ELECTRON ACCELERATION IN THE CRAB NEBULA

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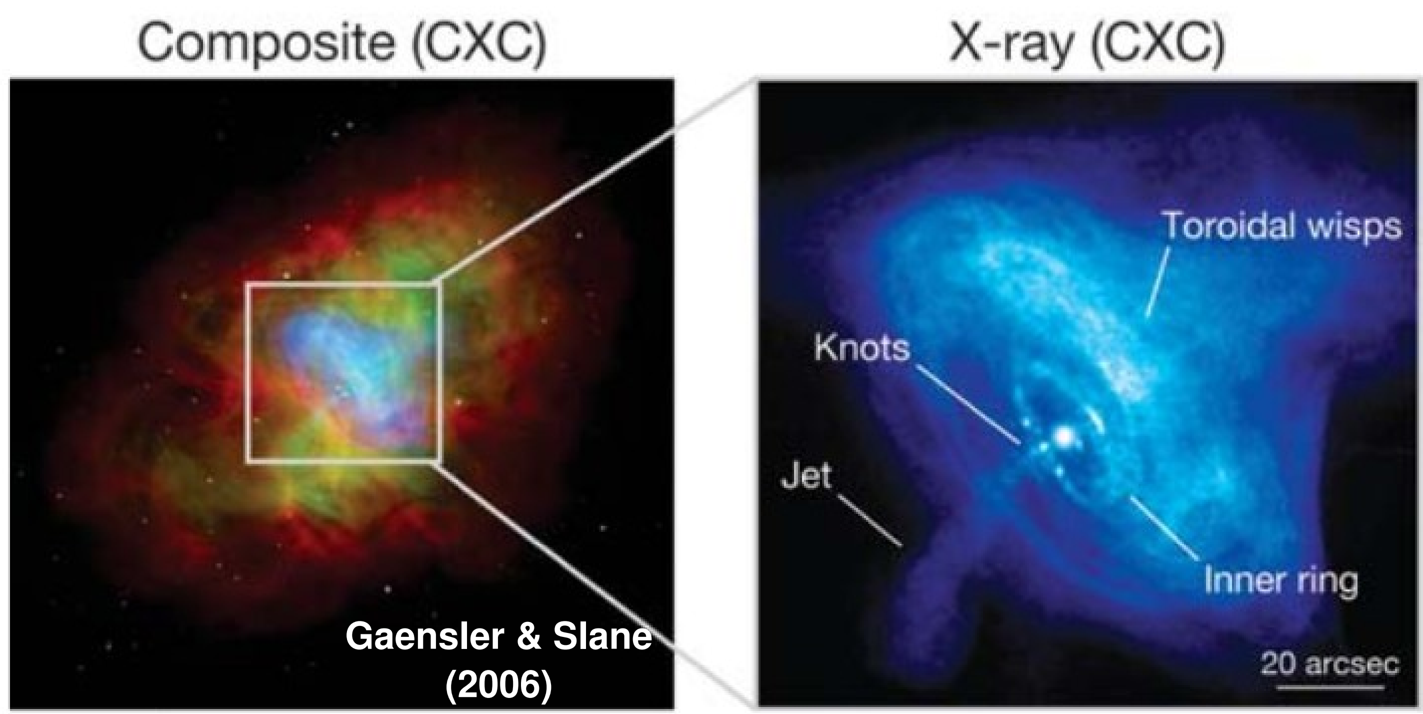
Based on :

GG & Kirk,

ApJ **863**, 18 (2018)



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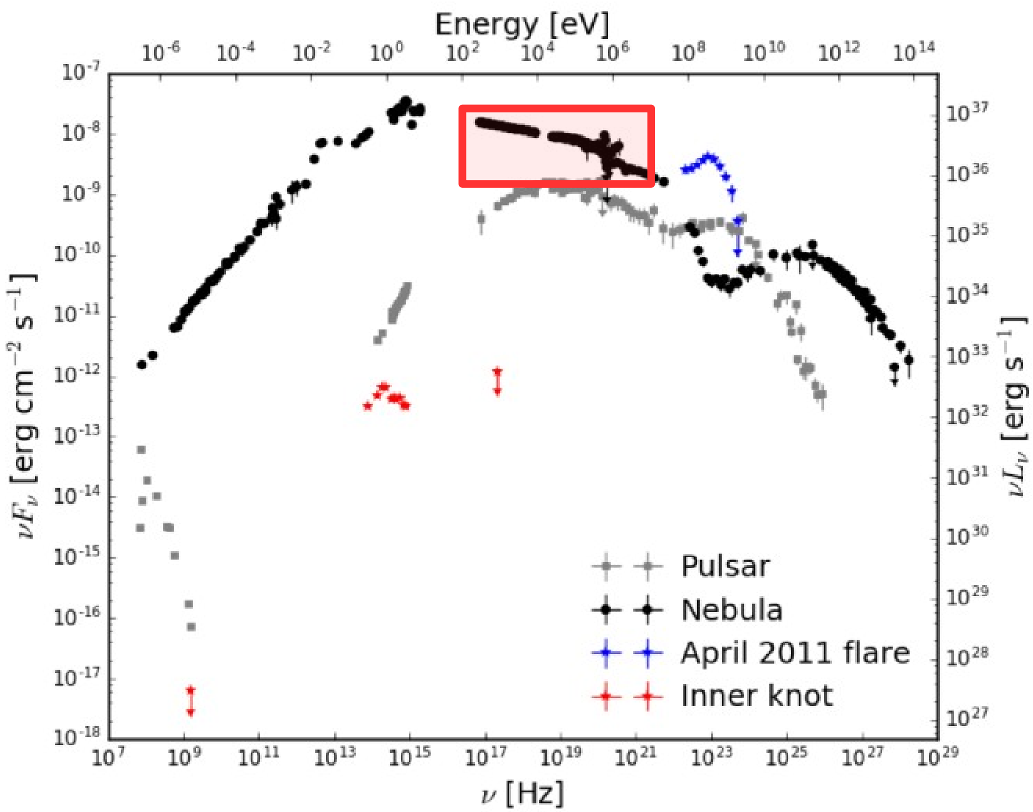
Crab Nebula – Observations

(1) Spectrum :



Buehler & Blandford (2014)

→ **X-ray spectral index :**

$d(\ln N_\gamma) / d(\ln \nu) = -2.1$

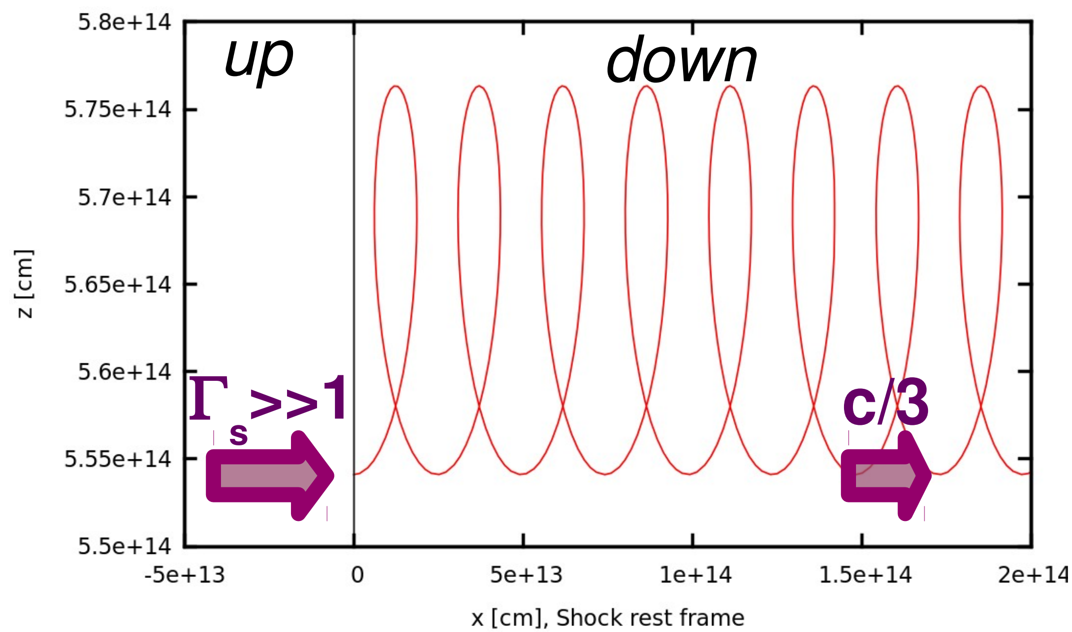
→ **Predicted particle spectrum at ultra-relativistic shocks :**

$d(\ln N_e) / d(\ln \gamma) = \mathbf{-2.2}$

Seems to be in perfect agreement...

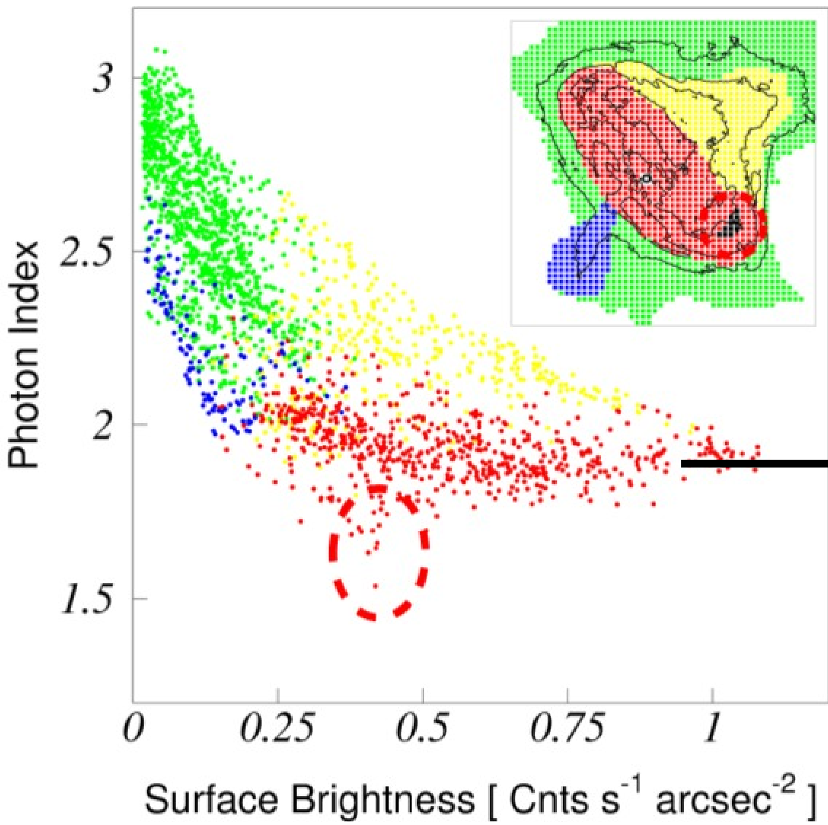
BUT perpendicular shock,

=> 1st order Fermi inoperative!



Crab Nebula – Observations

(2) Spectral index map (Chandra) - Mori *et al.*, ApJ (2004):

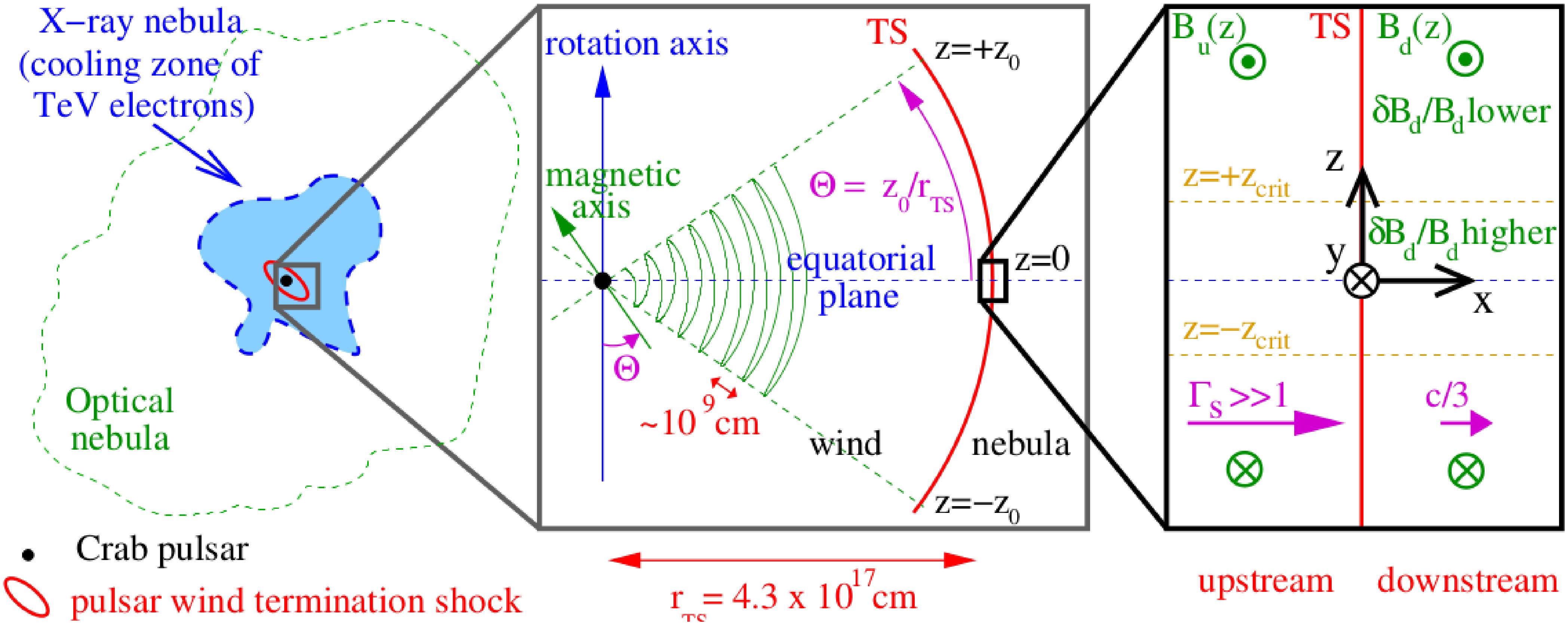


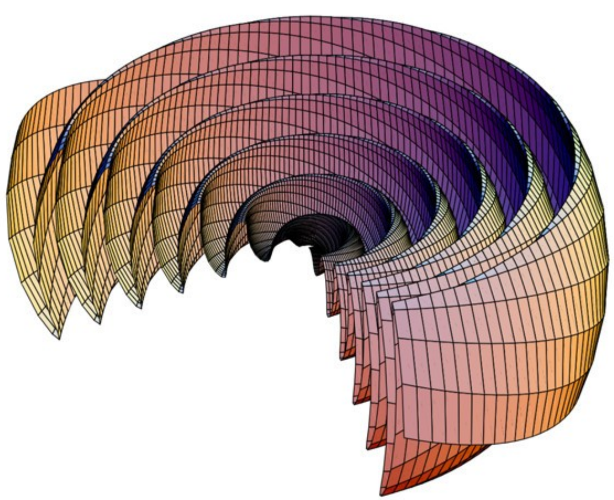
Hard spectrum close to the shock, in the equatorial plane

Photon index s ~ 1.9

=> $d(\ln N_{e-}) / d(\ln \gamma)$ **~ -1.8 !**

Model

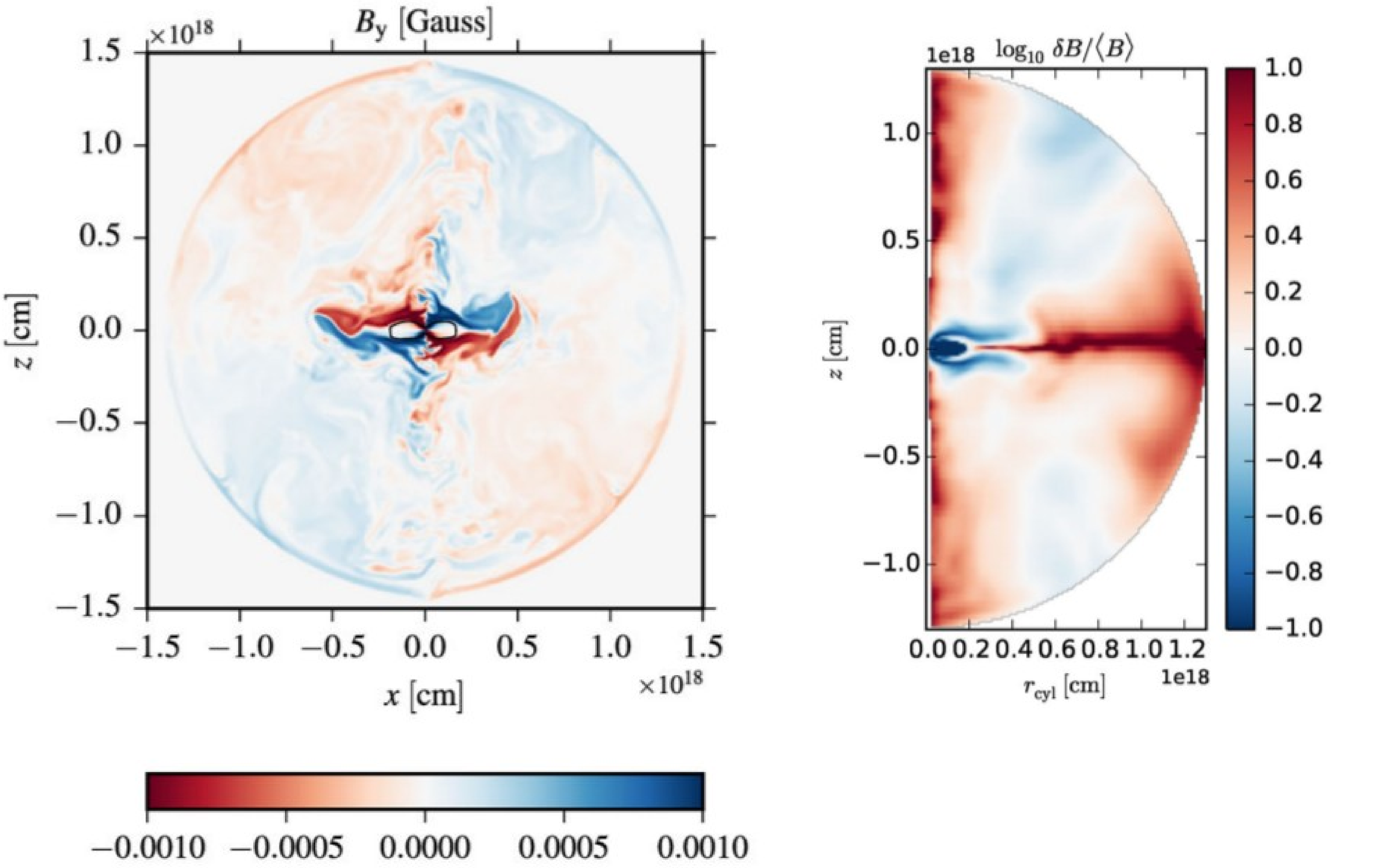




$$\Theta \simeq 13^\circ \rightarrow z_0 = 10^{17}\,\mathrm{cm}$$
$$\Theta \simeq 80^\circ \rightarrow z_0 = 6 \times 10^{17}\,\mathrm{cm}$$

MHD simulations of the Crab Nebula

Porth *et al.* (2014, 2016)

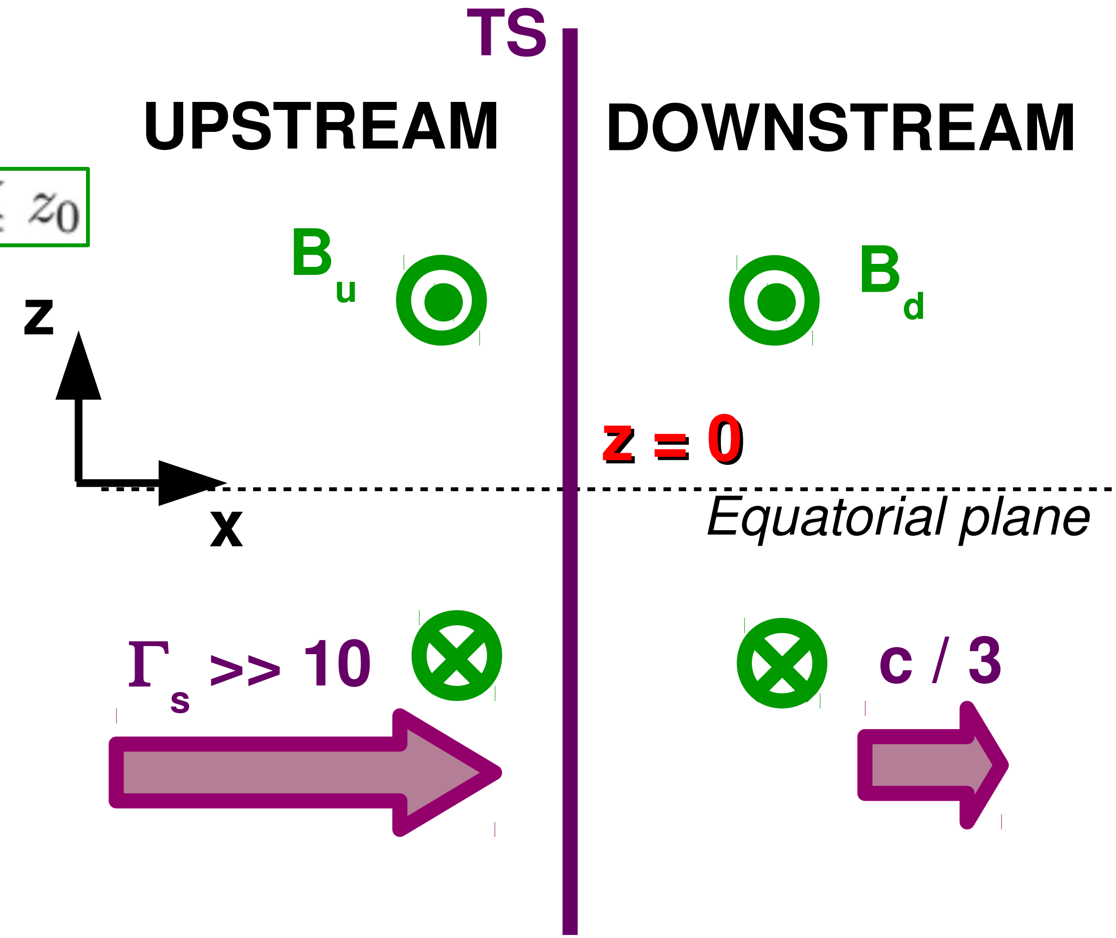


Model and numerical simulations

OUR MODEL (PLANAR 1D) :

$$\mathbf{B}_{\mathrm{u}}(z) = -B_{\mathrm{u},0}(z/z_0)\hat{\mathbf{y}} \quad \text{if } |z| \leq z_0$$

Jump conditions :
$B_{u,RF} = (\Gamma_d/3\Gamma_u)B_{d,RF}$



$$\mathbf{B}_{\mathrm{d}}(z) = -B_{\mathrm{d},0}(z/z_0)\hat{\mathbf{y}} \quad \text{if } |z| \leq z_0$$

$B_{d,0} = +1\text{mG}$

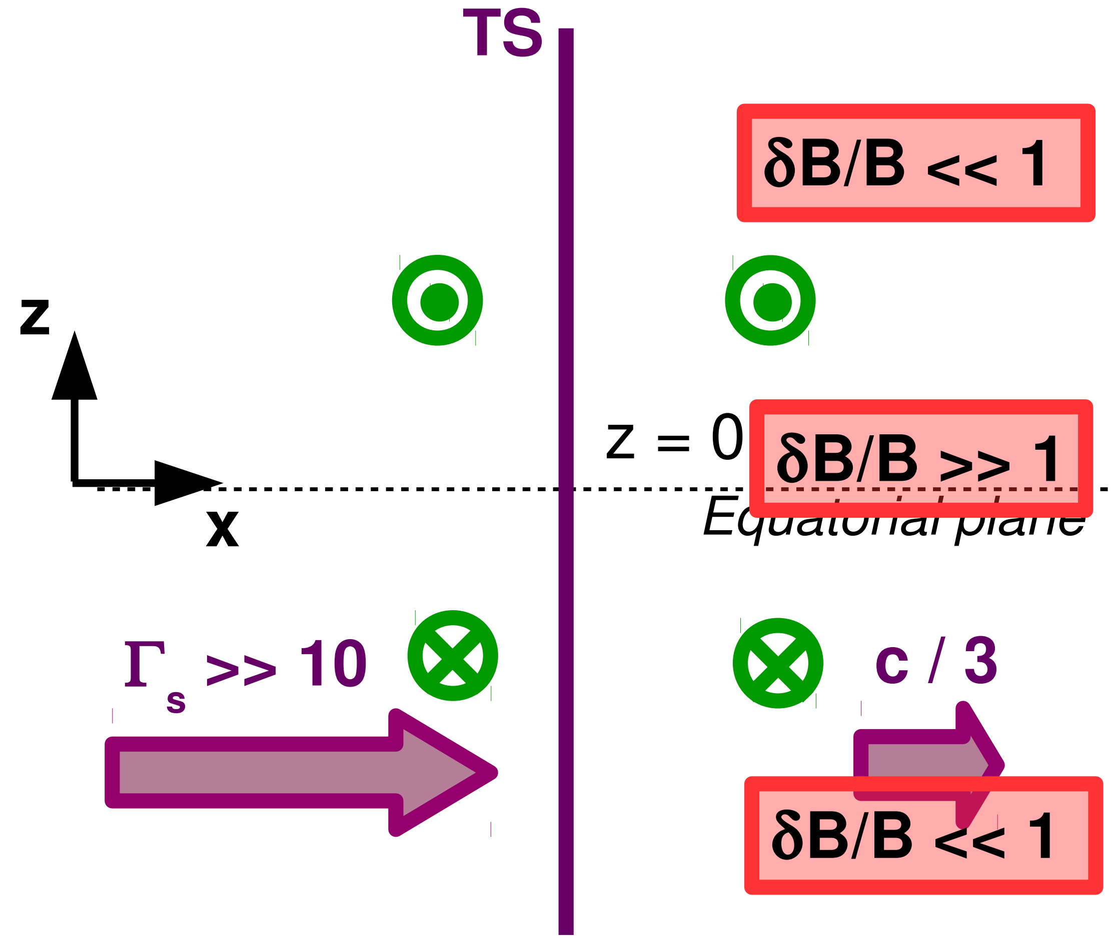
Model and numerical simulations

→ **3D turbulent magnetic field on a grid with $N^3 = 256^3$.**

$$\delta B_{\rm d} = (0.3 - 400)\,\mu{\rm G}$$

$$= \text{ cst. of } z$$

OUR MODEL (PLANAR 1D) :



Model and numerical simulations

INJECTION :

Energy per particle in units of $m_e c^2$ after dissipation of the entire Poynting flux (isotropic wind):

$$\mu = \frac{L_{\rm s.d.}}{\dot{N}_{\pm} m_e c^2}$$

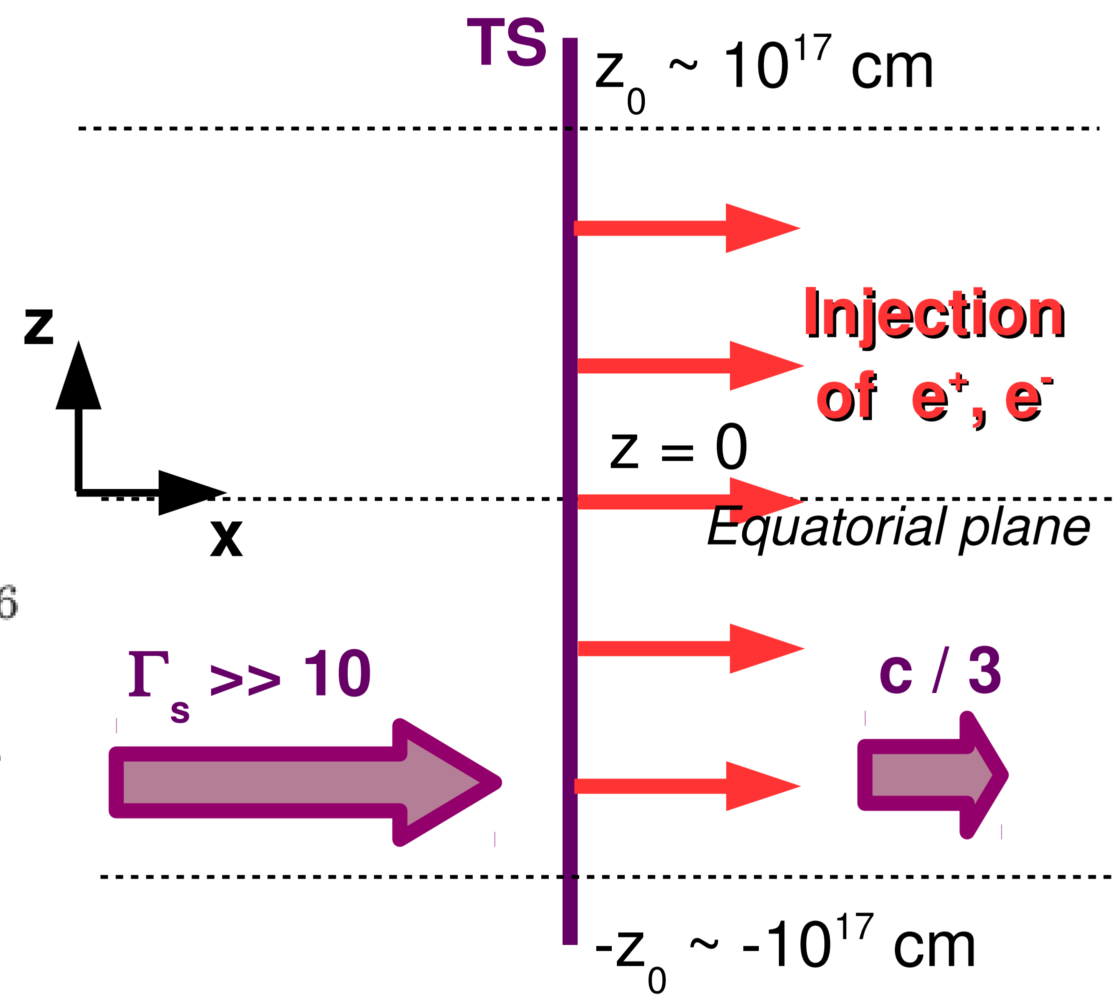
Crab (Olmi+'16): $10^4 \lesssim \mu \lesssim 10^6$

Amano & Kirk (2013) + Giacchè & Kirk (2017) =>

$$E_{\rm inj,d} = \gamma_{\rm inj,d} m_e c^2 \approx \mu m_e c^2$$

=> $E_{\rm inj,d} = 1\,{\rm TeV}$

OUR MODEL (PLANAR 1D) :



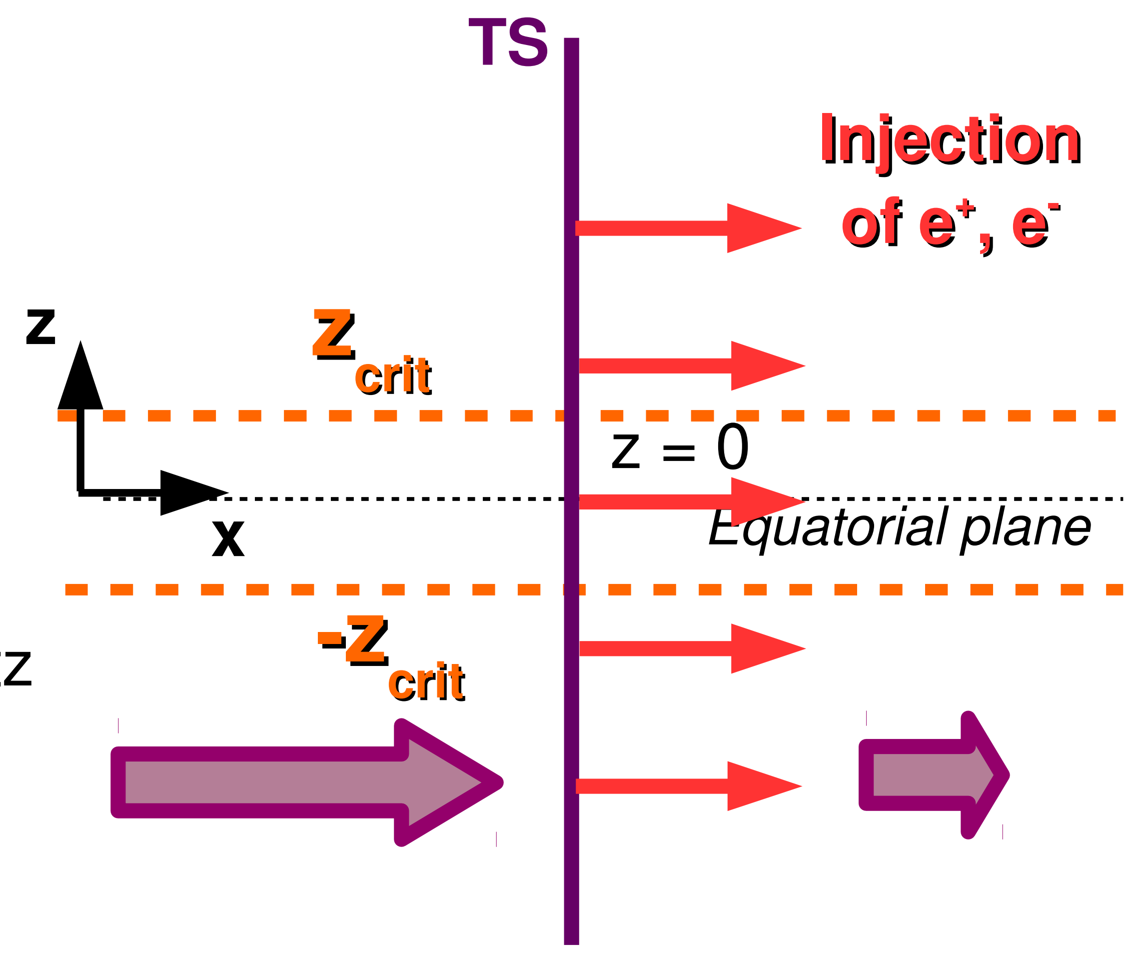
Model and numerical simulations

OUR MODEL (PLANAR 1D) :

→ Integrate the **trajectories** of **individual particules** in **3D** (**test particle limit**),

→ Integrate in the Upstream or Downstream Rest Frames,

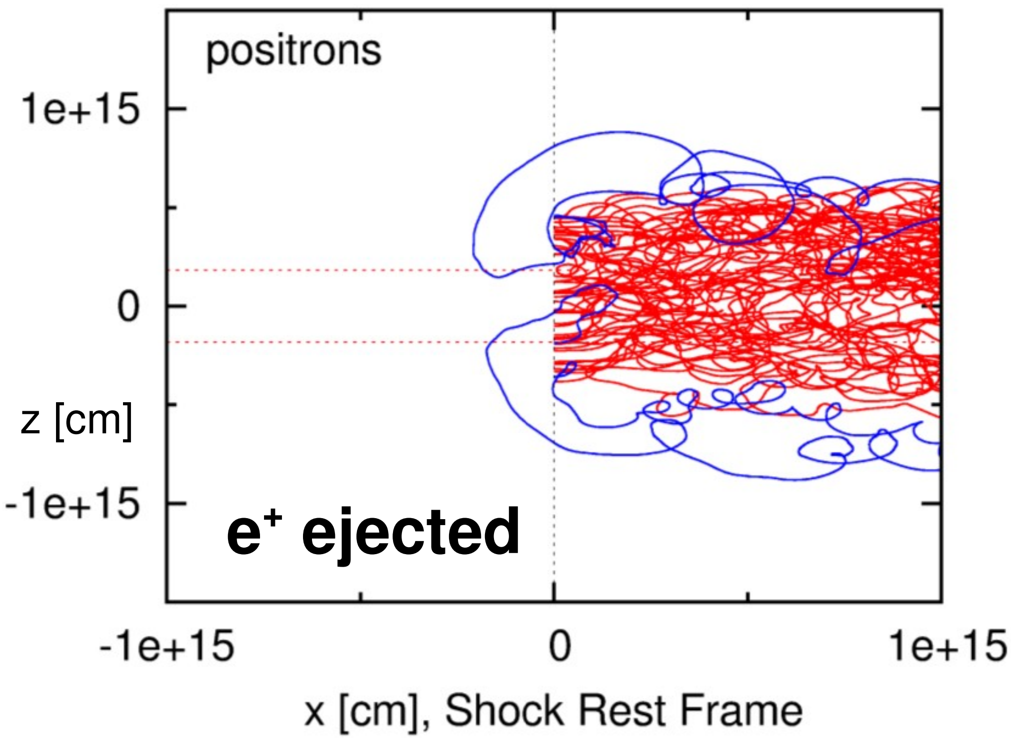
→ Shock crossing: Do the Lorentz transformation.

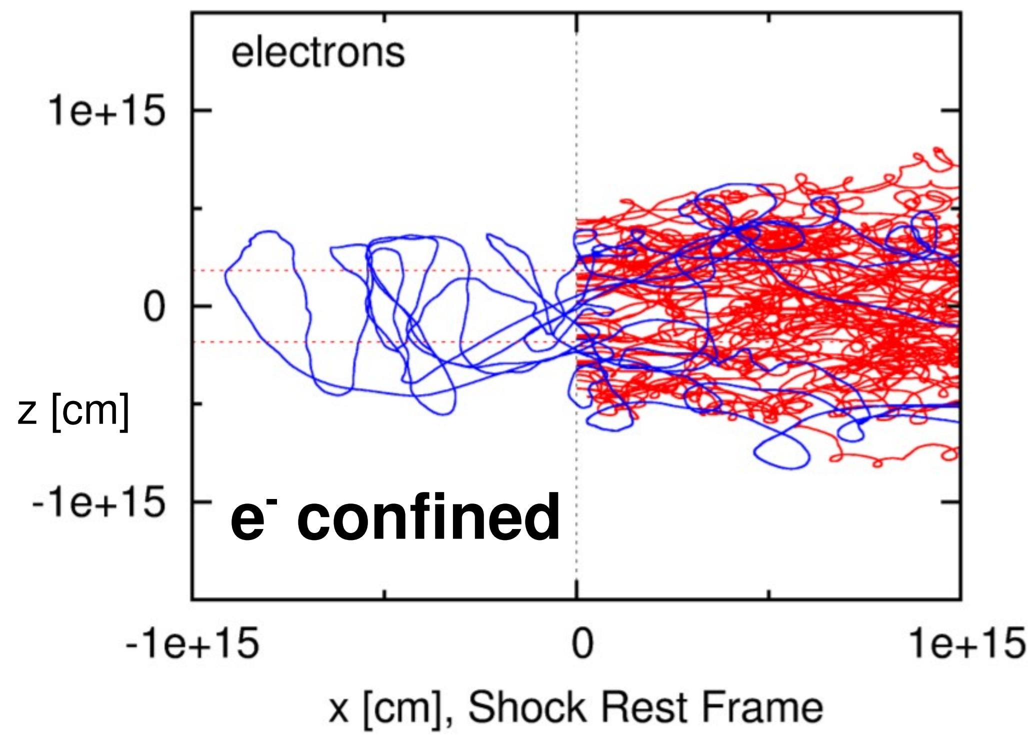


$$z_{crit} = r_L[E_{inj,d}; B_d(z_{crit})] \simeq 5.8 \times 10^{14}\ \mathrm{cm} \sqrt{\frac{z_{0,17} E_{\mathrm{inj,d,12}}}{B_{\mathrm{d,0,-3}}}}$$

Zone with acceleration ~ several z_{crit}

Numerical simulations



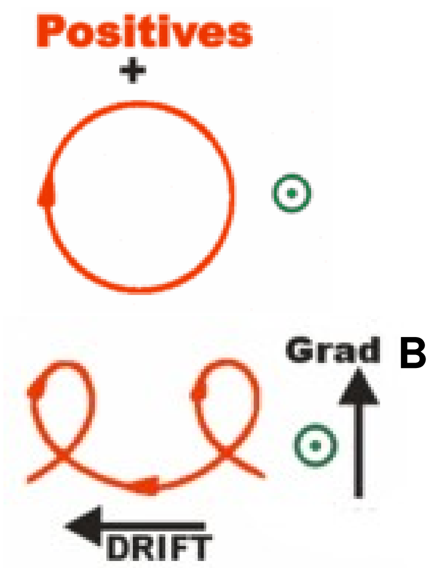


No/little acceleration

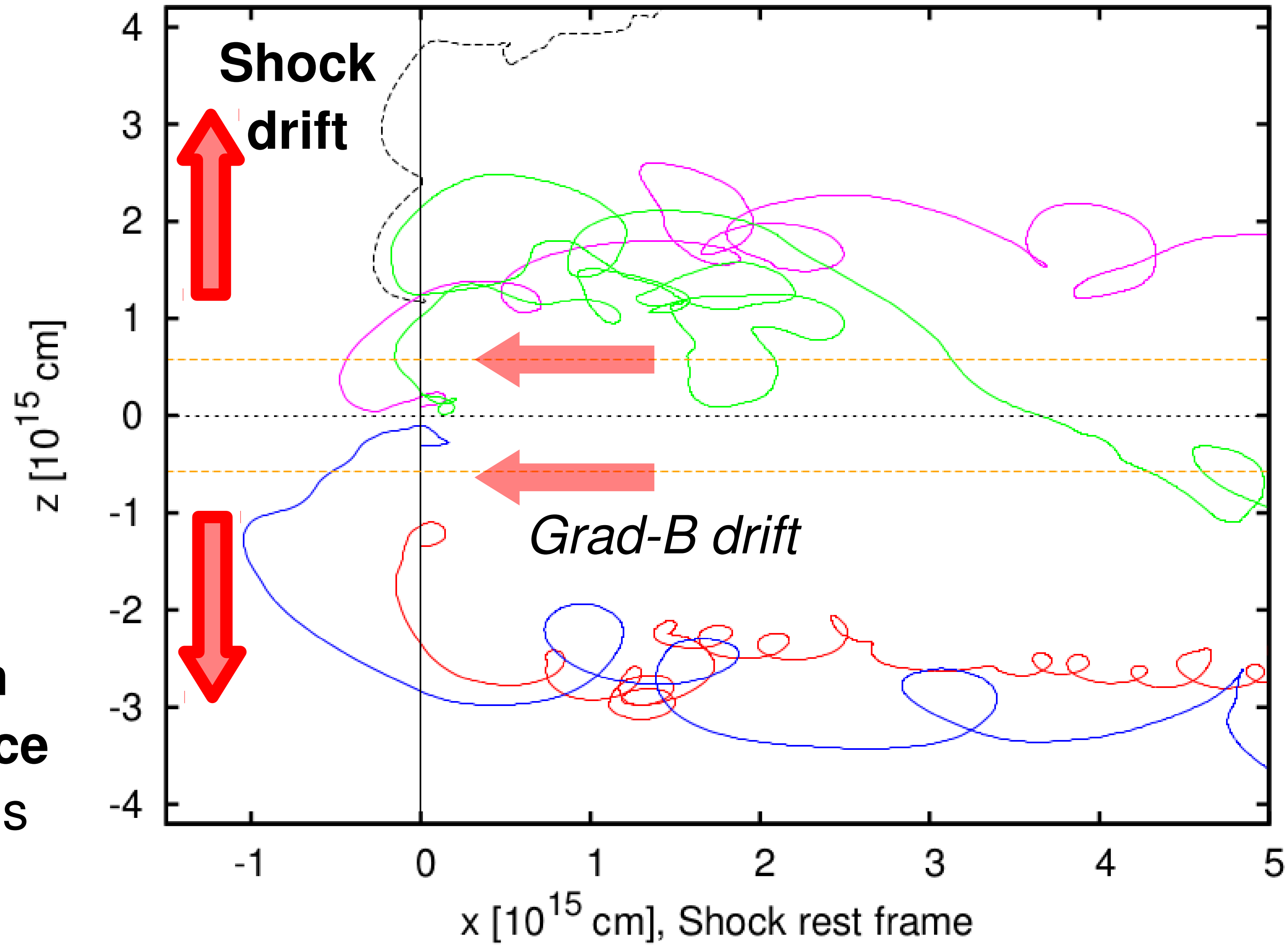
Acceleration

Positrons

(… or electrons - depends on the polarity)

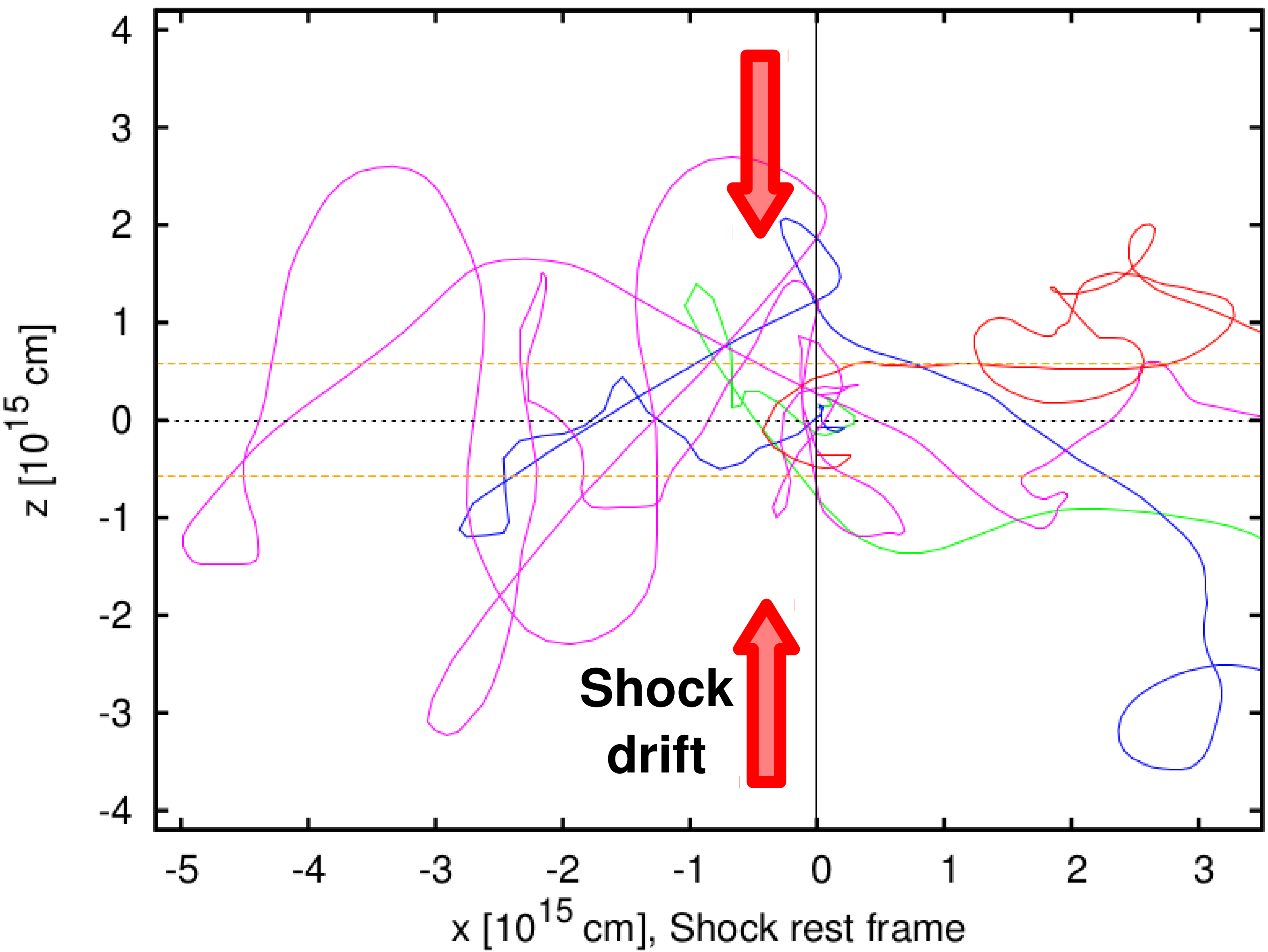


Grad-B drift



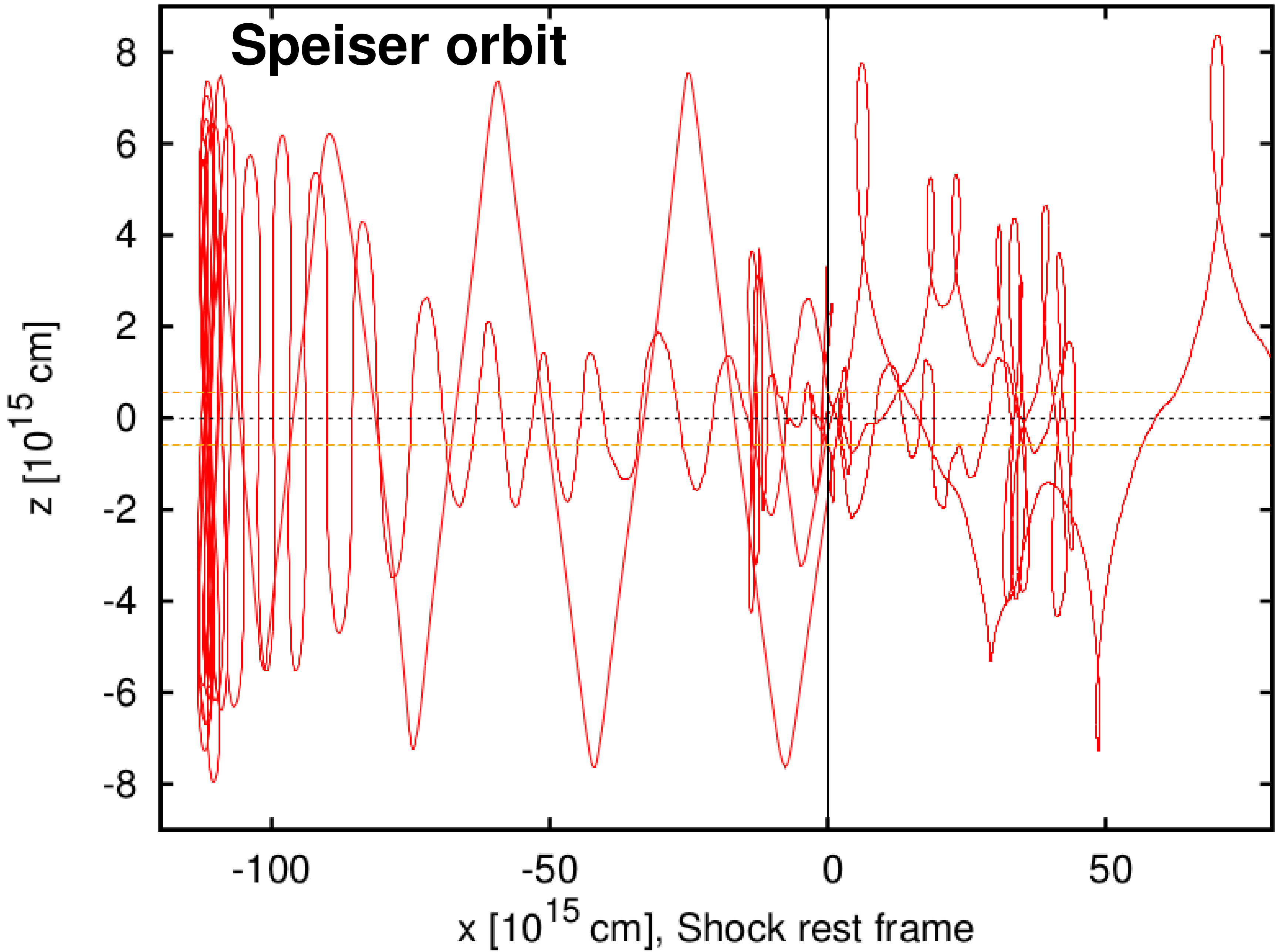
Drift motions on the shock surface eject the positrons

Electrons

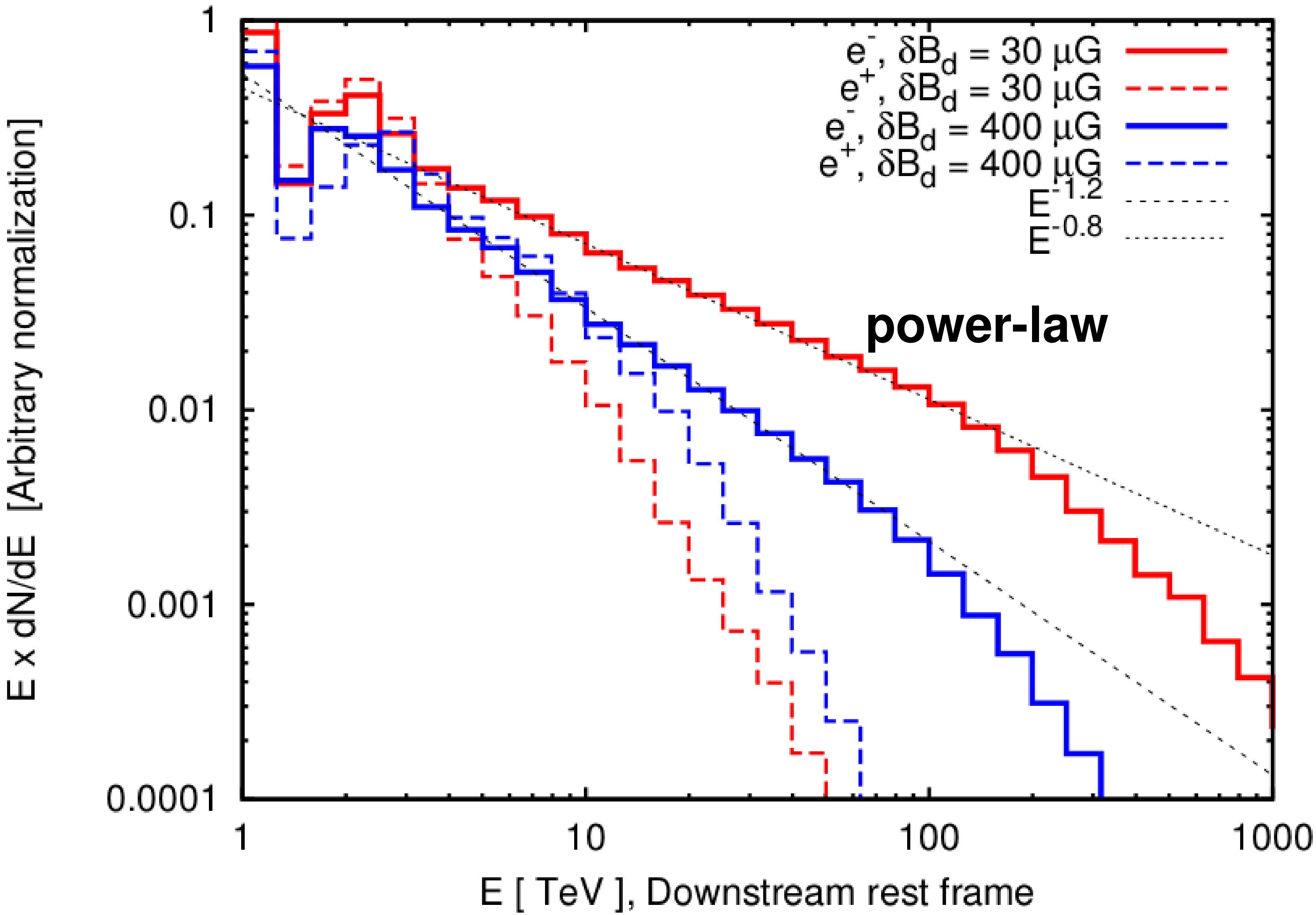


Shock
drift
z [10^15 cm]
x [10^15 cm], Shock rest frame
4
3
2
1
0
-1
-2
-3
-4
-5
-4
-3
-2
-1
0
1
2
3

Electrons


Speiser orbit
8
6
4
2
0
-2
-4
-6
-8
z [10^{15} cm]
-100
-50
0
50
x [10^{15} cm], Shock rest frame

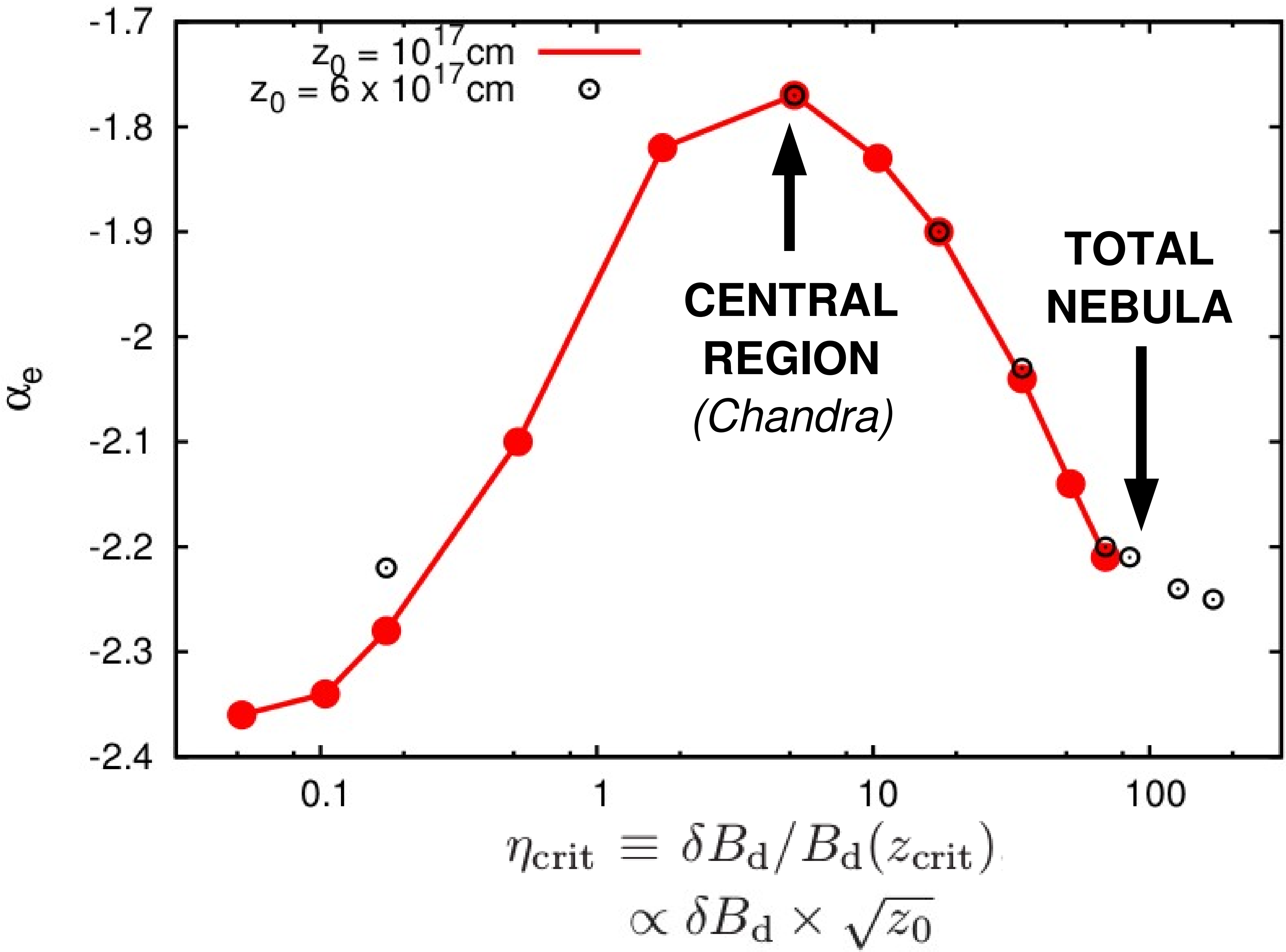
Electron and positron spectra



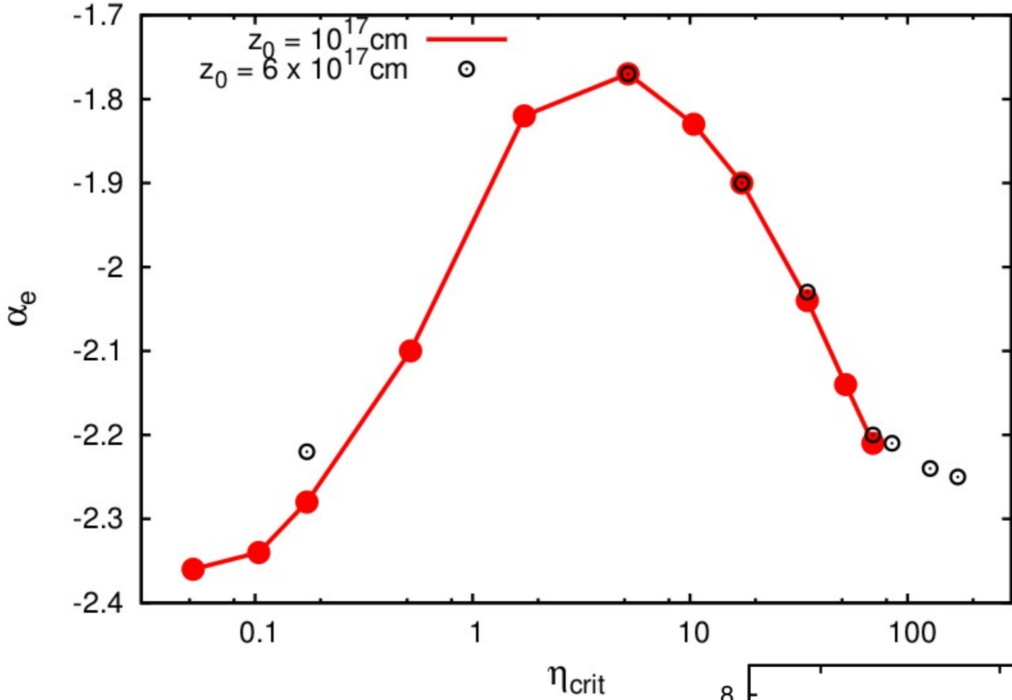
$t_{synch} \sim t_{gyr}$ =>

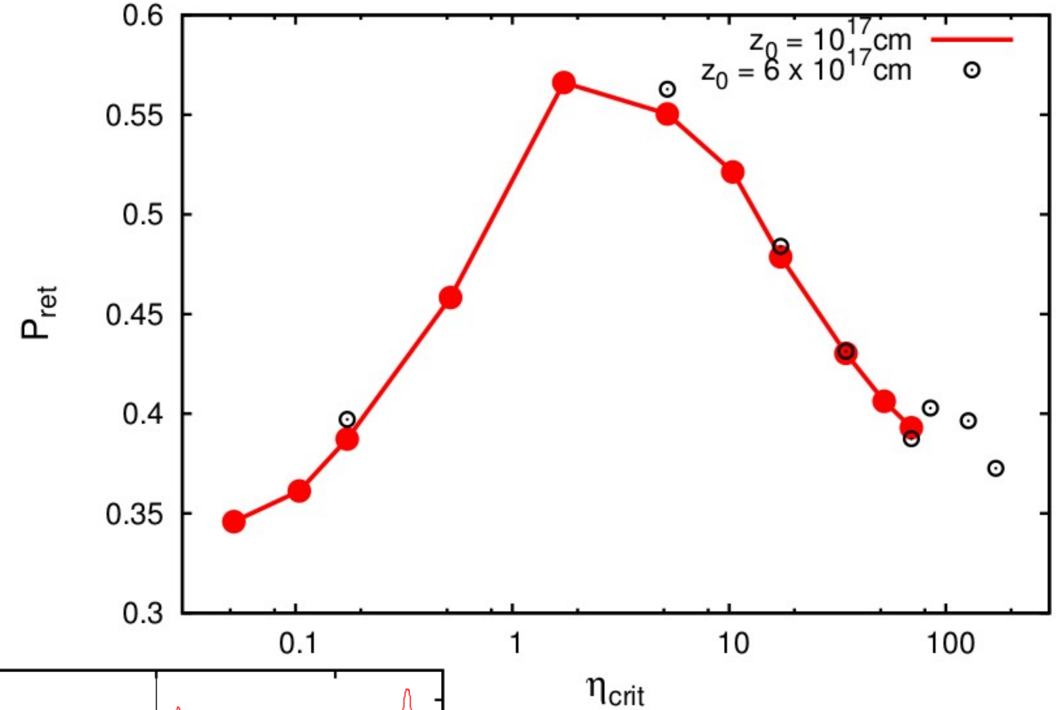
$$E_{\max} = \sqrt{\frac{3 m_e^2 c^5 \mu_0 e}{2\pi \sigma_T B}} \simeq 1.1\,\mathrm{PeV}\ B_{d,0,-3}^{-1/2}$$

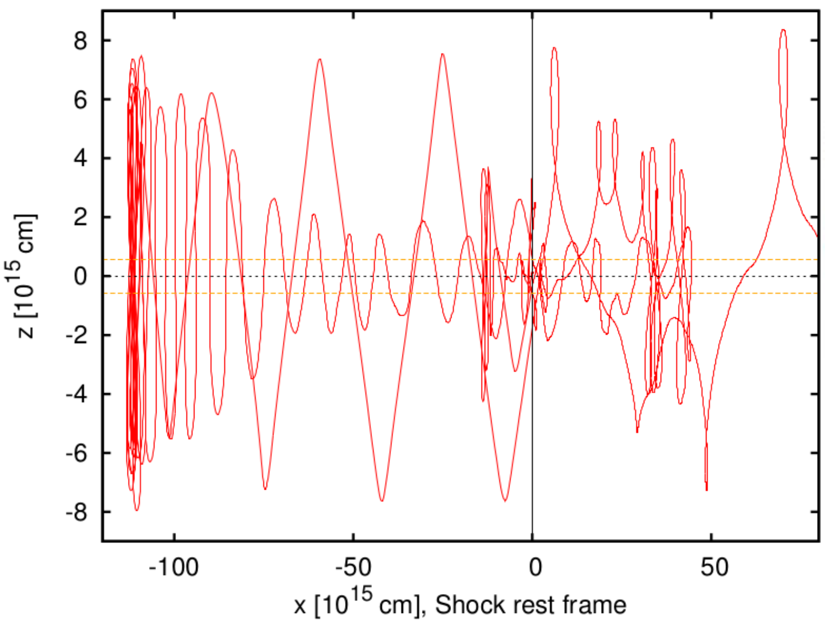
Spectral index of the electrons

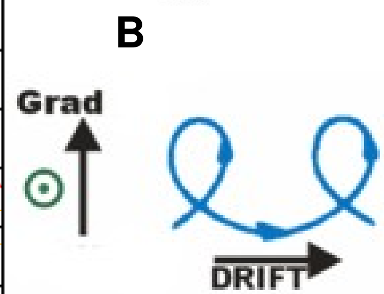


Spectral index vs Probability to return into the upstream

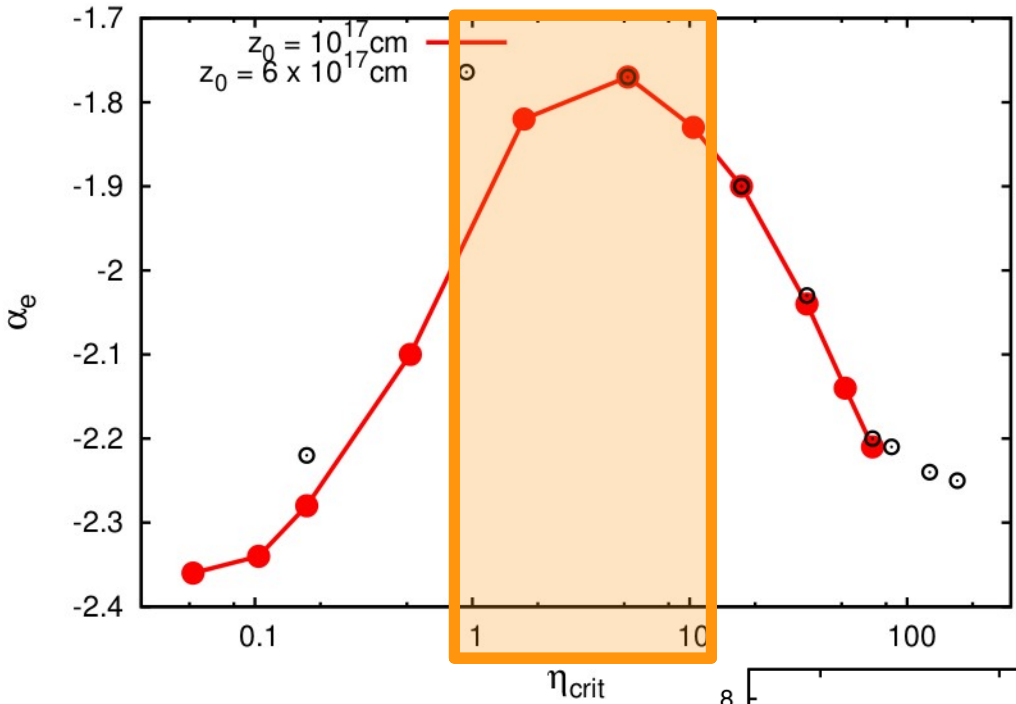


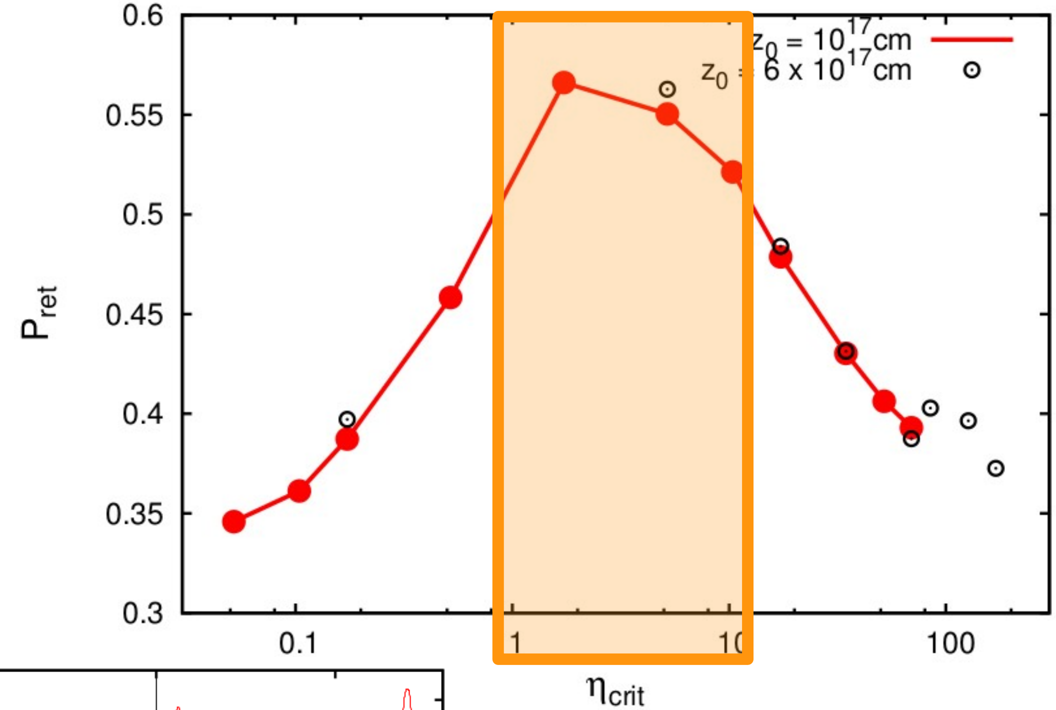


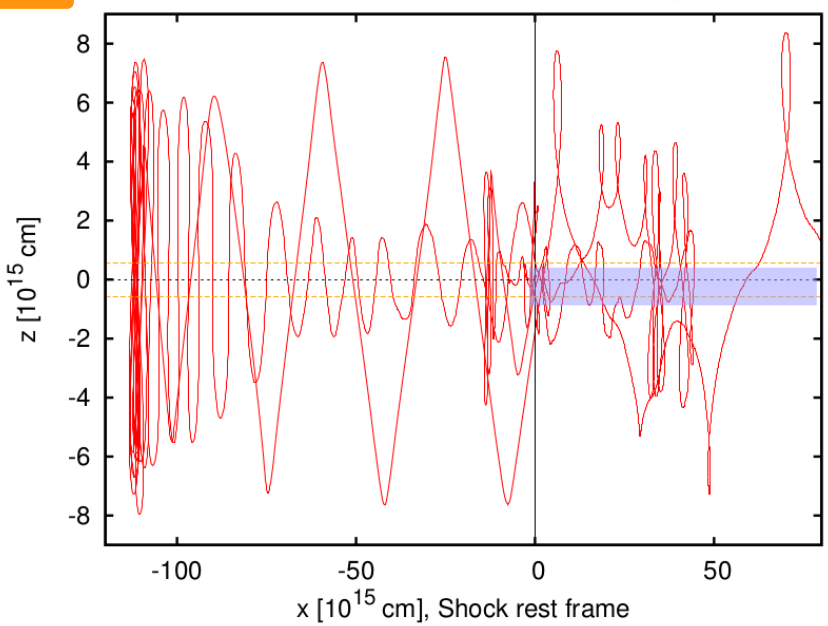


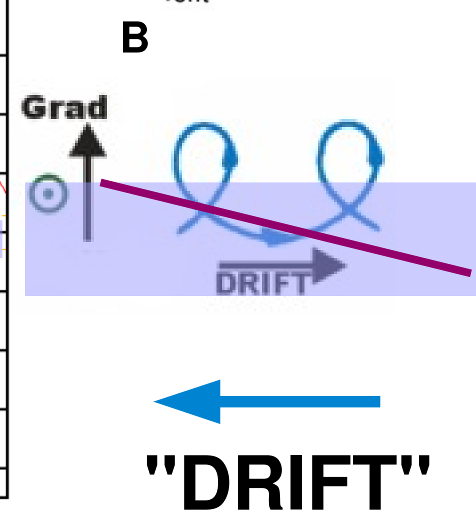


Spectral index vs Probability to return into the upstream

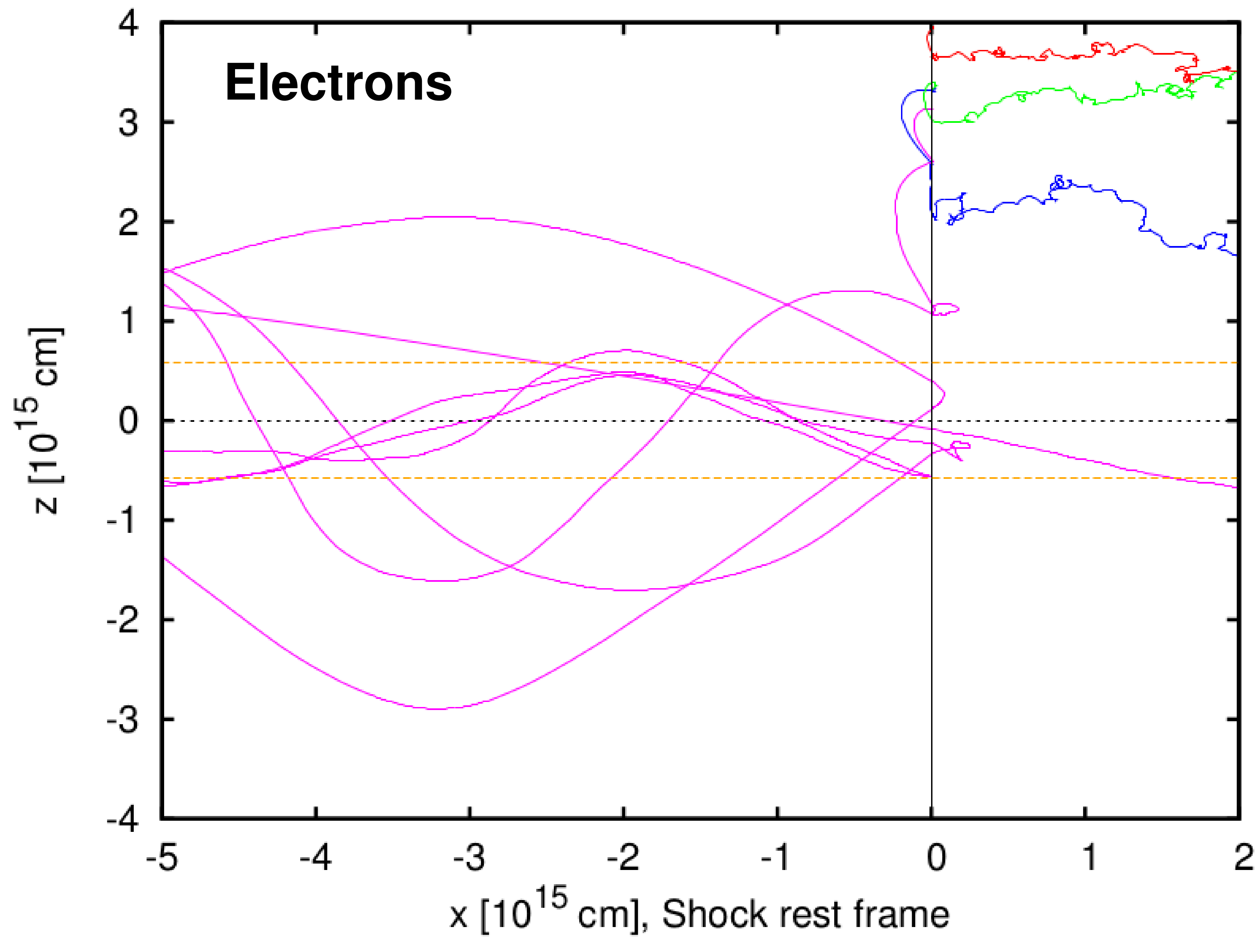






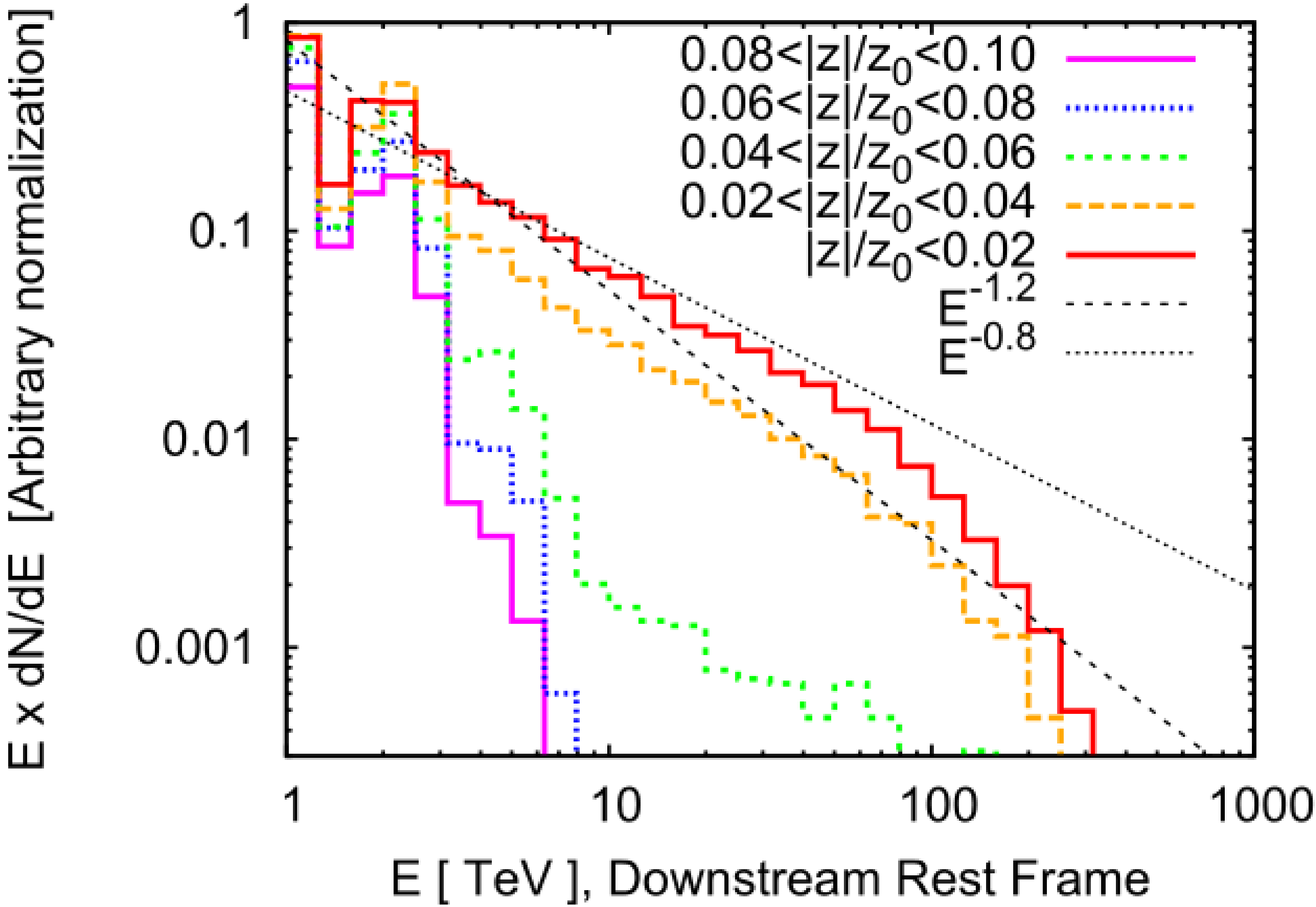


Injection further from the eq. plane



Injection further from the eq. plane

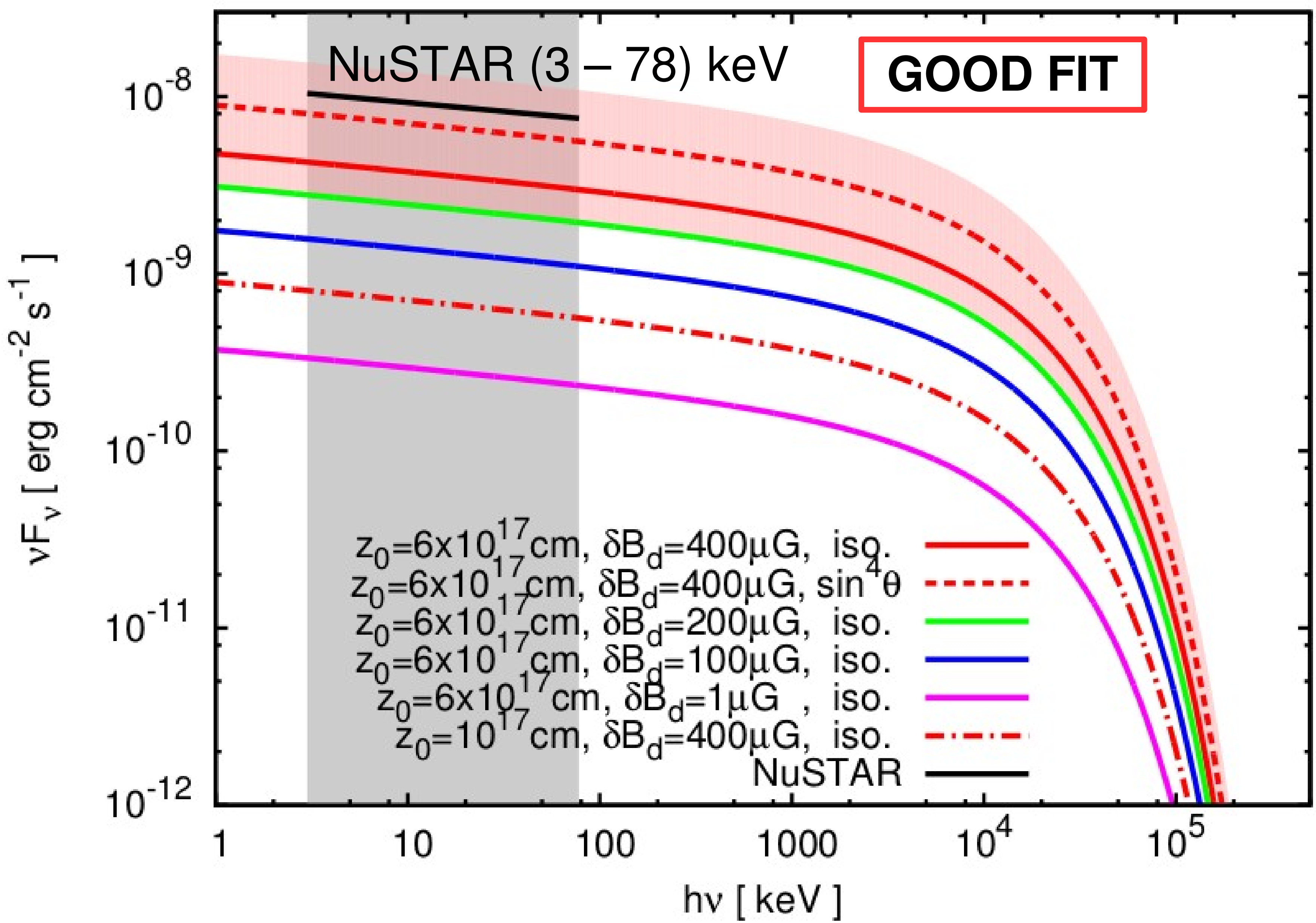
$z_0 = 10^{17}\,\mathrm{cm}$ $\Theta \simeq 13^\circ$ $\delta B_\mathrm{d} = 100\,\mu\mathrm{G}$



Synchrotron emission (X-rays)

$E_{\max} = 1\,\mathrm{PeV}$ $\alpha_e \simeq -2.2$ $B = 0.5\,\mathrm{mG}$

$D_{\mathrm{Crab}} = 2.0\,\mathrm{kpc}$ $(\pm 0.5\,\mathrm{kpc})$ $L_{\mathrm{s.d.}} = 5 \times 10^{38}\,\mathrm{erg\,s^{-1}}$



Conclusions

→ **X-ray emitting particles in the Crab Nebula can be accelerated at the termination shock by 1st order Fermi**,

→ **Either e^{-} or e^{+}** acc. to HE, depending on the pulsar **polarity,**

→ **Shock-drift** helps; Particles remain on **Speiser (drift) orbits close to the eq. plane**,

→ Spectral **index** ~ **-2.4 … -1.8**,

→ Can **fit** the **HE synchrotron spectrum** of the Crab Nebula
---> Explains observations from **XMM-Newton** and **NuSTAR**,

→ Explains the **hard spectrum** mesured by **Chandra** (photon index ~ -1.9) in the central regions of the Nebula.