Feedback: The Local Truth

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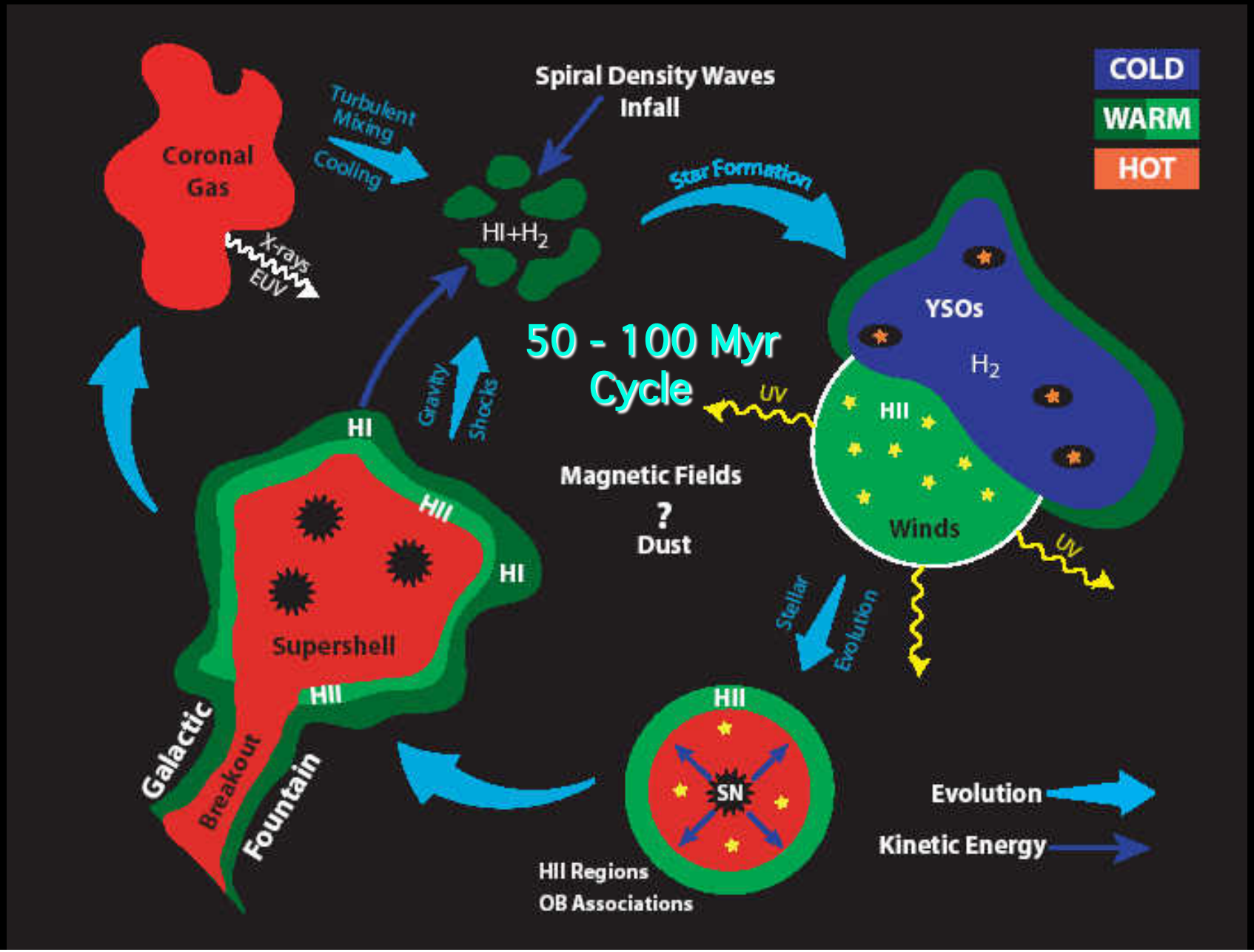
Galactic Ecology: Star Formation & the Interstellar Medium



Conclusions

Self-Regulation in Star Formation

What stops accretion & determines the IMF?

Feedback + N-body dynamics

The "Feedback Ladder"

Progression of ever stronger feedback impacts

Protostar Outflows =>
FUV/heating =>
EUV/ionization =>
Stellar winds =>
Radiation pressure =>
M.S. dynamic interactions / mergers =>
Post-M.S. outflows =>
SNe

local, low M_*

global, high M_*

Feedback failure => High SFE & bound clusters?

The Feedback Ladder

Energy & Momentum injection is multi-scale !

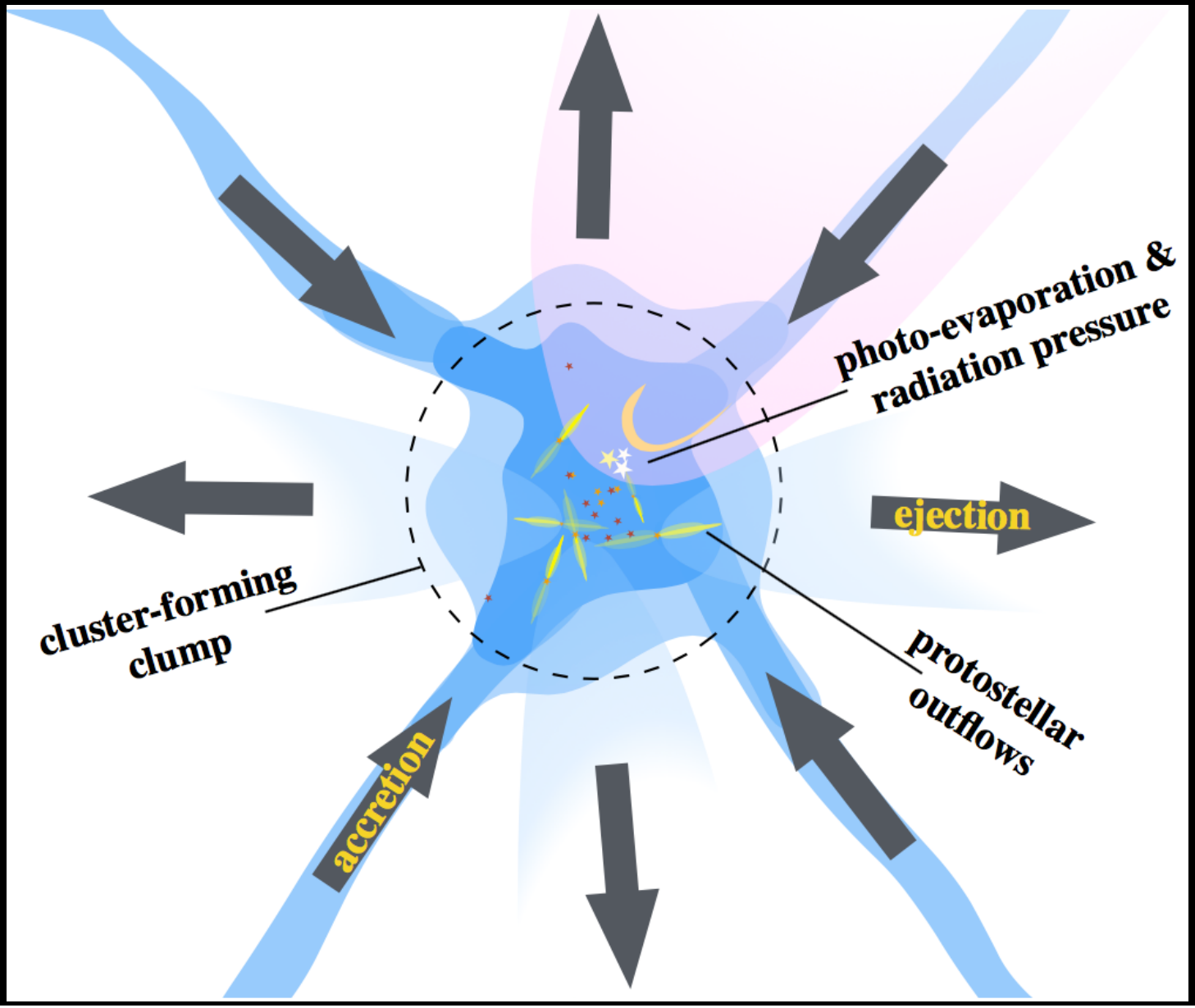
- Jets/outflows < ~3 M_o & earliest phases of massive stars
  E = 10^{41-48} erg M ~ 0.01 - 100 M_o N~ 10^5
  V ~ 10 - 10^3 km/s t ~ 0.1 Myr

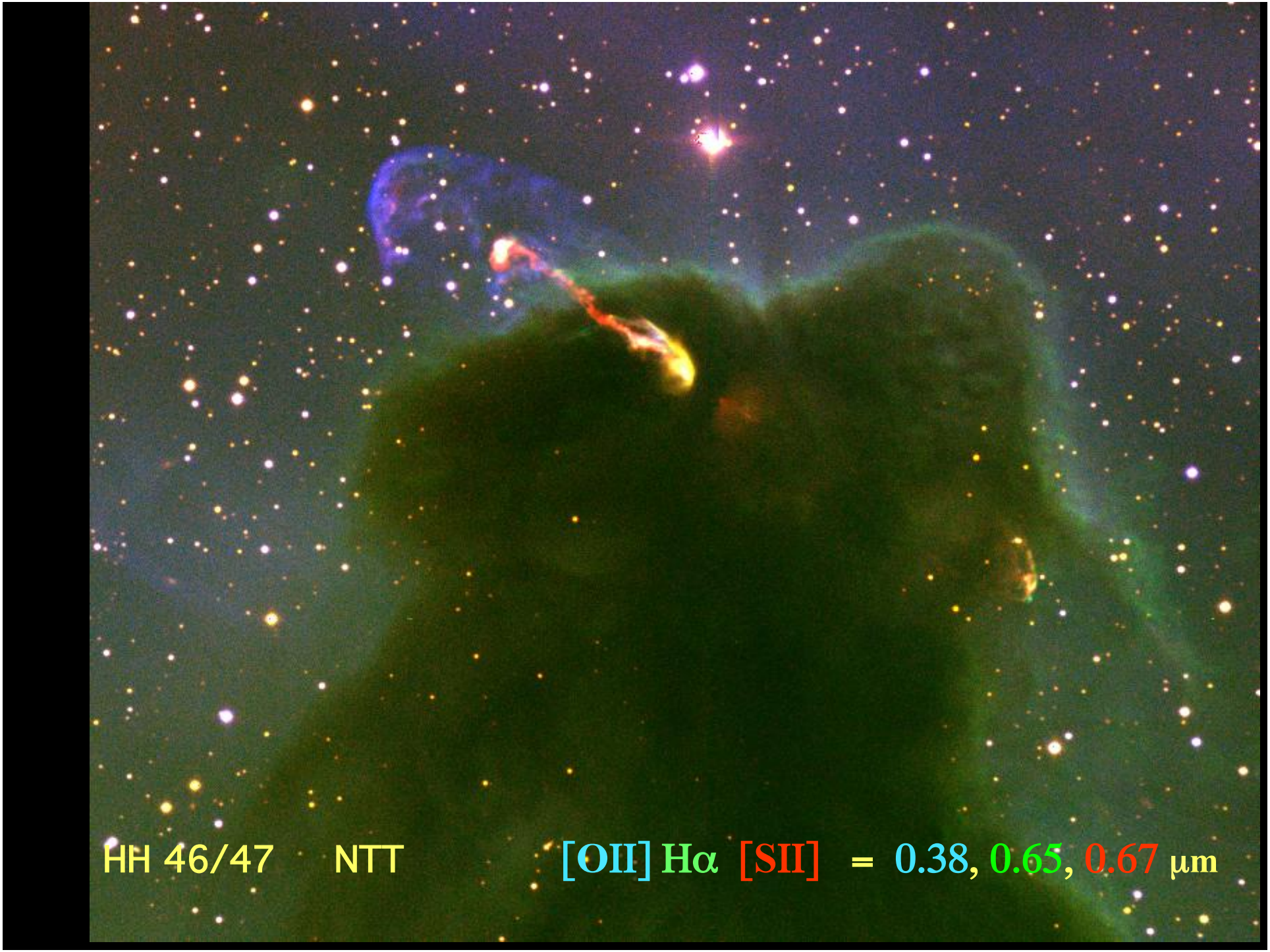
- FUV (non-ionizing) ~ 2 M_o < M < 10 M_o N~10^8
  Nγ ~ 10^{45} – 10^{50} s^{-1} PDRs C_s ~ 3 km/s t > 1-100 Myr

- Ionizing EUV > 10 M_o 3 < t < 40 Myr N~10^5
  Nγ ~ 10^{45} – 10^{50} s^{-1} HII regions + FUV C_s ~10 km/s
- Stellar winds
  dM/dt ~ 10^{-8} – 10^{-5} M_o yr^{-1} bubbles V_w ~ 10^3 km/s
- Radiation Pressure
  L ~ 10^{3-6} L_o $P\gamma \sim L\tau / 4\pi c R^2$
- Symbiotics & post Main Sequence
  dM/dt ~ 10^{-6} – 10^{-3} M_o yr^{-1} @ V_w ~ 10^{1-3} km s^{-1} + Explosions
- Supernovae
  E ~10^{51} ergs M ~ 1 M_o V~10^4 km/s N~10^{-2} yr^{-1}

Feedback regulated cluster formation

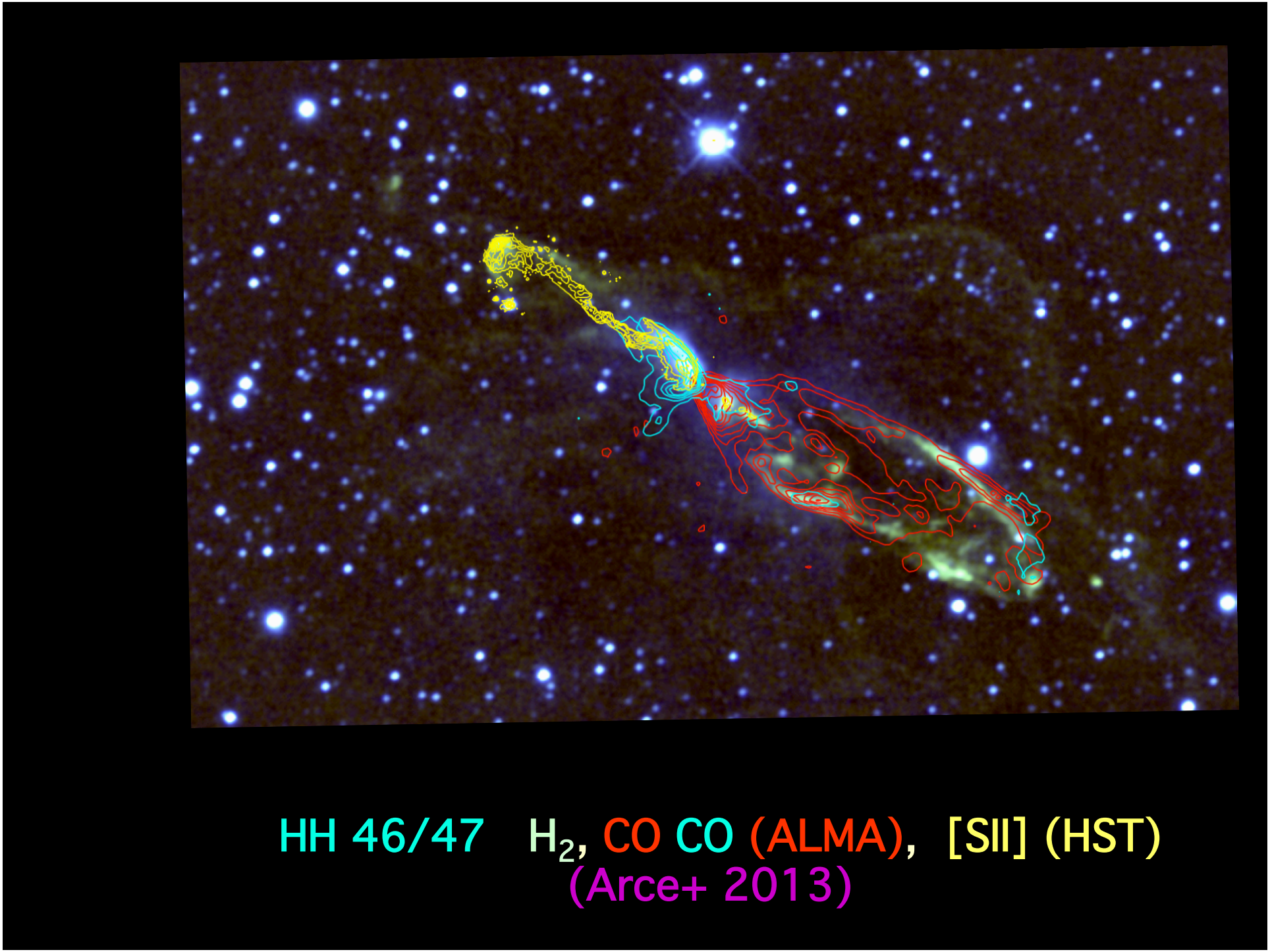
(Matzner & Jumper 2015 ApJ; Nakamura, F. & Li 2007 – 2014)



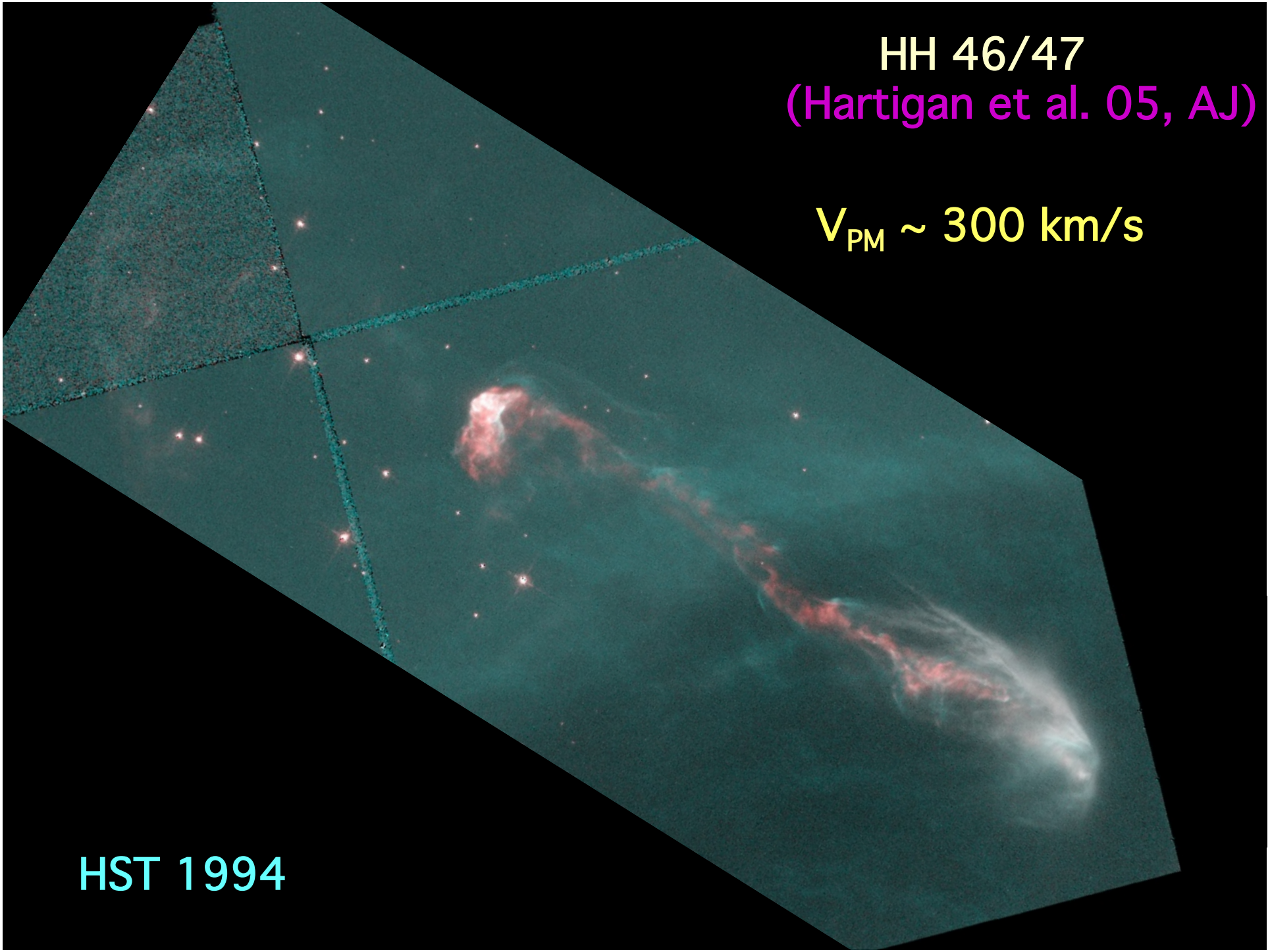

HH 46/47 NTT
[OII] Hα [SII] = 0.38, 0.65, 0.67 μm

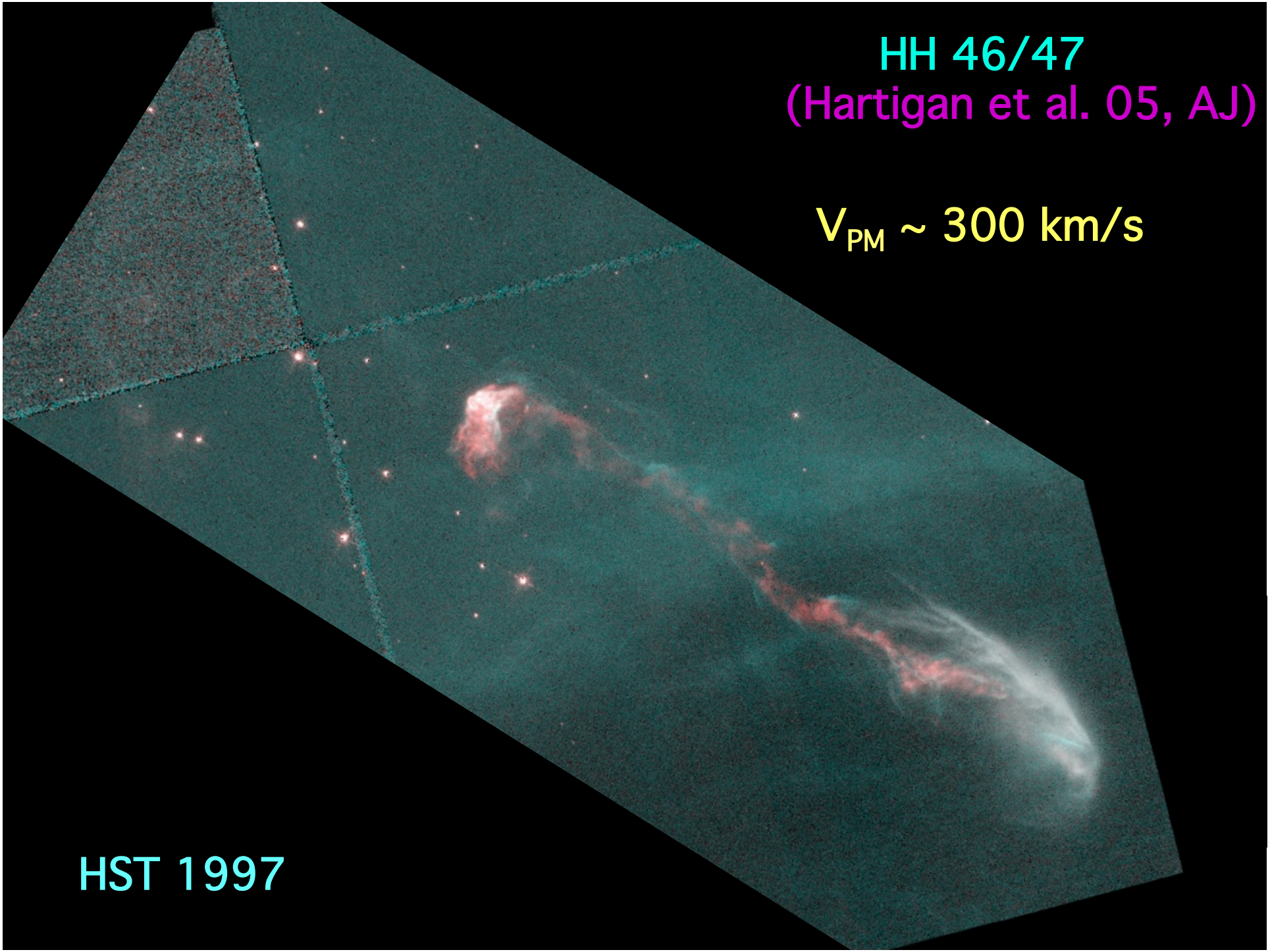
HH 46/47 Spitzer
(Noriega-Crespo+ 04)

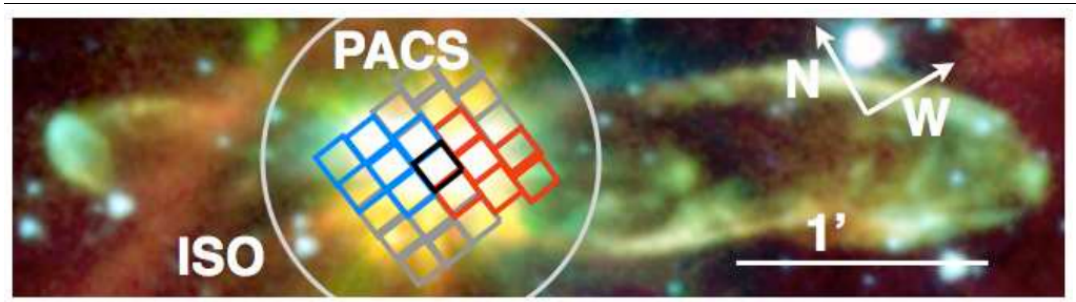
H_2 PAH 3.6, 4.5, 8 μm

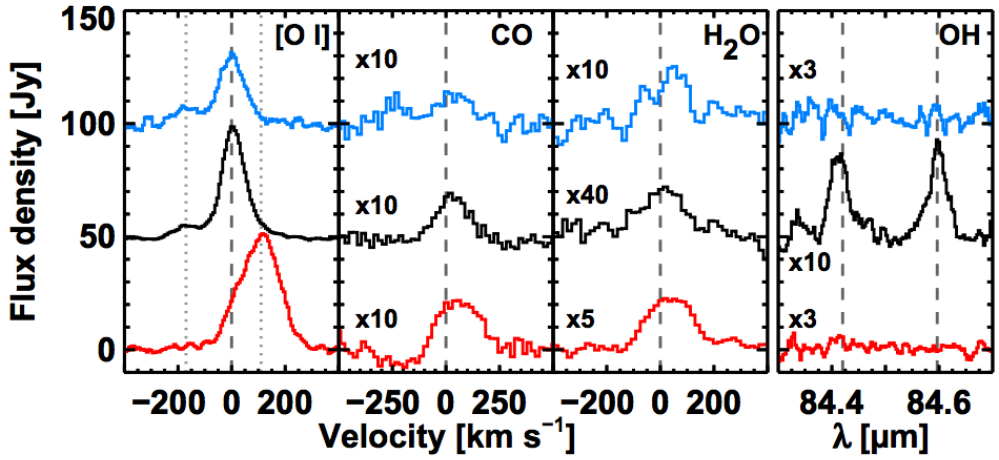


HH 46/47 H_2, CO CO (ALMA), [SII] (HST)
(Arce+ 2013)

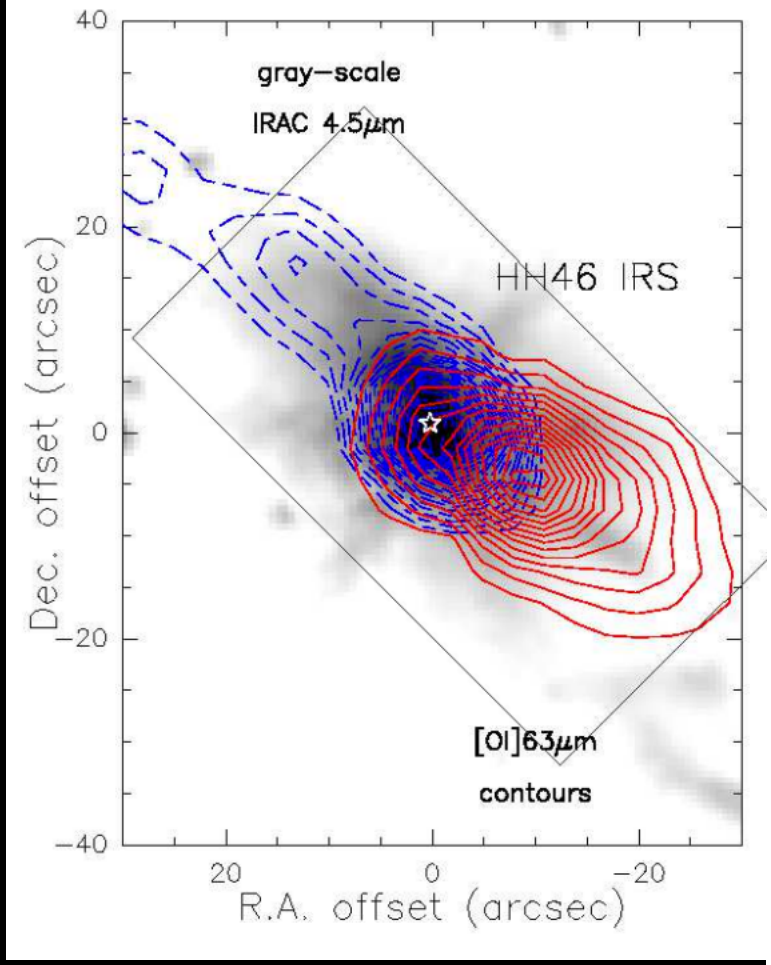

HH 46/47
(Hartigan et al. 05, AJ)
V_{PM} ~ 300 km/s
HST 1994


HH 46/47
(Hartigan et al. 05, AJ)
V_{PM} ~ 300 km/s
HST 1997





Van Kempen+ (2011)



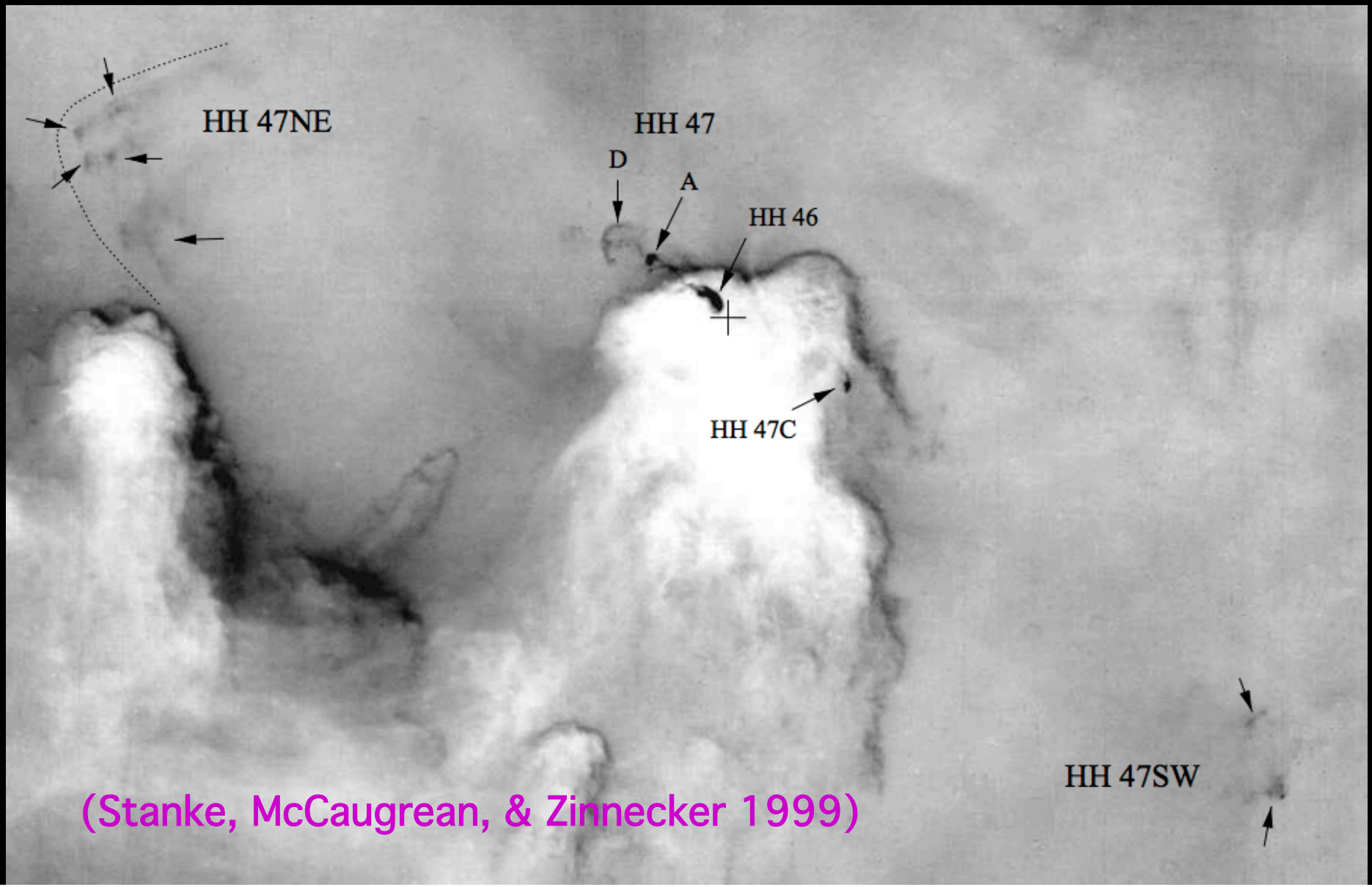
Nisini+ (2015)

HH 46/47 63 μm [OI]: Herschel / PACS

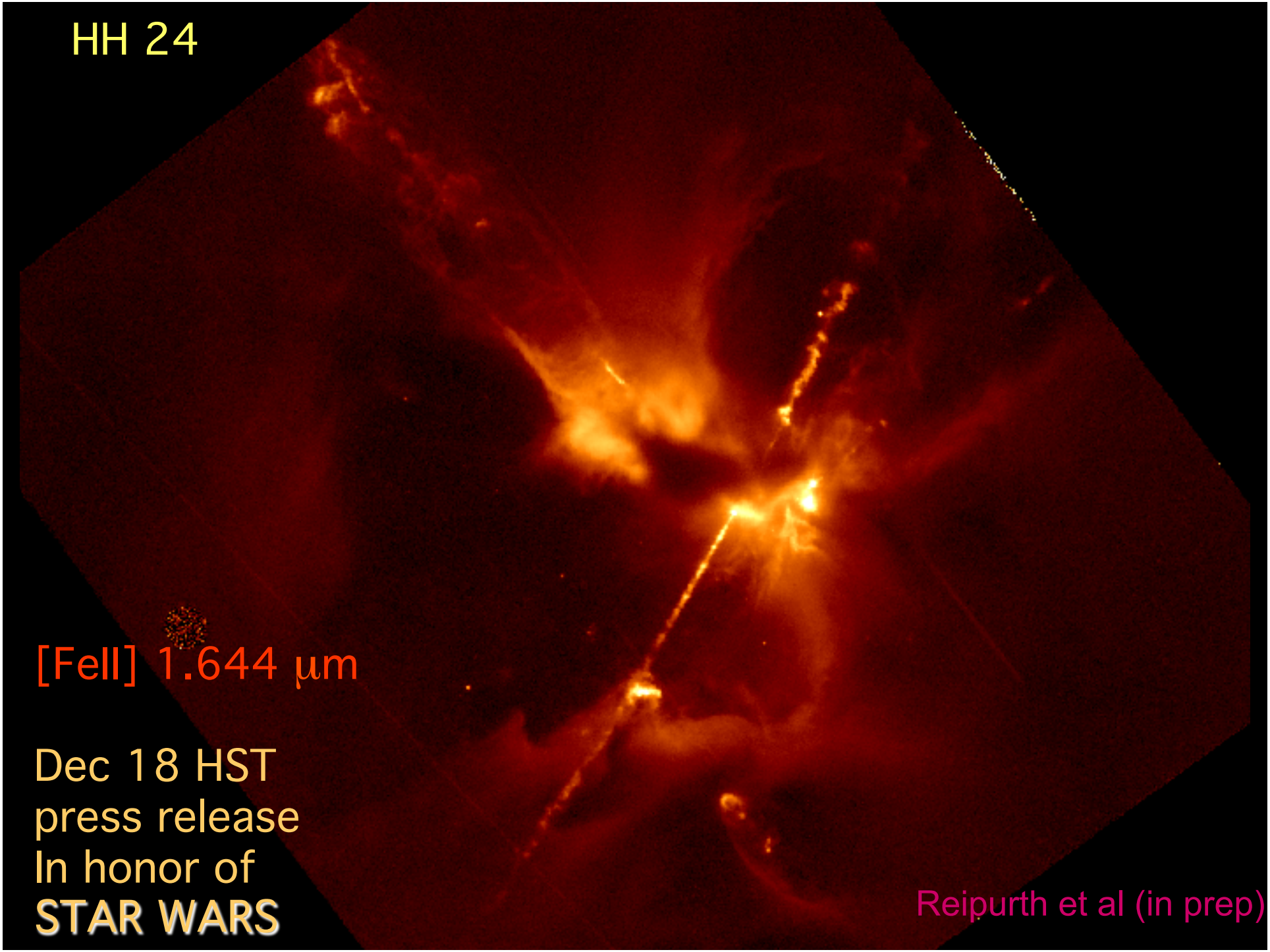
Outflows: [OI], High-J CO, hot H_2O ....

HH 46/47 Hα

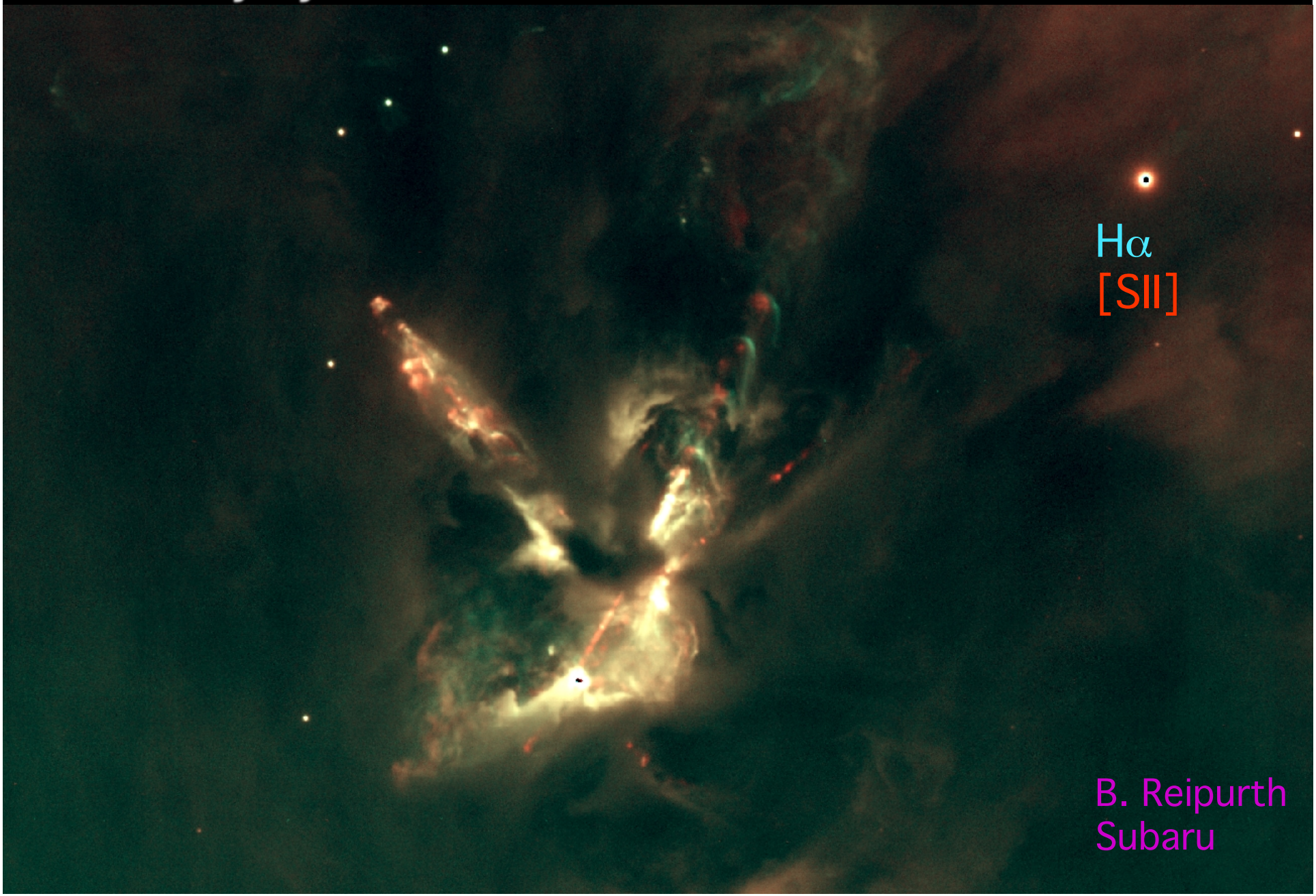
CO confined to <10% of Size & Velocity !

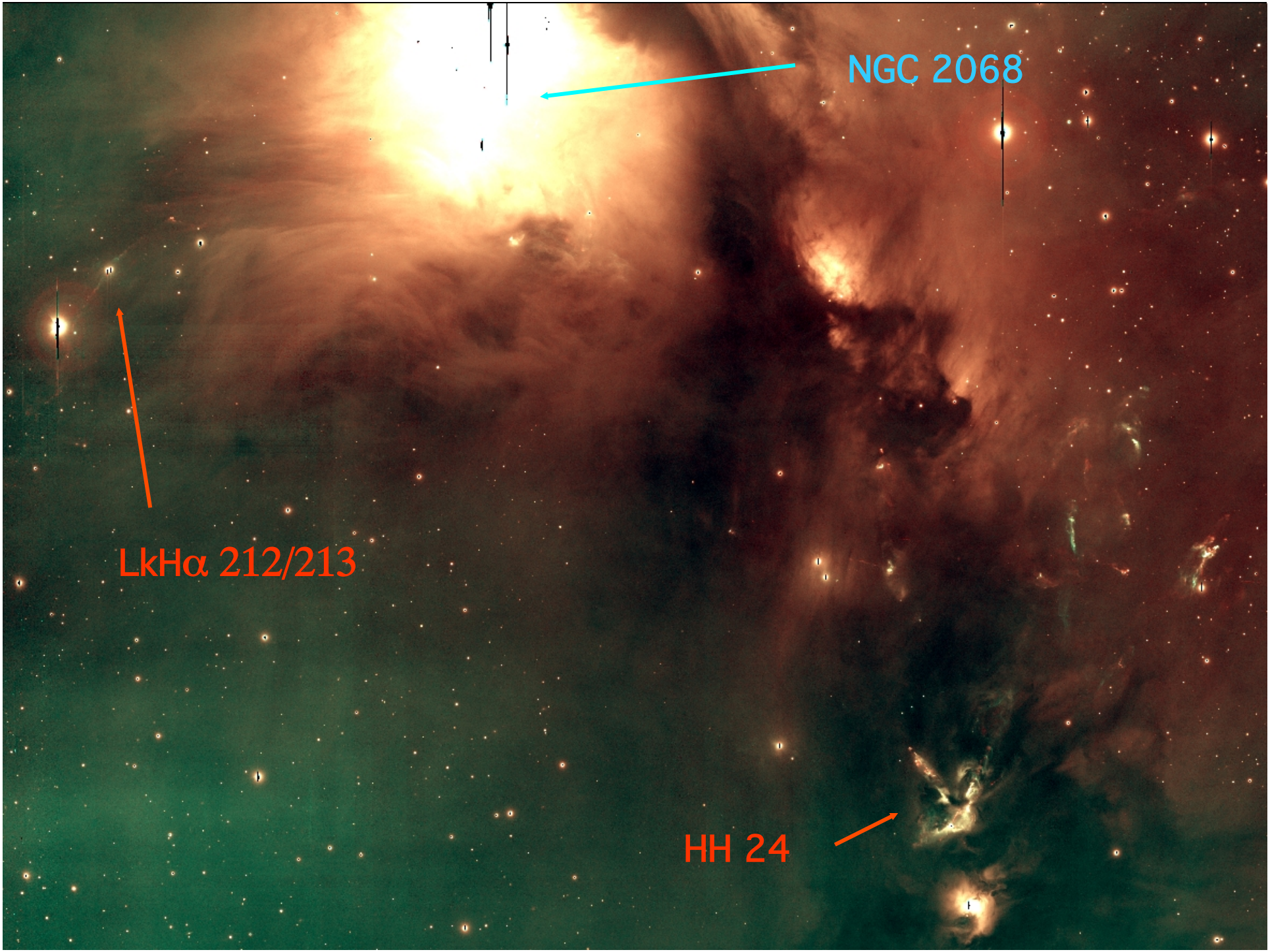


(Stanke, McCaugrean, & Zinnecker 1999)

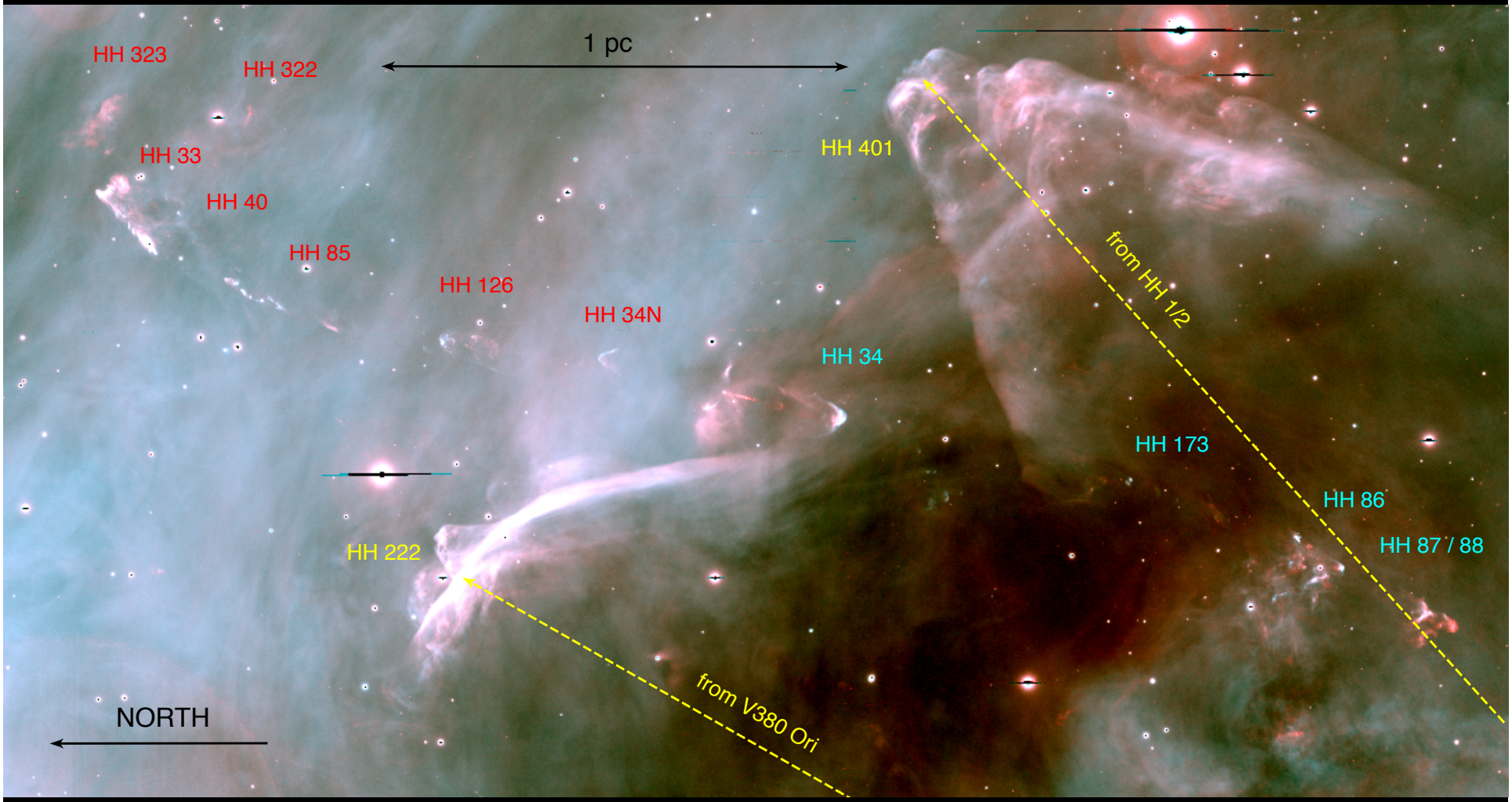

HH 24
[FeII] 1.644 μm
Dec 18 HST
press release
In honor of
STAR WARS
Reipurth et al (in prep)

N-Body dynamics: > 6 YSOs + jets



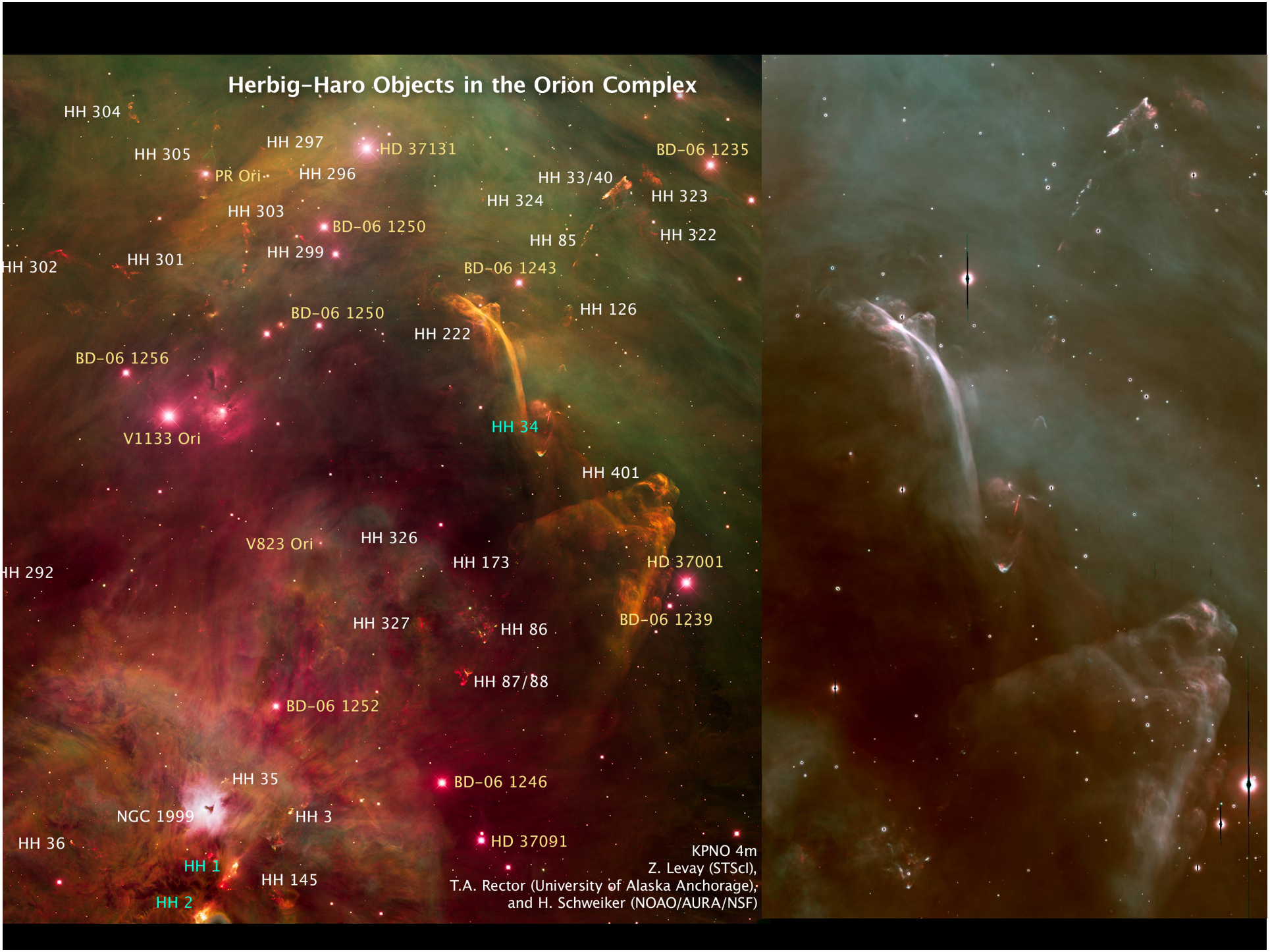

NGC 2068
LkHα 212/213
HH 24

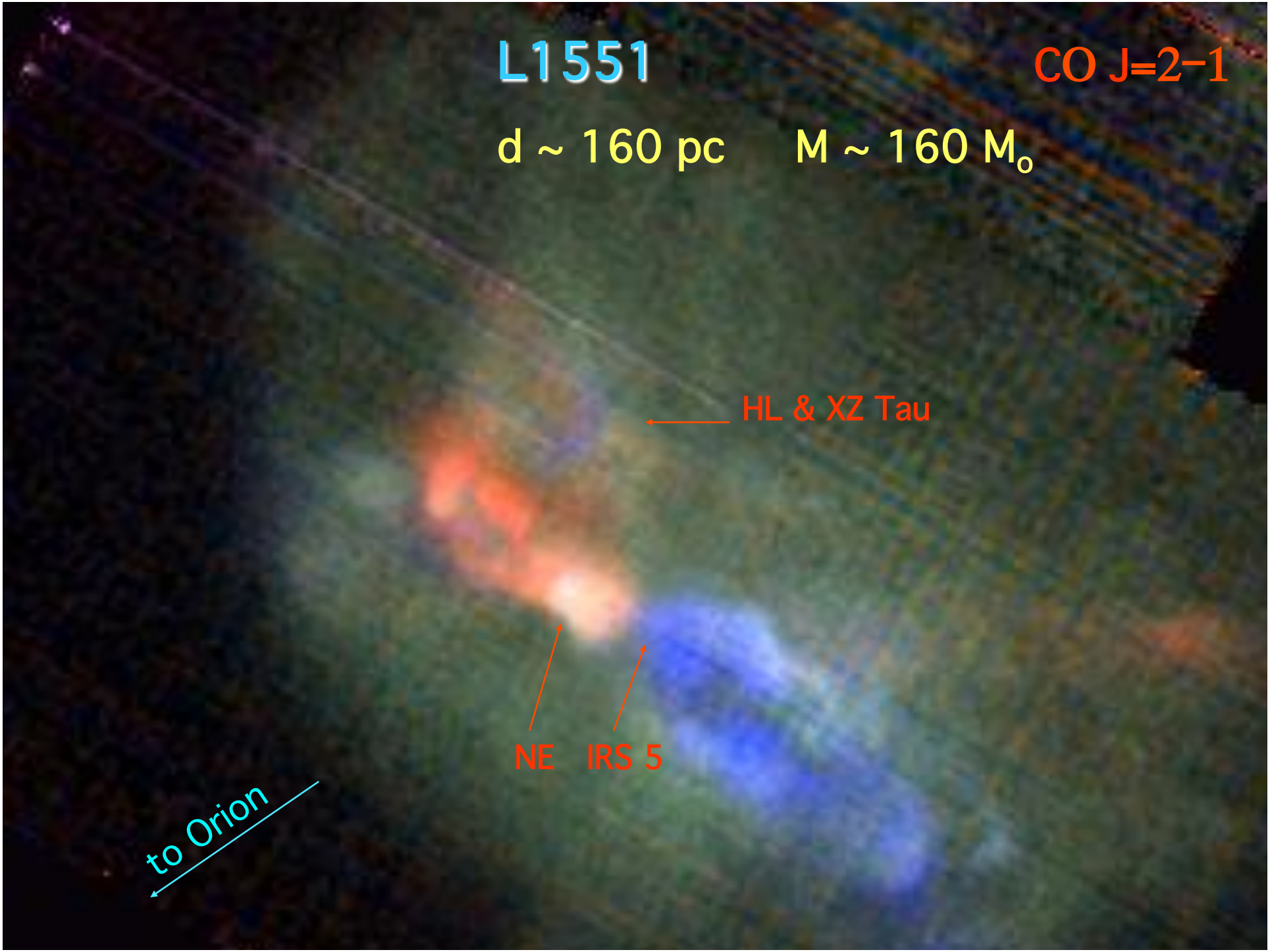
Giant outflows in Orion:
HH 34 , HH 222, HH 401



Visual & Near IR: Only samples low A_V

Need SOFIA for high A_V SOFIA O I, C II, O III, Si II …

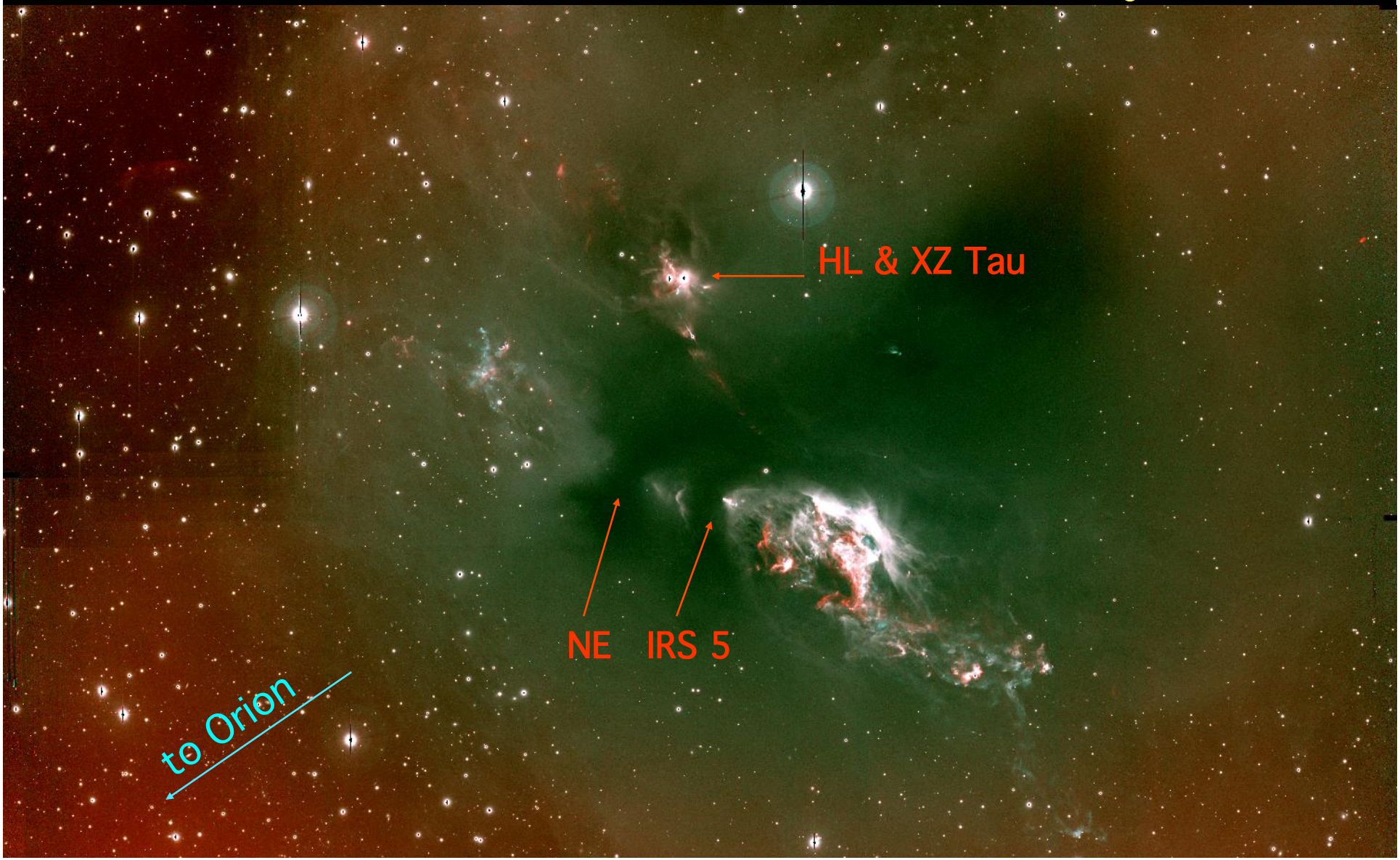

Herbig-Haro Objects in the Orion Complex
HH 304
HH 305
HH 297
HD 37131
BD-06 1235
PR Ori
HH 296
HH 33/40
HH 324
HH 323
HH 303
BD-06 1250
HH 85
HH 322
HH 299
HH 302
HH 301
BD-06 1243
BD-06 1250
HH 126
HH 222
BD-06 1256
HH 34
V1133 Ori
HH 401
V823 Ori
HH 326
HH 173
HD 37001
HH 292
HH 327
HH 86
BD-06 1239
HH 87/88
BD-06 1252
HH 35
BD-06 1246
NGC 1999
HH 3
HH 36
HD 37091
HH 1
HH 145
HH 2
KPNO 4m
Z. Levay (STScI),
T.A. Rector (University of Alaska Anchorage),
and H. Schweiker (NOAO/AURA/NSF)


L1551
CO J=2–1
d ~ 160 pc
M ~ 160 M$_o$
HL & XZ Tau
NE
IRS 5
to Orion

L1551

Hα [SII]

d ~ 160 pc M ~ 160 M_o

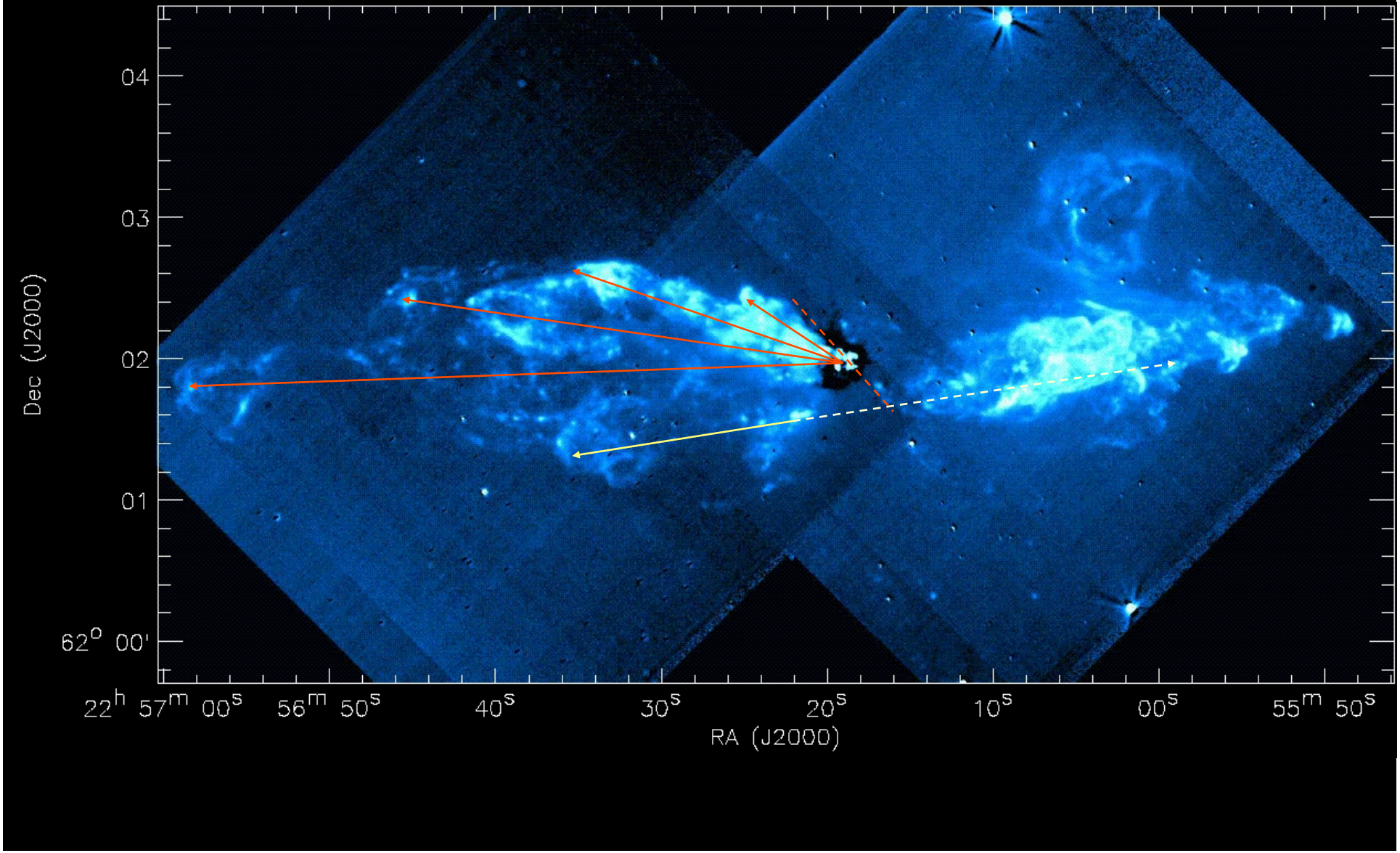


Cepheus A J, H, K_s

Cunningham et al 2009

A precessing jet: P ~ 2 x 10^3 yr ?

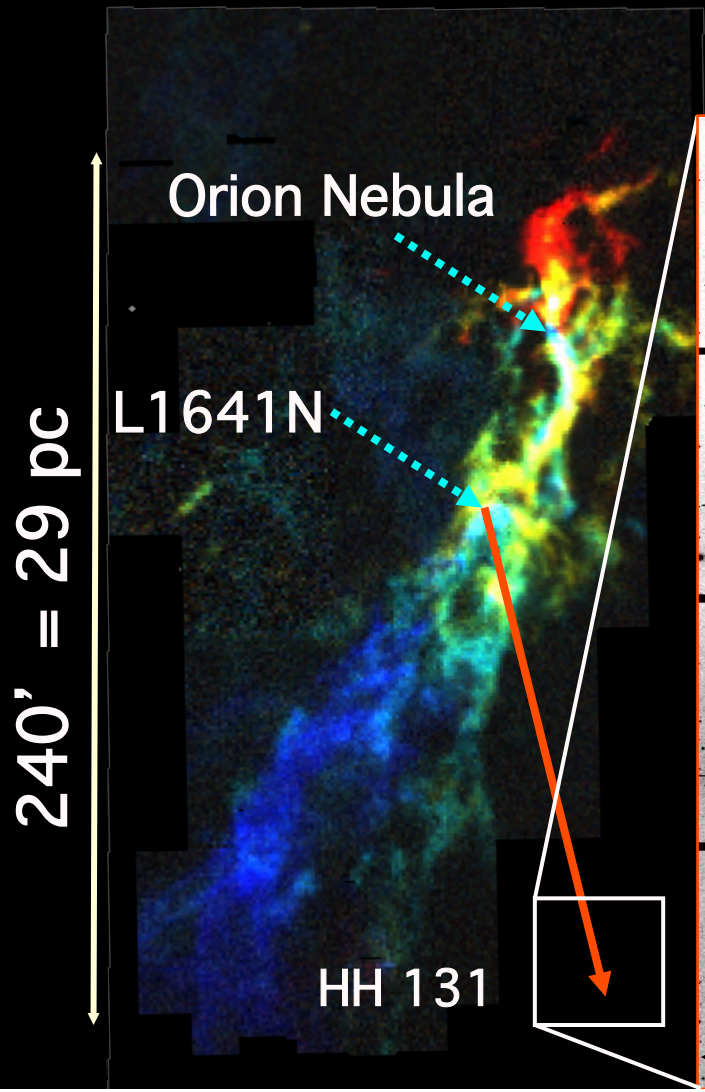
Cunningham, Moeckel, & Bally 2009

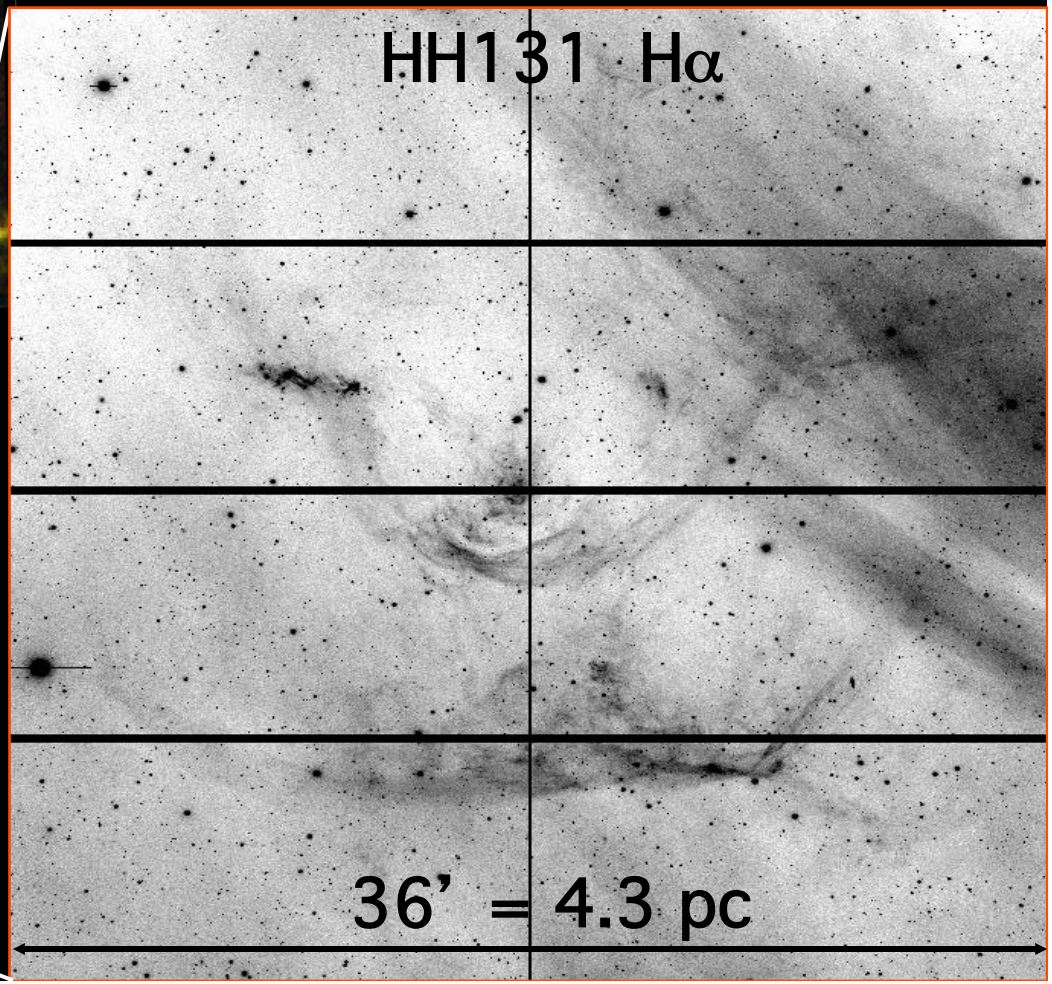


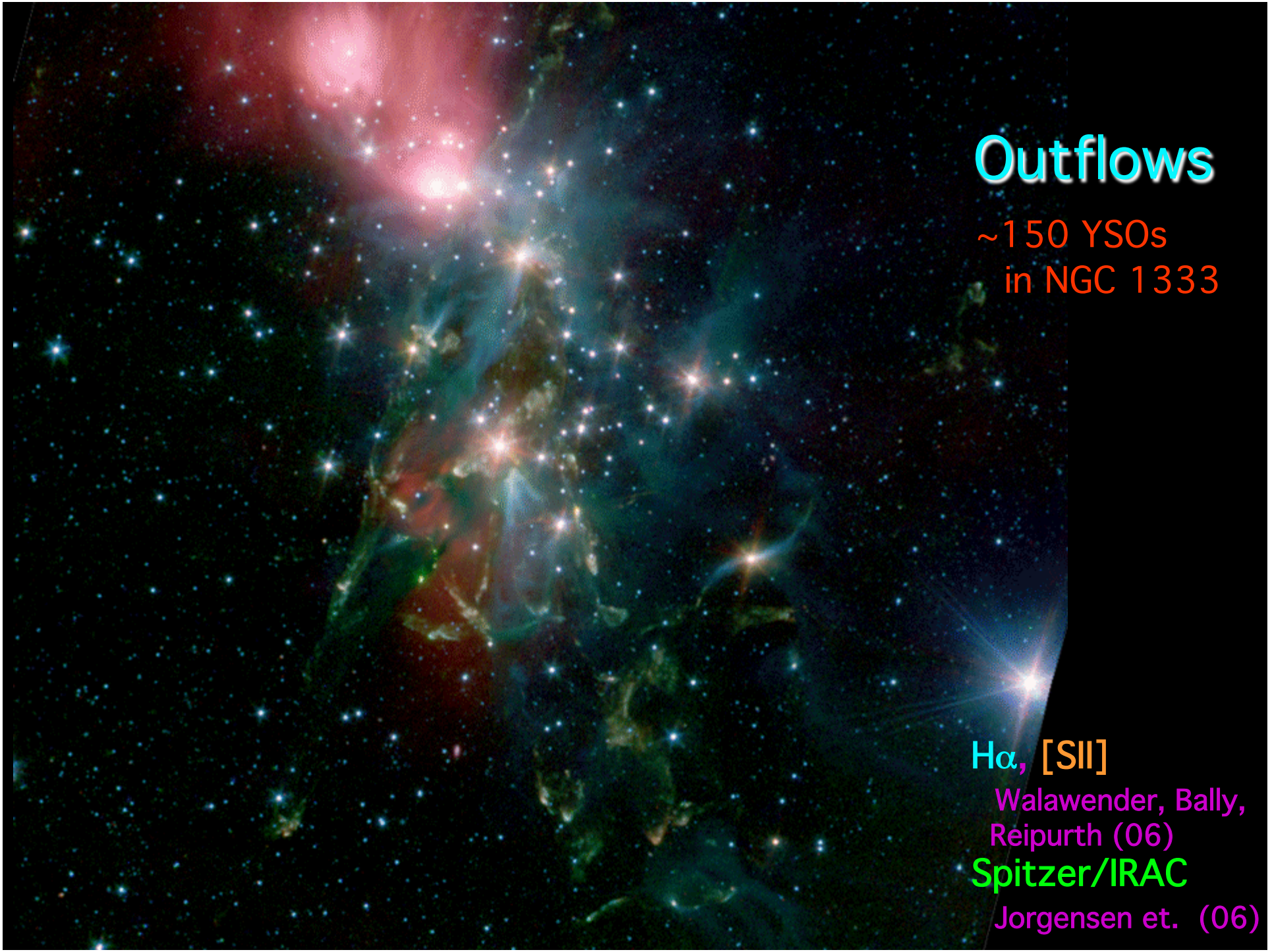
Giant Outflows

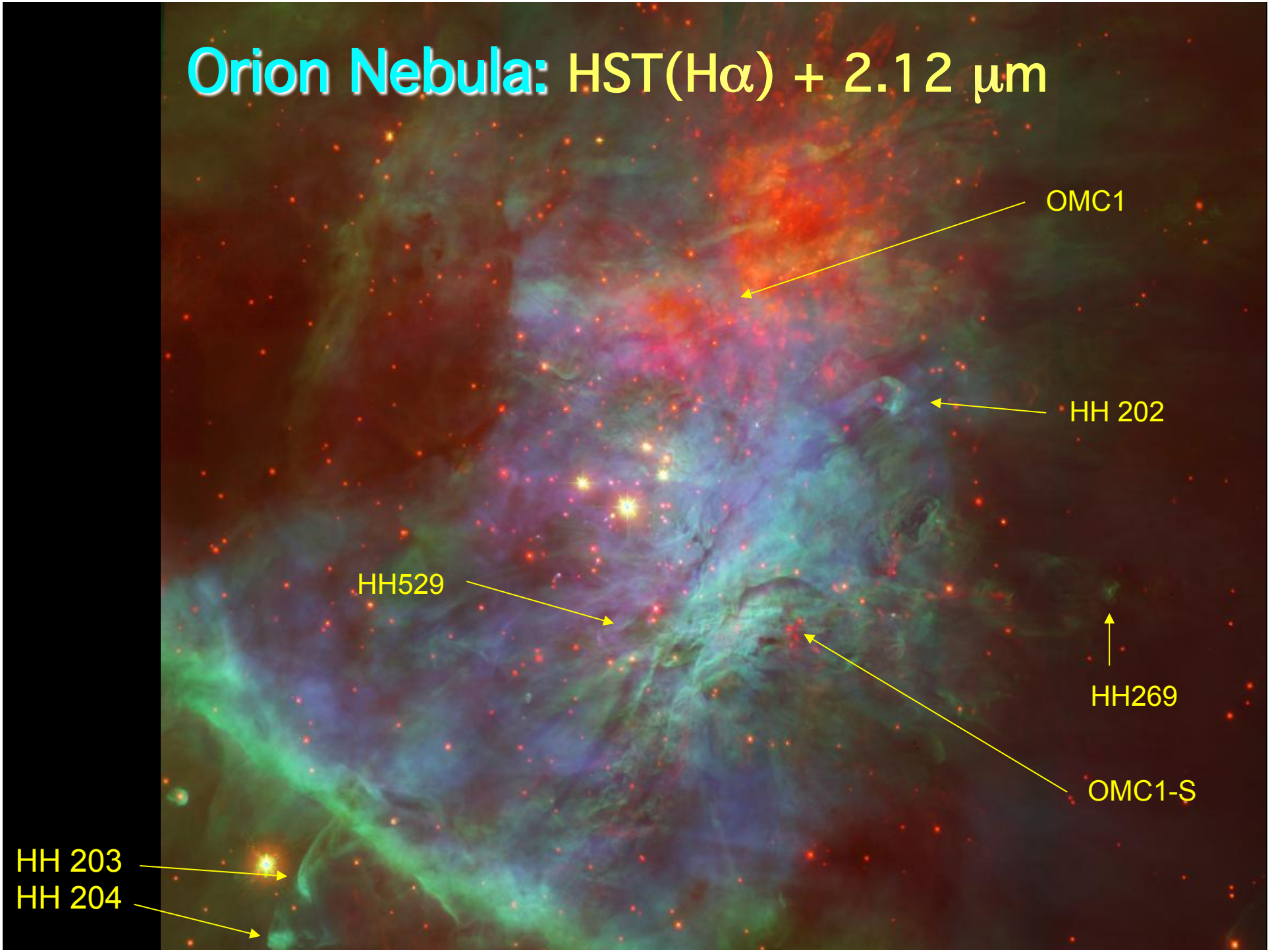
Orion Nebula

- HH131: End of > 17 pc long !!
  Outflow lobe from L1641N ?
  (Ogura 1991; Wang+ 2005)

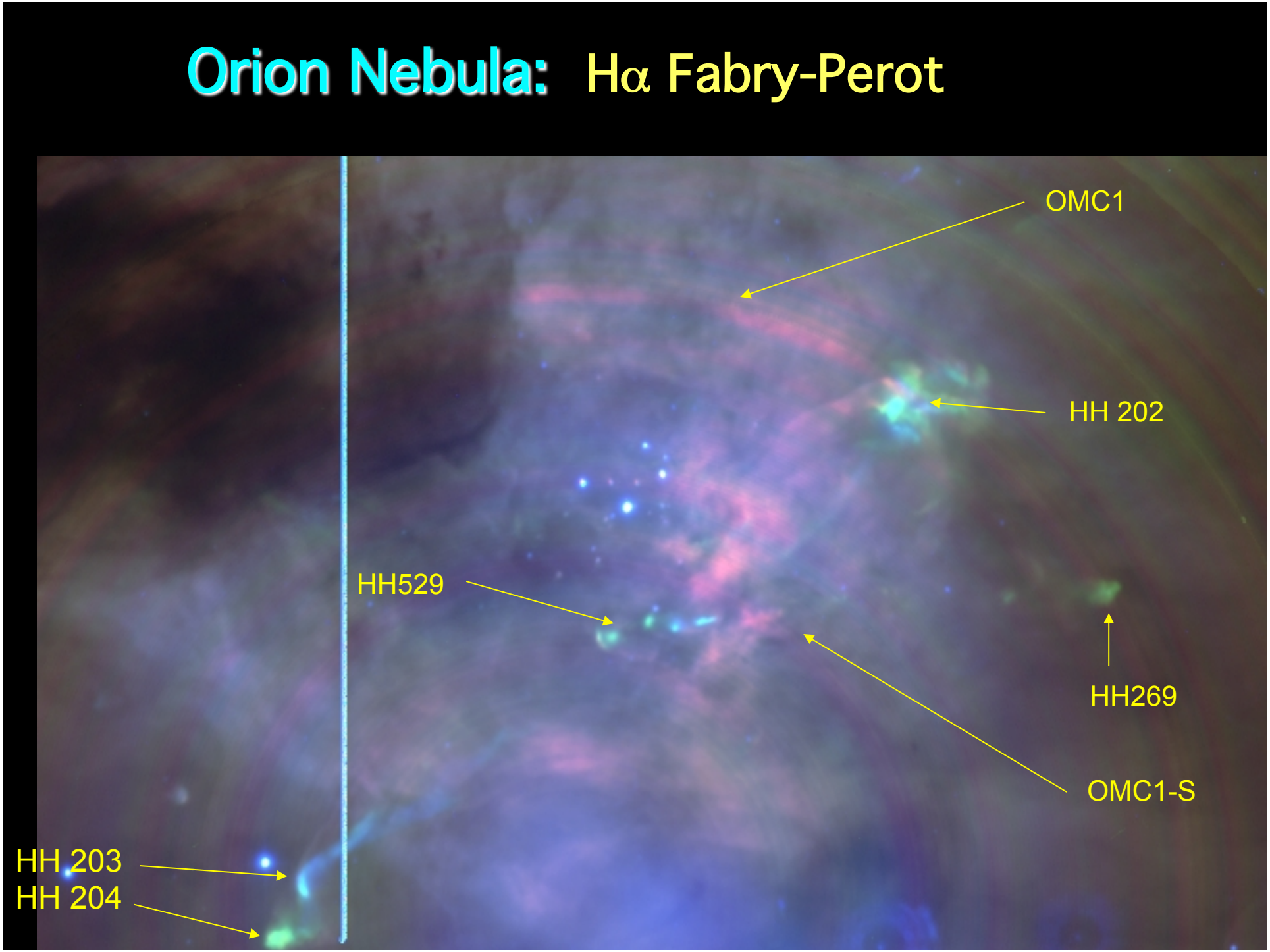





Outflows
~150 YSOs
in NGC 1333
Hα, [SII]
Walawender, Bally,
Reipurth (06)
Spitzer/IRAC
Jorgensen et. (06)


Orion Nebula: HST(Hα) + 2.12 μm
OMC1
HH 202
HH529
HH269
OMC1-S
HH 203
HH 204

Orion Nebula: Hα Fabry-Perot



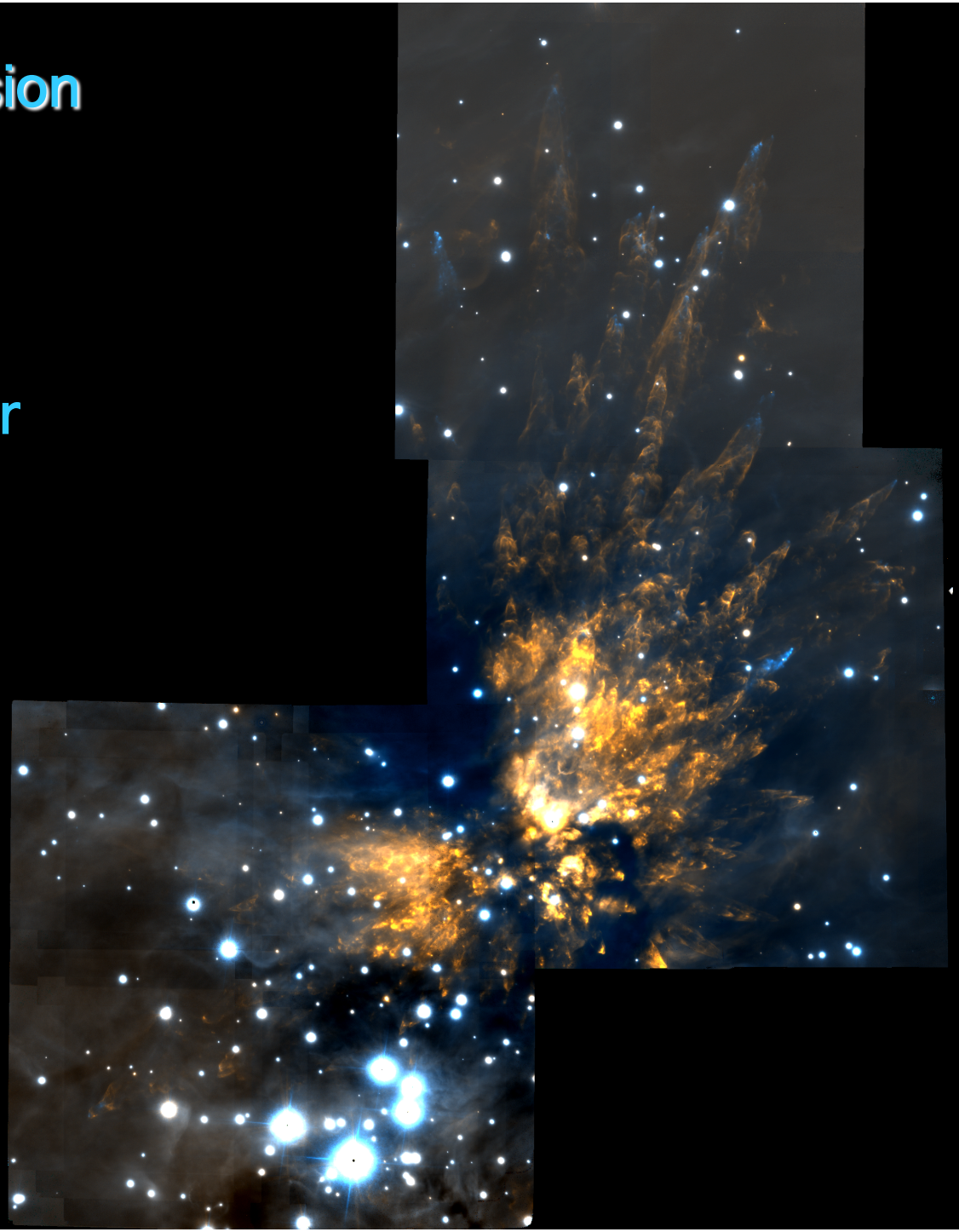
The Orion Explosion

E ~ 10^{48} erg

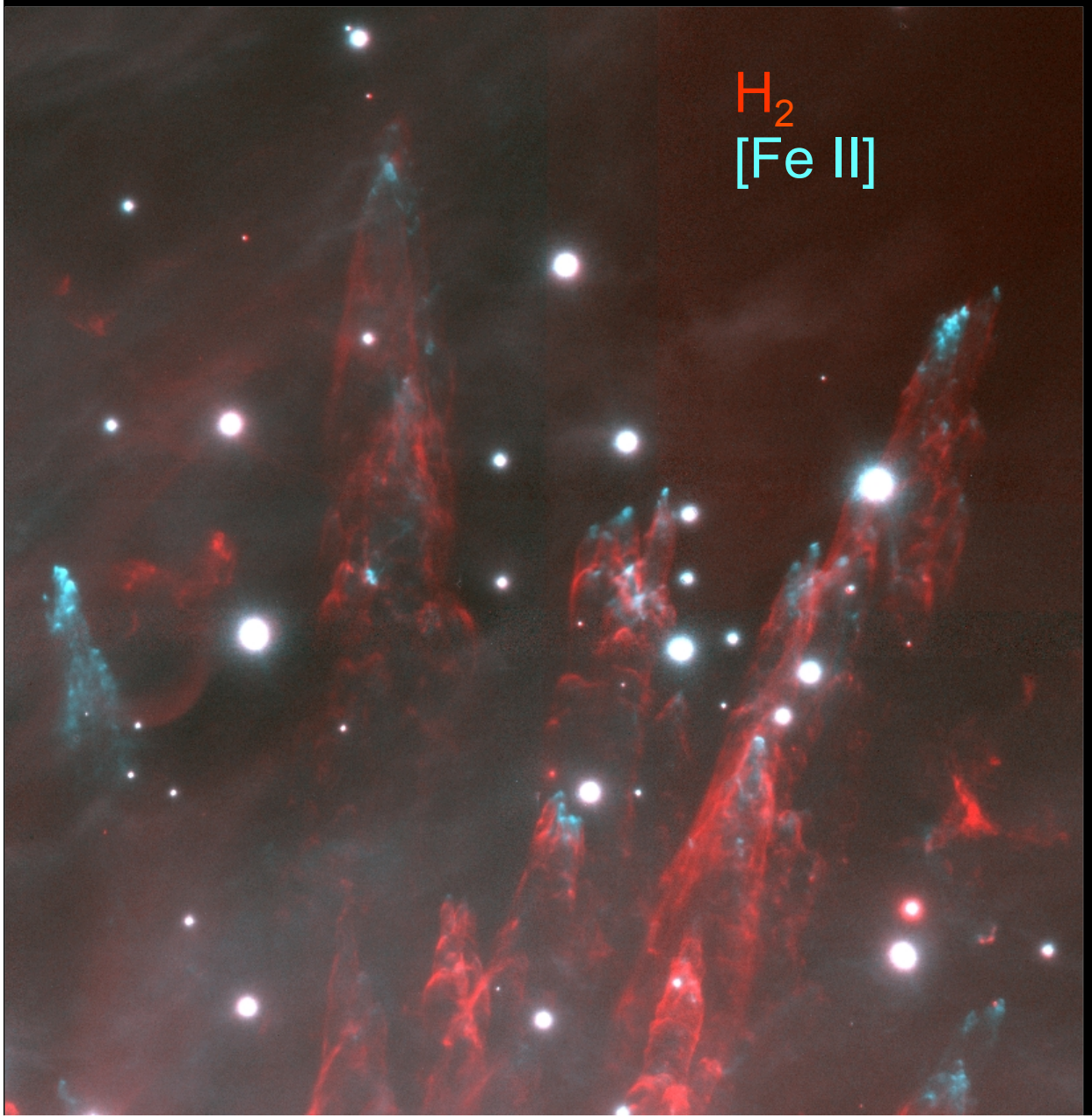
Adaptive Optics Image in the near infrared

Gemini South Adaptive Optics Imager

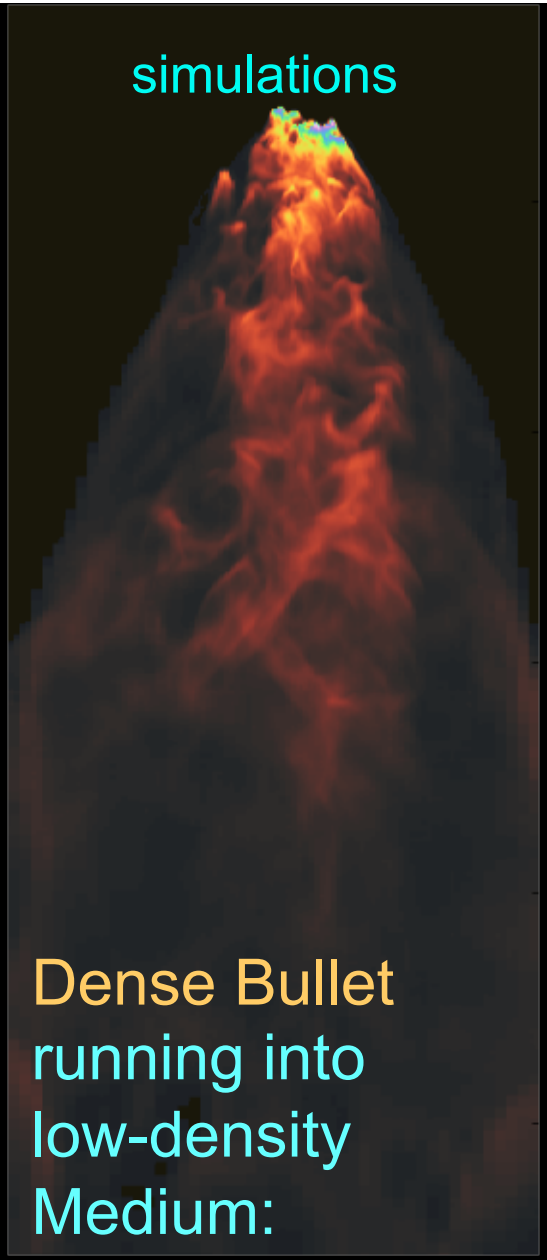
8 -meter
5 laser AO



Devin Silvia 3D ENZO MHD

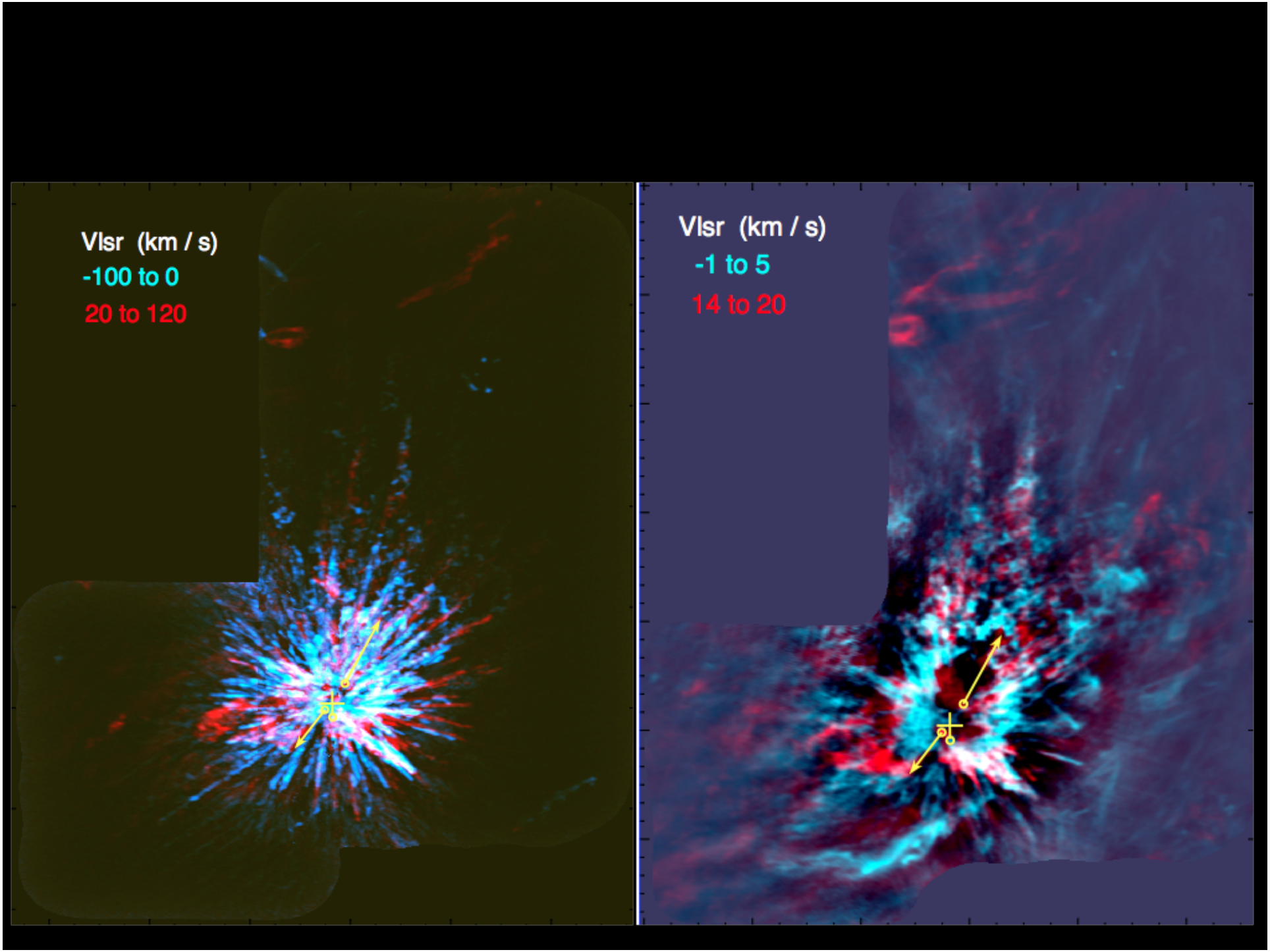


simulations



Dense Bullet running into low-density Medium:

10^3 initial density contrast

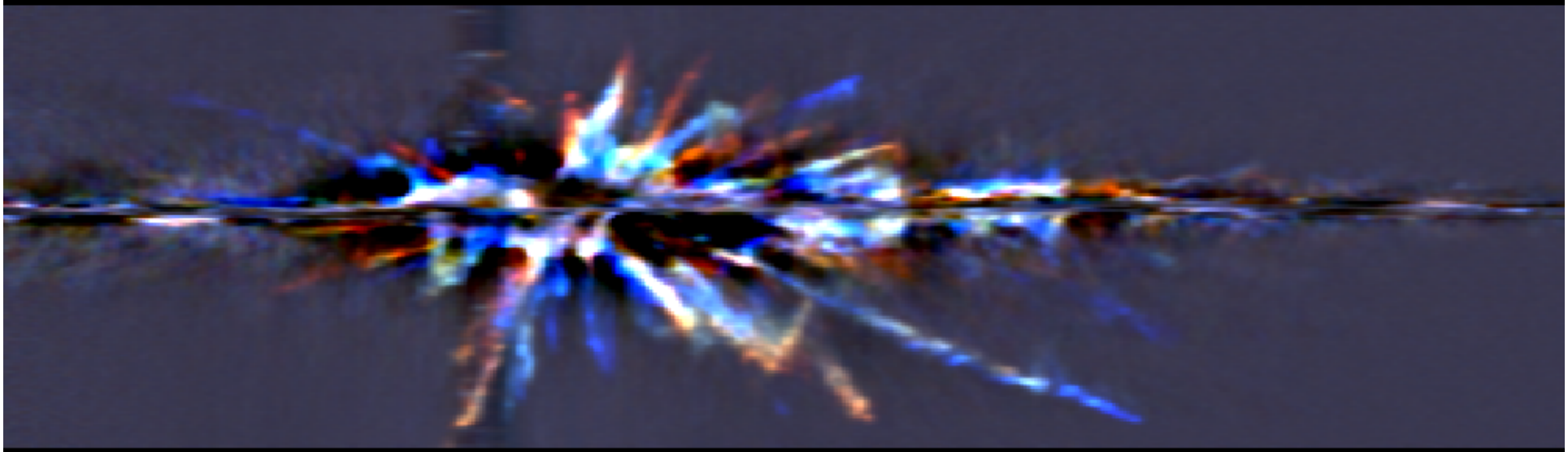

Vlsr (km / s)
-100 to 0
20 to 120
Vlsr (km / s)
-1 to 5
14 to 20

North-South Cut

South
North

120”

V =+120 km / s



V = -120 km/s

Constant dV/dr ! => No deceleration !

n ~ 100 linear ejecta streams with $V = C_n R$

$\rho >> \rho_{ambient}$ $\rho > 10^8$ cm^{-3}

$N \sim 10^3$ clumps with $M_{clump} \sim 10^{28} - 10^{30}$ grams ?

the "Shock Sandwich"

Equal density

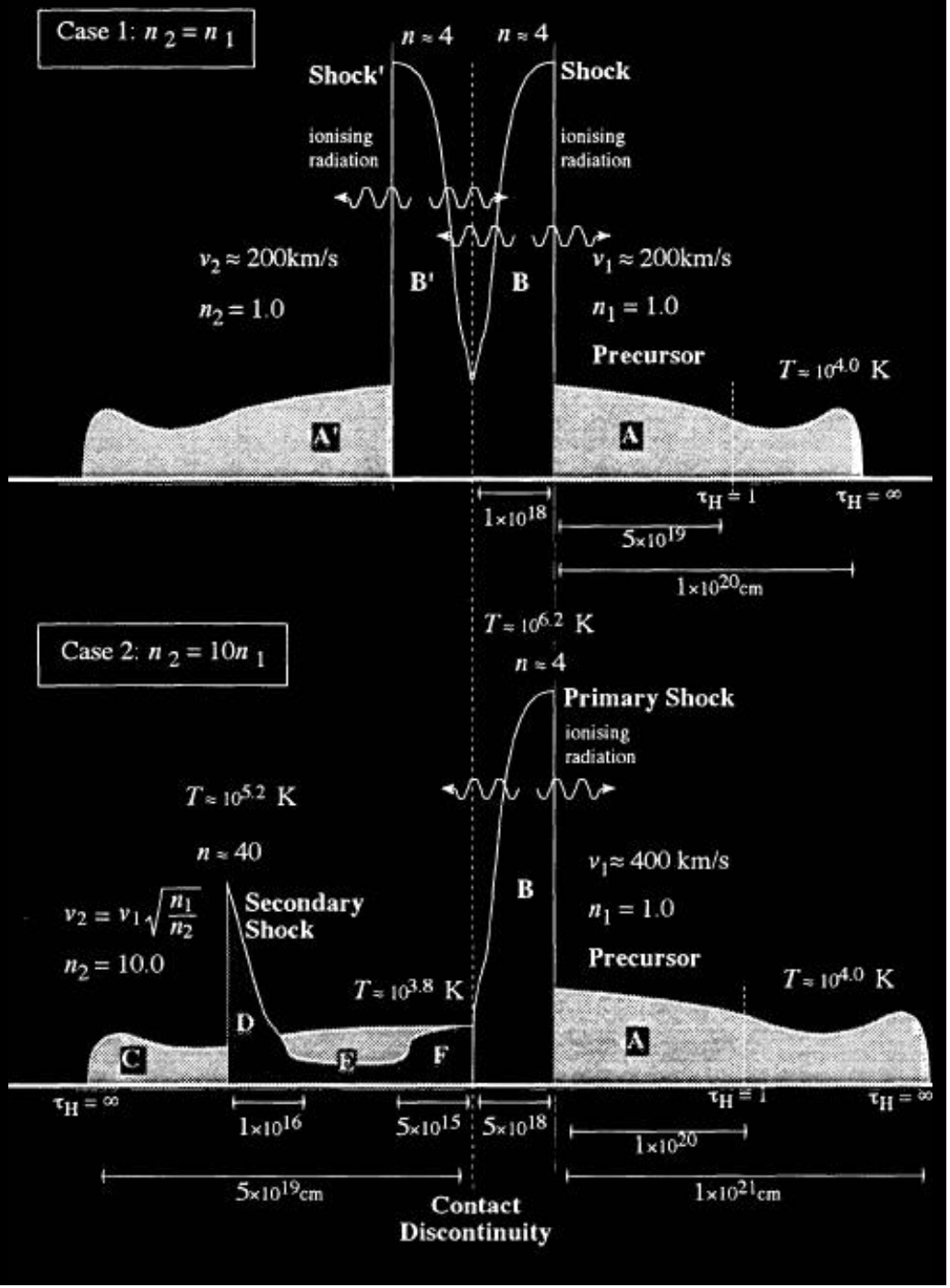
$\tau_{cool} \sim \varepsilon / \Lambda n^2 = 3\ nkT / 2\Lambda n$

$= 9\ \mu m_H V_s^2 / 32\ \Lambda n$

$L_{cool} \sim V_s\ \tau_{cool}$

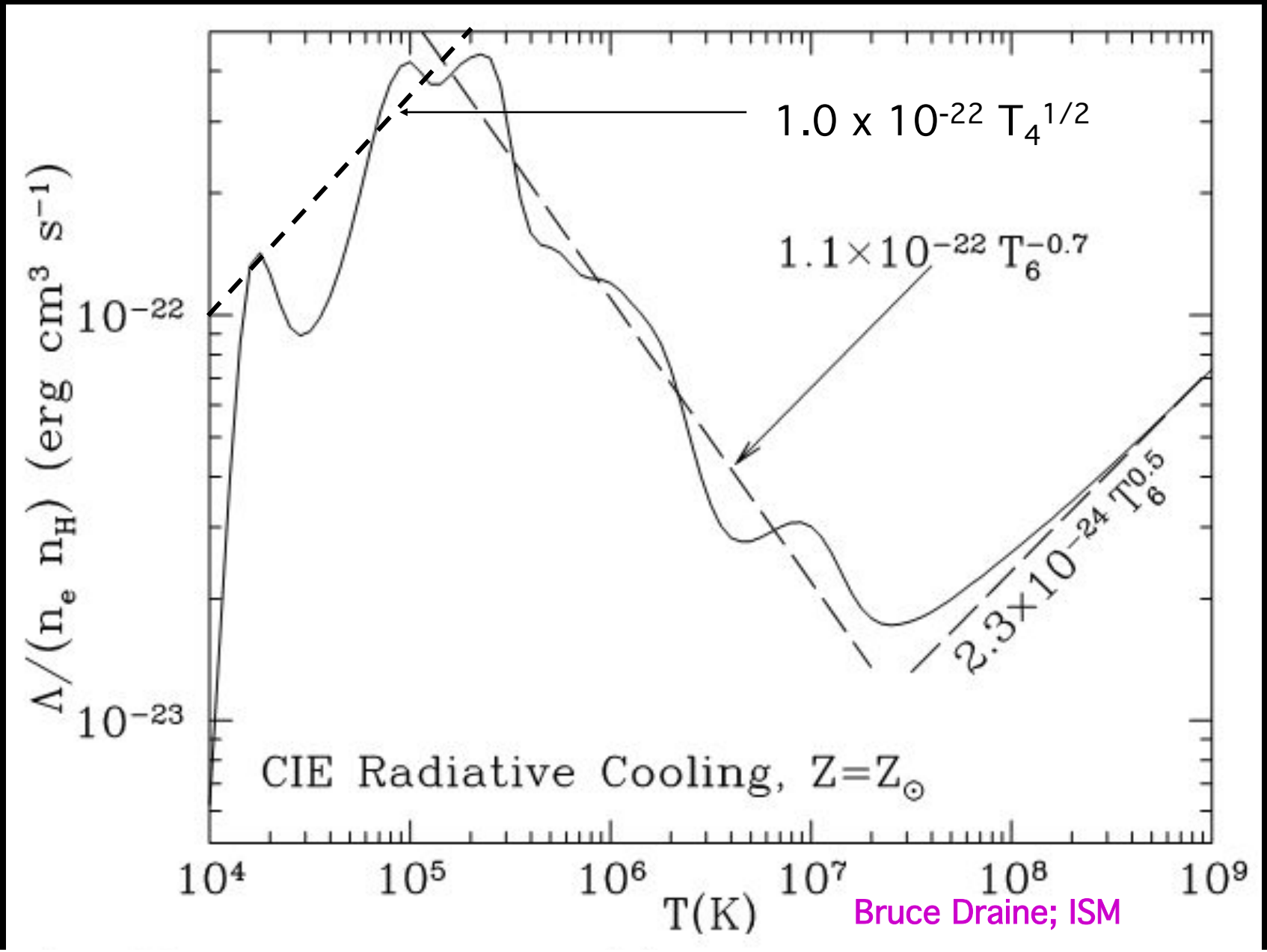
$= 9\ \mu m_H V_s^3 / 32\ \Lambda n$

Unequal density



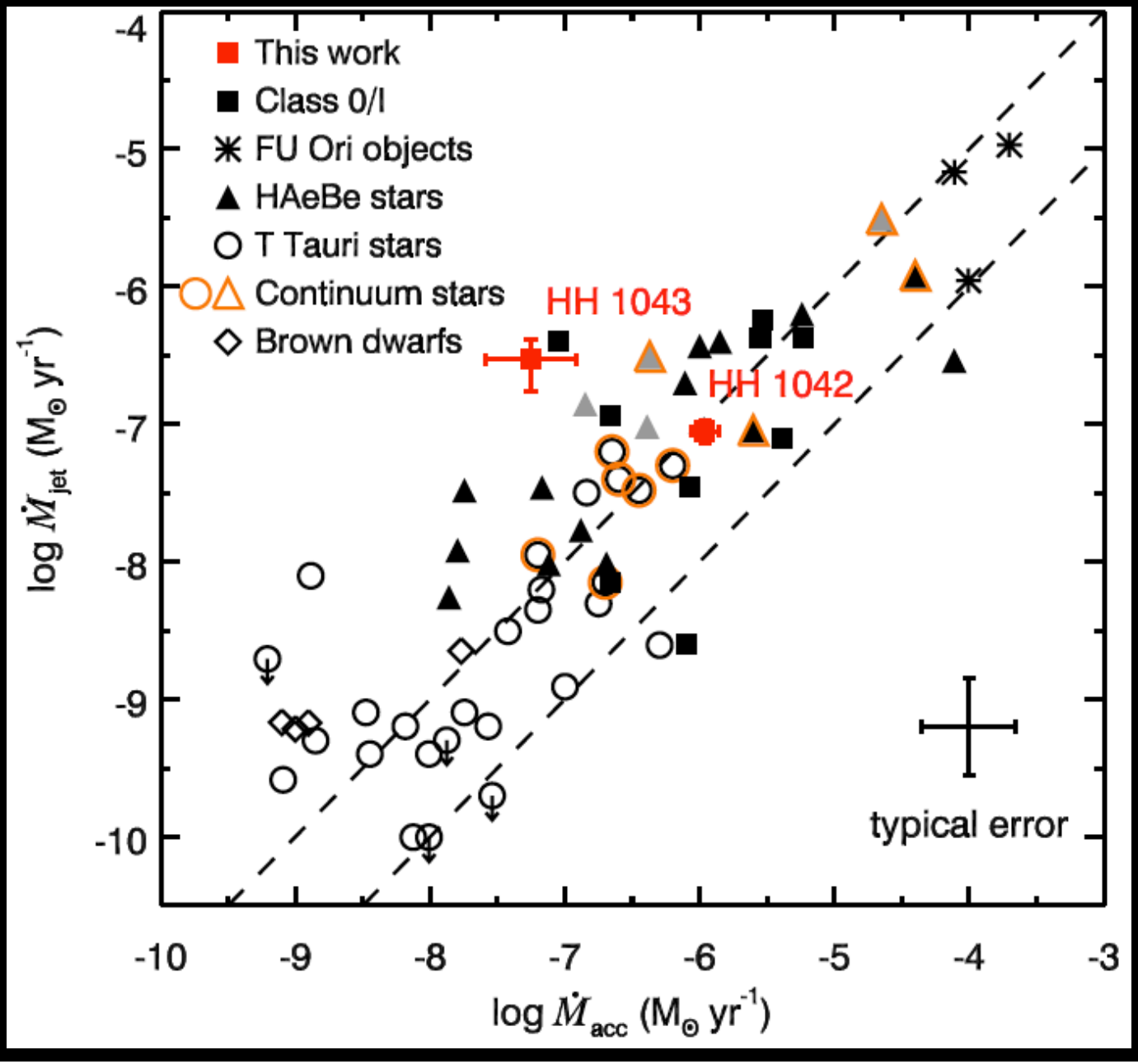
Cartoon from
Ralph Sutherland &
Mke Dopita

Cooling of warm & hot cosmic plasma

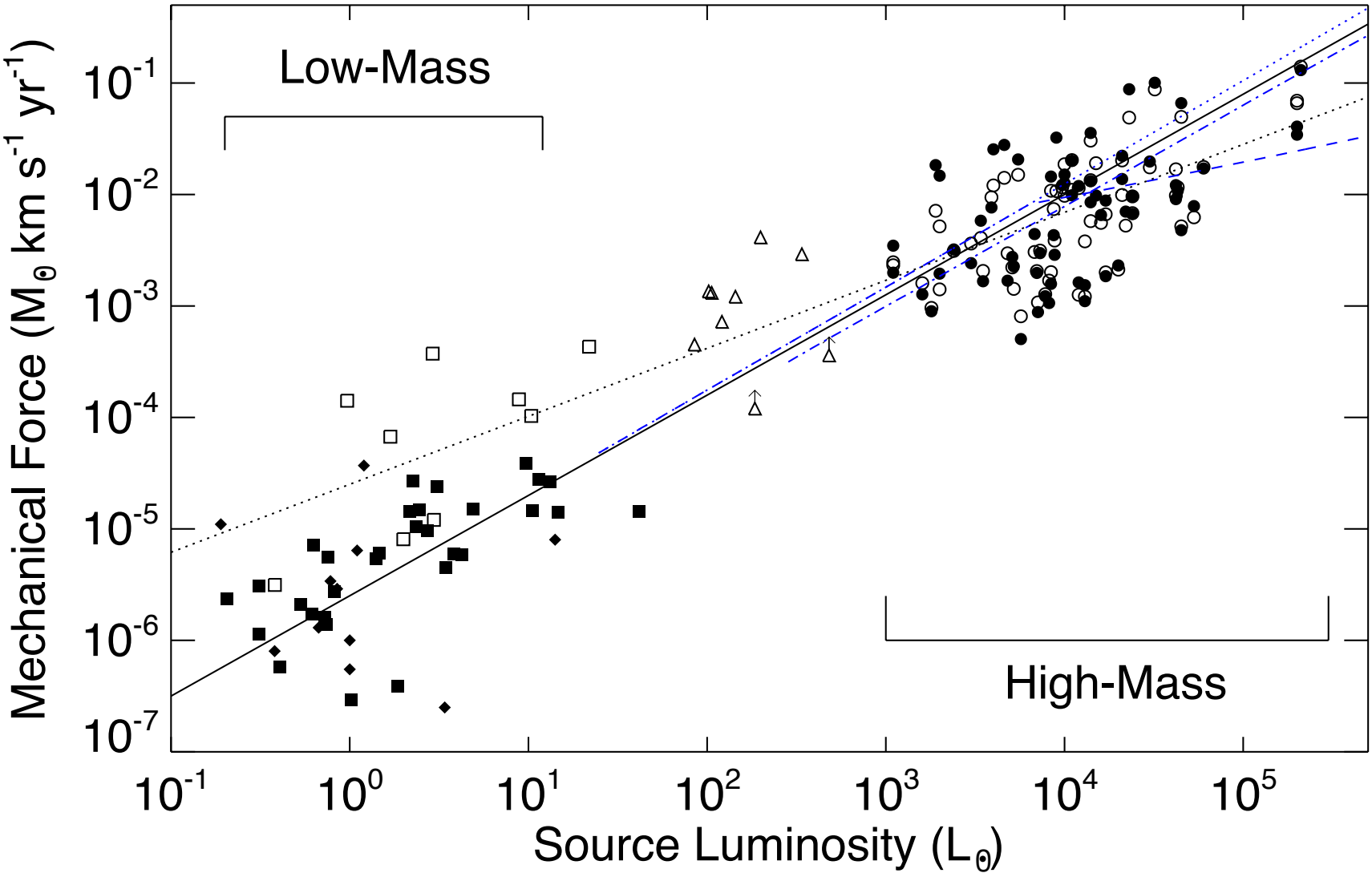


Bruce Draine; ISM

Low-Mass Outflows

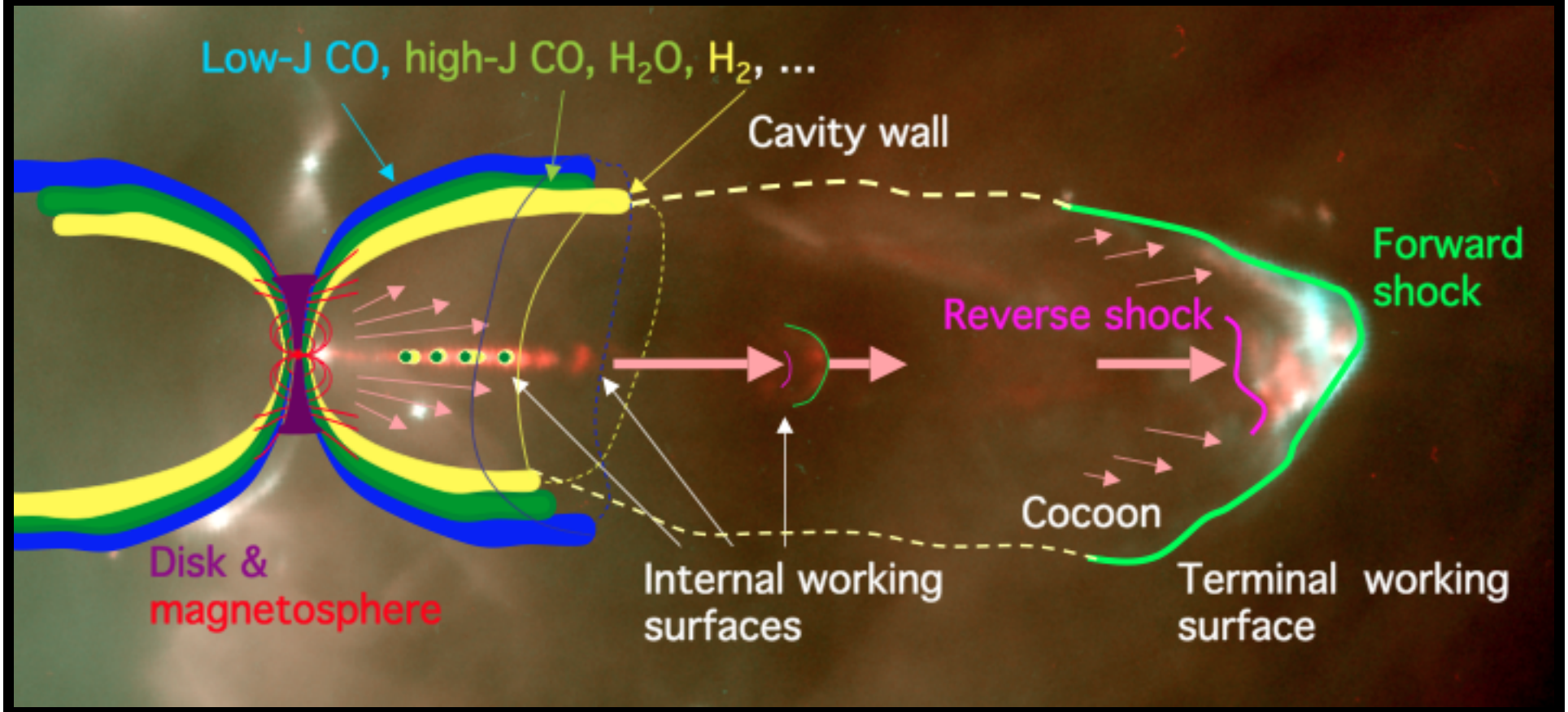


Ellerbroek+2015


Low-Mass
High-Mass
Mechanical Force ($M_\odot$ km s^{-1} yr^{-1})
Source Luminosity ($L_\odot$)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

Maud+ 2015

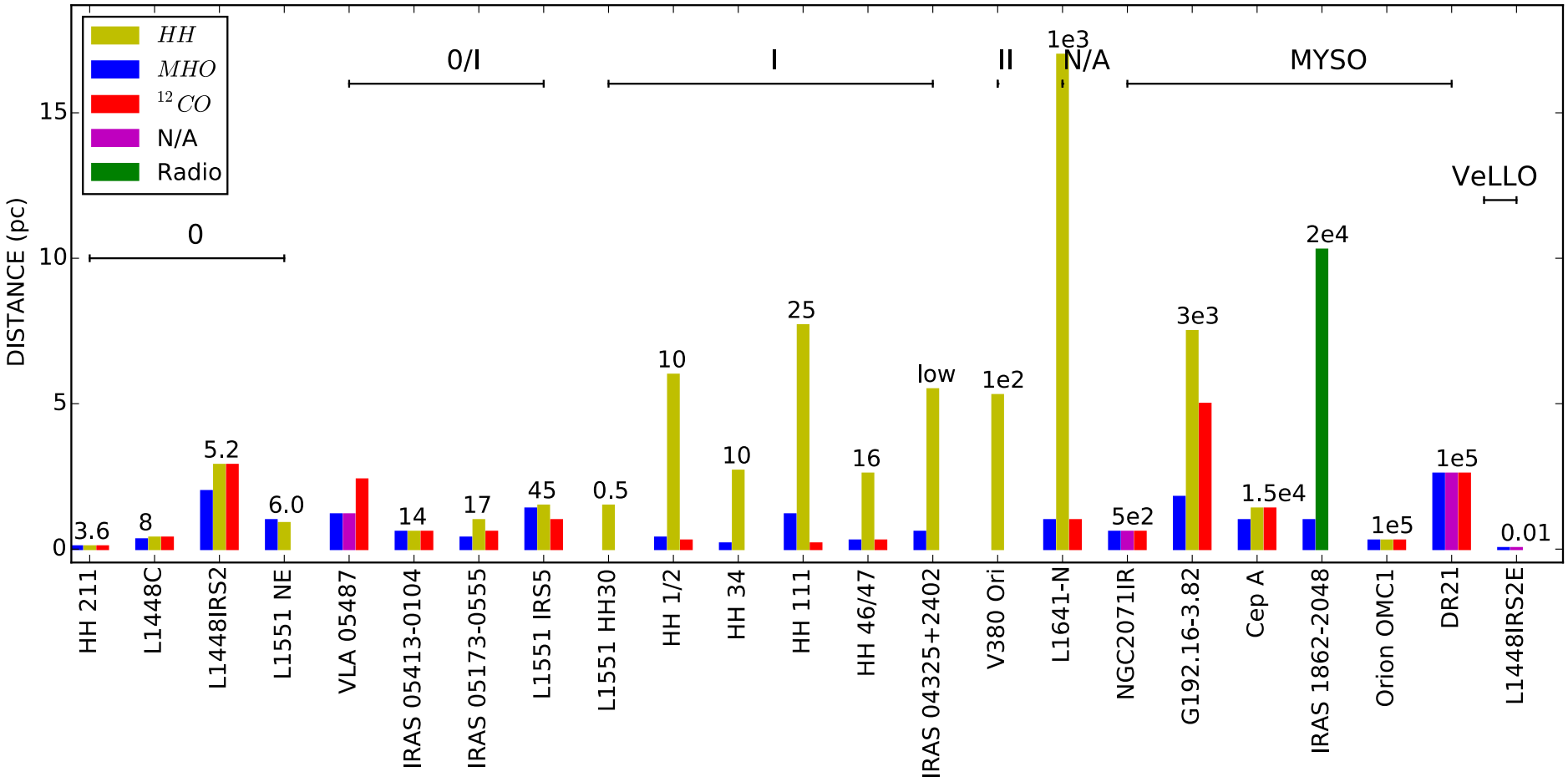
Protostellar Outflow Feedback:

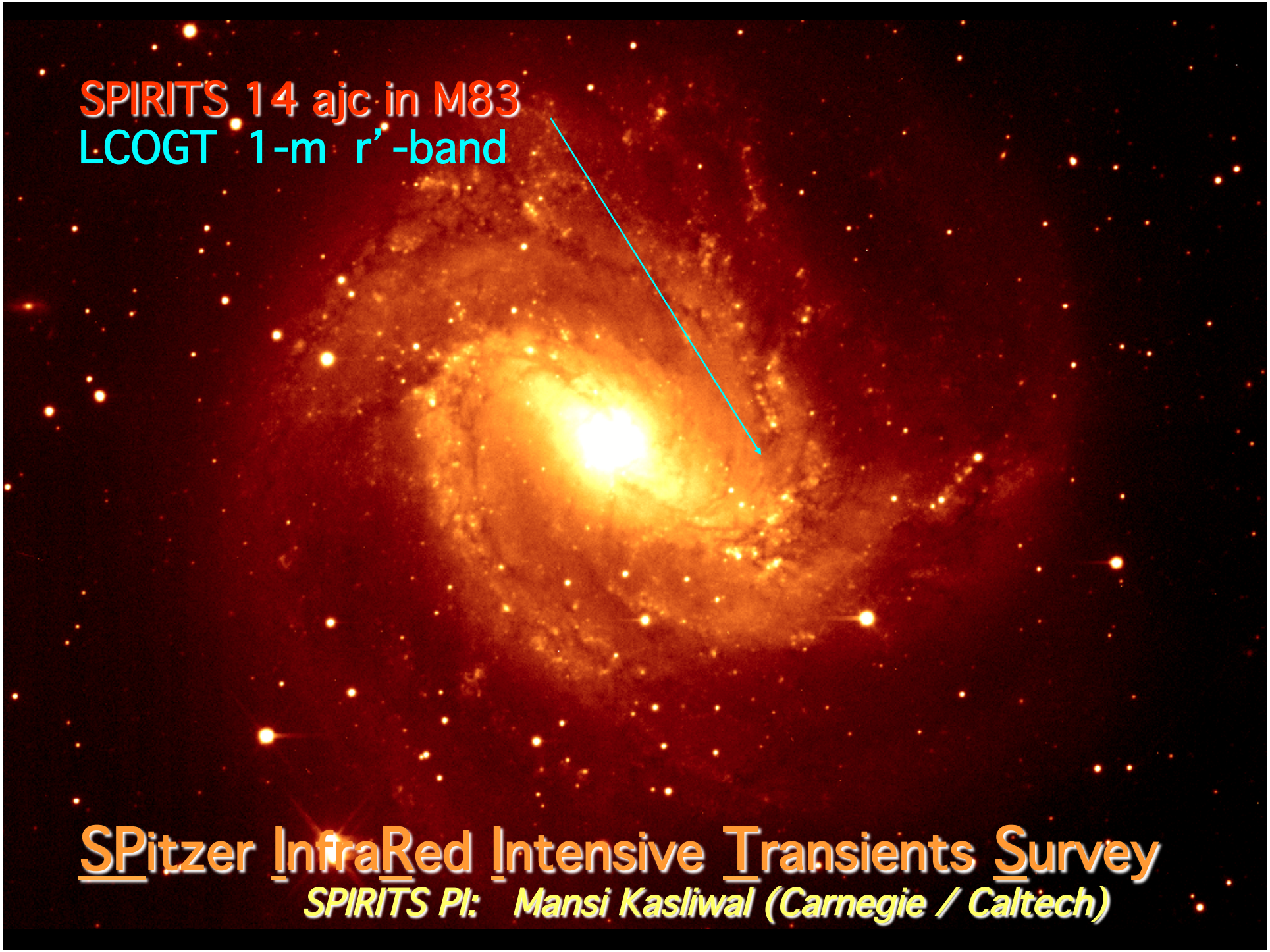


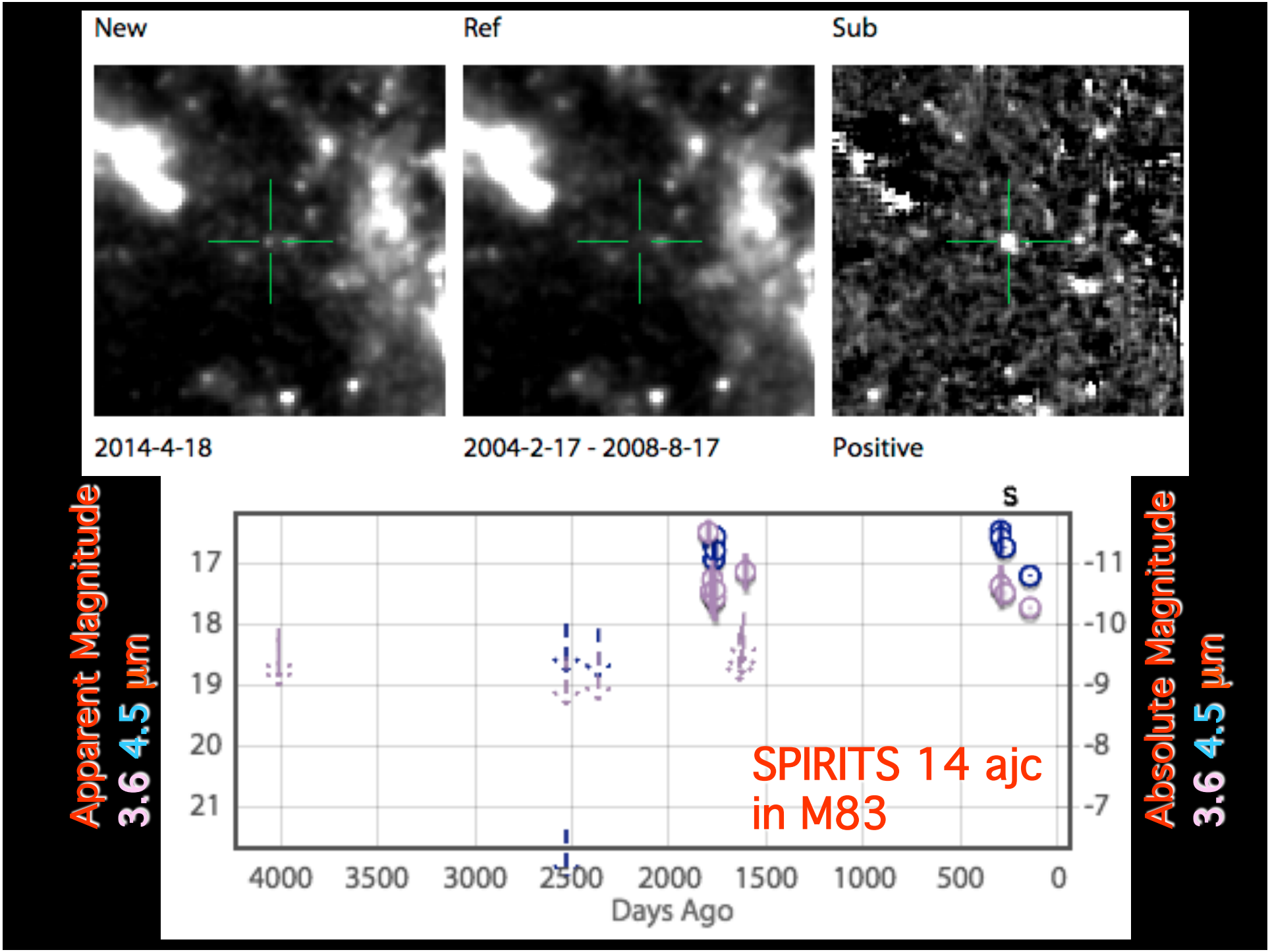
Protostellar Outflow Feedback:

Small, V< 100 km/s, molecular component ....

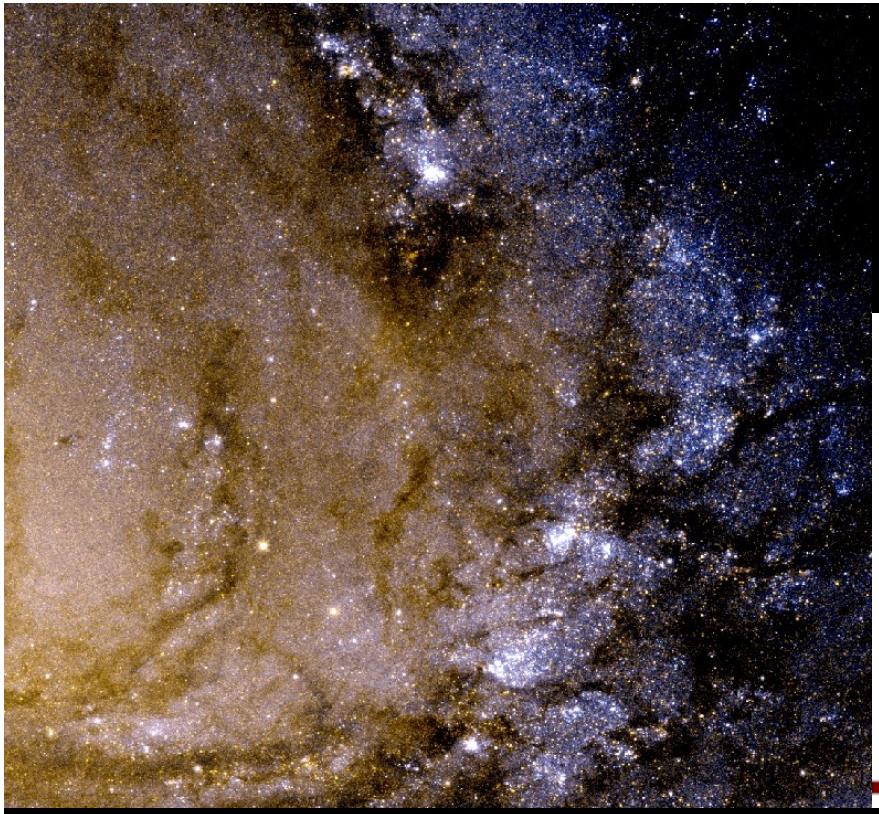
.... giant plasma outflows



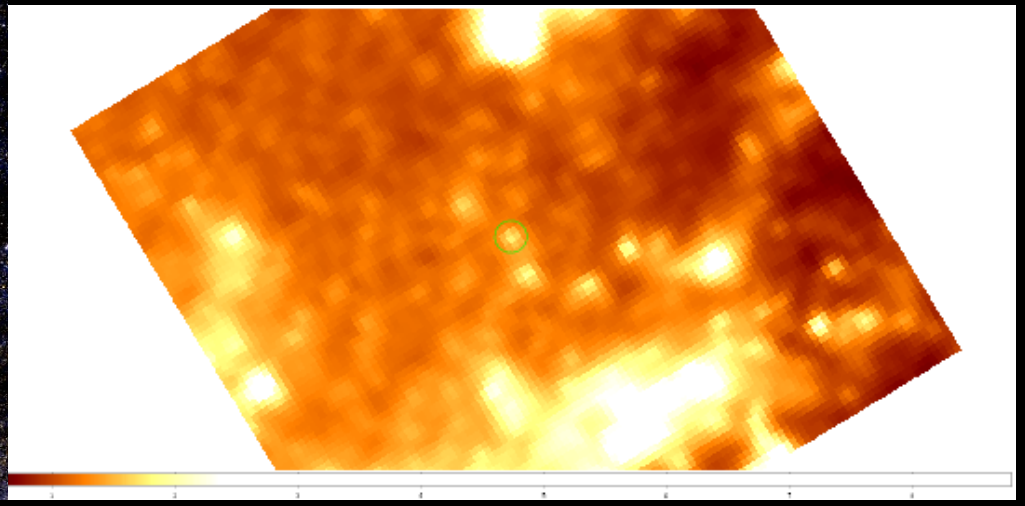

SPIRITS 14 ajc in M83
LCOGT 1-m r'-band
SPitzer InfraRed Intensive Transients Survey
SPIRITS PI: Mansi Kasliwal (Carnegie / Caltech)


New
Ref
Sub
2014-4-18
2004-2-17 - 2008-8-17
Positive
Apparent Magnitude
3.6 4.5 μm
Absolute Magnitude
3.6 4.5 μm
S
17
18
19
20
21
-11
-10
-9
-8
-7
4000
3500
3000
2500
2000
1500
1000
500
0
Days Ago
SPIRITS 14 ajc
in M83

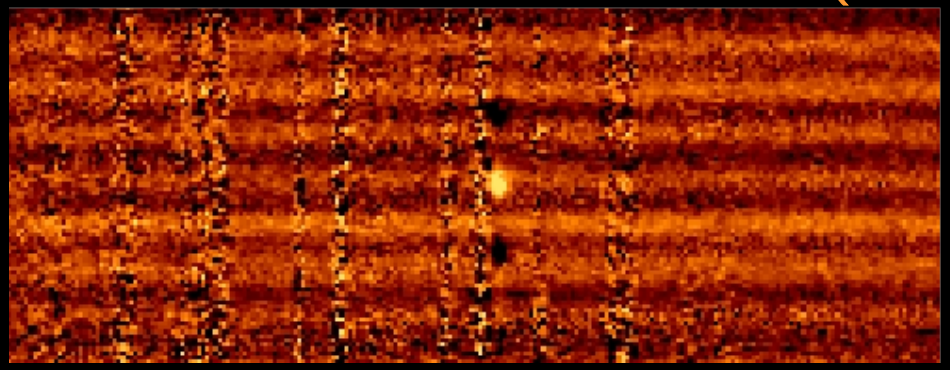
SPIRITS 14 ajc in M83



Archival HST image



SPIRITS 4.5 μm / HST TOO i
(Howard Bond)



Keck / Mosfire H2 S(1) line 2.1218 μm line

ΔV < 100 km/s
Compact (< 0.8”)
< 10 pc

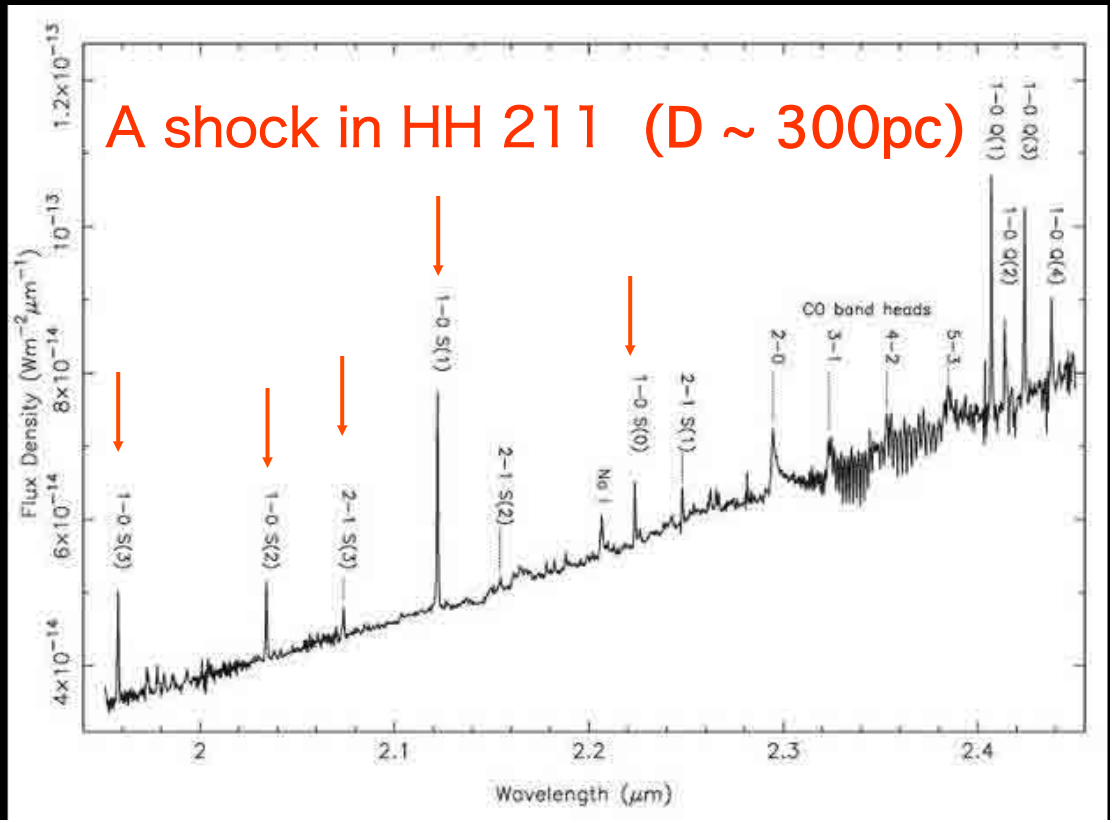
M83 SPIRITS 14ajc

A pure near-IR (K-band) molecular hydrogen Emission line Spectrum

Rest λ	Transition	Rel. Intensity
1.9576	1-0 S(3)	0.64
2.0338	1-0 S(2)	0.26
2.0735	2-1 S(3)	0.20
2.1218	1-0 S(1)	1.00
2.2235	1-0 S(0)	0.28

$L(H_2) \sim 10^2 - 10^4\ L_o$!
From R < 10 pc region

(for $F[H_2\ S(1)] \sim 10^{-18} - 10^{-16}$ erg s^{-1} cm^{-2})



FUV (912 A < λ < ~2,000 A) Feedback:

Soft-UV Heating:

E > 6 eV

T ~ 1000 K

Intermediate Mass Stars (2 - 9 M_O)

NGC 2023 in Orion

Stellar Wind + EUV + FUV Feedback:

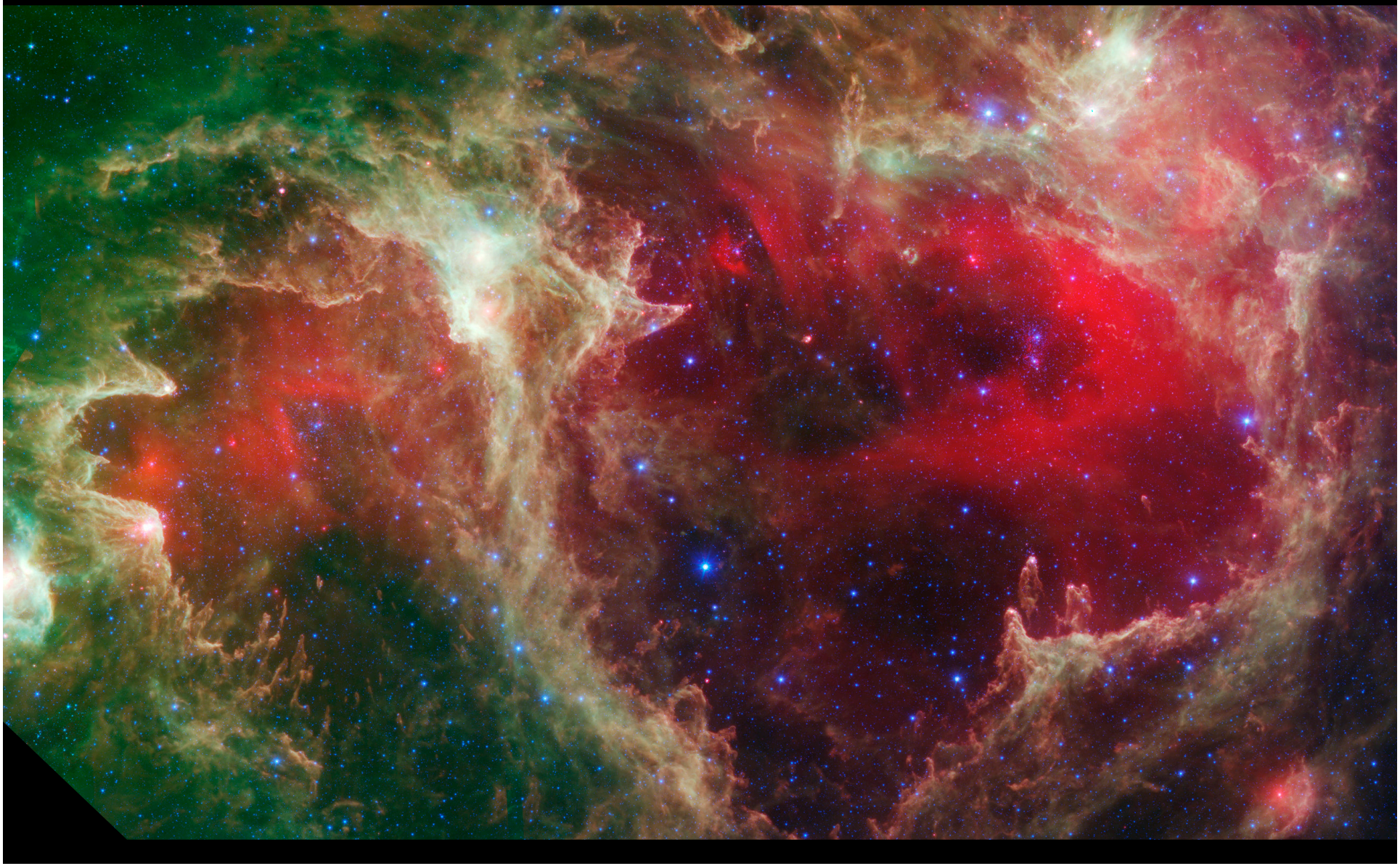
Thor's helmet:
NGC 2359

A wind-bubble blown by a massive star

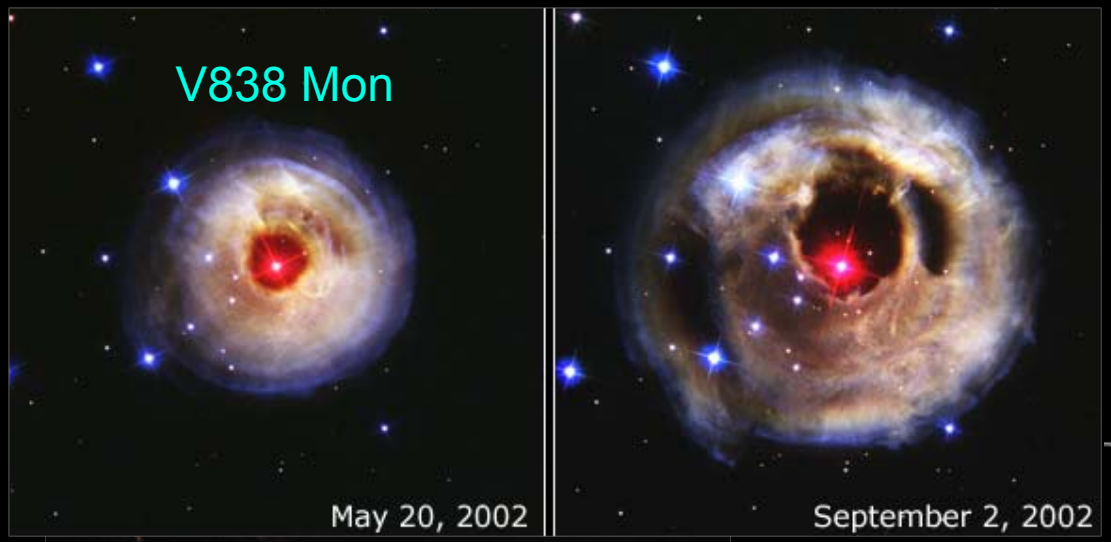
HD 56925

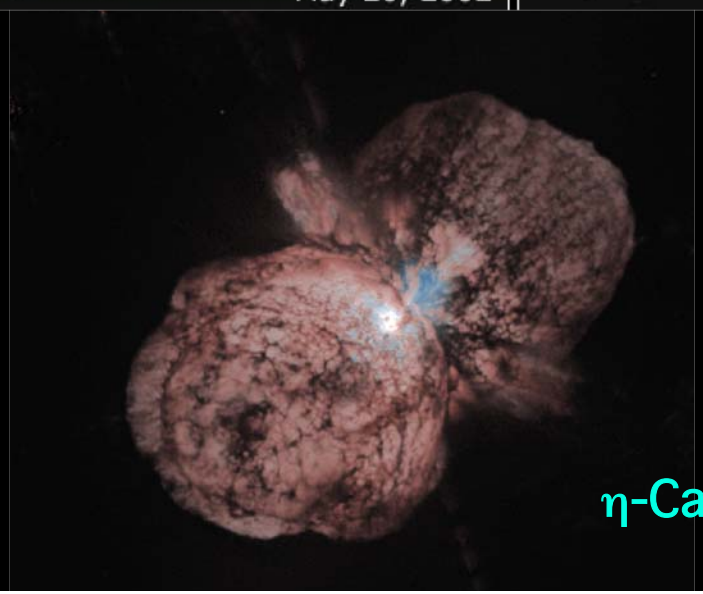
Ionizing-UV ($\lambda < 912$A) Feedback: W5 HII region

4.5, 8, 24 μm



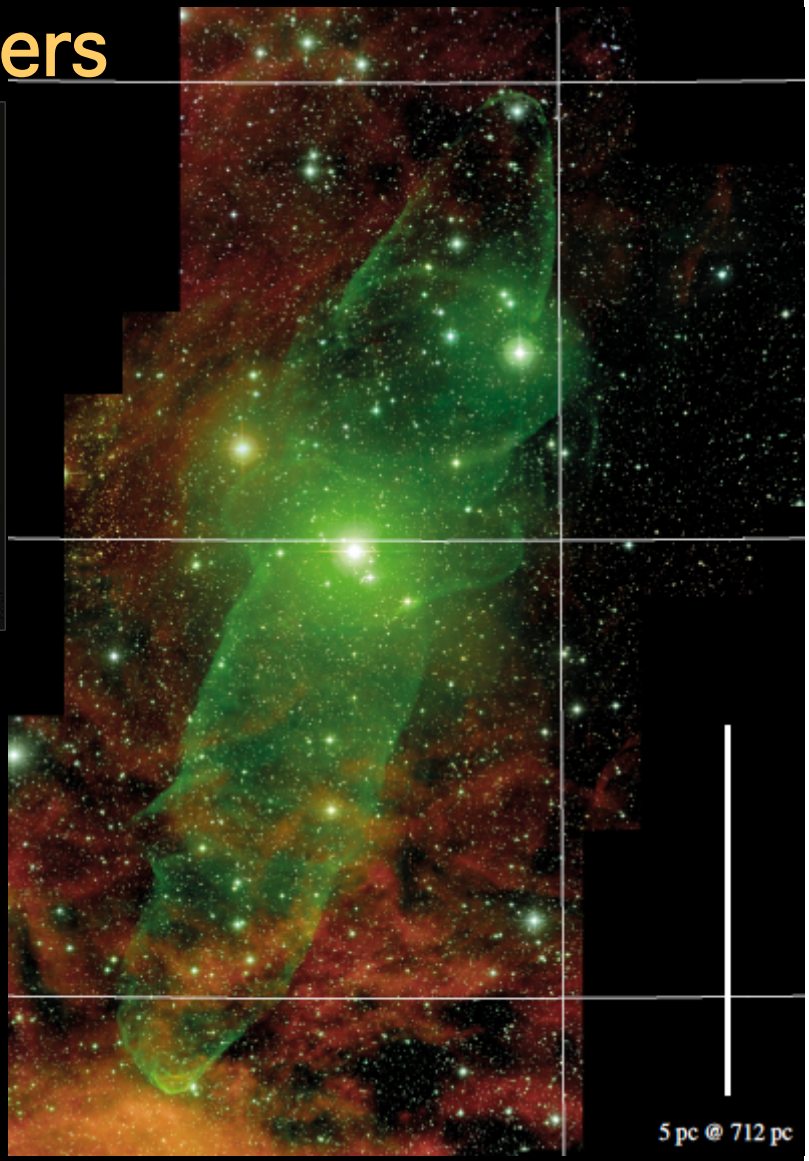
Post-Main-sequence Feedback:
WR stars, LBVs, RSGs, Close-binaries & mergers

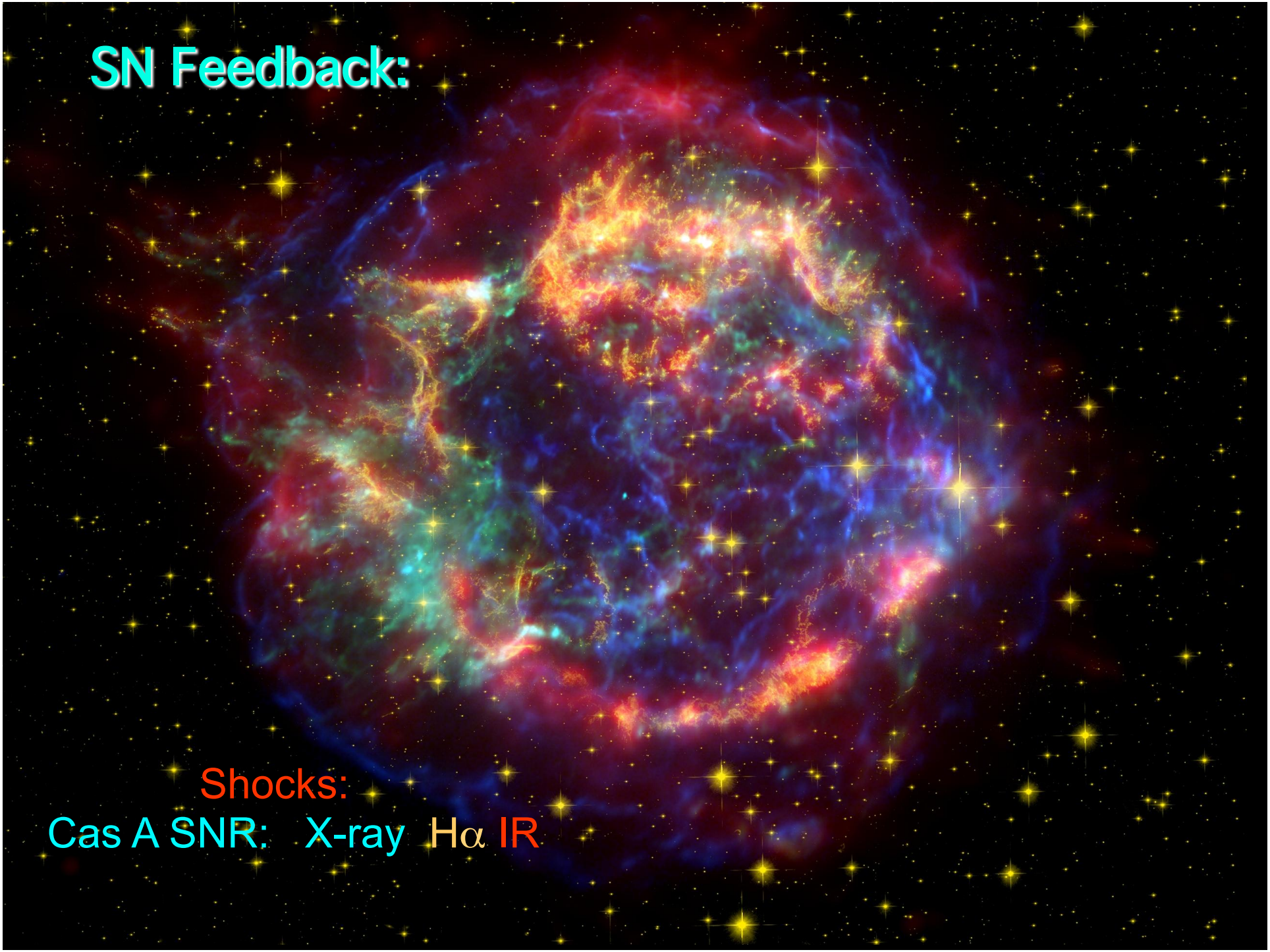


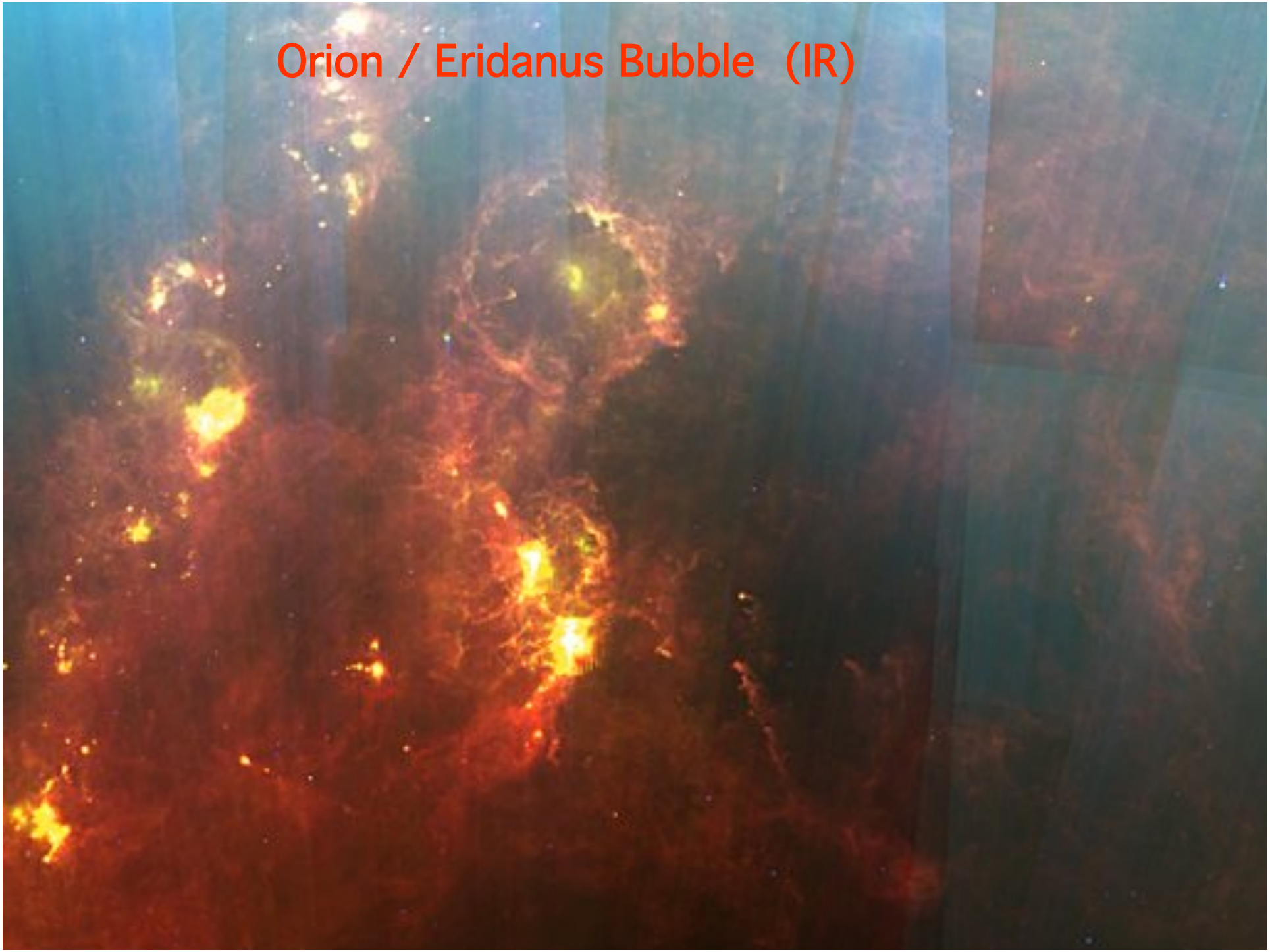


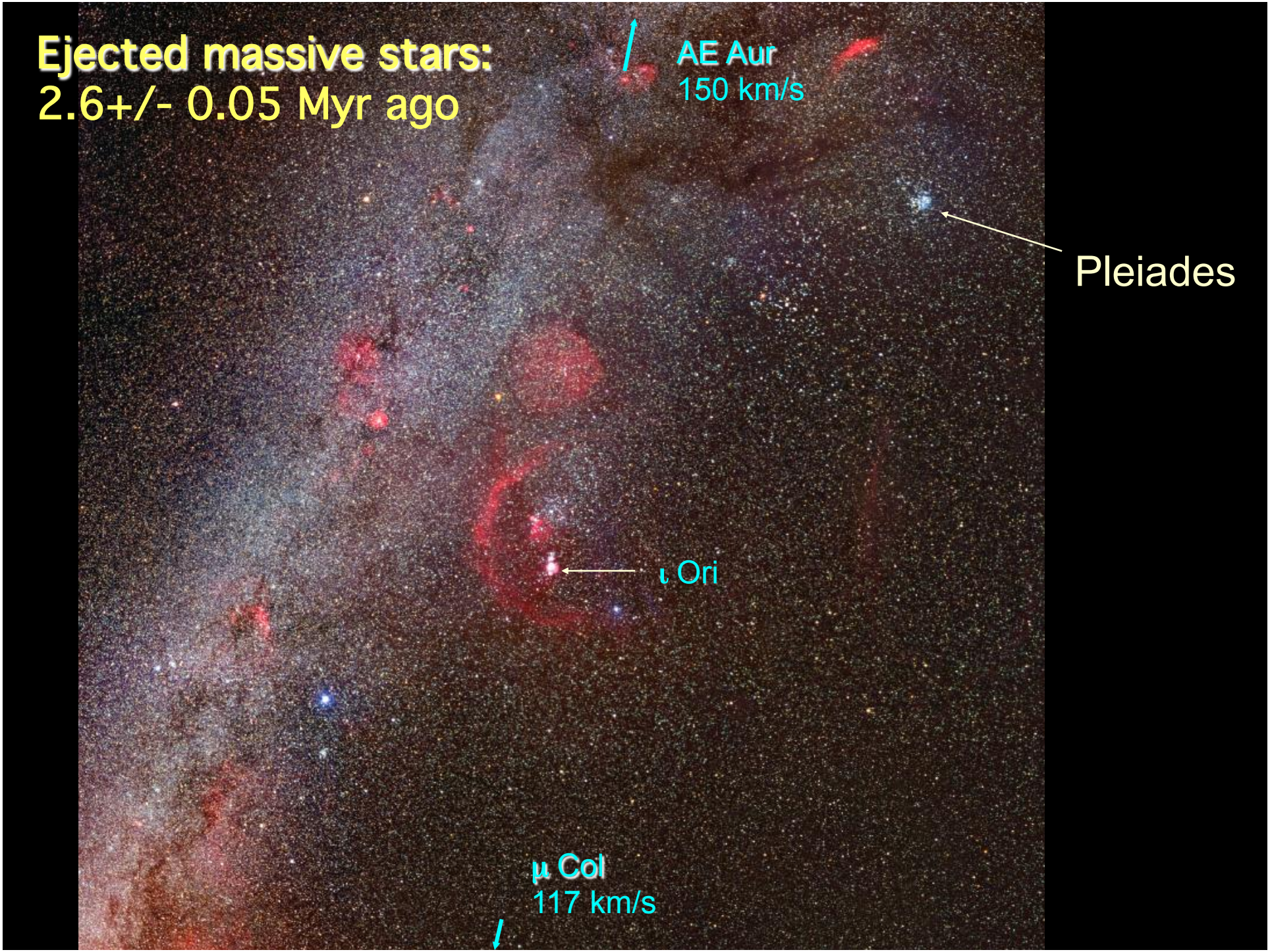
η-Carina

Ou4 (Corradi 2014) in Sh2-129



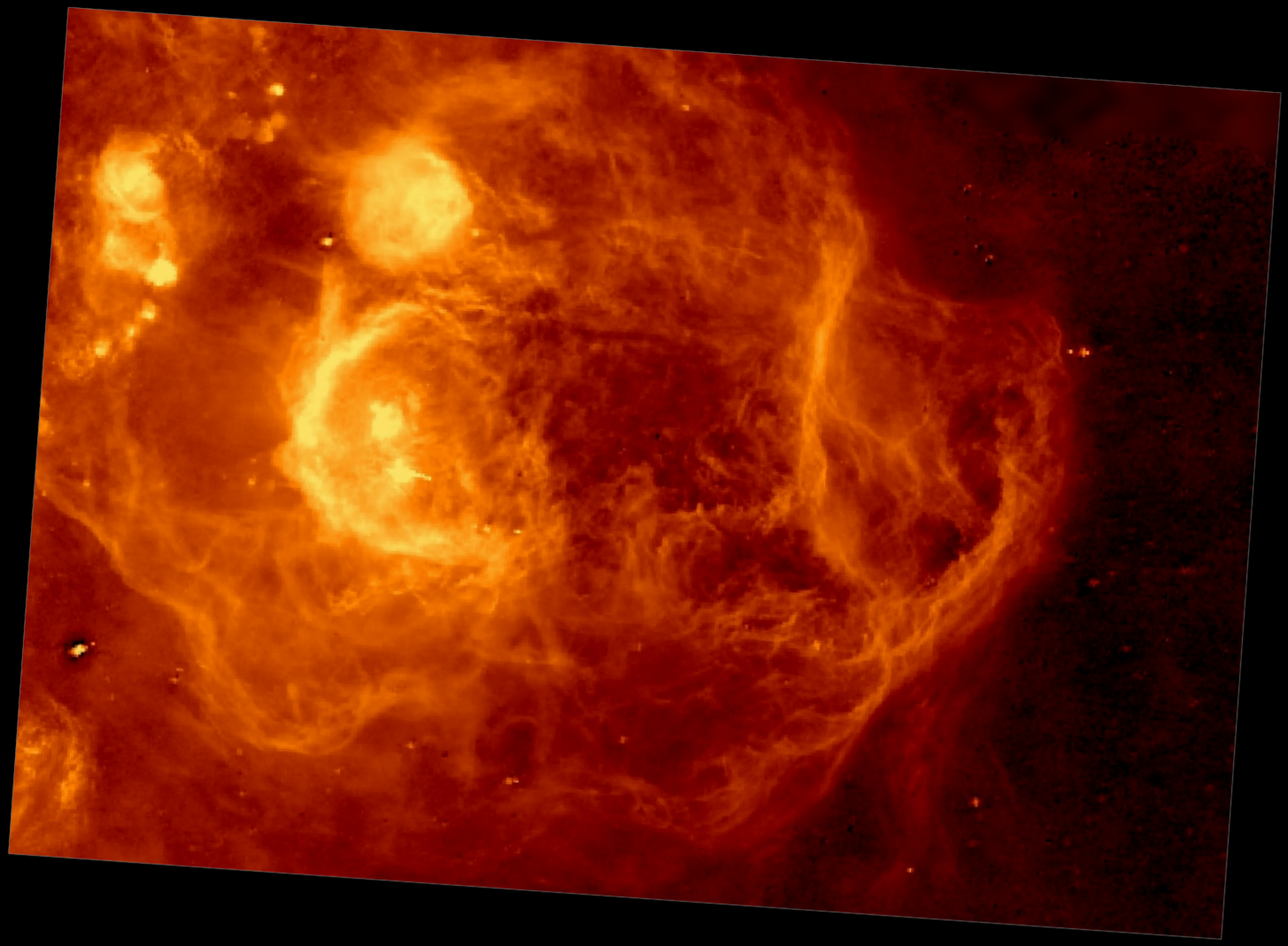

SN Feedback:
Shocks:
Cas A SNR: X-ray Hα IR

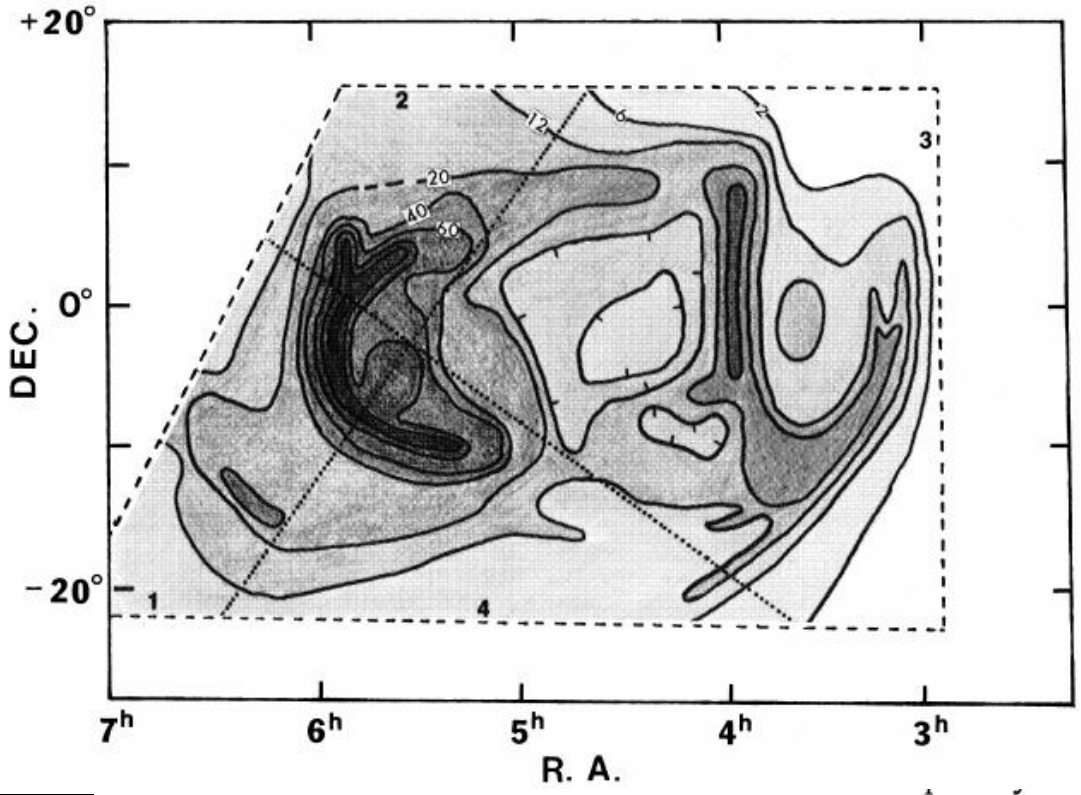

Orion / Eridanus Bubble (IR)

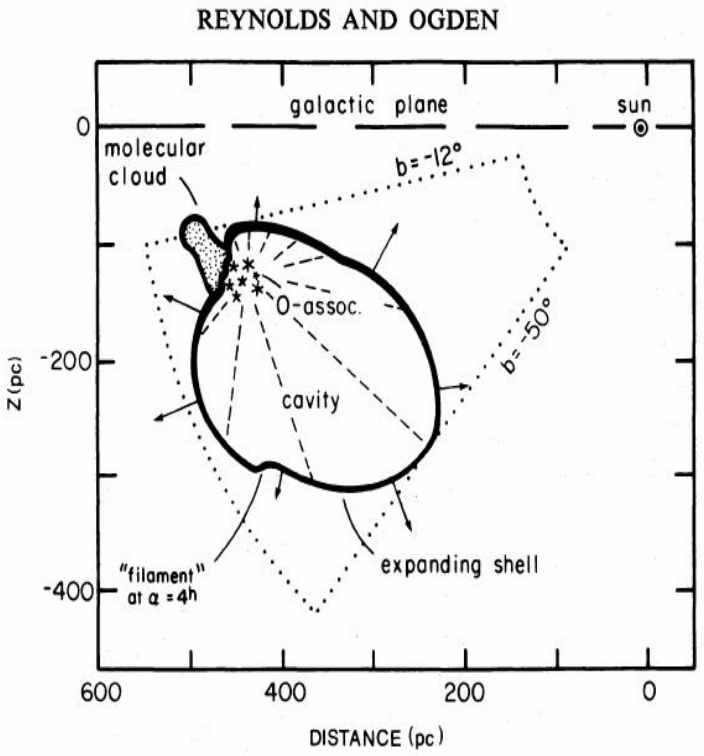

Ejected massive stars:
2.6+/- 0.05 Myr ago
AE Aur
150 km/s
Pleiades
ι Ori
μ Col
117 km/s

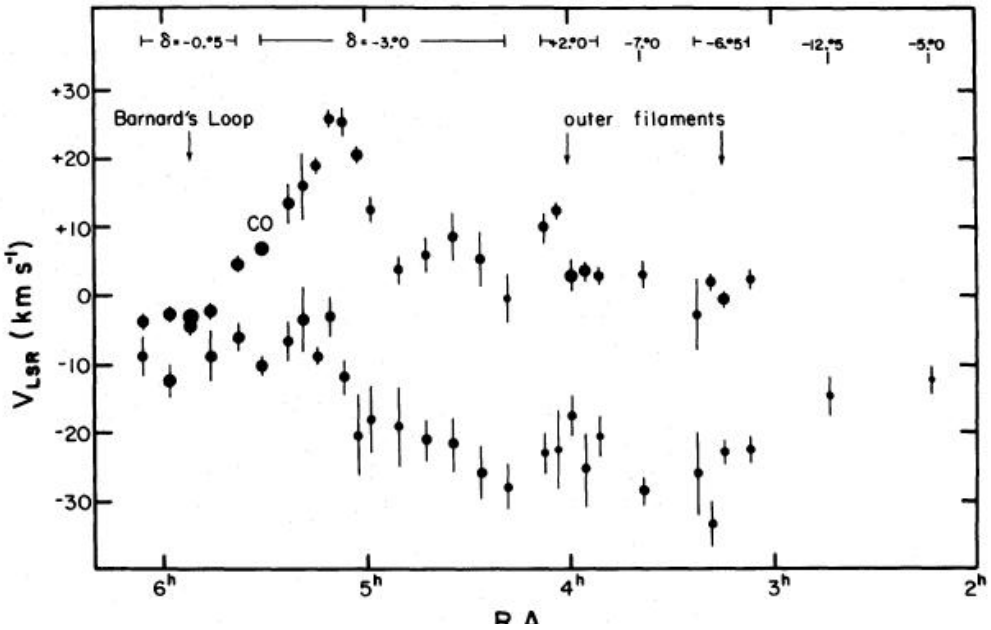
Orion / Eridanus superbubble: Hα

Pon, Johnstone, Bally, & Heiles 2014





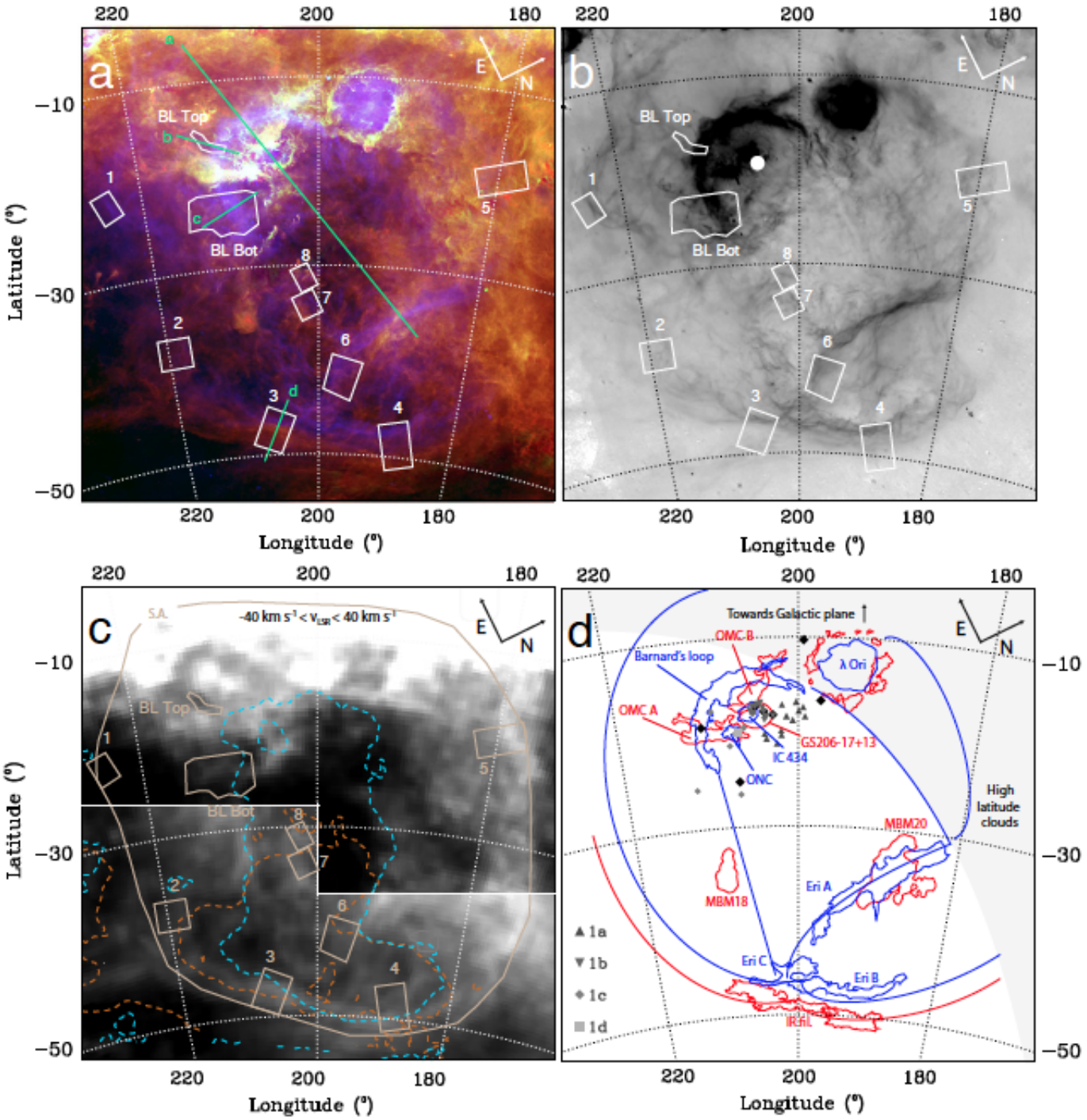




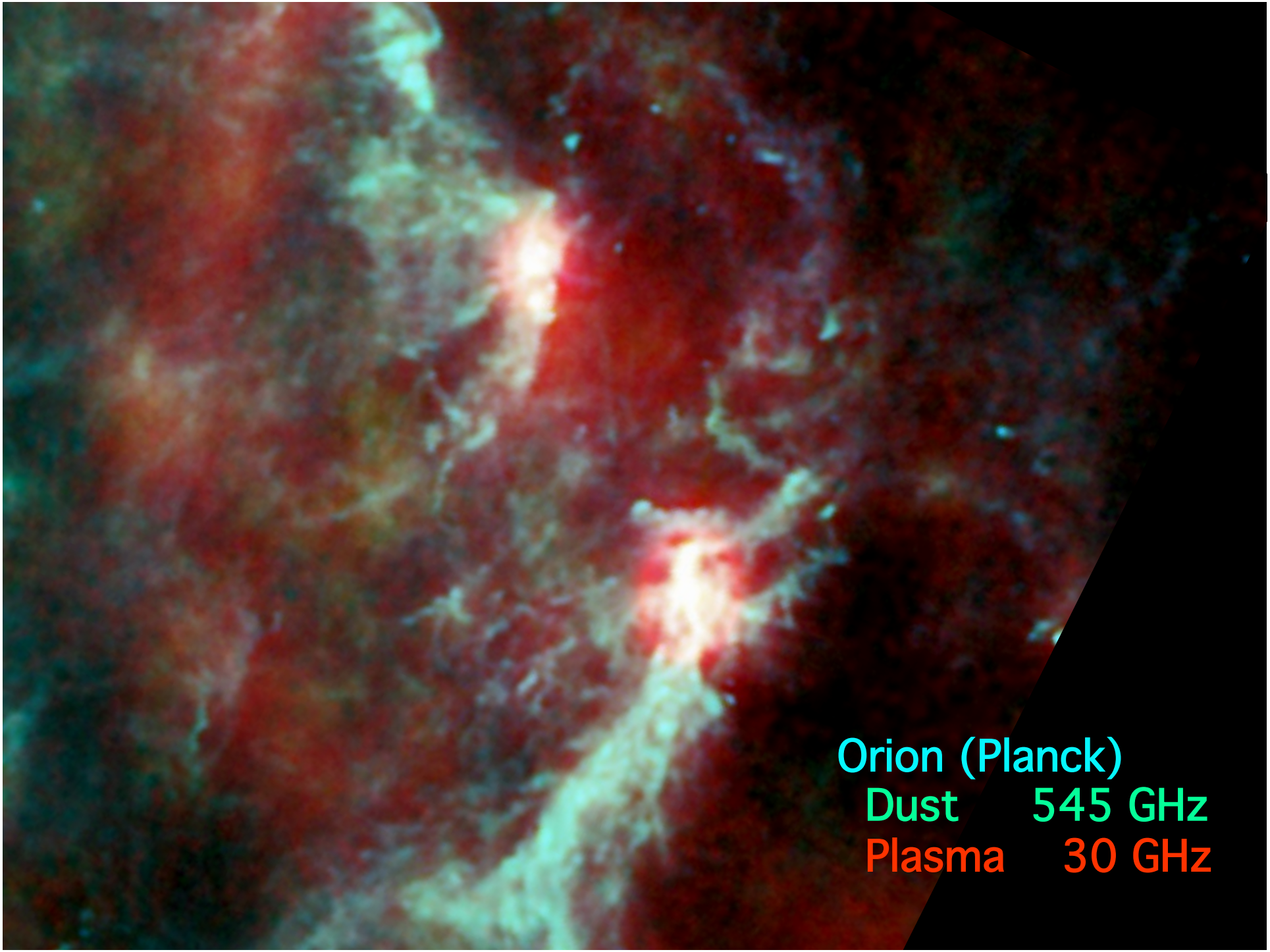
Orion / Eridanus superbubble & Barnard's Loop

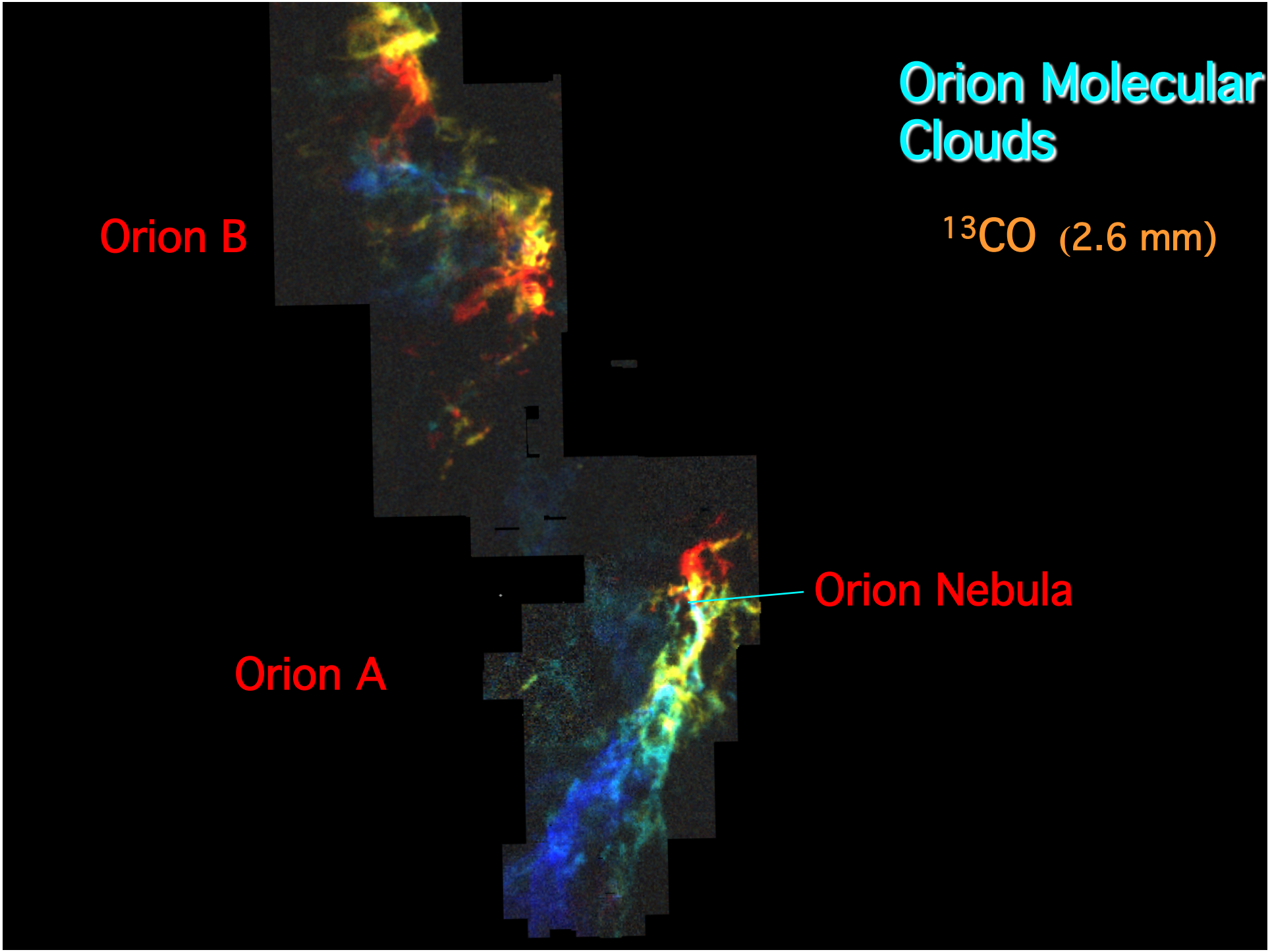
Hα (Reynolds & Ogden 79)

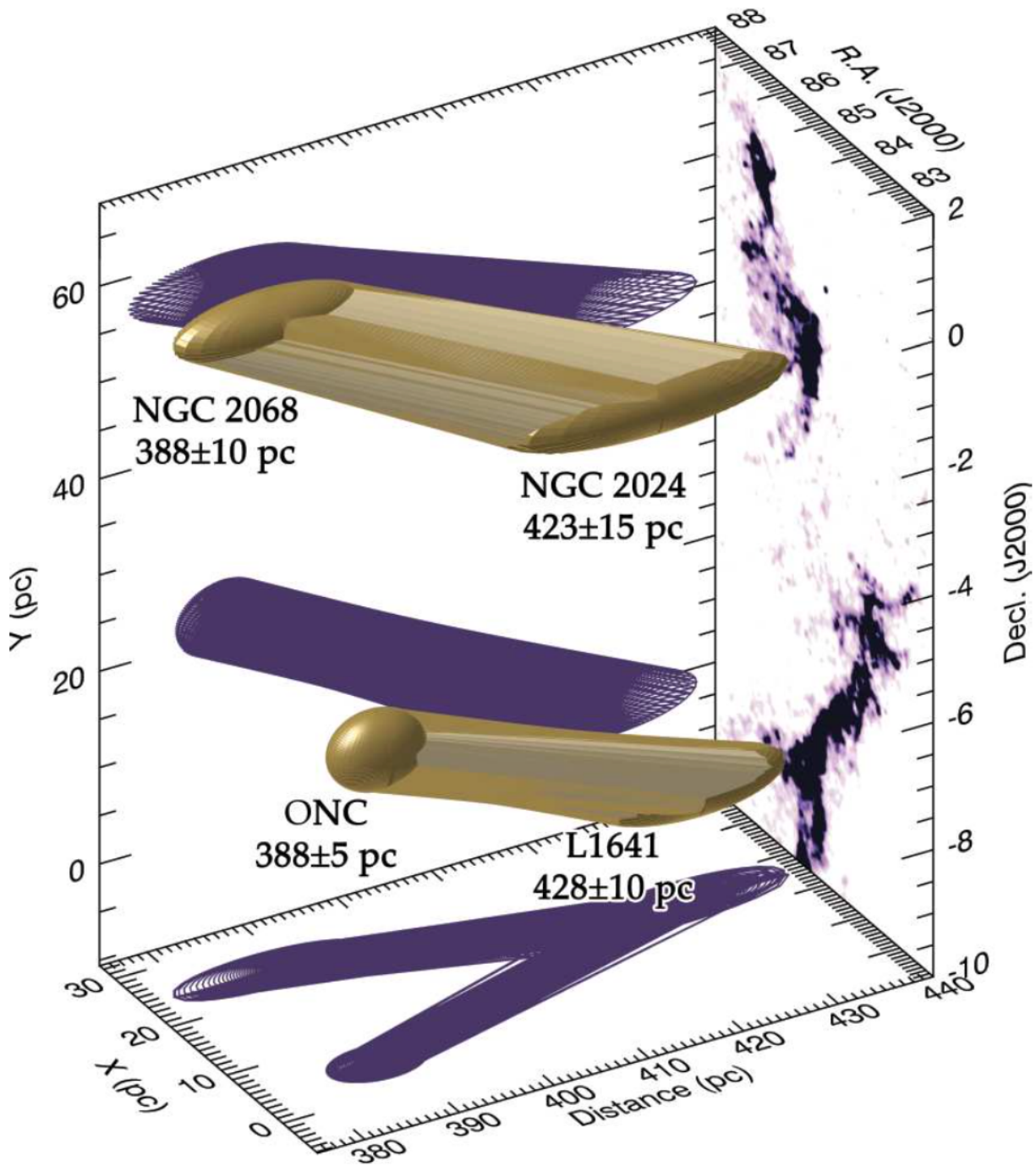
- recent (0.3 Myr) SNR (Ochsendorf+ 15)
- soft X-ray (Cowie+ 79)
- ^{26}Al + ^{60}Fe (Diehl+ 04; 06)



Bram Ochsendorf (2015)


Orion (Planck)
Dust 545 GHz
Plasma 30 GHz


Orion Molecular Clouds
^{13}CO (2.6 mm)
Orion B
Orion Nebula
Orion A

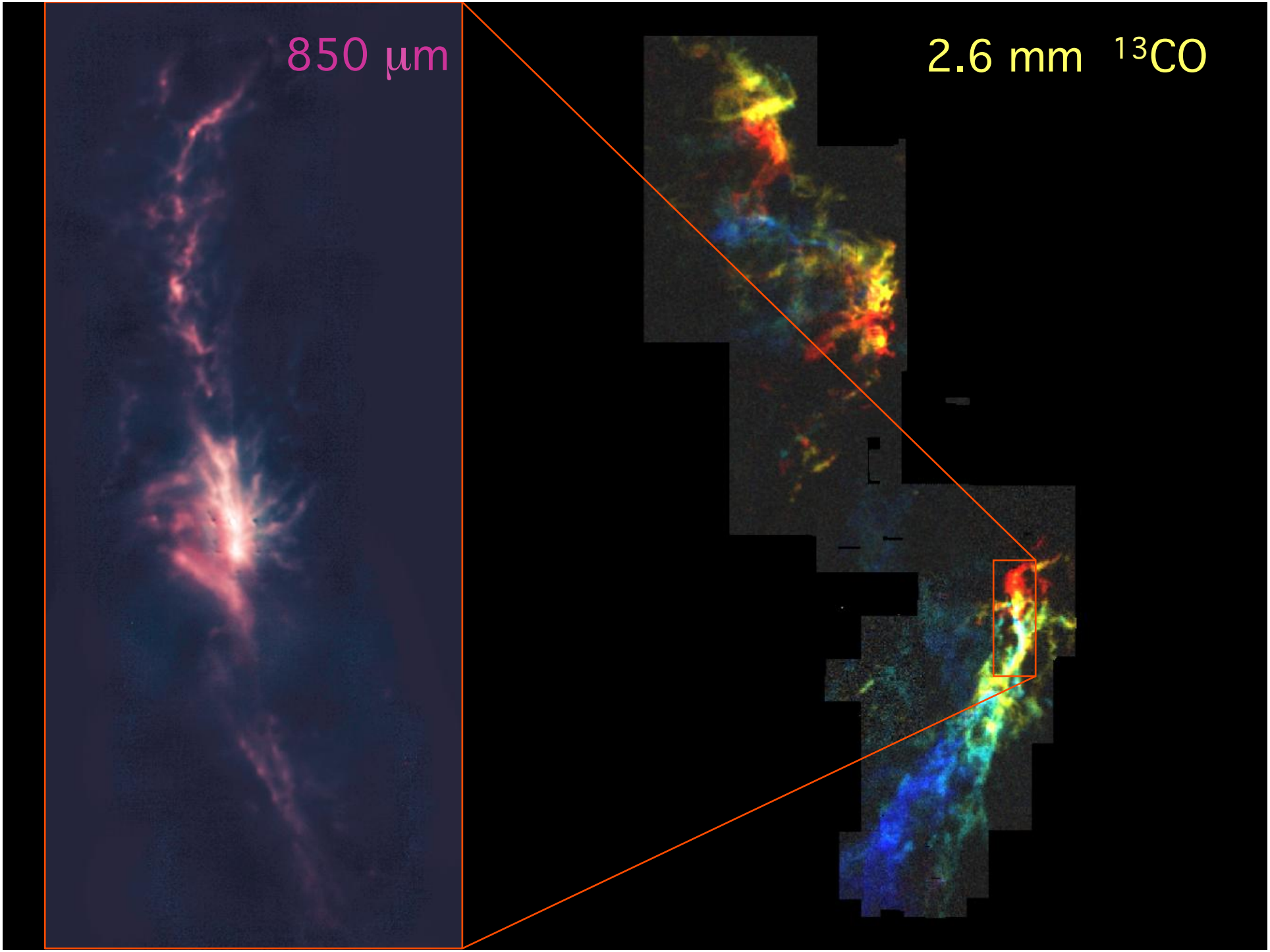


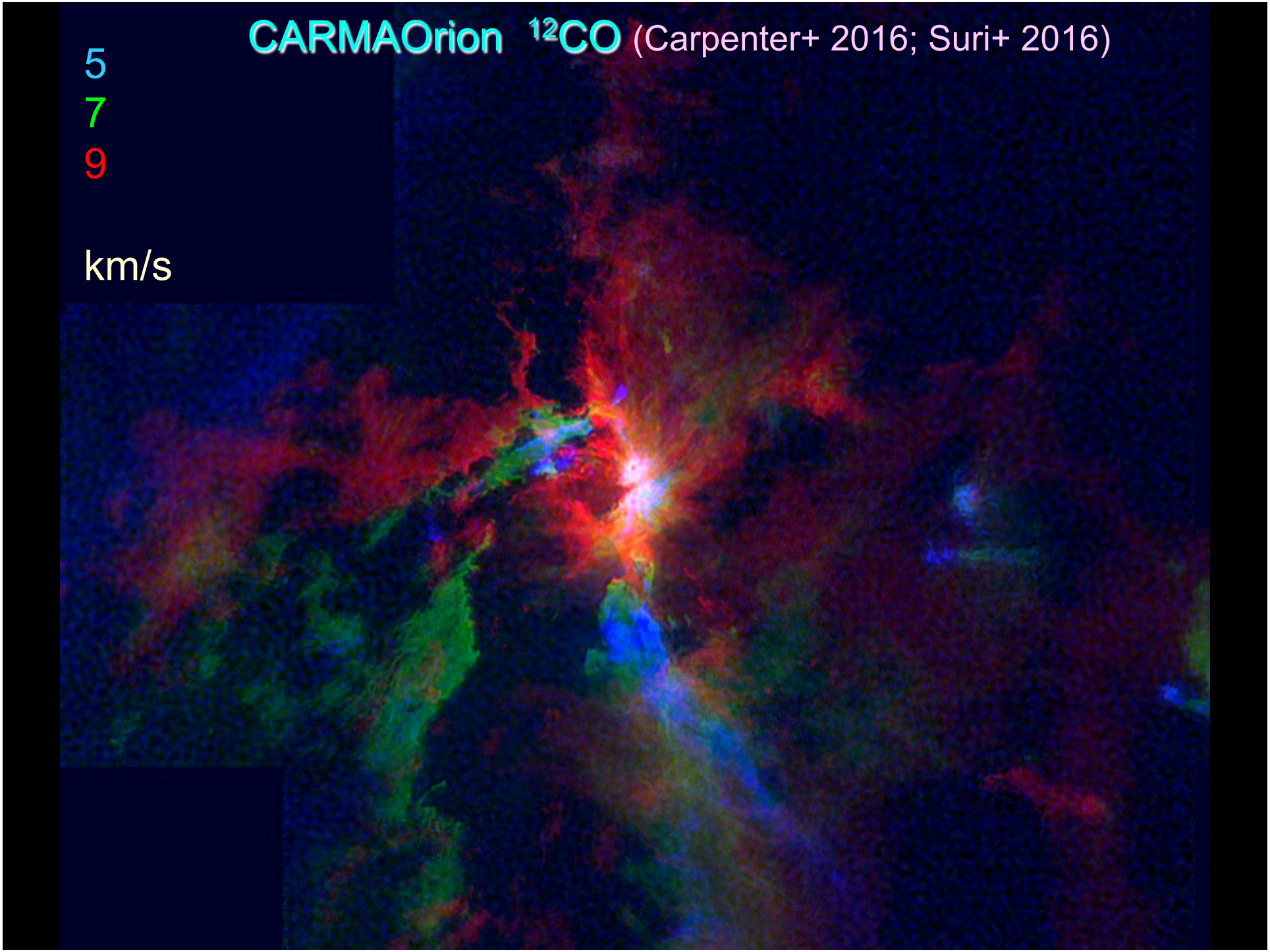
Orion Distances:

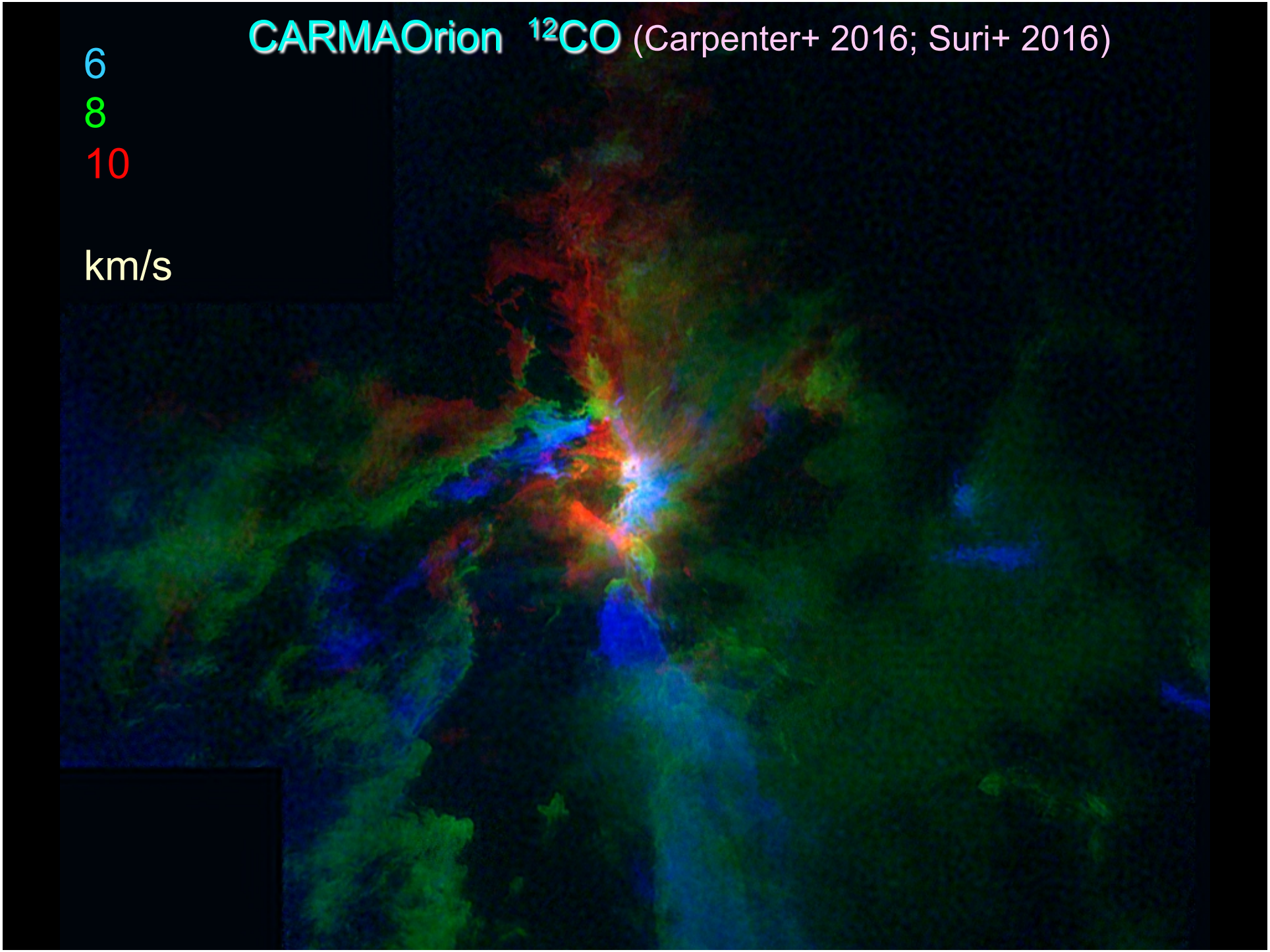
VLBA
radio parallax

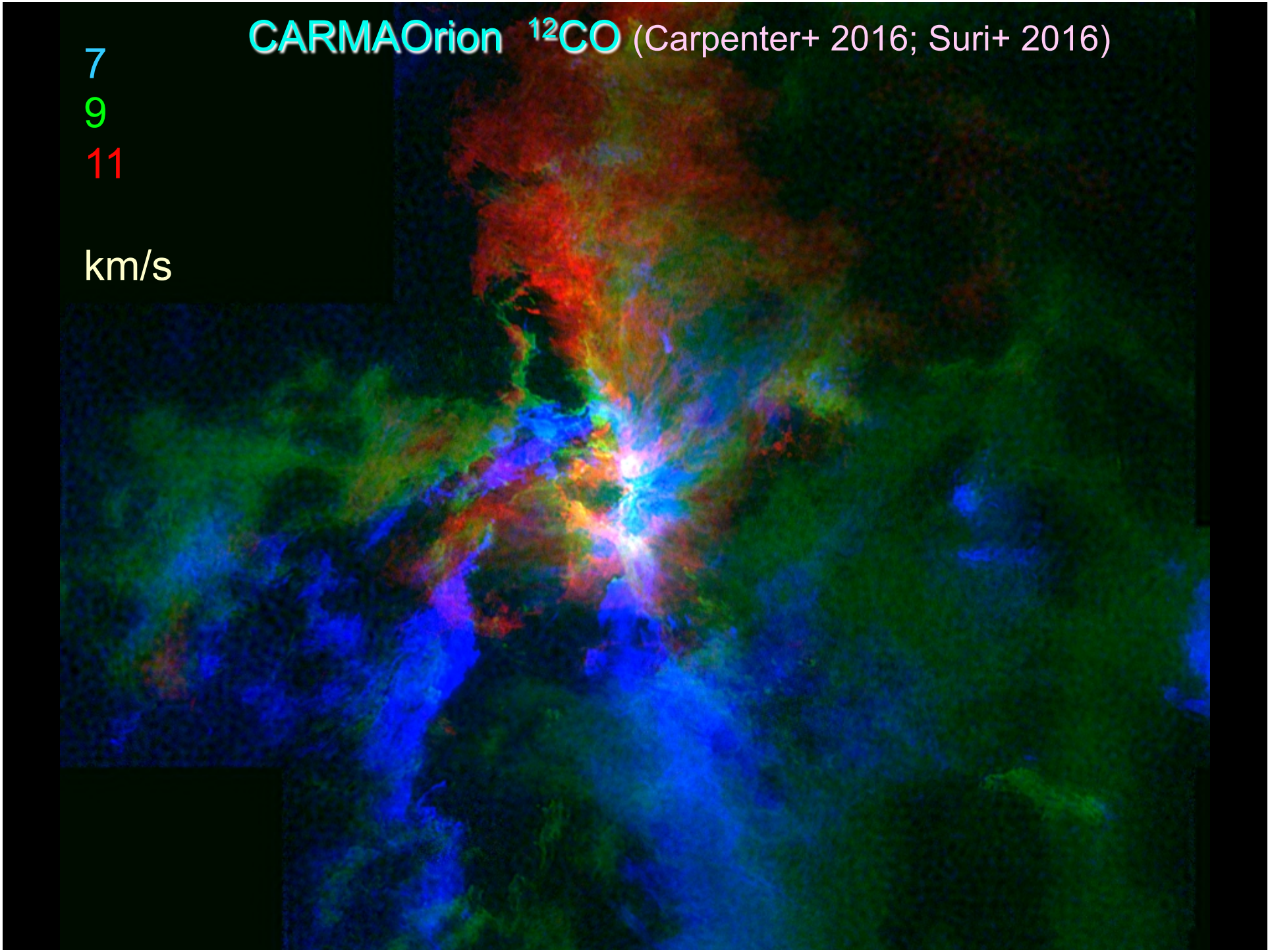
Kounkel M. et al.
2014, ApJ, 790, 49

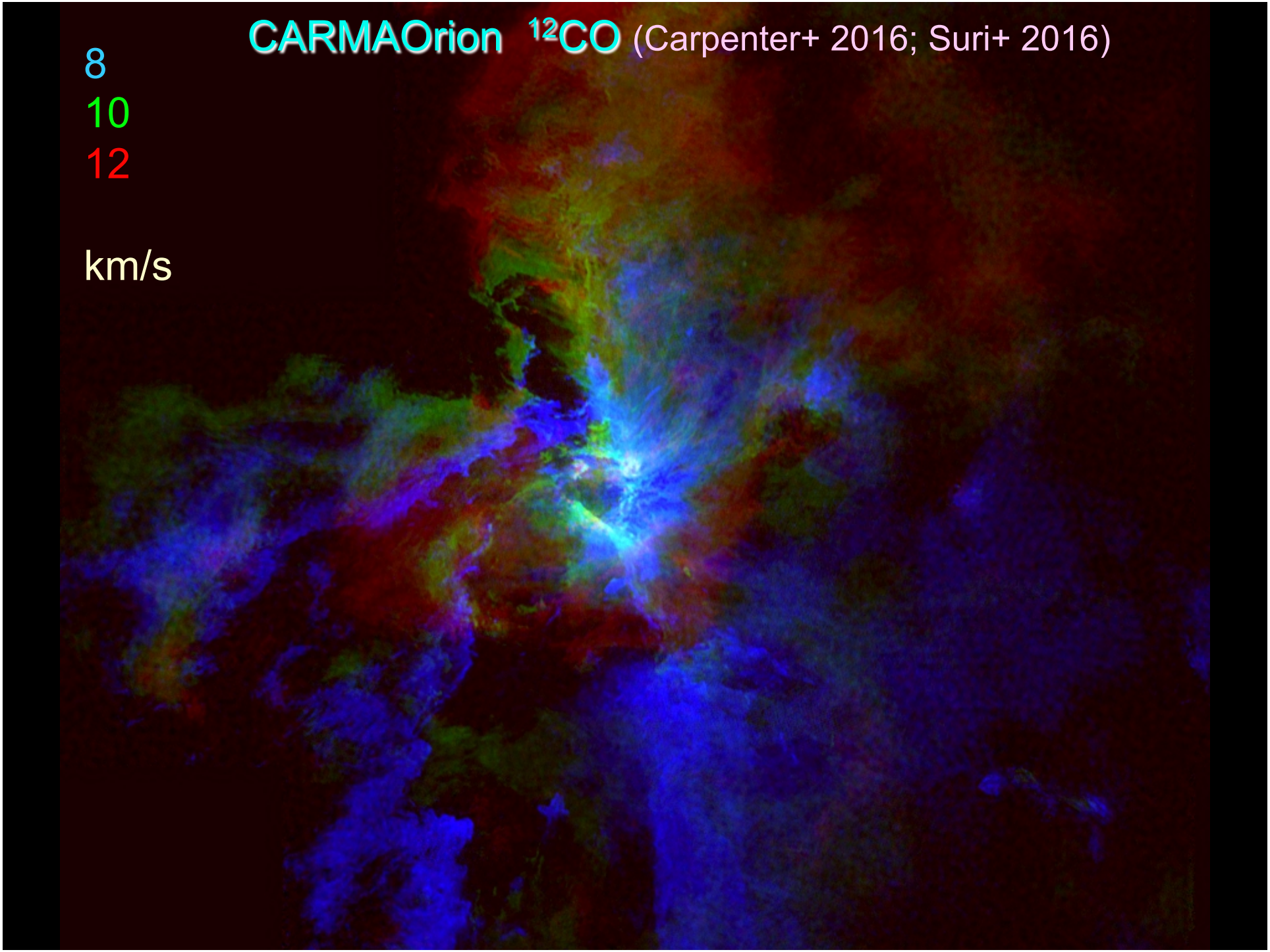
Kounkel M. et al.
2016,
arXiv1609.04041v1


850 μm
2.6 mm ^{13}CO


CARMAOrion ^{12}CO (Carpenter+ 2016; Suri+ 2016)
5
7
9
km/s


CARMAOrion ^{12}CO (Carpenter+ 2016; Suri+ 2016)
6
8
10
km/s

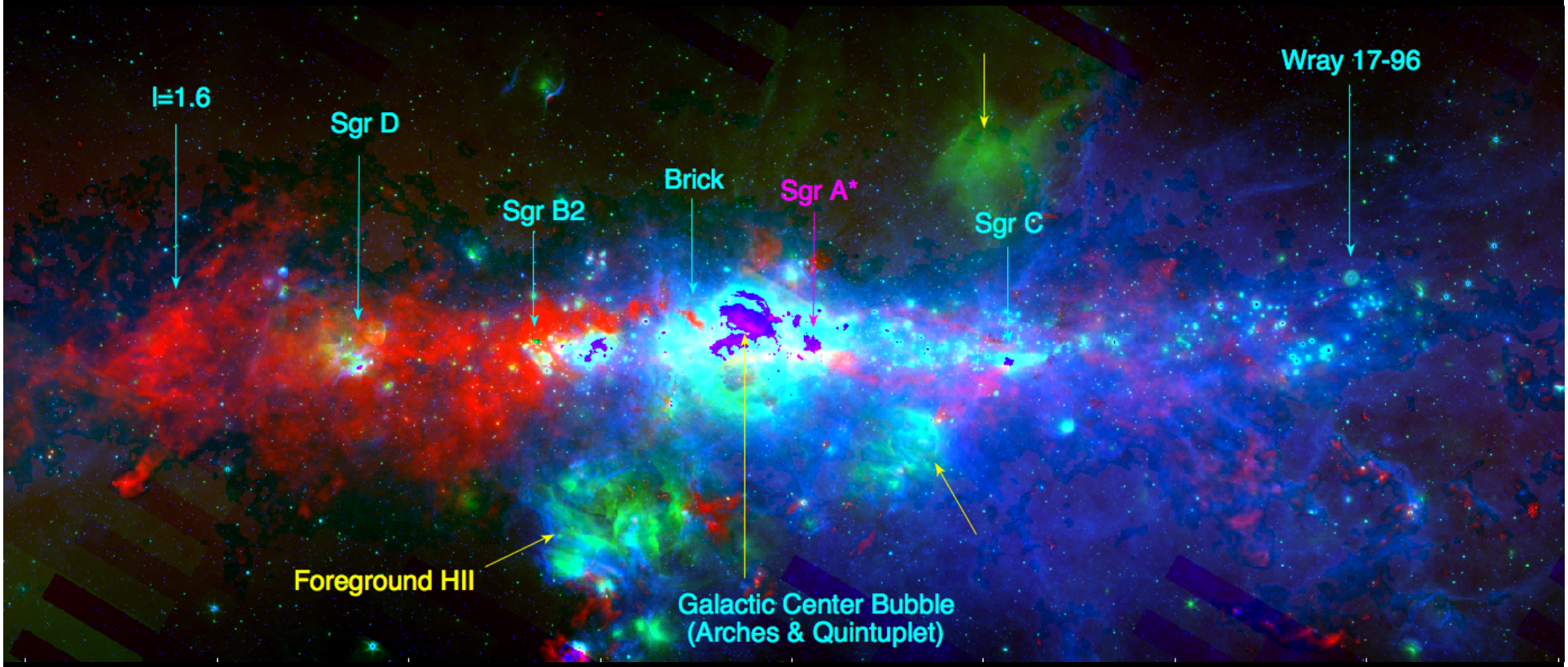

CARMAOrion ^{12}CO (Carpenter+ 2016; Suri+ 2016)
7
9
11
km/s


CARMAOrion ^{12}CO (Carpenter+ 2016; Suri+ 2016)
8
10
12
km/s

Galactic Center

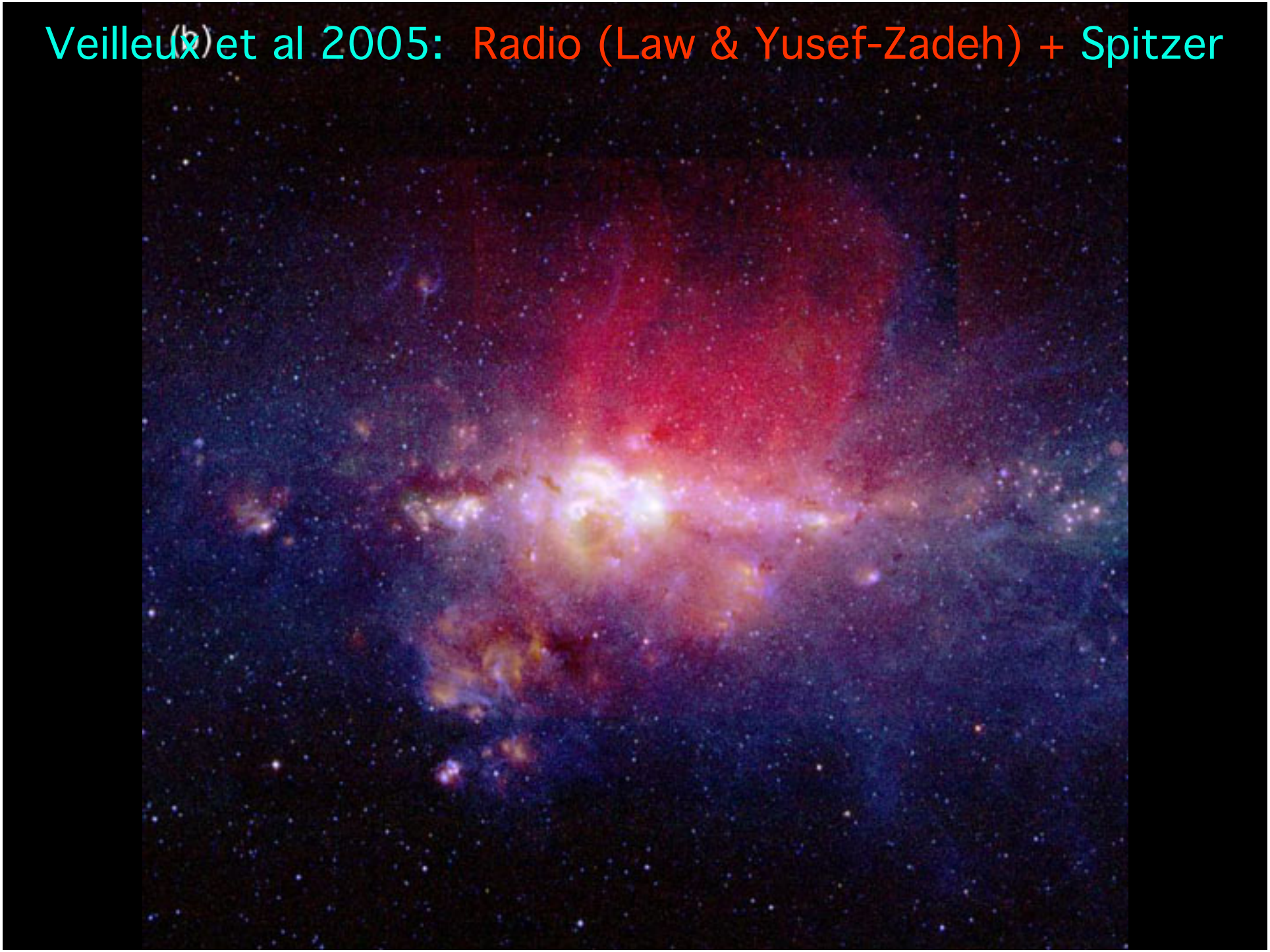
8 μm 24 μm NH_2

Asymmetries caused by Feedback ?

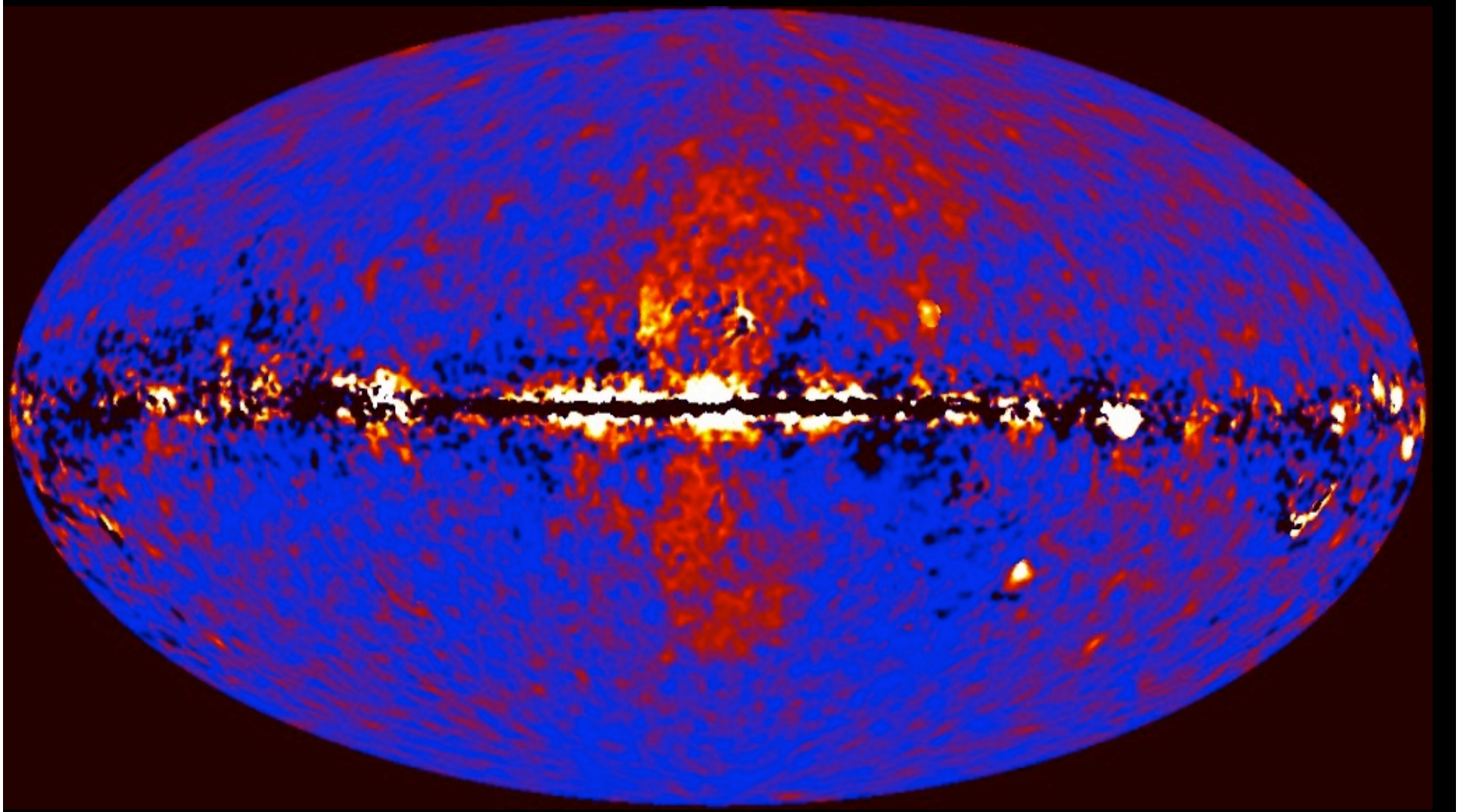


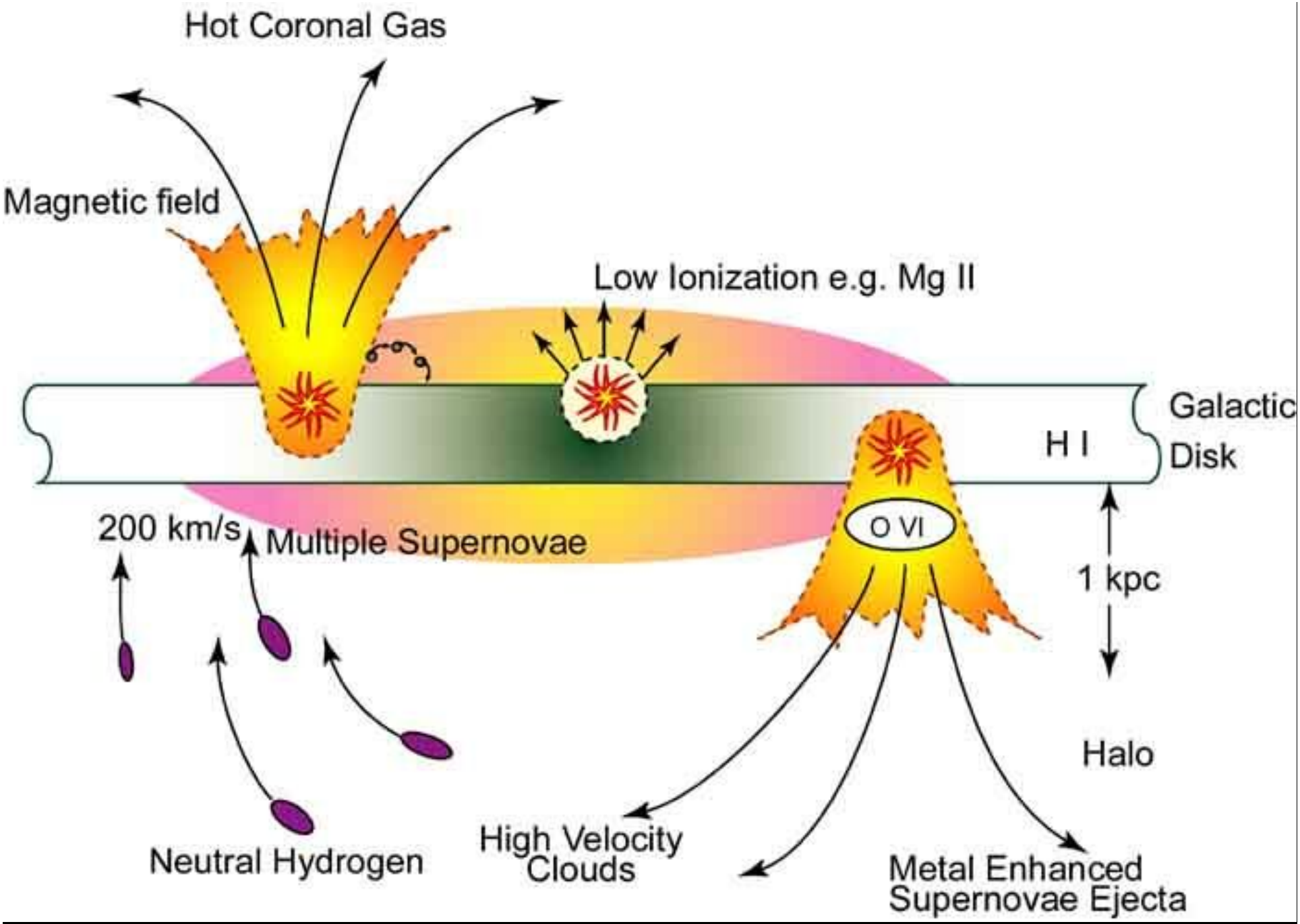
4 Degrees (600 pc)

Veilleux et al 2005: Radio (Law & Yusef-Zadeh) + Spitzer



Fermi/LAT Bubble γ-ray (~1 - 5 GeV) bubble z ~ 5 - 6 kpc




Hot Coronal Gas
Magnetic field
Low Ionization e.g. Mg II
Galactic
Disk
H I
O VI
200 km/s
Multiple Supernovae
1 kpc
Halo
Neutral Hydrogen
High Velocity
Clouds
Metal Enhanced
Supernovae Ejecta

Conclusions: I

Self-Regulation in Star Formation

What stops accretion & determines the IMF?

Feedback + N-body dynamics

The "Feedback Ladder"

Progression of ever stronger feedback impacts

Protostar Outflows =>
FUV/heating =>
EUV/ionization =>
Stellar winds =>
Radiation pressure =>
M.S. dynamic interactions / mergers =>
Post-M.S. outflows =>
SNe

local, low M_*

global, high M_*

Feedback failure => High SFE & bound clusters?

Conclusions: II

Feedback Impacts: far-IR & SOFIA :

- [OI],[CII], [OIII], [NII], high-J CO, hot H_2O at high A_V

  Inner parts of nearby Class O/I YSOs
  MYSOs in Galactic plane & CMZ
  Star-burst galaxies

- High-ionization O, C, N, Si, at high A_V

  Wind bubbles, SNR, Starburst,
  Base of galactic superwinds ...