Stratospheric Observatory For Infrared Astronomy

SOFIA Splinter Session

International Astronomical Union General Assembly XXIX

5 August 2015

Agenda

- Opening – Moderator Ravi Sankrit
- The SOFIA Observatory and Science Highlights – Erick Young
- Star Formation Studies with SOFIA – Hans Zinnecker
- How You Can Participate in SOFIA – Tom Roellig
- Questions and Answers

The SOFIA Observatory and Science Highlights

Erick Young

SOFIA Science Center

International Astronomical Union General Assembly XXIX

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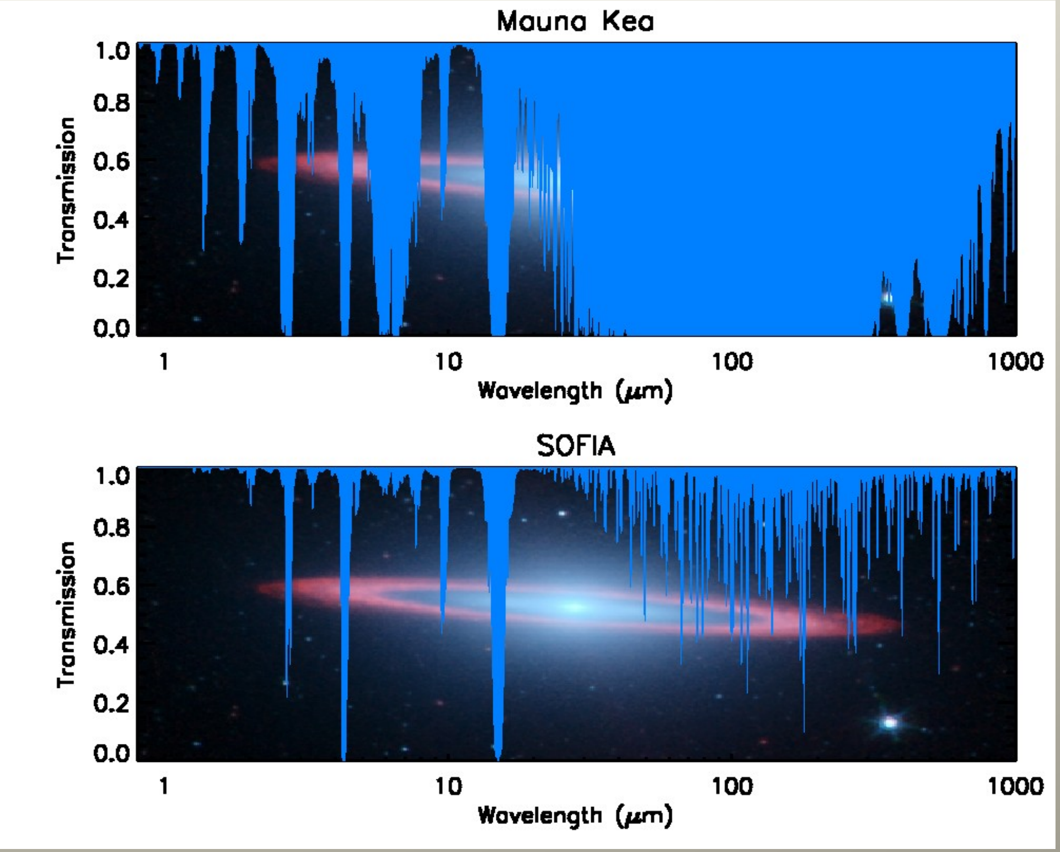
Motivation for SOFIA

- The infrared is a key part of the spectrum for studying young stars, galaxies, planets, and the interstellar medium.
- The Earth's atmosphere is opaque to large parts of the infrared wavelength range. Water vapor absorbs much of this radiation.
- Go to a place where there is much less water vapor.



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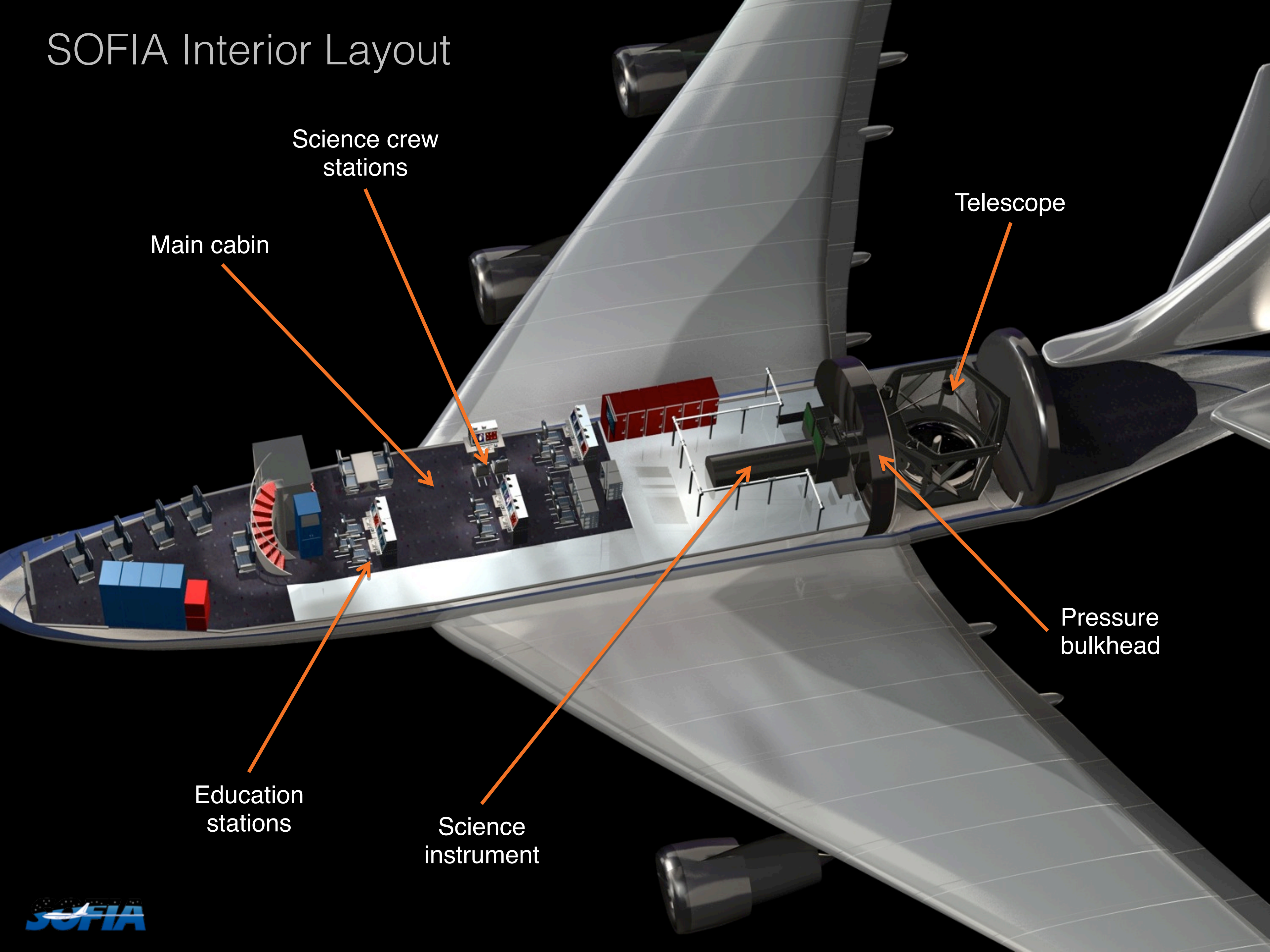
SOFIA
Stratospheric Observatory for Infrared Astronomy

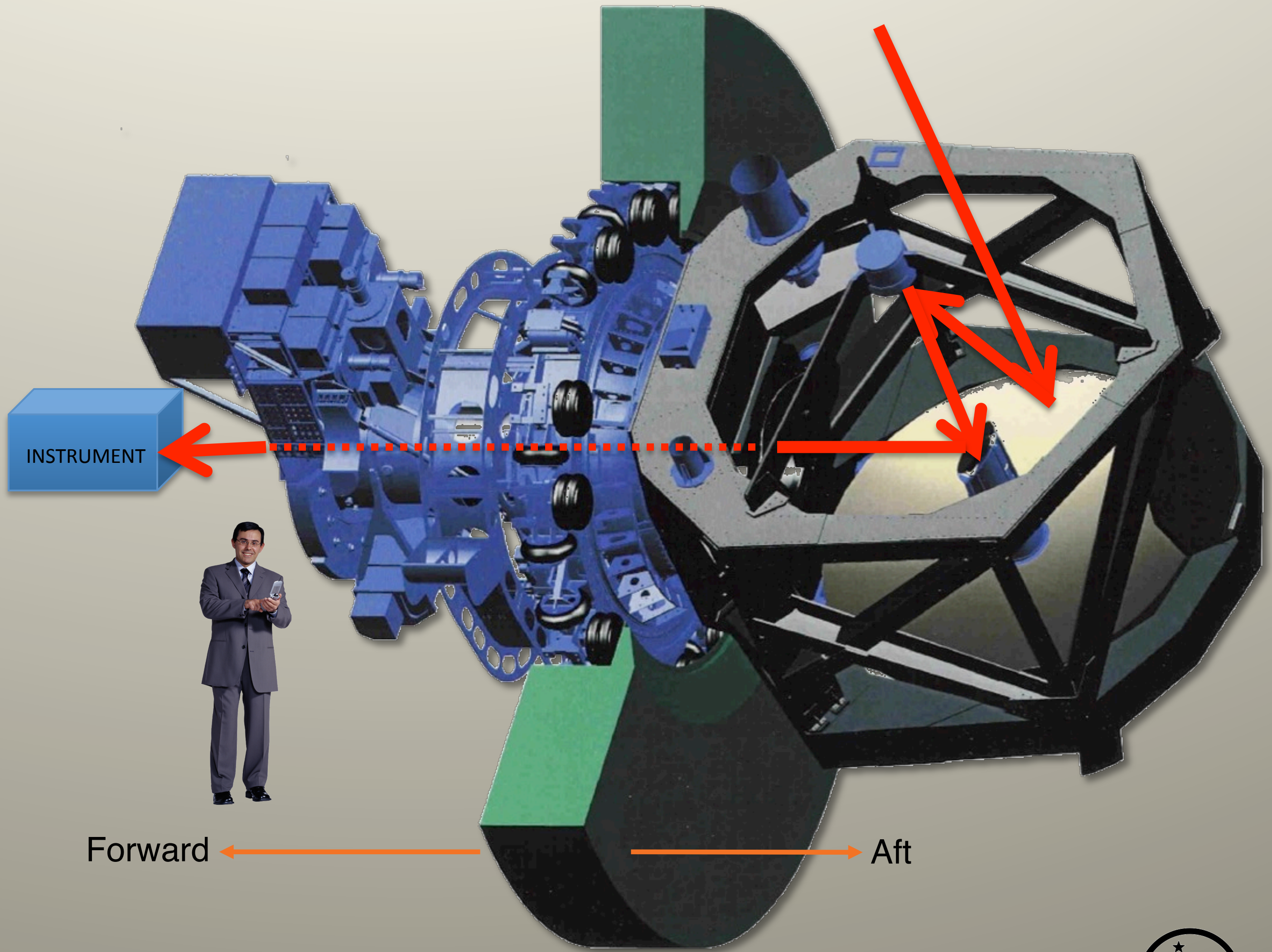
- **Collaboration between NASA and DLR**
- **Highly modified 747-SP aircraft with a 2.7-m telescope**
- **Flies up to 13.7 km (45,000 feet), above 99.9% of the water vapor in the atmosphere**
- **Suite of infrared imagers and spectrometers**
- **Provides access to the infrared to the worldwide astronomical community**

SOFIA Interior Layout

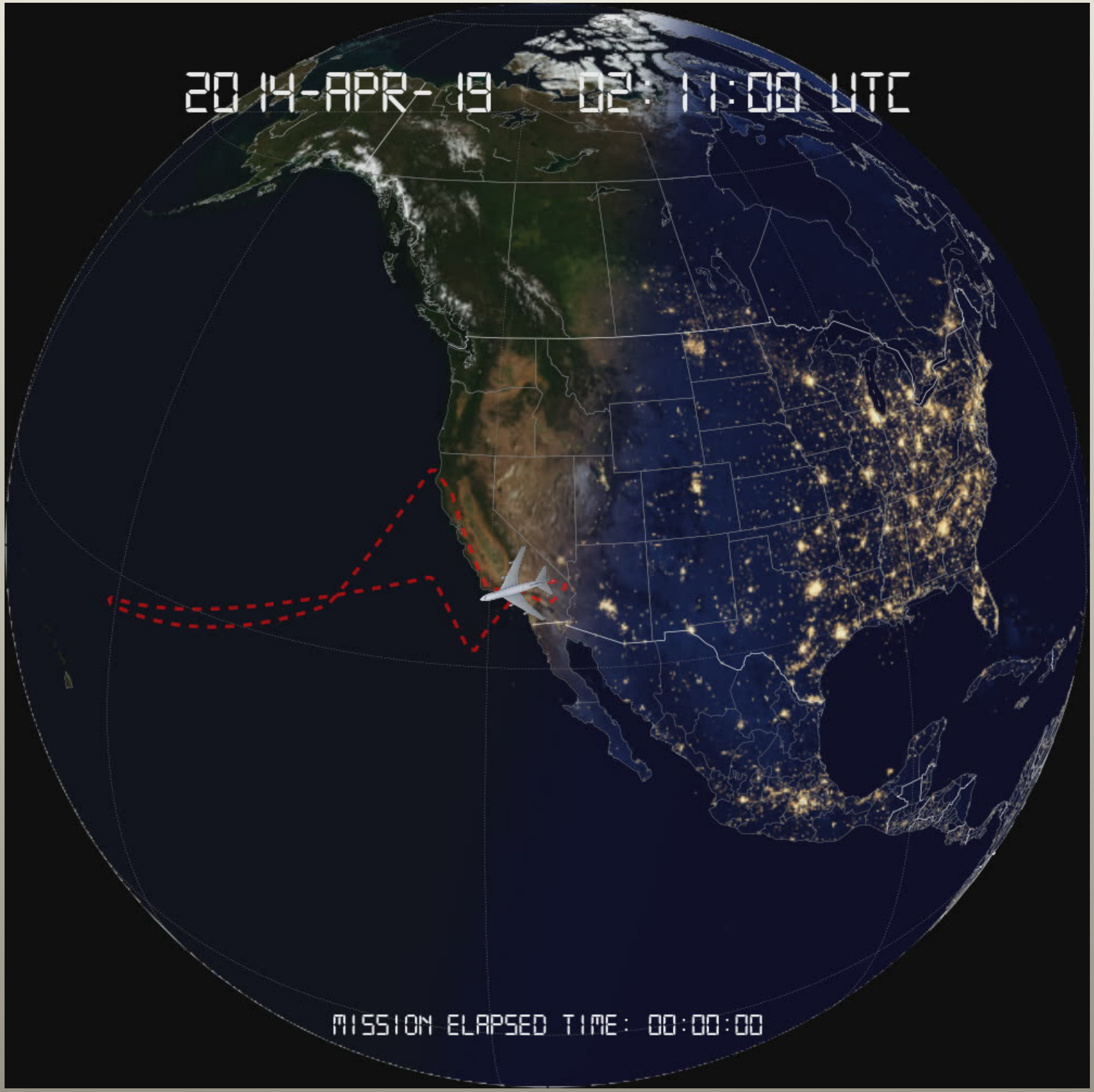


THE SOFIA TELESCOPE

- The telescope is a major contribution from Germany
- 2.7 meter diameter mirror
- Wavelength: 0.3 to 1,600 microns
- Installed weight: 17 metric tons



Typical SOFIA Flight



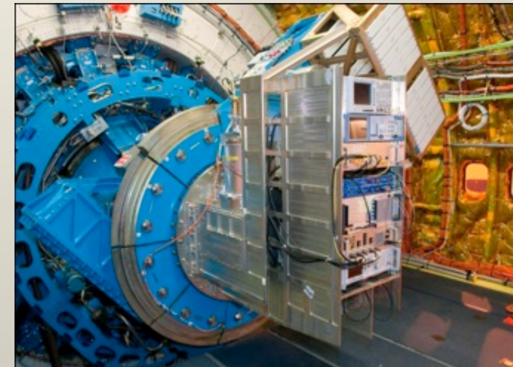
SOFIA Instruments

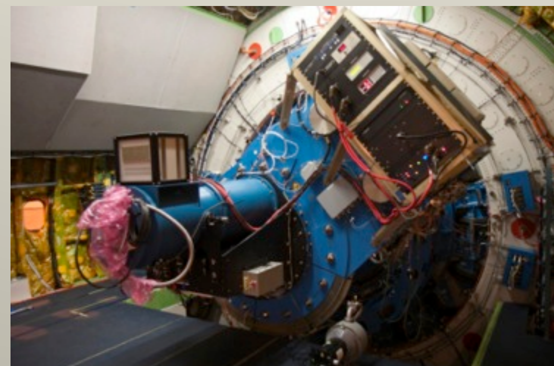
Science Instrument	Type*	Developing Institution	Principal Investigator	Instrument Description
FORCAST	FSI	Cornell University	Herter	Simultaneous Dual Channel Imaging and Grism Spectroscopy (5-25 μm and 25-40 μm)
GREAT	PSI	Max Planck Institute, Bonn	Güsten	High Resolution ($R > 10^6$) Heterodyne Spectrometer (1.6-1.9 THz; 2.4-2.7 THz; 4.7 THz)
HIPO	SSI	Lowell Observatory	Dunham	Visible Light High-Speed Camera (0.3-1.1 μm)
FLITECAM	FSI	UCLA	McLean	Near Infrared Imaging and Grism Spectroscopy, (1-5.5 μm); Can be used in combination with HIPO
FIFI-LS	PSI [illegible] FSI	University of Stuttgart	Krabbe	Dual Channel Integral Field Grating Spectrometer (42-110 μm; 100-210 μm)
EXES	PSI	UC Davis	Richter	High Resolution ($R > 10^5$) Echelle Spectrometer (5-28 μm)
HAWC [illegible] HAWC+	FSI	University of Chicago [illegible] JPL	Harper [illegible] Dowell	High-Angular Resolution Wide-Band Camera with 4 Channels (50 μm, 100 μm, 160 μm, 200 μm)

Current Instrument Complement

FORCAST
Mid-IR Camera

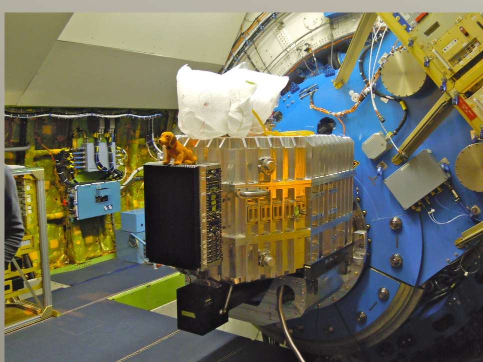
GREAT
Heterodyne spectrometer





FLITECAM
Near IR Camera

HIPO
Occultation Photometer

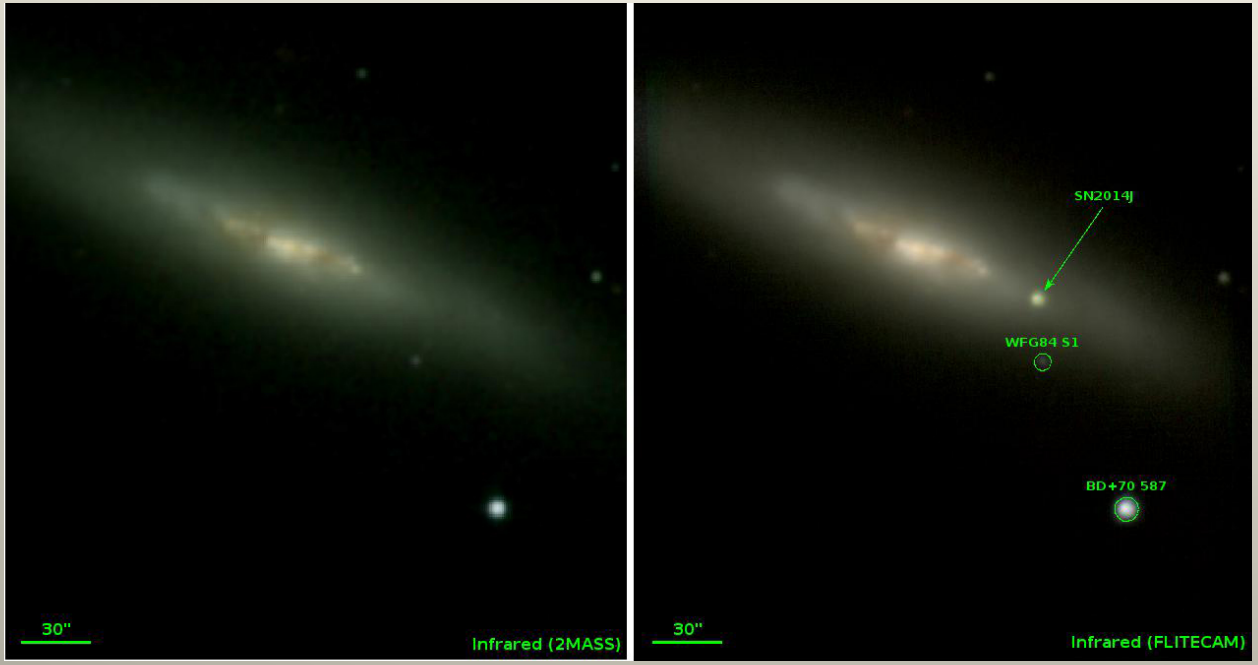


FIFI-LS
Integral Field Spectrometer

EXES
High Resolution IR Spectrometer

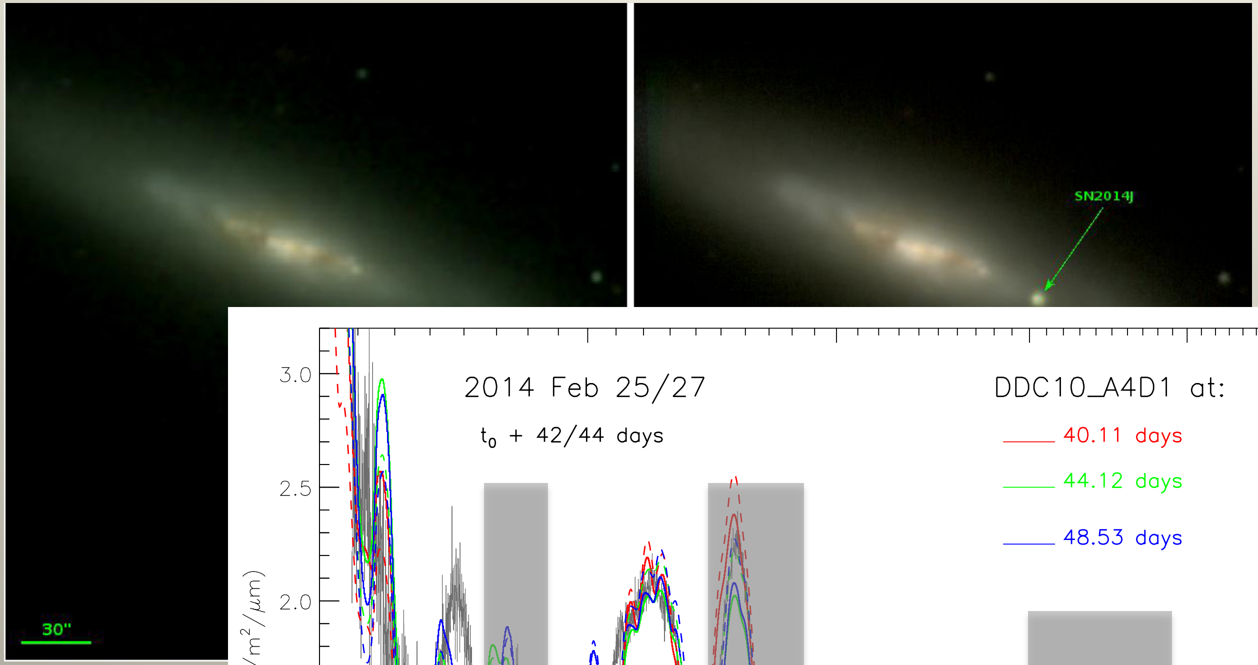
And for Cycle 4: Focal Plane Imager and HAWC+

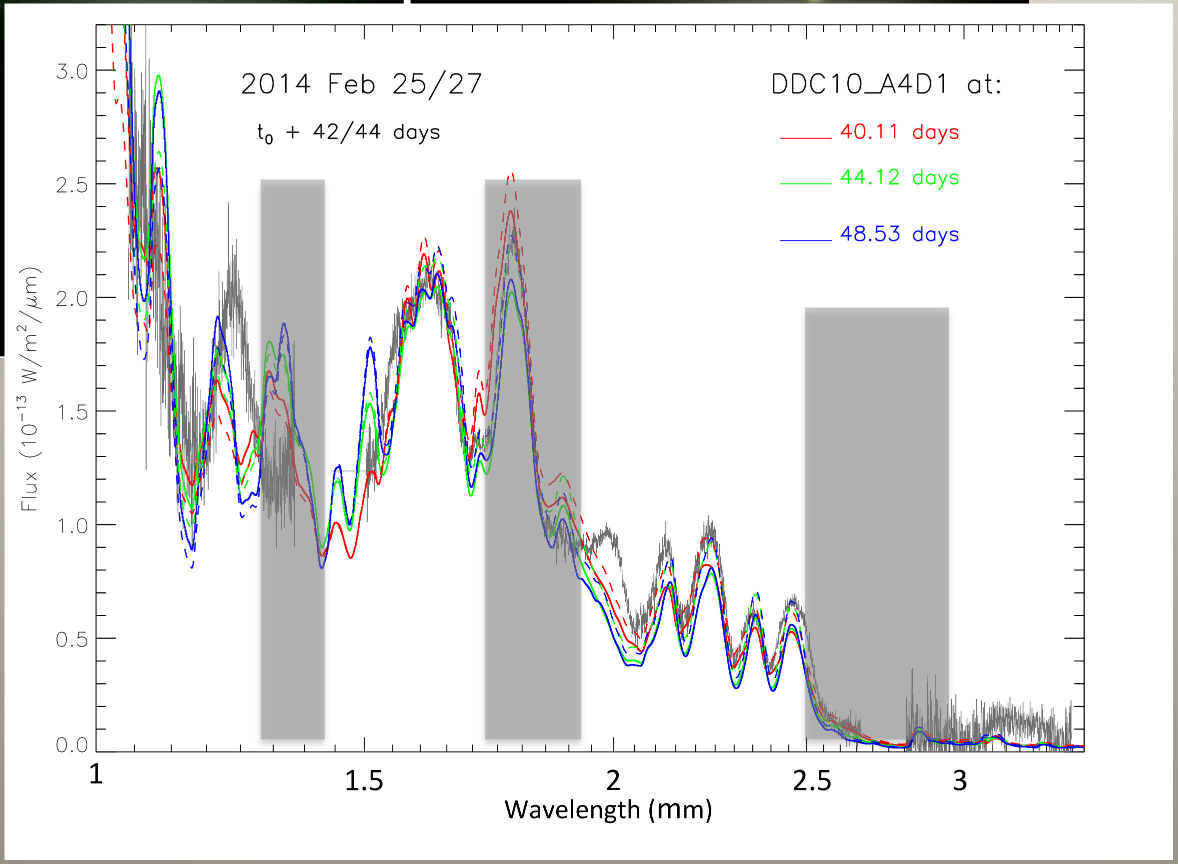
SOFIA Observes Supernova 2014J



Vacca et al. 2015

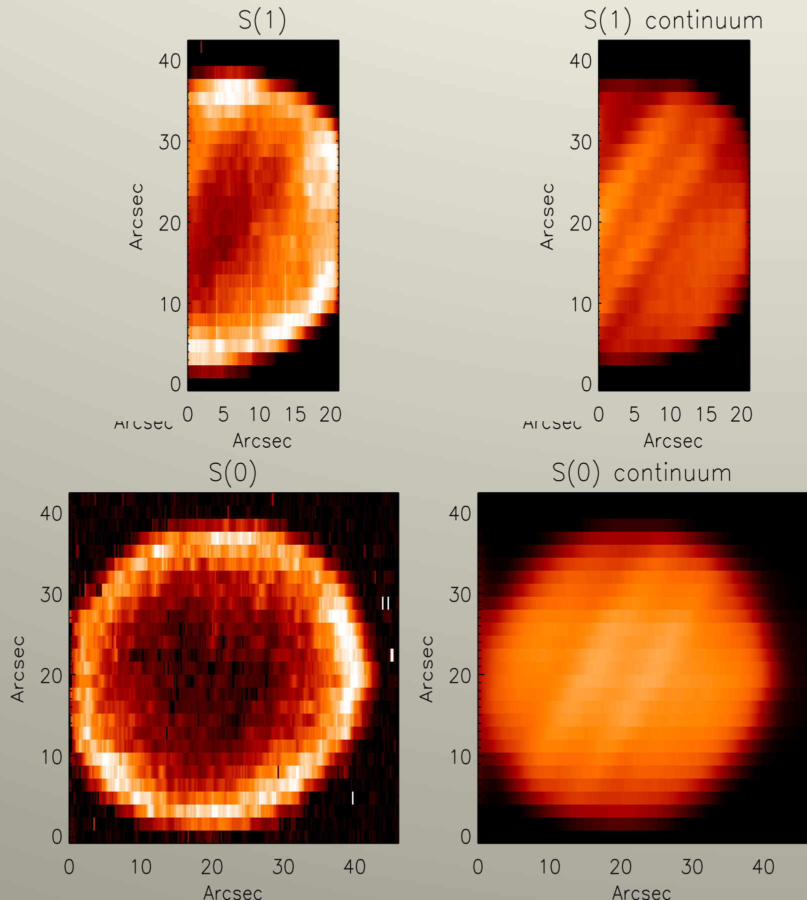
SOFIA Observes Supernova 2014J





Vacca et al. 2015

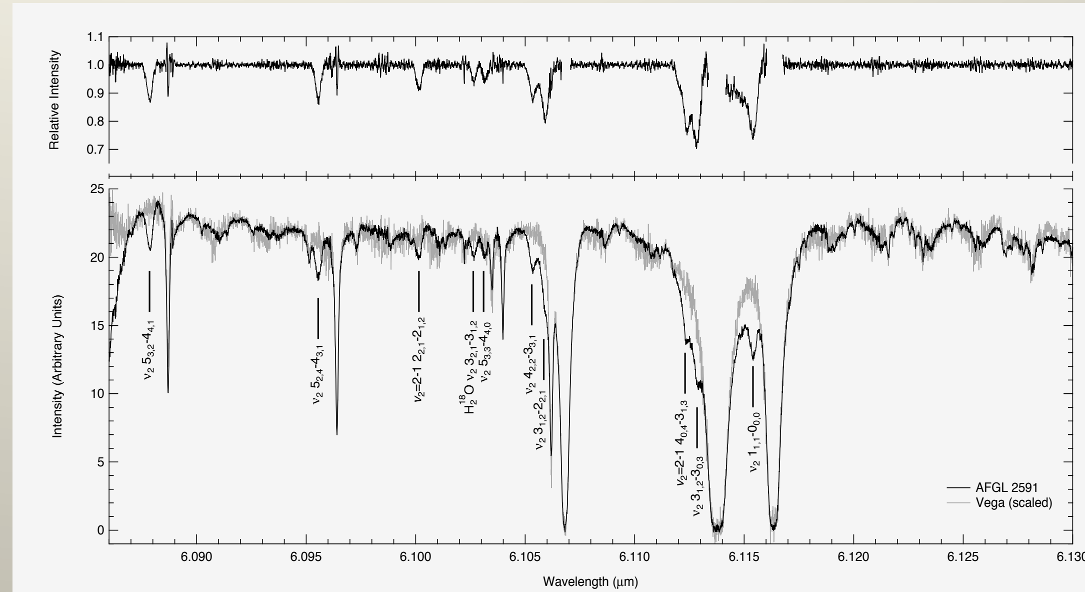
EXES Science: Ortho/para H_2 maps of Jupiter



- Spectral maps produced by stepping slit position across extended sources
- Stratospheric emission from H_2 shows limb brightening
- S(0) at 28.3um is cannot be observed from ground.
- S(1)/S(0) gives temperature, with long latency
- The ortho-para ratio measures vertical transport of H_2 in the Jovian atmosphere. High ratios (3) are from warm clouds deeper inward that rise.

EXES Detects H_2O in the AFGL 2591 Star Forming Region

- Water is one of the key components of the interstellar medium and protostellar environments.
- Most observations of H_2O (even from space) have been of ***emission*** from excited (hot) water.
- The important and dominant low excitation levels are best observed in ***absorption*** against a background source.
- Absorption observations require high spectral resolution– uniquely provided in the mid-IR by EXES
- First spectrally resolved observations of n_2 lines from H2O and $H_2{}^{18}O$.
- Water column density in outflow much higher than previously inferred.



(A) Spectrum of AFGL 2591 divided by standard star spectrum showing residual water in disk of young star.

(B) Spectra of young star AFGL 2591 and standard star Vega. Most of the deep absorptions are due to H_2O in the Earth's atmosphere, but blue-shifted H_2O is present in the young star spectrum.

Indriolo et al. (2015)

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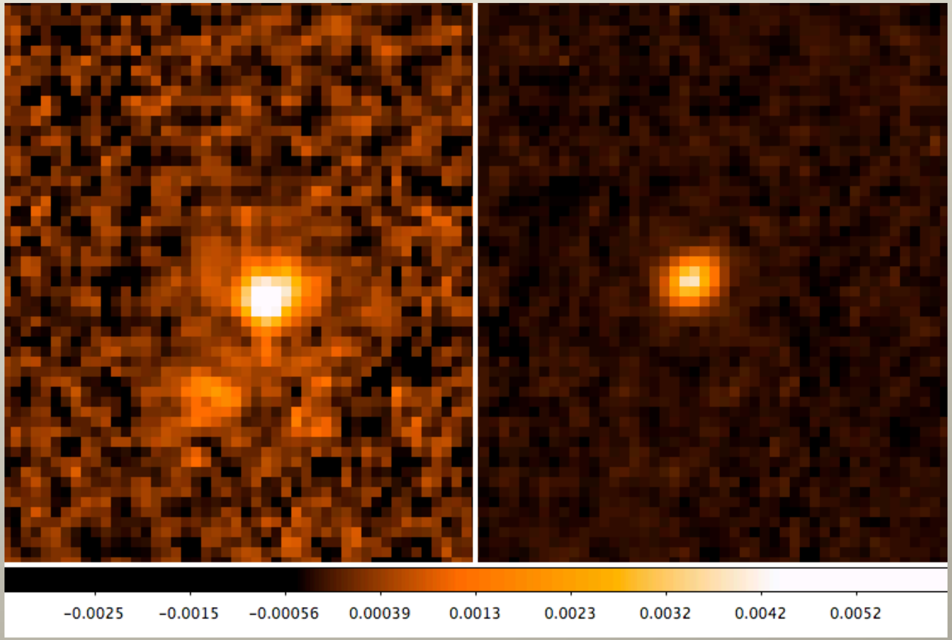
Far IR Detection of an Outbursting FU Ori Object

- Accretion during the formative stages of low-mass star evolution is an important component of the total luminosity.
- This accretion is known to be episodic with long periods of quiet between events
- Archetype of the most dramatic type of outburst in FU Ori which increased in in brightness by 6 magnitudes in 1936 and has remained bright since then.
- 2MASS J06593158-0405277 is a recently discovered member of this class and gives an opportunity to make IR measurements of this rare event.
- DDT proposal was submitted by Jochen Eisloffel (Thuringer Landessternwarte Tautenburg, Germany) and accepted.
- FORCAST and FIFI-LS used to make photometric measurements
  - FIFI-LS has made the first Far Infrared observations of this class of object in outburst



FORCAST observations of 2MASS J06593158-0405277
at 37 mm (left) and 11 mm (right).
This is a rare FU Ori type young star that has suddenly brightened. Corresponding far-IR observations with FIFI-LS were also taken in March.

DDT Program of Jochen Eisloffel

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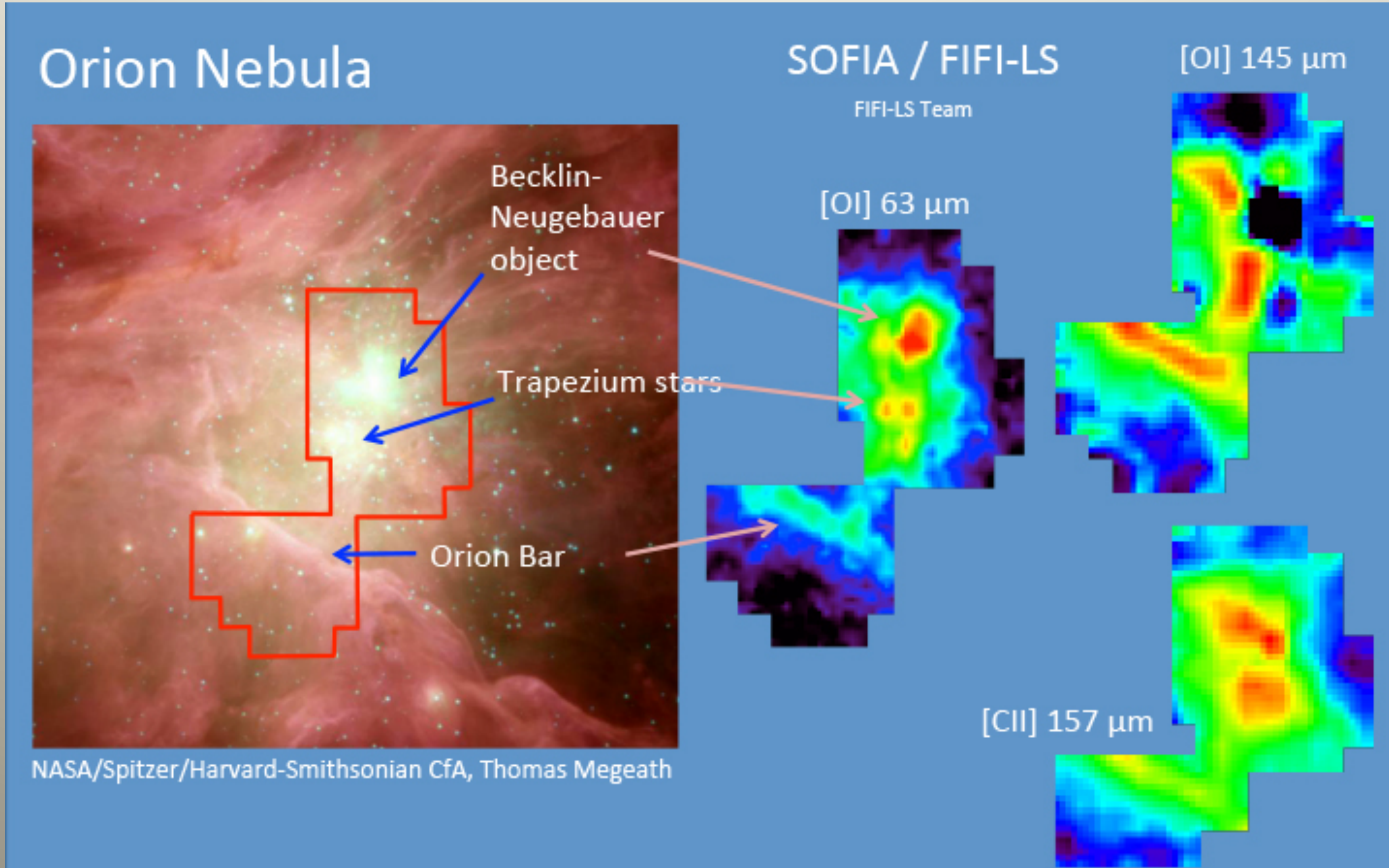
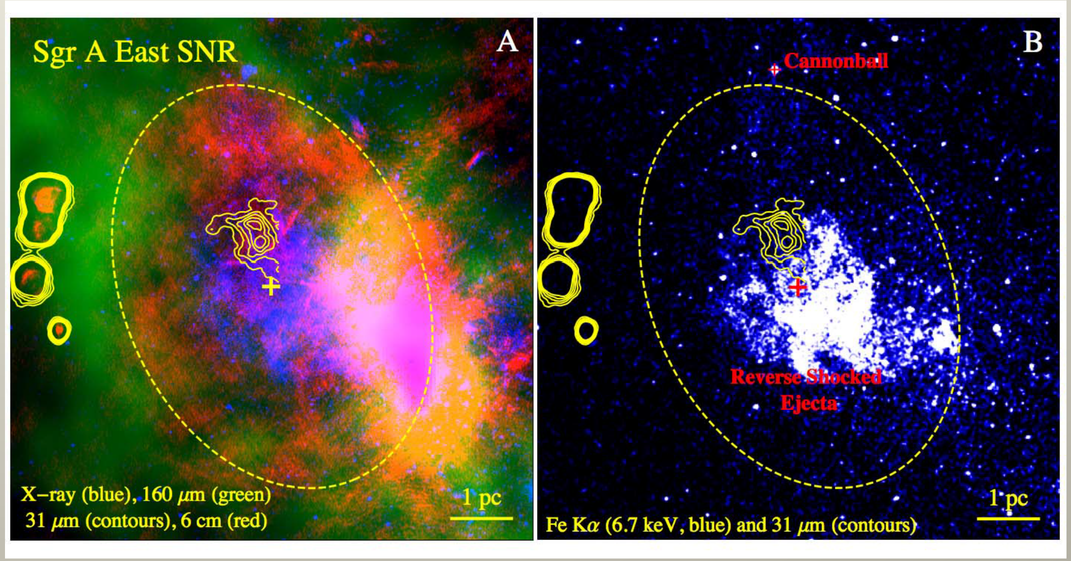
FIFI-LS Orion Nebula Observations



FORCAST Observations of SNR at Galactic Center

- Where did the dust in the early universe come from?
- Does ejecta-formed dust survive the interaction with hot, shocked gas in supernova?
- Observations of Sgr A East remnant near the Galactic Center with FORCAST
- First discovery of dust in an older SNR that has survived the passage of the reverse shock
- Supports hypothesis that supernovae may have been responsible for the formation of the early dust



(A) Composite false-color image of the Sgr A East SNR overlaid with contours of the 31.5 μm emission east of the Circumnuclear Disk. Blue: 2 - 8 keV (Chandra), green: 160 μm (Herschel), red: 6 cm (VLA).

(B) Fe Kα (6.7 keV) emission from the SNR overlaid with the 31.5 μm emission

Lau et al. (2015) , Science

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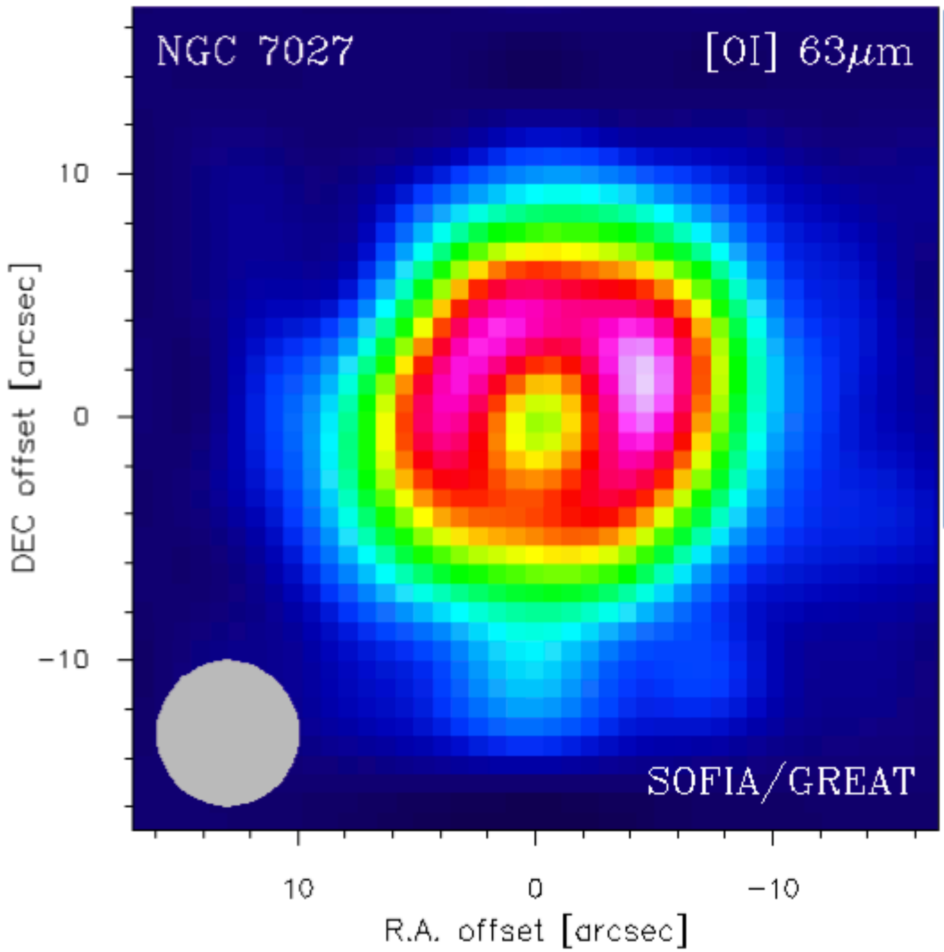
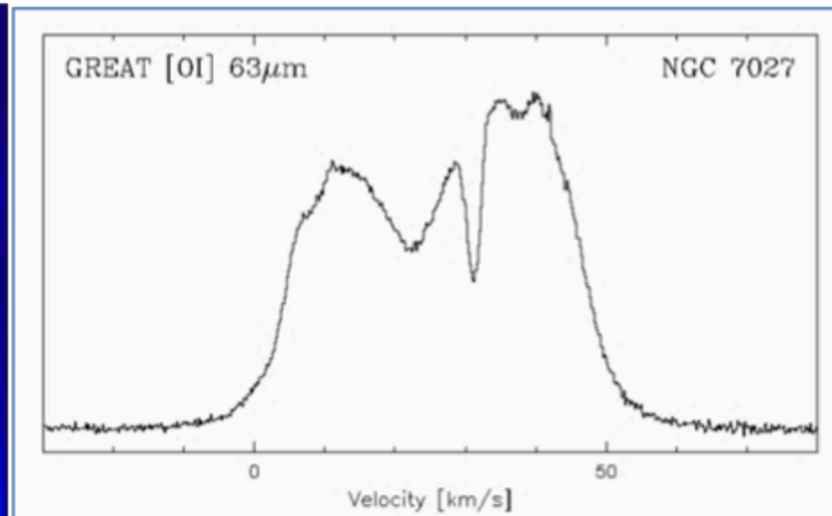
GREAT 4.7 THz First Light



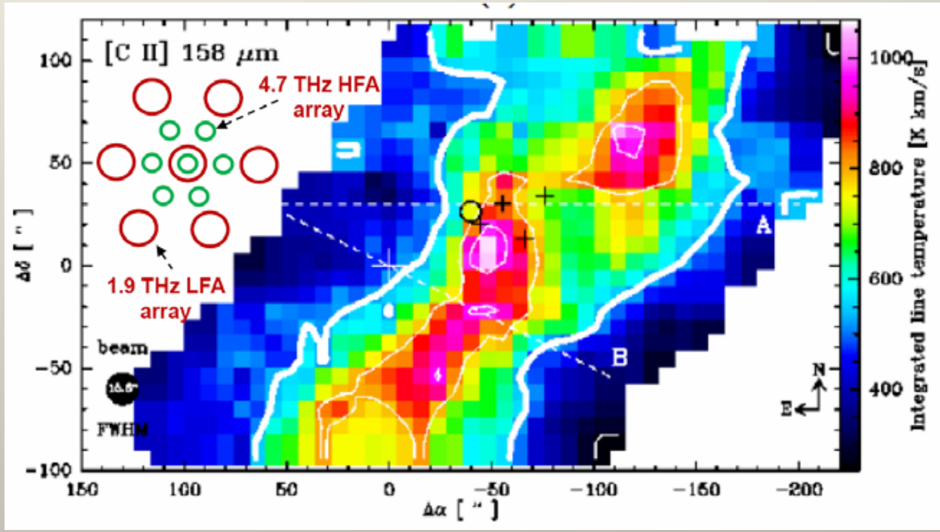


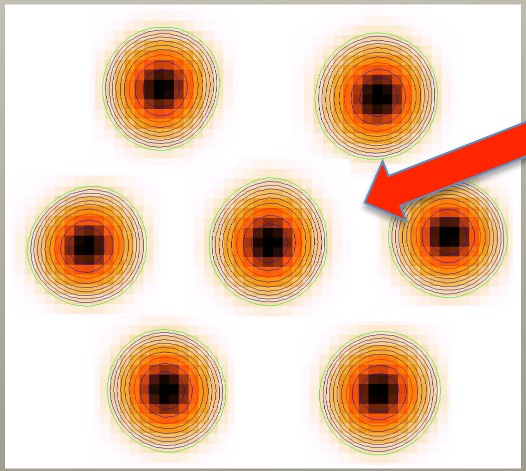
Velocity resolved observations allow study of gas dynamics in objects.

(Rolf Güsten & the GREAT Team)

SOFIA is a Platform for New Technology: upGREAT

- upGREAT an enhancement of the GREAT heterodyne instrument developed by Rolf Güsten and collaborators.
- The instrument was commissioned in May 2015
- Compact heterodyne arrays
  - 7 pixels x 2 polarizations @ 1.9 THz
  - 7 pixels @ 4.7 THz [O I] (ready in 2016)
- Maps ***more than an order of magnitude faster*** than the previous instrument

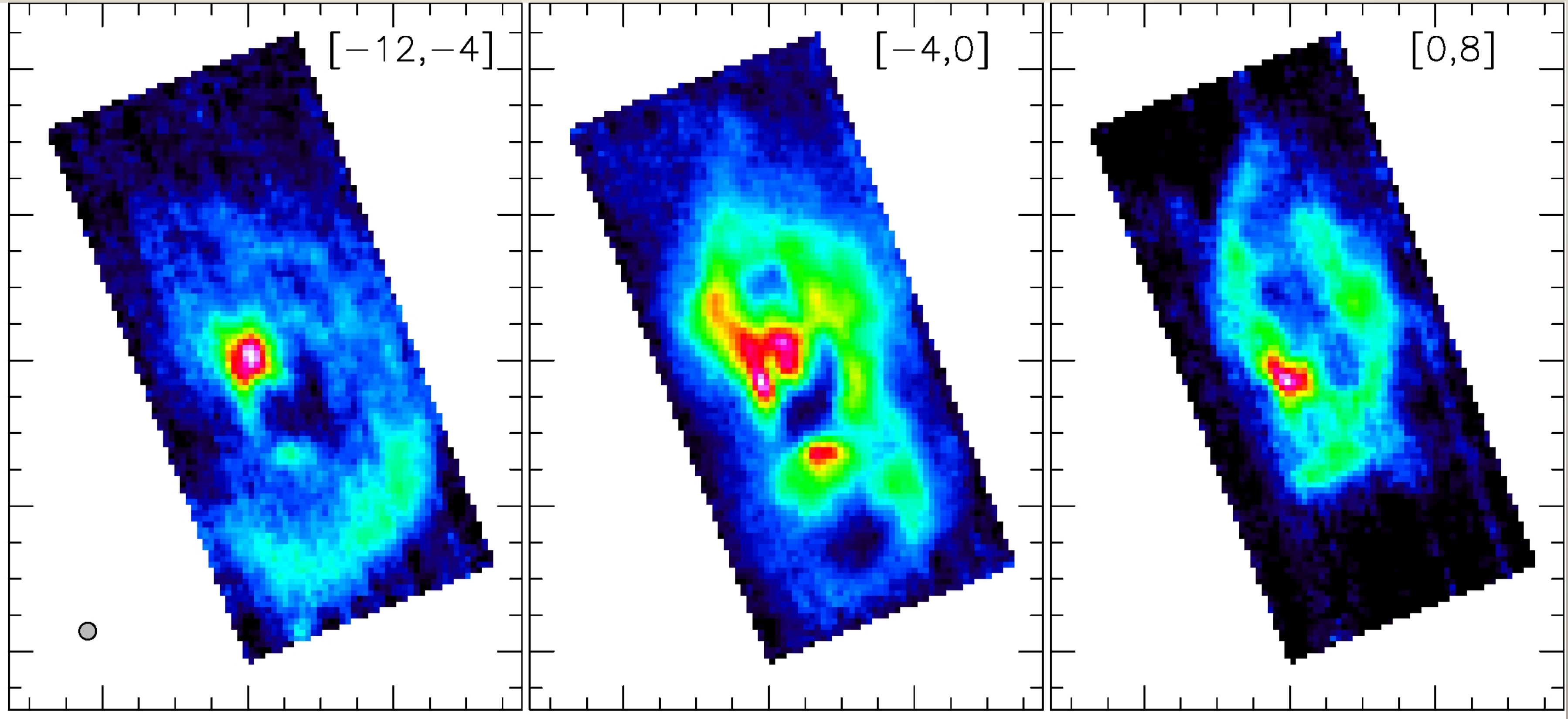




What was one beam on the sky is now seven beams

Measured upGREAT beam profiles

upGREAT Mapping of S106

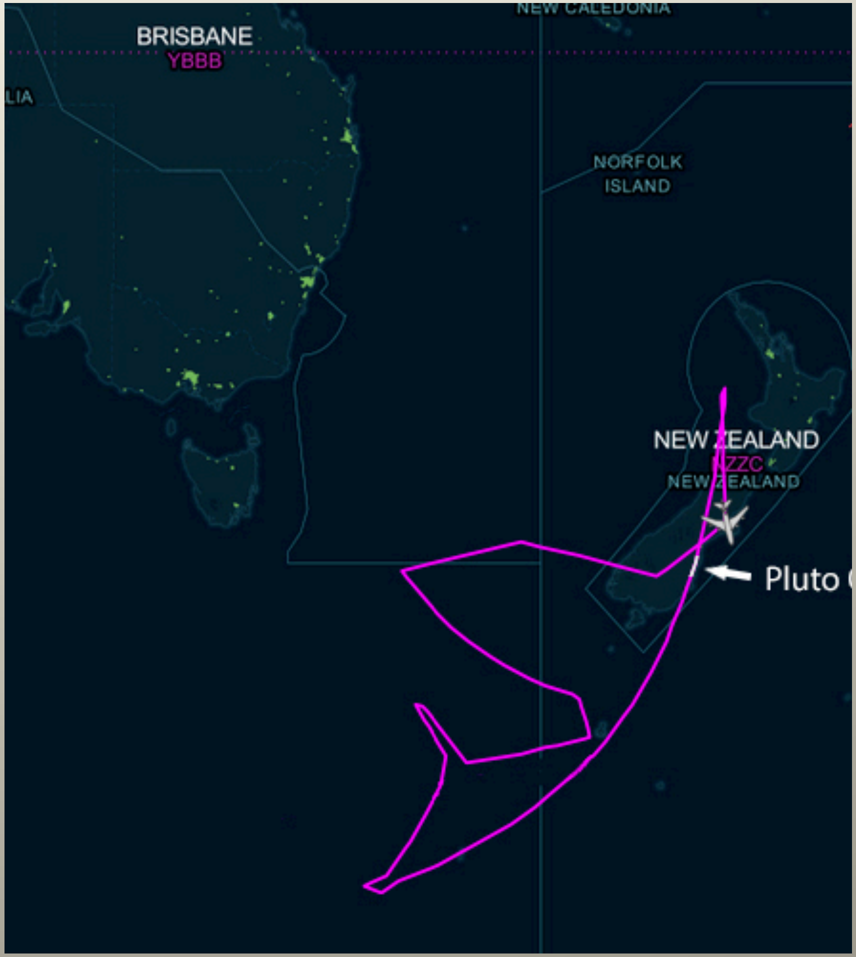


158 mm Fine Structure Line of [C II]
3 velocity bins are plotted

Rolf Güsten and GREAT Consortium (MPIfR)

Pluto Occultation on 29 June 2015

- Occultation of 12-mag star by Pluto on 2015 June 29
- Simultaneous SOFIA observations with HIPO, FLITECAM, & Focal Plane Imager.
- Final ground-based shadow updates required course adjustments of 230 km
  - Updates to shadow path kept coming even after the plane took off.
  - Mobility of SOFIA was key to getting the observation



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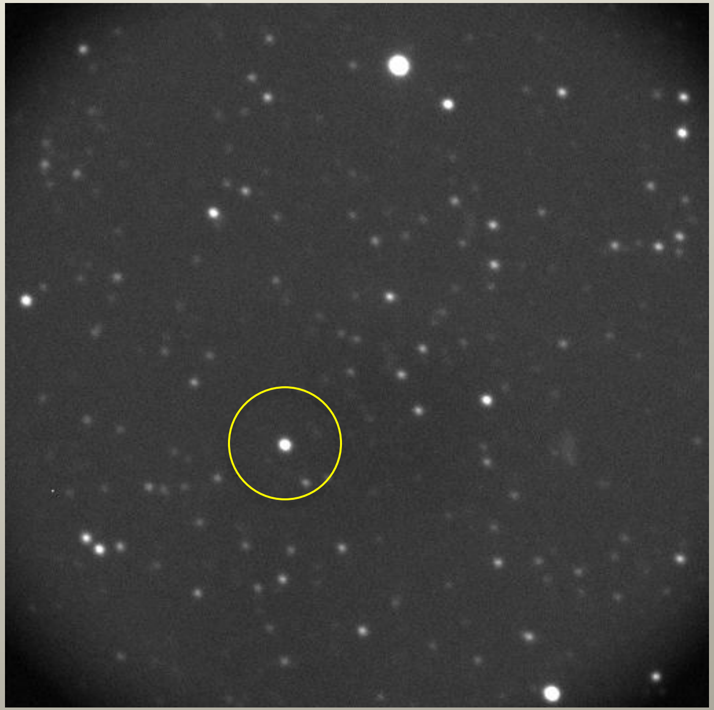
Science Highlight: Pluto Occultation

- Detection of strong "central flash" confirms accuracy of course corrections

- Comparison of multi-wavelength observations will allow detailed analysis of atmospheric profiles and aerosol content.



Focal Plane Imager+ observation of Pluto occultation event on UT 2015-06-29 16:55. Video is approximately 4X real time.

Summary

- SOFIA is a 2.7-m aperture airborne telescope that provides the world astronomical community with access to wavelengths obscured by water vapor, particularly in the infrared and sub-millimeter
- SOFIA has a wide array of scientific instruments with imaging and spectroscopic capabilities
- SOFIA is able to deploy to distant locations, particularly the Southern Hemisphere as required by the science
- SOFIA is operational and producing important science in many astronomical areas.

NASA

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Star Formation Studies with SOFIA

Hans Zinnecker
Deutsches SOFIA Institut
NASA-Ames and Univ. of Stuttgart

SOFIA special session at IAU-GA, Honolulu, 5 Aug 2015

Star formation is a fundamental process in the interstellar medium.

SOFIA can provide unique capabilities to study star formation regions.

Here, we will illustrate some examples of SOFIA's discovery space.

OUTLINE

Orion BN/KL SED (FORCAST)
Orion BN/KL PDR (FIFI-LS)
infall in high-mass clumps (GREAT)
cloud age in low-mass core (GREAT)
Galactic Center CND (FORCAST)
nuclear starburst M82 (FIFI-LS)

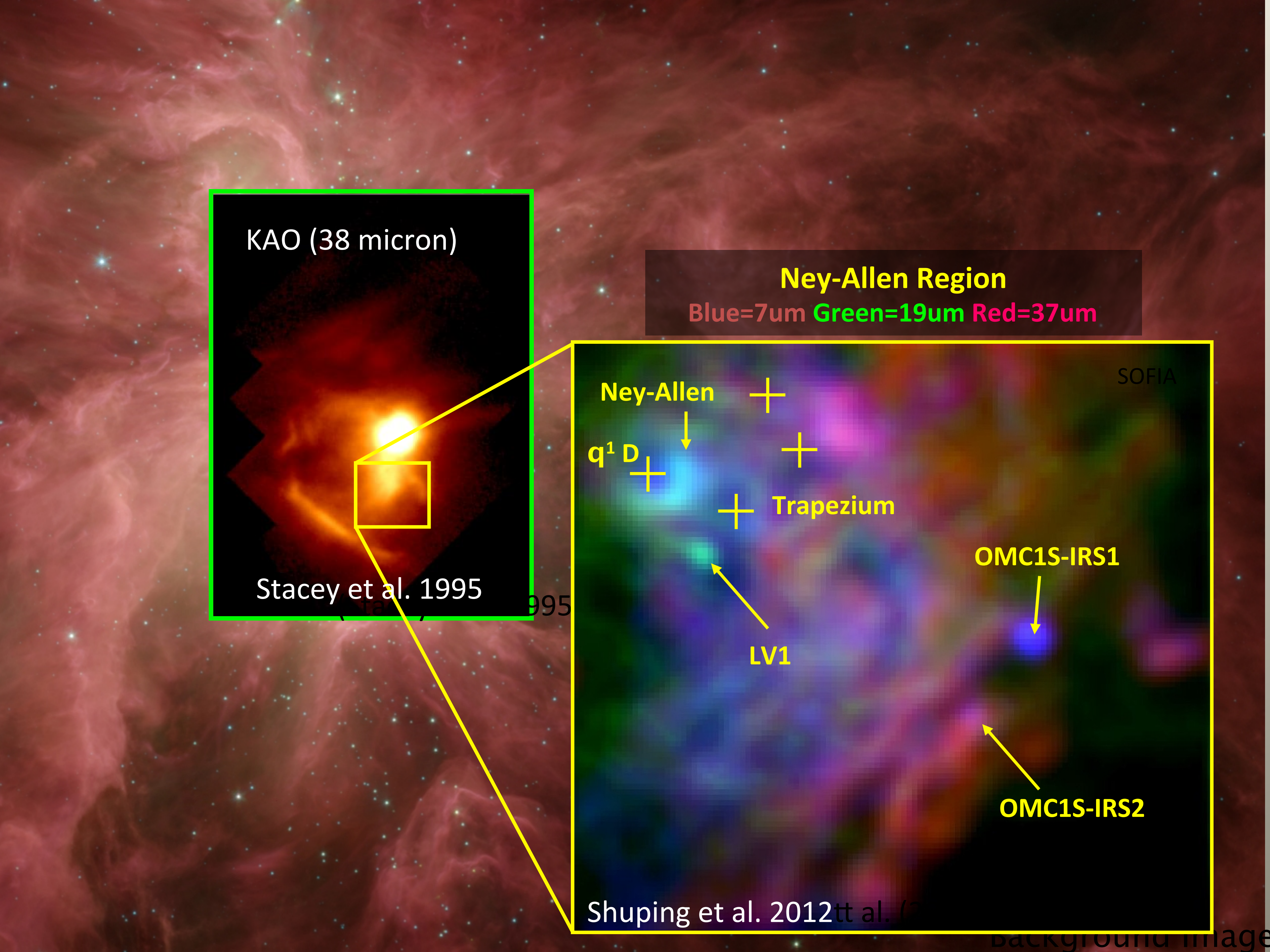
outlook
magnetic fields (HAWC-pol)

ORION

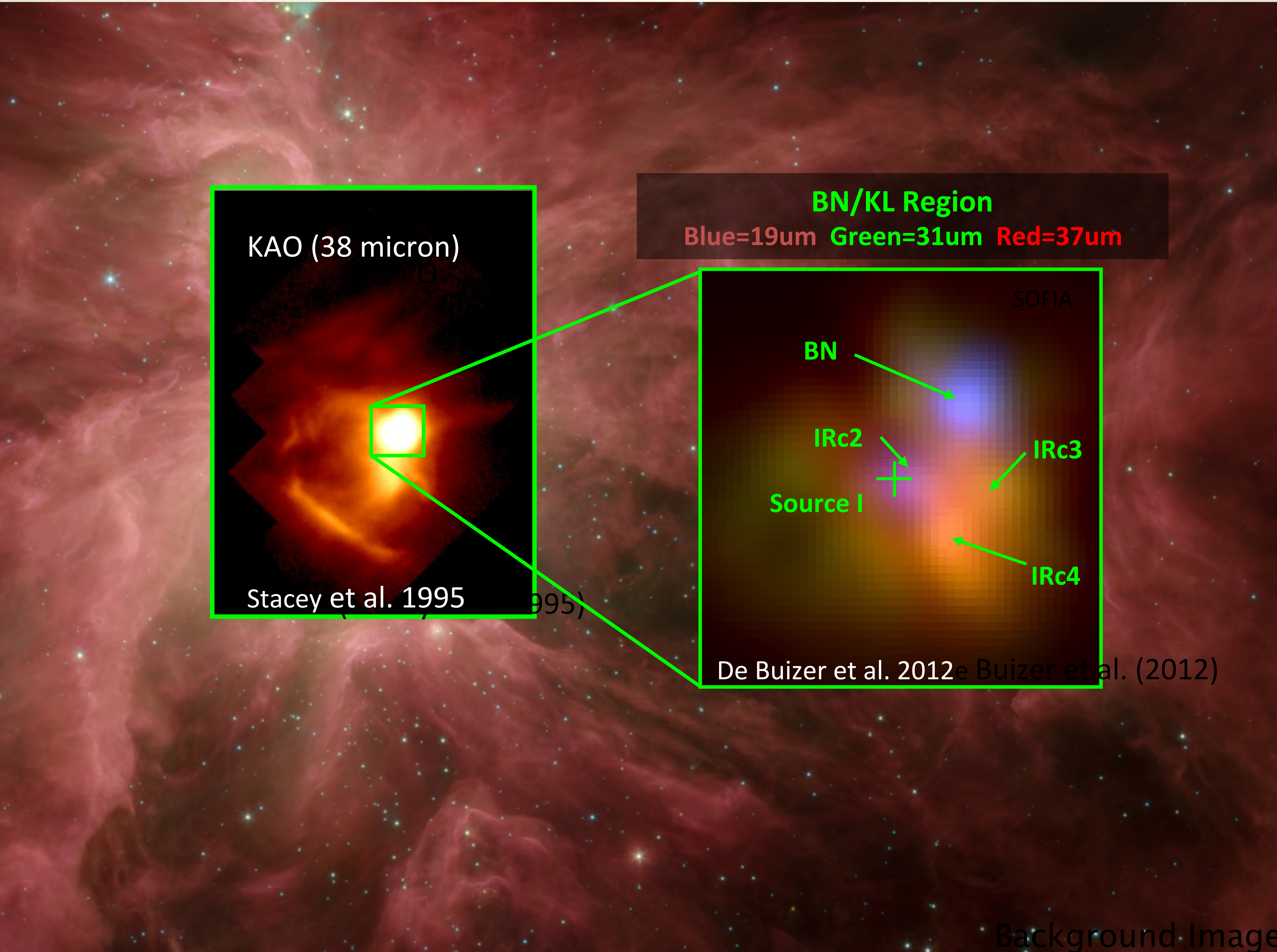
BN/KL, Trapezium cluster, Bar

FORCAST (19, 31, 37 micron)

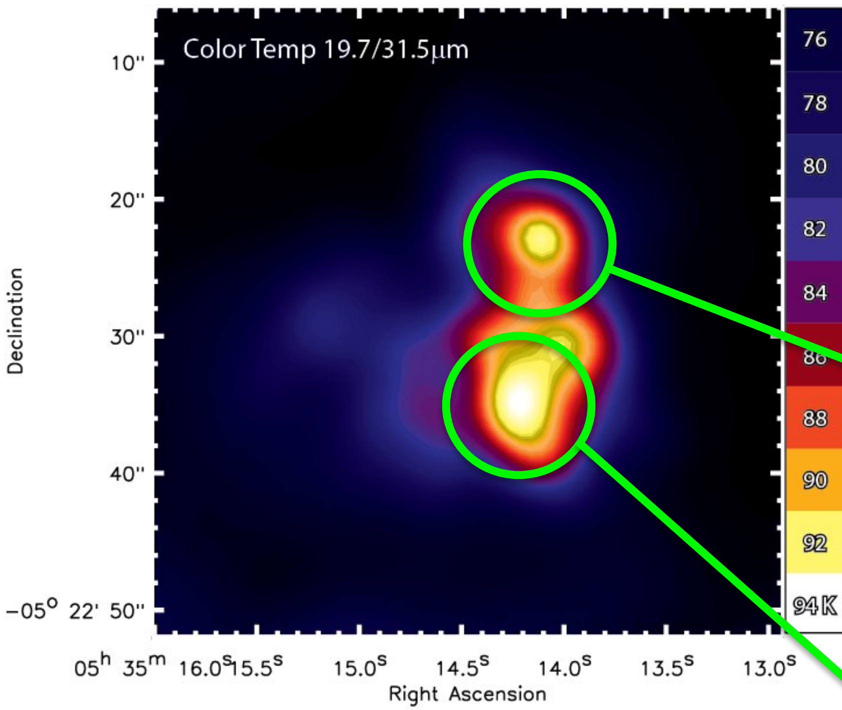
FIFI-LS (158 micron C+ line, cont)



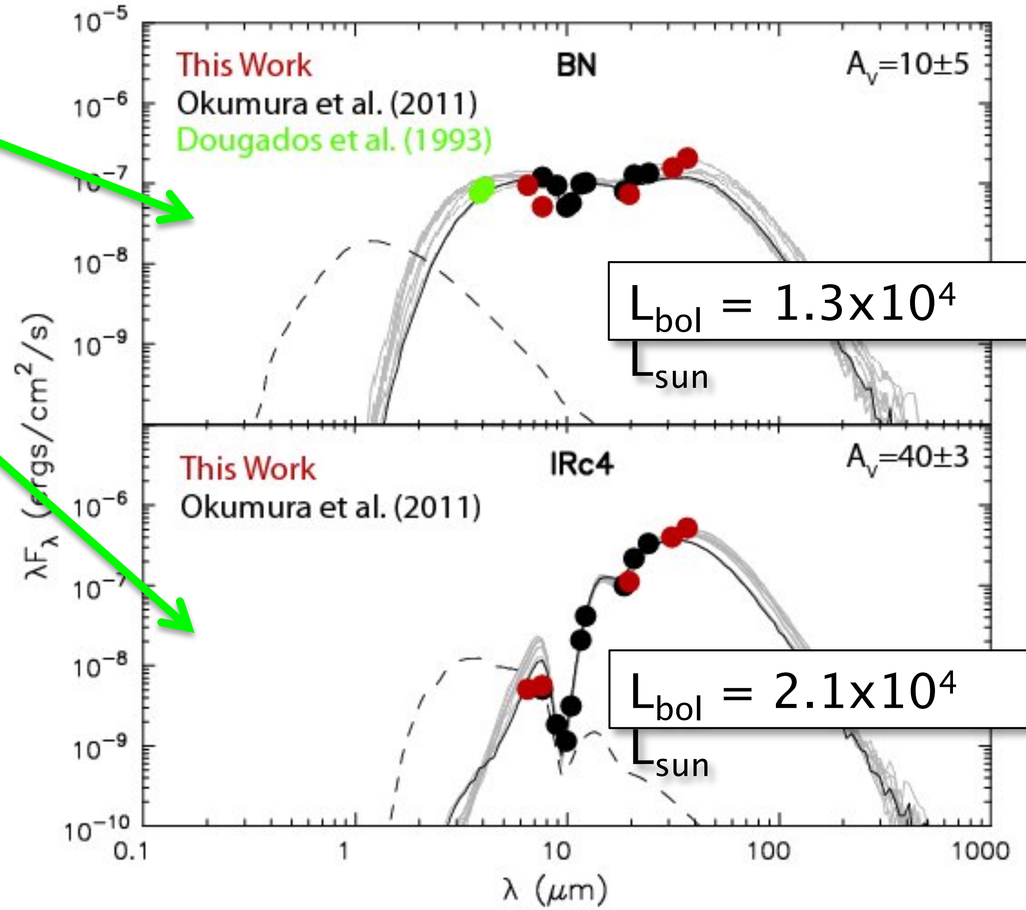
KAO (38 micron)
Stacey et al. 1995
Ney-Allen Region
Blue=7um Green=19um Red=37um
SOFIA
Ney-Allen
q1 D
Trapezium
OMC1S-IRS1
LV1
OMC1S-IRS2
Shuping et al. 2012



KAO (38 micron)
Stacey et al. 1995
BN/KL Region
Blue=19um Green=31um Red=37um
BN
IRc2
IRc3
Source I
IRc4
De Buizer et al. 2012



Like BN, IRc4 is a self-luminous source

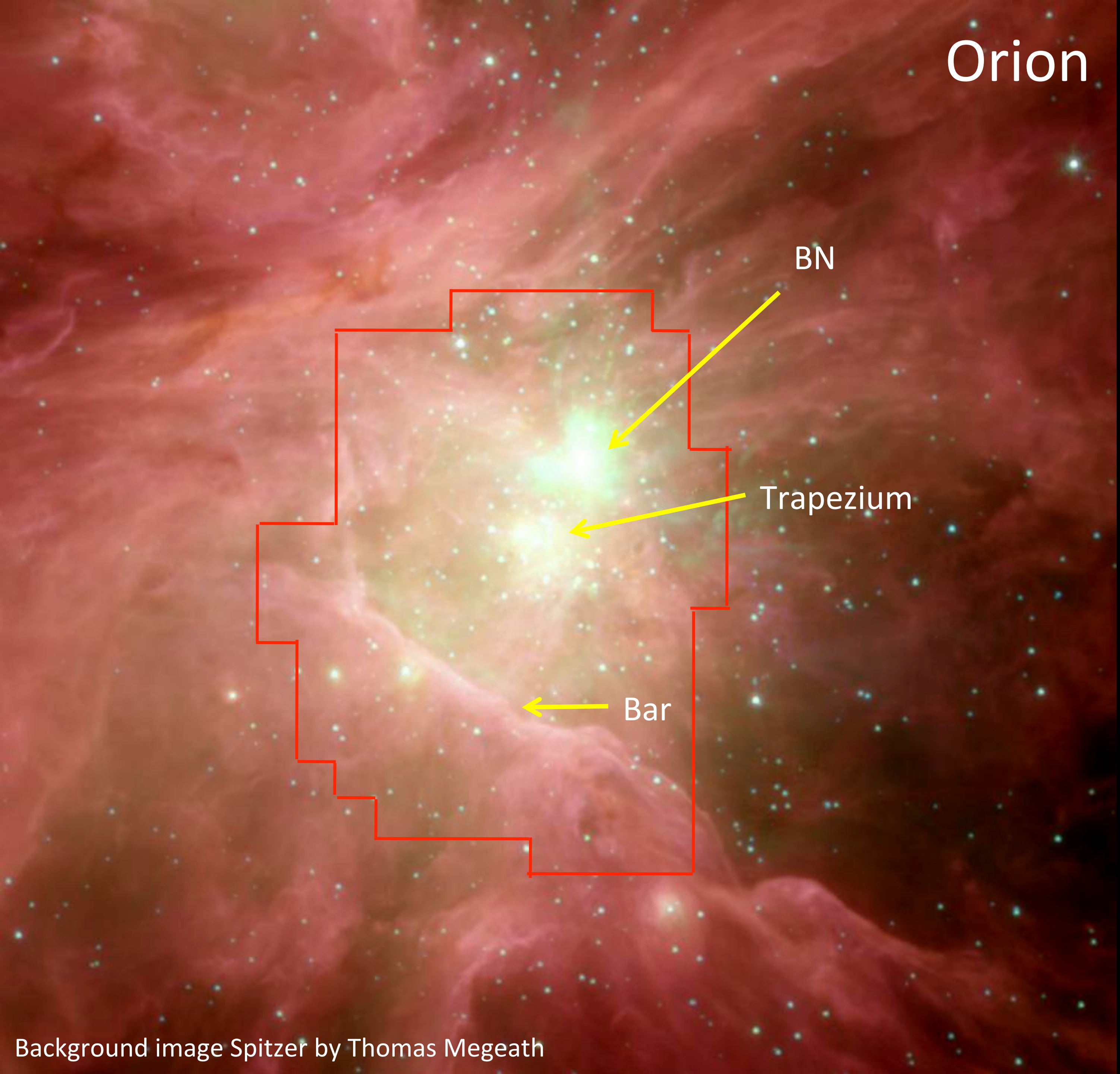


IRc4 luminosity is too high to be caused by external heating

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

De Buizer et al. (2012)

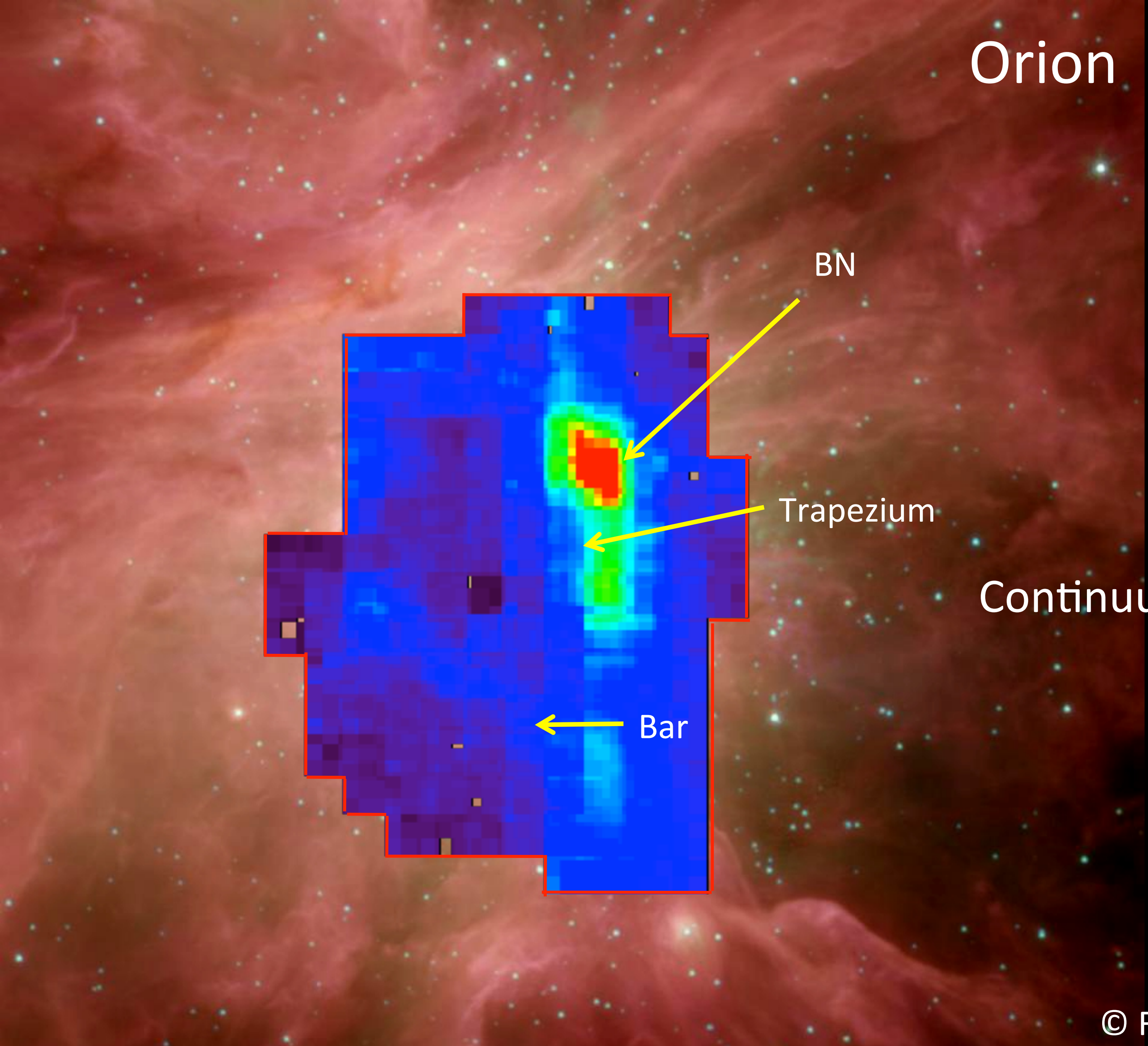
Orion



Background image Spitzer by Thomas Megeath

Orion

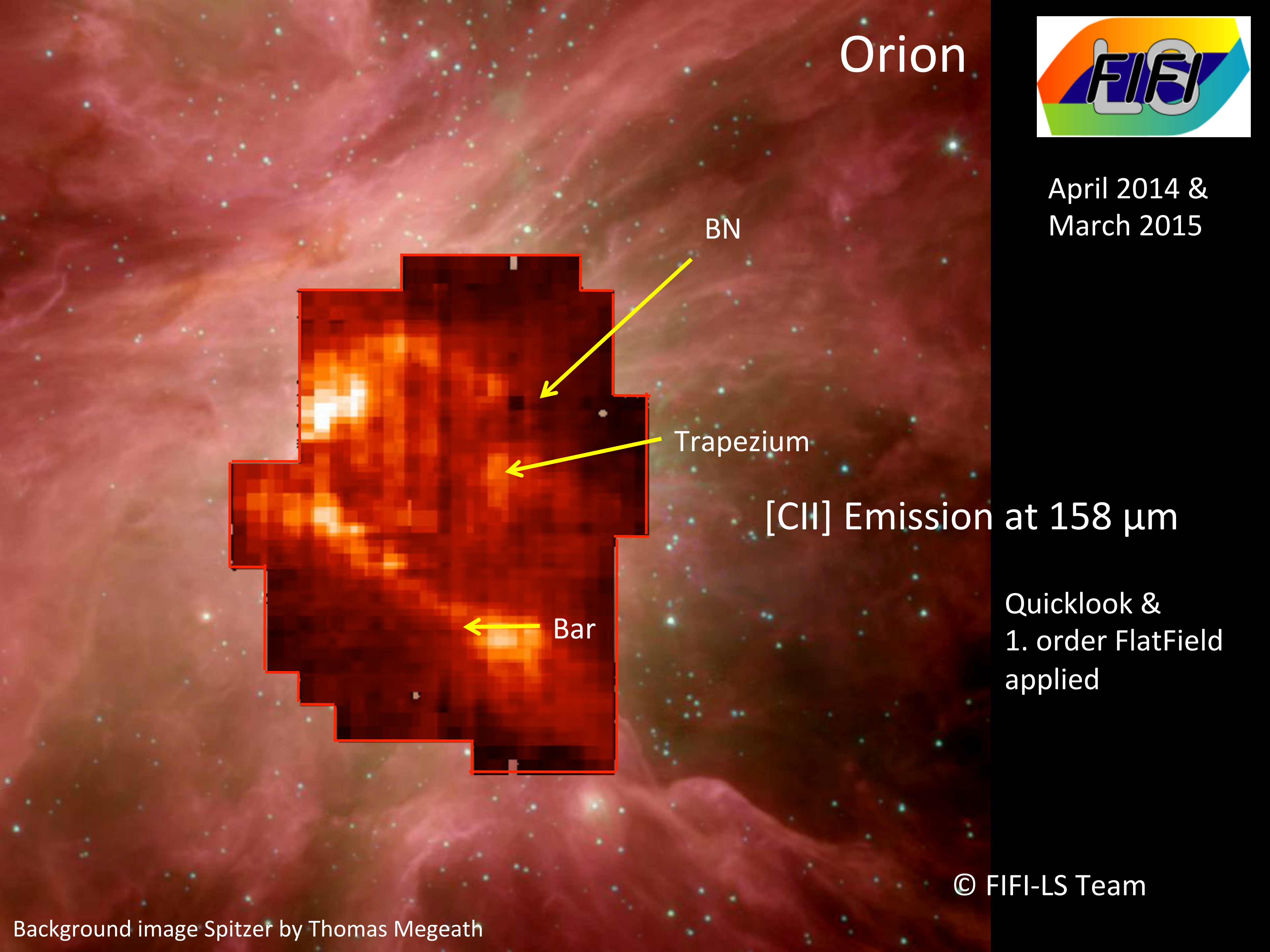
April 2014 &
March 2015



Continuum at 158 µm

Quicklook &
1. order FlatField
applied

Background image Spitzer by Thomas Megeath

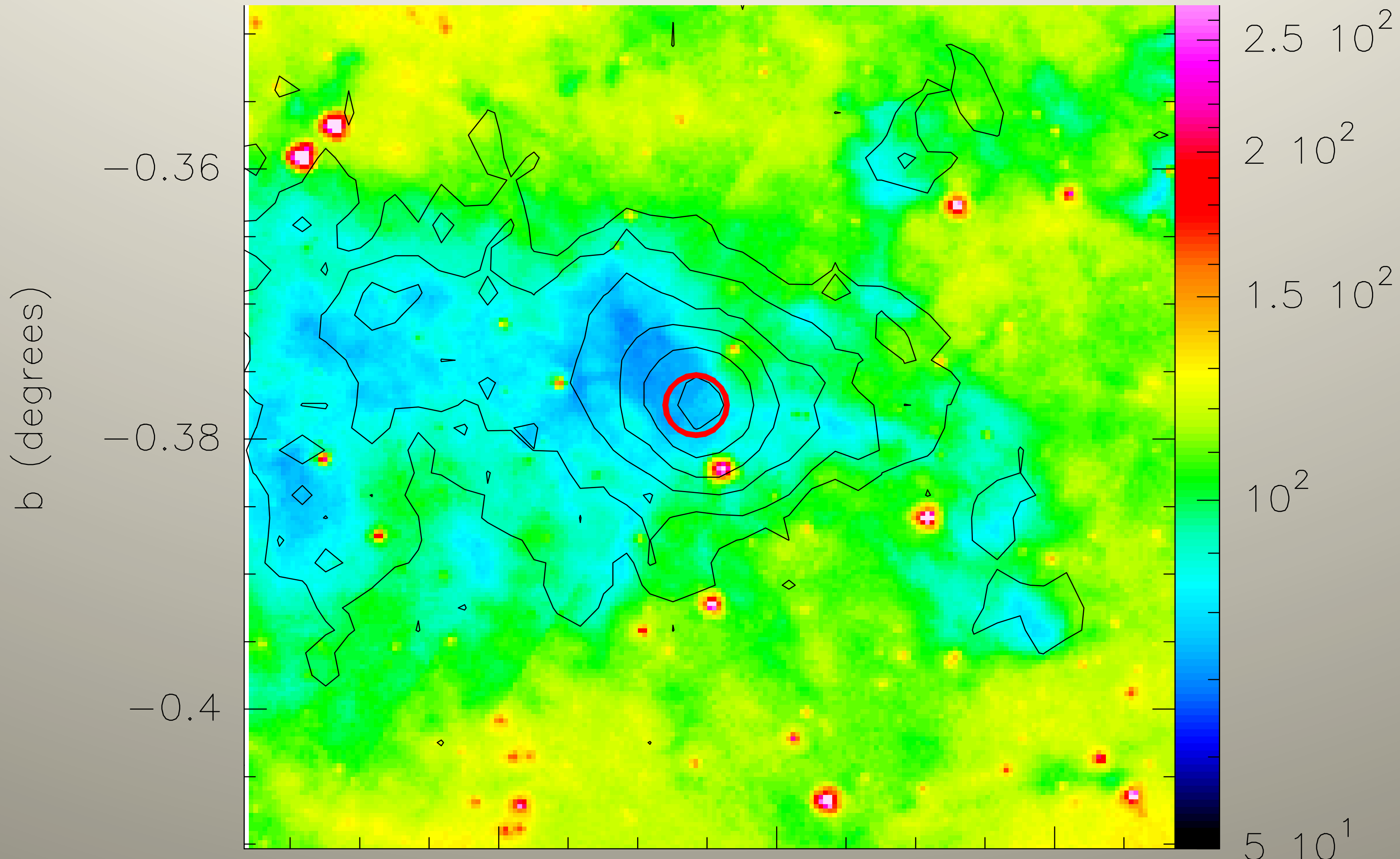

Orion
April 2014 &
March 2015
BN
Trapezium
[CII] Emission at 158 µm
Bar
Quicklook &
1. order FlatField
applied
© FIFI-LS Team
Background image Spitzer by Thomas Megeath

Infall in high-mass clumps
(ATLAS-GAL submm cont source G23.31)

GREAT 1.81 THz spec. (3-2 NH3 rot line)
redshifted absorption:

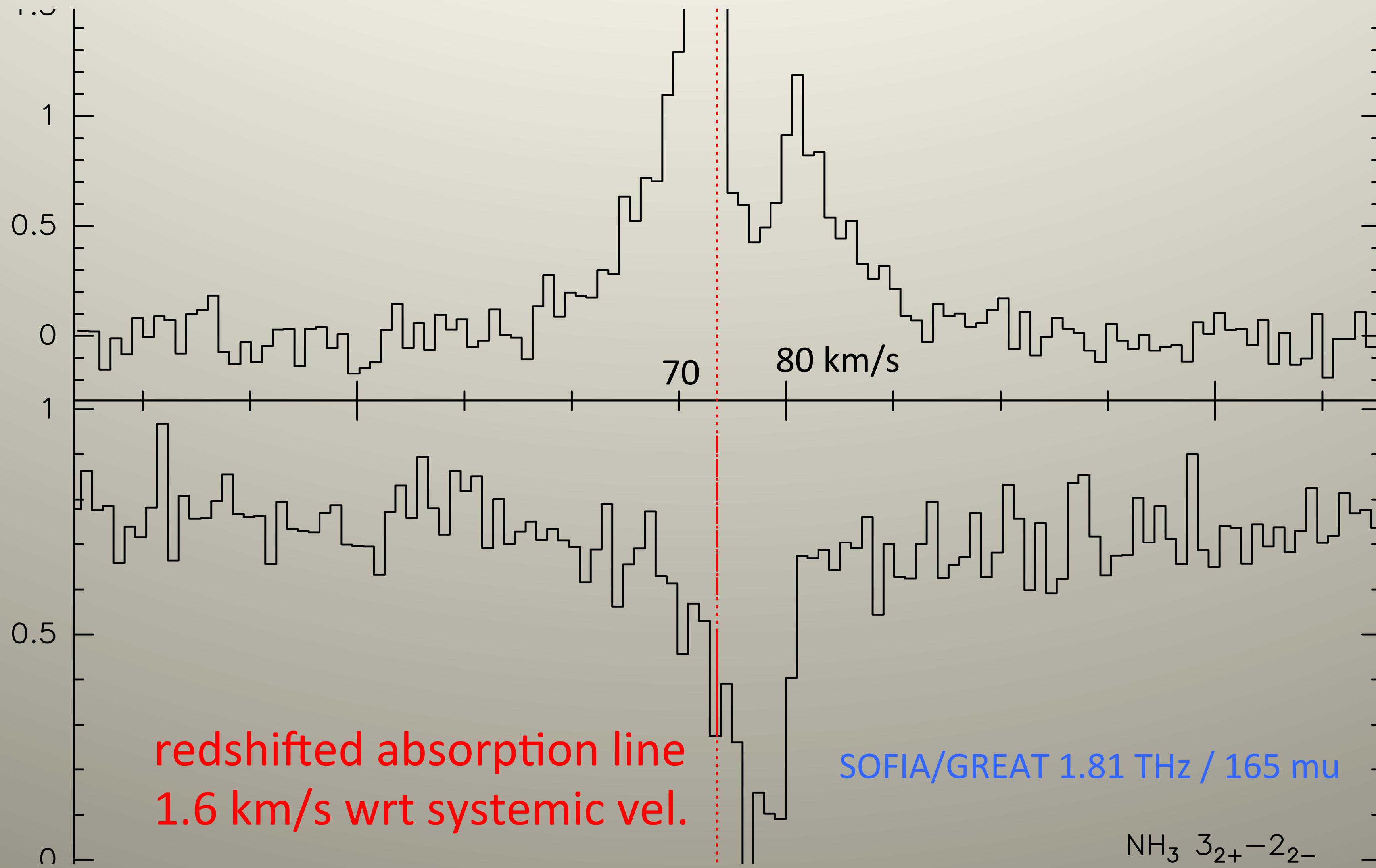
infall rate fraction of free fall rate
derive mass accretion rate

ATLASGAL submm clump G23.21



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



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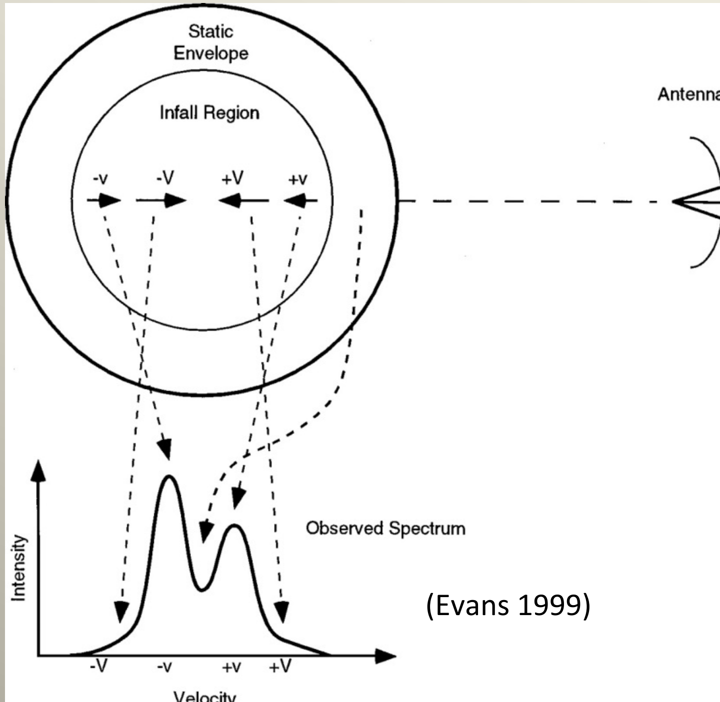
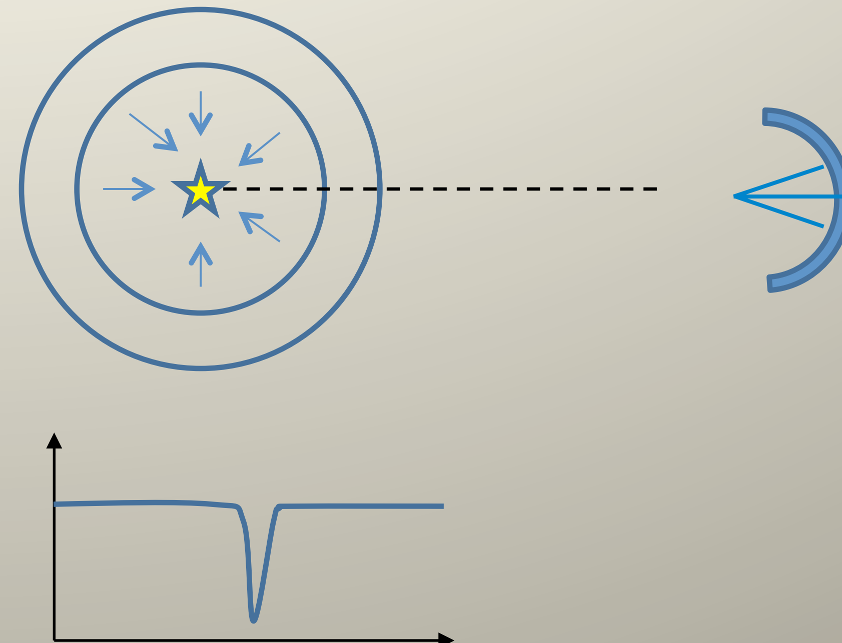
Using THz Lines to Probe Infall



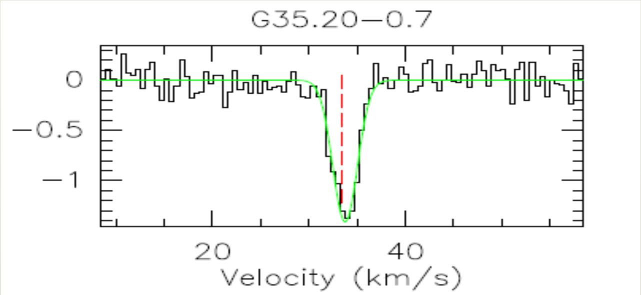


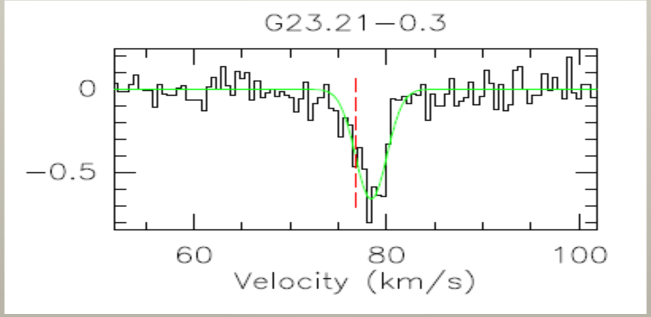
Interpretation of infall using optically thin emission lines is difficult, due to complicated radiative transfer and possible contributions from outflowing molecular gas.

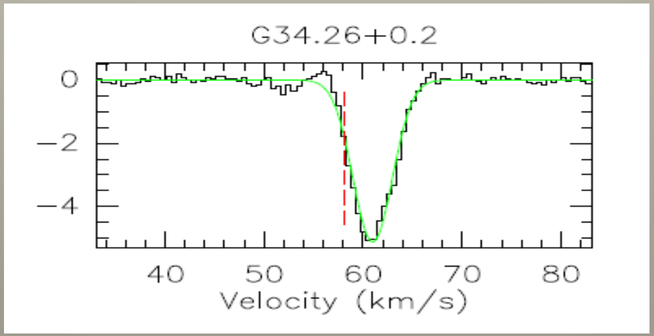
Absorption measurements against a FIR continuum source are much more straightforward to interpret. Infall ("collapse") is the Holy Grail of star formation, and SOFIA THz absorption allows us to measure the gas infall rate ("accretion rate").

1.81 THz Detection of Infall. . .

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







IRAS 16293-2422
(low-mass protostellar core in Oph)

detection of para-H_2D^+
with GREAT at 1.37 THz in absorption
(not accessible to Herschel)

APEX measured ortho-H_2D^+ in emission ortho/para (parallel/antiparallel spins)

ortho-para ratio of in H2 in H2D+

can be used as a chemical clock:

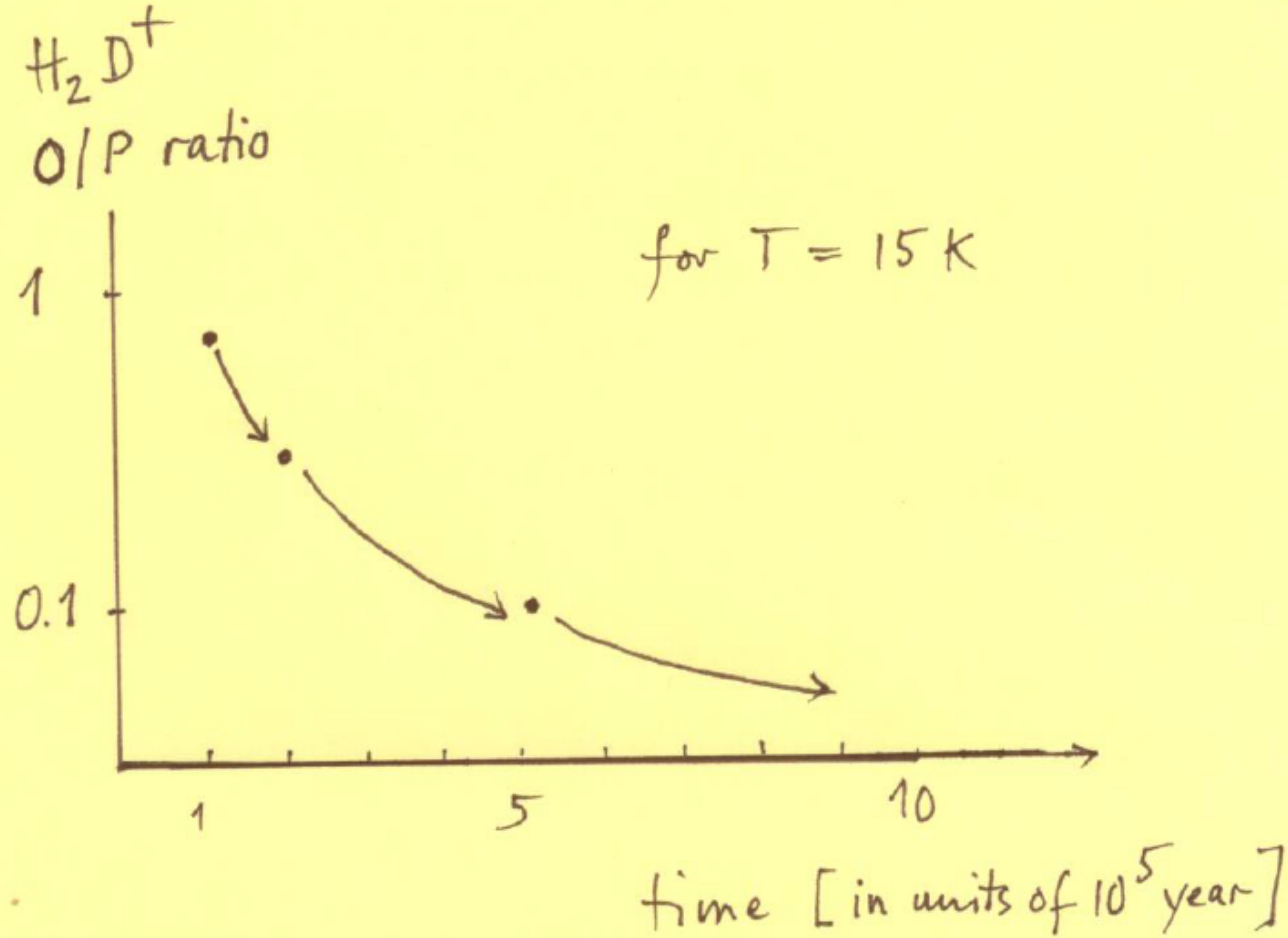
more and more para from initial ortho

due do collisional exchange reactions

meanwhile, even HD2+ detected !

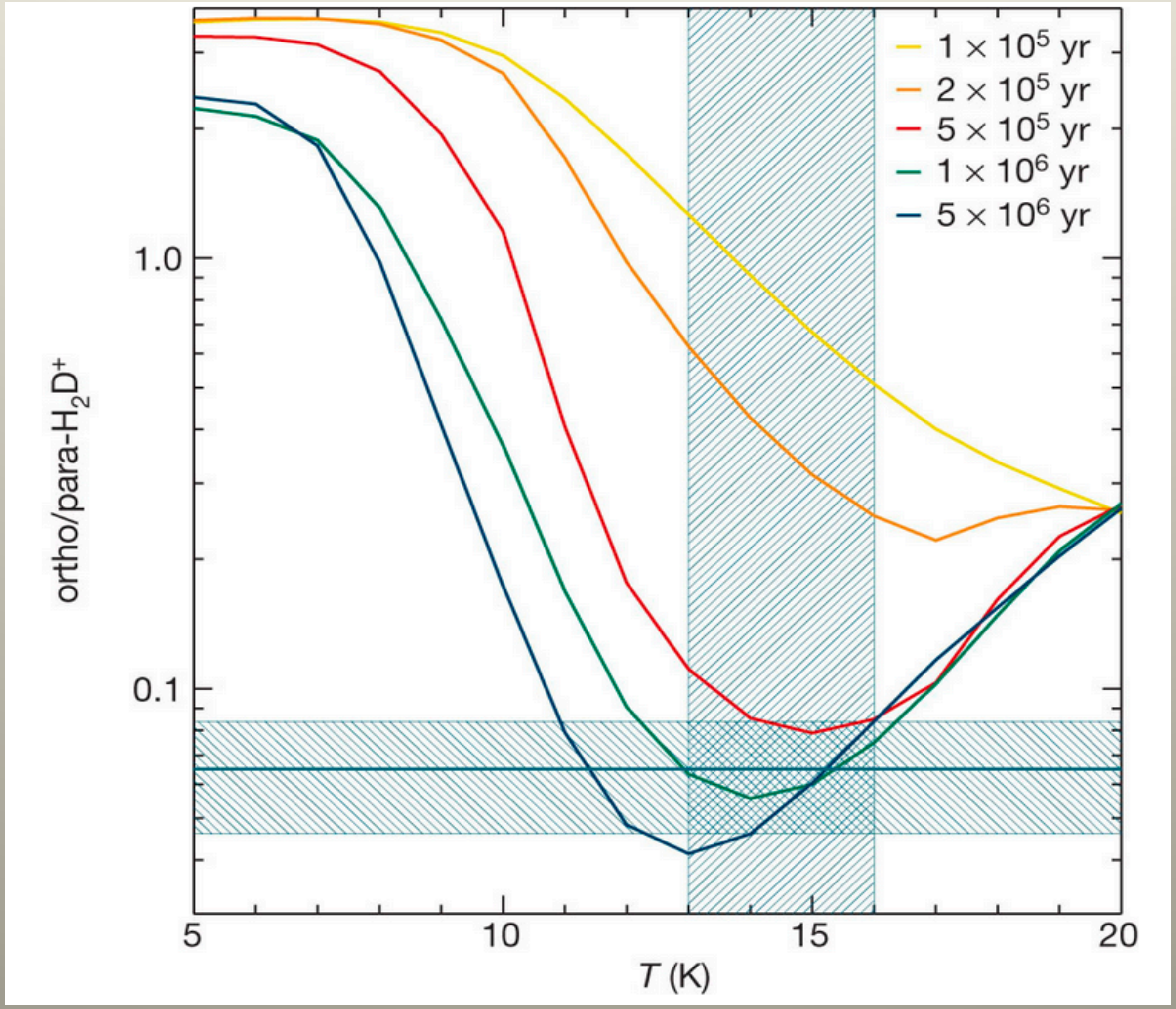
likely an even better chemical clock

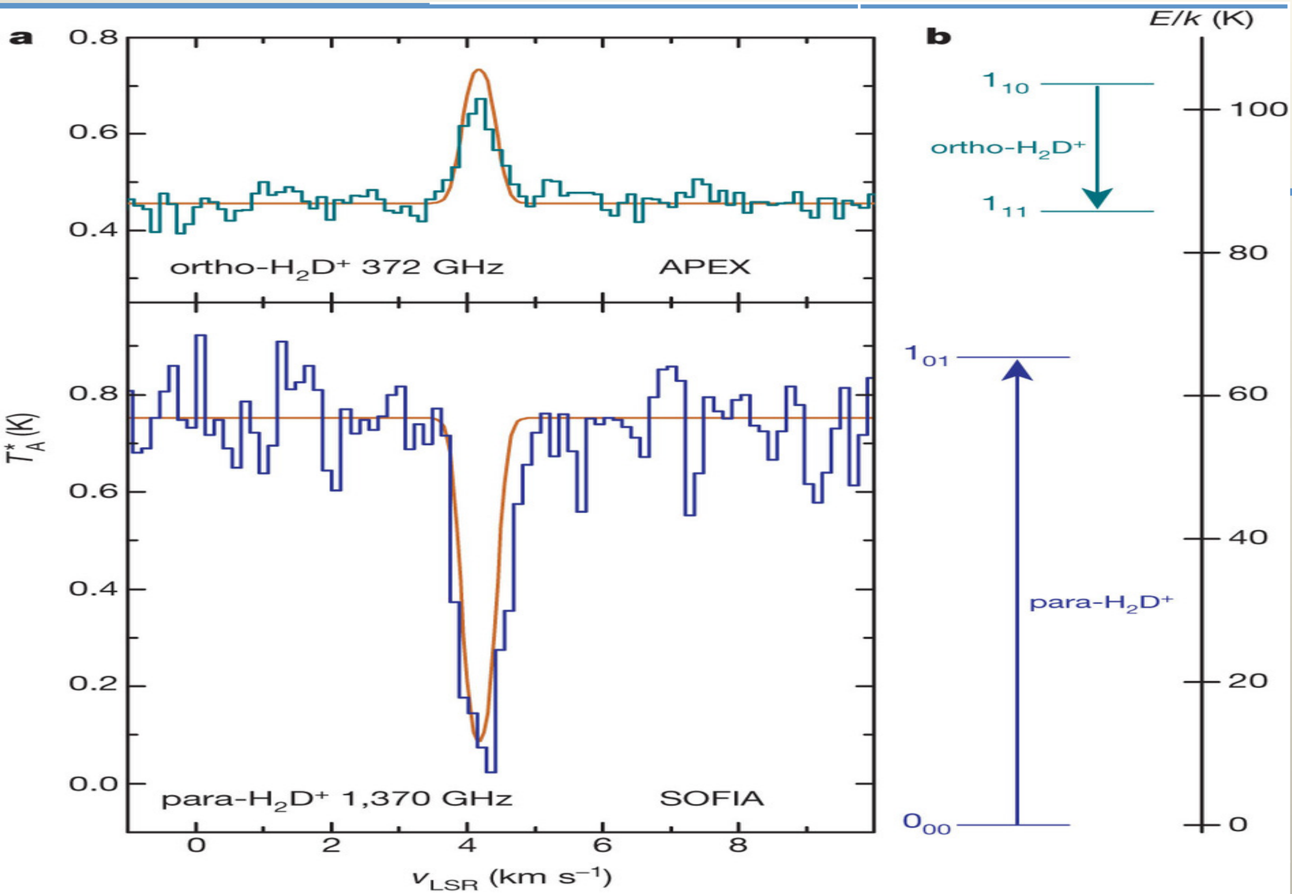
new way to calibrate cloud core ages

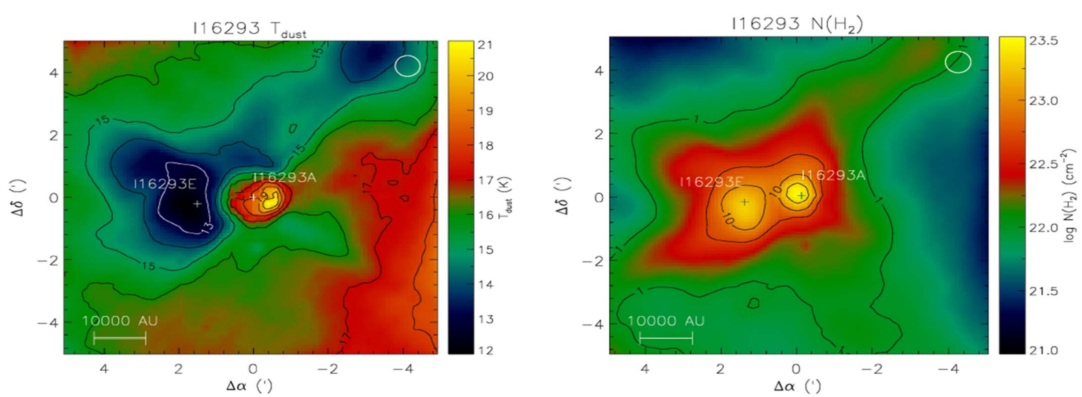


H_2D^+
O/P ratio
for T = 15 K
1
0.1
1
5
10
time [in units of 10^5 year]

ortho-para-H2D+ ratio as f(T,t)







IRAS 16293-2422

Star-forming core

DLR

APEX
Ortho-H_2D+ @ 372 GHz
[upper panel]

compared with:

SOFIA/GREAT
Para-H_2D+ @ 1370 GHz
(219 mm)
[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).

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IRAS 16293-2422

Star-forming core (summary)

H_2D+ ortho-to-para ratio provides a molecular clock; age of this core is found to be ~ 10^6 yrs (after modelling)

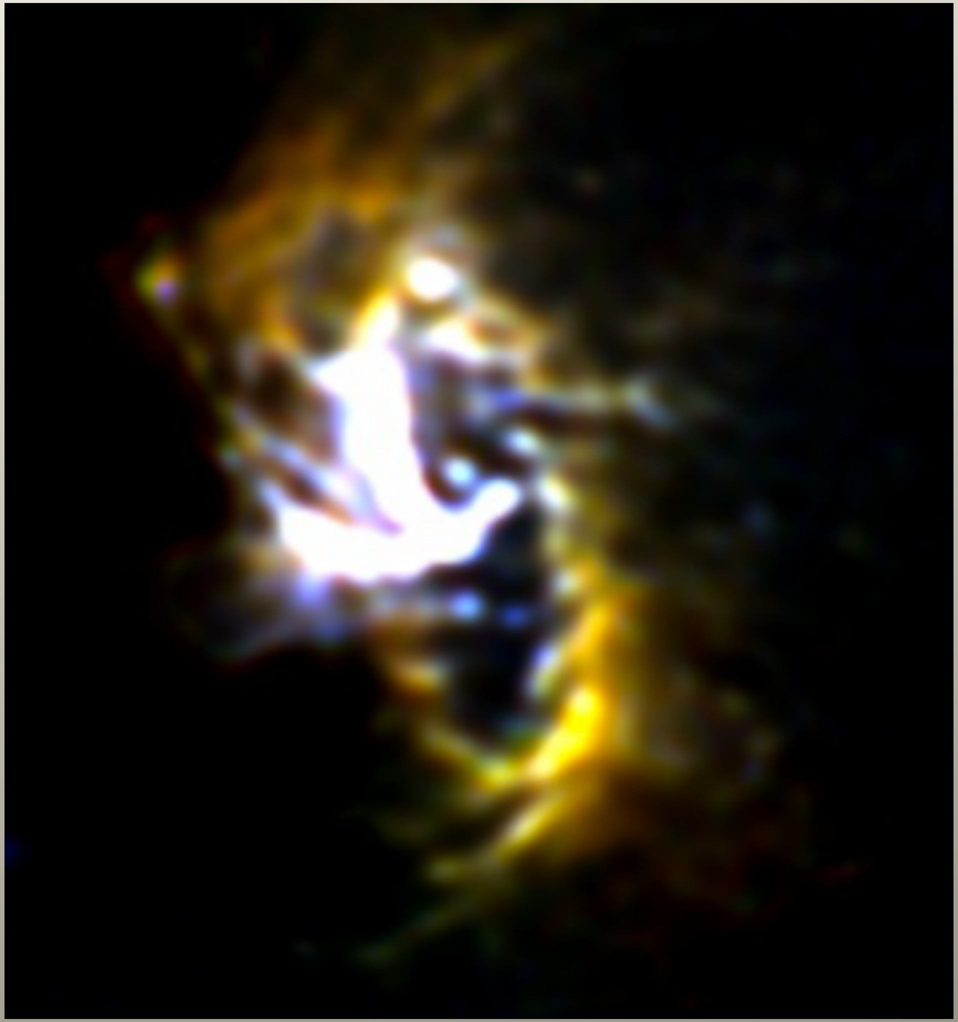
Previous results gave an age of ~ 10^5 yrs using an N2H+ clock that 'turns off' sooner.

Brünken et al. 2014 (Nature)

Huge potential to apply this new method to many other protostellar mol cloud cores!

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

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 the hot 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
- The ring is resolved with a width of about 0.3 pc (no star formation along the ring, perhaps too much tidal shear vs. gravity)
- The ring is heated by the massive stars inside the ring (their origin is a

M82 galaxy
nuclear (1kpc) starburst
central dust disk, powerful galactic wind

FORCAST (6.6, 31.5, 37 micron)
FIFI-LS ([CII] 158mu , [OIII] 52mu)

M82 imaging with SOFIA (FORCAST)

M82 inner 1 arcmin

M82 inner 1kpc
FORCAST
3-color image

Red=6.6mu (PAH)
Green=31.5mu
Blue=37.1mu

RESULTS:
Dust temp. 68K
at the two emission
peaks, dust mass
of order 10(4) Mo
L_bol=10(10) Lo, and
Av=18mag at main peak
(5" WSW of BH)

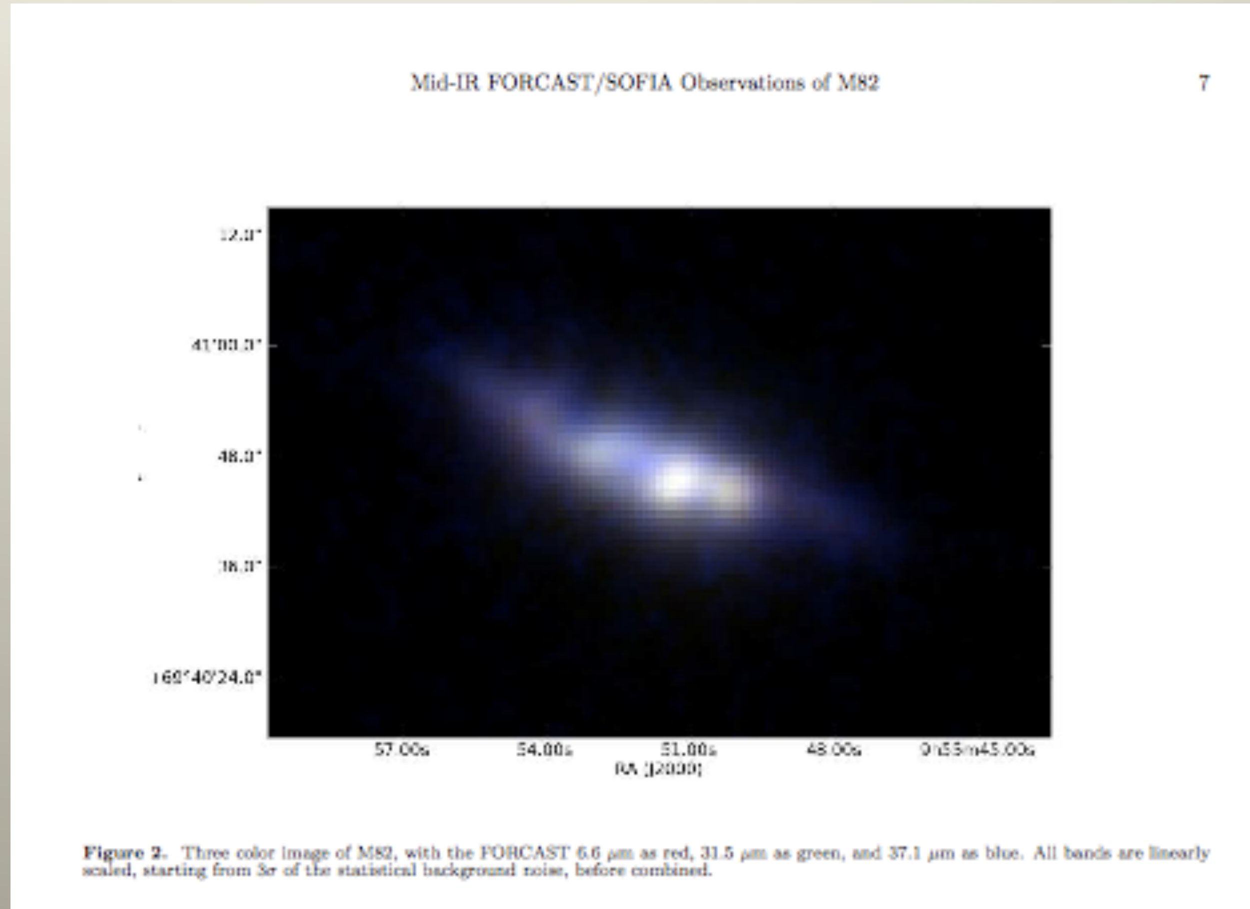
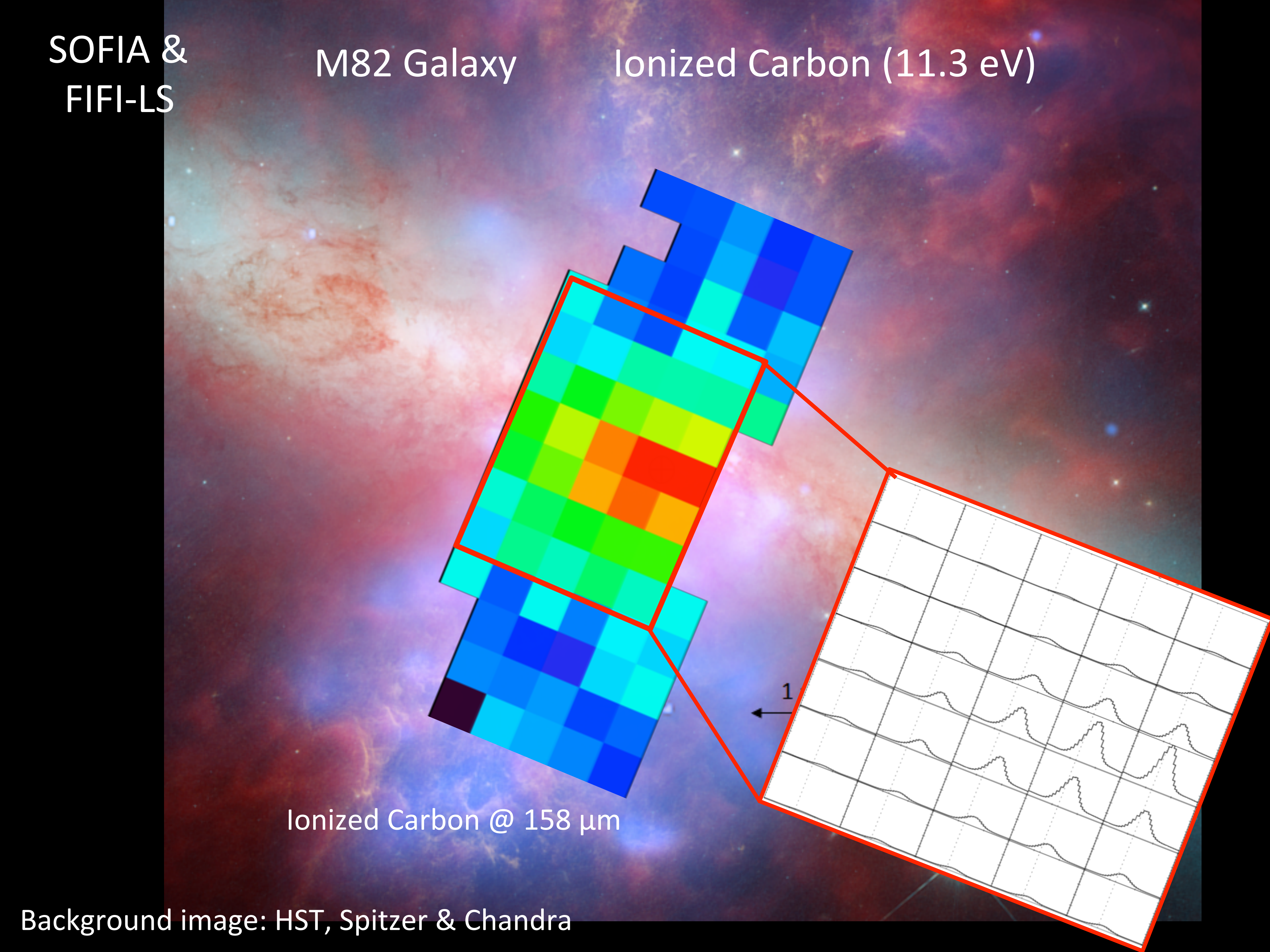

Mid-IR FORCAST/SOFIA Observations of M82 7

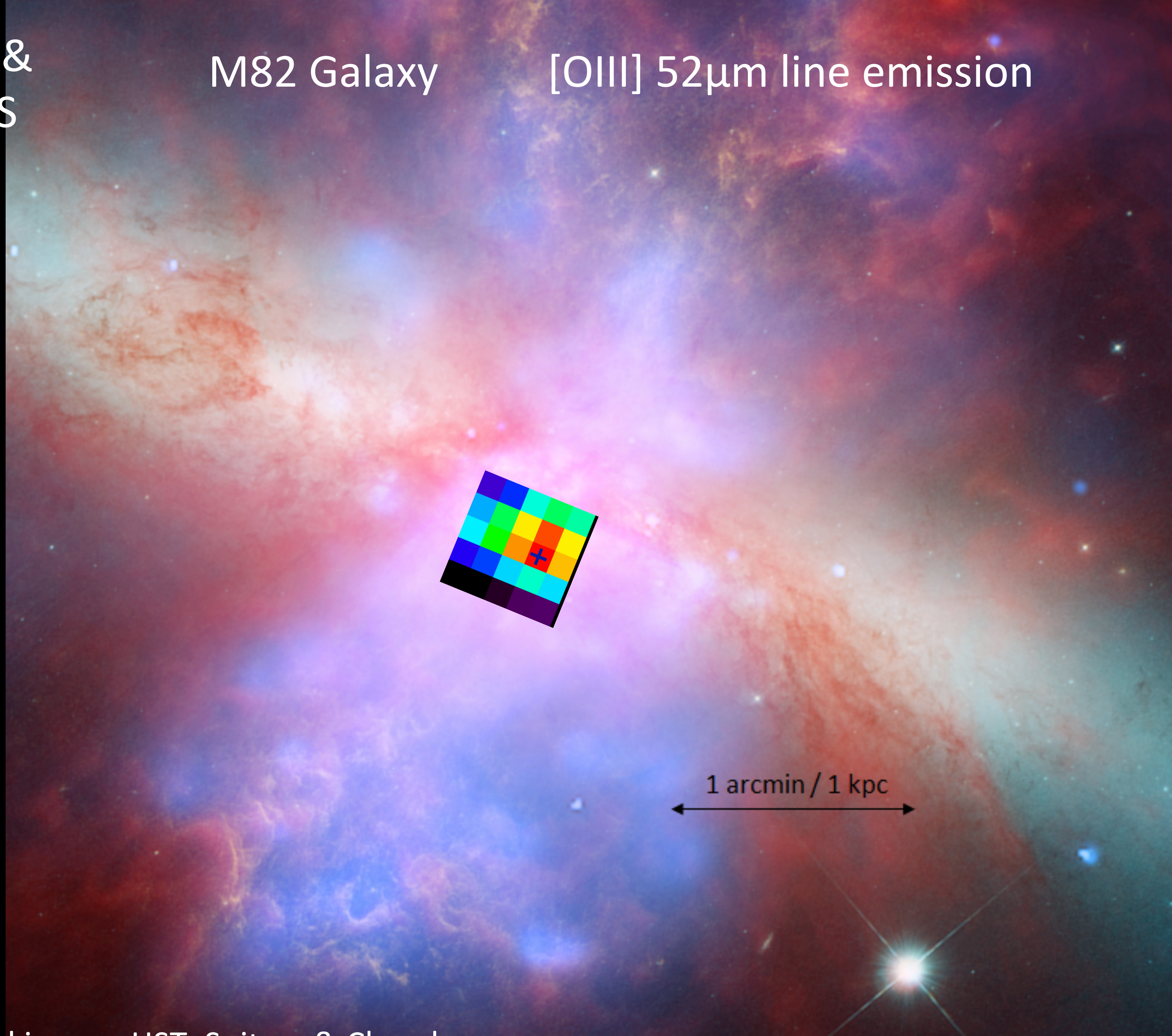
Figure 2. Three color image of M82, with the FORCAST 6.6 μm as red, 31.5 μm as green, and 37.1 μm as blue. All bands are linearly scaled, starting from 3σ of the statistical background noise, before combined.

Nicola et al. 2012 ApJL


SOFIA &
FIFI-LS
M82 Galaxy
Ionized Carbon (11.3 eV)
Ionized Carbon @ 158 µm
Background image: HST, Spitzer & Chandra

SOFIA & FIFI-LS

M82 Galaxy [OIII] 52µm line emission



Background image: HST, Spitzer & Chandra

FIR Dust Continuum Emission Polarimetry

- Far Infrared polarimetry will help elucidate the role of magnetic fields in the energetics of the interstellar medium and star formation
- With the advent of HAWC+ (40x64 pixel array camera) and its 5 narrow-band filters (from ~50 mu to ~200 mu) SOFIA will have a unique FIR polarimetric capability that was missing on Herschel and will complement Planck and ALMA mm and submm polarimetry (HAWC+ beam size ~ 5 to 20”).

Magnetic fields play a crucial if not regulating role in low- vs. high-mass star formation and in helping to solve the angular momentum problem

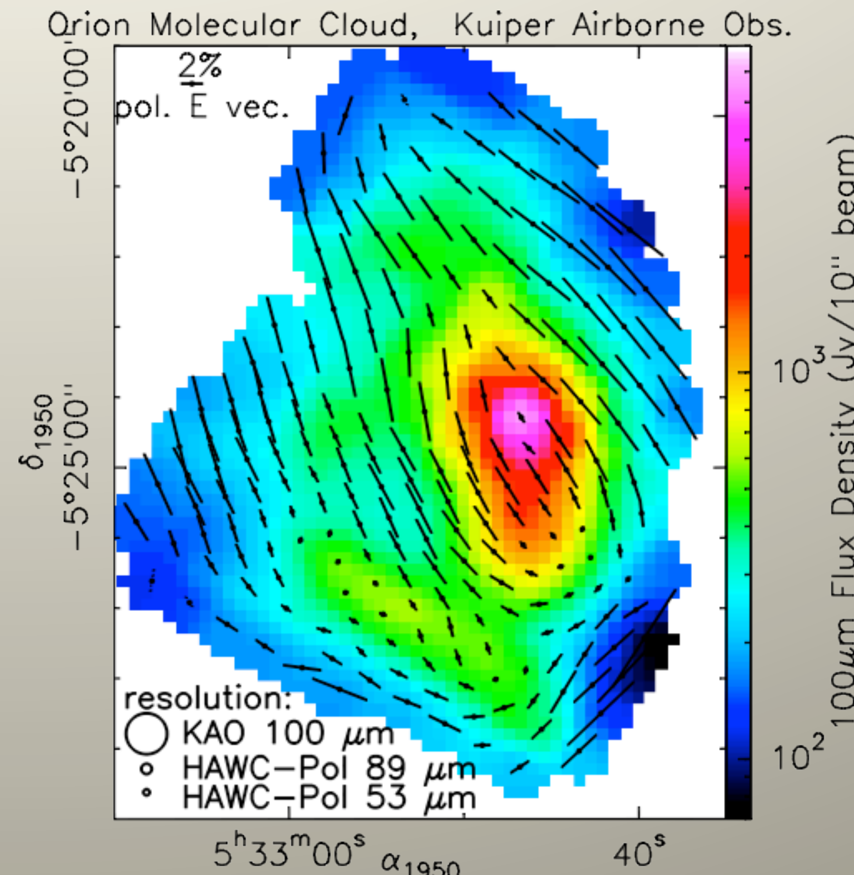


Figure 5. Linear polarization of the Orion Nebula at 100 μm measured with the KAO by Schleuning (1998) . Shown are the beam sizes of the KAO polarimeter and HAWC+ (PI Darren Dowell, JPL)

USRA DSI

Summary

SOFIA with its multi-instrument suite
is providing the "local truth"
for distant star formation regions.

In synergy with ALMA/APEX/IRAM,
SOFIA will revolutionize Galactic
and nearby extragal. ISM/SF studies


NASA
DLR
SOFIA
34
30

How ***You*** Can Participate in SOFIA

Apply for Observing Time

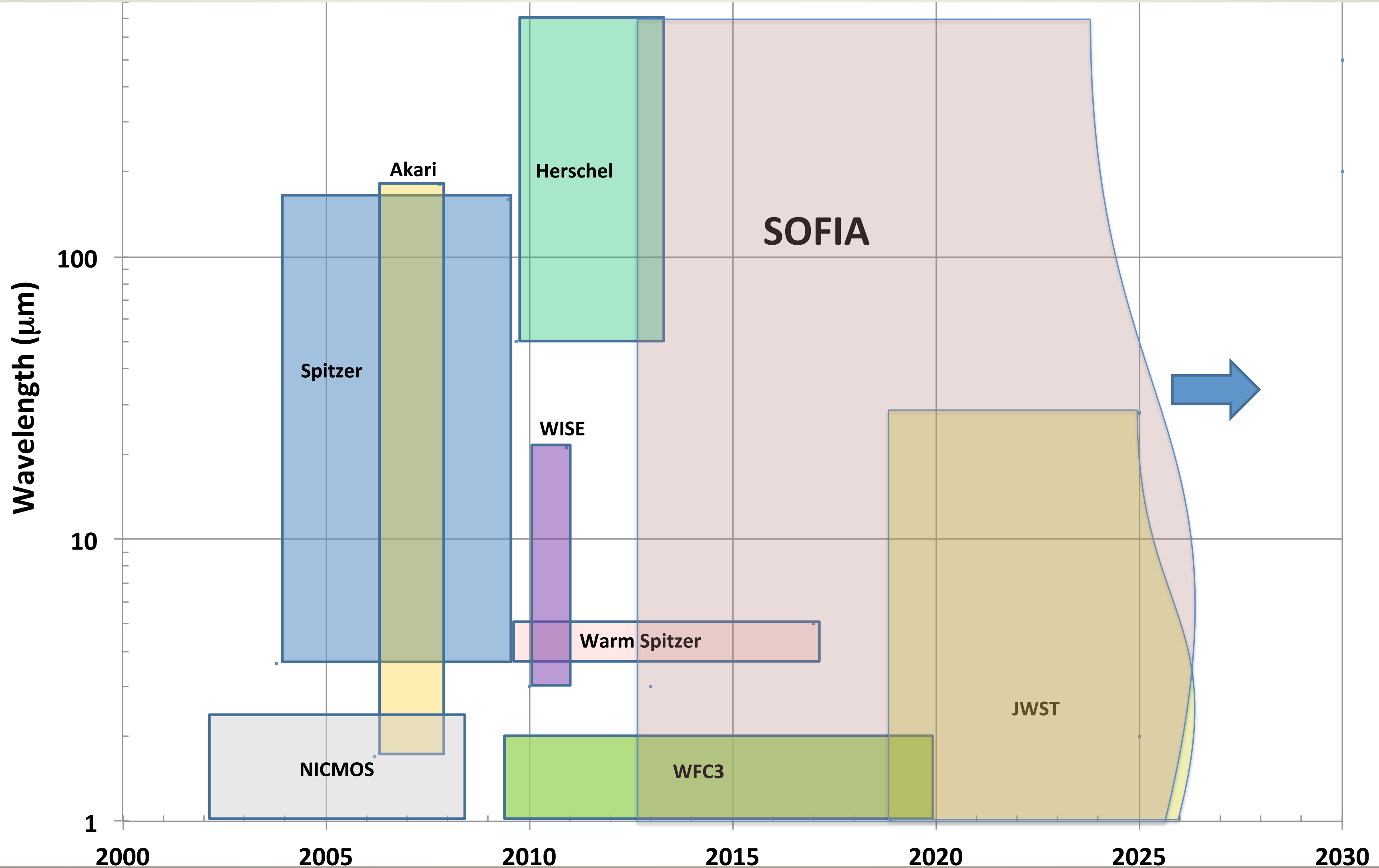
Develop a New SOFIA Science Instrument

SOFIA Partnership Opportunities

Thomas L. Roellig

SOFIA Deputy Project Scientist

SOFIA Provides Your Access to the Far Infrared



USRA

Applying for Time on SOFIA

- Annual Observing Calls – Due Dates Mid-Summers
  - *Open to the worldwide scientific community*
  - *Southern Hemisphere deployments*
  - *Full range of scientific instruments*

- Cycle 4 just closed on July 10, and the proposals will be evaluated in the next month, with the selections announced ~ Oct. 1

- The nominal Cycle 4 observing period runs from March 2016 to February 2017, ~ 500 hours available

Types of Programs

- Regular Programs
- Impact Programs
  - *Large (~50-100 hrs), multi-year programs addressing high-importance issues in astrophysics*
- Survey Programs
  - *A sub-set of a large number of targets*
  - *Used to enable efficient use of flight time*
- Target of Opportunity Programs
  - *Known type of targets but unknown timing*
- Director's Discretionary Time
  - *Proposals accepted to observed unanticipated phenomena*
  - *Turn-around time as fast as 10 days possible*

Other Information

- A limited fraction (~5%) of the Regular Programs will be categorized as "guaranteed observations" and may be carried over to the next observing cycle if they fail to be scheduled during their nominal cycle

- 1-year data proprietary period, starting after PI gets access to flux-calibrated data

- Data reduction funding will be provided by NASA for successful US-based proposers under an funding allocation algorithm

- ***Some*** support and accommodation for PIs on their SOFIA flights

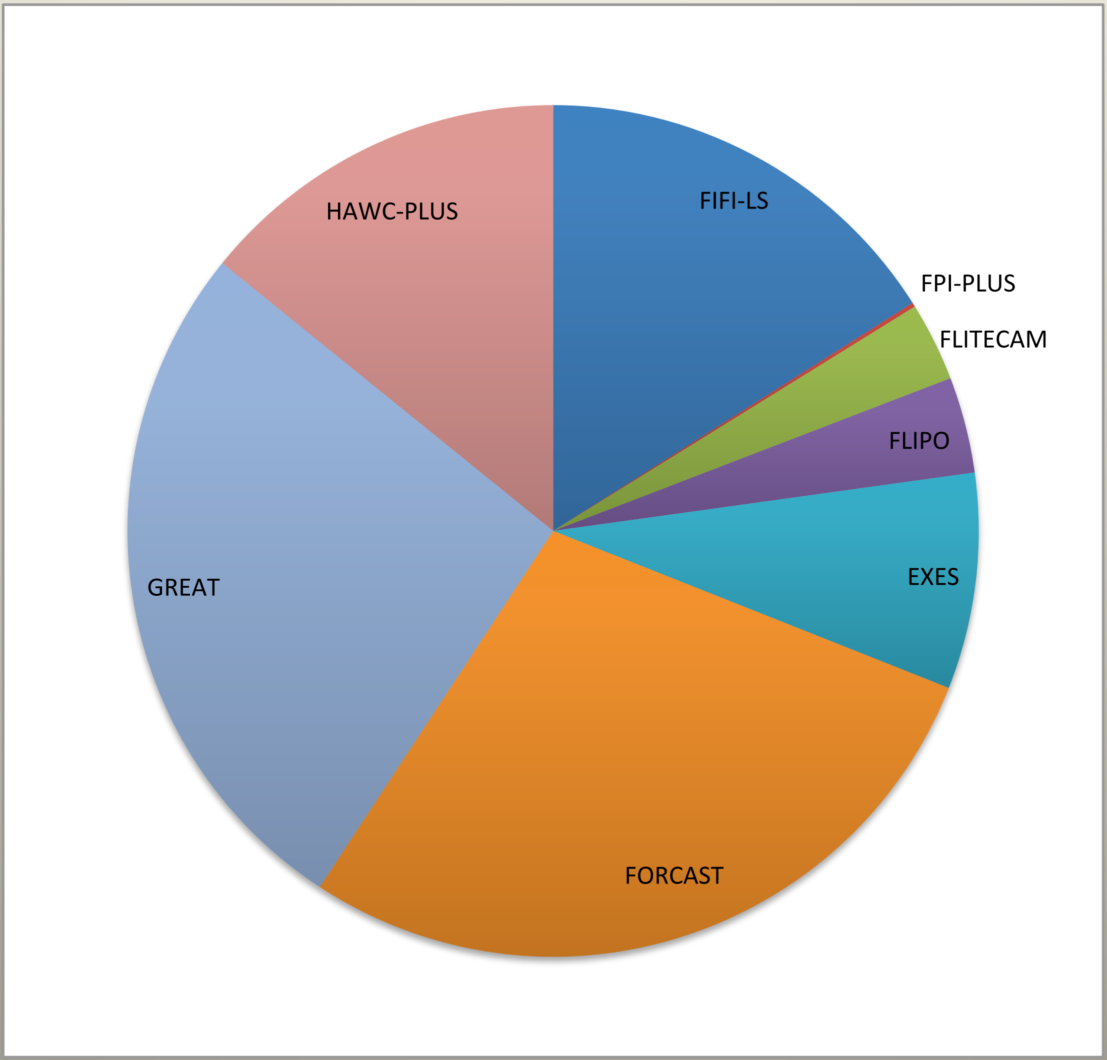
- For more information see the SOFIA web site: *http://www.sofia.usra.edu*

SOFIA Data Archive

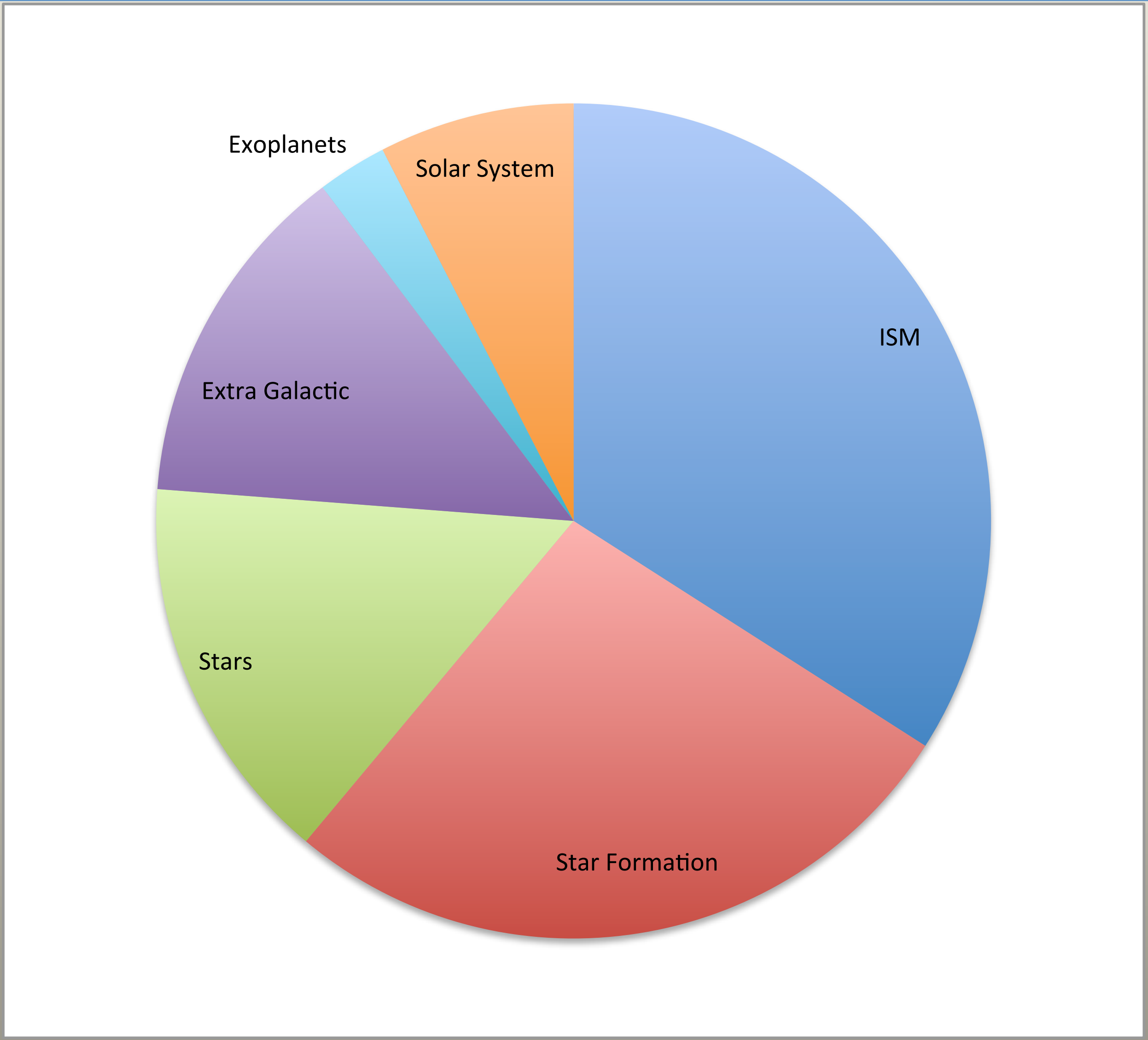
- Repository for all SOFIA science data
- Once proprietary period ends any access restrictions are lifted and data is available to the entire science community
- Can be found at: http://www.sofia.usra.edu/Science/DataProducts/index.html
- ***More and more SOFIA data is becoming available – check it out!***

Cycle 4 Requested Instrument Distribution

Chart Revision 30 Jun 2015



Cycle 4 Guest investigator Research Areas



Third Generation Instrument

- NASA is soliciting a new **SOFIA Facility Science-class Instrument** (we are not looking for upgrades to current instruments or technology demonstration instruments)
- Call for Proposals issued July 9
- Planned funding: **$17M over FY2016-FY2019**, not more than $5M in any one FY
- **Rapid development period: new instrument will be commissioned in CY2018**
- Both commissioning and guaranteed time will be made available to the instrument development team, with the amount of each TBD depending on the instrument commission plan and the development performance of the instrument team

Multi-Step/Phase Selection Process

- Phase 1, Step 1
  - **Mandatory prerequisite for any subsequent steps**
  - Similar to a Notice of Intent
    - Submitted by PI's Institution, not the PI
    - 2 pages
    - Lists all investigators
    - Short description of proposed science
    - Short description of the proposed instrument
    - **Due August 19, 2015** ***(Soon!)***

Multi-Step/Phase Selection Process (2)

- Phase 1, Step 2
  - Typical large NRA proposal (25 pages Science, Technical, Management)
  - ***Due Oct. 7, 2015***
  - Intent is to focus on science rationale Why the science potential is important and broad-based
    - Why it can only be done from SOFIA
    - Provide initial design concept
    - Need to make plausible argument for technical feasibility
    - Notional development schedule
    - Cost estimate (not highest fidelity)

Multi-Step/Phase Selection Process (3)

- Phase 2
  - ***Two*** proposals from Phase 1, Step 2 will be accepted for funded Instrument Concept Studies (ICS)
  - **Expect to provide funds for ICS though grants at the $250k/team level**
  - Studies start ~3 months after Phase 1, Step 2 due date
  - At end of this study it is expected that the instrument designs will be at the Preliminary Design Review-level of maturity
  - **Emphasis will be on a higher level of technical, cost, and management understanding, not on refining the science case**
  - Studies will last at most 4 months
  - At the end of this phase NASA will make a down-select based on a more formal TMC review to ***one*** instrument for development

Other Items of Note

- The SOFIA Program intends to supply ~3 staff members to help the winning instrument team navigate the various required reviews and analyses

- Regularly check the 3rd Generation Call for Proposals site in NSPIRES (http://nspires.nasaprs.com/external/) for new information

International Partnership Opportunities

- Observing time is in addition to the existing funded US and German time

- Contribute support to the SOFIA Program (under the standard no-exchange-of-funds rules)

- Full Partners
  - *20 -100 hours annually of observing time*
  - *Can develop their own instruments*
- Limited partners
  - *Allocated as little as 2 hours of flight observation hours*
  - *Use existing SOFIA science instruments*

Ride-Along Partnership Opportunities

- International Educational Community Partners
  - *Much like the existing Airborne Astronomy Ambassadors Program*
  - *Educators ride along on SOFIA flights*
- International, Domestic, and Other US Government Agency Research Partners
  - *Long-term, in situ measurements*
  - *Bring their own equipment*
- Bio-fuel Industry partners
  - *Test and monitor bio-fuels during regularly-scheduled SOFIA flights*

- For more information see the brochures available at this meeting or contact http://www.nasa.gov/sofia/partnerships

More information at:
http://www.sofia.usra.edu

Near-Term Schedule

Chart Revision 7/6/15