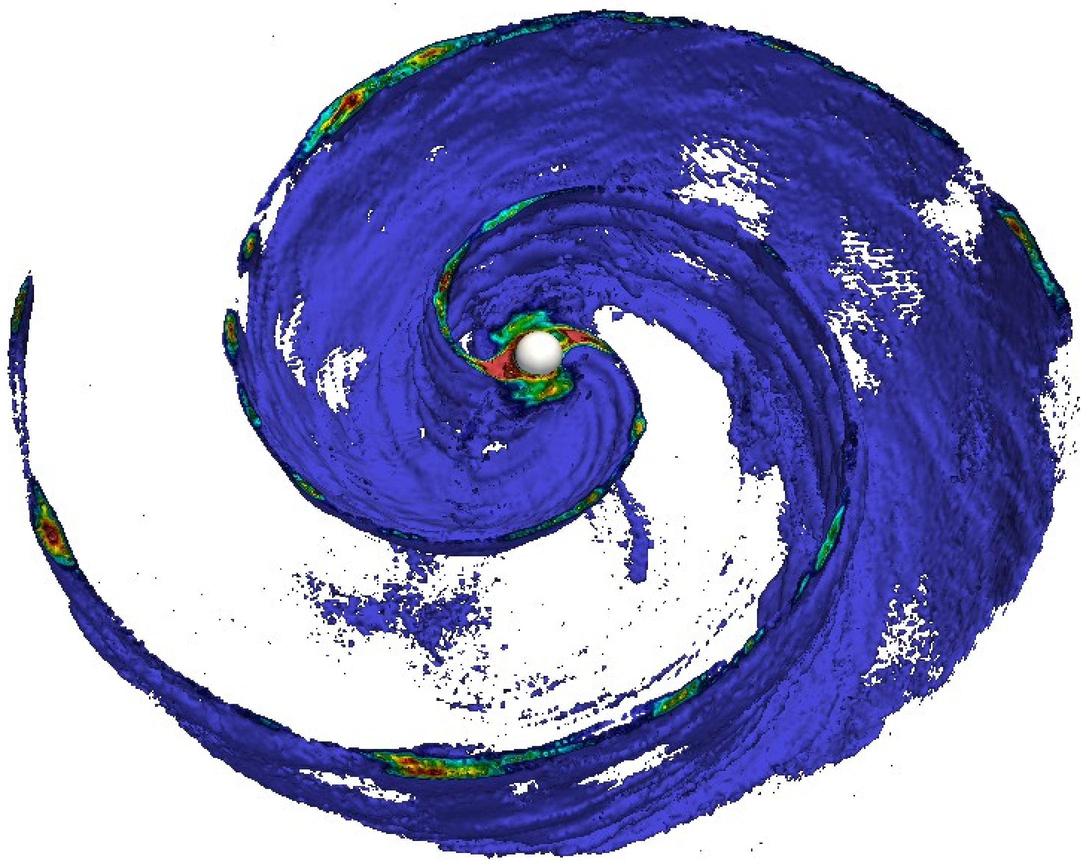
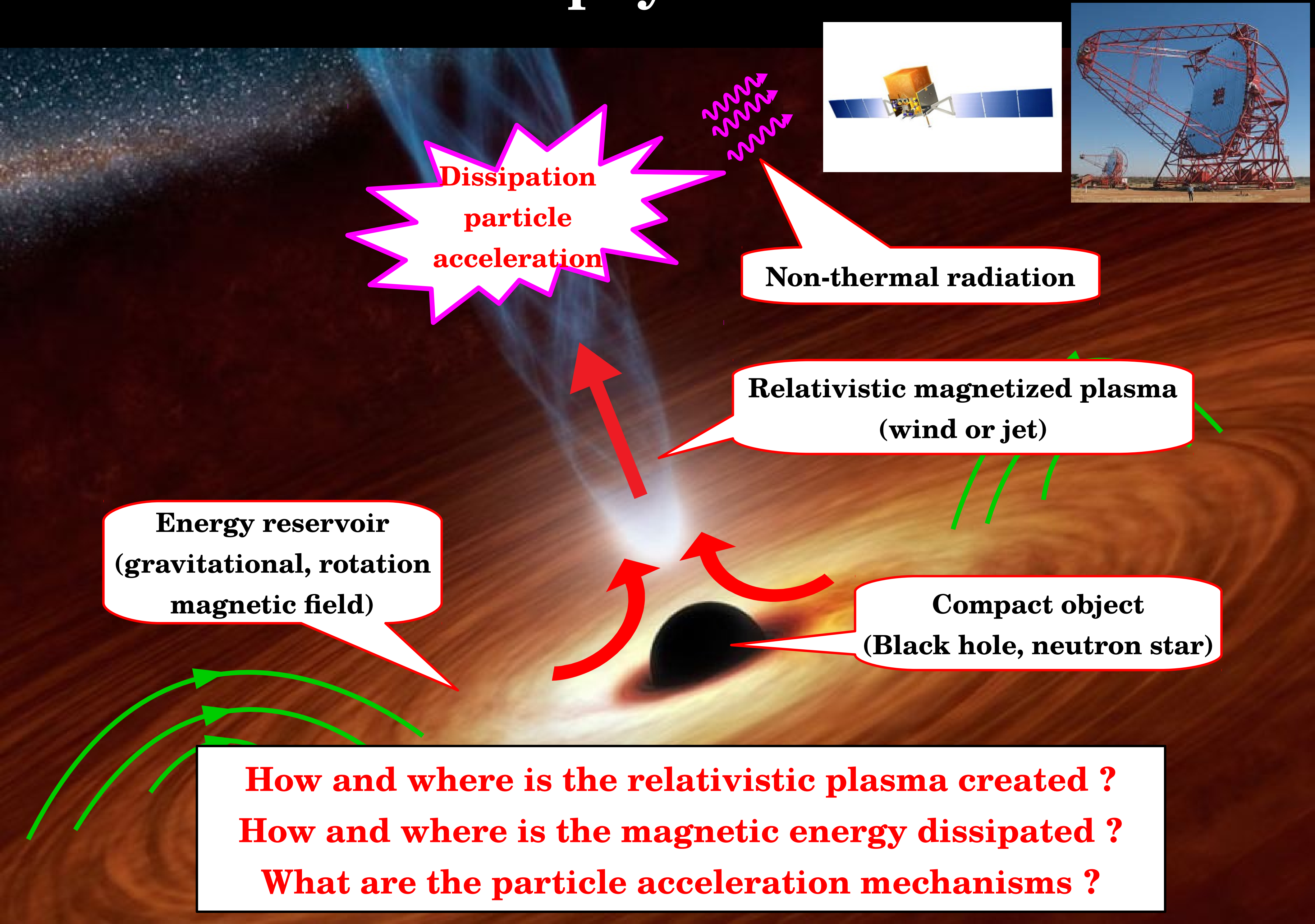
# Relativistic magnetospheres under the PICoscope

**Benoît Cerutti**, *Univ. Grenoble Alpes, CNRS, IPAG*



*Astrosim, Lyon, Oct. 8-11, 2018*

# General astrophysical motivations

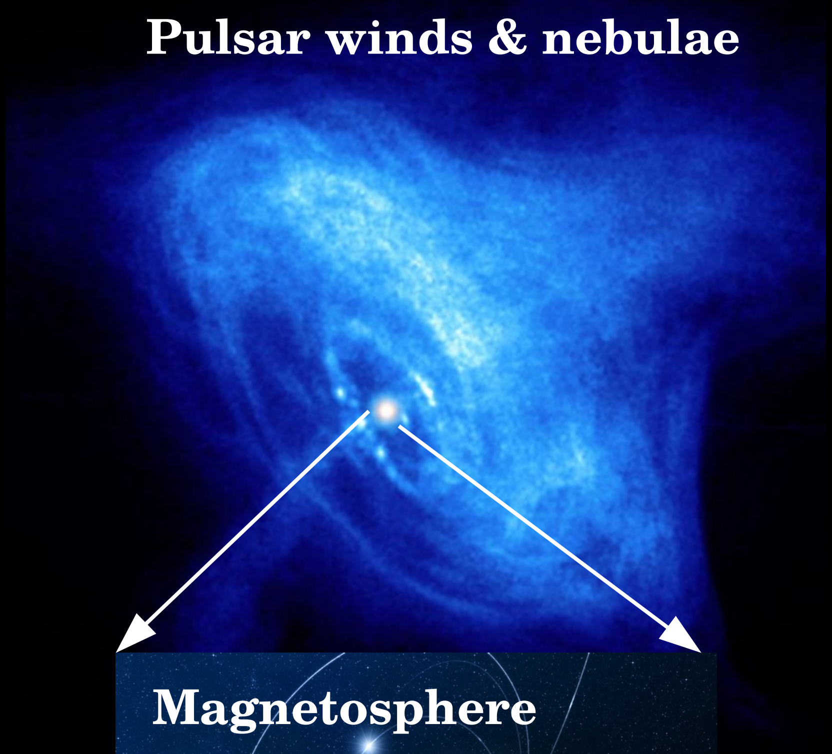



**How and where is the relativistic plasma created ?**

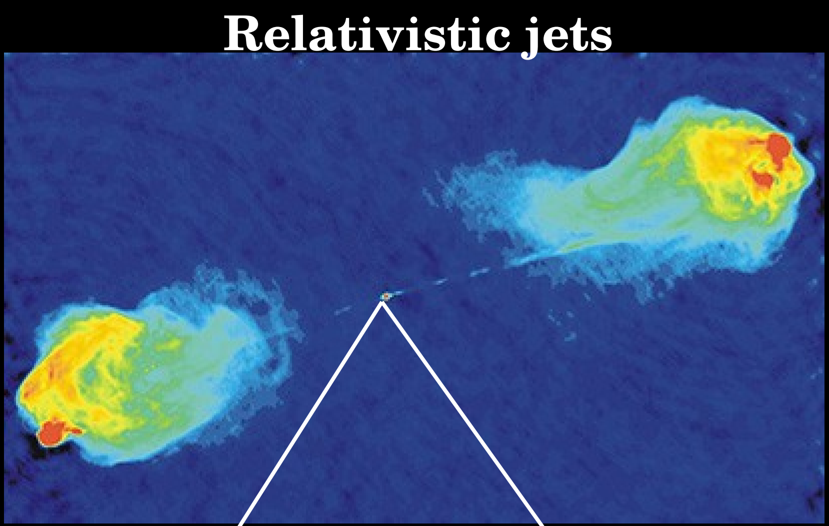
**How and where is the magnetic energy dissipated ?**

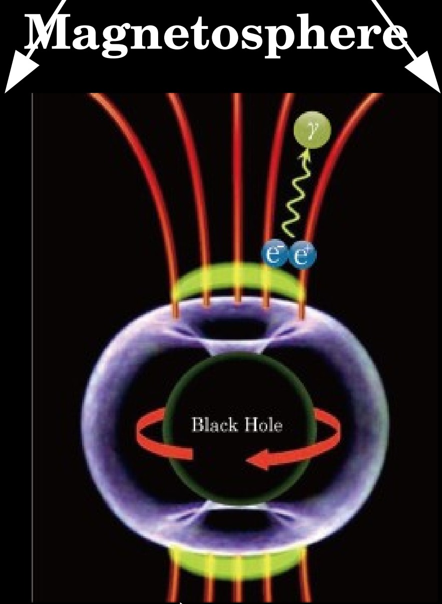
**What are the particle acceleration mechanisms ?**

# Relativistic magnetospheres







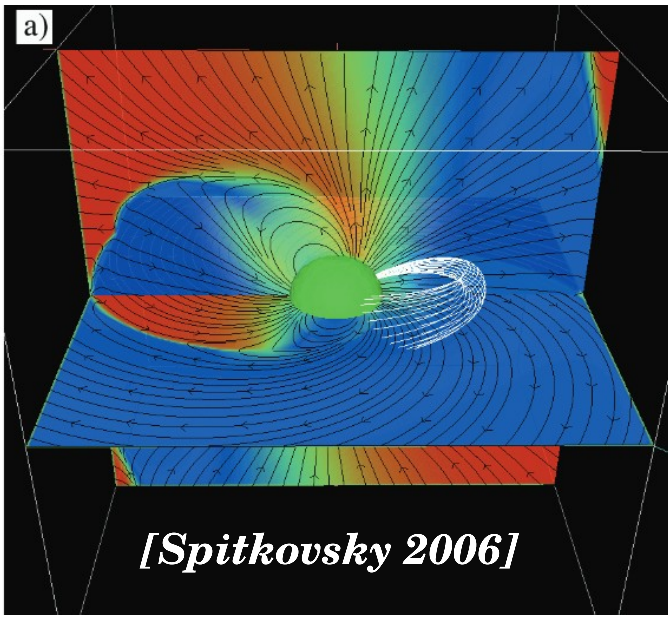

Plasma regime :

- Relativistic (GR, pair creation, ...)
- Collisionless (No Coulomb)
- Ultra-magnetized
- Non-thermal, and radiative

# The need to go beyond MHD

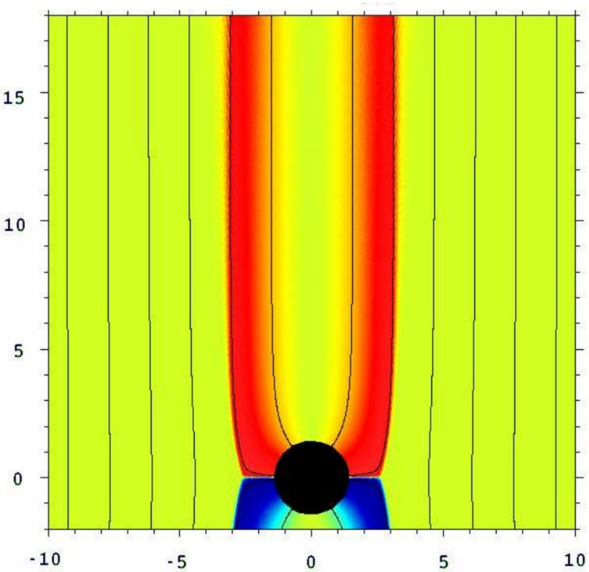
**MHD simulations**

**Oblique pulsar magnetosphere**




*[Spitkovsky 2006]*

**Kerr black hole in uniform B field**




*[Komissarov 2005]*

MHD simulations give the overall magnetospheric structure, fields and currents right.

But they cannot capture :

- particle acceleration and non-thermal radiative processes
- dissipative collisionless processes (e.g., reconnection)
- plasma generation (pair creation)
- very low densities, or plasma gaps (density floor)
- highly magnetized plasmas (magnetization $\sigma \gg 1$)

**Needs for more physics => Kinetic approach**

# Two numerical approaches to solve Vlasov

**Kinetic & Collisionless :**

$$\frac{\partial f}{\partial t}+\frac{\boldsymbol{p}}{\gamma m}\cdot\frac{\partial f}{\partial \boldsymbol{r}}+q\left(\boldsymbol{E}+\frac{\boldsymbol{v}\times\boldsymbol{B}}{c}\right)\cdot\frac{\partial f}{\partial \boldsymbol{p}}=0$$

**Ab-initio model, no approximations**

## Directly with a Vlasov-code

**Treat phase space as a continuum fluid**

**Advantages:**

- **No noise**, good if tail of f is important dynamically (steep power-law).
- No issue if plasma very **inhomogeneous**.
- **Weak** phenomena can be captured

**Limitations:**

- Problem **(6+1)D**, hard to fit in the memory, limited resolution.
- Filamentation of the phase space
  But becoming more competitive, new development to come, stay tuned!

## Indirectlty with a PIC code

**Sample phase space with particles**

**Advantages:**

- Conceptually **simple**
- **Robust** and **easy to implement.**
- Easily **scalable** to large number of cores

**Limitations:**

- **Shot noise**, difficult to sample uniformly f,
- Artificial collisions, requires many particles
- Hard to capture weak/subtle phenomenas
- Load-balancing issues

# The particle approach

The Vlasov equation can be written in the form of **an advection equation:**

$$\frac{\partial f}{\partial t}+\frac{\boldsymbol{p}}{\gamma m}\cdot\frac{\partial f}{\partial \boldsymbol{r}}+q\left(\boldsymbol{E}+\frac{\boldsymbol{v}\times\boldsymbol{B}}{c}\right)\cdot\frac{\partial f}{\partial \boldsymbol{p}}=0 \quad \Rightarrow \quad \frac{\partial f}{\partial t}+\nabla\left(f\,\boldsymbol{U}\right)=0$$

Vlasov equation can be solved along **characteristics curves** along which it has the form of a set of ordinary differential equations (the method of characteristics):

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

Lorentz-Newton equation

$$\frac{d\boldsymbol{r}}{dt}=\boldsymbol{v}$$

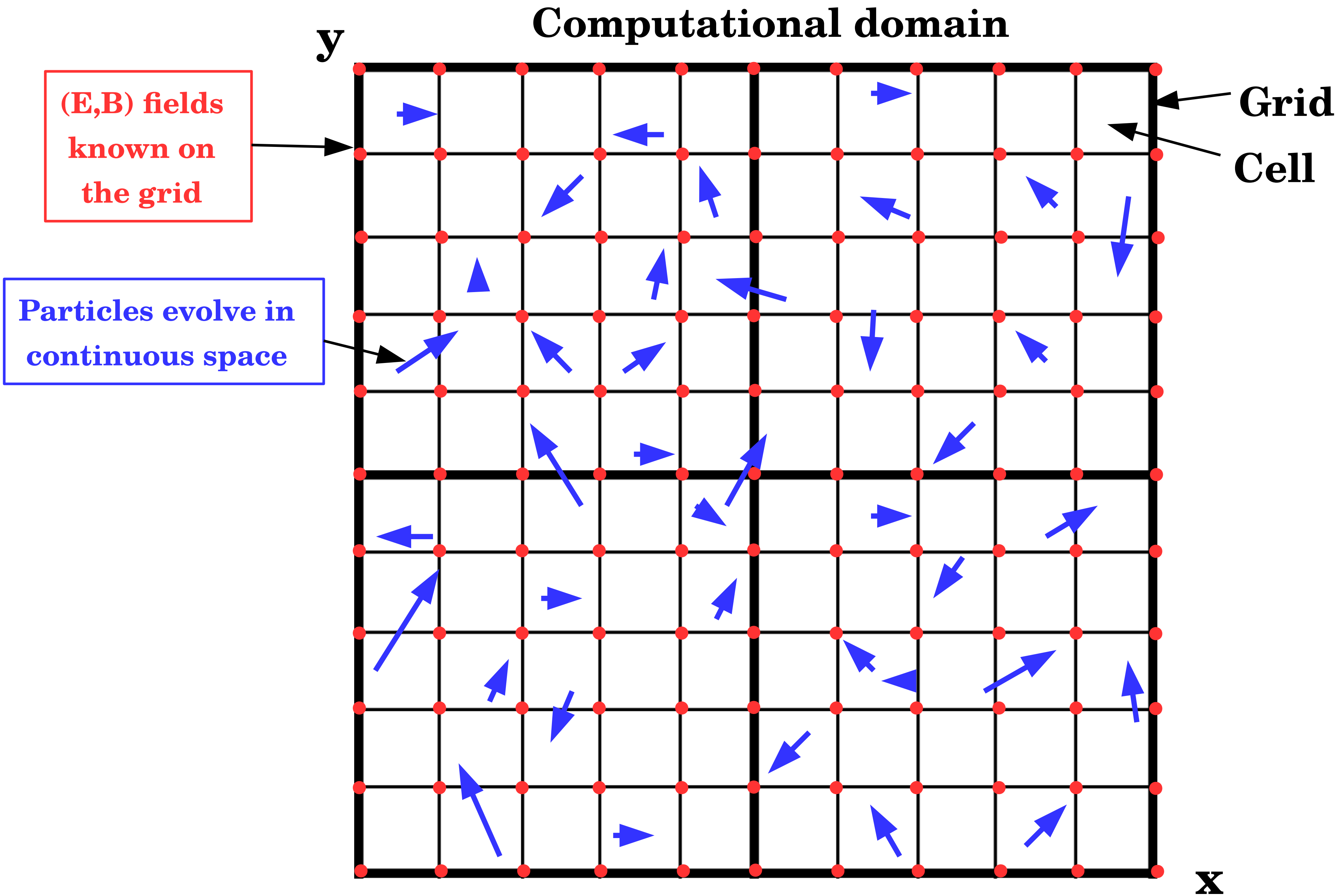
The **characteristics curves** corresponds to the **trajectory of individual particles**!

Hence, we can **probe Vlasov equation by solving for the motion of particles**, the larger number, the better!

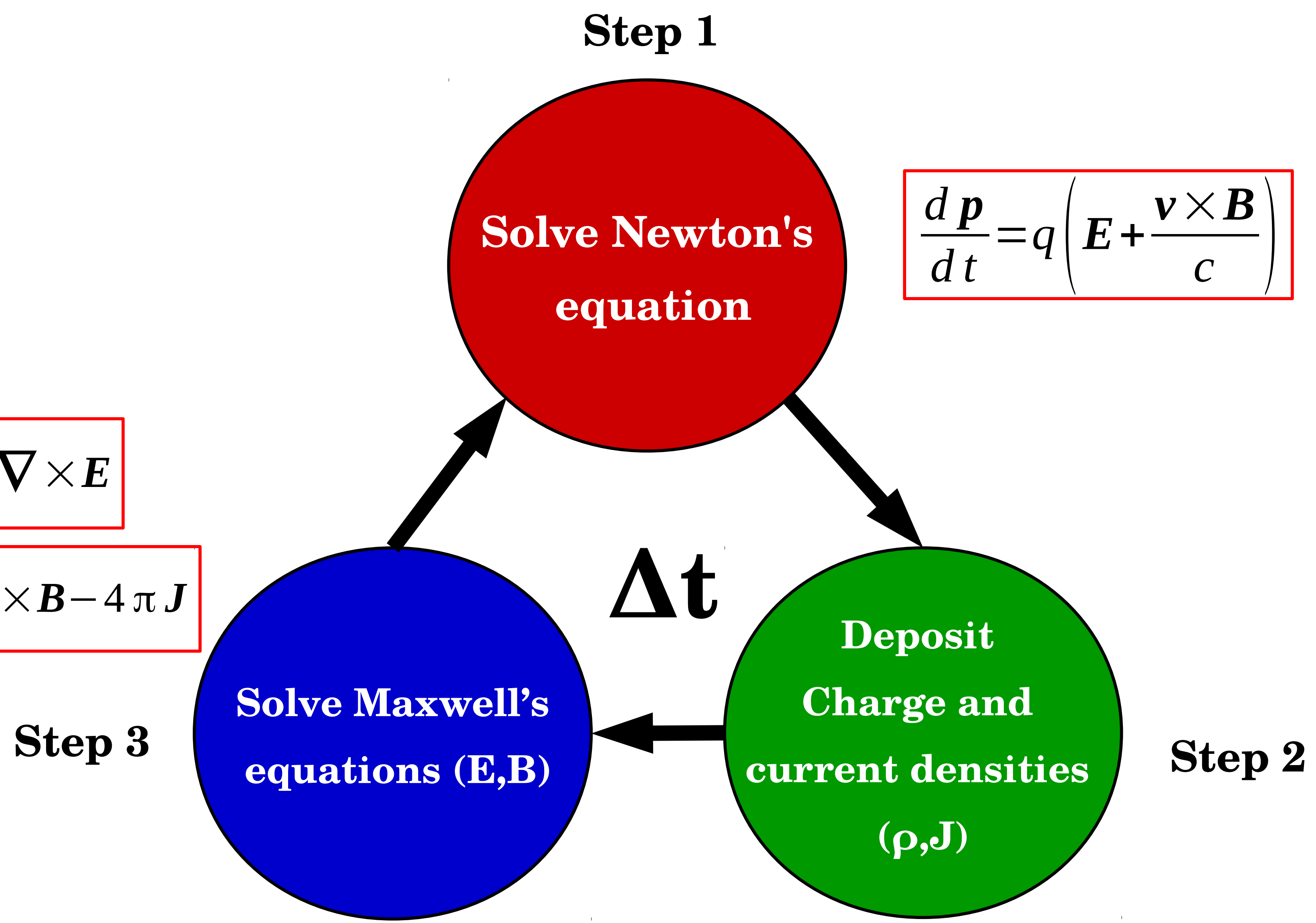
**B. Cerutti**

# The Particle-In-Cell (PIC) approach

Follow motion of millions of charged **particles** and evolved the **electromagnetic fields**



# Computation procedure per timestep in PIC




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

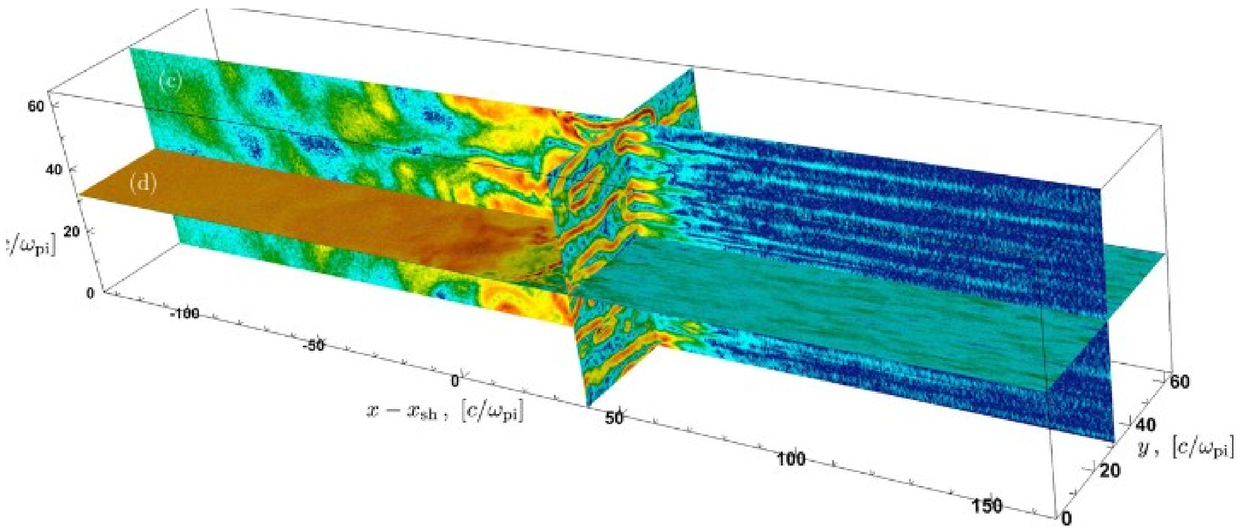
$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\,\nabla\times\boldsymbol{E}$$

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

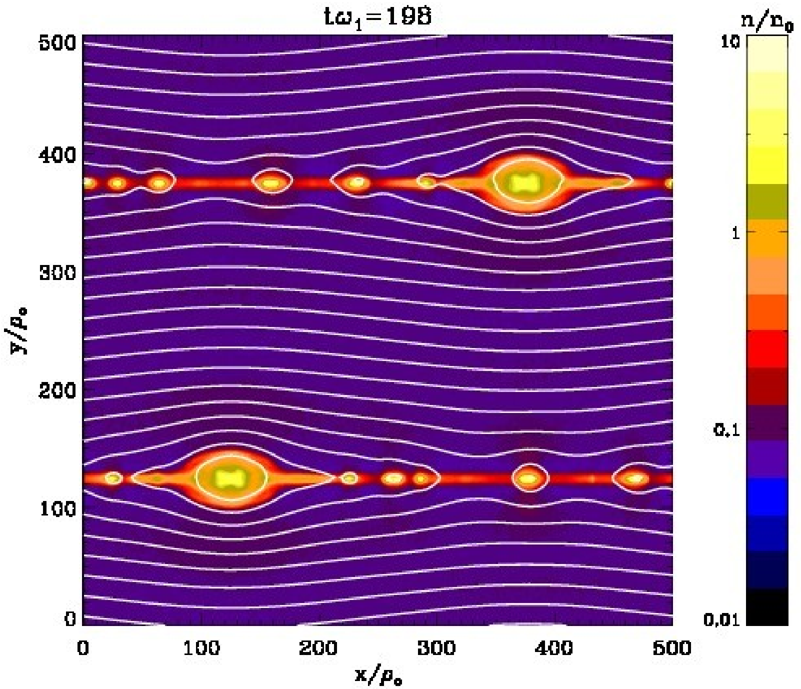
B. Cerutti

# Astrophysical applications of the PIC methods

Particle acceleration in **collisionless shocks** and **reconnection**




**[Sironi et al. 2013]**




**[Cerutti et al. 2013]**

**Challenges:**

**- Huge separation of scales between microscopic plasma processes and macroscopic system-size scales. Rescaling needed**

**- Large number of particles for a good sampling of phase space**

***=> Expansive simulations, need for HPC resources!***

# The Zeltron code

***URL:*** ***http://ipag.osug.fr/~ceruttbe/Zeltron***

Created in 2012 and Cartesian version published in 2015.

The Zeltron code

- Home
- Features
- Download
- Quickstart
- User guide
- Gallery
- Publications
- Developers
- Contact

## The Zeltron code project

Zeltron is an explicit 3D relativistic electromagnetic Particle-In-Cell code, ideally suited for modeling particle acceleration in astrophysical plasmas. The code is efficiently parallelized with the Message Passing Interface, and can be run on a laptop computer or on multiple cores on current supercomputers.

The Zeltron code is freely available here, and runs on linux and OS X operating systems.

Learn more ›   Download




**Code used during the Astrosim school on 2017**

# General presentation

***Zeltron*** is an **explicit, relativistic 3D PIC code** originally designed to study particle acceleration in relativistic magnetic reconnection sites applied to astrophysics. *Git repository available for the Cartesian version.*

**Main developers:**


**Benoît Cerutti** *(CNRS / Univ. Grenoble Alpes)*

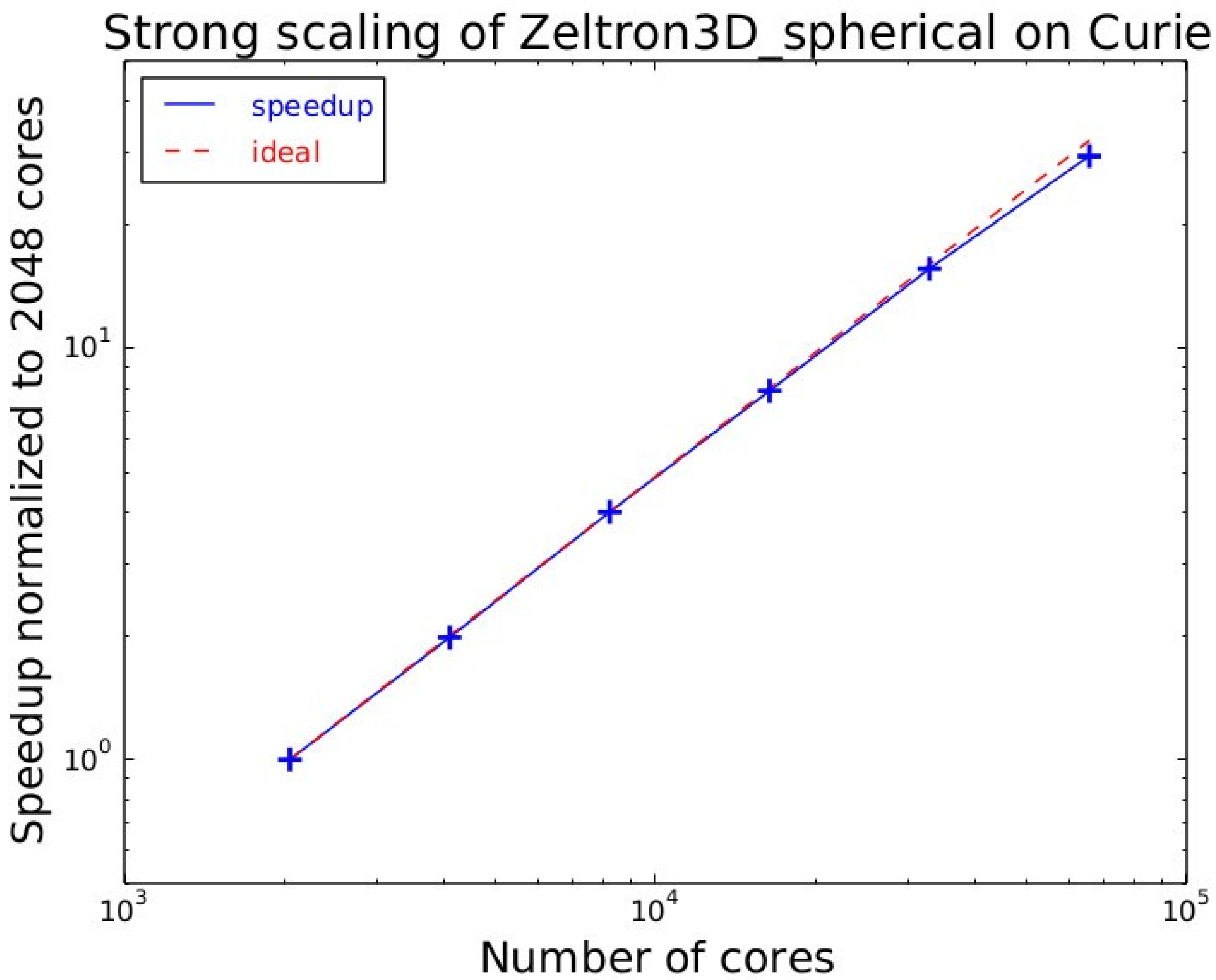
**Greg Werner** *(University of Colorado)*


**Some general features**

- Written in **Fortran 90**
- **Yee FDTD** algorithm for the fields
- **Boris push** for the particles
- **Efficiently parallelized** with MPI (3D domain decomposition)
- Includes **synchrotron** and **inverse Compton** radiation reaction forces
- **Non Cartesian-mesh**: spherical, cylindrical, Schwarzschild (not public)
- Large set of tools for **data reduction** and **data analysis** on the fly
- Set of **boundary conditions** (absorption, creation, open, reflective, …)
- **No need** for **external libraries**

# PIC codes usually scale well on #CPU>>1

*Example of the strong scaling plot of 3D spherical Zeltron on TGCC-Curie*

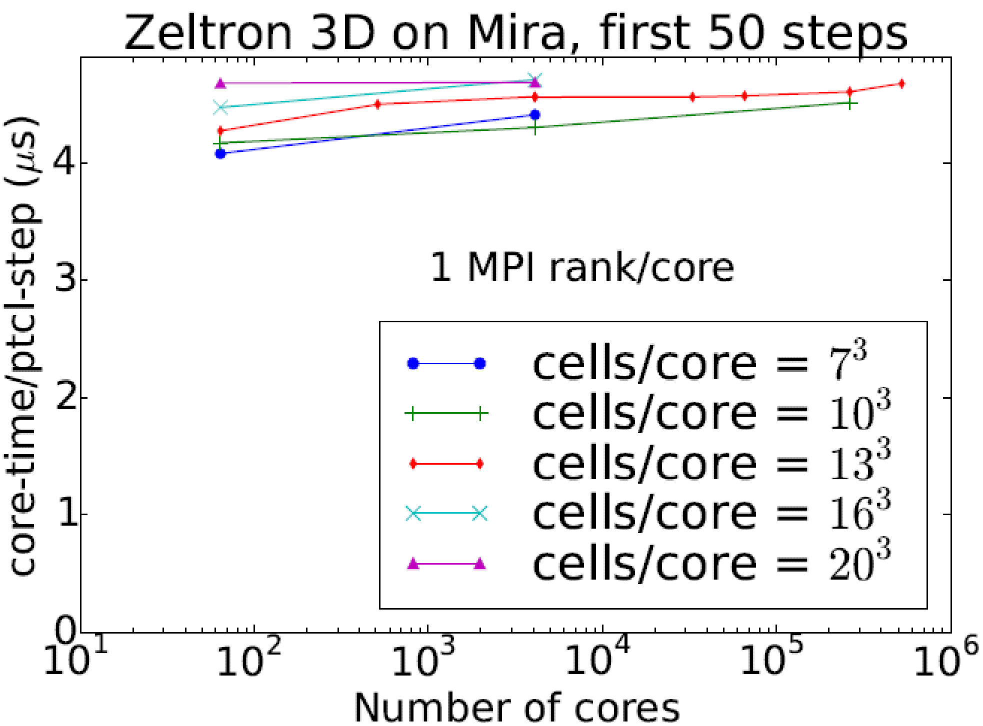


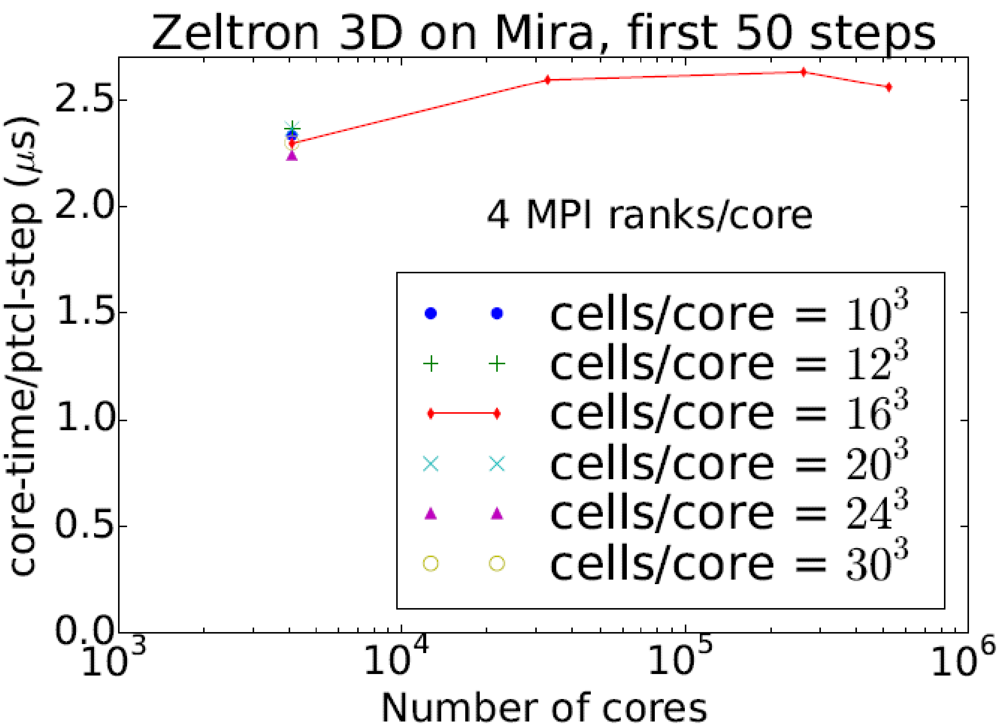

… but real life scaling is usually **limited by load-balancing** issues.

# Towards the exascale ?

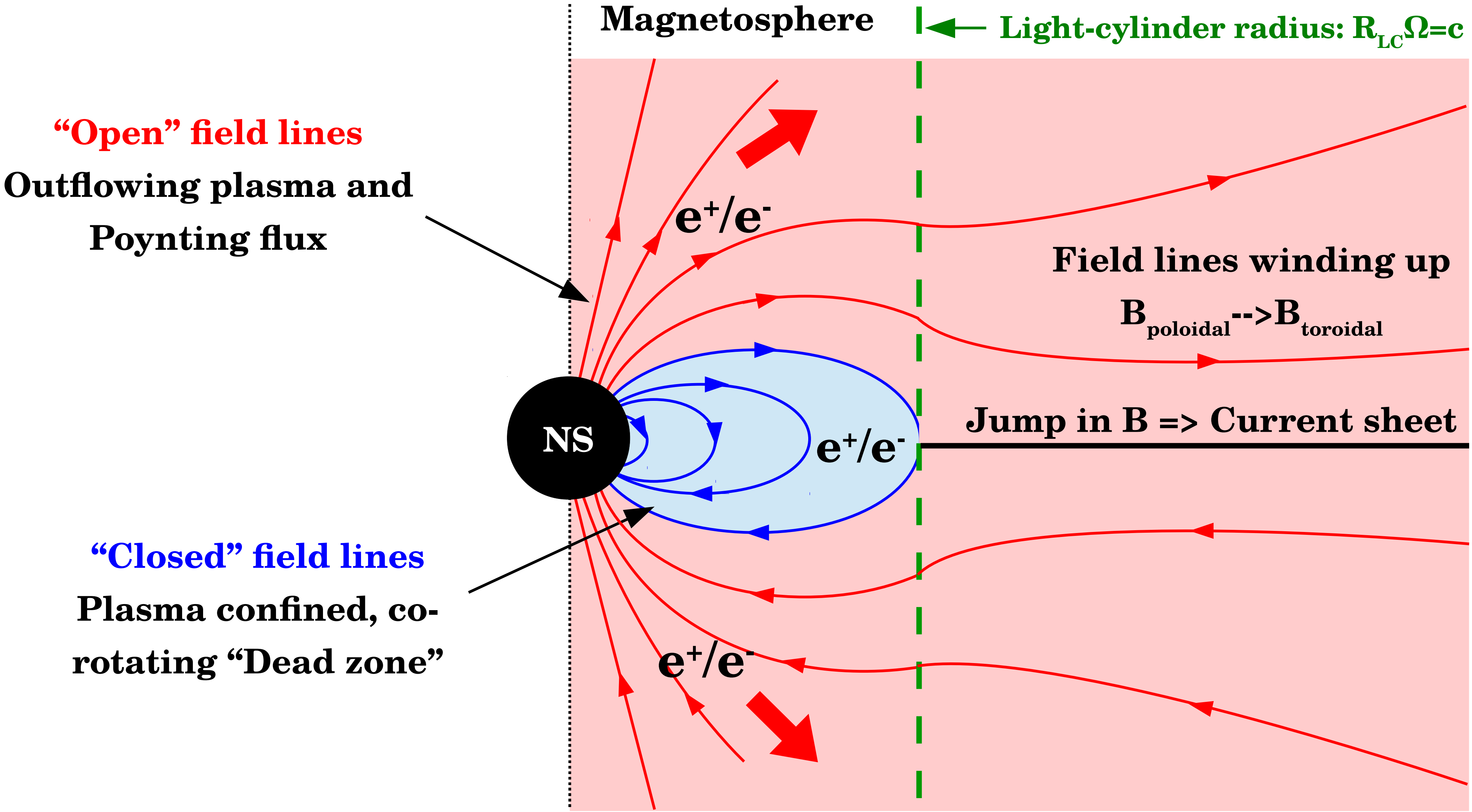
Production runs with ~>$10^5$ cores for 3D reconnection studies with Zeltron *(see Cerutti et al. 2014 ; Werner & Uzdensky 2017)*

**INCITE allocation** in 2016 with **93 million CPU-hrs on Mira** (PI : D. Uzdensky) Blue Gene/Q cores (~30 million hrs on intel cores)

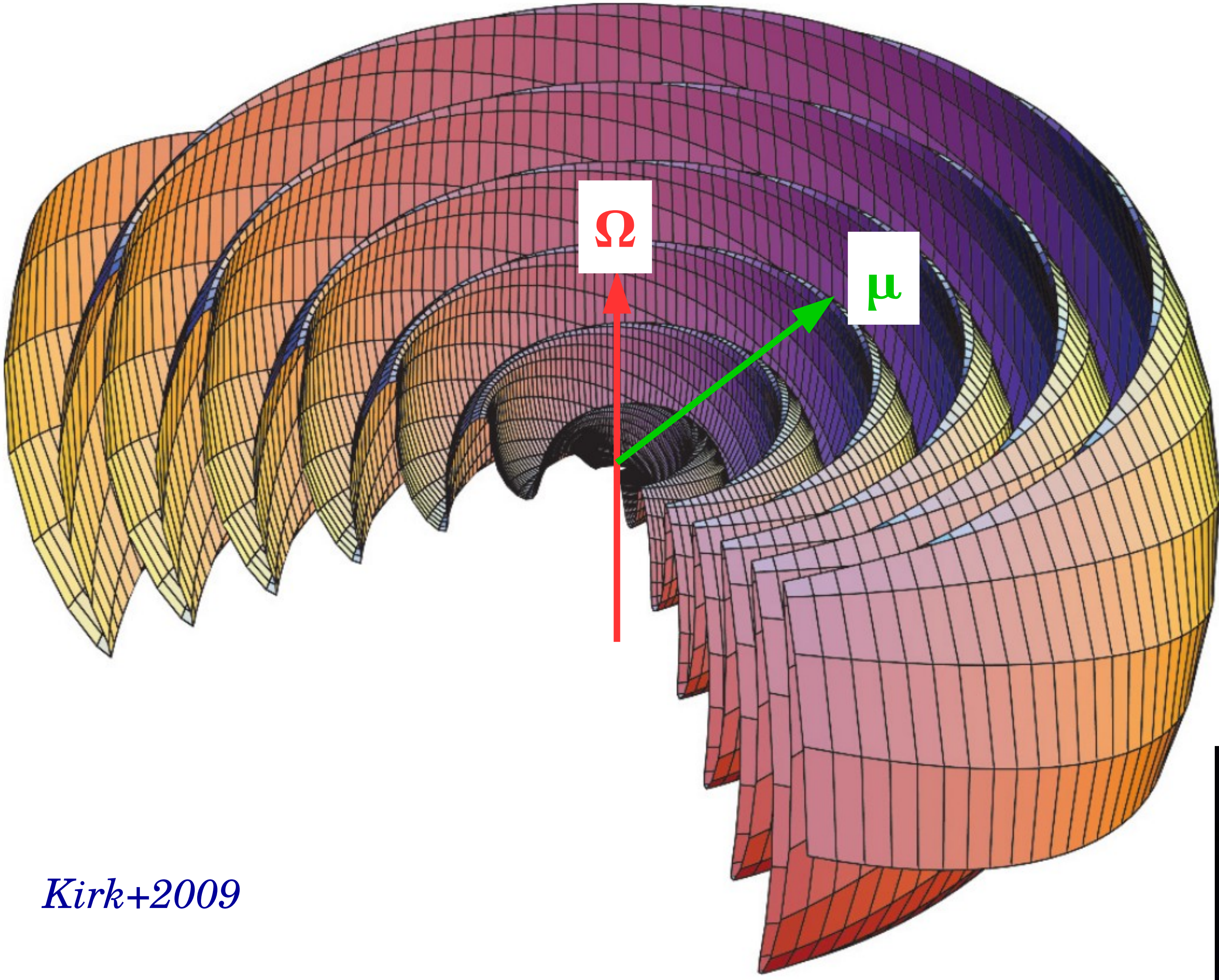


# Application I: Pulsar magnetospheres

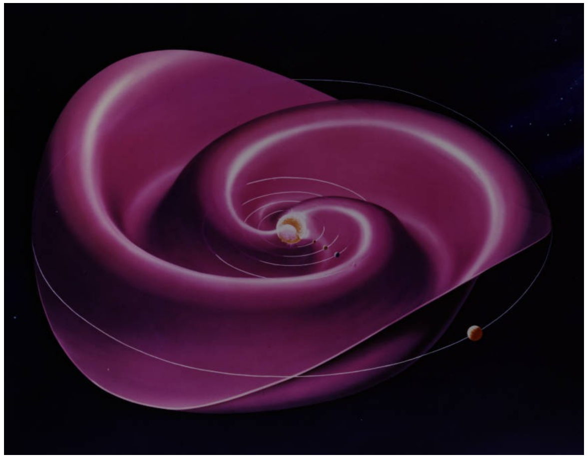


# Equatorial current sheet of the oblique rotator

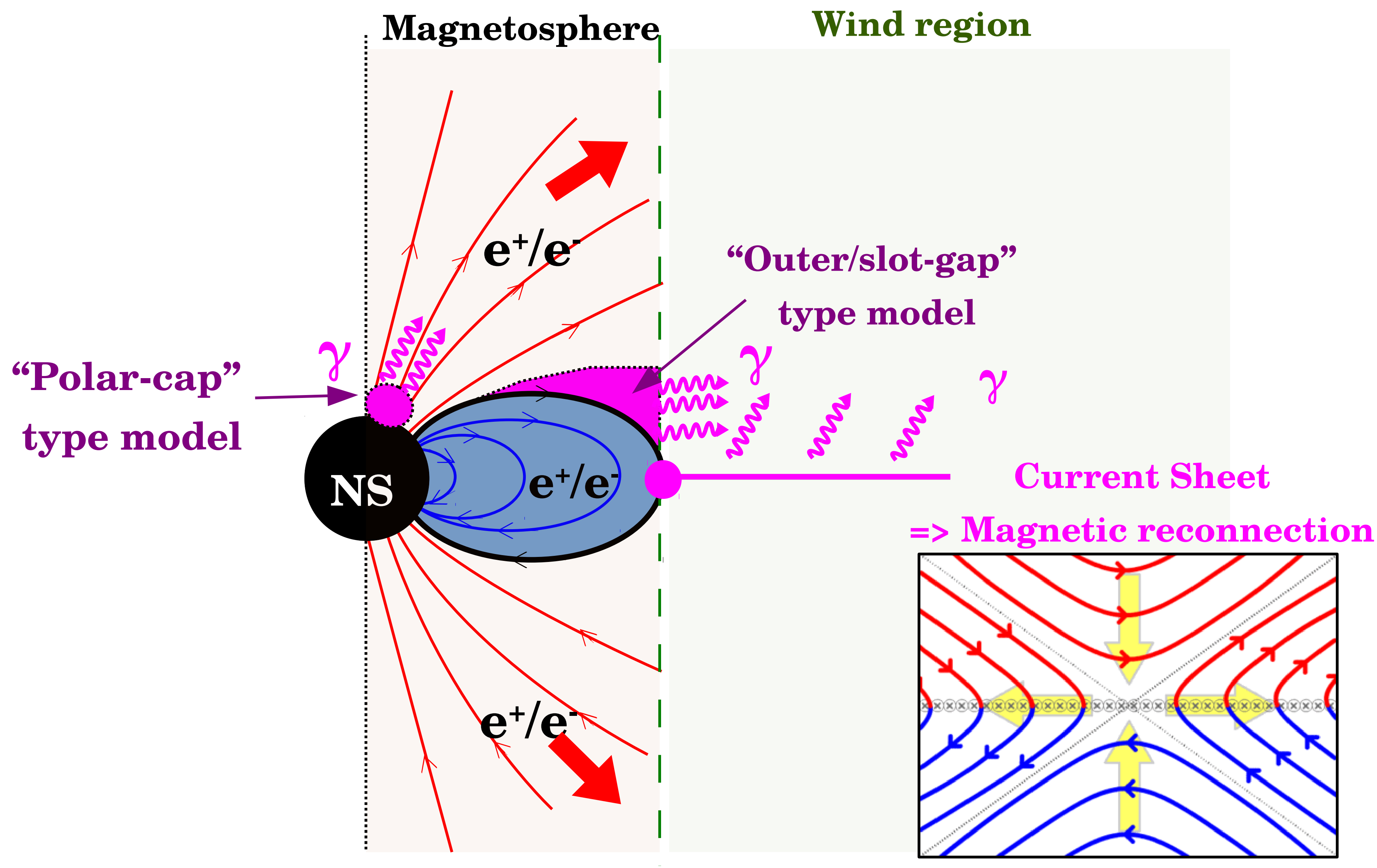



*Kirk+2009*

… Relativistic analog of the **heliospheric current sheet.**

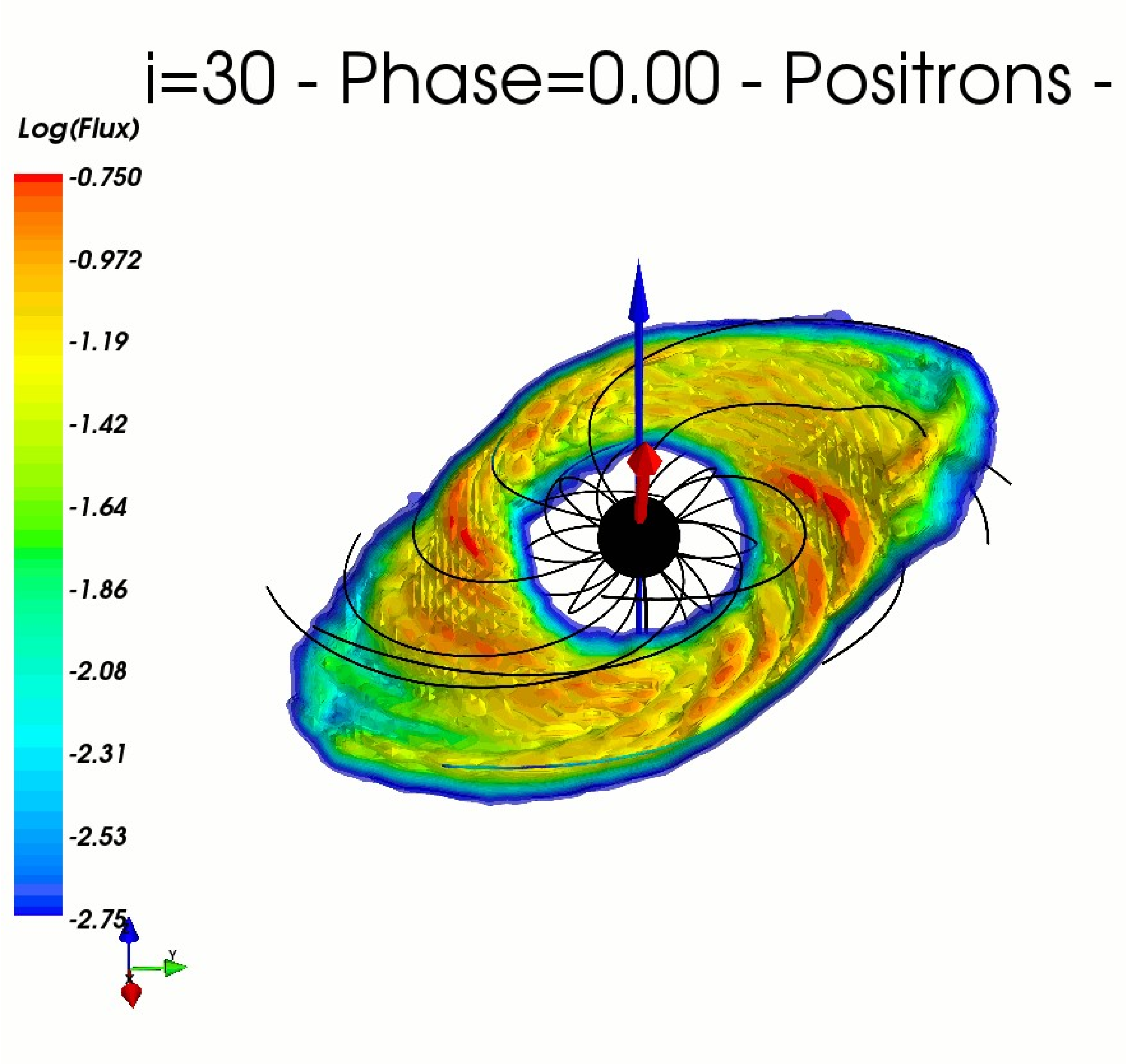


# Proposed sites for particle acceleration




Non-ideal regions, impossible to model with MHD => Global PIC

# ... and the answer is :




*Cerutti+2016*

**PIC results : Particle acceleration via relativistic reconnection in the sheet !**

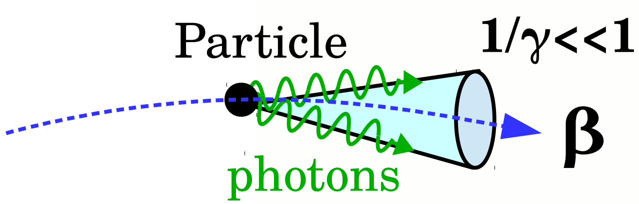
# Observed high-energy radiation flux ($\nu>\nu_0$, $\chi=30°$)

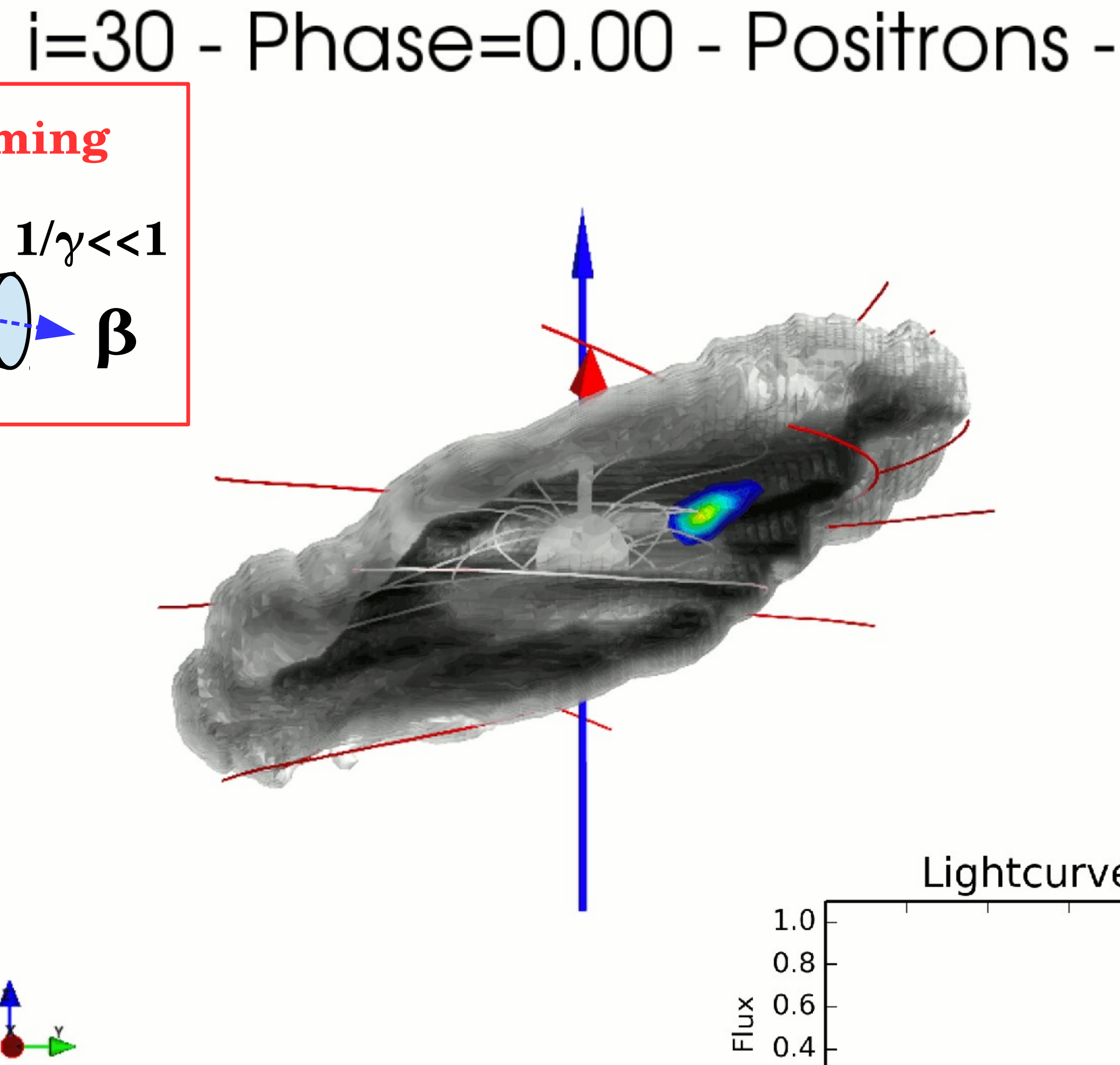
**Gray** : **Total** flux (all directions)

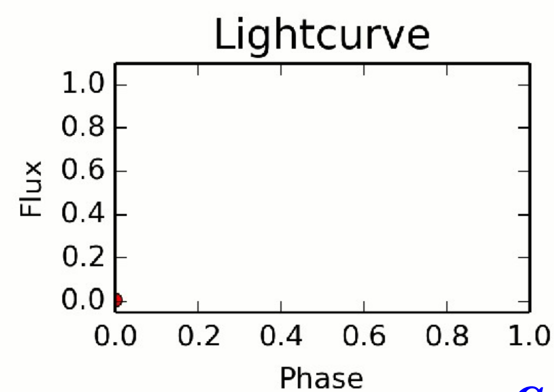
**Color** : **Observed** flux

**Light curve shaped by the geometry of the current sheet**

**Relativistic beaming**




**One pulse per crossing of the current sheet**

**B. Cerutti**

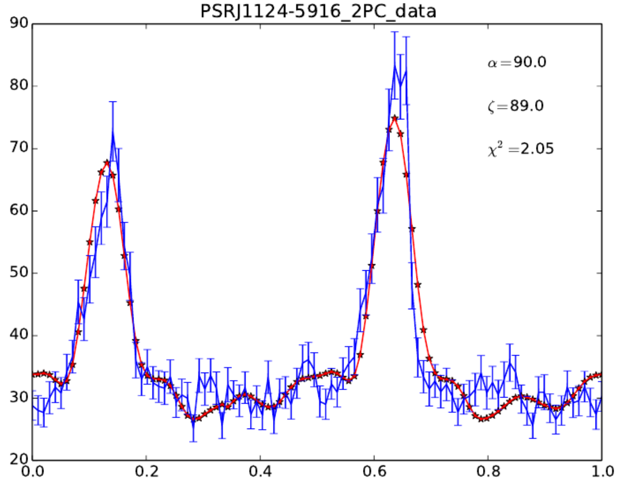
***Cerutti et al. 2016***

# From PIC simulations to observations

**Fermi-LAT lightcurve fitting**

**Observations**

**PIC model**



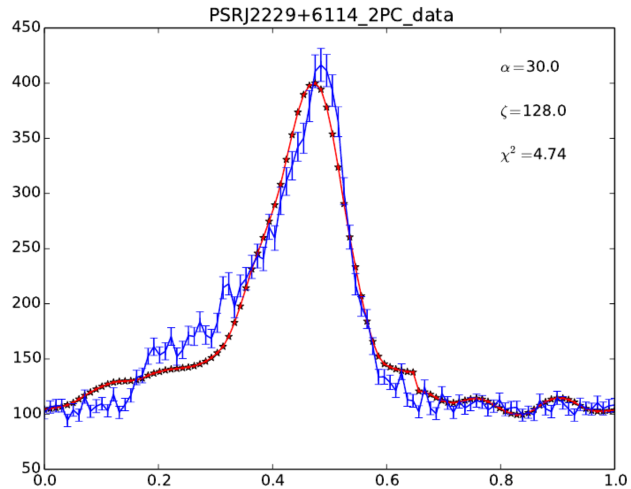
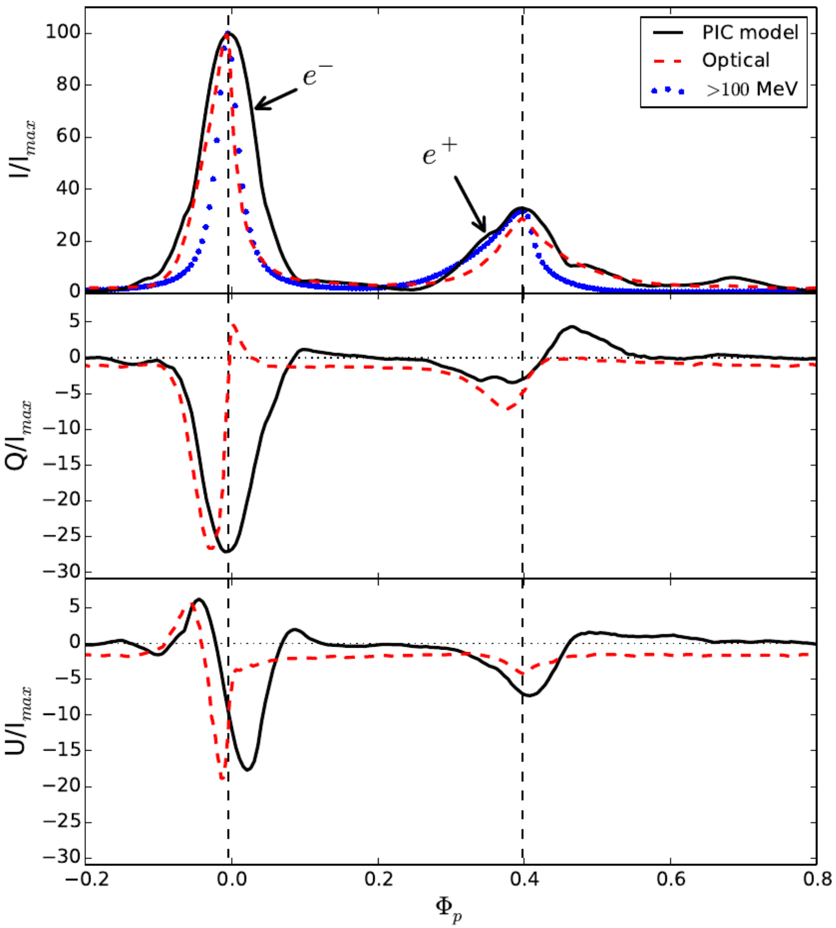




Figure courtesy of **Aloïs de Valon**

**Crab pulsar + polarization**




**Magnetic inclination ~60°**

**Viewing angle ~130°**

**Degree of polarization ~15-30 %**

*[Cerutti, **Mortier**, Philippov 2016]*

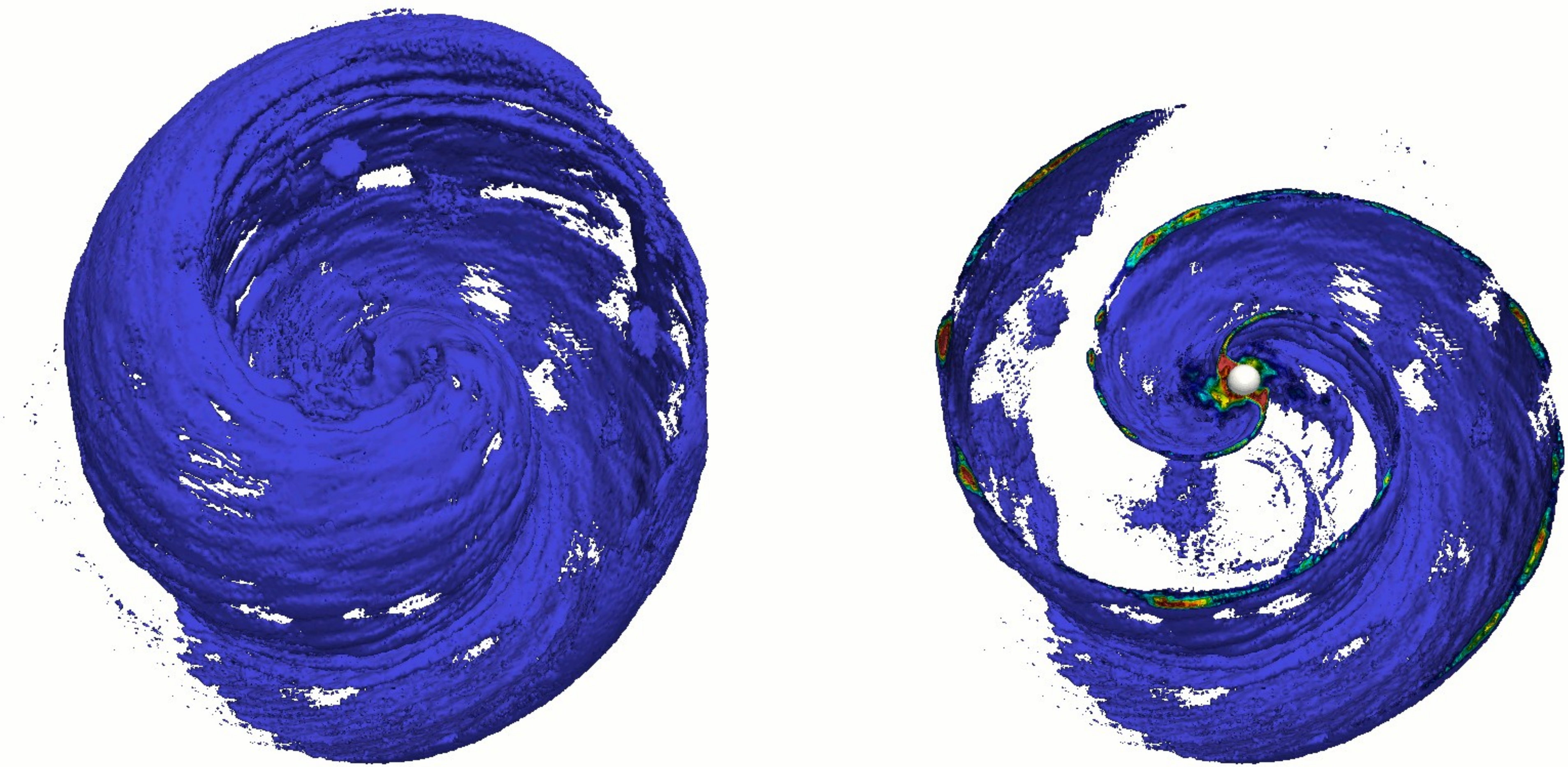
**B. Cerutti**

# The FROMTON project


**FROm the Magnetosphere TO the Nebula :**

**PRACE allocation 27.6 million CPU-hrs on TGCC-Irene SKL**

**Goal:** Study dissipation and particle acceleration in **3D pulsar winds** and at the **termination shock.** **Stay tuned !**

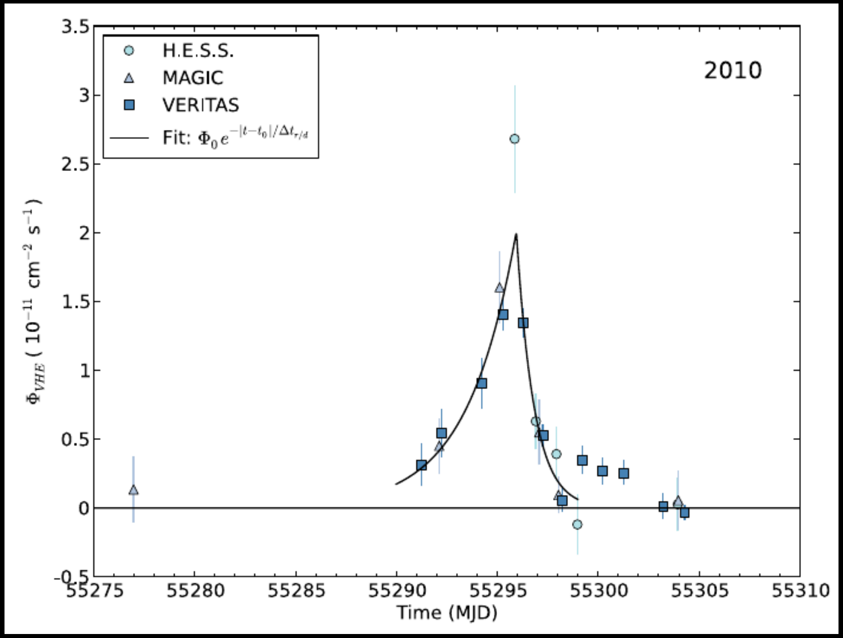


# Application II : Black hole magnetospheres

Ultra-short TeV flares from blazars ~ few days or less => Emitting region ~ few $\mathbf{r}_g$

**A magnetospheric origin ?**

*Example : M87*



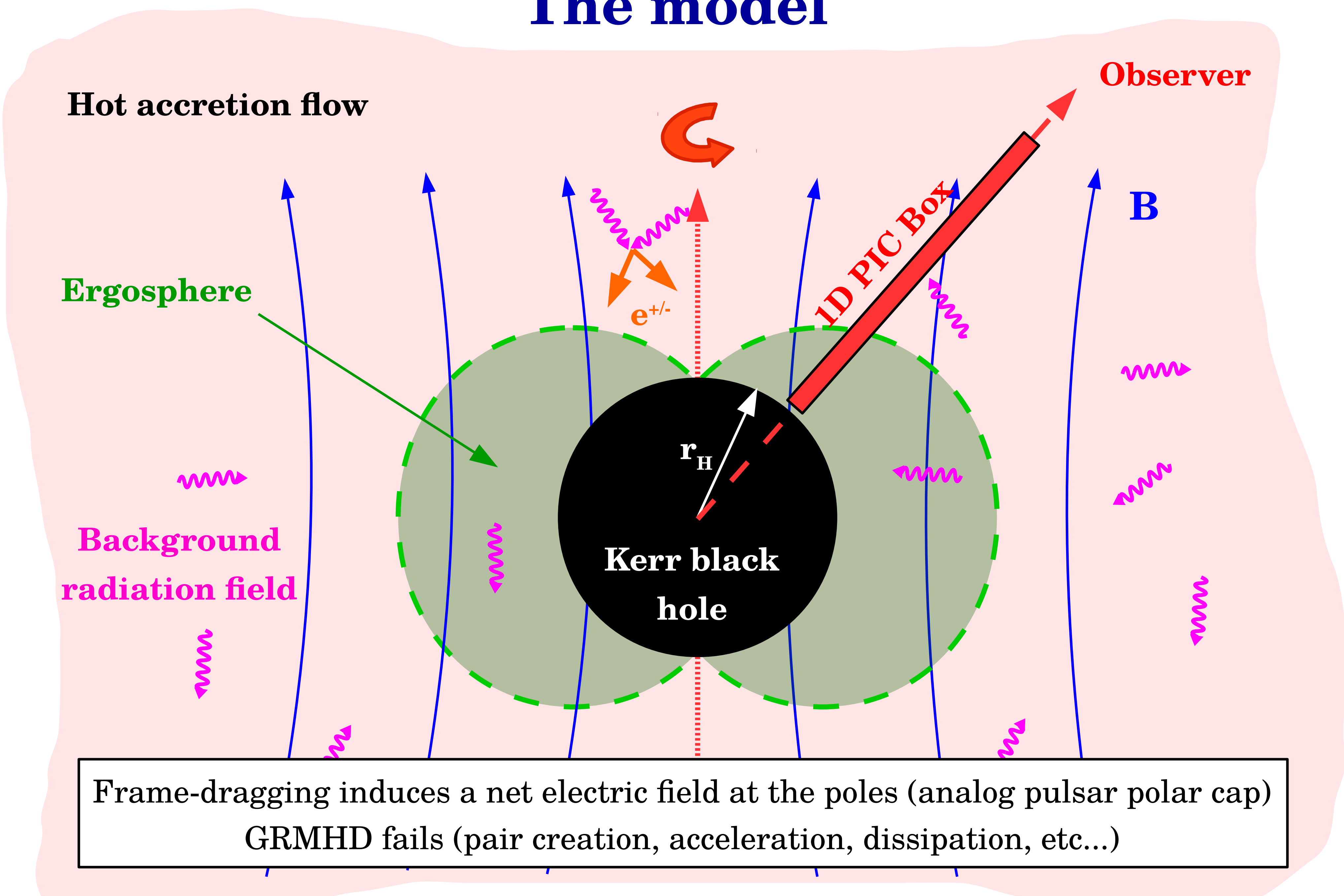

*[Abramowski+2012]*

Electromagnetic extraction of the BH spin requires a plasma (Blandford-Znajek)

M87 or SgrA*: Low accretion rate, starved magnetospheres => Sparks and pair creation

**Does it work ?!**

# The model




Frame-dragging induces a net electric field at the poles (analog pulsar polar cap)
GRMHD fails (pair creation, acceleration, dissipation, etc...)

**Need for GRRPIC = PIC + GR + Radiation (Pair creation & IC with Monte Carlo)**

# Implementation of GR

We use the **3+1 formalism** of GR commonmy used in numerical relativity *(Gourgoulhon 2007)*

$$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}\left(dx^i + \beta^i dt\right)\left(dx^j + \beta^j dt\right)$$

- **Maxwell equations**

$$\frac{1}{\sqrt{\gamma}}\frac{\partial\left(\sqrt{\gamma}\boldsymbol{B}\right)}{\partial t} = -c\nabla\times\boldsymbol{E} \qquad \boldsymbol{E} = \alpha\boldsymbol{D} + \boldsymbol{\beta}\times\boldsymbol{B}$$

$$\frac{1}{\sqrt{\gamma}}\frac{\partial\left(\sqrt{\gamma}\boldsymbol{D}\right)}{\partial t} = c\nabla\times\boldsymbol{H} - 4\pi\boldsymbol{J} \qquad \boldsymbol{H} = \alpha\boldsymbol{B} - \boldsymbol{\beta}\times\boldsymbol{D}$$

- **Equation of motion**

$$\frac{\mathrm{d}x^i}{\mathrm{d}t} = v^i = \frac{\alpha}{\Gamma}\gamma^{ij}u_j - \beta^i,$$

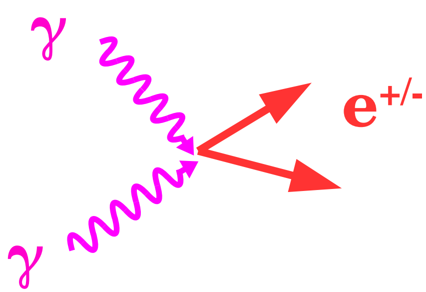
$$\frac{\mathrm{d}u_i}{\mathrm{d}t} = -\Gamma\partial_i\alpha + u_j\partial_i\beta^j - \frac{\alpha}{2\Gamma}\partial_i(\gamma^{lm})u_l u_m + \frac{\alpha}{m}\mathcal{L}_i$$

*Metric induced terms*

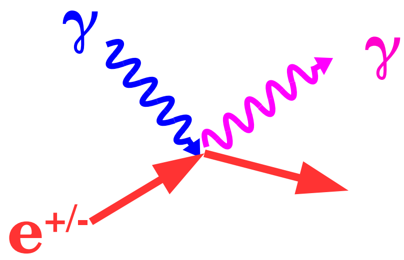
**=> More computationally expansive than flat space PIC**

# Implementation of the radiative transfer

**Pair production**

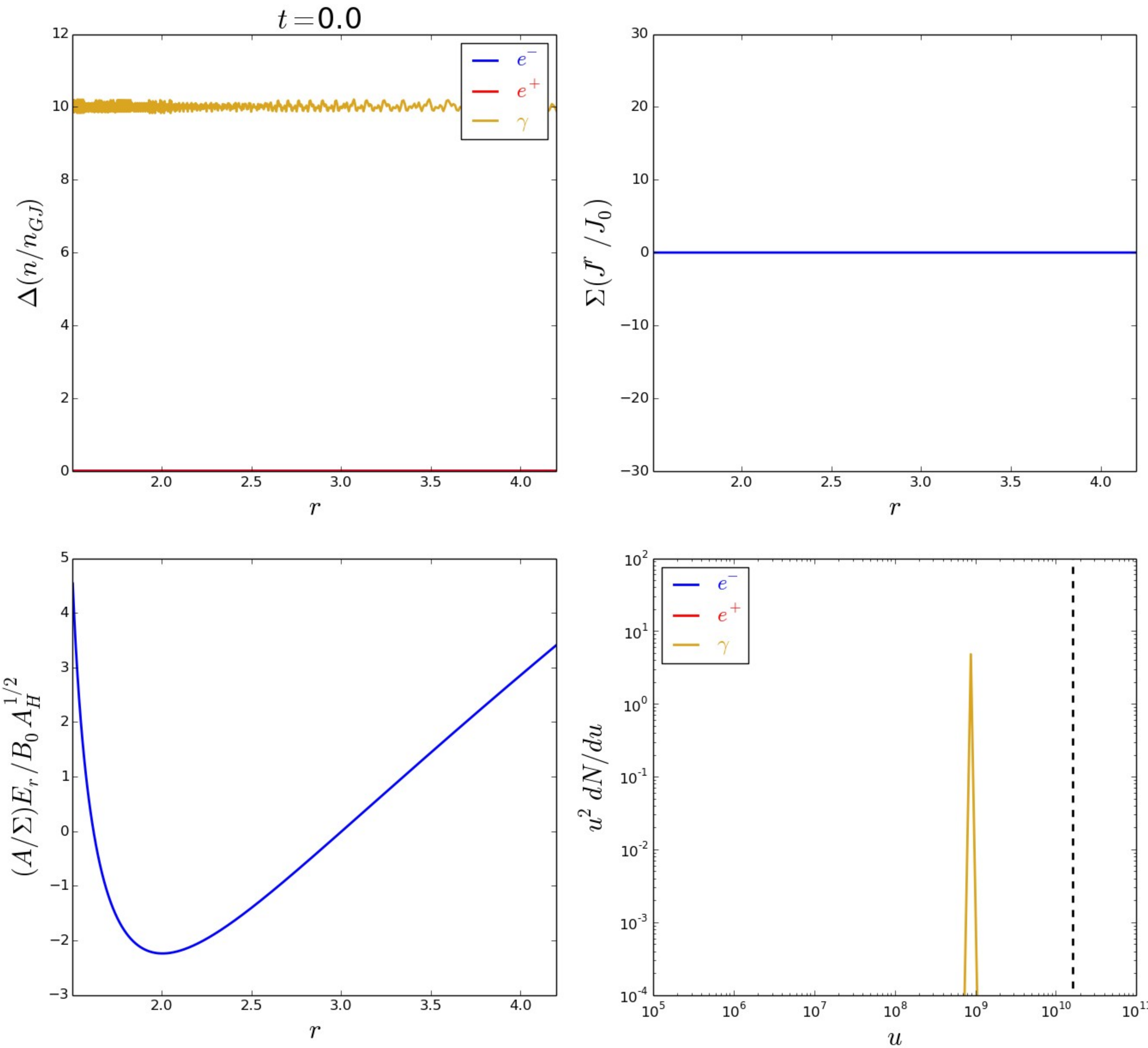



**Inverse Compton**



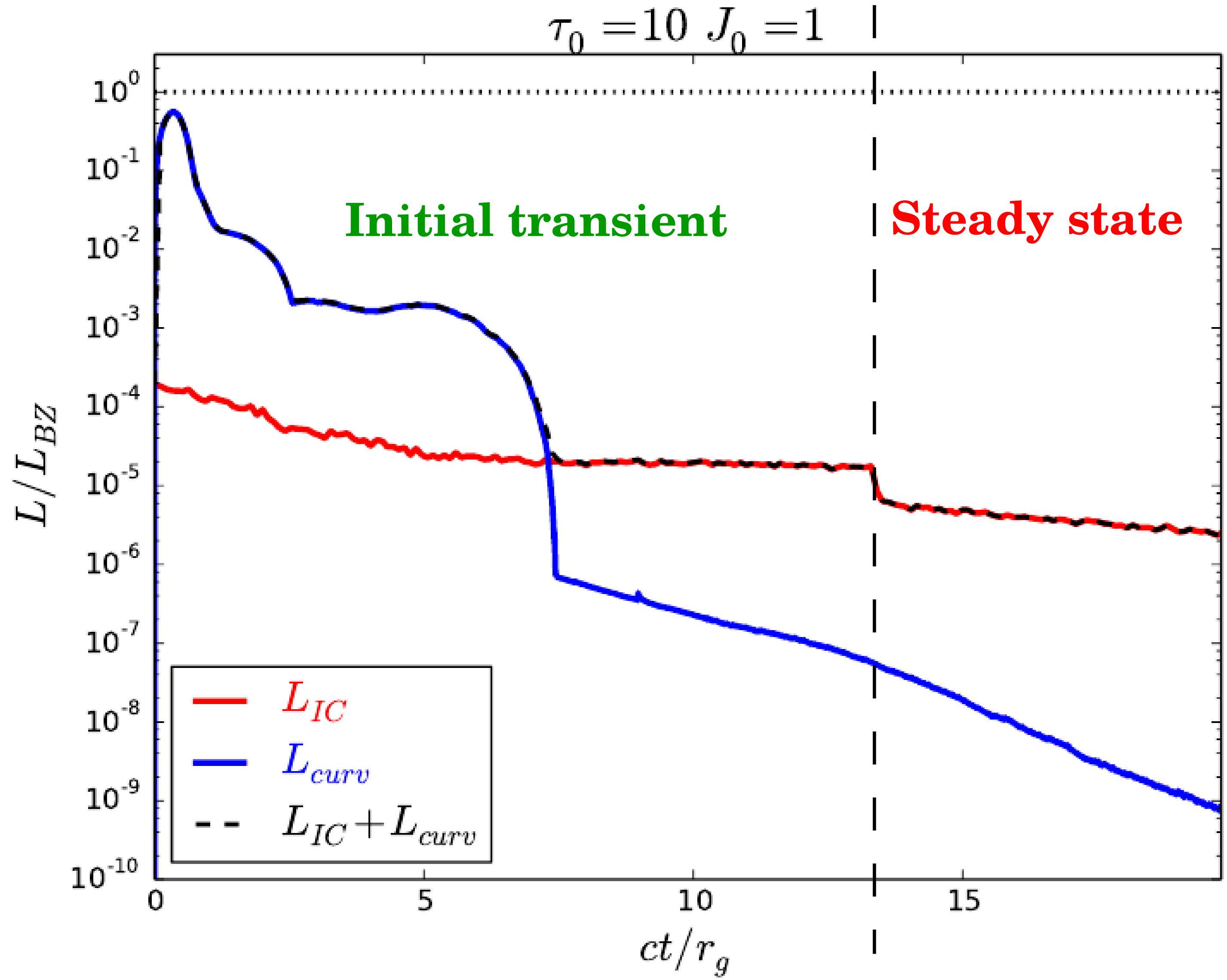

**Monte Carlo approach**

- Calculation of optical depth
- At each time step : Compute the scattering probabilities
- If scattering, creation/annihilation of the particles in the box
- Photons are modeled as discrete simulations (neutral) particles



$t = 0.0$
$\Delta(n/n_{GJ})$
$\Sigma(J^r/J_0)$
$(A/\Sigma)E_r/B_0 A_H^{1/2}$
$u^2\, dN/du$
$r$
$u$
$e^-$
$e^+$
$\gamma$

# Gamma-ray luminosities




**Initial flare**

**$t \sim r_g/c$**

**$L_\gamma \sim L_{BZ}$**

**Steady state :**

**$L_\gamma \sim 10^{-6}\text{-}10^{-5} \, L_{BZ}$**

***Levinson & Cerutti 2018***

**Application to the TeV emission and flare in M87**

**Flare could reflect charge starvation in the magnetosphere**

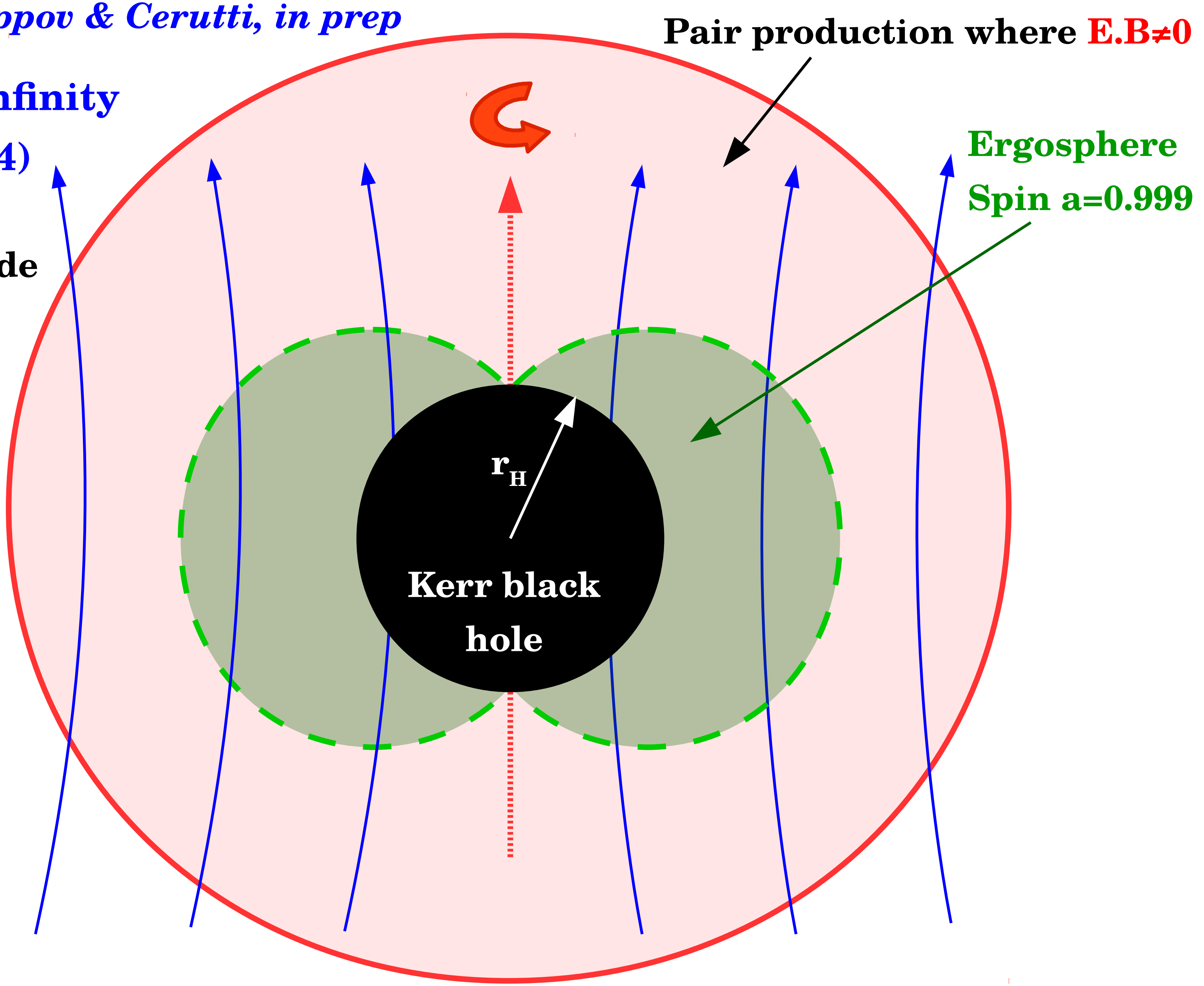
**Caveat : Ad-hoc gap, no magnetospheric feedback => need to go global !**

# First global 2D axisymmetric simulations

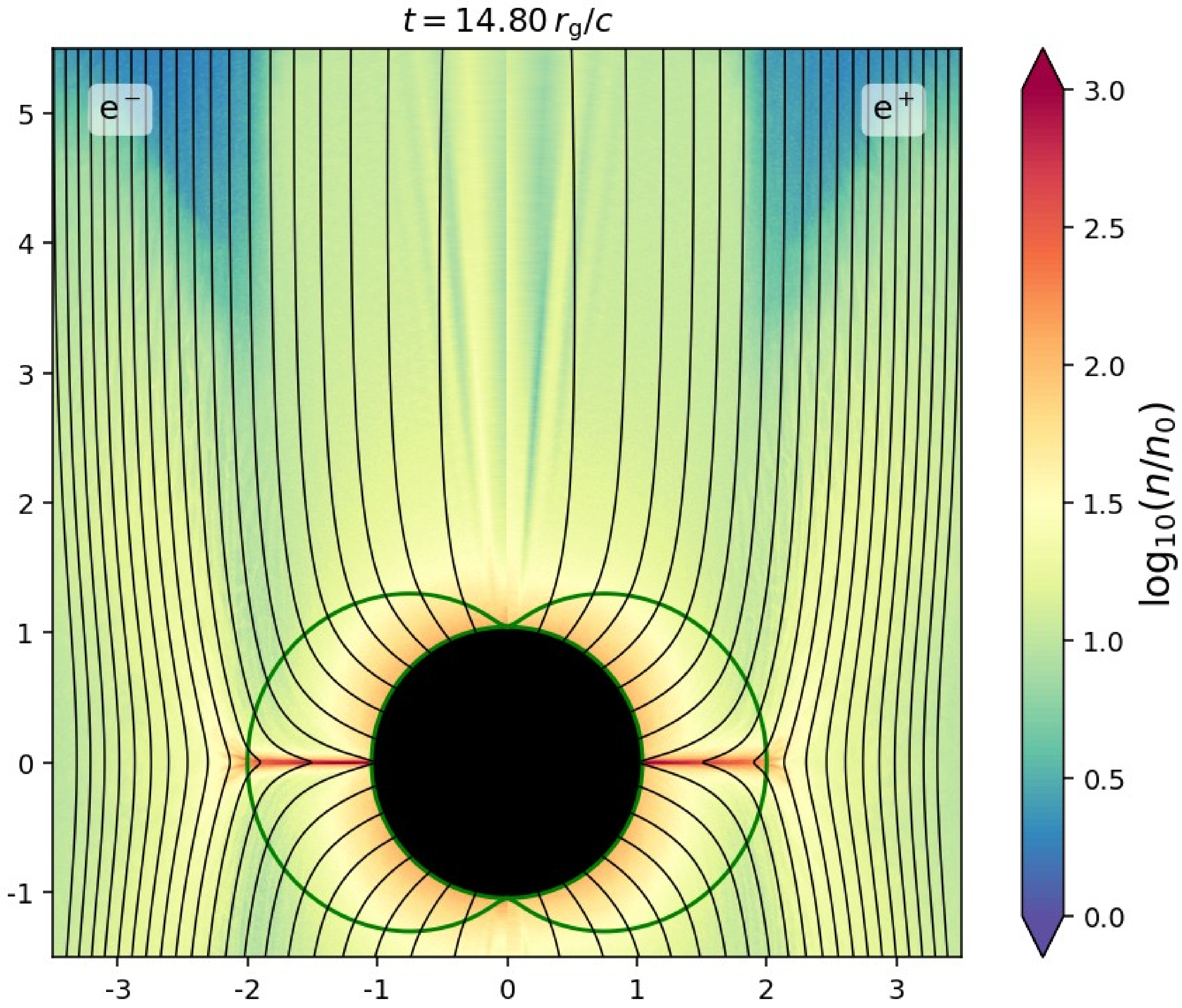
*Parfrey, Philippov & Cerutti, in prep*

**B uniform @ infinity**
**(Wald 1974)**

**Fully GRPIC code**
**3+1 method**
**Kerr-Schild**
**coordinates**



# Plasma density plot

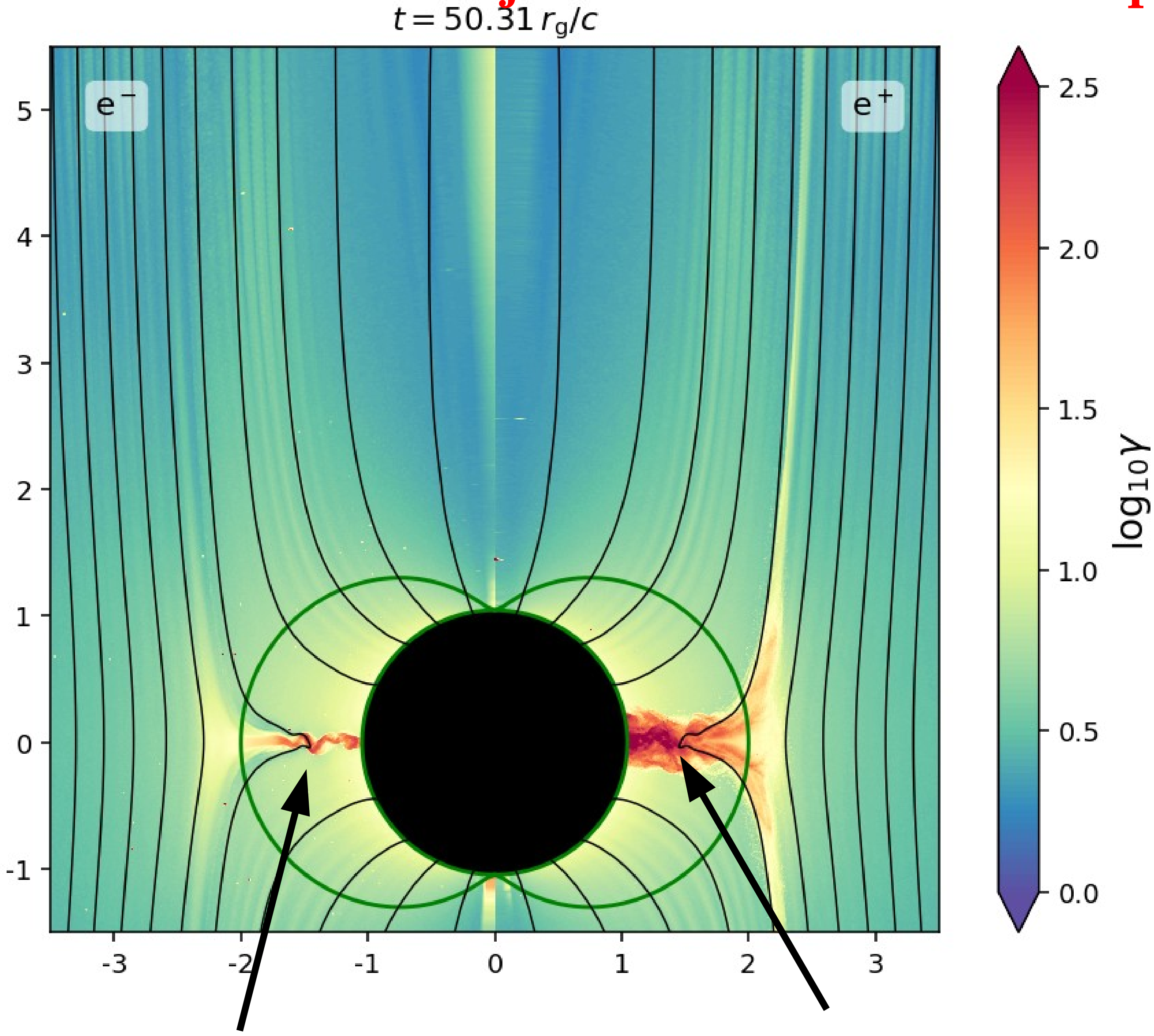



*Courtesy K. Parfrey*

# Dissipation & particle acceleration

**Net Poynting flux away from the poles, BH spin extraction.**

**Observation of the Blandford-Znajek mechanism from first principles !**




**Reconnection and particle acceleration in the equator.**

*Courtesy K. Parfrey*

# Summary

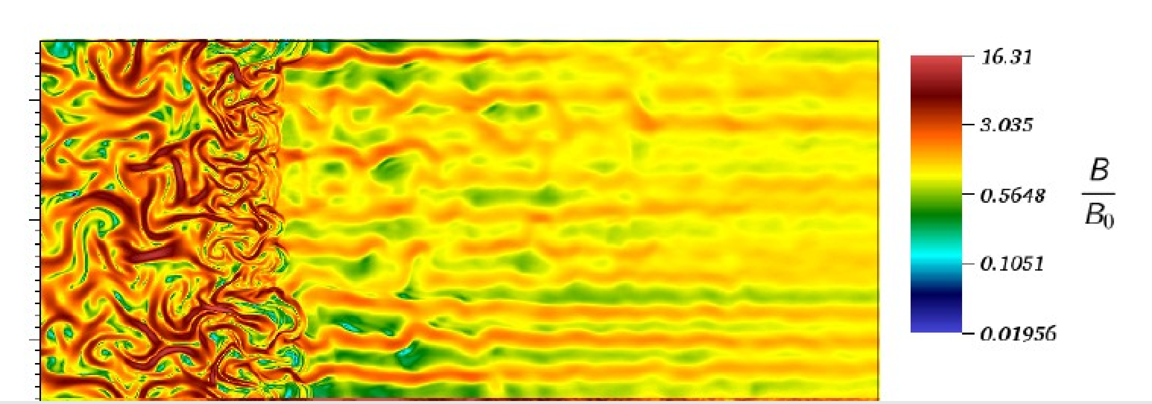
- Modeling particle acceleration and dissipation require a **fine kinetic approach.**
- The **PIC method** has become a successful tool to explore these processes from first principles.
- The study of relativistic magnetospheres show how strongly connected microscopic and system size are connected. **Global simulations needed.**
- Simulations can now **produce observables** (e.g., lightcurves, polarization) that can directly be compared or even predict observations. **=> Numerical observatory**

# Personal view on the future evolutions

- **More and more physics** needed in codes (pair production, GR, radiation, QED…)

- Huge separation of scales hard to overcome with full PIC,
  **=> Need for hybrid codes** (e.g., coupling MHD and PIC, Monte Carlo, etc…).

  Example: PIC and MHD for particle acceleration in collisionless shocks
  *(Bai+2015, Van Marle+2018, Mignone+2018)*
  *Caveat: Need a prescription for injecting particles*




*Van Marle+2018*

- **Vectorization** and **hybrid Open-MP & MPI** parallelization appropriate for the particle mover (~90% computing time). AMR for the MPI decomposition also good for load balancing too.