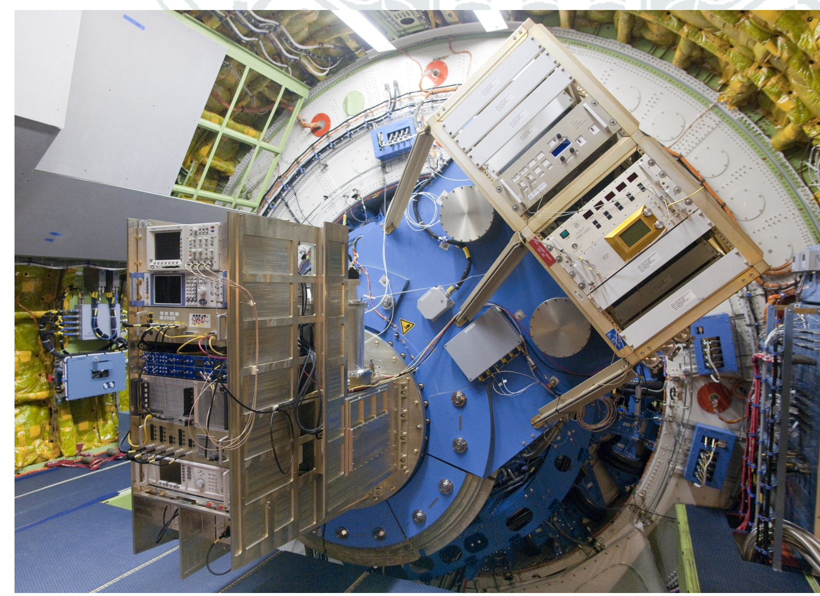
The first six years of SOFIA science: Observatory status and science highlights

Stratospheric
Observatory
For
Infrared
Astronomy

Robert Simon (I. Physikalisches Institut, Universität zu Köln)

SOFIA status

- >400 flights so far
- Full operational capability in mid-2014
- ~100 flights per year
- ~560 hours of actual science
- 8 Science instruments
- Open to US/German and intern. community



(up)GREAT at the telescope

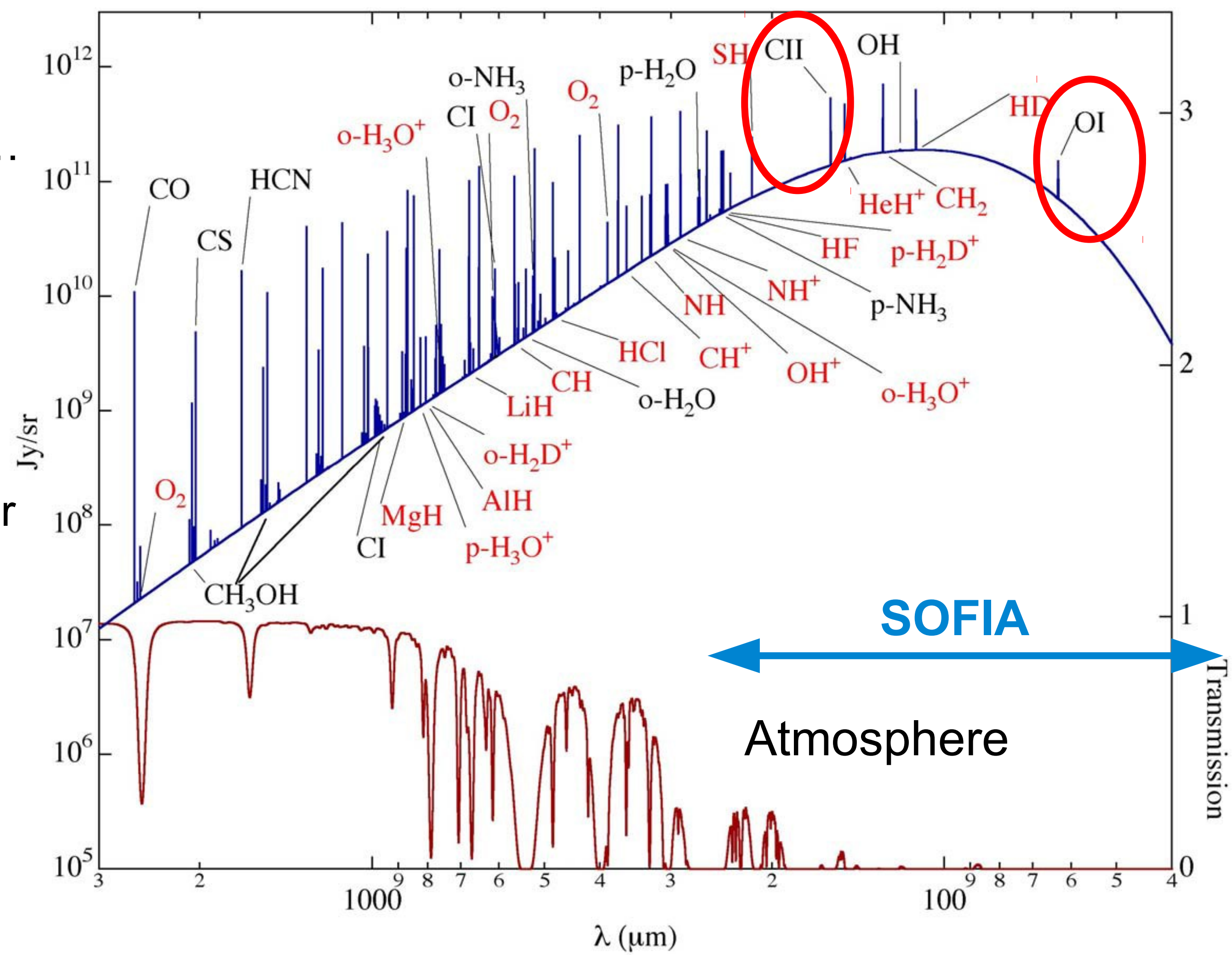
Why flying into the stratosphere and observe in the far-IR?

- Star formation and evolution of galaxies
  - Formation of clouds and stars
  - Stellar feedback
    - Winds, outflows, UV radiation, SNe
  - Heating: UV radiation (mainly photo-electric effect)
  - Cooling: thermal radiation of dust, atomic and molecular lines
  - Equilibrium at 10 – 100 K → Far-infrared

Why flying into the stratosphere and observe in the far-IR?

- Observations of star forming regions and cool gas
  - Continuum (maximum shifted into submm and far-IR)
  - Fine structure and CO lines: [CII], [OI], [NII], high-J CO
  - Other lines: OH, OD, H_2D^+, NH_3, HD, …
  - Most of the energy of star-forming regions in far-IR
  - Most important emission lines for energy balance and other atomic/molecular tracers in far-IR

Spectrum of a molecular cloud (Bergin 2008)



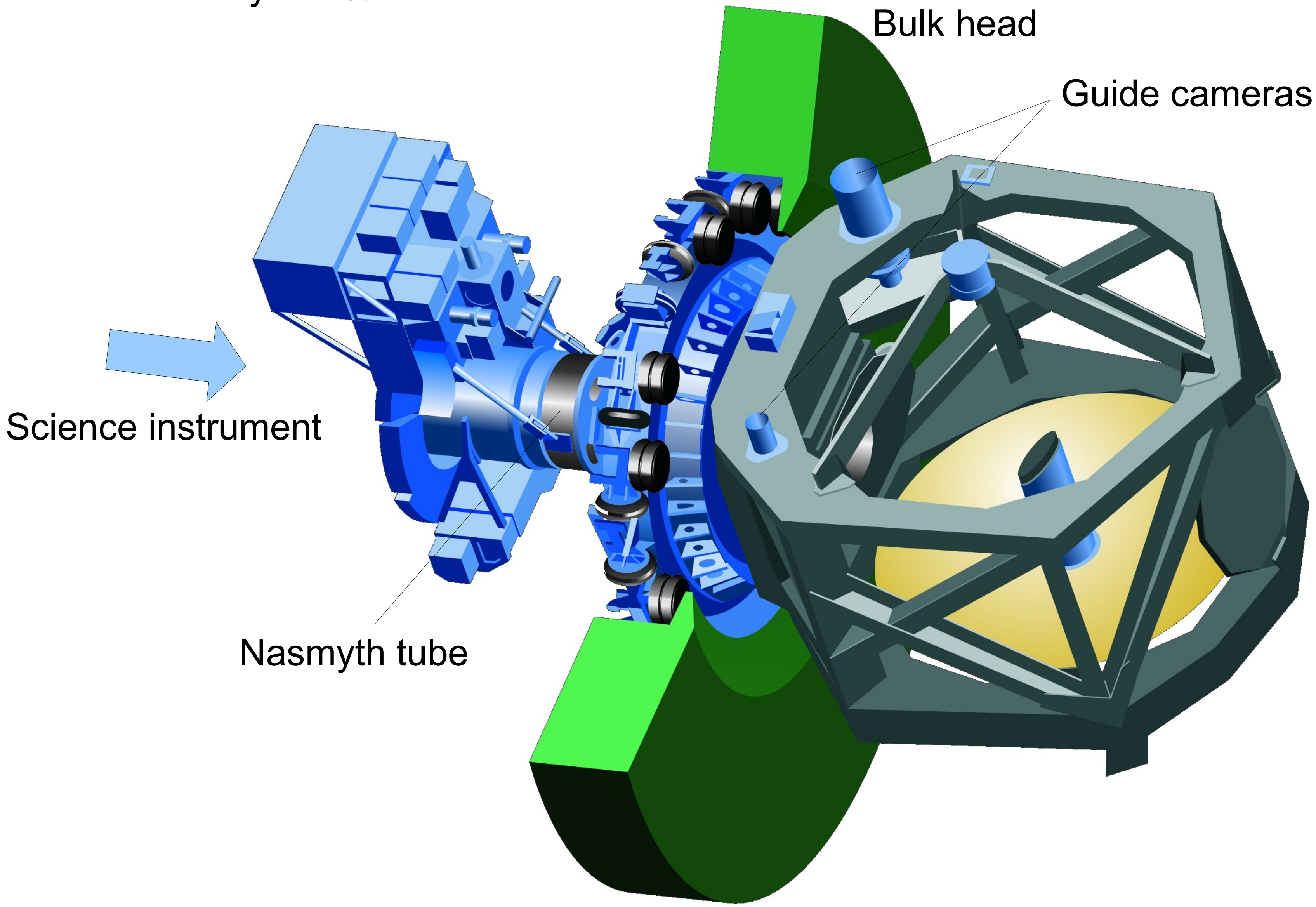
SOFIA observatory

- Modified B747-SP with a 2.7 m telescope
- US (80%) and German (20%) project
- SOFIA operations
  - SOFIA Science Center: NASA Ames, Mountain View, CA
    SOFIA Flight Operations: Armstrong Flight Research Center, Palmdale, CA
  - Deutsches SOFIA Institut (DSI), Stuttgart
- Operated at a flight altitude of 12-14 km (residual water vapor <1 % of ground)
- Flexible world wide deployment
  (southern sky from, e.g., New Zealand)
- Typical observing flight duration:
  10 hours (8 hours at observing altitude)
- 100 flights per year in routine operation
- Planned lifetime 20+ years

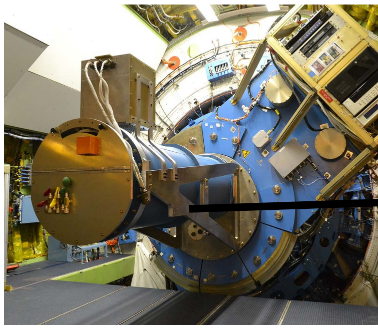
www.sofia.usra.edu
www.dsi.uni-stuttgart.de

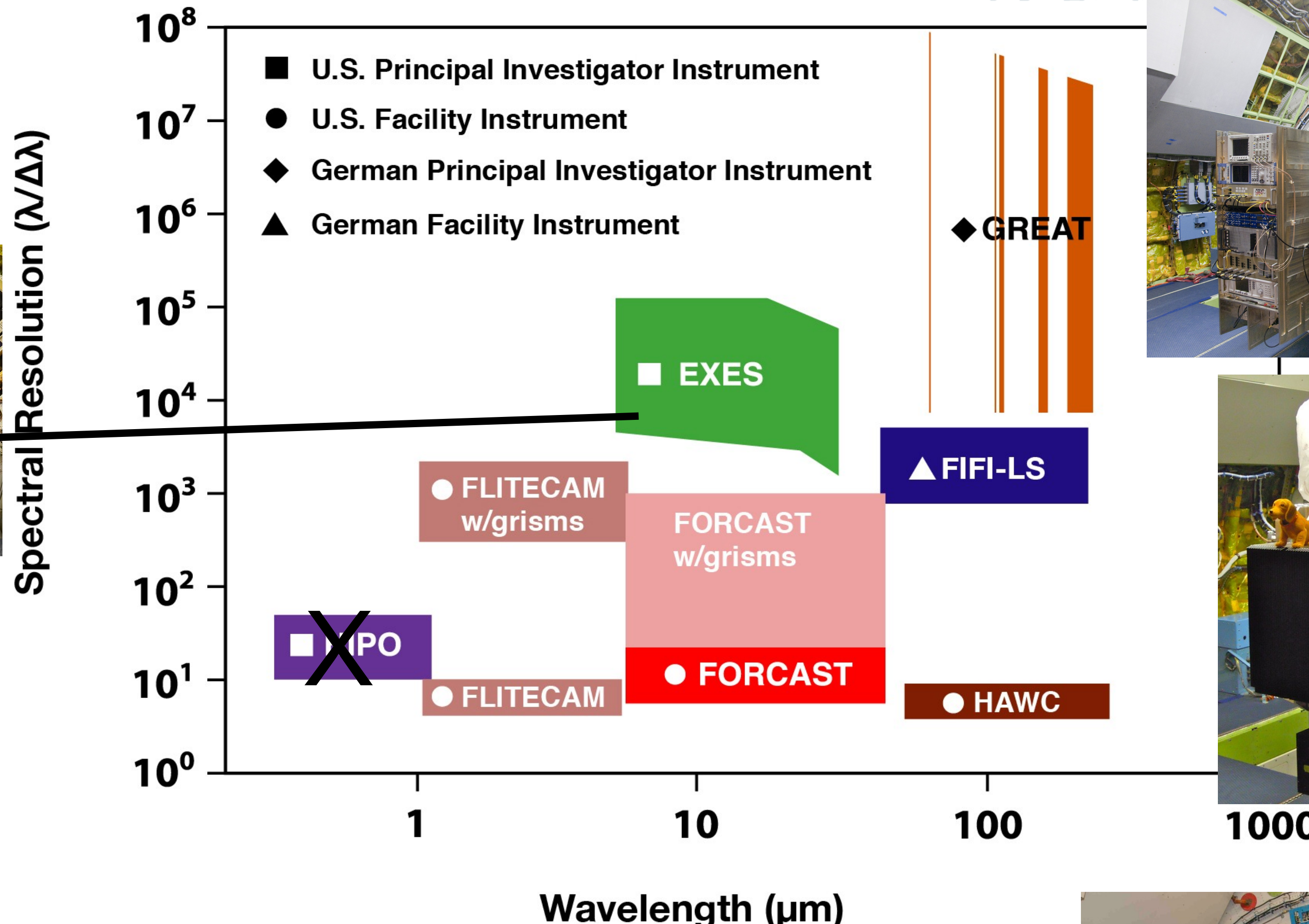
SOFIA Telescope

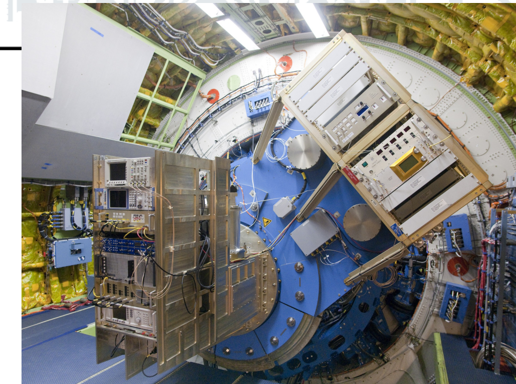
- Telescope
  2.5 meter effective aperture, diffraction limited at λ>20μm, optics temperature 240K
  Emissivity ~15%

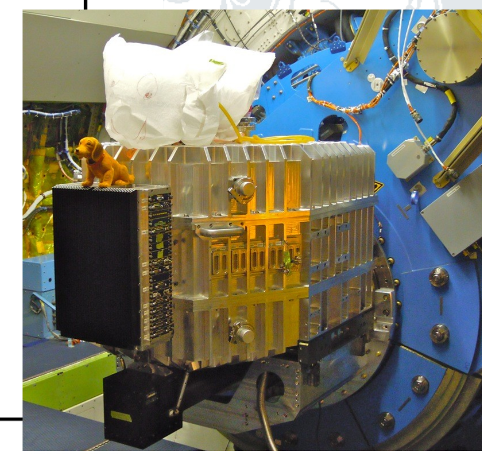


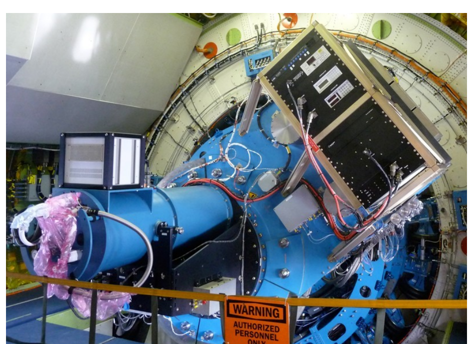
SOFIA Science Instruments

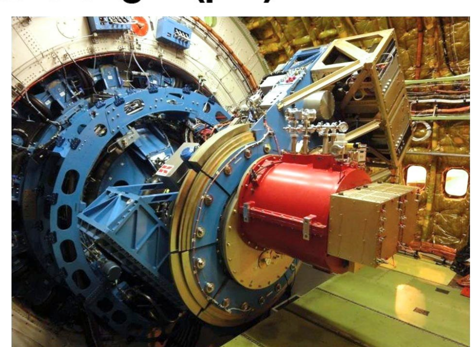


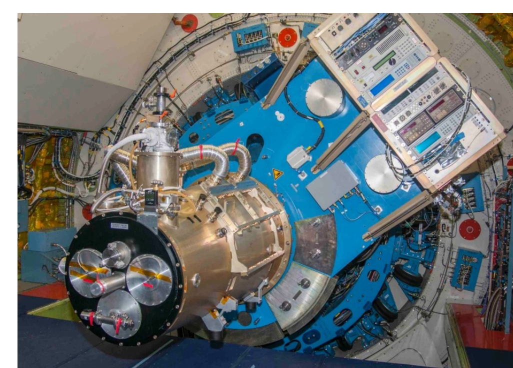






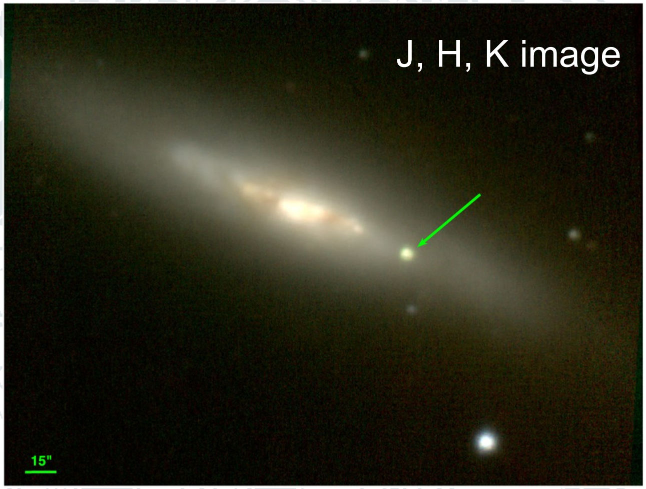


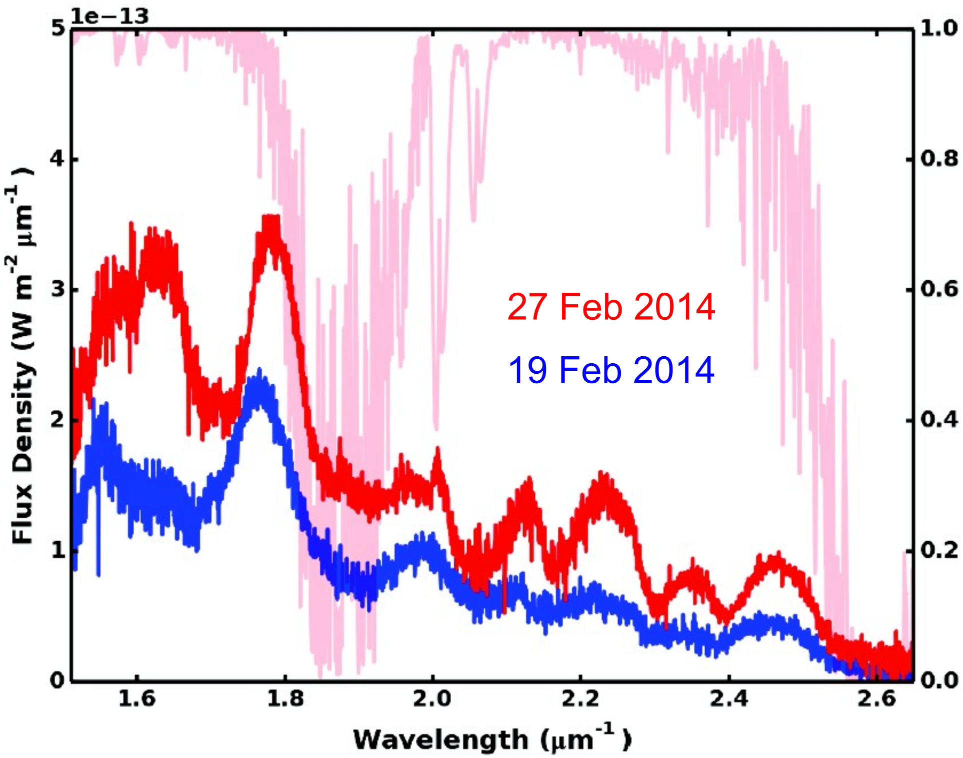




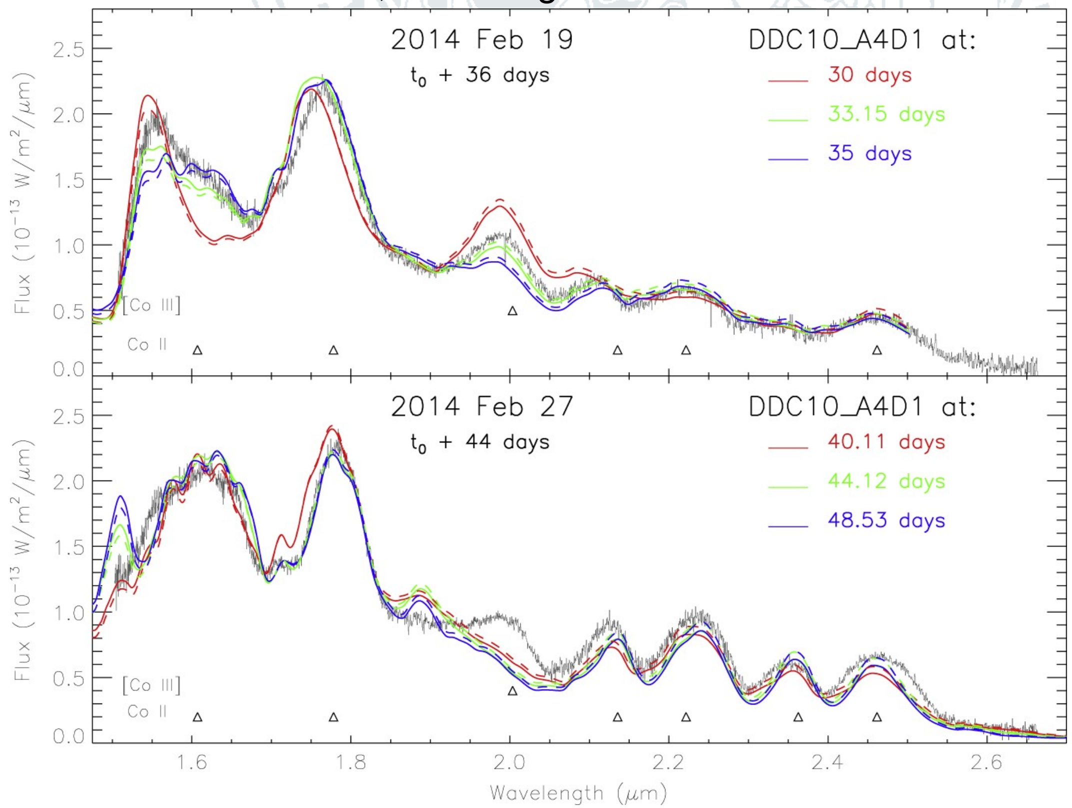
SOFIA Science Highlights: FLITECAM First Light Infrared Test Camera

- FLITECAM (UCLA, PI: Ian McLean)
  Near Infrared Imaging and Grism Spectroscopy (1–5.5 µm)
  - PAH/Pa α emission and search for Brown Dwarfs
  - Pluto occultation (June 29, 2015) in support of NASA's New Horizons Mission
  - SN 2014J (M82) near-IR spectrum, evolving with time (ionized Cobalt lines)

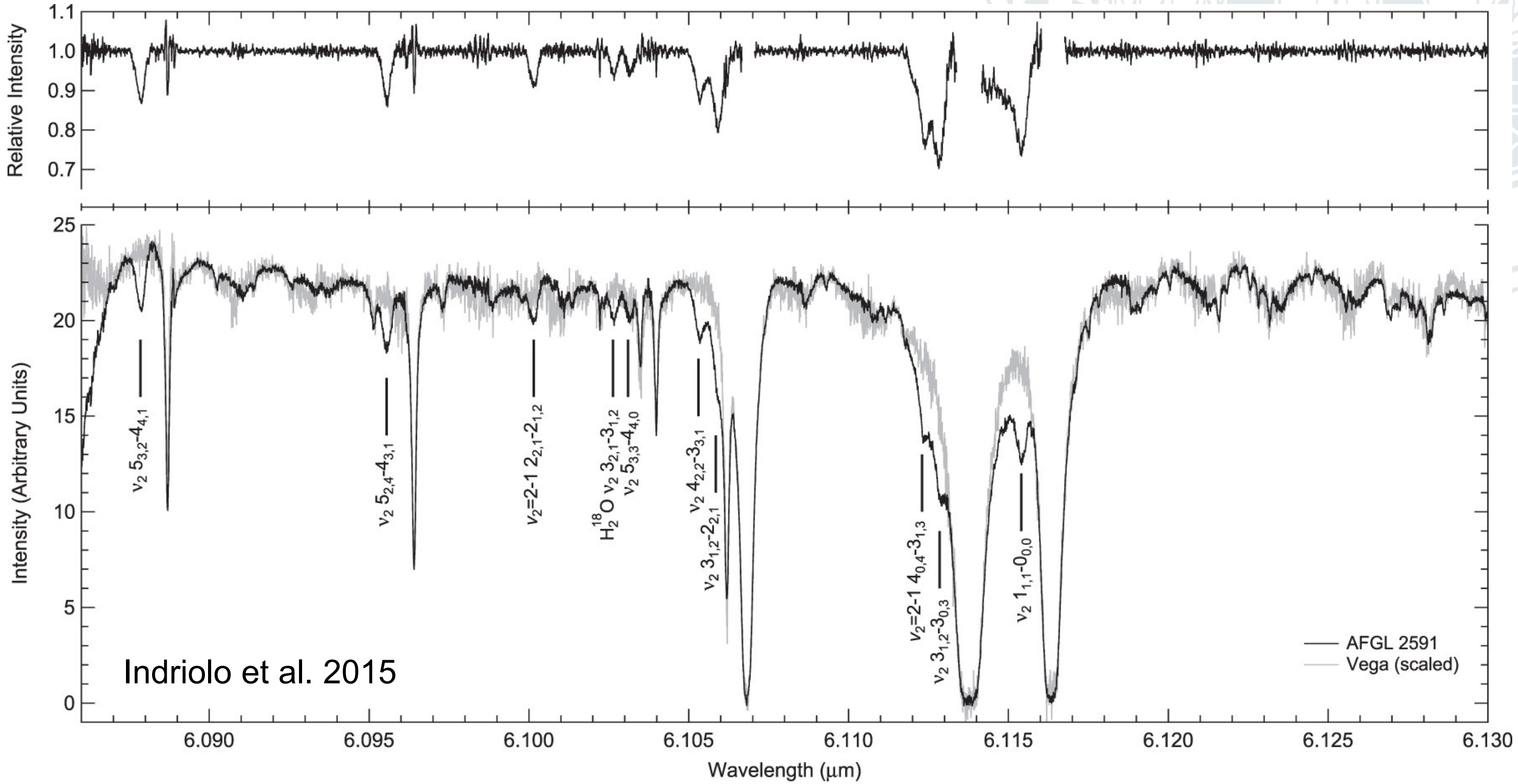




Vacca et al. 2015; modelling: Dessart et al. 2014



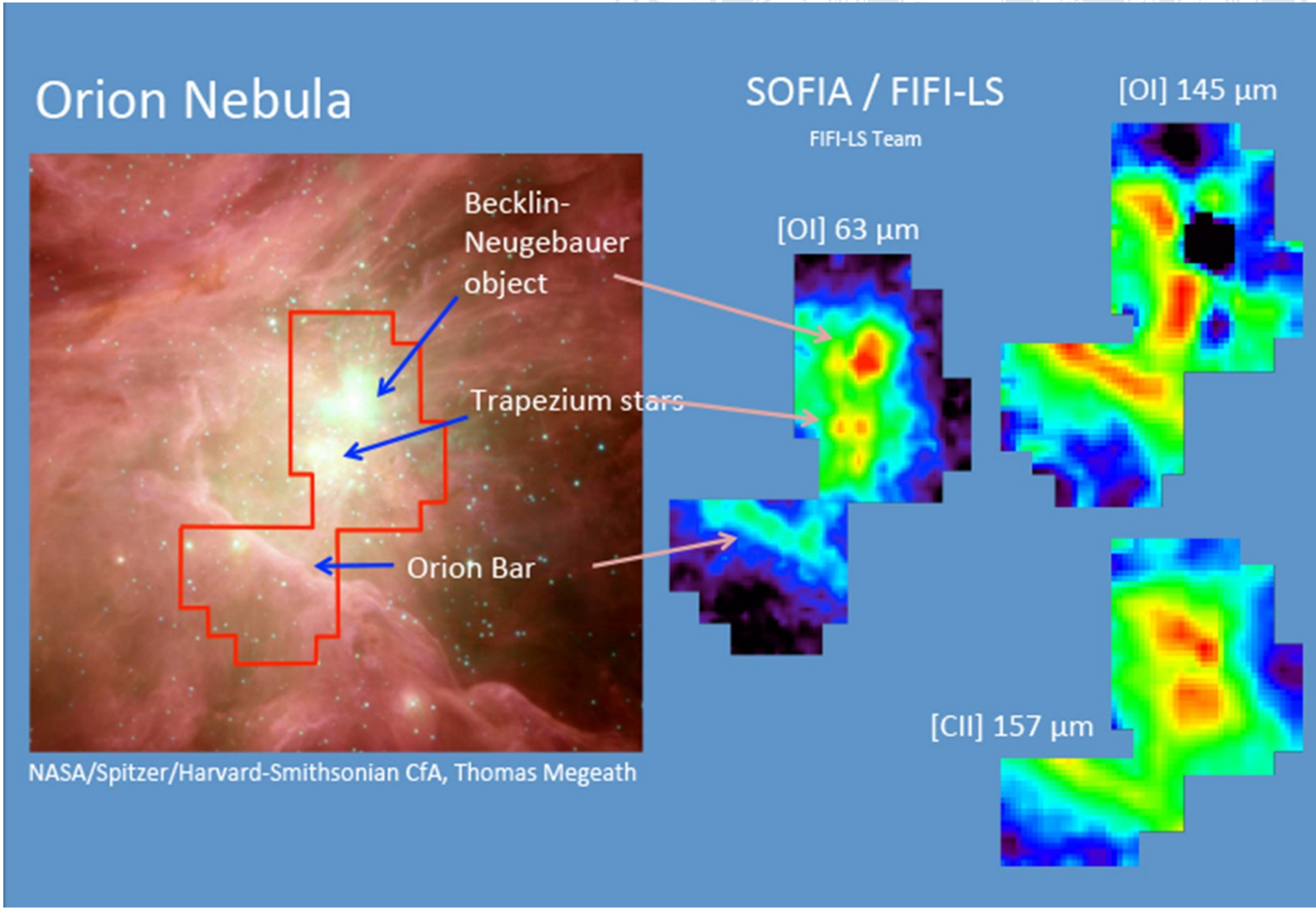
- EXES (Ames/UC Davis, PI: Matt Richter)
  High Resolution ($R=10^5$) Echelle Spectrometer (5–28 μm)
  - 28/17 μm para/ortho H_2 emission
  - Water in protoplan. disk AFGL 2591
    - 10 lines detected (7 g.s., 1 $H_2^{18}O$)
    - Constraints on temperature and column density: T = 640 K, $N(H_2O) = 10^{19}$ cm^{-2}



SOFIA Science Highlights: FIFI-LS Far Infrared Field-Imaging Line Spectrometer

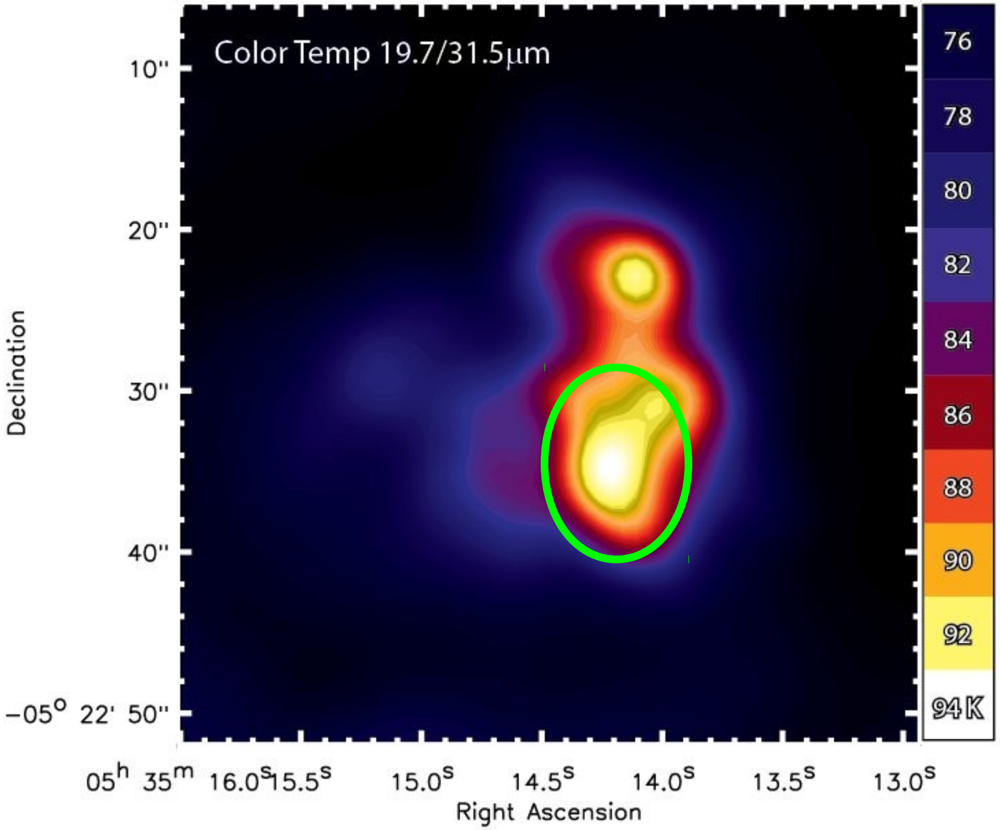
- FIFI-LS (DSI, Stuttgart U., PI: Alfred Krabbe)
  Dual Channel Integral Field Grating Spectrometer (50–110 µm; 100–200 µm)
  - [CII] 158 µm, [OI] 63, 145 µm, [OIII] 52, 88 µm

Orion
M82, M51
Gal. Center



SOFIA Science Highlights: FORCAST Faint Object infraRed CAmera for the SOFIA Telescope

- FORCAST (Cornell, PI: Terry Herter)
  Simultaneous Dual Channel Imaging and Grism Spectroscopy (5–25 μm and 25–40 μm)
  - A new mid-IR self-luminous source in Orion BN-KL (IRc4, brighter than BN)
  - A mid-IR dusty circumnuclear ring (CNR) in the Galactic Center (3 pc diameter)
  - Dust emission in Sgr A East supernova remnant (dust surviving shock)



De Buizer et al. (2012)

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Lau et al. (2013), 19 31 37 micron

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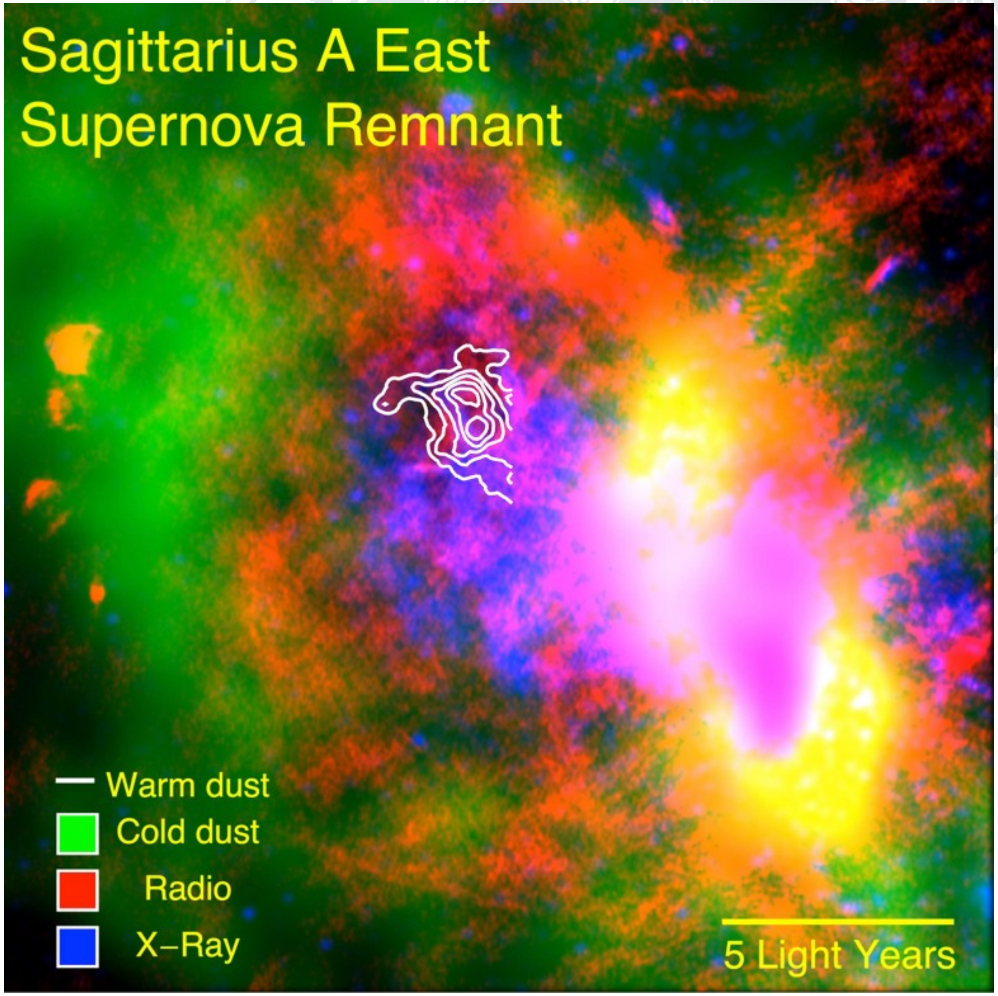
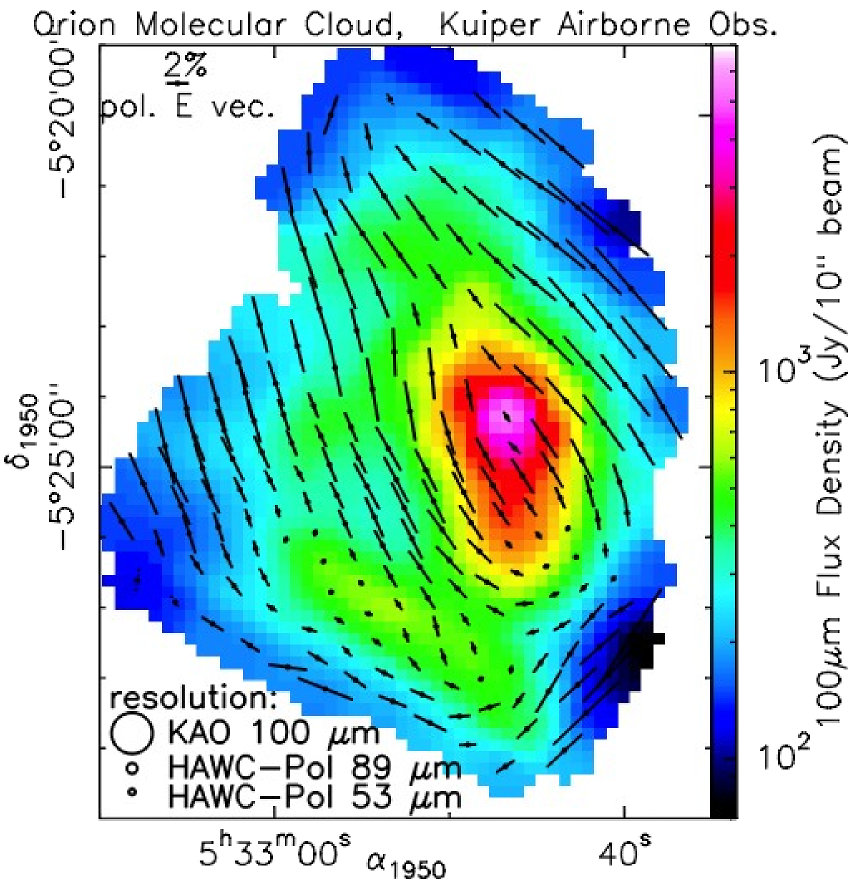


Lau et al. (2015, Science)

SOFIA Science Highlights: HAWC+ High-resolution Airborne Wideband Camera

- HAWC+ (U. Chicago, PI: Charles Dowell)
  High-Angular Resolution Wide-Band Camera/Polarimeter
  5 Channels (53 µm, 62 µm, 88 µm, 155 µm, 215 µm)



Linear polarization of the Orion Nebula at 100 µm (KAO, Schleuning 1998). Beam sizes of the KAO polarimeter and HAWC+ (Dowell et al. 2007)

- SOFIA unique opportunity
- In commissioning

SOFIA Science Highlights: HAWC+ High-resolution Airborne Wideband Camera

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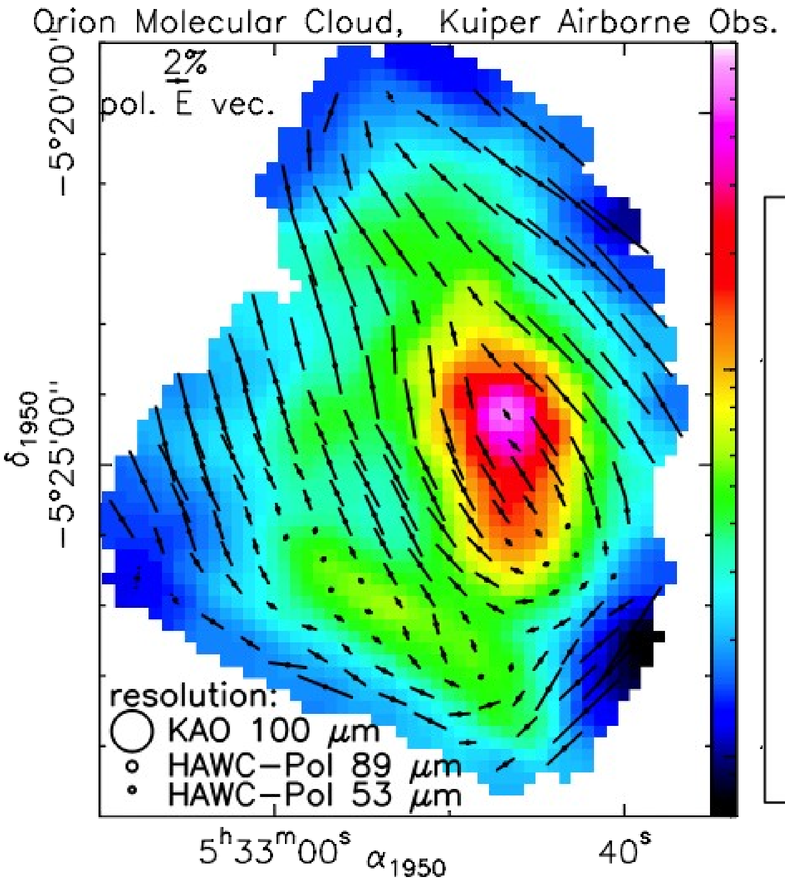
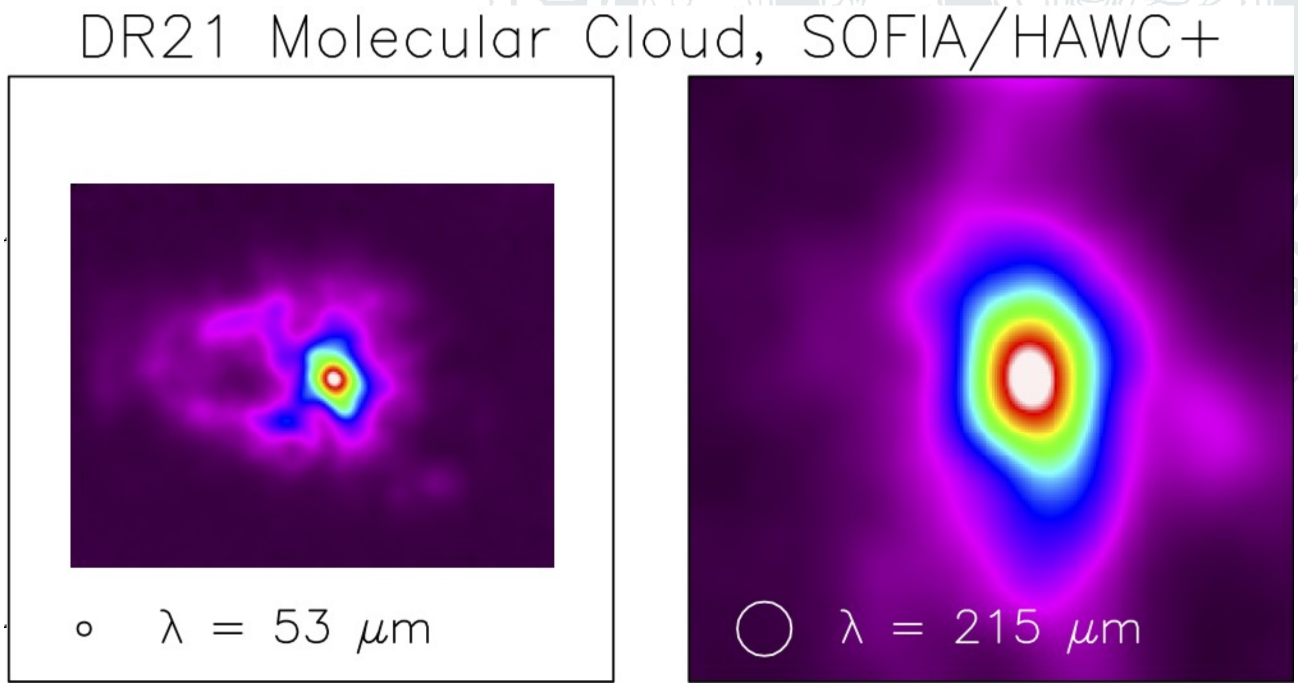


Linear polarization of the Orion Nebula at 100 μm measured with the KAO by Schleuning (1998). Beam sizes of the KAO polarimeter and HAWC upgrade. (Dowell et al. 2007)

HAWC+ first light



SOFIA Science Highlights: GREAT German REceiver for Astronomy at Terahertz Frequencies

- (up)GREAT (PI: Rolf Güsten (MPIfR, Bonn),
  co-I Jürgen Stutzki, Universität zu Köln,
  plus DLR Institut für optische Informationssysteme, Berlin,
  MPI Sonnensystemforschung, Göttingen)
  High resolution (10^8) heterodyne spectrometer (1.26 – 4.7 THz)
- Modular dual channel receiver
  - 1.26 < f < 4.7 THz (22" – 6" beam)
- upGREAT: extension of GREAT into 2 FIR arrays

Channel		**Frequencies [THz]**	**Lines of interest**	**T_{min}[K] / BW_{3dB} [GHz]**
low-frequency	L1	1.26 – 1.52	[NII], CO series, OD, H_2D^+	500 / 2.5
low-frequency	L2	1.82 – 1.91	NH_3, OH, CO(16-15), [CII]	700 / 2.5
mid-frequency	Ma/b	2.49 – 2.56, 2.67	$^{(18)}OH(^2\Pi_{3/2})$, HD	1500 / 2.5
high-frequency	H	4.74	[OI]	800 / 2.5
upGREAT	LFA	2x7 (1.9 – 2.5)	CO series, [CII], [OI], OH	1000 / 3.3
upGREAT	HFA	7x (4.74)	[OI]	End of 2016

Since 2017: 4GREAT, 4 pixels at lower frequencies

SOFIA Science Highlights: GREAT German REceiver for Astronomy at Terahertz Frequencies

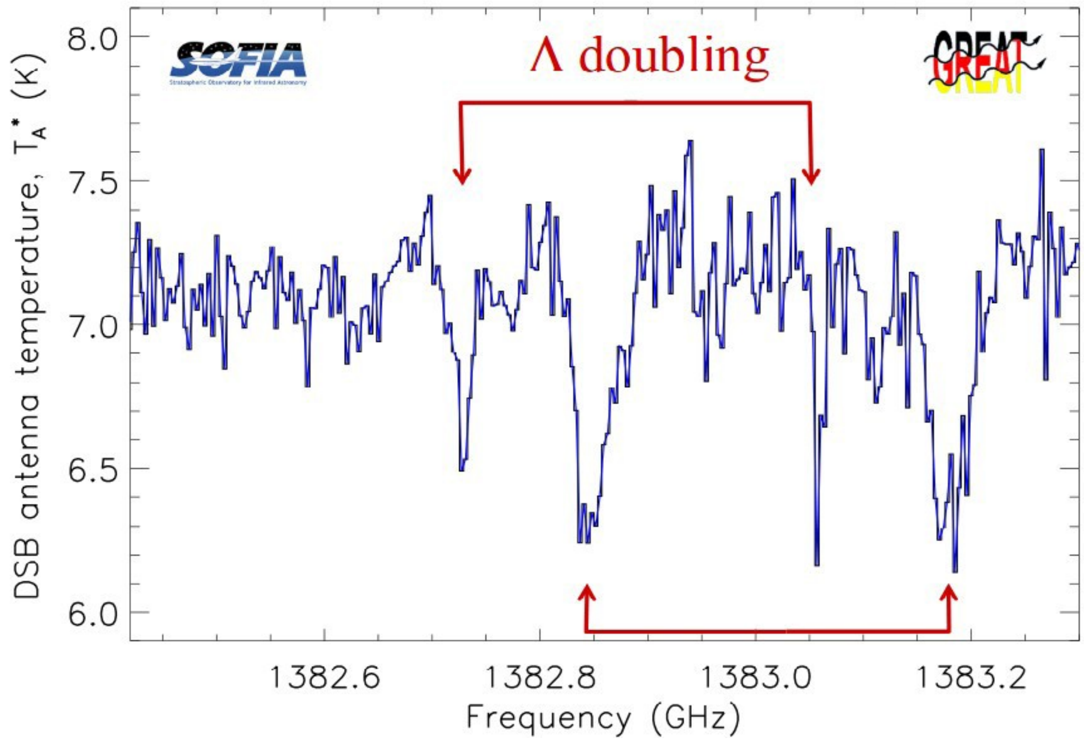
- Science with GREAT
  - Absorption studies
    - New molecules
    - Chemistry
  - Emission lines
    - Mapping in prominent cooling lines: [CII], [OI], high-J CO

SOFIA Science Highlights: GREAT and absorption lines

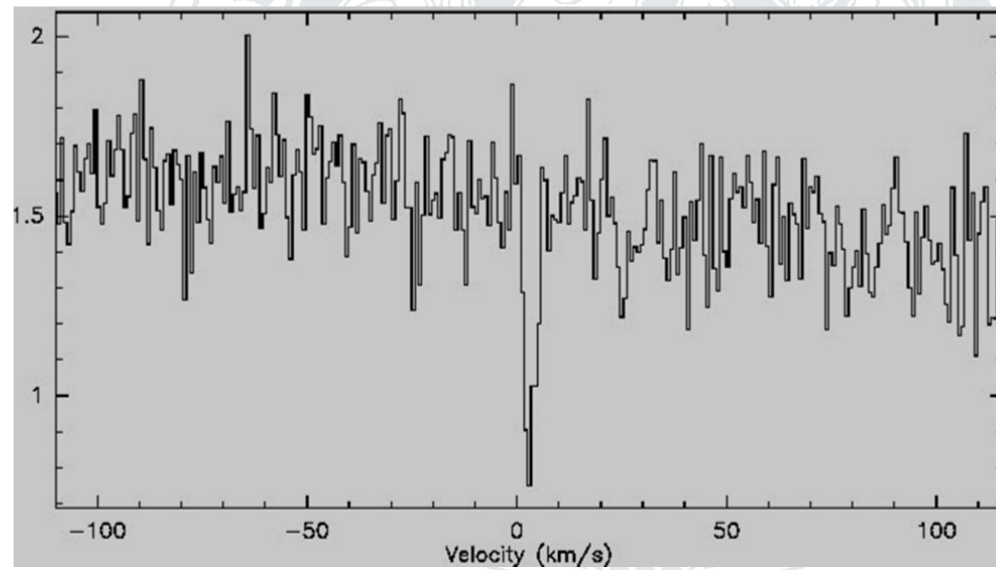
- Detection of new molecules
  - SH radical (Neufeld et al. 2012, 2014)

OD in a protostar (Parise et al. 2012)

W49



IRAS 1629A



Warm diffuse chemistry,
shock modelling

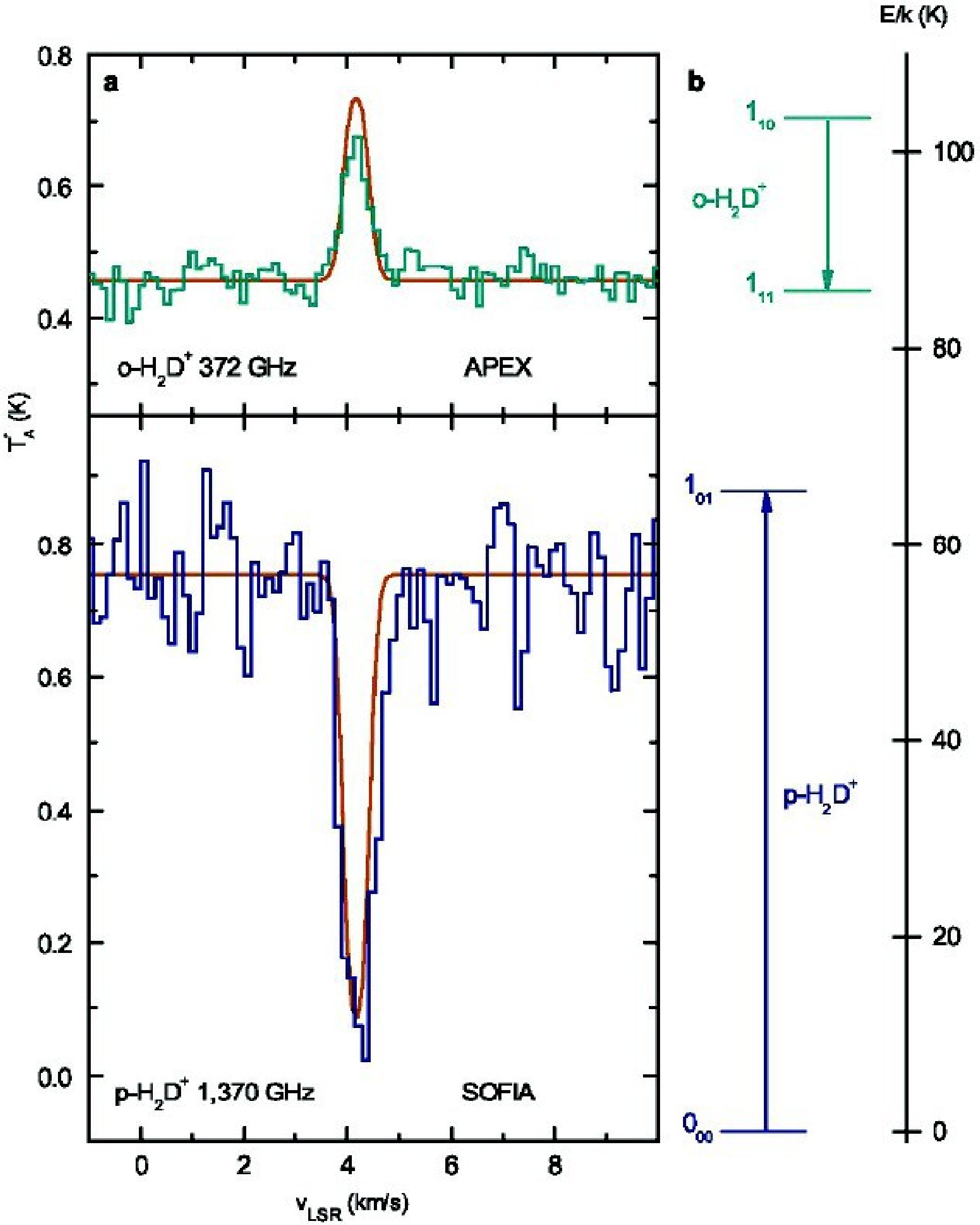
Deuteration, D/H

SOFIA Science Highlights: GREAT and absorption lines

- First detection of p-H_2D^+ IRAS16293-2422
  - Measure o/p ratio in H_2 through o/p of H_2D^+
  - At low T
    p-H_2D^+ + o-H_2 → o-H_2D^+ + p-H_2
    dominates over back reaction
  - Chemical clock

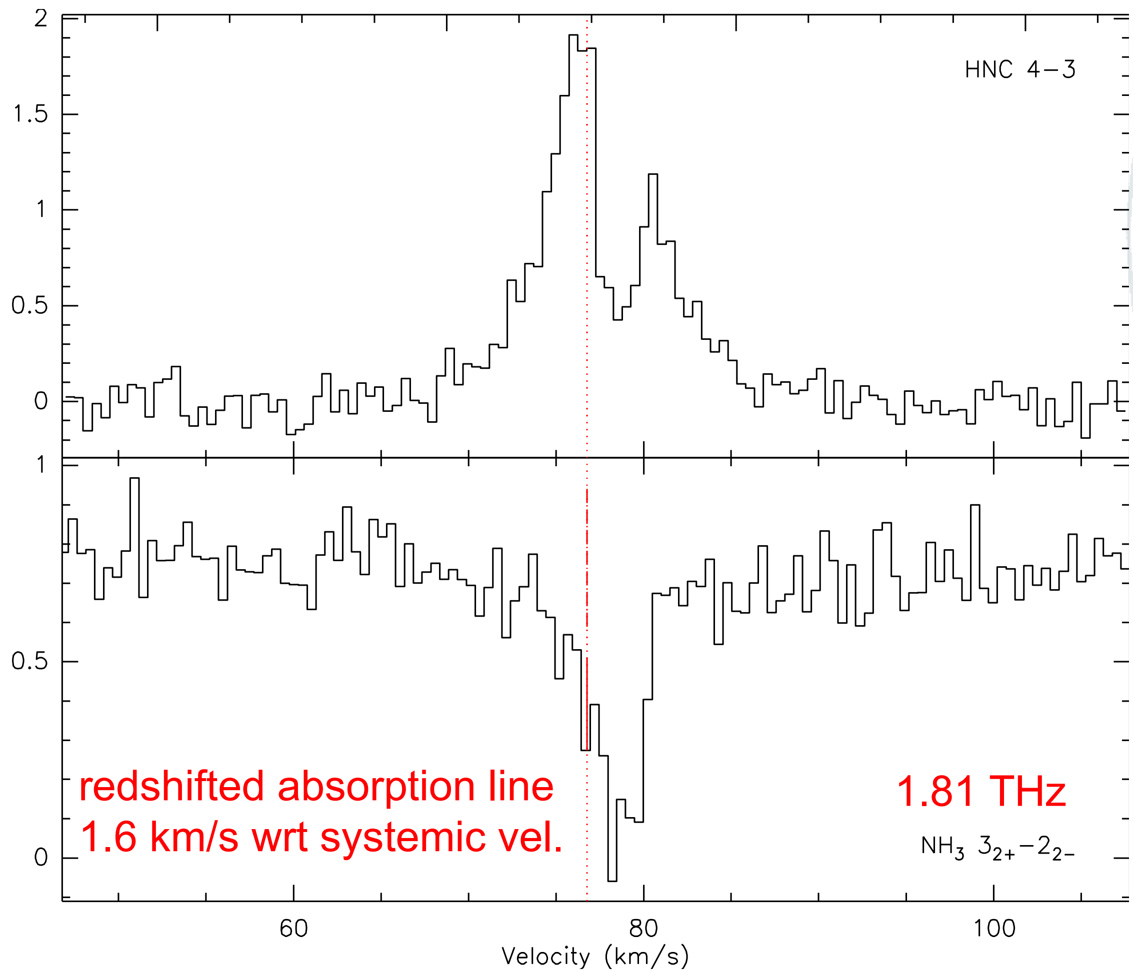
    Cold gas in dense envelope for 5 10^5 – 5 10^6 yr

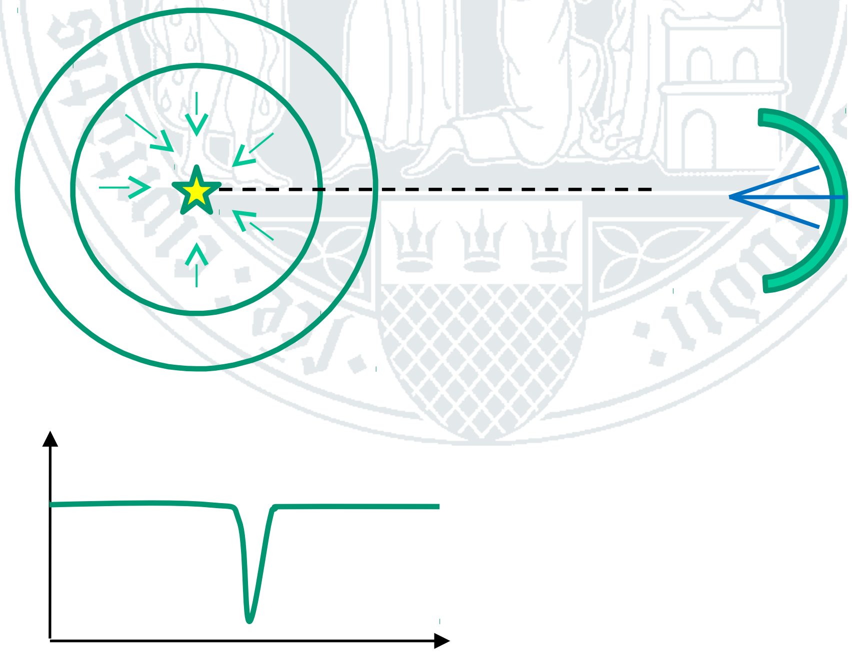
    Brünken et al. 2014 (Nature)



SOFIA Science Highlights: GREAT and absorption lines

- Using THz lines to probe infall: G23.21 (Wyrowski et al. 2016)

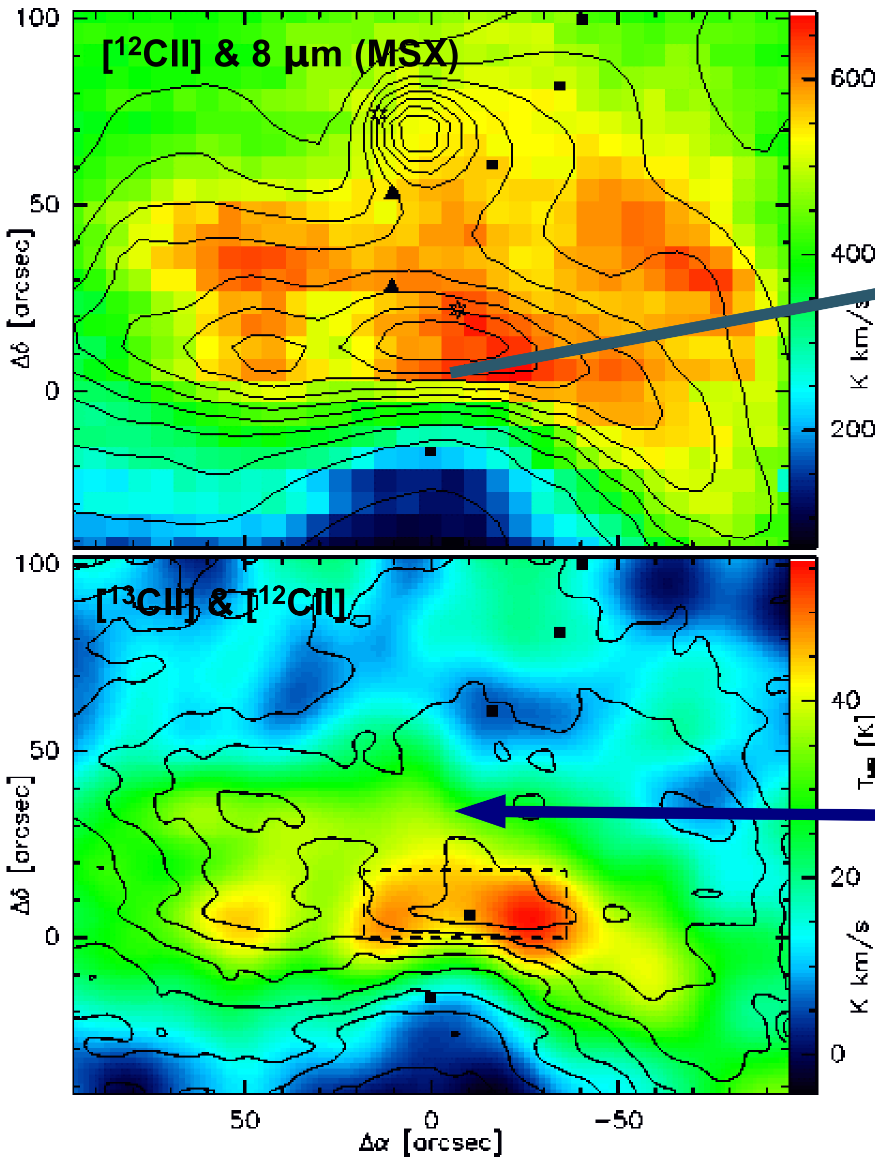




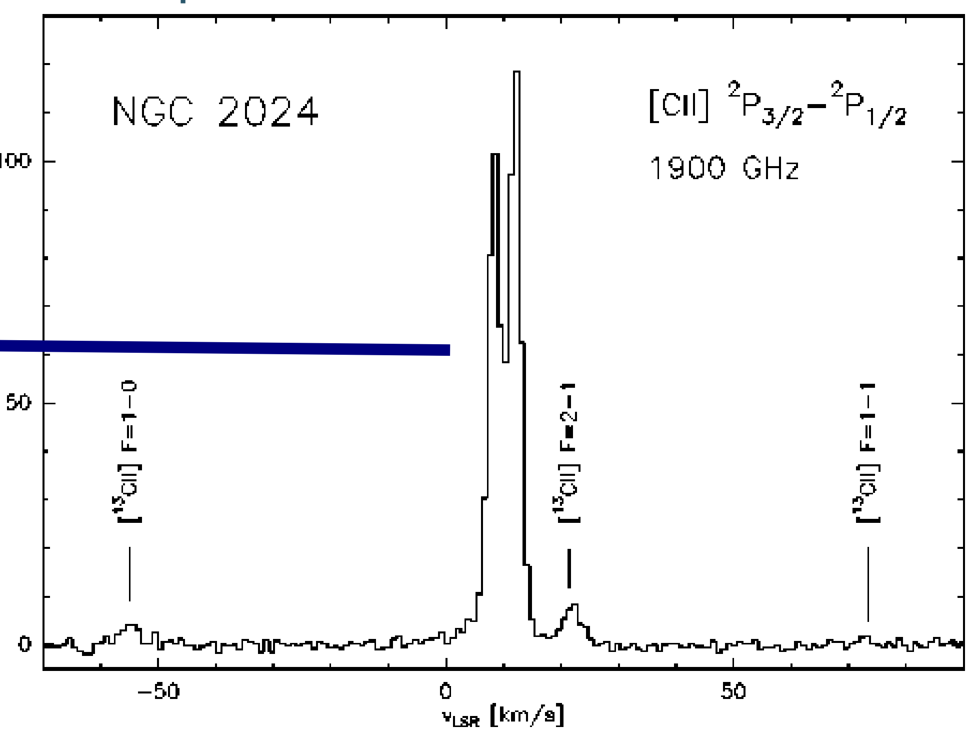
SOFIA Science Highlights: GREAT and emission lines

- [CII] and [OI] are the main coolants for PDR gas

Graf et al. 2012

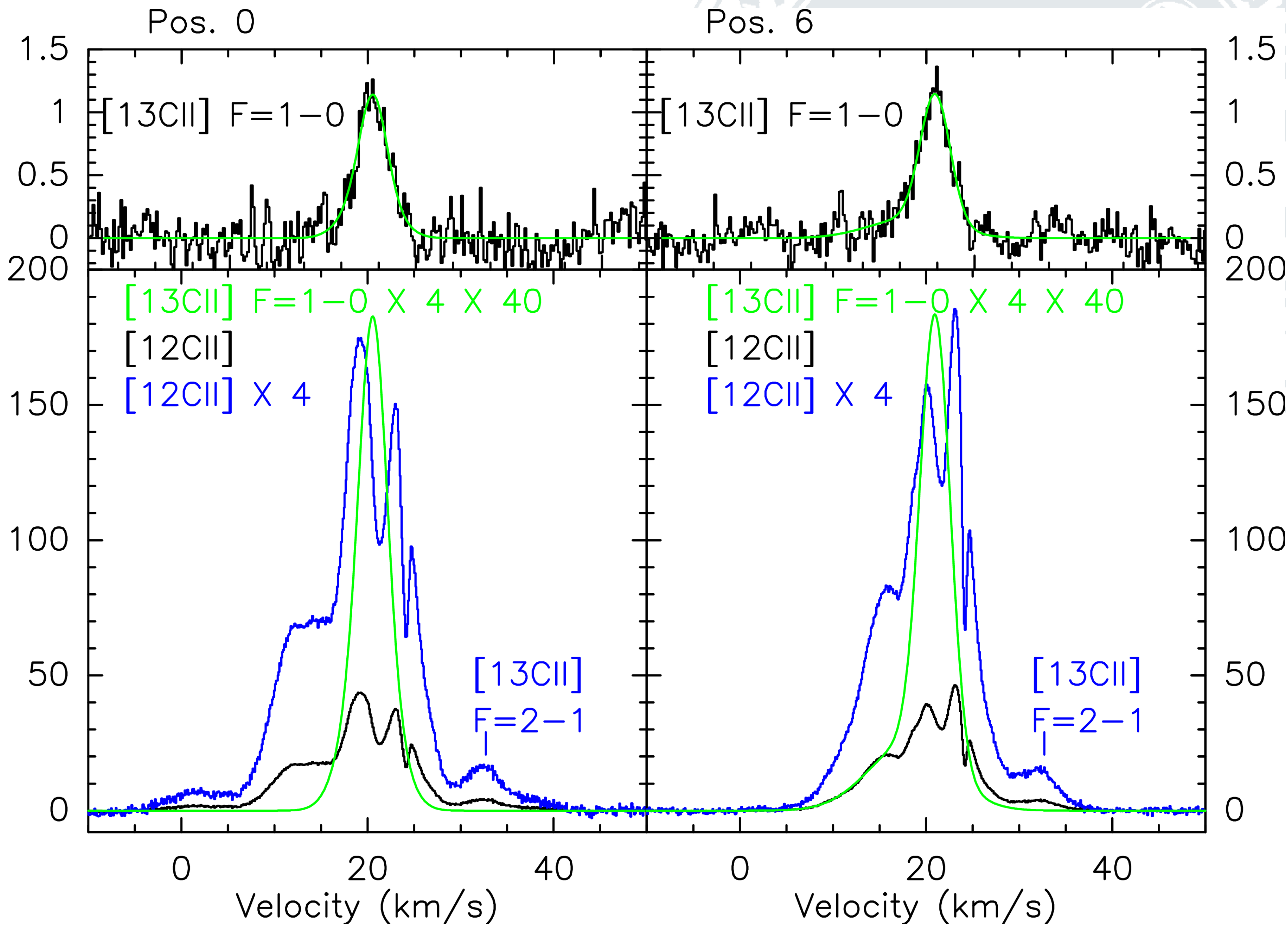


All three [^{13}CII] HFS satellites detected
→ requires 1.6 10^{23} cm^{-2}



SOFIA Science Highlights: GREAT and emission lines

- M17 (Guevara et al. in prep.)



SOFIA Science Highlights: GREAT and emission lines

- Large scale [CII] mapping
  - Joint impact programs
    - M51
    - Galactic Center
    - Orion

SOFIA Science Highlights: GREAT and emission lines

[CII] mapping M51, PIs: Pineda, Stutzki

- M51

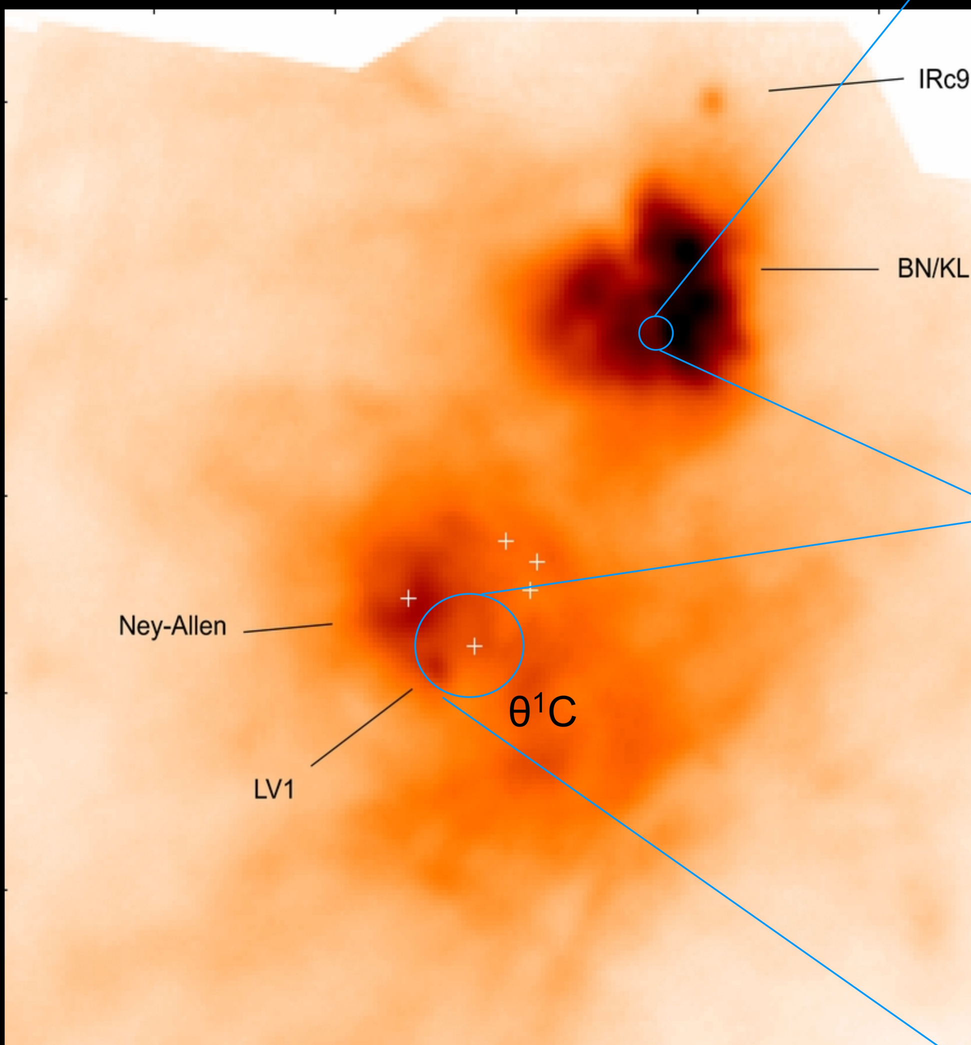
SOFIA Science Highlights: GREAT and emission lines

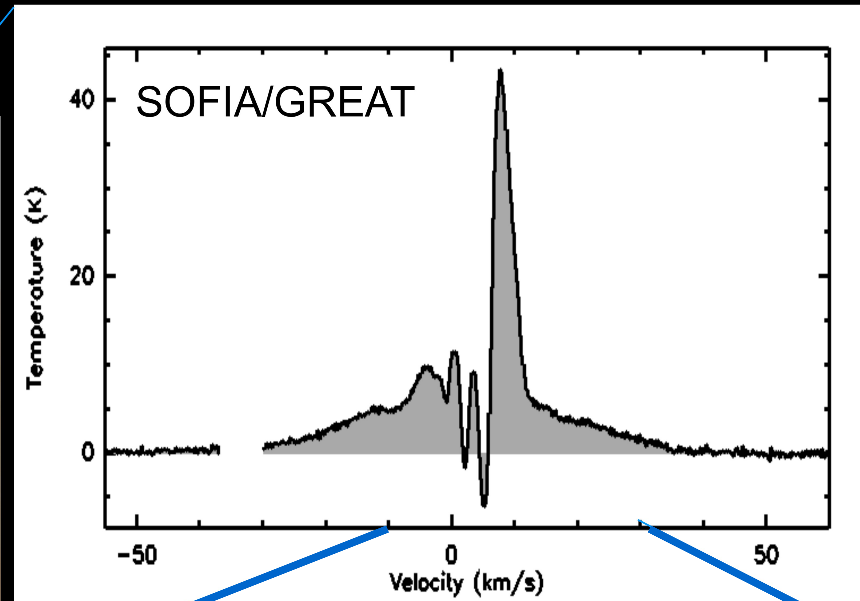
[CII] mapping: Orion

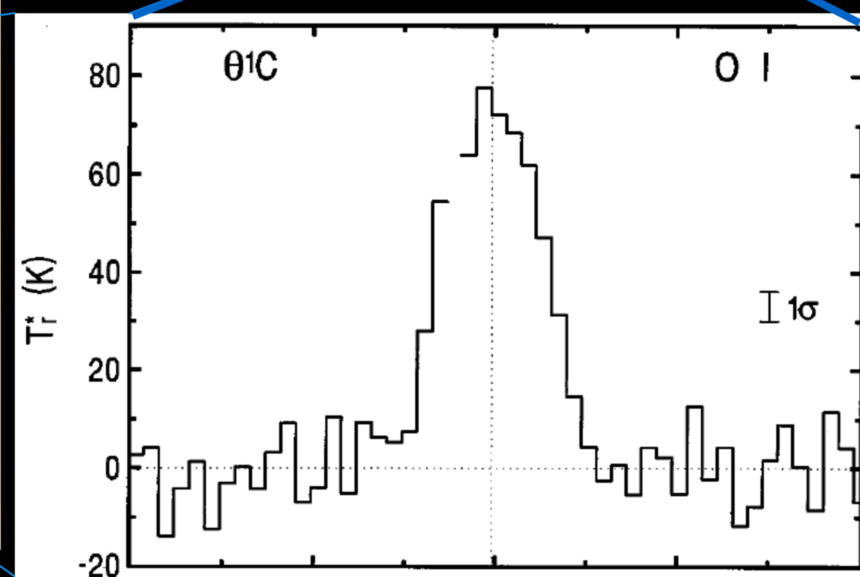
- PI: X. Tielens
- 0.3 km/s resolution.
- 12 flights
- 42 hours of flight time
- 2.2 million spectra
- 1.2 square degrees

SOFIA Science Highlights: GREAT and OI

Cooling the gas in the Orion hot core and photodissociation region: Fine-structure O I Line (63 μm)







SOFIA/FORCAST λ19.7 μm)

KAO spectrum (Boreiko & Betz, 1996)

- FIR cooling in massive star forming cores (G5.89: Leurini et al. 2015):
  - [OI] is main coolant (75% of total line luminosity)
    High velocity emission
    Large scale molecular outflow driven by atomic jets

PACS

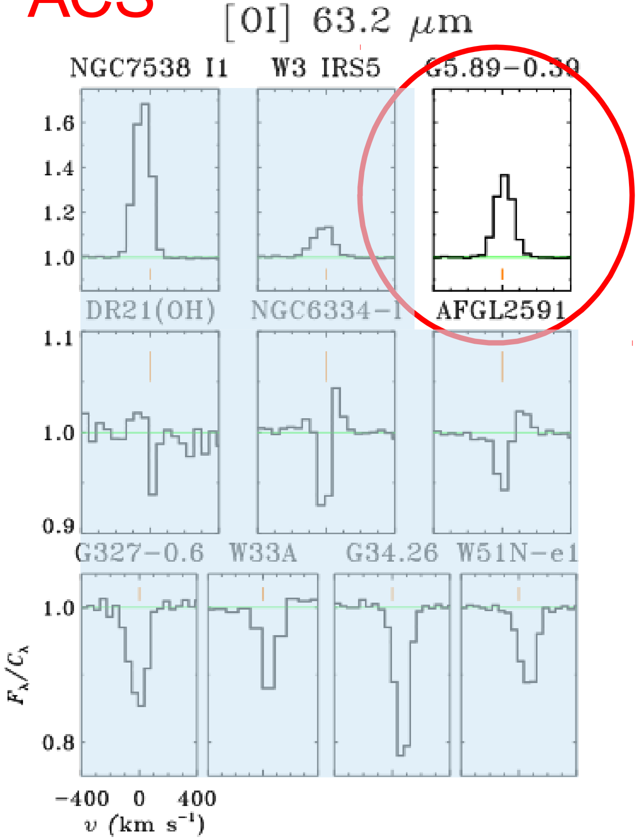
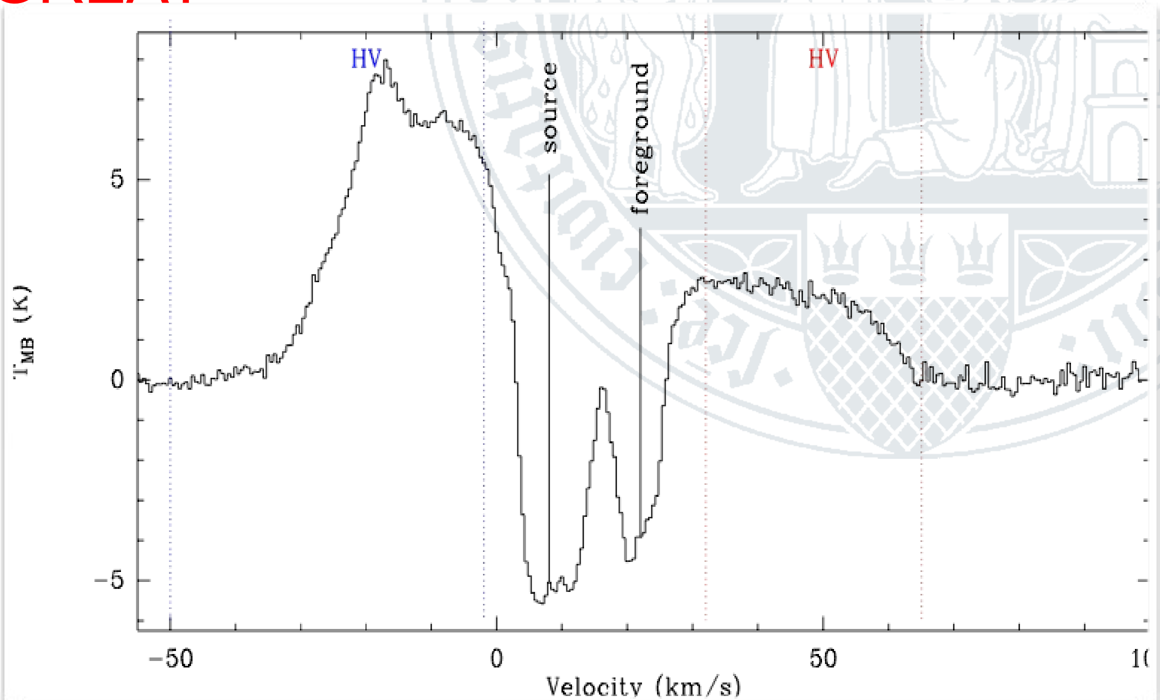


Fig. 2. Herschel-PACS profiles of the [O I] 63.2 μm line at central position.

from Karska et al. 2013

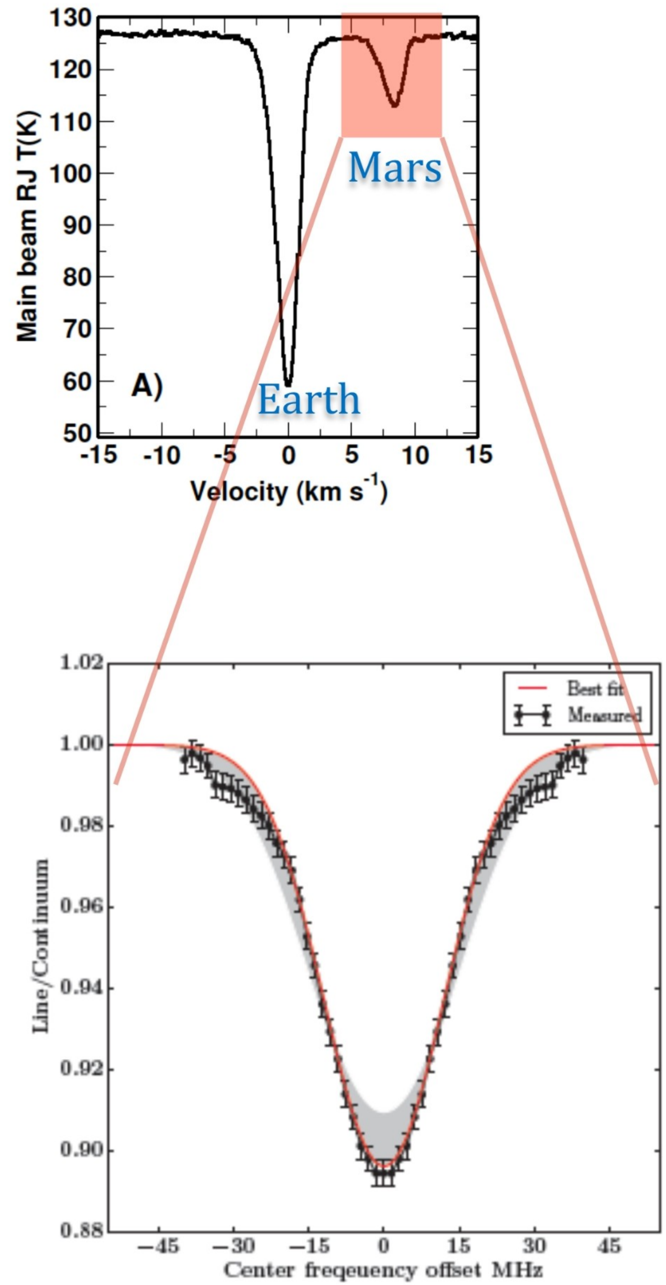
GREAT



The line luminosity at high velocities can be used as tracer of the mass-loss rate of the jet since [OI] is the main coolant of the gas in this velocity regime.

SOFIA Science Highlights: GREAT and OI

- Oxygen in Mars' atmosphere → Rezac et al. 2015
  - Oxygen column density
  - Compare with models (photo-chemical, GCM)
  - Monitoring: time variability



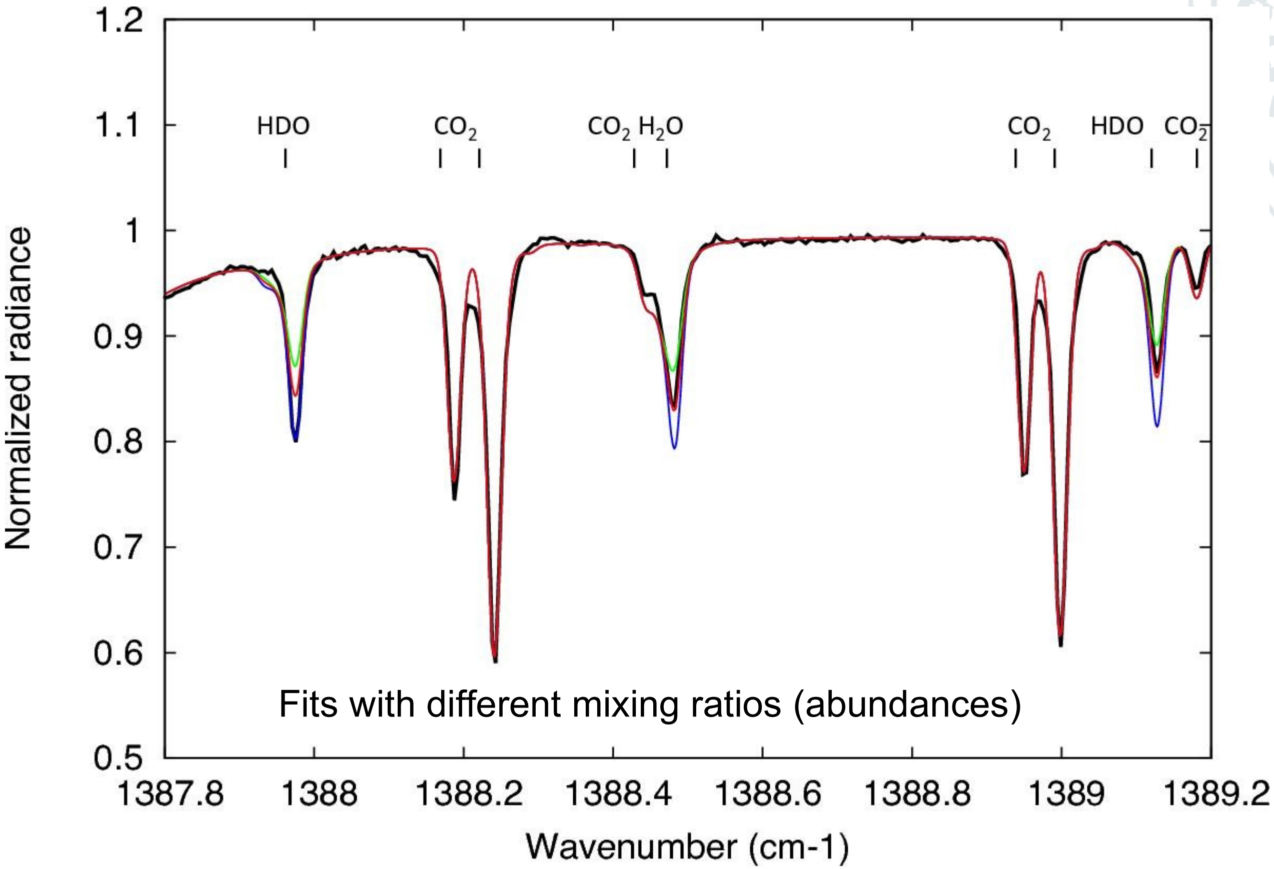
SOFIA Science Highlights: Wrap-up

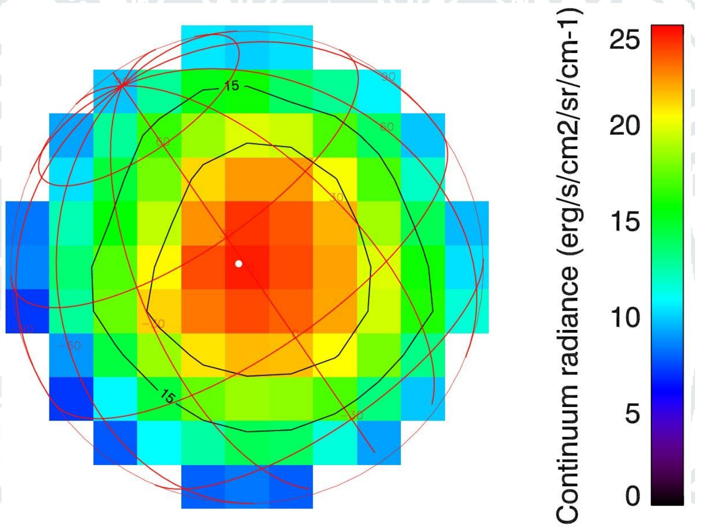
- Developments
  - Progress due to steady improvement and upgrade of the instruments
    - Extragalactic observations (LMC, SMC, M51, M33, ...)
    - Large and joint impact proposals: Orion, Gal. Center, M51 for GREAT/FIFI-LS
    - 4.7 THz array (HFA) for GREAT, commissioning in late 2016
    - Extended frequency coverage of GREAT
      - LFA: 1.8 – 2.5 THz (e.g., 145 micron [OI] line), commissioning in late 2016
      - 4GREAT: single pixels at 4 lower frequencies, absorption studies, planned for 2017
    - HAWC+ commissioning
  - Third generation instrument selected:
    High Resolution Mid-InfrarEd Spectrometer (HIRMES), PI H. Moseley, NASA Goddard.
    Spectroscopy of protoplanetary disks at wavelengths between 28 and 112 microns.
- Lots of exciting ISM science has been done and is foreseen to be done with SOFIA
  - Great variety of studies in continuum and spectroscopy
  - Many are (and will be) only doable with SOFIA

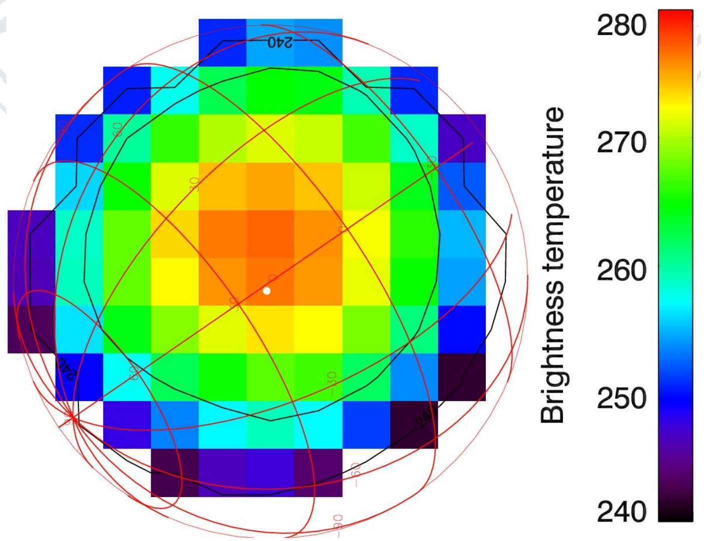
SOFIA Science Highlights: EXES Echelon-Cross-Echelle Spectrograph

- Mars 7.2 µm continuum
  Martian surface temperature from Global Climate Model
- Disk integrated spectra + abundance modelling
  - D/H ratio
    History of water on Mars
    Sources and sinks of water

Encrenaz et al. 2016

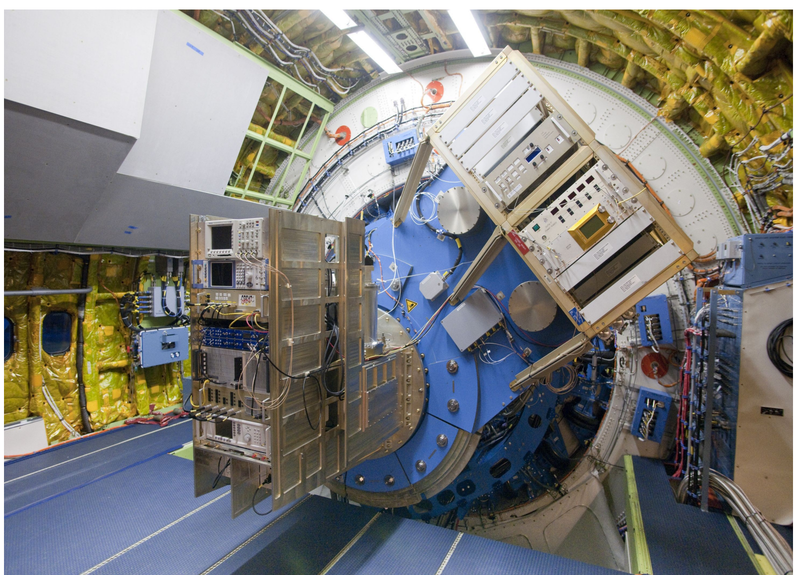






(up)GREAT (German Receiver for Astronomy at THz Frequencies)

- Principle Investigator instrument – funded, developed, and operated by
  - MPI für Radioastronomie, Bonn
  - Universität zu Köln, KOSMA
  - DLR Planetenforschung, Berlin
  - MPI Sonnensystemforschung, Göttingen
- Available to SOFIA communities in collaboration with the GREAT consortium
- Operation in service mode only



NZ deployment 2015

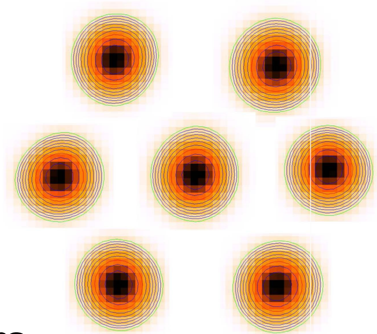
SOFIA statistics

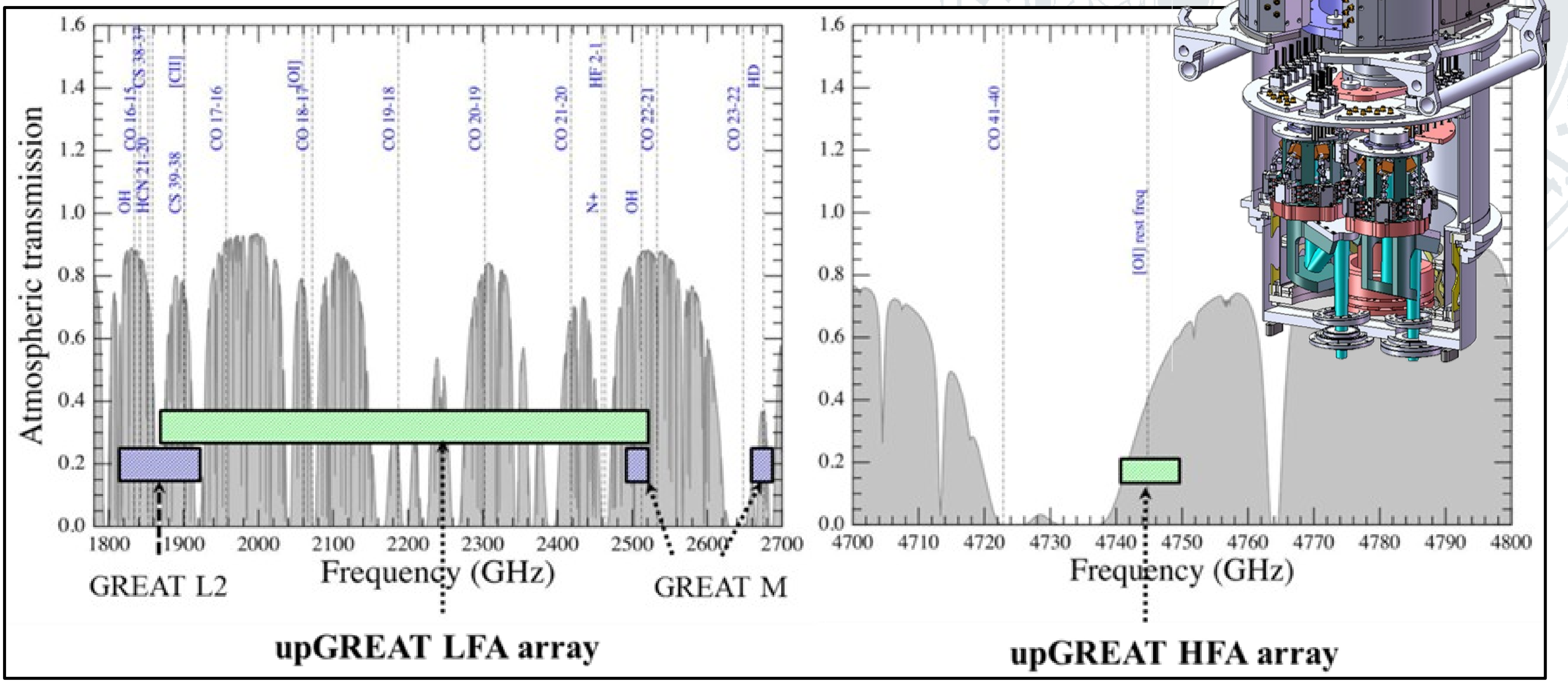
	Basic Science	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Release date	04/19/2010	11/21/2011	04/29/2013	05/23/2014	05/01/2015	04/29/2016
Instruments offered	FORCAST GREAT	FORCAST GREAT FLITECAM HIPO	FORCAST GREAT FLITECAM HIPO EXES FIFI-LS	FORCAST GREAT FLITECAM HIPO EXES FIFI-LS	FORCAST GREAT FLITECAM HIPO EXES FIFI-LS HAWC+	FORCAST GREAT FLITECAM EXES FIFI-LS HAWC+ FPI+
US hours offered	75	200	175	450	500	476
German hours offered	24	48	47	45	80	75
US proposals received	59	133	90	122	156	179
German proposals received	22	39	22	32	31	27
US hours requested Oversubscr.	270 4	1269 6	548 3	1075 2.5	1924 4	1750 4
German hours req. Oversubscr.	56 2.5	186 4	88 2	104 2.5	303 4	224 3

Courtesy of A. Krabbe & B. Reach

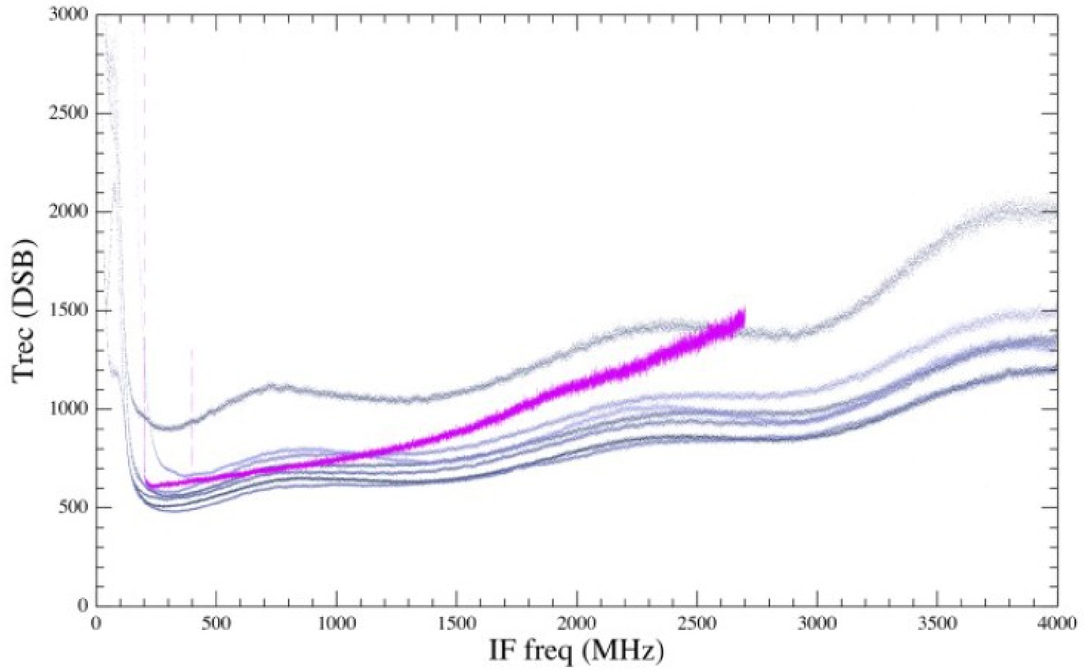
upGREAT: GREAT multiplexed

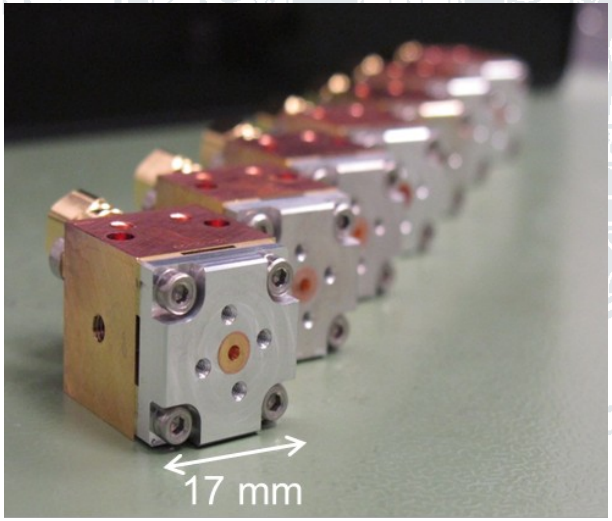
- 2 hexagonal arrays, operating in parallel
  - 2 x 7 low freq. Pixels (LFA)
  - 1 x 7 high freq. Pixels (HFA)
  - Or combinations with GREAT single pixel detectors





- Novel mixers
  - Waveguide-based HEB NbN devices on thin Si membrane (KOSMA) for better noise and bandwidth, LO coupling by beam splitter single LO source per polarization, distribution via phase grating





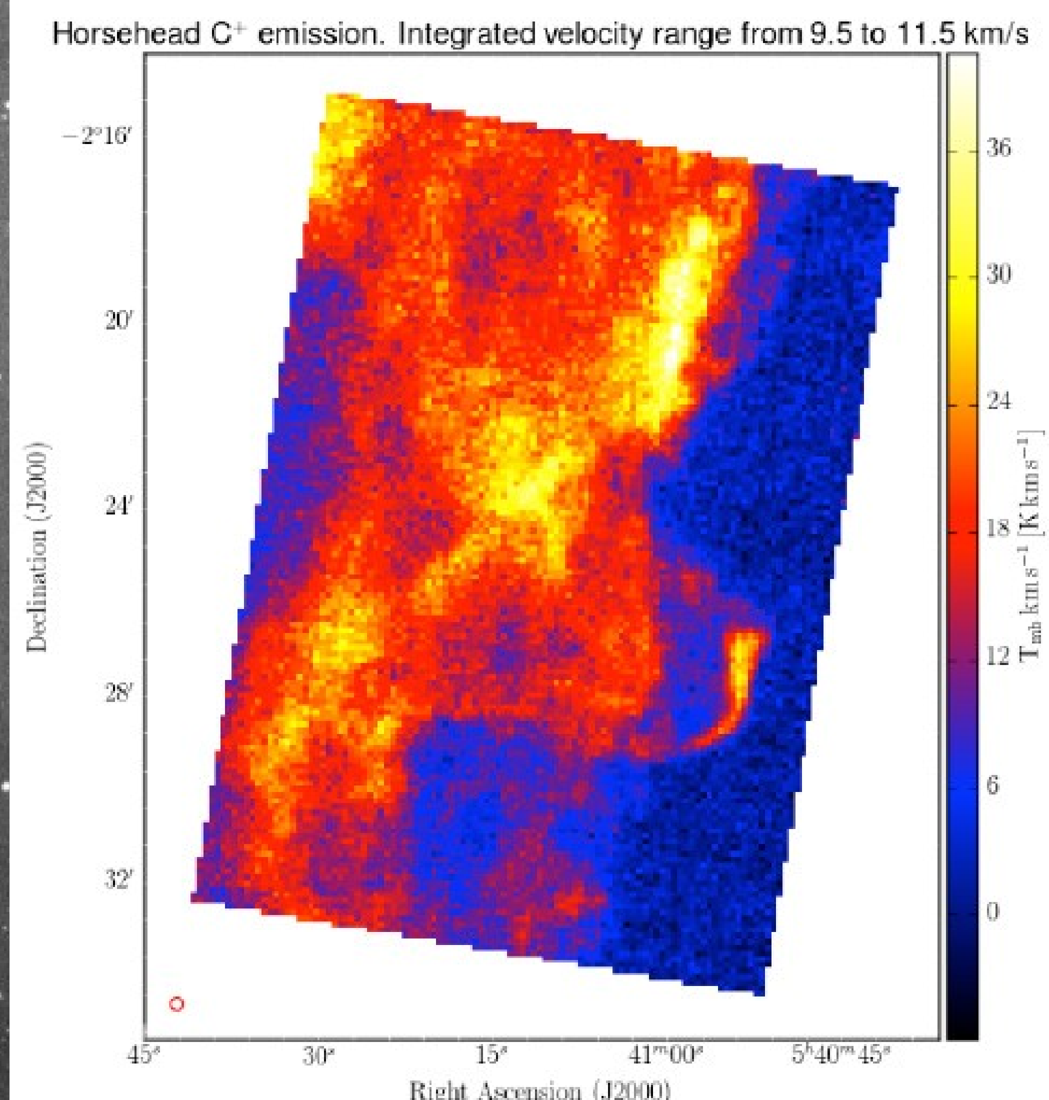
Uncorrected in-flight LFA receiver temperatures. For comparison, the L2 single-channel performance is shown, with its much faster IF roll-off.

SOFIA Science Highlights: GREAT conclusions

- [CII] and [OI] are the main coolants for PDR gas
  - [CII]+[OI] to FIR continuum cooling (measure of gas heating efficiency) between $10^{-4.5}$ – 10^{-2}
  - [CII] emission from dense PDRs (~45%), with smaller contributions from CO-dark H_2 gas (~30%), cold atomic gas (~20%), and ionized gas (~5%)
  - A lot of [CII] at velocities far from the cloud velocity, no high density counterpart → large scale flows and photo-evaporation
  - Large fraction of gas only seen in [CII]
  - [OI] and [CII] often show high optical depths in many sources indication for substantial density and radiation field
  - Full information on gas reservoir only from velocity resolved observations of many species: CO, CI, CII, OI, OH, and OH+

SOFIA Science Highlights: GREAT and emission lines

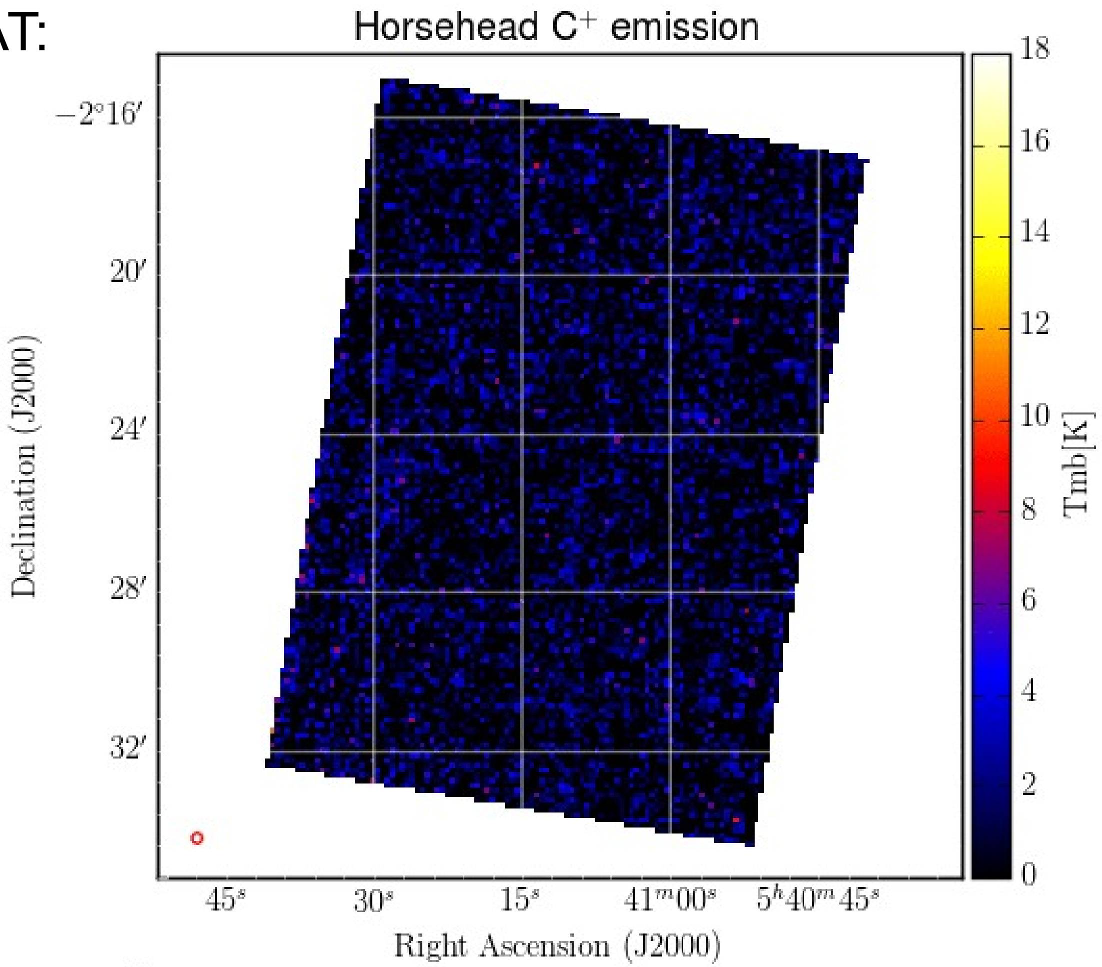
- The Horsehead PDR with upGREAT: 4 hours director's discr. time

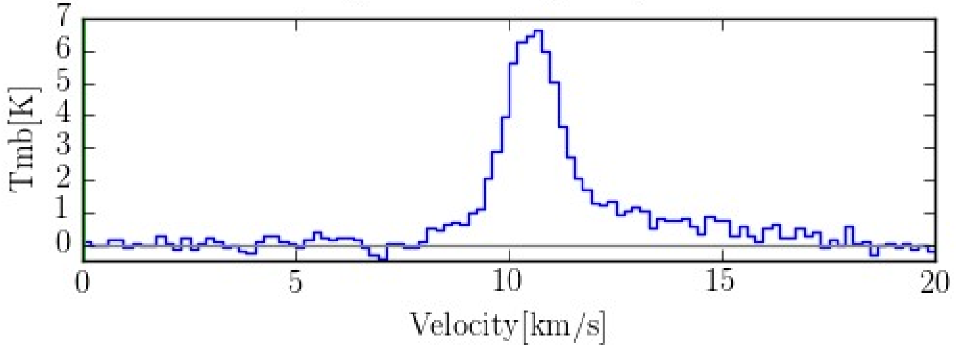


SOFIA Science Highlights: GREAT and emission lines

- The Horsehead PDR with upGREAT: velocity channel maps
- Large scale [CII] mapping
  - Joint impact programs
    - Orion
    - Galactic Center
    - M51

→ SOFIA splinter Talk on first results for M51 (M. Ziebart)





SOFIA Science Highlights: GREAT and absorption lines

- Detection of 2.5 THz OH absorption

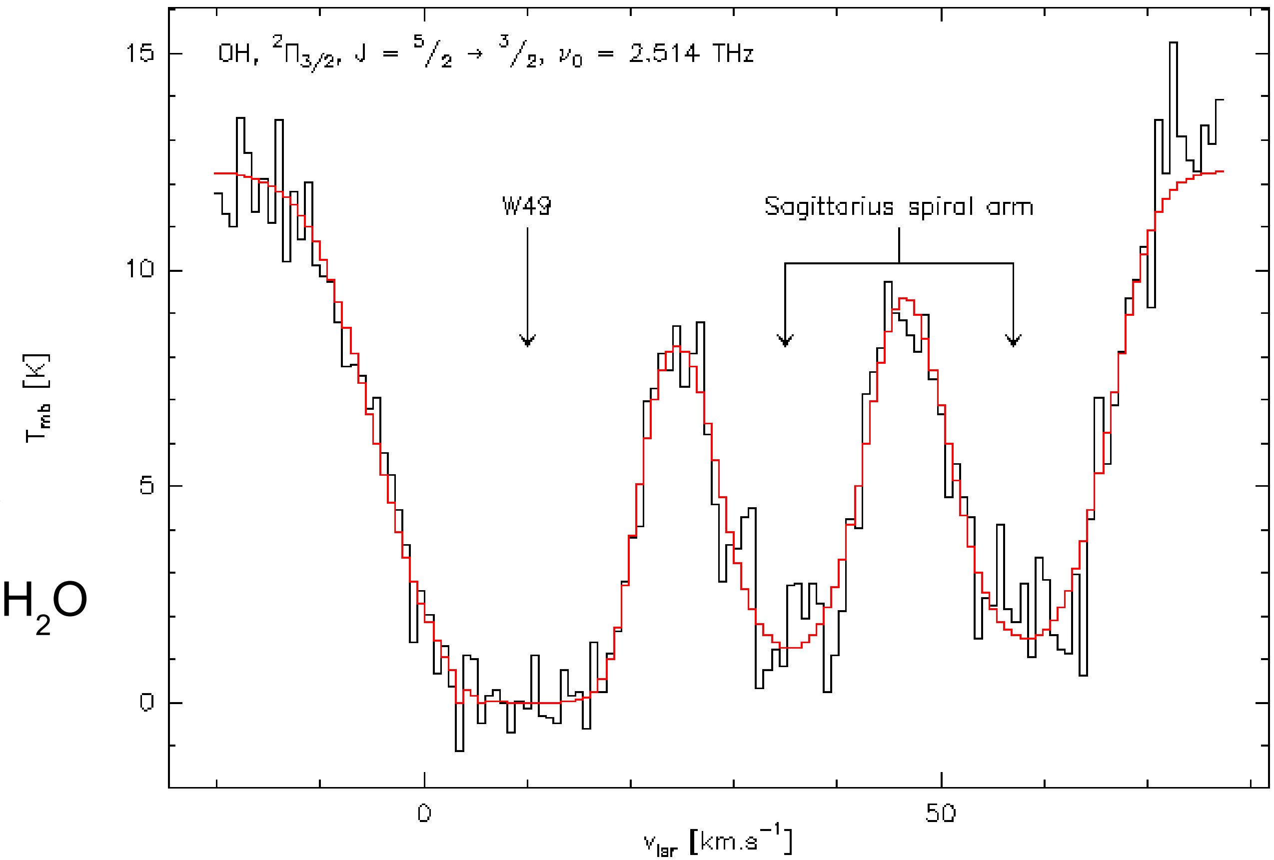
  - First >2 THz spectrum from SOFIA

    Discovery of ^{18}OH towards W49N core

    OH/OH^+ trace molecular/atomic diffuse gas

    Close correlation of OH and H_2O
    Chemical modelling

    Wiesemeyer et al. 2012

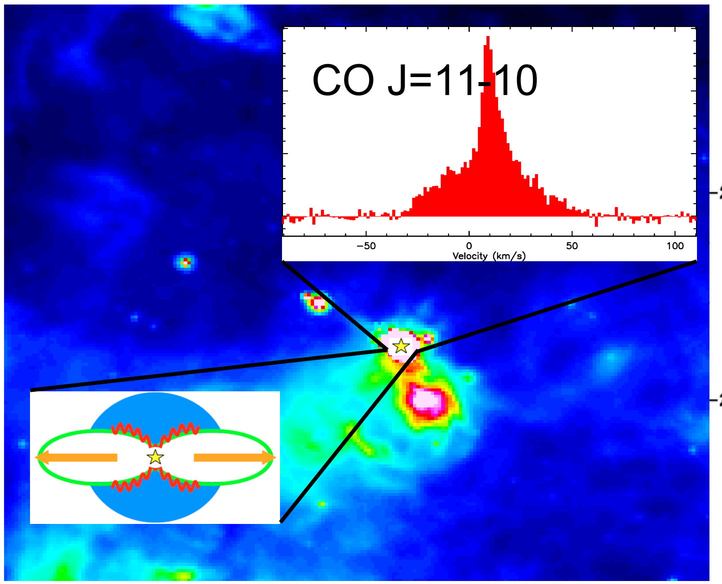


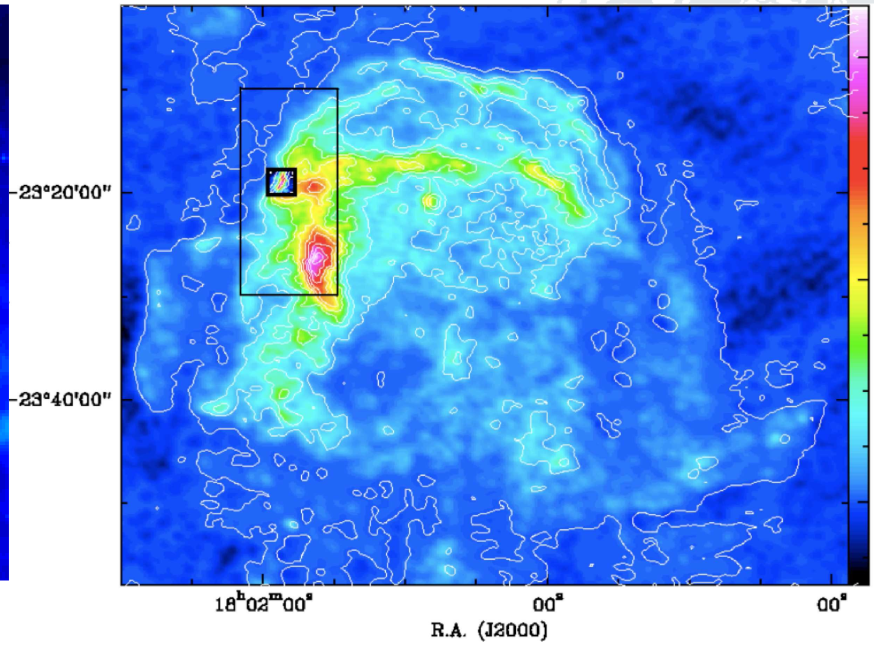
→ SOFIA splinter Talk on tracers of oxygen chemistry in diffuse clouds

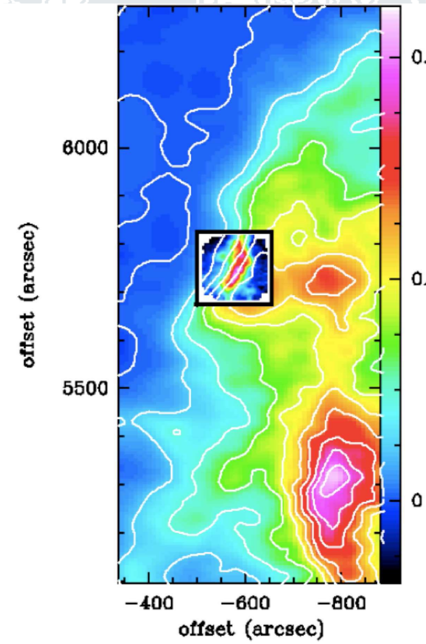
- High-J CO lines

Outflows: G5.89

MHD shocks: SNR W28





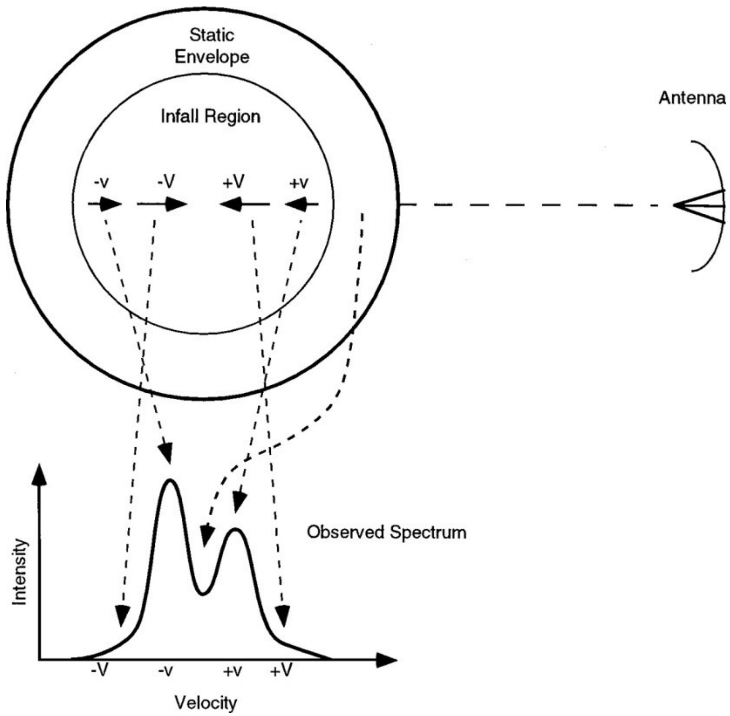


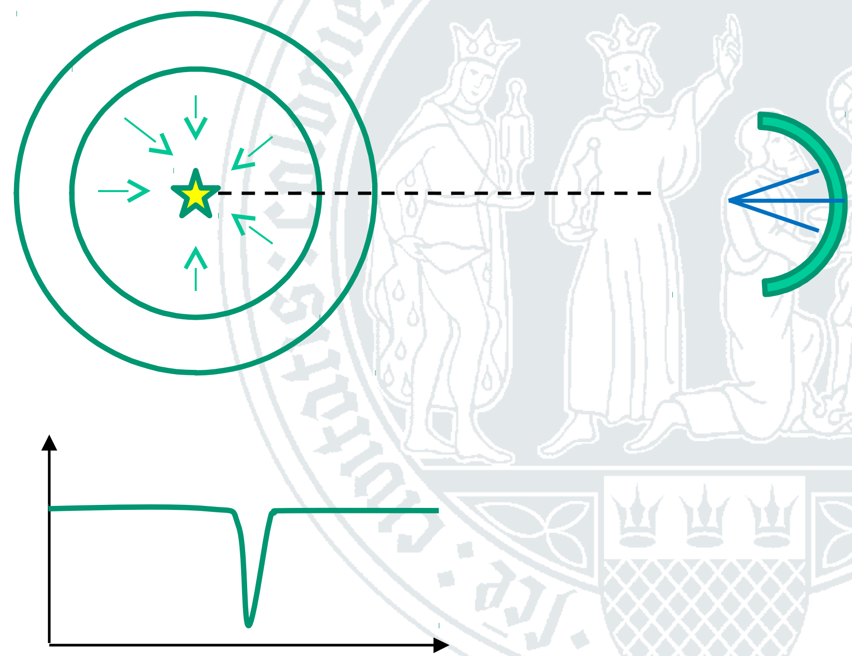
Background: IRAC 8 µm
Güsten and Gusdorf et al.

327 MHz cont.

Box: CO 6-5

Feedback: Interaction of high velocity/shocked CO with the cloud





Absorption measurements against a FIR continuum source are much more straight forward to interpret.

Infall ("collapse") is the Holy Grail of star formation, and SOFIA THz absorption allows us to measure the gas infall rate ("accretion rate").

Interpretation of infall using optically thin emission lines is difficult, due to complicated radiative transfer and possible contributions from outflowing molecular gas.