SOFIA's legacy in star formation and future FIR horizons

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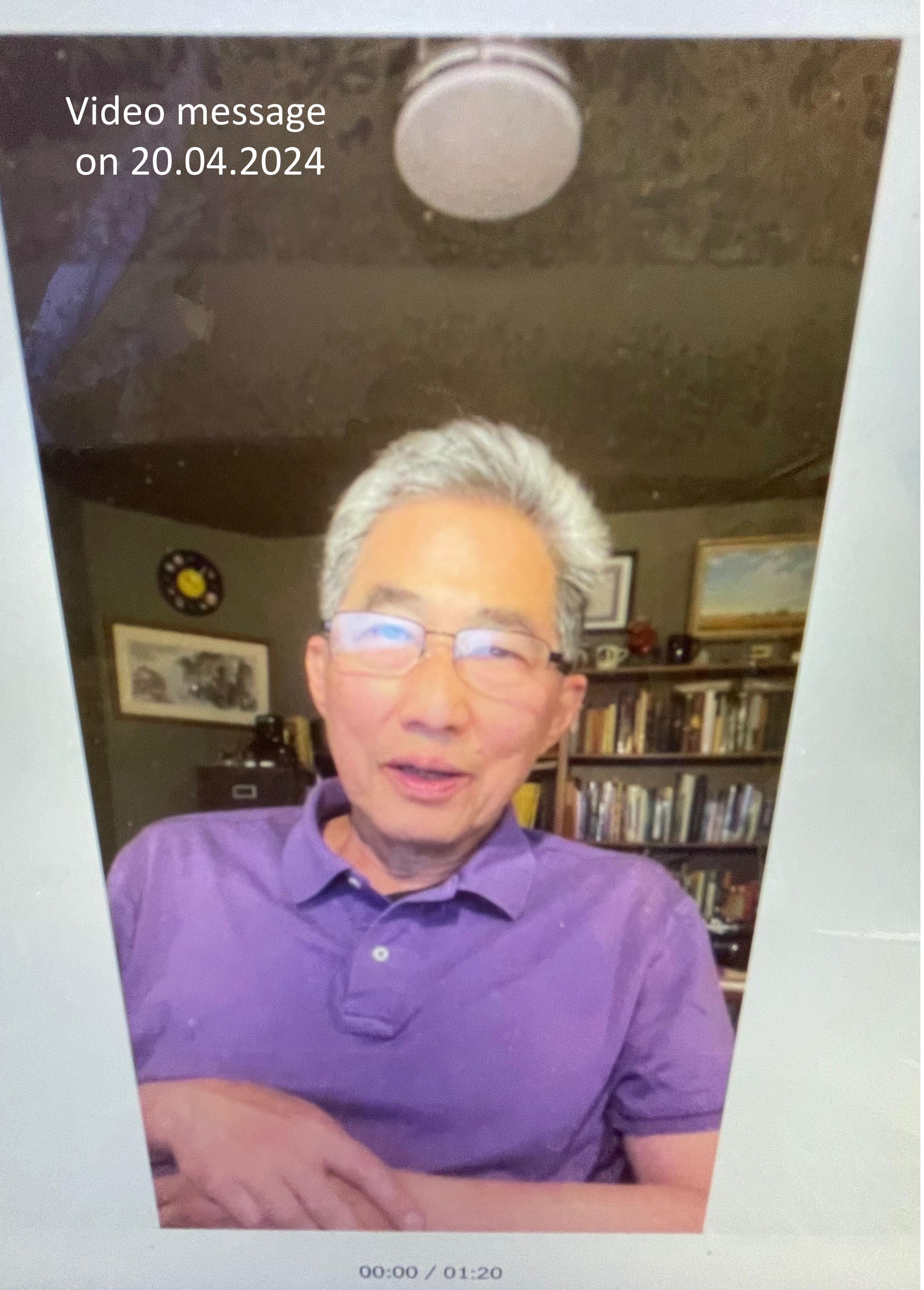
A message from Erick Young

- Video on https://www.dropbox.com/scl/fi/… 0bwpxzbkx100oubi0r5kc/Stuttgart_video.MOV?
- Rather than play the video, I will read his words
- Erick was the first Director of the SOFIA SMO (Science Center at NASA Ames, Moffett Field)
- “ASTRONOMY CANNOT ESCAPE THE FAR-IR”



SOFIA inauguration event
Oct 15. 2010 (Mt. View. CA)
for Erick Young and myself.
Pity we have no joint picture.

Yorke, Becklin, HZ, Young (TAC? 2015)

Helen Hall and Hans-Peter Roeser

2011: my first of 10 flights on SOFIA

Astron. Nachr. / AN **334**, No. 6, 558 – 575 (2013) / **DOI** 10.1002/asna.201311908 2013 Review

SOFIA: first science highlights and future science potential

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Key words infrared: general – instrumentation: miscellaneous – techniques: spectroscopic – telescopes

SOFIA, the Stratospheric Observatory for Infrared Astronomy, is a joint project between NASA and the German Aerospace Agency (DLR) to develop and operate a 2.5 m airborne telescope in a highly modified Boeing 747SP aircraft that can fly as high as 45 000 feet (13.7 km). This is above 99.8 % of the precipitable water vapor which blocks much of the mid- and far-infrared radiation from reaching ground-based telescopes. In this review, we briefly discuss the characteristics of the Observatory and present a number of early science highlights obtained with the FORCAST camera in 5–40 micron spectral region and with the GREAT heterodyne spectrometer in the 130–240 micron spectral region. The FORCAST images in Orion show the discovery of a new high-mass protostar (IRc4), while GREAT observations at 1 km s^{-1} velocity resolution detected velocity-resolved, redshifted ammonia spectra at 1.81 THz in absorption against several strong far-infrared dust continuum sources, clear evidence of substantial protostellar infall onto massive (non-ionizing) protostars. These powerful new data allow us to determine how massive stars form in our Galaxy. Another highlight is the stunning image taken by FORCAST that reveals the transient circumnuclear 1.5 pc radius (dust) ring around our Galactic center, heated by hundreds of massive stars in the young nuclear star cluster. The GREAT heterodyne spectrometer also observed the circumnuclear ring in highly excited CO rotational lines, indicative of emission from warm dense molecular gas with broad velocity structure, perhaps due to local shock heating. GREAT also made superb mapping observations of the [C II] fine structure cooling line at 158 microns, for example in M17-SW molecular cloud–star cluster interface, observations which disprove the simple canonical photodissociation models. The much better baseline stability of the GREAT receivers (compared to *Herschel* HIFI) allows efficient on-the-fly mapping of extended [C II] emission in our galaxy and also in other nearby spiral galaxies. Of particular note is the GREAT discovery of two new molecules outside the solar system: OD (the deuterated OH hydroxyl radical) as well as mercapto radical SH, both in absorption near 1.4 THz, a frequency gap where *Herschel* was blind. A special highlight was the 2011 June 23 UT stellar occultation by Pluto using the HIPO high speed photometer and the FDC fast diagnostic camera. This difficult but successful observation, which was both space-critical (within 100 km) and time-critical (within 1 min), proved that SOFIA can be in the right place at the right time, when important transient events occur.

1 What is SOFIA?

SOFIA is short for “Stratospheric Observatory for Infrared Astronomy”. SOFIA is a substantially modified Boeing 747SP (SP = special purpose) aircraft that carries a ∼20 ton gyro-stabilized telescope in its rear fuselage (Fig. 1) with a mirror diameter of 2.7 m (2.5 m clear aperture), similar in size to the Hubble Space Telescope. Yet while Hubble in orbit observes in the UV, optical, and near-infrared part of the electromagnetic spectrum, SOFIA mainly observes and excels in the mid- and far-infrared (30–300 microns, but see below). These wavelengths represent radiation coming from cool ($T = 10$ K) to warm ($T = 100$ K) celestial objects, both interstellar gas and dust, that would not reach ground-based observing sites, as they would be absorbed by significant amounts of water vapor in the atmosphere. SOFIA typically flies at altitudes of 41 000 to 45 000 ft (12–13.7 km), i.e. above 99.8–99.9 % of the precipitable water vapor (Stutzki 2006; Becklin & Gehrz 2009). The first SOFIA open door flight took place in December 2009 and the first SOFIA science flight in December 2010 (with FORCAST).

SOFIA is a bi-lateral project between NASA and the German Aerospace Agency DLR, with the US side being the major partner (80 %) and Germany the minor partner (20 %). The percentages refer to the share of the total cost including maintenance and fuel, and indeed also to the ratio of observing time between the two countries. In essence, NASA provided the aircraft (including the modifications) while DLR paid for the design and installation of the telescope. NASA runs the programme through its subcontractor USRA (Universities Space Research Association), while DLR assigned the task to Deutsches SOFIA Institute (DSI) at Raumfahrtzentrum at University of Stuttgart (through a renewable 4 year contract). The SOFIA plane operates out of NASA-Dryden Airforce Operations Facility (DAOF) in Palmdale, Southern California (1 hour north of Los Angeles), while the SOFIA Science Center is located at NASA-Ames, Moffett Field in Northern California (1 hour south

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Fig. 1 The SOFIA B747SP aircraft with open door flying over the Sierra Nevada in California (photo NASA).

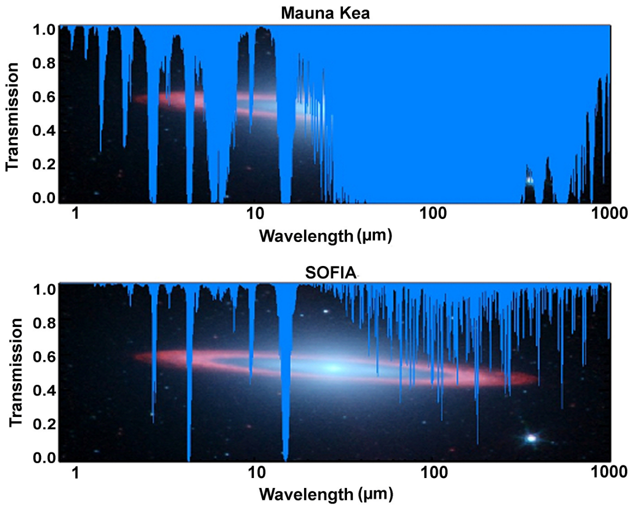


Fig. 2 Comparison of atmospheric transmission in the infrared (1 to 1000 microns) for SOFIA in the stratosphere and the Mauna Kea ground-based observing site (figure taken from The Science Vision of SOFIA, NASA-Ames 2009).

What was SOFIA's science mission?

THE BIG PICTURE and its special relevance to STAR FORMATION

SOFIA was primarily a 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

The unique role ("wisdom") of SOFIA

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

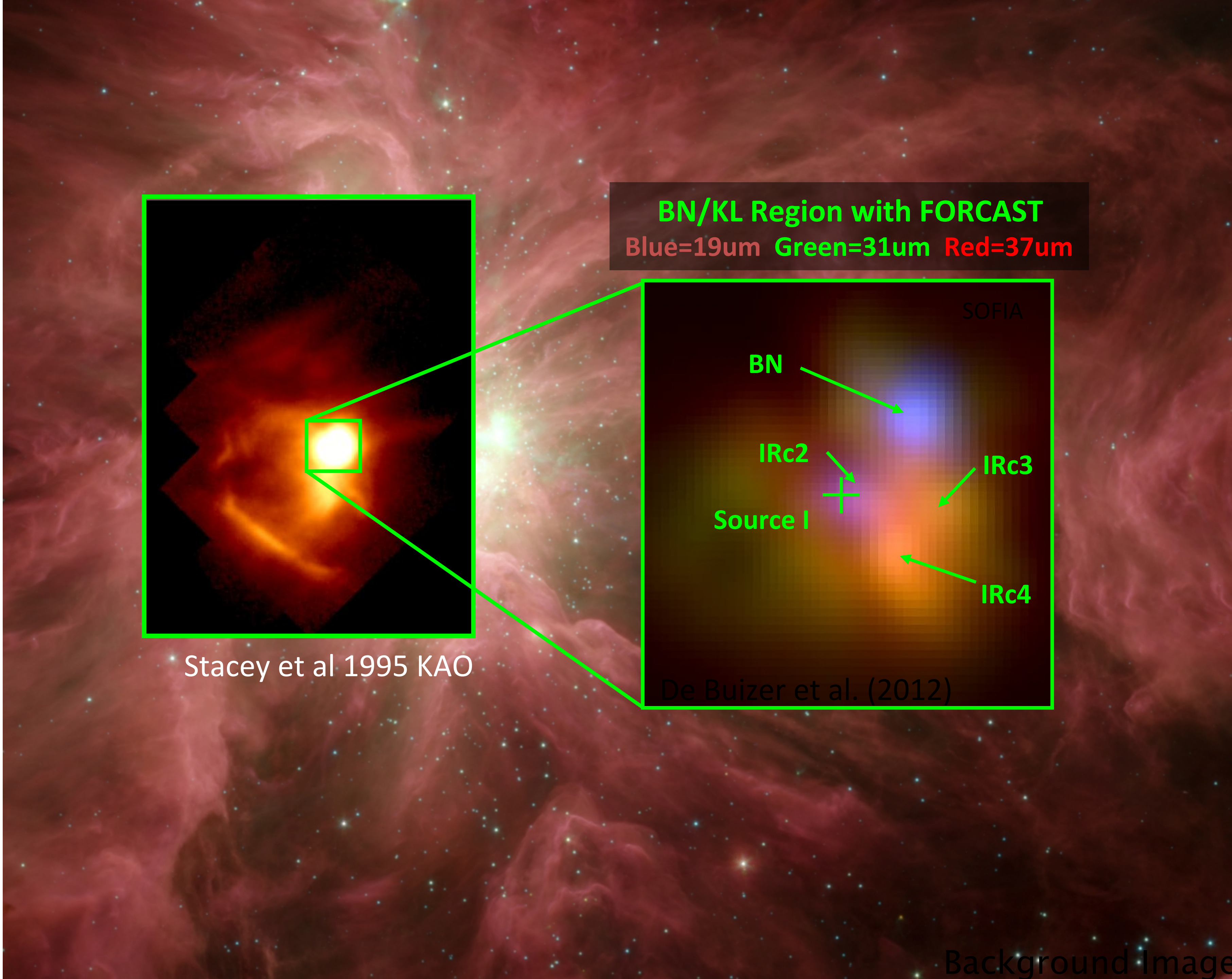
- far-IR dust cont. polarimetry (HAWC+)
- mid-IR high-resolution spectroscopy (EXES)

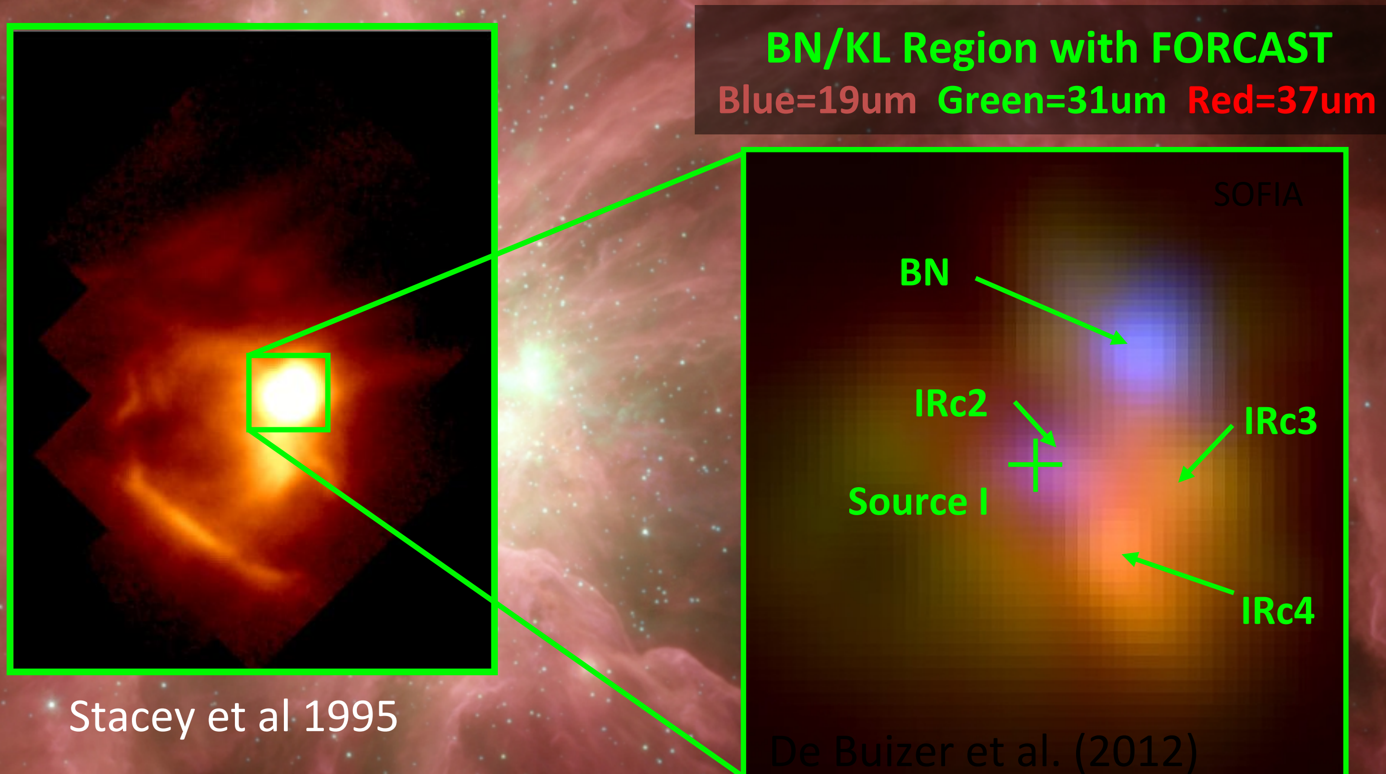
- follow-up on Spitzer & Herschel (and beyond)
- ***complementary to ALMA/NOEMA and JWST***

The logical successor to SOFIA would be SALTUS (14m mirror), a proposed NASA FIR probe mission, SALTUS meaning "JUMP"

Outline of this brief review on SOFIA's legacy in star formation

- Example1: Orion BNKL/IRc4 luminous protostar
- Example2: Orion Trapezium HII region feedback
- Example3: protocluster cloud collapse/infall
- Example4: protostellar disk accretion outbursts
- Example5: imaging the Central Molecular Zone
- Example6: imaging the GC circum-nuclear ring
- Example7: studying dark molecular gas in LMC
- Example8: mapping [CII] in spiral galaxies (SFR)
- Example9: mapping magnetic field structures


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

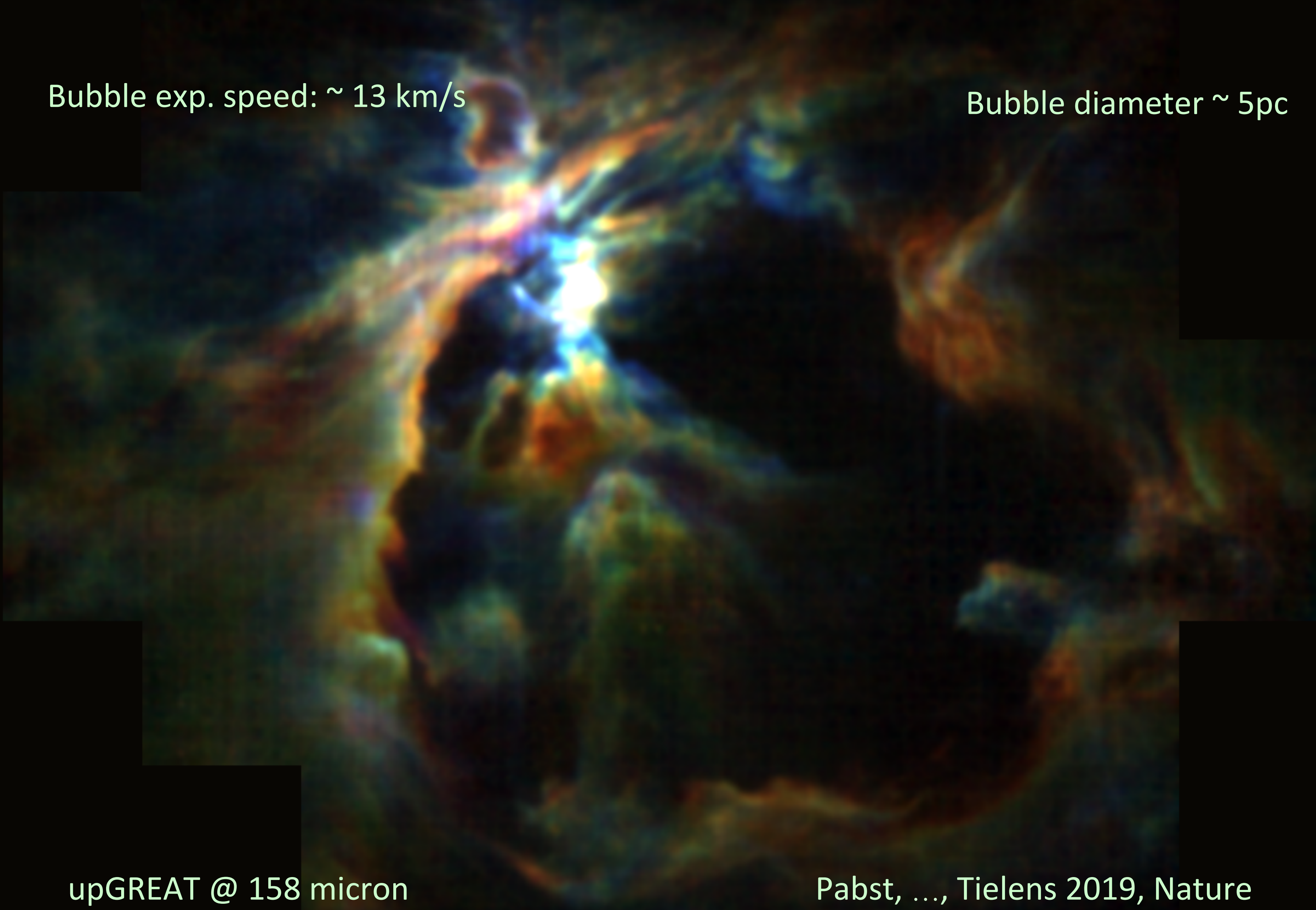


De Buizer, Herter, Becklin et al. 2012

IRc4 is the dominant luminosity source (~10^4 Lo) in Orion BN/KL

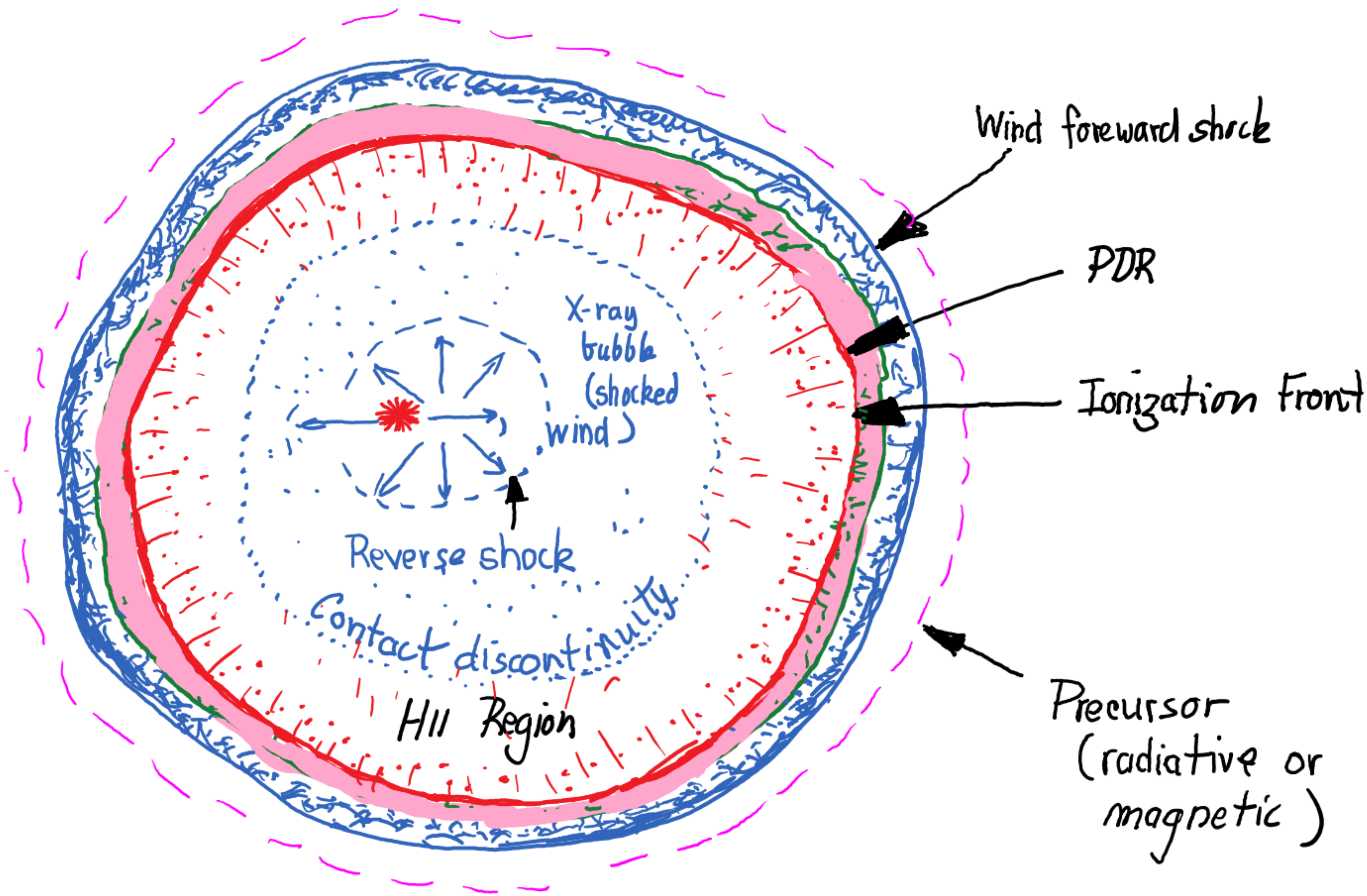
Background Image

Orion Nebula [CII] bubble created by theta-1 Ori C wind



Wind-Dominated HII Region (Pabst+2019)

Cartoon courtesy
John Bally



FEEDBACK

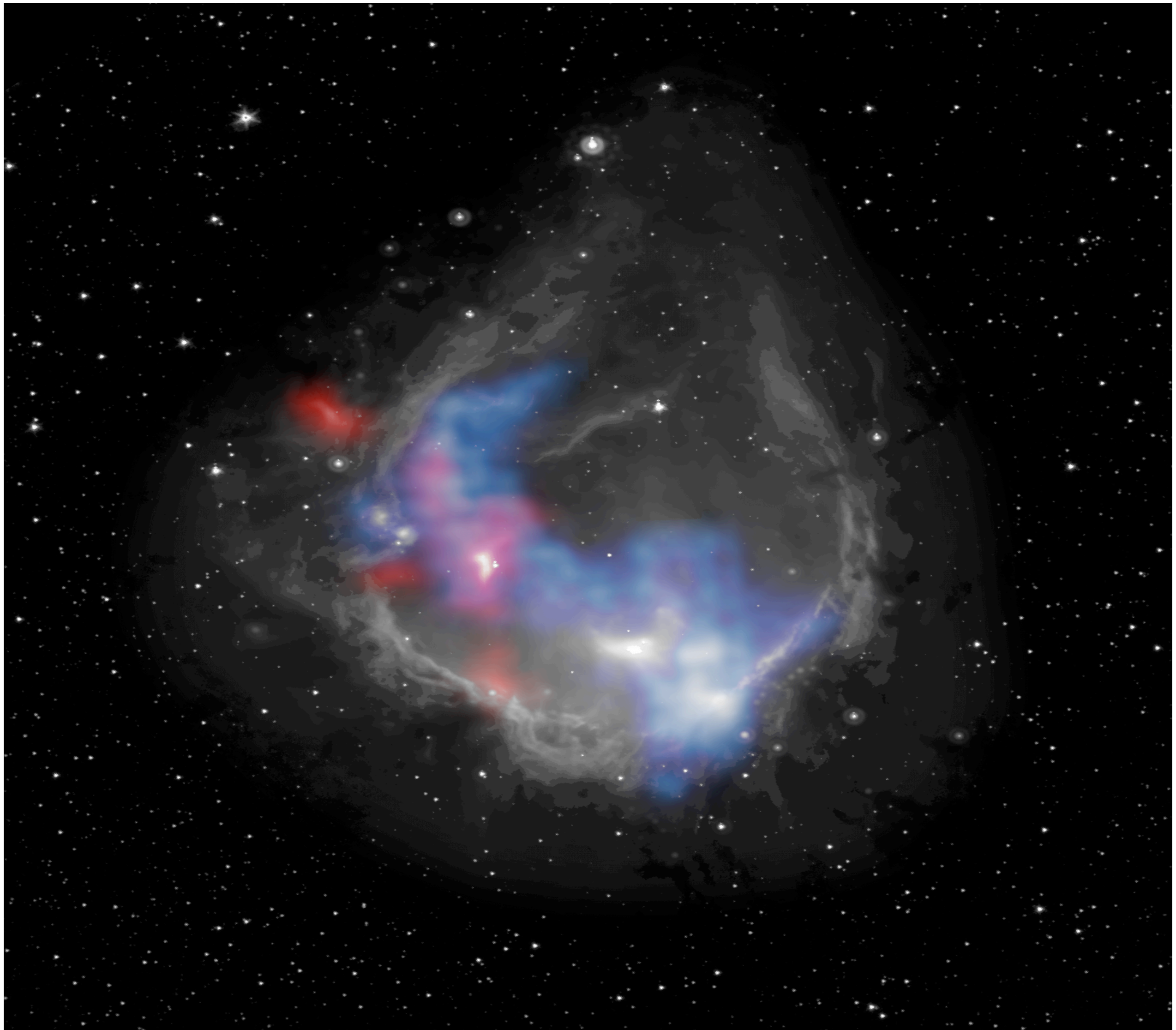
SOFIA Legacy Program to study stellar feedback
in regions of high-mass star formation (~100 hr)
(PIs Nicola Schneider & Xander Tielens, Cycle 7)

11 galactic high-mass star forming regions selected
for upGREAT [CII] 158mu & [OI] 63mu observations
to understand feedback dynamics (stellar winds,
thermal expansion, radiation pressure) from OB
stars in a range a small and rich clusters, PDR/XDR

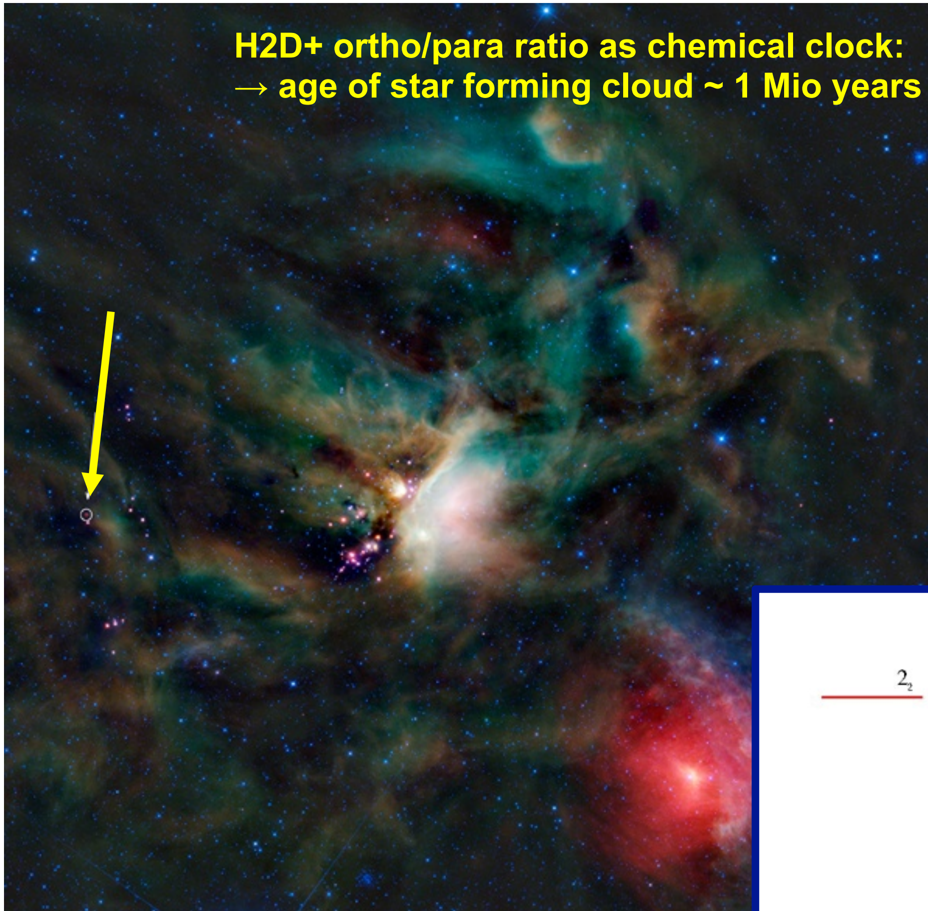
targets: CygX, M16, M17, NGC 7538, NGC 6334,
W40, W43, and RCW36/49/79/120 HII regions
(all targets have been observed, several results
have been published, cf. OMC1-cavity, RCW120)

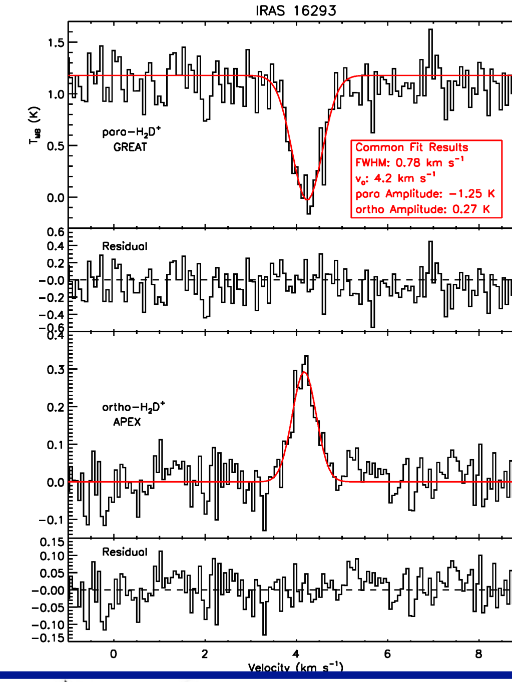
key reference: N. Schneider et al. (2020): PASP 132

RCW 120 HII regions in [CII]



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

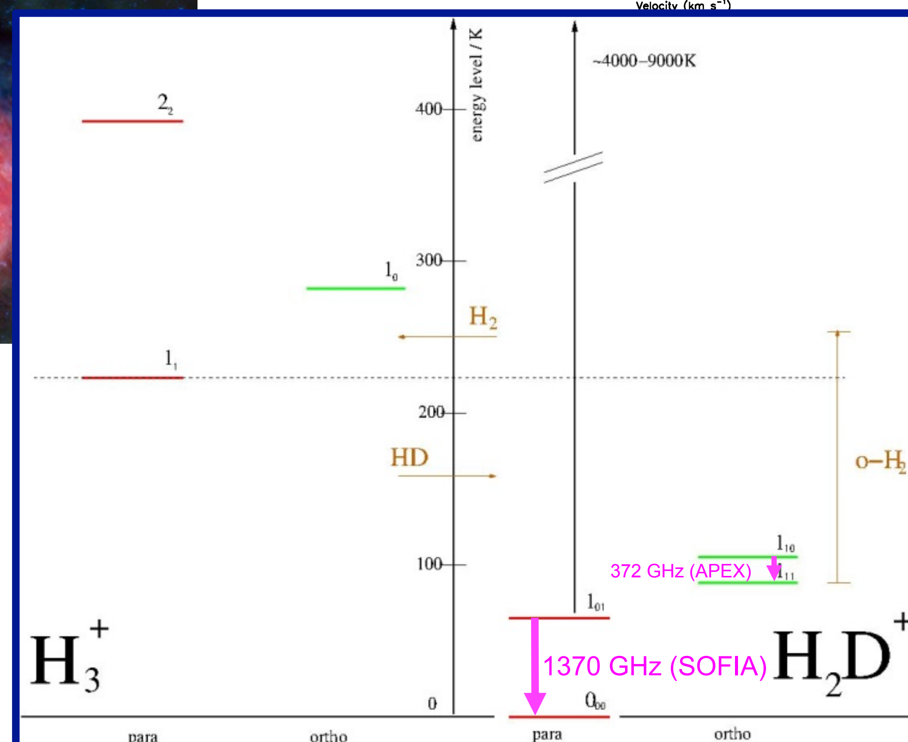




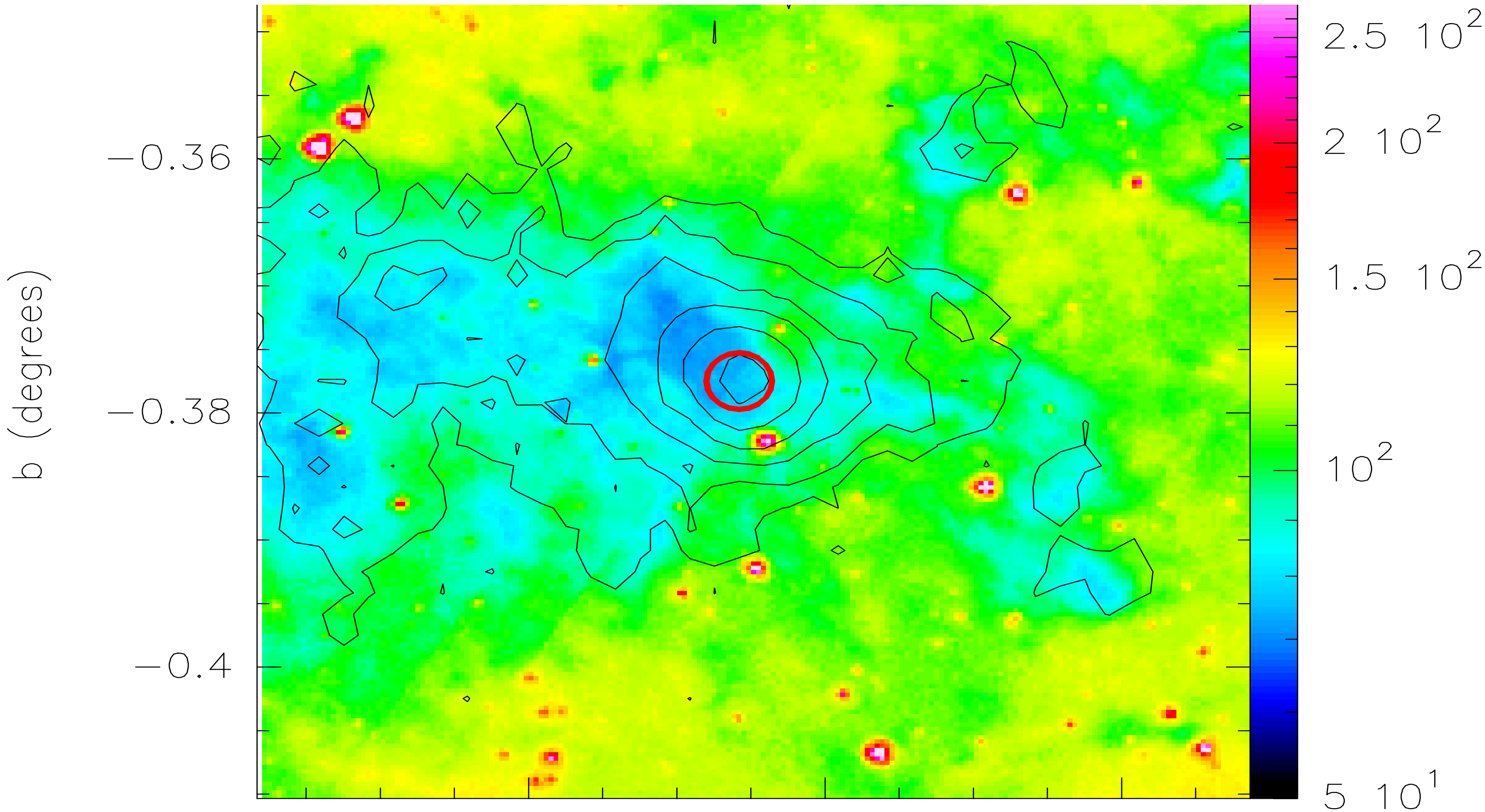
$$
\begin{array}{rcl}
H + H & \xrightarrow{\text{dust}} & H_2 \\
H + \text{cr}/\gamma & \longrightarrow & H^+ + e \\
C + \text{cr}/\gamma & \longrightarrow & C^+ + e \\
 & & \\
H_2 + H^+ & \longrightarrow & H_3^+ \\
 & \longrightarrow & H + H + H^+ \\
H_3^+ + HD & \longrightarrow & H_2D^+ + H_2 \\
 &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

Nature paper:
Brünken et al, 2014

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



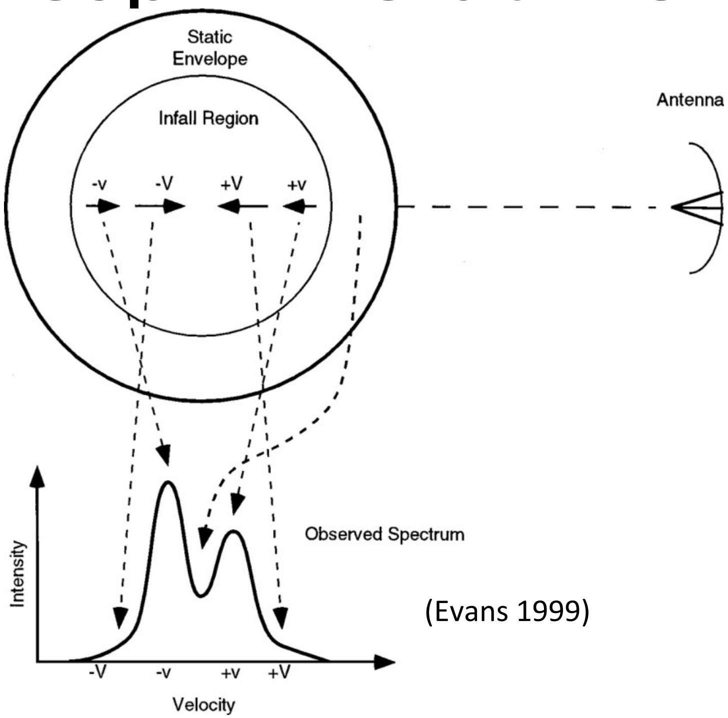
ATLASGAL submm clump G23.21 (Spitzer IRDC)



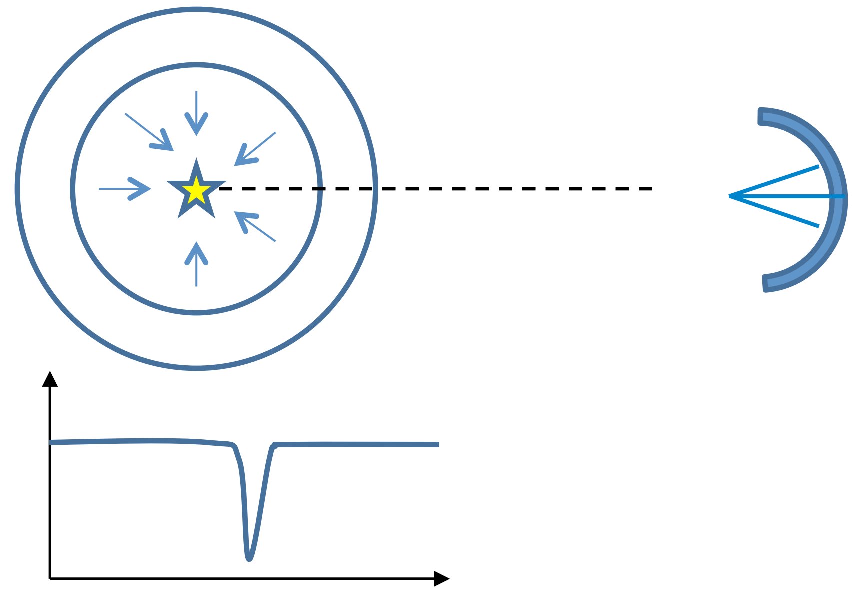
Spitzer Infrared Dark Cloud IRDC), with FIR continuum source.
Molecular clump mass: ~ 10(3) Mo, infall rate: ~ 10(-3) Mo/yr.

Using THz Lines to Probe Infall

esp. NH3 at 1.81 THz, Wyrowski 2015



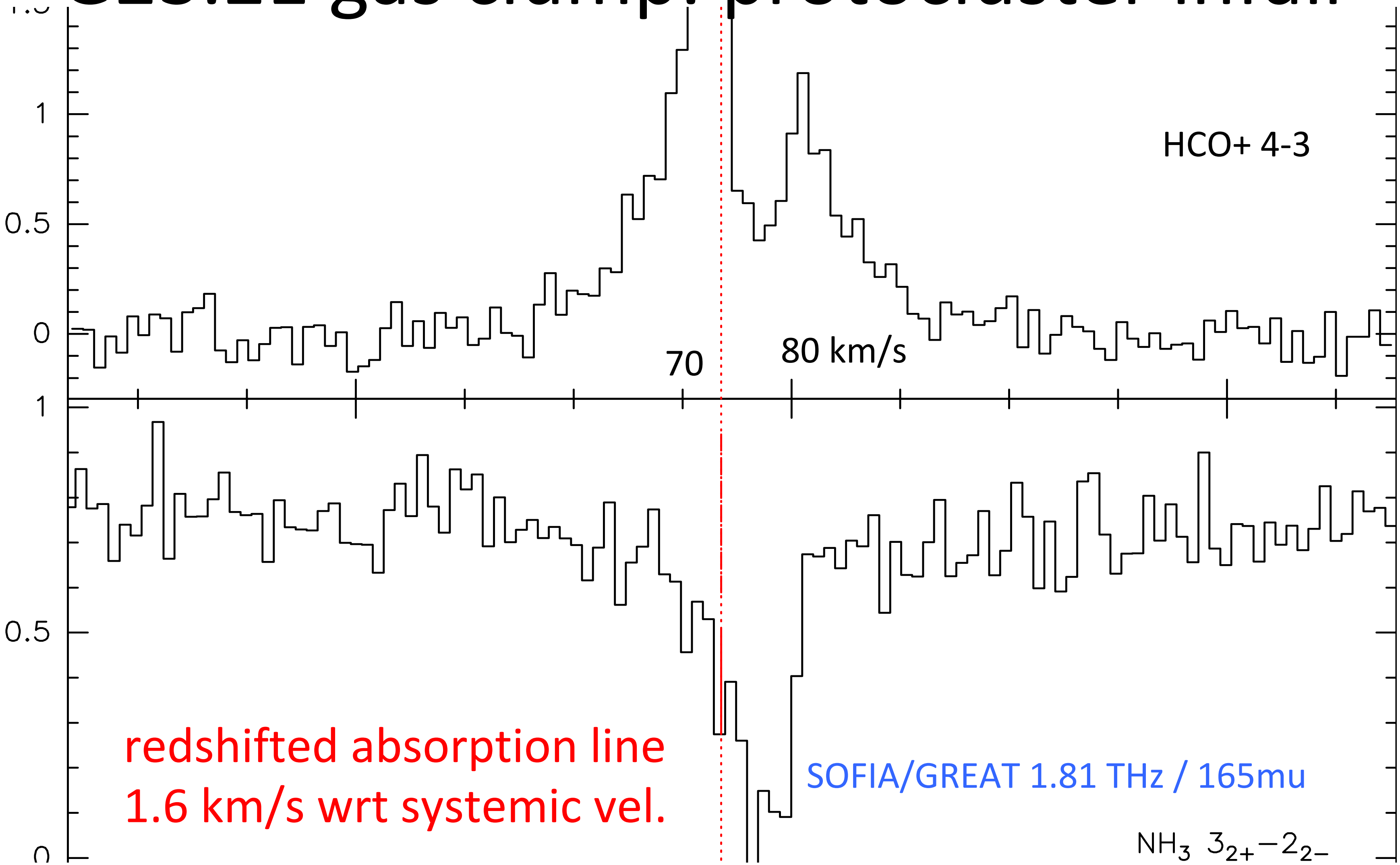
(Evans 1999)



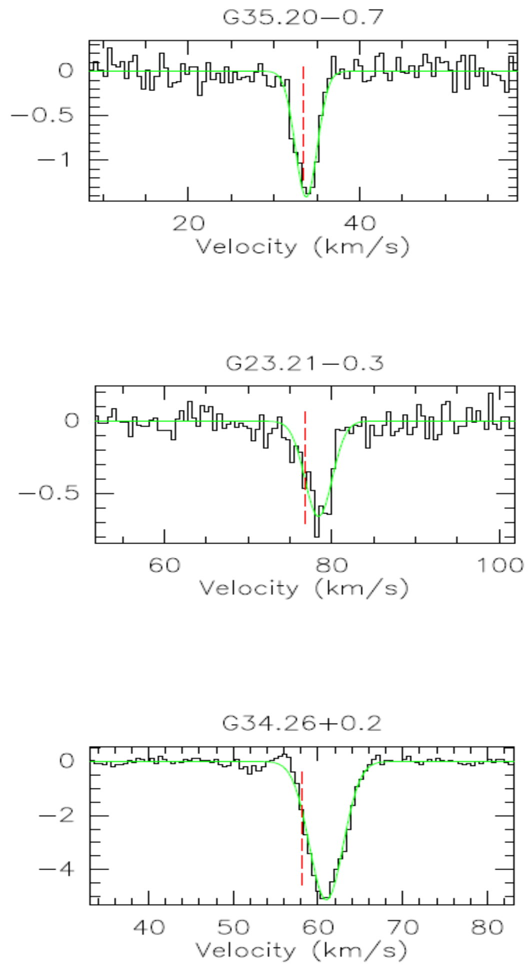
Interpretation of infall using optically thick emission lines is difficult, due to complicated radiative transfer and possible contributions from outflowing molecular gas.

Absorption measurements against a FIR continuum source are much more 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").

G23.21 gas clump: protocluster infall



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



See also Hajigholi et al. 2016 (Herschel NH3 multi-level transitions)

EXES Commissioning : Water in abs. in AFGL 2591 outflow

i

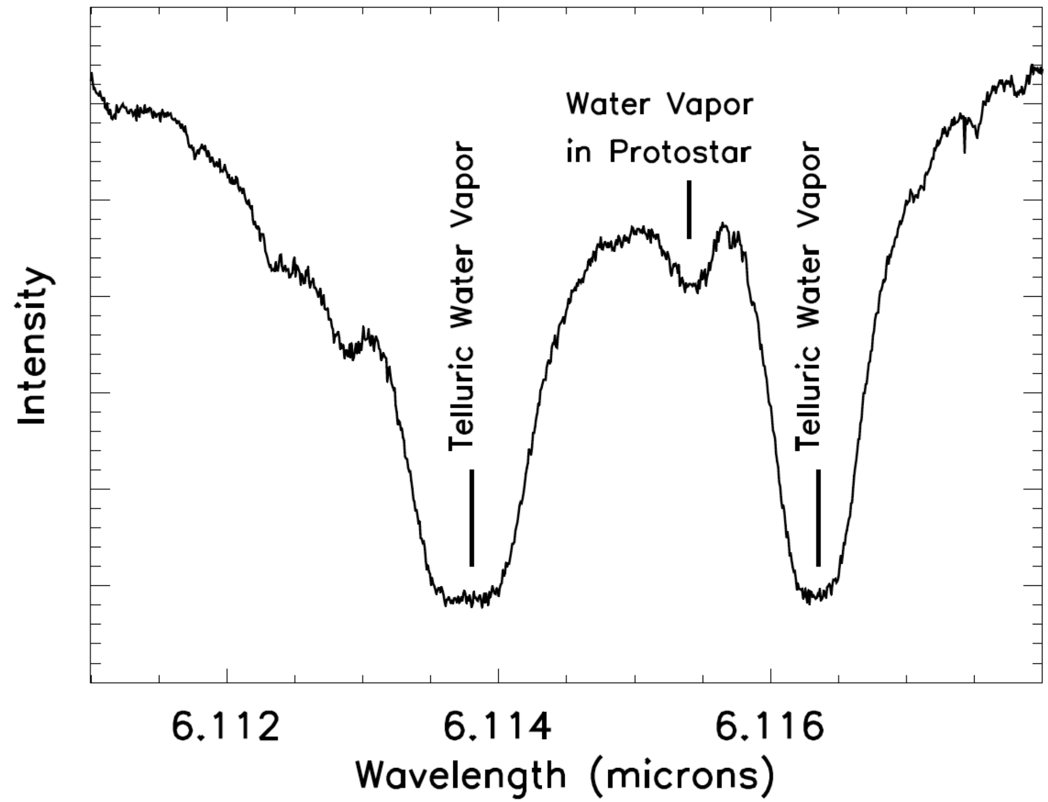
10 Mo protostar in Cygnus

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 studies

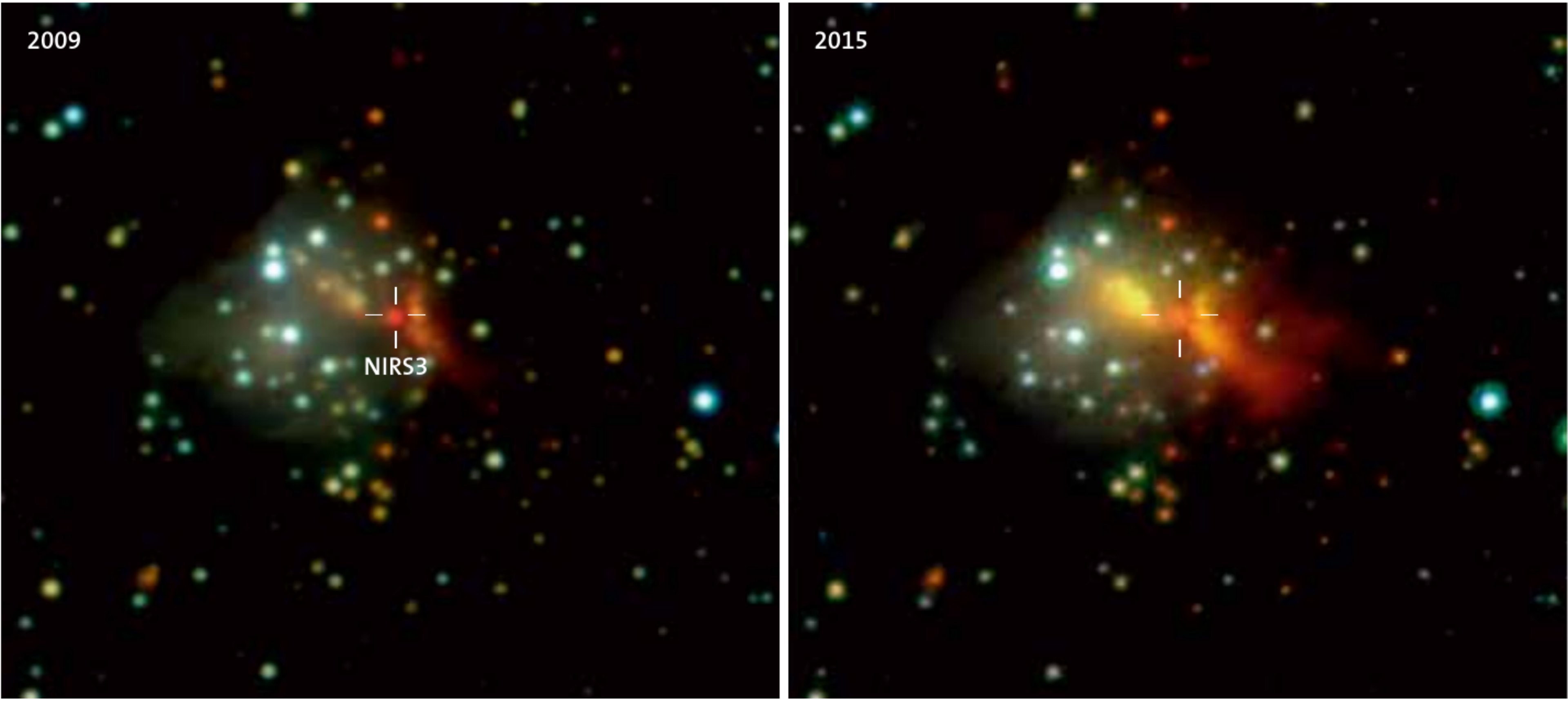
paper: Indriolo et al. 2015, ApJ

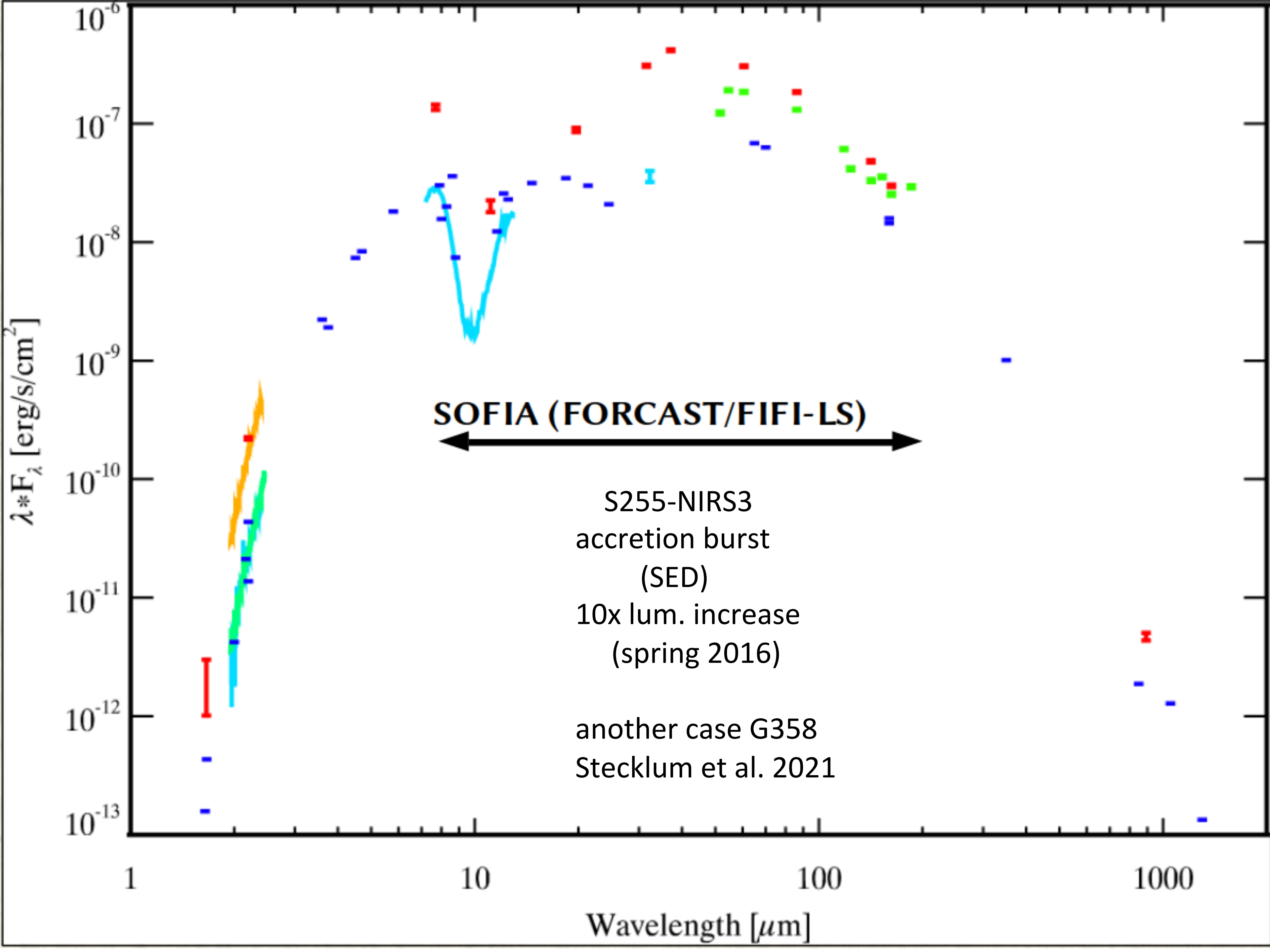


Accretion outburst in S255-NIRS3

(images: Stecklum, priv. commun.)

highly cited paper: Caratti o Garatti et al. 2017 Nature Physics





SOFIA (FORCAST/FIFI-LS)
S255-NIRS3
accretion burst
(SED)
10x lum. increase
(spring 2016)
another case G358
Stecklum et al. 2021
$\lambda * F_\lambda$ [erg/s/cm^2]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
1
10
100
1000
Wavelength [μm]

FORCAST survey Giant HII Regions

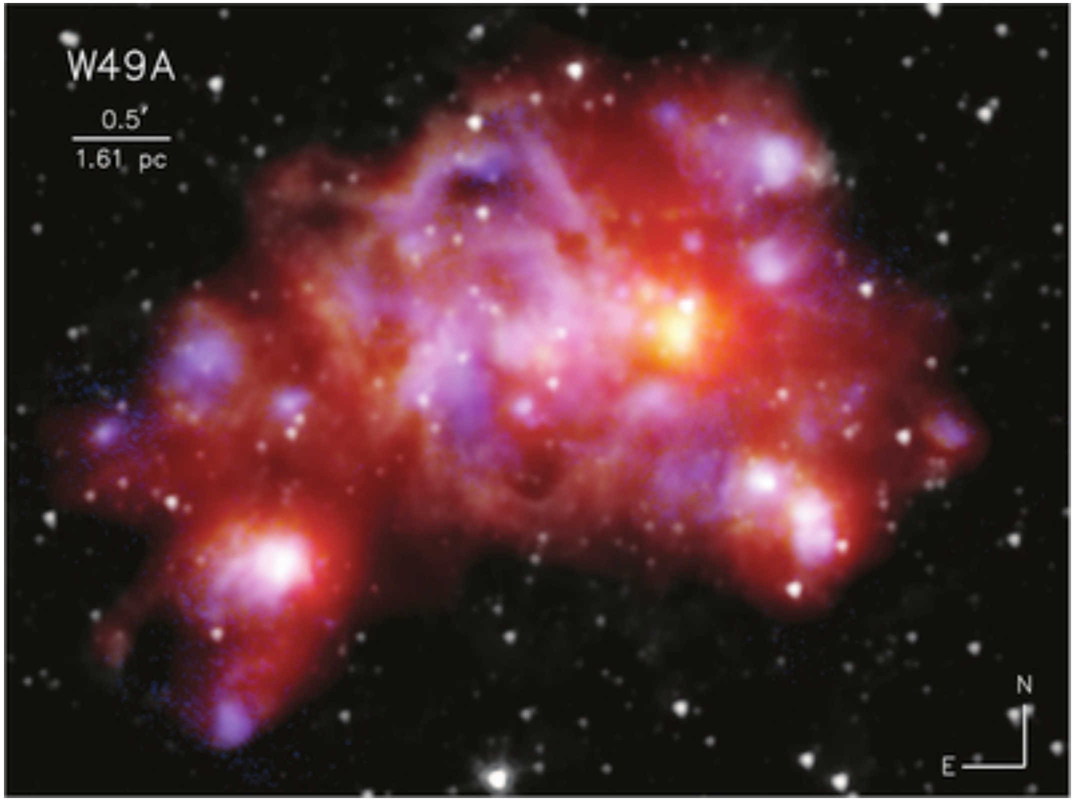
De Buizer, Lim, Radomski et al. (2019-2023)

5 papers on classical giant galactic HII regions
W51A, M17, W49A, SgrD/W42, DR7/K3-50

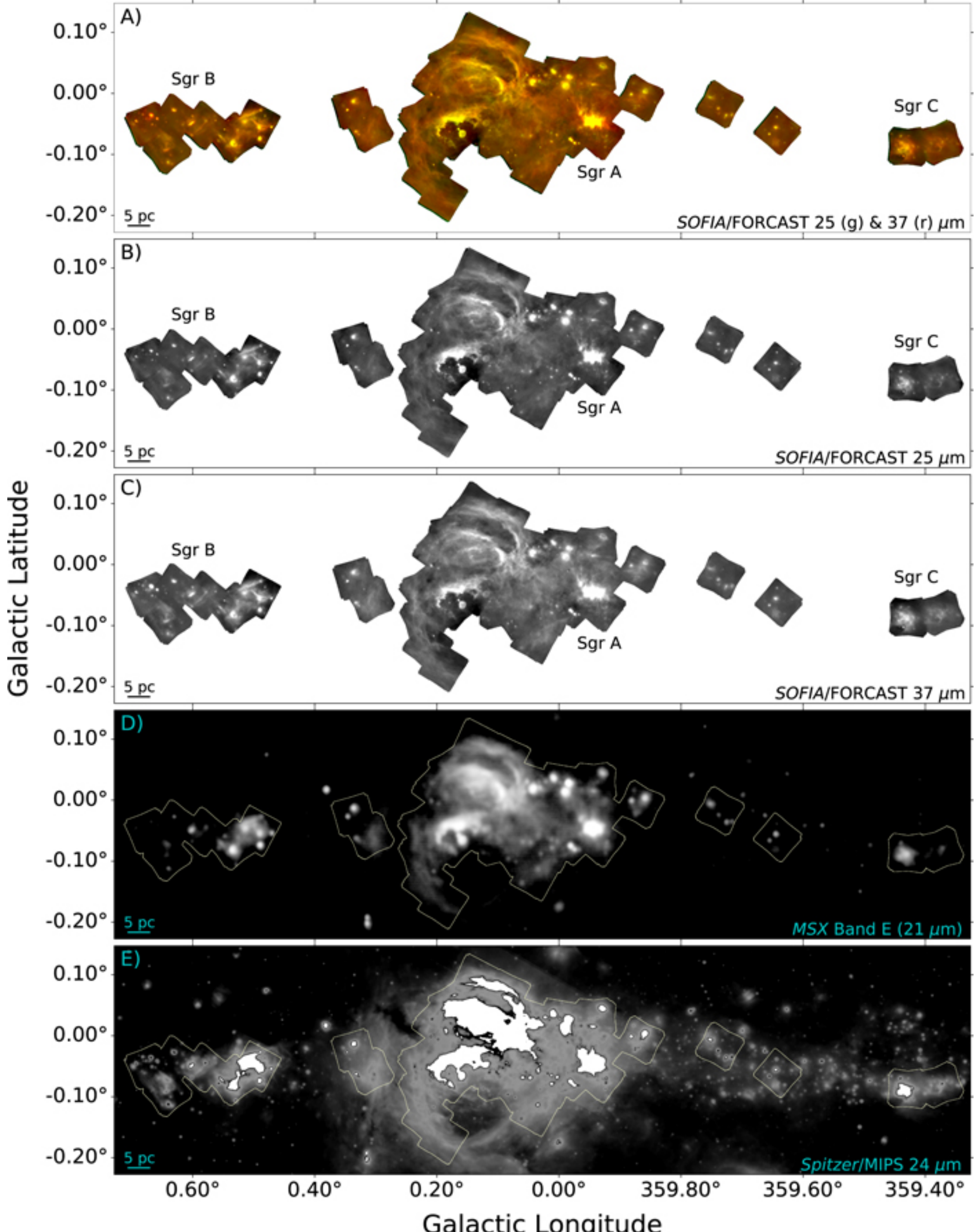
goal: find MYSOs in mid-IR and provide SEDs
census: 14 of 56 HII regions (25%) non-giant

see also J. Tan's SOMA survey (MYSO SEDs)

W49A giant HII region with FORCAST (20, 37mu) and PACS (70mu)

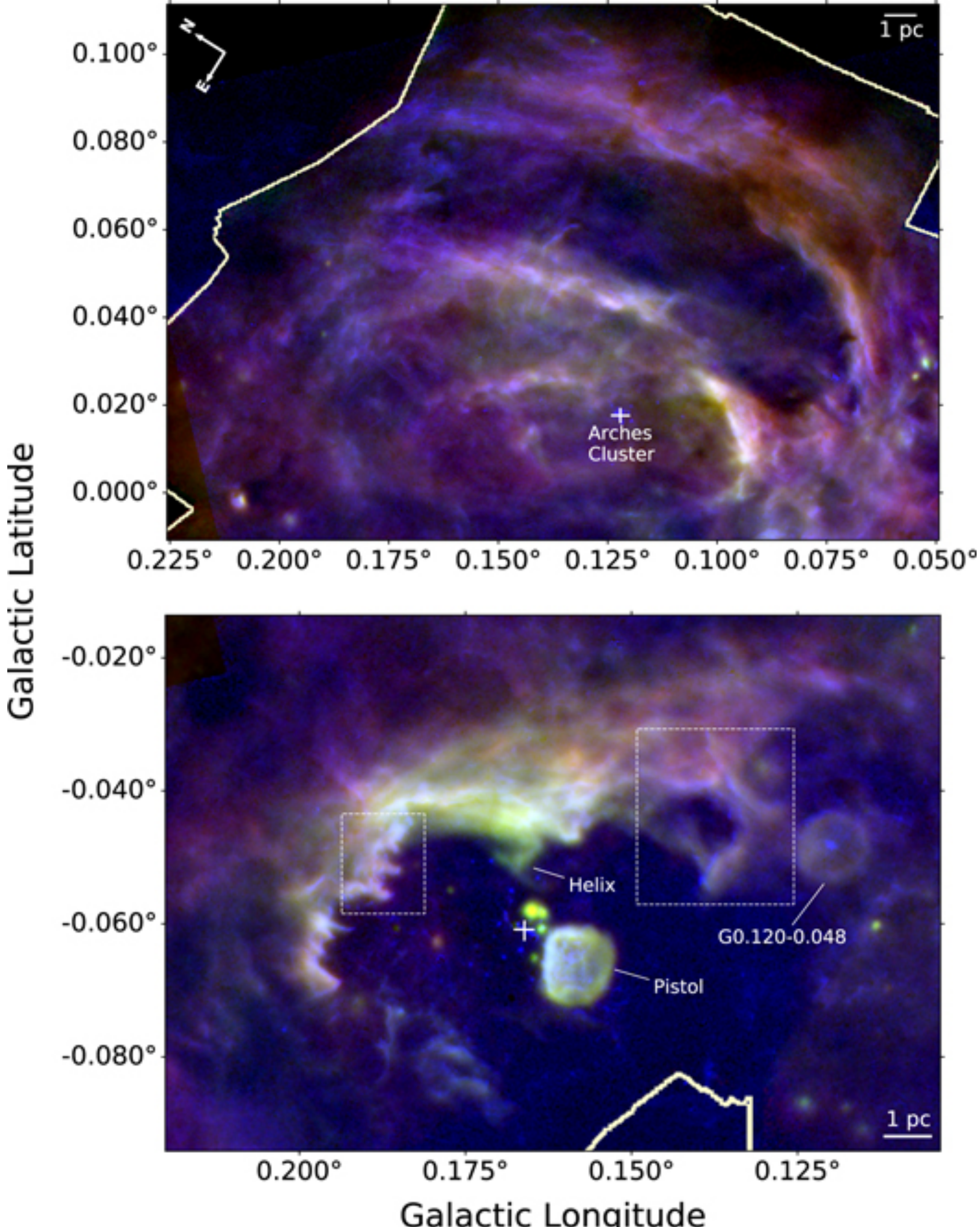


De Buizer et al. 2021 ApJ; paper III



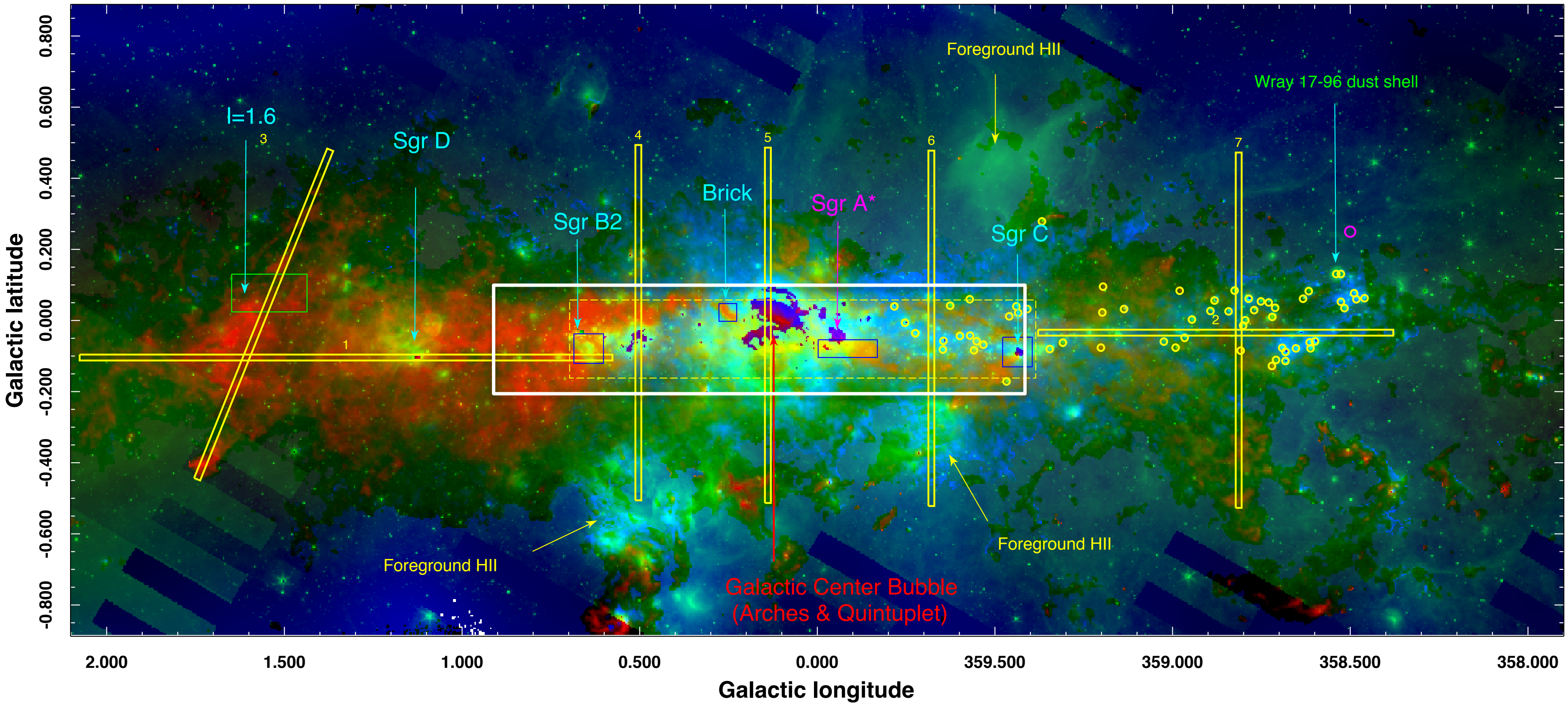
Hankins et al. 2020, ApJ

Cycle 7 first SOFIA Legacy Project (~400 squ-aremin)



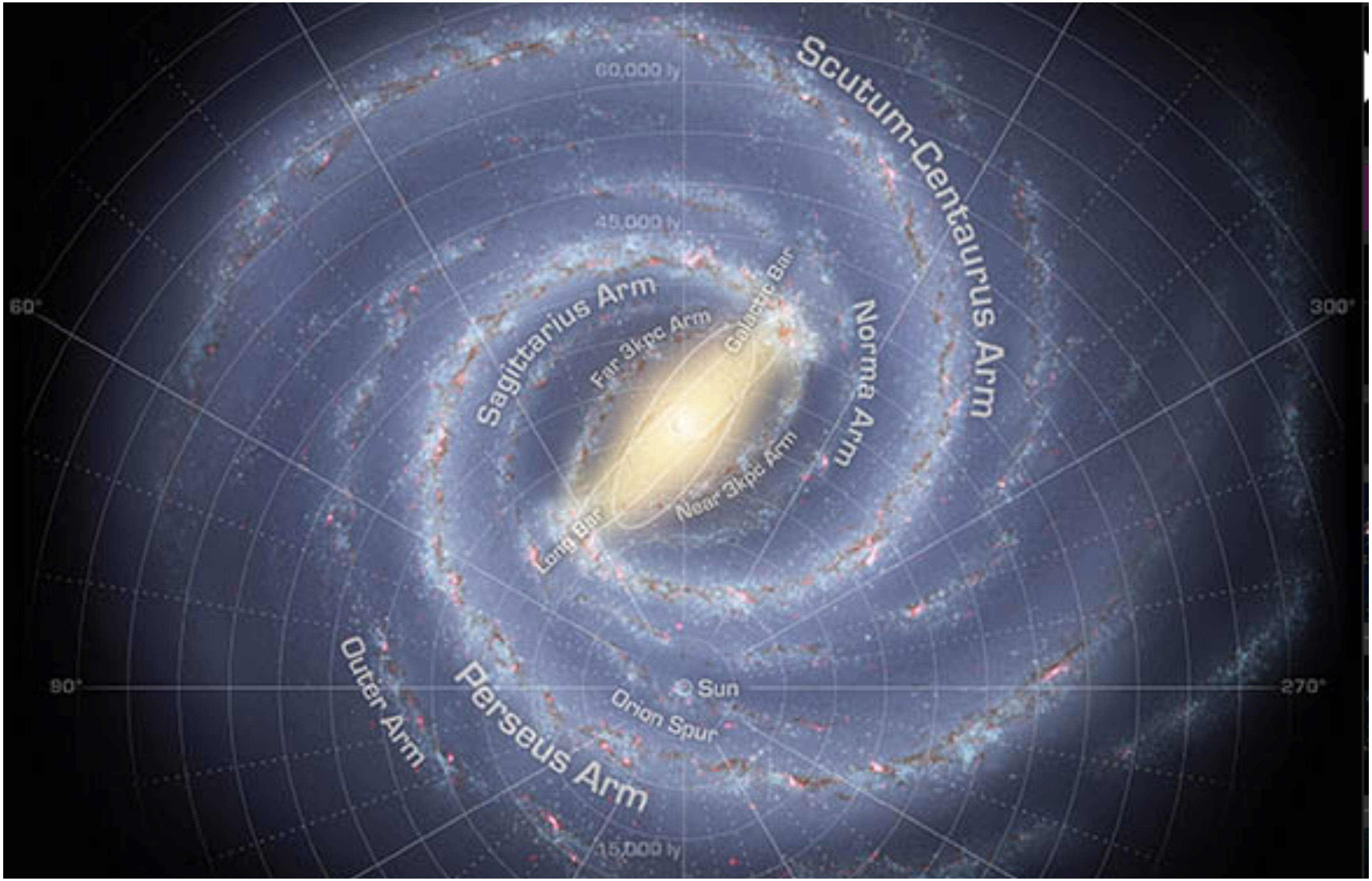
1 pc
N
E
0.100°
0.080°
0.060°
0.040°
0.020°
0.000°
Arches
Cluster
0.225°
0.200°
0.175°
0.150°
0.125°
0.100°
0.075°
0.050°
Galactic Latitude
-0.020°
-0.040°
-0.060°
-0.080°
Helix
Pistol
G0.120-0.048
1 pc
0.200°
0.175°
0.150°
0.125°
Galactic Longitude

Joint impact proposal Cy 5 on Galactic Center CMZ



Yellow: Bally
White: Harris-Güsten

face-on view of our Milky Way Galaxy



[CII] emission as a measure for the star formation rate in high-z galaxies ?

- The [CII] line at 158 micron has been observed in in high-z galaxies in the early universe at submm wavelength: lambda = lambda_o (1+z)
- At z=5, the [CII] line is emitted at 948 micron
- The origin of the [CII] emission is due to PDRs, i.e. photoionization by uv photons (< 11.3 eV)
- 1-3 % of total FIR luminosity emitted in C+ line

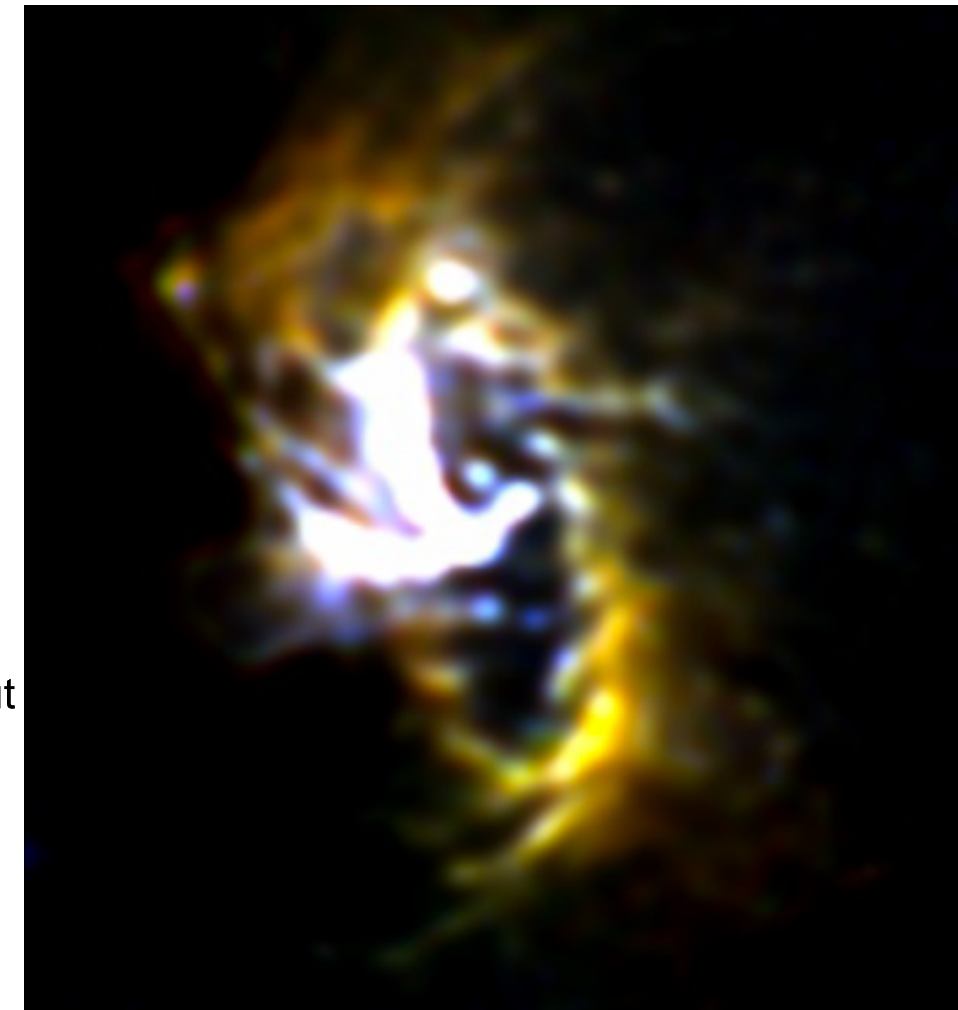
  and the FIR luminosity is good proxy for SFR…

Galactic Center circum-nuclear ring (CNR) at 19(blue), 31(green) and 37(red) micron

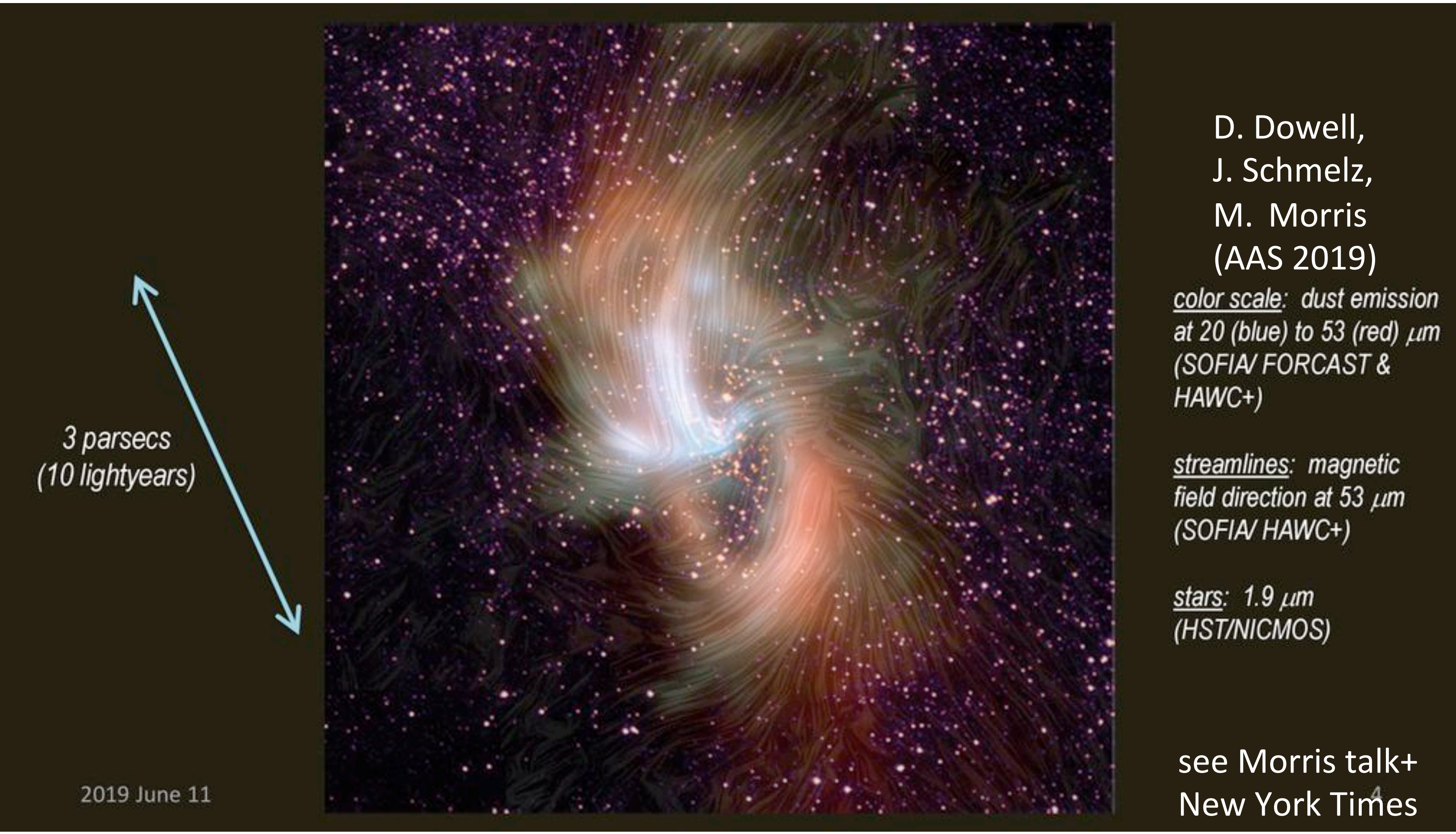
R. Lau, Herter, Morris, Becklin, Adams 2013 ApJ

This is the highest resolution image of the CircumNuclear Ring obtained with ~3 arcsec FWHM

- 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.

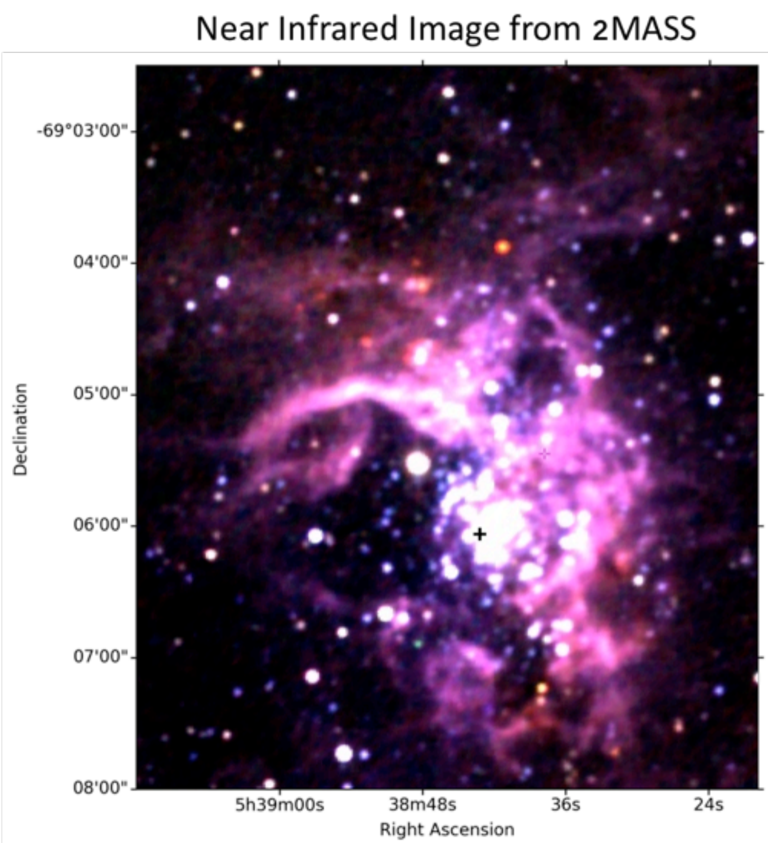


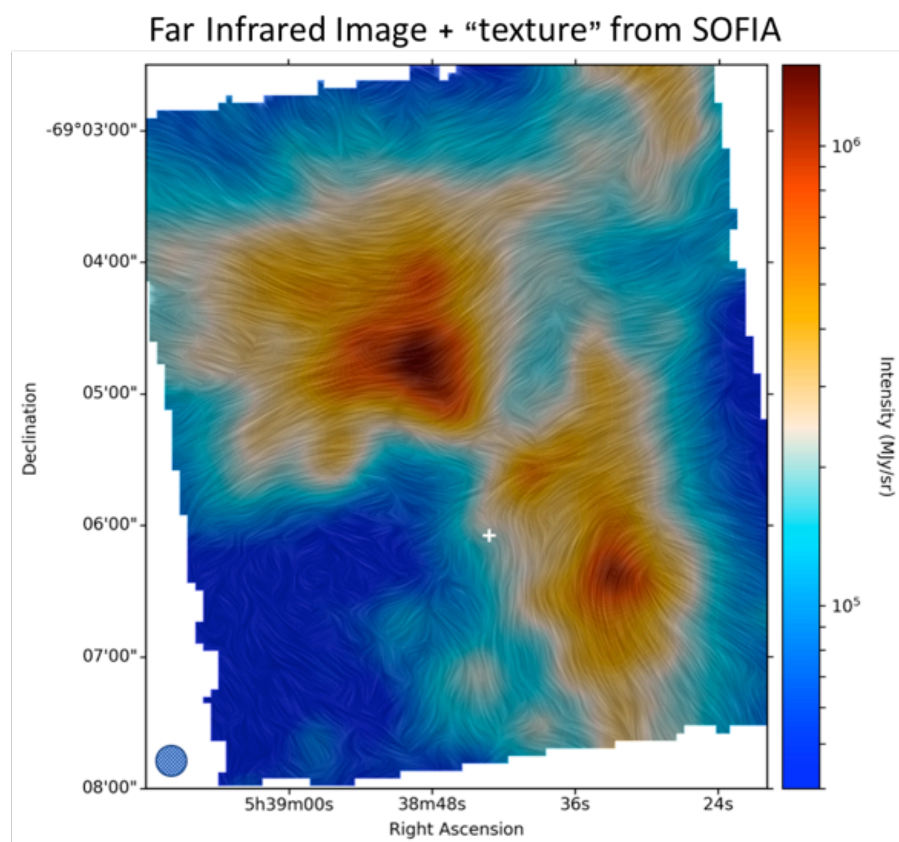
HAWC+ polarimetric 53 micron image of the Galactic Center region



FIFI-LS [CII] and [OI] maps of the BH circum-nuclear disk (inflow vs. outflow): Iserlohe etal. 2019

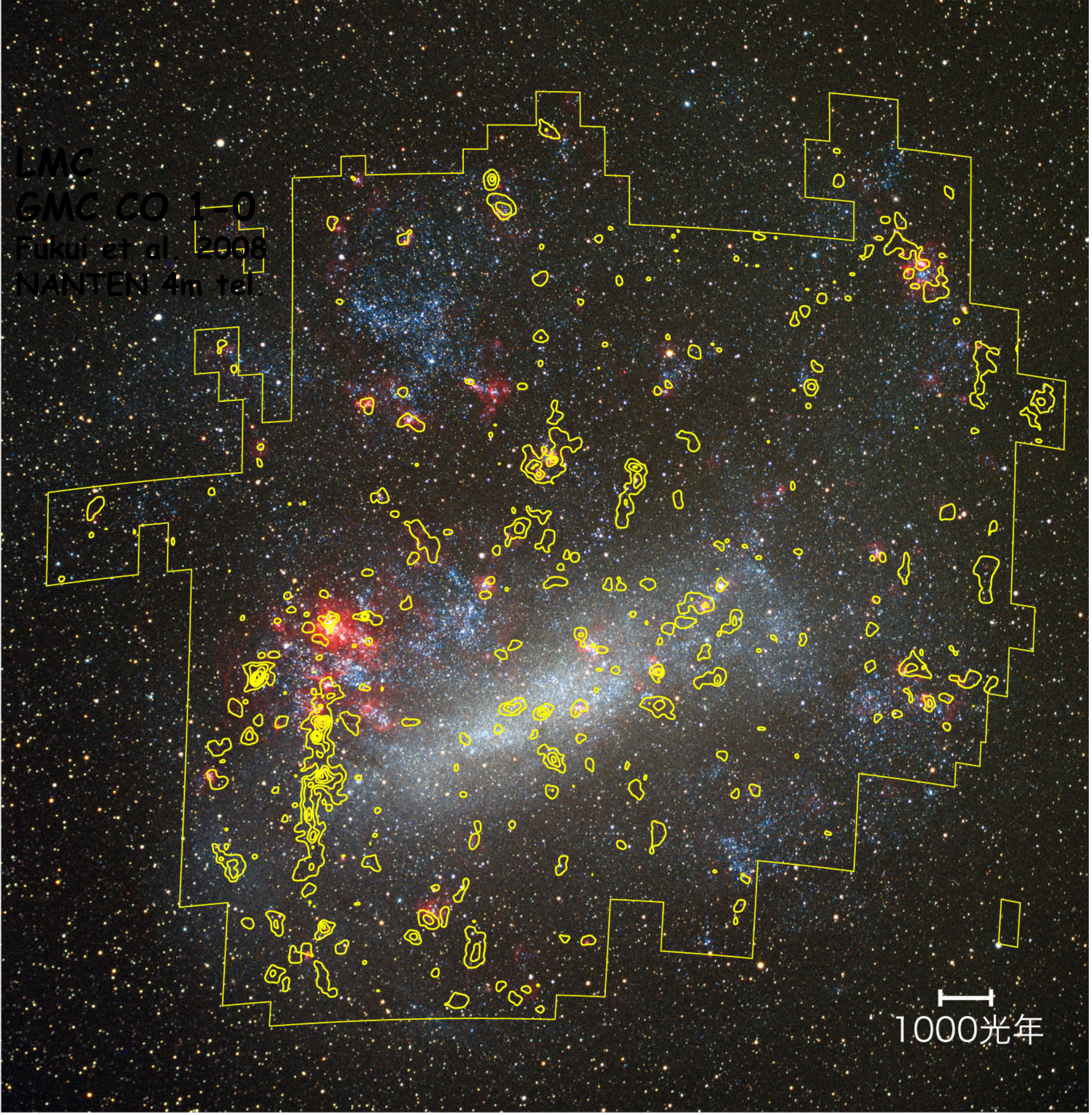
30 Dor: Far-IR polarimetric image





+ 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.



The question
of CO-dark H2 gas

C+ is a key tracer:
LMC+ FIFI-LS map
south of 30 Doradus
(partially completed)
S. Madden/A. Krabbe

SOFIA star formation highlights etc

Appendix: Major science highlights of SOFIA

Here we briefly summarize a number of major science highlights[1] that SOFIA obtained over the years (some 30 discoveries in total), sorted by the individual scientific instruments:

- GREAT:

first detection of the elusive HeH^+ molecule at 1.49 THz, in NGC7027, with implications for the early universe (Güsten et al., 2019); detection of infall motion in dense protocluster clouds via redshifted NH_3 absorption lines at 1.81 THz (Wyrowski et al., 2012), mapping the Orion Nebula [C II] velocity resolved PDR bubble at 1.9 THz, implying wind dominated stellar feedback in HII regions (Schneider et al., 2020; Pabst et al., 2019); detection of para H_2D^+ (Brünken et al., 2014) and ortho D_2H^+ (Harju et al., 2017) at 1.37 and 1.47 THz, key molecules to initiate deuterium chemistry; detection of SH at 1.37 THz tracing warm gas from pockets of turbulent dissipation (Neufeld et al., 2012); OH ground state absorption at 2.5 THz tracing cold H_2 gas in the LOS towards Galactic star forming regions (Wiesemeyer et al., 2012); imaging spectroscopy of the 1.9 THz [C II] line emission in the Sgr B2 region (Harris et al., 2021). Note that a history of [C II] heterodyne spectroscopy with GREAT and upGREAT was given by Stutzki p. 34.

- FIFI-LS:

accretion bursts in high-mass protostars (e.g., S255 NIR3), including luminosity jumps and FIR light echos (Caratti o Garatti et al., 2017; Stecklum et al., 2021); dual channel IFU large-scale mapping of FIR fine structure lines, tracers of diffuse and dense gas in spiral galaxies (Bigiel et al., 2020); mapping of FIR fine structure line to trace the large-scale dynamics of the Galactic Center region and to test inflow motion towards the circumnuclear ring (Iserlohe et al., 2019); tracing the extent of the ionized galactic superwind from the M82 starburst galaxy via [C II] and [O III] FIR spectroscopy (Fischer et al., in prep.); measuring the disk scaleheight of [C II] emission in edge-on spiral galaxies, e.g., chimneys and fountains, in NGC 891 (Reach et al., 2020)

- FORCAST:

multi-color mid-IR imaging of the iconic 1.5pc circumnuclear ring around Sgr A* heated by the Galactic Center nuclear OB star cluster (Lau et al., 2013); detection of warm dust in the SgrE SNR, proving dust formation in SN-ejecta and survival in reverse shock (Lau et al., 2015); detection of IRS4 as a dominant high-luminosity source in Orion-BNKL (De Buizer et al., 2012); mid-IR survey of embedded massive star formation in Galactic giant HII regions (Lim & De Buizer, 2019); detection of a concentrated dust belt in the eps Eri debris disk (Su et al., 2017); detection of water on the sunlit side of the Moon, potentially very important for NASA missions (Honniball et al., 2021)

- HAWC+:

mapping of magnetic field structure near the Galactic Center (Dowell et al., 2019a); mapping of magnetic field structure of dense filaments (Pillai et al., 2020); mapping of magnetic field structure in the M82 outflow (Dowell et al., 2019b, Dowell et al., in prep.), mapping the magnetic field structure in the 30 Dor HII region (Gordon et al., 2018, directors discretionary time); detection of the FIR continuum in a $z = 1$ lensed starburst galaxy (Ma et al., 2018); grain alignment in the circumstellar shell of IRC+10216 (Andersson et al., 2022).

- EXES:

detection of water in a high-mass protostar at 6.1 μm in absorption (Indriolo et al., 2015); detection and spectral maps of the 28 and 17 μm lines of H_2 in emission from Jupiter (Fletcher et al., 2017); ro-vibrational spectra of organic molecules, such as C_2H_2, and search for methane on Mars (Aoki et al., 2018), as well as measurement of the D/H ratio on Mars (Encrenaz et al., 2016).

- FLITECAM/HIPO/FLIPO/FPI+:

Detection of variable 1.8 μm ionized Co-60 lines in a type Ia supernova in M82 (Vacca et al., 2015); two Pluto occultations, confirming Pluto's atmospheric haze and supporting NASA's New Horizons 2015 Pluto fly-by (Person et al., 2013, 2021).

These major results testify to the success of SOFIA and remain a lasting legacy. In addition, SOFIA conducted 9 large Legacy programs the details of which cannot be discussed here, due to lack of space. They were: FEEDBACK (Schneider et al., 2020), Galactic Center Map (Hankins et al., 2020), B Fields in Galaxies (Borlaff et al., 2021), HyGAL (Jacob et al., 2022), FIELDMAPS (Stephens et al., 2022), LMC+ (Madden et al. p. 60), B Fields in Galactic Center (FIREPLACE, PI Chuss), SIMPLIFI (PI Pillai), and Lunar Water Survey (PI Lucey).

THE FUTURE OF FAR-INFRARED ASTRONOMY BEYOND SOFIA

H. Zinnecker[1] and A. Krabbe[2]

Abstract. SOFIA, the Stratospheric Observatory for Infrared Astronomy, is gone, terminated prematurely by NASA/DLR at its peak of producing science, following an unfair recommendation by the Decadal Review Astro2020. After 2013, when the Herschel Space Observatory stopped observing, SOFIA was the only far-infrared observatory in the world and its demise leaves a gap that neither ALMA nor JWST can fill. It was complementary to both. It will be missed by many astronomers who wonder why this hasty decision was taken and actually by whom. It seems a simple and flawed 1-dimensional metric (cost per paper) was used to justify the downing of SOFIA. Yes, SOFIA was expensive to operate, not least because of NASA's regulations concerning safety procedures, but was worth its money, given its unique role obtaining key data in the difficult to access far-infrared wavelength regime where most of the luminosity in the cosmos is emitted. SOFIA was a great success, fundamental for studies of star formation (e.g., magnetic fields) and ISM science (e.g., molecular spectroscopy), and ultimately also proved to be highly productive, as productive as the Herschel Space Observatory (2009-2013). NASA/DLR should have scheduled a SOFIA Senior Review and in case of a negative outcome should have allowed for a ramp-down period of 2-3 years. The future of far-infrared astronomy without SOFIA is unclear. NASA's promised probe mission (if selected against X-ray competition) won't be launched until the mid-2030, by then much of the key FIR expertise and community will be lost. Perhaps a long-duration stratospheric balloon platform or some other automatic system can fill the gap, if a safe landing technology can be deployed.

1 The Birth of SOFIA

SOFIA was conceived as the sequel of the successful NASA Kuiper Airborne Observatory (KAO) which operated for 20 years (1975-1995) with a 91cm mirror on a Lockheed C-141A Starlifter jet transport aircraft. After a long period of engineering and some financial hiccups, SOFIA (a Boeing 747SP with a 2.7m mirror, 3 times the size of the KAO mirror) took off for its first open door science flight on Dec 18, 2010 and reached full operational capability in 2014. On the US side, the two main fathers of SOFIA were Ed Erickson (NASA-Ames) and Larry Caroff (NASA-Ames), and another protagonist was infrared astronomer Eric Becklin (UCLA). On the German side, the idea of SOFIA was pushed by the late Peter Mezger (MPIfR) and the late Hans-Peter Roeser (DLR and later University of Stuttgart) who deserve credit for their foresight and energy.

From the beginning, SOFIA was run by USRA (Universities Space Research Association) on behalf of NASA and by DSI (Deutsches SOFIA Institut, University of Stuttgart) on behalf of DLR, with a staff of about 80 and 40 people, respectively. NASA's own additional staff for SOFIA exceeded 120. With an operating budget approaching 100 million dollars per year and a NASA/DLR 80:20 share of the cost (and the observing time), SOFIA became the largest bilateral science project between the US and Germany, with the US side providing the Boeing 747SP plane and most of the infrastructure, while the German side provided the mirror and telescope assembly, a masterpiece of engineering. Making stable astronomical observations from an aircraft flying at Mach 0.85 in turbulent air at 40,000 feet and above (to avoid atmospheric absorption of the incoming infrared radiation due to water vapor) is not a simple matter, particularly with an open door. Ensuring flight safety has always been a primary concern for NASA and contributed to the high cost of SOFIA. SOFIA flew out of Palmdale, southern California, while its science center was located at NASA-Ames at Moffett Field, northern California. The fact that (for political and operational reasons) SOFIA was divided into two NASA centers was unfortunate but unavoidable and sometimes caused communication

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Other highlights (---> other talks)

HeH+ first molecule and cooling agent in the early universe

Atomic jets ([OI] 63 micron) from Class 0 and I protostars

Debris disk (resolved dust ring) in eps Eridani at 35 micron

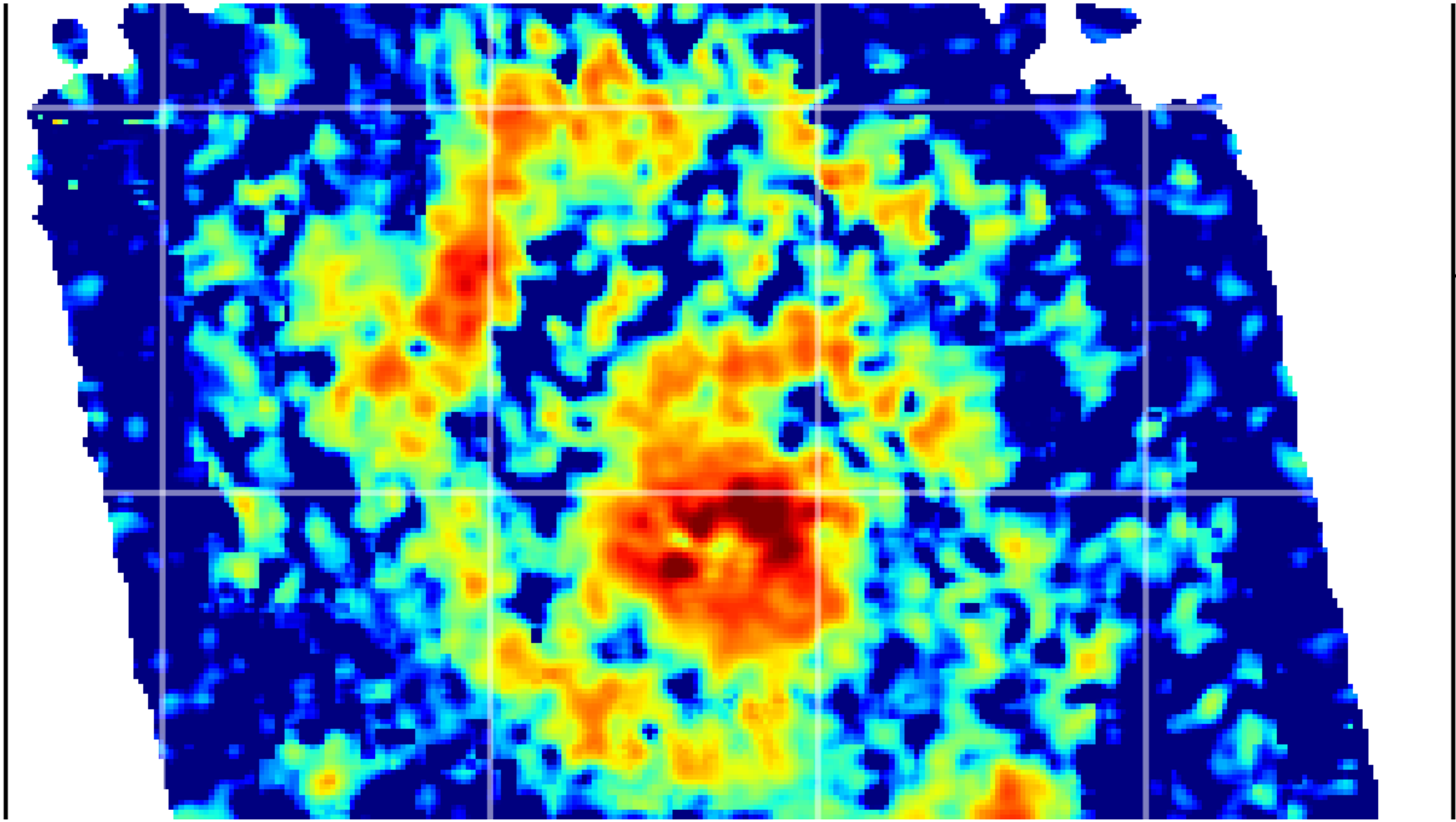
many more FIR polarimetric images of Galactic dark clouds

Extragalactic Star Formation: [CII] in M51, arm vs. interarm

Central starburst in M82: superwind ([OIII] 52/88 line ratios)

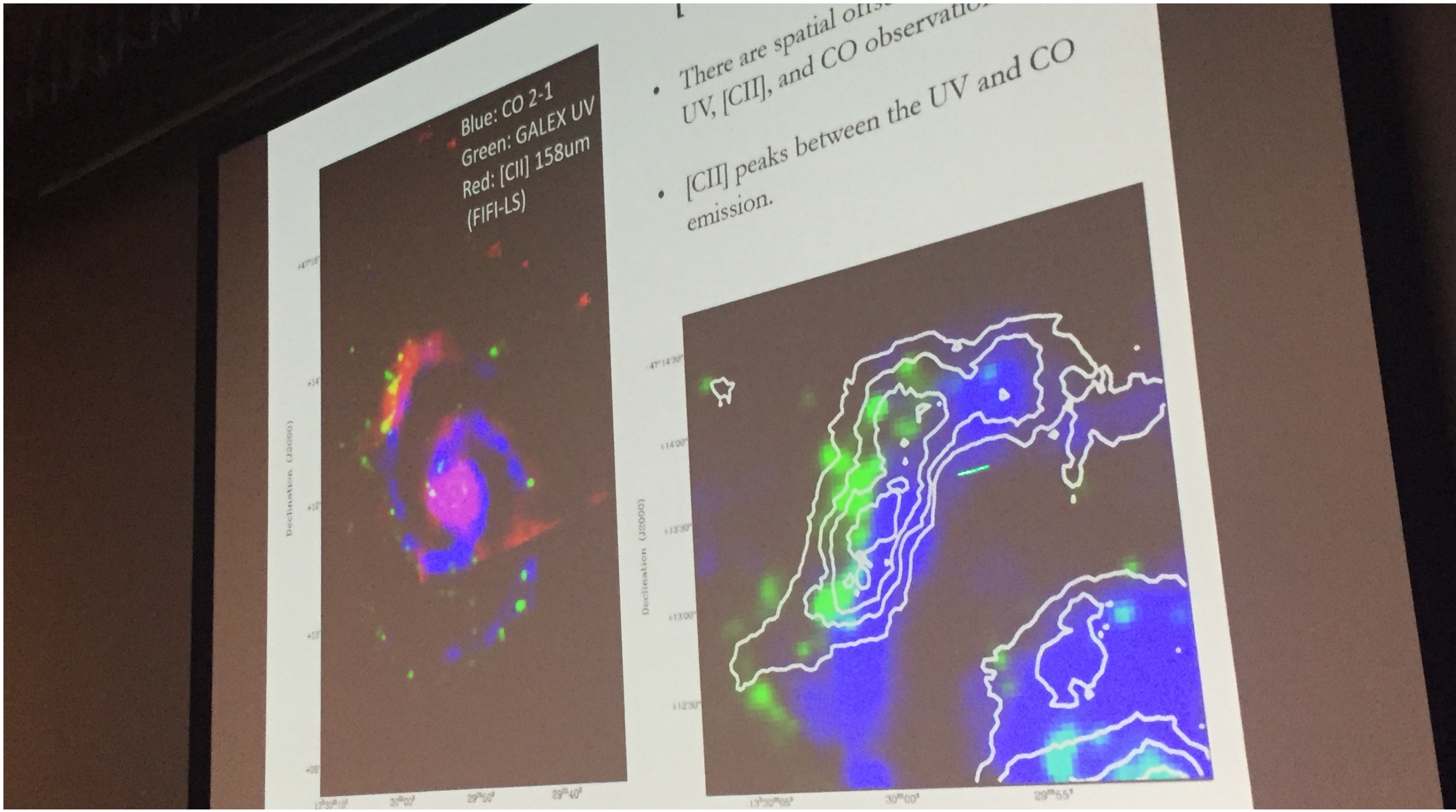
Extragalactic magnetism (Legacy): see Lopez-Rodriguez talk

M51 C+ map with SOFIA/upGREAT



PI: Pineda/Stutzki 2016, upGREAT beam size at 158mu is 16” = 800 pc, box=5x5kpc

M51: CII peaks between UV and CO



Proceedings of the 7th Chile-Cologne-Bonn-Symposium: Physics and Chemistry of Star Formation
V. Ossenkopf-Okada, R. Schaaf, I. Breloy, J. Stutzki (eds.)

Fischer et al. 2022 M82 starburst wind

PROBING THE IONIZED GAS IN THE CORE AND OUTBURST OF THE NEARBY STARBURST GALAXY M82 WITH FIFI-LS/SOFIA

C. Fischer[1], W. Vacca[2], C. Iserlohe[1], S.T. Latzko[1] and A. Krabbe[1]

Abstract. At a distance of ~ 3.5Mpc (1arcsec ~ 16pc), M82 is one of the nearest and brightest starburst galaxies. The central (~1kpc) region hosts a fairly young (~5Myr; Förster-Schreiber et al., 2001) powerful starburst, which appears to be driving a bipolar wind, or outflow, along the minor axis of the galaxy (i.e., perpendicular to the disk), and which has been shown to comprise multiple components. The disk is nearly edge-on ($i \sim 81°$, i.e., the northern outflow is receding from us and therefore has higher extinction than the southern lobe), which provides an ideal orientation for studying the outflow and its connection to the nuclear starburst. We use recent observations with SOFIA/FIFI-LS to investigate the spatial variation of electron density in the starburst region, disk, and outflow.

1 Observations and data reduction

Observations of the [OIII] 52μm line were obtained with SOFIA/FIFI-LS during multiple missions between 2016 and 2020 as FIFI-LS guaranteed time as well as open time project 07_0217 (PI Latzko) with varying integration time and noise throughout the map. To obtain the [OIII] line ratio we used observations of the [OIII] 88μm line with Herschel/PACS that we retrieved from the archive. For the telluric correction water vapor values were derived from the ECMWF data base. The line fluxes, center, and widths were measured in the PACS and FIFI-LS data by fitting Gaussian profiles at each spatial point. Fit limits for the FIFI-LS [OIII] 52μm lines center and width were determined from the PACS data.

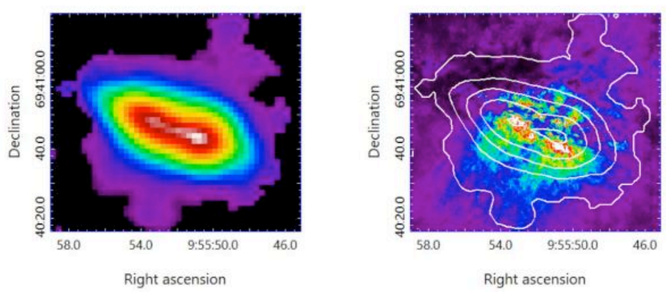


Figure 1: *Left panel:* Integrated line fit for the [OIII] 52μm line from FIFI-LS/SOFIA in log scale (only fits with S/N >= 3 shown) *Right panel:* Contours of [OIII] from the left panel overplotted on a HST F658N Hα image (continuum subtracted).

FIFI-LS
Result

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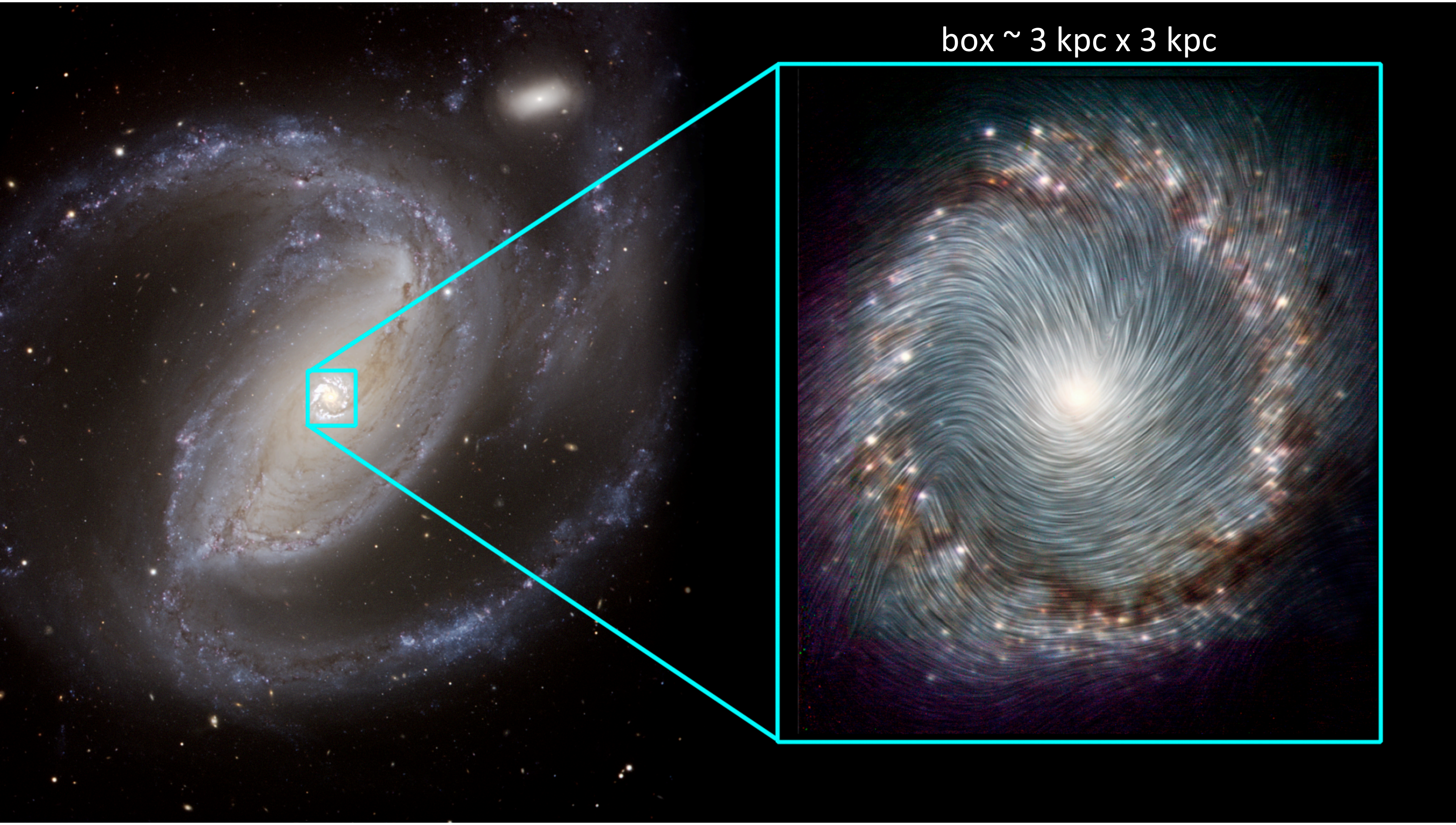
Magnetic field structure in NGC1097



Lopez-Rodriguez et al. 2021 ApJ: Legacy “extragalactic magnetism” with SOFIA/HAWC+

The termination of SOFIA – which key science has been lost

More detailed Galactic Center and CMZ study:
role of BH, turbulence, and shear in star formation;
why so much dense CMZ gas does not form stars?
feedback: positive/negative (triggering, dissipation)?

Better understanding of the role of magnetic fields
--in star formation: help or hindrance?
--in feeding SMBH: accretion rate and outflow rate
--magnetic field structure and magnetic field strength

My last working day
at DSI on Oct9 2017

Palmdale 2016: farewell from SOFIA


SOFIA in the PIMA Air & Space Museum in Tucson/AZ
SOFIA
STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY
NASA
DLR
Photo courtesy: Bernhard Schulz (2024)

How to evaluate scientific infrastructures scientifically?
A case study of SOFIA

Draft for resubmission to Nature Astronomy Nice outline and structure of the paper

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1 Evaluation, Objectivity, and Impacts of Science 2
2 Methods of investigation 3
3 Evaluation criteria for scientific missions 4
3.1 Optimal Methods of Evaluation 5
3.2 Actual Methods of Evaluation 6
4 Types of criteria for scientific evaluation 6

The Future of FIR star formation

- NASA probes: PRIMA, FIRSST, SALTUS, SPICE(?)
- Need for spatial resolution (~10m = 4 x SOFIA)
- Need for HIRMES-like spectrometer (25-120mu)
- Int'l balloon facility: soft landing, steerability, etc
- Blimps/Zeppelins: what is the development cost?

- Study protostars in Central Mol. Zone (census)
- Study the role of magn fields in star formation
- Study protoplanetary disks (H2/H2O reservoir)
- Study massive stars disk accretion bursts (stats)
- Study the "local truth" to bridge the gap to the distant universe (z ~ 1-3). Q: Can JWST do this?

The Local Truth: Star Formation and Feedback in the SOFIA Era

Celebrating 50 Years of Airborne Astronomy

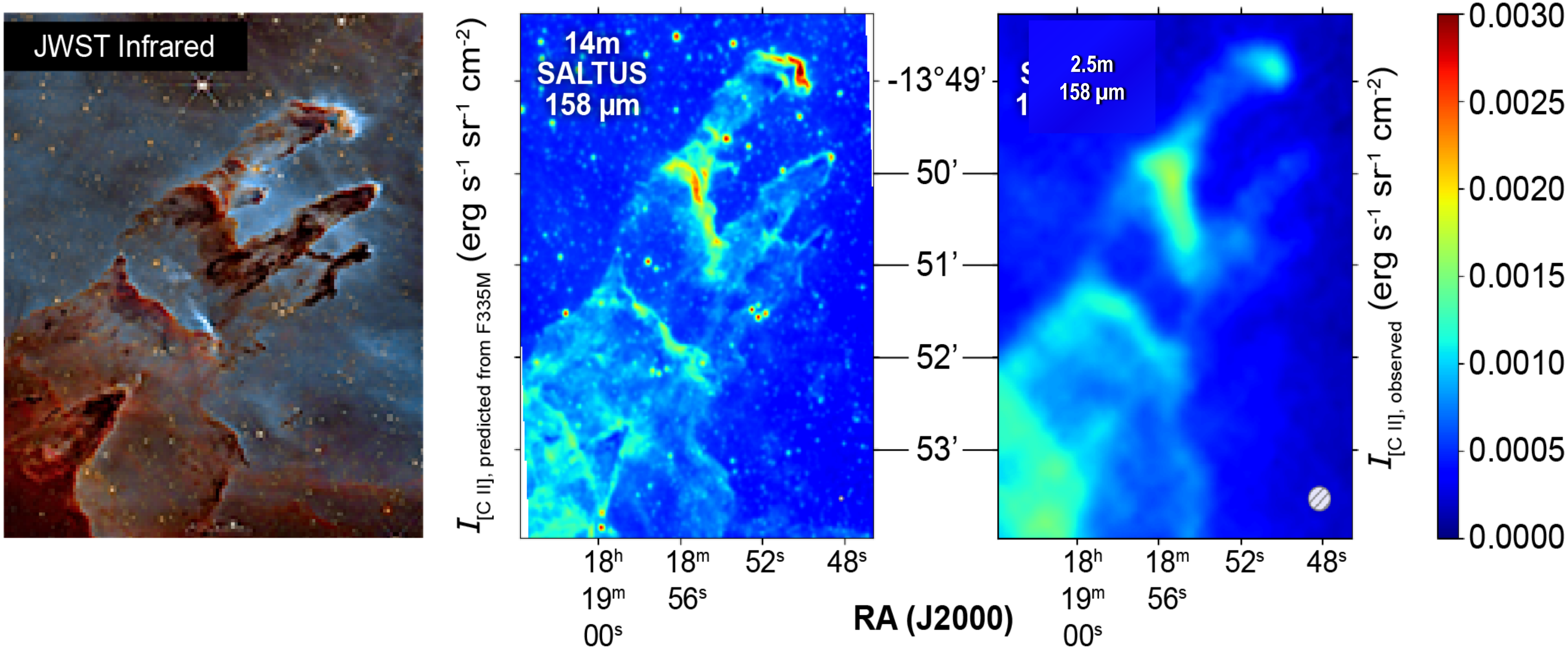
Asilomar Conference Grounds

SALTUS: *Single Aperture Large Telescope for Universe Studies*

- 14m Reflector
- $\leq$ 45K Optics
- Coherent & Incoherent Spectroscopy/Imaging
- ~30 to 660 µm
- >5 yrs Baseline Mission
- >3.5 yrs of Guest Observations

Addresses many Science Objectives within the Astro 2020 Decadal

Large Aperture Provides High Angular Resolution



Simulated *SALTUS* image at 2.5" angular resolution (middle) of the [CII] 158µm emission in NGC 6611 (Pillars of Creation) is similar to the *JWST* image (left) and compared to a 2.5m reflecting telescope-created map (right). SAFARI-Lite can map this 10 arcmin^2 region in 10 hours and simultaneously provide maps in all diagnostic lines of photo-dissociation regions (PDRs) and HII regions in our galaxy and the local group, probing the physical environment produced by radiation feedback of massive stars and its link to stellar clusters and its molecular core.

1) Trace Formation and Evolution of Planetary Systems

How does habitability develop during planet formation?

Distribution of mass and C/N/O in 1000 protoplanetary disks

- What is the mass?: Target HD
- Where is O?: Target H_2O vapor & ice
- Where is N?: Target NH_3
- Where is C?: Target High J CO

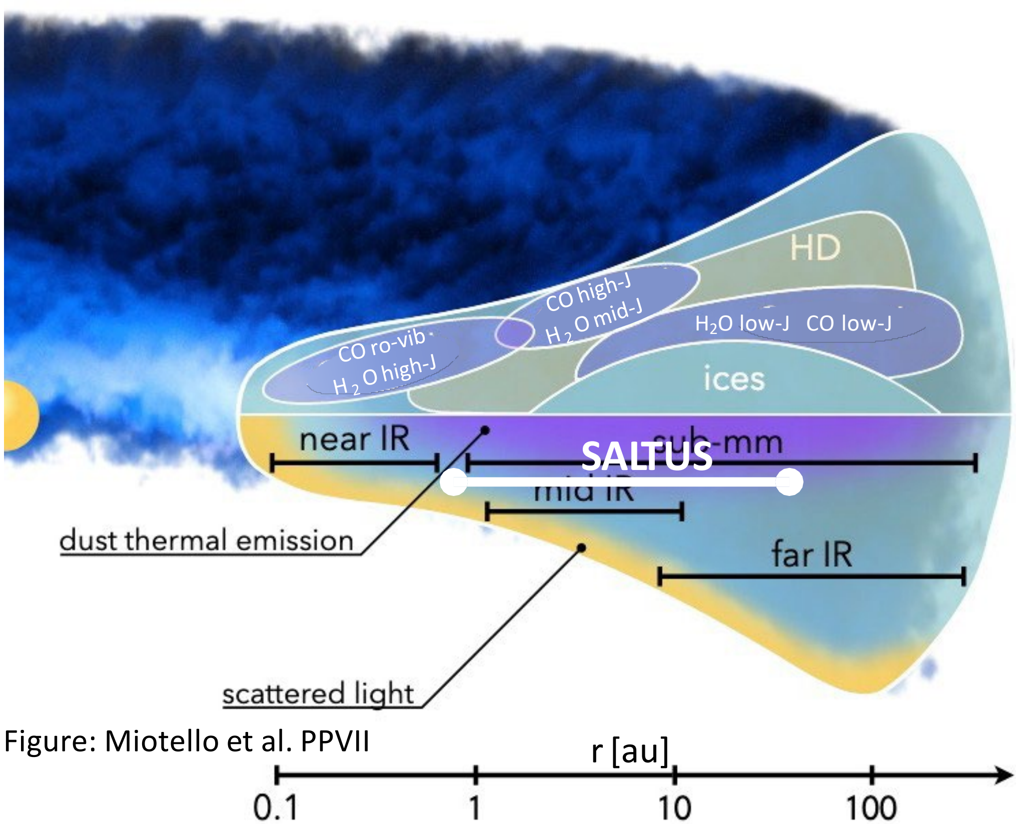
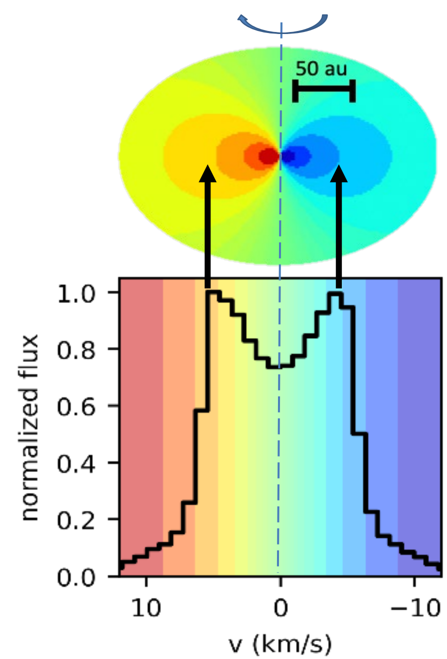
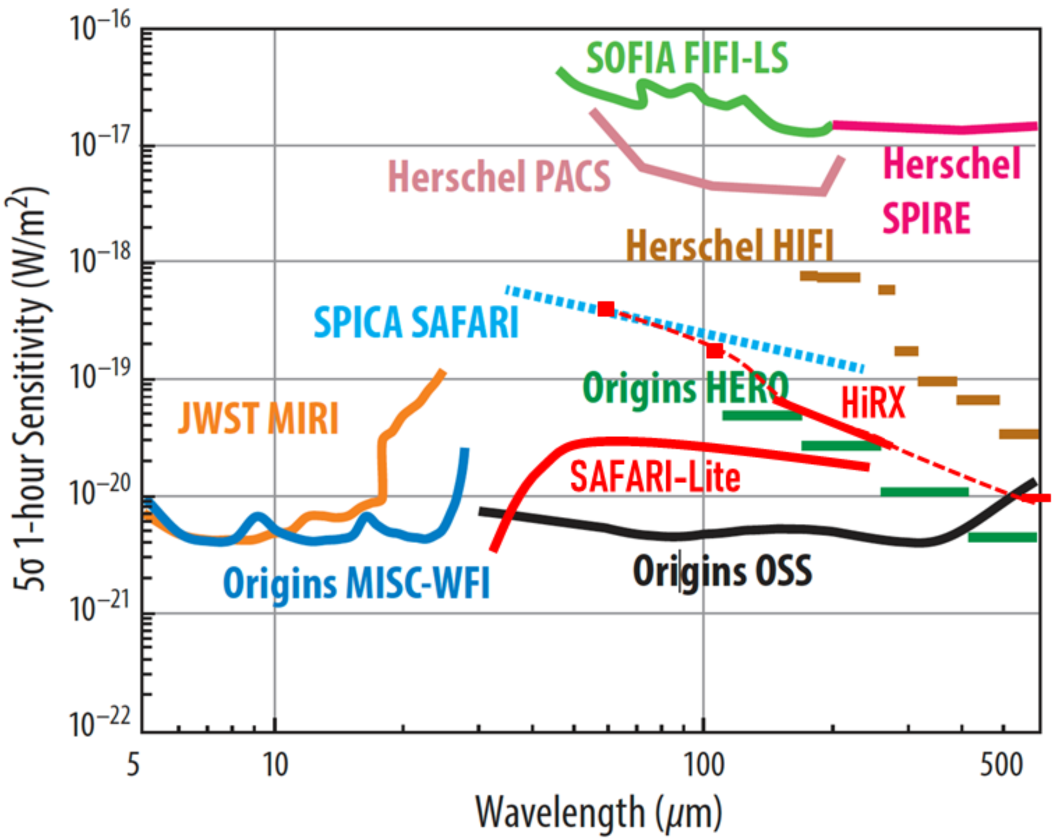


Figure: Miotello et al. PPVII



Heterodyne Spectroscopy → **Doppler Tomography of HD and H_2O Disk Spectra $R \sim 10^6$**

Large Aperture Provides High Sensitivity



Instruments

SALTUS Far-IR Spectrometer (SAFARI-Lite)
- 34 to 230 μm (4 Bands)
- Instantaneous coverage
- ~180 pixel KID arrays, spectroscopic
- R = 300
- *Existing technology*

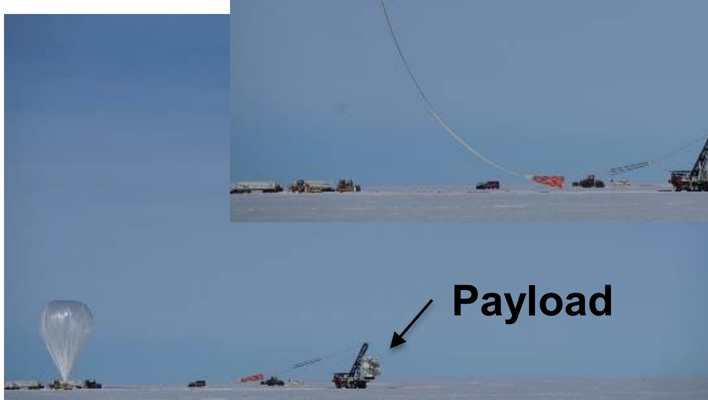
SALTUS High Resolution Receiver (HiRX)
- 56 to 300 μm
  4 Bands HEB mixers
- 520 to 660 μm
  Dual Polarization SIS
- R = ~$10^{6\text{-}7}$
- *GUSTO Heritage*

GUSTO

Launch: Jan 31!

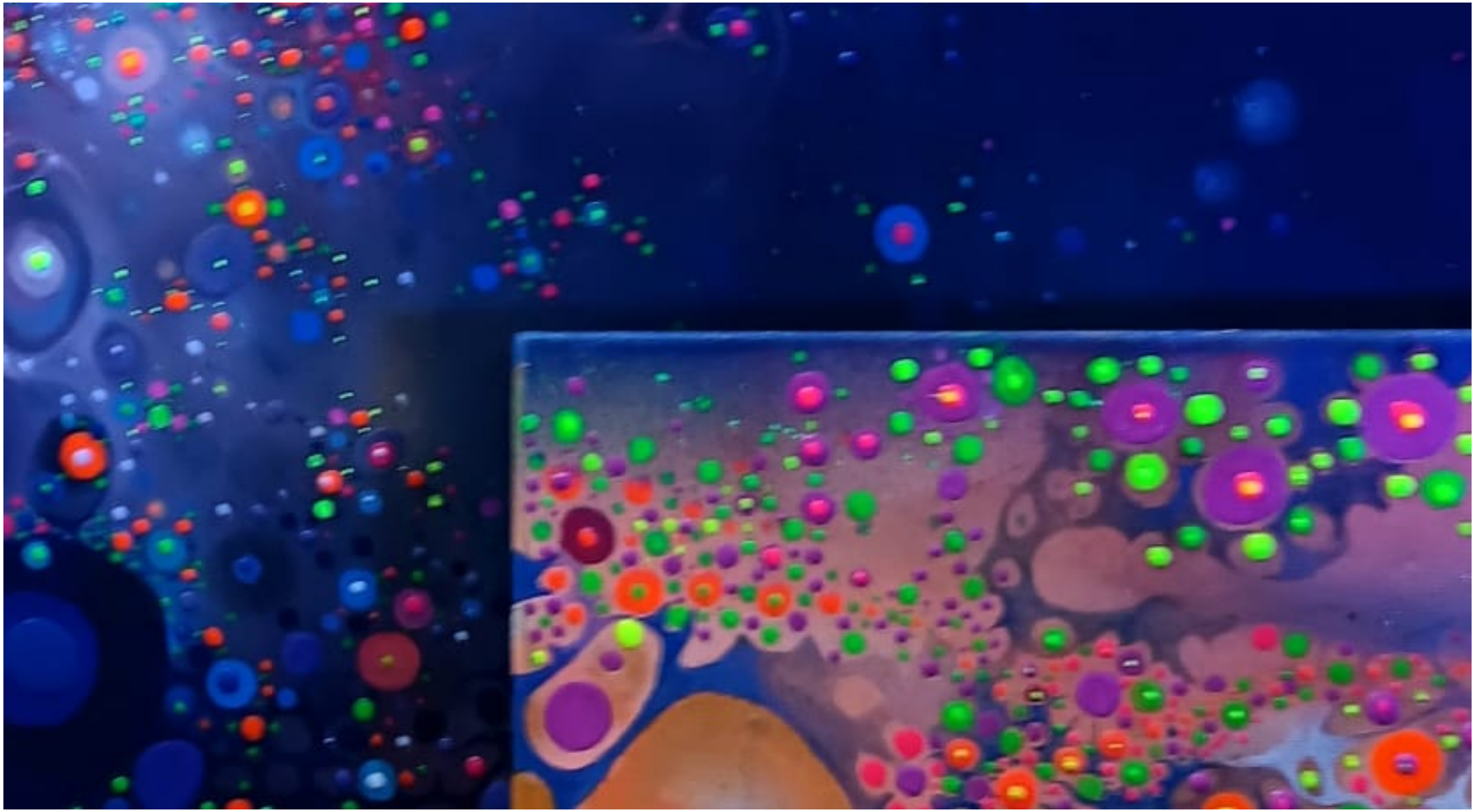
PI Chris Walker,
Univ. of Arizona

Balloon Release



Balloon Inflation

Huris Pacheco, painting star formation



Summary: SOFIA & SF (Q/A)

- What can we learn from [CII]/FSL observations?
- dynamics (ionisation, winds), feedback, dark gas
- What can we learn from FIR continuum obs?
- SEDs, L-bol, time variability of disk accretion
- What can we learn from FIR cont. polarimetry?
- grain alignment theory, magn. fields geometry
- What can we learn from FIR molecular lines?
- dynamics (collapse NH3), mol gas masses (H2)

- Star Formation = SFE, SFR, IMF (SOFIA's impact)