CIPS

Extreme particle acceleration in the Crab Nebula

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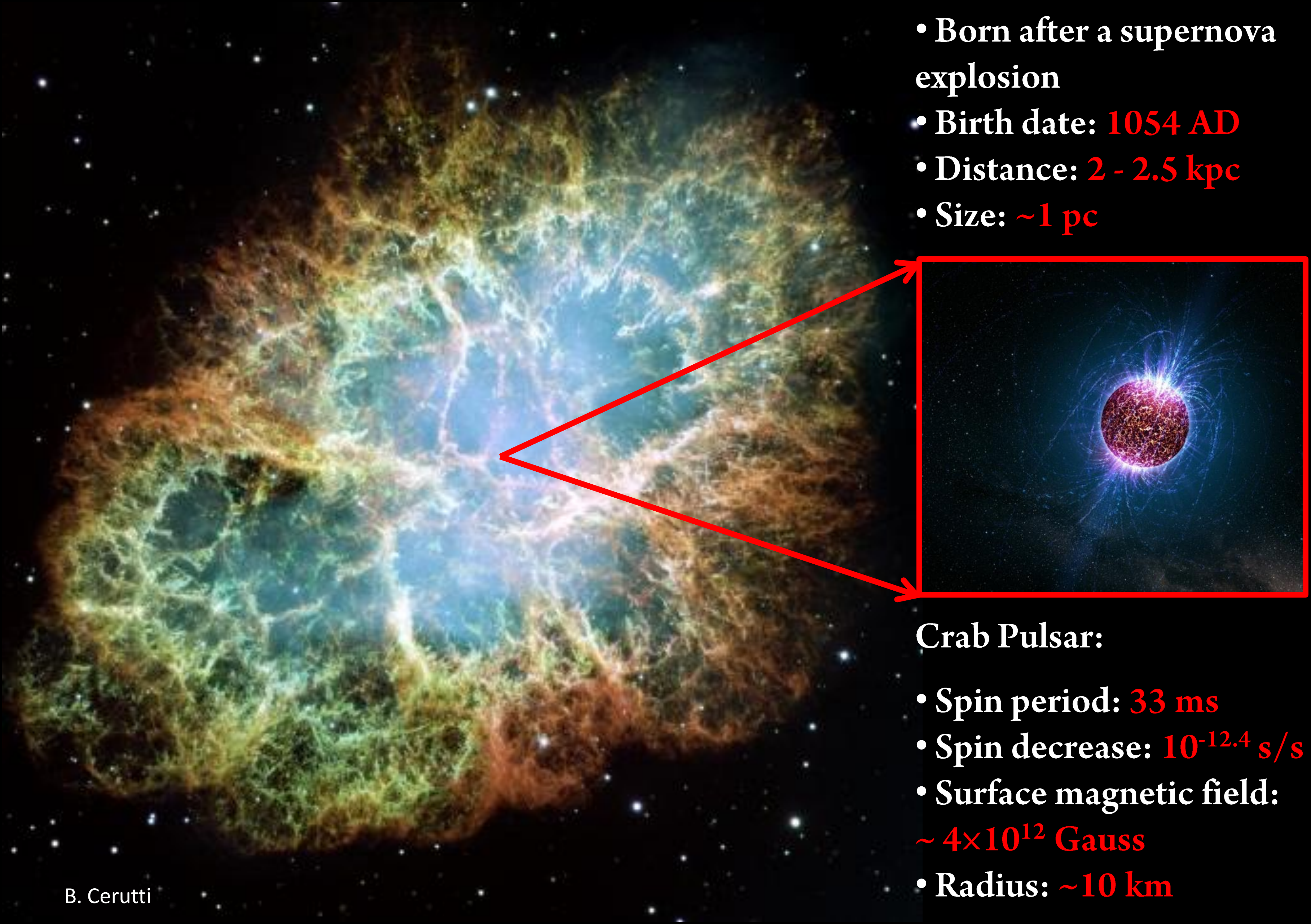
Introduction

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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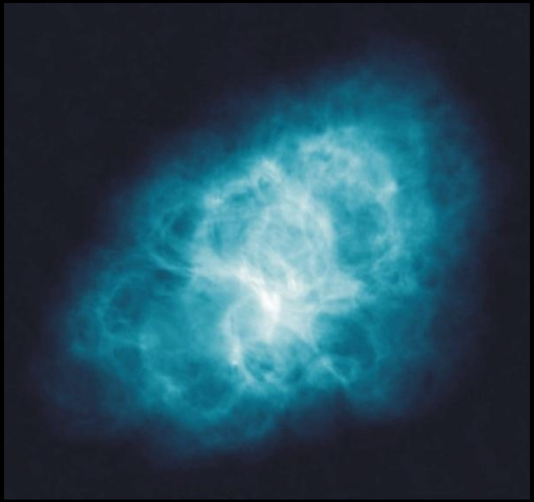
The Crab Nebula is bright at all accessible wavelengths

VLA @ 5 GHz

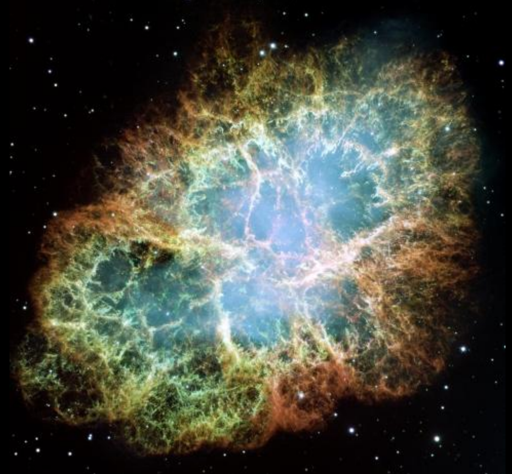


© NRAO/AUI and M Bietenholz

Spitzer 3.6-24 μm

© NASA/JPL-Caltech Univ. Minn.: R.Gehrz

Hubble



© NASA/ESA J. Hester and A. Loll

Chandra 0.3-3 keV

© NASA-CXC-SAO F.Seward et al.

… and is a standard candle in X-ray and gamma-ray astronomy

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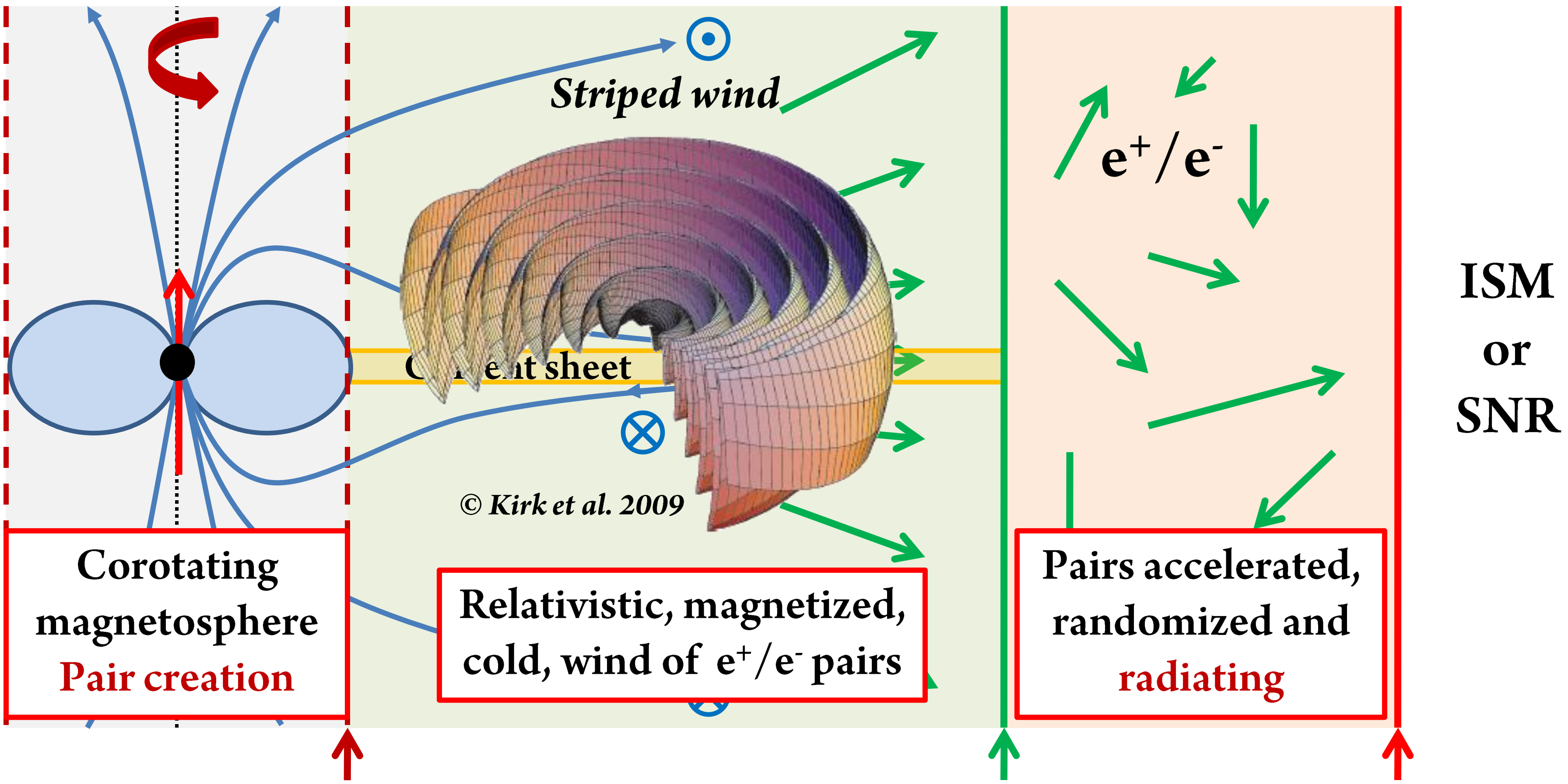
The classical (simplified) picture of pulsar wind nebulae

[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

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

Termination shock radius
(~0.1 pc in Crab)

Contact discontinuity
(~1 pc in Crab)

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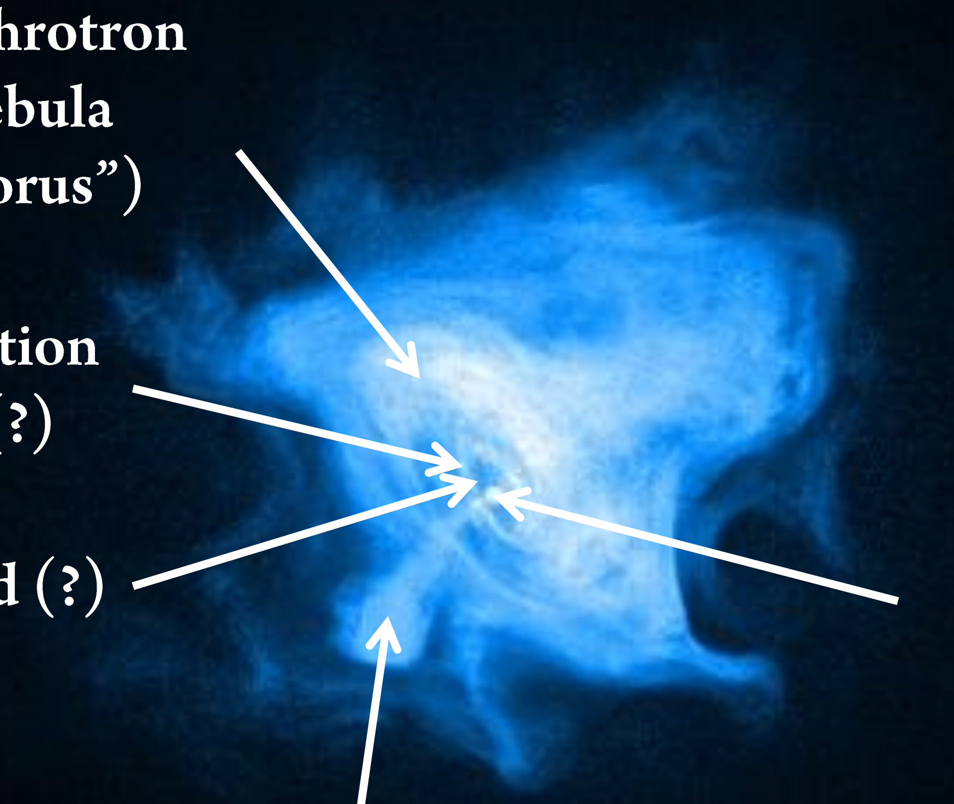
The synchrotron bubble in X-rays



Synchrotron nebula (“torus”)

Termination shock (?)

Pulsar wind (?)

Pulsar

Jet

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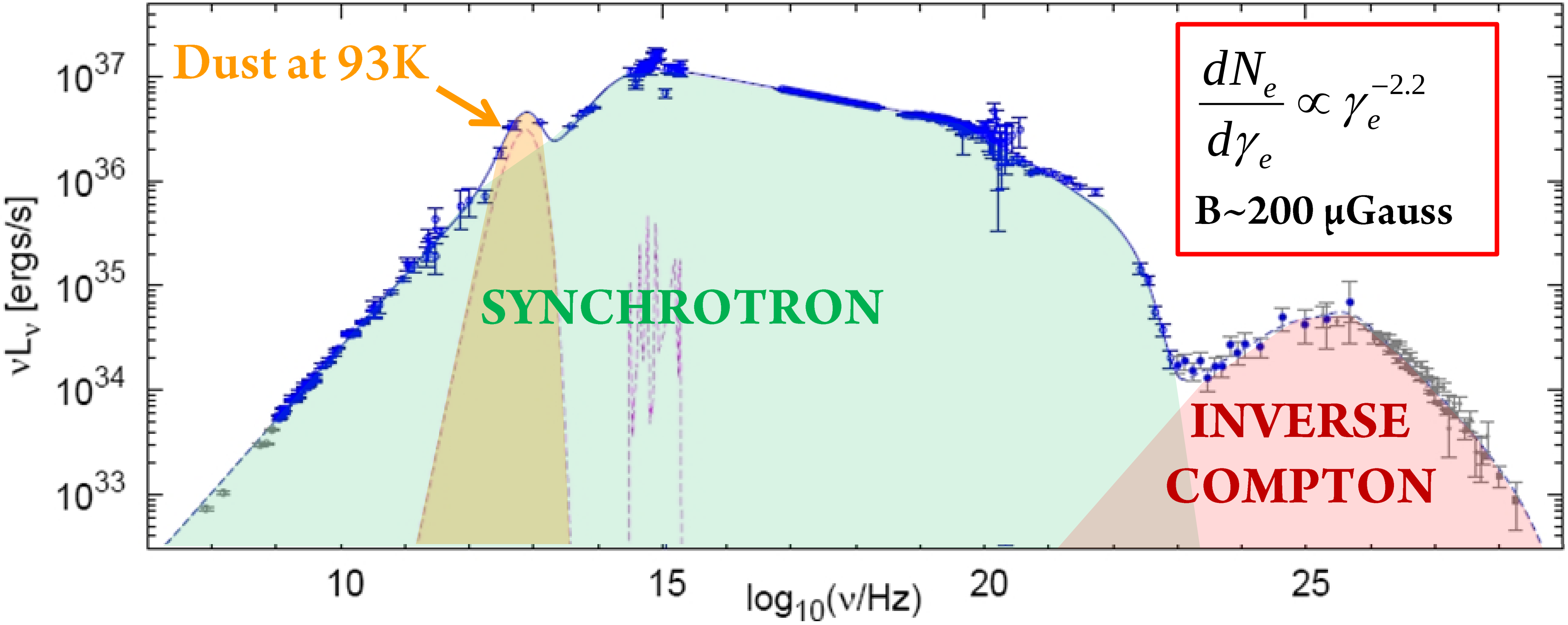
The Spectral Energy Distribution of the Crab Nebula

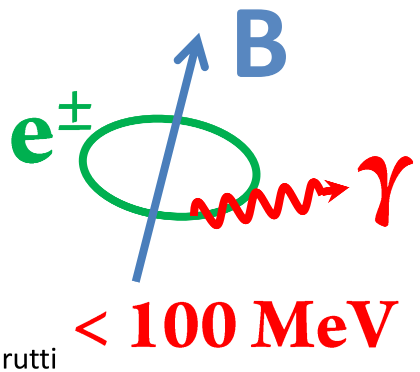
[Meyer et al. 2010]



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

B~200 μGauss

Synchrotron radiation

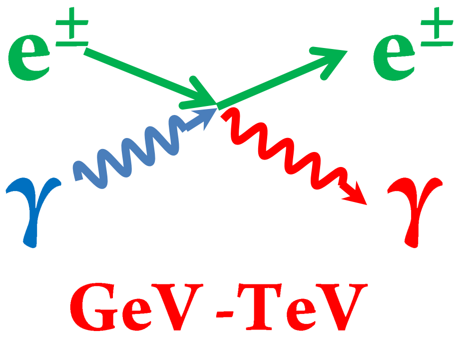


< 100 MeV

Inverse Compton scattering

Target photons:

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



GeV -TeV

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The gamma-ray flares in the Crab Nebula

The gamma-ray space telescopes *Fermi* and *Agile*

Energy range: 30 MeV-300 GeV

Energy resolution: < 10%

Angular resolution: ~ 0.1-3.5°

Launched 2008

Launched 2007

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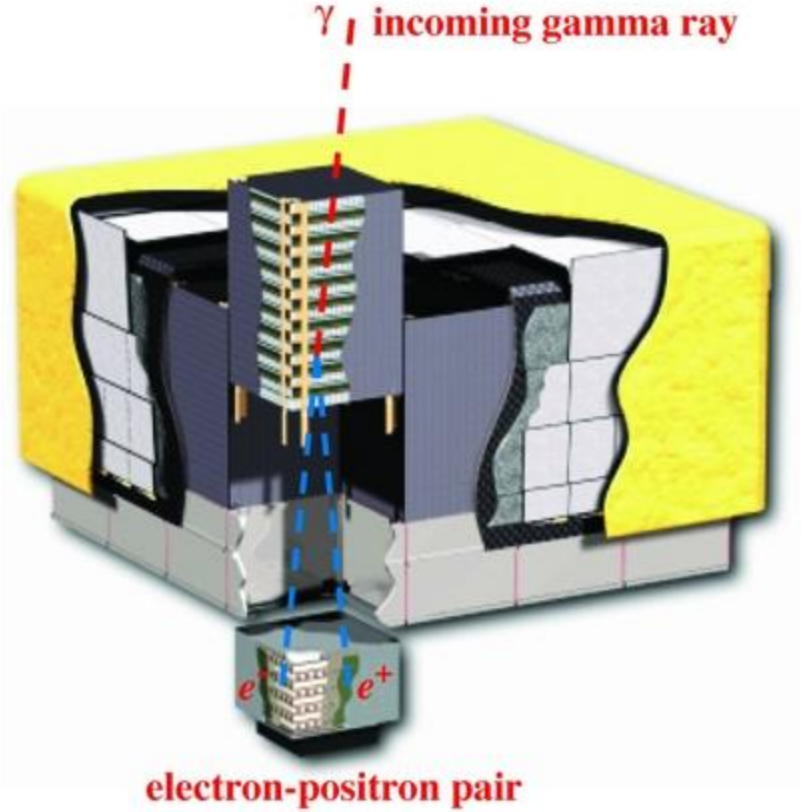
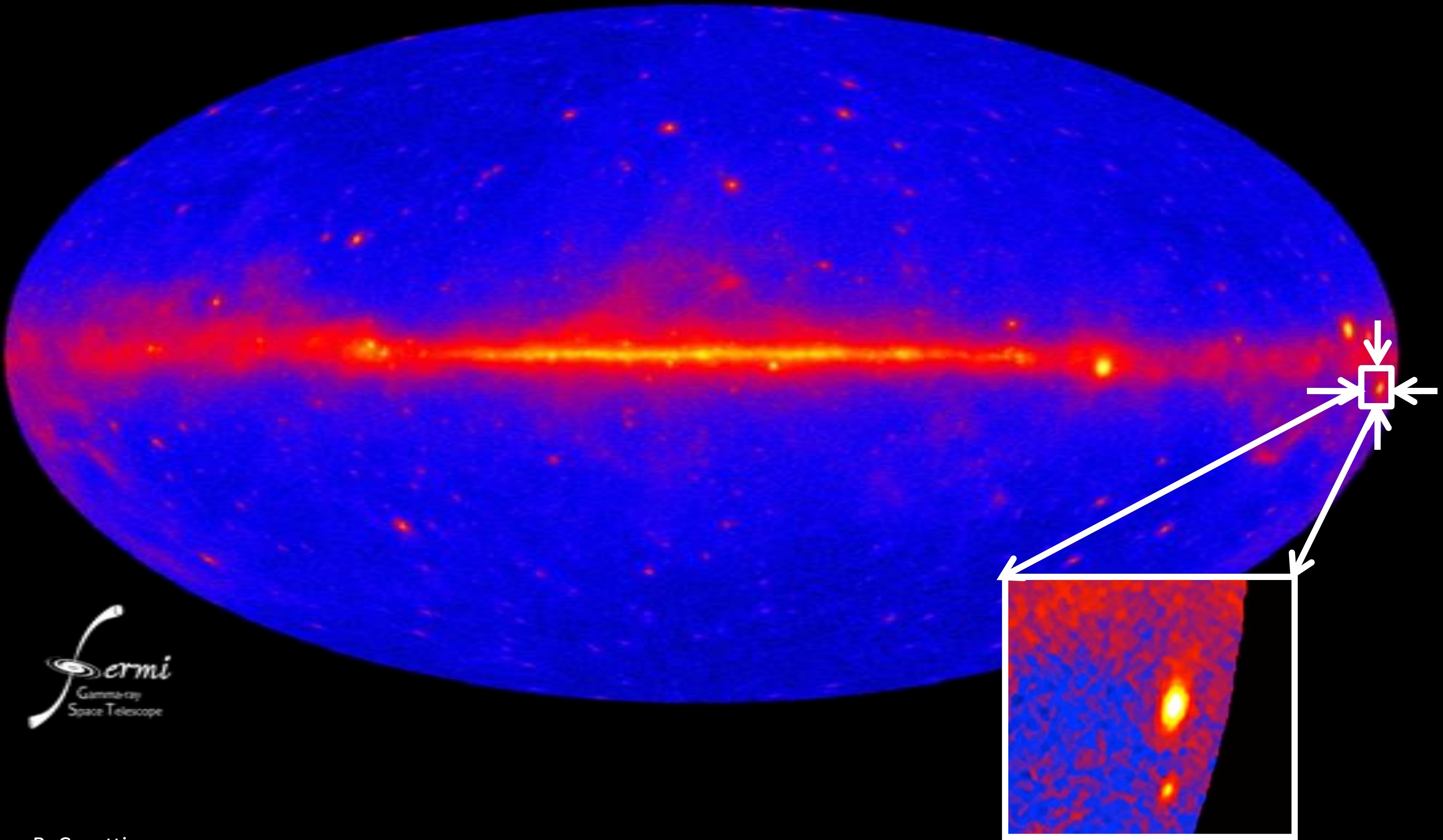
***Fermi*-LAT**



The Crab Nebula in the gamma-ray sky

Galactic coordinates

1 year of exposure



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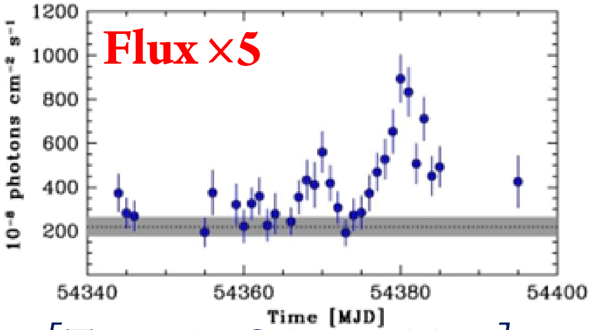
The Crab Nebula

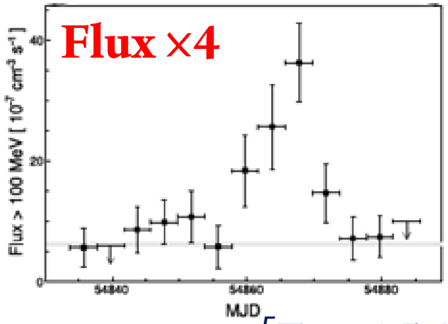
Fermi and *Agile* detected short and powerful gamma-ray flares in the Crab Nebula

Oct. 07, 14 days

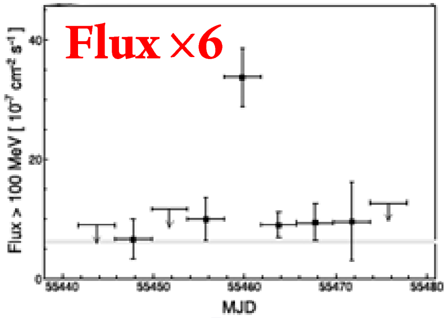


[Tavani+, Science, 2011]

Feb. 09, 16 days



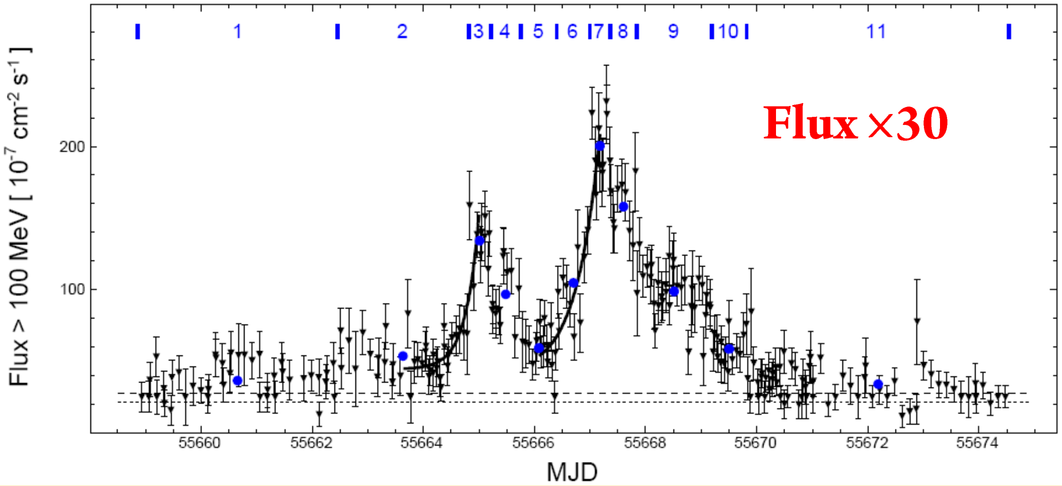
Sep. 10, 4 days



[Fermi-LAT, Science, 2011]

Apr. 11, 9 days

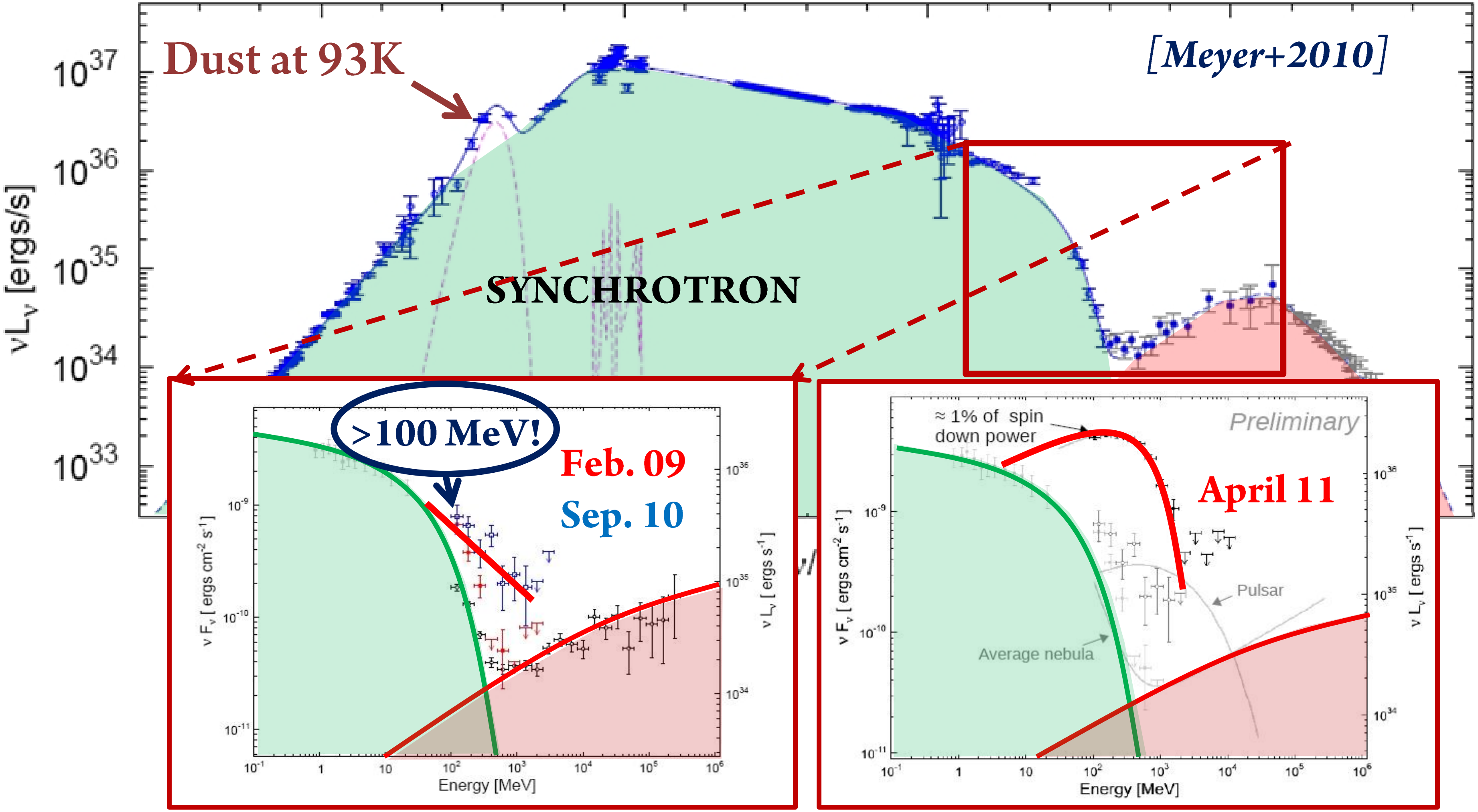
[Buehler+, 2011]



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

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

Spectral variability at high energies



Dust at 93K

[Meyer+2010]

SYNCHROTRON

>100 MeV!

Feb. 09

Sep. 10

April 11

[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: $\varepsilon_{max}=3/2\,\gamma_e^2\hbar\,(eB/m_ec)>100$ MeV**

➔ $\gamma_e m_e c^2 > 10^{15}$ 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: $f_{rad}=2/3\,r_e^2\,\gamma^2 B^2$

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

- Synchrotron photon energy: $\varepsilon_{max}=3/2\,\gamma^2_{max}\hbar\,\omega_c = 160\times(E/B)$ 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 $D\approx 3\text{-}4$, unlikely in the Crab Nebula (bulk motion < 0.5 c) *[Hester+2002]*

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Extreme particle acceleration in magnetic reconnection layers

The puzzles we want to solve:

- Synchrotron photons >100 MeV/ PeV particles in mG field
- Little emission at other wavelength
- The spectral shape
- The variability
- The energetics of the flare

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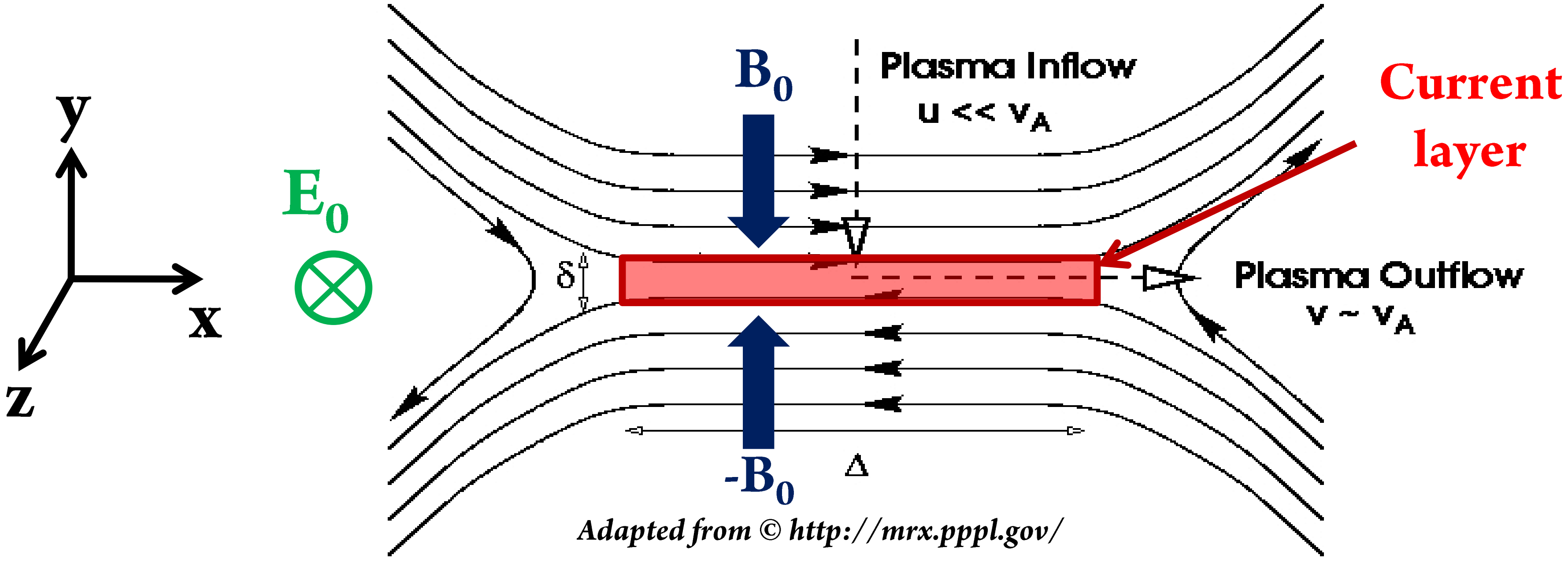
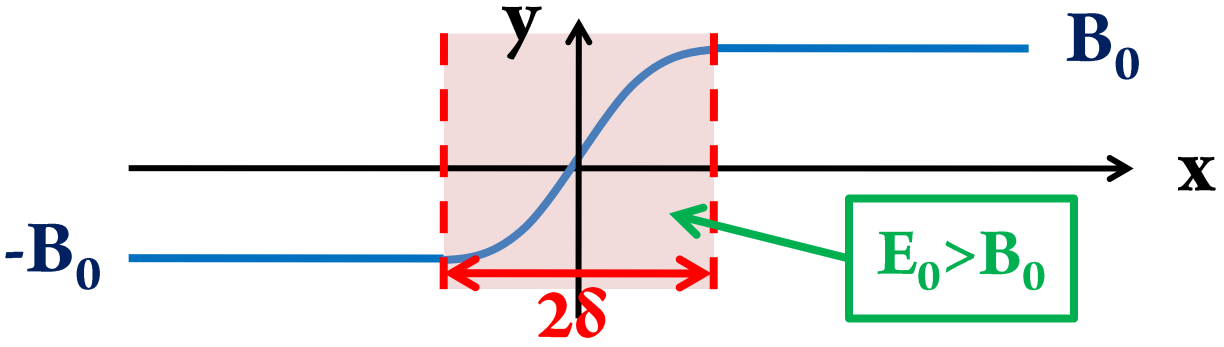
Extreme particle acceleration could occur at magnetic reconnection sites in the Crab Nebula



Adapted from © http://mrx.pppl.gov/

Collisionless, relativistic, pair plasma reconnection

The reconnecting magnetic field vanishes inside the current layer:



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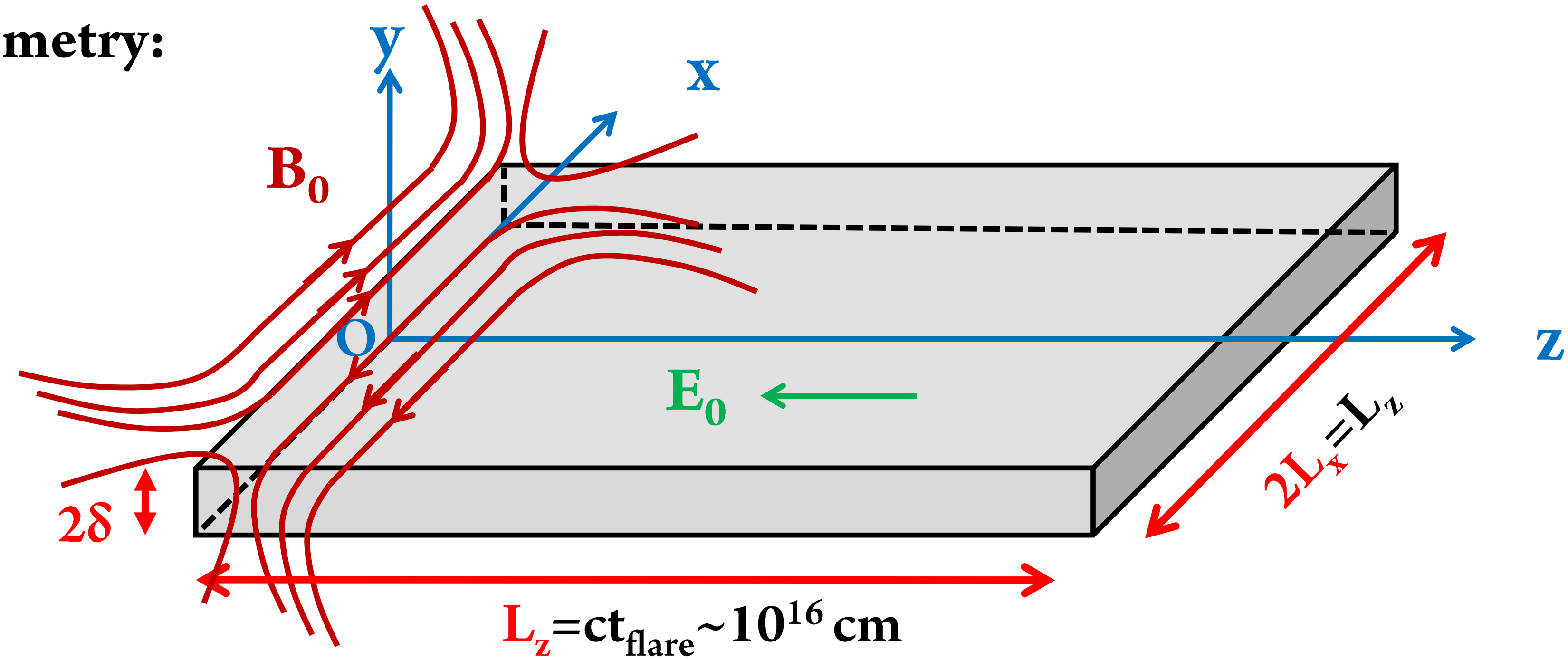
Assumptions on the reconnection layer

Geometry:



δ: Larmor radius of the bulk particles in the plasma (lower-limit)

$\delta=\gamma_{bulk}m_e c^2/eB \sim 3.4\times10^{11}(\gamma_{bulk}/10^6)$ cm

Large-scale Fields:

- $B_x(y)=B_0\tanh(y/\delta)$: Reconnecting field
- $B_y(x)=\beta_{rec}B_0(x/L_x)$: Reconnected field
- $E_z=\beta_{rec}B_0$: Reconnection electric field

β_{rec}: reconnection rate

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Motion of the highest-energy particles

- We are interested in particles with a Larmor radius $R_L \sim L_z >> \delta$.
- Unique situation compared with other astrophysical objects!
- The high-energy particles feel the large-scale fields only.
- Motion of low energy particles sensitive to small-scale, turbulent structures

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

(Abraham-Lorentz-Dirac)

$$m_e c \frac{du^\mu}{ds} = -\frac{e}{c}F^{\mu\nu}u_\nu + g^\mu$$

Lorentz 4-force

Radiation reaction 4-force

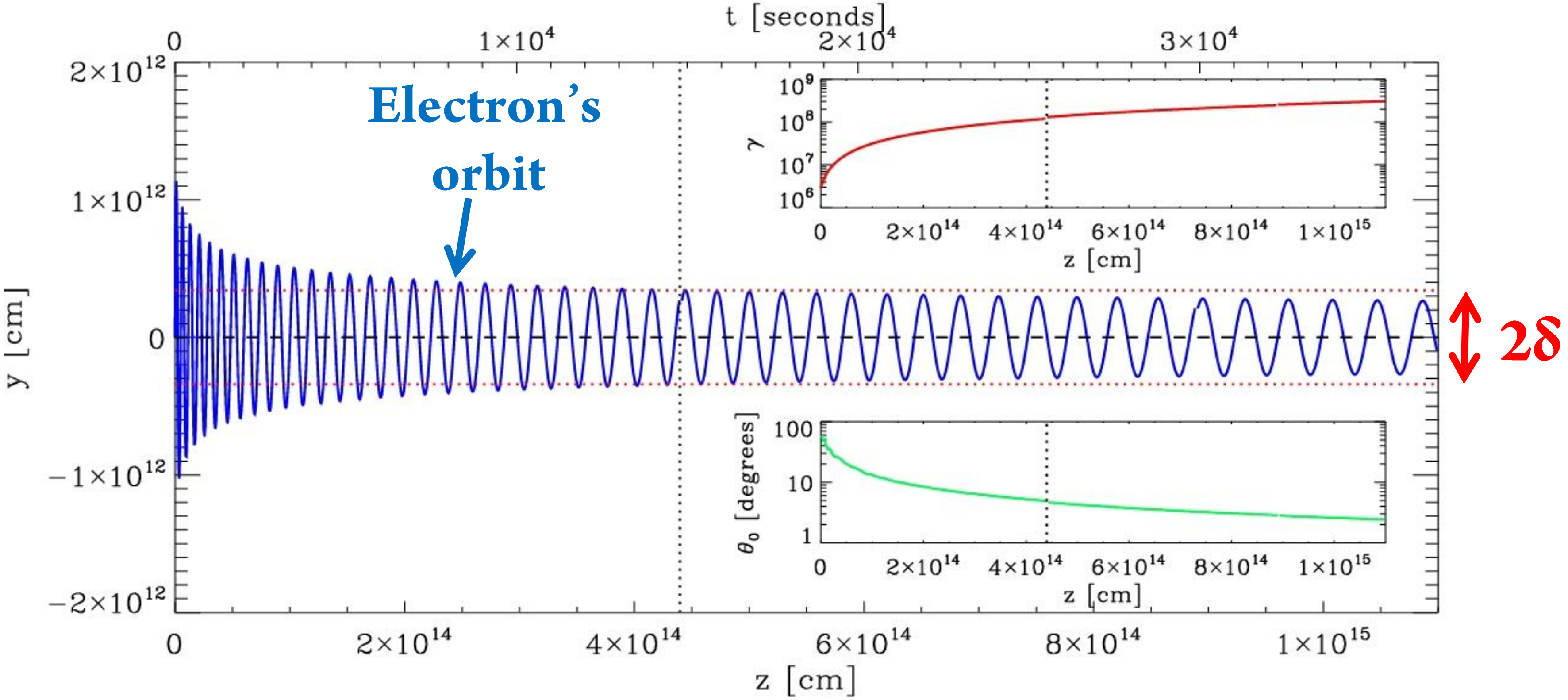
u^μ : 4-velocity

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

$ds = c\,dt/\gamma_e$: Relativistic interval

Exemple of a numerically integrated orbit

Integration numerical method: Explicit Runge-Kutta 8th order



Electron's orbit

2δ

The particle orbit shrinks toward the midplane, where E>B

This behavior was first found with an analytical study.

[see Uzdensky, Cerutti & Begelman, 2011, ApJ Letters]

[Kirk, PRL 2004]

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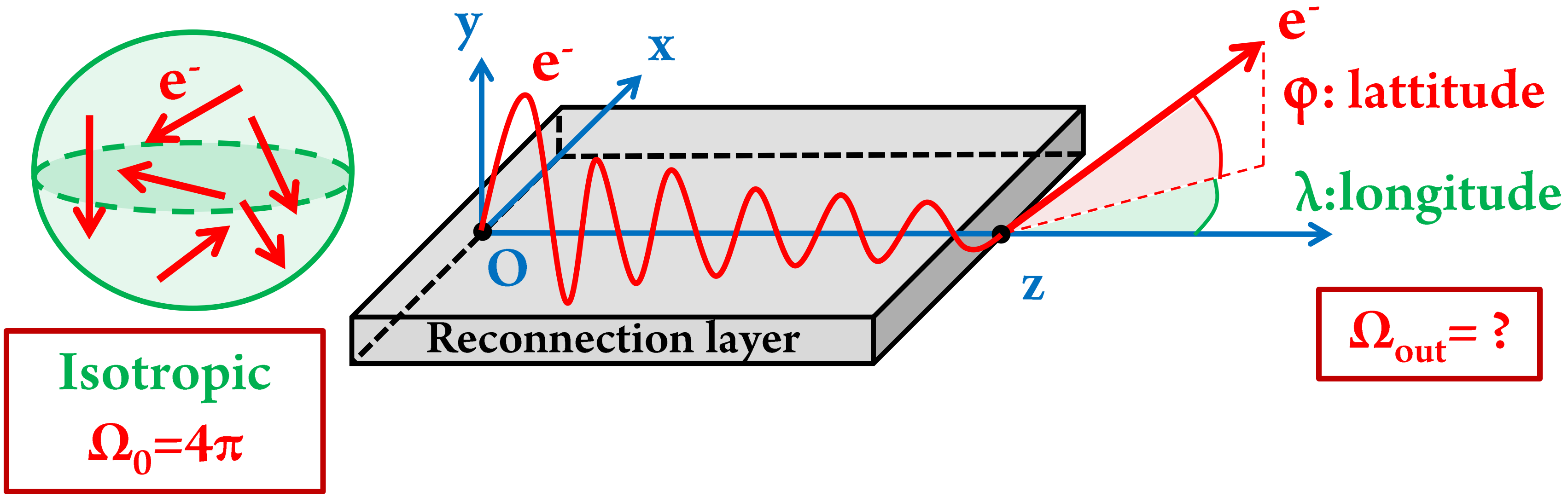
Population studies: simulation setup



Initially, the electrons are:

- Uniformly distributed along x and y
- Isotropic $\theta_0=[0,\pi]$, $\varphi_0=[0,2\pi]$
- Preaccelerated and distributed in a power-law: $dN_0/d\gamma_0=K_0\gamma_0^{-2}$, $10^6<\gamma_0<10^8$
- $\delta=3\times10^{11}$ cm, $L_z=2L_x=1.2\times10^{16}$ cm (4 light-days)
- $\beta_{rec}=0.1$

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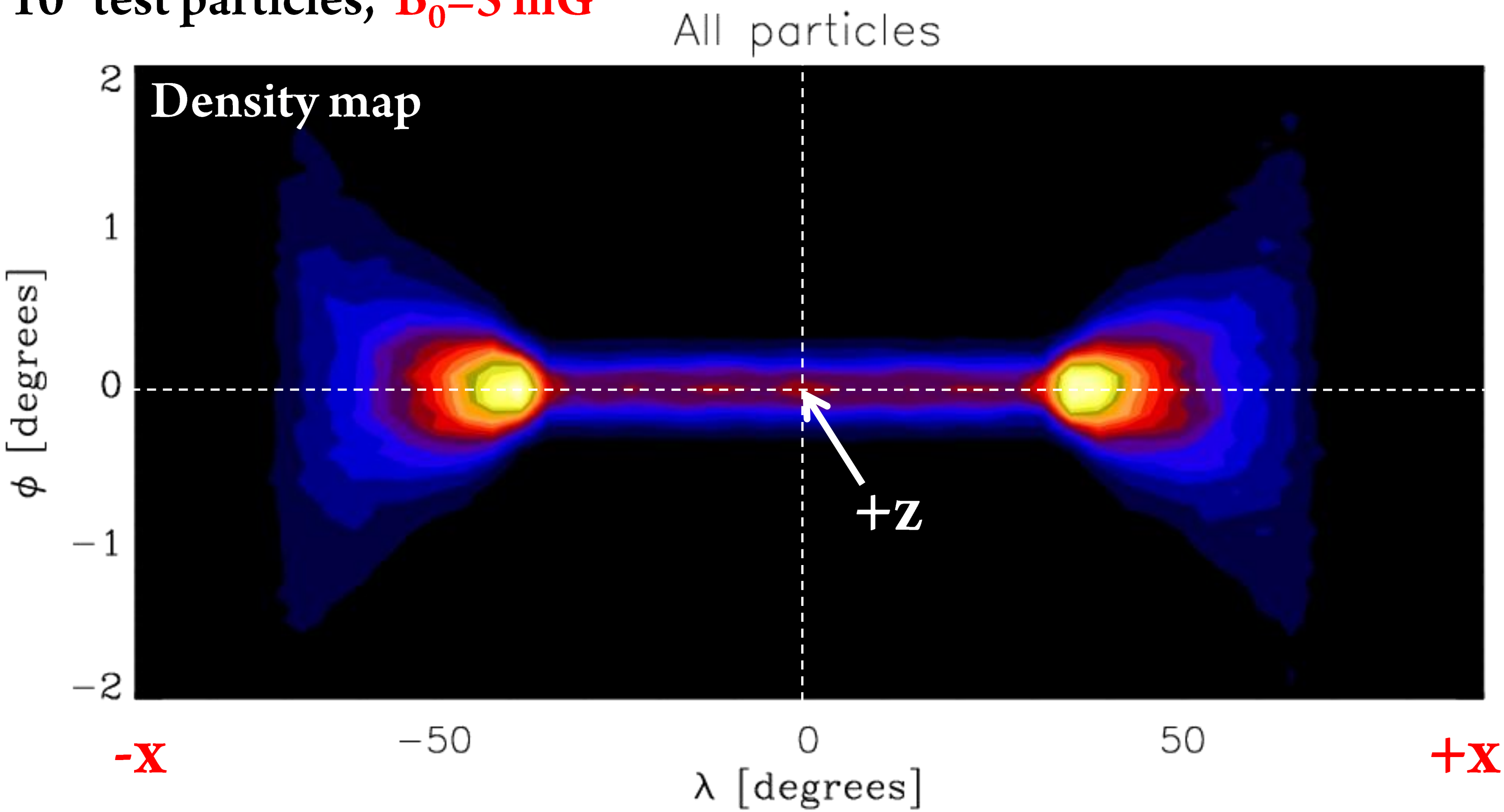
Outgoing angular distribution

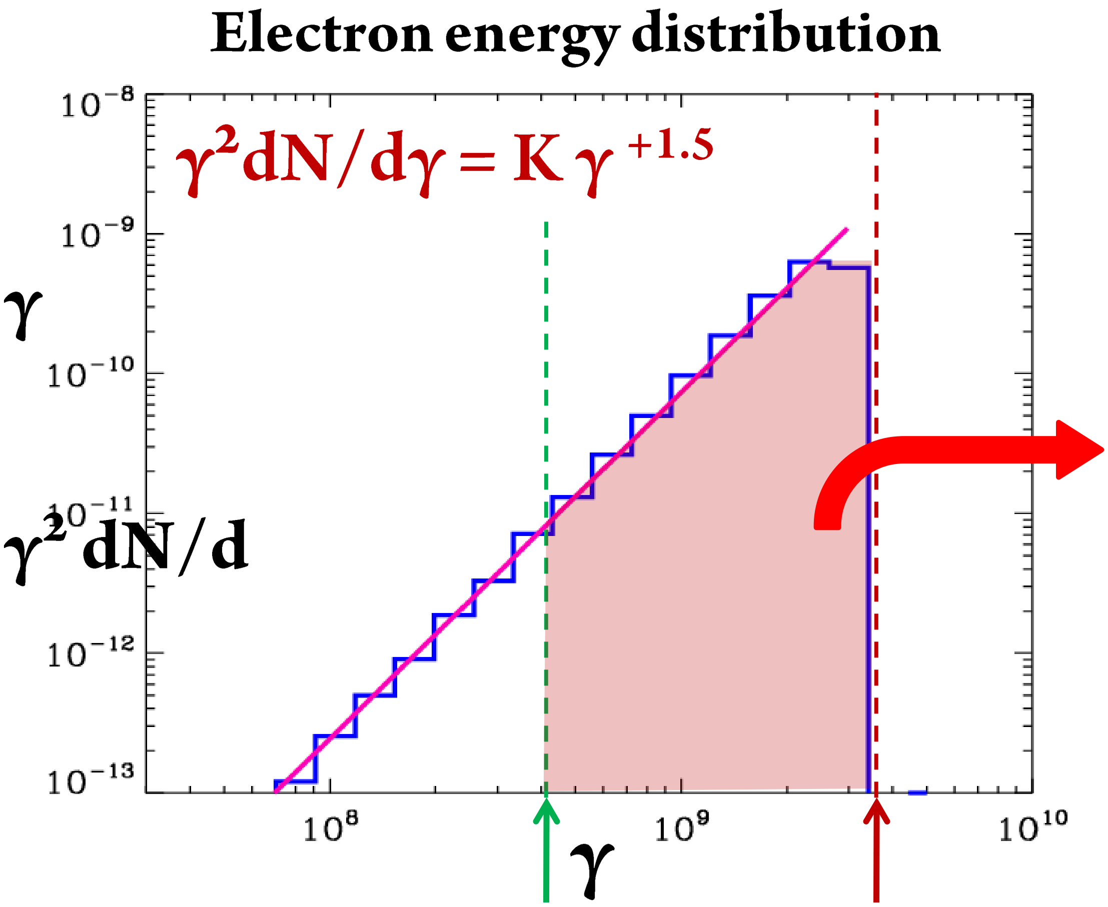
10^6 test particles, B_0=5 mG



Fan beam: $\Omega_{90\%}\approx 0.1$ sr

[Cerutti, Uzdensky, Begelman, ApJ, 2012]

Outgoing electron energy distribution



$\gamma^2 dN/d\gamma = K\gamma^{+1.5}$

Synchrotron radiation >100 MeV

$\gamma_{rad} = (3c\beta_{rec}/2r_e\omega_0)^{1/2} \approx 4\times10^8$

$\gamma_{max} = eEL_z/m_ec^2 \approx 3.5\times10^9$

The particles pile up at the maximum energy available eEL_z

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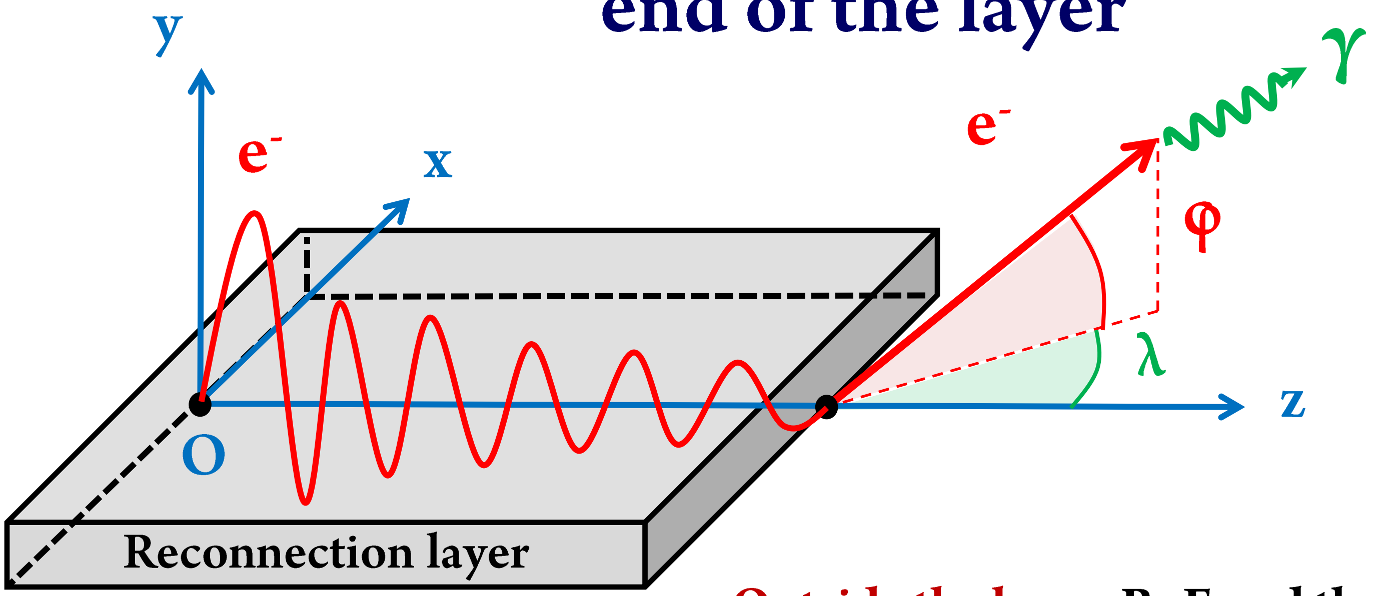
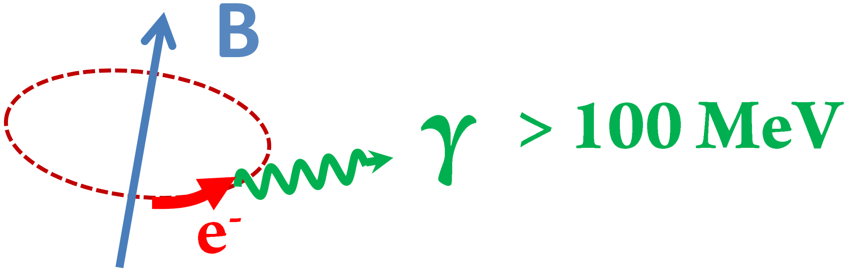
The highest-energy particles will radiate quickly at the end of the layer



Inside the layer, the particle does not radiate much E>B, synchrotron losses are negligible

Outside the layer, B>E and the particle radiates quickly, before one full Larmor turn (radiation reaction limit).



Strong anisotropy of the >100 MeV synchrotron radiation

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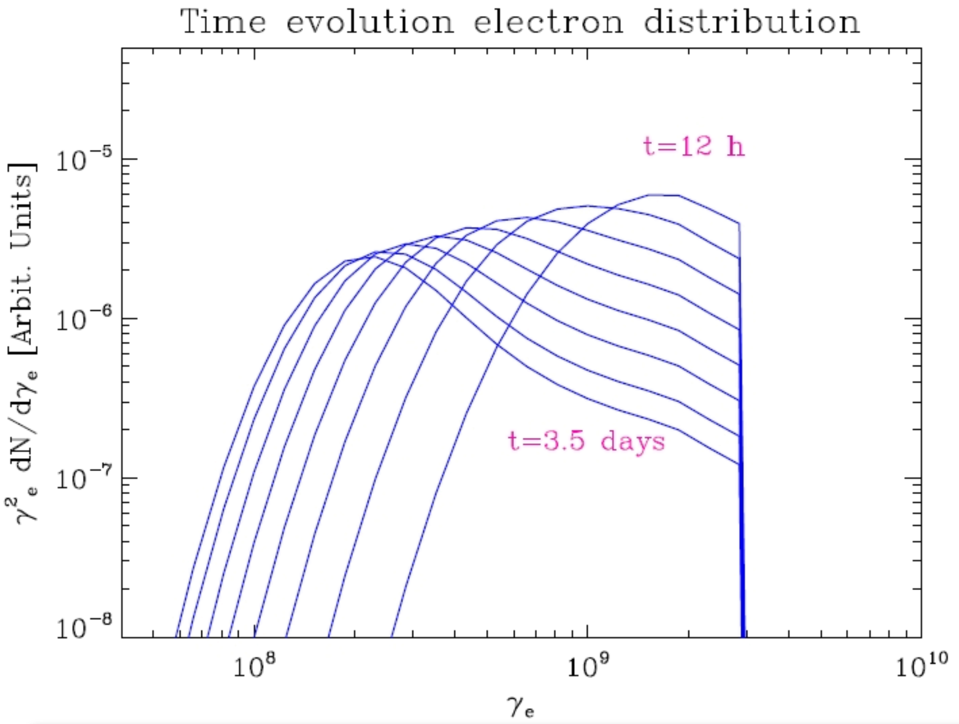
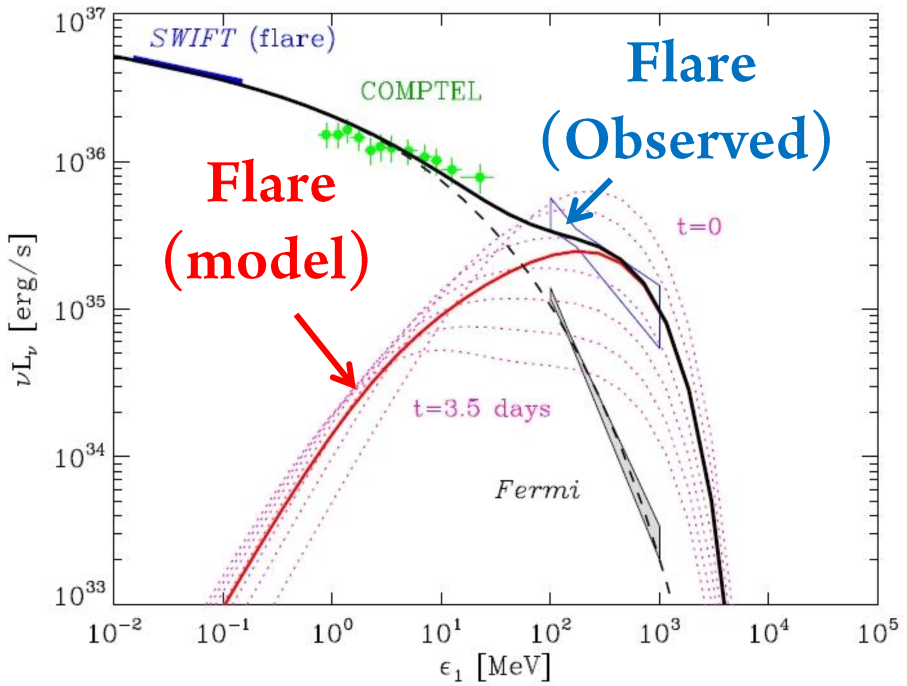
Application of the model to the Crab Nebula flares

[Cerutti, Uzdensky, Begelman, ApJ, 2012]


Time evolution electron distribution

Spectral Energy Distribution (photons)



- Continuous injection of fresh particles and synchrotron cooling during the duration of the flare.
- Energetics: $E_{pairs} < 0.02\, E_{mag}$ (about 35% if no beaming), with $E_{mag} = 4\beta_{rec}(B_0^2/8\pi)\times(ct_{flare})^3 \approx 4.4\times10^{41}$ erg.
- Inverse Compton emission negligible, and little emission at other wavelengths

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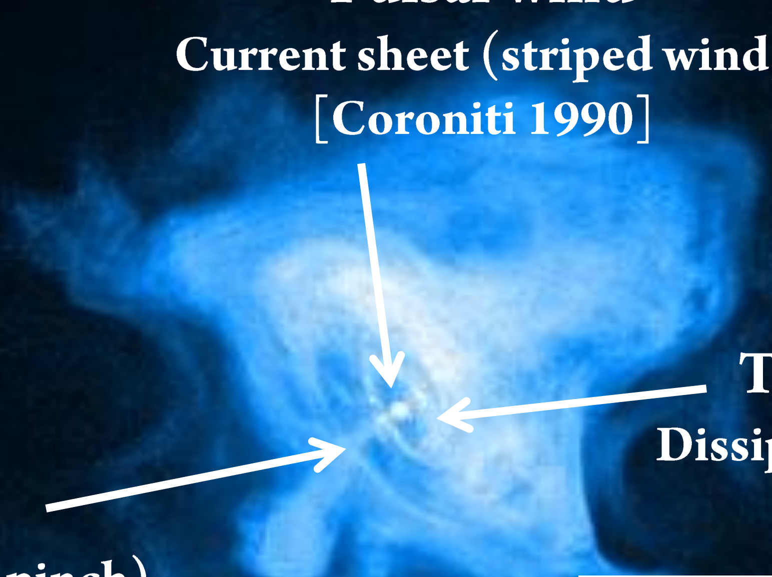
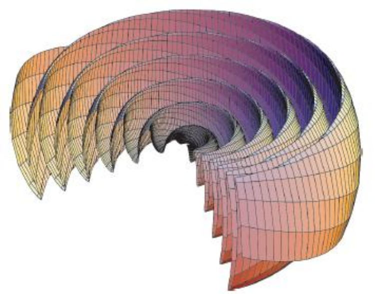
Where could magnetic reconnection operate in the Crab?



Pulsar wind

Current sheet (striped wind)

[Coroniti 1990]

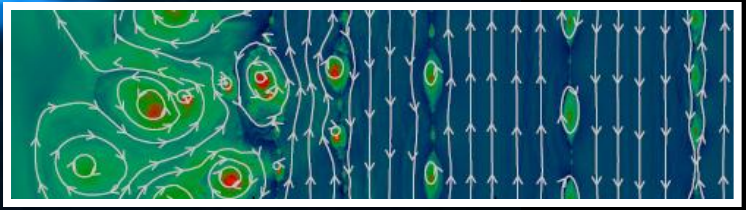


© *Kirk et al. 2009*

Termination shock

Dissipation of the striped wind

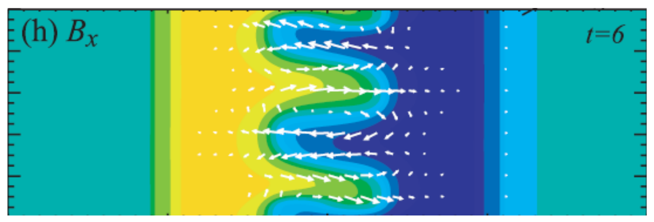
[Lyubarsky 2003]



© *Sironi & Spitkovsky 2011b*

Polar region

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



© *Mizuno et al. 2010*

© *NASA-CXC-SAO F.Seward et al.*

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Summary I

- **Synchrotron photons >100 MeV:** Acceleration deep inside the layer where E>B ✓

- **The spectral shape:** Synchrotron emission from ≈ monoenergetic pairs ✓

- **The variability:** Acceleration in a few light-days long layer ✓

- **The energetics of the flare:** Strong beaming of the particles ($\Omega \approx 0.1$ Sr) ✓

- **Little emission at other wavelength:** Pairs pile up at the maximum energy eEL_z ✓

Caveats

- Big uncertainties on the fields in the layer. Need for a more consistent approach.
➔ Relativistic pair plasma PIC simulations + the radiation reaction force.
[Jaroschek & Hoshino, PRL, 2009]

- Origin of the short intra-flare variability? Effect of instabilities (kink, tearing)?

Particle-In-Cell (PIC) simulations of relativistic pair plasma reconnection

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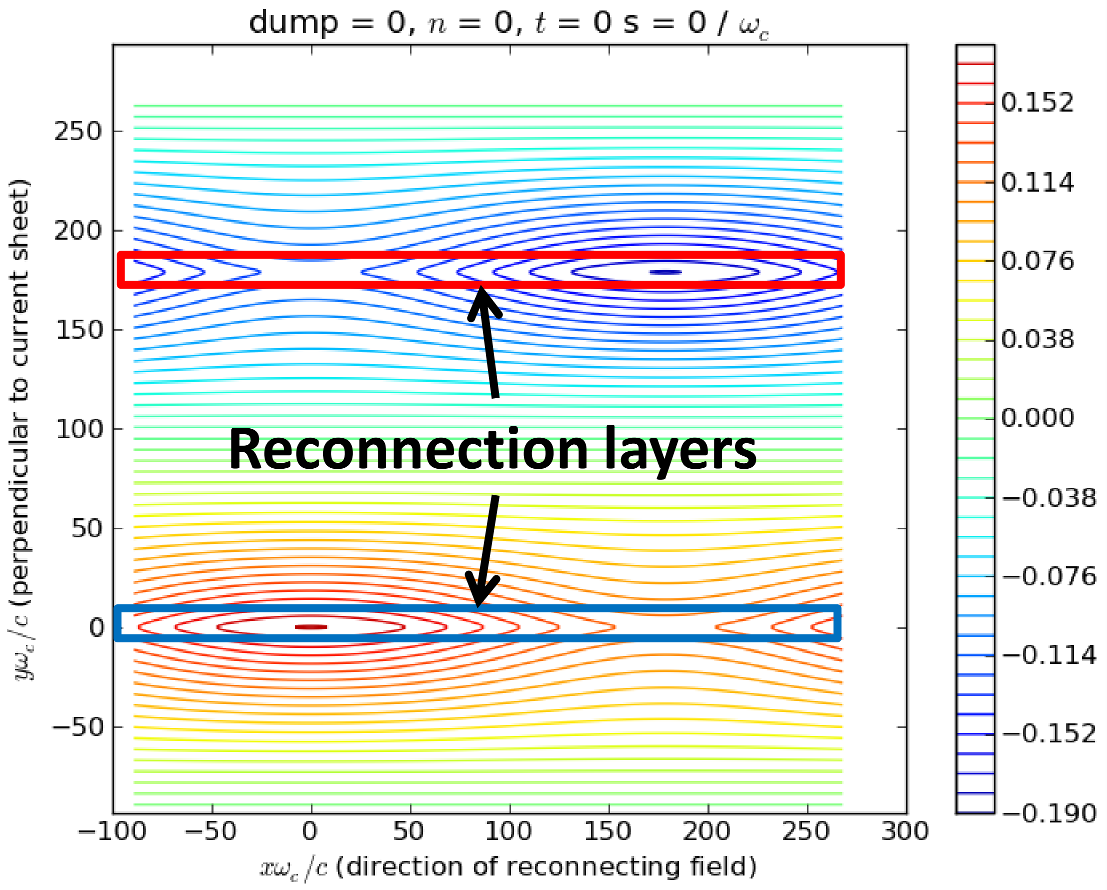
We carried out 2D PIC simulation of relativistic pair plasma reconnection with VORPAL

Initial magnetic field lines (xy-plane)



[Simulations done by G. Werner]

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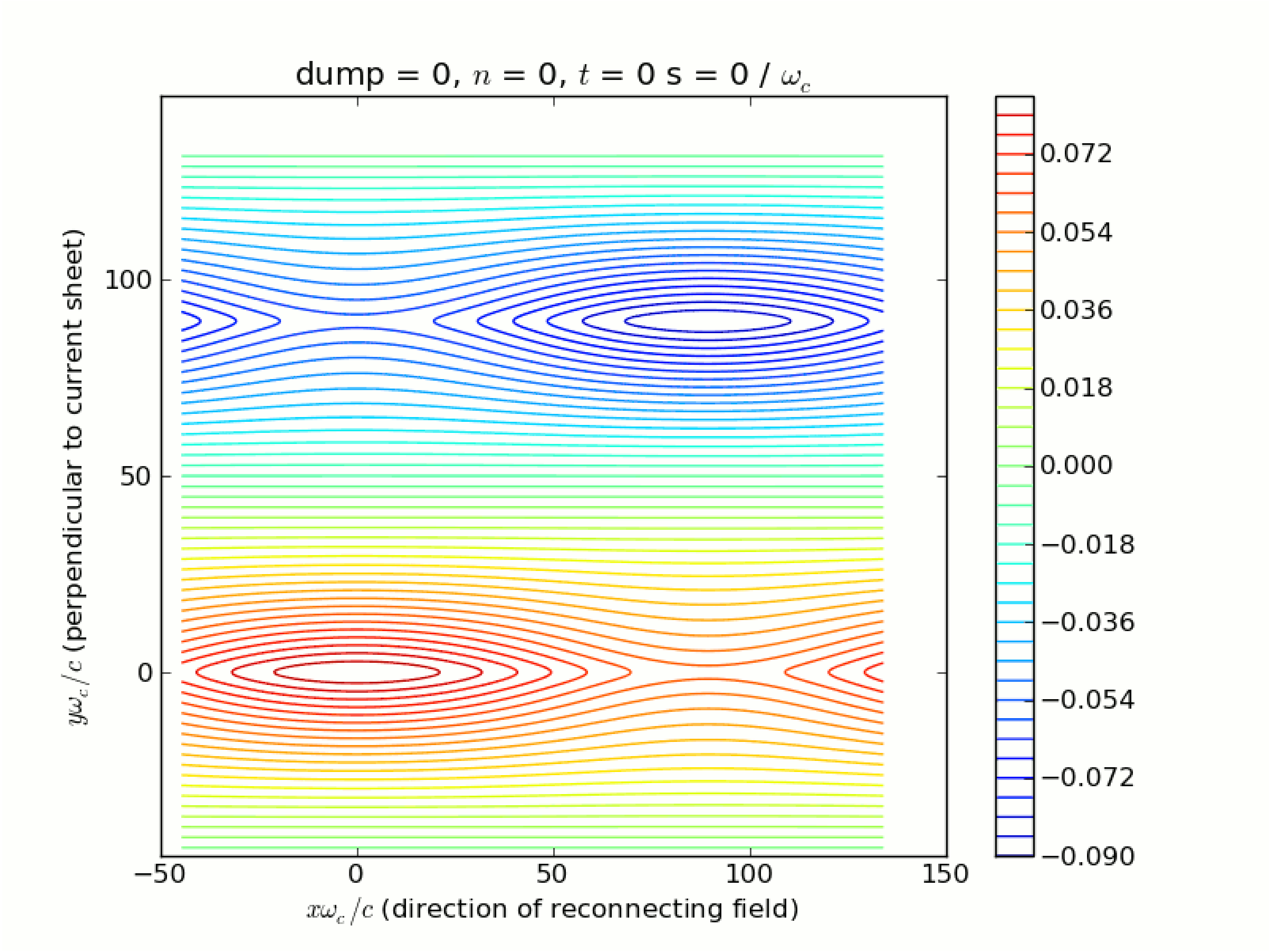
Simulation setup:

- Grid: 2048×2048
- Resolution: 8 cells per ρ_c
- Thickness: ρ_c
- # particles-per-cell: 64
- Total # particles: 2.7×10^8
- Double periodic boundary conditions
- Initial Harris equilibrium with small perturbation y-direction
- Background particles initially isotropic with $T=mc^2$

Time evolution of the magnetic field lines



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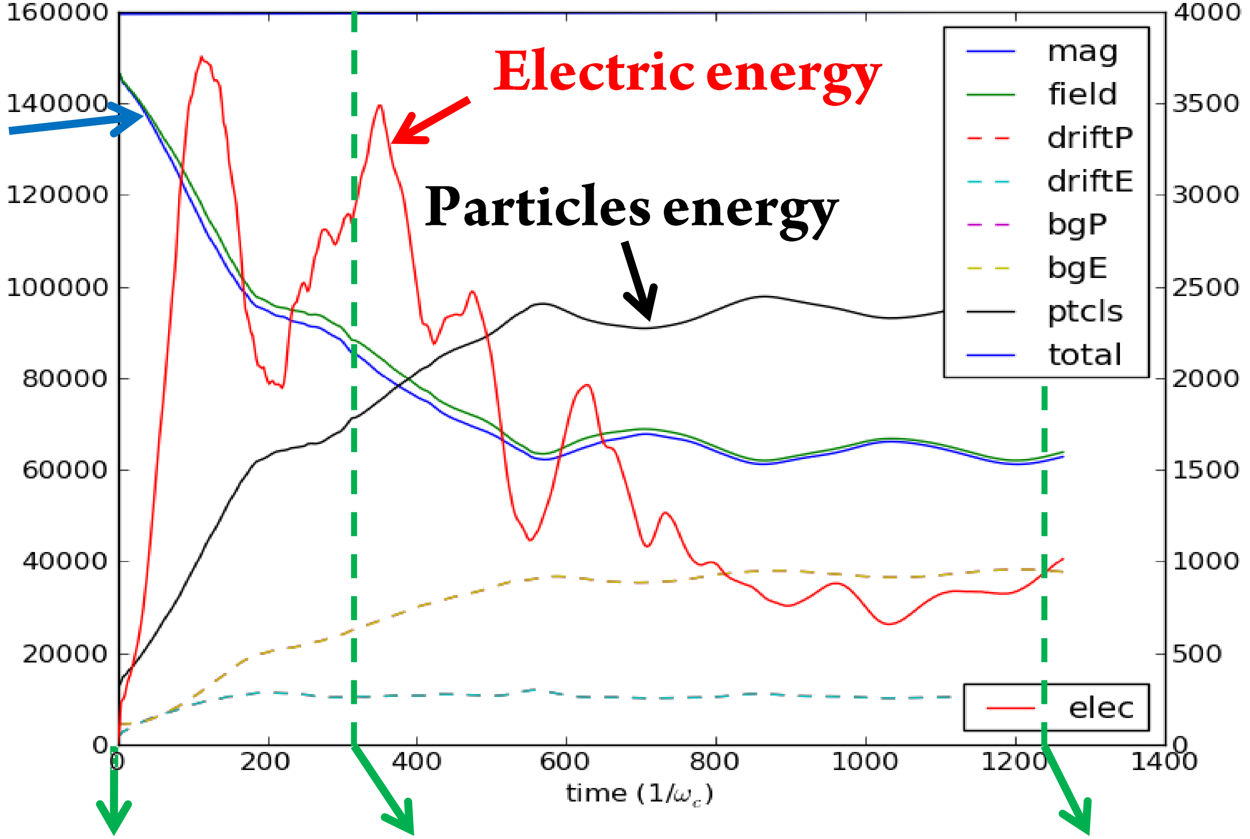
The layers is unstable to tearing modes.

Energy transfer during reconnection

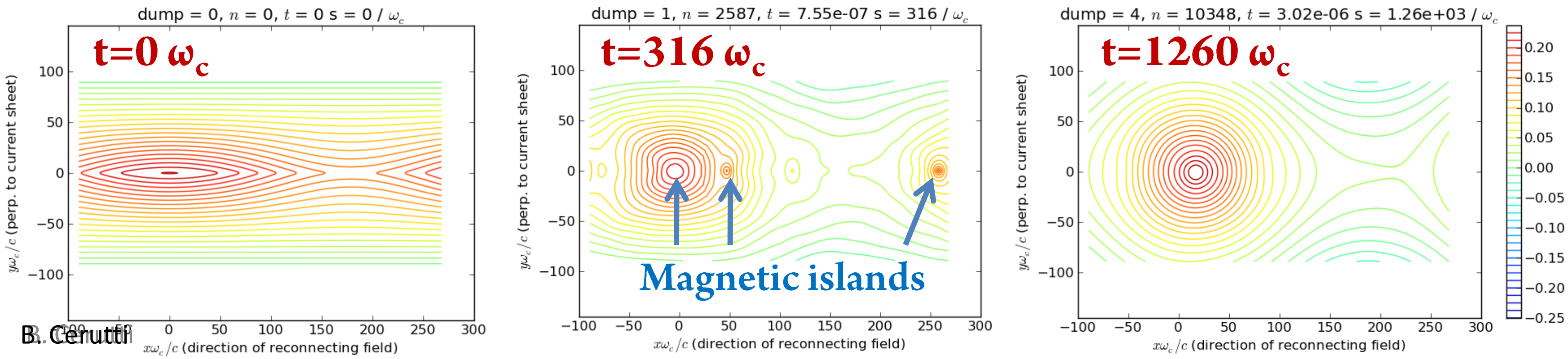


Magnetic energy

Electric energy

Particles energy

The total energy is conserved with <1% error



$t=0\ \omega_c$

$t=316\ \omega_c$

$t=1260\ \omega_c$

Magnetic islands

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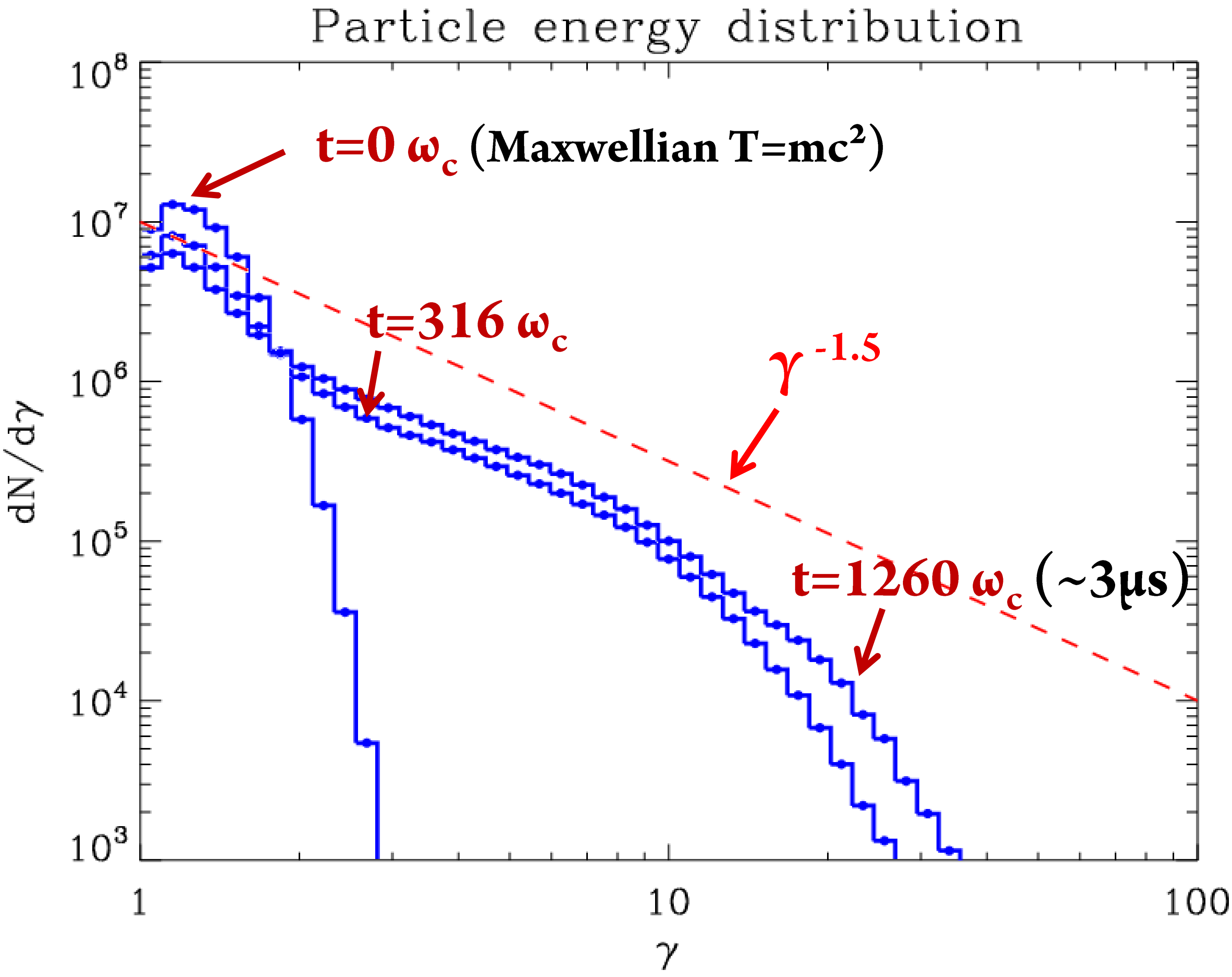

Particle energy distribution

t=0 ω_c (Maxwellian T=mc^2)

t=316 ω_c

$\gamma^{-1.5}$

t=1260 ω_c (~3μs)

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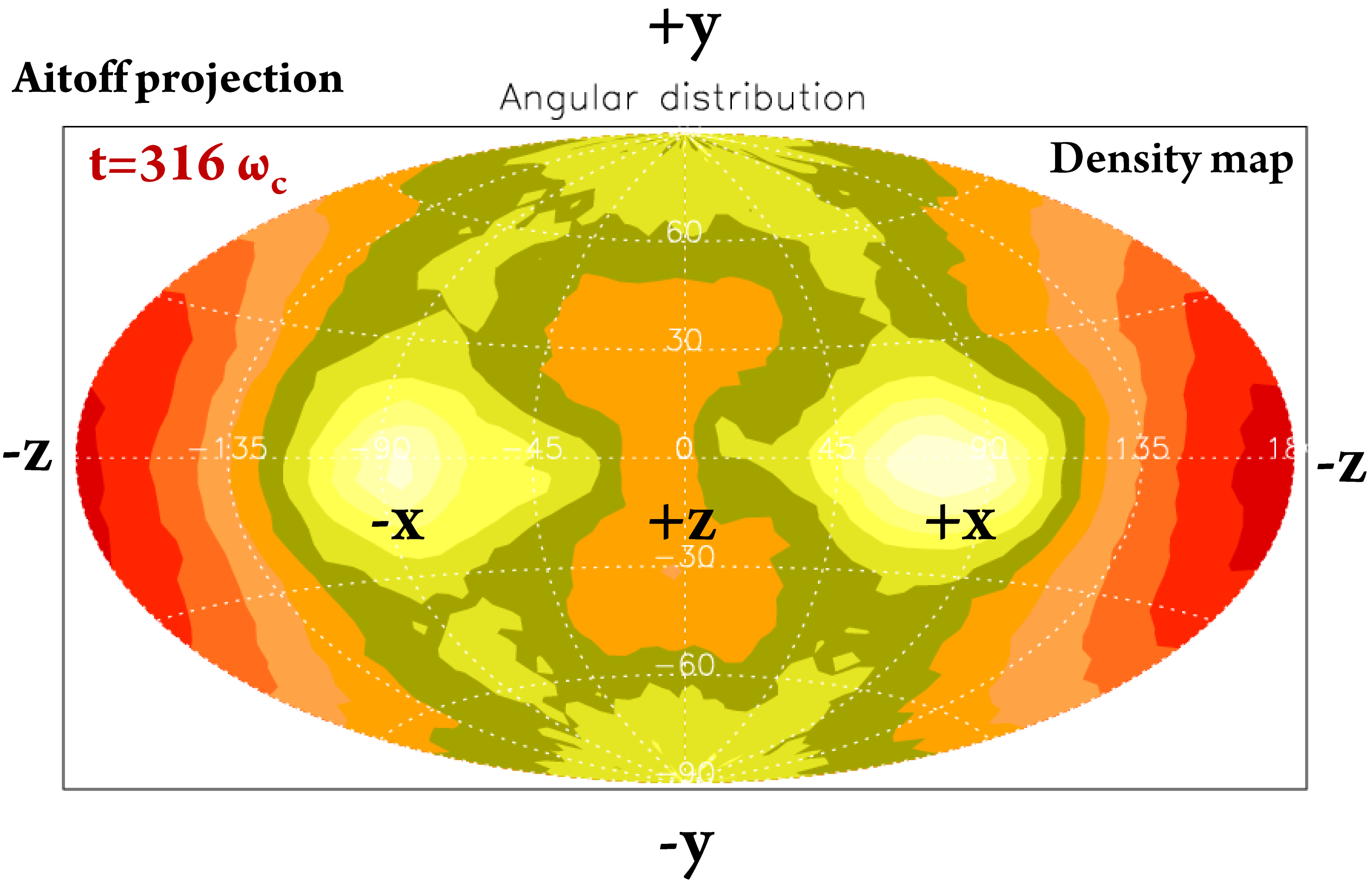
Background positrons angular distribution: All particles

Aitoff projection



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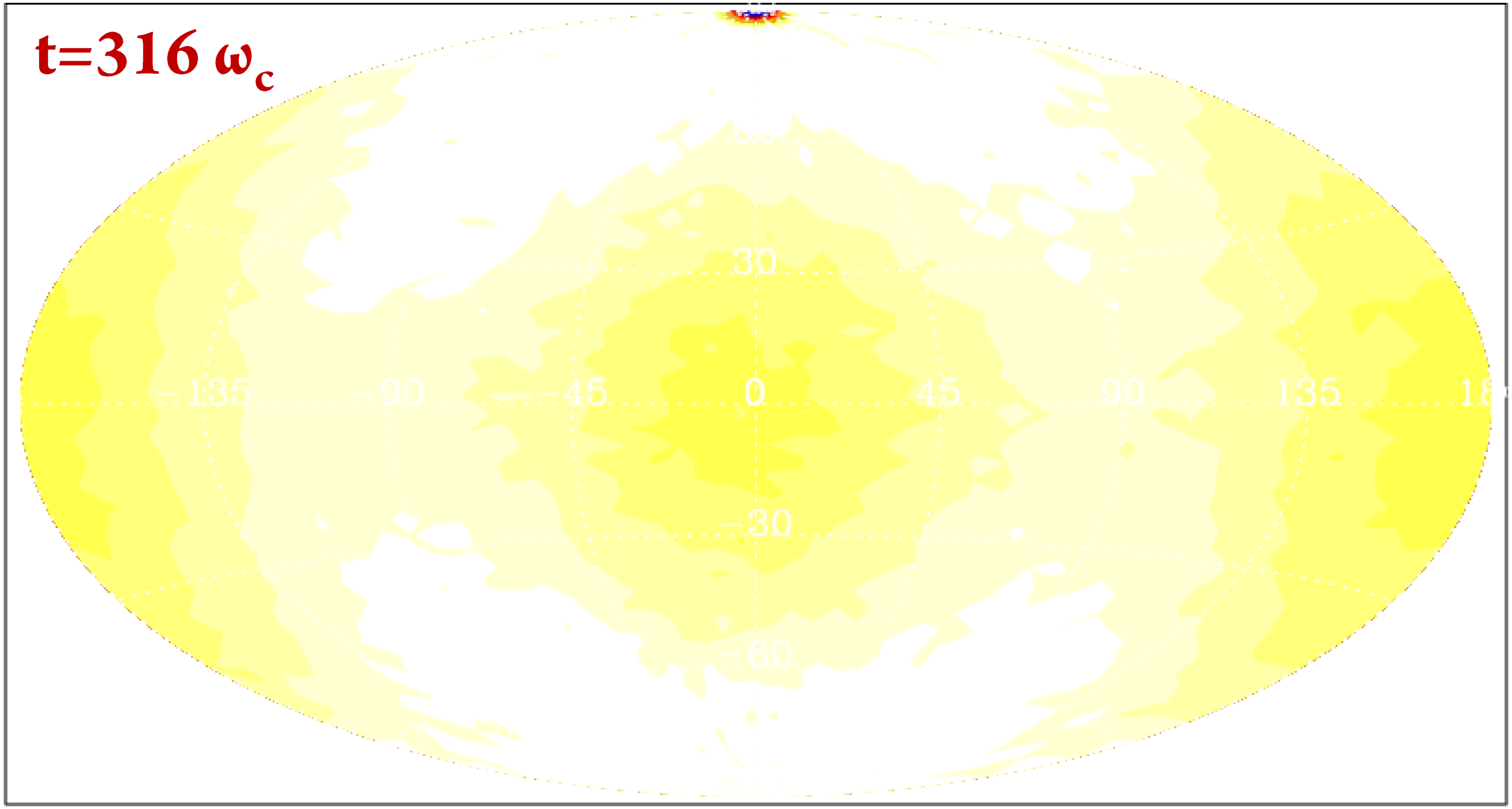
Energy-resolved angular distribution



$1.0 < \gamma < 1.3$

Solid angle within which half of the particles are contained →

$$\boxed{\Omega_{50\%}/4\pi = 0.55}$$

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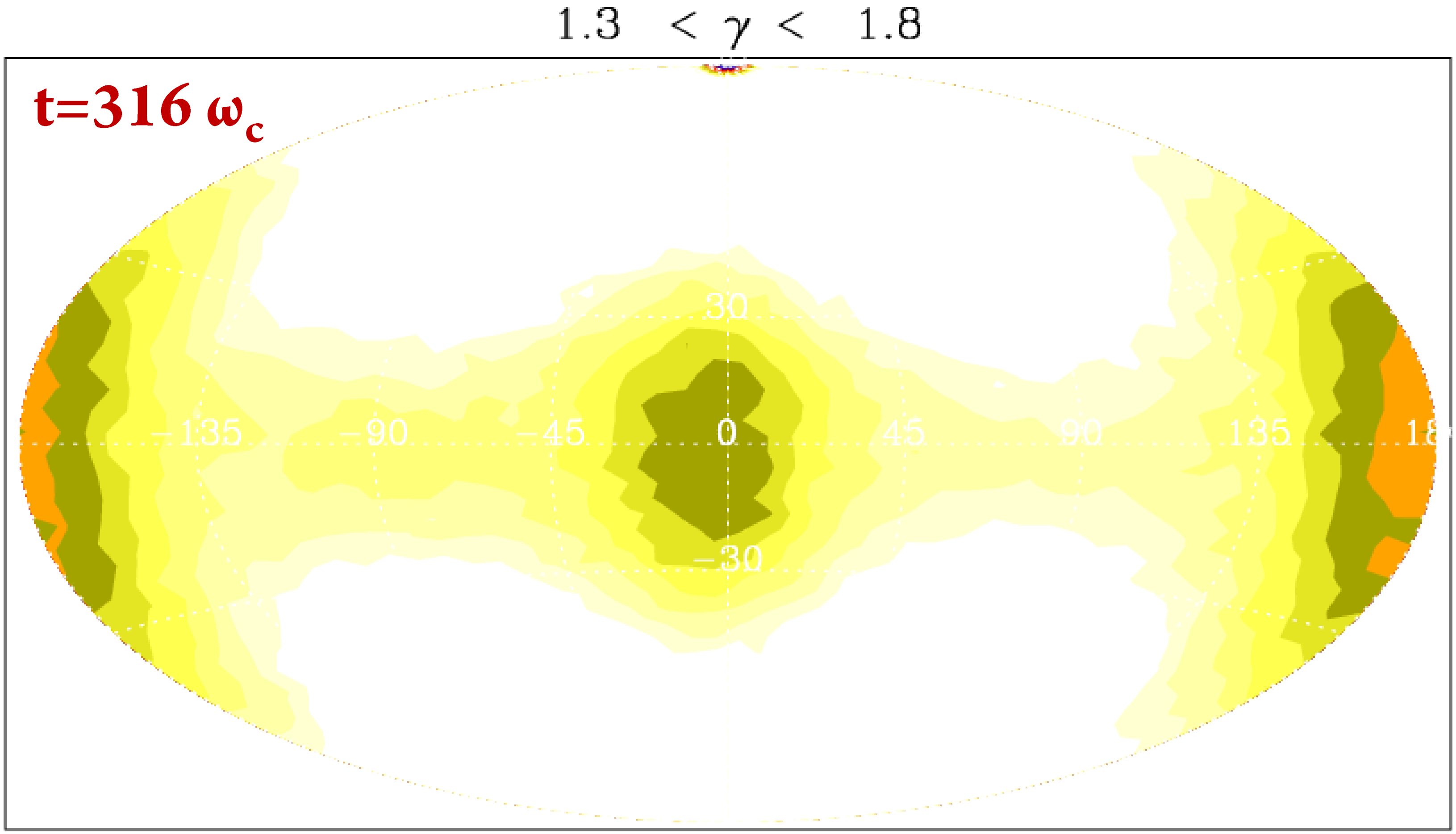
Energy-resolved angular distribution



$$\boxed{\Omega_{50\%}/4\pi = 0.54}$$

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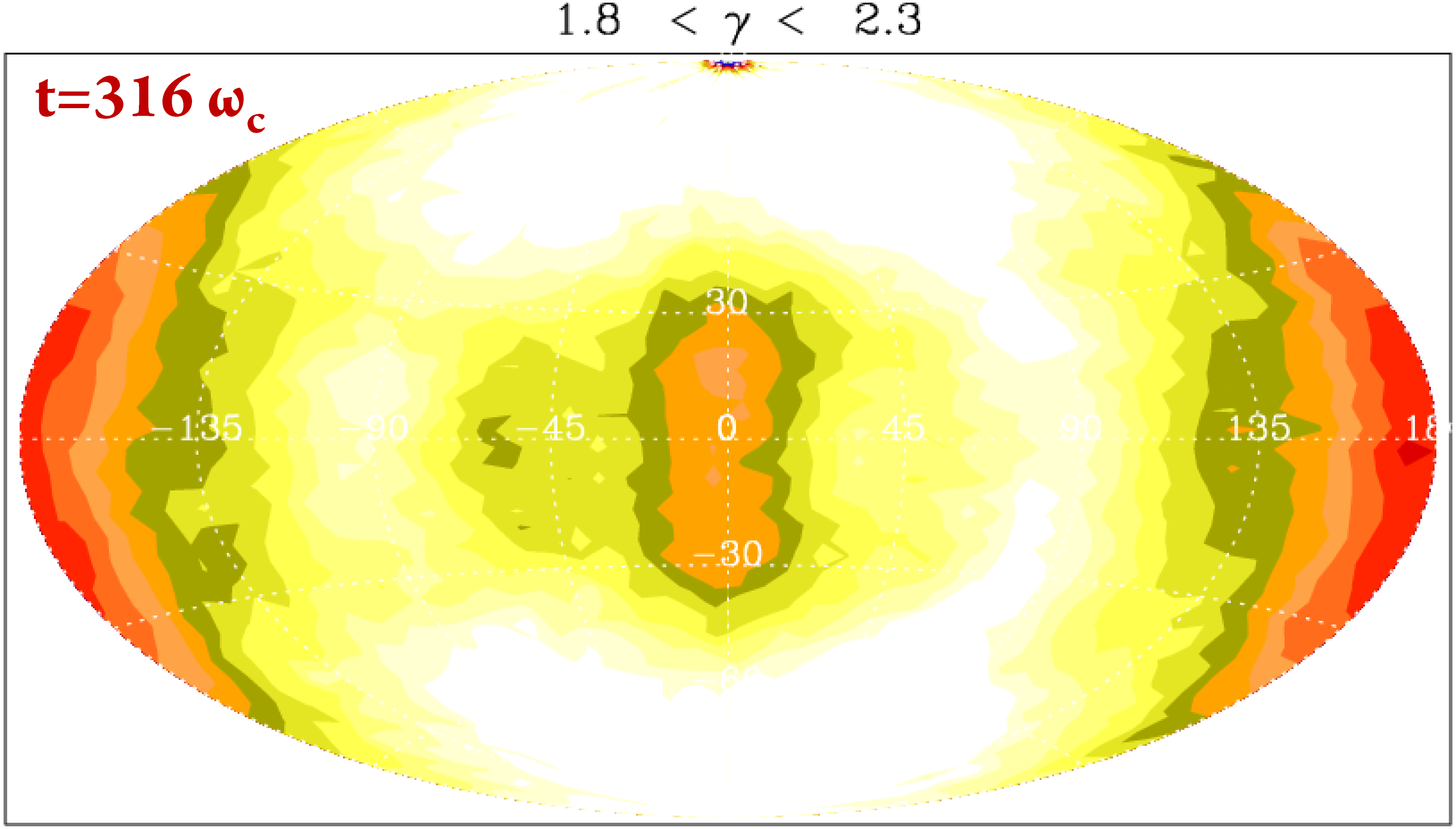
Energy-resolved angular distribution



$\boxed{\Omega_{50\%}/4\pi = 0.53}$

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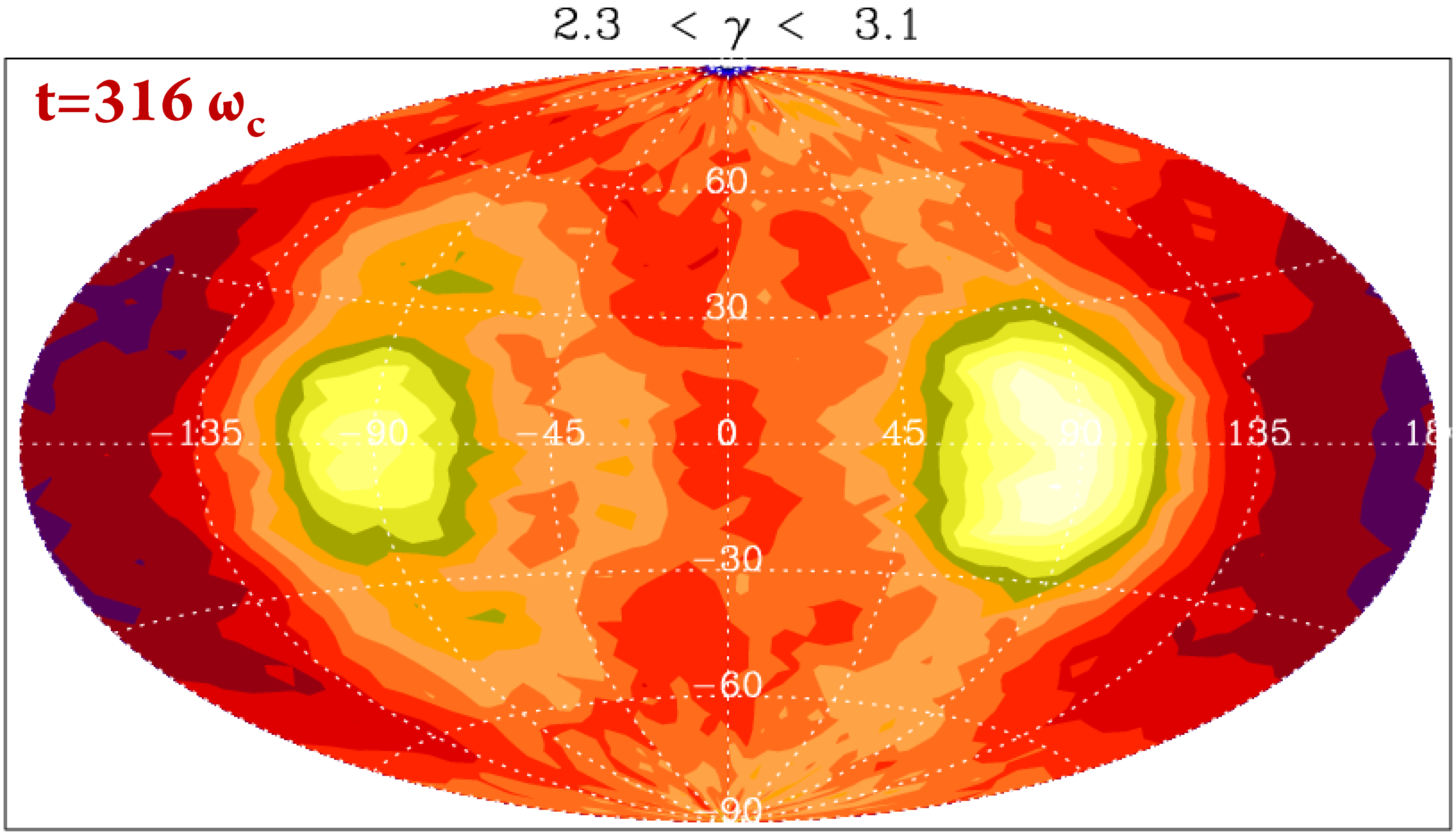
Energy-resolved angular distribution



$t=316\ \omega_c$

$$\boxed{\Omega_{50\%}/4\pi = 0.45}$$

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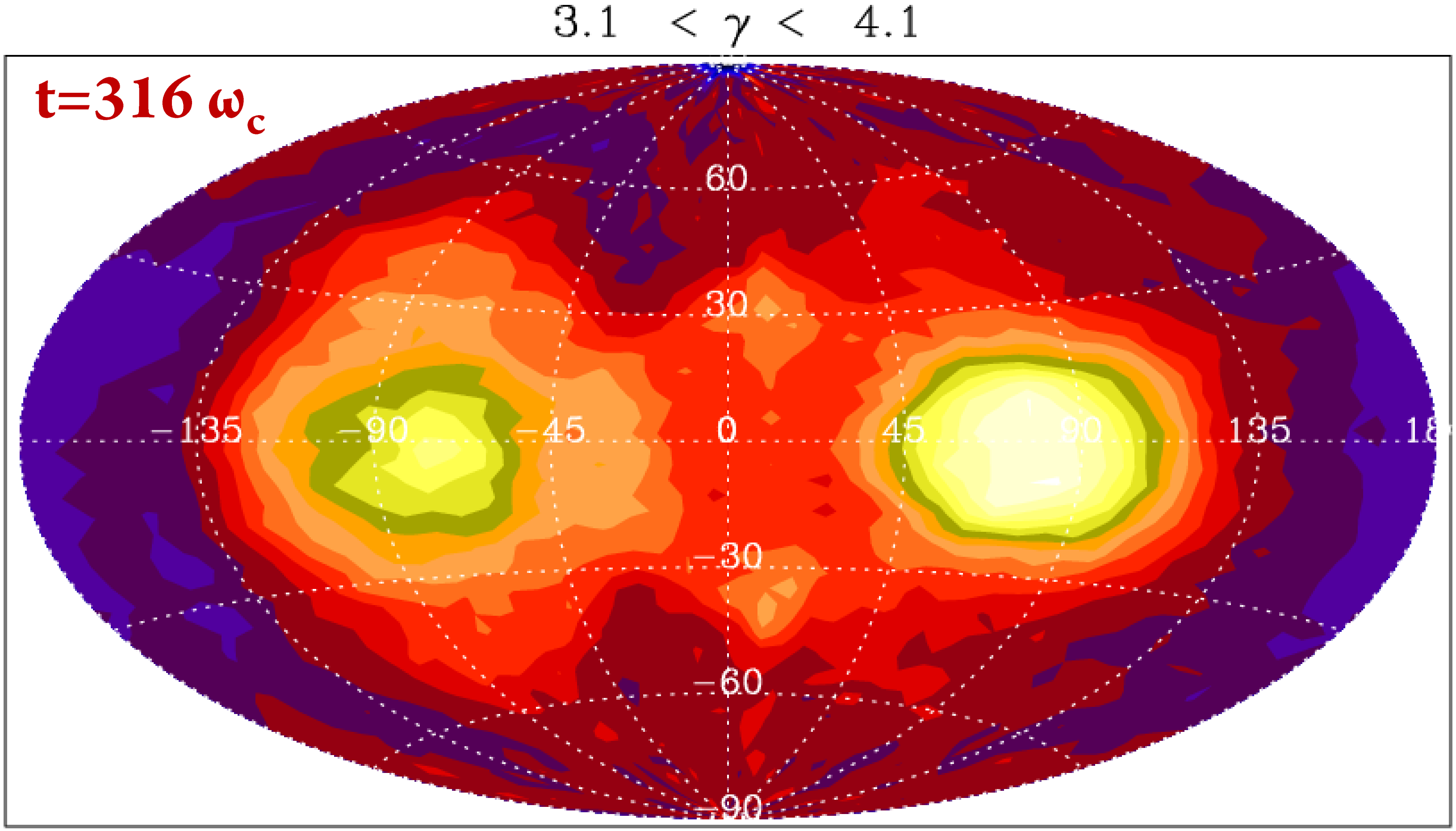
Energy-resolved angular distribution



$$\boxed{\Omega_{50\%}/4\pi = 0.40}$$

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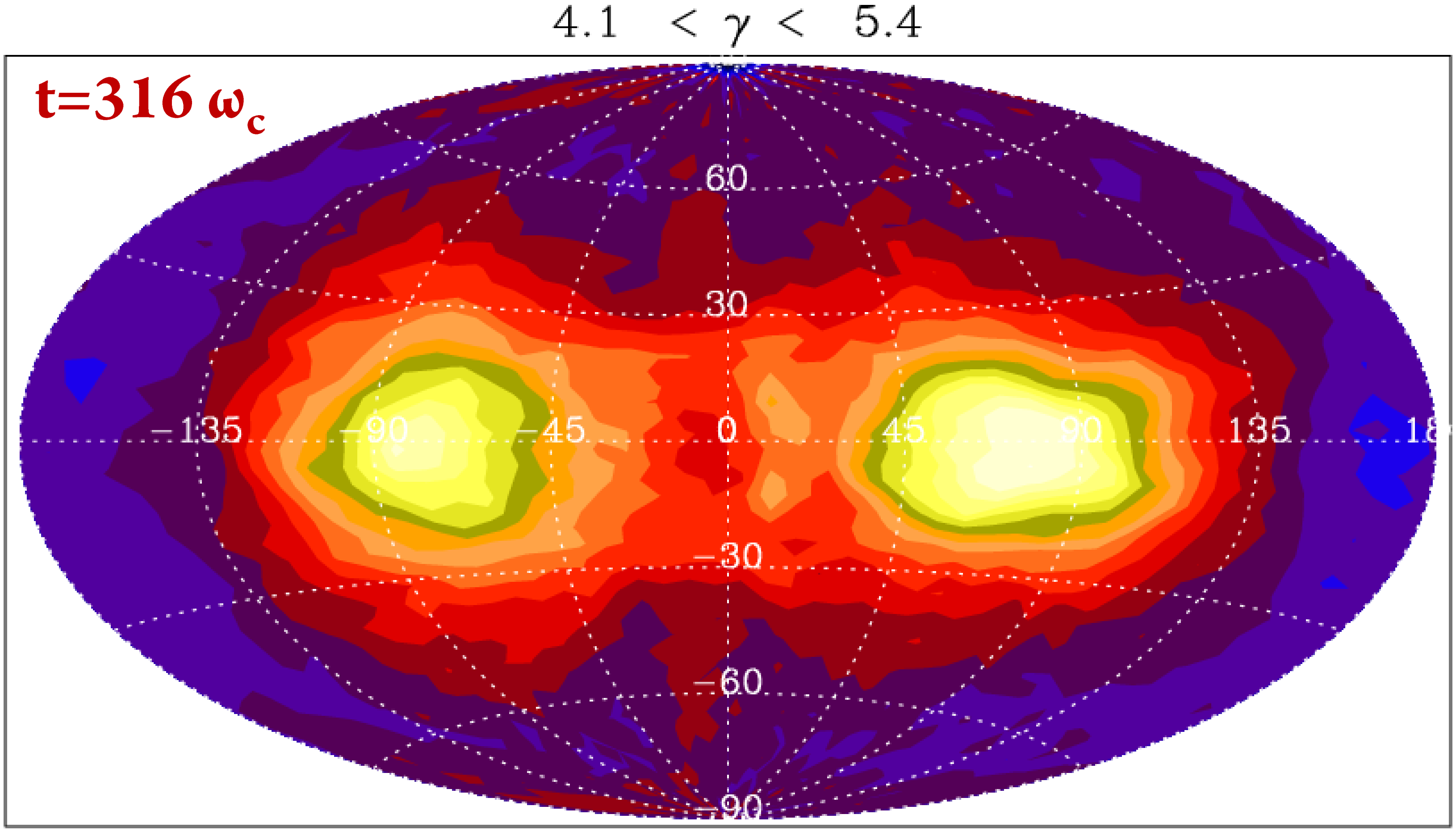
Energy-resolved angular distribution



$$\boxed{\Omega_{50\%}/4\pi = 0.37}$$

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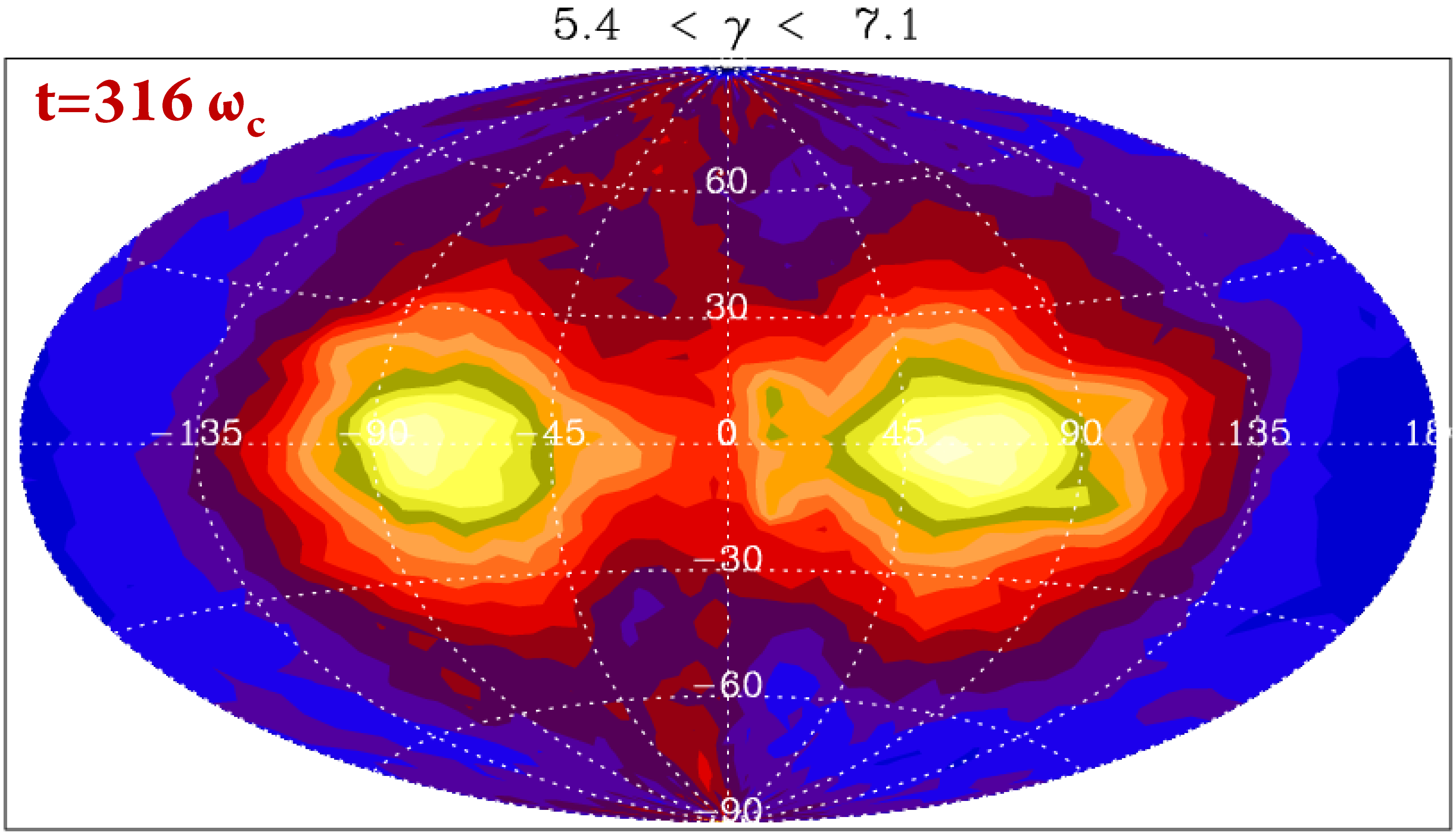
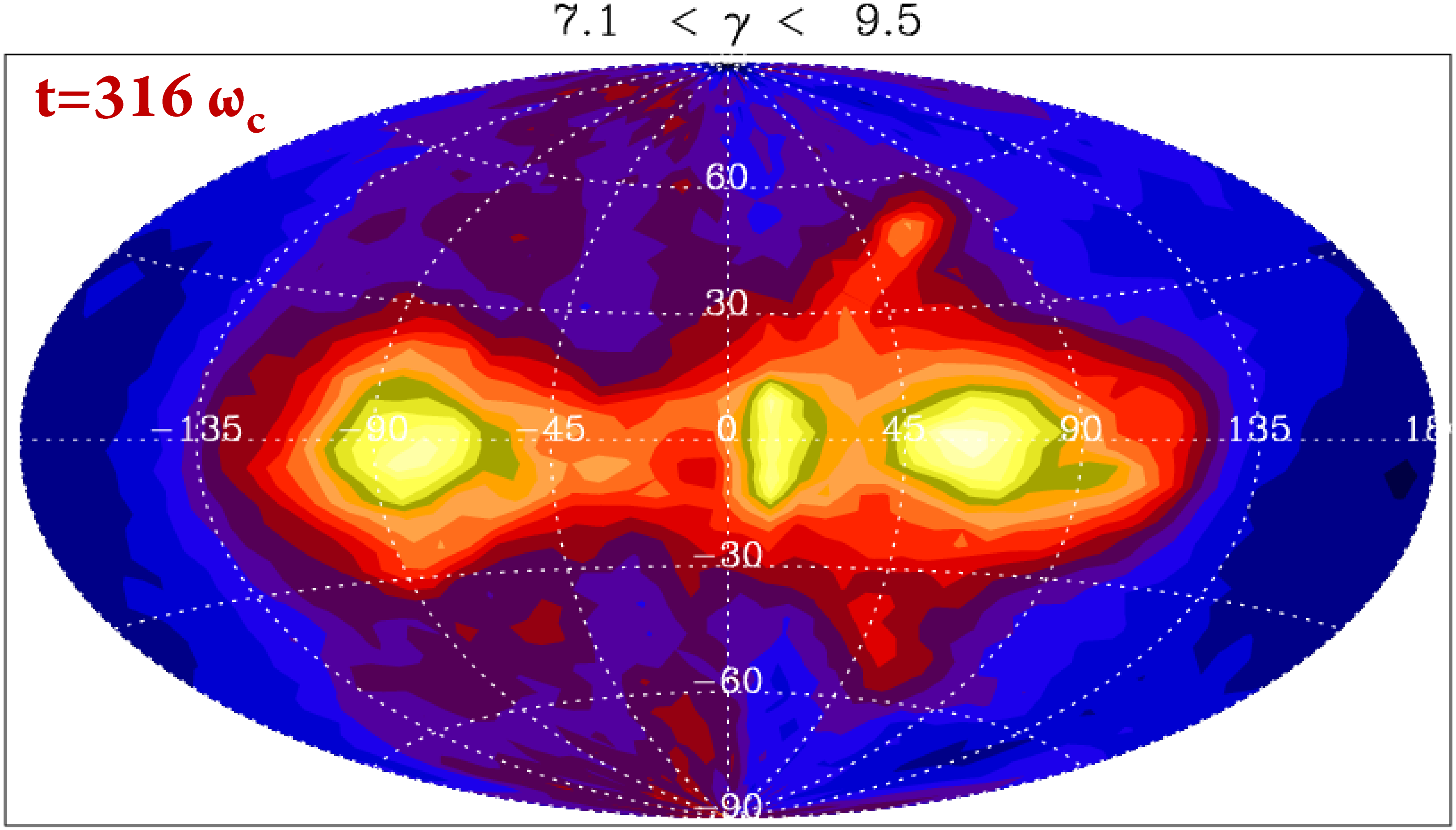
Energy-resolved angular distribution



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

B. Cerutti

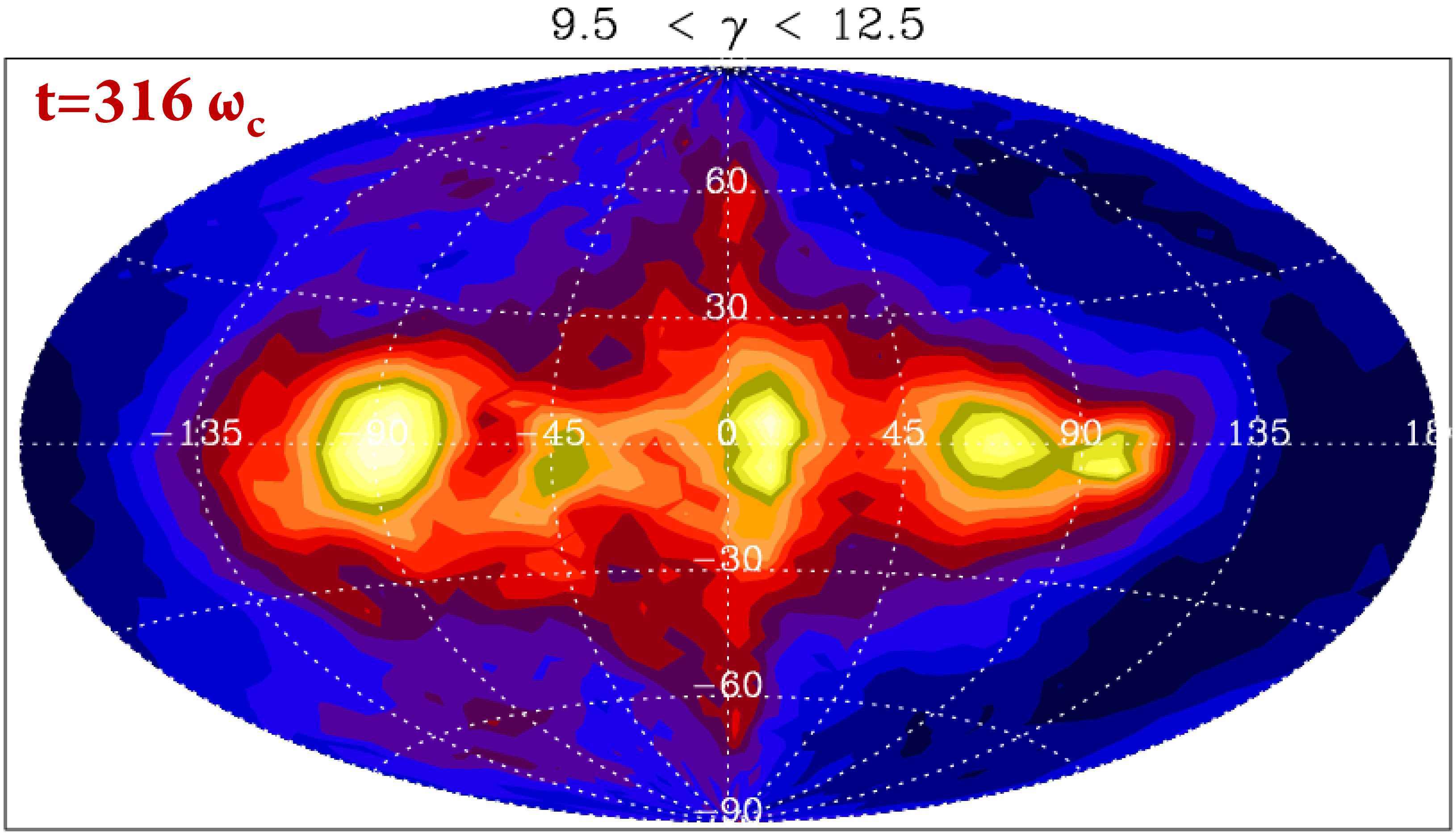
Energy-resolved angular distribution



$$\boxed{\Omega_{50\%}/4\pi = 0.32}$$

B. Cerutti

Energy-resolved angular distribution

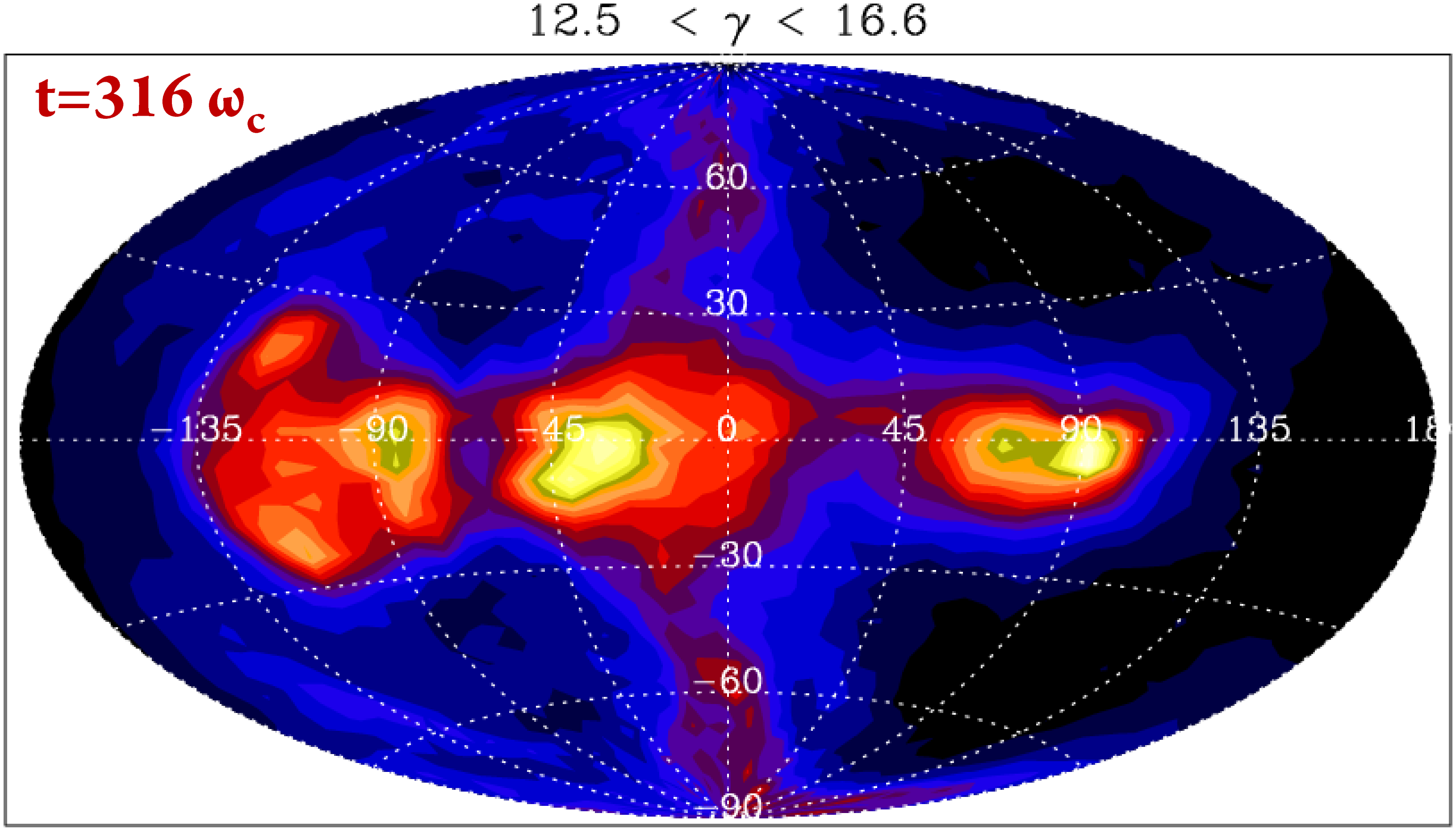


$9.5 < \gamma < 12.5$

$$\Omega_{50\%}/4\pi = 0.29$$

B. Cerutti

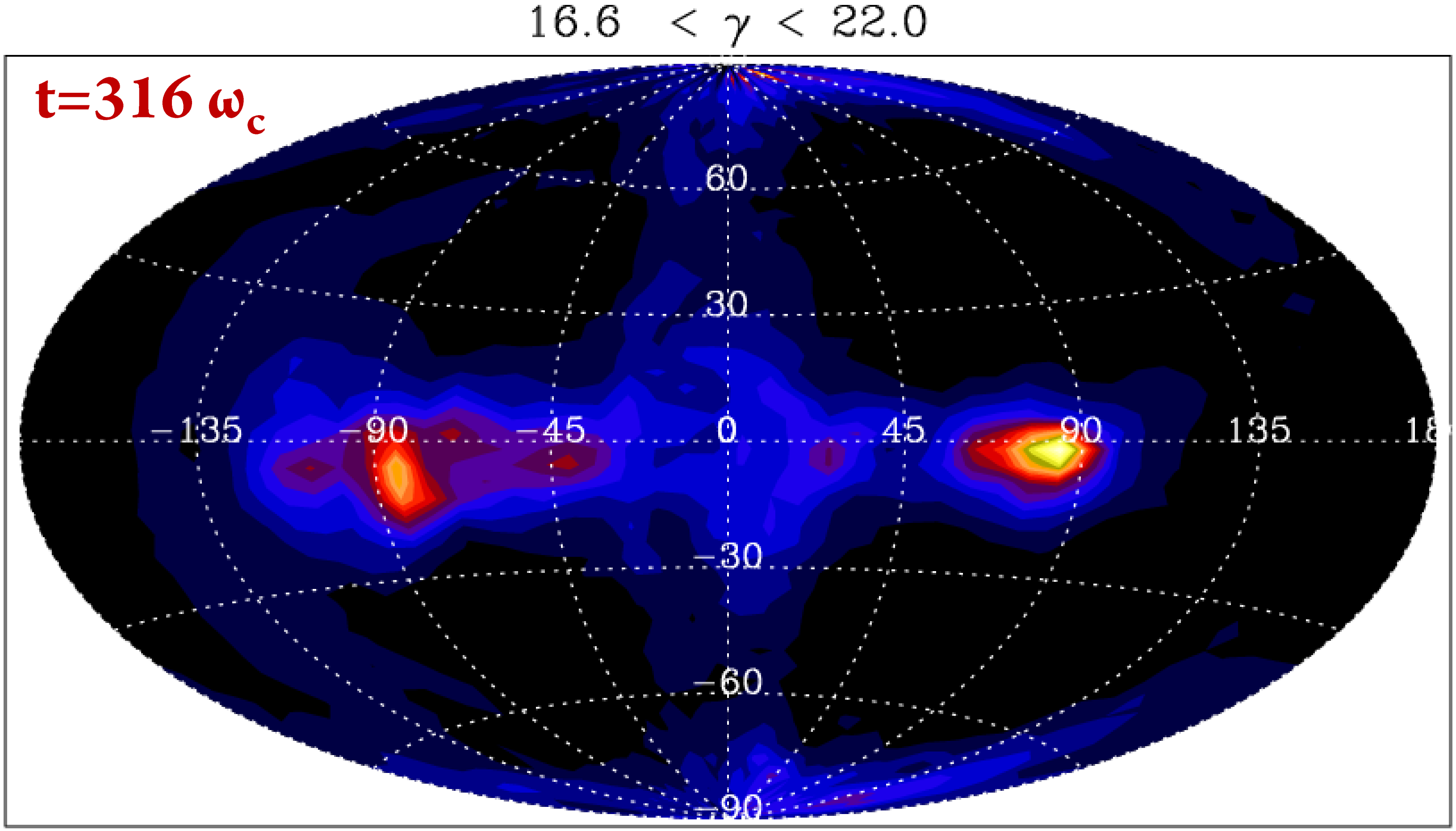
Energy-resolved angular distribution



$$\Omega_{50\%}/4\pi = 0.22$$

B. Cerutti

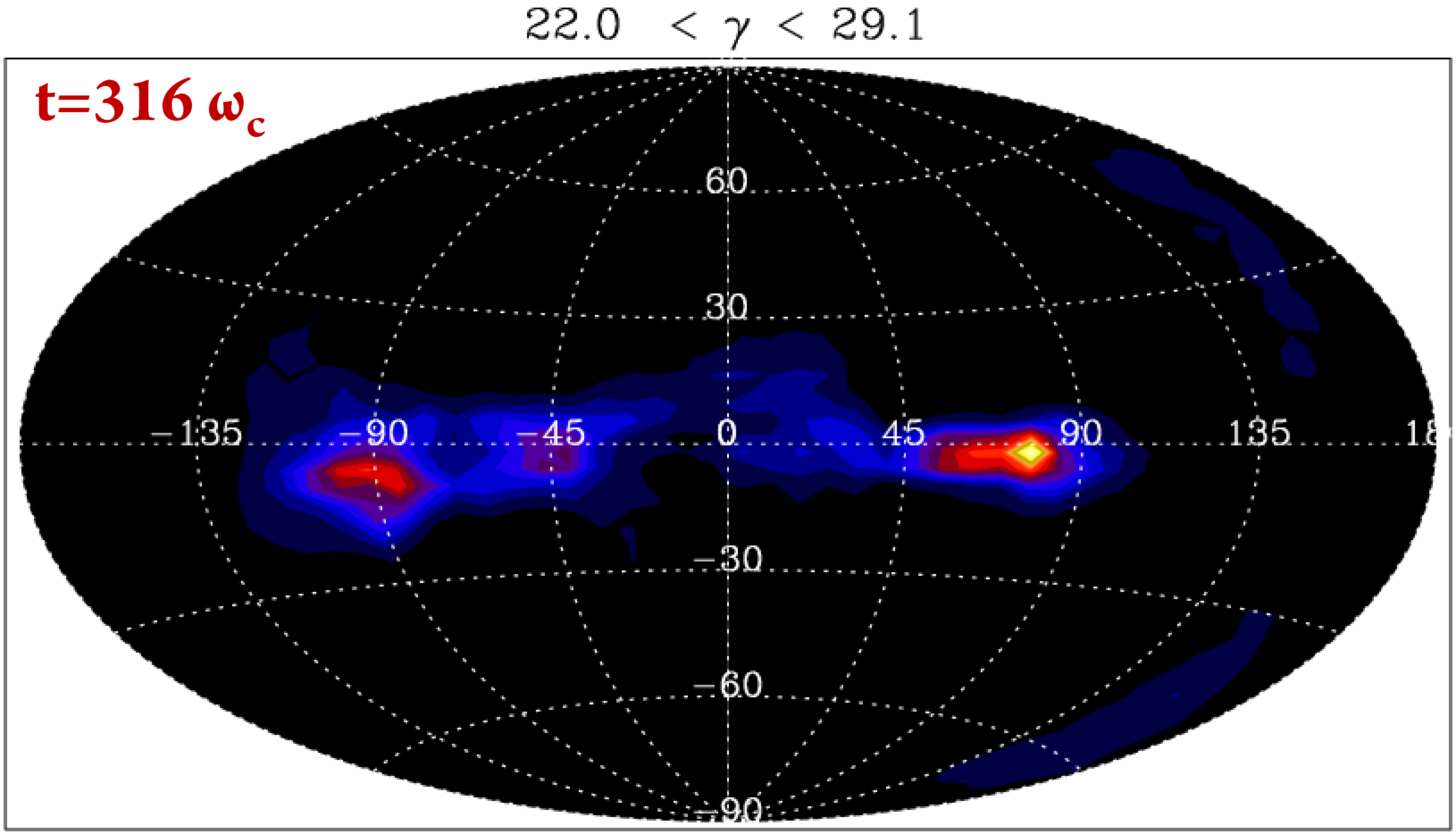
Energy-resolved angular distribution



$\boxed{\Omega_{50\%}/4\pi = 0.19}$

B. Cerutti

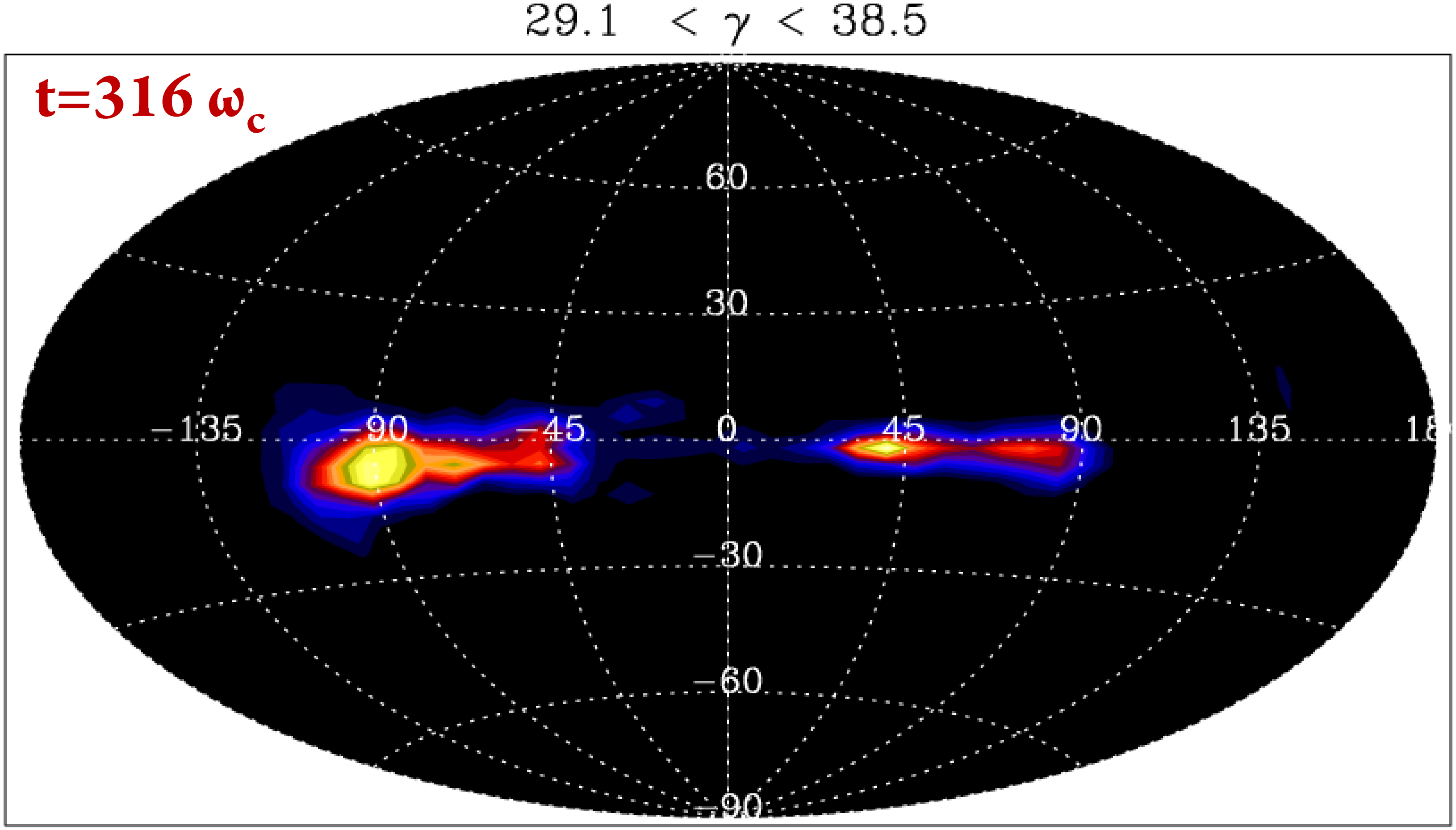
Energy-resolved angular distribution



$$\boxed{\Omega_{50\%}/4\pi = 0.07}$$

B. Cerutti

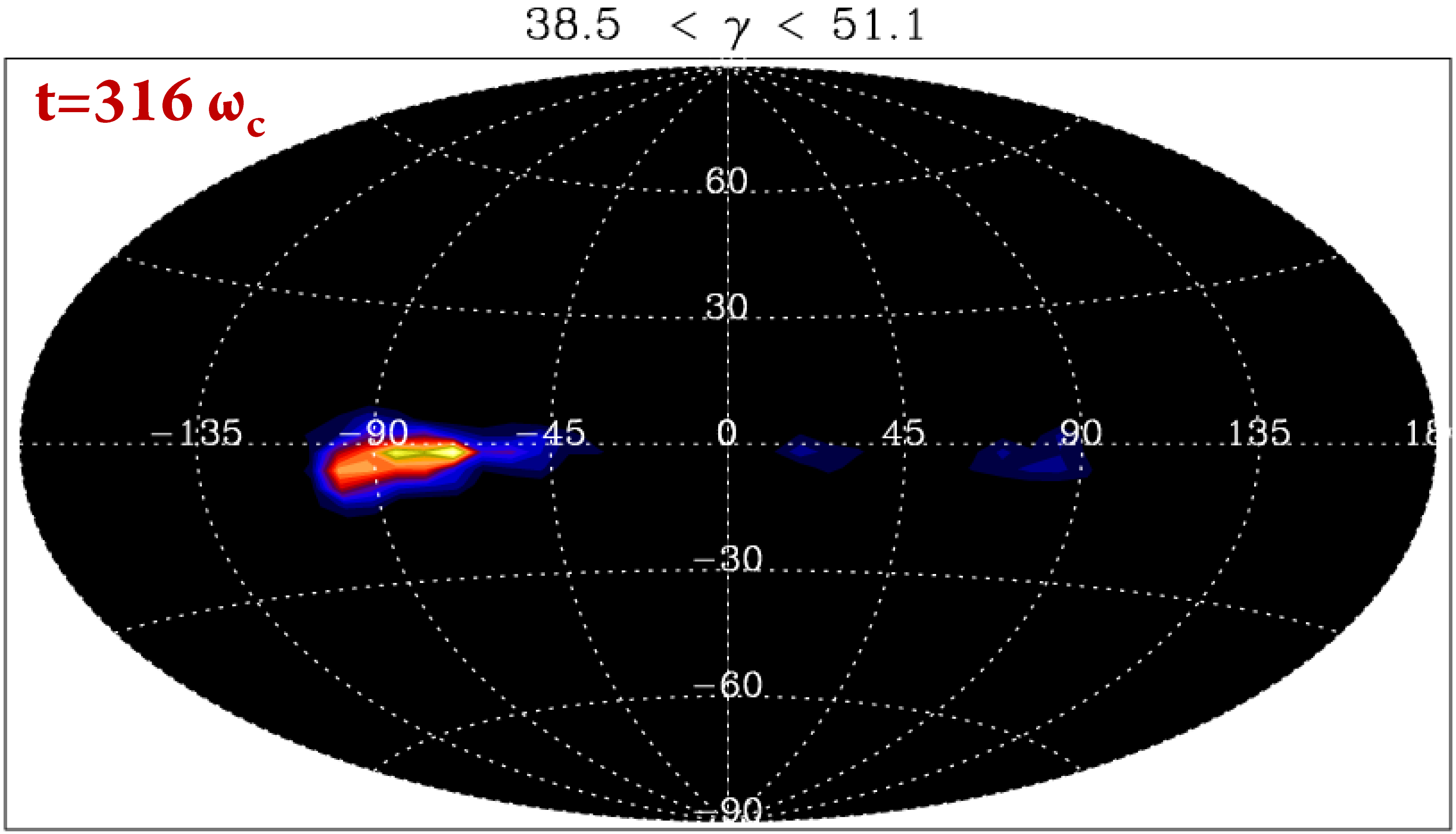
Energy-resolved angular distribution



$\Omega_{50\%}/4\pi = 0.02$

B. Cerutti

Energy-resolved angular distribution

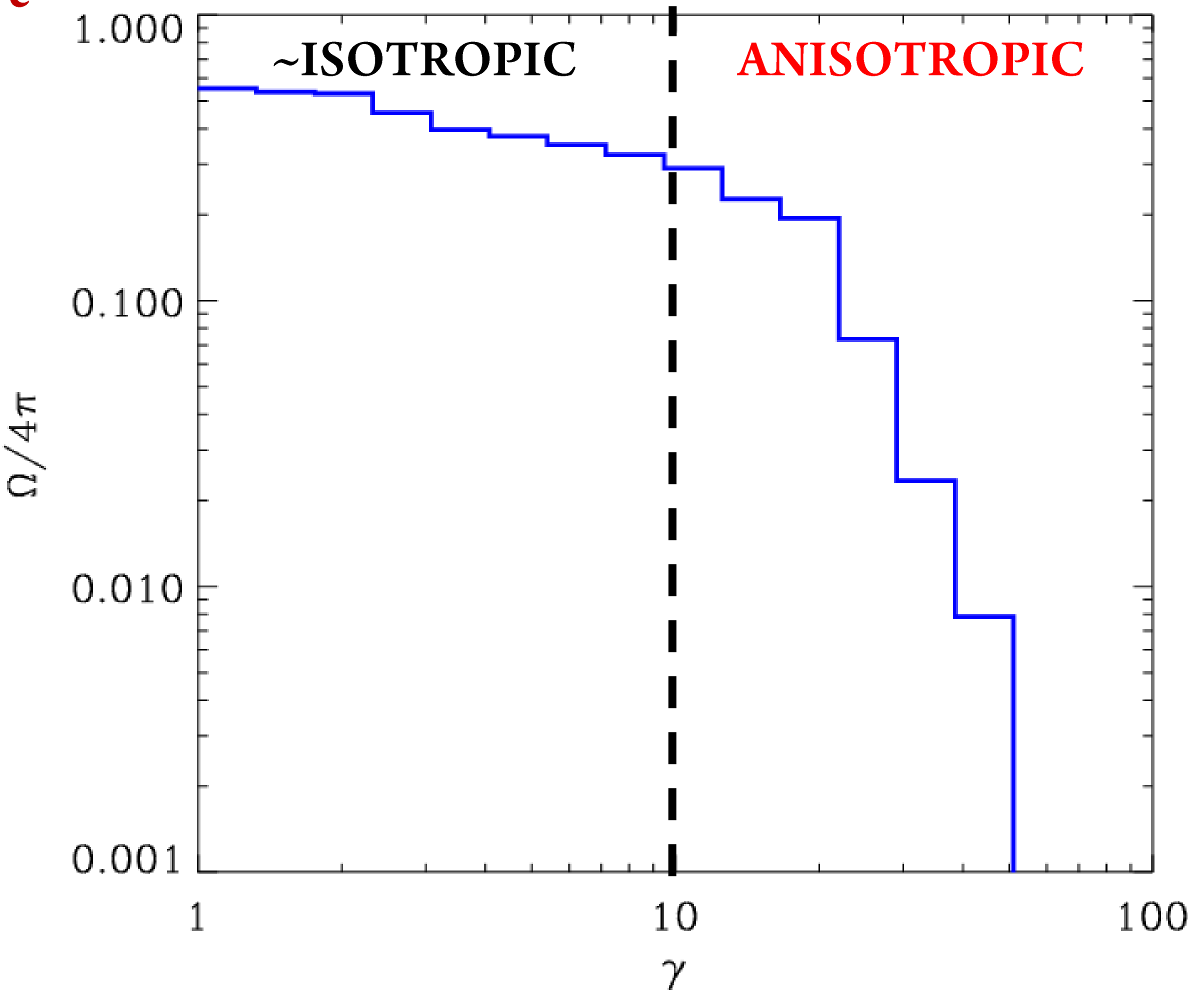


$$\boxed{\Omega_{50\%}/4\pi = 0.01}$$

B. Cerutti

The particle distribution is highly anisotropic at high energies

$t=316\ \omega_c$



[Cerutti et al., in preparation, 2012]

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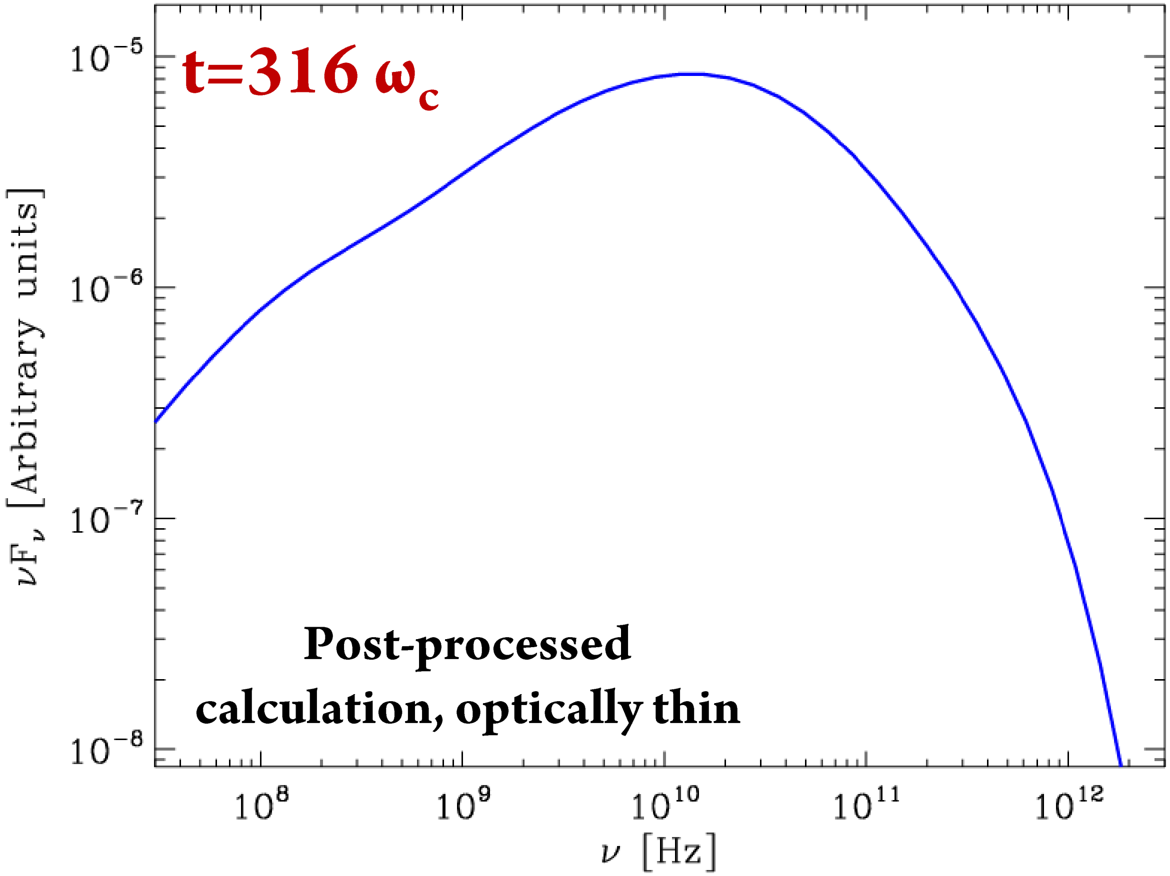
Resulting synchrotron radiation spectral energy distribution

Flux of a single particle: f_ν=function(γ, B, pitch angle α)

Synchrotron critical frequency: $\nu_c=(3eB\gamma^2\sin\alpha)/(4\pi mc)$



Post-processed calculation, optically thin

The radiation reaction force is not included, but unimportant as these energies.

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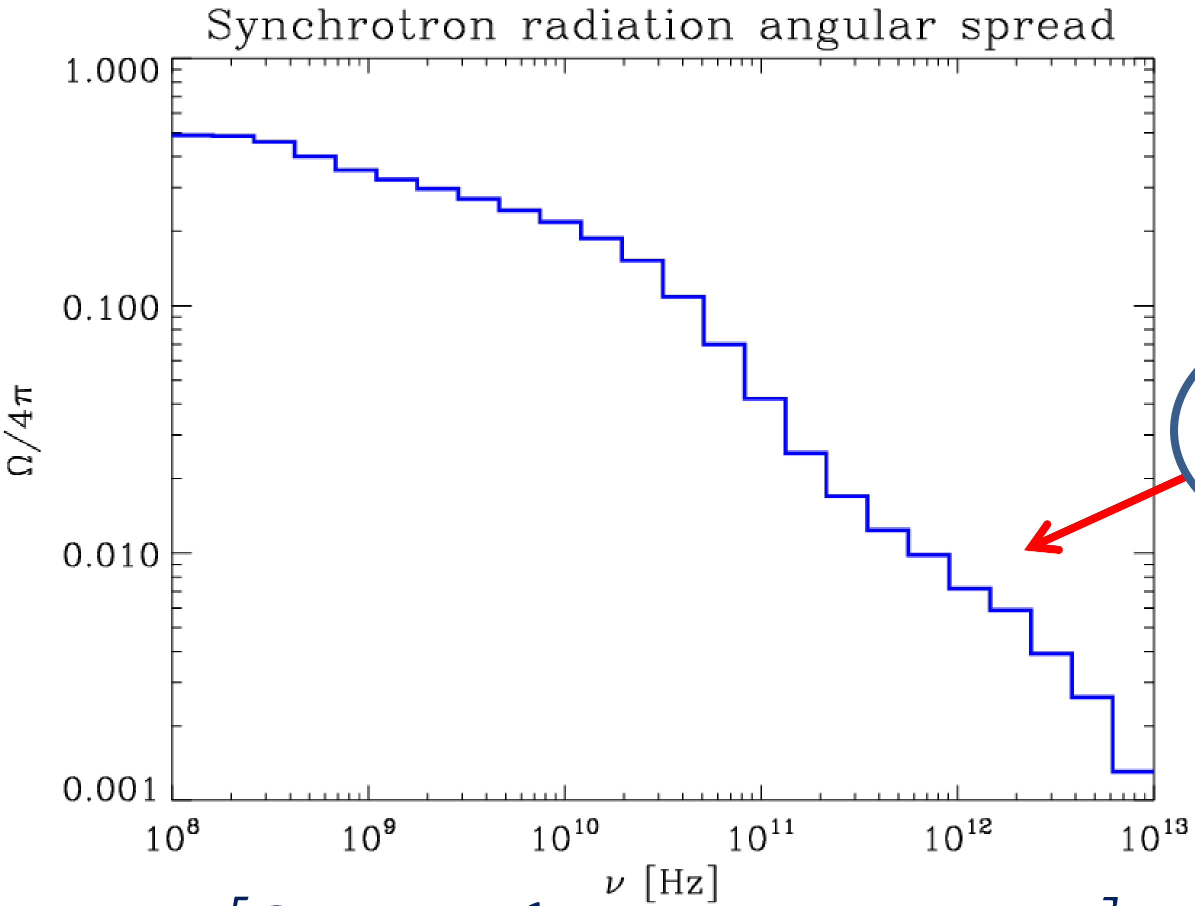
Synchrotron radiation emitted by the most energetic particles is highly anisotropic

Assumption:

Photons are emitted in the same direction as the particles (good for γ_e>>1)



Synchrotron beam!

[Cerutti et al., in preparation, 2012]

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Summary II and future directions

2D pair plasma PIC simulations reveal a strong anisotropy of the highest energy particles accelerated in the layer.

➔Important radiative signature: highest energy photons beamed (different from relativistic Doppler beaming)

Application to flaring objects: e.g. AGN, Crab Nebula, where the apparent isotropic luminosity can challenge the energetic constraints

Futures simulations:

- 3D with guide field. Effect of the kink instability on anisotropy?

- Test extreme particle acceleration mechanism. Need for higher energy particles and radiation reaction force in VORPAL