ACCELERATION D'ELECTRONS AU CHOC TERMINAL D'UN VENT DE PULSAR

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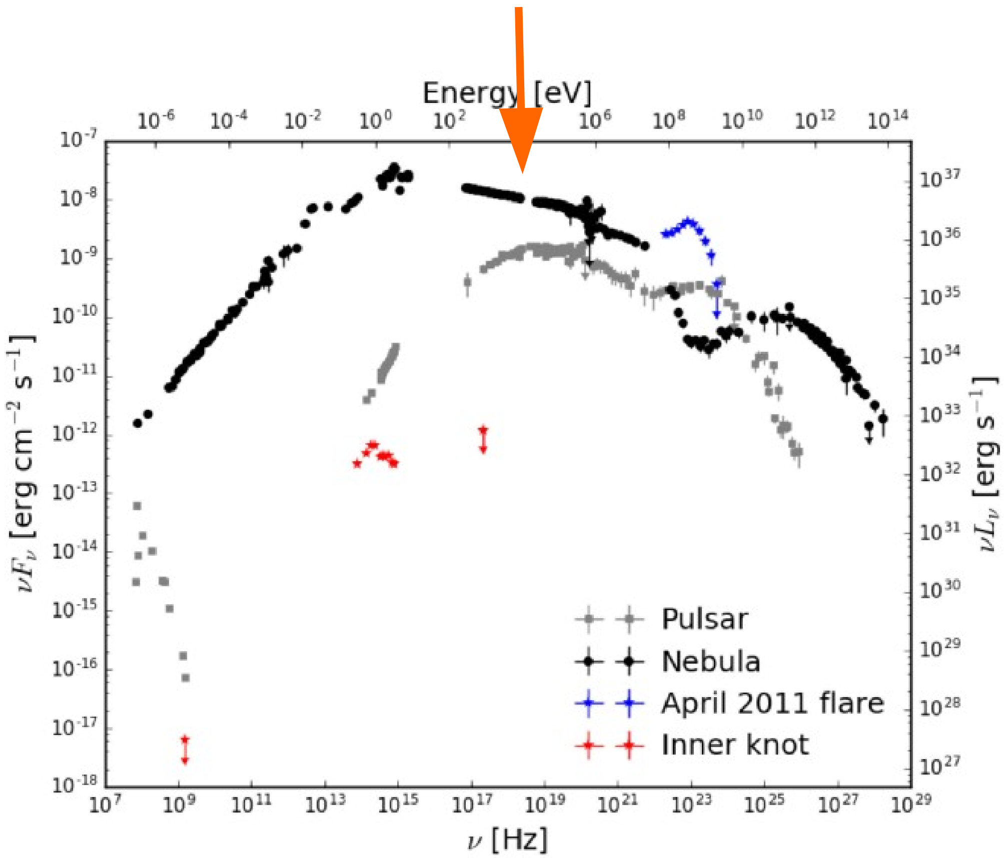
Nebuleuse du Crabe – Observations

(1) XMM-Newton, NuSTAR :

RAYONS X



Buehler & Blandford (2014)

→ **Indice spectral (rayons X) :**

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

→ **Prediction spectre electrons (chocs ultra-relativistes) :**

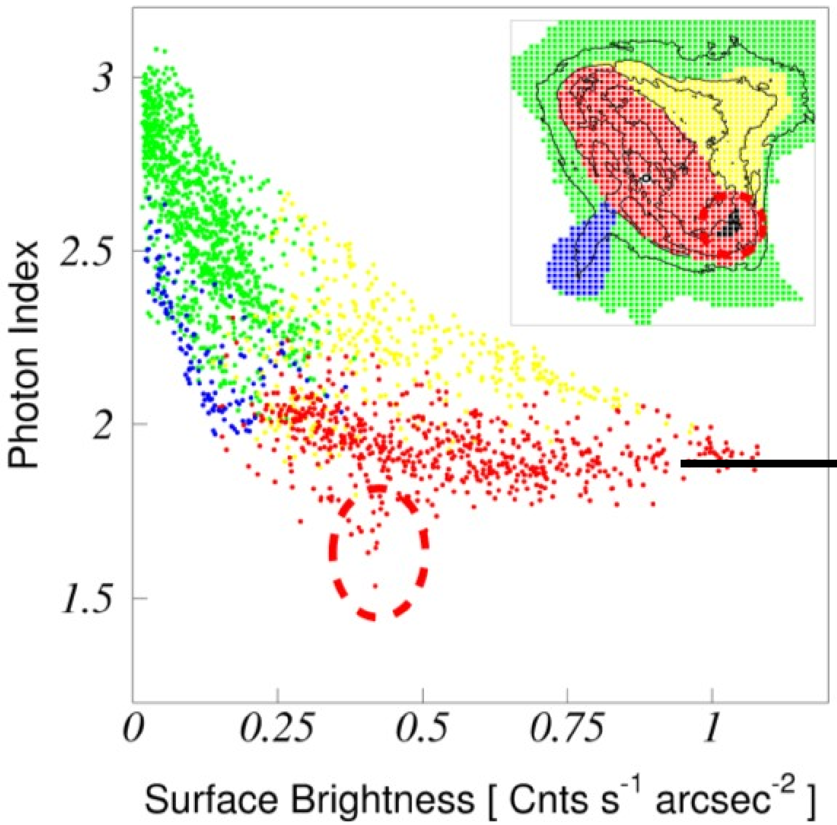
$d(\ln N_e) / d(\ln \gamma) =$ **- 2.2**

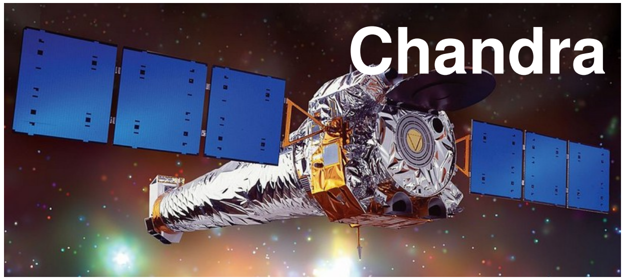
Semble etre en parfait accord...

MAIS… Choc perpendiculaire,
=> Fermi 1st ordre ne marche pas!

Nebuleuse du Crabe – Observations

(2) **Carte indice spectral - Mori *et al.*, ApJ (2004):**





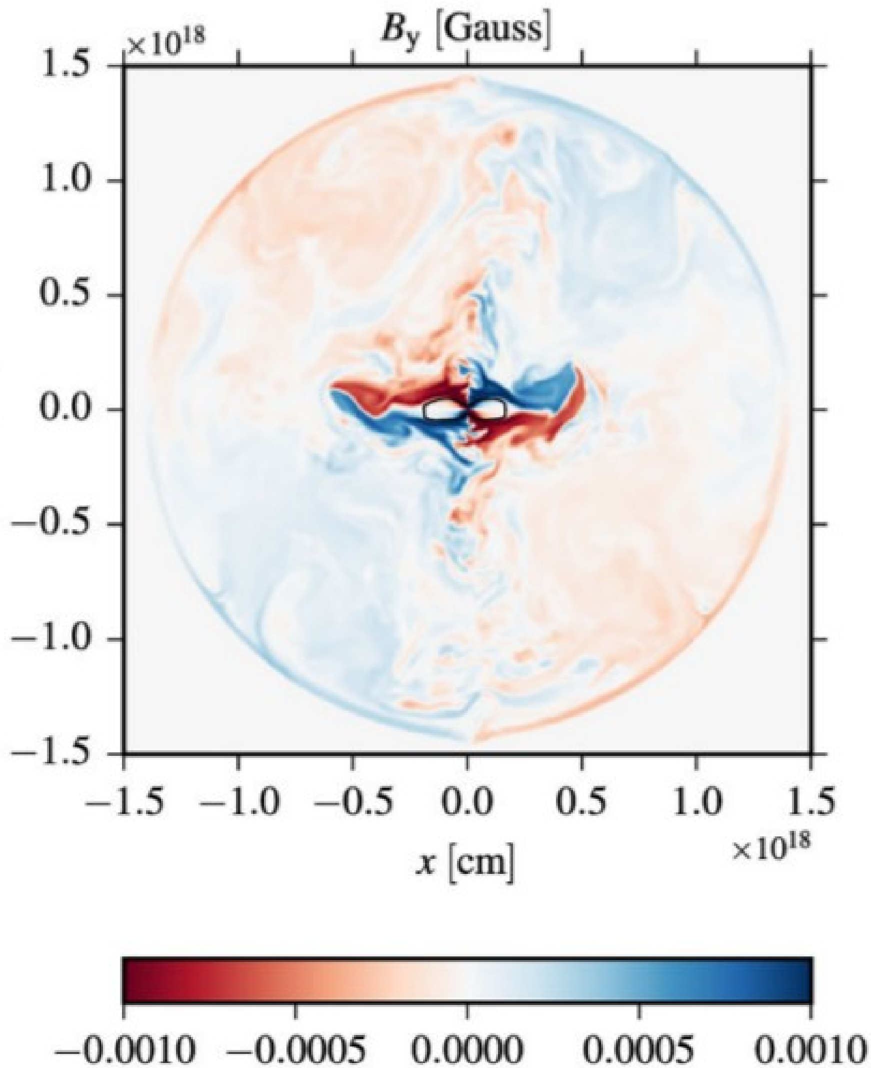
Spectre dur proche du choc, dans le plan equatorial

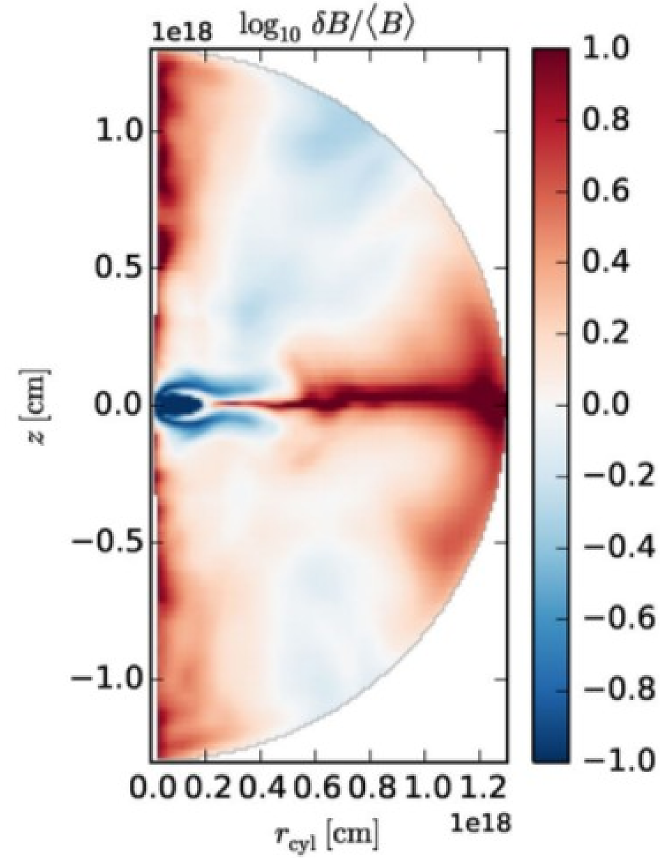
Photon index s ~ 1.9

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

Simulations MHD – nebuleuse du Crabe

Porth *et al.*
(2014, 2016)

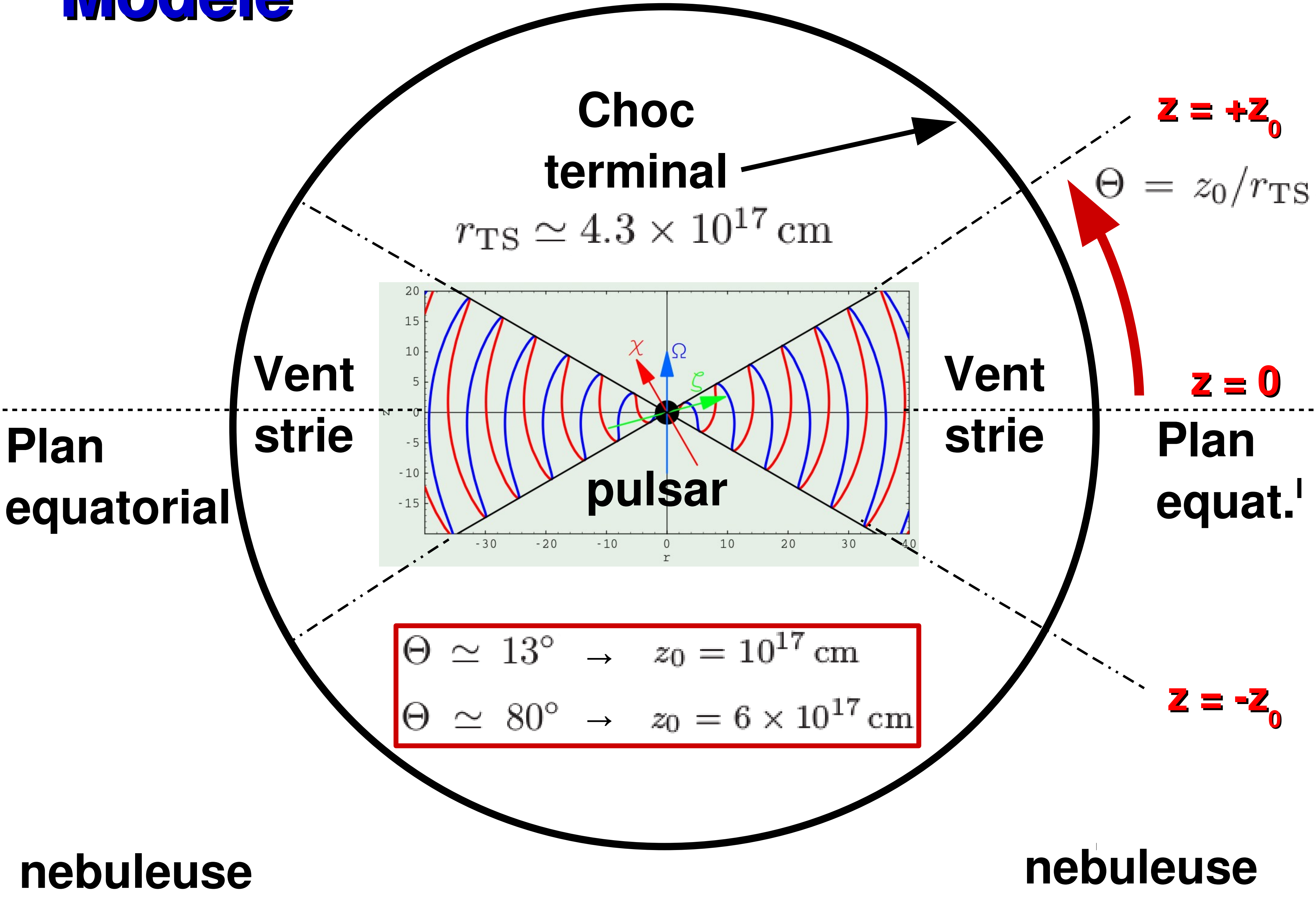




→ **B** ∝ f(z) $\mathbf{u}_y$ pour |z| <~ 10^{17} cm ; **f(z) α z ?**

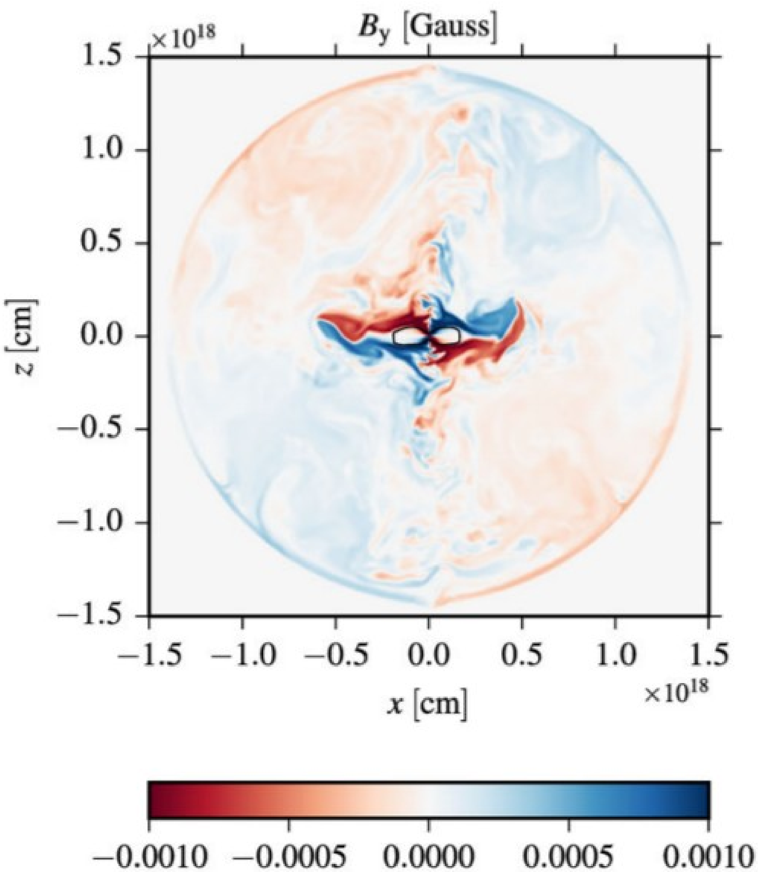
→ A z ~ ± 10^{17} cm: δB/B << 1; A z=0: δB/B >> 1

Modele

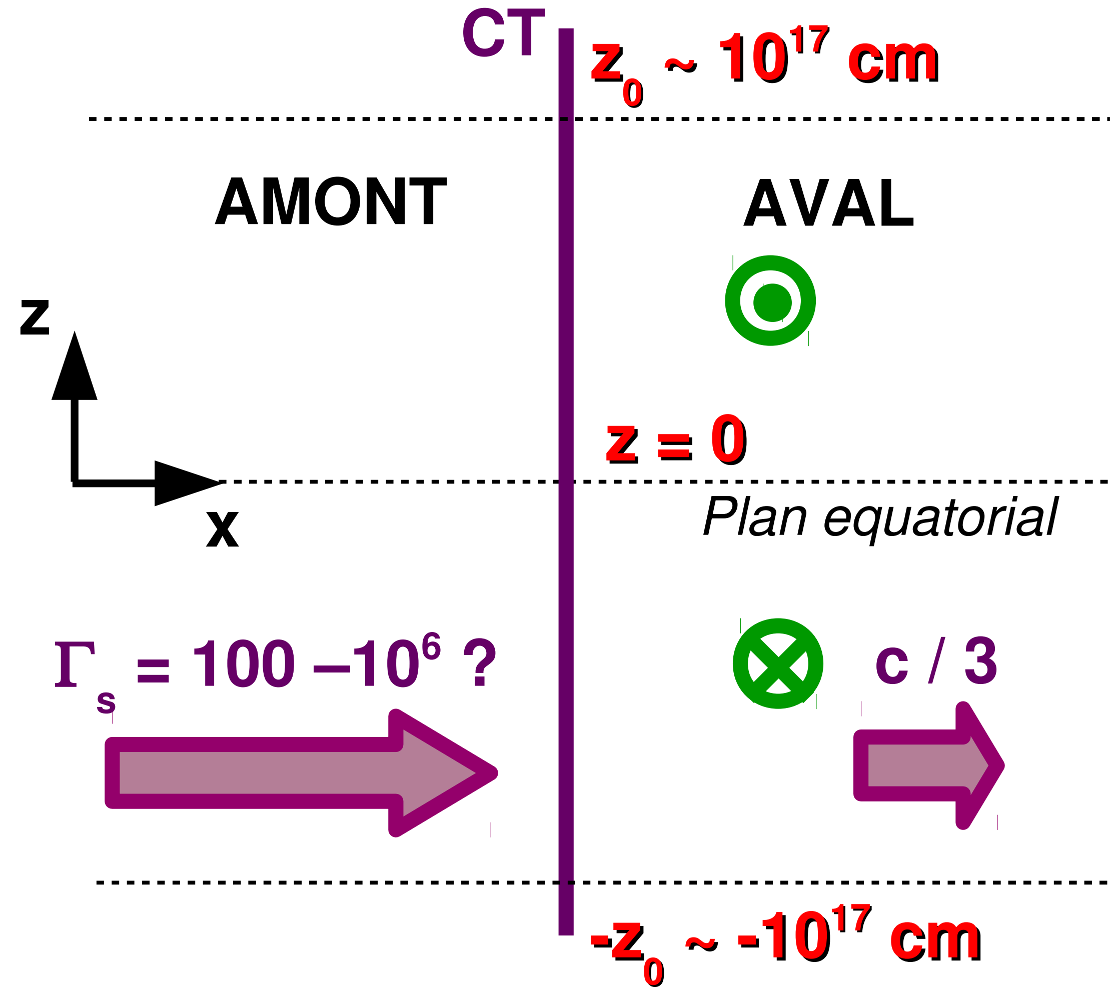

Choc
terminal
$r_{TS} \simeq 4.3 \times 10^{17}$ cm
$z = +z_0$
$\Theta = z_0/r_{TS}$
$z = 0$
Vent
strie
Vent
strie
Plan
equatorial
Plan
equat.'
pulsar
χ
Ω
ζ
r
z
$\Theta \simeq 13° \rightarrow z_0 = 10^{17}$ cm
$\Theta \simeq 80° \rightarrow z_0 = 6 \times 10^{17}$ cm
$z = -z_0$
nebuleuse
nebuleuse

Modele et simulations numeriques

Porth *et al.* (2014, 2016):



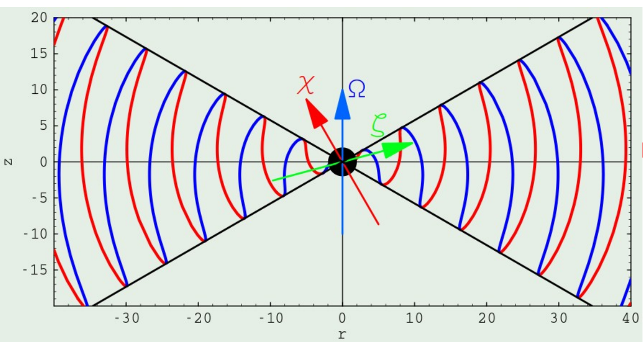
NOTRE MODELE (PLANAIRE) :



$$\mathbf{B}_{\rm d}(z) = \begin{cases} -B_{\rm d,0}\hat{\mathbf{y}} & \text{if } z > z_0 \\ -B_{\rm d,0}(z/z_0)\hat{\mathbf{y}} & \text{if } |z| \leq z_0 \\ +B_{\rm d,0}\hat{\mathbf{y}} & \text{if } z < -z_0 \end{cases}$$

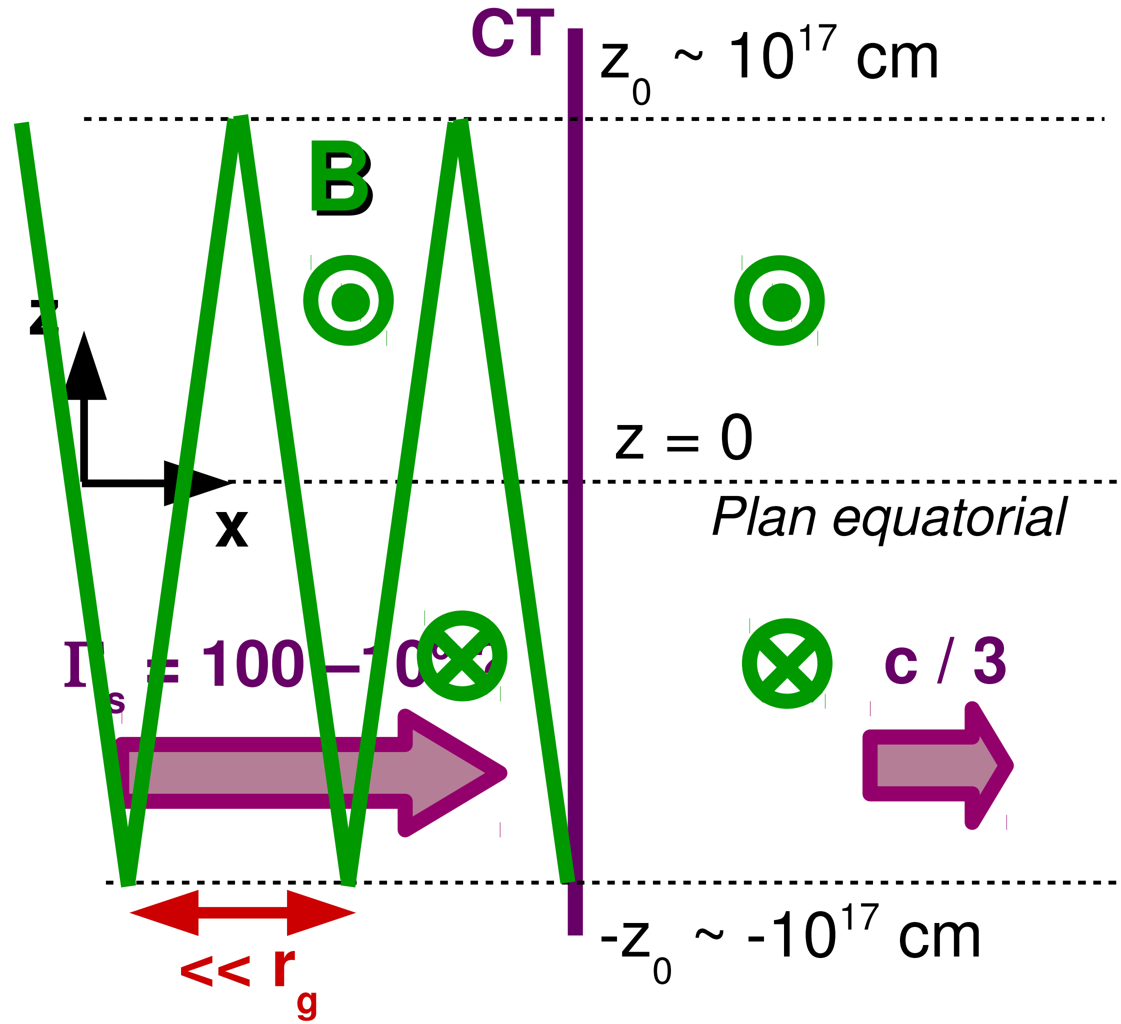
$B_{d,0} = +1\text{mG}$

Modele et simulations numeriques



Vent strie

NOTRE MODELE (PLANAIRE) :

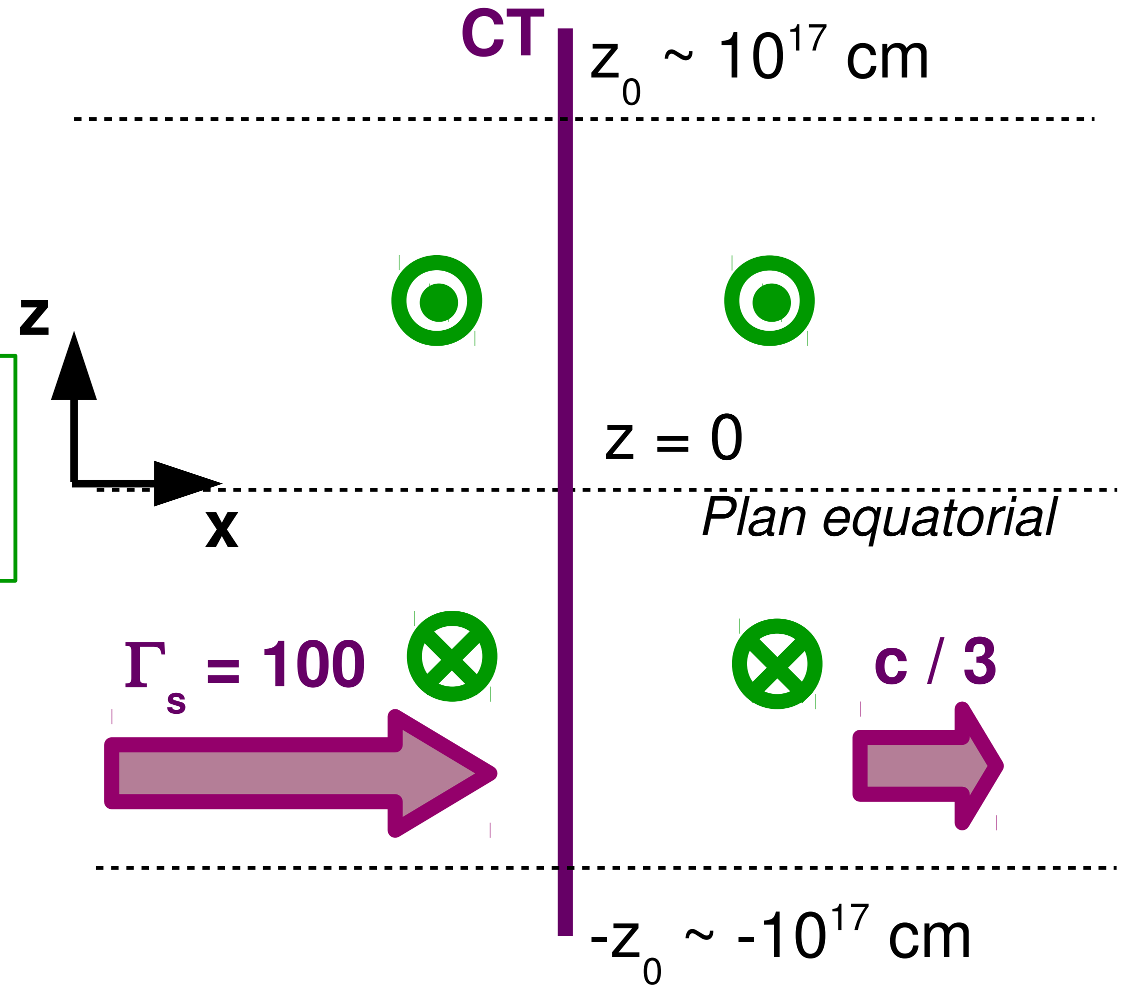


Modele et simulations numeriques

$$\mathbf{B}_\mathrm{u}(z) = \begin{cases} -B_{\mathrm{u},0}\hat{\mathbf{y}} & \text{if } z > z_0 \\ -B_{\mathrm{u},0}(z/z_0)\hat{\mathbf{y}} & \text{if } |z| \leq z_0 \\ +B_{\mathrm{u},0}\hat{\mathbf{y}} & \text{if } z < -z_0 \end{cases}$$

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

NOTRE MODELE (PLANAIRE) :

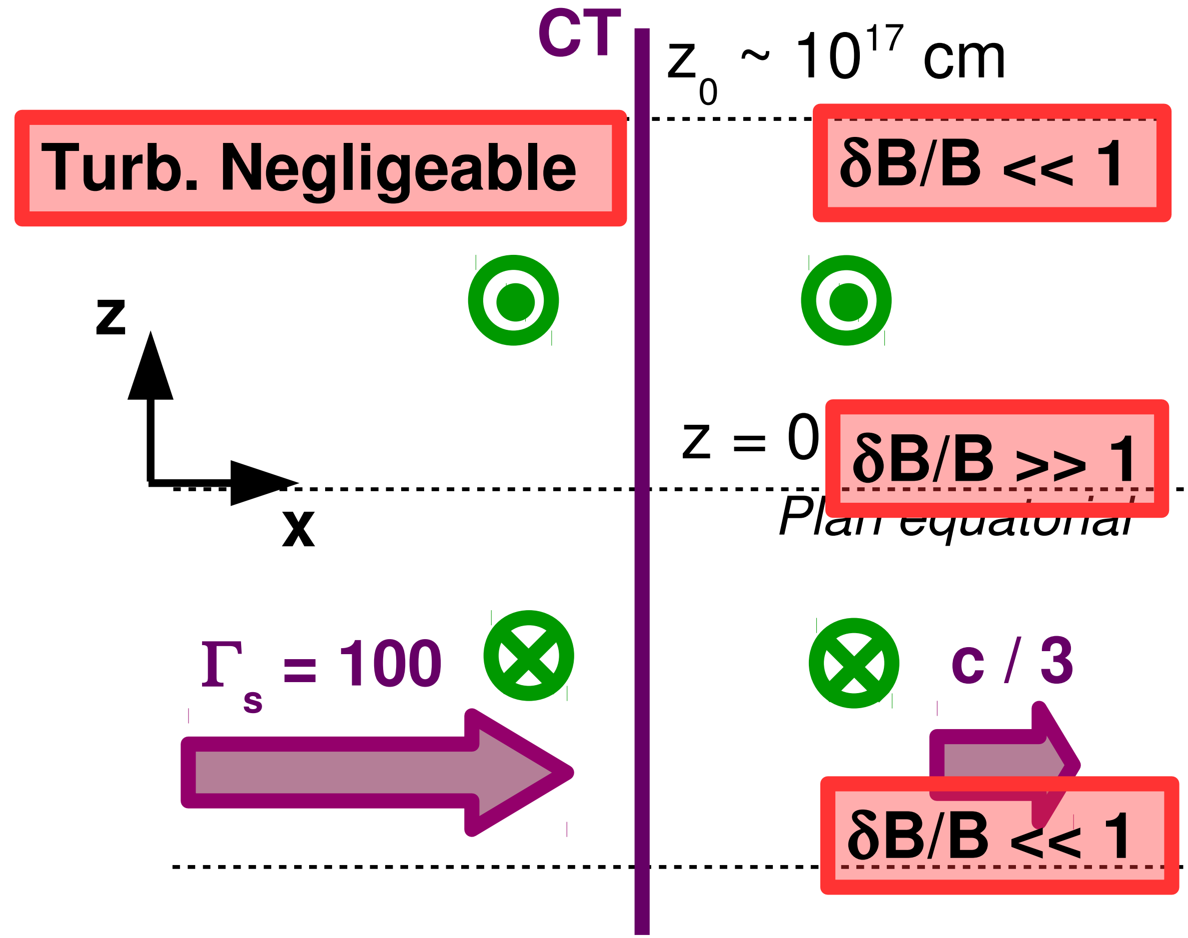


Dans le Ref. du choc, E_u et B_u ne dependent pas de Γ_s, si $\Gamma_s >> 10$.

Modele et simulations numeriques

NOTRE MODELE (PLANAIRE) :

TURBULENCE :



→ **Champ magnetique turbulent 3D sur une grille avec $N^3 = 256^3$.**

$\delta B_{\rm d} \equiv (\langle \delta \mathbf{B}_{\rm d}{}^2 \rangle)^{1/2} > 0$ $\qquad$ $\delta B_{\rm d} = (0.3 - 400)\,\mu{\rm G}$ = cst. de z

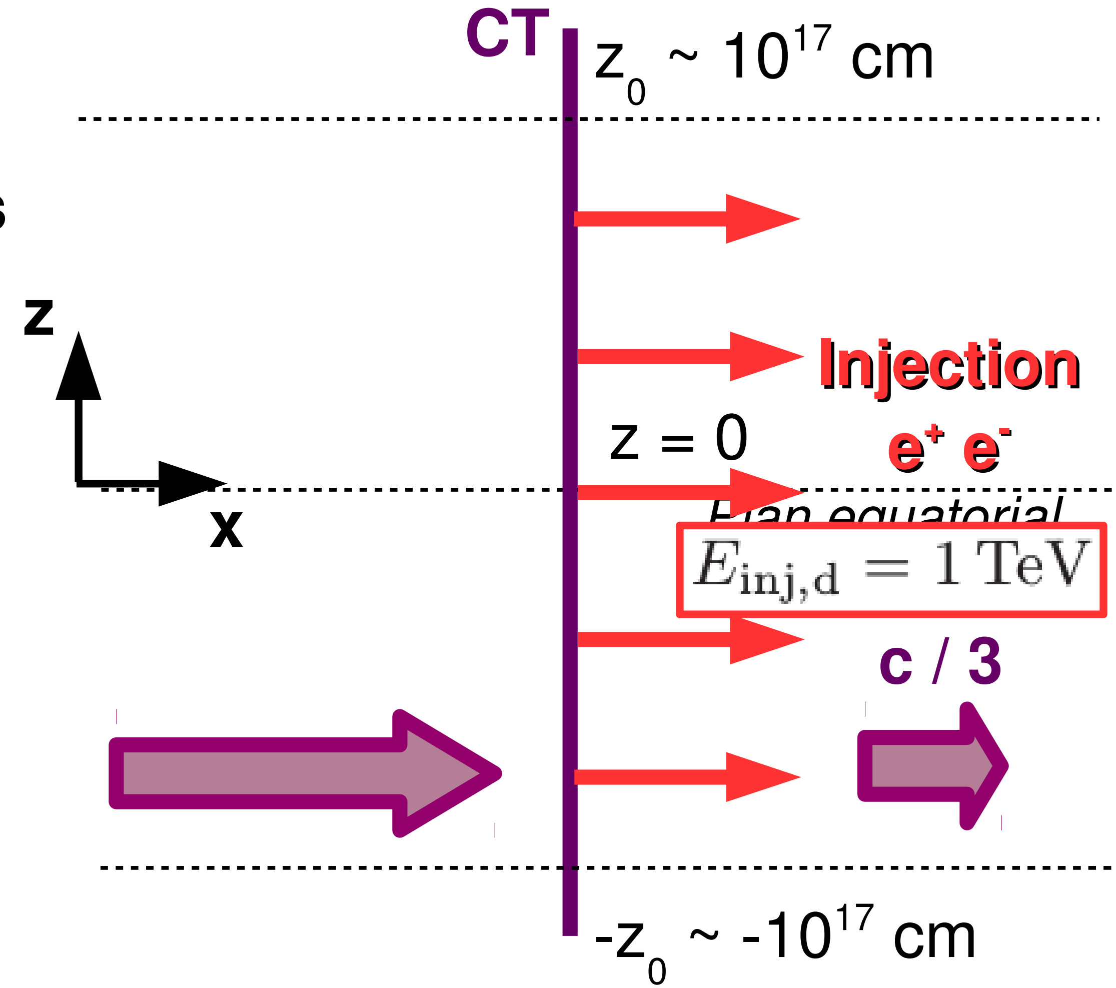
Modele et simulations numeriques

→ Calcule en **3D** les **trajectoires individuelles** des particules (limite de la **particule test**),

→ Calculs dans les Referentiels "Amont" ou "Aval" (i.e., E=0),

→ Si franchit le choc: Fait la transformation de Lorentz.

NOTRE MODELE (PLANAIRE) :



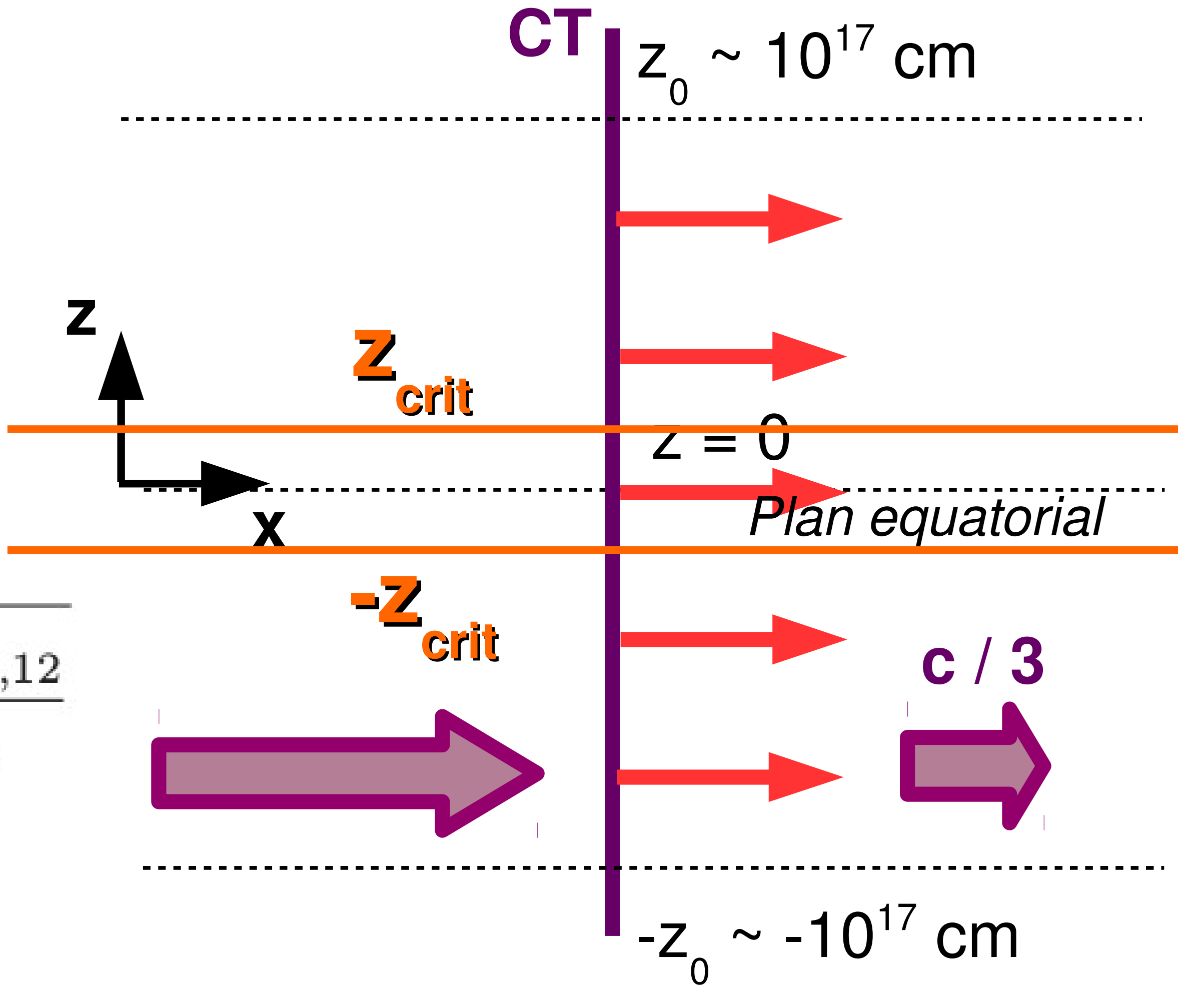
Modele et simulations numeriques

NOTRE MODELE (PLANAIRE) :

$z_{crit} = r_L[E_{inj,d}; B_d(z_{crit})]$:

$$z_{\rm crit} = \sqrt{\frac{z_0 E_{\rm inj,d}}{ecB_{\rm d,0}}}$$

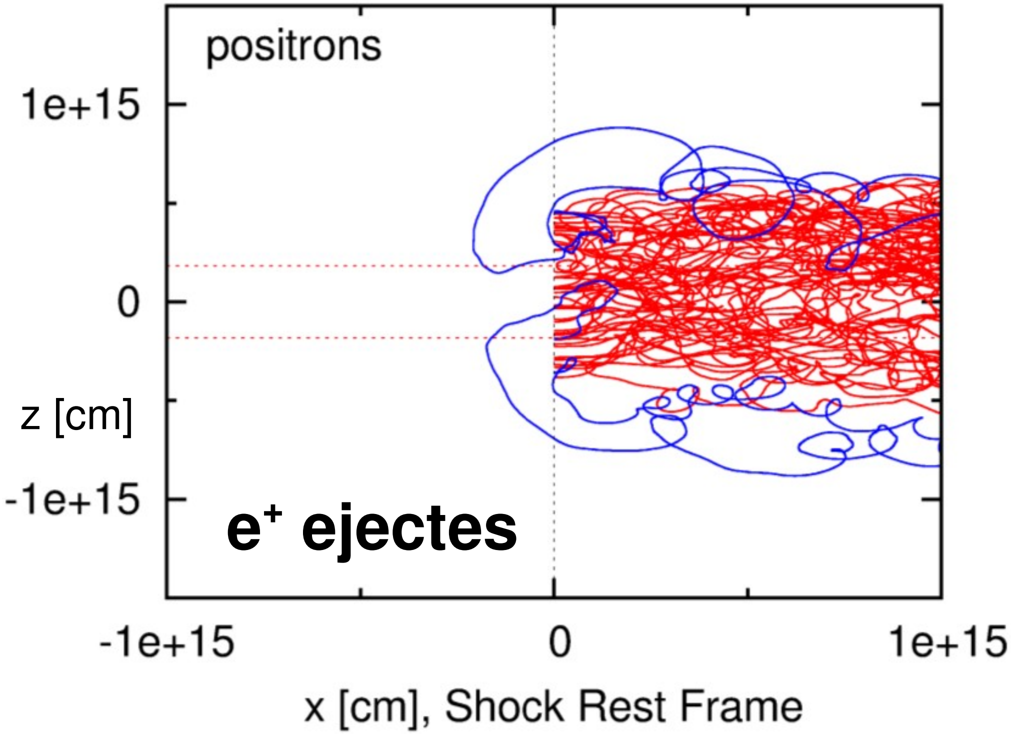
$$\simeq 5.8\times10^{14}\,{\rm cm}\sqrt{\frac{z_{0,17}E_{\rm inj,d,12}}{B_{\rm d,0,-3}}}$$

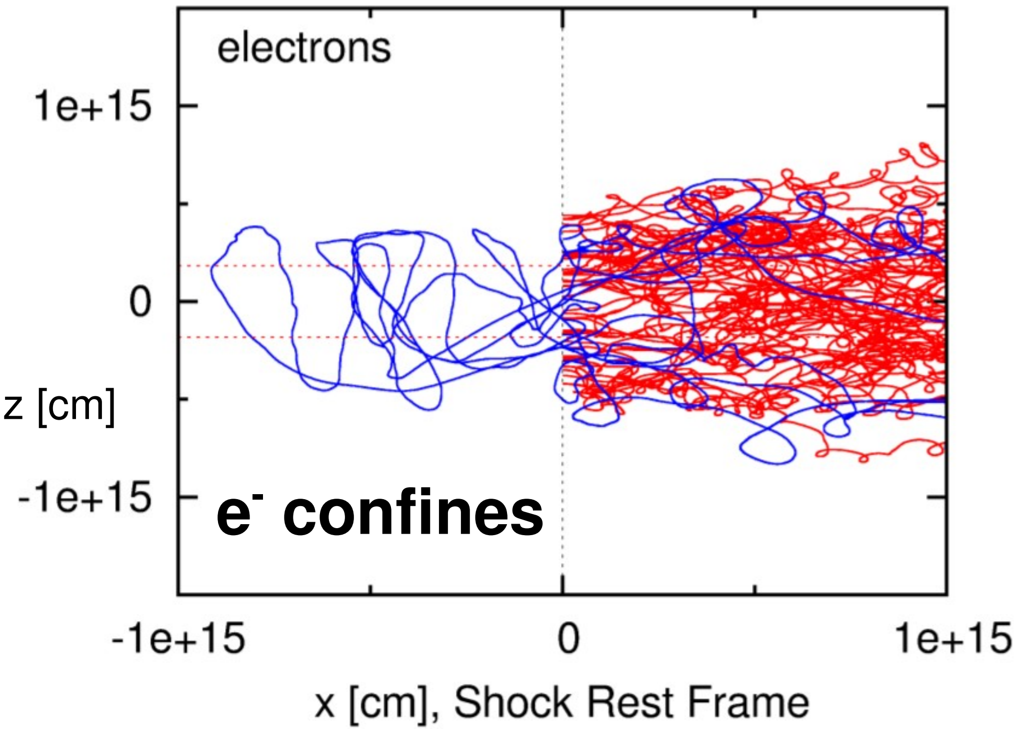


$$z_{\rm w} \propto z_{\rm crit} \propto \sqrt{z_0}$$ ~ plusieurs z_{crit}

Simulations numeriques

Dans la feuille de courant equatoriale :



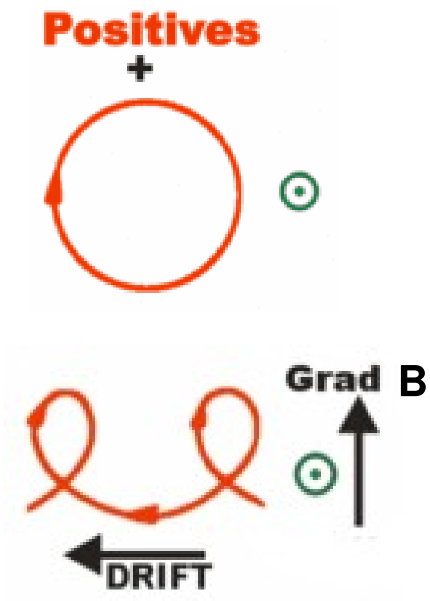


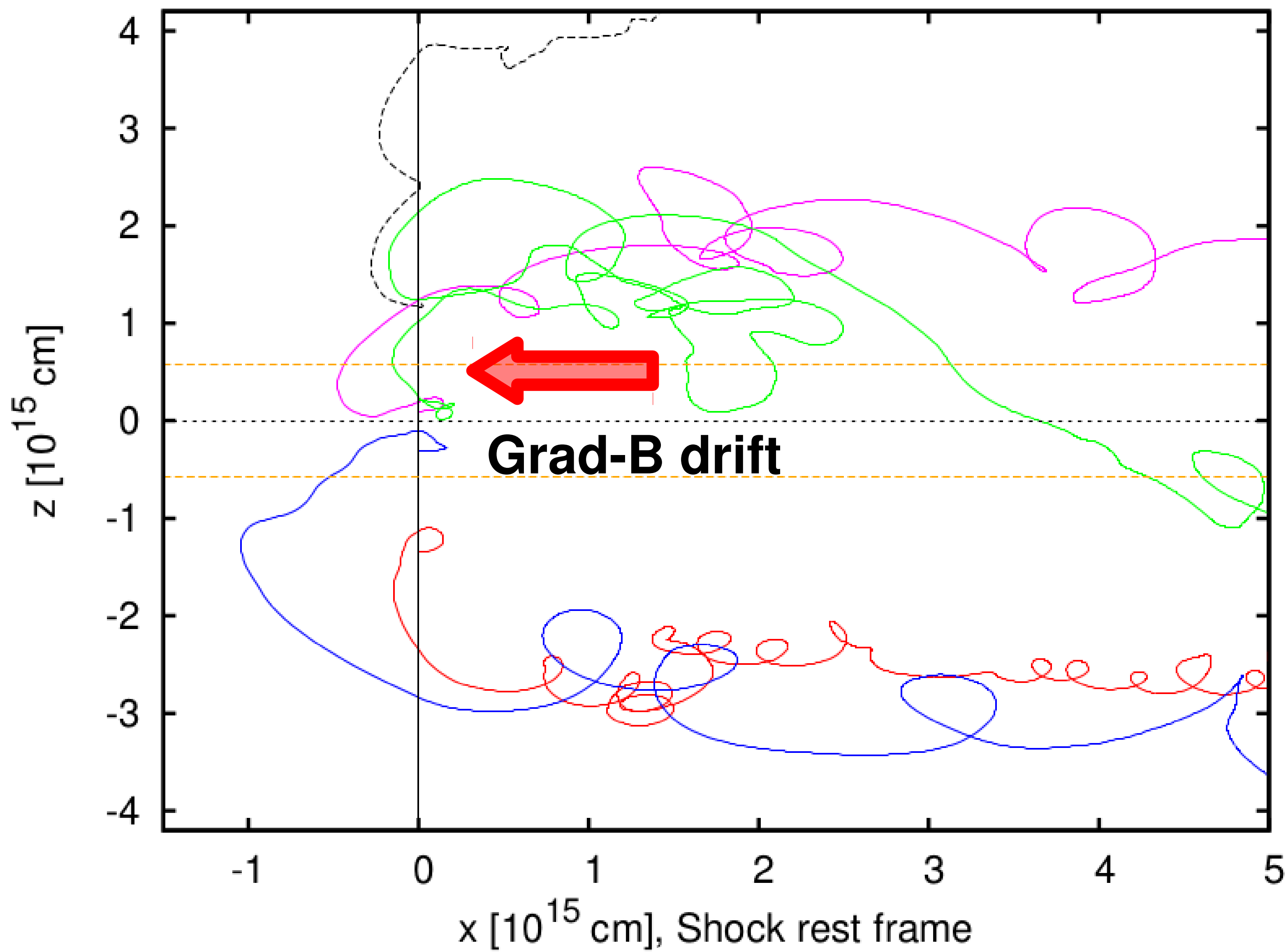
Peu/pas d'acceleration

Acceleration

Positrons

(… ou electrons - depend de la polarite)

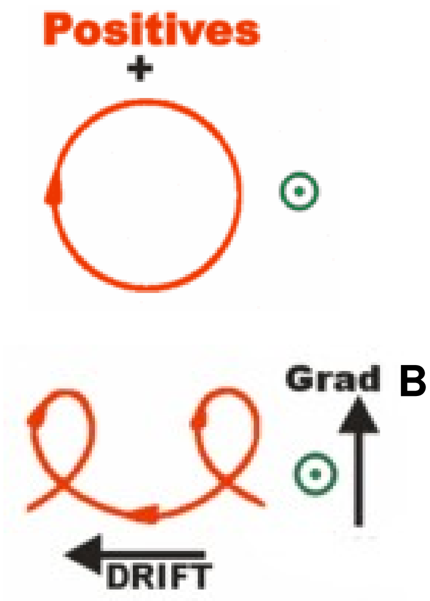




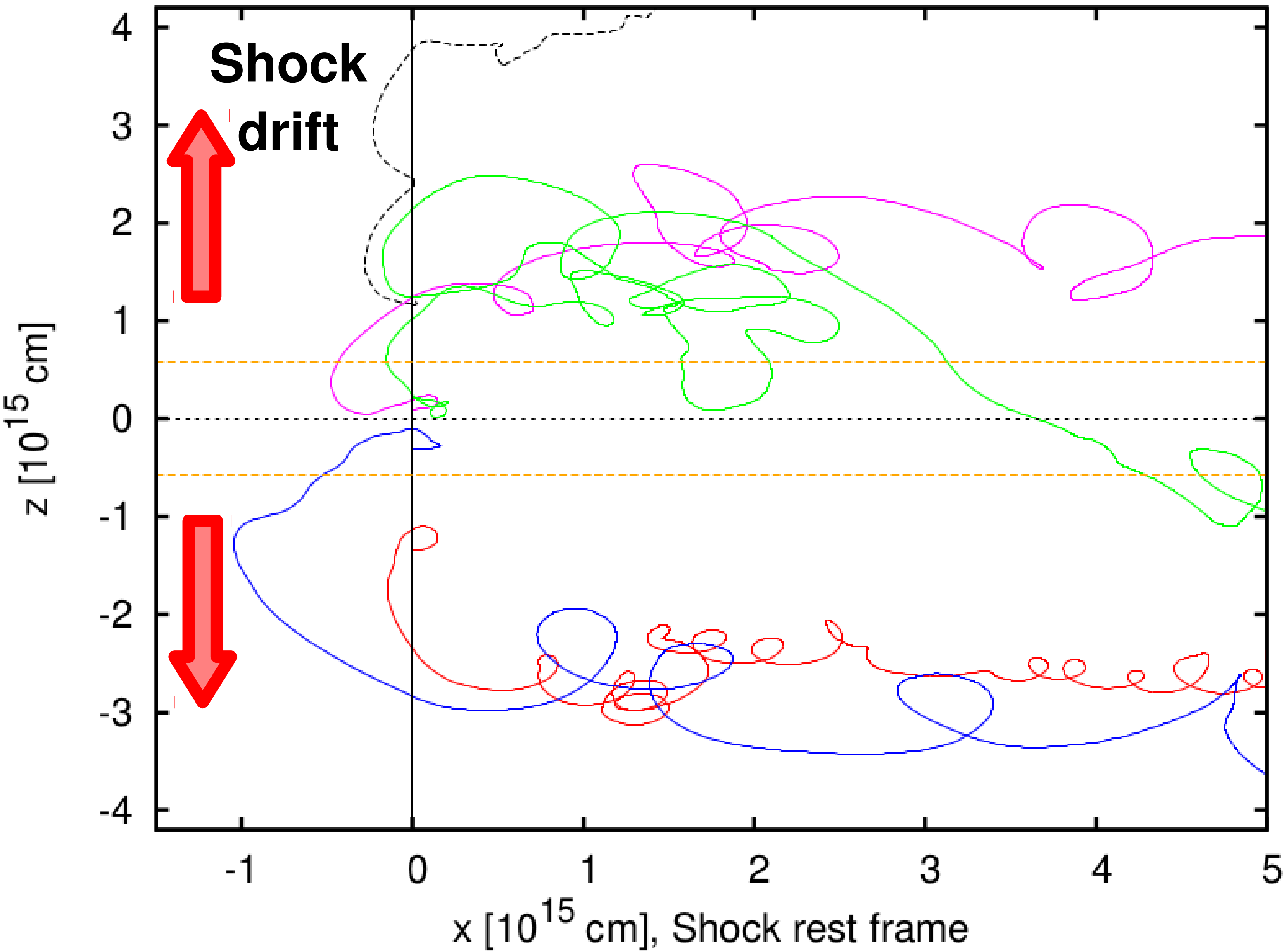
Grad-B drift : peut contrer l'advection a c/3 proche de $z \sim \pm z_{crit}$

Positrons

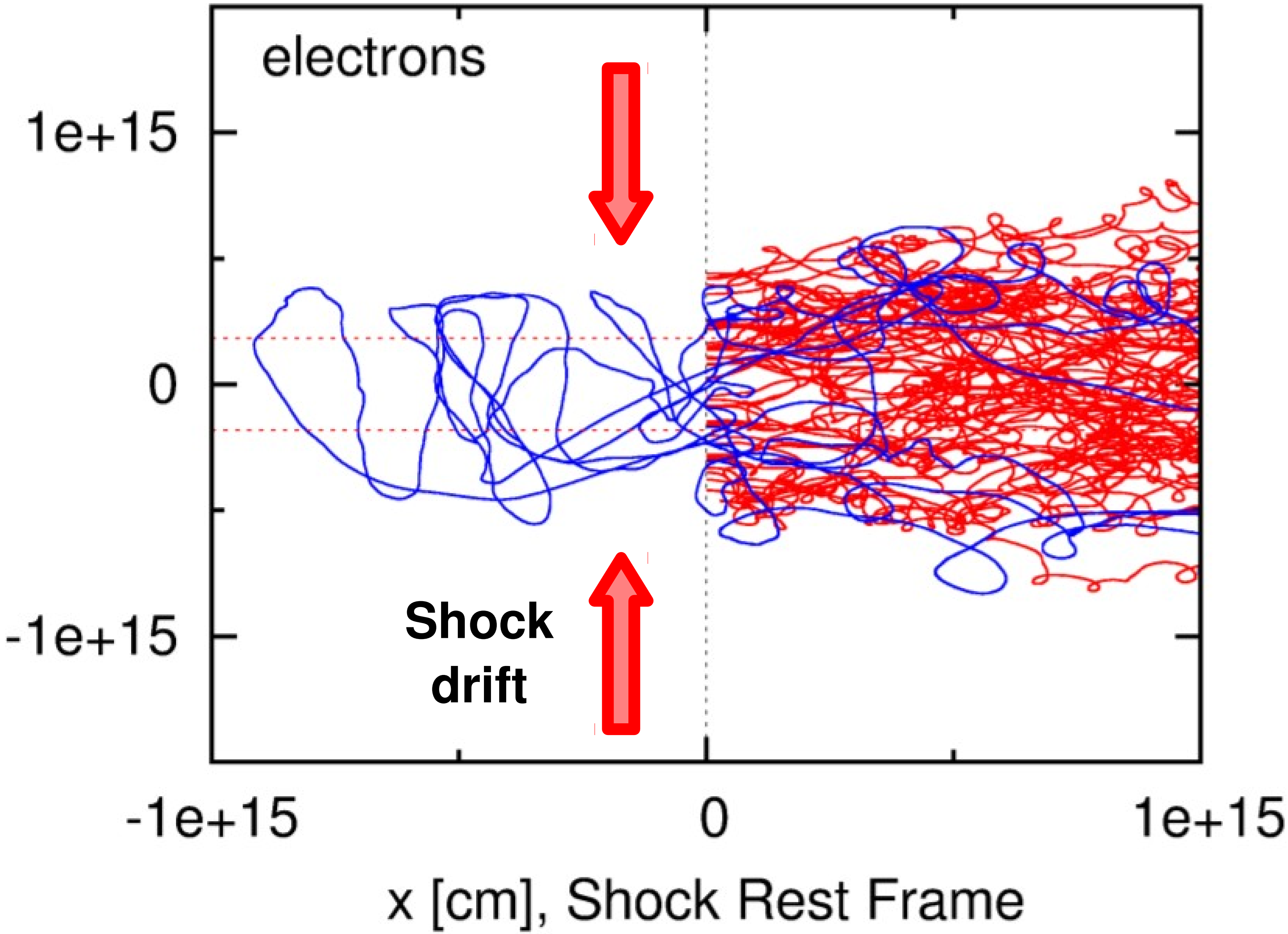
(… ou electrons - depend de la polarite)



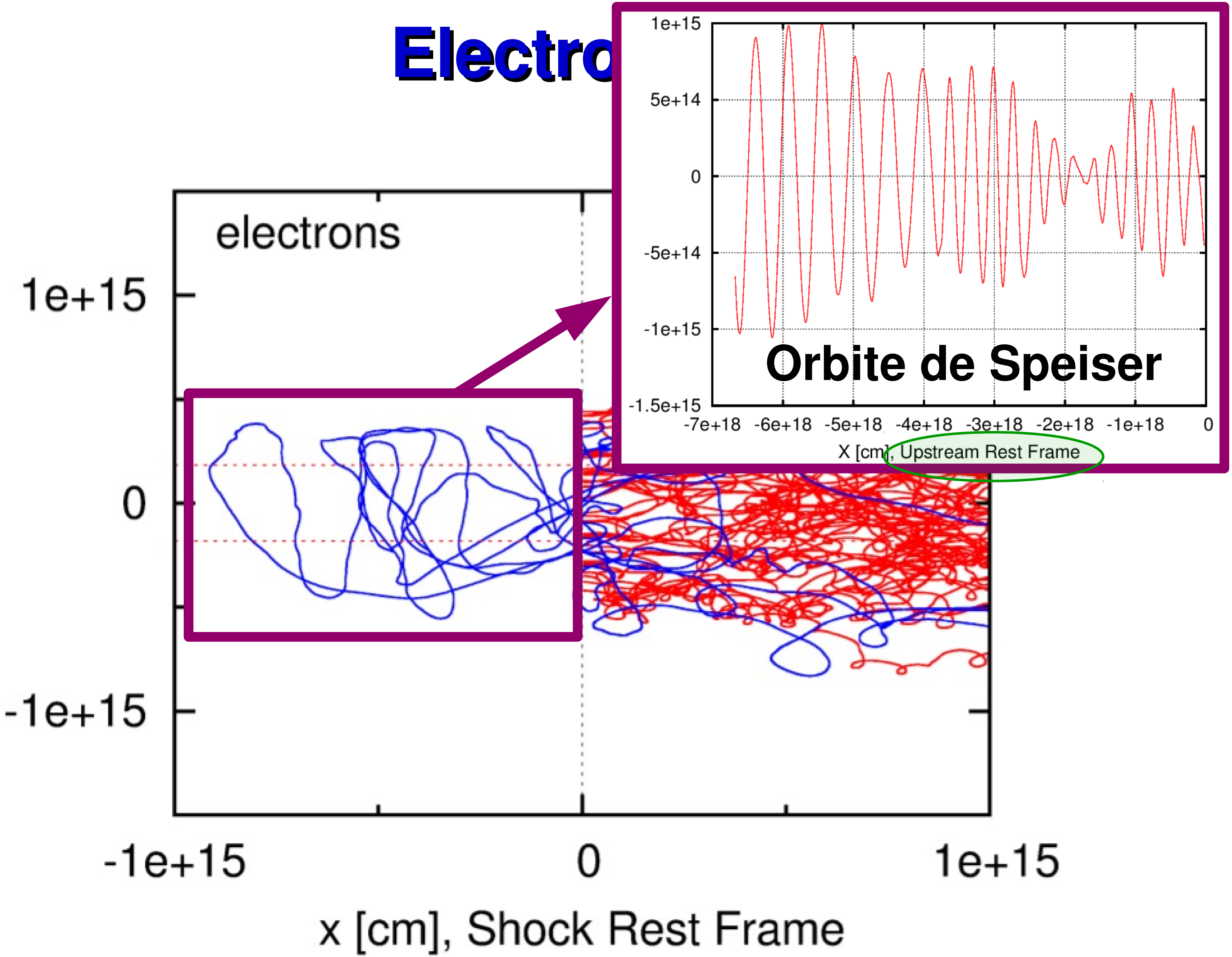
Shock-drift :
ejecte les
positrons



Electrons

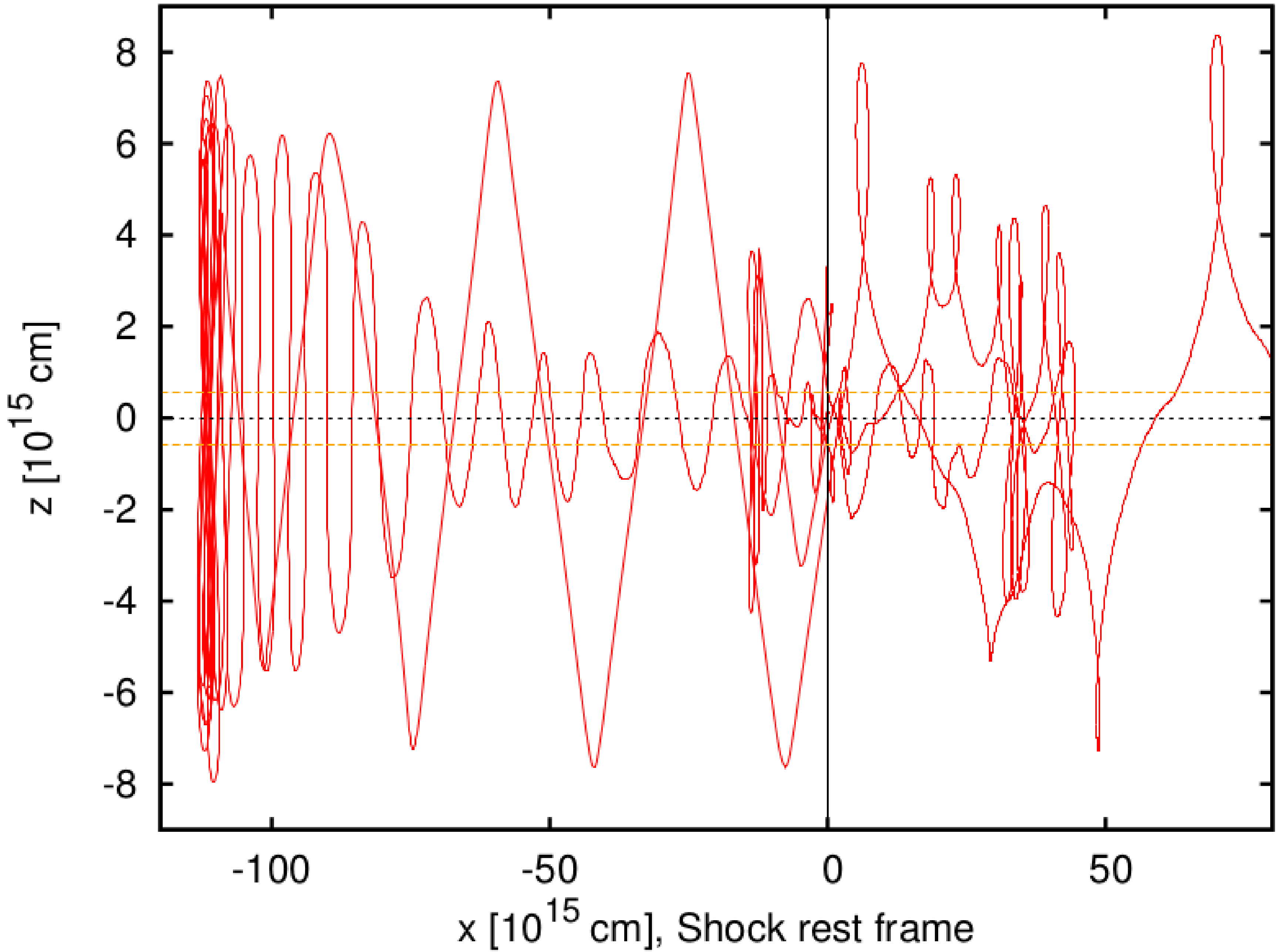

electrons
1e+15
0
-1e+15
Shock
drift
-1e+15
0
1e+15
x [cm], Shock Rest Frame

Electro

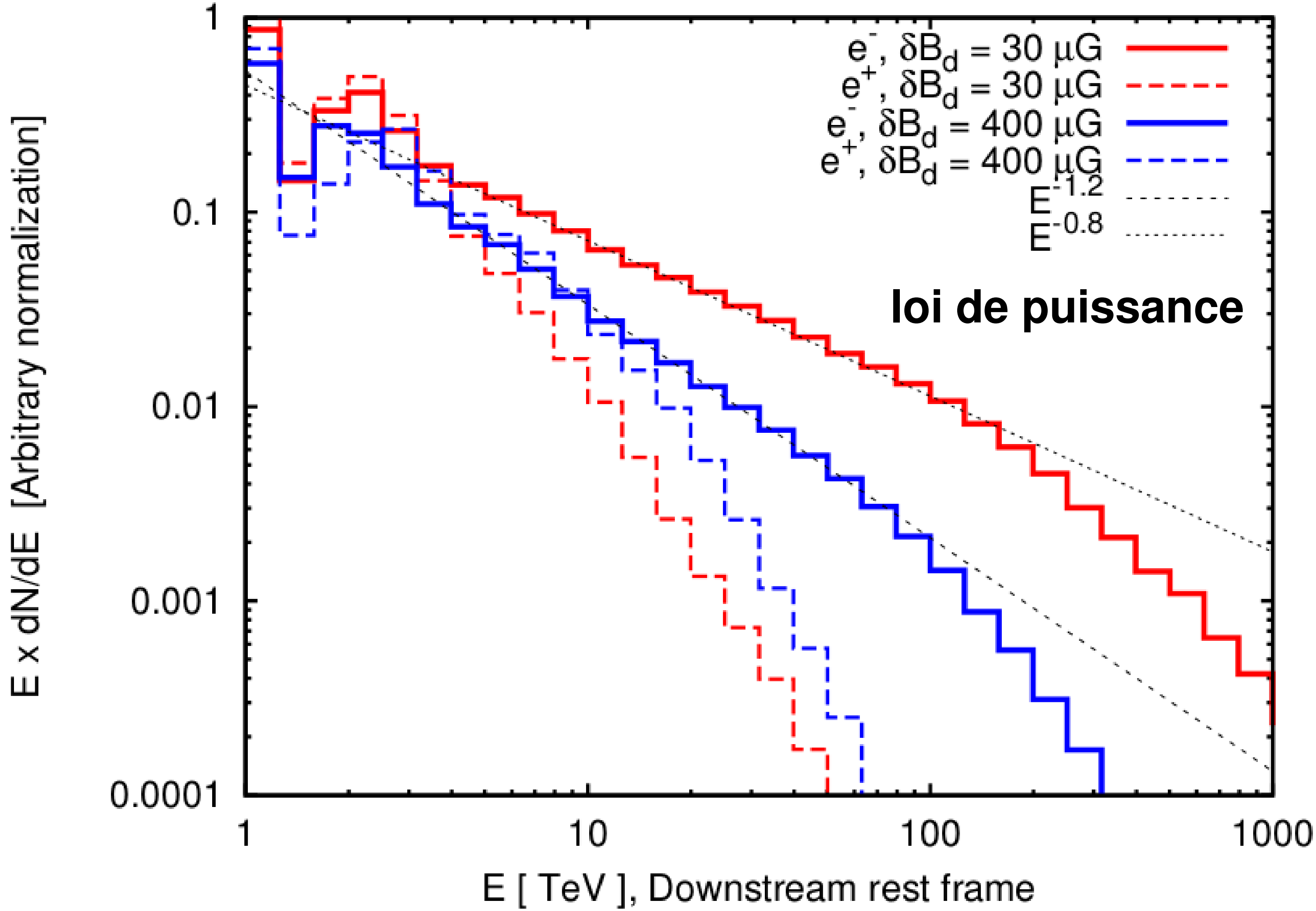


electrons
1e+15
0
-1e+15
-1e+15
0
1e+15
x [cm], Shock Rest Frame
1e+15
5e+14
0
-5e+14
-1e+15
-1.5e+15
-7e+18
-6e+18
-5e+18
-4e+18
-3e+18
-2e+18
-1e+18
0
X [cm], Upstream Rest Frame
Orbite de Speiser

Electrons



Spectres electrons et positrons

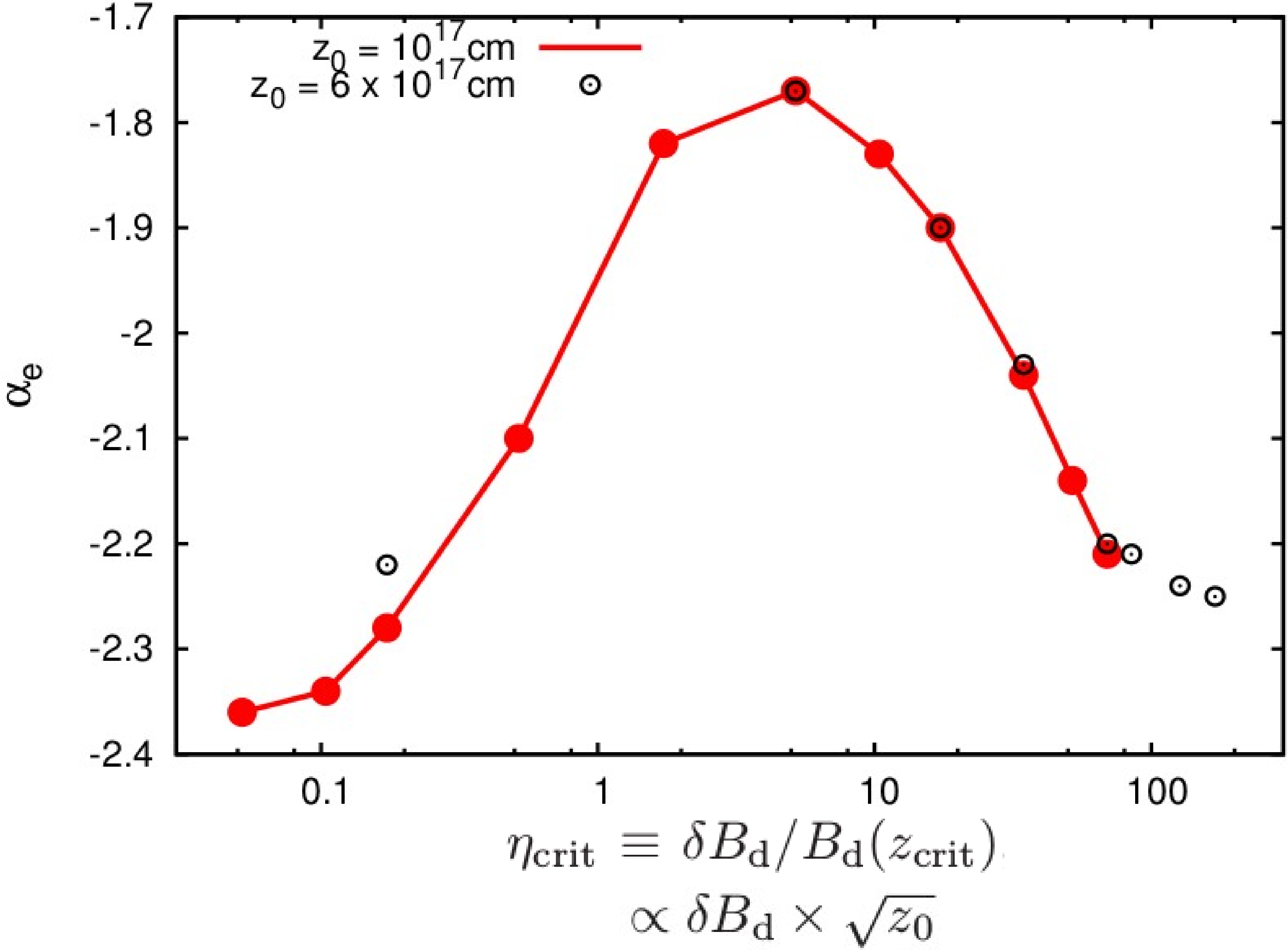


(5 – 9)%
> 3 TeV

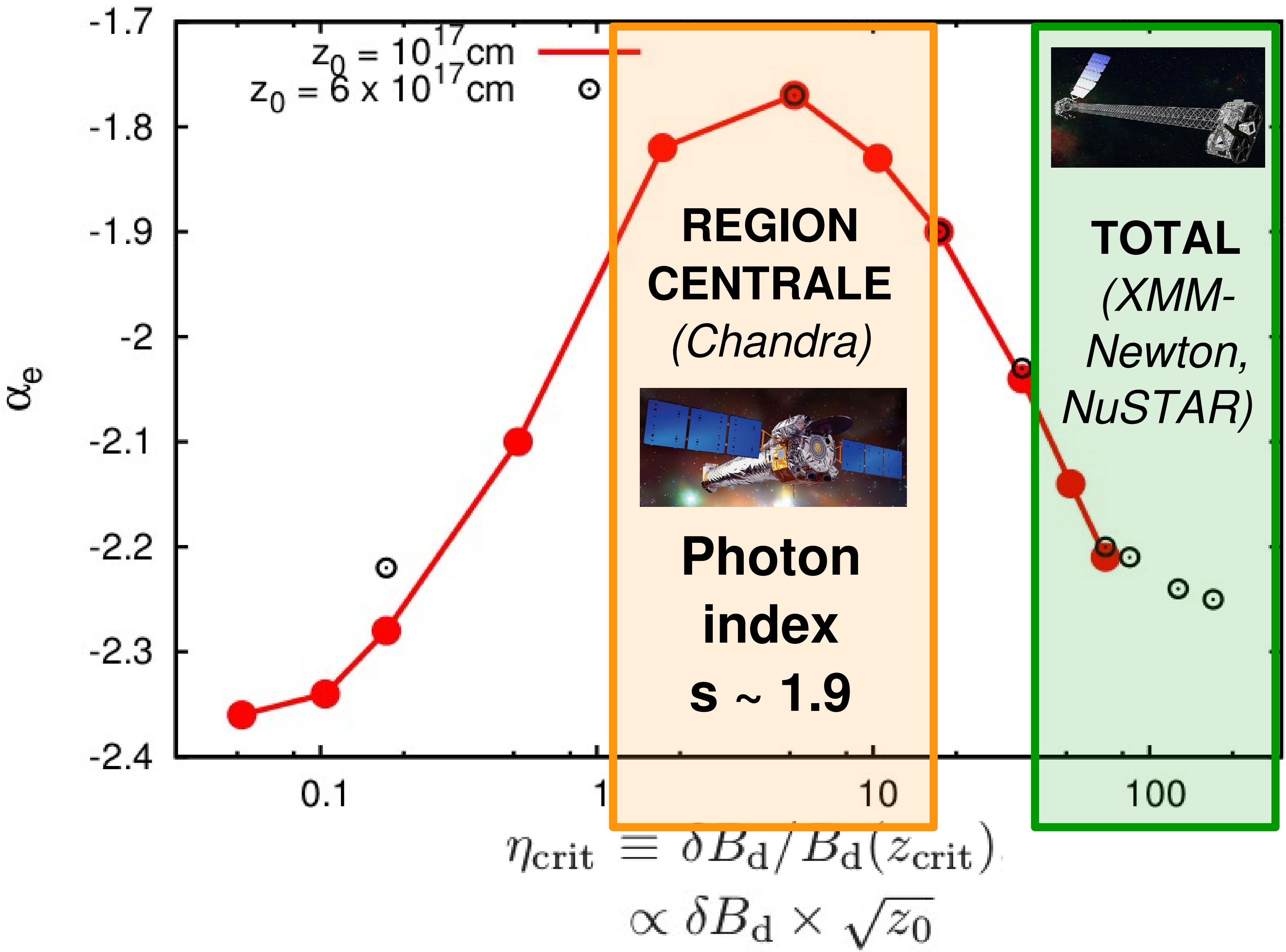
$t_{synch} \sim t_{gyr}$ =>

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

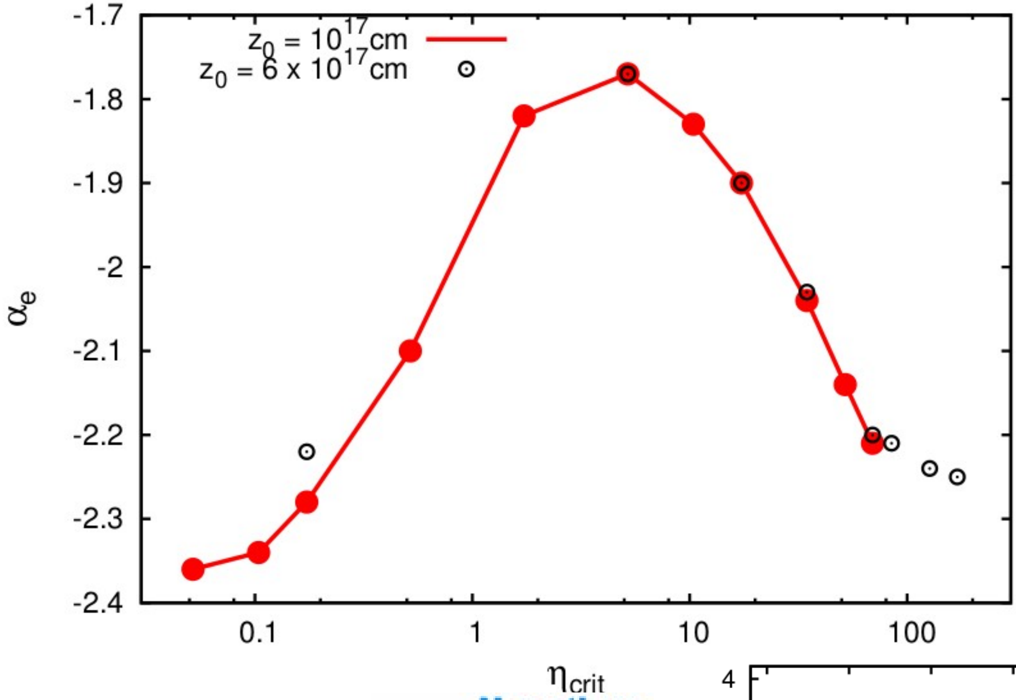
Indice spectral (electrons)

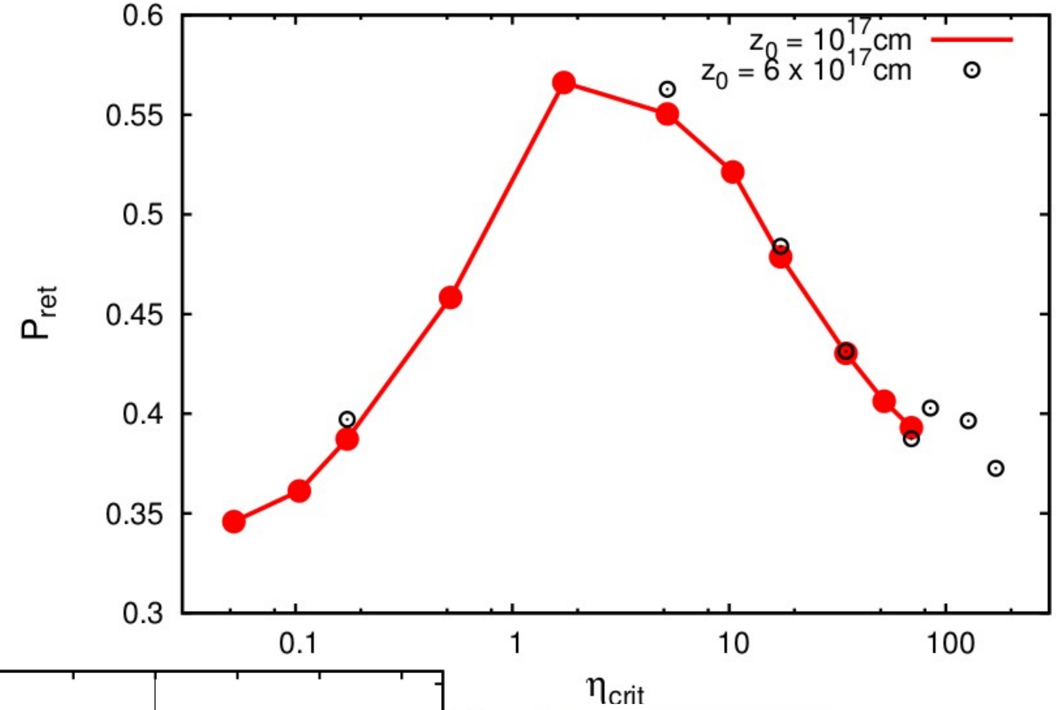


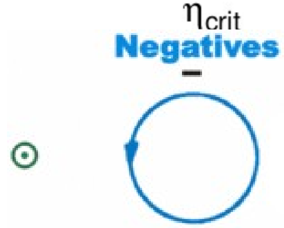
Indice spectral (electrons)

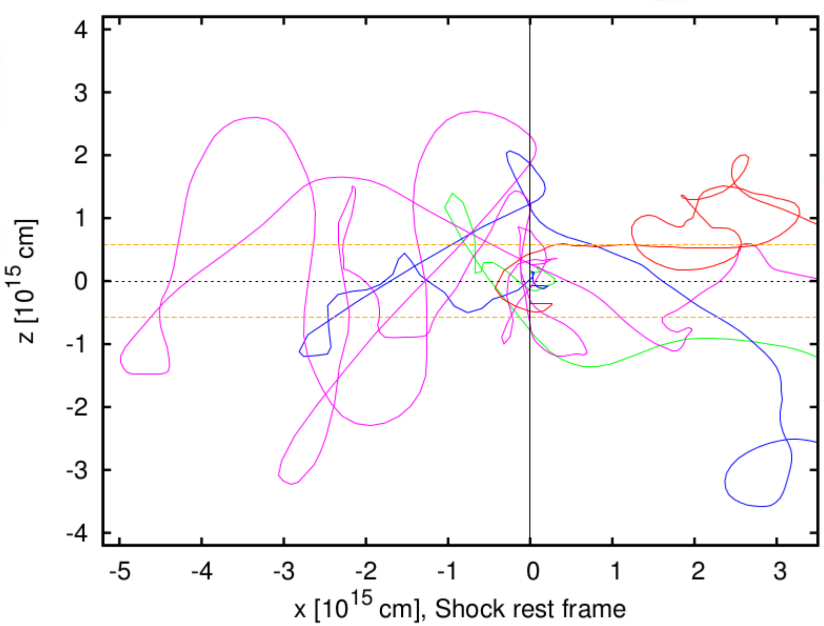


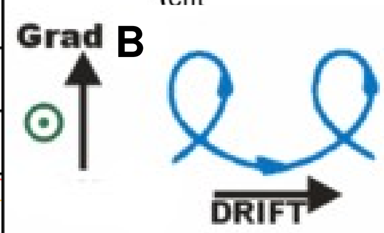
Indice spectral vs Probabilite de retourner dans la region en amont du CT



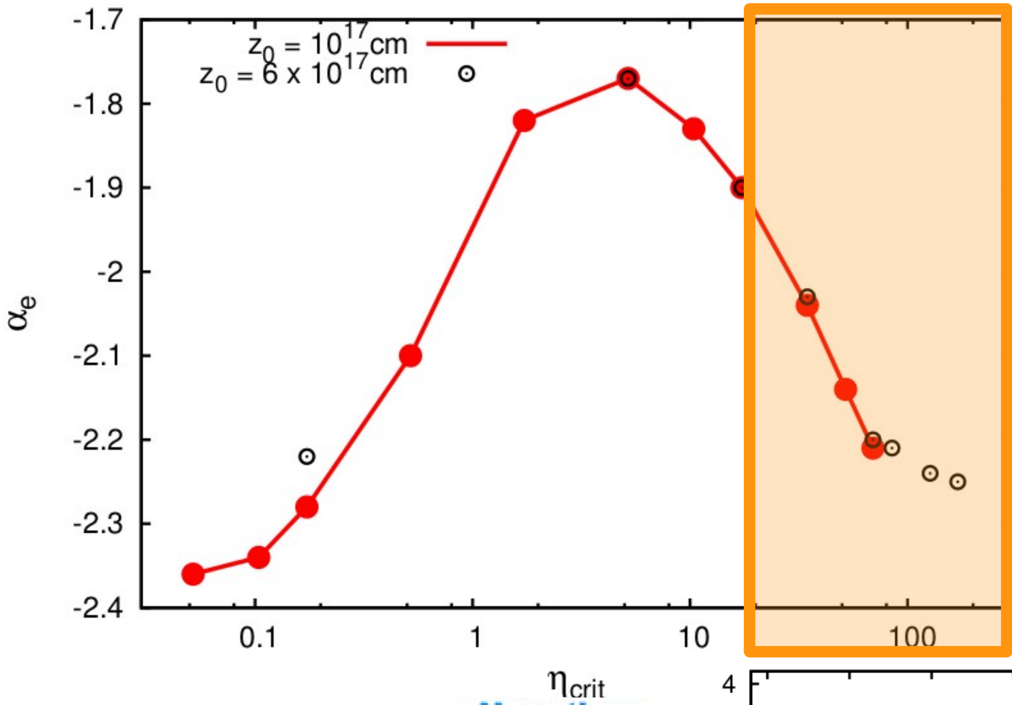


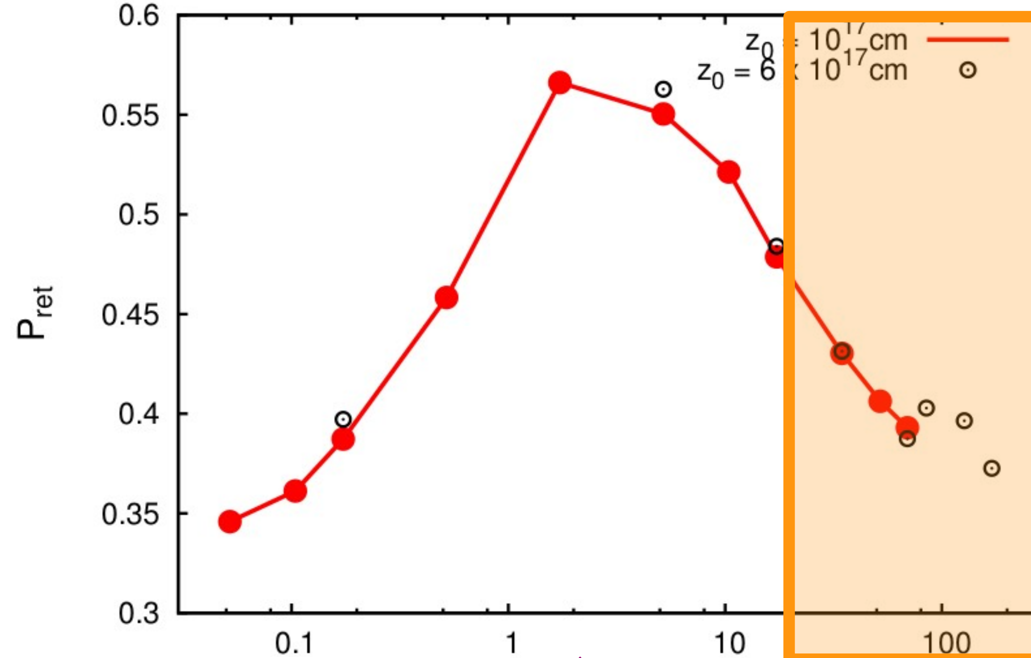


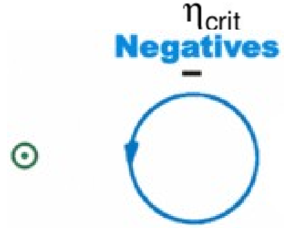


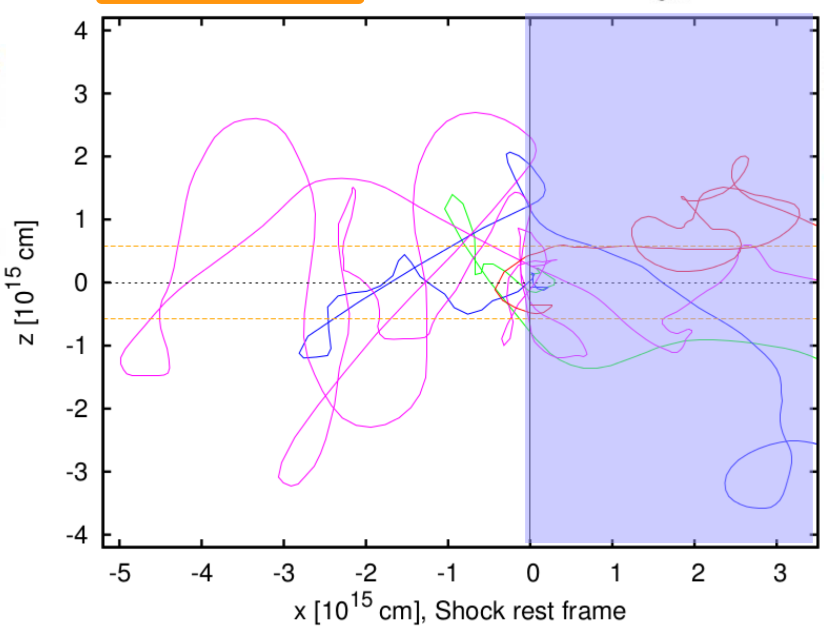


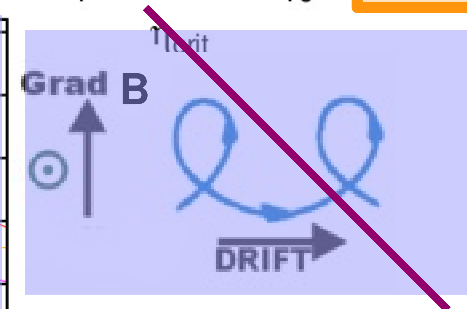
Indice spectral vs Probabilite de retourner dans la region en amont du CT

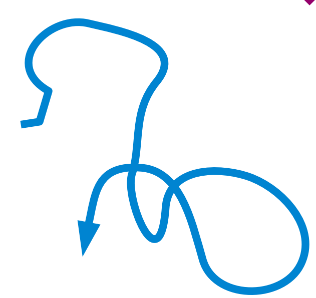




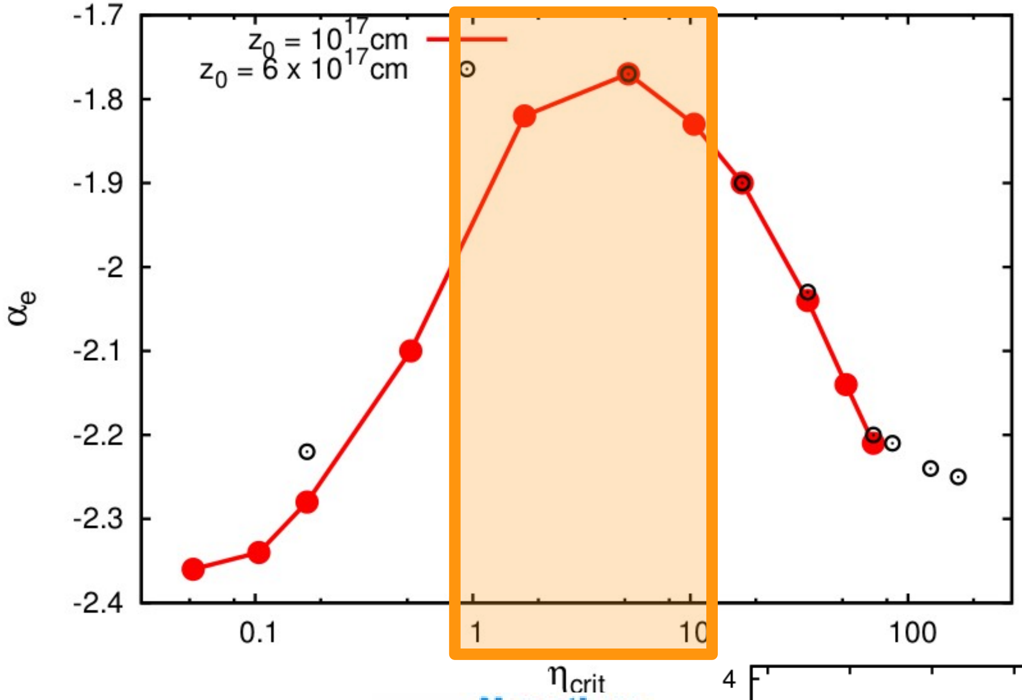


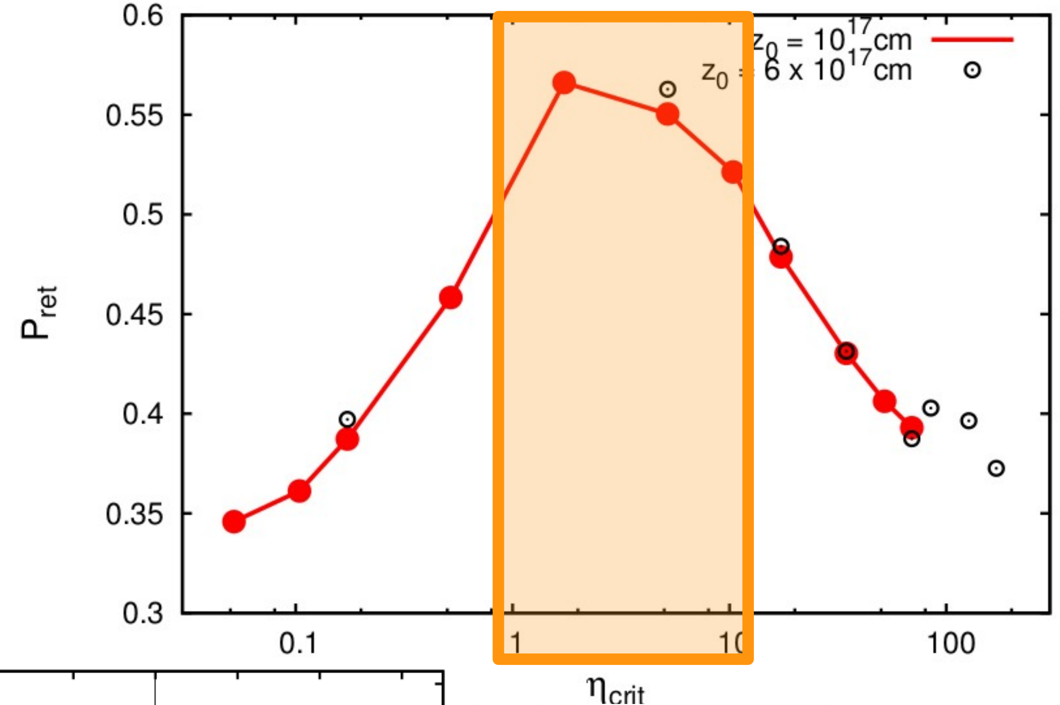


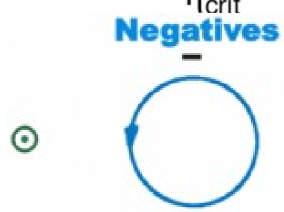


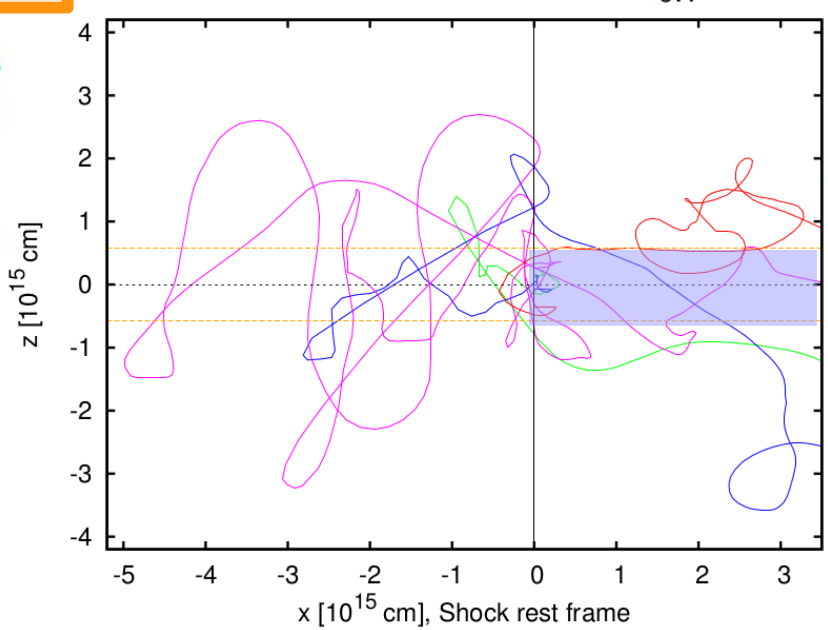


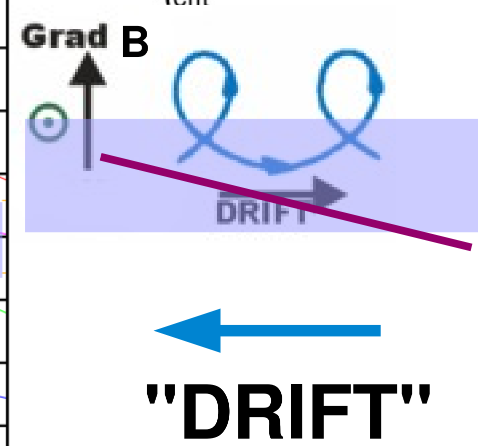
Indice spectral vs Probabilite de retourner dans la region en amont du CT



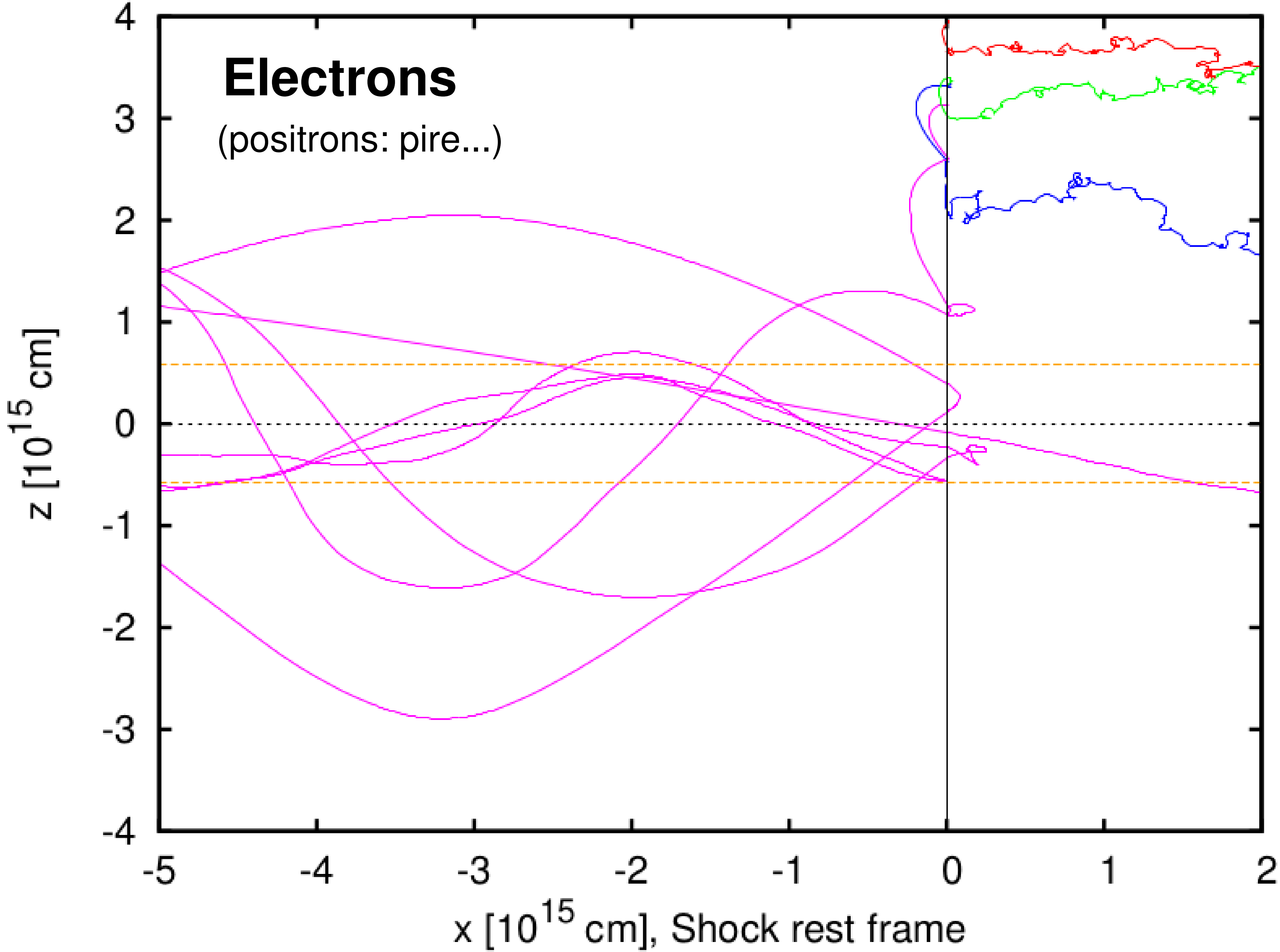








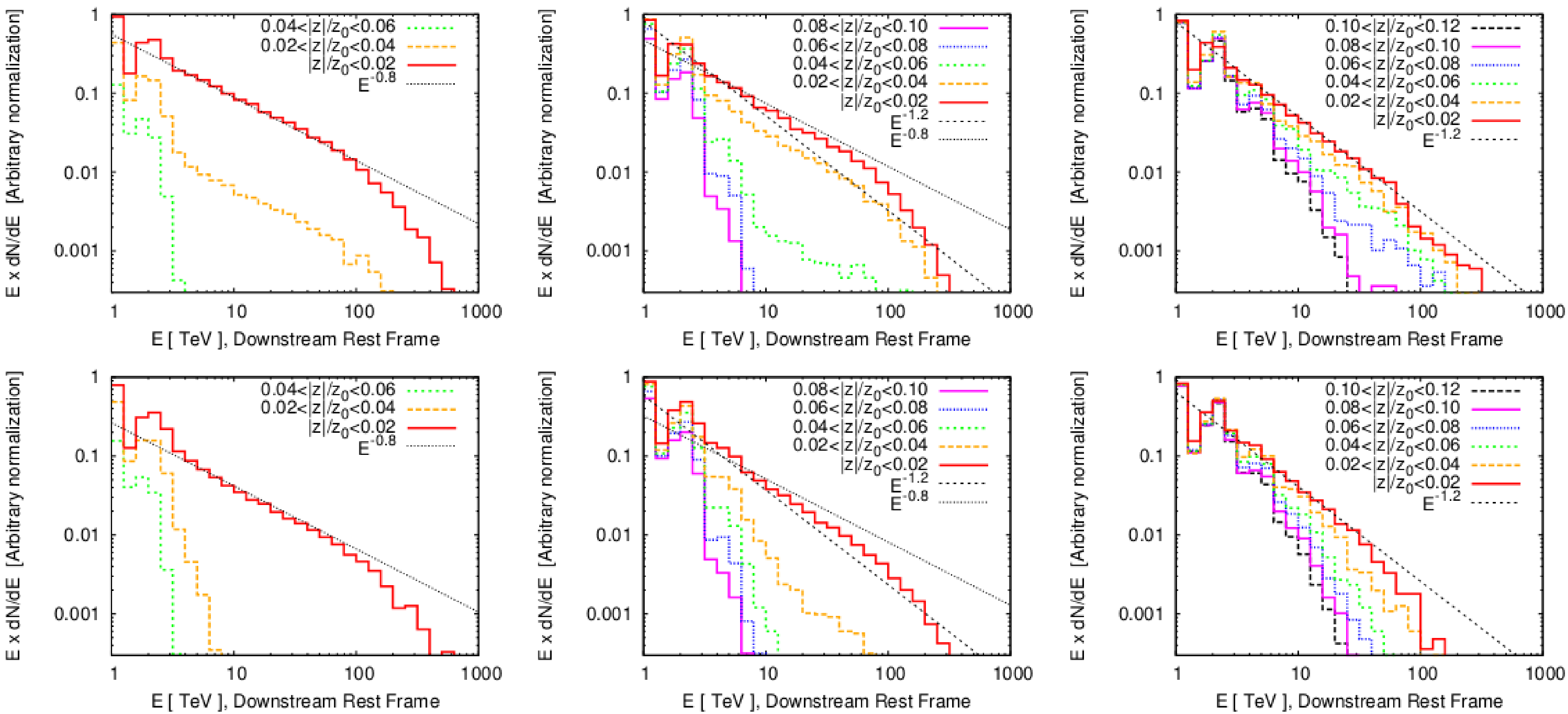
... Et plus loin du plan equatorial ?



… Et plus loin du plan equatorial ?

ligne 1 : $z_0 = 10^{17}\,\mathrm{cm} \quad \Theta \simeq 13°$ ligne 2 : $z_0 = 6 \times 10^{17}\,\mathrm{cm} \quad \Theta \simeq 80°$

$\delta B_{\mathrm{d}} = 30\,\mu\mathrm{G}$ $\delta B_{\mathrm{d}} = 100\,\mu\mathrm{G}$ $\delta B_{\mathrm{d}} = 400\,\mu\mathrm{G}$

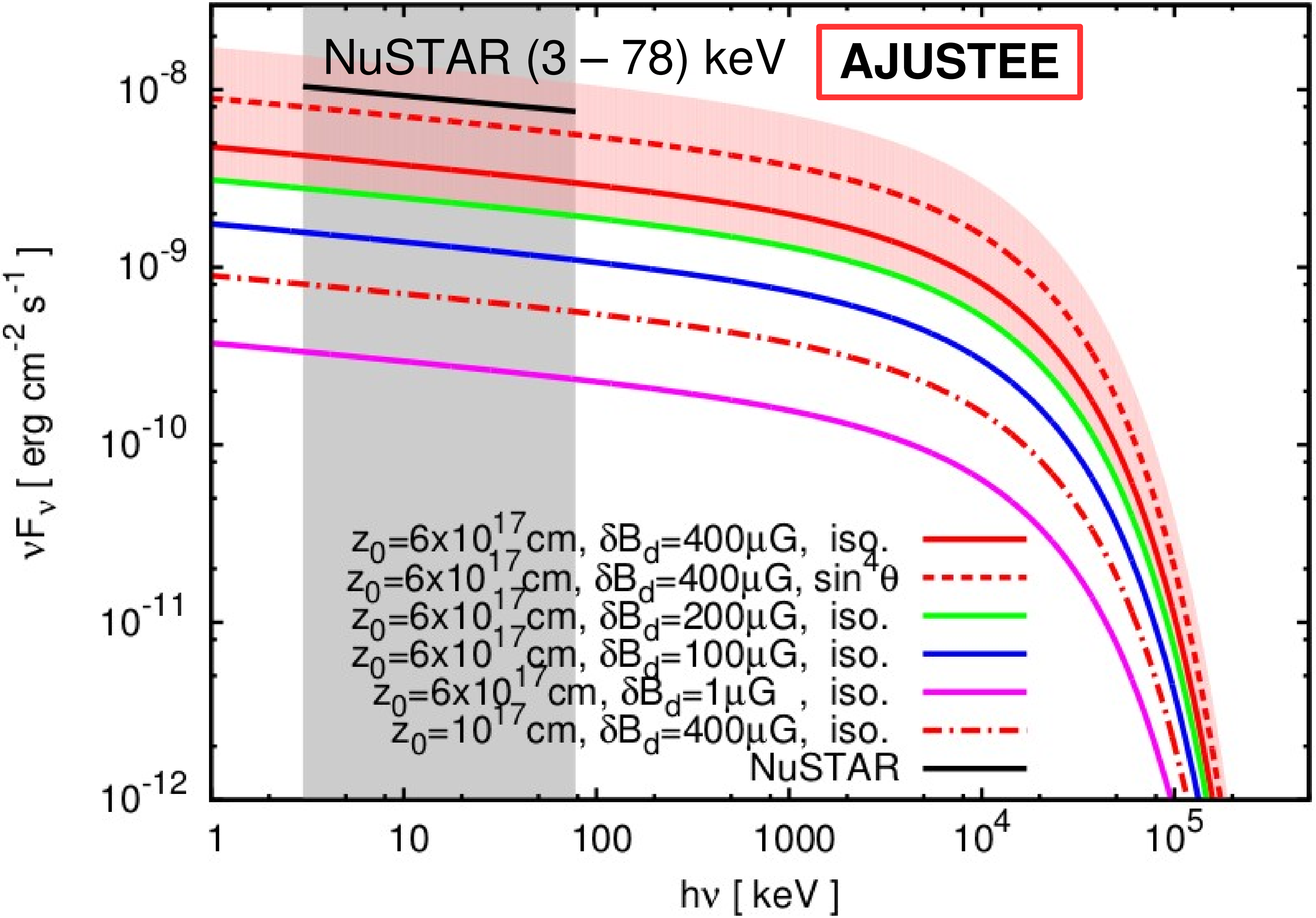


$z_{\mathrm{w}} \propto z_{\mathrm{crit}} \propto \sqrt{z_0}$ $z_{\mathrm{w}}/z_0 \propto 1/\sqrt{z_0}$ → Frac. e⁻ acc.

Emission synchrotron en X - Crabe

$E_{\rm max} = 1\,{\rm PeV}$ $\alpha_{\rm e} \simeq -2.2$ $B = 0.5\,{\rm mG}$

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



Conclusions

→ e^-, e^+ acceleres au **choc terminal** par le mecanisme de **Fermi du 1^er^ ordre**, proche du **plan equatorial** (region en **anneau**),

→ **e^- OU e^+ pref.^t^ acceleres** en fonction de la **polarite** du pulsar,

→ Du au **shock-drift** (une confinee sur des **orbites de Speiser**),

→ **Indice** spectre ~ **-2.4 … -1.8**,

→ **Ajuste le spectre synchrotron** HE de la nebuleuse du Crabe
- - - > Observations de **XMM-Newton**, et **NuSTAR**,

→ Explique le **spectre dur** mesure par **Chandra** (photon index ~ -1.9) proche de la region centrale de la nebuleuse.

Transparents supplementaires

Inductive Spikes in the Crab Nebula: A Theory of γ-Ray Flares

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(Received 29 August 2017; published 21 November 2017)

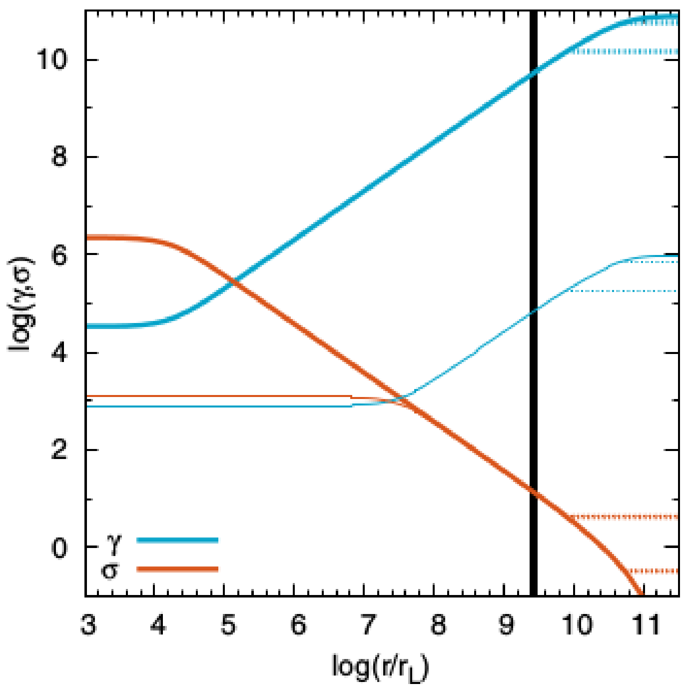


FIG. 1. The radial evolution of the magnetization parameter σ and fluid Lorentz factor γ in a pulsar wind for high pair loading ($\mu = 10^6$, thin lines) and low pair loading ($\mu = a_L$, thick lines), for parameters corresponding to the Crab ($a_L = 7.6 \times 10^{10}$). The position of the termination shock [26] is shown as a thick vertical line. For phase-averaged, dc magnetic fields equal to 90% and 50% of the field magnitude at launch, the horizontal, dotted lines show the solutions after the dissipation of the wave energy, i.e., in the regions $r \gtrsim 10^{10} r_L$ and $r \gtrsim 10^{11} r_L$, respectively.

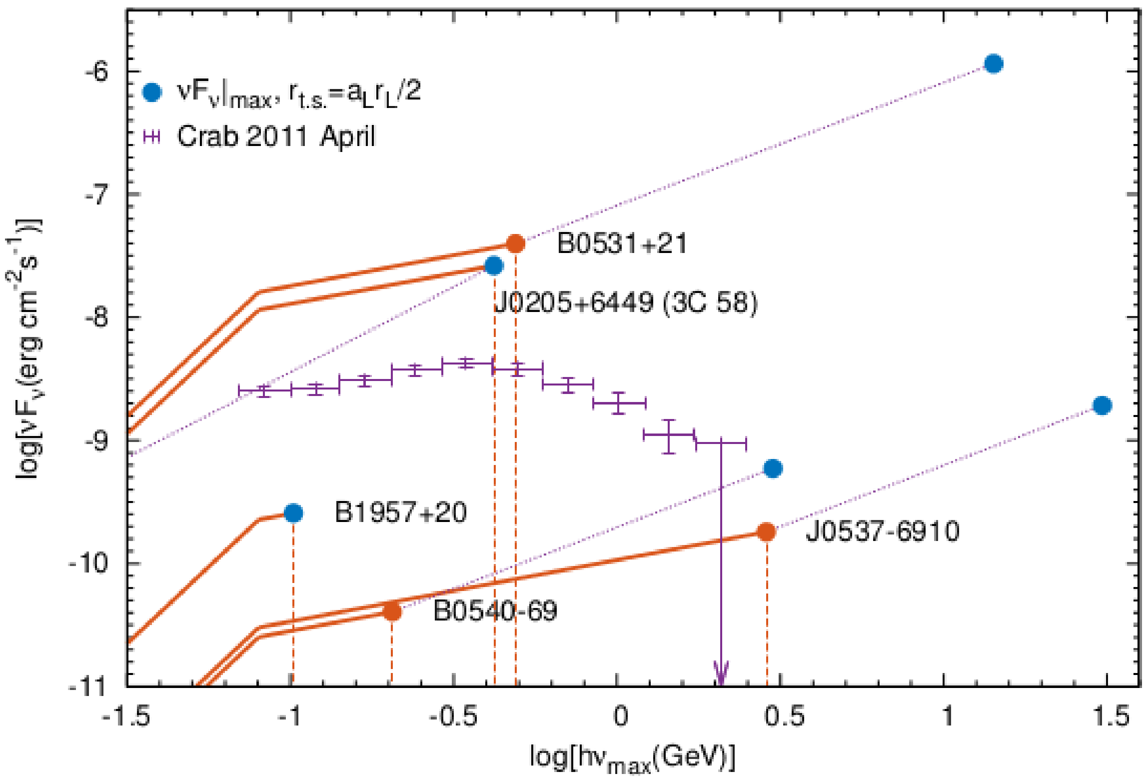
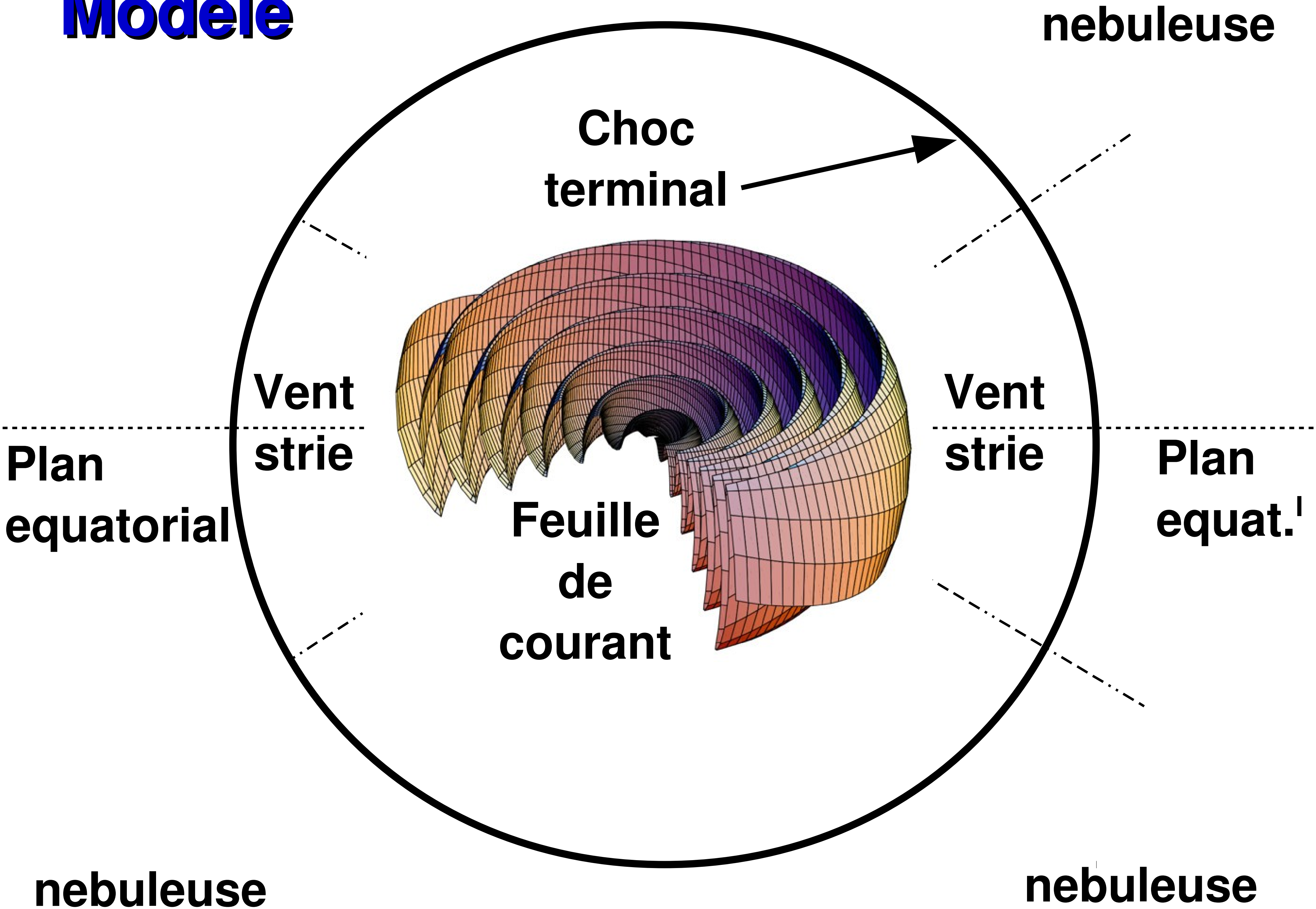


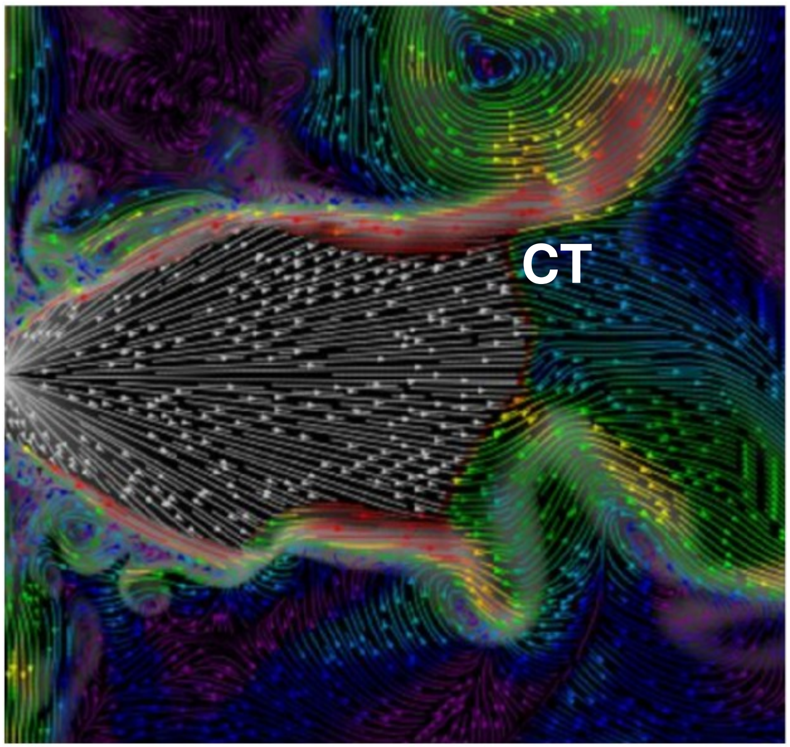
Figure 2: The predicted flare spectrum (solid lines), for the three most powerful known pulsars: the Crab (B0531+21), and two objects in the Large Magellanic Cloud, assuming a turnover at $h\nu_t = 80$MeV and a filling factor $f = 1$. For B0531+21, J0537−6910 and B0540−69, dotted lines trace the locus of the peak flux as the position of the termination shock is varied between the observed value (orange dots) and $a_L r_L/2$ (blue dots). For J0205+6449 (3C 58) and B1957+20 only the (optimistic) blue dots and the corresponding spectra are shown. Fermi observations of the powerful flare from the Crab Nebula in April 2011 are also shown — points taken from Fig 6, epoch 7 of Ref. [3].

Modele

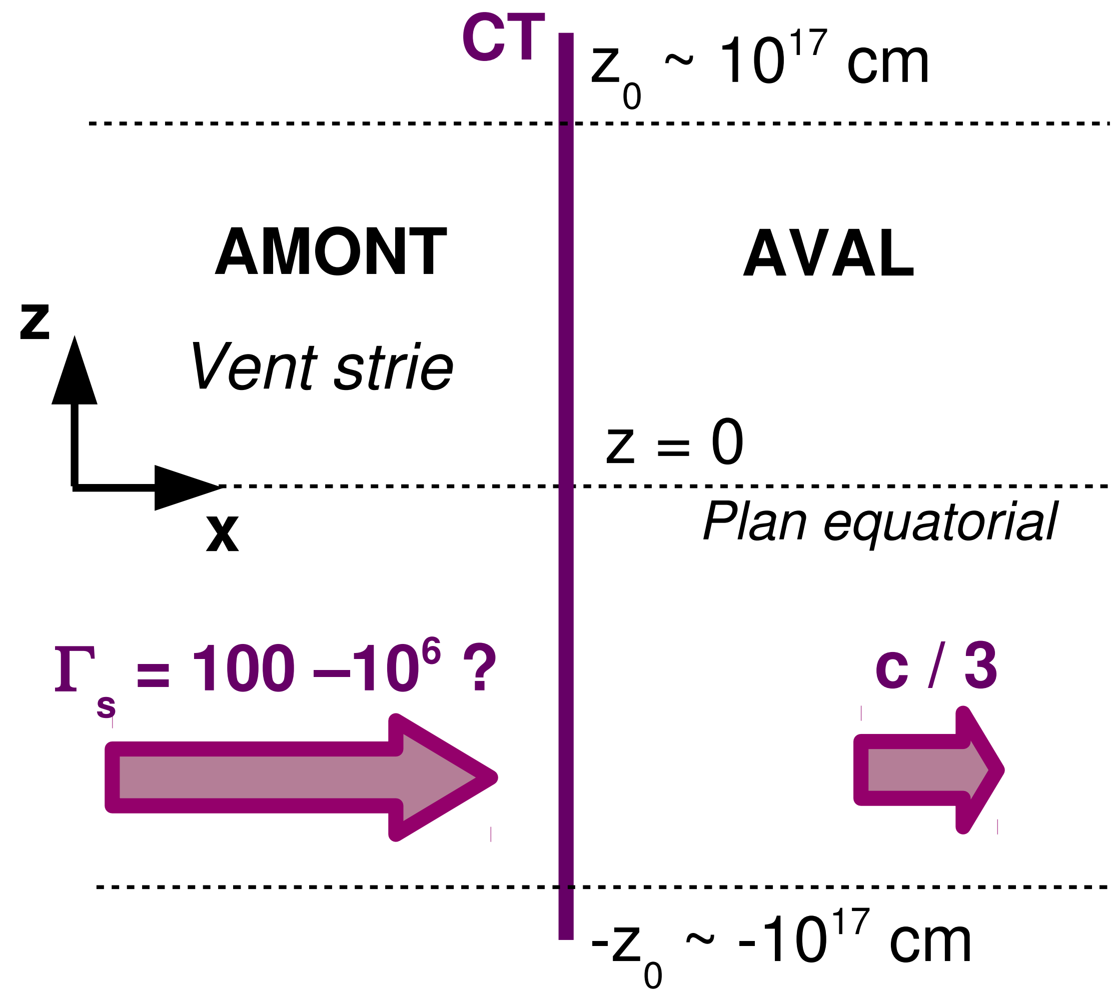

nebuleuse
Choc terminal
Vent strie
Plan equatorial
Vent strie
Plan equat.
Feuille de courant
nebuleuse
nebuleuse

Modele et simulations numeriques

Buehler & Giomi (2016) :

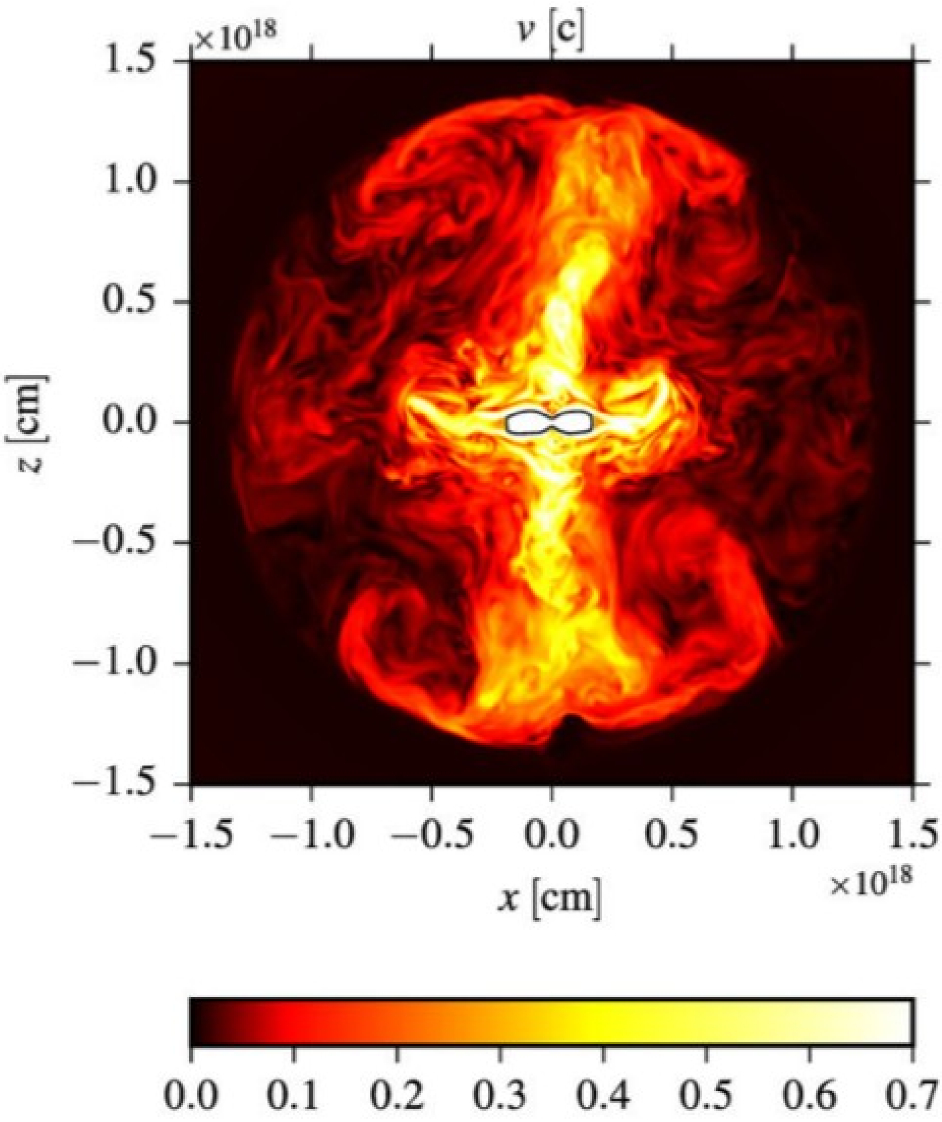


NOTRE MODELE (PLANAIRE) :

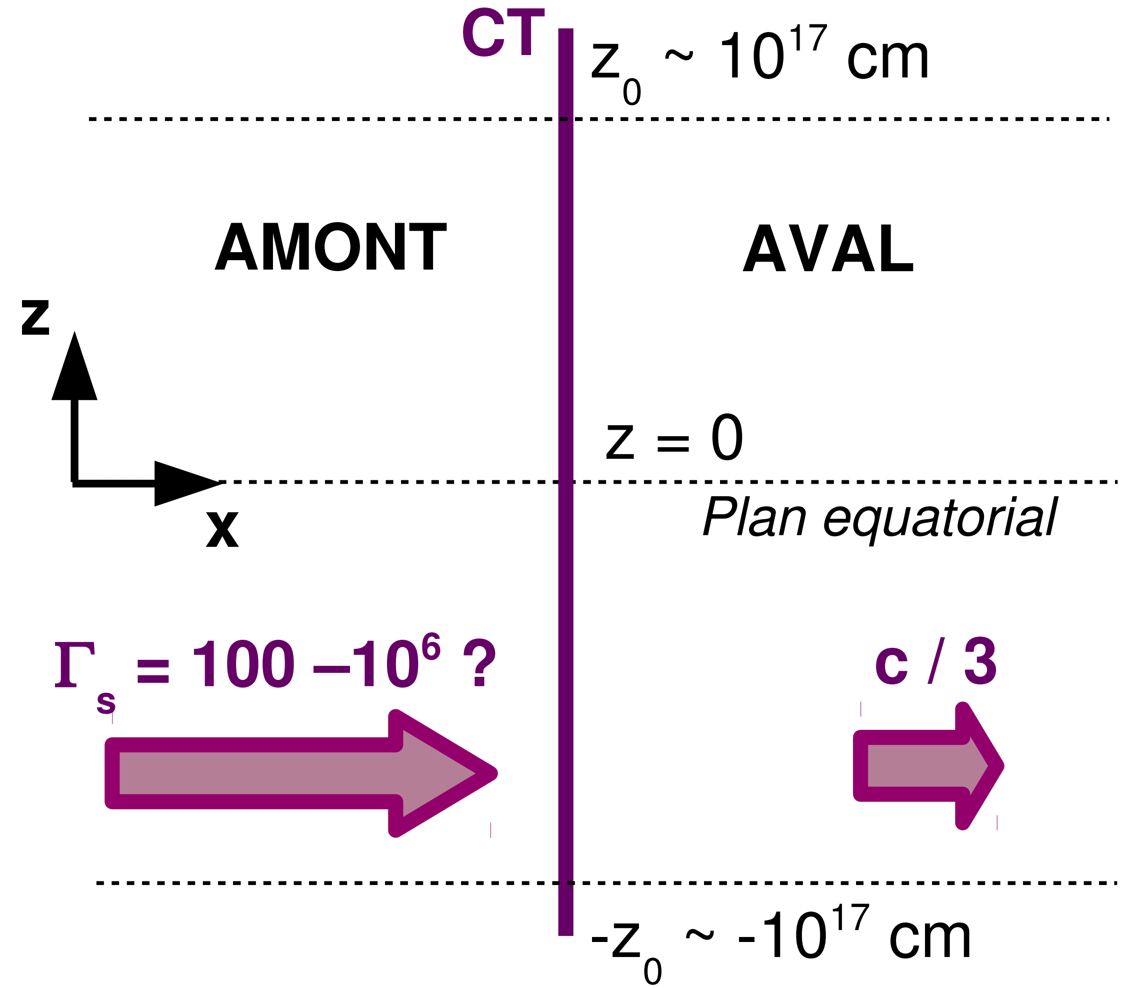


Modele et simulations numeriques

Porth *et al.* (2014, 2016):



<u>NOTRE MODELE (PLANAIRE) :</u>



Modele et simulations numeriques

NOTRE MODELE (PLANAIRE) :

$$\mathbf{B}_{\mathrm{u}}(z) = \begin{cases} -B_{\mathrm{u},0}\hat{\mathbf{y}} & \text{if } z > z_0 \\ -B_{\mathrm{u},0}(z/z_0)\hat{\mathbf{y}} & \text{if } |z| \leq z_0 \\ +B_{\mathrm{u},0}\hat{\mathbf{y}} & \text{if } z < -z_0 \end{cases}$$

"Jump conditions" :

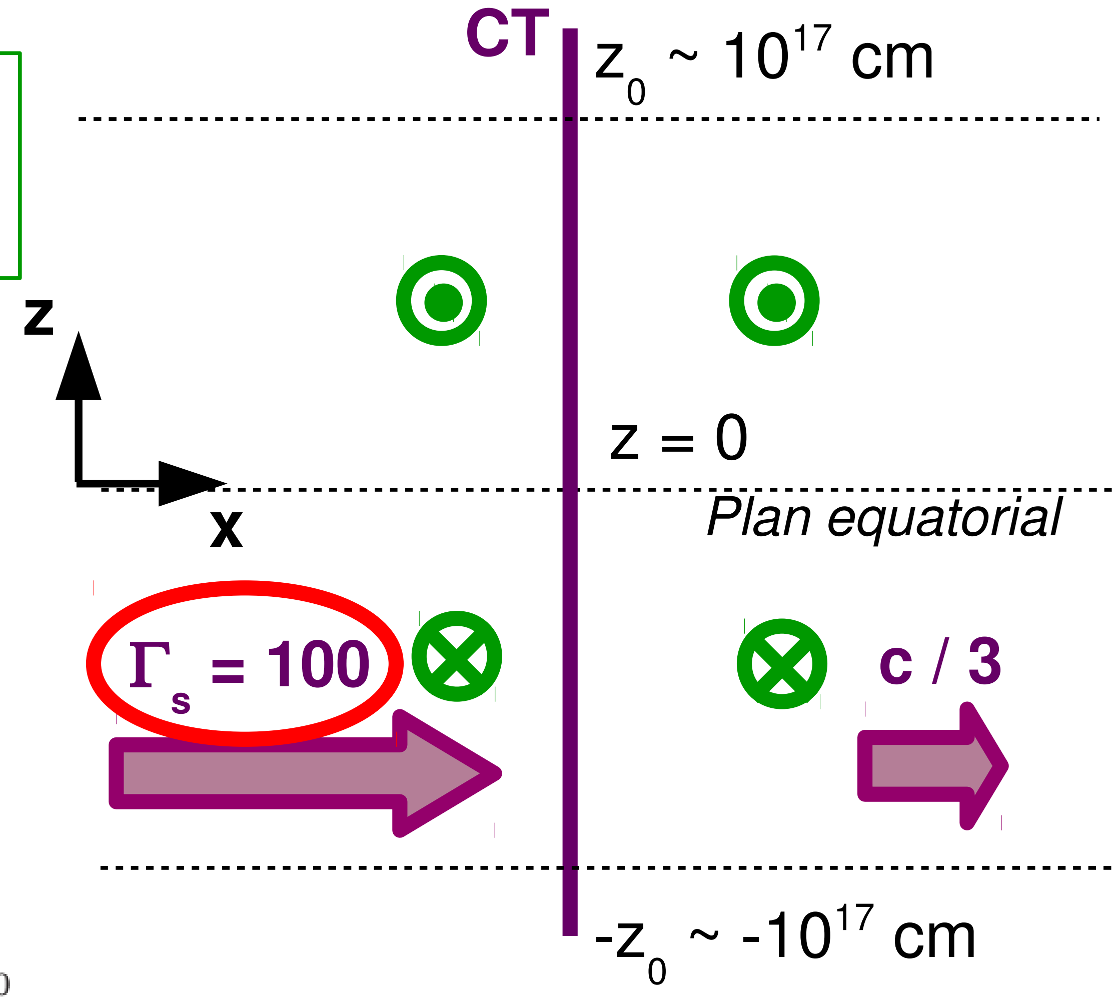
$B_{u,RF} = (\Gamma_d/3\Gamma_u)B_{d,RF}$

Dans le Referentiel du choc :

$$\mathbf{E}'_{\mathrm{u}}(z) = \frac{1}{2\sqrt{2}} \times \begin{cases} -B_{\mathrm{d},0}\hat{\mathbf{y}} & \text{if } z > z_0 \\ -B_{\mathrm{d},0}(z/z_0)\hat{\mathbf{y}} & \text{if } |z| \leq z_0 \\ +B_{\mathrm{d},0}\hat{\mathbf{y}} & \text{if } z < -z_0 \end{cases}$$

$$\mathbf{B}'_{\mathrm{u}}(z) = \frac{1}{2\sqrt{2}\beta_{\mathrm{u}}} \times \begin{cases} -B_{\mathrm{d},0}\hat{\mathbf{y}} & \text{if } z > z_0 \\ -B_{\mathrm{d},0}(z/z_0)\hat{\mathbf{y}} & \text{if } |z| \leq z_0 \\ +B_{\mathrm{d},0}\hat{\mathbf{y}} & \text{if } z < -z_0 \end{cases}$$

≈ 1 (si ultrarelativiste)



Modele et simulations numeriques

INJECTION :

Energie par particule en unites de $m_e c^2$ apres dissipation du flux de Poynting (vent isotrope):

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

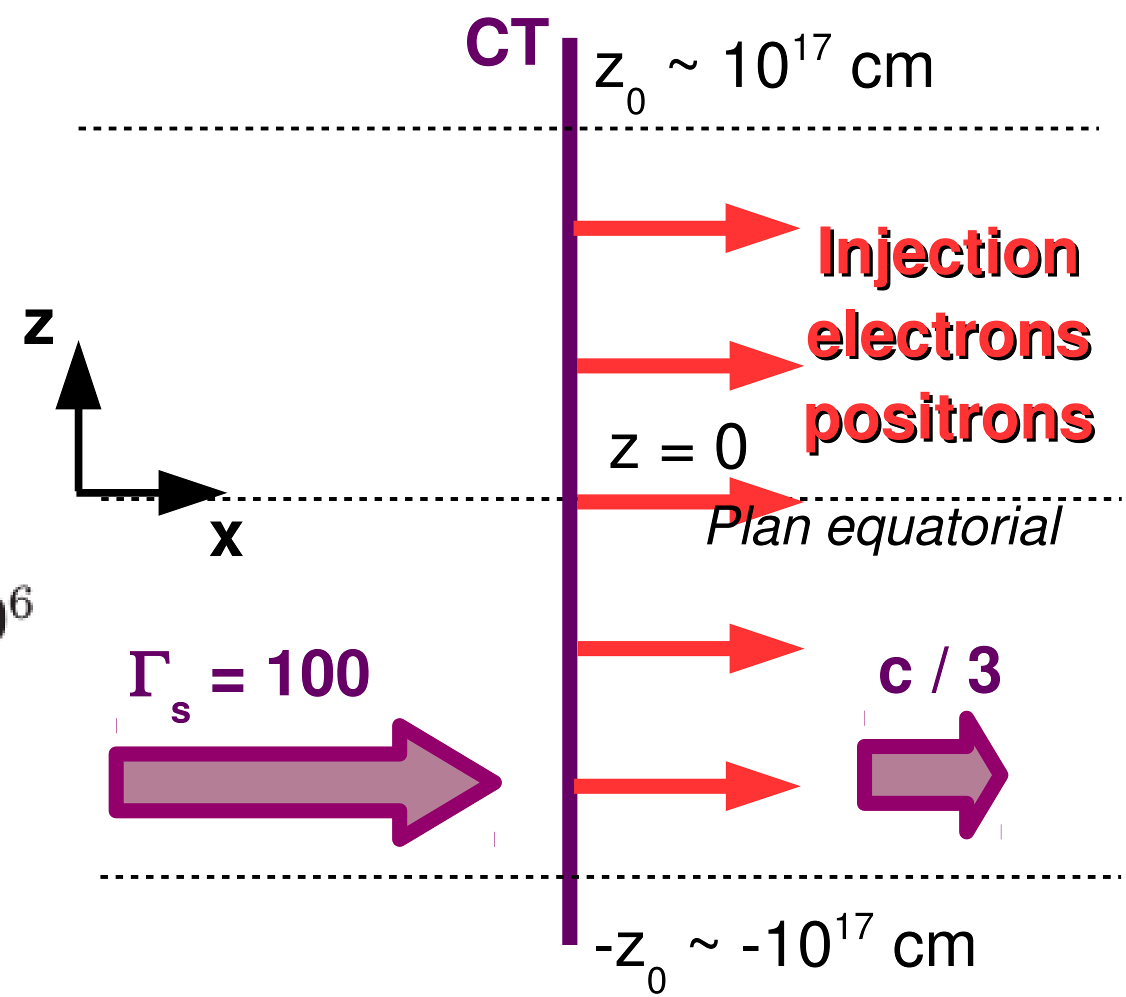
Crabe (Olmi+'16): $10^4 \lesssim \mu \lesssim 10^6$

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

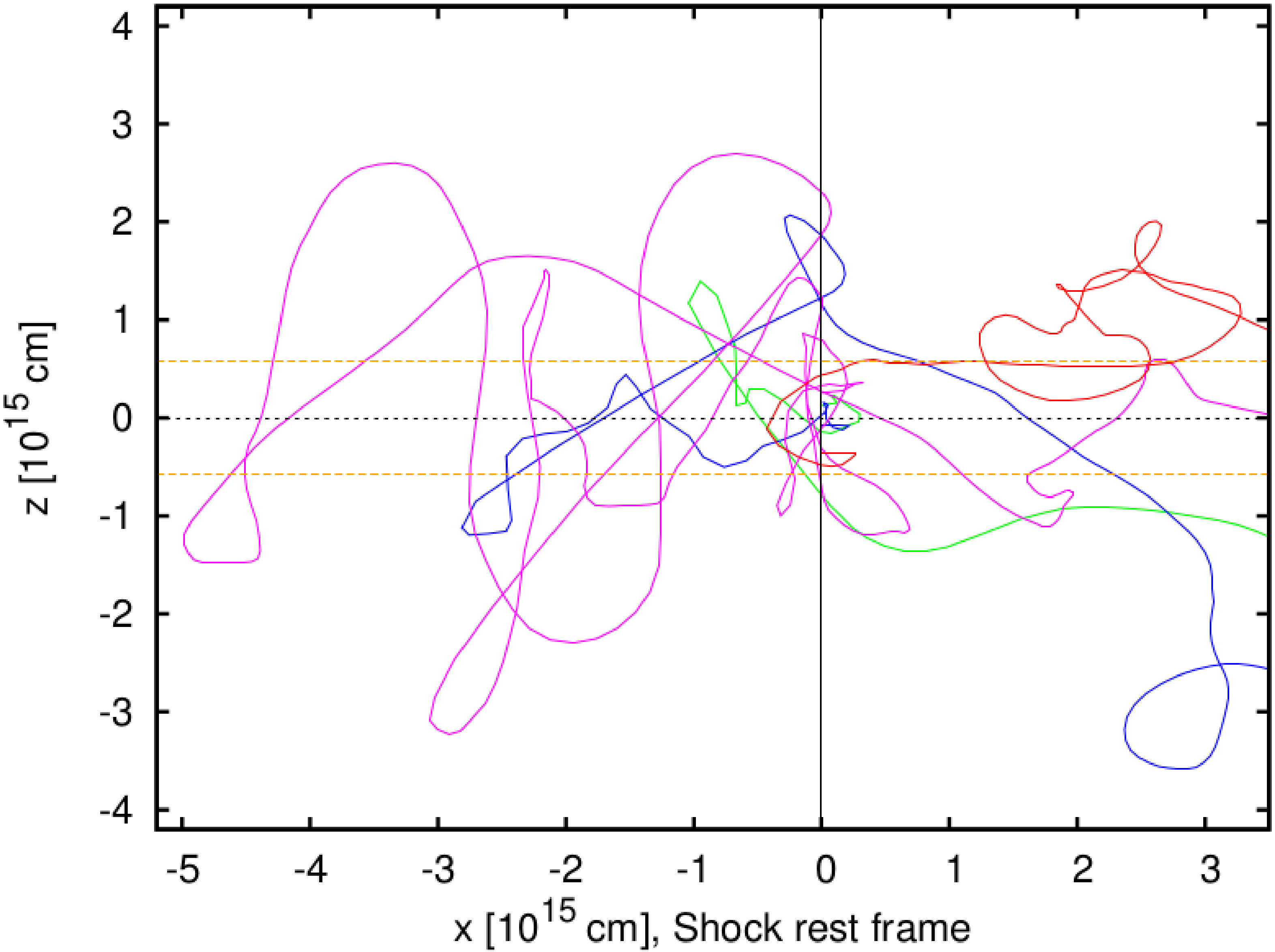
$$E_{\rm inj,d} = \gamma_{\rm inj,d} m_{\rm e} c^2 \approx \mu m_{\rm e} c^2$$

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

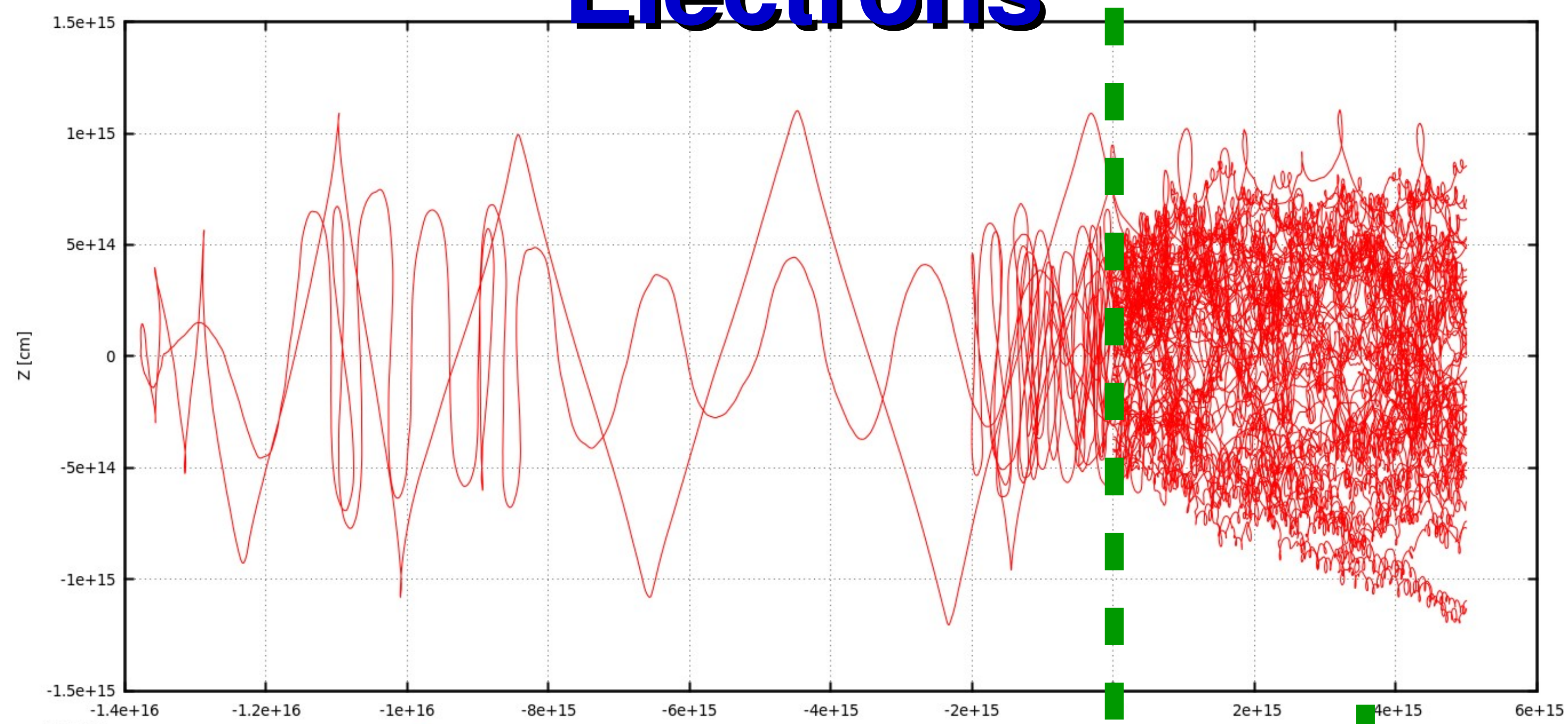
NOTRE MODELE (PLANAIRE) :



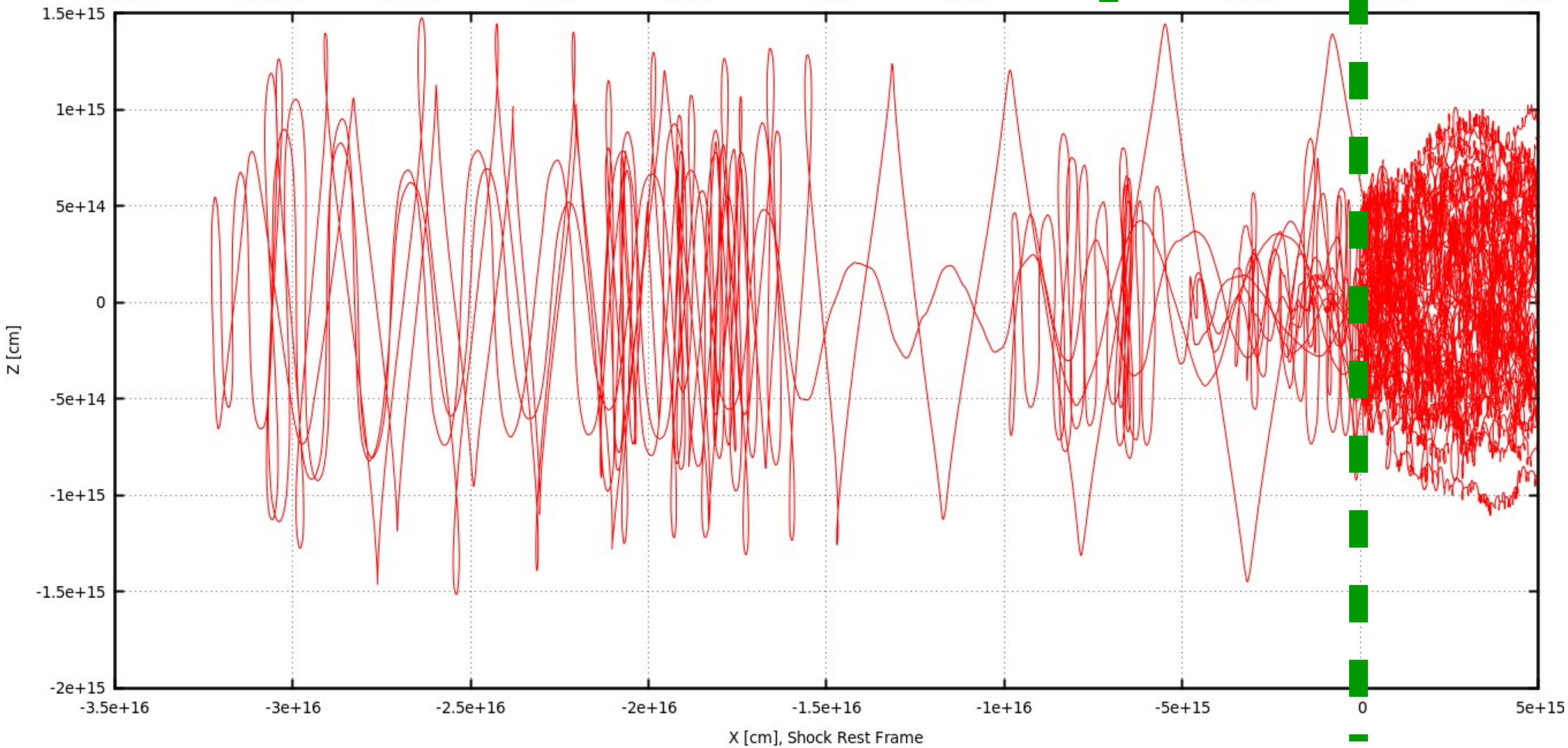
Electrons



Electrons

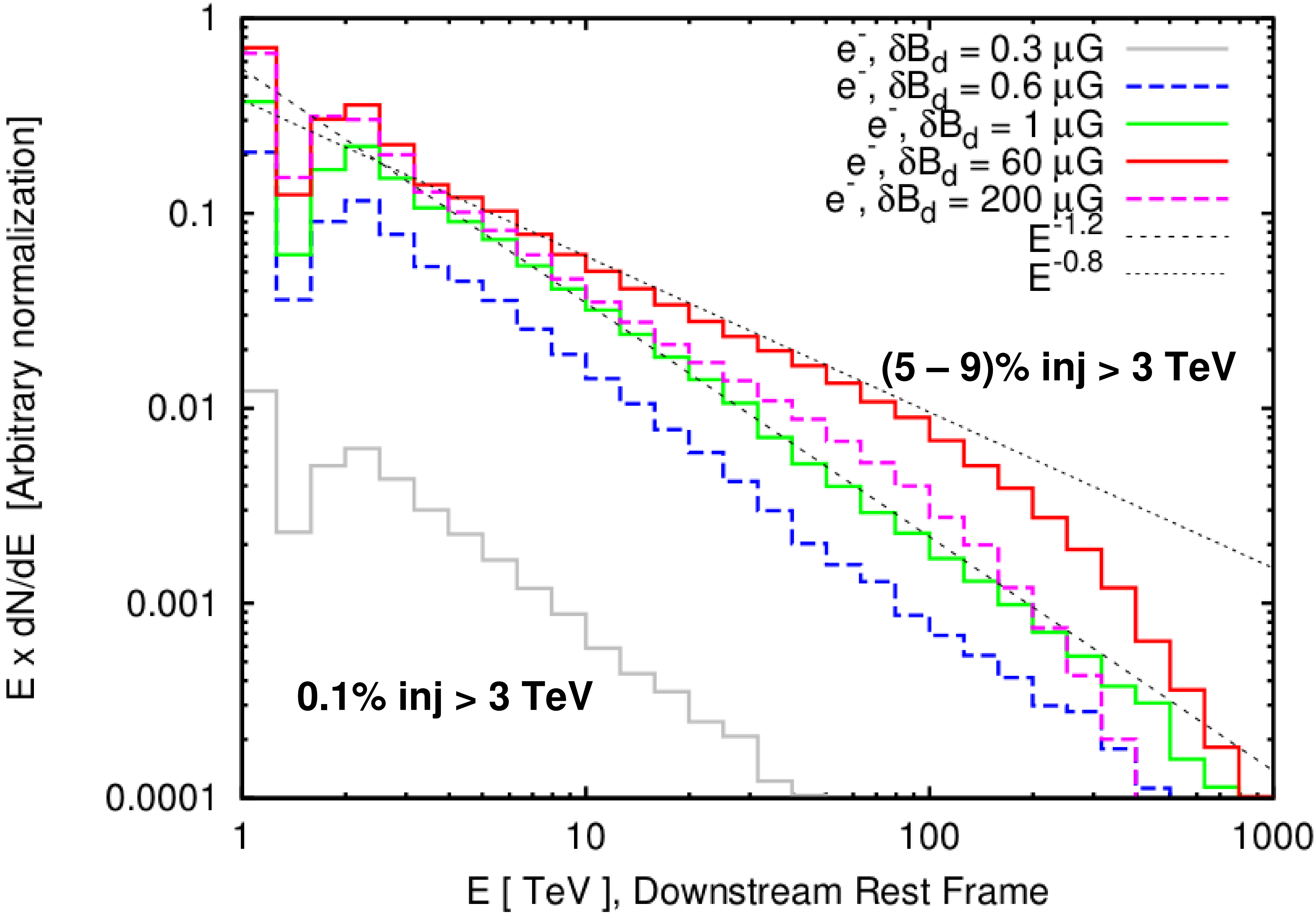


1.5e+15
1e+15
5e+14
0
-5e+14
-1e+15
-1.5e+15
Z [cm]
-1.4e+16
-1.2e+16
-1e+16
-8e+15
-6e+15
-4e+15
-2e+15
2e+15
4e+15
6e+15

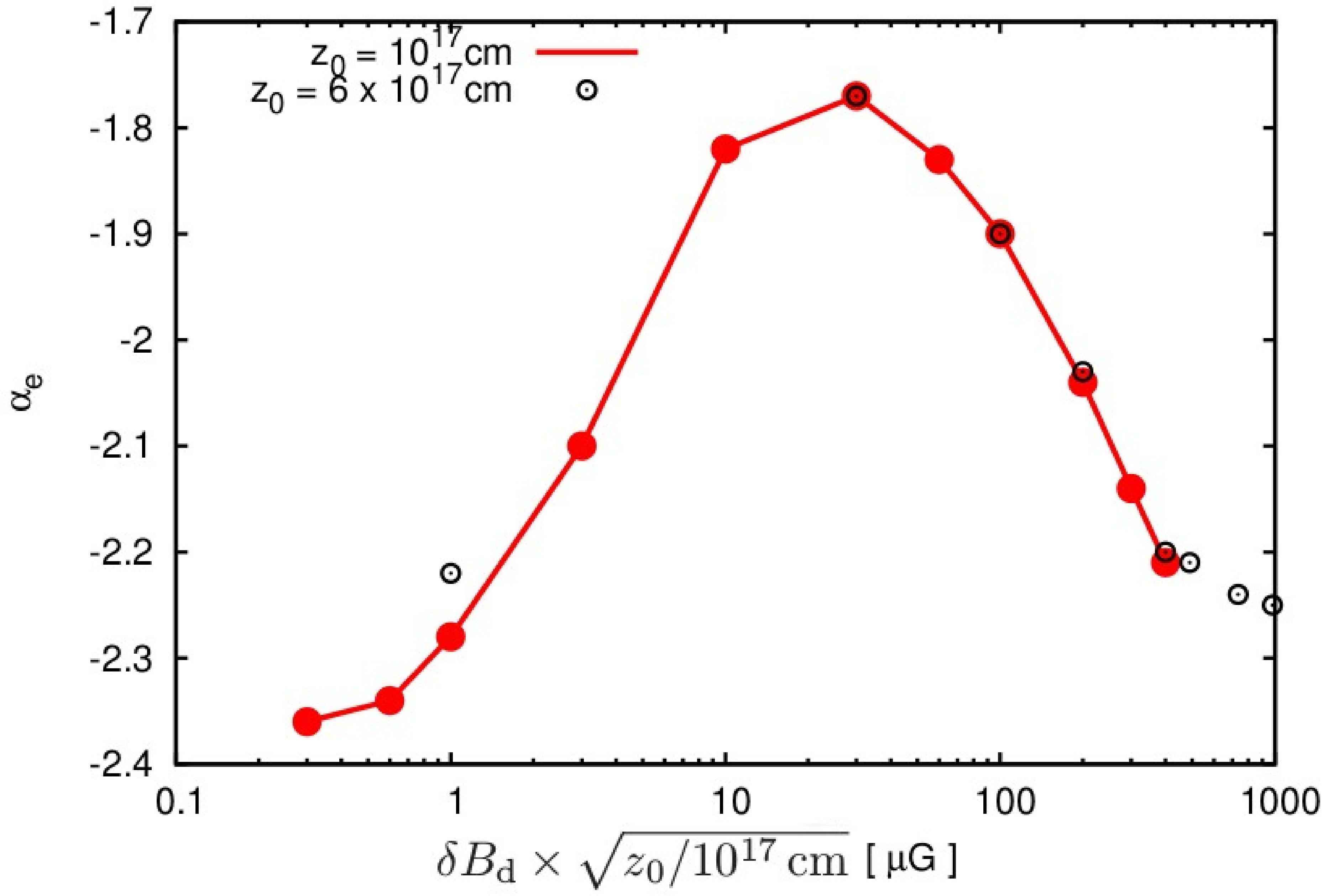


1.5e+15
1e+15
5e+14
0
-5e+14
-1e+15
-1.5e+15
-2e+15
Z [cm]
-3.5e+16
-3e+16
-2.5e+16
-2e+16
-1.5e+16
-1e+16
-5e+15
0
5e+15
X [cm], Shock Rest Frame

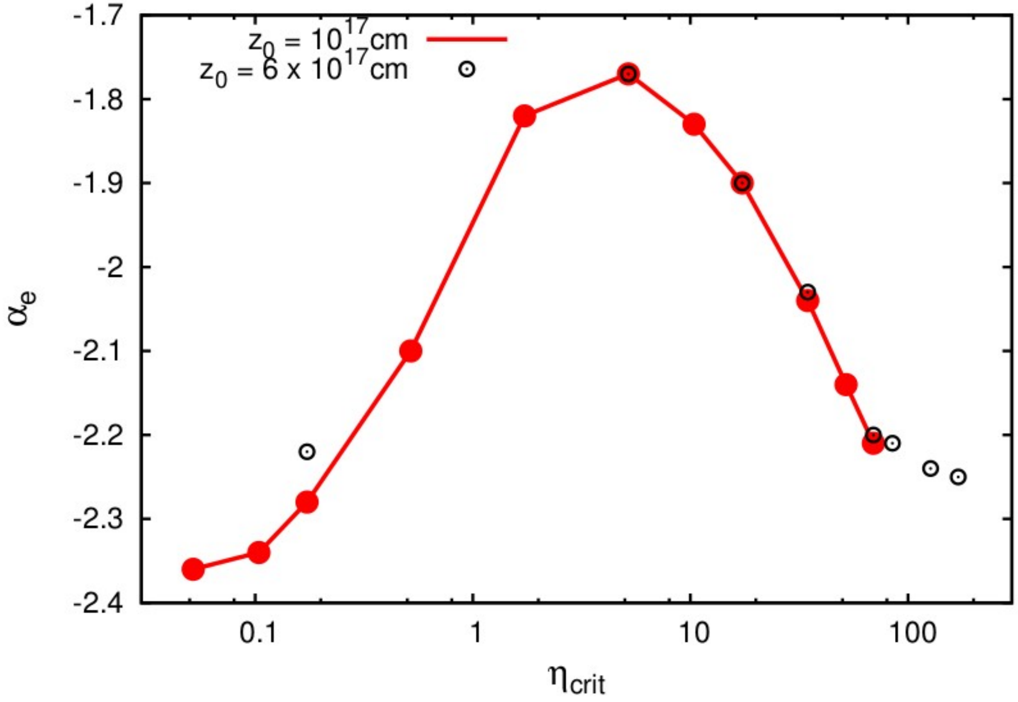
Spectre electrons vs niveau turbulence

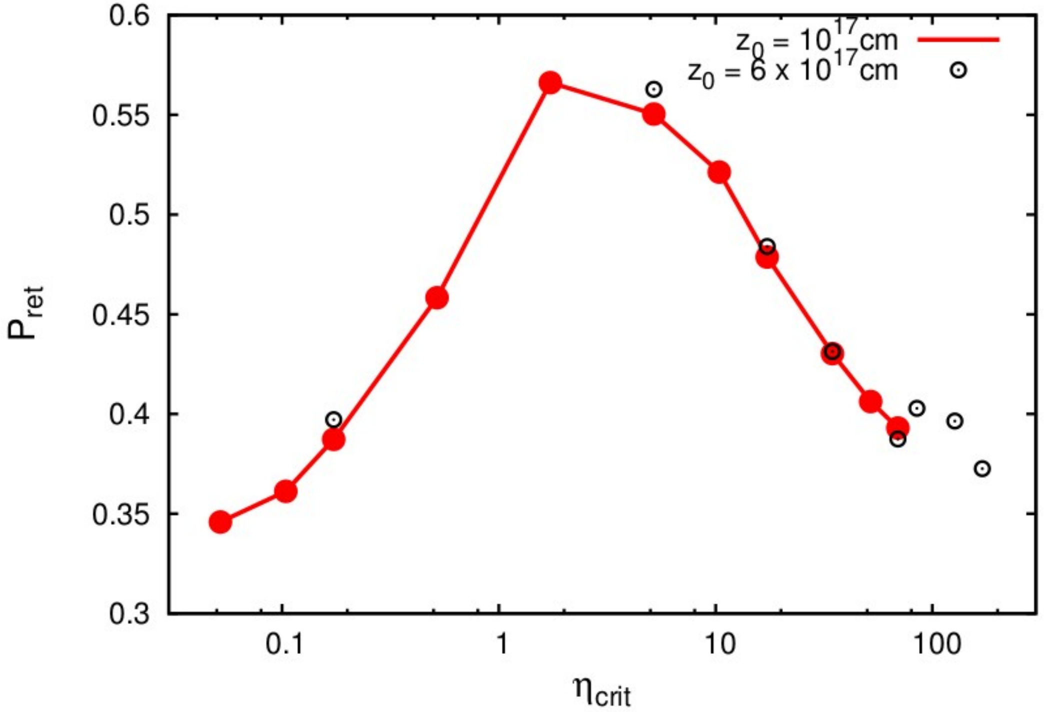


Indice spectral (electrons)



Indice spectral vs Probabilite de retourner dans la region en amont du CT





Fortement correles!

e^- injectes dans la region equatoriale

SPECTRUM, RETURN PROBABILITY AND ENERGY GAIN PER CYCLE FOR ELECTRONS INJECTED AT $|z|/z_{\rm crit} \le 2.6$

$z_0/(10^{17}\,{\rm cm})$	$\delta B_{\rm d}/(1\,\mu{\rm G})$	$\eta_{\rm crit}$	$\alpha_{\rm e}$	$\mathcal{P}_{\rm ret}$	$(\Delta E/E)_{\rm d}$	$\epsilon_{\rm acc,3}$
1	0.3	5.2×10^{-2}	-2.36 ± 0.03	0.35	1.05	1.1×10^{-3}
1	0.6	0.10	-2.34 ± 0.02	0.36	1.07	2.1×10^{-2}
1	1	0.17	-2.28 ± 0.02	0.39	1.06	4.4×10^{-2}
1	3	0.52	-2.10 ± 0.02	0.46	1.08	6.9×10^{-2}
1	10	1.7	-1.82 ± 0.03	0.57	1.07	8.4×10^{-2}
1	30	5.2	-1.77 ± 0.01	0.55	1.10	5.7×10^{-2}
1	60	10	-1.83 ± 0.01	0.52	1.11	5.3×10^{-2}
1	100	17	-1.90 ± 0.01	0.48	1.09	5.2×10^{-2}
1	200	35	-2.04 ± 0.01	0.43	1.09	4.7×10^{-2}
1	300	52	-2.14 ± 0.02	0.41	1.09	4.8×10^{-2}
1	400	69	-2.21 ± 0.01	0.39	1.08	4.5×10^{-2}
6	0.41	0.17	-2.22 ± 0.01	0.40	1.05	3.2×10^{-2}
6	12	5.2	-1.77 ± 0.01	0.56	1.09	6.3×10^{-2}
6	41	17	-1.90 ± 0.01	0.48	1.11	5.0×10^{-2}
6	82	35	-2.03 ± 0.02	0.43	1.14	4.4×10^{-2}
6	163	69	-2.20 ± 0.03	0.39	1.13	4.7×10^{-2}
6	200	85	-2.21 ± 0.03	0.40	1.16	
6	300	1.3×10^2	-2.24 ± 0.04	0.40	1.14	
6	400	1.7×10^2	-2.25 ± 0.05	0.37	1.16	

NOTE. — "$|z|/z_{\rm crit} \le 2.6$" corresponds to "$|z|/z_0 \le 0.015/\sqrt{z_0/(10^{17}\,{\rm cm})}$". $E_{\rm inj,d} = 1$ TeV and $B_{\rm d,0} = 1$ mG.

… Et plus loin du plan equatorial ?

FRACTION OF ACCELERATED ELECTRONS OVER THE WHOLE TS

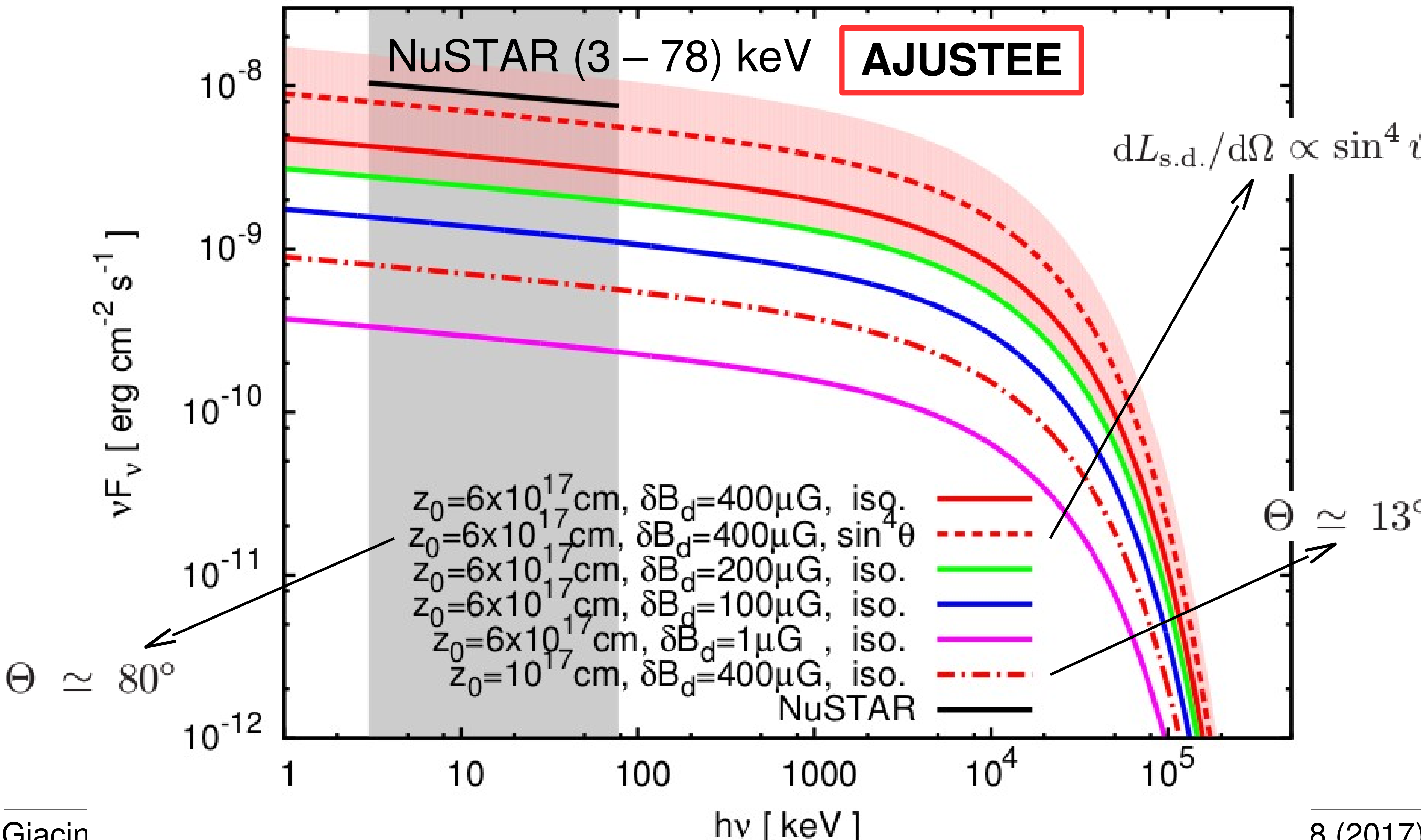
$z_0/(10^{17}$ cm$)$	$\delta B_d/(1\,\mu$G$)$	η_{crit}	$\epsilon_{acc,7}$	$\mathcal{F}_{inj}$
1	0.6	0.10	3.19×10^{-4}	0.05
1	1	0.17	2.06×10^{-3}	0.05
1	3	0.52	6.99×10^{-3}	0.05
1	10	1.7	5.72×10^{-3}	0.05
1	30	5.2	1.01×10^{-2}	0.055
1	60	10	7.22×10^{-3}	0.08
1	100	17	5.78×10^{-3}	0.1
1	200	35	7.59×10^{-3}	0.1
1	300	52	6.42×10^{-3}	0.12
1	400	69	5.93×10^{-3}	0.17
6	0.6	0.25	3.24×10^{-4}	0.05
6	1	0.42	1.39×10^{-3}	0.05
6	3	1.3	3.47×10^{-3}	0.05
6	10	4.2	3.56×10^{-3}	0.05
6	30	13	4.15×10^{-3}	0.055
6	60	25	3.48×10^{-3}	0.08
6	100	42	3.33×10^{-3}	0.1
6	200	85	5.84×10^{-3}	0.1
6	300	1.3×10^2	5.26×10^{-3}	0.12
6	400	1.7×10^2	5.27×10^{-3}	0.17

NOTE. — Electrons are injected at $|z|/z_0 \leq \mathcal{F}_{inj}$. $E_{inj,d} = 1\,$TeV and $B_0 = 1\,$mG.

Emission synchrotron en X - Crabe

$E_{\rm max} = 1\,{\rm PeV}$ $\alpha_{\rm e} \simeq -2.2$ $B = 0.5\,{\rm mG}$

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



Electrons

→ Does not depend on spectrum of turb. in upst.

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