Modeling the non-thermal emission from stellar bow shocks

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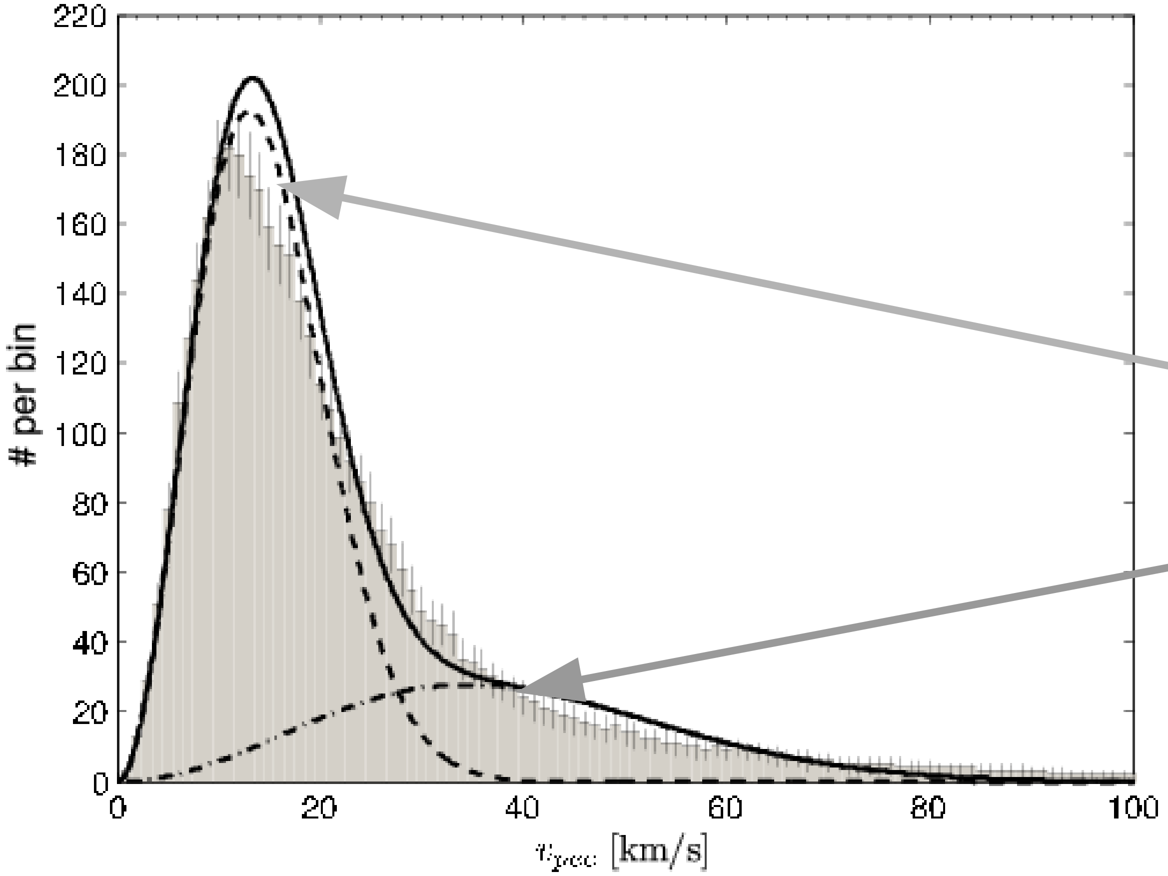
2018 TeV Particle Astrophysics

Runaway stars

Distribution of Galactic star velocities



Two populations!

Runaway stars have V > 30 km / s

Runaway stars

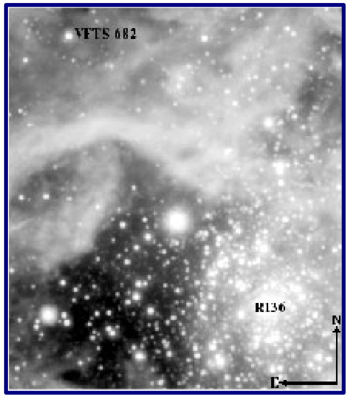
Stars run away from their birth places

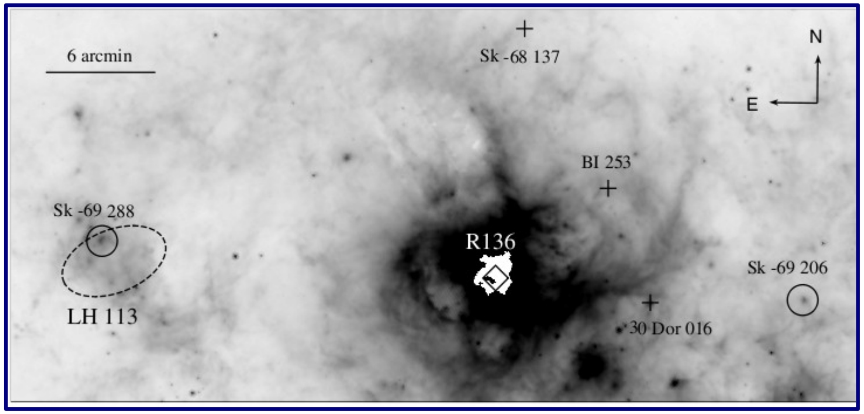
Two mechanisms:

- Expelled in Supernova explosion of binary companion

- Expelled in close encounters in massive clusters (produces more!)

Bestenlehner et al. 2011





Gvaramadze et al. 2011

Bow shock

Star moves supersonically through ISM

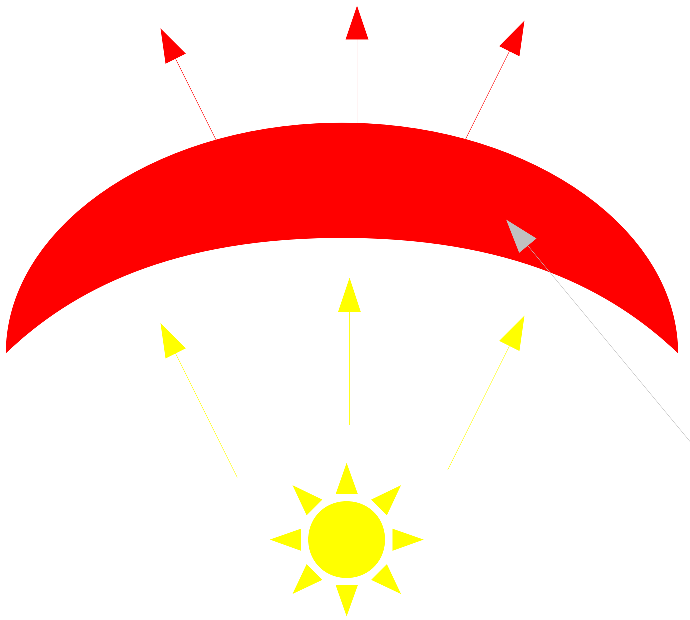
IR emission!

Catalogs in the Galaxy

Peri+ 2012, 2015
Kobulnicky+ 2017

Bow shock

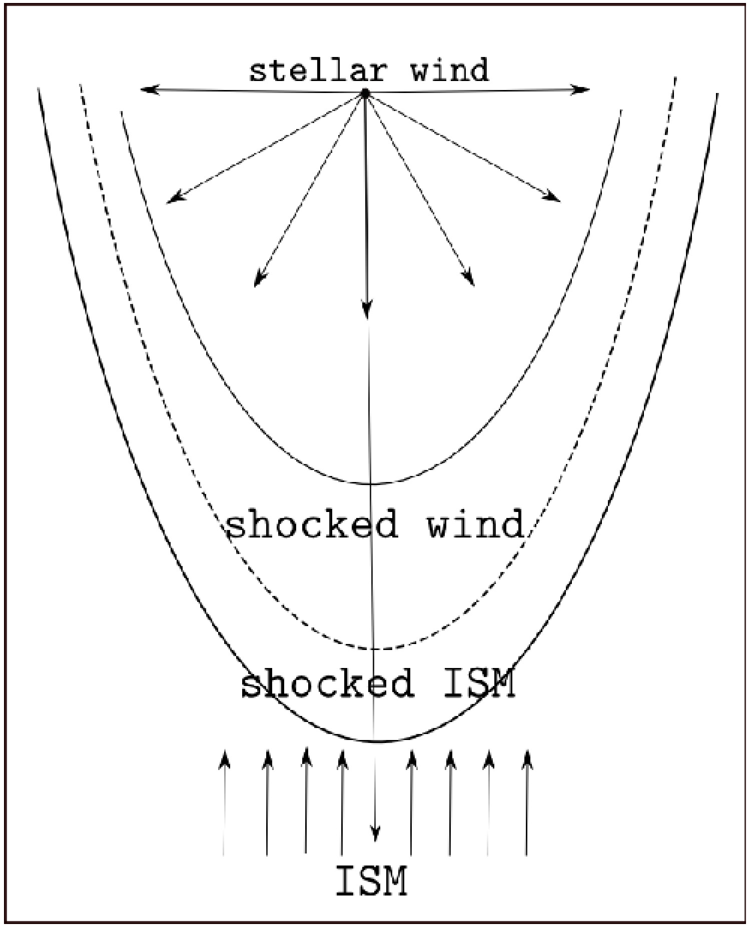
IR emission!



Massive star, very hot
Very luminous!

Swept dust and gas

Colliding plasmas



Pressure balance

$$\rho_w V_w^2 = \rho_a V_\star^2 :$$

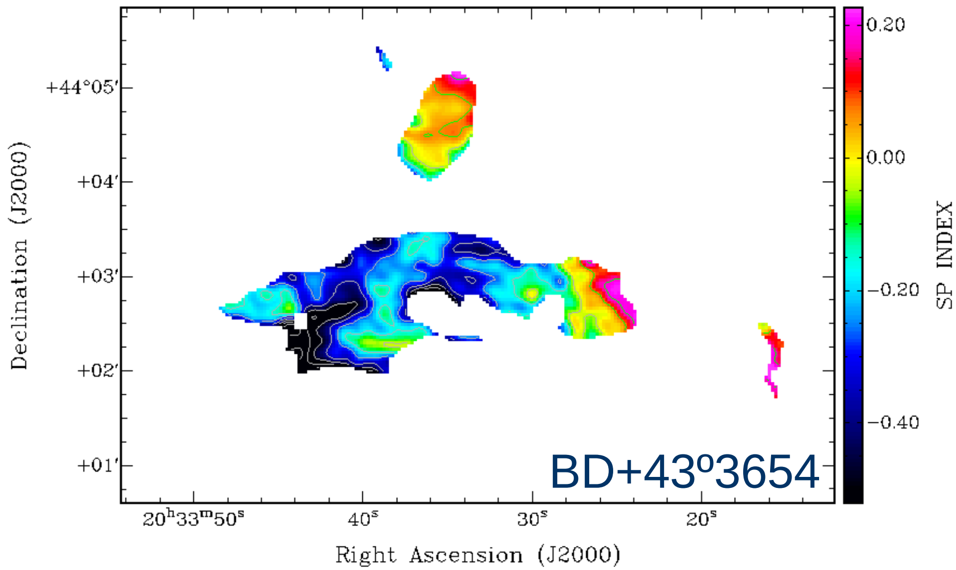
$$R_0 = \sqrt{\frac{\dot{M}_w V_w}{4\pi \rho_a V_\star^2}}$$

System of two shocks forms: wind (reverse) and ISM shock (forward)

Reverse:
Adiabatic, fast V ~ 2000 km s^{-1}

Forward
Radiative, slow V ~ 30 – 100 km s^{-1}

Non-thermal emission detected



Benaglia+ 2010

Synchrotron emission from massive runaway star

Non-thermal emission
Bow shock region

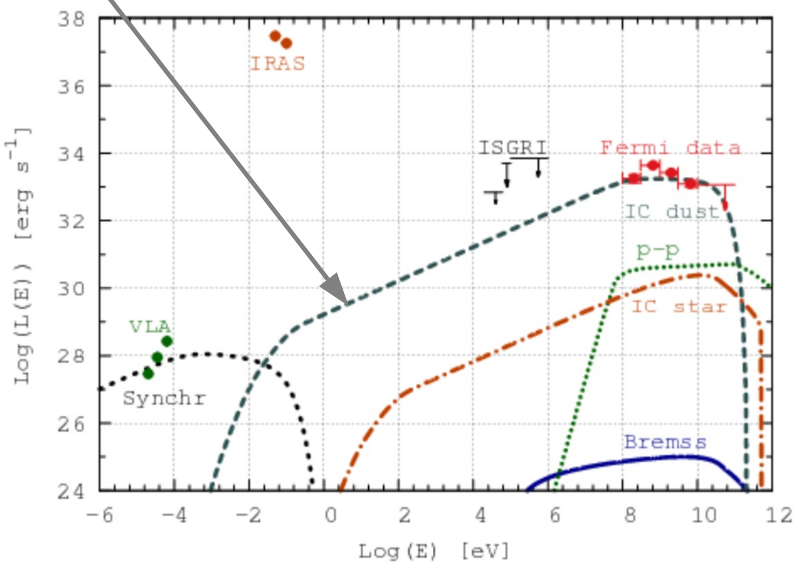
Implies B ~ 100 μG

There are relativistic electrons in the source

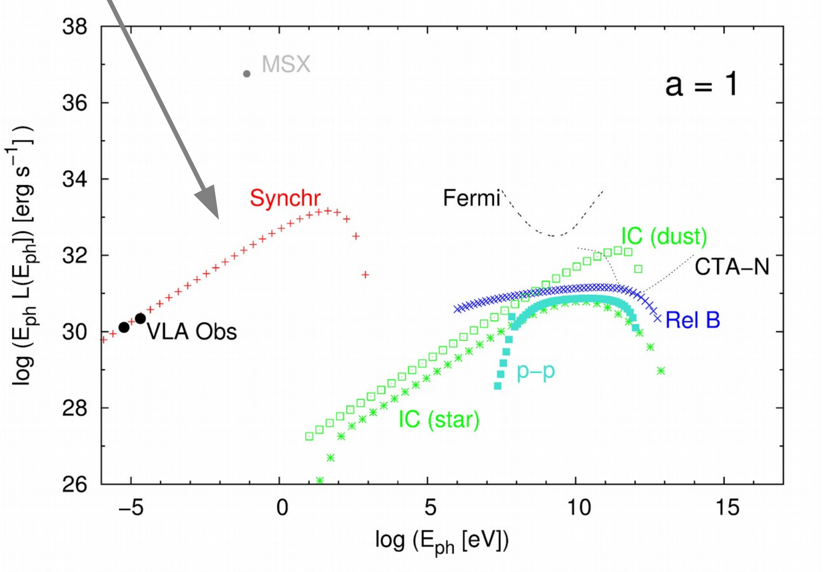
Non-thermal emitters at higher energies?

- Simple models predict gamma and X-rays:

Particles accelerated at the reverse shock emit mainly:
Inverse Compton: target dust photons
Synchrotron: target local magnetic field



del Valle+ 2012
del Valle+ 2014



Benaglia+ 2010

Looking for more:

@ gamma rays:

- *Fermi* from archive data (Schulz et al. 2014), sample E-BOSS ~ 30 (Peri +2012), no data. Upper limits too high or predictions too optimistic, or both ;)
- H.E.S.S. new sample (H.E.S.S. Collaboration 2018) Upper limits also too high,

L (E > 1 TeV) < 10^{-2} L_w

@ X-rays (motivated AE Aurigae)

- *XMM* two very energetic sources (Toalá+ 2016):

no emission reveled

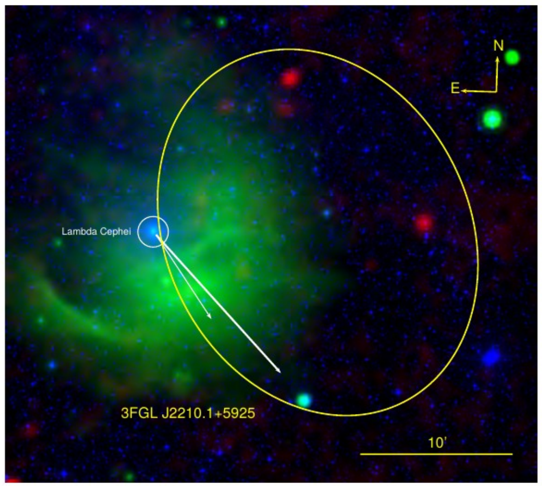
- More *XMM*: five targets from proposal 2014

(de Becker, del Valle+2017): upper limits.

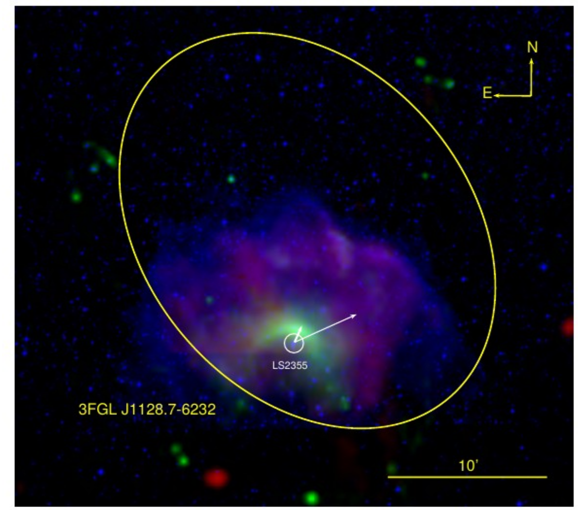
For X-rays better resolution is needed to distinguish thermal from non-thermal (at least one order of magnitude).

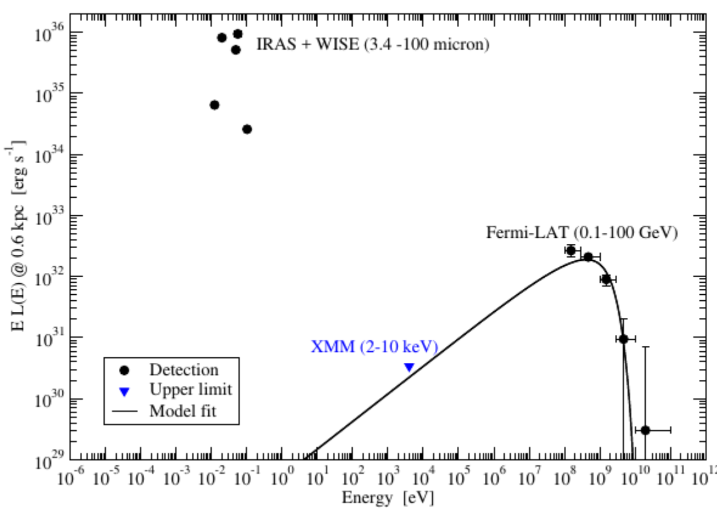
Recently two candidates: *Fermi* 3FGL sources

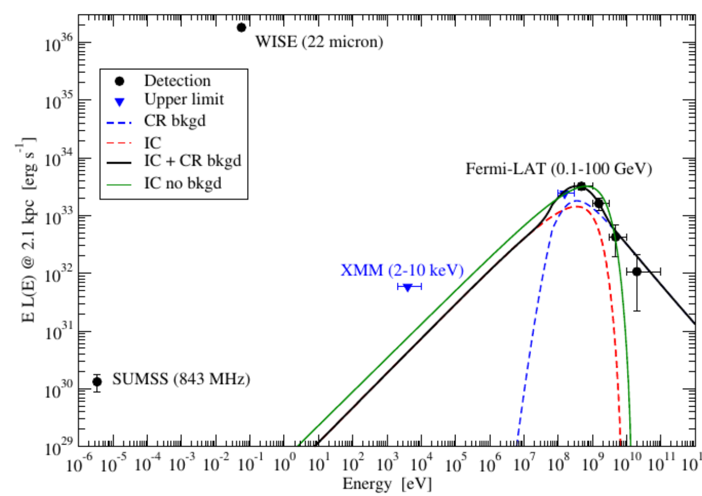
λ Cep



star LS 2355







Sanchez-Ayaso, del Valle +2018

More complex model:
HD structure + non-thermal particles

- Density and velocity field from HD simulations

  B needed for non-thermal particles

  (it is not dynamically important in the fluid structure)
- System reaches stationary state → we use simulation results as a background for solving transport of energetic particles
- Solve the transport equation (linear approx.) for injected electrons and protons → Estimate non-thermal emission
- Explore parameter space

HD simulations

The problem can be considered as axisymmetric: we use cylindrical coordinates:

r and z

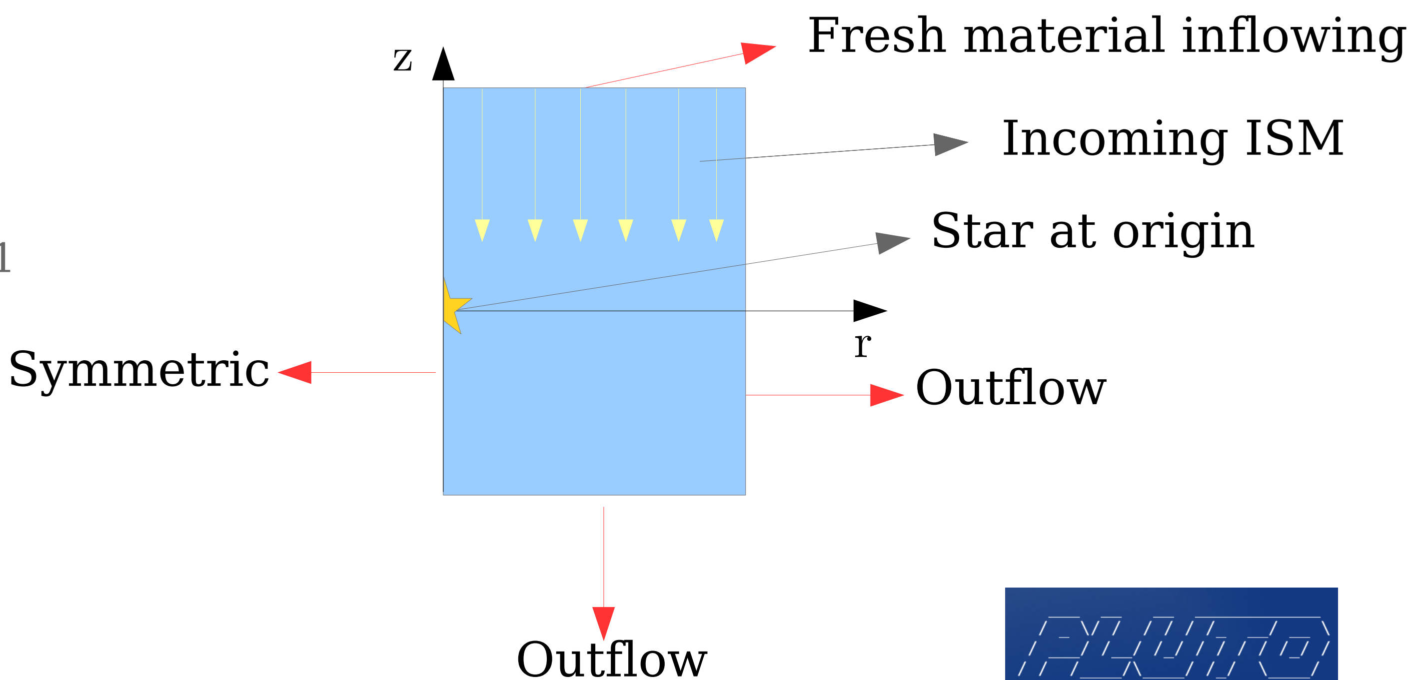
Domain is a cylindrical rectangular box

O star:

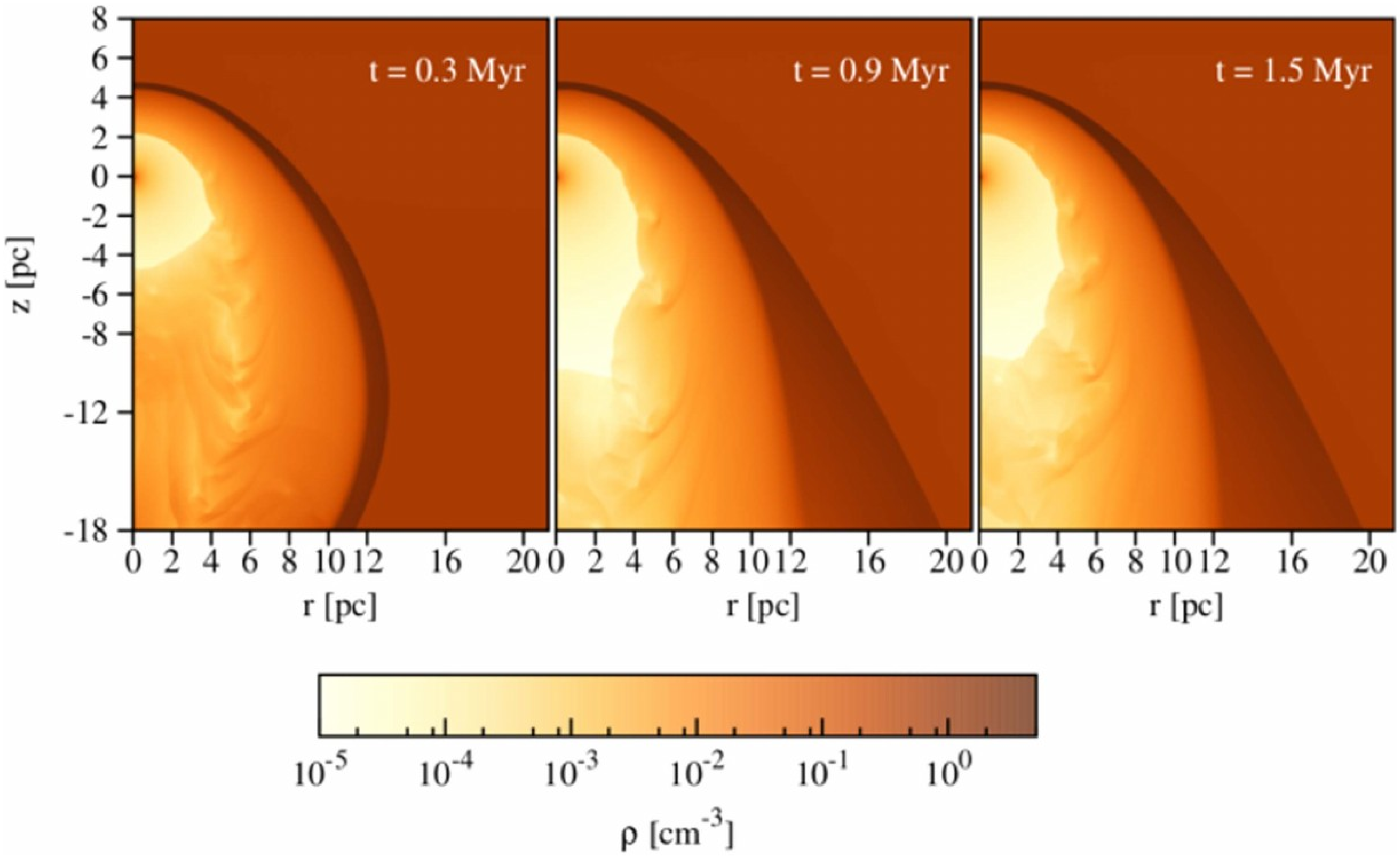
$\dot{M} = 10^{-6}\,M_s\ \ yr^{-1}$

$V_w = 2000\ km\ s^{-1}$

$V_* = 40\ km\ s^{-1}$



Results

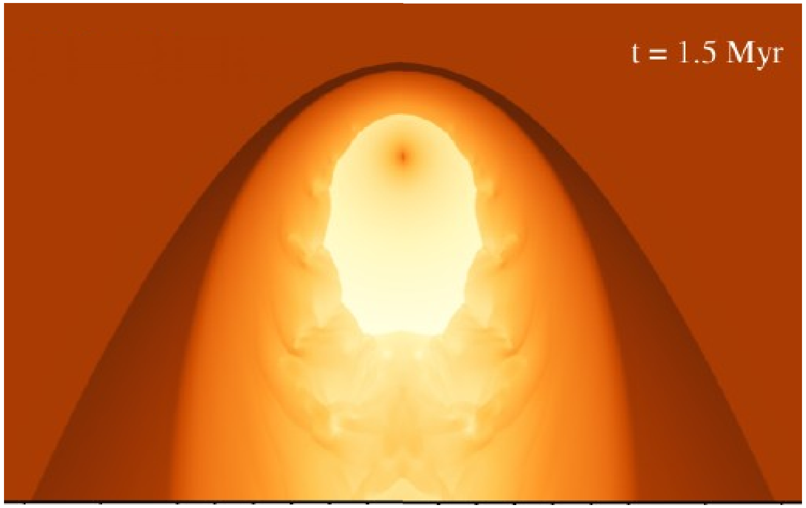


t = 0.3 Myr
t = 0.9 Myr
t = 1.5 Myr
z [pc]
8
6
4
2
0
-2
-4
-6
-8
-12
-18
0 2 4 6 8 10 12 16 20
r [pc]
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
ρ [cm^{-3}]

Relativistic particles

Domain from the HD simulation

Solve the transport equation for electrons and protons



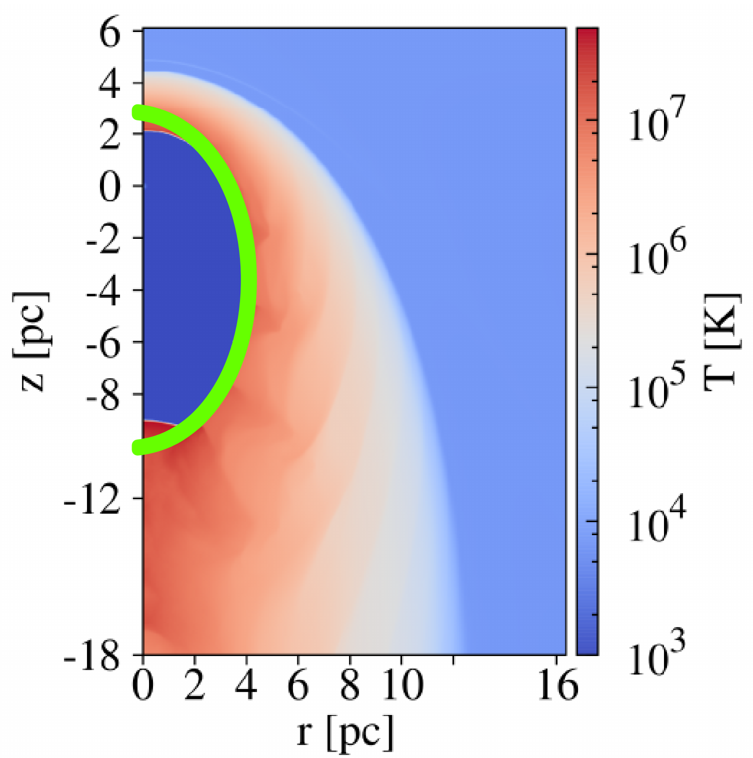
$$\frac{\partial N(E,\vec{x},t)}{\partial t} = \nabla(D(E,\vec{x},t)\nabla N(E,\vec{x},t)) - \nabla(\mathbf{V}(\vec{x},t)N(E,\vec{x},t)) - \frac{\partial}{\partial E}(P(E,\vec{x},t)\,N(E,\vec{x},t)) + Q(E,\vec{x},t).$$

2D spatial cylindrical coordinates + energy

Own code

Injection

Particles are injected at the reverse shock, which is strong through all the solid angle



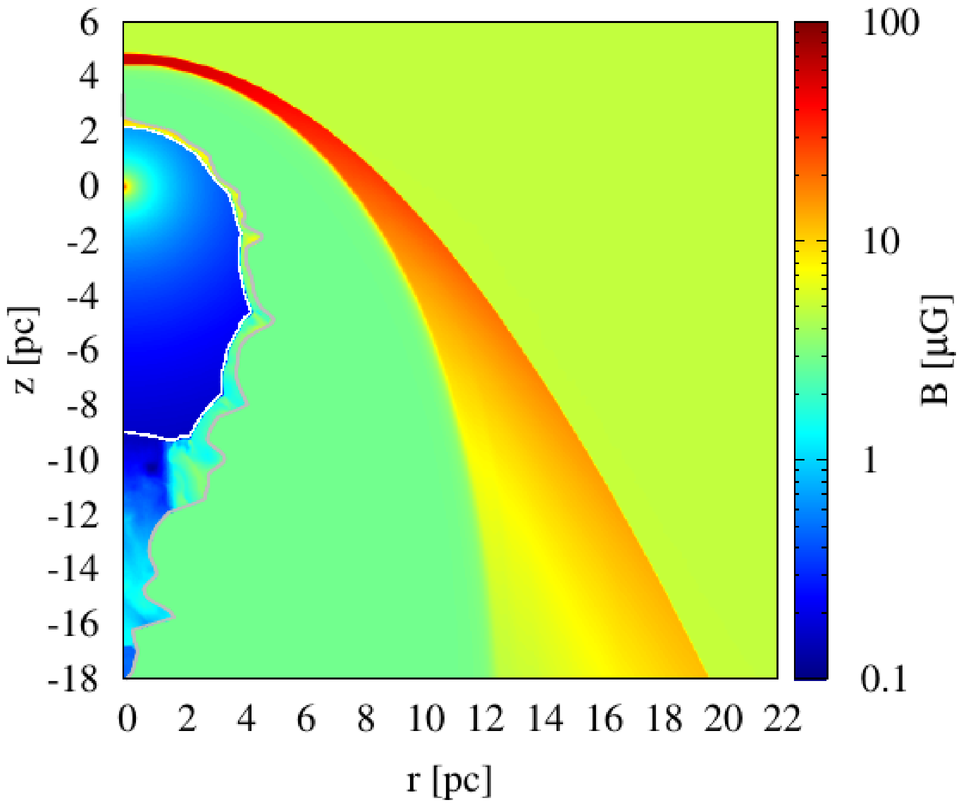
$$Q(t,\ E,\ r,\ z)\ =$$

$$Q_0\, E^{-\alpha}\, \rho(r,z)/\rho_0\ \delta^2\,((r,\ z) - (r_{\rm rs}, z_{\rm rs}))$$

Powered by wind kinetic energy:

$$L_{\rm w}\ =\ 0.5\dot{M}V_{\rm w}^2$$

Losses: Magnetic field



Four regions:

- Stellar wind
- Shocked wind
- Shocked ISM
- ISM

$B_* \sim 100$ G
$R_* \sim 10^{12}$ cm

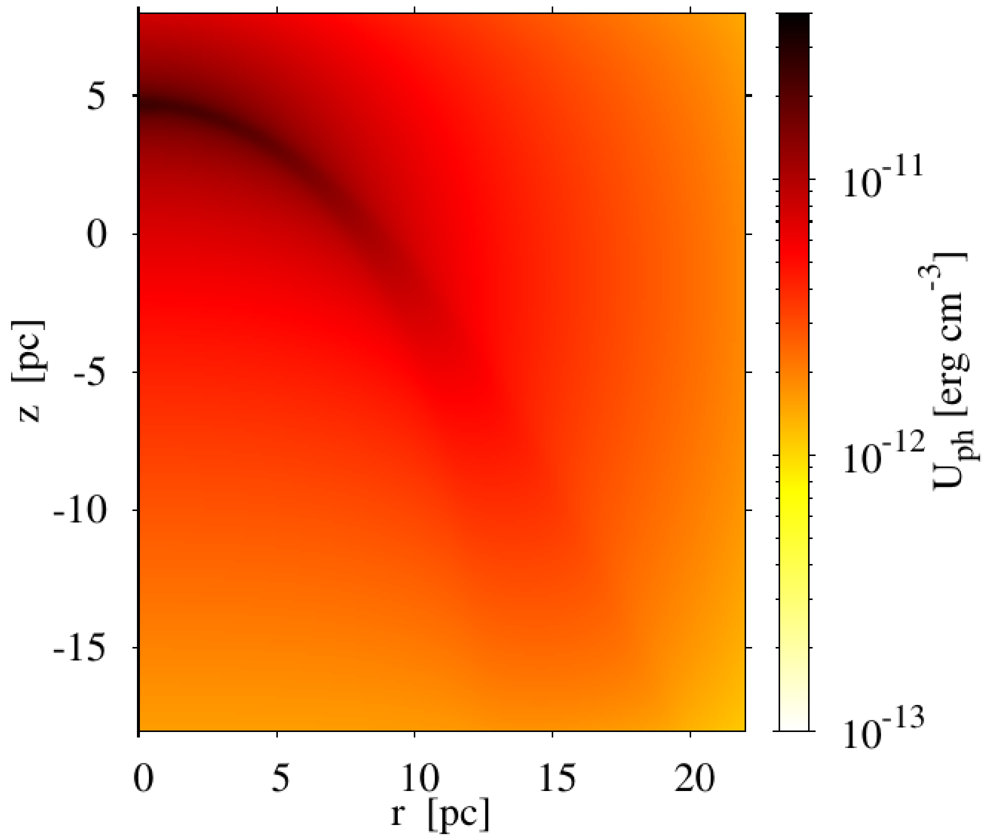
$$B_{\text{wind}} = B_\star \left[1 + \left(\frac{V_{\text{w}}}{V_{\text{rot}}}\right)^2\right]^{-1/2} \left(\frac{R_\star}{R}\right) \left[1 + \left(\frac{R_\star V_{\text{w}}}{R\, V_{\text{rot}}}\right)^2\right]^{1/2}$$

Stellar wind (follow Volk & Forman 82)

Losses: radiation fields

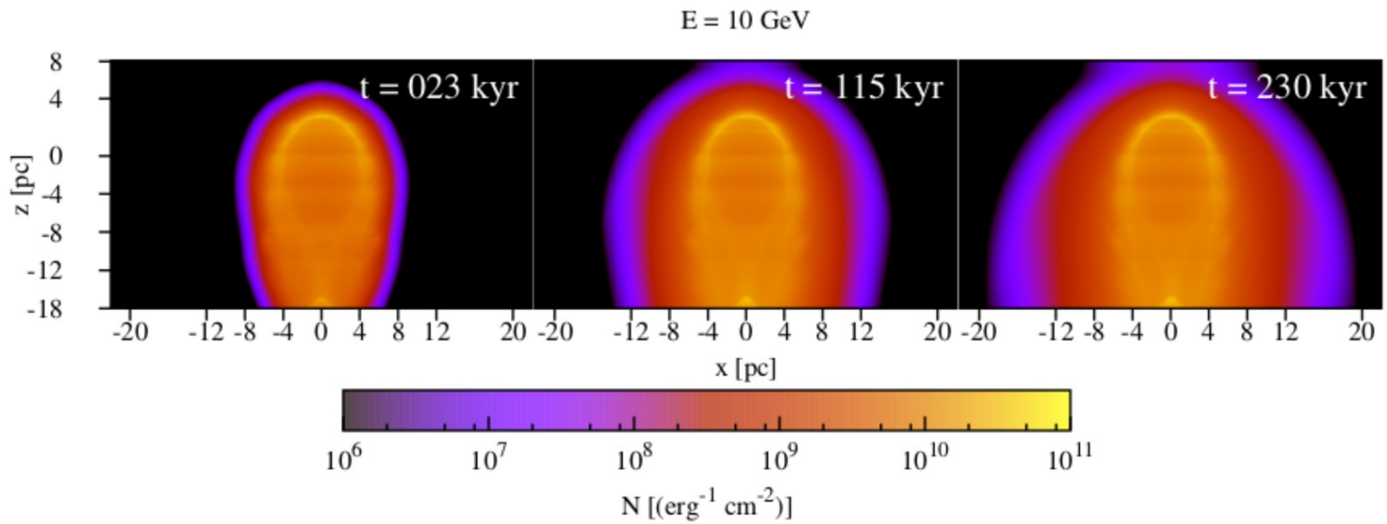
- Stellar radiation field, BB T ~ 10^4 K, U ∝ R^{-2}
- Dust emitted photons:

$$T_{\rm gr} = \left(\frac{R_\star}{\sqrt{r^2 + z^2}} \right)^{1/3} \frac{T_\star^{2/3}}{(4\pi \langle Q_0 \rangle)^{1/6} a_{\mu \rm m}^{1/3}}.$$

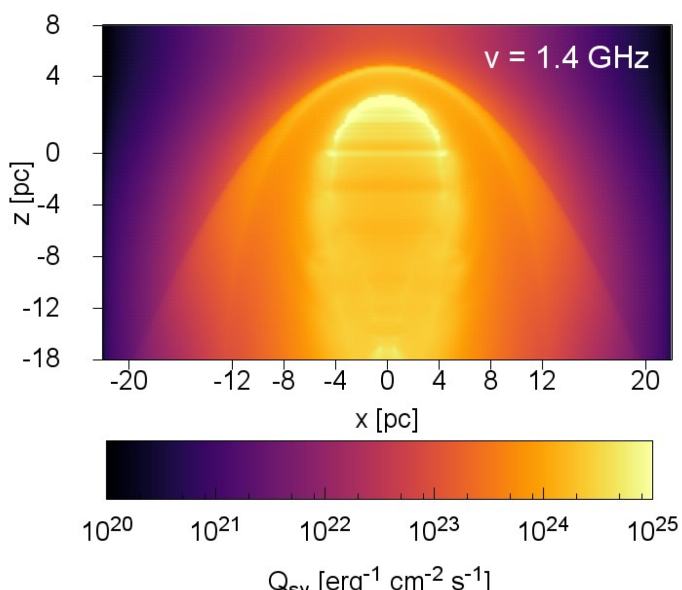


Results

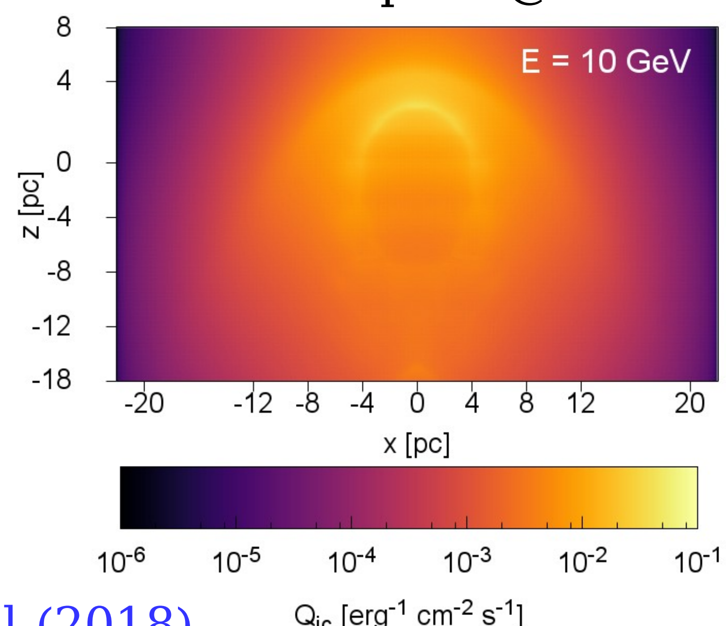
Electrons @ 10 GeV



Synchrotron @ 1.4 GHz

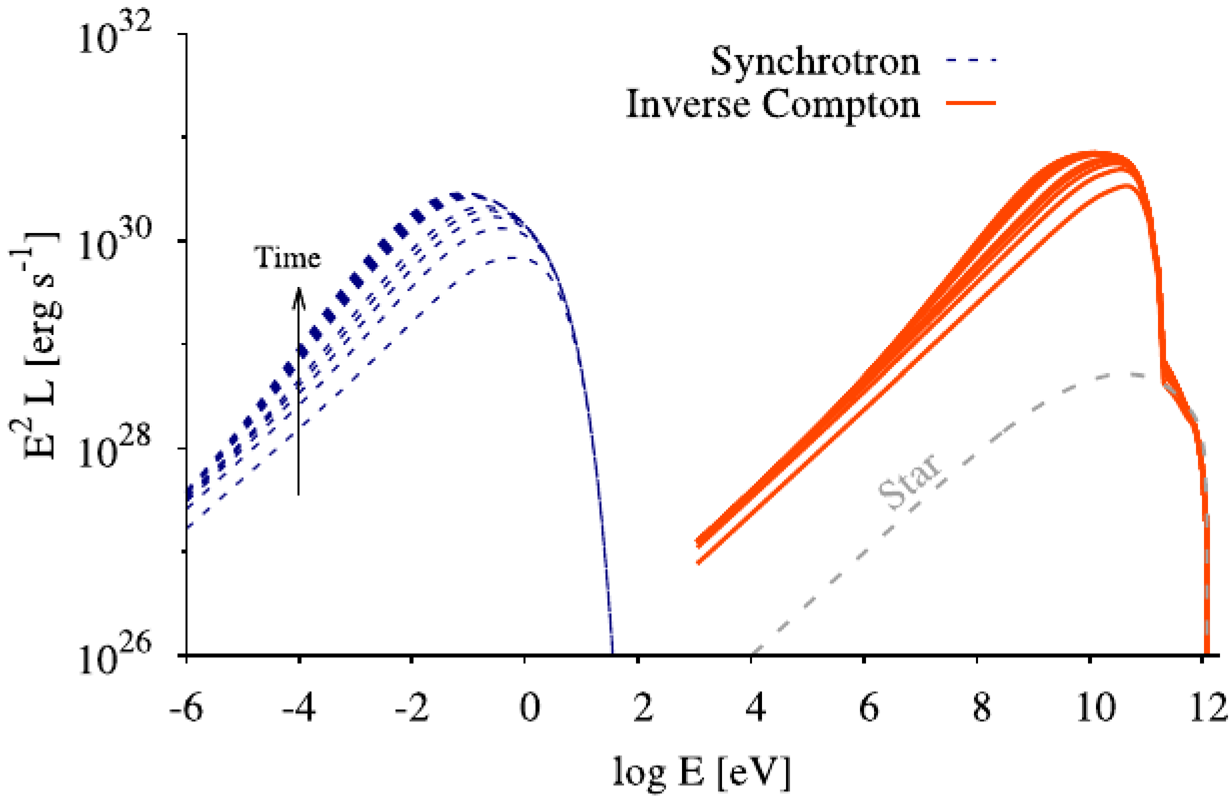


Inverse Compton @ 10 GeV



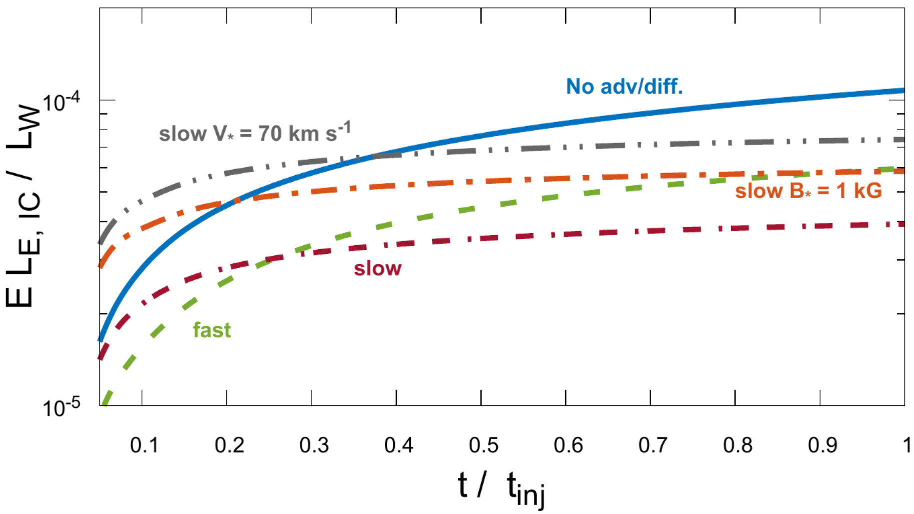
del Valle & Pohl (2018)

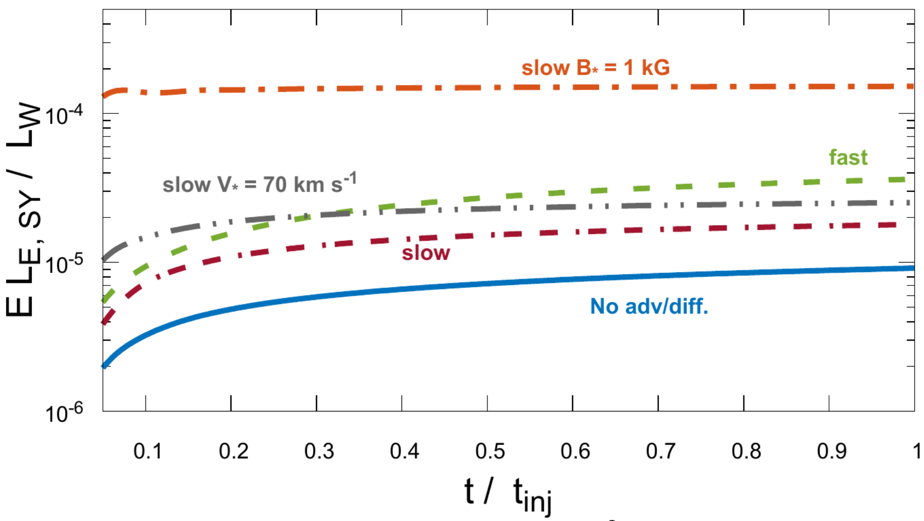
SED

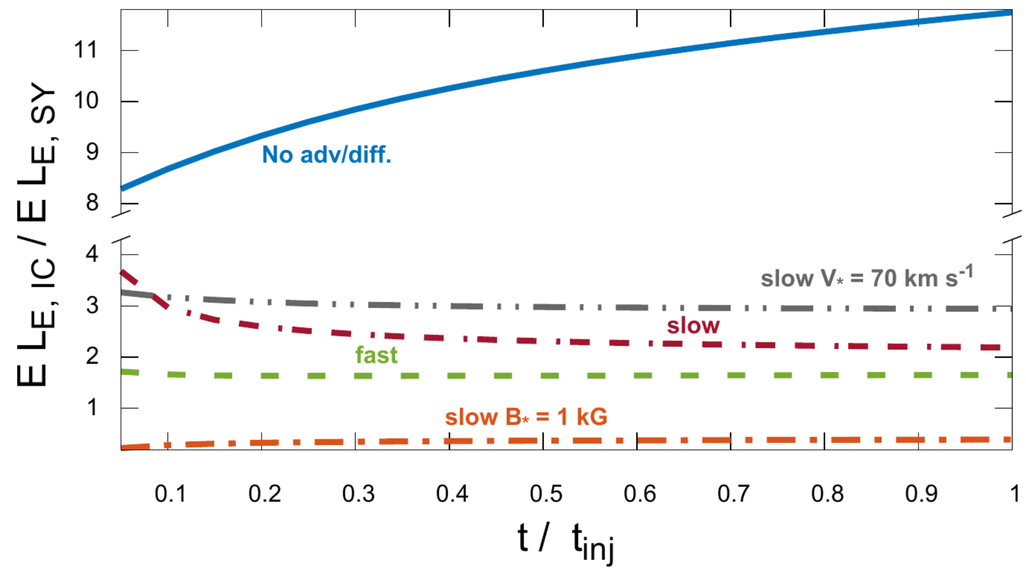


del Valle & Pohl (2018)

Results







del Valle & Pohl (2018)

$$L_{\rm IC} \lesssim 10^{32}\left(\frac{\dot{M}}{10^{-6}M_\odot{\rm yr}^{-1}}\right)\left(\frac{V_{\rm w}}{2000\,{\rm km\,s^{-1}}}\right)^2\left(\frac{\chi_{\rm IC}}{10^{-4}}\right)\left(\frac{40}{a}\right)\left(\frac{\xi}{0.05}\right){\rm erg\,s^{-1}},$$

$$L_{\rm Sy} \lesssim 5\times10^{31}\left(\frac{\dot{M}}{10^{-6}M_\odot{\rm yr}^{-1}}\right)\left(\frac{V_{\rm w}}{2000\,{\rm km\,s^{-1}}}\right)^2\left(\frac{\chi_{\rm S}}{5\times10^{-5}}\right)\left(\frac{40}{a}\right)\left(\frac{\xi}{0.05}\right){\rm erg\,s^{-1}}$$

Summary

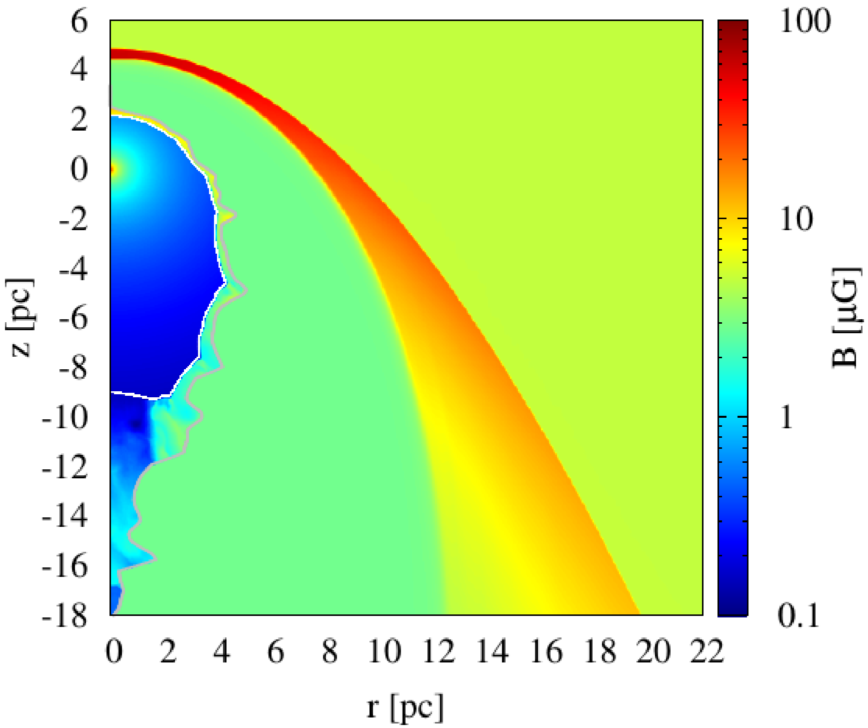
- The interaction of the relativistic electrons produce non-thermal emission:
- Synchrotron (maximum energy ~ visible, important at radio)
- Inverse Compton scattering:

  IR field & Stellar field (maximum energy ~ 100 GeV)
- Low emission X-rays (requires high B)
- Transport effects are very important, particle lose only 0.4% of their power
- Protons diffuse almost without losing their energy as predicted in previous works

➔ Next step: MHD simulations + polarization (see poster GR 25)

Thanks!

Losses: Magnetic field



Four regions:

Stellar wind
Shocked wind
Shocked ISM
ISM

Reverse shock $\rho_{rshock}(r,z)$ discontinuity

ISM:
$B_{ISM} \sim \mu G$
After shock: compress with density
$B(r,z) = B_{ISM} \times F_2$

After shock: compress with density
$B(r,z) = B(r_p, z_p) \times F_1$

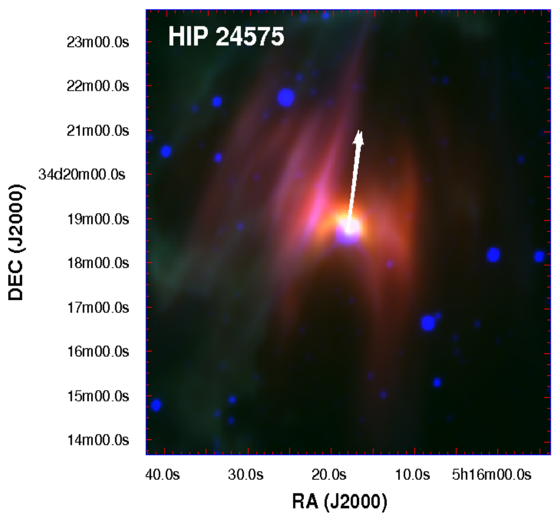
$B_* \sim 100$ G
$R_* \sim 10^{12}$ cm

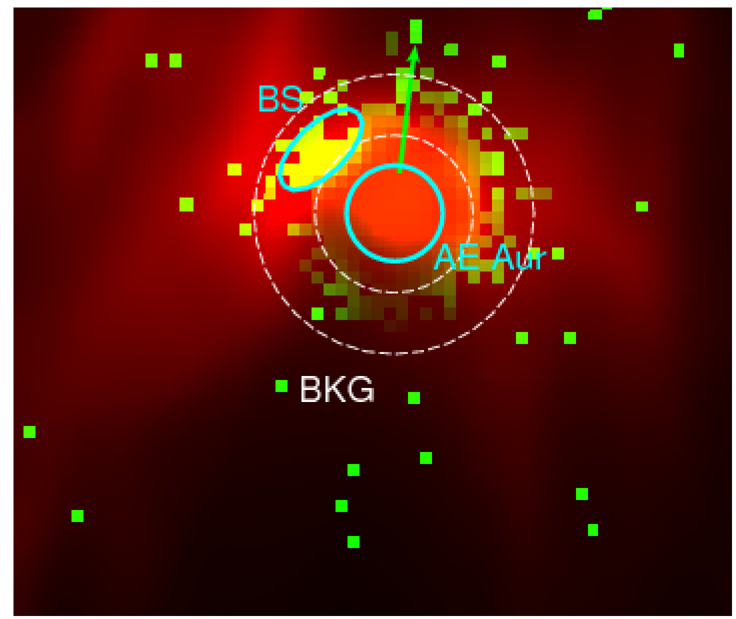
Where $\mathcal{F}_{1,2} = \sqrt{2(\mathcal{K}_{1,2}^2 - 1)/3 + 1}$, with $\mathcal{K}_1 = \rho(r_{rs}, z_{rs})/\rho(r, z)$, and $\mathcal{K}_2 = \rho(r_{ISM}, z_{ISM})/\rho(r, z)$.

$$B_{wind} = B_\star \left[1 + \left(\frac{V_w}{V_{rot}}\right)^2\right]^{-1/2} \left(\frac{R_\star}{R}\right) \left[1 + \left(\frac{R_\star V_w}{R\, V_{rot}}\right)^2\right]^{1/2}$$

Stellar wind (follow Volk & Forman 82)

@ X-rays!





Lopez-Santiago+ 2012

XMM archive observations reveal X-ray emission from AE Aurigae bow shock !!

Apparently Non-thermal: IC e + dust photons

Ingredients

$$\frac{\partial N(E,\vec{x},t)}{\partial t} = \nabla(D(E,\vec{x},t)\nabla N(E,\vec{x},t)) - \nabla(\mathbf{V}(\vec{x},t)N(E,\vec{x},t)) - \frac{\partial}{\partial E}\left(P(E,\vec{x},t)\,N(E,\vec{x},t)\right) + Q(E,\vec{x},t).$$

Analytical
But depends
on ρ(r,z)

D power-law in E

From simulation:
Velocity field

From simulation:
Density field ρ(r,z)
From density B(r,z)

Analyzing the no-data

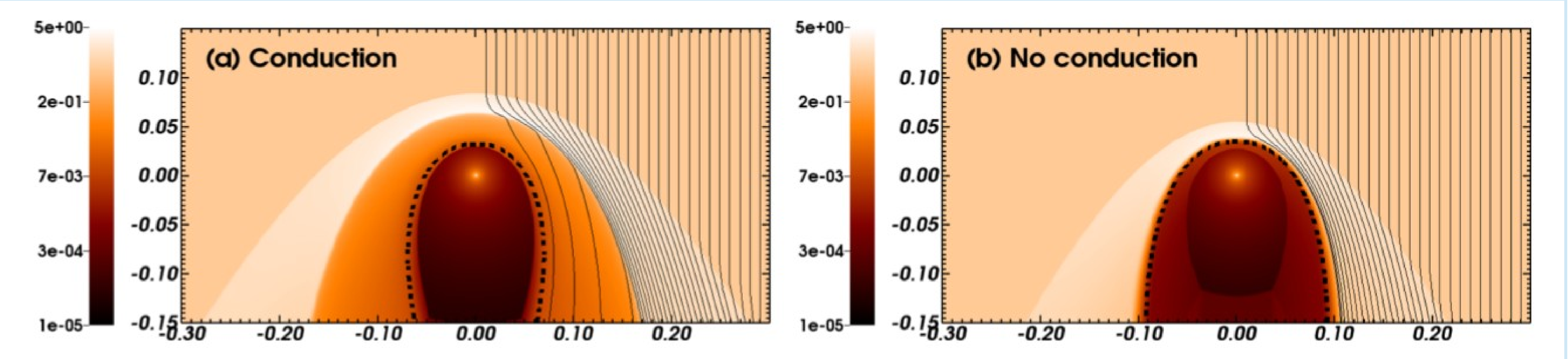
We use simple model to fit the upper limits for our 5 targets: fit fundamental parameters:

Source	B (G)	$\chi_{\rm rel}$	α	$E_{\rm max}$ ($m_e c^2$)	$\chi_{\rm IR}$	$\mathcal{D}$
#1	10^{-4}	1.0	1.8	6.4×10^{3}	1.0	5.2×10^{-1}
#2	8.9×10^{-6}	0.3	2.1	5.5×10^{5}	0.4	5.9×10^{-3}
#3	2.6×10^{-5}	0.1	2.1	4.3×10^{5}	0.1	8.1×10^{-3}
#4	1.6×10^{-5}	0.06	2.4	7.2×10^{5}	0.05	1.3×10^{-2}
#5	1.4×10^{-5}	0.1	2.1	3.4×10^{5}	0.2	1.0×10^{-2}

Thermal conduction

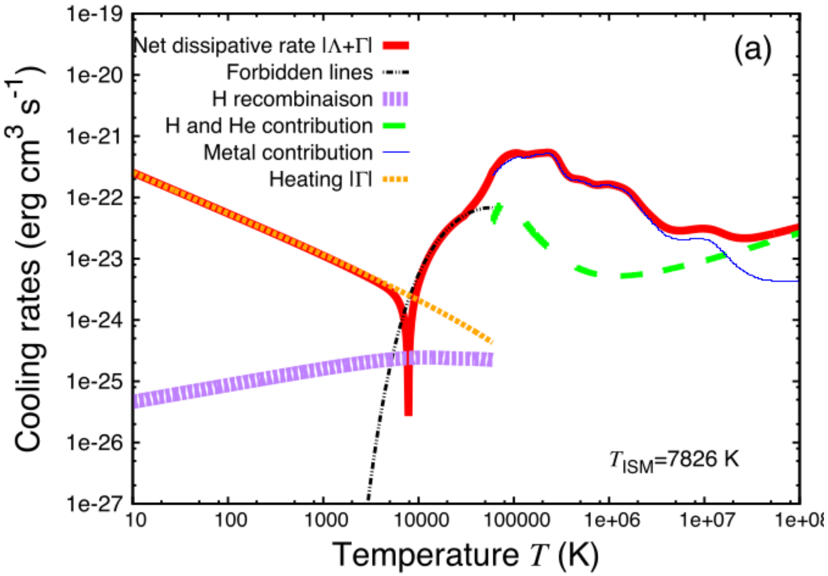
Circumstellar material presents strong temperature gradients → thermal conduction

Their effects on massive star winds well studied, can not be neglected



ISM

- Medium is flowing with – V_*
- Density ~ 0.57 cm^{-3} , μ = 0.67 (fully ionized)
  Strömgren radius >> R_o
- T ~ 8000 K



Meyer et al. 2016

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Maybe

Mmmm nope ...

4 out of 5

HD simulations

$$\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho + \rho (\nabla \cdot \mathbf{v}) = 0,$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \frac{\nabla p}{\rho} = \mathbf{0},$$

$$\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p + \rho c_s^2 \nabla \cdot \mathbf{v} = (\gamma - 1) \left[\Phi(T, \rho) + \nabla \cdot \mathbf{F}_{\mathrm{c}} \right];$$

$$E = \frac{p}{(\gamma - 1)} + \frac{\rho v^2}{2},$$

$$c_{\mathrm{s}} = \sqrt{\gamma p / \rho}$$

$$T = \mu \frac{m_{\mathrm{H}}}{k_{\mathrm{B}}} \frac{p}{\rho},$$

$$\Phi(T, \rho) = n_{\mathrm{H}}^{\alpha} \Gamma_{\alpha}(T) - n_{\mathrm{H}}^{2} \Lambda(T),$$

http://plutocode.ph.unito.it/

Wind model

Injected within a radius located in the origin

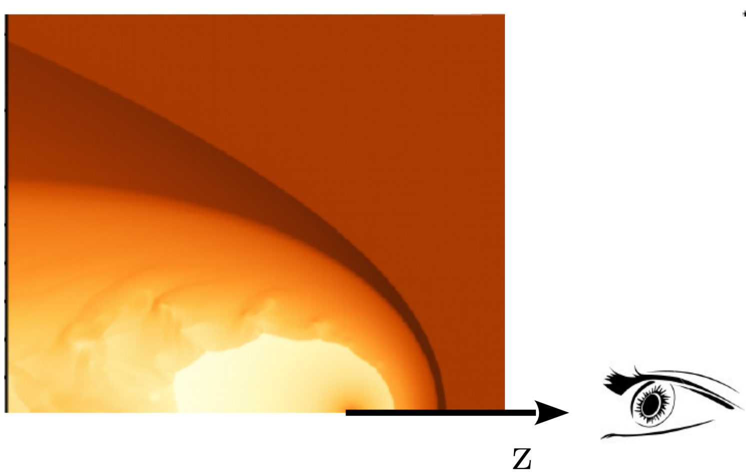
$$\rho_w = \frac{\dot{M}}{4\pi r^2 v_w}$$

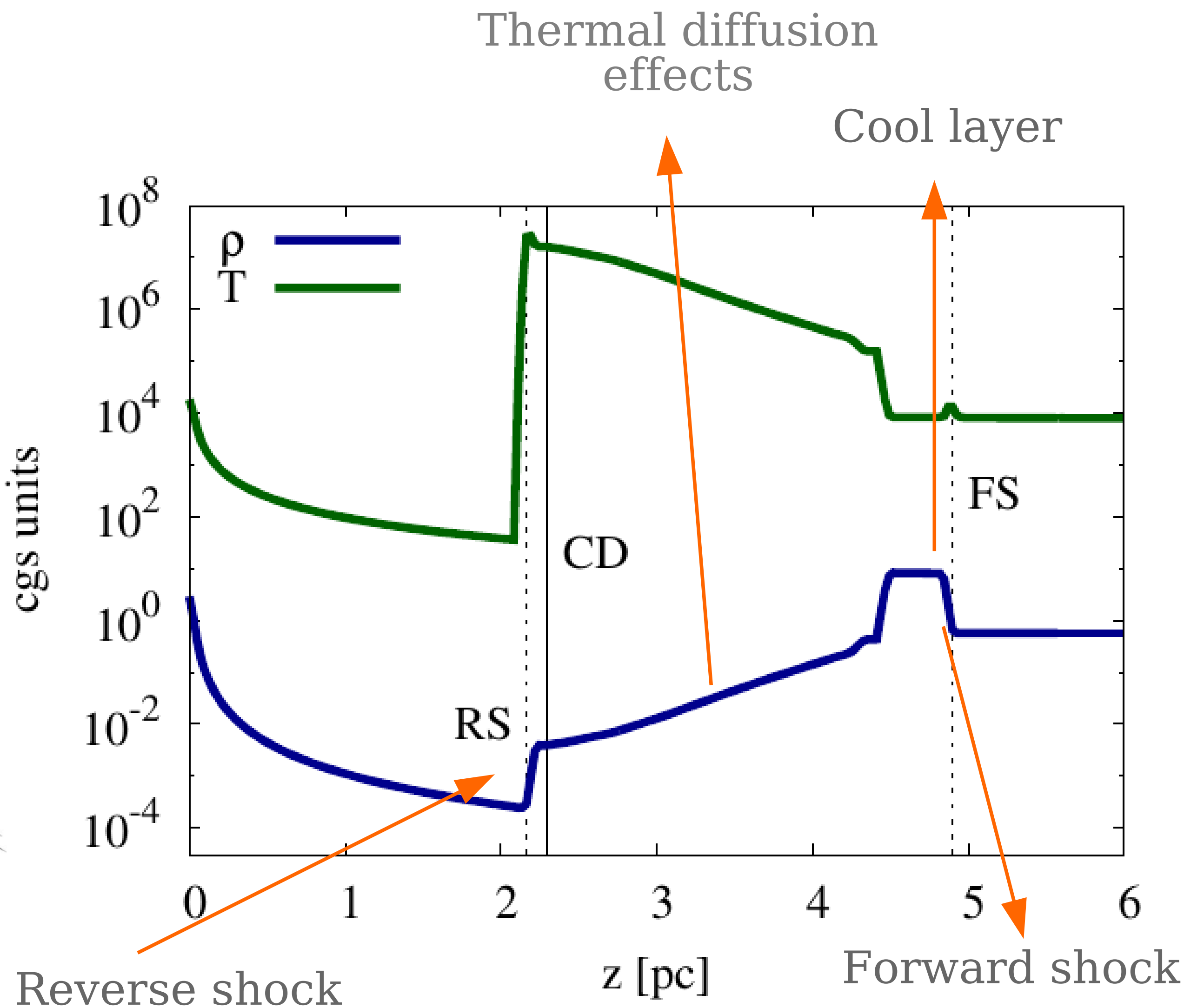
$T_{\rm eff} \sim 10^4$ K → Typical O star

$\dot{M}$: 10^{-6} M_s yr^{-1}

v_w: 2000 km s^{-1}

Closer look





Reverse shock → stronger, acceleration of particles