Massive Star & Cluster Formation

John Bally

Center for Astrophysics and Space Astronomy (CASA)
Department of Astrophysical and Planetary Sciences (APS)
University of Colorado, Boulder

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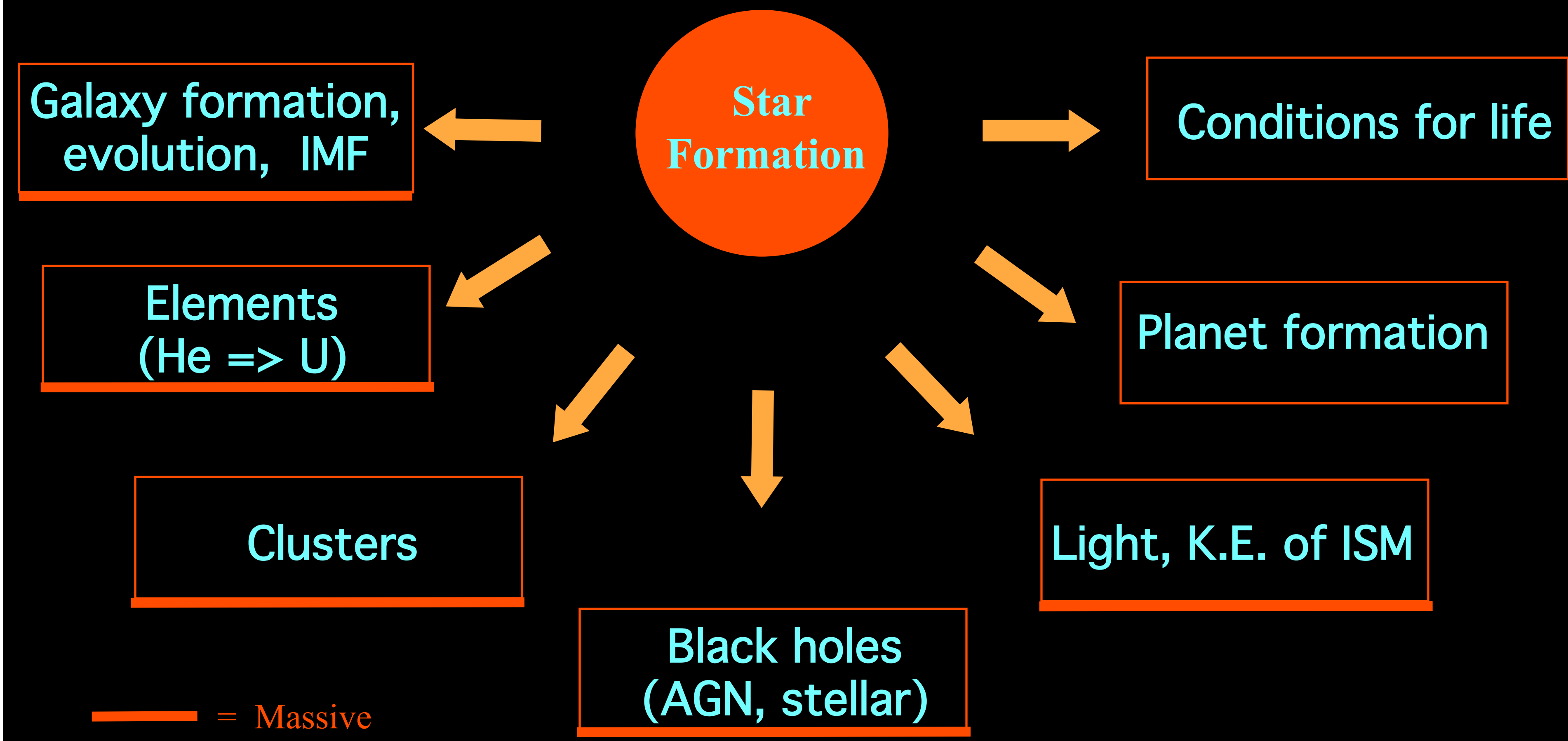
Star Formation

The fundamental cosmic (baryonic) process

Determines cosmic fate of normal matter



Outline

Introduction:

- Star Formation
- Properties of Massive Stars
- Theories of massive star and cluster birth
- Challenges, Controversies, Unknowns

Massive star forming regions:

- Orion: n-body dynamics, explosions
- Cepheus A: Capture-formed binary?
- W43: “Mini-starburst”
- Galactic center: Extreme conditions

Conclusions

<u>Massive Star Formation</u> is in SOFIA “sweet spot”

5 => 100 μm, bright objects

Needed SOFIA Capabilities

- High-R spectro-imaging or Multi-object spectra
- Polarimetry: line, continuum

Isolated (low-mass) Star Formation:

Most born in clusters!

Shrink r by 10^7; increase n(H) by x 10^{21}

- Giant Molecular Cloud Core

  Raw material for star birth

- Gravitational Collapse & Fragmentation

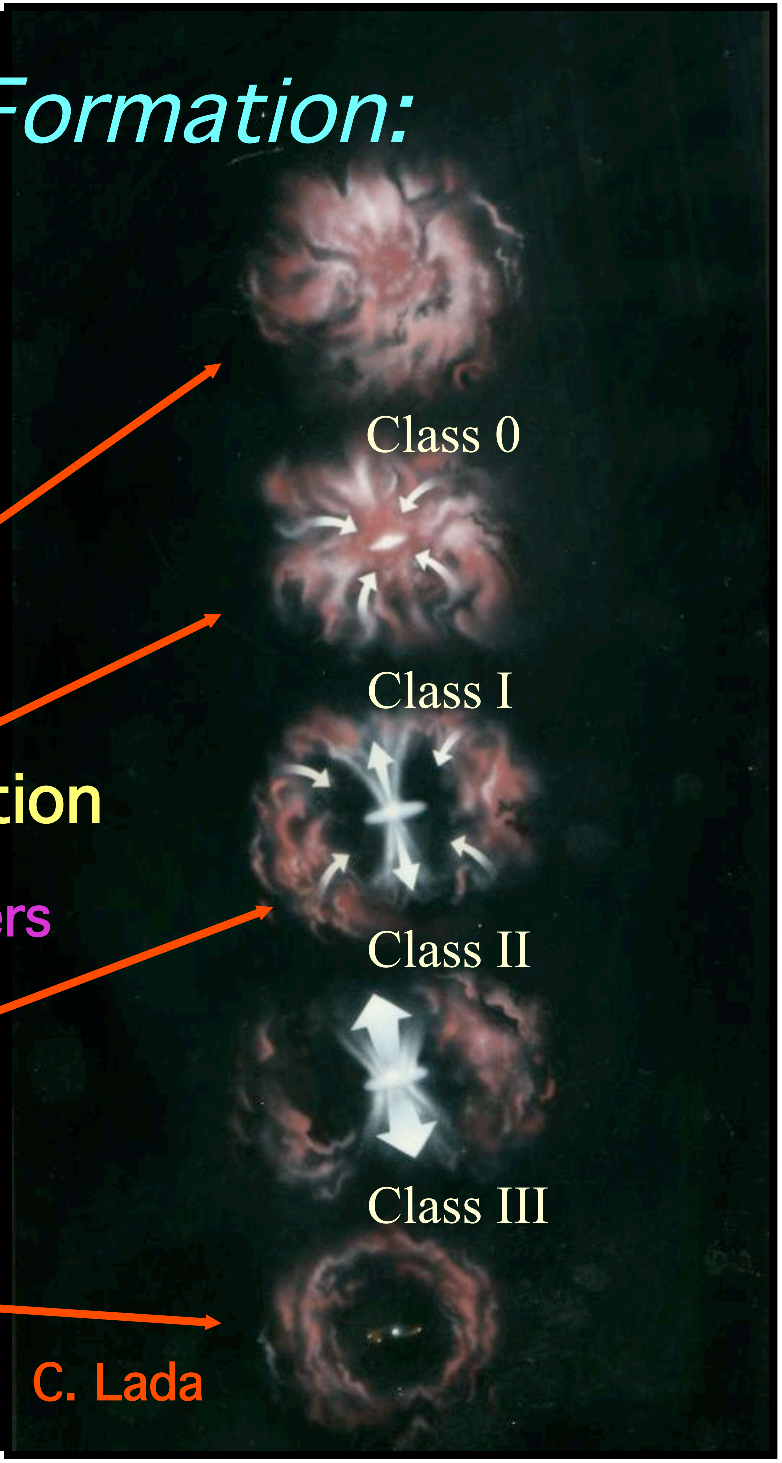
  Proto-stars, proto-binaries, proto-clusters

- Rotation & Magnetic Fields

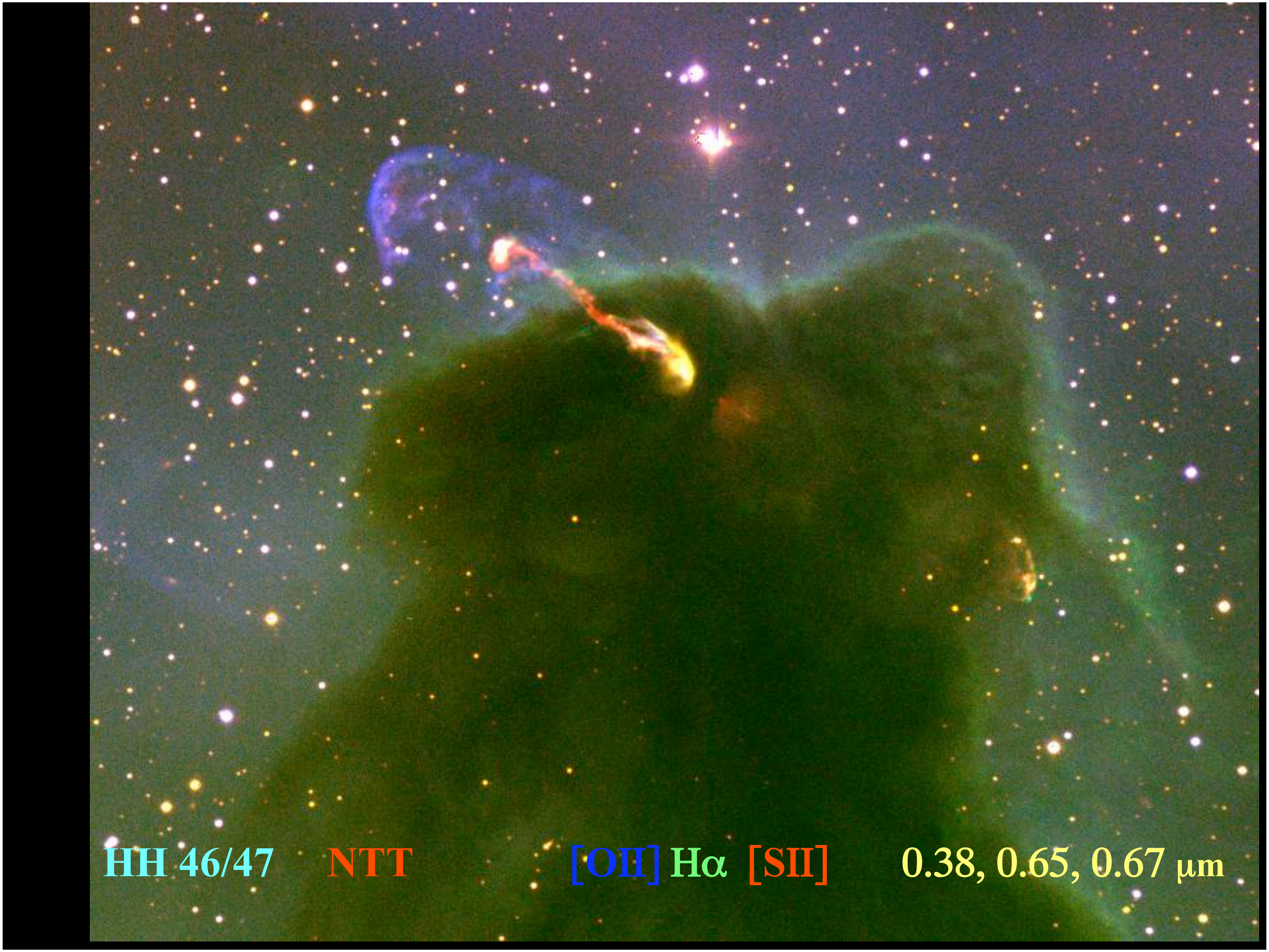
  Accretion disks, jets, & outflows

- Planets

  Most may form in clusters!

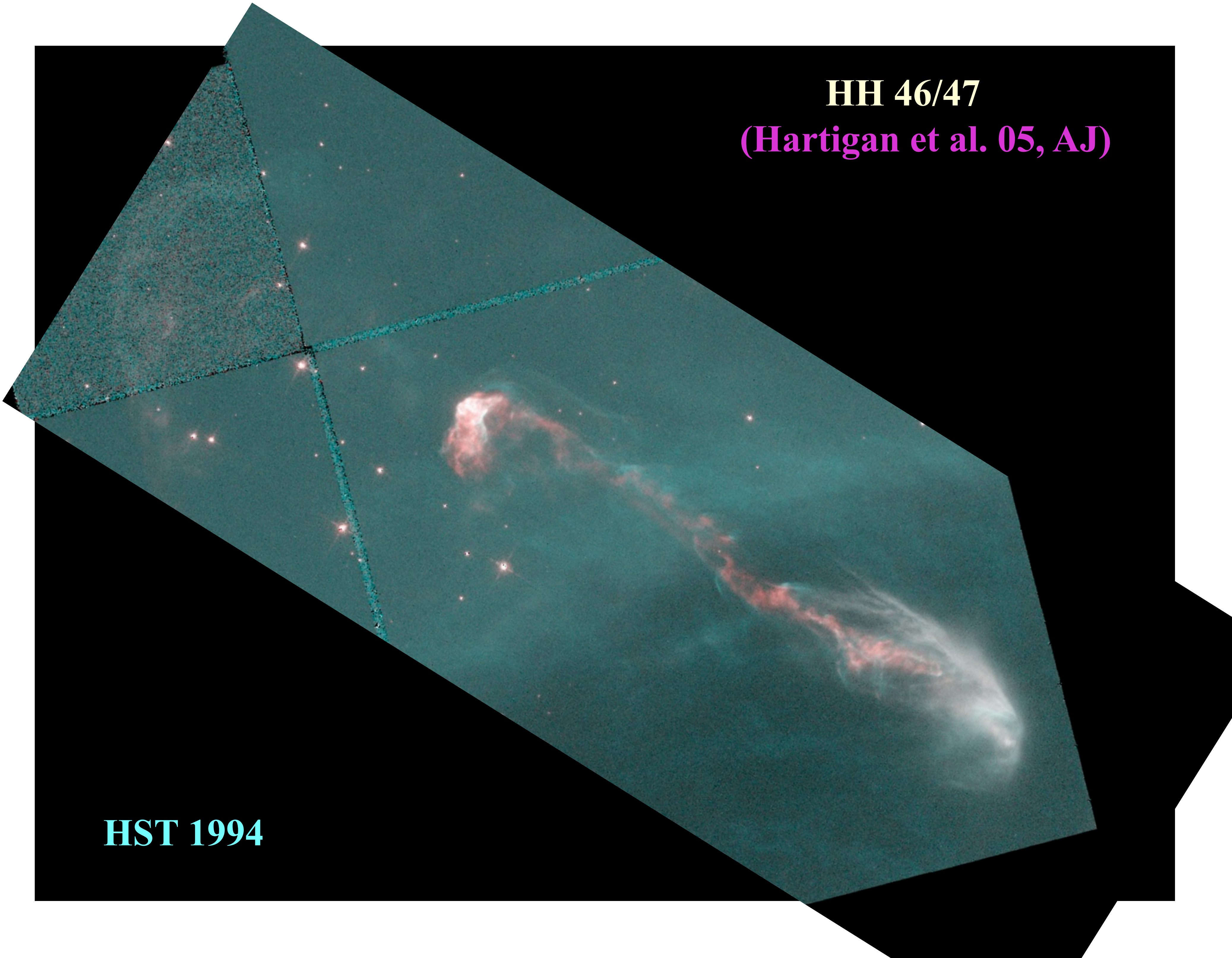


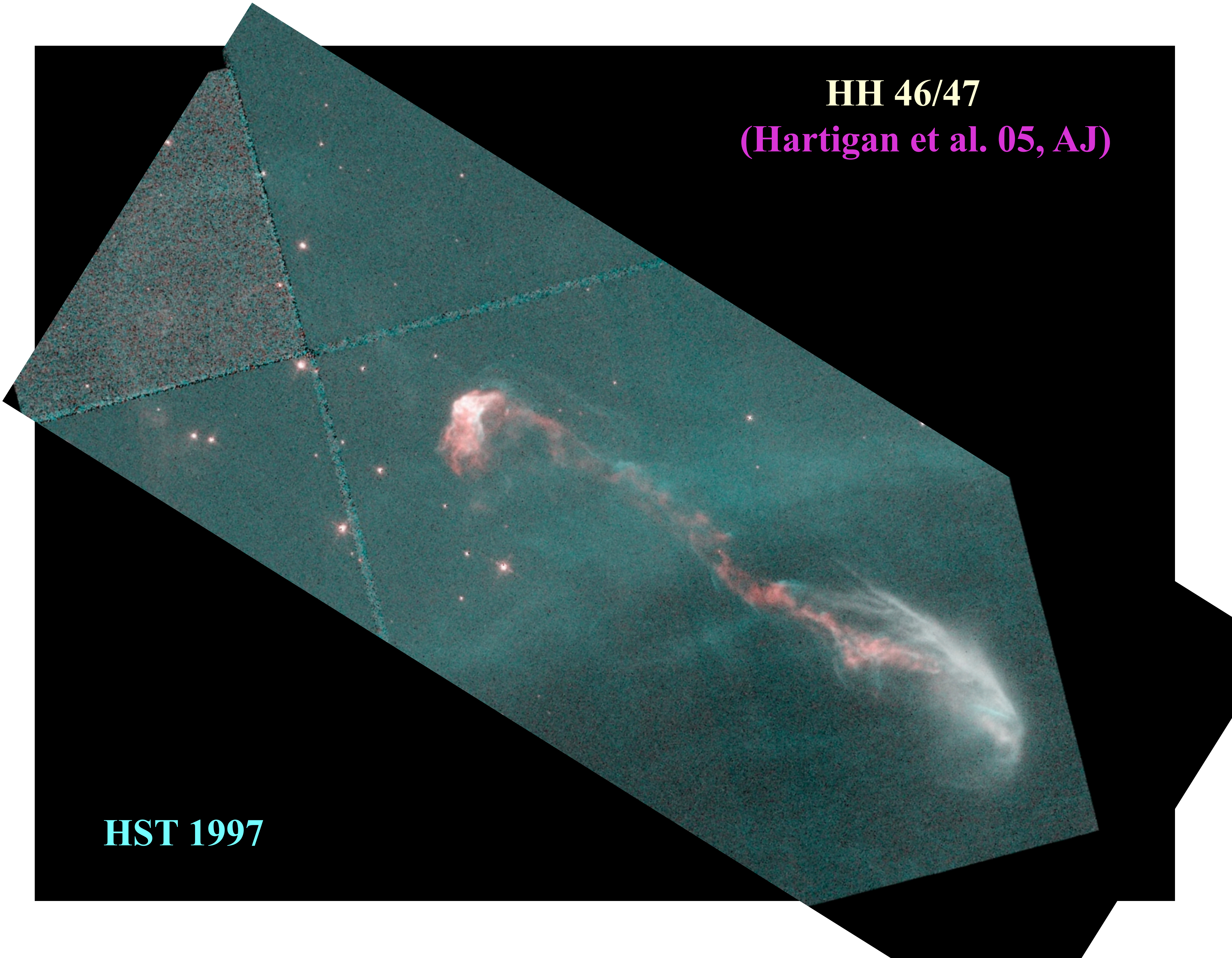
C. Lada


HH 46/47
NTT
[OII] Hα [SII]
0.38, 0.65, 0.67 μm

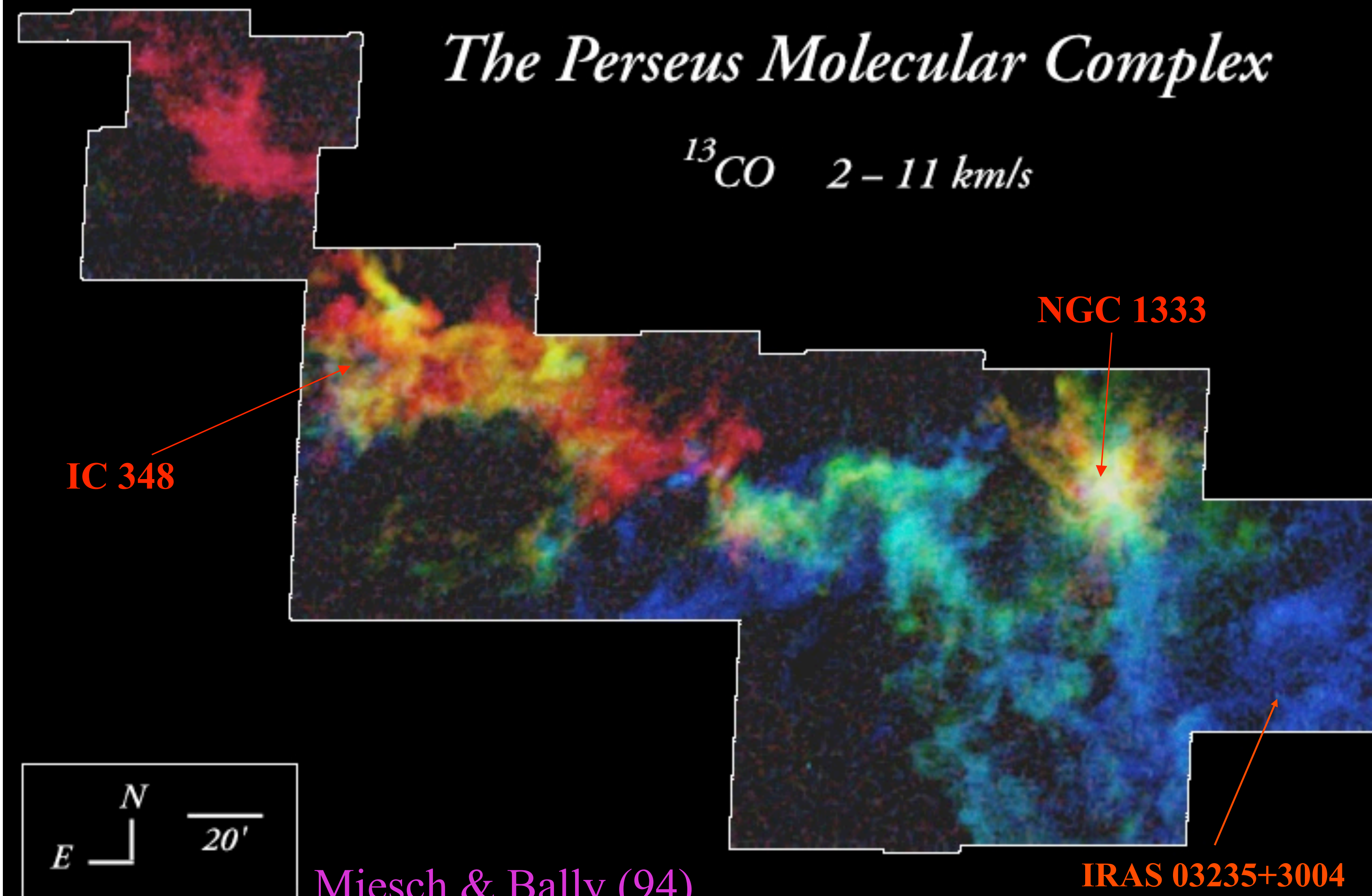
HH 46/47 Spitzer H_2 PAHs 3.6, 4.5, 8 μm

(Noriega-Crespo 04)


HH 46/47
(Hartigan et al. 05, AJ)
HST 1994


HH 46/47
(Hartigan et al. 05, AJ)
HST 1997

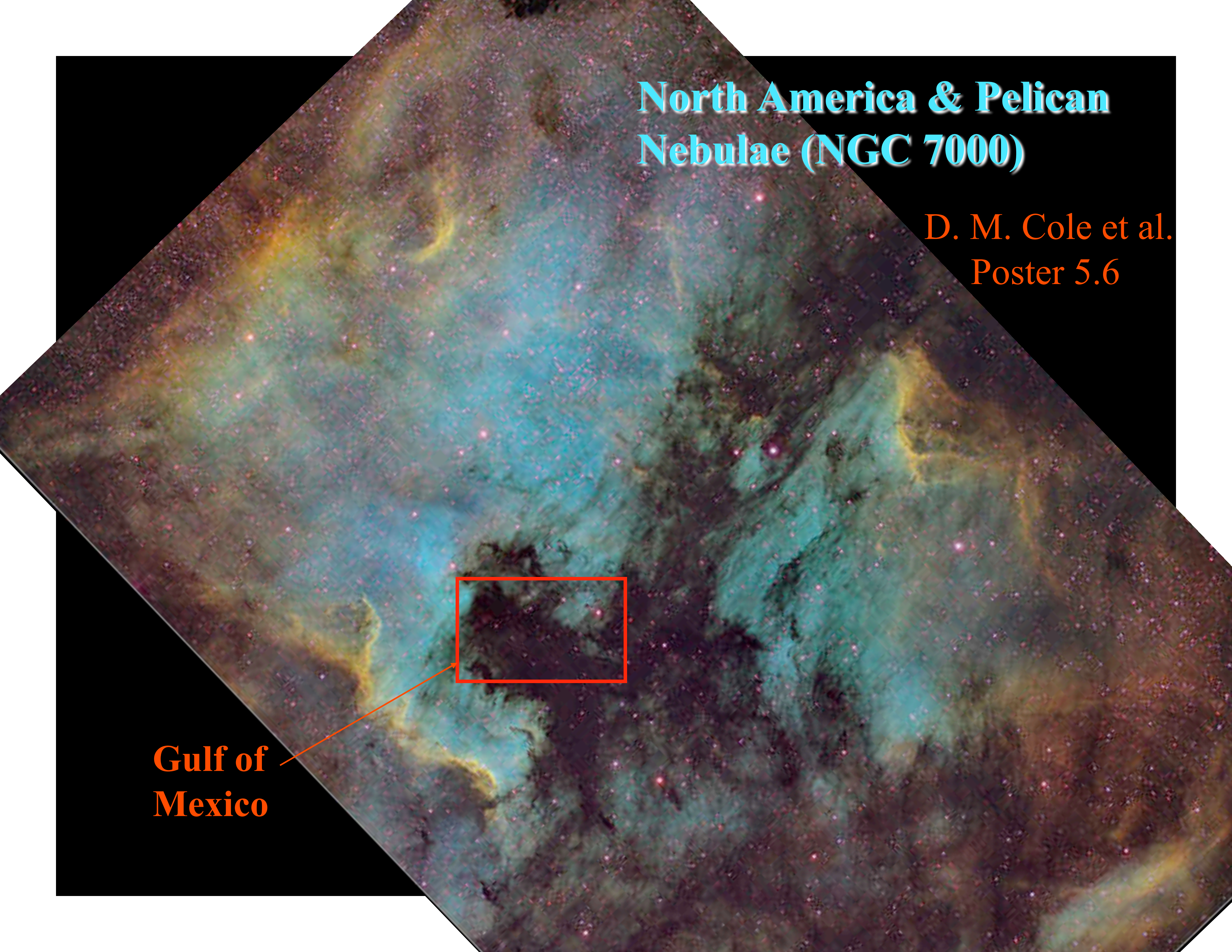
Clustered low- intermediate-mass Star Formation



Miesch & Bally (94)

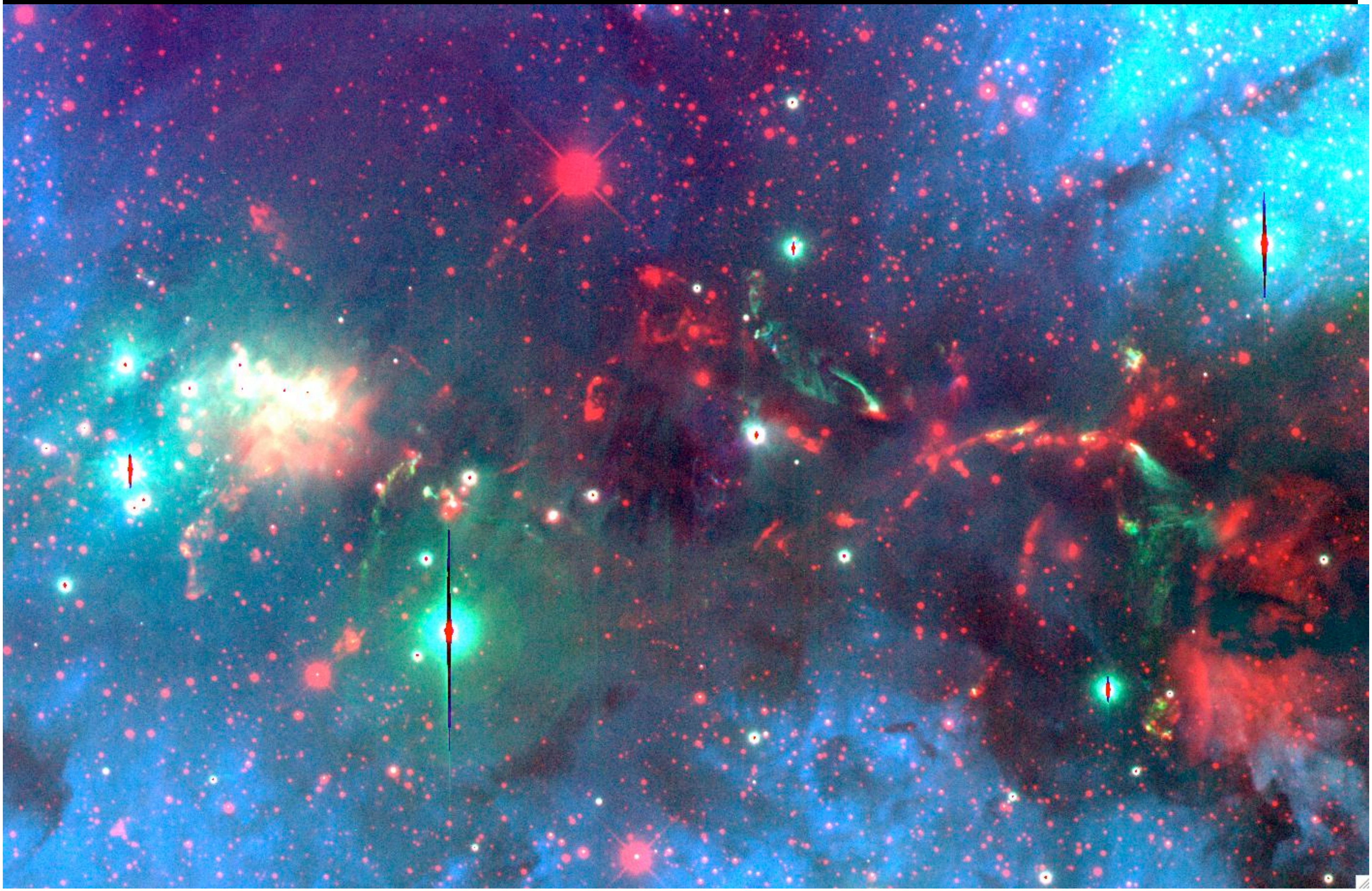
NGC 1333

Ha, [SII]
Walawender, Bally, Reipurth (06)
Spitzer/IRAC
Jorgensen et. (06)


North America & Pelican
Nebulae (NGC 7000)
D. M. Cole et al.
Poster 5.6
Gulf of
Mexico

Clustered Star Formation in the Gulf of Mexico (NGC 7000)

Ha, [SII], H_2 (2.12 μm)



Massive Stars

Multiplicity high

Companion fraction ~ 1.5 vs. 0.5 for Sun

(Zinnecker et al. 2005, PPV)

High-velocity run-away stars

10% V > 100 km/s

30% V > 20 km /s

(Gies & Bolton 1986, ApJS, 61, 419)

Born in clusters

(Lada & Lada 03; PPV proceedings)

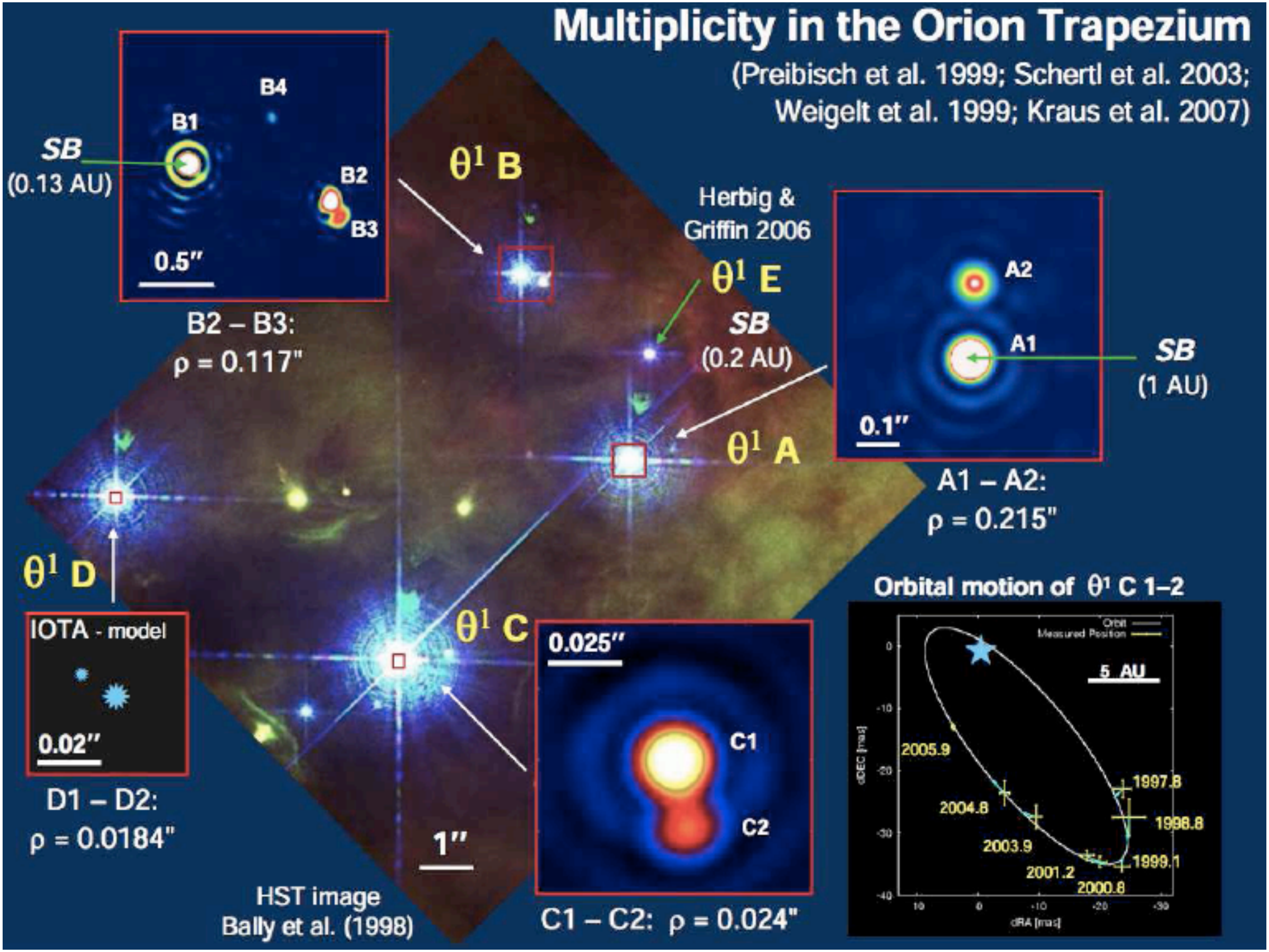
No pre-main sequence phase

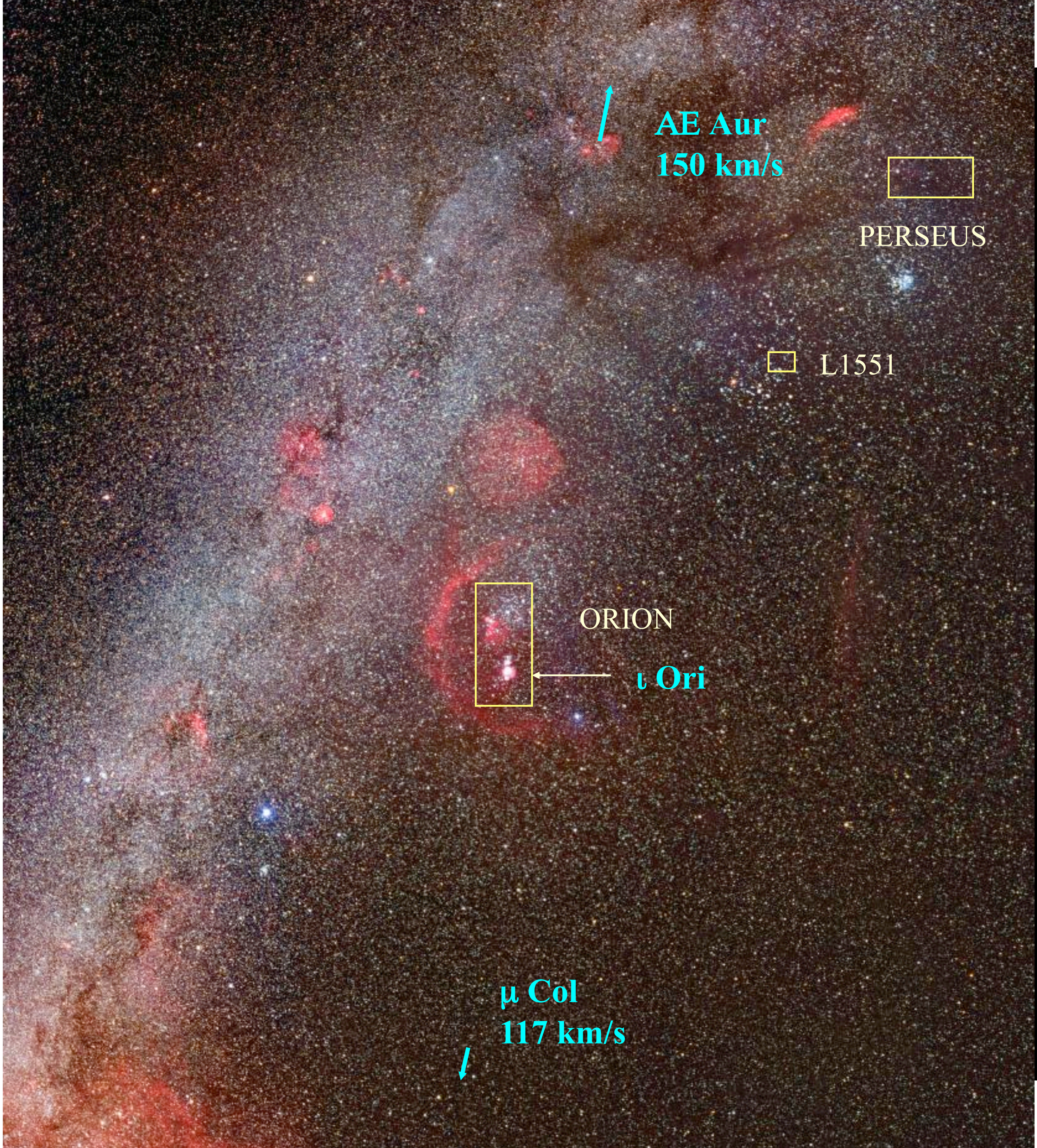
$t_{accretion} > t_{contraction}$

Mass Segregation

Massive stars form in cluster center

(Zinnecker & Yorke 07, McKee & Ostriker 07, ARAA)

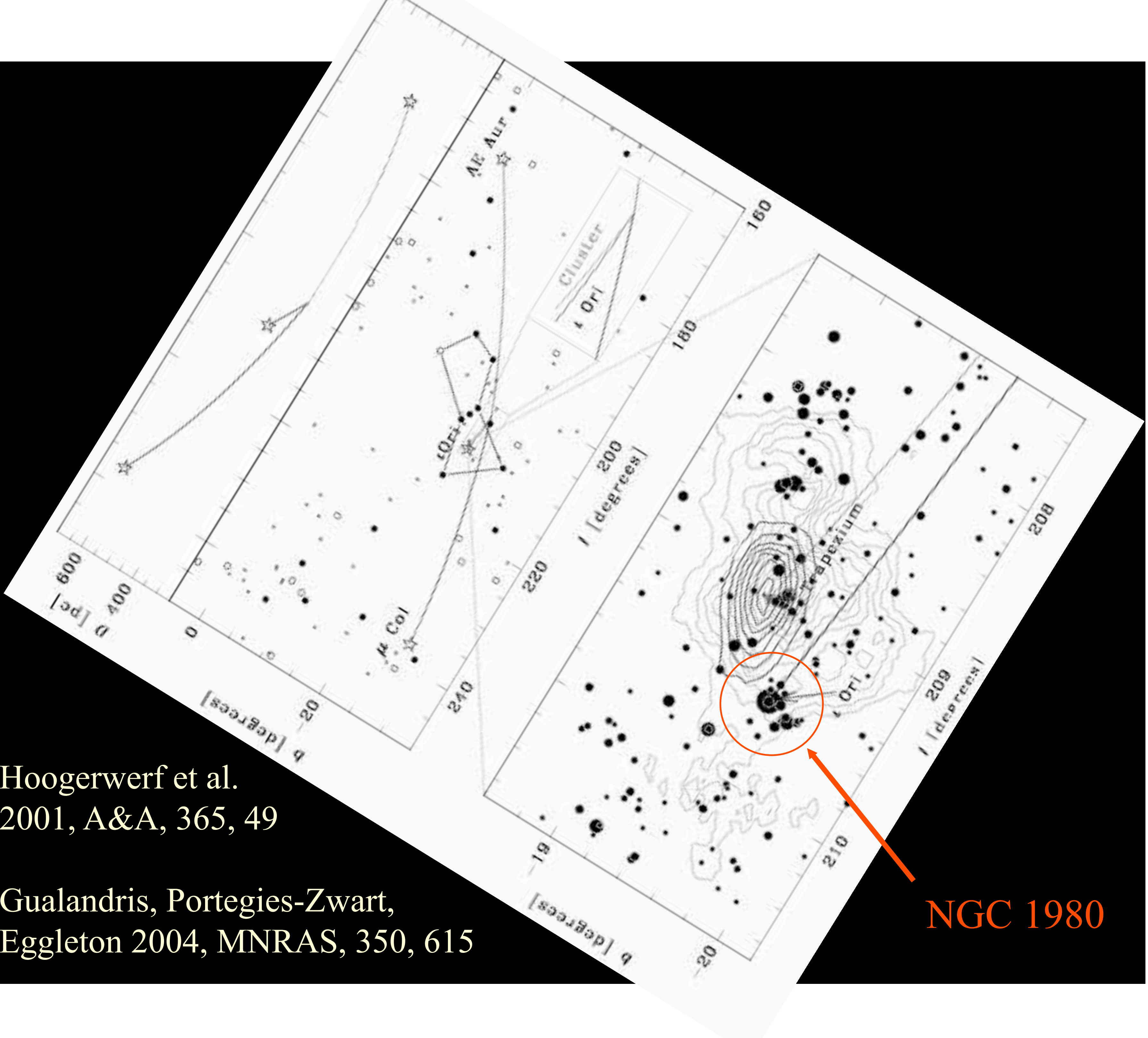

Multiplicity in the Orion Trapezium
(Preibisch et al. 1999; Schertl et al. 2003;
Weigelt et al. 1999; Kraus et al. 2007)
B4
B1
SB
(0.13 AU)
B2
B3
0.5″
B2 – B3:
ρ = 0.117"
θ1 B
Herbig &
Griffin 2006
θ1 E
SB
(0.2 AU)
A2
A1
SB
(1 AU)
0.1″
θ1 A
A1 – A2:
ρ = 0.215"
θ1 D
IOTA - model
0.02″
D1 – D2:
ρ = 0.0184"
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
Orbit
Measured Position
5 AU
2005.9
2004.8
2003.9
2001.2
2000.8
1999.1
1998.8
1997.8
dDEC [mas]
dRA [mas]



Orion Run-away stars:

AE Aur
μ Col
53 Aries
…

Wei-Hao Wang



Hoogerwerf et al.
2001, A&A, 365, 49

Gualandris, Portegies-Zwart,
Eggleton 2004, MNRAS, 350, 615

NGC 3603

Compact
cluster

~ 50 OB stars

τ < 5 Myr

HST

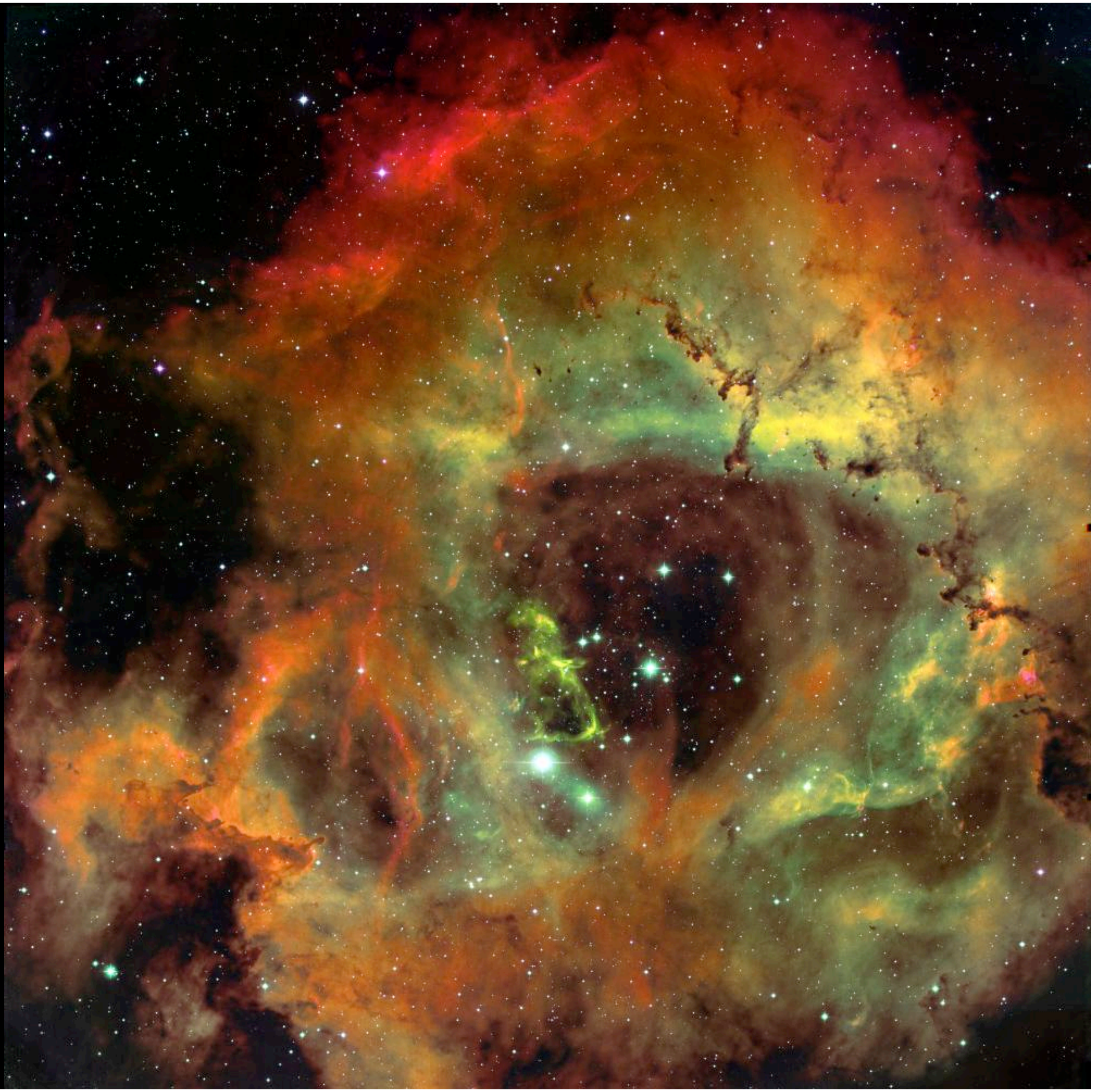
Rosette

Loose
cluster

~ 10 OB stars

τ < 5 Myr

NOAO 4m



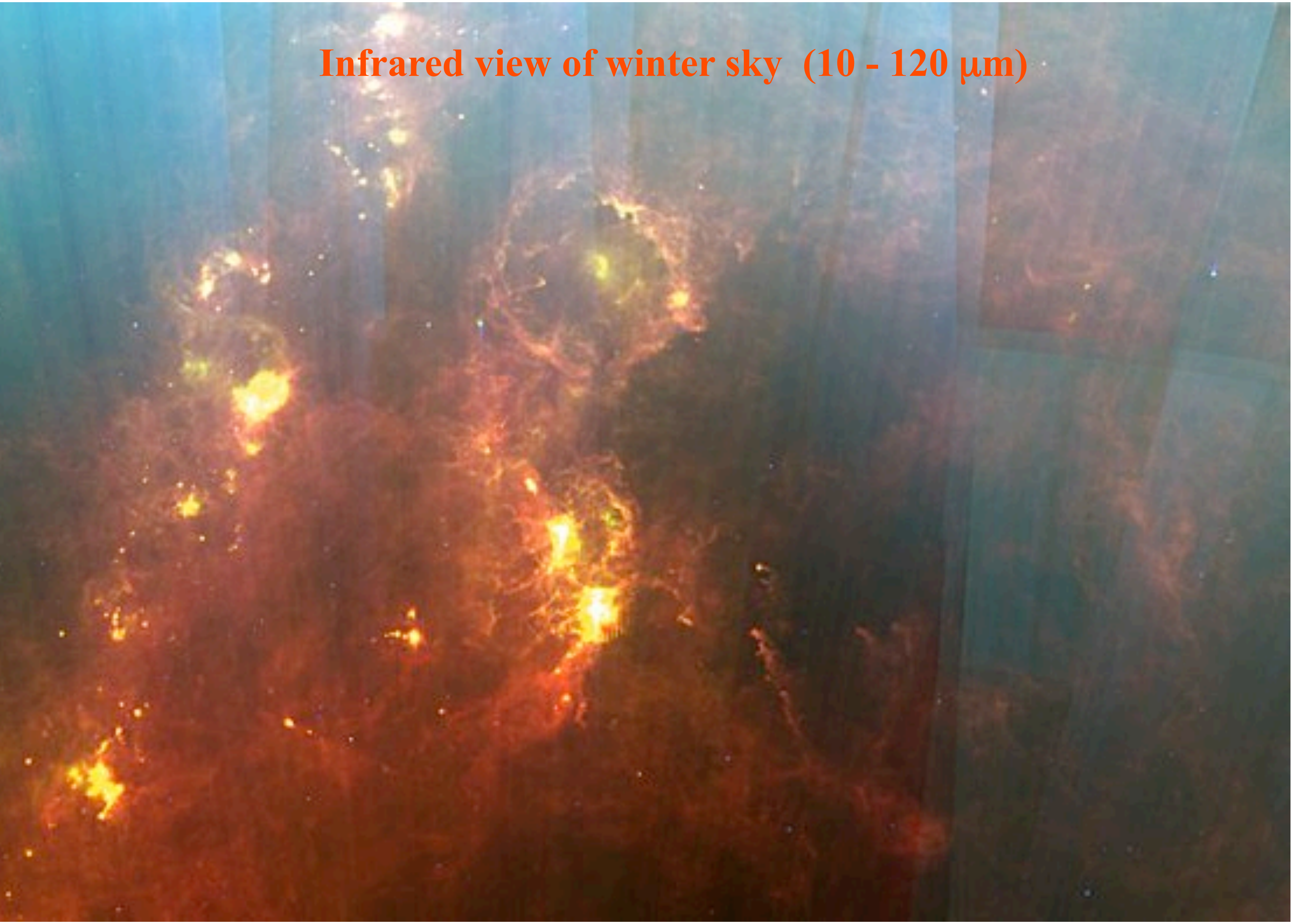
Orion

OB Association

~ 10 - 50 OB stars

$\tau < 15$ Myr

50 mm camera + Hα

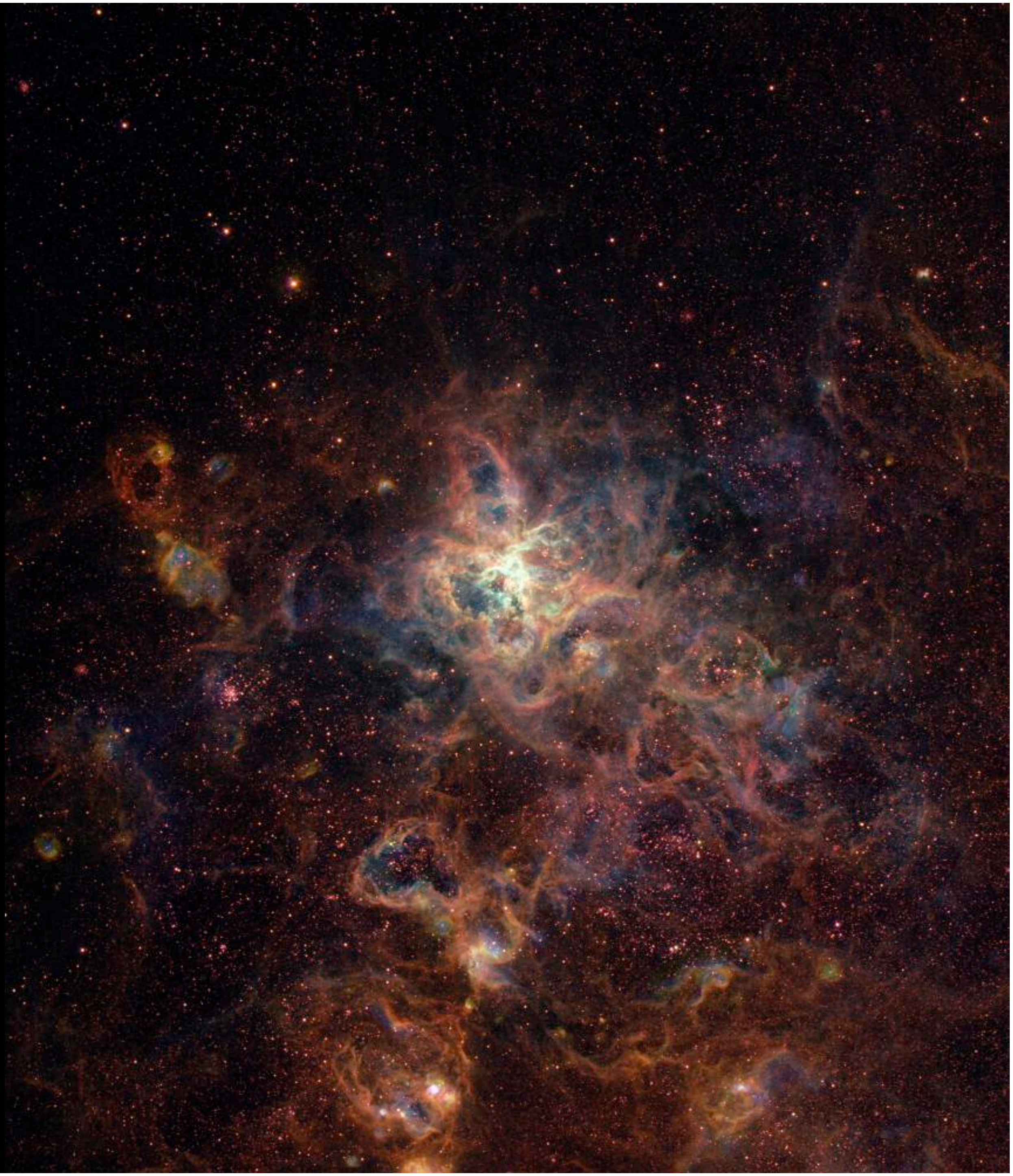

Infrared view of winter sky (10 - 120 μm)

30 Dor / Tarantula

OB Association
+ R136 cluster

~ 200 - 500 OB stars

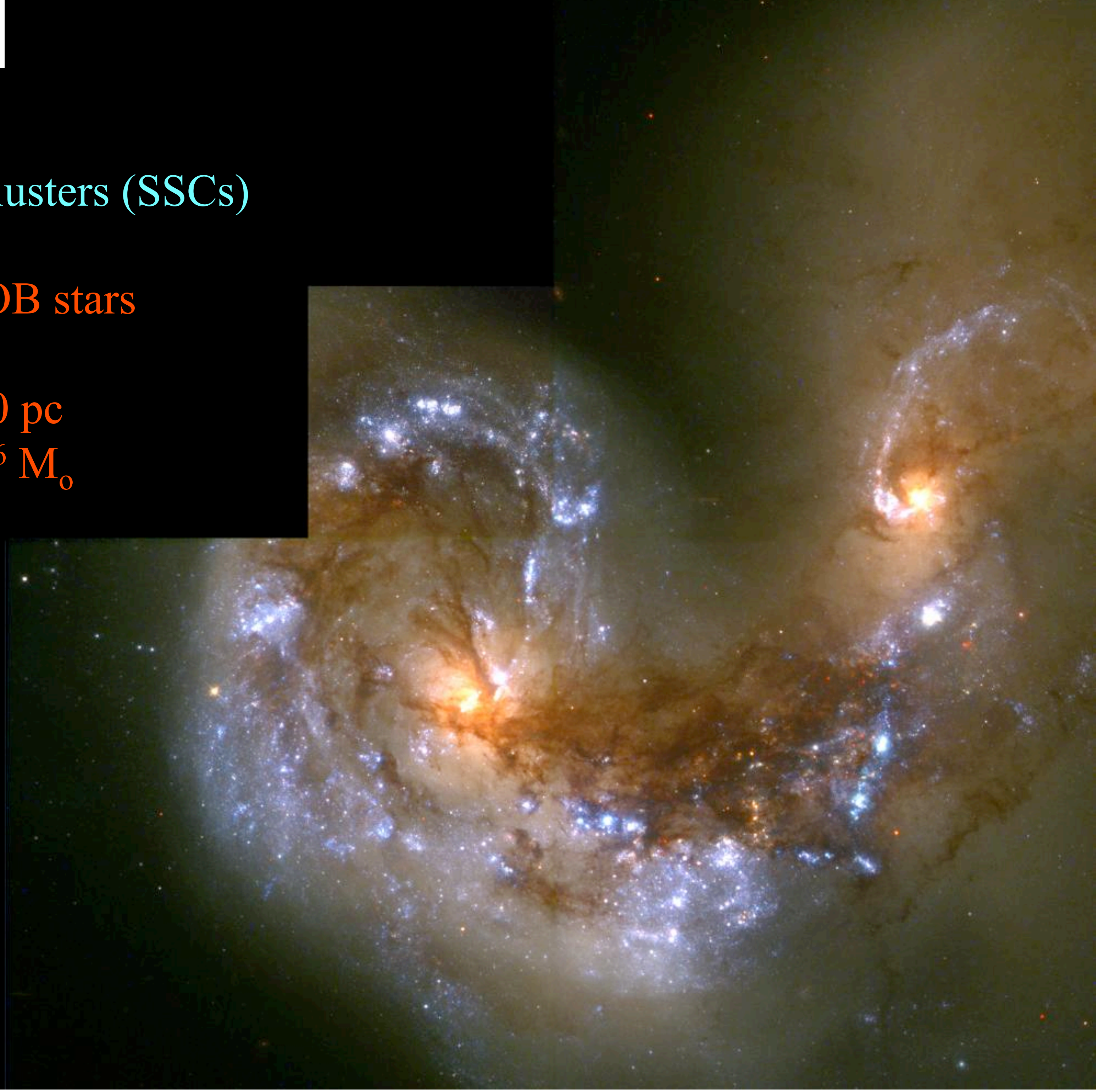
τ < 15 Myr



Antennae
Super Star Clusters (SSCs)

500 - 5,000 OB stars

Sizes = 1 - 10 pc
M = 10^4 - 10^6 M_o
τ < 15 Myr



HST

Massive Star Formation

GMC =>Turbulent fragmentation=> clump => core => star

Isolated Monolithic Collapse

Scaled-up low-mass star formation

High-P , high surface density (> 1 g cm^{-2})

- Mc Kee, Krumholtz, Tan, Klein (2004 => ...)

Clustered Competitive Accretion

Cores interact, compete for matter from reservoir

Most massive stars grow fastest, and in center

- Bonnell, Bate, Zinnecker (1998 => ...)

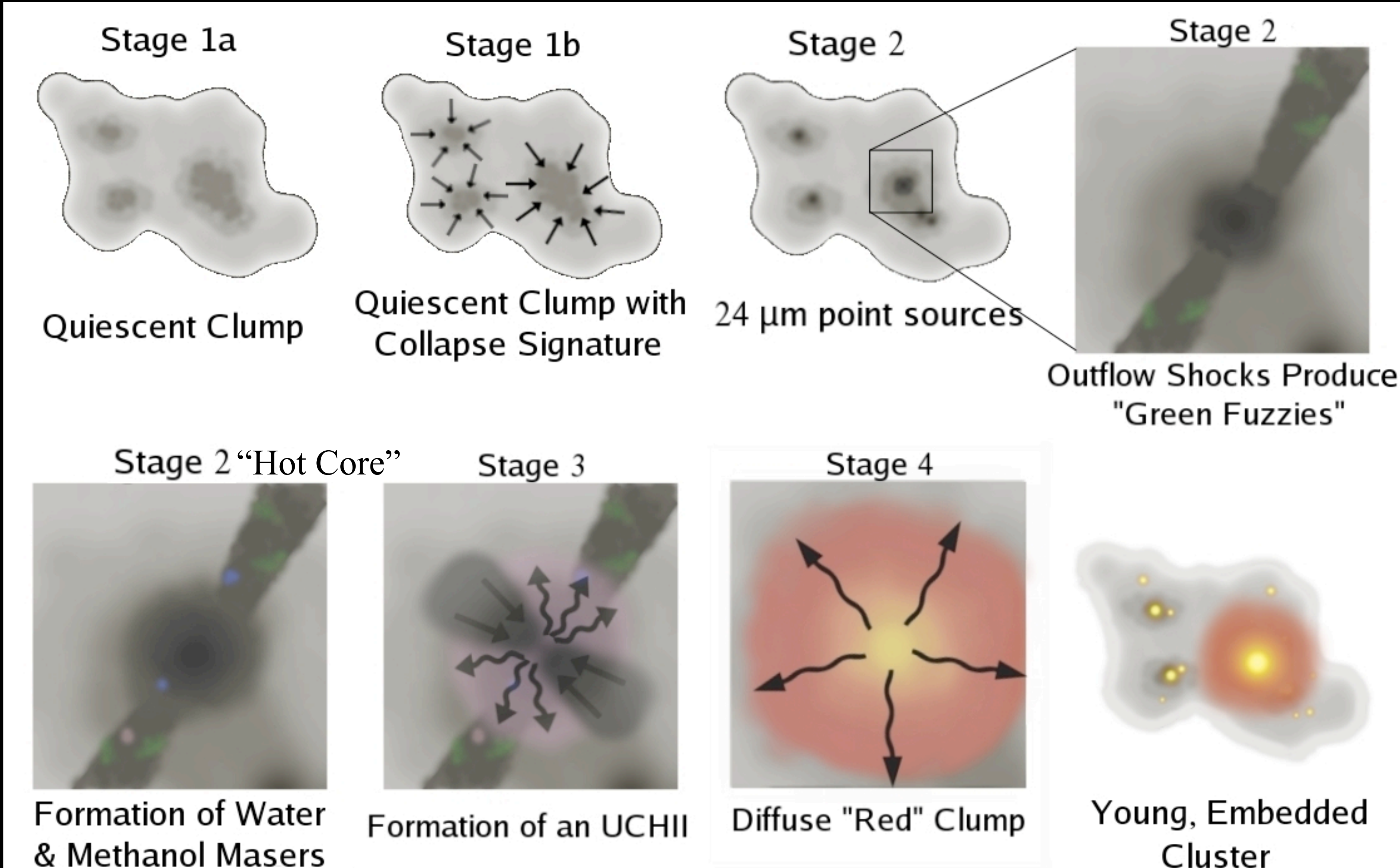
Co-Operative Accretion (in super star clusters)

Near Eddington limit, effective gravity disappears

Secondary stars grow to M_{edd}

- Keto (2003 => ...), Peters et al. (2010)

IRDC / Dust Clump Evolution Sequence



Cara Battersby et al. (2010)

G34.43+0.24

Spitzer/IRAC
+ 1.2 mm MAMBO-2

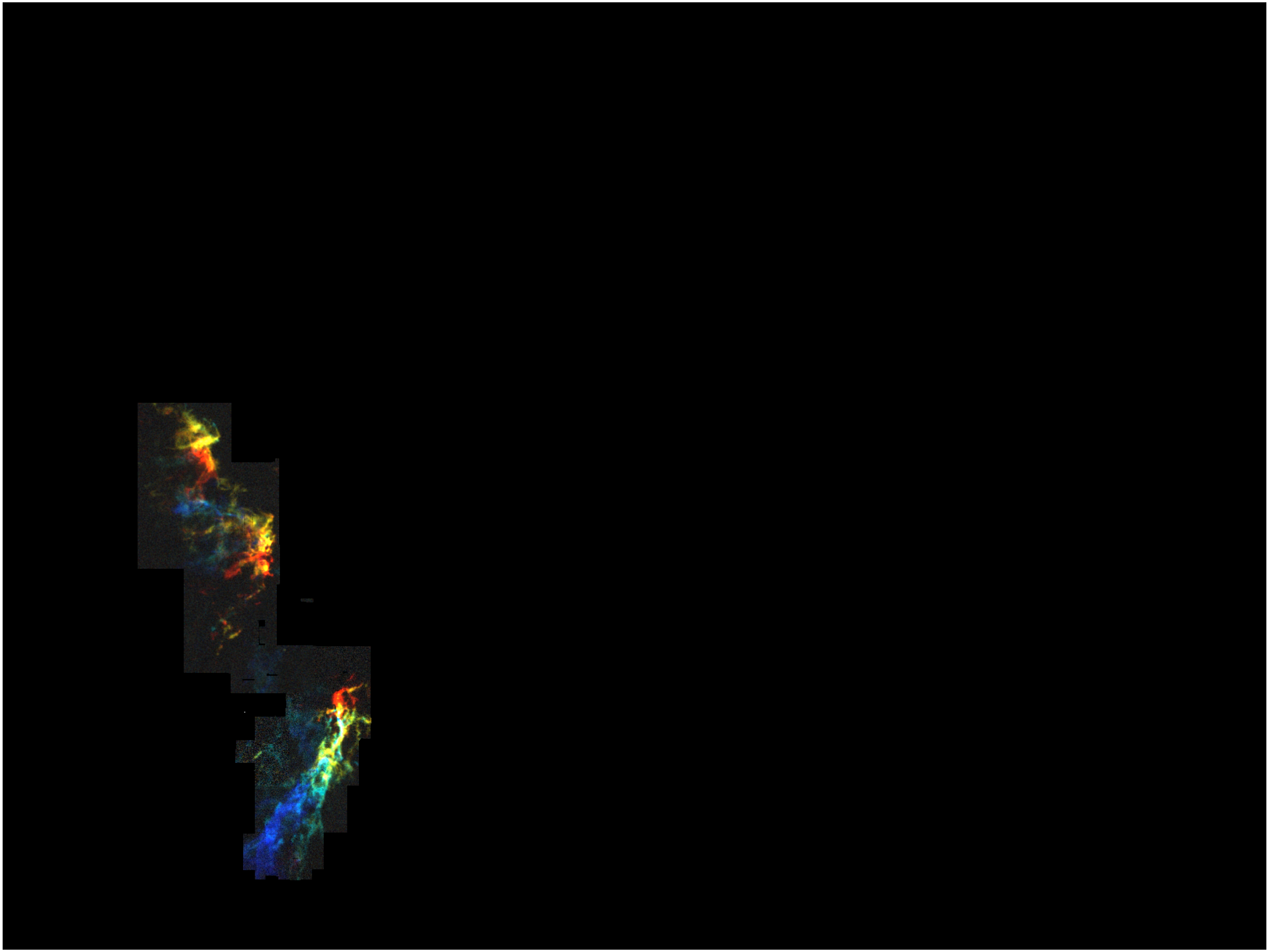
Spitzer/24 μm
+ 1.2 mm MAMBO-2

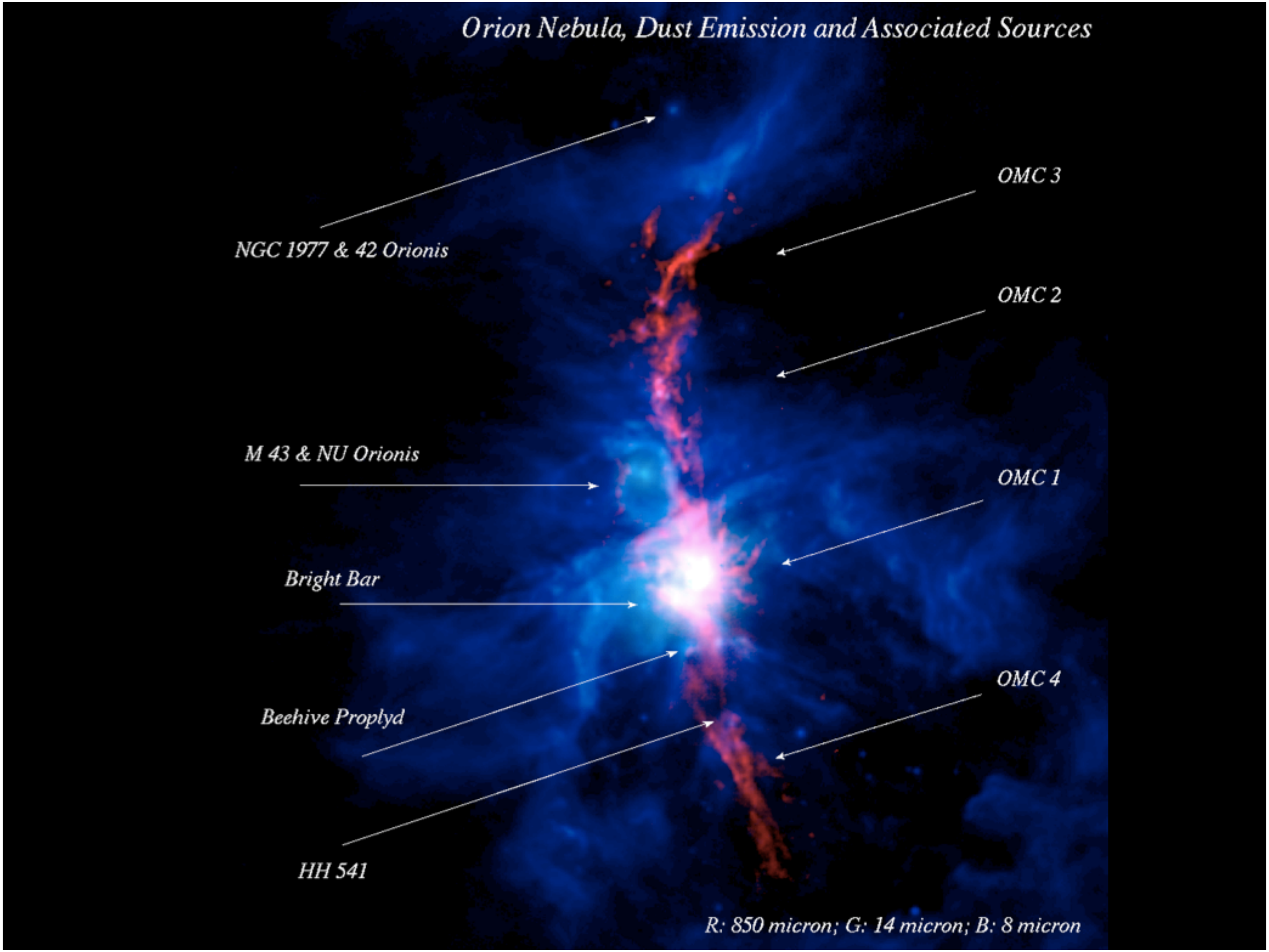
The Feedback Ladder

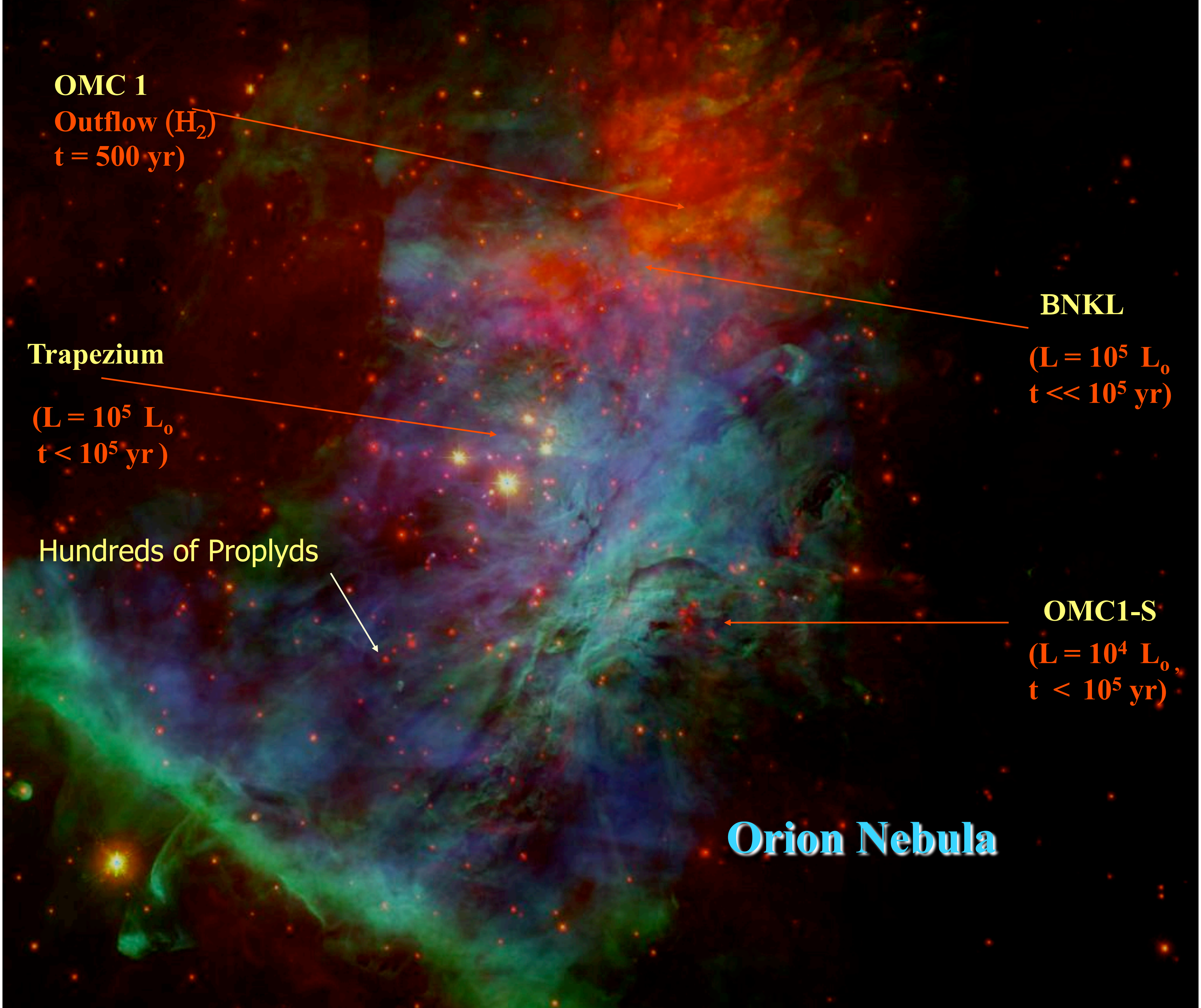
Feedback energy / momentum

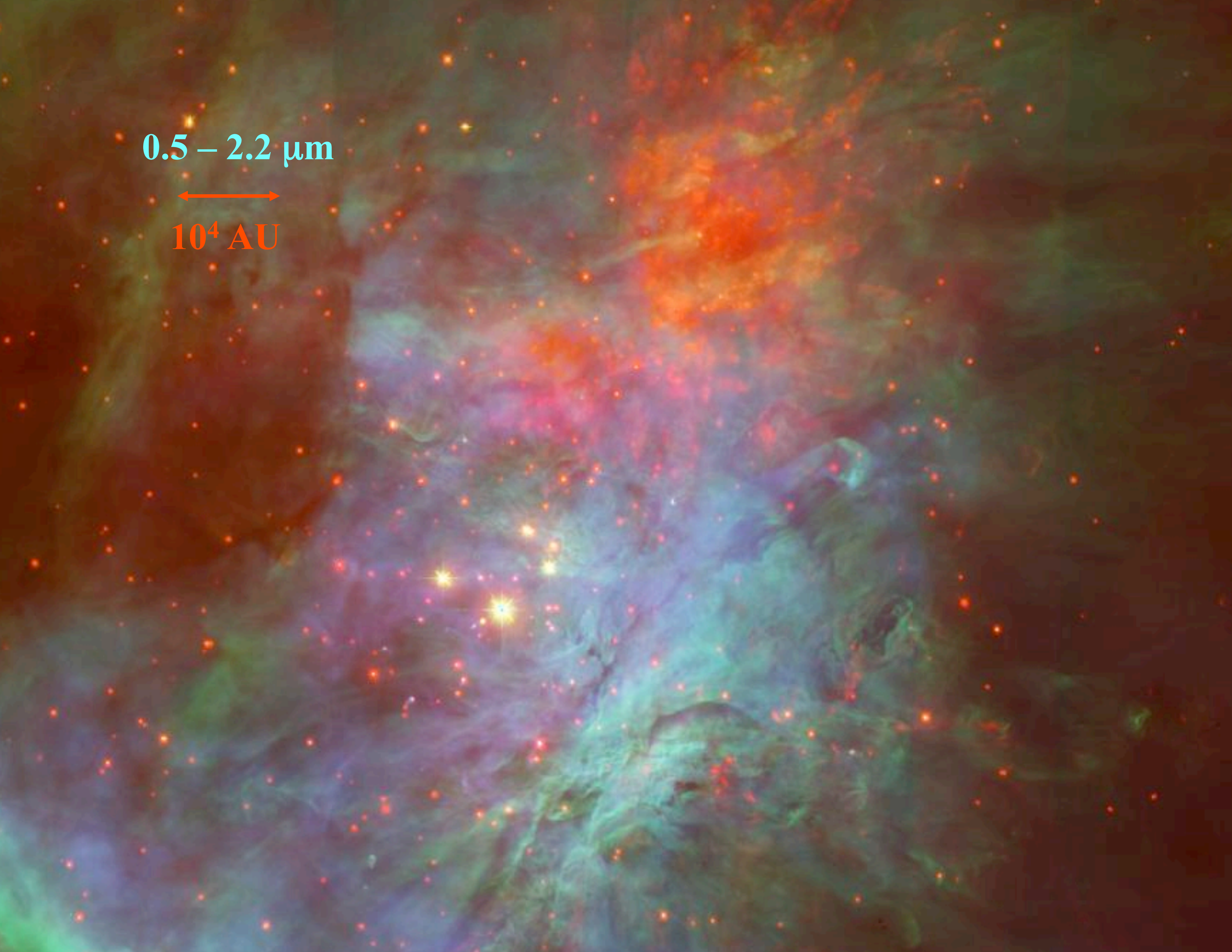
- Protostellar jets / outflows - Low Mass
- Soft UV - Moderate Mass
- Stellar Winds - High Mass
- Ionizing UV “
- Stellar Winds “
- Radiation Pressure “
- Supernovae “


α Ori: 20 km/s
D = 136 - 260 pc
β Ori:
D = 236 pc



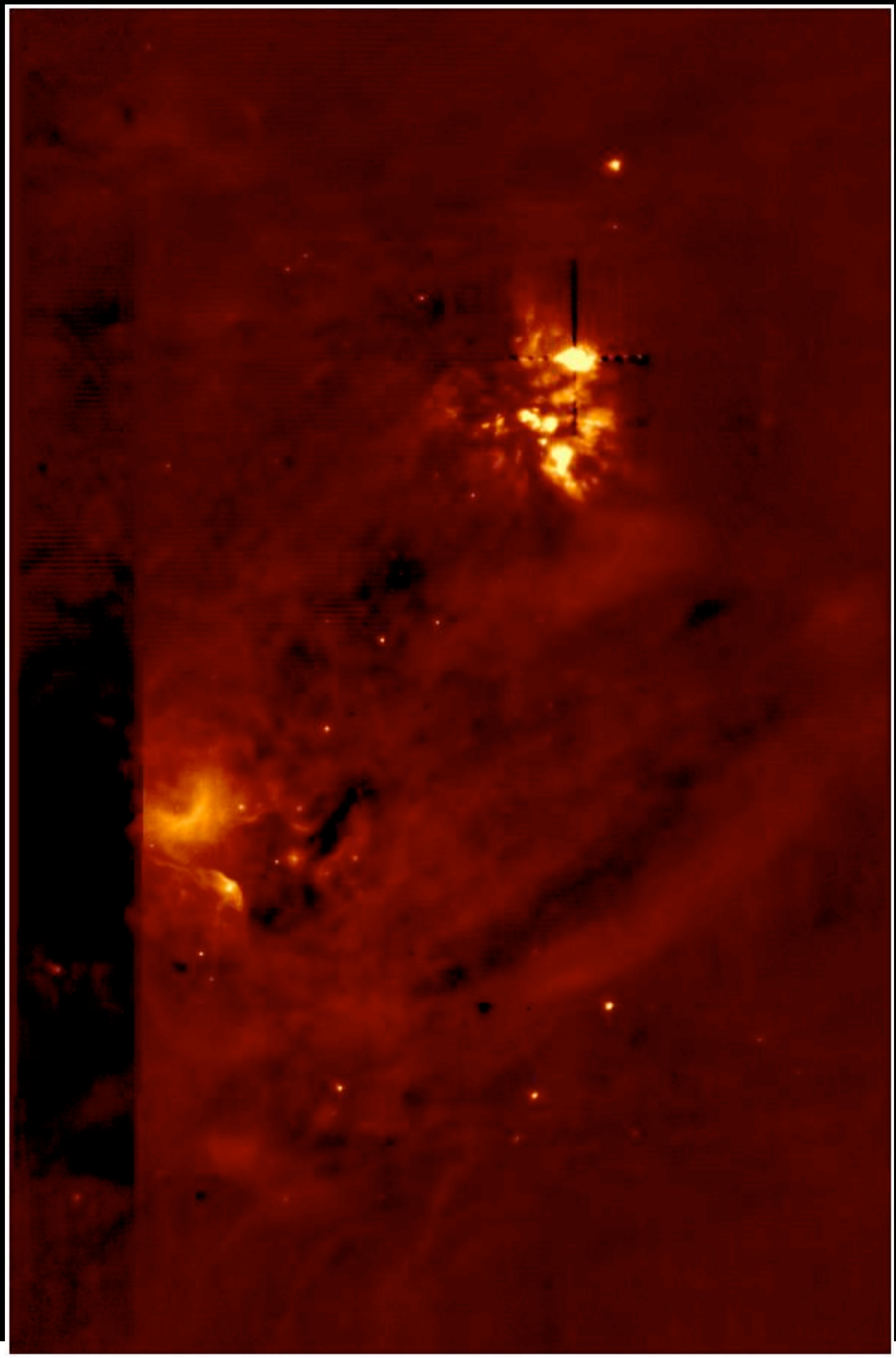

Orion Nebula, Dust Emission and Associated Sources
OMC 3
NGC 1977 & 42 Orionis
OMC 2
M 43 & NU Orionis
OMC 1
Bright Bar
OMC 4
Beehive Proplyd
HH 541
R: 850 micron; G: 14 micron; B: 8 micron


OMC 1
Outflow (H_2)
t = 500 yr)
BNKL
(L = 10^5 L_o
t << 10^5 yr)
Trapezium
(L = 10^5 L_o
t < 10^5 yr)
Hundreds of Proplyds
OMC1-S
(L = 10^4 L_o ,
t < 10^5 yr)
Orion Nebula


0.5 – 2.2 μm
10^4 AU

11.7 μm

10^4 AU



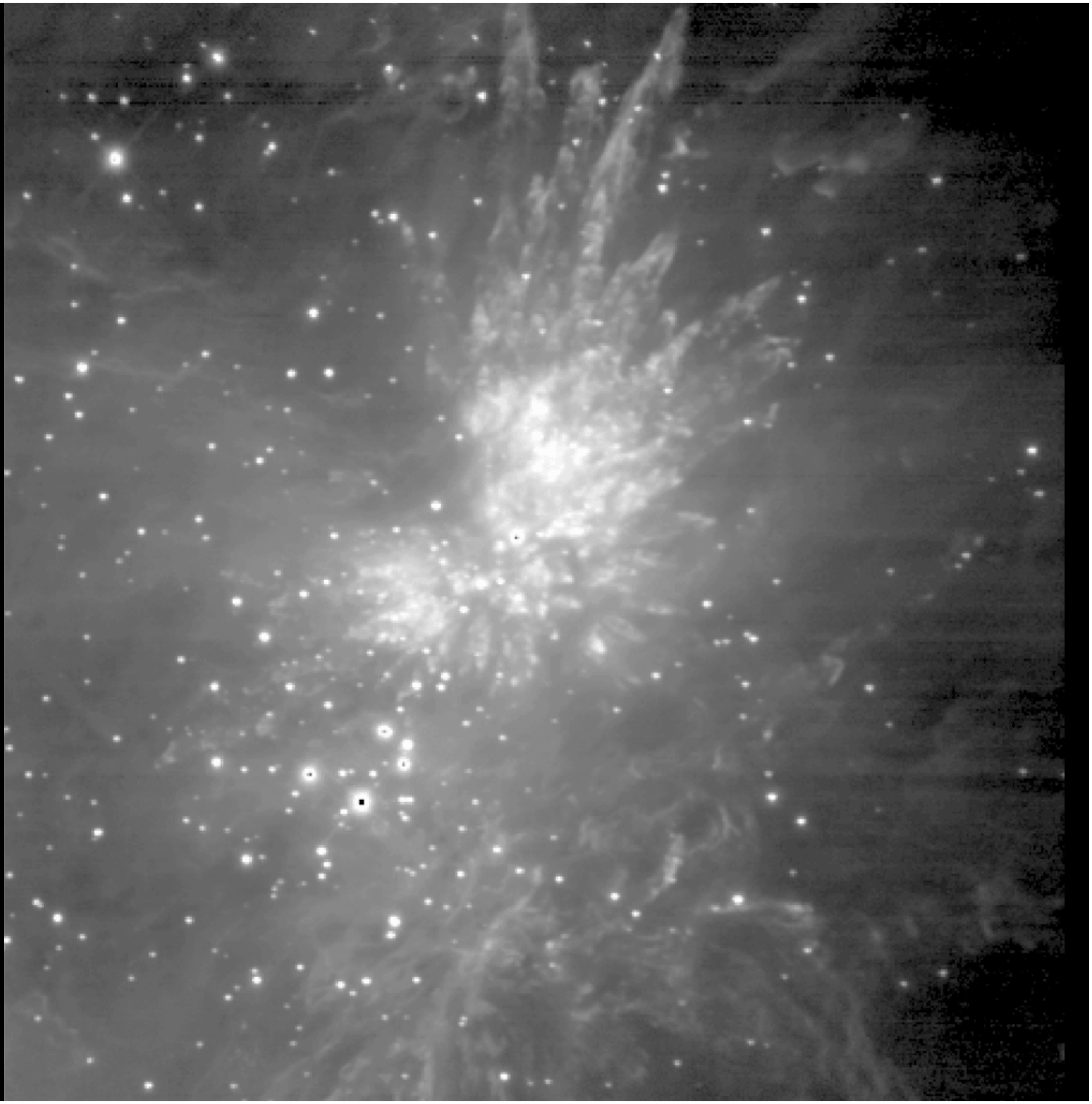
Orion
BN/KL
H_2 fingers

E ~ 10^{48} erg

Dynamical
Decay of
Sub-cluster of
massive stars

~ 500 years ago

(N. Cuningham
2006 PhD thesis)



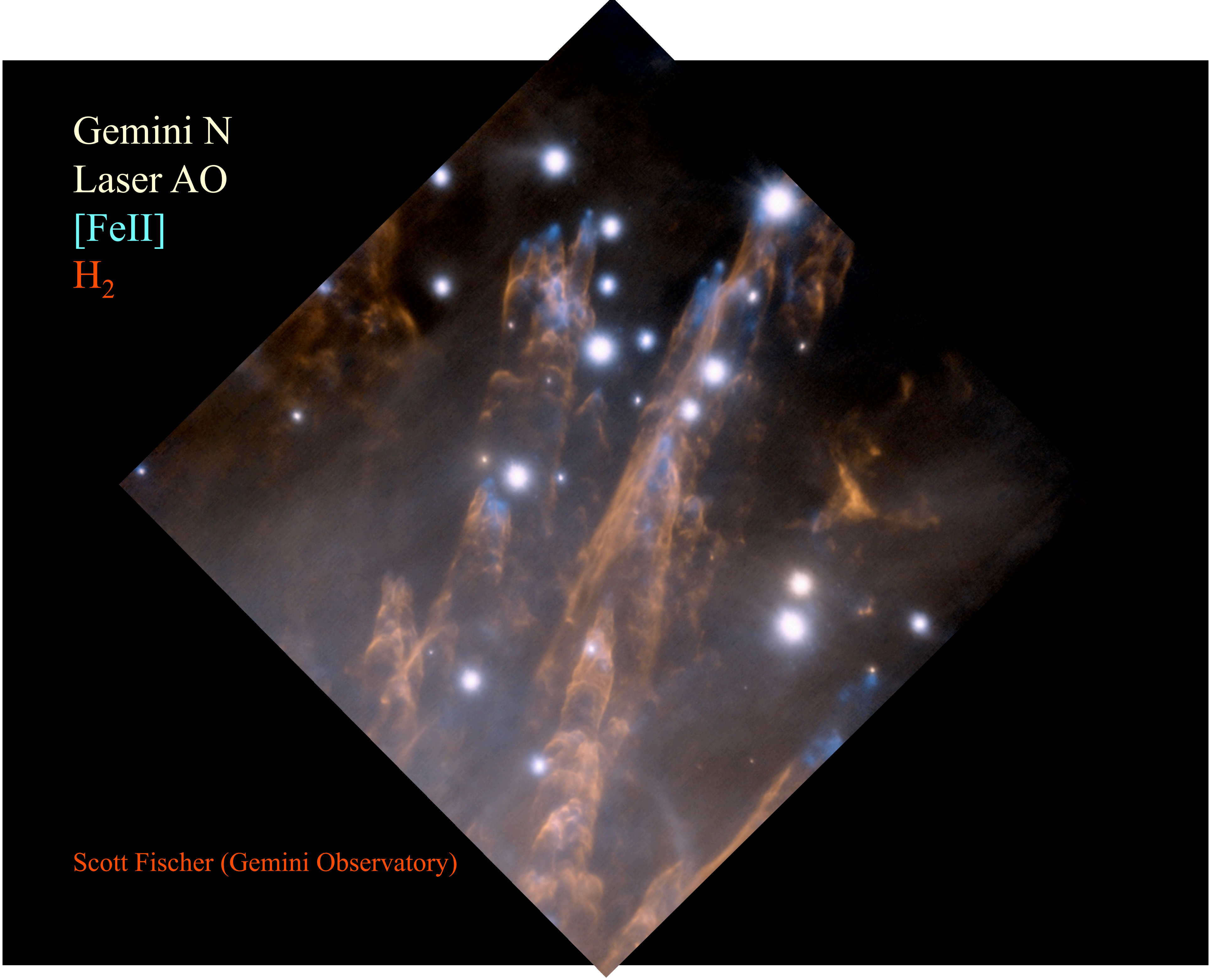
2.12 μm H_2 (blue)

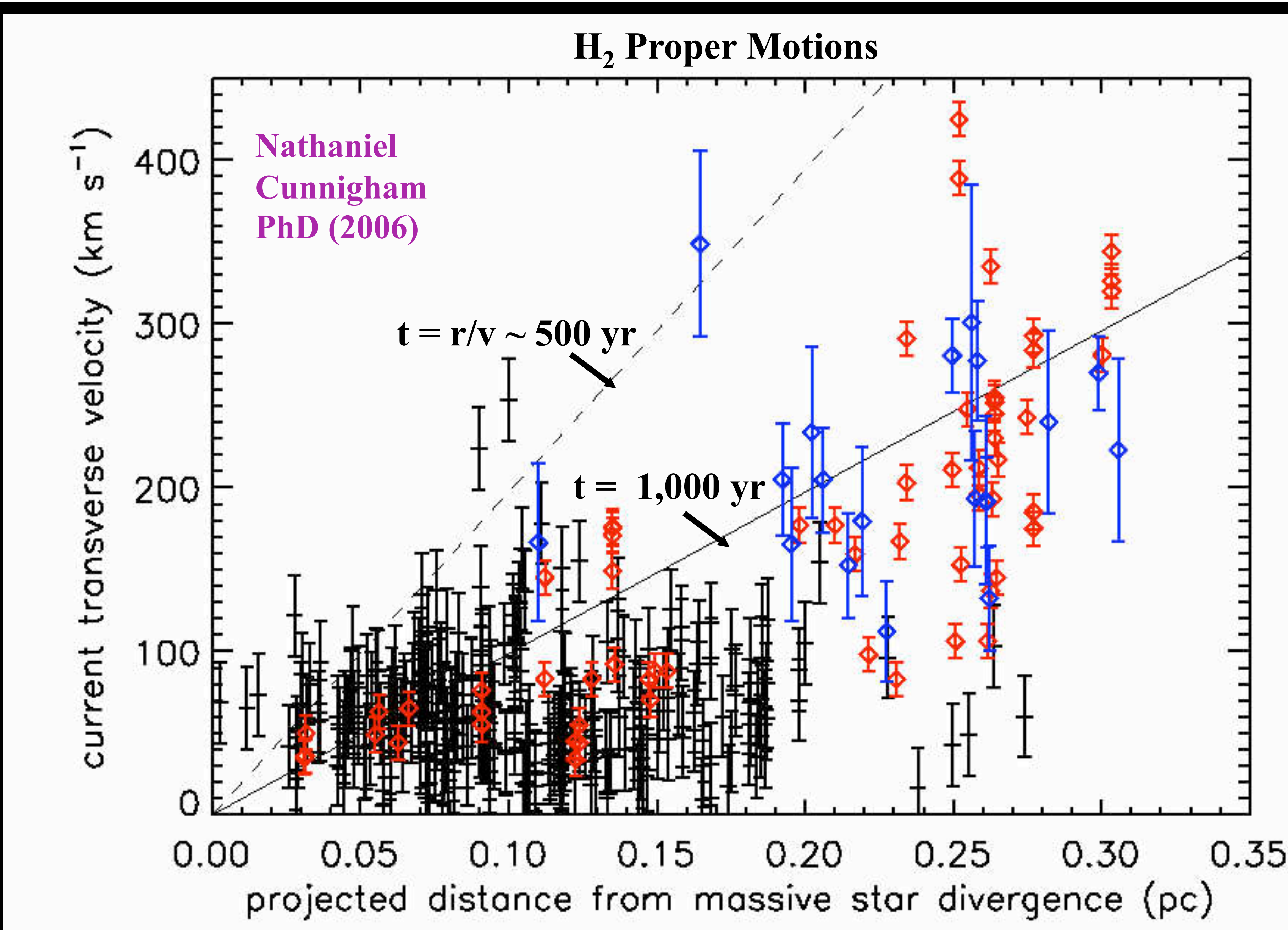
11.7 μm (orange)

Smith et al. (2005)

+

Cunningham (2008)


Gemini N
Laser AO
[FeII]
H_2
Scott Fischer (Gemini Observatory)



N. Cunningham, (PhD thesis 2006) ; Bally et al. (in prep)

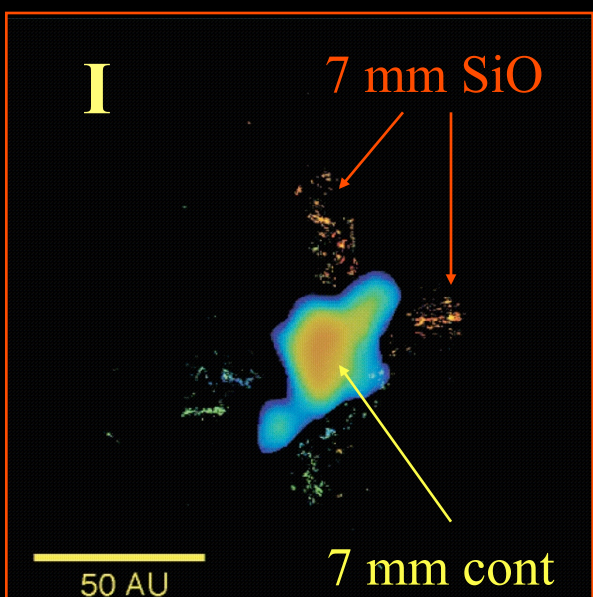
High-velocity stars: I , BN , n

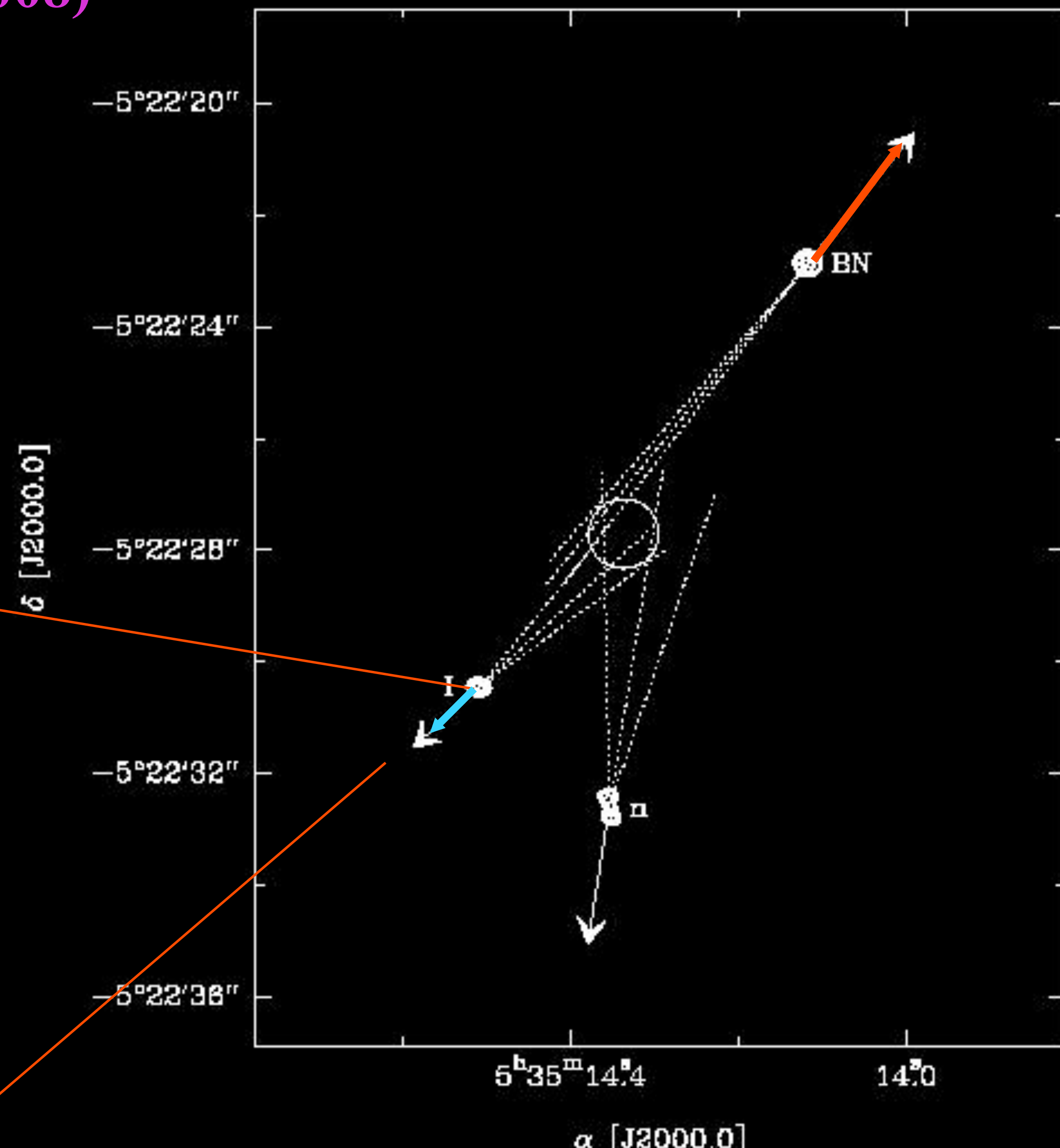
(Gomez et al. 2005, 2008)

BN: V~ 30 km s^{-1}

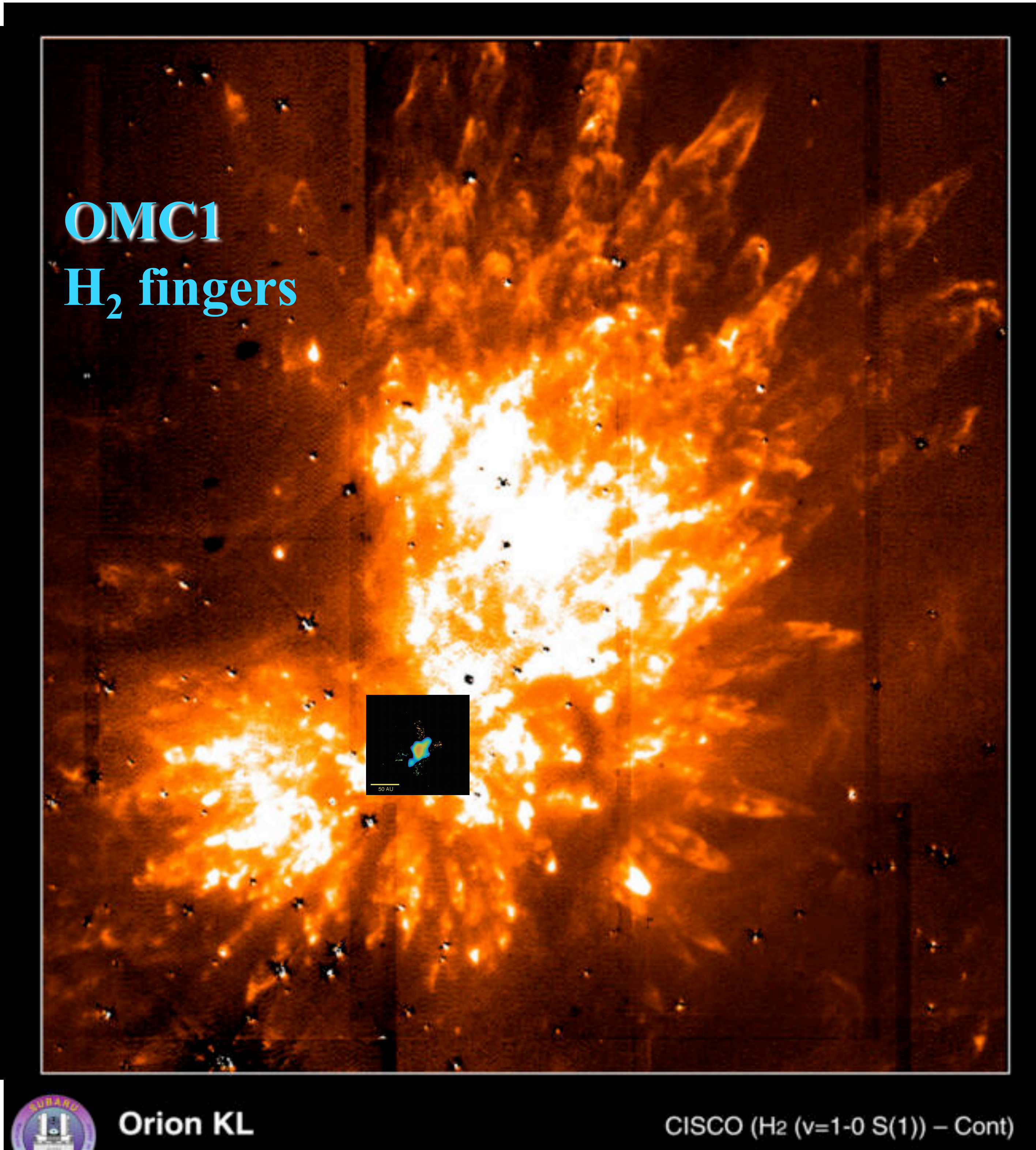
I: V~ 13 km s^{-1}

n: V~ 20 km s^{-1}

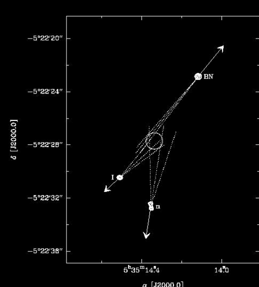





BN
I (me)
Zinnecker



Kaifu et al. (00); Underhill et al. (01)


−5°22′20″
−5°22′24″
−5°22′28″
−5°22′32″
−5°22′36″
δ [J2000.0]
BN
I
n
5h35m14.s4
14.s0
α [J2000.0]

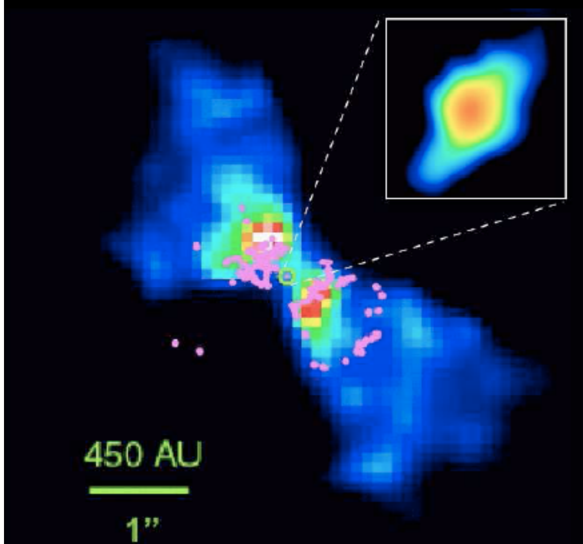
Source I:

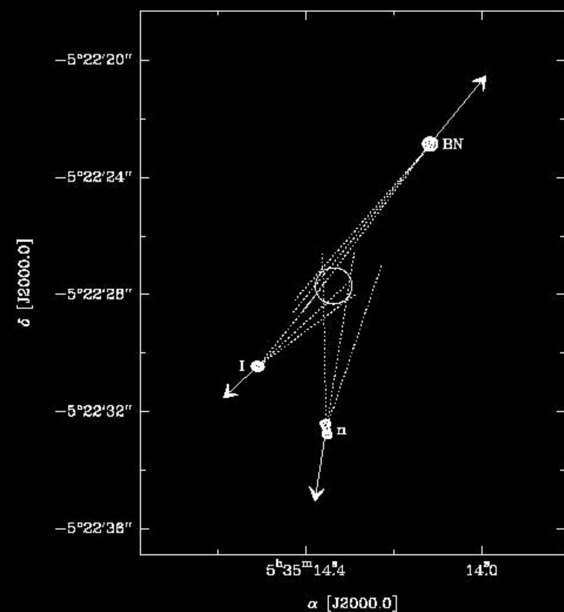
SiO

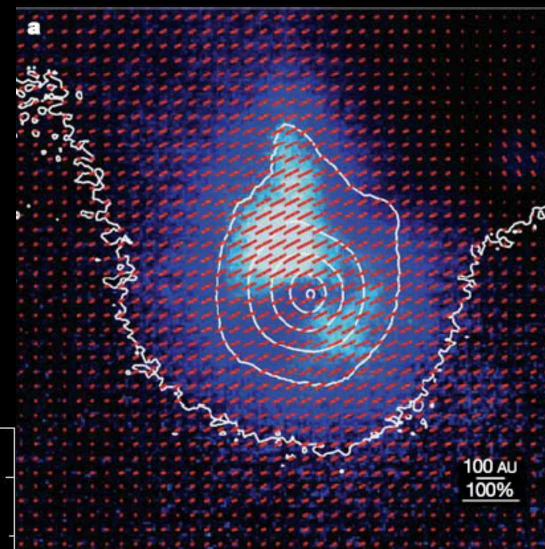
H_2O

7 mm continnum (H^-)

(Reid 07, ApJL)

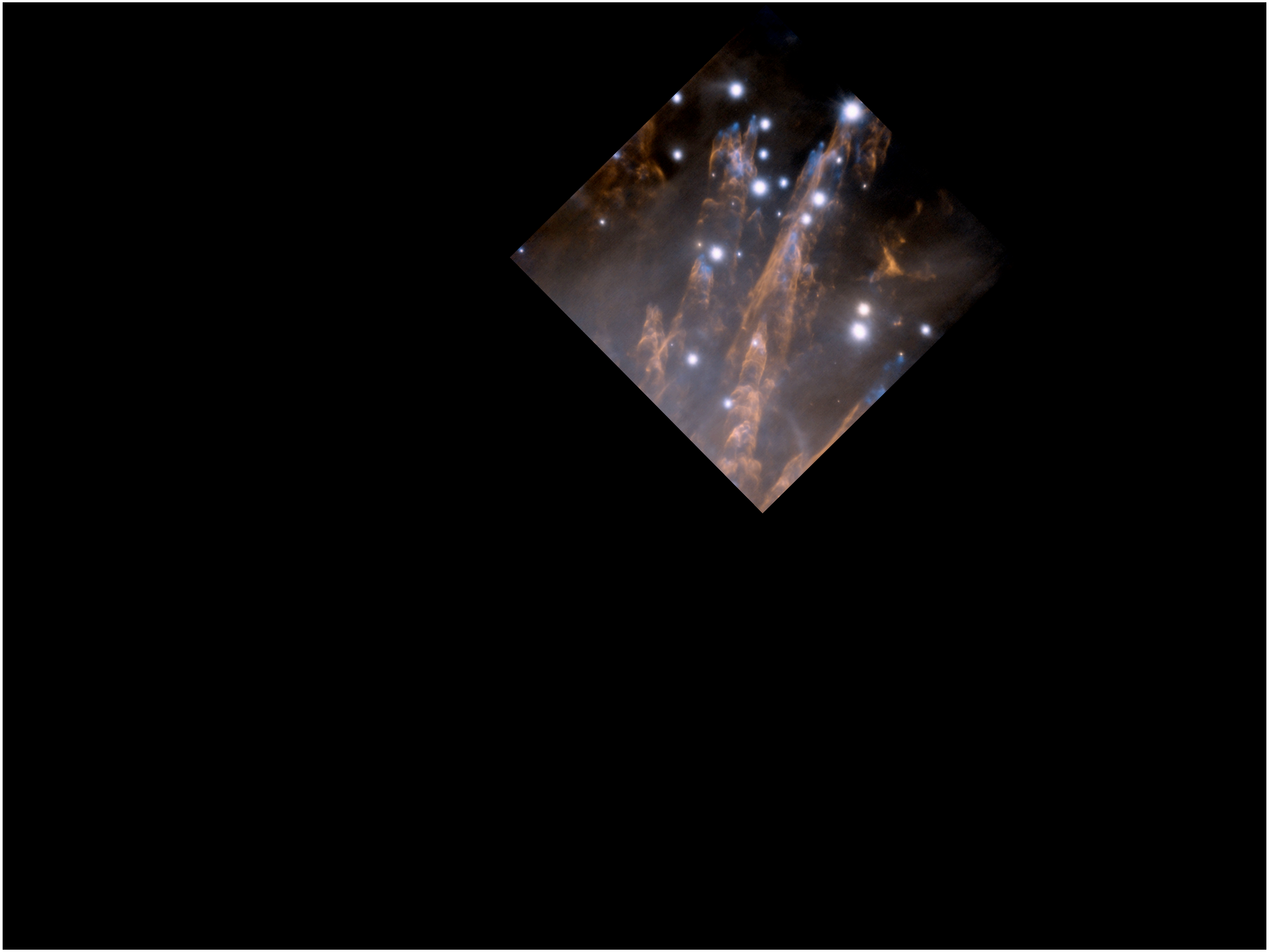




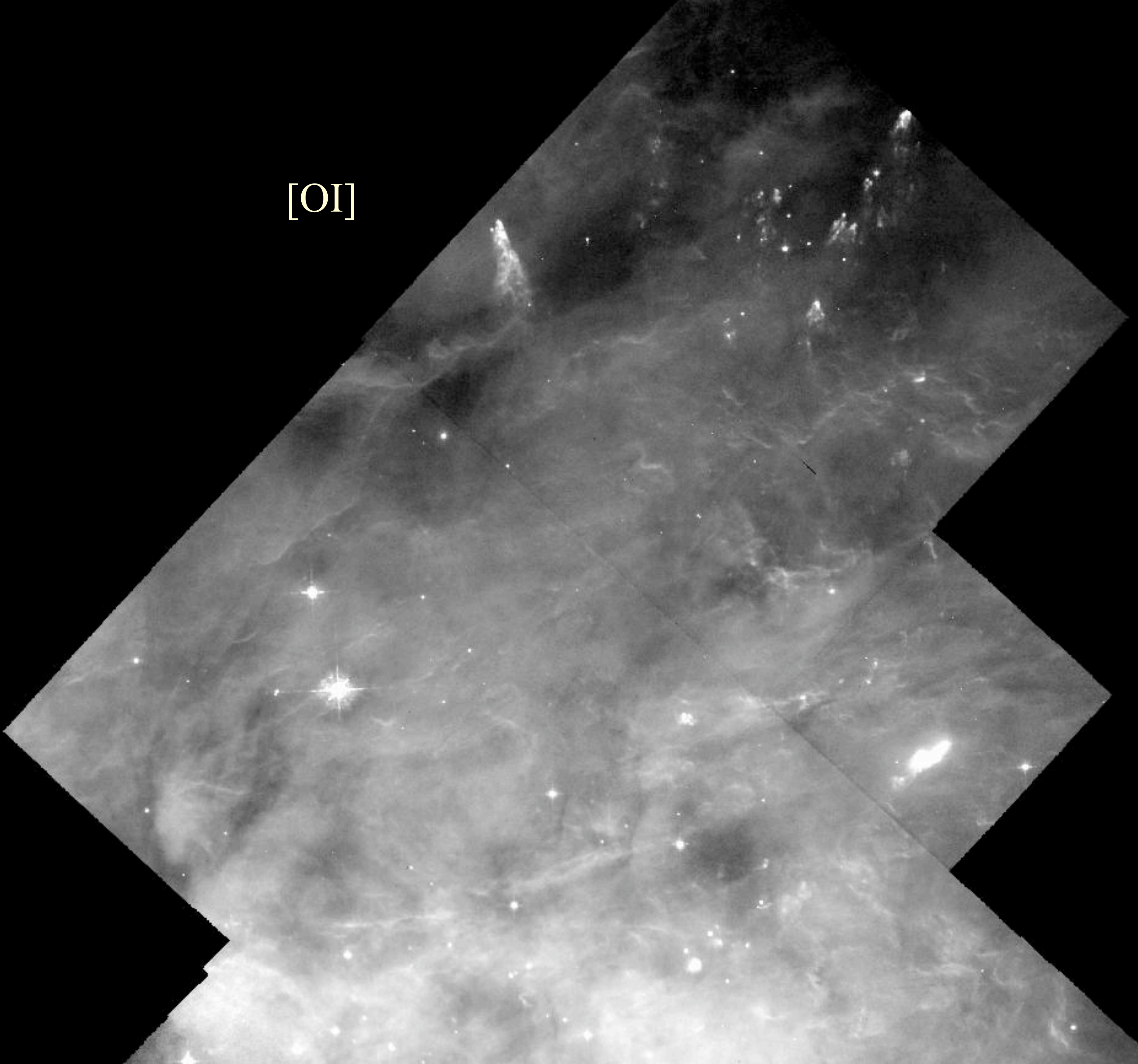


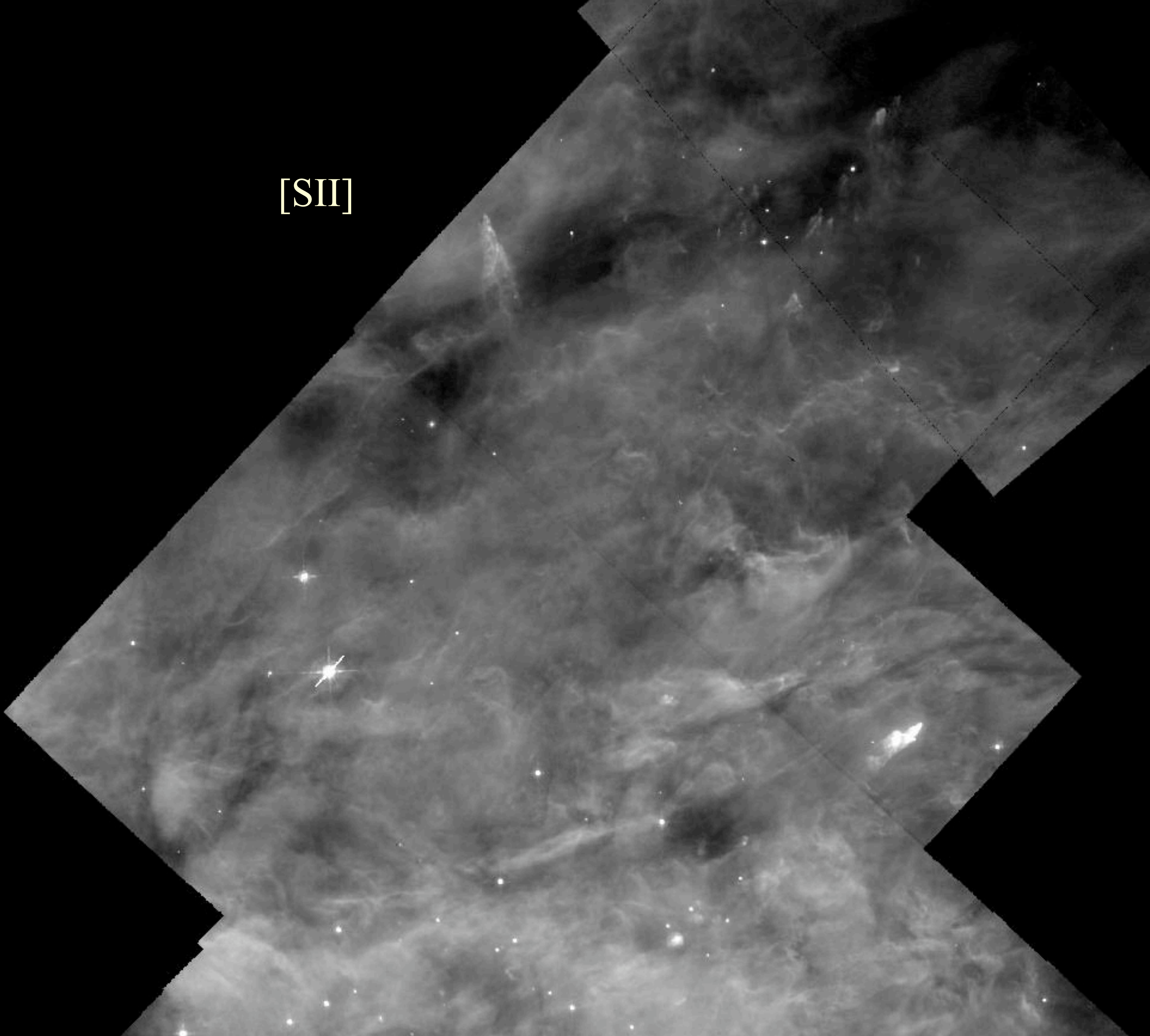
BN polarization

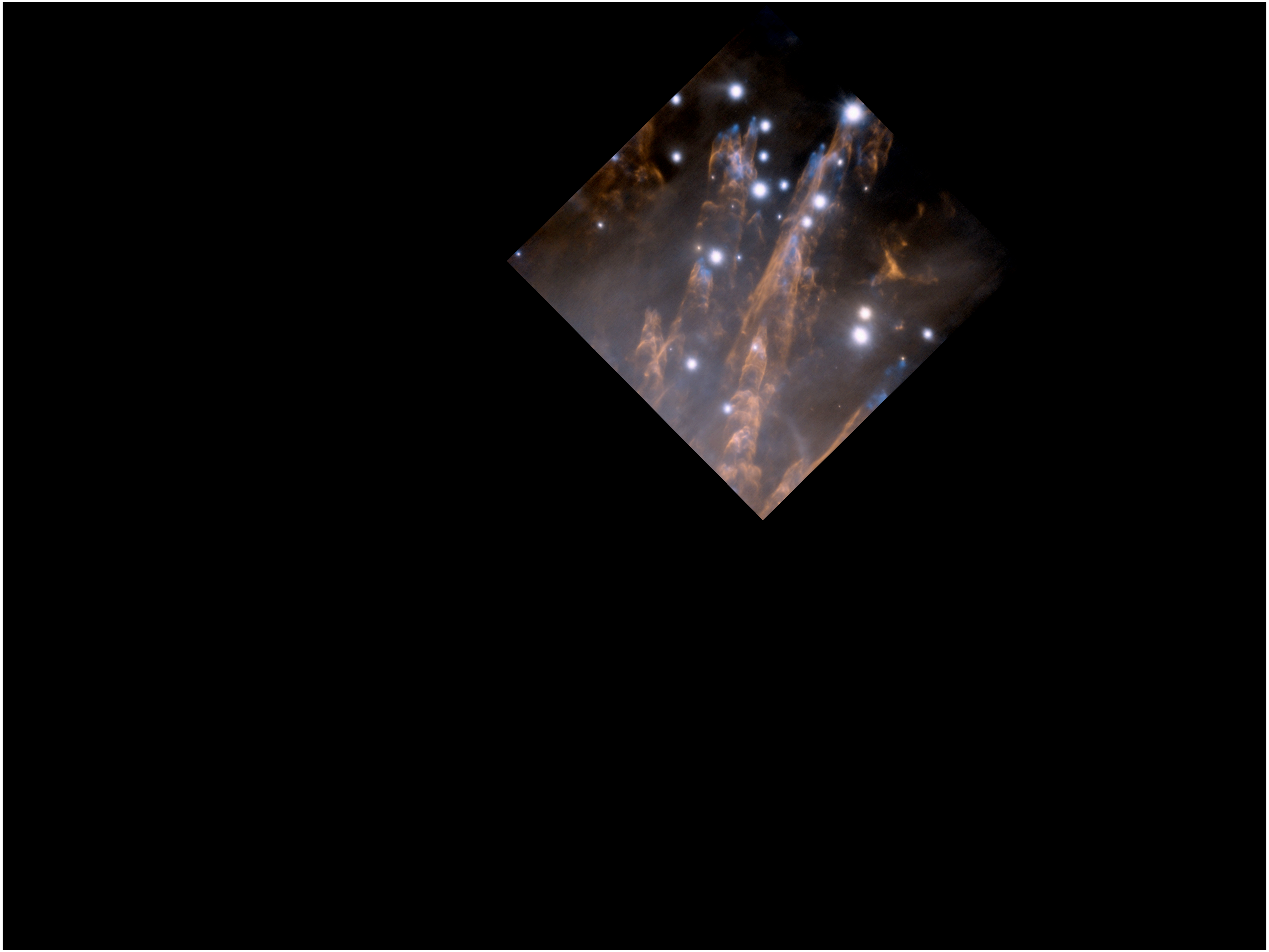
(Jiang 06, Nature)

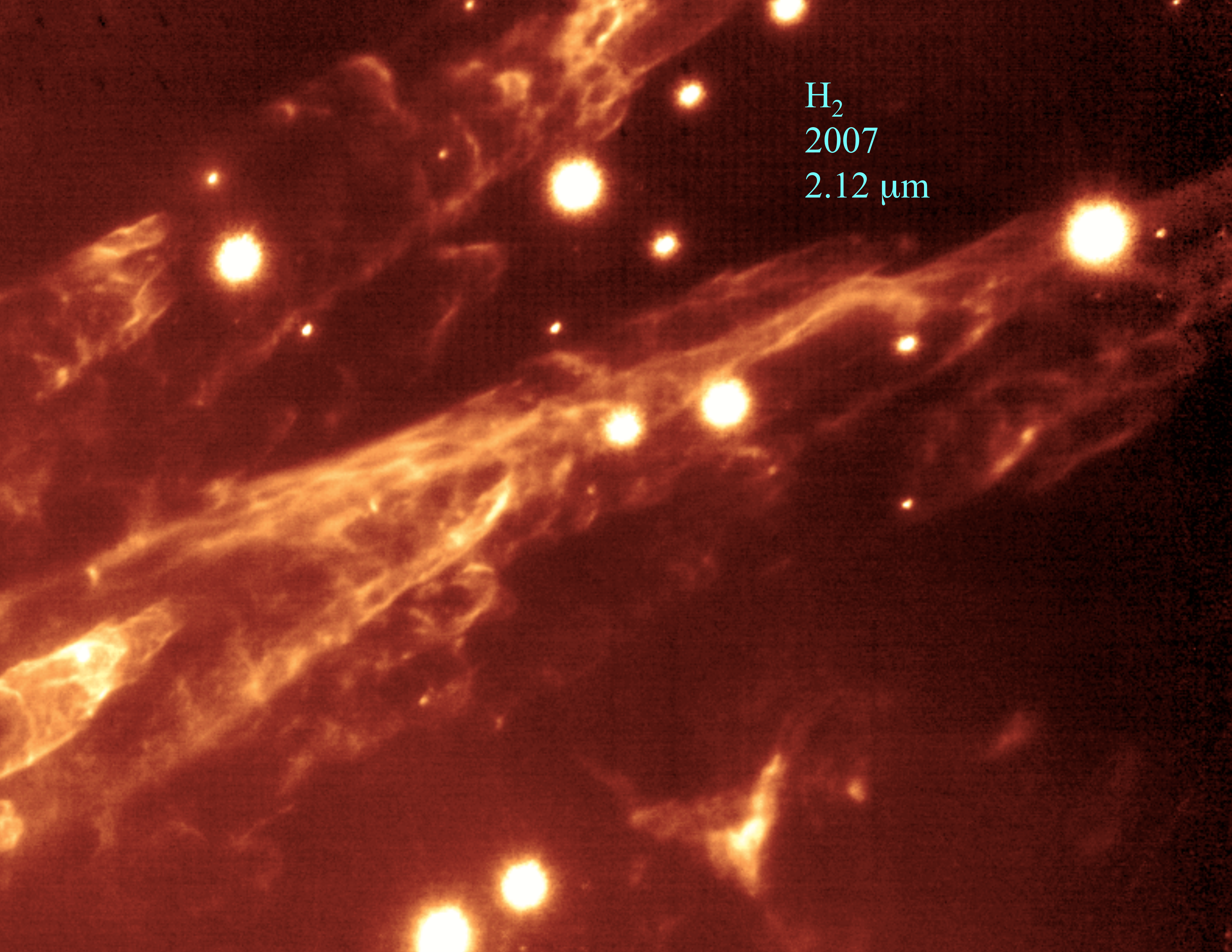


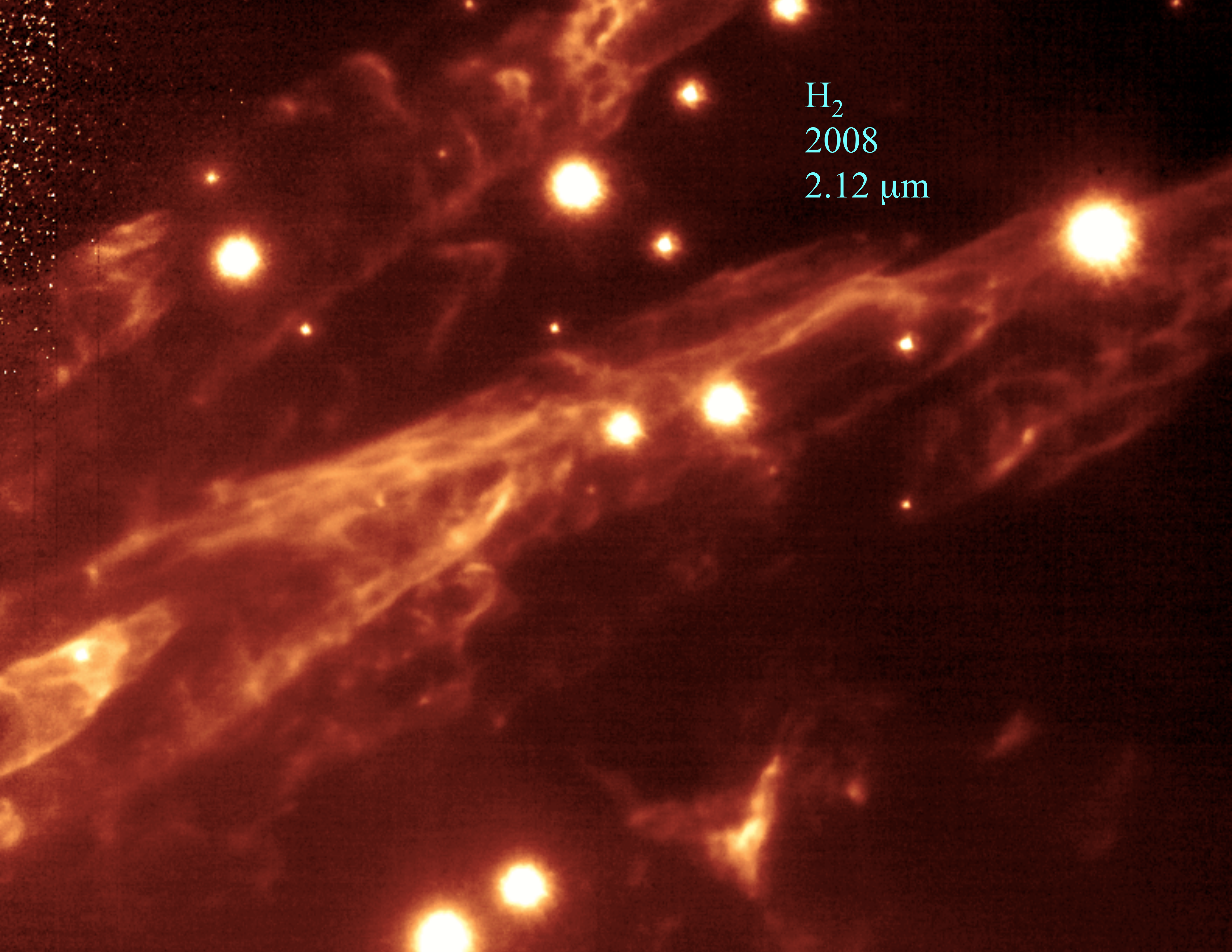

H_2

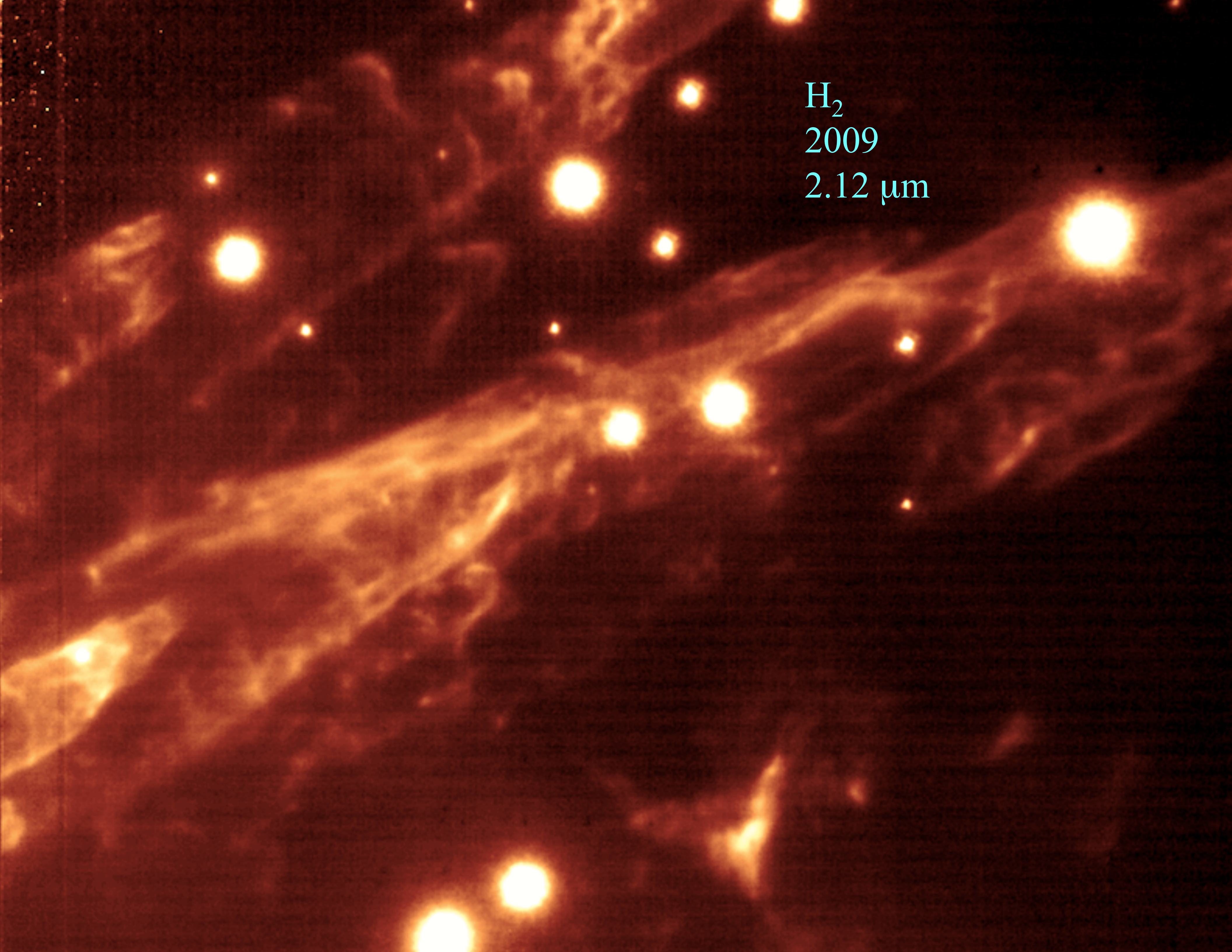

[OI]


[SII]

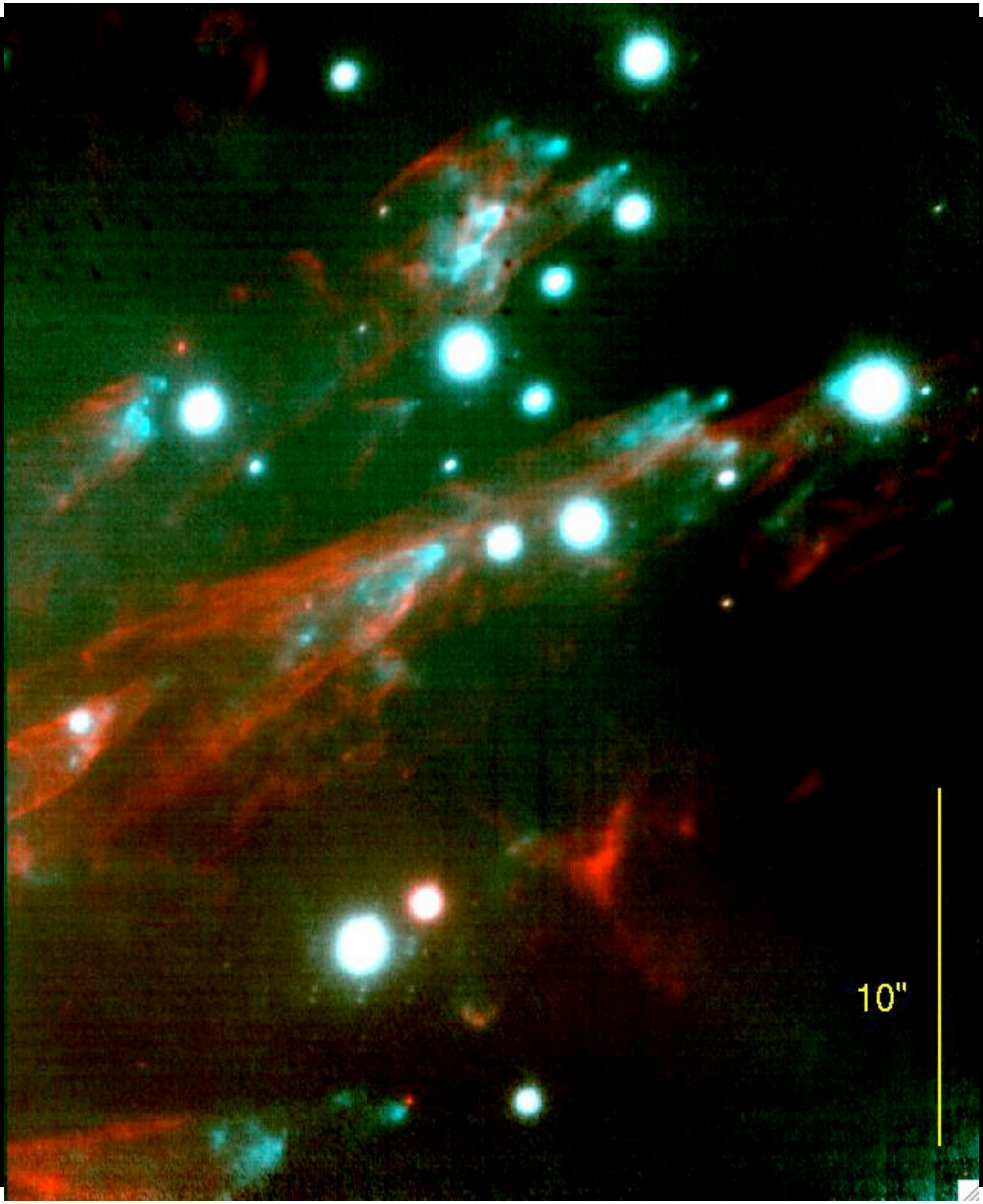



H2
2007
2.12 µm

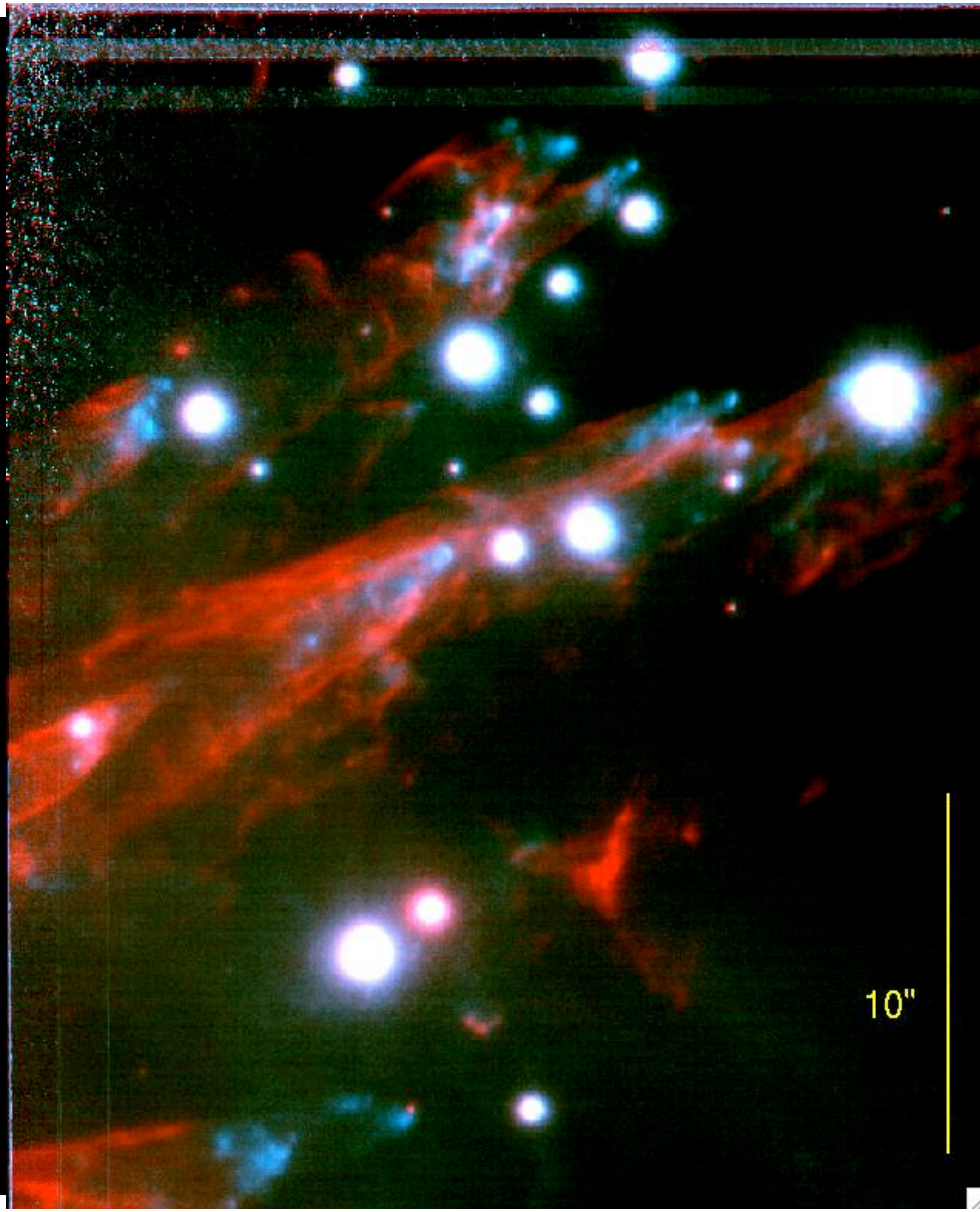

H_2
2008
2.12 µm

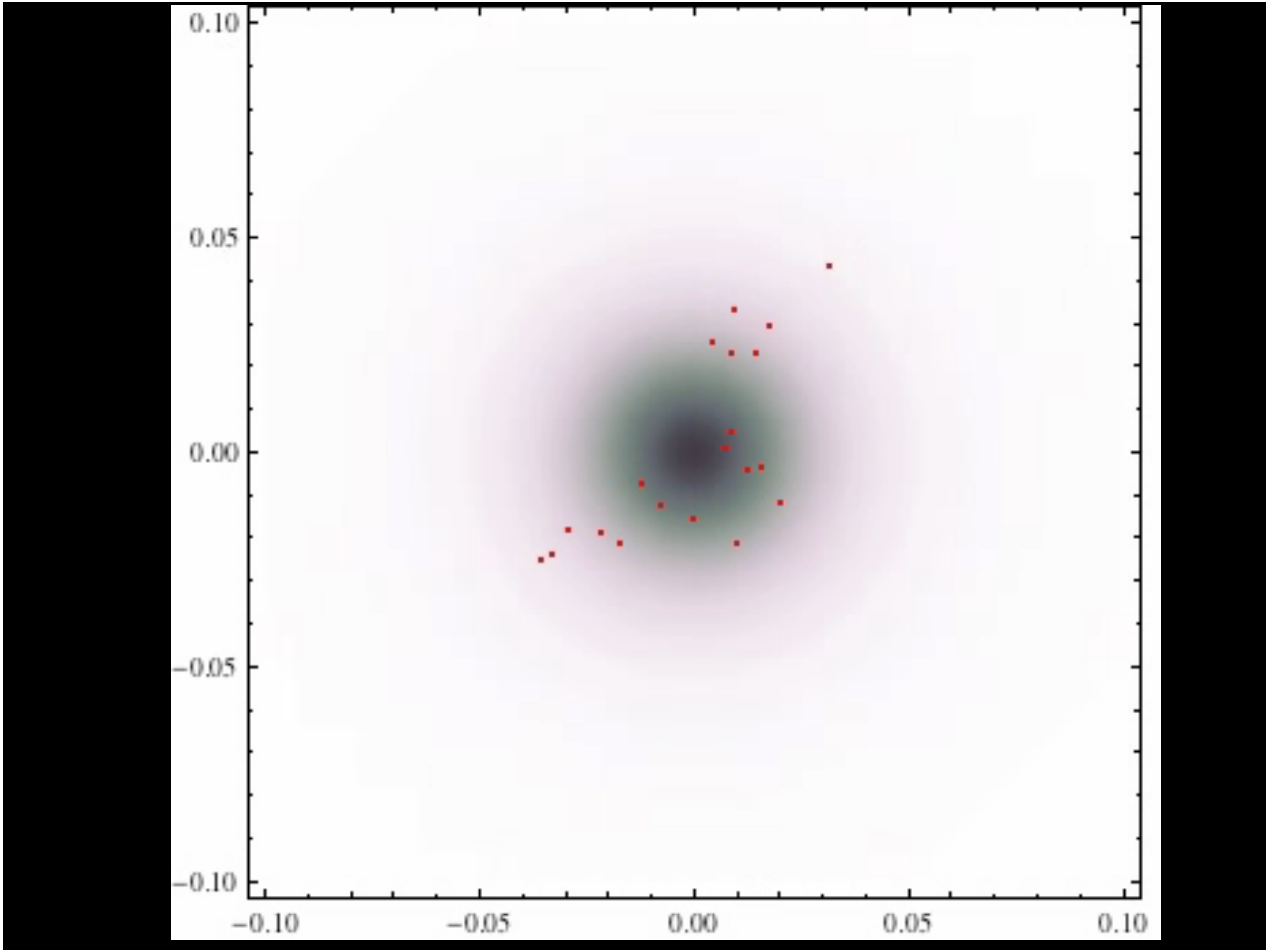

H_2
2009
2.12 μm

[FeII], H_2
2007



[FeII], H_2
2008



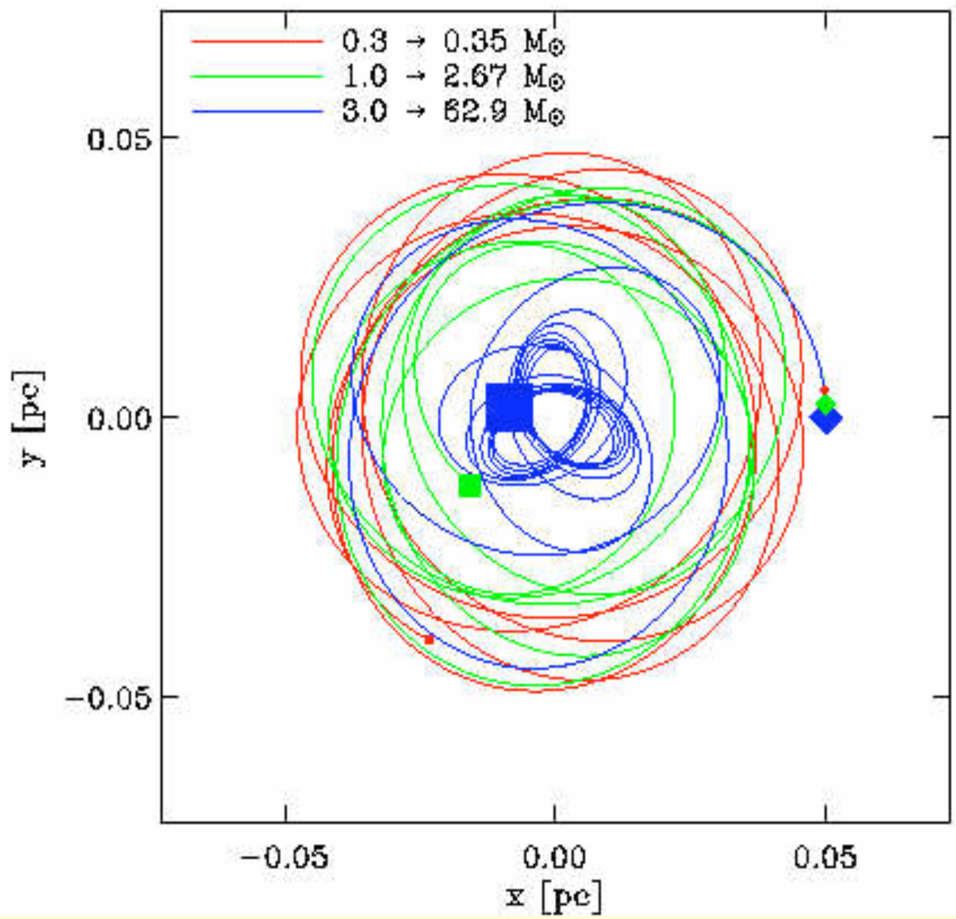


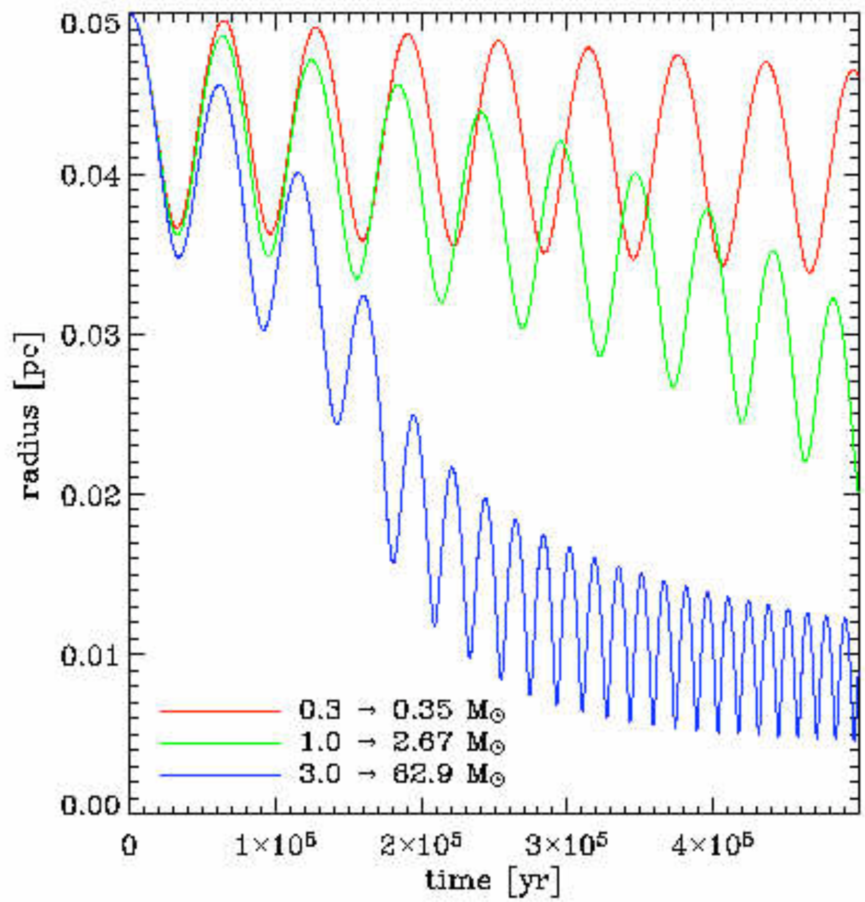
0.10
0.05
0.00
−0.05
−0.10
−0.10
−0.05
0.00
0.05
0.10

Orbit Decay:

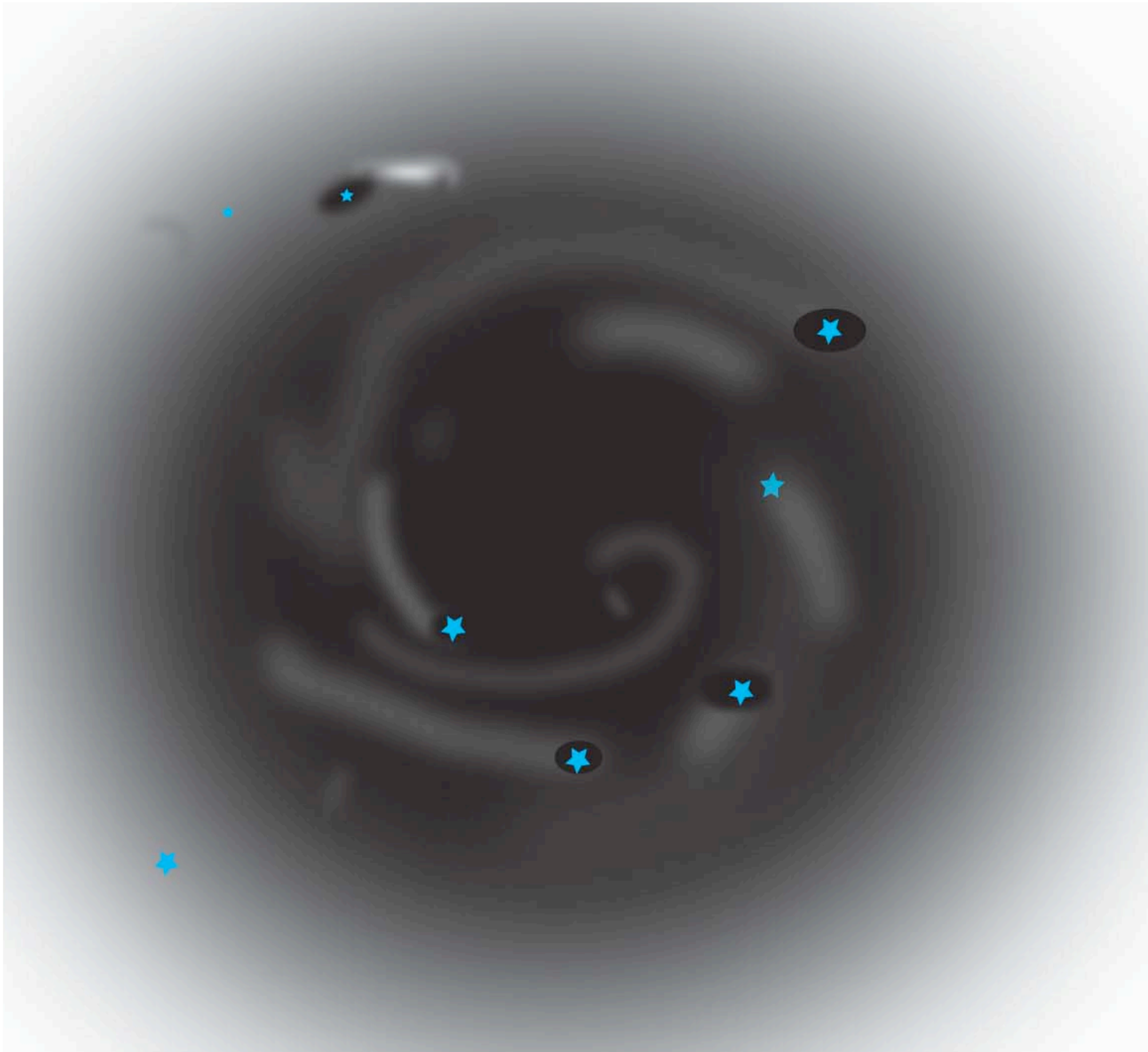
Massive stars orbiting in r^{-2} sphere of gas

Bondi-Hoyle accretion + dynamic friction => migration of massive *s



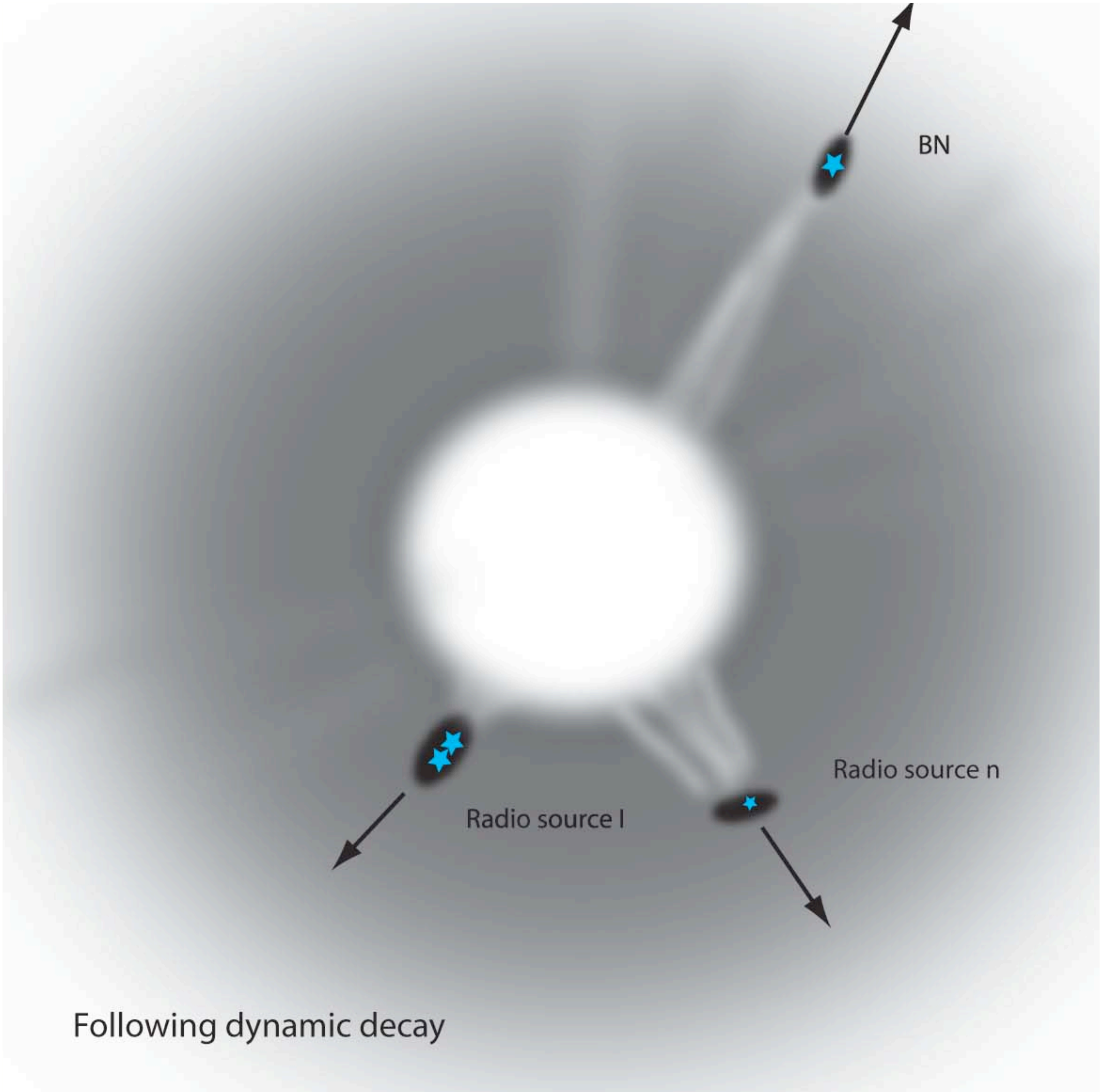


Nick Moeckel PhD Thesis (CU Boulder,2008)



Before formation of non-hierarchical multiple of massive stars

Massive non-hierarchical system of massive protostars. Before dynamic decay

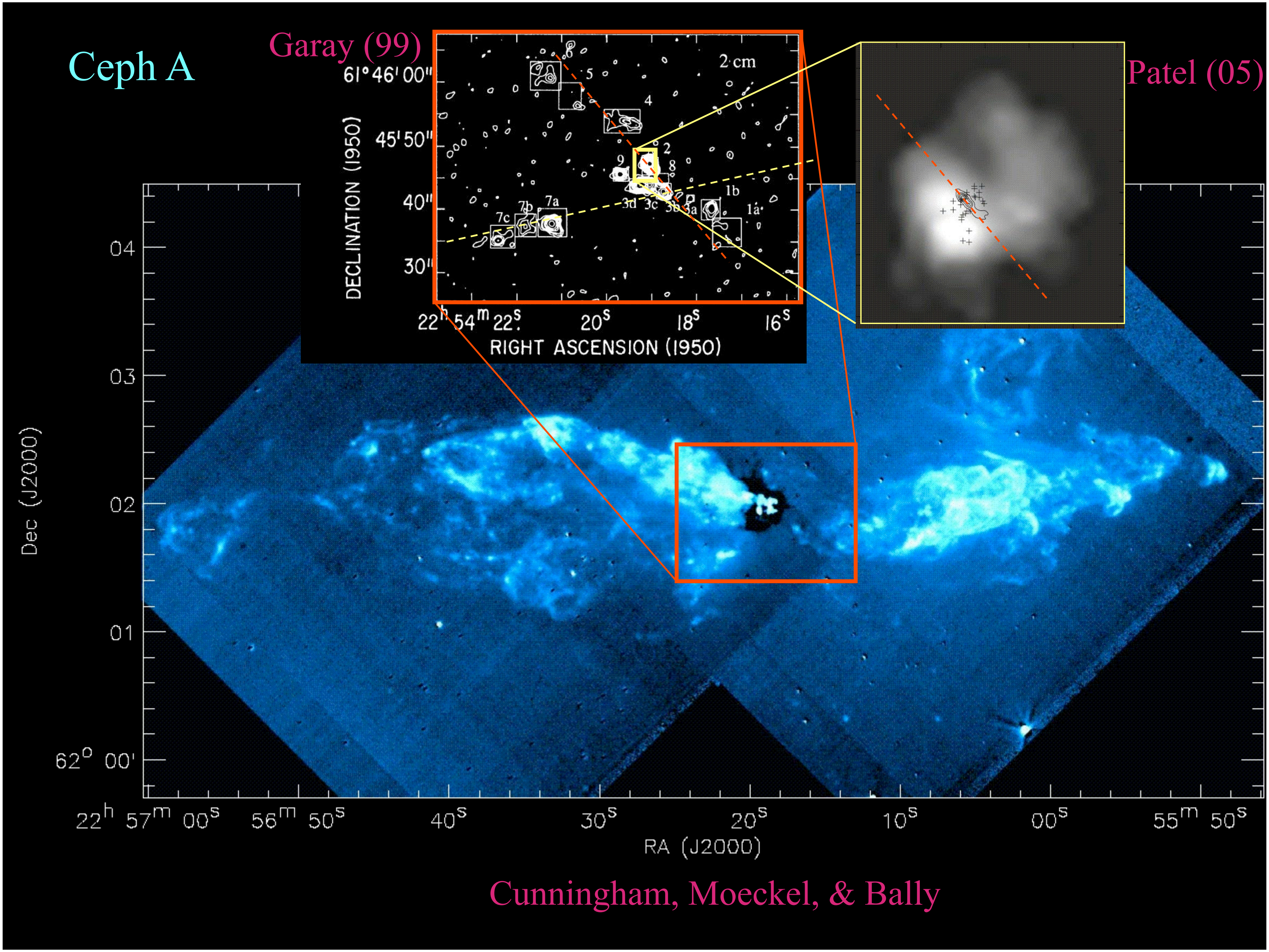

BN
Radio source n
Radio source I
Following dynamic decay

Cepheus A

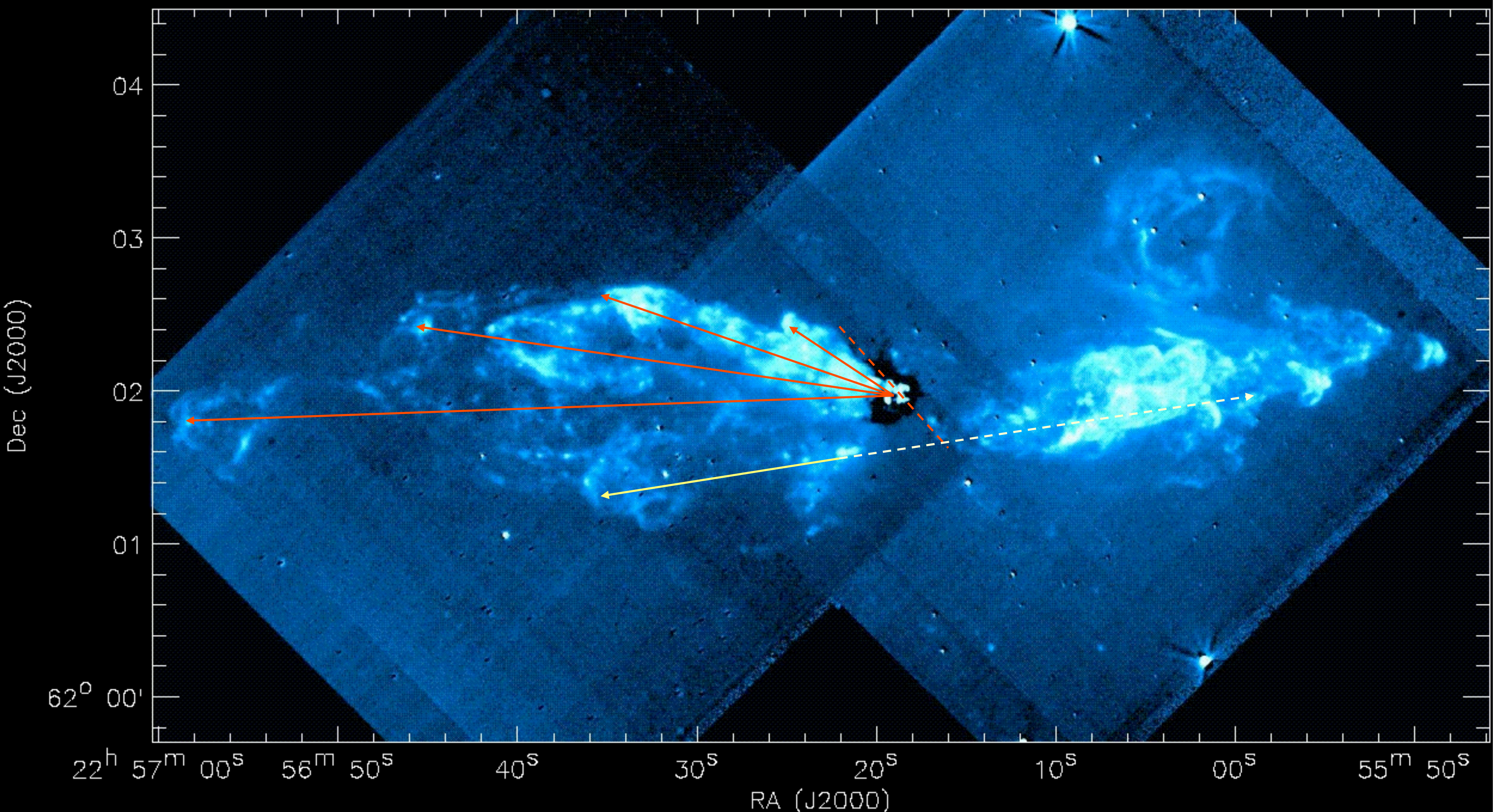
Cunningham, Moeckel, & Bally

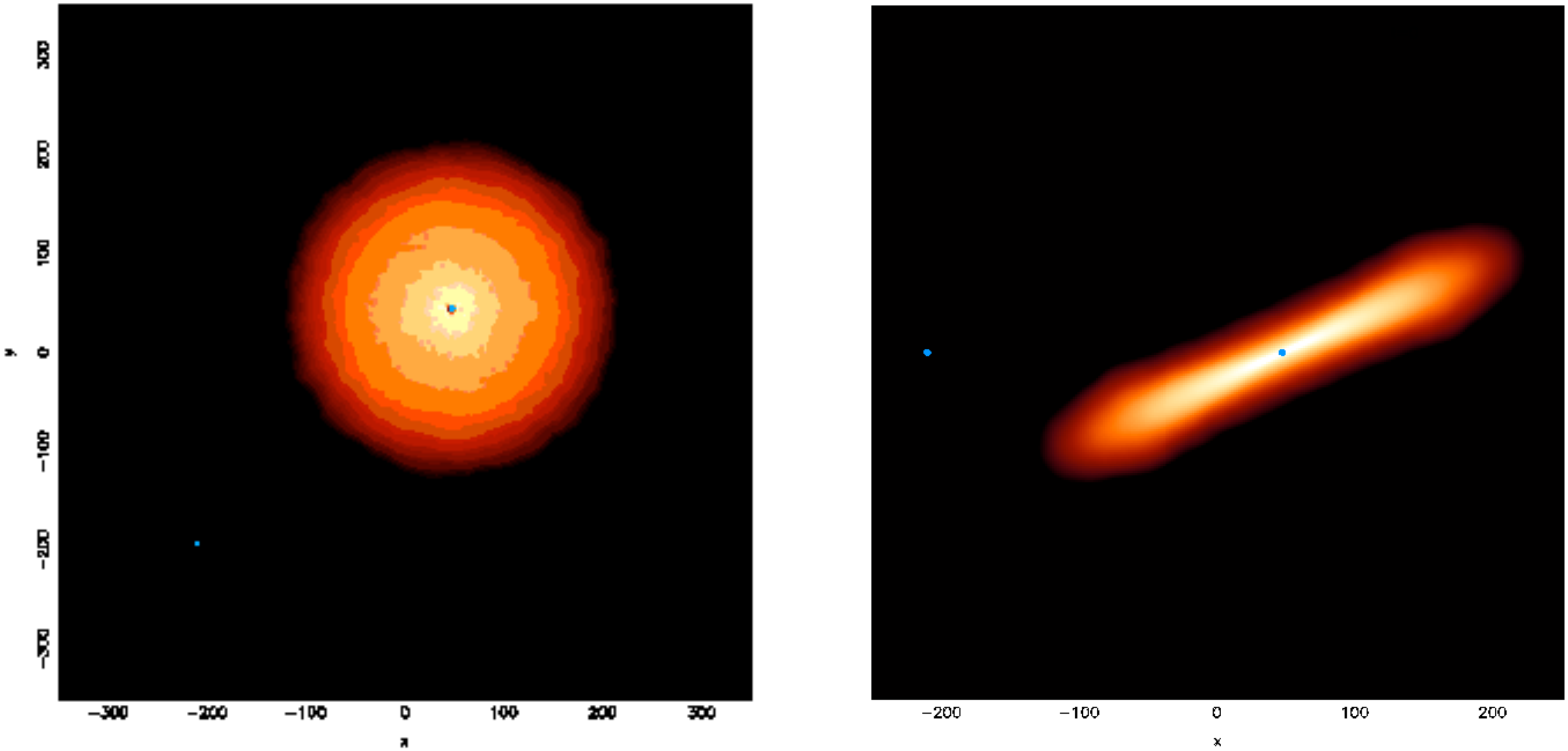
Cepheus A

Cunningham, Moeckel, & Bally


Ceph A
Garay (99)
Patel (05)
2 cm
61°46'00"
45'50"
40"
30"
DECLINATION (1950)
22h54m22s
20s
18s
16s
RIGHT ASCENSION (1950)
5
4
2
8
9
1b
1a
3d
3c
3b
3a
7a
7b
7c
Dec (J2000)
04
03
02
01
62° 00'
22h 57m 00s
56m 50s
40s
30s
20s
10s
00s
55m 50s
RA (J2000)
Cunningham, Moeckel, & Bally

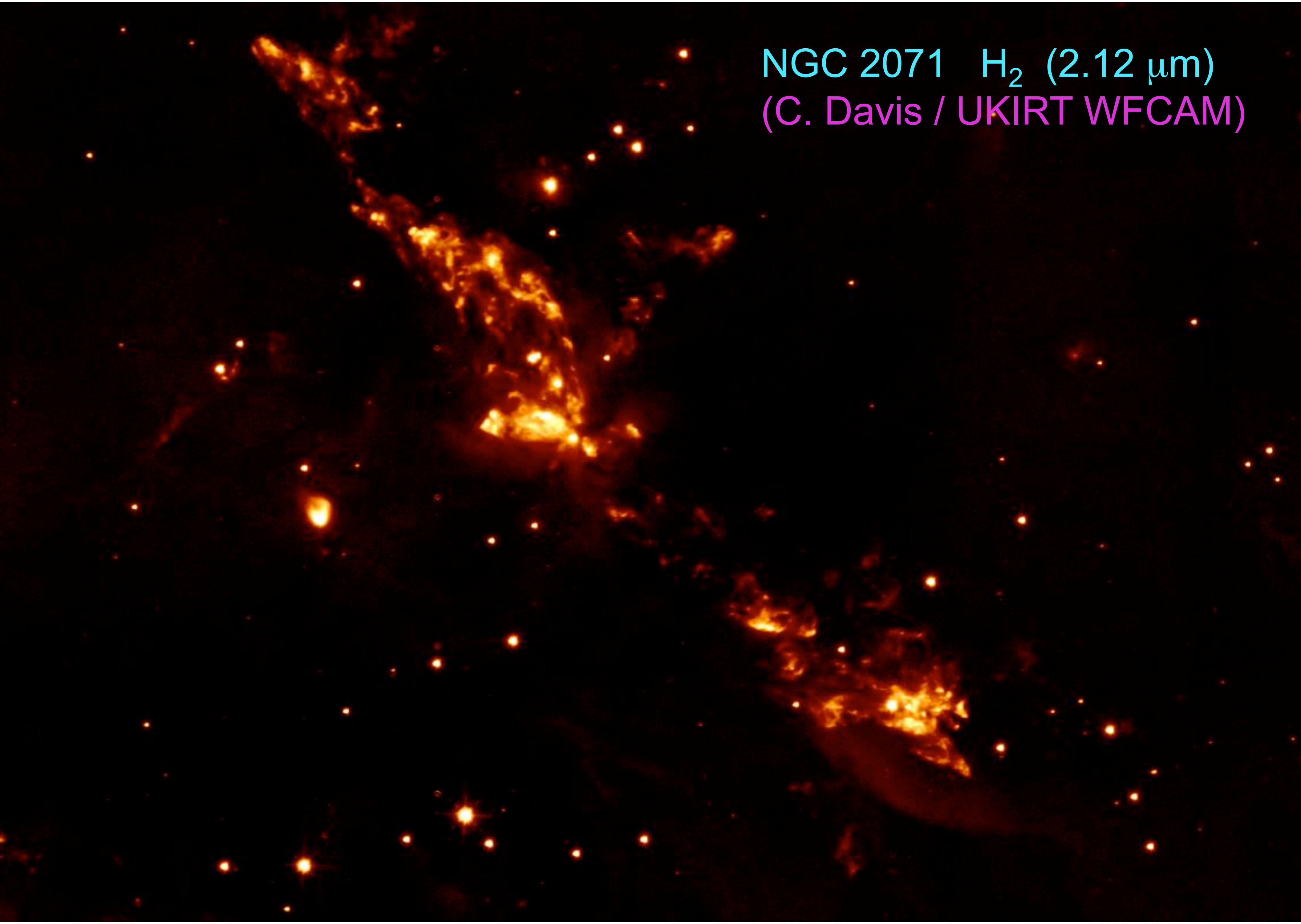
Ceph A precessing jet: P ~ 2 x 10^3 yr ? Cunningham, Moeckel, & Bally





Moeckel & Bally (2005, 2006, 2007) SPH:

Massive star capture-formed binary: Disk orientation change


NGC 2071 H_2 (2.12 μm)
(C. Davis / UKIRT WFCAM)

W43

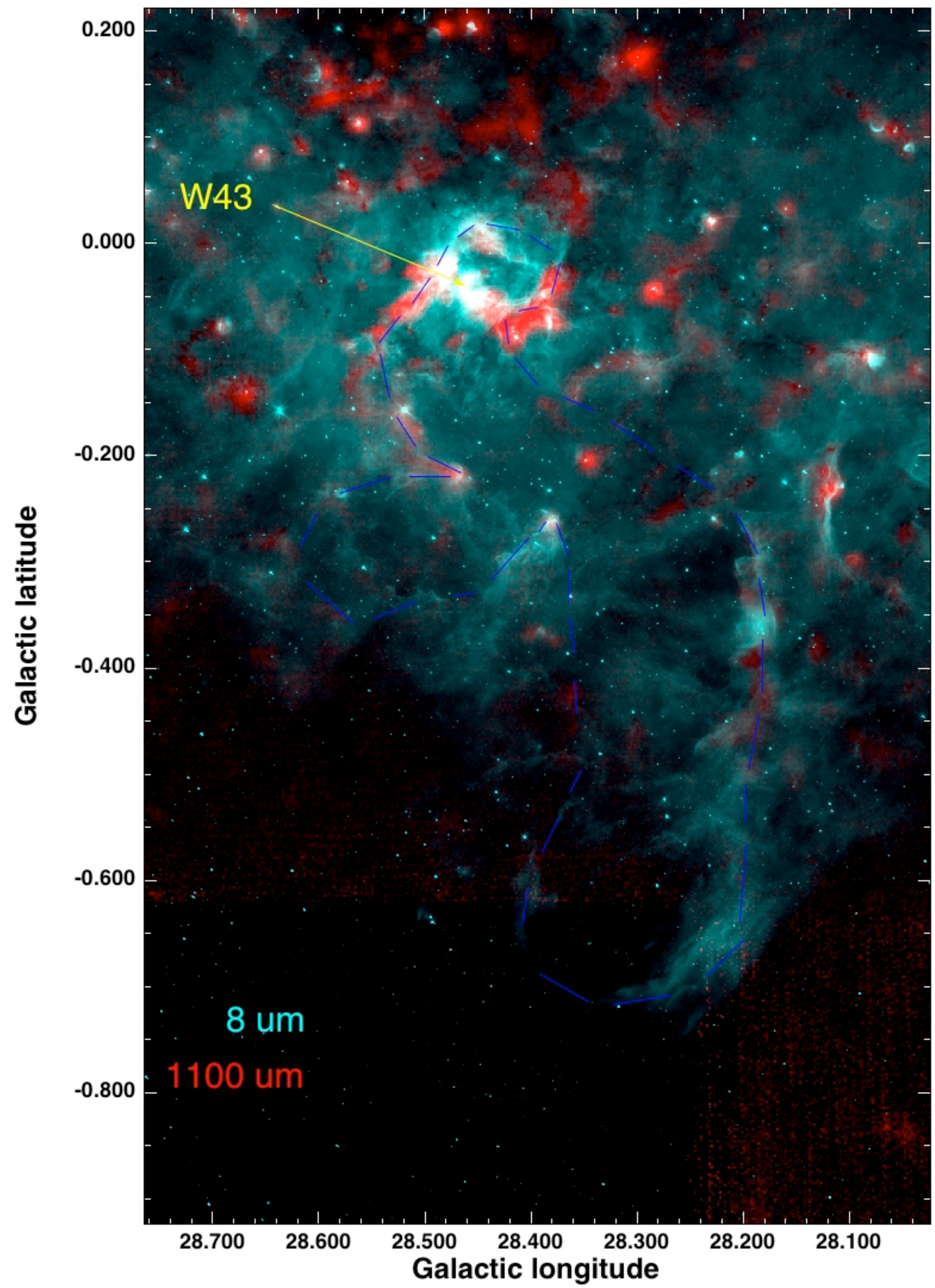
Giant HII region -mini-starburst

$[l,b]$ = 30.77, -0.04
Vlsr ~ 86 to 106 km/s

D ~ 5.5 kpc
$L > 3.5 \times 10^6 L_o$
$M_{GMC} \sim 10^6 M_o$

$L_{LyC} \sim 10^{51}$ ionizing γ s^{-1}
(50 x Orion Neb.
=> 50 O7 stars!)

O3 and WR stars
=> age >3 Myr



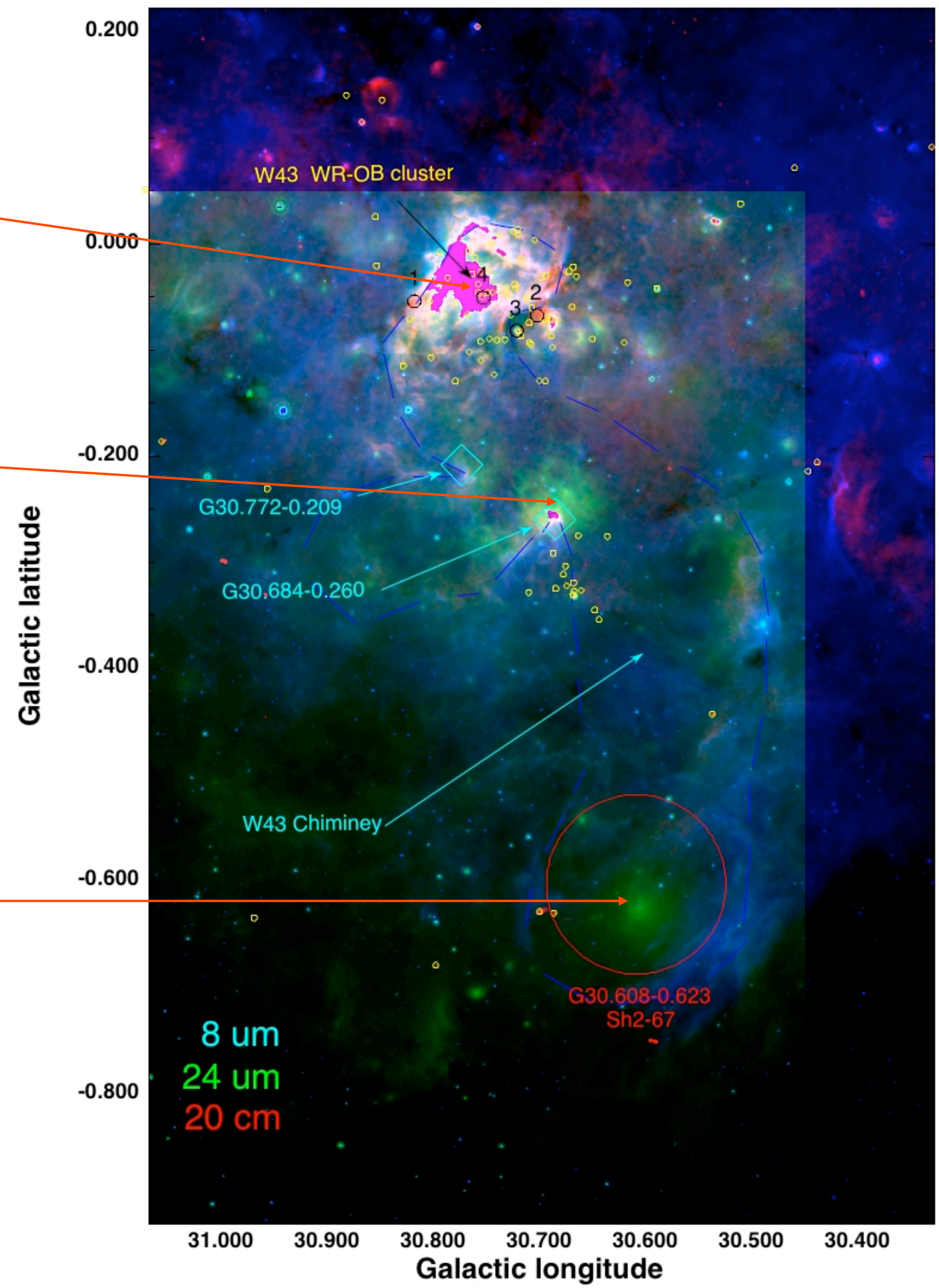
W43

Suspected older OB association

Green => hot dust heated by massive star

Sh2-67 is in foreground V_{lsr} ~ 18 km/s

But, dust rim is mostly at V_{lsr} ~ 86 - 106 km/s



A multi-Spectral `romp' through the the W43 Region

from 3.6 um to 20 cm

All images registered

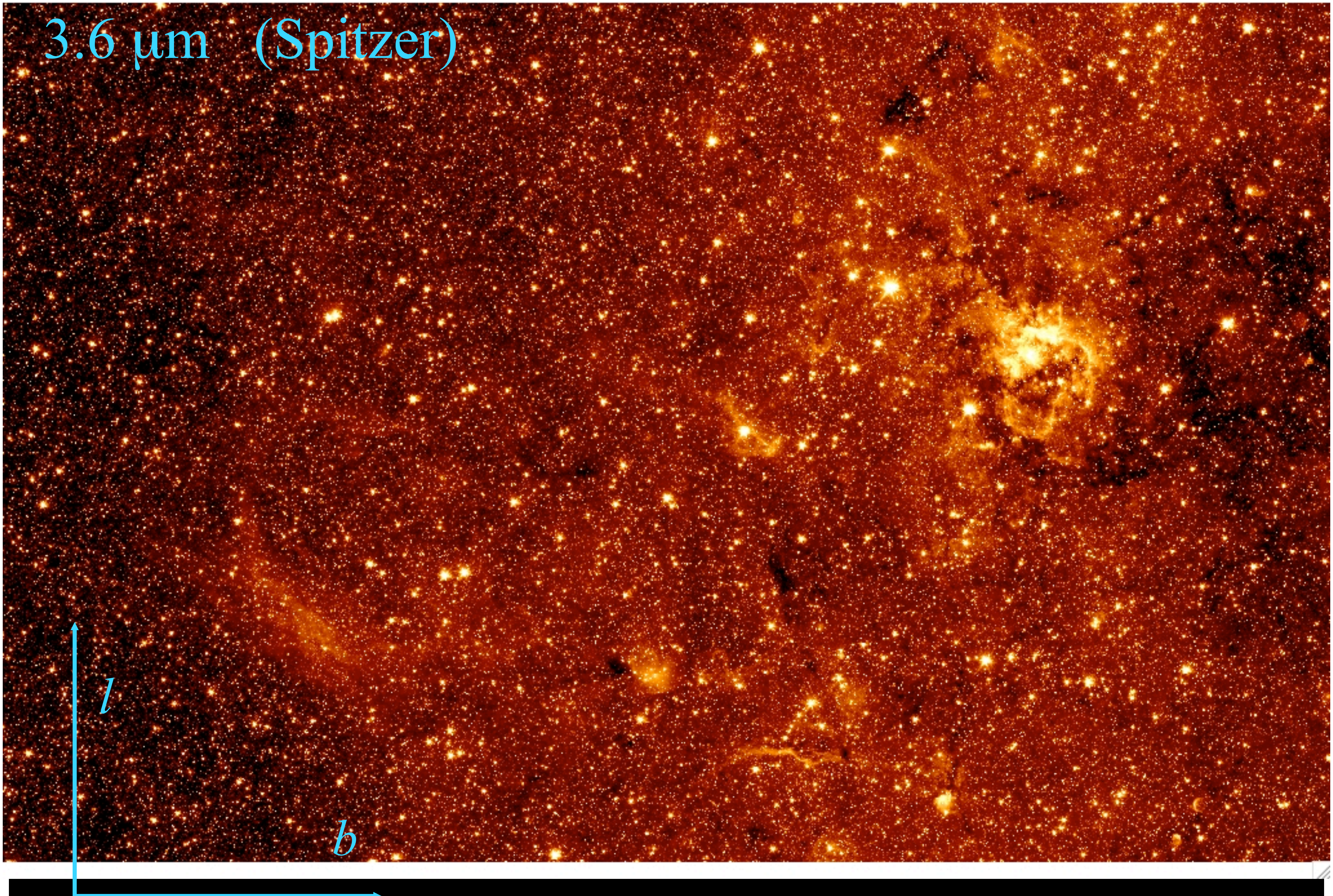
FOV ~ 60 x 100 pc @ 5.5 kpc

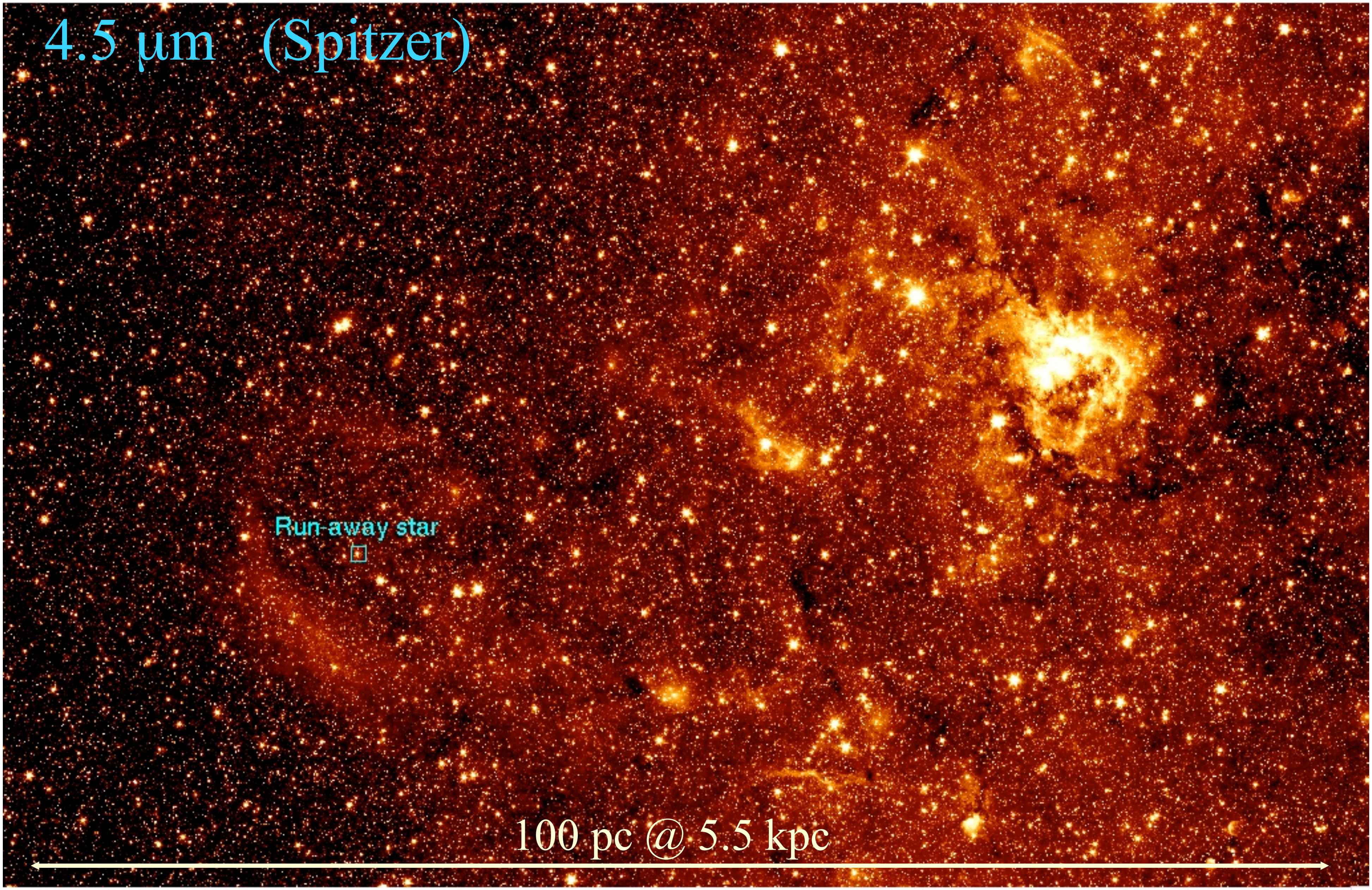
The images:

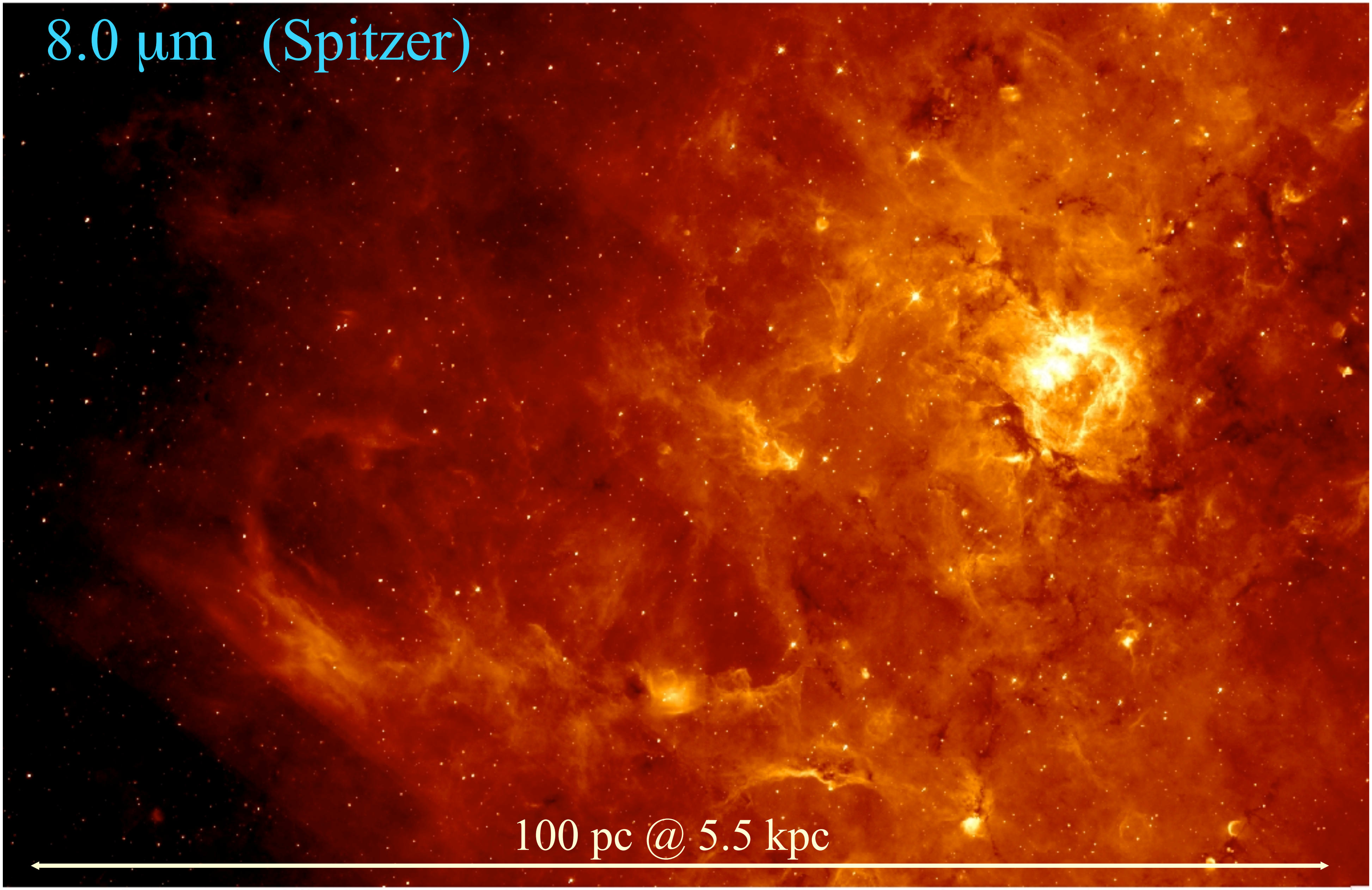
3.6, 4.5, 8.0 μm	(Spitzer / IRAC / GLIMPSE)
24 μm	(Spitzer / MIPS/MIPSGAL)
70, 170, 250, 350, 500 μm	(Herschel Hi-GAL)
1100 μm	(CSO 10.4 m BGPS)
20 cm	(VLA / MAGPIS)
^{13}CO	(FCRAO 14 m GRS)

Each ^{13}CO image shows three ΔV = 2 km/s slices

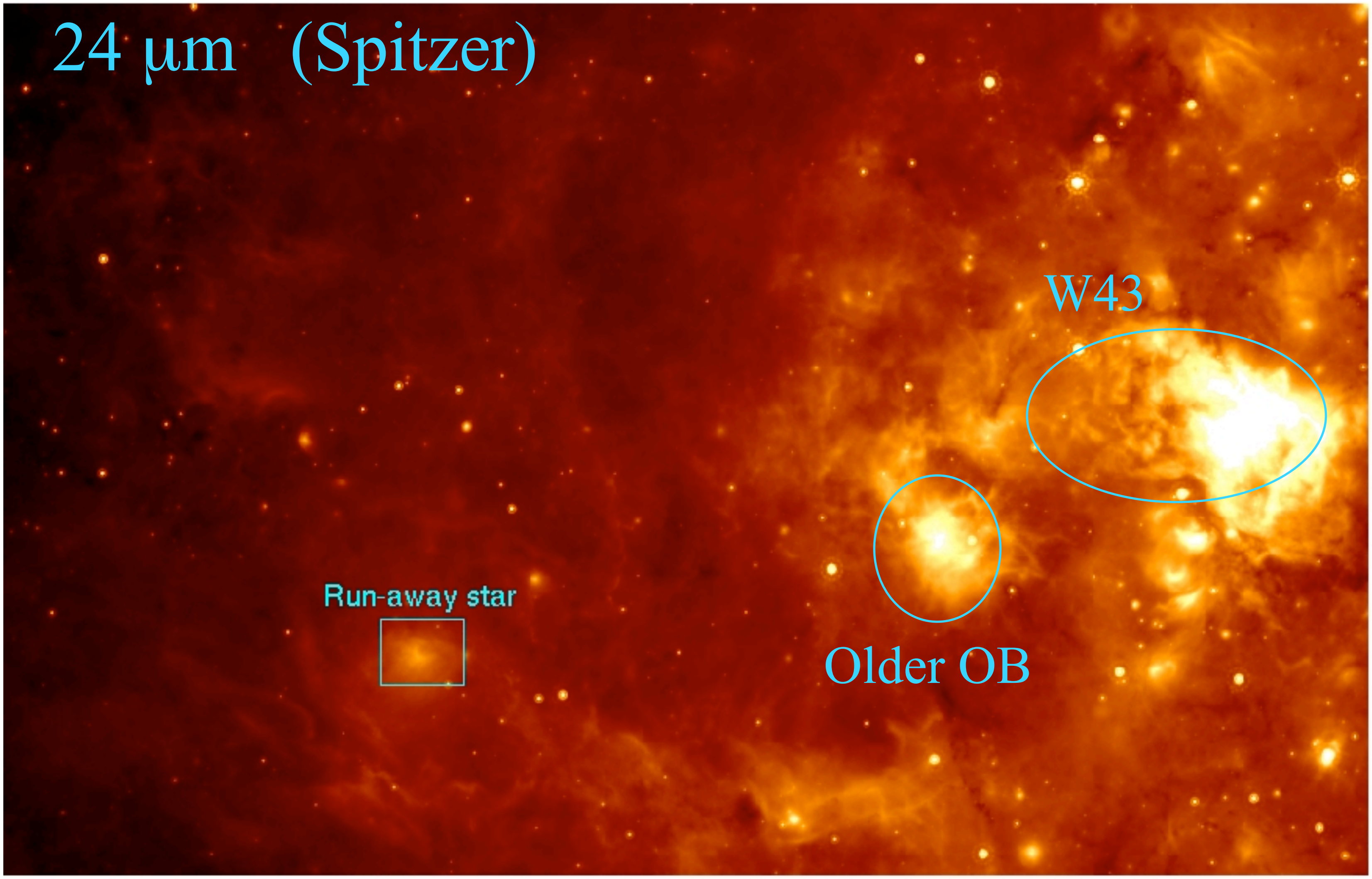
blue	V - 2	km/s
green	V	km/s
red	V + 2	km/s


3.6 μm (Spitzer)
l
b


4.5 μm (Spitzer)
Run-away star
100 pc @ 5.5 kpc

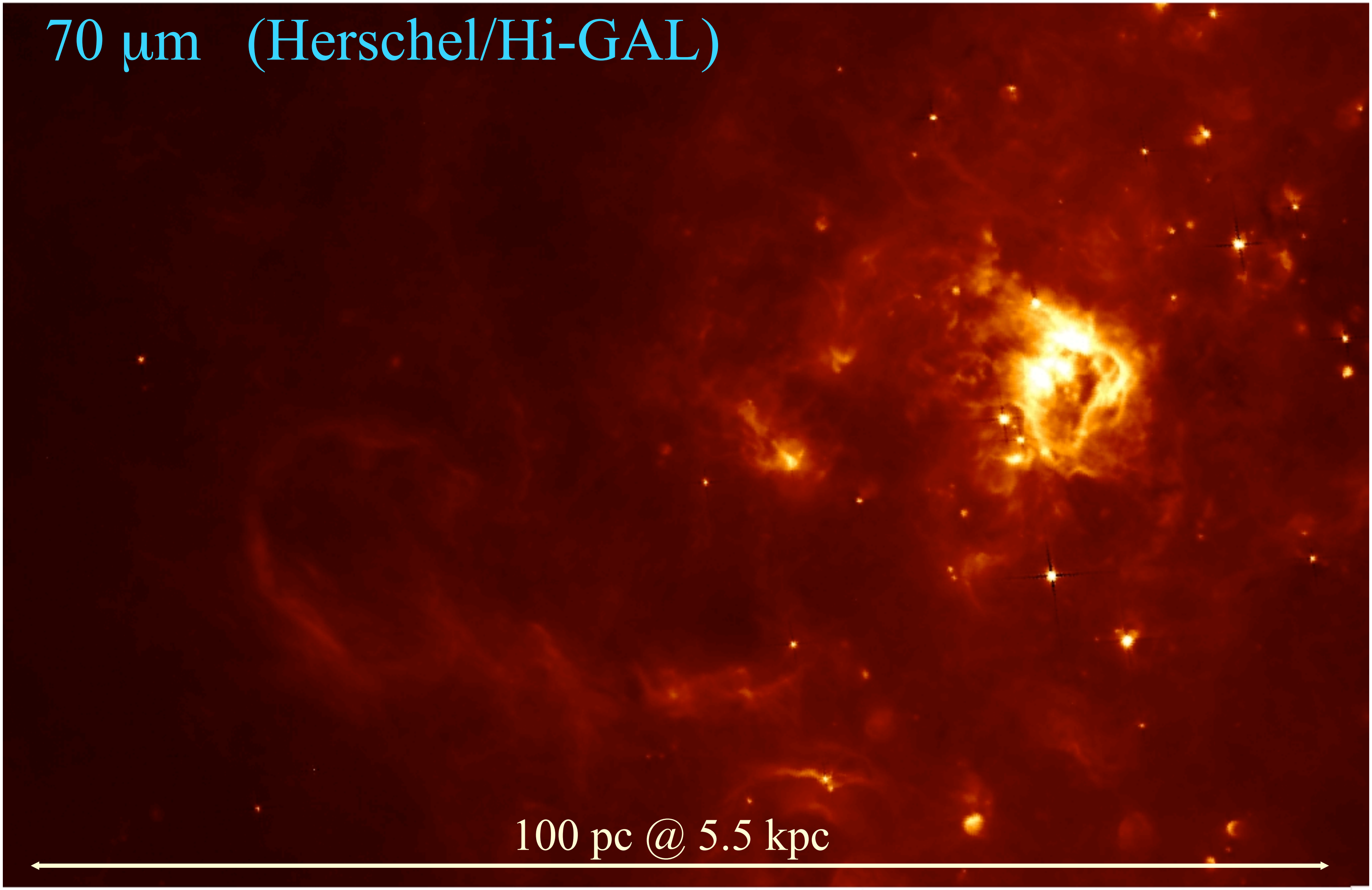

8.0 μm (Spitzer)
100 pc @ 5.5 kpc

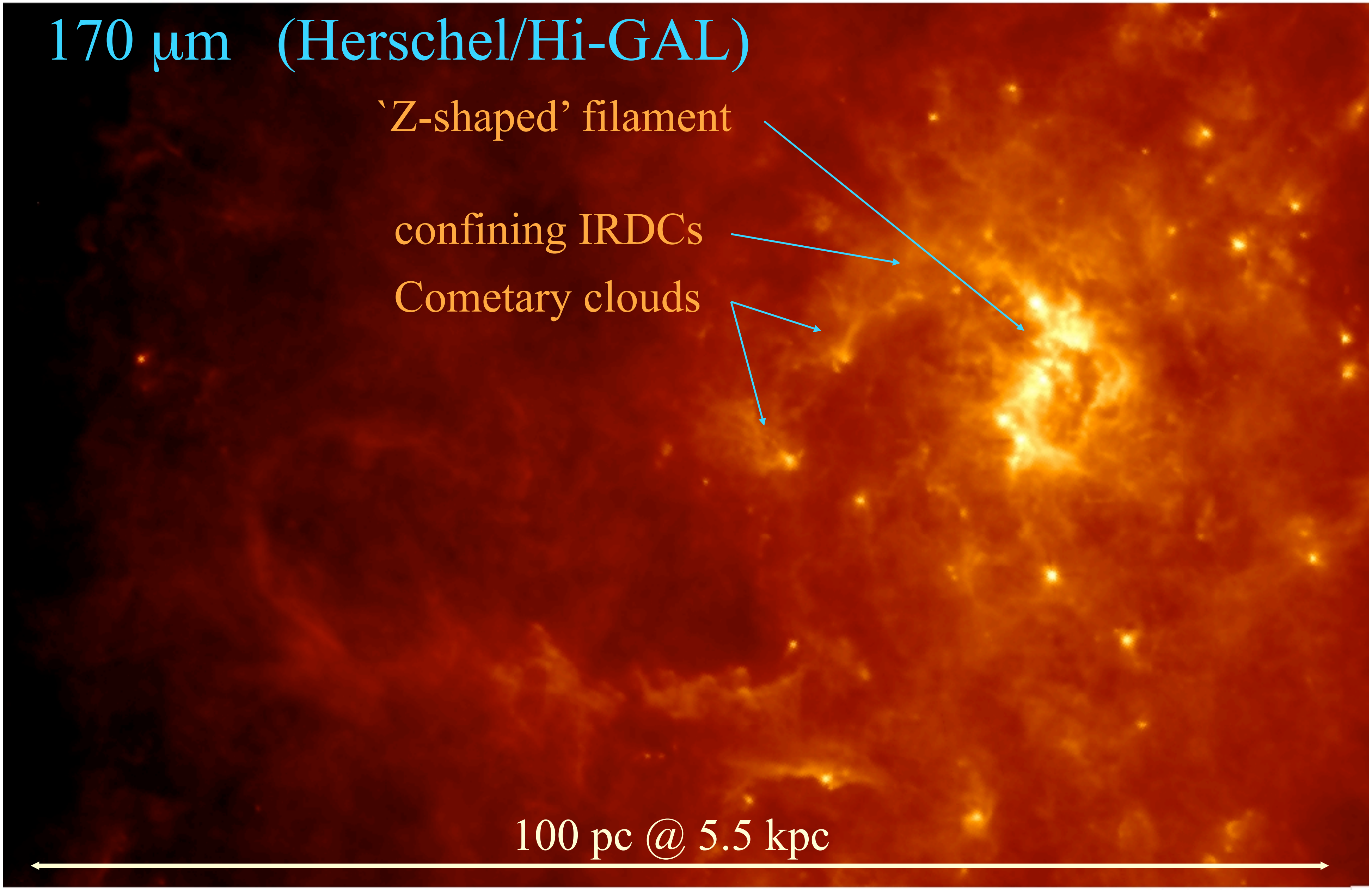
[redacted]



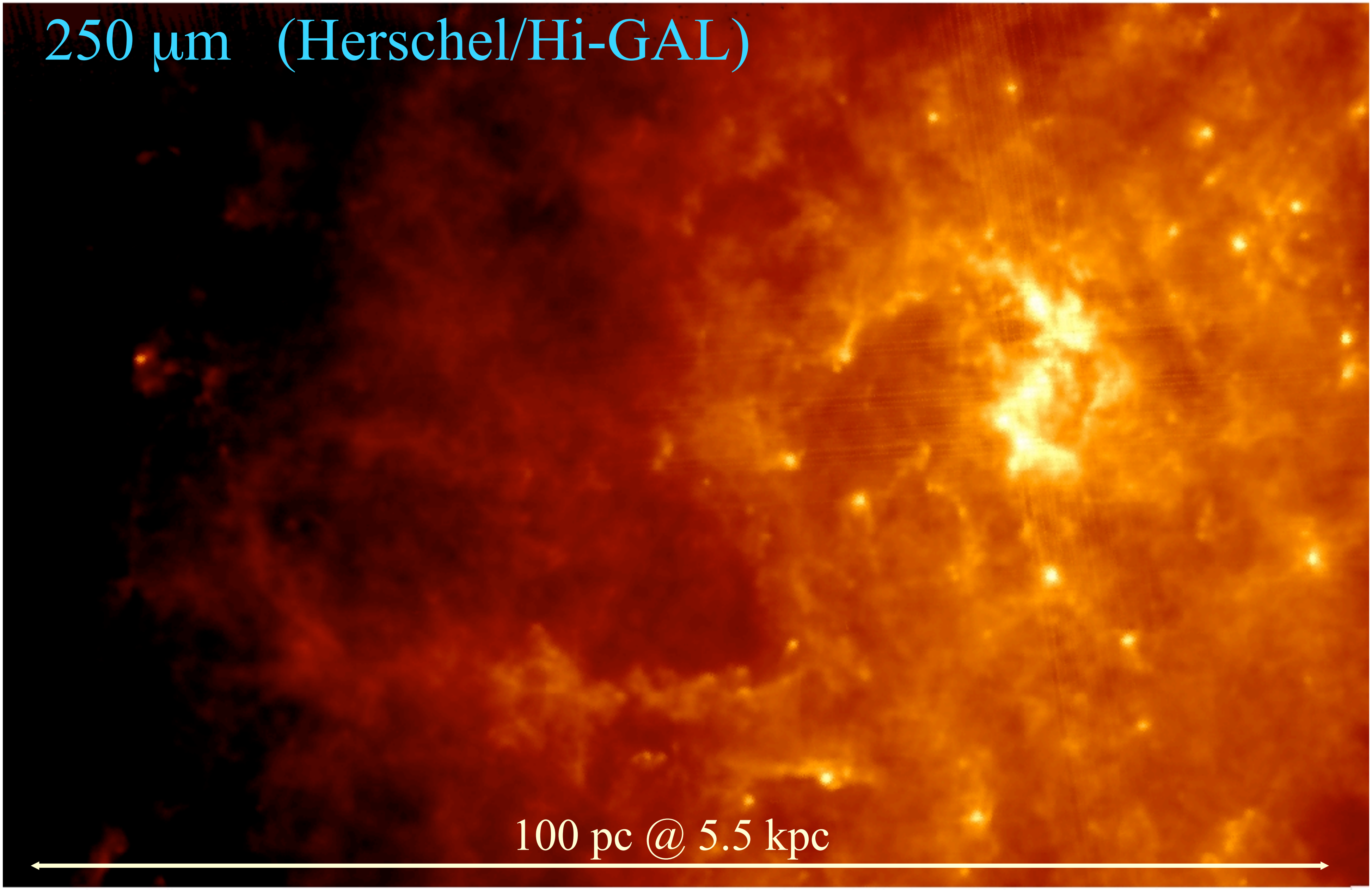
100 pc @ 5.5 kpc

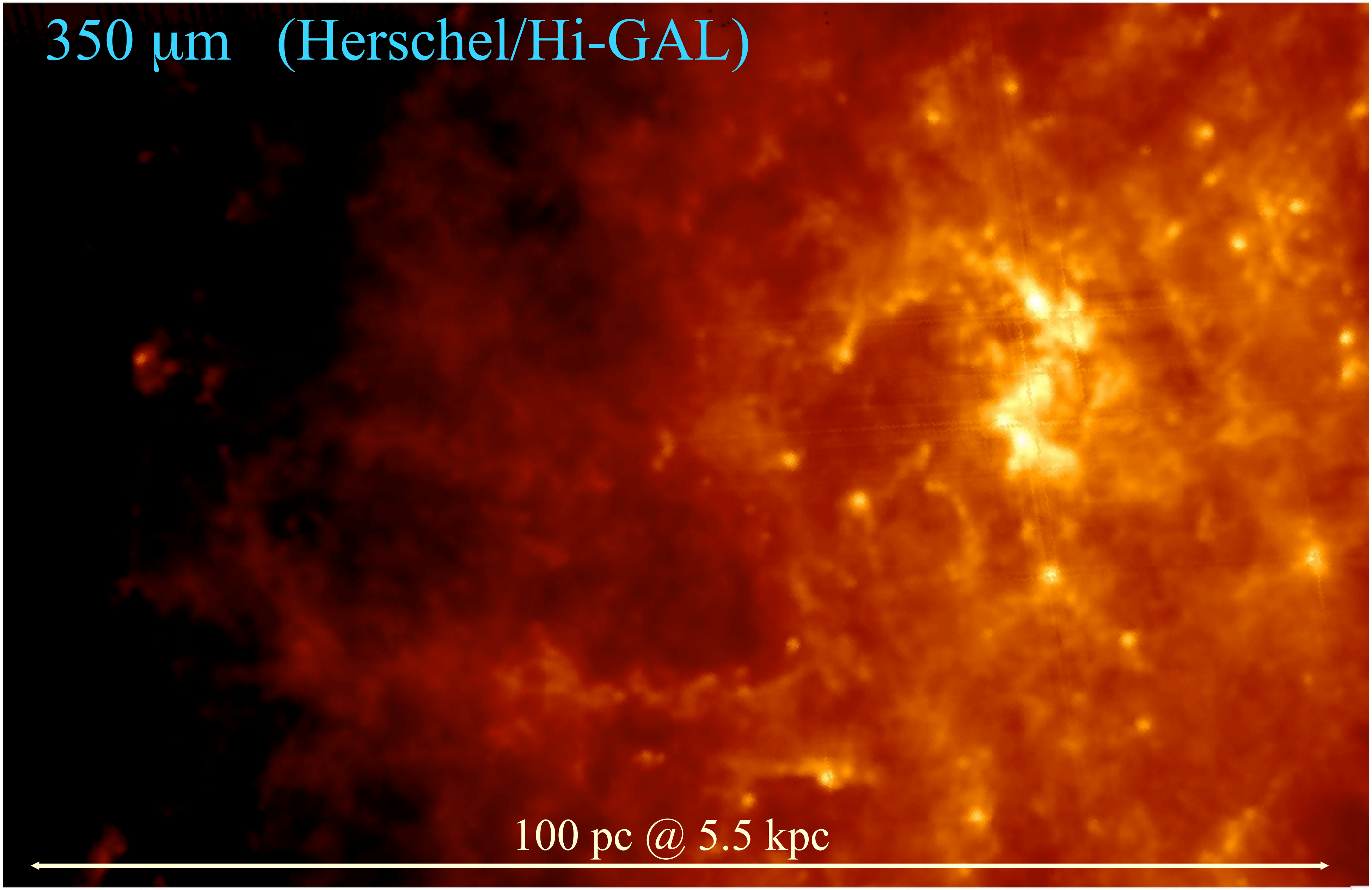
[redacted]

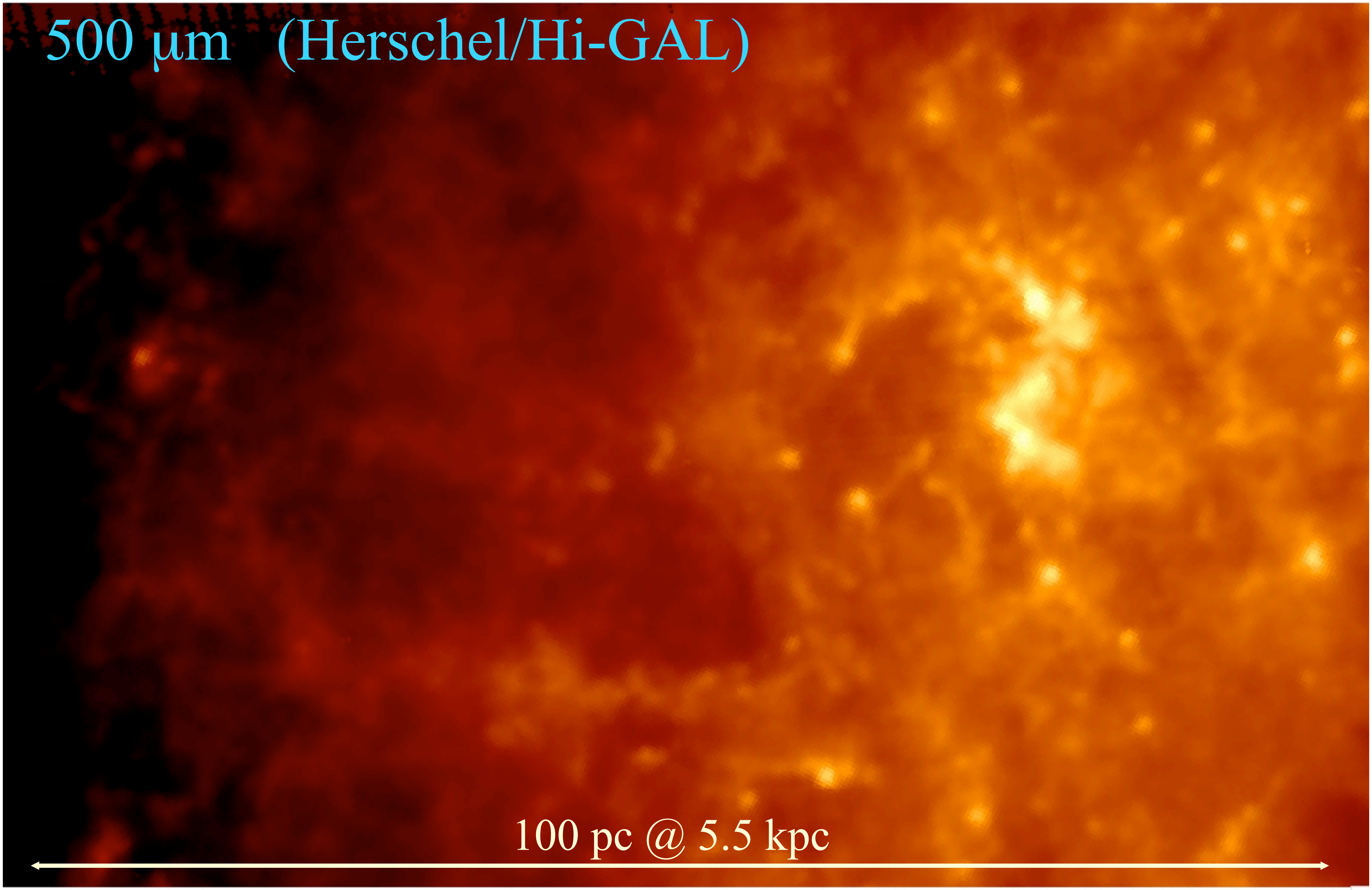

70 µm (Herschel/Hi-GAL)
100 pc @ 5.5 kpc

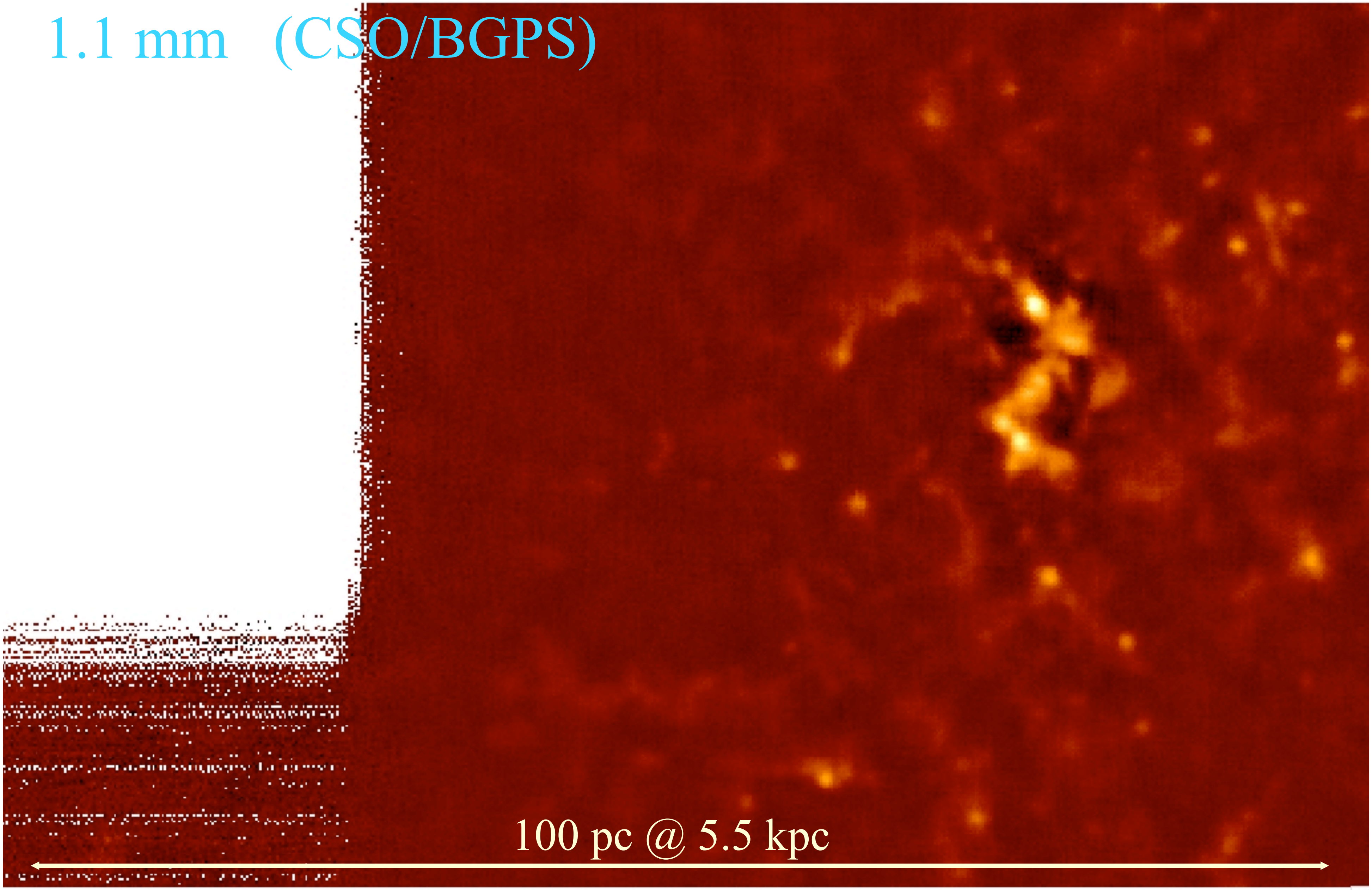


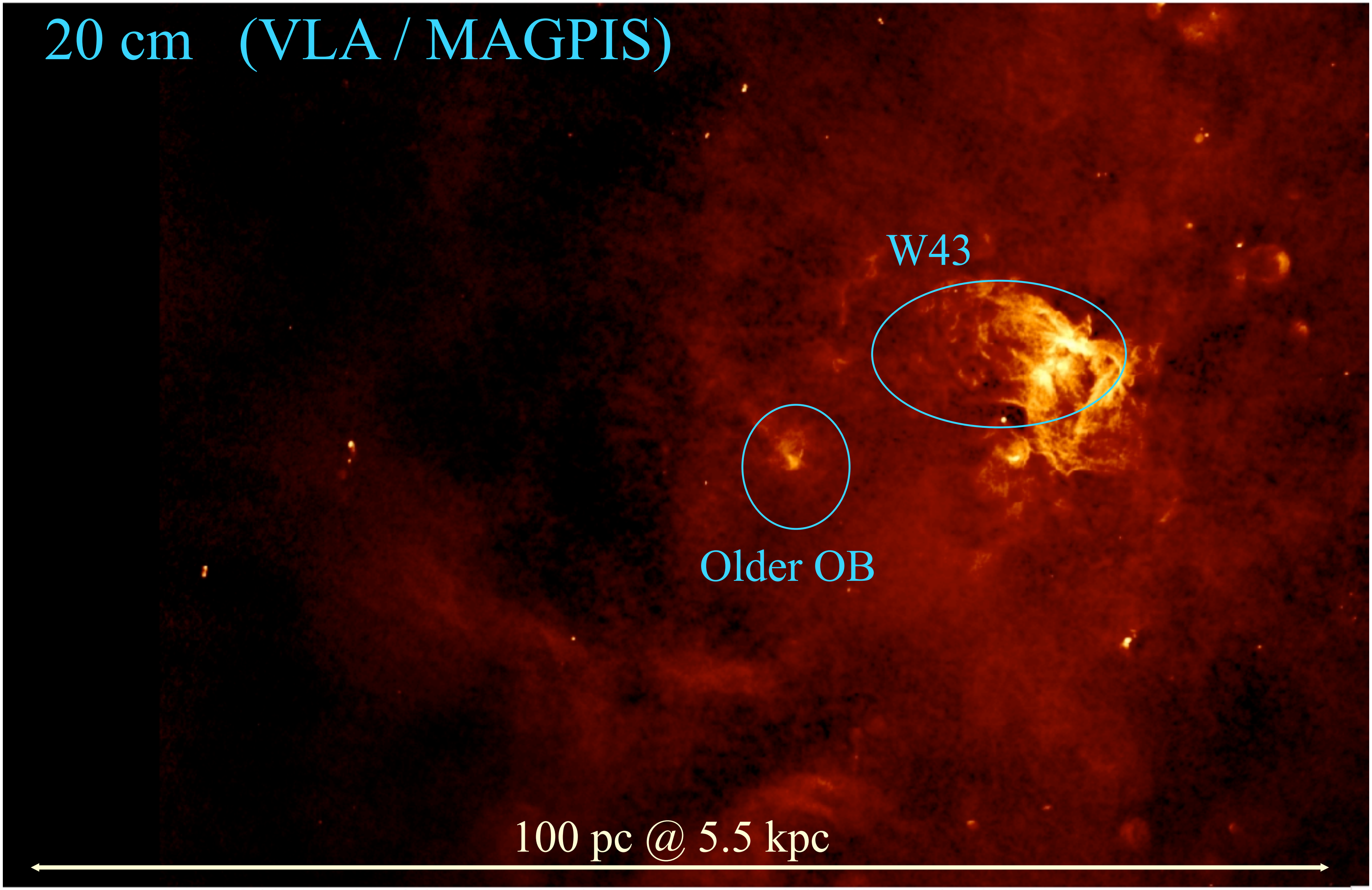
170 μm (Herschel/Hi-GAL)
`Z-shaped' filament
confining IRDCs
Cometary clouds
100 pc @ 5.5 kpc


250 µm (Herschel/Hi-GAL)
100 pc @ 5.5 kpc

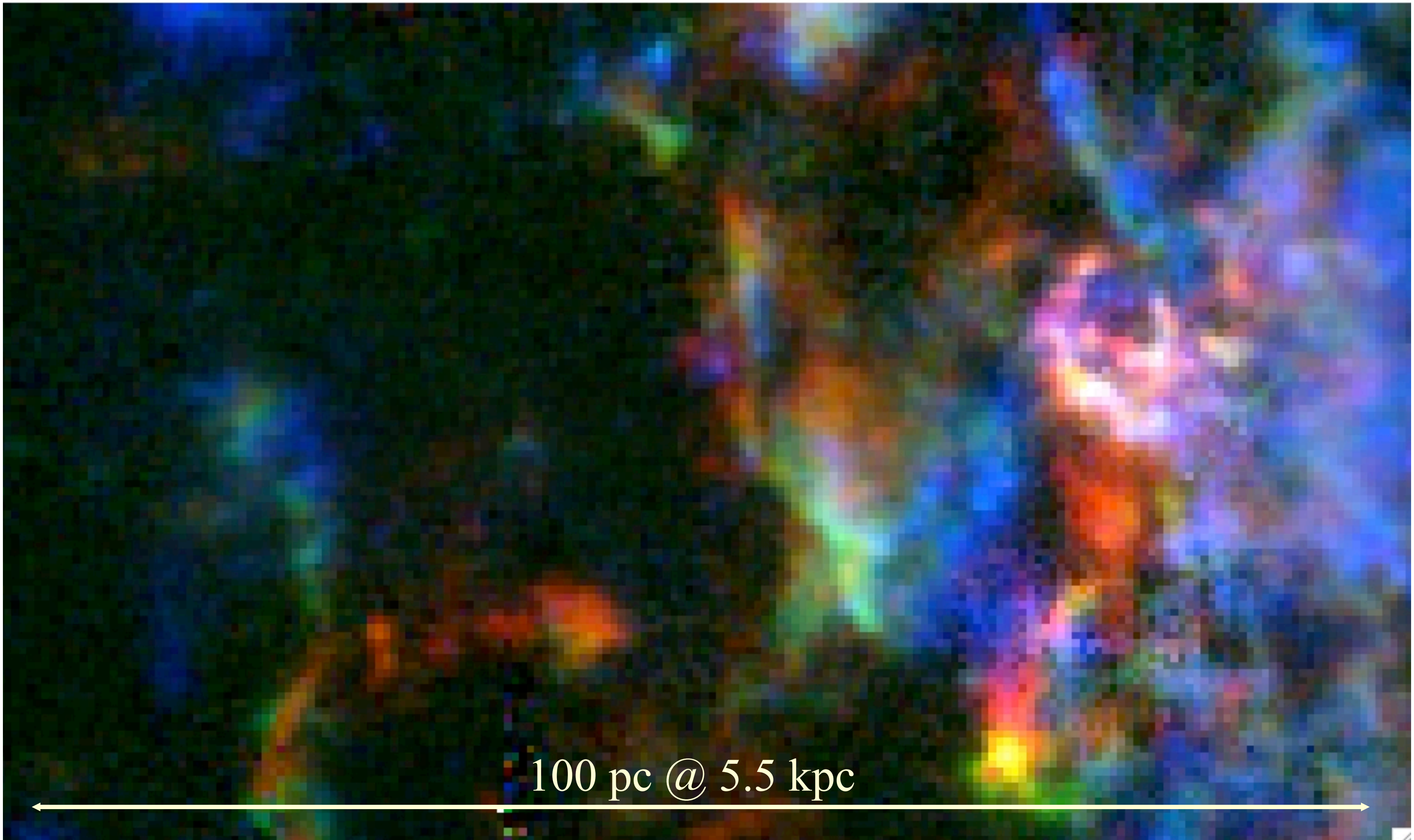

350 µm (Herschel/Hi-GAL)
100 pc @ 5.5 kpc


500 µm (Herschel/Hi-GAL)
100 pc @ 5.5 kpc

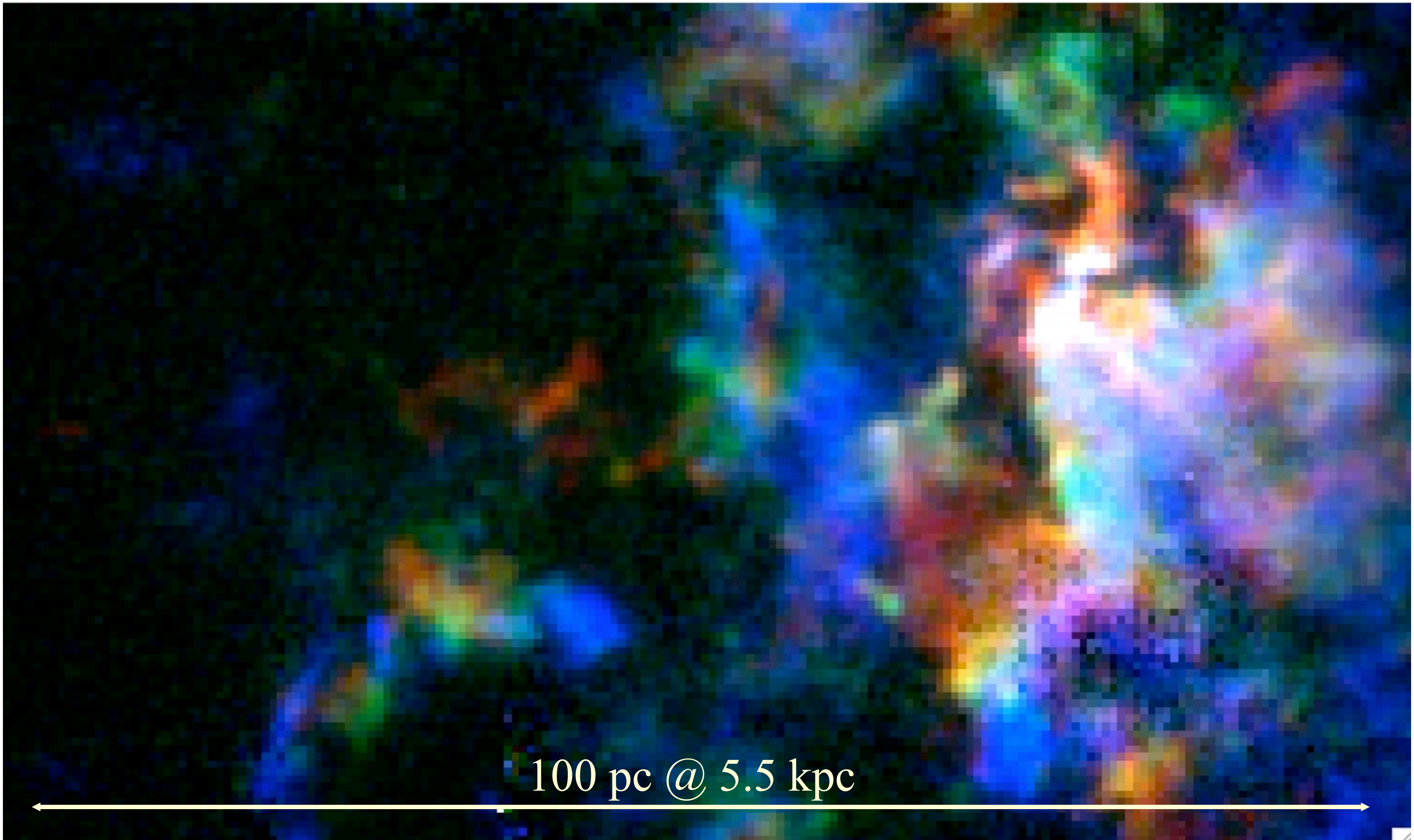

1.1 mm (CSO/BGPS)
100 pc @ 5.5 kpc


20 cm (VLA / MAGPIS)
W43
Older OB
100 pc @ 5.5 kpc

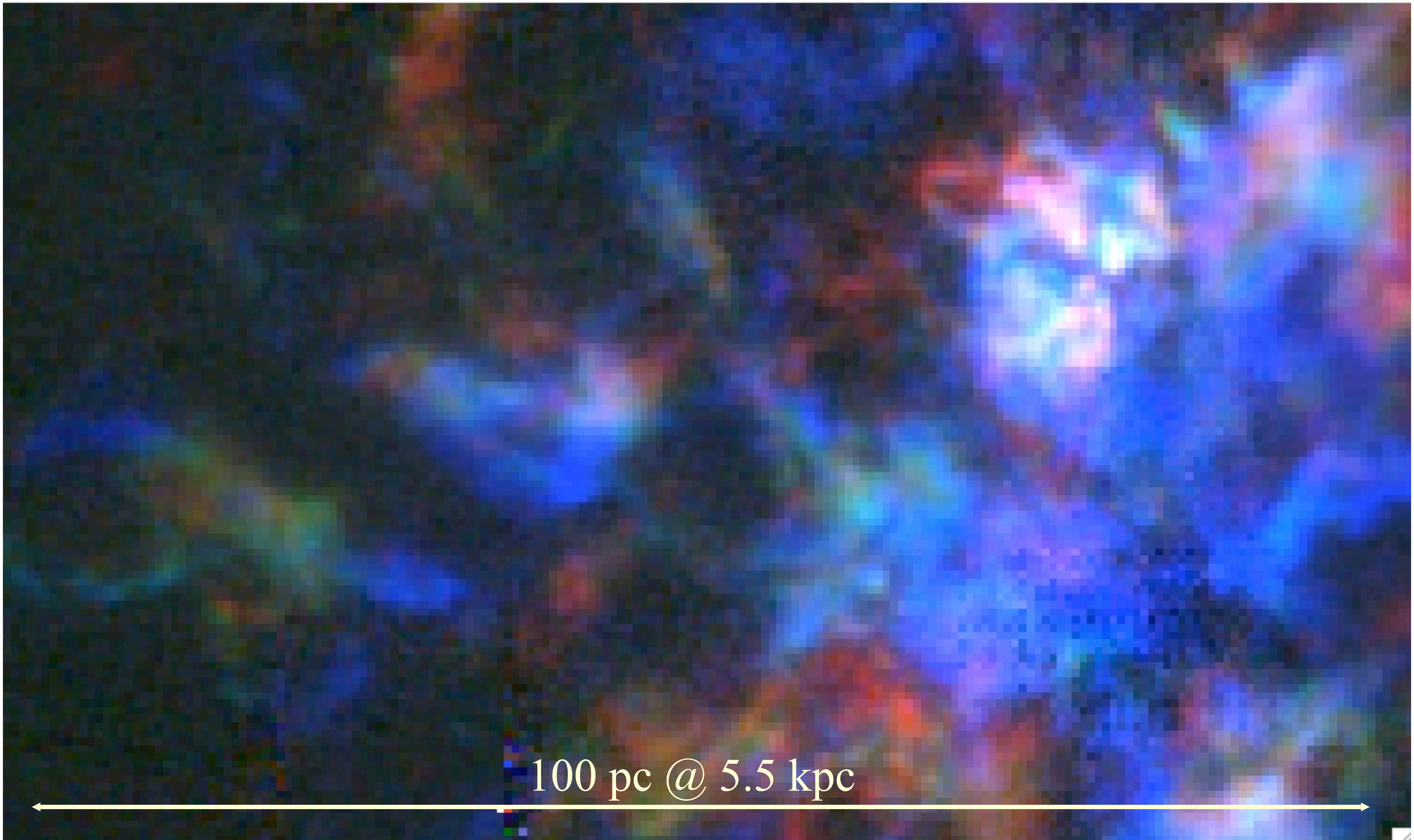
^{13}CO V_{lsr} = 84 86 88 (km/s)



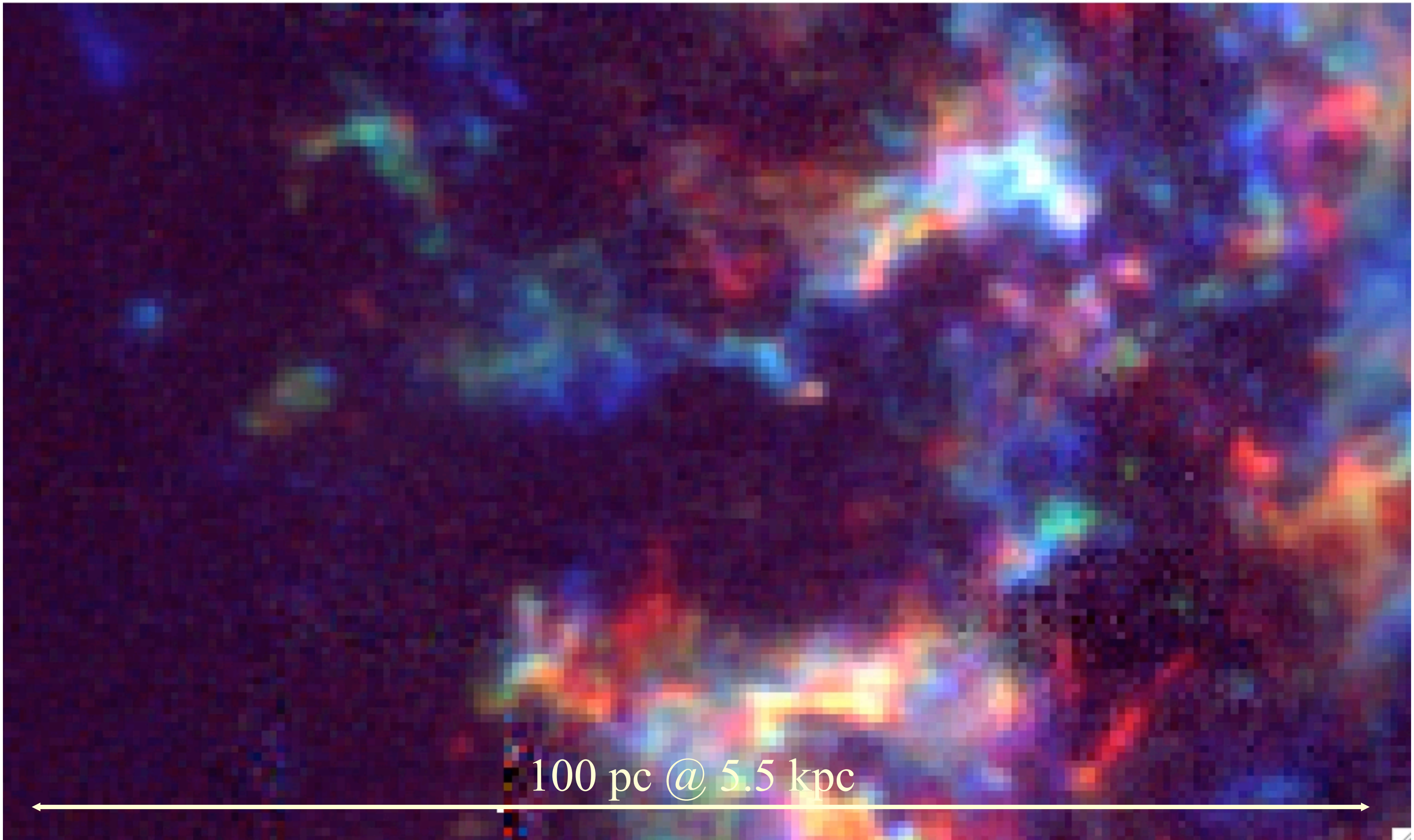
$^{13}CO \quad V_{lsr} =$ 88 90 92 (km/s)



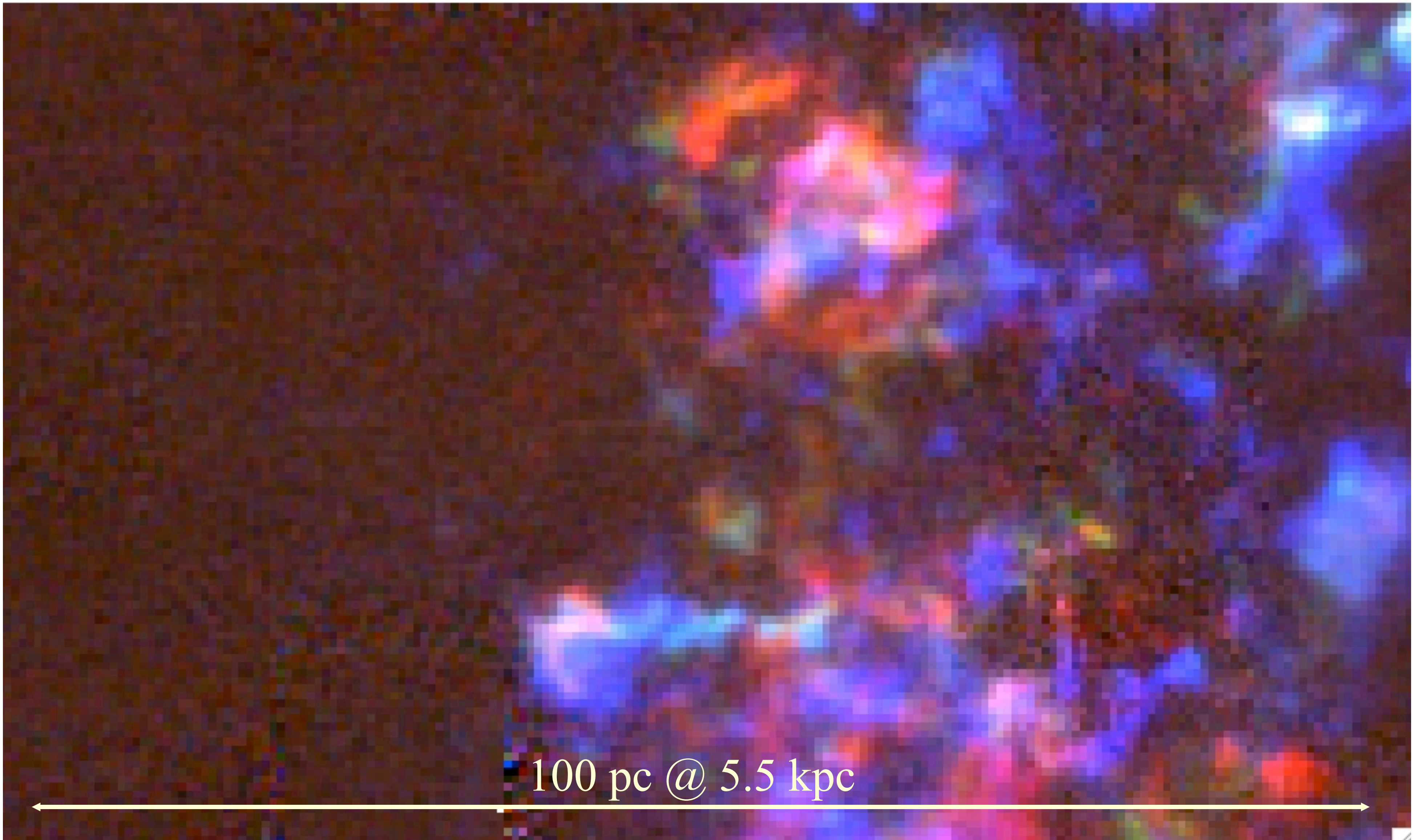
^{13}CO V_{lsr} = 94 96 98 (km/s)

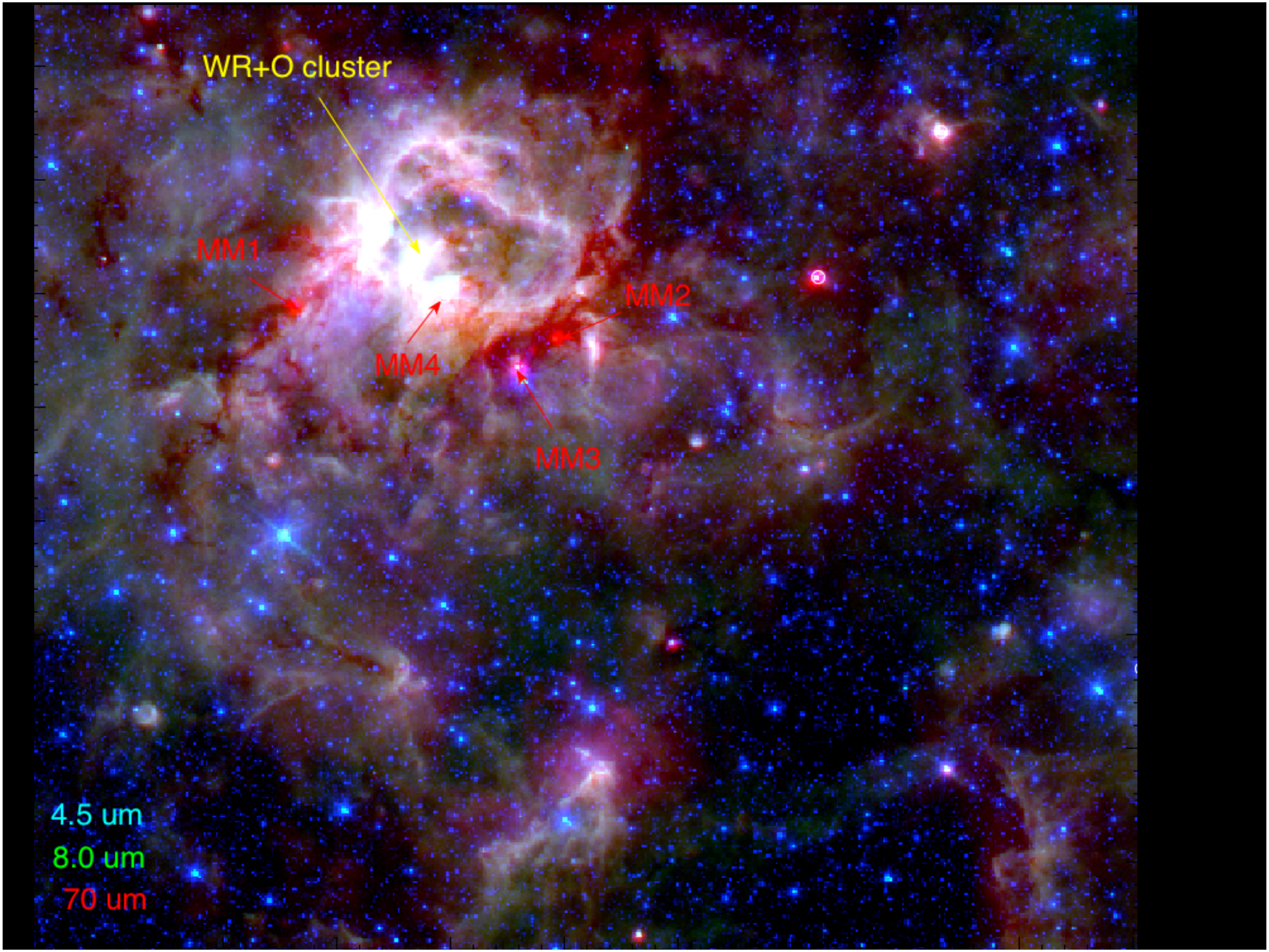


^{13}CO V_{lsr} = 100 102 104 (km/s)



^{13}CO V_{lsr} = 106 108 110 (km/s)

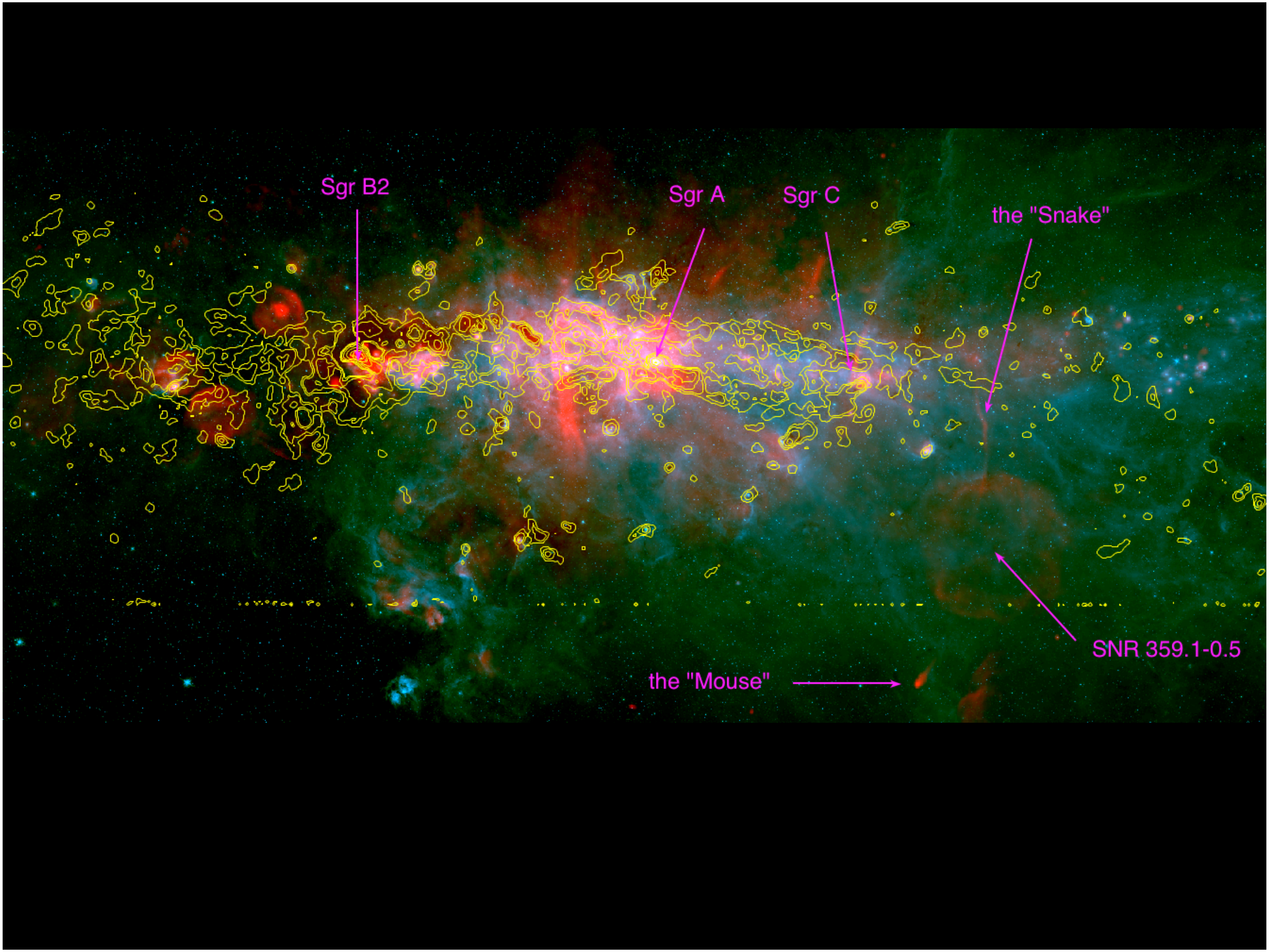


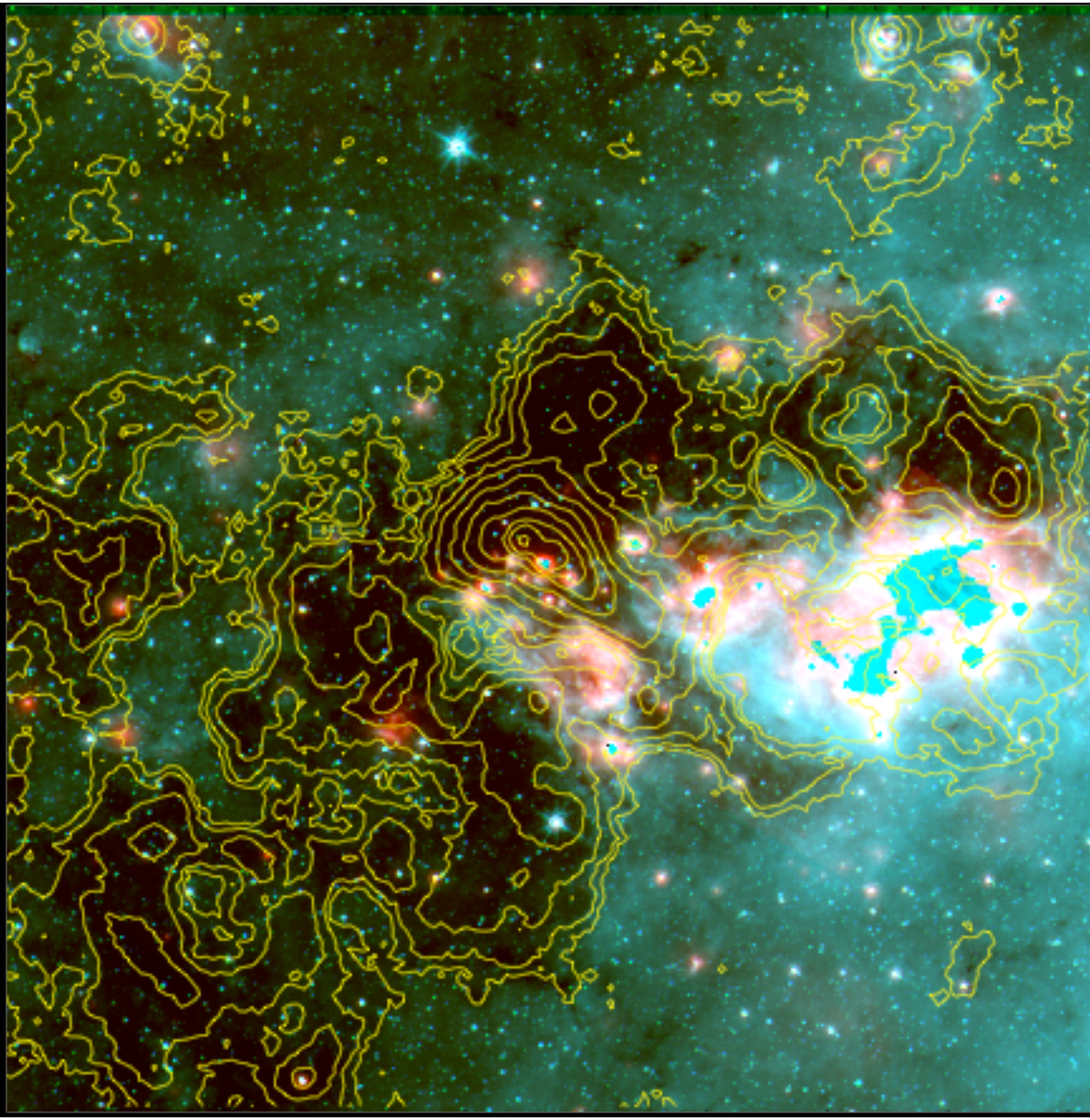

WR+O cluster
MM1
MM2
MM3
MM4
4.5 um
8.0 um
70 um

3.6 - 8 μm 1.1 mm 20 cm

Adam Ginsburg: NRAO 2008 photo-contest First Prize!

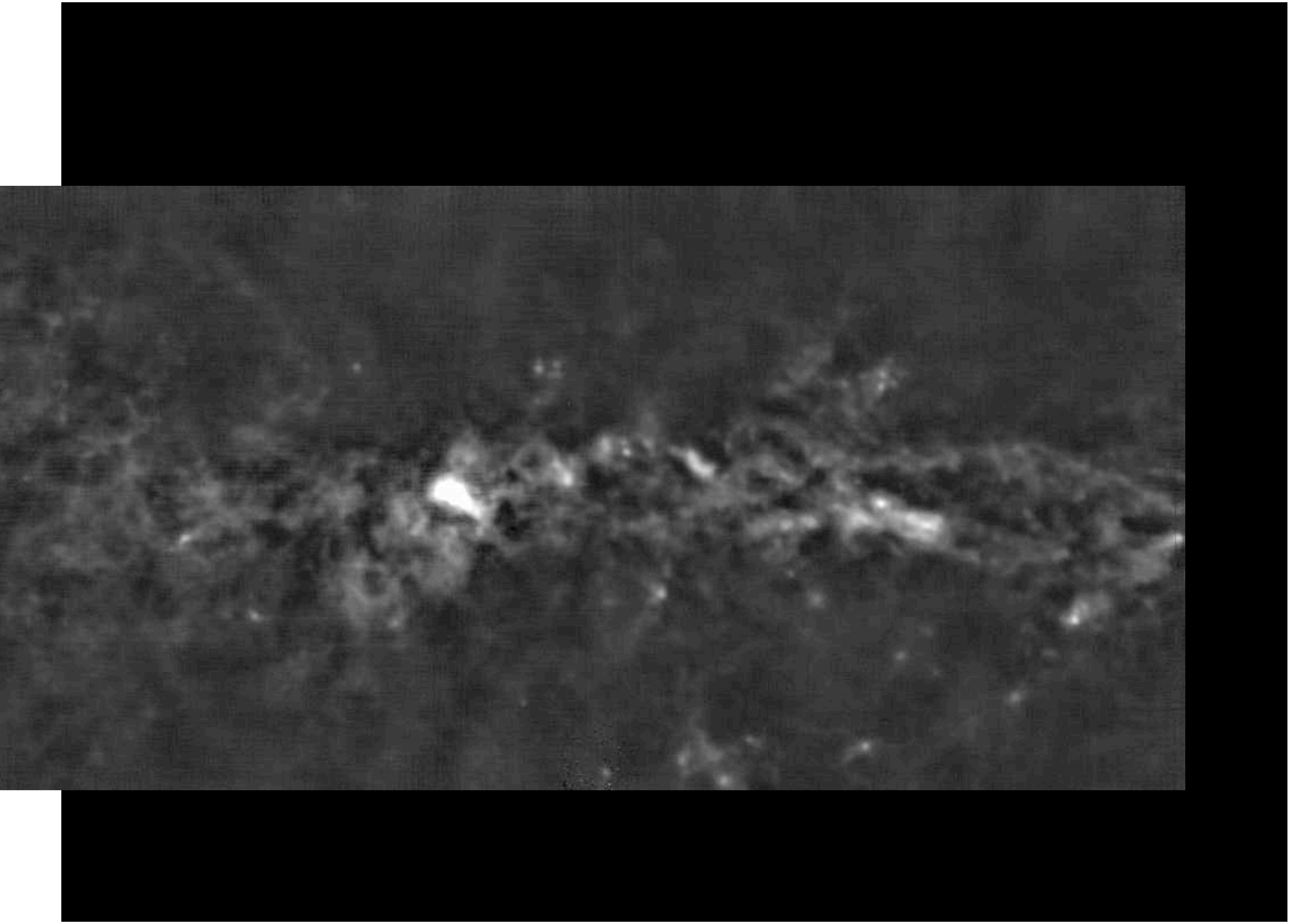
NRAO submission for AAS Calendar, 2009 Feb

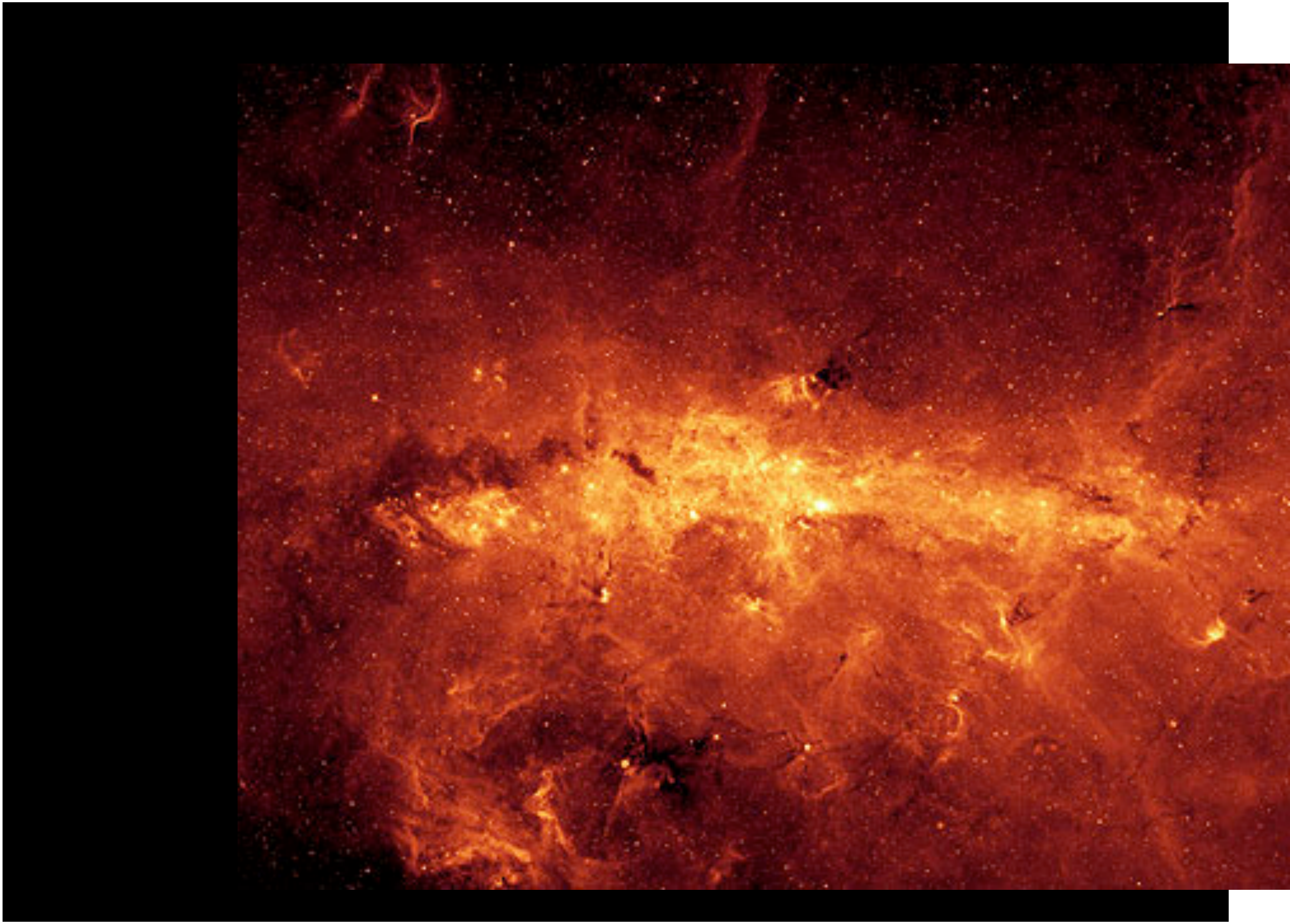

Sgr B2
Sgr A
Sgr C
the "Snake"
SNR 359.1-0.5
the "Mouse"

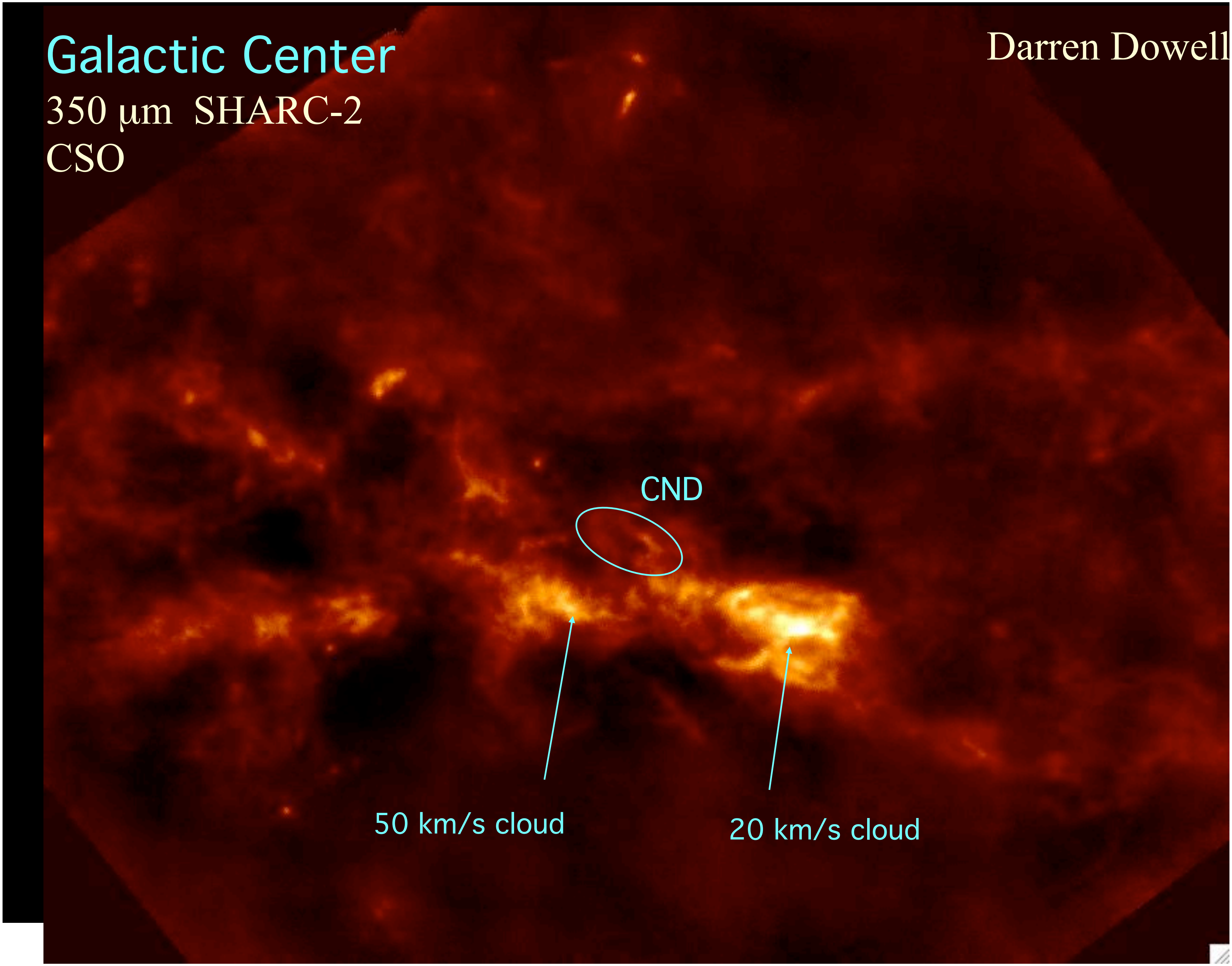


The Center of the Milky Way Galaxy
NASA / JPL-Caltech / S. Stolovy (Spitzer Science Center/Caltech)

Spitzer Space Telescope






Galactic Center
350 μm SHARC-2
CSO
Darren Dowell
CND
50 km/s cloud
20 km/s cloud

SOFIA Roles

Current:

- FORCAST imaging of MYSOs & embedded clusters
- High-resolution spectroscopy of FIR lines
  - Herschel Hi-GAL bright-source follow-up

Next-Gen Needs (wish list):

- Narrow-band, velocity resolved wide-field imaging
  - Tunable filters, FPs, Slit-scanning
    - $R \sim 10^4$; $\lambda \sim 3 - 300$ μm
  - Multi-object heterodyne spectroscopy
    - $R > 10^6$; $\lambda \sim 3 - 300$ μm
  - Line & Continuum Polarimetry
    - linear, circular, multi-object, W-FOV
  - Simultaneous Multi-order spectroscopy
    - dichroic split, MKIDs, bolometers?

Conclusions

Orion:

Decay of non-hierarchical multiple star system

Ejected BN, I, n with V ~ 10 to 30 km/s 500 years ago!

Orion OMC1 outflow (~few x 10^{47} erg)

Disruption of inner disks => fastest ejecta

Recoil of outer envelope + disk => slow ejecta

Boost by expansion of wrapped-up B? => slow ejecta

Cep A:

Pulsed, precessing jet (P ~ 2,000 years)

Capture-formed binary?

Lessons:

In the two nearest massive star forming regions ...

Small-N Dynamics play important roles in massive star formation !

High multiplicity => Capture formation

Ejection => High-velocity stars

Stored Energy Release => Explosive Outflows

SOFIA: Best instrument to probe SEDs & spectra of MYSOs

Bright, SED peaks @ 10 to 100 μm

Velocity Resolved Spectroscopy

Variability (?) => Episodic accretion?


The End

[redacted]