SOFIA Tomorrow: Understanding Star Formation in the Era of JWST and ALMA

10 May 2017

Harold W Yorke

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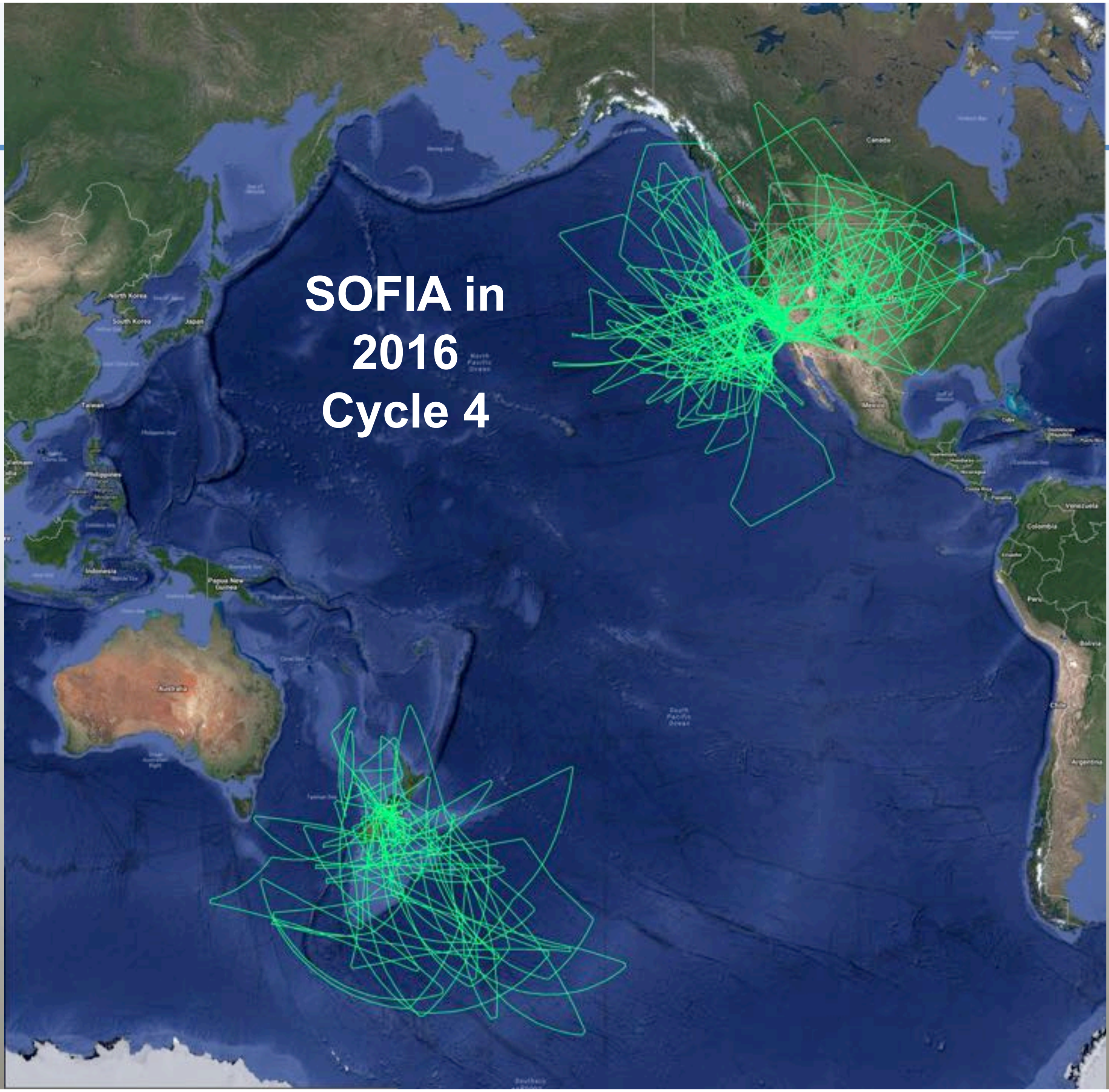
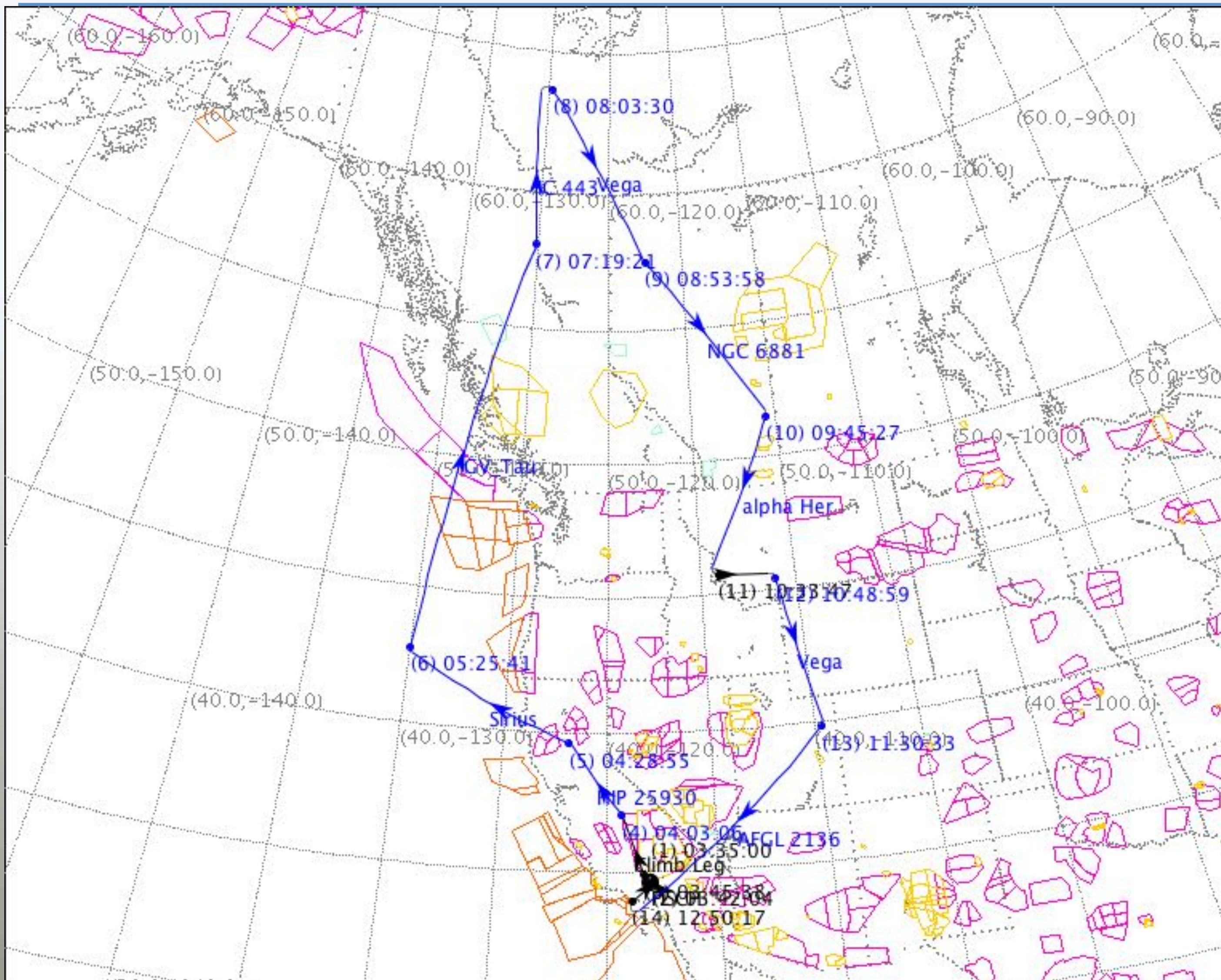
Setting the Stage

- SOFIA is not a space mission
  - Hardware repairs & updates are in principal possible on a relatively short time scale
  - New instruments can be added to address current relevant science questions
  - SOFIA Yesterday differs from SOFIA Today, which differs from SOFIA Tomorrow


SOFIA in
2016
Cycle 4

Setting the Stage



Constraints

- We point the telescope by pointing the airplane
- Telescope elevation should be between 22º and 58º
- We take off and return to Palmdale

=> SOFIA needs targets scattered across the sky

Setting the Stage

Consequences

- Flight plans are 10 weeks in the making
- Observing legs are ≤ 3.5 hours
- In order to fill flight plans without "dead legs" with the best possible science, we knowingly
  - Over-accept proposals by about 50%
  - Include "Do if Time" targets in flight plans
  - Encourage "SOFIA Survey" proposals
  - Actively search for good DDT targets
  - Pick and choose calibration targets in the right part of the sky
- If no good science or calibration targets are available, we utilize dead legs for engineering tests or practice runs of occultations

Constraints

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=> SOFIA needs targets scattered across the sky

New SOFIA Policies

- Advertise “dead legs” to the community with a short turn-around time ~1 week => Flash Email and post on SOFIA website requesting DDT proposal
- Allow “mini deployments” to airports other than Palmdale
- Include “sky density maps” for each instrument with Cycle 6 Call for Proposals, emphasizing where targets are needed to complement popular areas of the sky

(https://www.sofia.usra.edu/science/proposing-and-observing/proposal-calls/cycle-6/complementary-sky-positions-cycle-6)

(
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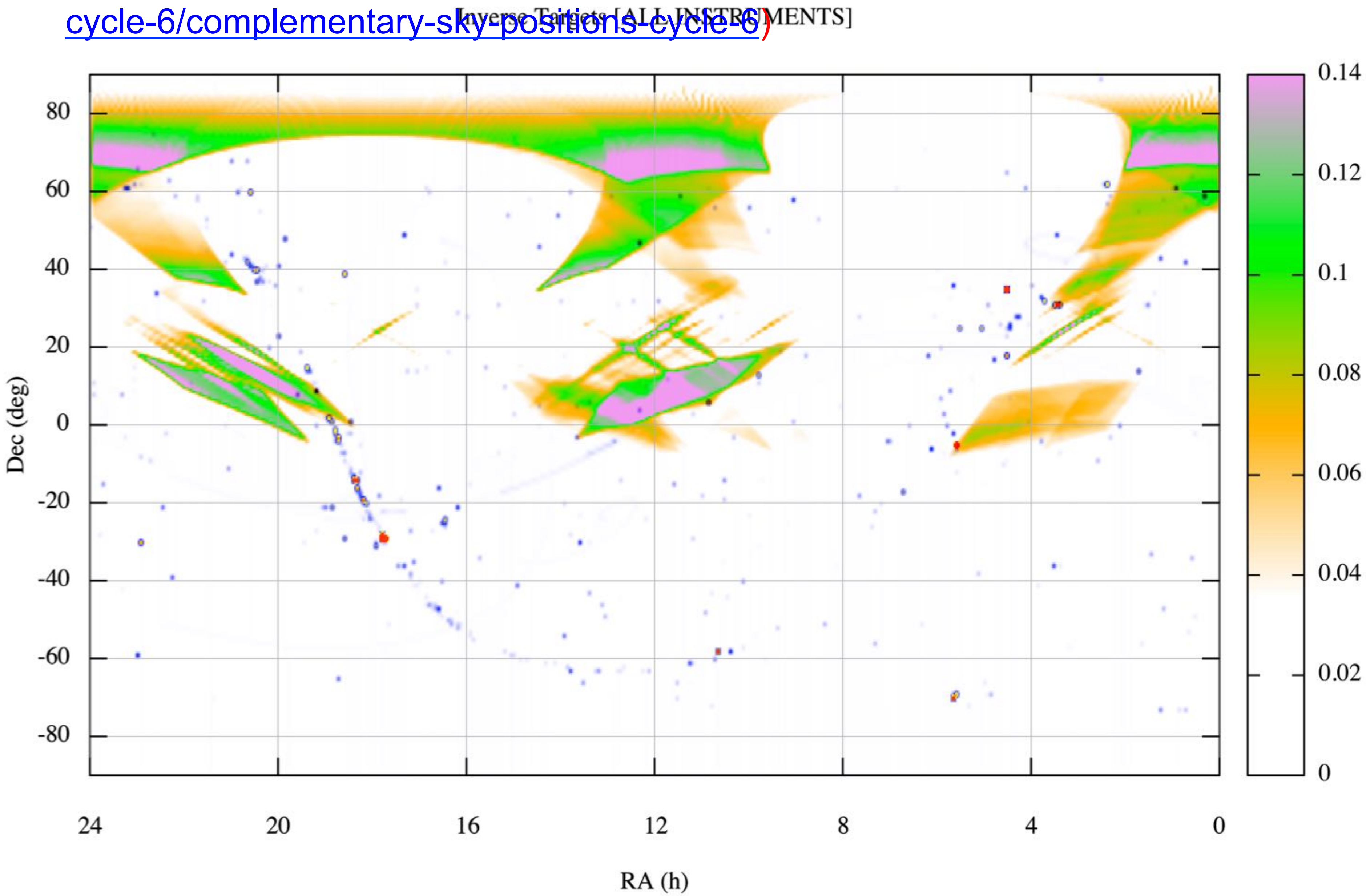


Cycle 6: Feb 2, 2018 – Feb 1, 2019

Stratospheric Observatory for Infrared Astronomy

(SOFIA)

Observing Cycle 6

Call for Proposals

May 1, 2017

Version 1.0

US Proposal Deadline: June 30, 2017 21:00 PDT
(July 1, 2017 04:00 UTC)

Please check the USRA website on June 5th for updates to call.

This document and all other information pertaining to SOFIA observing Cycle 6 may be found at https://www.sofia.usra.edu/Science/proposals/Cycle6/.

Cycle 6 Call for Proposals

Selection Categories:

- Explicit, selection bands to be introduced and advertised in CfP
  - **Priority 1**– Will strongly drive scheduling; carry-over to next cycle if incomplete, ~25% of time
  - **Priority 2**– Similar to “Must do” category in previous cycles, ~50% of time
  - **Priority 3**– Similar to “Do if time” category in previous cycles, ~50% of time
  - Exact selection fractions in each band will depend on target locations and competition
- Funding schedule
  - **Priority 1**– can release full GO funding at acceptance
  - **Priority 2**– release $7k at acceptance, remainder after first target observations executed
  - **Priority 3**– release $7k at acceptance, increment after each observation executed

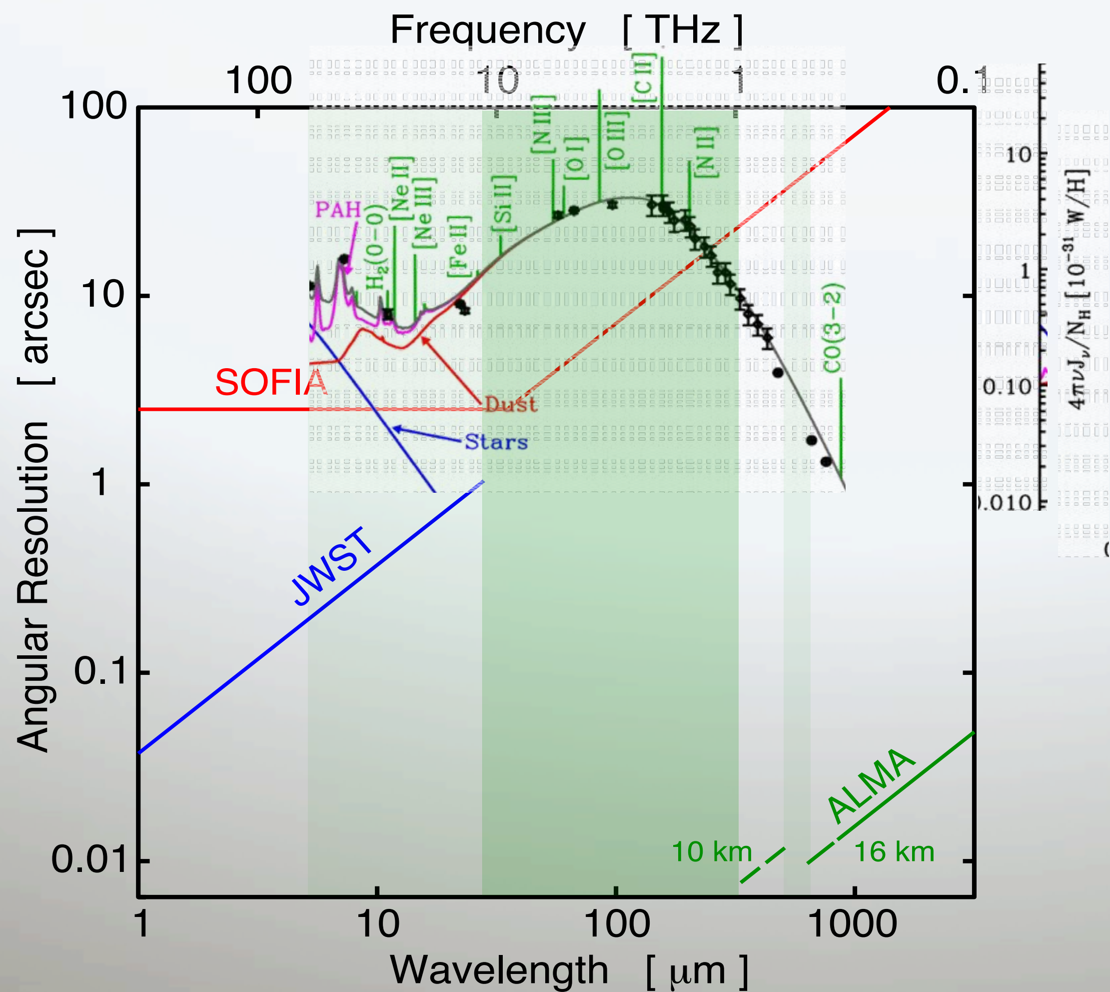
Cycle 6 Call for Proposals

- Standard
- Impact/ Joint Impact
- Thesis Enabling Program - New
  - Enabling PhD thesis research “based in a substantial part” on SOFIA observations.
  - If accepted, place in the “Priority 1” category
  - Grant funding
    - Up to 2 yrs of fully burdened grad. student cost plus travel support; bounded by $100k per year)
- SOFIA Survey
  - Include additional visual guidance to under-represented areas of the sky in CfP - New
- ToO

Preparing for the Senior Review 2019

- Formulate the most important science accessible to SOFIA based on NASA's vision => "Origins"
- Define how SOFIA can uniquely address this science or uniquely contribute important pieces in synergy with other observatories
- Must make investments and prioritize efforts to focus on the science themes that SOFIA can do well and can do uniquely => filling gaps between JWST & ALMA
- Must restrict the suite of instruments offered

Wavelength Gap between JWST and ALMA



SED of LMC, based on data from Spitzer, IRAS and FIRAS (F. Galliano)

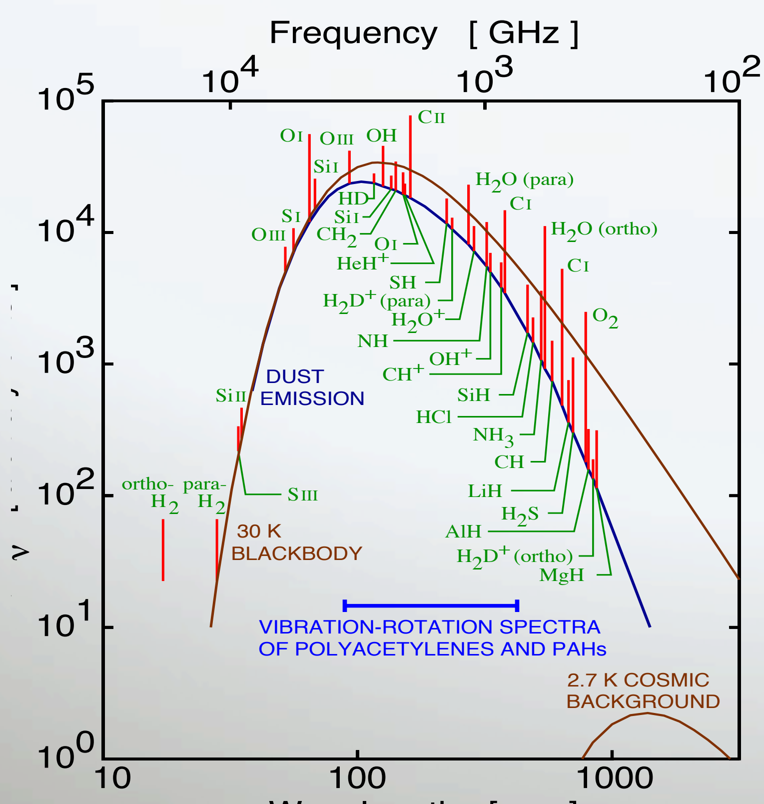
JWST will offer unprecedented resolution and sensitivity from long-wavelength (orange-red) visible light to the mid-infrared (0.6 to 28 μm).

ALMA offers ~0.01 arcsecond resolution in its highest frequency bands. Band 10 (planned) will extend to 950 GHz (≈ 320 μm).

SOFIA is the only telescope that currently operates in 28-320 μm wavelength range.

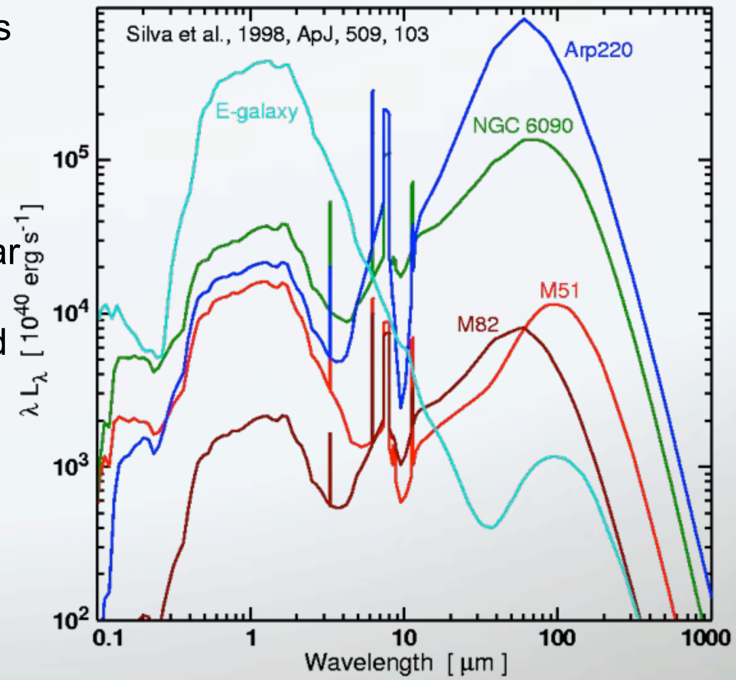
There is great science potential for observing in ALMA-JWST gap.

Emission from Star Forming Regions

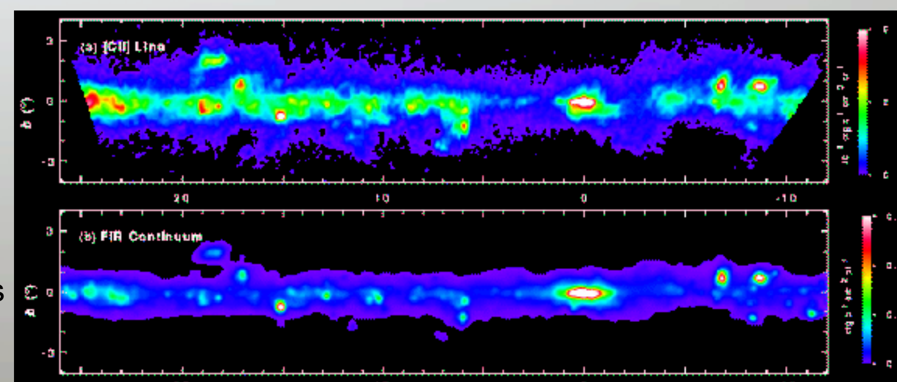


Emission from a star forming region (~70K) with spectral lines imposed on the dust continuum.

Dusty galaxies emit mostly in the Far-IR. These wavelengths probe their star formation properties and evolution



C+ at 158 µm, the strongest cooling line in the ISM. BICE Galactic maps of C+ at very low spectral resolution (top) and dust emission (bottom).



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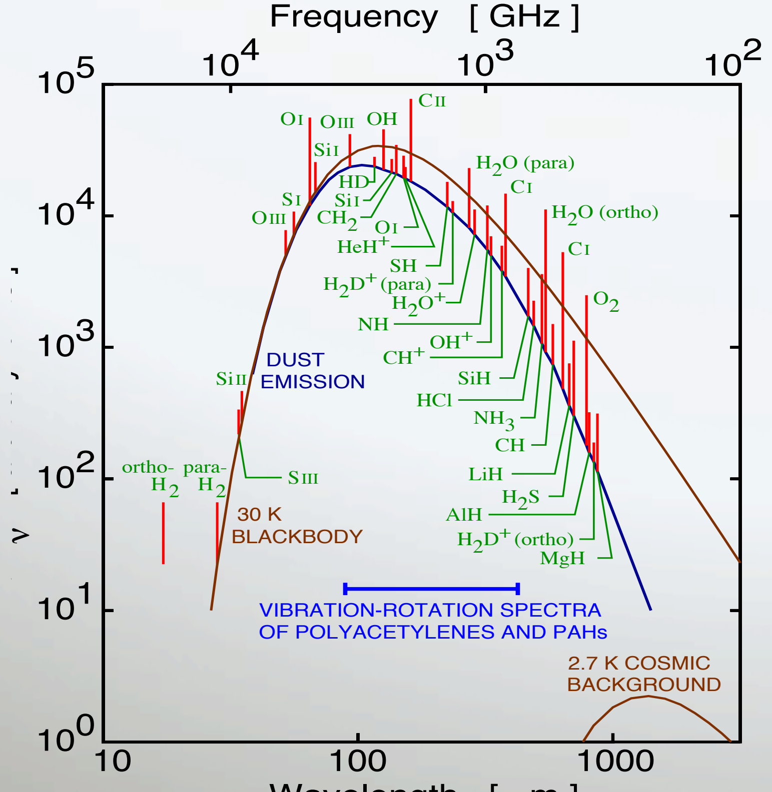

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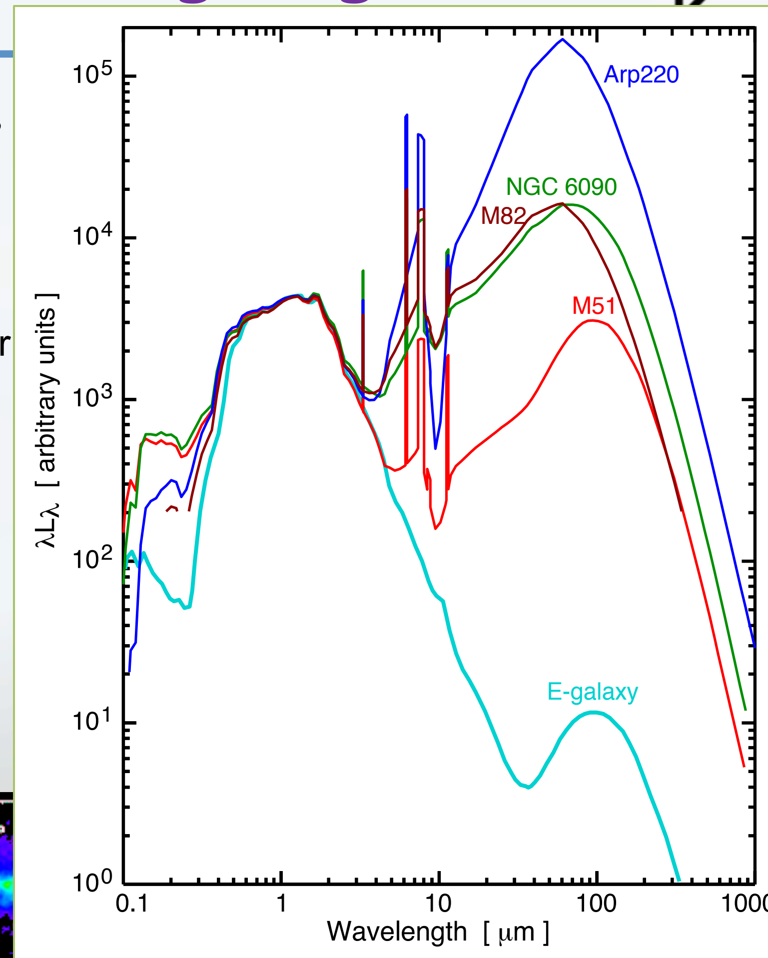

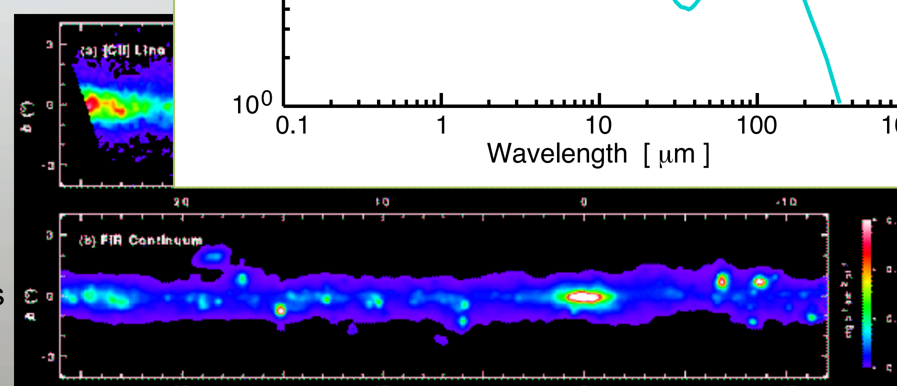

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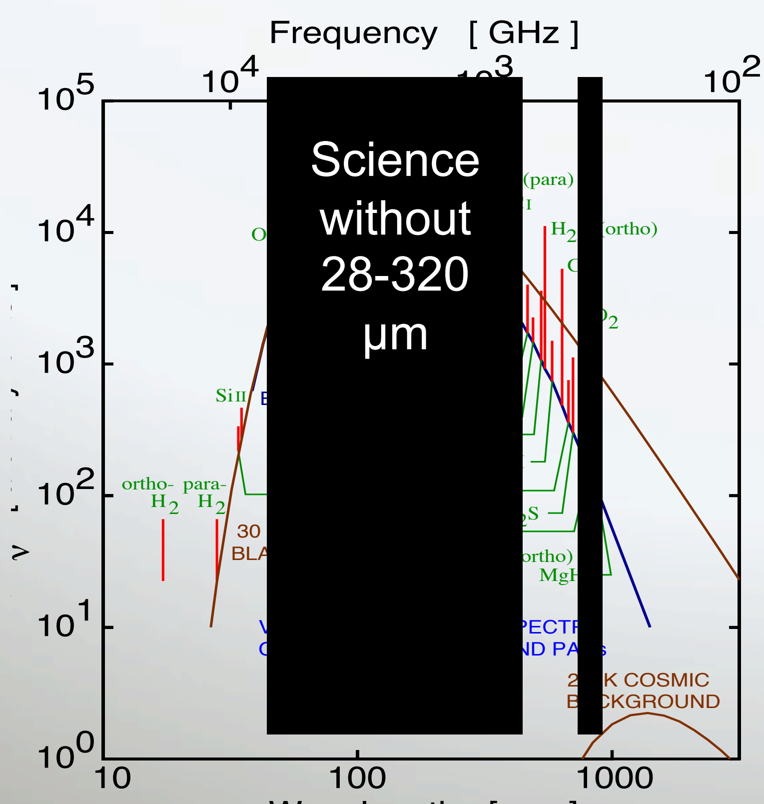

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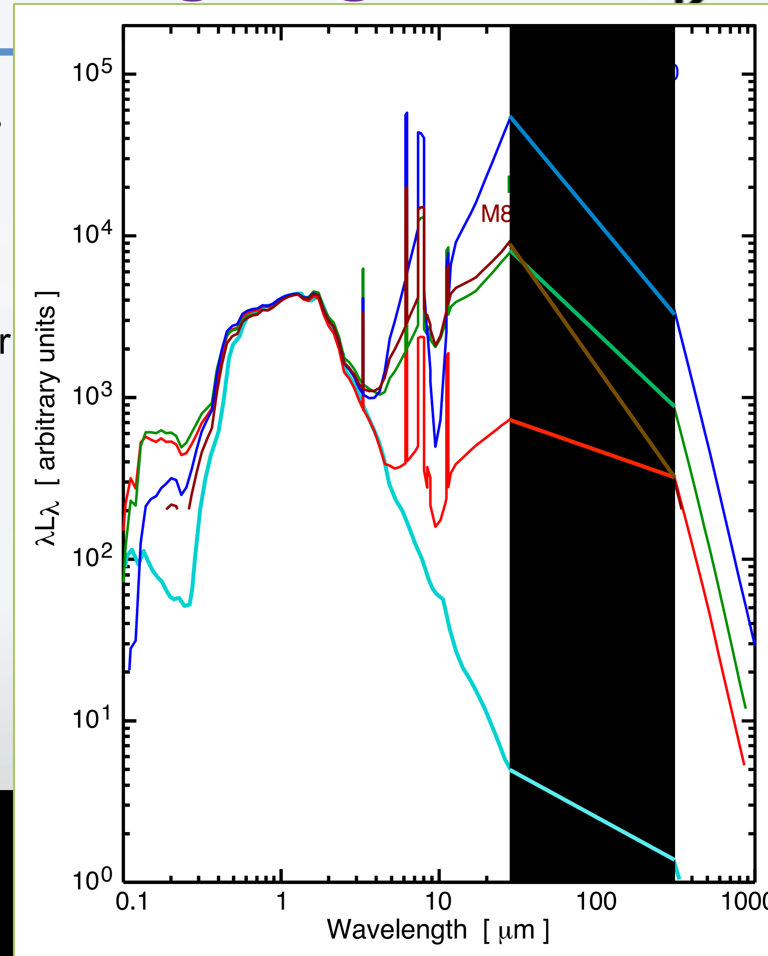

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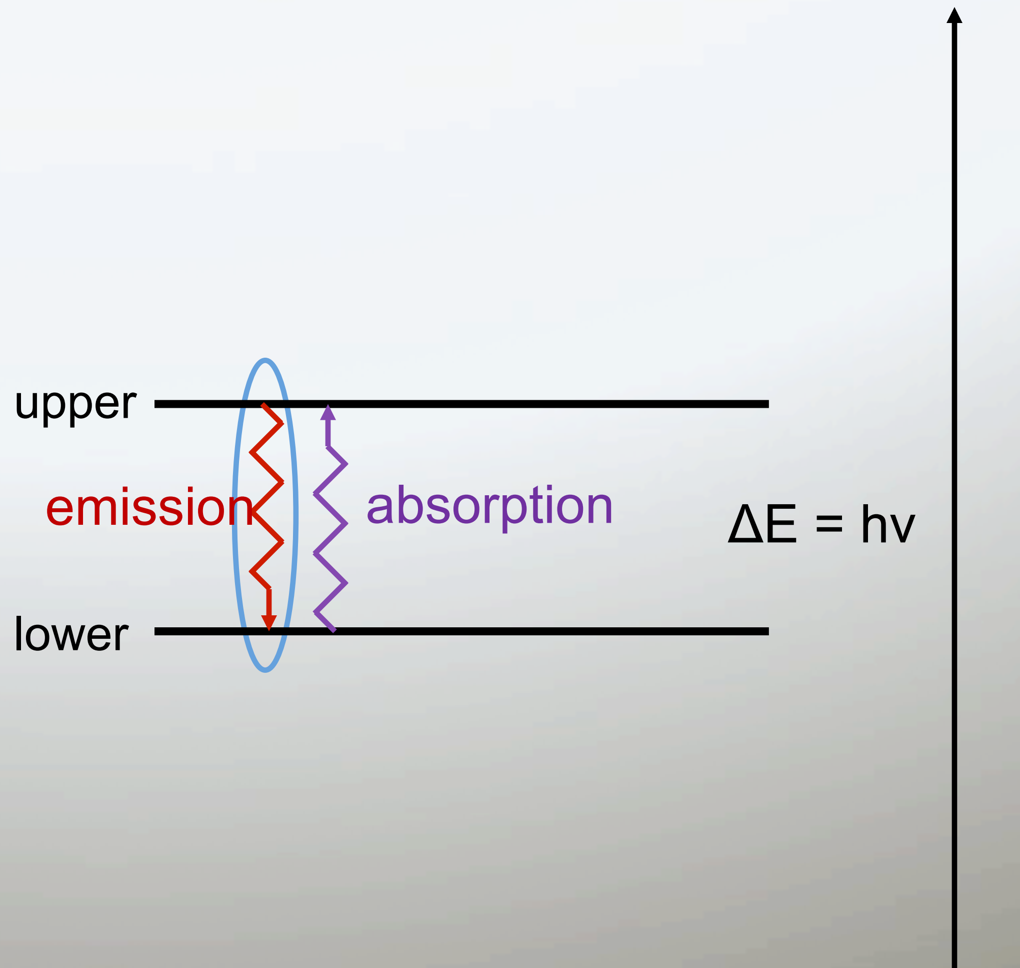
[redacted]

Why (high resolution) Spectroscopy?

- $R=10^5$ gives 3km/s velocity resolution
- Different species appear in different environments
- Need many different transitions to characterize environments



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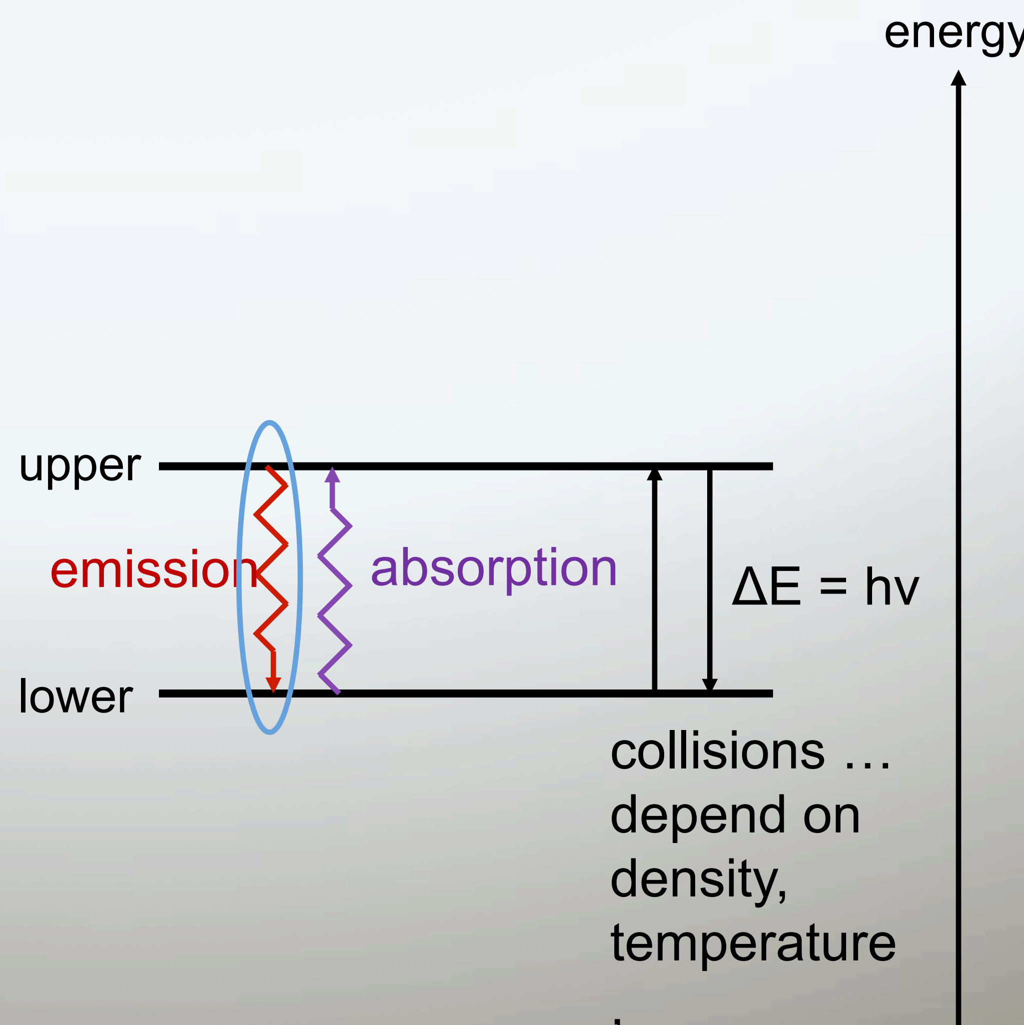

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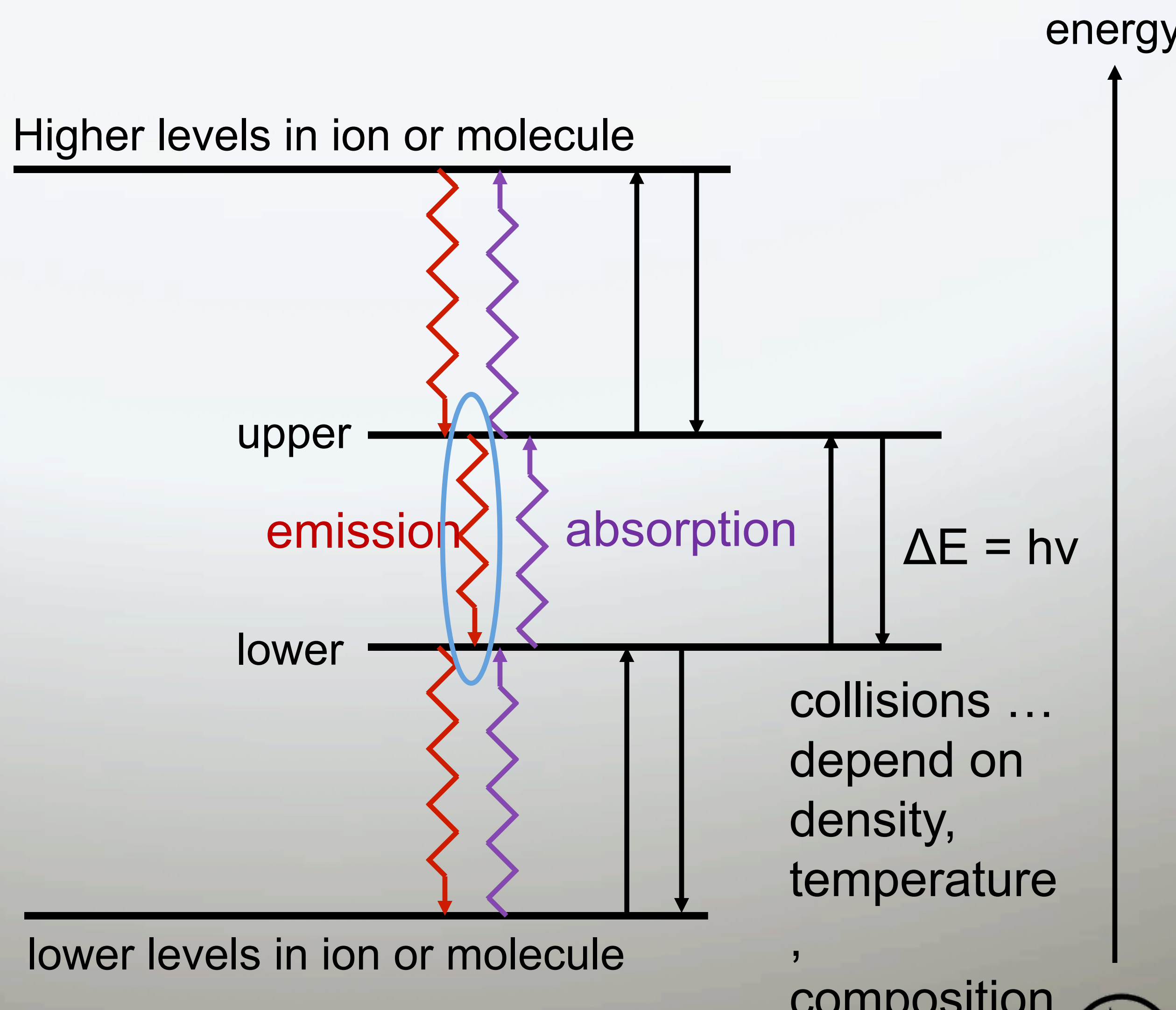

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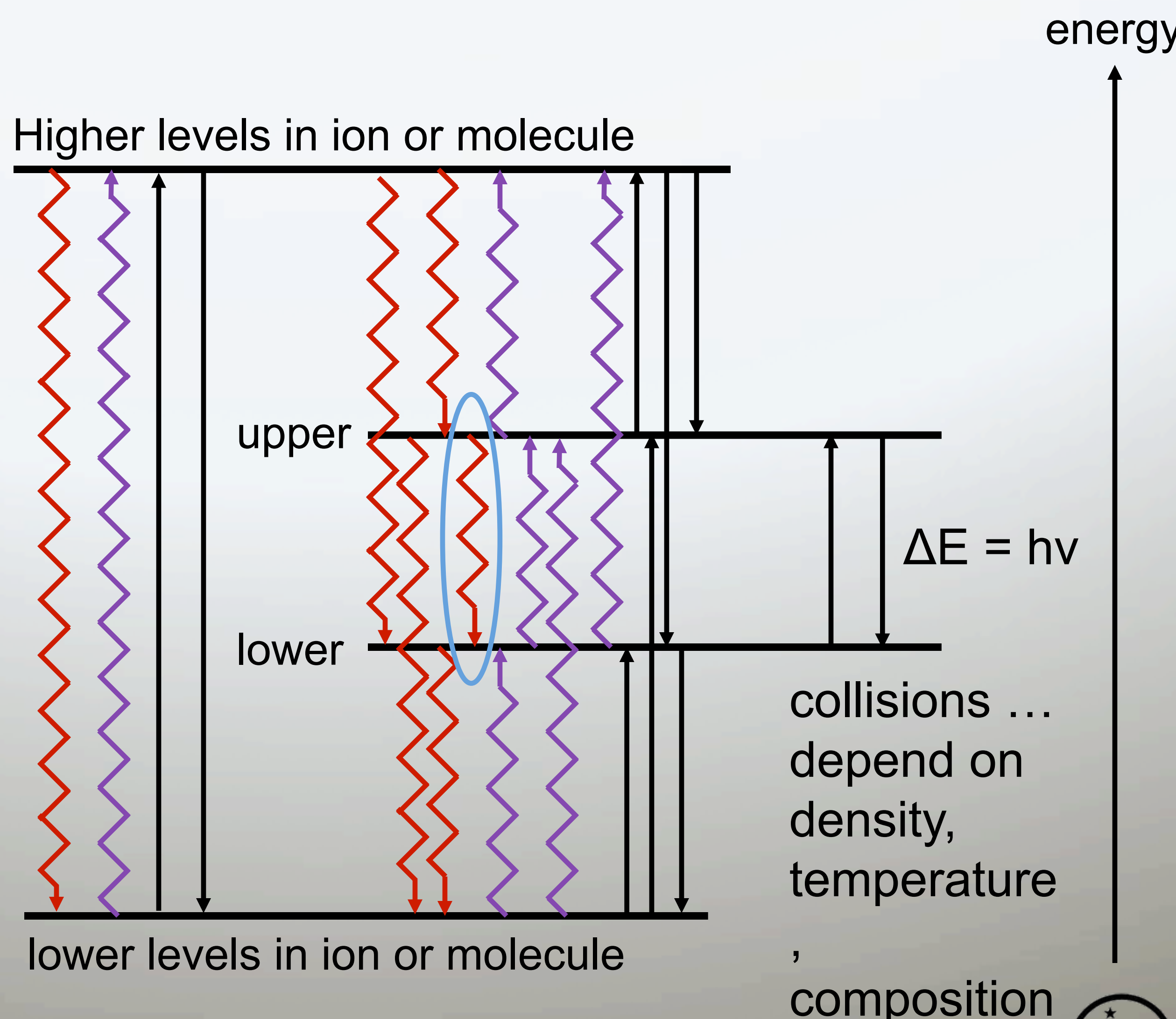
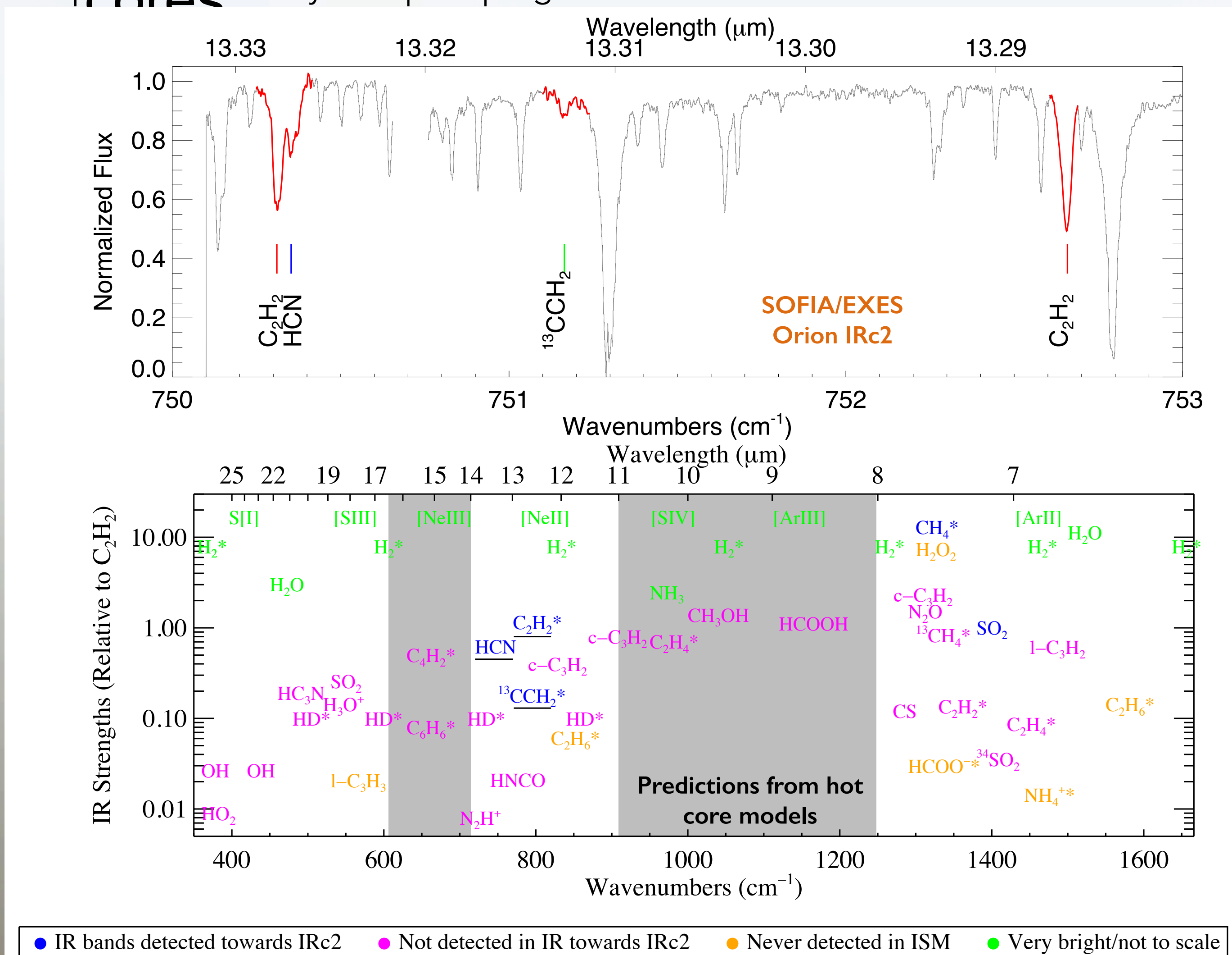


Unbiased molecular line survey in star forming regions

- EXES High-Resolution Molecular Line Survey towards hot cores

Spectrum from Cycle 3 pilot program toward IRc2



Unique data set covers fundamental ro-vibrational bands of key organic species and provides a new view of the organic inventory of these regions.

Likely molecules from hot core models

05_0043 Rangwala
05_0041 Tielens

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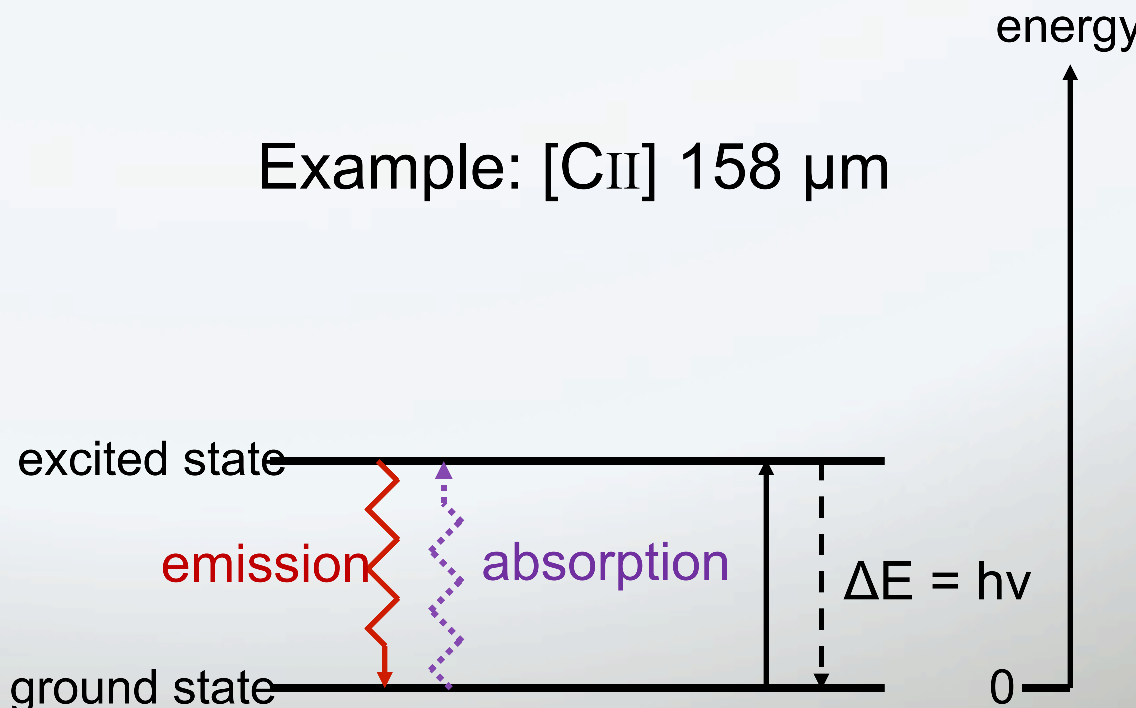
Example: [CII] 158 μm



collisions … depend on density, temperature , composition etc.

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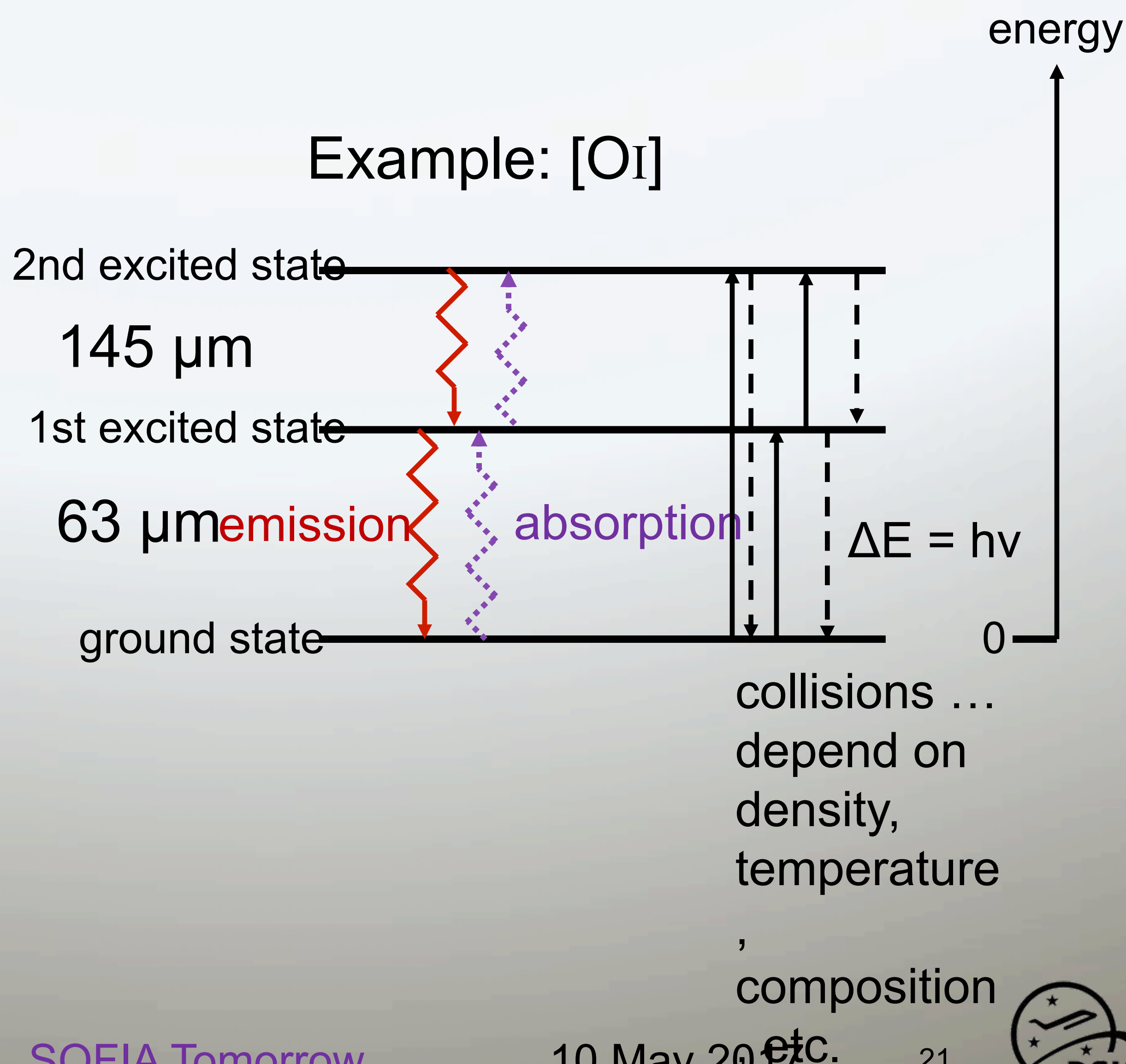
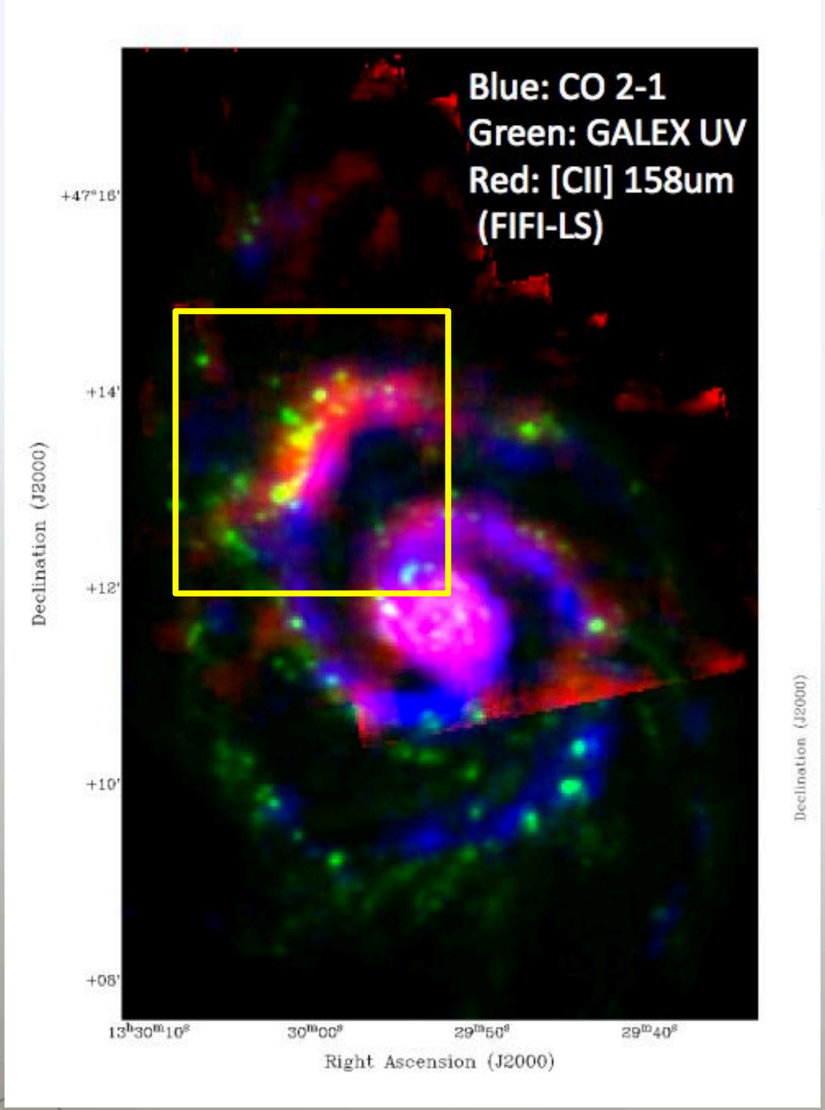
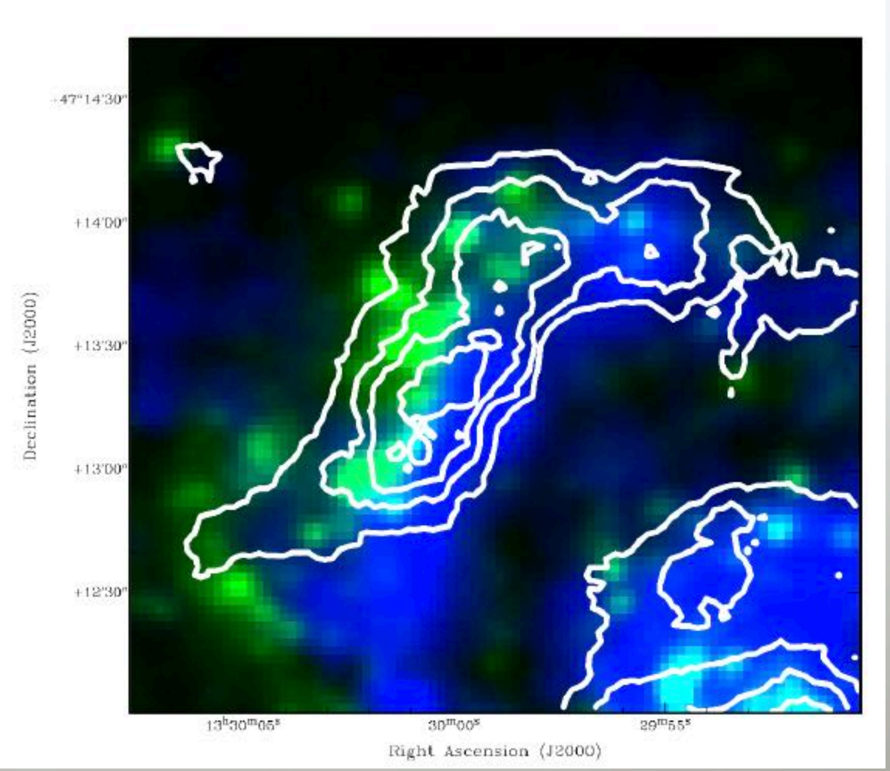


CII Cooling in M51



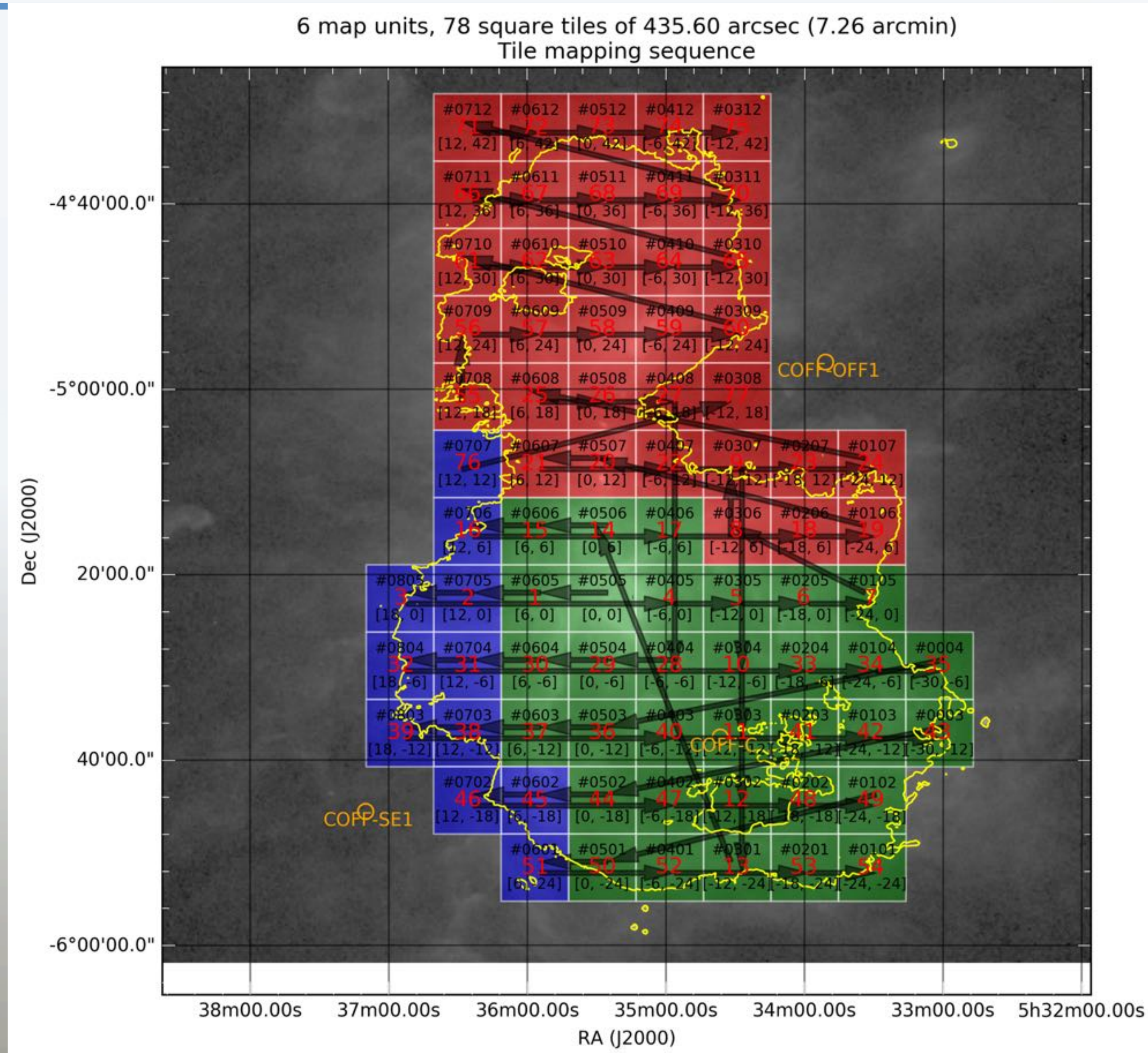
Here [CII] is shown with contours overlaid over the dense gas (blue) and hot stars (green)



Pineda, J. et al, 2017 in prep.

upGREAT C+ Map of Orion

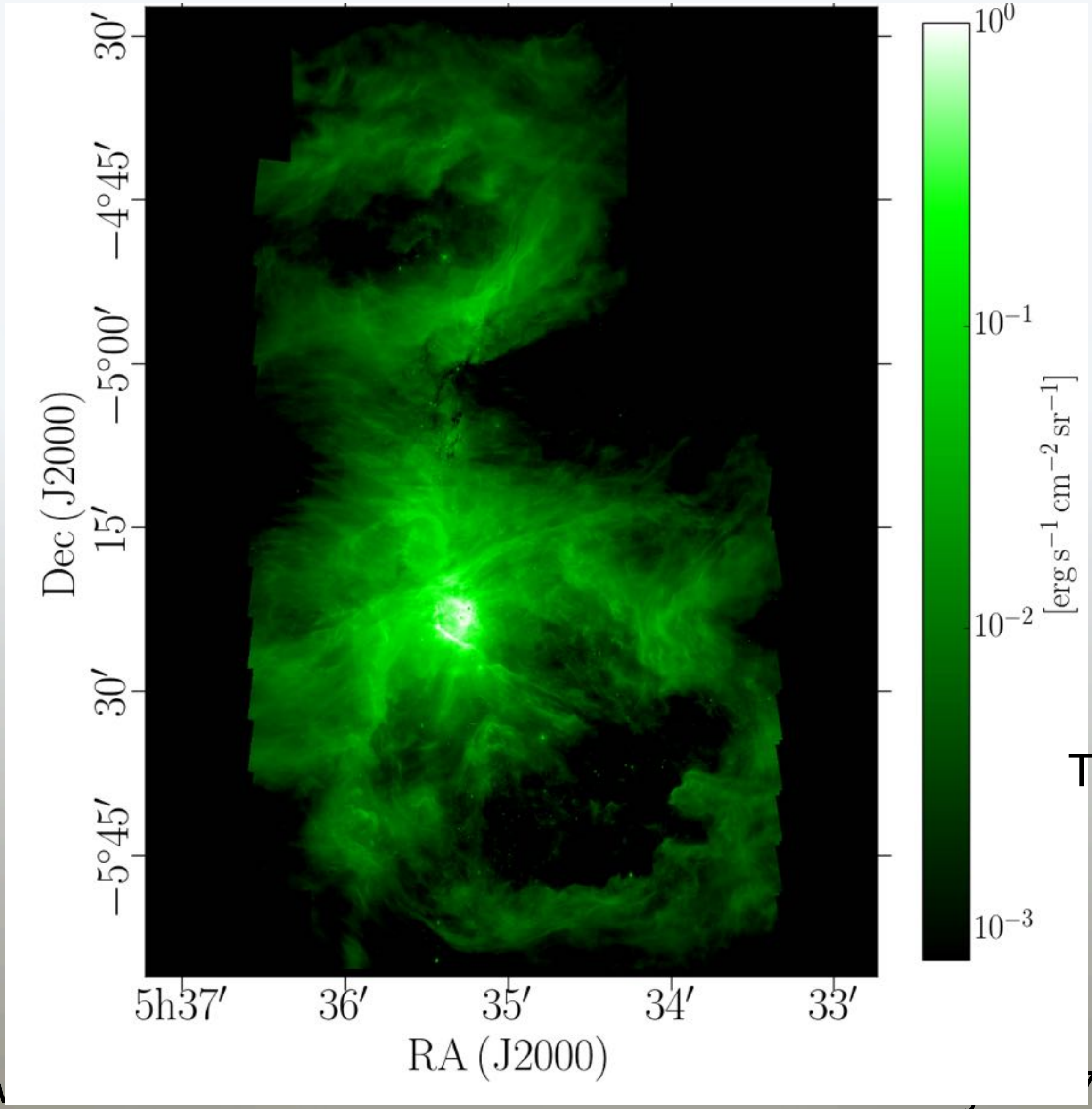
- Cycle 4 Impact program
- PI (Tielens) showed movie of C+ emission while moving through velocities (Ringberg)
- GO requested modification of observing plan to take advantage of efficient observing strategies and map larger region
  - Approved and executed
  - Subject of several PhD theses



Orion Nebula in Visible

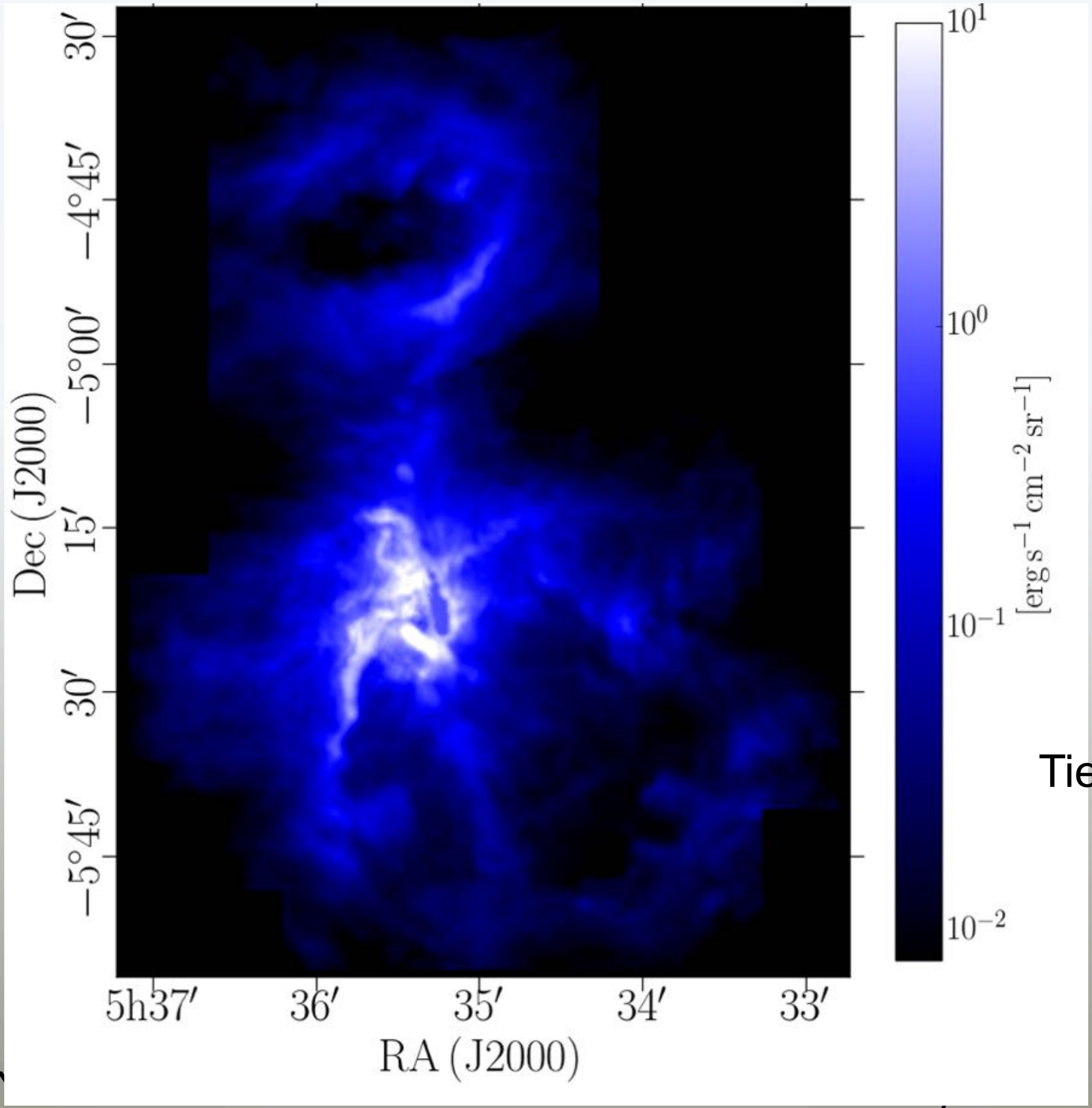
Brian Davis

Spitzer IRAC/8um PAHs



Tielens & C+Squad

Herschel PACS/70um dust



Tielens & C+Squad

SOFIA upGREAT @ [CII] 158µm

Central bright PDR associated with the HII region

C+ provides unique velocity information not present in other tracers

Embargoed

Northern bubble blown by radiation pressure on dust associated with the NGC 1973, 1975, 1977 area

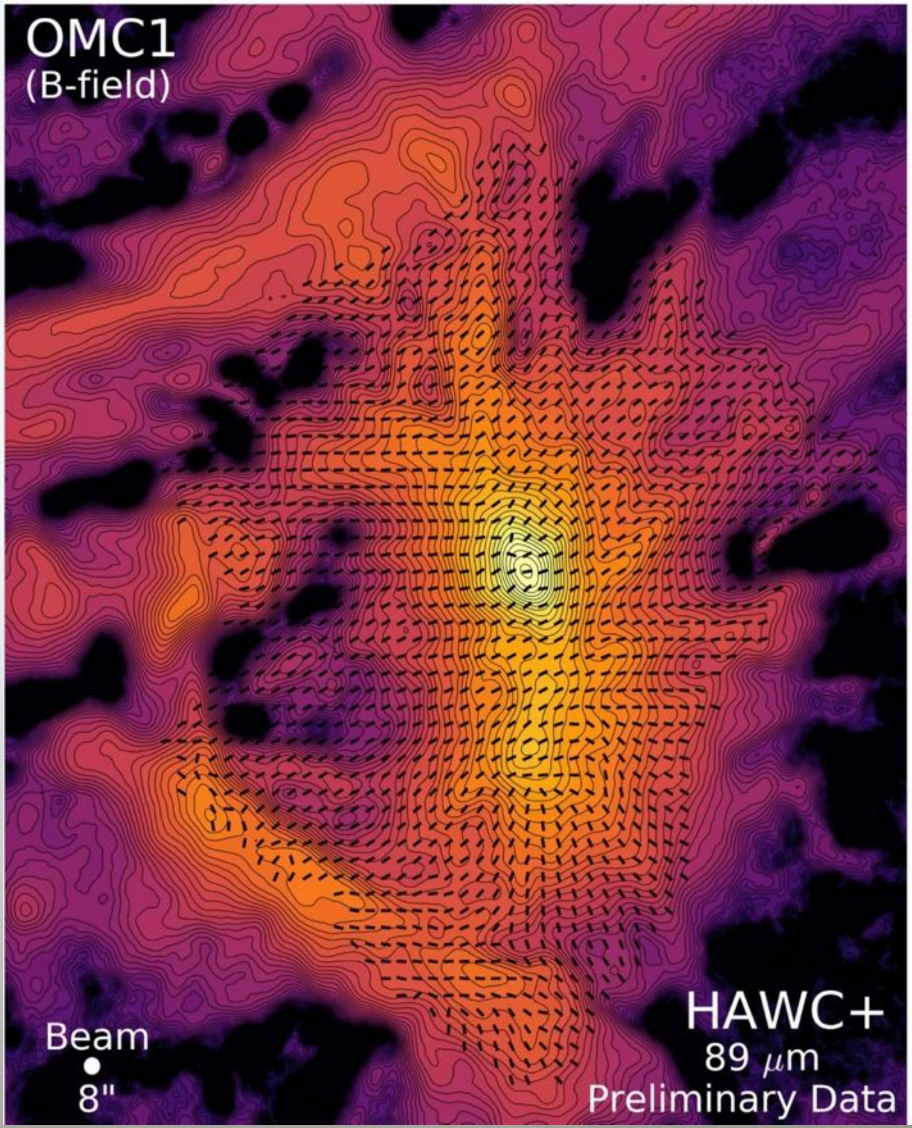
Kinematic & morphological structures associated with HH objects & YSOs

Tielens & C+Squad

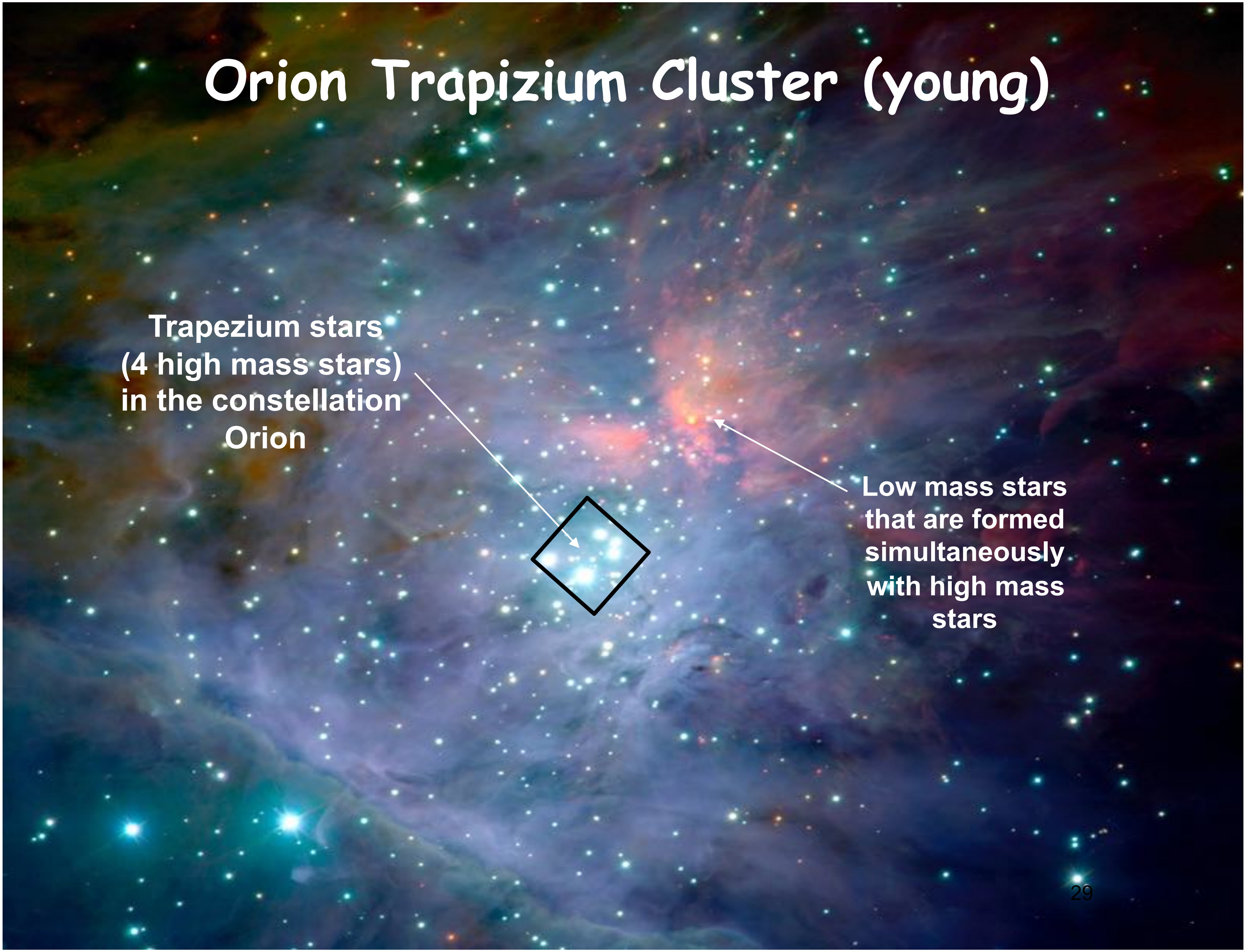
Large scale, wind-blown, stellar bubble to the South

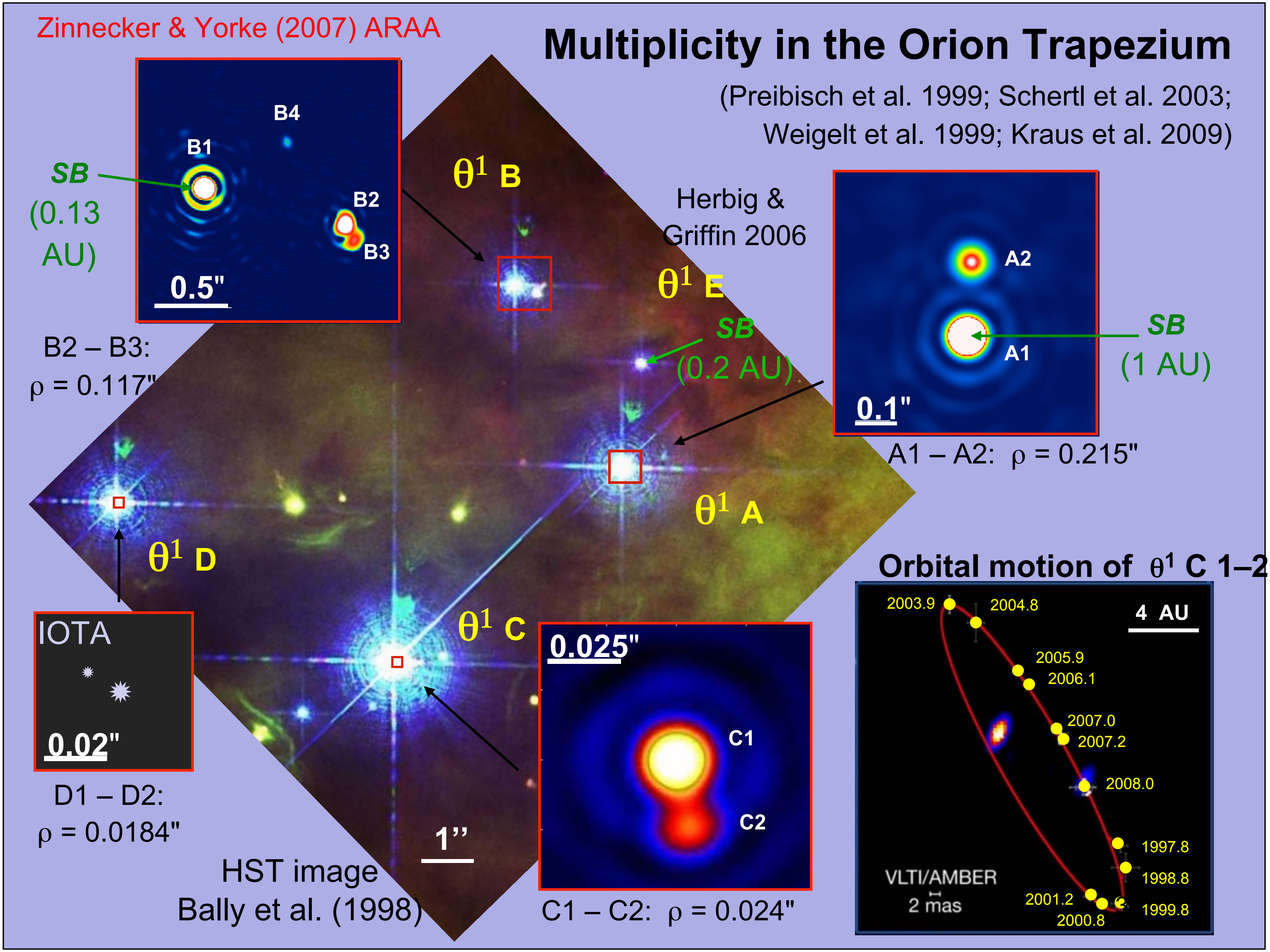
Orion Again – Magnetic Fields

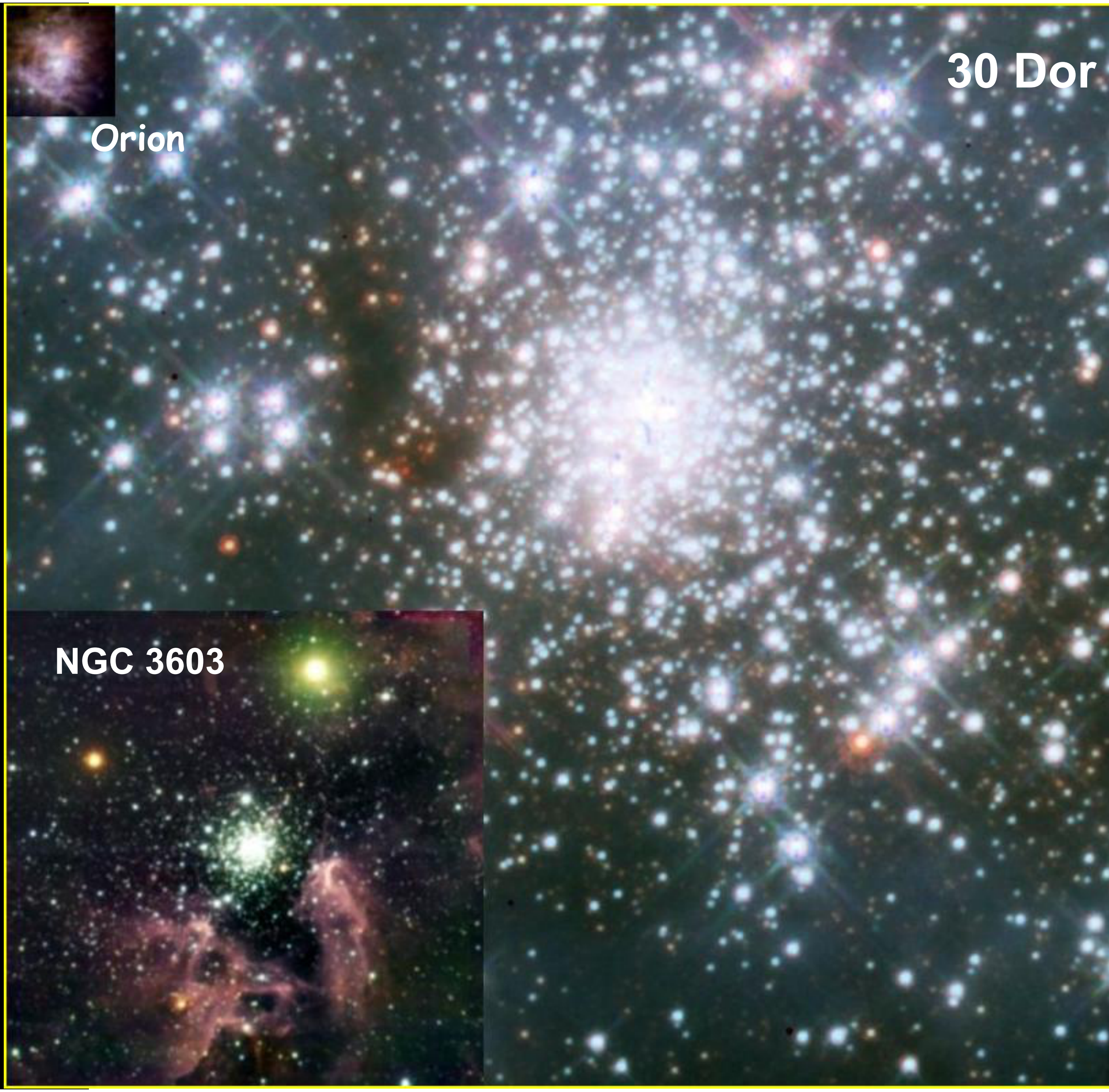
- Recently commissioned HAWC+ adds the capability of observing polarization in the Far-IR
- Far-IR polarization of thermal radiation is due to emission of aligned dust grains, whereas Near-IR polarization has the component of scattered light.
- Far-IR gives the orientation of magnetic fields



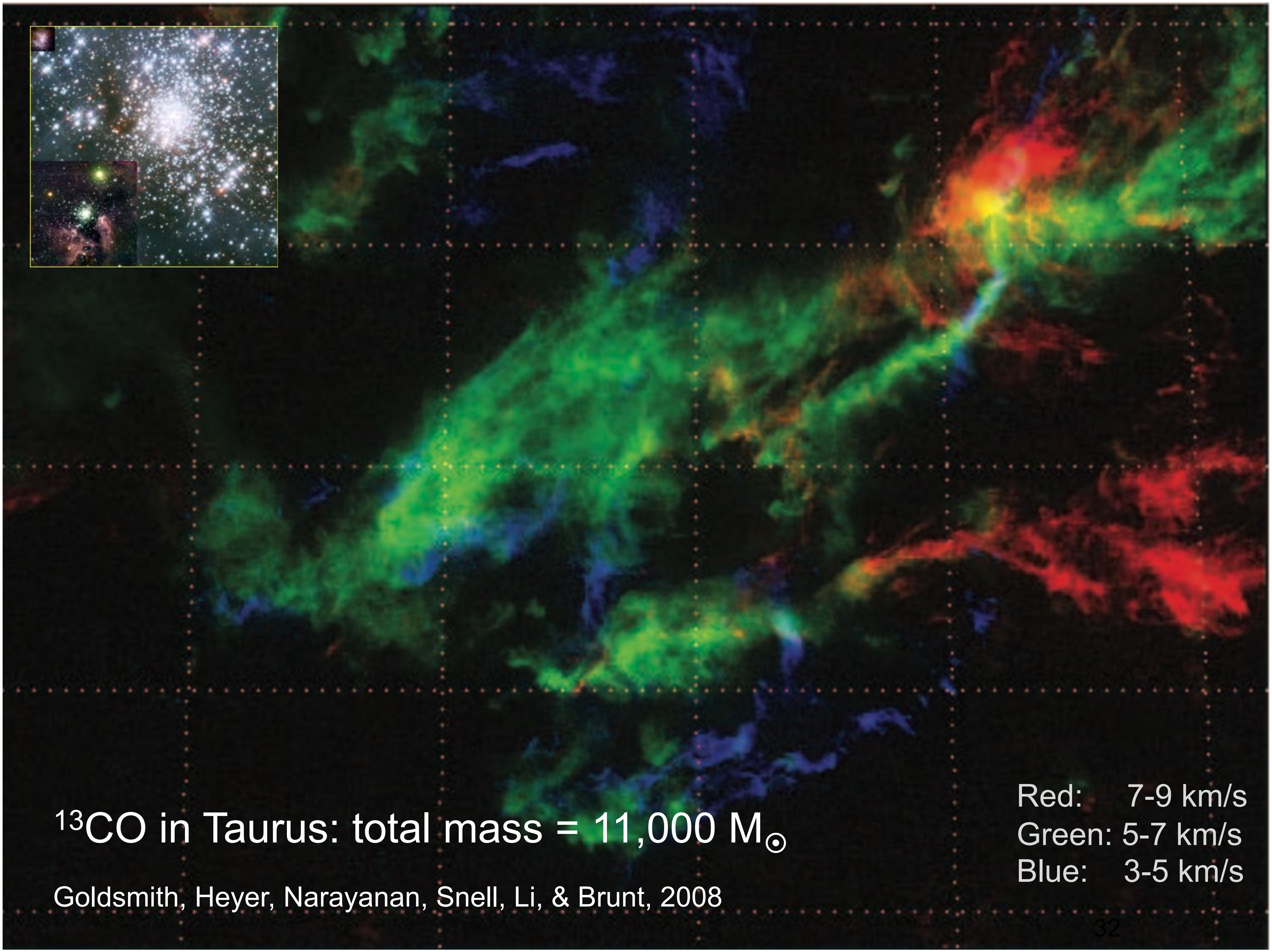
Orion Trapizium Cluster (young)




Zinnecker & Yorke (2007) ARAA
Multiplicity in the Orion Trapezium
(Preibisch et al. 1999; Schertl et al. 2003;
Weigelt et al. 1999; Kraus et al. 2009)
B4
B1
SB
(0.13
AU)
B2
B3
0.5"
B2 – B3:
ρ = 0.117"
θ1 B
Herbig &
Griffin 2006
θ1 E
SB
(0.2 AU)
A2
A1
SB
(1 AU)
0.1"
A1 – A2: ρ = 0.215"
θ1 A
θ1 D
IOTA
0.02"
D1 – D2:
ρ = 0.0184"
θ1 C
0.025"
C1
C2
C1 – C2: ρ = 0.024"
1''
HST image
Bally et al. (1998)
Orbital motion of θ1 C 1–2
4 AU
2003.9
2004.8
2005.9
2006.1
2007.0
2007.2
2008.0
1997.8
1998.8
1999.8
2001.2
2000.8
VLTI/AMBER
2 mas



Zinnecker &
Yorke 2007

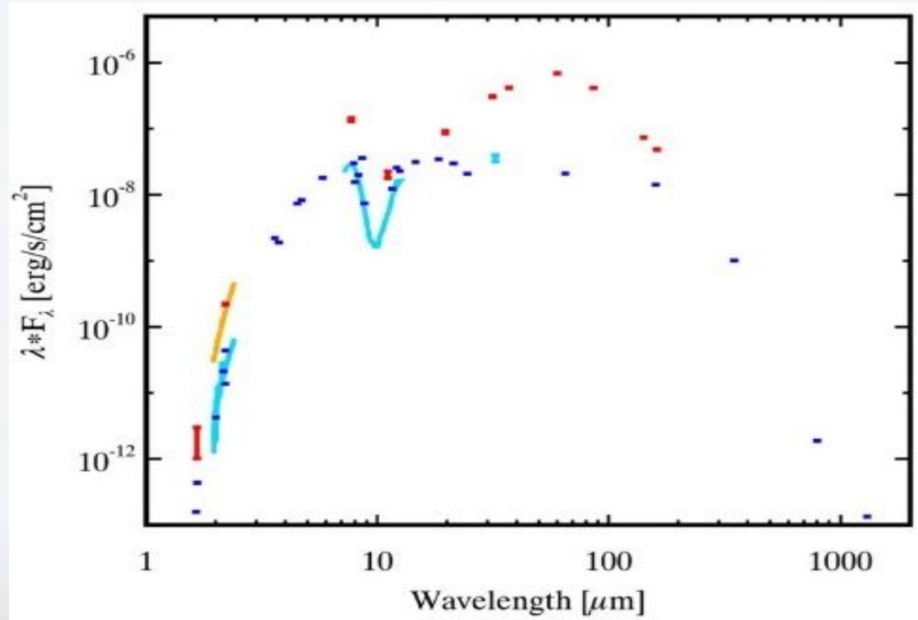

^{13}CO in Taurus: total mass = 11,000 $M_\odot$
Goldsmith, Heyer, Narayanan, Snell, Li, & Brunt, 2008
Red: 7-9 km/s
Green: 5-7 km/s
Blue: 3-5 km/s
32

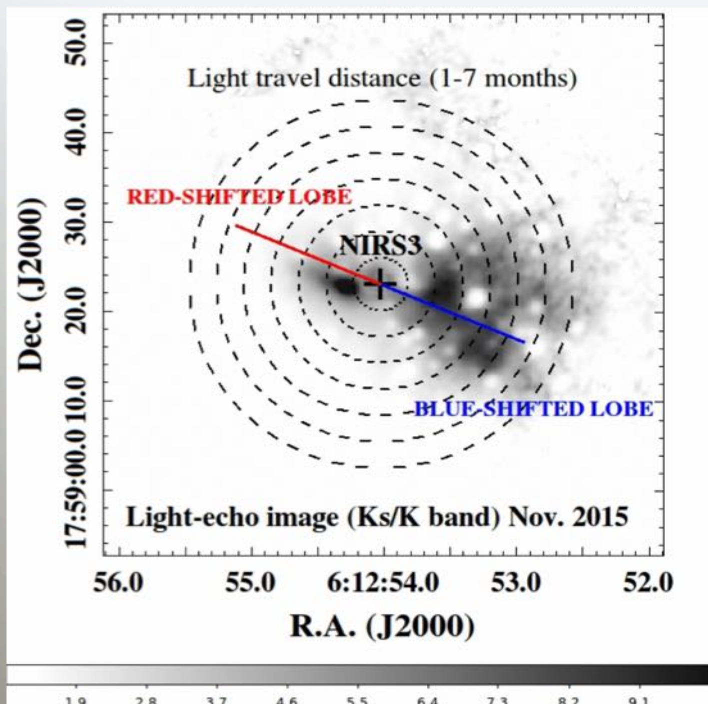
Formation of Massive Stars: Growth of stellar mass by accretion

- Molecular core non-homologous collapse produces several-Jupiter-mass objects (=protostars) that subsequently accrete material
- These protostars contract on Kelvin-Helmholtz time scale t_{KH} towards H-burning (and main sequence), while still accreting material from their surrounding disk as the disks accrete material from molecular cloud
- At high accretion rates, an accreting protostar bloats up and cools down ($t_{KH} > t_{acc}$)
- Short accretion bursts can cause significant long-term bloating
- Once on the main sequence massive stars copiously emit hard UV radiation and photoevaporate disks in the vicinity.
- Holy Grail of star formation: Observing accretion onto protostars
- What prevents, what initiates star formation?
- Role of magnetic fields still unclear

Disk-mediated accretion burst in a high-mass YSO

SOFIA data of S255IR NIRS 3 obtained using FORCAST (at 7.7, 11.1, 19.7, 31.5, and 37.1 microns) and FIFI-LS (at 90, 140, and 160 microns), were crucial to derive fundamental parameters of the accretion burst such as the mass accreted during the event and the total energy being released by the burst.





Images taken a few months apart reveal motion of light-echo, from which Caratti o Garatti, et al. (2016, *Nature Physics*) could infer that the burst began in June 2015.

FIFI-LS Field Imaging Far-Infrared Line Spectrometer

FORCAST Faint Object InfraRed CAmera for the SOFIA Telescope

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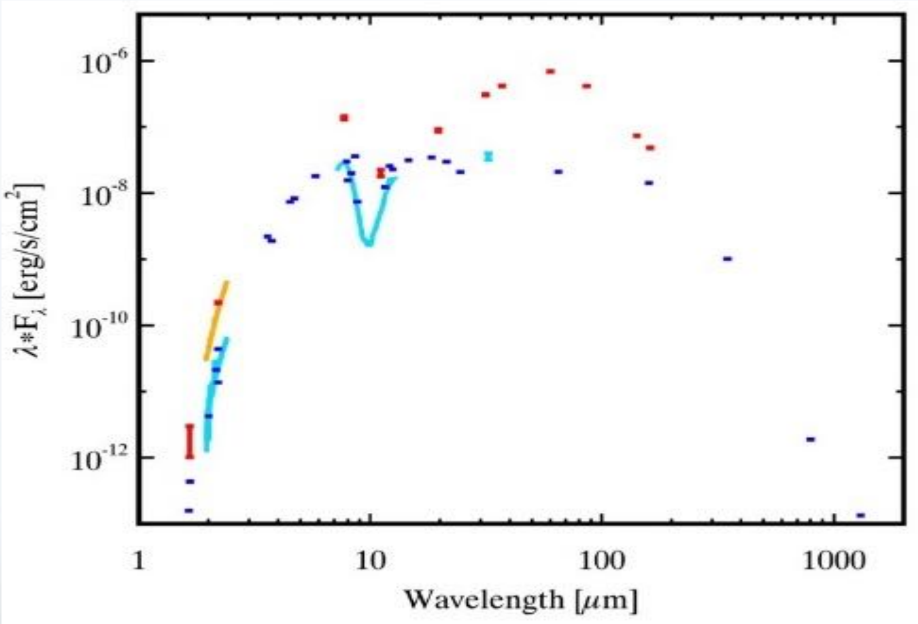

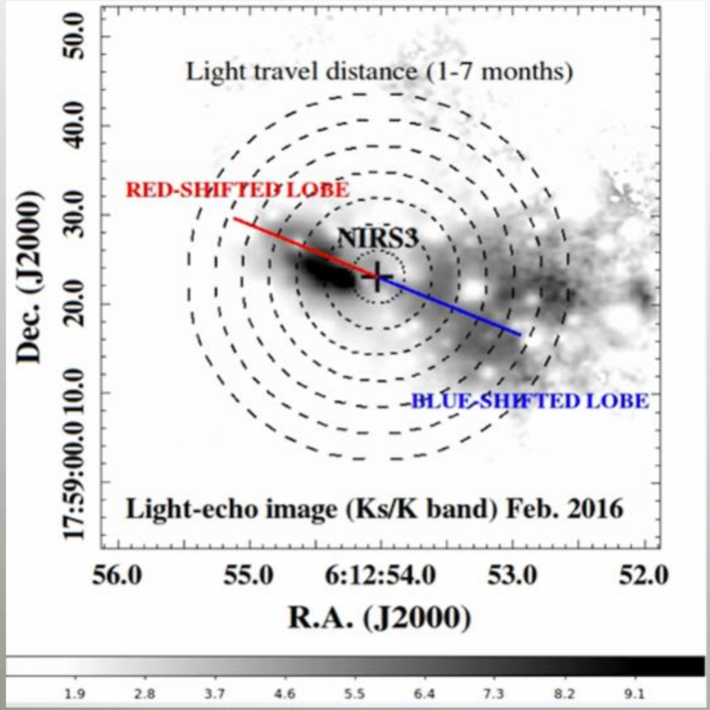

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Why is Far-IR essential for Understanding Astrophysical Processes? (1/2)

General Comments

- Dust continuum emission peaks in the Far-IR/submm at cosmological redshifts $0 < z < 5$
- Many important diagnostic molecular & fine structure lines not available from ground (HD, H_2O/HDO, OH, other hydrids, fs-lines, bending modes of hot complex molecules, high-J CO)
- Far-IR/submm atmospheric "windows" do not permit access to all needed diagnostic lines at any given redshift z
- 8 – 12μm PAH features shift into Far-IR window beyond $z > 2.5$
- Kinematics of astrophysical processes using FIR/submm lines: in young protostars (jets, outflows, & infall), in dust-producing evolved stars, and in molecular clouds, including the Galactic Center region require high resolution spectra
- Astrochemistry of pre-biotic molecules: Understanding the chemical formation networks requires high resolution spectra of a wide variety of molecules and transitions

Why is Far-IR essential for Understanding Astrophysical Processes? (2/2)

Determine the "local truth" before making far-reaching conclusions

- Properties of the interstellar medium (ISM) as a function of location (temperature, density, metallicity, UV radiation hardness and density).
- Star formation rate (SFR) from characteristic Far-IR radiation as a function of location (spiral arms, nuclear starburst, etc...) and of local ISM conditions
- Influence of neighboring galaxies on SFR and ISM properties.
- Calibrate and test different SFR tracers locally

Where is SOFIA's "Sweet Spot"?

- SOFIA is the only observatory in 28 μm – 320 μm range
- With its warm optics SOFIA sensitivity is limited for broad band photometry
  - Optics, support structure, atmosphere contribute to background
  - Fortunately, nature has helped by putting 50% of its energy into the Far-IR
- Can reduce background radiation $F_{\nu}\Delta\nu$ by reducing bandwidth $\Delta\nu$ => high resolution spectroscopy
  - e.g. GREAT (heterodyne), EXES, HIRMES
  - Detailed studies of emission and absorption lines

Future of Far-IR Science?

- For any future Far-IR observatory, including several space-based cryogenic Far-IR observatories under study
  - Far-IR is not militarily or commercially useful
  - Must conceive, develop, build & test detectors and read-out electronics: very little is "off the shelf"
  - Must have a facility that uses detectors in order to develop them
  - Must have a cadre of interested Far-IR scientists and engineers
- For the general science community, SOFIA provides the only access to the Far-IR for some time to come

Ask not what SOFIA can do for you, but what you can do for SOFIA

- It is time for every SOFIA observer to exercise his/her duty to vote.
- For the upcoming Senior Review of SOFIA, two metrics will be important: published papers and proposals for observing time.
- If continuing SOFIA beyond 2019 is important to you, we are asking you to vote with your feet, namely by writing SOFIA papers and proposing to Cycle 6.
- Lots of papers need to be published asap:

  "Vote early and vote often"


Thank You
http://www.sofia.usra.edu