Some Puzzles of Massive Star & Cluster Formation; from Orion, to the `mini-starburst' in W43, to the Galactic Center

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Outline

Introduction:

Review properties of massive stars
Theories of massive star and cluster birth

Observations of Galactic massive star forming regions:

Orion OMC-1
- An explosive outflow
- Dynamical ejection of stars (VLA)
- Laser guide star AO imaging (Gemini-N)

W43
- BGPS & Herschel Hi-GAL
- SOFIA / FORCAST plans

The Central Molecular Zone (CMZ)
- Spitzer, Herschel, VLA, Bolocam

Conclusions
- The Roles of Dynamic Interactions and Radiation

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)

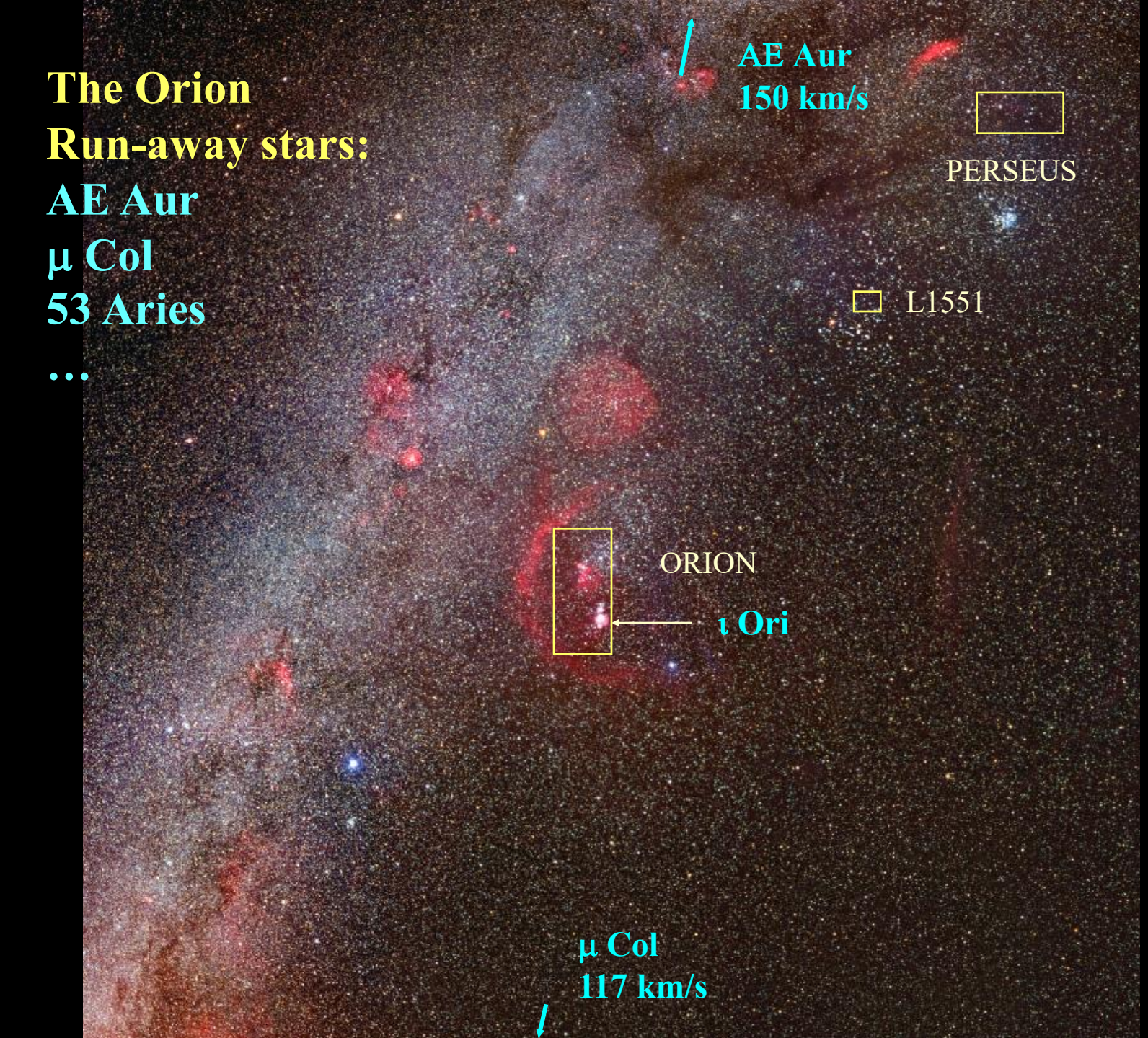
No pre-main sequence phase

$t_{accretion} > t_{contraction}$

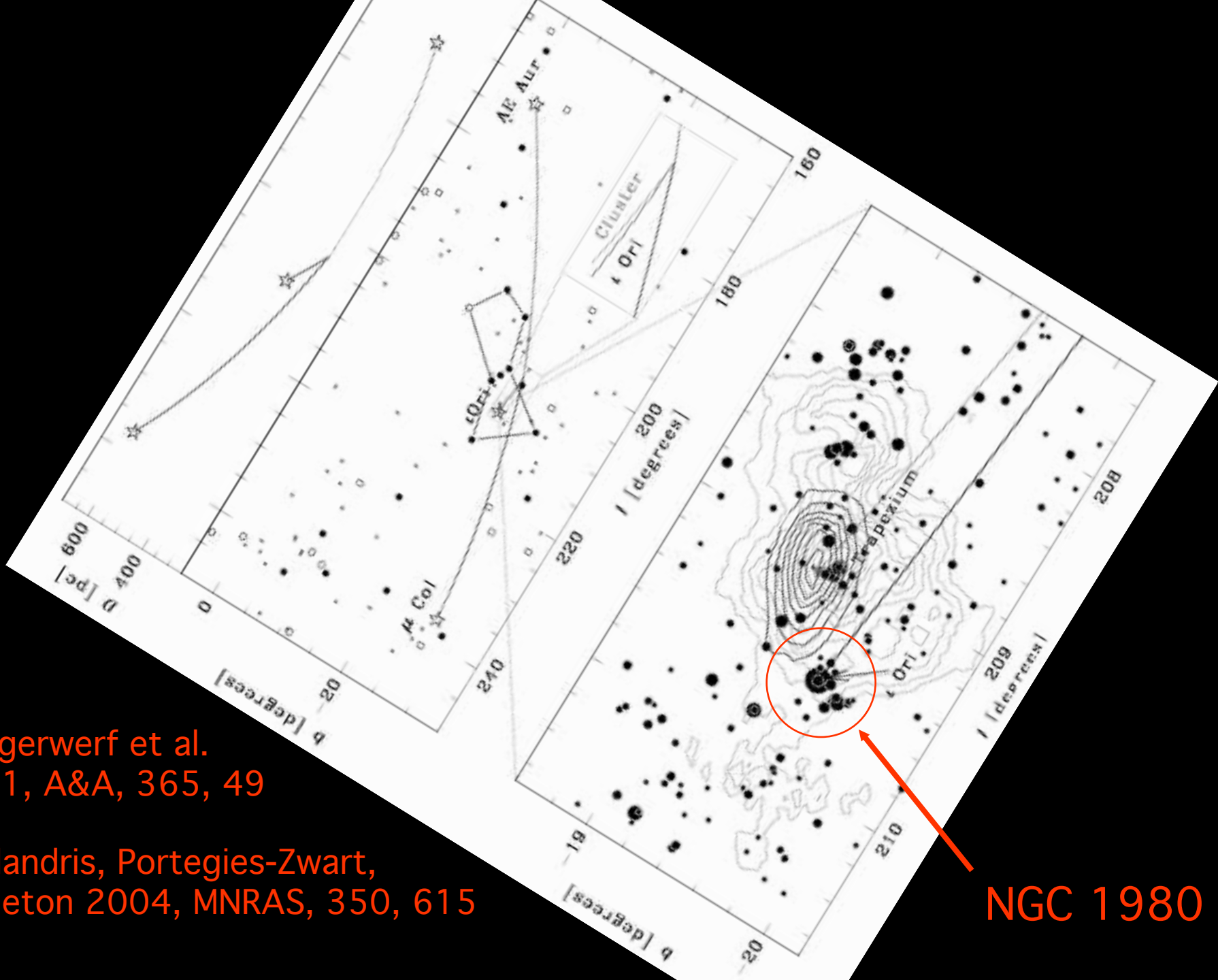
Mass Segregation

Massive stars form in center

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


The Orion
Run-away stars:
AE Aur
μ Col
53 Aries
…
AE Aur
150 km/s
PERSEUS
L1551
ORION
ι Ori
μ Col
117 km/s

Wei-Hao Wang



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

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

NGC 1980

Massive Star Formation

(Least Understood)

Isolated Monolithic Collapse

Scaled-up low-mass star formation

High-P , Σ (> 1 g cm^{-2})

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

Clustered Competitive Accretion

Cores interact, compete for matter

Massive stars grow fastest, and in center

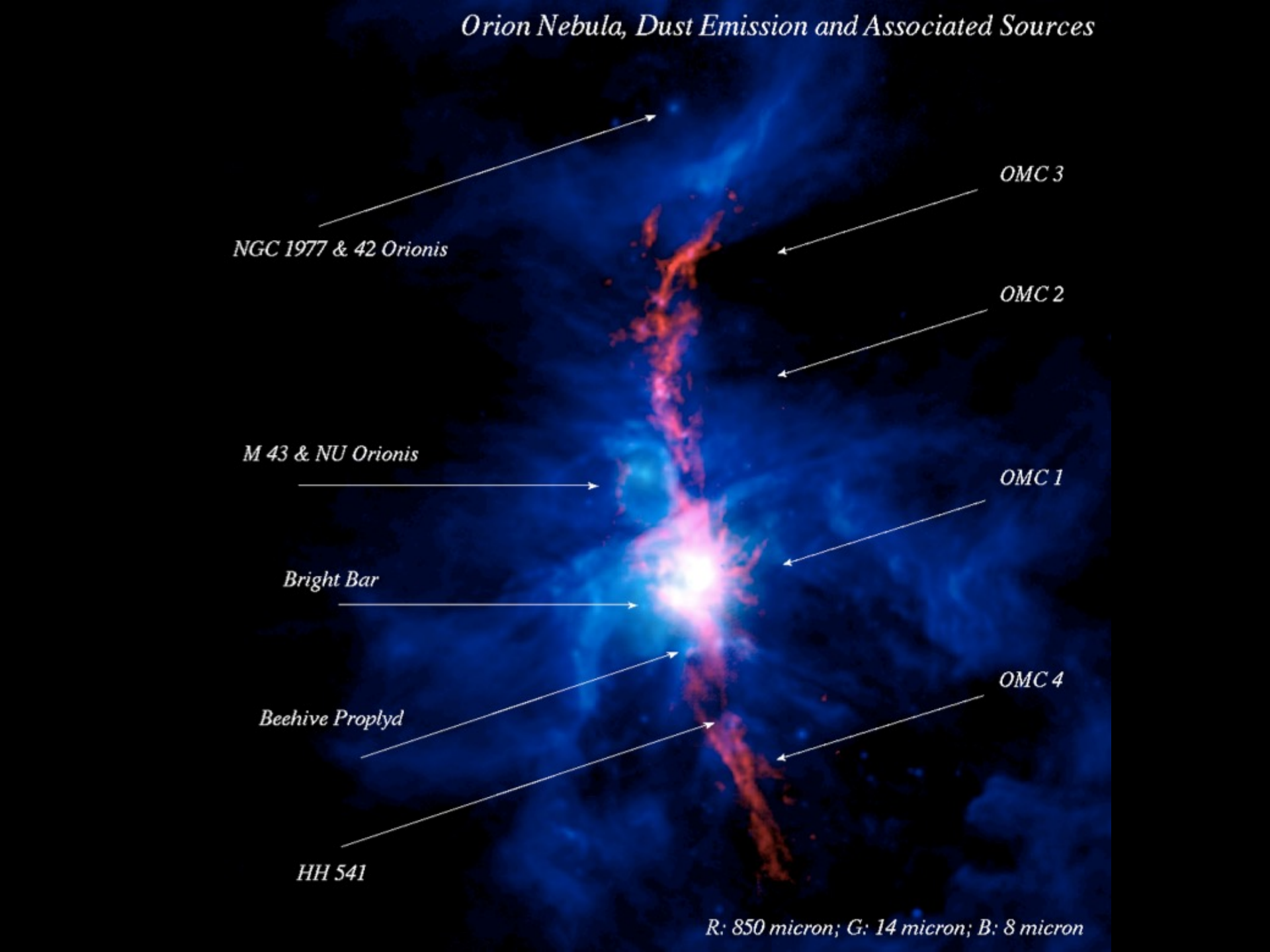
- Bonnell, Bate, Zinnecker (1998 => ...)

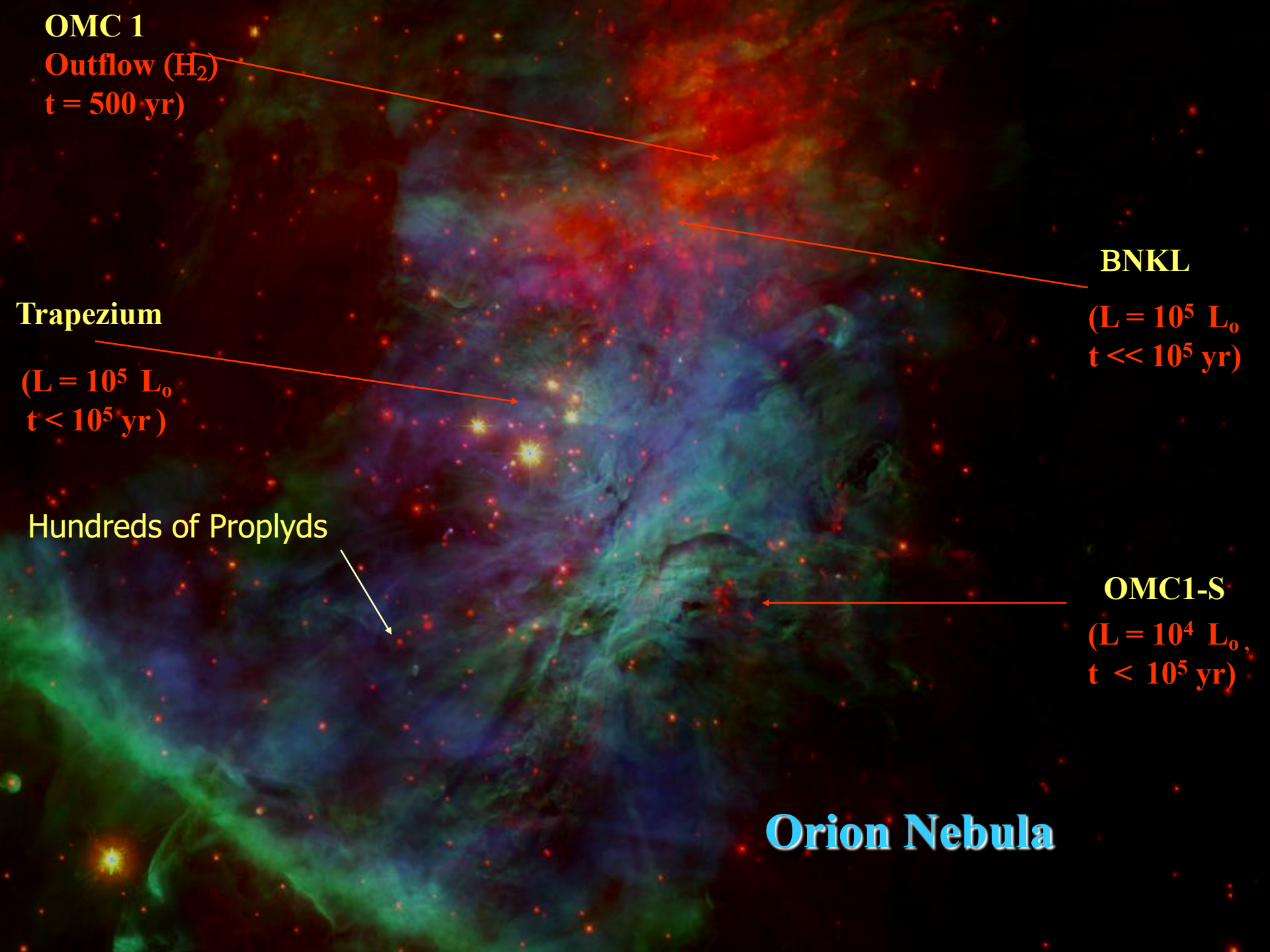
Co-Operative Accretion (super star clusters)

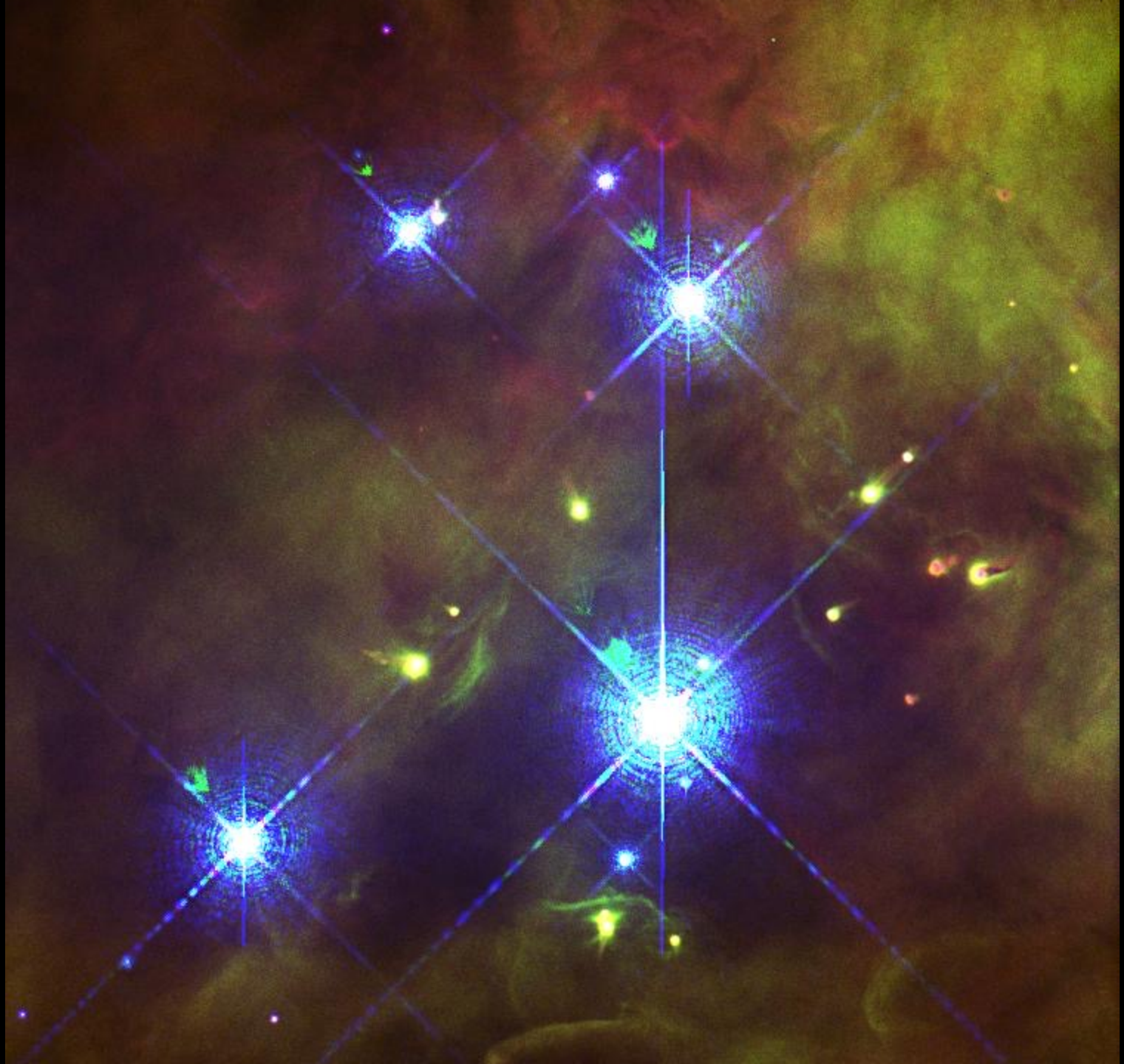
~ Eddington limit, effective gravity disappears

Secondary stars grow to M_{edd}

- Keto (2003 => ...)

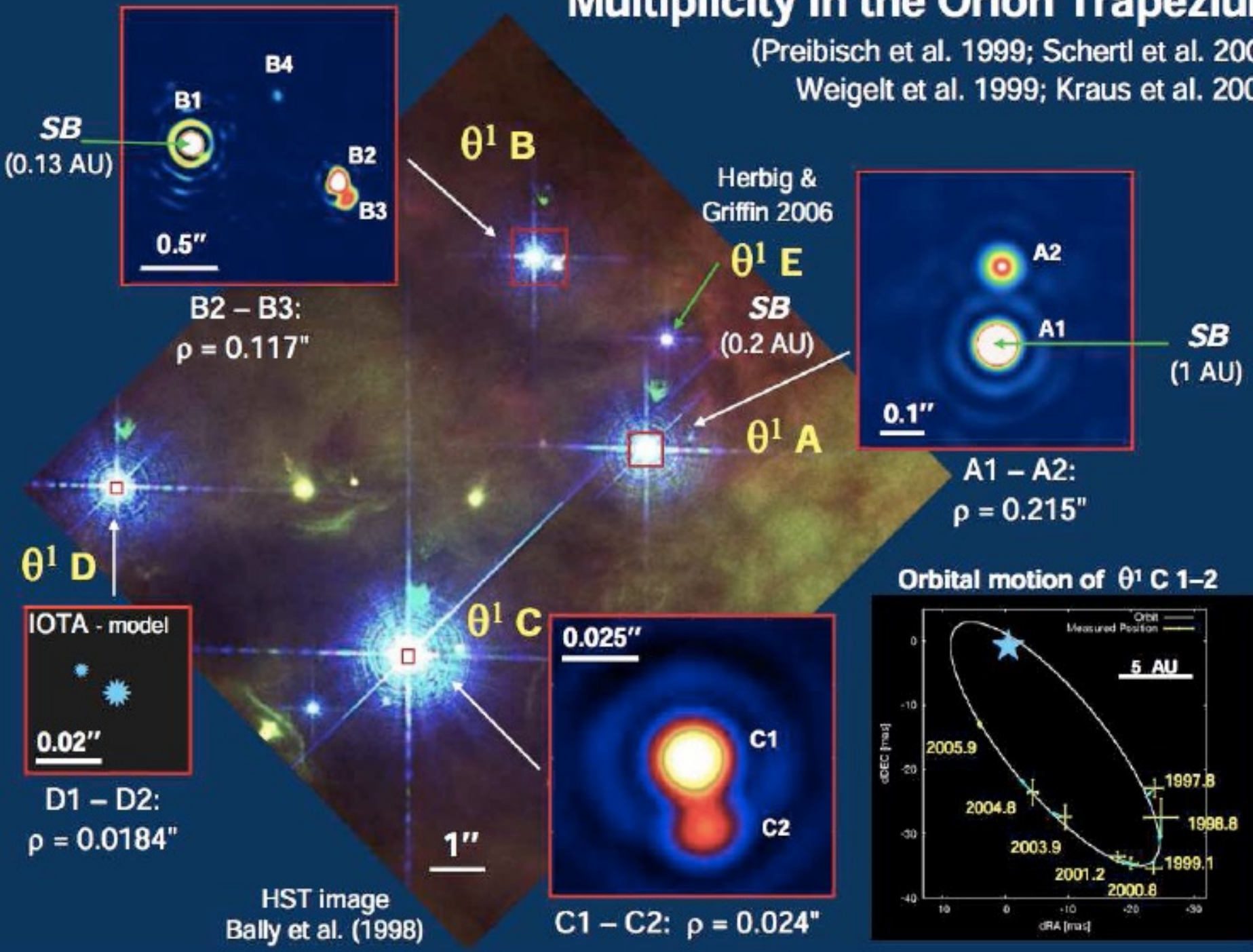

Orion Nebula, Dust Emission and Associated Sources
NGC 1977 & 42 Orionis
OMC 3
OMC 2
M 43 & NU Orionis
OMC 1
Bright Bar
Beehive Proplyd
OMC 4
HH 541
R: 850 micron; G: 14 micron; B: 8 micron

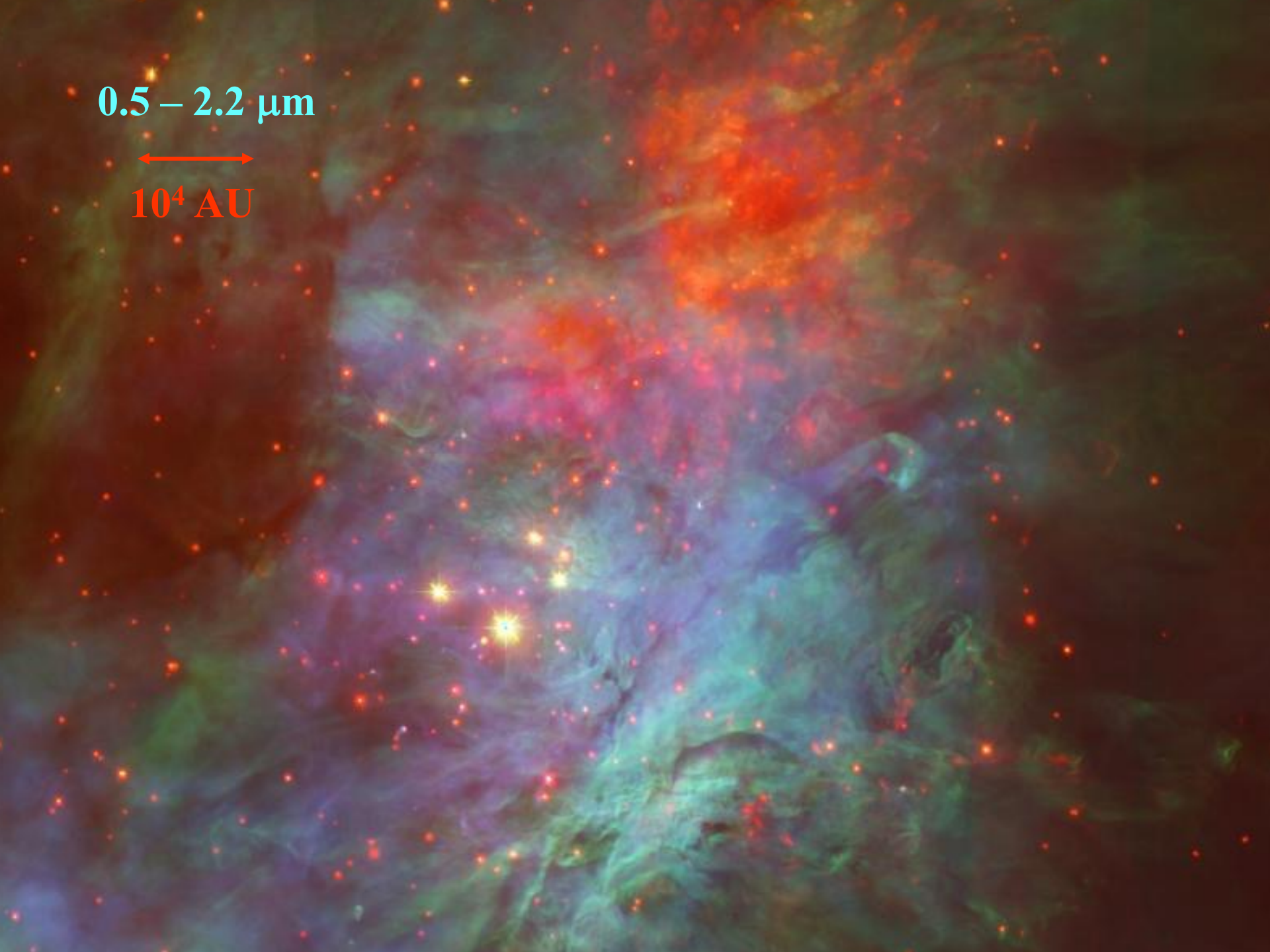

OMC 1
Outflow (H_2)
t = 500 yr)
BNKL
($L = 10^5\ L_o$
$t << 10^5$ yr)
Trapezium
($L = 10^5\ L_o$
$t < 10^5$ yr)
Hundreds of Proplyds
OMC1-S
($L = 10^4\ L_o$,
$t < 10^5$ yr)
Orion Nebula



Multiplicity in the Orion Trapezium

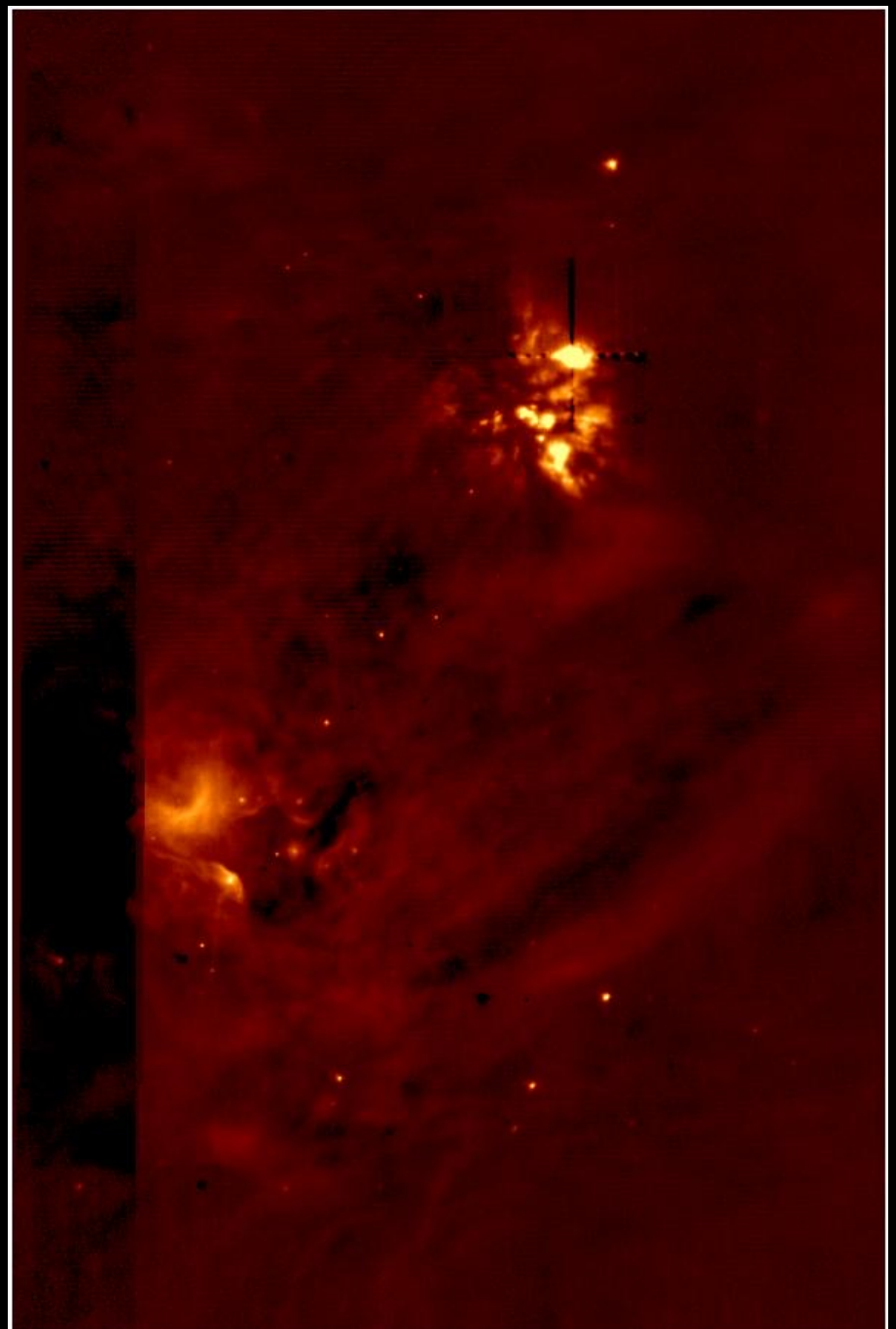
(Preibisch et al. 1999; Schertl et al. 2003; Weigelt et al. 1999; Kraus et al. 2007)




0.5 – 2.2 μm
10^4 AU

11.7 μm

10^4 AU



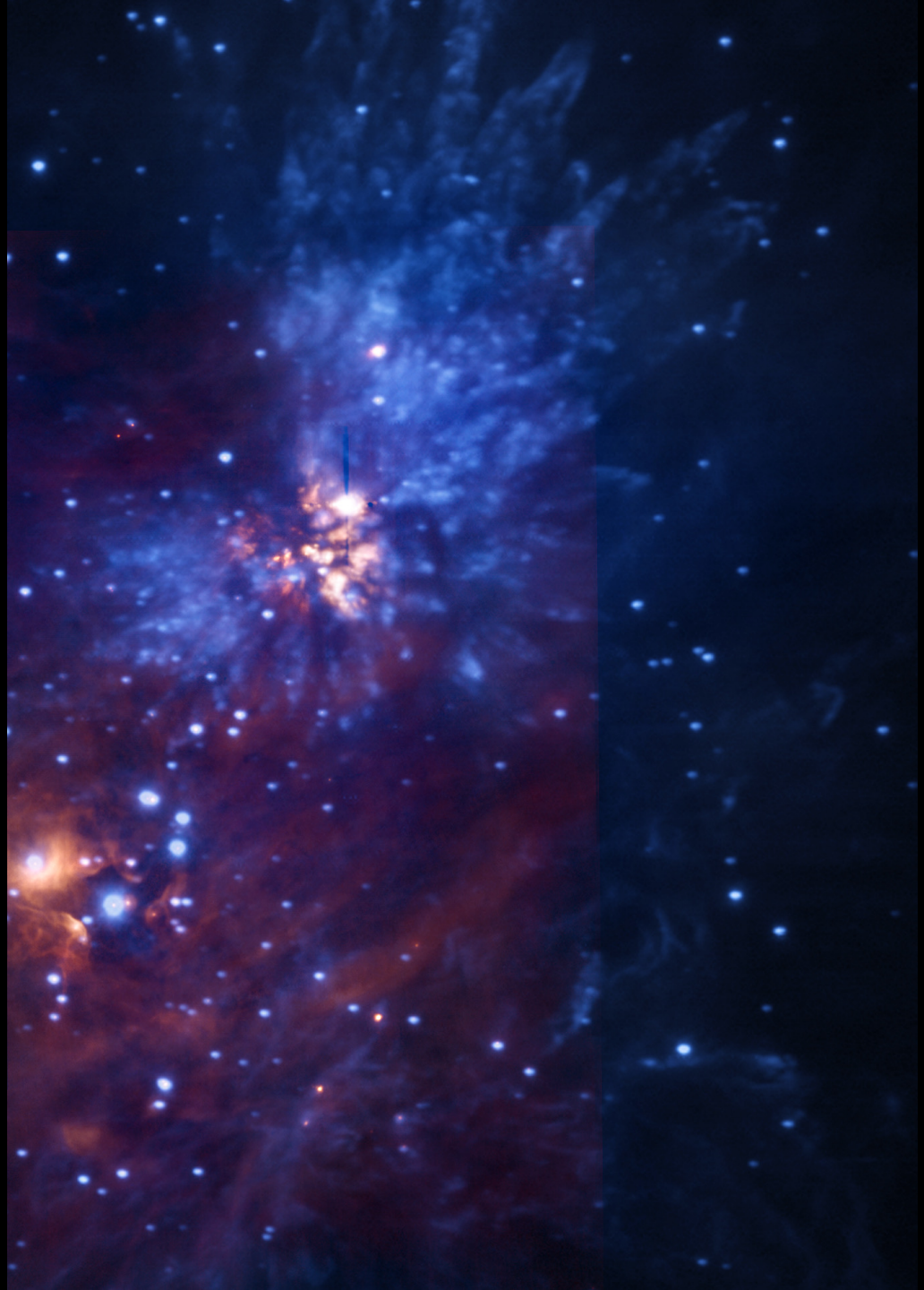
2.12 μm H_2 (blue)

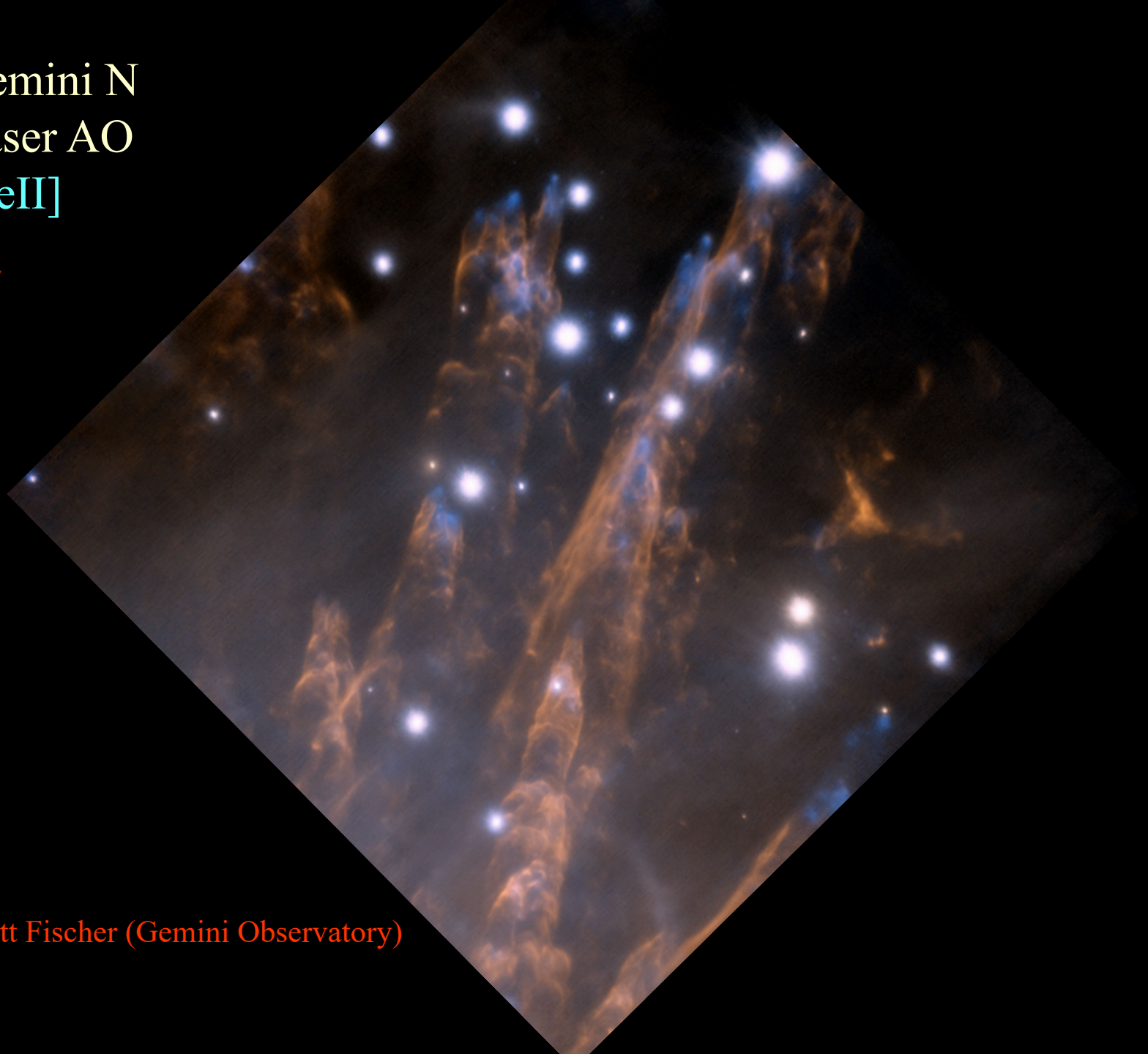
11.7 μm (orange)

Smith et al. (2005)

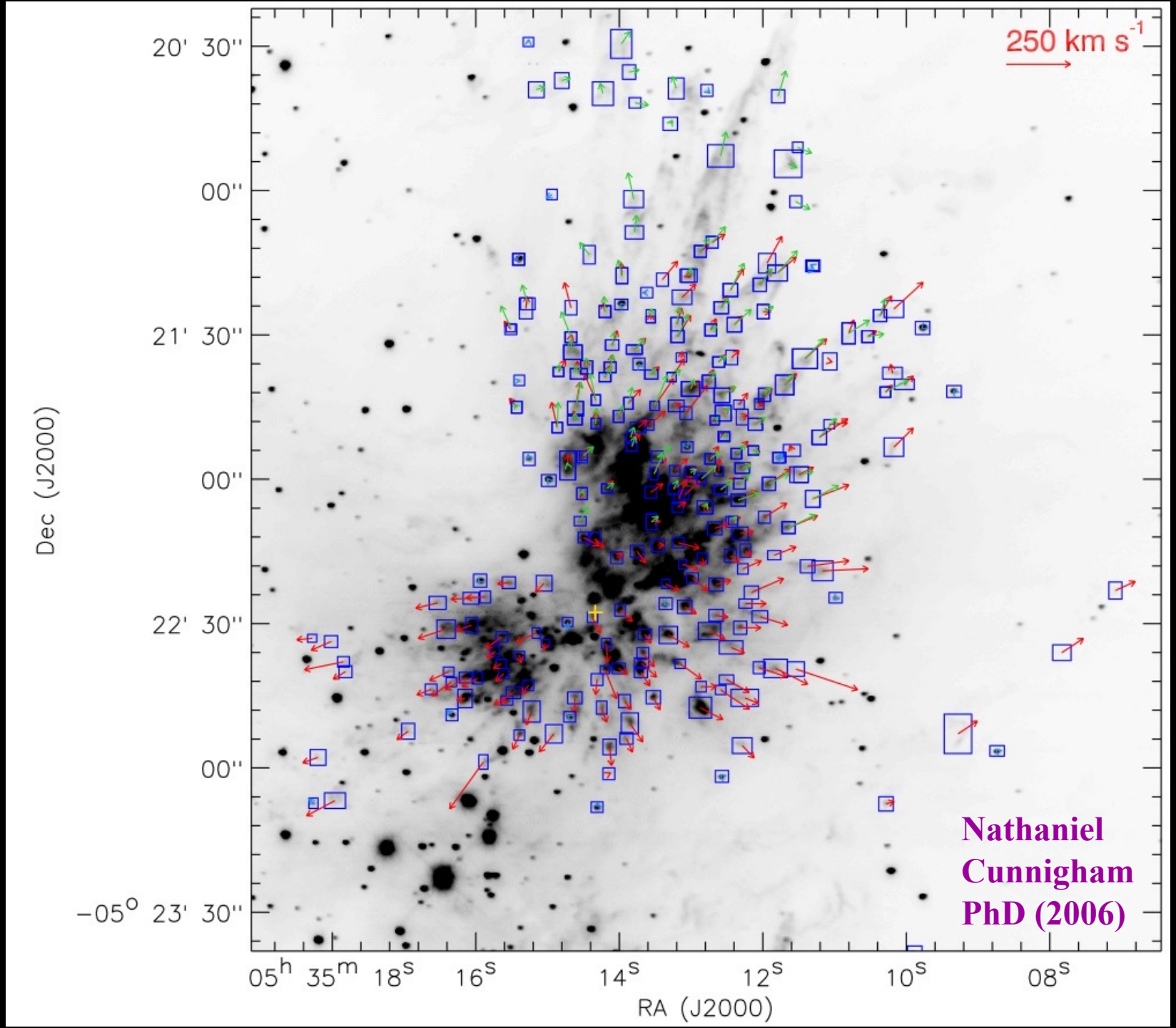
+

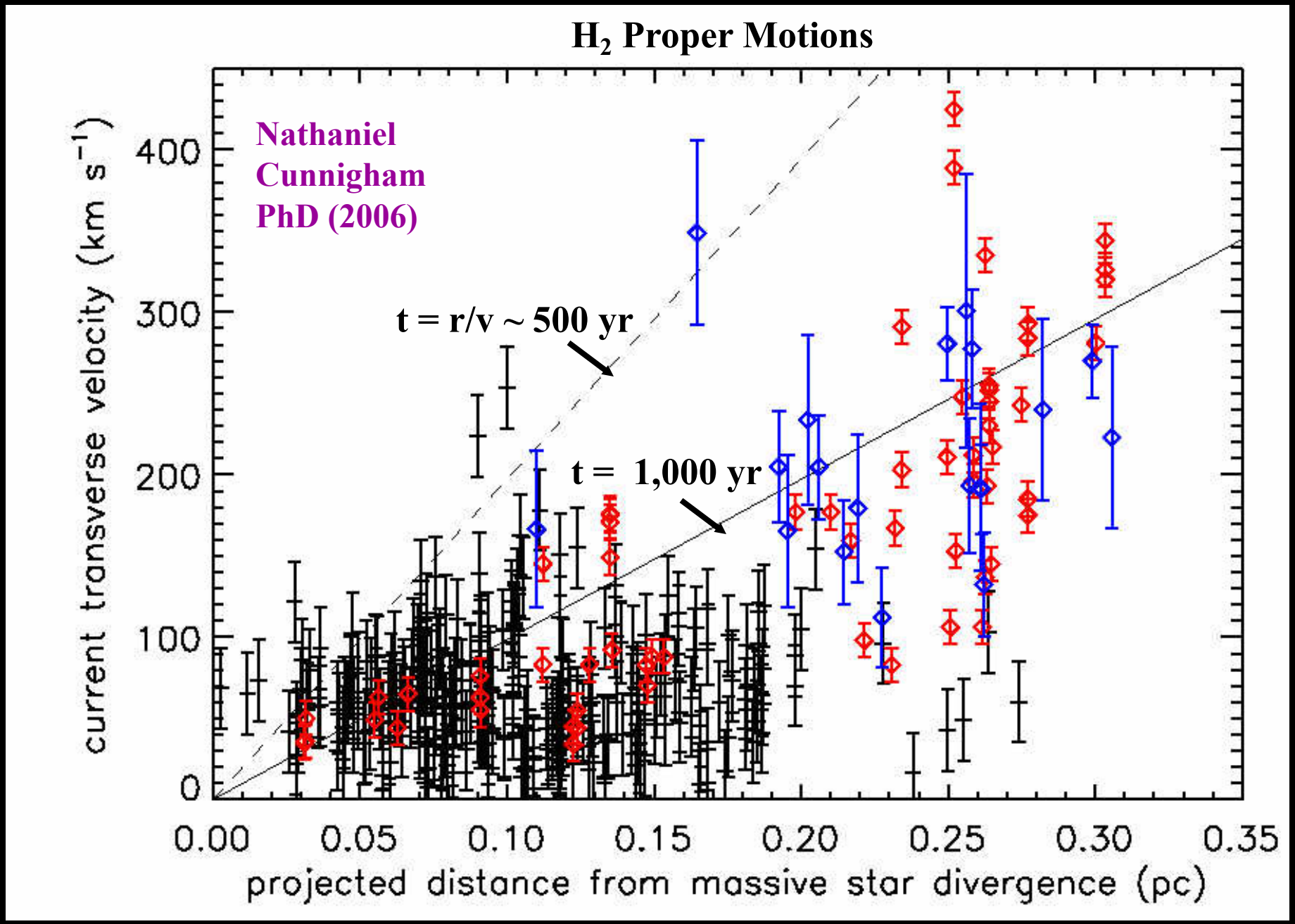
Cunningham (2008)





Scott Fischer (Gemini Observatory)


250 km s-1
20' 30"
00"
21' 30"
00"
22' 30"
00"
−05° 23' 30"
Dec (J2000)
05h 35m 18s
16s
14s
12s
10s
08s
RA (J2000)
Nathaniel
Cunnigham
PhD (2006)



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

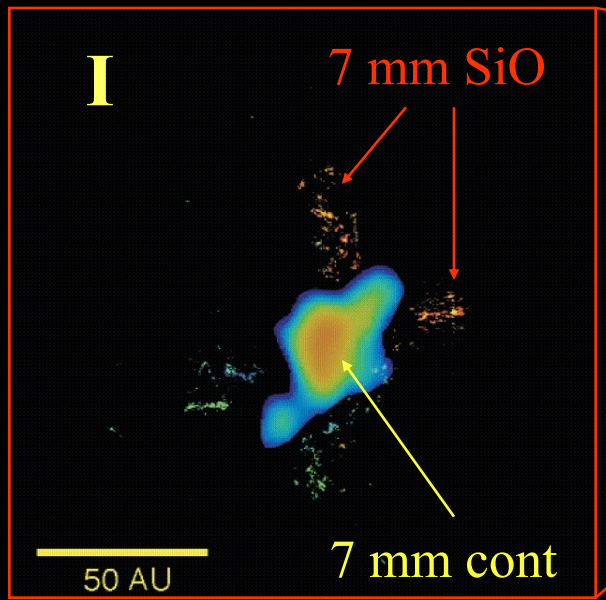
High-velocity stars: I , BN , n

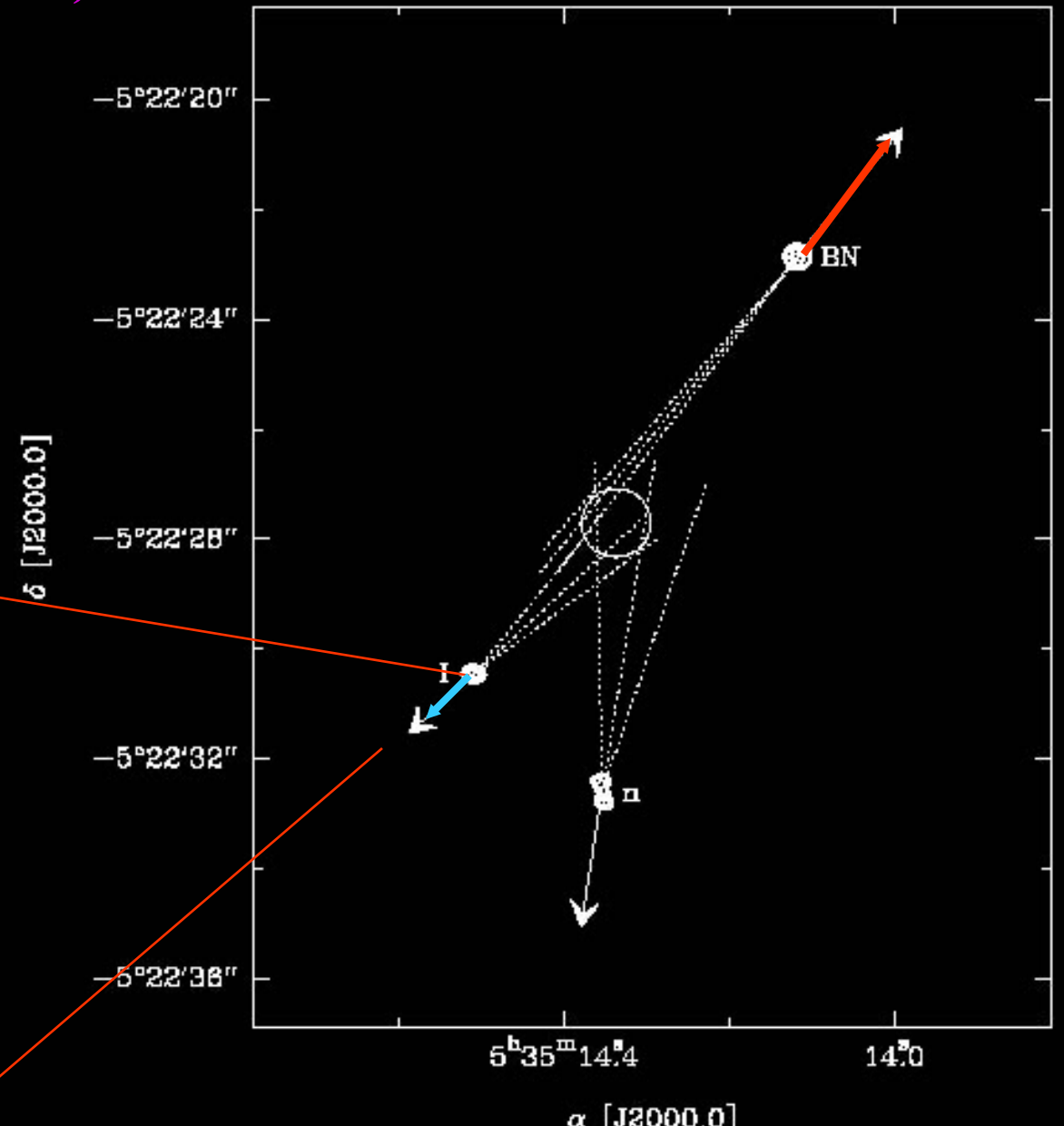
(Gomez et al. 2005, 2008)

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

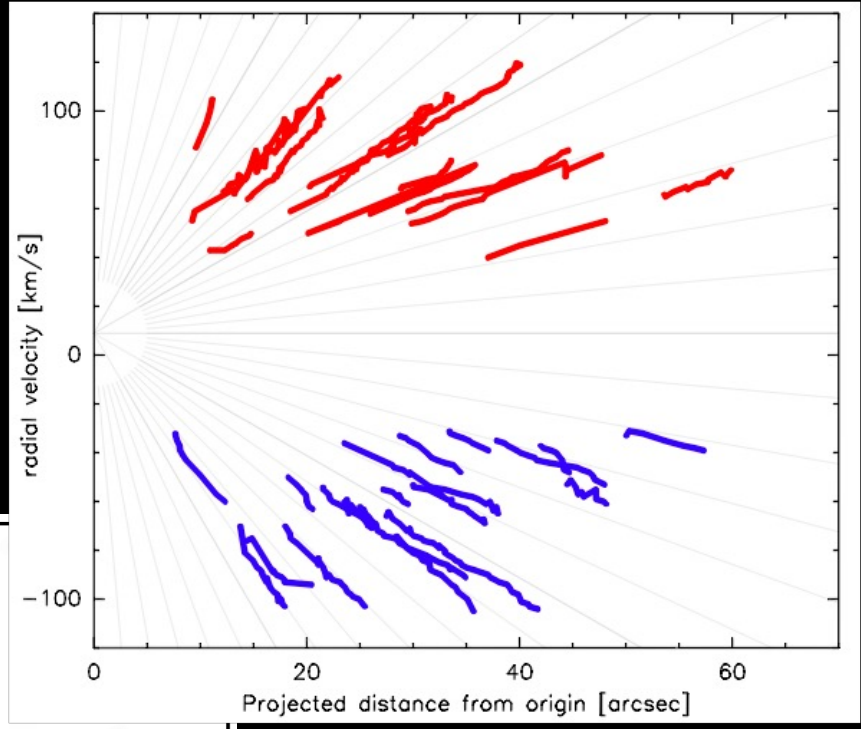
I: V~ 13 km s^{-1}

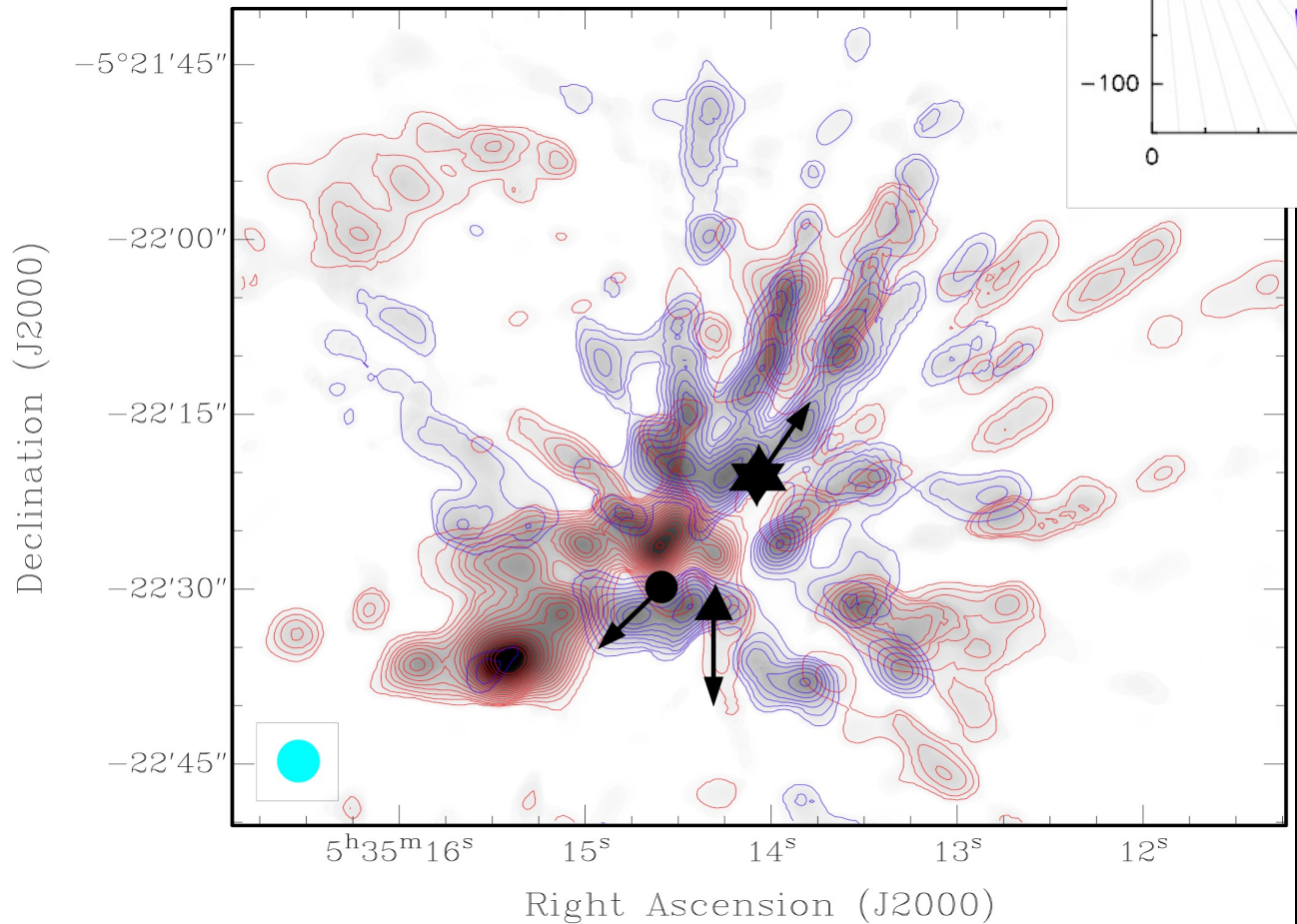
n: V~ 20 km s^{-1}

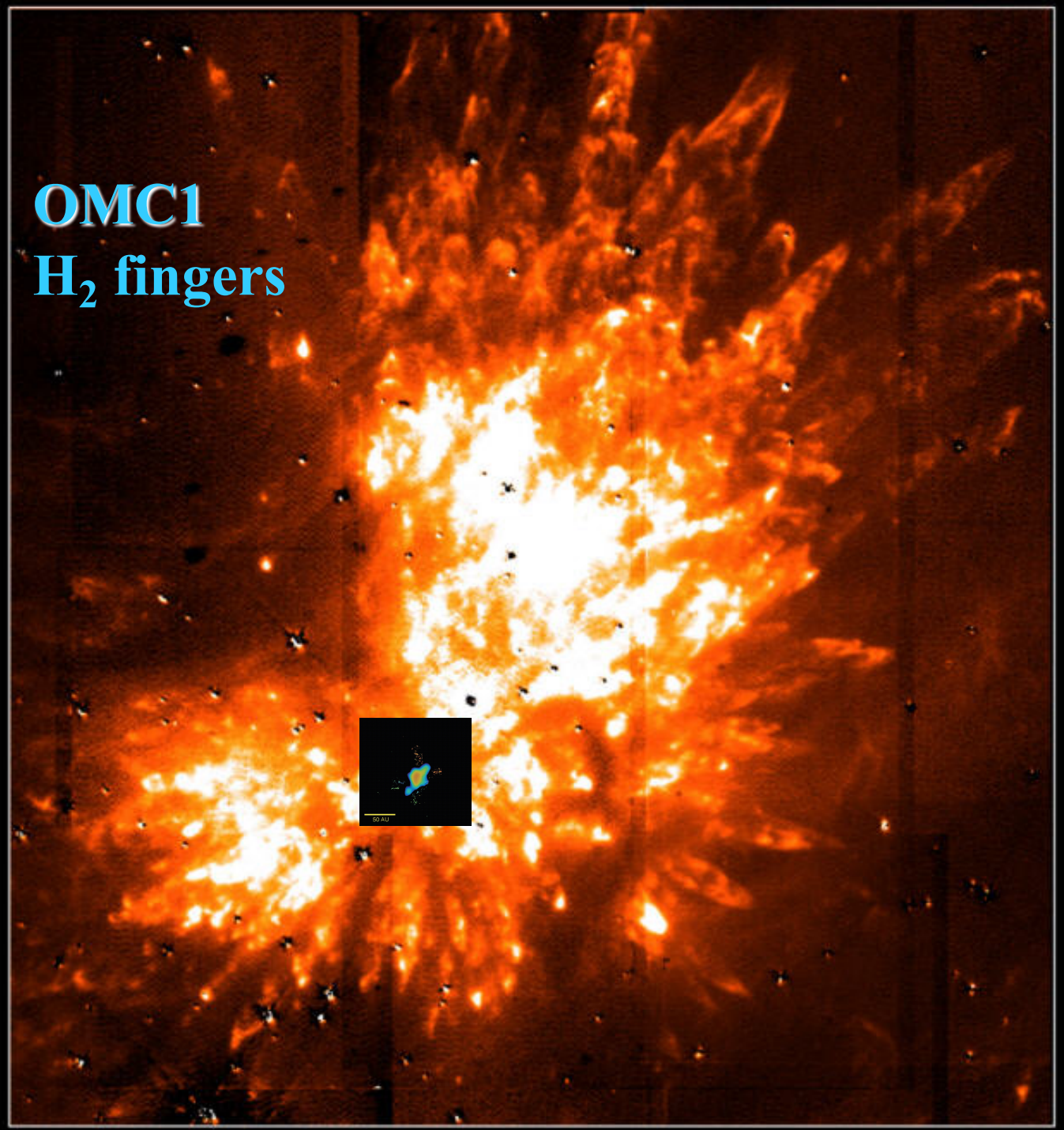




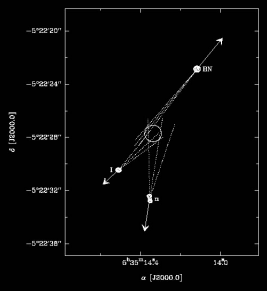
CO J = 2-1
(SMA)
Zapata et al. 2010







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]
8h30m14.8s
14.7s
α [J2000.0]
BN
I
n

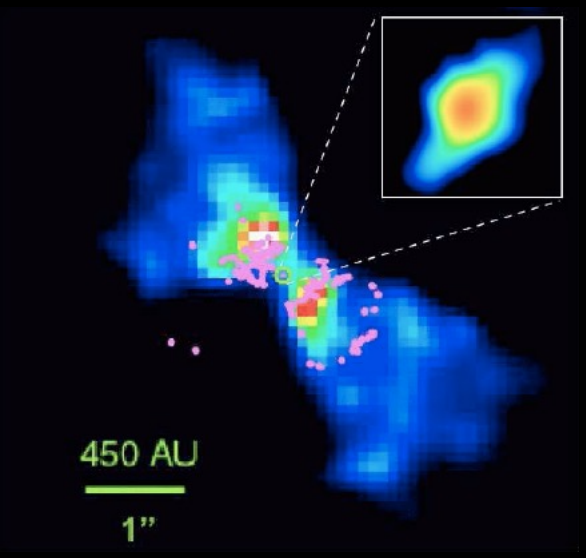
Source I:

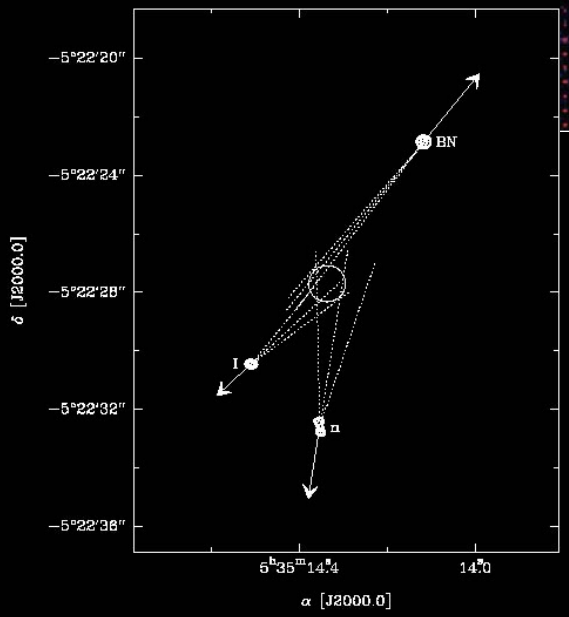
SiO

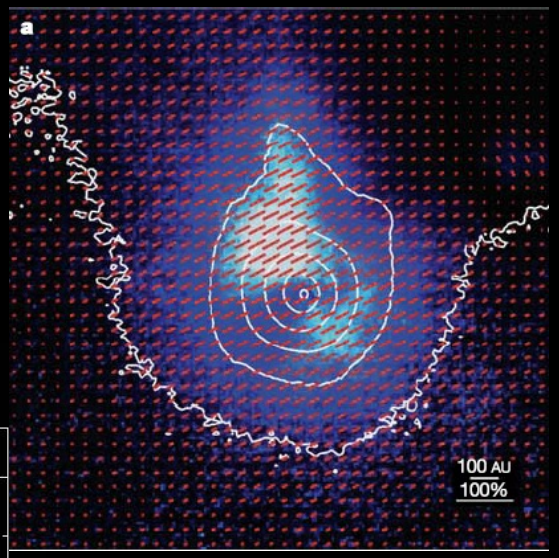
H_2O

7 mm continnum (H^-)

(Reid 07, ApJL)

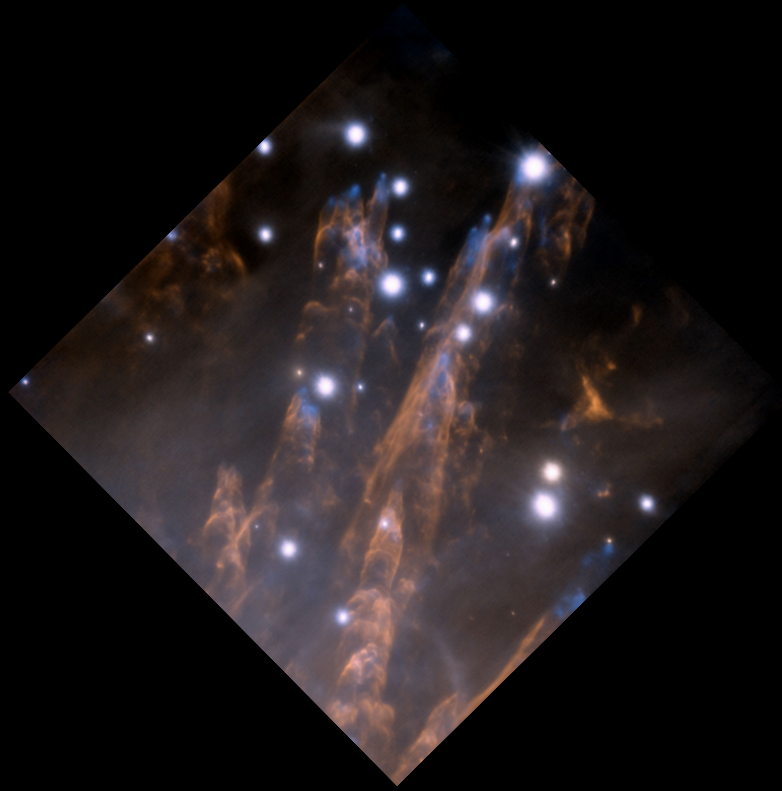


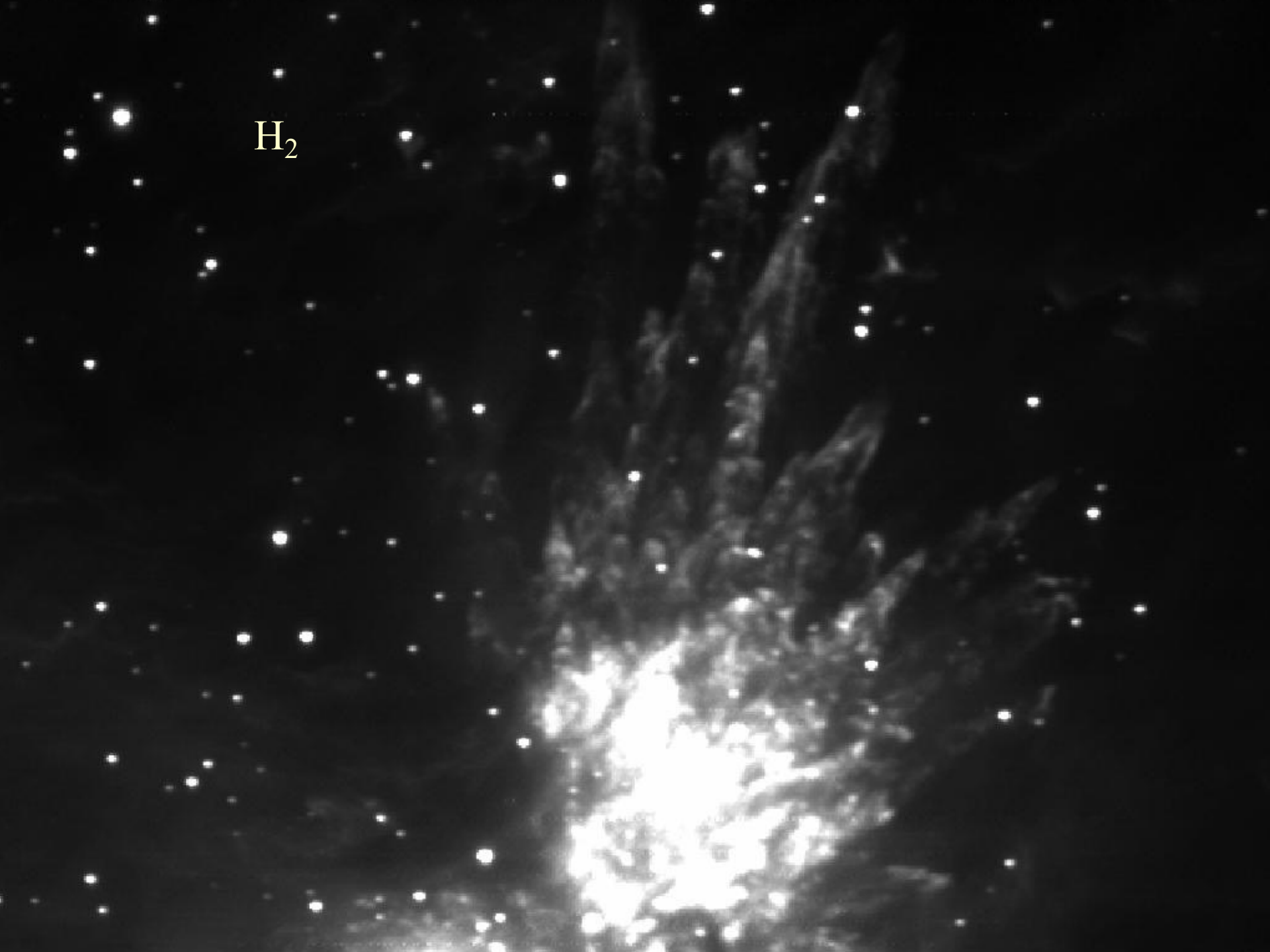


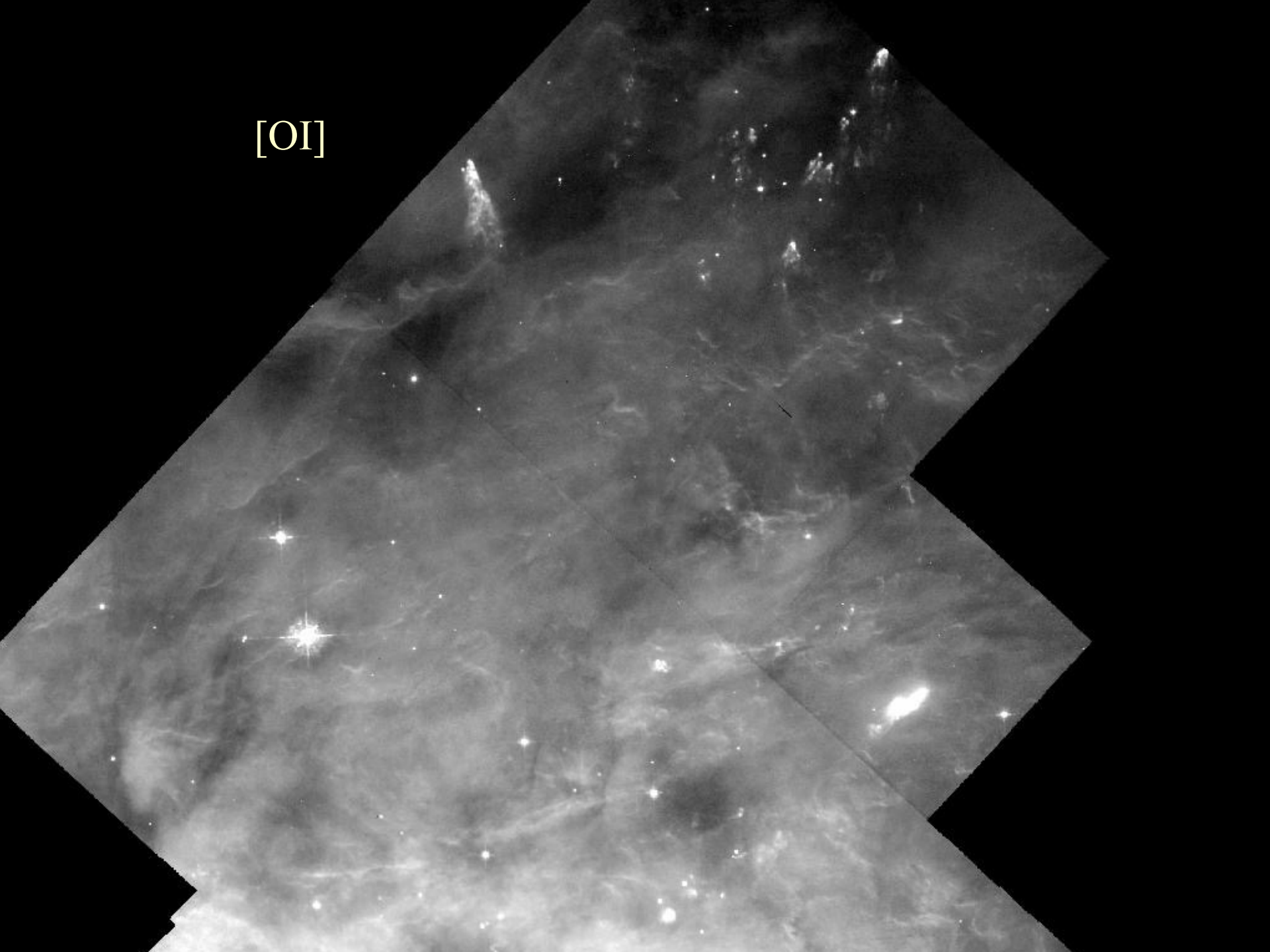


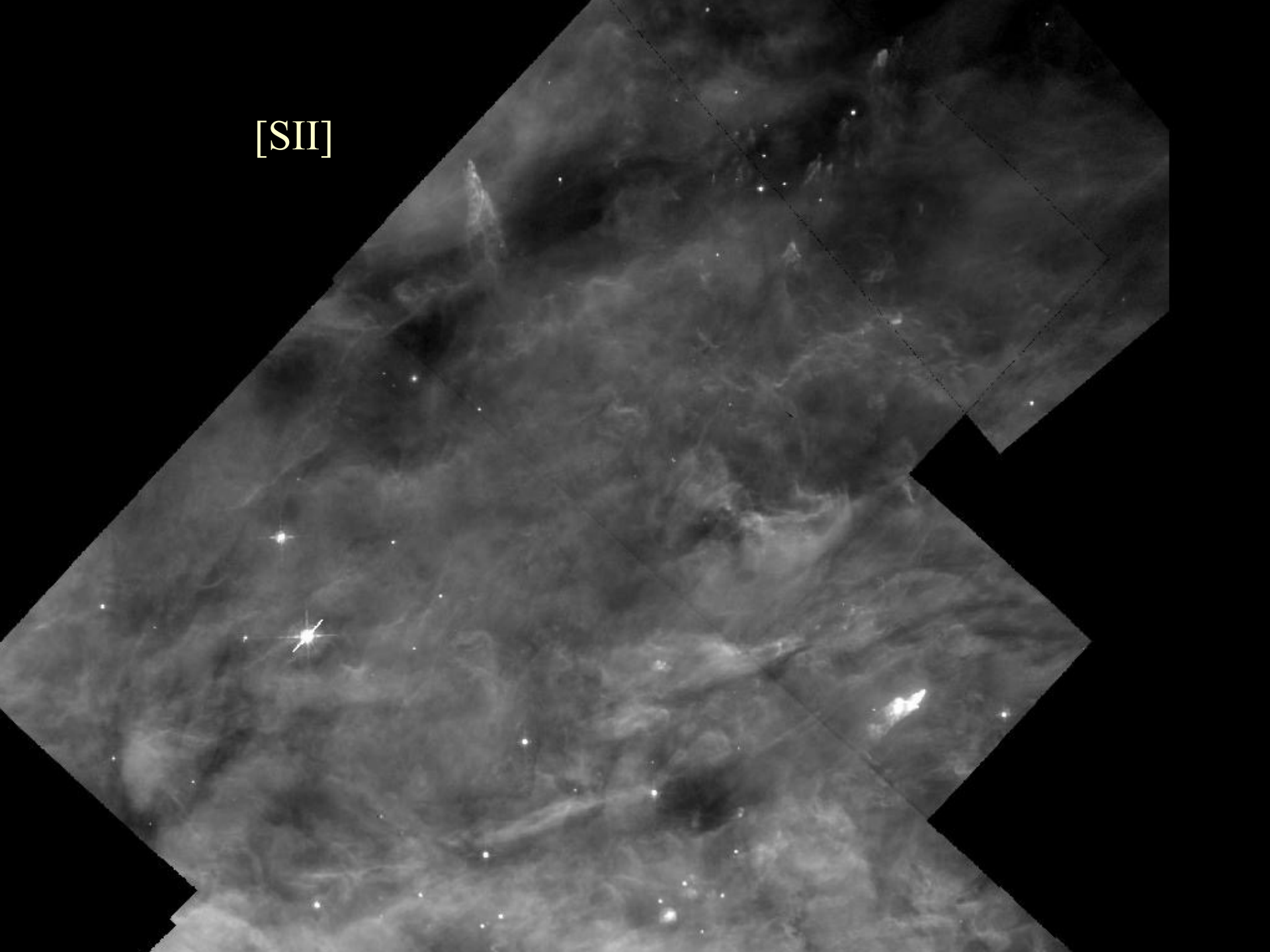
BN polarization

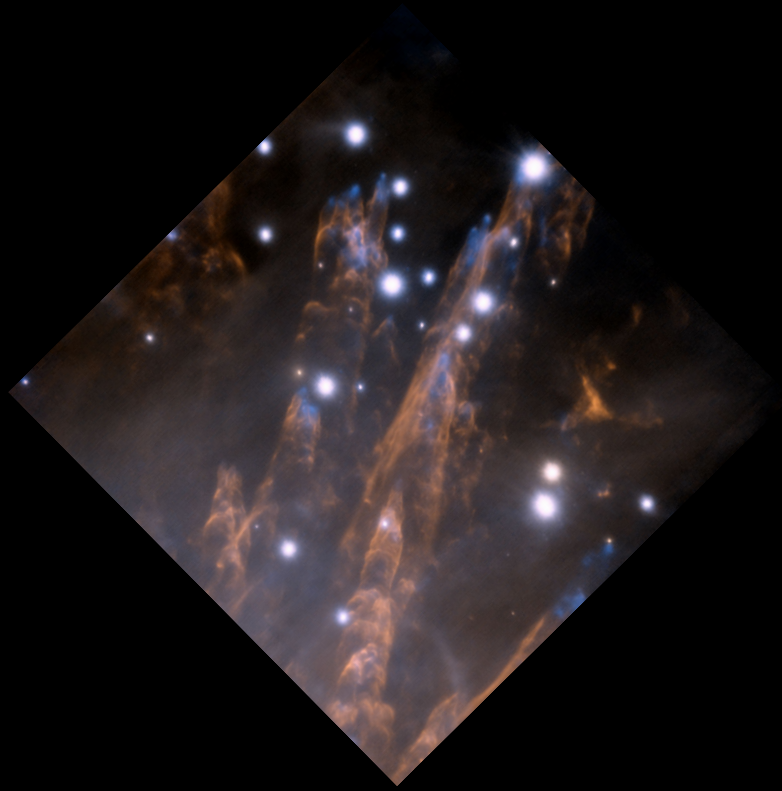
(Jiang 06, Nature)




H_2

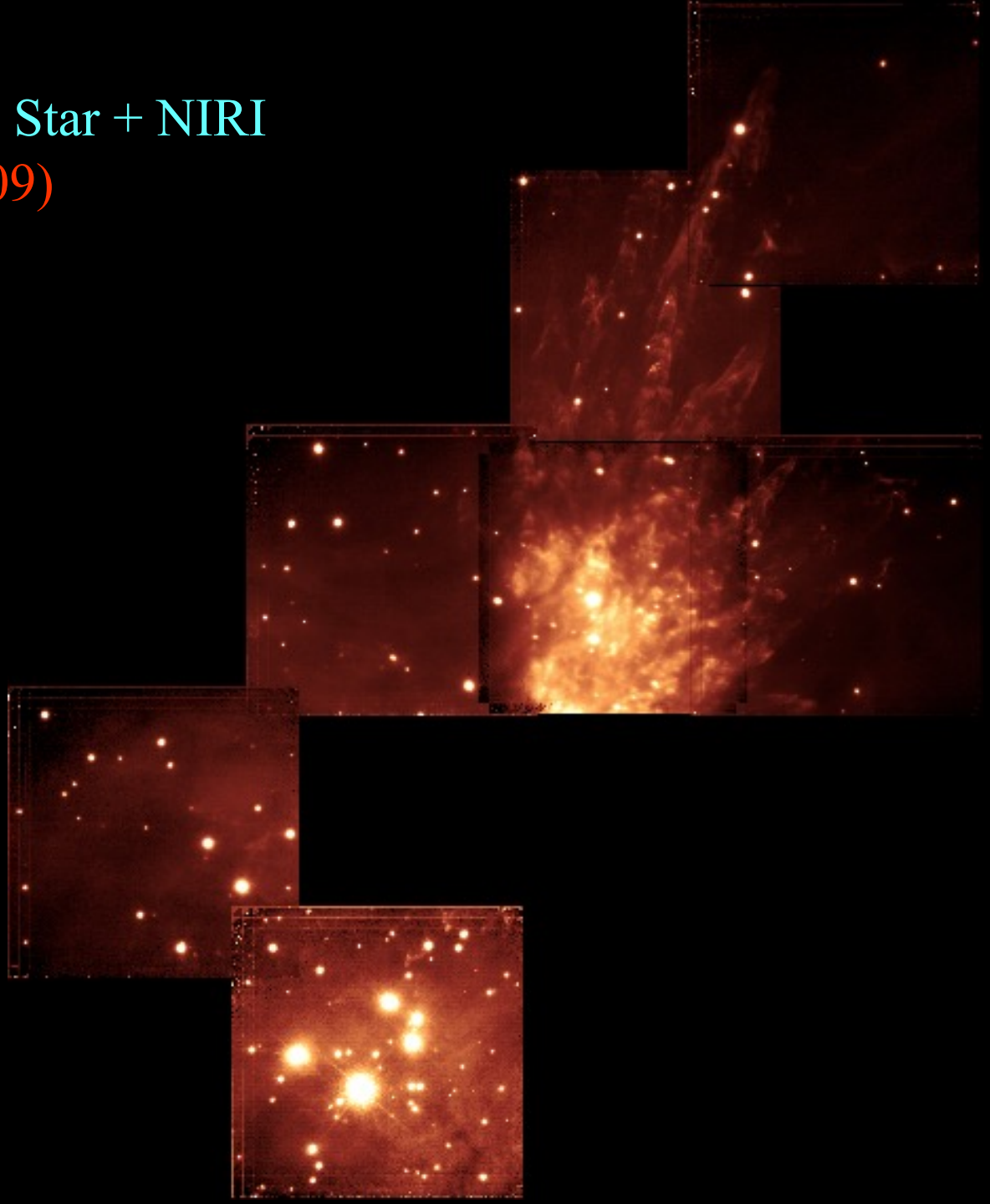

[OI]

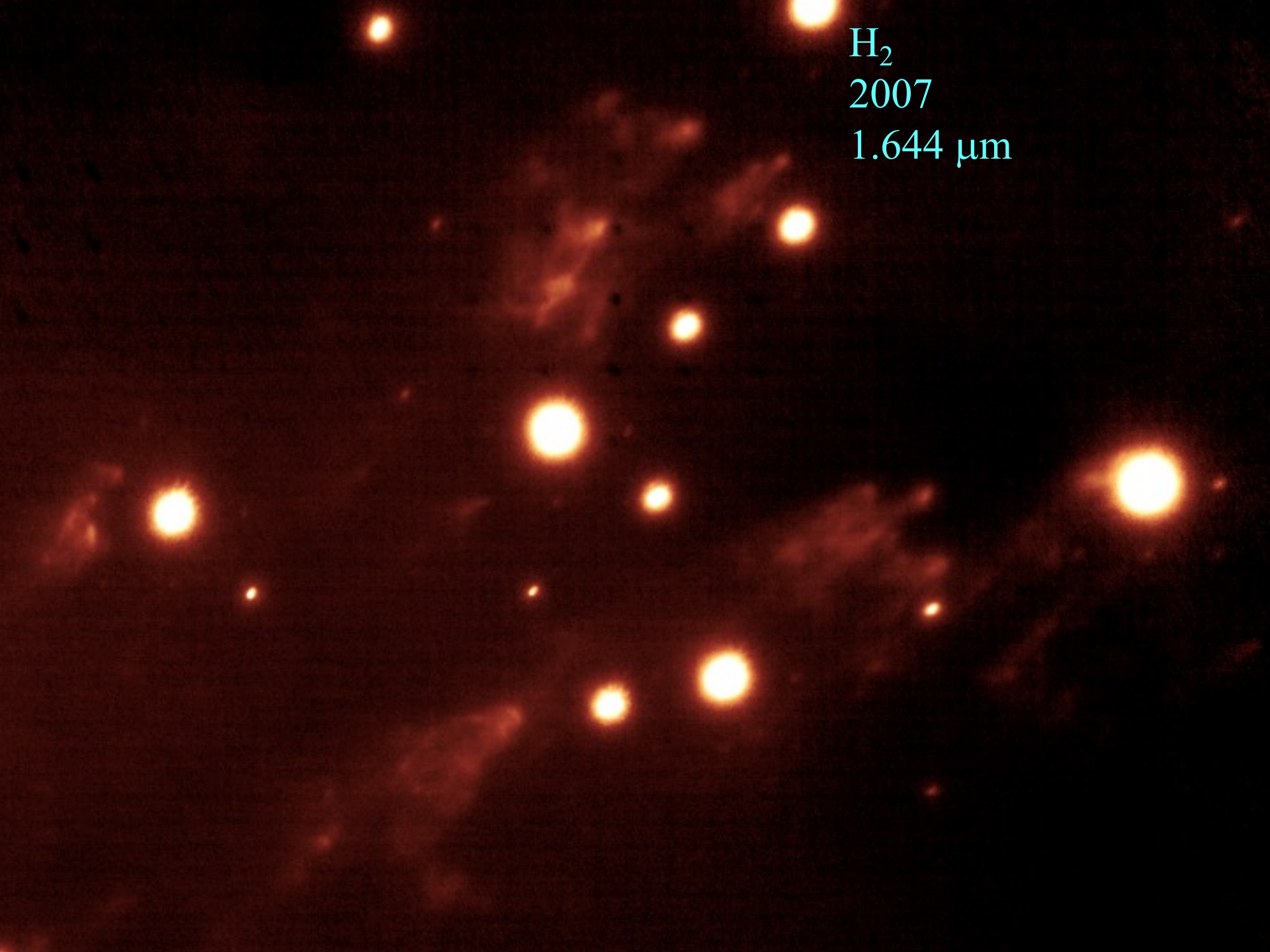

[SII]

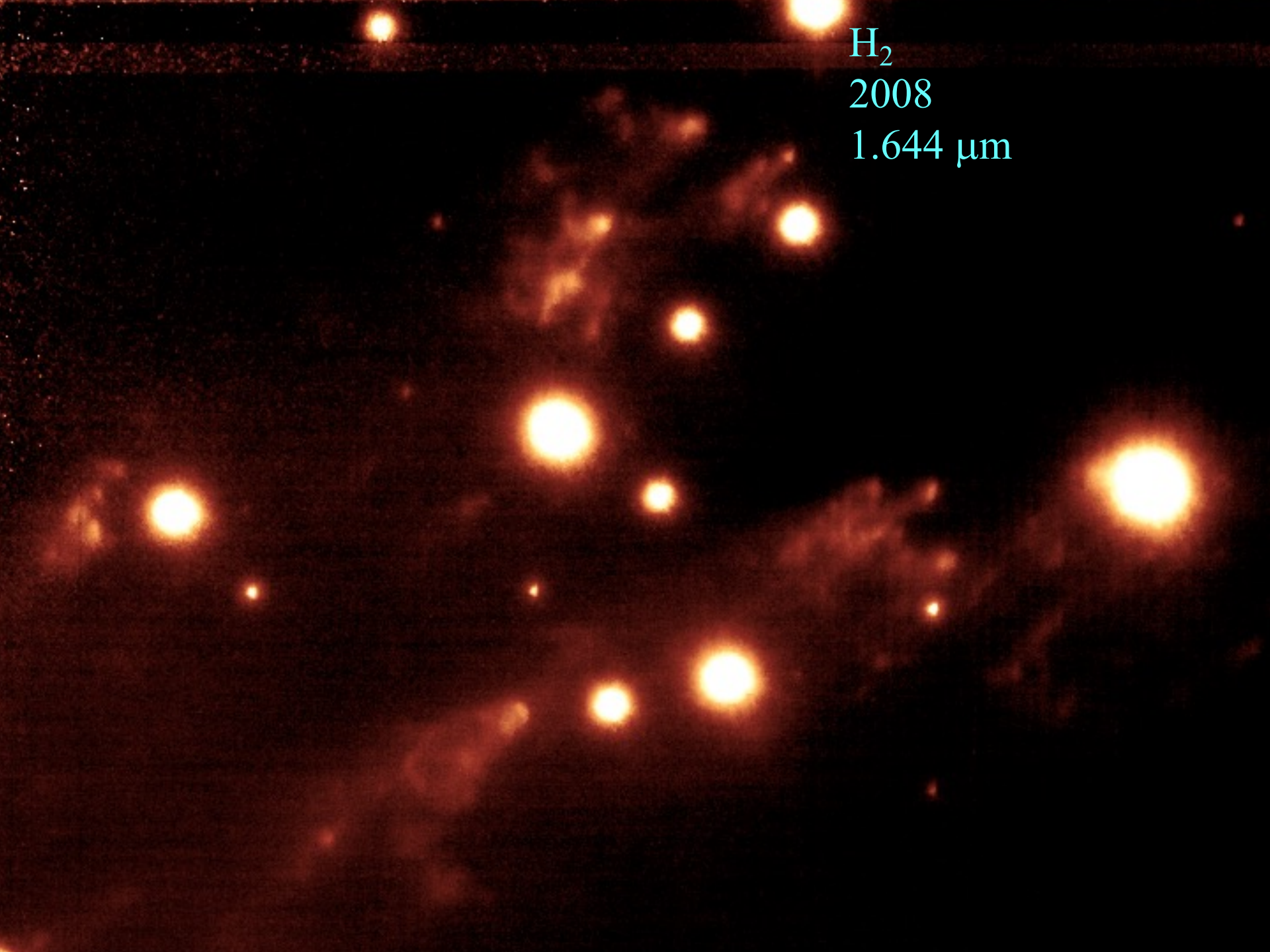


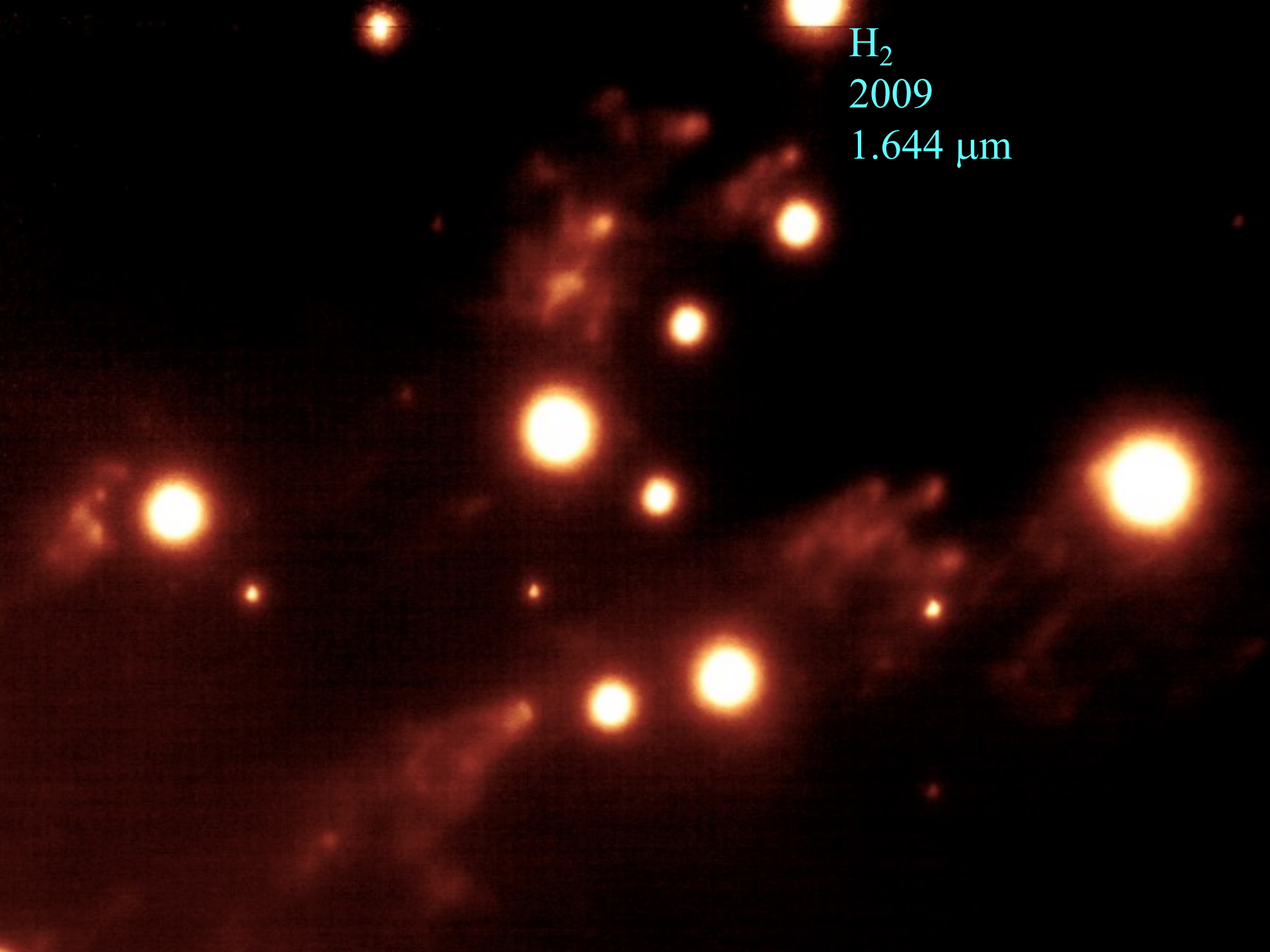
Gemini N Laser Guide Star + NIRI

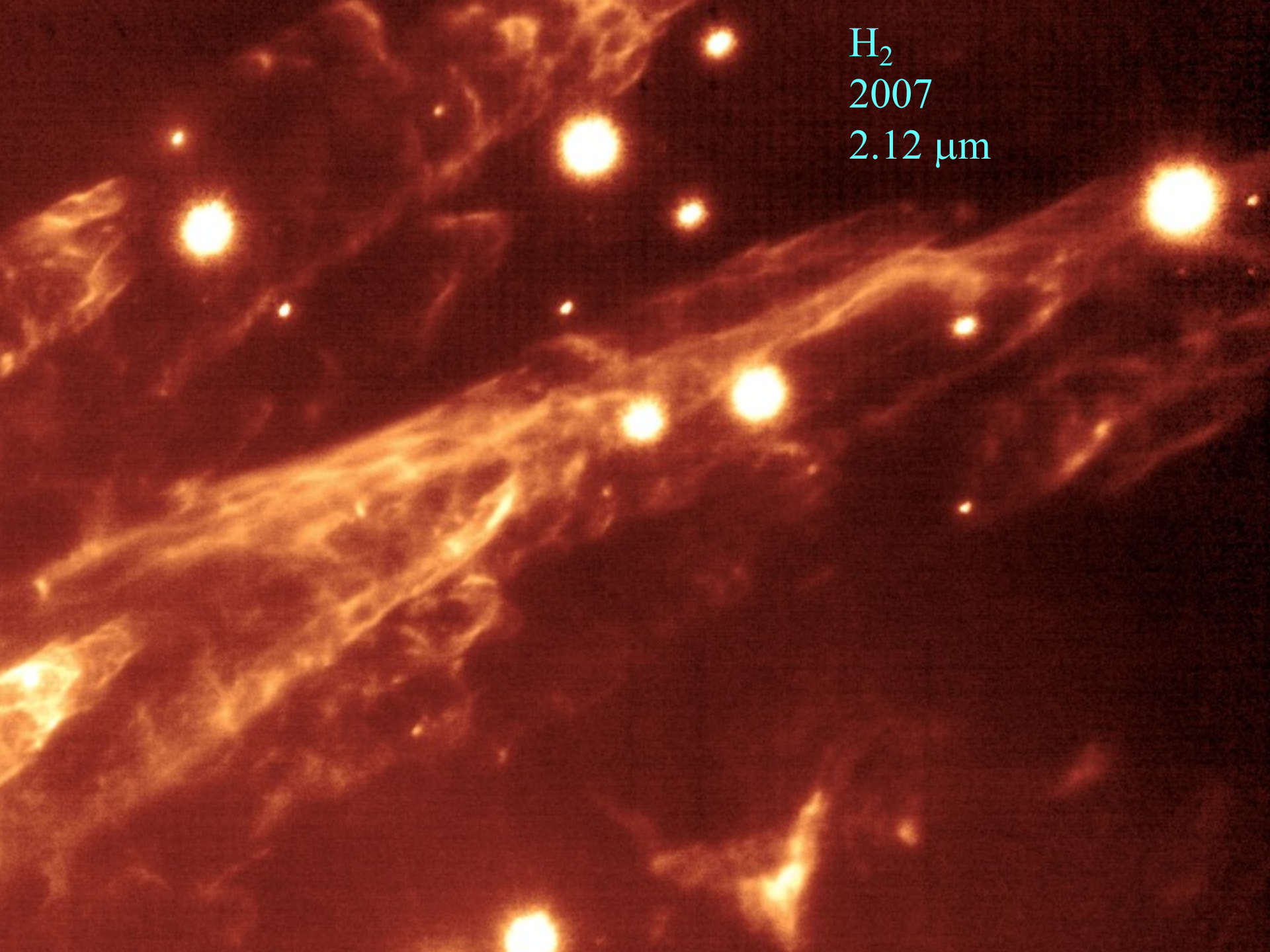
H_2 mosaic (2008 - 2009)

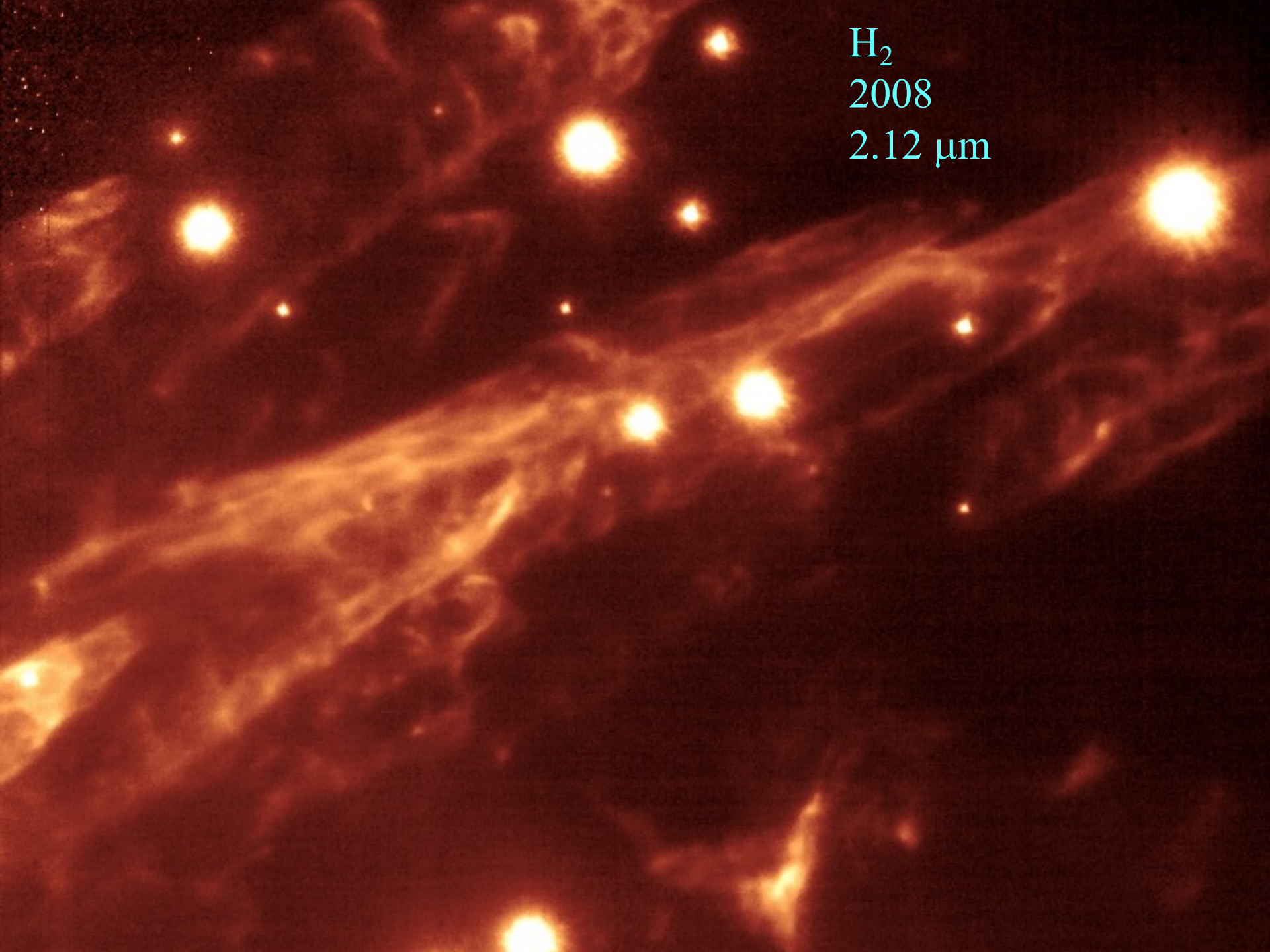


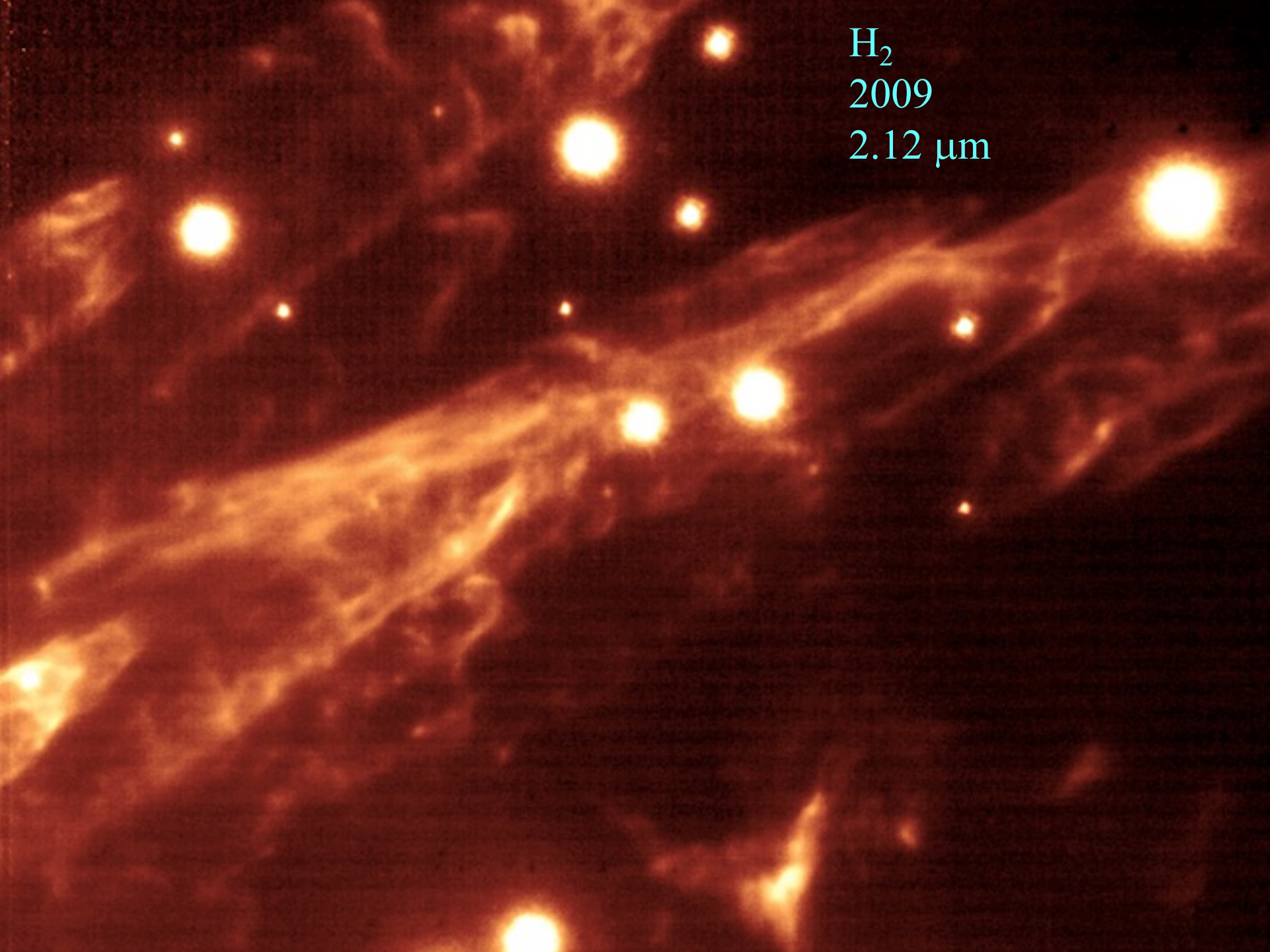

H_2
2007
1.644 μm

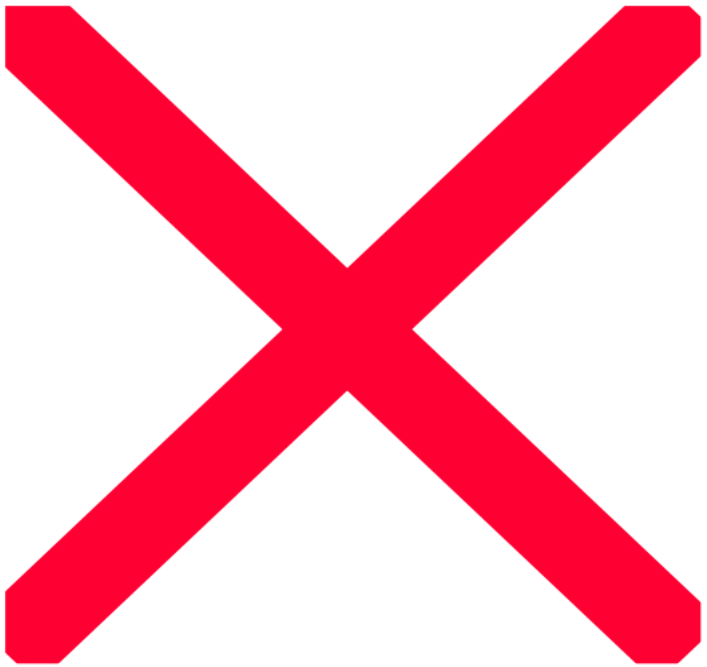

H_2
2008
1.644 μm


H_2
2009
1.644 μm


H_2
2007
2.12 μm


H_2
2008
2.12 μm

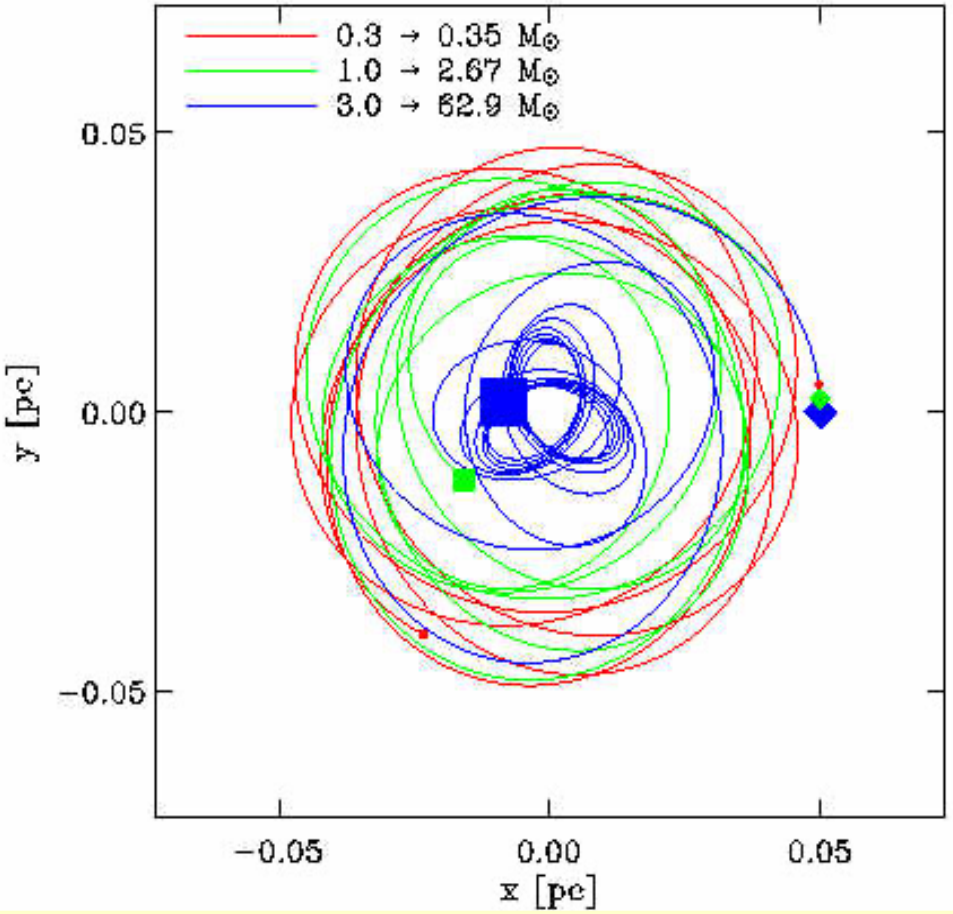

H_2
2009
2.12 μm

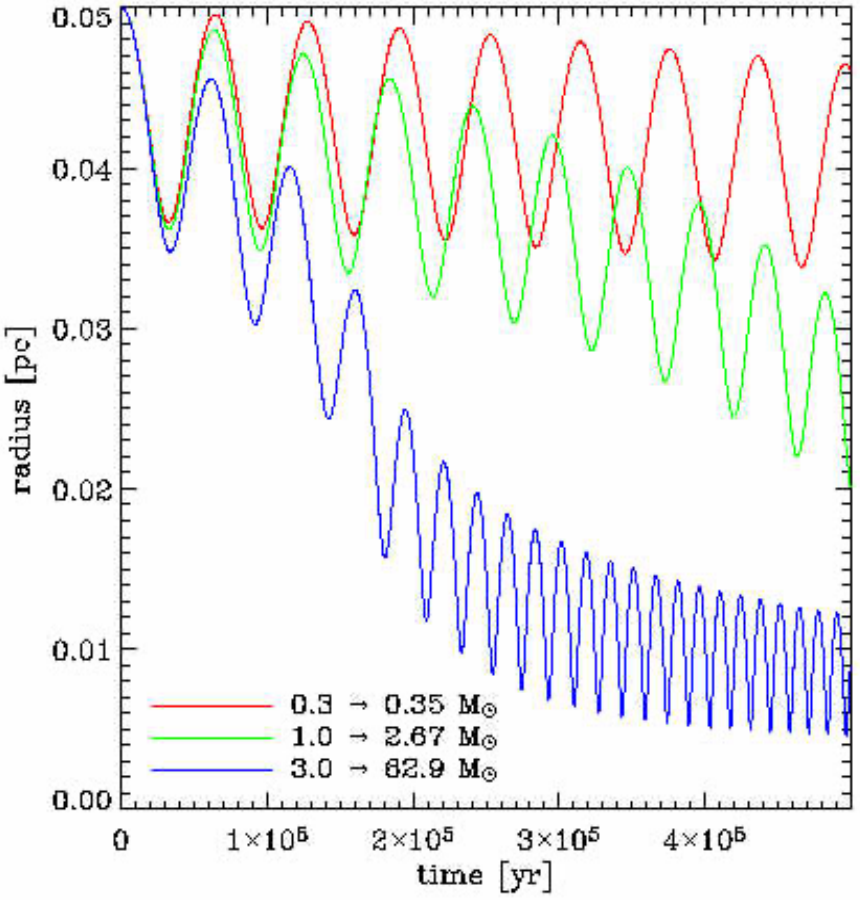


Orbit Decay:

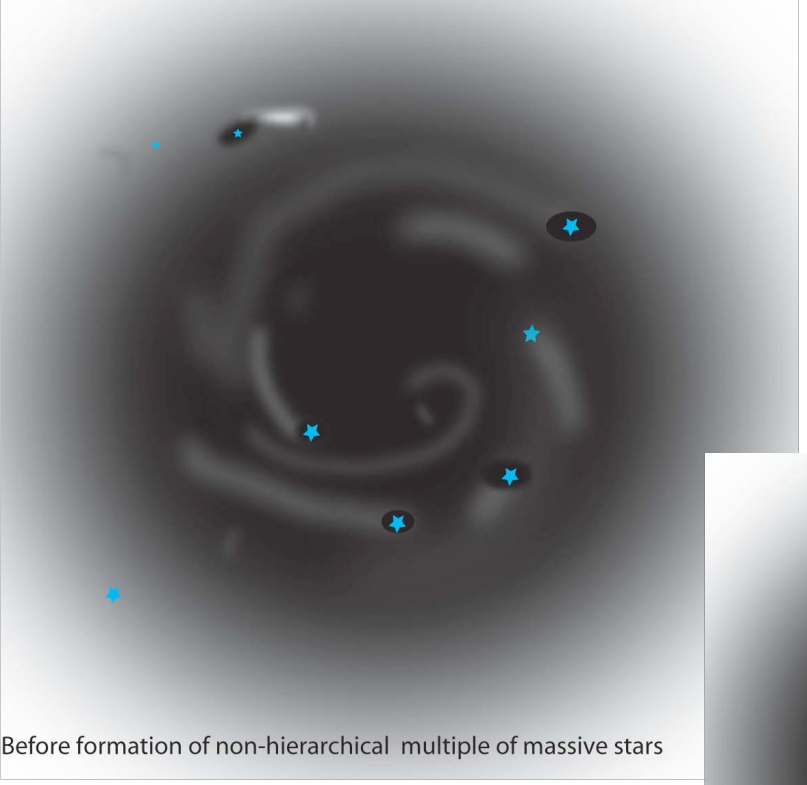
Massive stars orbiting in r^{-2} sphere of gas

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

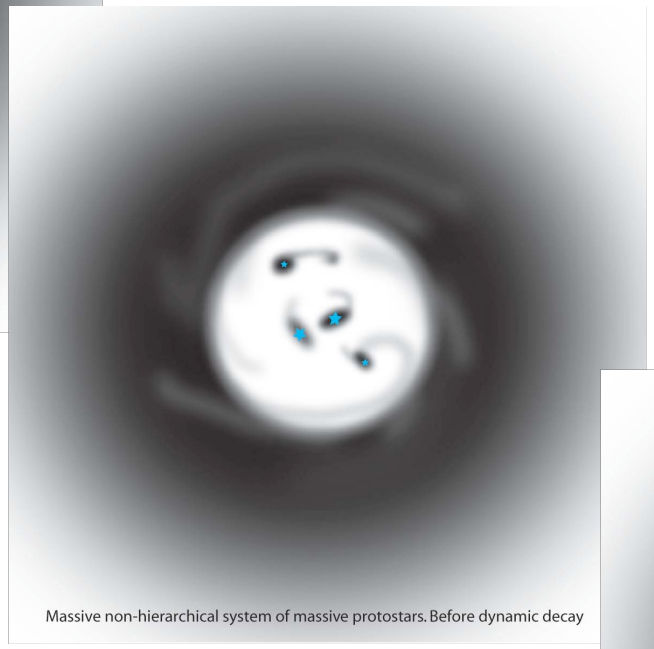




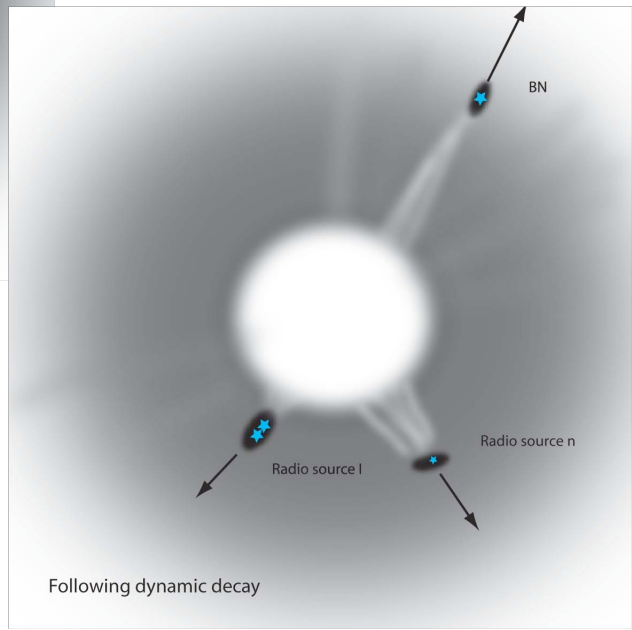
Nick Moeckel PhD Thesis (CU Boulder,2008)



Before formation of non-hierarchical multiple of massive stars



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



Following dynamic decay

The OMC1 Explosion

- ~10^5 to 500 year ago:
  - Velocity damping + orbit decay
  - 200 AU sub-cluster of 4+ massive stars in OMC1
  - Shear dynamo: = > Equipartition B-field

    $E_B \sim 10^{48}$ ergs

- 500 years ago:
  - Dynamical decay of non-hierarchical system: $E_* \sim 3 \times 10^{47}$ ergs
  - Ejection of high velocity stars (BN, I, n)

    => $\langle V \rangle \sim V_* \sim 20$ km/s $E_{out} \sim 3 \times 10^{47}$ ergs

  - Disruption of (magnetized) circumstellar disks & core:

    $V_{fast} \sim 500$ km/s

=> Explosive, wide-angle outflow!

Dynamical Decay => Explosion in Gas

40 M_o stars in ~100 M_o core. Dynamically eject 40 M_o from R ~ 30 to 200 AU

Recoil of Extended Envelope

r ~ 400 to 6,000 AU V_{esc} ~ 3 to 10 km/s

M_{env} ~ 10 M_o E_{env} ~ 4 x 10^{46} erg

Disruption of Inner Disks

r ~ 0.1 to ~ 30 AU V_{esc} ~ 20 to 400 km/s

M_{env} ~ 0.1 M_o E_{env} ~ 5 x 10^{46} erg

Energy stored in magnetic fields (equipartition)

r ~ 200 AU B ~ 1 -10 gauss

$B^2/8\pi$ ~ 10^{47} ergs V_A ~ 10 - 100 km/s

Dynamical Decay => Explosion in Gas

Slow ejecta from outside

Overrun by fast ejecta from inside

Energy boosted by magnetic fields

= > R-T instability and production of fingers

Fast wind overtakes slow shell

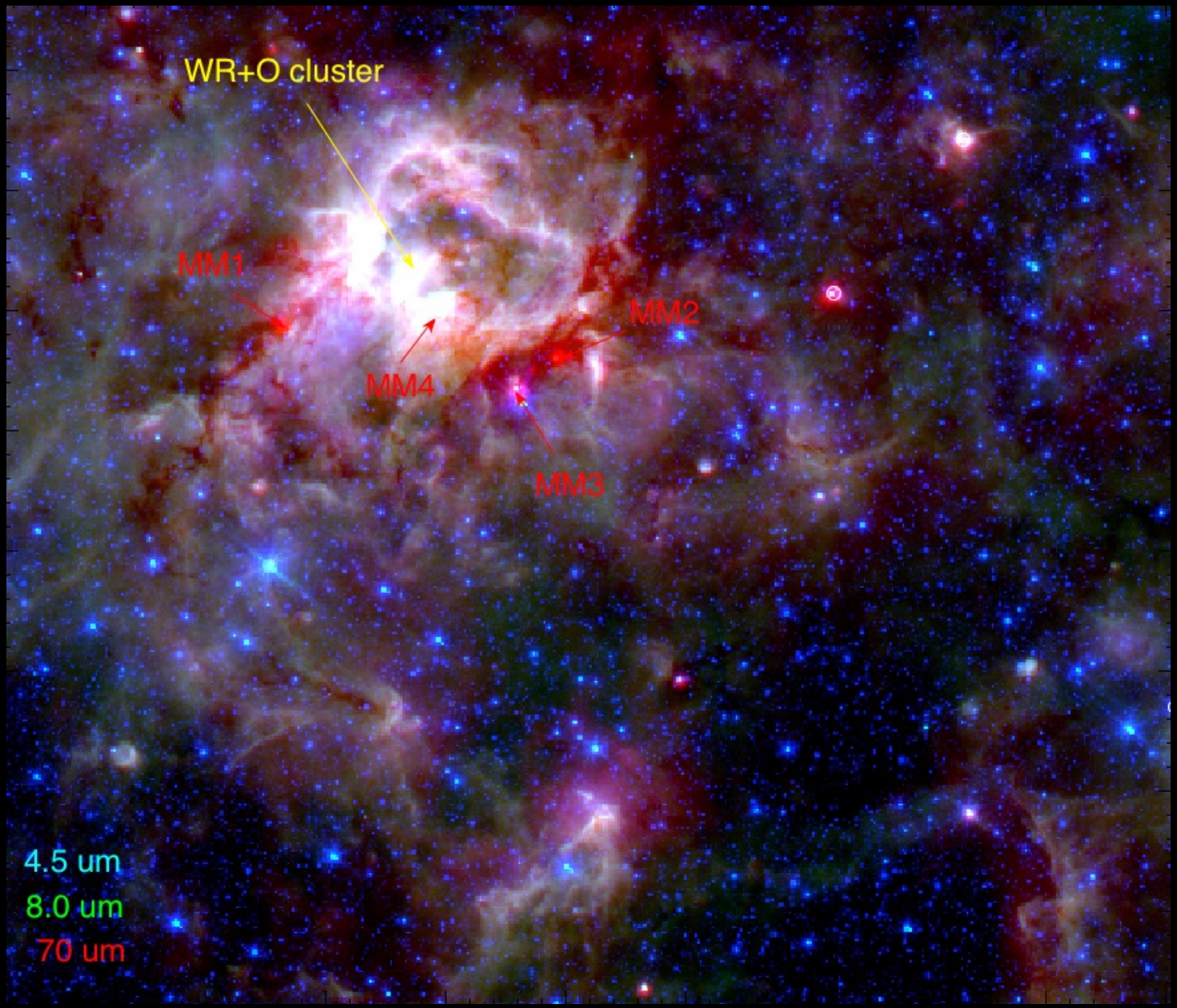
- Stone, Xu, Mundy 1995, Nature, 377, 315
- McCaughrean Mac Low 1997, AJ, 113, 391

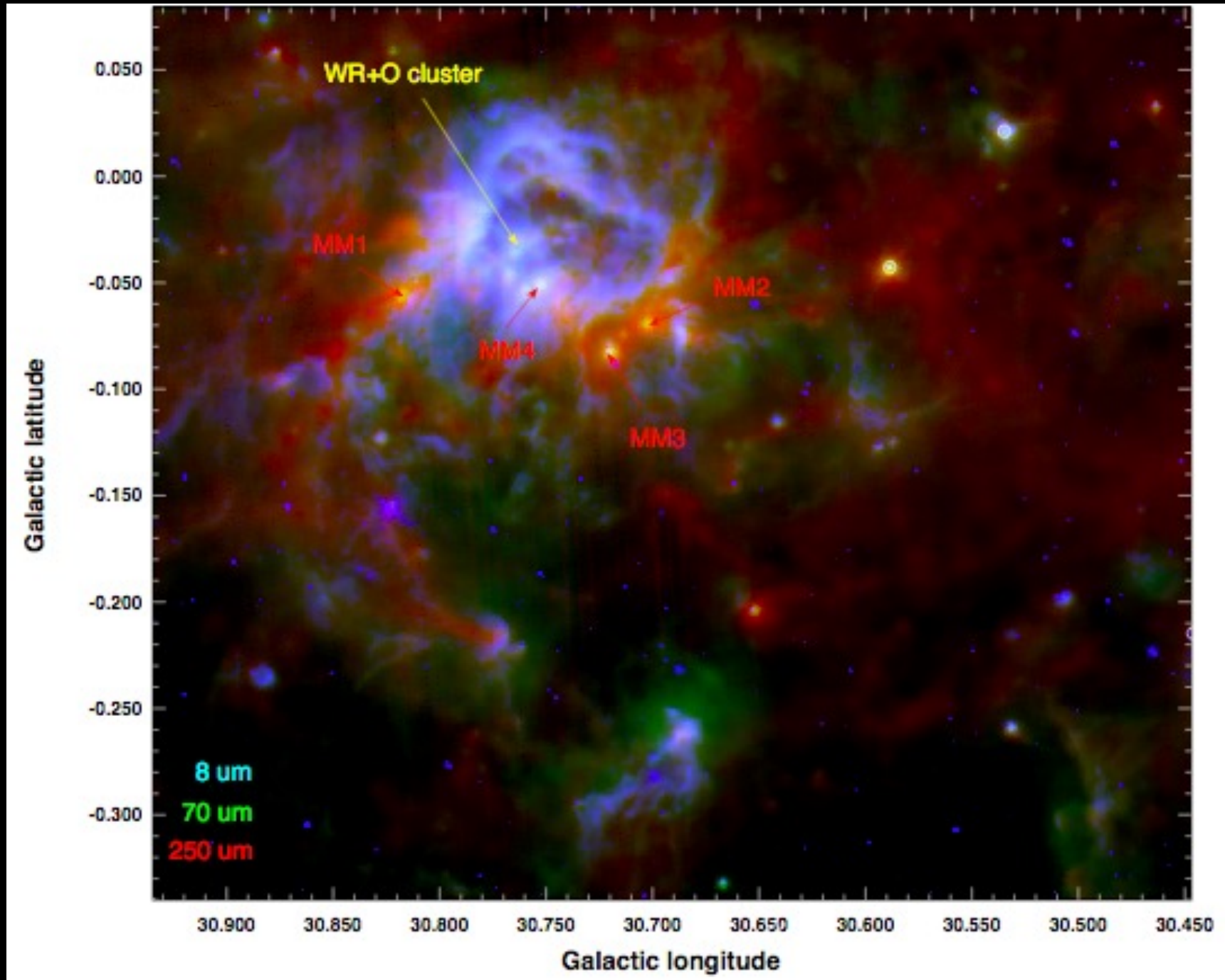
W43
Giant HII region
mini-starburst

[l,b] = 30.77, -0.04
V_{lsr} ~ 86 to 106 km/s

D ~ 5.5 kpc
L > 3.5 x 10^6 L_o
M_{GMC} ~ 10^6 M_o

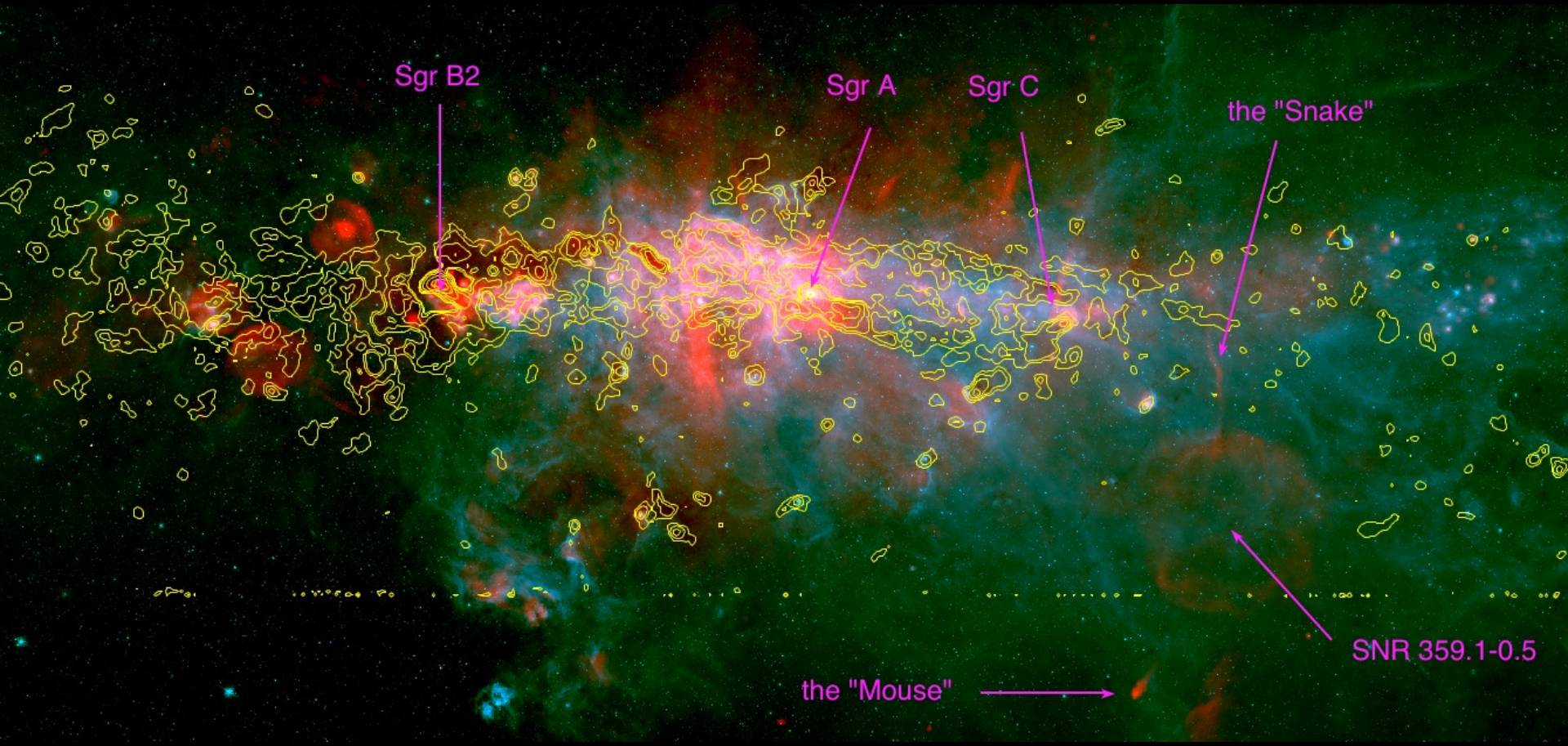
L_{LyC}~ 10^{51} ionizing γ s^{-1}
(50 x Orion Neb.
=> 50 O7 stars!)
O3 and WR stars
=> age >3 Myr


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


WR+O cluster
MM1
MM2
MM4
MM3
8 um
70 um
250 um
0.050
0.000
-0.050
-0.100
-0.150
-0.200
-0.250
-0.300
Galactic latitude
30.900
30.850
30.800
30.750
30.700
30.650
30.600
30.550
30.500
30.450
Galactic longitude

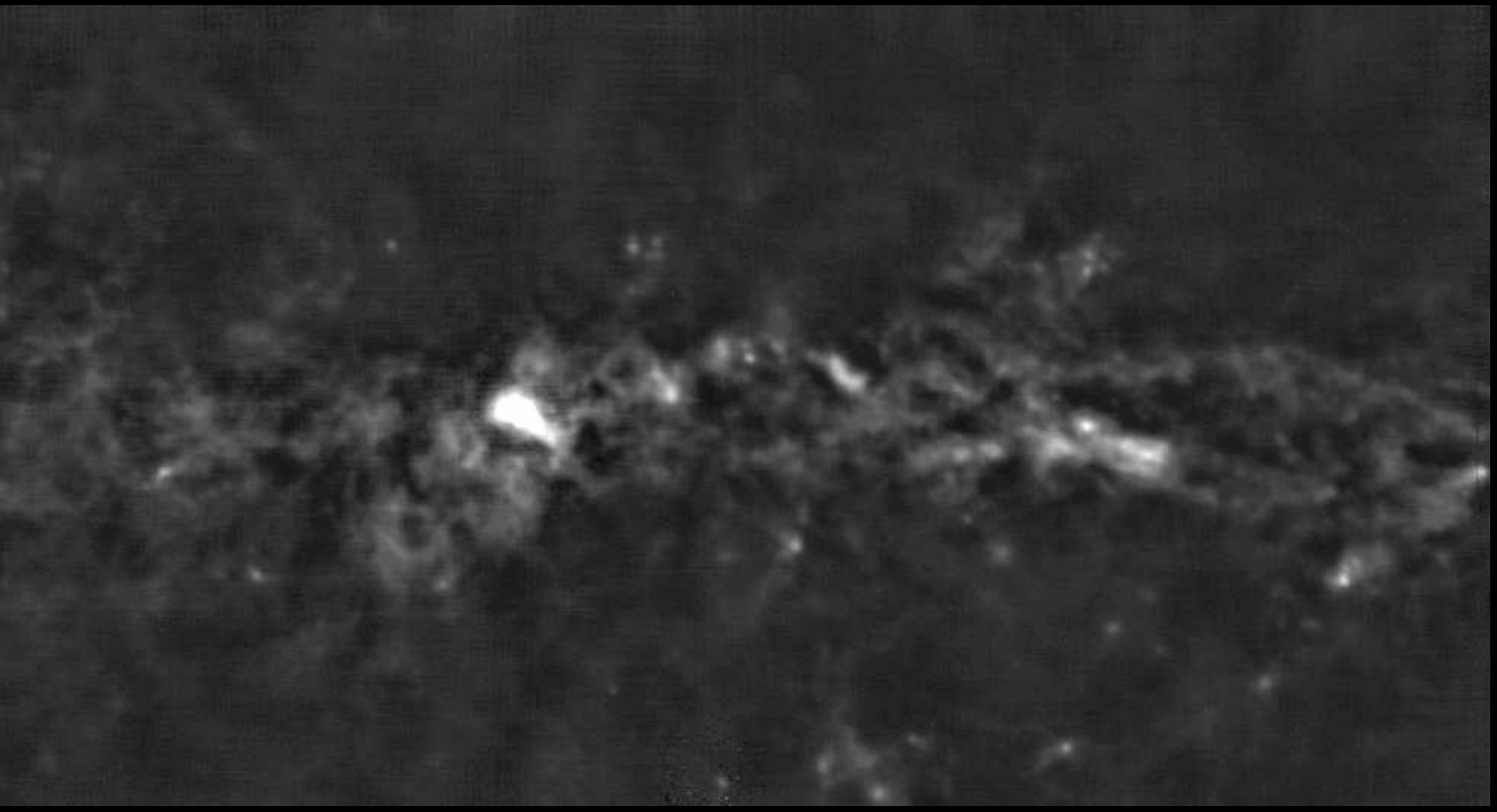
3.6 - 8 μm 1.1 mm 20 cm

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

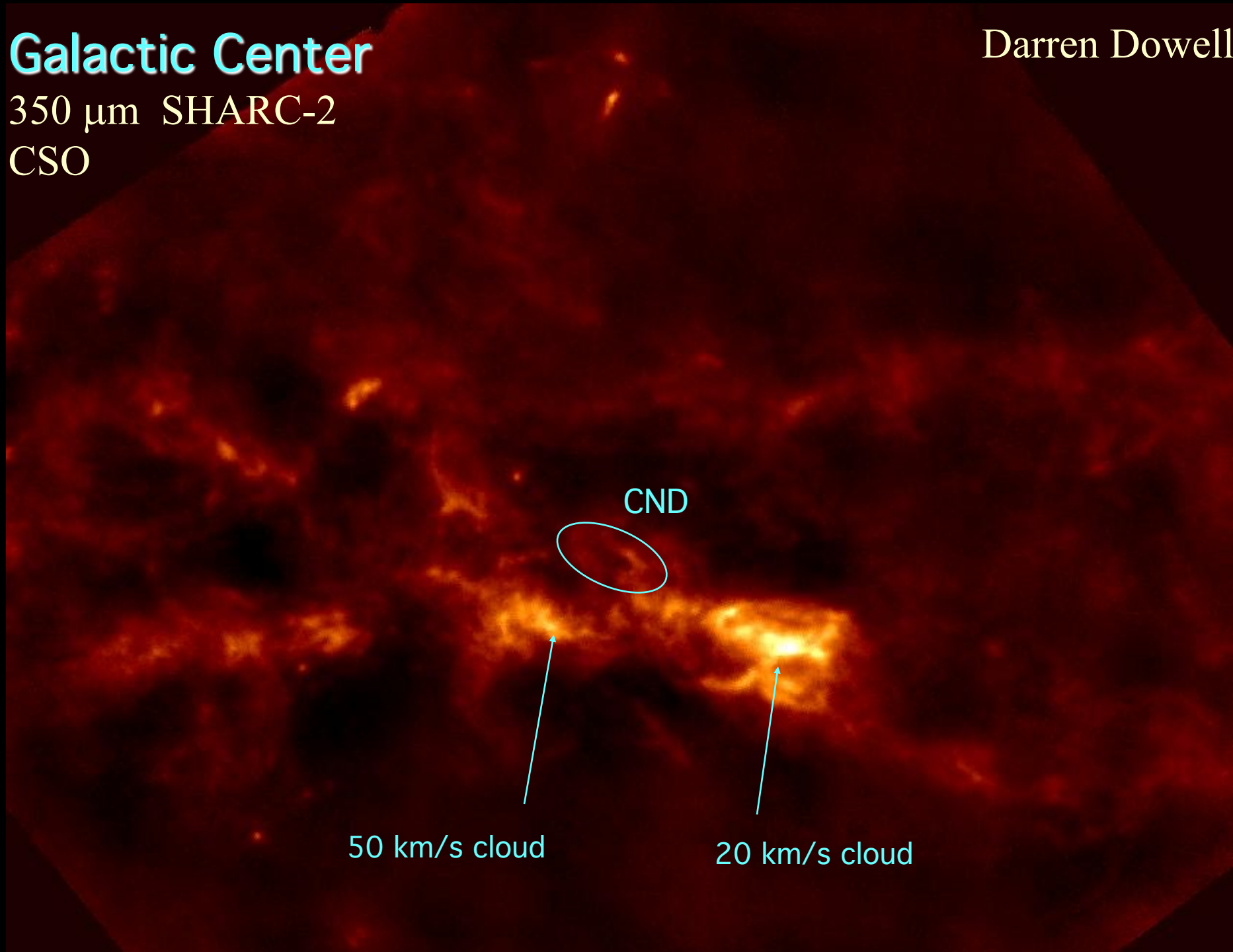
Spitzer Space Teles



Galactic Center

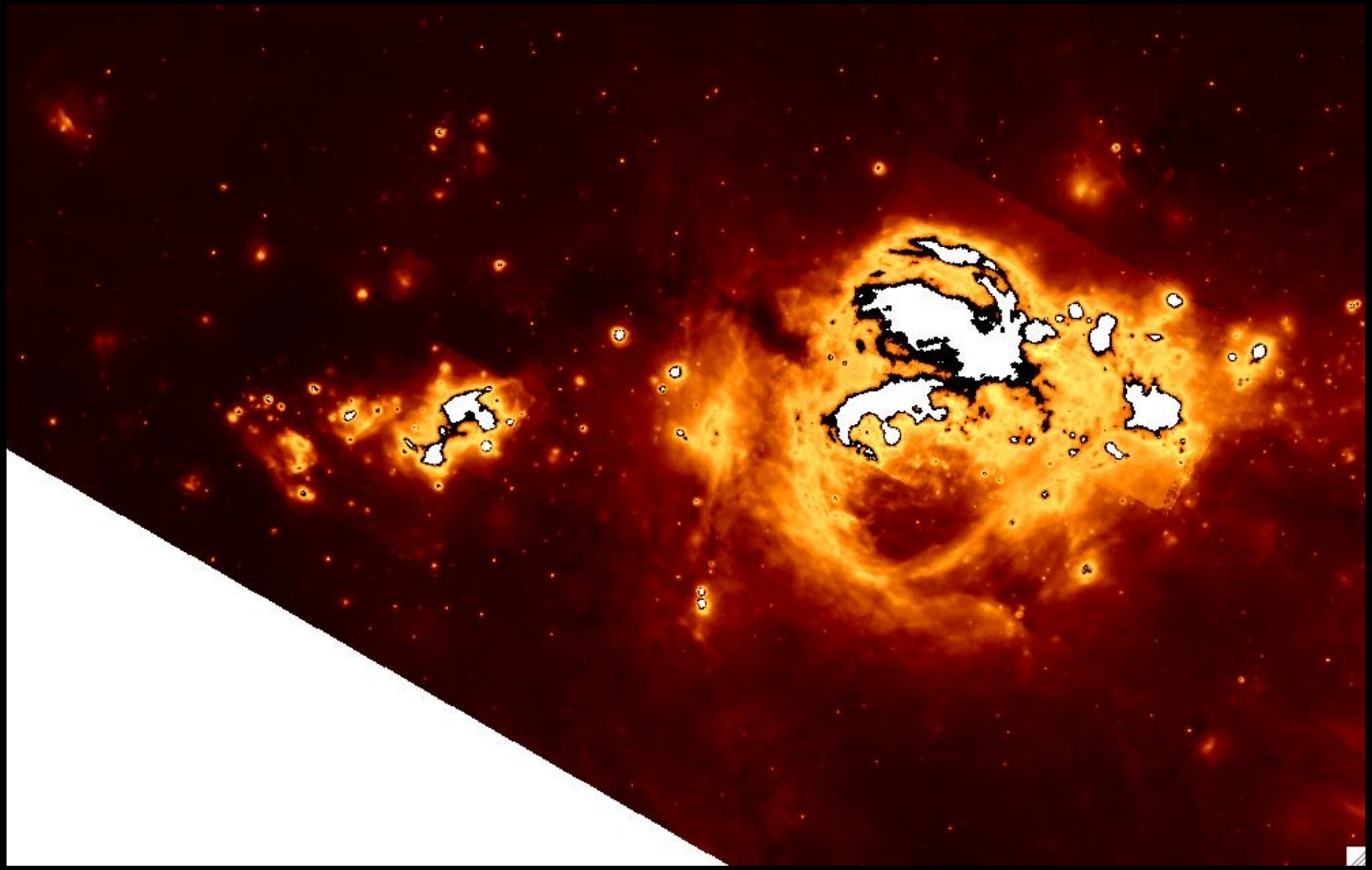
350 μm SHARC-2
CSO

Darren Dowell

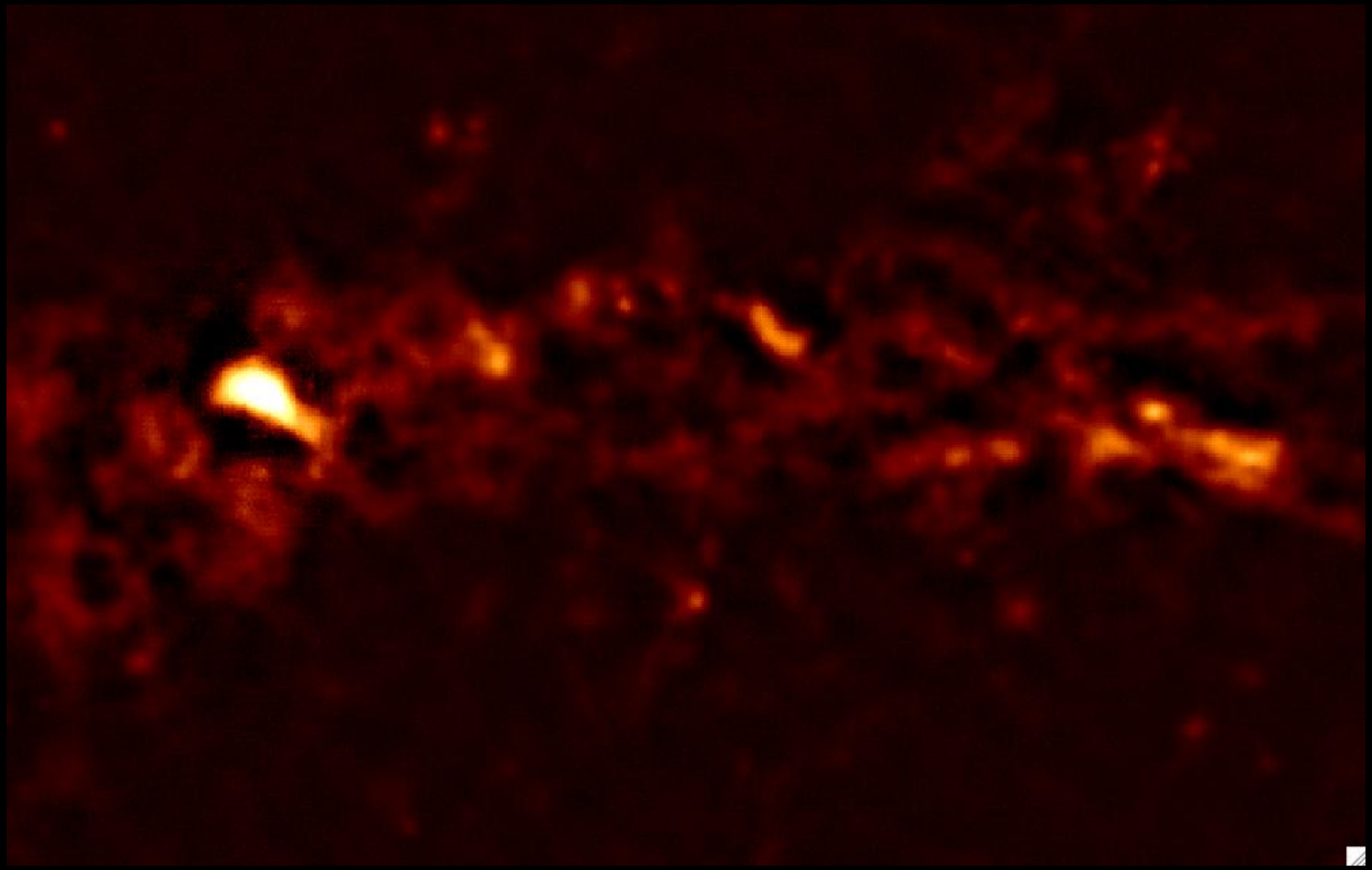


Galactic Center: 8 μm

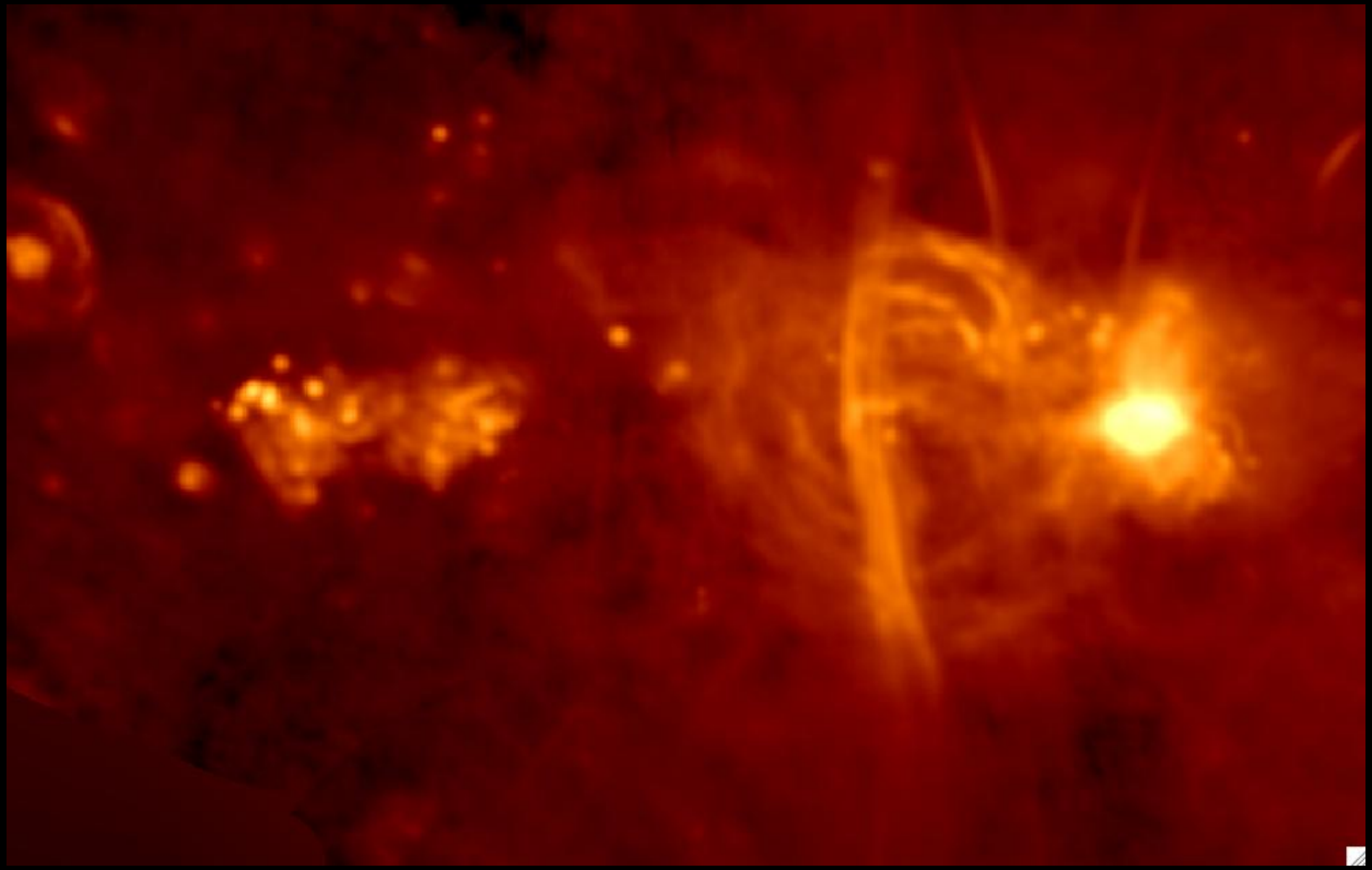
Galactic Center: 24 μm

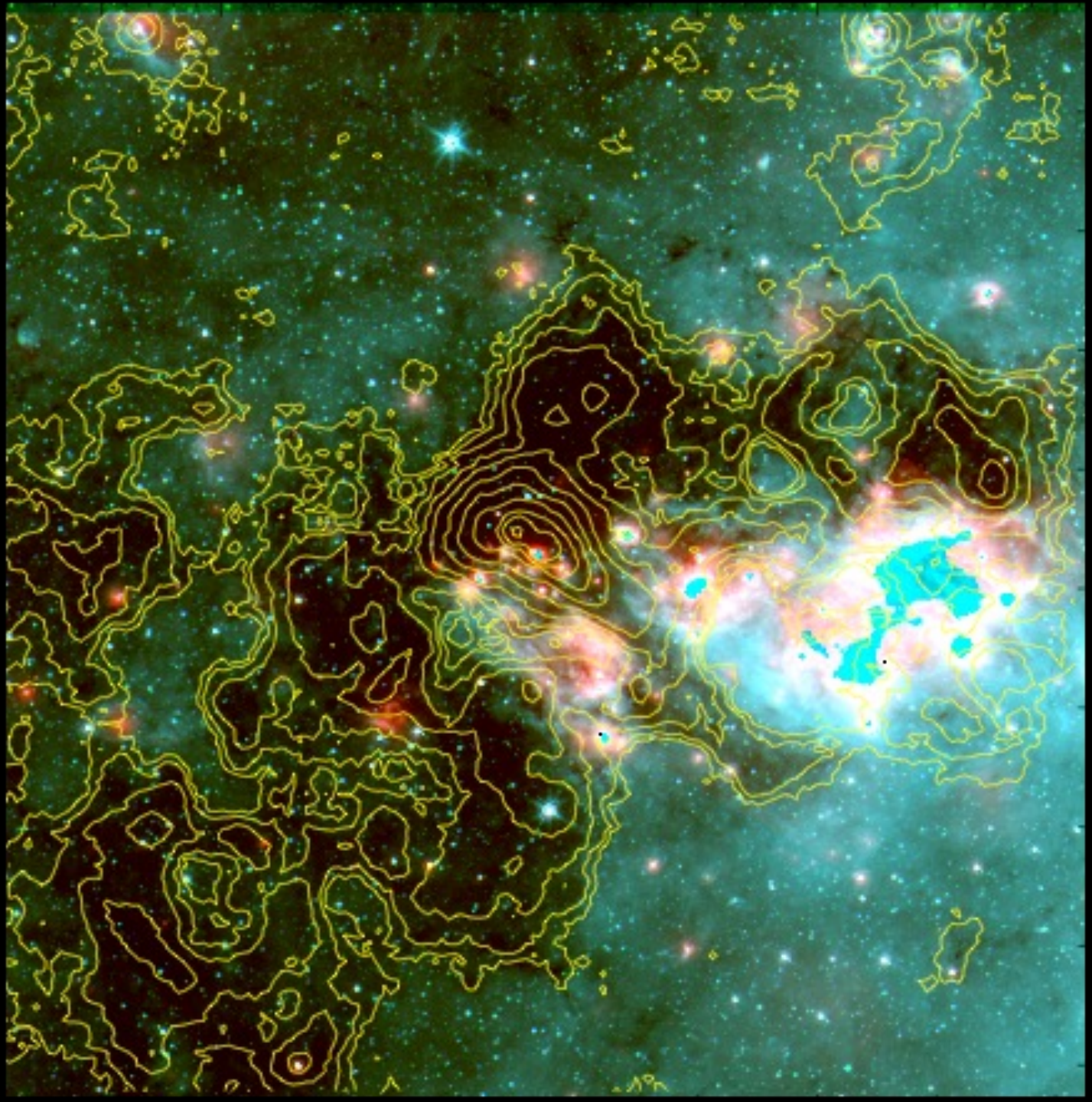


Galactic Center: 1100 μm

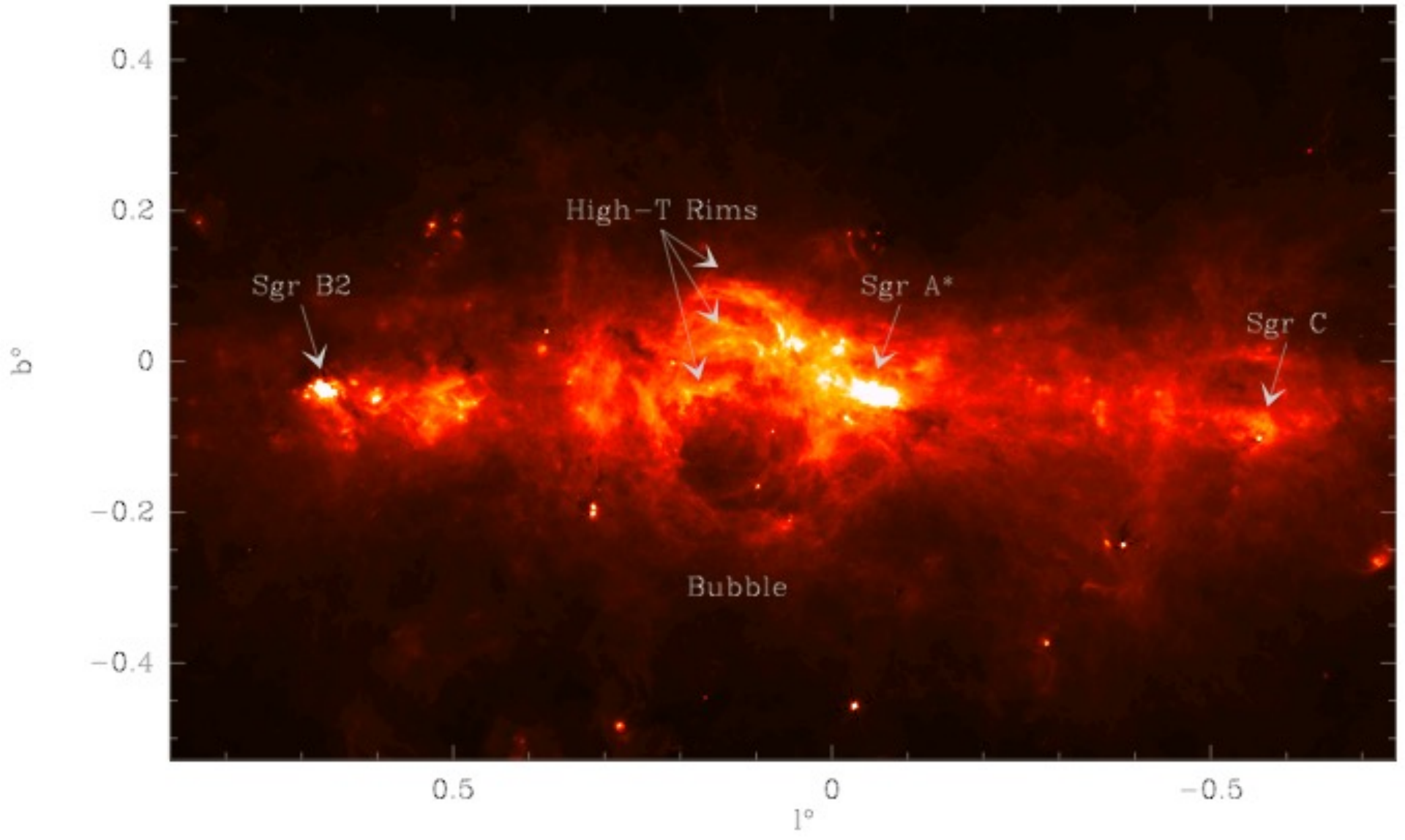


Galactic Center: 20 cm

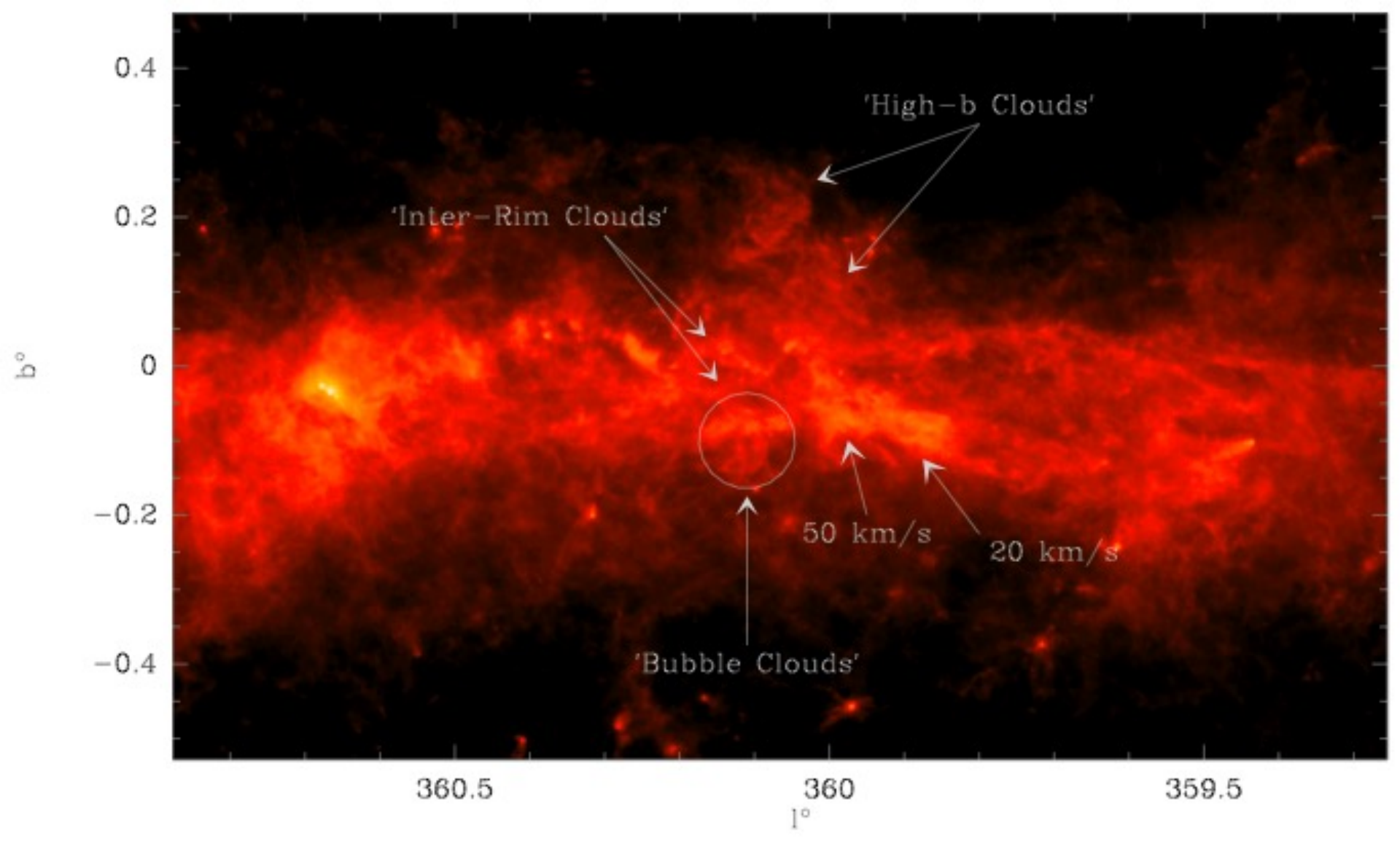




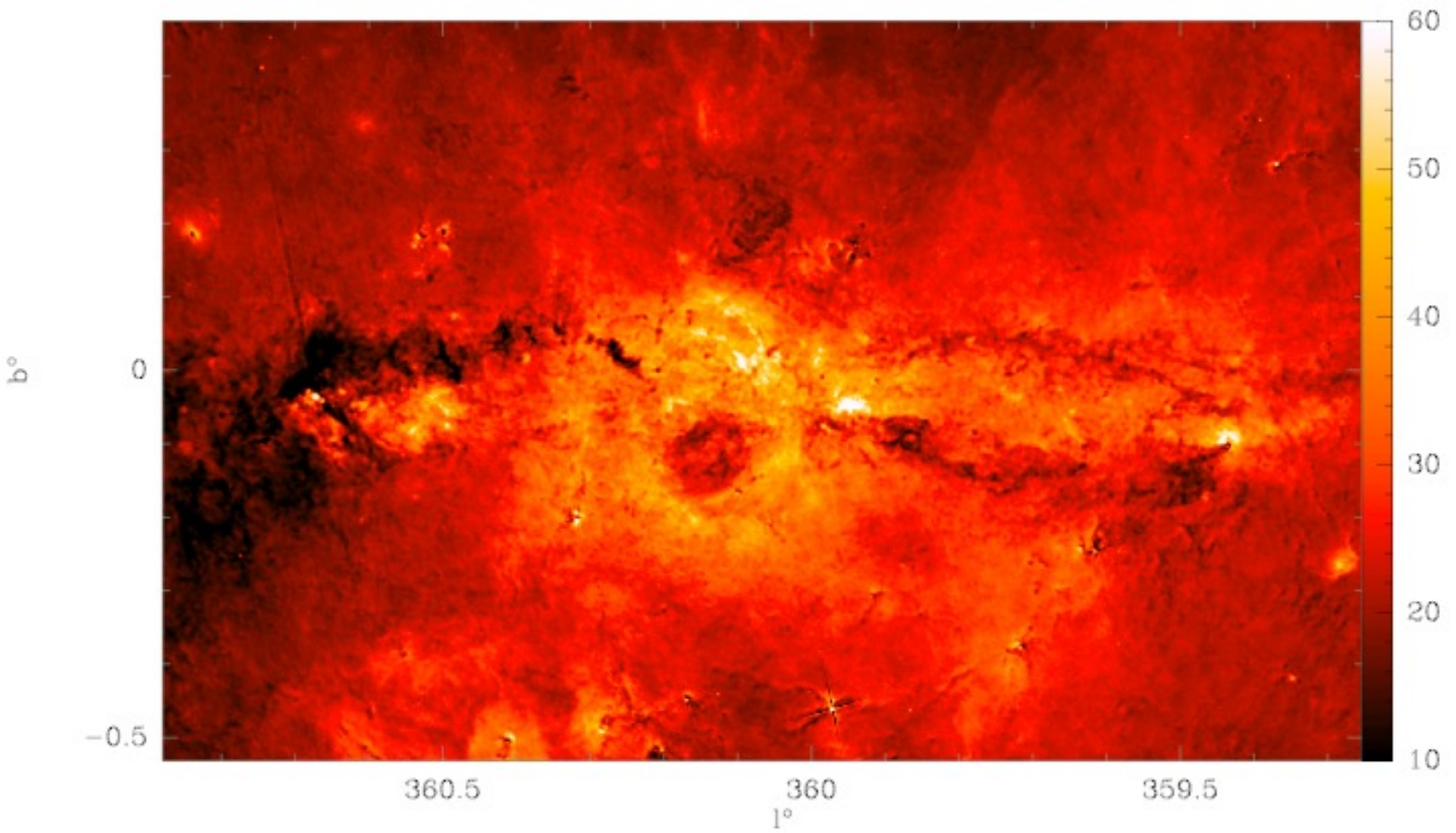
Herschel Hi-GAL 80 μm



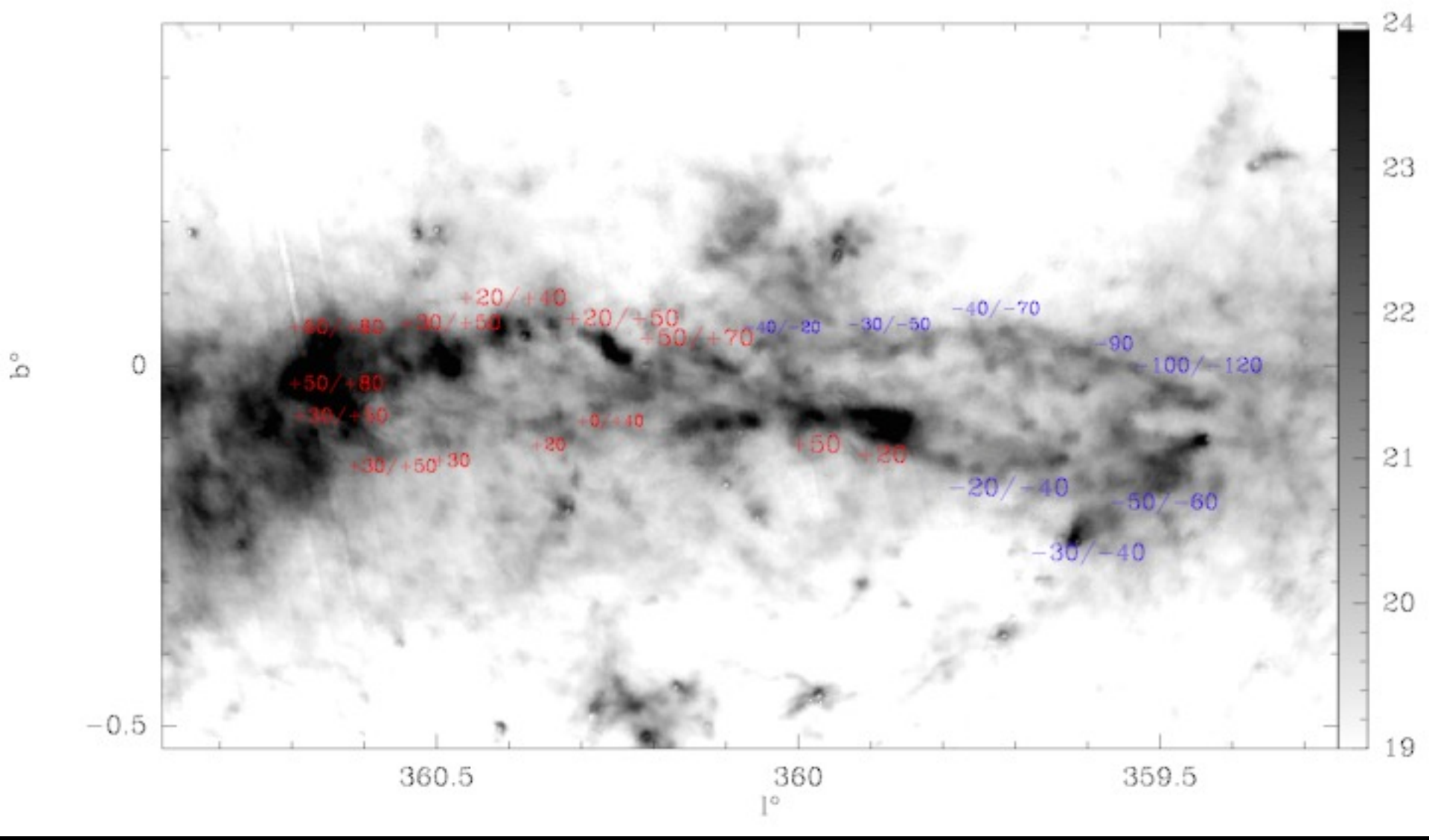
Herschel Hi-GAL 250 μm



Dust temperature



Dust column density



Conclusions

Small-N Dynamics in massive star formation !

Orion OMC1:

- Decay of non-hierarchical multiple star system
  - Eject BN, I, n V ~ 10 to 30 km/s 500 years ago!
- OMC1 outflow (~few x 10^{47} erg)
  - Disrupt inner disks => fastest ejecta
  - Recoil of outer envelope => slow ejecta
  - B? => slow ejecta

Lessons:

- High multiplicity => Capture formation
- Ejection => High-velocity stars
- Stored Energy Release => Explosive Outflows


The End