Modeling the non-thermal emission from high velocity stars

Universität Potsdam

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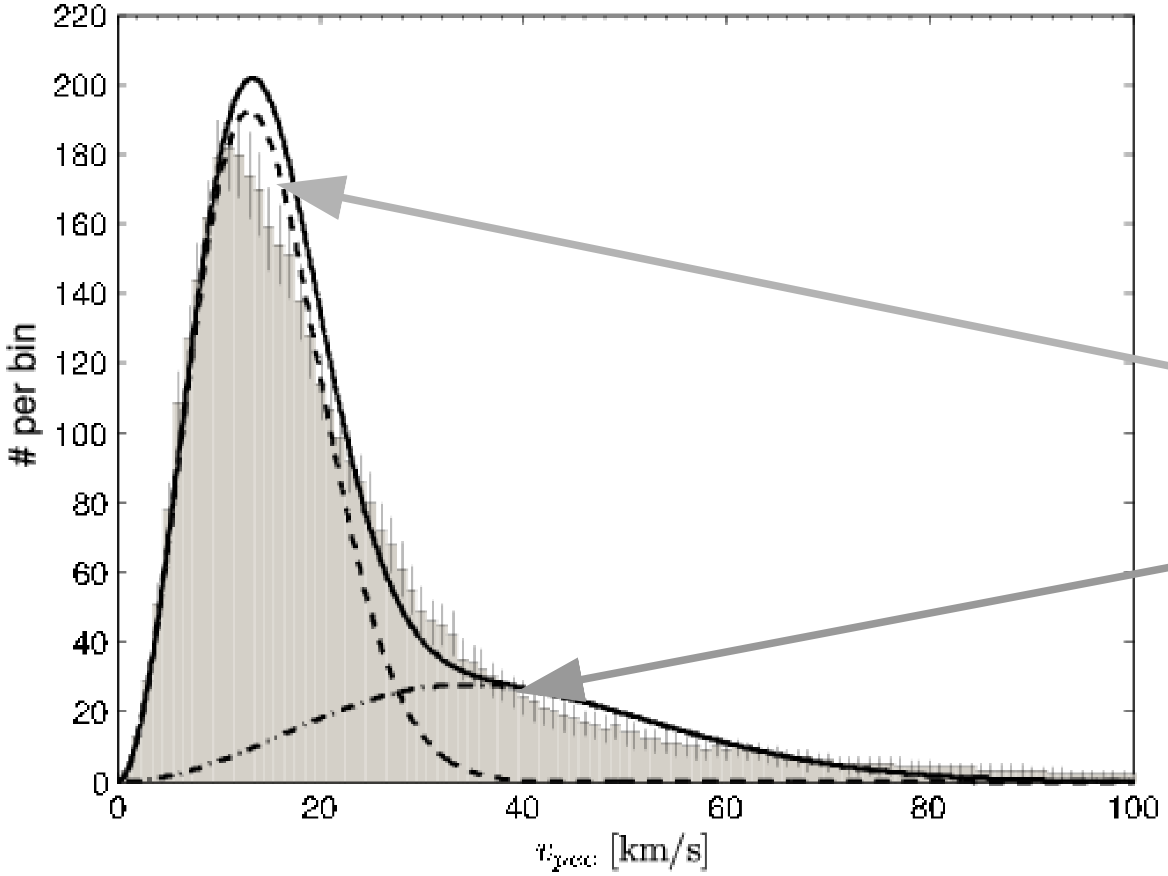
Fermi summer school 2018

Runaway stars

Distribution of Galactic
star velocities



Two populations!

Runaway stars have V > 30 km / s

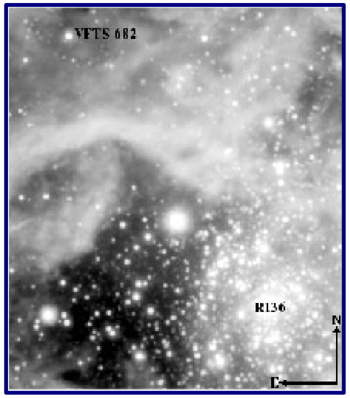
Runaway stars

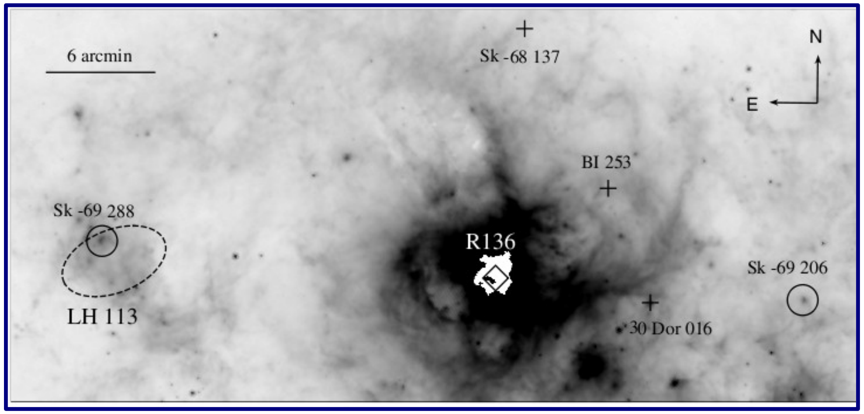
Stars run away from their birth places

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

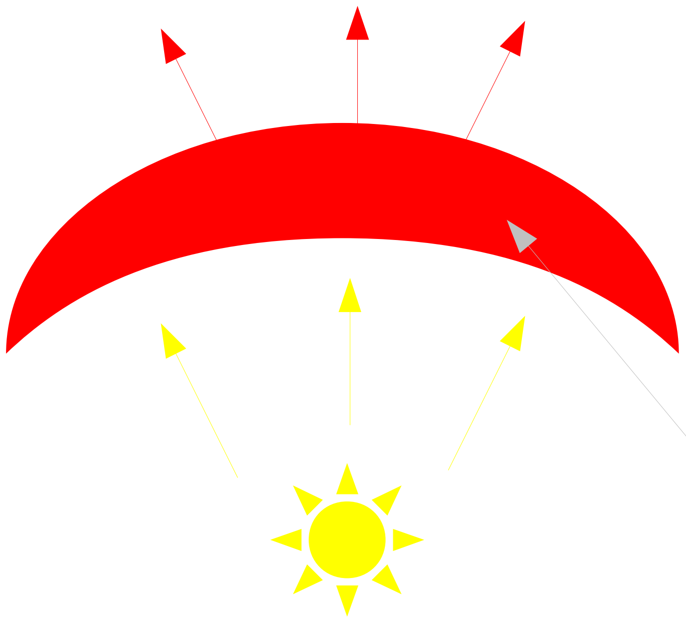
IR emission!

Catalogs in the Galaxy

Peri+ 2012, 2015
Kobulnicky+ 2017

Bow shock

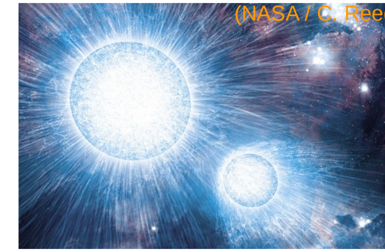
IR emission!

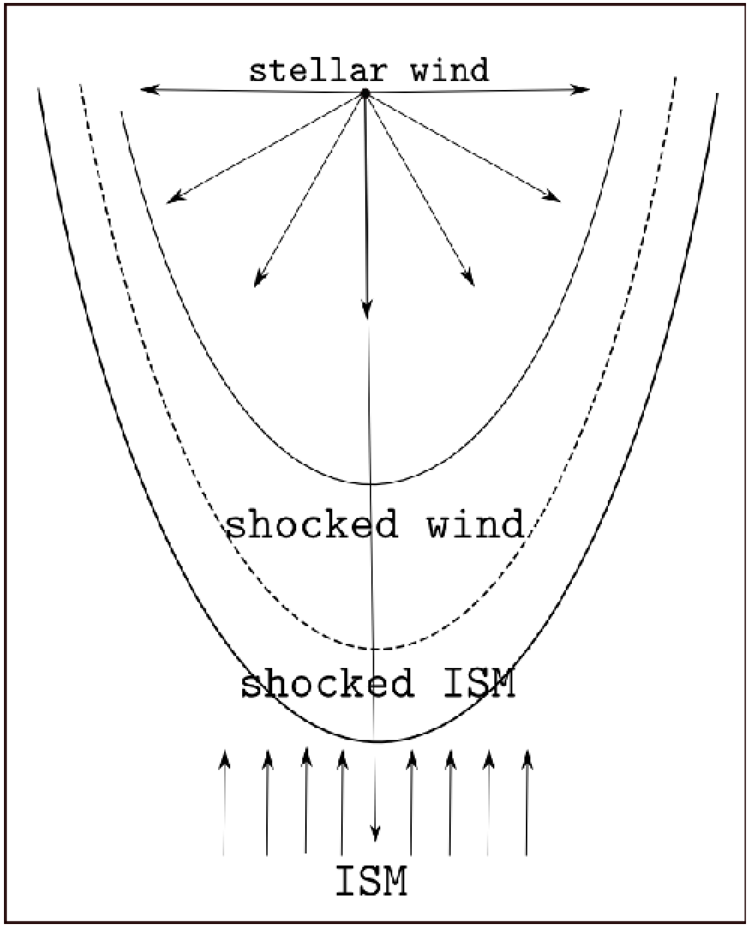


Massive star, very hot
Very luminous!

Swept dust and gas

Colliding plasmas



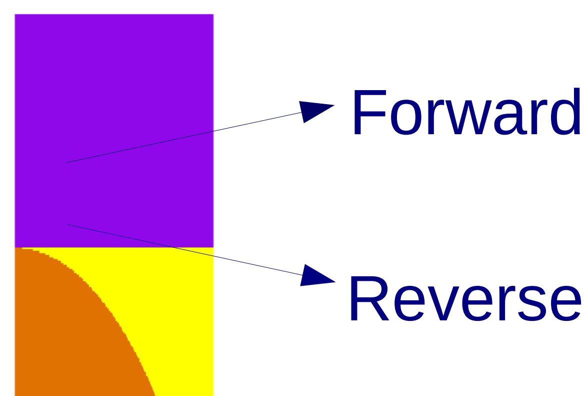


Pressure balance

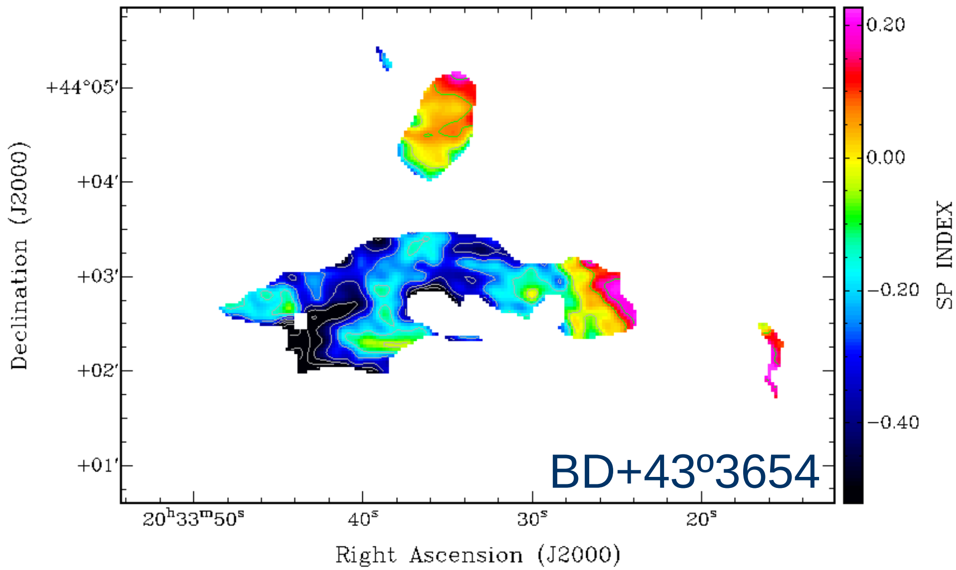
$$\rho_w V_w^2 = \rho_a V_\star^2 :$$

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

System of two shocks forms



Non-thermal emission detected



Benaglia+ 2010

Synchrotron emission from massive runaway star

Non-thermal emission Bow shock region

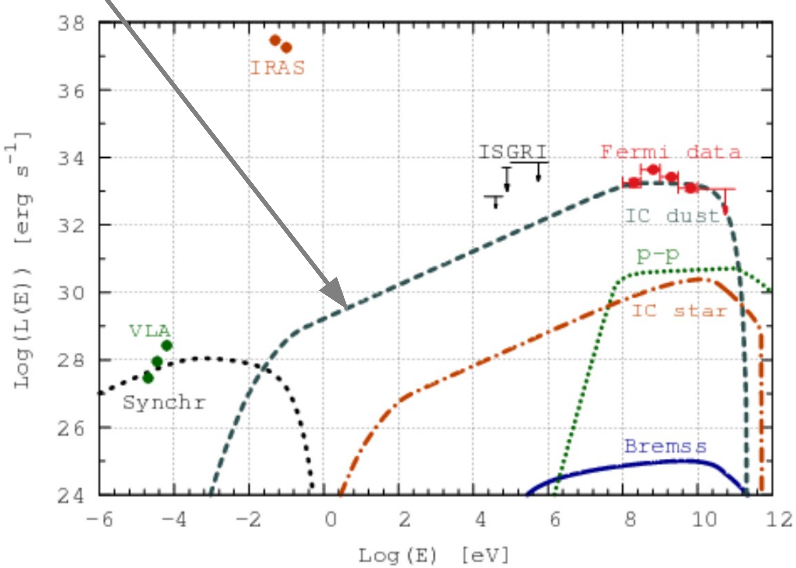
Implies B ~ 100 μG

There are relativistic electrons in the source

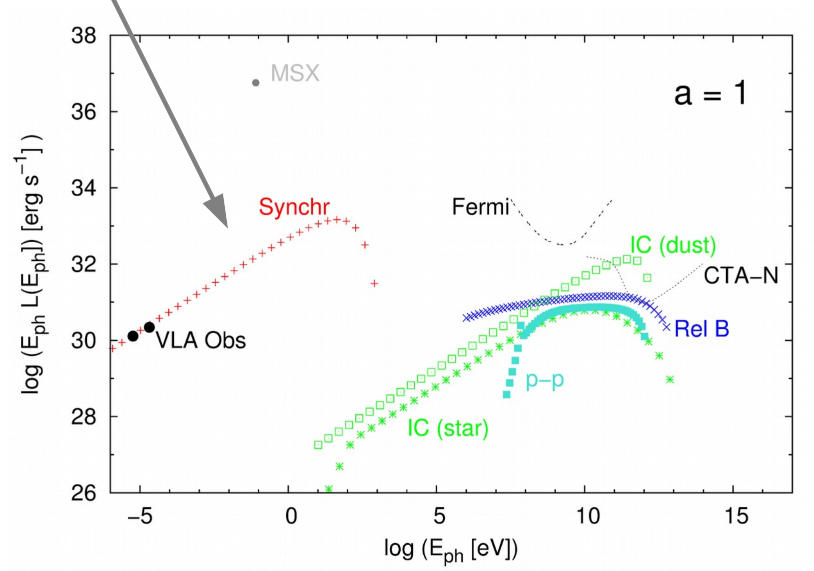
Non-thermal emitters at higher energies?

- 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. (Collaboration 2017) Upper limits also too high,

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

@ X-rays (motivated AE Aurigae)

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

  no emission reveled
- More *XMM*: five targets from proposal 2014

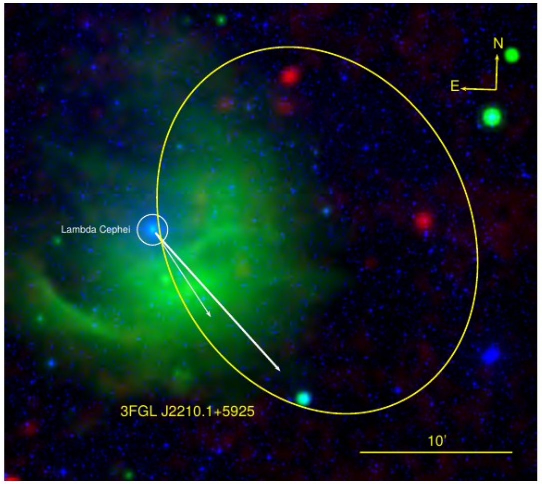
  (de Becker, del Valle+2017): upper limits.

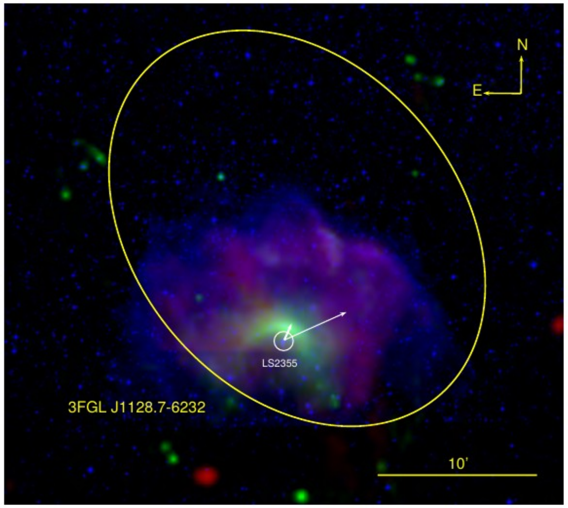
  For X-rays better resolution is needed to distinguish thermal from non-thermal (at least one order of magnitude).

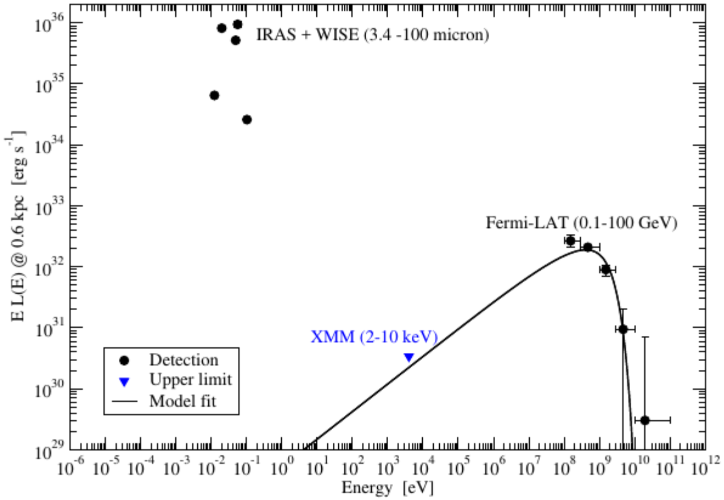
Recently two candidates: *Fermi* 3FGL sources

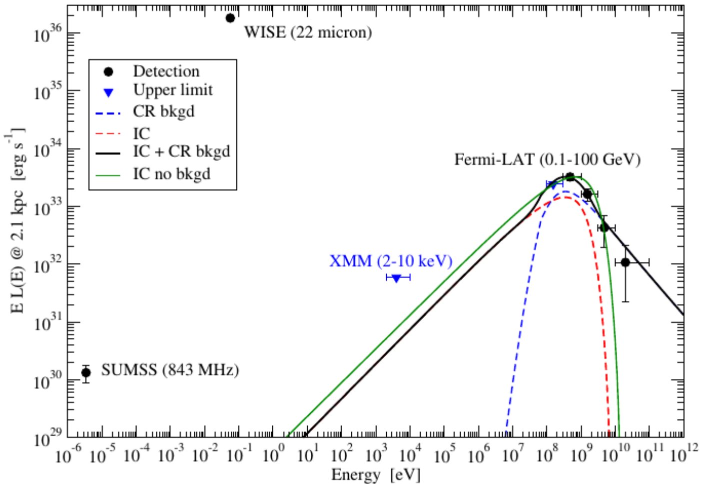
λ Cep

star LS 2355









Sanchez-Ayaso, del Valle +2018

Are these systems producing non-thermal emission then?

Is it too faint to be detected?

Better model → better predictions

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

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

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

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

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

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

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

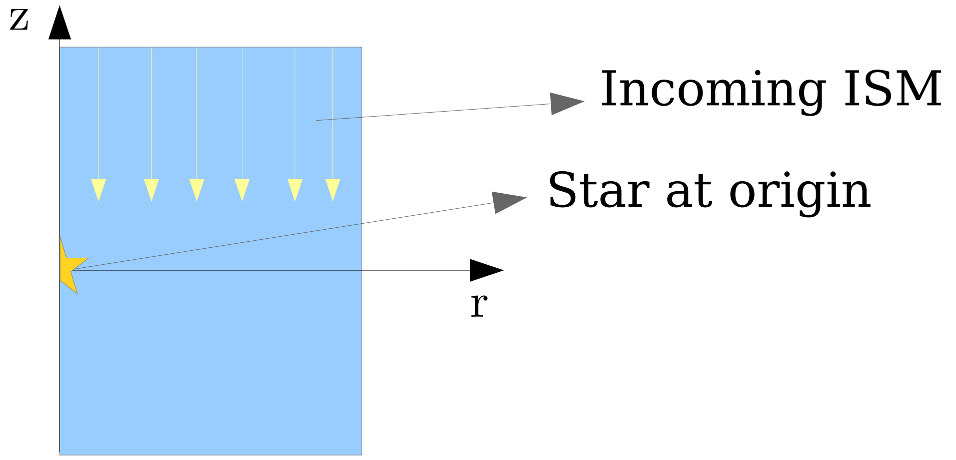
$$\Phi(T, \rho) = n_\mathrm{H}^\alpha \Gamma_\alpha(T) - n_\mathrm{H}^2 \Lambda(T),$$

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

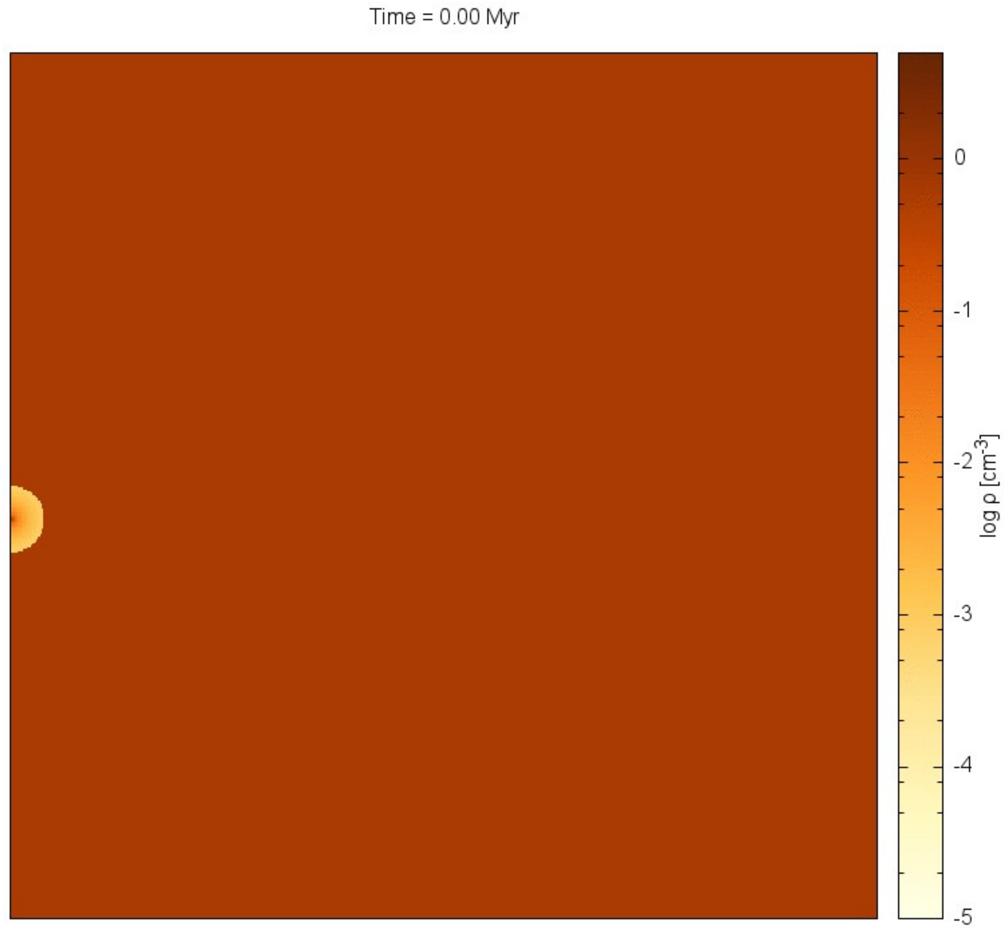
HD simulations

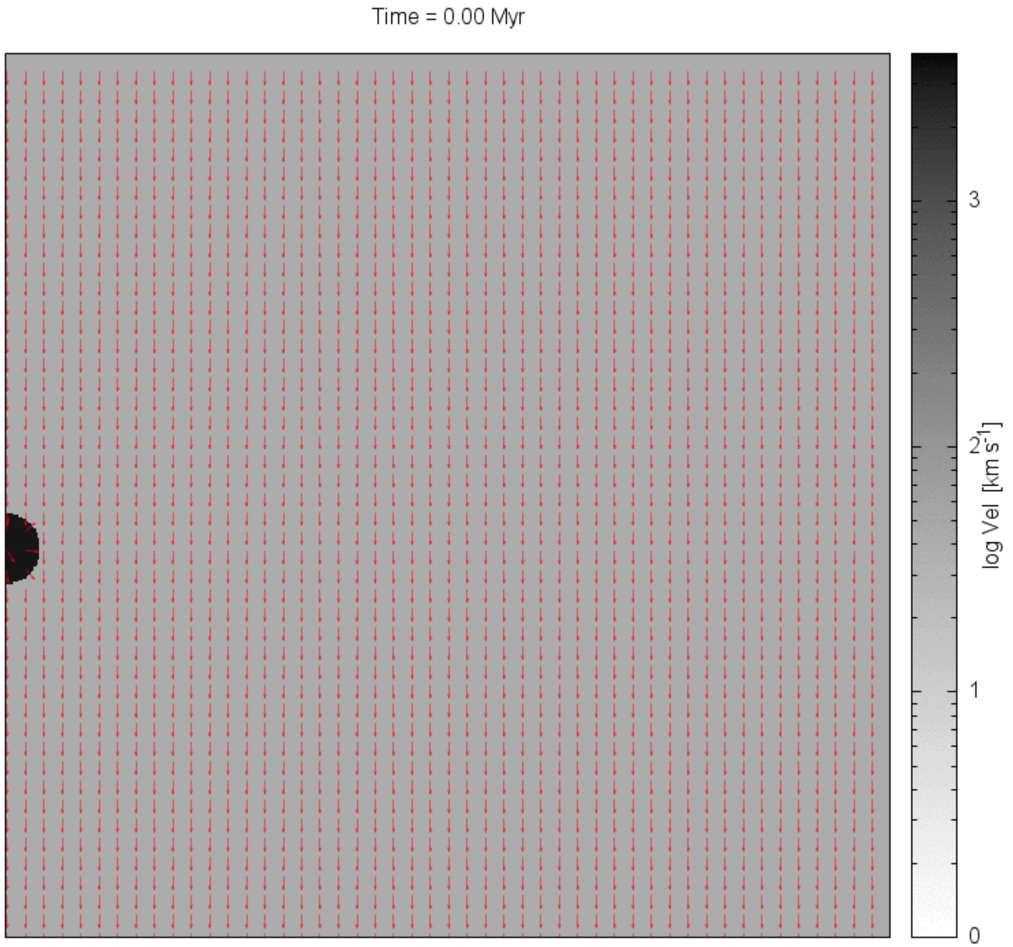
The problem can be considered as cylindrically symmetric: we use cylindrical coordinates: r and z

Domain is a cylindrical rectangular box



Results

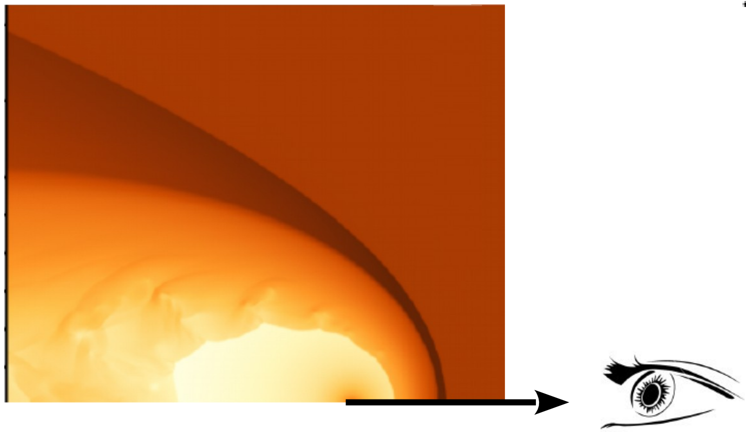


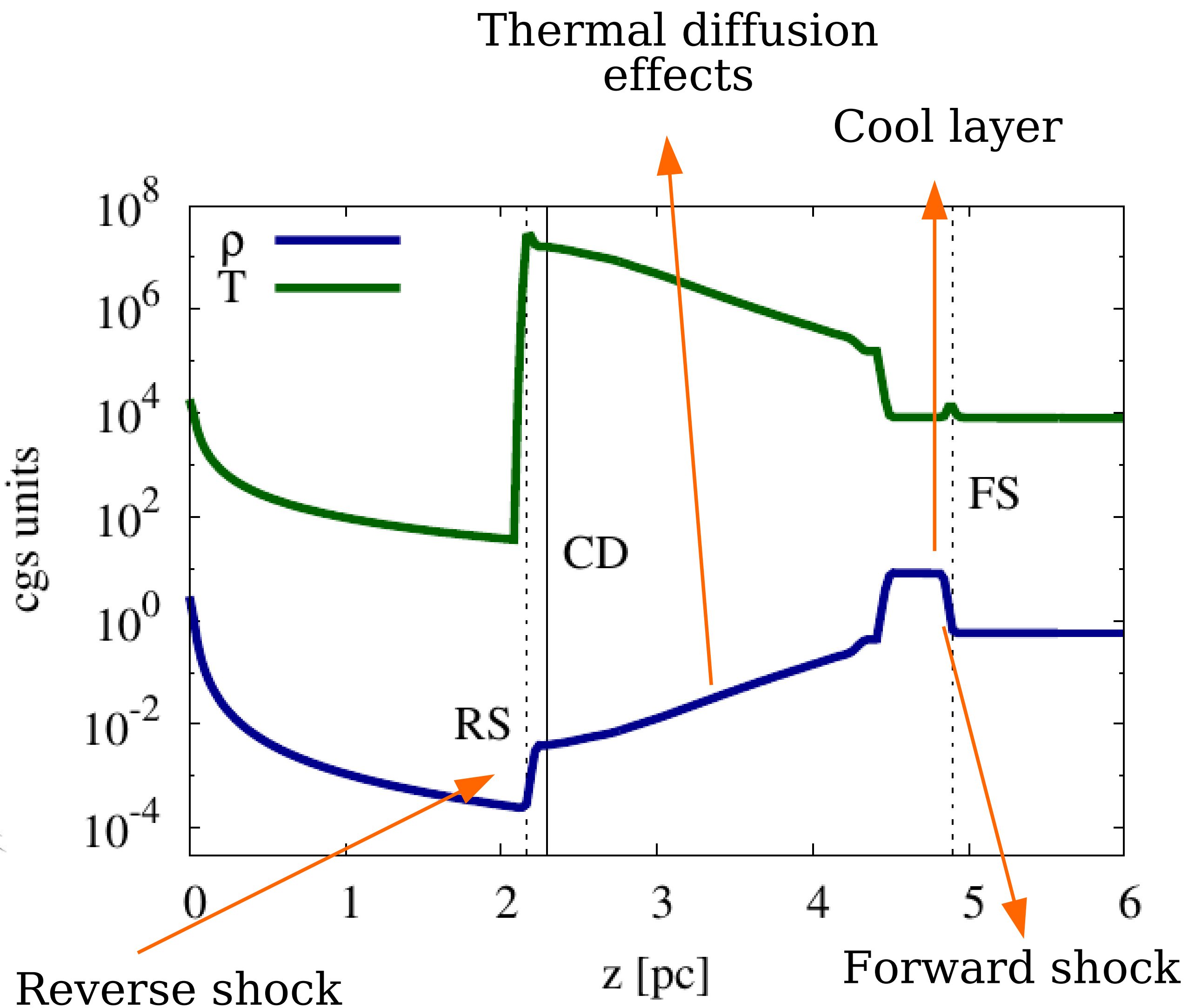


Density

Velocity

Closer look

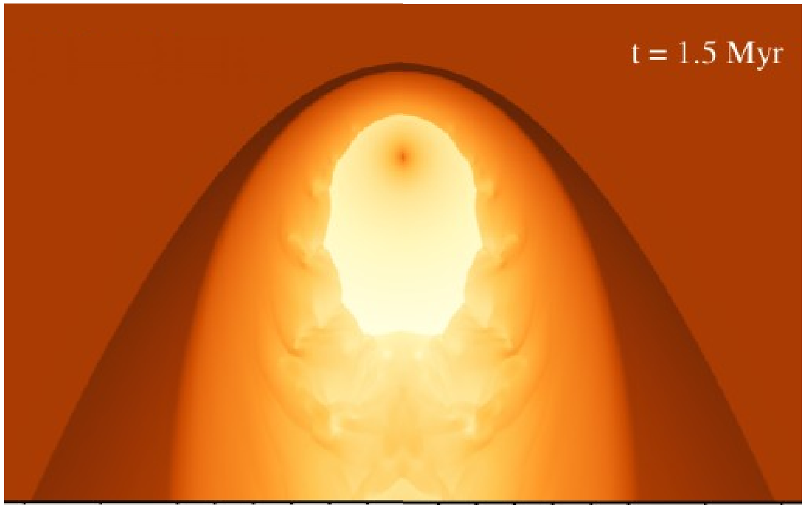




Reverse shock → stronger, acceleration of particles

Relativistic particles

Domain from the HD simulation



Solve the transport equation for electrons and protons

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

2D spatial cylindrical coordinates + energy

Own code

Ingredients

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

D power-law in E

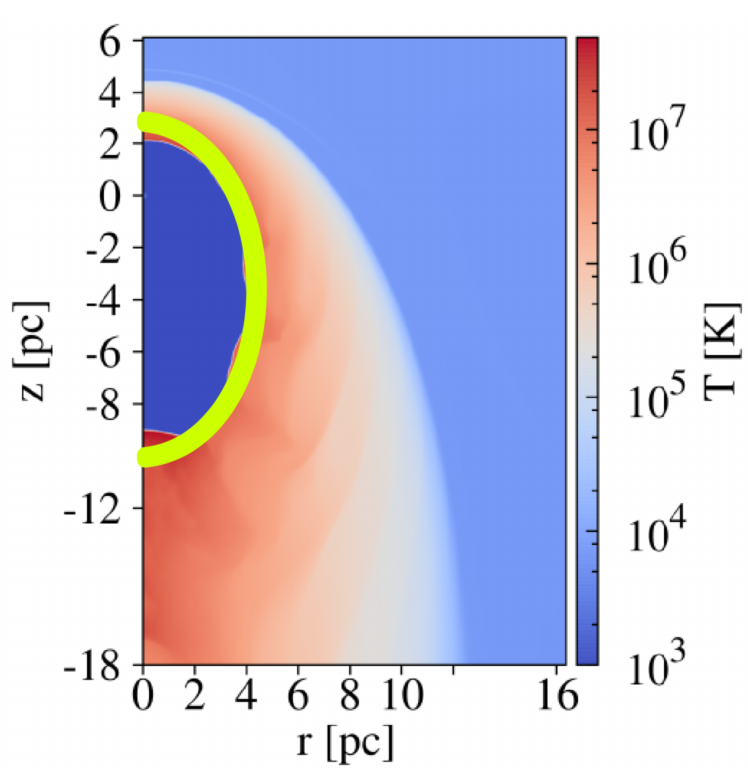
From simulation:
Density field ρ(r,z)
From density B(r,z)

From simulation:
Velocity field

Analytical
But depends
on ρ(r,z)

Injection

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



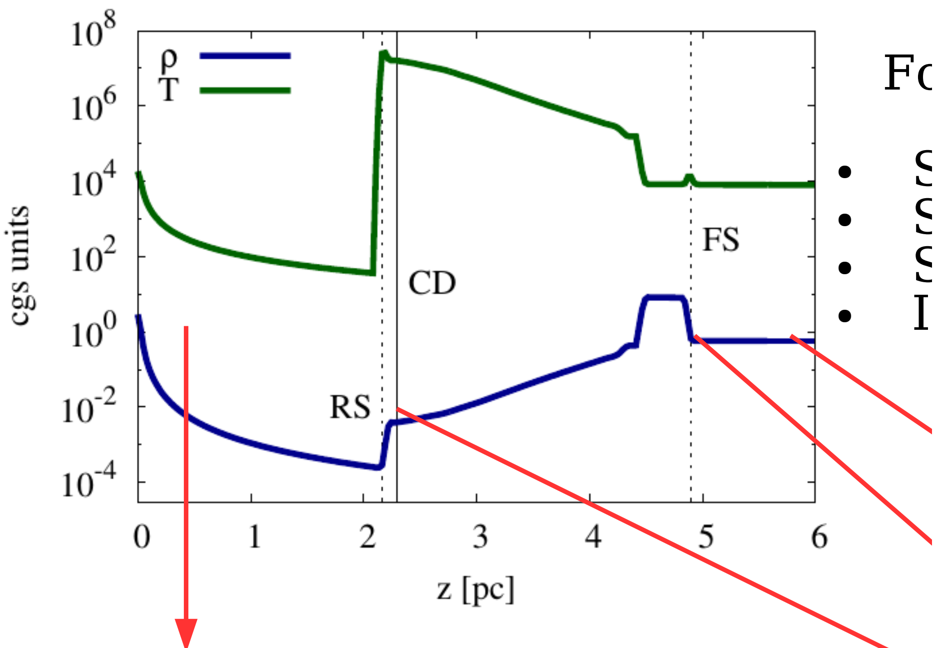
$$Q(t,\ E,\ r,\ z)\ =$$

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

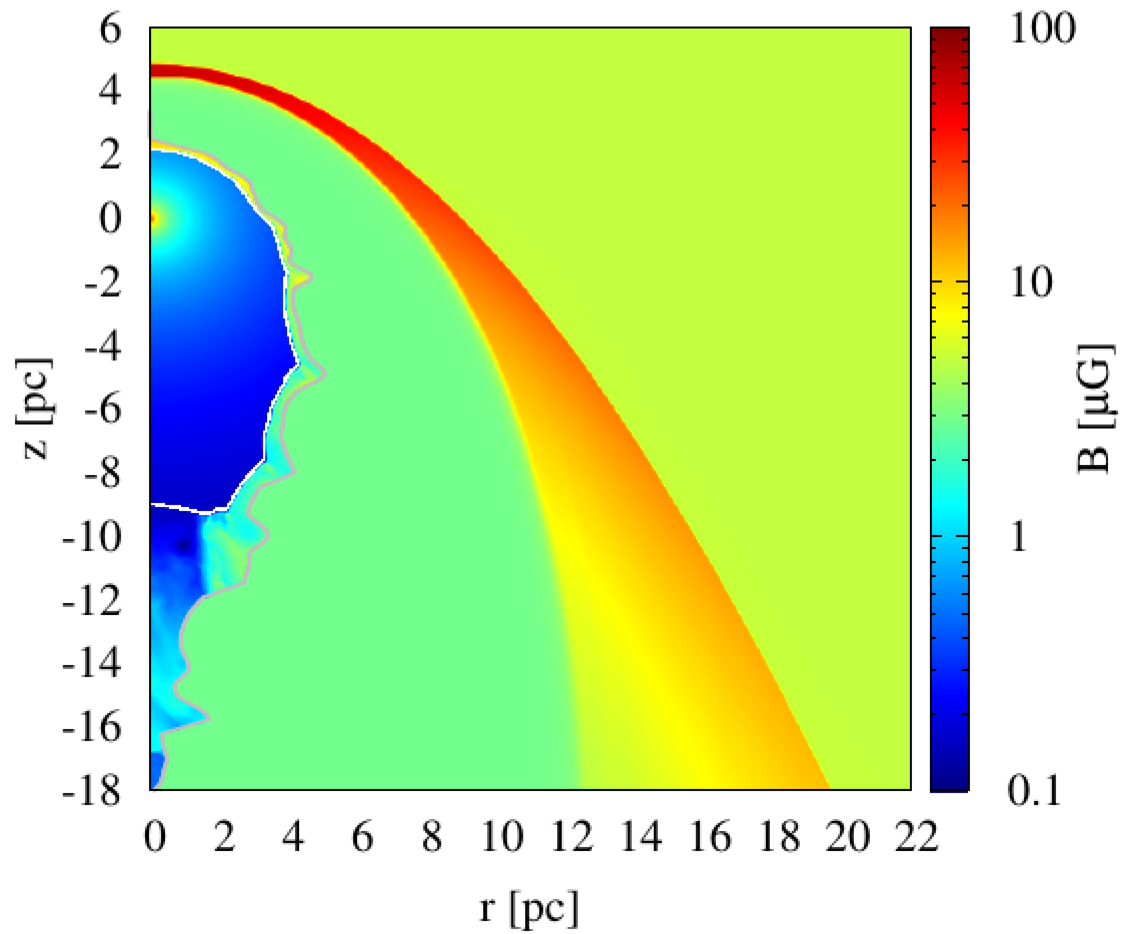
Powered by wind kinetic energy:

$$L_w\ =\ 0.5\dot{M}V_w^2$$

Losses: Magnetic field



Fo



Stellar wind (follow Volk & Forman 82

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

Where $\mathcal{F}_1$,

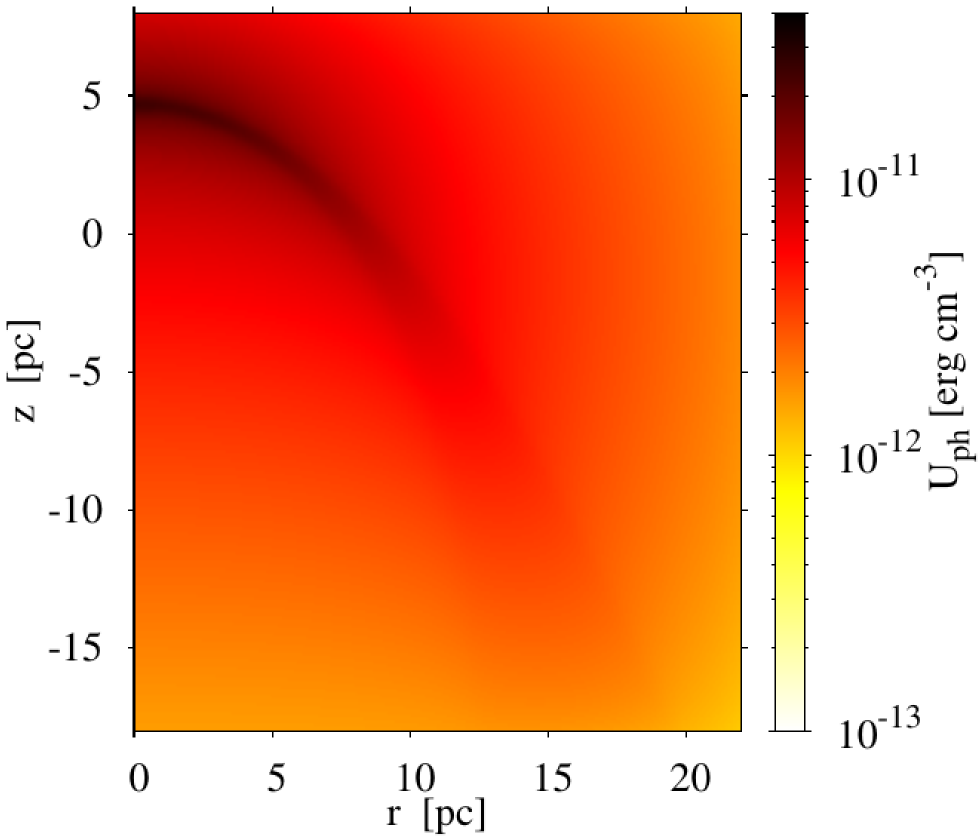
and $\mathcal{K}_2 = \rho(r_{\rm ISM}, z_{\rm ISM})/\rho(r, z)$.

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

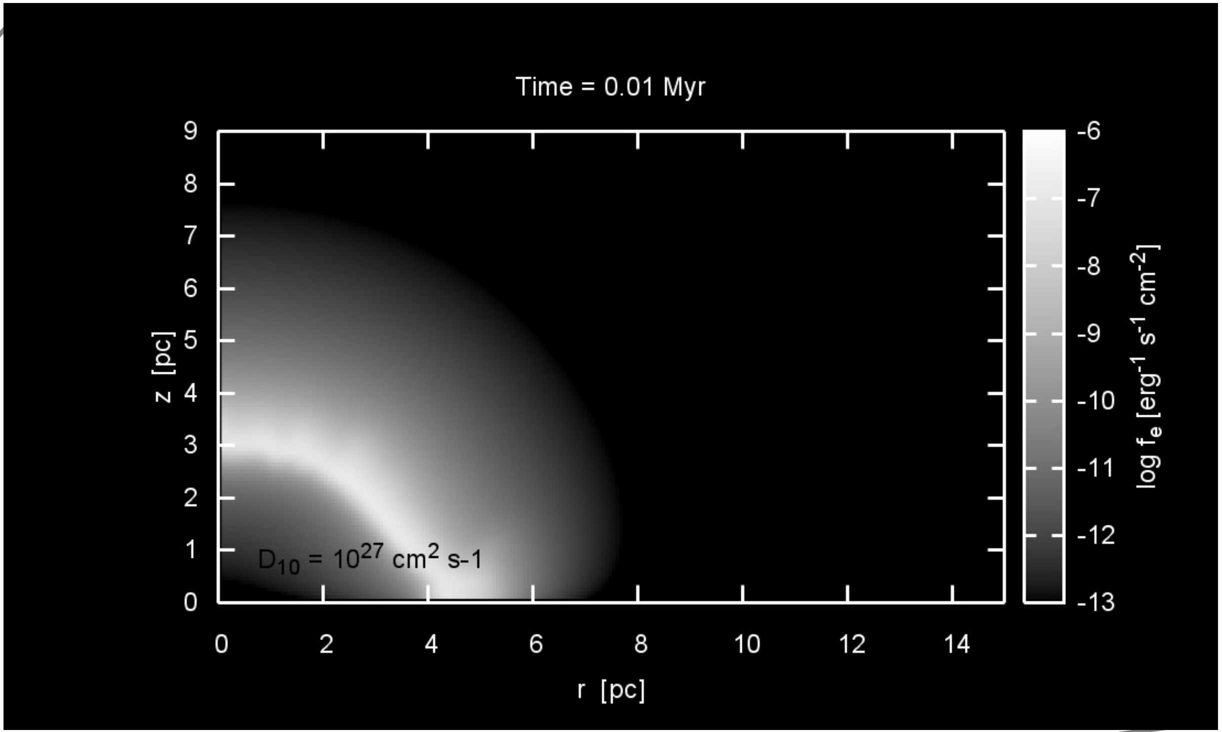
Losses: radiation fields

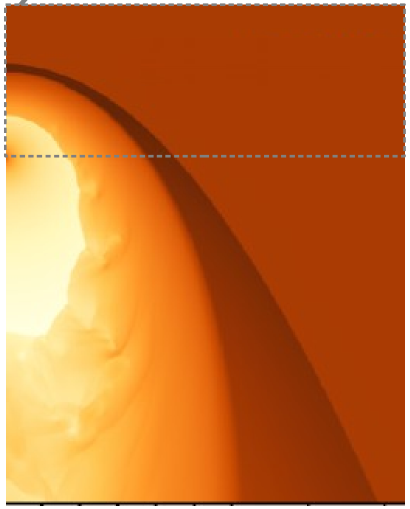
- Stellar radiation field, BB T ~ 10^4 K, U ∝ R^{-2}
- Dust emitted photons:

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



Results





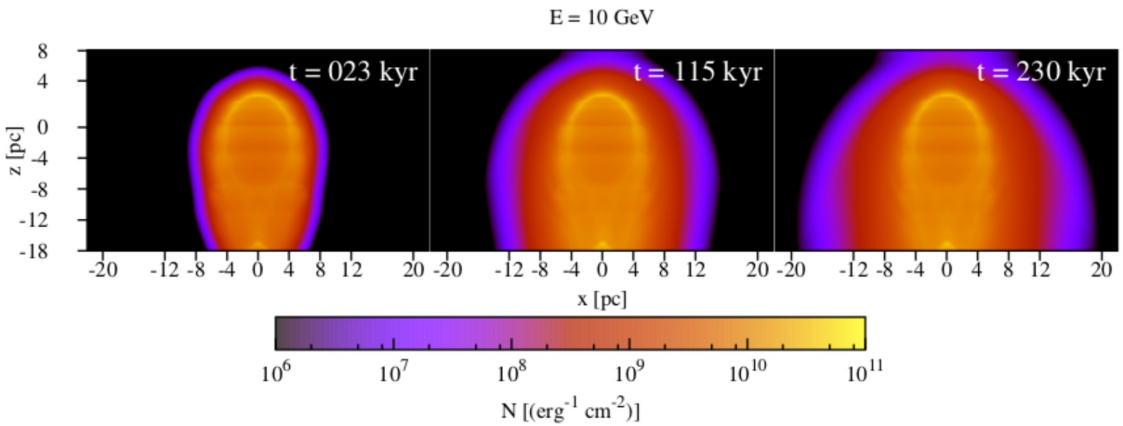
Z > 0

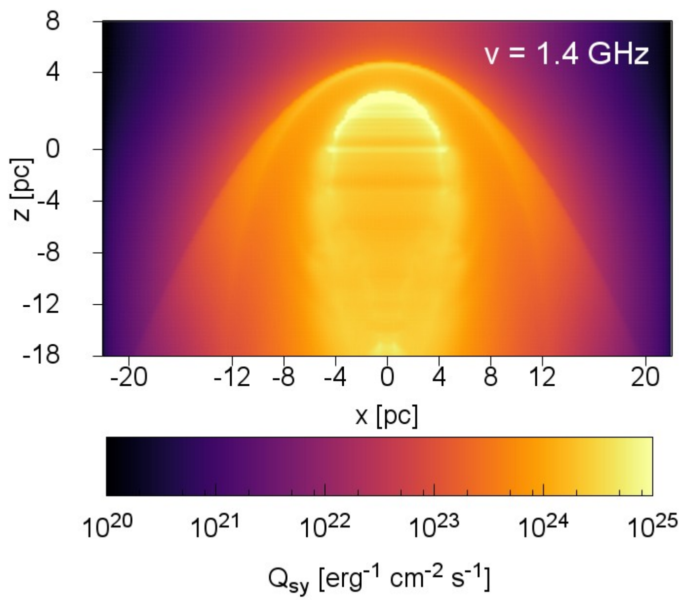
Electrons Bolometric

del Valle & Pohl, sub.

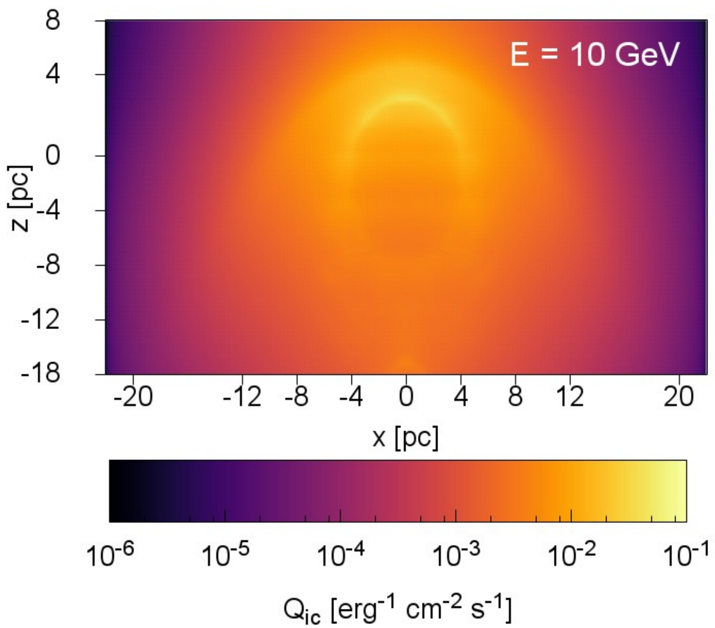
Results

Electrons @ 10 GeV



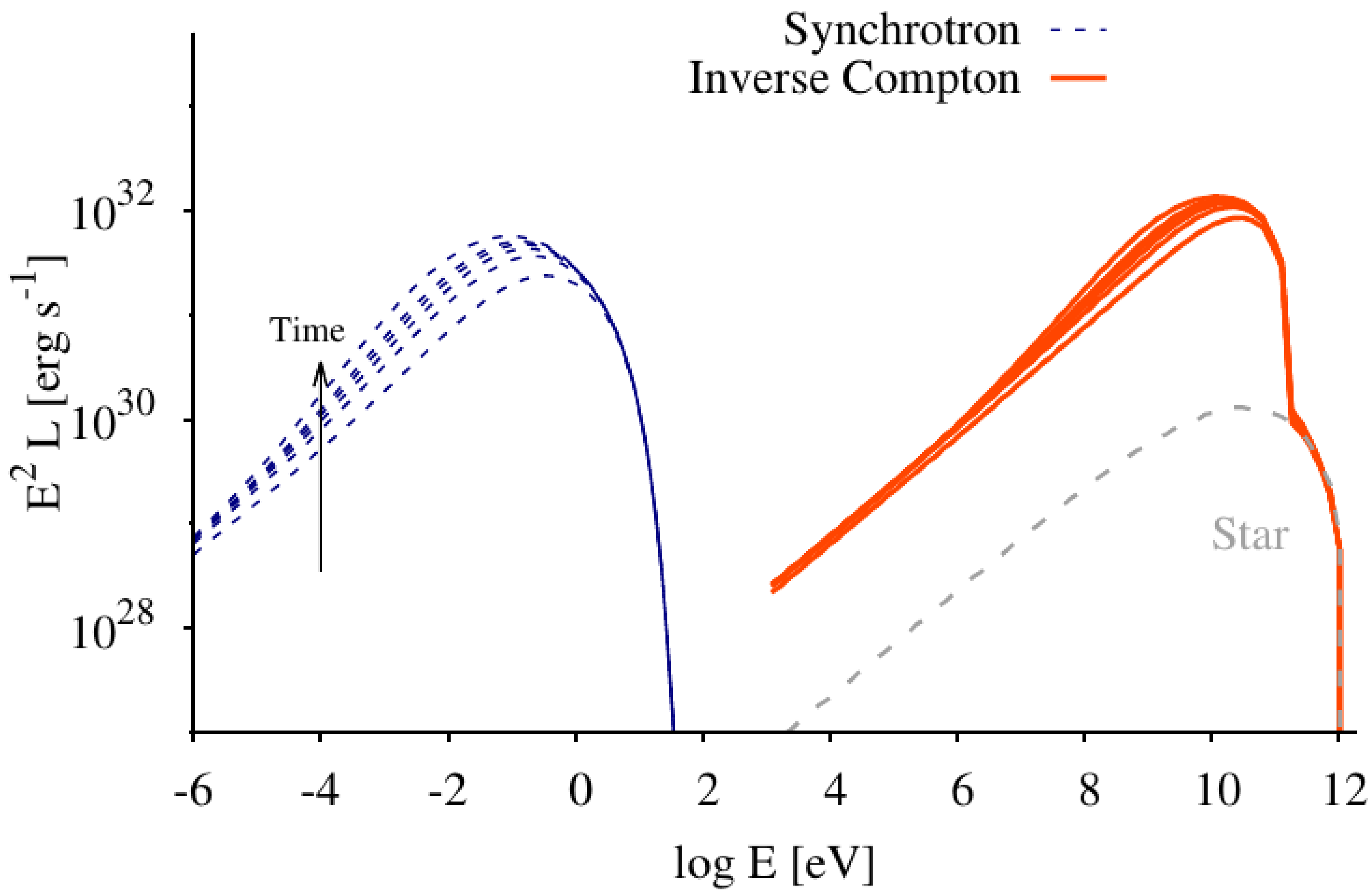


Synchrotron @ 1.4 GHz



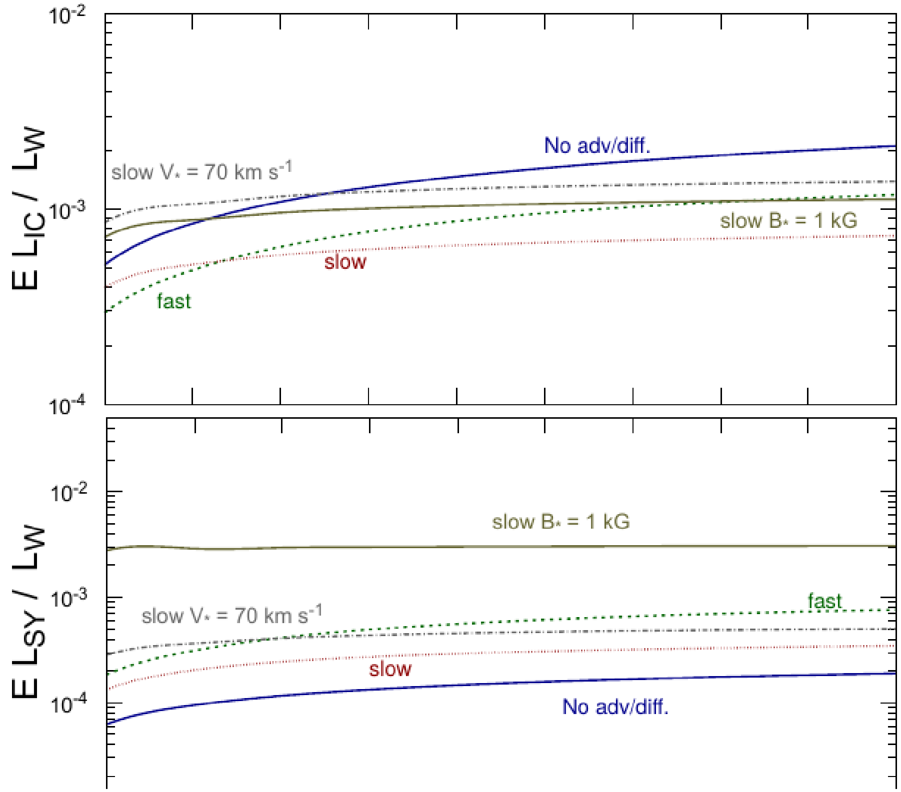
Inverse Compton @ 10 GeV

Results



Synchrotron
Inverse Compton
Time
Star
10^{32}
10^{30}
10^{28}
E^2 L [erg s^{-1}]
-6
-4
-2
0
2
4
6
8
10
12
log E [eV]

Energy injected in the ISM as non-thermal emission

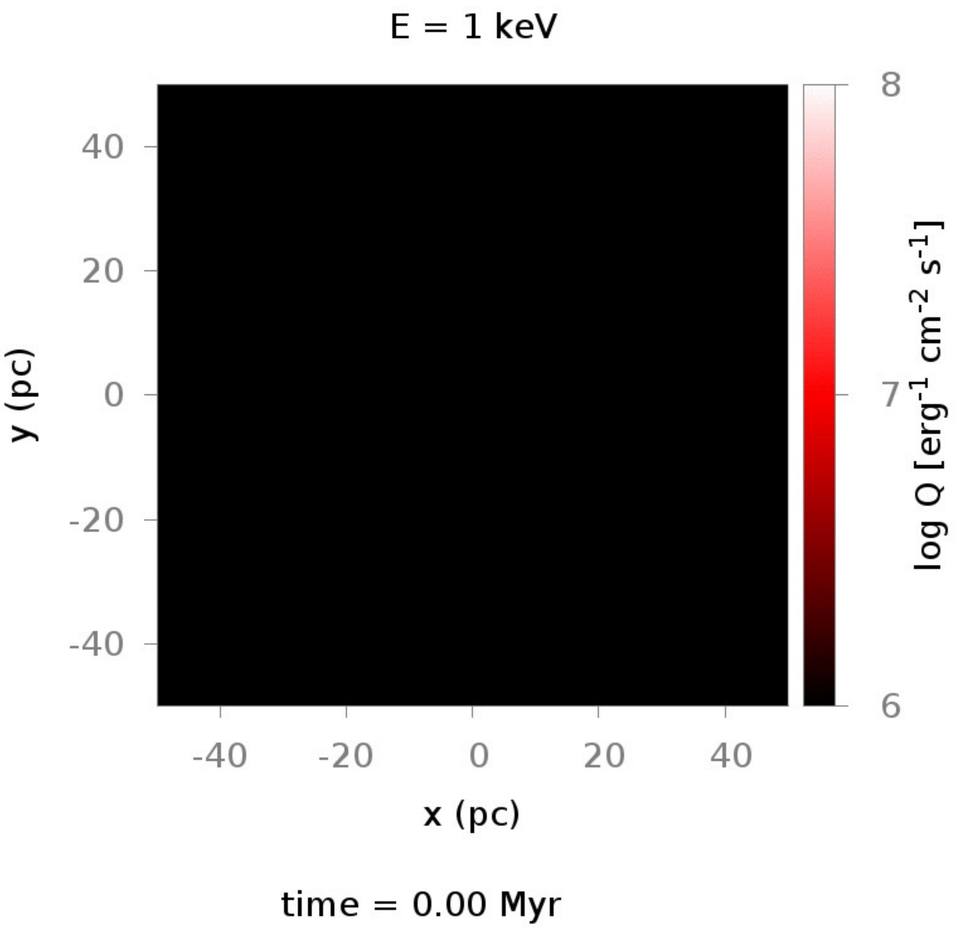


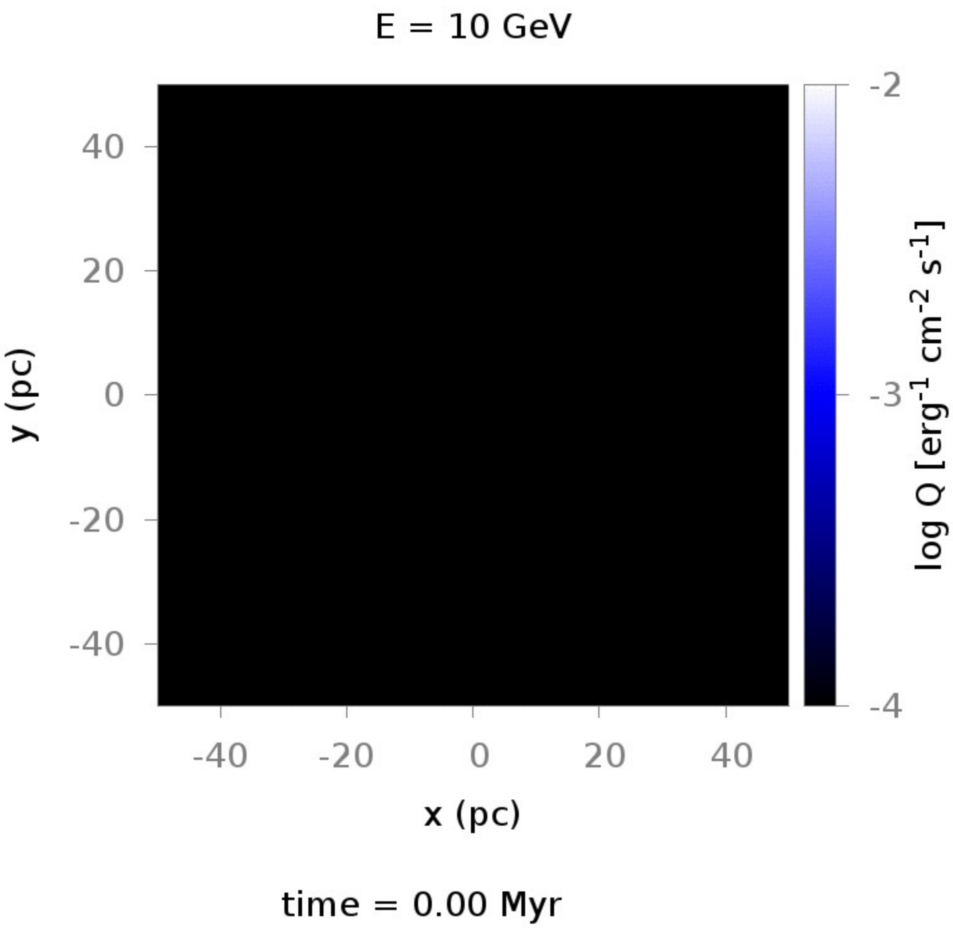
$$L_{\mathrm{IC}} \lesssim 10^{33}\left(\frac{\dot{M}}{10^{-6}M_{\odot}\mathrm{yr}^{-1}}\right)\left(\frac{V_{\mathrm{w}}}{2\times10^{3}\mathrm{km\,s}^{-1}}\right)^{2}\left(\frac{\chi_{\mathrm{IC}}}{10^{-3}}\right)\mathrm{erg\,s}^{-1},$$

$$L_{\mathrm{Sy}} \lesssim 5\times10^{32}\left(\frac{\dot{M}}{10^{-6}M_{\odot}\mathrm{yr}^{-1}}\right)\left(\frac{V_{\mathrm{w}}}{2\times10^{3}\mathrm{km\,s}^{-1}}\right)^{2}\left(\frac{\chi_{\mathrm{S}}}{5\times10^{-4}}\right)\mathrm{erg\,s}^{-1}$$

What about protons?

Very low energy losses, they advect-diffuse in the ISM (del Valle +2015)





Summary

- The interaction of the relativistic electrons produce significant non-thermal emission:
- Synchrotron (maximum energy ~ visible, important at radio)
- Inverse Compton scattering:
  IR field & Stellar field (maximum energy ~ 100 GeV)
- Wind kinetic energy ~ 10^{-3} in non-thermal emission
- Low emission X-rays
- Transport effects are very important
- Protons diffuse almost without losing their energy as predicted in previous works (del Valle+ 2012, 2014, 2015)

➔ Next step: study particular sources

Thanks!