International Science Ideas for SOFIA (extended mission)

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SIS, NASA-Ames

Disclaimer (concerns)

- From a distance (reading SOFIA flash reports in Chile), I am now more worried about SOFIA aircraft reliability than about SOFIA science.

- I am also worried that SOFIA does not feature in any of the conference announcements in the Star Formation Newsletters (No 298/299).

What is SOFIA's science mission?

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

-atomic[ii]/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+)

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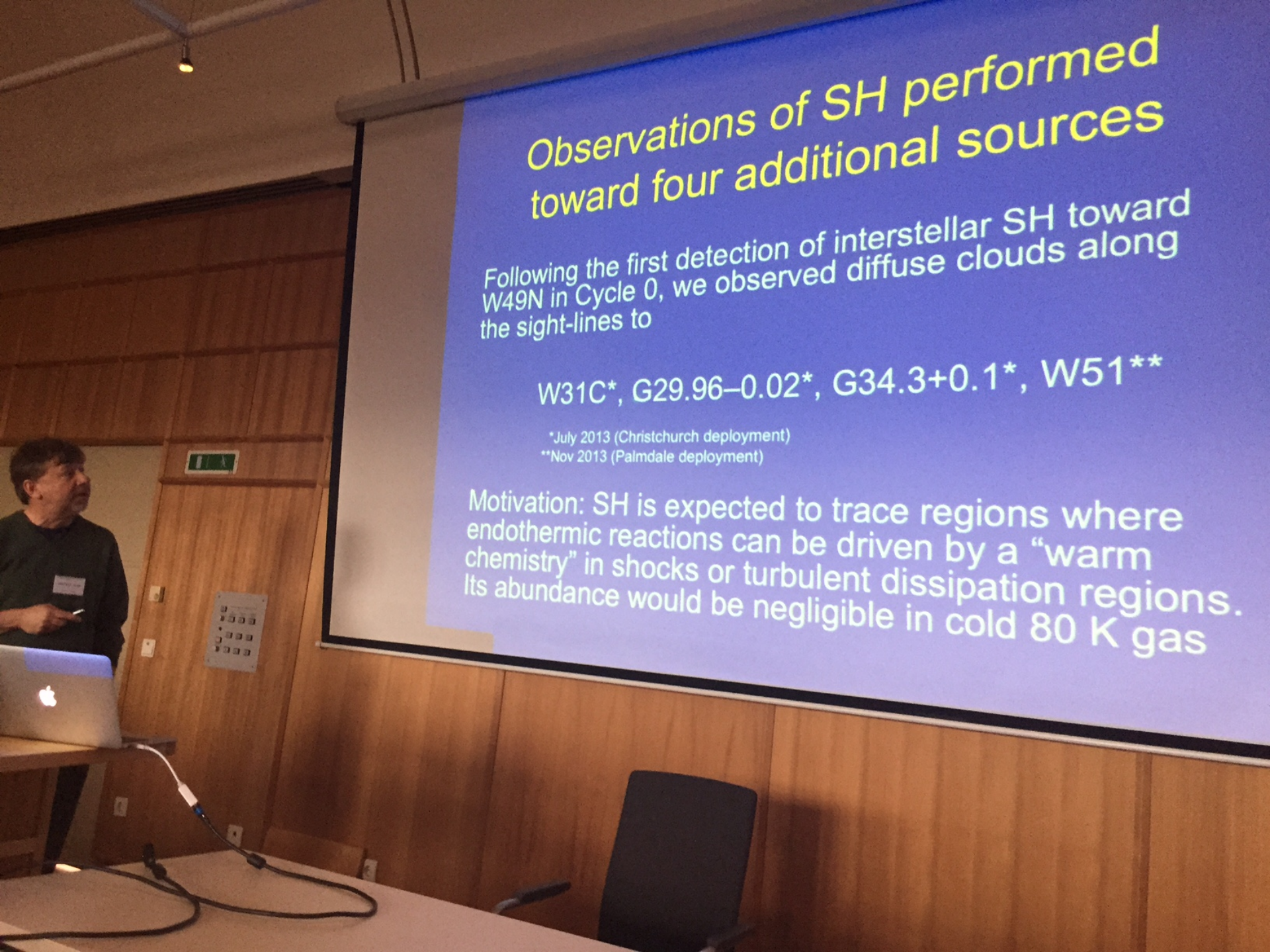
Follow-up of IRAS, ISO, Spitzer and Herschel observations

Future international SOFIA science

- C+ survey of 100 nearby galaxies (L_C+/L_tot)
- C+ study of mol cloud formation & destruction
- SH survey: study mol. cloud turbulent heating
- Synchrotron FIR polarization study (jets, AGN)
- Circumstellar chemistry in evolved stars (AGB)


Observations of SH performed toward four additional sources
Following the first detection of interstellar SH toward W49N in Cycle 0, we observed diffuse clouds along the sight-lines to
W31C*, G29.96–0.02*, G34.3+0.1*, W51**
*July 2013 (Christchurch deployment)
**Nov 2013 (Palmdale deployment)
Motivation: SH is expected to trace regions where endothermic reactions can be driven by a "warm chemistry" in shocks or turbulent dissipation regions. Its abundance would be negligible in cold 80 K gas

Future international science, ctd.

- H2 & HD in the Galactic Center CMZ: em./abs.
- Magellanic Clouds: CO-dark H2 gas (X-factor)
- H2 gas mass in T Tauri circumstellar dust disks
- The role of SF feedback: Carina region (2kpc)
- The role of magnetic fields in star formation: from Bok globules, to filaments, to giant MCs
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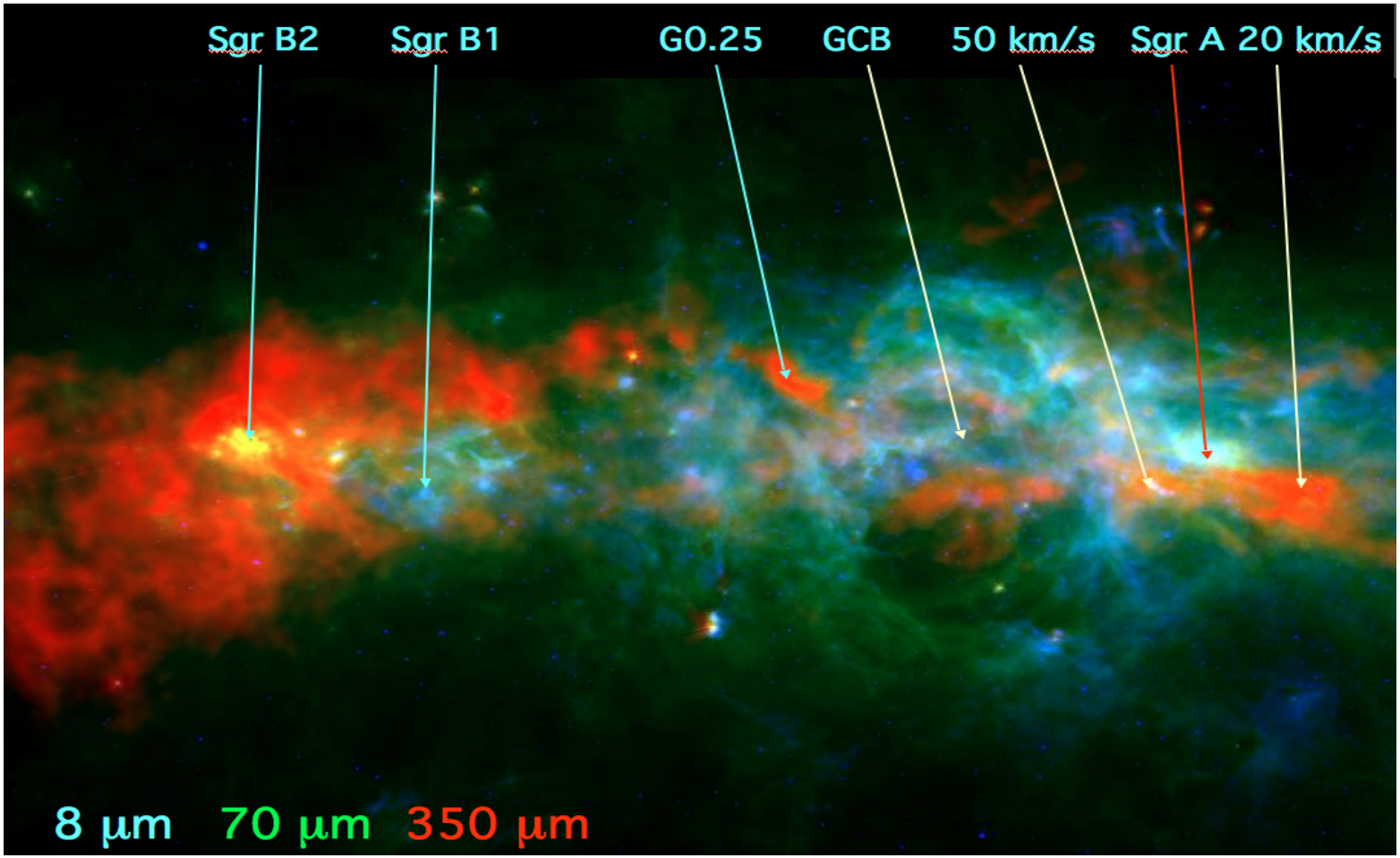
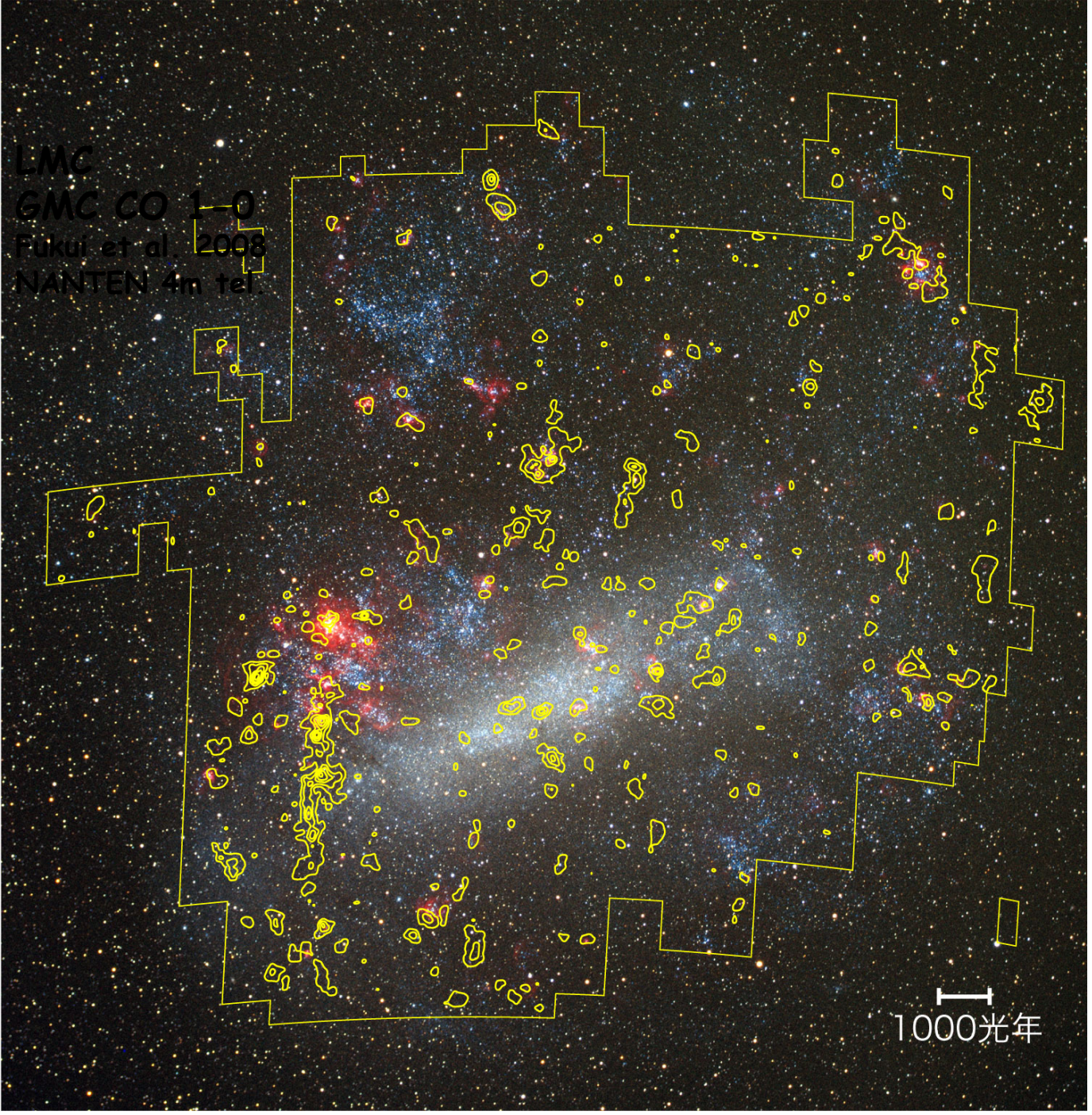
- Emphasize what Herschel could not achieve
- Look for synergies with ALMA/APEX, (CCAT')

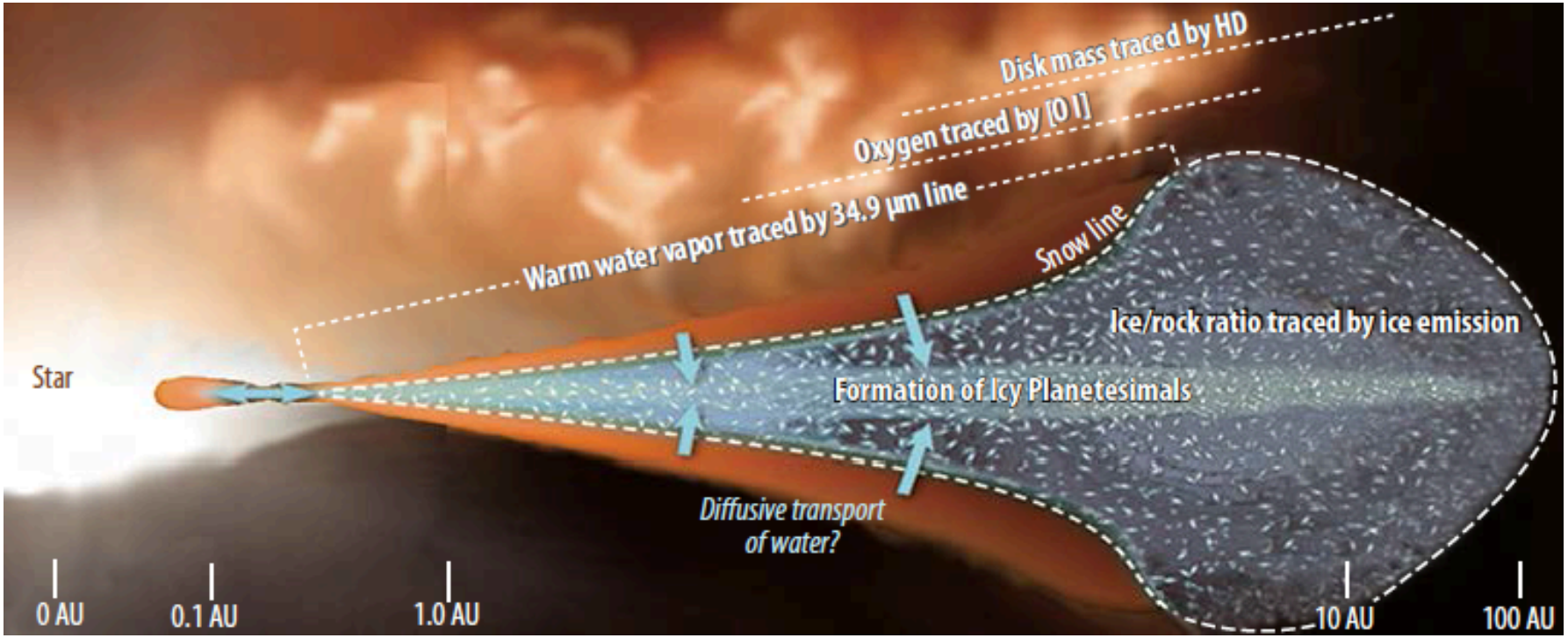
Galactic Center IR/submm image (Bally)




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

In 2019: HIRMES (High Resolution Mid-InfrarEd Spectrometer)

- Wavelength range: 25µm – 122µm; diffraction limited
- Variety of observing modes
  - Spectroscopy with R=600 to R=100,000
  - Spectral imaging capabilities for a few selected emission lines



Potential international SOFIA scientists

- C+ galaxy survey: Bolatto, Testi, Walter, HZ
- Turbulence: E. Falgarone, D. Lis, + D. Neufeld
- Synchrotron FIR pol: S. Markoff, Ed van Heuvel
- AGB chemistry: J. Cernicharo, R. Bachiller, Hans Oloffson, Goeran Oloffson, Lars Nyman
- GMC formation/destruction: Inutsuka, Fukui

Potential international SOFIA scientists

- H2 and HD in CMZ: A. Sternberg, F. Boulanger
- CO dark H2 gas in Mag. Clouds: M. Rubio etal. (Herrera-Camus, M. Chevance, + Sue Madden)
- H2 gas in T Tauri disks: T. Henning + E. Bergin
- Carina HII region: T. Preibisch + Nathan Smith
- Magn. fields: P. Andre, P. Bastien + G. Novak

- The idea is to form international working groups (invite those scientists to next SOFIA conference)

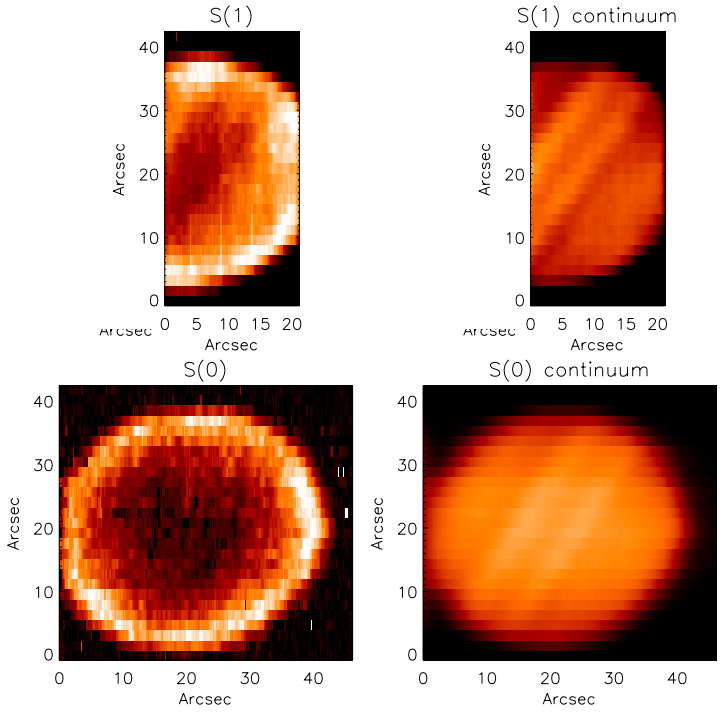
past and future PR opportunities

- Pluto occultation vs. New Horizons Mission!
- Triton occultation, MU 69 asteroid (?), TNOs
- Jupiter H2 limb 28/17 micron detections (OPR)
- more solar system: Mars (D/H, [OI]), Venus CO2

- luminosity outbursts (S255-IRS3, follow-up)
- HL Tau (SOFIA disk, synergy with ALMA disk)

- SNIa 2014 J in M82. Are we ready for a bright (perhaps obscured) Galactic supernova type II?

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(0) at 28.3 mu unobservable from ground

S(1)//S(0) gives temperature, with long latency

Combined with other temperature measurements implies convective motion into the stratosphere and circulation

unpublished (?) → relation to exoplanets

A new (updated) science vision for SOFIA (1)

Formation of Stars and Planets old vision ok,
but…

- not only high-mass, also low-mass SF (HD)
- cloud formation, cloud destruction (C+ maybe)
- CO dark gas, tracing H2 envelopes (C+, OH, CH)
- infall studies instead of SED studies (NH3, HD)
- turbulent vs. magnetic field support (SH, FIR-pol)
- disk spectroscopy instead of disk SEDs ([OI], HD)
- luminosity outbursts (disk instabilities) (FIR cont.)
- separate accretion shocks from outflows ([OI)]

A new (updated) science vision for SOFIA (2)

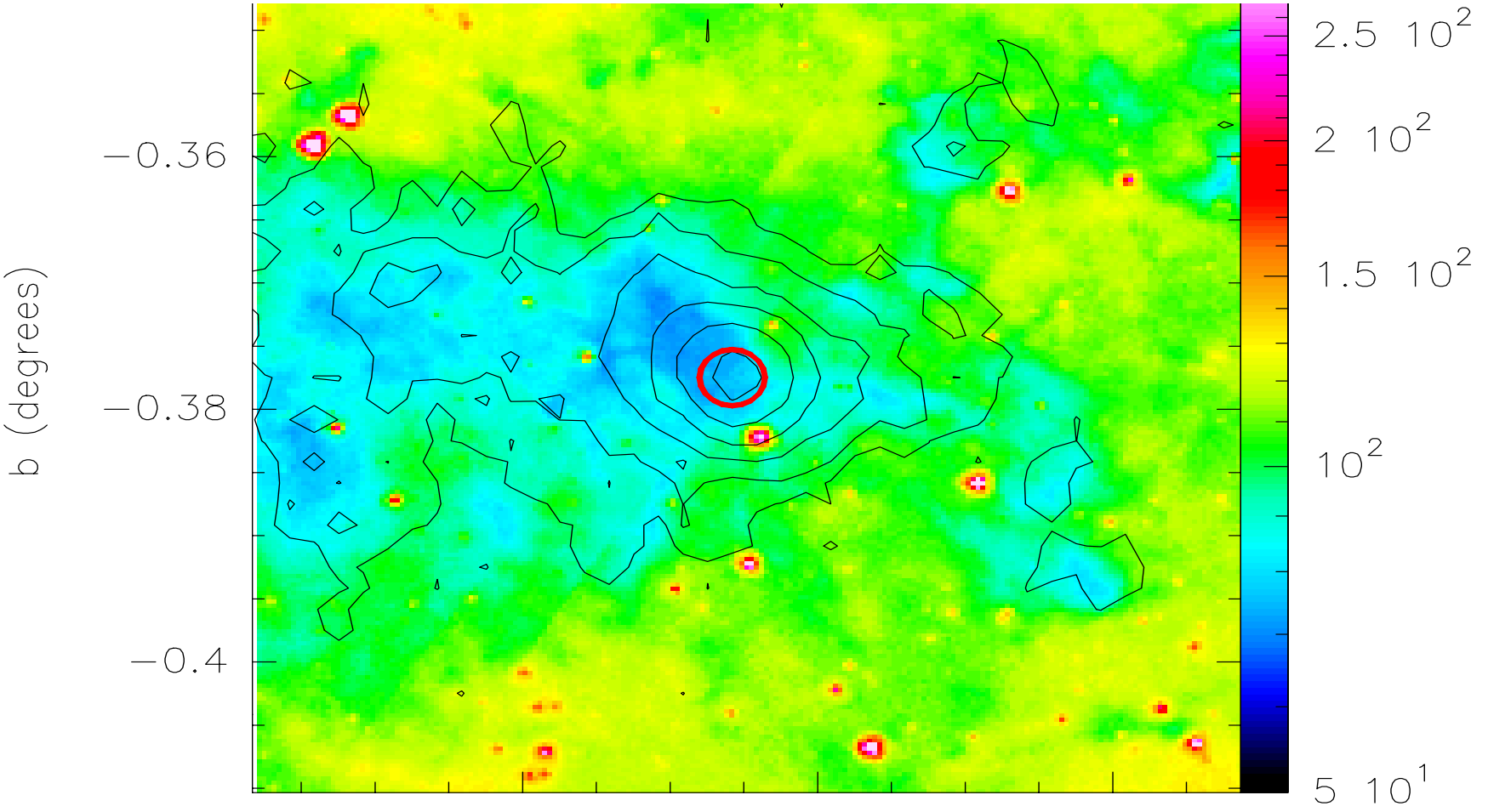
ISM in the Galactic Center

- CMZ ([CII], [OI], LFA/HFA upGREAT maps)
- CND (gas accretion, [CII], CO, [OI] FIFI-LS)
- CMZ/CND (magn. field, HAWC+ polarimetry)

ISM in nearby (and high-z) Galaxies

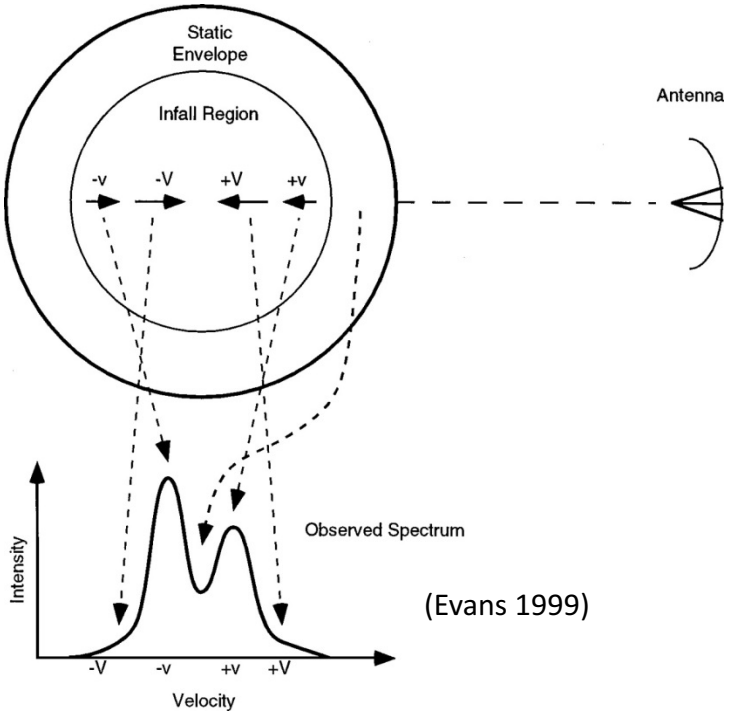
- ISM in spiral arms vs. interarm (e.g. M51, [CII])
- [CII] as a star formation tracer (galaxy samples)
- Dust emission in z~2 lensed galaxies (HAWC+)

ATLASGAL submm clump G23.21 (Spitzer IRDC)



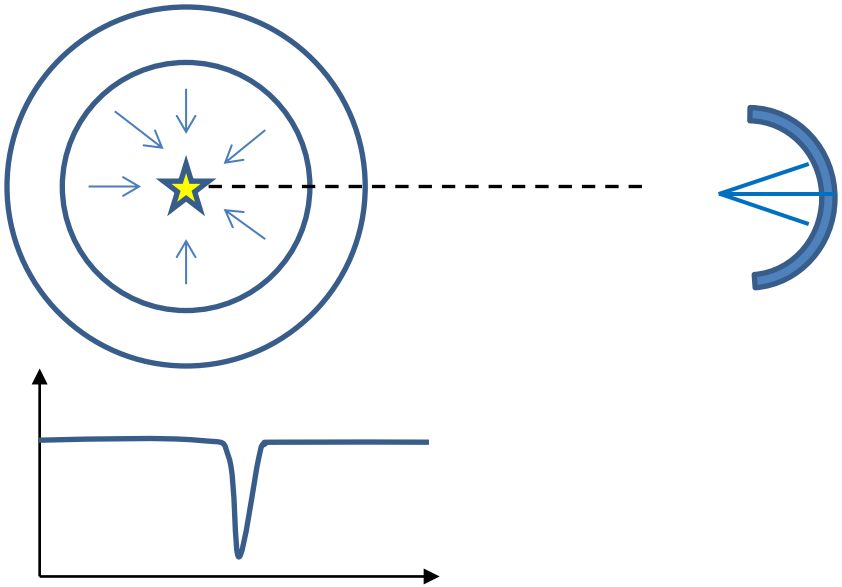
Spitzer Infrared Dark Cloud IRDC), with FIR continuum source.
Molecular clump mass: ~ 10(3) Mo, infall rate: ~ 10(-3) Mo/yr.

Using THz Lines to Probe Infall



(Evans 1999)

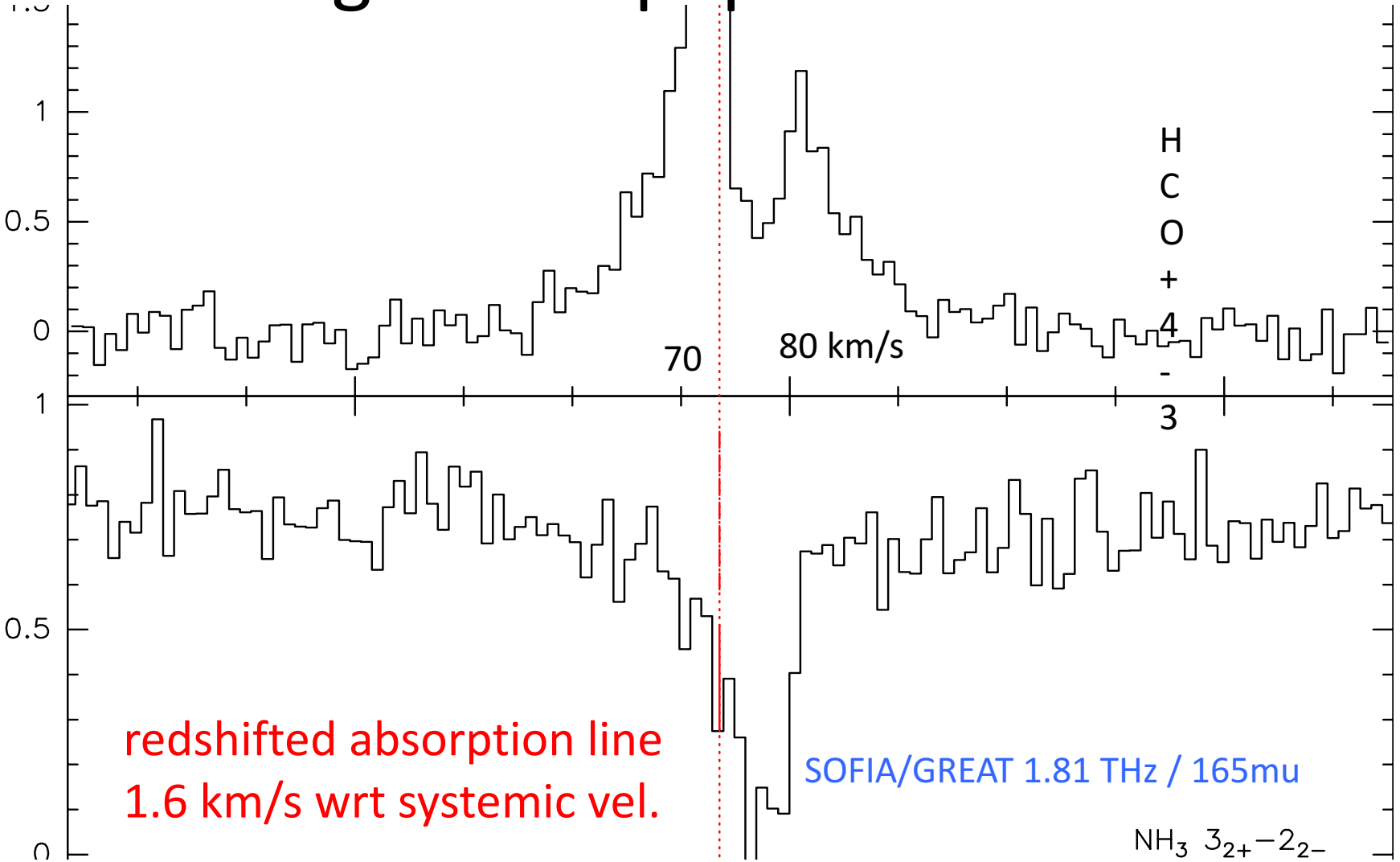
Interpretation of infall using optically thick emission lines is difficult, due to complicated radiative transfer and possible contributions from outflowing molecular gas.



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").

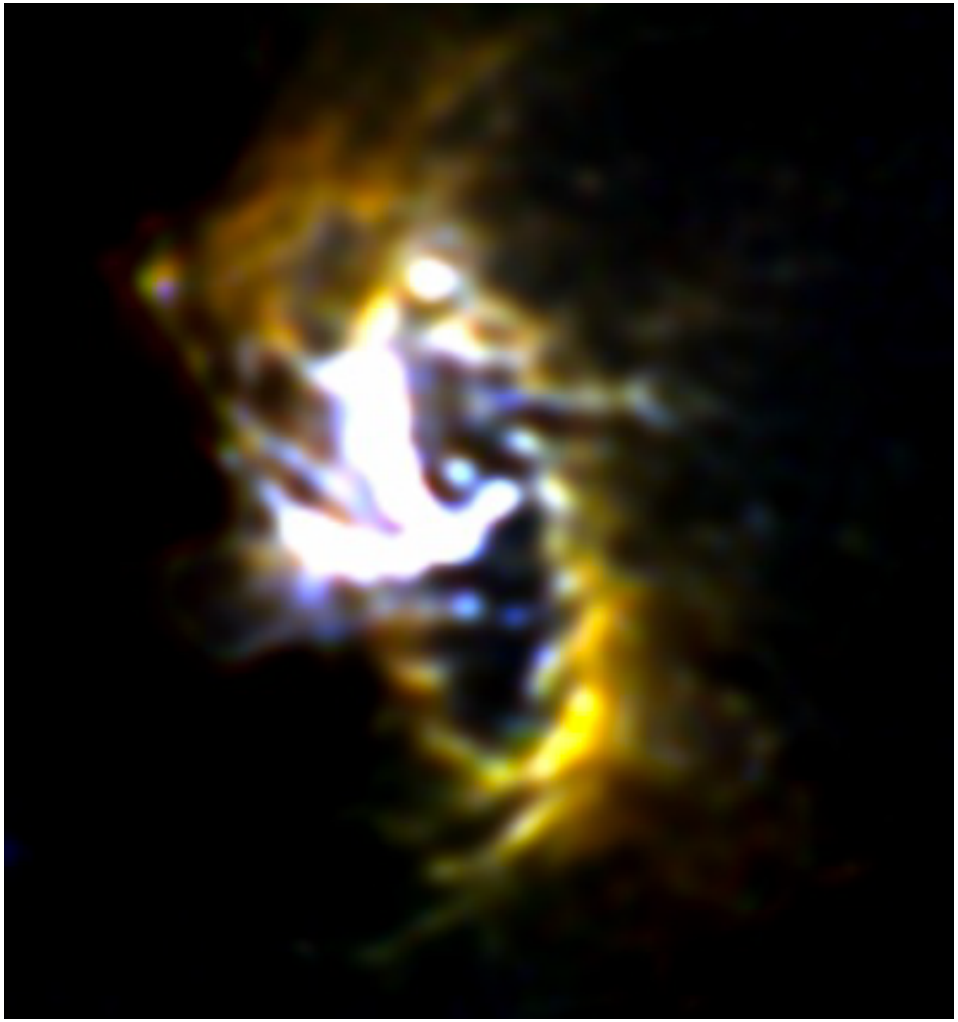
G23.21 gas clump: protocluster infall



F. Wyrowski et al. AA 2012, 2016

GC-CNR at 19(blue), 31(green), and 37(red) micron

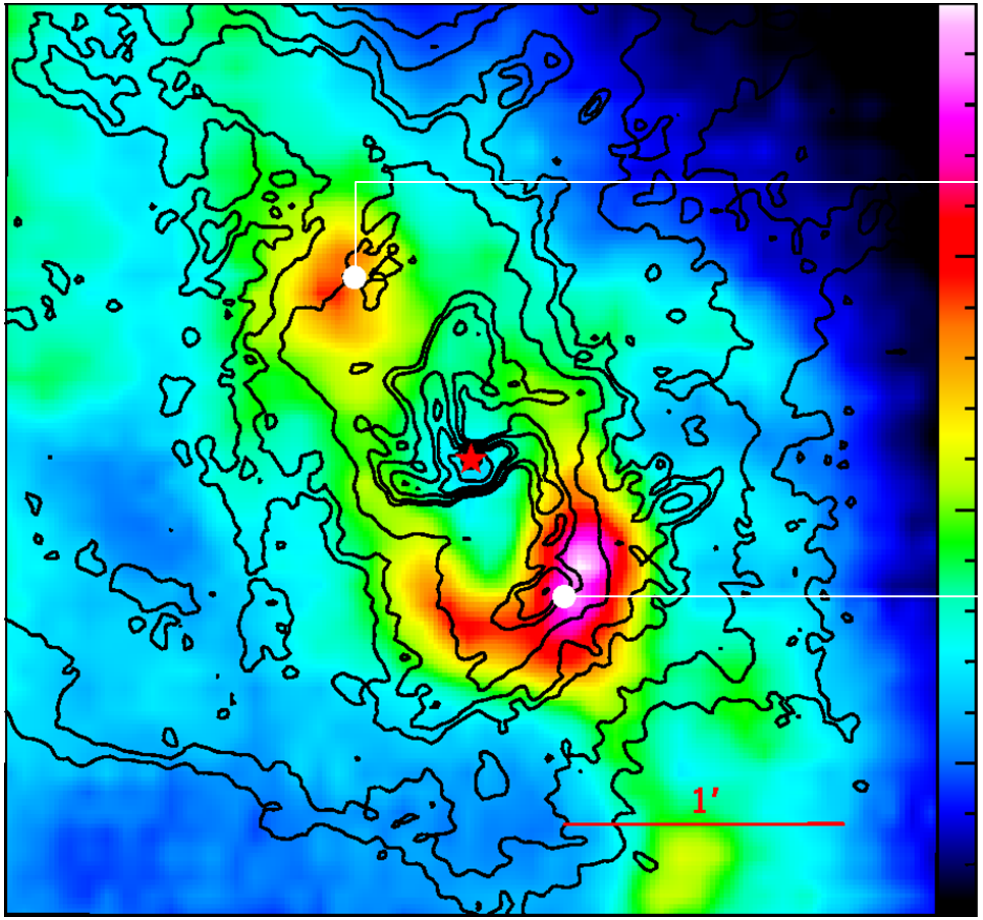
This is the highest resolution image of the CircumNuclear Ring ever obtained with ~3 arcsec FWHM (R. Lau et al. 2013, ApJ)



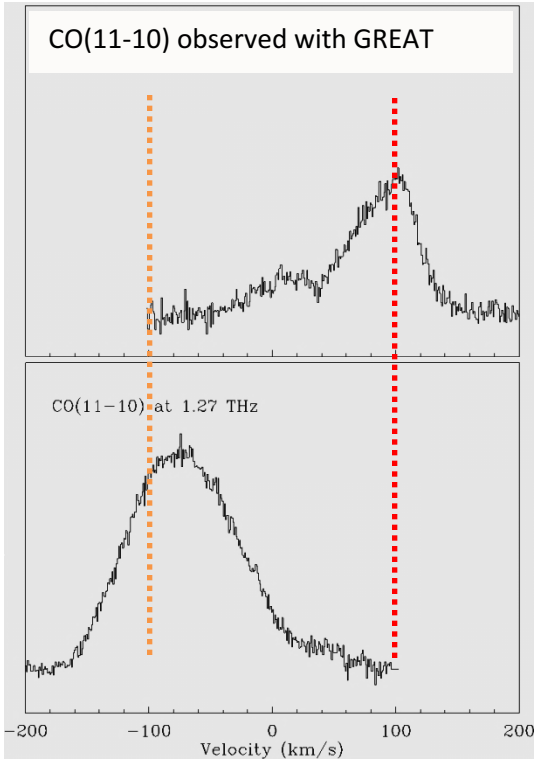
- White central emission is from the hot dust heated by ionized gas of the northern and eastern arms
- Almost perfect 1.5 pc radius ring is seen in cooler dust (T~100K) centered on the Massive Black Hole and tilted about 18 degrees to the LOS and The Galaxy, heated by the central OB stars (not BH)
- 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 tidallly stable.

The circum-nuclear disk in the GC

a massive gas disk is rotating around & feeding the black hole in the Galactic center



carbon monoxid (CO) in orbit around the central mass



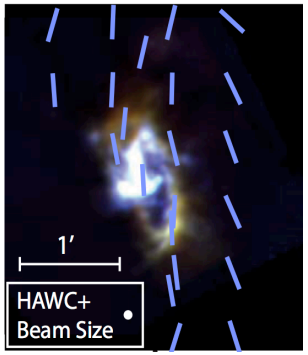
GRREAT will

Requena-Torres et al. 2012, A&A

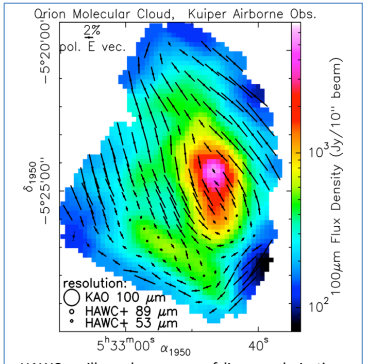
HAWC+ science and instrument sheet

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.



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 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.

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.

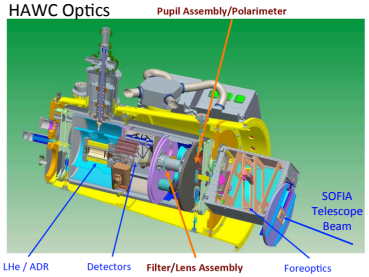
HAWC Specifications

Principal Investigator: Dr. Darren Dowell,
Jet Propulsion Laboratory

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

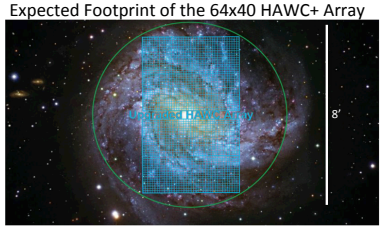
HAWC+ is designed to offer imaging and polarimetry in each of five bands from λ = 53 to 216 μm. NASA/Goddard and NIST are producing the two bolometer detector arrays for HAWC+. For SOFIA far-IR continuum bands, the detectors will deliver background-limited performance with high quantum efficiency. The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

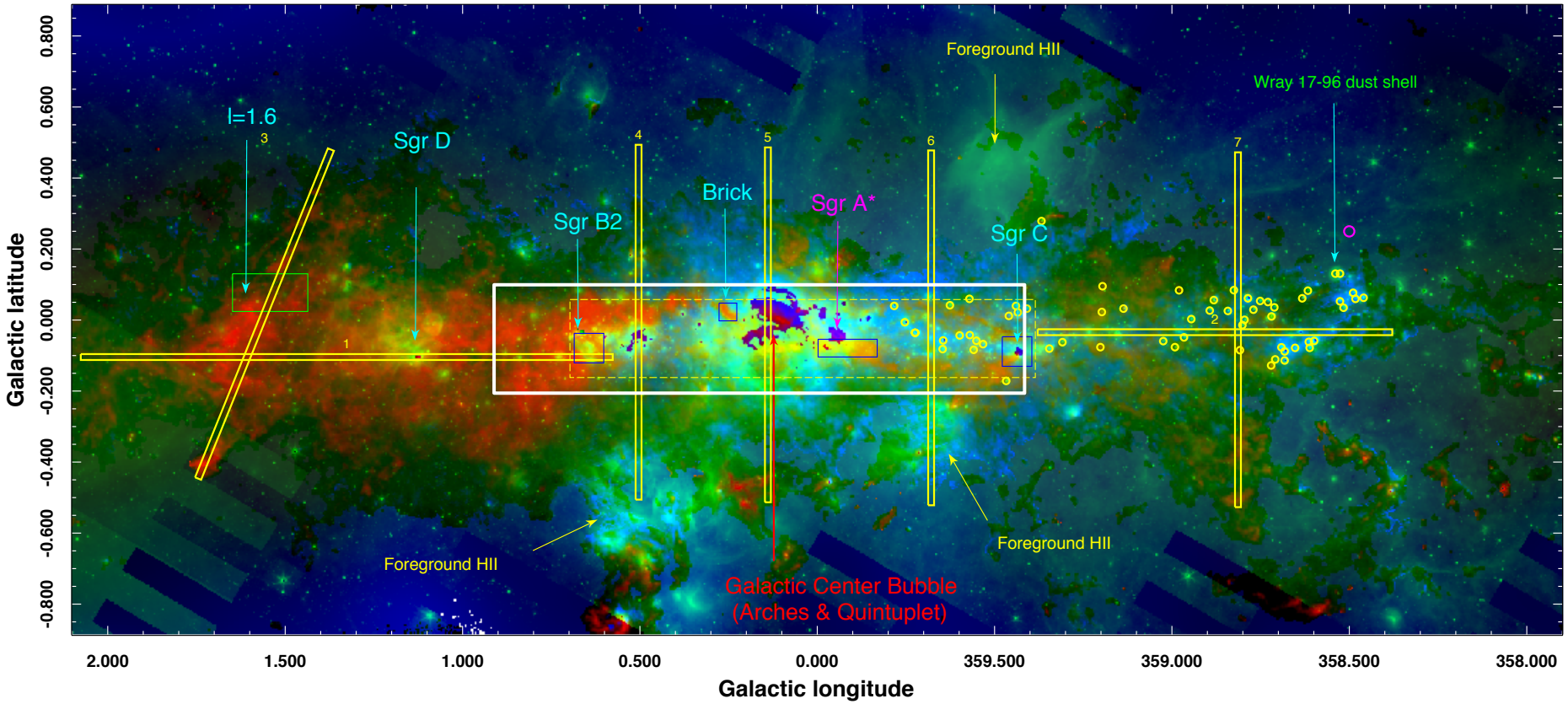
Expected Footprint of the 64x40 HAWC+ Array



Predicted performance for continuum imaging and polarimetry

Instrument Parameter	Band A	Band B	Band C	Band D	Band E
Wavelength (μm)	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 σ(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 σ(P) < 0.3% in 1 hr (MJy/sr)	13,500	8200	4100	1090	480
Min. column density in 1 beam for σ(P) < 0.3% in 1 hr (A_v)	0.9	1.2	2.5	5	5

Joint impact proposal Cy 5 on Galactic Center CMZ



Yellow: Bally

White: Harris-Güsten

Other int'l SOFIA friends

- M. Burton (UK, mid-IR spectroscopy: H2, shocks)
- M. McCaughrean (UK, embedded young clusters)
- B. Reipurth (Hawaii, jets and outflows from YSOs)
- G. Sandell/X. Tielens (ro-vib spectral line surveys)

- You-Hua Chu (Taiwan; Magellanic Clouds, X-rays)
- J. Davidson (Australia; ex-KAO, to be reactivated)
- J. Storey (Australia; retired; Antarctic FIR science)
- Nobody xxx (some liaison from Christchurch, NZ)

- Ewine von Dishoeck (?): water trail, pp snow line
- Therese Encrenaz (Mars H/D from HDO/H2O, OI)
- M.-Y. Gerin (astrochemistry light hydrides, ArH+)
- S. Molinari/L. Spinoglio (Herschel/SPICA experts)


NASA
DLR
SOFIA
Thank you all !

SOFIA Cycle 5