Particle acceleration in reconnection sites

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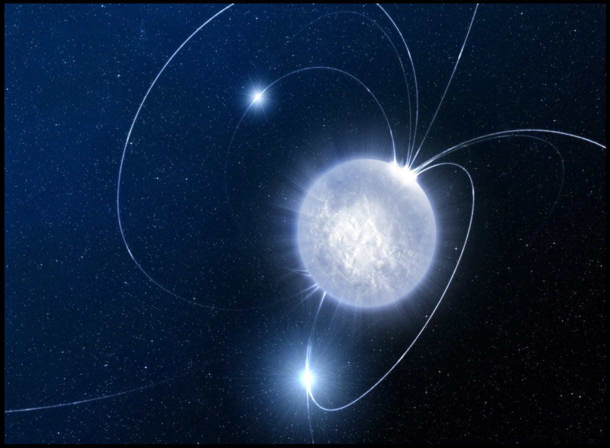
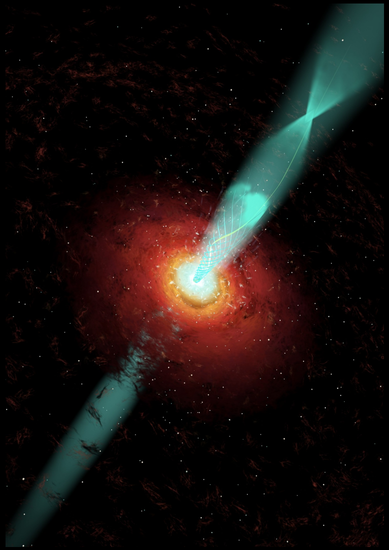
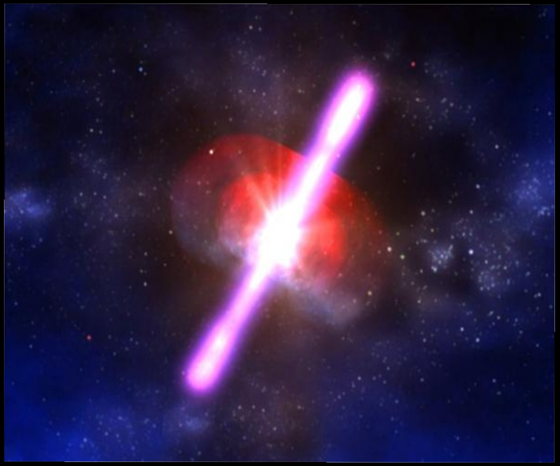


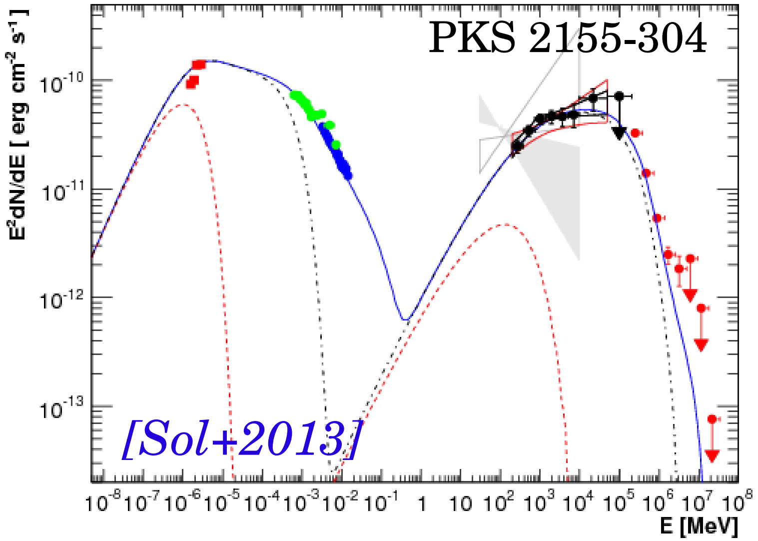




From laboratories to astrophysics: the expanding universe of plasma physics, May 1-12 2017, Les Houches.

Broad non-thermal distributions

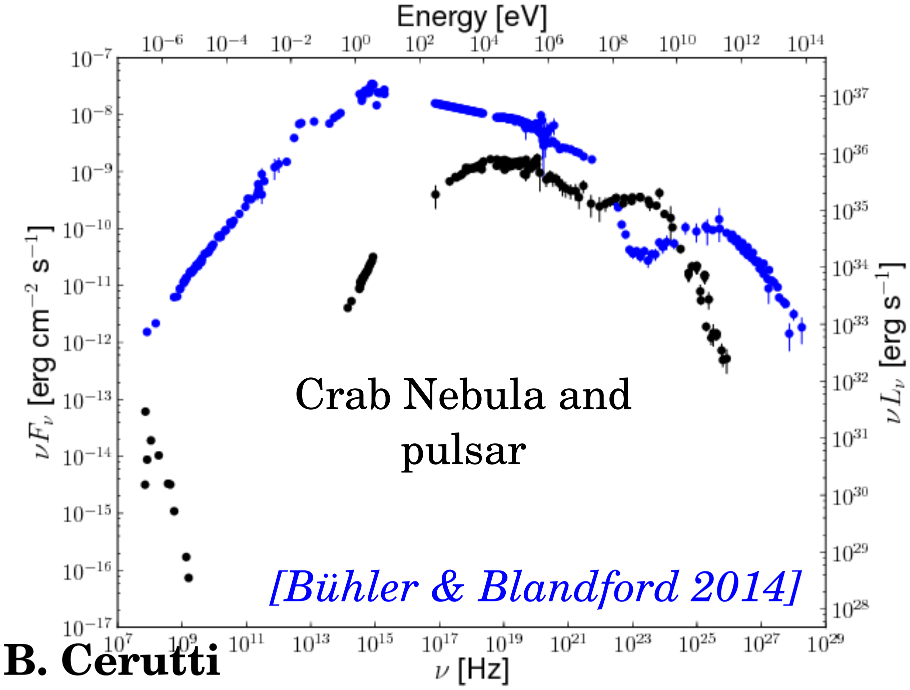
Blazars



PKS 2155-304

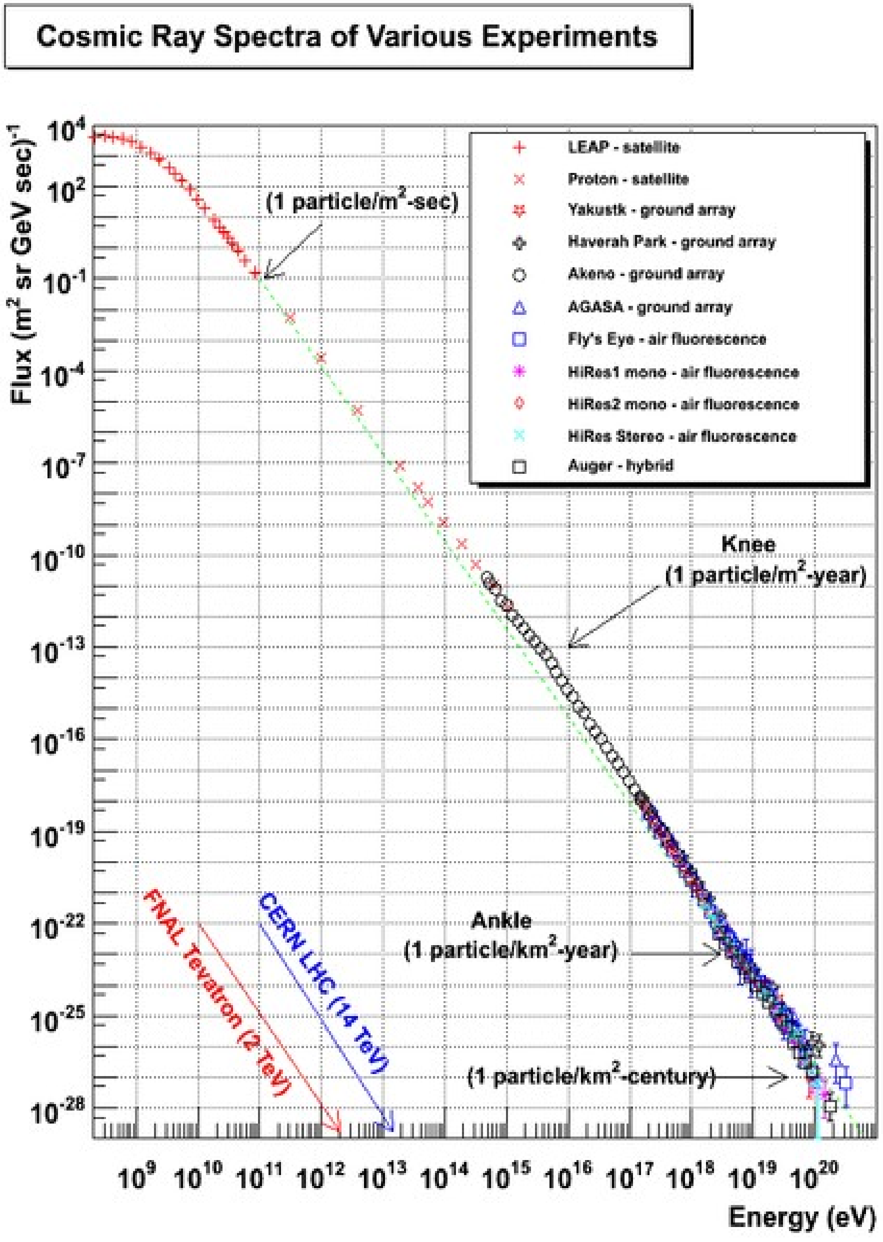
[Sol+2013]

Pulsars & Pulsar Wind Nebulae



Crab Nebula and pulsar

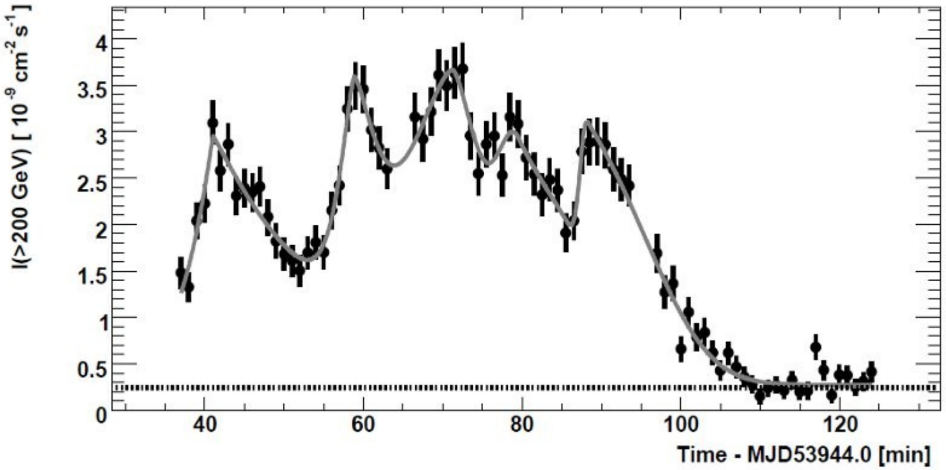
[Bühler & Blandford 2014]



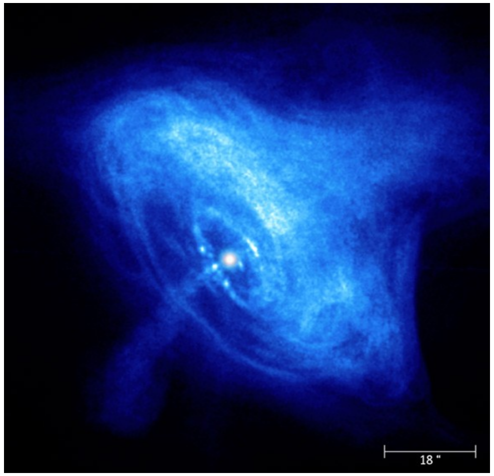
[http://www.physics.utah.edu/~whanlon/spectrum.html]

Diffuse shock acceleration cannot explain :

Ultra-rapid time variability
Too slow !

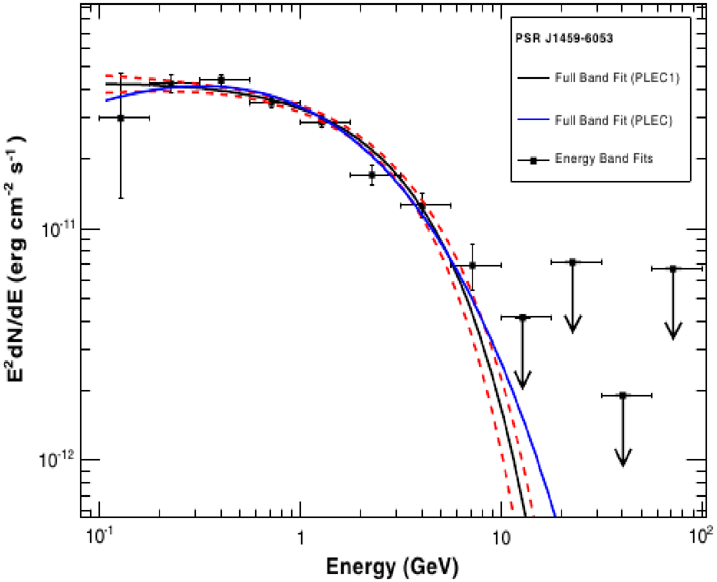


Aharonian et al. 2007 (H.E.S.S. Collaboration)



Particle acceleration at ultra-relativistic
… and magnetized shock.

Hard particle spectra
$p<2$



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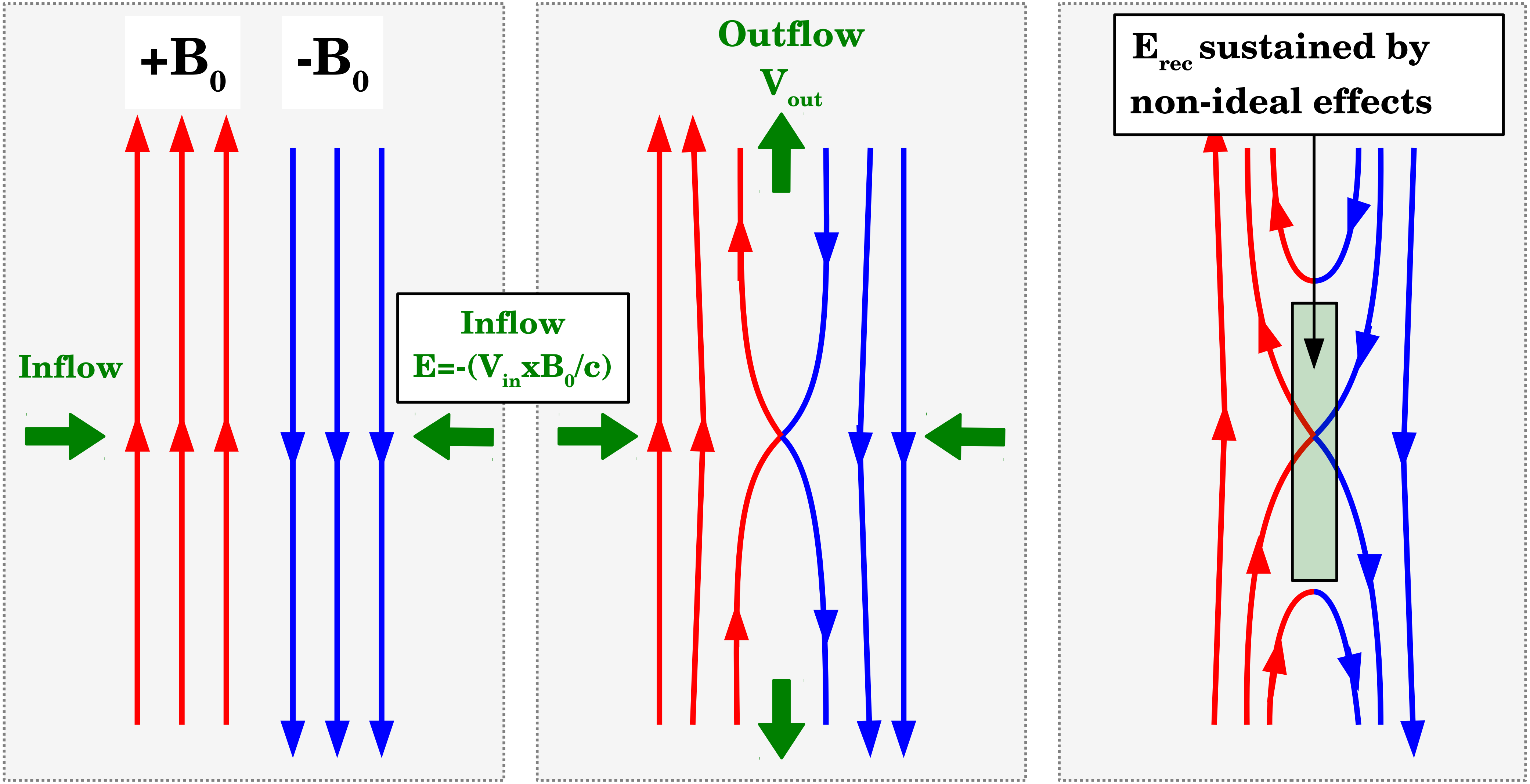
I. Relativistic reconnection

Collisionless magnetic reconnection

[See reviews by Zweibel & Yamada, 2009, Yamada 2010, Kagan et al. 2015]



Inflow
$E=-(V_{in} x B_0/c)$

E_{rec} sustained by non-ideal effects

Reconnection rate: $\beta_{rec}=V_{in}/V_{out}$

Magnetic energy =► Plasma kinetic energy (heating+non-thermal particles)

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Relativistic collisionless reconnection

Upstream plasma magnetization parameter :

$$\boxed{\sigma = \frac{B_0^2}{4\pi(nmc^2 + P)}}$$

If **σ>>1**, magnetic energy density **exceeds** the rest mass energy density (and pressure) of the plasma. *[Blackman & Field 1994 ; Lyutikov & Uzdensky 2003 ; Lyubarsky 2005]*

The Alfvén speed approaches the speed of light : $V_A = c\sqrt{\frac{\sigma}{1+\sigma}} \approx c$

Dissipation of magnetic energy => relativistic particles !

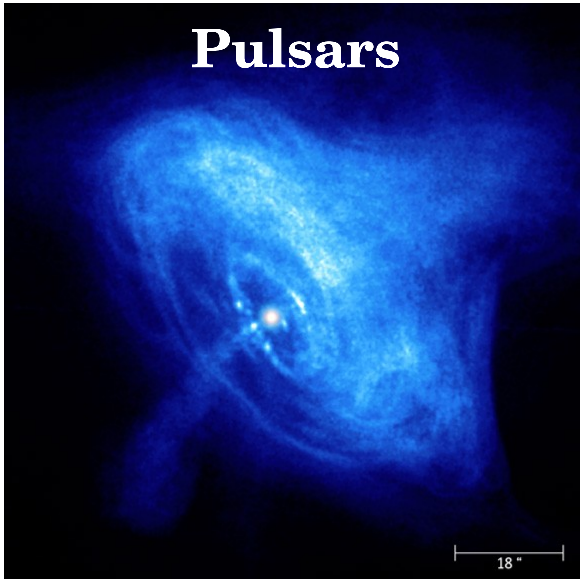
Focus on :

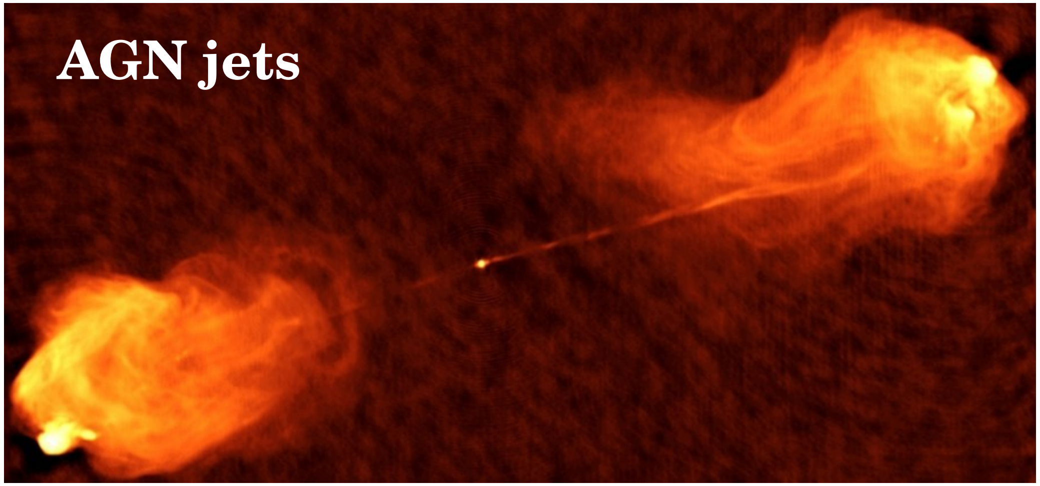
- Relativistic **electron/positron pair** plasmas : no mass ratio effects, i.e., no Hall effect. Also relevant to **ultra-relativistic electron/ion plasmas**

- **Collisionless plasmas :** Mean free path >> system size

- **Optically thin**

Relevant astrophysical environments



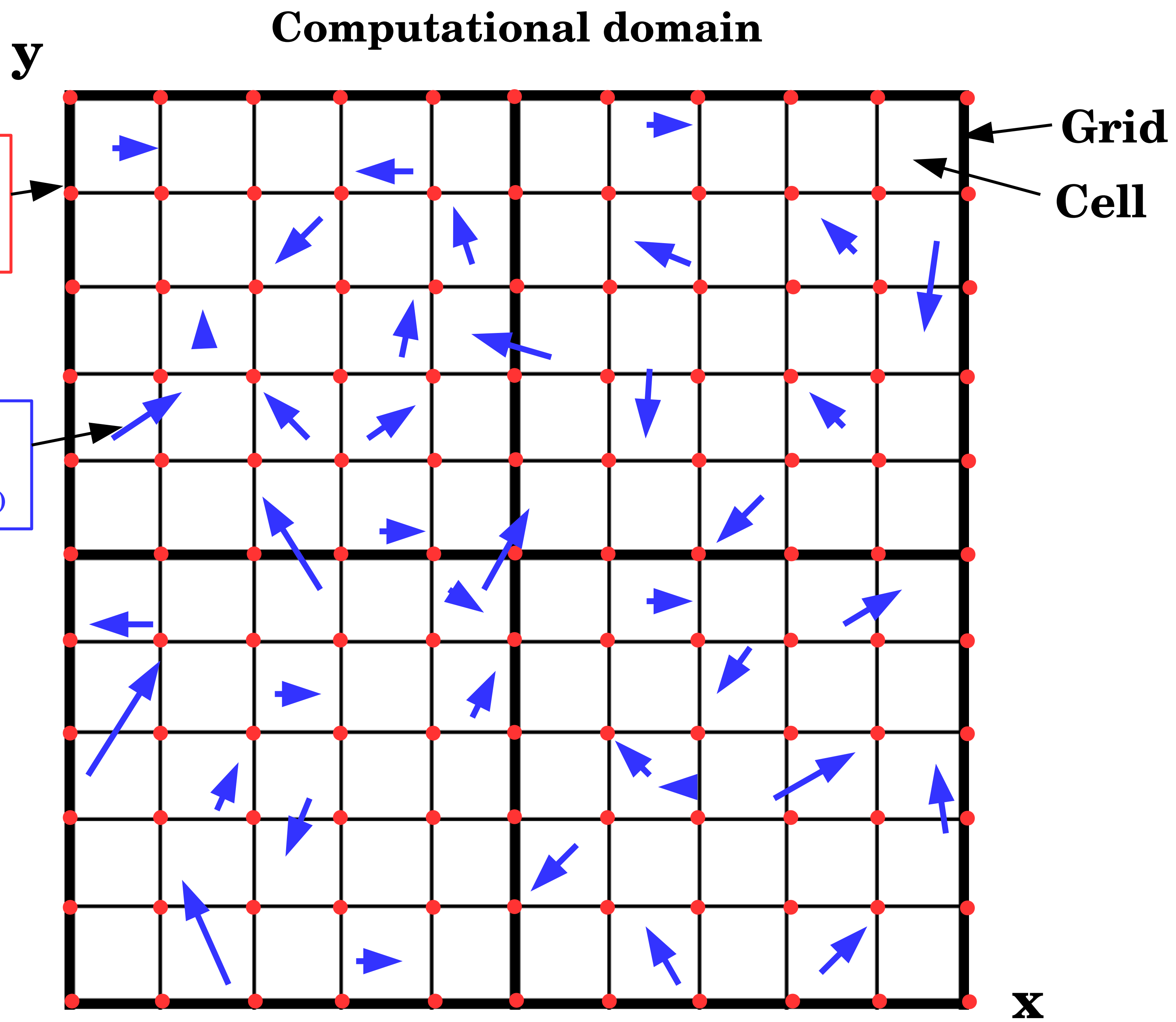


Questions :

- **How fast is reconnection ?**
- **How is the magnetic energy transferred to particles ?**
- **How are the particles accelerated and what is the spectrum ?**
- **What are the radiative signatures ? Photon spectra, lightcurves…**
- **Where does reconnection operate in astrophysical systems ?**

Reconnection dynamics

The Particle-In-Cell (PIC) approach


Computational domain

y

x

Grid

Cell

(E,B) fields known
on the grid
(Eulerian approach)

Particles evolve in
continuous space
(Lagrangian approach)

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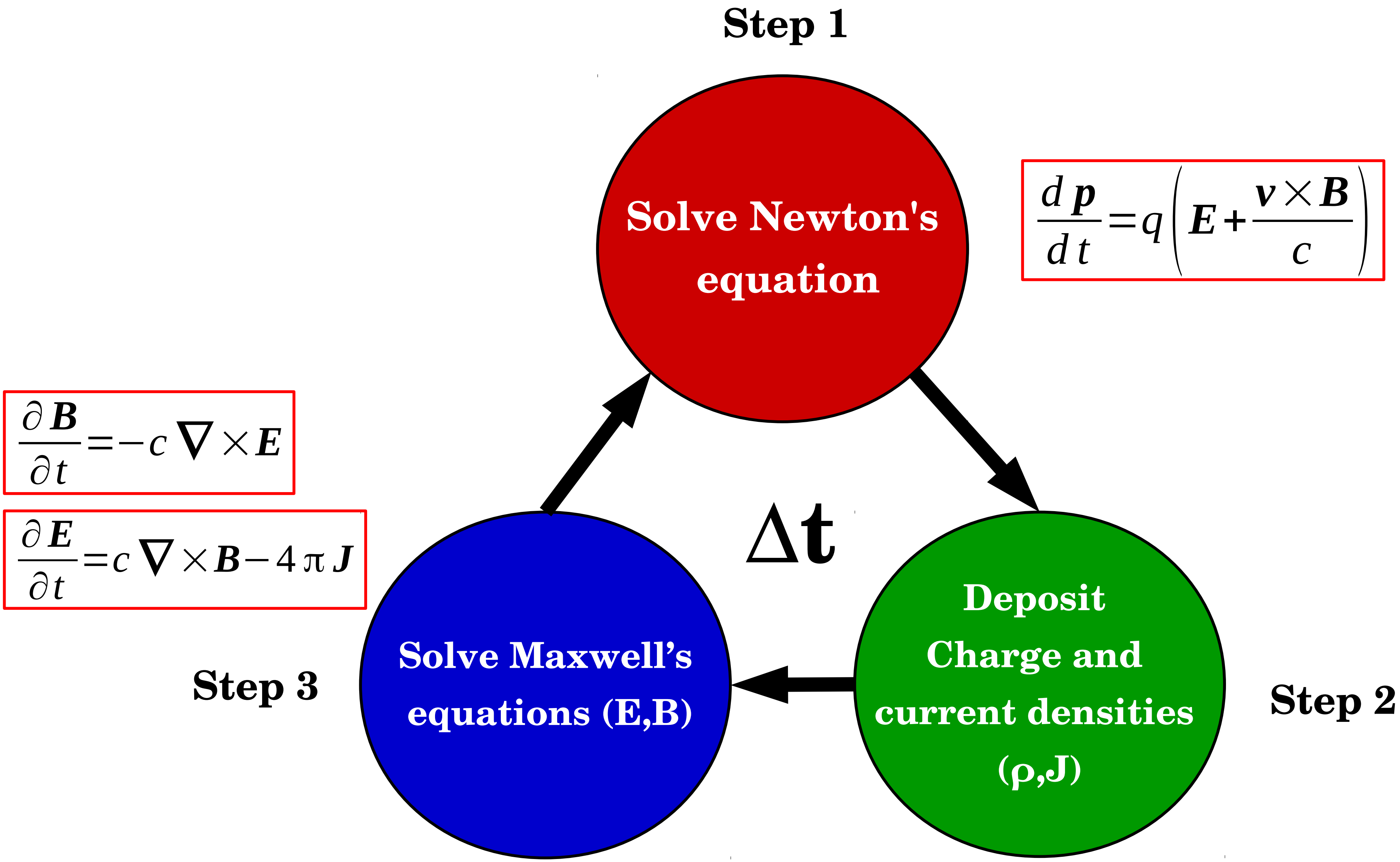
Computation procedure per timestep in PIC



Step 1

Solve Newton's equation

$$\frac{d\boldsymbol{p}}{dt} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}}{c}\right)$$

Step 2

Deposit Charge and current densities (ρ,J)

Step 3

Solve Maxwell's equations (E,B)

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\nabla \times \boldsymbol{E}$$

$$\frac{\partial \boldsymbol{E}}{\partial t} = c\nabla \times \boldsymbol{B} - 4\pi \boldsymbol{J}$$

Δt

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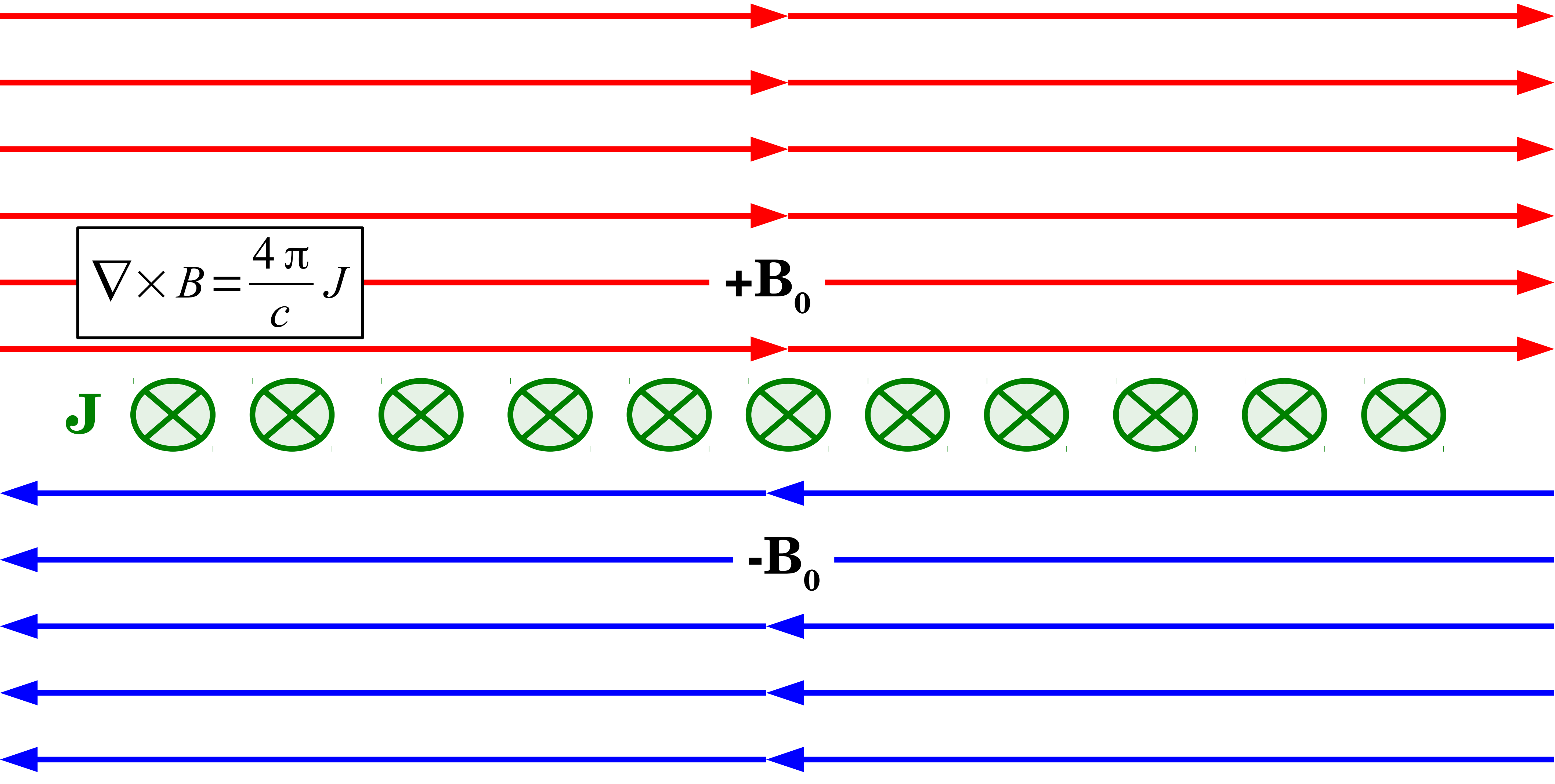
Numerical setup : Harris sheet

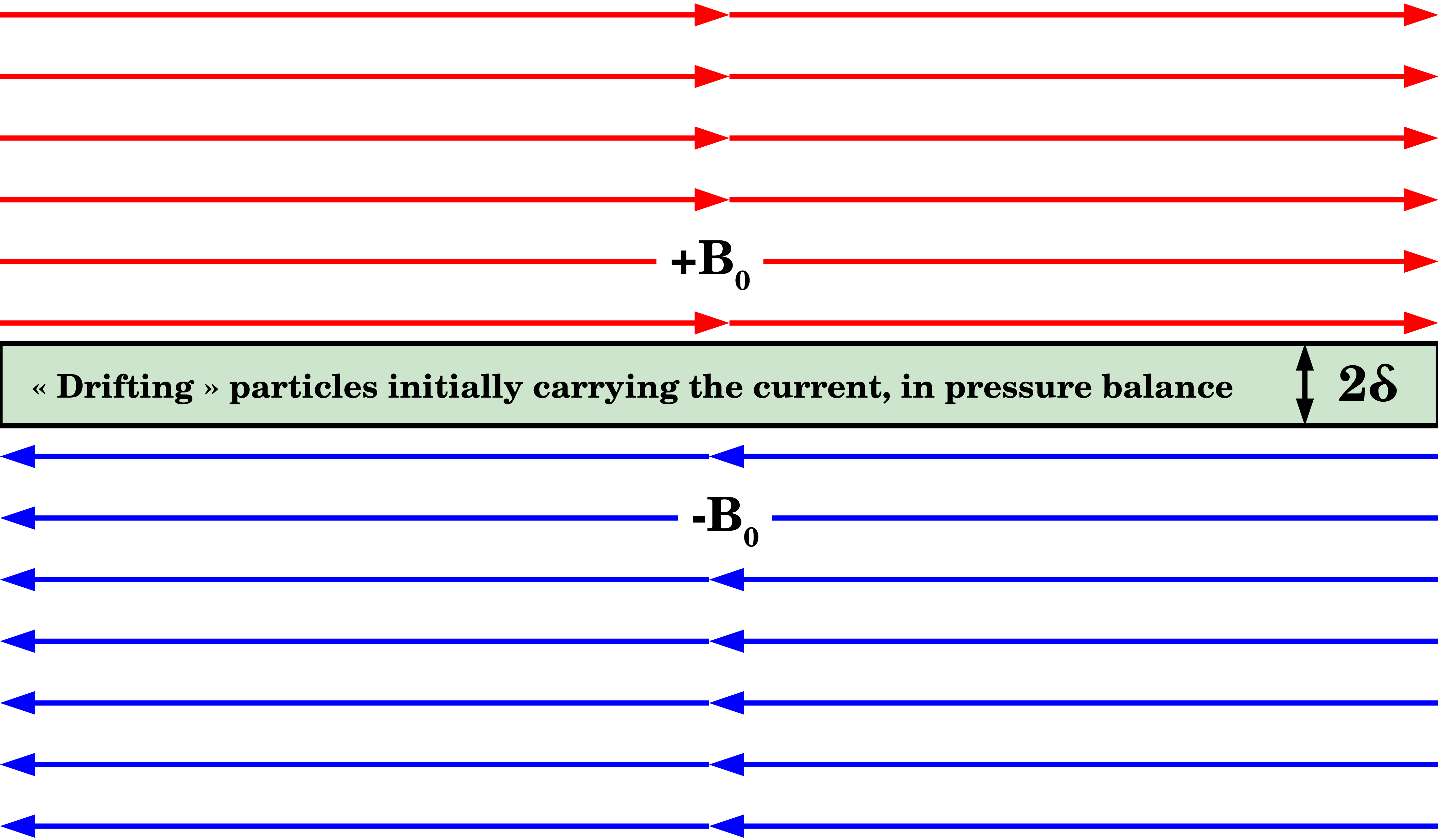


$$\nabla \times B = \frac{4\pi}{c} J$$

Other setup investiagted :

- « **Force-Free** » current sheet (e.g., *Guo et al. 2015*)
- « **ABC** » equilibrium setup **see Journal club** (*Nalewajko+2016 ; Lyutikov+2016*)

Numerical setup : Harris sheet



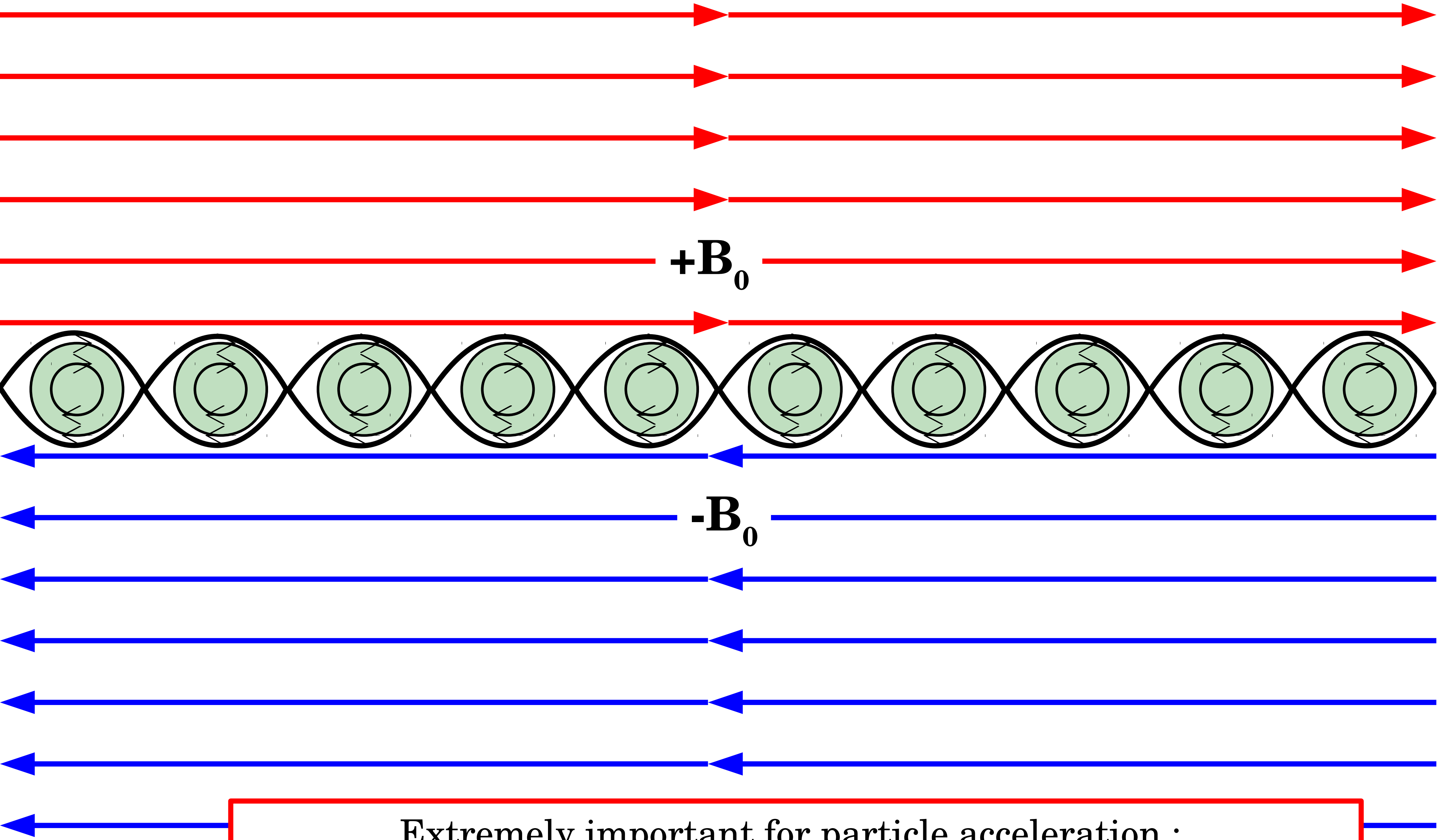
$+B_0$

« **Drifting** » **particles initially carrying the current, in pressure balance** 2δ

$-B_0$

A long thin current sheet is tearing unstable

[Zelenyi & Krasnoselskikh 1979 ; Zenitani & Hoshino (2007) ; Pétri & Kirk 2007]



Extremely important for particle acceleration :
Mediate fast reconnection and non-thermal particle acceleration

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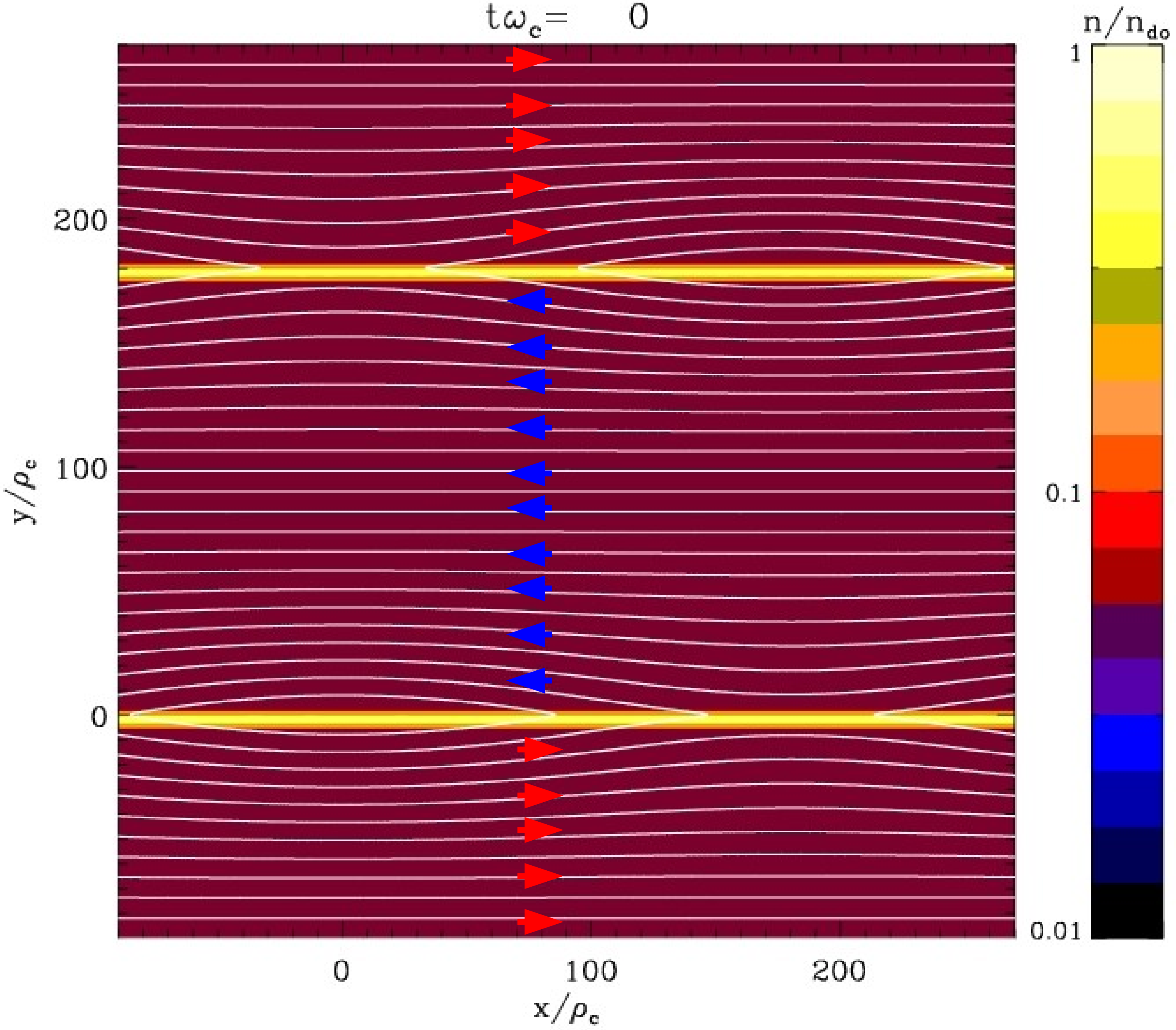
2D PIC simulation



2δ ~ skin depth

Periodic

Periodic

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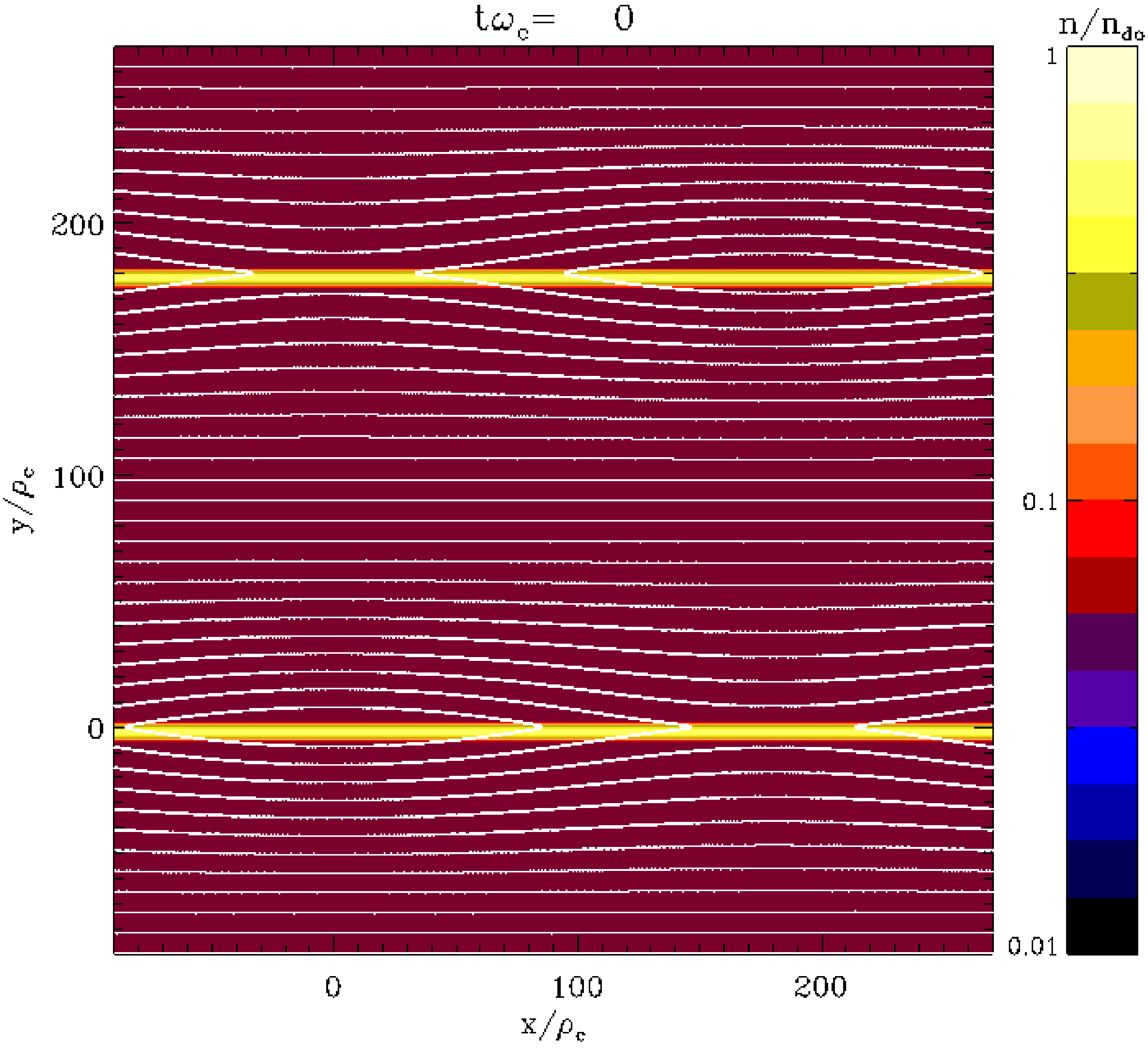
2D PIC simulation



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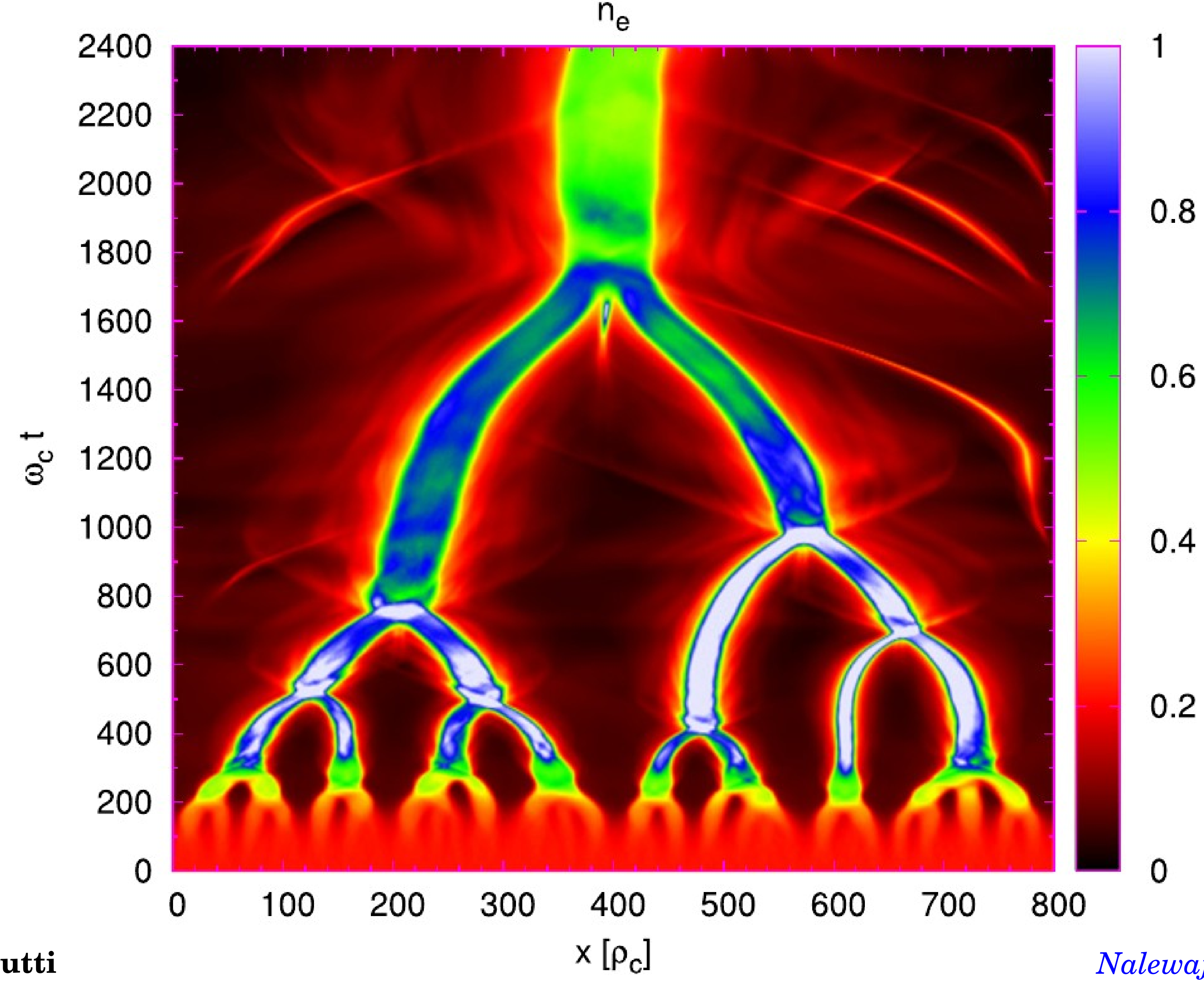
Space-time diagram: Merger tree



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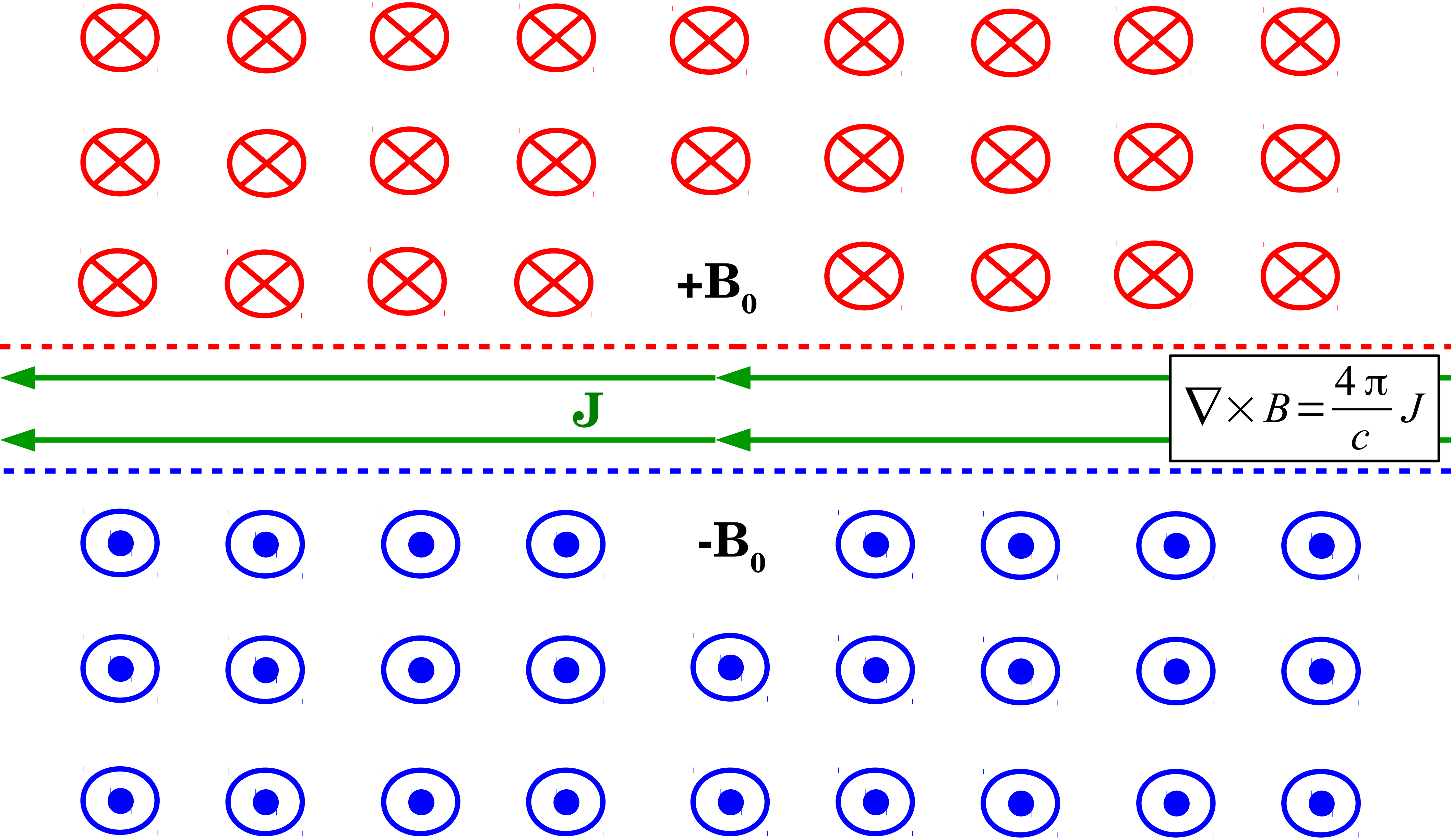
Nalewajko+2015

The sheet is also kink unstable



$$\nabla \times B = \frac{4\pi}{c} J$$

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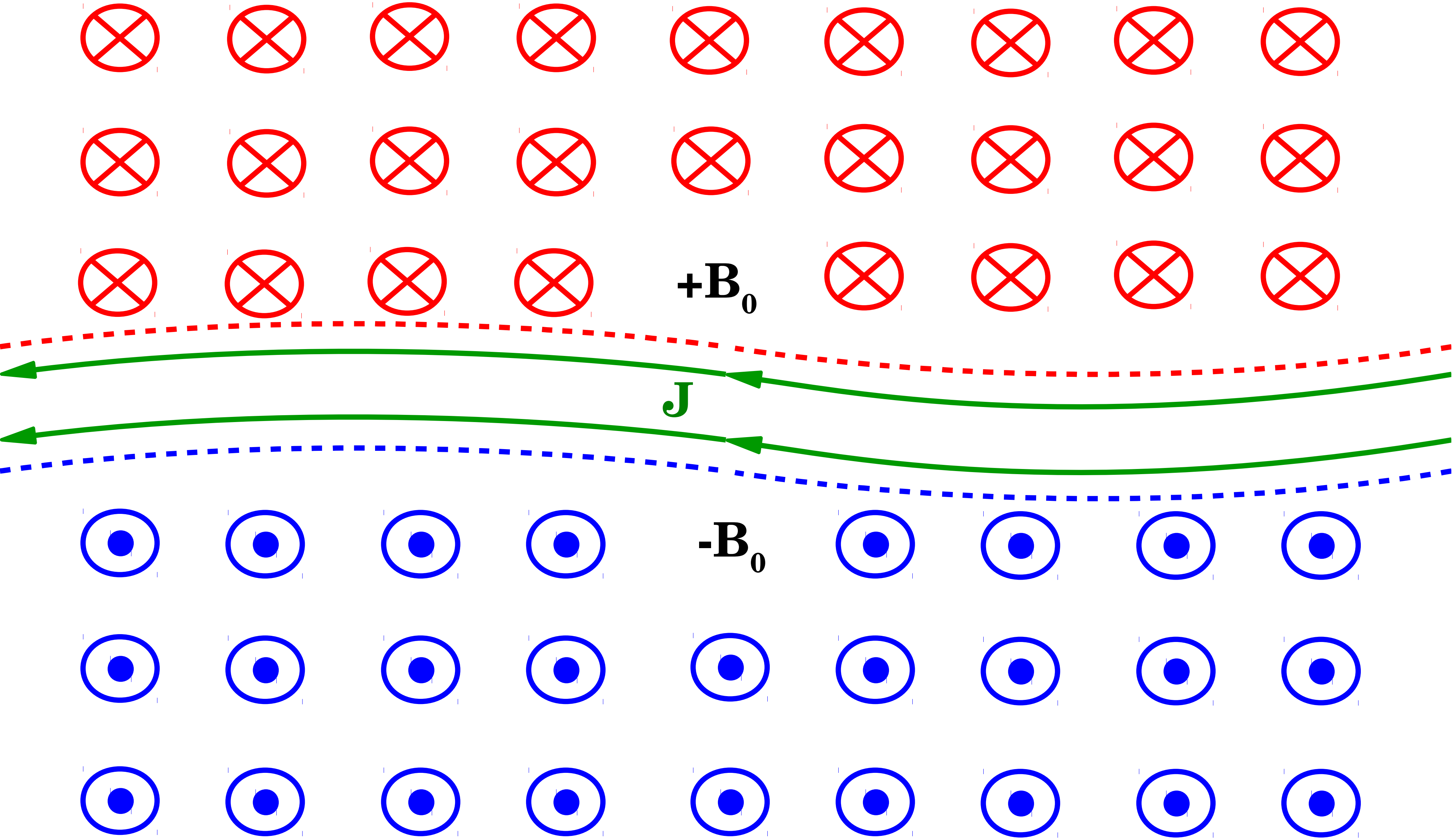
The sheet is also kink unstable



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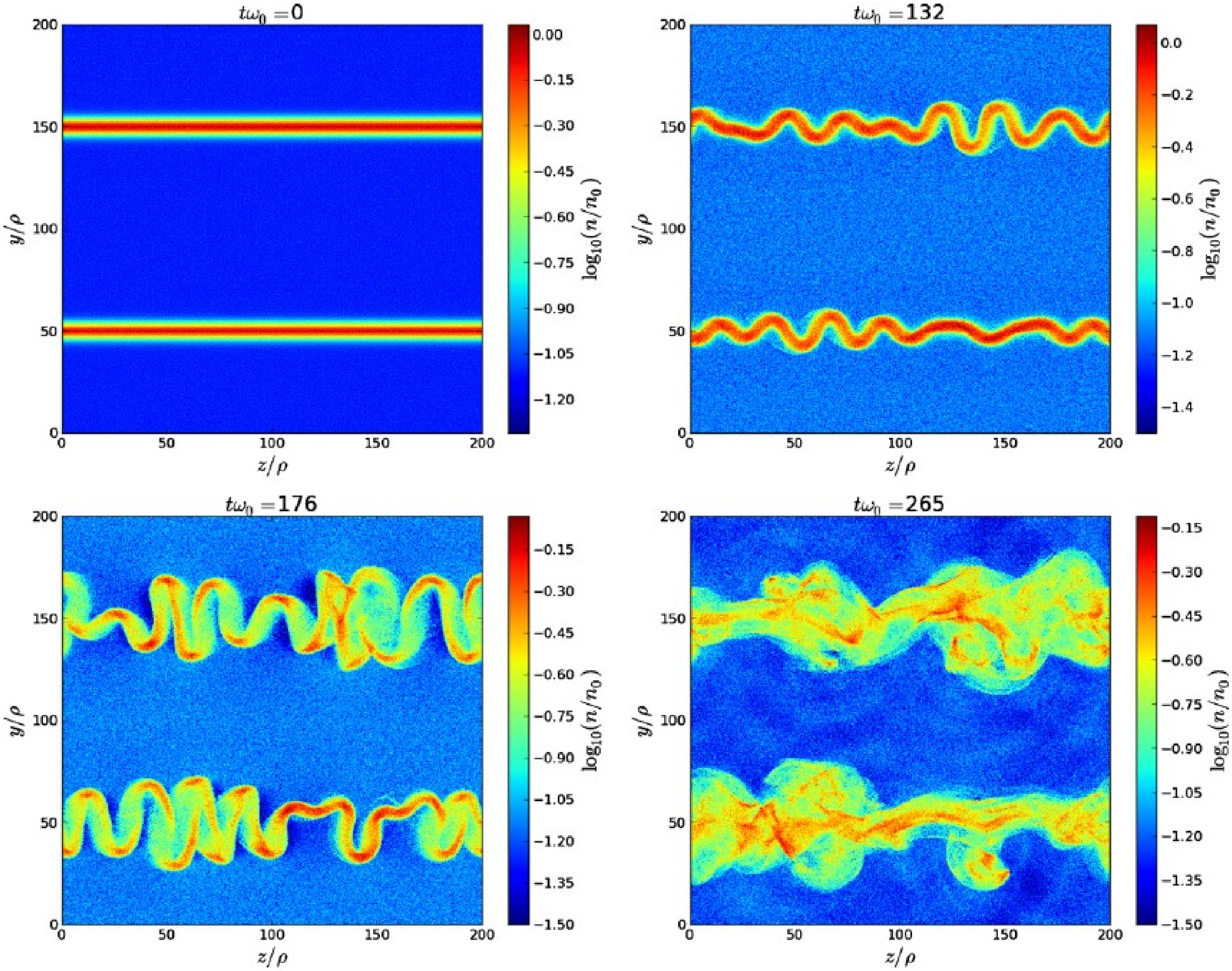
Relativistic drift kink mode

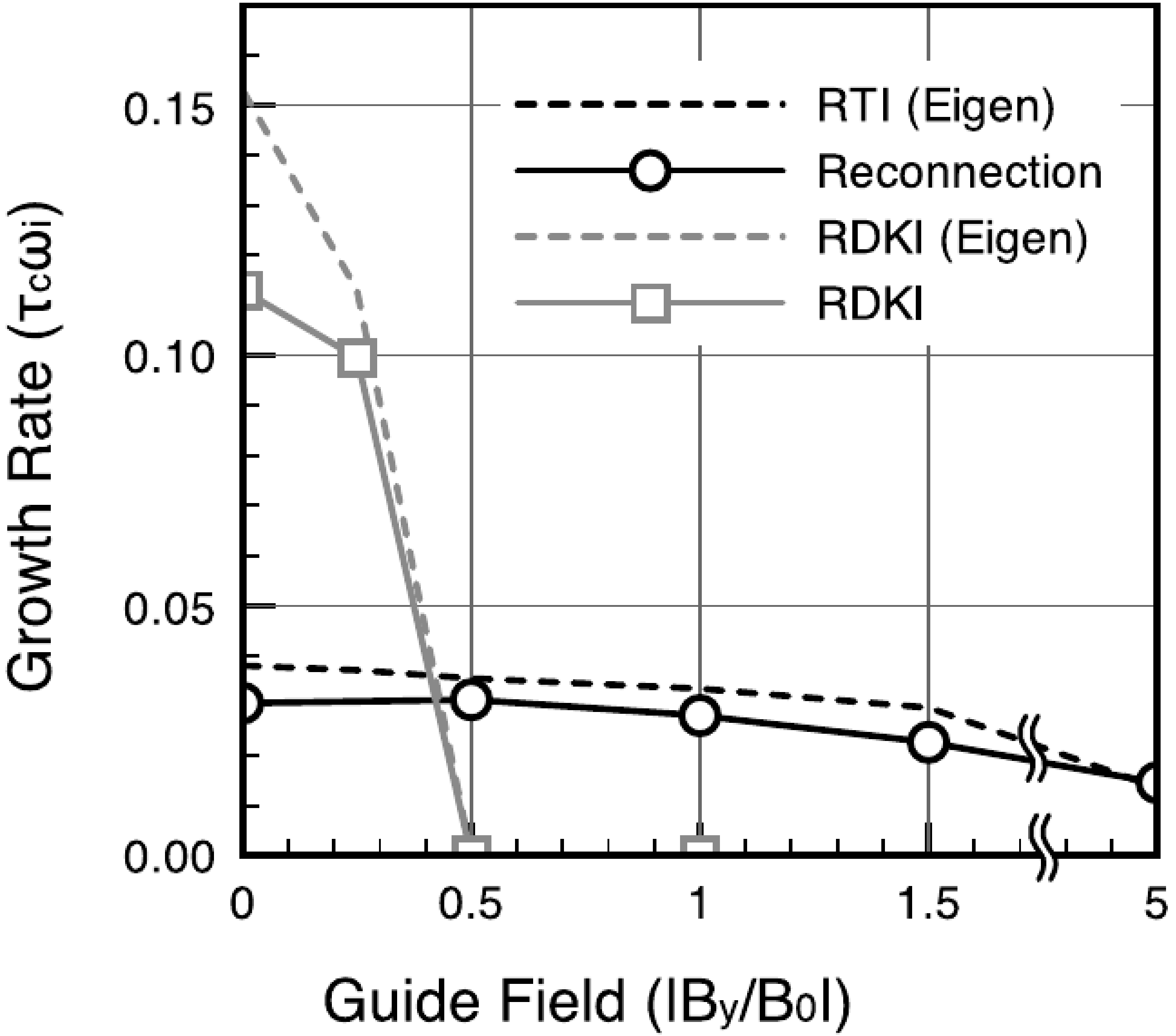
Zenitani & Hoshino 2008 ; Cerutti et al. 2014

Broadens or even **disrupt** the layer



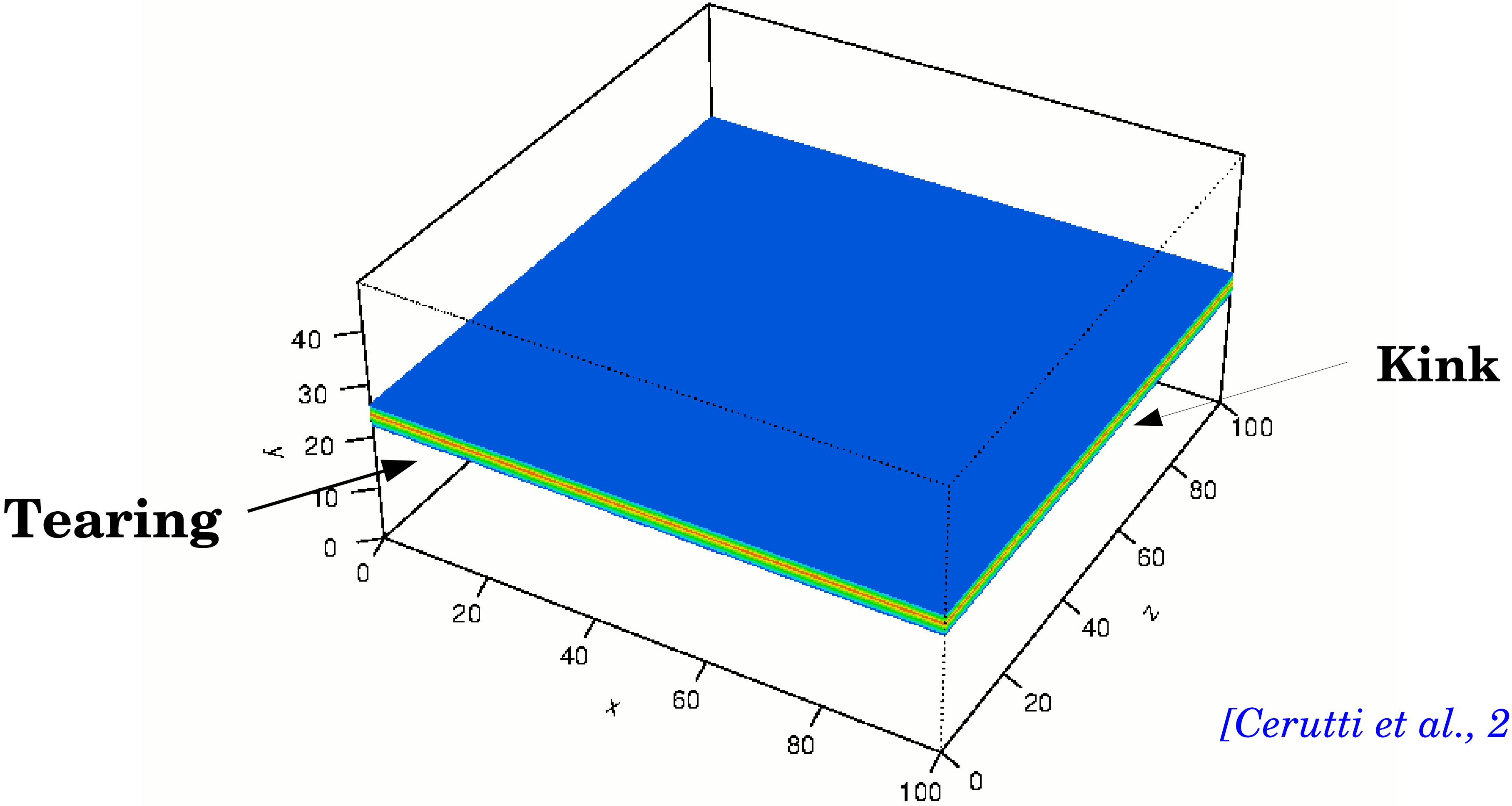
Particle heating, non-thermal **particle acceleration** **quenched.**

Guide field stabilizes the layer against kink



Zenitani & Hoshino (2008)

3D evolution



[Cerutti et al., 2014a]

The kink dominates the early stages of the layer…

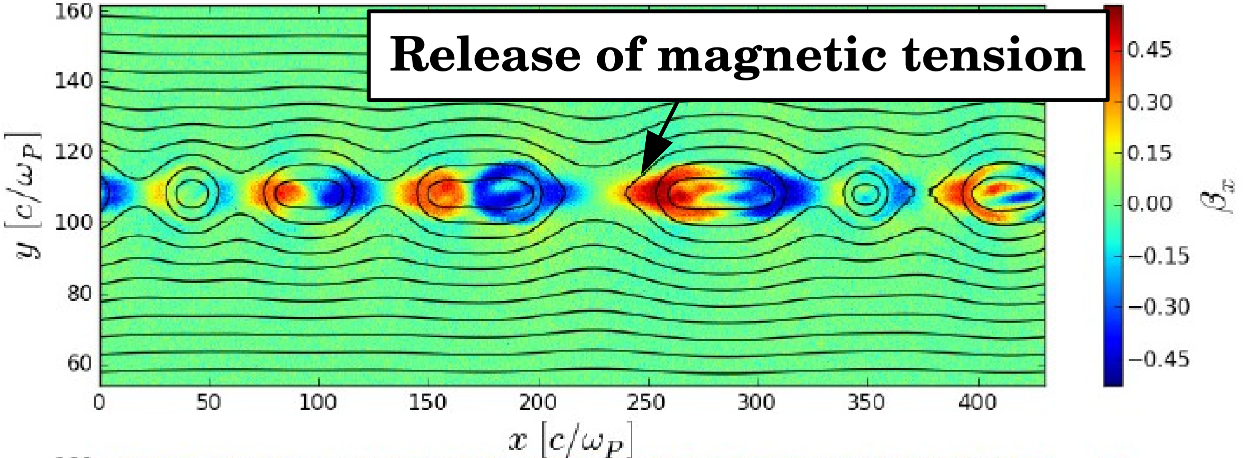
… but the tearing controls the later evolution, so that 3D ≈ 2D !

=> Non-thermal particle acceleration still efficient in 3D without guide field

[Sironi & Spitkovsky 2014]

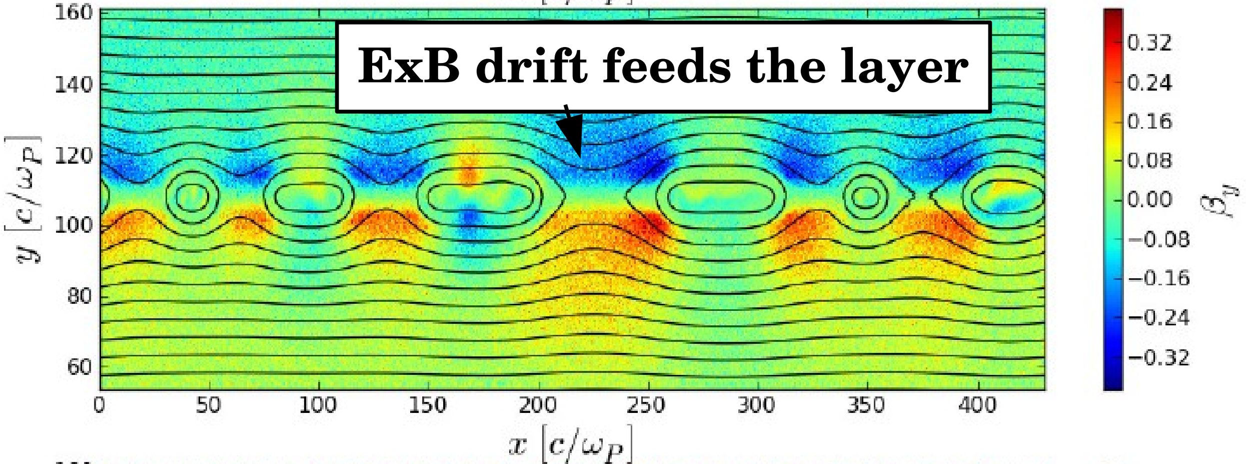
Flow velocity structure

Outflow velocity



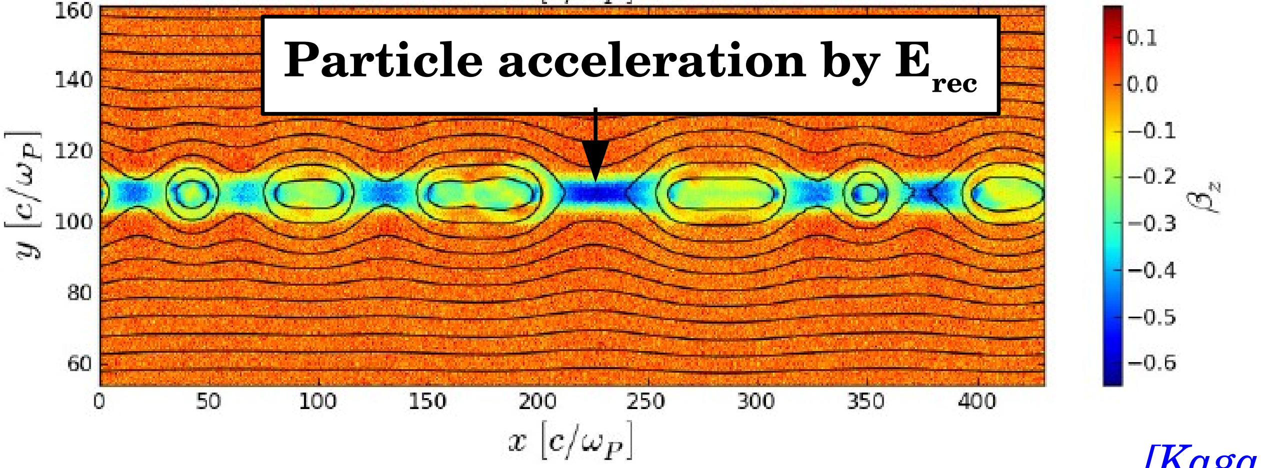
Release of magnetic tension

Inflow velocity



ExB drift feeds the layer

Out-of-plane velocity

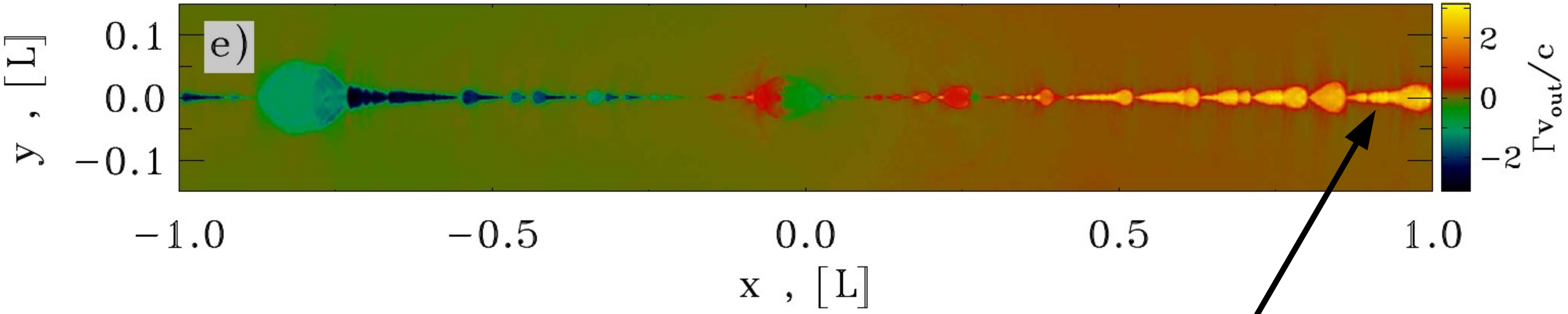


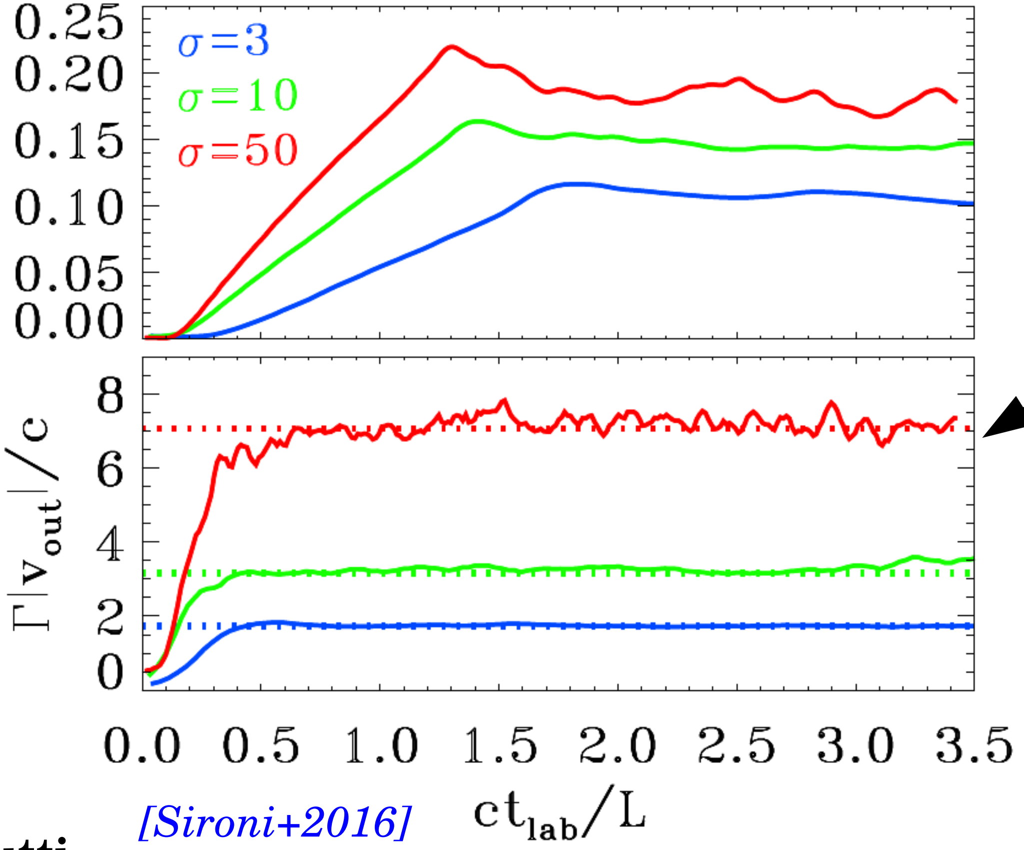
Particle acceleration by $\mathbf{E}_{\mathbf{rec}}$

[Kagan+2015]

Relativistic bulk flows

Large box with open boundaries





[Sironi+2016]

Terminal velocity of reconnection outflow is **ultra-relativistic for σ >>1.**

Scales as the Alfvén speed :

$$\boxed{\frac{V_A}{c}=\sqrt{\frac{\sigma}{\sigma+1}}\rightarrow\Gamma\approx\sqrt{\sigma}}$$

[Lyubarsky 2005]

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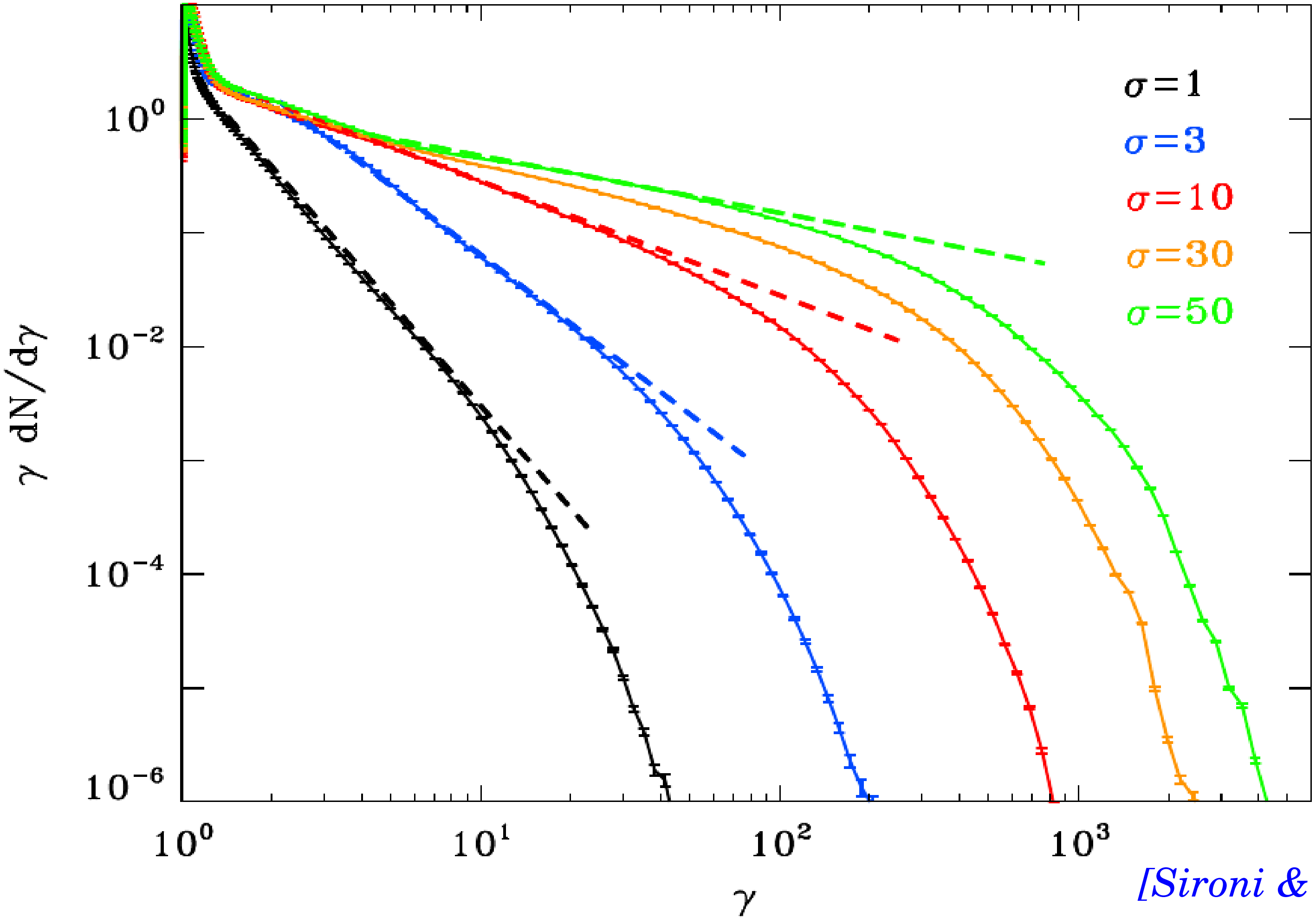
Particle acceleration

Particle acceleration in relativistic reconnection

[Zenitani & Hoshino; Jaroschek et al.; Bessho & Bhattacharjee; Pétri & Lyubarsky; Sironi & Spitkovsky; Liu et al., Cerutti et al.; Kagan et al., Guo et al., Werner et al., ...]



[Sironi & Spitkovsky 2014]

Non-thermal particle acceleration is **efficient for highly magnetized plasmas** (σ>>1), =>Need for **large** computational box and **late** time evolution of the system.

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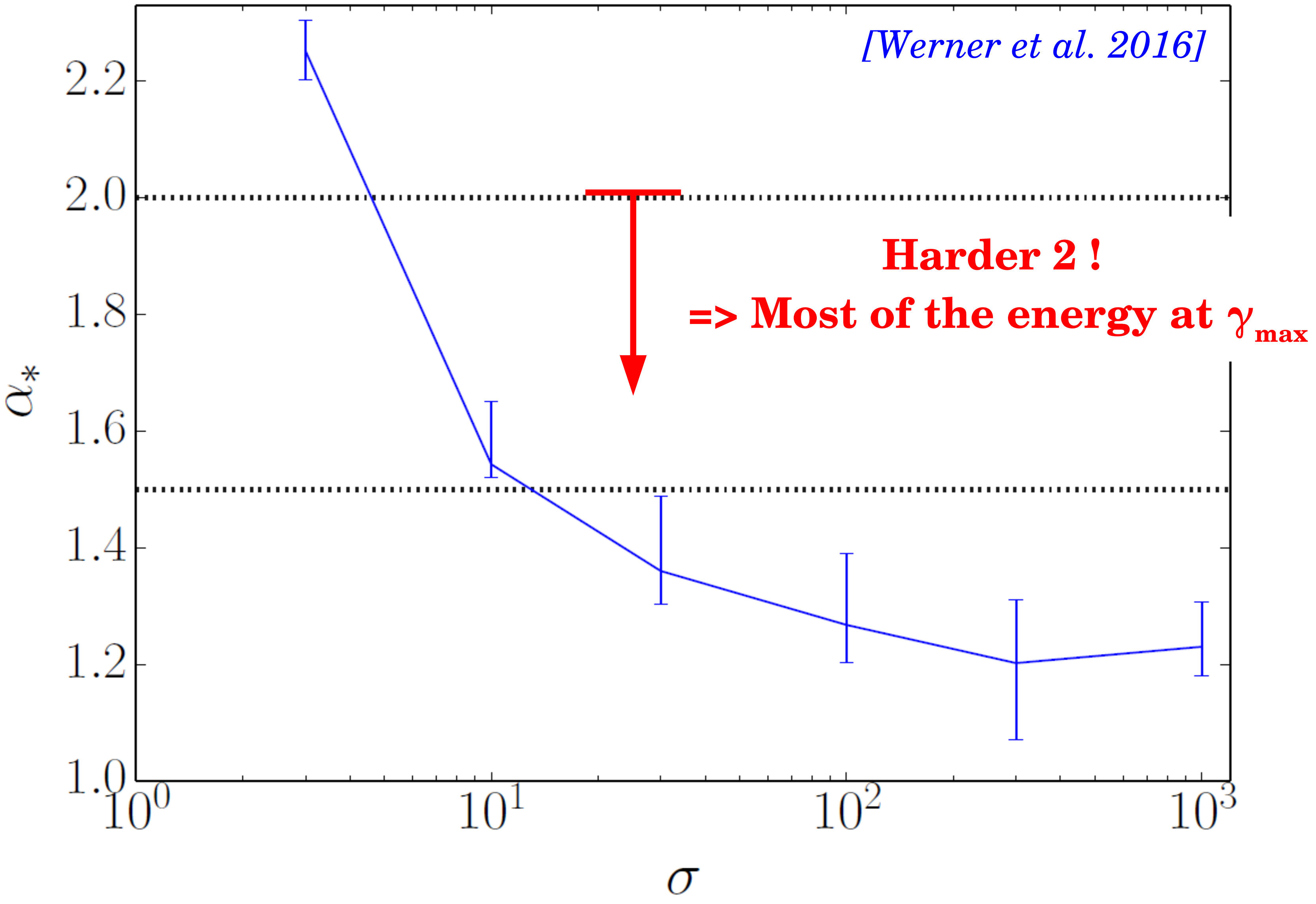
Spectral hardening with sigma



Harder 2 !

=> Most of the energy at γ_{max}

Spectral index converges towards p=1-1.5 at high magnetization

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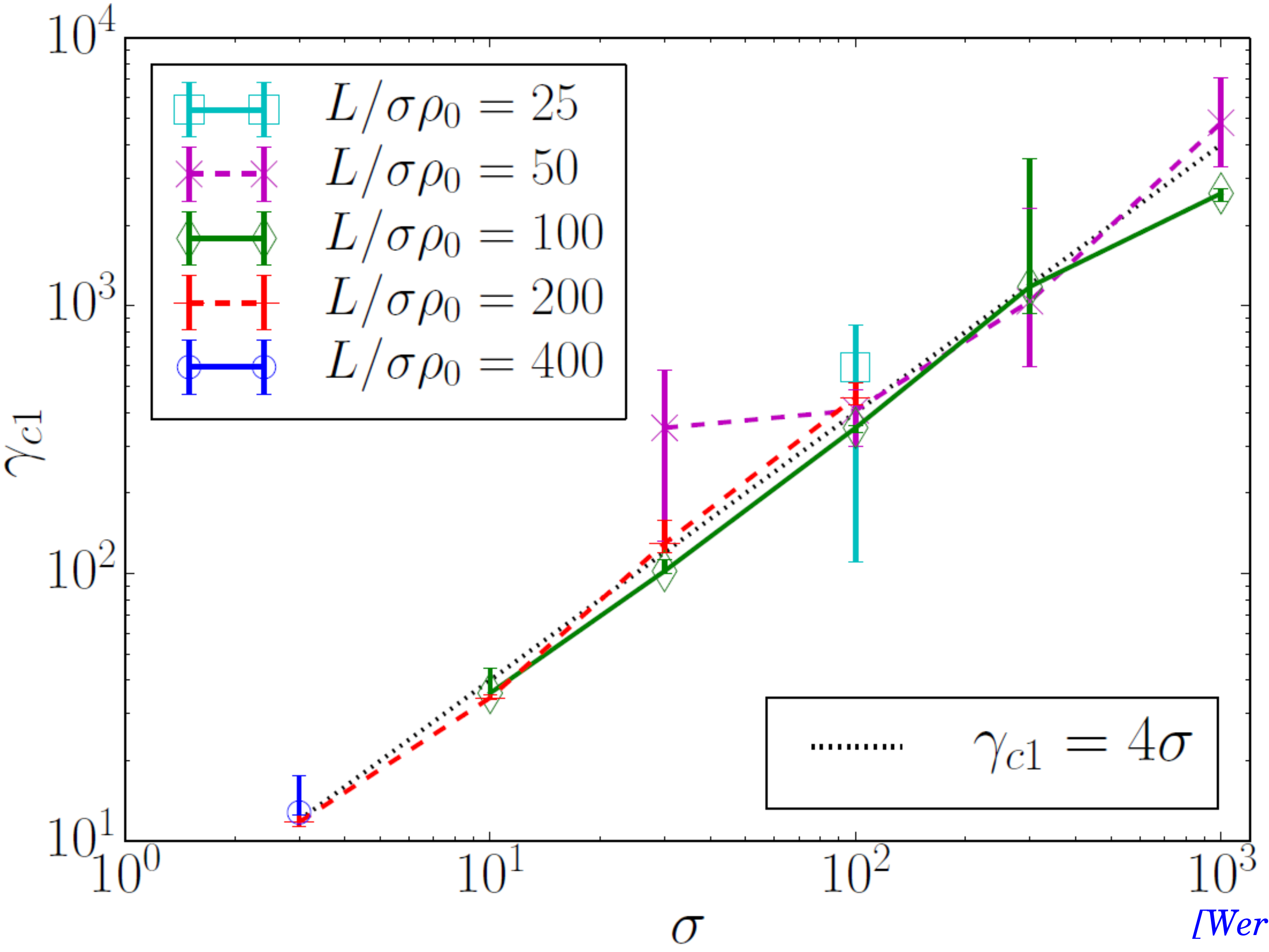
[See also Sironi & Spitkovsky 2014 ; Guo et al. 2014]

Large box-size limit



[Werner et al. 2016]

If L>> $\sigma\rho_0$, the the spectrum cuts exponentially with a cut-off given by

$$\boxed{\gamma_{max}=4\sigma}$$

Maximum energy limited by the <u>energy budget</u> (σ) !

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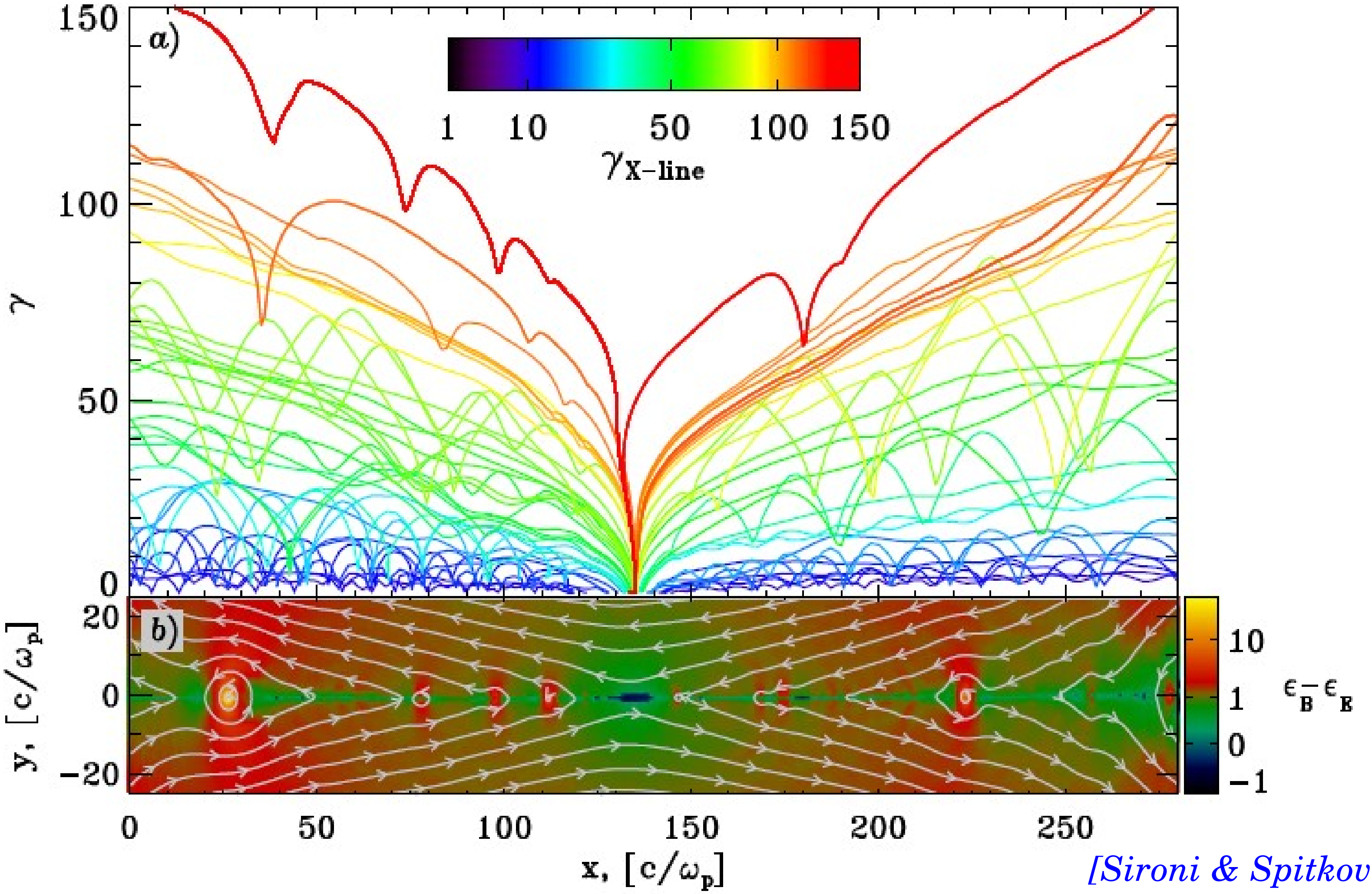
Acceleration meachnism #1 : X-points



[Sironi & Spitkovsky 2014]

The final particle energy depends how close from the X-point they are injected, leads to a **wide distribution** in energy.

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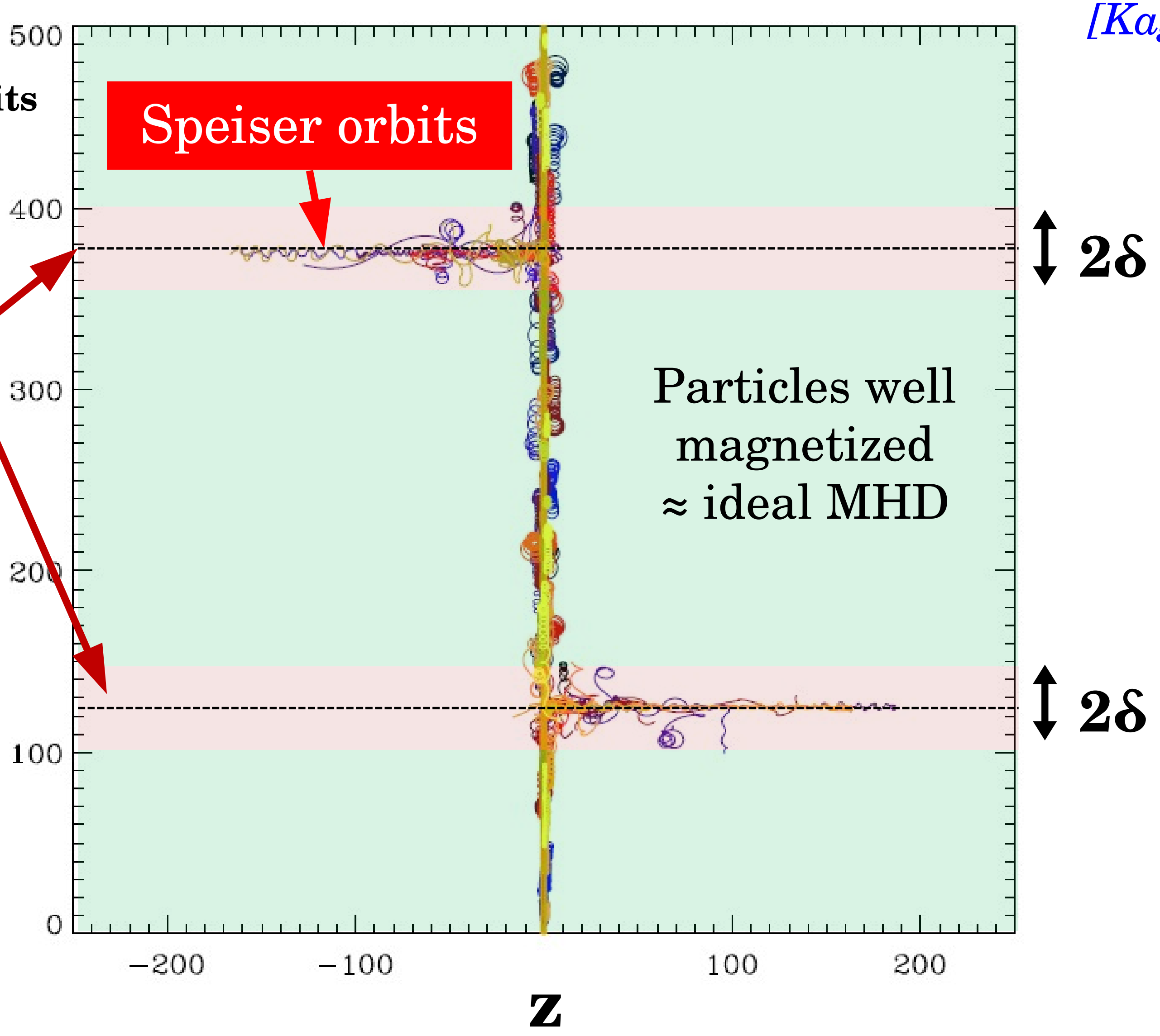
[see also Larrabee et al. 2003 ; Bessho & Bhattacharjee 2012]

Strong particle acceleration at X-points

[Kagan+2015]

Sample of 150 particle orbits



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

Particles well magnetized ≈ ideal MHD

Particle energy **increases linearly with time**
Fast compared with diffusive time sqrt(time) as in DSA.

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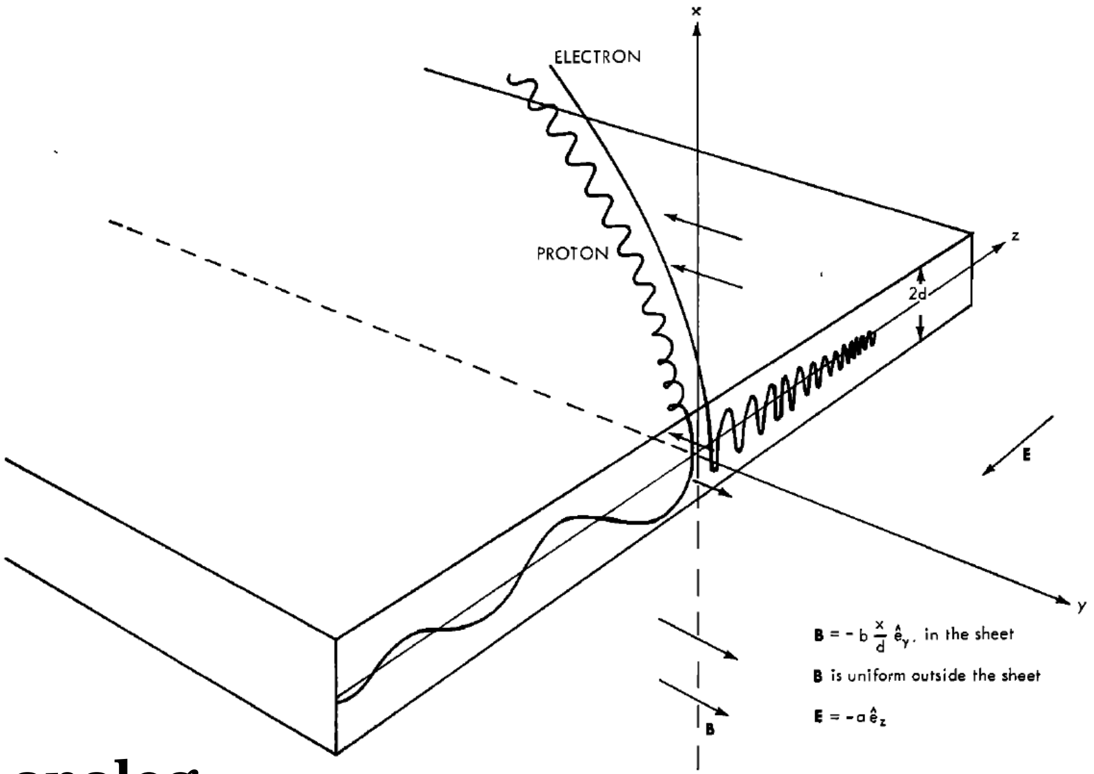
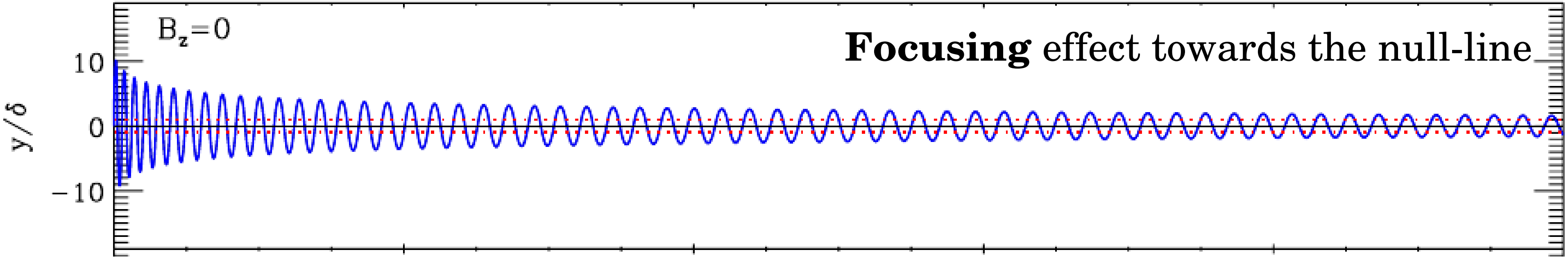
Speiser orbit



[Speiser 1965]

Relativistic analog

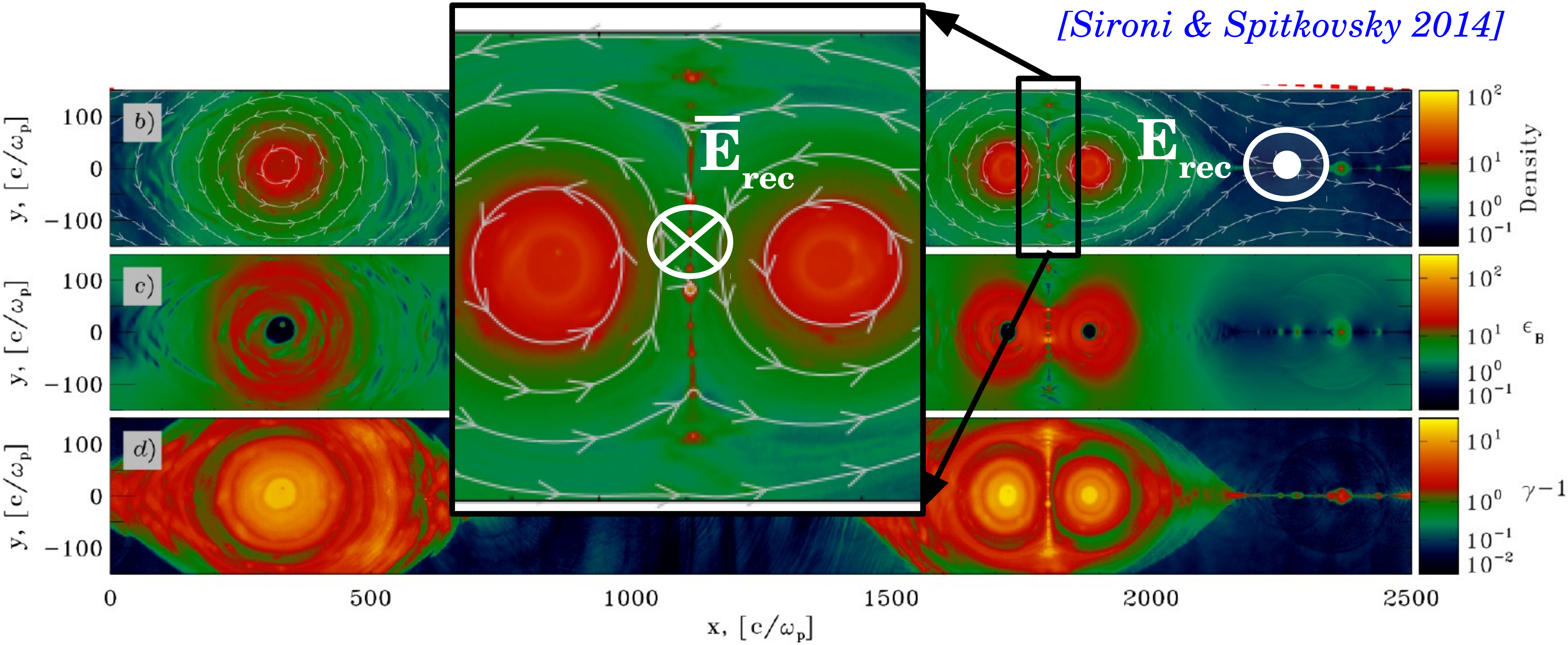


Focusing effect towards the null-line

ExB drifting of the particle orbit guiding center towards the center of the sheet.

[Uzdensky+2011 ; Cerutti+2012]

Acceleration meachism #2 : Plasmoid mergers

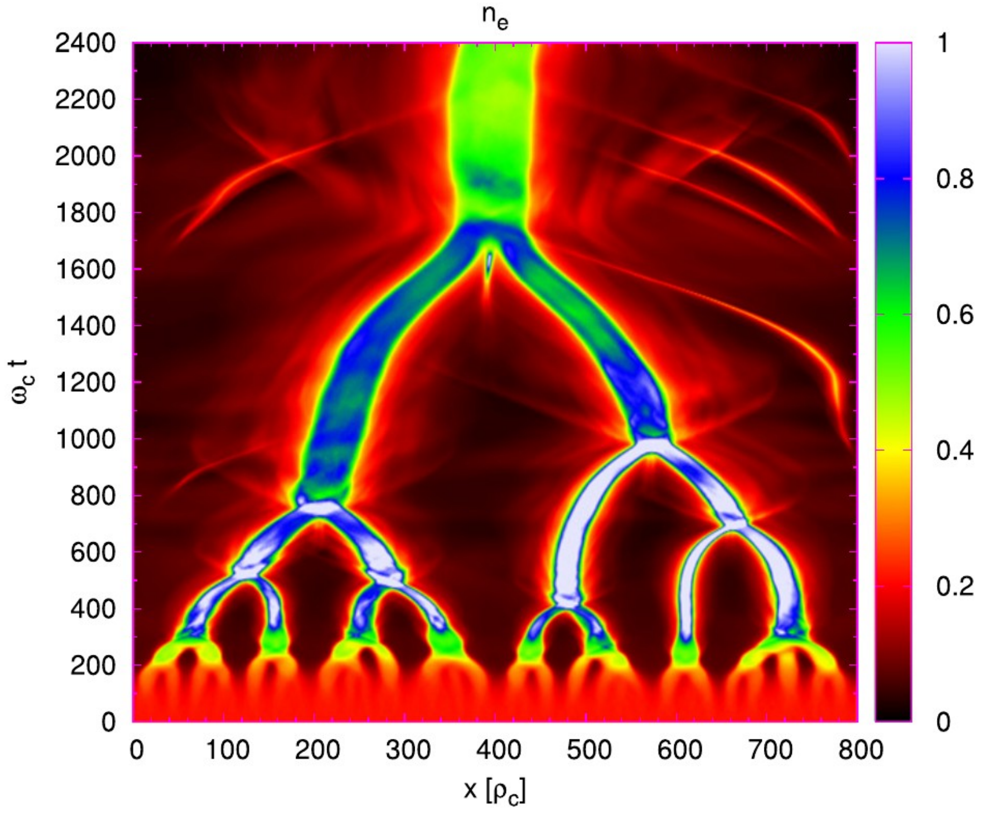


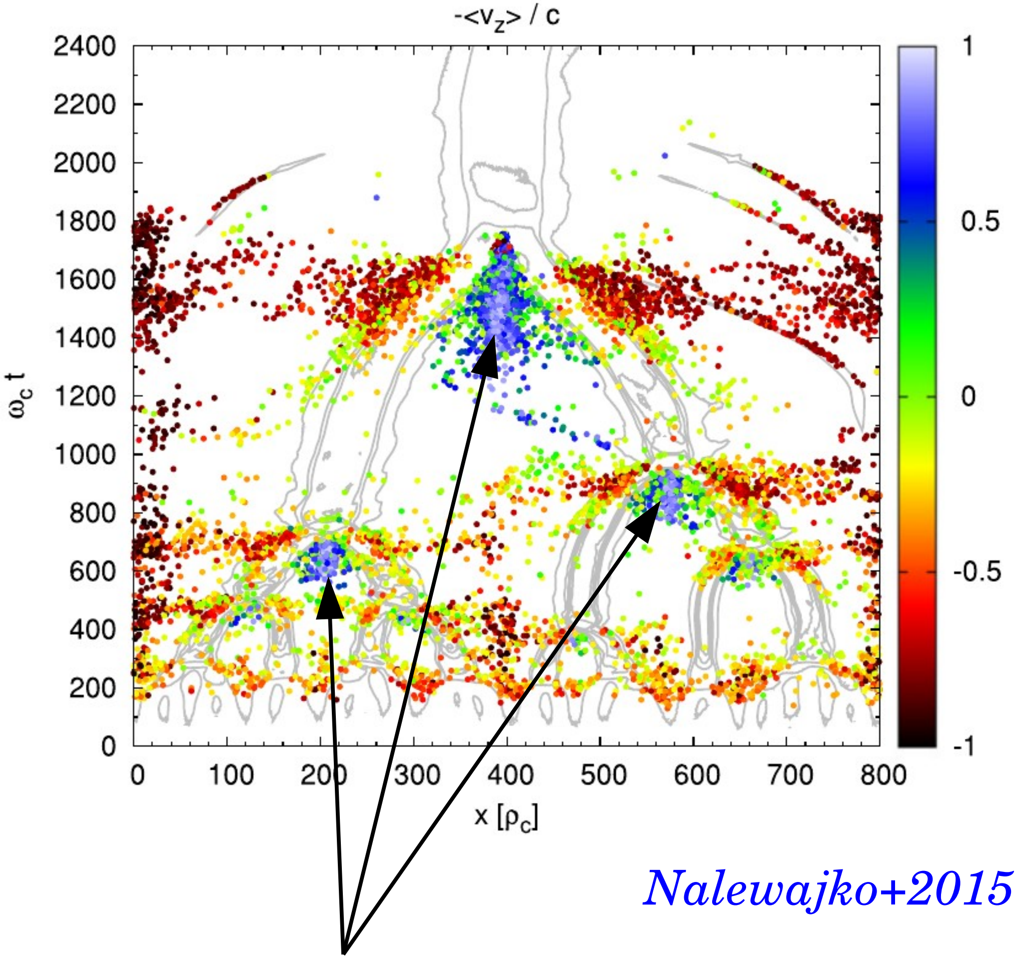
[Sironi & Spitkovsky 2014]

[See also Oka et al. 2010 (non relativistic), Nalewajko et al. 2015]

Extra particle acceleration by the **anti-reconnection electric field** between merging islands: **increase the maximum energy!**

Space-time diagram: Merger tree





Nalewajko+2015

Anti-reconnection sites

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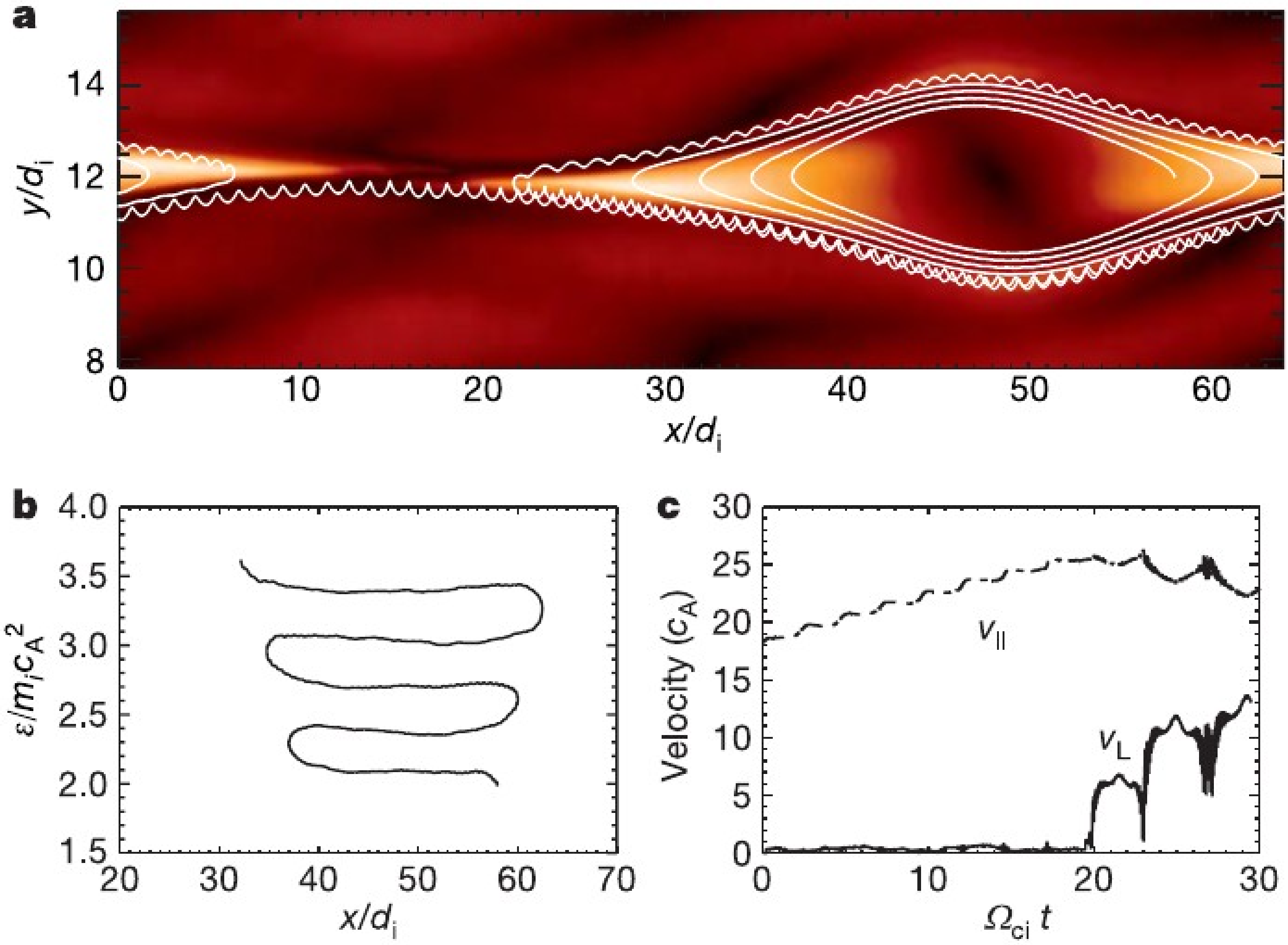
Acceleration meachnism #3 : Contracting islands



Drake+2006

Fermi-like process, particles bounce back and forth between the island edges as it circularizes.

But, negligible in the relativistic regime, too fast ! *[Nalewajko+2015]*

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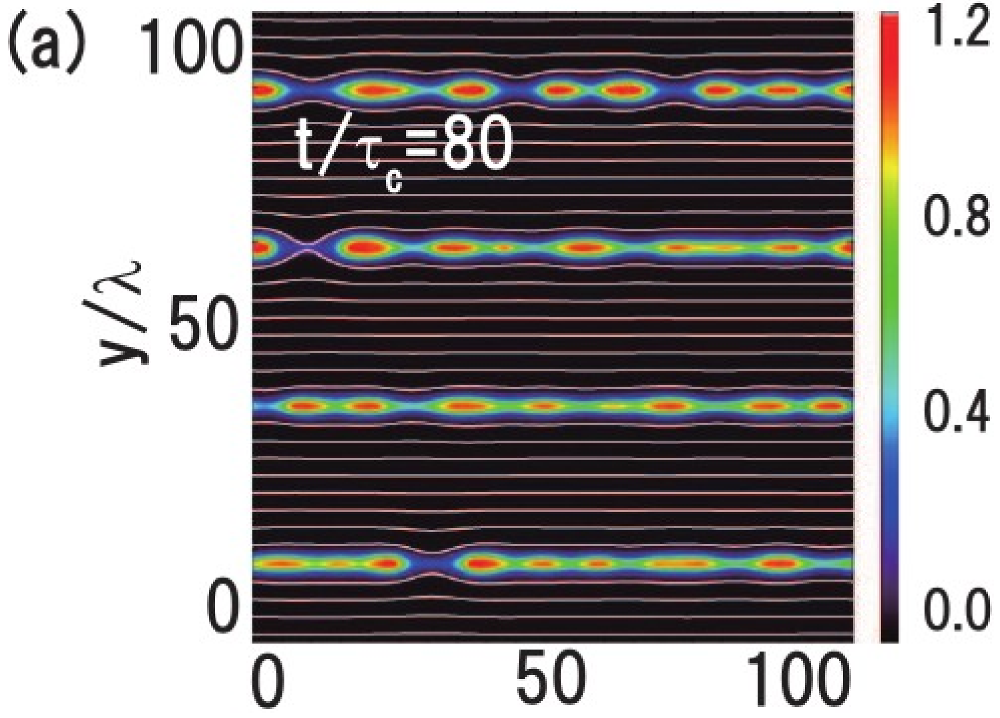
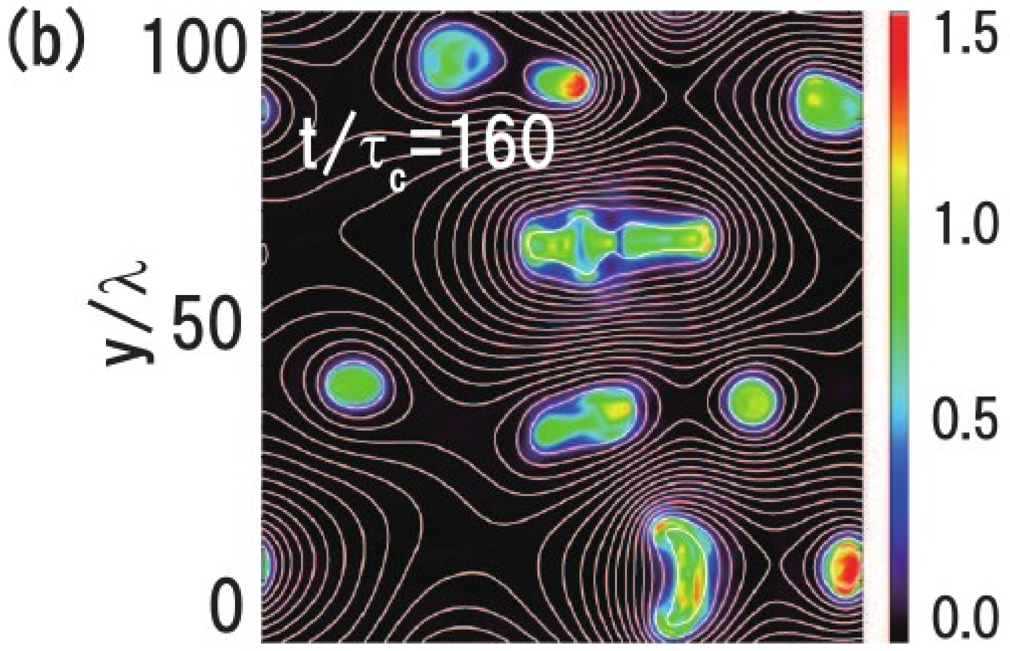
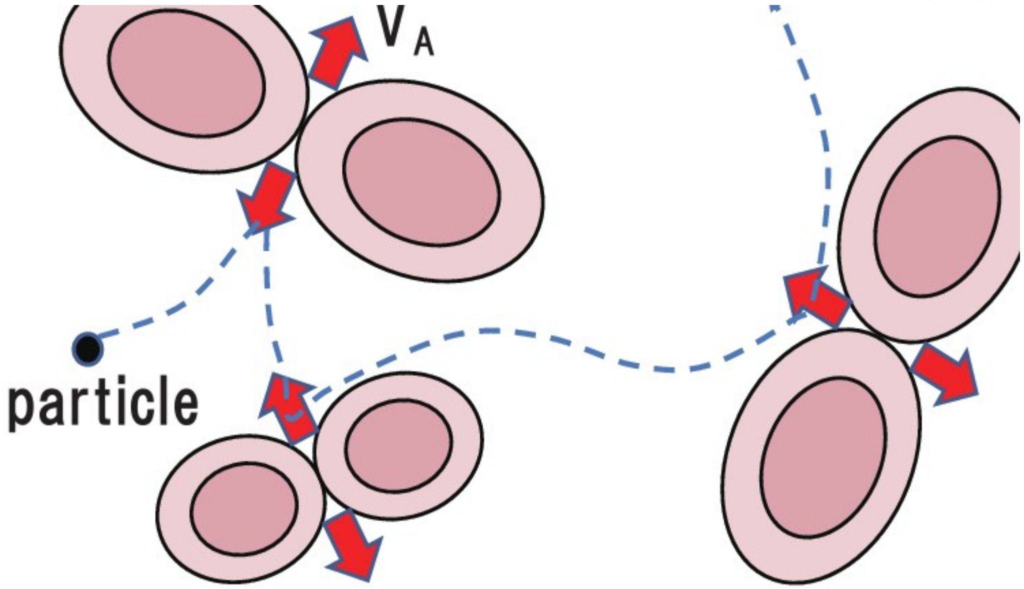
Acceleration meachnism #4 : Multi-island scattering







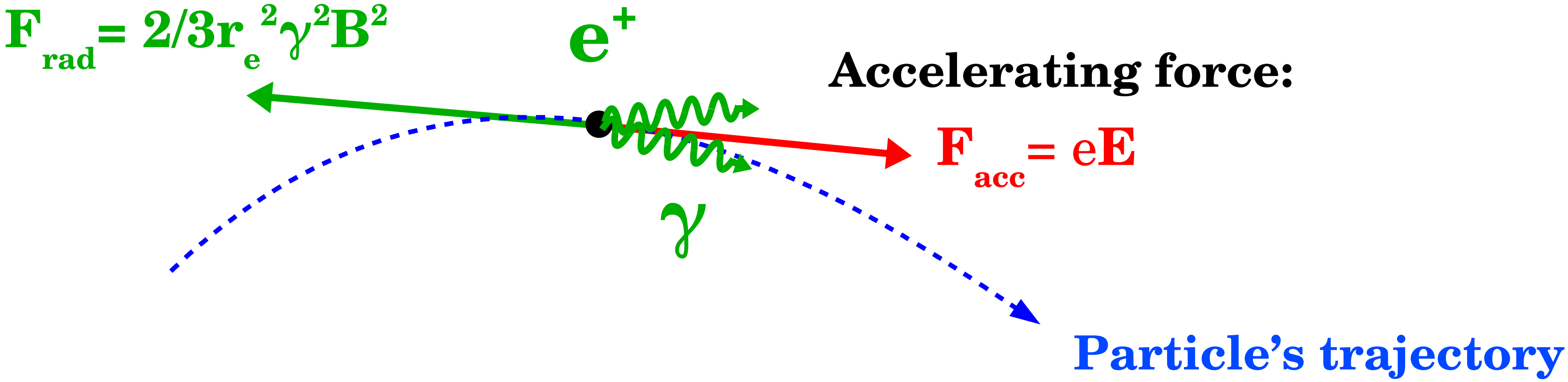
Stochastic acceleration between plasmoids. Fermi-like acceleration.

Special conditions needeed : Needs a stack of current layers **interacting** with each other.

Hoshino+2012

Radiation-reaction-limited particle energy

Radiation reaction force:



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

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

Under ideal MHD conditions: E<B (ideal MHD) =? ε_{max} < 160 MeV

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

But this limit does not stricly apply to reconnection where E>B in the layer

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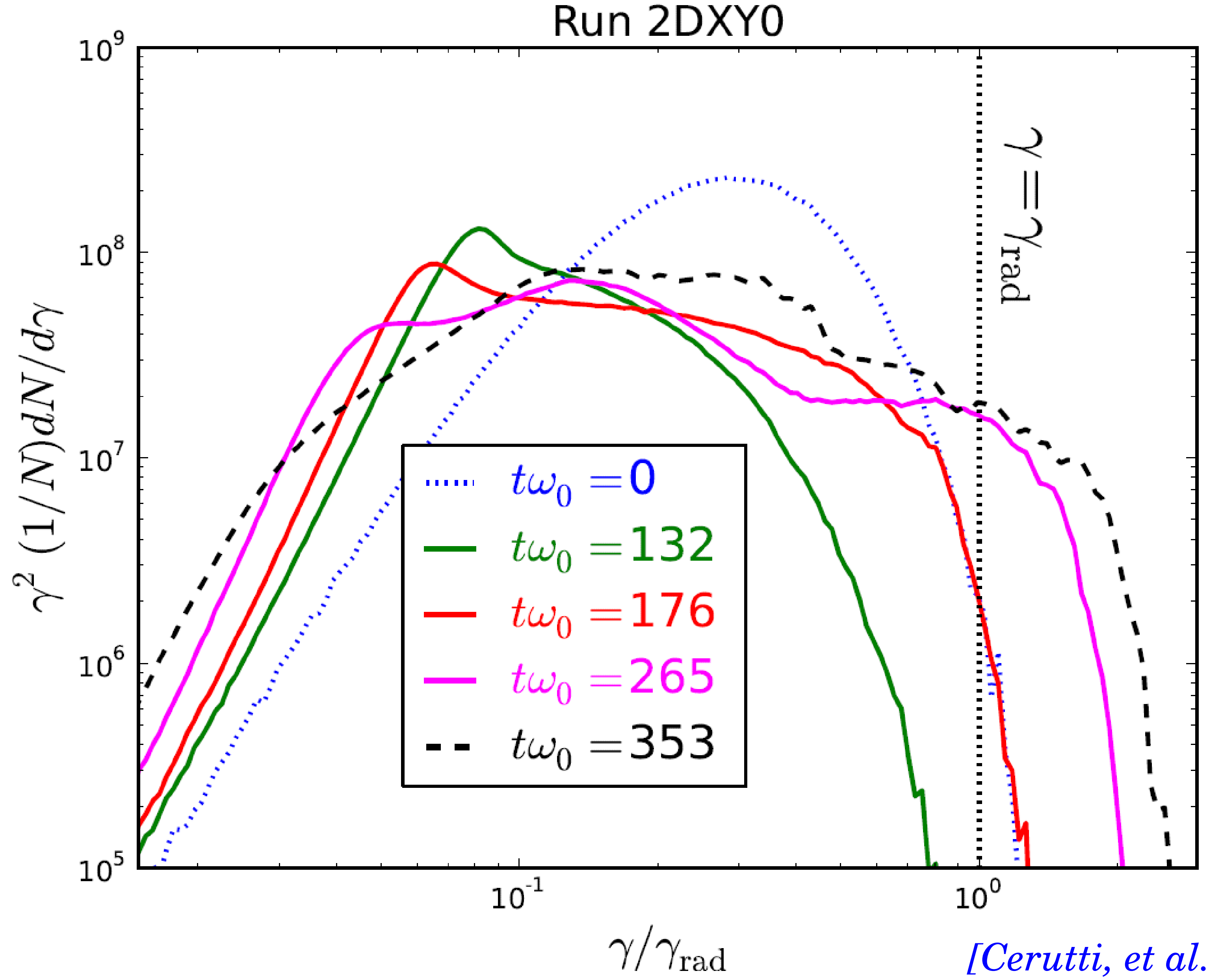
Particle acceleration beyond radiation reaction limit

2D PIC with radiation reaction force



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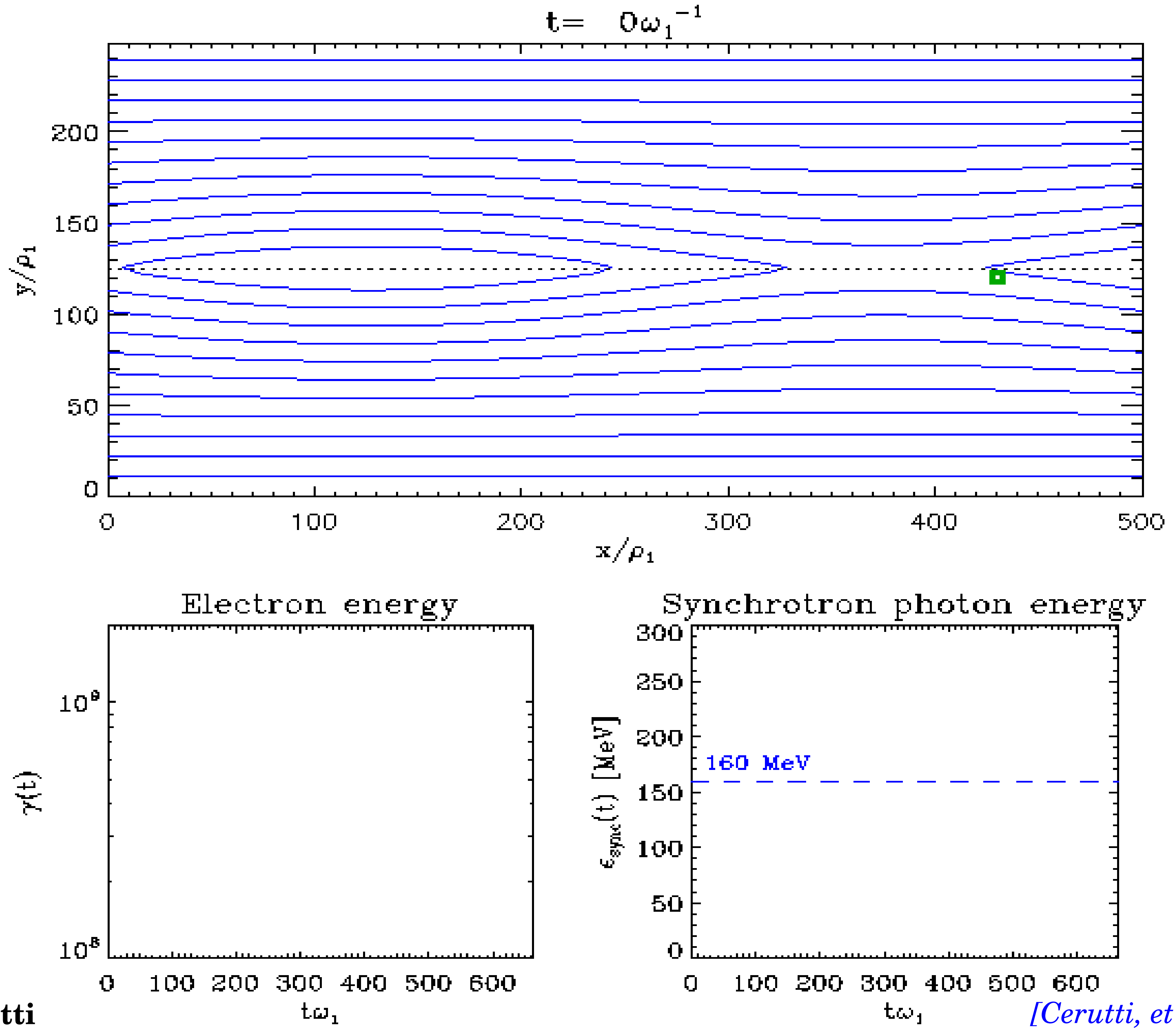
[Cerutti, et al. 2013, 2014]



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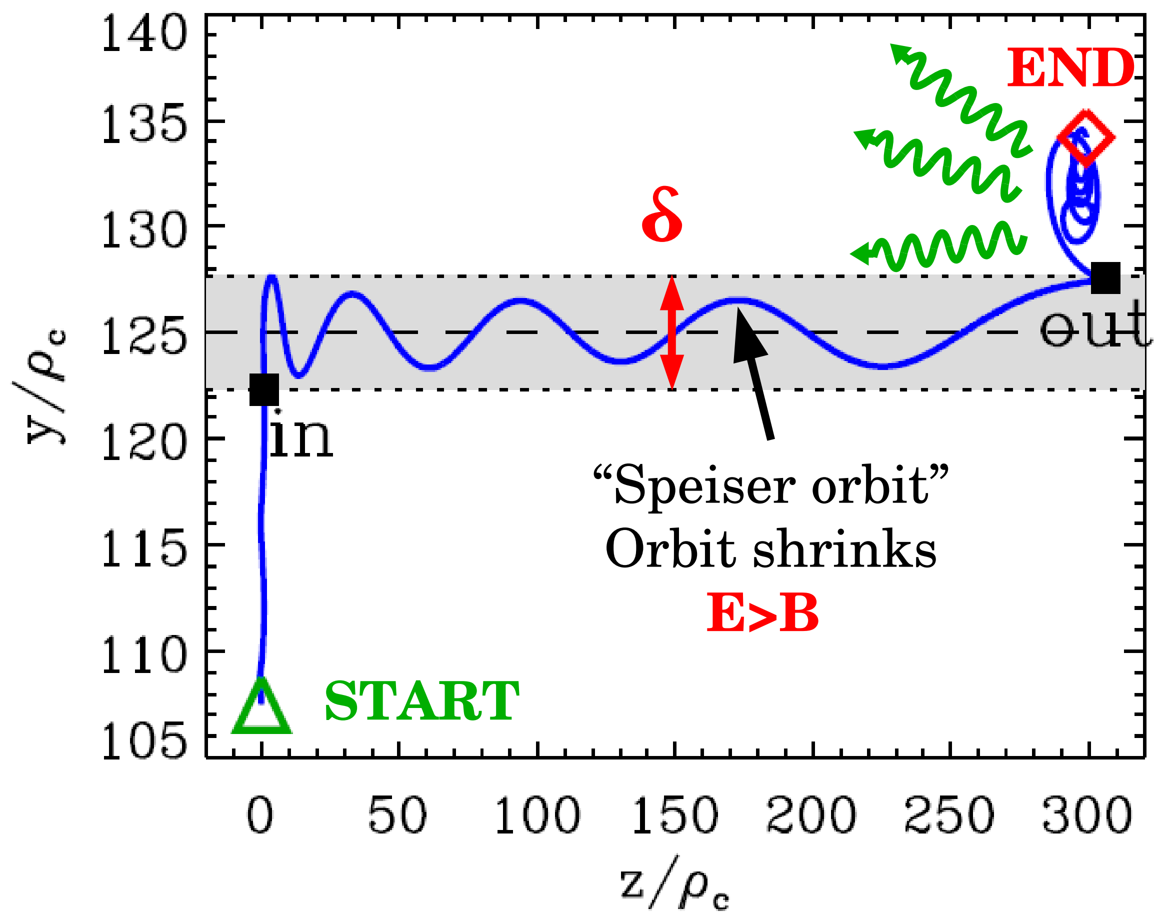
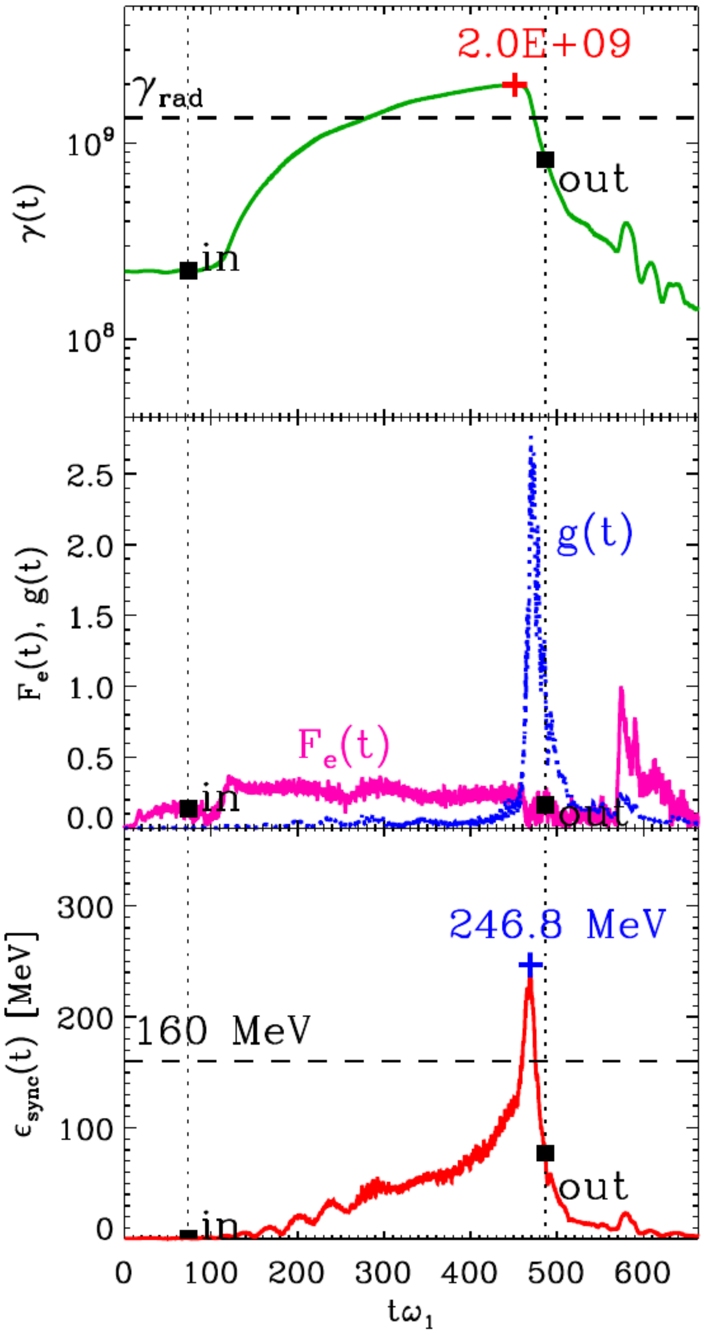
[Cerutti, et al. 2013]

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



“Speiser orbit”
Orbit shrinks
E>B



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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Relativistic electron-ion reconnection

Regime relevant to **hot collisionless accretion flows** (e.g., Sgr A*), black hole **coronae**, **AGN jets.**

$$\boxed{\sigma_e = \frac{B_0^2}{4\pi n_e m_e c^2}} \qquad \boxed{\sigma_i = \frac{B_0^2}{4\pi n_i m_i c^2} = \sigma_e \left(\frac{m_e}{m_i}\right)}$$

- **Non-relativistic regime** : $\sigma_i \ll 1$, $\sigma_e \ll 1$: Poor particle acceleration for both species, steep power laws.
- **Semi-relativistic regime** : $\sigma_i \ll 1$, $\sigma_e \gg 1$: Midly relativistic ions, ultra-relativistic electrons. *Melzani+2014* (**see Journal Club**), *Werner+2017.*
- **Ultra-relativistic regime** : $\sigma_i \gg 1$, $\sigma_e \gg 1$: Identical to pair plasmas since γmc^2 enters in plasma scales (skin depth, Larmor radius & frequencies...), if ignoring radiative effects.

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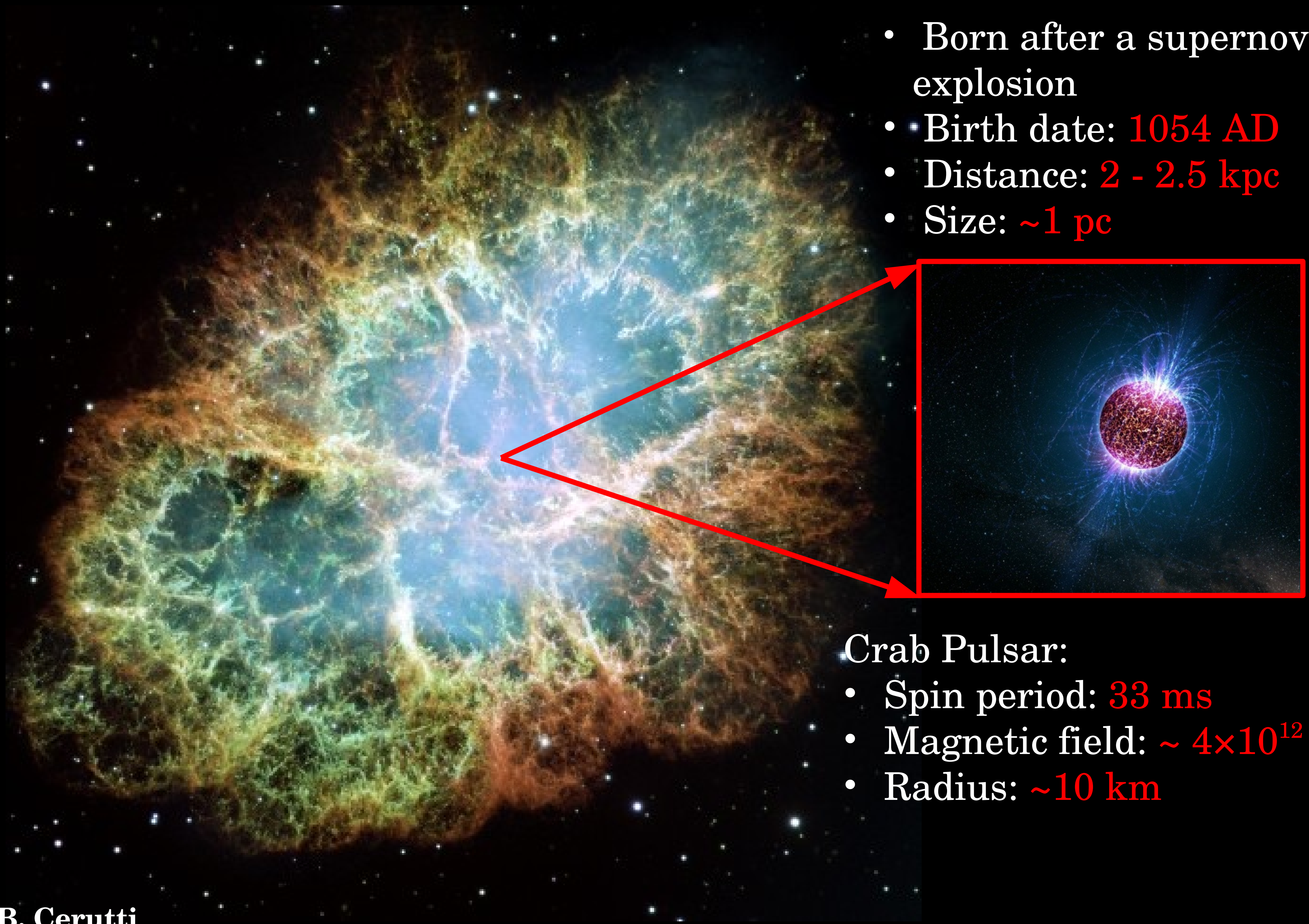
II. Astrophysical applications

Astrophysical flares

What is the Crab Nebula ?



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

Crab Pulsar:

- Spin period: 33 ms
- Magnetic field: ~ 4×10^{12} G
- Radius: ~10 km

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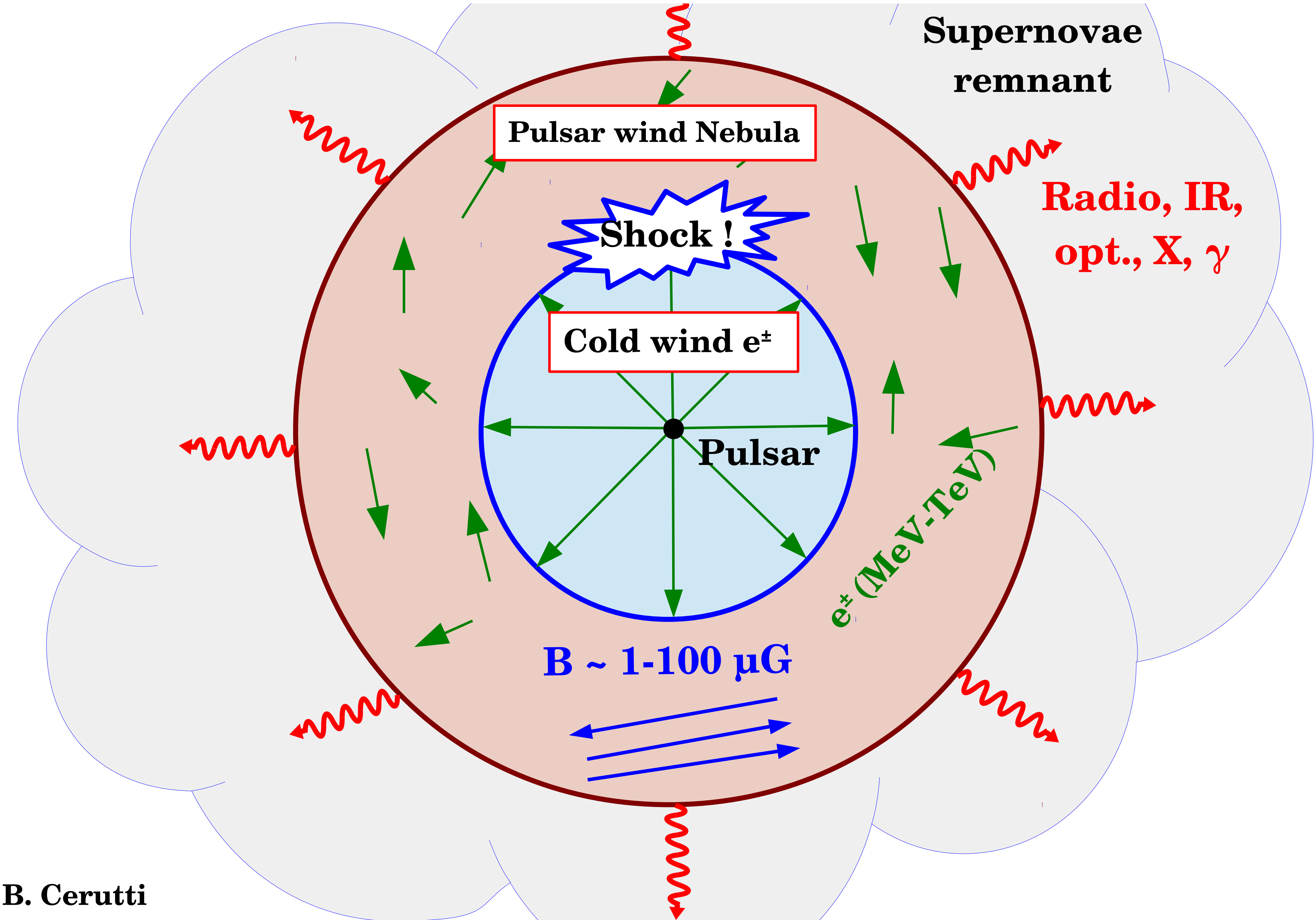
Pulsar wind nebulae



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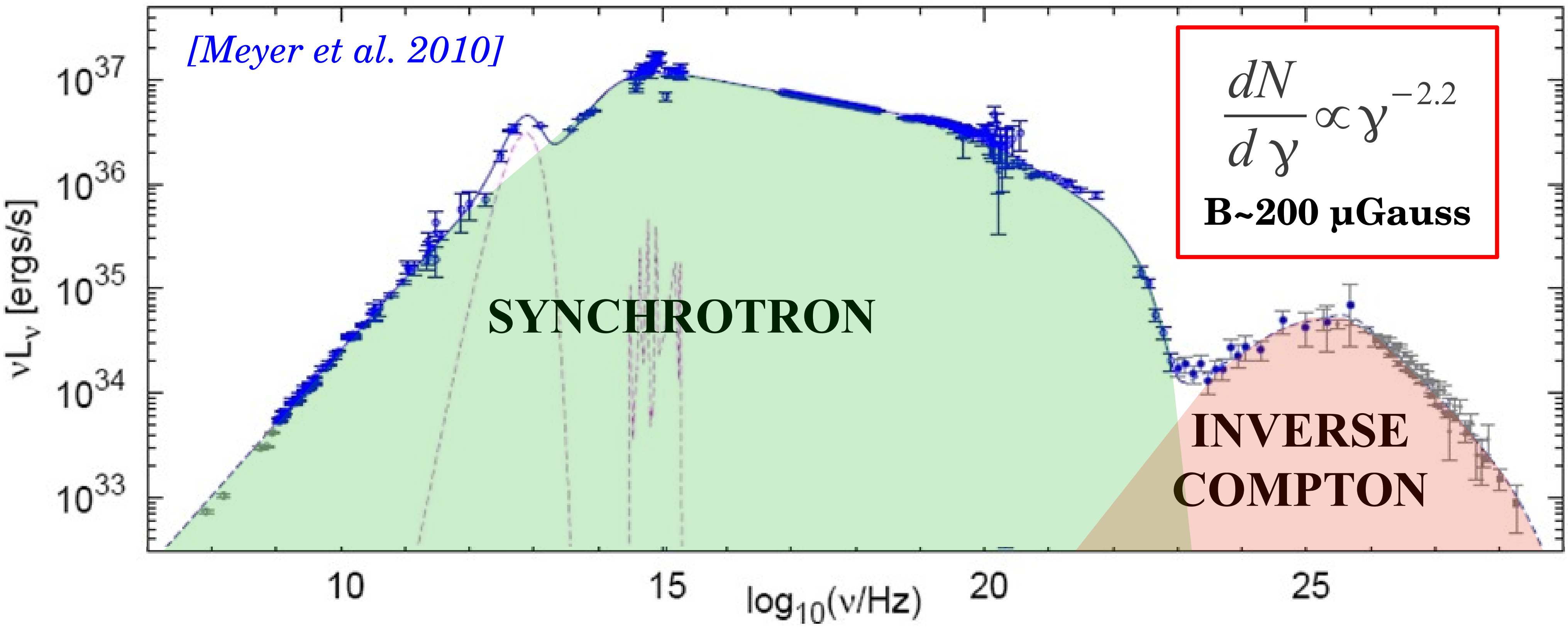
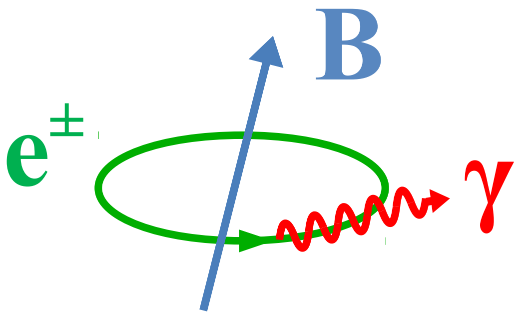
Crab nebula broad band emission



$$\frac{dN}{d\gamma} \propto \gamma^{-2.2}$$

B~200 μGauss

Synchrotron radiation

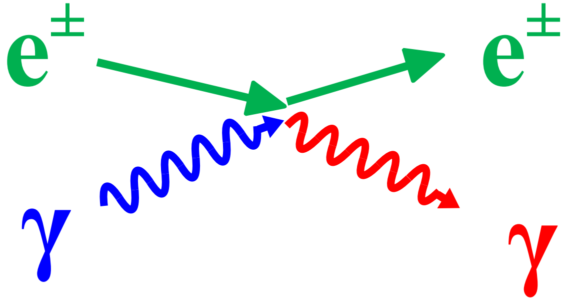


< 100 MeV

Inverse Compton scattering

Target photons:

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



GeV -TeV

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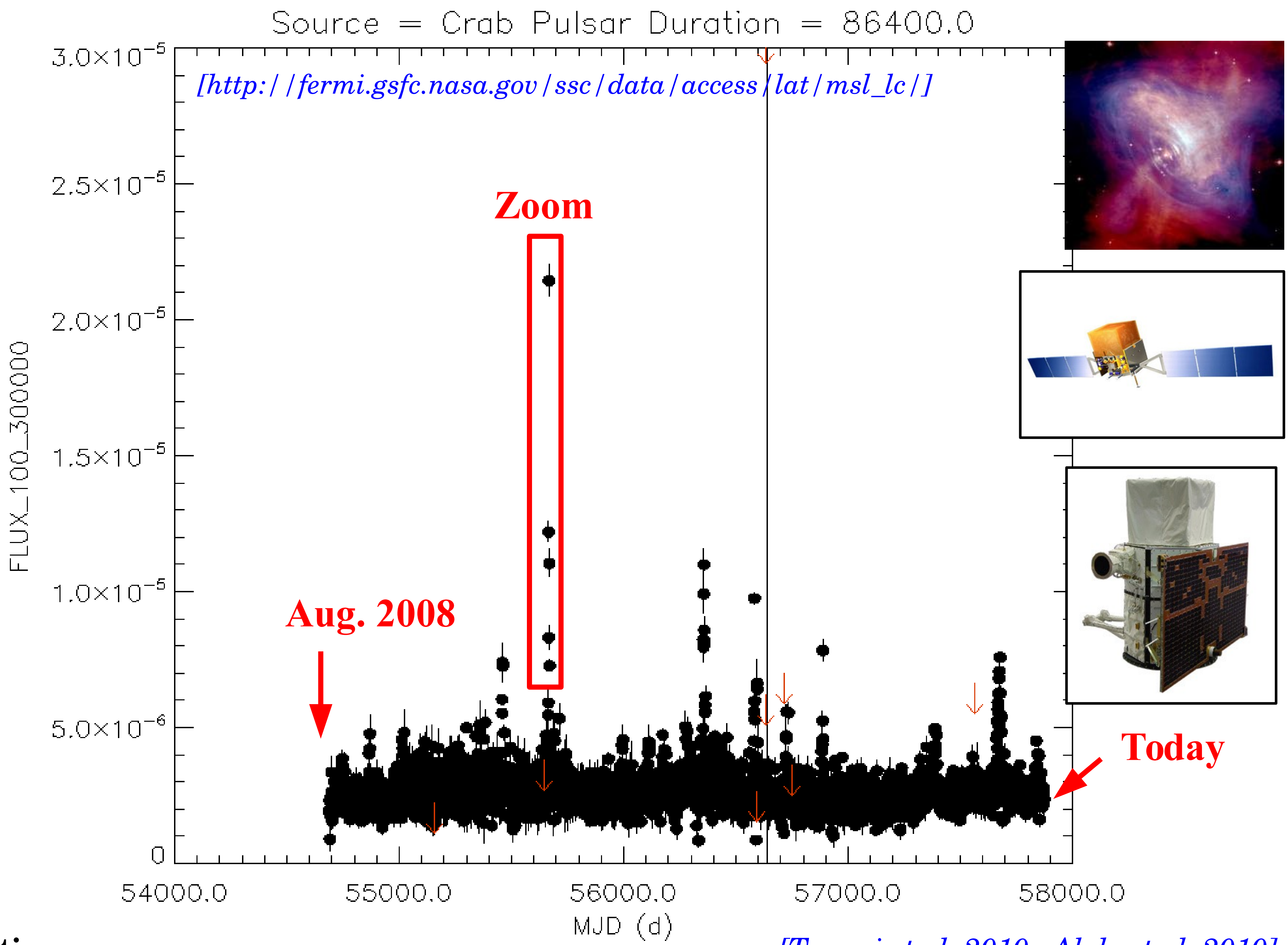
Time variations in the >100 MeV flux



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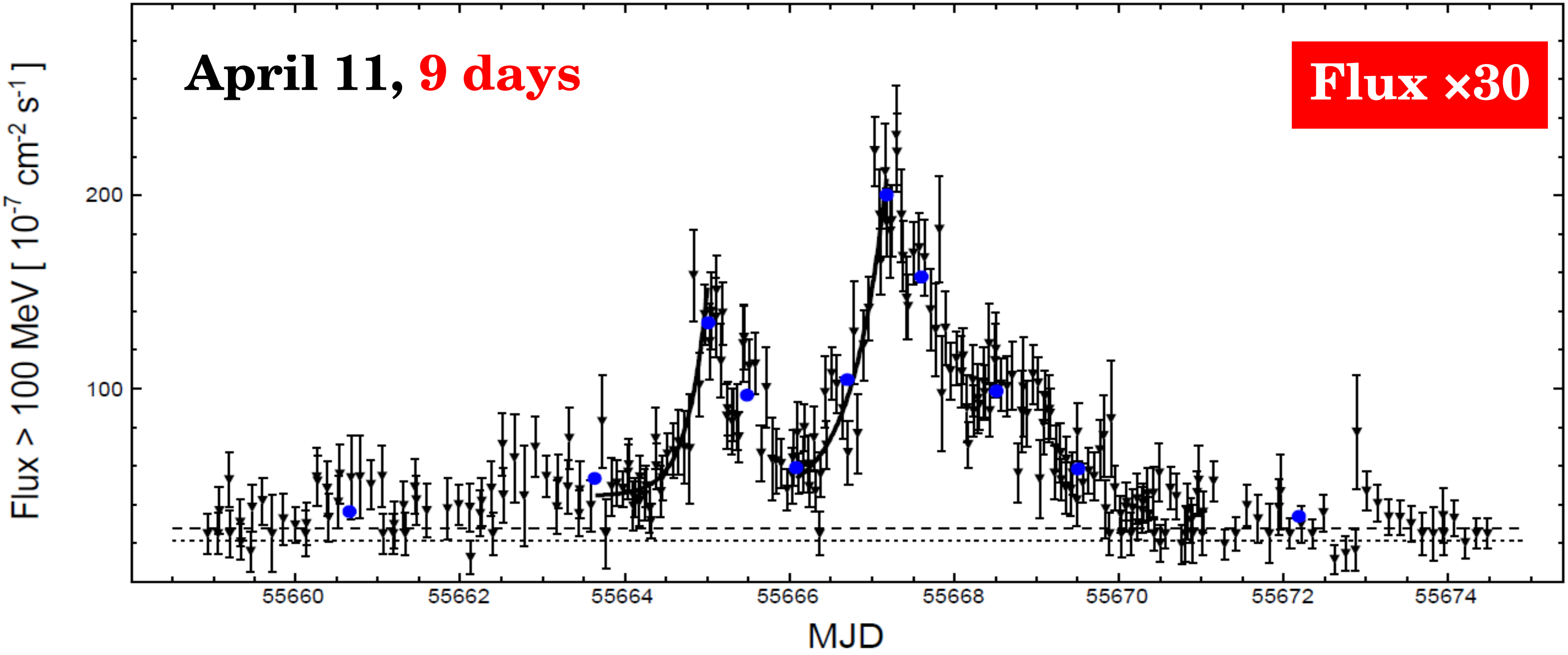
[Tavani et al. 2010 ; Abdo et al. 2010]

Ultra-short time variability

[Buehler et al., 2012]

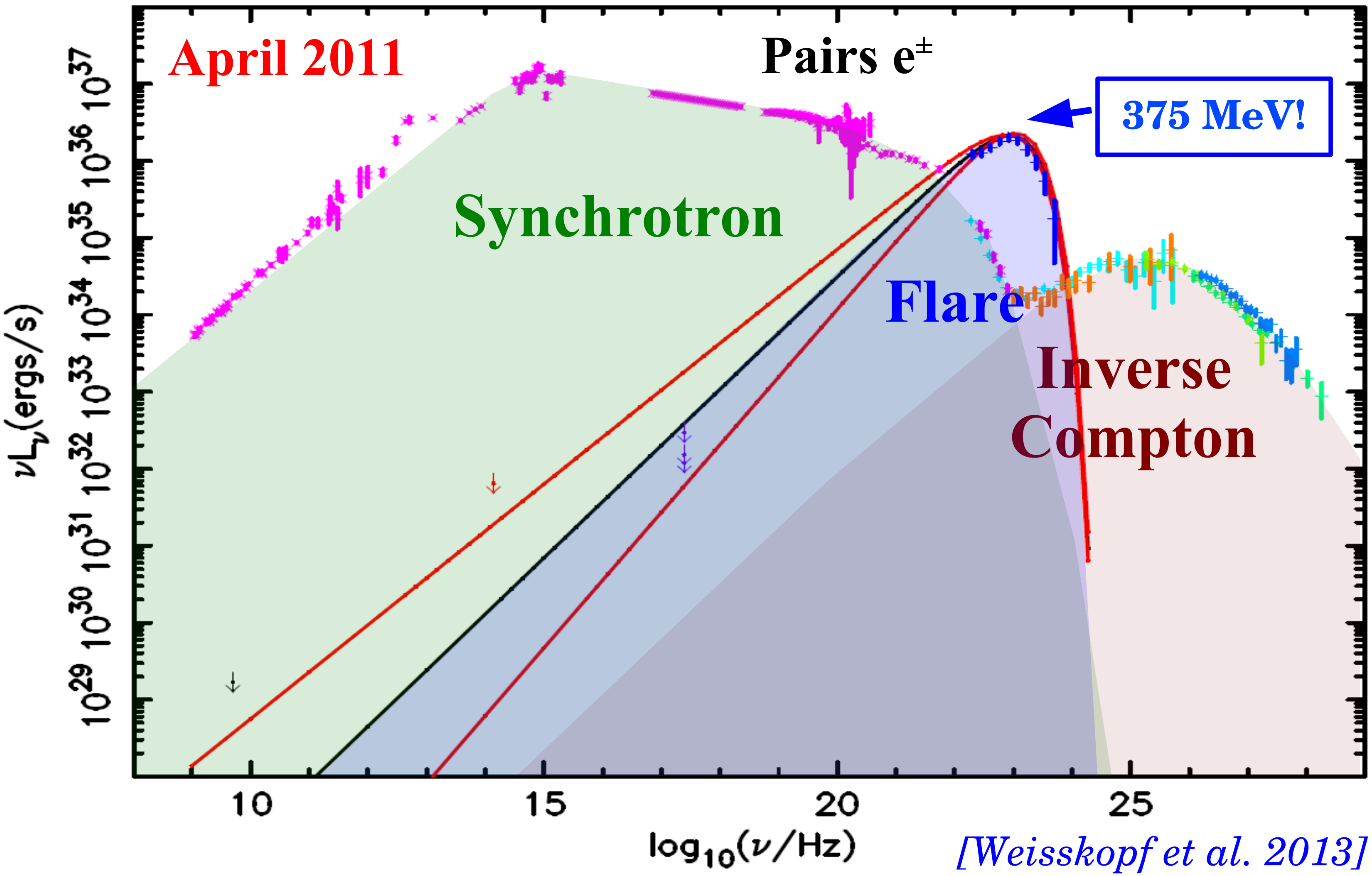


(1) Size : ct_{flare}~10^{16} cm, ~1% radiates 30 times the whole Nebula flux

(2) If t_{flare} = t_{sync} =► B ~ few mG >> 200 μG, and PeV pairs

(3) PeV pairs => $t_{gyration}$ ~ t_{flare} , pairs accelerated within ~1 Cyclotron orbit
Inconsistent with diffuse shock acceleration
The acceleration is turned ON during the gamma-ray flare

Flare spectral component



[Weisskopf et al. 2013]

(1) **No obvious counter-parts** (radio, IR, opt., X, TeV)

(2) **Spectrum ~mono-energetic**, inconsistent with shock-acceleration

(3) Synchrotron photons **> 100 MeV**

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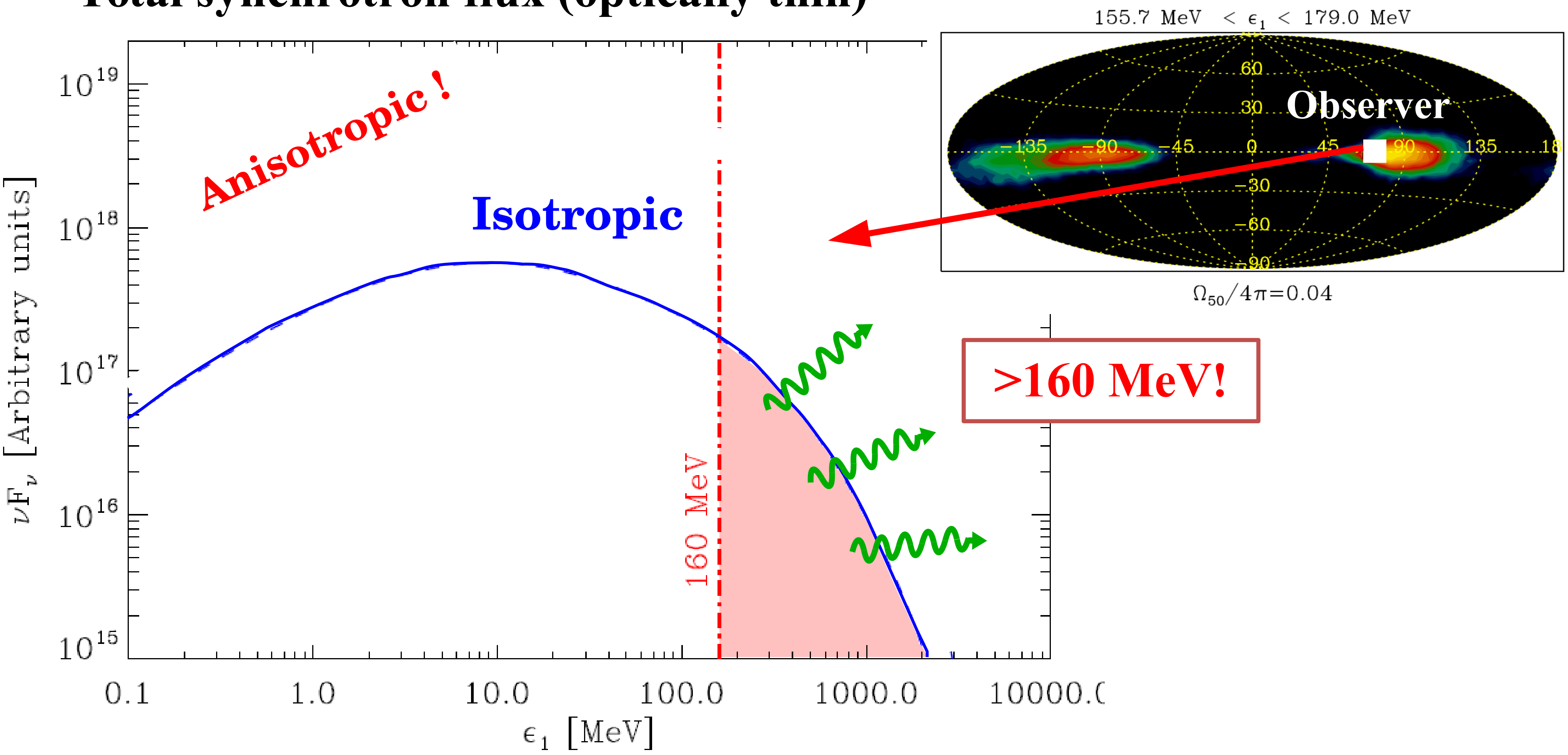
PIC simulations of radiative relativistic reconnection

Total synchrotron flux (optically thin)



[Cerutti et al. 2013]

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

Good to reduce the energetic constraints !

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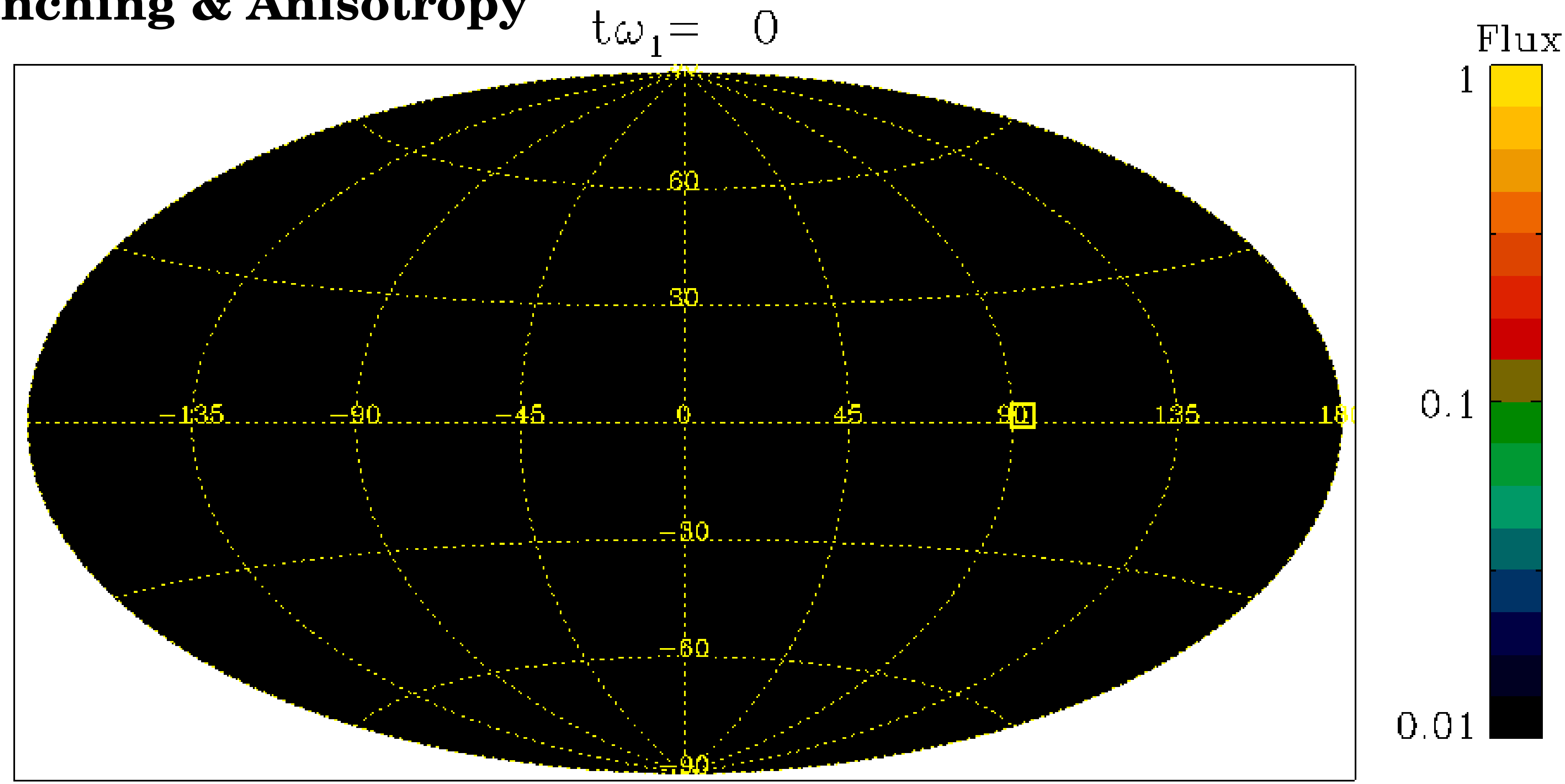
Time variations of the >100 MeV emission

Bunching & Anisotropy



The beam of high-energy radiation sweeps across the line of sight intermittently =► <u>bright symmetric flares.</u>

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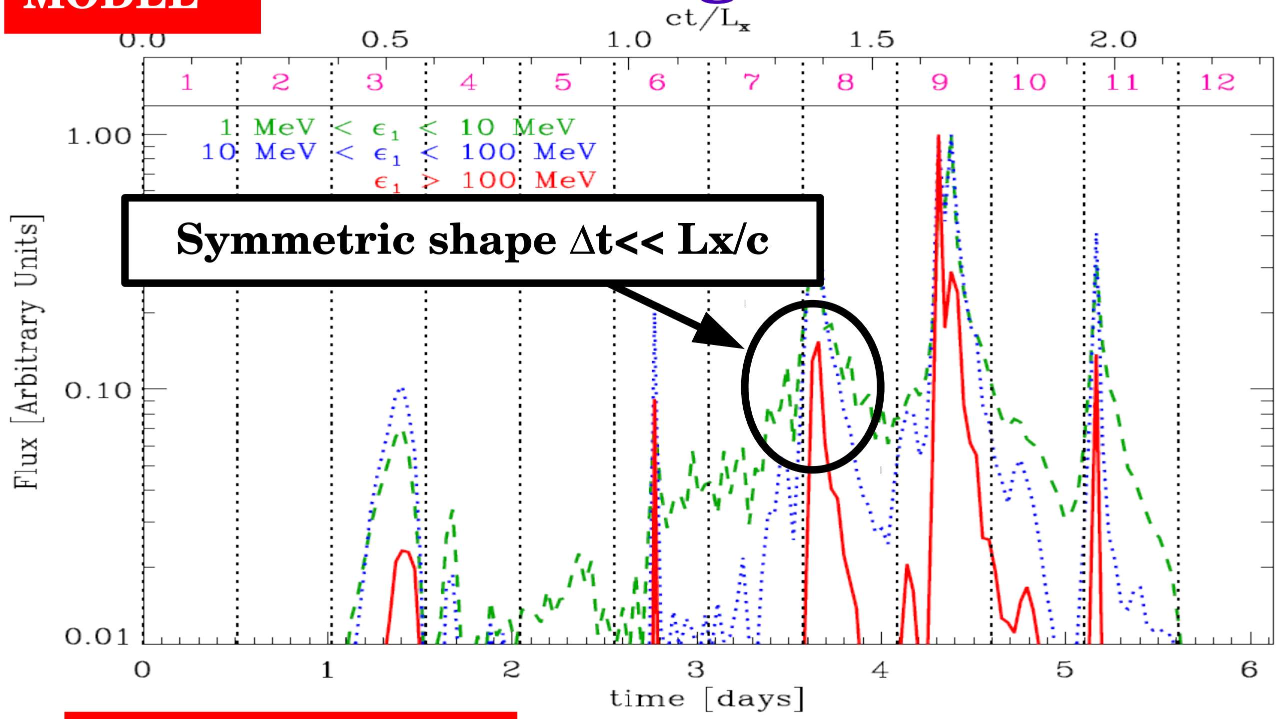
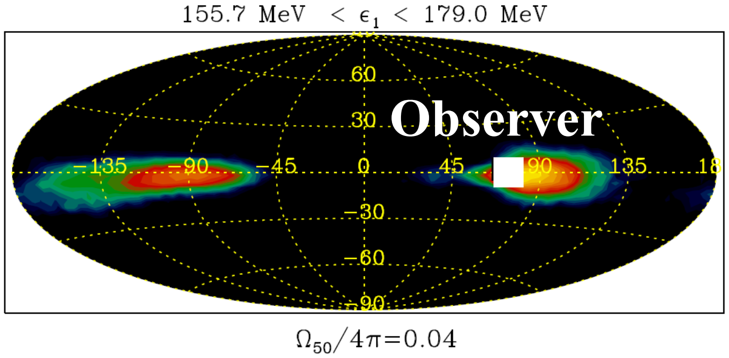
Light curve modelling

MODEL



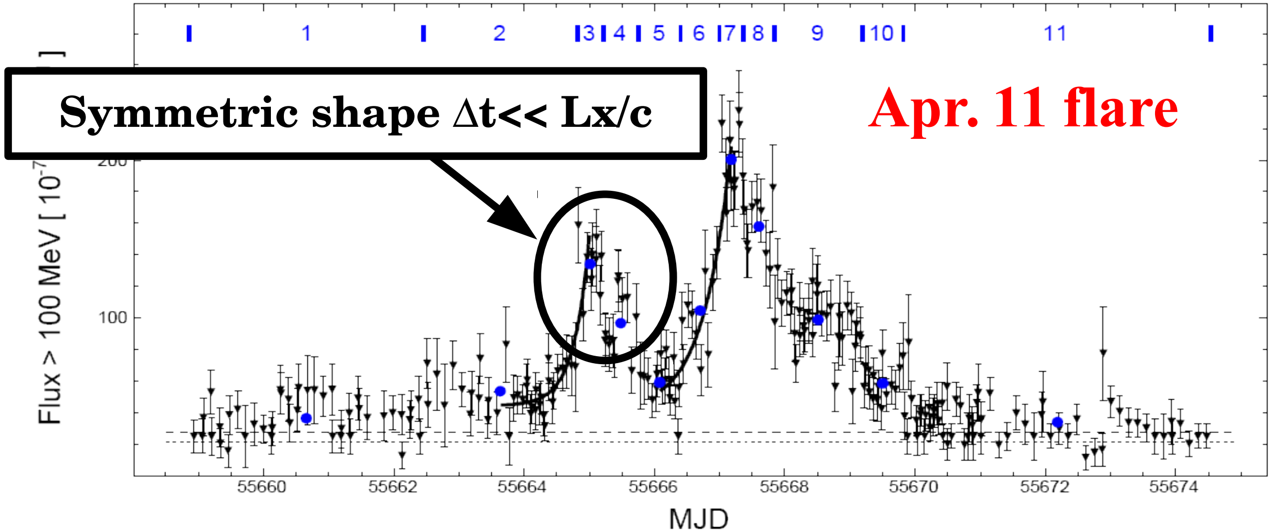
Symmetric shape Δt<< Lx/c

[Cerutti et al. 2013]



Ultra-short time variability < 6 hours due to particle bunching and anisotropy

OBSERVATIONS



Symmetric shape Δt<< Lx/c

[Buehler et al., 2012]

Observed ultra-short time variability < 8 hours

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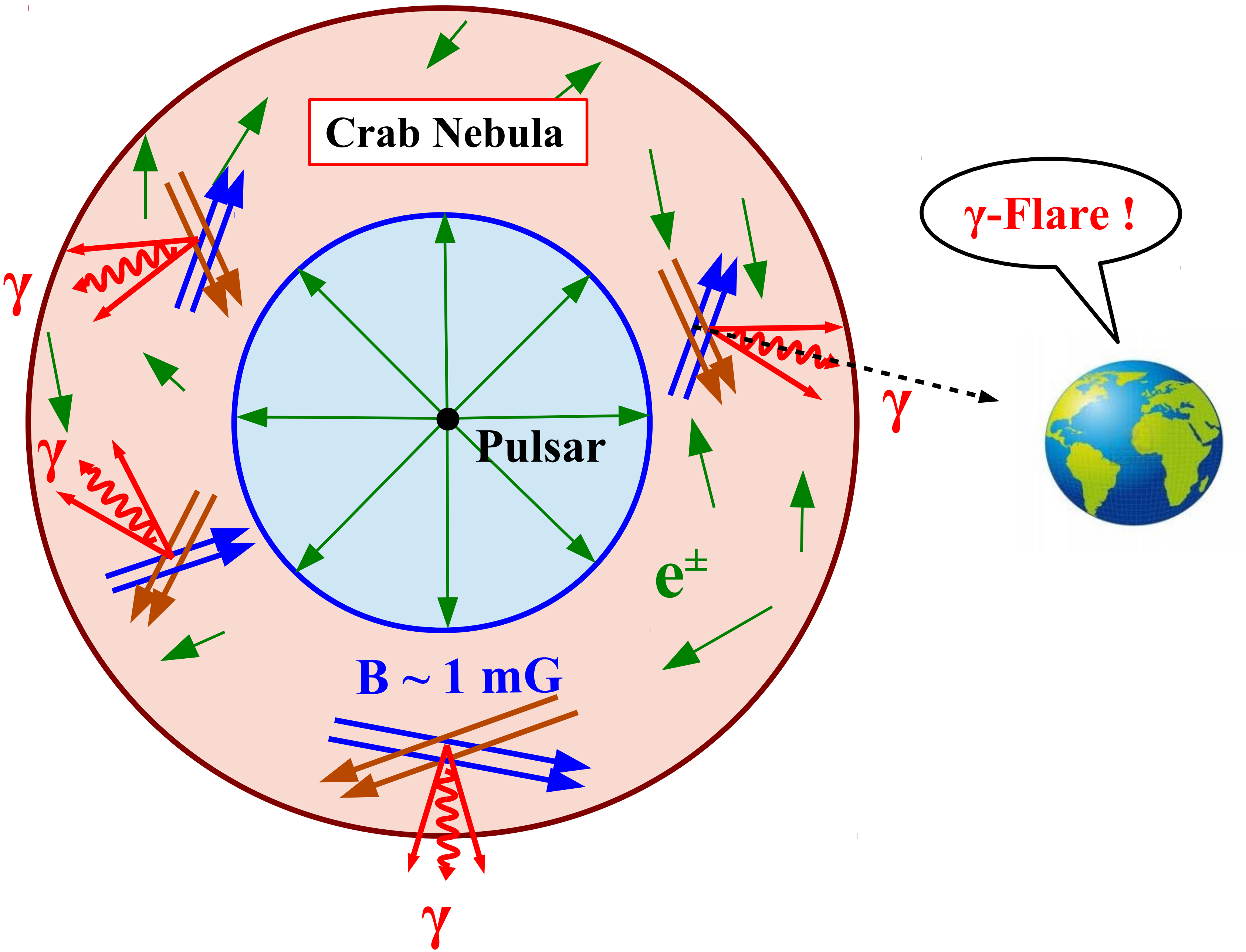
Flare when reconnection site oriented towards Earth



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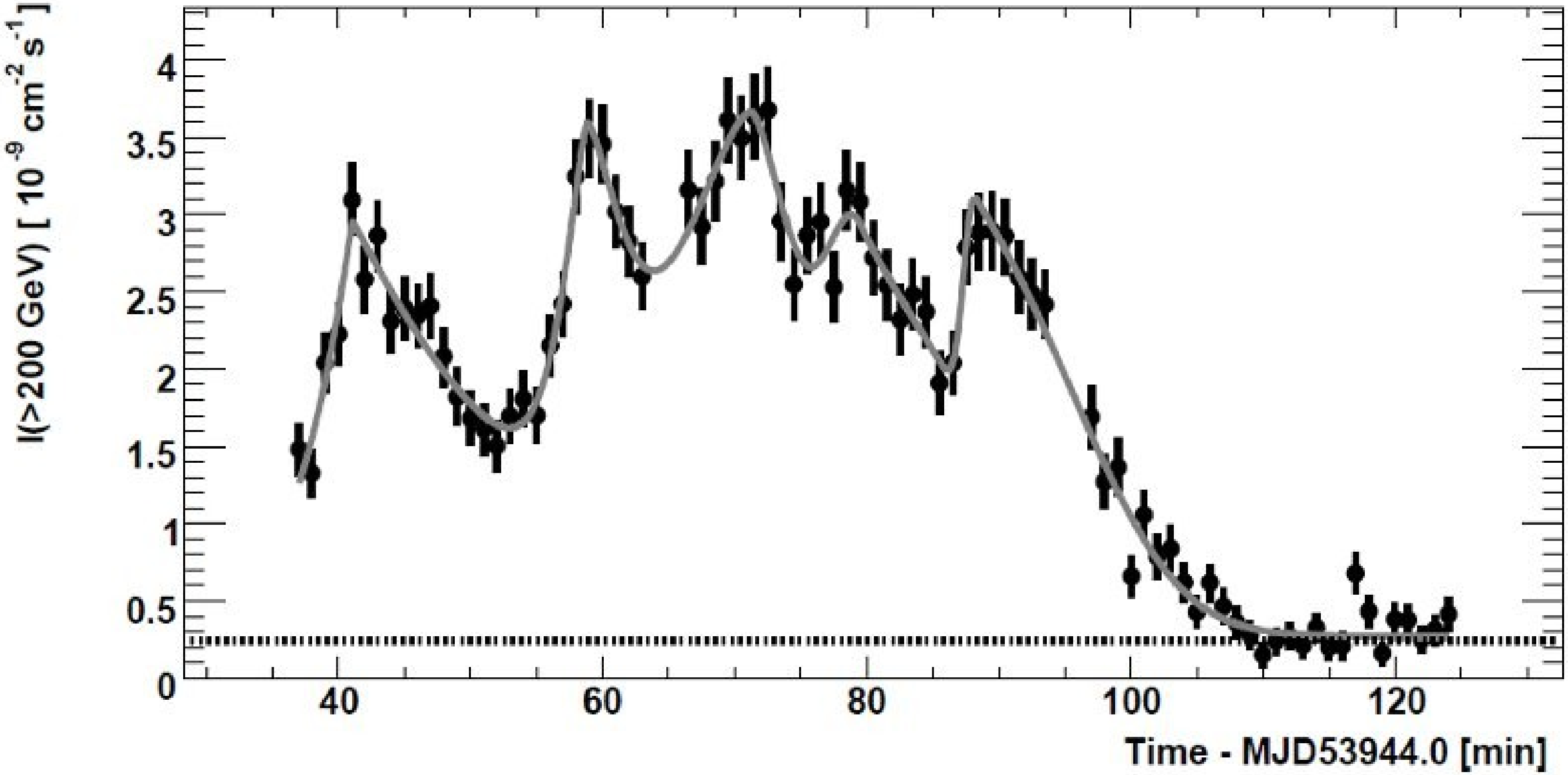
Application to TeV blazar flares ?

PKS 2155-304 (and others !): short-time variability ~200 s << R_{BH}/c.

=>Requires high Doppler factor $\delta_{dopp} > 50$.

[Saugé & Henri 2006 ; Begelman et al. 2008]



Aharonian et al. 2007 (H.E.S.S. Collaboration)

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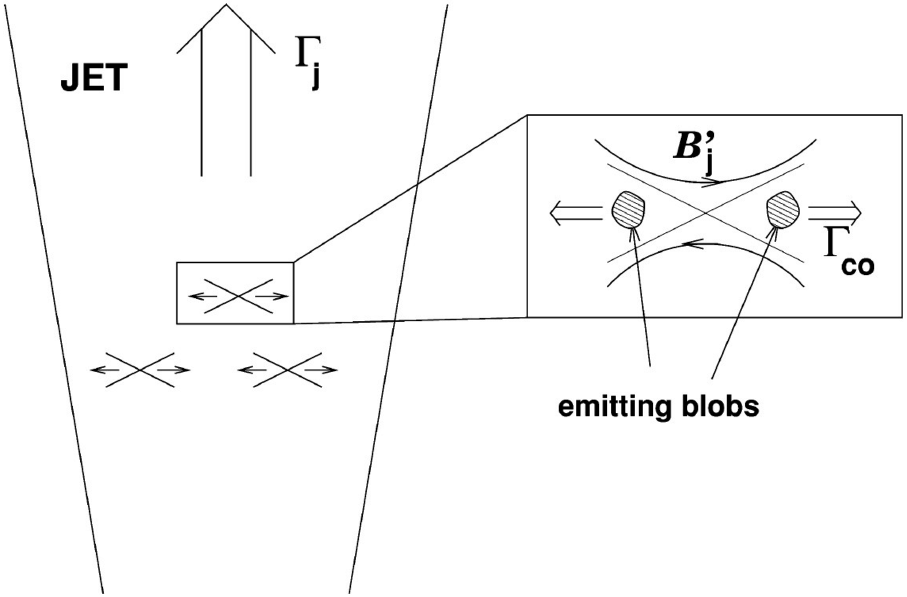
Jet-in-a-jet scenario for blazar super-fast flares

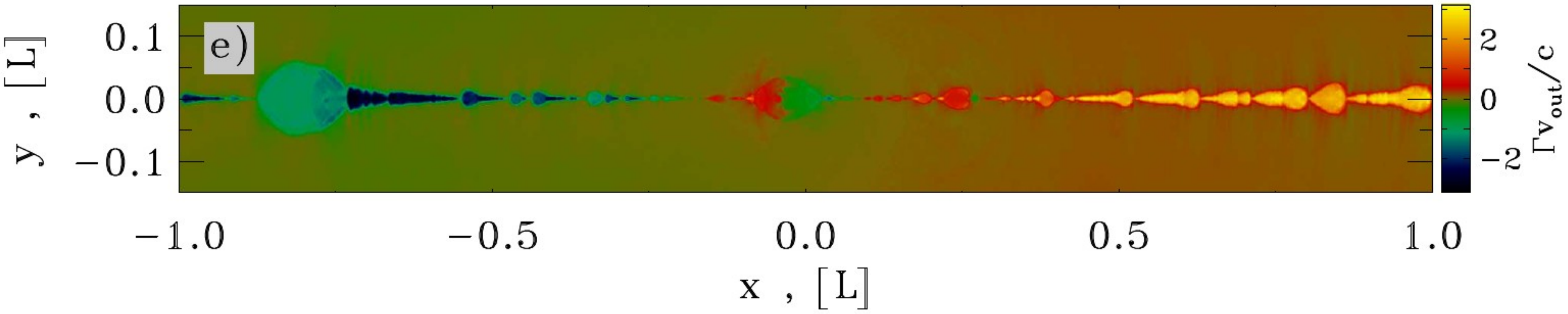


Jet bulk Lorentz factor combined with ultra-relativistic reconnection outflows :

$$\Gamma_{\rm em} = \Gamma_{\rm j}\Gamma_{\rm co}(1 + v_{\rm j}v_{\rm co}\cos\theta')$$

$\Gamma_{co} \approx \sqrt{\sigma}$ *[Lyubarsky 2005]*

[Giannios et al. 2009 ; Giannios 2013]



[Sironi+2016]

Application to pulsars

Some of the big questions

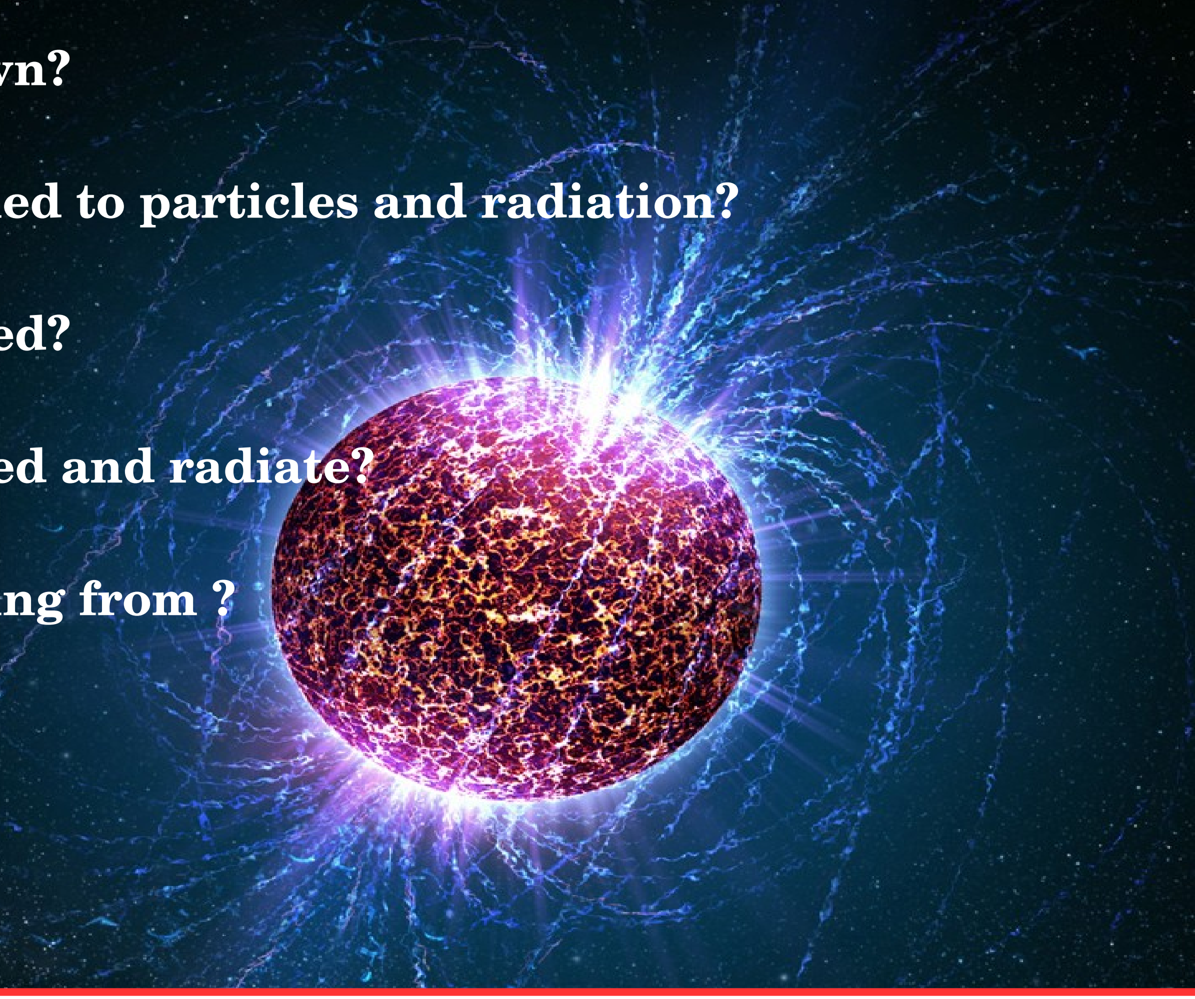
How does the star spin-down?

How is this energy channeled to particles and radiation?

How is the plasma generated?

How are particle accelerated and radiate?

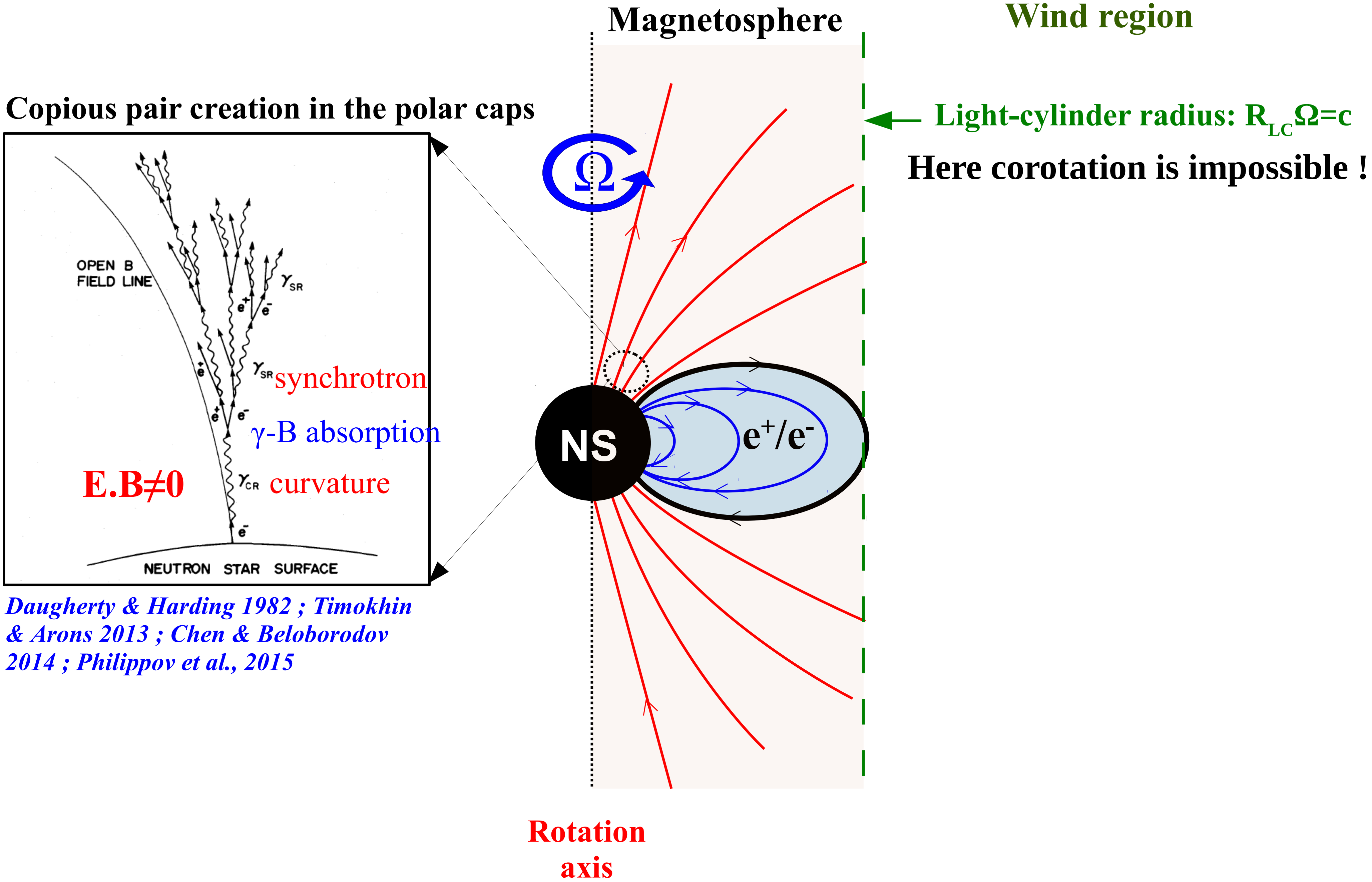
Where is the emission coming from ?



© Casey Reed

=> To address these questions, we need a model of the magnetosphere!

Elements of a pulsar magnetosphere



Magnetosphere

Wind region

Copious pair creation in the polar caps

synchrotron

γ-B absorption

curvature

E.B≠0

Daugherty & Harding 1982 ; Timokhin & Arons 2013 ; Chen & Beloborodov 2014 ; Philippov et al., 2015

Light-cylinder radius: $R_{LC}\Omega=c$

Here corotation is impossible !

Rotation axis

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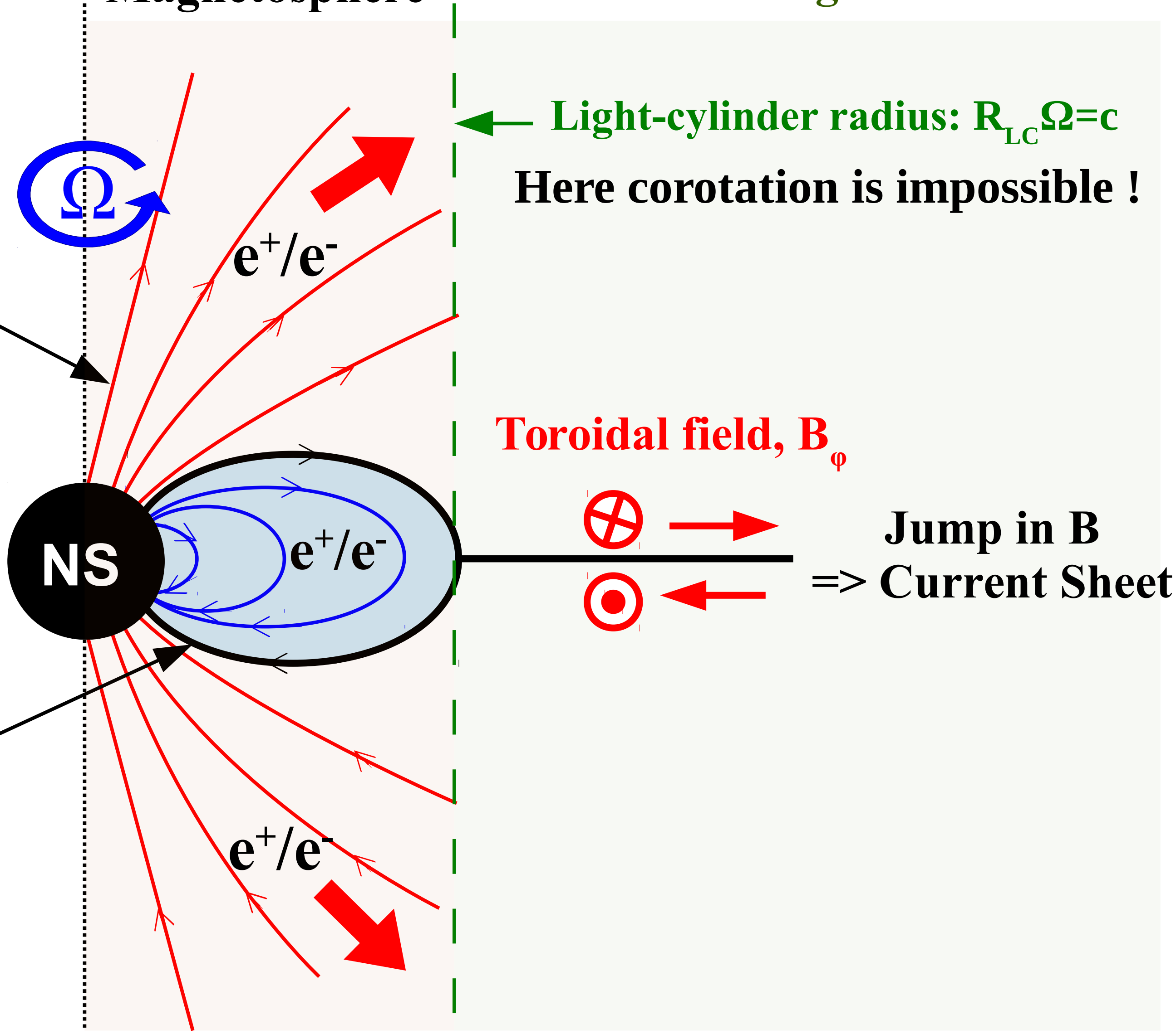
Elements of a pulsar magnetosphere



Magnetosphere

Wind region

“Open” field lines
Outflowing plasma and Poynting flux

Light-cylinder radius: $R_{LC}\Omega=c$

Here corotation is impossible !

Toroidal field, B_φ

Jump in B
=> Current Sheet

“Closed” field lines
Plasma confined, co-rotating
“Dead zone”

Rotation axis

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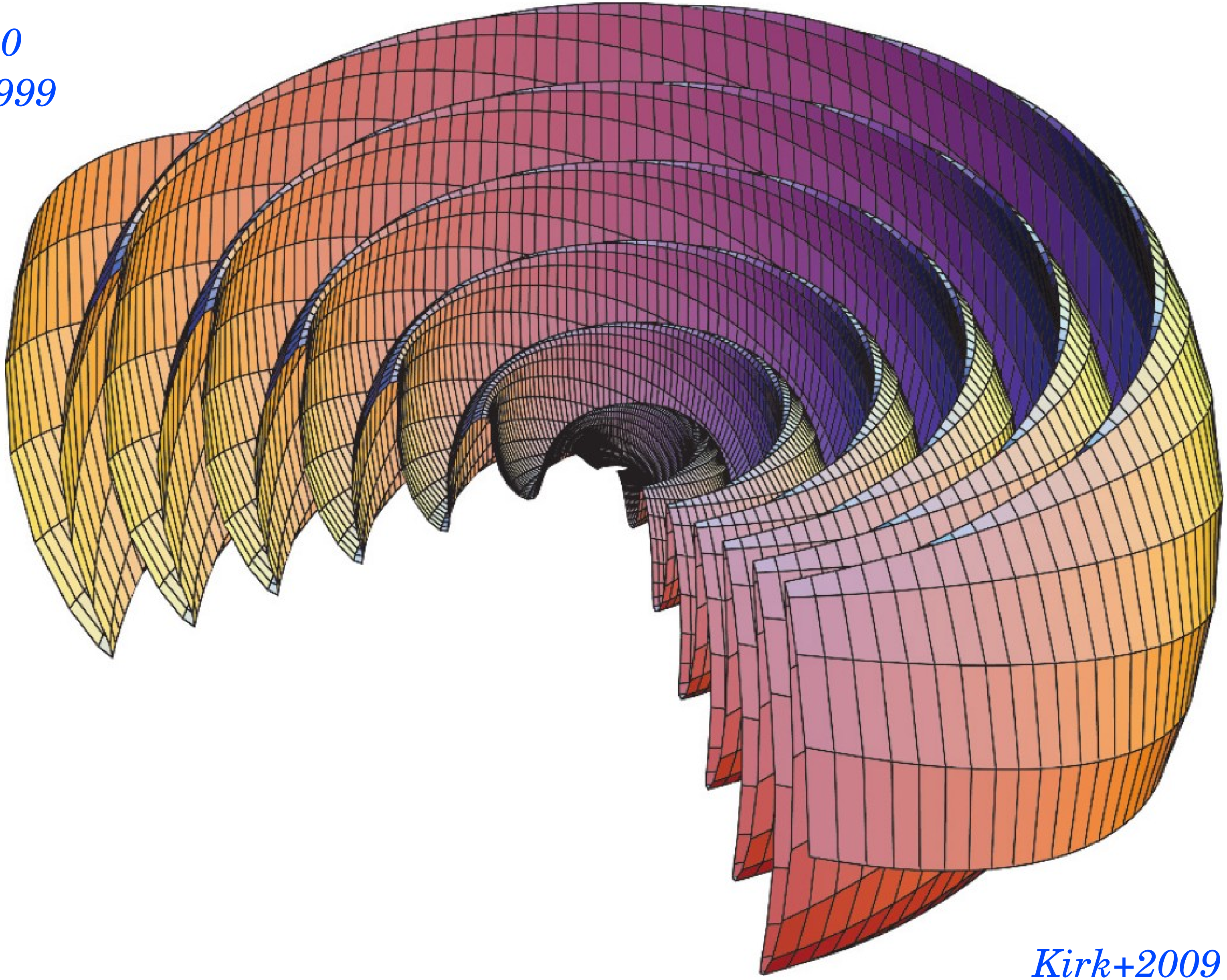
Inclined rotation : « Striped » pulsar current sheet

Coroniti 1990
Bogovalov 1999



Kirk+2009

Relativistic analog of the heliospheric current sheet

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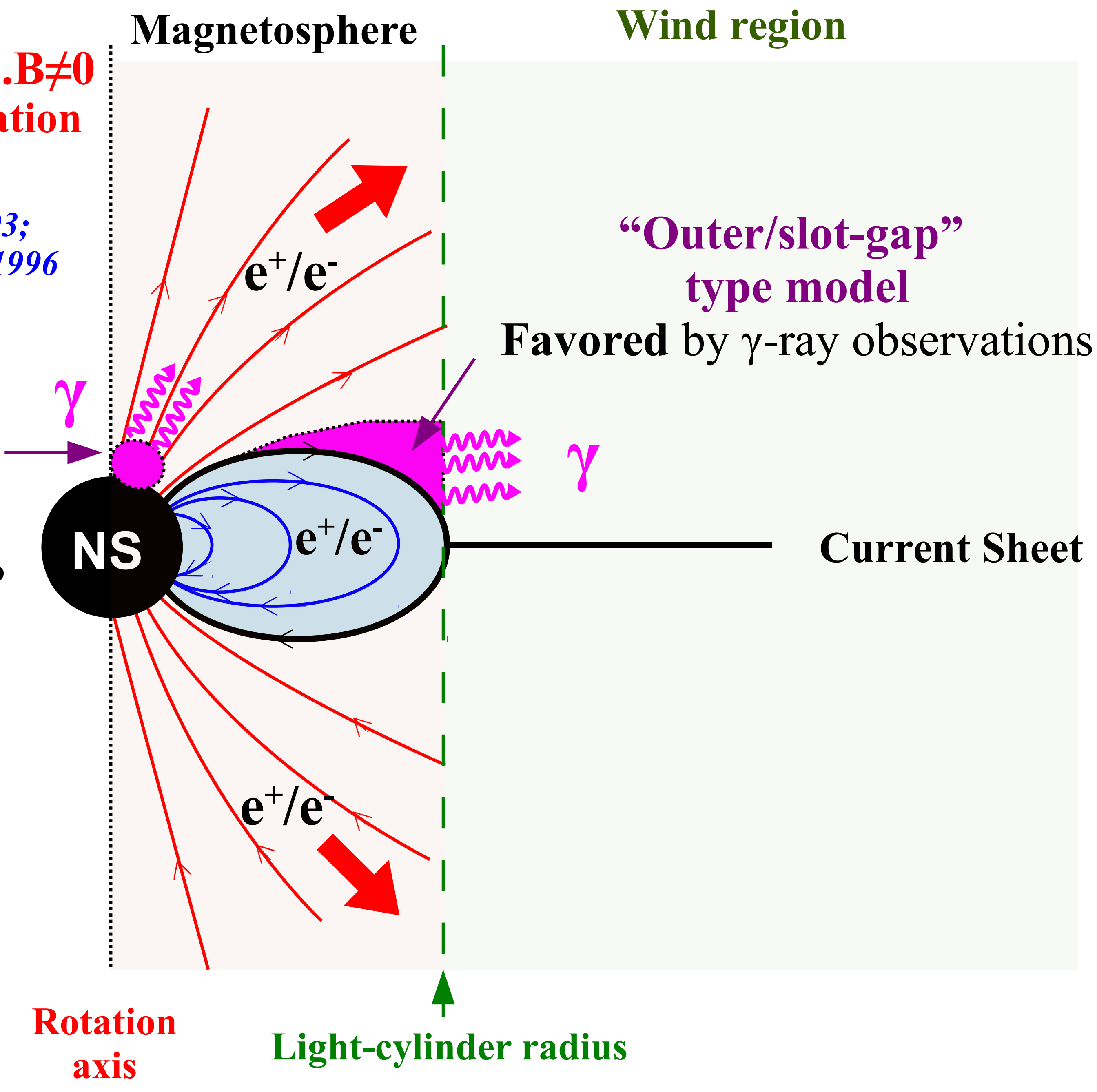
Proposed sites for particle acceleration

Acceleration in gaps, E.B≠0
γ-ray : curvature radiation

e.g. Arons 1983;
Muslimov & Harding 2003;
Cheng et al. 1986; Romani 1996



"Polar-cap" type model

- Radio emission ?
- γ-rays ?

Unlikely because absorbed by B

"Outer/slot-gap" type model

Favored by γ-ray observations

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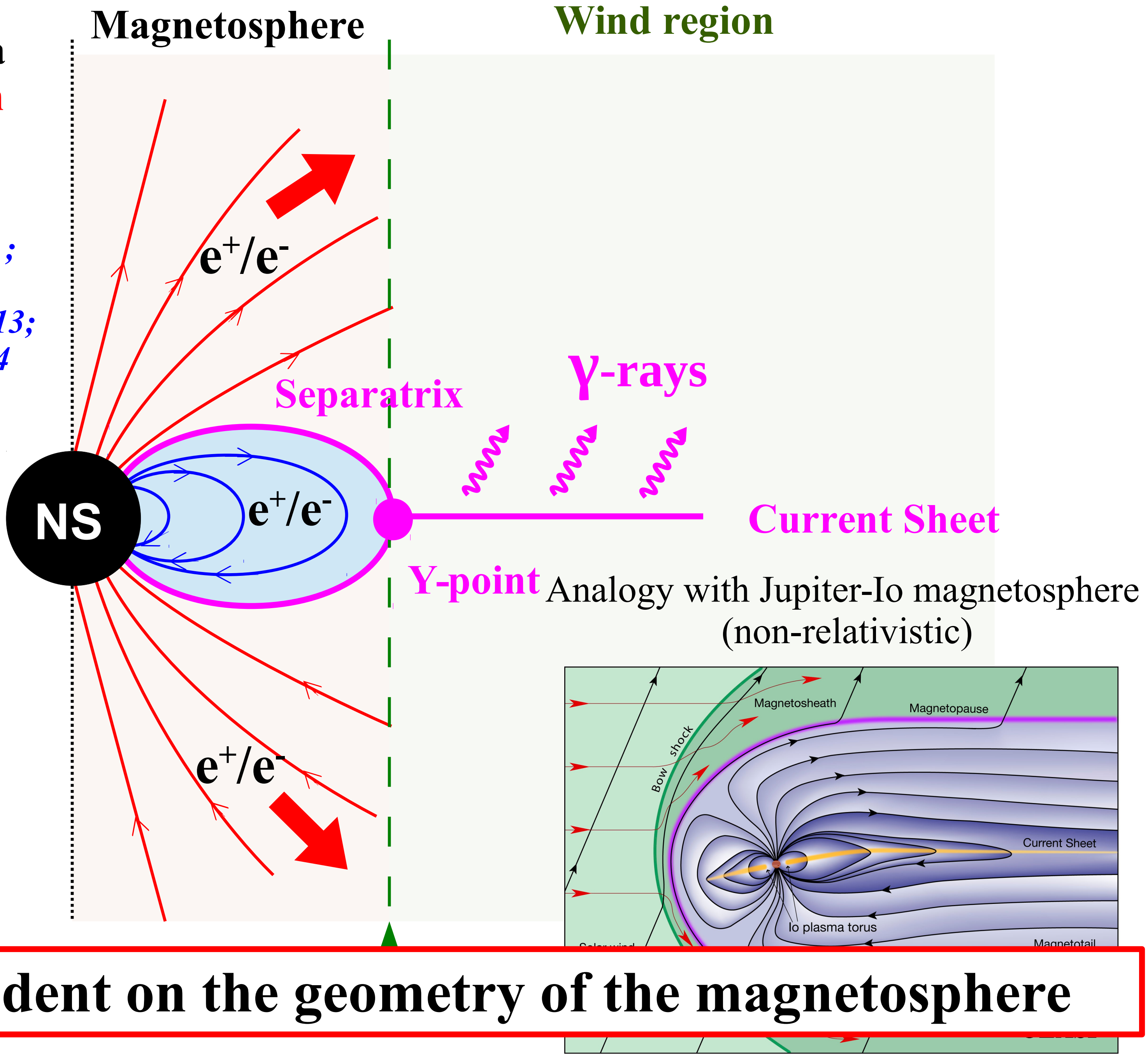
Proposed sites for particle acceleration

Particle acceleration via
relativistic reconnection
γ-ray: Synchrotron

Coroniti 1990 ;
Lyubarskii 1996 ; Kirk+2002 ;
Bai & Spitkovsky 2010 ;
Pétri 2012 ; Arka & Dubus 2013;
Uzdensky & Spitkovsky 2014
Mochol & Pétri 2015



Analogy with Jupiter-Io magnetosphere
(non-relativistic)

Models dependent on the geometry of the magnetosphere

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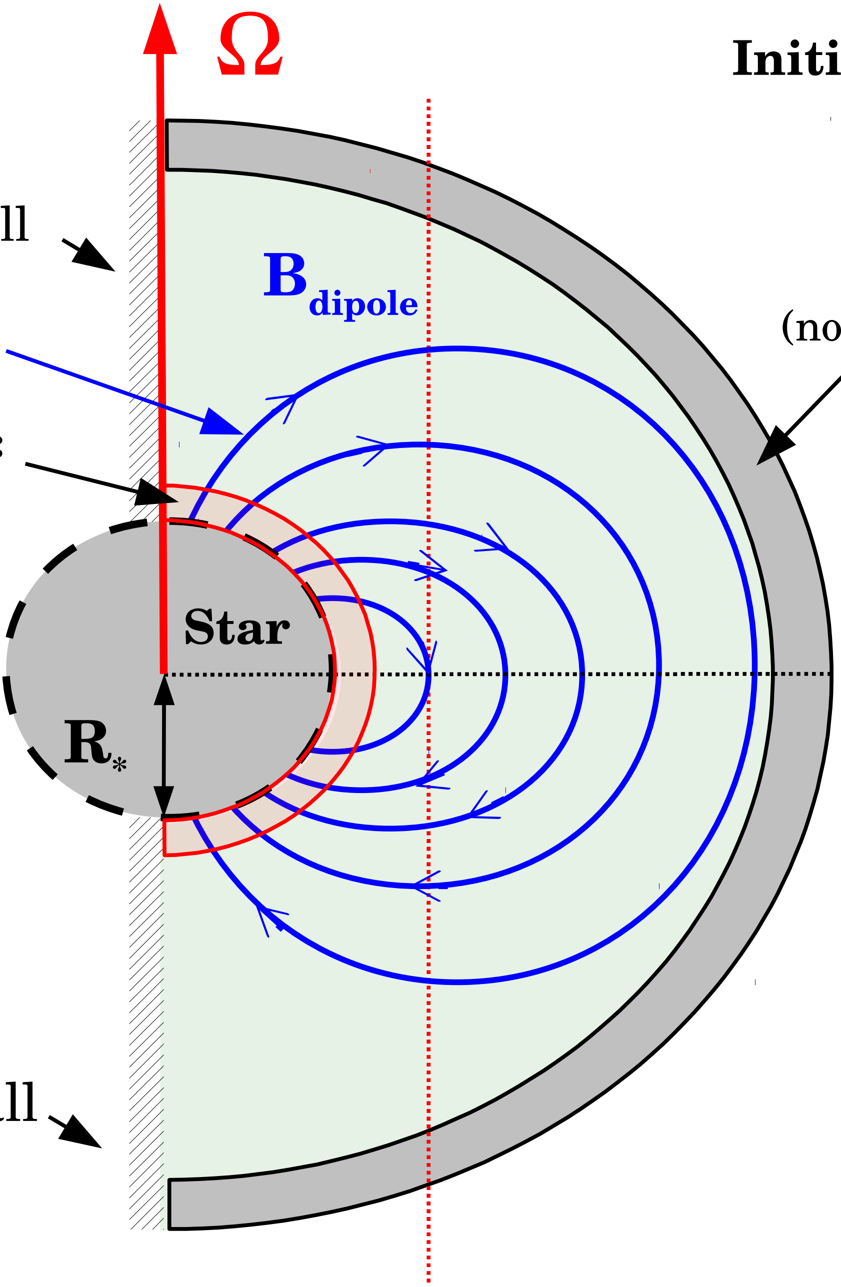
PIC setup : Aligned rotator (2D)

Philippov & Spitkovsky 2014
Chen & Beoborodov 2014
Cerutti et al. 2015
Belyaev 2015



Initially in vacuum

Reflecting wall

Dipole in vacuum

Absorbing layer
(no plasma, λE, λ*B terms)

Injection of particles :
Création of pairs e^+/e^-

Reflecting wall

Light cylinder radius

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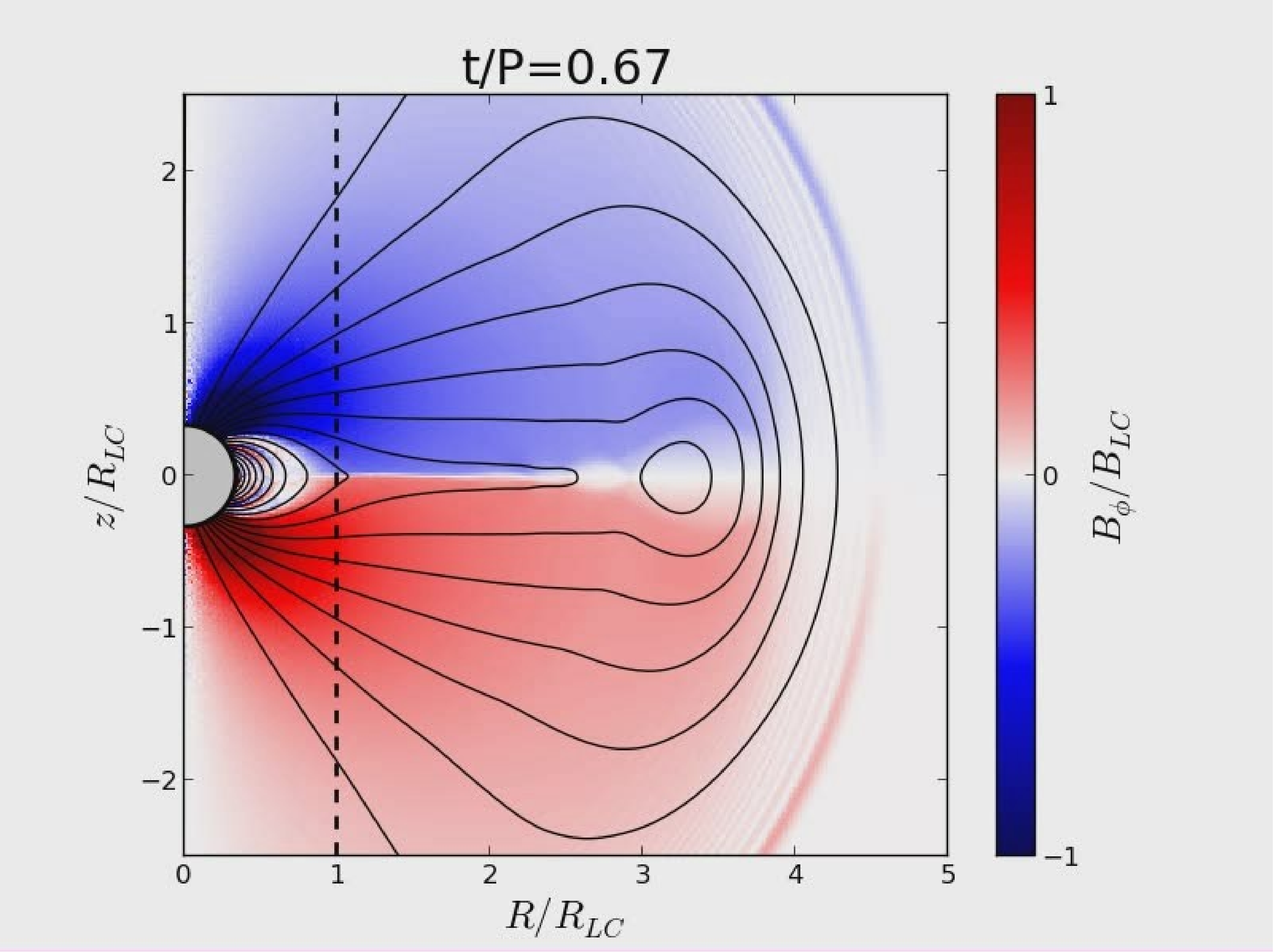
Toroidal magnetic field



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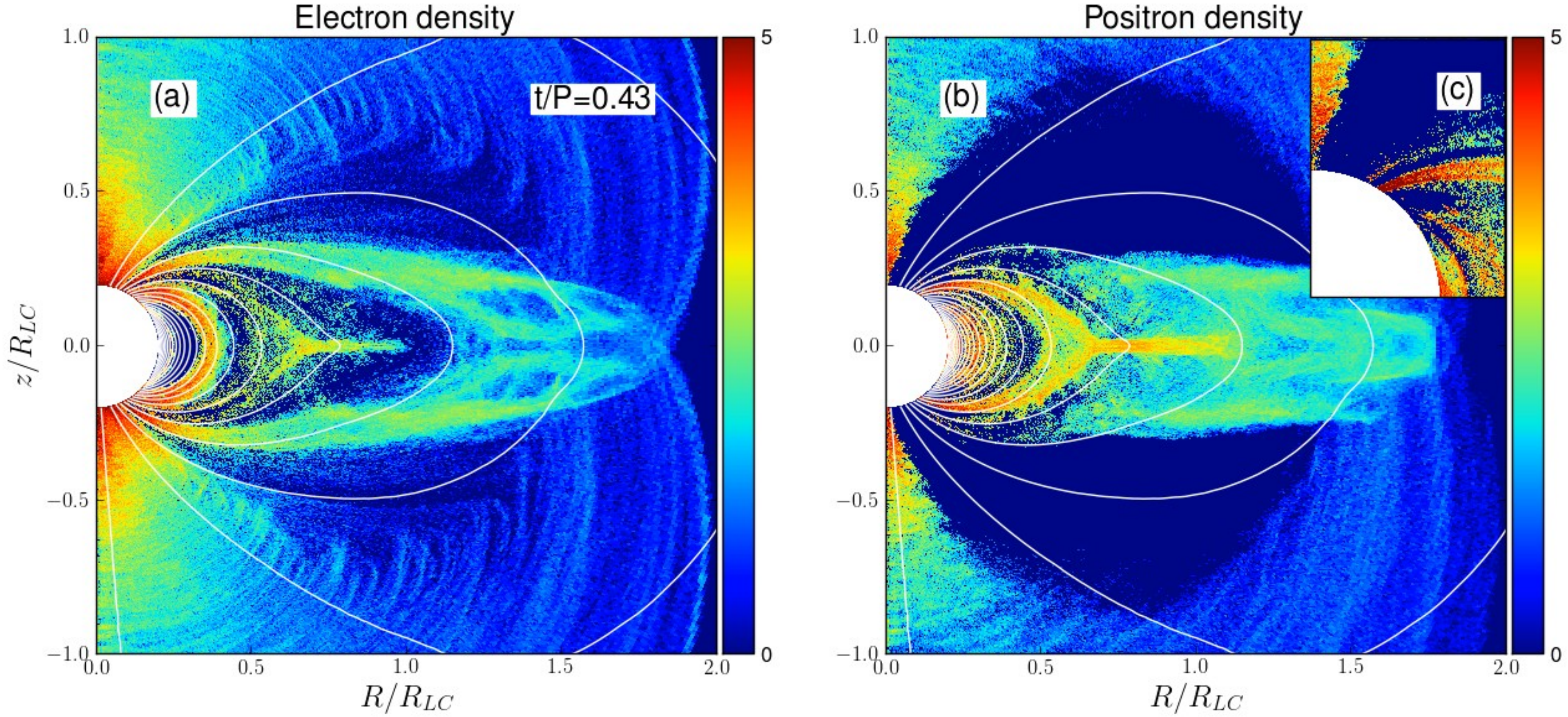
Cerutti et al. 2015

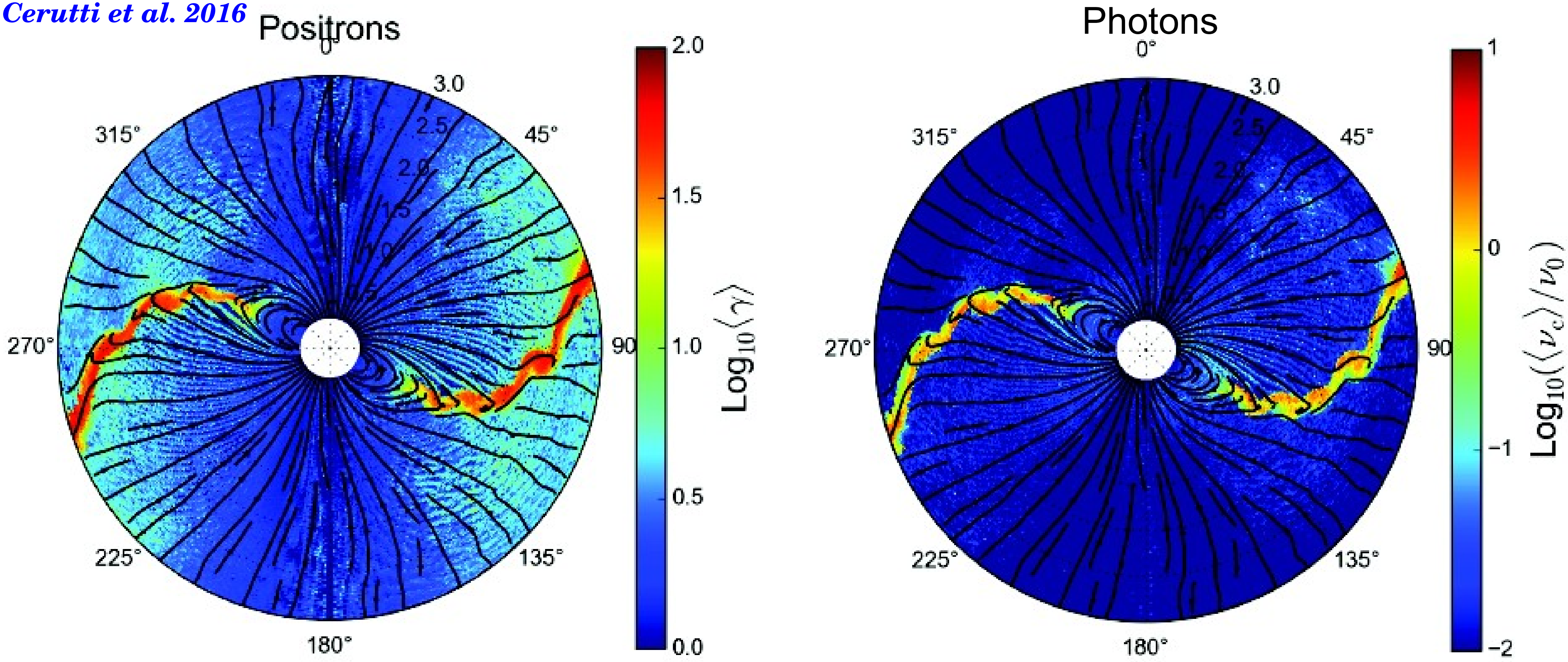
Plasma density, pair creation



Philippov et al. 2015

3D PIC : Particle / radiation mean energy (χ=30°)

Cerutti et al. 2016



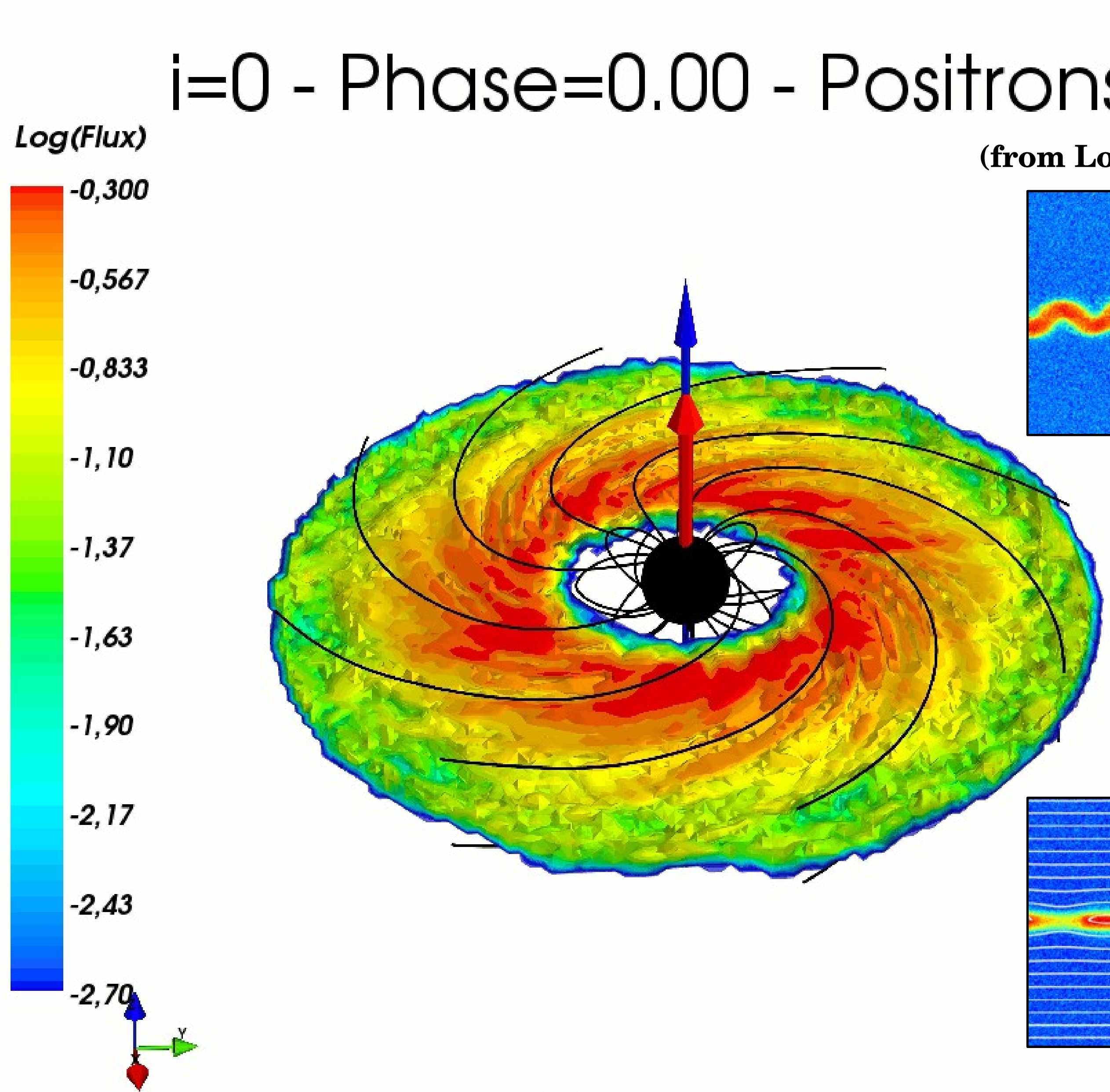
Particle acceleration via relativistic reconnection in the current sheet
High-energy radiation is synchrotron radiation

Particle energy in the sheet given by :

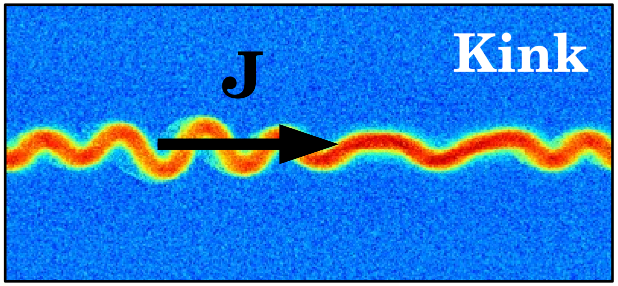
$$\boxed{\sigma_{LC}=\frac{B_{LC}^2}{4\pi\Gamma n_{LC} m_e c^2}\approx 50}$$

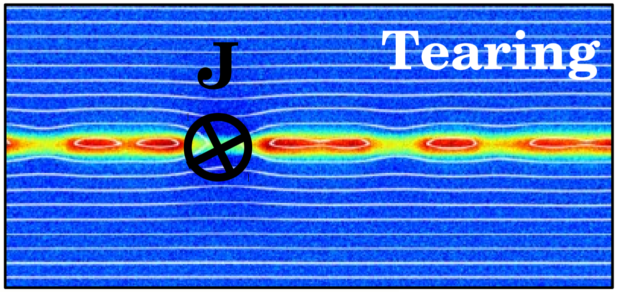
(here)

High-energy radiation flux ($\nu>\nu_0$, $\chi=0^\circ$)



(from Local reconnection simulations)





Presence of spatial irregularities due to kinetic instabilities in the sheet
e.g., kink and tearing modes

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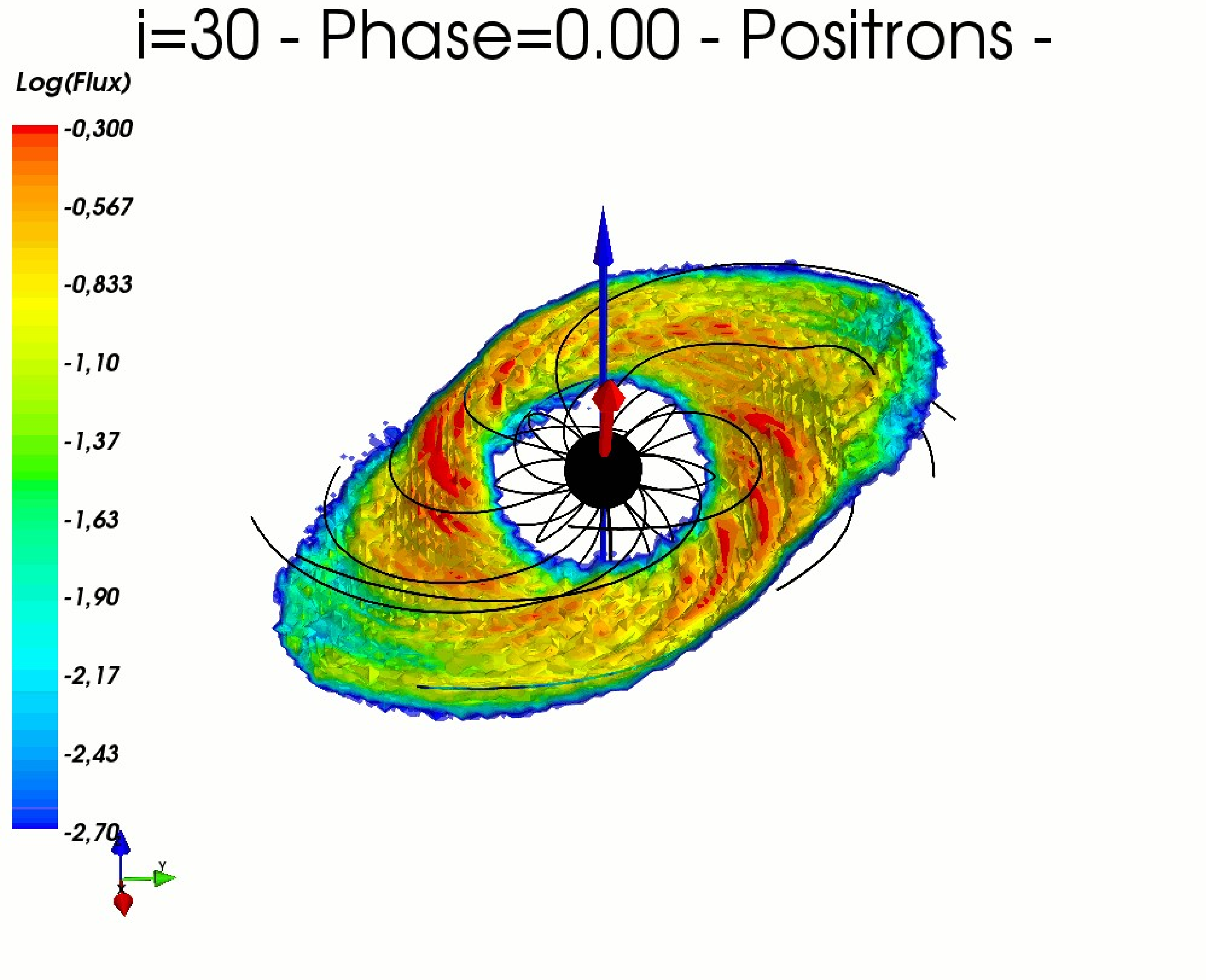
Cerutti et al. 2016

High-energy radiation flux ($\nu > \nu_0$, $\chi = 30°$)



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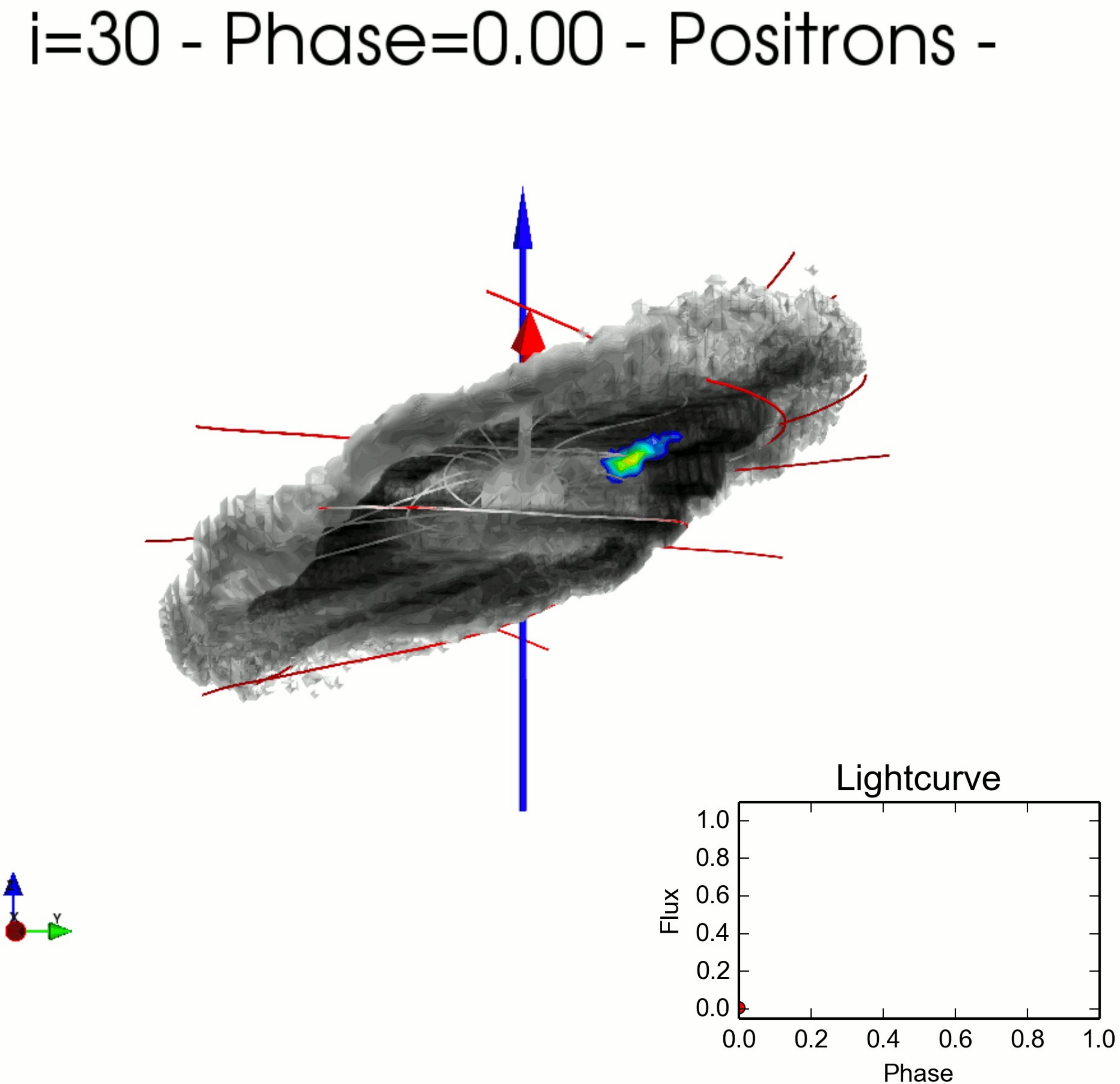
Cerutti et al. 2016


i=30 - Phase=0.00 - Positrons -
Z
X
Y
Lightcurve
Flux
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Phase

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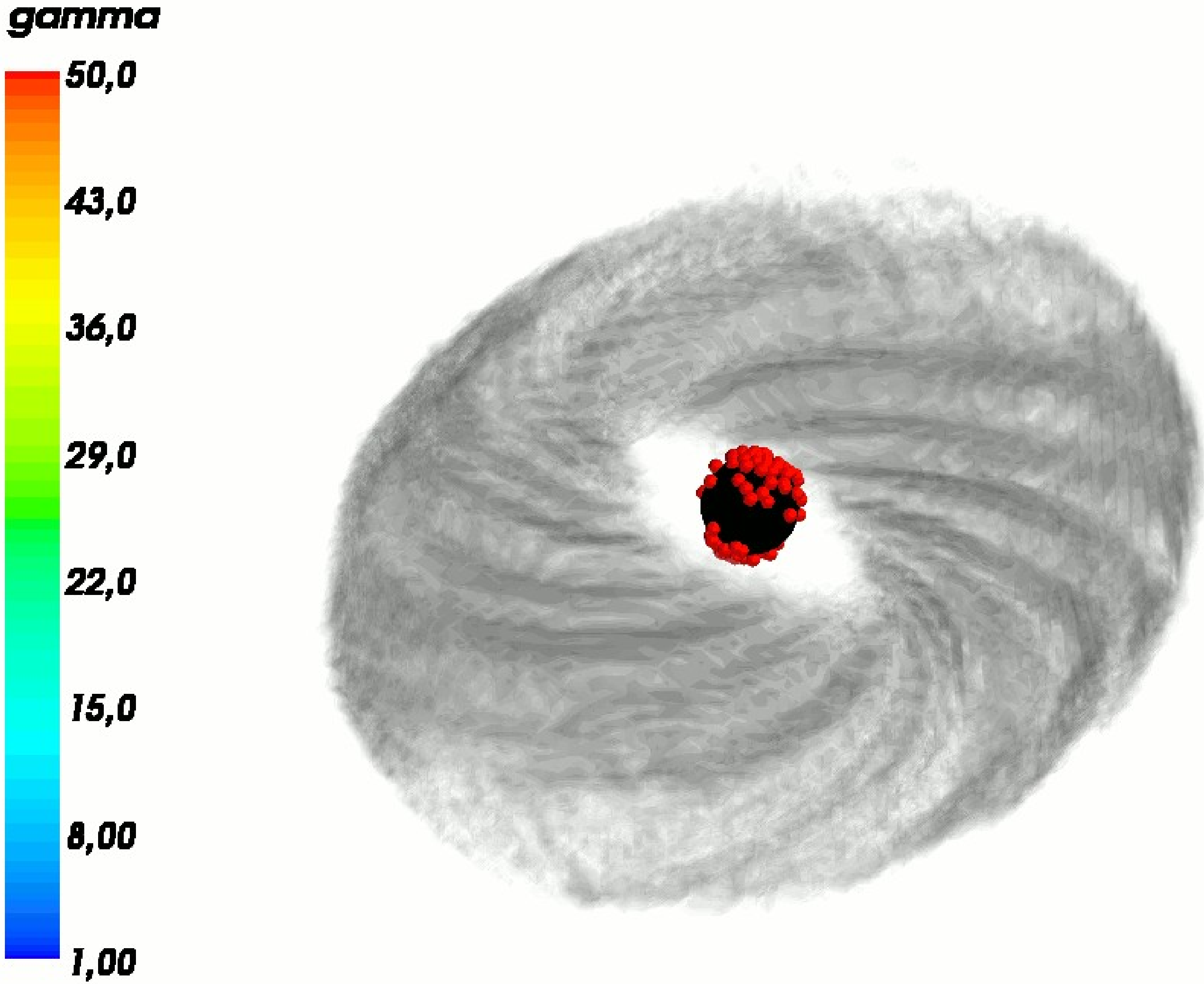
Tracked positrons



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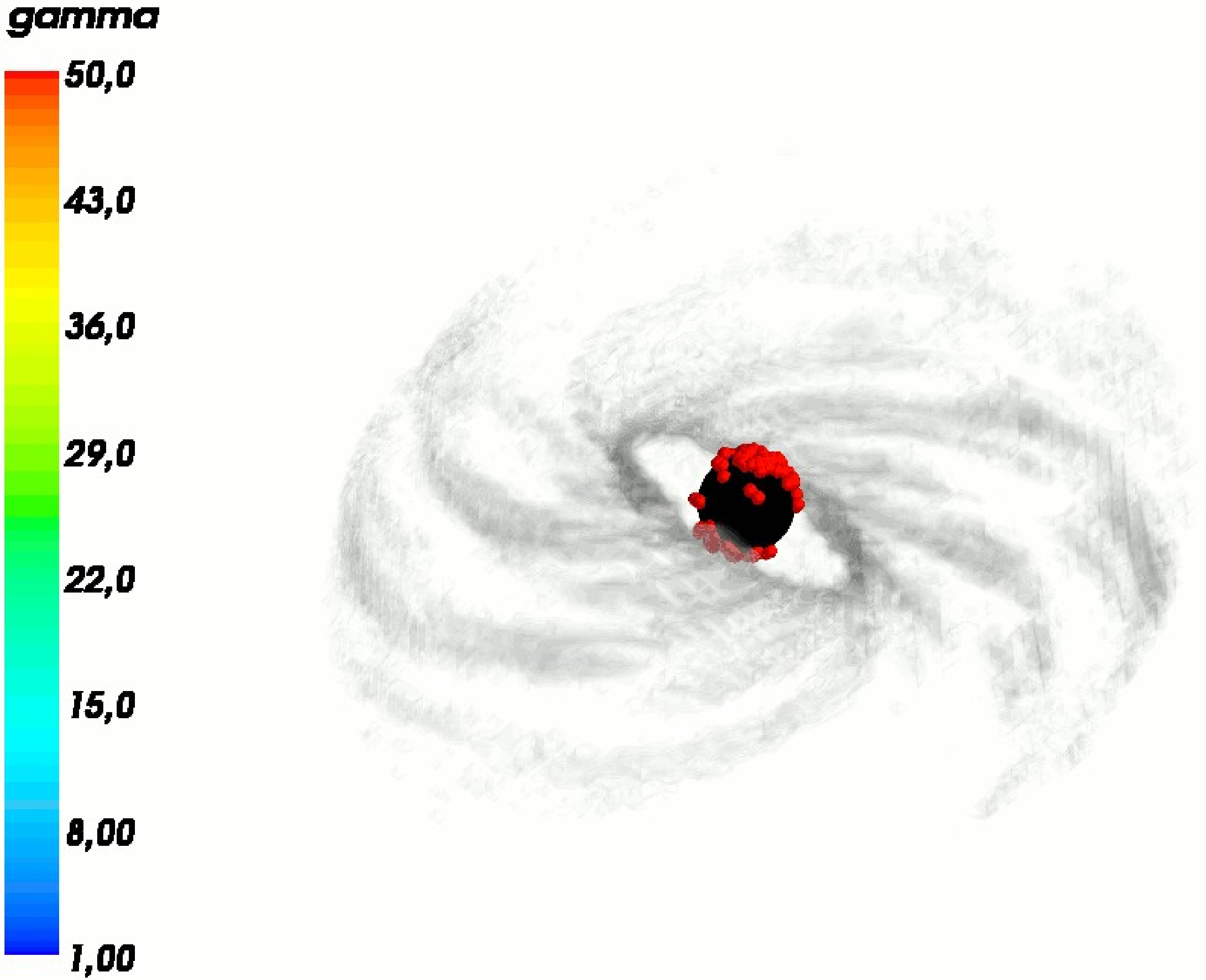
Tracked electrons



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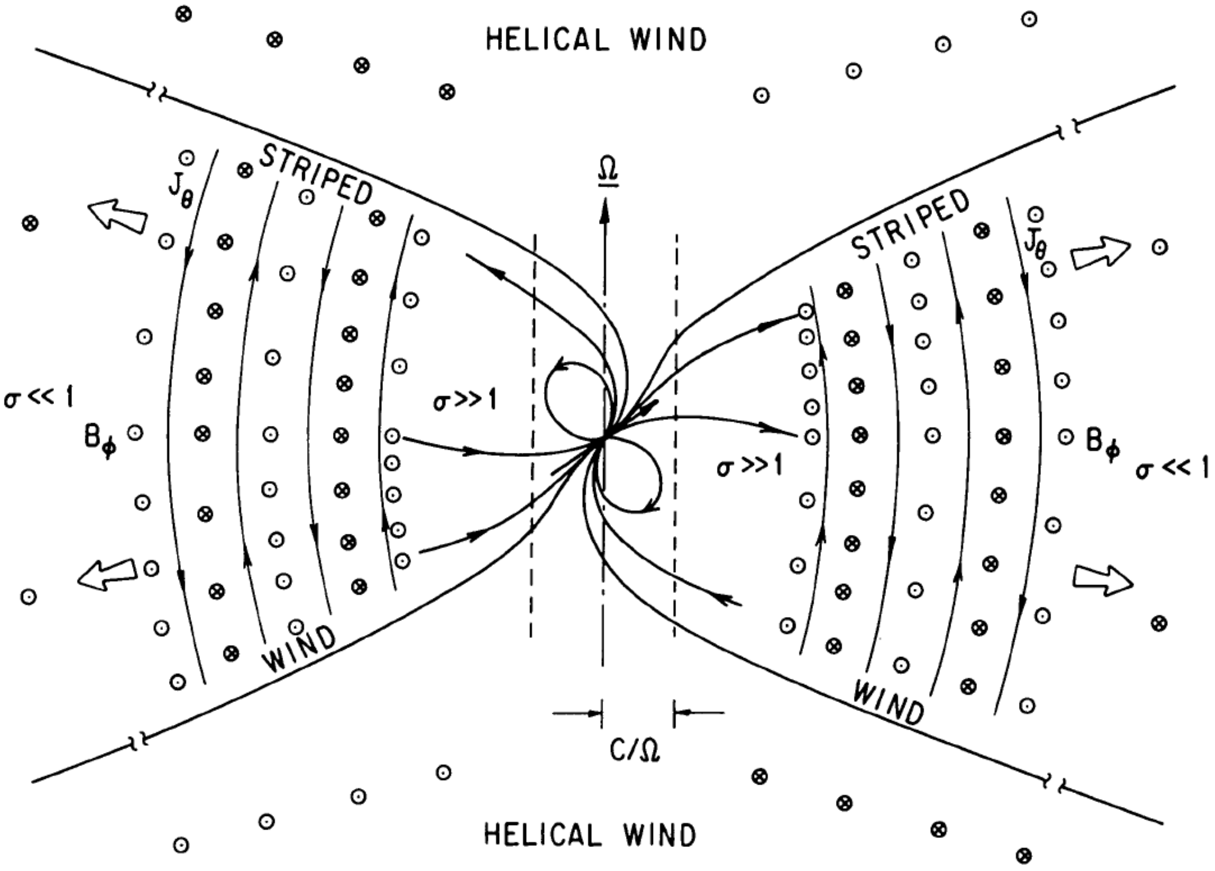
Dissipation in the wind

Close to light cylinder: ultra-magnetized plasma (σ>>1)
Nebula: Particle dominated (σ<<1)
=> Dissipation somewhere in between needed!

Coroniti 1990 ; Michel 1994 ; Lyubarsky & Kirk 2001 ; Kirk & Skjæraasen 2003 ; Zrake & Arons 2016



How far does magnetic reconnection proceeds in the wind?

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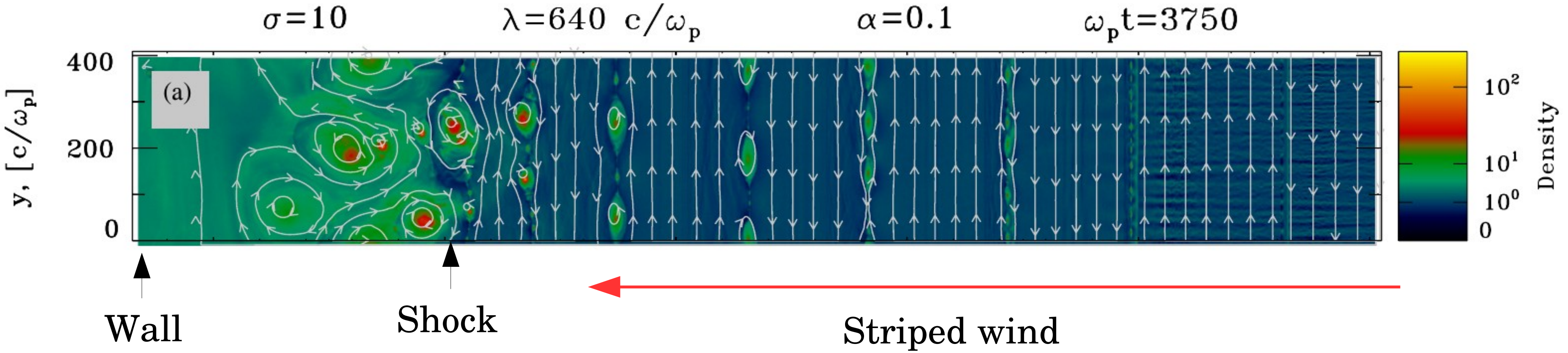
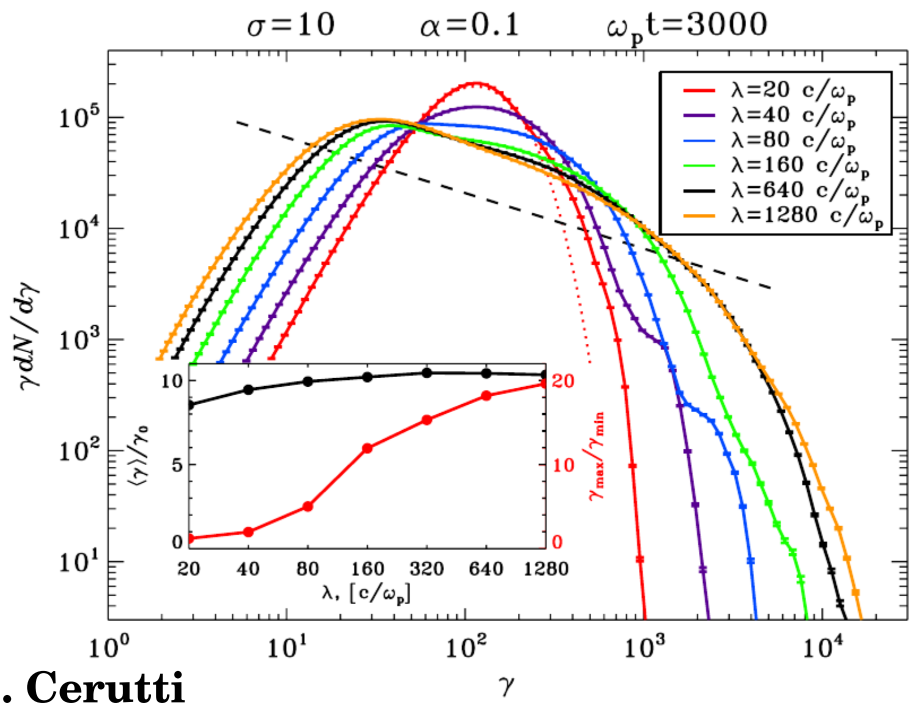
Shock-driven reconnection

If dissipation does not happen before the shock :

=> Shock-driven reconnection at the termination shock

[Lyubarsky 2003 ; Pétri & Lyubarsky 2007 ; Sironi & Spitkovsky 2011]





Non-nonthermal distribution if

$$\boxed{\frac{\lambda}{r_L \sigma} \gg 1}$$

<u>Otherwise</u> : **Maxwellian** distribution

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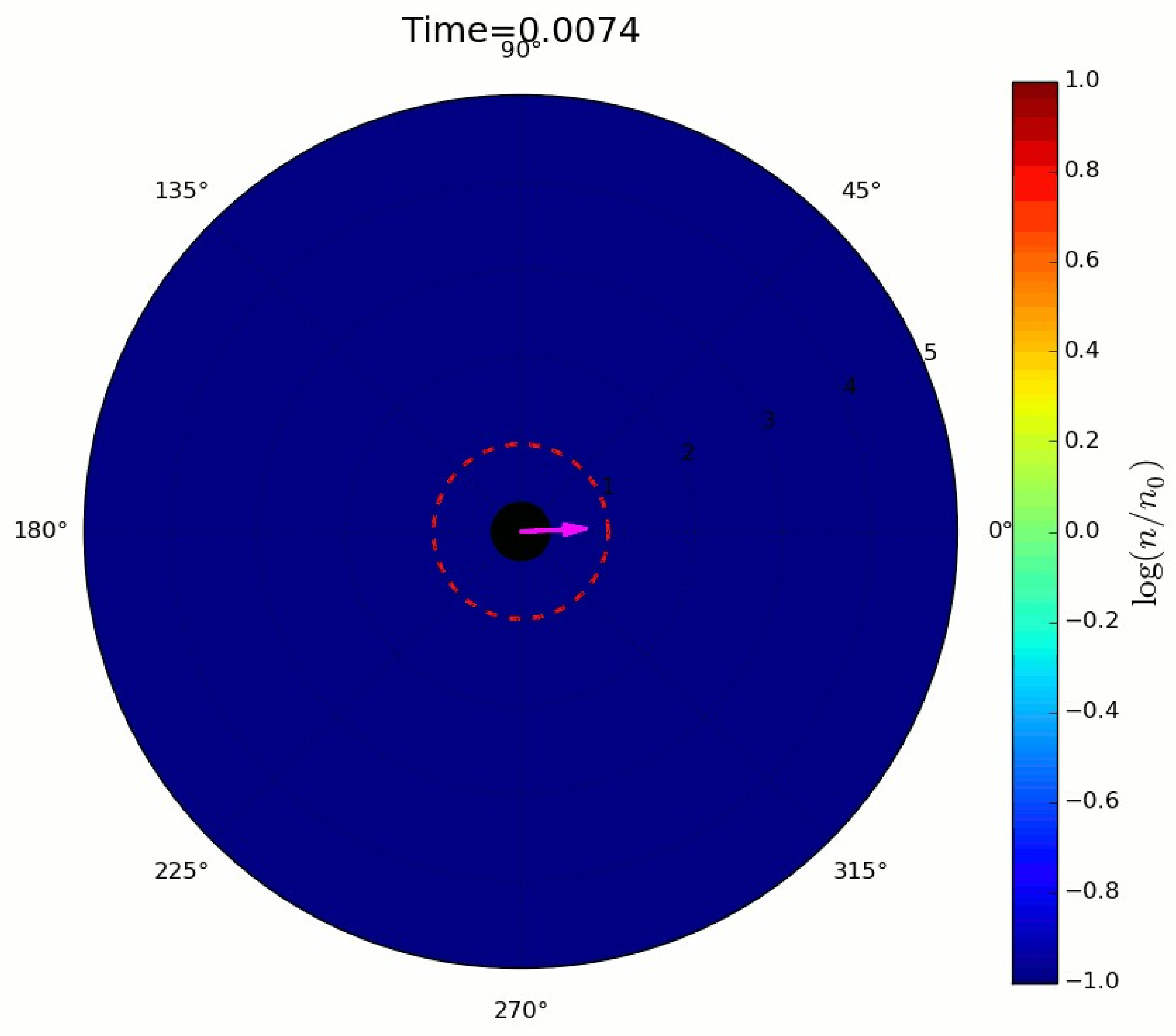

Small radii : *Turbulent-like* reconnection : Chain of plasmoids, mergers

Large radii (r>>RLC) : *Smooth, laminar dissipation*, islands frozen by adiabiatic expansion

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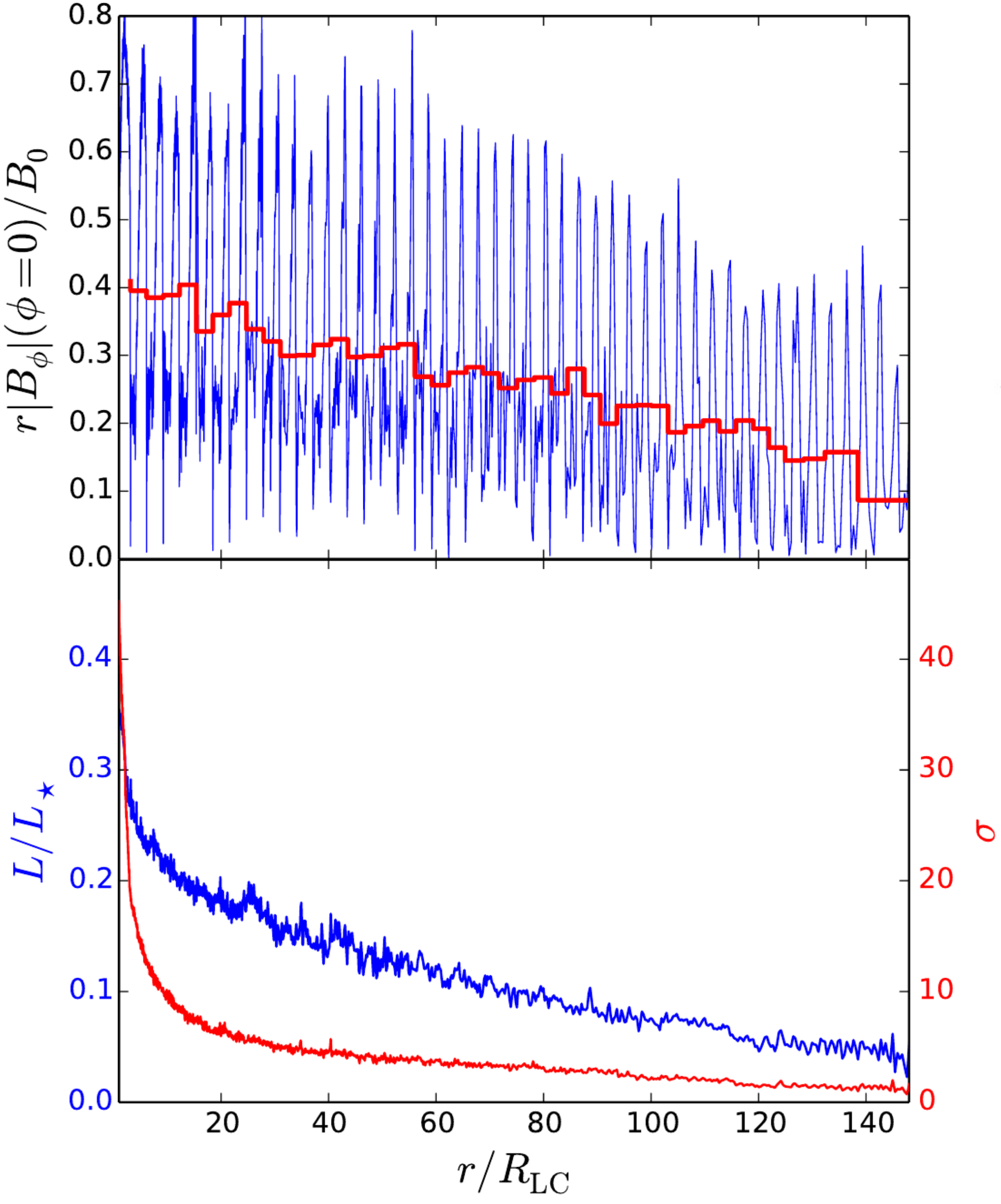
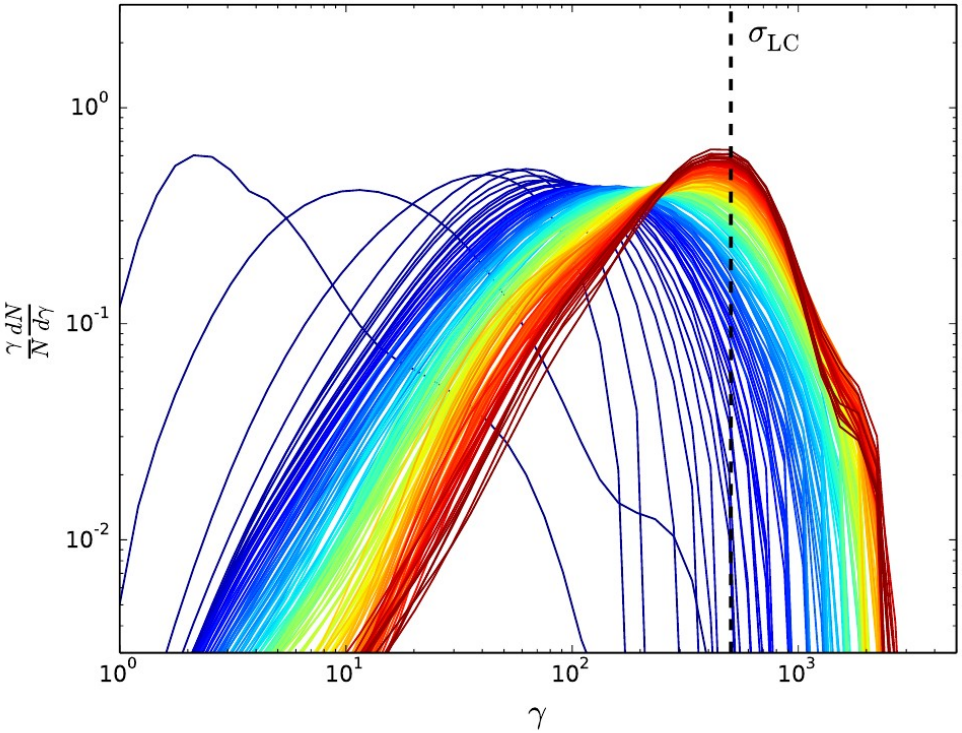
Cerutti & Philippov in prep

Dissipation in the wind



Particle spectra



Complete annihilation of the striped wind after a couple **100 $\mathbf{R_{LC}}$.**

Narrow particle energy distribution set by **$\boldsymbol{\sigma_{\rm LC}}$.**

Cerutti & Philippov in prep

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Conclusions

- Relativistic reconnection is **fast**, and **efficient at accelerating particles** !
  Viable **alternative to shock** acceleration in **magnetized environments**

- **Hard** particle energy spectra are expected.

- **Several acceleration sites identified, mostly X-points and mergers.**

- Maximum particle energy in the sheet not limited by **synchrotron losses**
  => Emission **>100 MeV synchrotron** radiation possible

- Crab gamma-ray flare most convincing case for relativistic reconnection.

- Application to **blazars flares**, **pulsar** magnetospheres, magnetized wind...

...and most likely more applications to come, stay tuned!