Radiative Feedback From Runaway Massive Stars

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see arXiv:1209.0455 and D. Meyer's poster.

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- Motivation and the example of Zeta Oph.
- 2D simulation results.
- 3D simulations (preliminary results).
- Conclusions and future work.

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The Low-Metallicity ISM: Chemistry, Turbulence and Magnetic Fields.
Göttingen, 8-12 October, 2012.

Introduction and Motivation

- O stars have ionising-photon energy outputs $E>10^{51}$ erg over their lifetimes... heating, shocks, shells.
- This is much larger than wind kinetic energy (especially at lower metallicity).
- Up to 25% of massive stars are exiled from their birthplace, as “runaways” ($V_* > 30$ km/s) or “field stars” (Gies, 1987).
- Their feedback effects are distributed more widely through the Galaxy, esp. out of the Galactic plane.
- They explode in random places (e.g. Eldridge, Langer, & Tout, 2011).
- Are they important to ISM structure or dynamics?

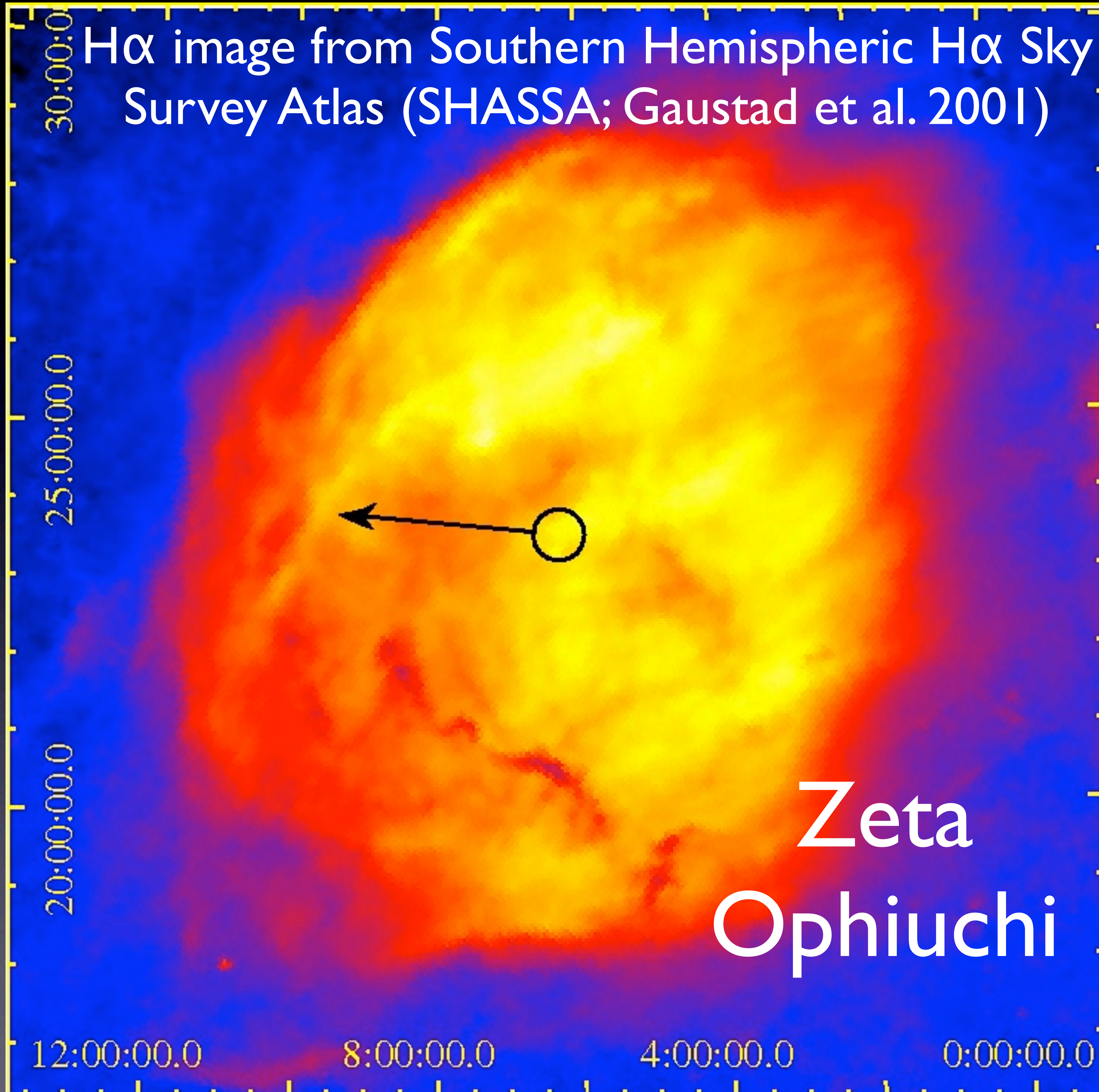
Questions to address

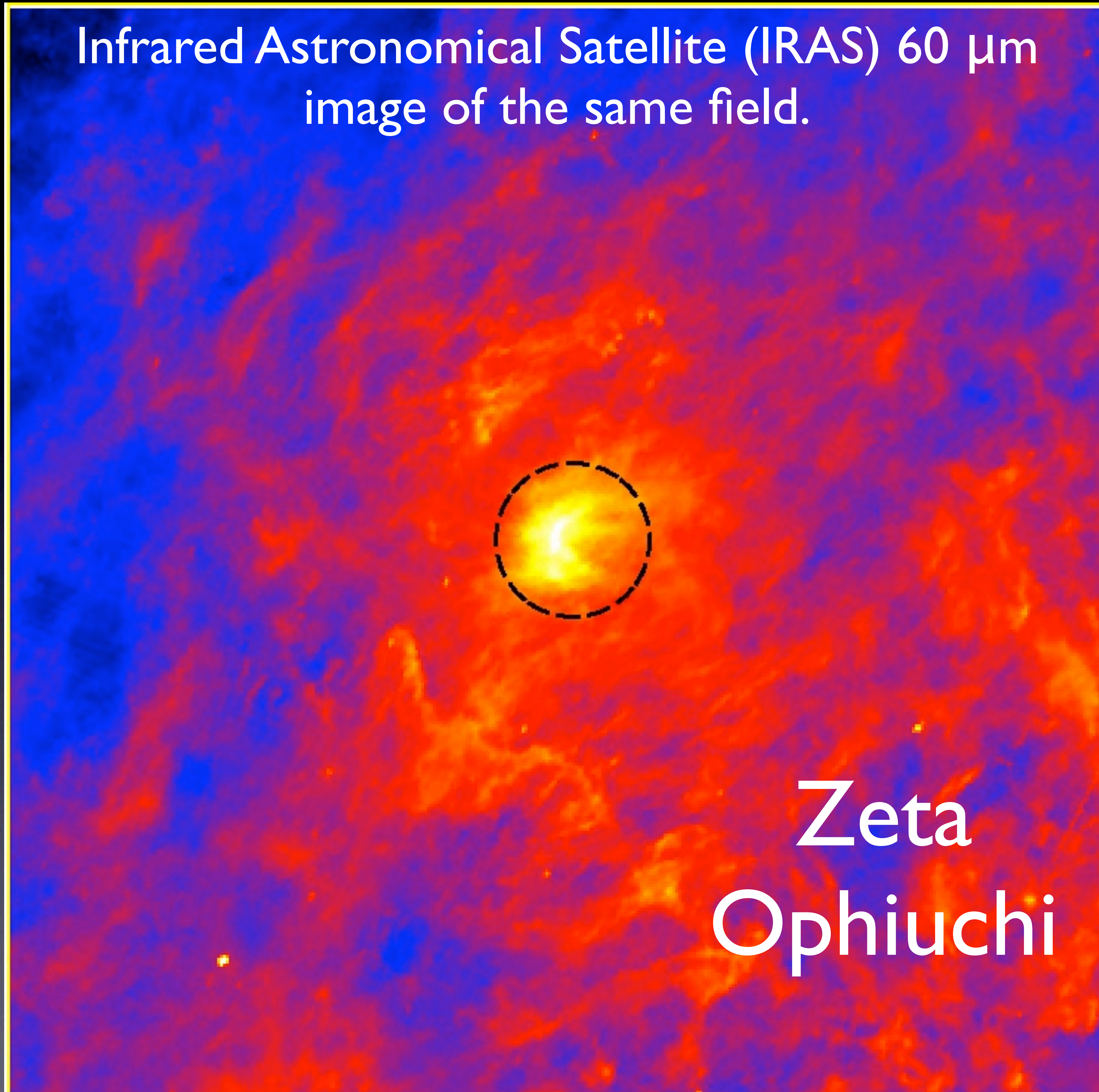
- How does photoionisation affect the ISM?
- How does photoionisation affect gas dynamics within the HII region?
- How do ISM dynamics, substructure, magnetic fields affect the HII region?
- What does all this mean for the wind bow shocks?
- What can we learn about the runaway star?

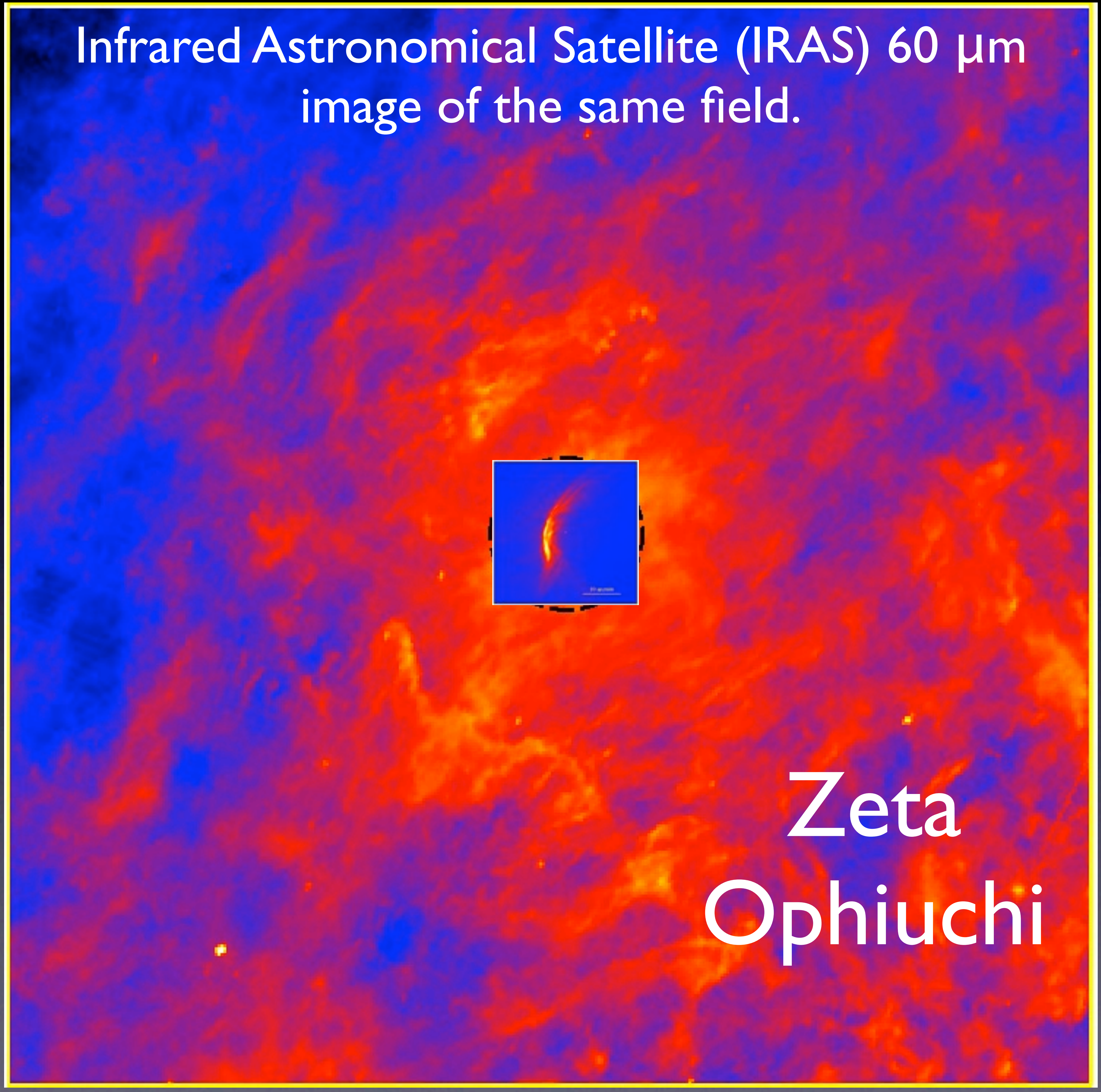
Zeta Ophiuchi

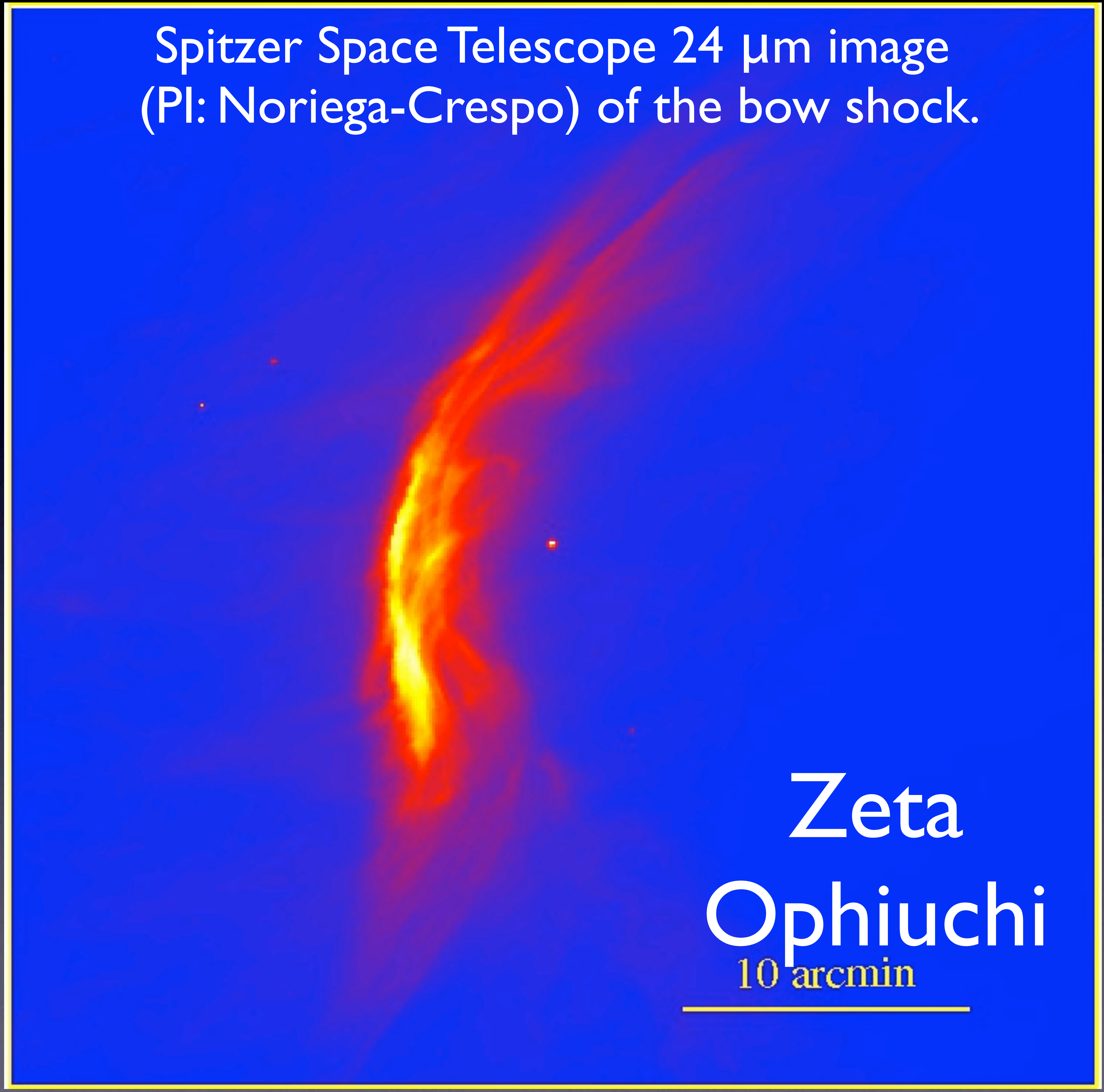
- O 9.5Vnn runaway star (Morgan, Code & Whitford 1955).
- Distance d≈112 pc (van Leeuwen 2007).
- Space Velocity in ISM v_*=26.5 km/s (for this distance).
- rapidly rotating (v sin *i* =400 km/s, Howarth & Smith, 2001) and He enriched, so secondary of a binary system with supernova?
- Has magnetic field ~150G (Hubrig+,2011, AN).
- Widely varying estimates of mass-loss rate, Mdot.
- Mdot(UV) ≈ $1.58\times10^{-9}\ M_\odot yr^{-1}$ (Marcolino+,2009), Mdot(Hα) ≈ $1.43\times10^{-7}\ M_\odot yr^{-1}$ (Mokiem+,2005), Mdot(theory) ≈ $1.29\times10^{-7}\ M_\odot yr^{-1}$ (Vink+,2000), Mdot(theory) ≈ $1.3\times10^{-8}\ M_\odot yr^{-1}$ (Lucy,2010).

Hα image from Southern Hemispheric Hα Sky Survey Atlas (SHASSA; Gaustad et al. 2001)




Infrared Astronomical Satellite (IRAS) 60 μm
image of the same field.
Zeta
Ophiuchi


Infrared Astronomical Satellite (IRAS) 60 μm
image of the same field.
Zeta
Ophiuchi


Spitzer Space Telescope 24 μm image
(PI: Noriega-Crespo) of the bow shock.
Zeta
Ophiuchi
10 arcmin

Constraining Mass-loss rate

Bow shock radius

$$R_0 = \left[\frac{\dot{M} v_\infty}{4\pi n(\mu m_{\rm H} v_*^2 + 2kT)}\right]^{1/2}$$

HII region radius

$$R_{\rm St} = \left(\frac{3S(0)}{4\pi\alpha_{\rm B} n^2}\right)^{1/3}$$

$$\dot{M}_{\rm obs} v_\infty = 1.57\times10^{25}\,{\rm g\,cm\,s^{-2}}\left(1+\frac{1}{M^2}\right)\left(\frac{R_0}{0.1\,{\rm pc}}\right)^2 \times\left(\frac{v_*}{10\,{\rm km\,s^{-1}}}\right)^2\left(\frac{S(0)}{10^{48}\,{\rm s^{-1}}}\right)^{1/2}\left(\frac{R_{\rm St}}{10\,{\rm pc}}\right)^{-3/2},$$

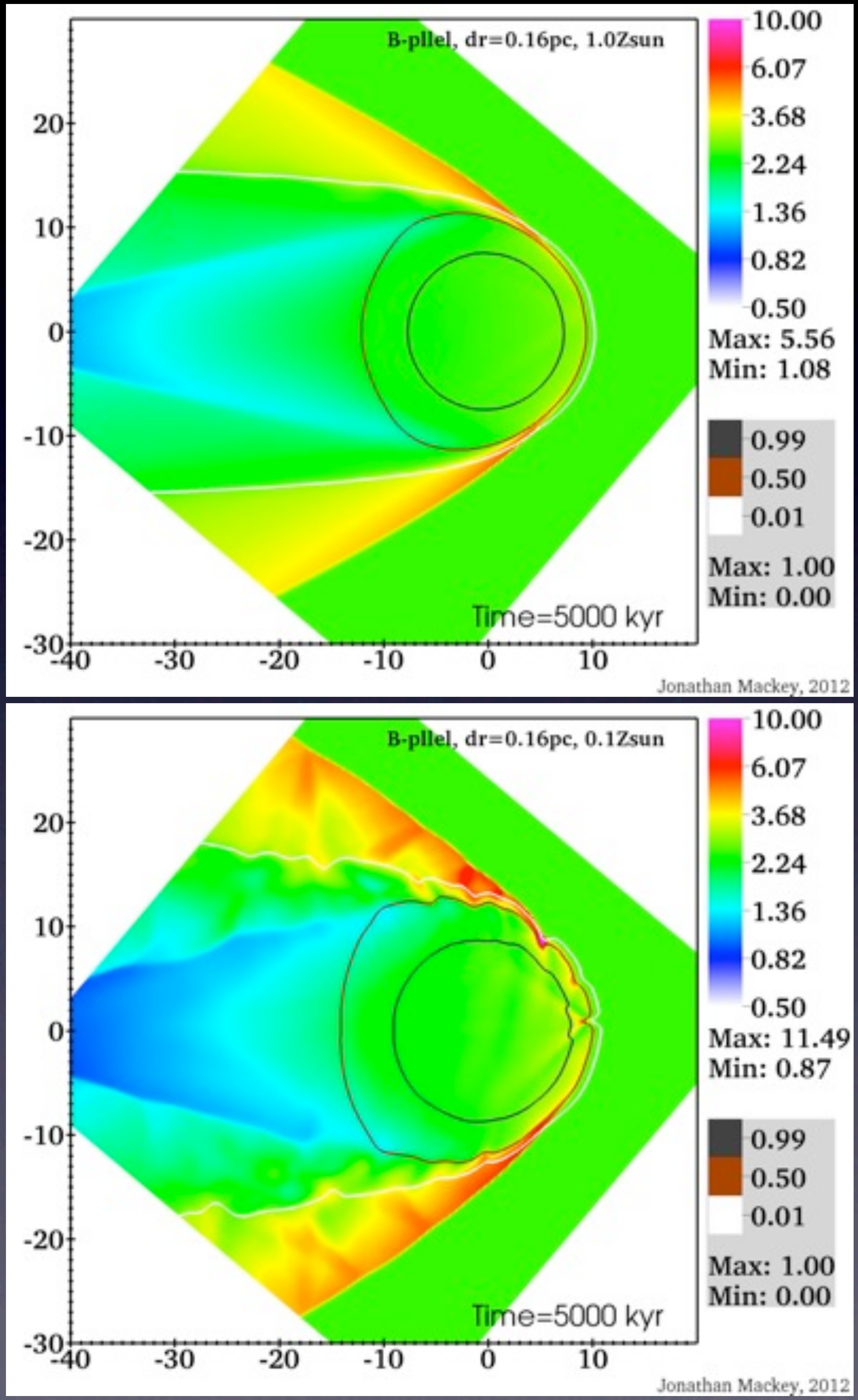
- Zeta Oph has: $\boldsymbol{R_0}$=0.16 pc, $\boldsymbol{v_*}$=26.5 km/s, $\boldsymbol{R_{St}}$ = 9.6 pc (observed), and ***S(0)*** = 3.6x 10^{47} s^{-1} from spectral type, ***M***=2.5 for T=10^4K.
- For $\mathbf{v_\infty}$ =1500 km/s, Mdot = $2.2 \times 10^{-8}\ M_\odot\ yr^{-1}$.

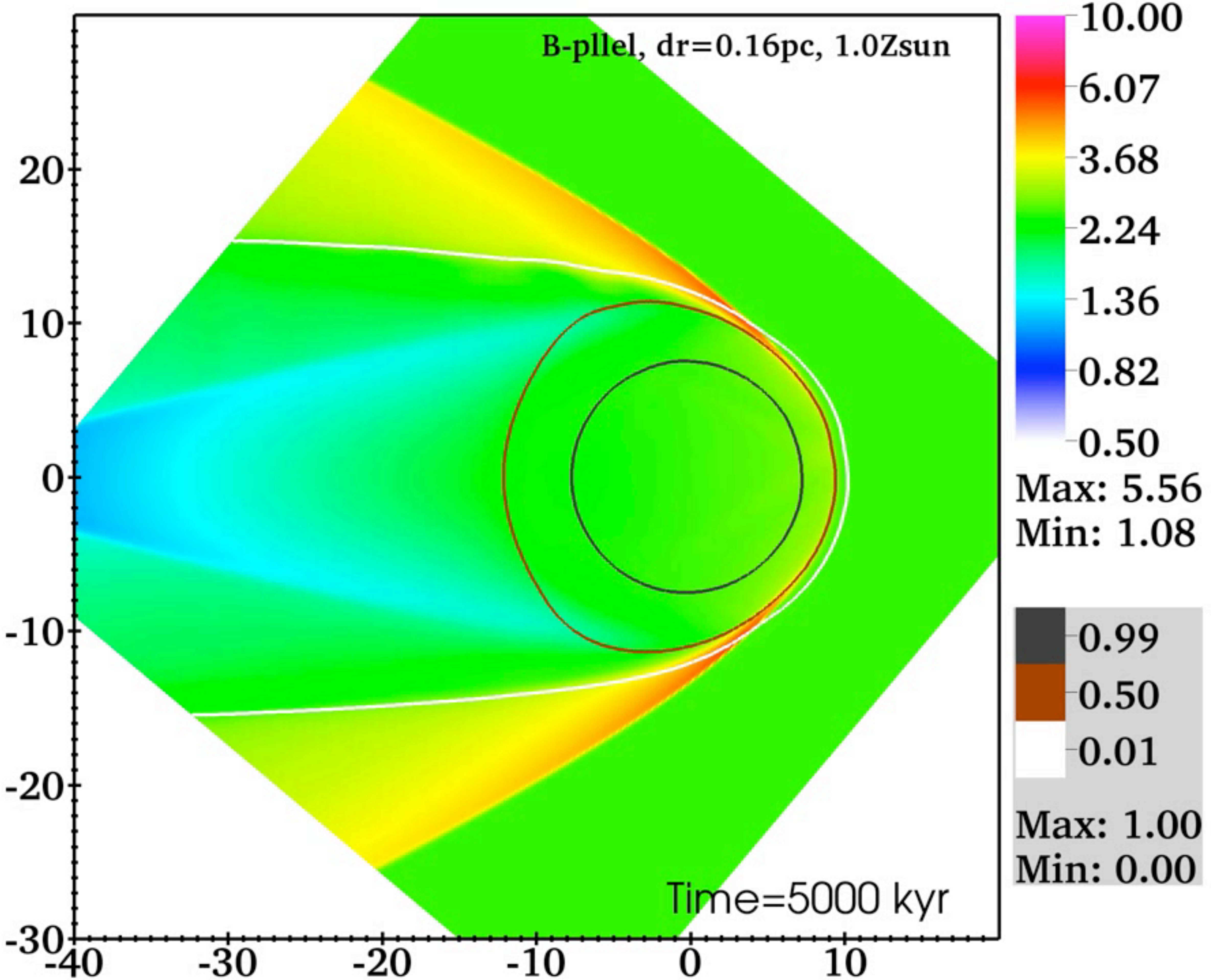
Simulations

- 1D, 2D, 3D Cartesian simulations with radiation-MHD using raytracing photoionisation (Mackey+,2010,2011).
- Star at origin; uniform ISM flowing past star with:
  (i) no B-field, or
  (ii) uniform B-field with B.v=1 (parallel), or
  (iii) B.v=0 (perpendicular).
- B-field strength 7muG. ISM density n_H=2.5 cm^{-3}.
- Neutral gas heating and cooling based on Wolfire+(2003), with metal/dust terms multiplied by a constant.
- Atomic H, He cooling calculated explicitly based on ion fraction (Frank & Mellema,1994, Hummer 1994).
- Photoionised gas has cooling from C,O, (Henney+2009).
- http://www.astro.uni-bonn.de/~jmackey/numerical.html

2D radiation-hydro/MHD simulations

- Cartesian dynamics on a 2D plane.
- Uniform ISM advects past star (at origin) at 26.5 km/s.
- O 9.5V star in ISM: ***n***=2.75 cm^{-3}.
- Ionising and FUV radiation included, but no stellar wind.
- Models run with parallel and perpendicular 7muG B-field, and pure hydrodynamics.
- Calculated for solar metallicity, 0.3x and 0.1x solar, and metal-free.
- Hot HII region expands, creating a shell at the sides (Raga+,1997).
- Simulations relax to a stationary state, but with instability in the ionisation front.





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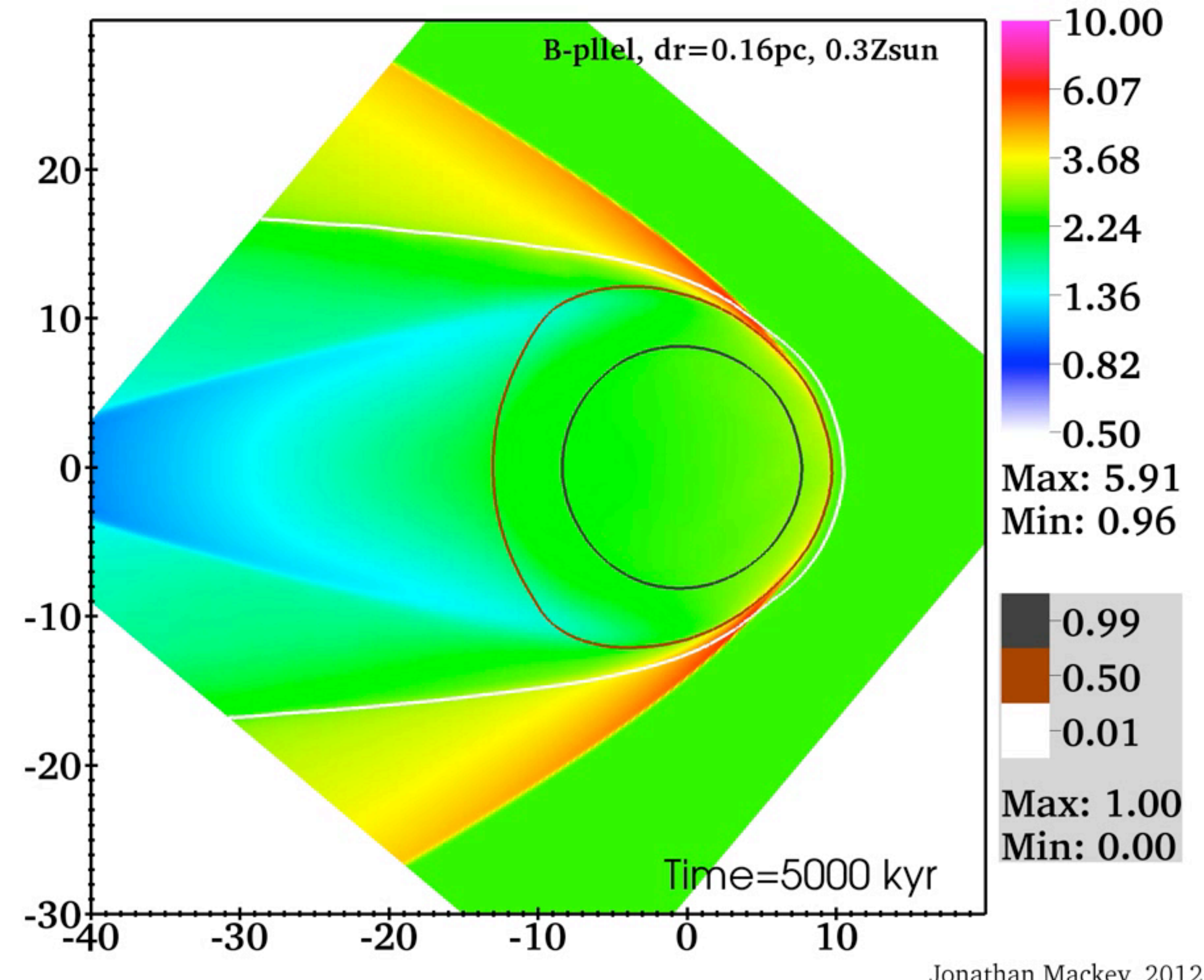
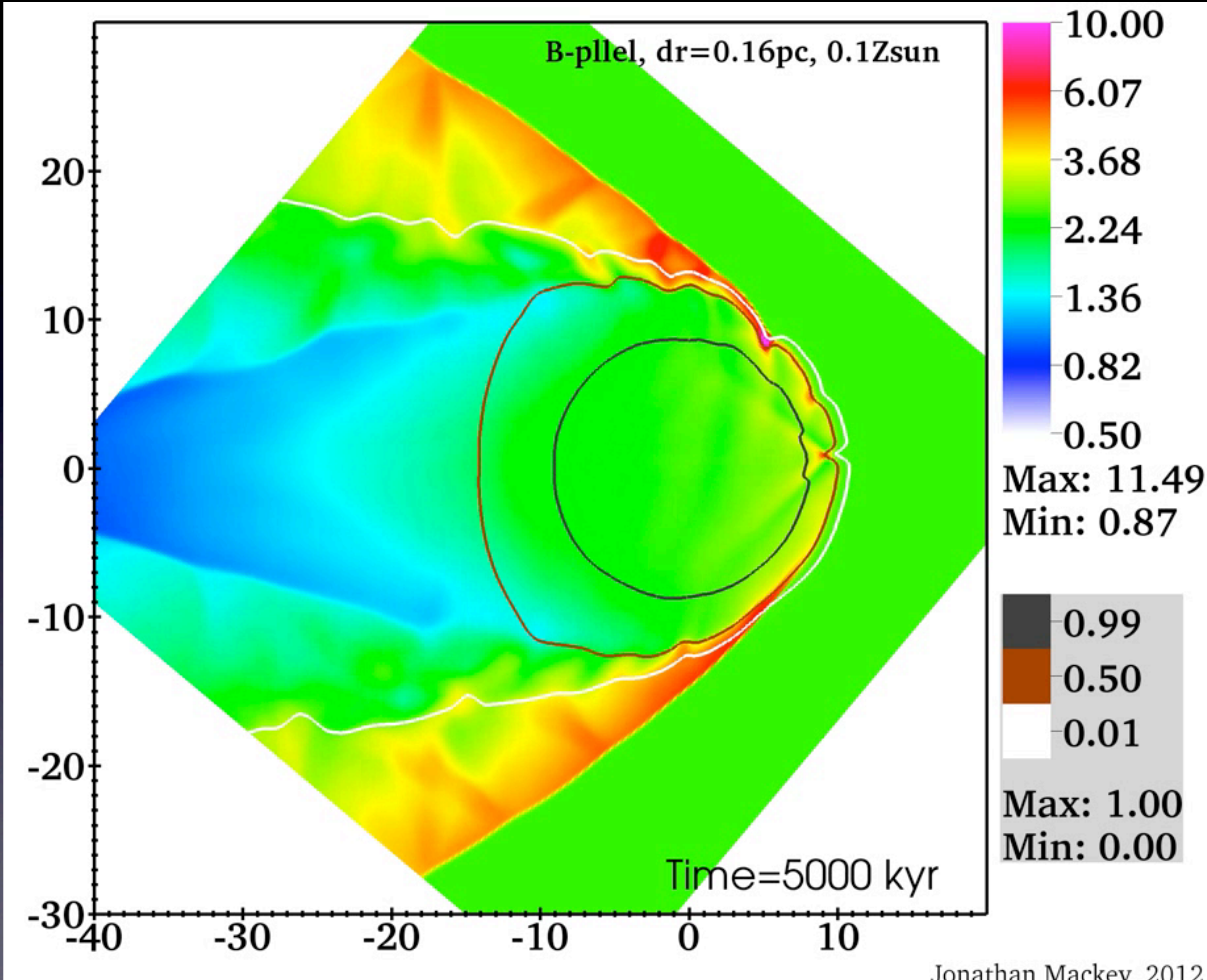
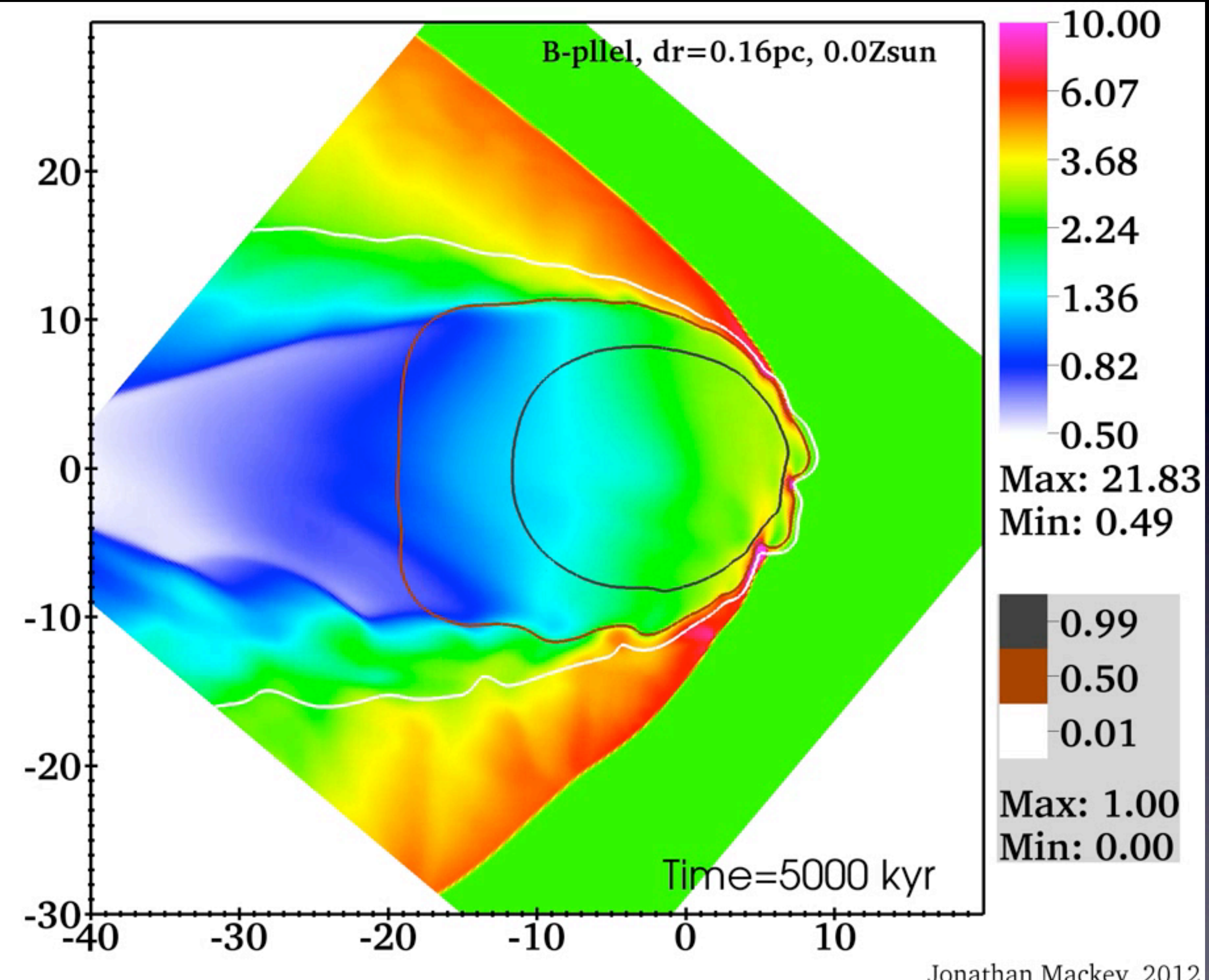
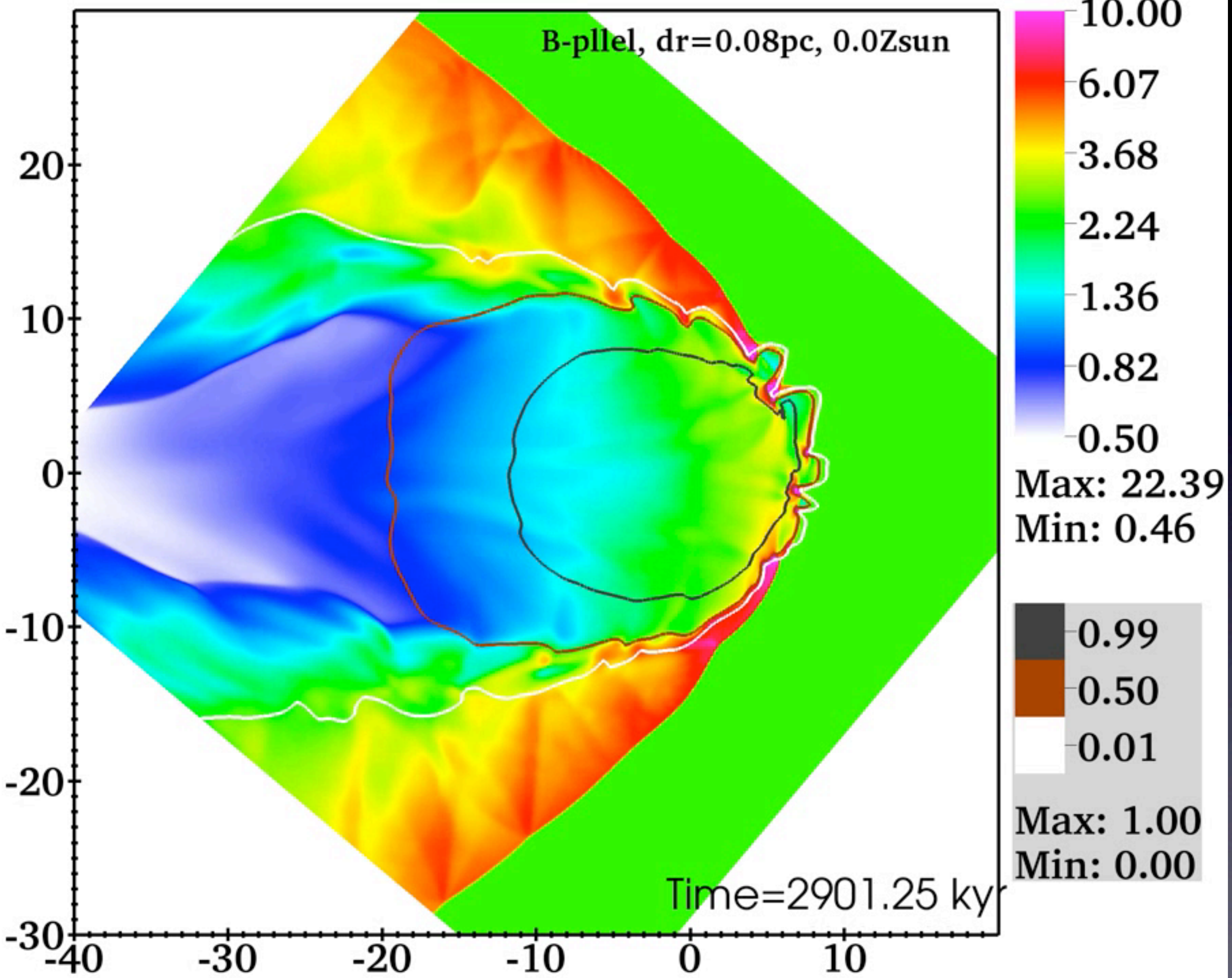

B-pllel, dr=0.16pc, 0.3Zsun
10.00
6.07
3.68
2.24
1.36
0.82
0.50
Max: 5.91
Min: 0.96
0.99
0.50
0.01
Max: 1.00
Min: 0.00
Time=5000 kyr
20
10
0
-10
-20
-30
-40
-30
-20
-10
0
10
Jonathan Mackey, 2012



B-pllel, dr=0.16pc, 0.1Zsun
10.00
6.07
3.68
2.24
1.36
0.82
0.50
Max: 11.49
Min: 0.87
0.99
0.50
0.01
Max: 1.00
Min: 0.00
Time=5000 kyr
20
10
0
-10
-20
-30
-40
-30
-20
-10
0
10
Jonathan Mackey, 2012



B-pllel, dr=0.16pc, 0.0Zsun
10.00
6.07
3.68
2.24
1.36
0.82
0.50
Max: 21.83
Min: 0.49
0.99
0.50
0.01
Max: 1.00
Min: 0.00
Time=5000 kyr
20
10
0
-10
-20
-30
-40
-30
-20
-10
0
10
Jonathan Mackey, 2012



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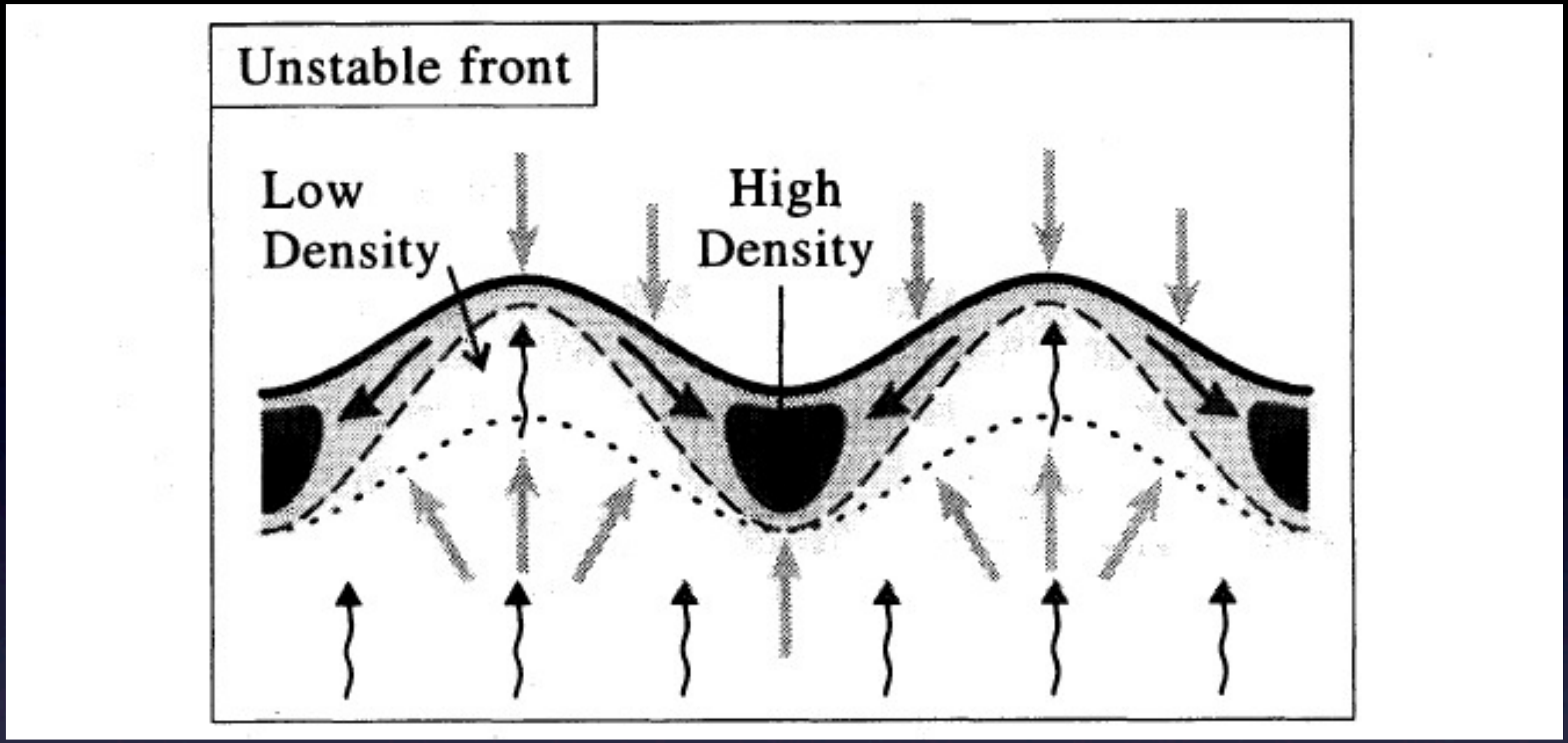
Ionisation-front Instability



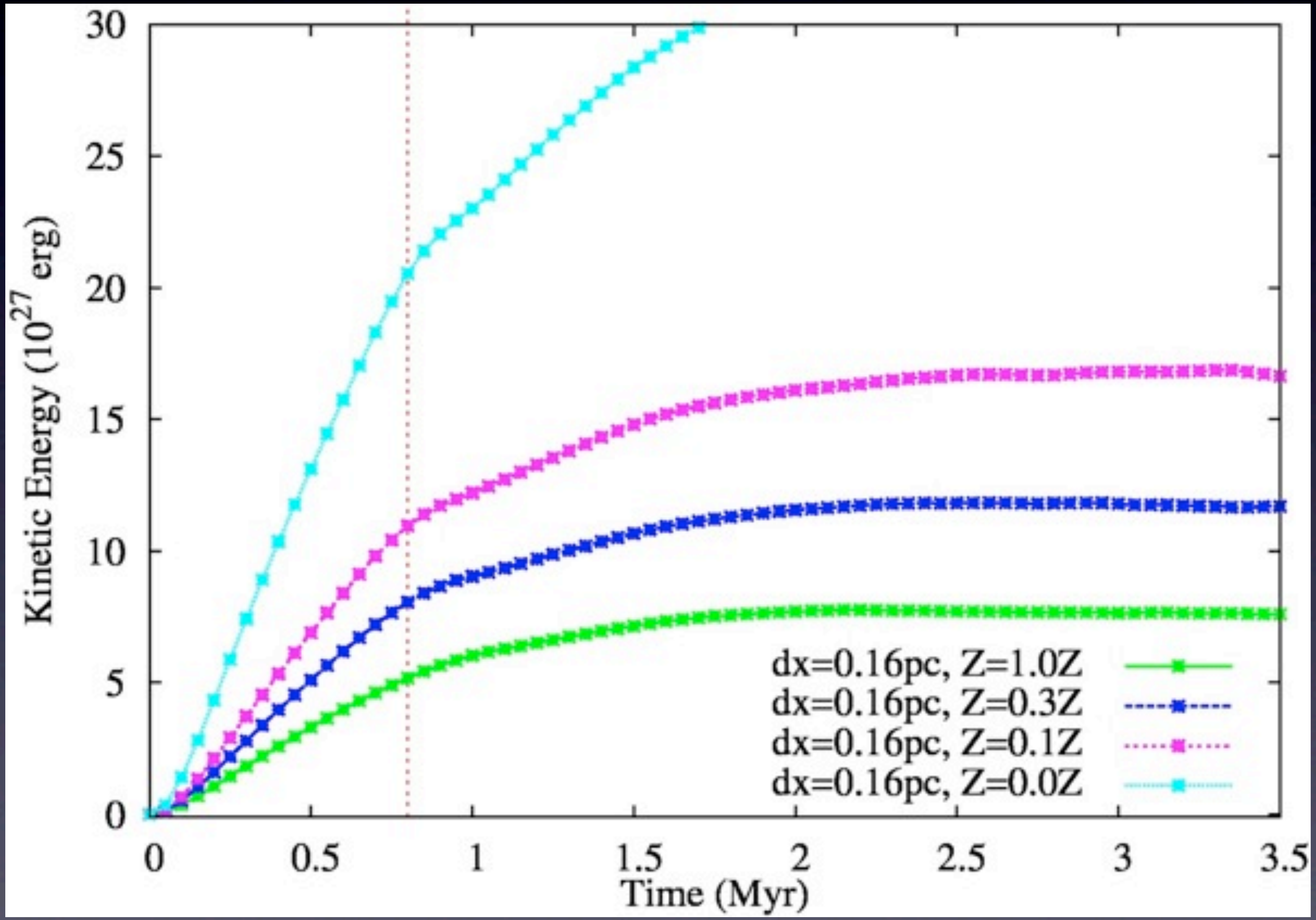
- Figure: Garcia-Segura & Franco (1996).
- We suggest that HII regions from runaway stars are the ideal place to study and observe this phenomenon.
- The ionisation front is (without instability) in steady state.
- Depending on star's velocity, can be R-type or D-type.

A few observations

- There is an expanding conical shell of overdense gas behind star.
- Region directly behind star is underdense, moreso at lower metallicity (will be exacerbated by shocked wind).
- Ionisation front seems unstable (cf. Garcia-Segura+,1996, Whalen & Norman,2008), moreso at lower metallicity.
- Instability gets stronger at higher resolution.
- Gas density at star not greatly changed from ISM value.
- Conversion of thermal to kinetic energy is more efficient at low metallicity.
- 2 reasons: HII region is hotter, shocks are less dissipative.

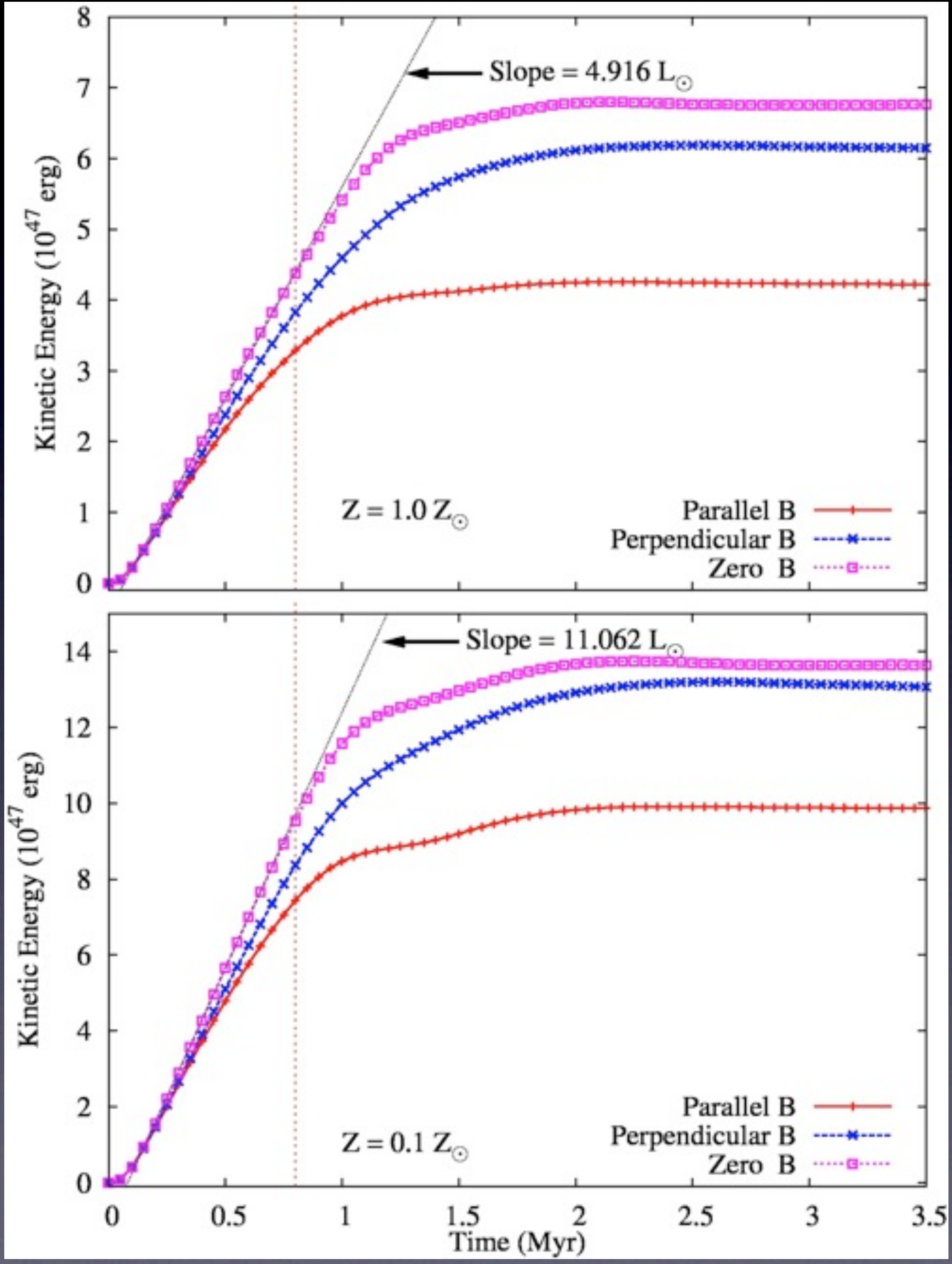
Kinetic Energy as a function of metallicity.

- Results shown for perpendicular B-field simulations.
- resolution dx=0.16pc.
- Steady increase of KE with decreasing metallicity.
- Reasons: hotter HII regions, less dissipation.
- HII region temperatures 6750 K, 8250 K, 9600 K, and 15000 K, respectively.
- Higher temperatures can drive stronger shocks.

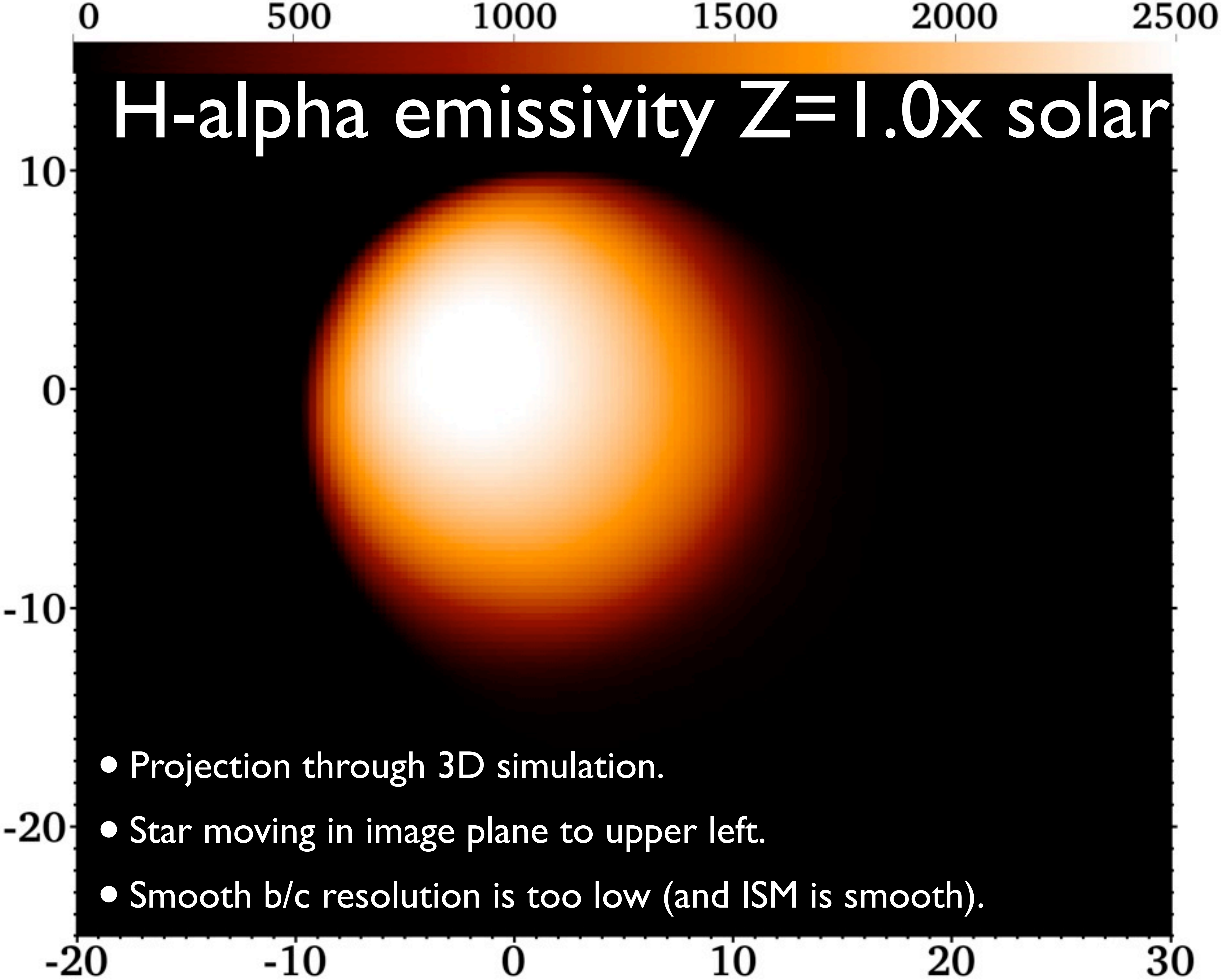


3D simulations (preliminary)

- Same stellar source, same velocity.
- Low resolution: 160^3, with cell size dx=0.32pc.
- Insufficient to resolve I-front instability.
- Same trend is seen, of increasing kinetic energy with decreasing Z.
- Efficiency of photon-to-K.E. conversion is low (0.25% for solar metallicity, ~1% for metal-free).
- Even still, K.E. of HII region shocks is larger than wind K.E. input even at solar metallicity.
- 160^3 needs ~300 cpu-hours, 320^3 ~ 5000 c.h, 640^3 ~ 100k c.h.

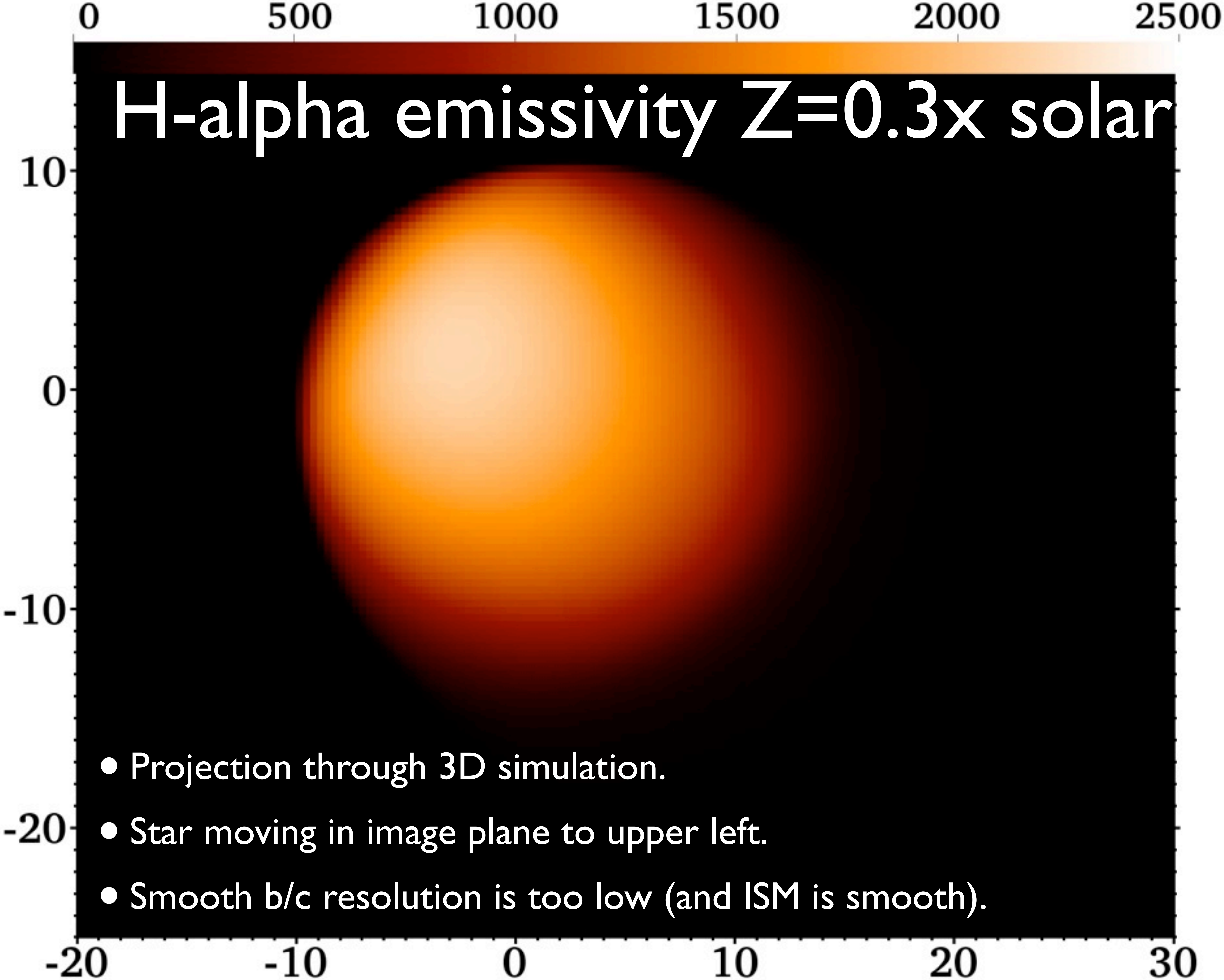


H-alpha emissivity Z=1.0x solar



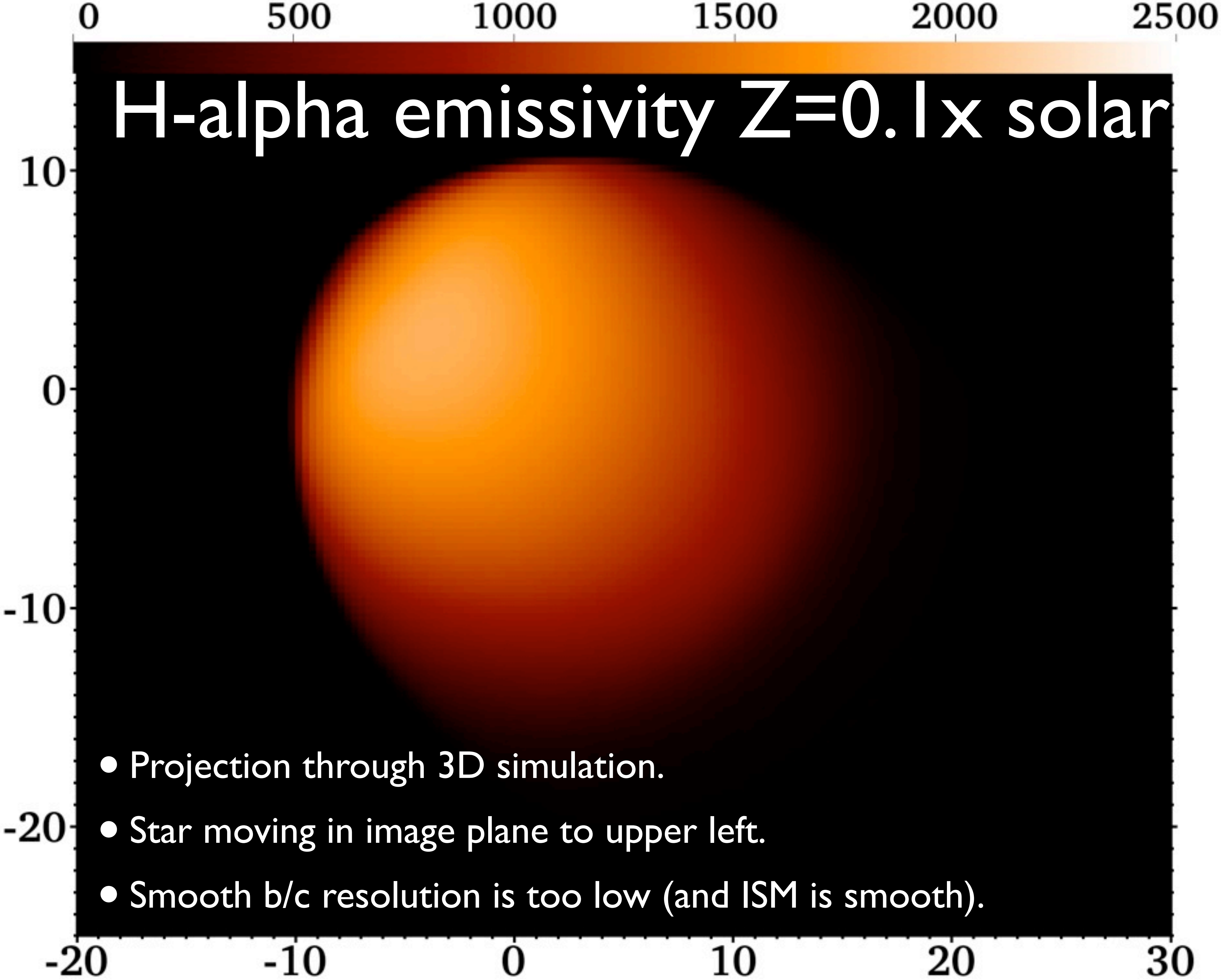
- Projection through 3D simulation.
- Star moving in image plane to upper left.
- Smooth b/c resolution is too low (and ISM is smooth).

H-alpha emissivity Z=0.3x solar



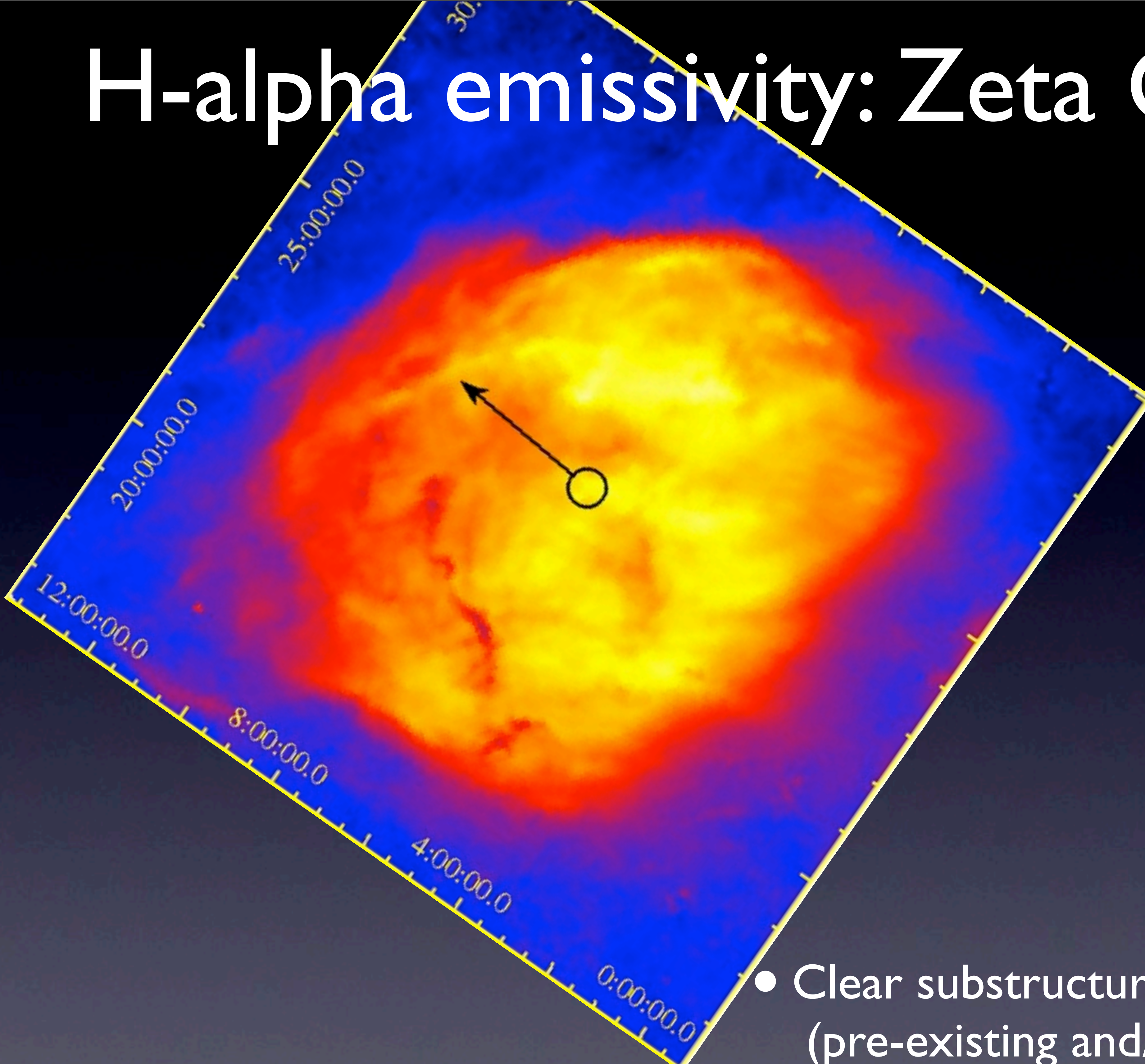
- Projection through 3D simulation.
- Star moving in image plane to upper left.
- Smooth b/c resolution is too low (and ISM is smooth).

H-alpha emissivity Z=0.1x solar



- Projection through 3D simulation.
- Star moving in image plane to upper left.
- Smooth b/c resolution is too low (and ISM is smooth).

H-alpha emissivity: Zeta Oph



- Clear substructure and clumpiness (pre-existing and/or self-generated)
- Upstream is bow-shaped, downstream is flatter.
- Modelling still needs a bit of work...

Conclusions and Future Work

- Dynamics of HII regions around moving stars is complicated.
- Runaway stars are ideal laboratories for observing/modelling ionisation fronts.
- 2D and 3D simulations have unstable ionisation fronts, forming dense knots of neutral gas (cf. Garcia-Segura & Franco, 1996).
- Kinetic energy is inefficiently generated from ionisation heating (~1% or less), but can still be at a greater rate than wind mechanical feedback.
- Despite the unstable ionisation front:
    - Global shape and properties of HII region are not much affected.
    - ISM density at star affected only at the 10-30% level.
- Future work:
  -- 3D simulations with higher resolution (in progress).
  -- Modelling stellar wind bow shocks (see D. Meyer's poster!).
  -- Non-uniform turbulent ISM (3D simulations cf. Mellema+,2006).
  -- Explode supernovae into the pre-computed circumstellar medium.