PARTICLE ACCELERATION AT PULSAR-WIND TERMINATION SHOCKS

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In Prep. (To be submitted soon)

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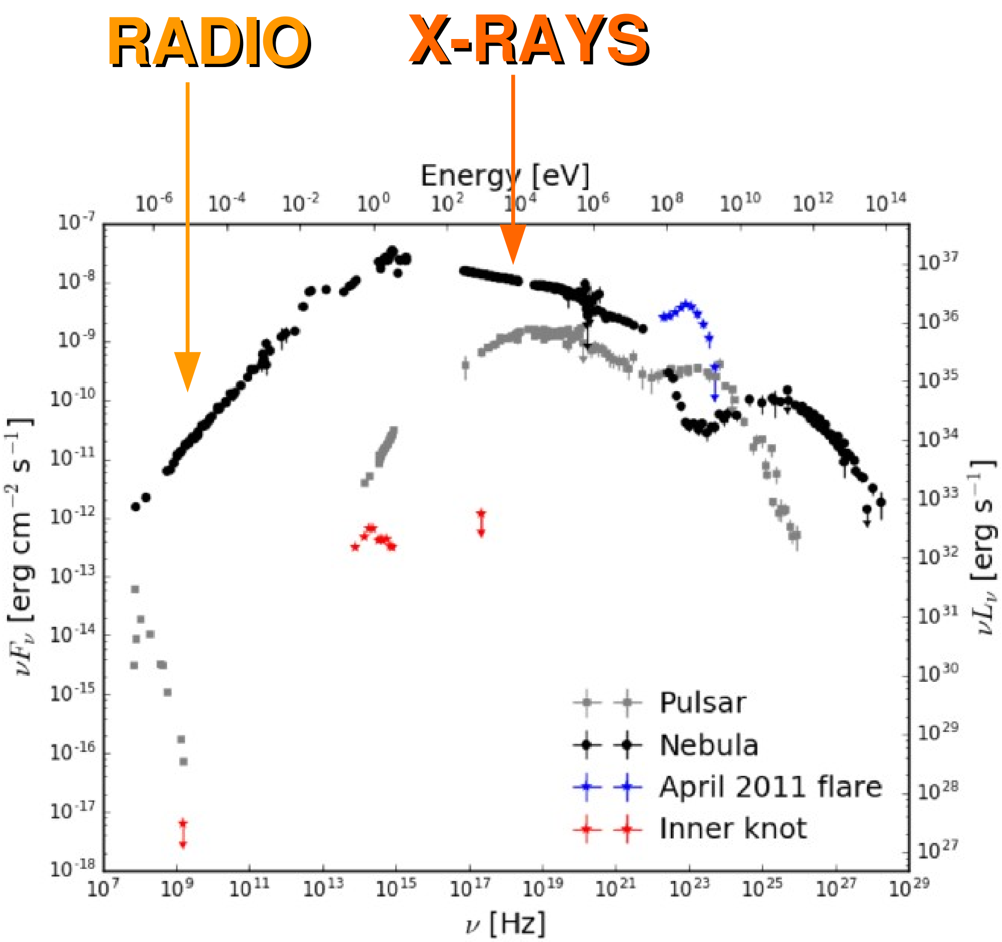
Observations of the Crab nebula



Buehler & Blandford (2014)

→ **X-ray spectral index :**

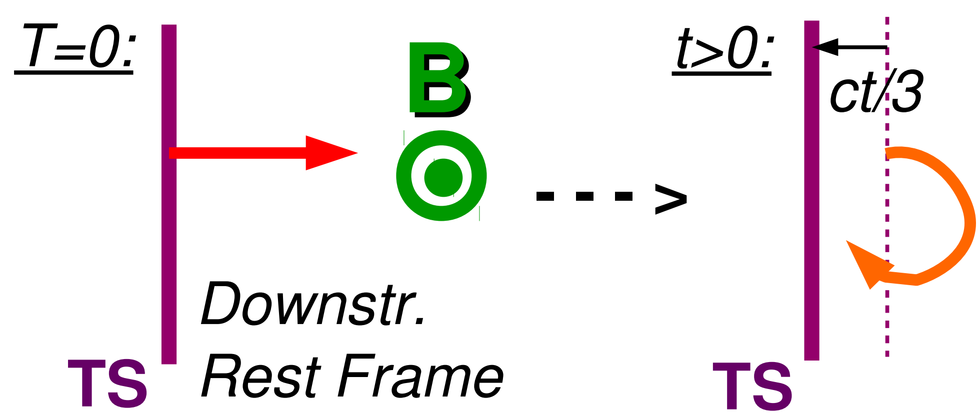
$d(\ln N_\gamma) / d(\ln \nu) = - 2.1$

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

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

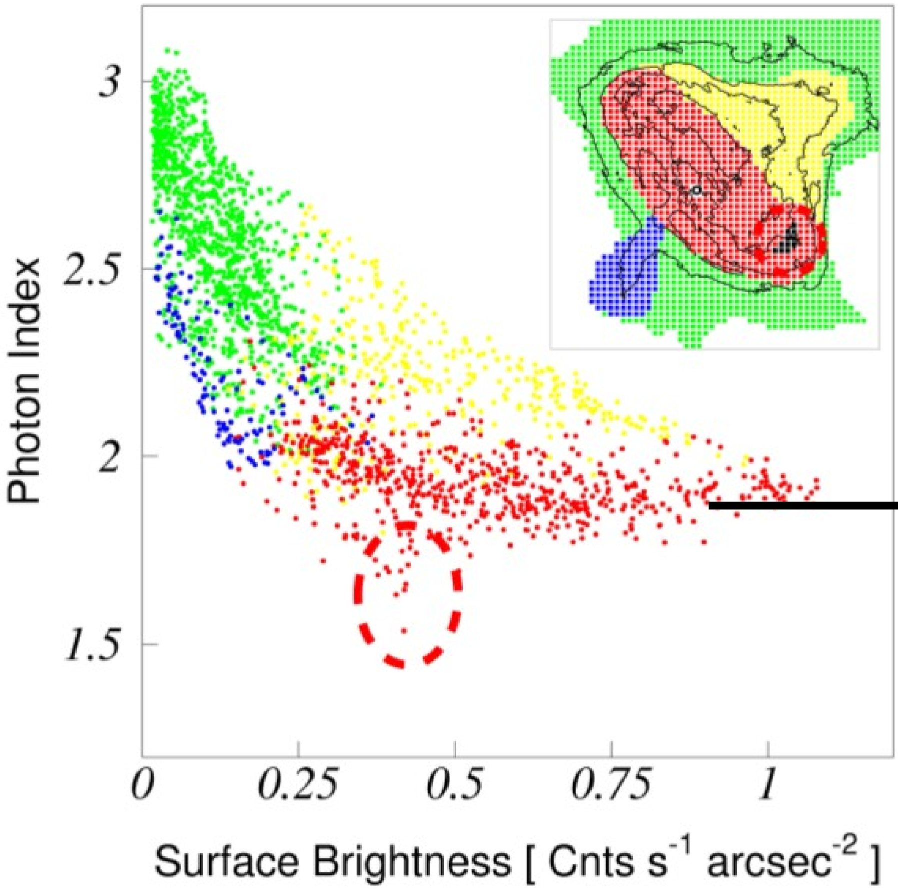
Seems to be in perfect agreement

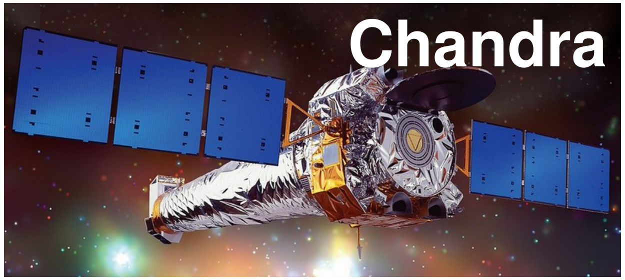
BUT… Perpendicular shock,
so **1st order Fermi inoperative !**



Observations of the Crab nebula

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





Hard spectrum close to the shock, in the equatorial plane

Photon index s ~ 1.9

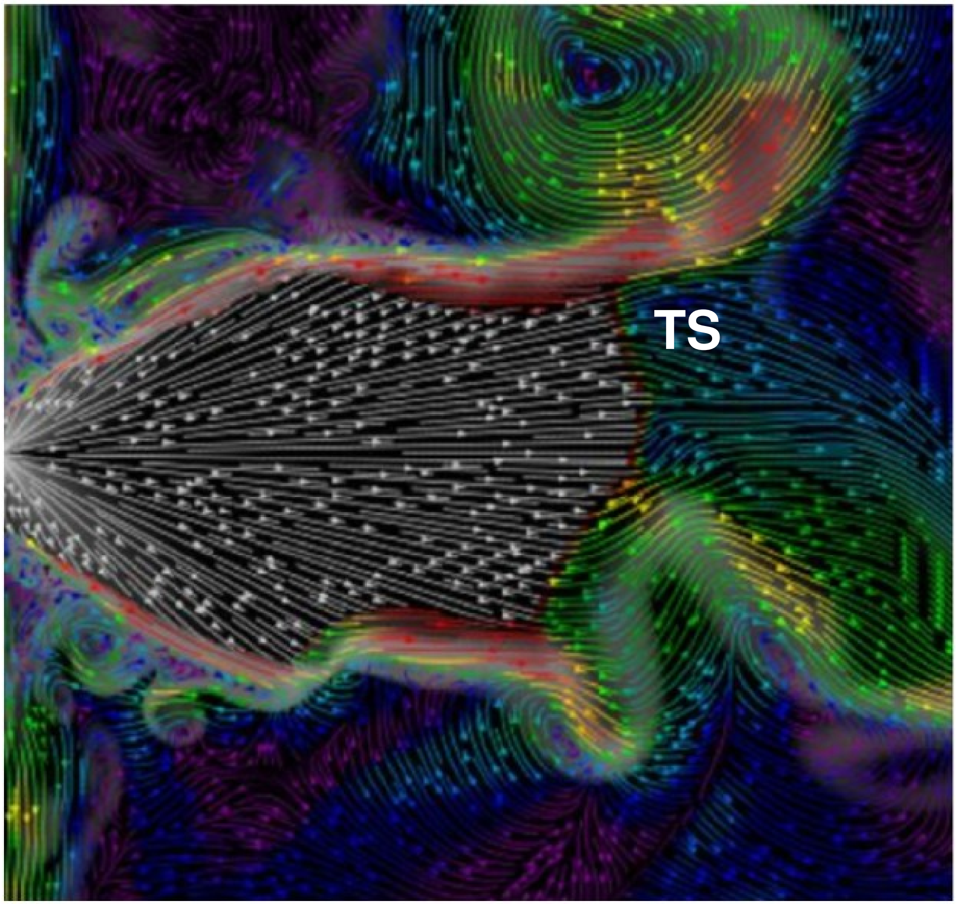
=> $d(\ln N_{e-}) / d(\ln \gamma) \sim -1.8$!

(2) How many X-ray emitting electrons ?

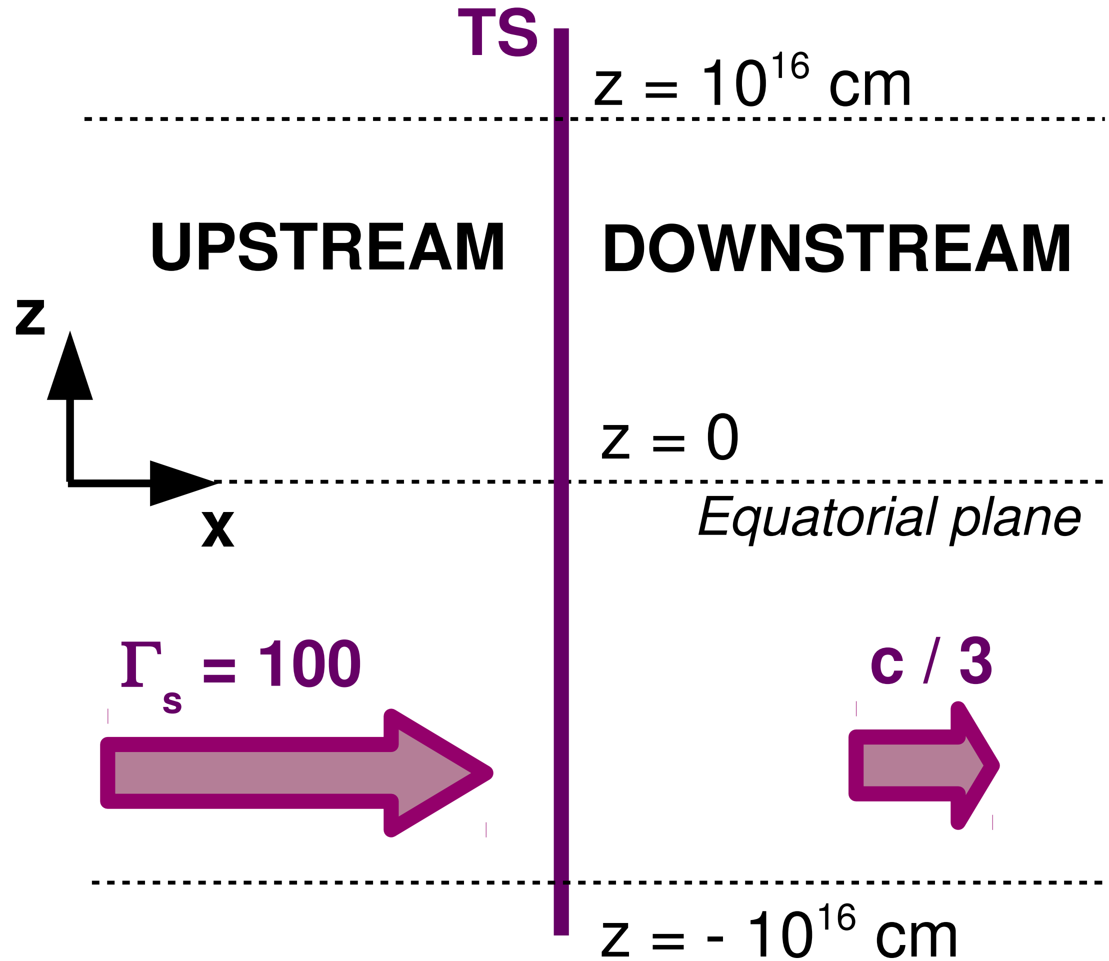
$N(e^-$ radio$)/N(e^-$ X-rays$) \sim 10^4$ - e.g. Olmi *et al.*, J. Plasma Phys. (2016).

Numerical simulations – Model

Simulations of Buehler & Giomi (2016) :

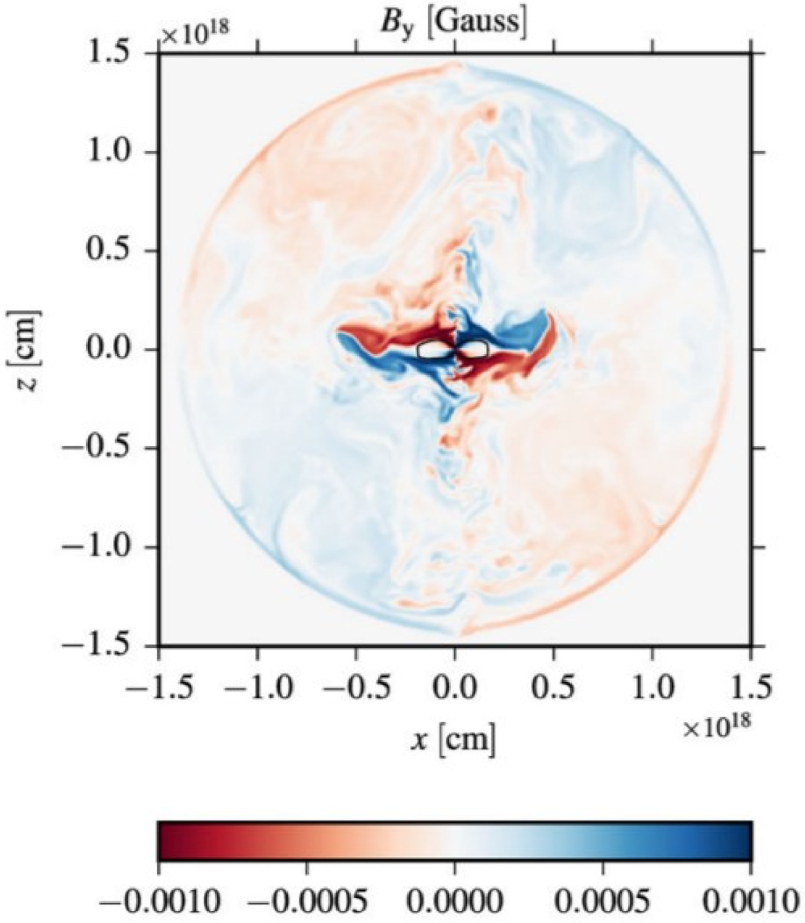


OUR MODEL (PLANAR 1D) :



Numerical simulations – Model

Simulations of Porth *et al.* (2014, 2016) – Crab nebula:



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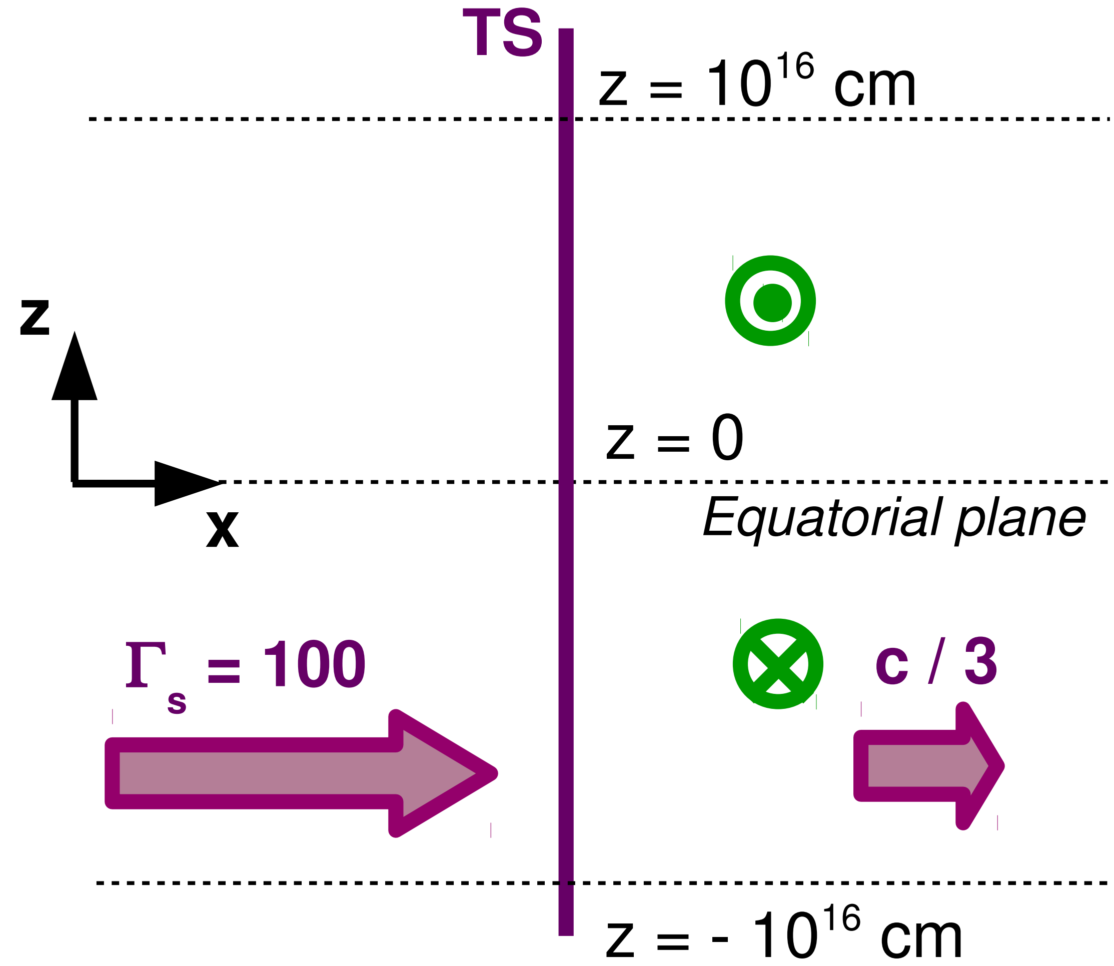
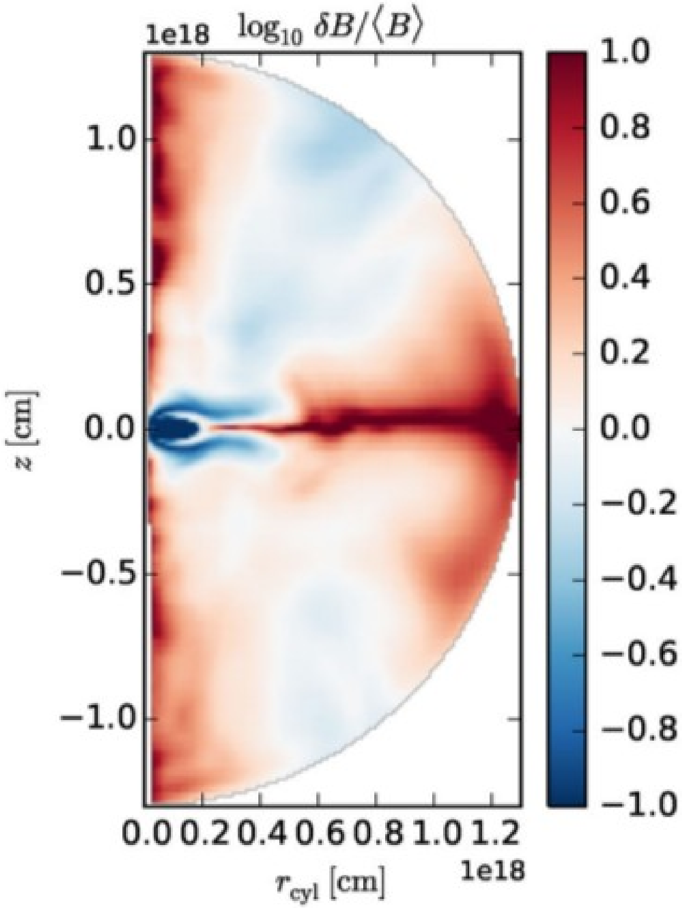


→ $\mathbf{B} \propto z\, \mathbf{u}_y$ for $|z| < 10^{16}$ cm,

→ At $z = \pm 10^{16}$ cm, $B = \pm 1$mG

Numerical simulations – Model

Simulations of Porth *et al.* (2014, 2016) – Crab nebula:



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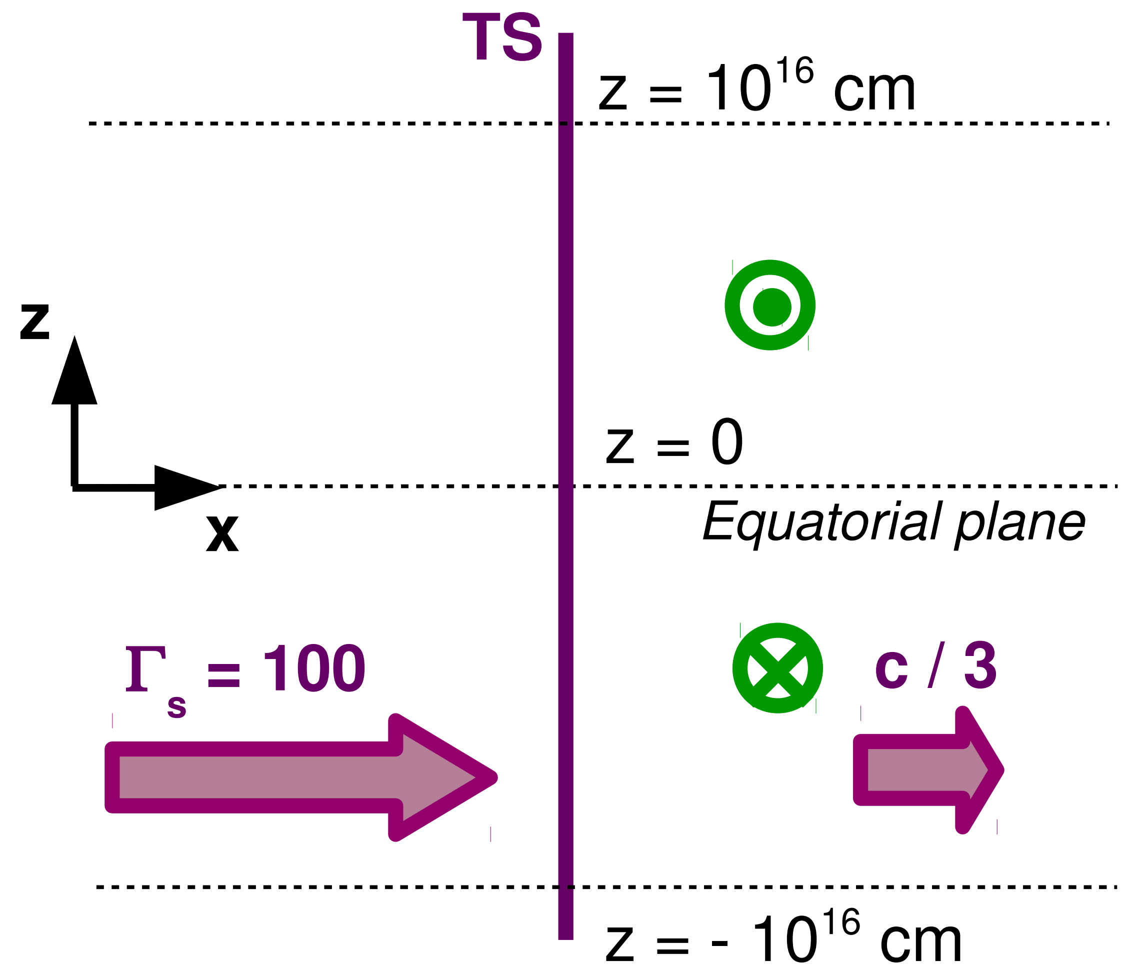
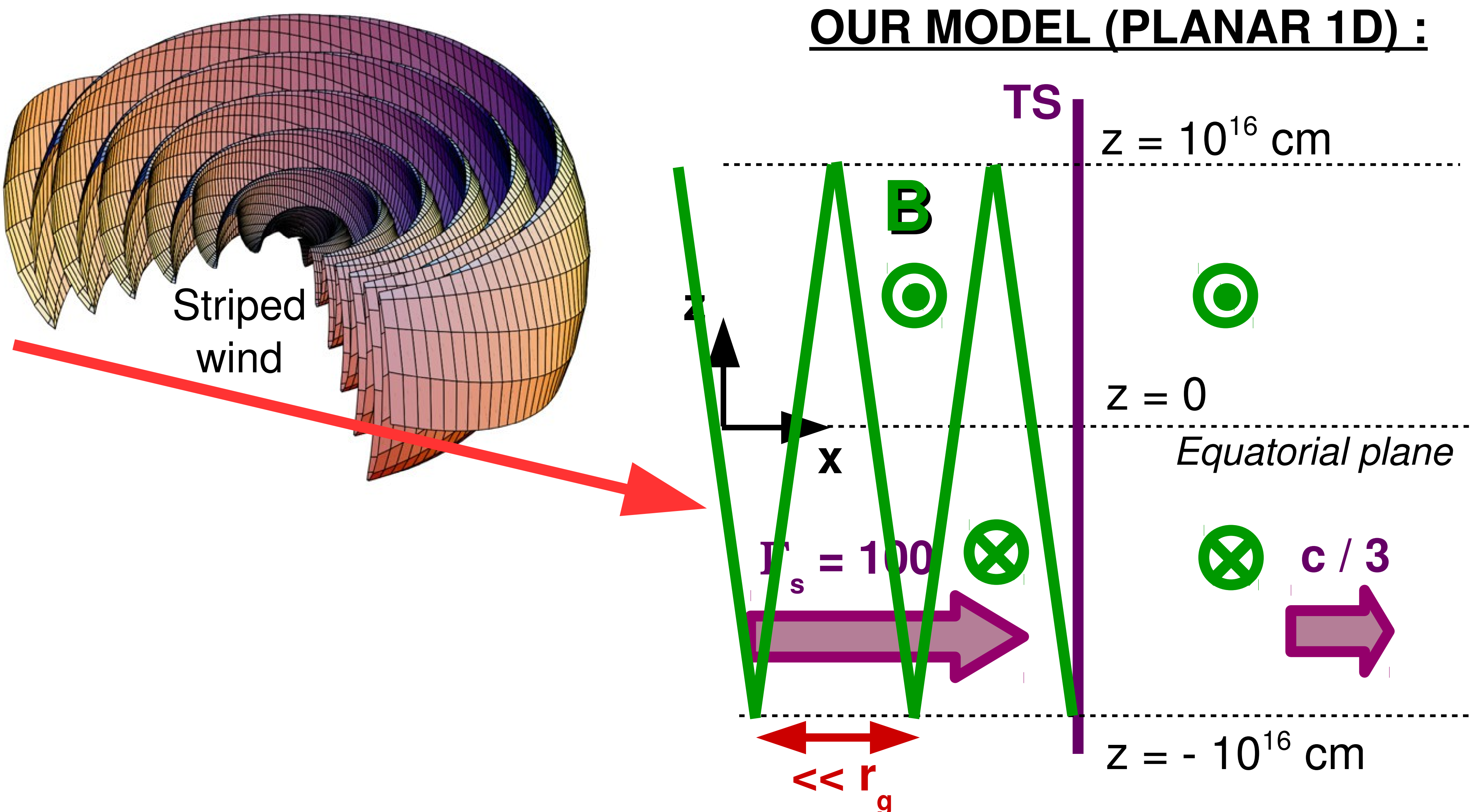


→ $\mathbf{B} \propto z\, \mathbf{u}_y$ for $|z| < 10^{16}$ cm,

→ At $z = \pm 10^{16}$ cm, $B = \pm 1$mG, $\delta B/B = 0.1$, cst. of *z*, Bohm.

Numerical simulations – Model

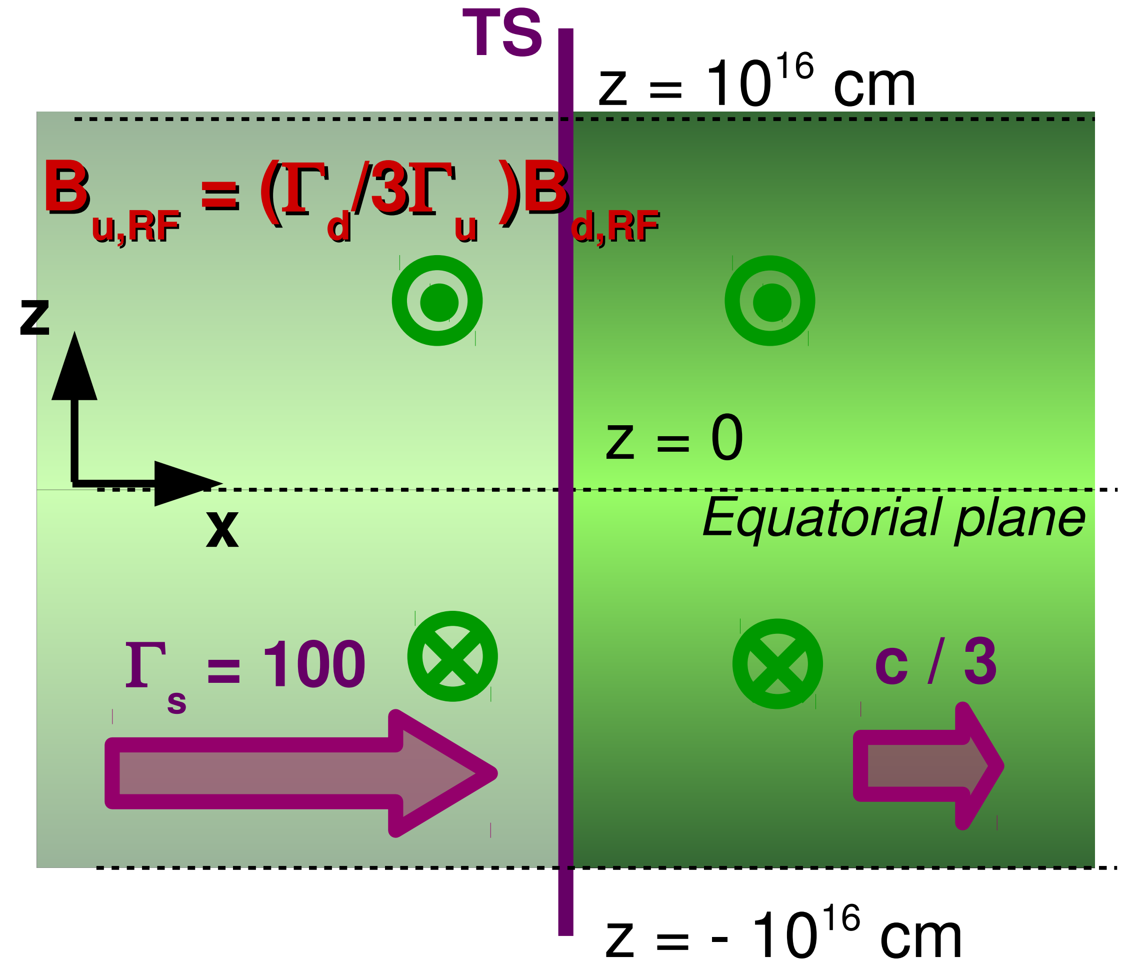


→ **B** ∝ z **u**$_y$ for |z| < 10^{16} cm,

→ At z = ±10^{16} cm, B = ±1mG, δB/B = 0.1, cst. of *z*, Bohm.

Numerical simulations – Model

OUR MODEL (PLANAR 1D) :



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Numerical simulations – Model

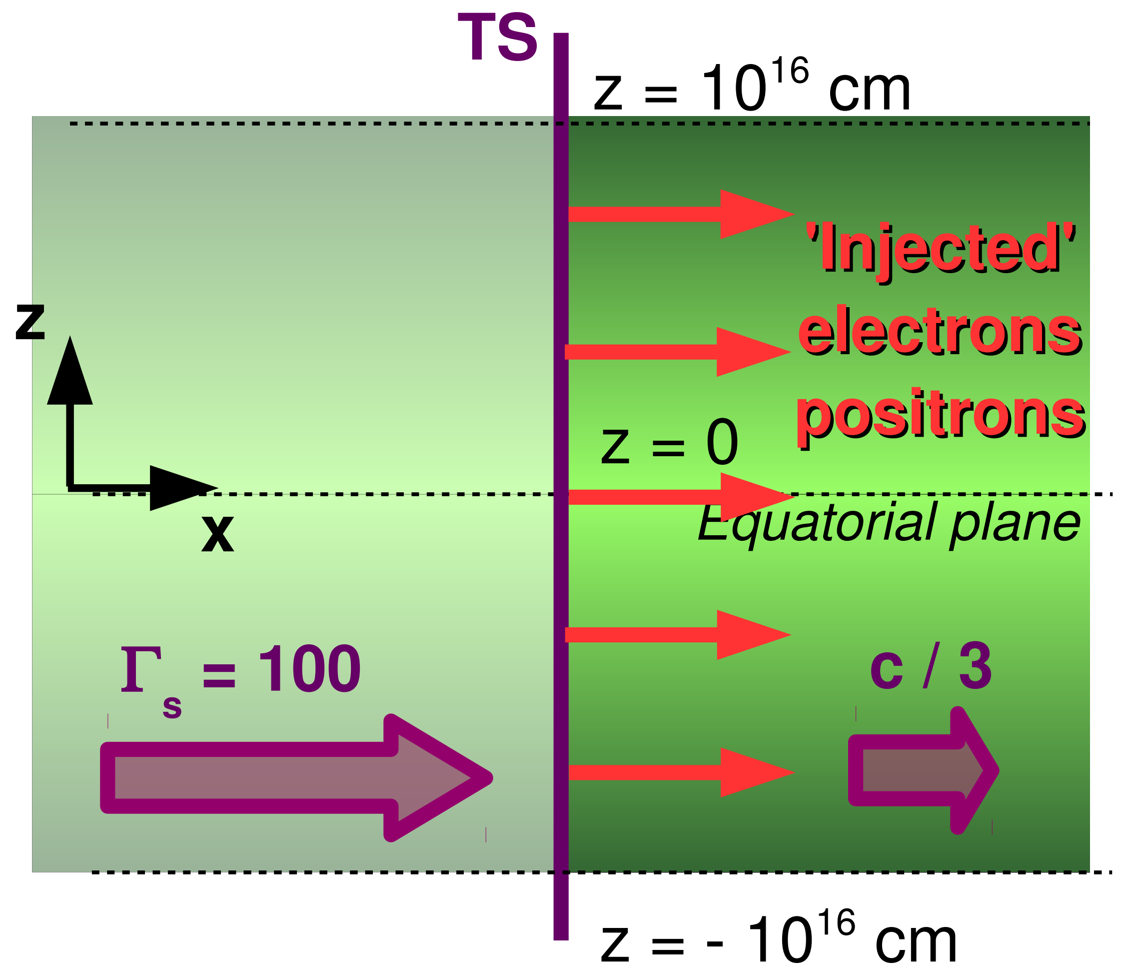
→ **Integrate trajectories of individual particles in 3D (test particle limit),**

→ **Use 3D realizations of turbulent B fields,**

→ **Integrate in Downstream or Upstream rest frame (E=0) ; If shock crossing: Do the Lorentz transfo. $(X_d,t_d) \leftrightarrow (X_u,t_u)$,**

→ **Obs. Fr. ~ Shock Fr. $\leftrightarrow (X_s,t_s)$.**

OUR MODEL (PLANAR 1D) :



Numerical simulations – Model

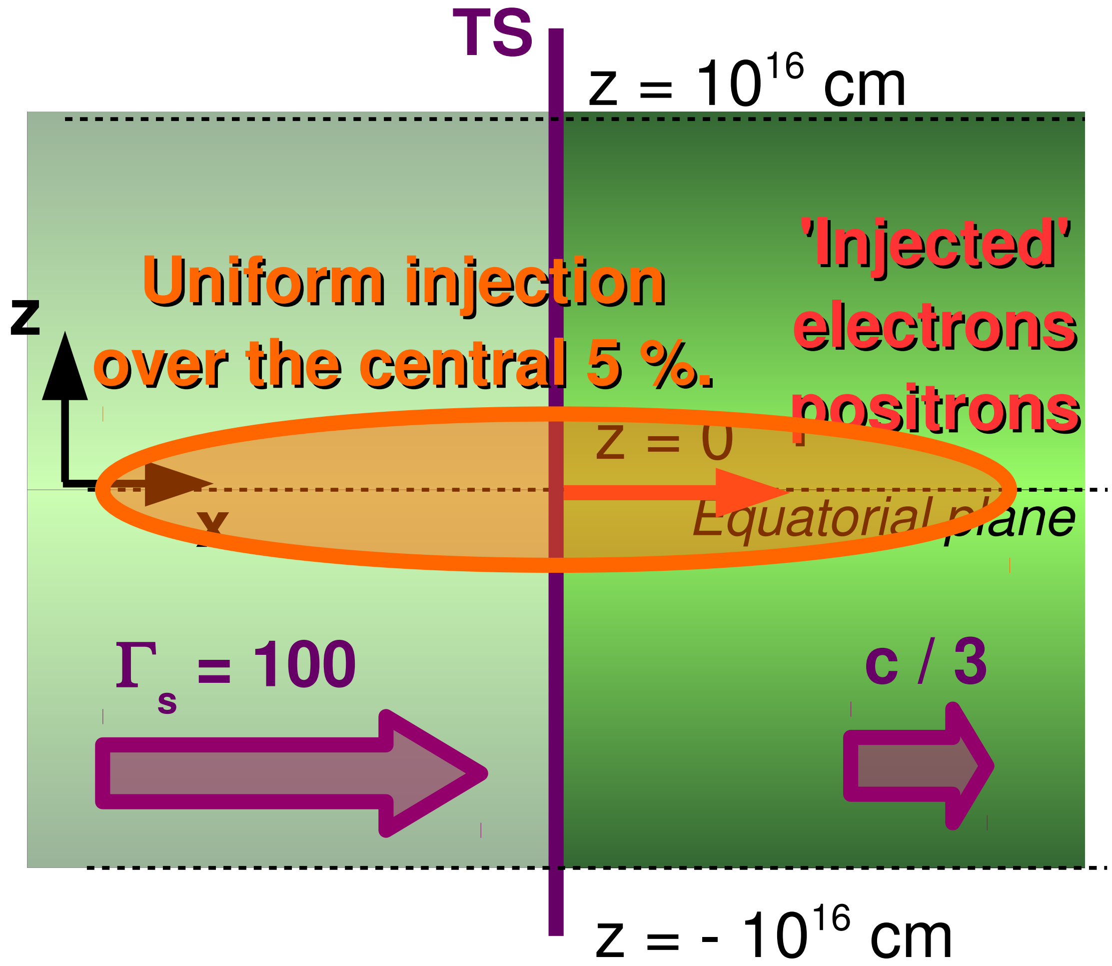
Wave period 33 ms, low density wind ⇒ MHD invalid.

Amano & Kirk (2013):
Two fluid simulations of a shock front in a Poynting-flux-dominated relativistic flow.

Giacchè & Kirk (2017):
Propagate individual $e^{\pm}$.

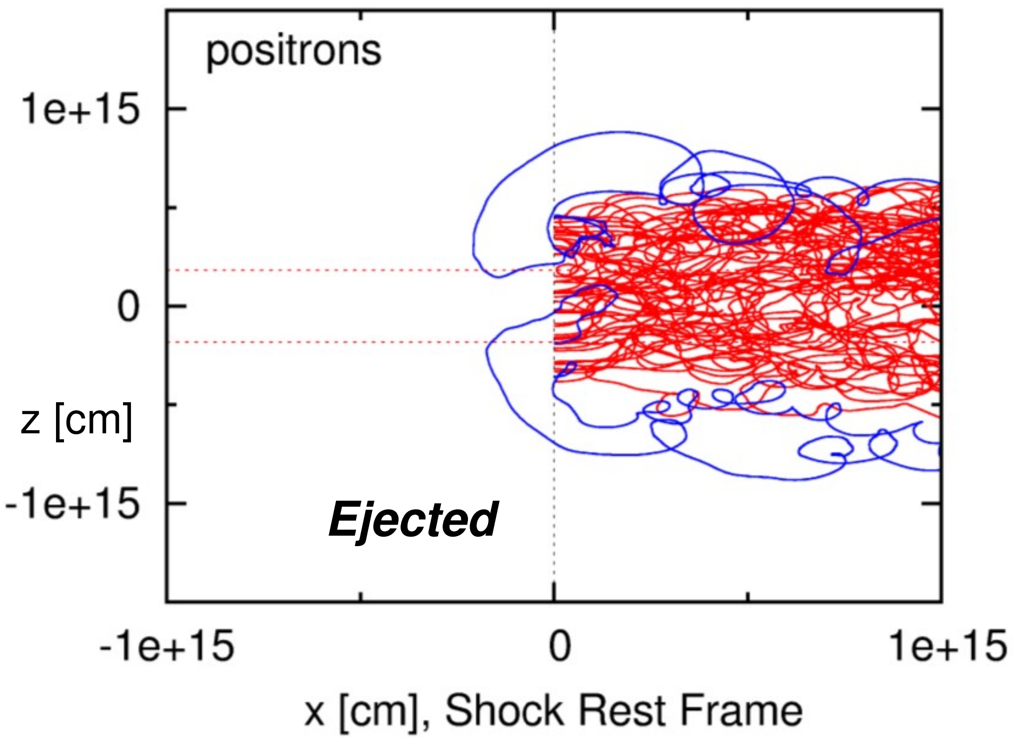
$\gamma_{inj} \sim 10^{4-6}$ **=> TeV electrons.**

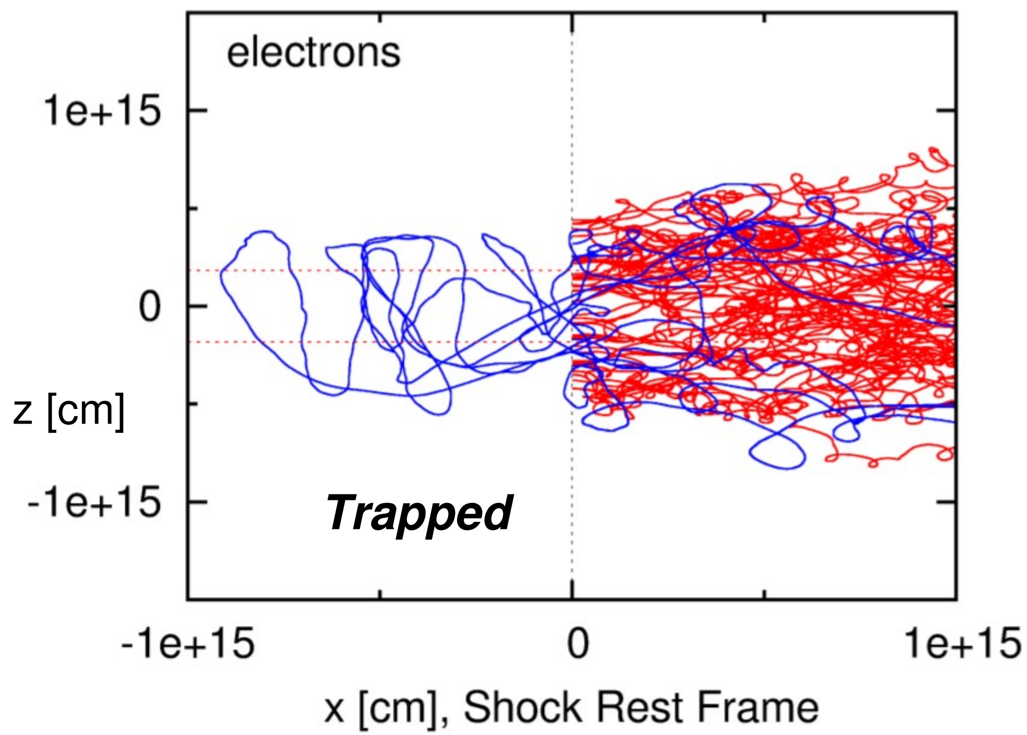
OUR MODEL (PLANAR 1D) :



Numerical simulations

In the equatorial current sheet :





d(ln N) / d(ln γ) ≈ - 6 … -5 < - 2.2

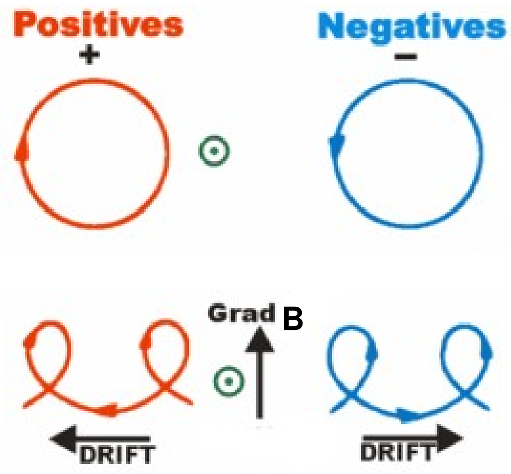
VERY SOFT

d(ln N) / d(ln γ) ≈ -1.8 > -2.2 !

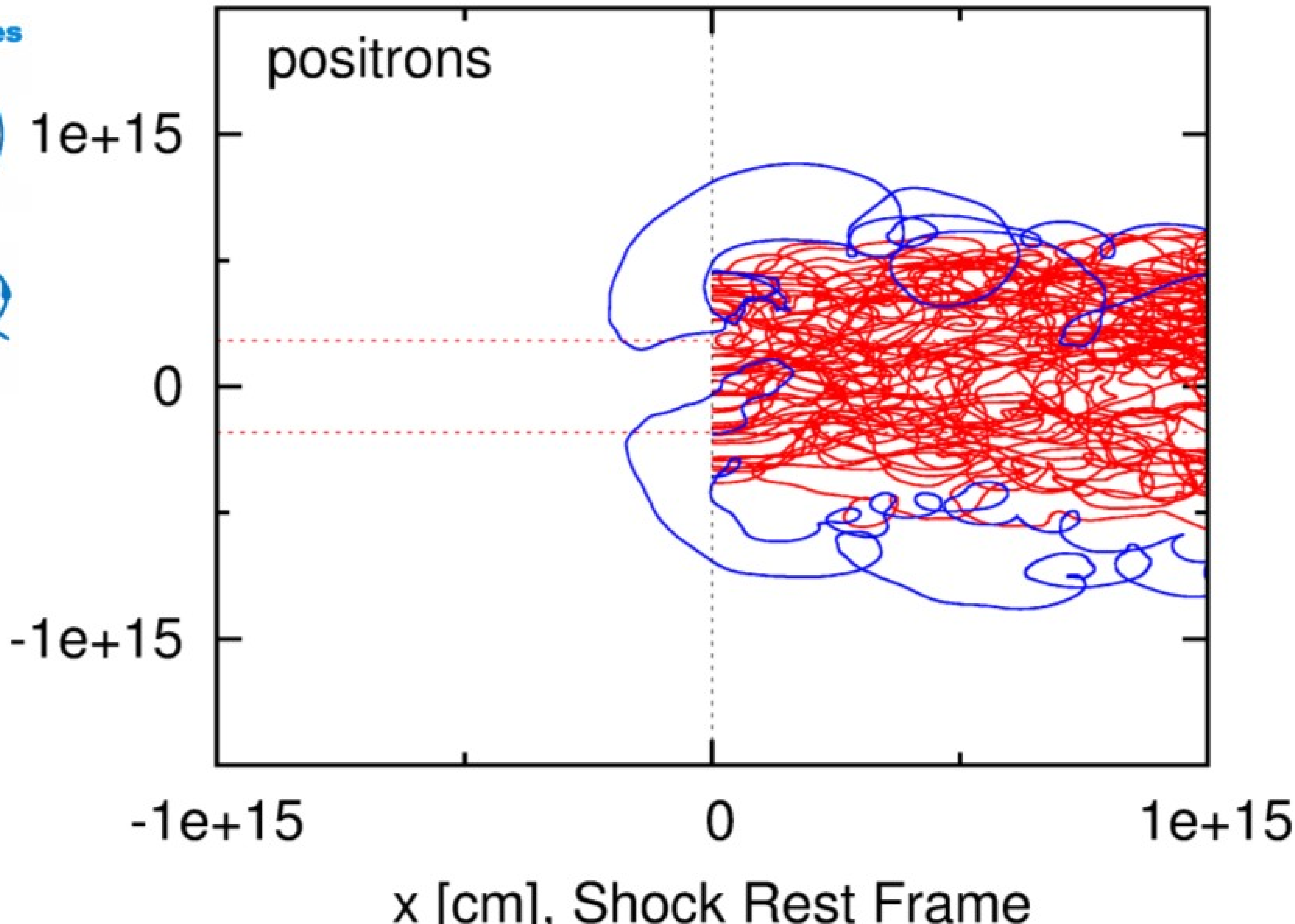
HARD

Positrons

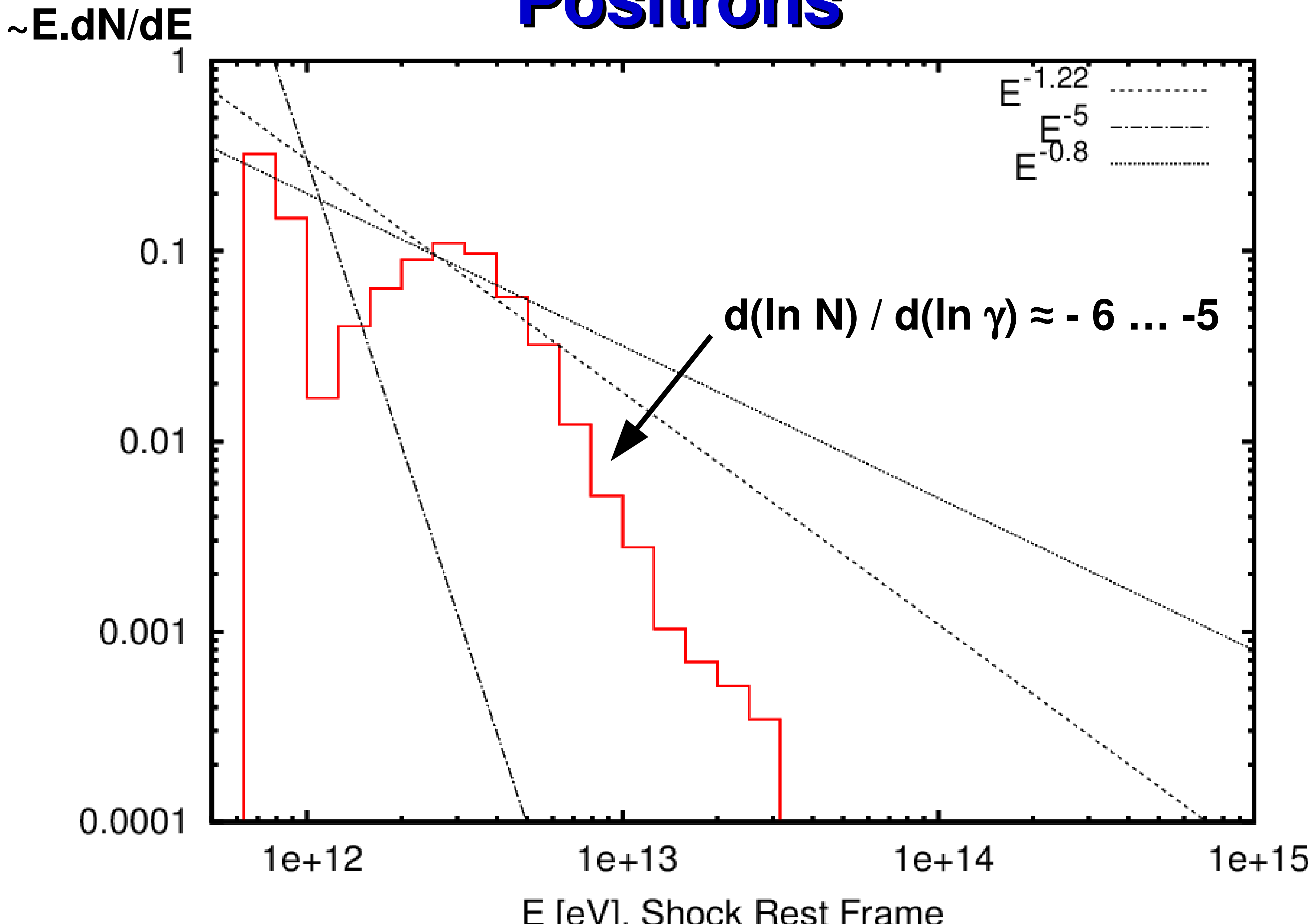
(… or electrons - depends on polarity)



Grad-B drift can beat the advection at c/3 in small regions close to z=0 (on both sides).

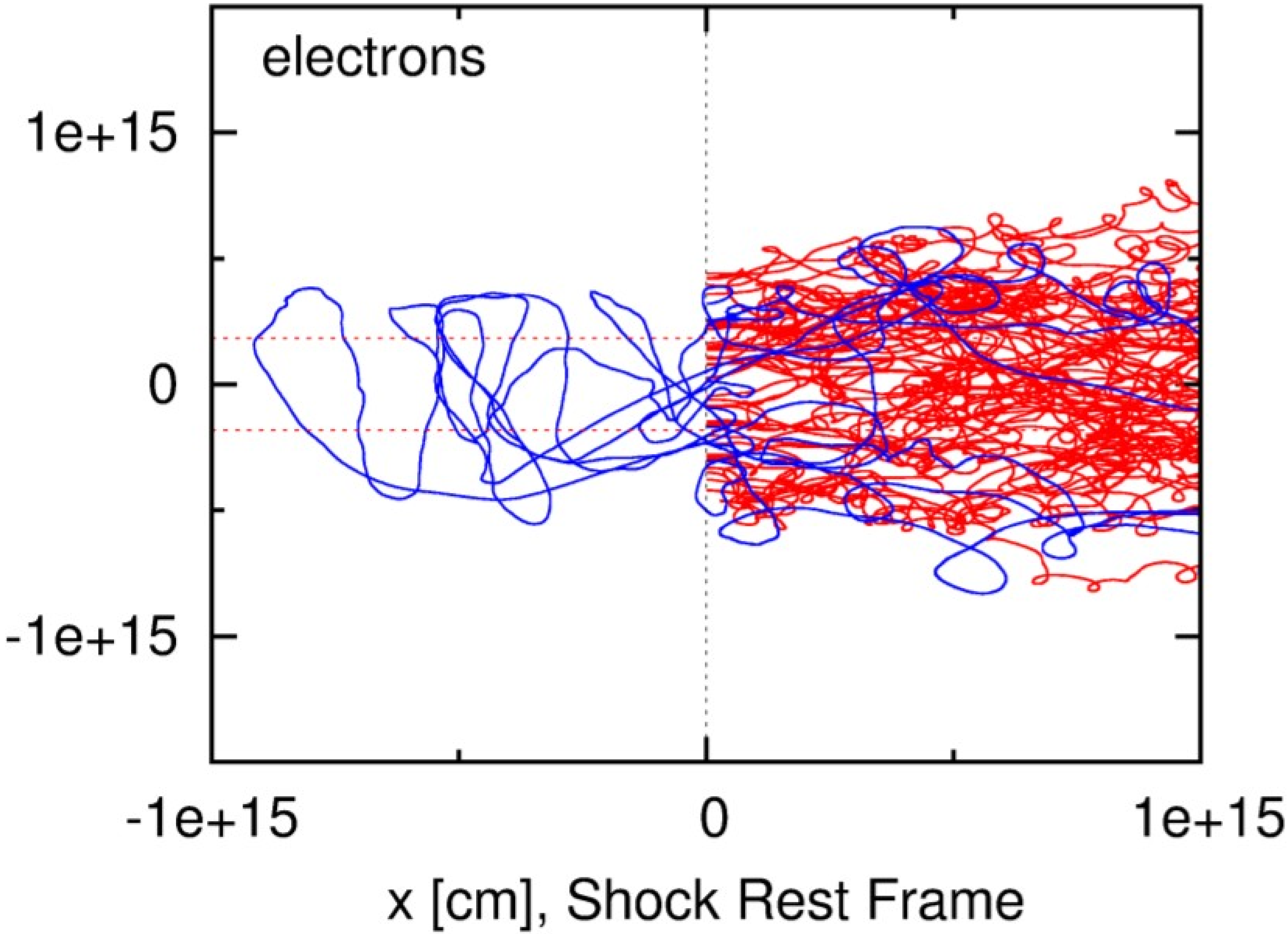


Positrons

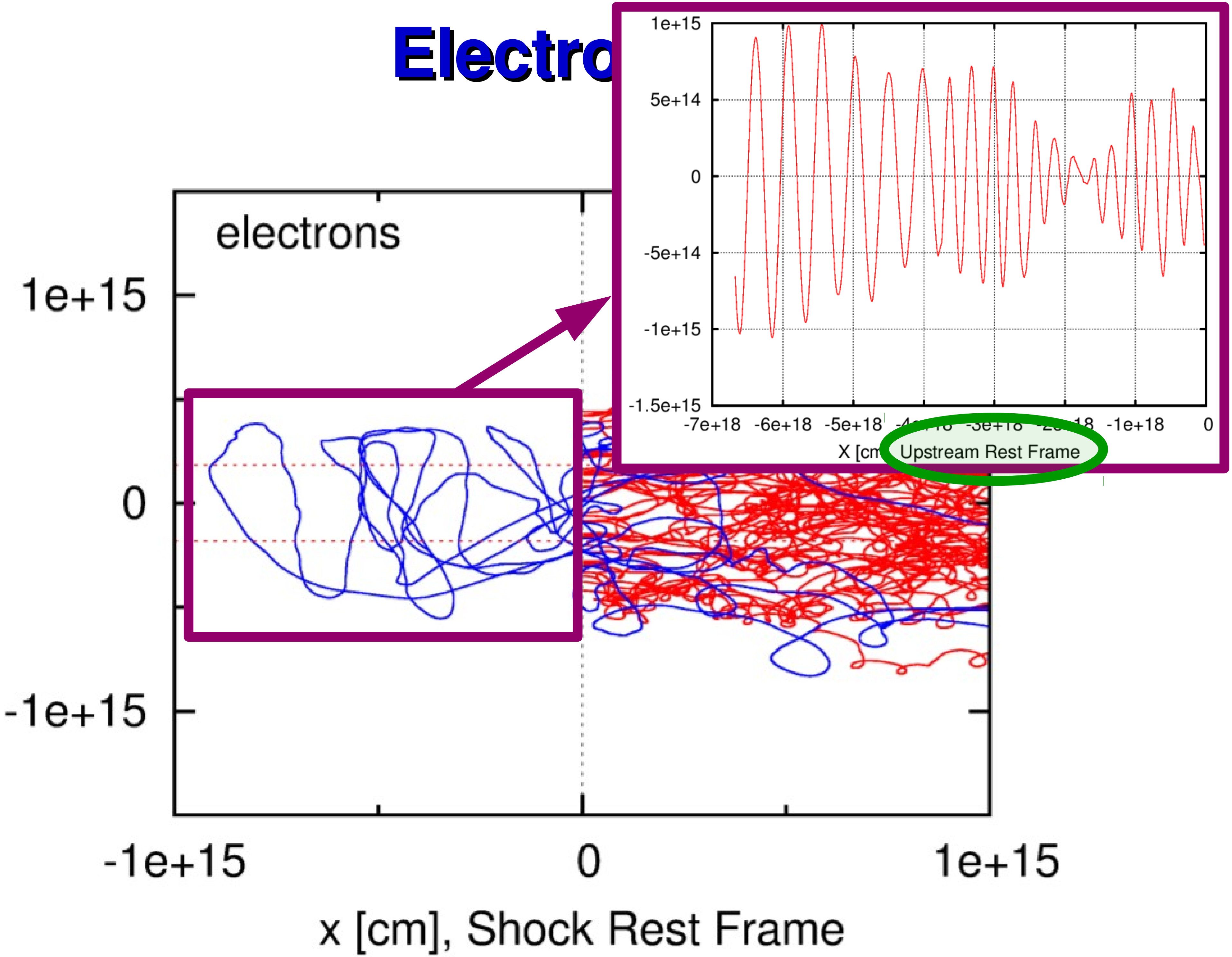


~E.dN/dE
1
0.1
0.01
0.001
0.0001
$E^{-1.22}$
E^{-5}
$E^{-0.8}$
d(ln N) / d(ln γ) ≈ - 6 … -5
1e+12
1e+13
1e+14
1e+15
E [eV], Shock Rest Frame

Electrons

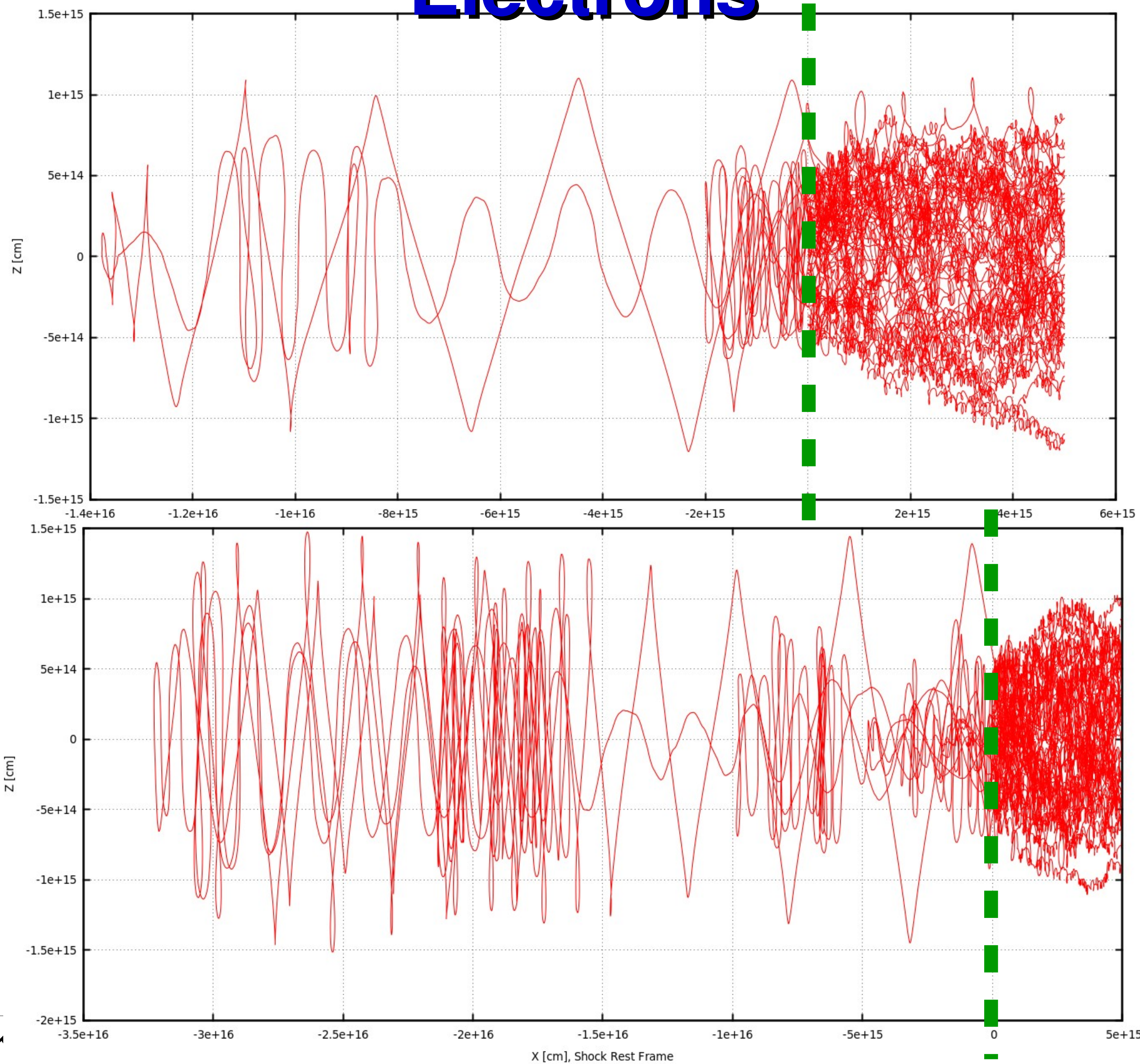


Electro

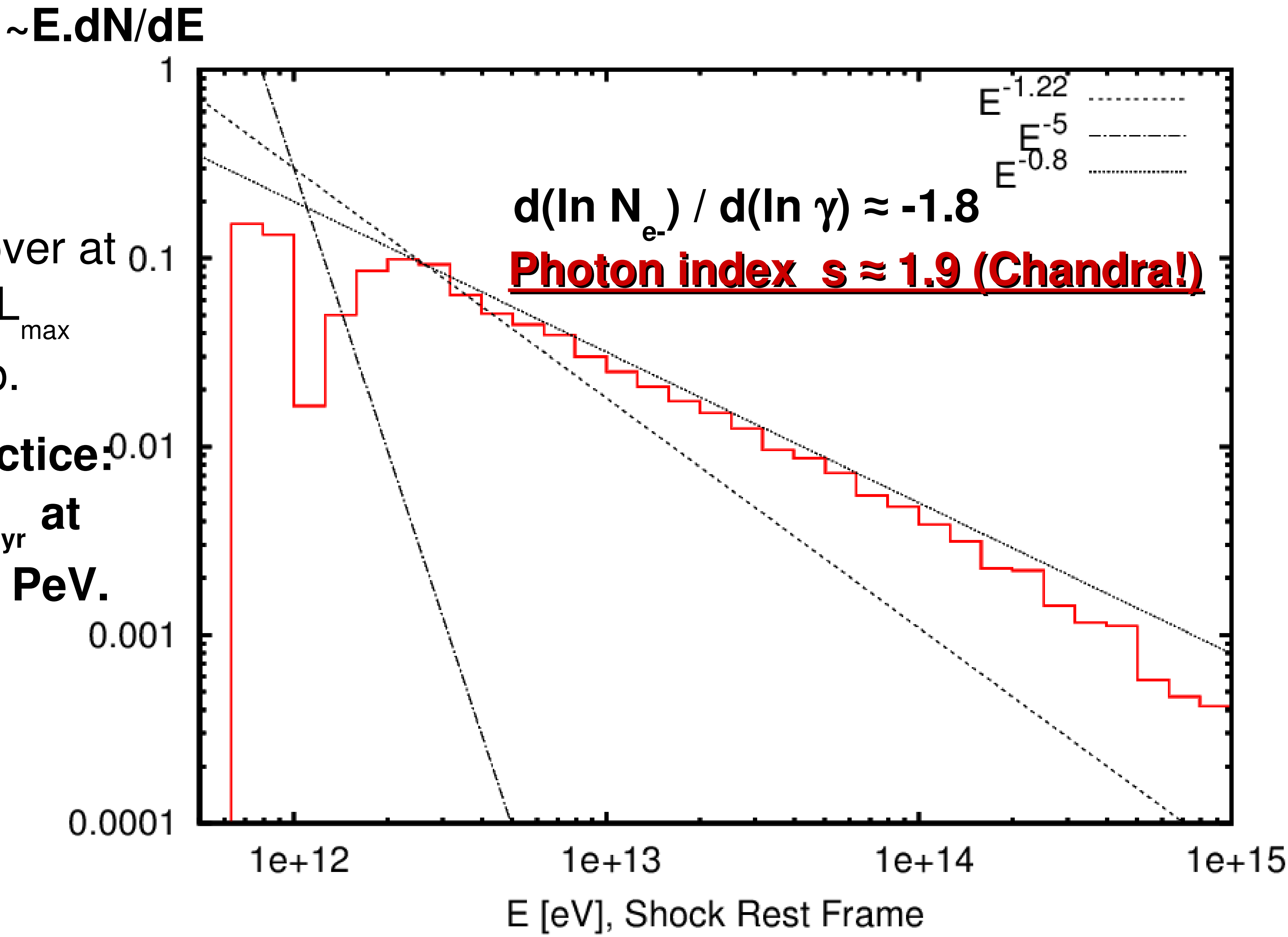


1e+15
5e+14
0
-5e+14
-1e+15
-1.5e+15
-7e+18
-6e+18
-5e+18
-1e+18
0
X [cm
Upstream Rest Frame
electrons
1e+15
0
-1e+15
-1e+15
0
1e+15
x [cm], Shock Rest Frame

Electrons



Electrons



$d(\ln N_{e-}) / d(\ln \gamma) \approx -1.8$

Photon index s ≈ 1.9 (Chandra!)

→ Turnover at high-E : L_{max} from turb.

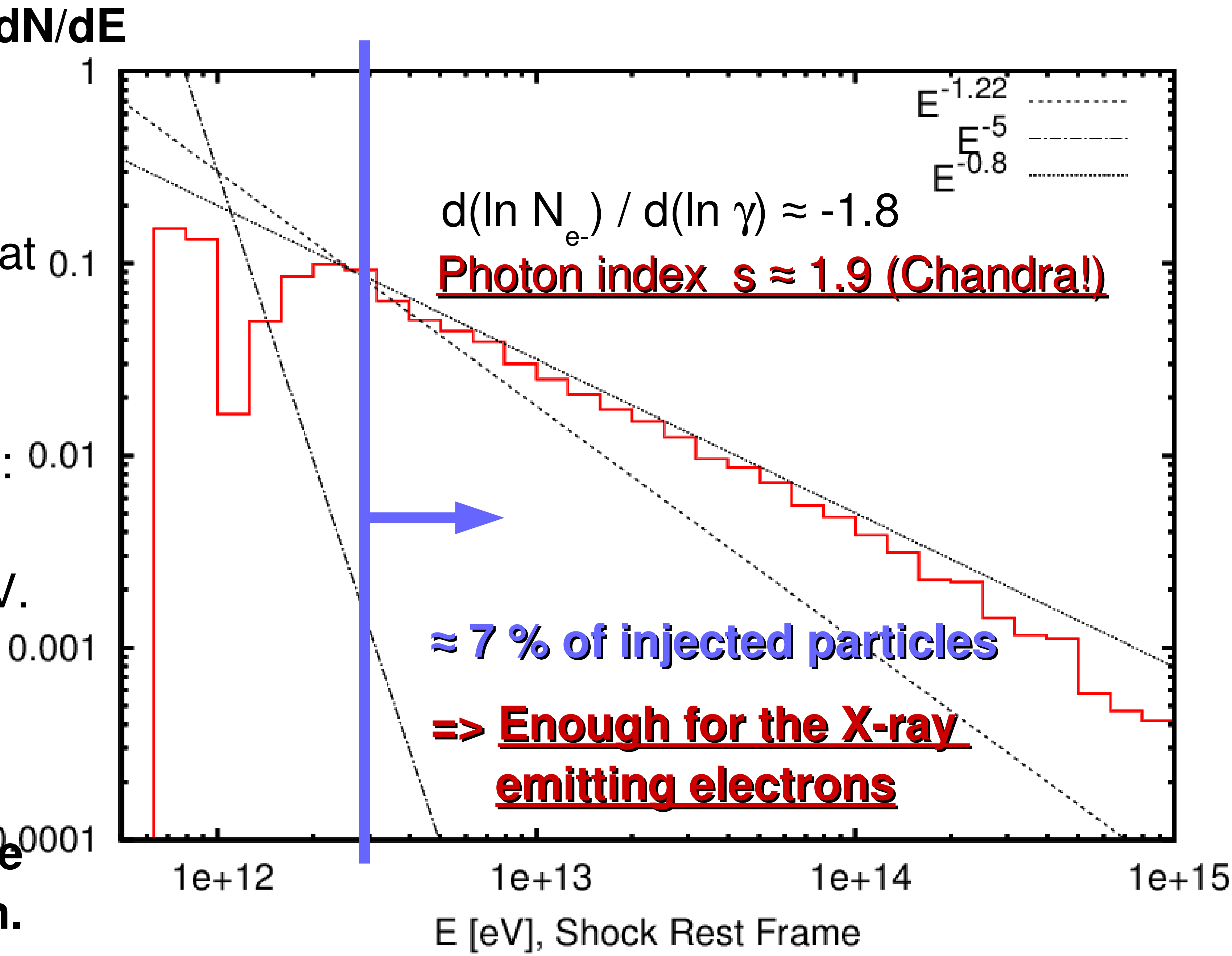
→ **In practice: $t_{synch} \sim t_{gyr}$ at E ~ 1-10 PeV.**

Electrons

→ Turnover at high-E : L_{max} from turb.

→ In practice: $t_{synch} \sim t_{gyr}$ at E ~ 1-10 PeV.

→ **Outside this ± 5 % region : No/Very little acceleration.**



Conclusions

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

→ Grad B-drift does not help (particles advected after ~ 1 cycle),

→ On the contrary, **shock-drift** helps : **Multiple shock crossings**, **hard electron (or positron) spectrum**,

→ Spectral hardening (photon index ~ -1.9) results from the drift of e^- (or e^+) along the shock and into the current sheet,

- - - > Chandra observations

→ Enough particles are accelerated to explain radio/X-ray obs.

(→ Reconnection probably relevant only for radio electrons.)