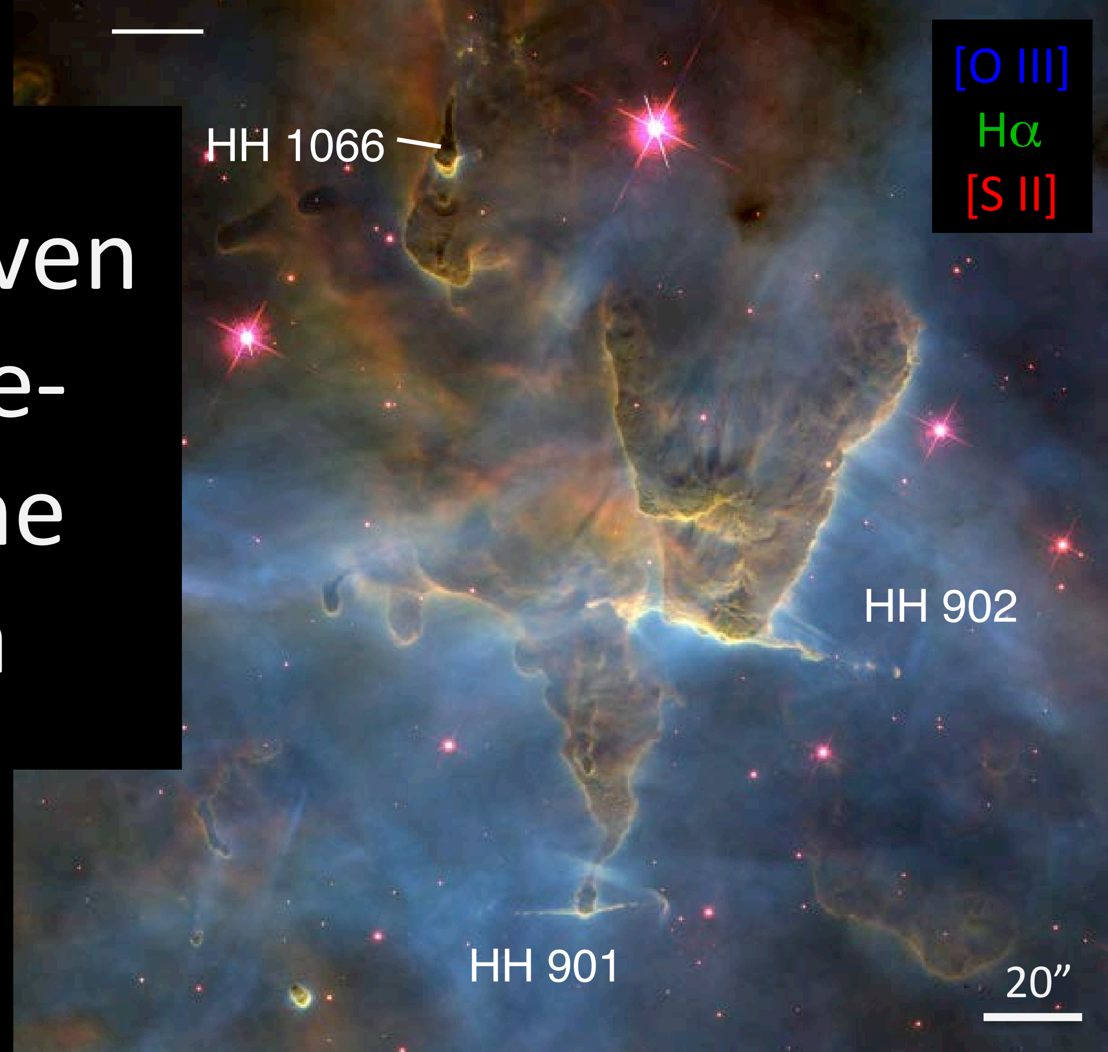
Powerful jets driven by intermediate-mass stars in the Carina Nebula

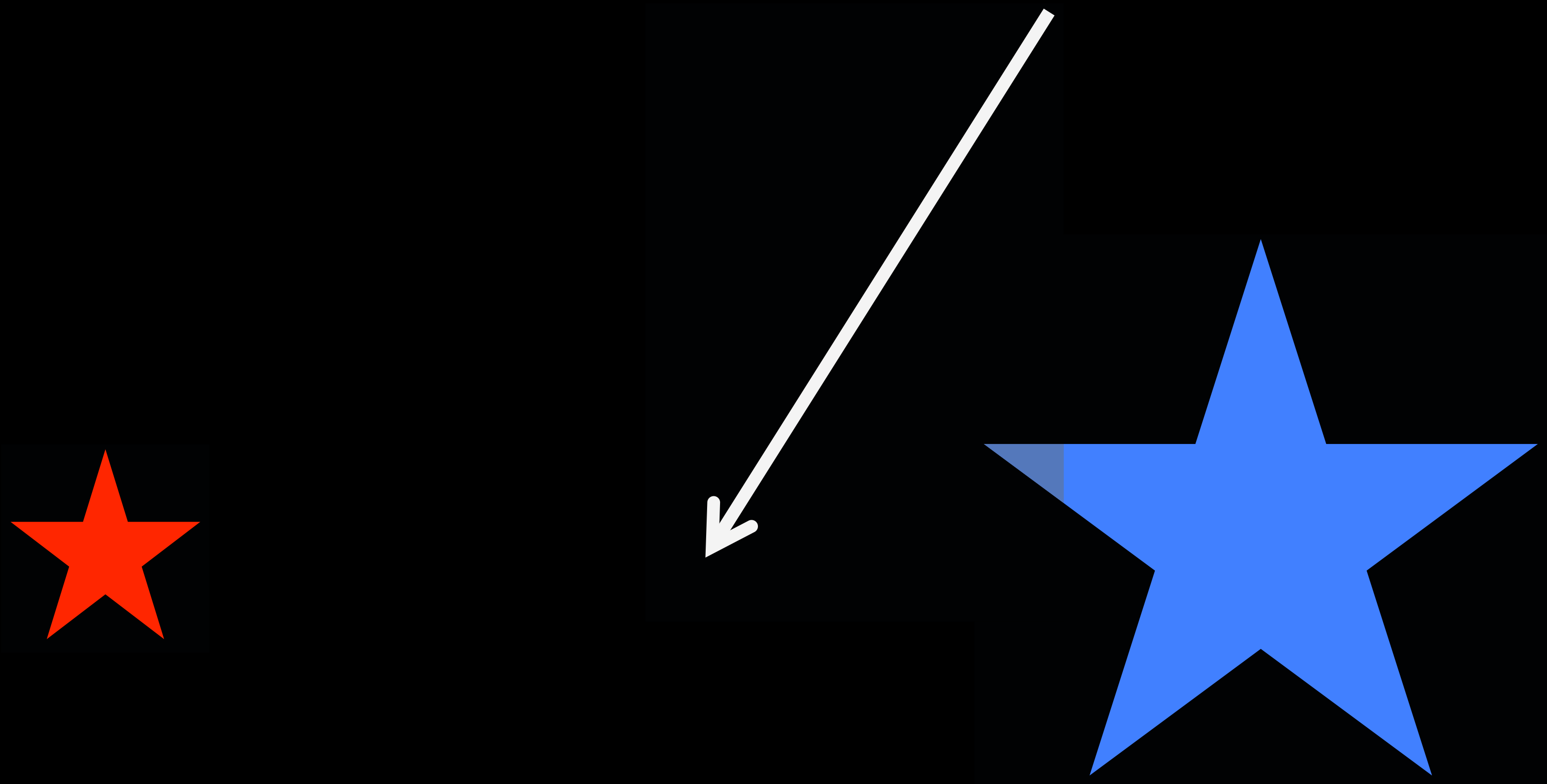
Megan Reiter

University of Arizona



With: Nathan Smith (UA), Megan Kiminki (UA), John Bally (U Colorado), Pat Hartigan (Rice)

Intermediate-mass ≈ 2-8 M_{sun}



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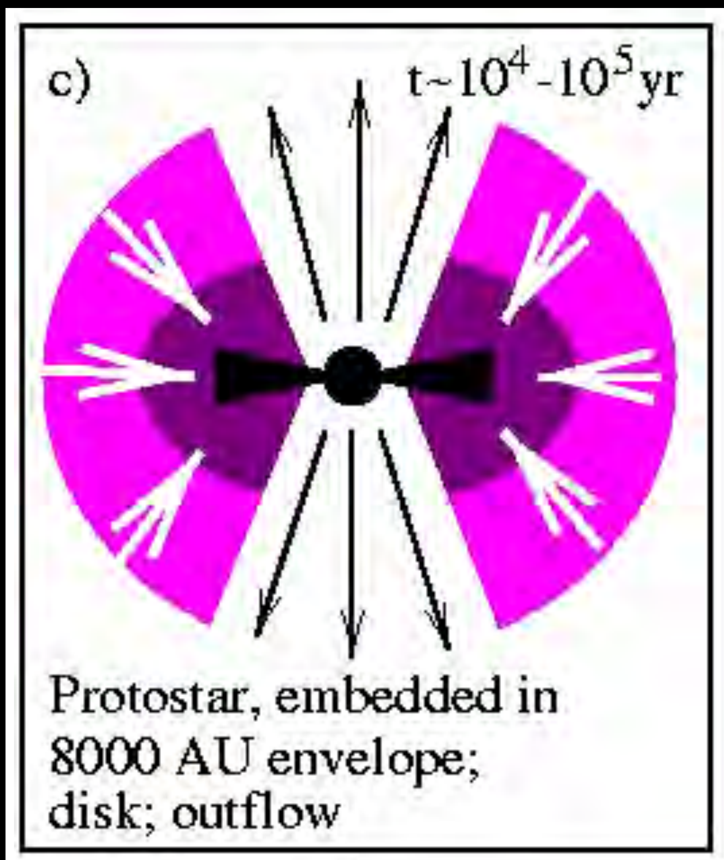
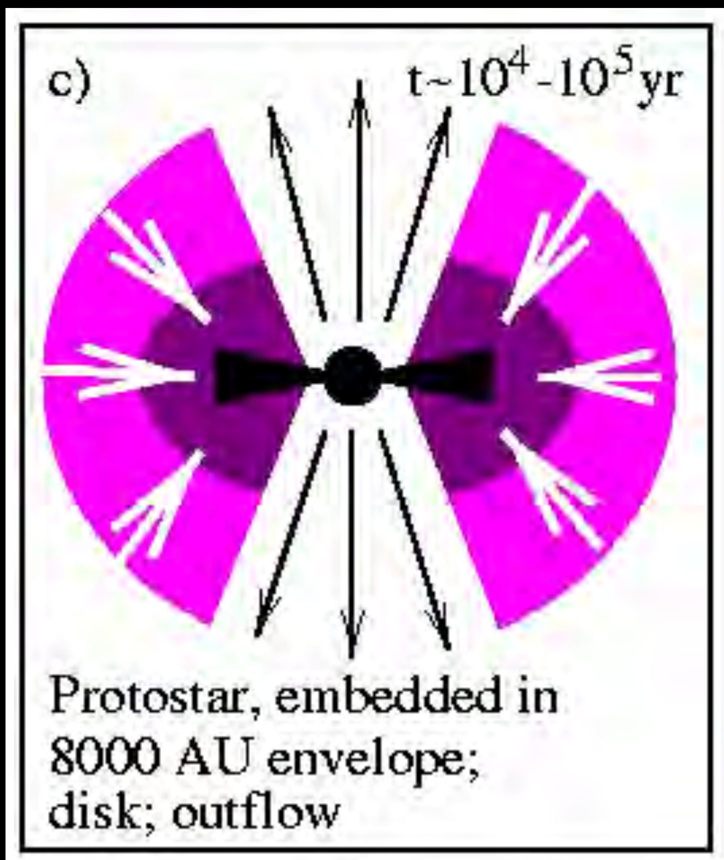


Hogerheijde 1998, after Shu et al. 1987

Intermediate-mass ≈ 2-8 M_{sun}

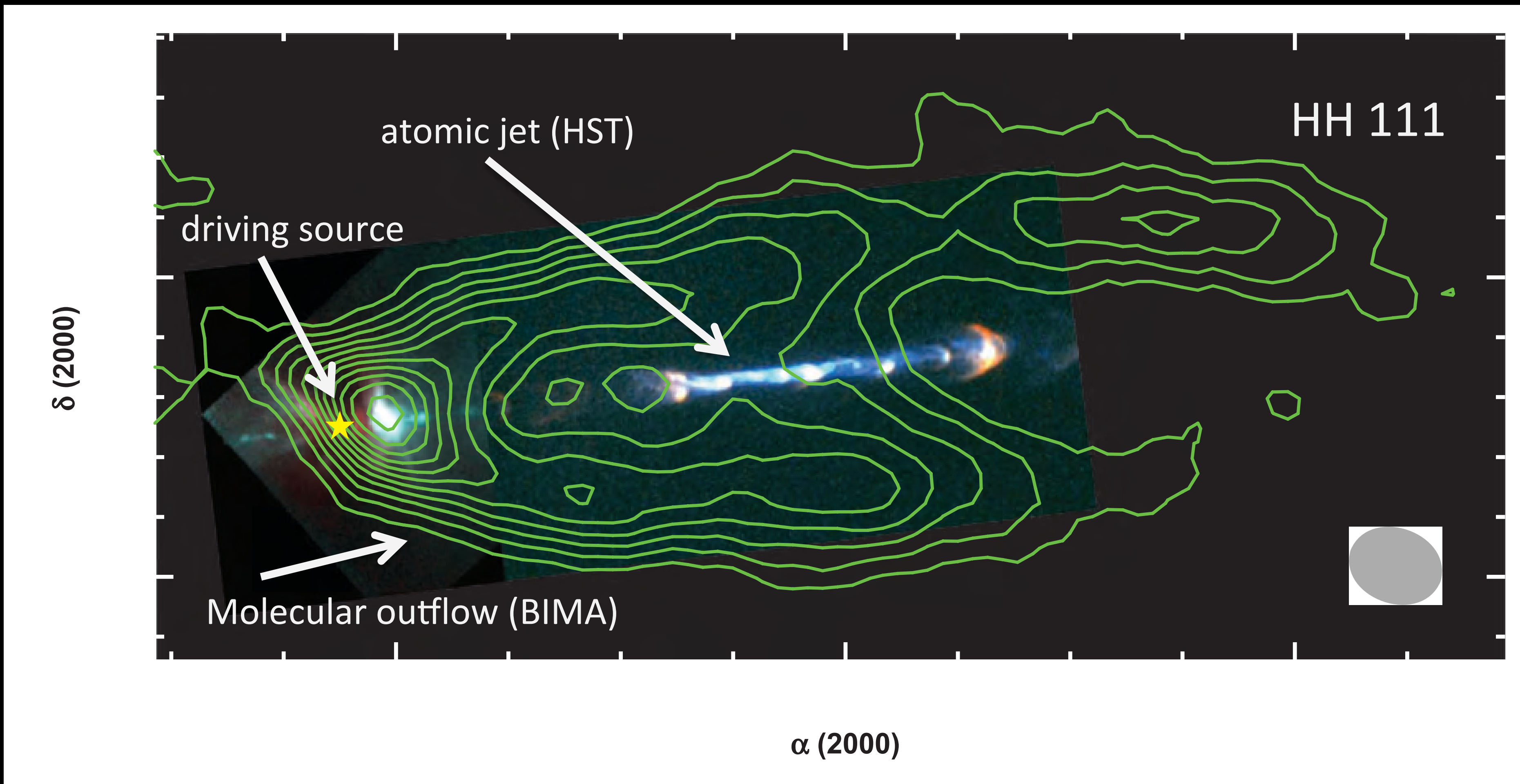


Hogerheijde 1998, after Shu et al. 1987

Transition?

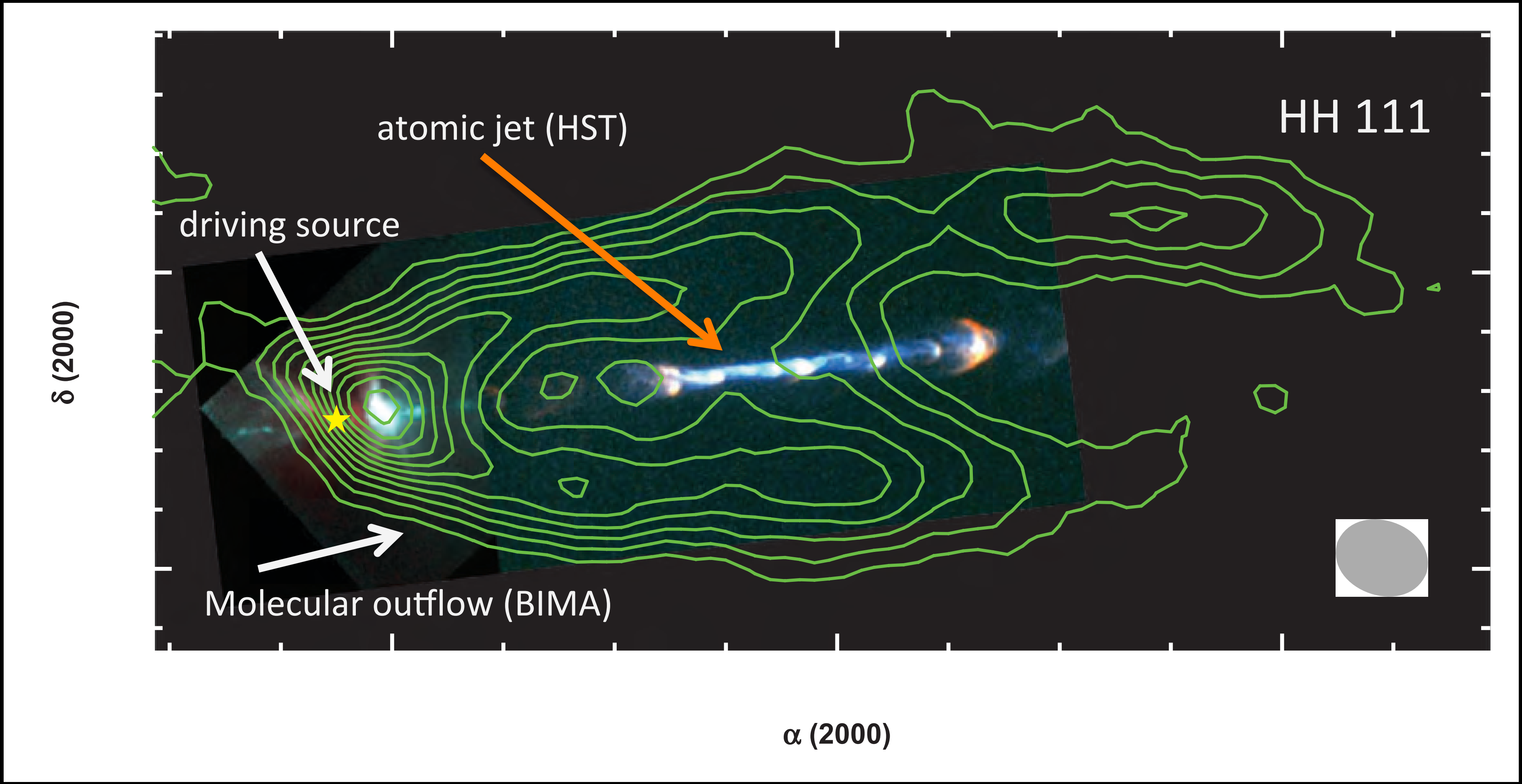
see: Vink et al. 2002
Wade et al. 2007
Donehew & Brittain 2011
Cauley & Johns-Krull 2014

Best outflow tracers?

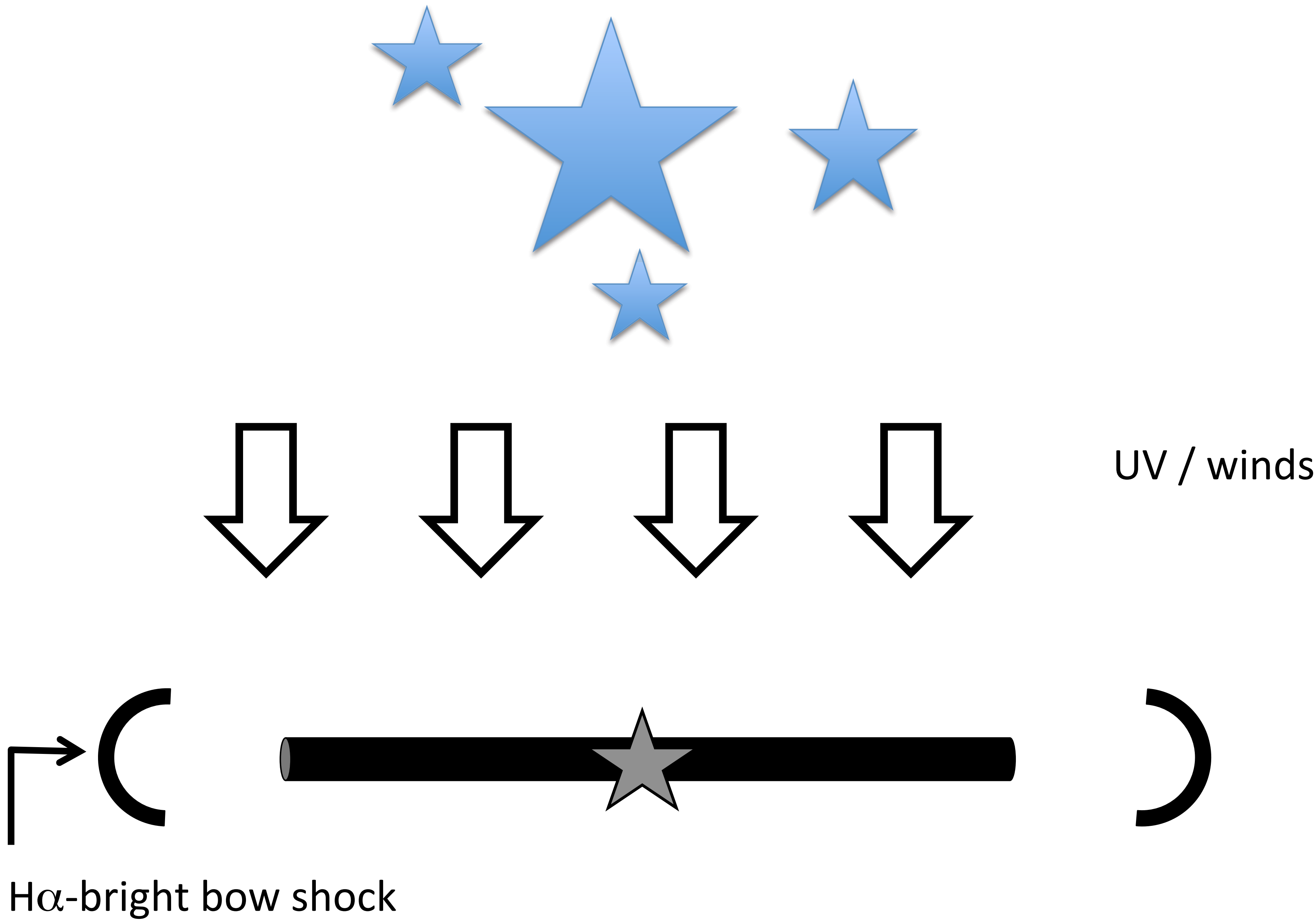


Reipurth et al. 1999, Lee et al. 2000, McKee & Ostriker 2007

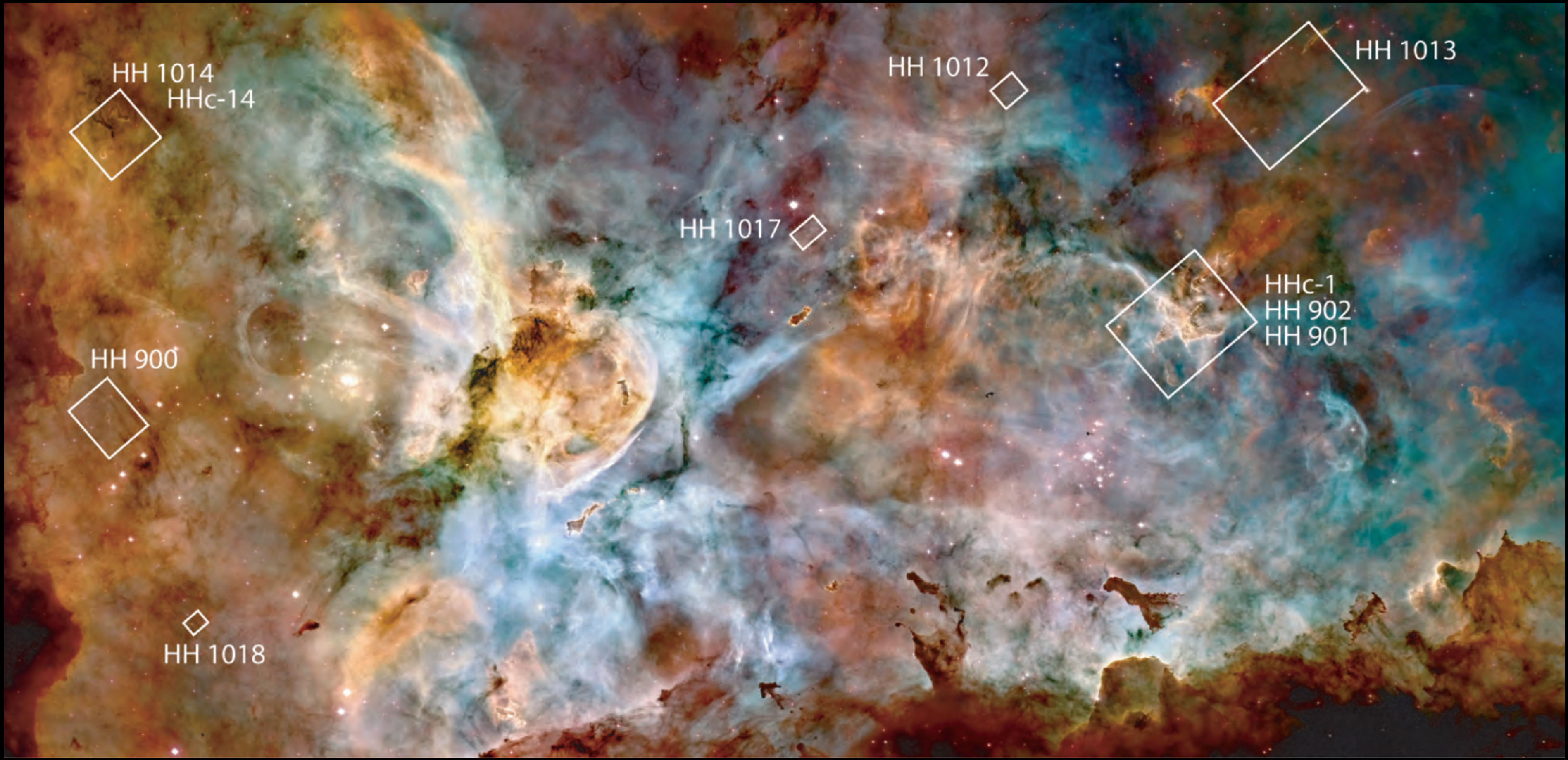
Best outflow tracers?



Reipurth et al. 1999, Lee et al. 2000, McKee & Ostriker 2007


UV / winds
Hα-bright bow shock

Carina Nebula



- 40 HH jets discovered with targeted ACS Hα imaging

Smith et al. 2010

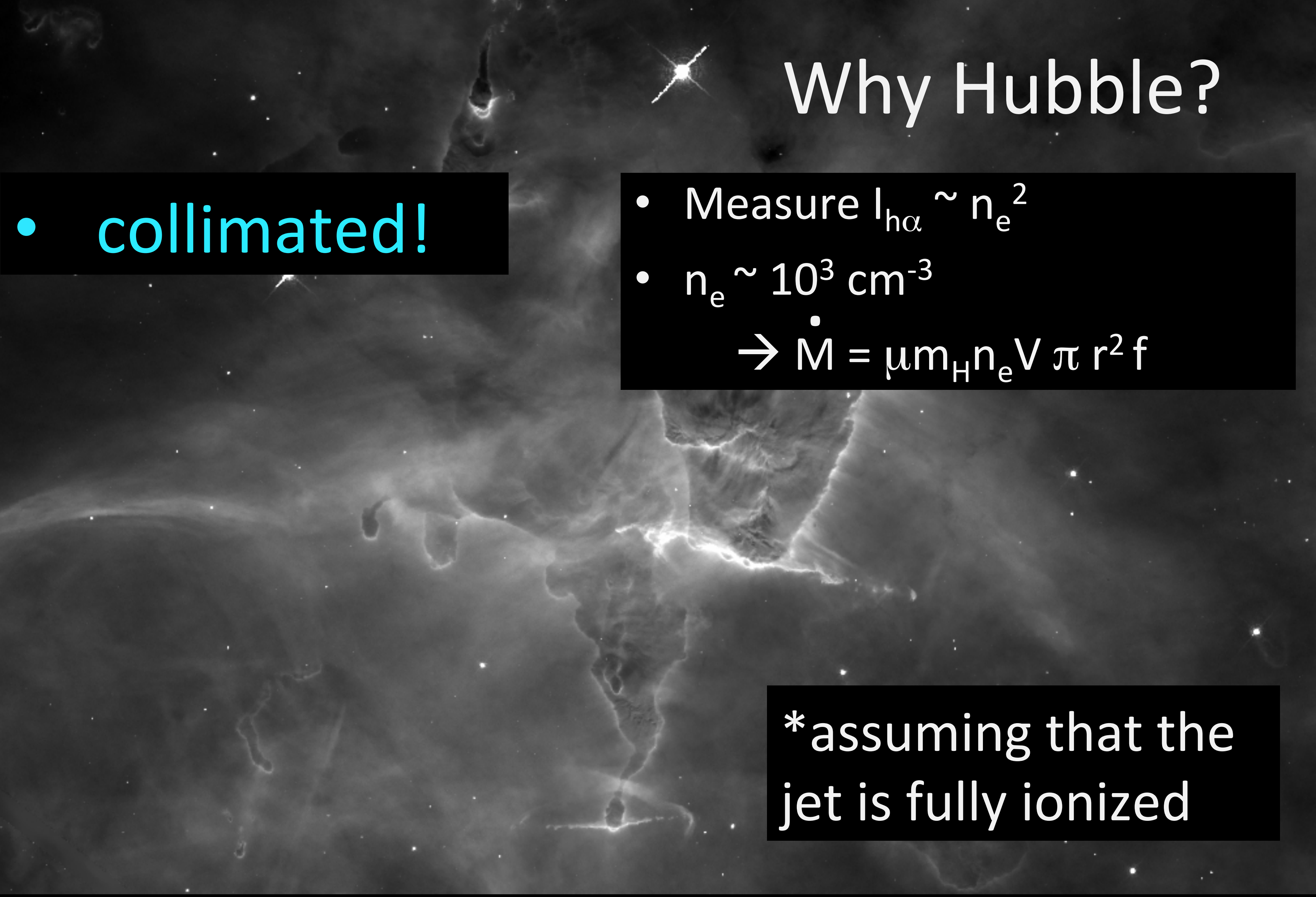
Why Hubble?

Why Hubble?

Why Hubble?

- collimated!

Why Hubble?



- collimated!

- Measure $I_{h\alpha} \sim n_e^2$
- $n_e \sim 10^3$ cm^{-3}

  → $\dot{M} = \mu m_H n_e V \pi r^2 f$

*assuming that the jet is fully ionized

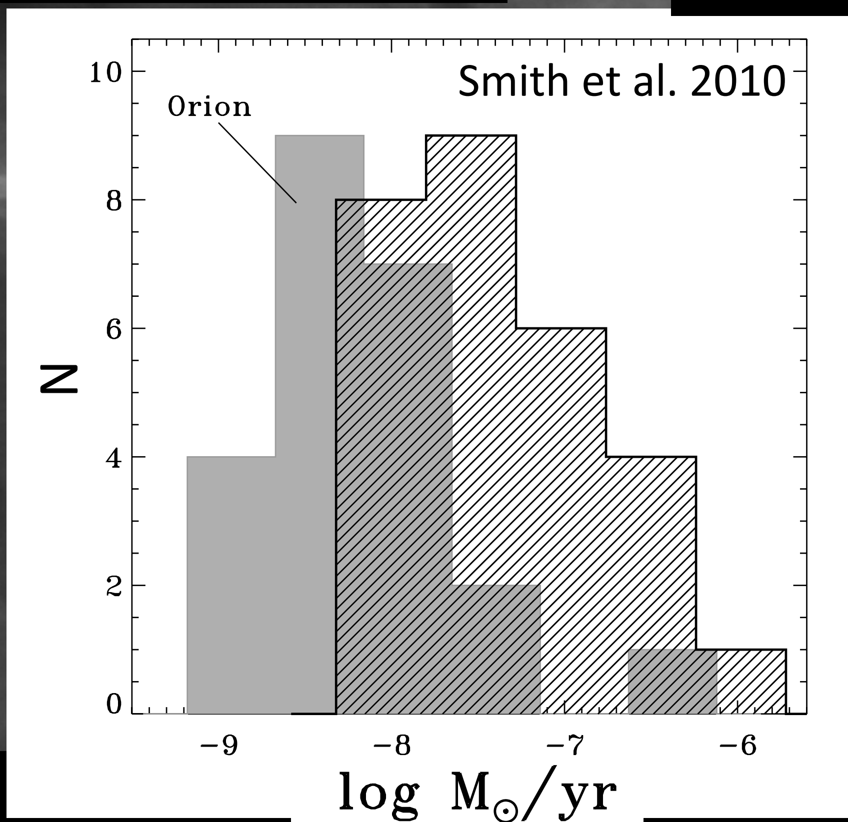
Bally & Reipurth 2001

Why Hubble?

- collimated!
- massive

- Measure $I_{h\alpha} \sim n_e^2$
- $n_e \sim 10^3$ cm^{-3}

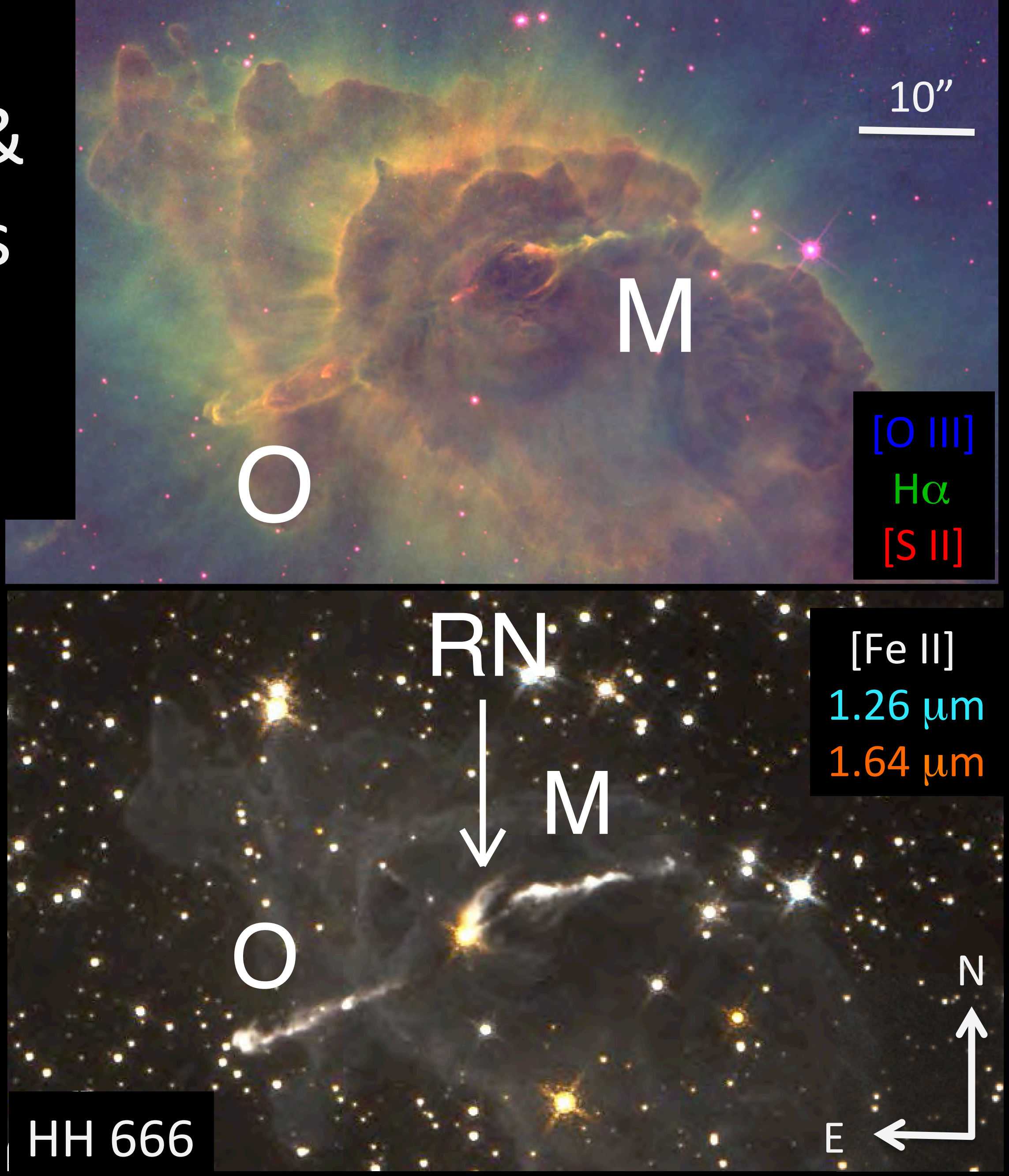
  $\rightarrow \dot{M} = \mu m_H n_e V \pi r^2 f$



*assuming that the jet is fully ionized

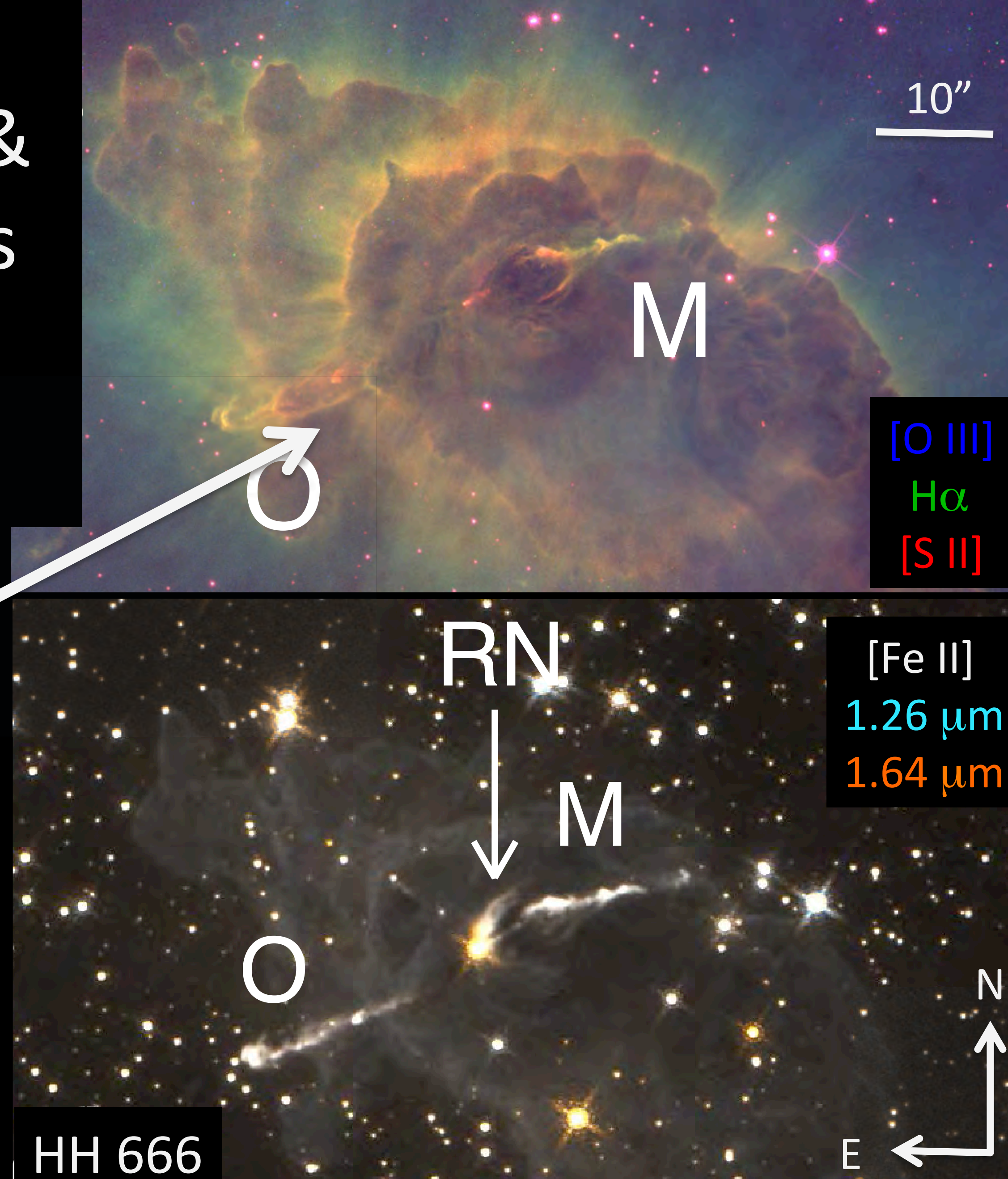
Bally & Reipurth 2001

[Fe II] 1.26 μm & 1.64 μm images from WFC3-IR

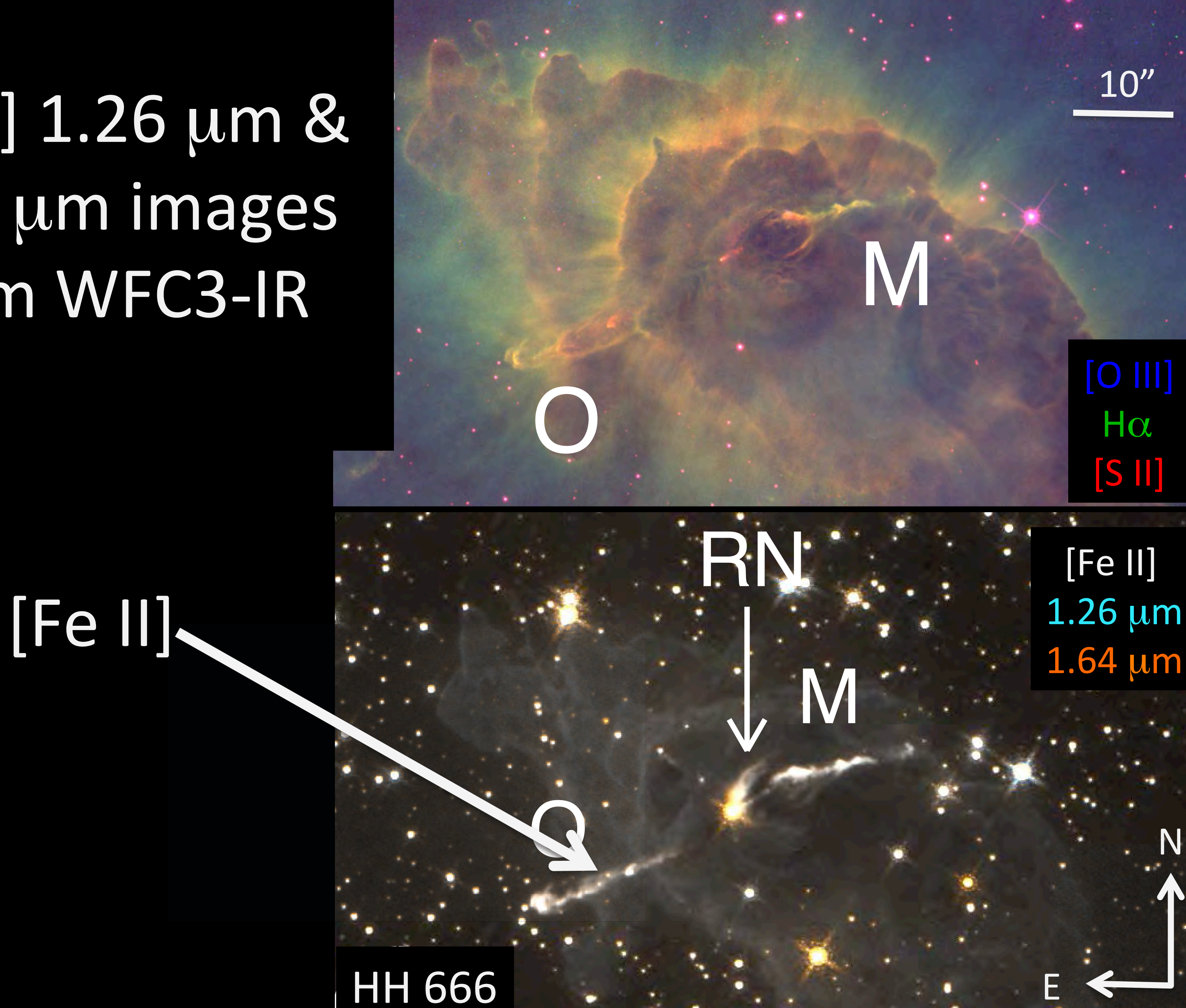


[Fe II] 1.26 μm & 1.64 μm images from WFC3-IR

Hα



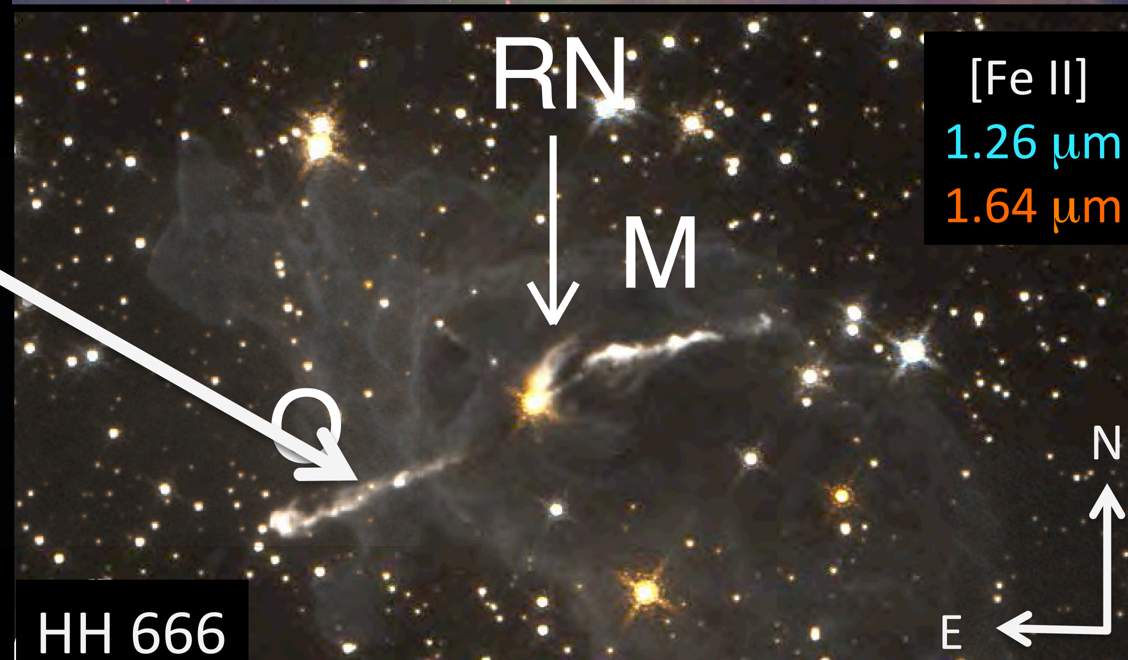
[Fe II] 1.26 μm & 1.64 μm images from WFC3-IR



[Fe II] 1.26 μm & 1.64 μm images from WFC3-IR

[Fe II]

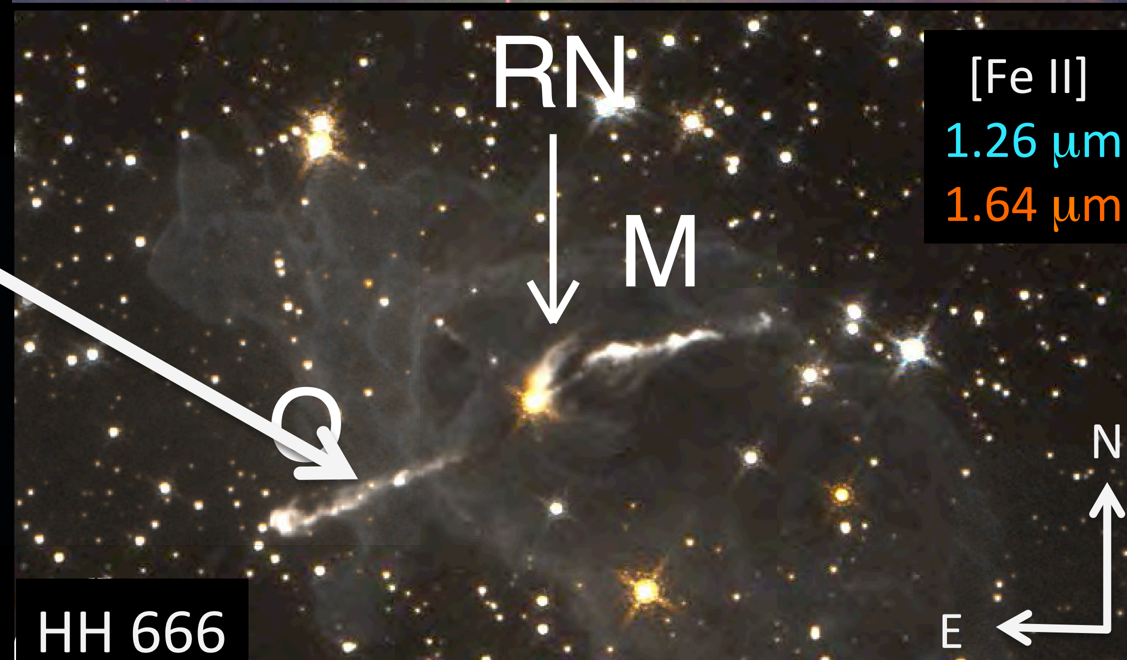
why not Fe^{++}?



[Fe II] 1.26 μm & 1.64 μm images from WFC3-IR

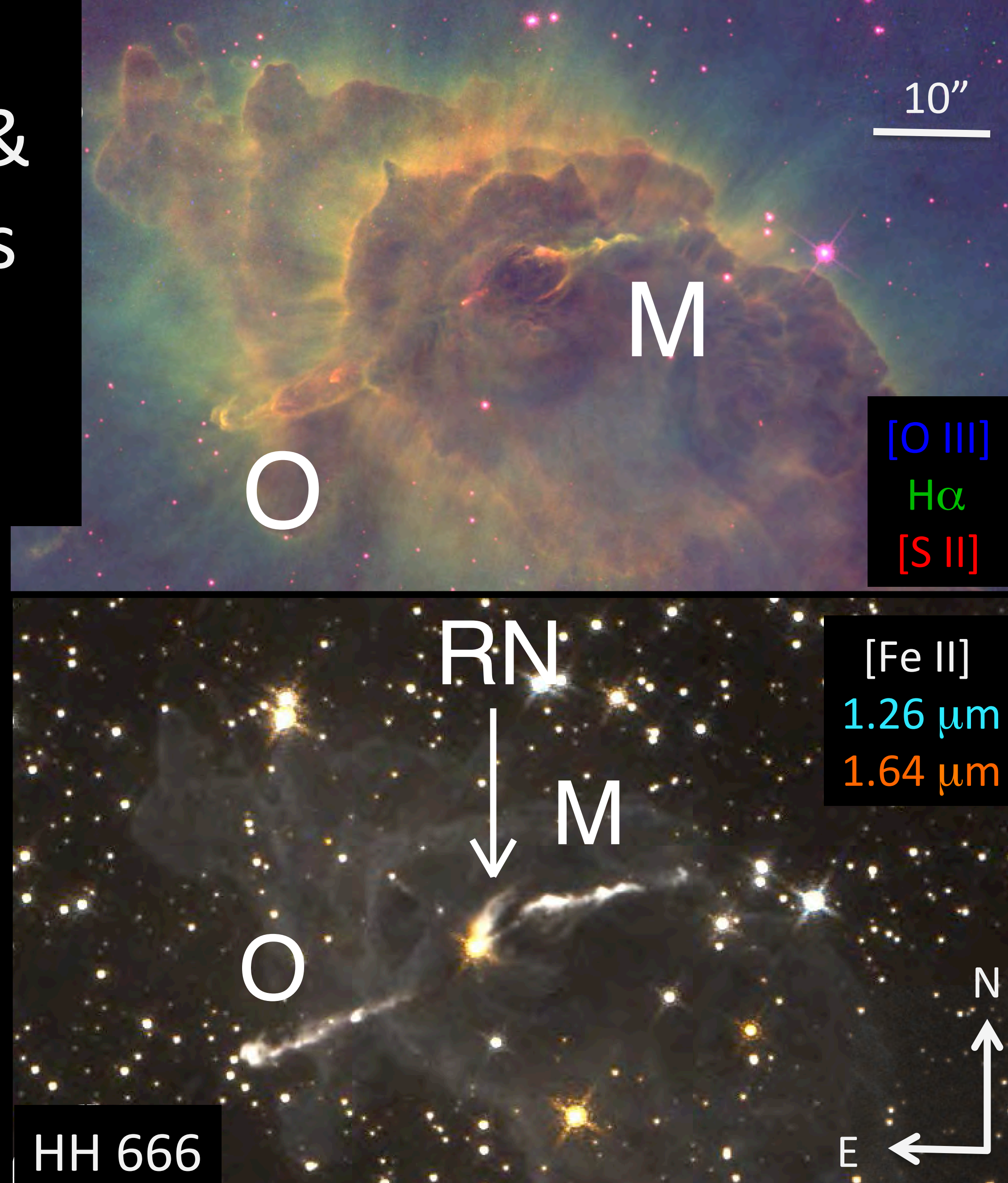
[Fe II]

why not Fe^{++}?
→ $n_H > 10^4$ cm^{-3}



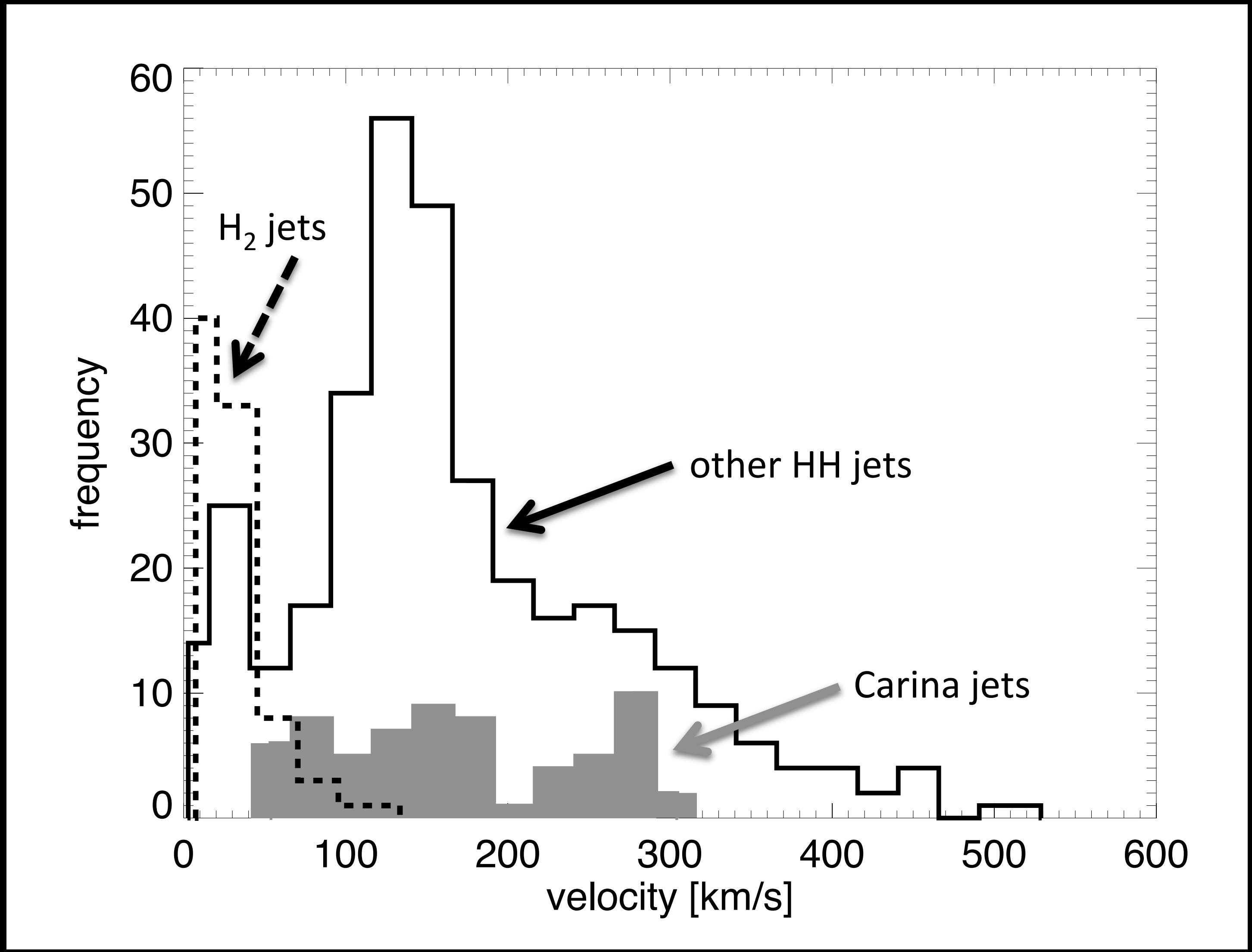
[Fe II] 1.26 μm & 1.64 μm images from WFC3-IR

- collimated!
- massive x 10



Faster?

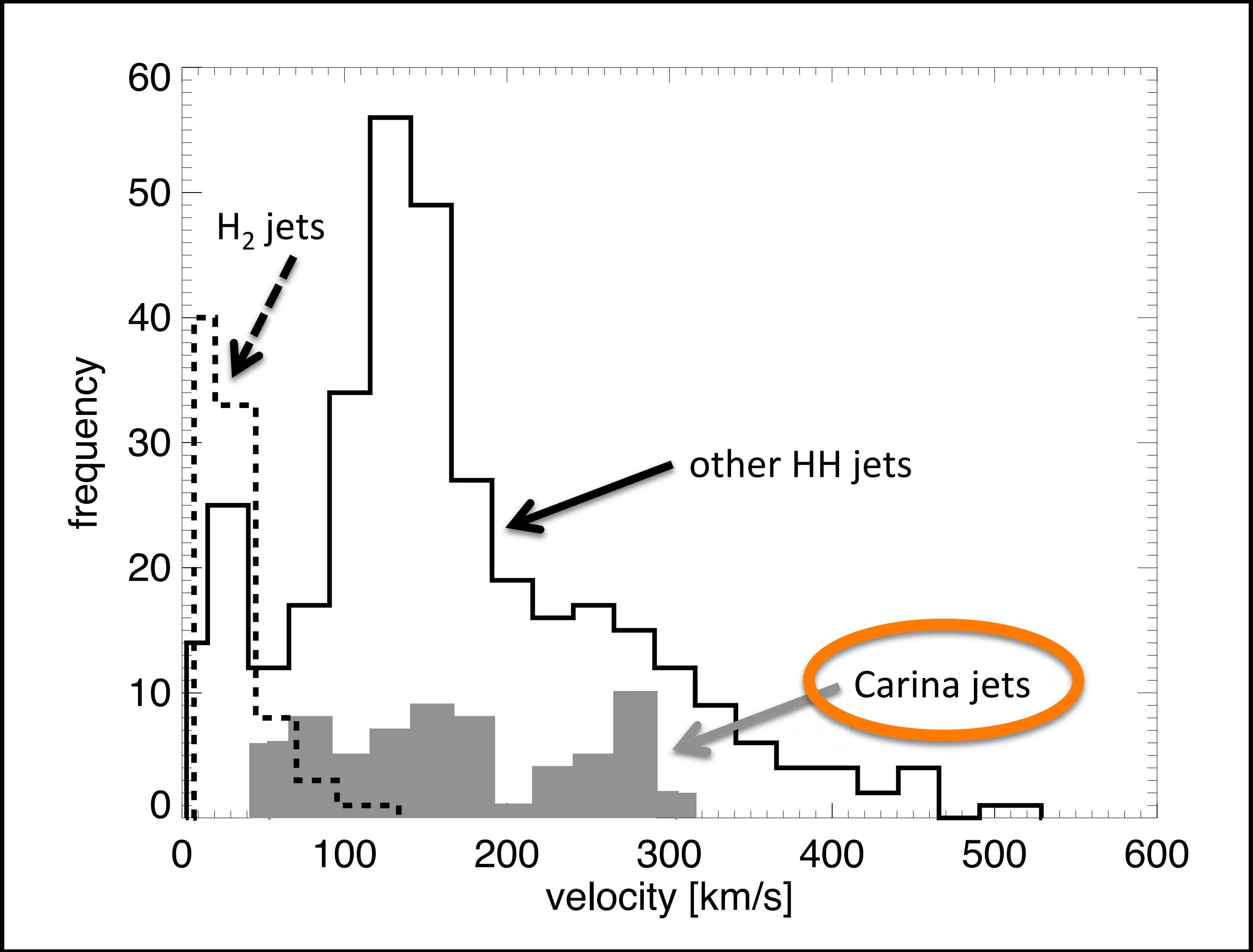
Faster?



Bally et al. (2002), Bally et al. (2012), Devine et al. (1997), Devine et al. (2009), Hartigan et al. (2001), Hartigan et al. (2005), Hartigan & Morse (2007), Kadjiˇc et al. (2012), McGroarty et al. (2007), Noriega-Crespo & Garnavich (2001), Reipurth et al. (2002), Smith et al. (2005), and Yusef-Zadeh et al. (2005). H_2 jet velocities from Zhang et al. (2013)

Reiter & Smith 2014

Faster?



Bally et al. (2002), Bally et al. (2012), Devine et al. (1997), Devine et al. (2009), Hartigan et al. (2001), Hartigan et al. (2005), Hartigan & Morse (2007), Kadjiˇc et al. (2012), McGroarty et al. (2007), Noriega-Crespo & Garnavich (2001), Reipurth et al. (2002), Smith et al. (2005), and Yusef-Zadeh et al. (2005). H_2 jet velocities from Zhang et al. (2013)

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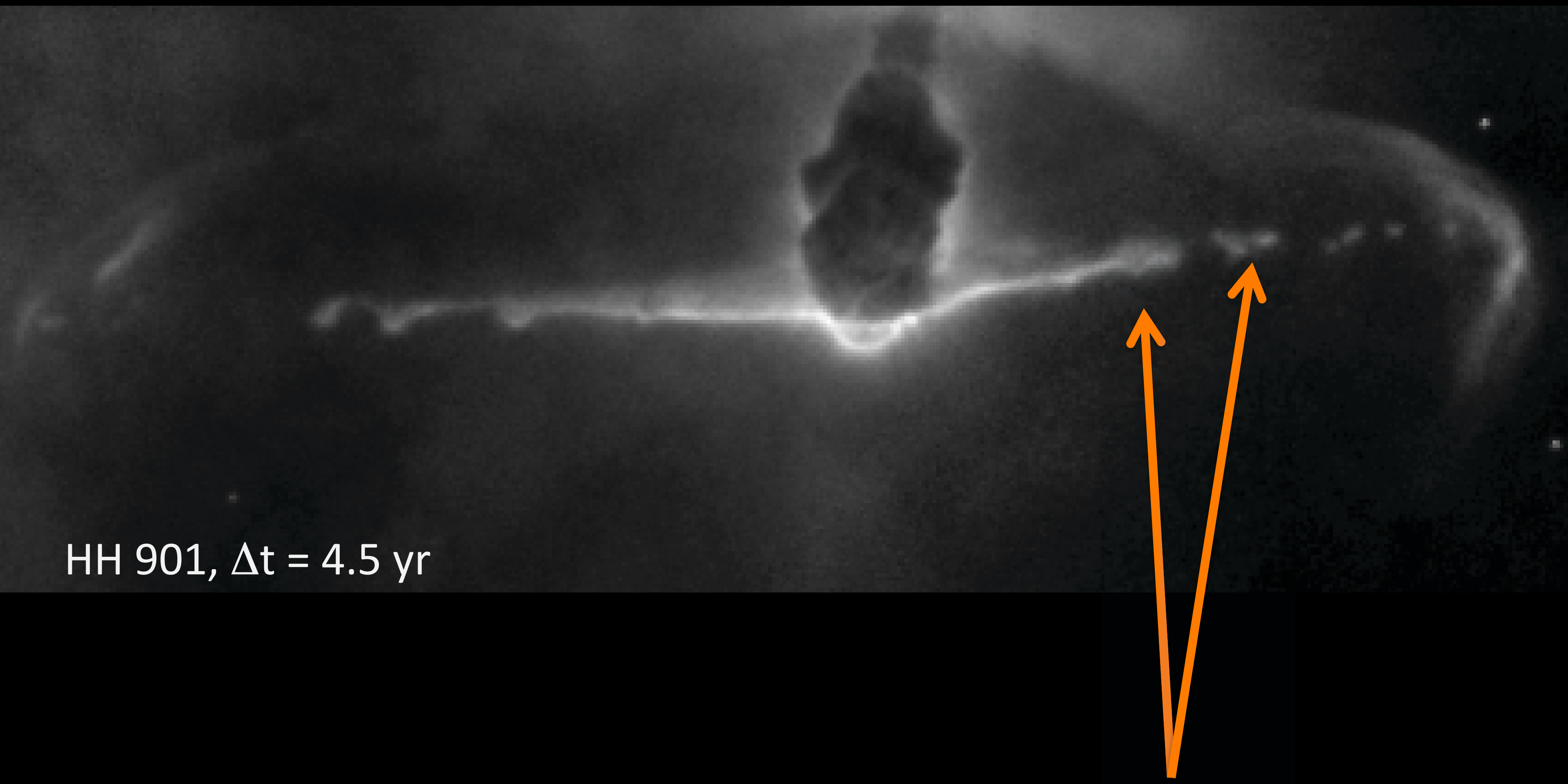
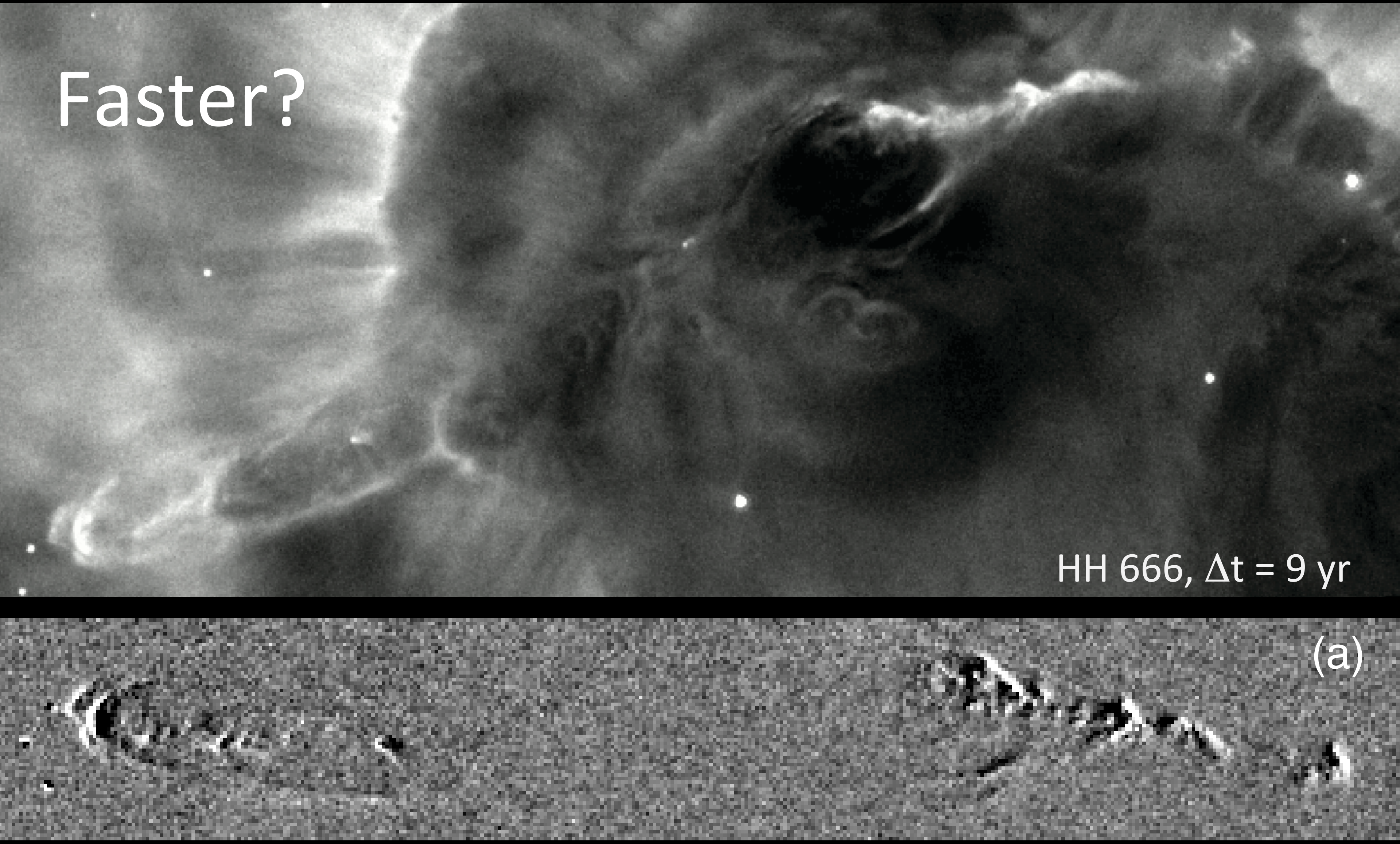
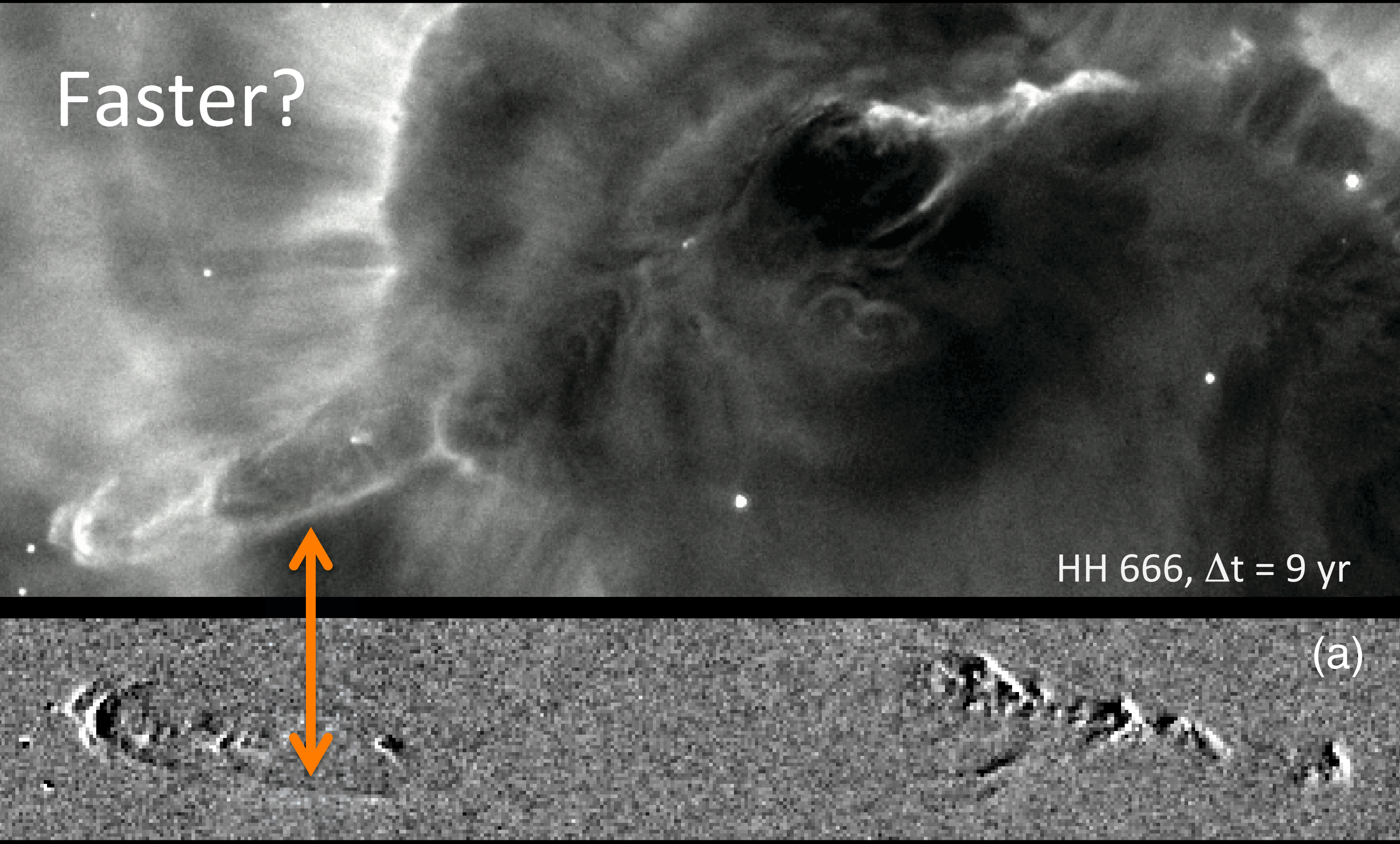
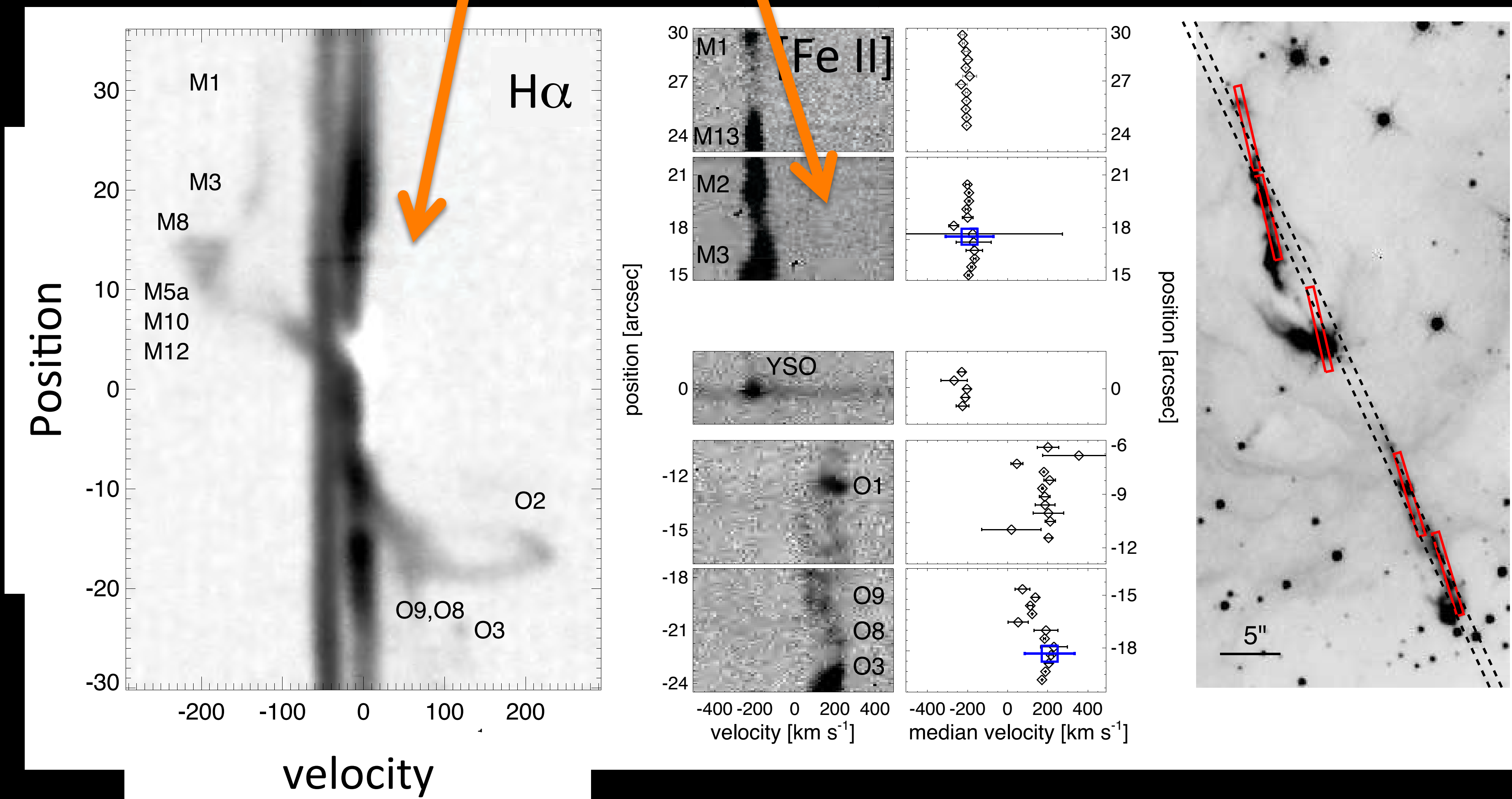


Faster?



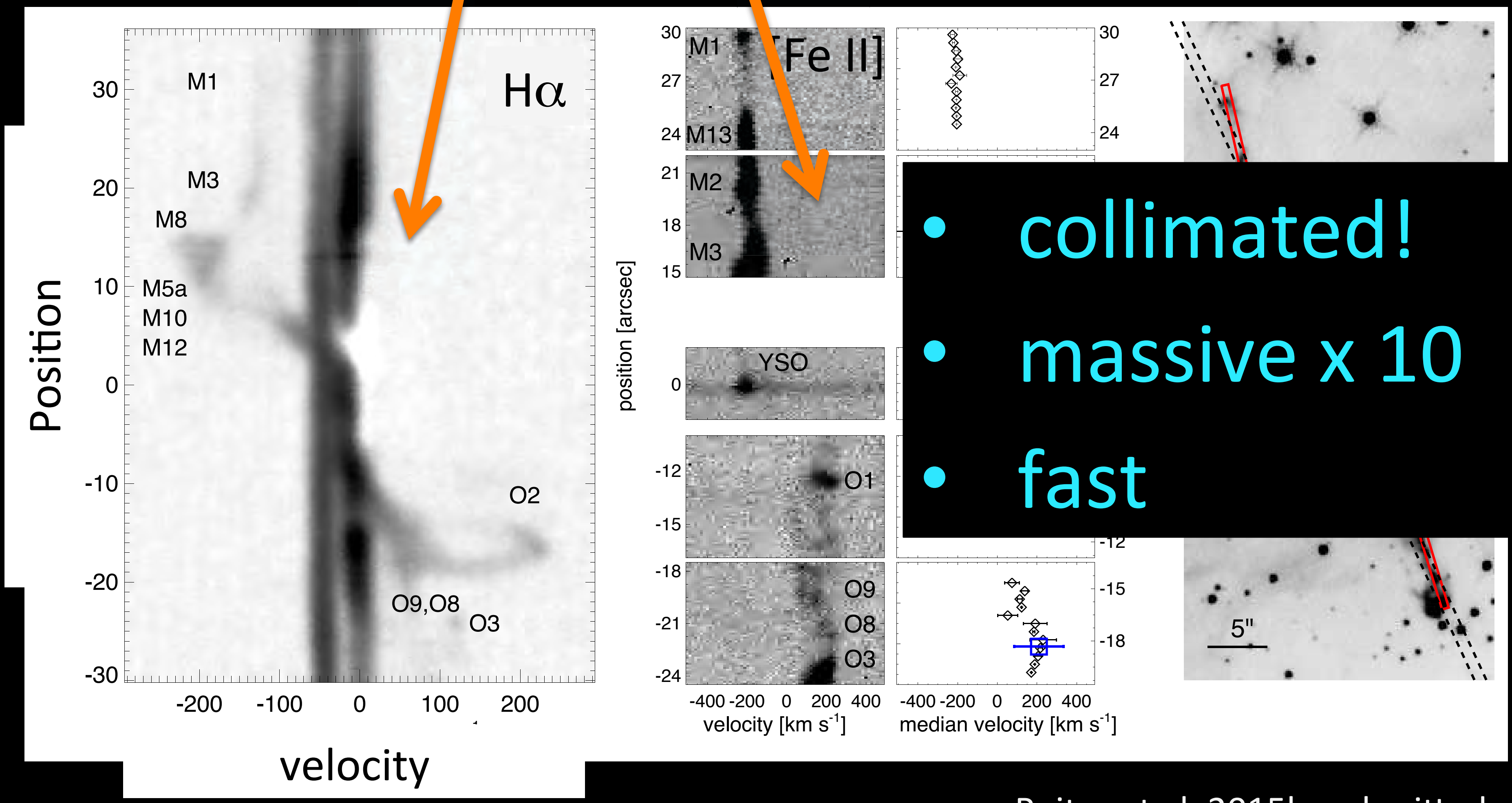

Faster?
HH 666, Δt = 9 yr
(a)

Irradiated outflow + jet



Reiter et al. 2015b, submitted

Irradiated outflow + jet



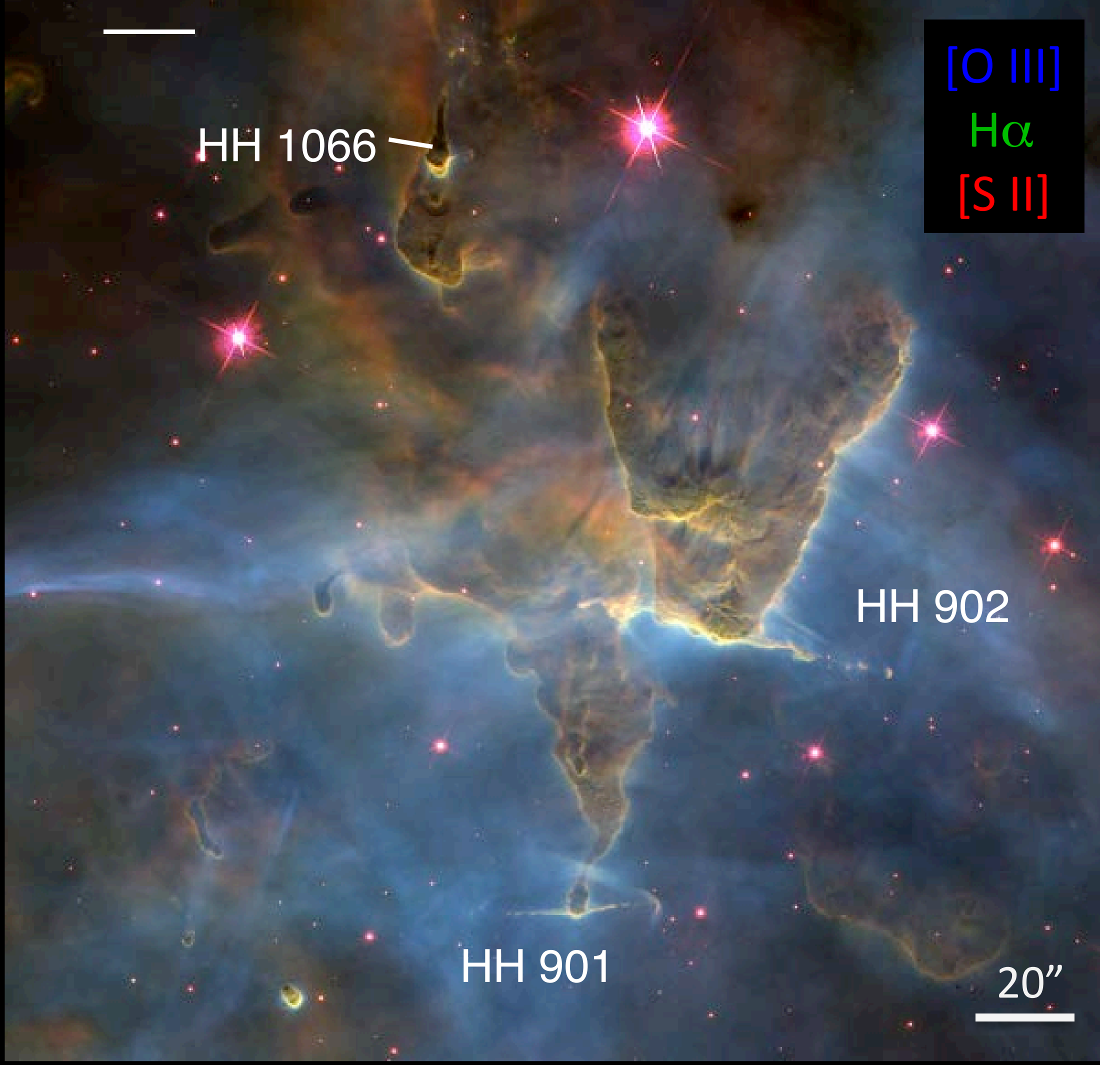
- collimated!
- massive x 10
- fast

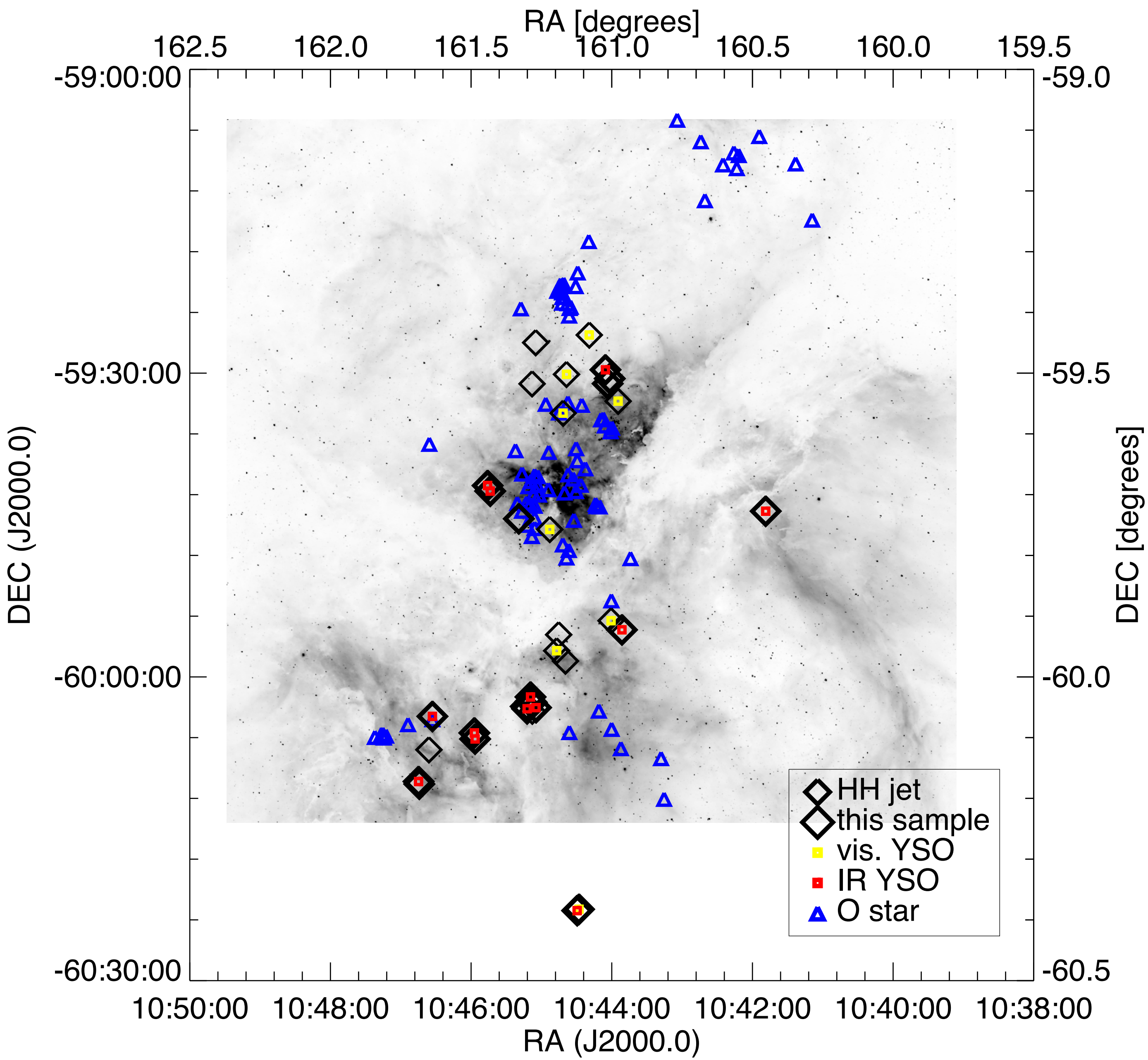
Reiter et al. 2015b, submitted

HH jets from intermediate-mass stars:

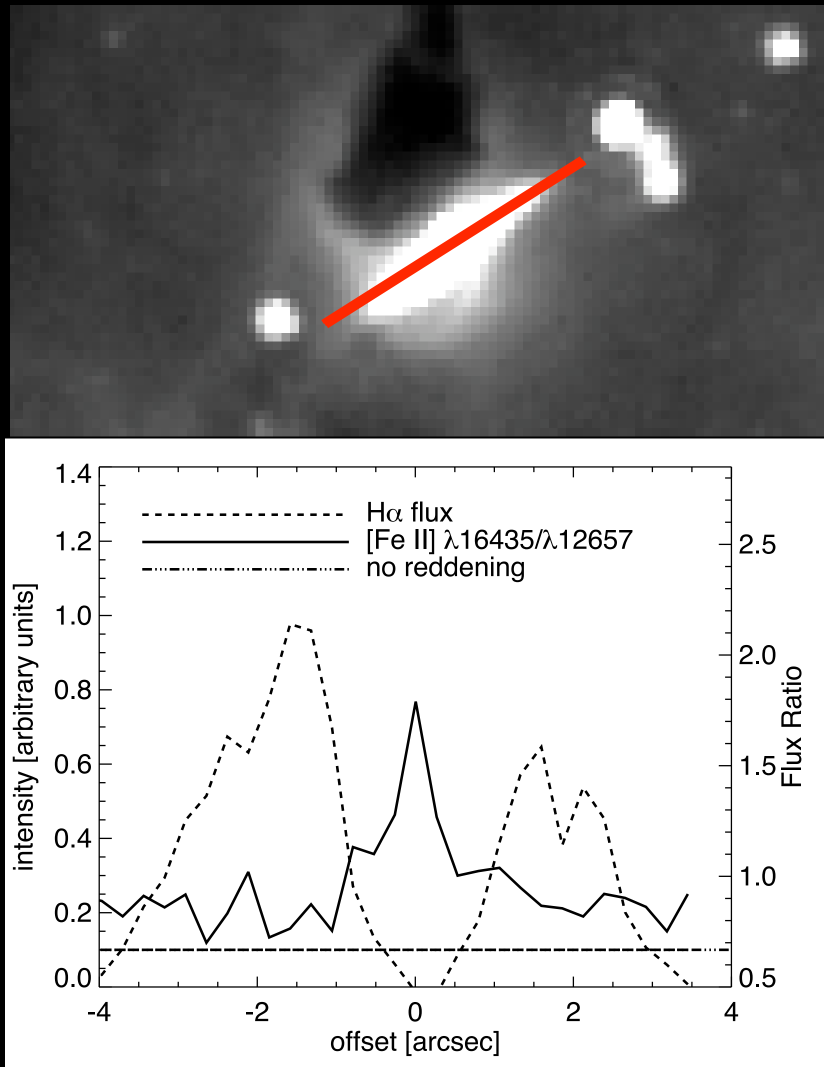
- collimated!
- massive x 10
- fast

→ look like scaled-up version of jets from low-mass stars





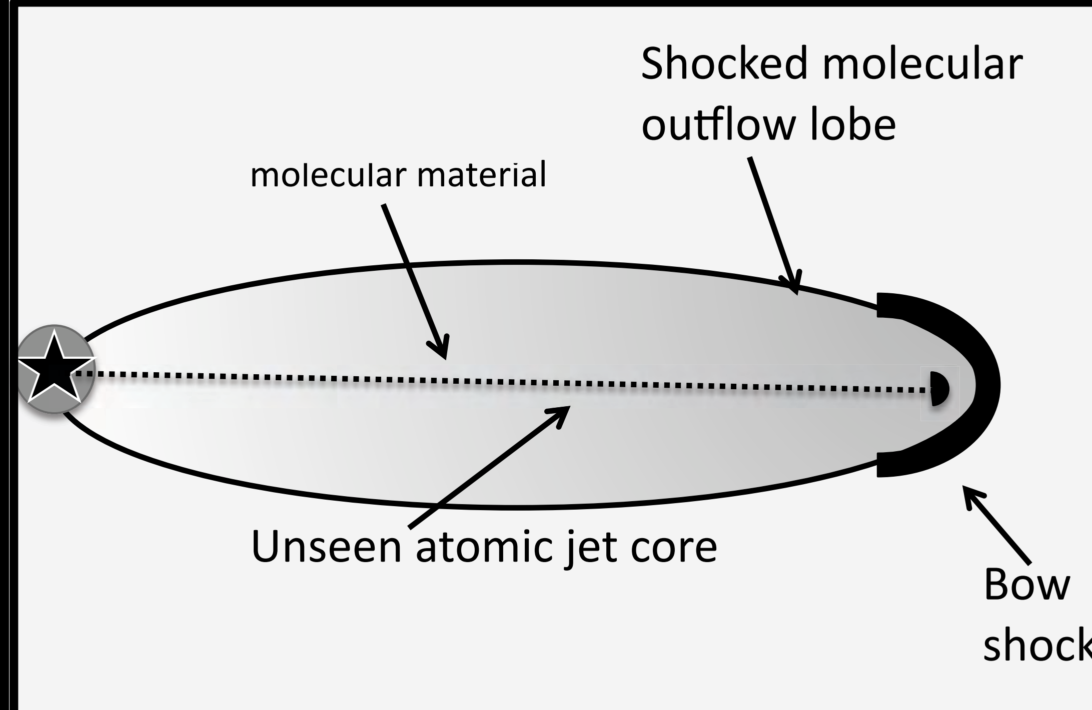
Reiter et al. in prep



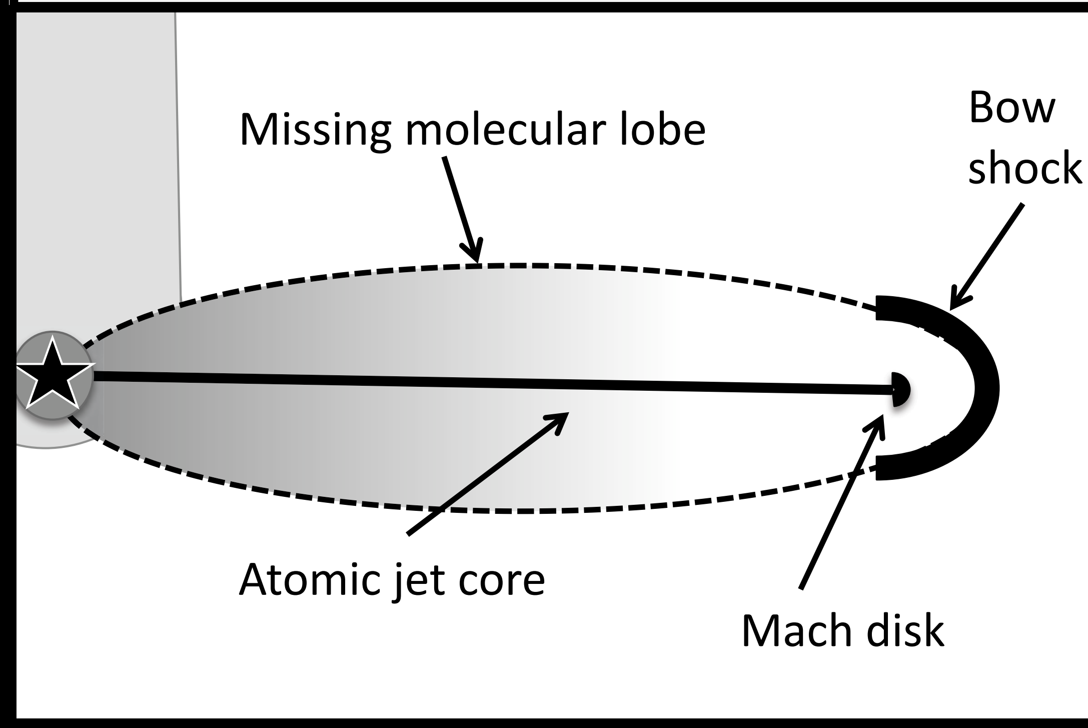
Use [Fe II] emission from the jet to probe the environment

Reiter & Smith 2013

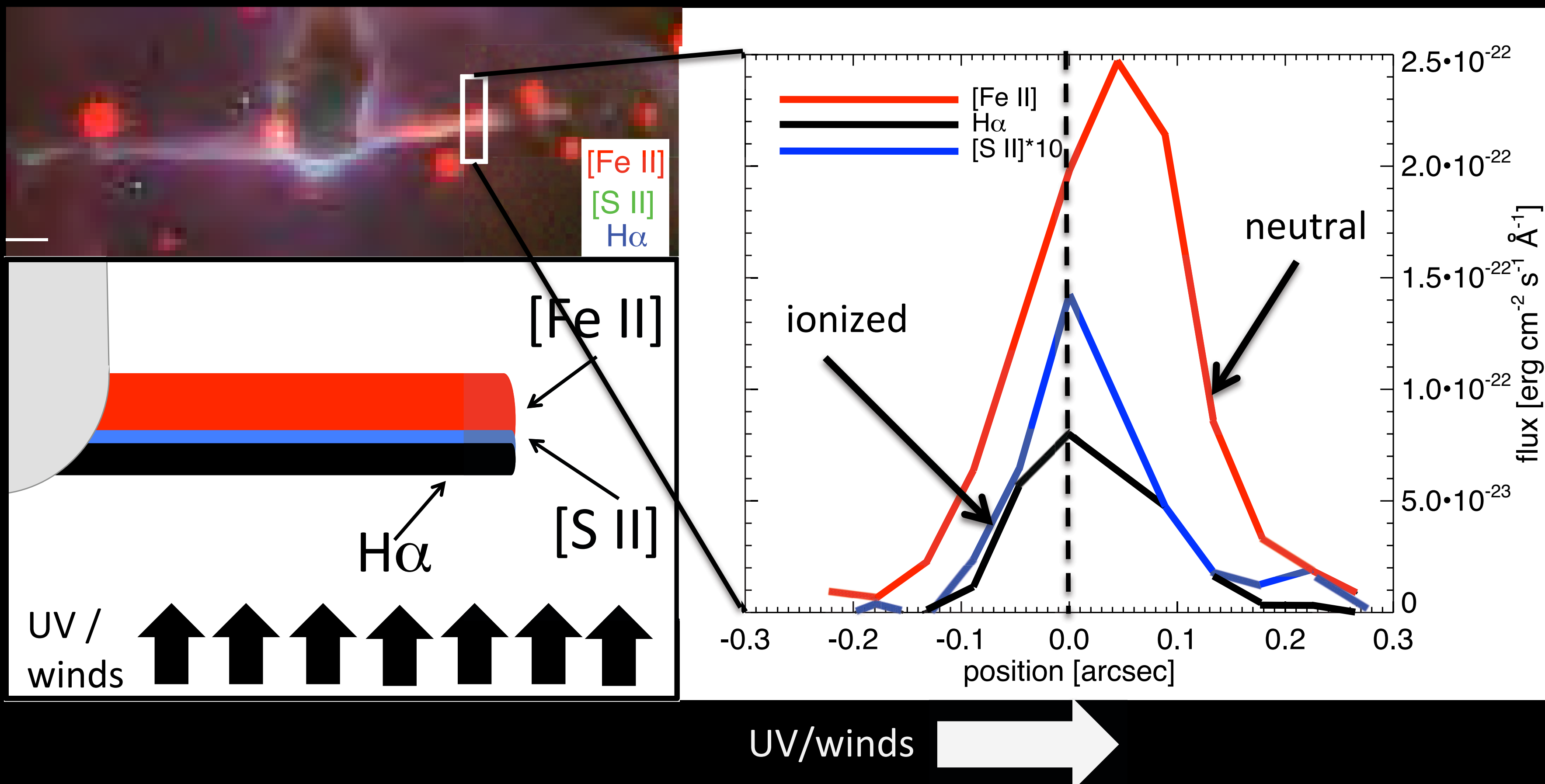
Normal (molecular) jet



Irradiated jet

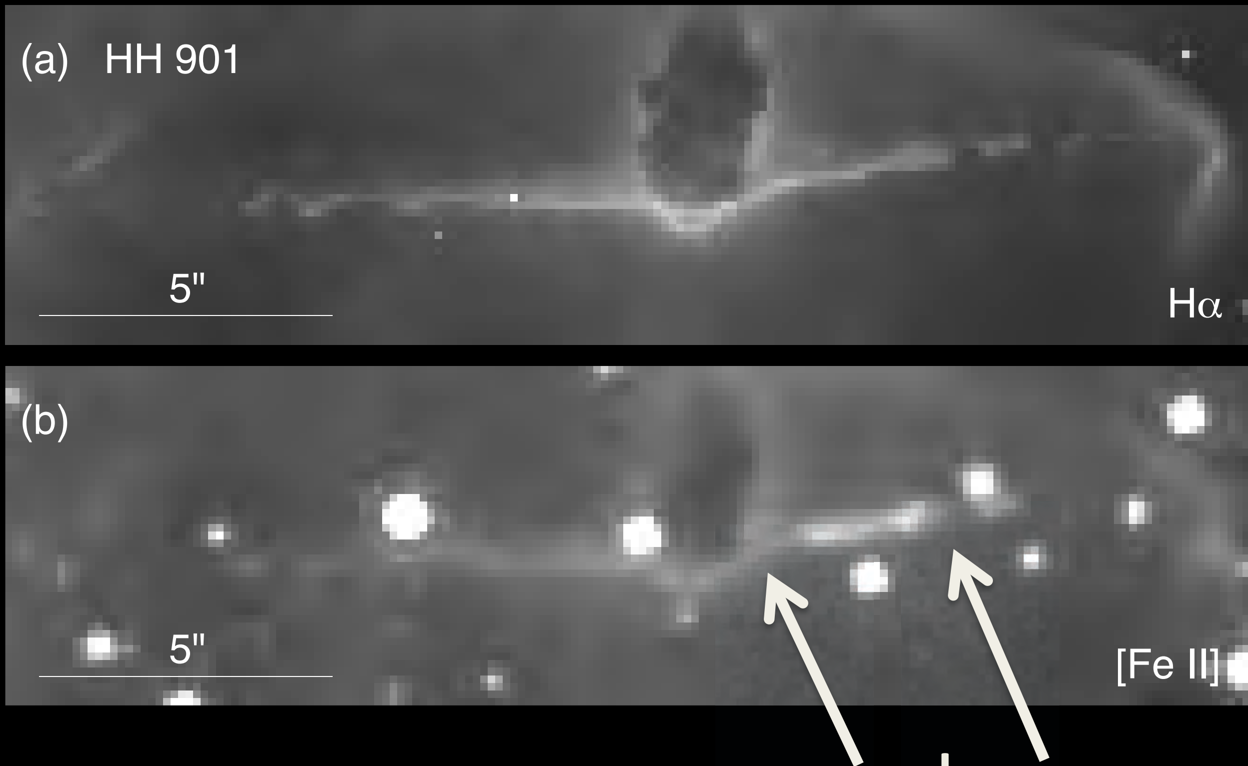


Ionization front in the jet…



Reiter & Smith 2013

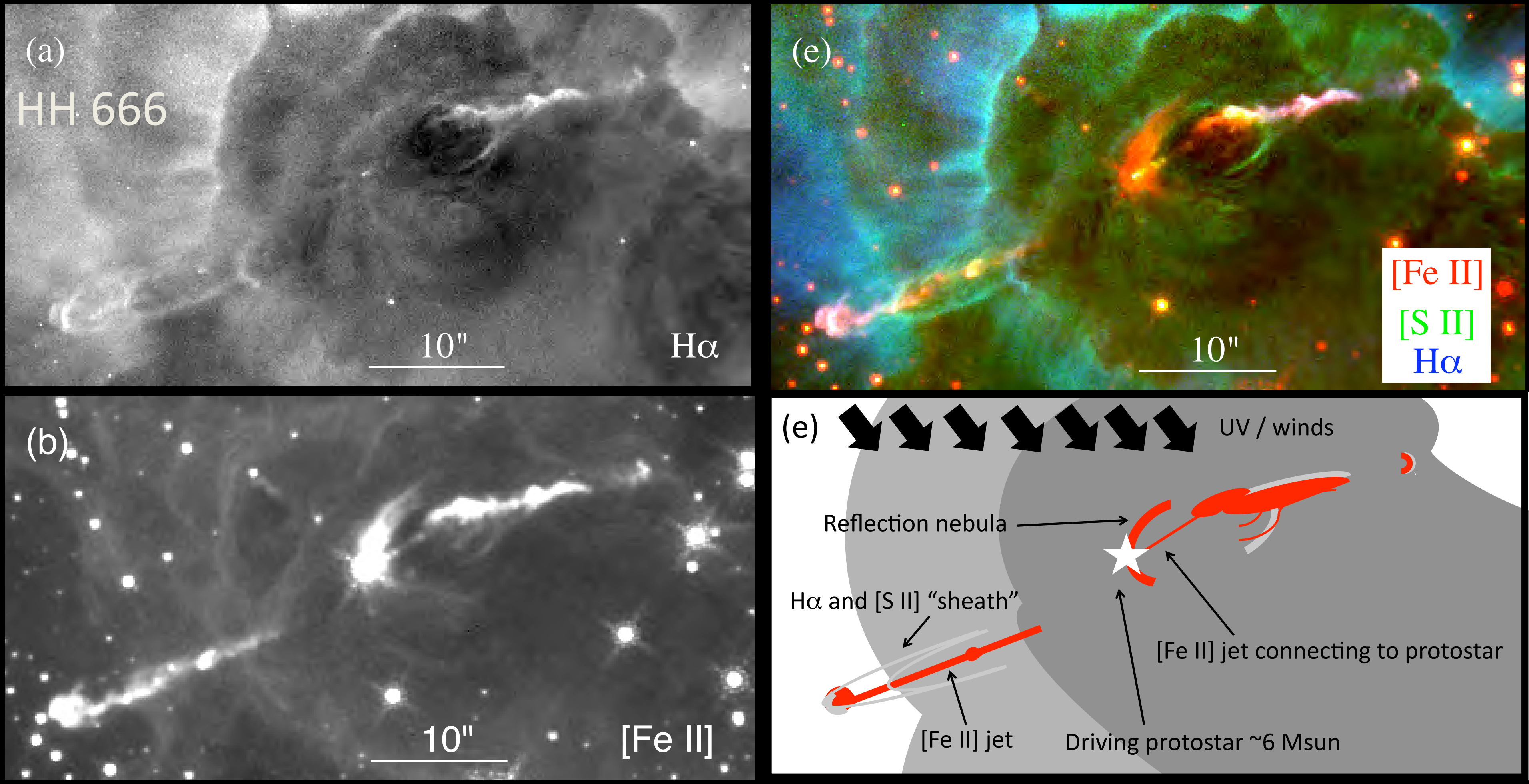

HH 1066
HH c-5
HH c-6*
HH 1014
HH 1007* & HH 1015
HH 901*
HH 902*
HH 1004
HH c-8
HH 900*
HH c-14
HH 1010
HH 1006
HH 1005*
HH 903
HH 666



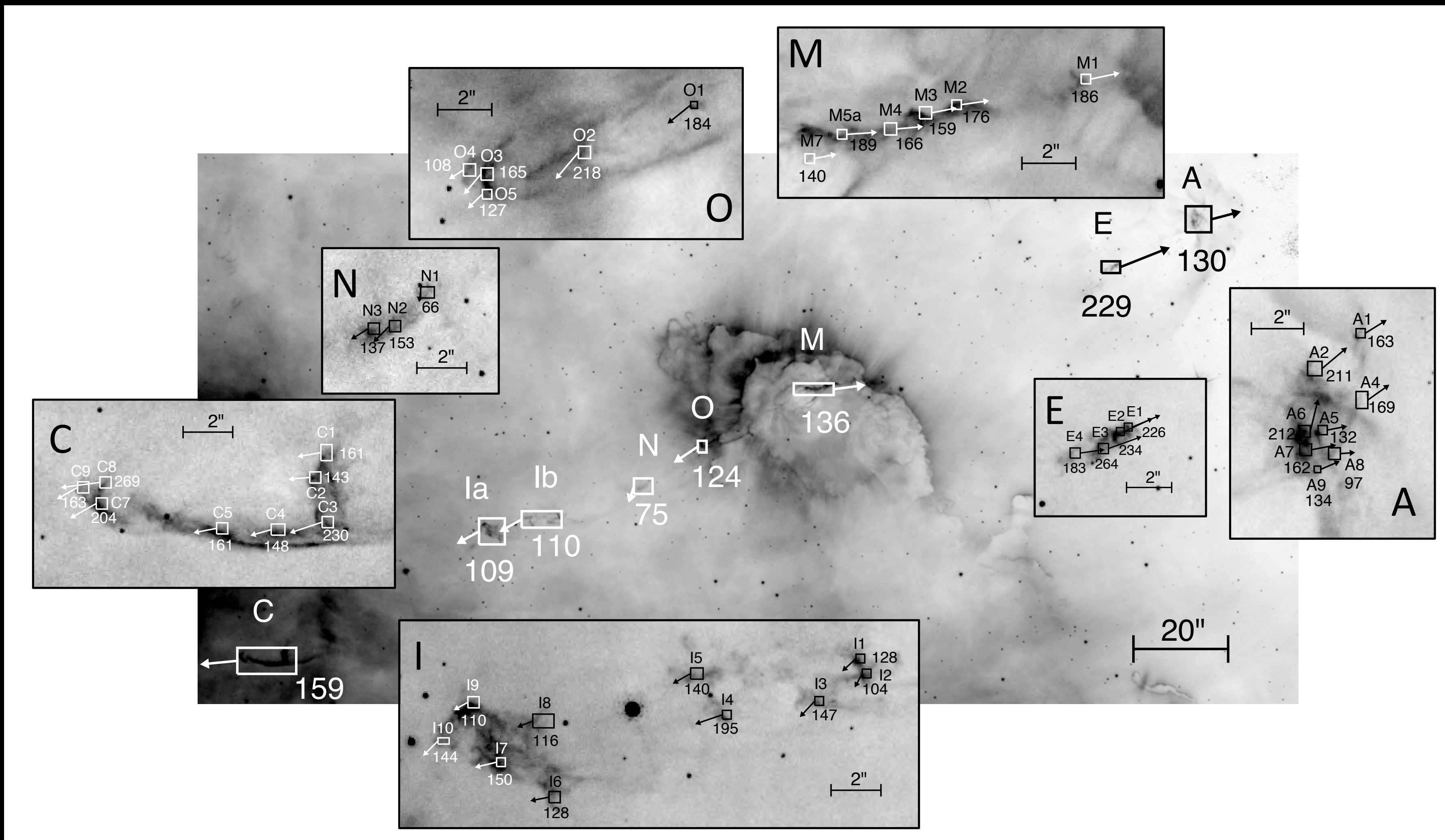
- Mass lost in jet at rate $9 \; 6 \; \rho \; 6 \; \pi$
- Jet photoablated at a rate $\dot{m} = f \pi \mu m_{\rm H} c_{\rm II} n_e(r_I) r(d)$
- Jet travel distance L_1 before completely evaporated $L_1 = \frac{\dot{M}}{\dot{m}}$

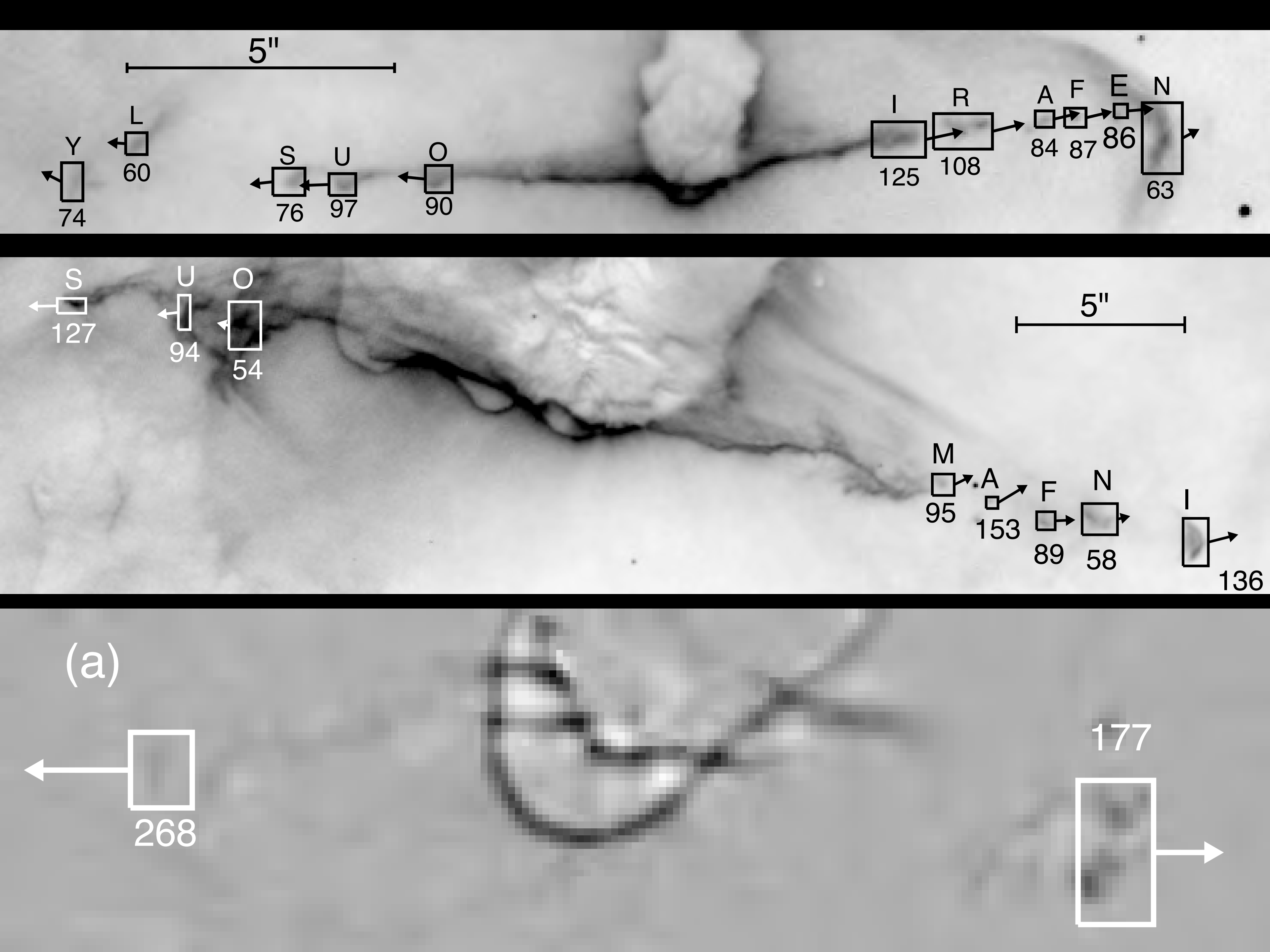
→ ~10x $\dot{M}$ from Hα EM

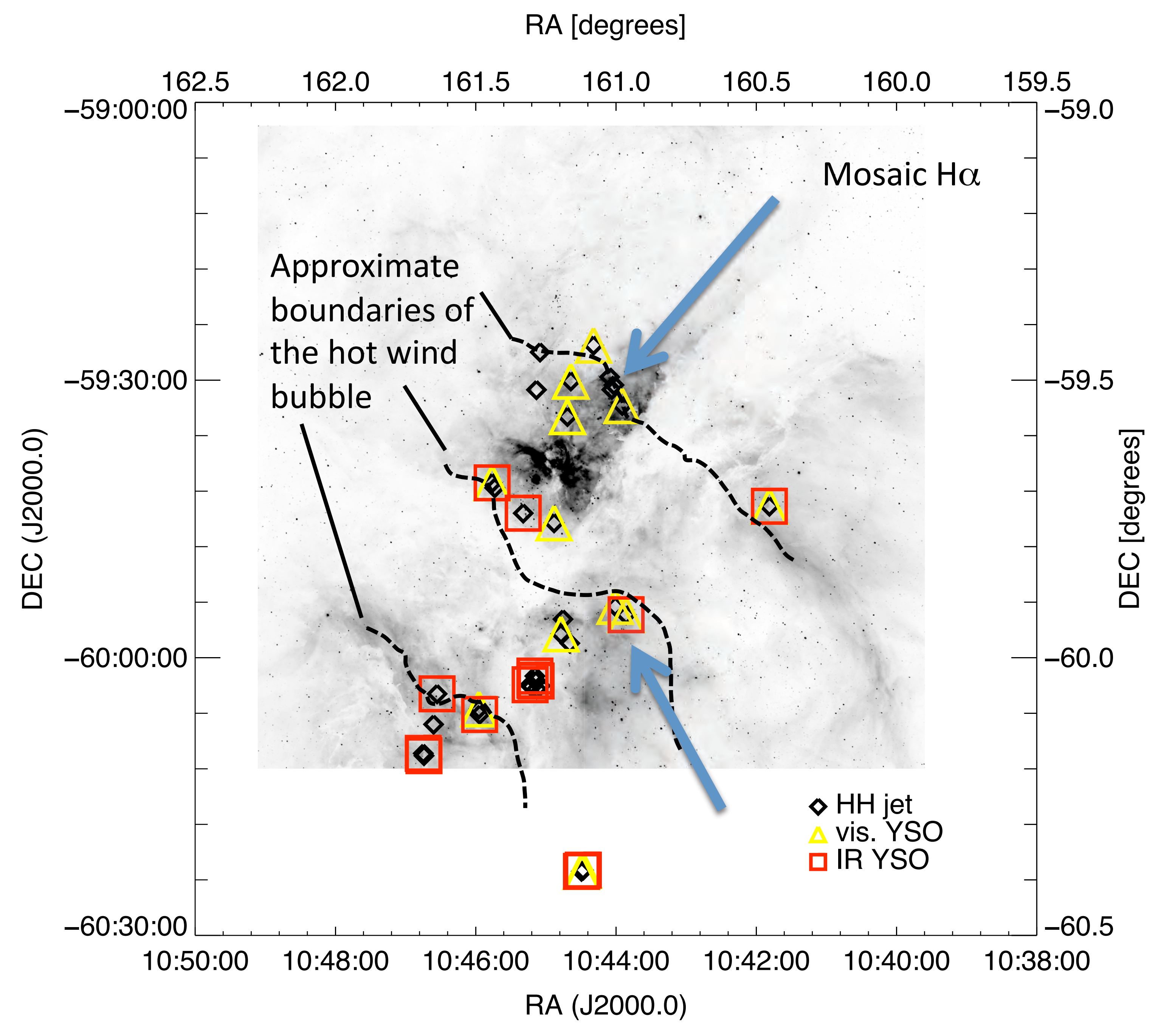
[Fe II] connects the jet to the driving protostar

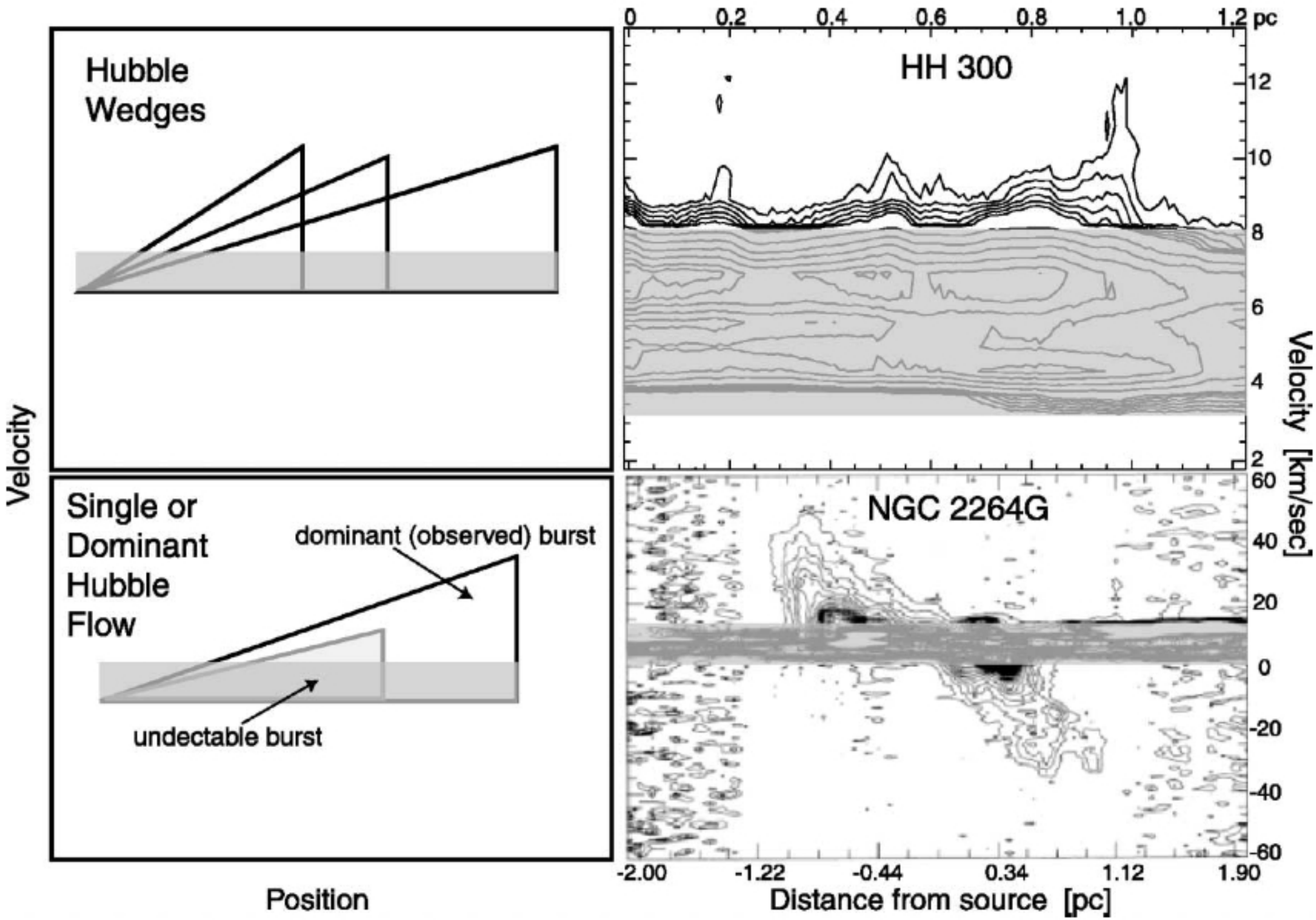


Reiter & Smith 2013

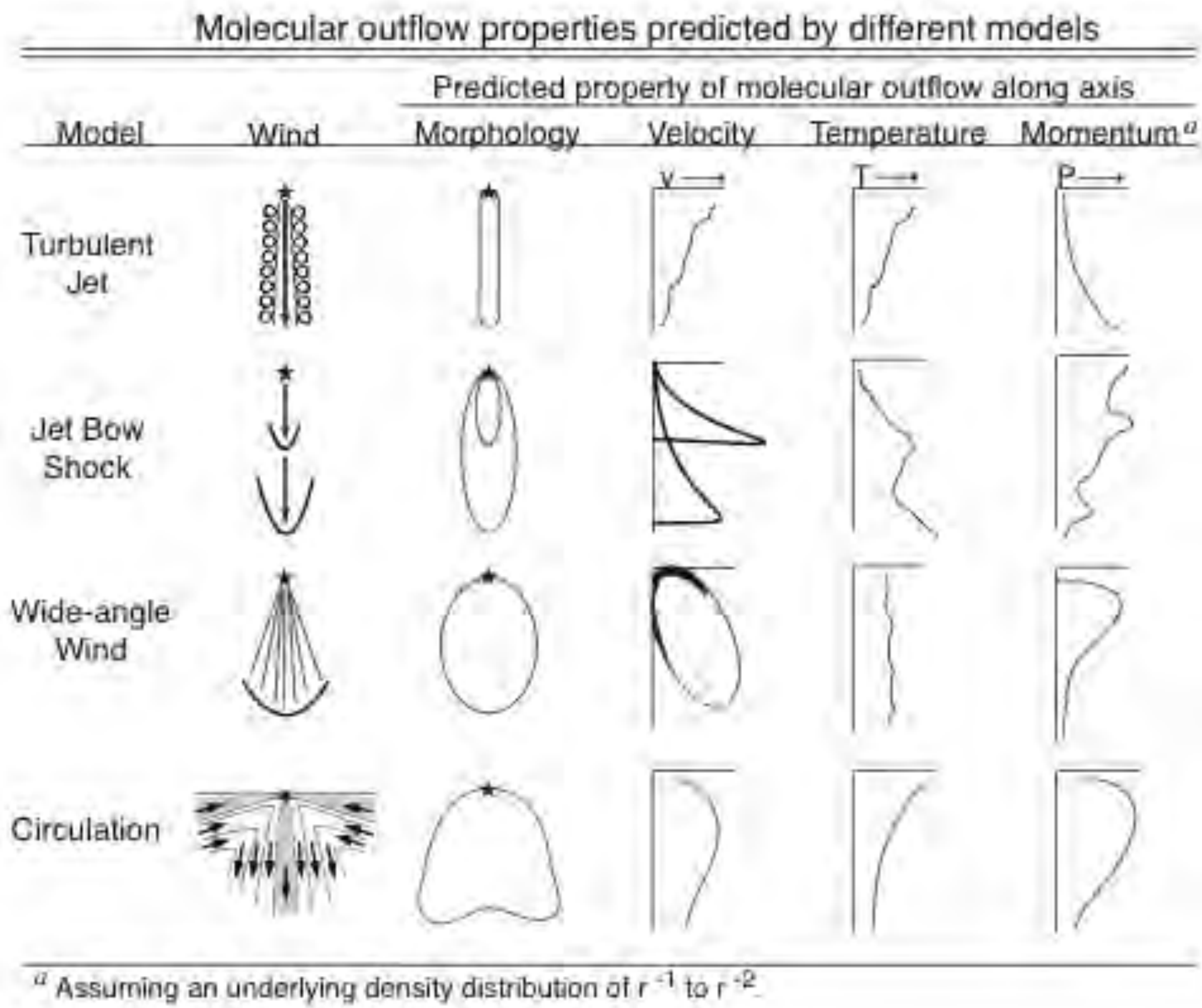

O
2"
O1
184
O2
218
O4
O3
108
165
O5
127
M
M1
186
M3
M2
M5a
M4
176
159
M7
189
166
140
2"
A
130
E
229
N
N1
66
N3
N2
137
153
2"
M
136
2"
A1
163
A2
211
A4
169
A6
A5
212
132
A7
A8
162
97
A9
134
A
E
E2
E1
E4
E3
226
234
183
264
2"
C
2"
C1
161
143
C2
C9
C8
269
163
C7
204
C5
C4
C3
230
161
148
O
124
N
75
Ia
Ib
110
109
C
159
20"
I
I5
140
I1
128
I2
104
I3
147
I4
195
I9
110
I8
116
I10
144
I7
150
I6
128
2"


5''
Y
74
L
60
S
76
U
97
O
90
I
125
R
108
A
84
F
87
E
86
N
63
S
127
U
94
O
54
5''
M
95
A
153
F
89
N
58
I
136
(a)
268
177

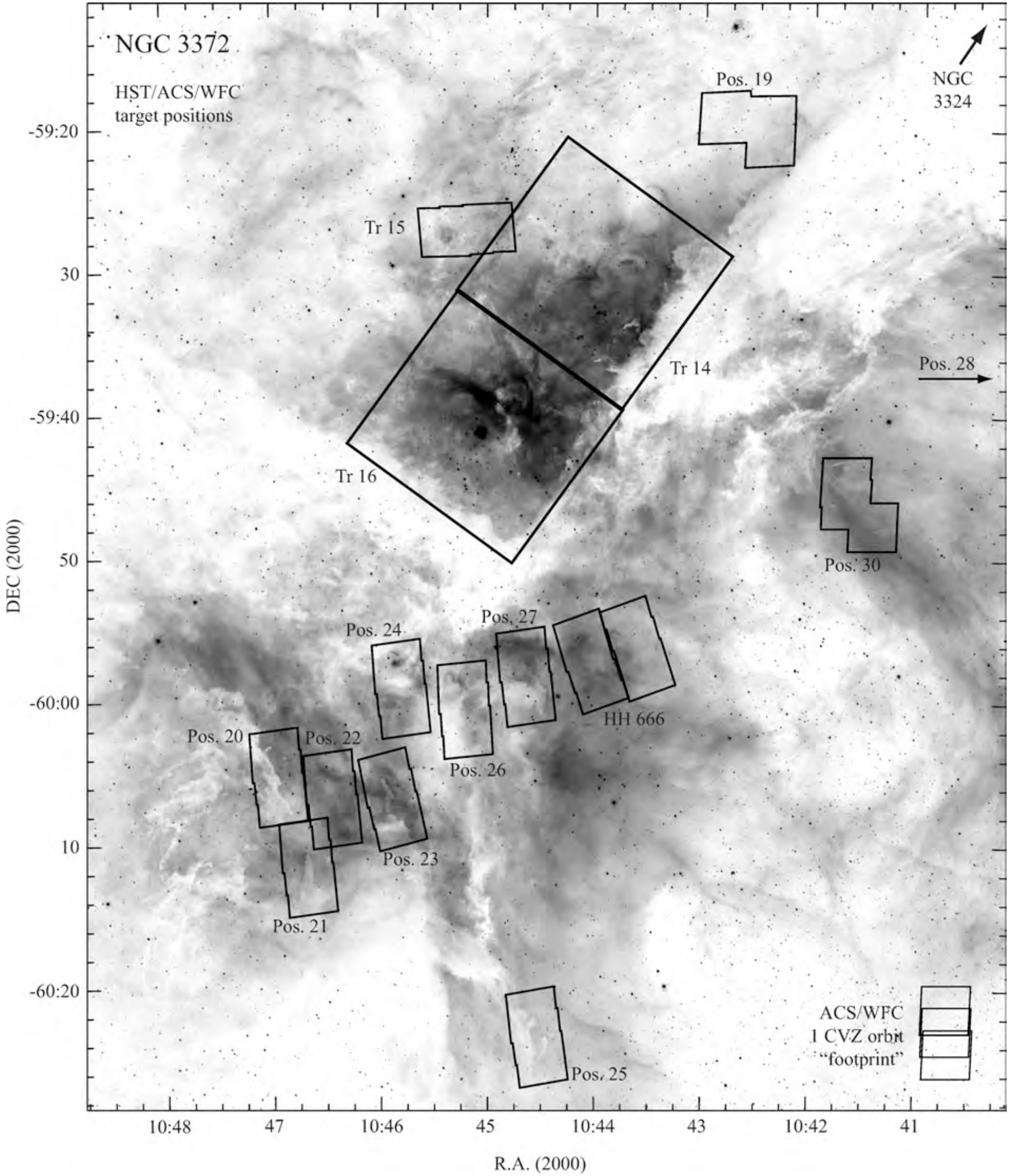

RA [degrees]
162.5
162.0
161.5
161.0
160.5
160.0
159.5
−59:00:00
−59:30:00
−60:00:00
−60:30:00
−59.0
−59.5
−60.0
−60.5
Mosaic Hα
Approximate boundaries of the hot wind bubble
HH jet
vis. YSO
IR YSO
DEC (J2000.0)
DEC [degrees]
10:50:00
10:48:00
10:46:00
10:44:00
10:42:00
10:40:00
10:38:00
RA (J2000.0)



Arce & Goodman 2001



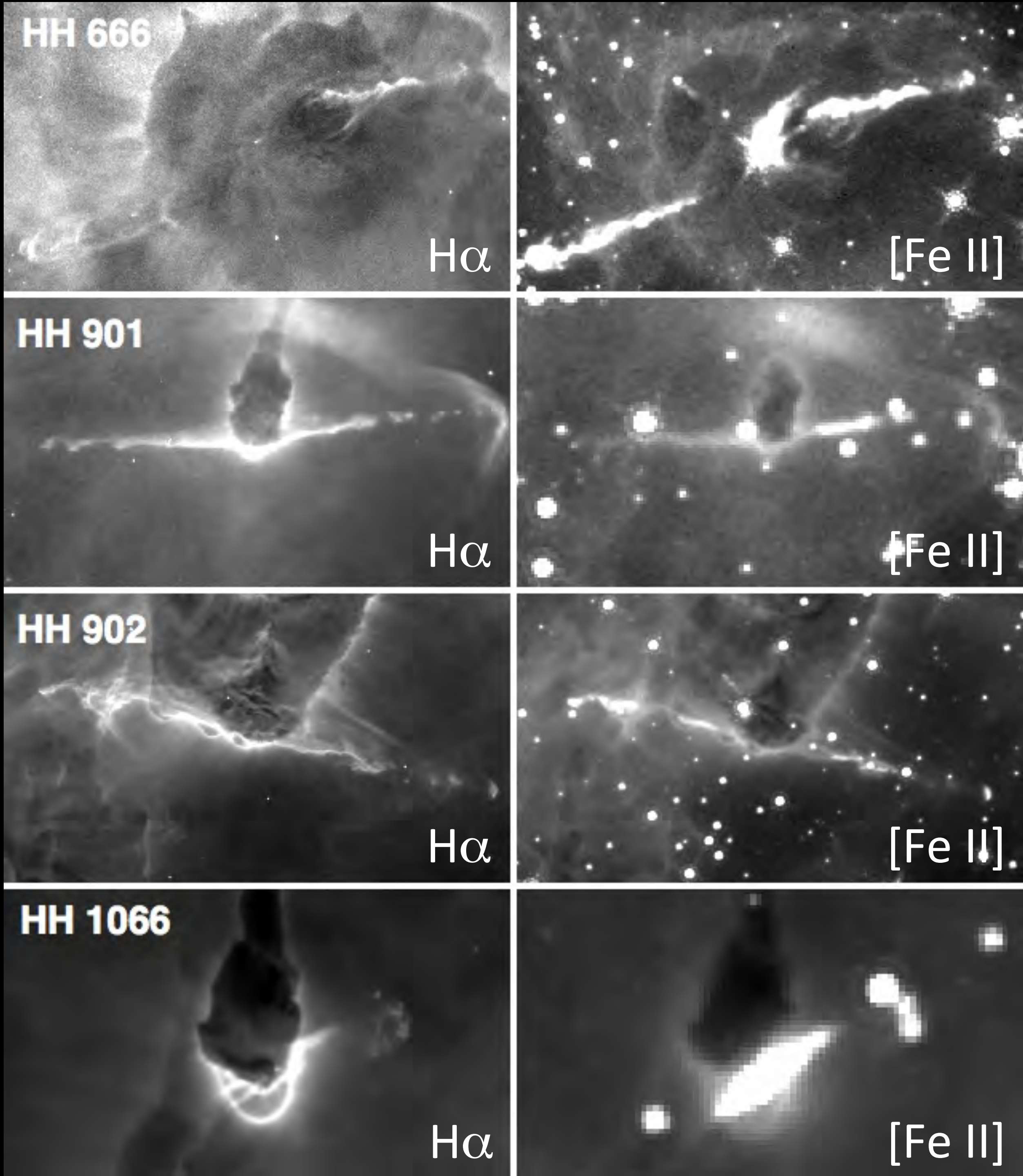
Arce et al. 2007

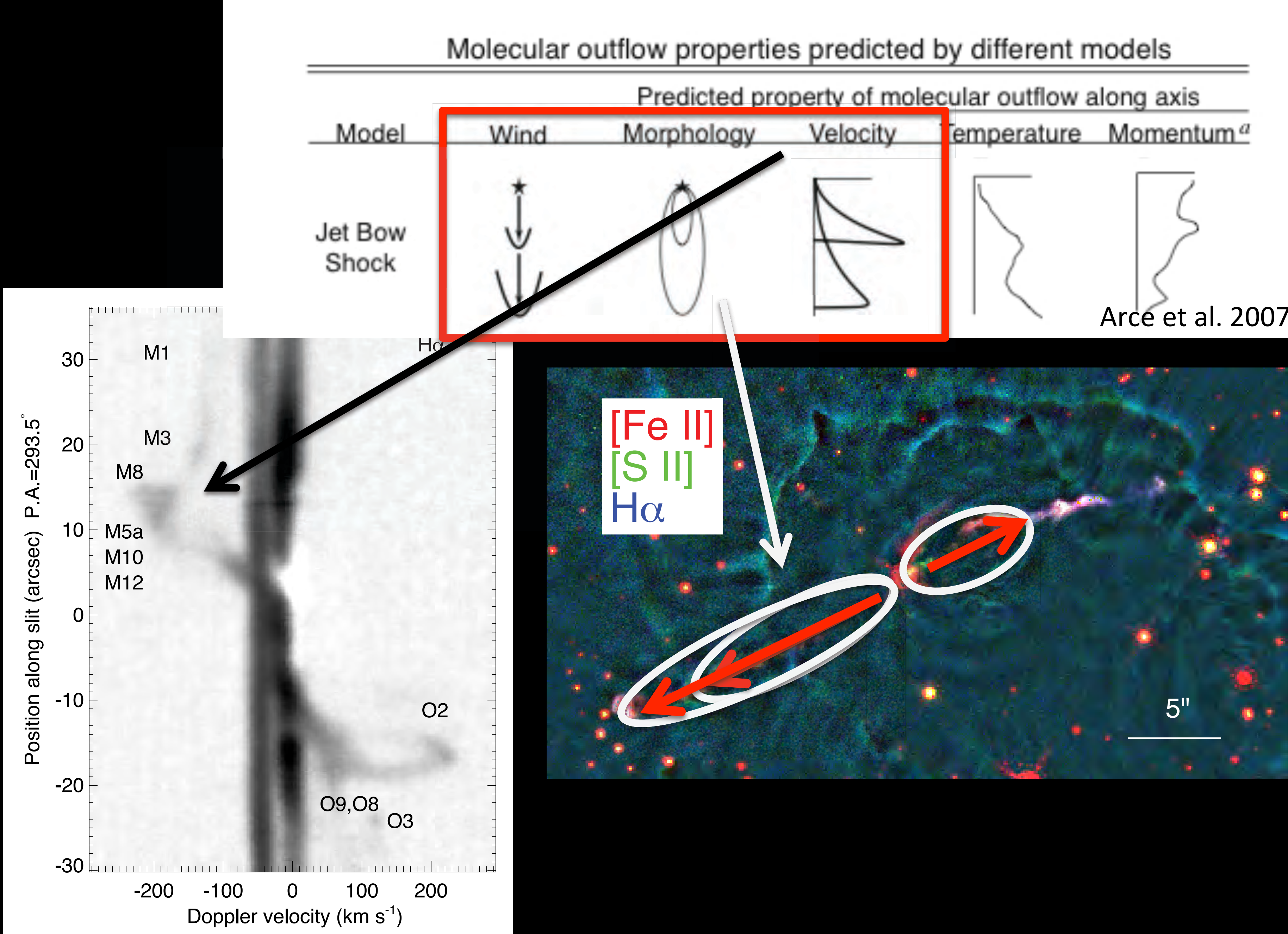


NGC 3372
HST/ACS/WFC
target positions
NGC
3324
Pos. 19
Tr 15
Tr 14
Tr 16
Pos. 28
Pos. 30
Pos. 24
Pos. 27
HH 666
Pos. 20
Pos. 22
Pos. 26
Pos. 23
Pos. 21
Pos. 25
ACS/WFC
1 CVZ orbit
"footprint"
-59:20
30
-59:40
50
-60:00
10
-60:20
DEC (2000)
10:48
47
10:46
45
10:44
43
10:42
41
R.A. (2000)

Irradiated HH jets in Carina

- Episodic?
- Efficiency?
- $\dot{M}(t)$





Reiter et al. 2015b, submitted

Carina Nebula