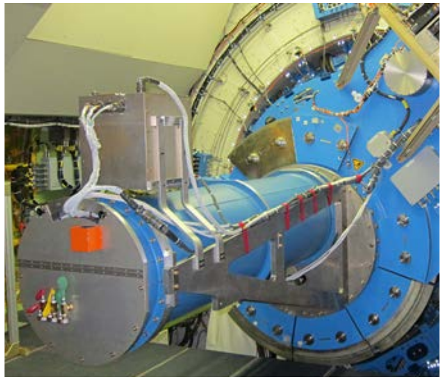


SOFIA Interior Layout



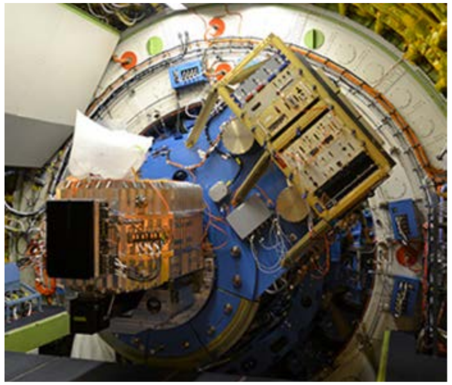
The Instruments in Real Life

EXES
Echelon-Cross-Echelle Spectrometer



λ = 4.5–28.3 µm
R = 1,000–10^5

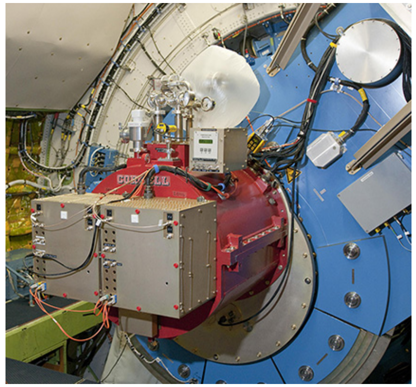
FIFI-LS
Far Infrared Field-Imaging Line Spectrometer



λ = 51–203 µm
R = 600–2,000

Grating Spectrometer

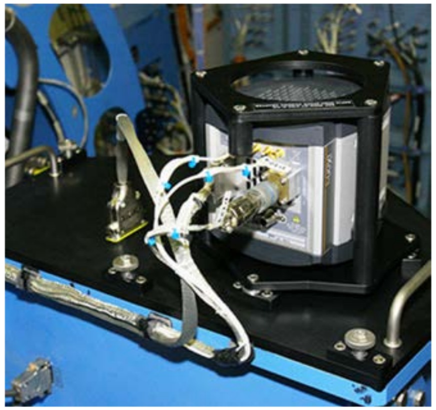
FORCAST
Faint Object Infrared Camera for the SOFIA Telescope



λ = 5–40 µm
R = 100–300

Grism Spectrometer

FPI+
Focal Plane Imager Plus



λ = 0.36–1.10 µm
R = 0.9–29.0

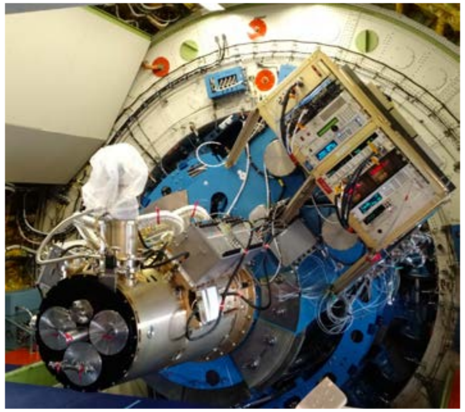
Optical Camera, always running

GREAT
German Receiver for Astronomy at Terahertz Frequencies

λ = 63–612 µm
R = 10^6–10^8

Heterodyne Spectrometer

HAWC+
High-resolution Airborne Wideband Camera Plus



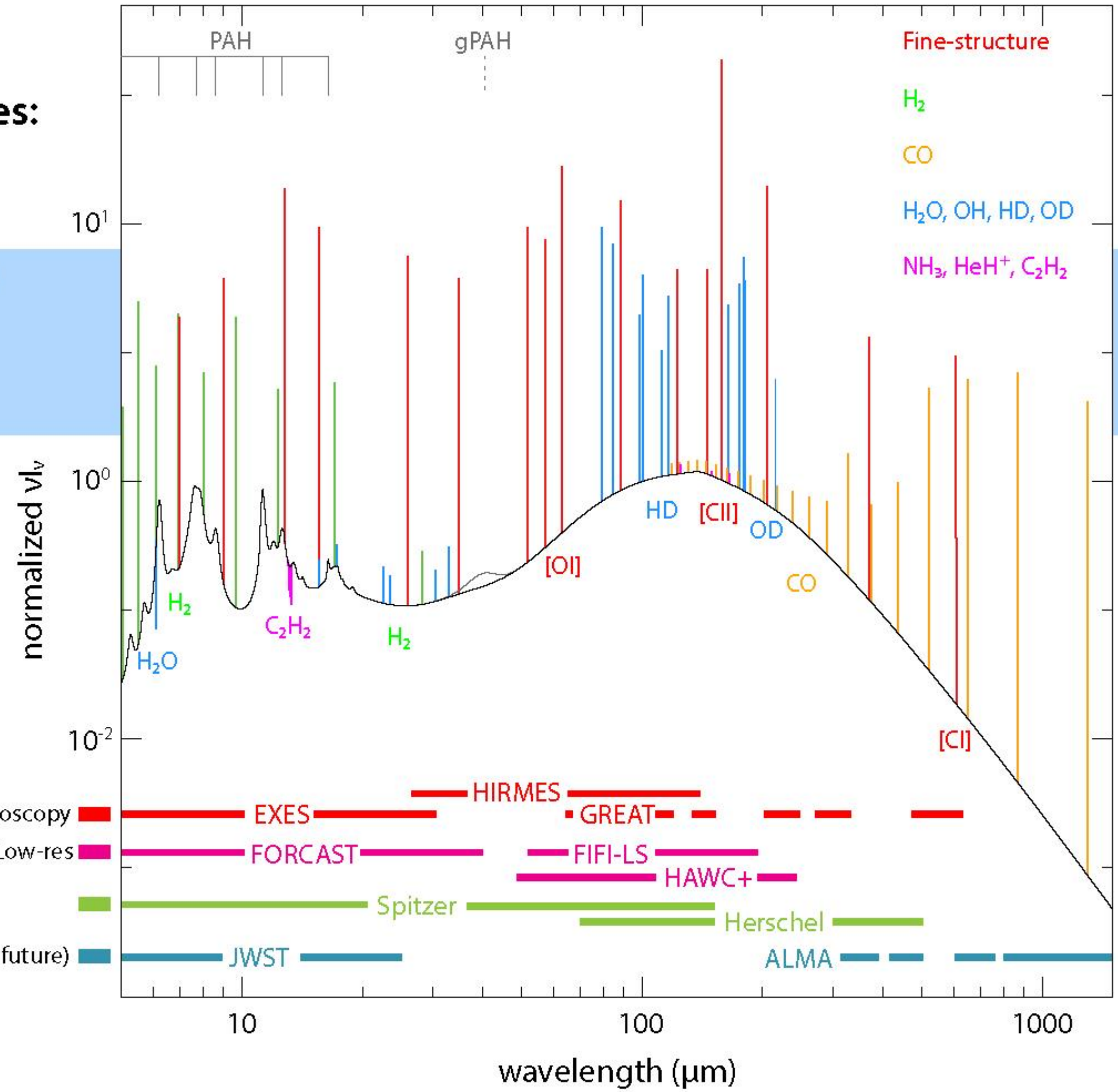
λ = 50–240 µm
R = 2.3–8.8

Bolometer Camera & Polarimeter

SOFIA Covers a Lot of IR Real Estate

SOFIA measures:

- CO
- Dust
- Fine structure
- Hydrides
- HD
- NH_3
- PAHs
- Water



To determine:

- Age
- Composition
- Density
- Gas Dynamics
- Magnetic fields
- Pressure
- Shocks
- Temperature

Species Accessible to SOFIA

Within many environments: Interstellar Medium, Diffuse Clouds, Molecular Clouds, Proto-stellar Disks, Debris Disks, Planetary Atmospheres, Comets

- Ionized Gas - [SI] 25.25 µm; [FeII] 25.99,35.35 µm, [SIII] 33.48 µm, [SiII] 34.81 µm; [Ne III] 36.0 µm, O [III] 52 µm, [N III] 57 µm, [O I] 63.18 µm (4.75 THz), [O III] 88.35 µm, [N II] 122 µm, [O I] 145 µm, and [C II] 158 µm; high-rotational CO
- Molecular - OH at 53 µm, 79 µm, 84 µm, 119 µm, and 163 µm, and H_2O at 58 µm, 66 µm, 75 µm, 101 µm, and 108 µm, NH_3 166 µm (1.8 THz)
- Hydrides – CH 149 µm (1.46 THz), SH 217 µm (1.38 THz), OD 119 µm (2.51 THz), (1.391 THz), HCl, HF (1.23 THz), ArH+, ^{13}CH+
- PAHs - 6.2, 7.7, 8.6 and 11.2 µm and longer wavelengths
- Water H_2O - 6.1, 8.91, 34.9, 58, 66, 75, 101, 108 µm, … 231 µm …
- Deuterated Hydrogen HD – 28.5 µm, 56.2 um, 112 µm (2.674 THz)
- Ices – Hydrocarbon, NH_3, H_2O - 43 µm, 63 µm (crystalline), 47 µm (amorphous)
- Organics/Nitriles – C_2H_2, C_4H_2, C_3H_3+, C_3H_4, C_2N_2, CH_4, "haystack condensate" at 45.45 µm
- Cations – ortho-D_2H^+ 203 µm (1.47 THz), para-H_2D^+ 219 µm (1.37 THz)

SOFIA Covers **Unique & Complementary** Infrared Real Estate

SOFIA measures:

- CO
- Dust
- Fine structure
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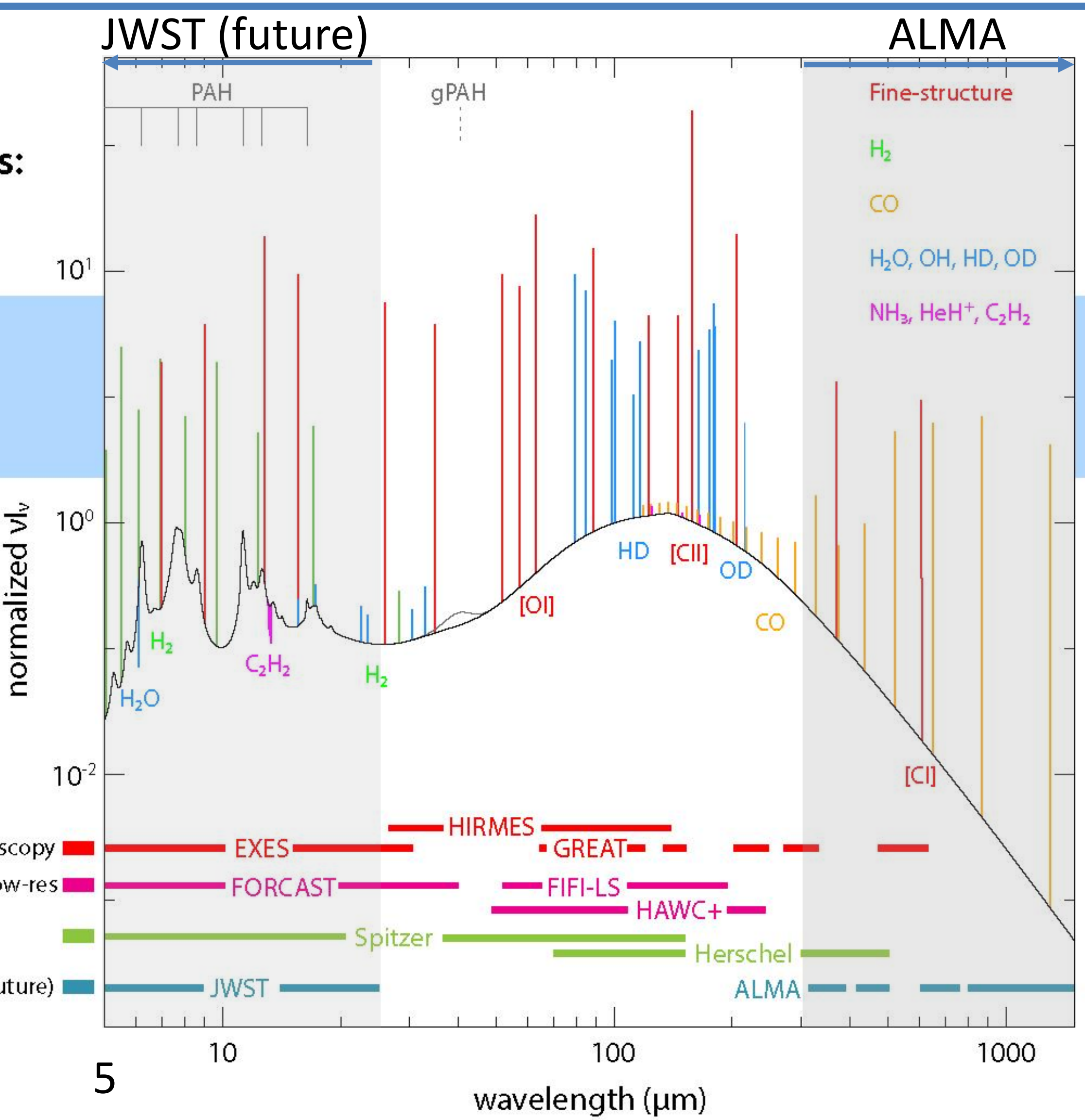
- NH_3
- PAHs
- Water



To determine:

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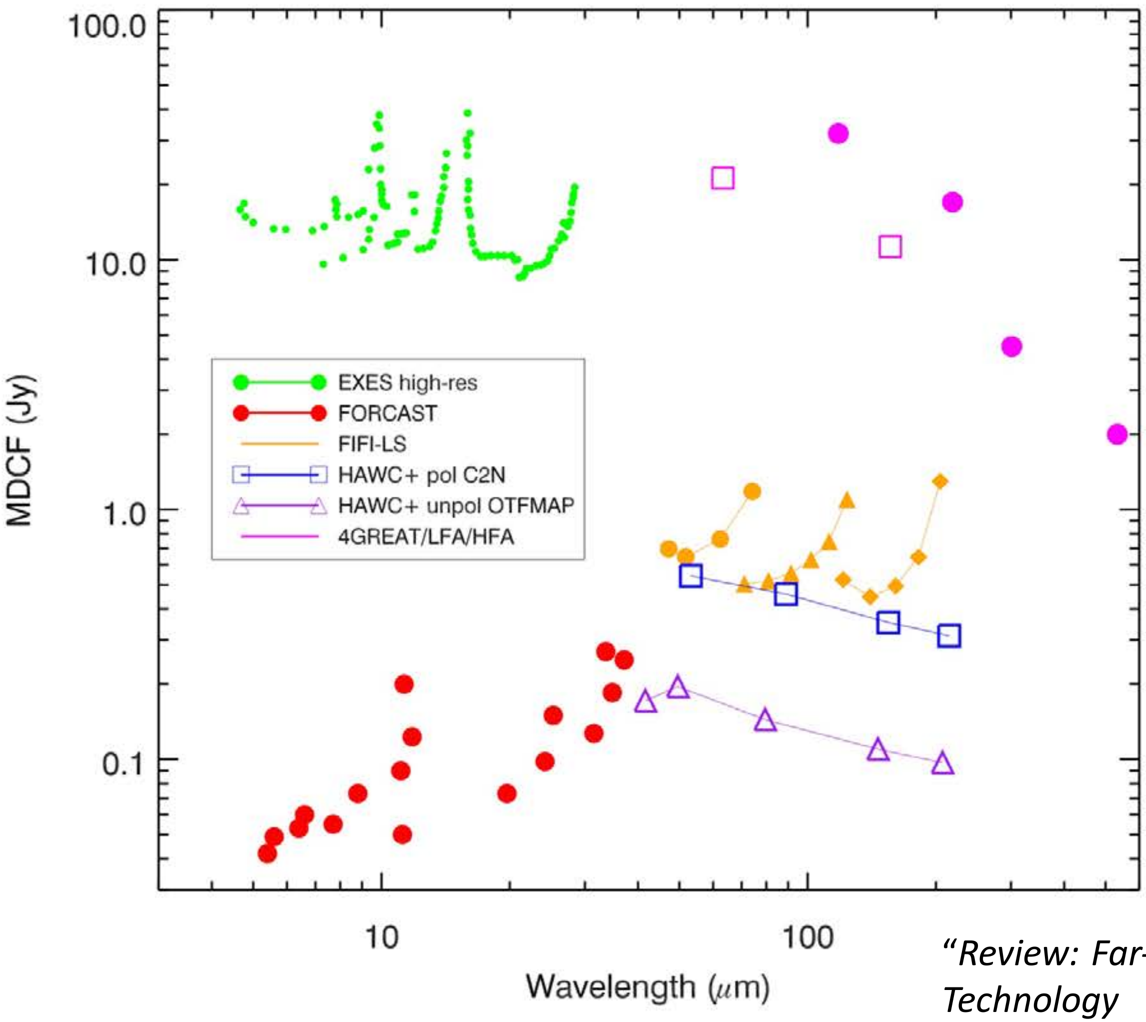
- Temperature

Science Instruments

Name	Principal Investigator	Description	Wavelength Range Resolving Power R=λ/Δλ	Field of View Features
HIRMES	Harvey Mosely, NASA Goddard	Mid-IR Bolometer Spectrometer *Facility Instrument*	**25 – 122 µm** R = 325 – 100,000	8.8” x 143” slit 119” x 103” imaging
EXES	Matthew Richter, UC Davis	Mid-IR Echelle Spectrometer *PI Instrument*	**4.5 – 28.3 µm** R = 1,000 – 105	1” – 180” slit lengths 1024x1024 Si:As
FIFI-LS	Alfred Krabbe, Universität Stuttgart, DSI	Far-IR Imaging Grating Spectrometer *Facility Instrument*	**51 – 200 µm** R = 600 – 2,000	30” x 30” (Blue) 60” x 60” (Red) 2x(16x25) Ge:Ga
FORCAST	Terry Herter, Cornell University	Mid-IR Camera & Grism Spectrometer *Facility Instrument*	**5 – 40 µm** R = 100 – 300	3.2’ x 3.2’ 2x(256x256) Si:As, Si:Sb
GREAT	Rolf Güsten, MPI für Radioastronomie, Bonn	Far-IR Heterodyne Spectrometer *PI Instrument*	**63 – 612 µm** R = 106 – 108	diffraction limited heterodyne receiver
HAWC+	Charles Dowell, JPL, Caltech	Far-IR Bolometer Camera & Polarimeter *Facility Instrument*	**50 – 240 µm** Δλ = 9 – 43 µm	from 1.4’ x 1.7’ (53 µm) to 4.8’ x 6.1’ (214 µm) 3x(32x40) bolometer
FPI+	Jürgen Wolf, Universität Stuttgart, DSI	Focal Plane Imager *Facility Instrument*	**0.36 – 1.10 µm** R = 0.9 – 29.0	8.7’ x 8.7’ 1024x1024 CCD

Sensitivities



Continuum sensitivities, as a function of wavelength, of SOFIA's mid- to far-infrared instrument suite.

MDCF = 4-σ Minimum Detectable Continuum Flux (MDCF) densities for point sources in Janskys for 900 s of integration time.

"Review: Far-Infrared Instrumentation and Technology Development for the Next Decade"
Farrah, D. et al, 2017, submitted to JAI

Technology Development and New Instruments

- SOFIA is an ideal platform for technology development for MIR and FIR instrumentation
  - Stable platform
  - In-flight access
  - Limited weight and size restrictions
- Future space projects like WFIRST or OST need mature detector hardware
- NASA is committed to an on-going instrument program
- Third Generation SOFIA instrument being built

  HIRMES (PI: H. Moseley, GSFC)

"Echelle spectrometer, with long-slit capability, covering the 25-122μm spectral range with resolving powers ranging from 600 to 100,000"

  - Instrument completion planned for 2018 – first light spring 2019
- Fourth Generation SOFIA instrument call just issued by NASA

SOFIA Is Unique

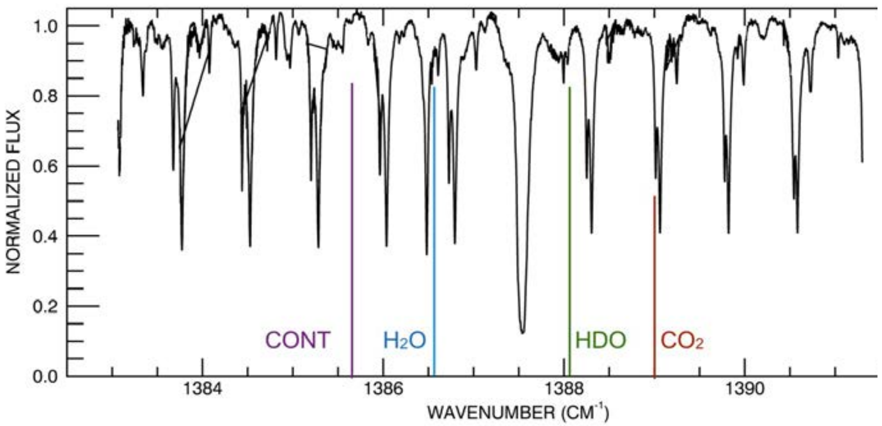
- Access to Mid- and Far-Infrared
  - No satellite mission beyond 28μm within the next decade
  - Unlike many balloon experiments the instruments are returned safely
  - Flexible and comprehensive instrument suite
- Fast turn-around for new instruments
  - State of the art technology (allowable to have "problems")
  - Instrument access in flight
  - Broken instruments can be repaired and flown again
- Inertial platform
  - Fast mapping
  - Small Sun-avoidance angle (40˚ sun above horizon, ~25˚ sun below horizon)
    - Venus, comets, ToOs (novae, SN etc.)
- World-wide access
  - Northern and Southern hemisphere
  - Occultations
- Long baseline temporal studies
  - Expected 20 year life time

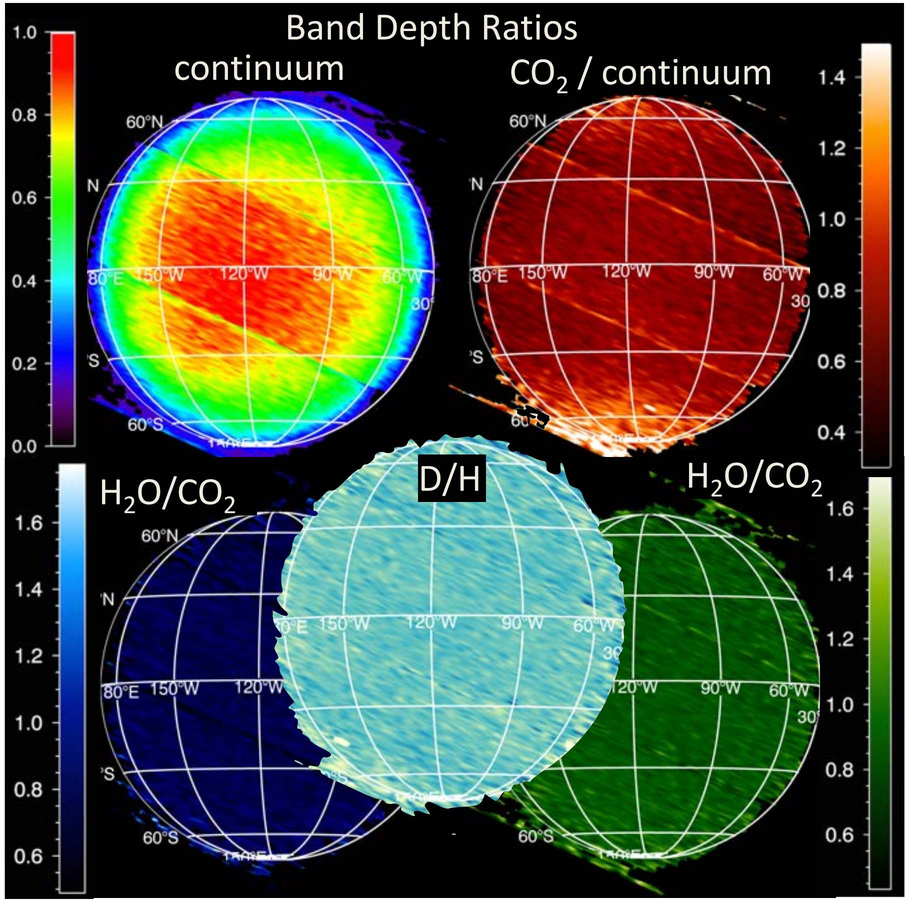
Science Examples

EXES

"*Measuring the D/H Ratio in the Atmosphere of Venus*", Tsang, Constantine, et al. In prep

Deuterated water is expected to be lost from the atmosphere of Venus more slowly than water. Understanding the present day abundances of the two can lead to a better understanding of the water loss mechanisms and the historical conditions in the atmosphere of Venus.



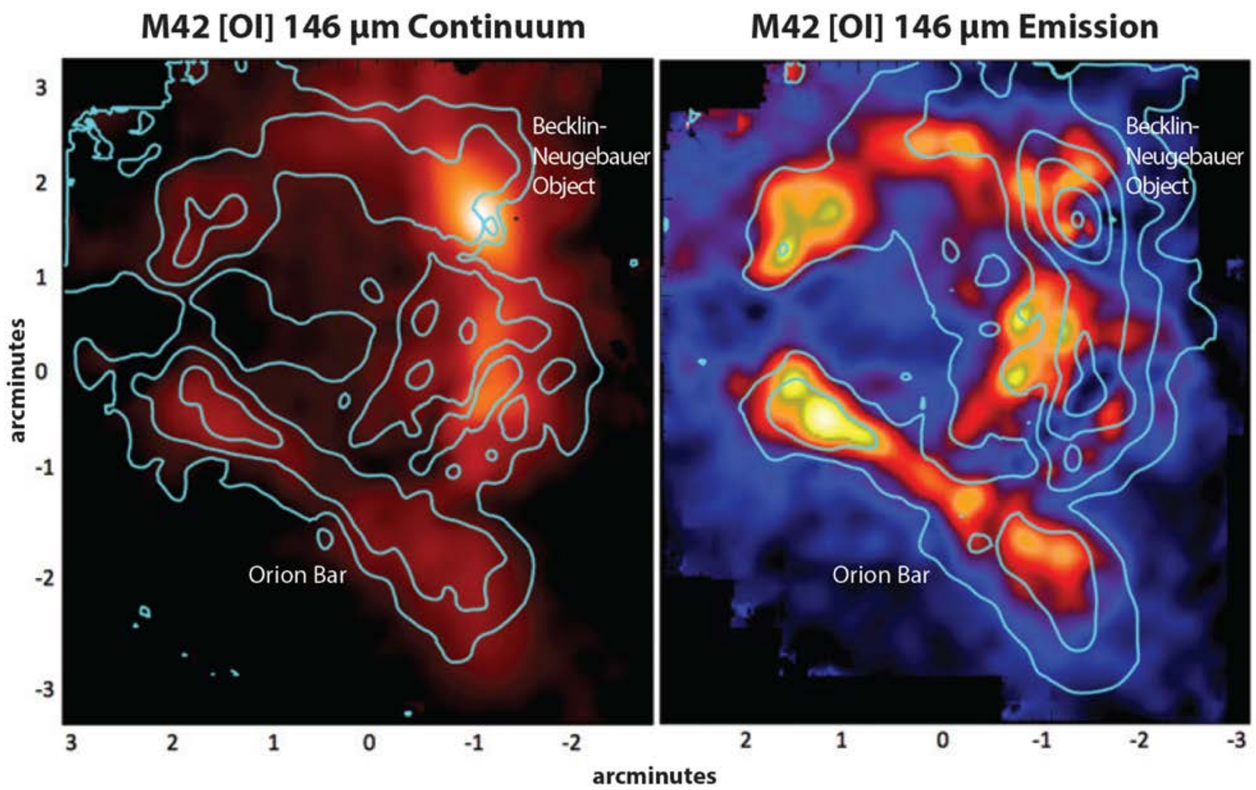


FIFI-LS

"FIFI-LS *Mapping of M42 at 146 µm*", L. Looney, et al. In prep

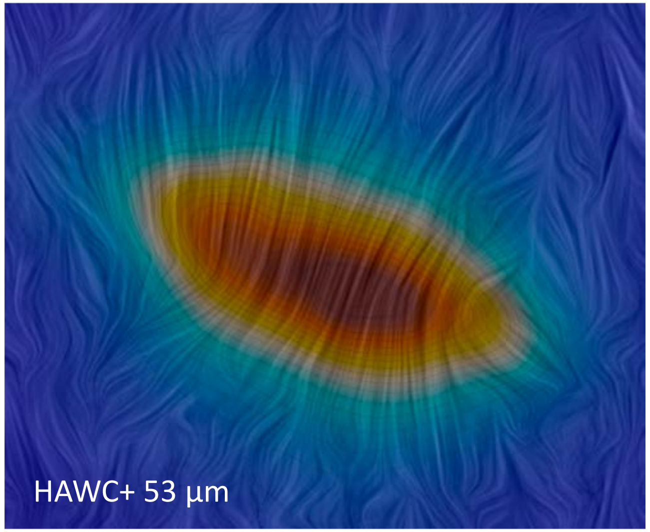
Left: The far infrared continuum is shown, which peaks at the Becklin-Neugebauer object but also clearly shows the Orion Bar and a similar structure to the north-east.

Right: Additionally, the [OI] line emission traces the photon-dominated regions around the Trapezium stars where the star's UV radiation irradiates the surrounding molecular cloud.

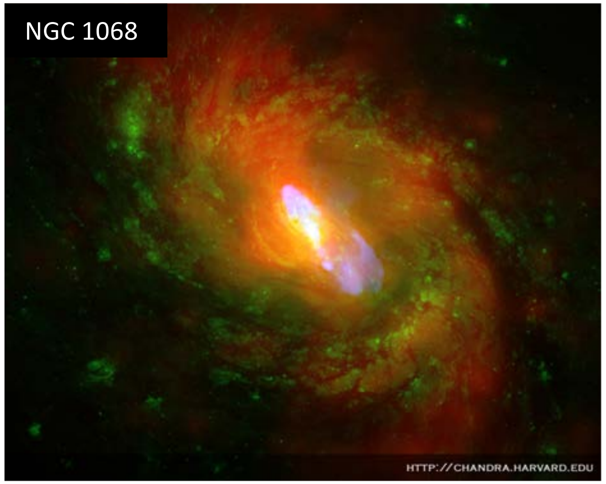


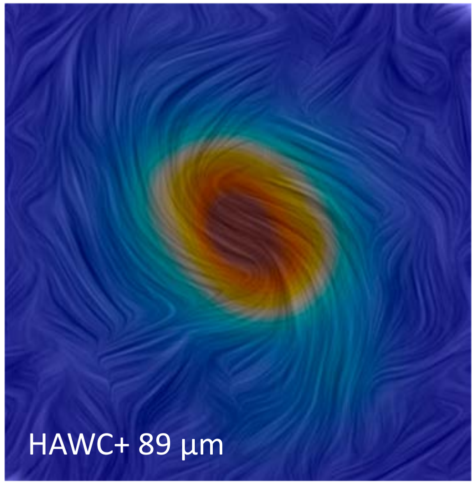
HAWC+

"SOFIA/HAWC+ Polarization in Galaxies: It's All About the Magnetic Fields", Lopez-Rodriguez 2018, AAS Press Release 123.07



M82 – Dust grain polarization aligned with starburst outflow.





NGC 1068 – Magnetic field is well ordered and traces spiral arms.

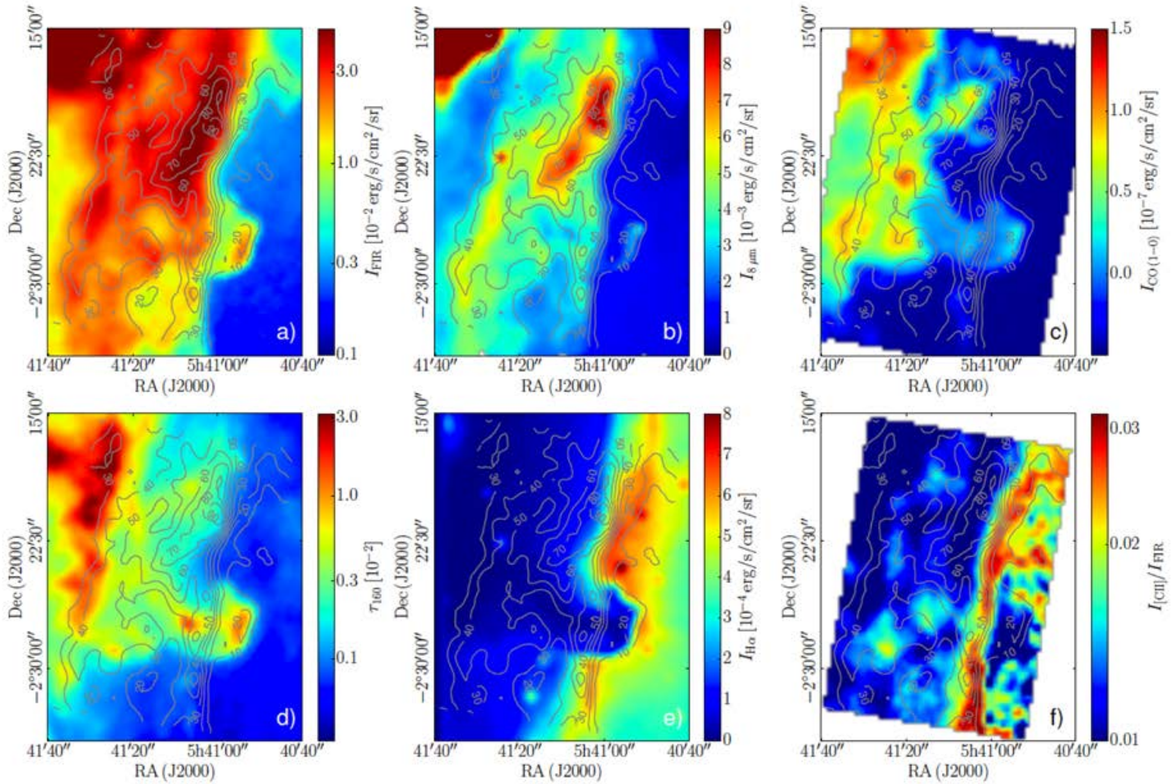
GREAT

[CII] emission from L1630 in the Orion B molecular cloud

Standard assumptions about gas heating mechanisms over-predict the observations by a factor of two.

Our fundamental understanding of small grain abundances in PDRs challenged by these SOFIA results.

Contours shown at right are [CII] 158 μm flux measured by SOFIA.



Pabst, C. et al 2017 https://arxiv.org/abs/1707.05976

https://www.sofia.usra.edu/science/proposing-and-observing/proposal-calls/sofia-directors-discretionary-time/horsehead-nebula