Jets from Young Stars

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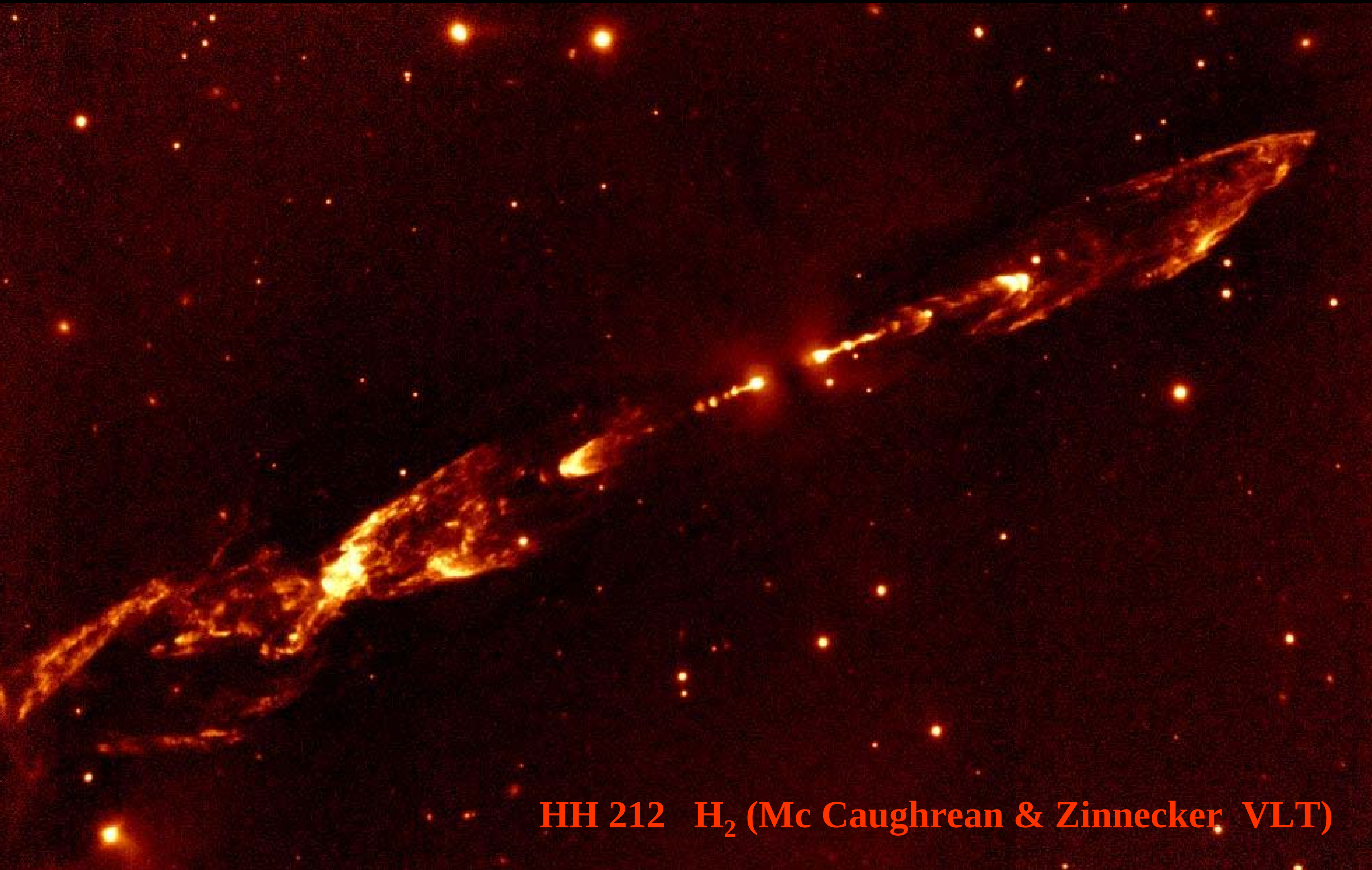


HH 212 H_2 (Mc Caughrean & Zinnecker VLT)

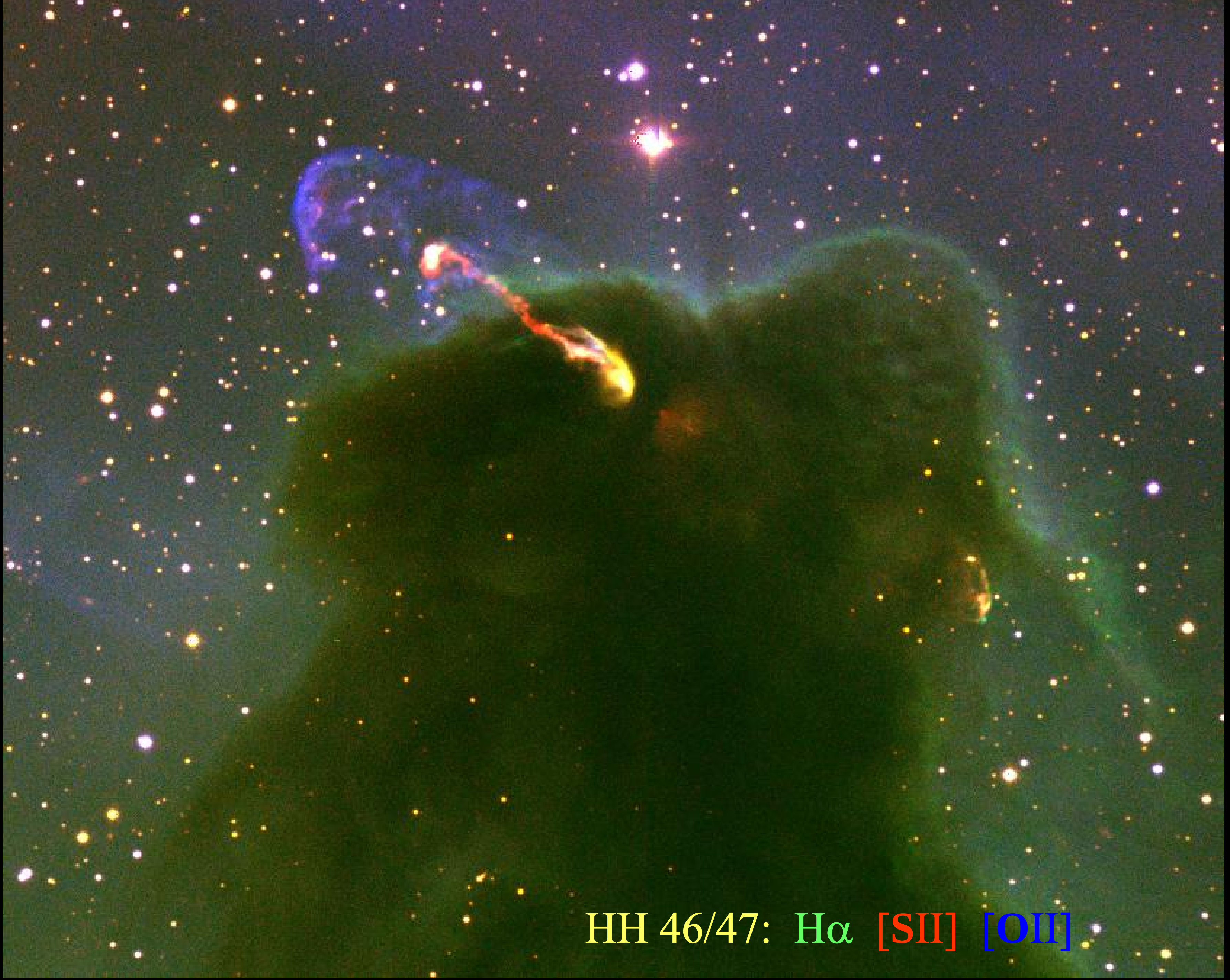
Why Study Jets from Young Stars?

- **Jets & Herbig-Haro Objects: They are beautiful!**
- **Jet Physics:**
  Launch, collimation, shocks, variations
- **Probes of Star Formation:**
  Symmetries (S, Z,C) => precession, motion, dynamics
- **Probes of ISM:**
  Side winds, ionization, chemical state, etc.
- **Impacts:**
  Feedback / Self-regulation of star formation
  Turbulence generation / Cloud disruption
- **Proximity:**
  Closest, most abundant jets in astrophysics
- **Lessons for all classes of astrophysical collimated flow**

Accretion + Rotation + Magnetic Fields => JETS

Outline:

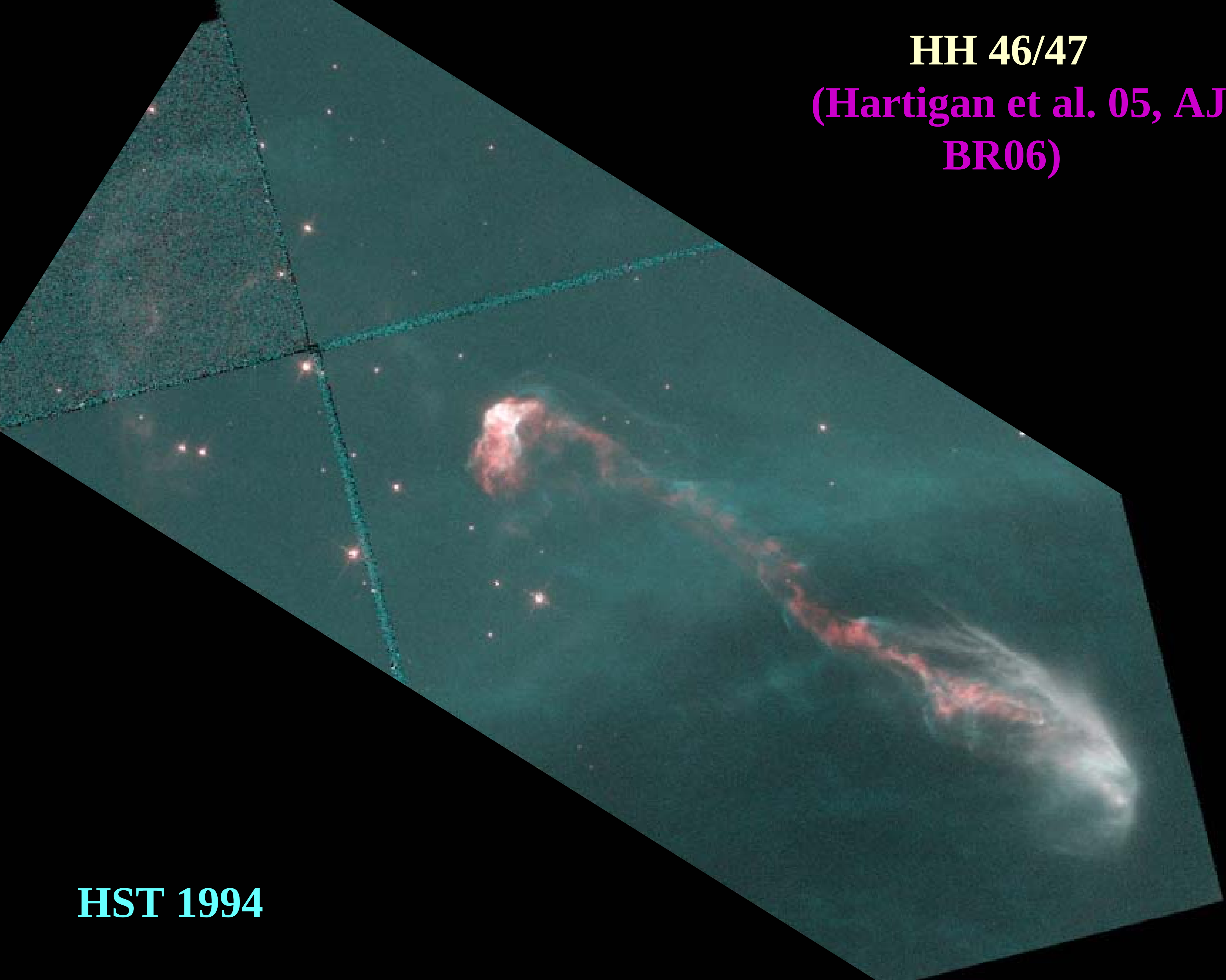
- \`Classical’ Herbig Haro Objects / Molecular outflows
  Rendered visible by shocks
- Irradiated Jets
  Rendered visible by ionnization
- Symmetries
  S, Z-shaped => precession, companions, dynamics
- Explosions
  Orion OMC1, NGC 7129, G24.26+0.15
- Launch & Collimation
  Disk- and X-winds, hoop stress, magnetic towers
- Isolated vs. cluster environments


HH 46/47: Hα [SII] [OII]

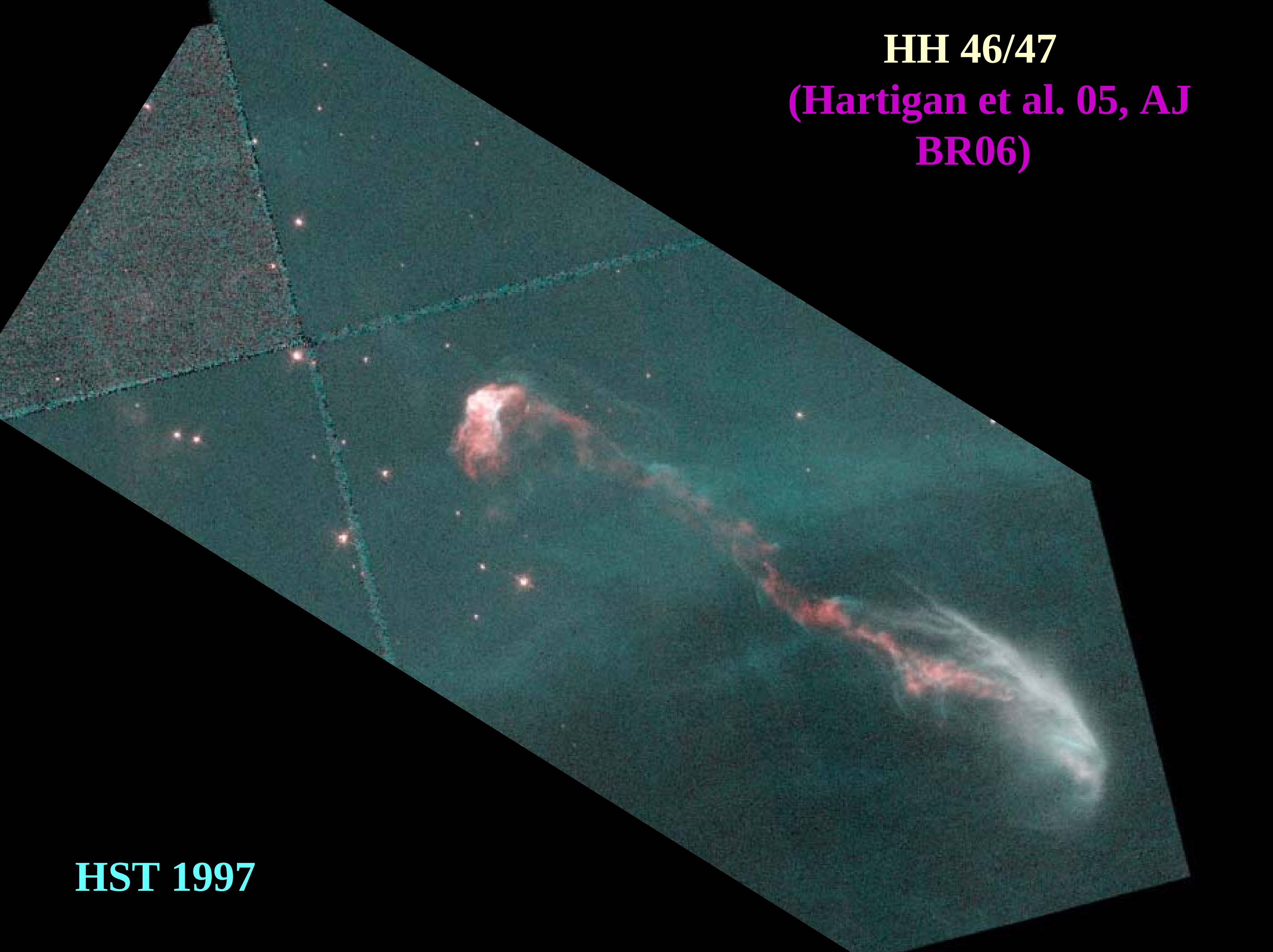
Spitzer IRAC: 3 – 8 μm

HH 46/47

(Hartigan et al. 05, AJ BR06)

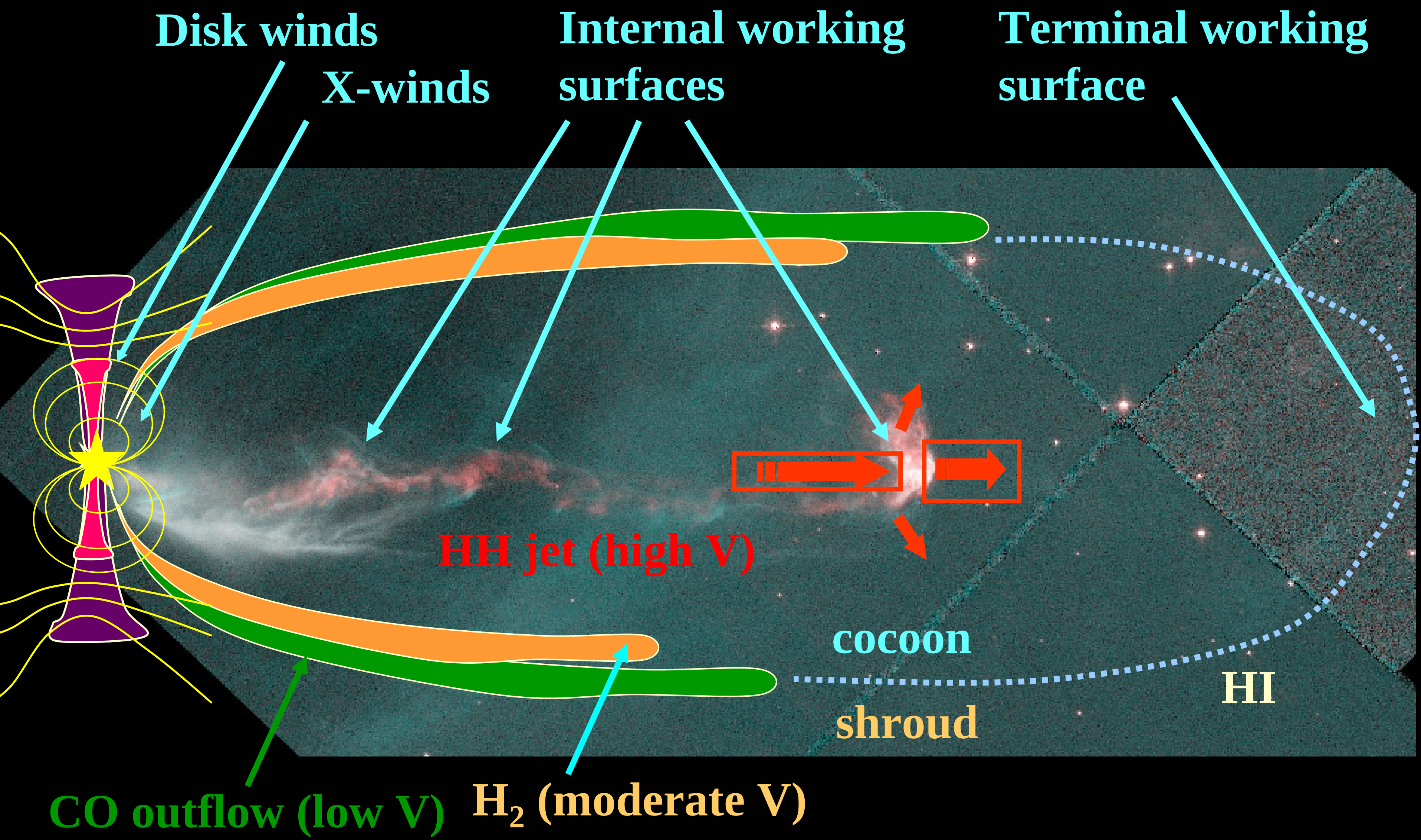


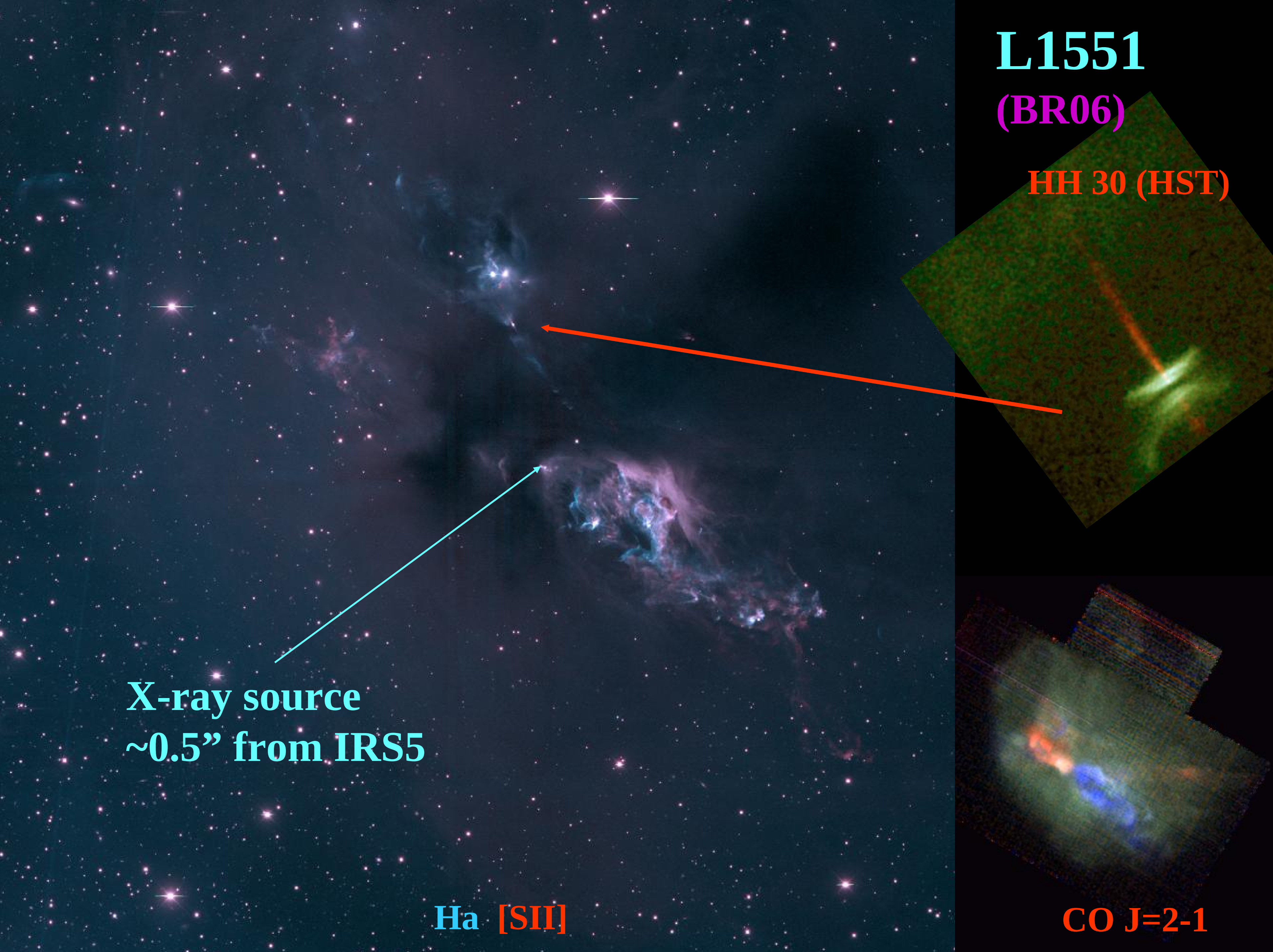
HST 1994

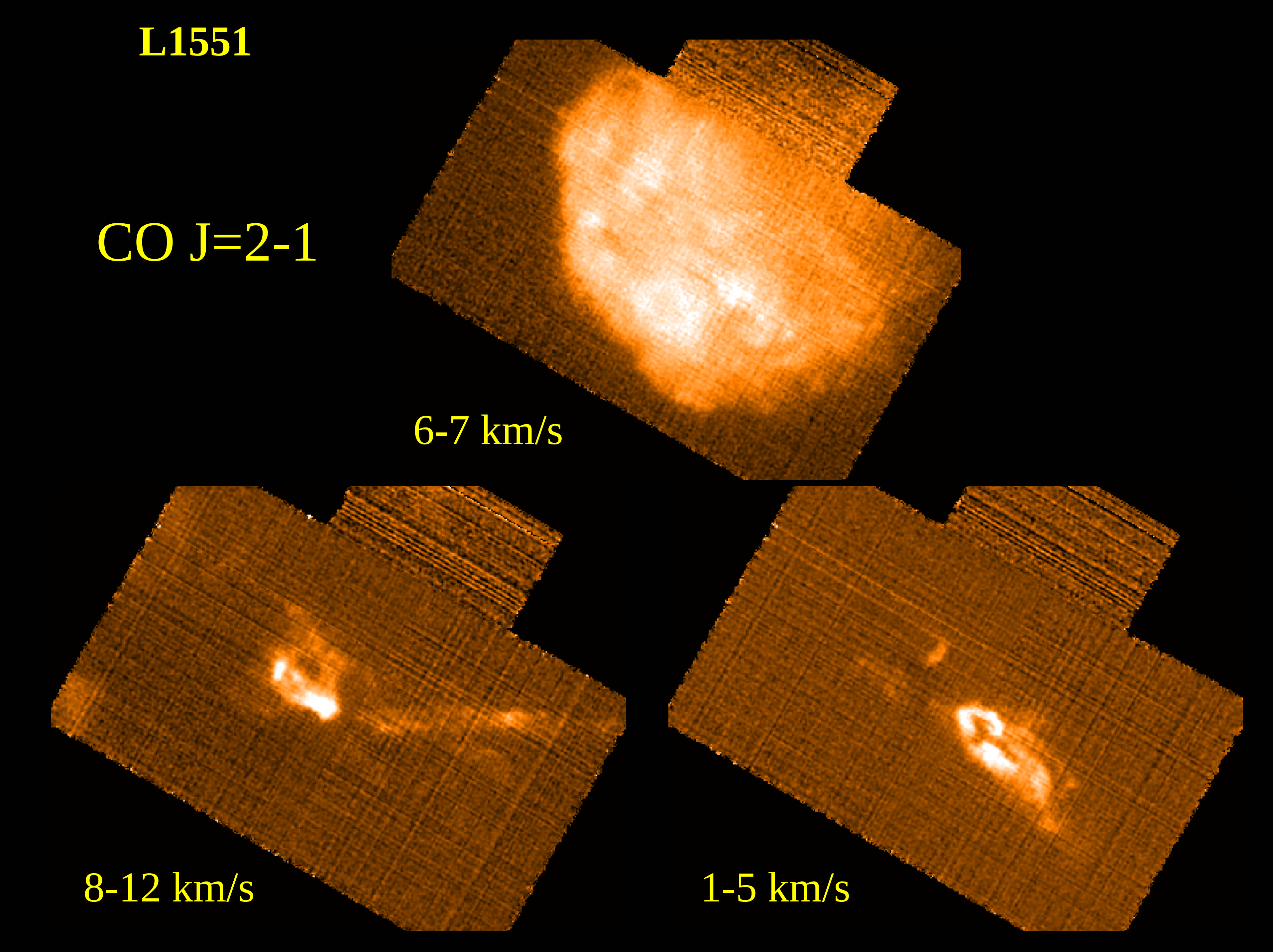

HH 46/47
(Hartigan et al. 05, AJ
BR06)
HST 1997

Outflows:

Jets, Winds => Wide-Angle Cavities

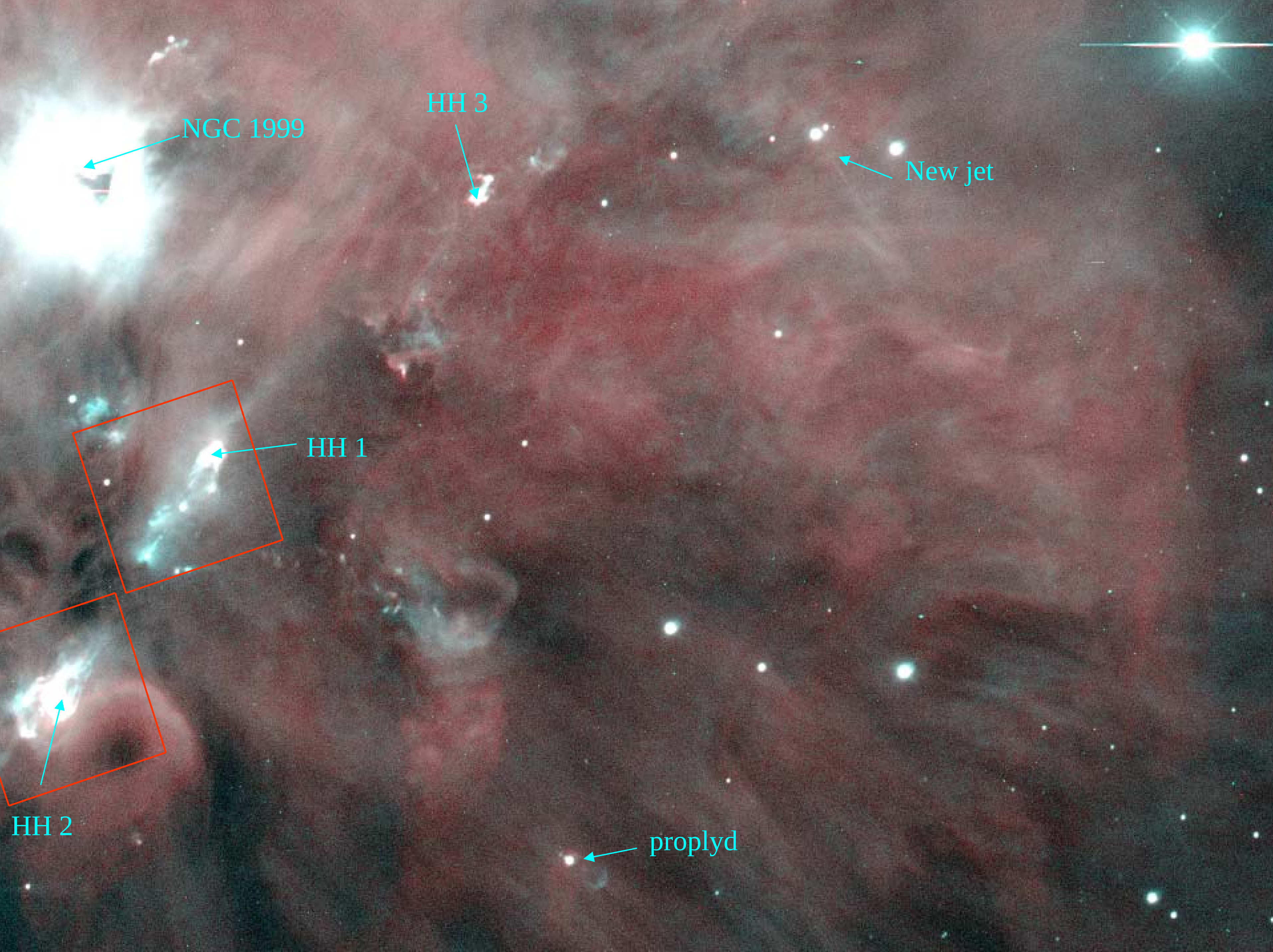



L1551
(BR06)
HH 30 (HST)
X-ray source
~0.5” from IRS5
Ha [SII]
CO J=2-1

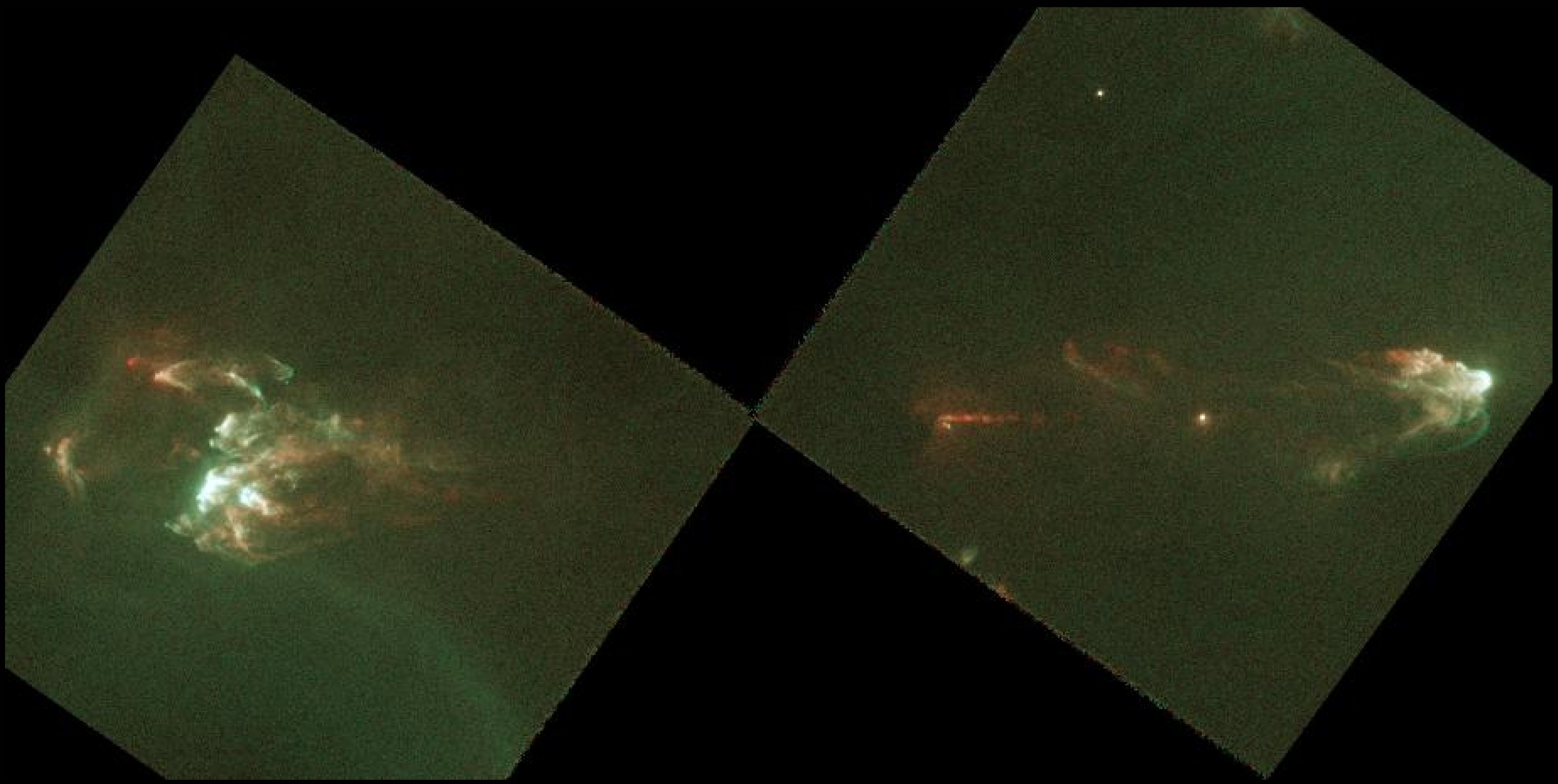

L1551
CO J=2-1
6-7 km/s
8-12 km/s
1-5 km/s

Jets from Young Stellar Objects (YSOs)

- **Tracers:** 10^6 K plasma — X-ray
  Ha, [SII], [NII], [OI], [OIII] — visual
  [FeII], H_2 — infrared
  CO, HCO^+, SiO — mm
  free-free, non-thermal, masers — cm
- **Manifestations of outflows:**
  Visual jets, micro-jets (jet beam)
  Herbig-Haro objects & NIR (H_2) shocks
  Molecular outflows (swept-up/entrained)
- **dM/dt** decrease with evolutionary stage
  Class 0: $> 10^{-5}$ Solar masses/year
  Class I: 10^{-6} Solar masses/year
  Class II/III: 10^{-7} 10^{-9} Solar masses/year
- **Velocity** Increase with evolutionary stage


HH 3
NGC 1999
New jet
HH 1
HH 2
proplyd

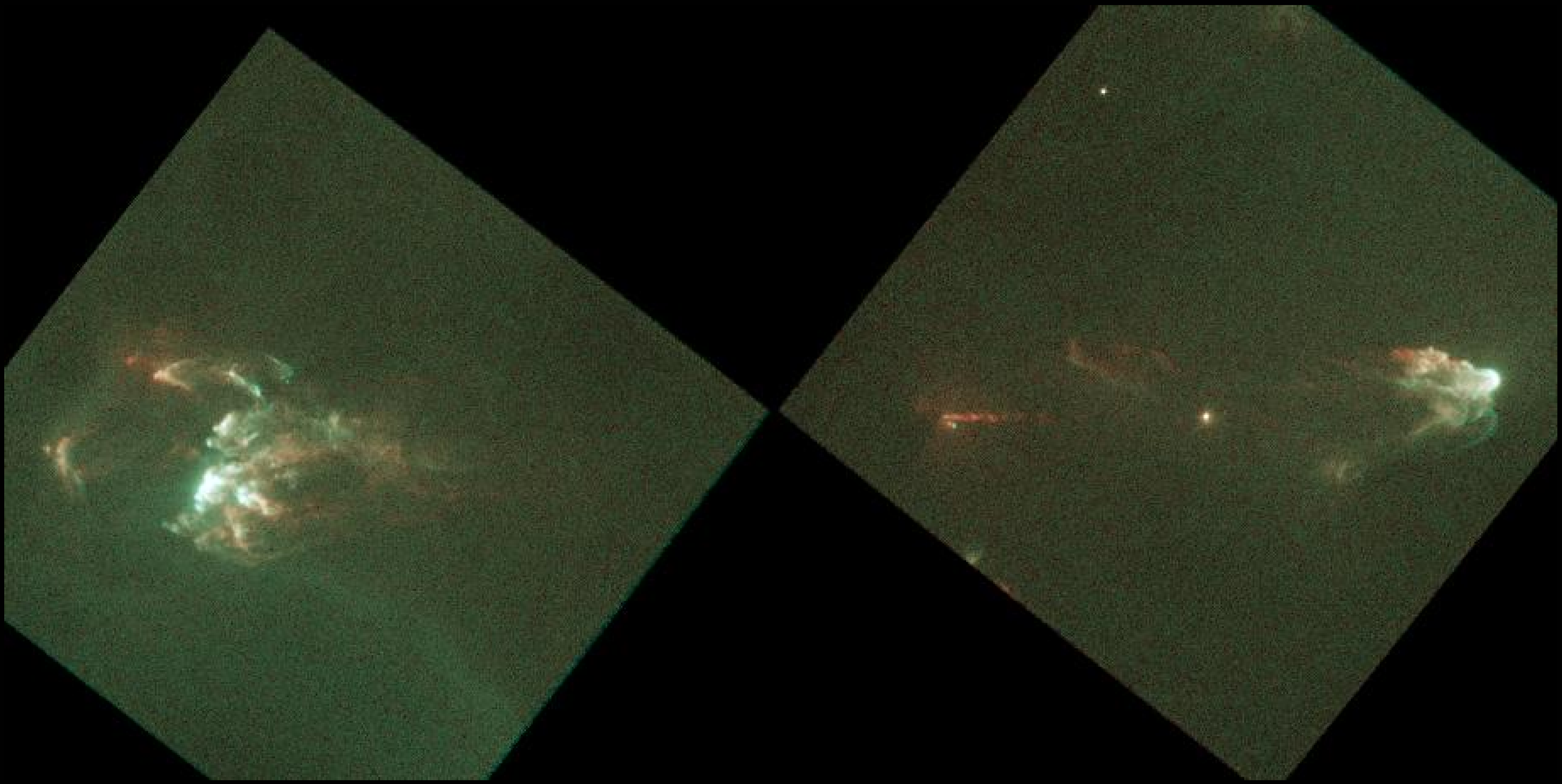
HH 2 **HH 1**



HST 1997 - 1994

HH 2

HH 1



HST 1997 - 1994

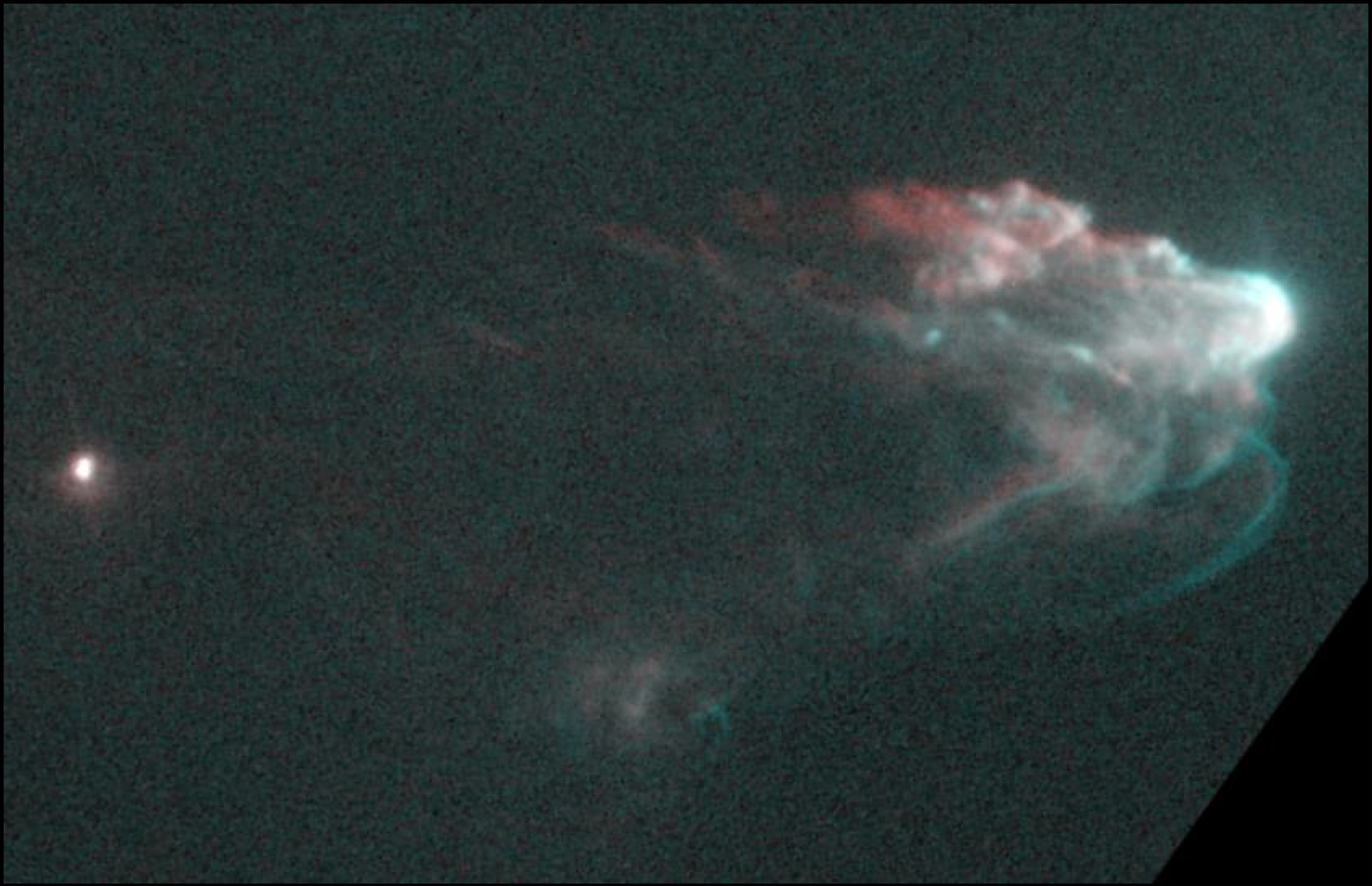
HH 1 jet

HST 1997 - 1994

HH 1 jet

HST 1997 - 1994

HH 1



HST 1997 - 1994

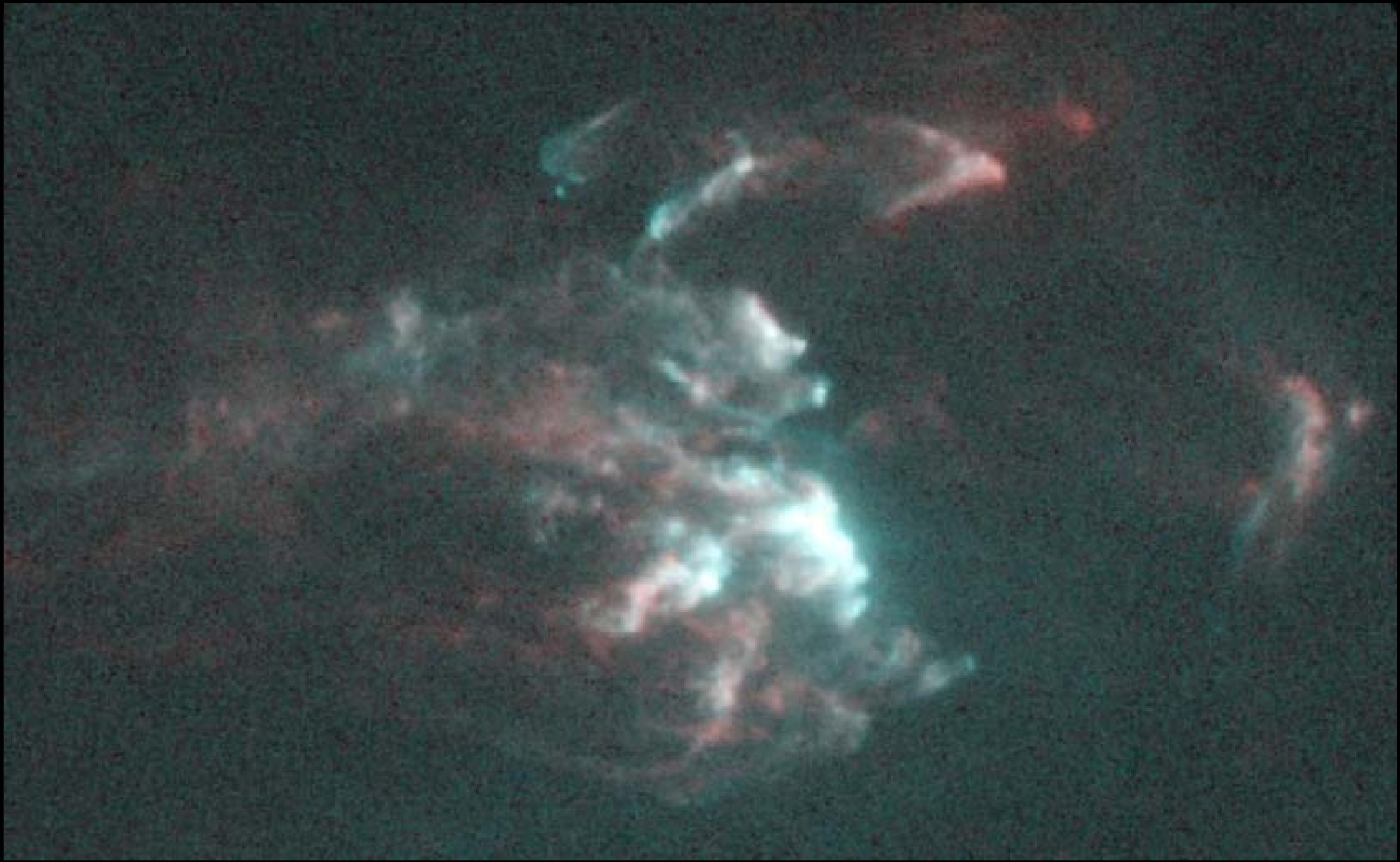
HH 1

HST 1997 - 1994

HH 2: Small scale chaotic structure (10^2 - 10^4 AU)

HST / WFPC2 1994 (Bally et al. 2000; BR06)

HH 2: Small scale chaotic structure (10^2 - 10^4 AU)



HST / WFPC2 1997 (Bally et al. 2000; BR06)

Irradiated Jets

- Nearby OB stars photo-evaoprate cores
  σ Ori (HH 444, 445, 446); Orion Nebula (Bally 06)

- Asymmetries:
  Brighter jet - slow
  Mass loading of fast beam
  Fainter jet - fast
- Lyman continuum:
  determine n, V, P, E
  independent of nonlinear shock physics
- Irradiated micro-jets from Orions proplyds
  $dM/dt \sim 10^{-9}\ M_o$
  low V (< 100 km/s)

HH 444/445
Irradiated jets: σ Ori

Reipurth et al 97
Andrews et al. 04

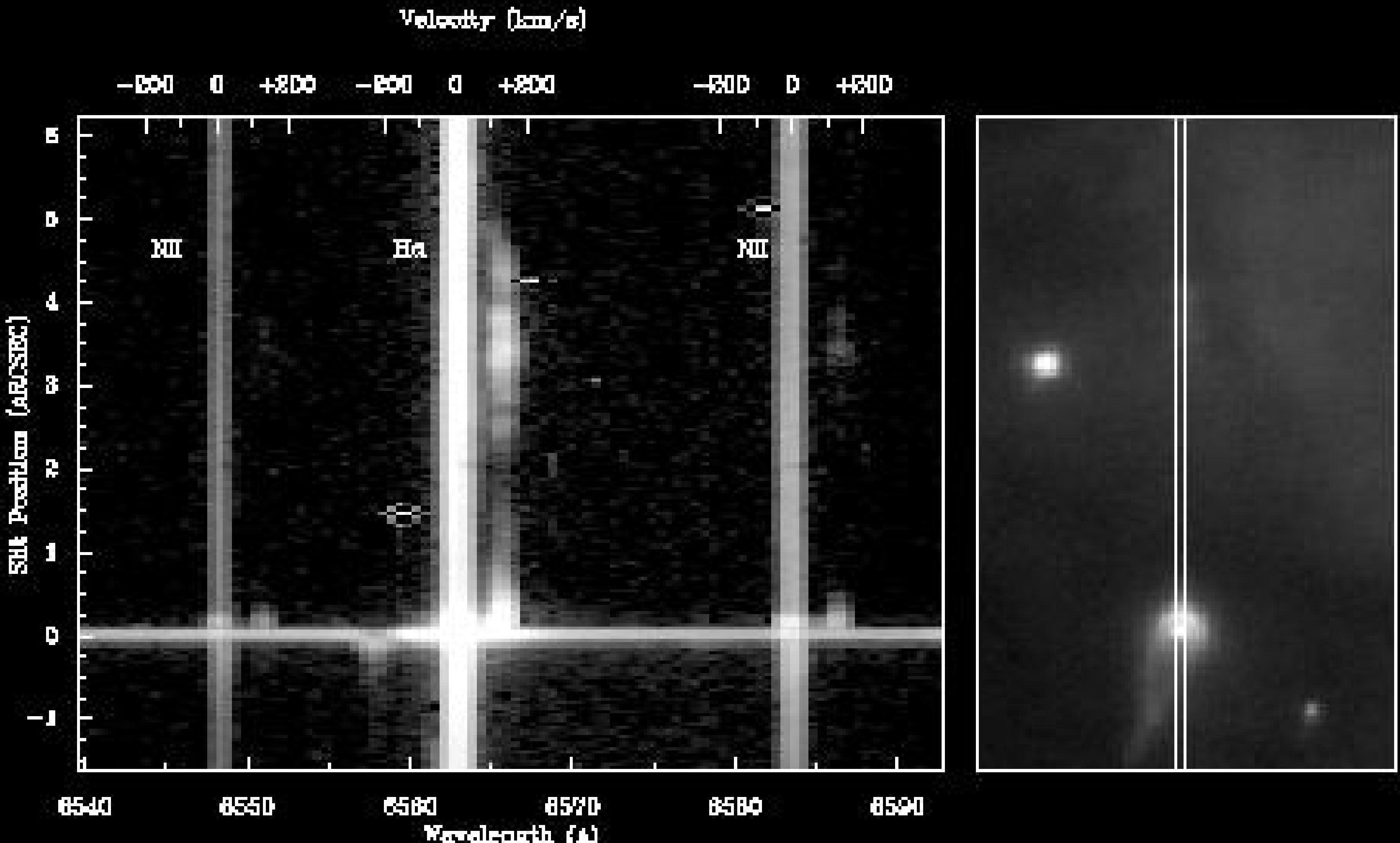
UV photo-ablation of disks & planet formation:

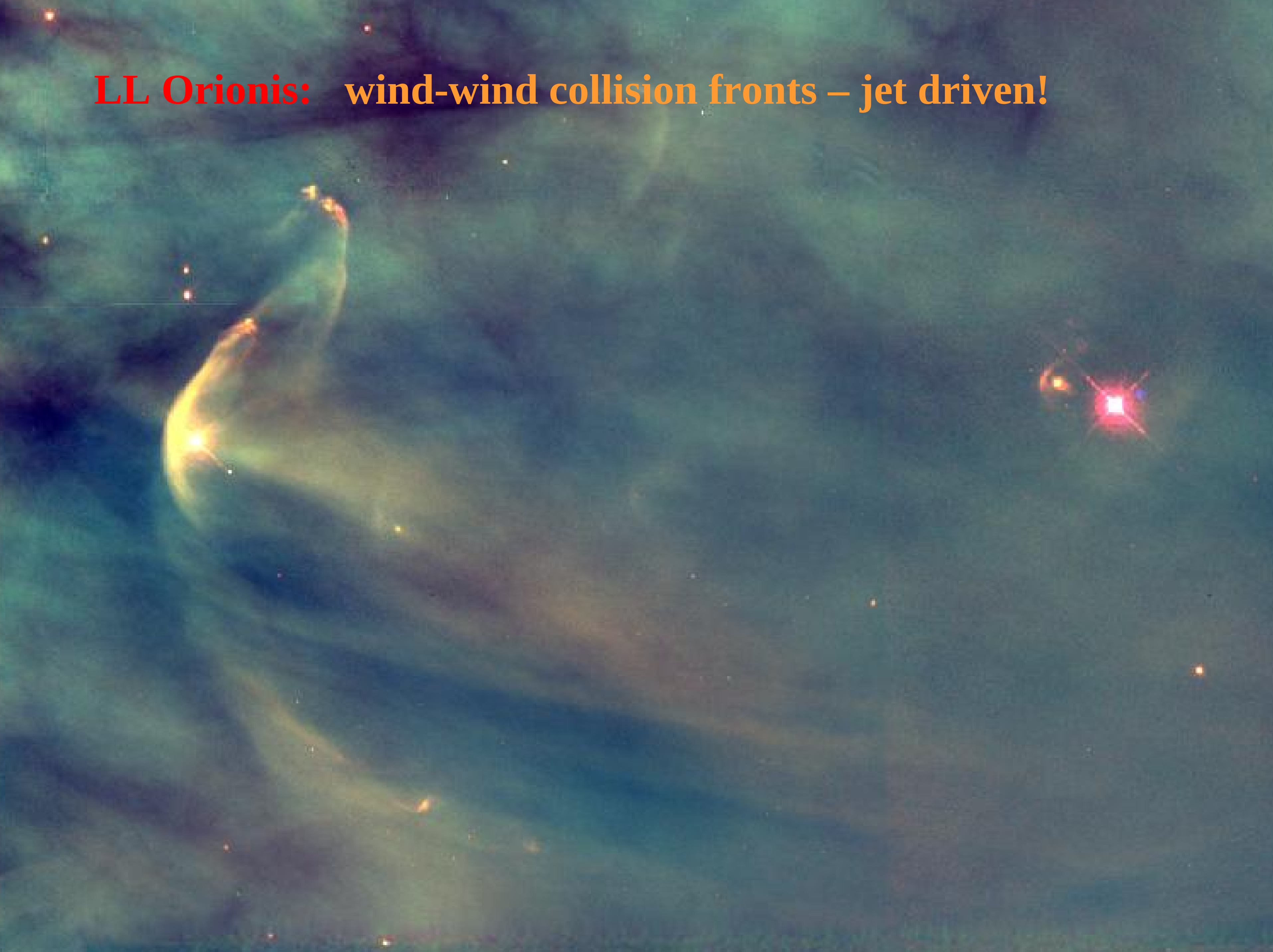
Smith, Bally, Licht, Walawender 05

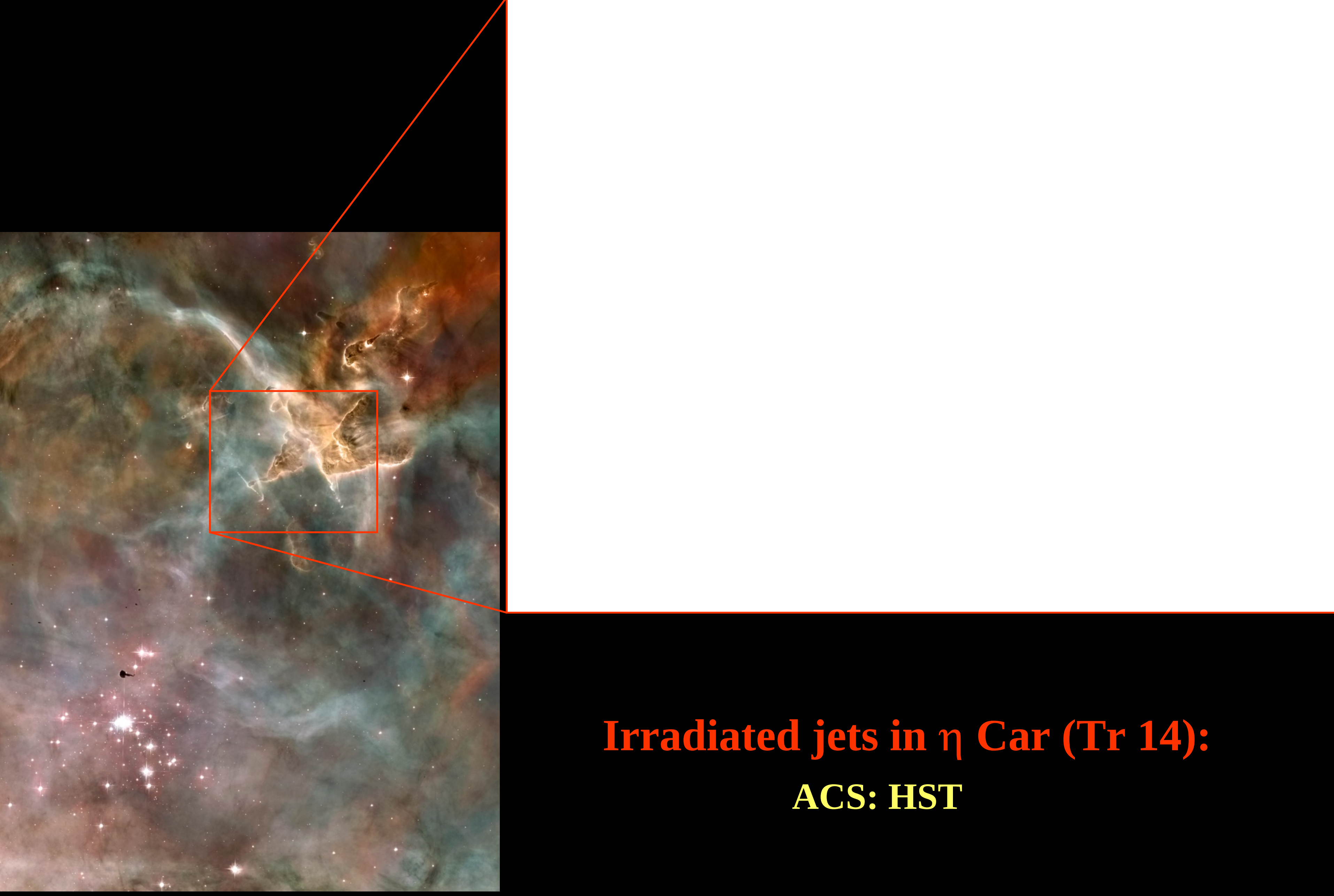
d253-535 in M43


LkHa 312/ 313
Ha [SII]
B. Reipurth / Subaru

HH 514 micro-jet in Orion: Hα, [HII] (HST/STIS)

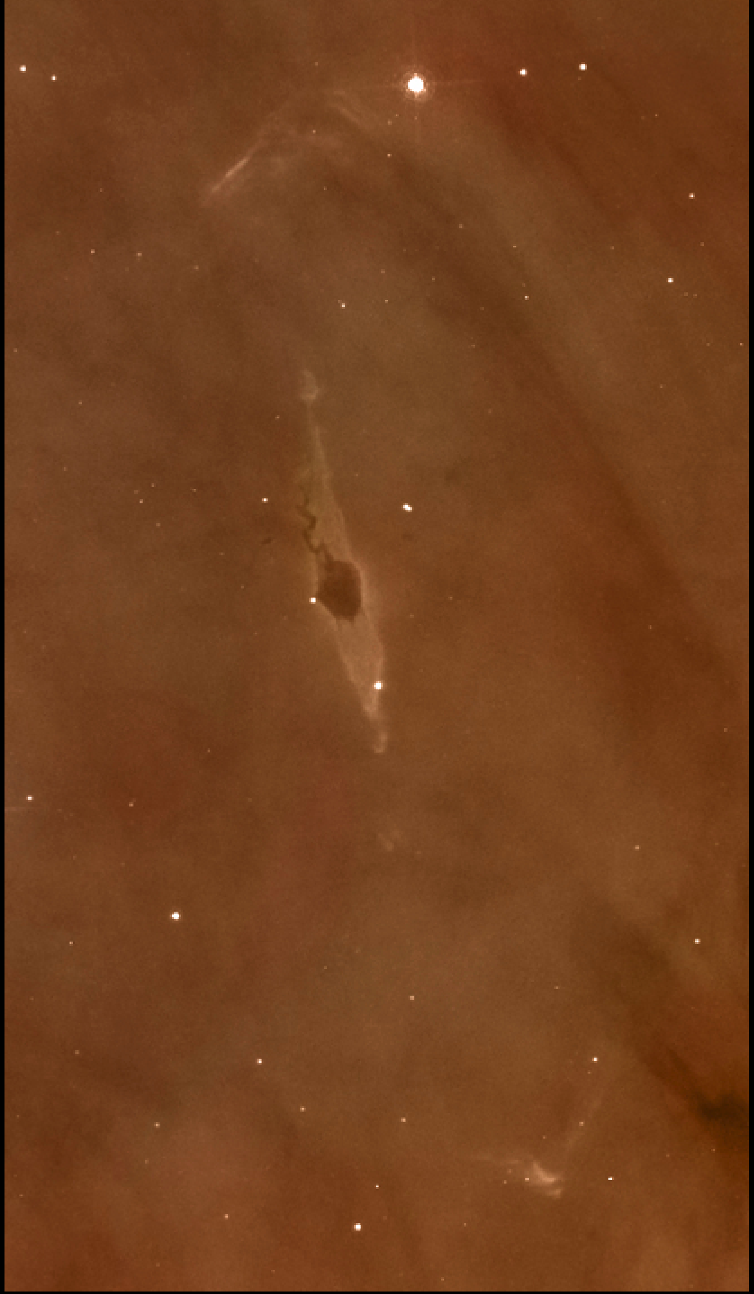



LL Orionis: wind-wind collision fronts – jet driven!



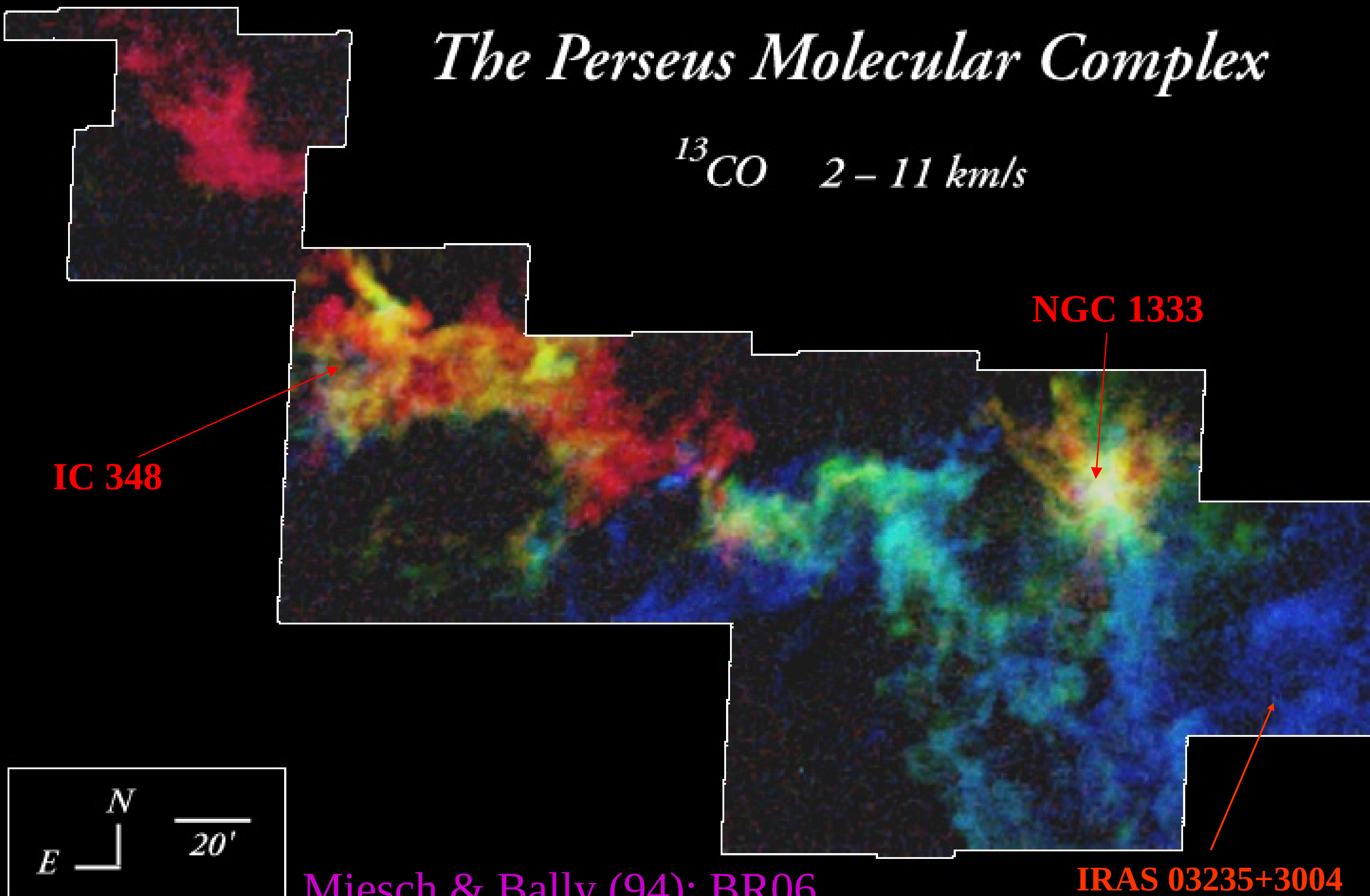
Irradiated jets in η Car (Tr 14):

ACS: HST



Irradiated jets in η Car

Outlfows in Clusters: Interactions



Miesch & Bally (94); BR06

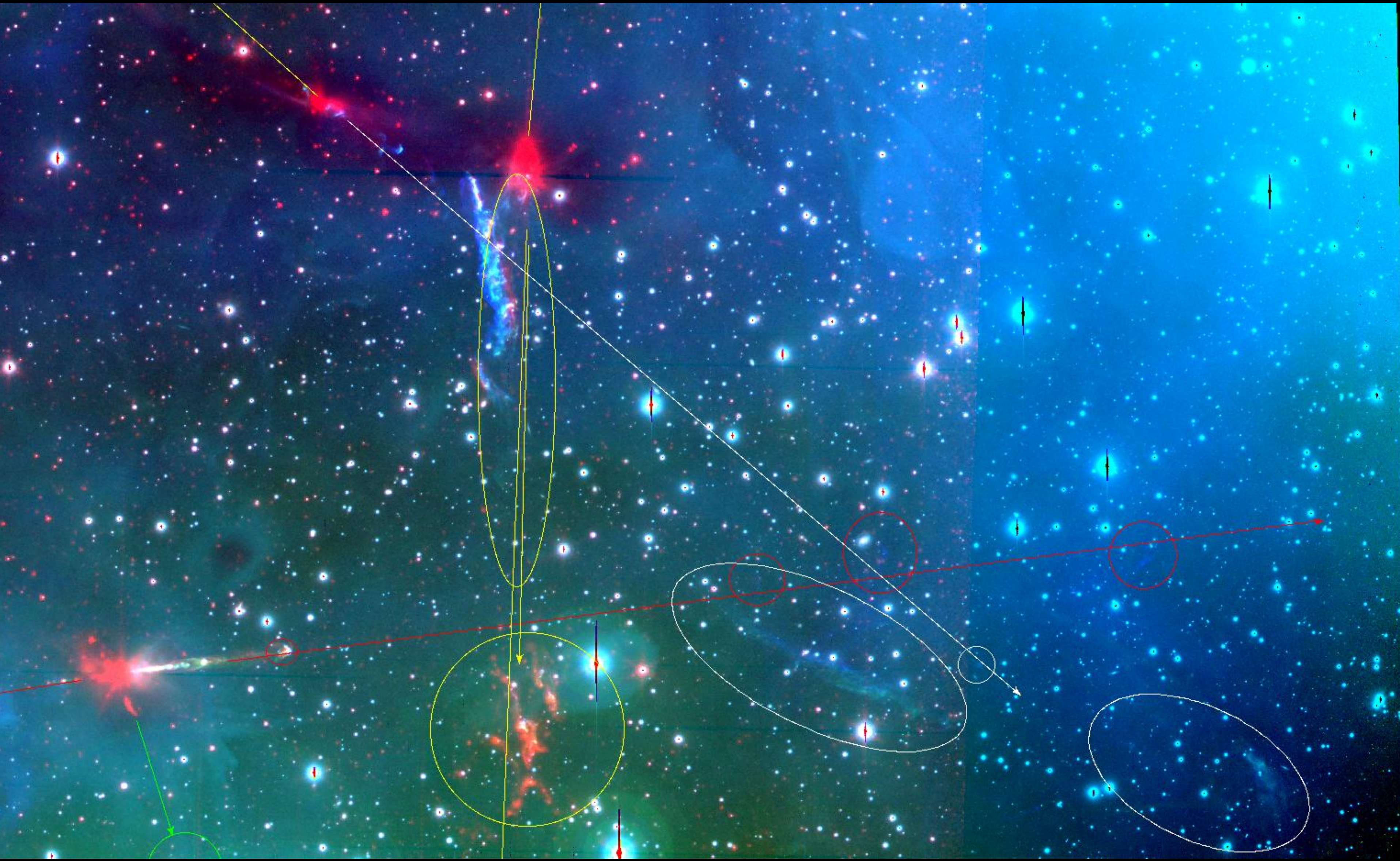

NGC 1333
Ha, [SII]
Walawender, Bally,
Reipurth (06)
Spitzer/IRAC
Jorgensen et. (06)

HH 111: Ha, [SII]

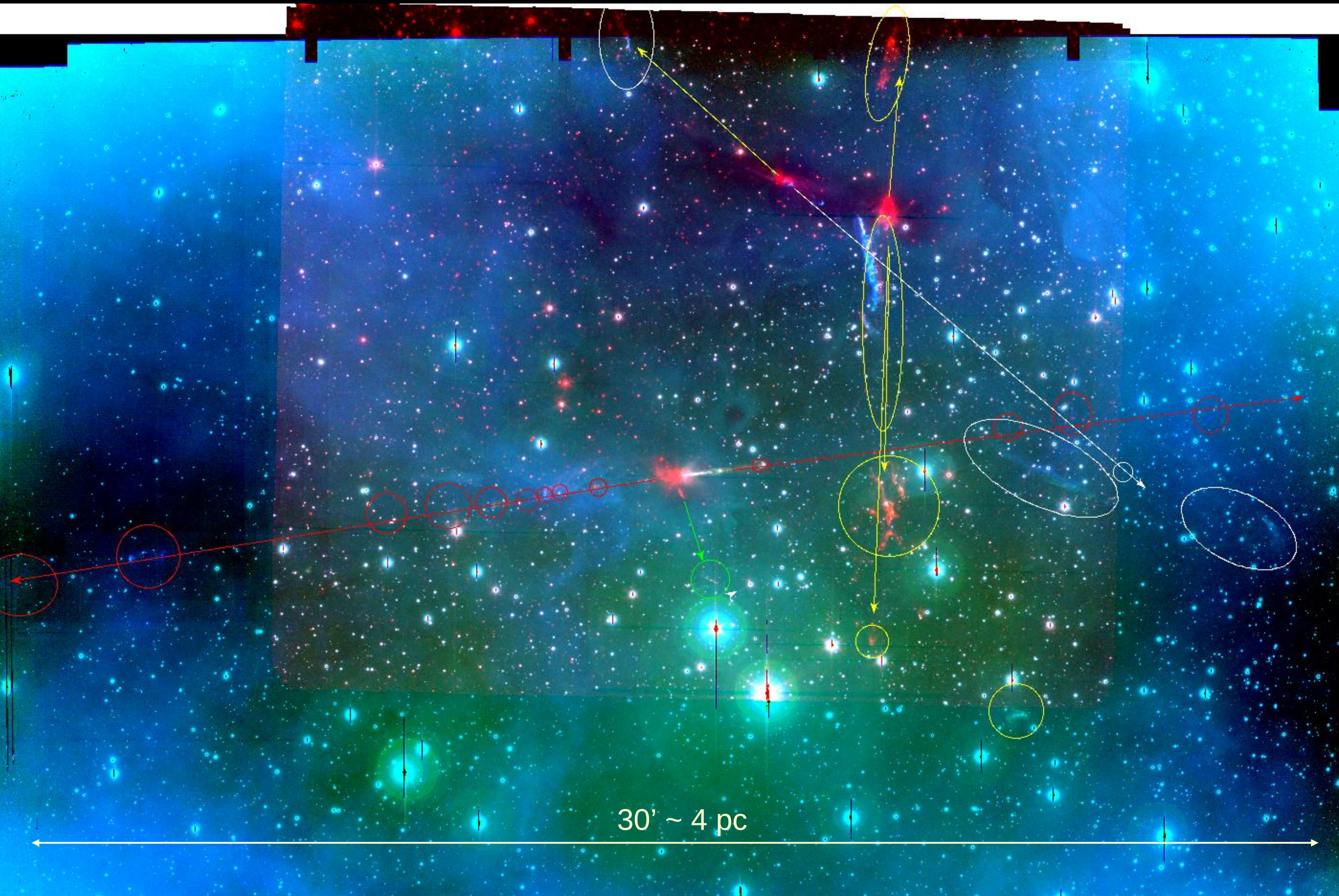
A flow - flow collision

HH 270 => HH 110,   IRAS 05486+0255 flow   Ha, [SII]

Ha, [SII], 4.5 μm (IRAC)



Ha, [SII], 4.5 μm (IRAC)



Giant Outflows

- Symmetries:
  C-shaped: ejection of star, wind interactions
  S-shaped: outfow orientation change
- Fossil record of Mass Loss (accretion) history

- Source of cloud turbulence

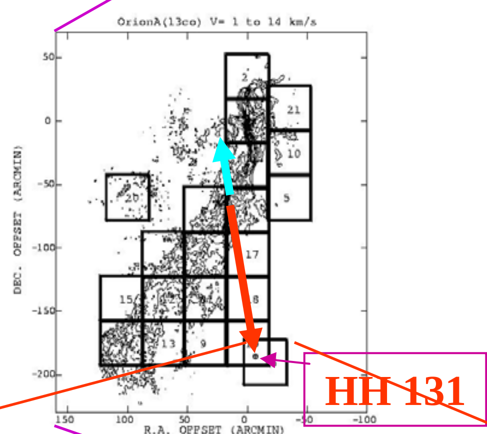
- Chemical Rejuvenation, CI, C^+ in ICM (inter-core medium)

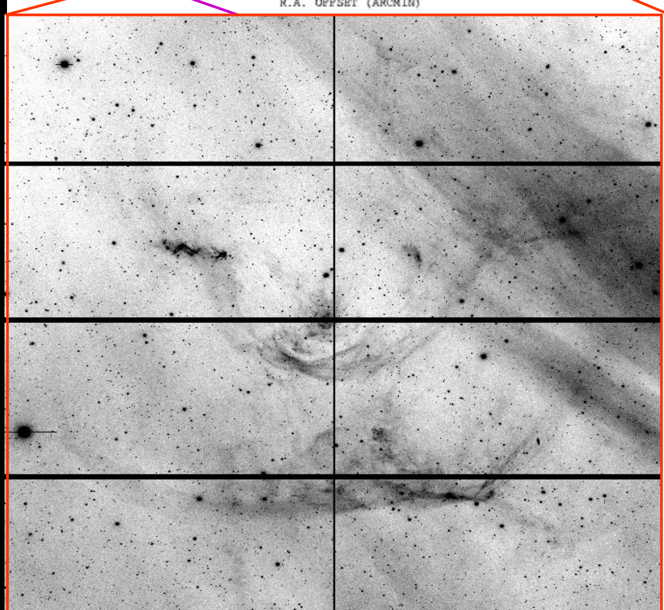
- Origin of Cloud Internal Structure (shells, holes: cf. Circinus)
  Structure + UV => Turbulence
- Major eruptions of YSO every few thousand years
  ejecta decelerates, blows out of cores
- Non-linear Evolution of Instabilities:
  cooling => structure

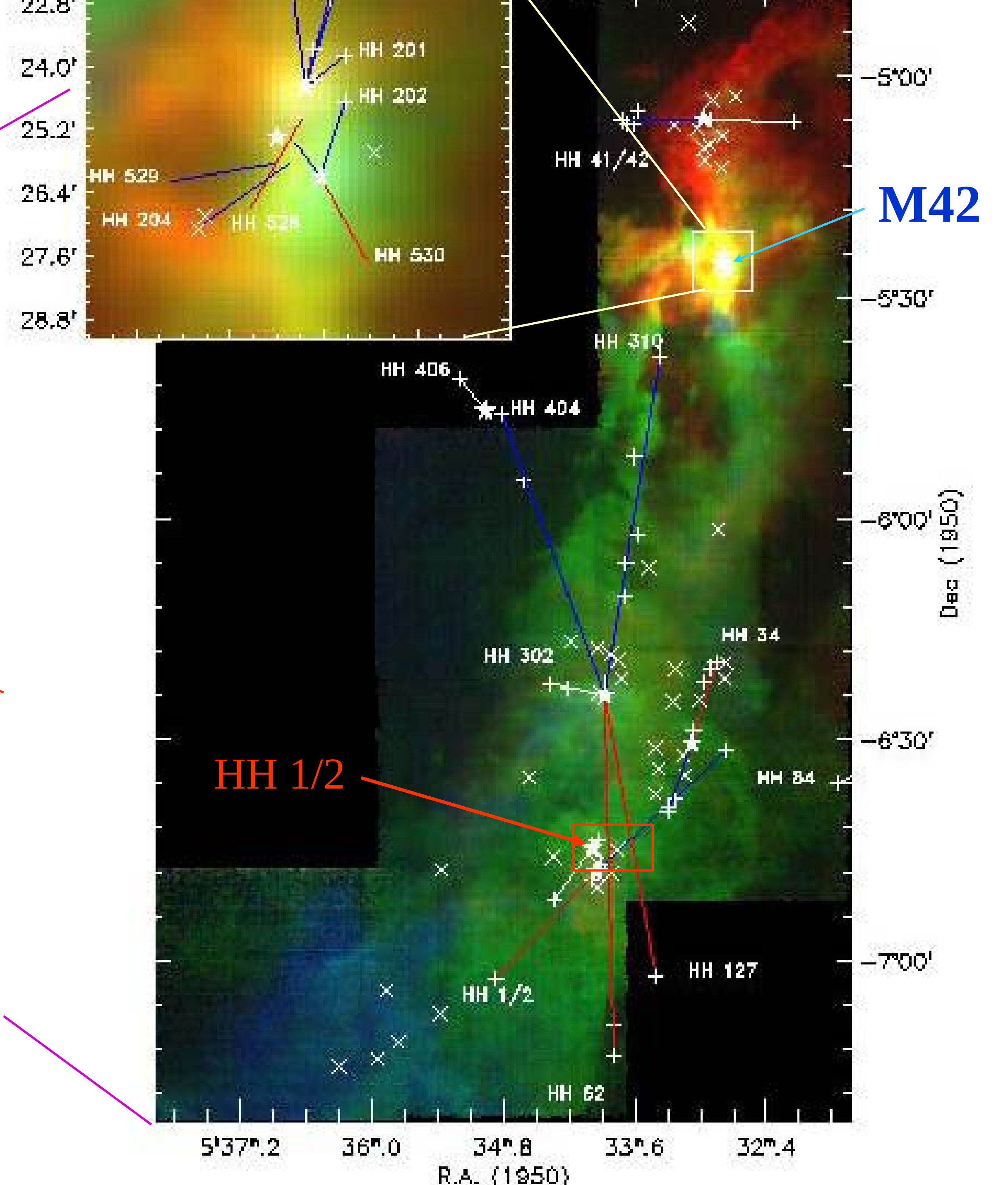

HH 34 parsec-scale flow
2.5 pc

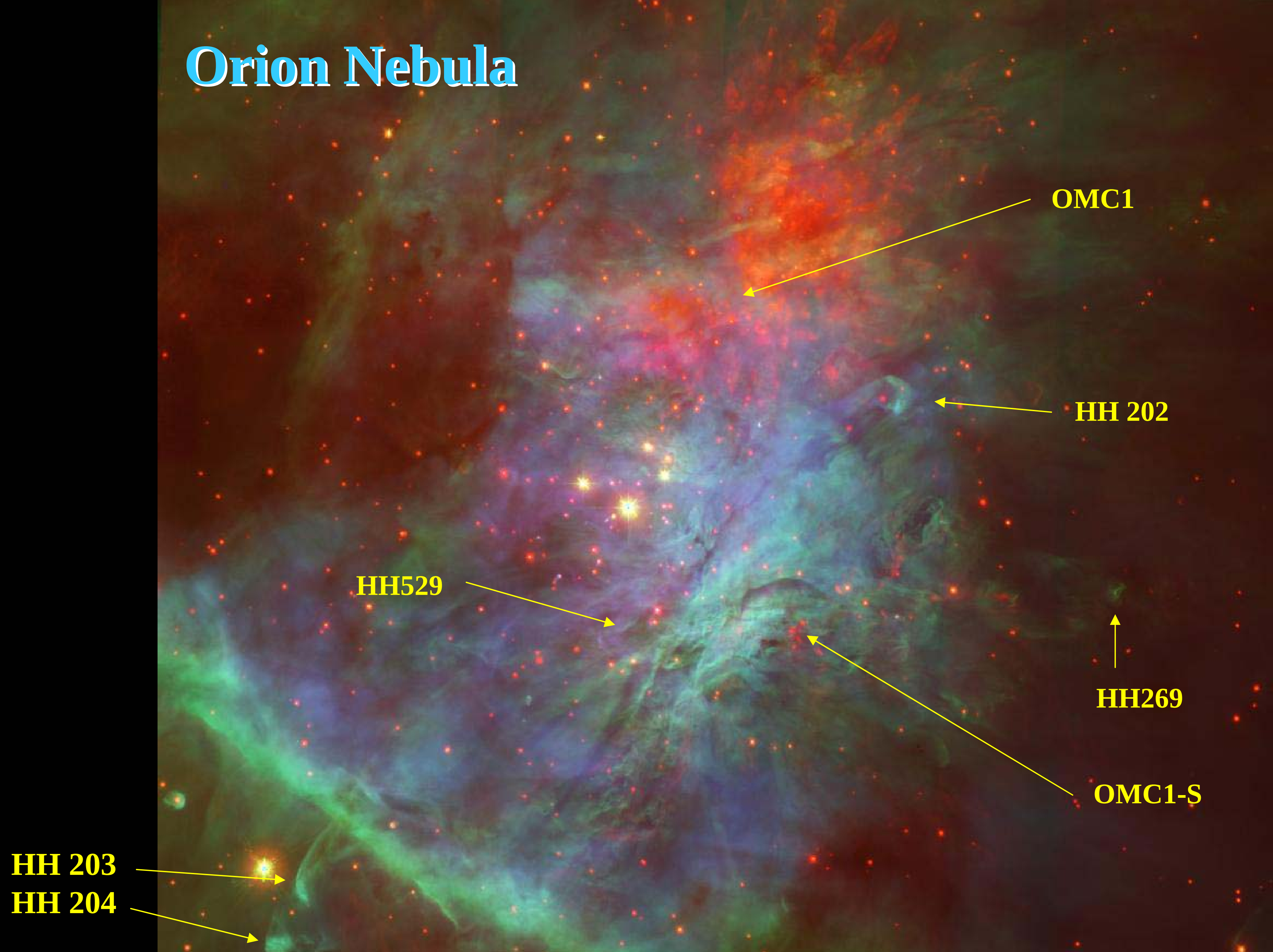
Orion A:

- Outflows up to 30 pc long !

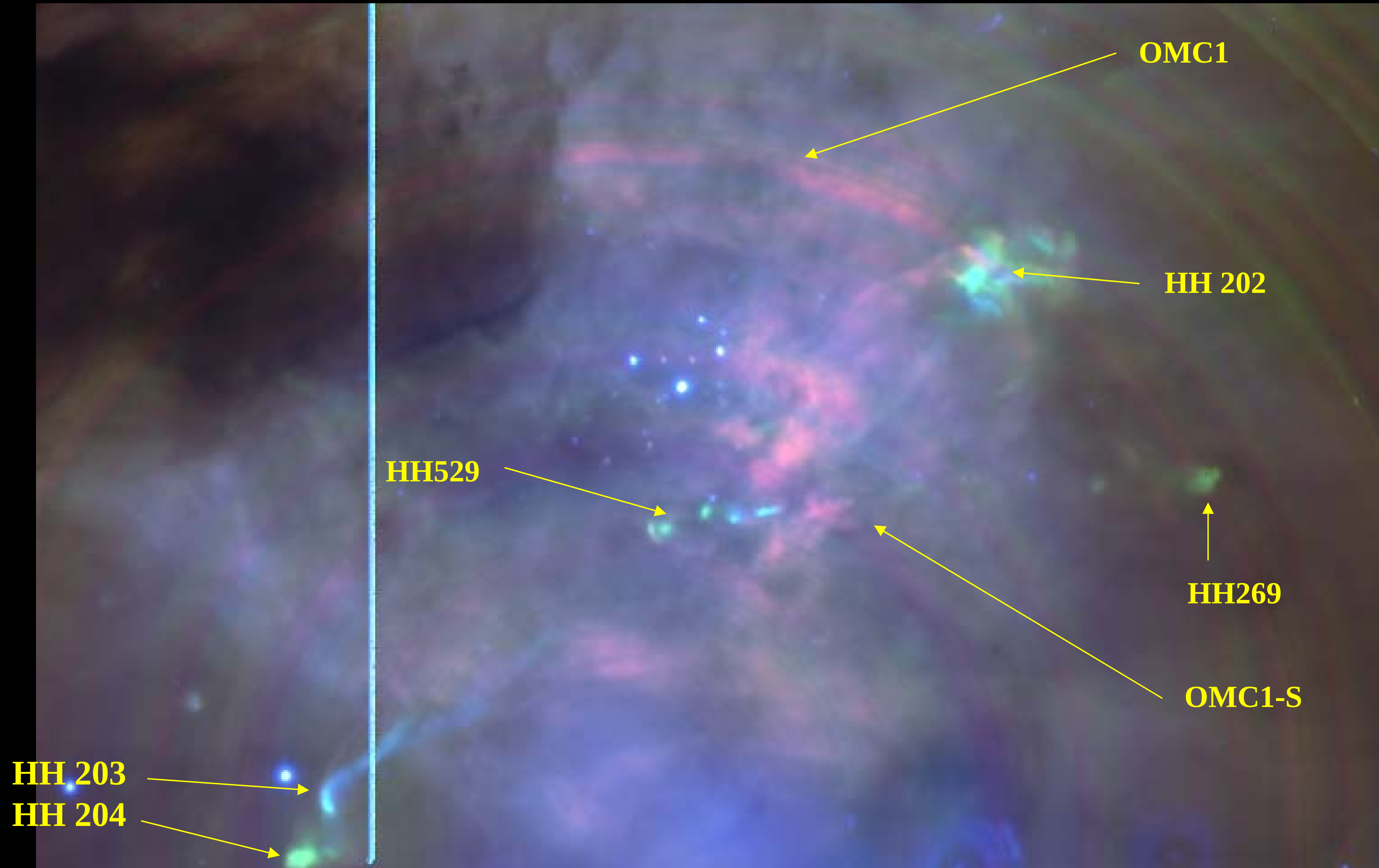






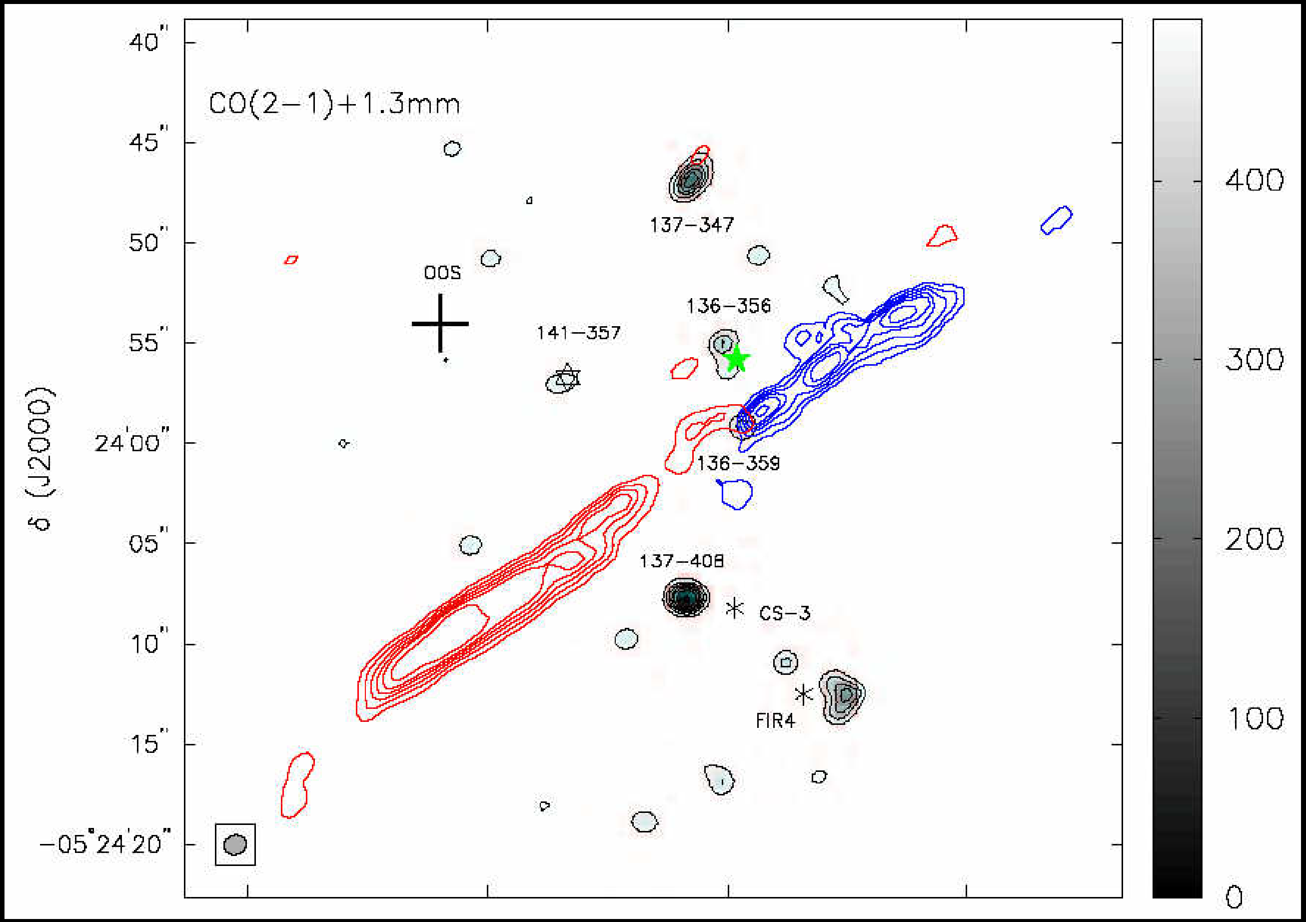

Orion Nebula
OMC1
HH 202
HH529
HH269
OMC1-S
HH 203
HH 204

Orion Nebula



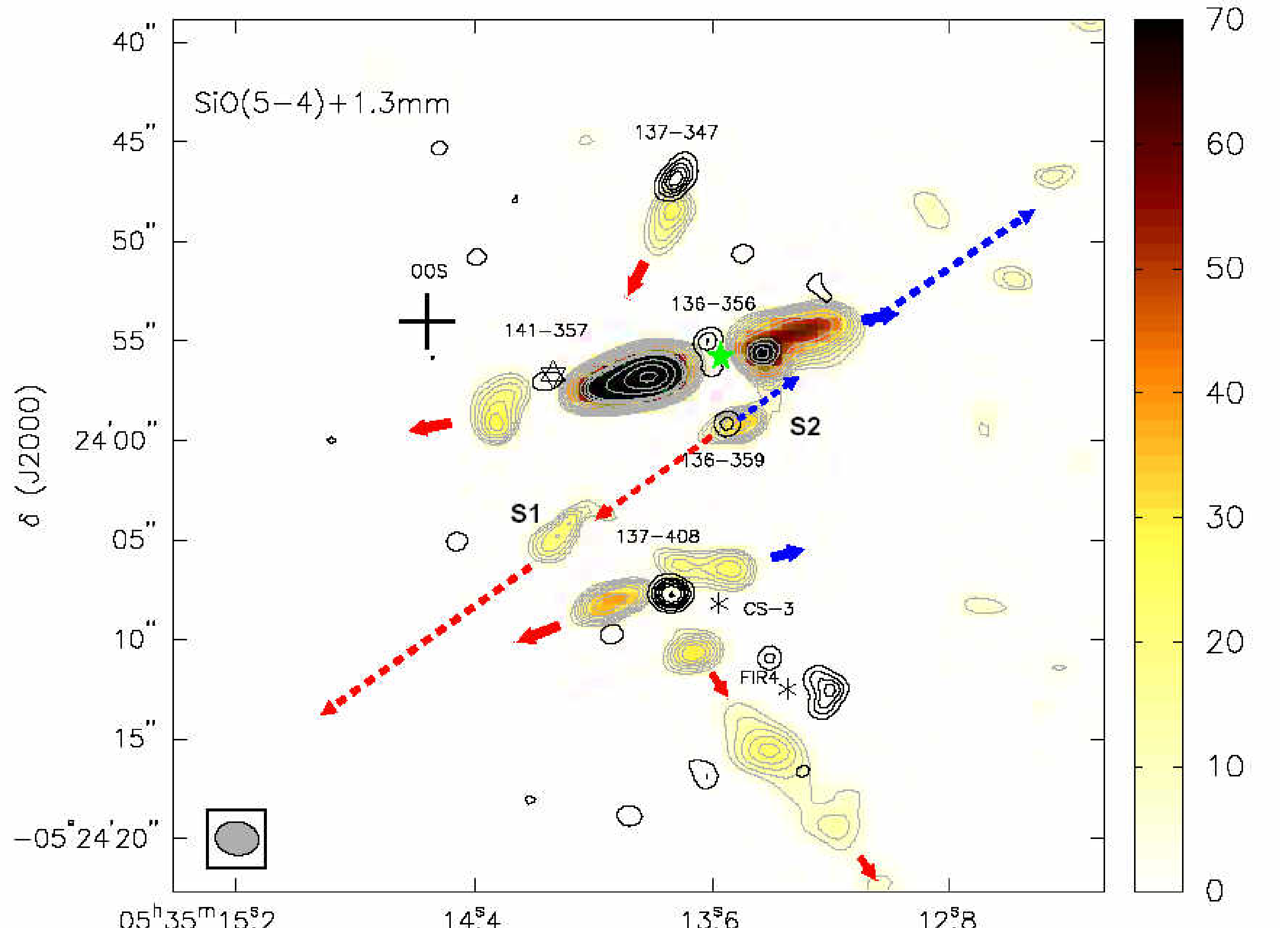
Zapata et al. (2005)

CO jets in OMC-1S

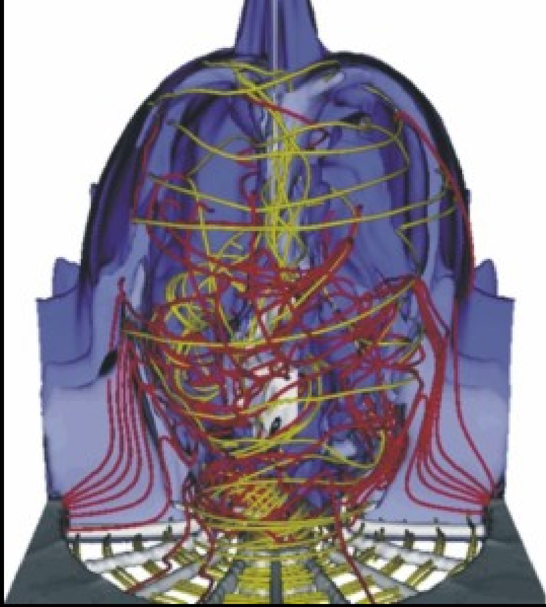


Zapata et al. (2006)

SiO Jets in OMC-1S



Acceleration & Collimation



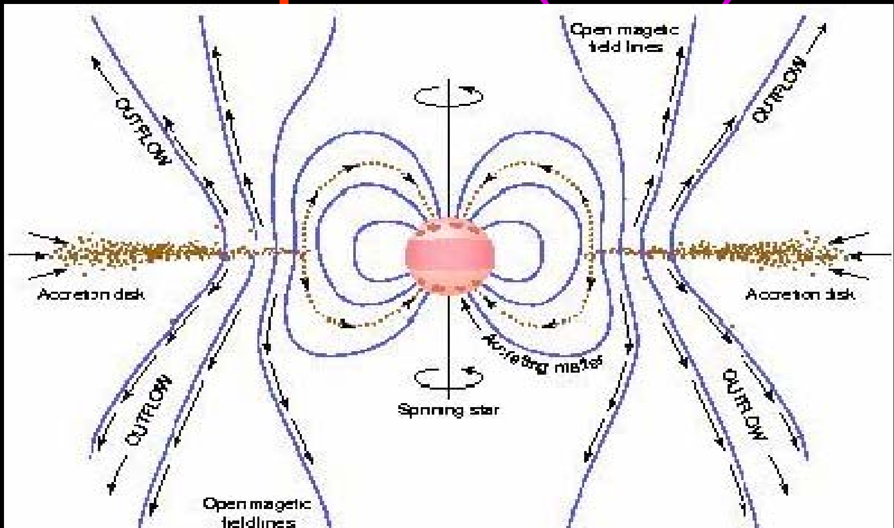
- dM /dt increases as $L^{0.8}$
- V increases as $L^{0.2}$

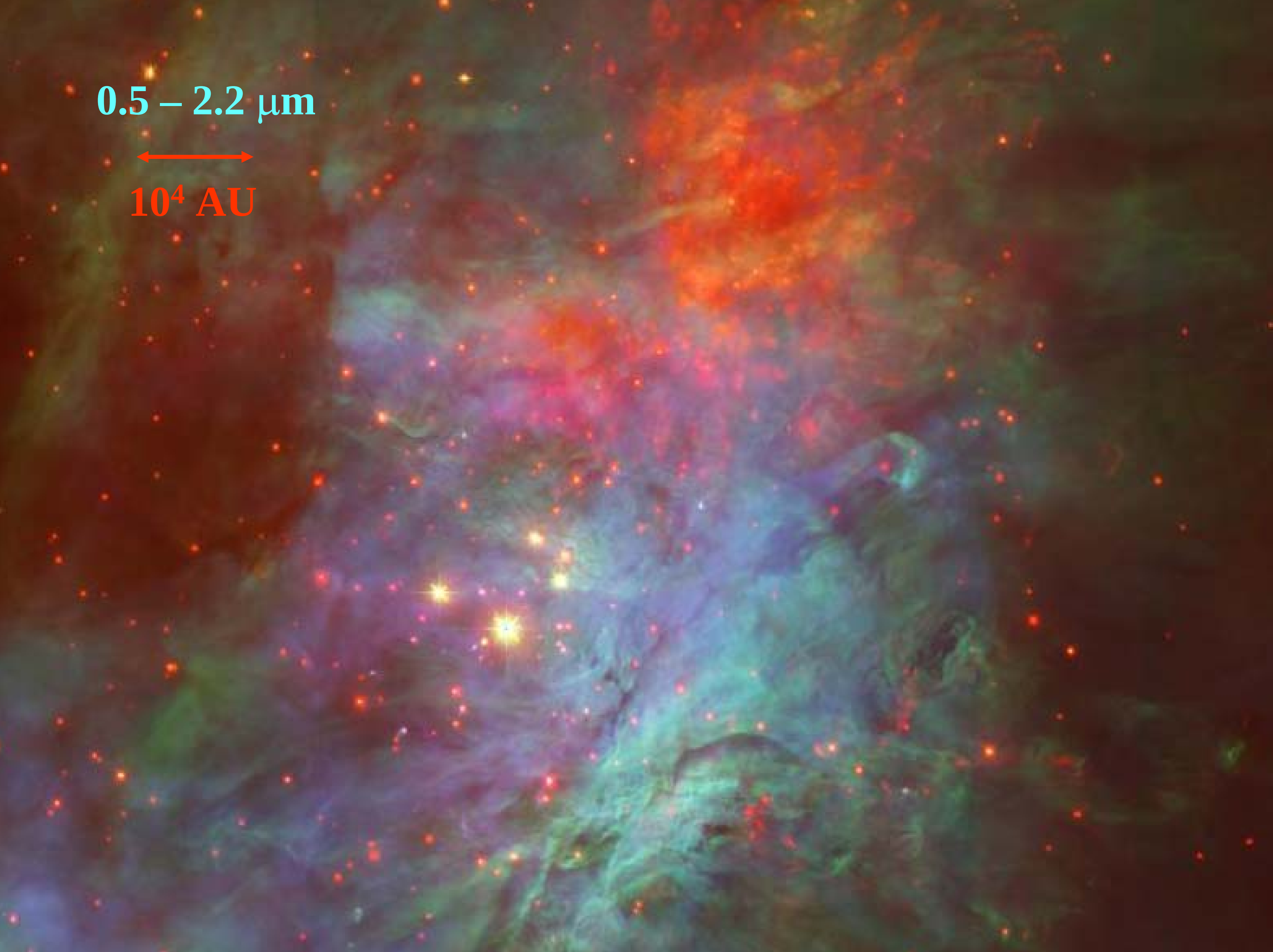
Acceleration Mechanisms:

- Radiation pressure ? NO - L/c too low
- Thermal pressure gradient? NO
- MHD YES!
  - Uchida-Shibata, Lovelace – helical torsion, impulsive
  - Pudritz-Norman disk wind - advected B, steady
  - Shu X-wind - stellar dynamo, steady
- Dynamical decay; release of gravitational potential (Orion)

Collimation:

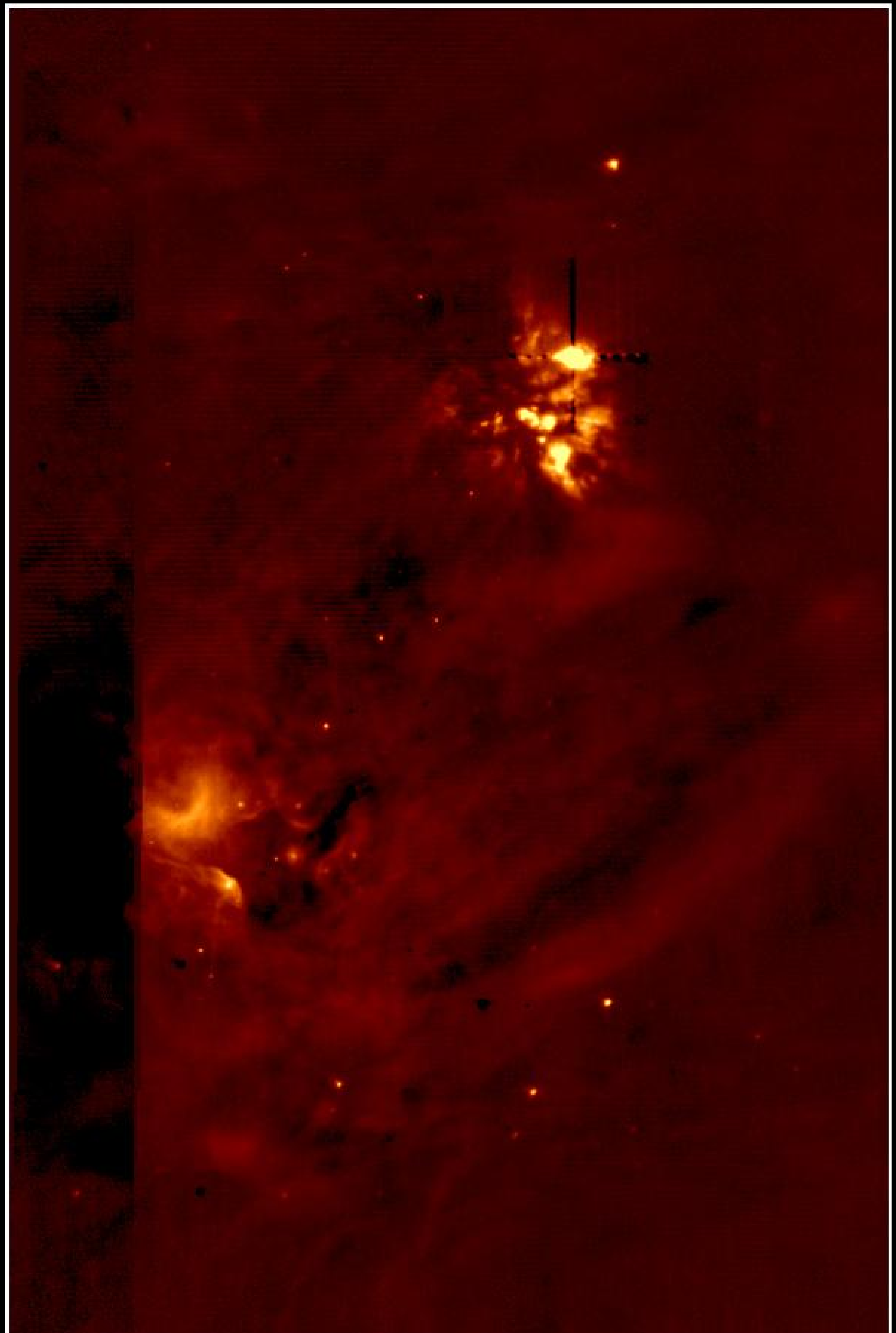
- Magnetic hoop stress
- Ambient density gradient
- Ram-pressure of infalling envelope




0.5 – 2.2 μm
10^4 AU

11.7 μm

10^4 AU



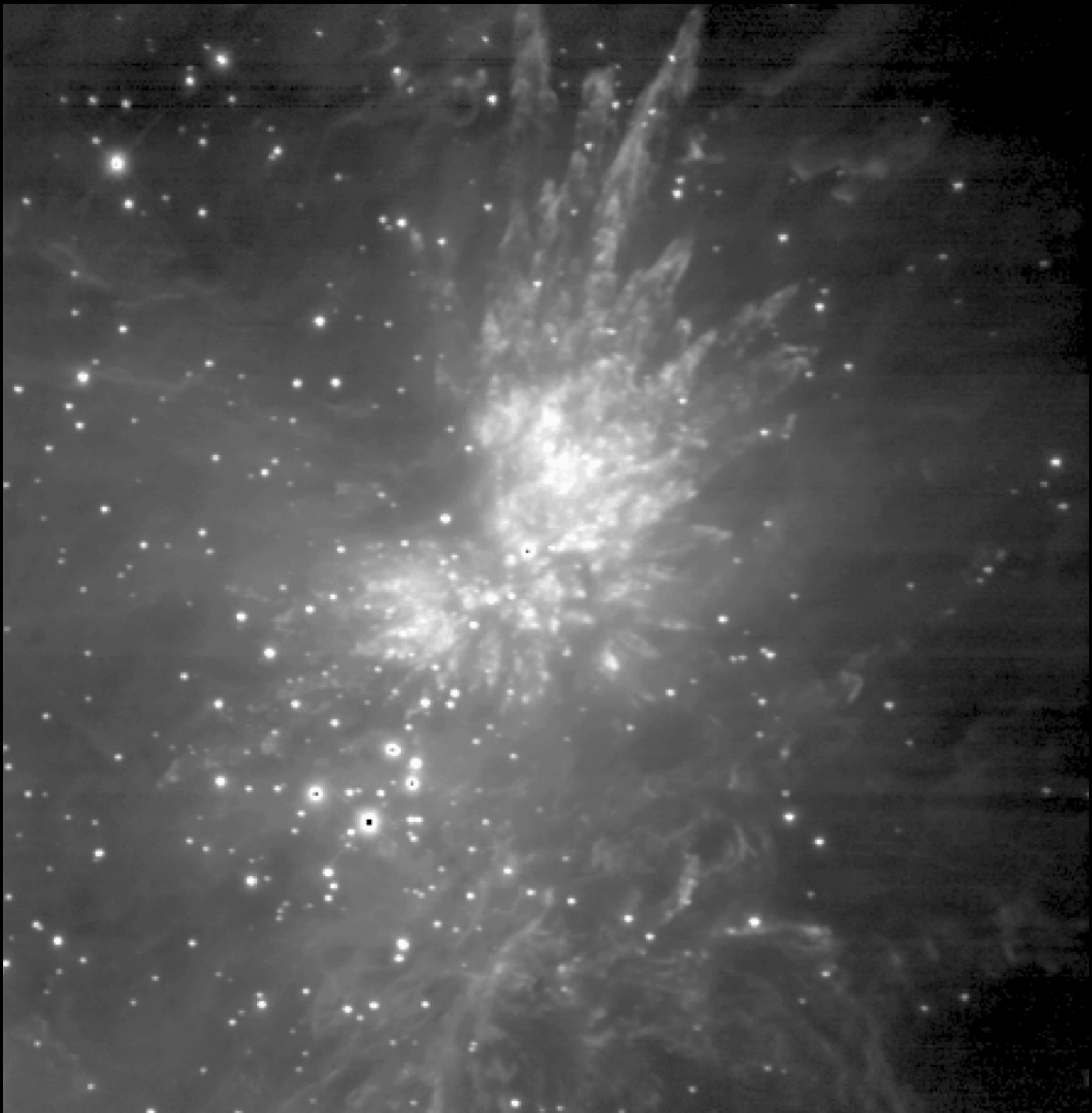
Orion
BN/KL
H_2 fingers

E ~ 10^{48} erg

Dynamical
Decay of
Sub-cluster of
massive stars

~ 500 years ago

(N. Cuningham
2006 PhD thesis)



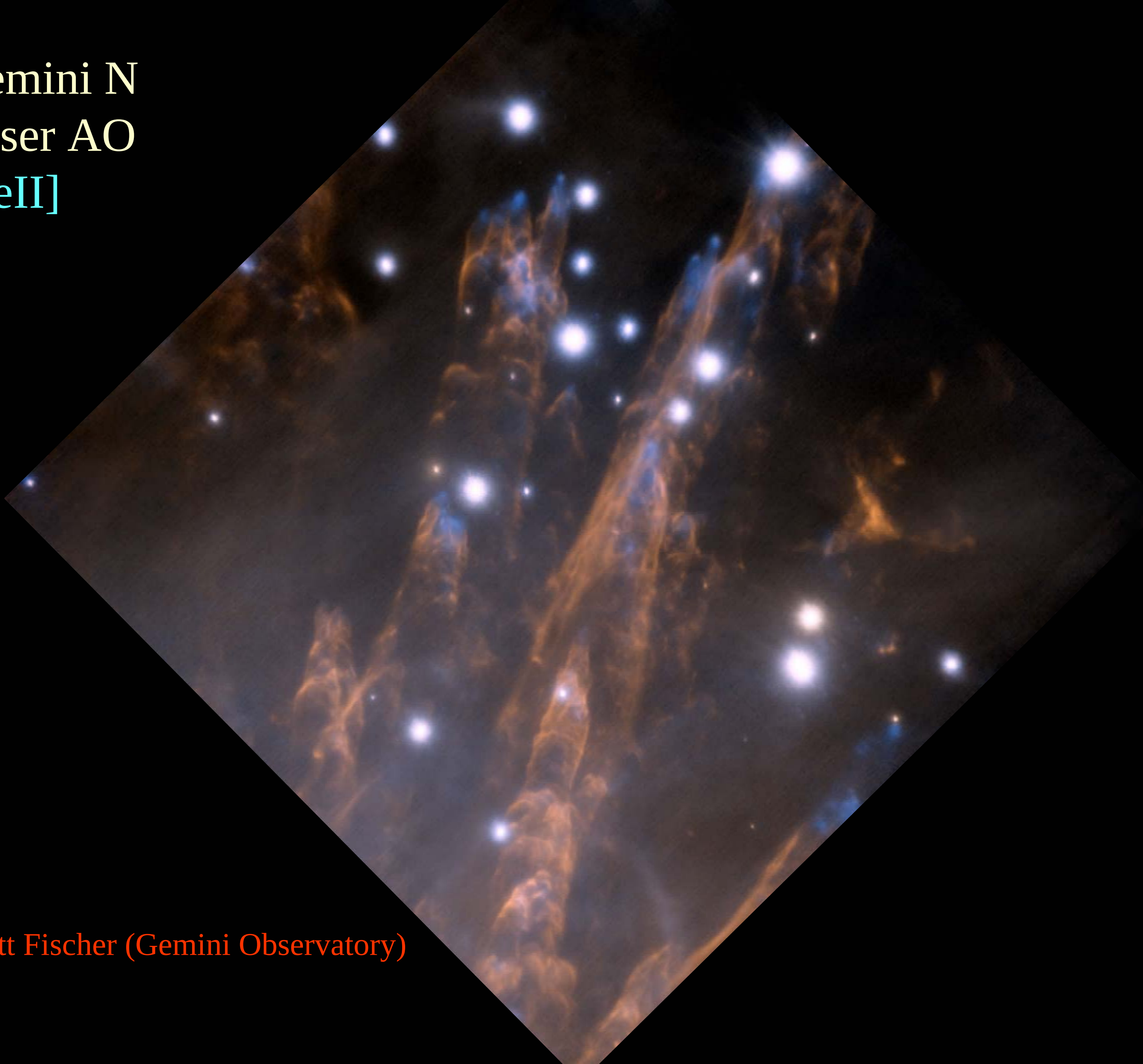
2.12 μm H_2 (blue)

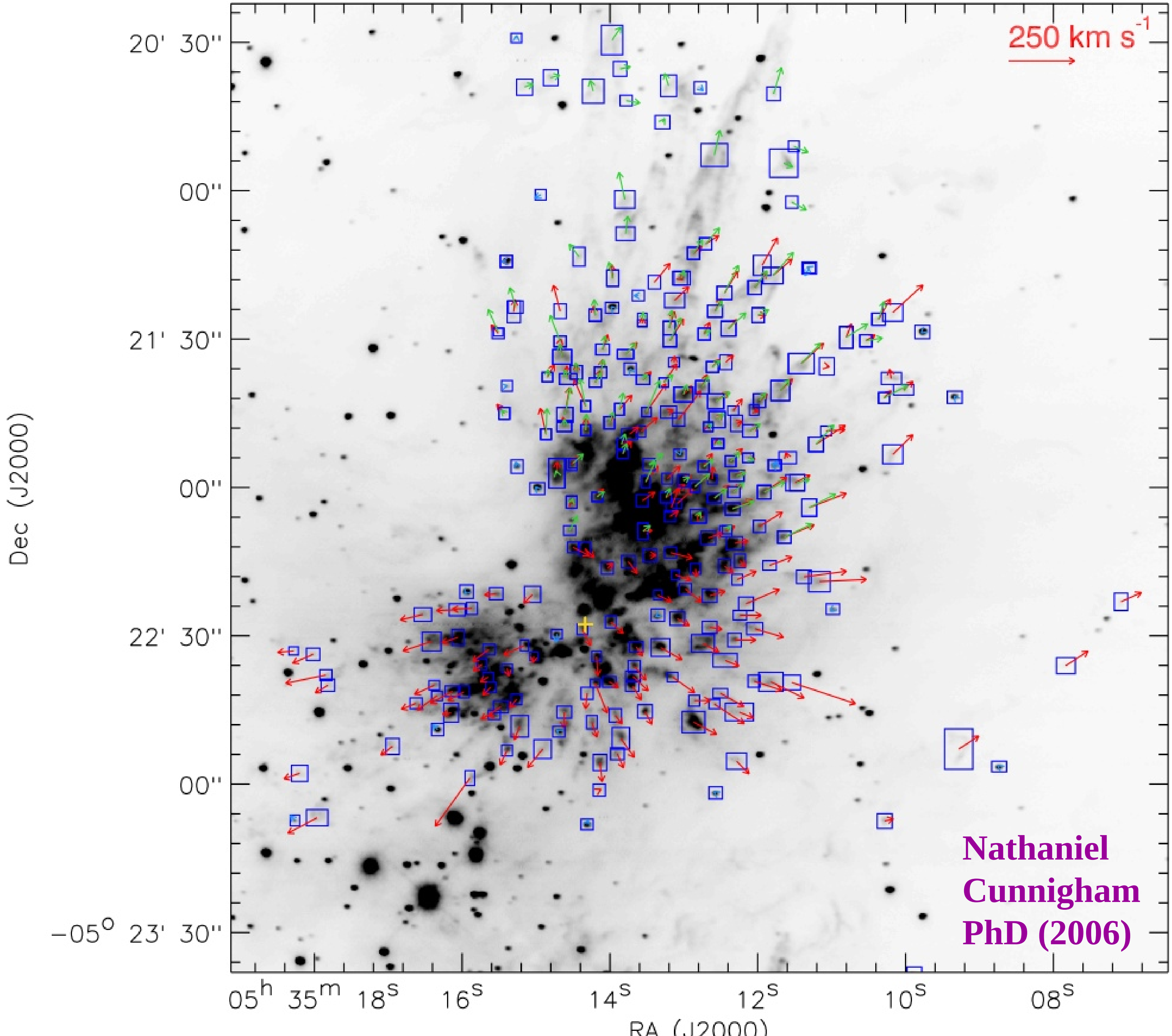
11.7 μm (orange)

Smith et al. (2005)

+

Cunningham (2008)


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



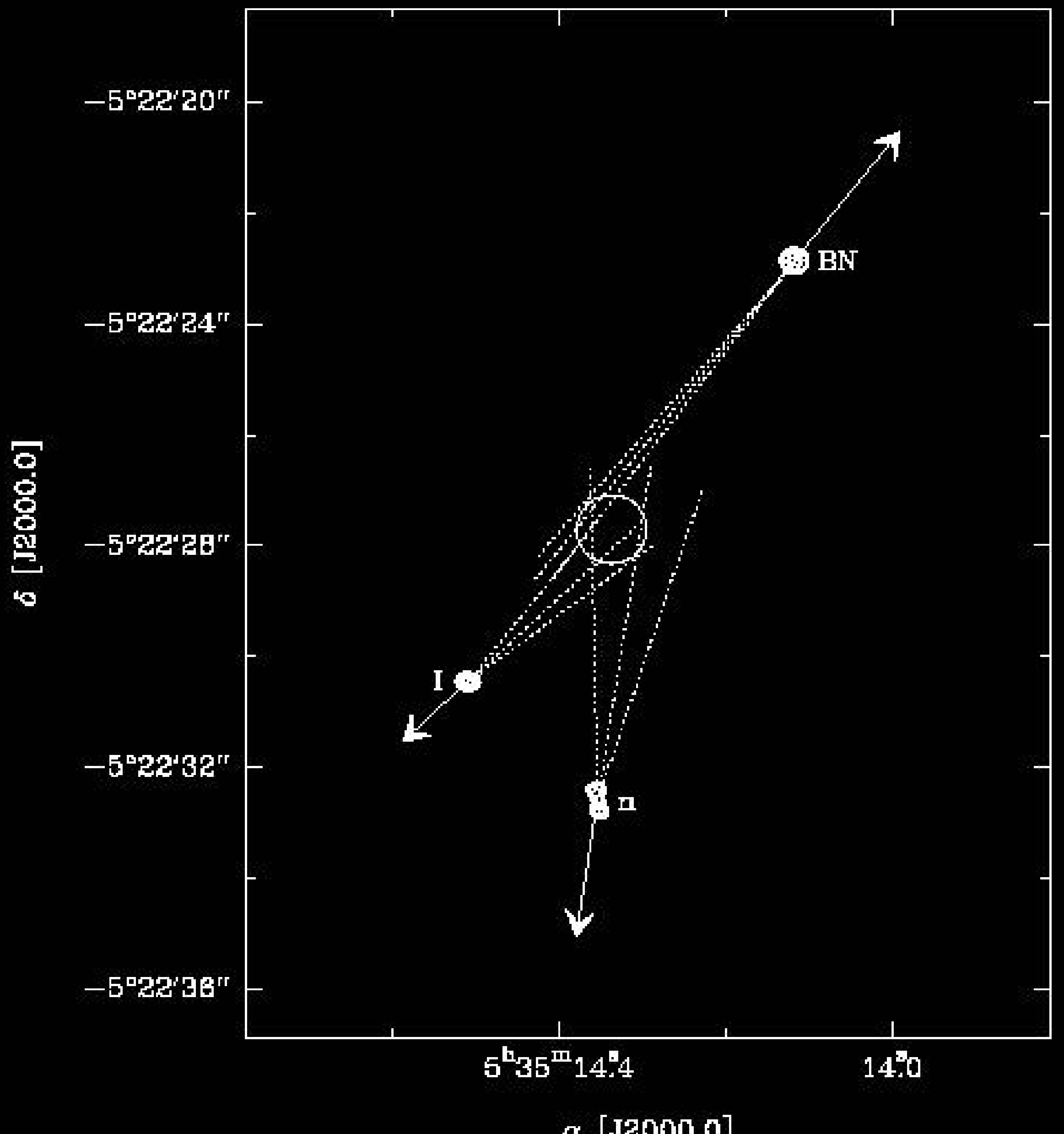
Nathaniel Cunnigham PhD (2006)

High-velocity stars: I , BN , n (Gomez et al. 05,08)

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

I:
~ 13 km s^{-1}

n:
~ 20 km s^{-1}



Cepheus A J, H, K_s

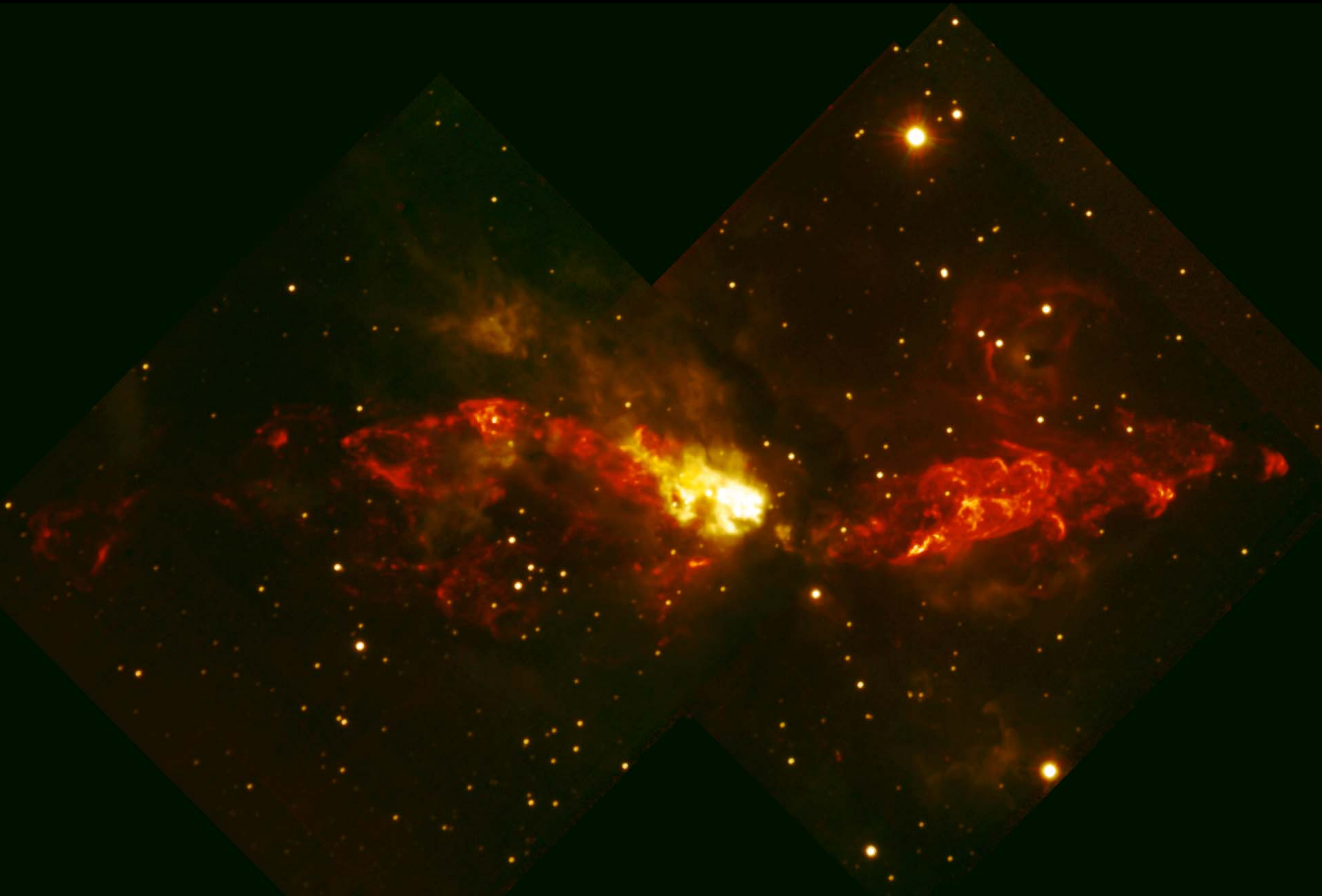
Cunningham, Moeckel, & Bally

Cepheus A: J, K_s, H_2

Cunningham, Moeckel, & Bally

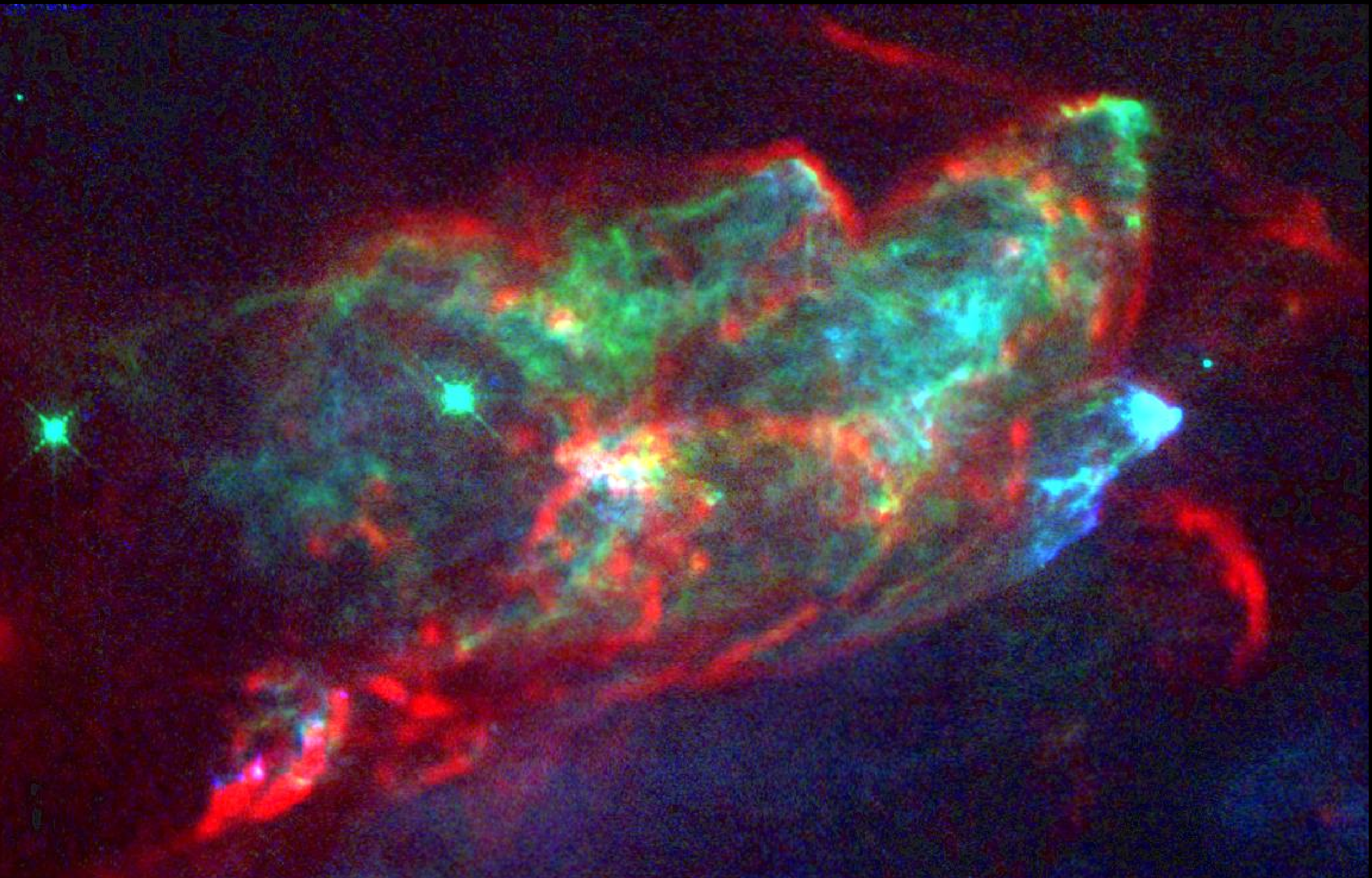
Cep A

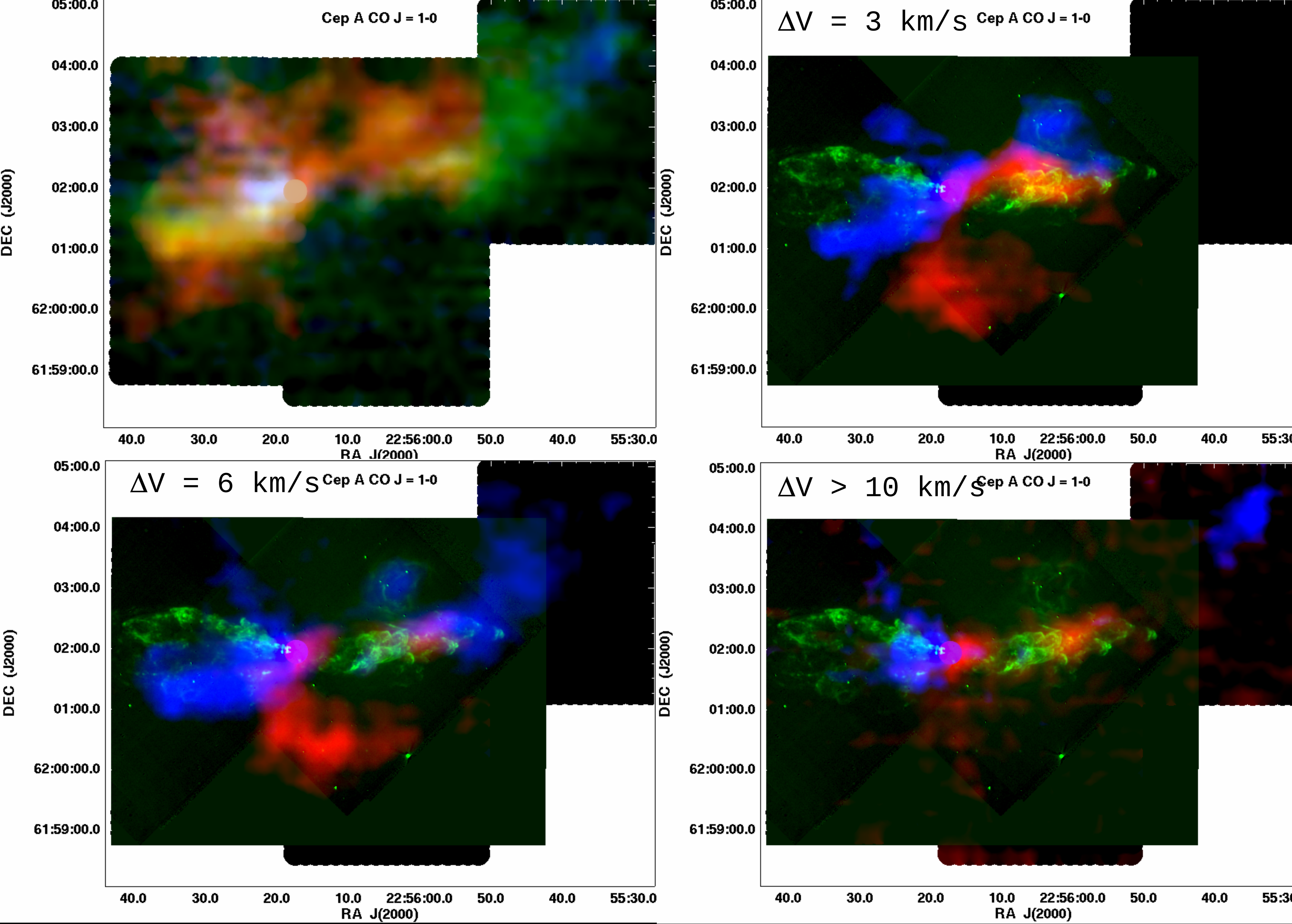
Cunningham, Moeckel, & Bally



Powerful outflows from luminous YSOs

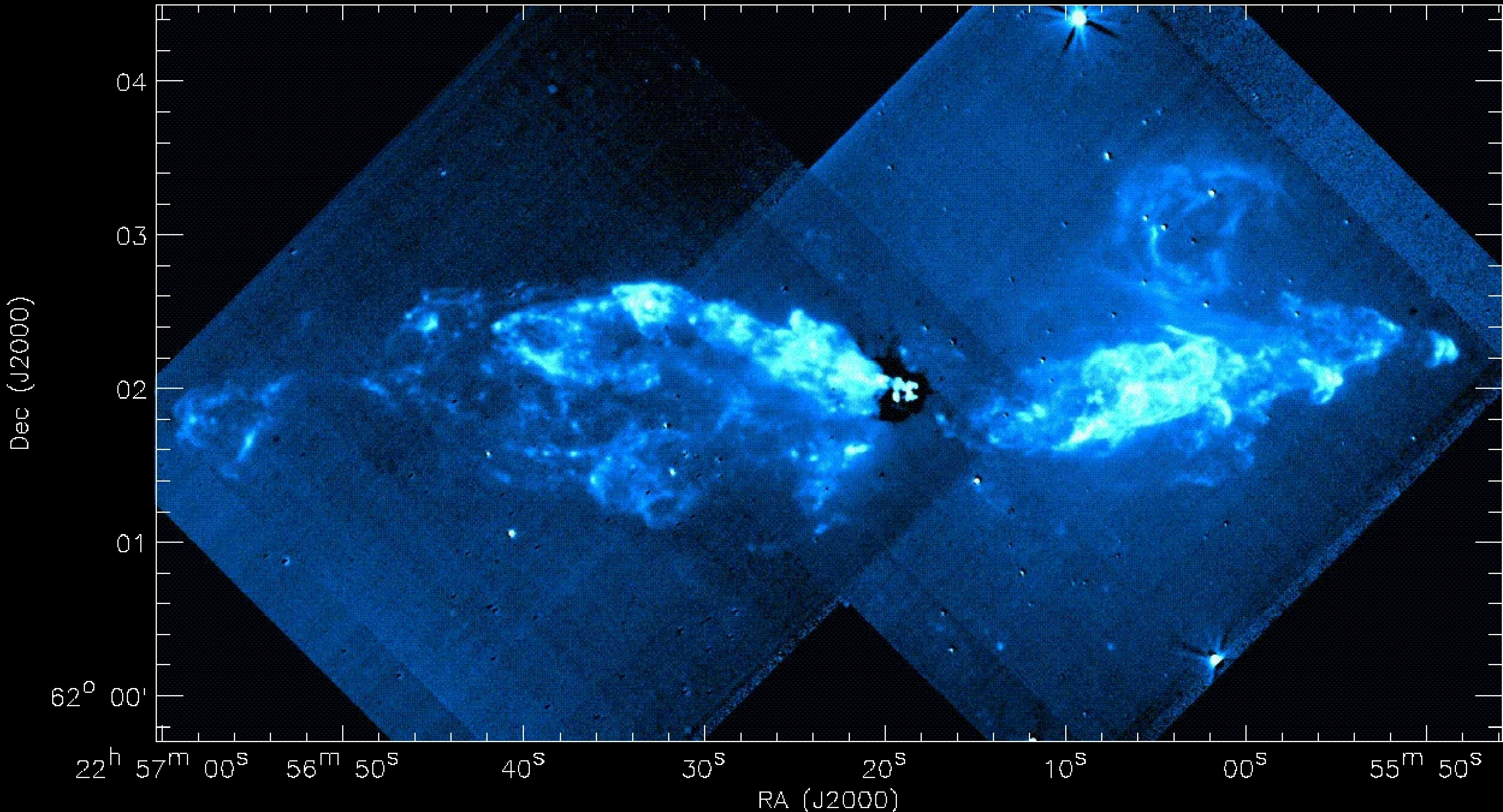
Cepheus A: Ha [S II] H2



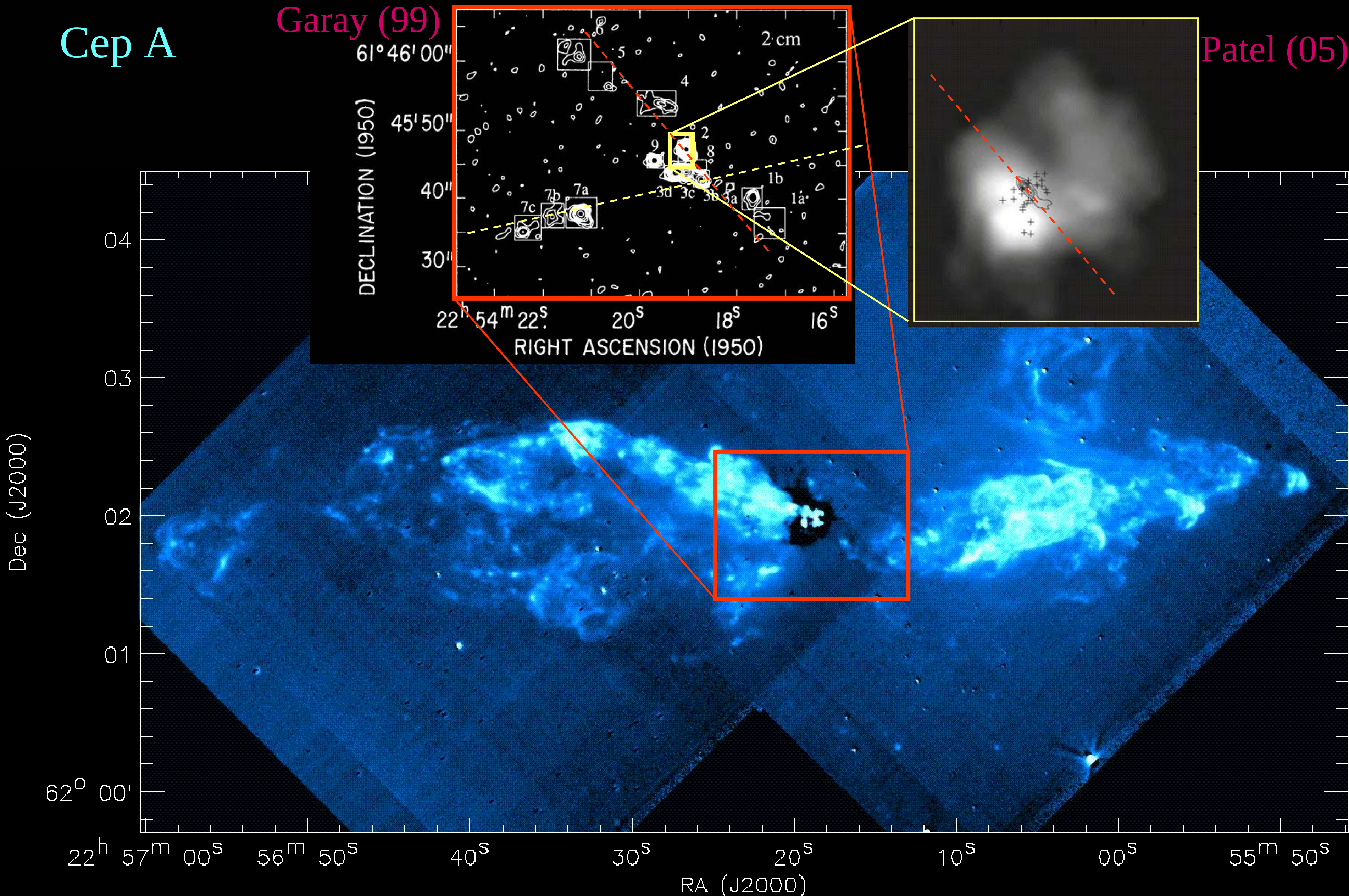

Cep A CO J = 1-0
ΔV = 3 km/s
Cep A CO J = 1-0
ΔV = 6 km/s
Cep A CO J = 1-0
ΔV > 10 km/s
Cep A CO J = 1-0
DEC (J2000)
RA J(2000)
05:00.0
04:00.0
03:00.0
02:00.0
01:00.0
62:00:00.0
61:59:00.0
40.0
30.0
20.0
10.0
22:56:00.0
50.0
40.0
55:30.0

Ceph A

Cunningham, Moeckel, & Bally

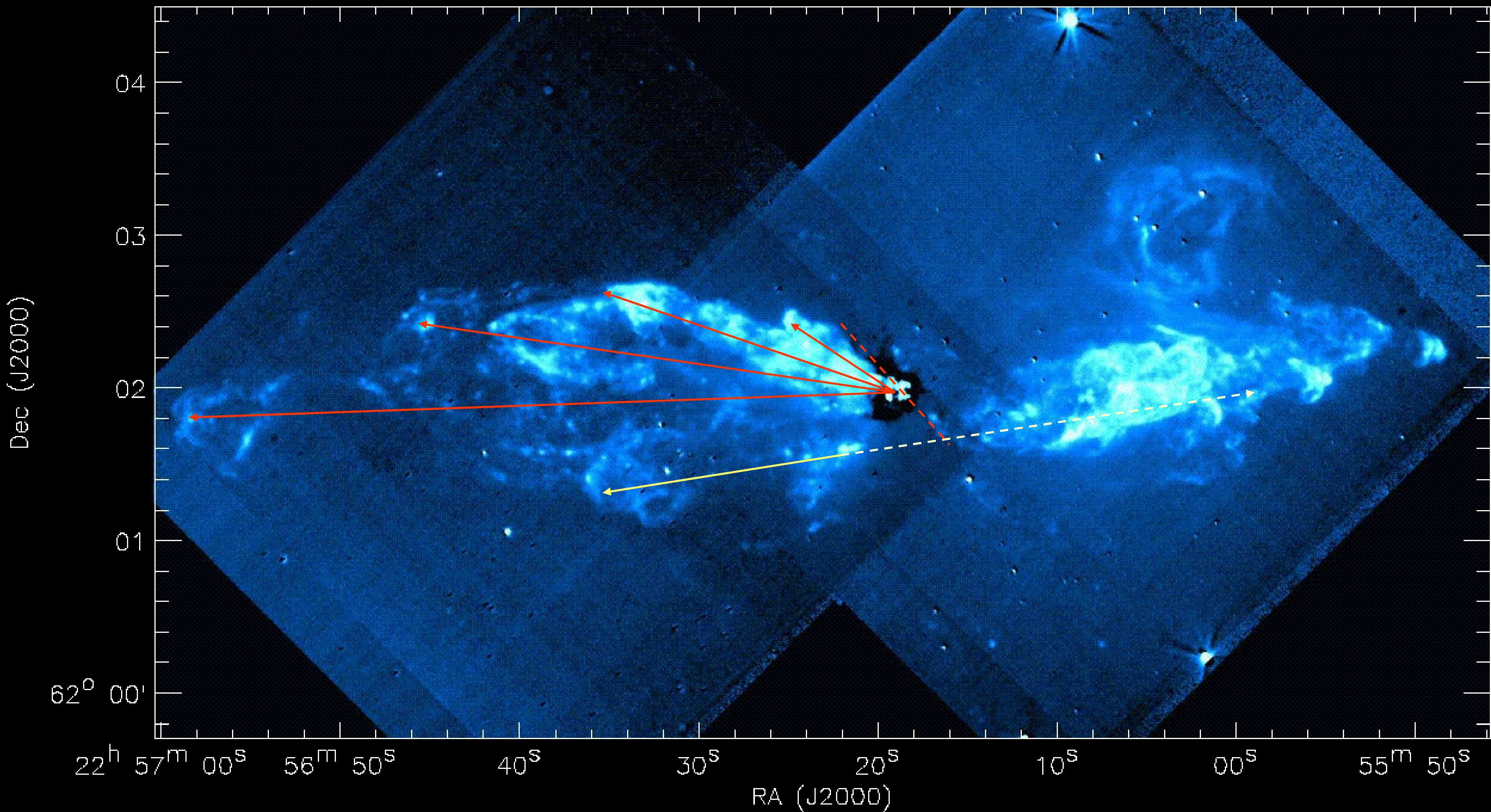


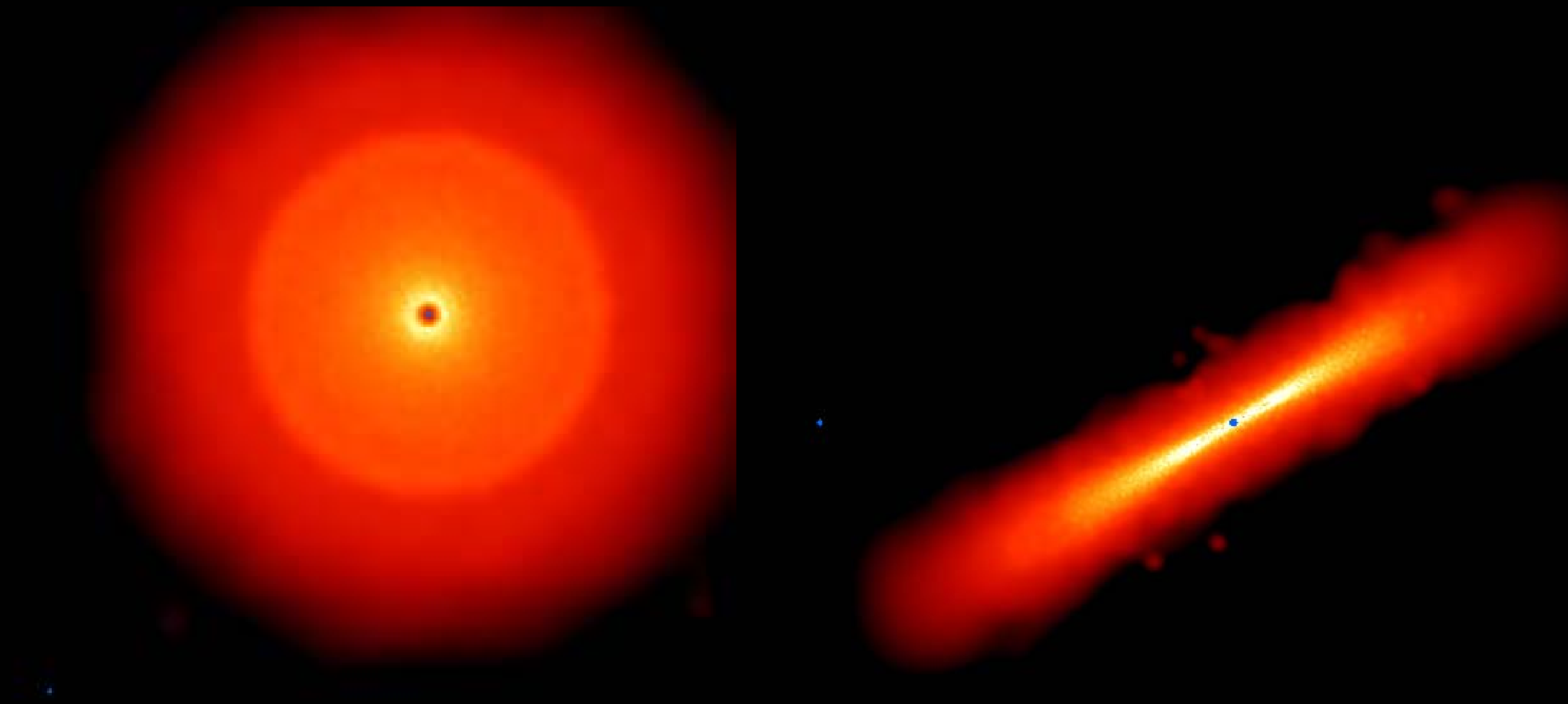
Cep A



Cunningham, Moeckel, & Bally

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





Nickolas Moeckel (2006) SPH:
Massive star capture-formed binary: Disk orientation change

What Next ?

- Calorimetry
  - Mass, energy, momentum in flows

    Sub-mm, mm, FIR spectroscopy / mapping ALMA, SOFIA
- Which Launch & Collimation Mechanism dominates?
  - Disk winds? X-winds? Magnetic towers ? Other ?
  - Hoop stress ? Ram P?

    LGS + AO on 8 - 40 meter telescopes Gemini, VLT, VLT-I, ELTs
- Measure & Map Magnetic Fields

  Polarimetry, Zeeman integral field spectroscopy
- Angular Momentum & Vorticity Transport
  - Do Jets Rotate ?

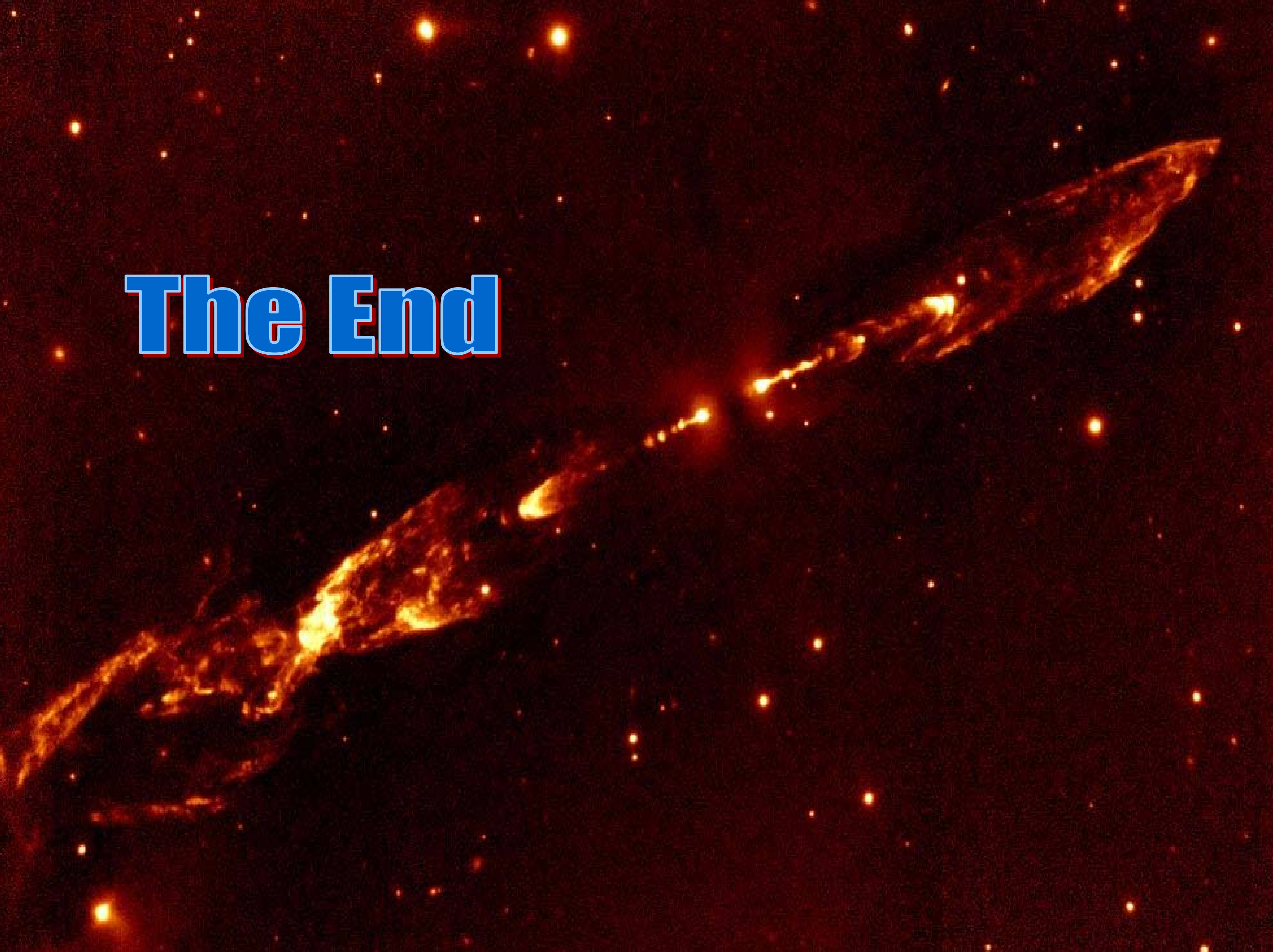
    1 to 100 mas resolution; interferometry
- Impacts on ISM & Feedback

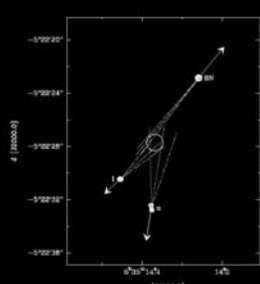
  Spectroscopy 1 to 1,000 μm Herschel, SOFIA, JWST
- High dynamic range numerical MHD simulations

  Supercomputing

Conclusions :

- Jets + wide angle winds
  - Turbulence generation / cloud disruption
  - Ionization / cloud chemical rejuvenation
- MHD launch /collimation?
  - Repetitive accretion events & Uchida-Shibata bursts
  - Advected B / disk winds
  - Dynamo generated B / X-winds
- Jet symmetries:
  - C-shaped, S-shaped, Z-shaped
  - Dynamical interactions
- Variability
  - dM/dt
  - V
  - Orientation
  - Degree of collimation

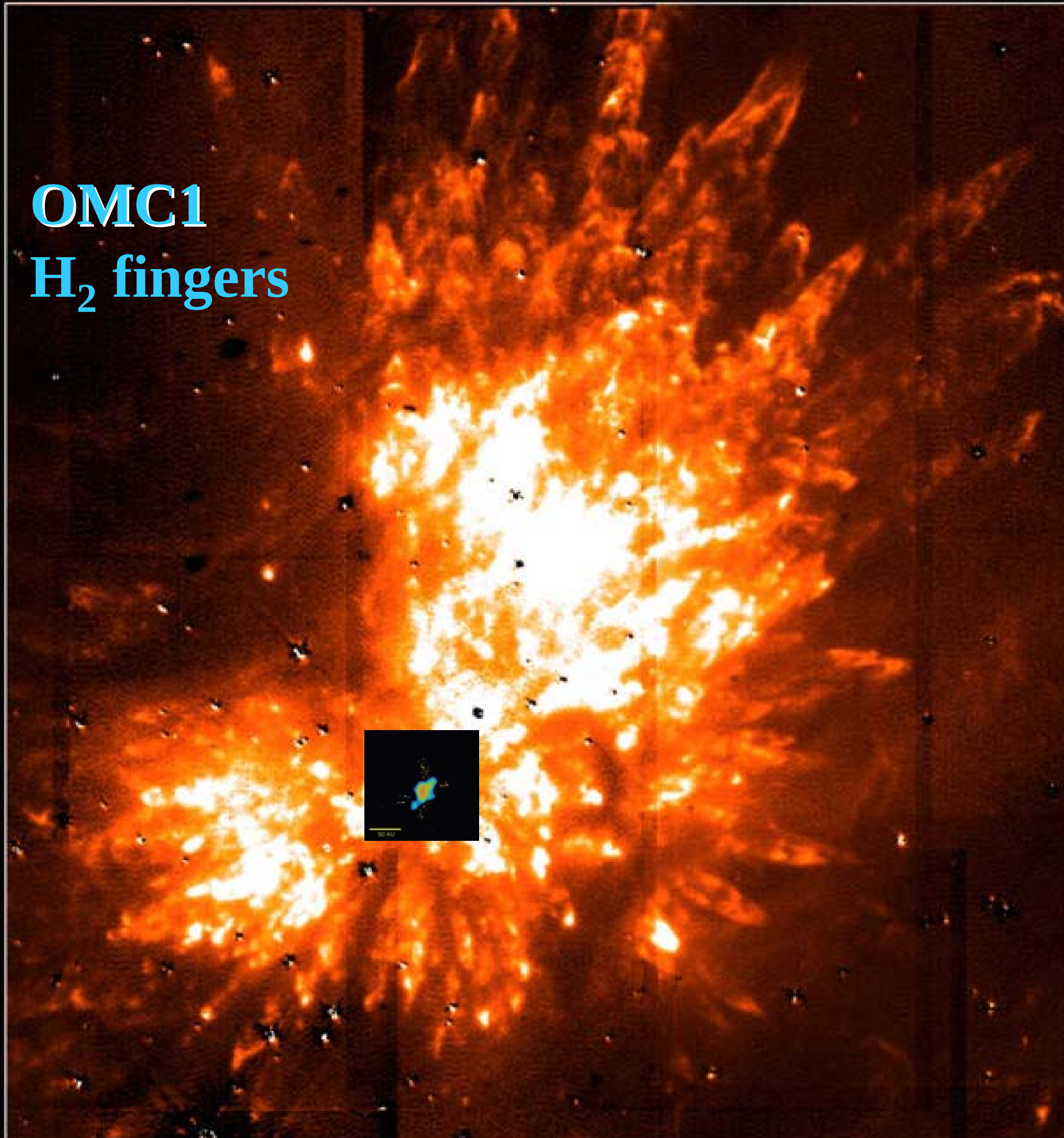

The End



BN
I
n
−5°22′20″
−5°22′24″
−5°22′28″
−5°22′32″
−5°22′36″
δ [J2000.0]
6h35m14.4s
14.0s
α [J2000.0]

Flow Properties

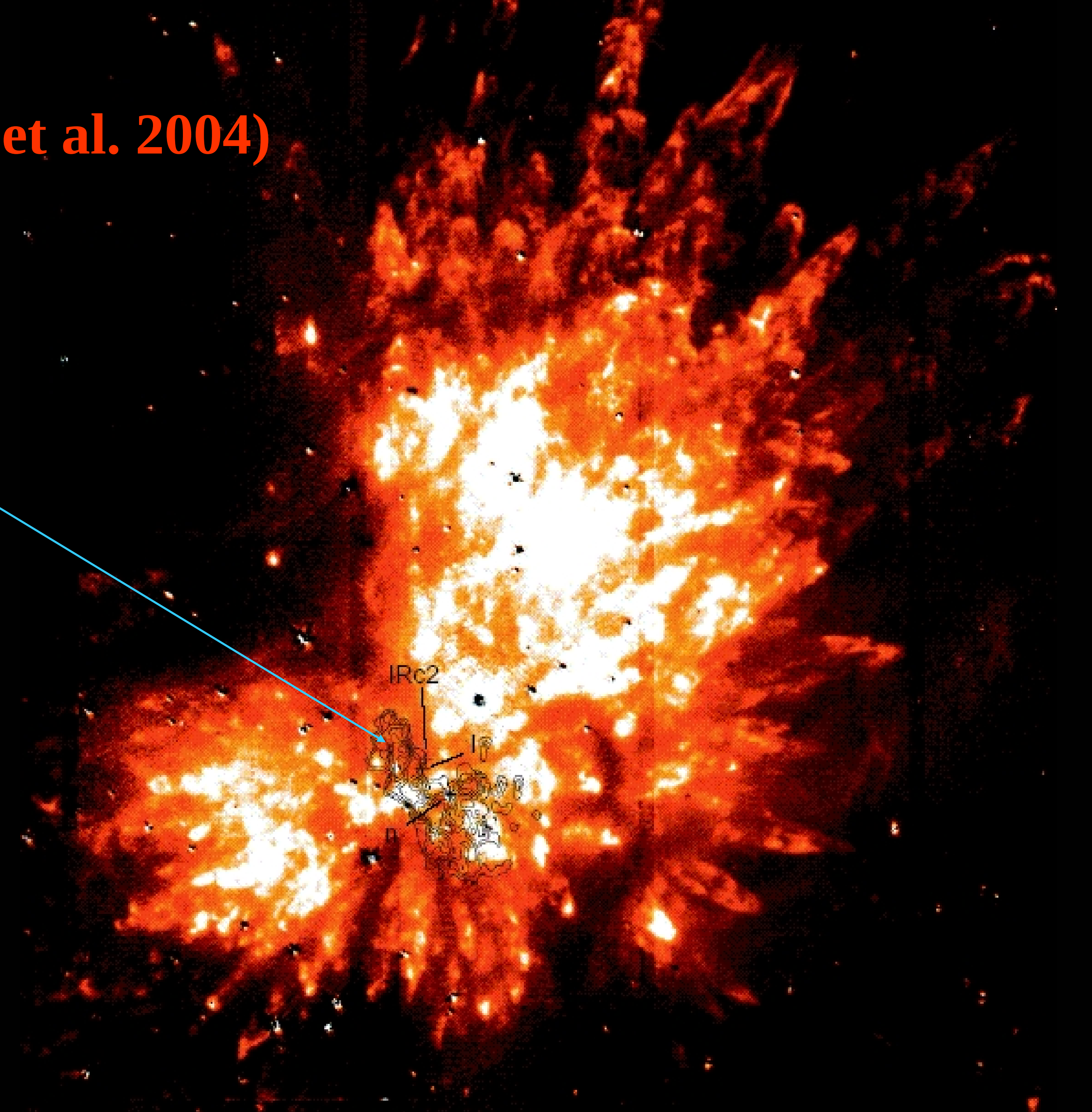
Parameter	(M<5 Solar)	(M>5 Solar)	unit
• Wind/jet velocity	100 - 1,000	100 - 1,000	km/s
• dM/dt	10^{-5} to 10^{-9}	10^{-5} to 10^{-2}	$M_o\ yr^{-1}$
• $M(H_2)$	0.001 to 10	1 to 3,000	M_o
• τ	10^4 (Class 0) 10^5 (Class I) 10^6 (>Class II)	10^4 to 10^5	yr yr yr
• Size:	1 to 10	1 to 20	pc
• E	10^{43} to 10^{47}	10^{46} to 10^{50}	erg
• L_{mech}	10^{-0} to 10^{-3}	10^{-1} to 10^3	L_o



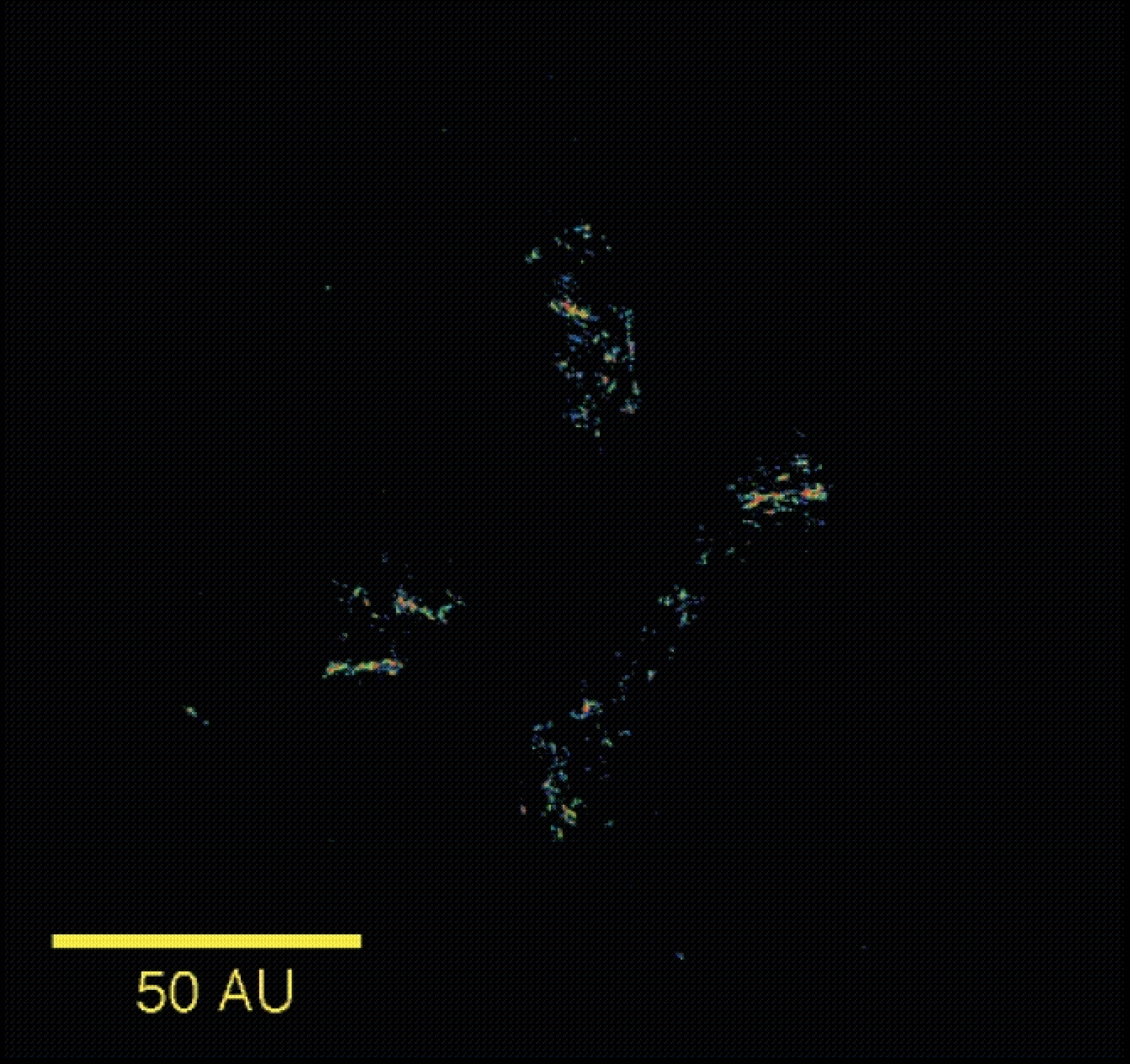
Kaifu et al. (00); Underhill et a
(01)

OMC1
(Shuping et al. 2004)

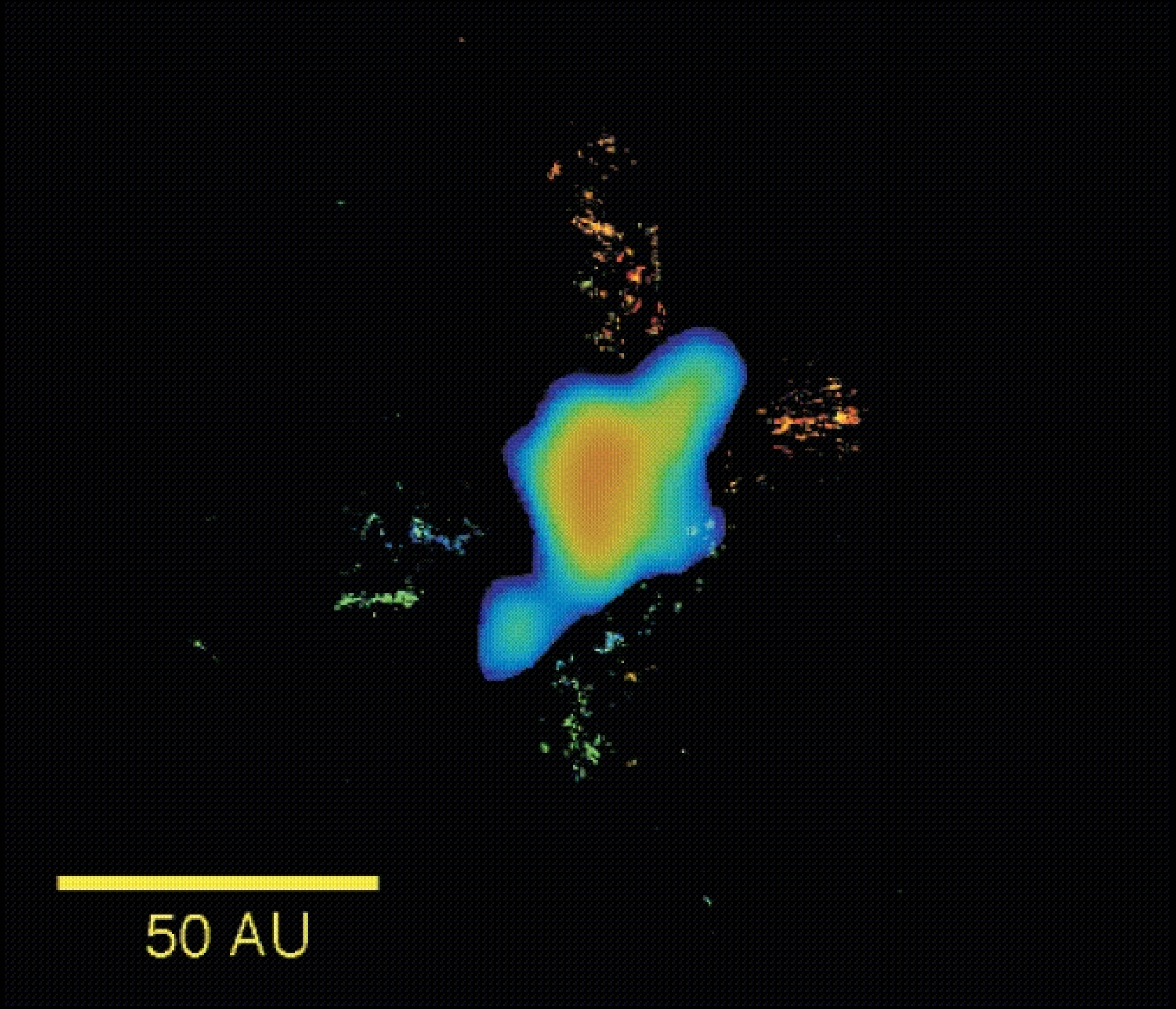
NH_3



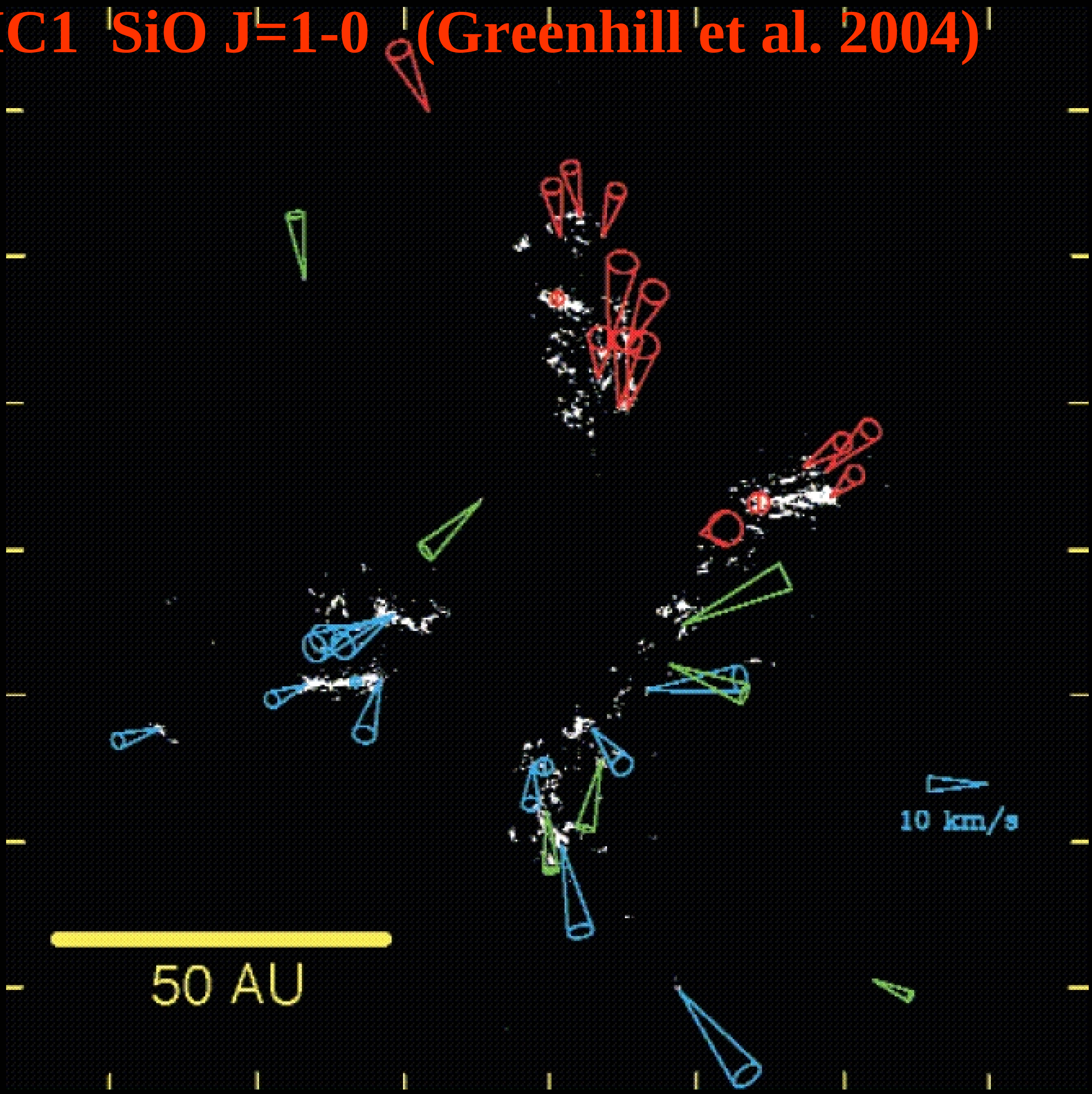
OMC1 SiO J=1-0 (Greenhill et al. 2004)



OMC1 SiO J=1-0 & 7mm continuum (Greenhill et al. 2004)

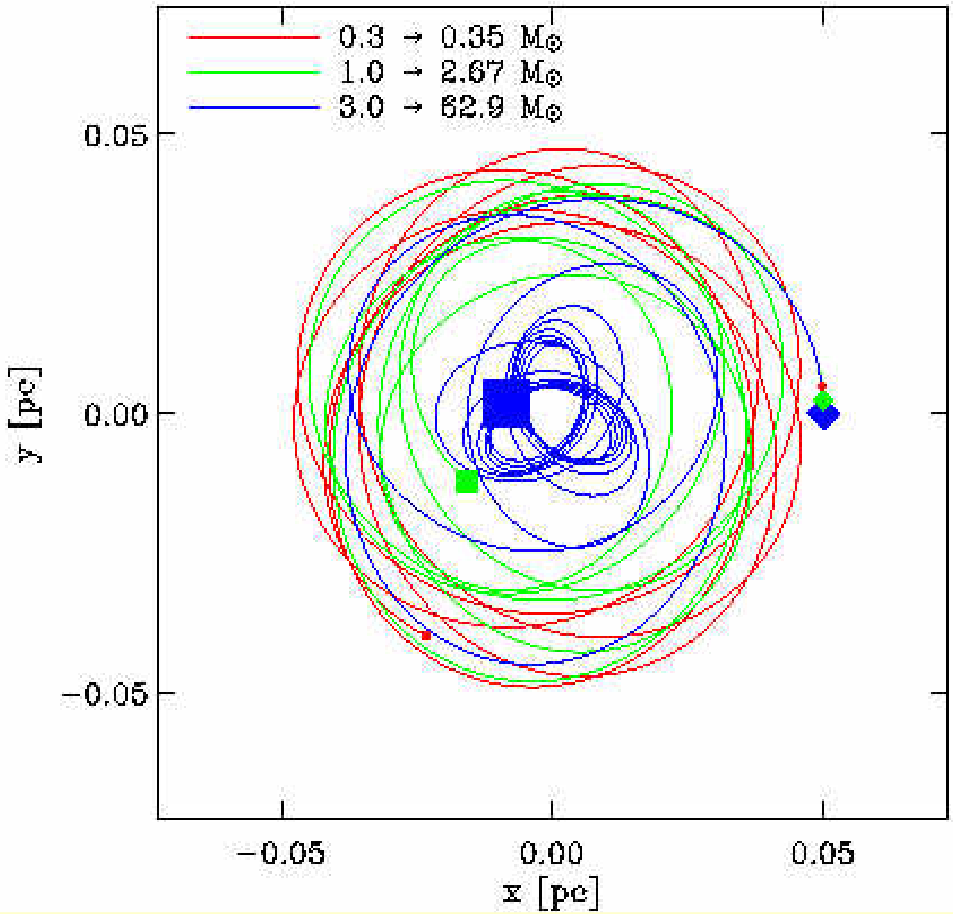


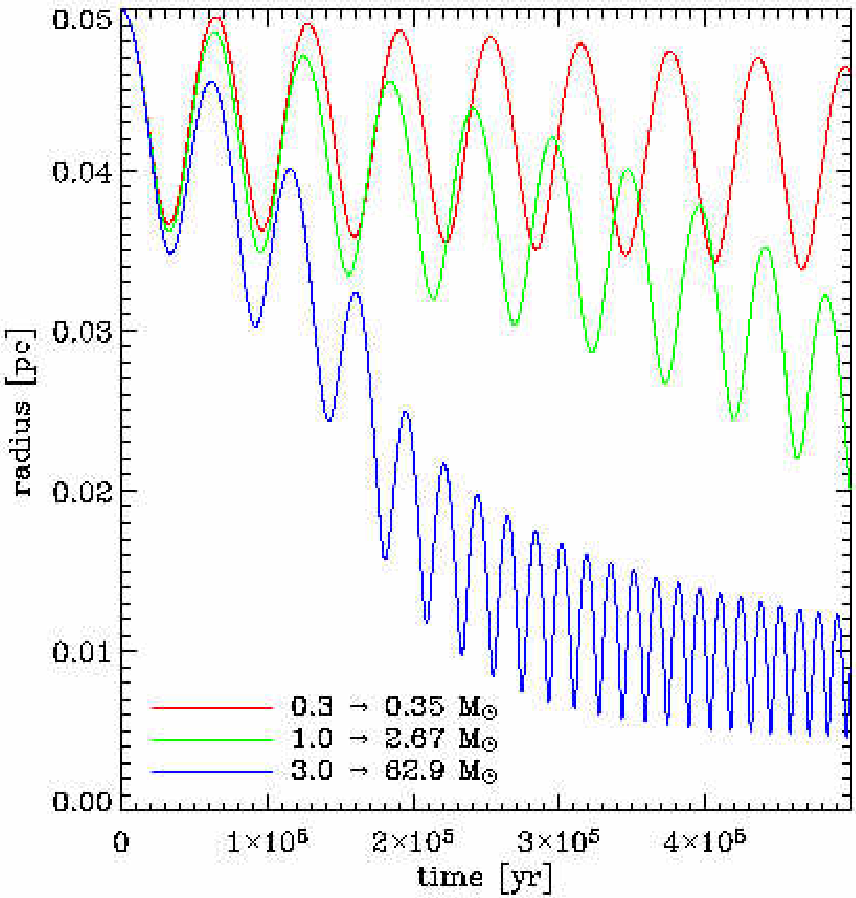
OMC1 SiO J=1-0 (Greenhill et al. 2004)



Orbit Decay:

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





Nick Moeckel PhD Thesis (CU Boulder, in preparation)