Universidade de São Paulo

X-rays, Gamma-rays and High energy particles from Colliding Wind Binaries: the case of Eta Carinae

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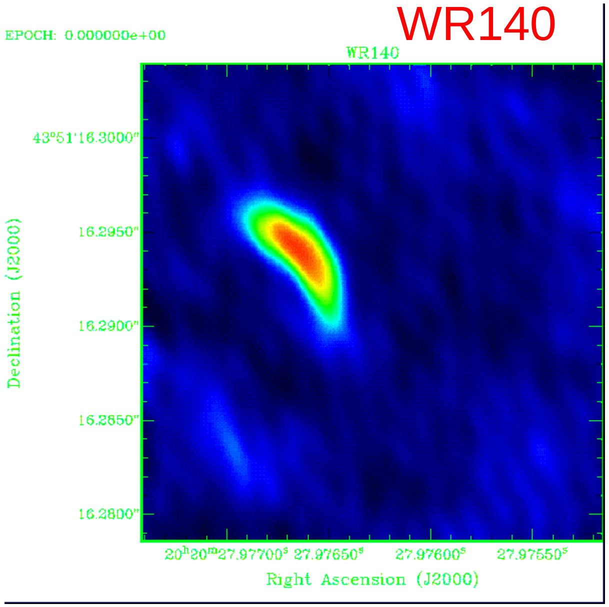
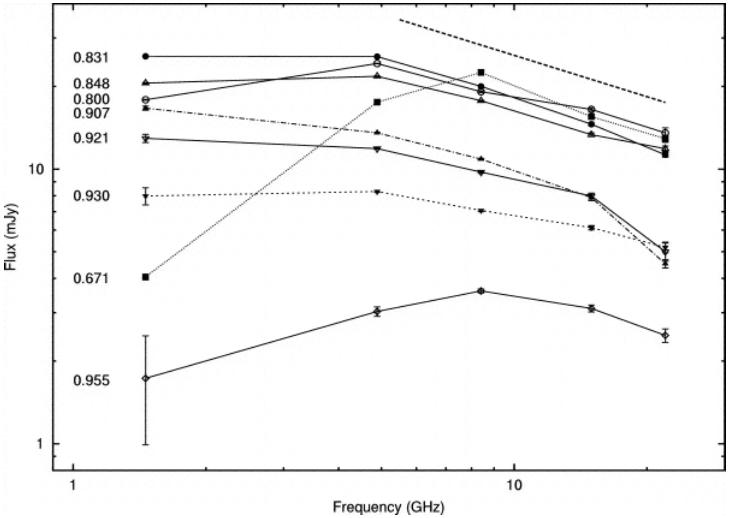
Motivation

- high mass loss rates: $dM/dt \sim 10^{-10} - 10^{-4}\ M_{\odot}/yr$
- supersonic winds: $u_{\infty} \sim 500 – 3500\ km\ s^{-1}$
- large binary fraction: > 50% massive stars formed, with relatively close orbits (Shenton et al. 2024)
- Wind-wind collisions are detected (X-rays & IR)
- Synchrotron emission commonly observed:

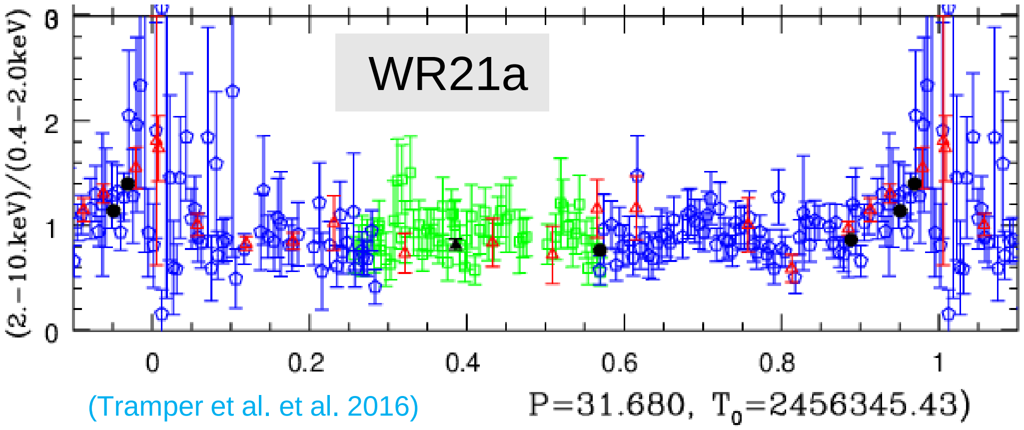




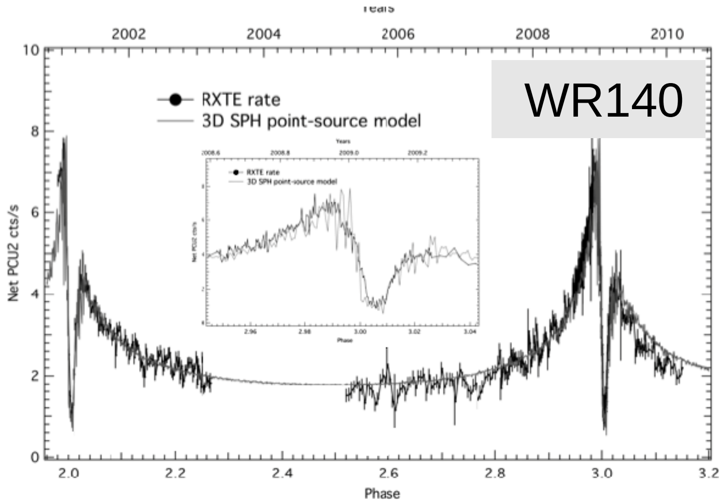
(Dougherty et al. 2004, 2006)

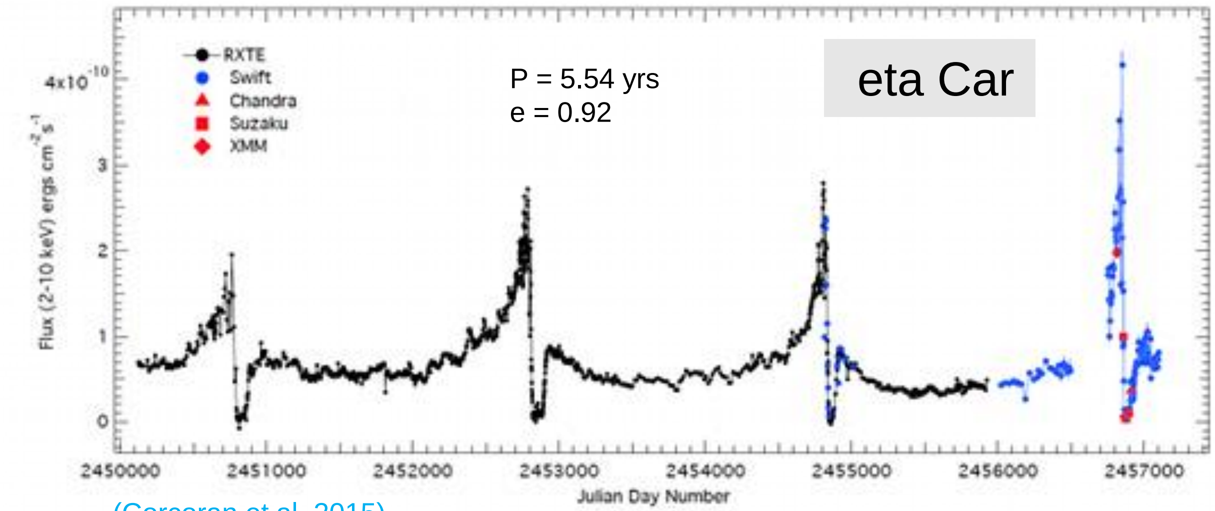
Motivation

Soft and Hard X-rays probe wind-wind collision



(Tramper et al. et al. 2016)





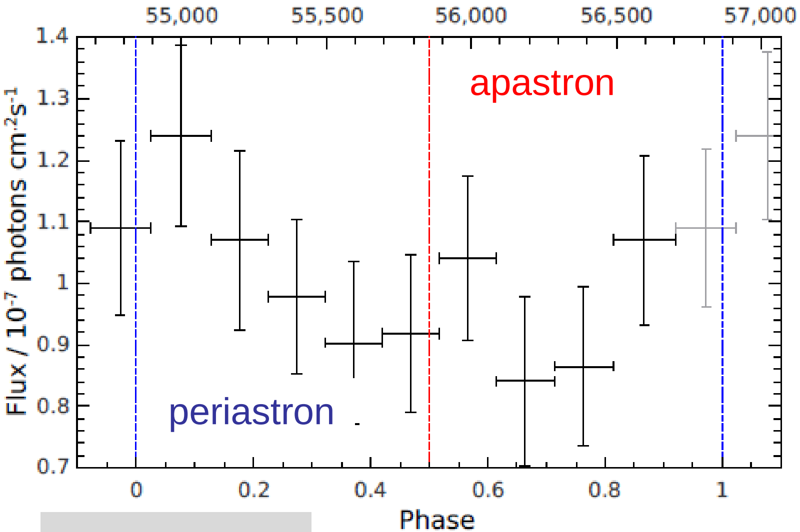
(Corcoran et al. 2015)

- Spectra compatible with bremstrahlung emission
- Hot plasma (T > 10^6 K)
- Reason: strong shocks
- Orbit modulated

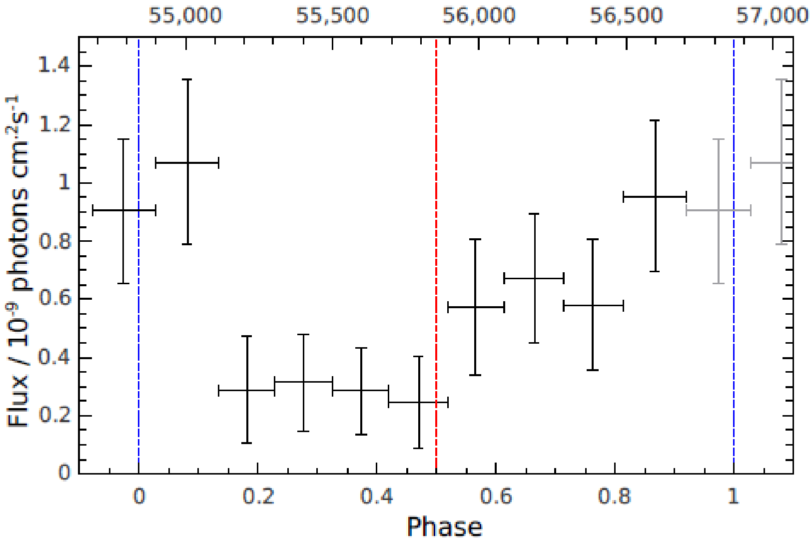
Motivation

“High” Energy photons from CWBs

0.2 – 10 GeV

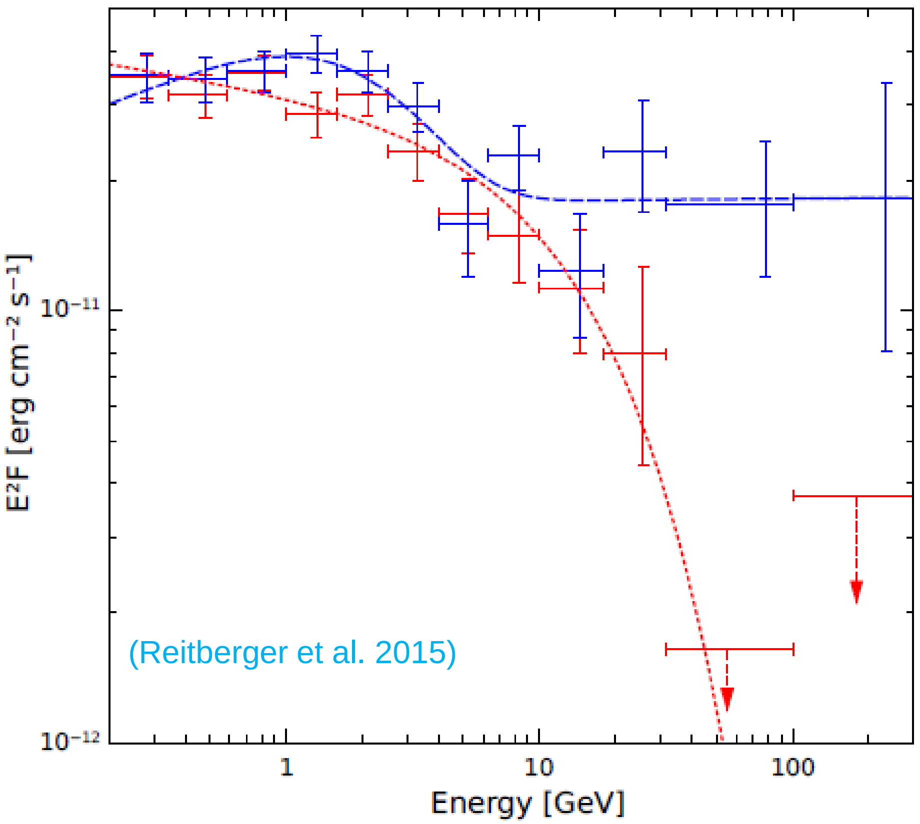


10 – 300 GeV



FERMI observations of eta Car

$$N(E)dE = CE^{-\sigma}dE \qquad \sigma \sim 1.3 – 2.3$$



(Reitberger et al. 2015)

Main questions

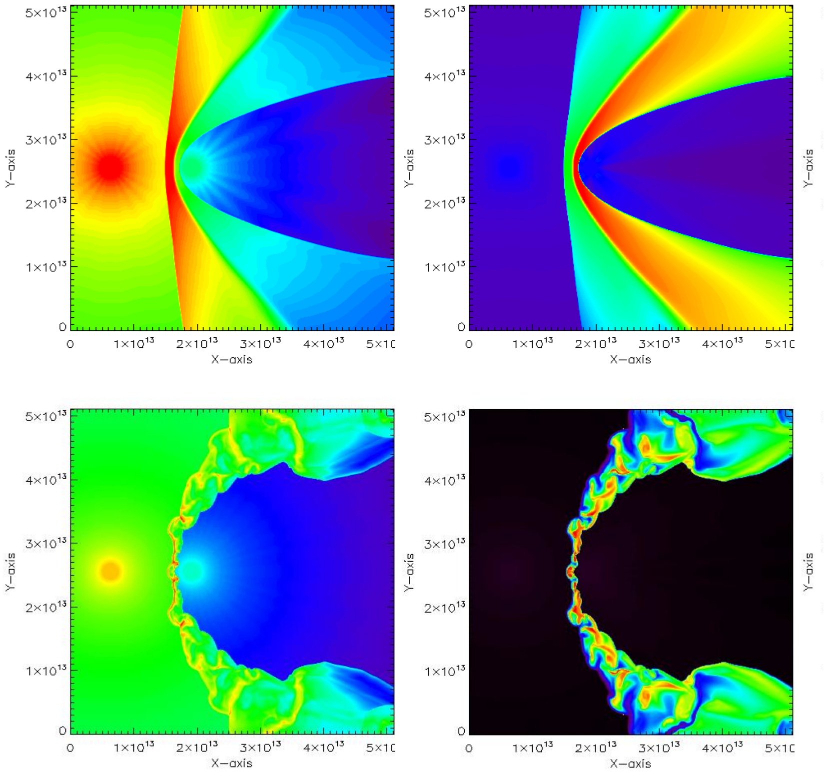
- Synchrotron radio emission indicates the presence of **relativistic electrons & magnetic fields**!
- High energy gamma-rays indicate presence of **relativistic particles (leptonic/hadronic?)**

Magnetic fields in wind shocks?

How particles become relativistic?

- non-linear dynamics of such shocks generate complexity not incorporated in analytical models for synthetic emissions,
- Numerical simulations are needed to fully describe the physics of wind-wind collision region.

Scenario



$$\frac{T_{\mathrm{shock}}}{n\,\Lambda(T_{\mathrm{shock}})} \ll \frac{l_{\mathrm{layer}}}{v_{\mathrm{exp}}}$$

(e.g. Falceta-Gonçalves et al. 2012, 2015, Kowal & Falceta-Goncalves 2021)

- Two massive stars with supersonic winds
- Adiabatic shocks result in a 3-surface problem: a contact discontinuity + 2 shock waves
- Analytical solutions (for static and pure adiabatic HD) provided by Eichler & Usov (early 1990´s)

Complexity factors:

- High mass loss rates & closeness of binaries may imply in fast cooling;
- Orbital motions;
- B-fields can be amplified;

Origin of the relativistic particles

1st Order Fermi Acceleration:

Initial: M_0 particles, E_0 energy

after each collision :

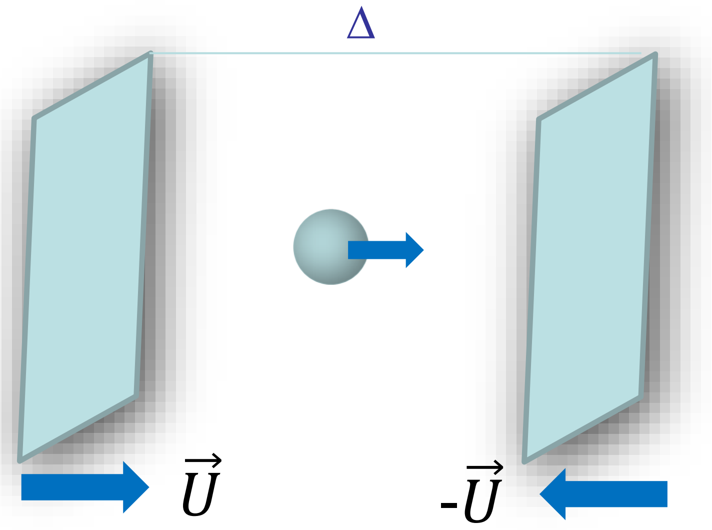
$<\delta E/E> \sim 2U/3c$

- after a cycle:

$$\beta \equiv \frac{E}{E_0} = 1 + \frac{4}{3}\left(\frac{U}{c}\right)$$

- after *j* cycles: $E = \beta^j E_0$
- keV ➡ TeV (i.e. $\sim\frac{9}{\log\beta}$ cycles), $\tau \sim 10^{4-5}\ \mathrm{s}$
- Diffusion/flow timescale is: $\tau \sim \frac{L}{\{v_{flow}, c\}} \sim 10^{3-7}\mathrm{s}$

Problems: time, collisionality, losses



Particles may be lost in the process,

if *P* is the probability of retainment:

$$\frac{\log(N/N_0)}{\log(E/E_0)} = \frac{\log P}{\log\beta}$$

$$N(E)dE = CE^{-\sigma}dE$$

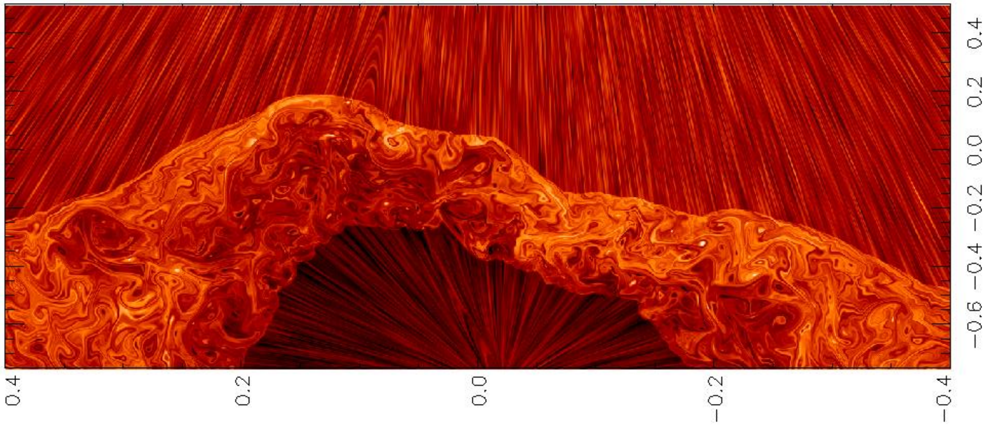
$$\sigma = 1 - \frac{\ln P}{\ln\beta} \sim 2$$

Origin of the relativistic particles

2nd Order Fermi Acceleration:

Randomness of colliders:

- acceleration is a diffusion process (net force is small)



$$\boxed{\frac{\partial f}{\partial t}+\frac{p_i}{m}\frac{\partial f}{\partial x_i}=\frac{\partial}{\partial p_i}\left(D_{ij}\frac{\partial f}{\partial p_j}\right)-\Lambda}$$

$$D_{ij}=\frac{1}{2}\frac{\langle\Delta p_i\Delta p_j\rangle}{\Delta t}\cong\frac{\langle\delta u^2\rangle p^2}{3\lambda c}\delta_{ij}\qquad\Lambda\cong-\frac{f}{\tau_e}$$

Steady state: $$\frac{\partial}{\partial p_i}\left(p^2\frac{\partial f}{\partial p_j}\right)=3\frac{\tau_{acc}}{\tau_e}f$$

$$\frac{\partial}{\partial p}\left(p^4\frac{\partial}{\partial p}\frac{N}{p^2}\right)=3\frac{\tau_{acc}}{\tau_e}N$$

$$N(E)dE=CE^{-\sigma}dE$$

$$\sigma=-\frac{1}{2}+\frac{2}{3}\left(1+\frac{4}{3}\frac{\tau_{acc}}{\tau_e}\right)^{1/2}$$

limit $\tau_{acc}<<\tau_e$ $\sigma\cong0.17$

Strong dependence on turbulence

λ~10^{8-9}cm

$<\delta u^2>$~50-100km/s

$\sigma\cong1-2$

Numerical Simulations

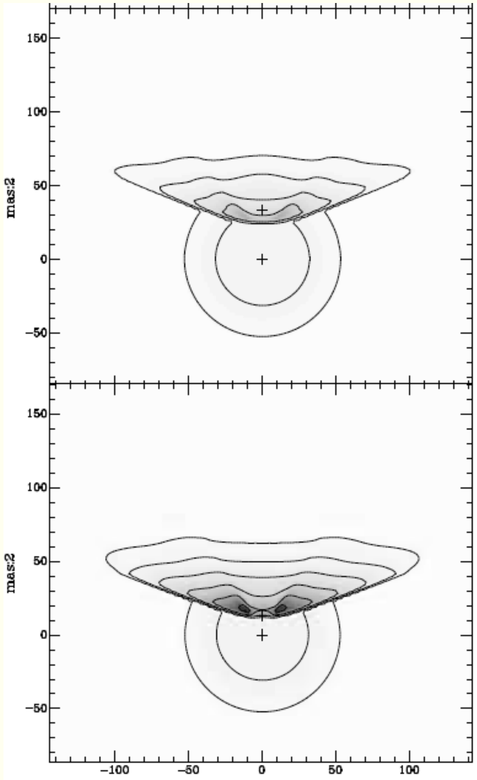
- So far **relativistic particles & magnetic fields** in models have been **ad hoc**

(e.g. Pittard & Dougherty 2006)

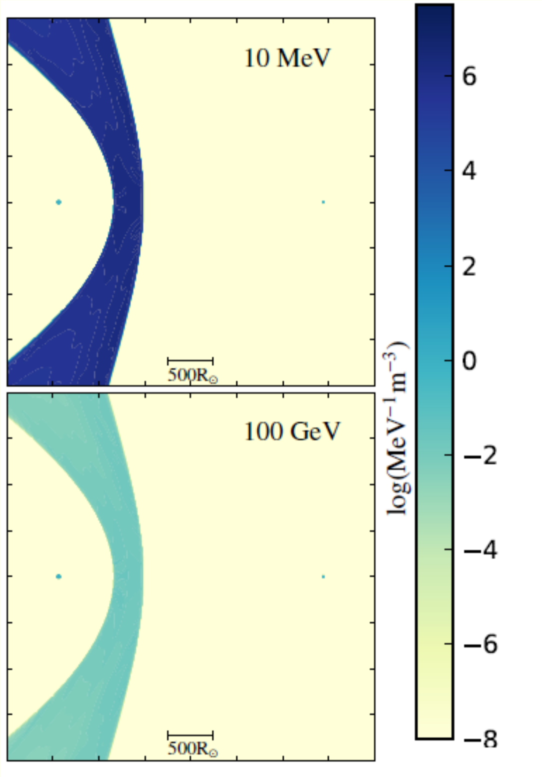
HD simulations

Ad hoc

- Particles moment distribution
- B-fields (equiipartition)



(e.g. Reitberger et al. 2014)



HD simulations
+
Stat. Mech. for particle dist.

Ad hoc

- Particle acceleration coefficients
- B-fields (equipartition)

Numerical Simulations

Ideal world:

- Self-consistent dynamics of shocks (cooling, instabilities, etc.)
- Self-consistent evolution of B-fields (MHD)
- Consistently obtain particle distributions from acceleration processes

Numerical Simulations

AMUN CODE

- MHD
- AMR, 7 levels of refinement, max res 2048^3
- Godunov scheme, with RK4 time integration method, MP-interpolation technique, and HLLD Rieman Solver.

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

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + \left(p + \frac{B^2}{2} \right) I - \mathbf{B}\mathbf{B} \right] = 0,$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{u} \times \mathbf{B}) = 0, \ \nabla \cdot \mathbf{B} = 0,$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + p)\,\mathbf{u} - (\mathbf{u} \cdot \mathbf{B})\,\mathbf{B}] = 0,$$

- explicit terms:

gravity, radiative losses and radiative ionization (pressure term)

Setup for eta Car

$$\dot{M}_1 \sim 2 \times 10^{-4}\ \mathrm{M_\odot\ yr^{-1}}$$

$$\dot{M}_2 \simeq 10^{-5}\ \mathrm{M_\odot\ yr^{-1}}$$

$$v_1 \sim 700\,\mathrm{km\,s^{-1}}$$

$$v_2 \simeq 3 \times 10^3\ \mathrm{km\,s^{-1}}$$

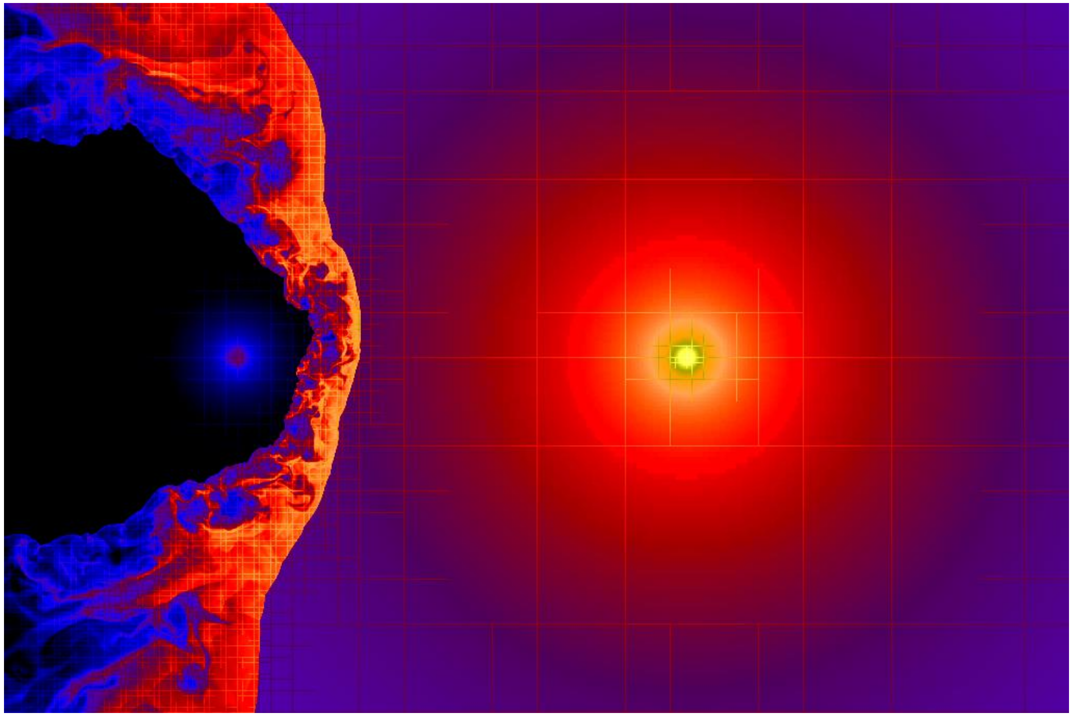
a = 15AU

e = 0.92

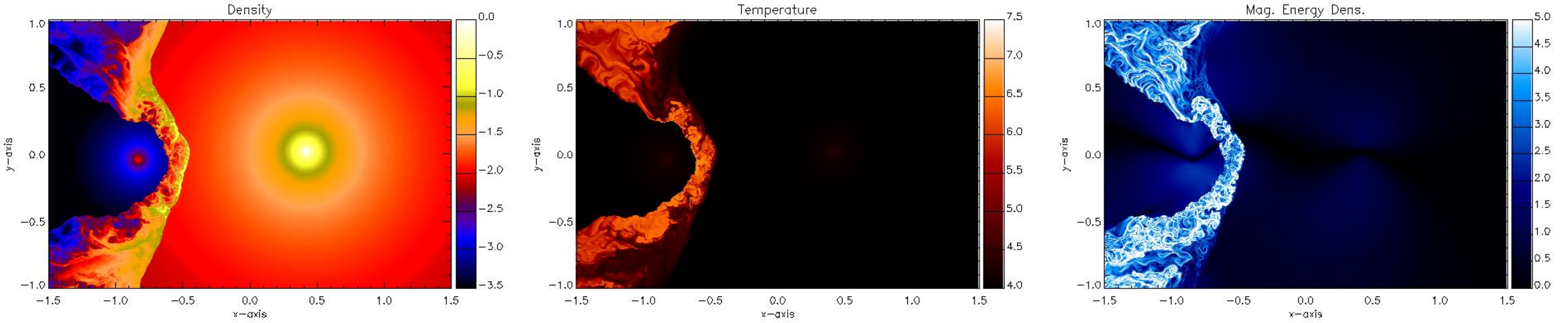
B = [1e-4 , 1] G

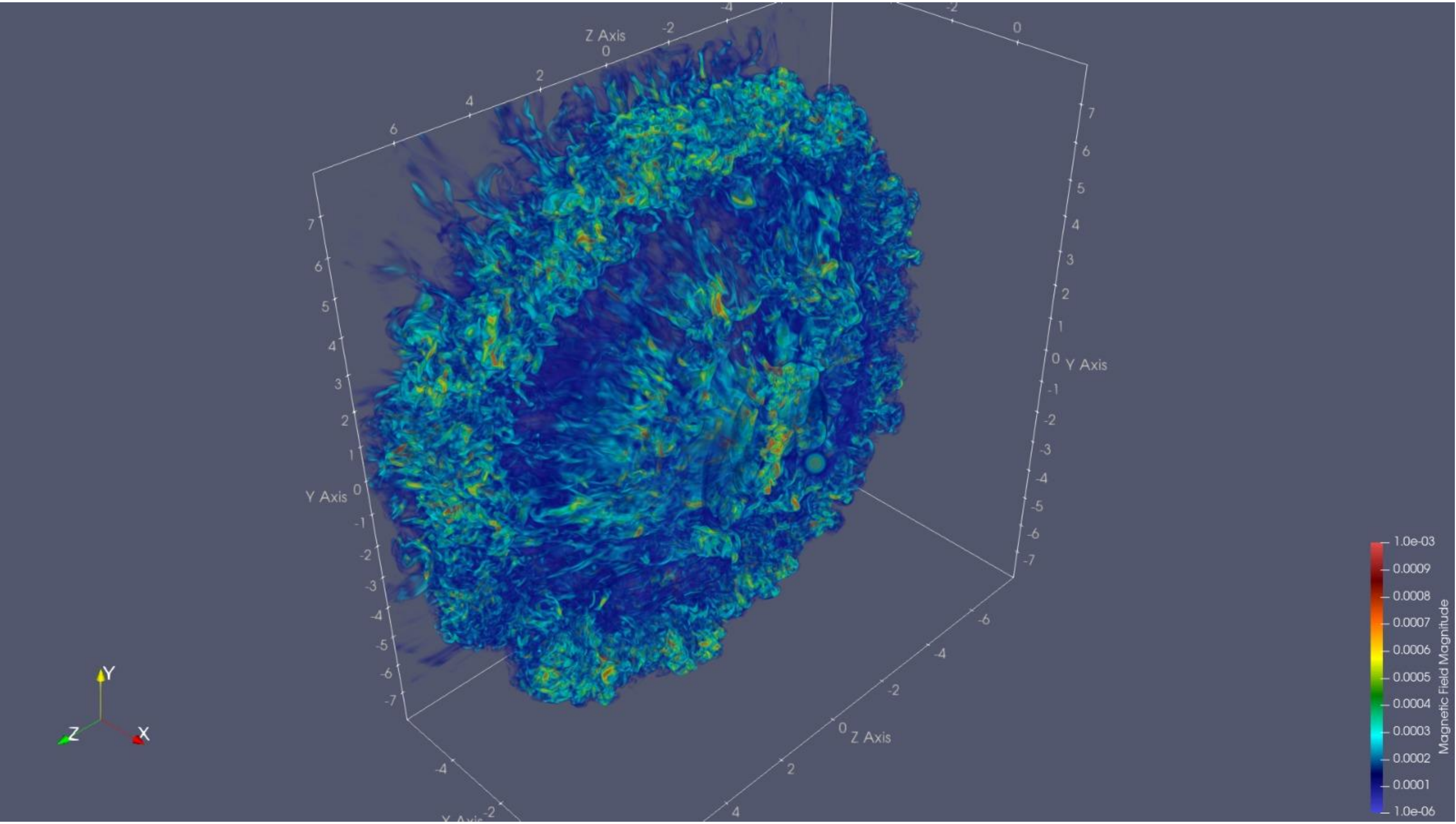
(Pittard & Corcoran 2002, Falceta-Gonçalves & Abraham 2005; Kashi & Soker 2008, Okasaki et al. 2009, and many others)

Results



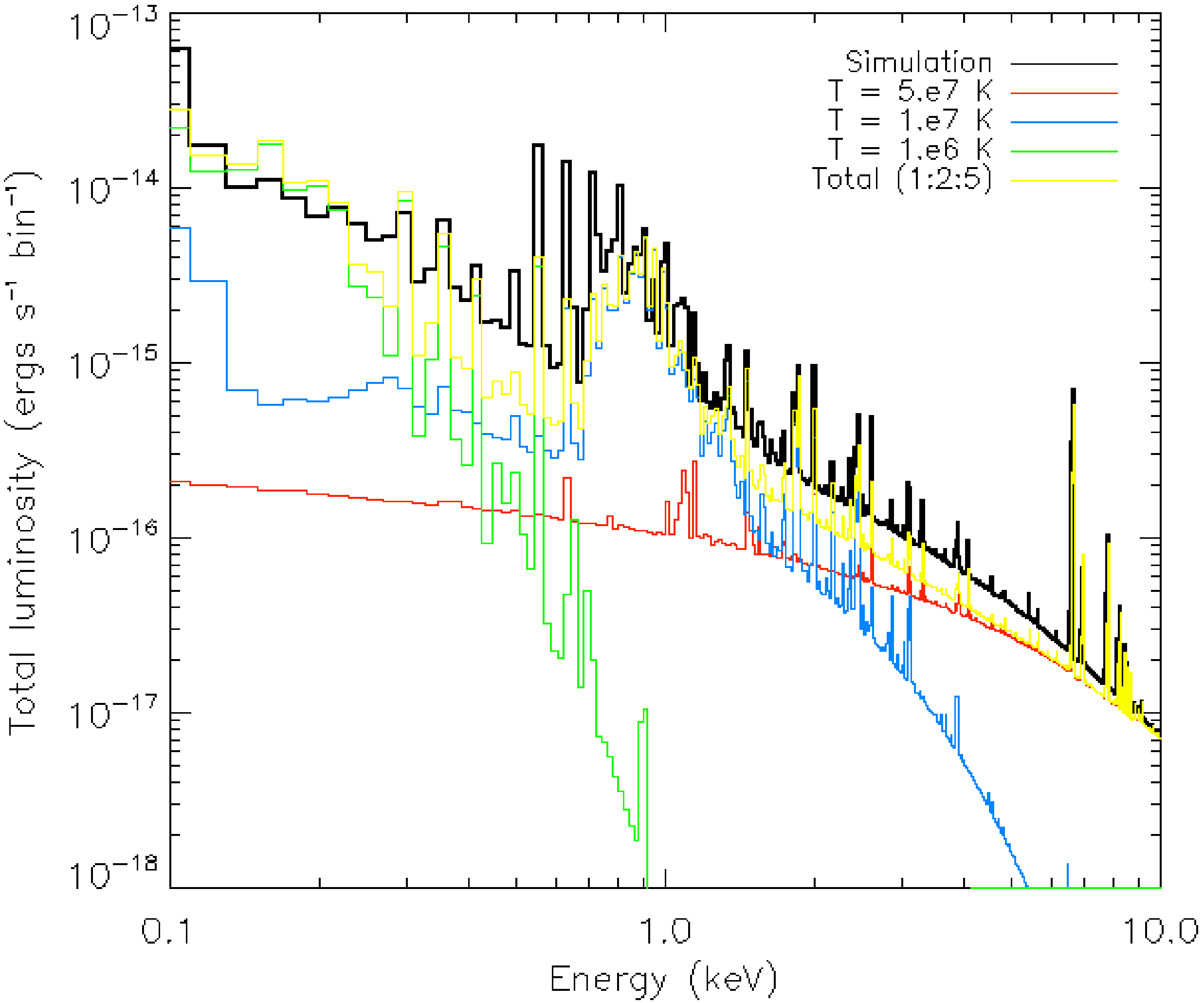
- Cooling is efficient;
- Density increases super-adiabatically
- Magnetic Fields are amplified at the shock
- Do not preserve equipartition
- Complex/turbulent geometry




Z Axis
-4
-2
0
2
4
6
-2
0
7
6
5
4
3
2
1
0
Y Axis
-1
-2
-3
-4
-5
-6
-7
Y Axis
-6
-4
-2
0
Z Axis
2
4
-4
X Axis -2
Y
Z
X
1.0e-03
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
1.0e-06
Magnetic Field Magnitude

Results

X-rays (ATOMDB code)



3-component "fit"

- hot diffuse (~12%)

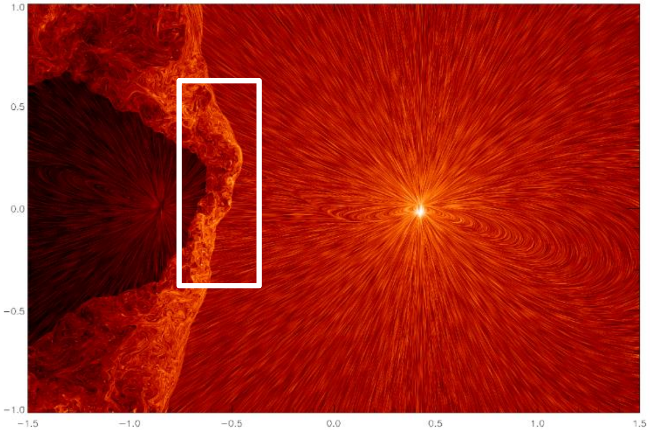
- mid-T diffuse(~24%)

- cool – denser (~64%)

cf. Pittard et al.; Parkin et al, Okasaki et al. and many others

Results

Particle Acceleration

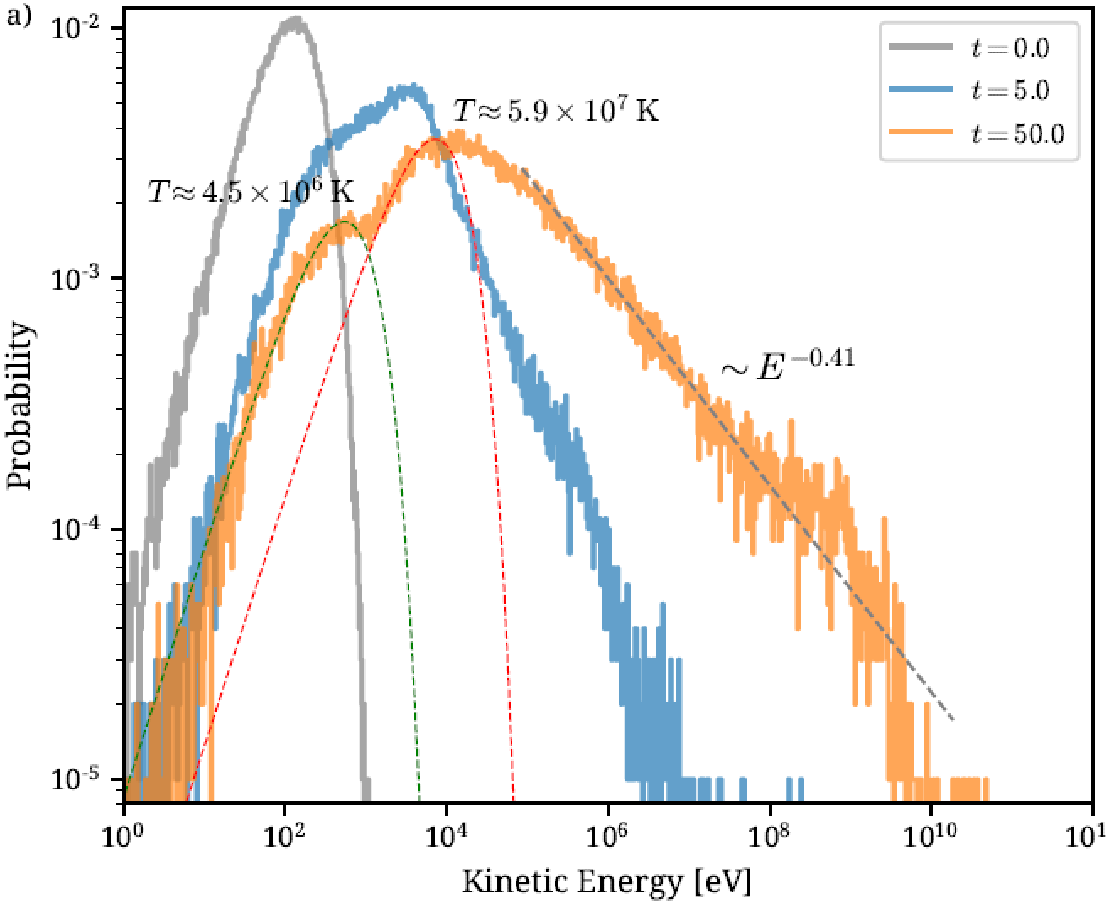


- 100 000 particles are injected with thermal distribution of randomly oriented momenta

- Trajectories are integrated following dynamical evolution:

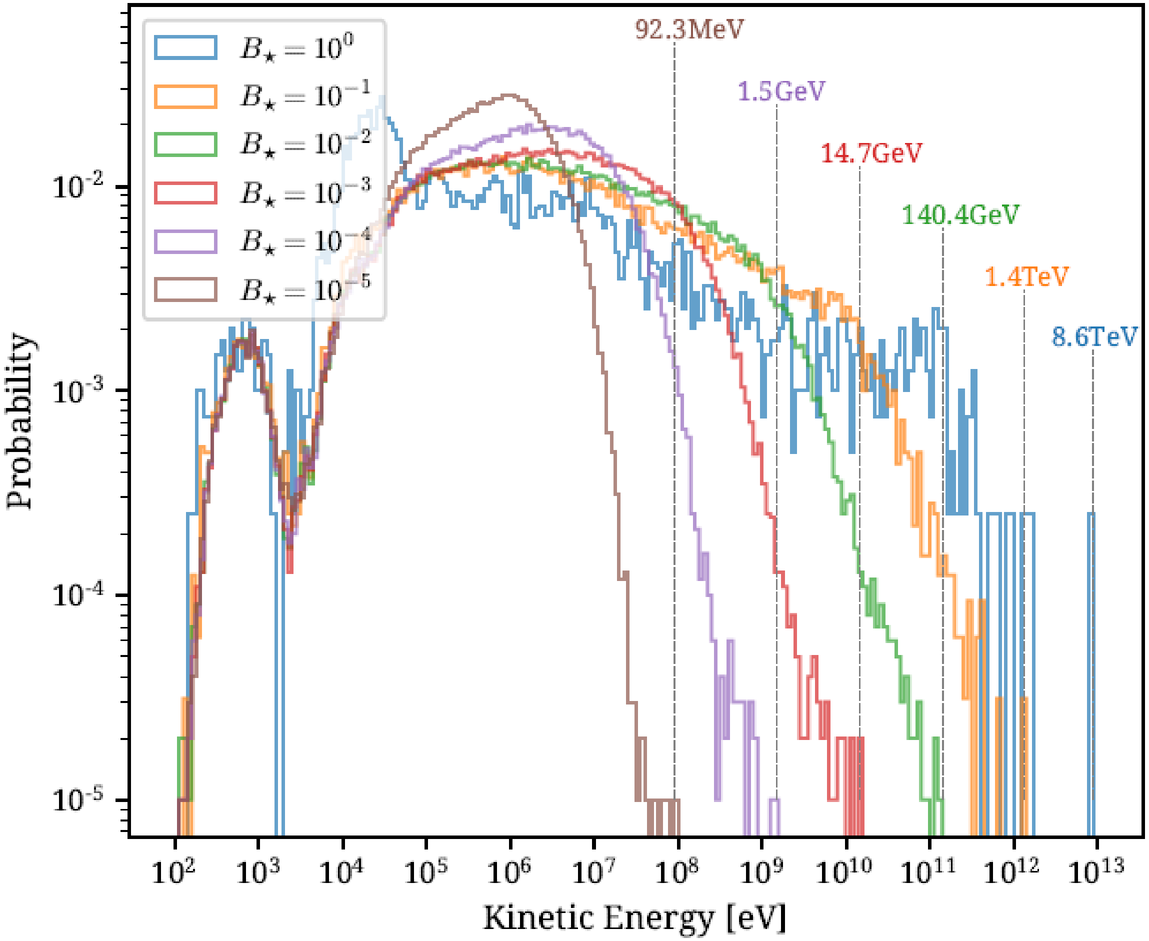
$$\frac{d}{dt}(\gamma \mathbf{v}) = \frac{q}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B})\,, \qquad \frac{d\mathbf{x}}{dt} = \mathbf{v},$$

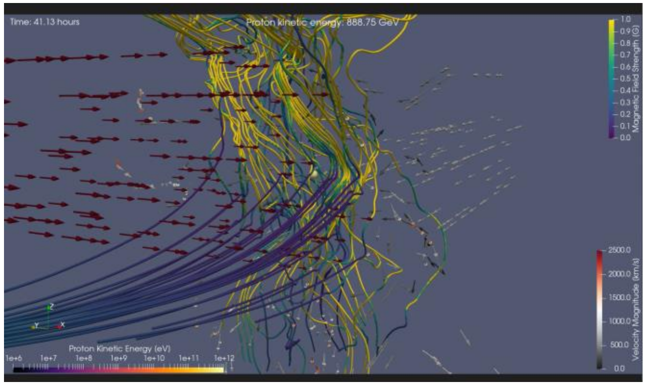
- 8th order Dormand-Prince Method with adaptive time-step

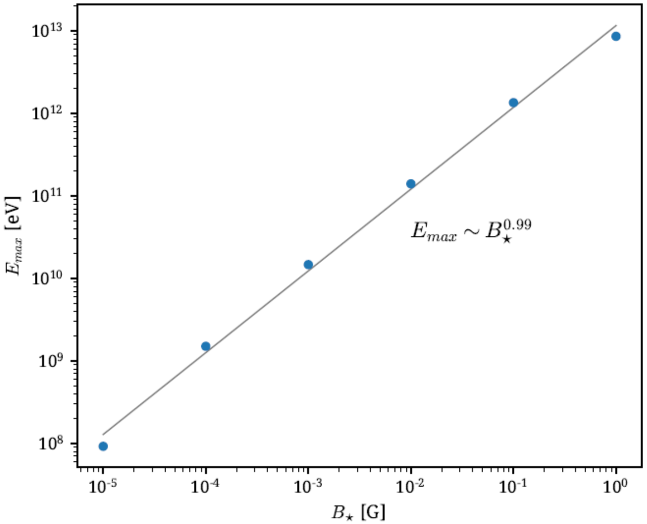


Results

Particle Acceleration





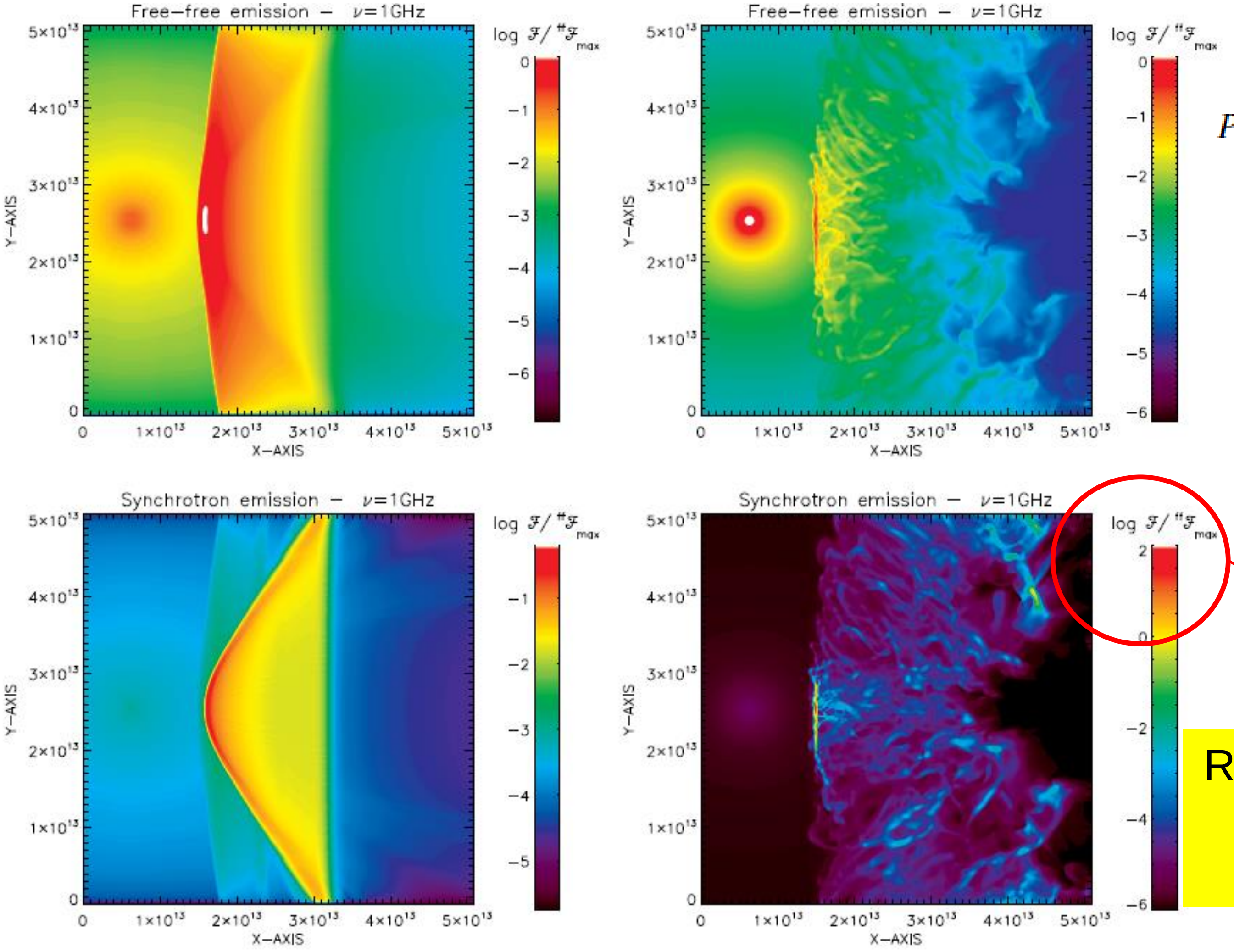


- Non-thermal distribution depend on stellar B;
- Max energies grow linearly to stellar B

Results

Synchrotron emission (1GHz)

$$P_\nu(i,j)^{\rm int} = V \times \sum_{k=1}^{k_{\rm max}=512} P_\nu(i,j,k)\,{\rm e}^{-\tau_\nu(i,j,k)}$$



$$P_\nu^{\rm ff} \sim 6.81 \cdot 10^{-38} Z^2 n_{\rm e} n_{\rm i} g_{\rm ff} T^{-\frac{1}{2}} {\rm e}^{-\frac{h\nu}{kT}}$$

$$\kappa_\nu^{\rm ff} \sim 3.7 \cdot 10^8 Z^2 n_{\rm e} n_{\rm i} g_{\rm ff} T^{-\frac{1}{2}} \nu^{-3} (1 - {\rm e}^{-\frac{h\nu}{kT}})$$

$$\tau_{\rm ff} = \int_0^l \kappa_\nu^{\rm ff}\, {\rm d}s$$

$$P_\nu^{\rm syn} \sim 10^{-20} (s-1) \chi n_{\rm e} p_{\rm inj}^{s-1} B^{1+\alpha} \nu^{-\alpha}$$

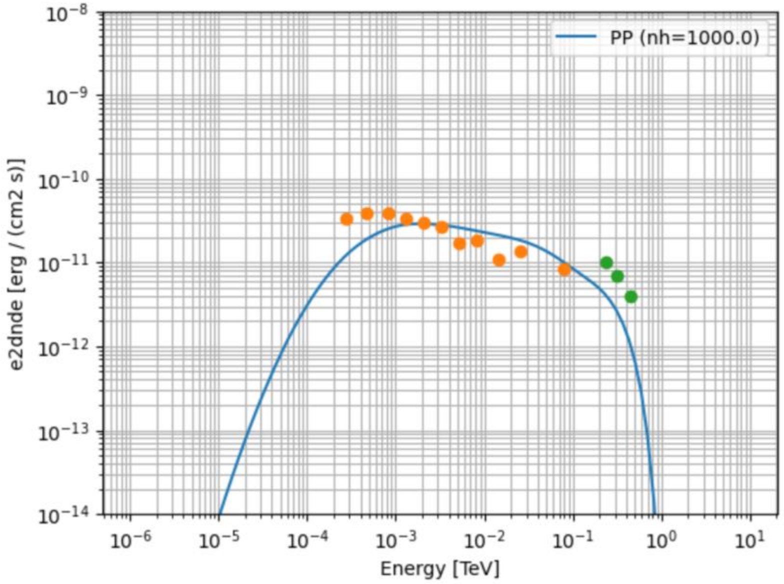
2 orders of magnitude larger than free-free!

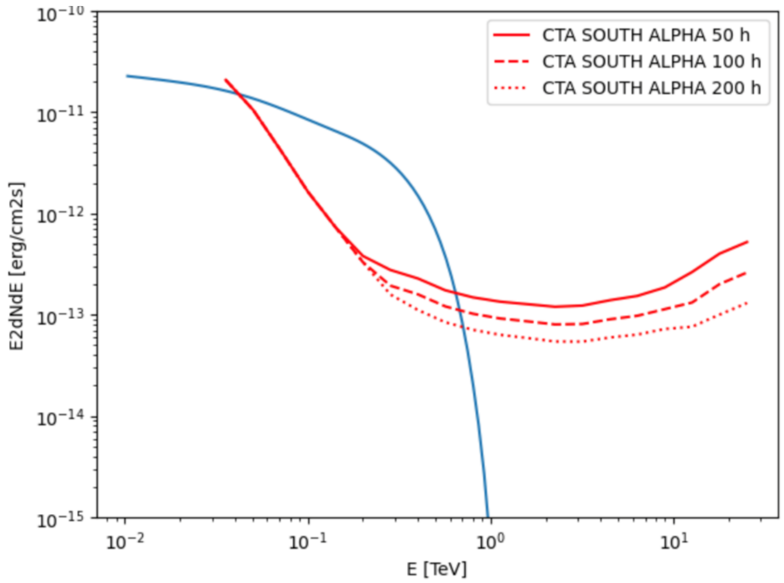
Reduced $P_{\rm th}$, decreased $V_{\rm a}$
Increased $B_{\rm sat}$
KEY!!

Results

Gamma rays emission (>1GeV)

- Proton-proton collisions;
- Production of píons;
- Píons decay into gamma rays;
- Secondary léptons (synchrotron);





Conclusions

- MHD simulations show that equipartition assumptions are far from reality;
- Uniform shock structures as well;
- Turbulence in the shock region is important for shock structure & particle acceleration (mostly DSA mechanism)
- CWBs are possible source candidates for Galactic VHE particles (future targets for CTA observations in star forming regions)