Herschel – SOFIA complementarity & differences

Hans Zinnecker
Deutsches SOFIA Institut
Univ. Stuttgart and NASA-Ames (retired)
& Universidad Autonoma de Chile

May 14, 2019
Herschel10@ESAC

Forthcoming Meetings of Interest

- Exploring the Infrared Universe: the promise of SPICA (May 20-23, 2019), Crete/Greece
- Astrochemistry – a symposium honoring John Black (June 24-28, 2019), Gothenburg
- German Astronomical Society Meeting (AG) in Stuttgart (Sept 16-20, 2019), SOFIA plane visit
- ALMA2019: science results and cross-facility synergies (October 14-18, 2019), Cagliari/Italy

Outline of this talk

- Basic facts about SOFIA (see also poster)
- Herschel vs. SOFIA instrument comparison
- SOFIA observations that Herschel could not do (incl. specific examples)
- Take-home message:
  Herschel community while waiting for SPICA should turn their attention to SOFIA and apply for SOFIA time (only FIR obs for years to come).
  At high spectral resolution, SOFIA performance at 40000+ ft exceeds that of Herschel in space.

Hans, SOFIA SMO DD (2010-2016)

Herschel ran out of cryogen in 4/2013, about when SOFIA reached full operational capability

2014: SOFIA development phase → operations phase
equivalent to “launch”

http://www.sofia.usra.edu

SOFIA has completed Cycle 6 observations (~100 flights/year)
now Cycle 7 observations, Cycle 8 proposals Sept 2019

Herschel 3.5 meter Space Observatory (2009-2013)

Three highly successful far-infrared Instruments:

- HIFI heterodyne spectrometer (PI Th. DeGrauuw, 480-1250 GHz and 1410-1910 GHz, single pixel)
- PACS integral field spectrometer (PI: A. Poglitsch; 60-210 micron, blue and red channel, R = 2000)
- SPIRE spectral & photometric imaging receiver (PI: M. Griffin; FTS R=1000 & direct detection bolometer at 250, 350, 500 mu, i.e. 3 FIR bands)

1/3 in guaranteed time (WISH, Prismas, HEXOS, GB-survey, PEP, etc)
1/3 in 21 open time key programmes OTKP (Hi-Gal, HOPS, DIGIT, etc)
The remaining 1/3 in individual open time, very different from SOFIA
Herschel Archive: > 20,000 hours observing time (to be exploited …)

SOFIA's Instrument Complement

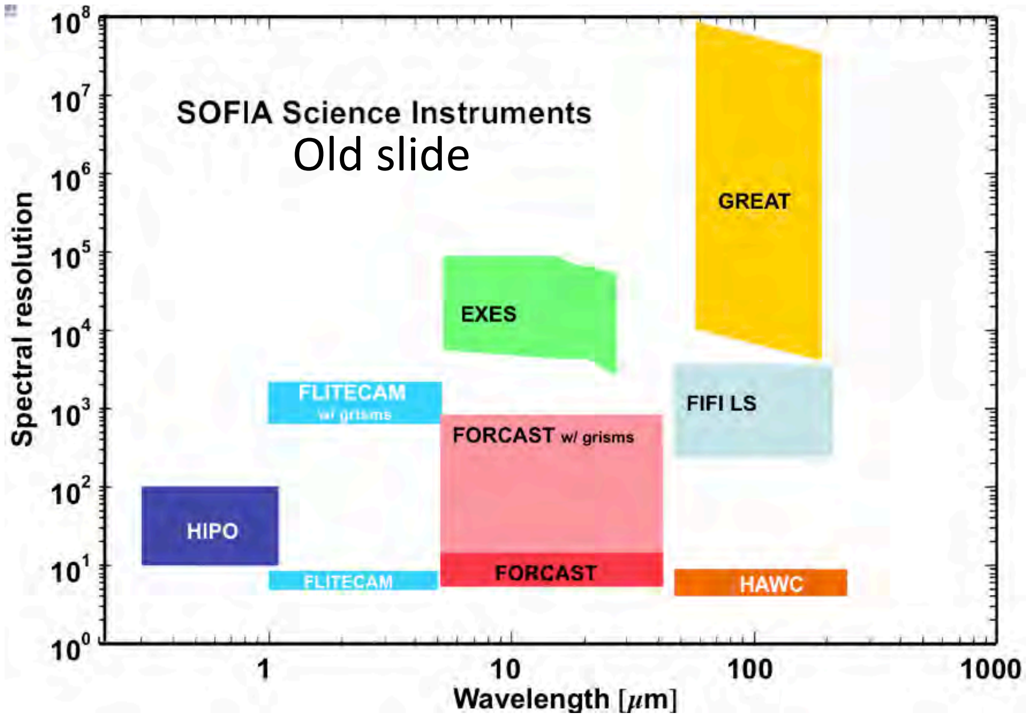
As an airborne mission, SOFIA supports a unique suite of instr.

- FORCAST
- GREAT, upGREAT (LFA/HFA), 4GREAT
- FIFI-LS
- FLITECAM (NIR, now retired)
- EXES
- FPI+ (opt/NIR guide camera)

- HAWC+ (2nd gen, polarimetry)

- 3rd gen instrument selection
- (HIRMES, 25-122 microns)

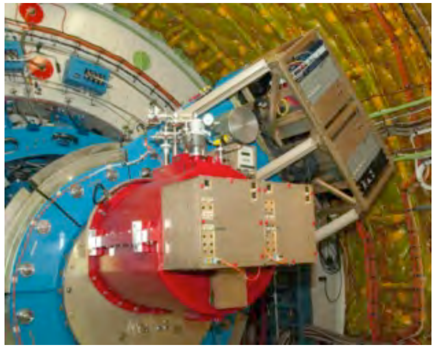
- SOFIA will take full advantage of improvements in instrument technology. The plan is one new instrument or major upgrade per year.



SOFIA: Wide Range of Interchangeable Instruments Available

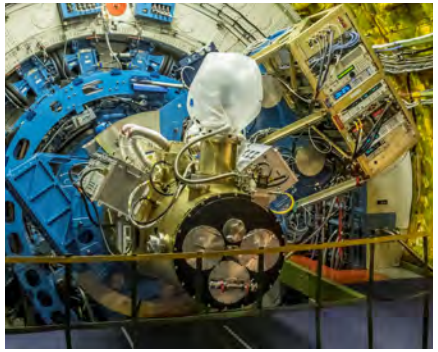
FPI+
Focal Plane
Imager

λ = 0.36–1.10 µm
R = 0.9–29.0



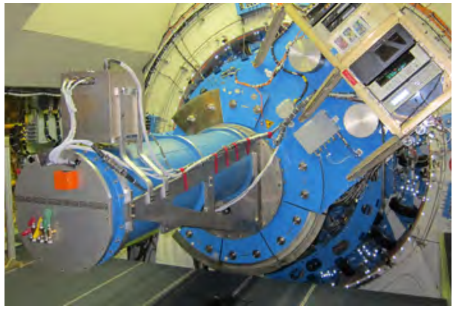
FORCAST
Faint Object Infrared
Camera for the SOFIA
Telescope

λ = 5–40 µm
R = 100–300
Grism Spectrometer



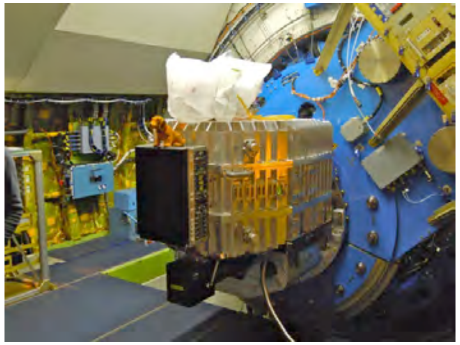
HAWC+
High-resolution
Airborne Wideband
Camera Plus

λ = 50–240 µm
R = 2.3–8.8
Far Infrared Camera
& Polarimeter



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

GREAT
German Receiver for Astronomy
at Terahertz Frequencies

λ = 63–612 µm
R = $10^6–10^8$
Heterodyne Spectrometer

SOFIA First Light Flight (Dec 2010)

What SOFIA can do for you ...

- mid-IR & far-IR imaging (FORCAST, HAWC+)
- far-IR spectroscopy (FIFI-LS, GREAT/upGREAT)

- far-IR dust continuum polarimetry (HAWC+)
- mid-IR high-resolution spectroscopy (EXES)

- Follow-on Spitzer & Herschel (saturation, frq gaps)
- synergy with ALMA/APEX/NOEMA (submm vs FIR)

PS. Recently (as of Cycle 7) SOFIA Legacy programmes (100 hr) were introduced

Herschel-SOFIA instrument comparison

- Basic instruments similar (also similar diff. limited spatial res.) HIFI → GREAT, PACS → FIFI-LS, SPIRE → HAWC+
- But SOFIA has additional instruments: FORCAST (Spitzer), EXES (JWST-MIRI), HAWC+ FIR-pol (between Planck & ALMA)
- Herschel had no FIR polarimetric facility, while SOFIA does (SPICA, too – see Roelftsema talk yesterday)
- Herschel HIFI single pixel, while SOFIA has multi pixel upGREAT LFA/HFA arrays (14 and 7 pixels) - allows dual channel mapping
- Herschel HIFI had a frequency gap (1.25-1.41 THz) and cannot go beyond 1.9 THz ([CII]), SOFIA filled the gap (with discoveries) and can tune to 2.0 THz (HeH+), 2.5 THz (OH), and 4.7 THz ([OI])
- Herschel PACs blue/red channel not independent, unlike SOFIA's FIFI-LS. FIFI-LS less sensitive, but mapping speed higher

SOFIA can take advantage of more recent detector and array technology (newest instrument HIRMES will study HD 1-0, 2-1)

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 (NZ)
- ~ 120 flights per year (goal) in full operation, ~250 staff.
- ~ 20 year projected lifetime, international observatory

KAO - SOFIA's predecessor (1974-1995)

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 40,000 ft -- can observe most of the infrared universe**
- **Airborne infrared telescopes can be more versatile -- and less expensive than space infrared telescopes**

What is SOFIA's science mission?

SOFIA is a primarily mid/far-IR Observatory for studying interstellar matter cycle + feedback processes:

-atomic/molecular gas spectroscopy (high spectral res.)

collapse, outflows, disks, shocks / heating, cooling, PDR

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

mid-IR/far-IR sources, PAH spectroscopy, magn fields

ASTROPHYSICS → dynamics, FS line cooling (eg. C+)

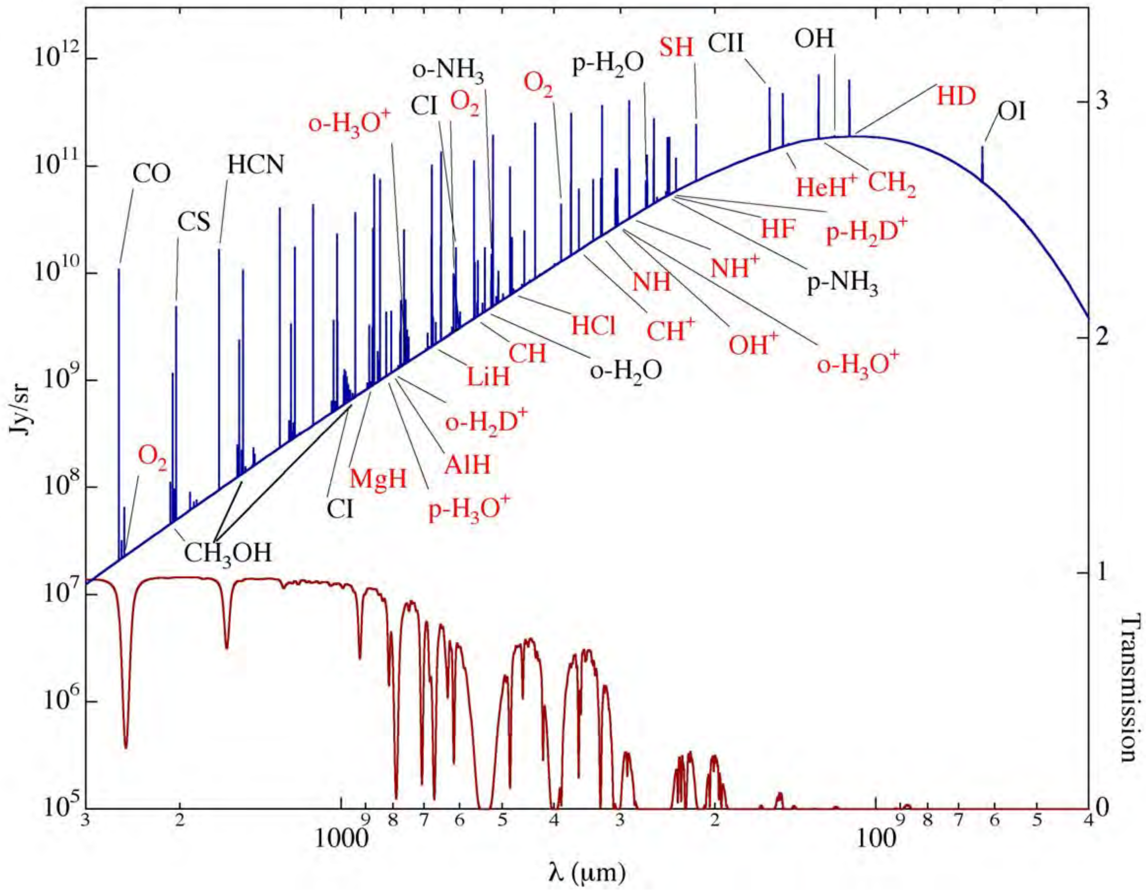
ASTROCHEMISTRY→ molecules, fractionation (H2D+)

Follow-up of IRAS, ISO, Spitzer and Herschel observations

Importance of Far IR / Sub-mm

- Most of the key atomic/ionic and molecular tracers of the InterstellarMedium are in the far-infrared and sub-mm regime
- SH, OH, OD, HD
- o-NH3, p-H2D+
- [CII], [OI], [OIII], [NII]

Molecular Cloud SED



Ted Bergin, 2008

Nature, April 2019

Astrophysical detection of the helium hydride ion HeH^+

The first molecule in the universe

Rolf Güsten[1*], Helmut Wiesemeyer[1], David Neufeld[2], Karl M. Menten[1], Urs U. Graf[3], Karl Jacobs[3], Bernd Klein[1,4], Oliver Ricken[1], Christophe Risacher[1,5] & Jürgen Stutzki[3]

During the dawn of chemistry[1,2], when the temperature of the young Universe had fallen below some 4,000 kelvin, the ions of the light elements produced in Big Bang nucleosynthesis recombined in reverse order of their ionization potential. With their higher ionization potentials, the helium ions He^{2+} and He^+ were the first to combine with free electrons, forming the first neutral atoms; the recombination of hydrogen followed. In this metal-free and low-density environment, neutral helium atoms formed the Universe's first molecular bond in the helium hydride ion HeH^+ through radiative association with protons. As recombination progressed, the destruction of HeH^+ created a path to the formation of molecular hydrogen. Despite its unquestioned importance in the evolution of the early Universe, the HeH^+ ion has so far eluded unequivocal detection in interstellar space. In the laboratory the ion was discovered[3] as long ago as 1925, but only in the late 1970s was the possibility that HeH^+ might exist in local astrophysical plasmas discussed[4–7]. In particular, the conditions in planetary nebulae were shown to be suitable for producing potentially detectable column densities of HeH^+. Here we report observations, based on advances in terahertz spectroscopy[8,9] and a high-altitude observatory[10], of the rotational ground-state transition of HeH^+ at a wavelength of 149.1 micrometres in the planetary nebula NGC 7027. This confirmation of the existence of HeH^+ in nearby interstellar space constrains our understanding of the chemical networks that control the formation of this molecular ion, in particular the rates of radiative association and dissociative recombination.

reaction networks[19,20] in local plasmas, and might ultimately invalidate present models of the early Universe.

The deployment of the German Receiver for Astronomy at Terahertz Frequencies (GREAT)[9] heterodyne spectrometer on board the Stratospheric Observatory for Infrared Astronomy (SOFIA)[10] has now opened up new opportunities. Although the HeH^+ $J=1$–0 transition at 149.137 μm (2010.183873 GHz; ref. [21]) cannot be observed from ground-based observatories, skies become transparent during high-altitude flights with SOFIA. The latest advances in terahertz technologies have enabled the operation of the high-resolution spectrometer upGREAT[22] at frequencies above 2 THz, allowing the HeH^+ $J=1$–0 line to be targeted. The resolving power of this heterodyne instrument, $\lambda/\Delta\lambda \approx 10^7$, permits the HeH^+ $J=1$–0 line to be distinguished unambiguously from other, nearby spectral features such as the CH Λ-doublet mentioned previously.

During three flights in May 2016, the telescope was pointed towards NGC 7027 (the total on-target integration time was 71 min). Weak emission in the HeH^+ $J=1$–0 line was clearly detected (Fig. 1), as was emission from the nearby CH doublet. Notably, the lines are well separated in frequency (Extended Data Fig. 1). The velocity profile of the HeH^+ line matches nicely that of the excited CO $J=11$–10 transition, which was observed in parallel. The velocity-integrated line brightness temperature, $\int T_{mb}\,dv = 3.6 \pm 0.7$ K km s^{-1}, corresponds to a line flux of 1.63×10^{-13} erg s^{-1} cm^{-2}. Because the 14.3″ half-power beam response of upGREAT includes most of the NGC 7027 ionized gas sphere, this result will be close to the total HeH^+ flux emitted in the $J=1$–0 line. The flux is

SOFIA Detection of HeH+ at 2.01 THz in NGC 7027

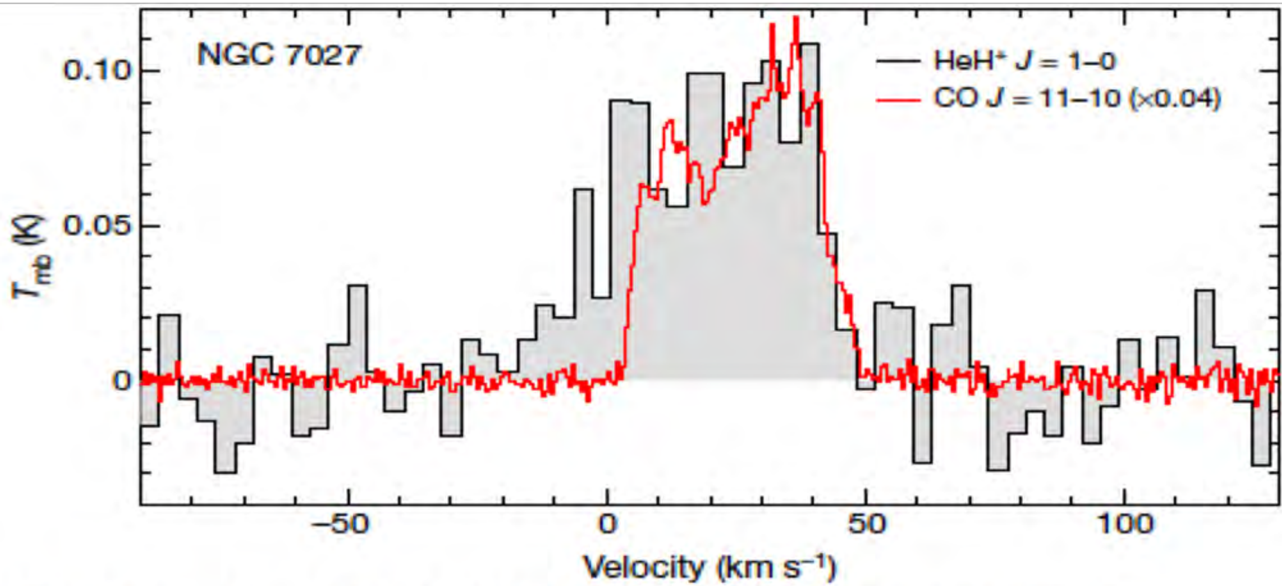
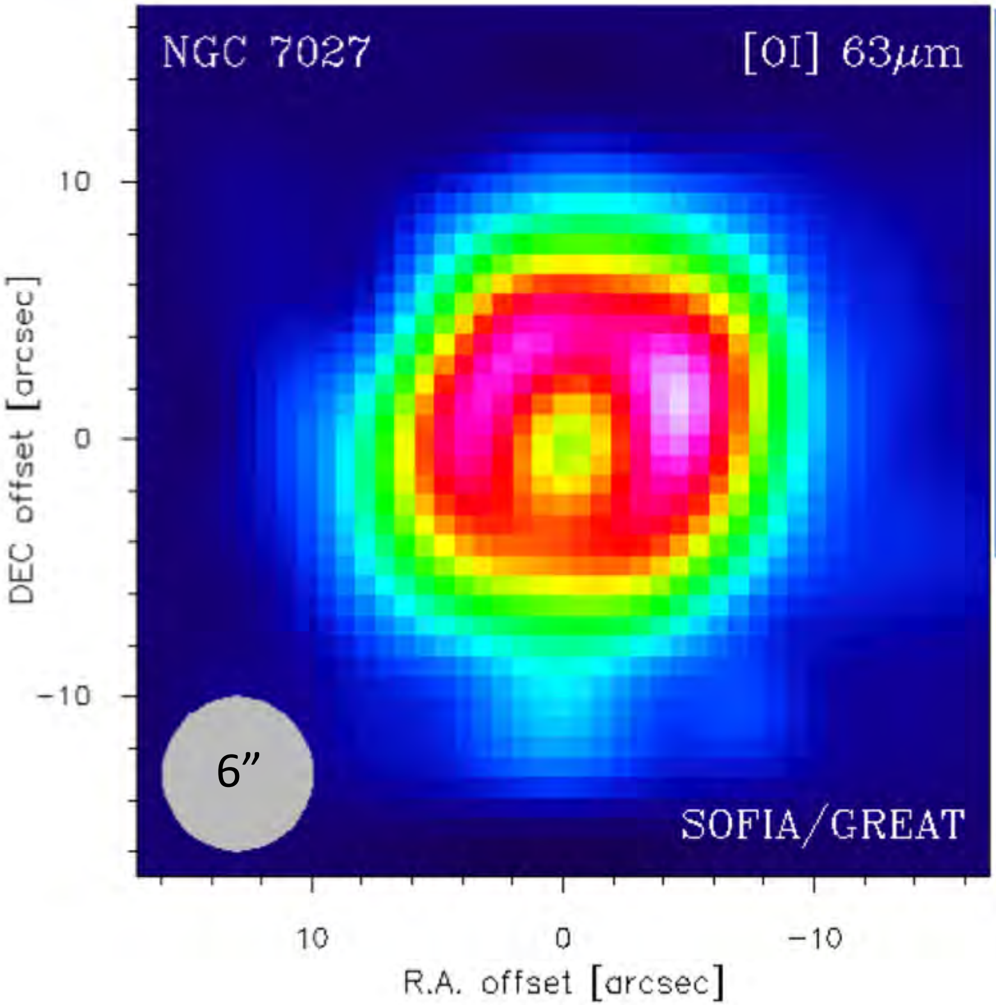
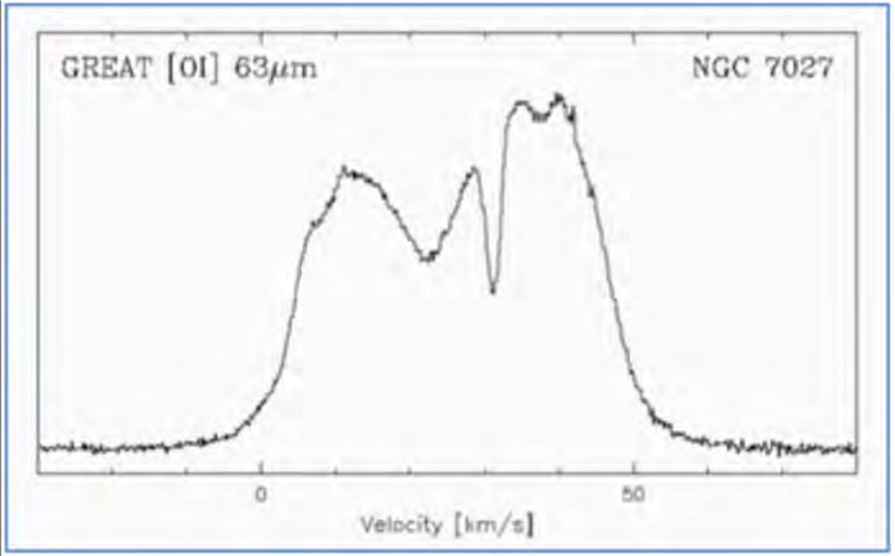


Fig. 1 | Spectrum of the HeH^+ $J = 1-0$ ground-state rotational transition, observed with upGREAT onboard SOFIA pointed towards NGC 7027. 'Contaminating' emission from the nearby but well separated CH Λ-doublet has been removed from the data (see Methods for details of data processing). The spectrum has been rebinned to a resolution of 3.6 km s^{-1} (24 MHz). For comparison, the CO $J = 11-10$ line is superimposed (at a spectral resolution of 0.58 km s^{-1}); this transition was observed in parallel and probes the dense inner edge of the molecular envelope near the ionization front from which the HeH^+ emission is expected to originate. T_{mb}, main-beam brightness temperature. The grey shading shows the area above and below the zero line for each spectral channel.

4.7 THz First Light ([OI] in NGC 7027) with SOFIA/GREAT (R=10^7)





(Tomography of a planetary nebula & the GREAT Team, perhaps unpublished)

SOFIA discoveries that Herschel could not make (1)

1.37 THz: SH, OD, p-H_2D^+ (GREAT)

2.0 THz: CH 1-0, HeH^+ (GREAT)

2.5 THz: OH g-state (GREAT)

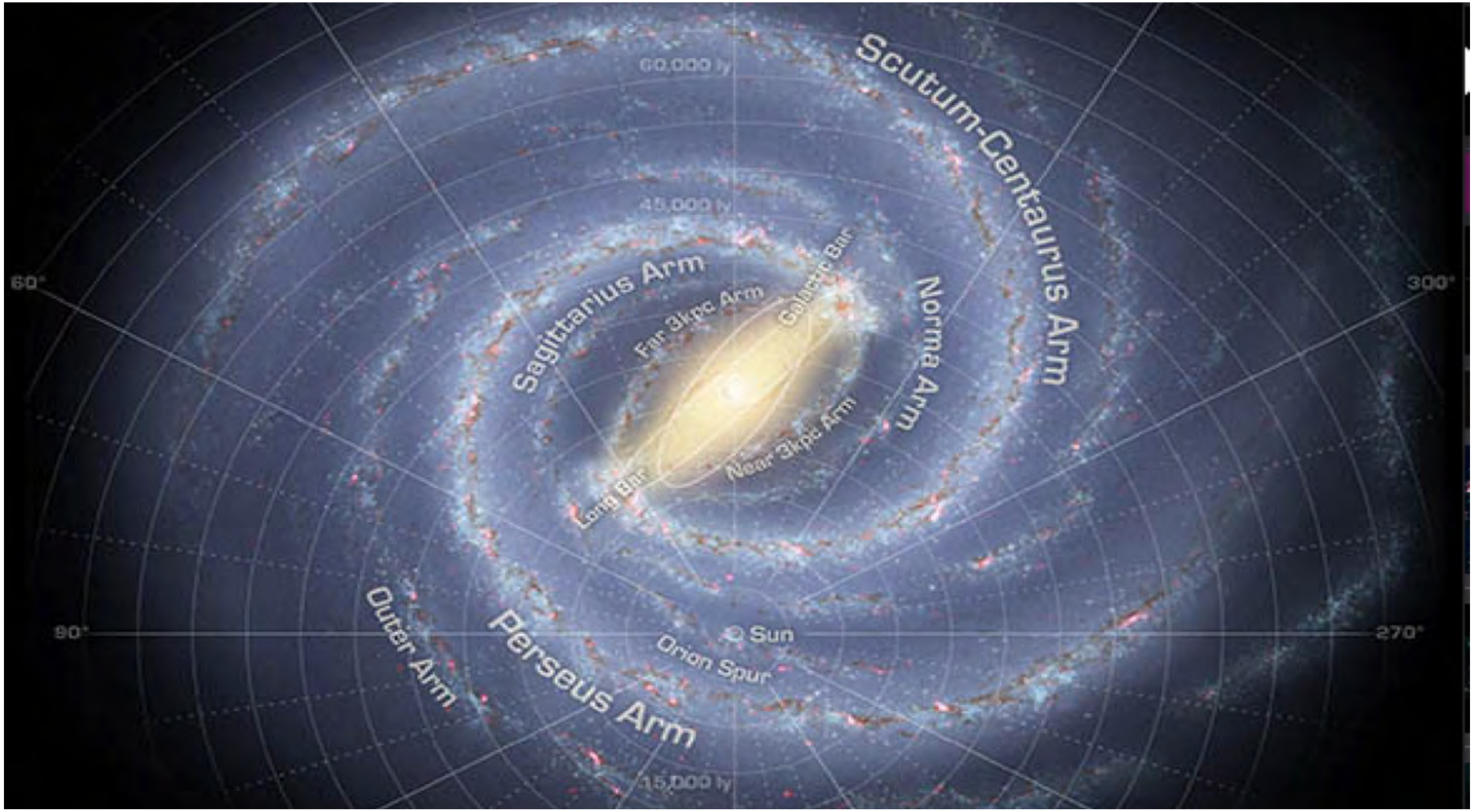
2.7 THz: HD 1-0 (GREAT)

4.7 THz: [OI] (GREAT)

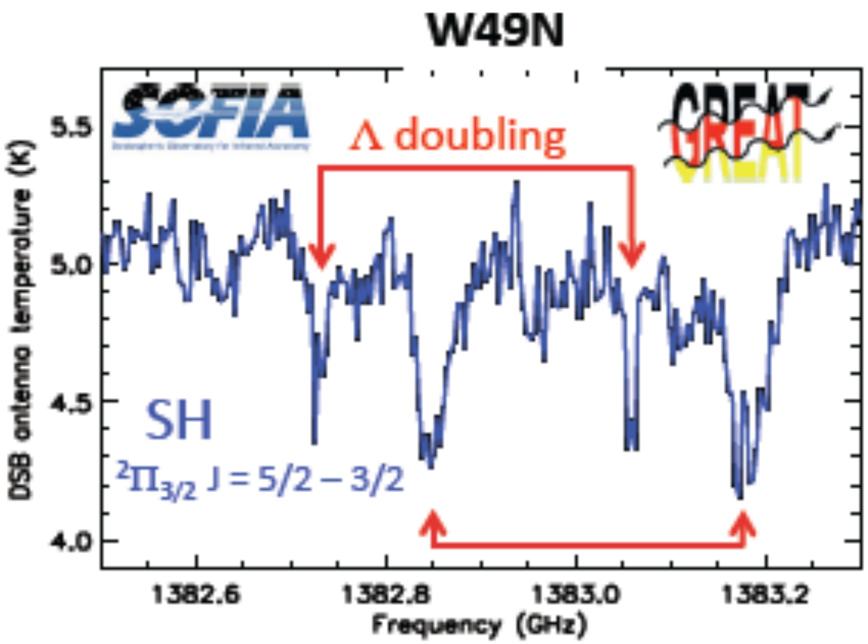
[CII], [OI] mapping (upGREAT)

1.81 THz: NH_3 3-2 (GREAT)

face-on view of our Milky Way Galaxy

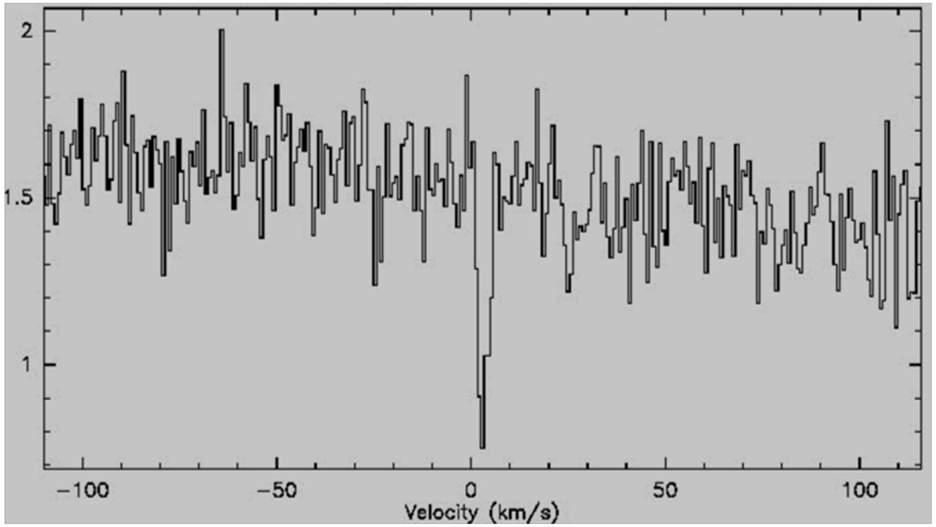


Early science highlights: new molecules in space



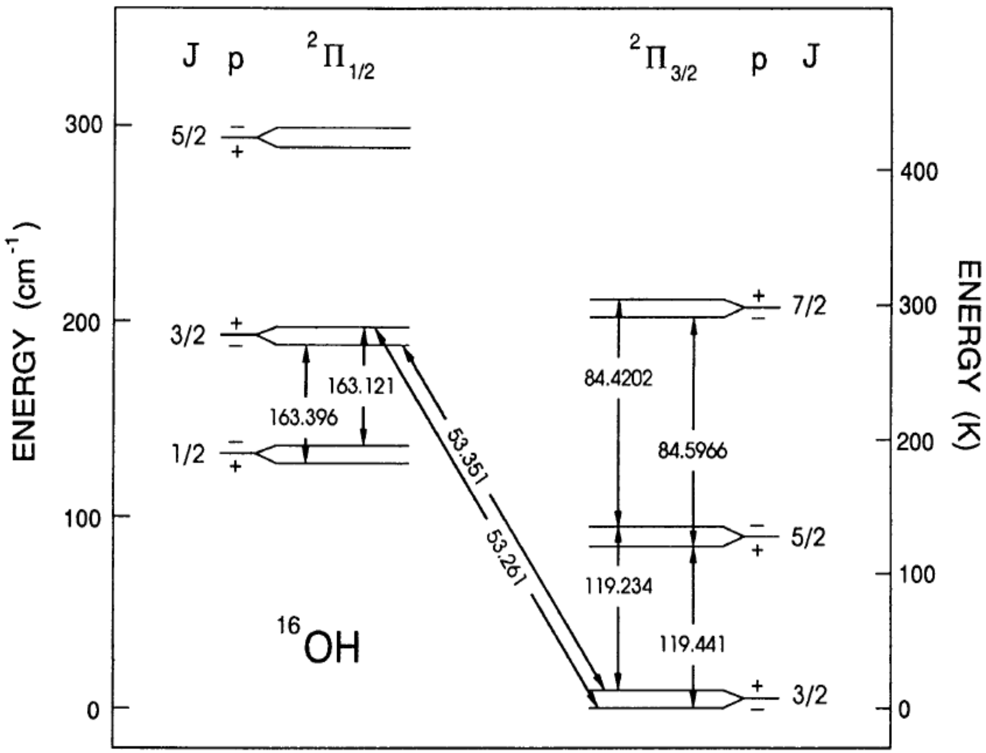
Neufeld 2012: discovery of interstellar mercapto radical in absorption against W49N.

SH is endothermic (9800 K): Evidence for warm chemistry



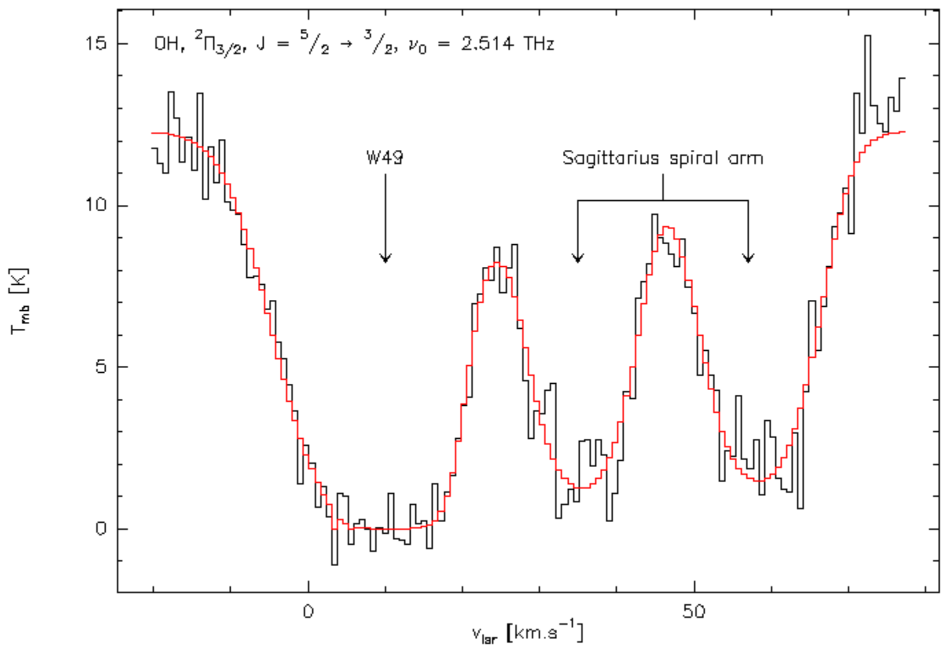
Parise 2012: beautiful detection of deuterated hydroxyl OD at 1.37THz towards the protostar IRAS1629A

GREAT SOFIA Science beyond Herschel: 2.5 THz **OH absorption**



First >2 THz spectroscopy from SOFIA

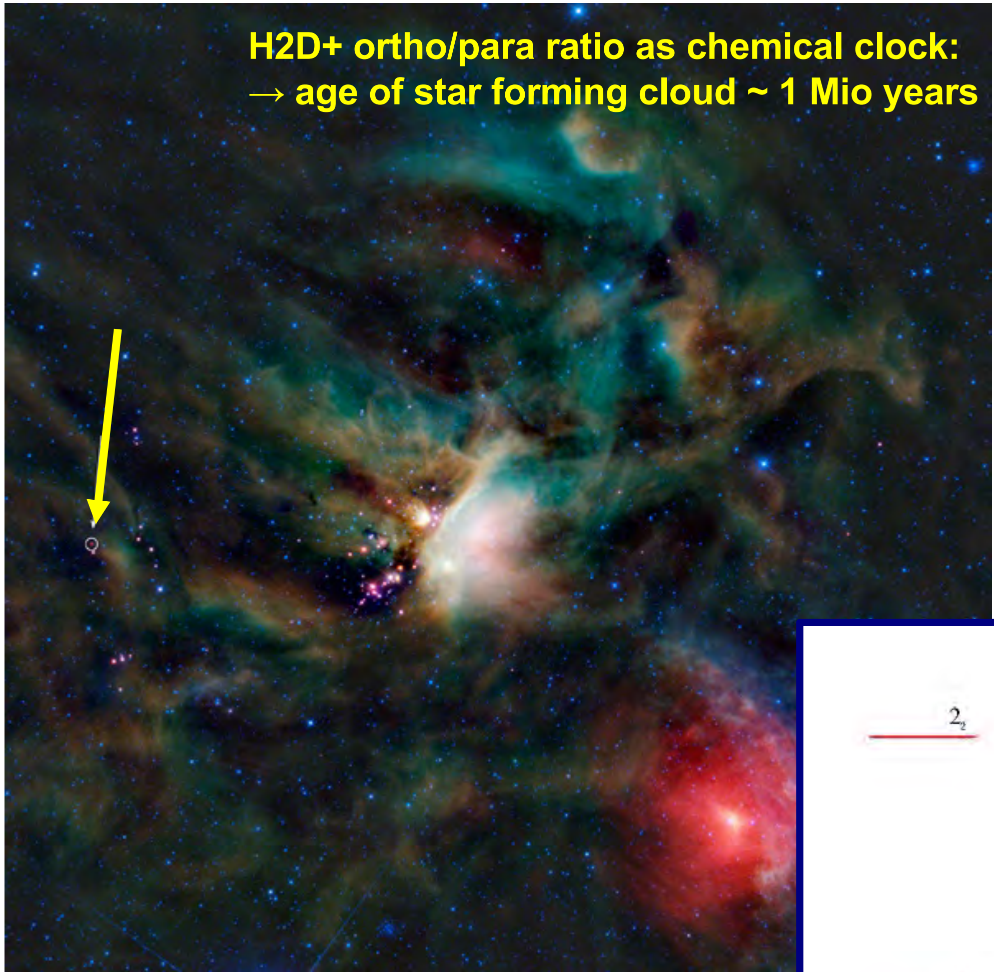
- OH ground-state absorption against W49N
- spectral features of Sagittarius spiral arm
- Optically thick, but 18OH optically thin
- possibility to study oxygen gas abundance

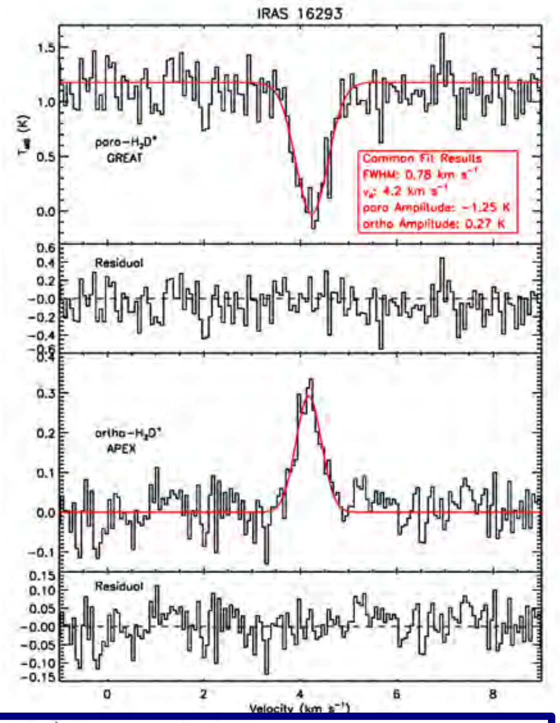


OH absorption towards W49N saturated

- discovery of ^{18}OH towards W49N core (Wiesemeyer et al. 2012, A&A 542, L7)

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

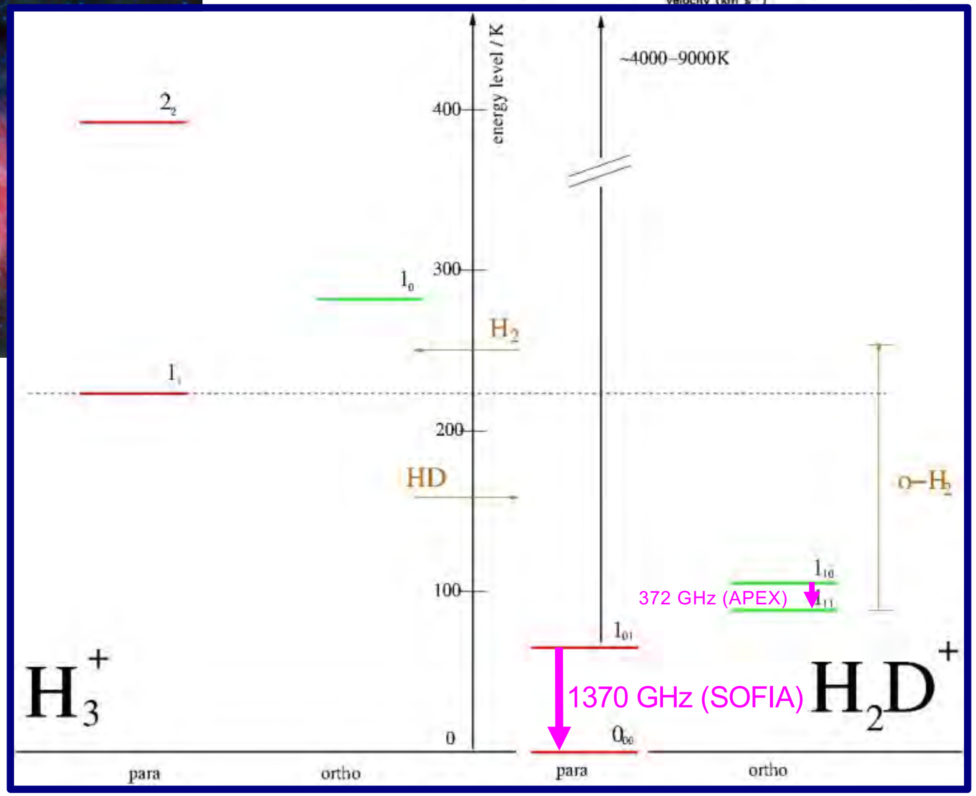




$$
\begin{aligned}
H + H &\xrightarrow{\text{dust}} H_2 \\
H + \mathrm{cr}/\gamma &\longrightarrow H^+ + e \\
C + \mathrm{cr}/\gamma &\longrightarrow C^+ + e \\
\\
H_2 + H^+ &\longrightarrow H_3^+ \\
&\longrightarrow H + H + H^+ \\
H_3^+ + HD &\longrightarrow H_2D^+ + H_2 \\
\\
H_2 + C^+ &\longrightarrow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

Nature paper:
Brünken et al, 2014

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



SOFIA discoveries that Herschel could not make (2)

52 mu in addition to 88 mu [OIII] (FIFI-LS)

Orion A, Gal. Ctr & 30 Dor, M82: dust pol (HAWC+)

expected future discoveries:

HD 1-0 (112 mu), 2-1 (56 mu)

In protoplanetary disks

with HIRMES

Astronomy Picture of the Day

Astronomy Picture of the Day

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

2019 February 27

Magnetic Orion
Image Credit & Copyright: NASA, SOFIA, D. Chuss et al. & ESO, M. McCaughrean et al.

Explanation: Can magnetism affect how stars form? Recent analysis of Orion data from the HAWC+ instrument on the airborne SOFIA observatory indicate that, at times, it can. HAWC+ is able to measure the polarization of far-infrared light which can reveal the alignment of dust grains by expansive ambient magnetic fields. In the featured image, these magnetic fields are shown as curvy lines superposed on an infrared image of the Orion Nebula taken by a Very Large Telescope in Chile. Orion's Kleinmann-Low Nebula is visible slightly to the upper right of the image center, while bright stars of the Trapezium cluster are visible just to the lower left of center. The Orion Nebula at about 1300 light years distant is the nearest major star formation region to the Sun.

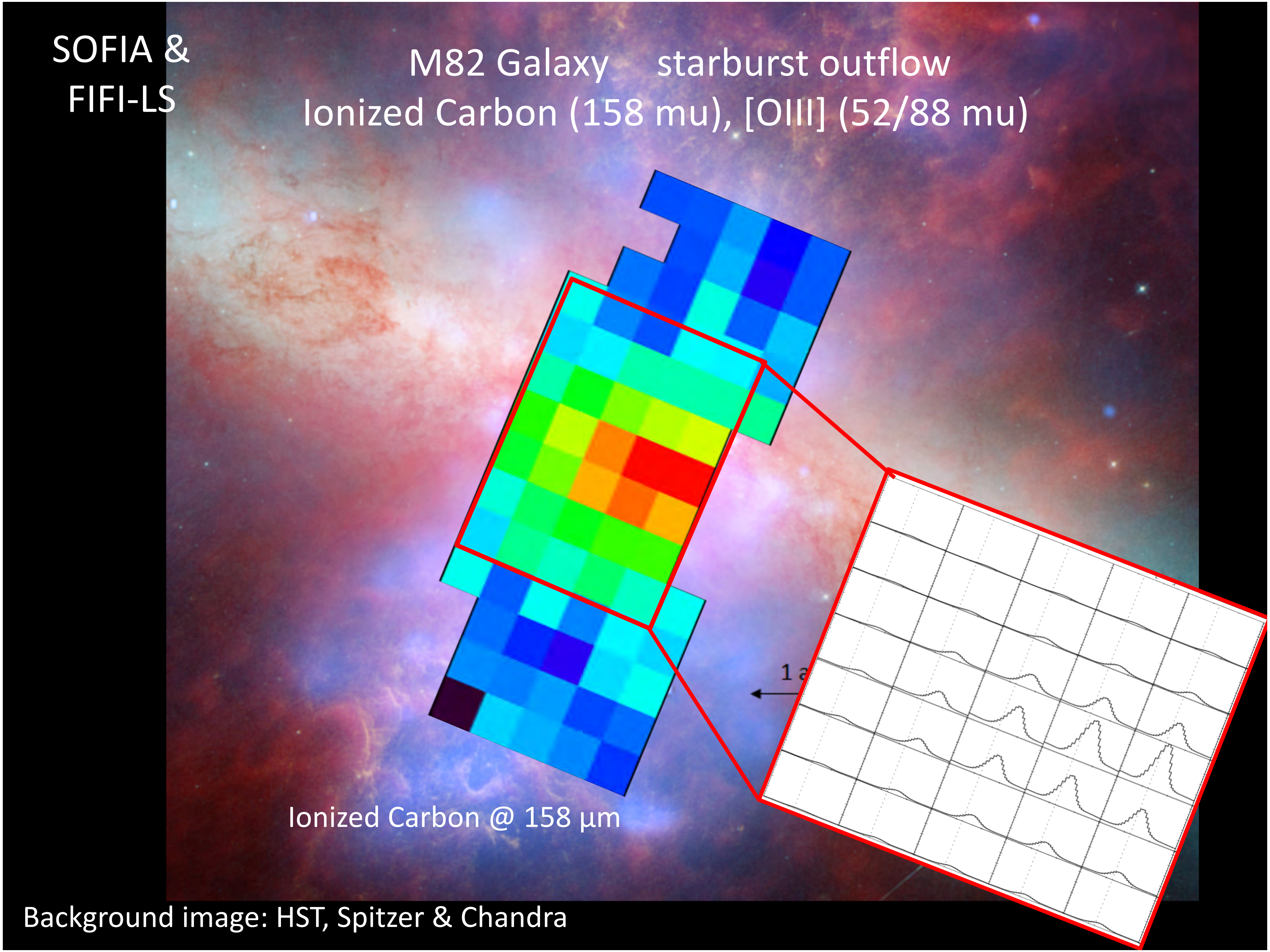
Astronomy Picture of the Day

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

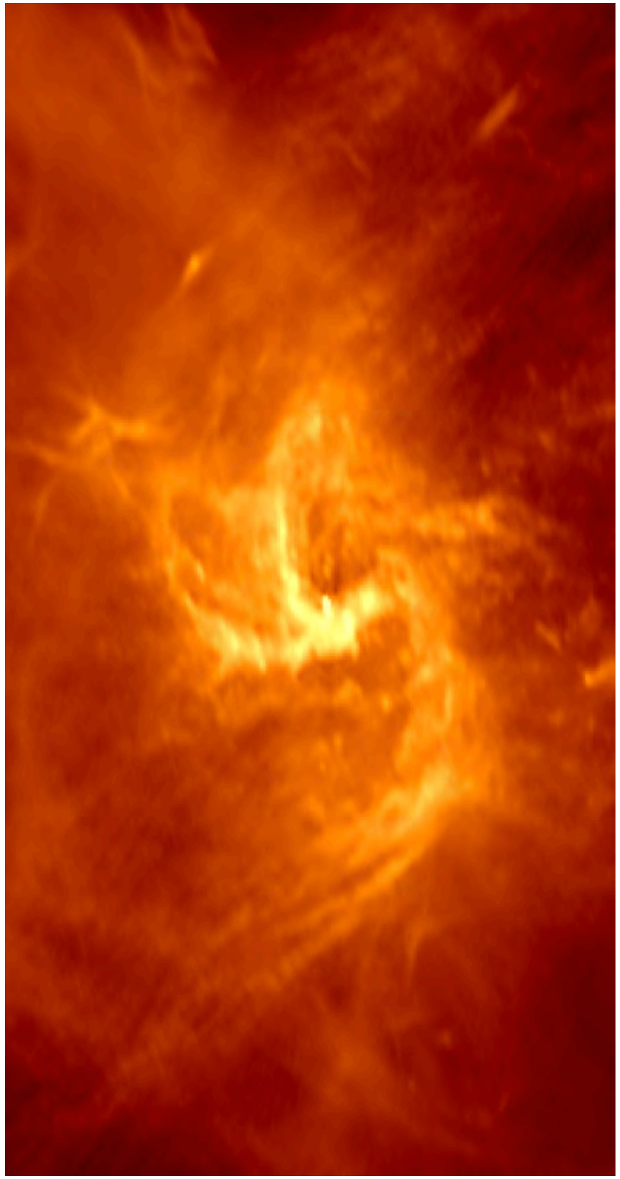
2019 March 11

The Central Magnetic Field of the Cigar Galaxy
Image Credit: NASA, SOFIA, E. Lopez-Rodriguez; NASA, Spitzer, J. Moustakas et al.

Explanation: Are galaxies giant magnets? Yes, but the magnetic fields in galaxies are typically much weaker than on Earth's surface, as well as more complex and harder to measure. Recently, though, the HAWC+ instrument onboard the airborne (747) SOFIA observatory has been successful in detailing distant magnetic fields by observing the polarized infrared light emitted by elongated dust grains rotating in alignment with the local magnetic field. HAWC+ observations of M82, the Cigar galaxy, show that the central magnetic field is perpendicular to the disk and parallel to the strong supergalactic wind. This observation bolsters the hypothesis that M82's central magnetic field helps its wind transport the mass of millions of stars out from the central star-burst region. The featured image shows magnetic field lines superposed on top of an optical light (gray) and hydrogen gas (red) image from Kitt Peak National Observatory, further combined with infrared images (yellow) from SOFIA and the Spitzer Space Telescope. The Cigar Galaxy is about 12 million light years distant and visible with binoculars towards the constellation of the Great Bear.


SOFIA &
FIFI-LS
M82 Galaxy starburst outflow
Ionized Carbon (158 mu), [OIII] (52/88 mu)
Ionized Carbon @ 158 µm
Background image: HST, Spitzer & Chandra

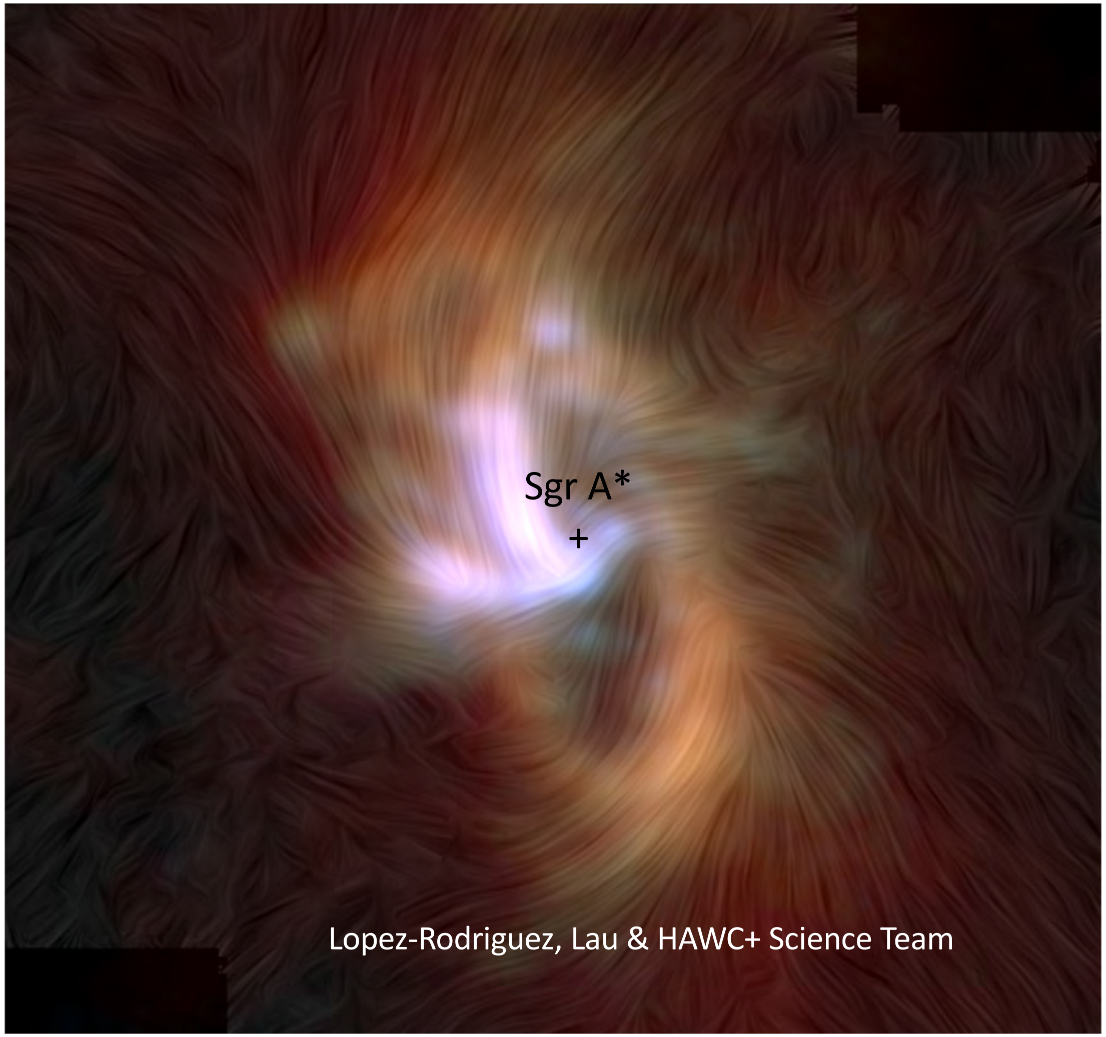
FORCAST & HAWC+, 6cm VLA
magn. field vectors



HAWC+

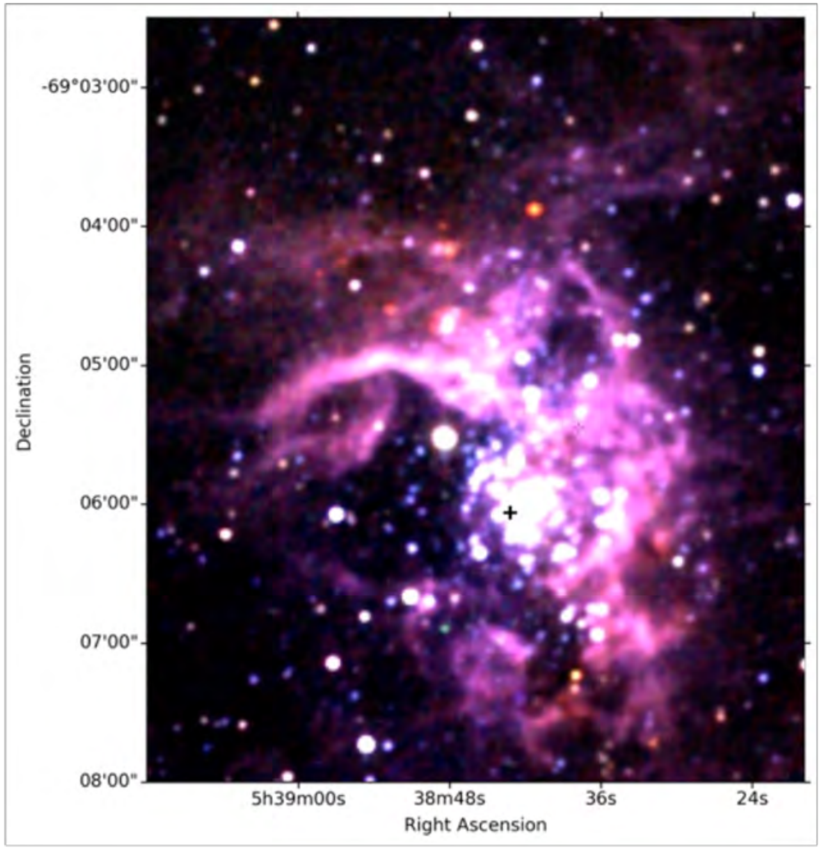
Magnetic Field at the Galactic Center

- SOFIA/HAWC+ polarimetry at 53µm traces magnetic field lines
- SOFIA/FORCAST reveals arcs of dusty material surrounding and possibly feeding the massive BH
- How strong would the magnetic field have to be to affect the galactic center dynamics?
- Does the magnetic field control or even quench the flow to the massive BH?

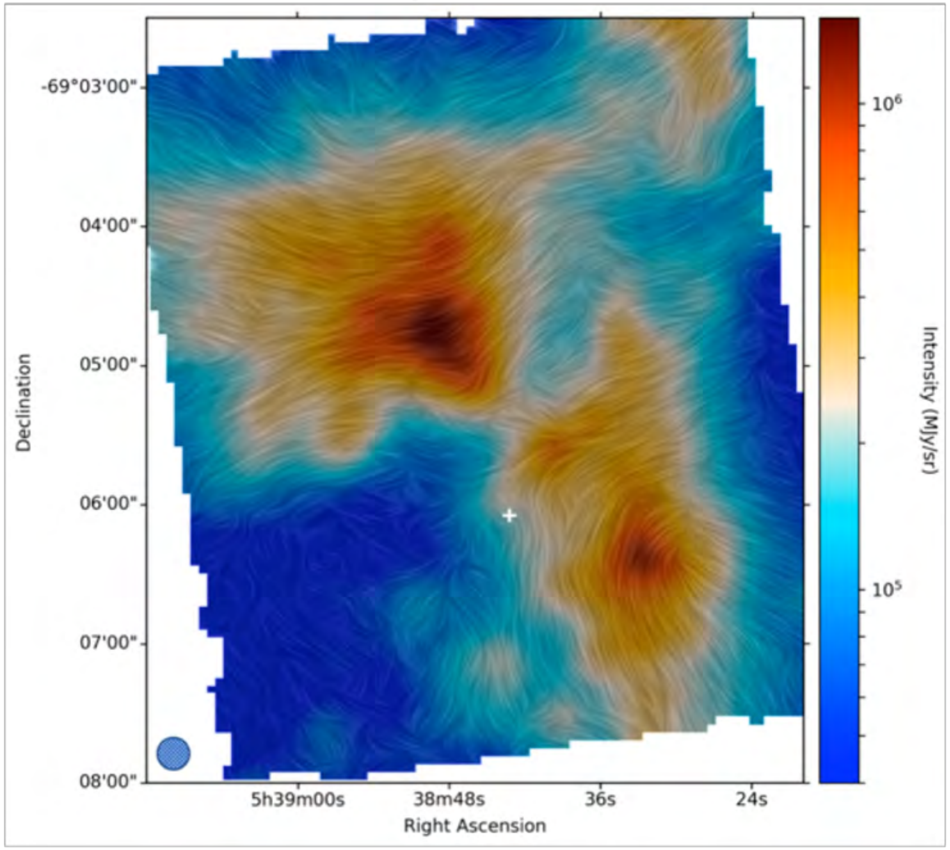


30 Dor: Far-IR polarimetric image

Near Infrared Image from 2MASS



Far Infrared Image + “texture” from SOFIA

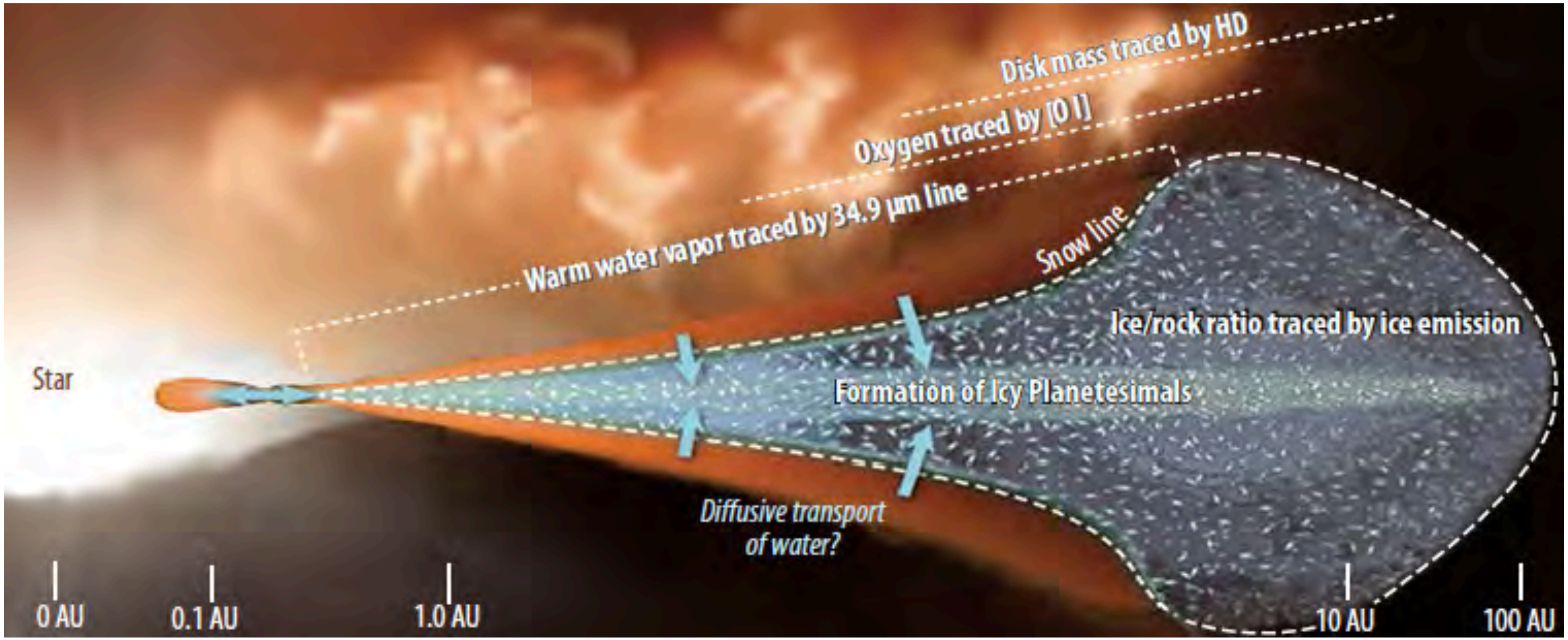


+ location of R136a, a starburst region

30 Doradus is one of the nearest laboratories to test the laws of star formation under extreme conditions. Near-IR shows older stars. Far-IR photometry reveals newer star forming regions. Never before seen magnetic fields structure (shown by ”texture”) at this scale.

In 2021: HIRMES (High Resolution Mid-InfrarEd Spectrometer)

- Wavelength range: 25µm – 122µm; diffraction limited
- Variety of observing modes
  - Spectroscopy: R=600 to R=100,000 (TES detector array)
  - Spectral imaging capabilities for a few selected emission lines, including H2 (J=2-0, 28mu) and HD (J=1-0, 112mu)



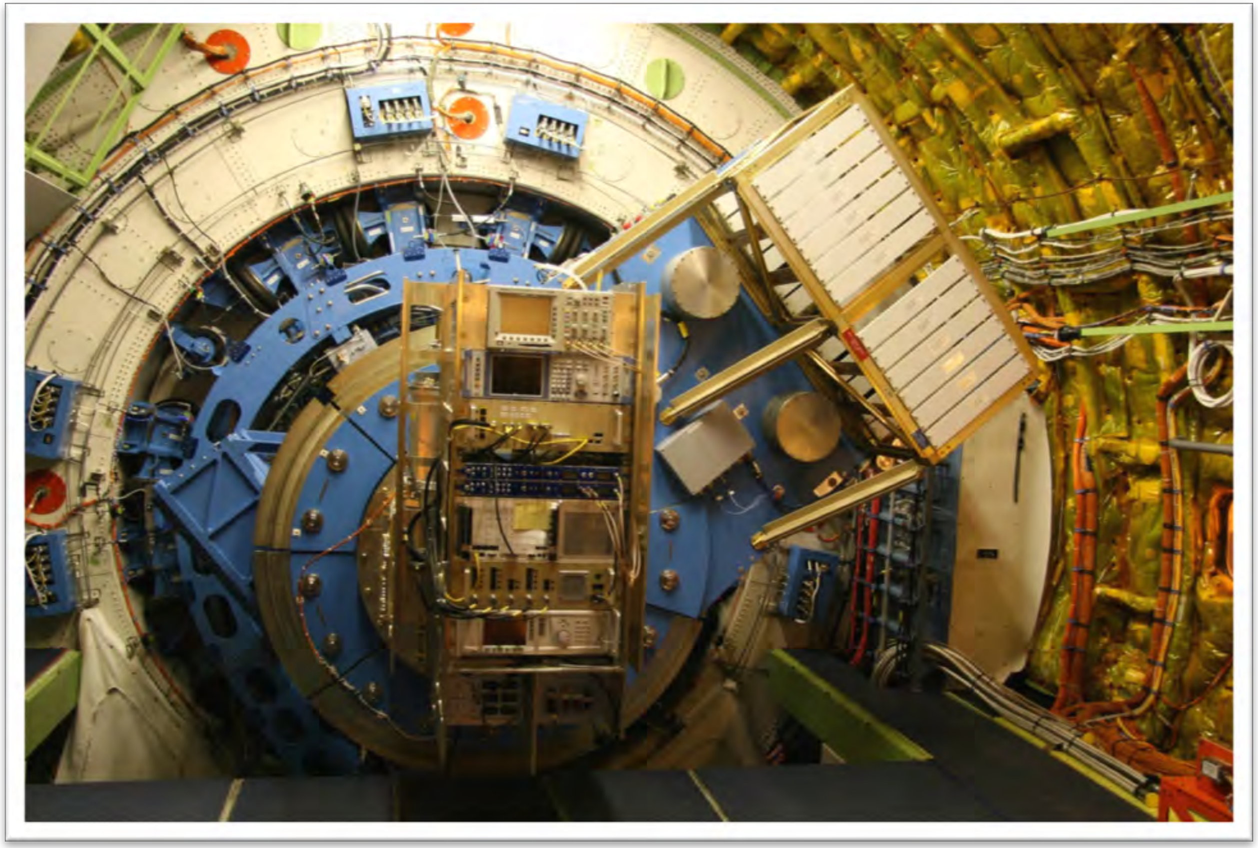
MDLF: High Resolution – R = 10^5

Line/ wavelength (μm)	V_{obs} (km/s)	Pixel	η_{atm} (%)	ε_{warm} (%)	η_{cold} (%)	P_{pixel} (Watts)	NEP ($W/Hz^{1/2}$)	η_{pix} (%)	NEF ($W/m^2/Hz^{1/2}$)	MDLF (W/m^2, 5σ/hr)
H_2O 34.9823	-40	2.9	94	20	35	8.4E-15	1.34E-17	60	2.4E-17	1.4E-18
	+20		84	28		2.4E-14	2.22E-17		4.4E-17	2.6E-18
	+40		93	20		8.5E-15	1.34E-17		2.4E-17	1.4E-18
[OI] 63.1837	-40	5.2	65	43	32	1.4E-14	1.33E-17	60	3.7E-17	2.2E-18
	0		62	45		1.5E-14	1.36E-17		4.0E-17	2.4E-18
	+40		59	48		1.6E-14	1.40E-17		4.4E-17	2.6E-18
HD 112.0725	-40	9.2	58	48	37	1.3E-14	1.00E-17	60	2.8E-17	1.6E-18
	0		58	48		1.3E-15	1.01E-17		2.8E-17	1.6E-18
	+40		56	50		1.4E-15	1.02E-17		3.0E-17	1.7E-18

These are for point sources!

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

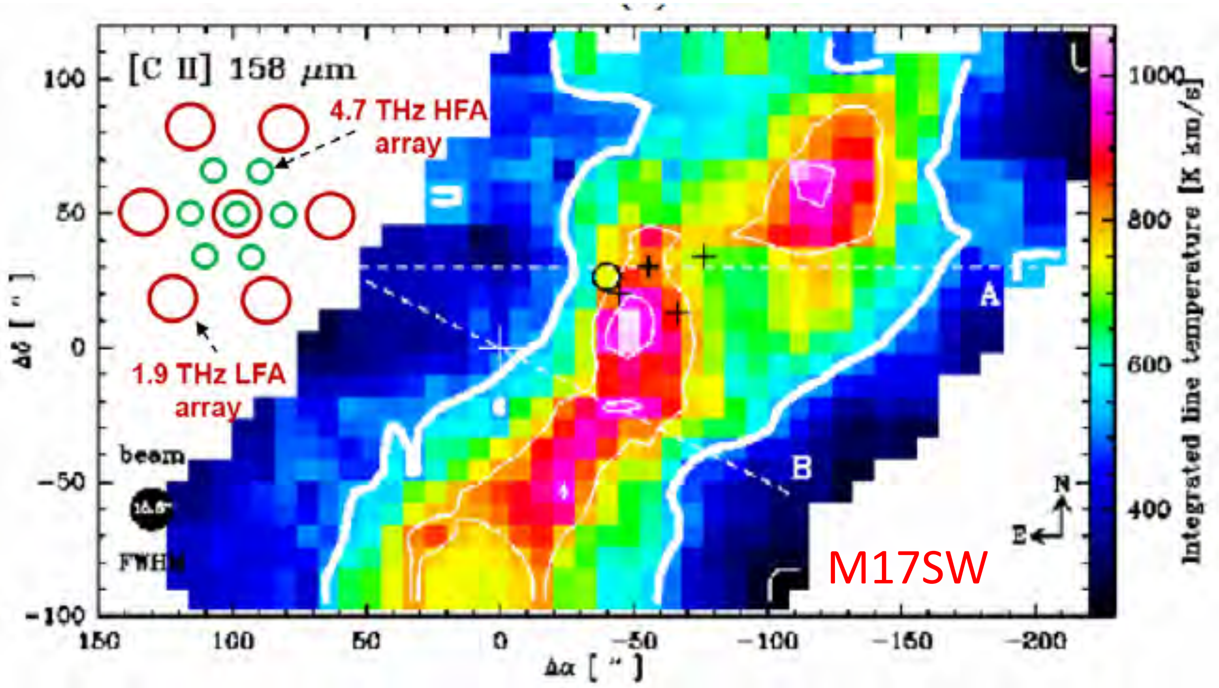
Channel	Frequencies [THz]	Astronomical lines of interest
low-frequency #1	1.25 – 1.50	[NII], CO(12-11), $^{(13)}$CO(13-12), HCN(17-16), H_2D^+
low-frequency #2	1.82 – 1.92	[CII], CO(16-15)
mid-frequency	2.4 – 2.7	HD, OH($^2\Pi_{3/2}$), CO(22-21), $^{(13)}$CO(23-22)
high-frequency	~ 4.7	[OI]



Note: Since 2016, upGREAT 7 pixel THz array

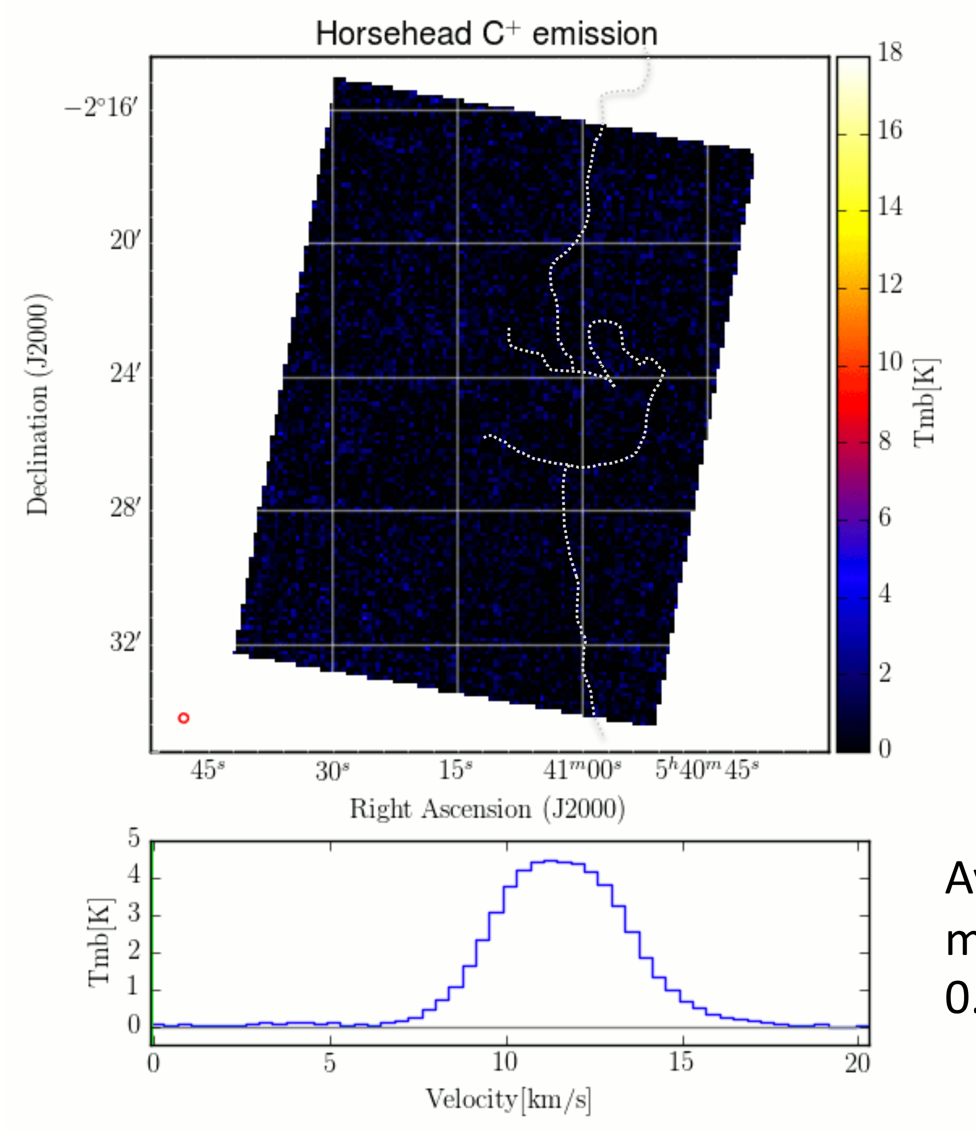
German Instrument Developments

- upGREAT, an enhancement of the GREAT heterodyne instrument, has been developed by Rolf Güsten (MPIfR) +collaborators and has been commissioned in Dec 2015
- Compact heterodyne arrays (for ISM fine structure lines)
  - 7 pixels x 2 polarizations @ 1.9 THz ([CII] cooling line) "LFA")
  - 7 pixels @ 4.7 THz [O I] "HFA" (simultaneous with "LFA")



Horsehead Nebula in Orion

efficient upGREAT [C II] Map (in DDT time)



Pabst et al 2017

Bally et al 2018

Averaged line profile over mapped region. Smoothed to 0.76 km/s velocity resolution

upGREAT [CII] and [OI] mapping

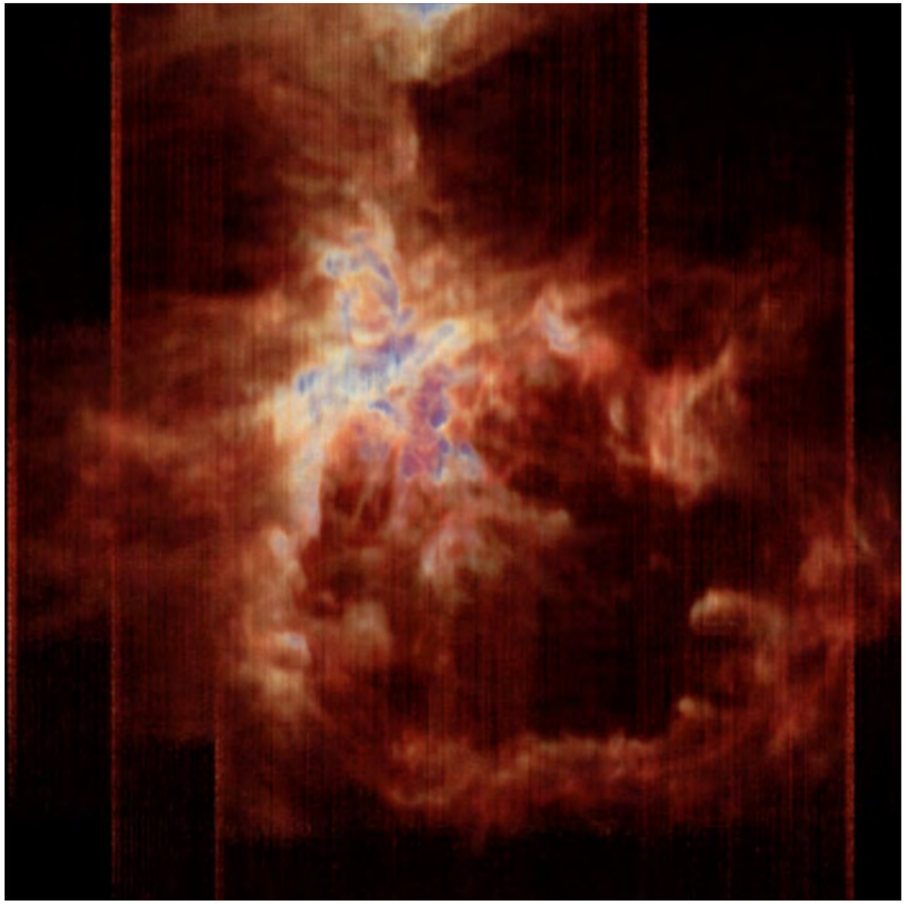
- [CII] 158 mu mapping of M51 (Pineda/Stutzki 2019, in prep.)
- [CII] 158 mu and [OI] 63 mu mapping of CMZ (Harris/Guesten 2019, in prep.)

- [CII] 158 mu 1 square degree Orion mapping (Pabst etal. 2019, Nature)
- [OI] 63mu mapping of the very Galactic Center (Morris et al. 2019, in prep.)
- Legacy proposal of Tielens/Schneider (feedback in Galactic star forming regions)

GREAT

The Dragon in Orion

3D representation of [CII] velocity data

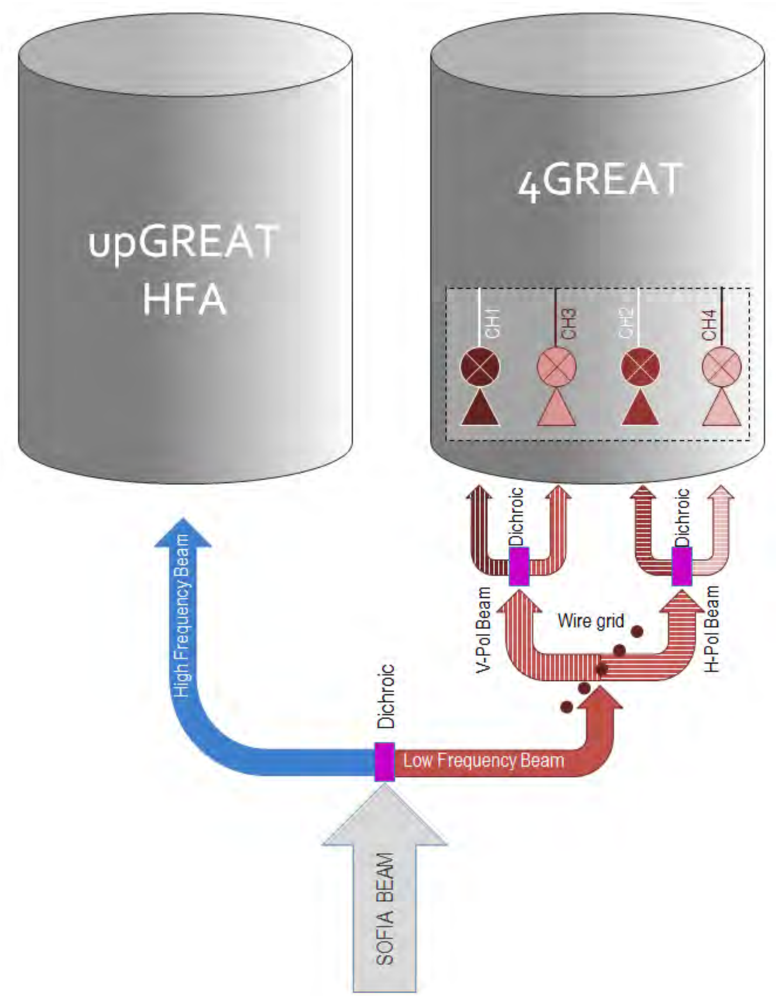


Pabst et al. (2019), Nature

- One square degree [CII] map (1.9 THz/158μm) of Orion SF-Region observed with upGREAT
- Measured in 40h where Herschel HIFI would have taken 2000h
- Interaction of massive stars with their environment regulates the evolution of star forming galaxies

4GREAT Configuration (sub THz)

- 4GREAT operated four channels simultaneously in a single cryostat
  - Cryostat uses same type of cryocooler as upGREAT
- 4GREAT makes use of spare Herschel HIFI mixers and local oscillators (frq < 1 THz)
- 4GREAT has recently been commissioned (in 2018) and operates in parallel with the upGREAT HFA (in Cycle 7, 8)

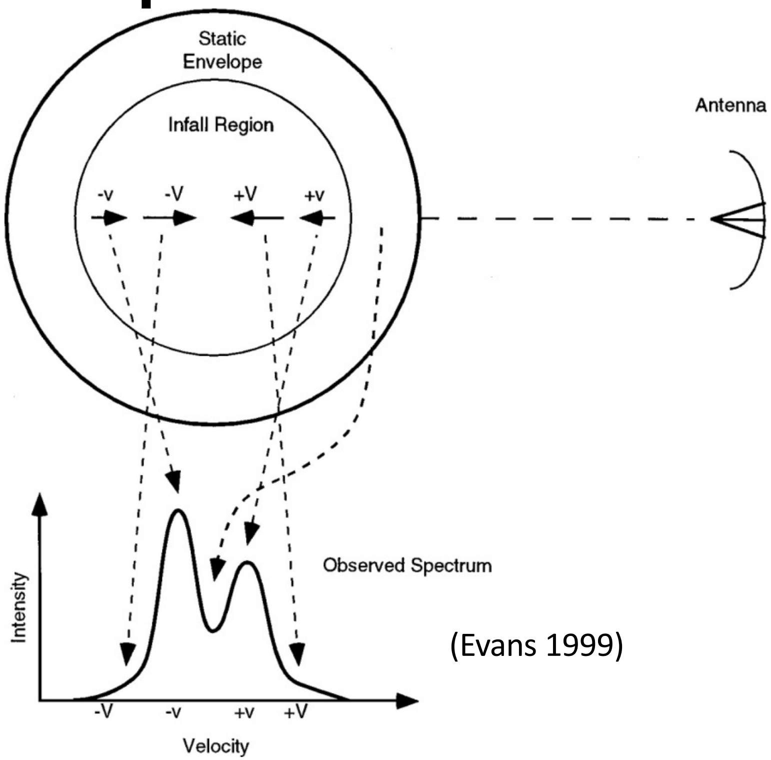


4GREAT Bands

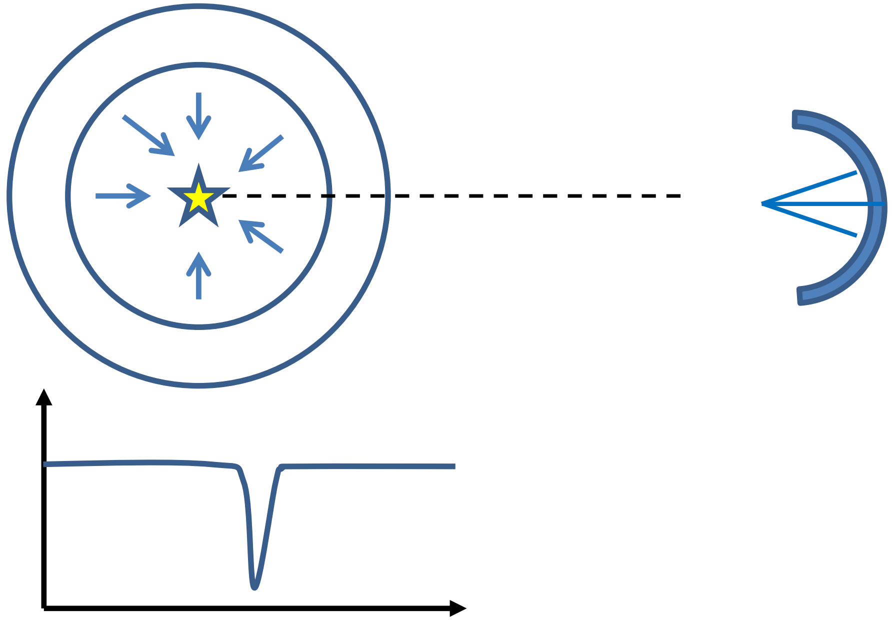
4GREAT Band	Frequency Range (THz)	Source of Mixer and Local Oscillator	Key Lines
1	0.490 – 0.635	HIFI Band 1 Spare Mixer (Observatoire de Paris) Virginia Diode LO Chain	Ground state transitions of NH_3, $H_2{}^{18}O$, CH, HCl, and HDO
2	0.890 – 1.110	HIFI Band 4 Spare (SRON) Virginia Diode LO Chain	Fine structure lines of OH^+ Ground state transitions of NH, NH_2, H_3O^+ Low lying line of $H_2{}^{18}O$
3	1.260 – 1.520	Existing GREAT L1 Band	CO(11-10), SH, OD, N^+
4	1.81 – 1.91 or 2.49 – 2.56	Existing GREAT L2 or Existing GREAT M	C^+ , OH, CO(15-16), NH_3 or HD

Using THz Lines to Probe Infall

esp. NH3 at 1.81 THz, Wyrowski 2015



(Evans 1999)

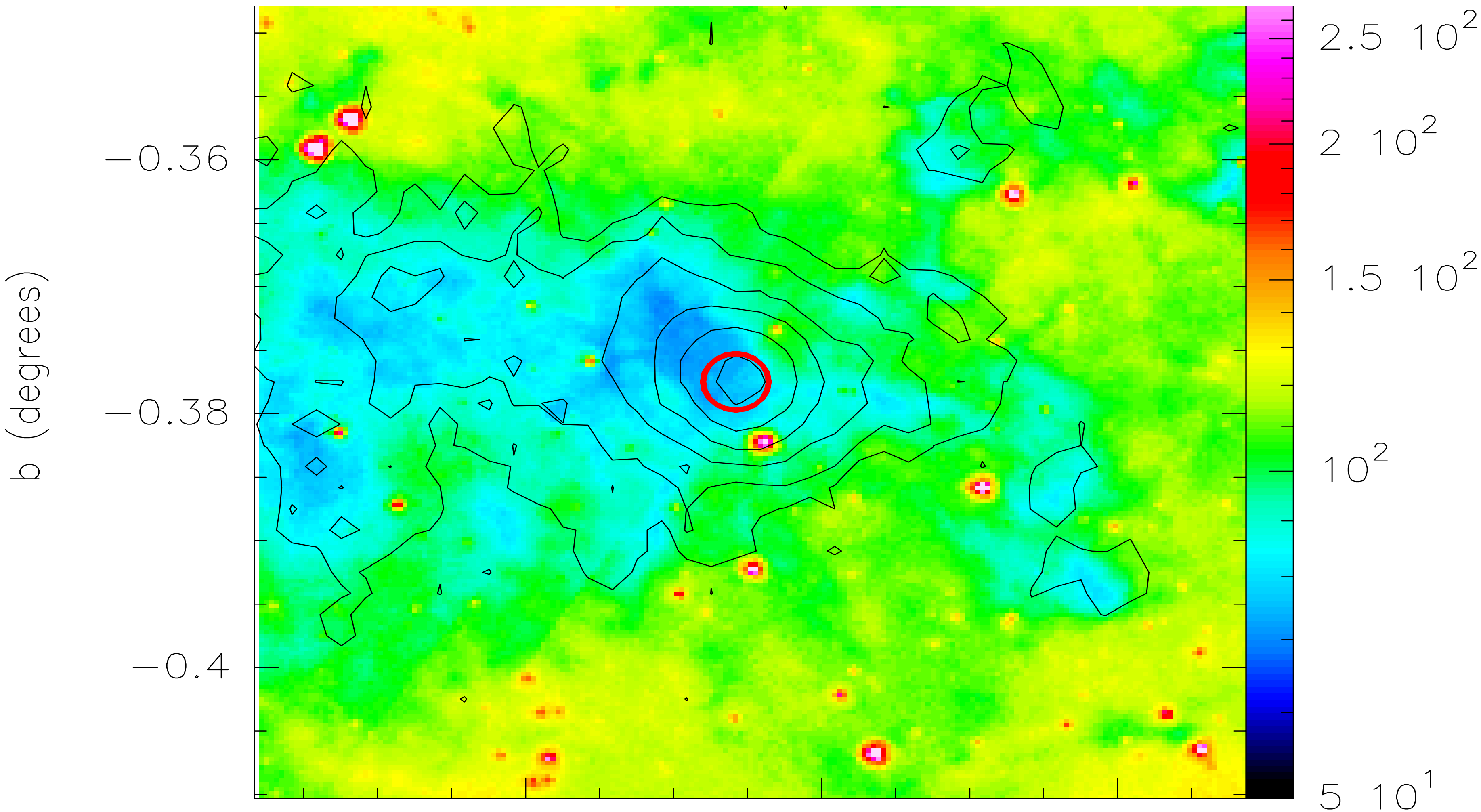


Interpretation of infall using optically thick emission lines is difficult, due to complicated radiative transfer and possible contributions from outflowing molecular gas.

Absorption measurements against a FIR continuum source are much more strainghtforward to interpret.measurements against a FIR continuum source re much more straightforward to interpr

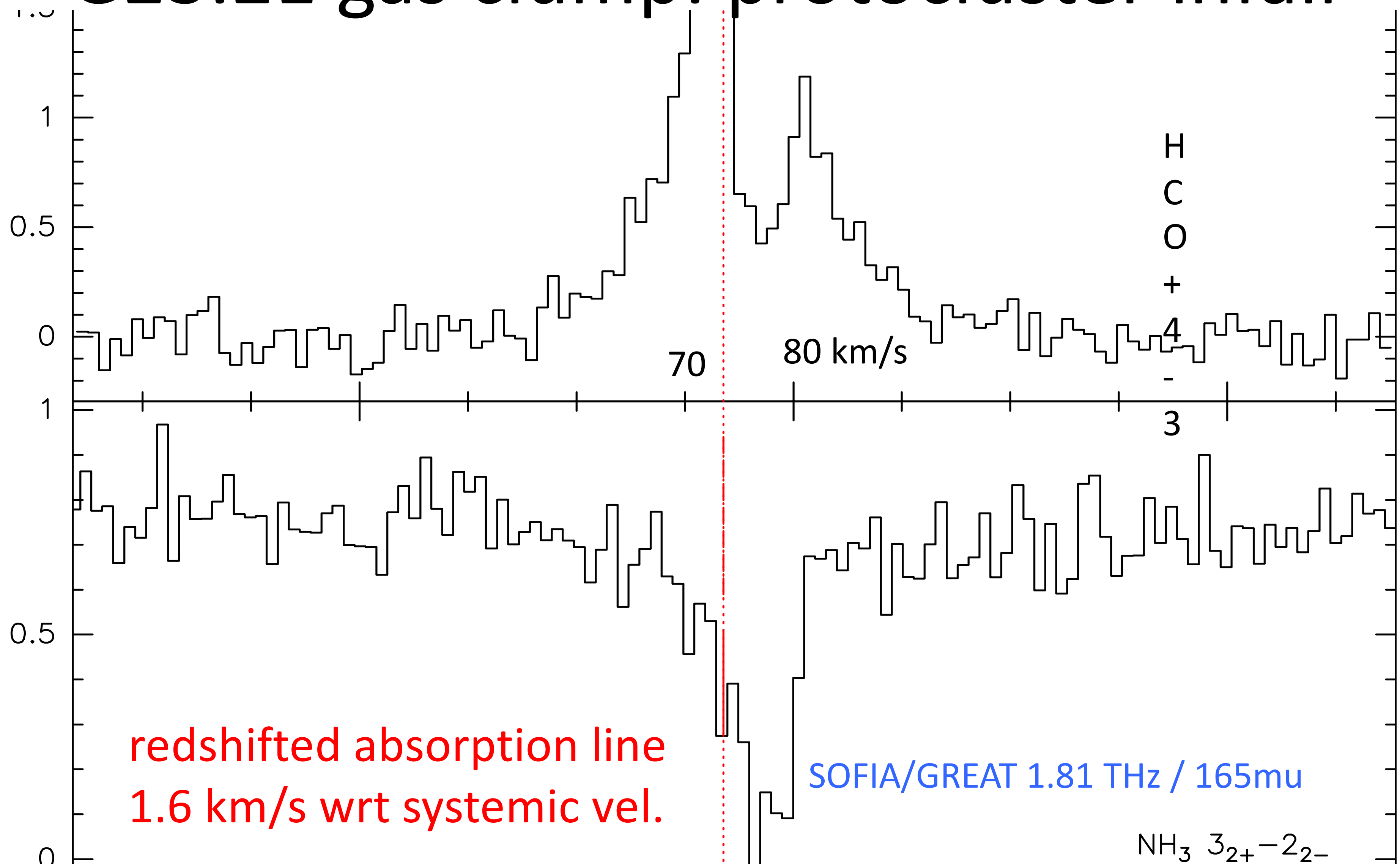
Infall ("collapse") is the Holy Grail of star formation, and SOFIA THz absorption allows us to measure the gas infall rate ("accretion rate").

ATLASGAL submm clump G23.21 (Spitzer IRDC)



Spitzer Infrared Dark Cloud IRDC), with FIR continuum source.
Molecular clump mass: ~ 10(3) Mo, infall rate: ~ 10(-3) Mo/yr.

G23.21 gas clump: protocluster infall



EXES Commissioning : Water in abs. in AFGL 2591

- M ~ 10 Mo protostar in Cygnus

  0(0,0)→1(1,1) H2O transition and other ro-vib. water lines

  unobservable from ground

  T ~ 500 K, likely produced by evaporation of grain mantles (base of molecular outflow)

  improves on R=2000 ISO studi

  paper: Indriolo et al. 2015 ApJ

i