Airborne Astronomy with SOFIA: Instrumentation & associated SF(ISM) science

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SOFIA Science Center
DSI Univ. Stuttgart & NASA Ames

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KITP conference, Santa Barbara

2014: SOFIA development phase → operations phase

SOFIA is doing Cycle 4 observations (~100 flights)
currently observing from New Zealand

What is SOFIA?

SOFIA = Stratospheric Observatory for Infrared Astronomy

flying at ~12-14km

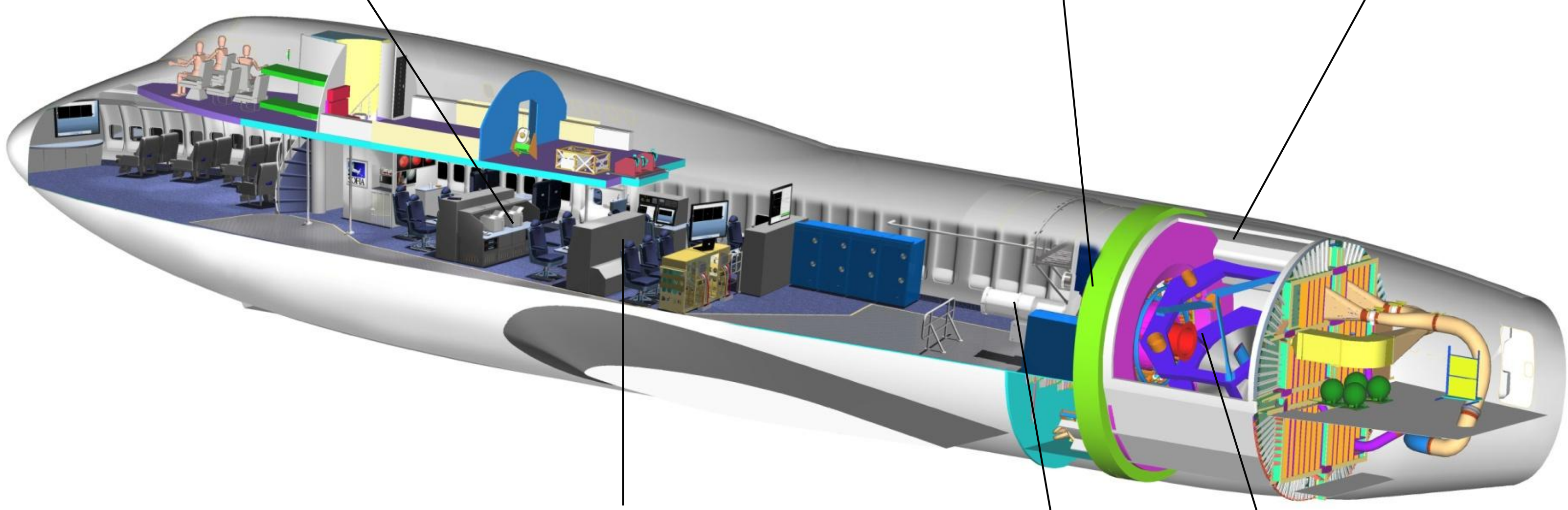
- International partnership:
  - 80% -- NASA (US)
  - 20% -- DLR (Germany)
- Global deployments, incl. southern hemisphere (NZ)
- ~ 120 flights per year (goal) in full operation, ~250 staff.
- ~ 20 year projected lifetime, international observatory

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

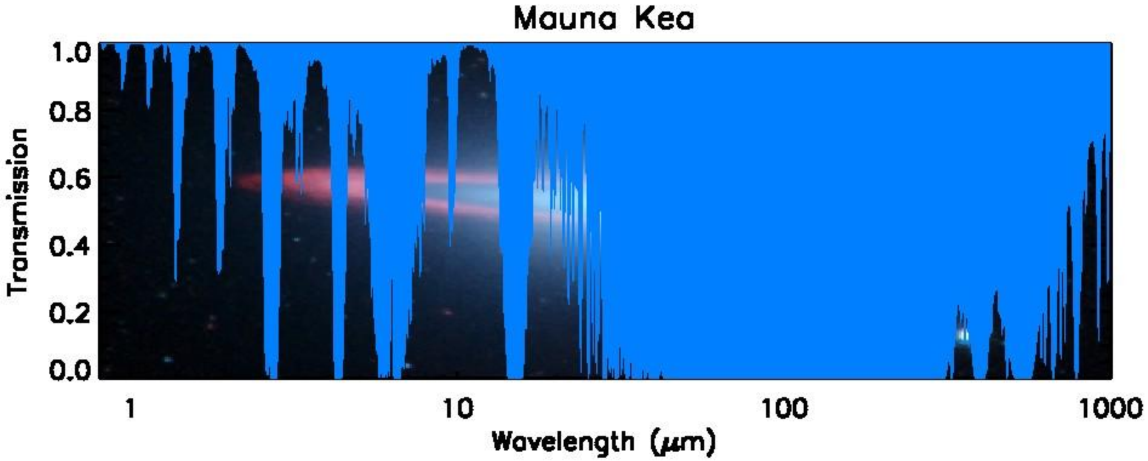
- **High-flying aircraft -- above 40,000 ft -- can observe most of the infrared universe**
- **Airborne infrared telescopes can be more versatile -- and less expensive than space infrared telescopes**

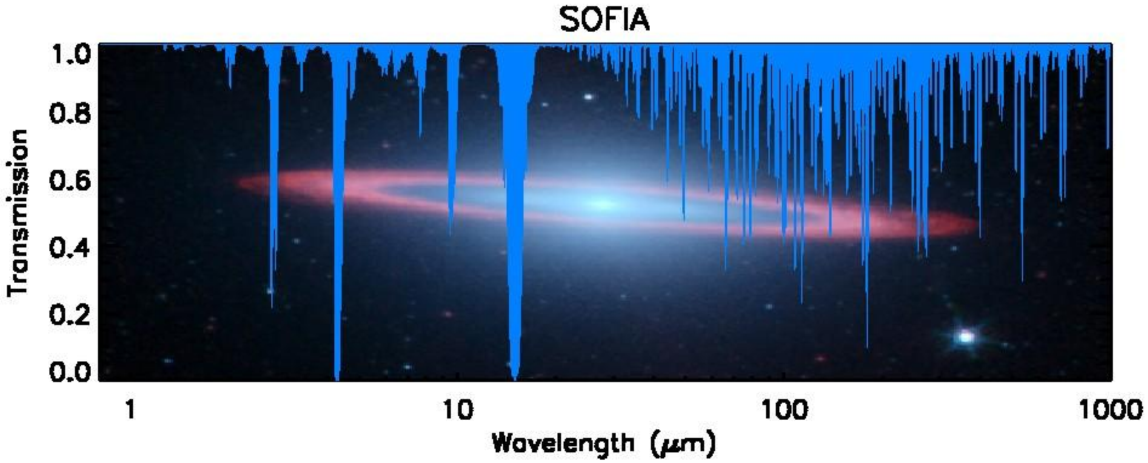
SOFIA – The Observatory




NASA
DLR
SOFIA
N747NA
NASA

Why SOFIA: Motivation for Airborne Astronomy





- For much of the infrared, the Earth's atmosphere blocks all transmission.
  - The problem is water vapor (telluric lines)
  - esp. 30-300 microns

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 than ALMA site

What is SOFIA's science mission?

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

-atomic/molecular gas spectroscopy (high spectral res.)
collapse, outflows, 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+)

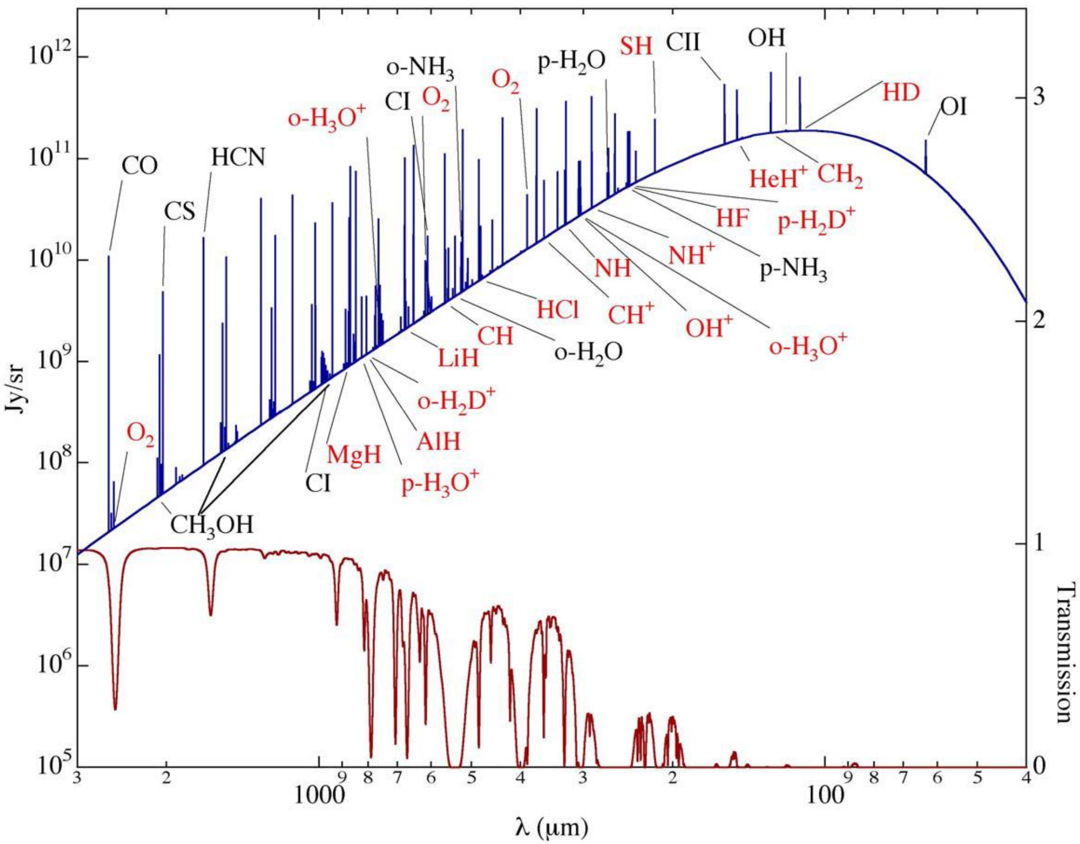
ASTROCHEMISTRY→ molecules, fractionation (H2D+)

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 Interstellar Medium are in the far-infrared and sub-mm
- SH, OH, OD, HD
- o-NH3, p-H2D+
- CII, OI, OIII, NII

Molecular Cloud SED



Ted Bergin, 2008

Multitude of mid-IR and far-IR instruments

SOFIA's suite of instruments comprehensively covers the wide range of wavelengths and spectral resolution (0.5-250 microns, spectral resolution up to 10,000,000)

spatial resolution is 2" for lambda < 20 microns (jitter)

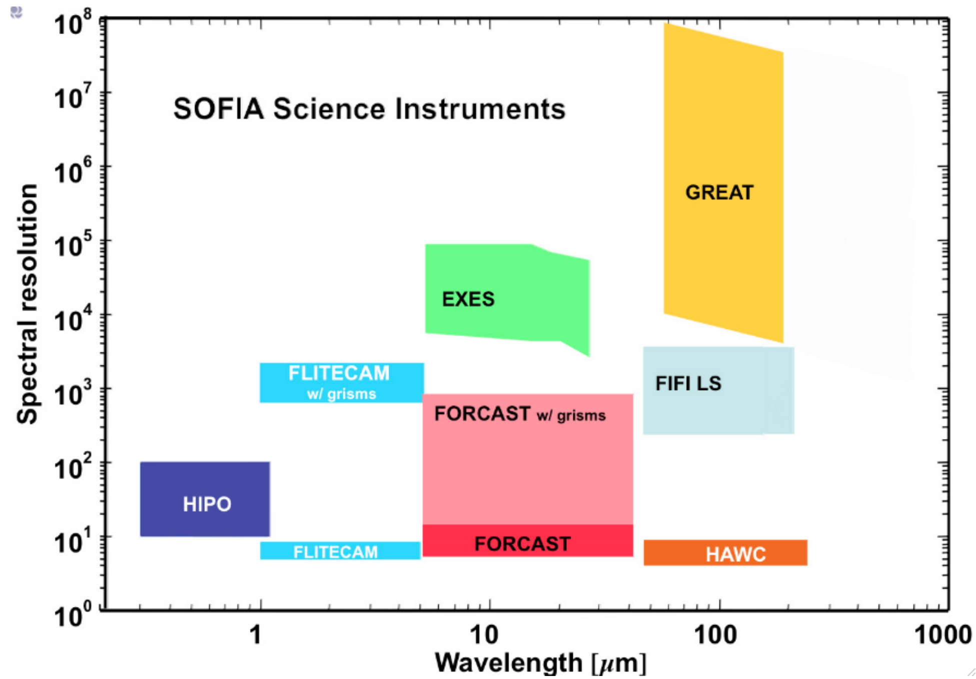
spatial resolution is 1/10 lambda in arcsec (10" at 100mu) for wavelengths > 20-30 microns (diffraction limited)

SOFIA's Instrument Complement

- FORCAST
- GREAT, upGREAT
- FIFI-LS
- FLITECAM
- EXES
- HIPO, FPI+

- HAWC-POL (2nd gen)

\- 3rd gen instrument selection



OUTLINE of this seminar

FORCAST science (Orion, GC)
GREAT science (cloud collapse)
FIFI-LS science (Orion, M82)
EXES science (water in protostar)
FLITECAM science (M82 SNIa)

upGREAT science (Horsehead)
HAWC+ science (polarimetry)

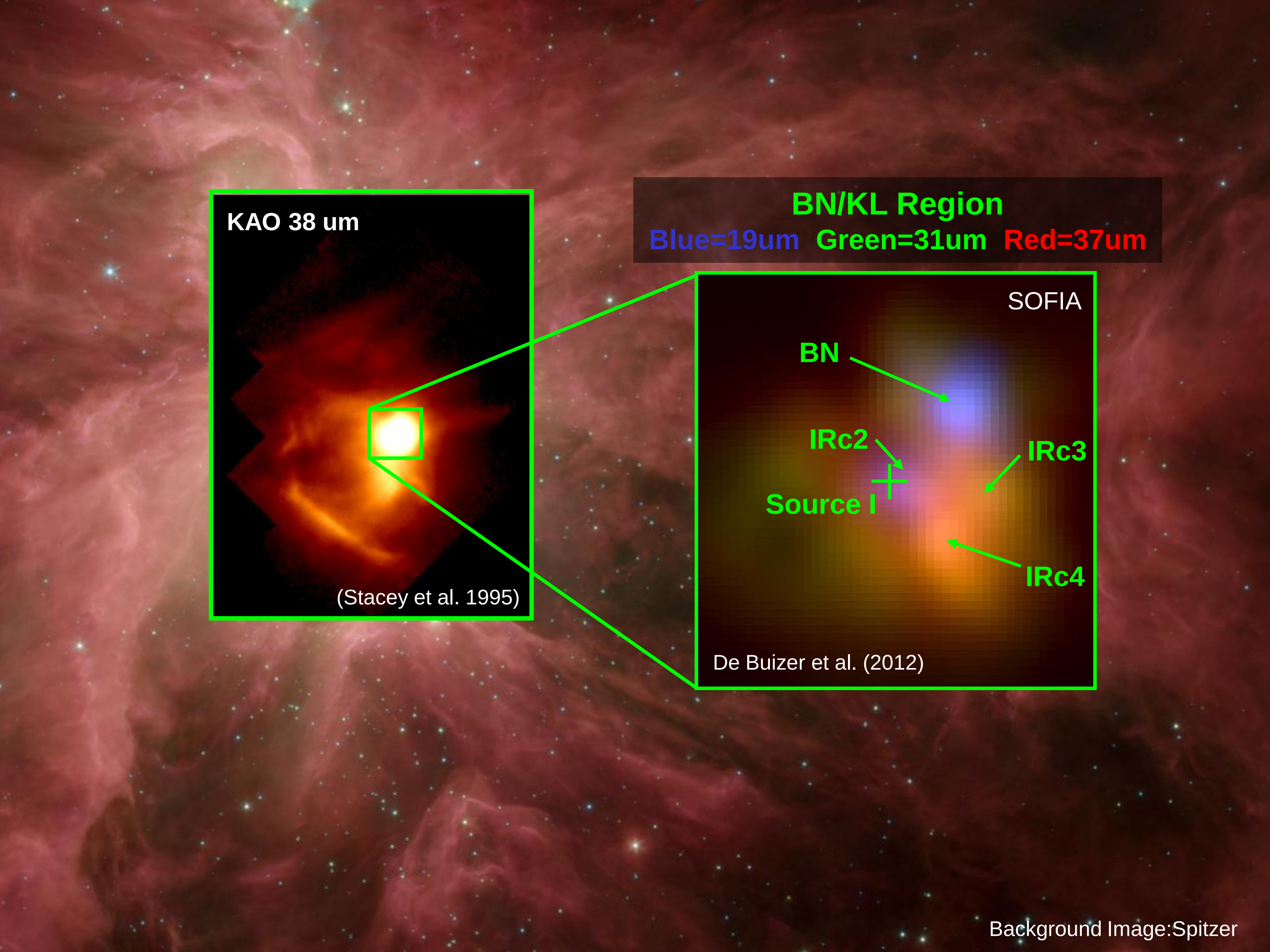
youtube/NASA movies
www.sofia.usra.edu

FORCAST

mid-IR imager 5-40 micron

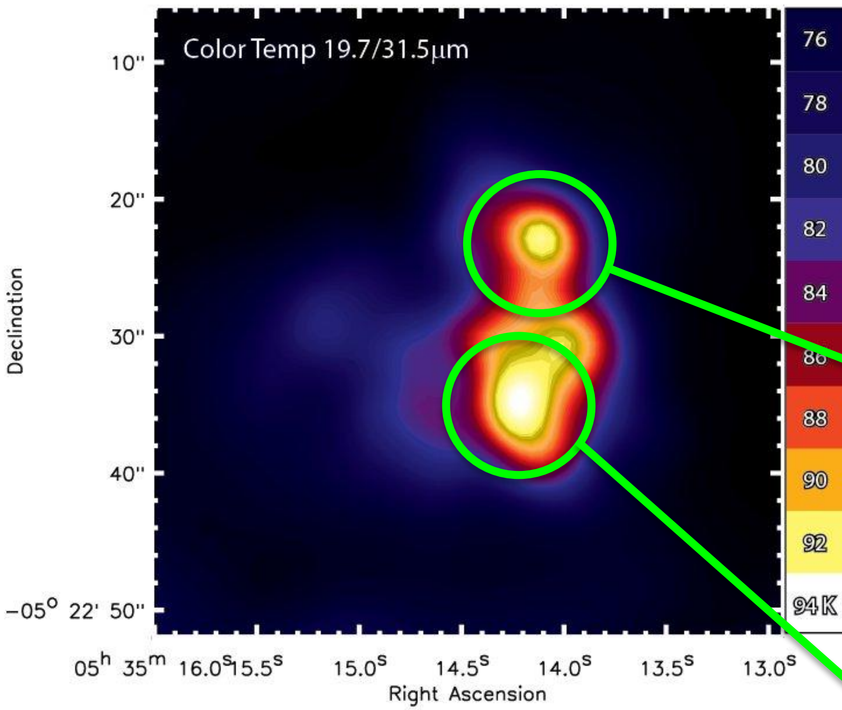
PI: Terry Herter, Cornell

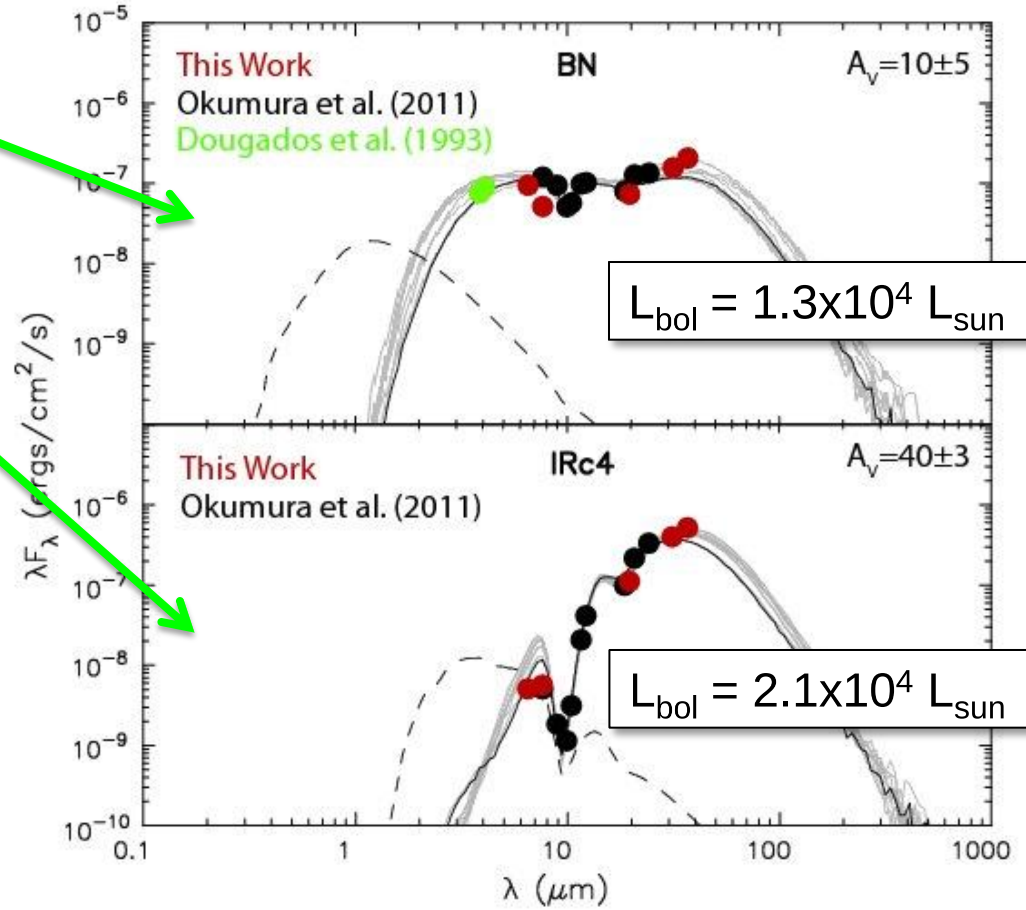
SOFIA First Science Flight (FORCAST, Dec 2010)



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

Like BN, IRc4 is a self-luminous source





IRc4 luminosity is too high to be caused by external heating

BN+IRc4 accounts for ~50% of the ~10^5 L_{sun} of the BN/KL region

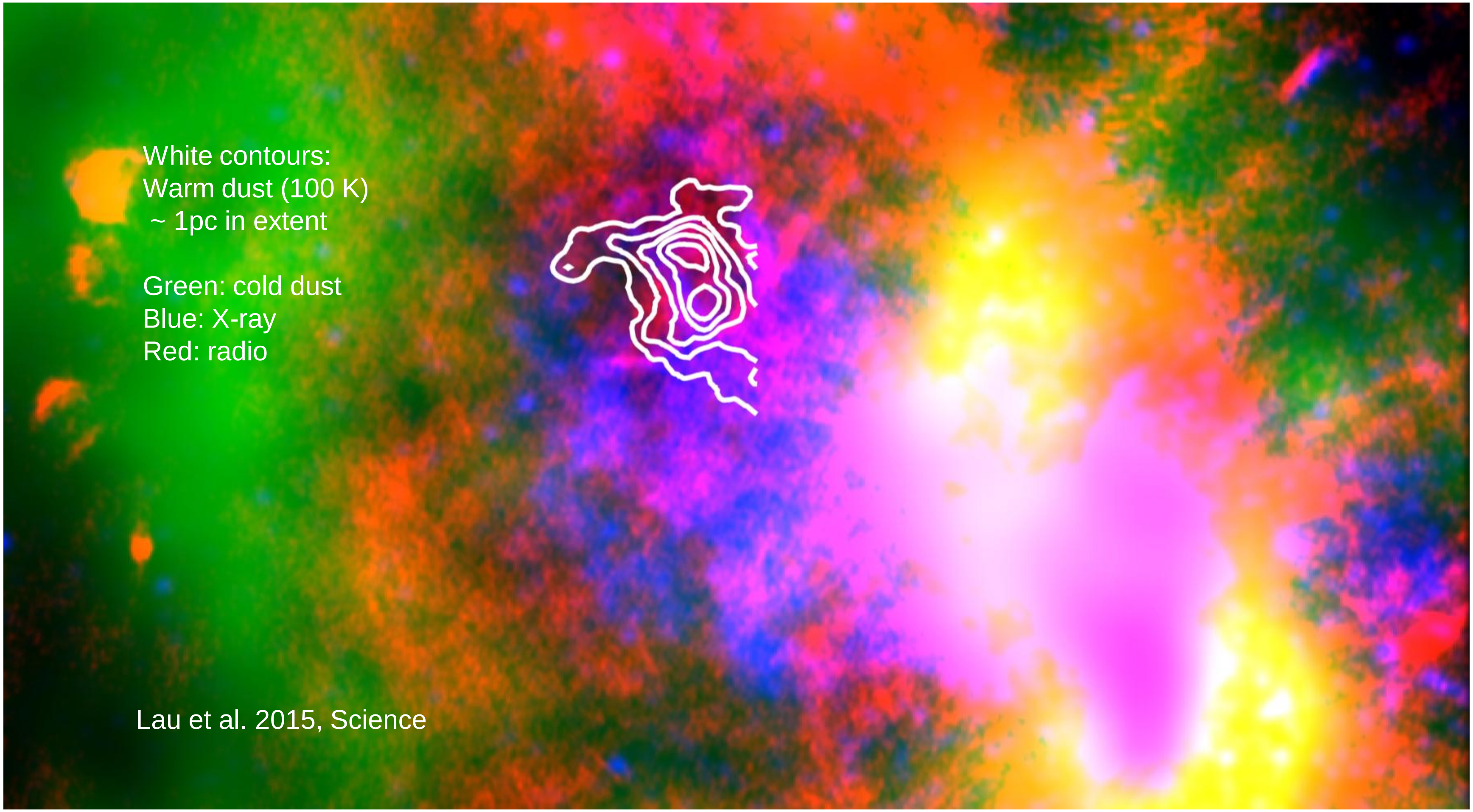
De Buizer et al. (2012)

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, heated by the central OB stars (not BH)
- The ring is resolved with a width of about 0.3 pc (no star formation along the ring)
- There are interesting small structures along the ring, almost periodic in nature. Ring structure most probably transient, not dense enough to be tidally stable.

SgrA East supernova remnant



GREAT

Heterodyne spectrometer

PI: Rolf Guesten, MPIfR

single pixel,

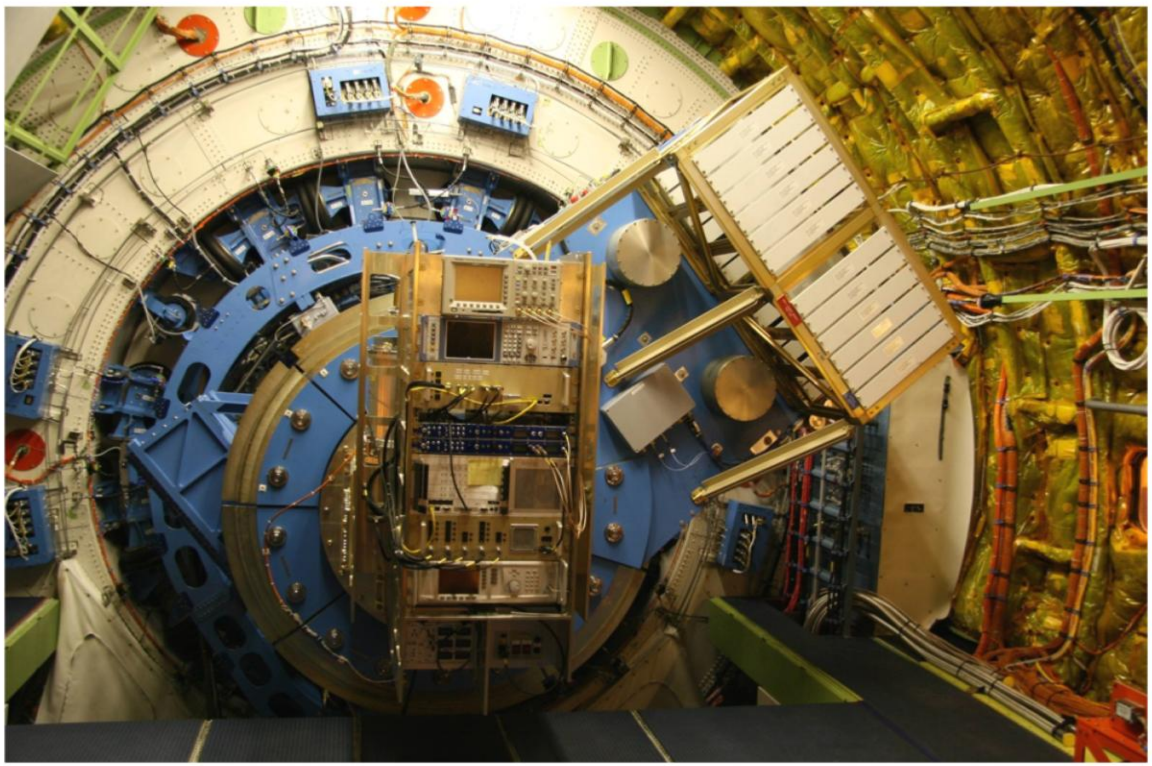
similar to HIFI

on Herschel,

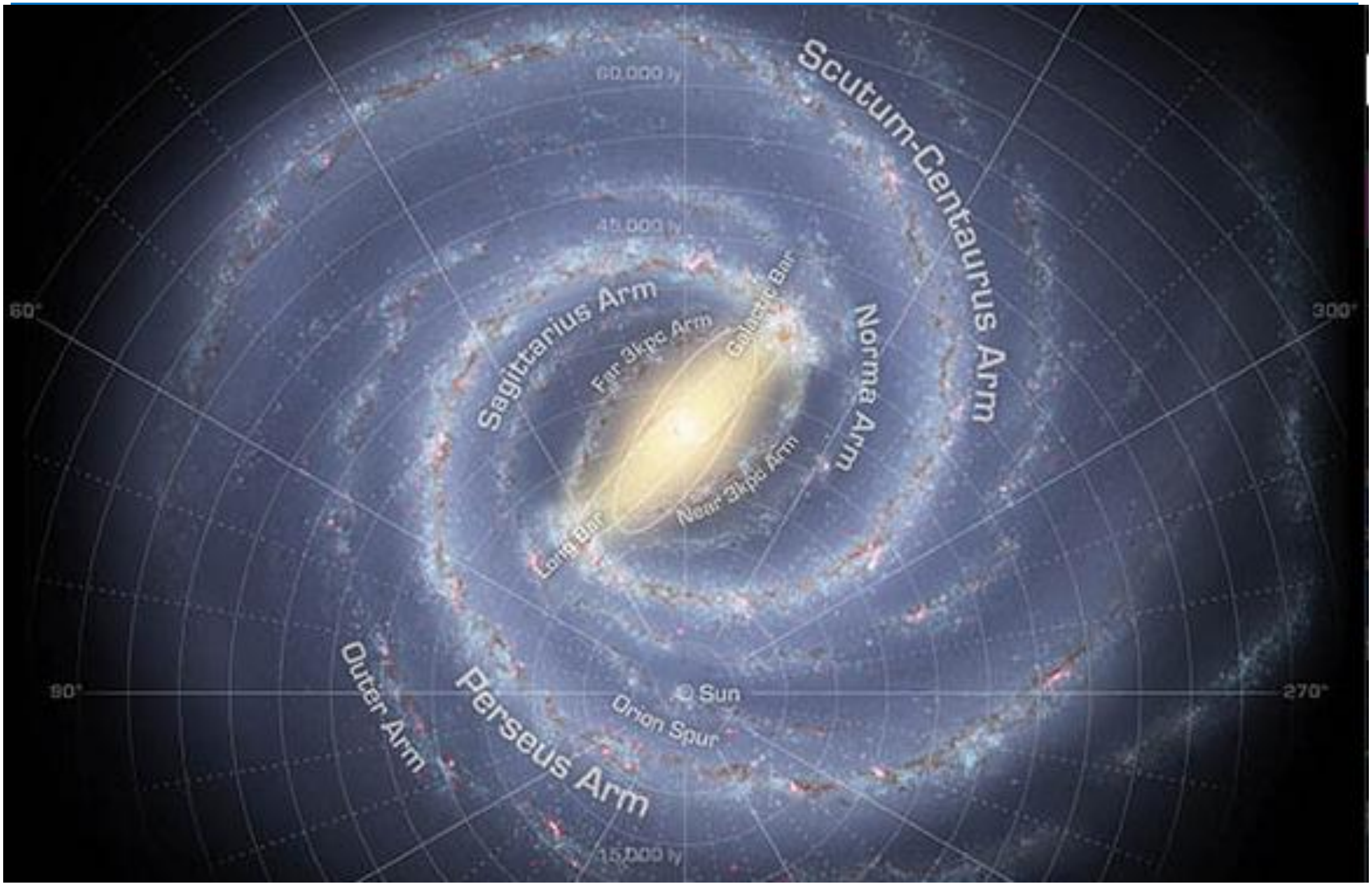
but more sensitive

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

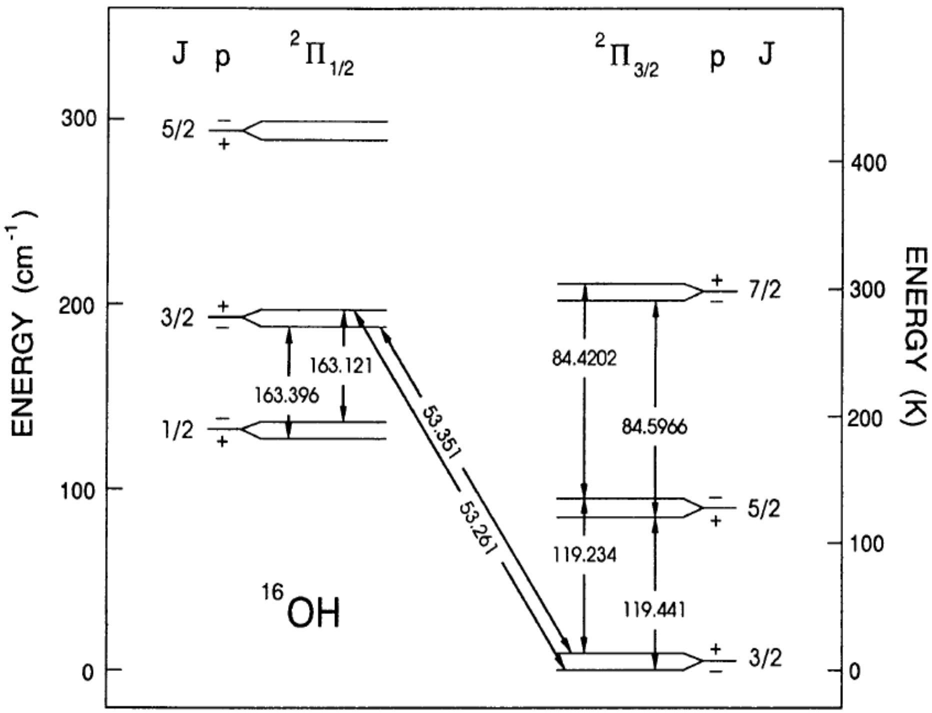
Channel	Frequencies [THz]	Astronomical lines of interest
low-frequency #1	1.25 – 1.50	[NII], CO(12-11), $^{(13)}$CO(13-12), HCN(17-16), H_2D^+
low-frequency #2	1.82 – 1.92	[CII], CO(16-15)
mid-frequency	2.4 – 2.7	HD, OH($^2\Pi_{3/2}$), CO(22-21), $^{(13)}$CO(23-22)
high-frequency	~ 4.7	[OI]



face-on view of our Milky Way Galaxy

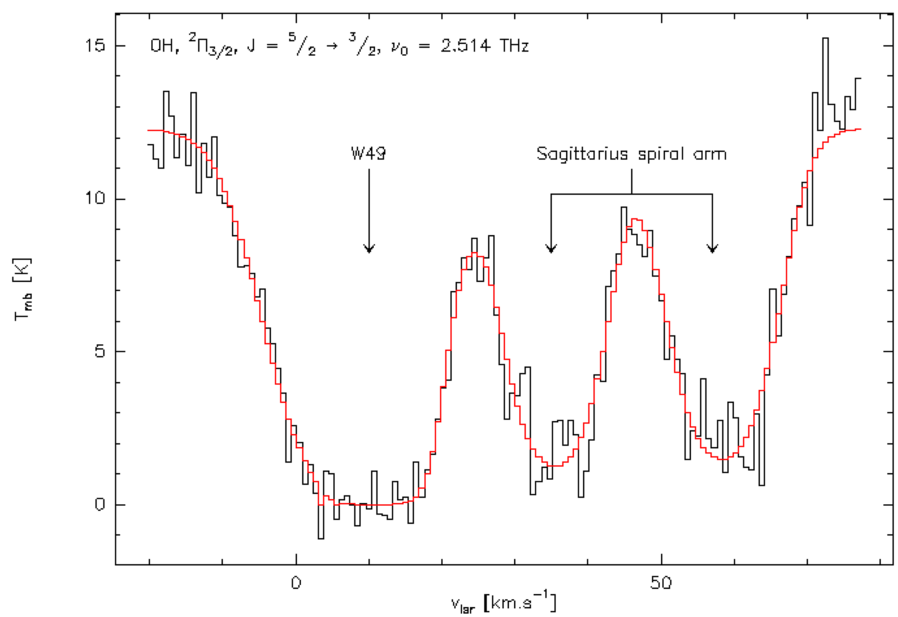


Science Results: 2.5 THz **OH absorption**



First >2 THz spectroscopy from SOFIA

- OH ground-state absorption against W49N
- spectral features of Sagittarius spiral arm



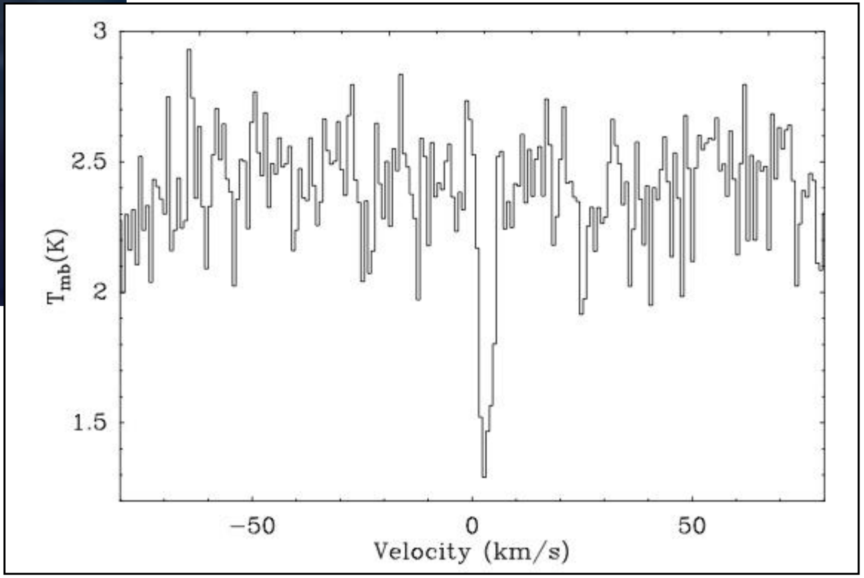
- discovery of ^{18}OH towards W49N core (Wiesemeyer et al. 2012, A&A 542, L7)

H. Wiesemeyer

Detection of OD Toward the Low-Mass Protostar IRAS16293

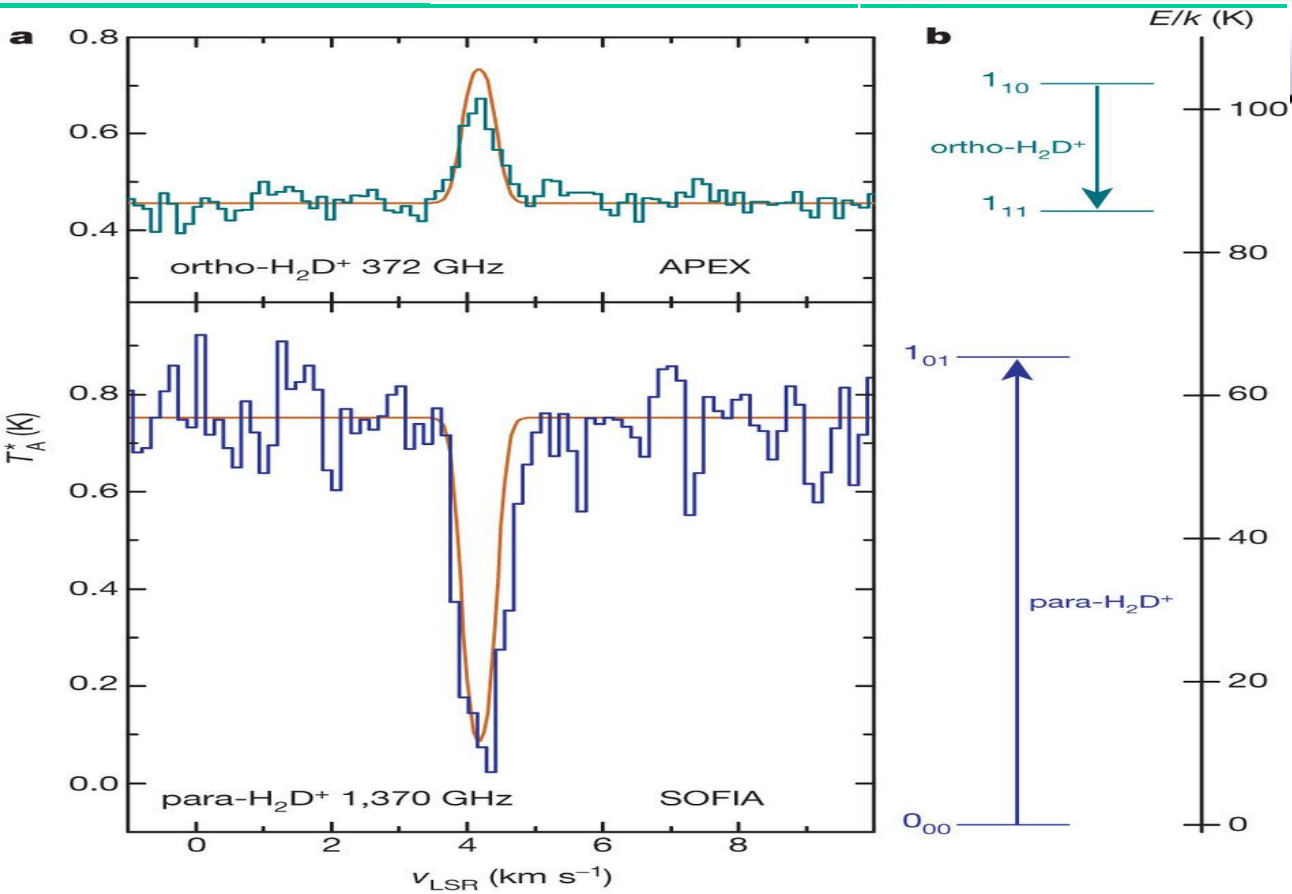
Detection of the OD ground state line at 1.39 THz in absorption toward the line-of-sight of a low-mass protostar.

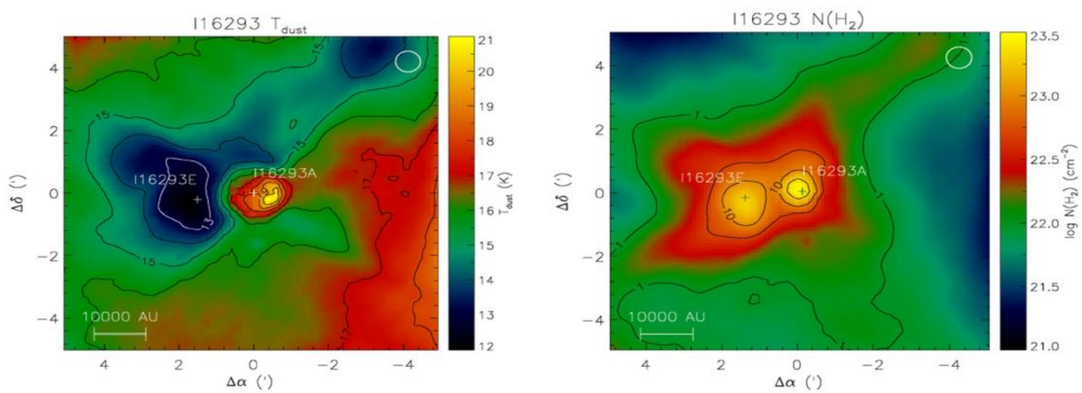
First detection of OD outside of the solar system.



Analysis is ongoing, but high OD abundance suggests a higher than predicted OH fractionization

B. Parise et al. (2012) and the GREAT Team





IRAS 16293-2422

Star-forming core

APEX

Ortho-H_2D+ @ 372 GHz [upper panel]

compared with:

SOFIA/GREAT

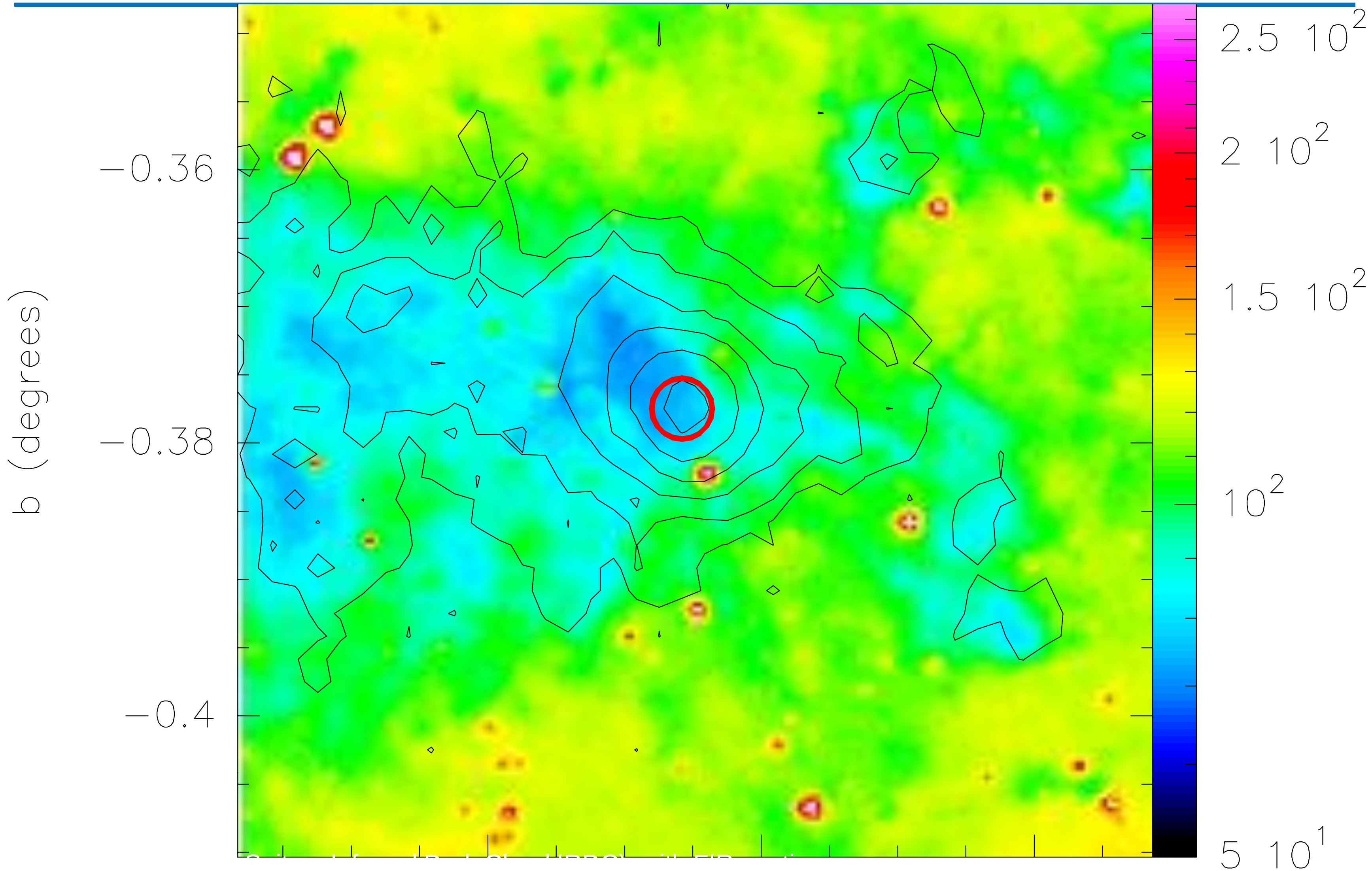
Para-H_2D+ @ 1370 GHz (219 μm) [lower panel]

ortho-to-para ratio gives an age of ~ 10^6 yr.

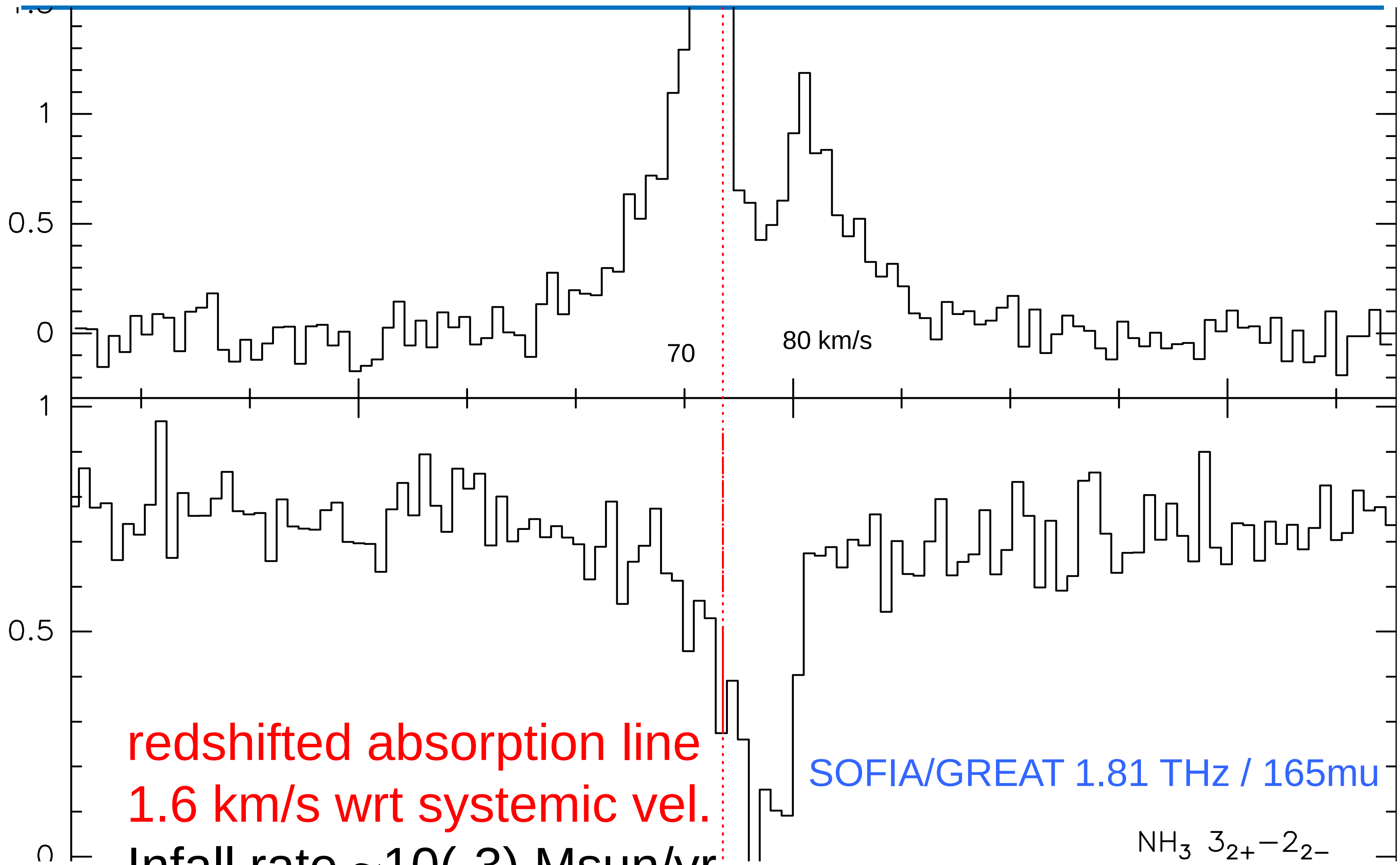
Brünken et al. 2014 (Nature)

Insets: Maps of source T_{dust} (left) and $N(H_2)$ (right).

ATLASGAL submm clump G23.21

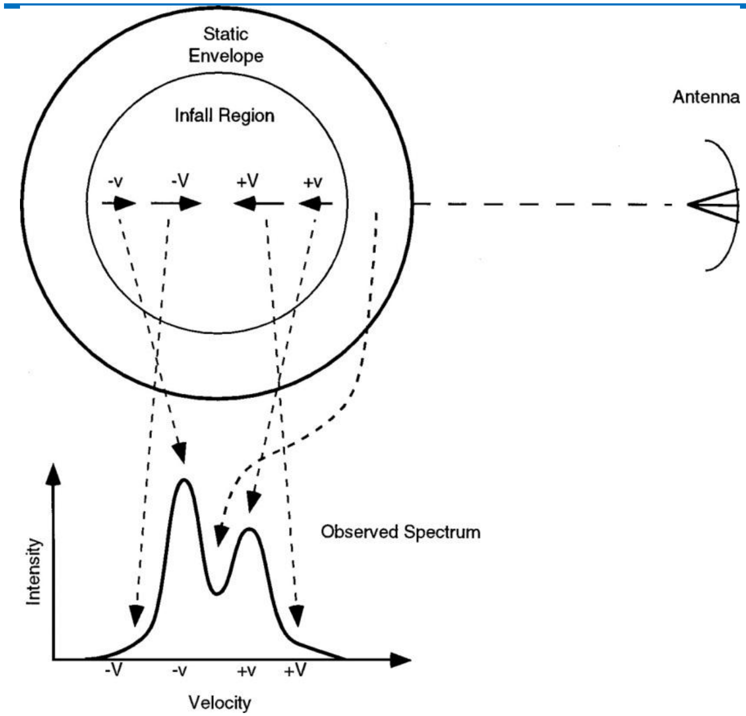


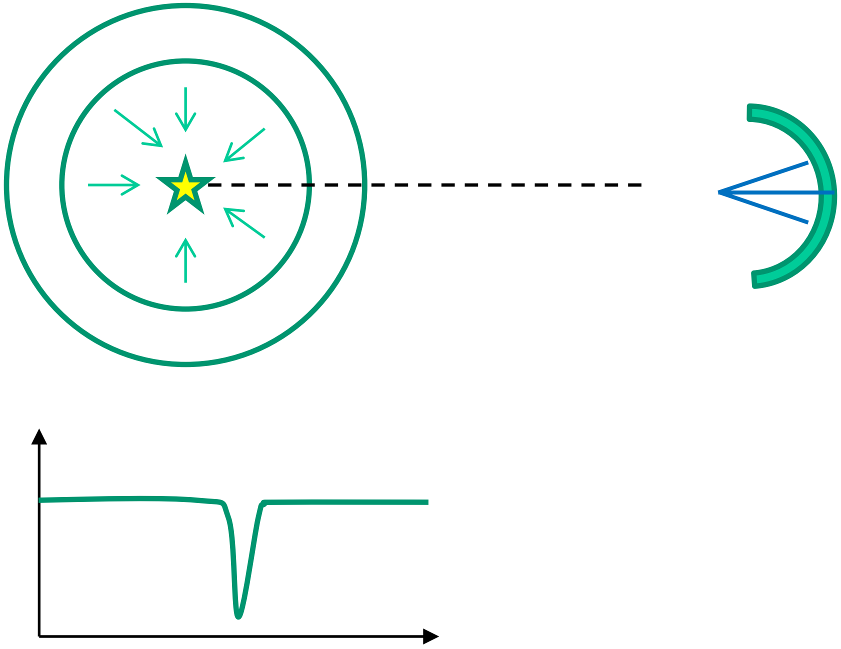
G23.21 gas clump: protocluster infall



redshifted absorption line
1.6 km/s wrt systemic vel.
Infall rate ~10(-3) Msun/yr

Using THz Lines to Probe Infall





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

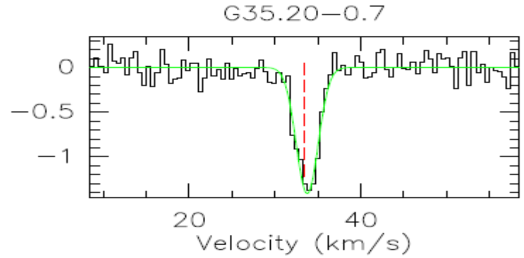
Absorption measurements against a FIR continuum source are much more straingthforward to interpret.

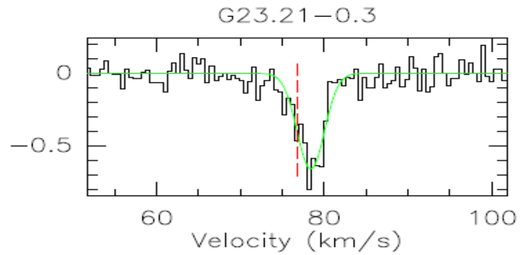
Infall ("collapse") is the Holy Grail of star formation, and SOFIA THz absorption allows us to measure the gas infall rate ("accretion rate").

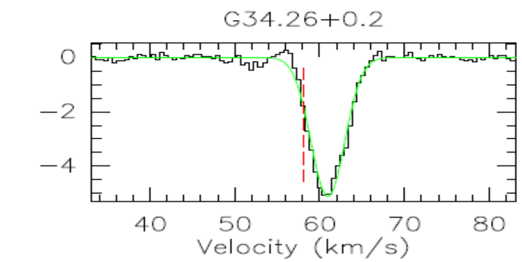
1.81 THz Detection of Infall (in NH3);

Wyrowski et al. 2015

More examples of 1.81 THz absorption lines
against bright FIR continuum sources (infall)







Probing outflow: GREAT dips into cradle of star formation

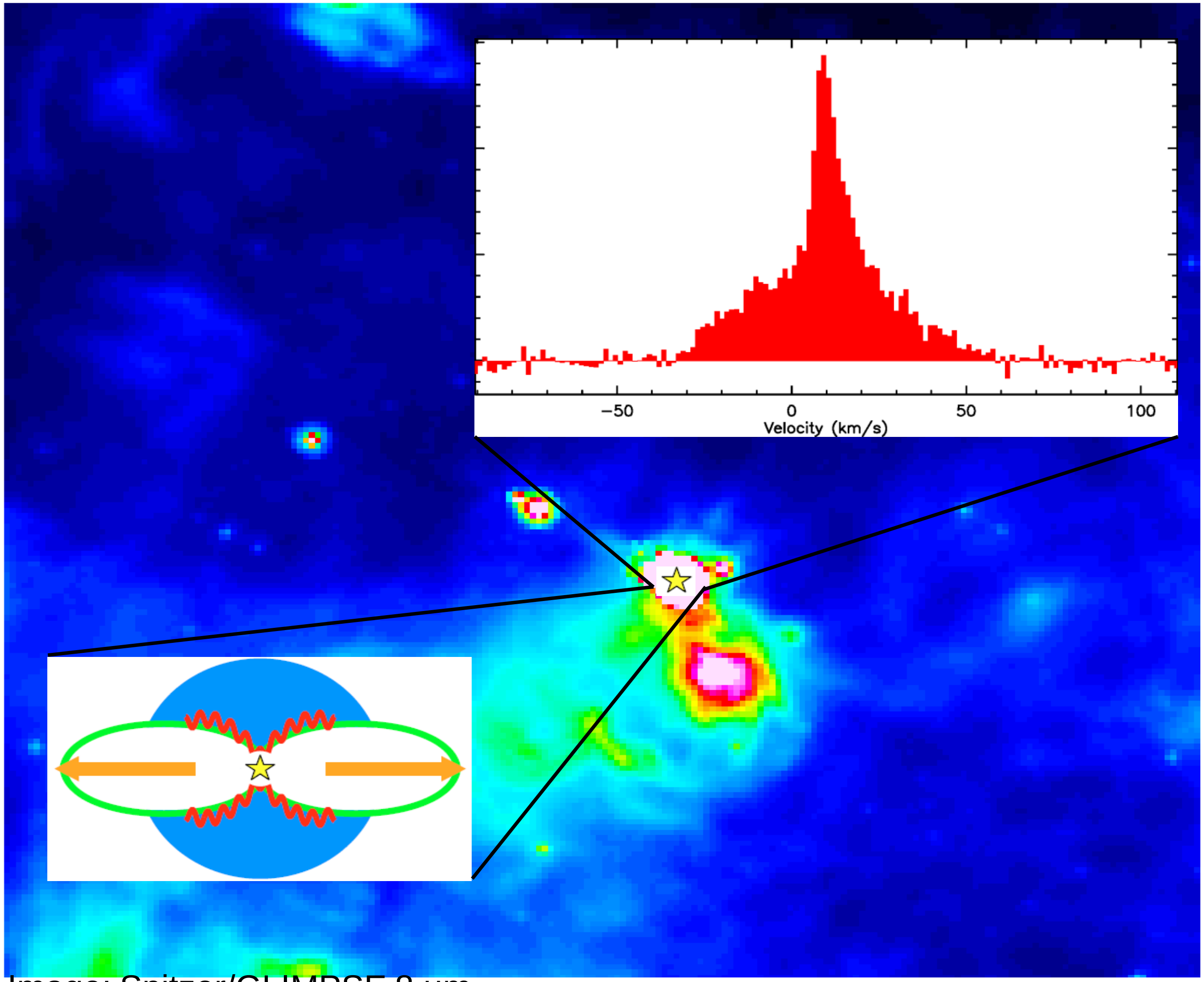
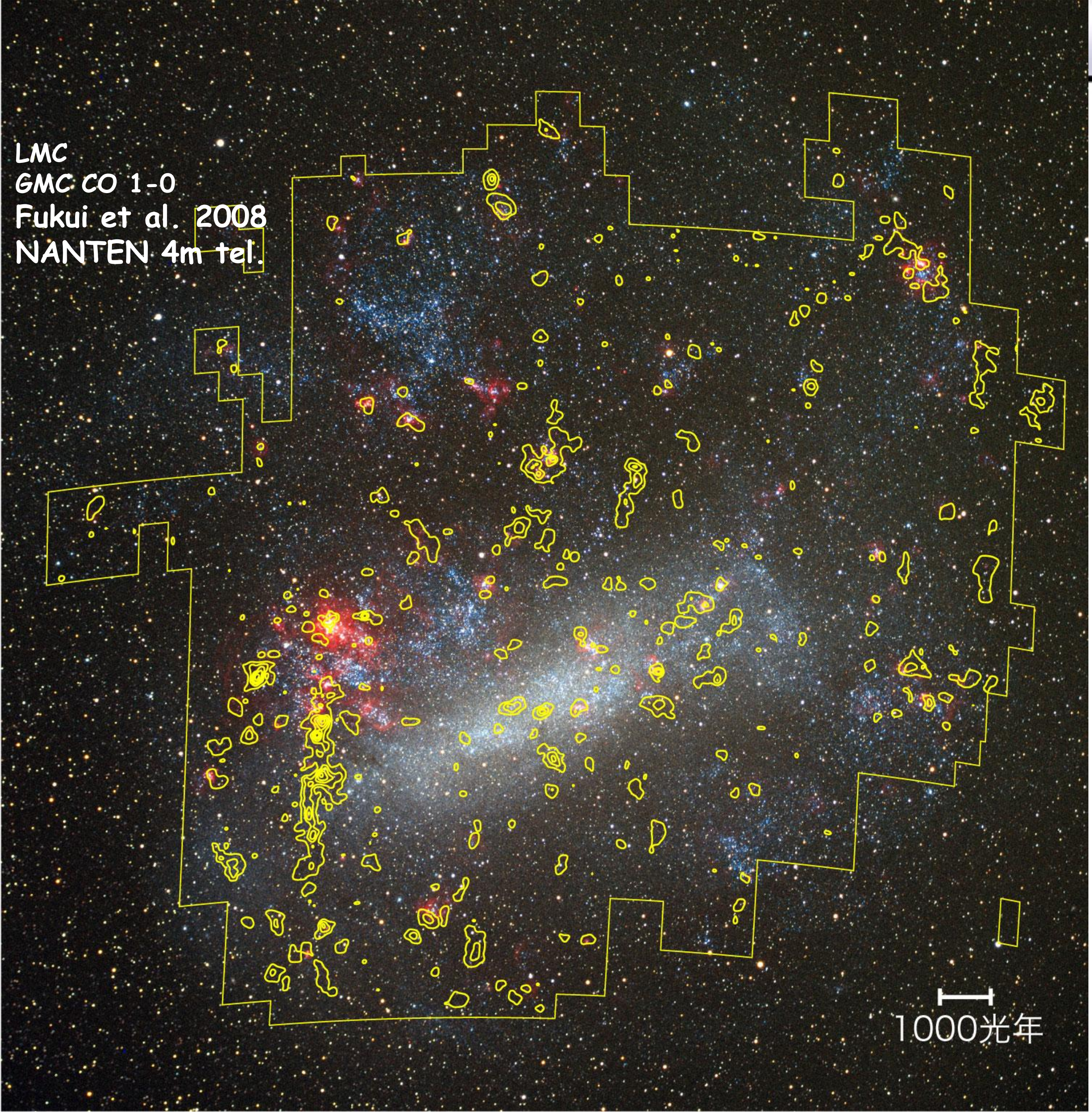


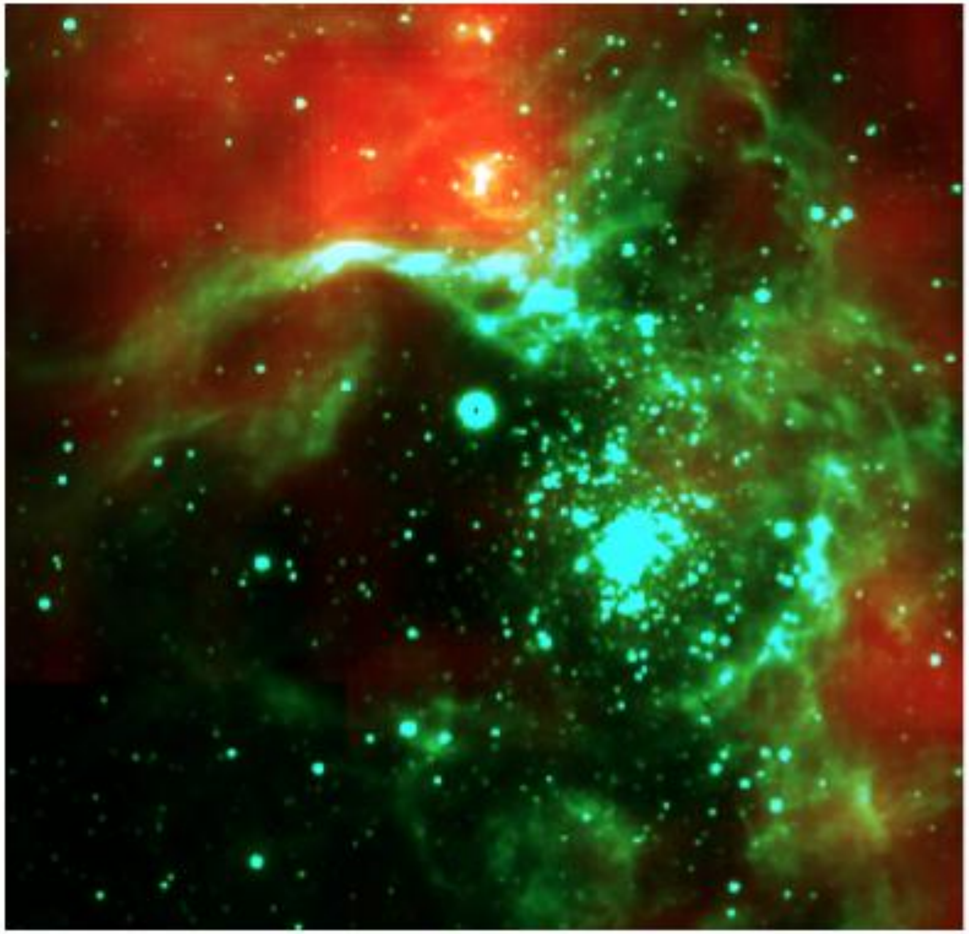
Image: Spitzer/GLIMPSE 8 µm

G5.89 ultracompact HII region

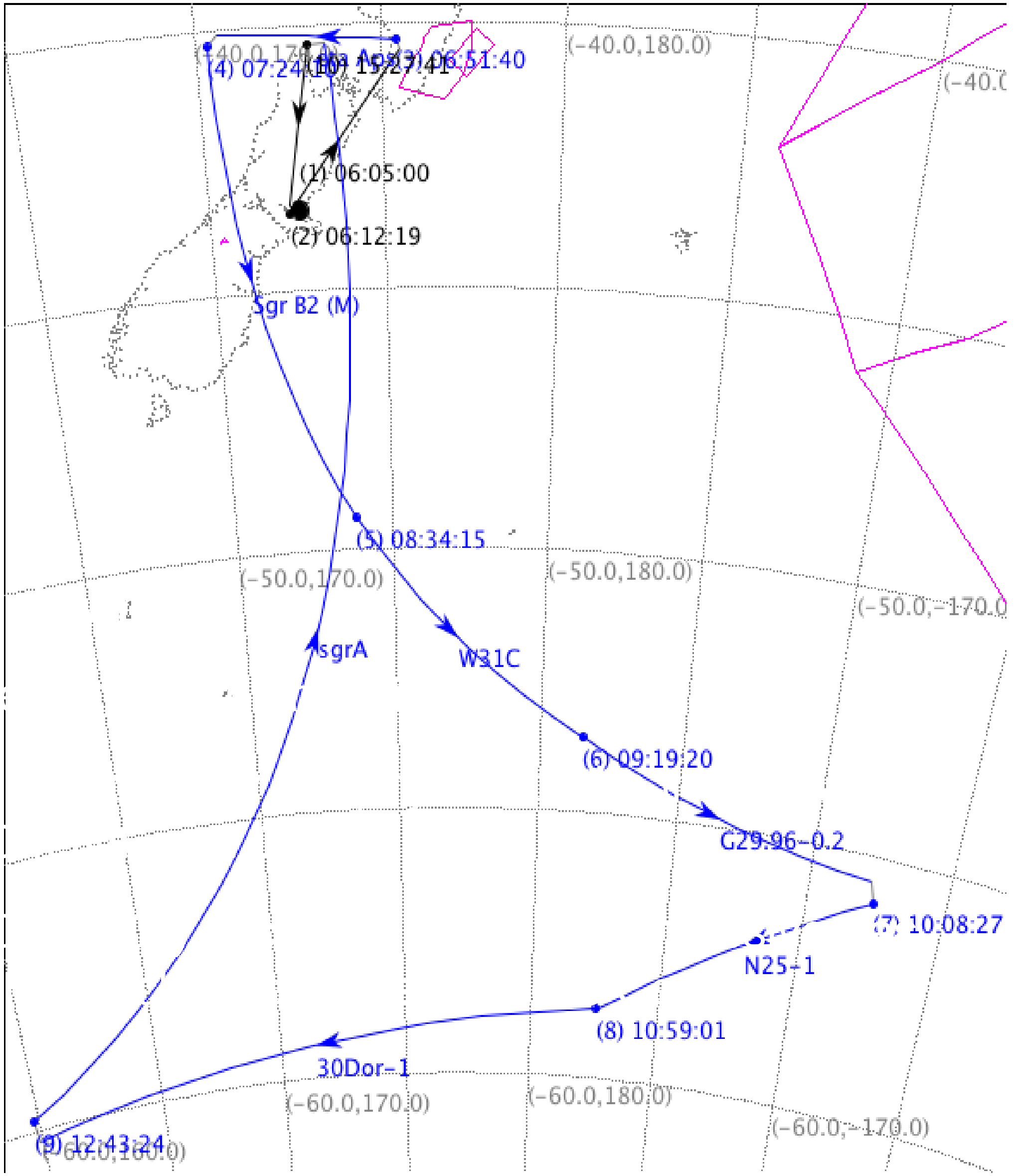
highly dust-obscured bipolar molecular outflow.


LMC
GMC CO 1-0
Fukui et al. 2008
NANTEN 4m tel.
1000光年

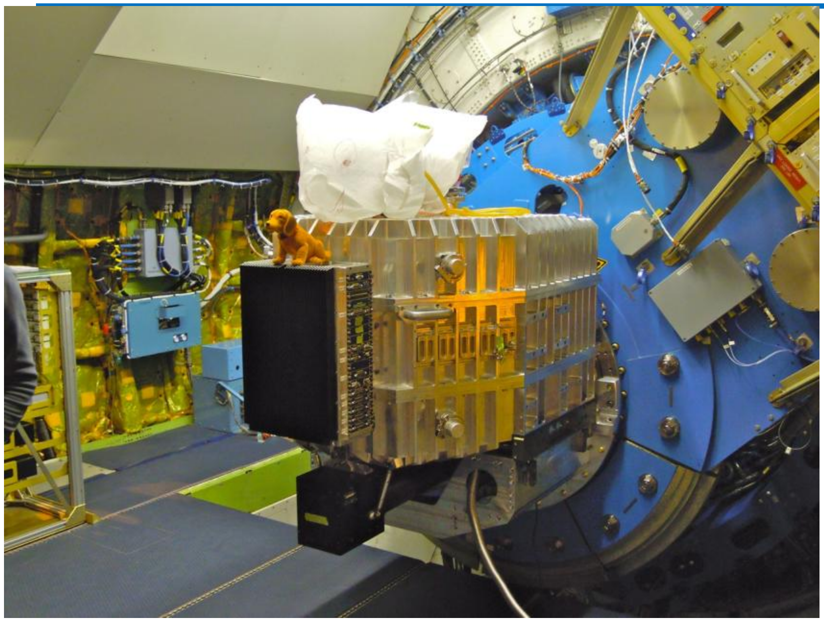
CII (red) in 30 Dor in LMC



New Zealand Deployment: flight path GC/30Dor



FIFI-LS and EXES First Light

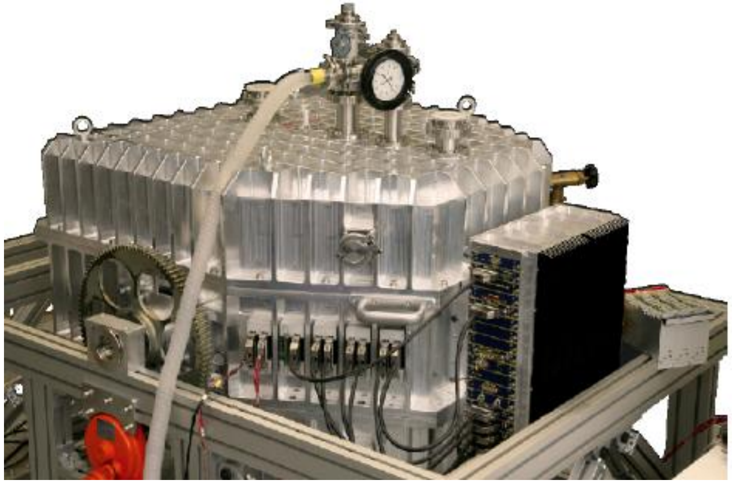


FIFI-LS on the telescope
Alfred Krabbe PI
←(Similar to PACS Spectrometer)

EXES Team after installation -->
Matt Richter PI
(Similar to TEXES)

FIFI-LS: Far-IR integral field Spectrometer

new PI: Krabbe@DSI



Detectors: Dual channel 16 x 25 arrays;
42 – 110 μm (Ge:Ga)
120 - 210 μm (Ge:Ga stressed)

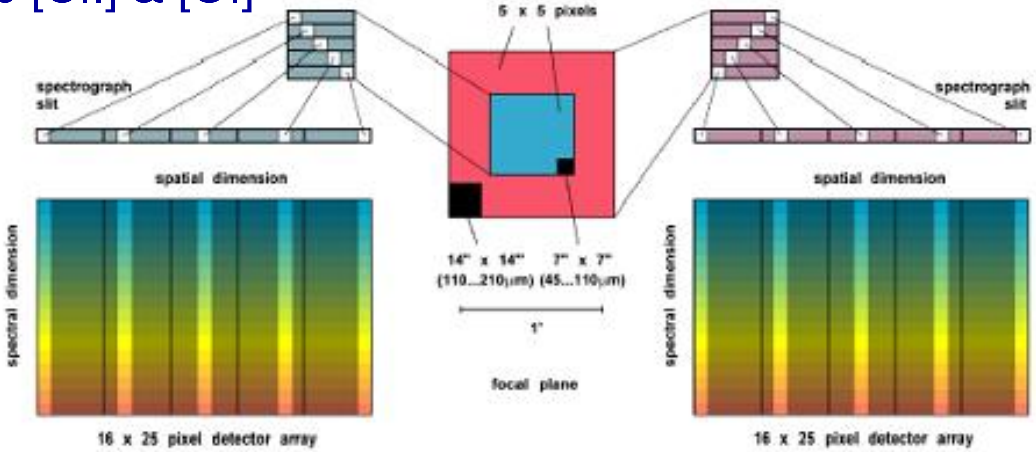
Field of View: 30” x 30” (blue), 60” x 60” (red)

R= 1500 - 6000

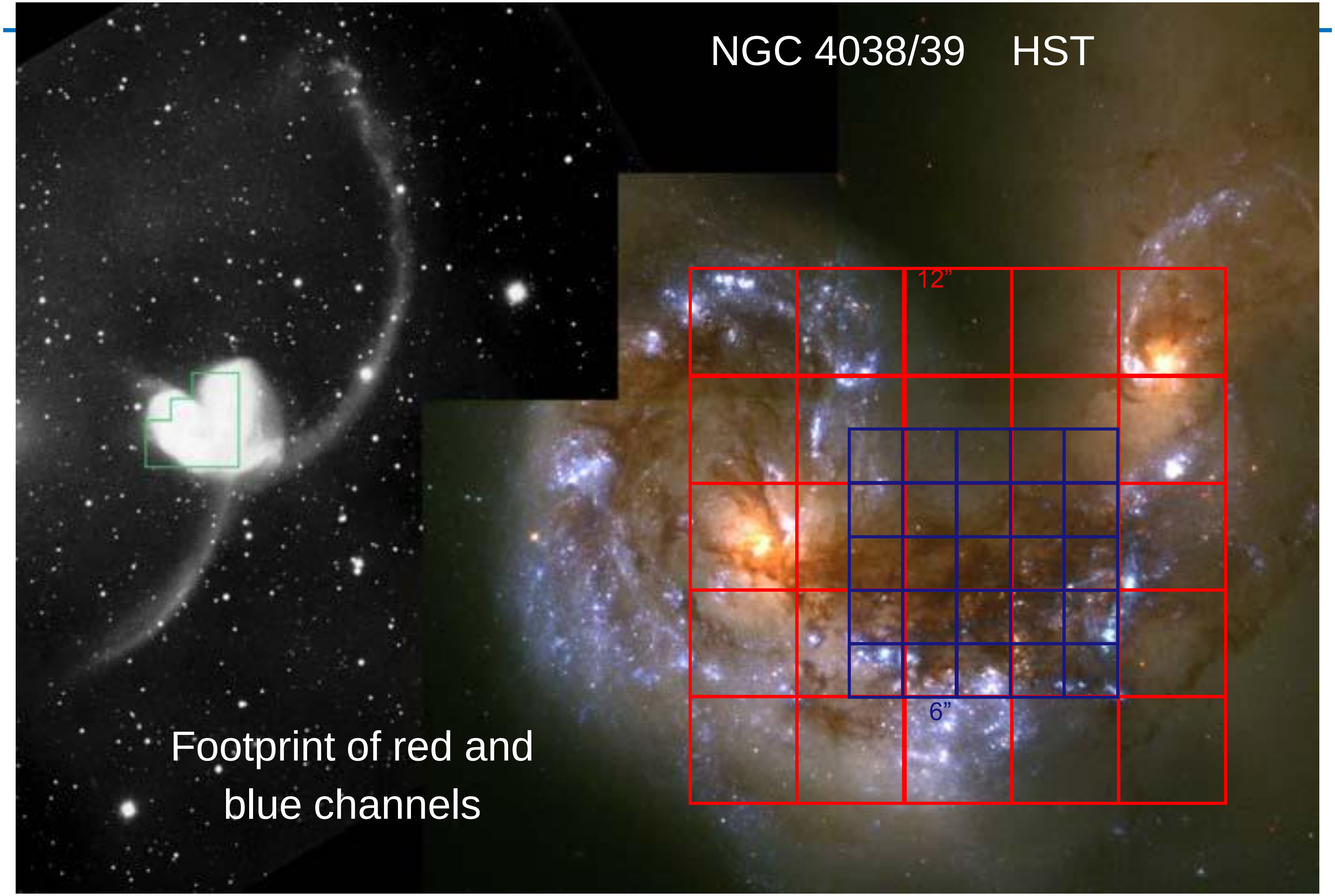
Science: Imaging of extragalactic [CII] & [OI]

Targets: Extragalactic systems

NB: Imaging array is 5 x 5 pixels



On sky orientation of ‘blue’ and ‘red’ channels

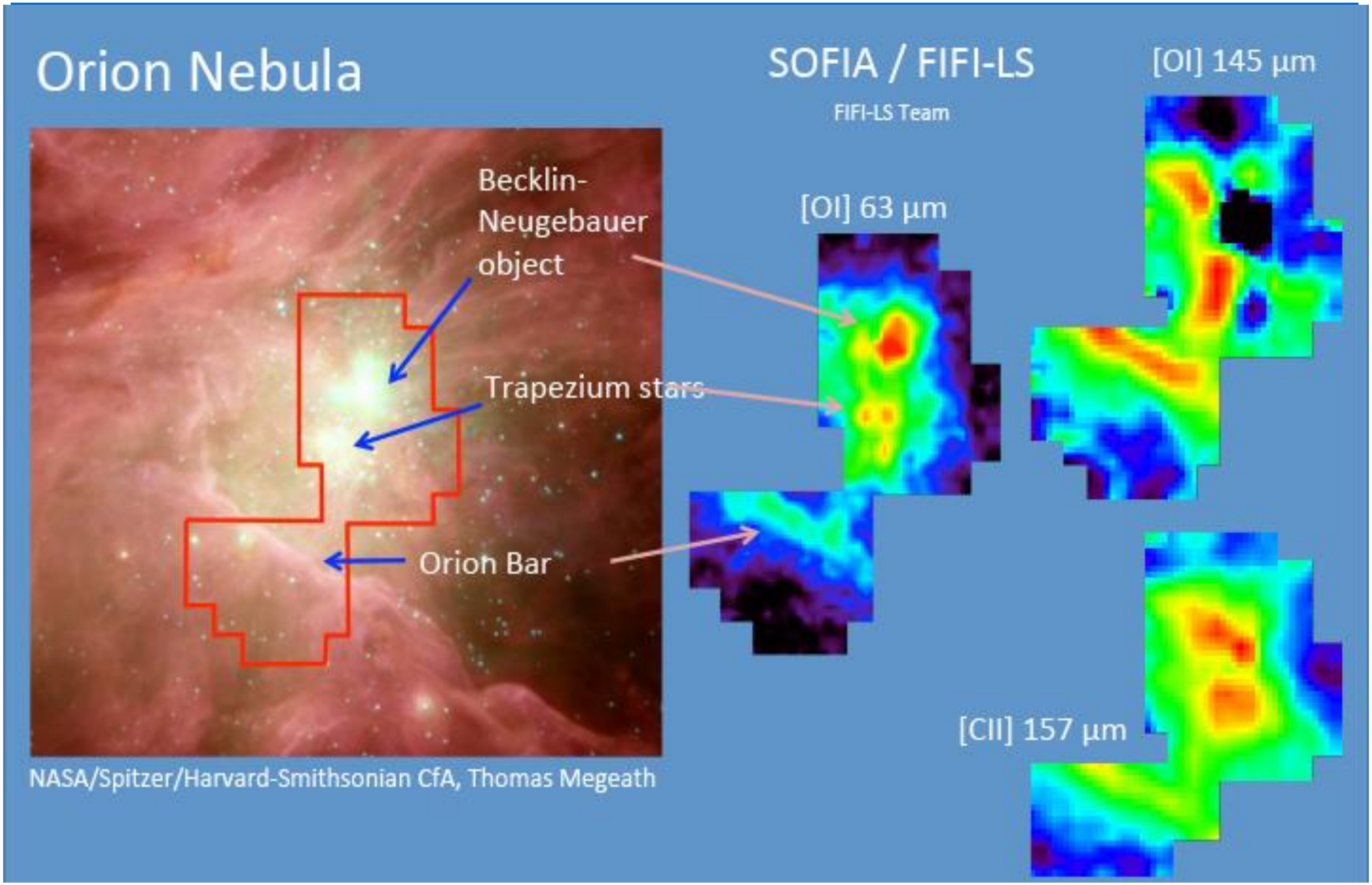

NGC 4038/39 HST
12”
6”
Footprint of red and
blue channels

FIFI-LS first science

- Orion nebula (classical PDR: CII, OI 63mu+145mu)
- Galactic Center circumnuclear disk (OI 63mu, cont.)
- Nearby galaxies (eg. M82, starburst wind: CII, OIII)

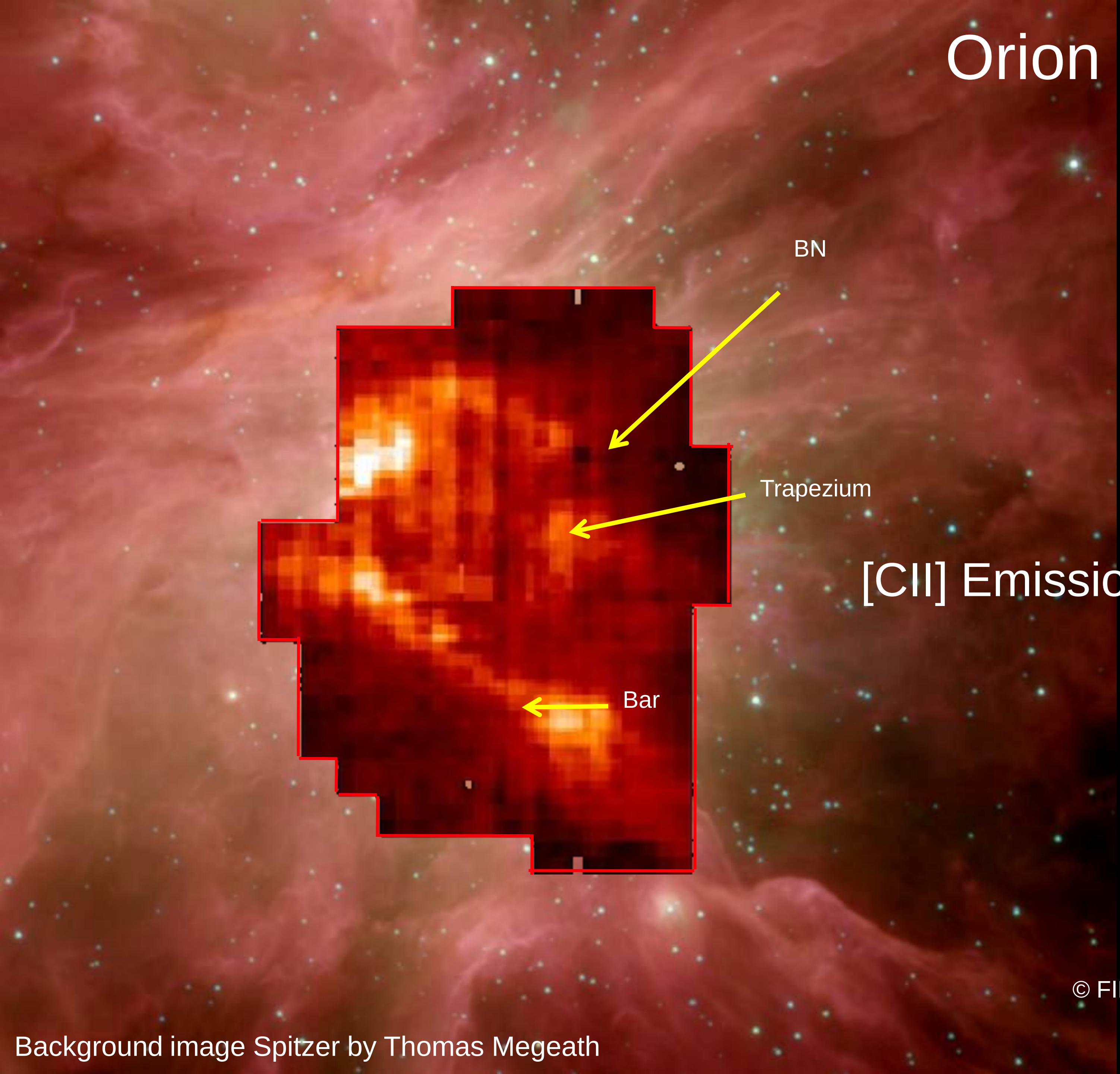
M51 CII map

FIFI-LS Orion Nebula Observations



Orion

April 2014 &
March 2015



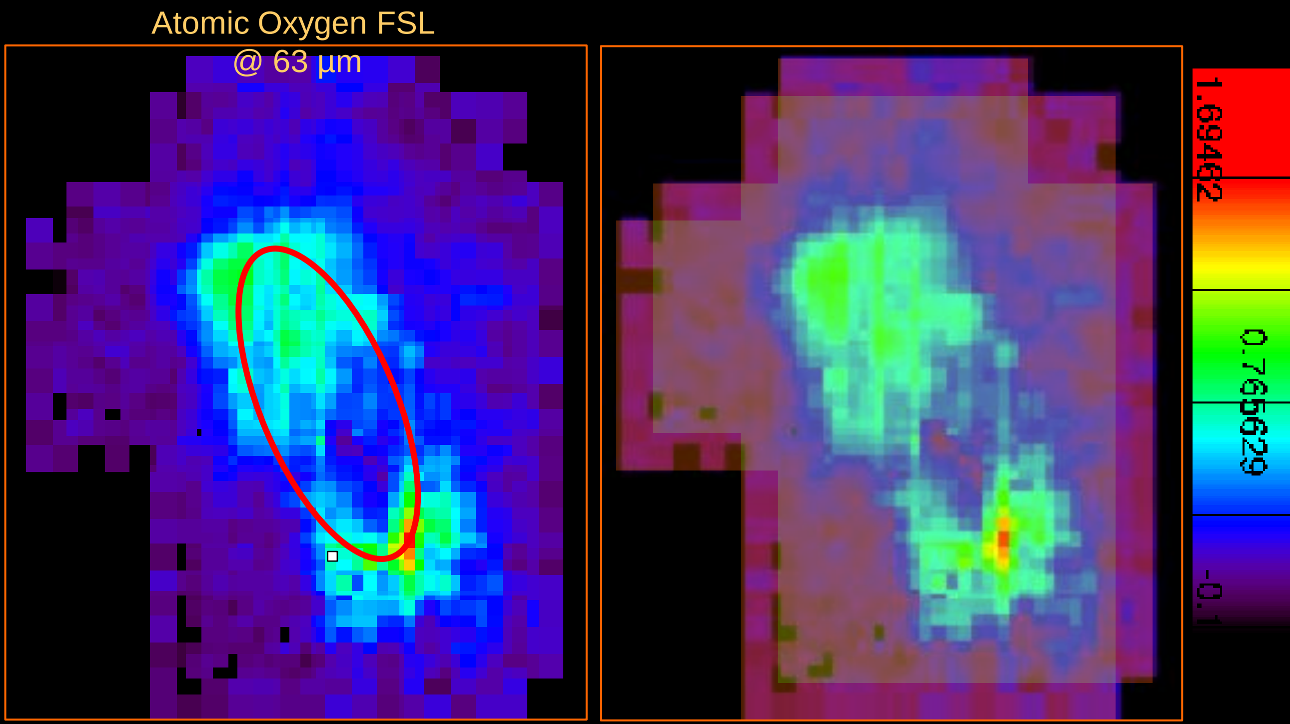
[CII] Emission at 158 µm

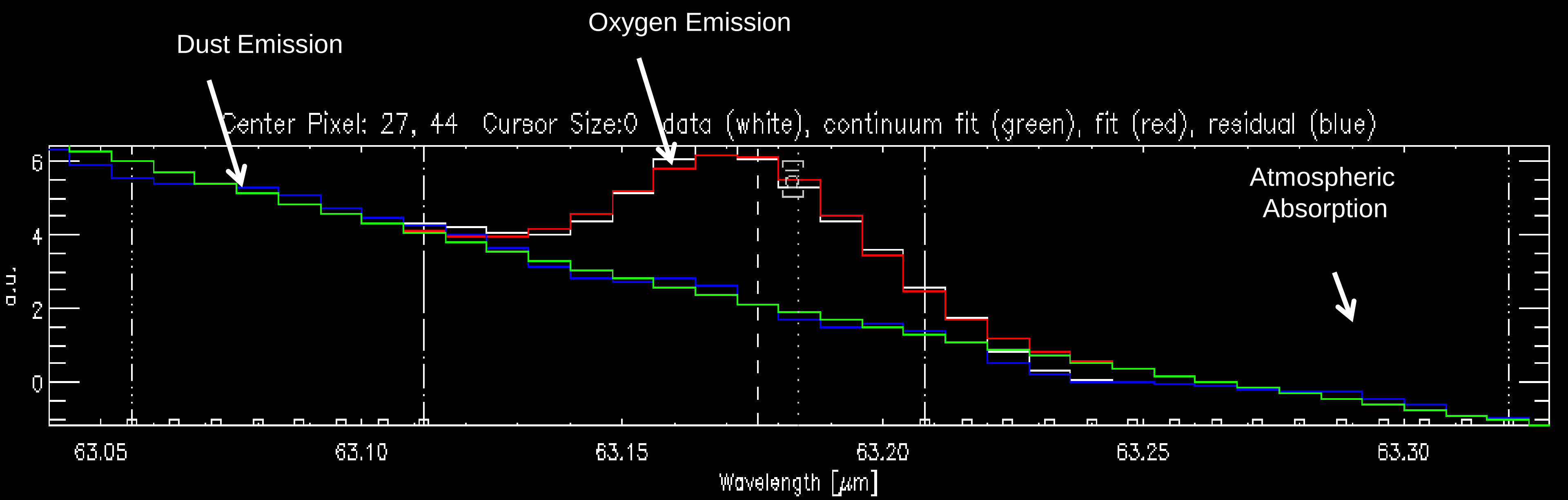
Quicklook &
1. order FlatField applied

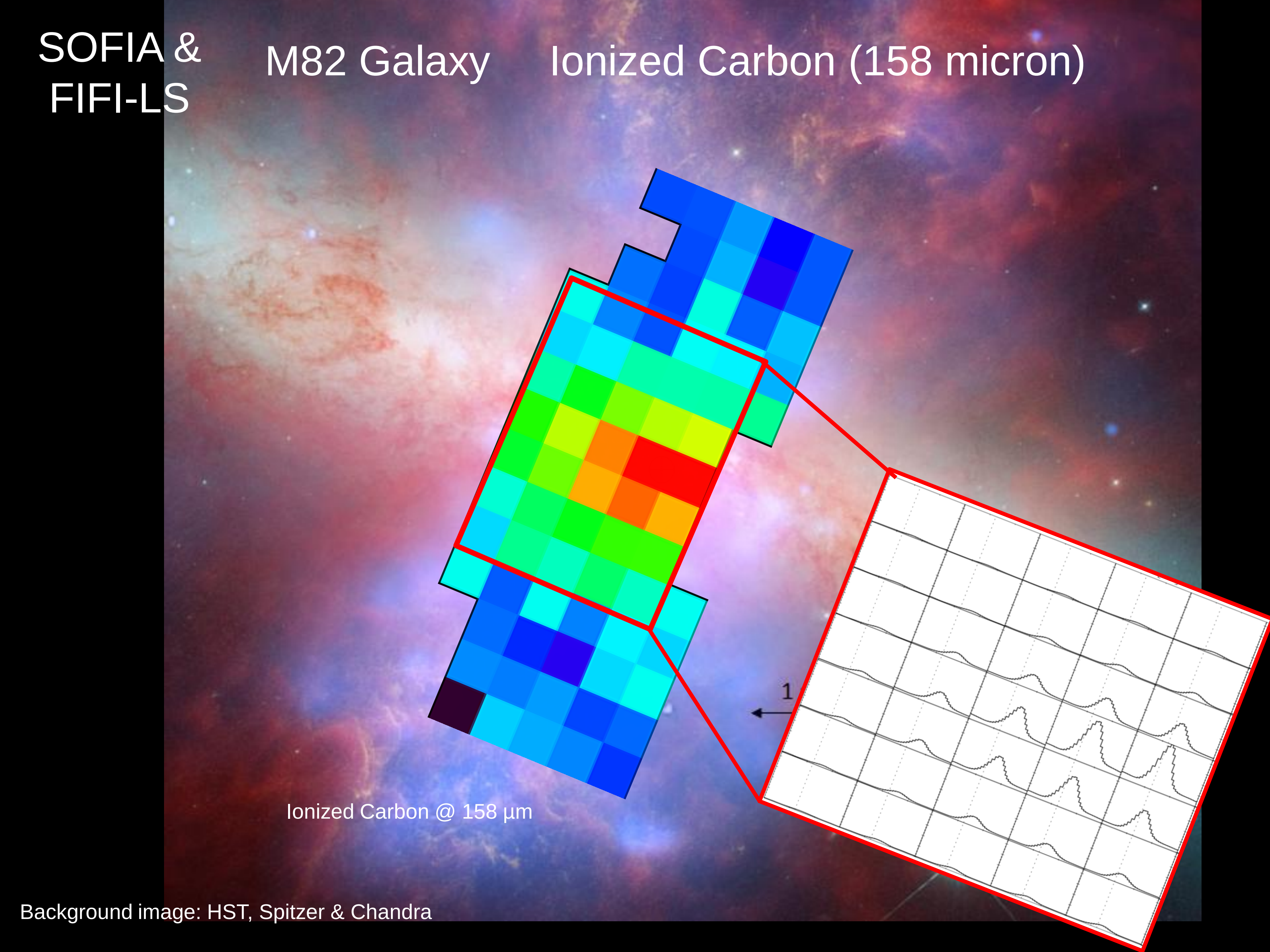
Background image Spitzer by Thomas Megeath

FIFI-LS GC


FORCAST
Lau et al. 2013

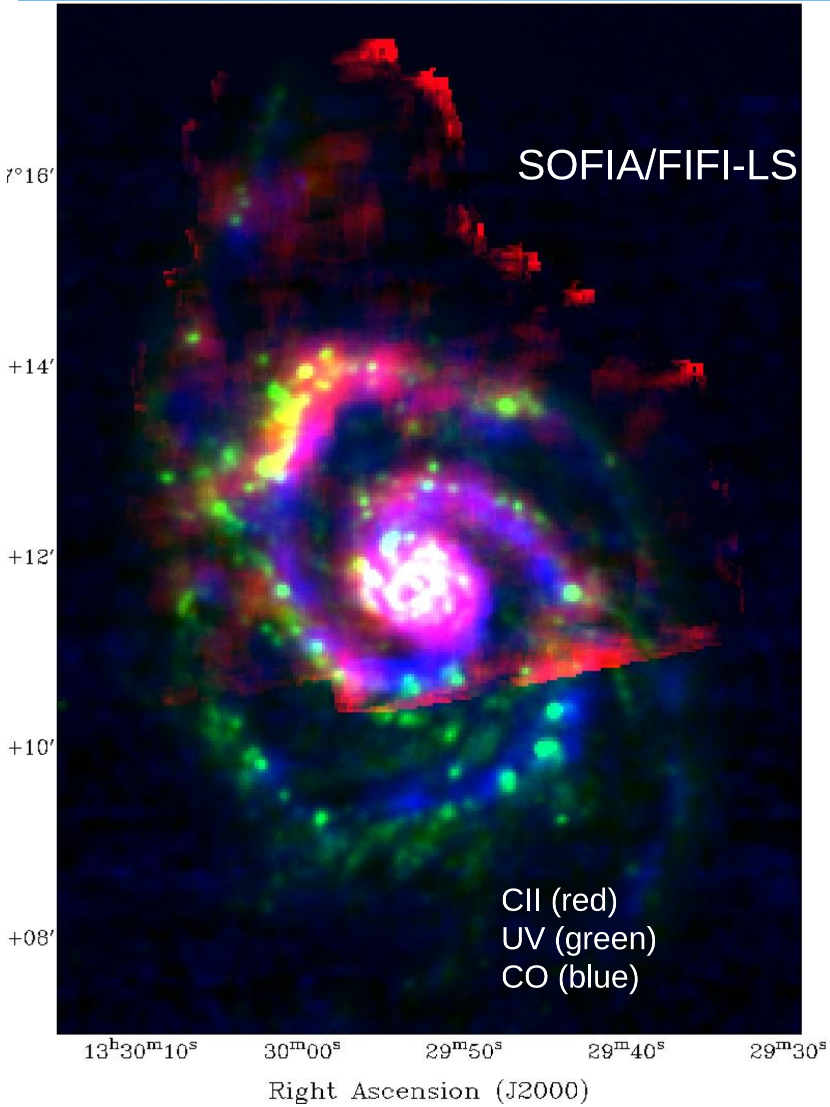

Atomic Oxygen FSL
@ 63 µm
1.69462
0.765629


Dust Emission
Oxygen Emission
Center Pixel: 27, 44 Cursor Size:0 data (white), continuum fit (green), fit (red), residual (blue)
Atmospheric Absorption
a.u.
6
4
2
0
63.05
63.10
63.15
63.20
63.25
63.30
Wavelength [µm]



SOFIA &
FIFI-LS
M82 Galaxy
Ionized Carbon (158 micron)
Ionized Carbon @ 158 µm
Background image: HST, Spitzer & Chandra

M51 galaxy with SOFIA (FIFI-LS) and Herschel/PACS



EXES

PI: Matt Richter, UC Davis

mid-IR spectrometer

(5-28 mu, R=10^5)

Exes Instrument (mid-IR high-res. Spectrometer)

EXES in lab

Mid- IR Spectrometer

EXES Commissioning : Water in abs. in AFGL 2591

10 Mo protostar in Cygnus

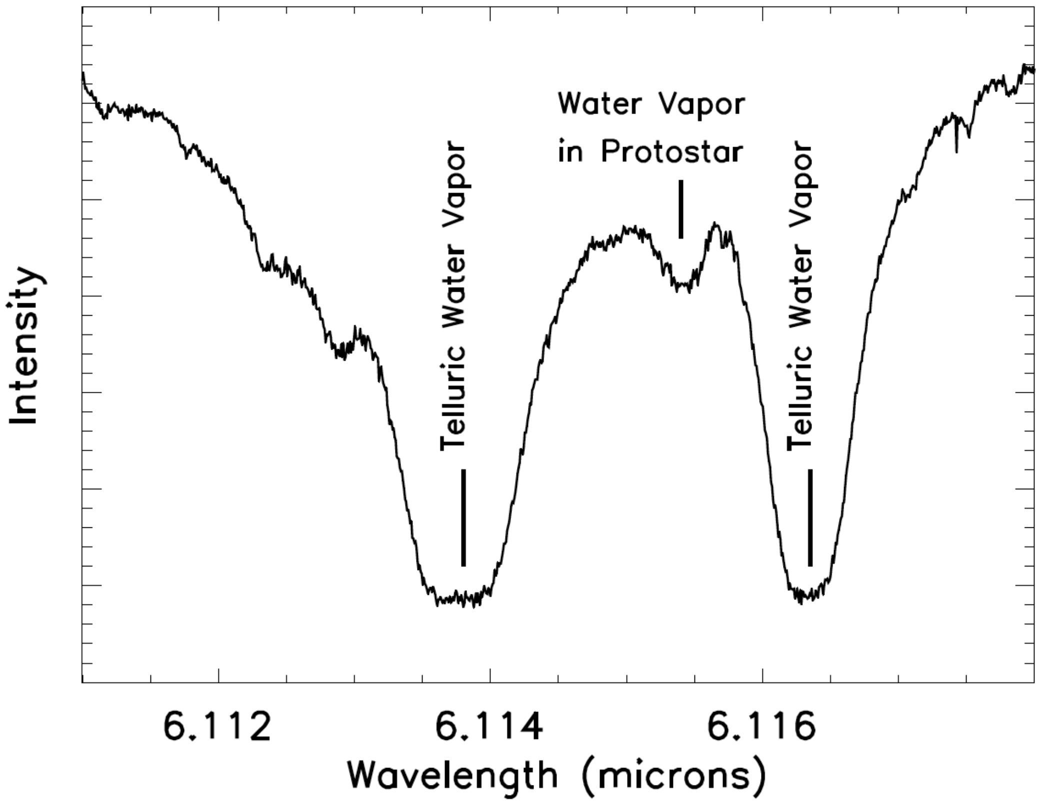
0(0,0)→1(1,1) H_2O transition and other ro-vib. water lines

unobservable from ground

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

improves on R=2000 ISO studies

paper: Indriolo et al. 2015, ApJ

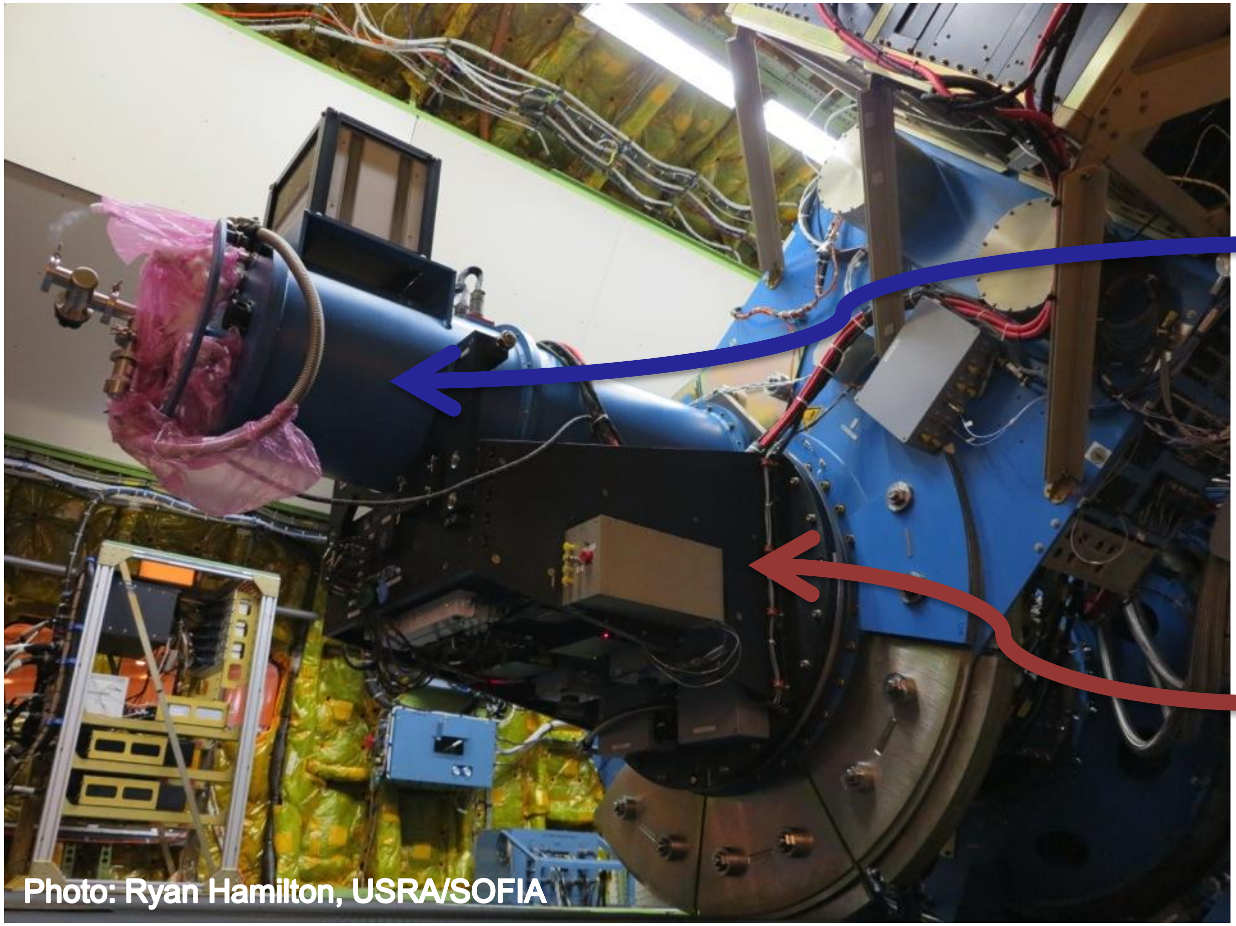


FLITECAM

near-infrared camera
1-5 micron

PI: Ian McLean, UCLA

FLIPO

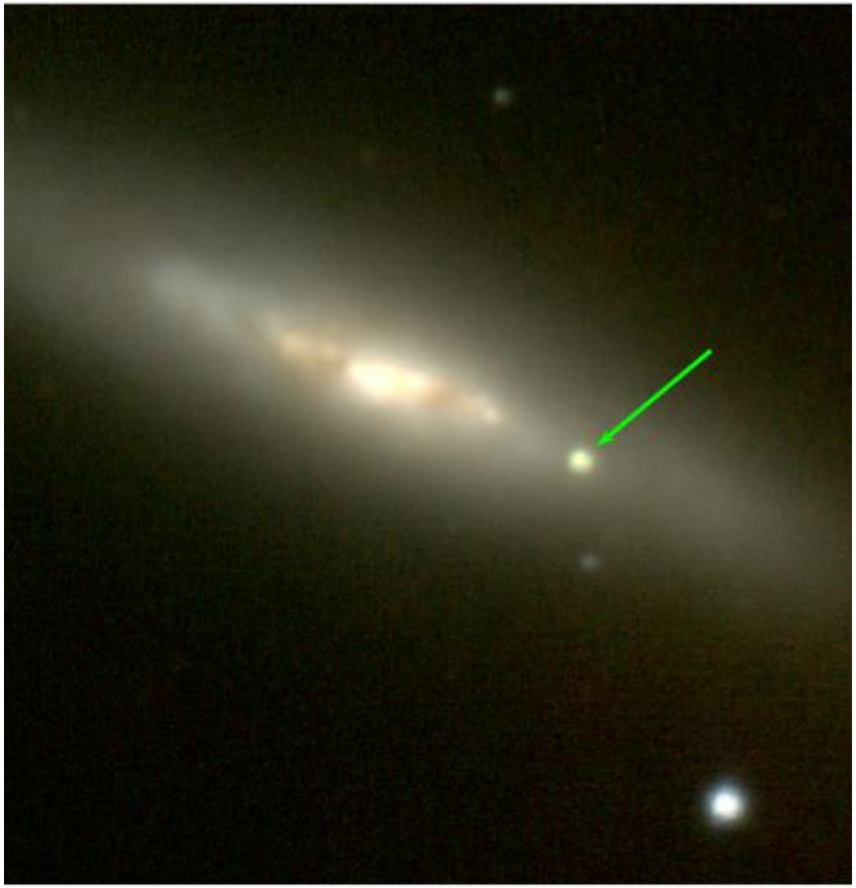


FLITECAM
Ian McLean, et al., UCLA

HIPO
Edward Dunham, et al., Lowell Observatory

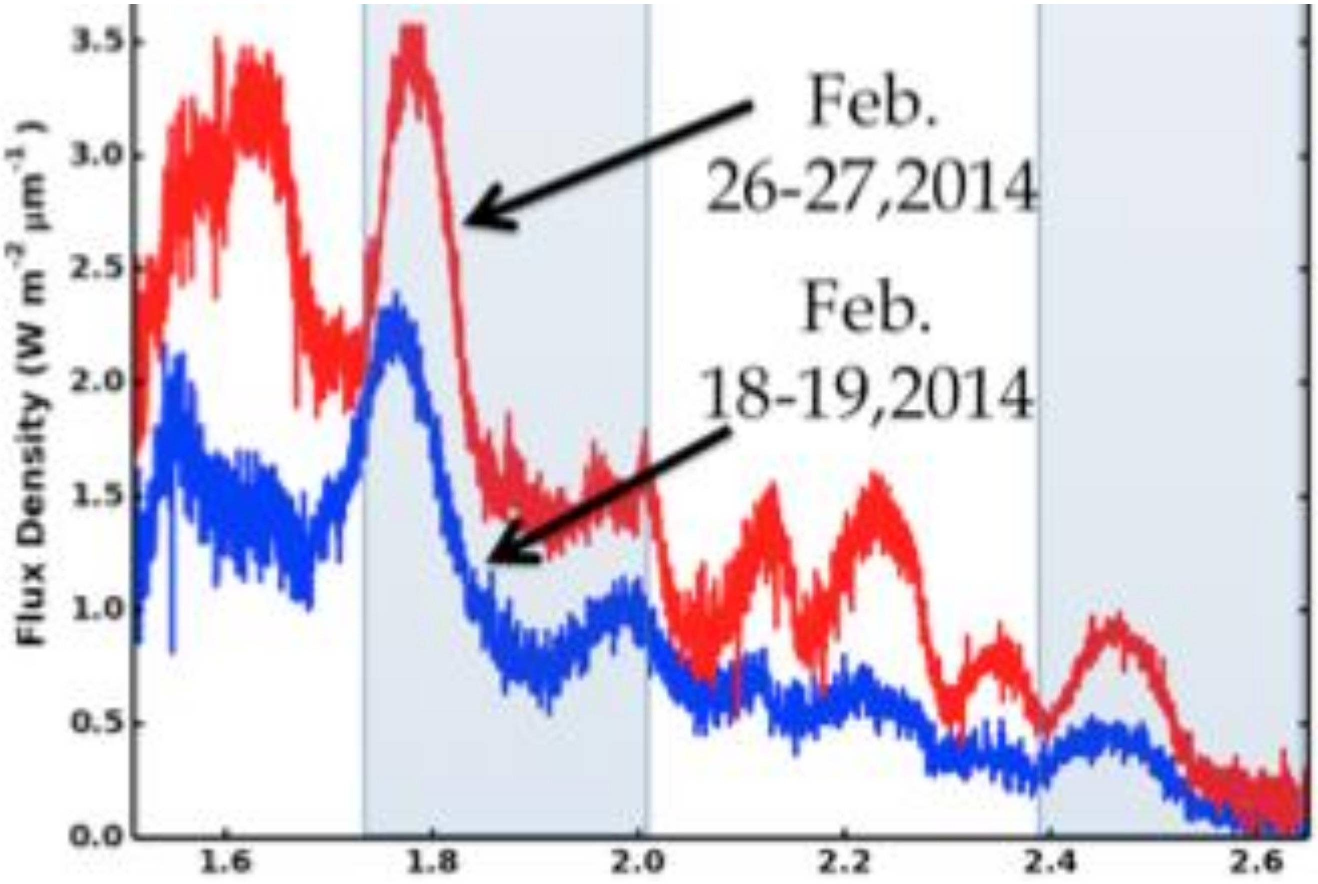
HIPO: 2 simultaneous optical photometric channels
FLITECAM: 1 NIR channel with photometry or spectroscopy

FLITECAM SN2014J Data



- Supernova Type Ia went off in Jan 2014
  - Taking data at T+36 days
  - Spectroscopy + imaging
  - Target of Opportunity
- Coverage R~1200 spectra 1 to 3.3 mu
- Results are published (Vacca etal 2015 ApJ)

FLITECAM and HIPO together (FLIPO): Supernova Type Ia 2014J in M82



upGREAT

(THz array)

1.9THz (C+)

4.7 THz (OI)

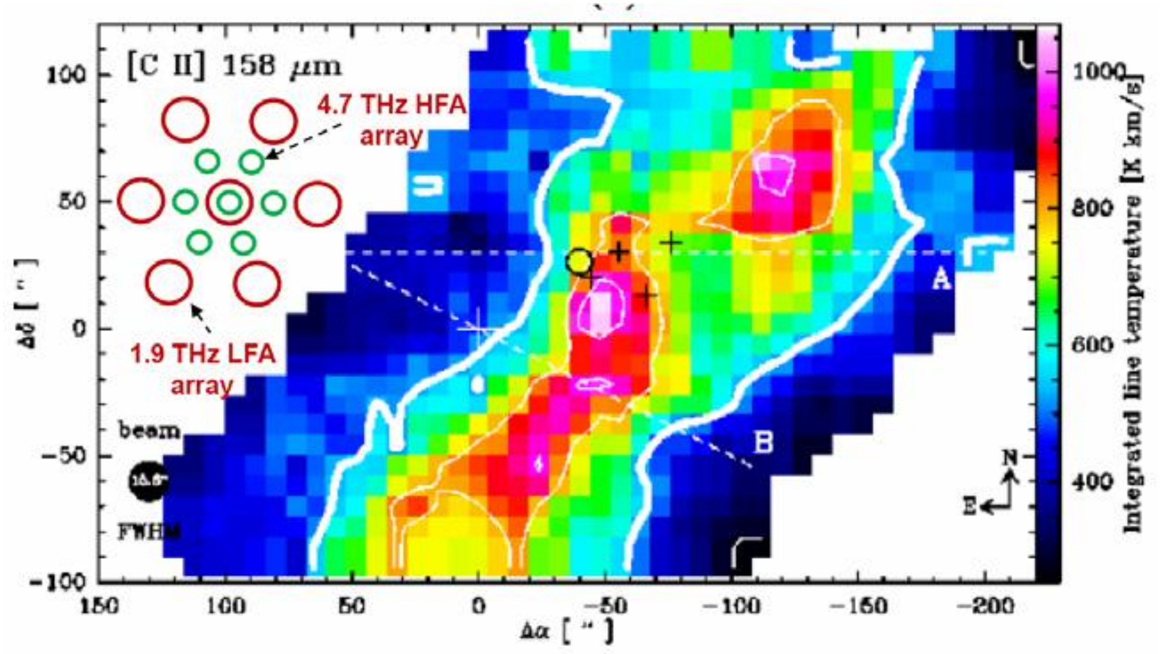
4GREAT

4+1 frq channels

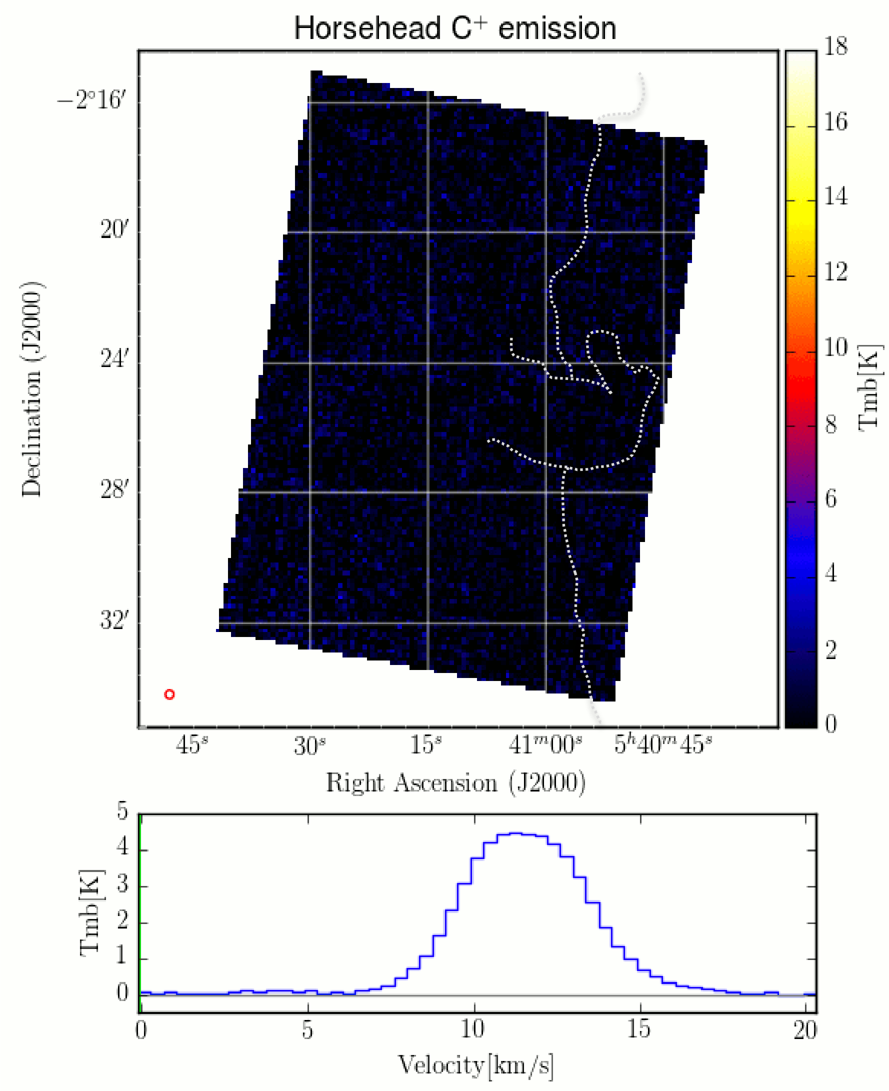
(<1 THz)

German Instrument Developments

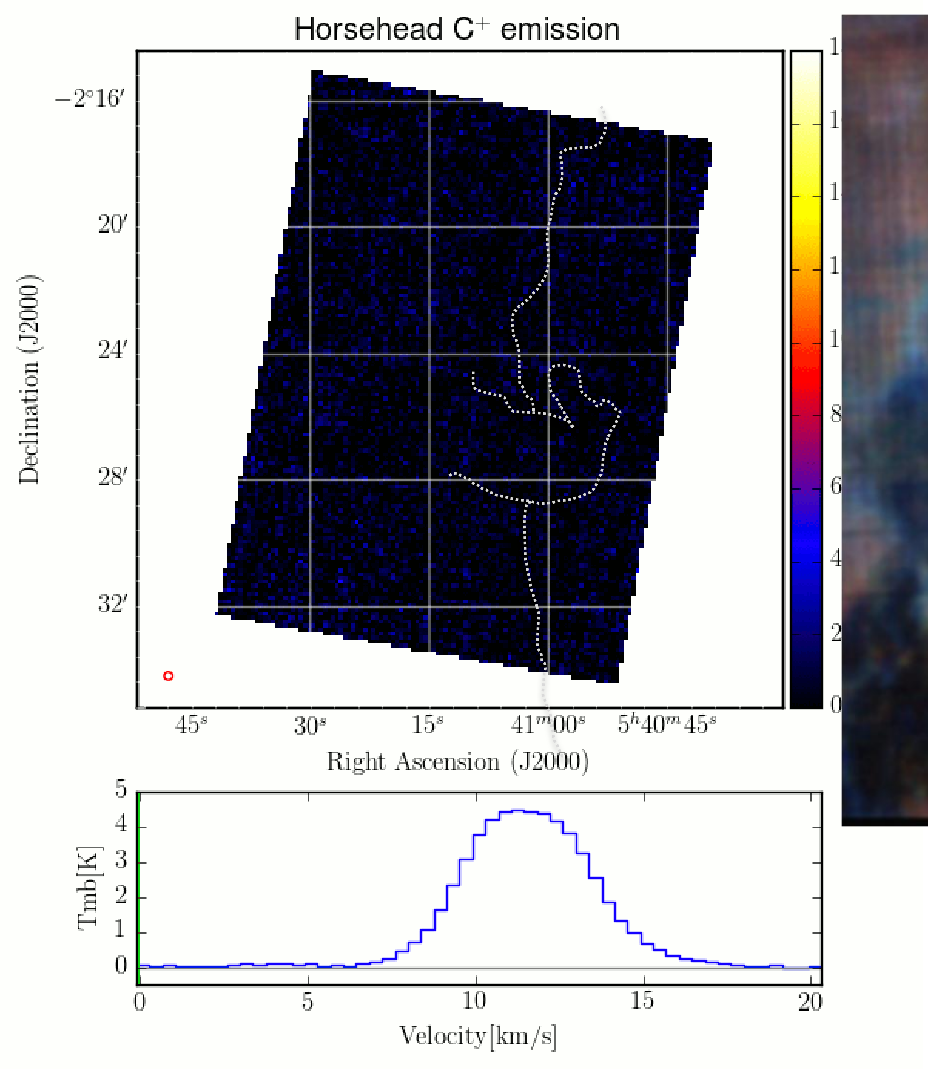
- upGREAT, an enhancement of the GREAT heterodyne instrument, has been developed by Rolf Güsten and collaborators and has been commissioned in Dec 2015
- Compact heterodyne arrays
  - 7 pixels x 2 polarizations @ 1.9 to 2.5 THz
  - 7 pixels @ 4.7 THz [O I]

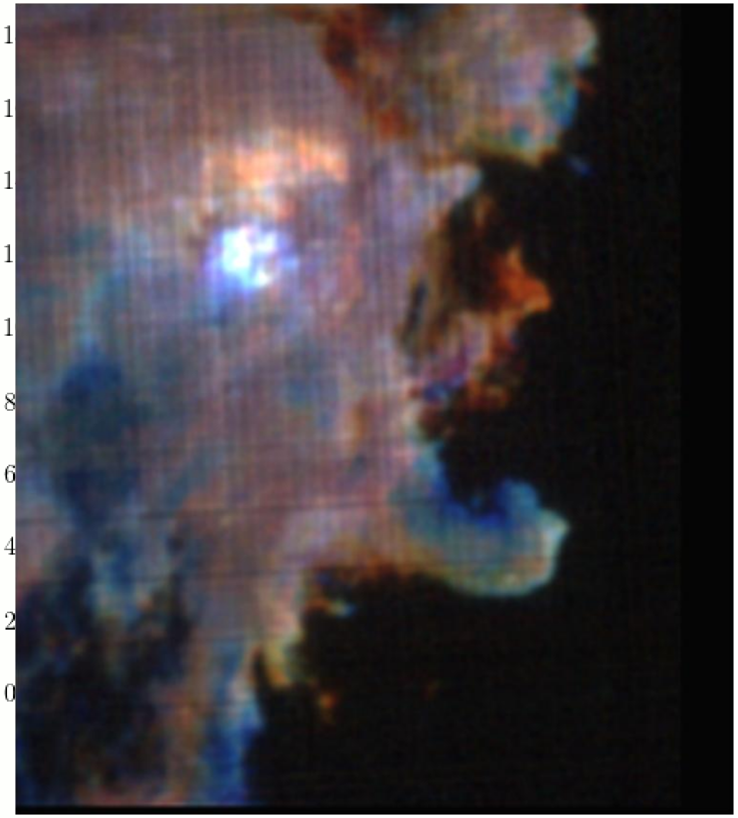


DDT Demonstration Observation upGREAT [C II] Map



upGREAT [C II] map (left), APEX CO 3-2 map (right)





HAWC+

PI: Darren Dowell, JPL

Far-infrared camera

4 x (32x40 pixels)

50-240 mu, 5 nb filters

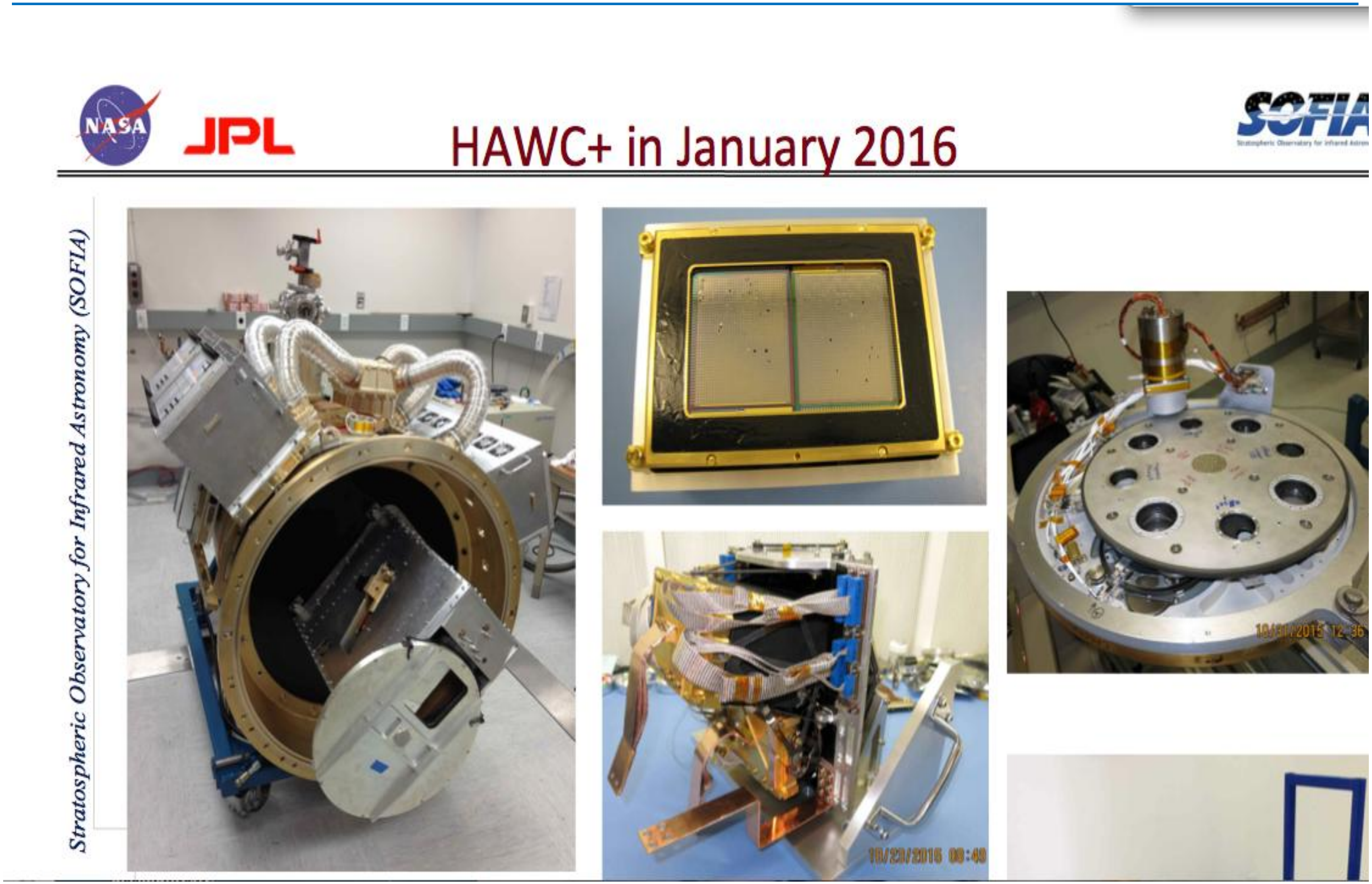
TES detectors@0.1K

polarimetric capability

(unlike Herschel)

HAWC+ upon arrival in Palmdale

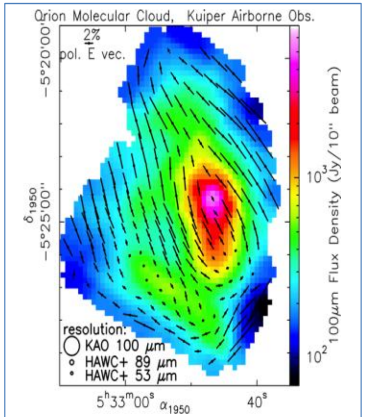
HAWC+ hardware



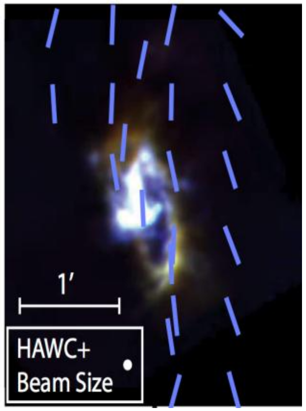
HAWC+ science and instrument sheet

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 polarization, akin to the Kuiper Airborne Observatory map of Orion (*above*; D. A. Schleuning 1998, ApJ 493:811). SOFIA/HAWC+ has much better sensitivity, 10-50× better areal resolution, and multiple wavelength bands. The polarization is due to dust grains aligned with respect to the interstellar magnetic field. Polarization mapping reveals the structure of magnetic fields and estimates their strength.



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 turbulent power spectrum in nearby molecular clouds
- Efficiency of dust grain alignment
- Magnetic field configuration of the Galactic Center
- Polarization and (potentially) the primary magnetic field orientation of T Tauri star disks and envelopes
- Magnetic structure in the dense interstellar medium of nearby bright galaxies

HAWC+ will obtain useful polarization maps and images with thousands of vectors in part of a single SOFIA flight.

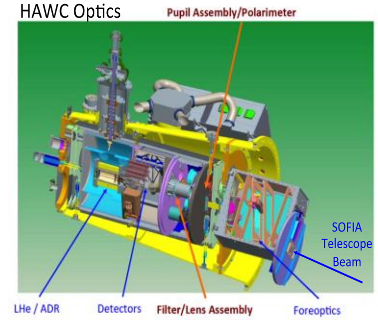
HAWC Specifications

Principal Investigator: Dr. Darren Dowell,
Jet Propulsion Laboratory

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

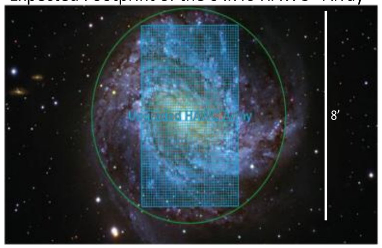
HAWC+ is designed to offer imaging and polarimetry in each of five bands from λ = 53 to 216 μm. NASA/Goddard and NIST are producing the two bolometer detector arrays for HAWC+. For SOFIA far-IR continuum bands, the detectors will deliver background-limited performance with high quantum efficiency. The 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

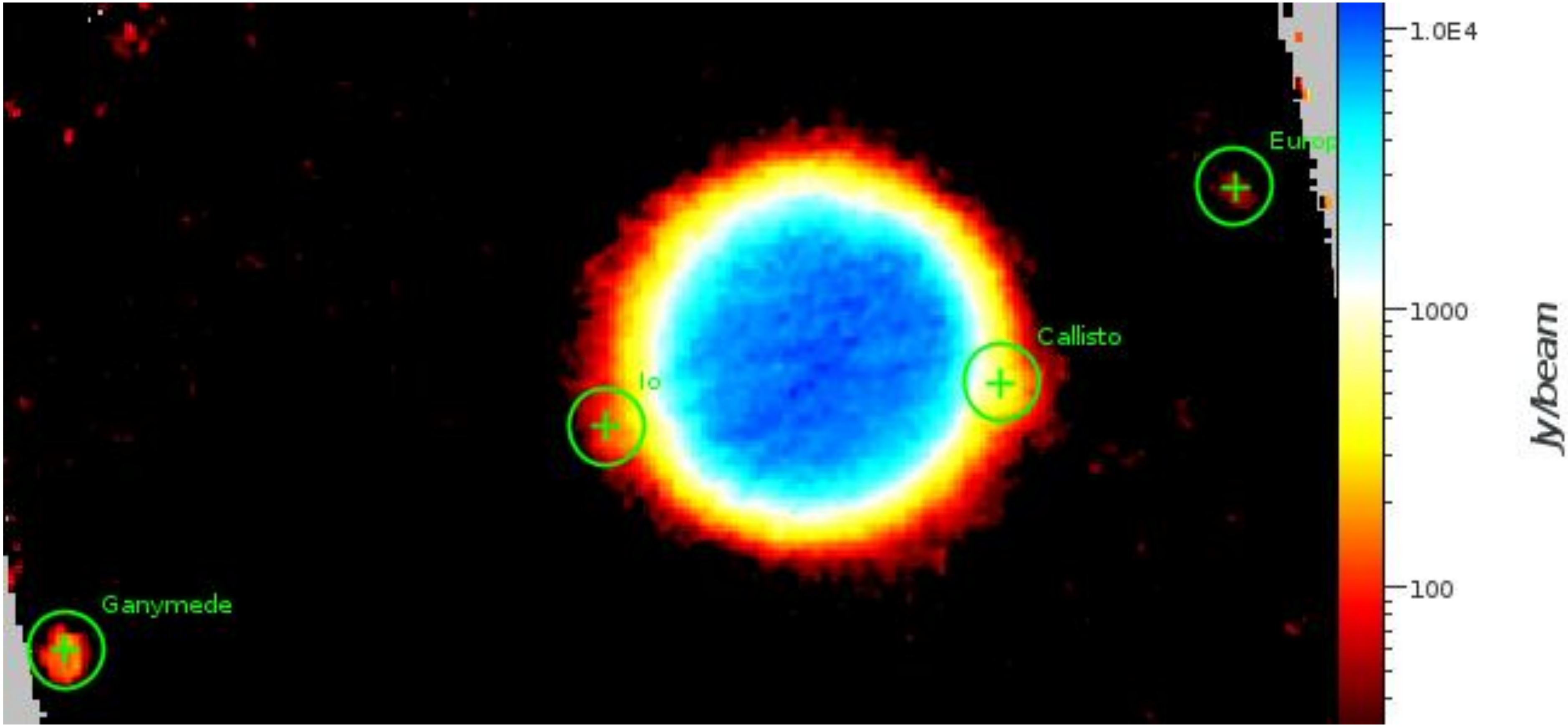
Expected Footprint of the 64x40 HAWC+ Array



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...)	0.9	1.2	2.5	5	5

Jupiter and its Galilean moons as seen by SOFIA/HAWC+ at 53 microns
HAWC+ first light image, April 2016



FIR Dust Continuum Emission Polarimetry

- Far Infrared polarimetry will help elucidate the role of magnetic fields in the energetics of the interstellar medium
- SOFIA now has a unique polarimetric capability that was selected as the 2nd Generation Instrument by NASA and met with great interest in CfP for Cycle 4. 1st commissioning done.

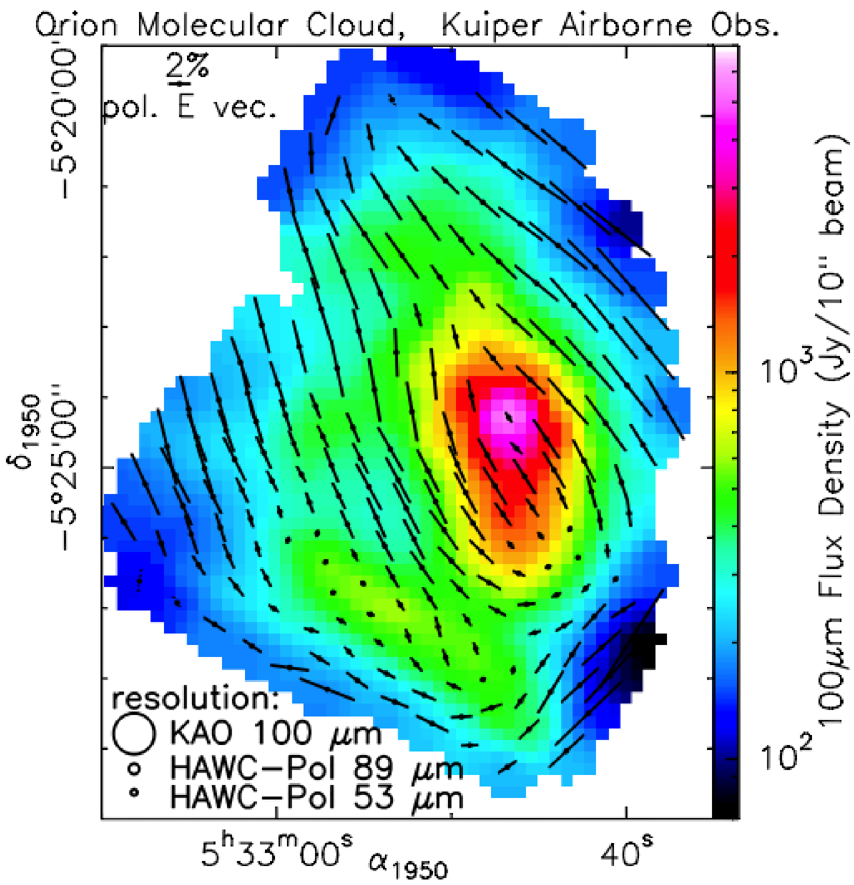


Figure 5. Linear polarization of the Orion Nebula at 100 μm measured with the KAO by Schleuning (1998) . Shown are the beam sizes of the KAO polarimeter and HAWC upgrade. (Dowell et al. 2007)

SOFIA in Context with Other Observatories

- Herschel ran out of cryogens in Spring 2013: SOFIA natural successor, Herschel community using SOFIA
- SOFIA will provide the only regular access for you to the far-IR (30 to 300 micron) for quite some time
- JWST (MIRI 5-28 micron), FIR Surveyor, balloons…
- Synergies with ALMA/APEX, IRAM/NOEMA, SMA, and the doomed CCAT (spatial res. similar to SOFIA)

SOFIA Cycle 5 important dates + numbers

Cycle 5 Call for proposals (CfP): 29 April 2016

Cycle 5 Proposal subm deadline: 1 July 2016

Large programs (>40 hours) encouraged, eg. LMC

Southern hemisphere deployment likely (as before)

NASA funding: 10 kU$ pro 1 hour awarded time !!

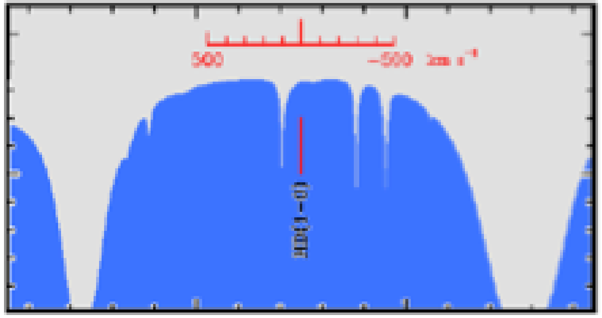
Future ISM science

- GC magnetic field studies (HAWC-pol camera)
- M51 C+ mapping (US/German legacy project)
- Low-Metallicity Magellanic Cloud ISM studies
- HD 112 mu line, H2 para/ortho (28mu/17mu)
  but much better sensitivity needed (3rd gen?)
  perhaps imaging of the warm gas in the CMZ
  or measuring gas mass in protoplanetary disks

USRA NASA DLR SOFIA

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 fe

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 sta rotational line at 112 microns accessible with SOFIA (HD in emssion and in absorptior

.

Detections with ISO means that GREAT high resolution spectroscopic study is possible

HD has a much lower excitation temperature and a dipole moment that almo compensates for the higher abundance of molecular hydrogen.

As pointed out by Bergin and Hollenbach, HD traces the cold molecular hydrogen

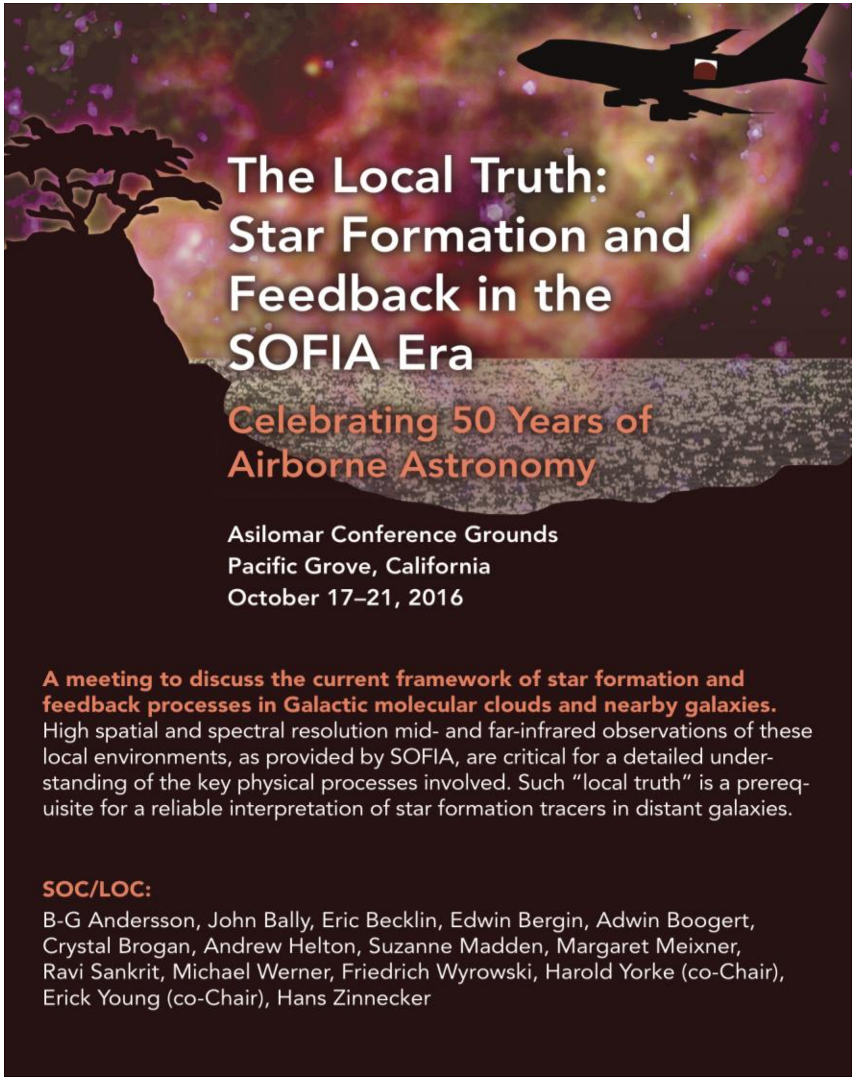
Take home messages

- SOFIA is in good shape (Cy4 in2016, ~100 flights)
- SOFIA is a SF/ISM machine, with unique potential including astrochemistry/disks (simple molecules).

- SOFIA is testing “local universe” and “local truth”.
- SOFIA is currently YOUR only far-IR observatory & fully supported by NASA/DLR for the next few years. NASA provides substantial $$ support for US PIs.


Come fly with us!
Next proposal deadline:
July 1, 2016
www.sofia.usra.edu

SOFIA conference



Annoucement in SF--Newsletter 282
Asilomar, California; Oct 21-24, 2016

Registration now open at website…
Abstracts contributed talks welcome!

Airborne Astronomy Ambassadors (AAA) Program

- The initial Airborne Ambassadors Pilot Program has proven the responsive chord that SOFIA provides to students
- Dozens of educators from all over the US are selected since 2012 to participate in AAS competitive program (and some teachers from Germany, too)

FYI

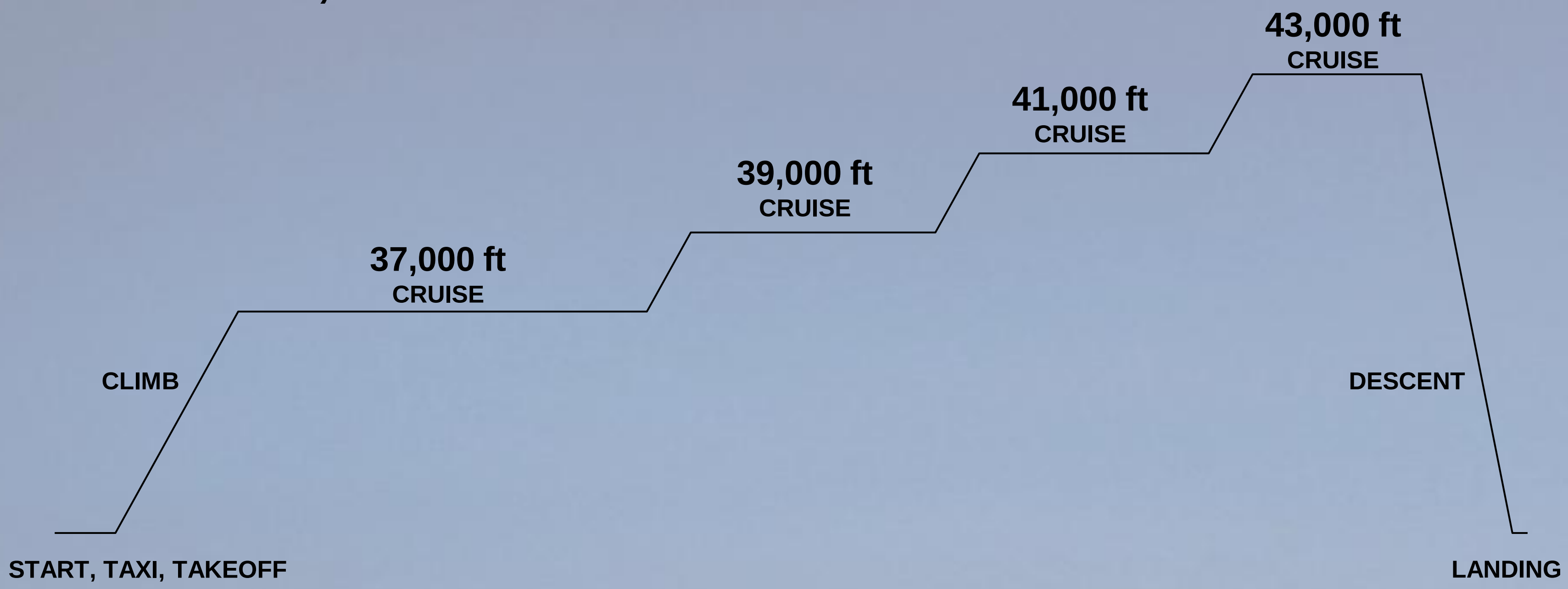
supplementary SOFIA material

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

SOFIA's ISM POTENTIAL
ISM cycle, feedback

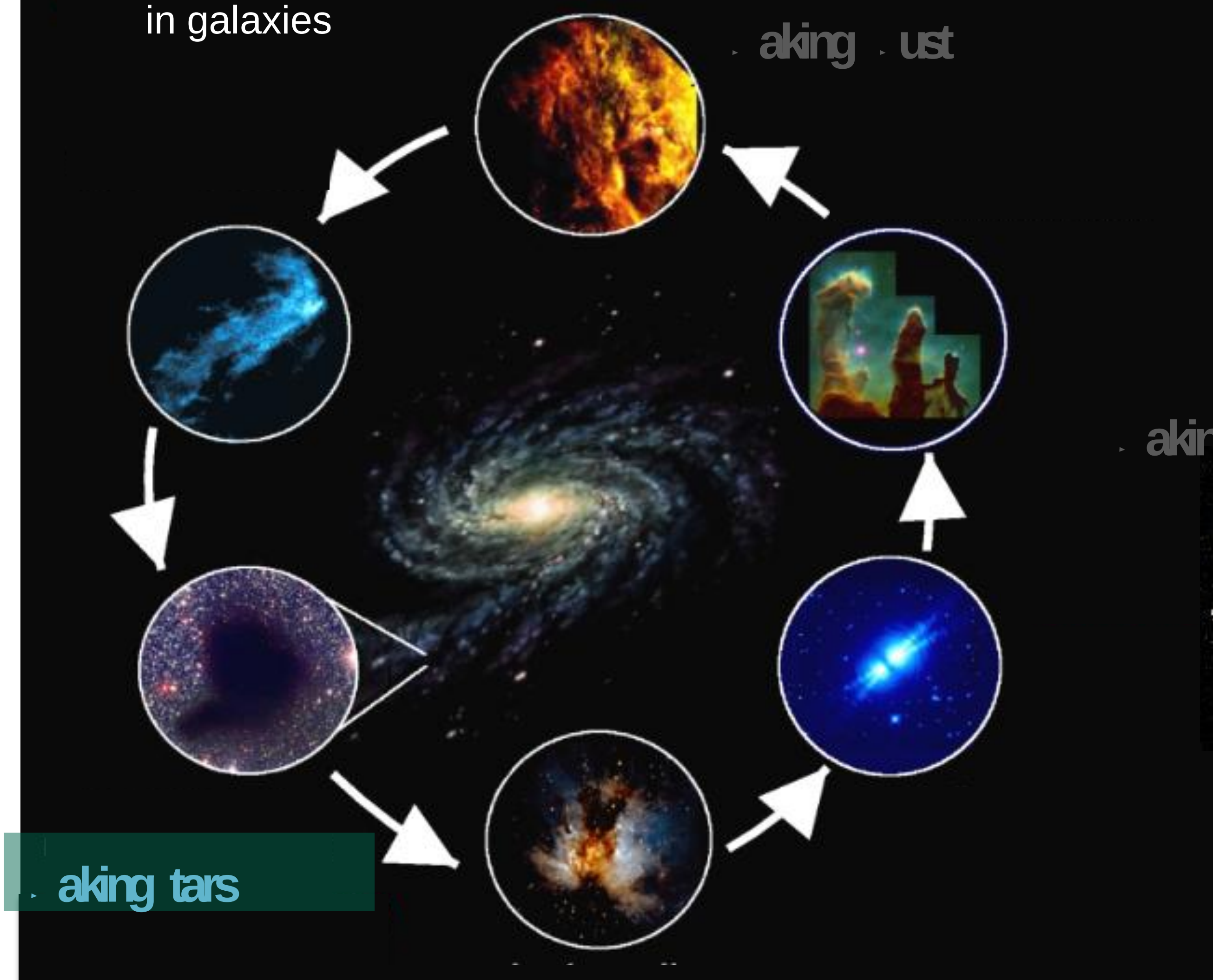
cycle: gas → stars → gas (molecules, dust)
feedback: ionis. radiation, winds, SN remnants

chemical enrichment (heavy elements, dust)
cooling, condensation, fragmentation, protostars

collapse, outflows, turbulence, mag. fields
shocks (dissipation, cooling), PDR/XDR (heating)

how much gas does not get recycled? (→D/H ratio)

The cycle of interstellar matter in galaxies



Courtesy: Pam Marcum (NASA)

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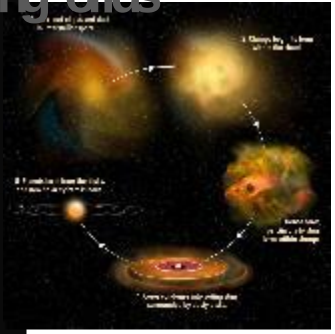
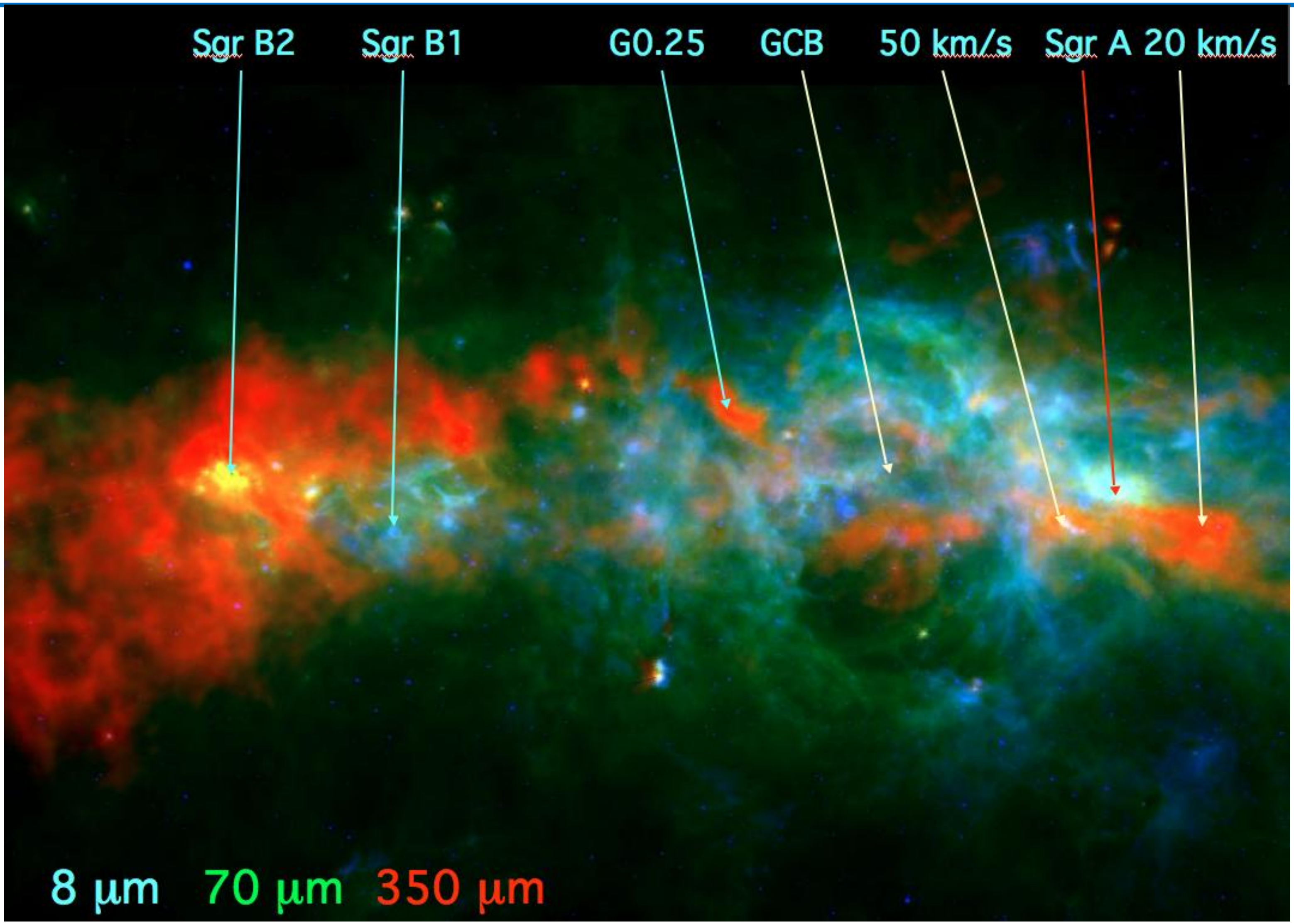


Galactic Center IR/submm image (Bally)



Brief summary of SOFIA ISM science highlights

FORCAST (5-40 mu) :
A new mid-IR self-luminous source in Orion BN-KL (IRc4, brighter than BN)
Young star clusters embedded in HII regions (e.g. W43, Wd1;Spitzer saturated)
A mid-IR dusty circumnuclear ring (CNR) in the Galactic Center (3pc diameter)
Dust emission in Sgr A East supernova remnant(dust surviving reverse shock)

GREAT (dual channel 1-5 THz spectrometer) [for upGREAT → R. Guesten talk]
Detection of two new molecules: SH, OD (THz rot transitions in Herschel gaps)
Detection of the ground-state OH absorption towards W49N at 2.5 THz (strong)
Detection of the ground-state HD emission towards SgrB2 at 2.7 THz (v. weak)
Detection of protocluster infall in absorption against ATLASGAL cont. sources
Detection of para-H2D+ in absorption towards IRAS 16293 (strong continuum)
High-res velocity-resolved spectroscopy of [OI] 63mu line in planetary nebulae
High-res velocity-resolved spectroscopy of [OI] 63mu line in outflow sources
Tracing MHD-shocks in supernova remnants via CO high J ladder (eg. IC433)
[CII] in 30 Dor and N11/LMC massive photodissociation regions (CO-dark H2)
Optically thick [CII] and optically thin [13CII] in NGC 2024, extragal. implication

Brief summary of SOFIA ISM science highlights

EXES (5-28mu, high-res. long-slit spectrometer)

28mu J=2-0 para-H2 emission, also 17mu J=3-1 ortho-H2 emission (on Jupiter)
6.1 mu high-res. ro-vib H2O absorption in AFGL 2591: outflow vs. disk origin?

FIFI-LS (FIR integral field spectrometer)

[CII] 158mu and [OI] 63mu and 145mu emission in the Orion Nebula+Bar (PDR)
[CII] 158mu, [OIII] 52mu and 88mu emission in M82 (rotation + starburst wind)
[CII] and [OI] mapping of GC CND, and nearby spiral galaxies (e.g. NGC6946)
CO J=16-15 emission in He2-10: XDR vs. PDR (BH), cf. A. Krabbe poster

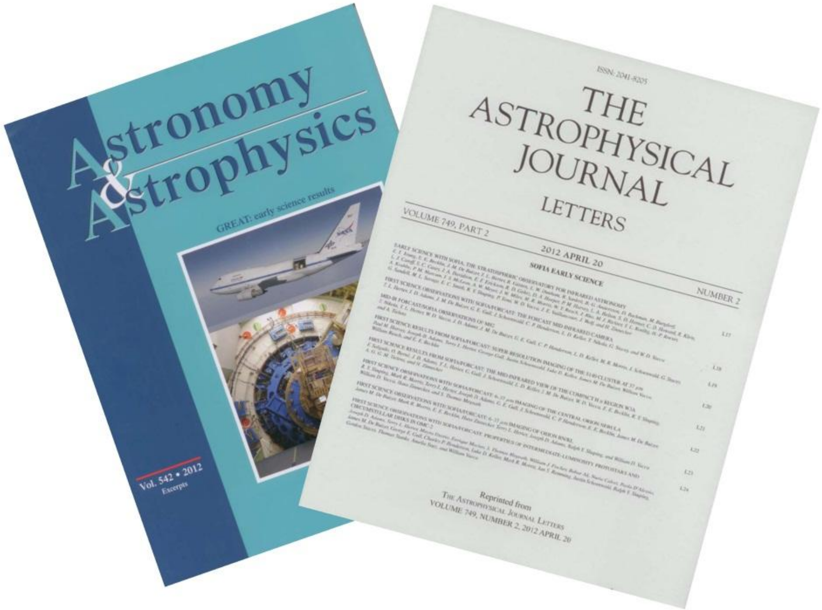
FLITECAM (1-5mu) and HIPO (FPI+) highlights

SN 2014J (M82) near-IR spectrum, evolving with time (ionised Cobalt lines)
Pluto occultation (June 29, 2015) in support of NASA's New Horizons Mission

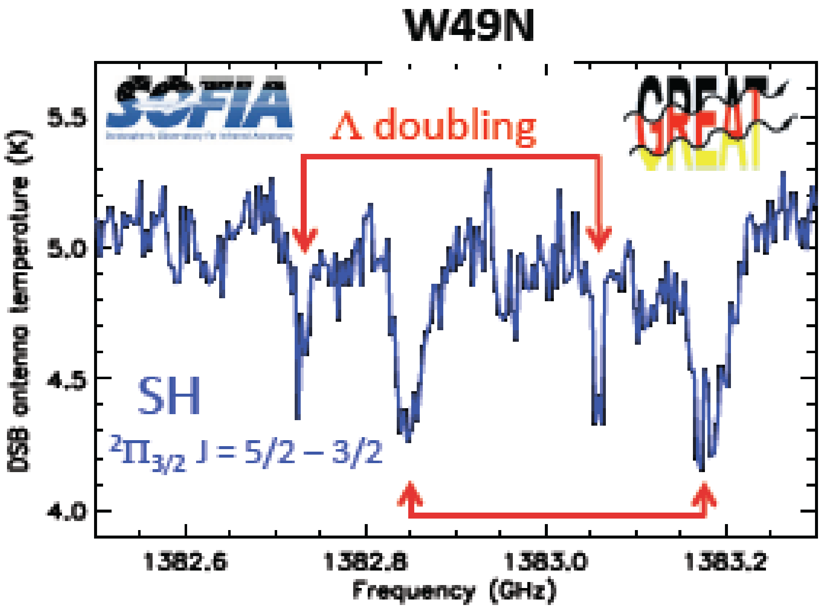
SOFIA publications from Early Science, Cycle 1 and Cycle 2+3 approaching 100

some SOFIA publications

- SOFIA early science published in two 2012 special issues that highlight the science accomplished then
- Many more results by now, 2016 (new A&A special issue coming)
- HZ SOFIA AG review AN 334, 558 (2013)
- HZ SOFIA highlights 5th Zermatt-Symp 2015

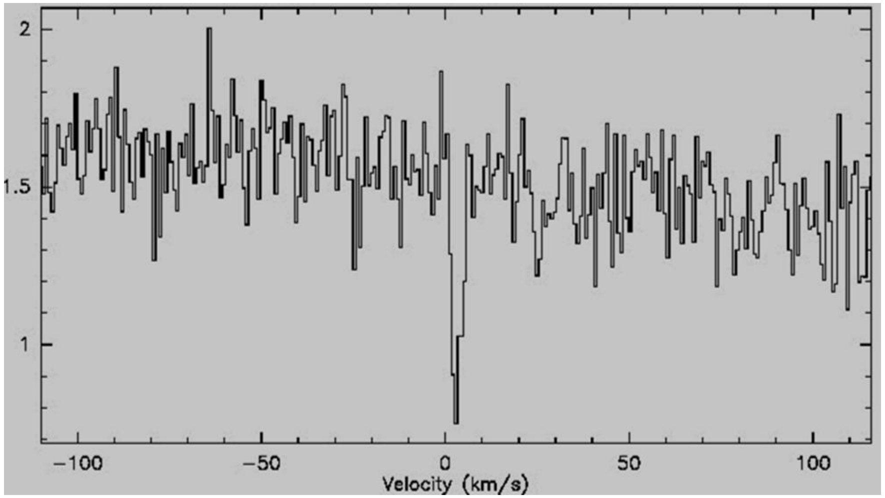


GREAT science highlights (new molecules)

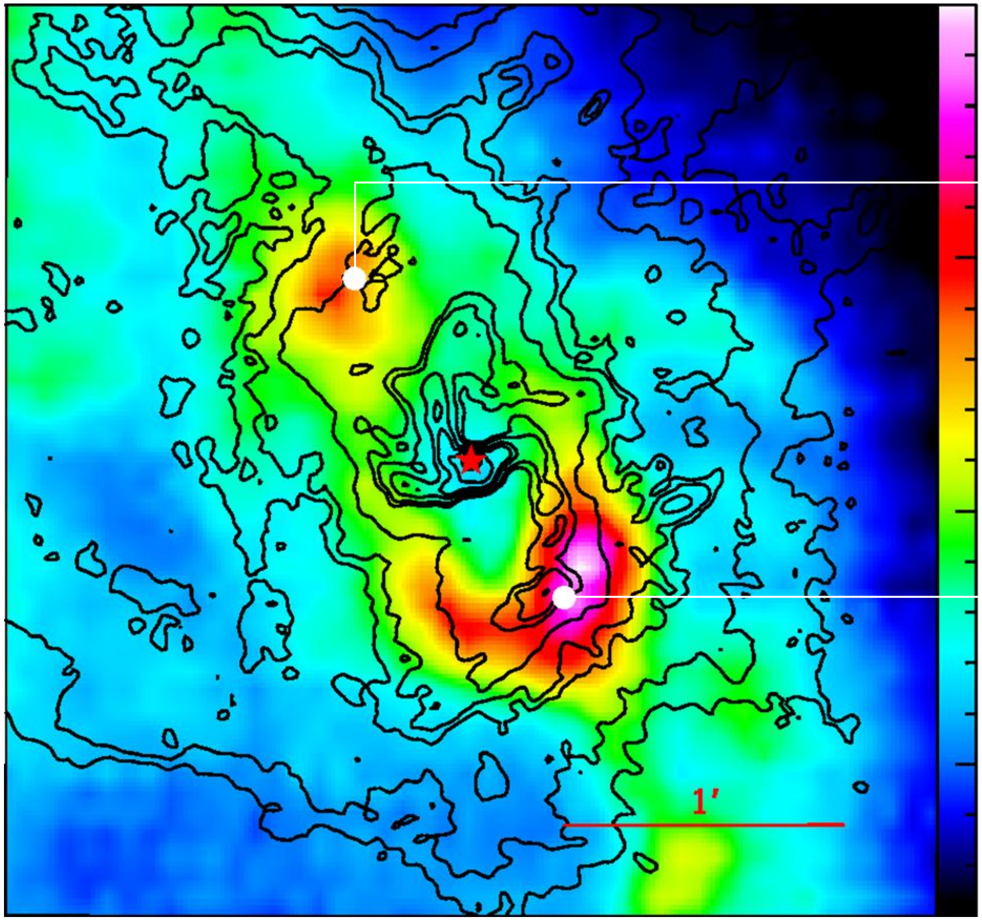


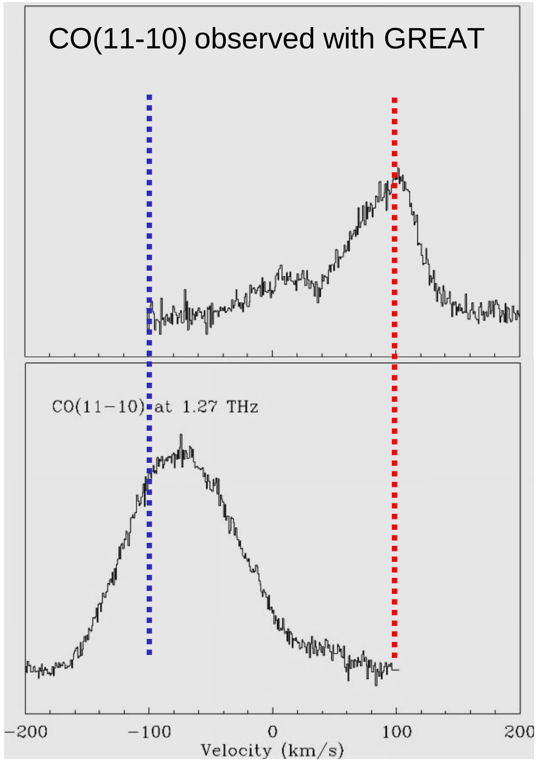
Neufeld: discovery of interstellar mercapto radical SH in absorption against W49N.

Parise: most beautiful detection of deuterated hydroxyl OD towards the protostar IRAS1629A



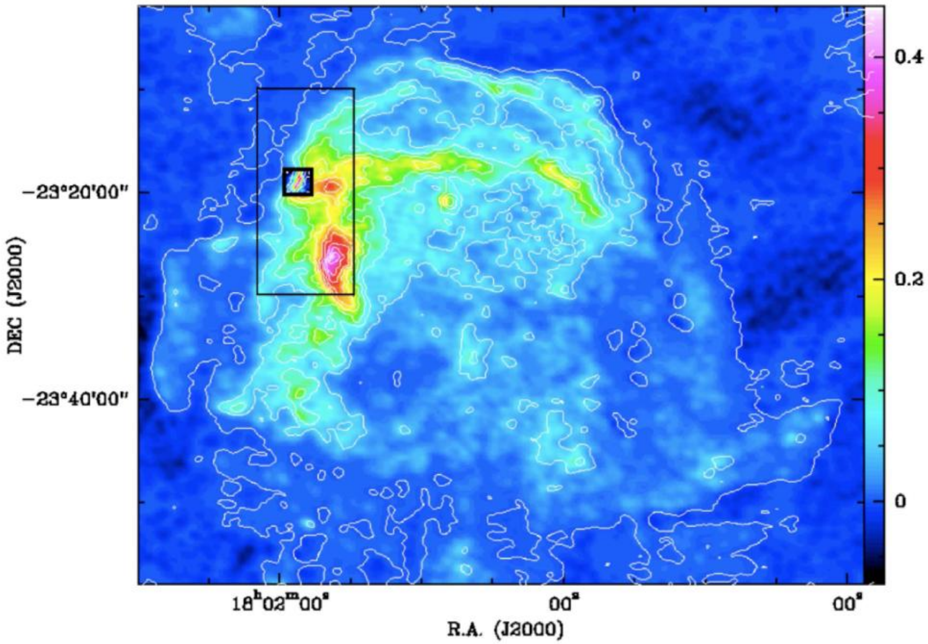
GREAT: The circum-nuclear disk in the GC





Requena-Torres et al. 2012, A&A

Probing MHD Shocks with high-J CO observations: W28F



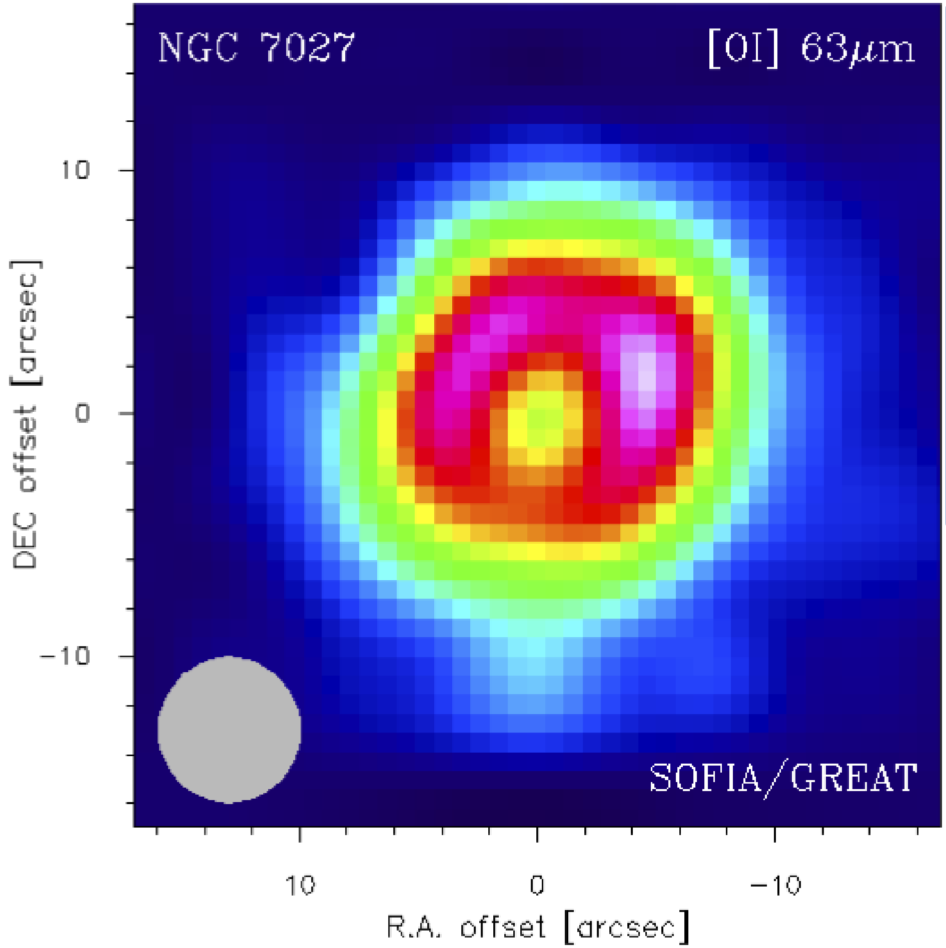
- APEX observations:
  13CO (3-2), (4-3), (6-5)

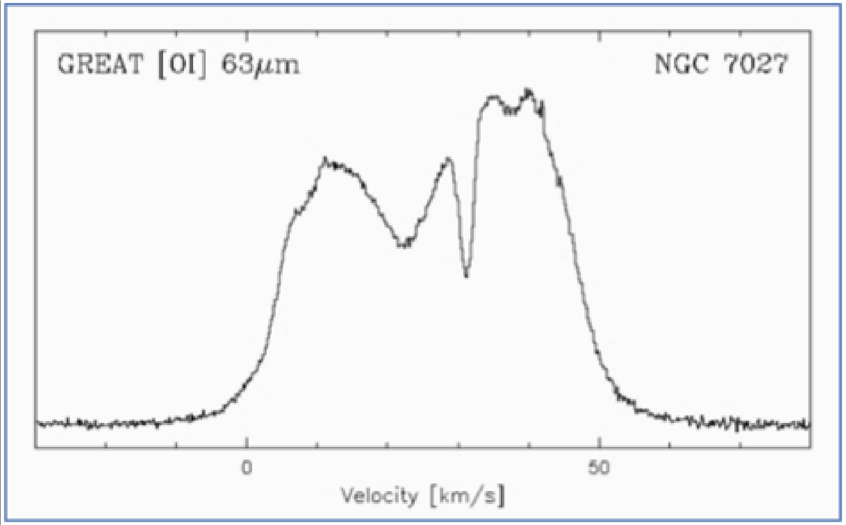
- SOFIA/GREAT observations:
  high-J 11-10 CO (tracing shocks)

1. W28 is a mature supernova remnant ($>2x10^4$ yr old) located in the Inner Galaxy (G6.4)
2. Shocked CO gas interacting with adjacent molecular clouds
3. Magnetic field: 2mG
4. High energy (TeV) γ-ray emission (H.E.S.S.) from acceleration of hadronic particles.

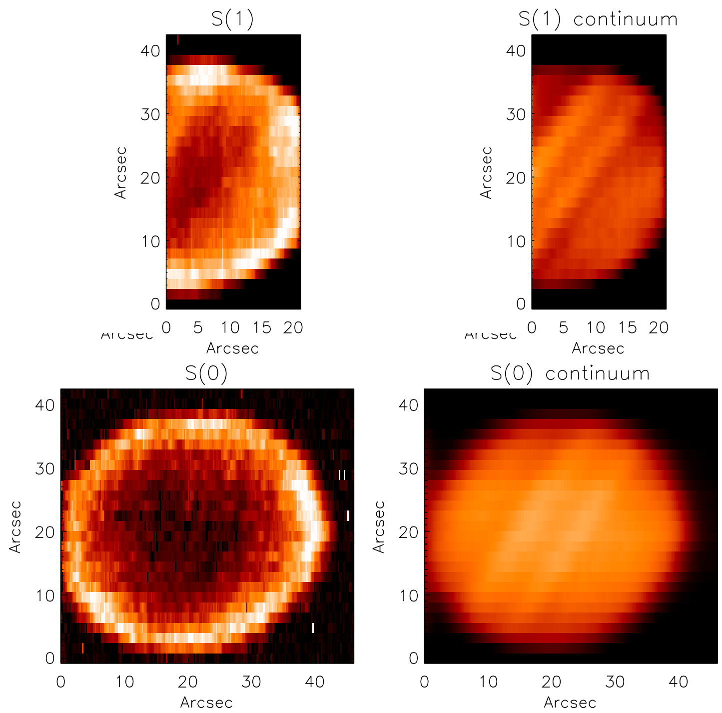
Gusdorf et al. (2012): stationary C-type shock explains CO data

GREAT 4.7 THz First Light





EXES Commissioning Science: Ortho/para H_2 maps on Jupiter



- spectral maps by stepping slit position across extended source
- Jupiter stratospheric H2 emission: limb brightening
- S()) at 28.3 mu unobservable from ground
- S(1)//S(0) gives temperature, with long latency
- Combined with other temperatiure measurements, implies convective motion into the stratosphere and circulation

unpublished

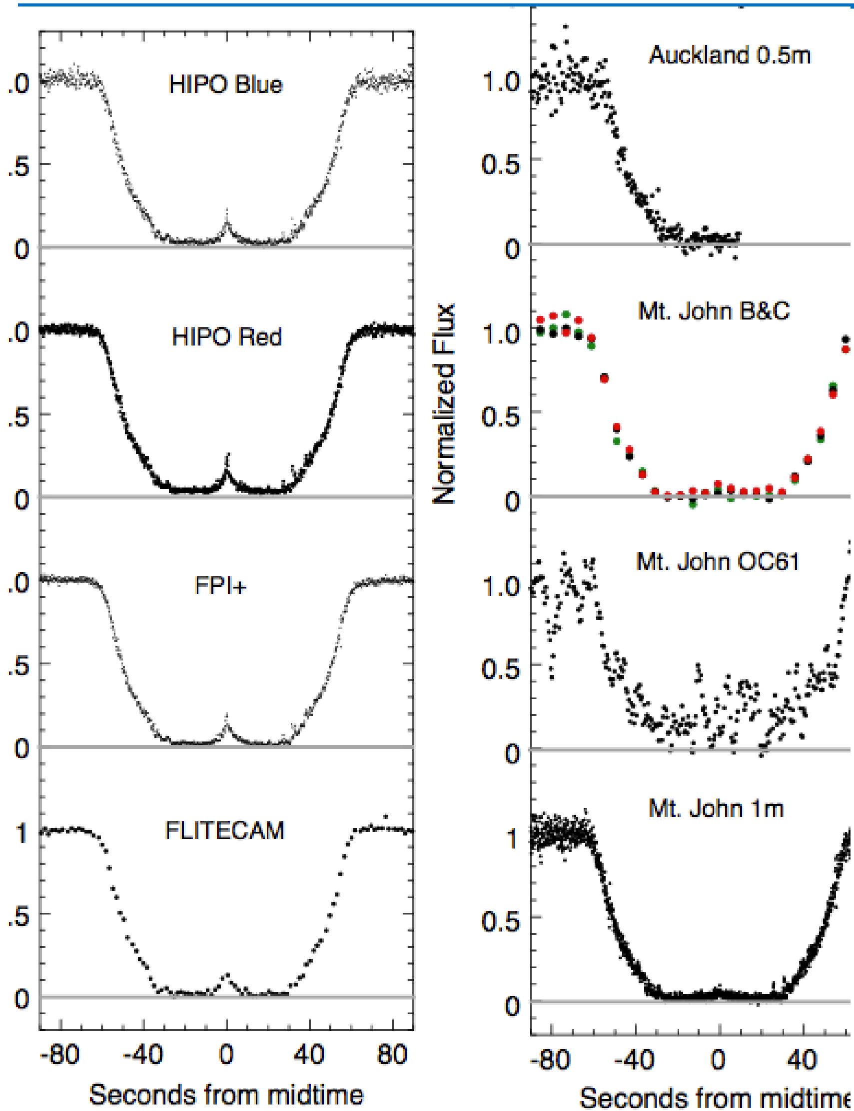
convective motion into the Stratospheric emission from

SOFIA observing Pluto occultations (2011, 2015)

- **Pluto Occultation of June 2011. Hit the center line, atmosphere still there.**
- **FliteCam, HIPO and FDC Pluto Occultation of June 29 2015, two weeks before the New Horizons fly by.**

Both experiments were highly successful.
Showed the importance of SOFIA's mobility.

Multi-wavelengths Pluto occultation (2015 June 29)

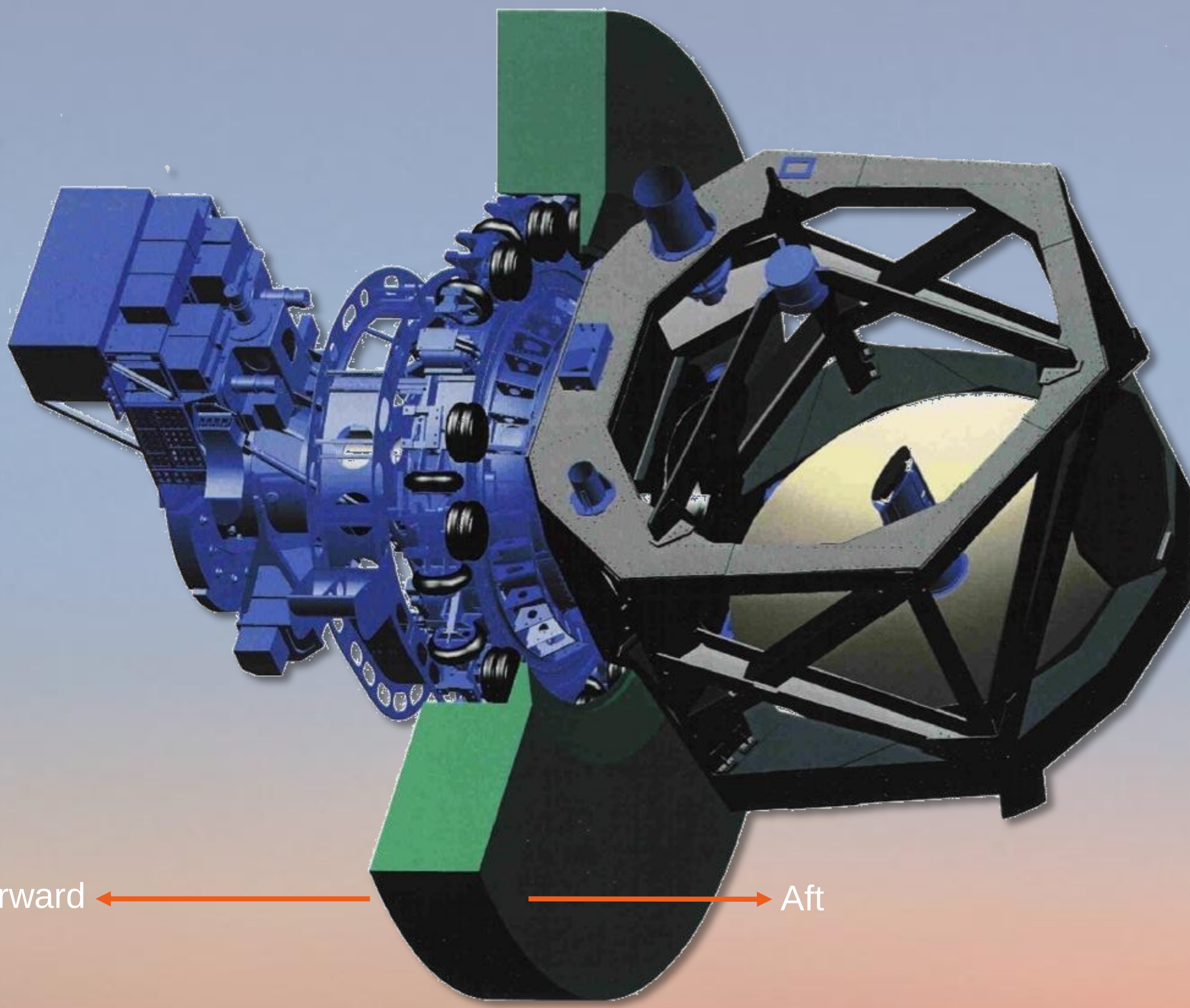


- Bosh et al. 2016 submitted to AJ

The SOFIA Telescope

Onboard telescope

- Bent Cassegrain, 2.7 meter diameter mirror (~10 feet)
- Wavelength: 0.3 to 1,600 microns
- Installed weight: 17 metric tons (37,478 pounds)



Nasmyth: Optical Layout

Observers in pressurized cabin have ready access to the focal plane