PRINCETON UNIVERSITY

Simulations of relativistic reconnection in pulsar wind nebulae and pulsar winds

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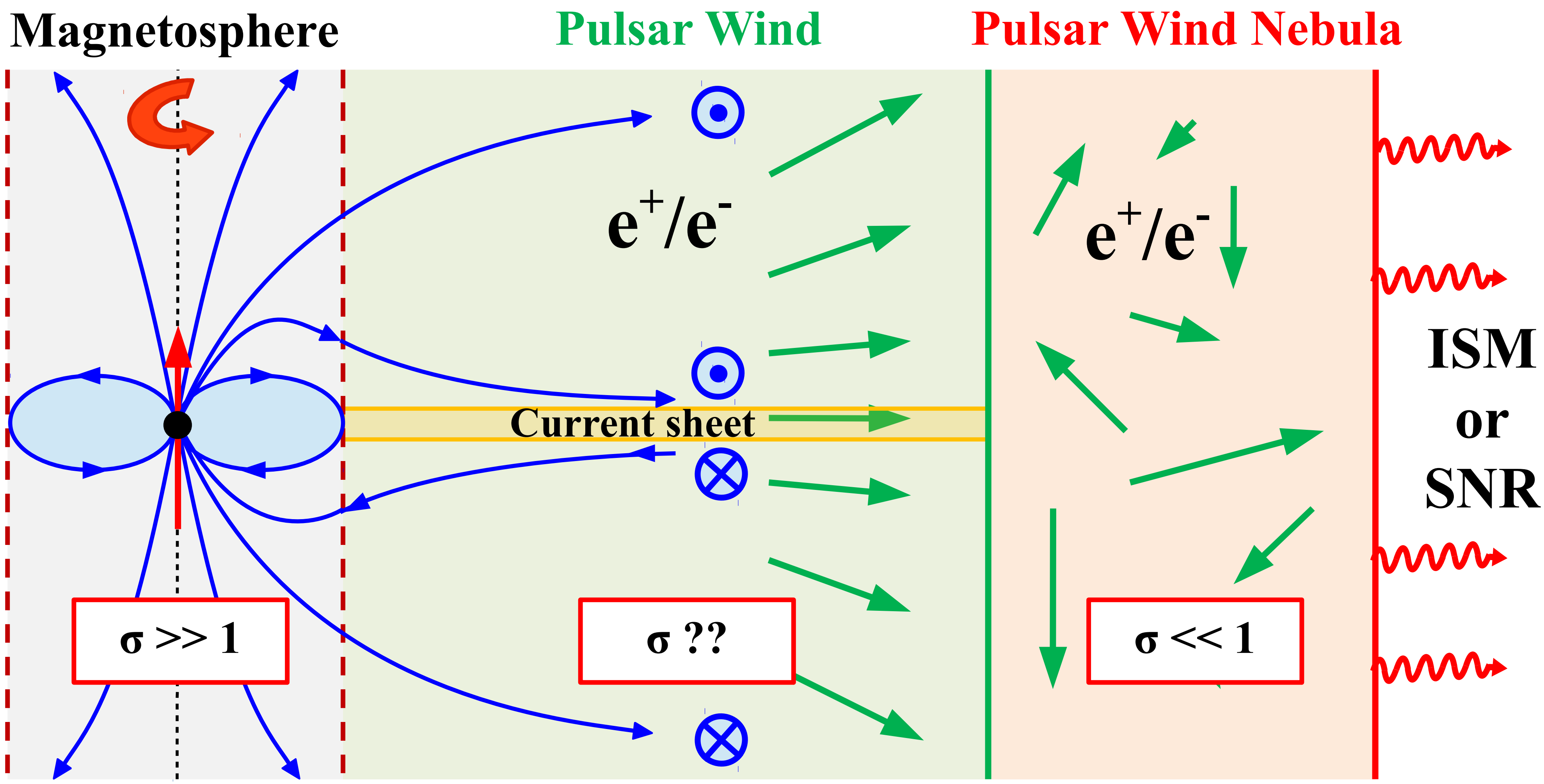
Workshop on Relativistic Plasma Astrophysics Purdue University, May 11-15, 2014

The "σ-problem"

[See reviews by e.g., Kirk et al. 2009, Arons 2012]



$$\sigma = \frac{\text{Poynting flux}}{\text{Particle kinetic energy flux}}$$

Transition σ >> 1 to σ << 1 unknown: "sigma" problem

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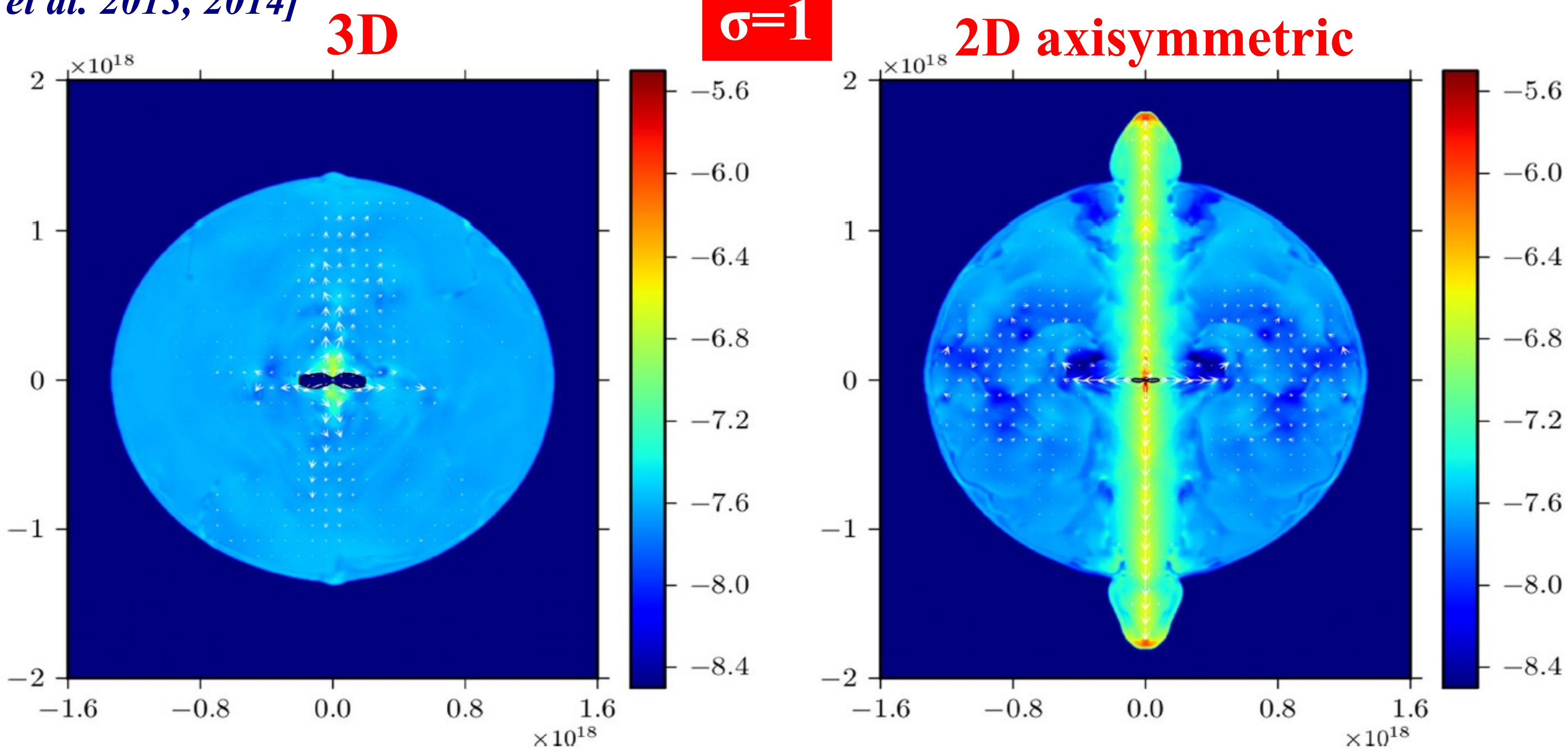
Solution of the σ-problem: 3D effects do matter!

[Porth et al. 2013, 2014]

σ=1

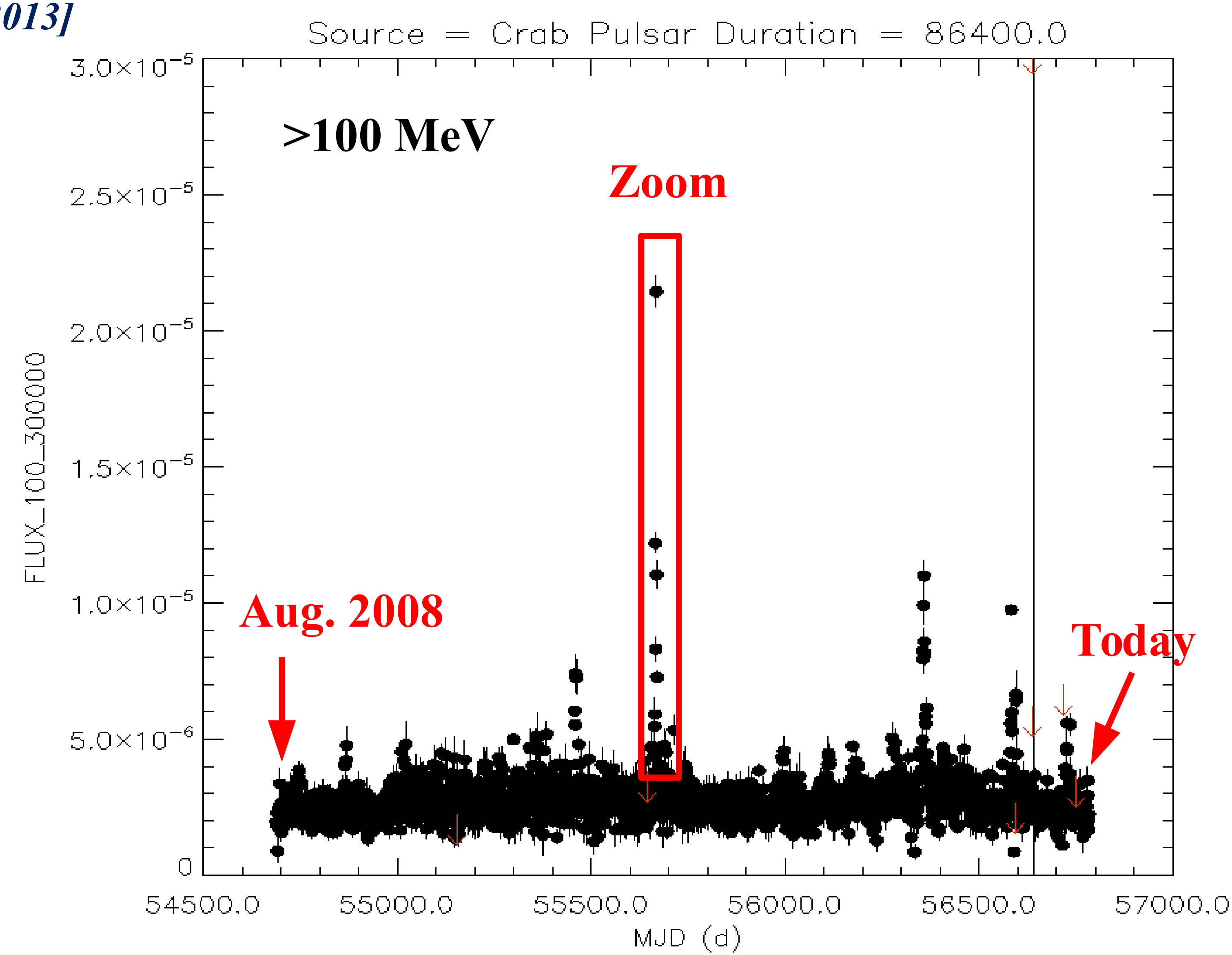


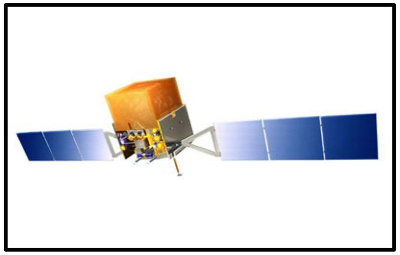
- The nebula is **kink unstable**, appears only in 3D.
  Predicted by ***Begelman 1998***, confirmed by ***Mizuno et al. 2011, Porth et al. 2013, 2014***
- **Morphology** well reproduced even with **high sigma wind, i.e. σ>~1**.
- The kink modes leads to **efficient dissipation** in the nebula => Low σ.

Relativistic reconnection at work?

Gamma-ray flares in the Crab Nebula: the smoking gun of magnetic dissipation?

[Tavani et al. 2010 ; Abdo et al. 2010; Balbo et al. 2011; Striani et al. 2011, 2013; Buehler et al. 2012; Mayer 2013]





[http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/]

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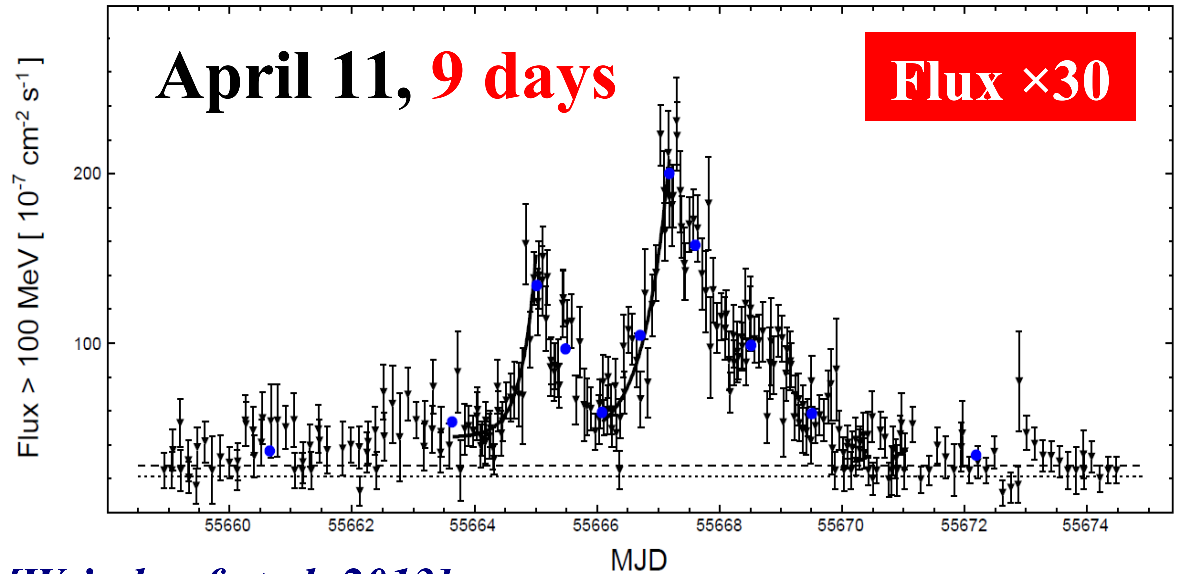
The puzzling temporal and spectral features of the flares

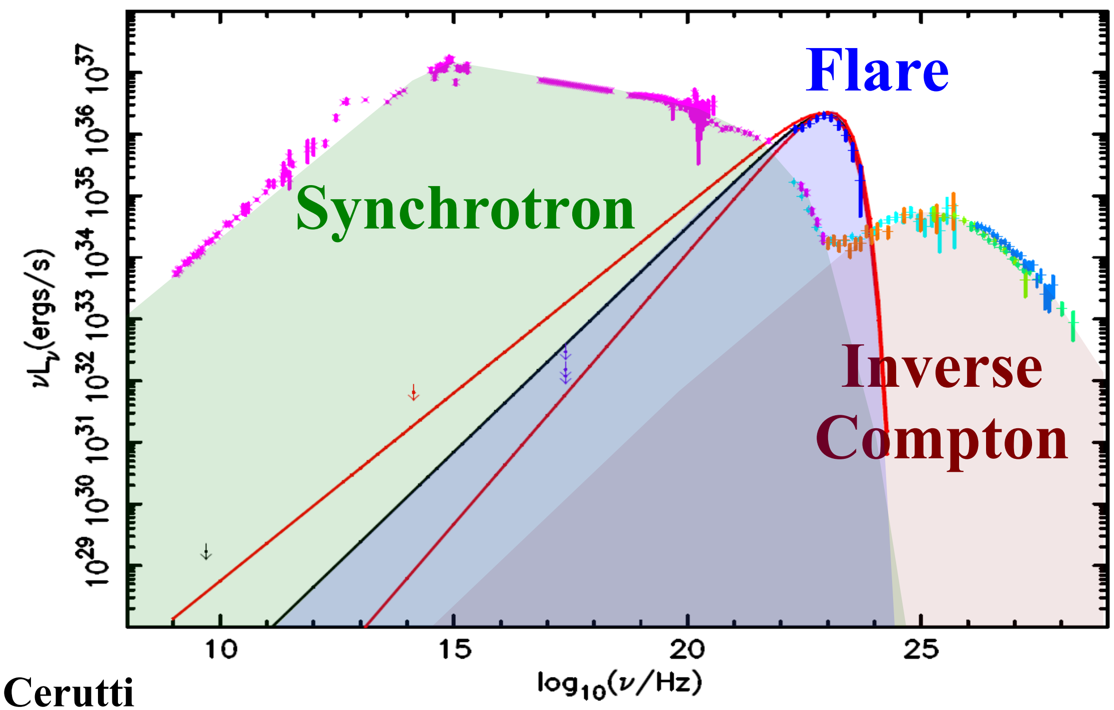
[Buehler et al., 2012]



Emitting region << Nebula
PeV pairs => $t_{gyration} \sim t_{flare}$
Acceleration ~1 Cyclotron orbit

Extreme particle acceleration!

[Weisskopf et al. 2013]



No counter-parts!
Spectrum ~mono-energetic
Synchrotron >100 MeV

=> Acceleration above the radiation-reaction limit!

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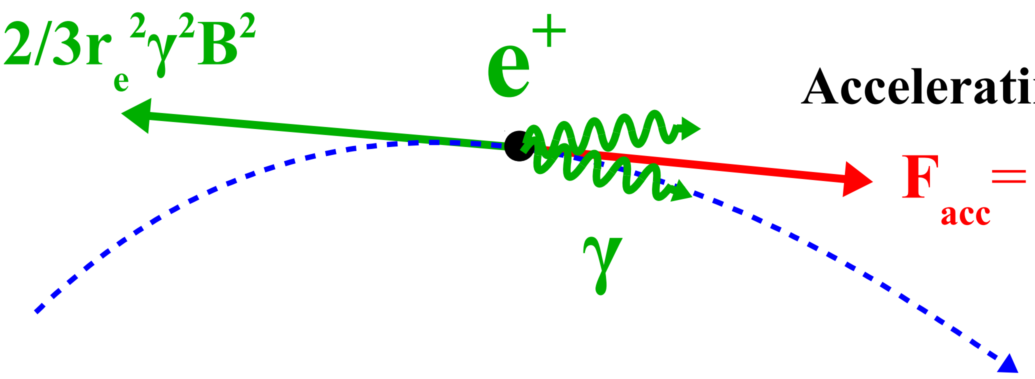
The production of synchrotron emission ≥160 MeV challenges classical models of acceleration

Radiation reaction force:

$F_{rad} = 2/3 r_e^2 \gamma^2 B^2$



Accelerating force:

$F_{acc} = eE$

Particle's trajectory

Radiation reaction limit: $\mathbf{F_{acc} = F_{rad}} \Rightarrow \gamma_{rad}$

Synchrotron photon energy: $\boldsymbol{\varepsilon_{max} = 3/2\, \gamma^2_{rad}\, \hbar\, \omega_c = (9 m_e c^2/4\alpha_F) \times (E/B) = 160 \times (E/B)}$ **MeV**

Under ideal MHD conditions: E<B (ideal MHD) $\Rightarrow \varepsilon_{max} <$ **160 MeV**

[e.g. Guilbert et al., 1983 ; de Jager et al., 1996 ; Uzdensky et al., 2011]

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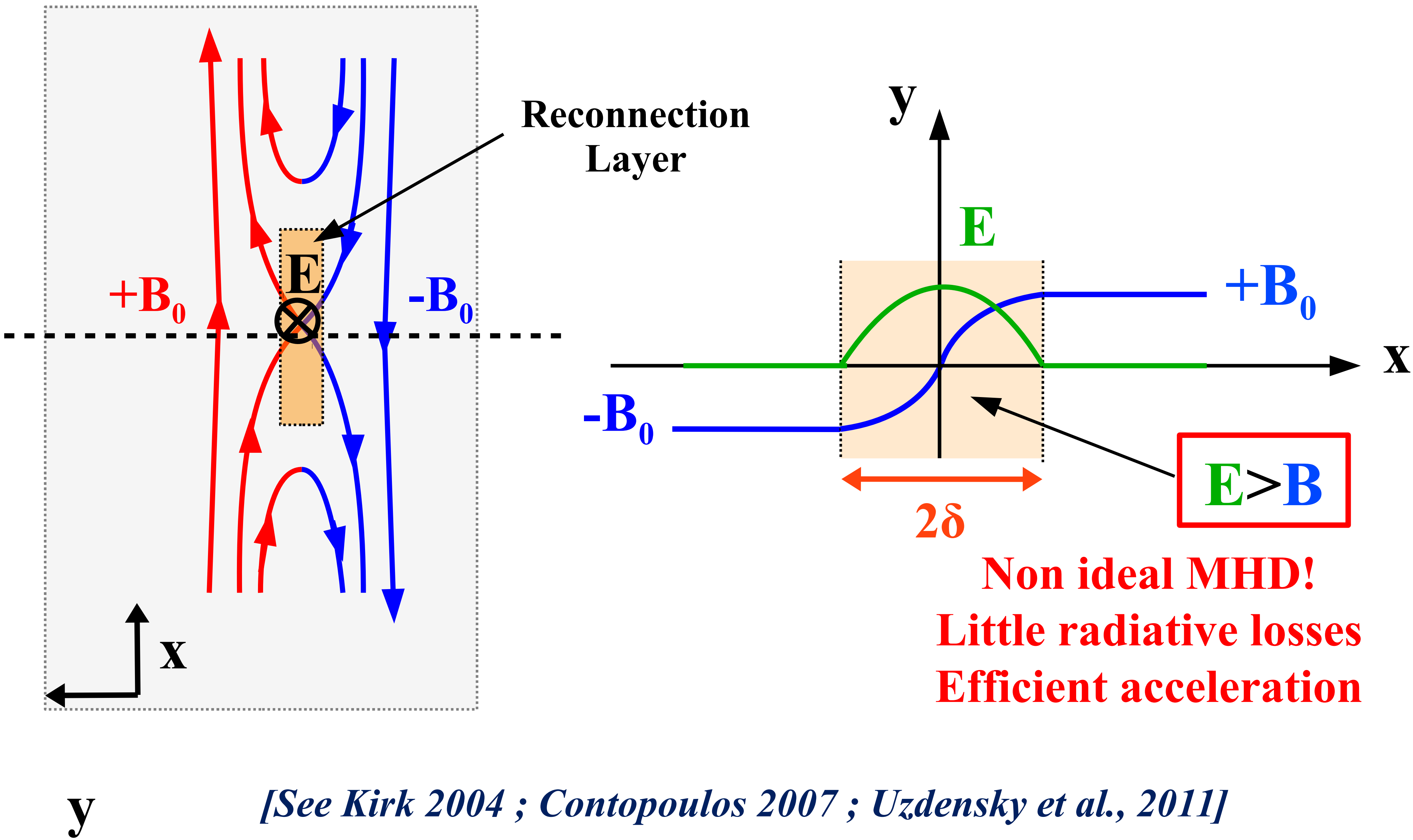
Extreme particle acceleration at reconnection sites?



Non ideal MHD!
Little radiative losses
Efficient acceleration

[See Kirk 2004 ; Contopoulos 2007 ; Uzdensky et al., 2011]

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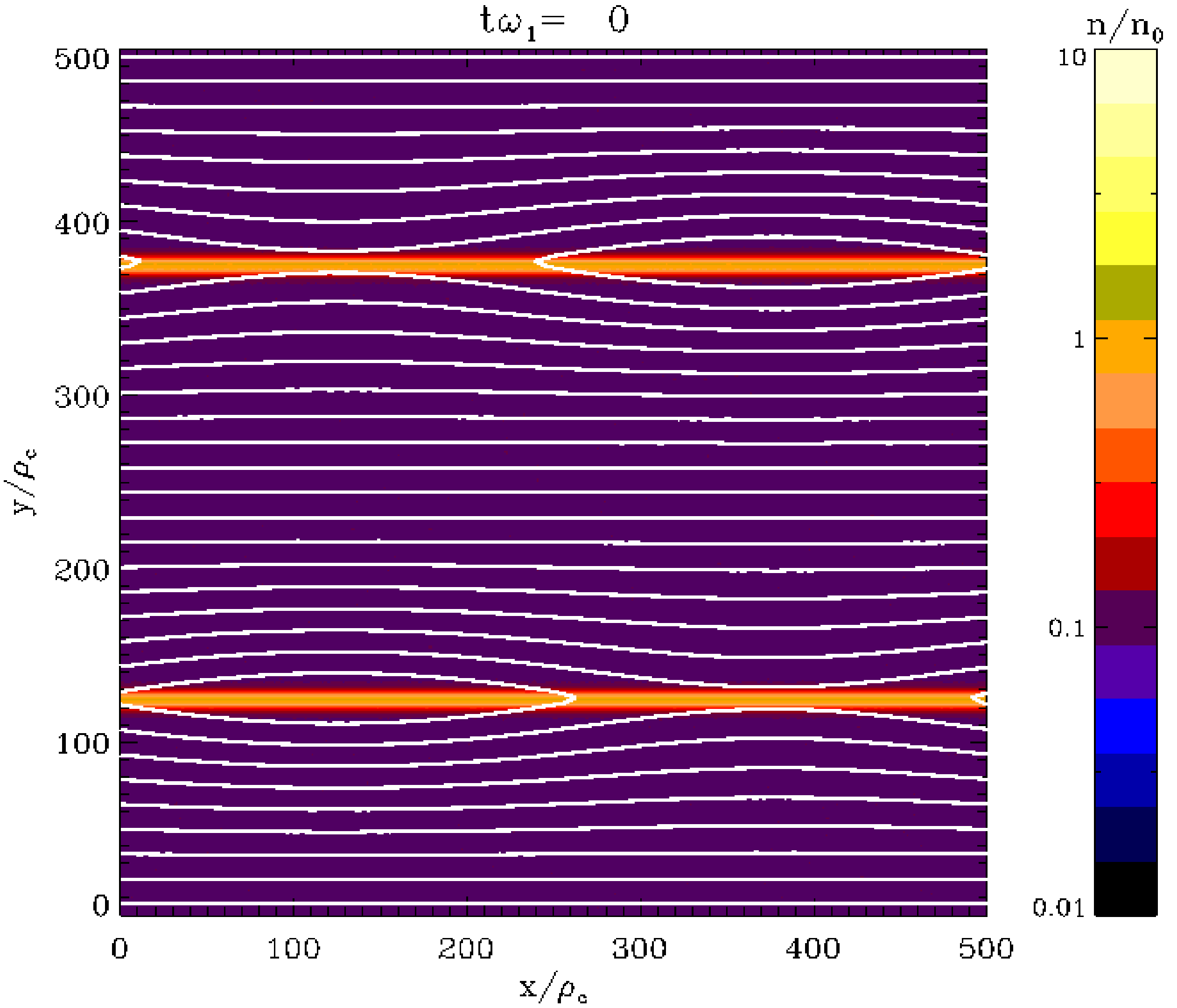
The PIC code Zeltron

General properties: (see also http://benoit.cerutti.free.fr/zeltron.html)

- **3D**, **parallel** (3D domain decomposition), **relativistic**, **electromagnetic** PIC code.
- Developed **from scratch**
- **Explicit** finite-difference scheme : Yee + Boris FDTD algorithm
- **Cartesian** grid + latest development: **Spherical grid**
- So far, ran on up to **100,000 cores (~90% of Kraken)**
- Includes **the radiation reaction force**

Overall time evolution of 2D reconnection

Zeltron simulations + radiation reaction force



Particles are accelerated at X-points along the ±z-direction, and deflected along the ±x-directions by the magnetic tension.

[Cerutti et al. 2013]

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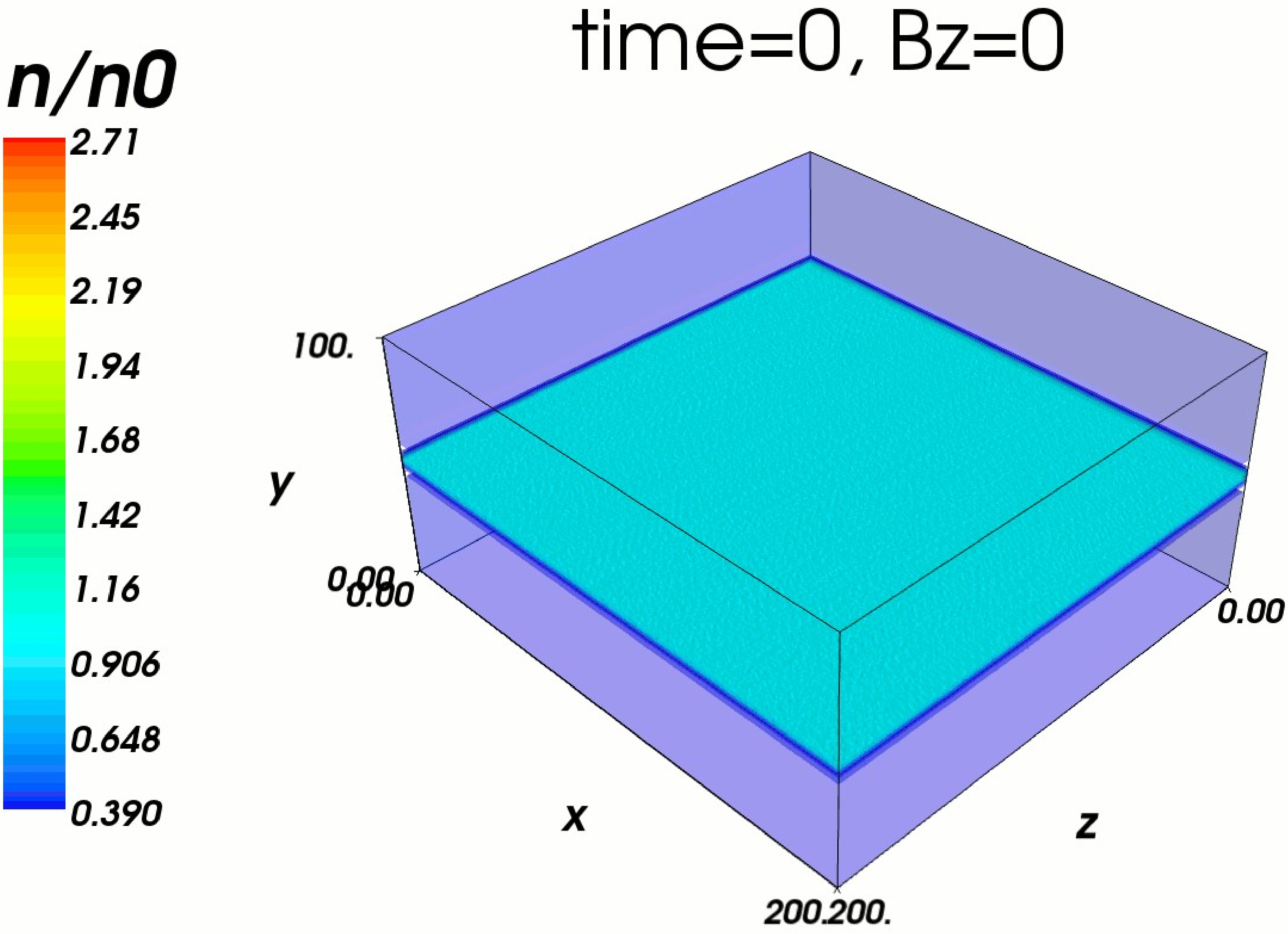
3D reconnection

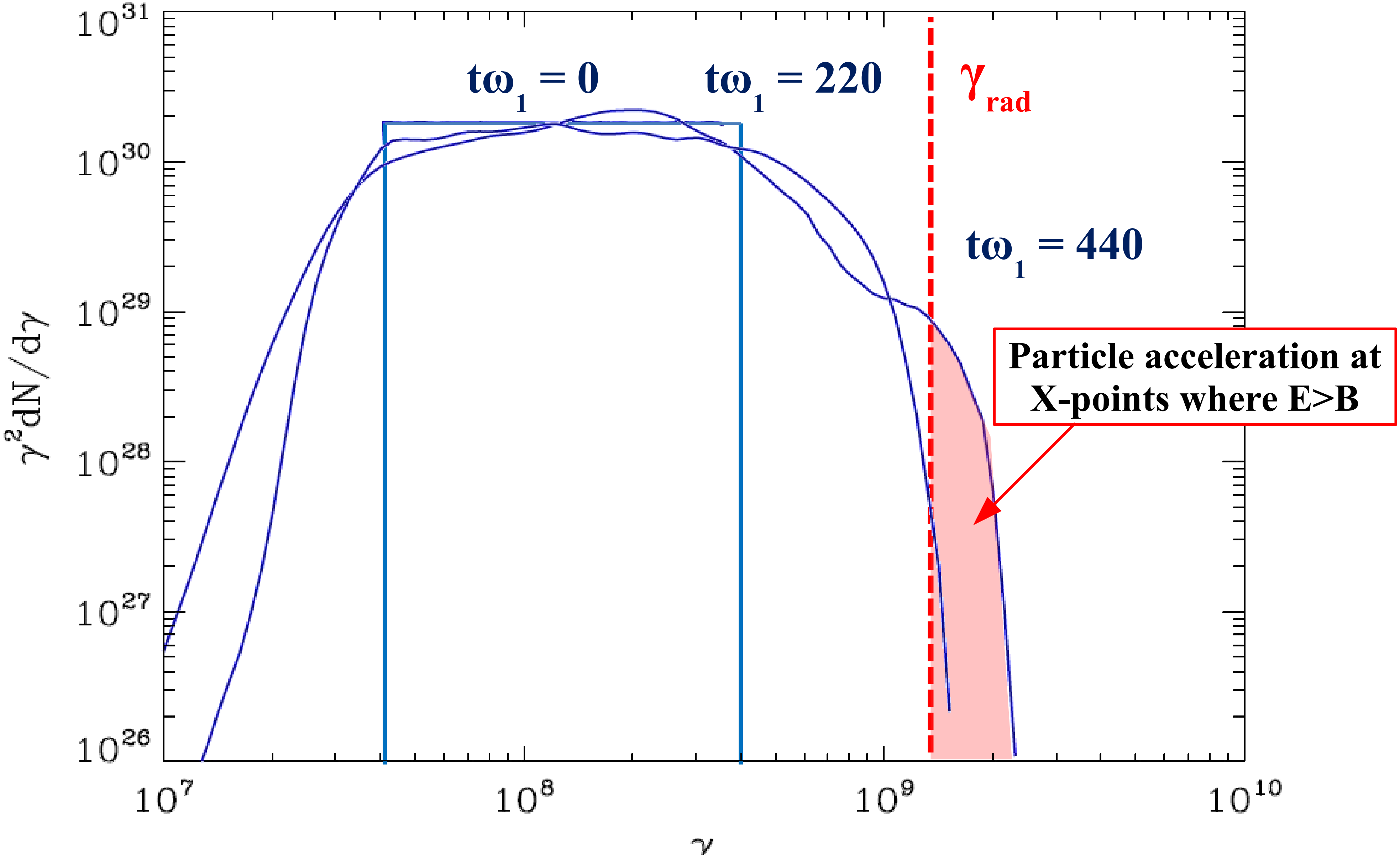
Zeltron simulations + radiation reaction force



1440^3 cells, $\sim 5\times10^{10}$ particles

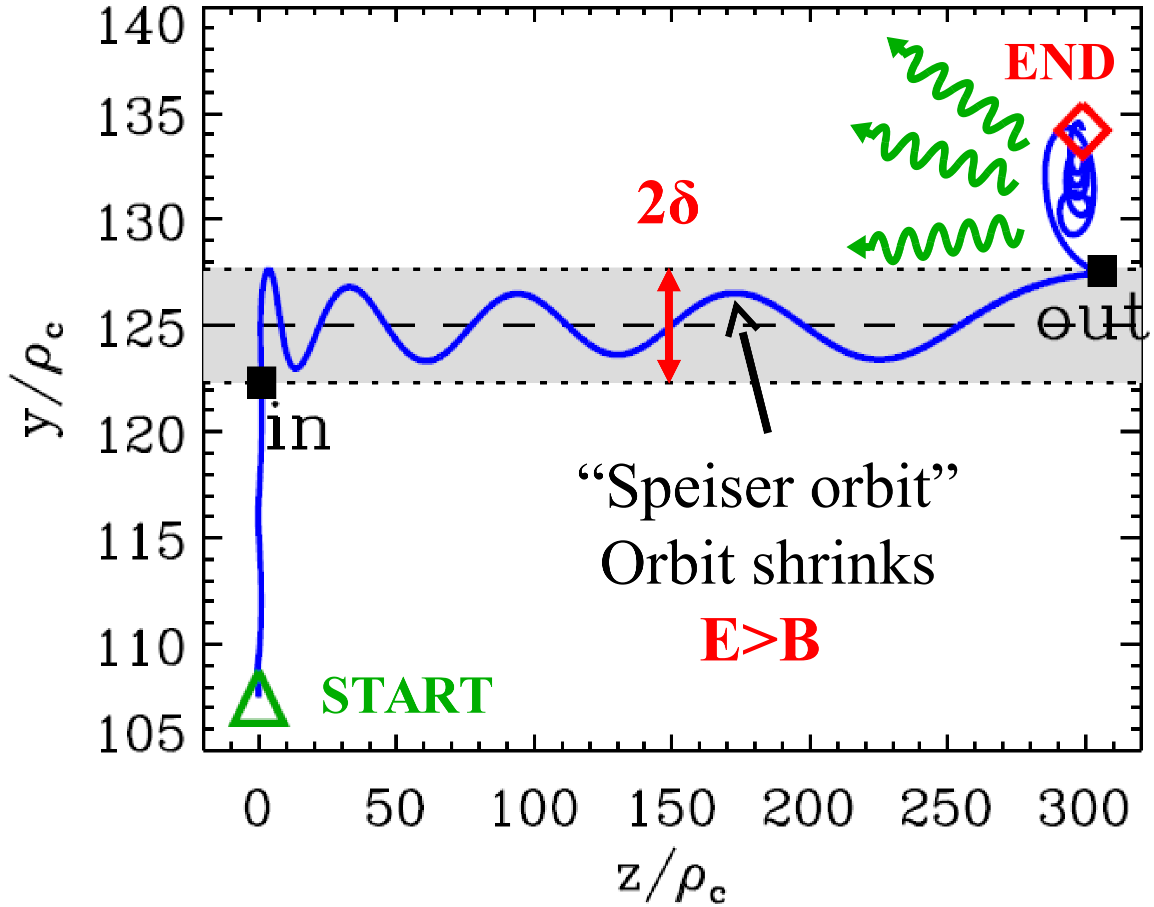
[Cerutti et al. 2014]

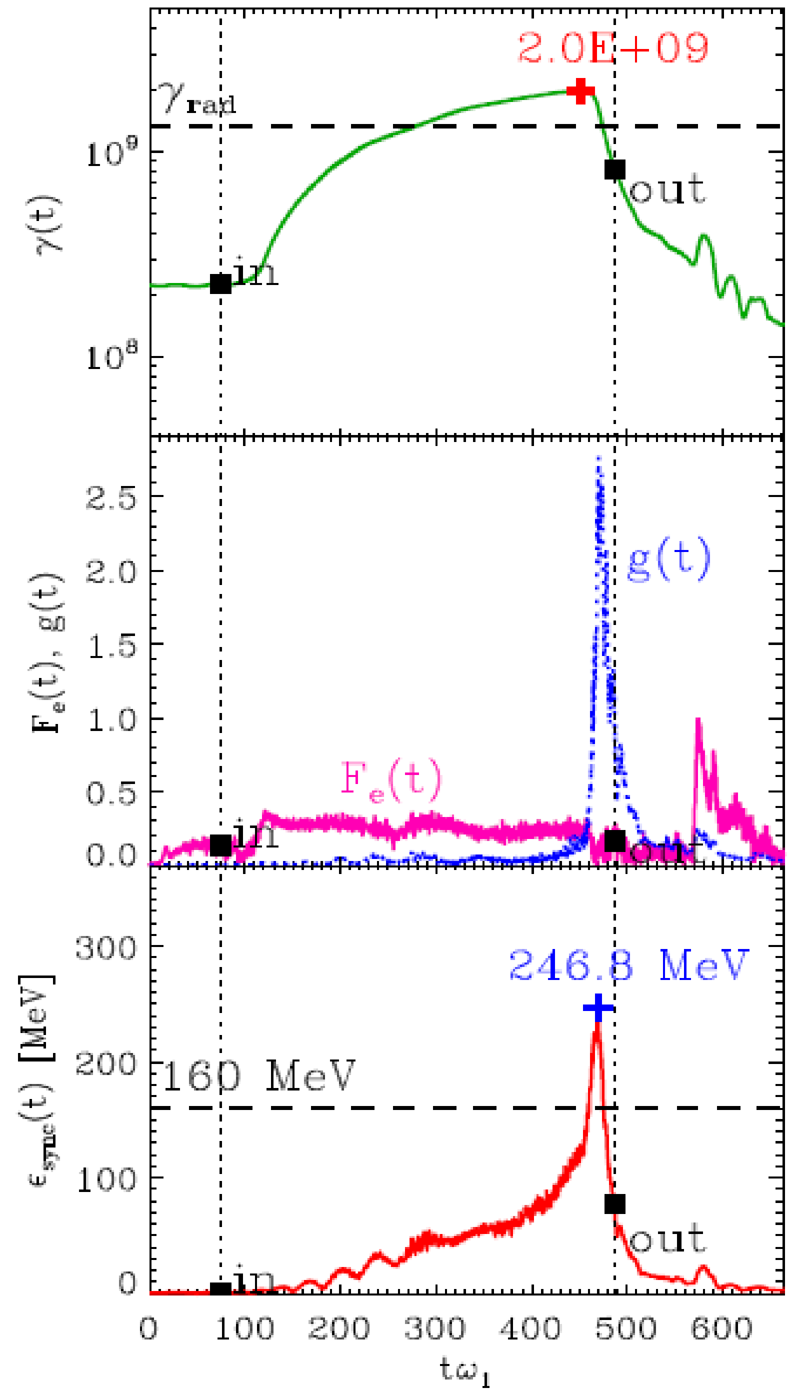
Time evolution of the particle energy distribution



[Cerutti et al. 2013a]

A typical high-energy particle orbit with $\gamma > \gamma_{rad}$





Phase 1. **Drifting towards the layer**

Phase 2. **Linear acceleration, weak rad. losses, where E>B (non-ideal MHD)**

Phase 3. **Ejection, fast cooling and emission of >160 MeV synchrotron**

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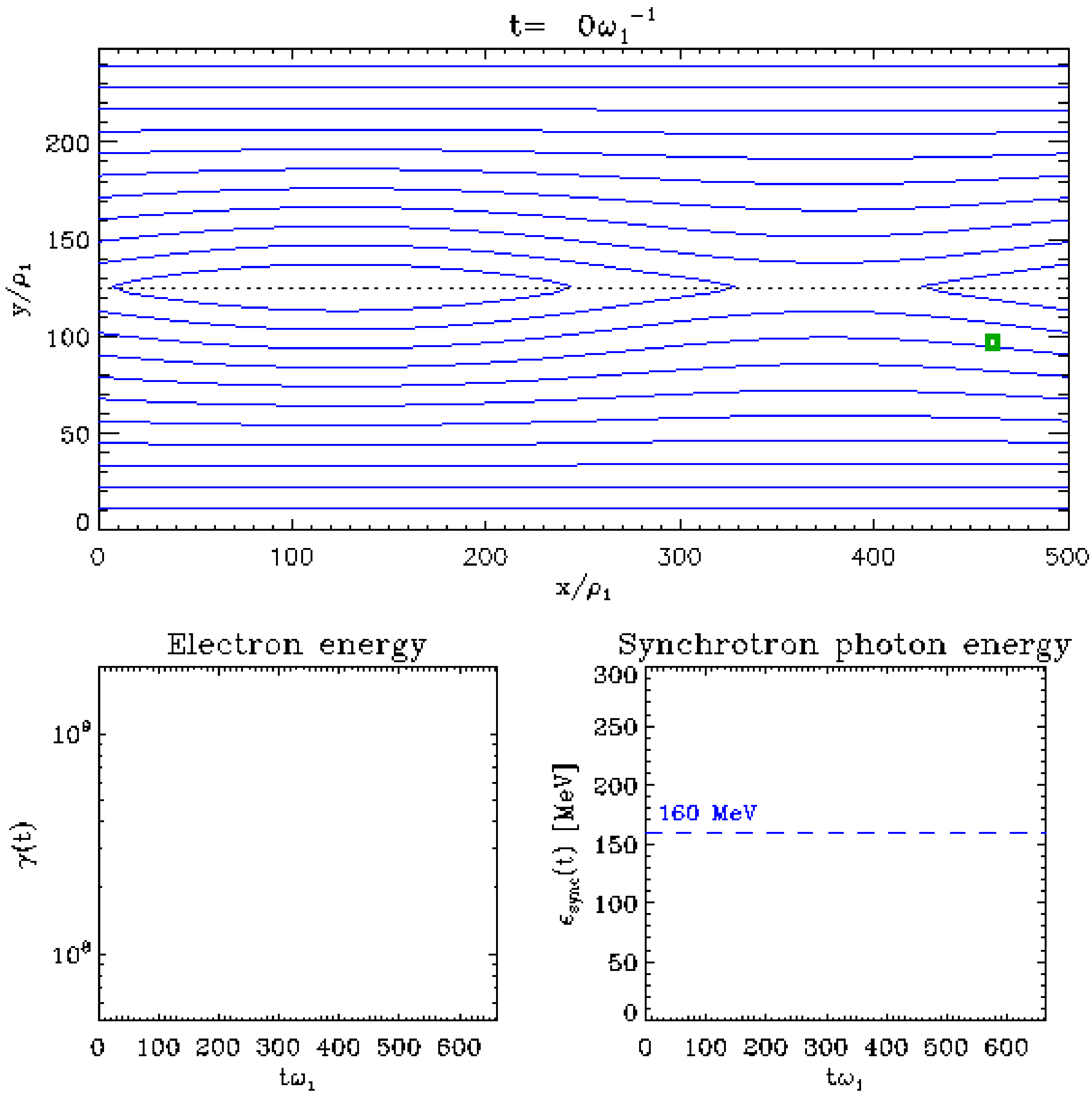

t= 0ω₁⁻¹
y/ρ₁
x/ρ₁
Electron energy
γ(t)
tω₁
Synchrotron photon energy
ε_sync(t) [MeV]
160 MeV
tω₁

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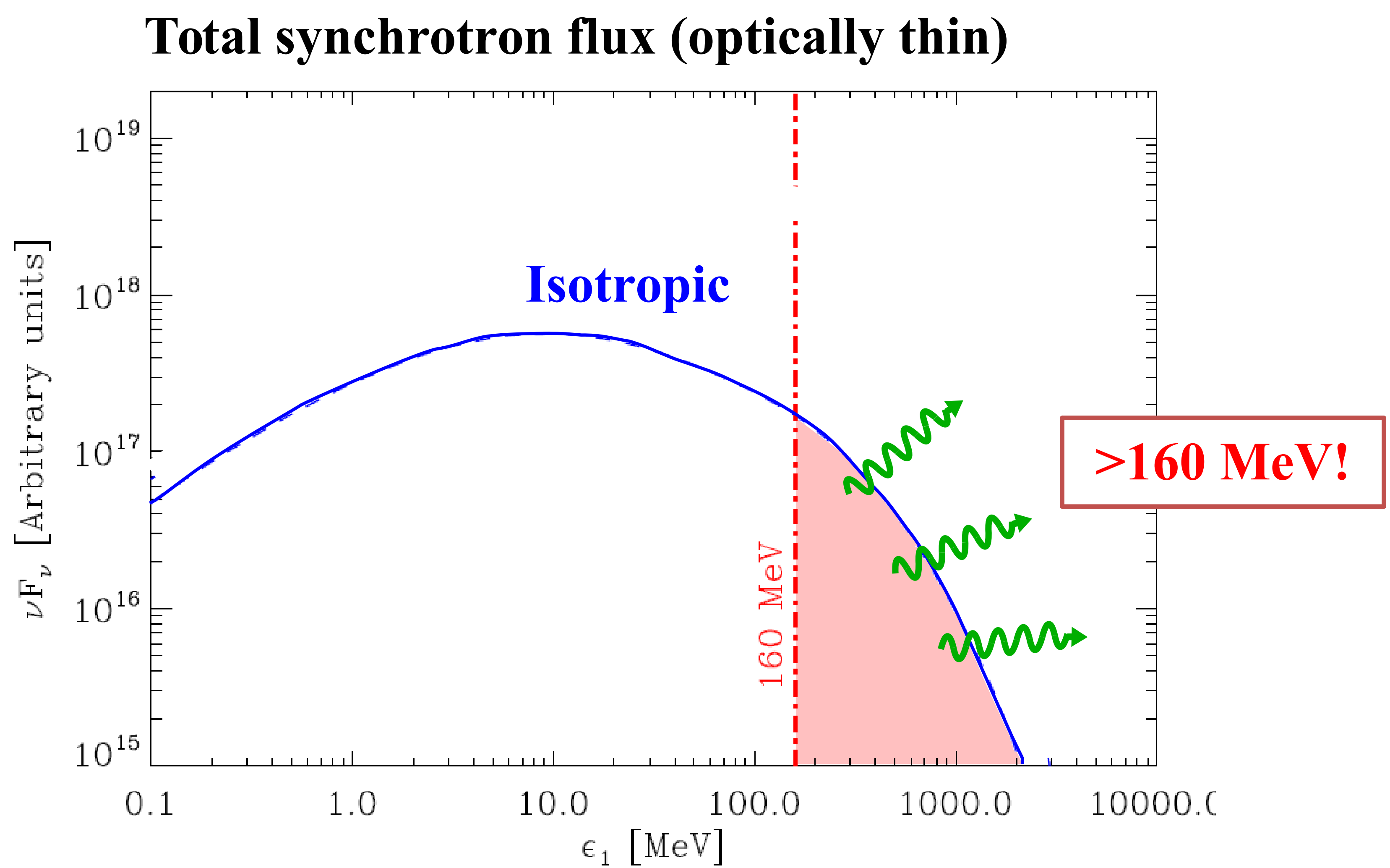
Evidence for >160 MeV synchrotron photons!



[Cerutti et al. 2013, 2014]

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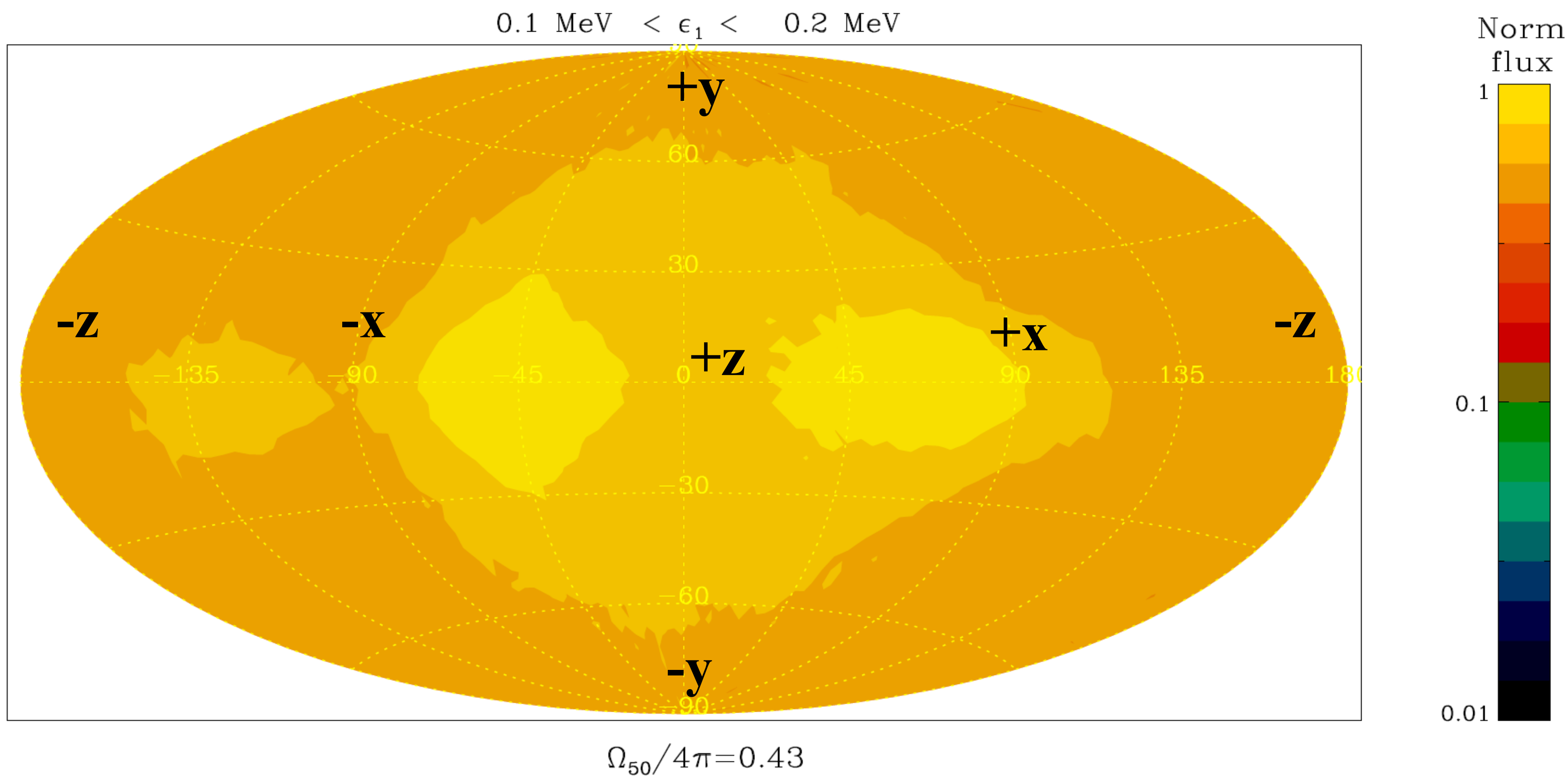
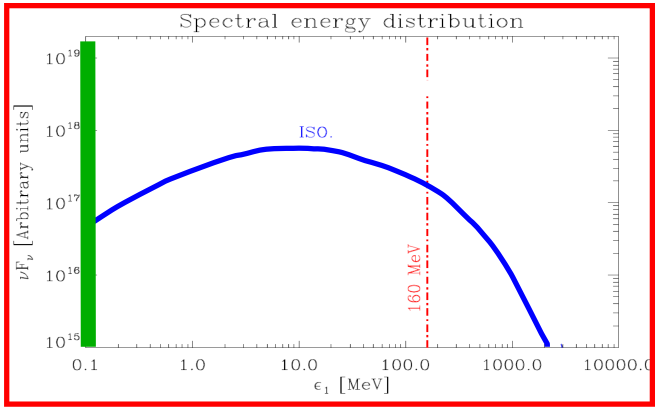
Energy-resolved radiation' angular distribution





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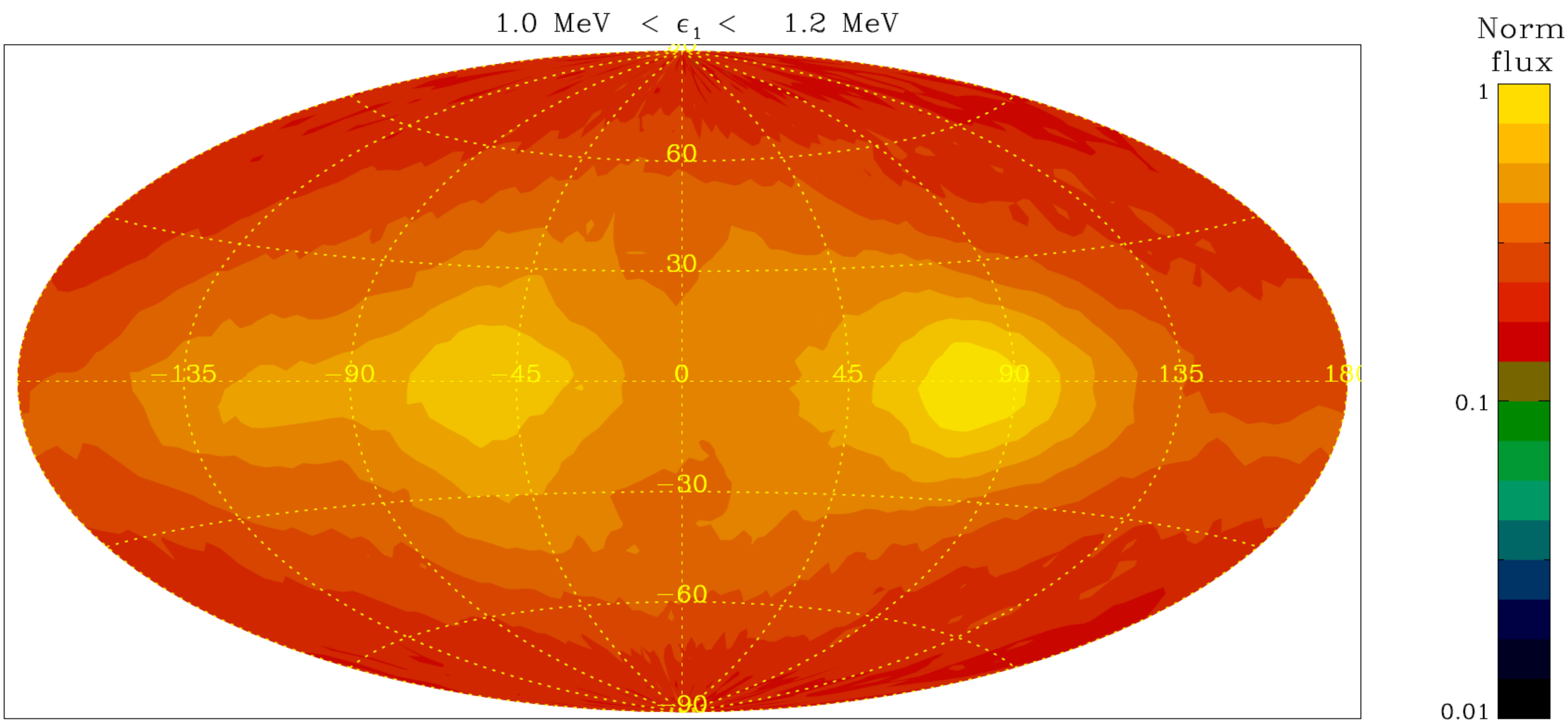
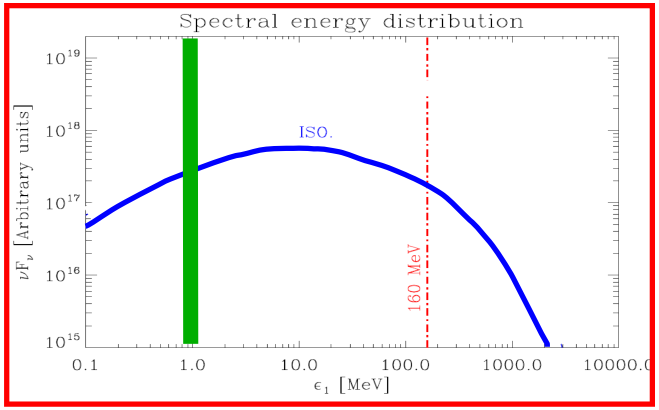
Energy-resolved radiation' angular distribution



$\Omega_{50}/4\pi=0.35$



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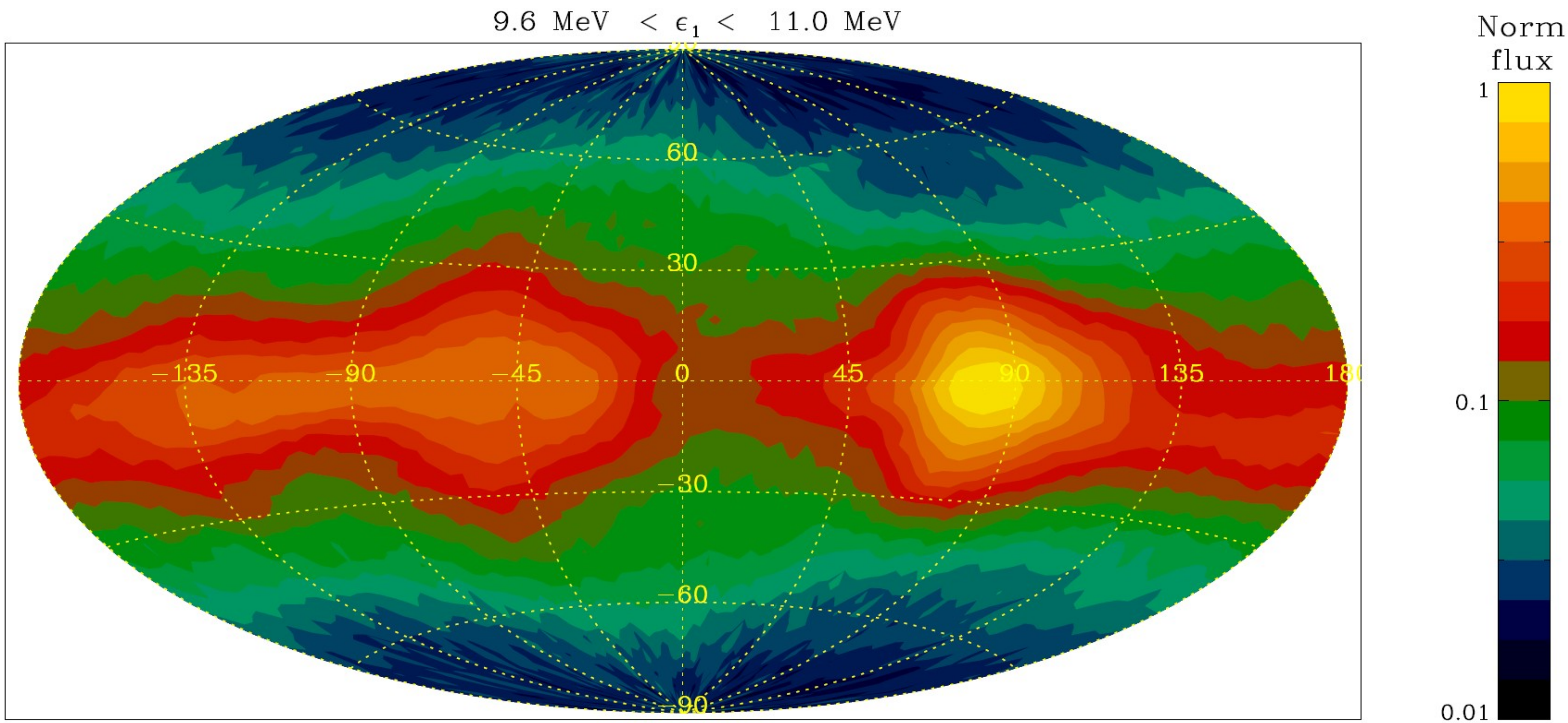
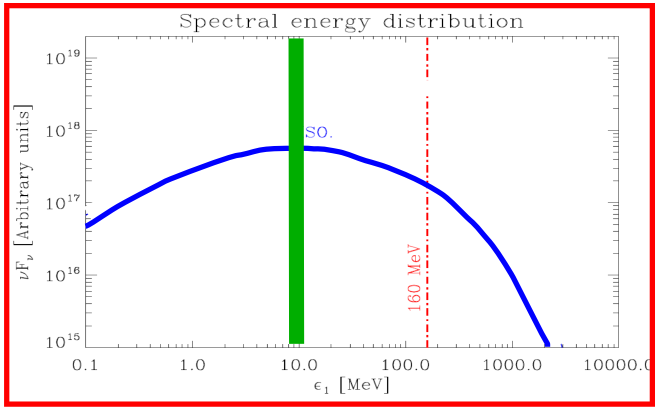
Energy-resolved radiation' angular distribution



$\Omega_{50}/4\pi=0.21$



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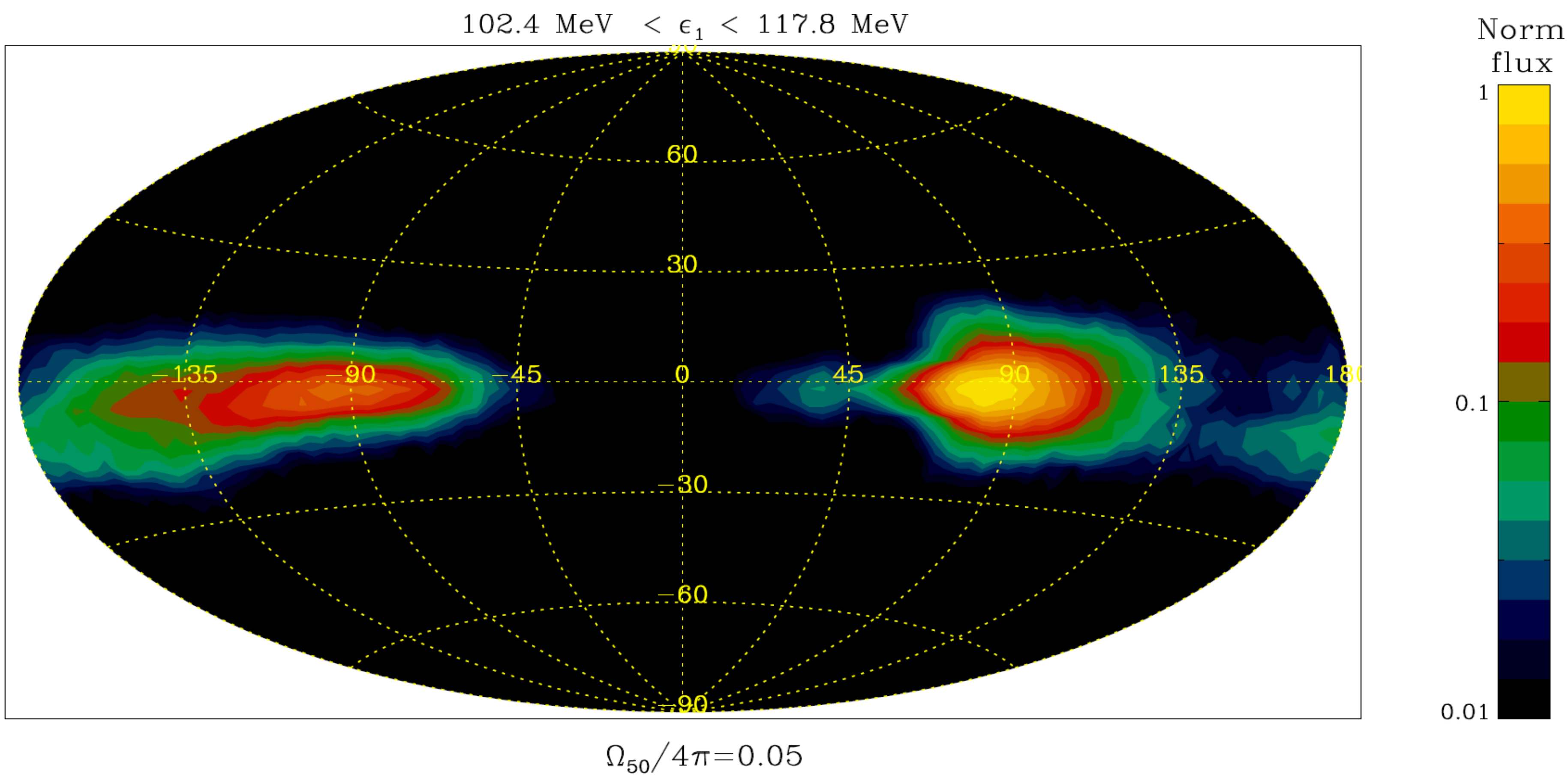
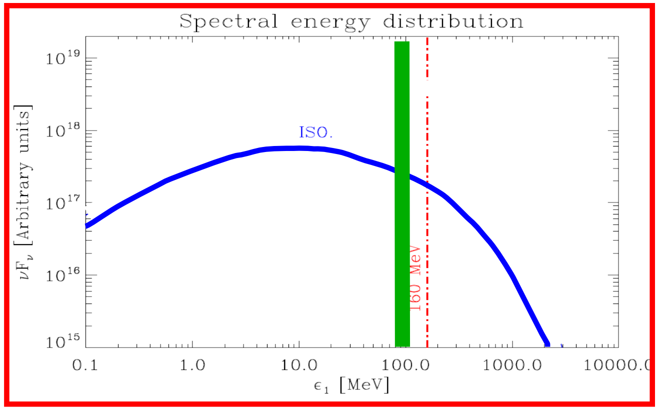
Energy-resolved radiation' angular distribution





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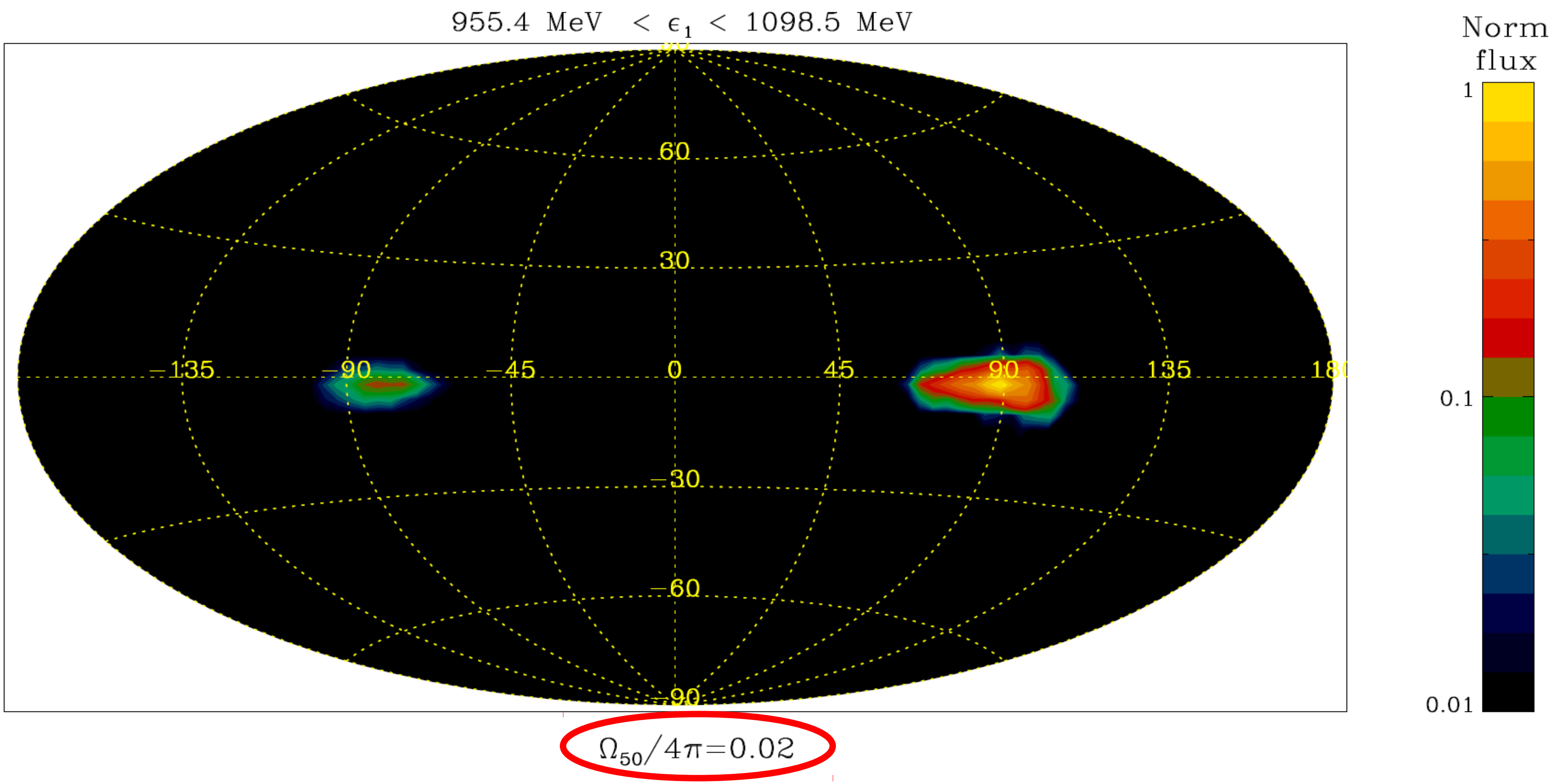
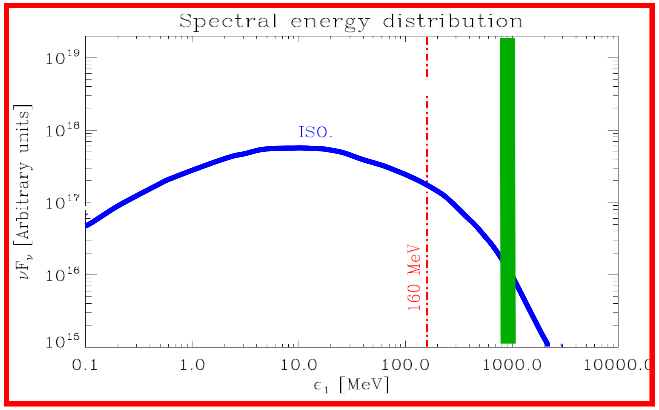
Energy-resolved radiation' **angular** distribution



Strong energy-dependent anisotropy of the energetic particle.
=▶ beaming of the high-energy radiation !



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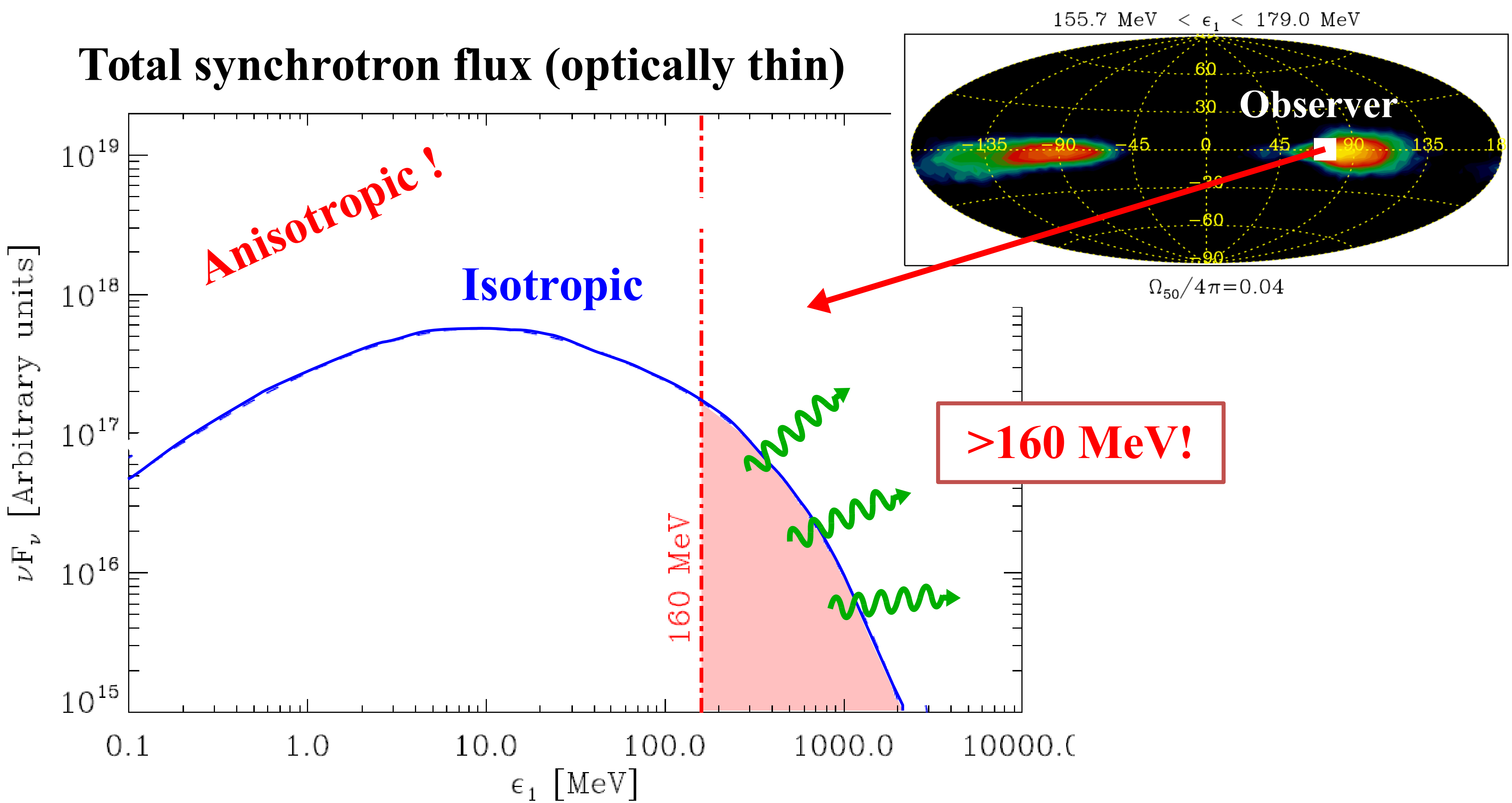
Evidence for >160 MeV synchrotron photons!

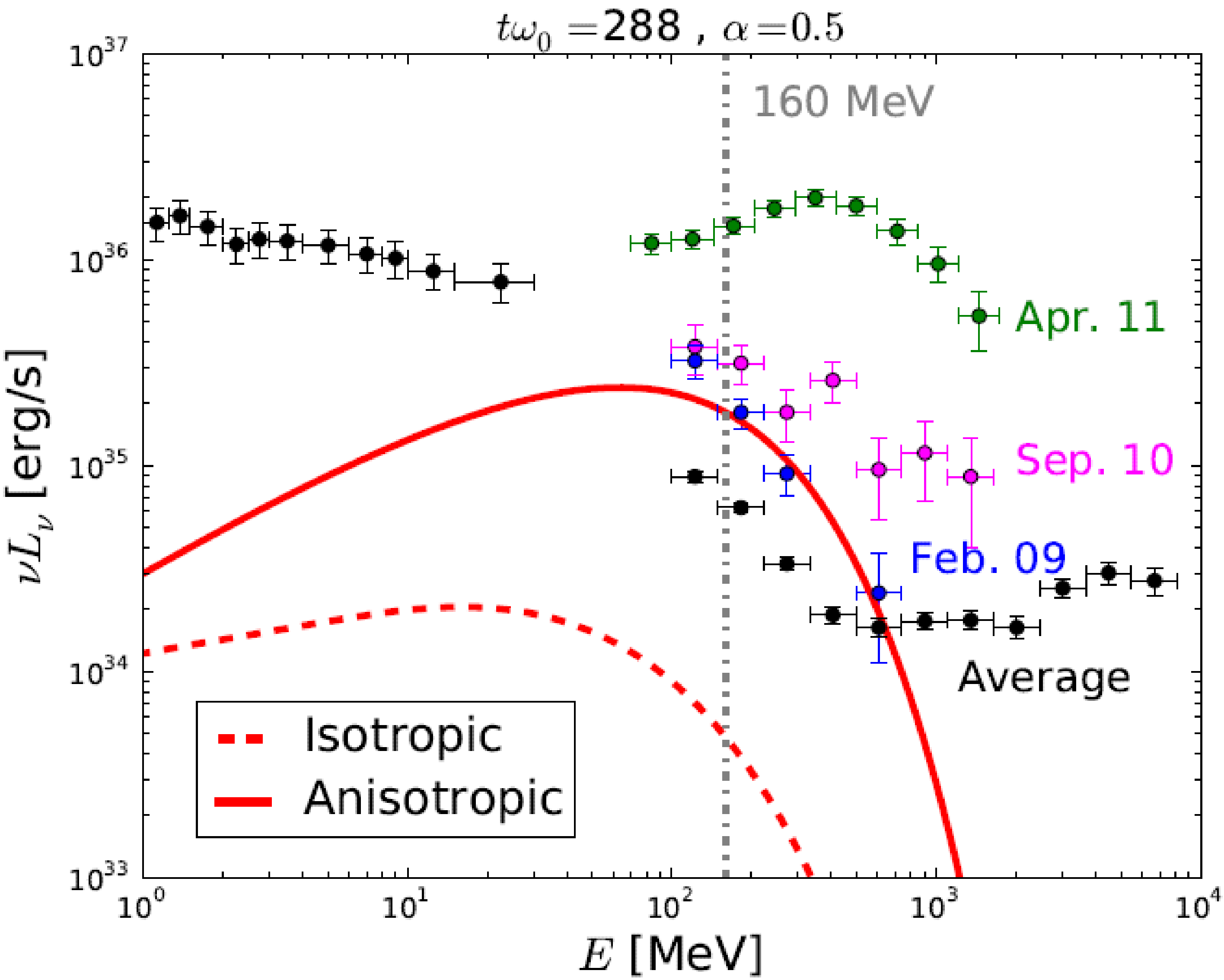


[Cerutti et al. 2013]

Apparent high-energy flux <u>INCREASED!</u>

Good to reduce the energetic constraints !

Comparison to the *Fermi*-LAT observations



Beaming needed to explain the energetics

[Cerutti et al., 2014]

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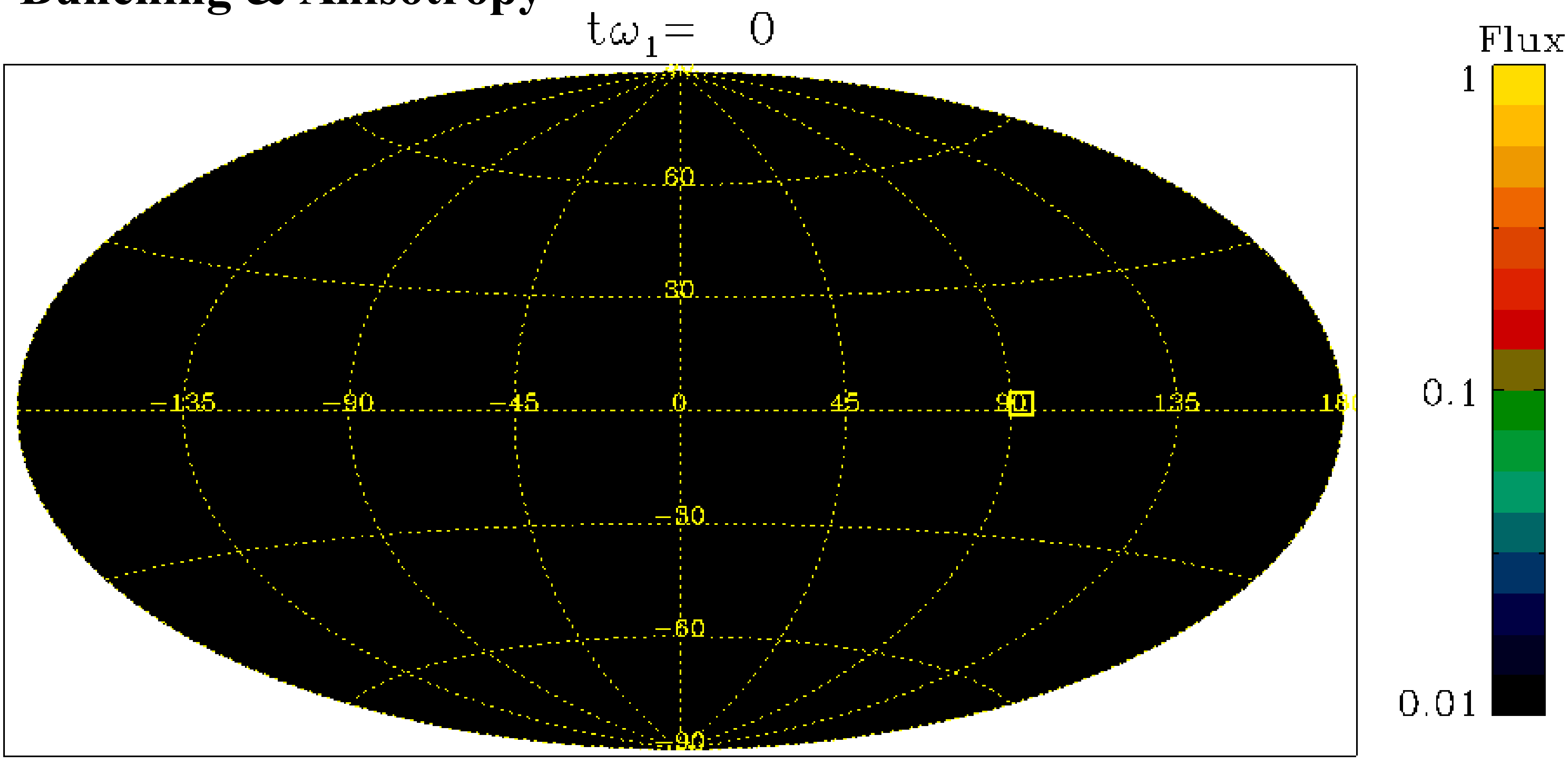
Time variation of the >100 MeV flux

Bunching & Anisotropy



The beam of high-energy radiation sweeps across the line of sight intermittently =► __bright symmetric flares.__

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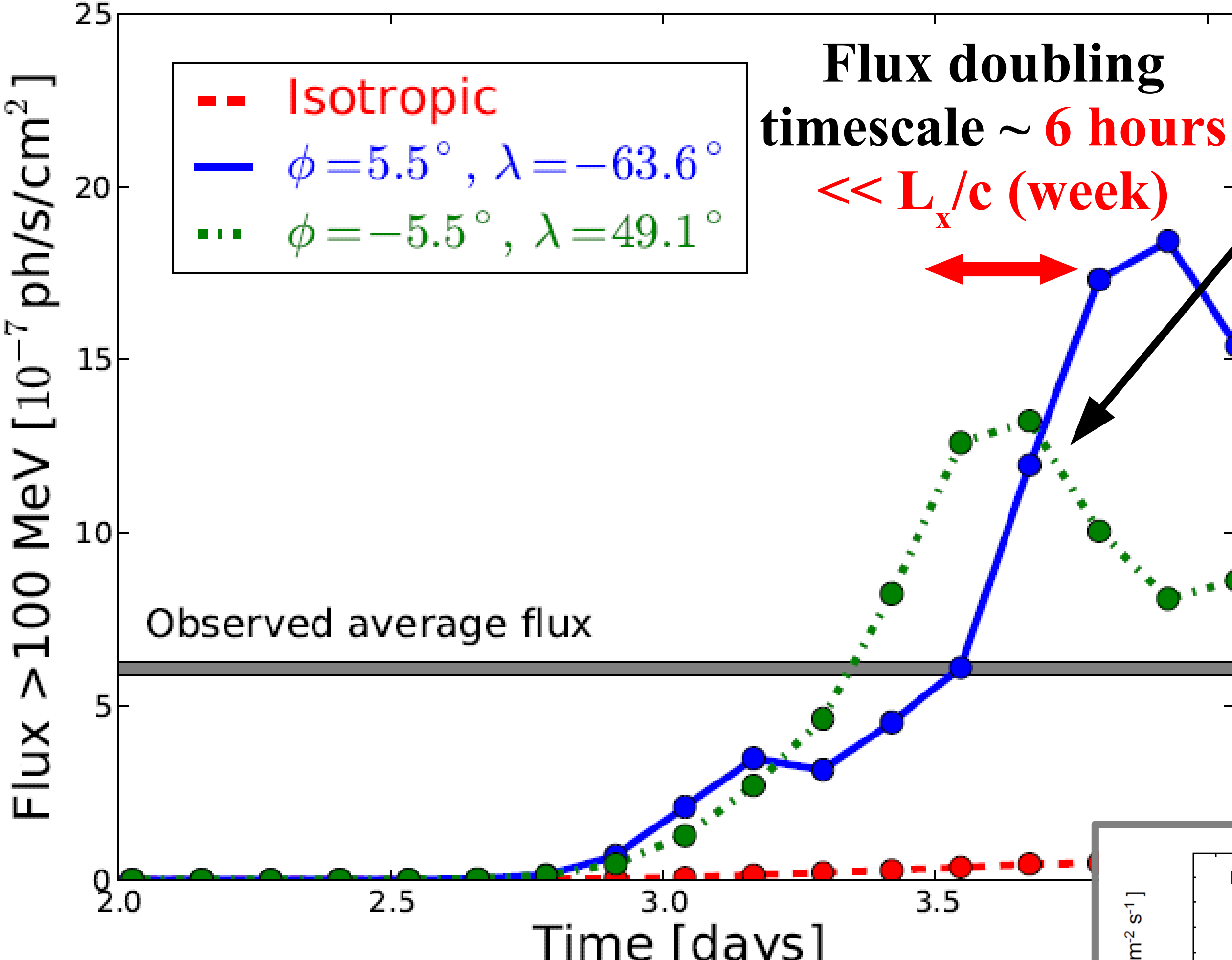
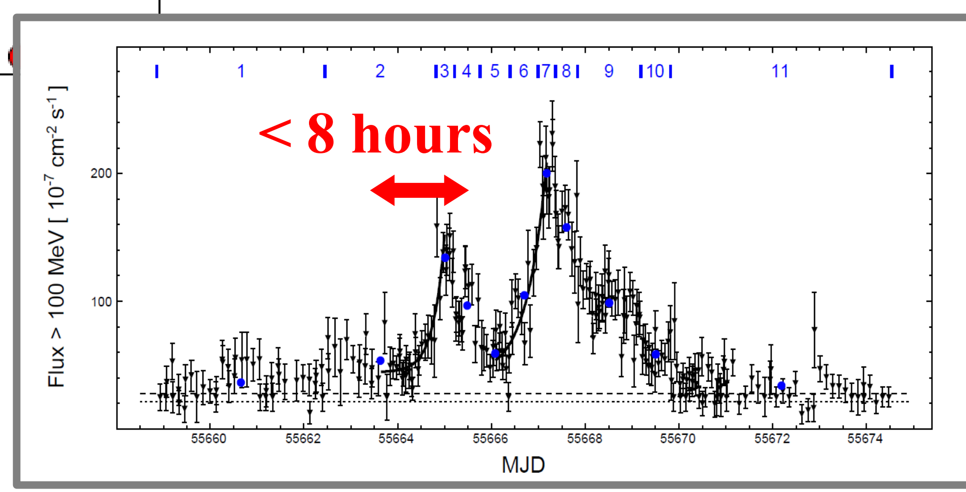
Expected lightcurves

MODEL (3D)

Beaming and bunching



Symmetric profile $t_{rise} \sim t_{decay}$
$\Delta t \ll Lx/c$



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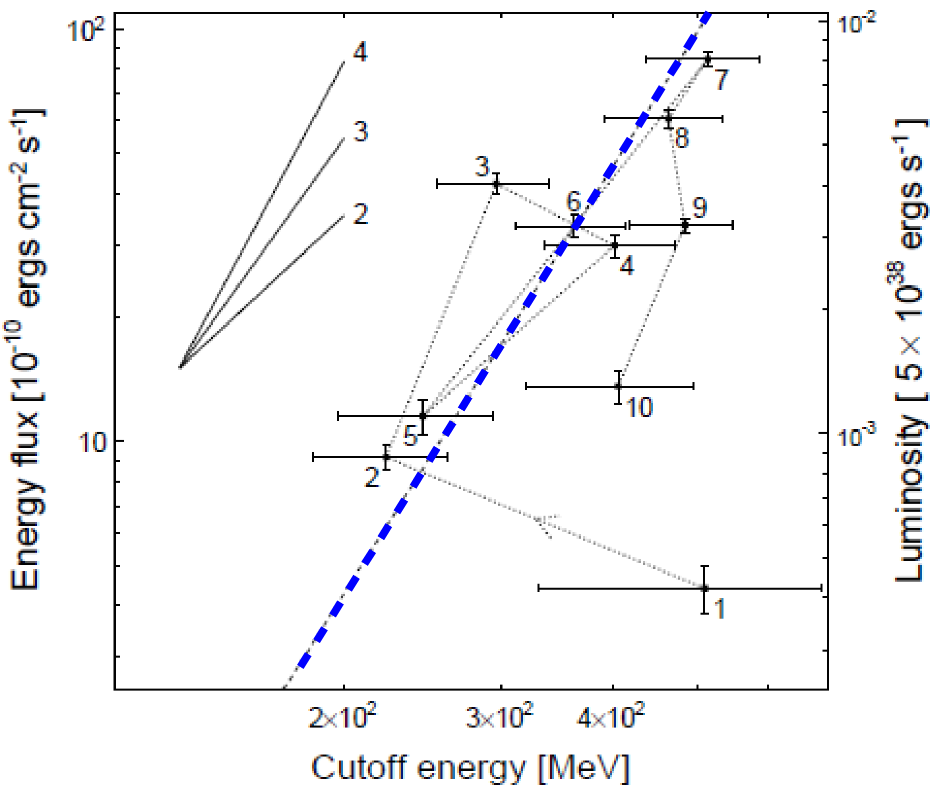
Expected correlation Flux/Energy

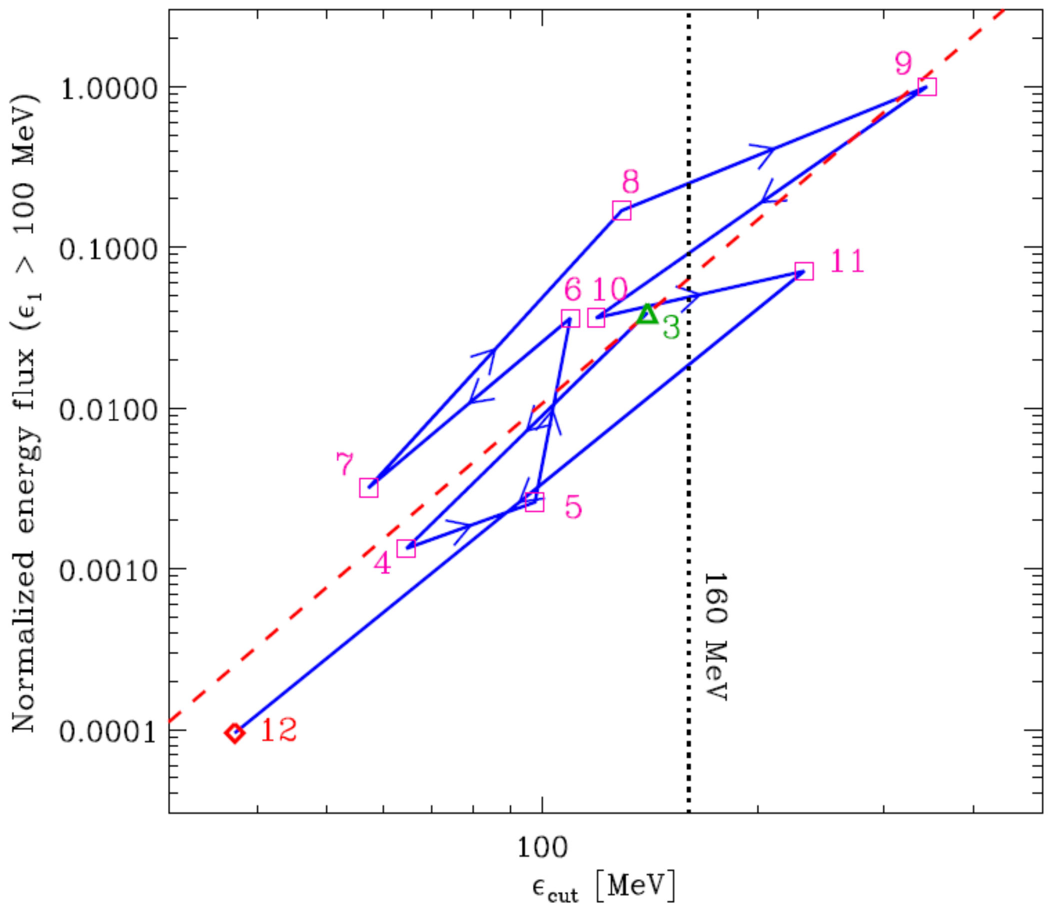
OBSERVATIONS



$$\text{Flux} = K\, \varepsilon_{\text{cut}}^{+3.42\pm0.86}$$

[Buehler et al., 2012]

MODEL



$$\text{Flux} = K\, \varepsilon_{\text{cut}}^{+3.8\pm0.6}$$

[Cerutti et al., 2013]

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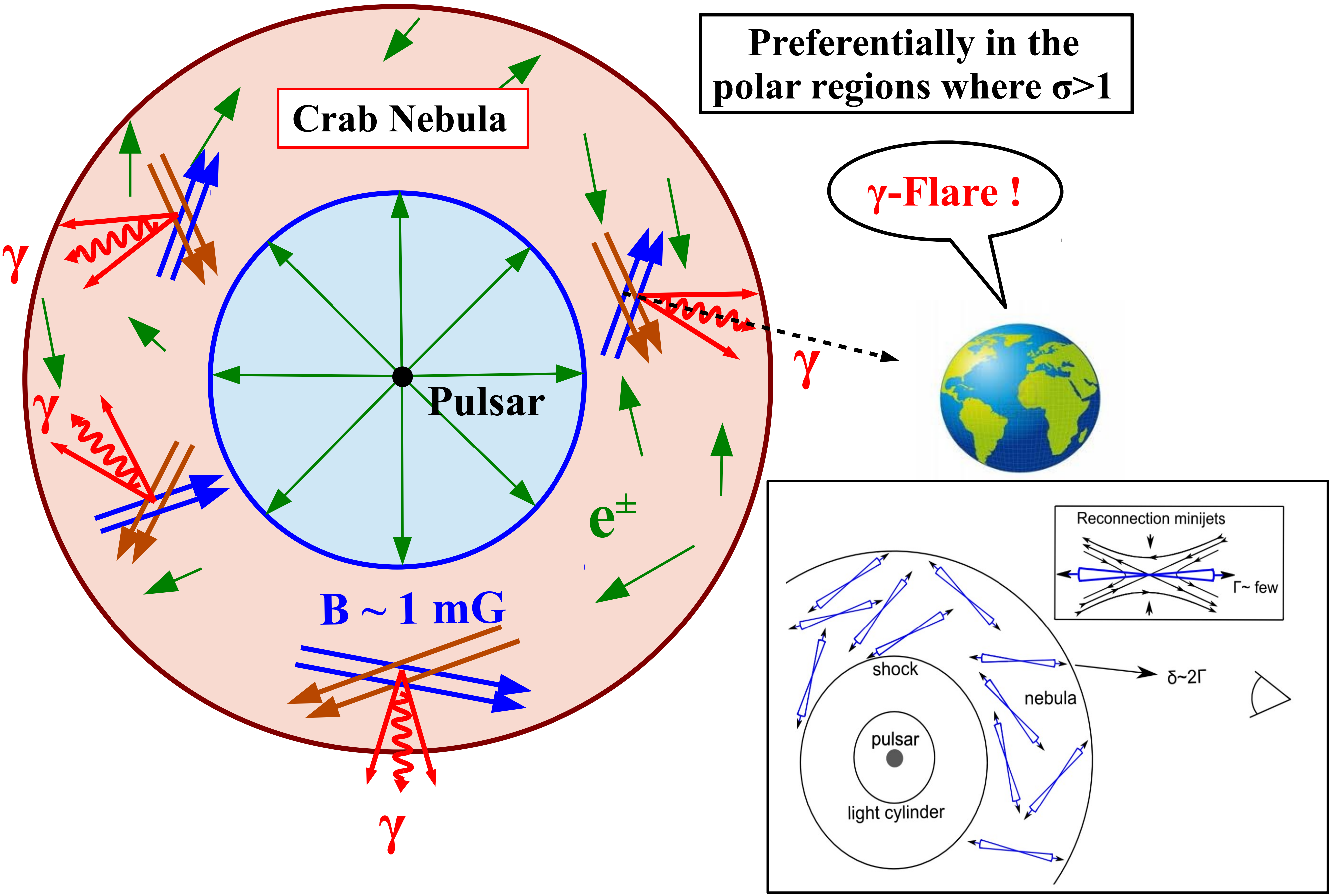
We see a flare when the beam crosses our line of sight



[Clausen-Brown & Lyutikov 2012]

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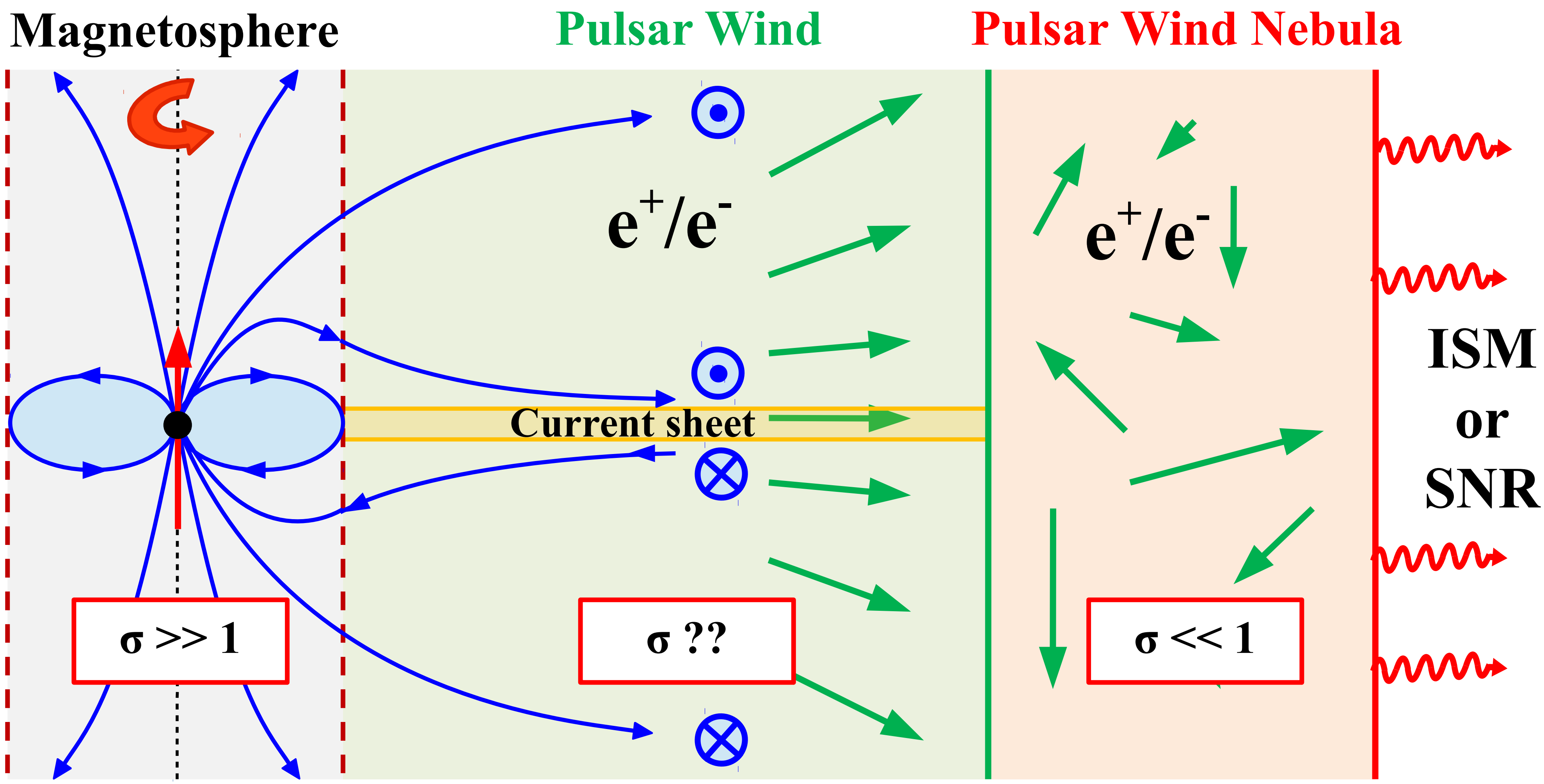
The “σ-problem”

[See reviews by e.g., Kirk et al. 2009, Arons 2012]



$$\sigma = \frac{\text{Poynting flux}}{\text{Particle kinetic energy flux}}$$

Transition σ >> 1 to σ << 1 unknown: “sigma” problem

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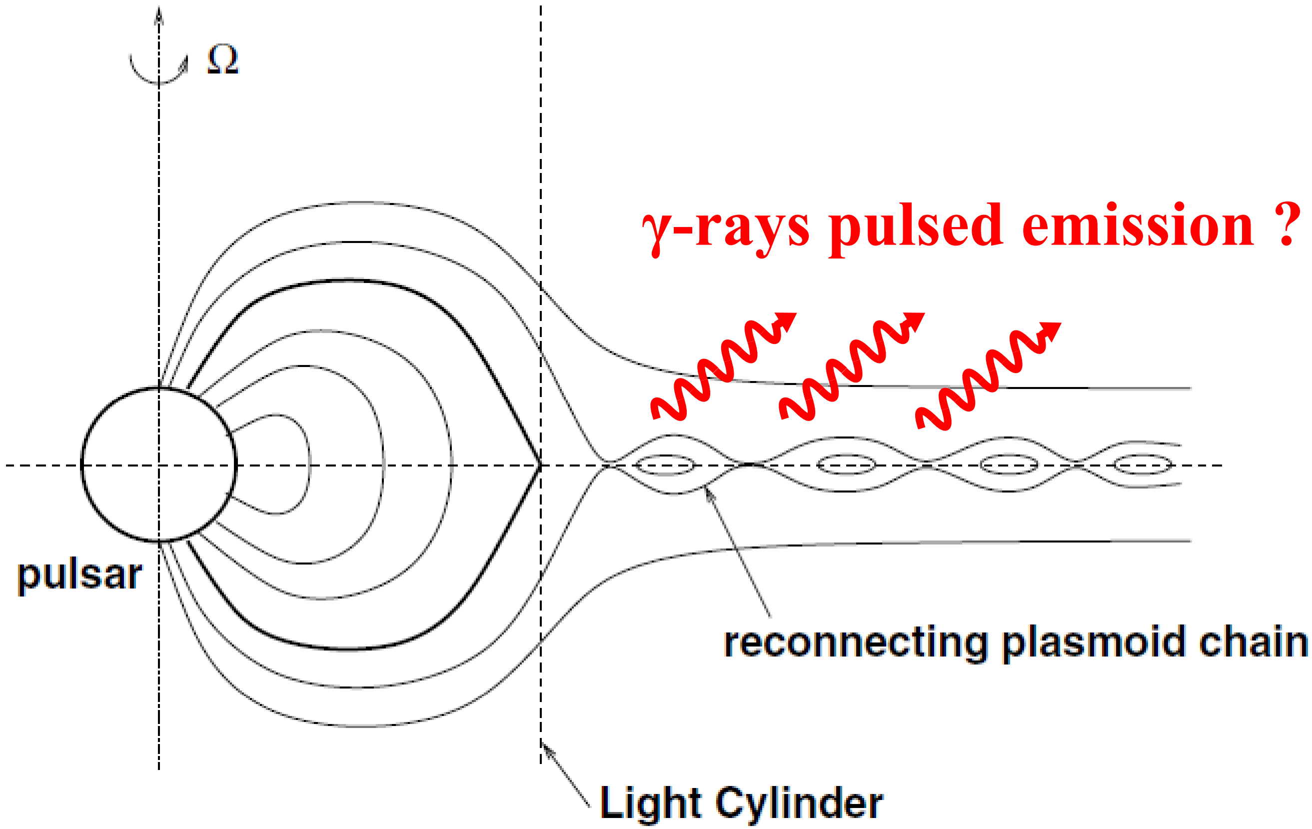
Reconnection in the equatorial current sheet

Fig. adapted from Uzdensky & Spitkovsky 2014



[Lyubarskii 1996 ; Kirk+2002 ; Pétri 2012 ; Arka & Dubus 2013; Uzdensky & Spitkovsky 2014]

How much, and where magnetic energy is dissipated?

Particle spectra, and photon spectra ?

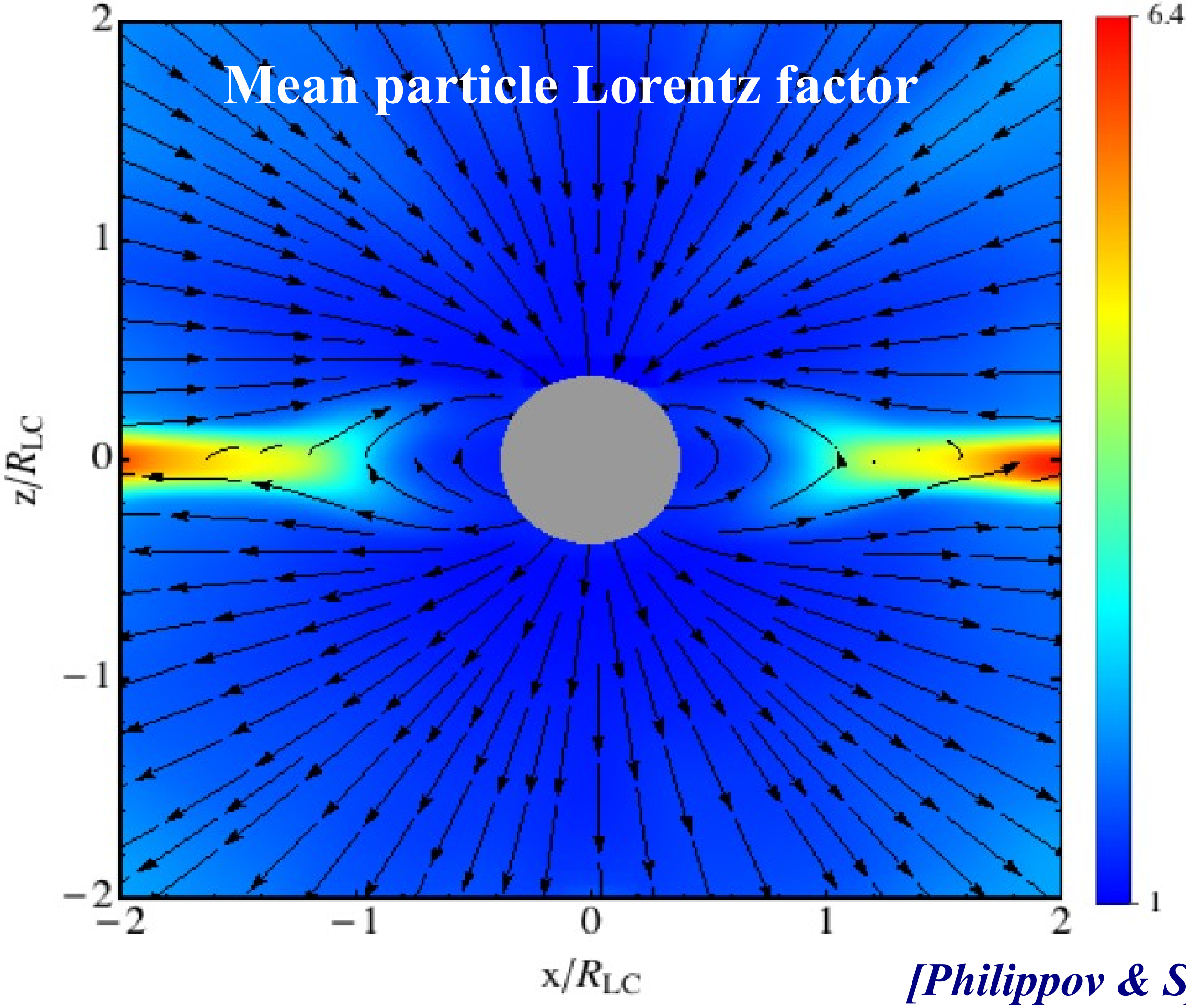
Reconnection rate, outflow velocities, currents ?

Simulation of the pulsar magnetosphere+current sheet self-consistently => PIC simulations!

Evidence of particle acceleration in the sheet

Sasha's talk!

3D Cartesian PIC simulation



[Philippov & Spitkovsky 2014]

The numerical setup

Aligned rotator => 2D axisymmetric problem

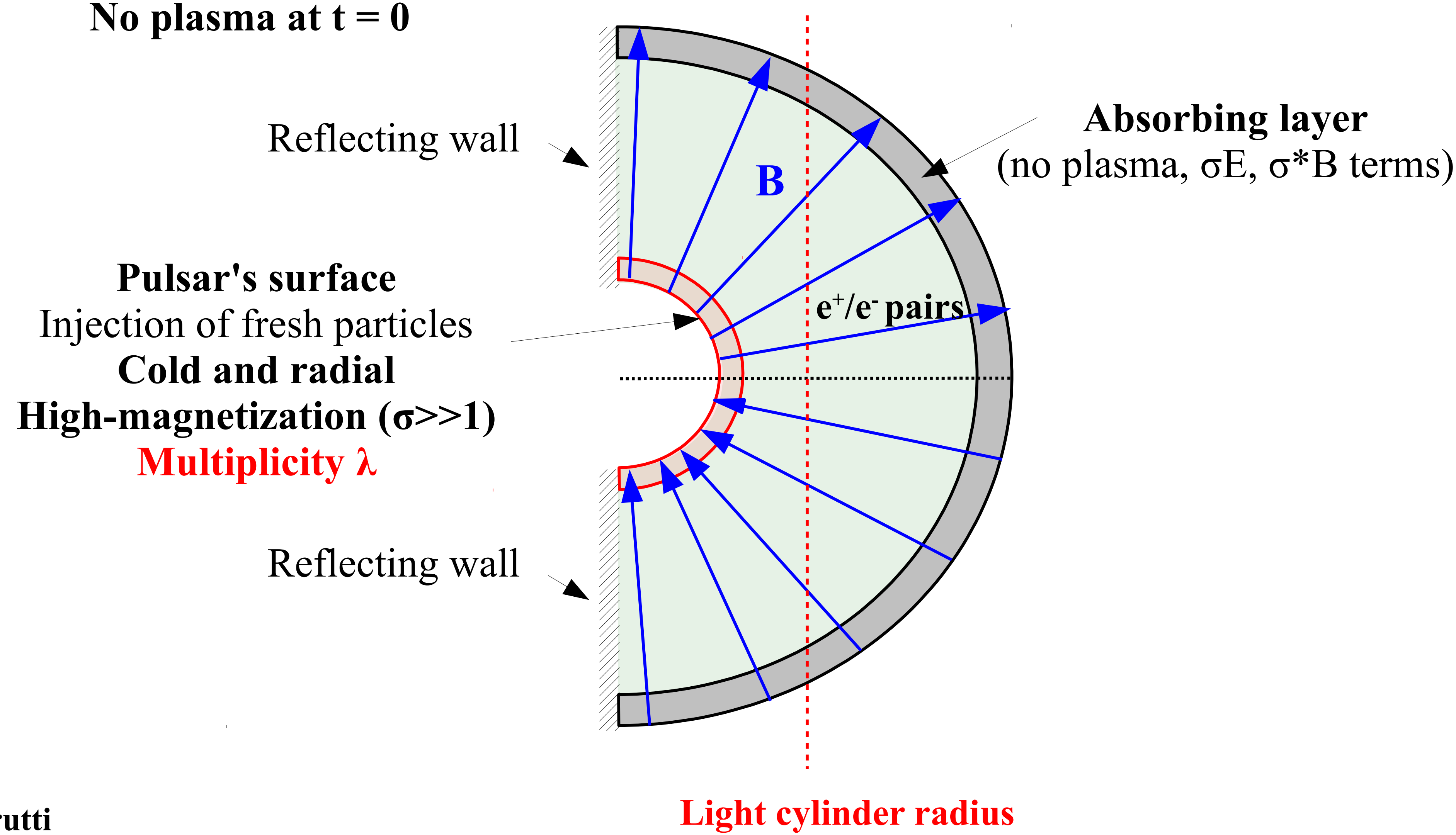
Computationally cheap => Follow the current sheet **over several light cylinder radii**

Development of Zeltron 2D, spherical axisymmetric

No radiation reaction in the following simulations!

<u>**Initial field:**</u> Michel's split monopole ***[Michel 1973]***, **aligned μ and Ω**

No plasma at t = 0



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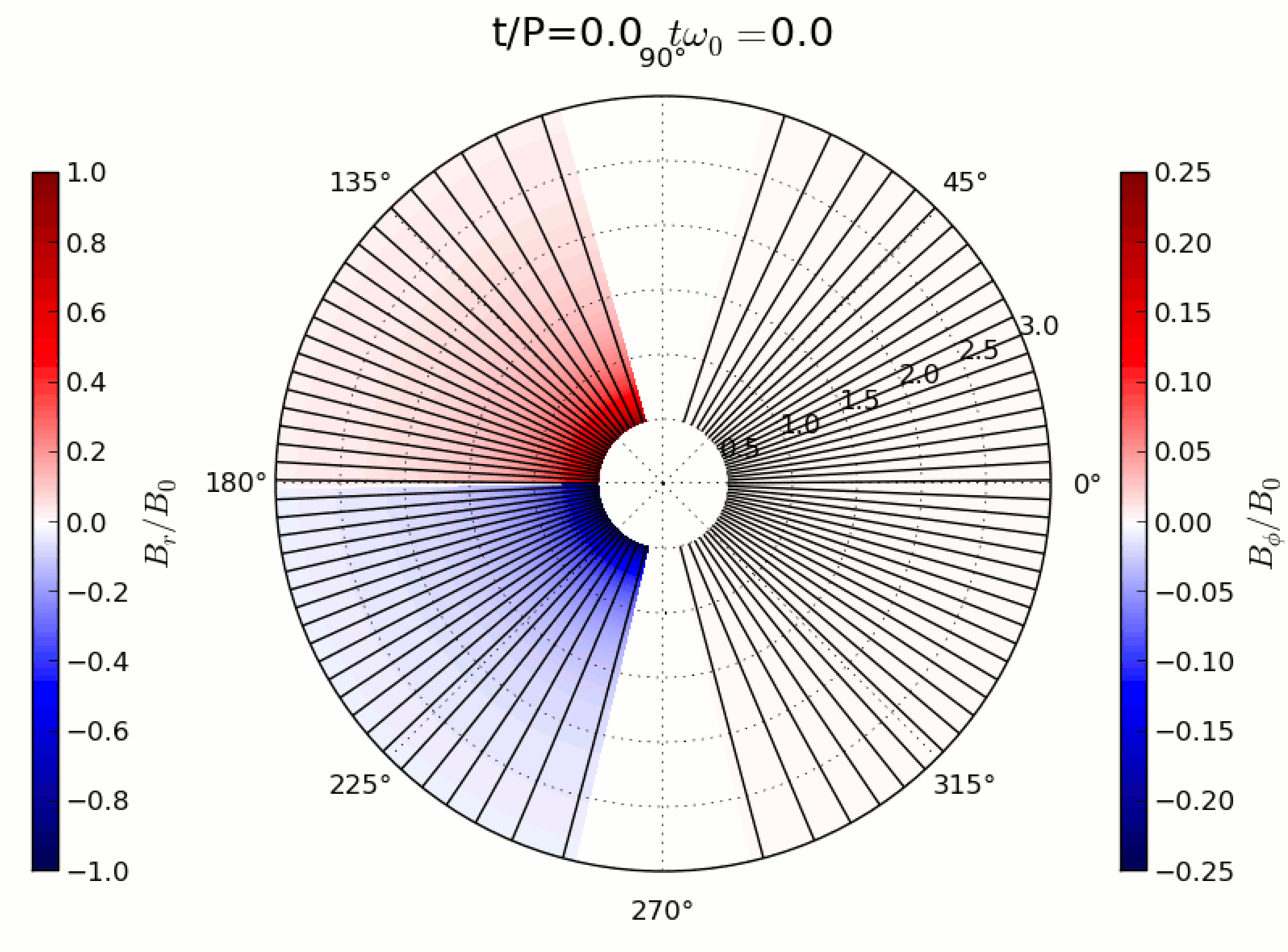
The magnetic field structure

Radial B-field **Multiplicity λ=5** **Toroidal B-field**



The current sheet kinks! (see also Sasha's simulation!)

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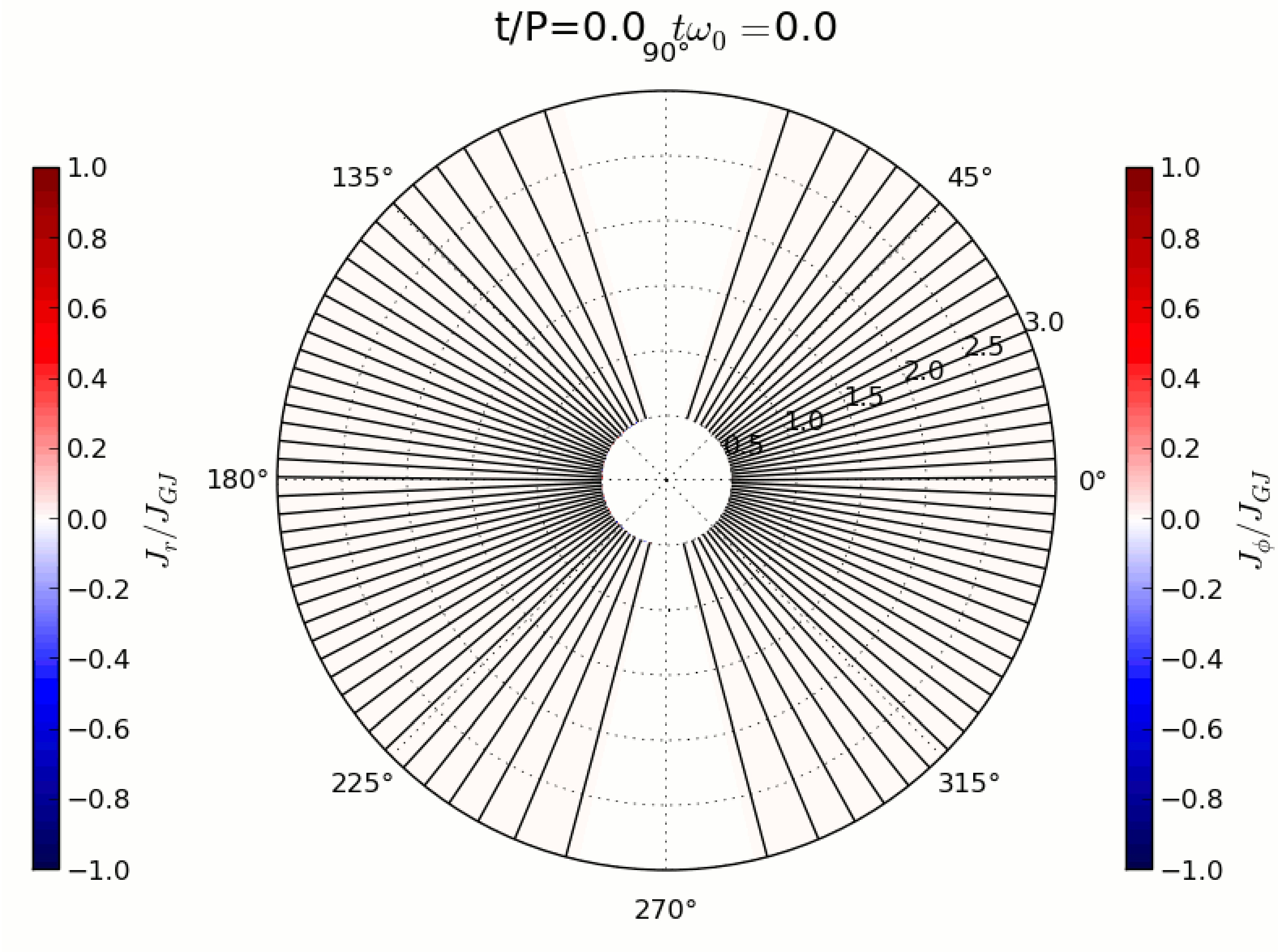
The current density structure

Radial current density **Multiplicity λ=5** **Toroidal current density**



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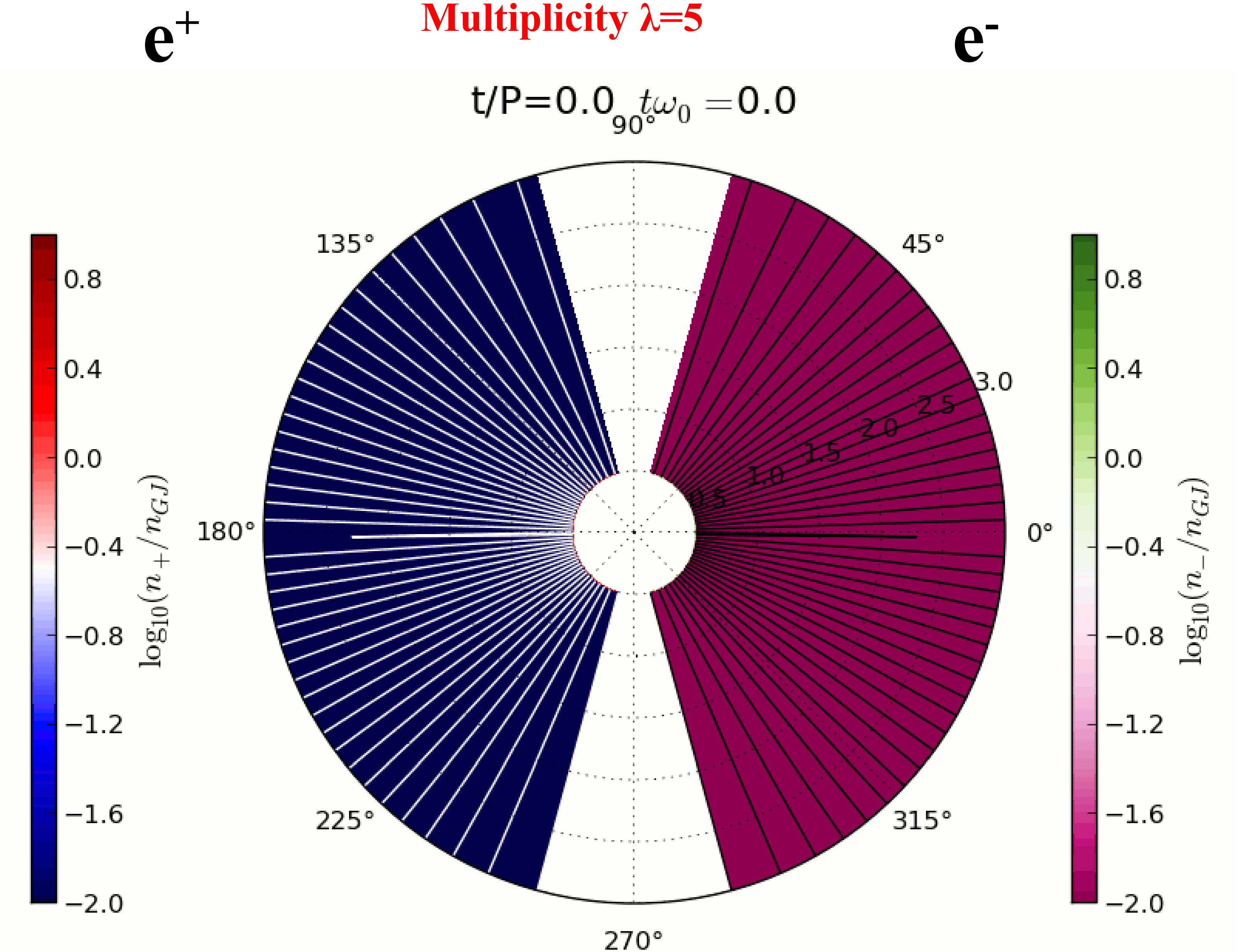
The plasma density

Multiplicity λ=5



The current sheet is positively charged.

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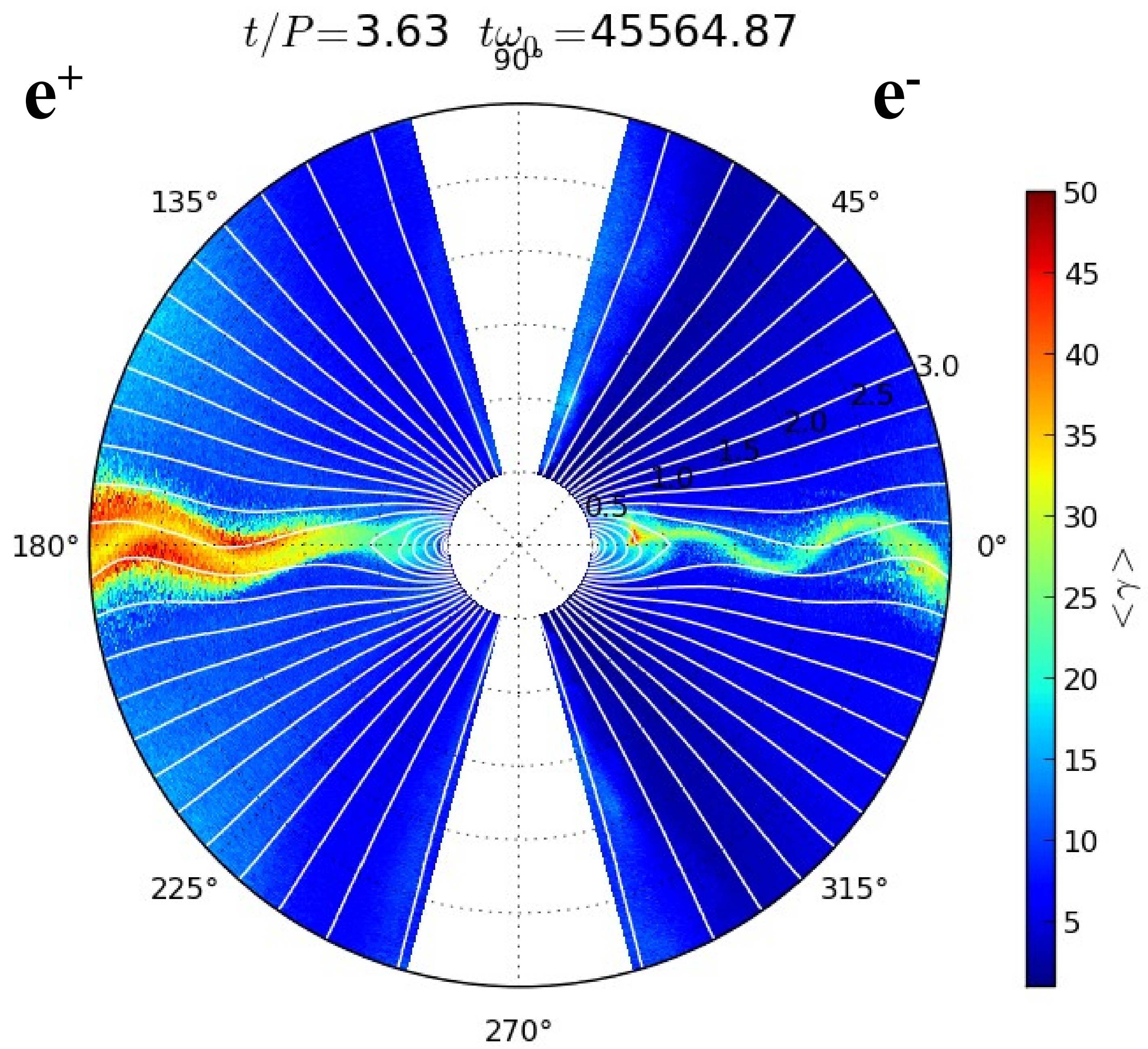
Spatial distribution of the energetic particles



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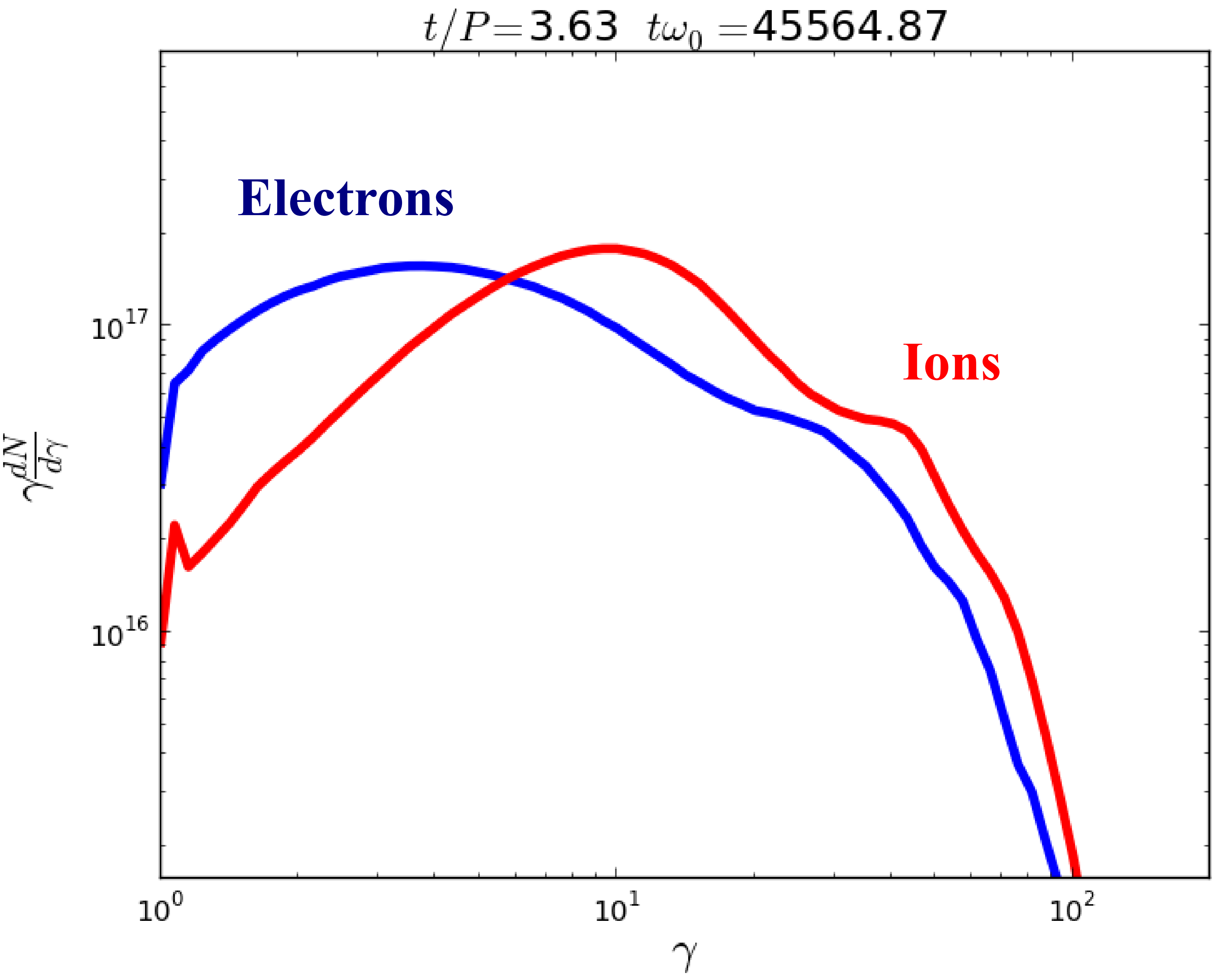
Total particle spectra (integrated over the box)



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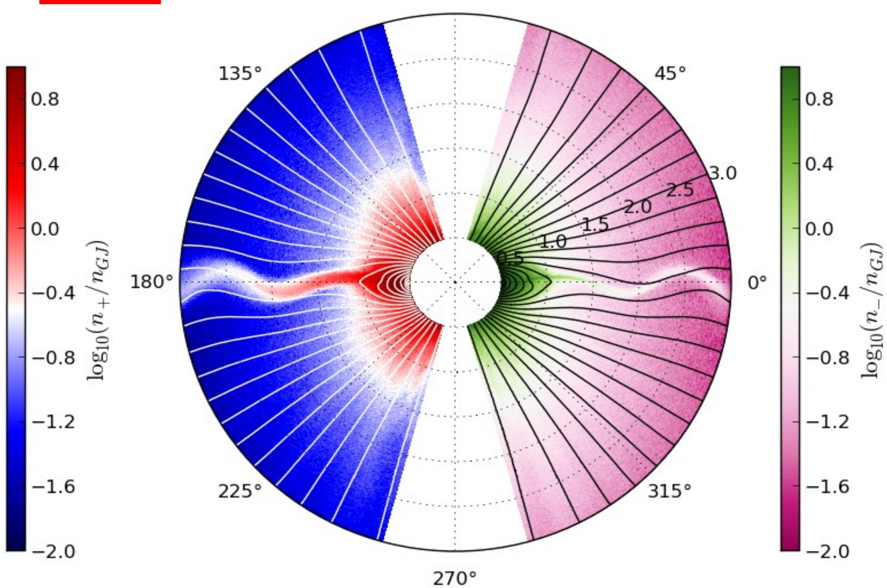
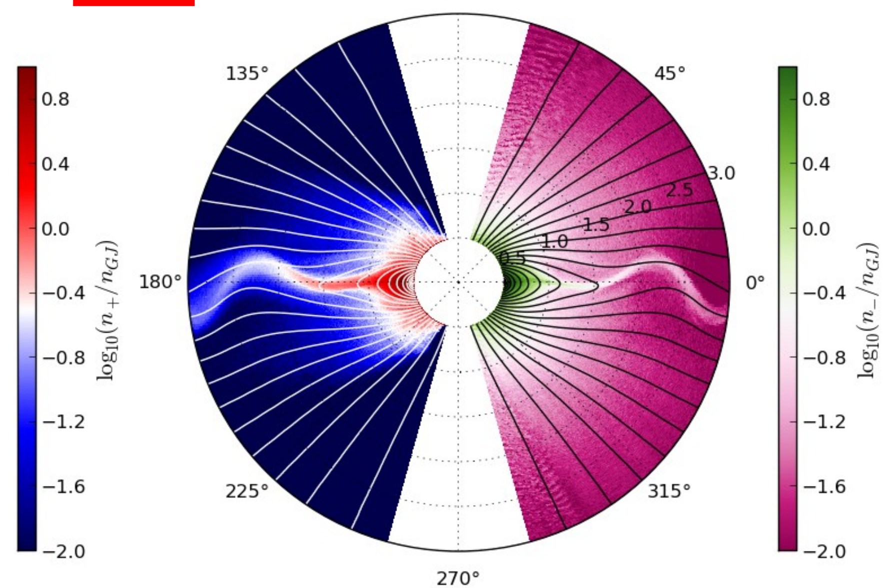
Effect of the multiplicity

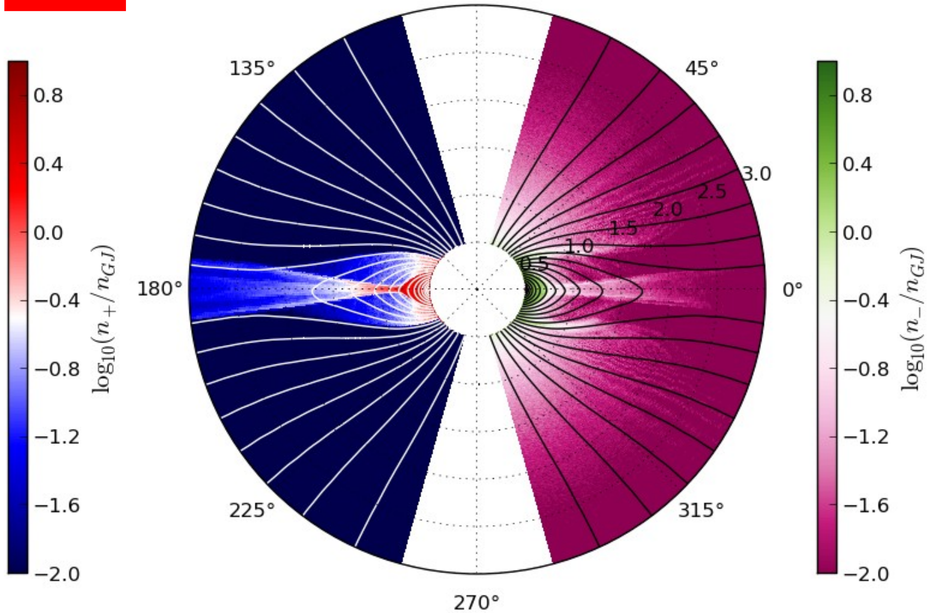
λ=5



λ=2



λ=1



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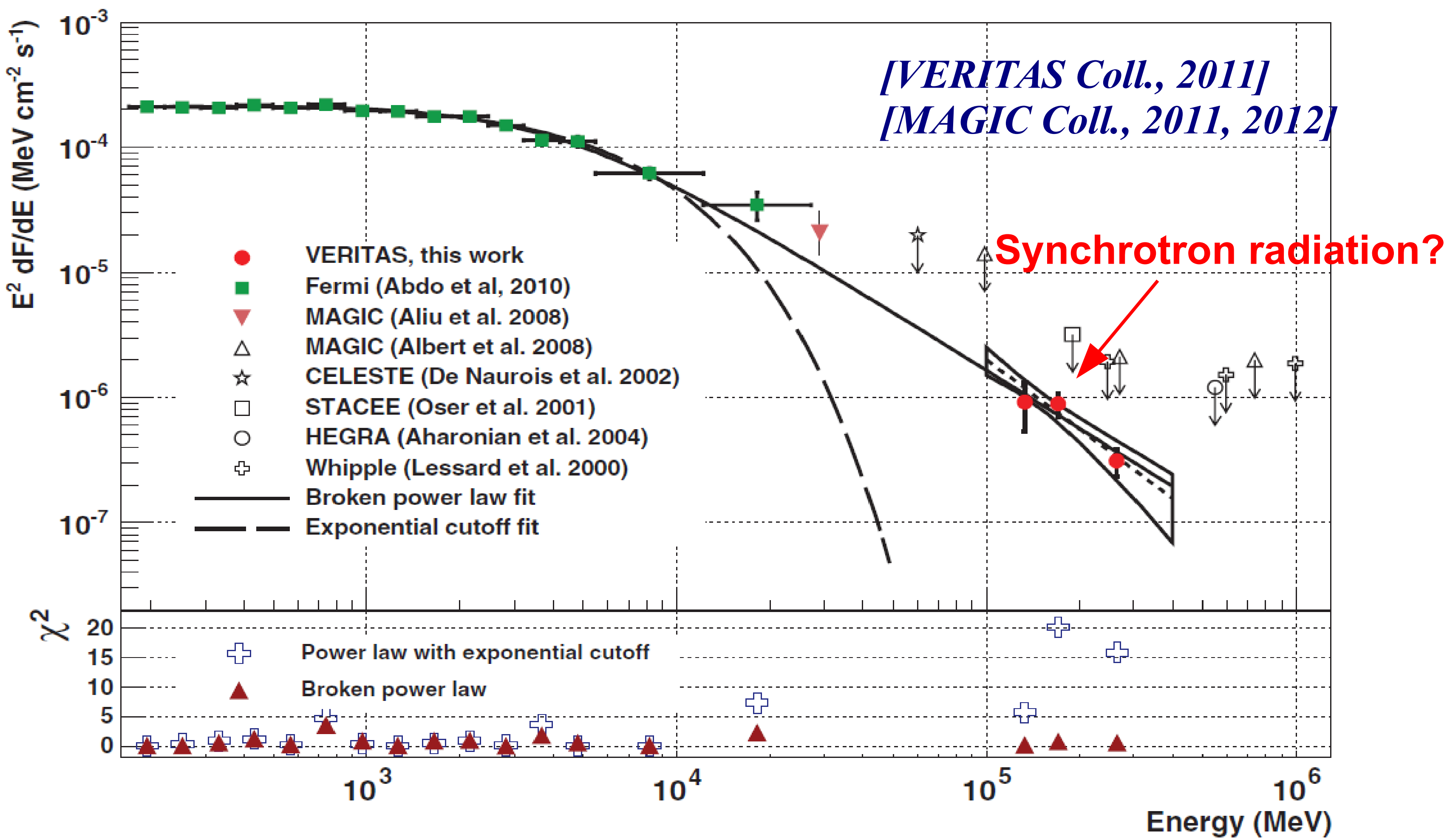
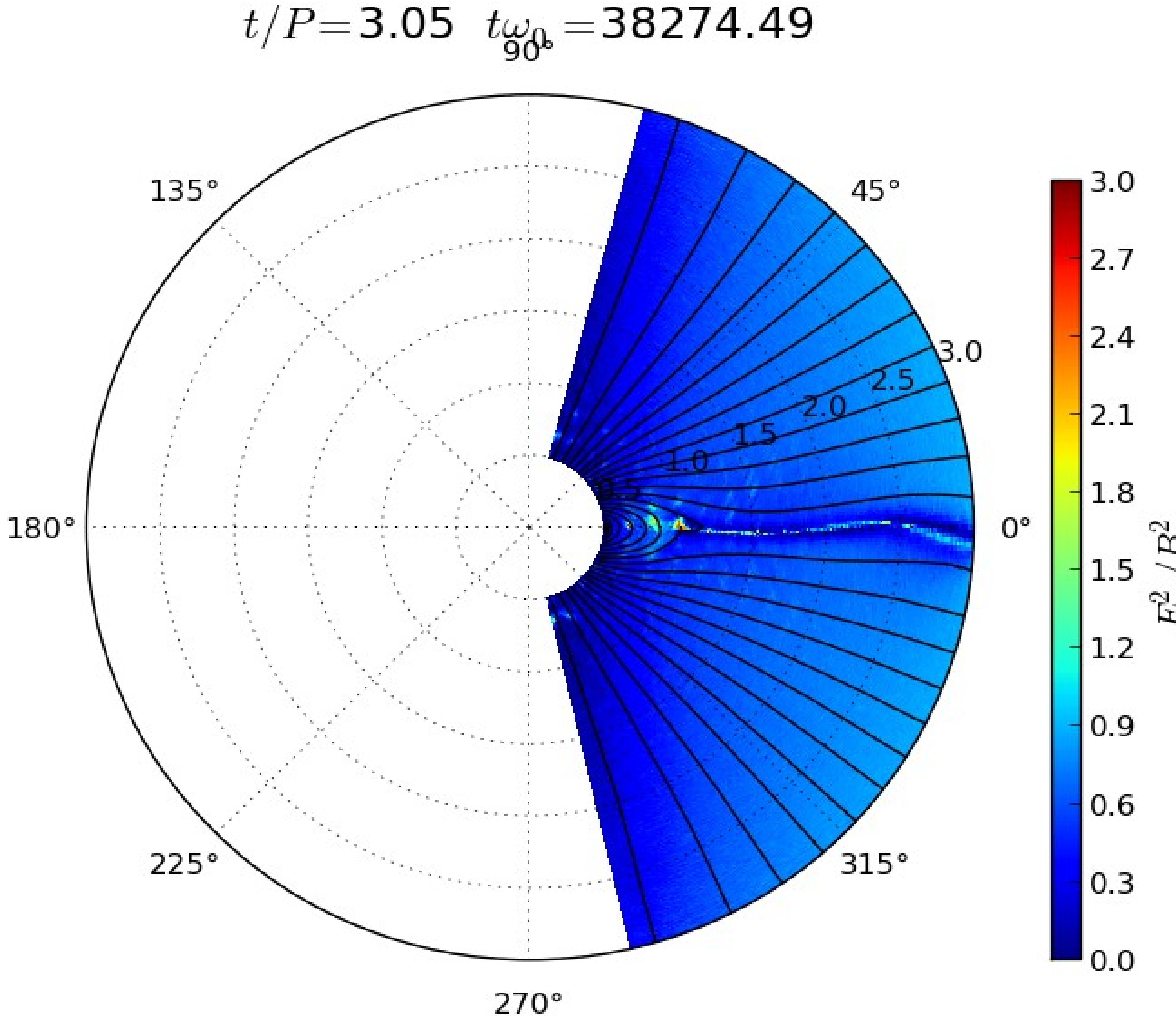
Another surprise from the Crab: Pulsed emission >100 GeV!



- Inconsistent with curvature radiation
- Inverse Compton scattering? ***[see e.g., Lyutikov 2012, Aharonian+2012]***
- Could this be due to **extreme particle acceleration in the current sheet (E>B)**? ***[Kirk 2004, Contopoulos 2007]***

… it could be!



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Summary

- Recent **global 3D simulations** suggest that **significant magnetic dissipation** should occur in PWNe (kink unstable)
- **Relativistic reconnection** is a viable mechanism for **magnetic dissipation and particle acceleration** in PWNe (high-σ nebula needed)
- **Crab Flares** = **Extreme particle acceleration** and radiation in a reconnection site, smoking gun of magnetic dissipation in PWNe?
- Possible application to **pulsar equatorial current sheet**, up to >100 GeV pulsed emission?
- **Next:** Large 2D simulations runs **radius>>R_{LC}**, **time>>P**, and **radiation reaction force.**

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