Particle acceleration beyond the synchrotron radiation reaction limit in the Crab Nebula

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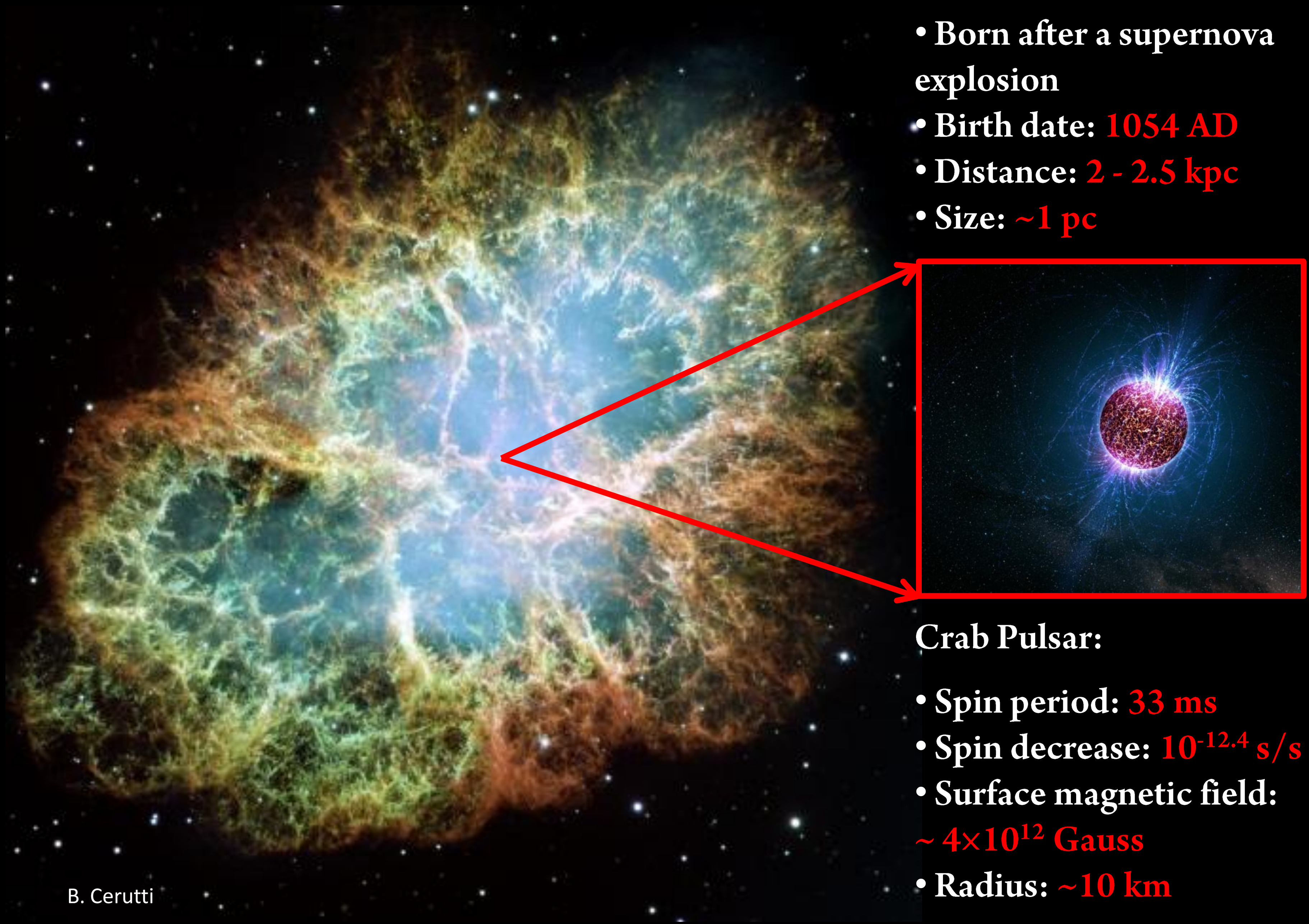
The Crab Nebula seen by the Hubble Space Telescope



- Born after a supernova explosion
- Birth date: 1054 AD
- Distance: 2 - 2.5 kpc
- Size: ~1 pc

Crab Pulsar:

- Spin period: 33 ms
- Spin decrease: $10^{-12.4}$ s/s
- Surface magnetic field: ~ 4×10^{12} Gauss
- Radius: ~10 km

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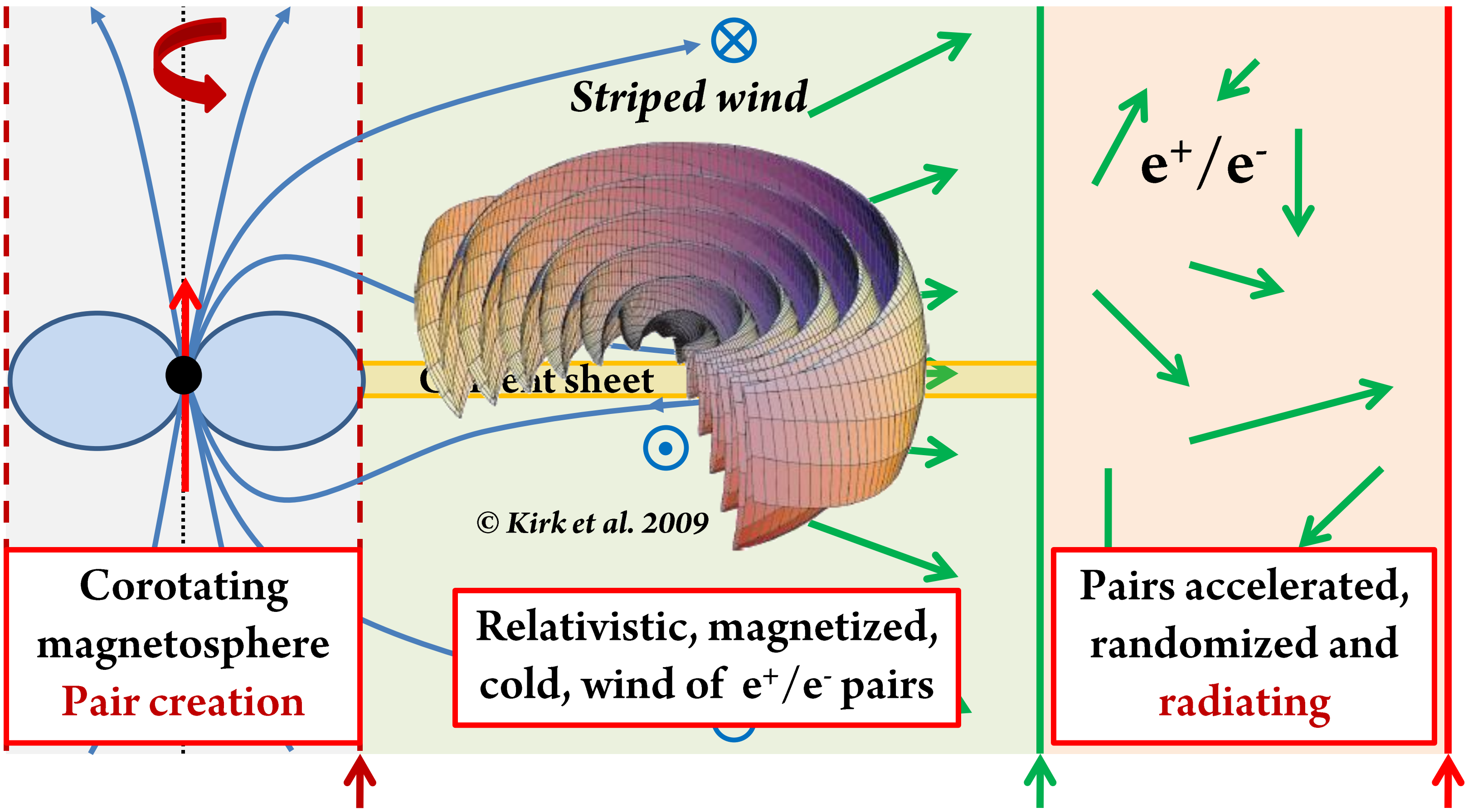
The classical (simplified) picture of pulsar wind nebulae

[See Review by Kirk et al. 2009]

Magnetosphere | **Pulsar Wind** | **Pulsar Wind Nebula**



Corotating magnetosphere
Pair creation

Relativistic, magnetized, cold, wind of e^+/e^- pairs

Pairs accelerated, randomized and radiating

ISM
or
SNR

Light cylinder
radius: $Pc/2\pi$
(~10^8 cm in Crab)

Termination
shock radius
(~0.1 pc in Crab)

Contact
discontinuity
(~1 pc in Crab)

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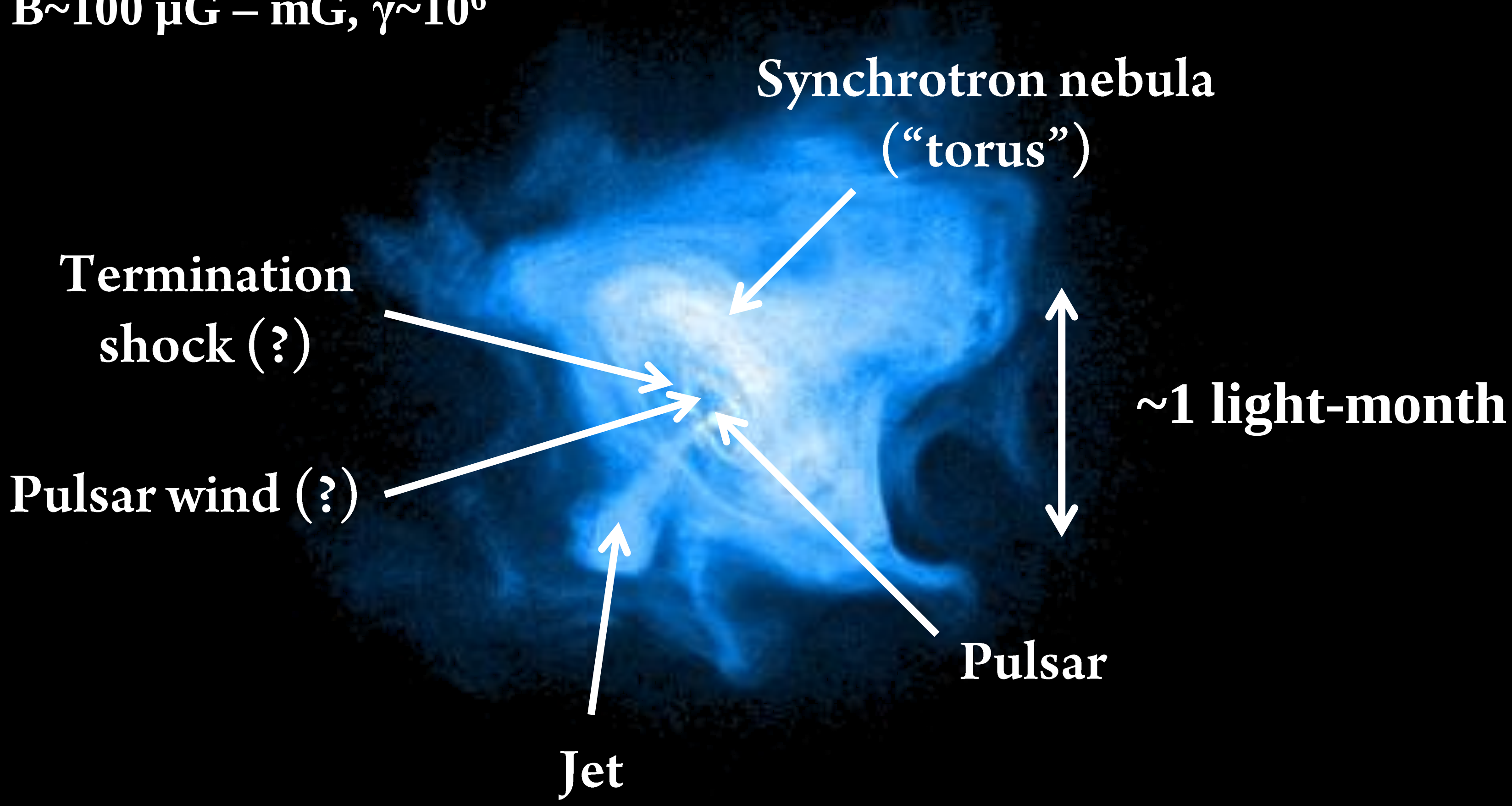
X-ray synchrotron bubble

Crab Nebula 0.3-3 keV

Synchrotron radiation from ultra-relativistic e^+/e^- pairs

B~100 μG – mG, $\gamma\sim10^6$



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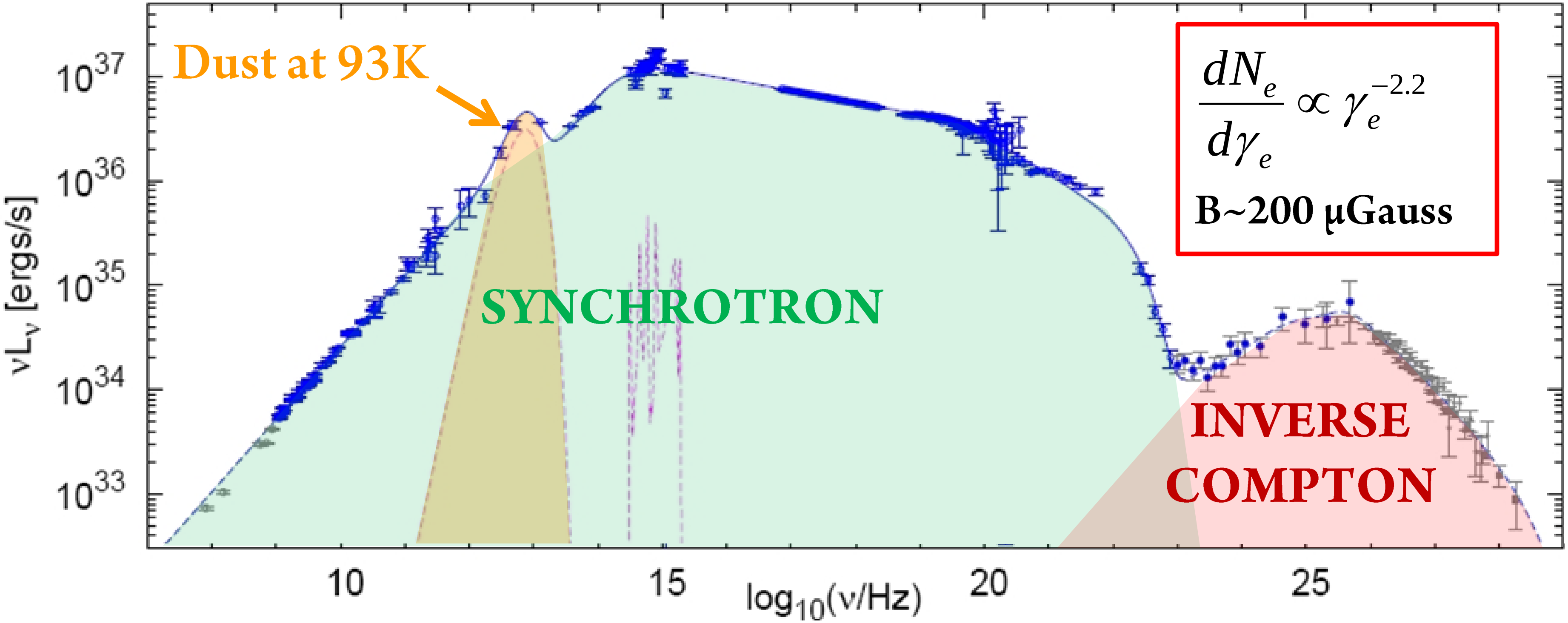
The Spectral Energy Distribution of the Crab Nebula

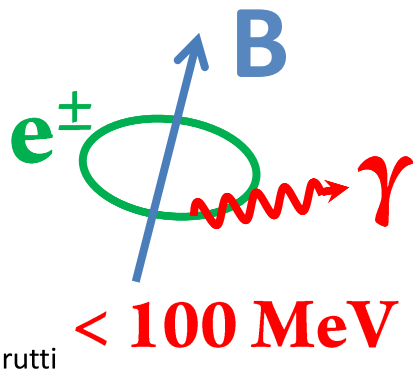
[Meyer et al. 2010]



$$\frac{dN_e}{d\gamma_e} \propto \gamma_e^{-2.2}$$

B~200 μGauss

Synchrotron radiation



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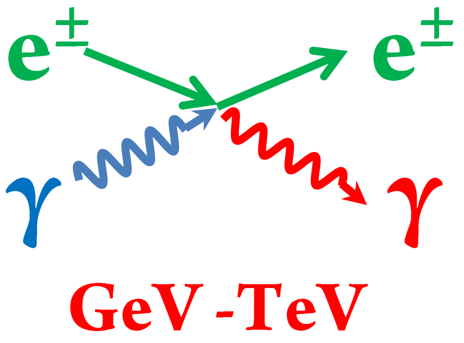
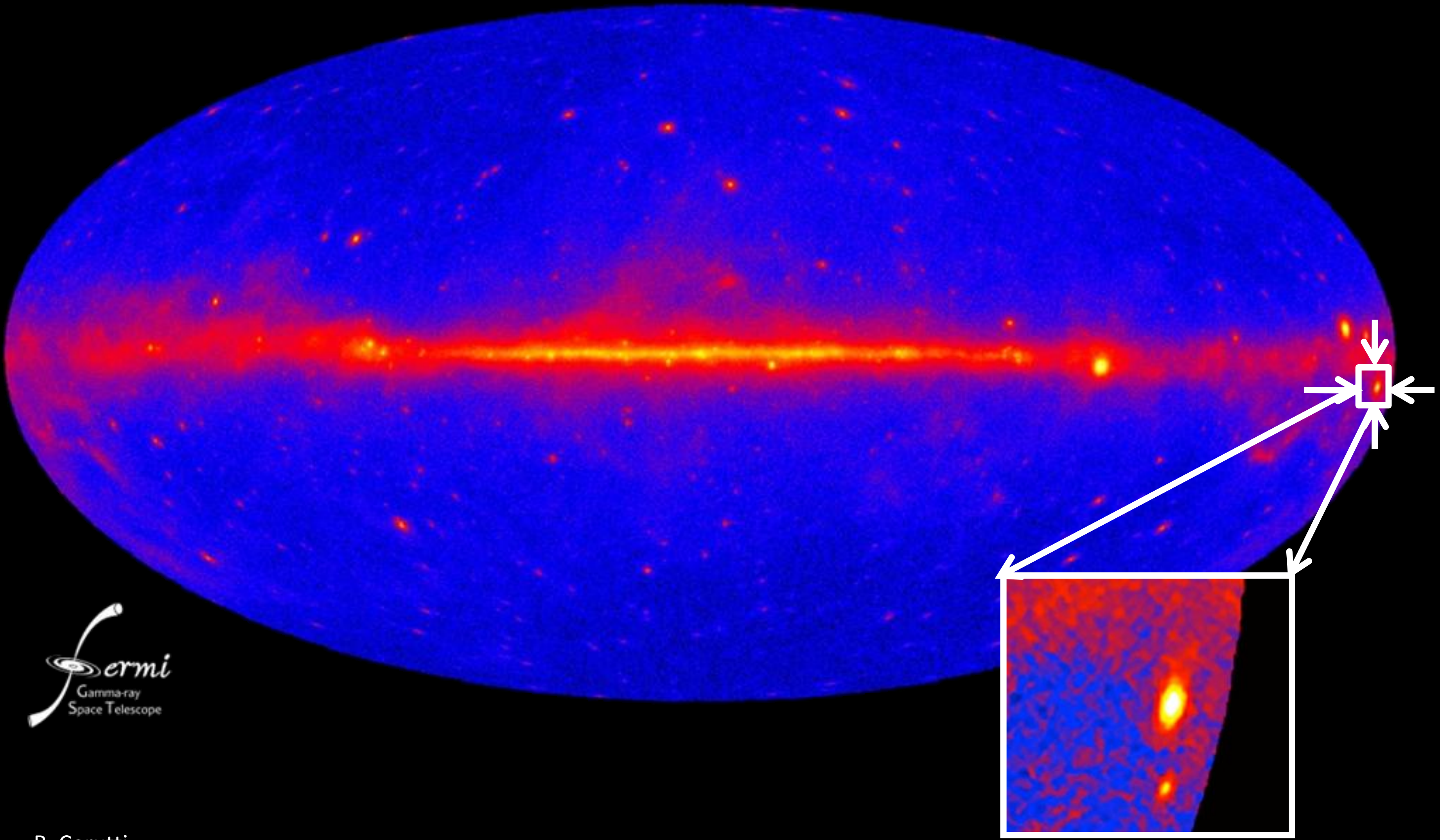
Inverse Compton scattering

Target photons:

- Synchrotron photons
- Dust (93 K)
- CMB (2.7 K)



The Crab Nebula in the gamma-ray sky



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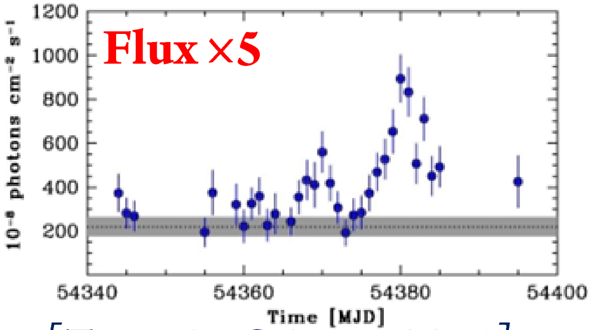
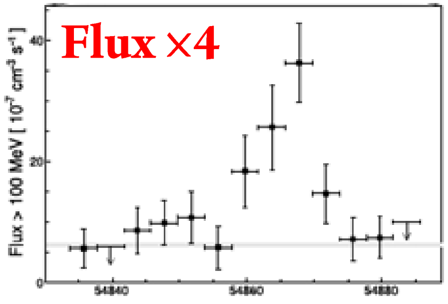
Fermi and *Agile* detected short and powerful gamma-ray flares in the Crab Nebula

Oct. 07, 14 days

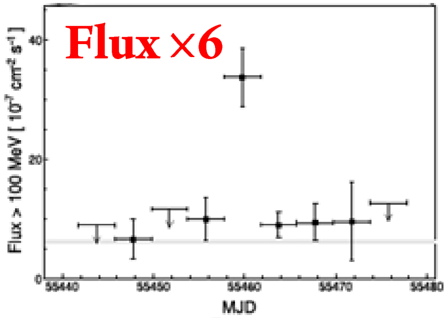


[Tavani+, Science, 2011]

Feb. 09, 16 days



Sep. 10, 4 days

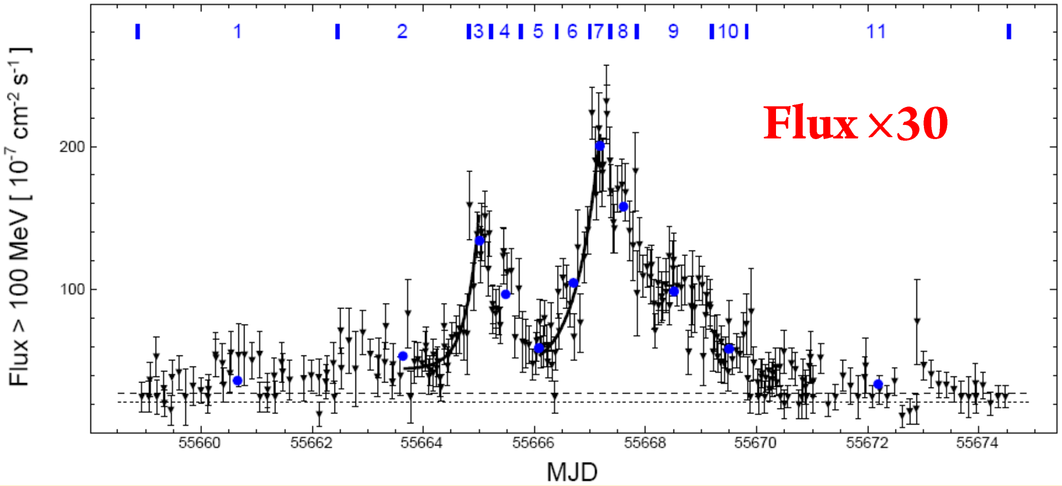


[Fermi-LAT, Science, 2011]

Apr. 11, 9 days

[Buehler +, 2012]

July 12, Few days



Flare 4 days ➔ emitting region size ct_{flare}~10^{16} cm << Nebula (~0.1 pc)

Shortest variability timescale ~1 hour. If $t_{flare}=t_{syn}$ ➔ B~few mG >> 200 μG

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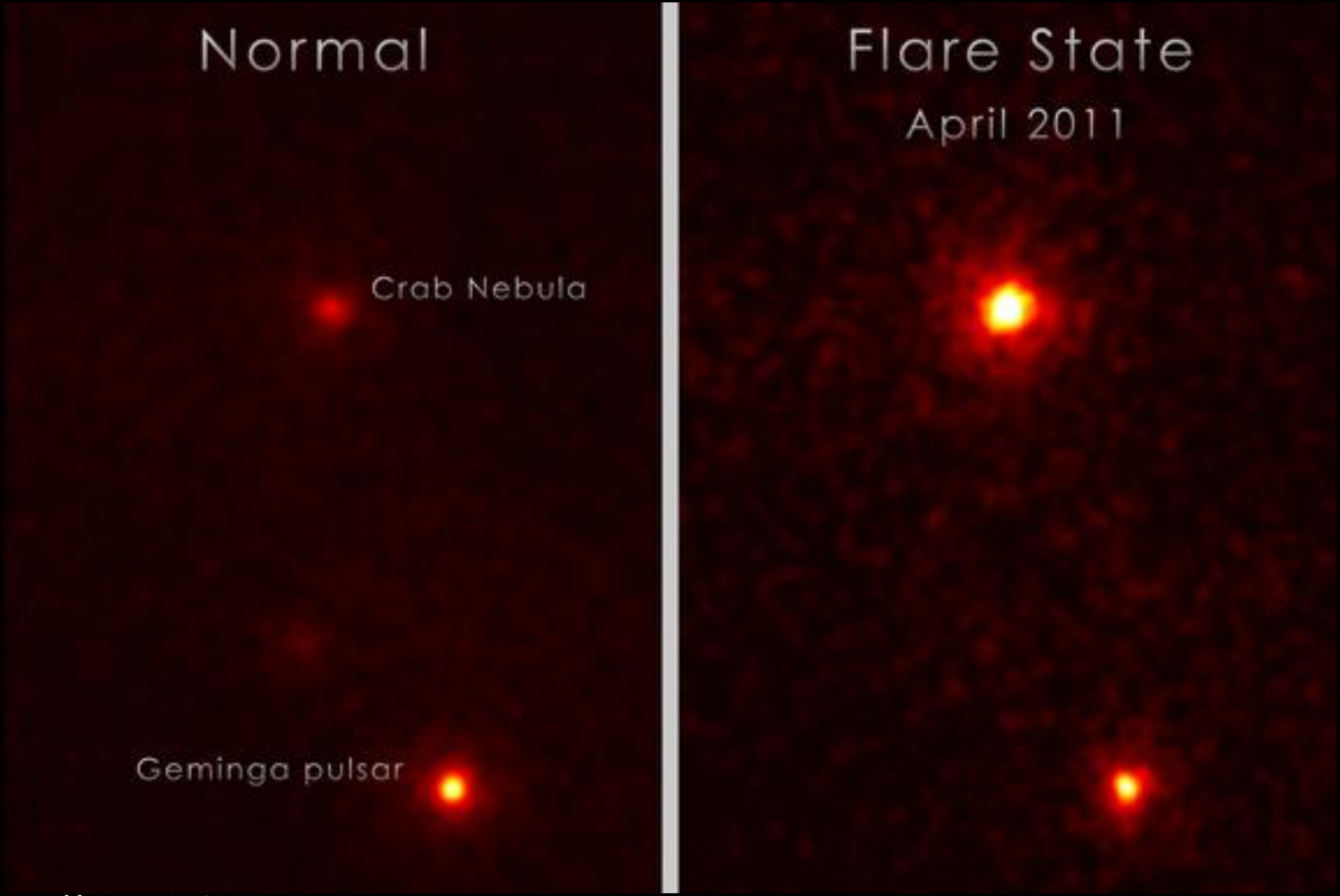
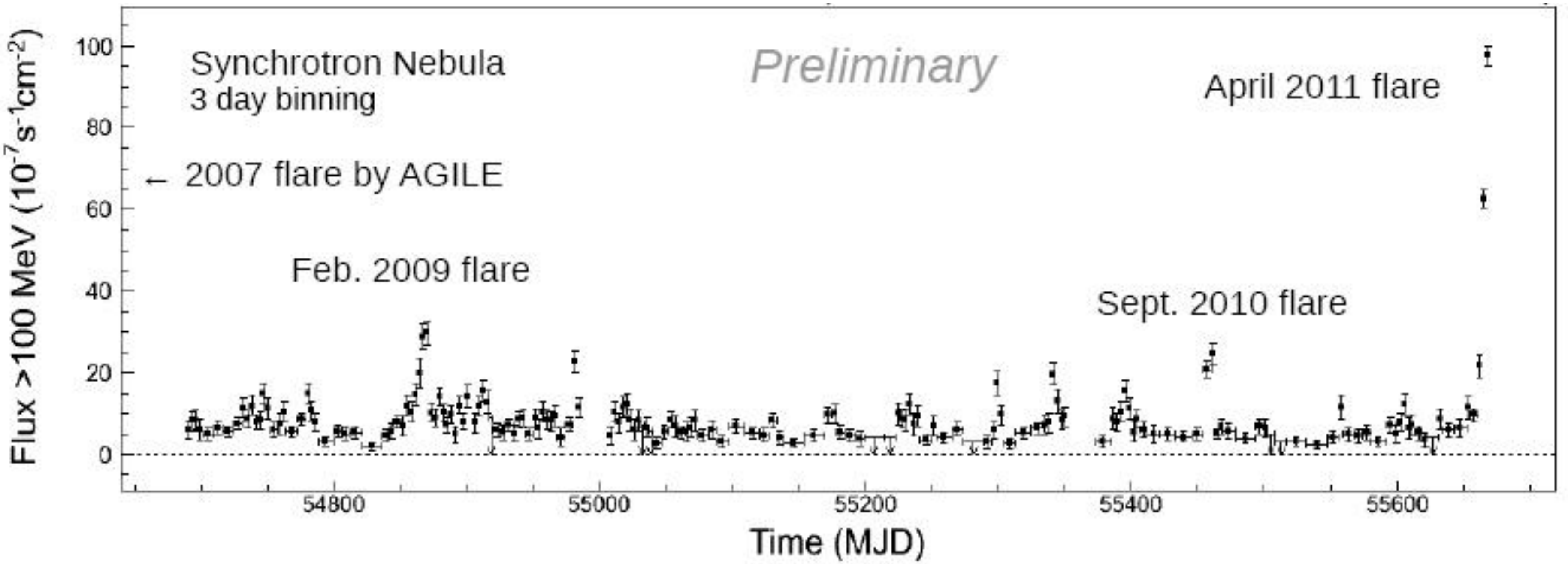
Fermi-LAT image during huge April 2011 flare



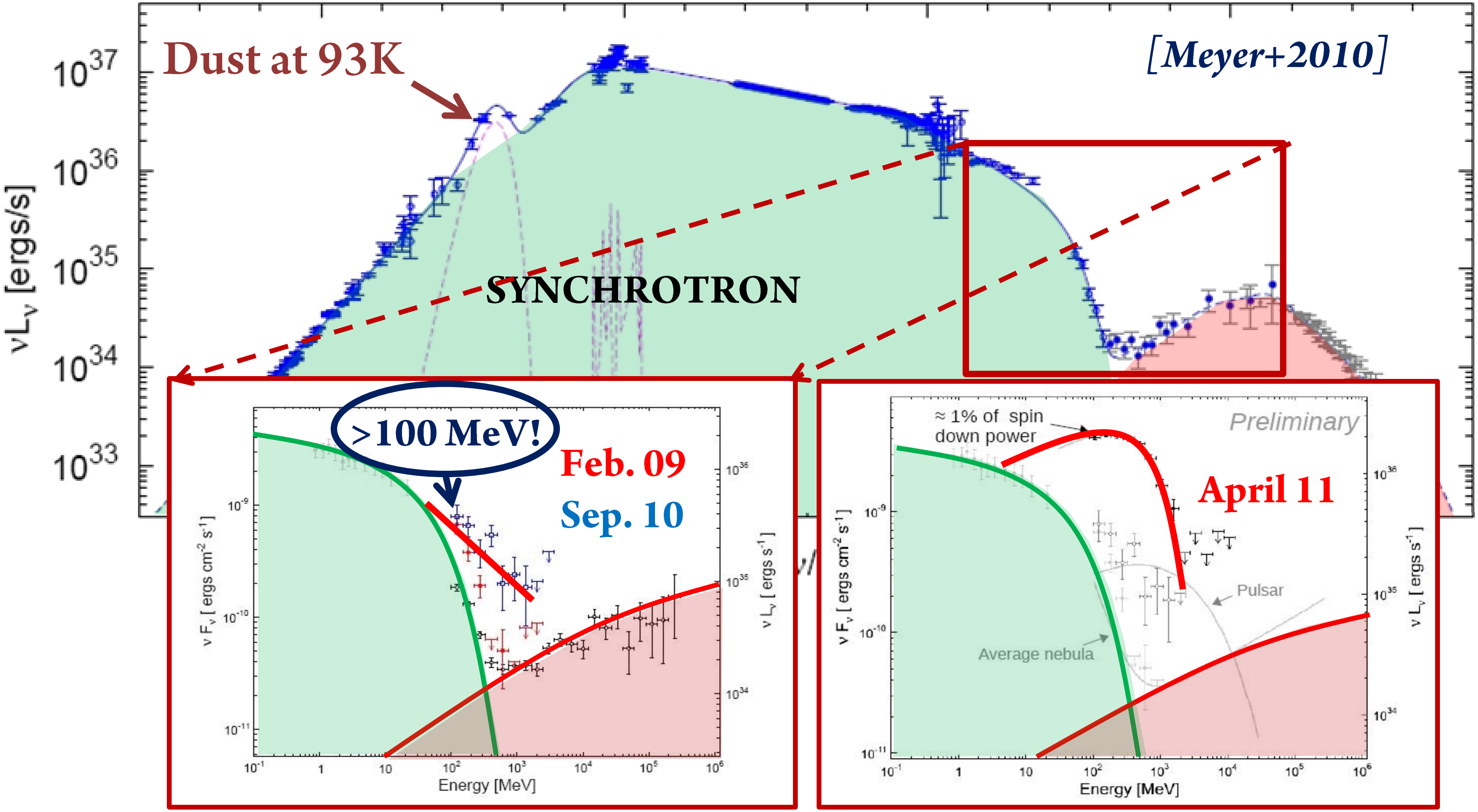
© R. Buehler, Fermi-LAT

The Crab Nebula is flaring all the time!



[R. Buehler 2011, Fermi-LAT Coll.]

Spectral variability at high energies



[Fermi-LAT, Science, 2011]

[Buehler+2011]

- **No obvious variability at other wavelength correlated with the flares.**
- **April 2011 spectrum is NOT a simple power-law**

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The production of synchrotron emission >100 MeV challenges classical models of acceleration

➢ Synchrotron photon energy: $\varepsilon_{max}=3/2\ \gamma_e^{2}\ \hbar\ (eB/m_ec)>100\ \text{MeV}$

➔ $\gamma_e\ m_ec^2 > 10^{15}\ \text{eV}$ **(B/1 mG), highest-energy particle associated with a specific astrophysical object!**

➢ **Maximum energy of electrons are limited by radiative losses:**

- Accelerating electric force: $f_{acc}=eE$
- **Radiation reaction force:** $f_{rad}=2/3\ r_e^{2}\ \gamma^2\ B^2$

$$\left.\begin{array}{l} f_{acc}=eE \\ f_{rad}=2/3\ r_e^{2}\ \gamma^2\ B^2 \end{array}\right\}\ f_{acc}=f_{rad} \rightarrow \gamma_{rad}$$

- Synchrotron photon energy: $\varepsilon_{max}=3/2\ \gamma^2_{rad}\ \hbar\ \omega_c = 160\times(E/B)\ \text{MeV}$

In classical acceleration mechanisms: E<B (ideal MHD) ➔ $\boxed{\varepsilon_{max}< 160\ \text{MeV}}$

➢ **Possible solution with relativistic Doppler boosting effect:**

[e.g. Komissarov & Lyutikov 2010, Bednarek & Idec 2011]

$$\varepsilon_{max}=D\times 160\ \text{MeV}$$

But then ***D≈3-4***, unlikely in the Crab Nebula (bulk motion < 0.5 c)

[Hester+2002]

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Abraham-Lorentz-Dirac equation

Equations of motion of a single relativistic electron: *[Jackson, 1975]*

$$m_e c\frac{\mathrm{d}u^\mu}{\mathrm{d}s}=\underbrace{-\frac{e}{c}F^{\mu\nu}u_\nu}_{\text{Lorentz 4-force}}+\underbrace{g^\mu}_{\text{Radiation reaction 4-force}}$$

u^μ : 4-velocity

$F^{\mu\nu}$: External electromagnetic field-strength tensor

$\mathrm{d}s=c\mathrm{d}t/\gamma_e$: Relativistic interval

Expression for the radiation reaction force

General expression: *[Landau & Lifshitz, 1971]*

$$g^{\mu} = \underbrace{\frac{2e^2}{3c}\frac{\mathrm{d}^2u^{\mu}}{\mathrm{d}s^2}}_{\substack{\text{“Schott” term}\\ \text{Negligible for } \gamma_e>>1}} - \underbrace{\frac{\mathcal{P}_{\mathrm{rad}}}{c^2}u^{\mu}}_{\substack{\text{Recoil due to}\\ \text{radiative losses}}} \rightarrow$$

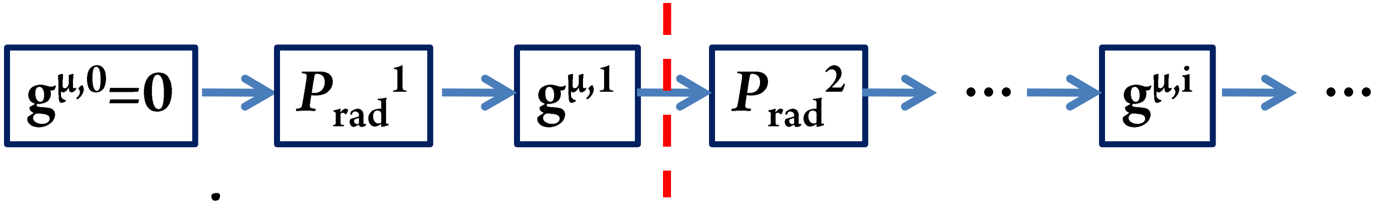
3-force for $\gamma_e>>1$:

$$\boxed{\mathbf{g} \approx -\frac{\mathcal{P}_{\mathrm{rad}}}{c^2}\mathbf{v}}$$

Continuous drag force

Relativistic Larmor formula: $\mathcal{P}_{\mathrm{rad}} = \frac{2}{3}e^2c\left(\frac{\mathrm{d}u^{\mu}}{\mathrm{d}s}\right)\left(\frac{\mathrm{d}u_{\mu}}{\mathrm{d}s}\right)$, depends on g^{μ}

Iterative method:



$$g^{\mu,0}=0 \rightarrow P_{rad}^{1} \rightarrow g^{\mu,1} \rightarrow P_{rad}^{2} \rightarrow \dots \rightarrow g^{\mu,i} \rightarrow \dots$$

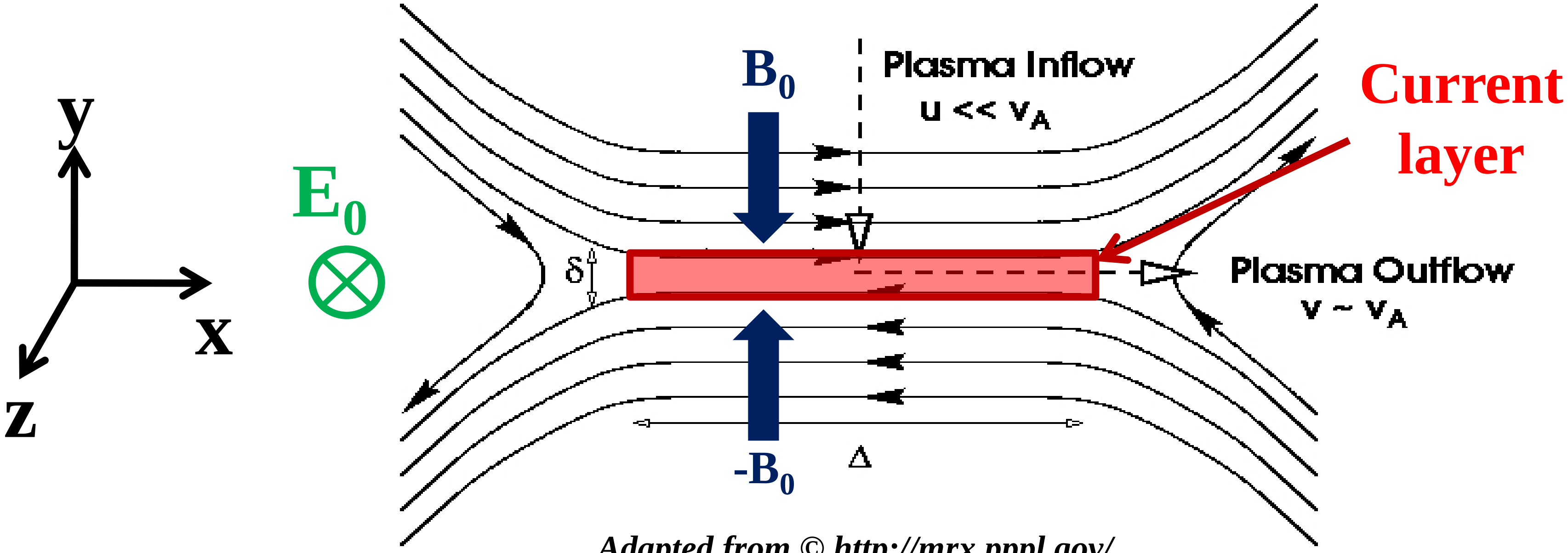
First order expression:

$$P_{rad}^{1} = \frac{2}{3}r_e^2c\gamma_e^2\left[\left(\mathbf{E}+\frac{\mathbf{v}\times\mathbf{B}}{c}\right)^2-\left(\frac{\mathbf{v}\cdot\mathbf{E}}{c}\right)^2\right]$$

valid if $\frac{\gamma_e B}{B_c} \ll 1$**, where** $B_c = m_e^2c^4/e^3 \sim 6\times10^{16}$ **Gauss**

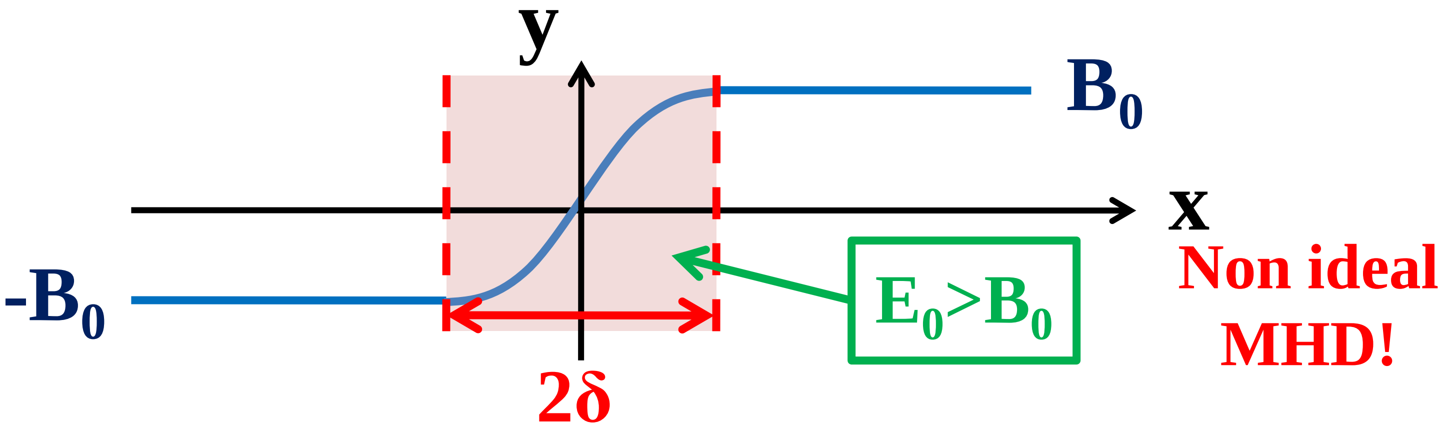
Valid in the Crab Nebula:
$\gamma_e \sim 10^9$
$B \sim 10^{-3}$ Gauss
$\gamma_e B/B_c \sim 10^{-11}$

Particle acceleration above the radiation reaction limit could occur at reconnection sites



Adapted from © http://mrx.pppl.gov/

The reconnecting magnetic field vanishes inside the current layer:



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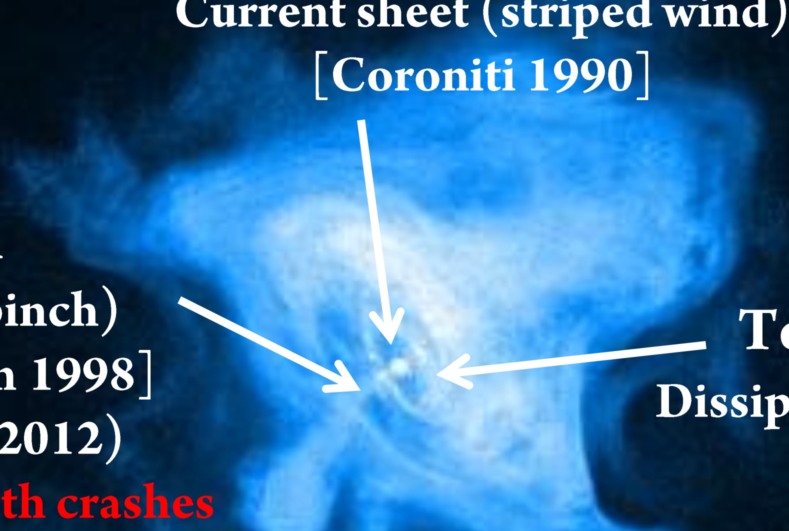
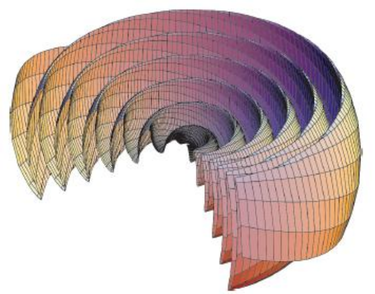
Where could magnetic reconnection operate in the Crab?



Pulsar wind

Current sheet (striped wind)

[Coroniti 1990]



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Polar region

- **High magnetic field (Z-pinch)**
- **Kink unstable [Begelman 1998]**

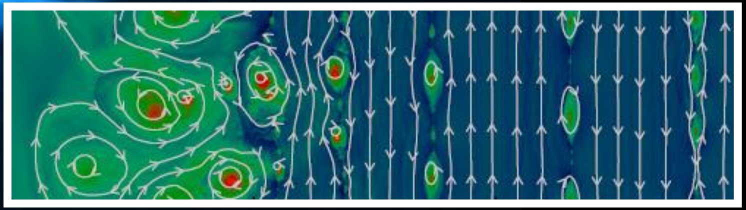
(See also Lyubarsky 2012)

Flares: Analog of Sawtooth crashes in tokamaks? [Uzdensky + 2011]

Termination shock

Dissipation of the striped wind

[Lyubarsky 2003]



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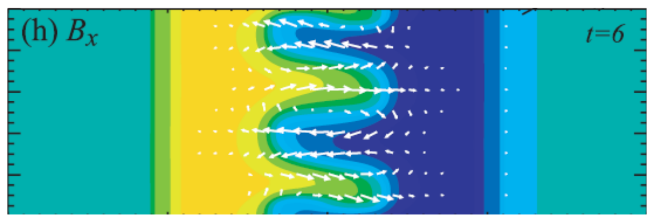

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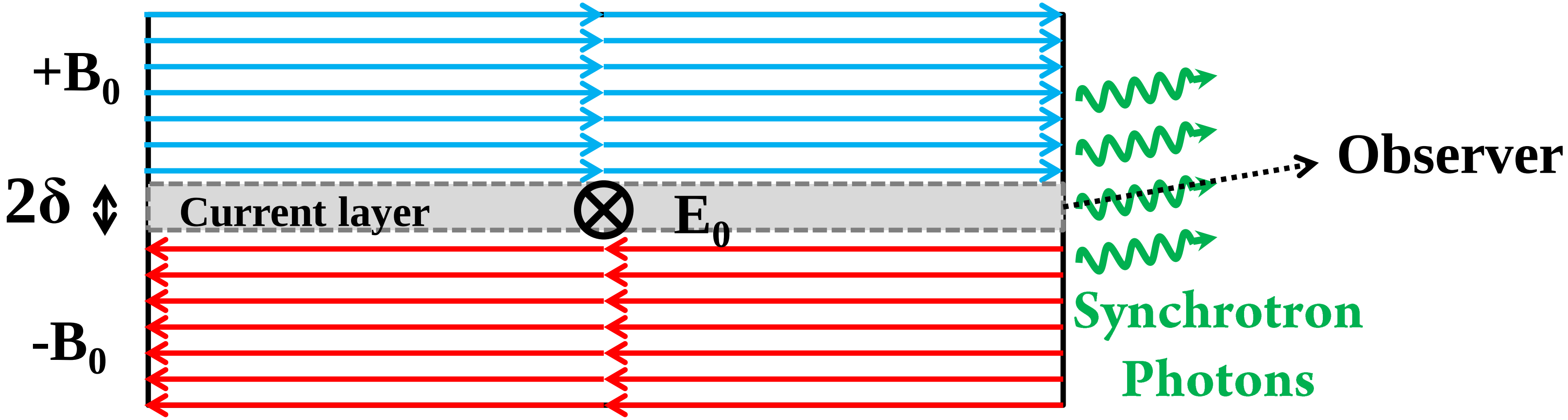
Goal

Study particle acceleration **in relativistic collisionless pair plasma reconnection**, and **its radiative signature** for an external observer.



PIC codes

VORPAL

Commercial software developped at the Univ. of Colorado and Tech-X Corporation. ***[Nieter & Cary 2004]***

Simus. done by G. R. Werner

ZELTRON

Developped from scratch by B.Cerutti at Univ. of Colorado. 2D and 3D relativistic parallel PIC with open MPI.

+ Radiation reaction force!

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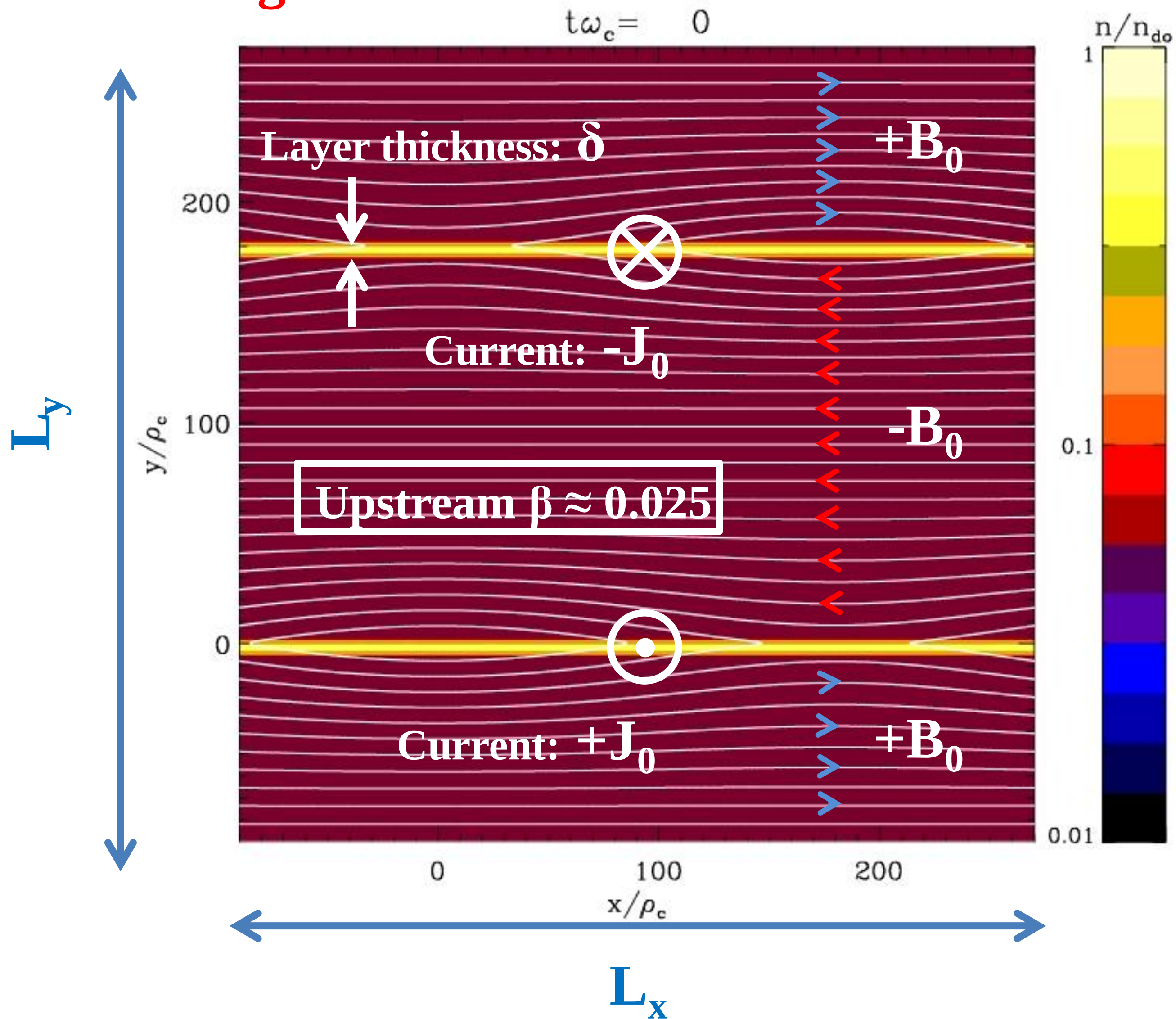
Initial setup: Relativistic Harris equilibrium

2.5 D & No guide field



Double periodic boundary conditions

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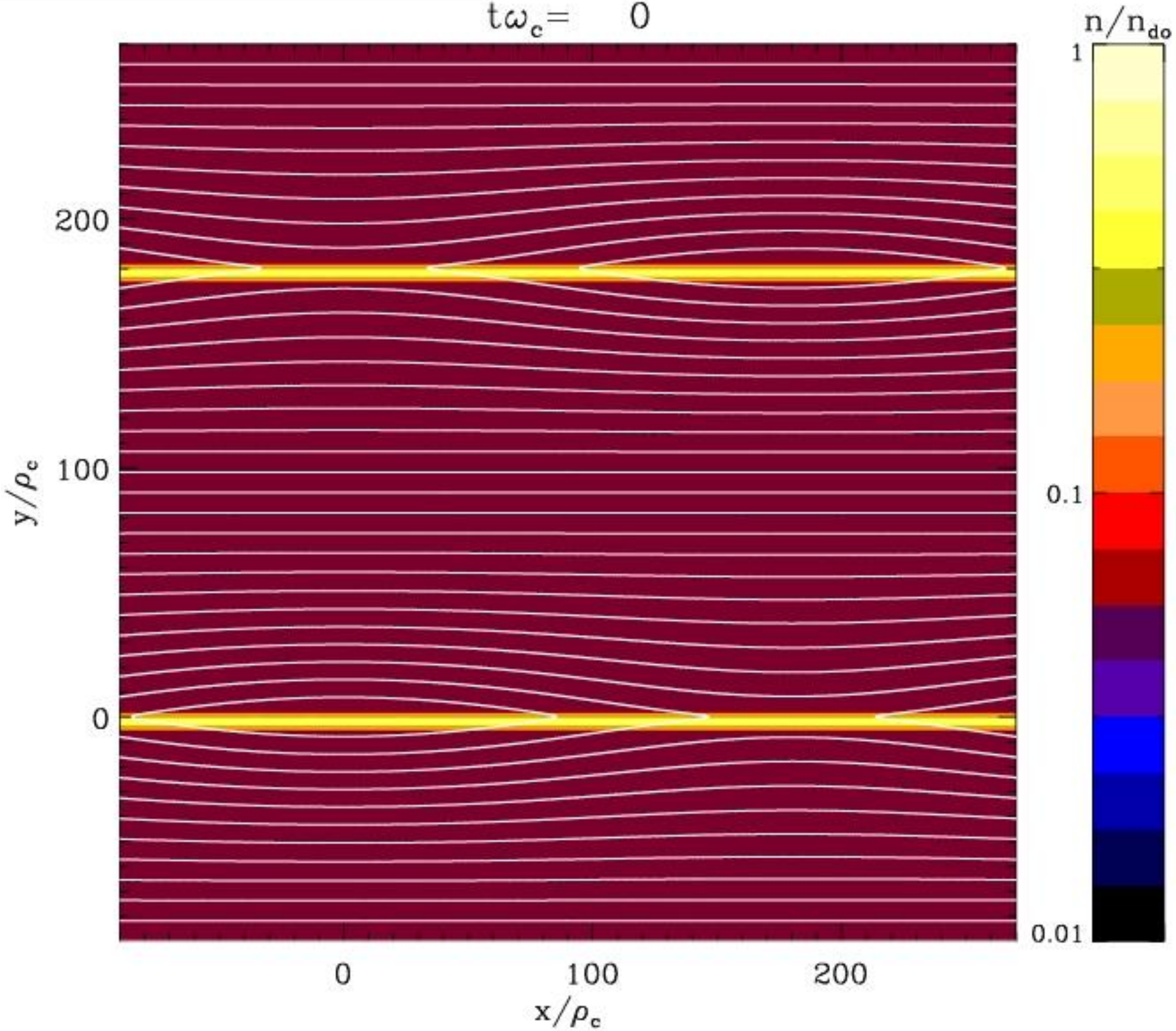
Time evolution of reconnection

NO radiation reaction force.

[Cerutti et al., ApJLetters, 2012b]

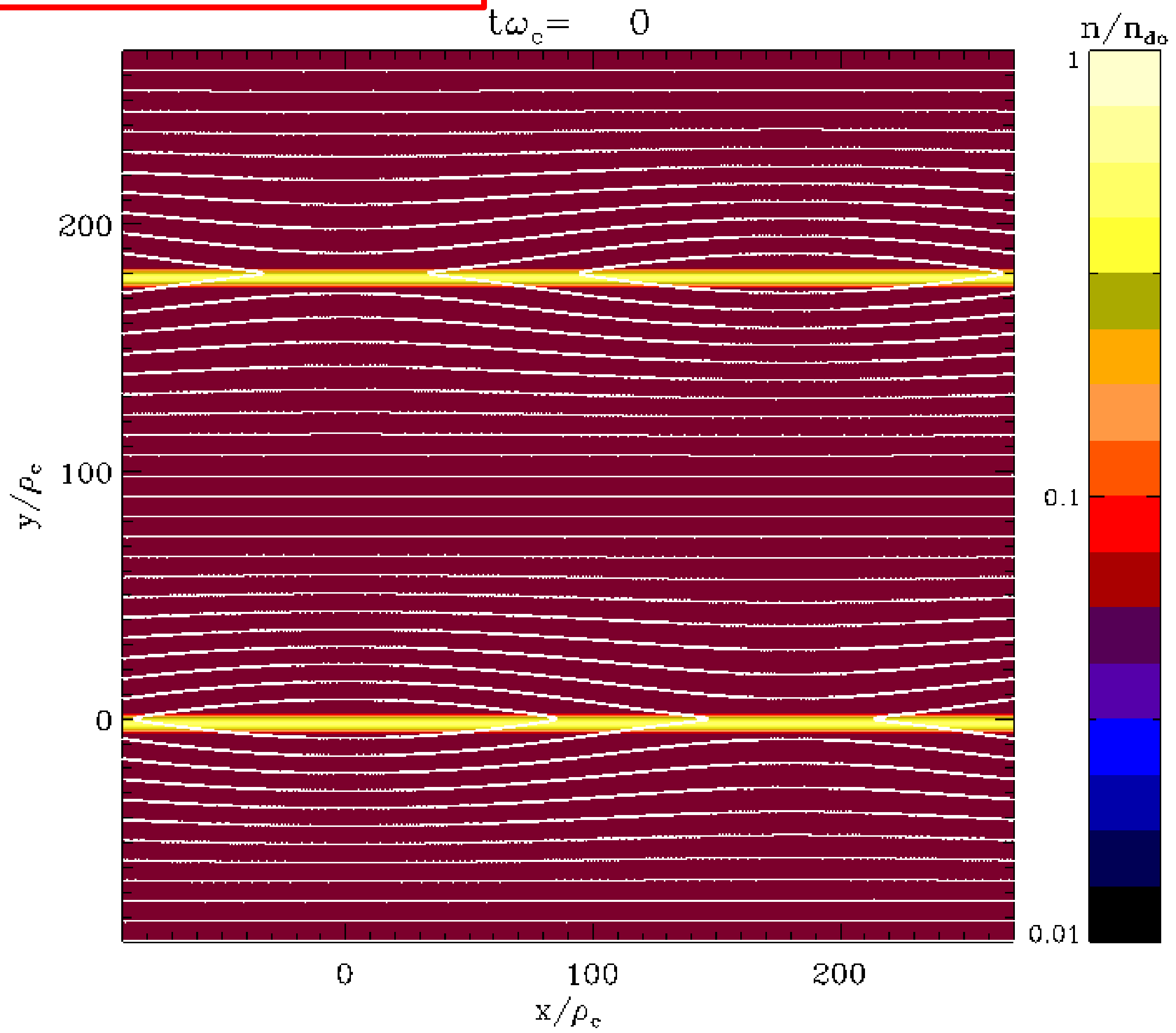


The layer is tearing unstable and breaks up into a chain of magnetic islands separated by secondary reconnection layers

Time evolution of reconnection

NO radiation reaction force.

[Cerutti et al., ApJLetters, 2012b]



Particles are accelerated at X-points along the ±z-direction, and deflected along the ±x-directions by the reconnected field B_y

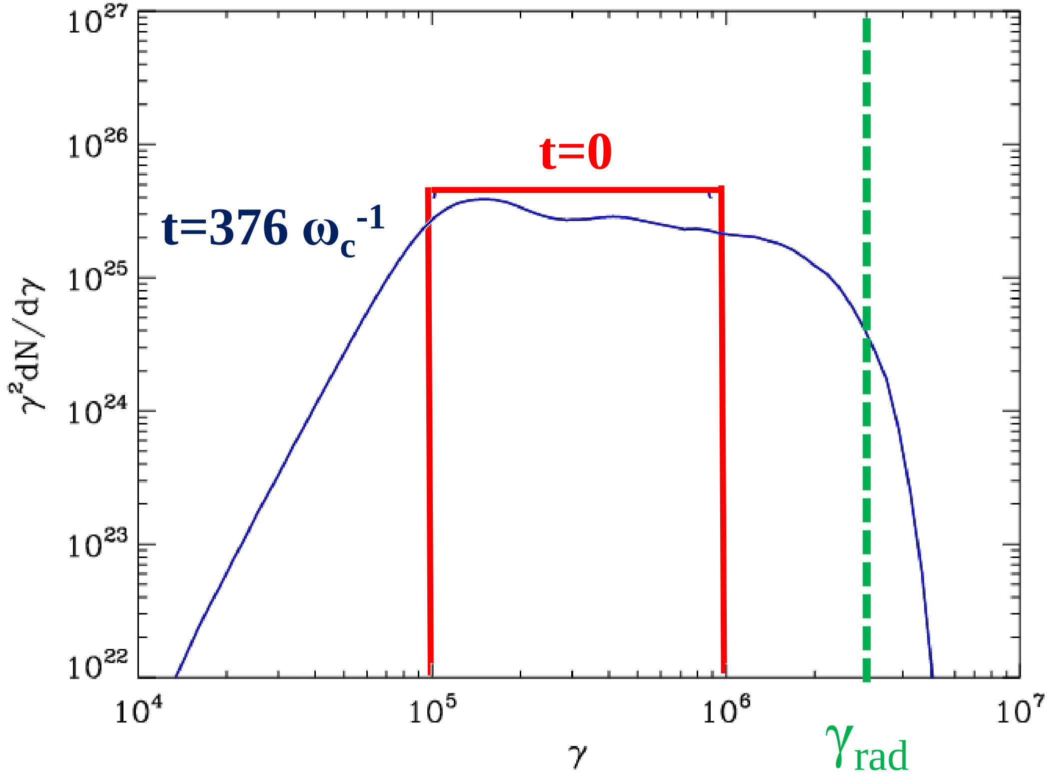
Simulation with the radiation reaction force and ultra-relativistic non-thermal background pairs

$L_x \times L_y = (1024\ \rho_c)^2$ with $\rho_c = mc^2/eB_0$

$B_0 = 1000$ Gauss

$\gamma_{rad}(E=B_0) = 3\times10^6$

Particle energy distribution



[Cerutti et al., in preparation, 2012]

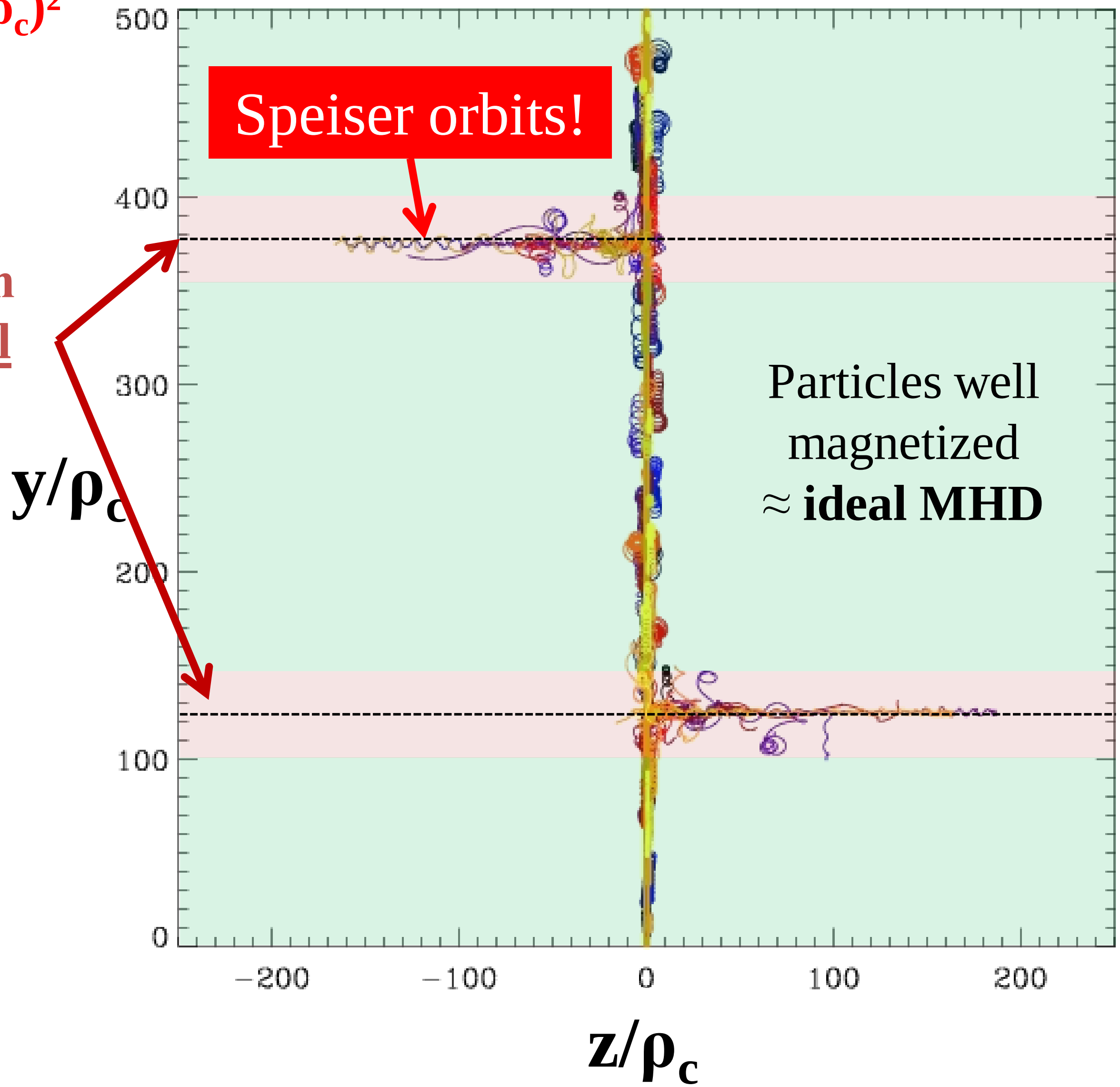
No clear evidence of non-thermal particle acceleration.

➔ May require a larger separation of scales (bigger box size?)

Evidence for relativistic Speiser orbits

Sample of 150 particle orbits

$L_x \times L_y = (500\ \rho_c)^2$



Speiser orbits!

Particles' beam
E>B, non-ideal
MHD!

Particles well
magnetized
≈ **ideal MHD**

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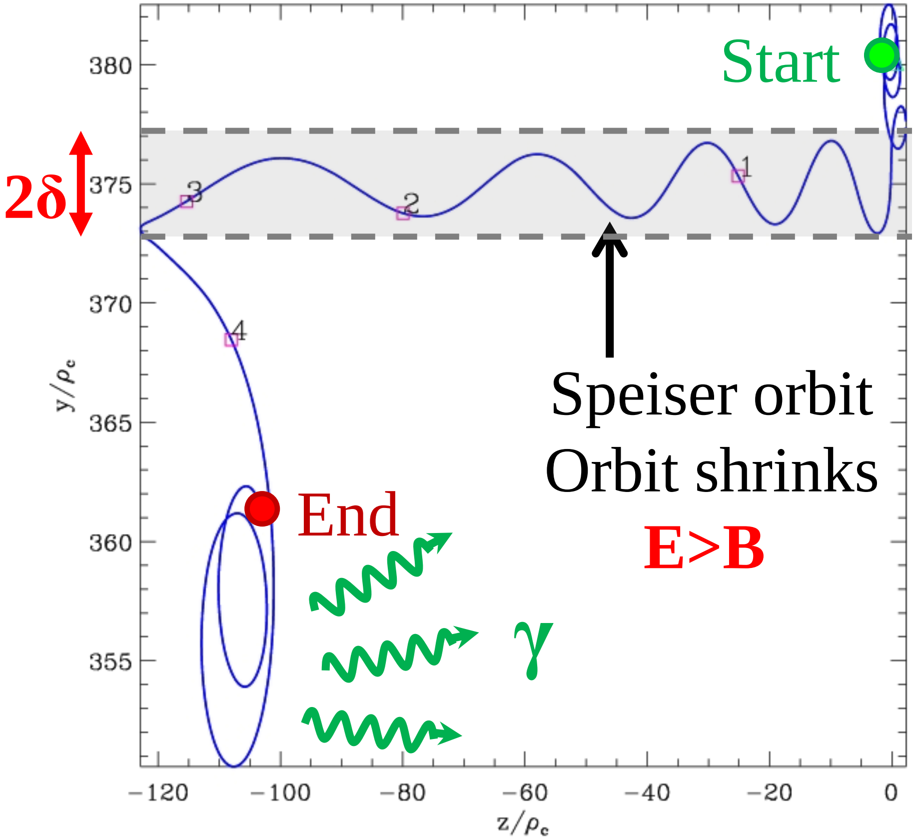
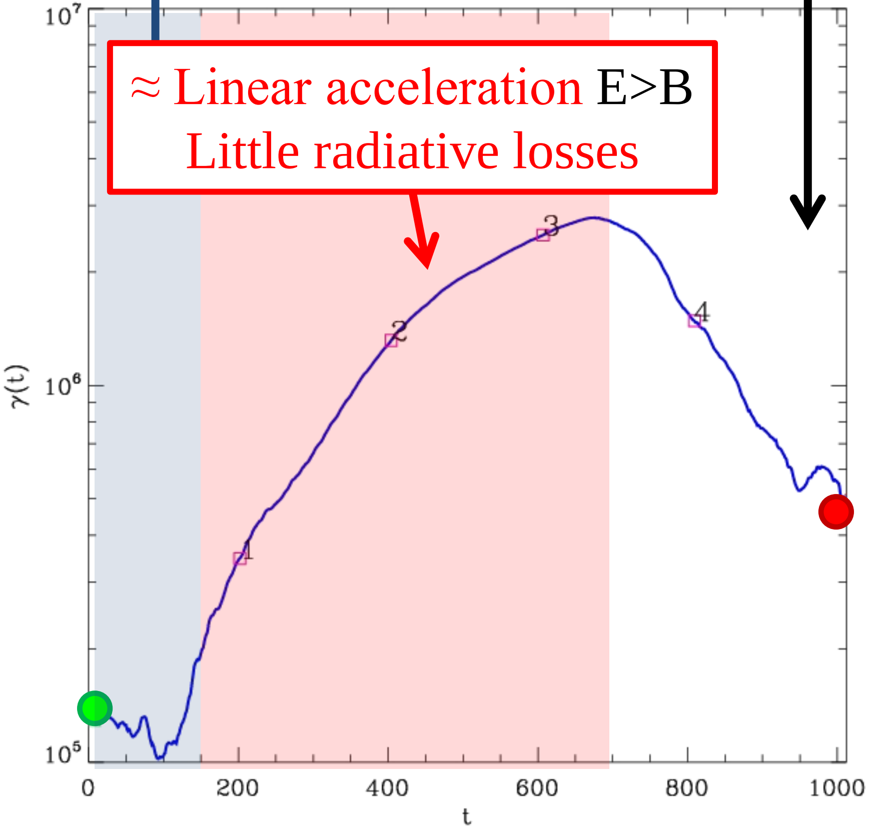
A typical high-energy particle orbit



Speiser orbit
Orbit shrinks
E>B

Low-energy and magnetized

Particle kicked out of the layer.
Magnetized and RADIATING! (E<B)

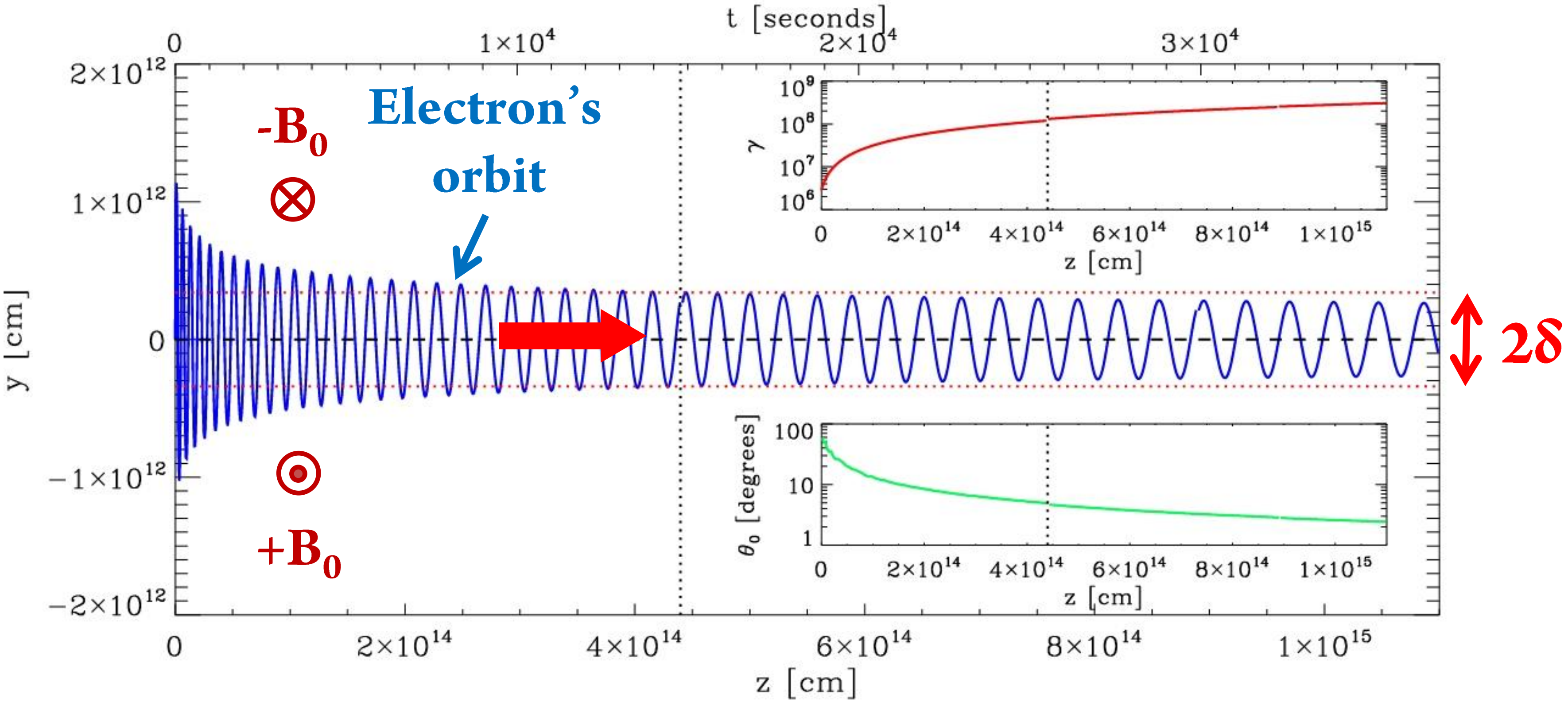


≈ Linear acceleration E>B
Little radiative losses

[Cerutti et al., in preparation, 2012]

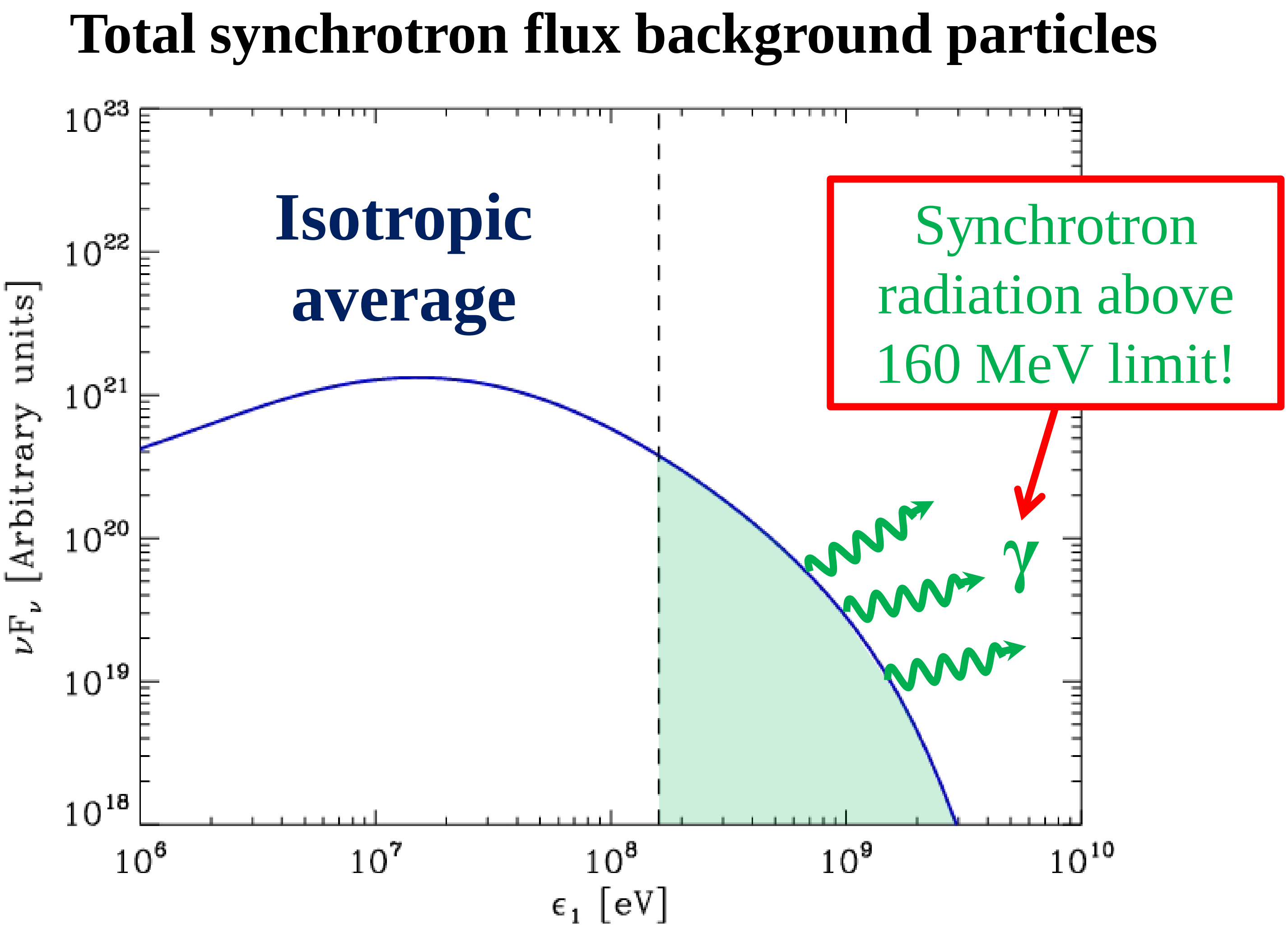
Comparison with semi-analytical expectations

Test particle simulation steady fields and radiation reaction force.



[see Uzdensky, Cerutti & Begelman, 2011, ApJ Letters]   [Kirk, PRL 2004]

Evidence for >160 MeV synchrotron photons!

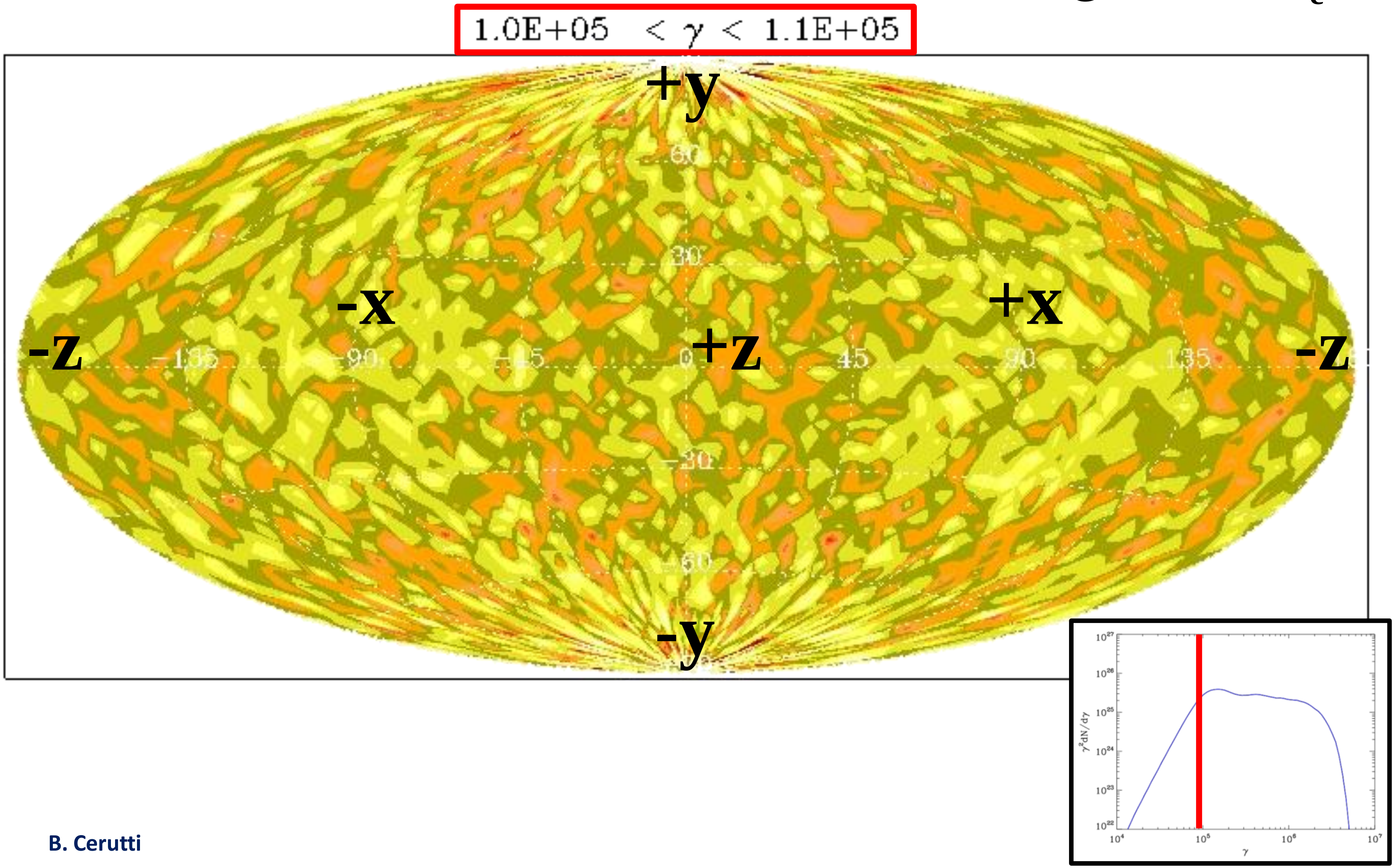


[Cerutti et al., in preparation, 2012]

Energy-resolved particles’ angular distribution

Using the Aitoff projection:

@ $t = 376\ \omega_c^{-1}$



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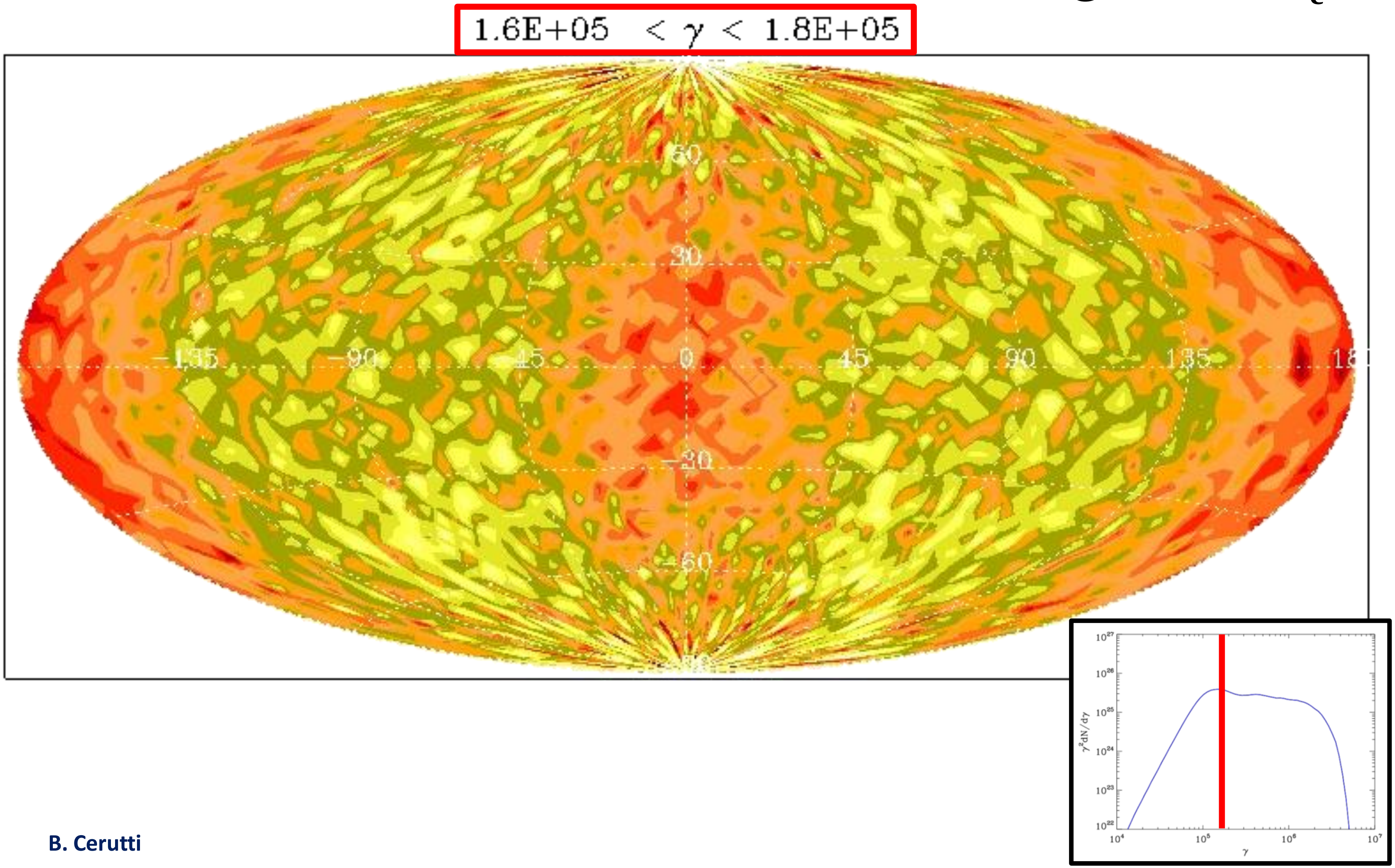
Energy-resolved particles’ angular distribution

@ t = 376 ω_c^{-1}



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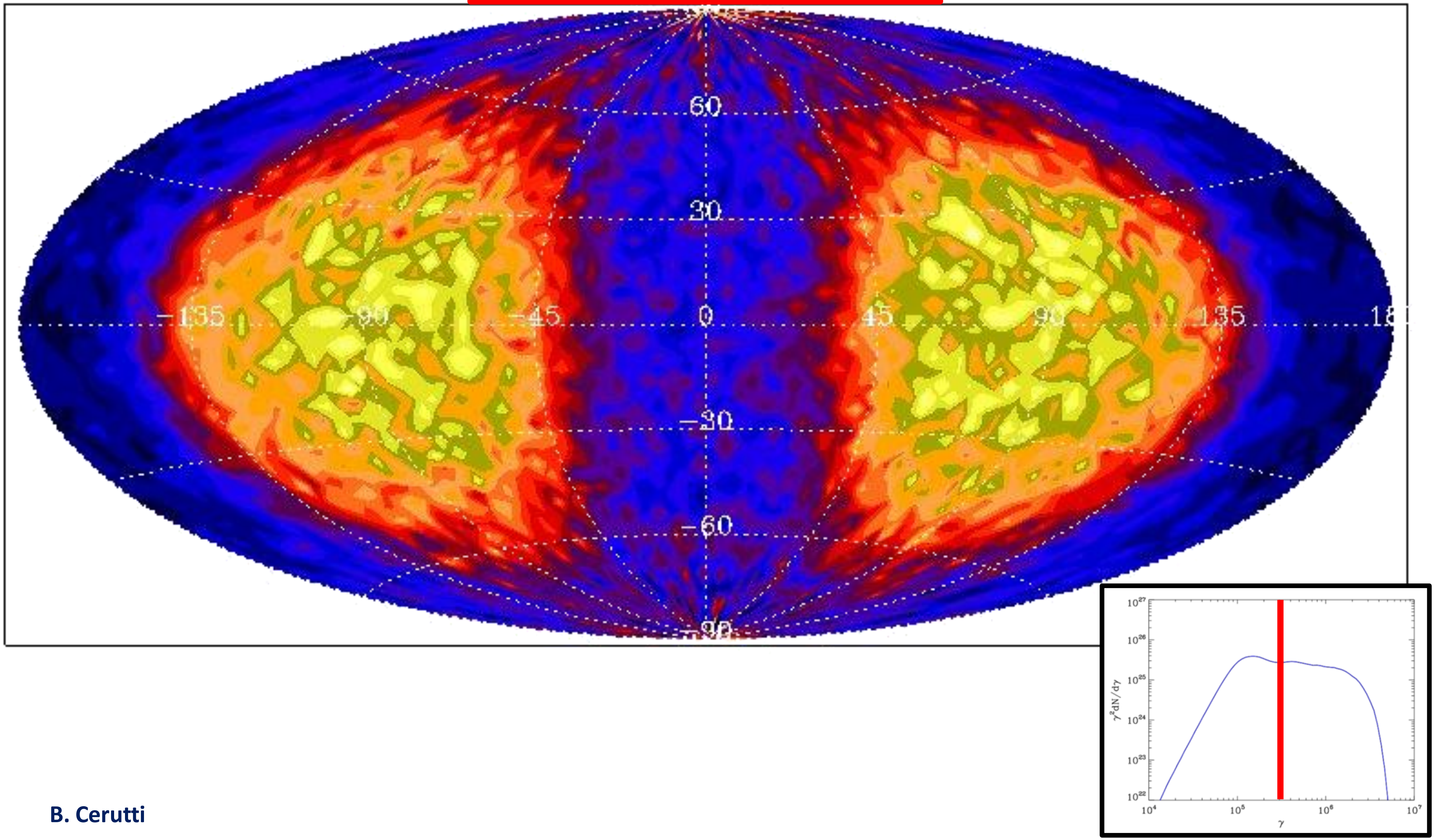
Energy-resolved particles' angular distribution

@ t = 376 ω_c^{-1}

$2.6E+05 < \gamma < 2.8E+05$



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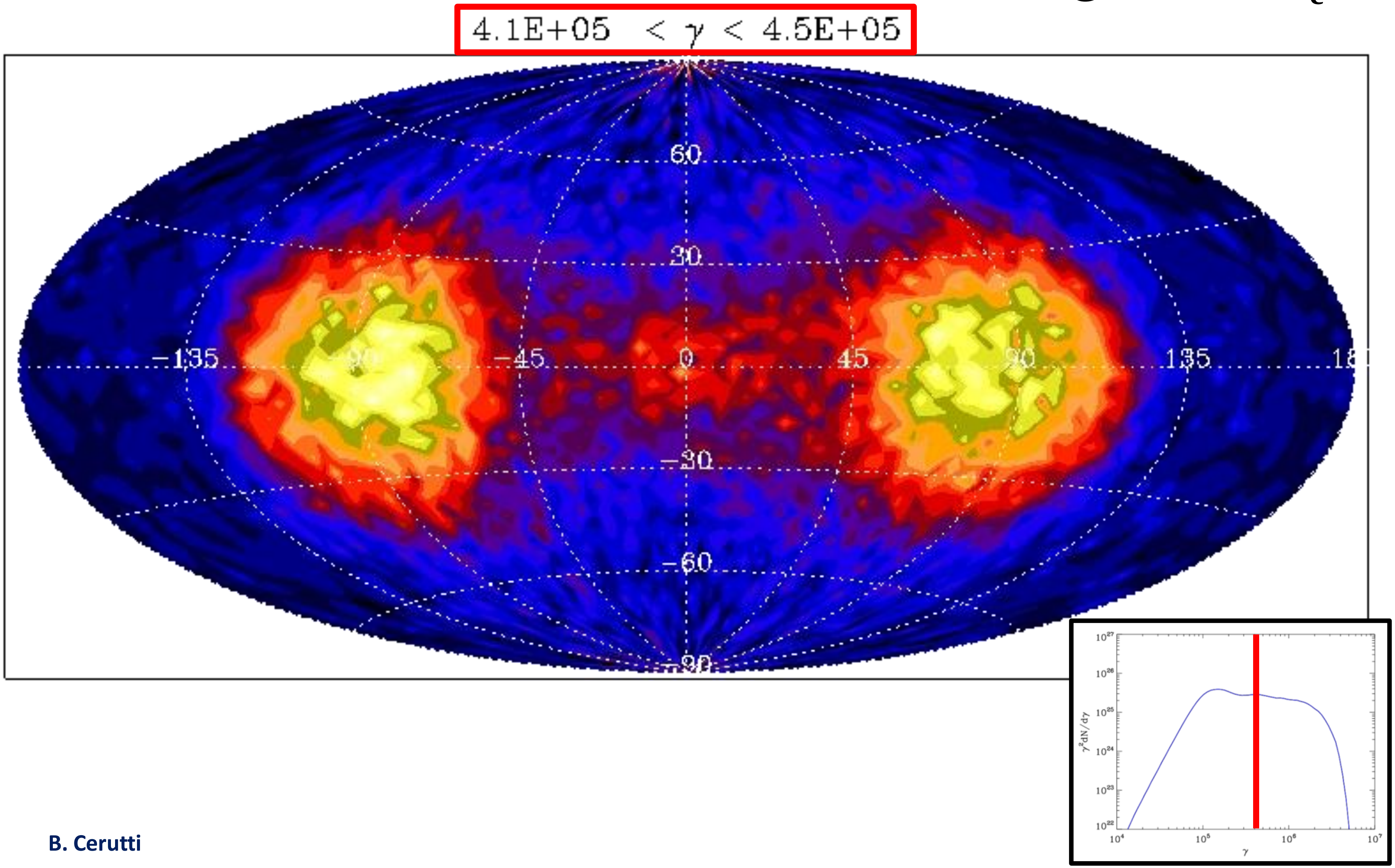
Energy-resolved particles’ angular distribution

@ t = 376 ω_c^{-1}



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Energy-resolved particles’ angular distribution

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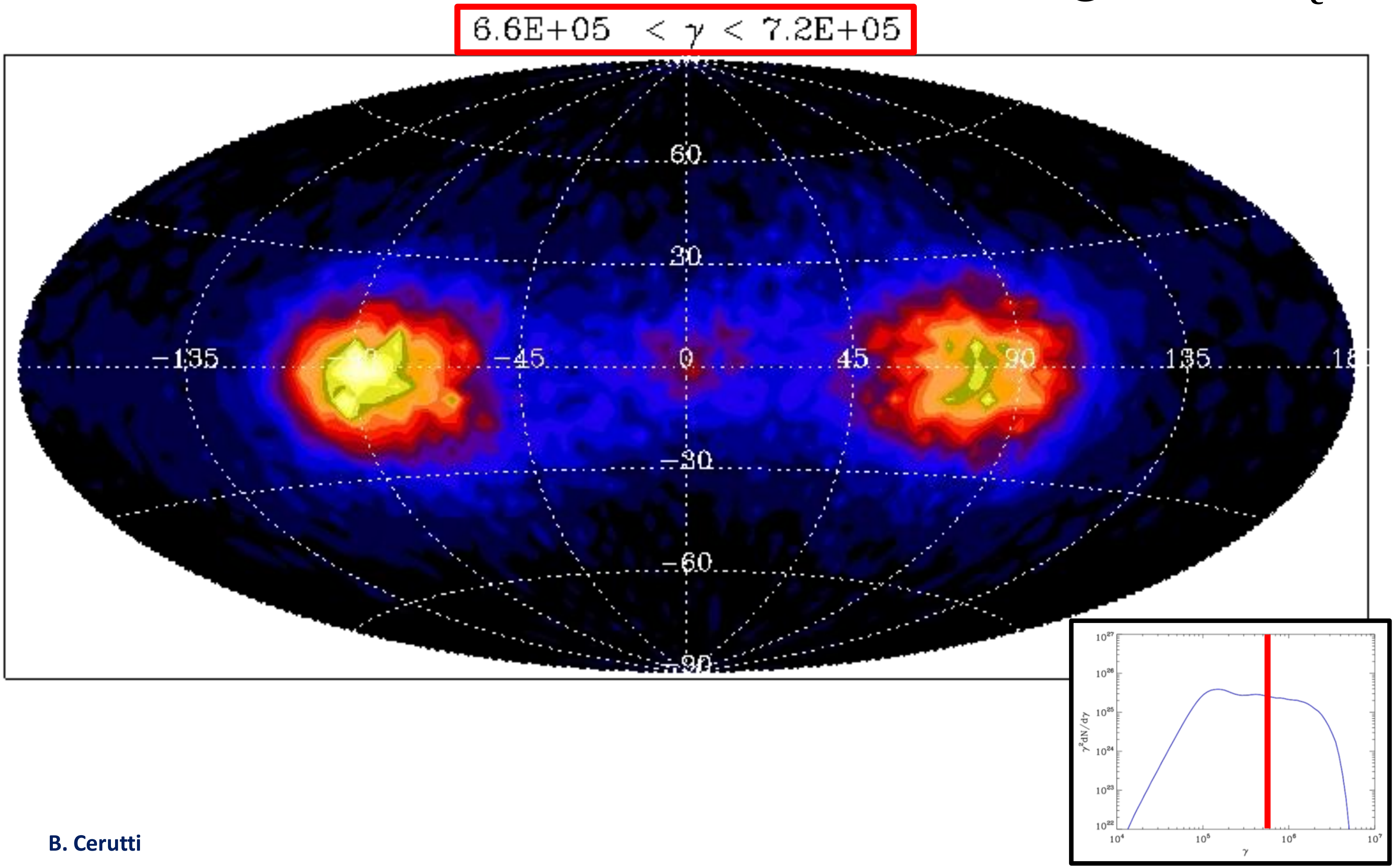

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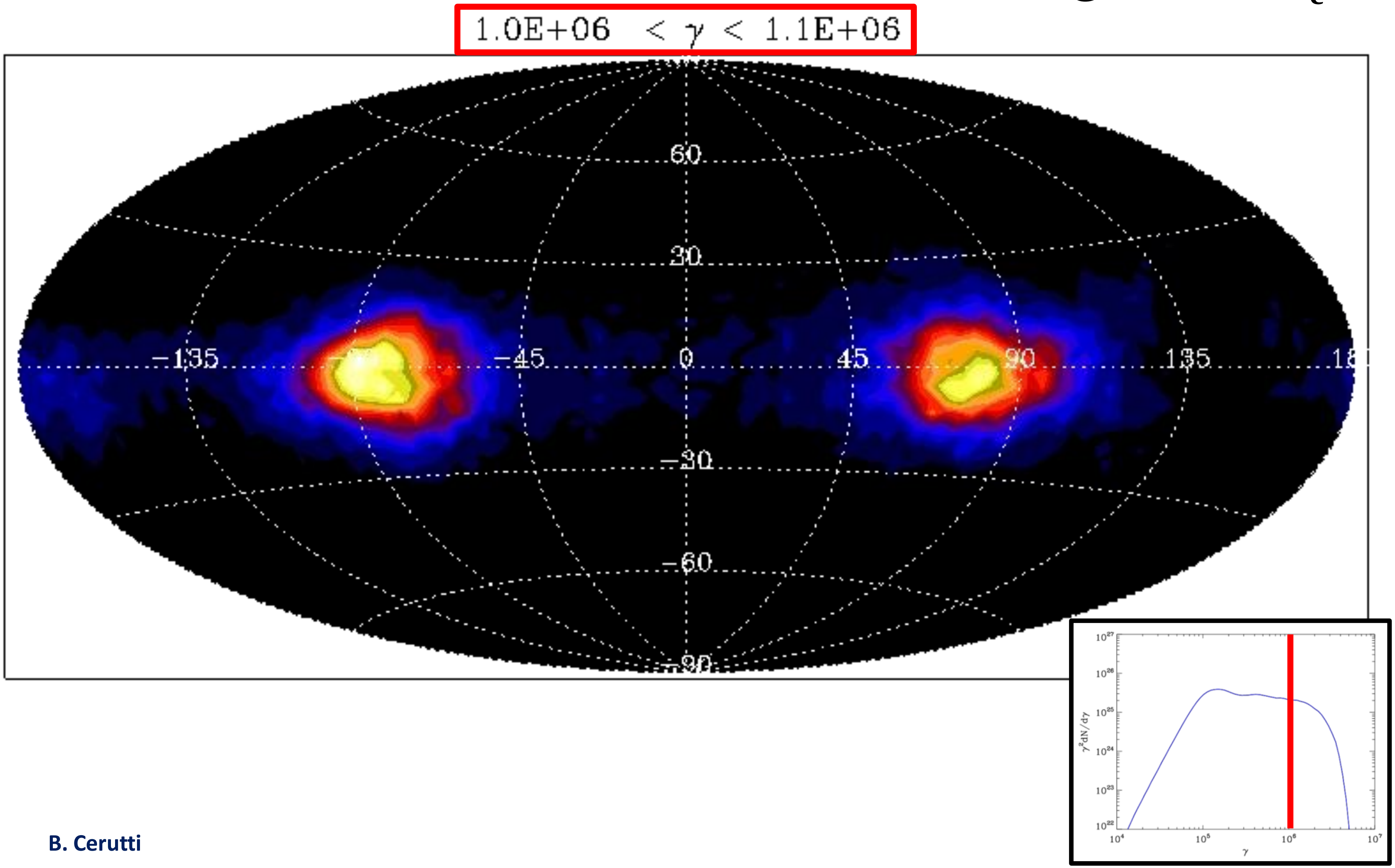

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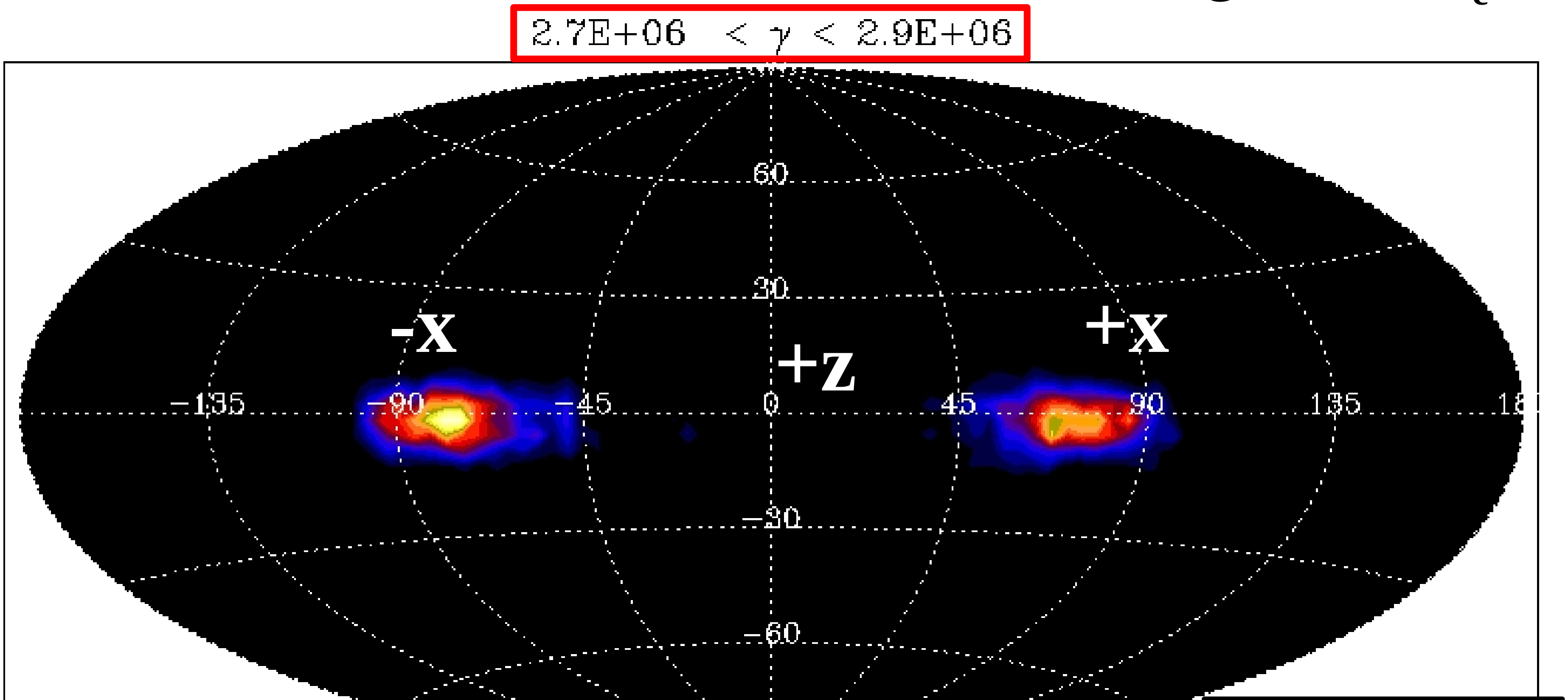

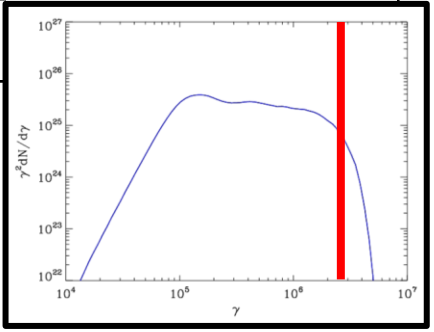

Strong energy-dependent anisotropy!

Same effect without the radiation reaction force

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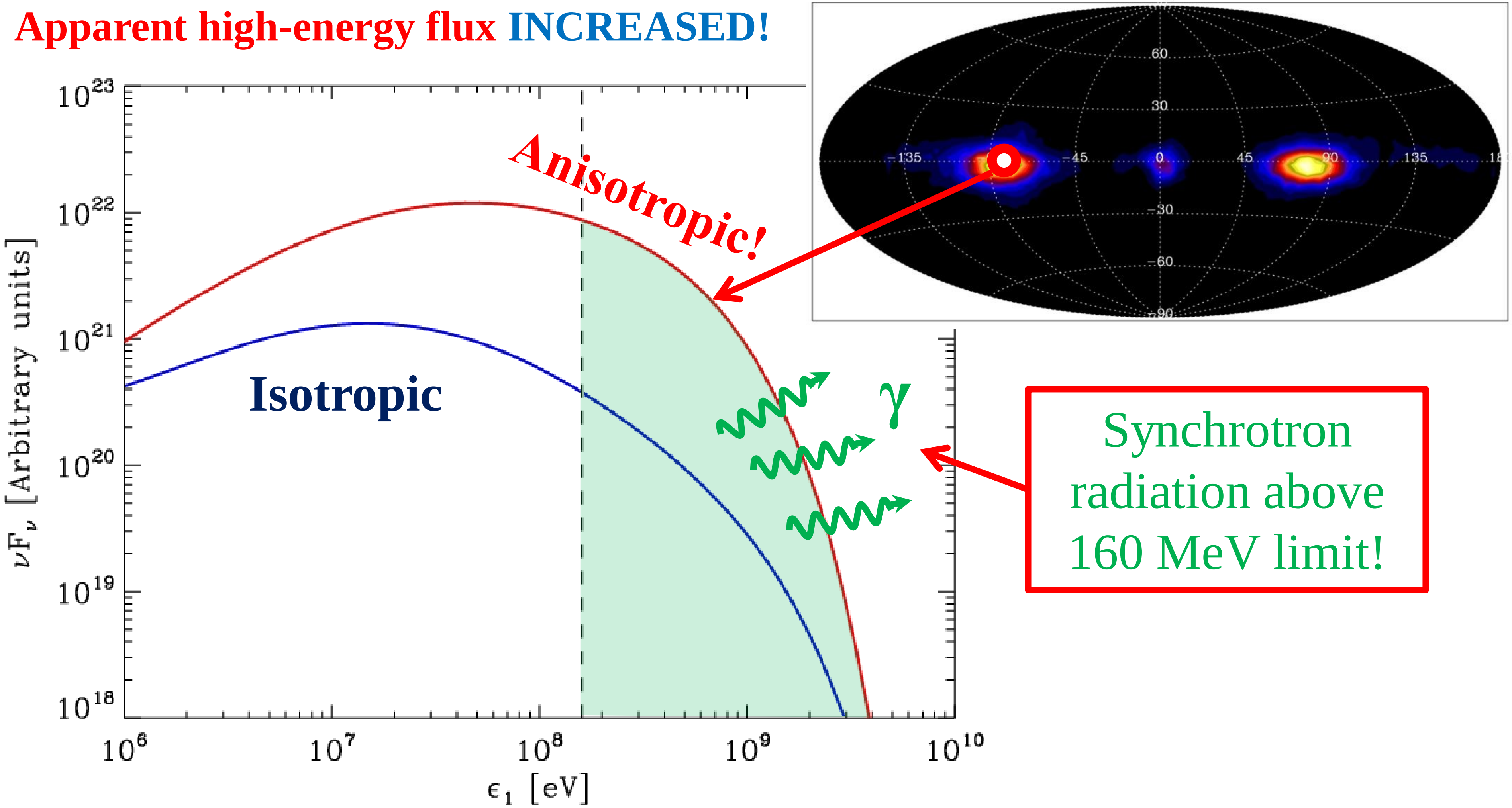
[Cerutti et al., ApJLetters, 2012b]

The high-energy radiation flux is highly anisotropic

Apparent high-energy flux INCREASED!

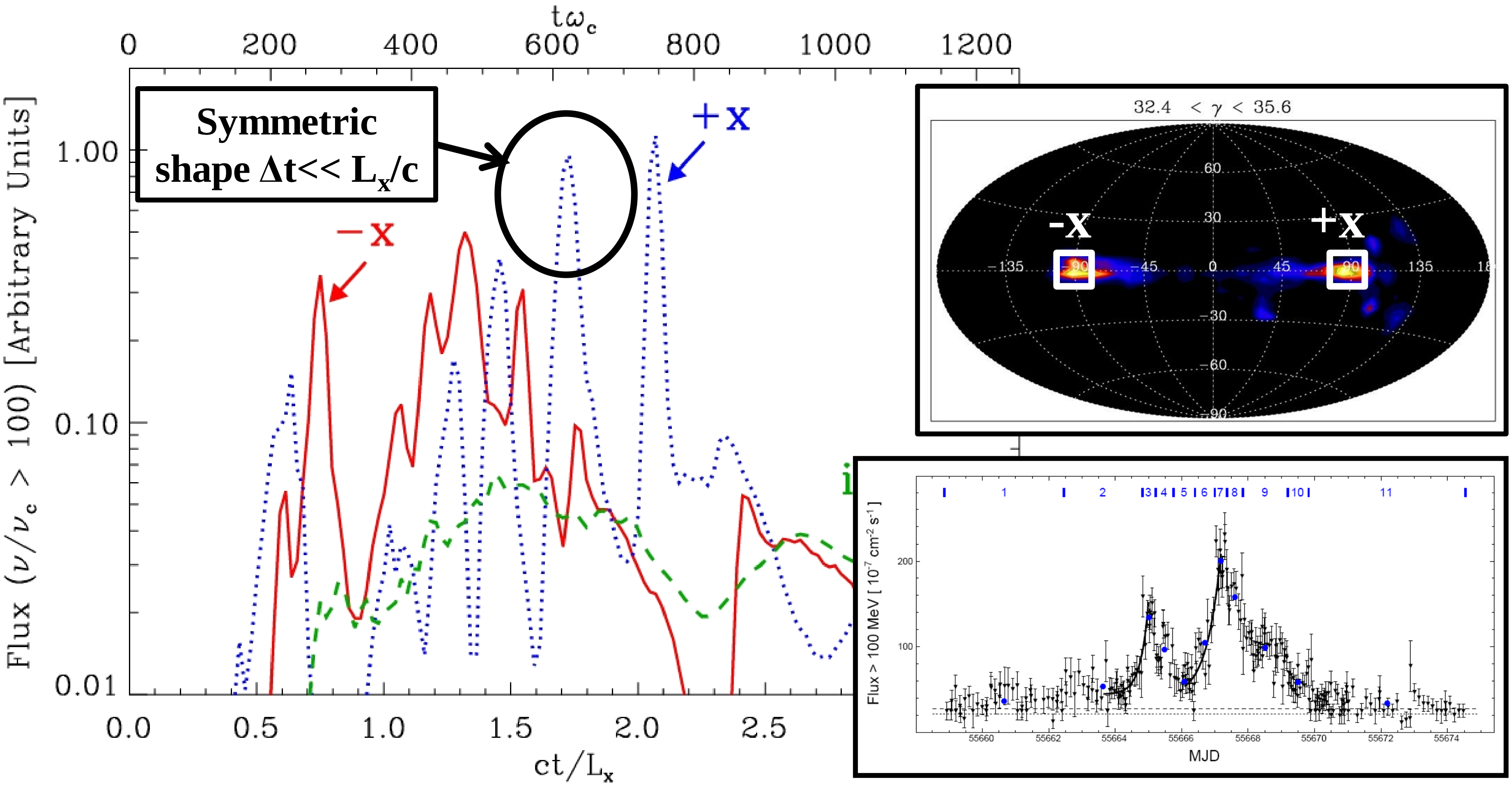
Photon energy >100 MeV



Synchrotron radiation above 160 MeV limit!

[Cerutti et al., in preparation, 2012]

High-energy lightcurves



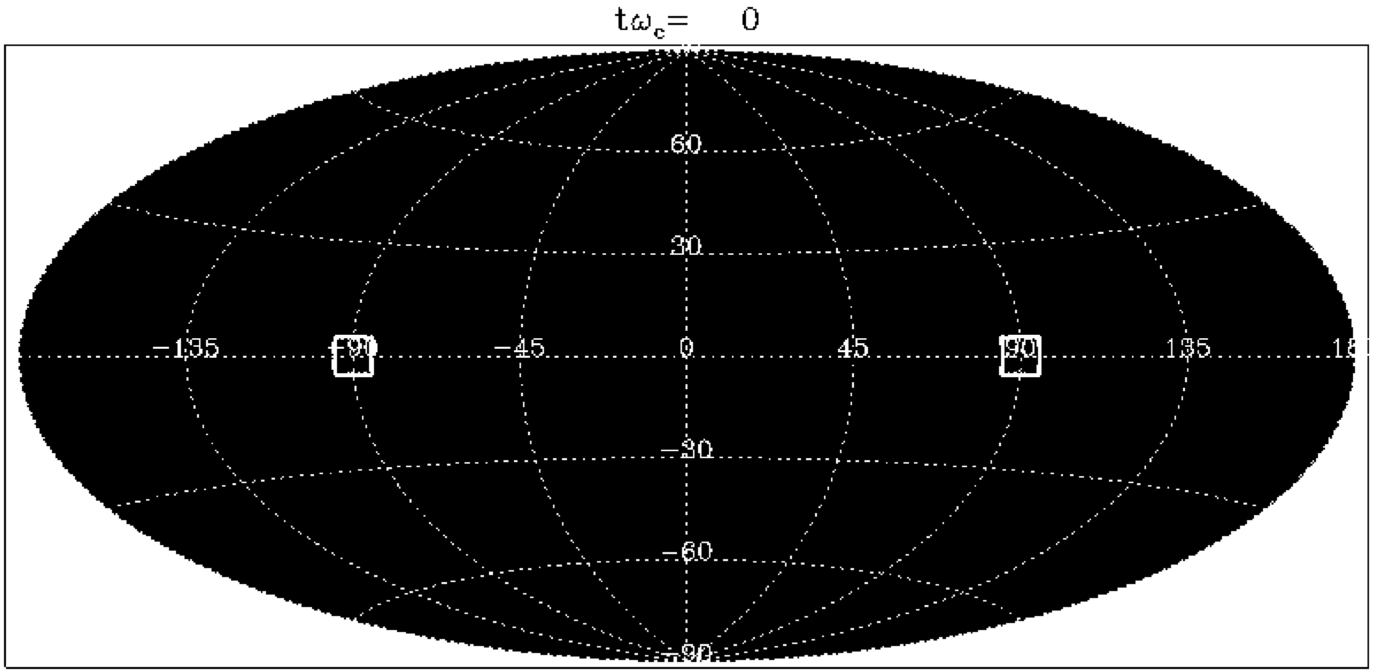
Symmetric shape Δt<< L_x/c

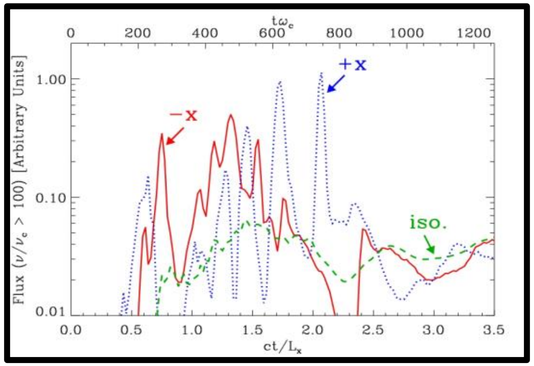
Reconnection naturally generates bright, ultra-rapid, symmetric sub-flares of radiation

[Cerutti et al., ApJLetters, 2012b]

High-energy particle anisotropy

High-energy particles only





The beam of high-energy particles sweeps across the line of sight intermittently: bright symmetric flares.

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Summary and future directions

We interpret the Crab flares as a **reconnection event**.
Relativistic pair plasma reconnection can explain:

- **Ultra-rapid time variability** of the flux (**sweeping beam**).
- **Energetics** of the flares (**strong beaming** of the high-energy radiation).
- **Synchrotron radiation >160 MeV** (particle acceleration **beyond the radiation reaction limit** inside the layer where **E>B**)

Futures directions:

- 3D with guide field: Effect of the **kink instability on anisotropy**? **Preliminary:** not much at early times.

- Application to other flaring astrophysical objects:
e.g. **Active Galactic Nucleii**, **Gamma-ray Bursts**…

- **Non-thermal particle acceleration** with reconnection?!