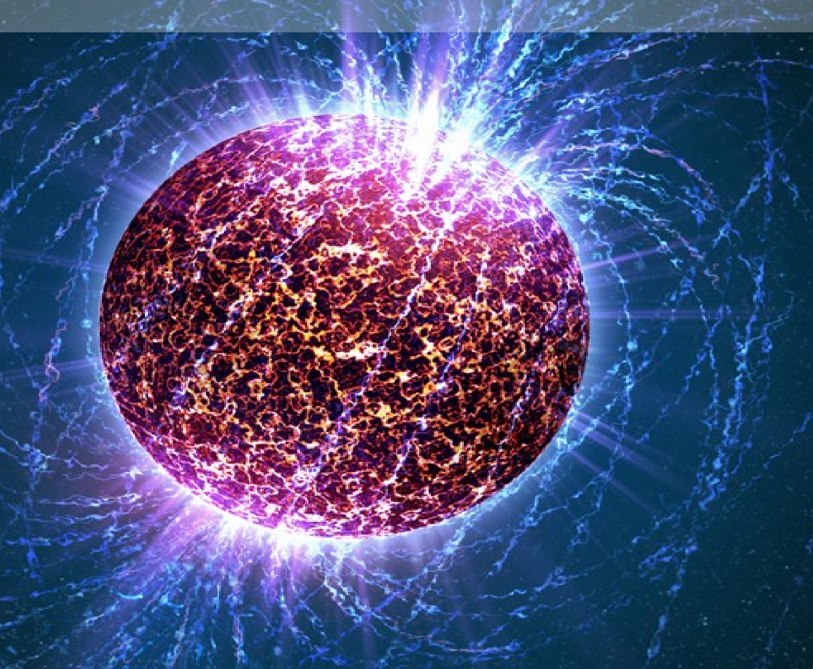
Les simulations numériques à l'assaut des pulsars



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Séminaire Dautreppe, 3-7 décembre 2018

The story begins 50 years ago

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Observation of a Rapidly Pulsating Radio Source

by

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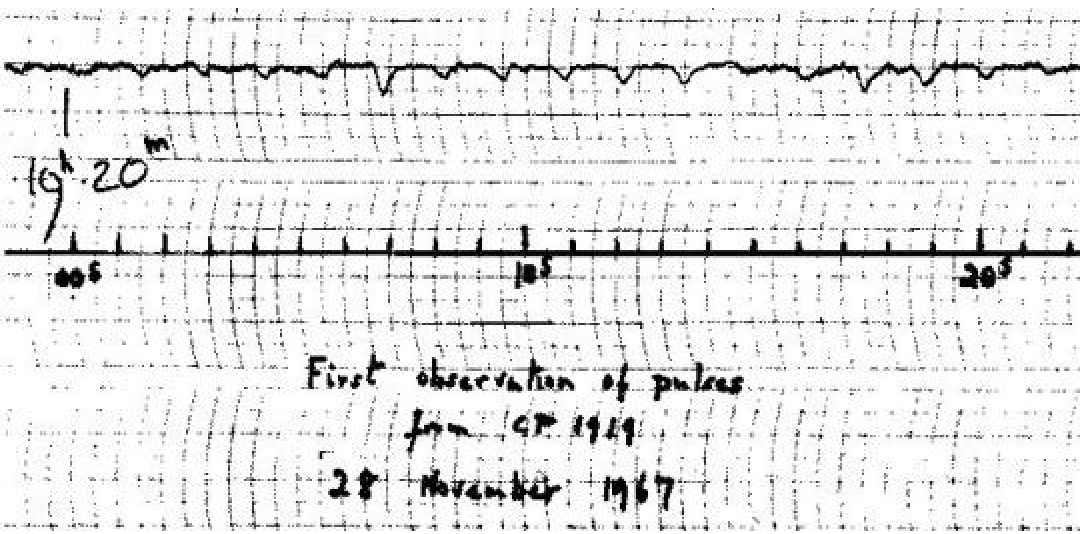
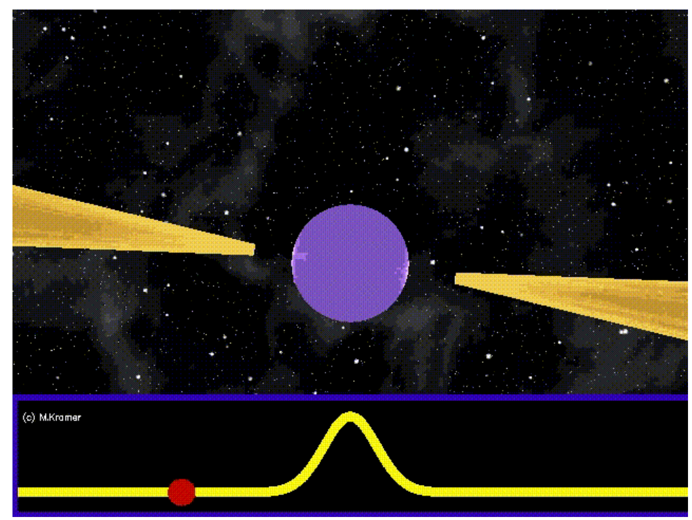
Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the gala‹y, and may be associated with oscillations of white dwarf or neutron stars.

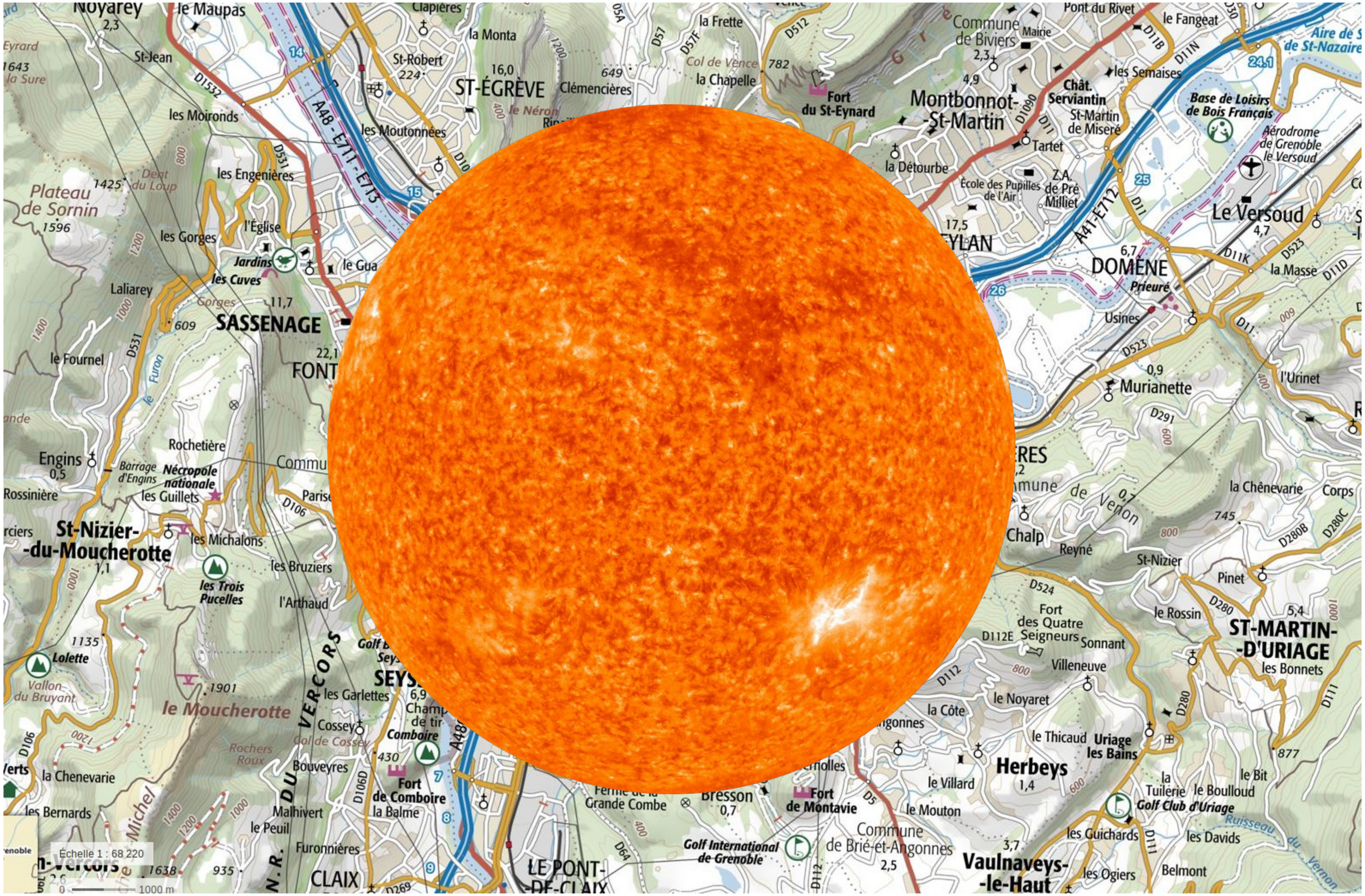




Credit: M. Kramer (JBCA, Unversity of Manchester)

More than 2000 pulsars known today

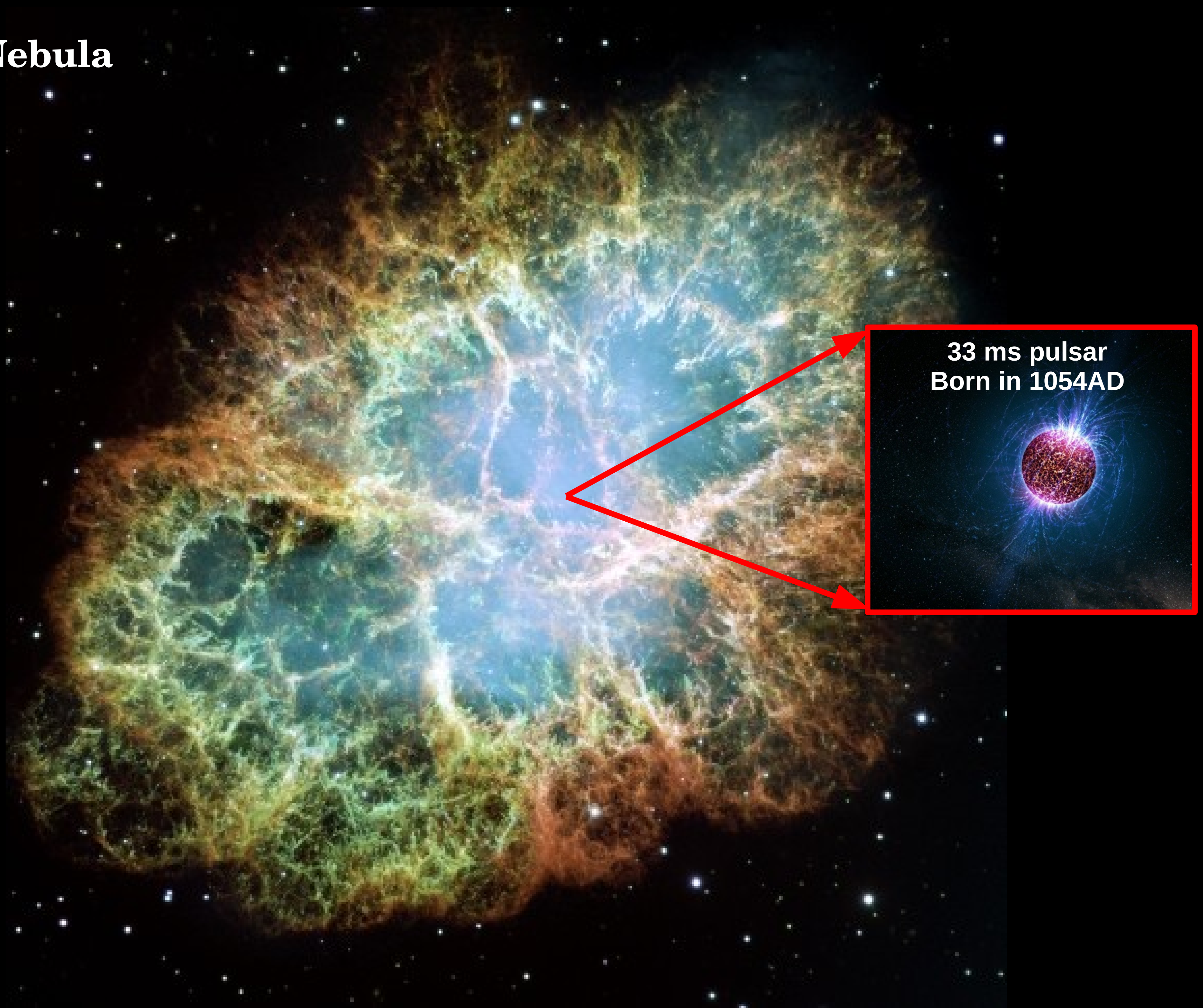
Just imagine...



The mass of the sun contained in a 10km radius sphere !

They form after the collapse of a massive dying star

The Crab Nebula



An extreme environment
(or why do physicists love pulsars)

- **Super-nuclear densities : ~6×10^{14}g/cm^{3}** (3 times the nuclei density)
  => *« Neutron stars » Theoretically predicted (1932) !*

All water from
the Annecy lake

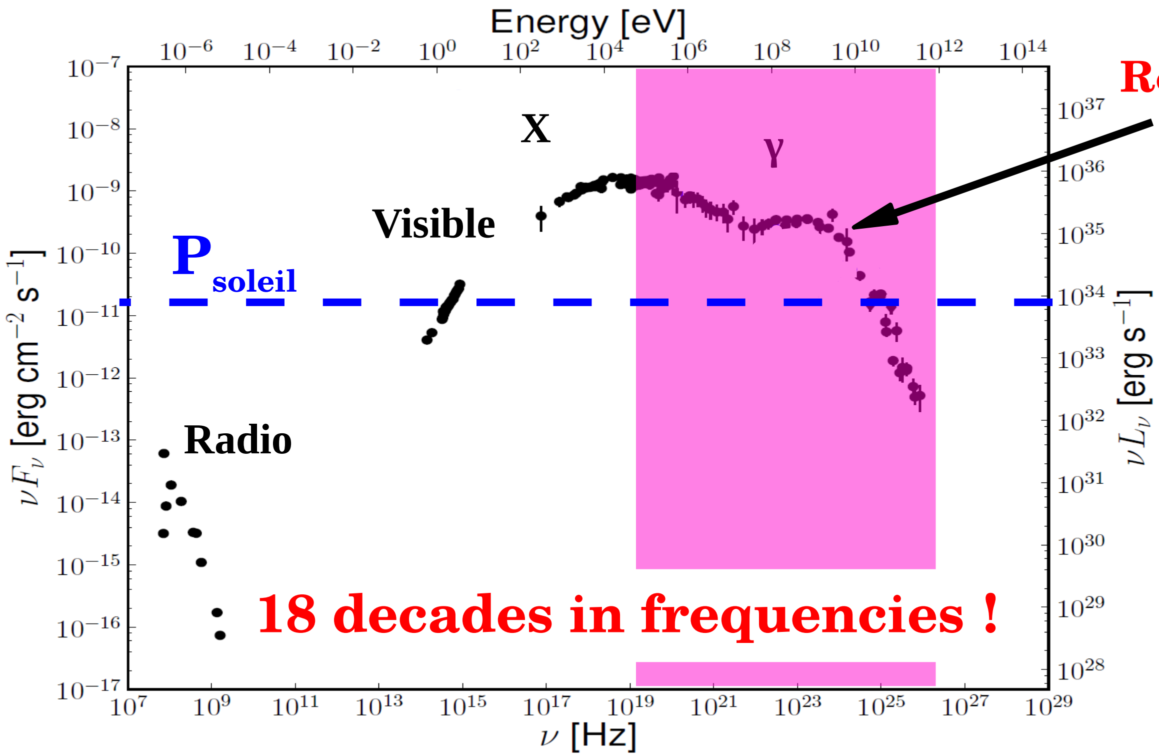
- **Surface gravity : ~10^{11}** times the terrestrial gravitational field.
  => *Tests for general relativity, see presentation B. Crinquand and tomorrow !*

- **Surface magnetic field : 10^{9}-10^{15}** times the Terrestrial field.
  => *Tests for quantum electrodynamics in strong fields*

- **Rotation period : few milliseconds** to **few seconds**

Pulsars shine throughout the electromagnetic spectrum: Multiwavelength astronomy

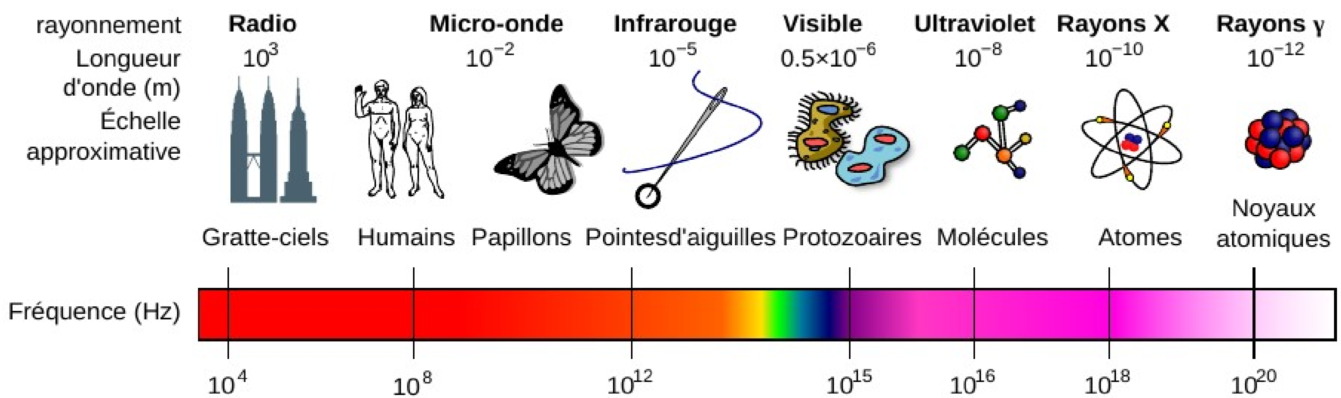
Crab pulsar spectrum



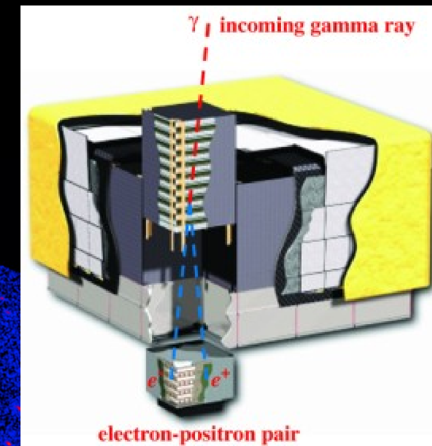
Relativistic particles Acceleration!

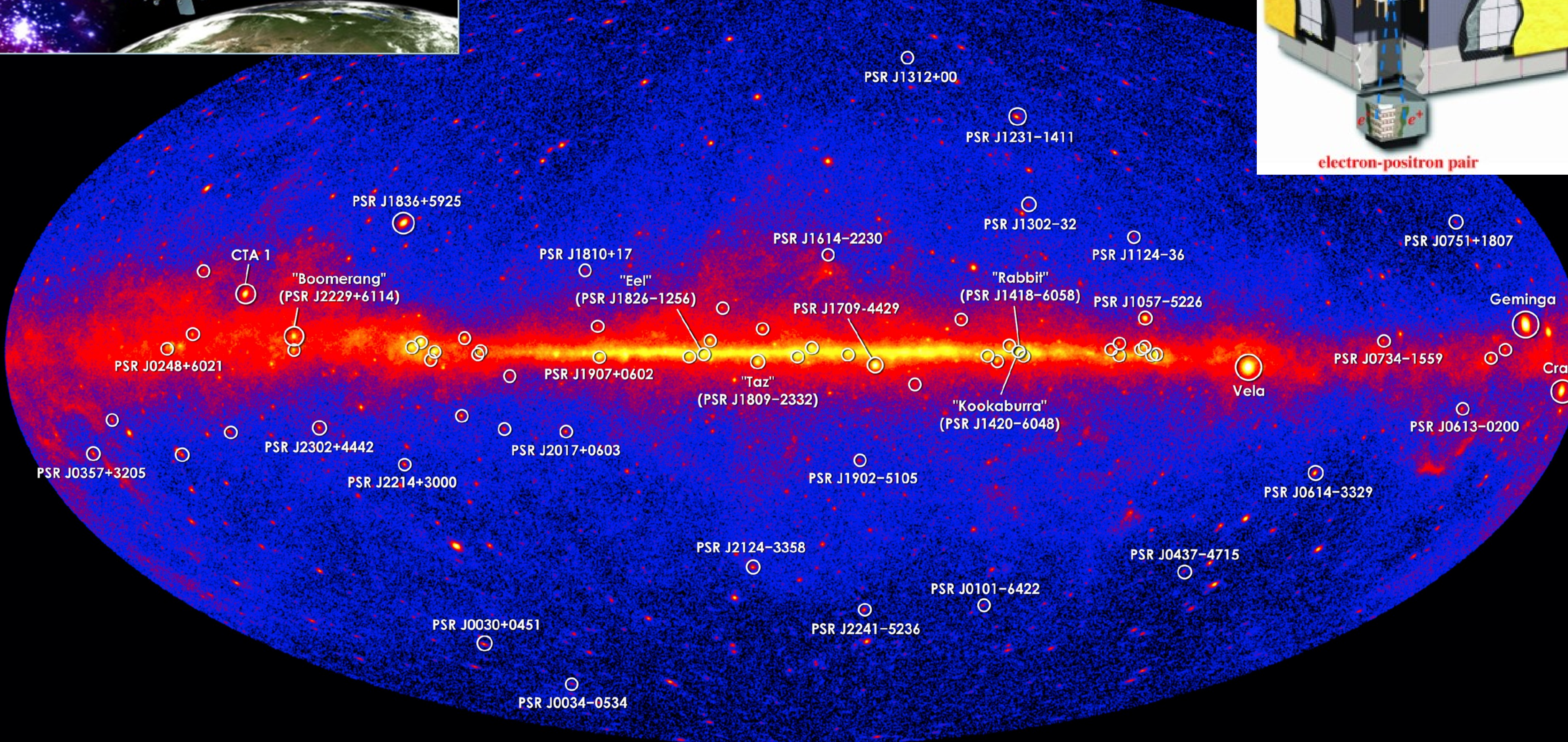
Where?

How?



Pulsars are the main source of high-energy gamma rays in the Galaxy





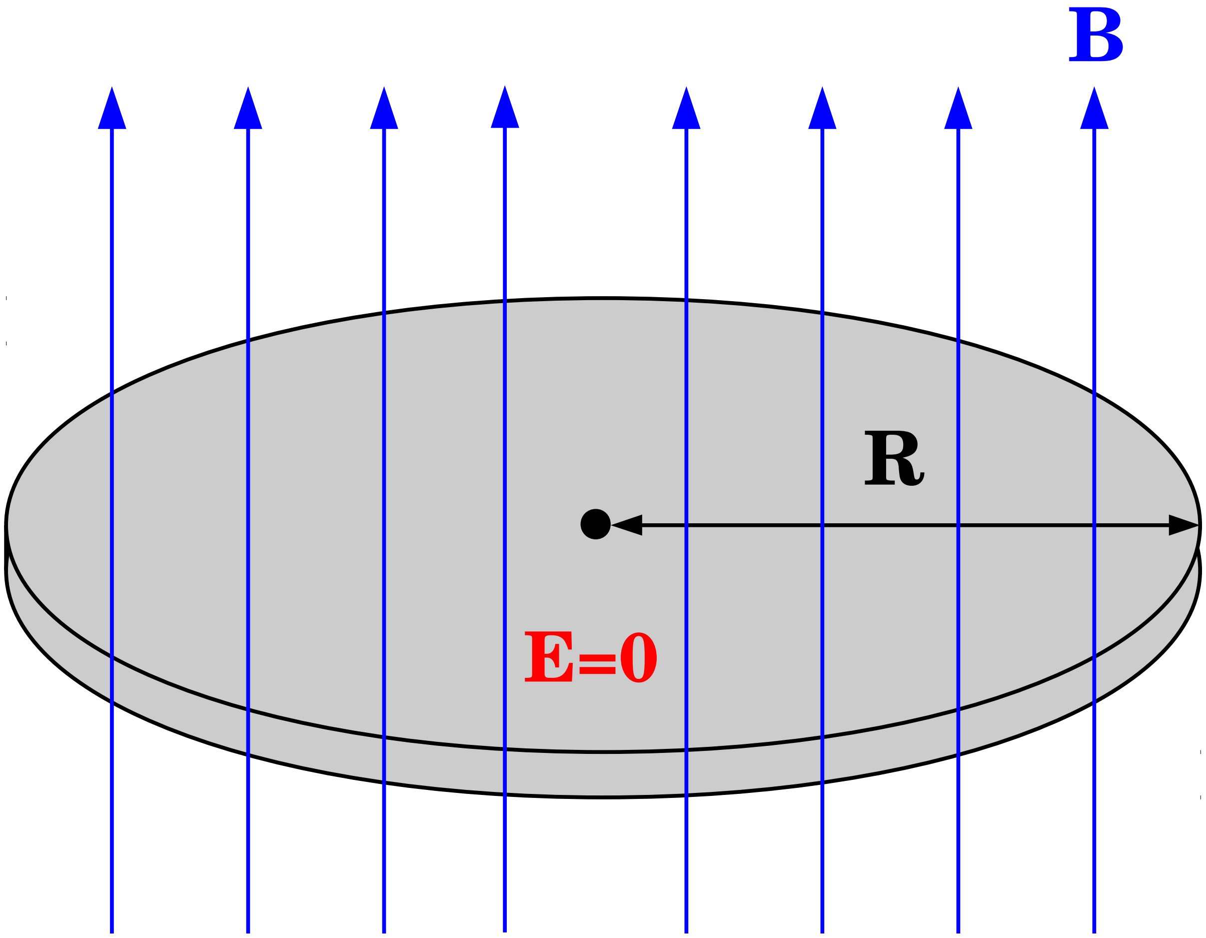
Pulsars are extremely efficient particle accelerators !
How do these beast work ?

A familiar analogy: Faraday's disk

No net charge

Static, perfectly conducting disk

Uniform B field



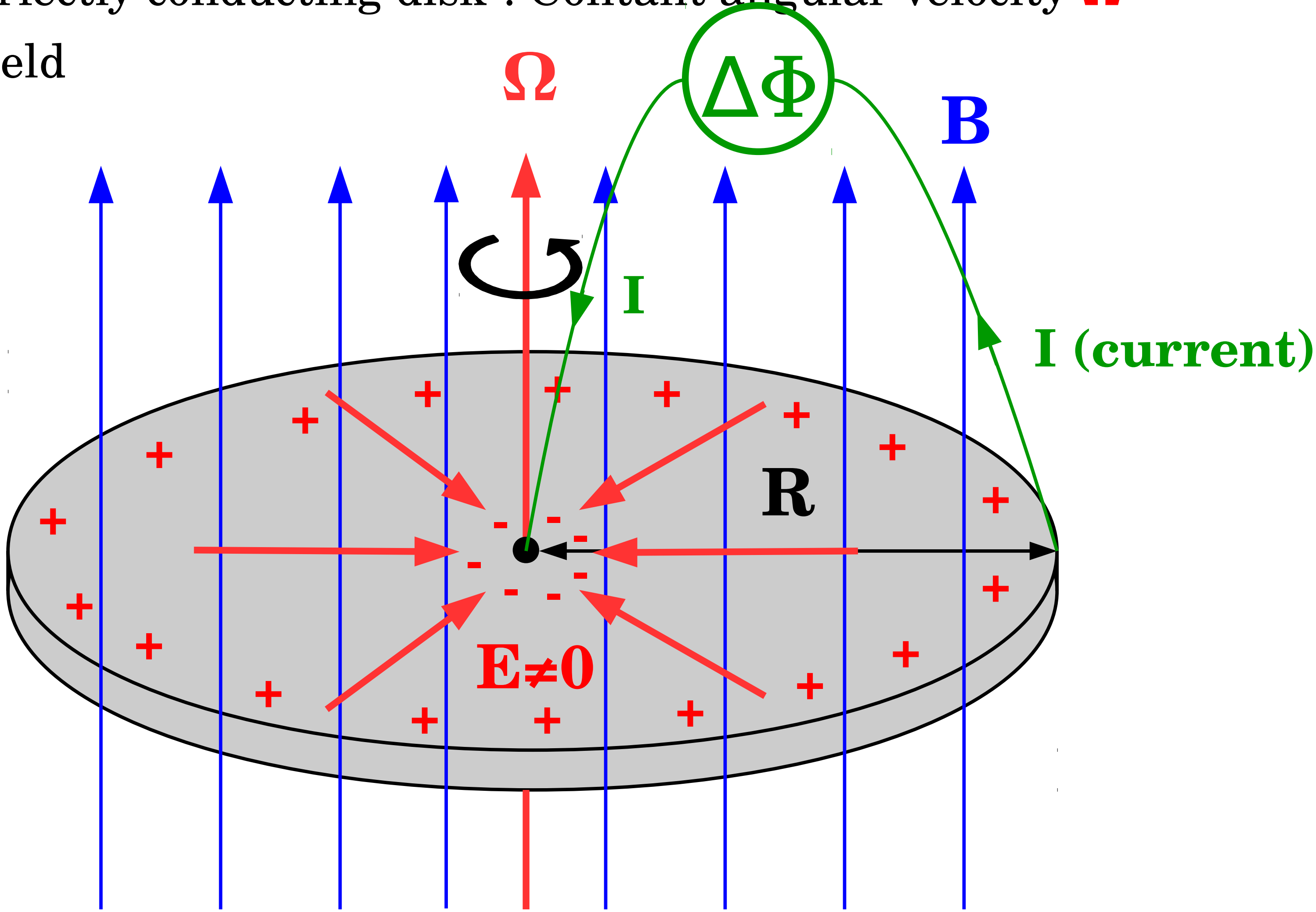
=> Electric field E=0

A familiar analogy: Faraday's disk

No net charge

Rotating, perfectly conducting disk : Contant angular velocity **Ω**

Uniform B field



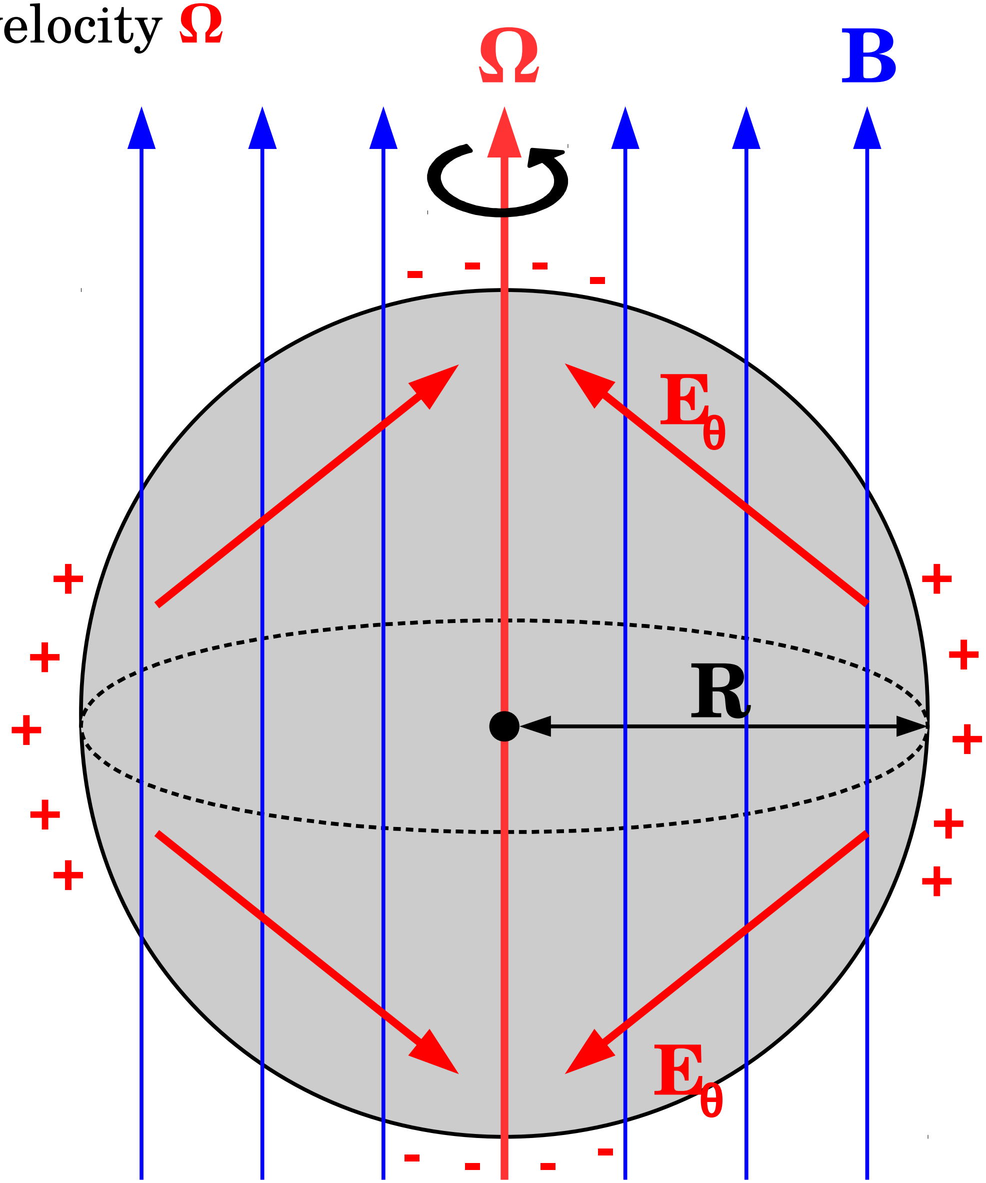
Induced electric field **E=-V×B/c=-(Ω×R)×B/c.** The disk is **polarized**.

=> Potential difference between the center and the outer radius

The spherical version

Contant angular velocity **Ω**

Uniform B field



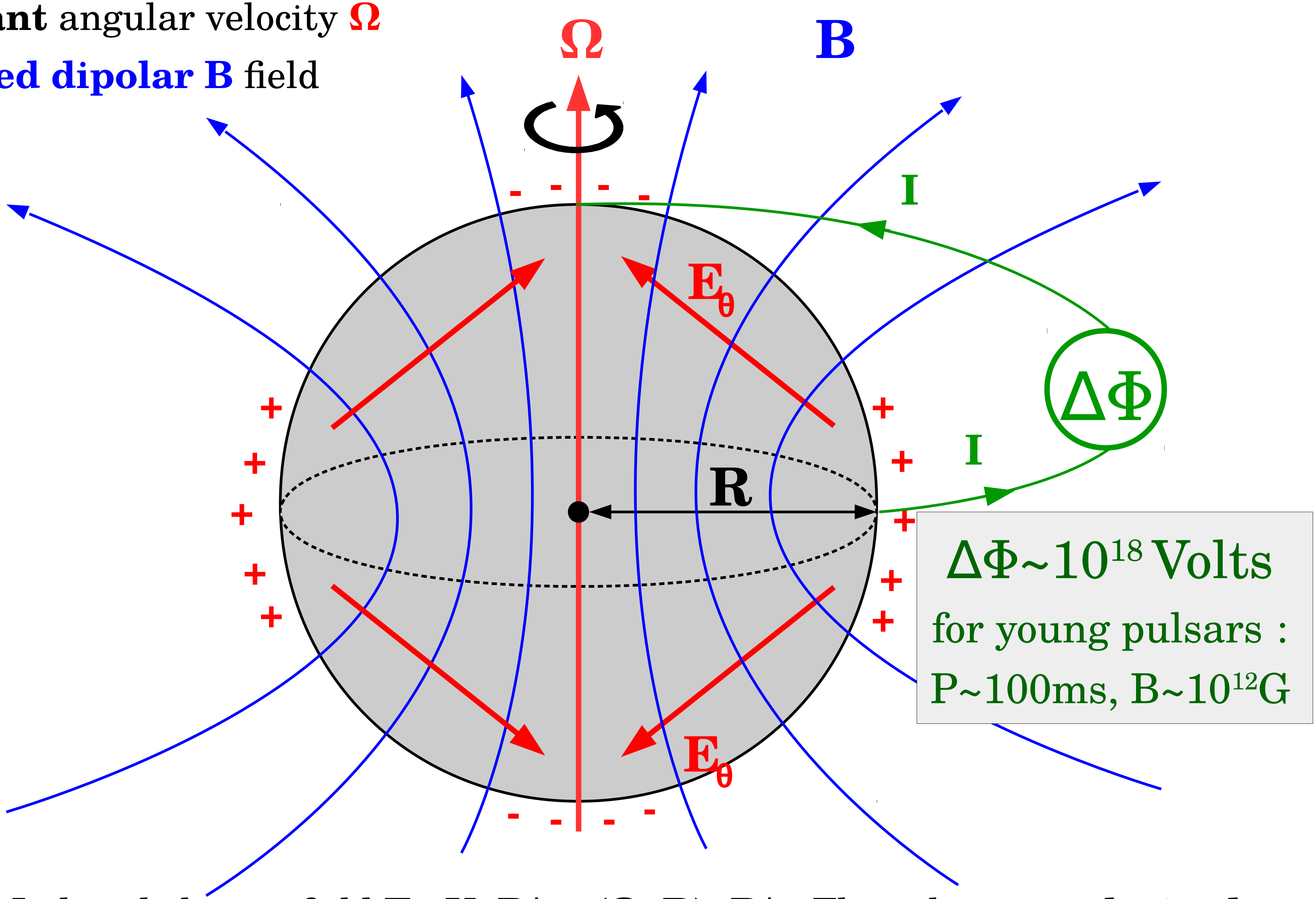
Induced electric field **E=-V×B/c=-(Ω×R)×B/c.** The sphere is **polarized**.

=> Potential difference between the <u>poles</u> and the <u>equator</u>

A proxy for a pulsar in vacuum...

Contant angular velocity **Ω**

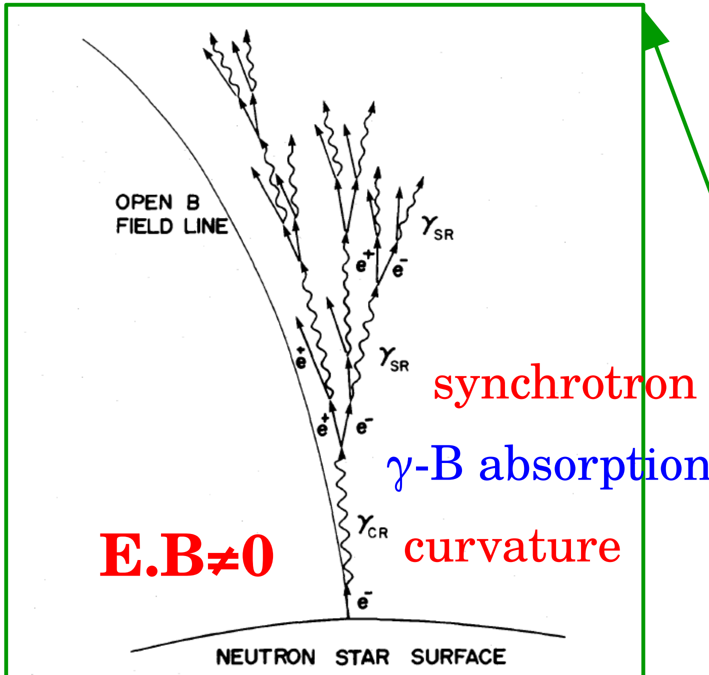
Aligned dipolar B field



Induced electric field **E=-V×B/c=-(Ω×R)×B/c.** The sphere is **polarized**.

=> Potential difference between the poles and the equator

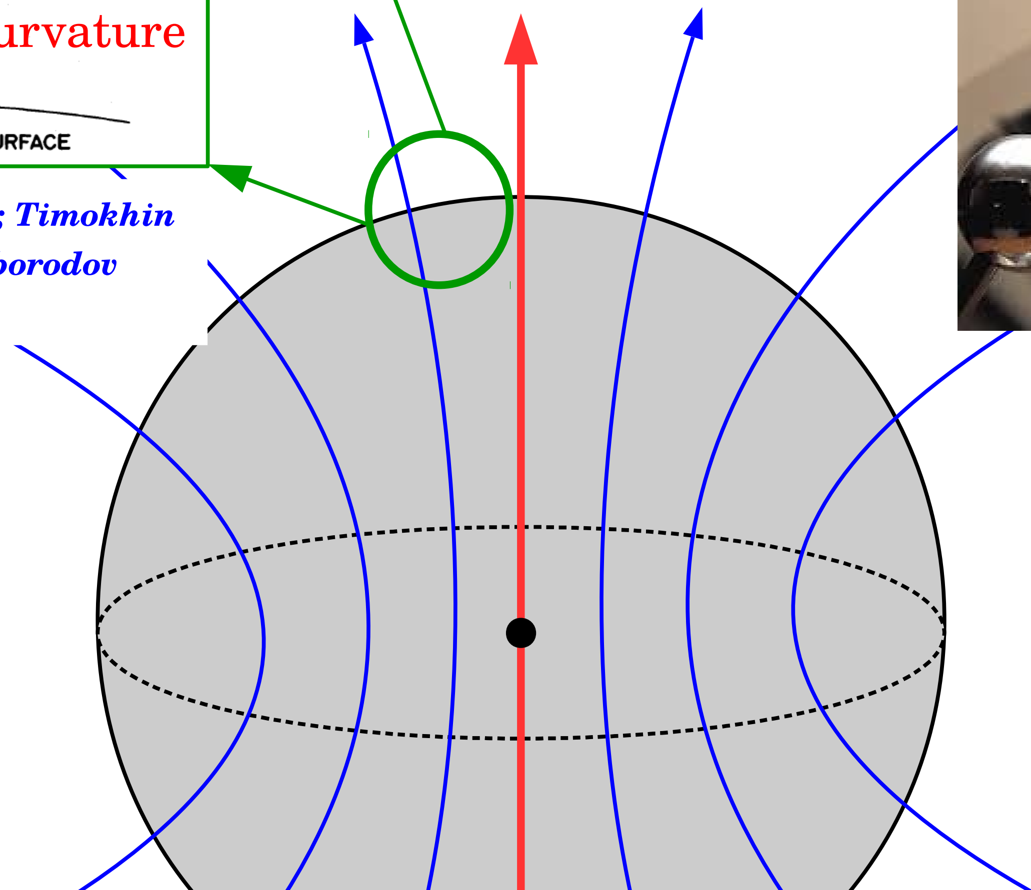
...but vacuum is not a good approximation



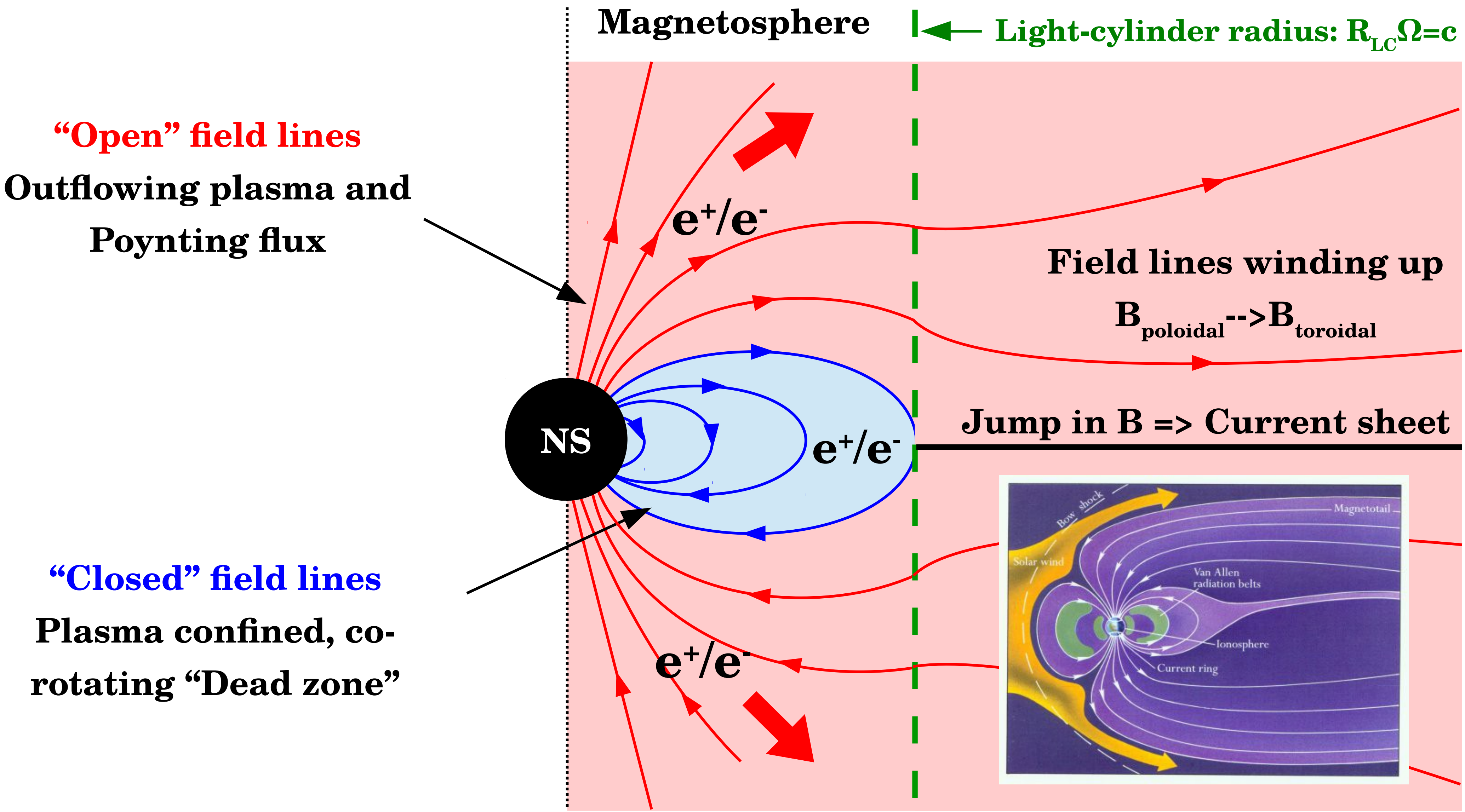
Daugherty & Harding 1982 ; Timokhin & Arons 2013 ; Chen & Beloborodov 2014 ; Philippov et al., 2015

Electric sparks and the **electromagnetic cascade** at star surface **breaks vacuum**.

The magnetosphere is mostly **filled with e^-/e^+ pairs**



Pulsar magnetosphere



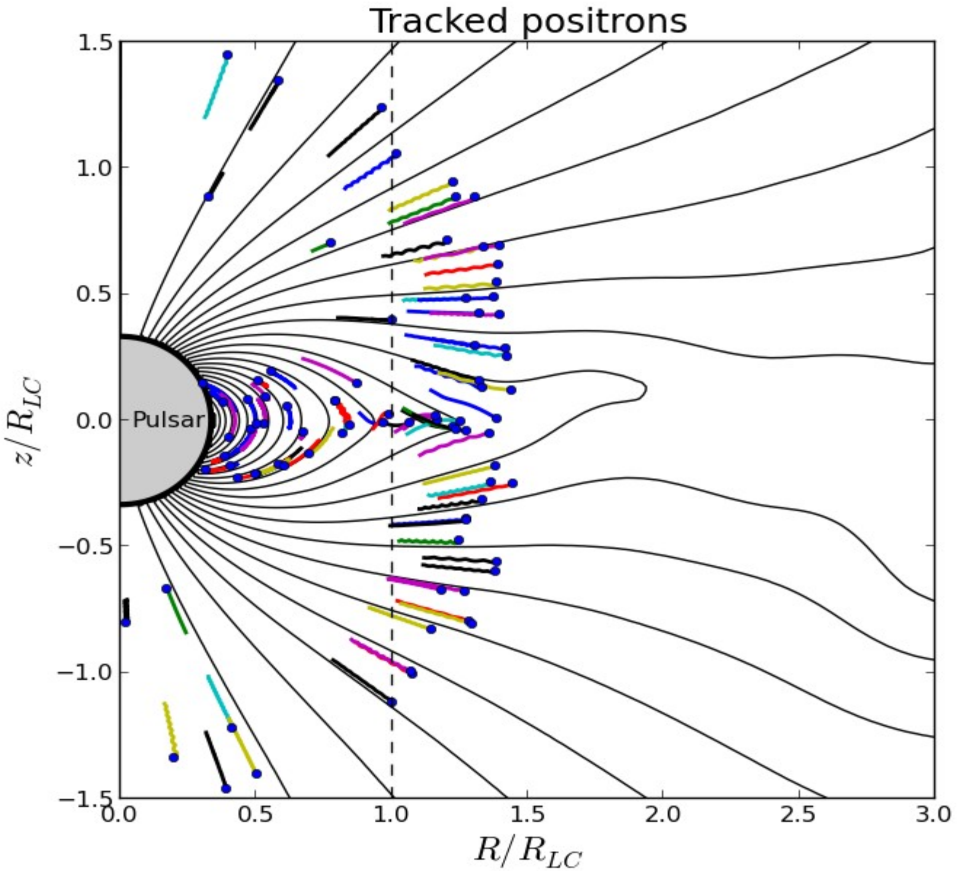
Problem unsolved analytically => Need for simulations!

The Particle-In-Cell (PIC) approach

Ab-initio numerical modeling to study particle acceleration in relativistic plasmas => the « **Particle-In-Cell** » **(PIC) method**

***Zeltron* : Code developped at l'IPAG**

- Follow **millions-billions of particles** (Newton)
- Evolves **electromagnetic fields** (Maxwell)



Numerical challenges : **Huge spatial and temporal scale separations**

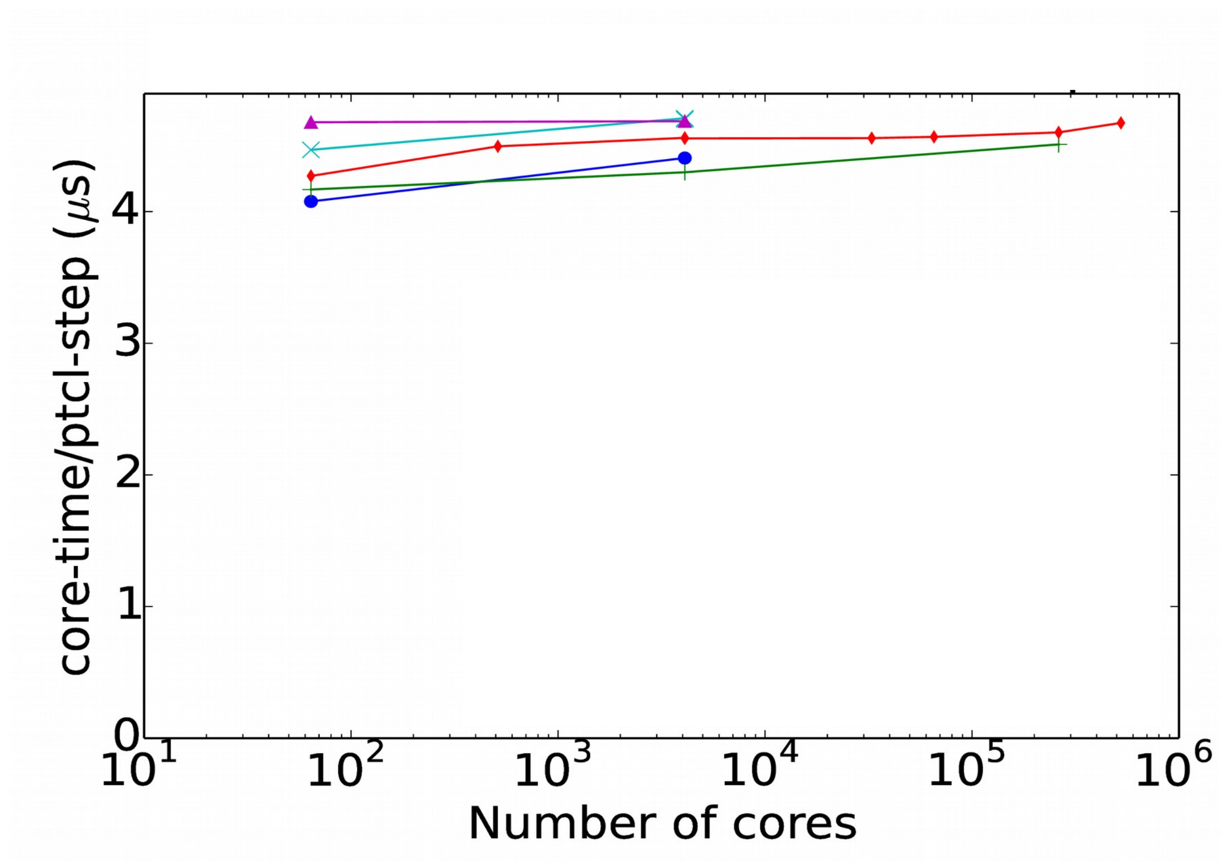
From microns to >1000 km ! => Need for parallel computing

PIC simulations : an example of high-performance computing for astrophysics

The Irene Supercomputer (CEA)

~100 000 cores

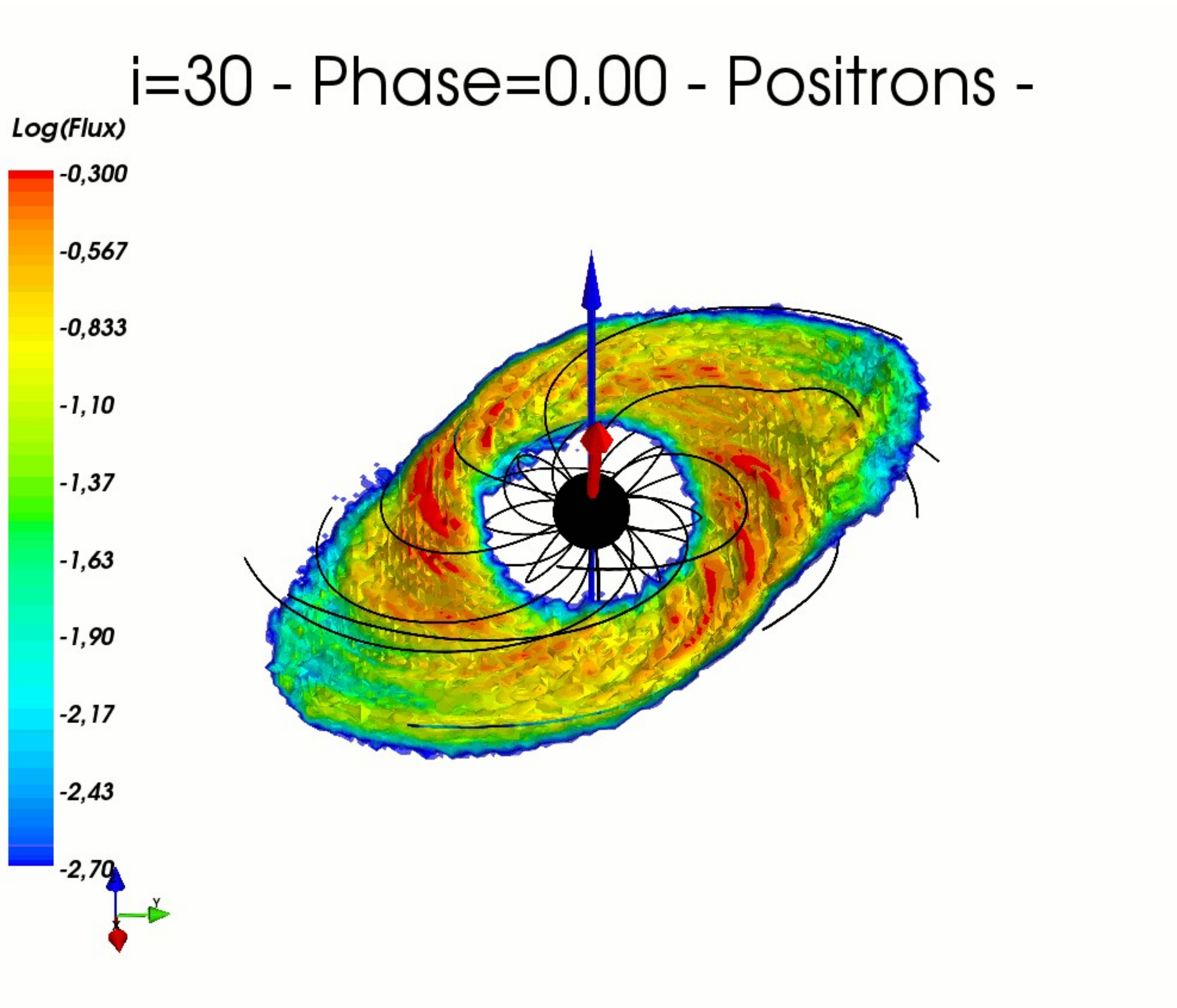
Parallelisation efficiency of the ***Zeltron code***



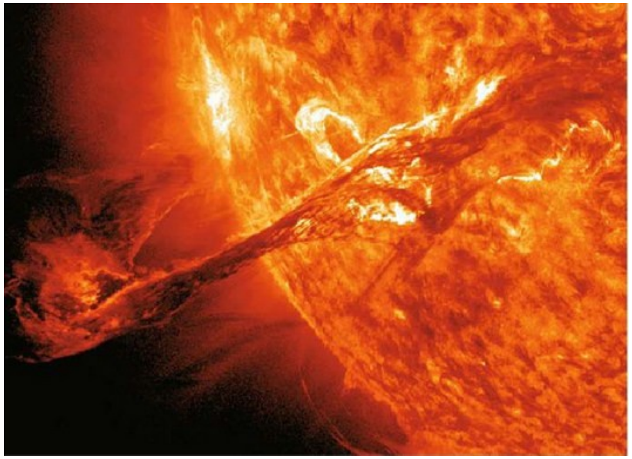
A long story short: results in a nutshell

Particle acceleration mechanism = Magnetic reconnection

Radiative process = Synchrotron radiation



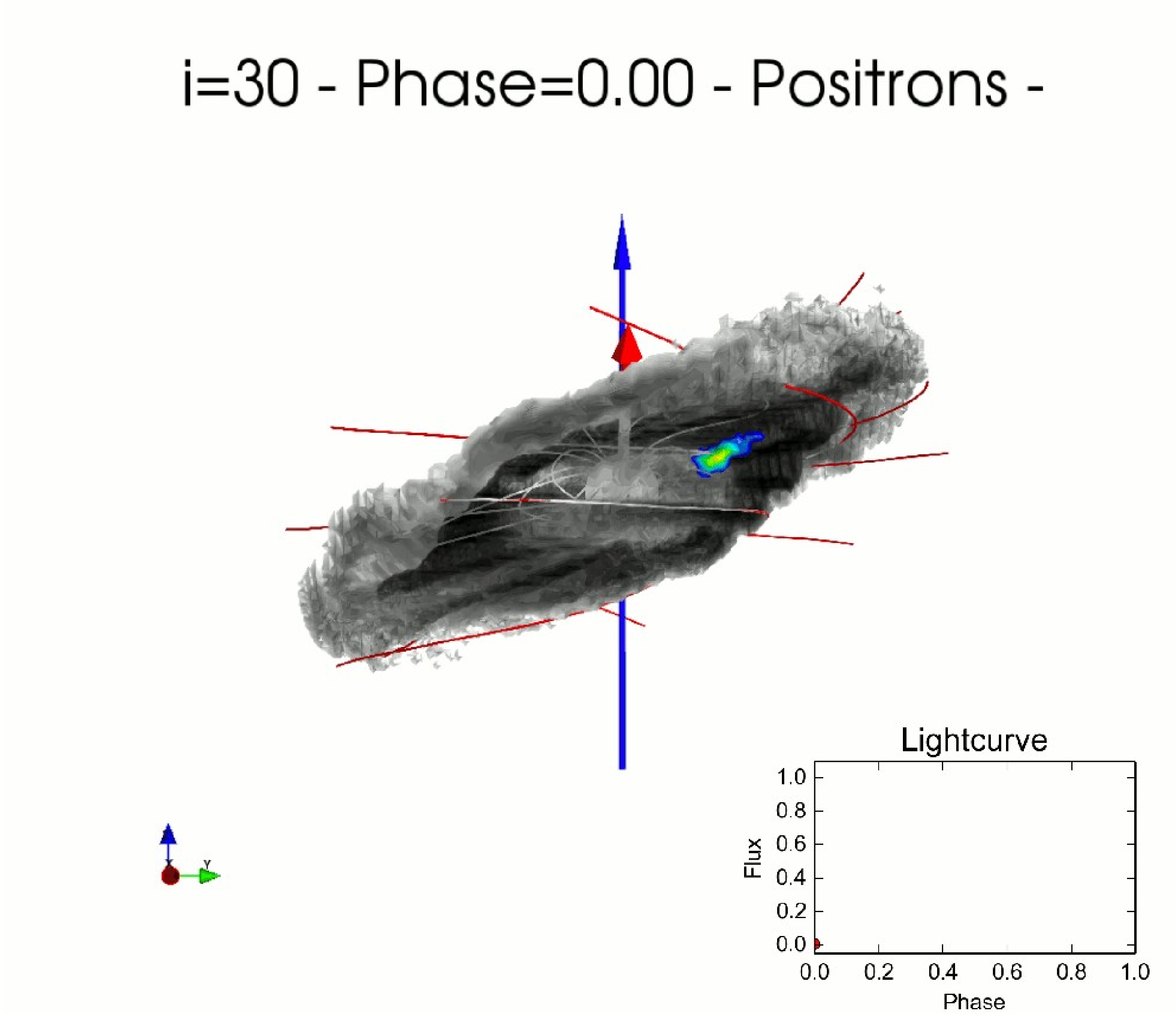
Solar flare



ESRF (Grenoble)

Main results in a nutshell

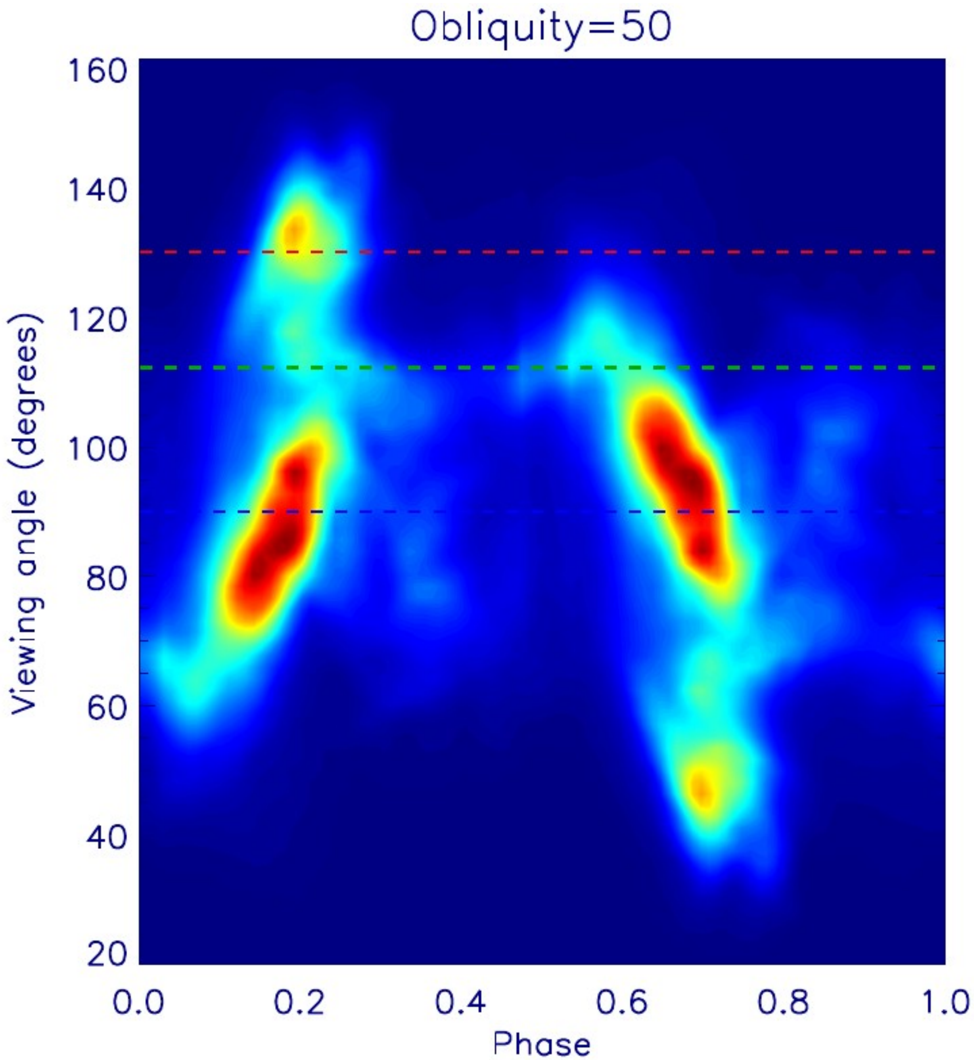
Emitting zones towards the observer



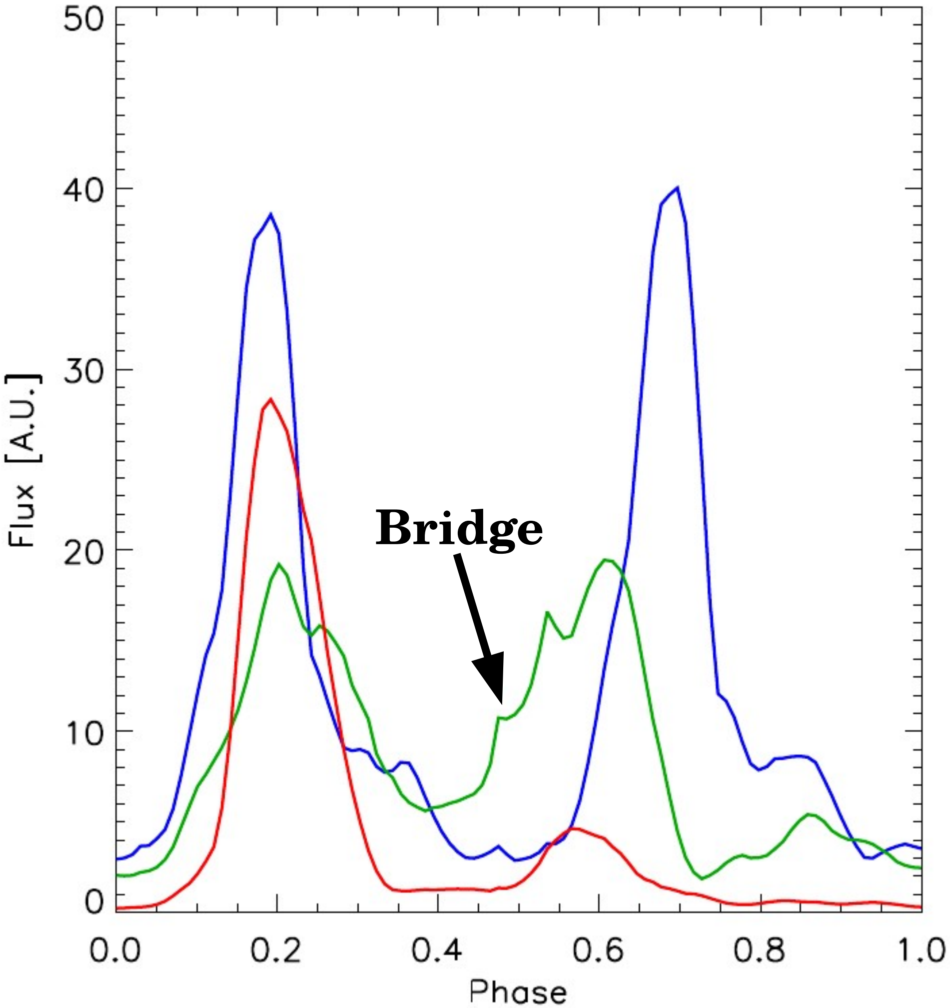
Caustic effect

A few typical lightcurves

Footprint on the sky



Pulse profiles



Cerutti et al. 2016

See also Philippov & Spitkovsky 2017

Kalapotharakos+2017

B. Cerutti

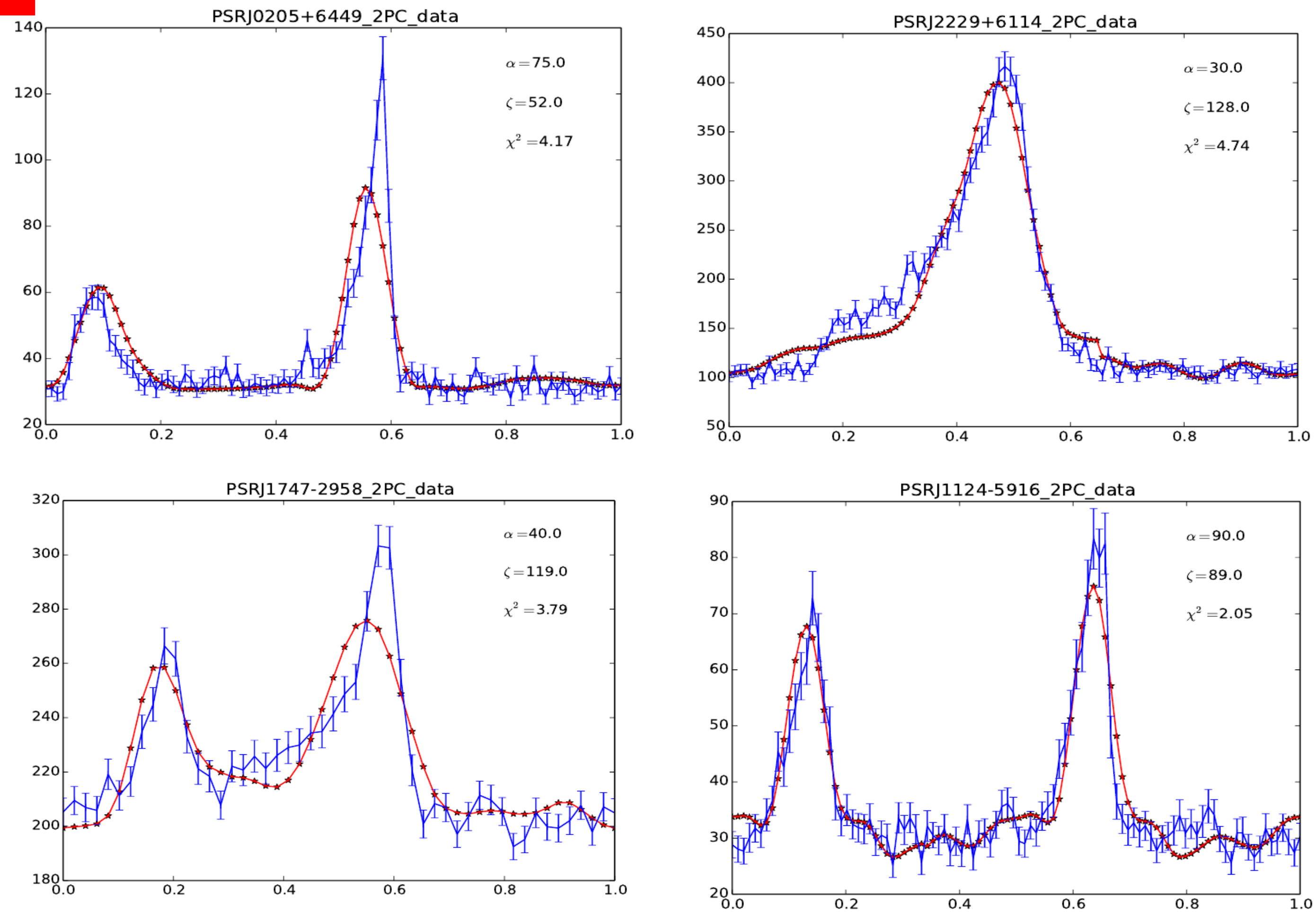
Fitting Fermi-LAT pulsar lightcurves

PRELIMINARY

Aloïs de Valon (Univ. Grenoble Alpes), Master thesis project

Observations

PIC model



Using the second catalog *(Abdo+2013)* : **117 pulsars**

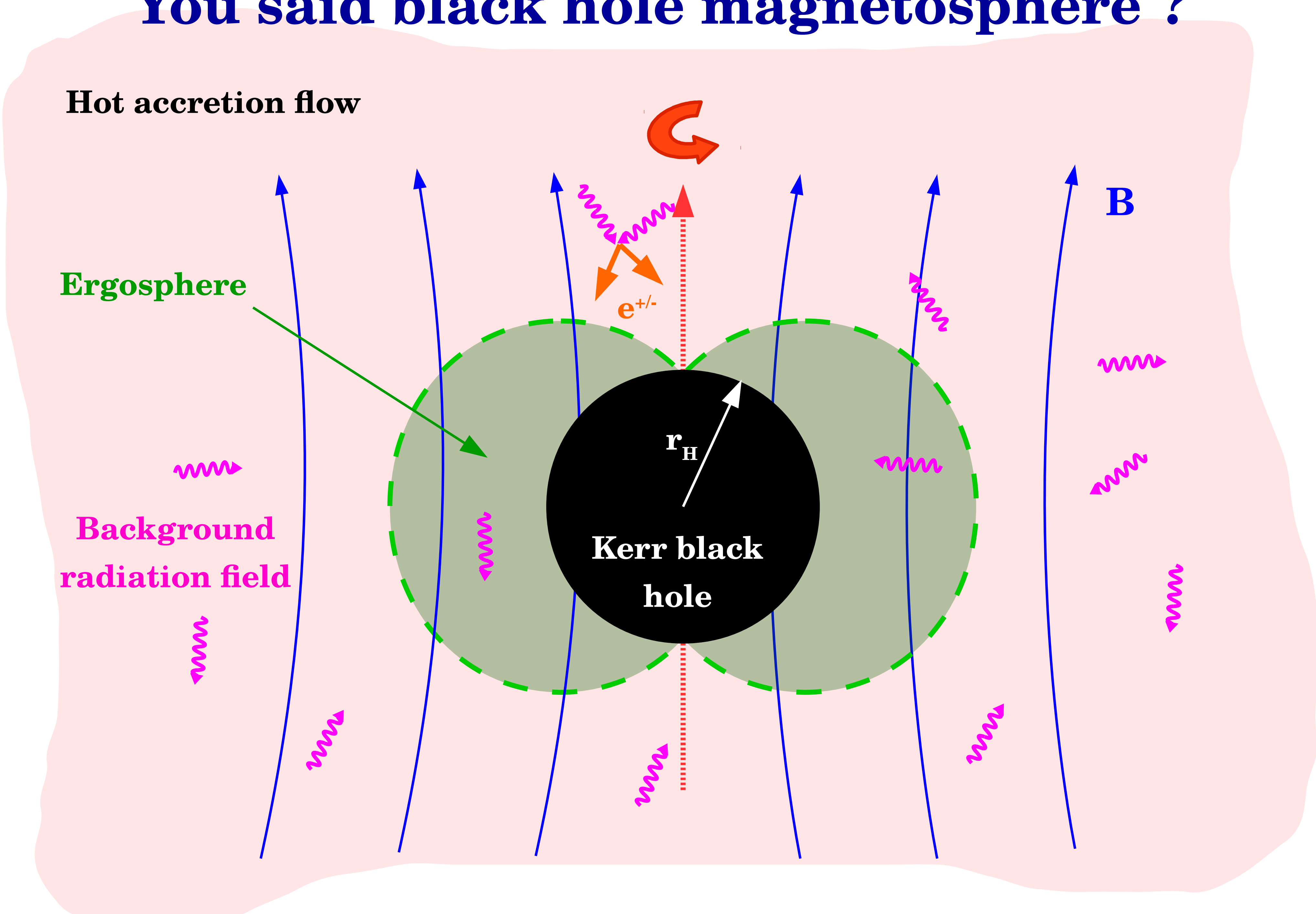
- Evidence for alignment with age, **alignment timescale 10^5-10^6 years.**
- **Magnetic axis** of very young pulsars nearly randomly distributed

  => **Random distribution at birth ?**

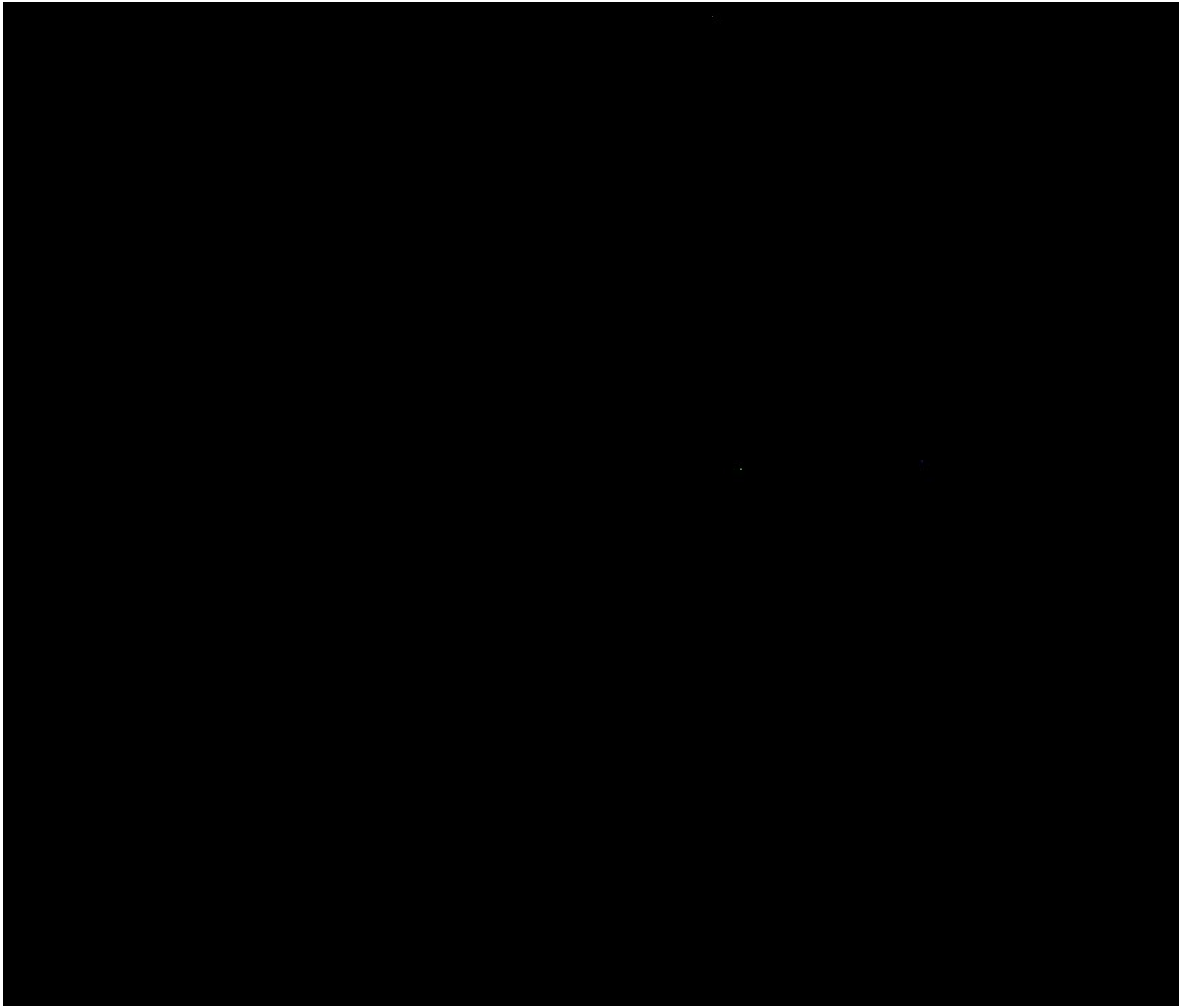
Looking forward: Black hole magnetospheres

Work in progress

You said black hole magnetosphere ?



Plasma density plot



Courtesy K. Parfrey