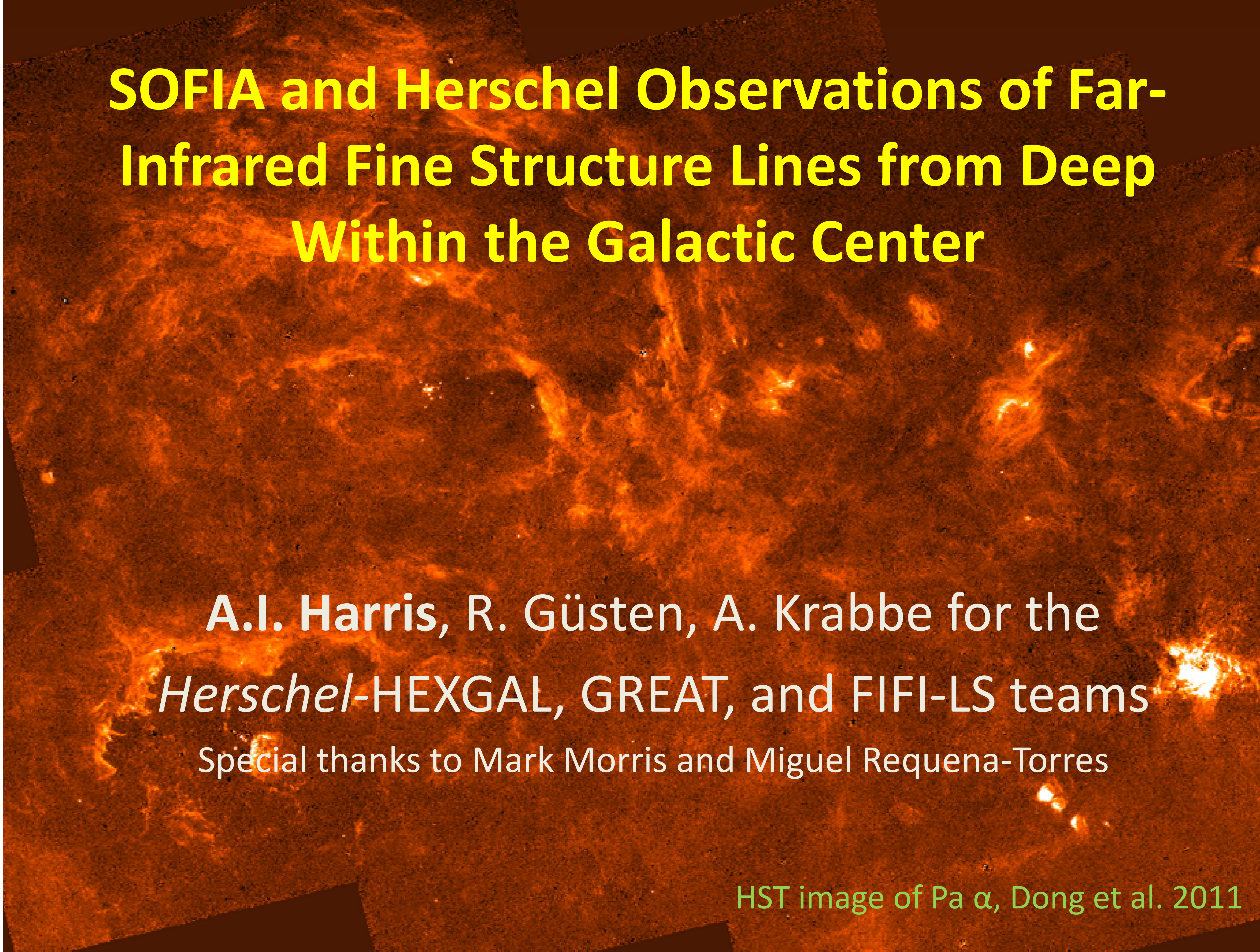
SOFIA and Herschel Observations of Far-Infrared Fine Structure Lines from Deep Within the Galactic Center

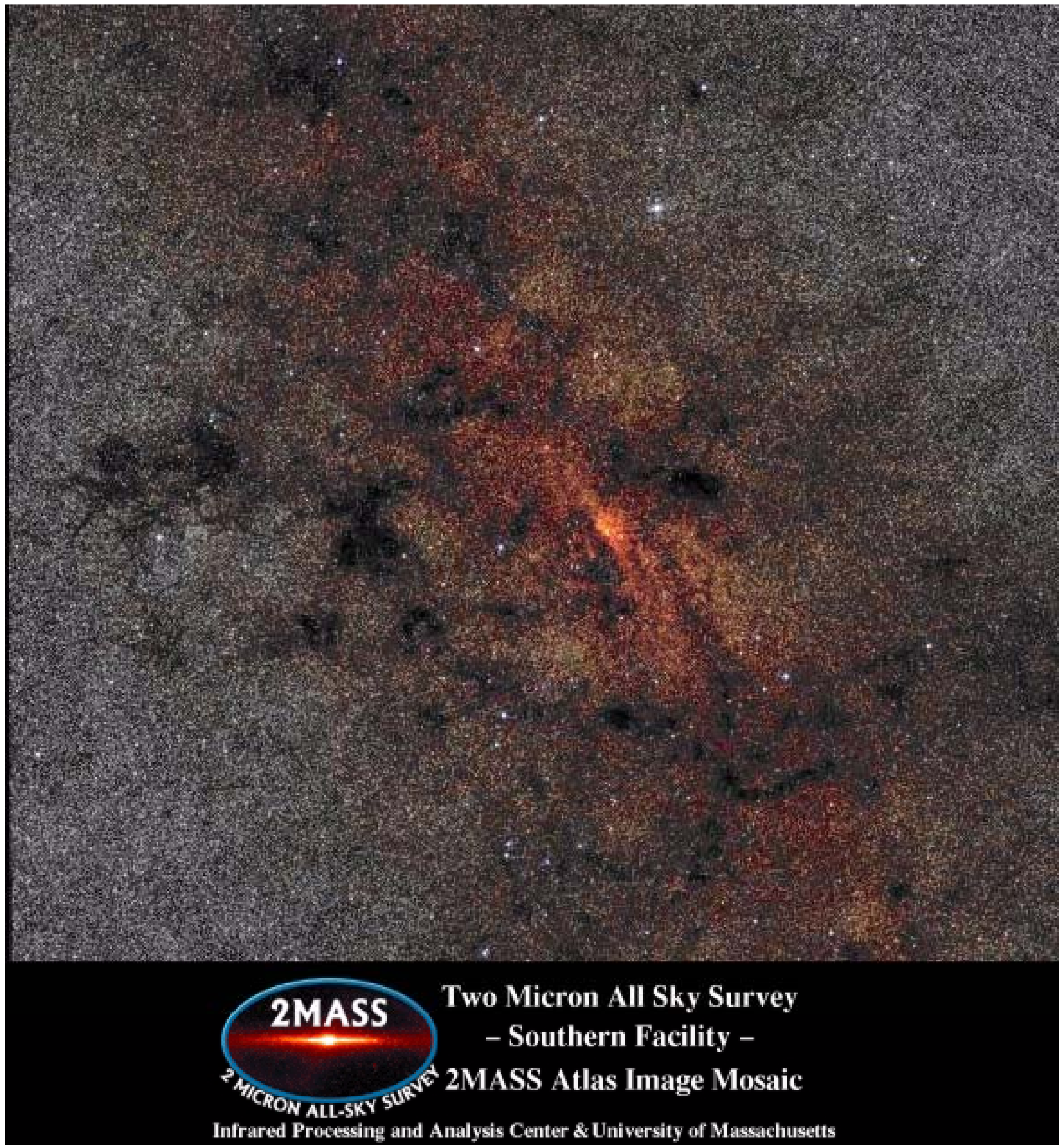
A.I. Harris, R. Güsten, A. Krabbe for the *Herschel*-HEXGAL, GREAT, and FIFI-LS teams

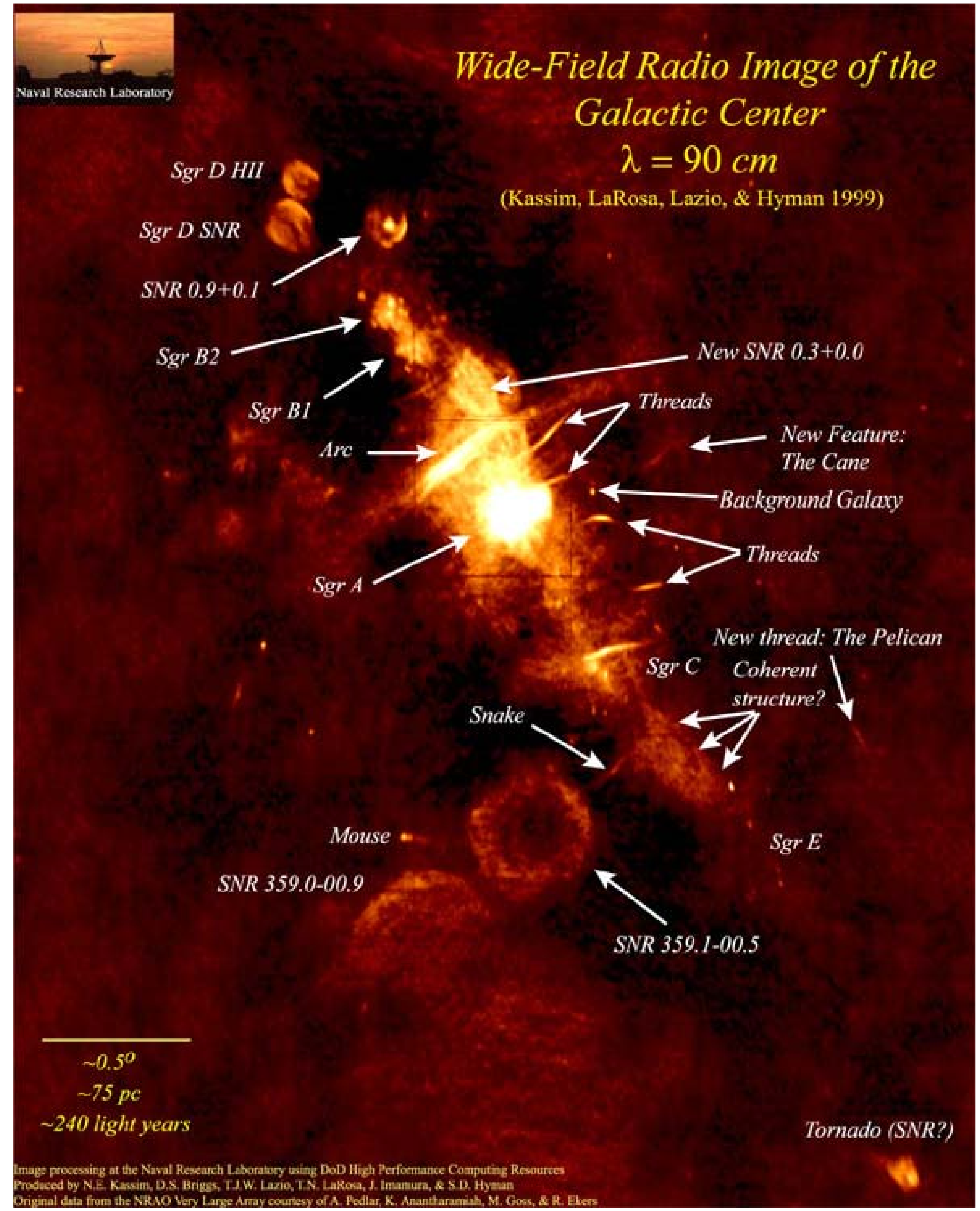
Special thanks to Mark Morris and Miguel Requena-Torres



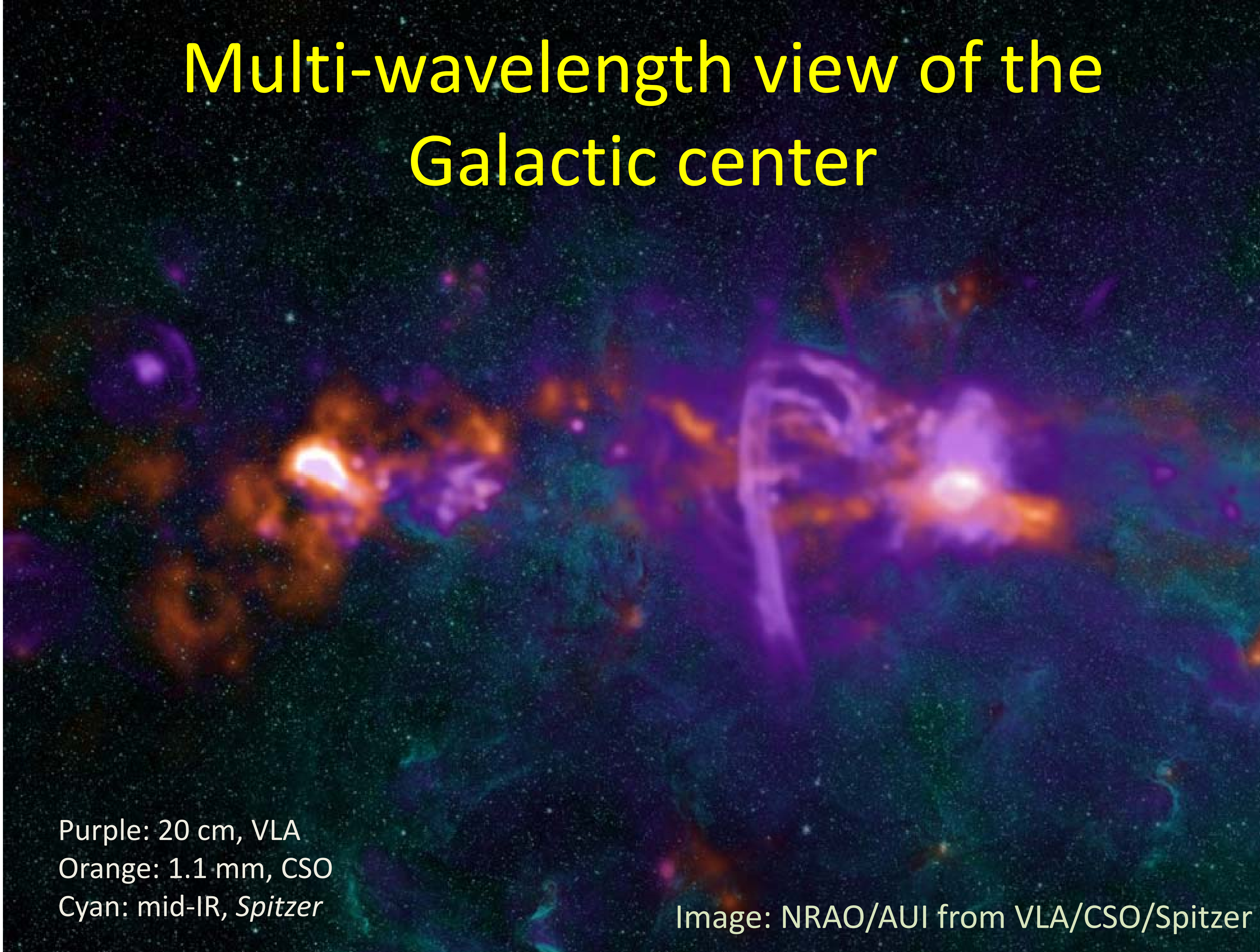
HST image of Pa α, Dong et al. 2011

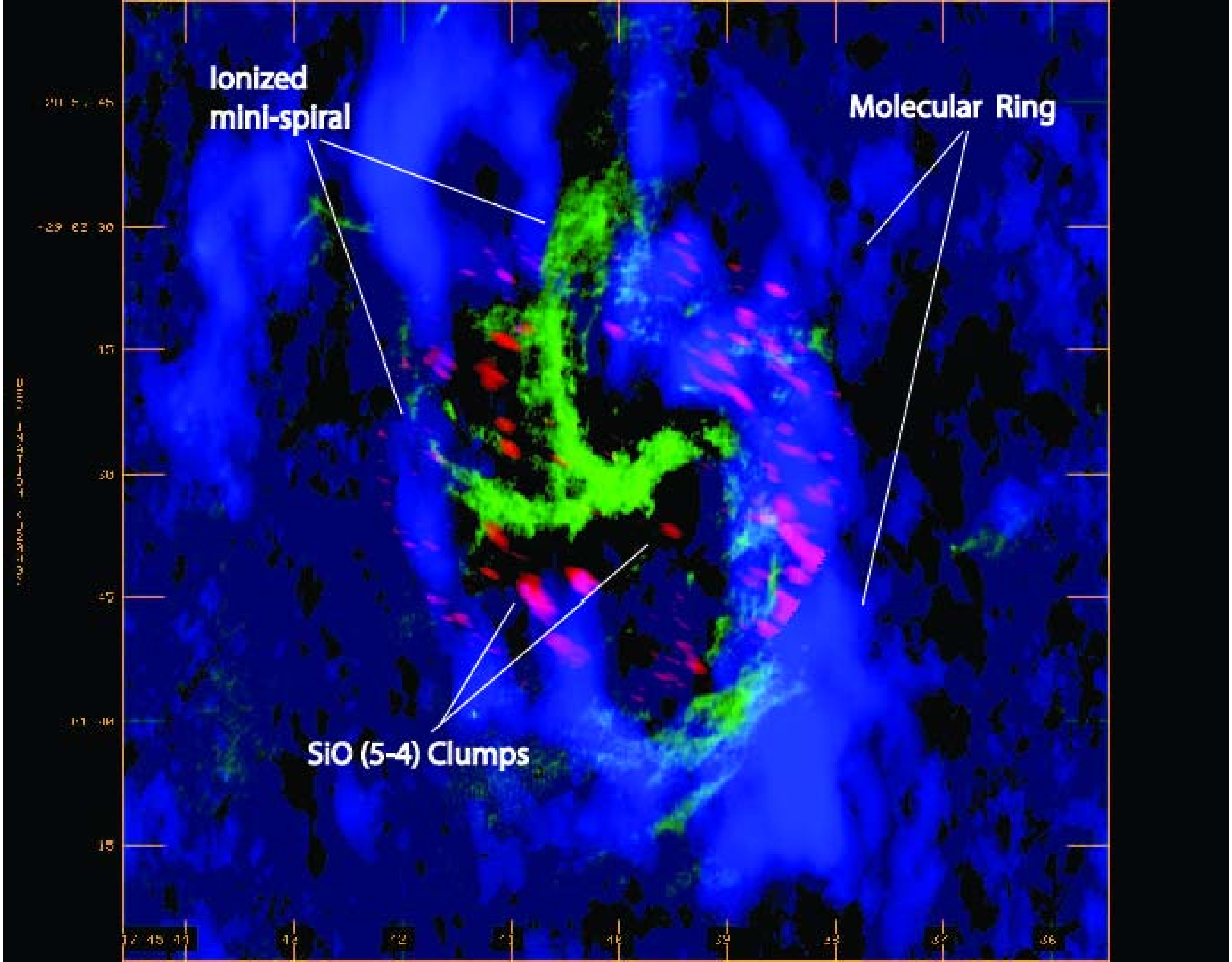
The Galactic center: IR and radio





Multi-wavelength view of the Galactic center




Ionized
mini-spiral
Molecular Ring
SiO (5-4) Clumps

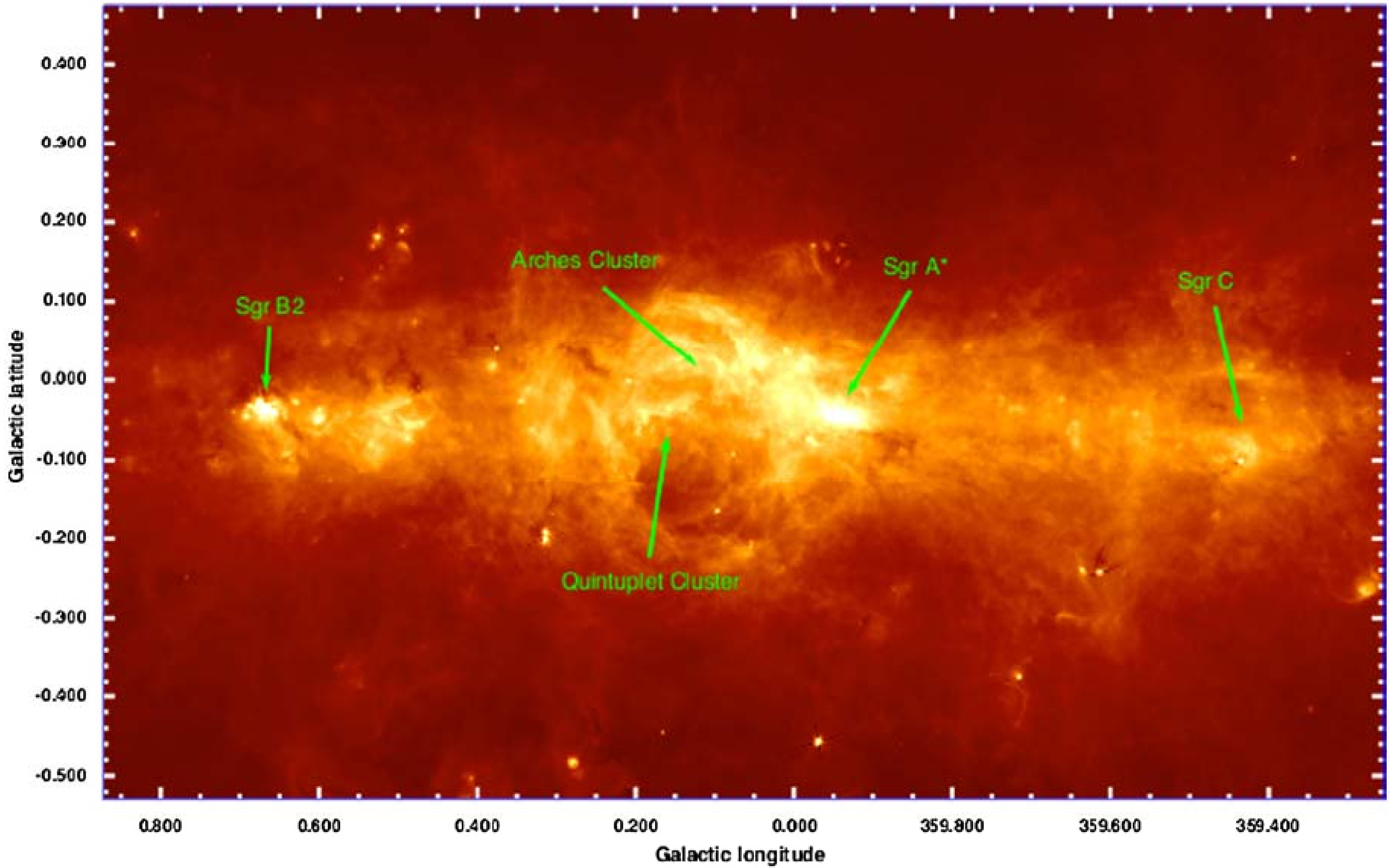
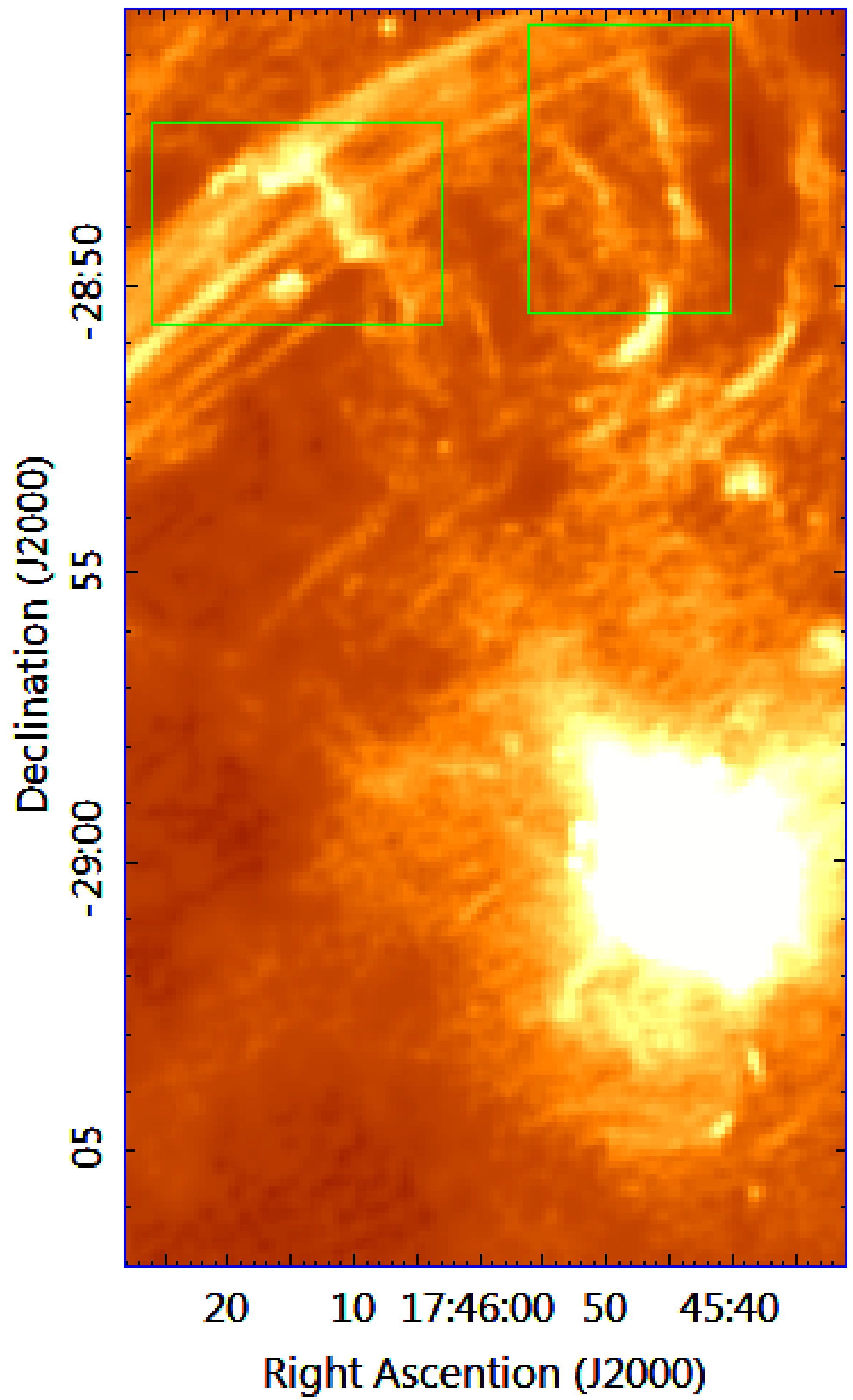


Figure 1. *Herschel* PACS 70 μm image of the Galactic center region. Labels identify known objects that are discussed in the text.

Molinari et al. 2011

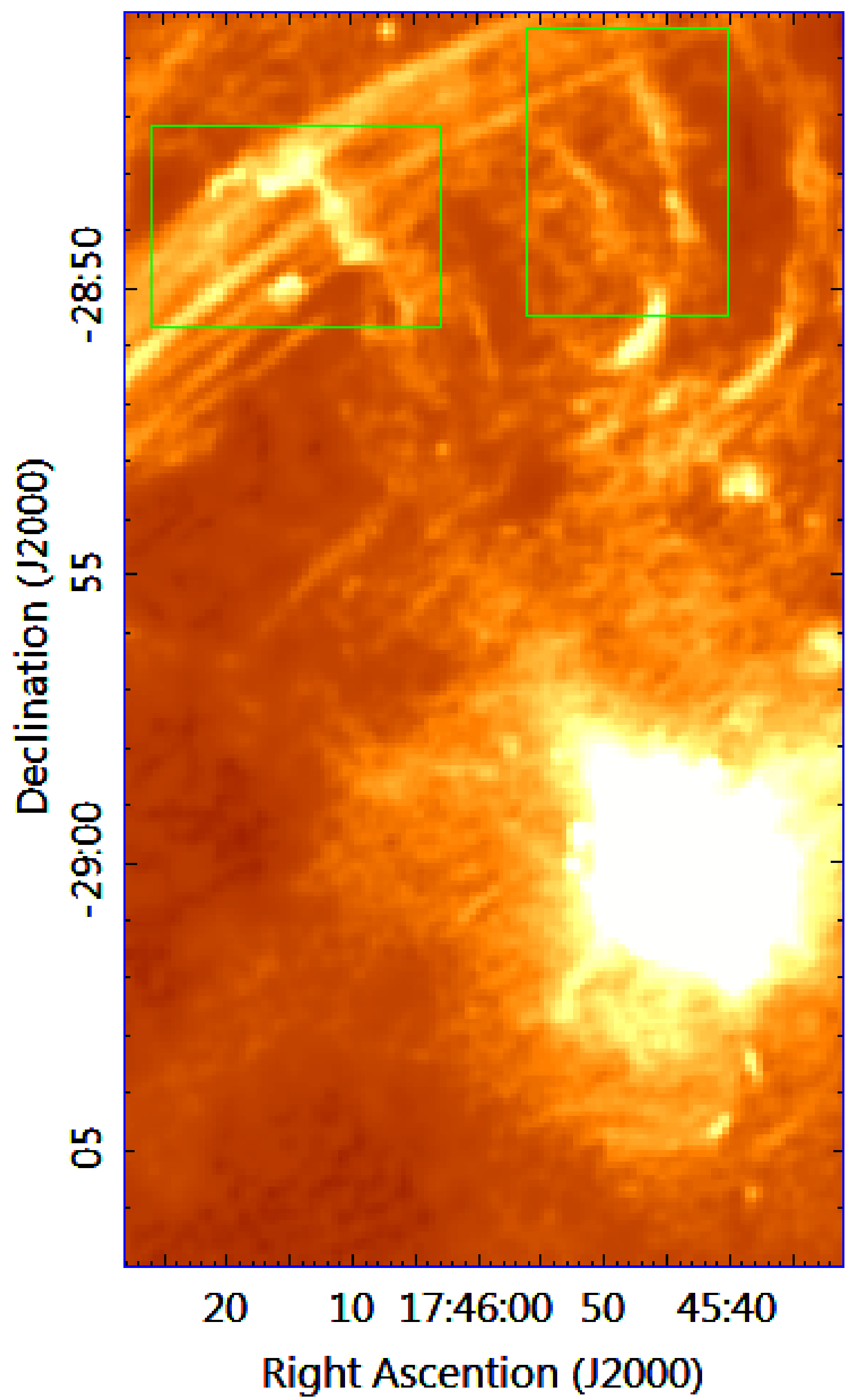
What heats and structures material in the Galactic center?



- A galactic nucleus we can understand in detail
  - At 8.3 kpc, 10” = 0.4 pc
- Center molecular clouds are substantially warmer than disk clouds (e.g. Güsten+85)
- Lots of energy available: a black hole, hot stars (UV), intersecting orbits and colliding stellar winds (shocks), X-rays, rigid magnetic fields, radio lobes… Pretty active but normal nucleus

Image Morris & Yusef-Zadeh 1989

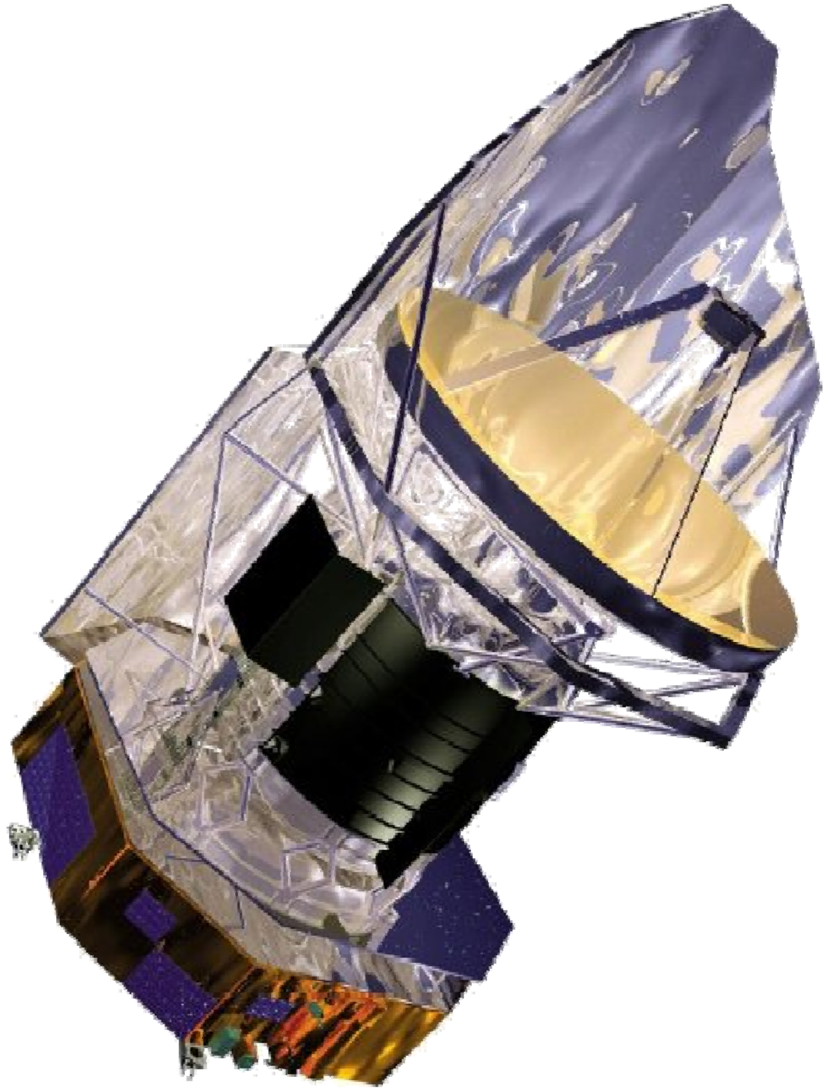
What heats and structures material in the Galactic center?



- We can probe structure and radiation field with far-IR atomic fine structure lines and continuum
- Then compare with other data set to trace molecules, ionized gas, …
- This talk:
  – *Herschel* and SOFIA imaging and spectroscopy of the Arches and Sickle regions
  – Implications, from the Galactic center to high redshift galaxies
  – Summary and future

Image Morris & Yusef-Zadeh 1989

Herschel and SOFIA: gateways to the far-infrared



Herschel Space Observatory
Pilbratt et al. 2010

Stratospheric Observatory For Infrared Astronomy
Young et al. 2012

Line properties

Species	λ [μm]	Exitation [eV]	Ionization [eV]	Transition	E_{upper} [K]	n_{crit} [cm^{-3}]
[O I]	63.2*	0	13.62	$J = 1 \rightarrow 2$	228	6×10^5
[O I]	145.5	0	13.62	$J = 0 \rightarrow 1$	327	$\geq 1 \times 10^5$
[C II]	157.7*	11.26	24.38	$J = 3/2 \rightarrow 1/2$	91	3000 (H_2)/50 (e^-)
[N II]	121.9	14.53	29.60	$J = 2 \rightarrow 1$	188	310
[N III]	57.3*	29.60	47.45	$J = 3/2 \rightarrow 1/2$	252	3000
[O III]	88.4*	35.12	54.93	$J = 1 \rightarrow 0$	164	510

~60 to ~160 µm

~100 to ~300 K
upper state energies

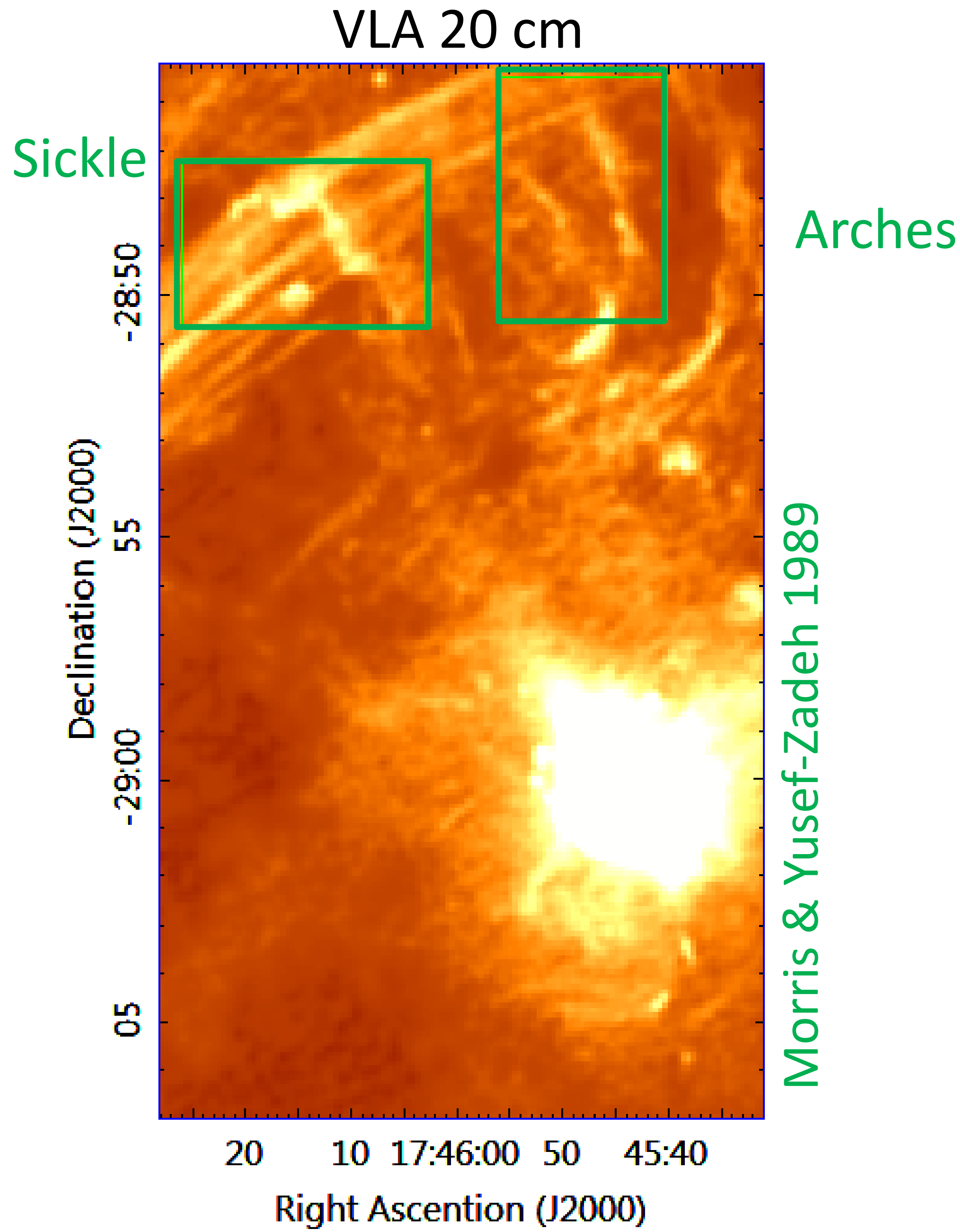
CNO: stellar
processing

Neutral to high
ionization atomic
states

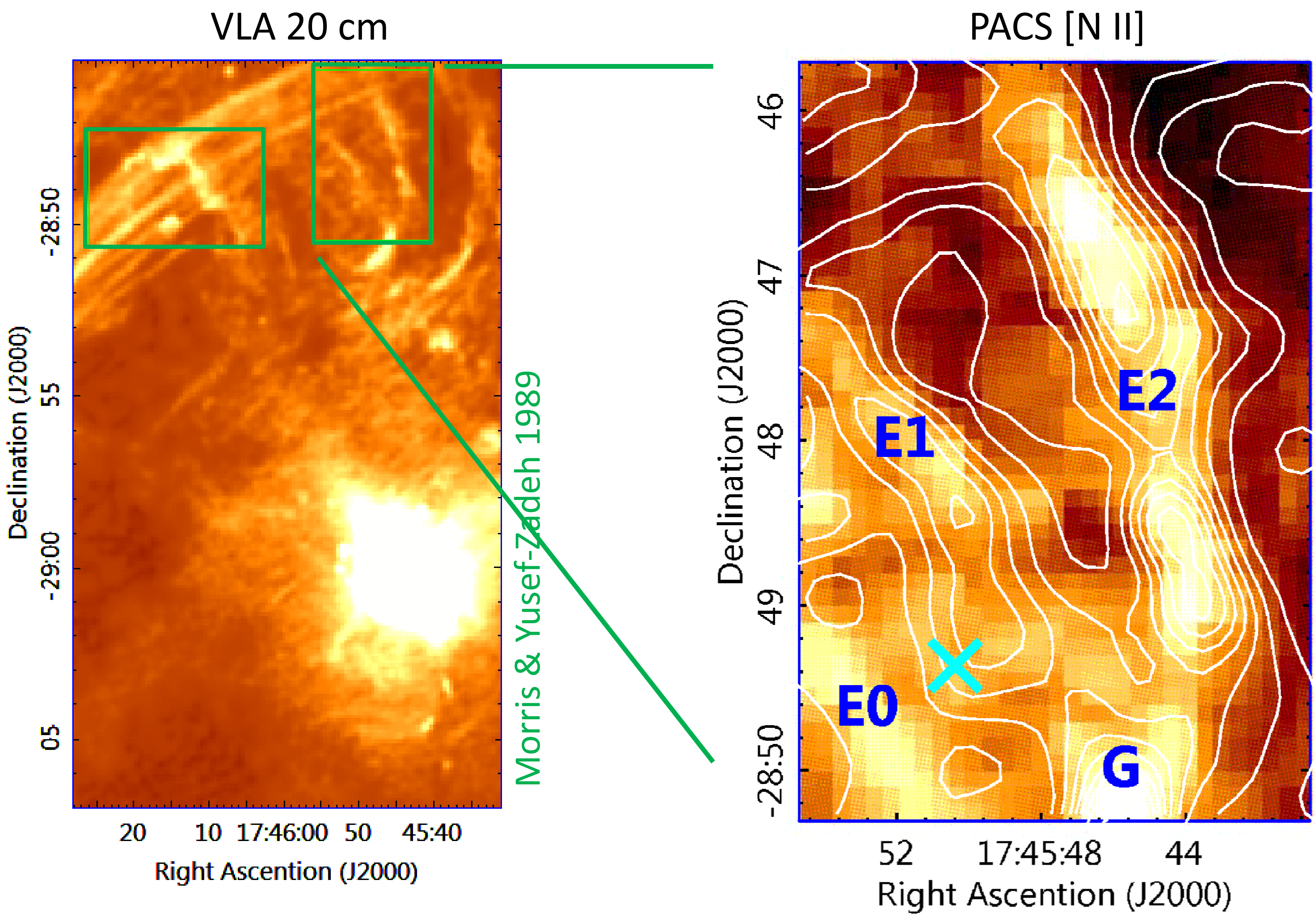
n ~ 300 to 3000
in ionized gas

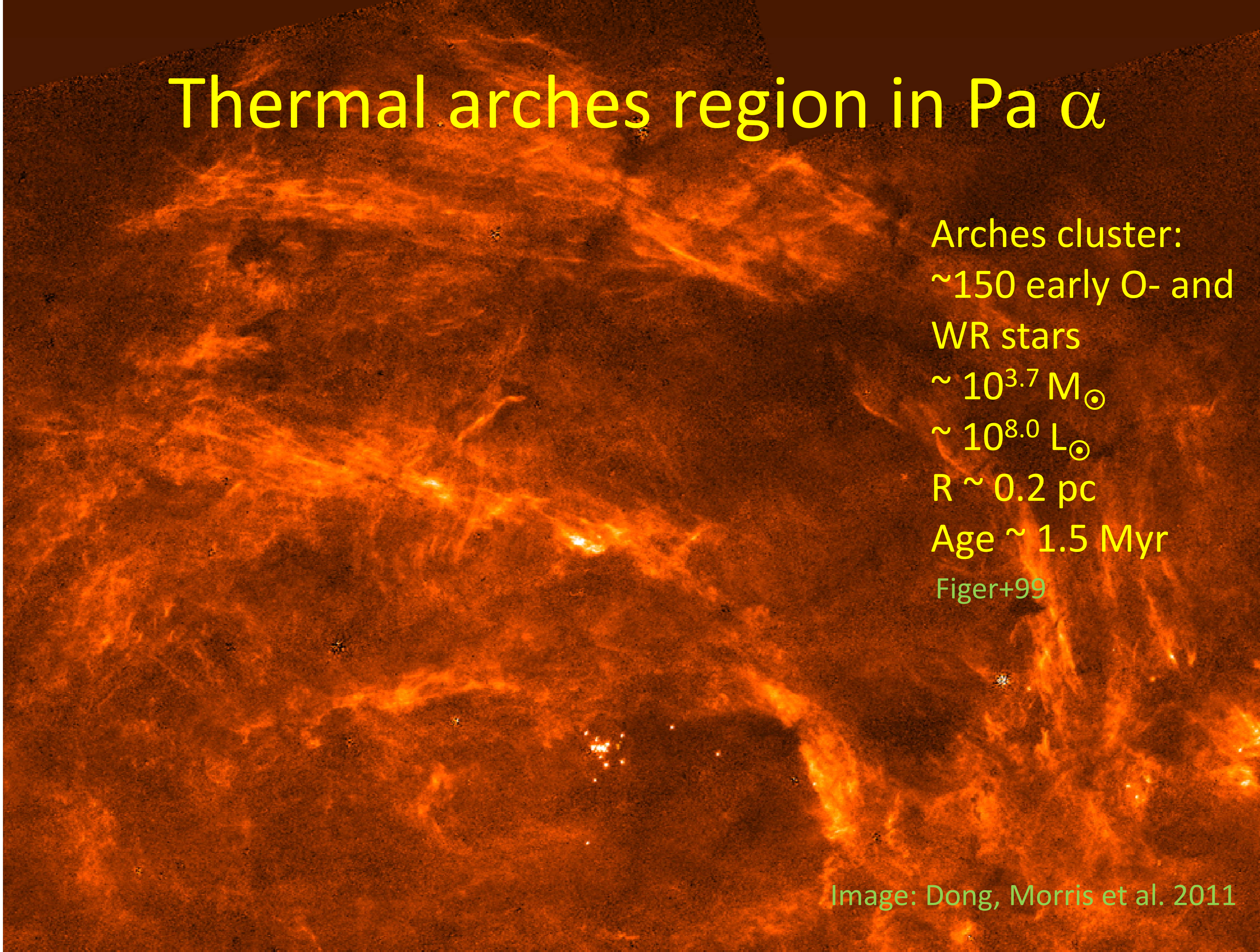
*Ground state

20 cm radio continuum, the Sickle, and the Arches

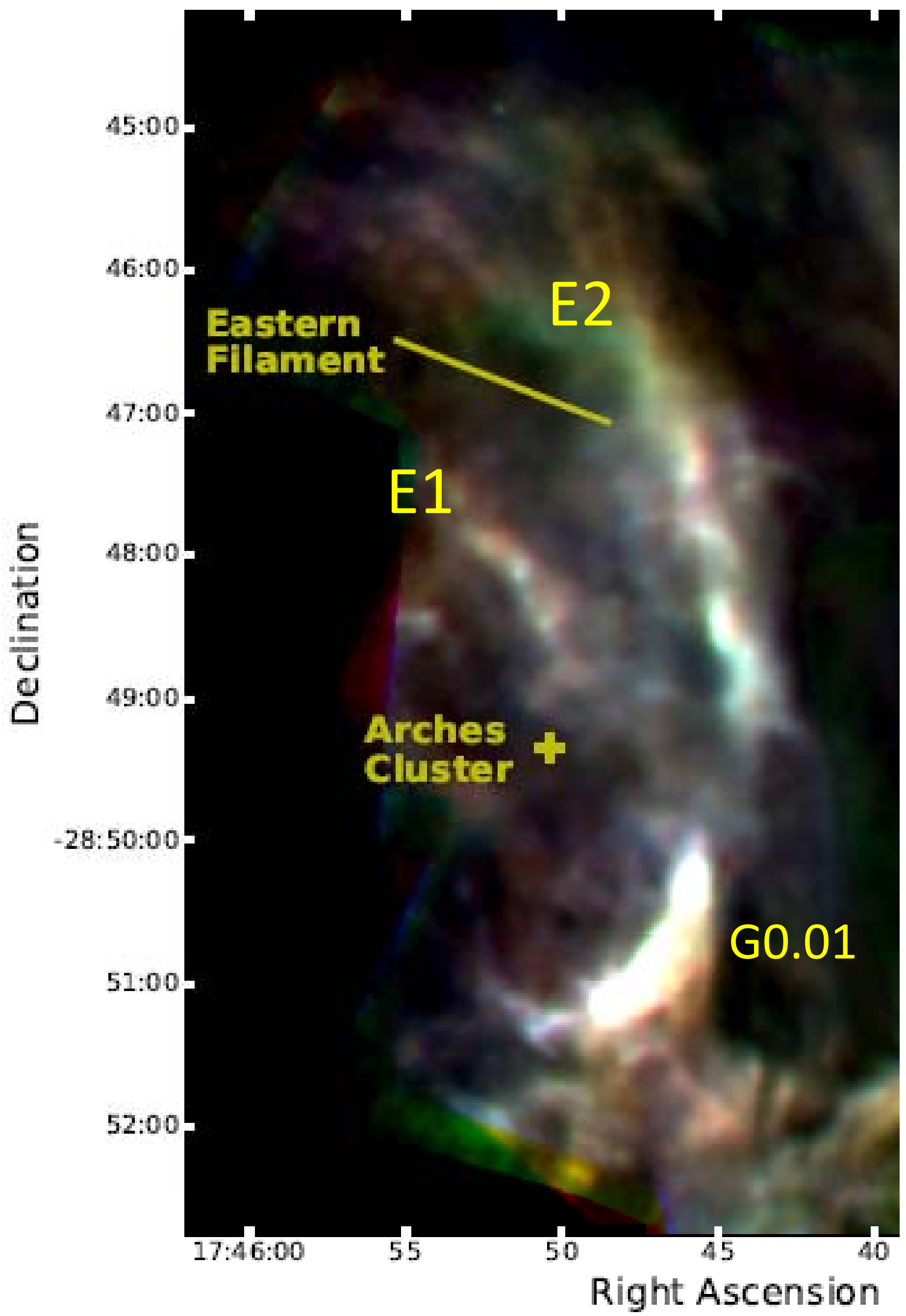


20 cm radio continuum and [N II]

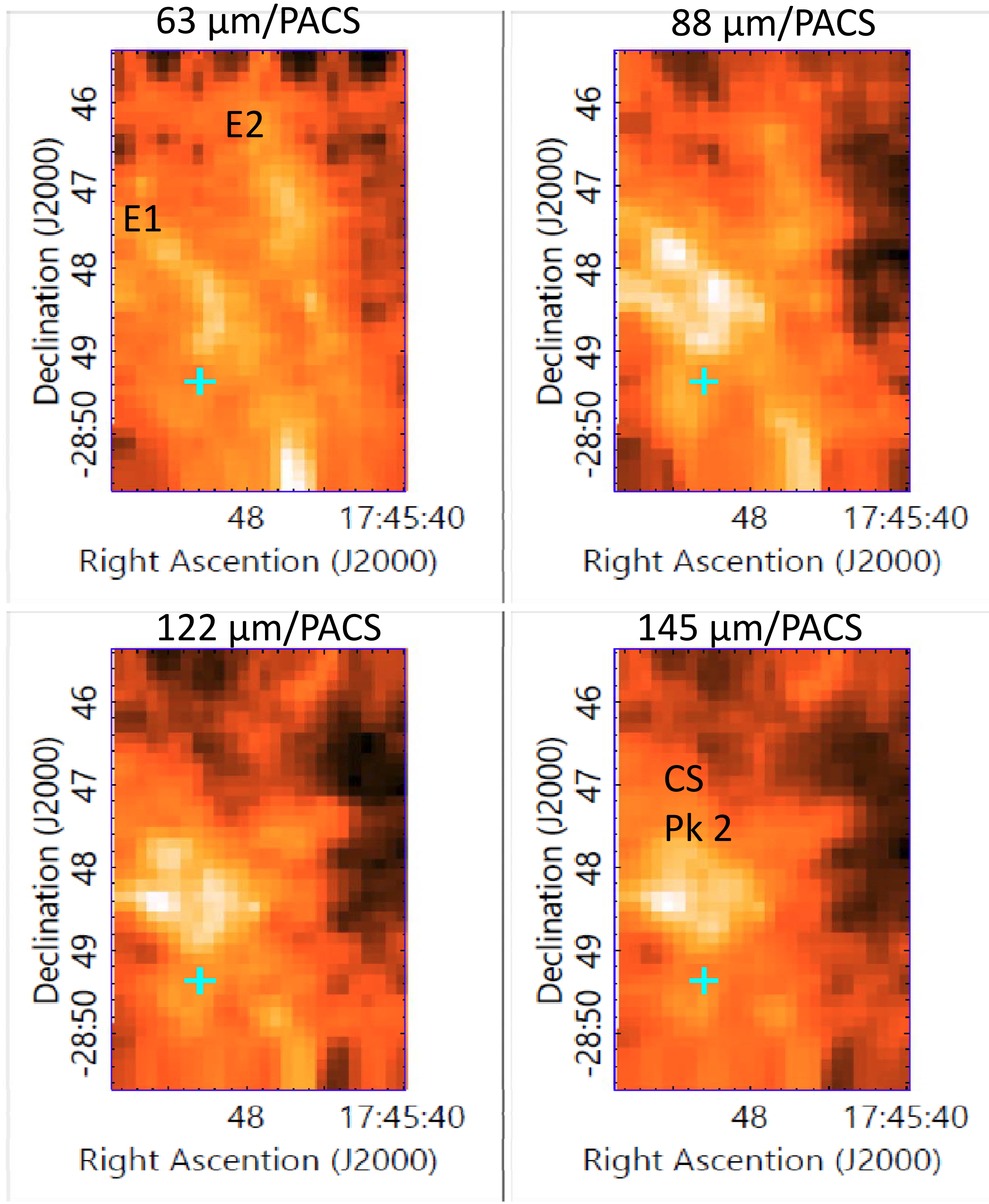



Thermal arches region in Pa α
Arches cluster:
~150 early O- and WR stars
~ $10^{3.7}$ $M_{\odot}$
~ $10^{8.0}$ $L_{\odot}$
R ~ 0.2 pc
Age ~ 1.5 Myr
Figer+99
Image: Dong, Morris et al. 2011

Arches continuum

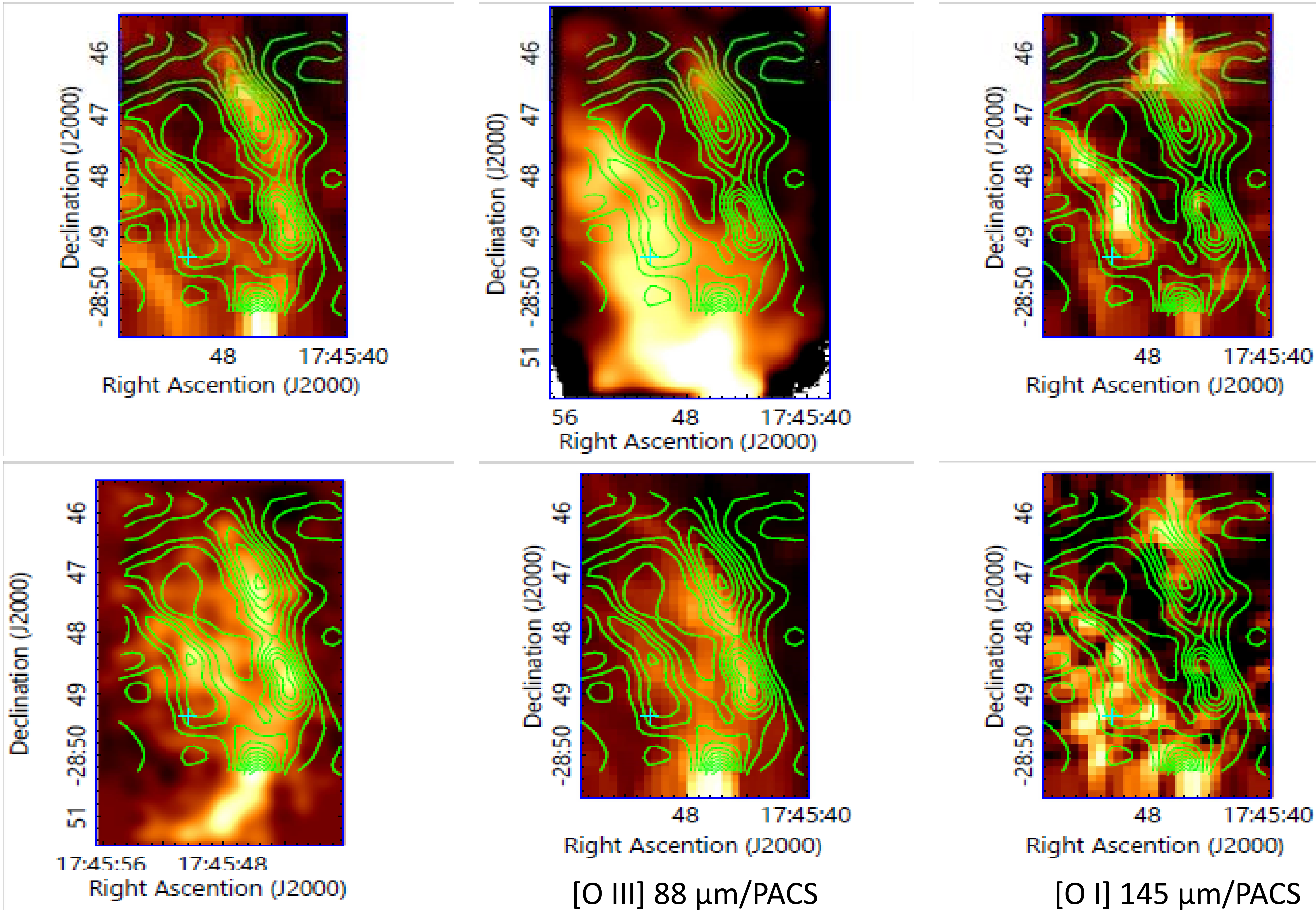


FORCAST, RGB 37, 31, 27 μm
(Hankins+17)



Arches fine structure lines

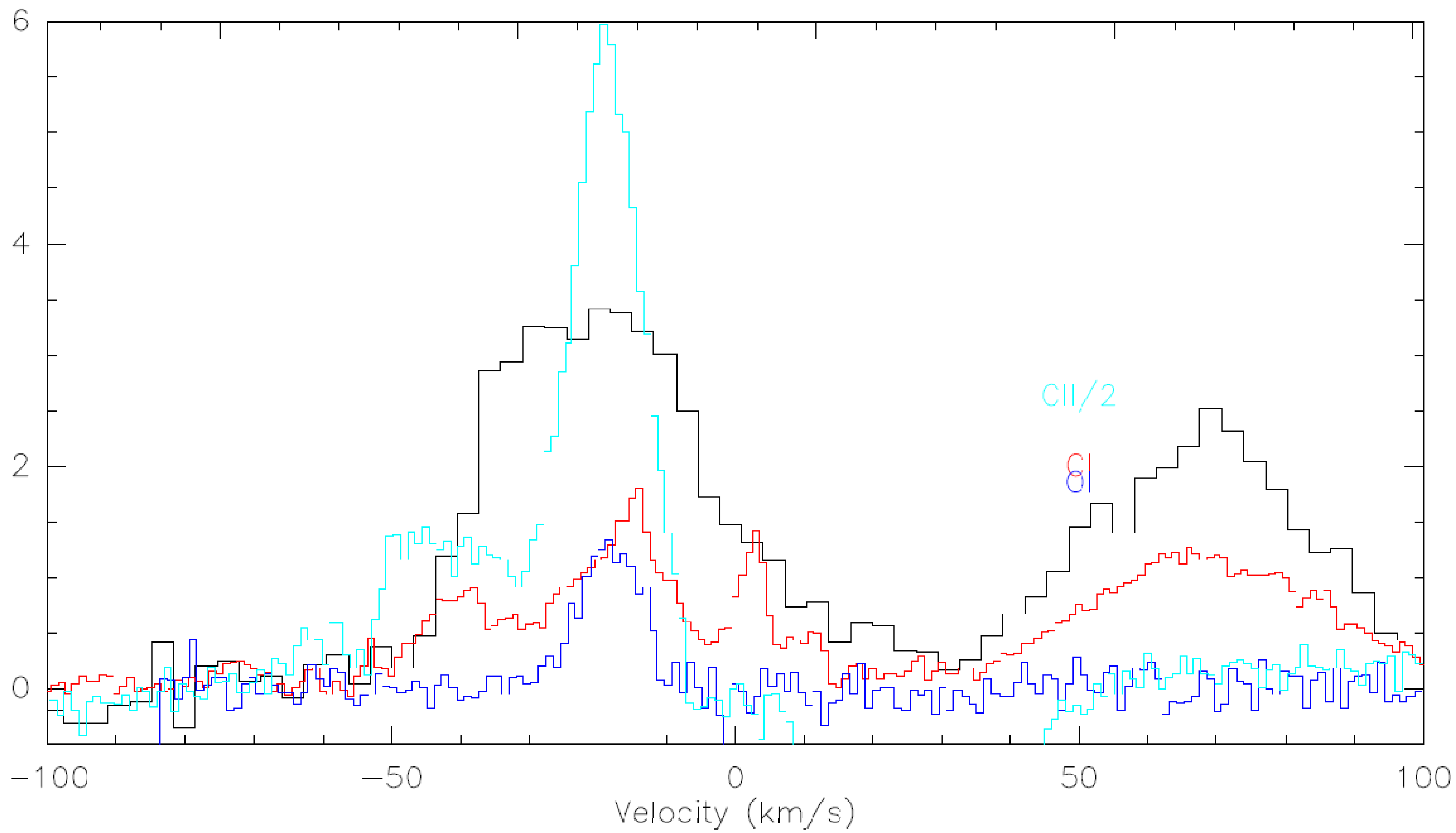
[N II] 122 μm/PACS | [C II] 158 μm/FIFI-LS | [O I] 63 μm/PACS



[N III] 57 μm/FIFI-LS | [O III] 88 μm/PACS | [O I] 145 μm/PACS

Green contours: 20cm continuum
Morris & Yusef-Zadeh 1989

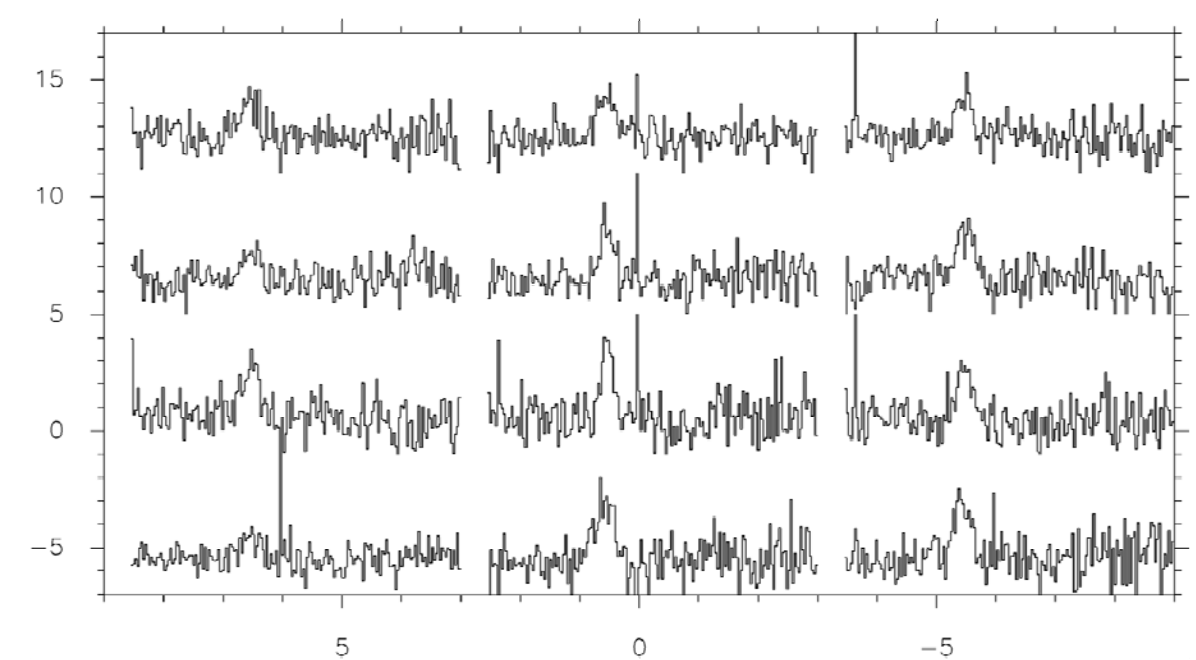
Tying molecular and ionized gas together in the E1(SW) knot



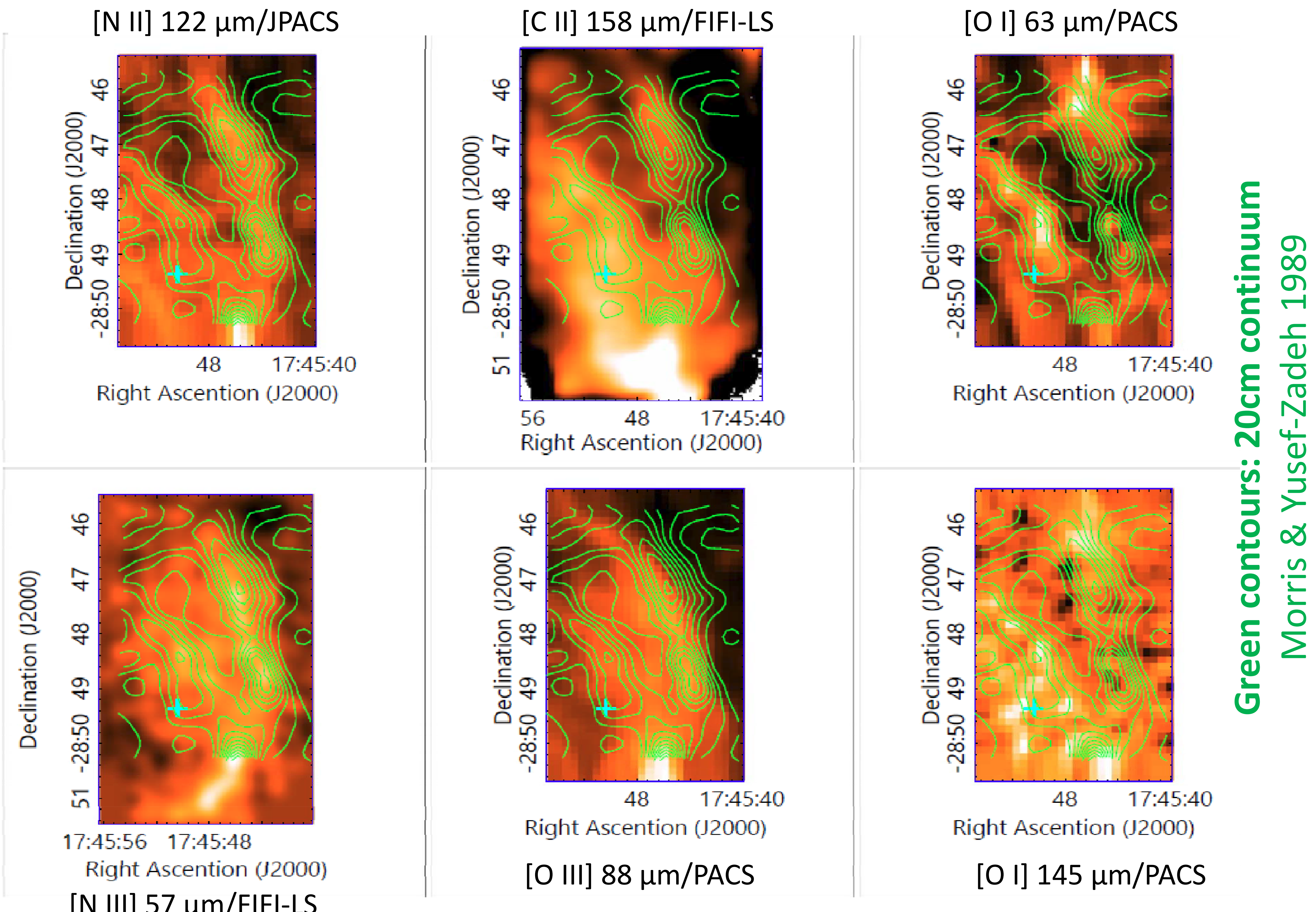
[C II]/2 (Herschel/HIFI)
[O I] (SOFIA/GREAT)
C I (APEX)
CO 6-5 (APEX)

All species share -20 km/s velocity centroid and similar widths

GREAT [O I] mapping shows no sign of self-absorption; we measure true [O I] flux



Arches fine structure lines



PACS 70μm sources in the Arches

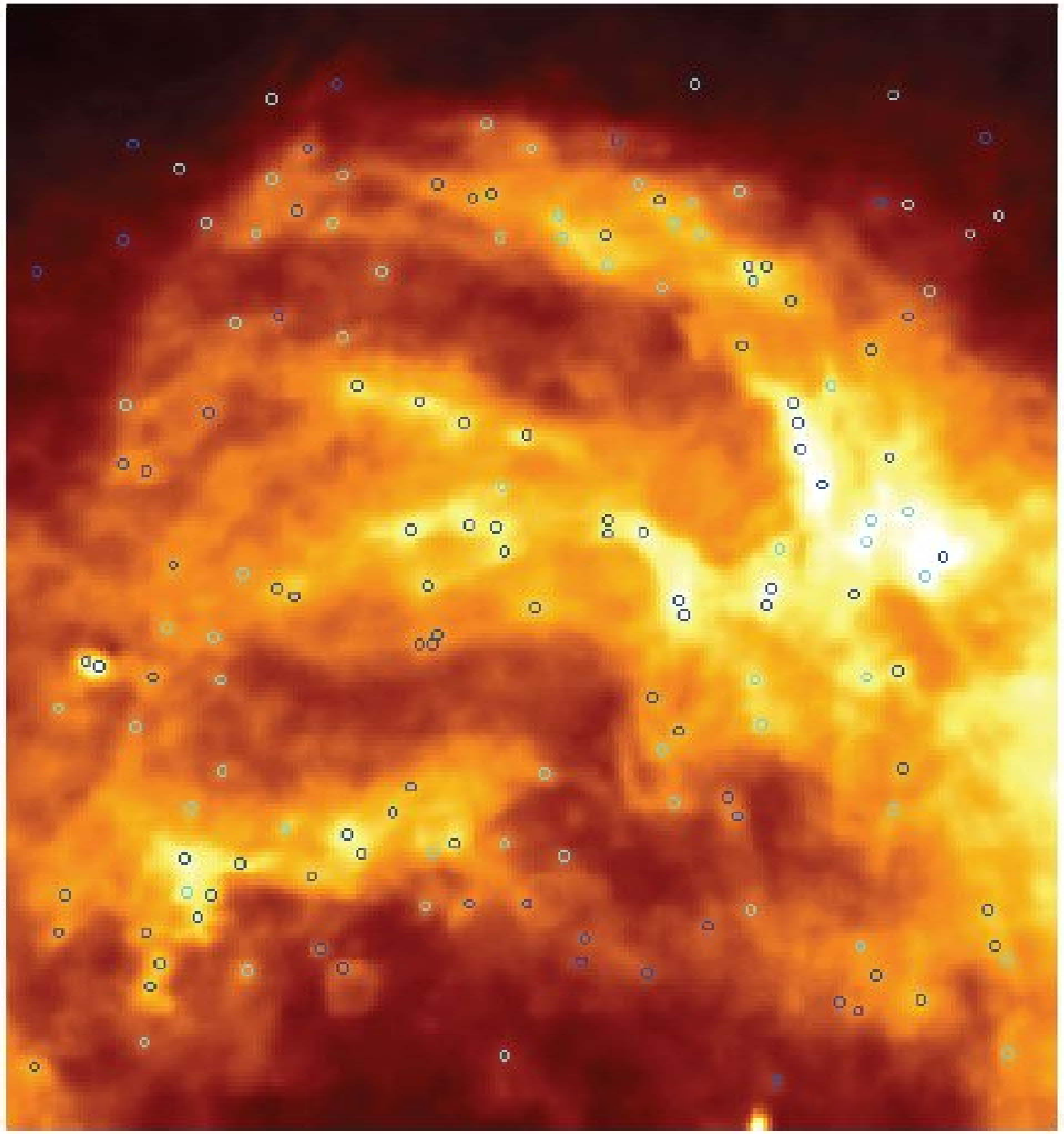


Fig. 3. Herschel PACS 70 μm image of the bright emission ridges corresponding to the thermal radio arches. Circles represent compact sources extracted from the Herschel images and with at least a valid flux at 70μm; cyan/blue circles represent sources with/without a counterpart in the Mid-IR from the MSX6C catalogue.

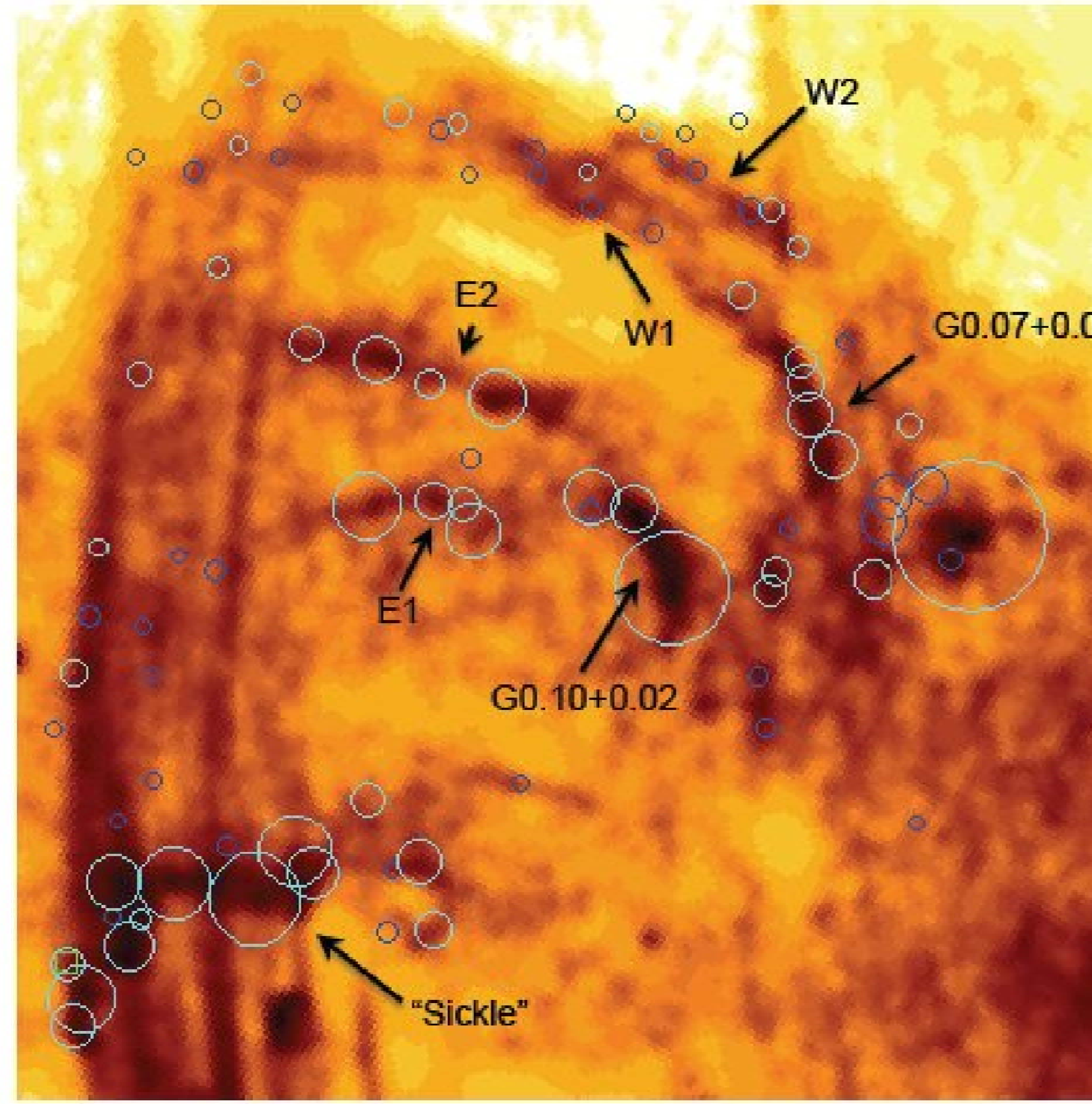
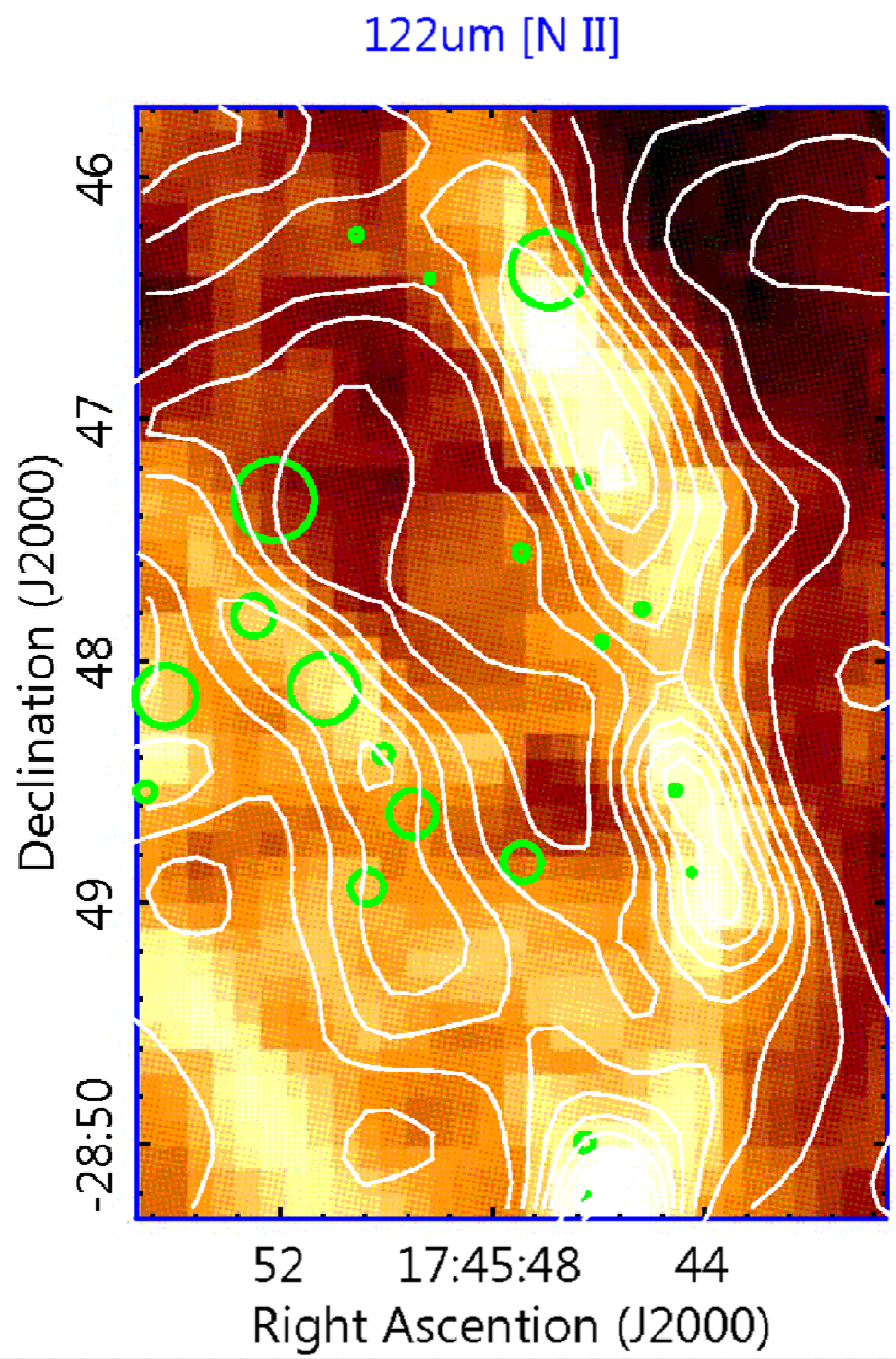


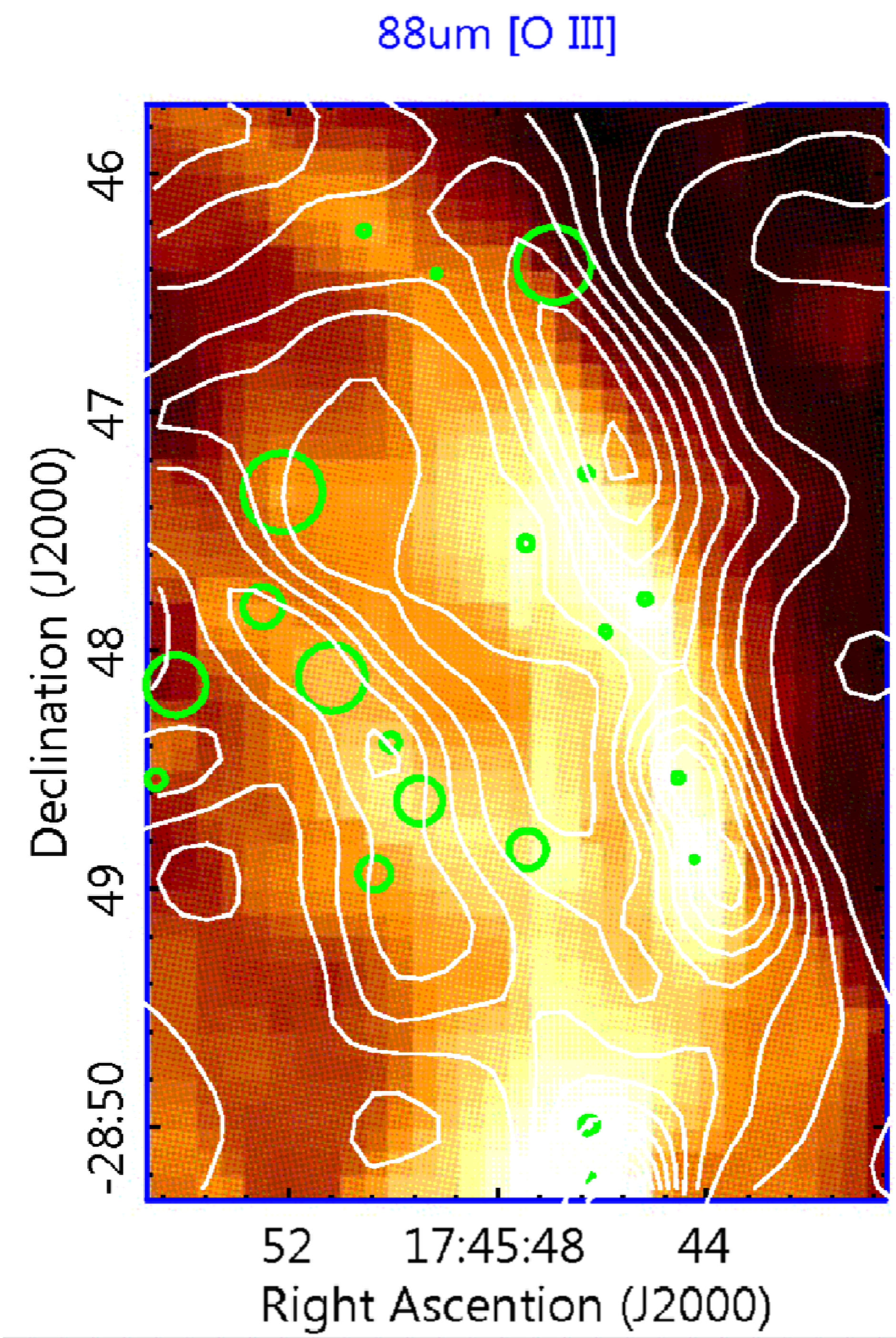
Fig. 4. VLA 20cm continuum map (courtesy F. Yusef-Zadeh), with superimposed circles representing the compact sources detected with Herschel. Sources in cyan/blue are those with/without MSX counterpart, respectively; the size of the circles proportional to the source bolometric luminosity. Nomenclature of radio features is reported following Morris & Yusef-Zadeh (1989).

De Crespo 19??; Molinari in prep.

Far-IR lines and MSX point sources

8 µm/24 µm flux ratios

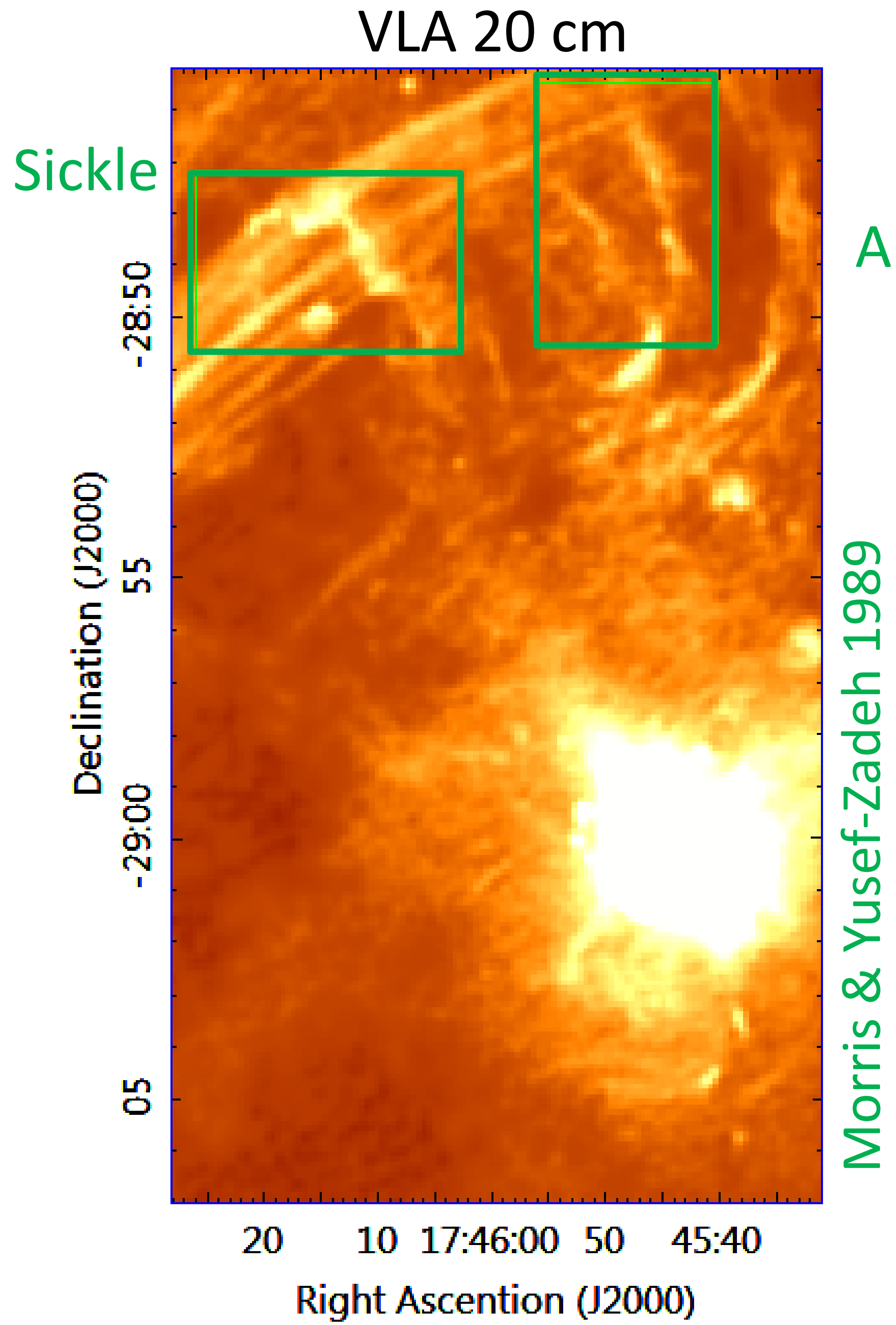




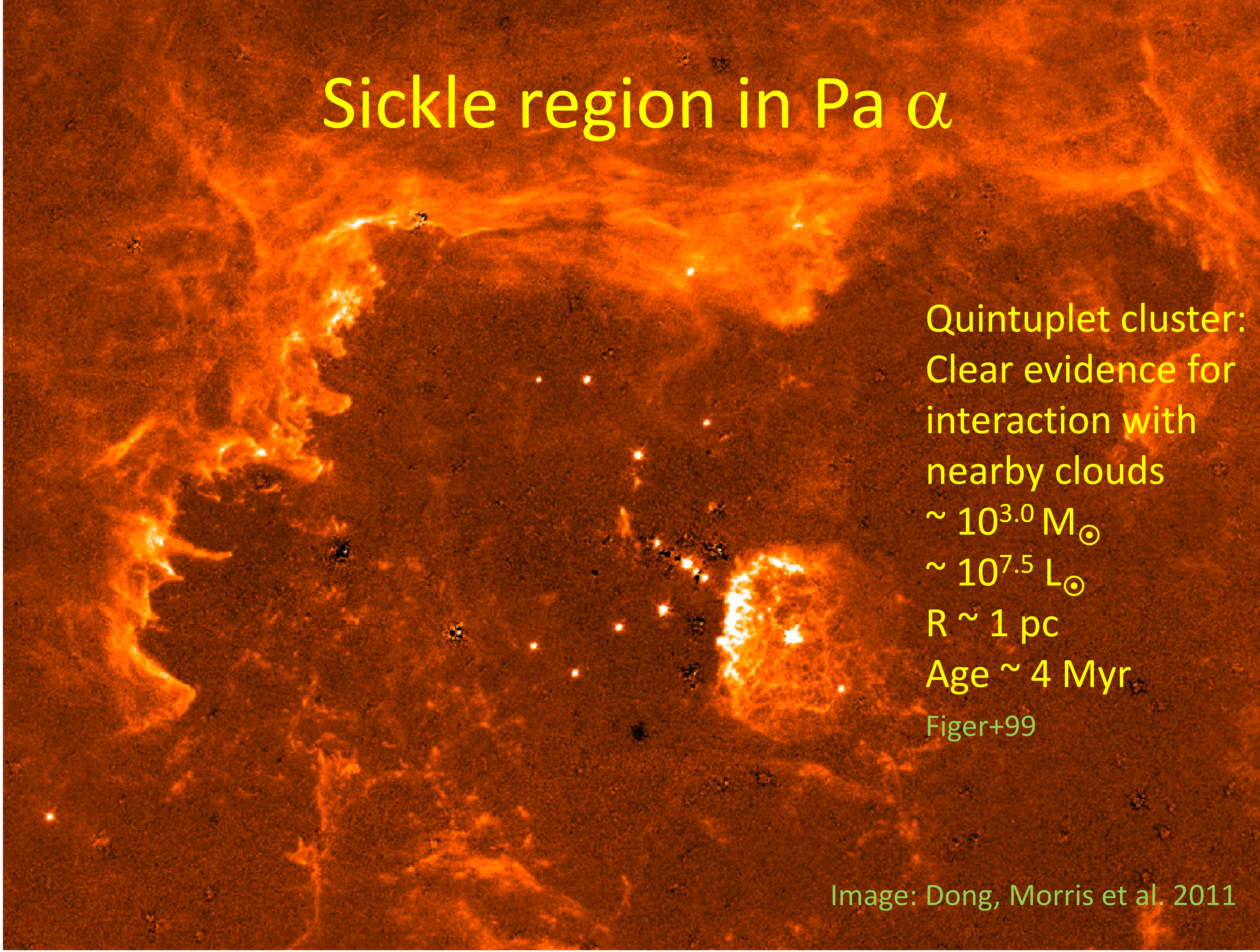
Top-level Arches subconclusions

- General haze of excited gas, plus E1 and E2 (and E0)
- By excitation, E1 and E2 are quite separate structures
- [N II] and [O III] are spatially distinct; ratio alone is an imprecise diagnostic
- [O I] is associated with molecular clouds cores; [C II] with outer regions; [C II]/[O I] ratio alone is imprecise diagnostic
- No morphological sign of heating by Arches cluster (~150 early O/W-R stars, ~$10^{8.0}$ $L_{\odot}$); heating must be more distributed. Winds unlikely. Ongoing star formation? Cosmic rays? X-rays?

20 cm radio continuum, the Sickle, and the Arches



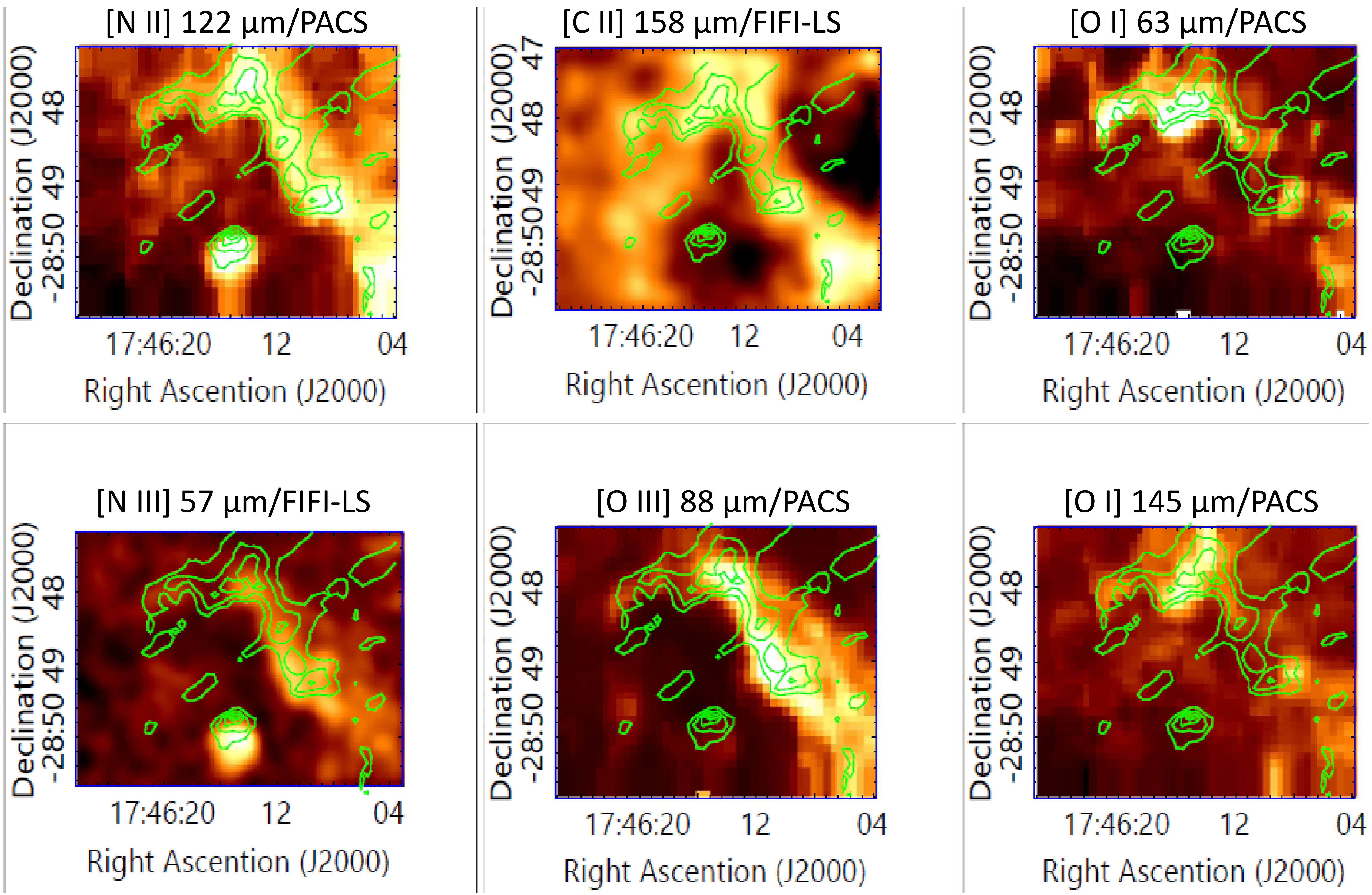
Sickle region in Pa α



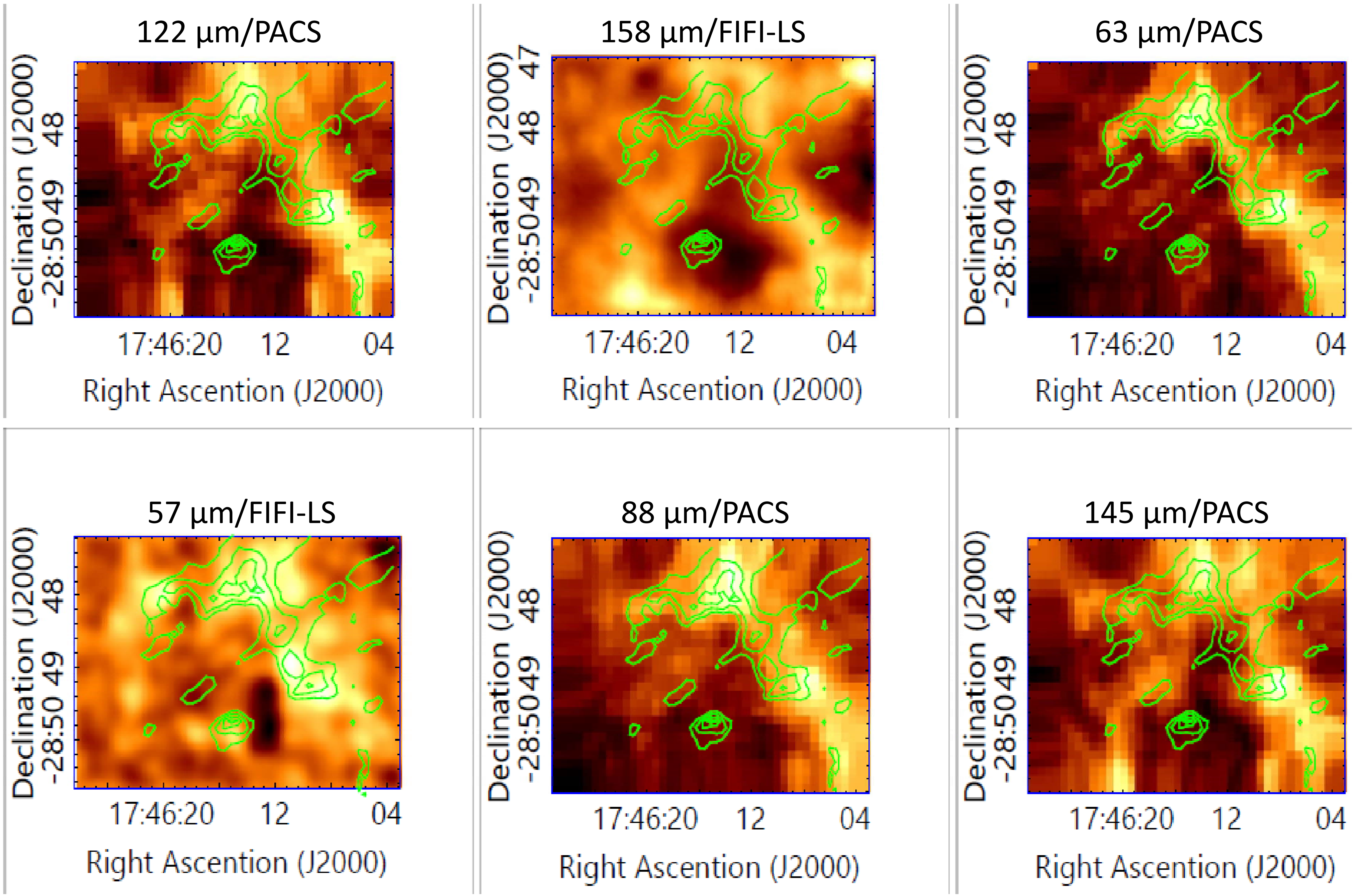
Quintuplet cluster:
Clear evidence for interaction with nearby clouds
~ $10^{3.0}$ $M_{\odot}$
~ $10^{7.5}$ $L_{\odot}$
R ~ 1 pc
Age ~ 4 Myr
Figer+99

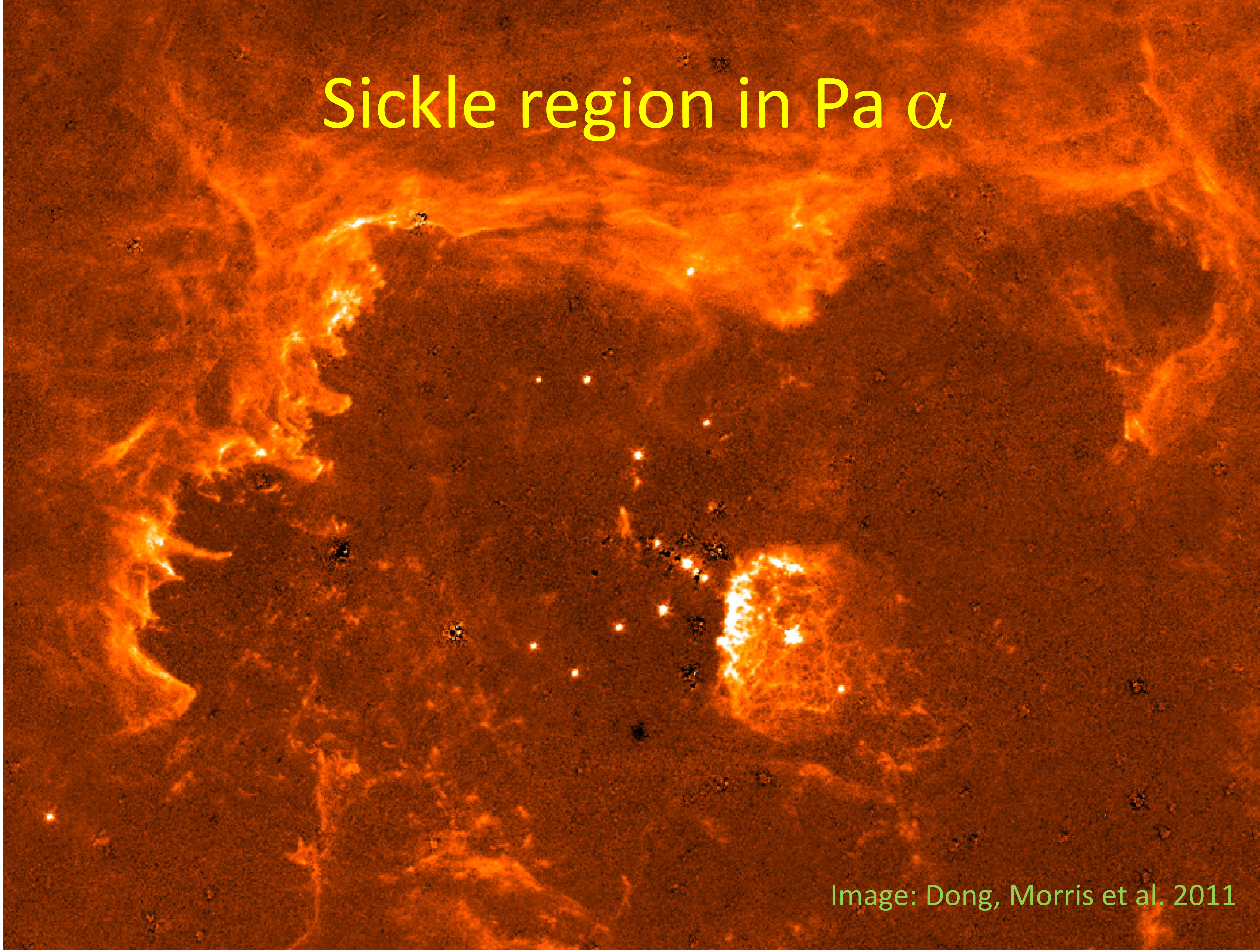
Image: Dong, Morris et al. 2011

Sickle fine structure lines

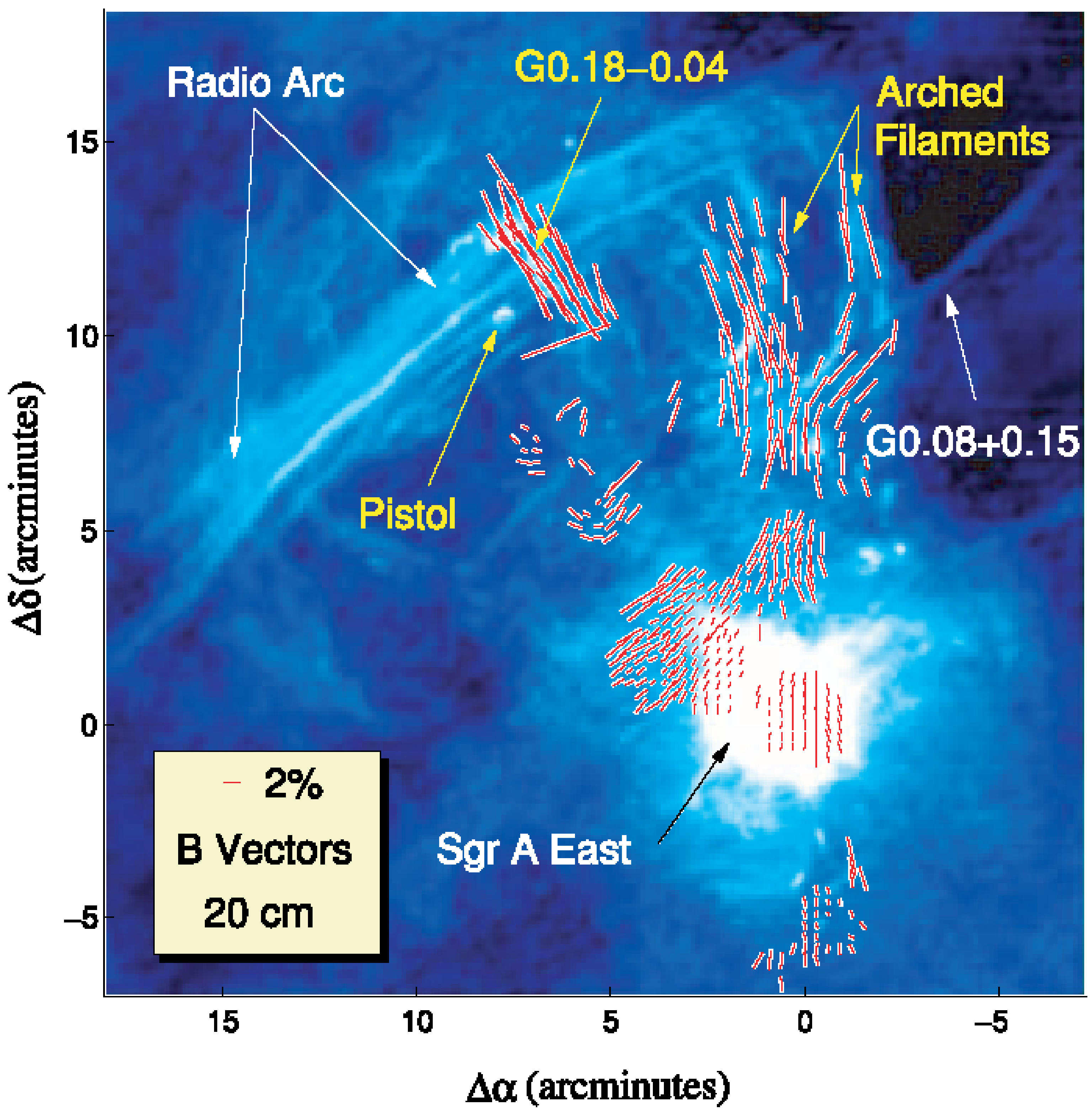


Sickle continuum




Sickle region in Pa α
Image: Dong, Morris et al. 2011

Magnetic fields across the Galactic center



Galactic center dust polarization at 350 μm with Hertz/CSO (B vectors) on 20 cm VLA radio continuum (Chuss et al. 2003; Yusef-Zadeh et al. 1984)

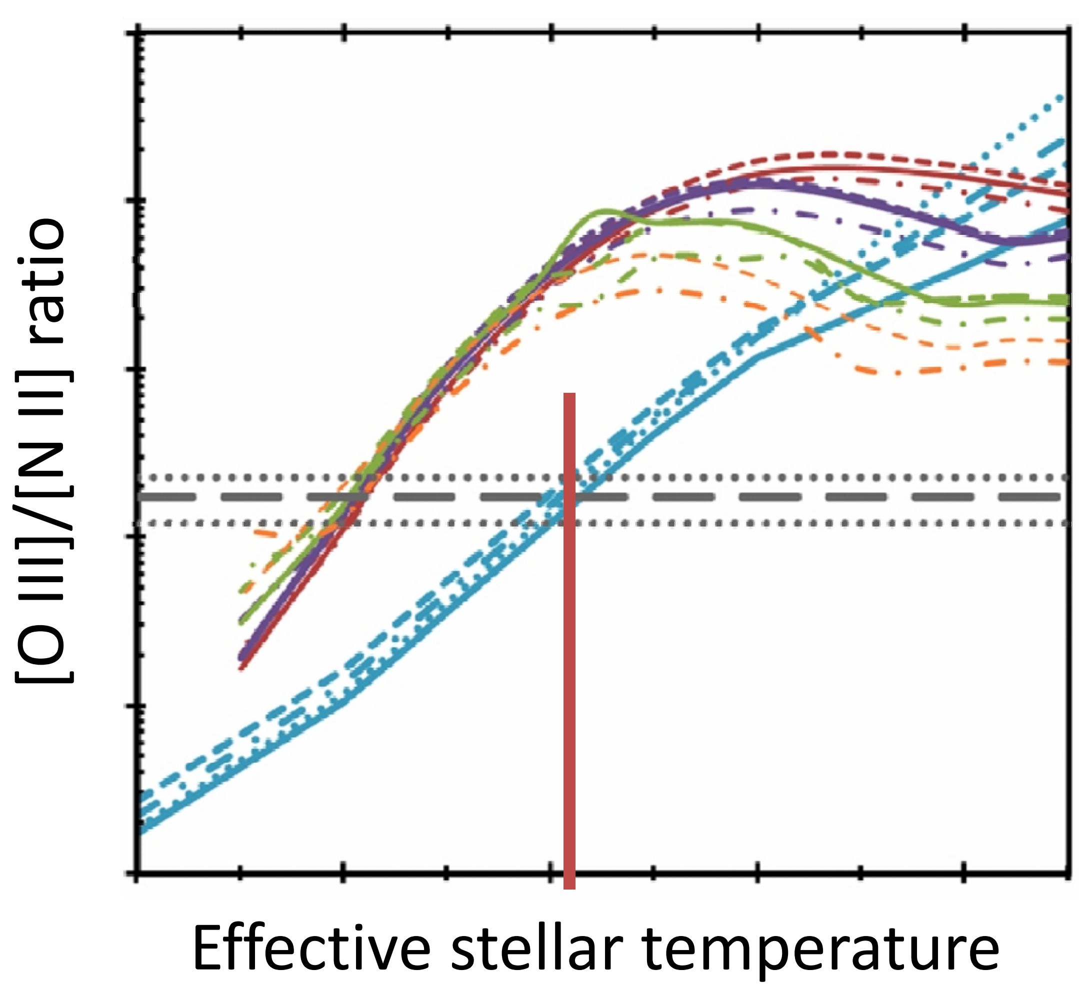
Radio Arc is synchrotron emission, while Arches are thermal free-free

Top-level Sickle subconclusions

- Fine structure lines show that the Sickle handle is very different than its head. Head has obvious UV interaction in Pa α. But is the handle a separate structure?
- Does high ionization state in Sickle handle have anything to do with its stronger magnetic field? No obvious connection with continuum emission. HAWC+ observations…
- Strong N enhancement in Pistol region (likely older WN stars), but not in Arches

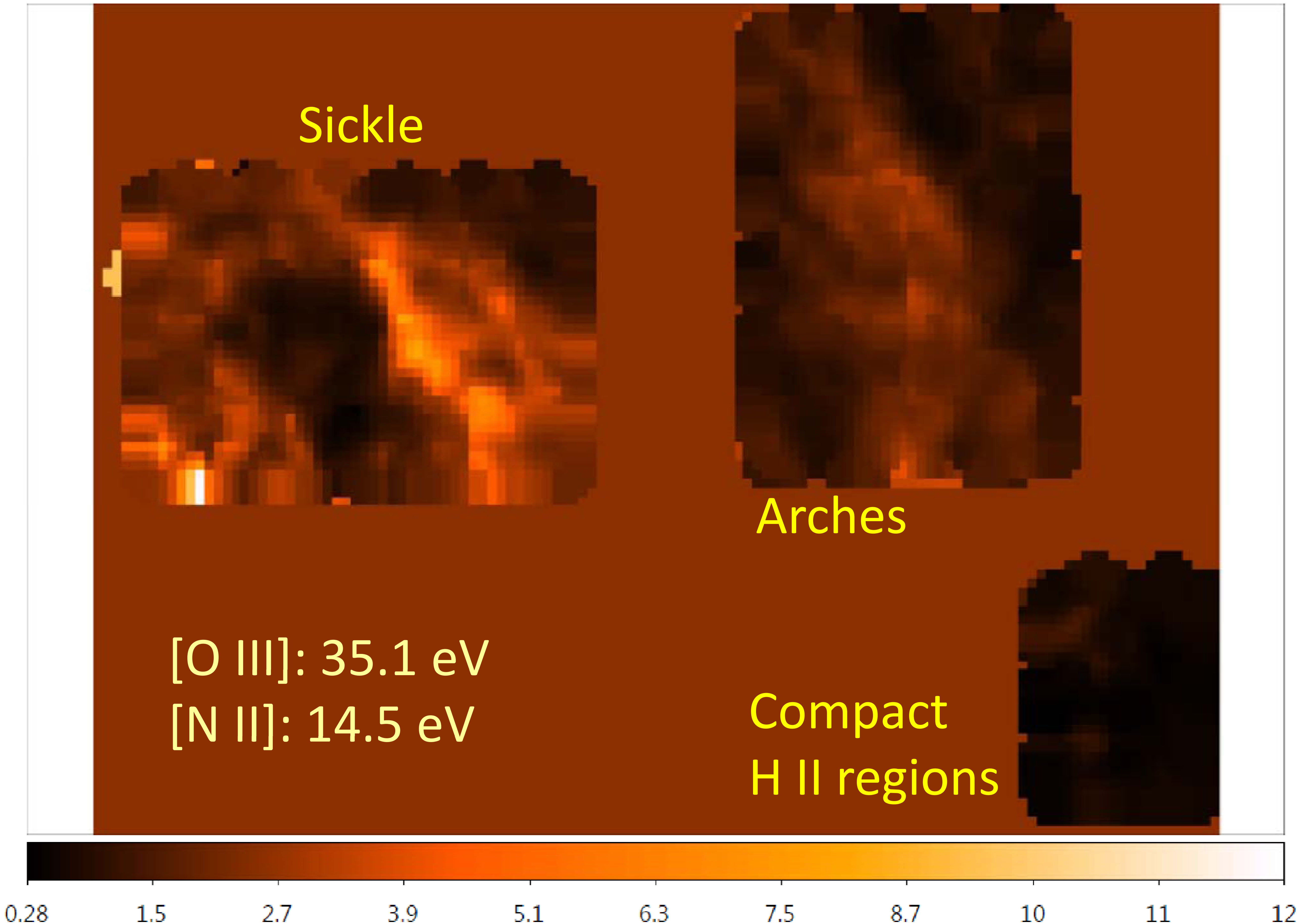
Line diagnostics of the UV field

Species	λ [μm]	Ex. Pot. [eV]	Ion. Pot. [eV]	Transition	E_{upper} [K]	n_{crit} [cm^3]
[N II]	121.9	14.53	29.60	$J = 2 \rightarrow 1$	188	310
[O III]	88.4	35.12	54.93	$J = 1 \rightarrow 0$	164	510

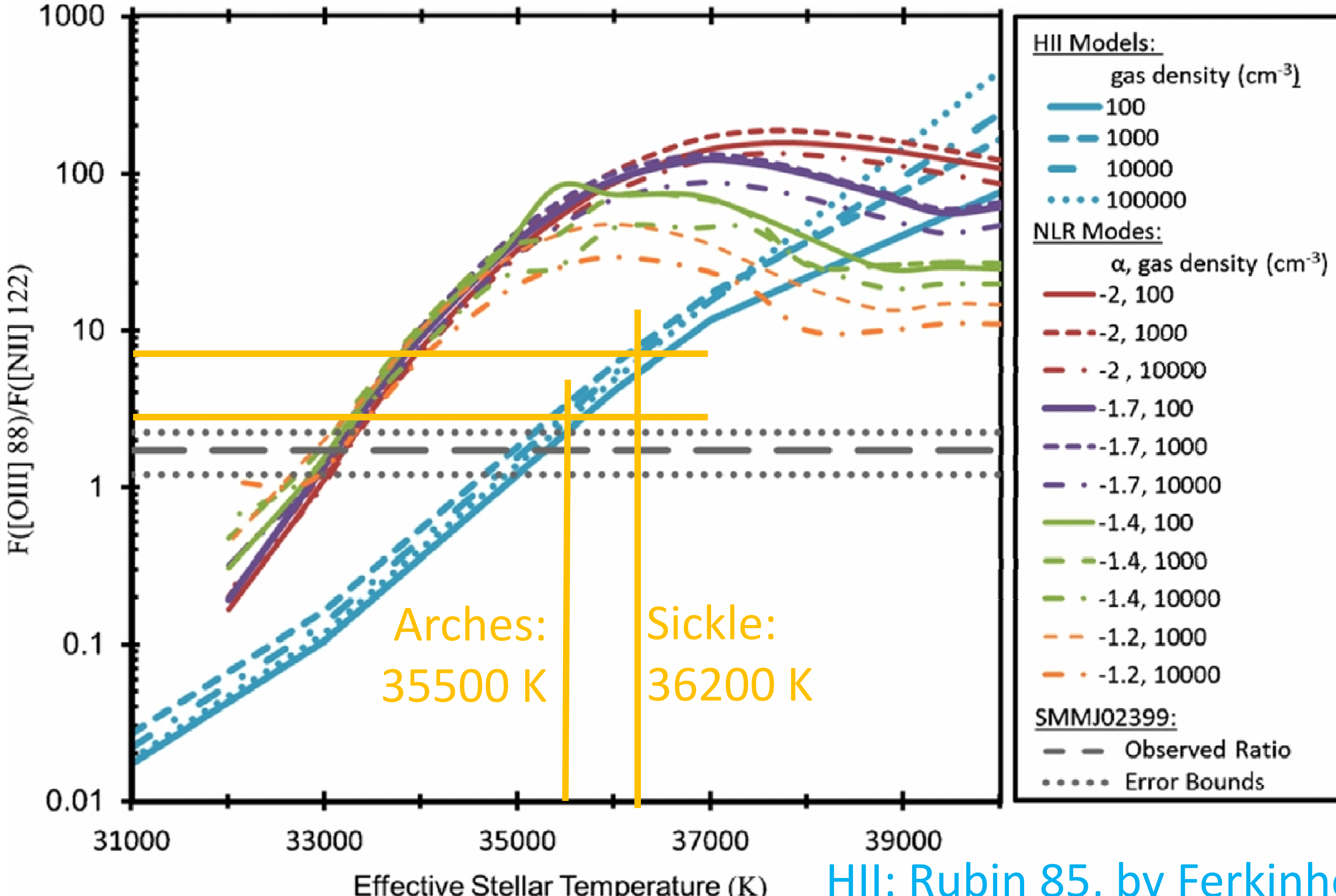


H II models from Rubin et al. 1985, plus AGN models (Ferkinhoff+11)

[O III]/[N II] "hardness maps"



[O III]/[N II] in J02399-0136 and in the Galactic center



HII: Rubin 85, by Ferkinhoff+11

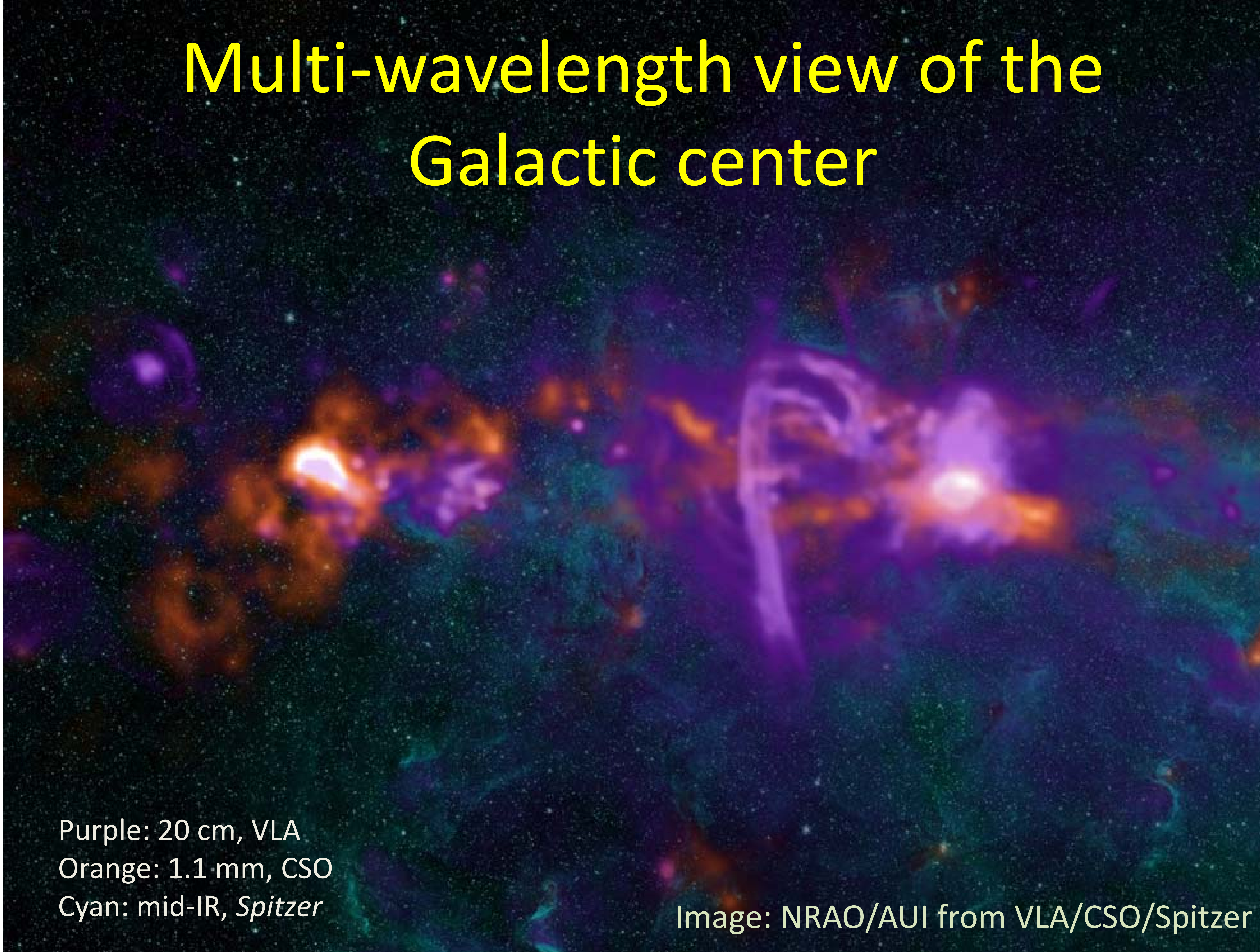
Summary

- Spatially-resolved observations of multiple tracers in the Galactic center are essential to untangle this complicated but very important region
- We explore spatial distributions of the far-IR lines and their spatial relationships to excitation sources to show that distributed heating dominates excitation at large scales
- The [O III]/[N II] ratio, a valuable tool for understanding the star formation history of galactic nuclei at all redshifts, is representative but not exact: it does not automatically characterize the highest-mass, hottest population
- The Galactic center continues to serve as a local laboratory for understanding processes in galactic nuclei near and far

Blatant attempt to influence the SOFIA Program science leadership's thinking

- Exploring and characterizing the Galactic center across the far-IR is a well-defined, coherent, high-impact program excellently suited to SOFIA's strengths and capabilities
  - SOFIA observations of our Galactic center provide high-resolution observations of processes typical of "normal" nuclei
  - Unique and important (and bright!) environment to study nuclear star formation with cutting-edge instrumentation
  - Vast quantities of data at other wavelengths; FIR traces main coolants with little obscuration by Galactic disk material
  - Extension to understanding galaxies at all redshifts
  - Explore effect of massive black hole on surroundings, and vice versa
- Exploits SOFIA's capabilities as a Southern hemisphere observatory for the US and German communities
  - Combine, collaborate, connect with data and programs from ALMA, APEX, ESO, …
  - Magellanic Clouds are "other flight legs" sources; low metallicity dwarfs expand understanding star formation in different environments, perhaps typical of early galaxies

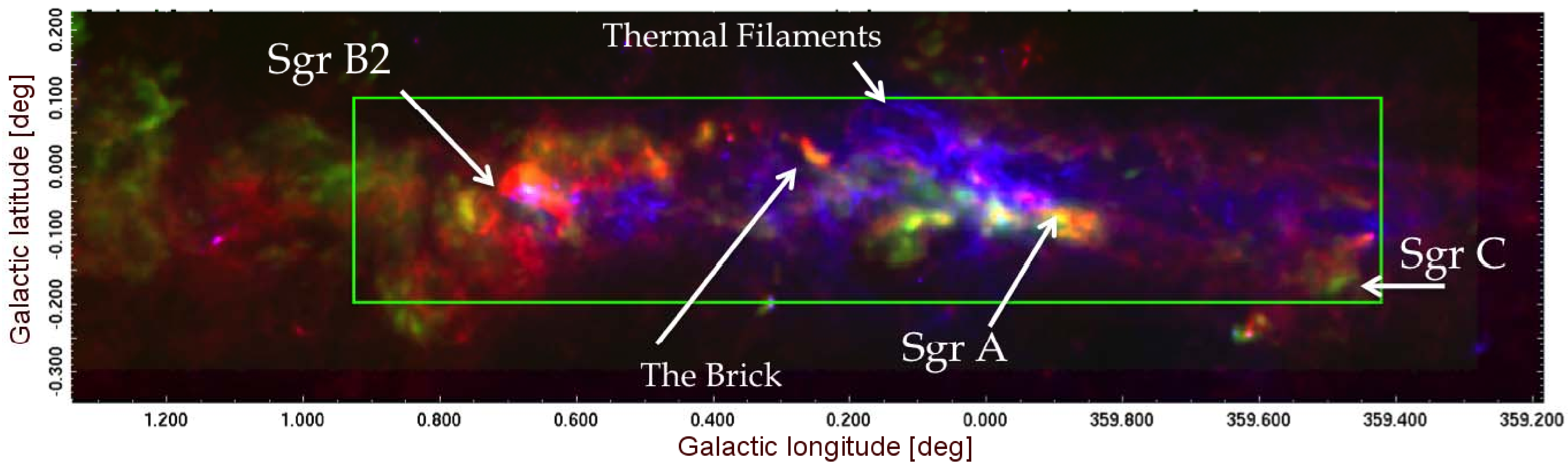
Multi-wavelength view of the Galactic center



A Galactic center program for the Senior Review to consider

- How do “normal” galactic centers work? Only in our own Galaxy can we assemble a detailed view across all wavelengths
  - Gas dynamics
    - Feeding the nuclear region, flows within the region, feeding and starving the black hole
    - Understanding large-scale gas orbits and why is our nucleus is so lop-sided
    - Distribution and dynamics of CO-dark dense gas
    - Magnetic field – gas interactions
  - Star formation
    - Establishing star formation rates and sites throughout the nucleus
    - Discovering why the young clusters are where they are, clues to formation of nuclear super star clusters
  - Energetics
    - Role of the black hole; signs of episodic activity
    - Dominant heating mechanisms within the center

Central Molecular Zone (CMZ)



Green box: 220 x 44 pc

Red: ATLASGAL 870 um continuum (Schuller et al. 2009)
Blue: *Herschel* 70 um continuum (Molinari et al. 2011)
Green: Dense molecular gas (Jones et al. 2012)

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