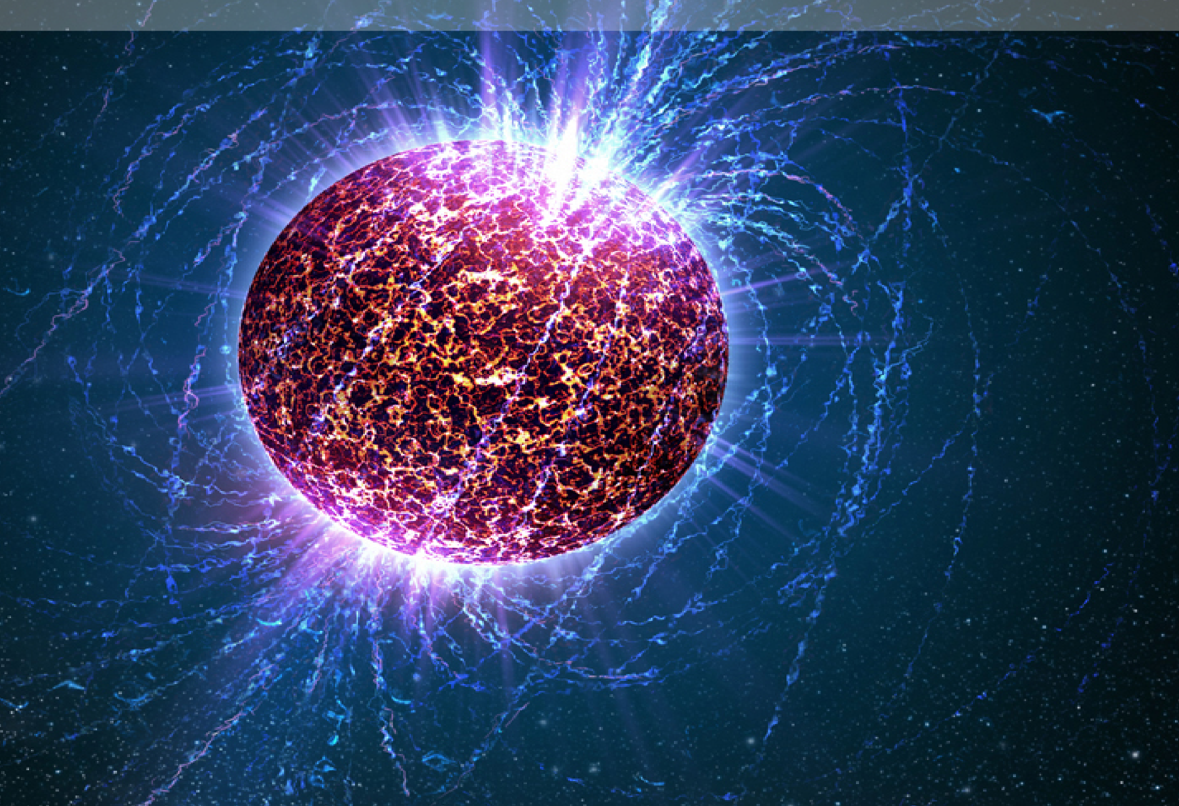
Pulsar magnetospheres



Benoît Cerutti

CNRS & Université Grenoble Alpes

Les Houches plasma physics school, May 13-24, 2019.

Pulsars are rapidly-rotating, high-magnetized neutron stars

NATURE, VOL. 217, FEBRUARY 24, 1968 709

Observation of a Rapidly Pulsating Radio Source

by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
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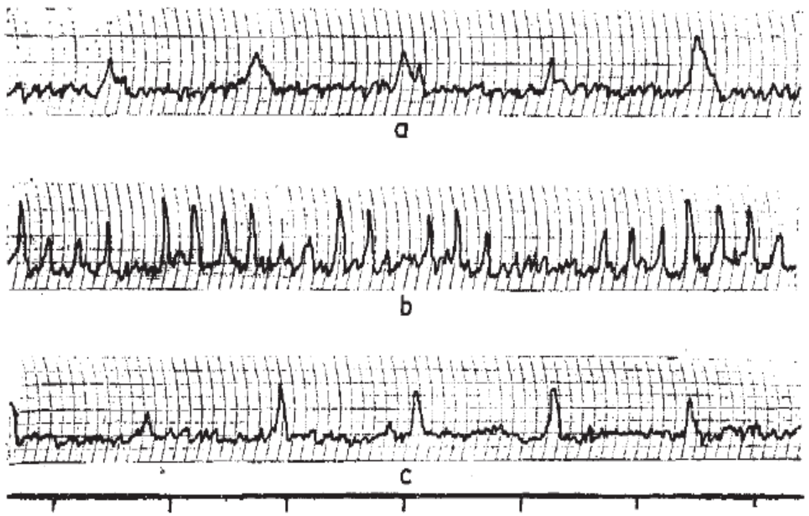
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

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 $\boxed{\text{with oscillations of white dwarf or neutron stars.}}$

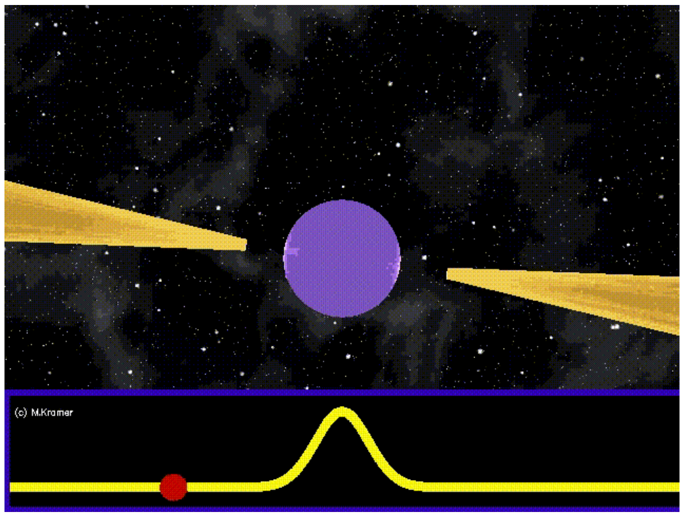


←—Time increasing Seconds

Fig. 1. Pulses observed with a recording time constant of about 0·03 s on March 21, 1968. (*a*) *CP*.0834. (*b*) *CP*.0950, during a period of intense activity. (*c*) *CP*.1133.

Quickly identified to a rotating **neutron star**

Radius~10km, Mass~1-2M_{sun} B~10^{9}-10^{15}G



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

Pulsars are fantastic laboratories : Tests for GR, nuclear densities, strong EM fields

The pulsar phenomena was predicted just few months before

NATURE, VOL. 216, NOVEMBER 11, 1967

F. PACINI
Center for Radiophysics and Space Research,
Cornell University,
New York.

LETTERS TO THE EDITOR

ASTRONOMY

Energy Emission from a Neutron Star

A newly formed neutron star is an excited object. Apart from its thermal content (which will be dissipated very fast because of neutrino processes), there will also be much energy stored in vibrational and rotational form. The problem therefore arises of finding out whether the energy stored in the neutron star plays an important part in connexion with the activity observed in some supernova remnants such as the Crab Nebula.

[...]

The same picture of an oblique rotator leads also to a different possibility, that is, that the neutron star might directly emit electromagnetic waves of very low frequency (in the kc/s range). This idea has been suggested by Hoyle, Narlikar and Wheeler[4] as a possible consequence of the vibrations of a magnetic neutron star. Because the rapid damping of the vibrations makes it difficult to retain this suggestion in the original form, I wish to point out that the oblique rotator model also results into an analogous emission of electromagnetic waves.

Rotating Neutron Stars as the Origin of the Pulsating Radio Sources

NATURE, VOL. 218, MAY 25, 1968

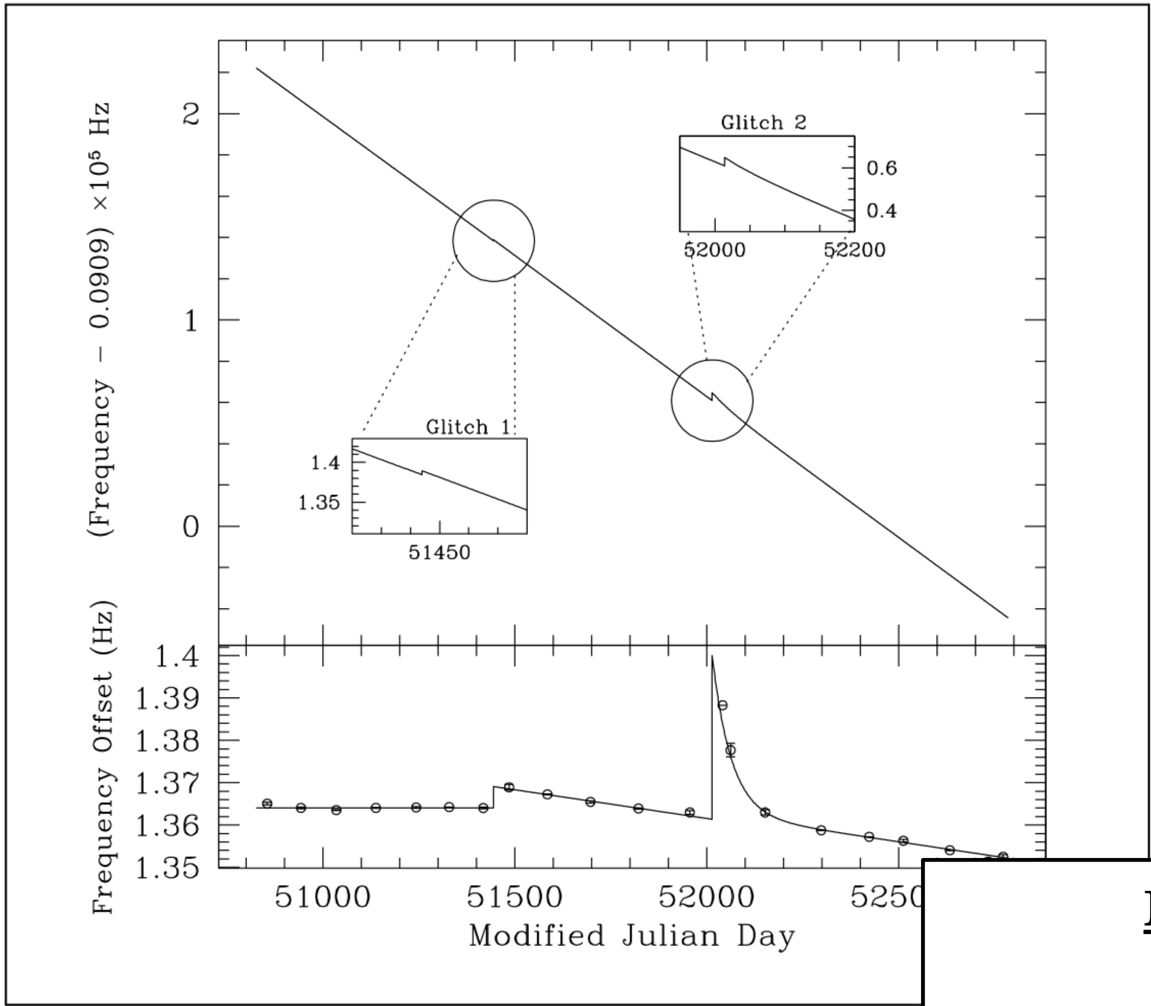
by

T. GOLD

Center for Radiophysics and Space Research,
Cornell University,
Ithaca, New York

The constancy of frequency in the recently discovered pulsed radio sources can be accounted for by the rotation of a neutron star. Because of the strong magnetic fields and high rotation speeds, relativistic velocities will be set up in any plasma in the surrounding magnetosphere, leading to radiation in the pattern of a rotating beacon.

Pulsars spin down



Kaspi & Gavrill (2003)

<u>Measured with high-accuracy :</u>

P : rotation period

Gives the total **rotational energy** available

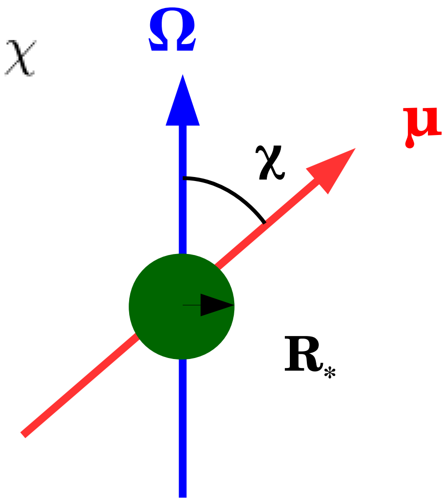
dP/dt : period slowdown (increase)

Gives the total **power release** (seen or unseen !)

Pulsars age and magnetic fields estimates

Asumption : **magnetic dipole in vacuum**

Power losses from the dipole radiation : $L_{\rm dipole} = \frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2\chi$



Rotational kinetic energy : $E_{\rm rot} = \frac{1}{2}I\Omega^2$

Moment of inertia of the star : $I = \frac{2}{5}MR_\star^2$

Characteristic surface magnetic field :

$$\frac{d\left(\frac{1}{2}I\Omega^2\right)}{dt} = L_{\rm dipole} \longrightarrow \boxed{B_\star \approx 3.3\times10^{19}\sqrt{P\dot{P}}\ G}$$

Characteristic pulsar age : $\boxed{\tau = \frac{P}{2\dot{P}}}$

The P-Pdot diagram : The HR diagram for pulsars

Magnetars (not discussed)

Powered by magnetic fields

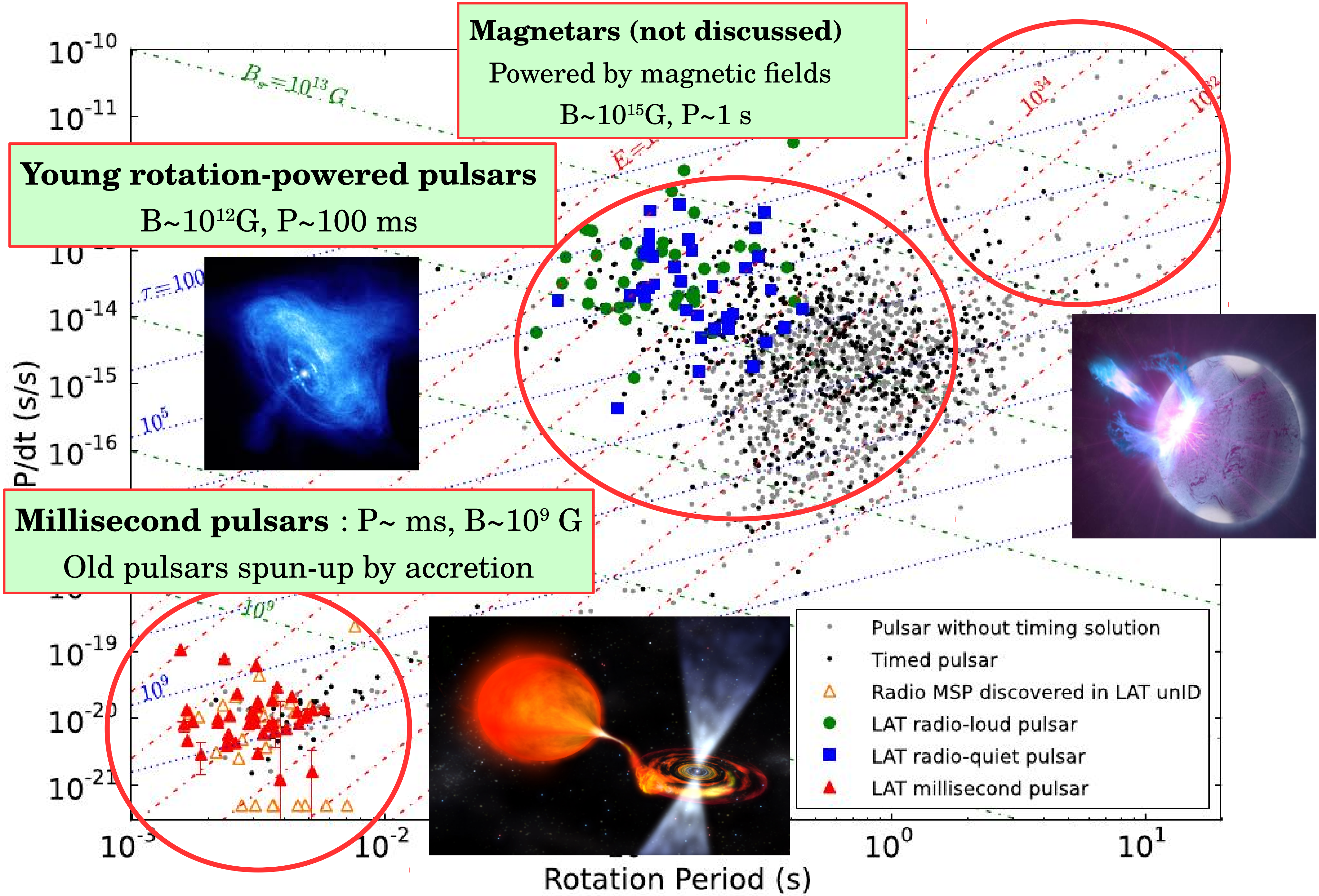
B~10^{15}G, P~1 s

Young rotation-powered pulsars

B~10^{12}G, P~100 ms

Millisecond pulsars : P~ ms, B~10^9 G

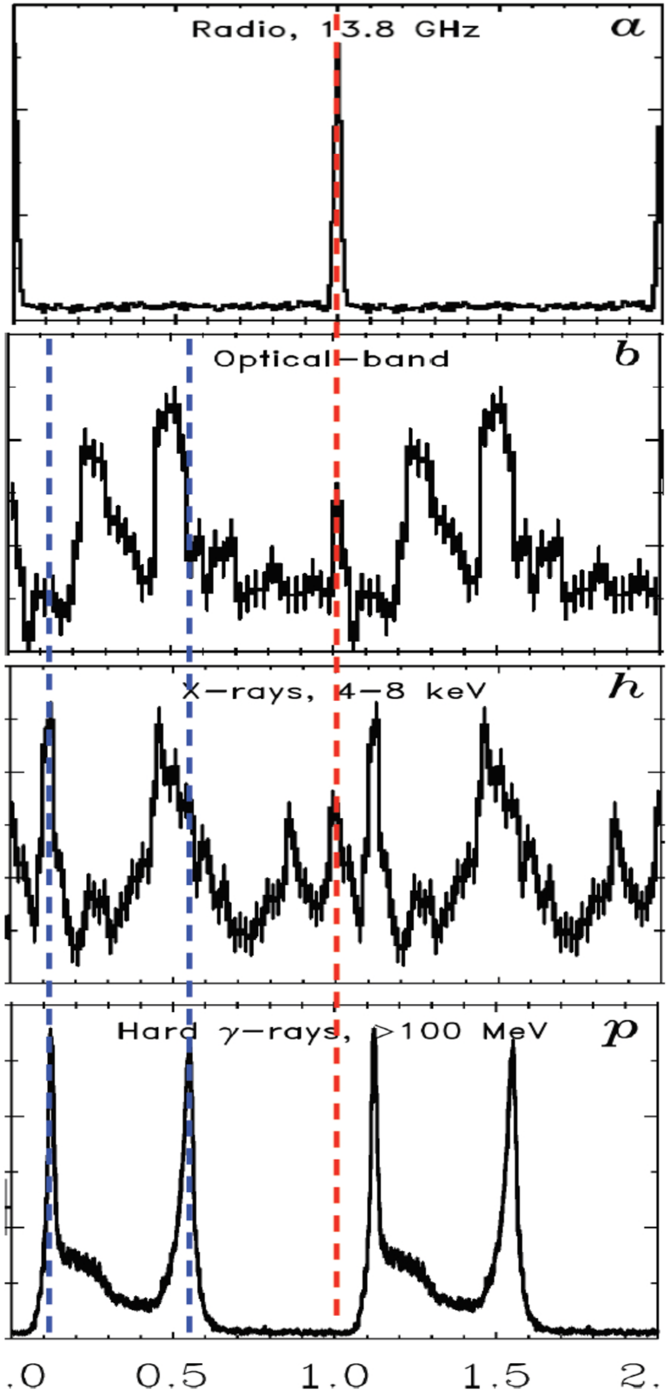
Old pulsars spun-up by accretion



[2nd Fermi-LAT pulsar catalog]

Pulsars shine throughout the electromagnetic spectrum

The Vela pulsar



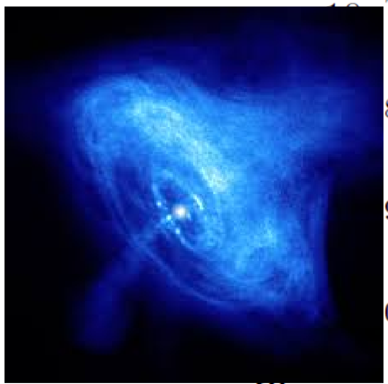
Relativistic particles !

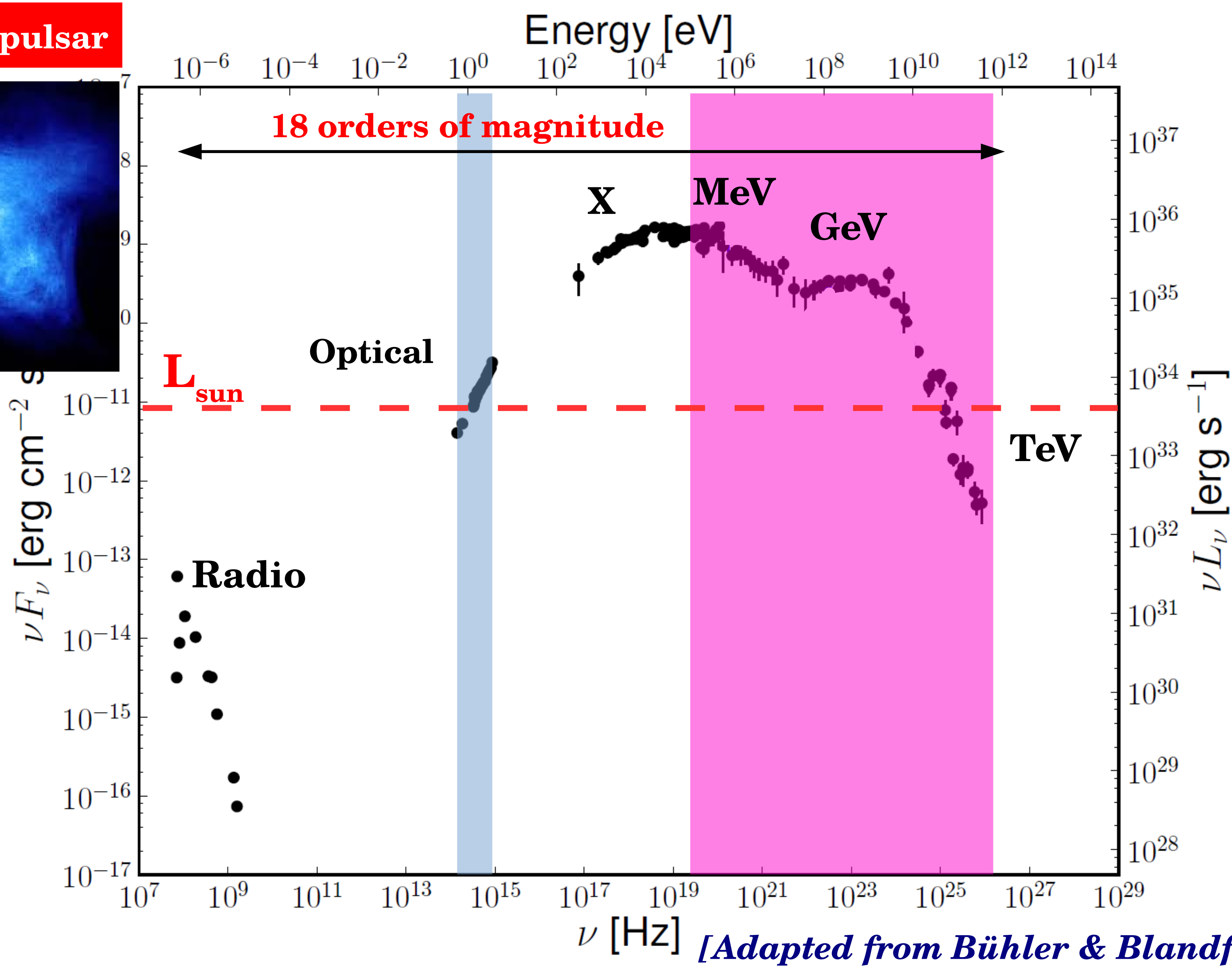
Presence of a plasma

Rudak 2018

Pulsars shine throughout the electromagnetic spectrum

The Crab pulsar



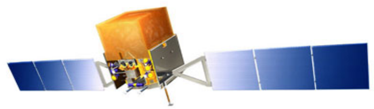


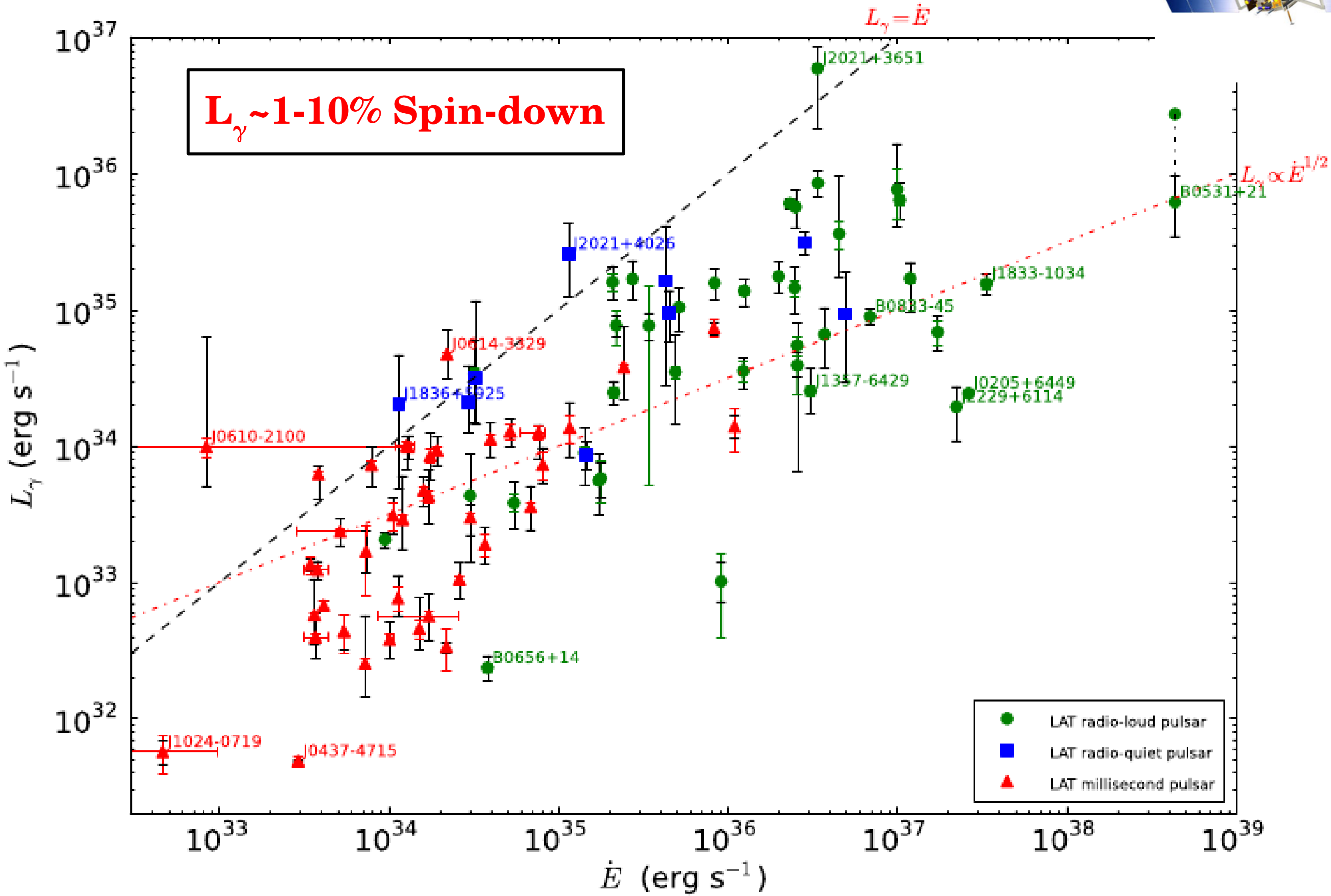
[Adapted from Bühler & Blandford 2014]

A large fraction of the pulsar spindown is released in light,
in particular in the gamma-ray band => Efficient particle acceleration !

Pulsars are efficient particle accelerators

Fermi γ-ray space telescope (**100MeV-100GeV**)





[2nd Fermi-LAT pulsar catalog]

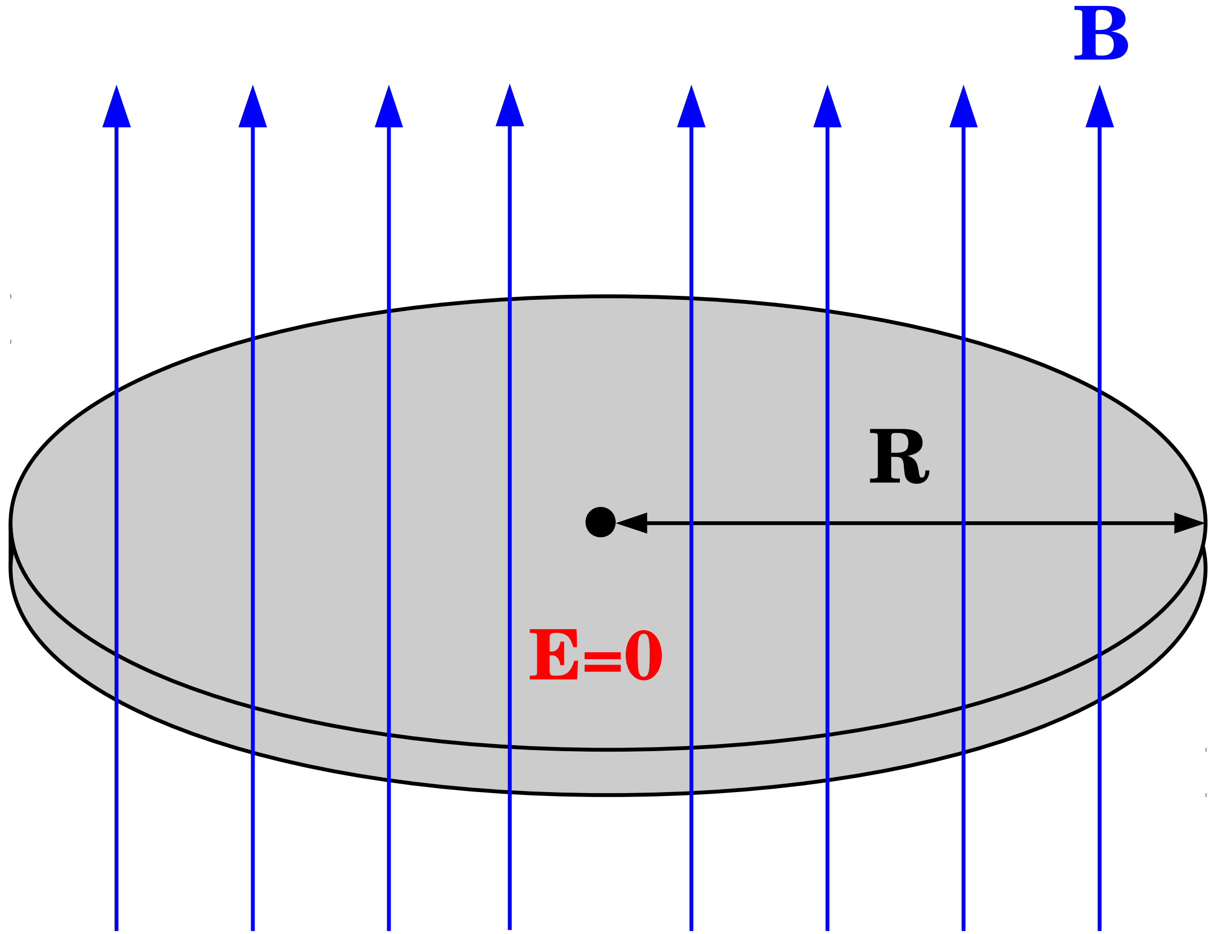
Pulsar electrodynamics

A familiar analogy: Faraday's disk

No net charge

Static, perfectly conducting disk

Uniform B field



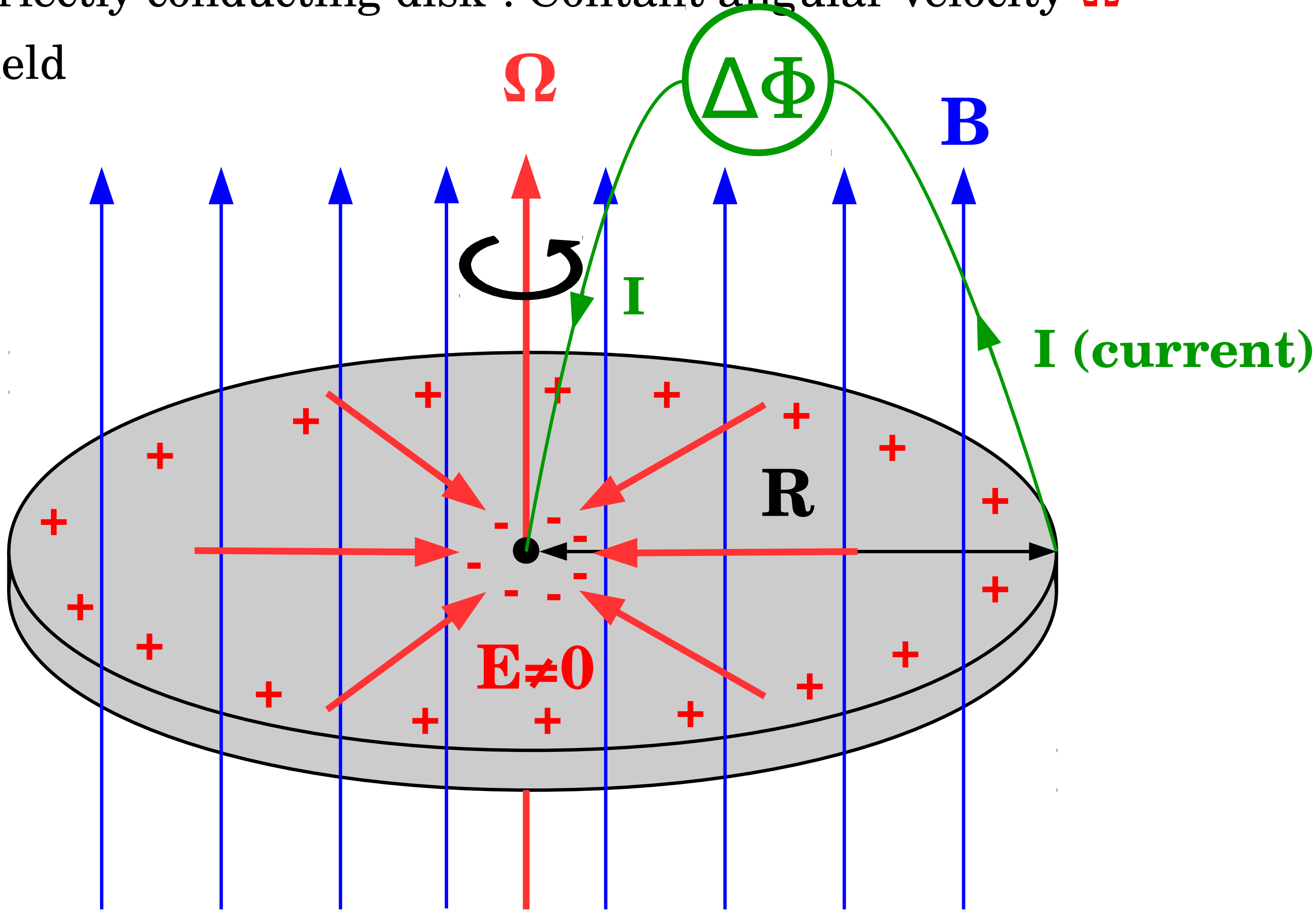
=> Electric field E=0

A familiar analogy: Faraday's disk

No net charge

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

Uniform B field



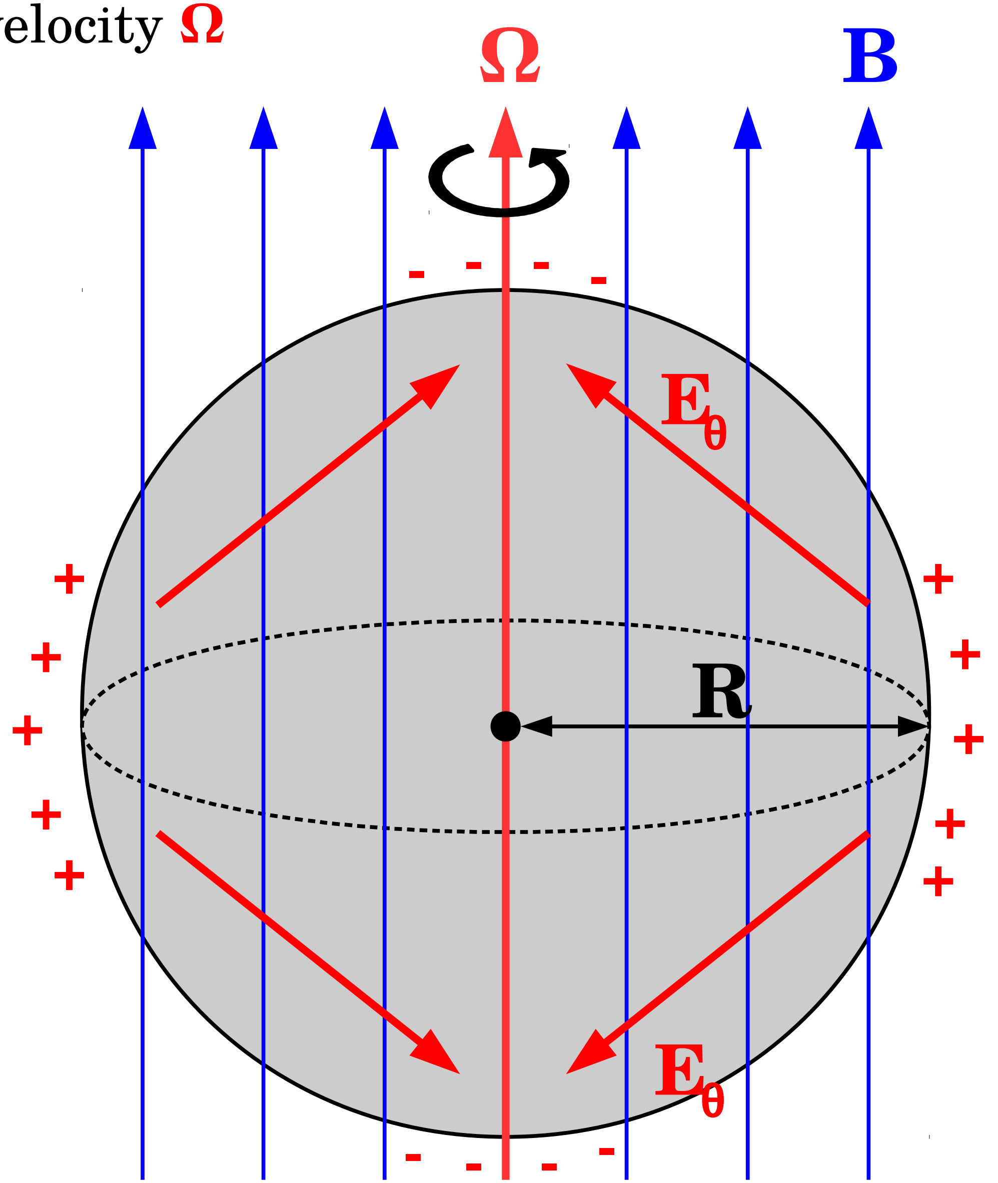
Induced electric field **E=-V×B/c=-(Ω×R)×B/c.** The disk is **polarized**.

=> Potential difference between the center and the outer radius

The spherical version

Contant angular velocity **Ω**

Uniform B field



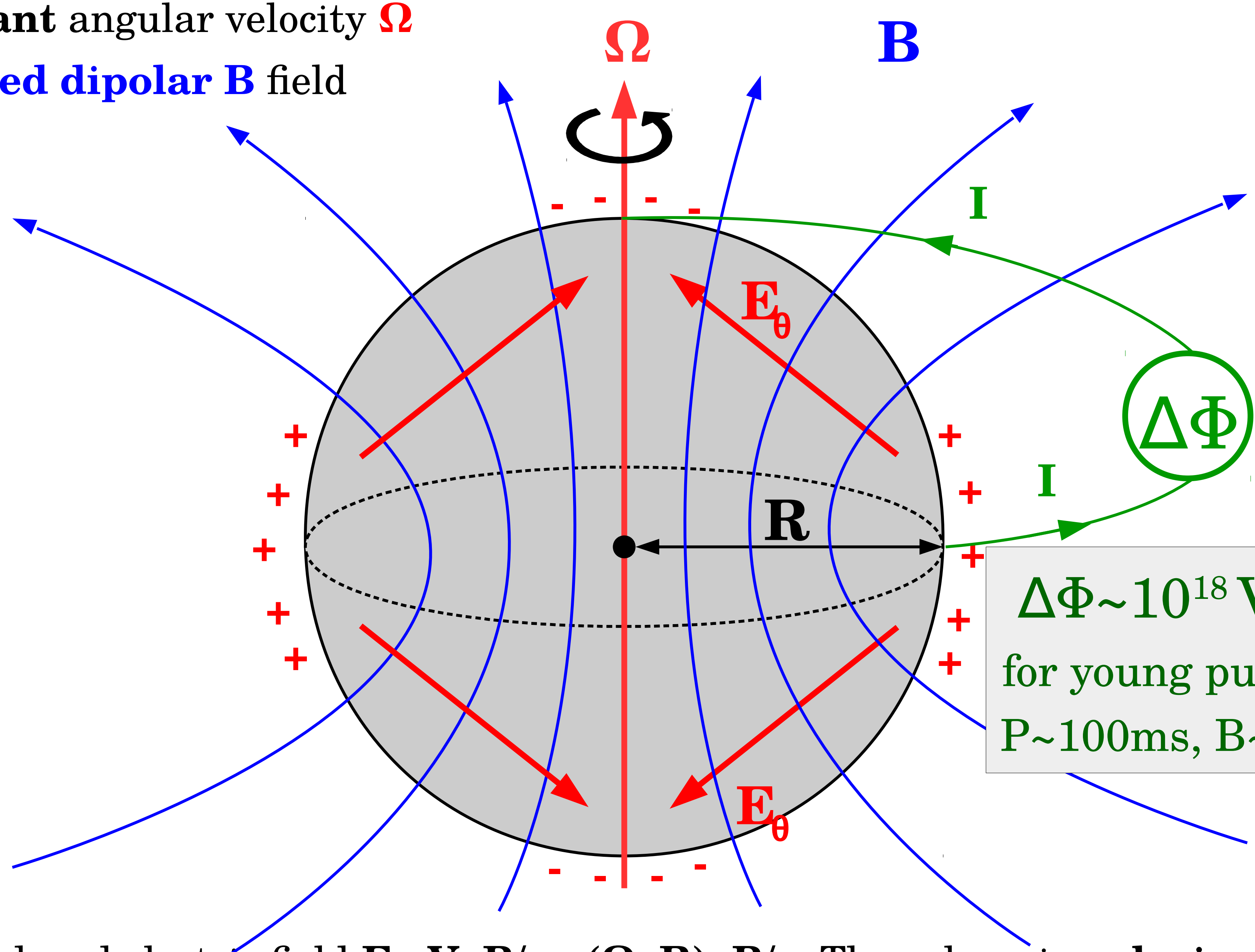
Induced electric field **E=-V×B/c=-(Ω×R)×B/c.** The sphere is **polarized**.

=> Potential difference between the poles and the equator

A proxy for a pulsar in vacuum...

Contant angular velocity **Ω**

Aligned dipolar B field



$\Delta\Phi \sim 10^{18}$ Volts

for young pulsars :

$P \sim 100$ms, $B \sim 10^{12}$G

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

=> Potential difference between the poles and the equator

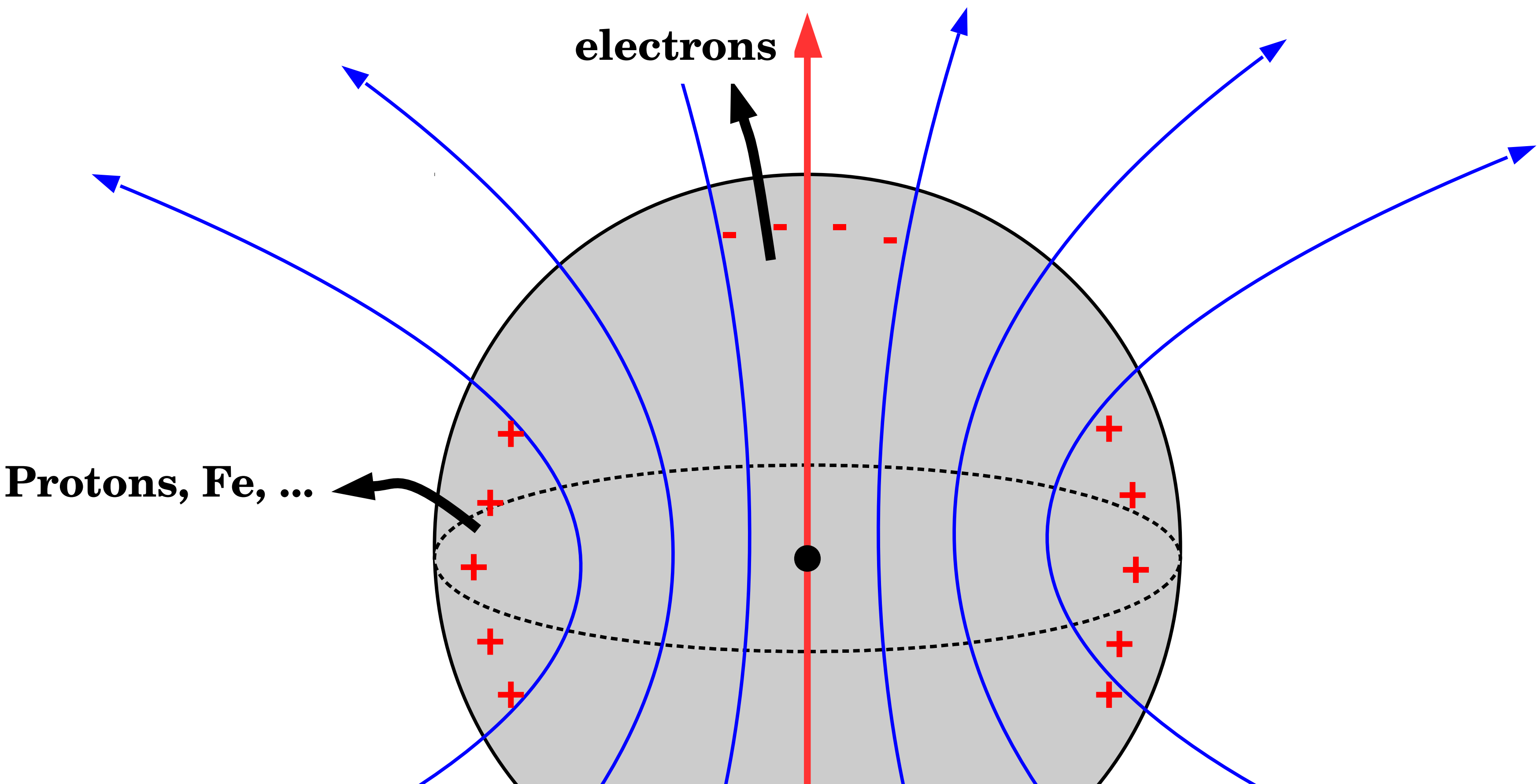
...but vacuum is not a good approximation

Surface electric field can lift charged particles from the star, the gravitational pull is negligible :

$$\frac{eE_{\parallel}}{F_{\mathrm{G}}} \sim 10^{12}$$

With B=10^{12} G, P=100 ms

Goldreich & Julian 1969



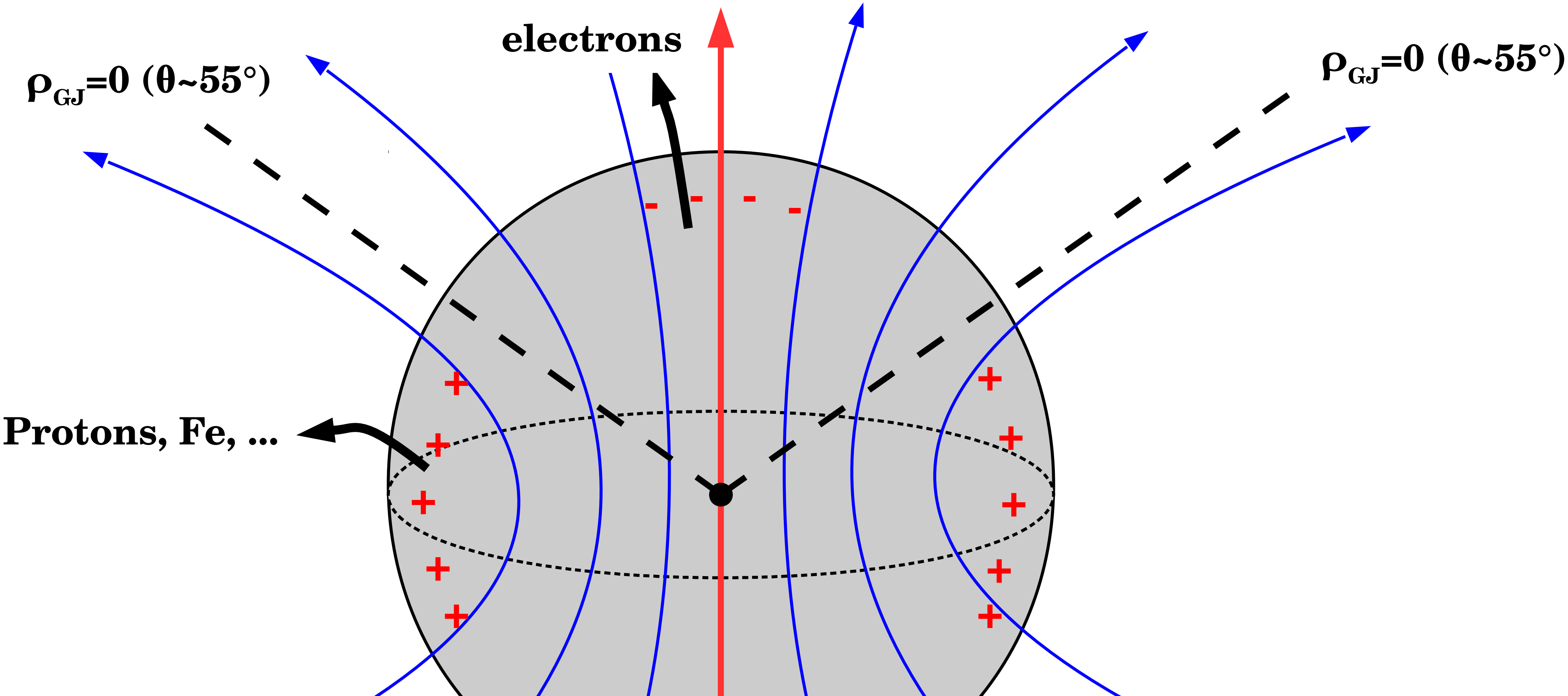
Goldreich-Julian charge density

Charge extraction screens the parallel electric field. The minimum density for complete screen is given by : *Goldreich & Julian 1969*

$$\rho_{\rm GJ} = \nabla\cdot\mathbf{E}/4\pi = -\frac{1}{4\pi c}\nabla\cdot((\mathbf{\Omega}\times\mathbf{R})\times\mathbf{B})$$

$$\boxed{\rho_{\rm GJ} \approx -\frac{\Omega\cdot\mathbf{B}}{2\pi c}}$$

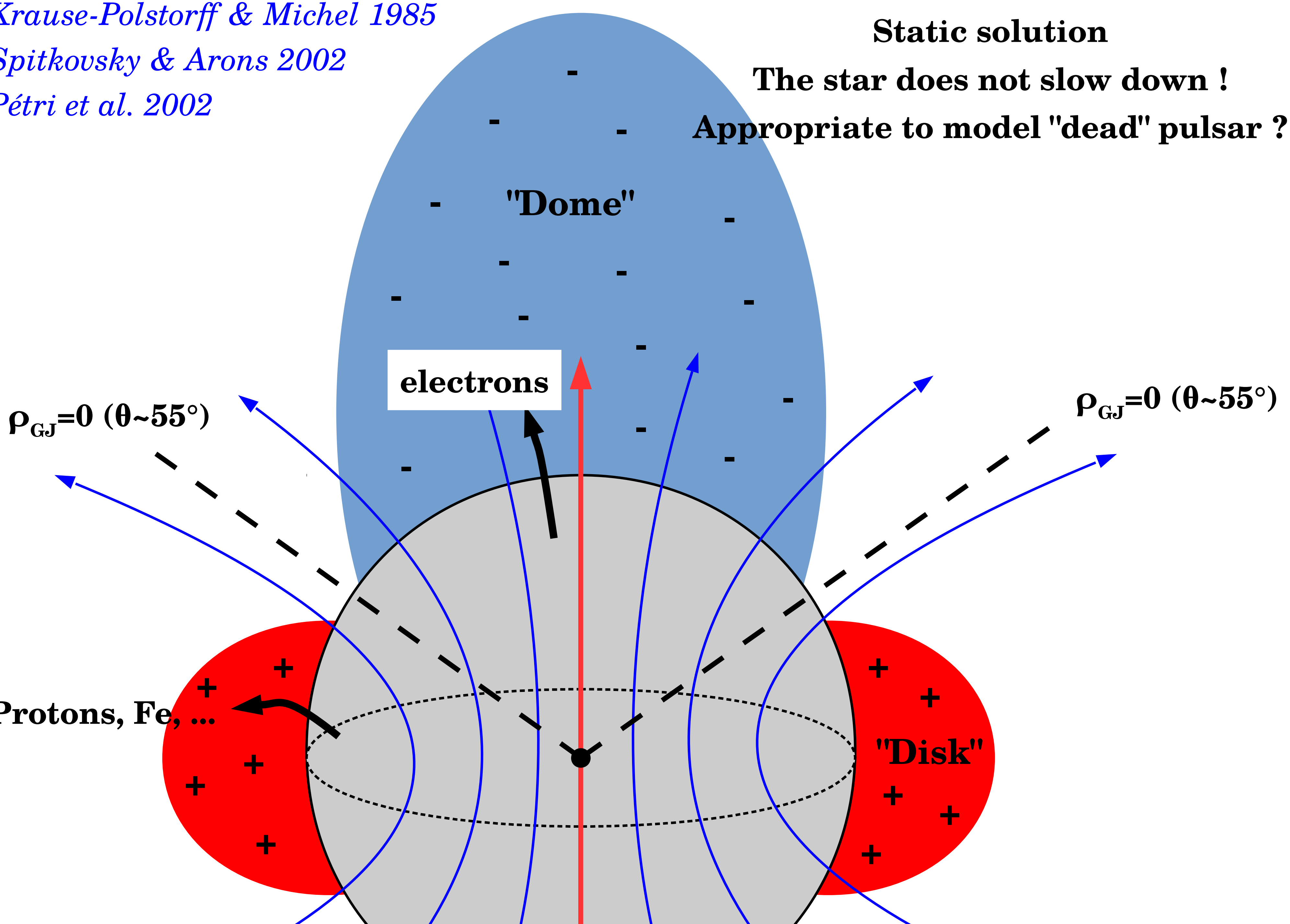
For a dipole : $\rho_{\rm GJ} = -\frac{B_\star}{2\pi c}\left(\frac{R_\star}{r}\right)^3\Omega\left(3\cos^2\theta - 1\right)$



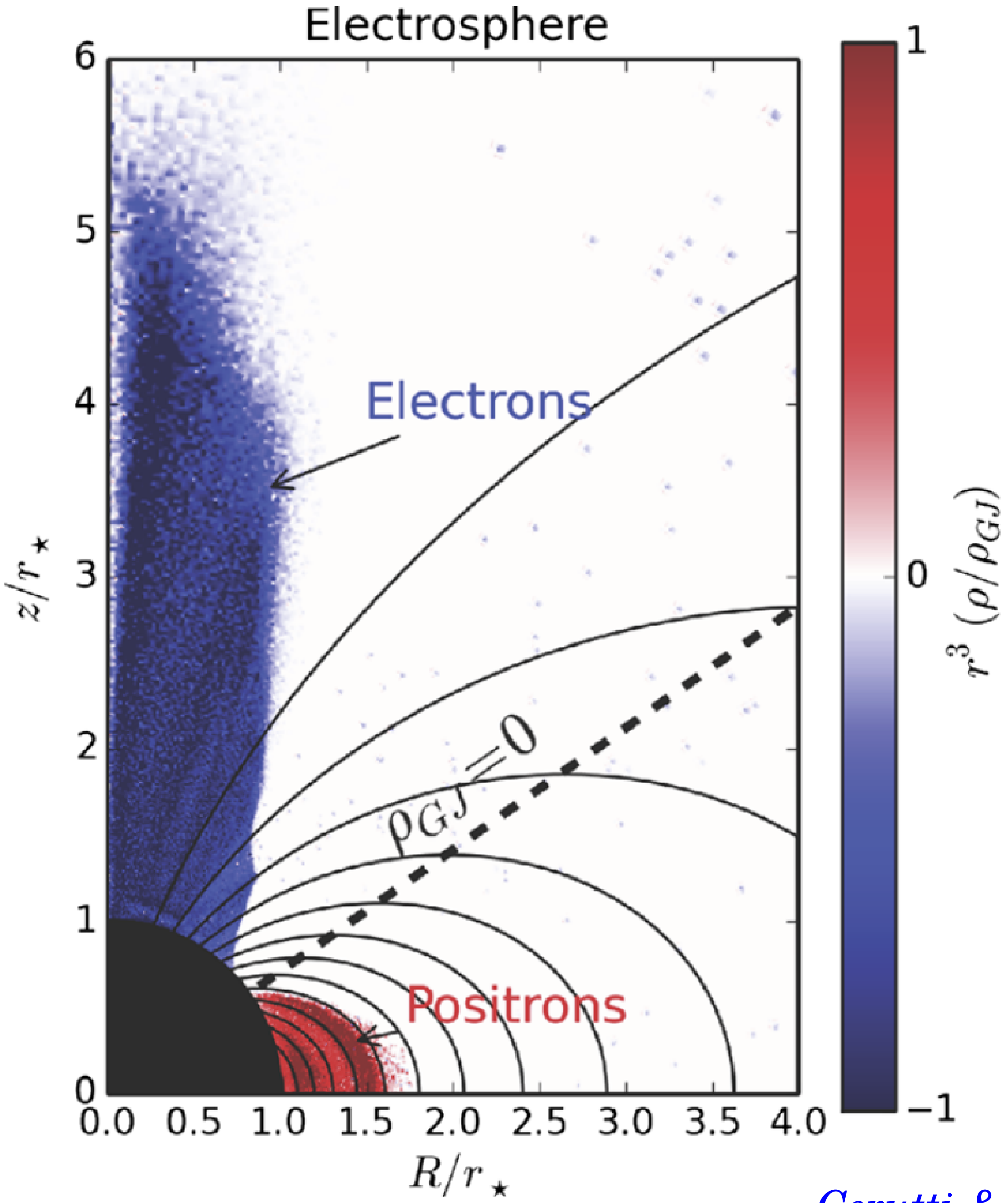
Electrosphere?

Krause-Polstorff & Michel 1985
Spitkovsky & Arons 2002
Pétri et al. 2002

Static solution
The star does not slow down !
Appropriate to model "dead" pulsar ?

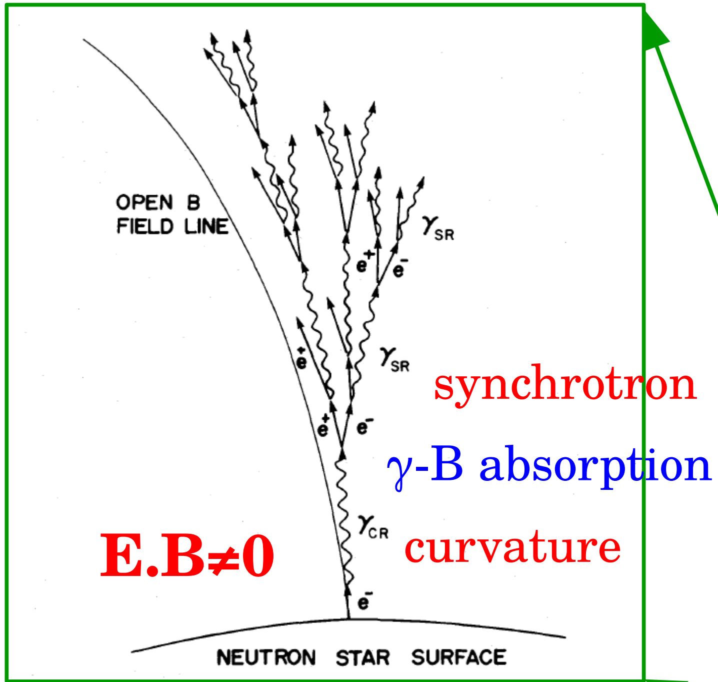


Electrosphere: PIC simulations



Cerutti & Beloborodov 2017

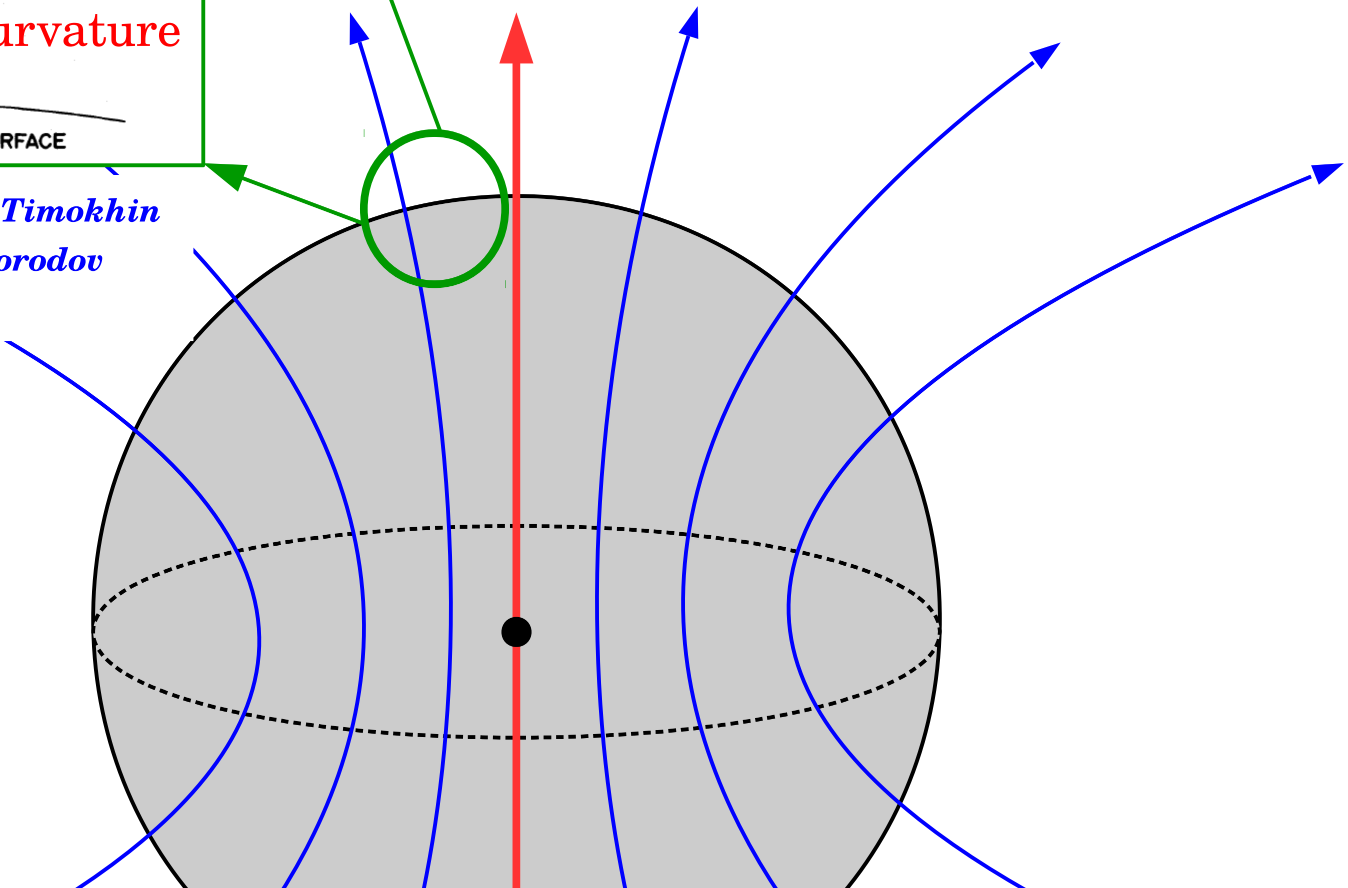
Pair production and plasma filled magnetospheres



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**



Force-free electrodynamic approximation

Lorentz force dominates over all others, including inertia.

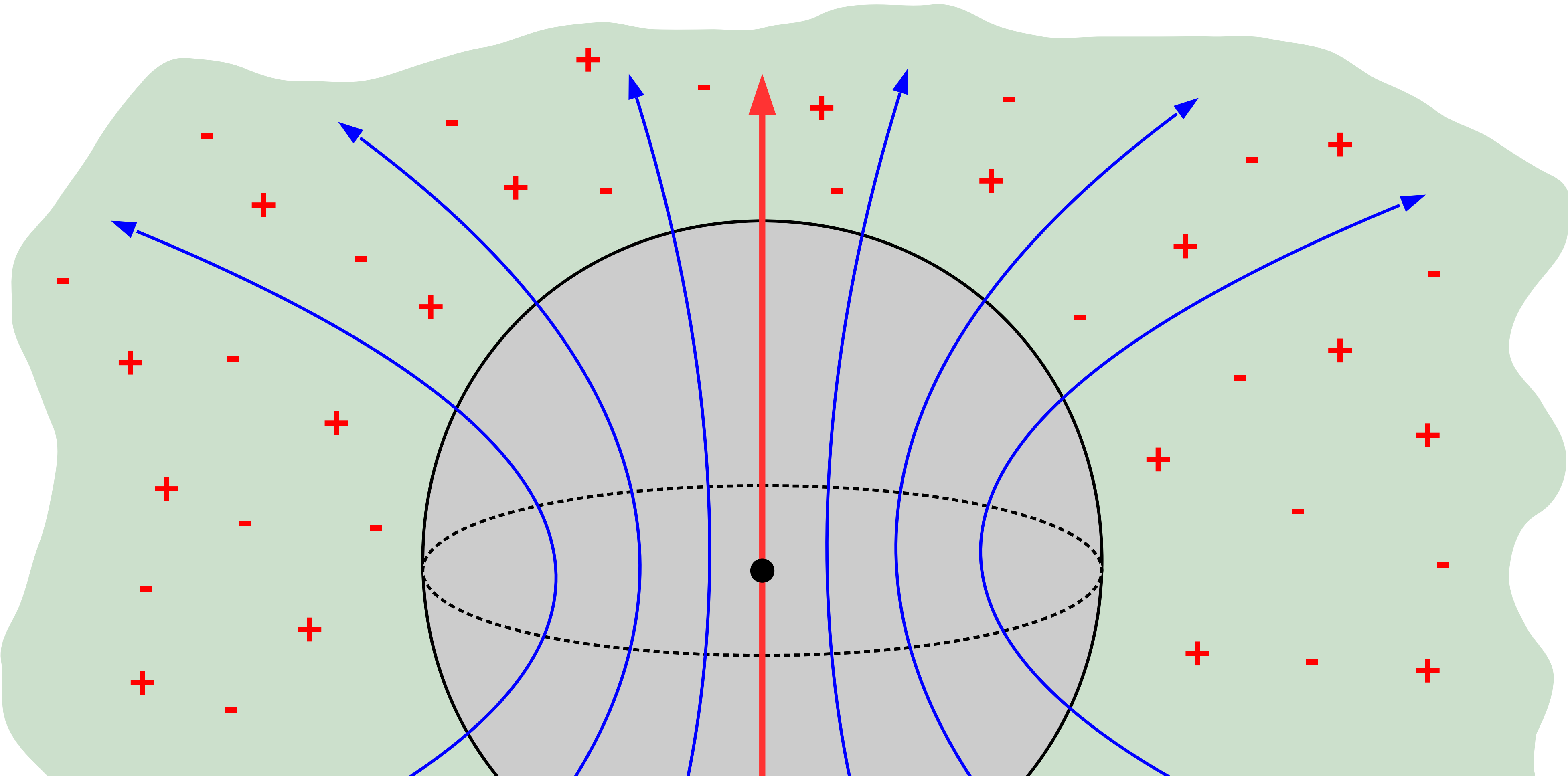
The equation of motion for the plasma is :

$$\boxed{\rho\mathbf{E} + \frac{\mathbf{J}\times\mathbf{B}}{c} = \mathbf{0},} \longrightarrow \begin{array}{c} \mathbf{E}\cdot\mathbf{B} = 0 \\ \mathbf{E}\cdot\mathbf{J} = 0 \end{array}$$

Parallel electric field perfectly screened everywhere

No particle acceleration (!)

But abundant supply of charges, $n >> n_{GJ}$



Force-free monopole: Michel solution (1973)

No analytical force-free solution for a dipole (even aligned !)

One known solution, the (split-)**monopole**, not very realistic but instructive !

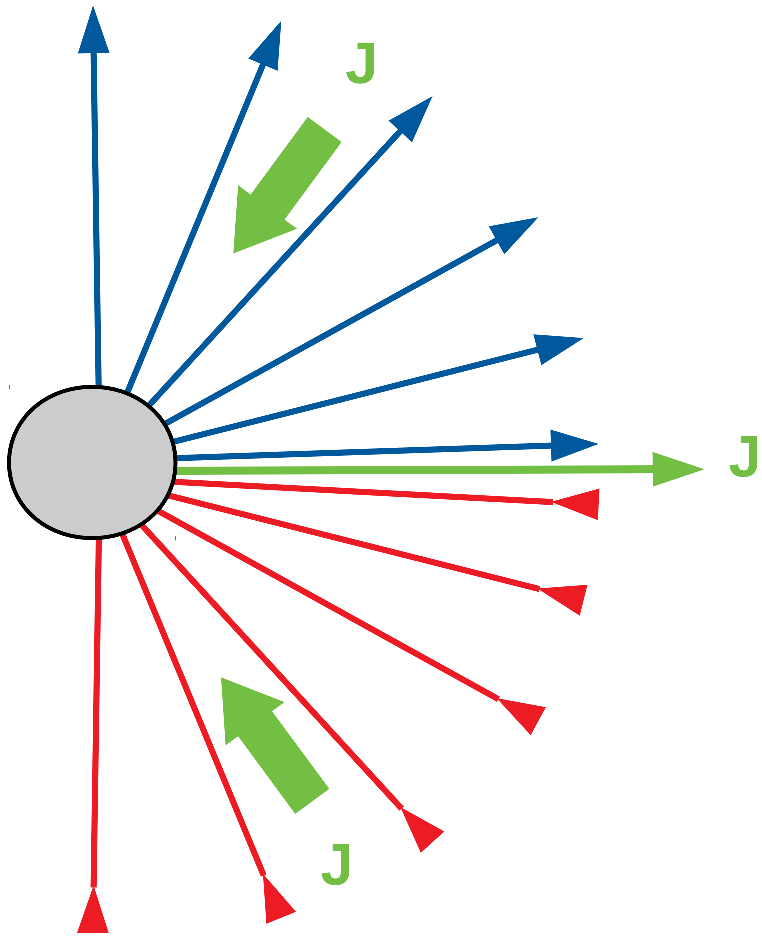
The exact FF solution *(Michel 1973)*:

$$\begin{cases} B_r = B_\star \left(\frac{r_\star}{r}\right)^2 \\ B_\theta = 0 \\ B_\phi = -B_\star \left(\frac{r_\star}{R_{LC}}\right)\left(\frac{r_\star}{r}\right)\sin\theta \\ E_r = 0 \\ E_\theta = B_\phi \\ E_\phi = 0. \end{cases}$$

Light-cylinder :

$R_{LC}=c/\Omega$

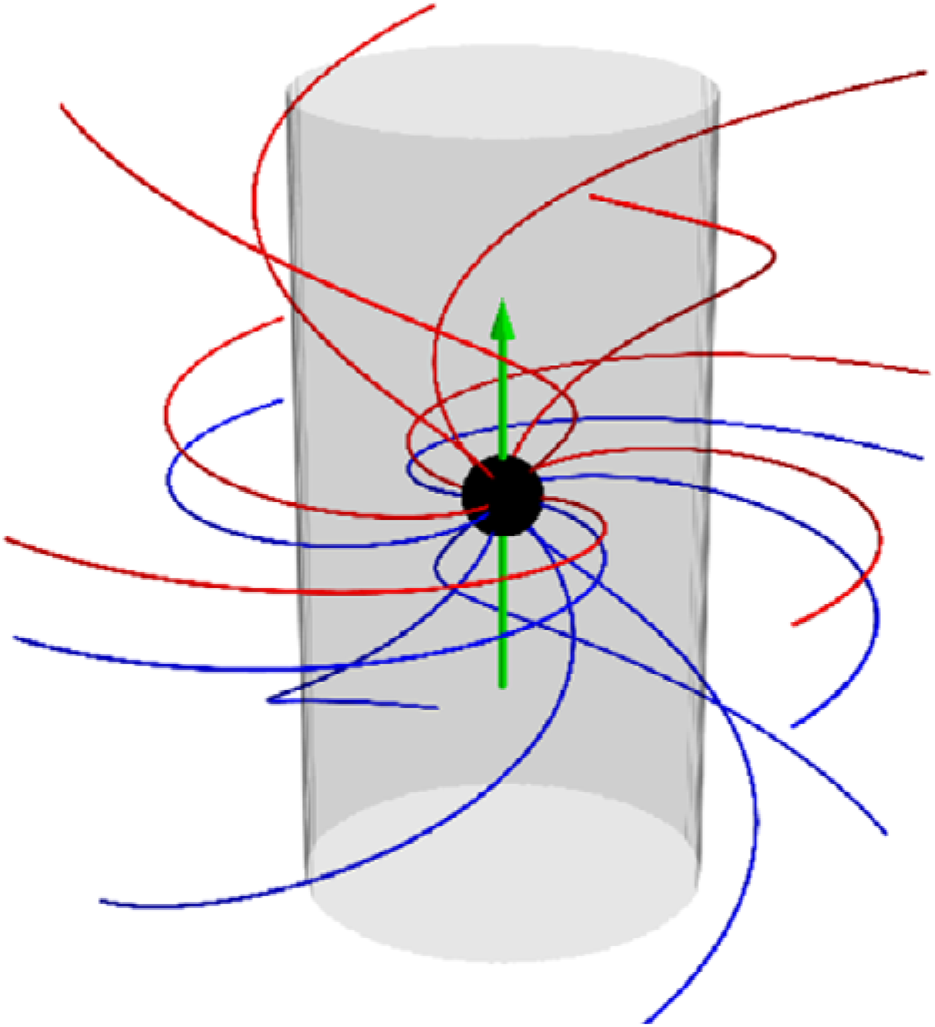
$B_r=B_\phi$ $(\theta=\pi/2)$



Purely radial current

$$\mathbf{J} = \frac{c}{4\pi}(\nabla \times \mathbf{B}) = -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi}\mathbf{e}_r = c\rho_{GJ}\mathbf{e}_r$$

A 3D view at the split-monopole



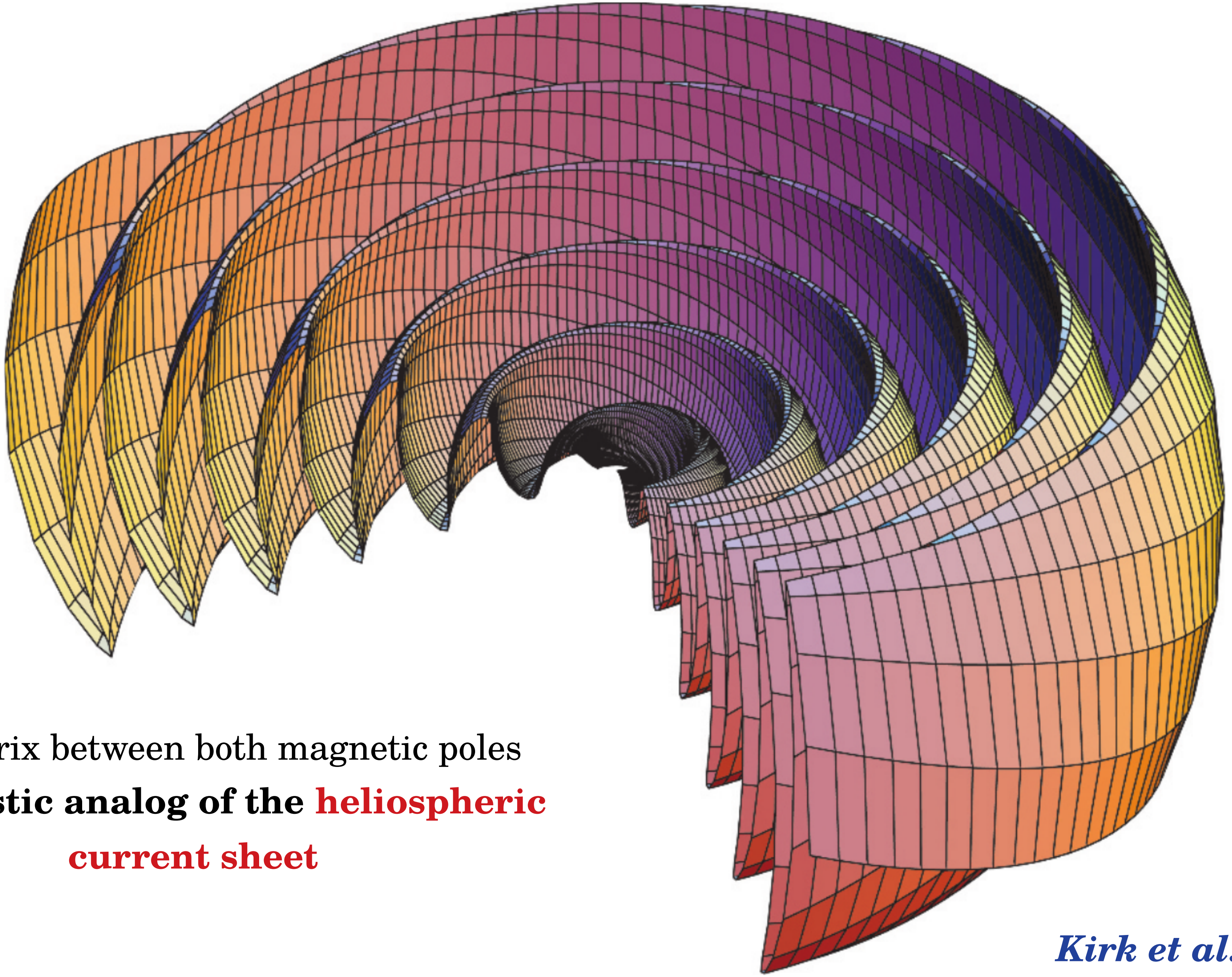
Field lines are winding up
=> Radial Poynting flux

$$L_{\rm mono} = \int \mathbf{\Pi} \cdot d\mathbf{S} = \frac{2cB_\star^2 r_\star^4}{3R_{\rm LC}^2}.$$

The star is braking !

A 3D view at the inclined split-monopole

Inclined split-monopole (analytical), see *Bogovalov 1999*



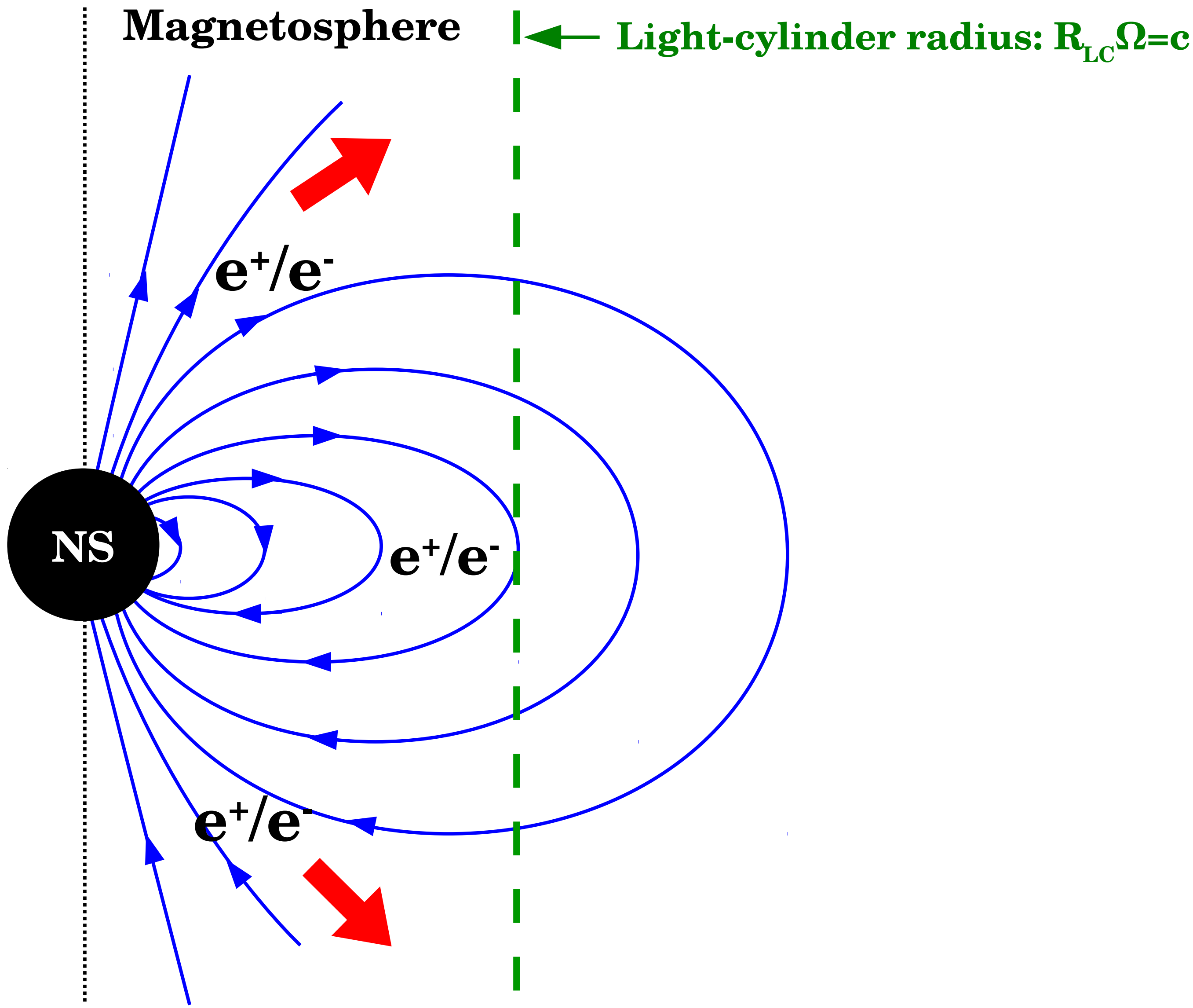
Separatrix between both magnetic poles

Relativistic analog of the heliospheric current sheet

Kirk et al. 2009

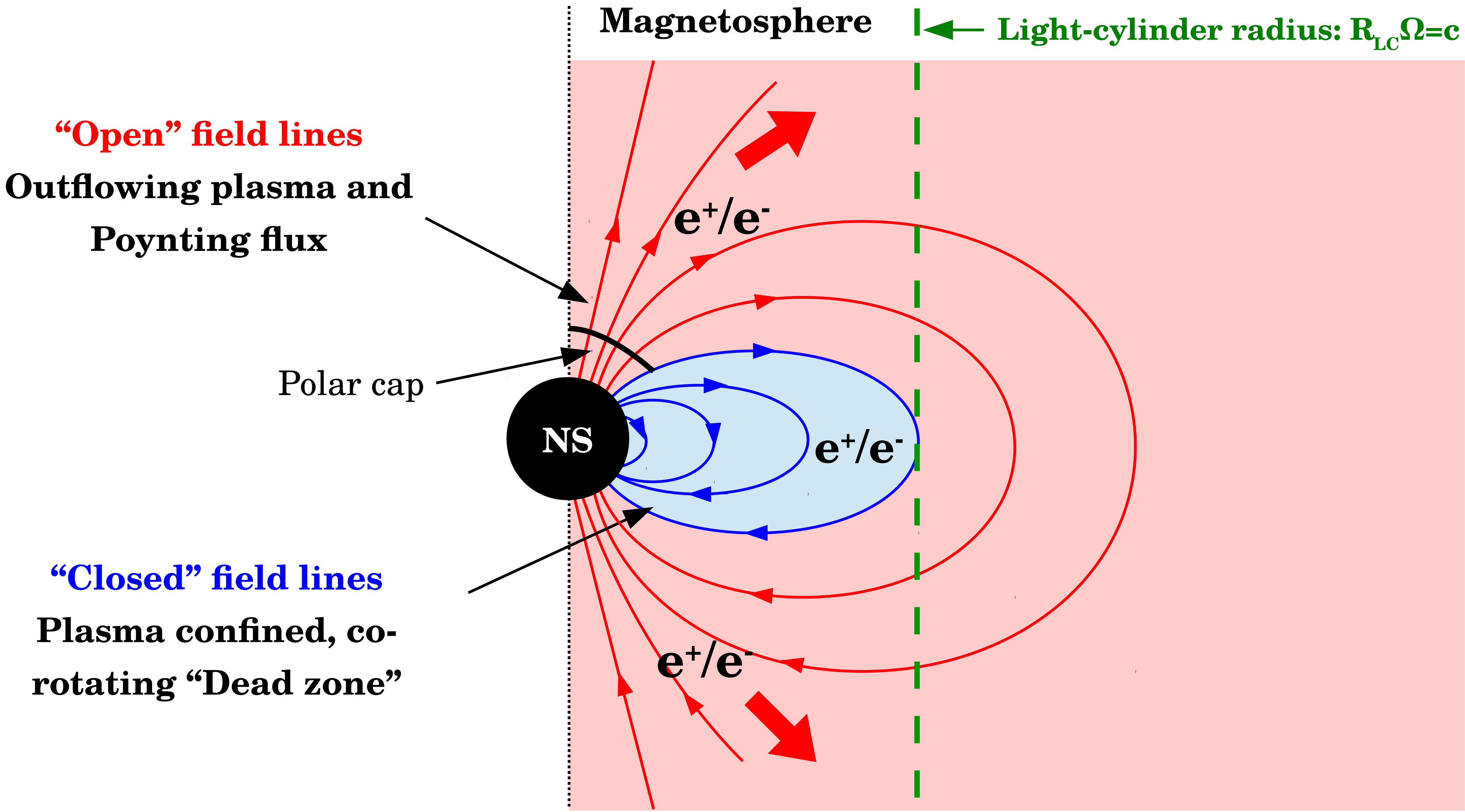
Back to the aligned dipole

The light cylinder radius defines the location where the co-rotation velocity equals the speed of light: $R_{LC}\Omega=c$ (~5000km for a 100ms pulsar)



The light cylinder

The light cylinder radius defines the location where the co-rotation velocity equals the speed of light: $R_{LC}\Omega=c$ (~5000km for a 100ms pulsar)



The light cylinder

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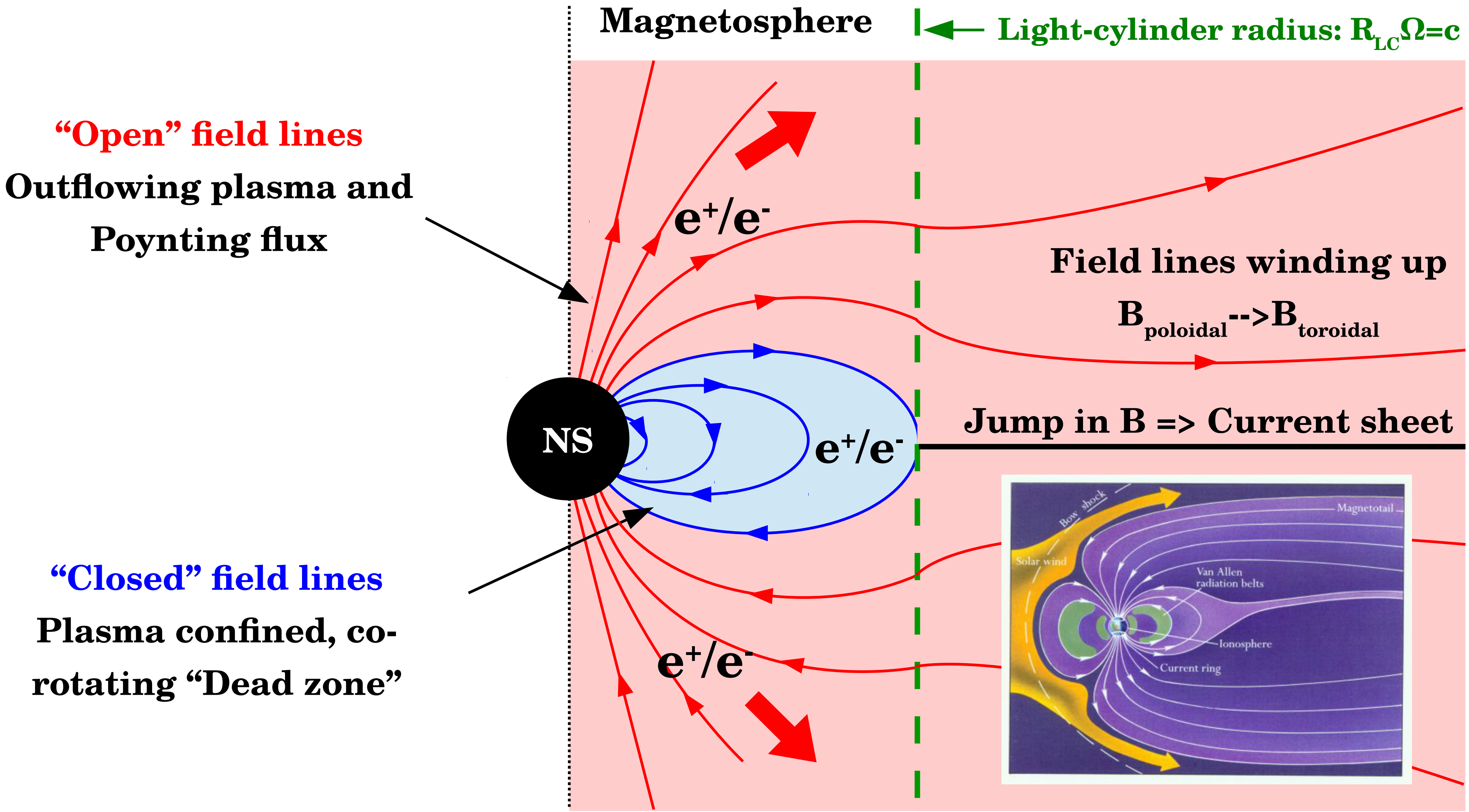
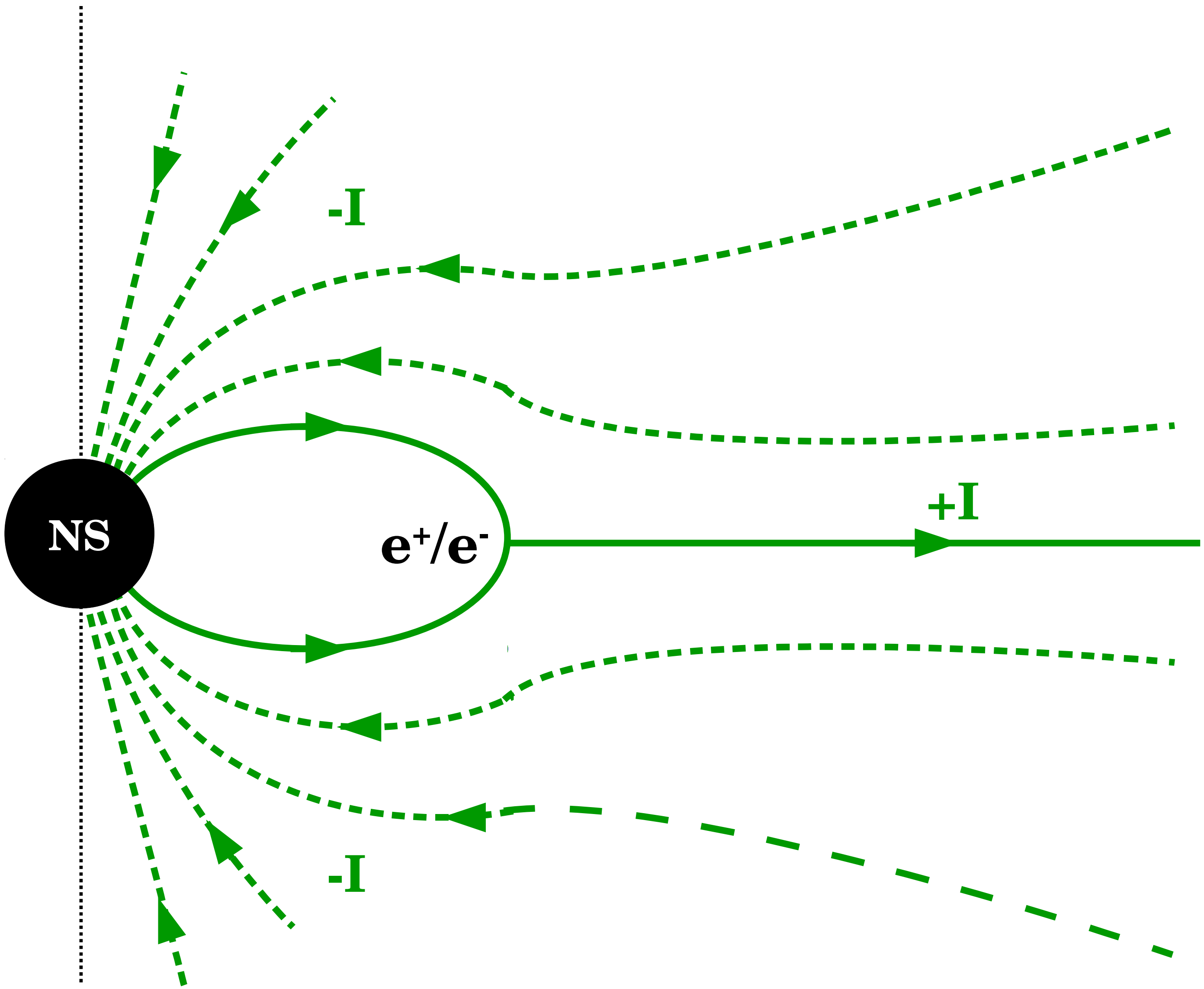
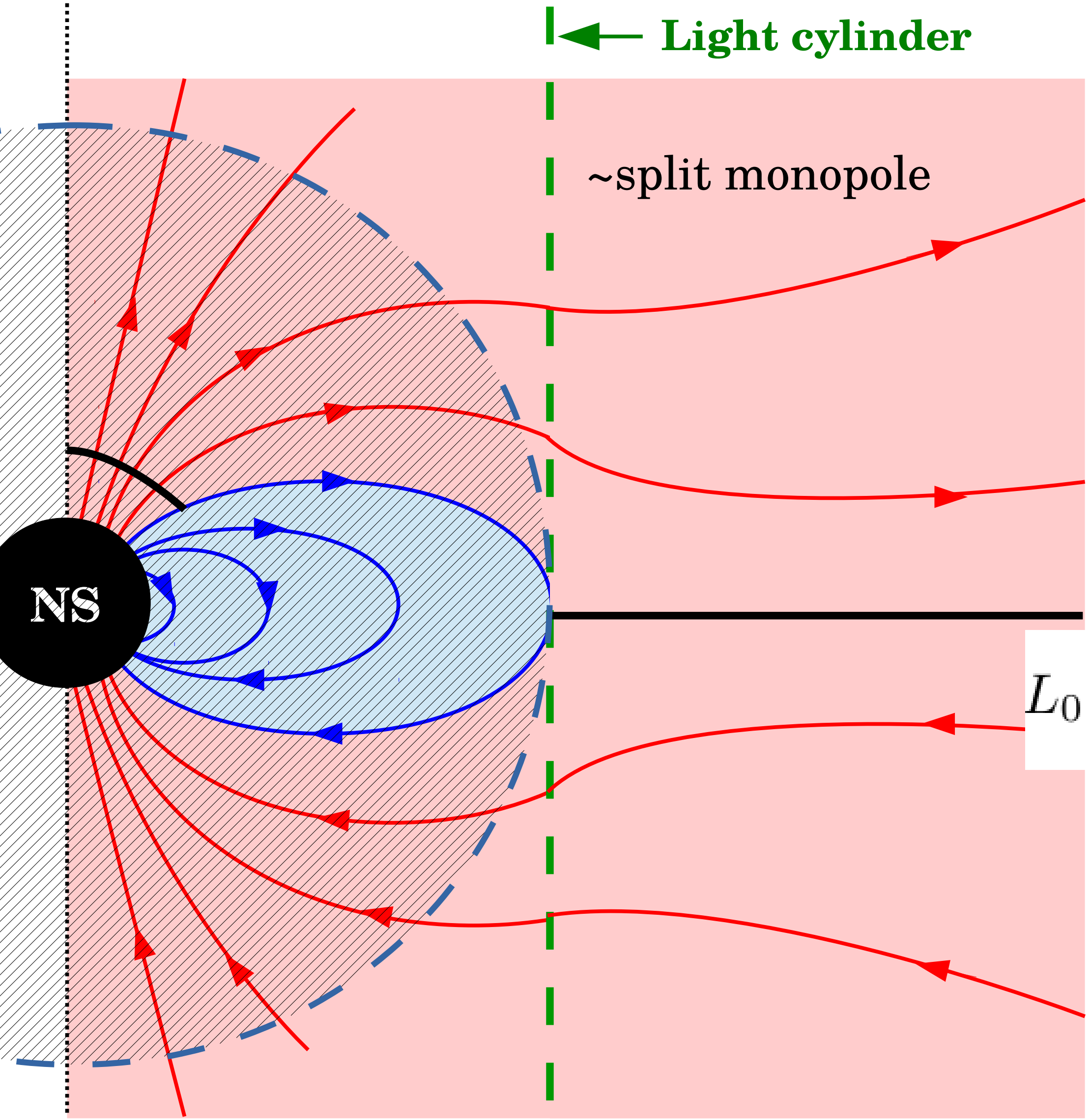


The electric circuit



Estimate of the spindown for an aligned dipole



Radial component of Poynting vector :

$$\Pi_r = \frac{c}{4\pi} E_\theta B_\phi$$

Remember the split monopole :

$B_\phi \sim B_{\rm Poloidal}$ @ Light cylinder

$E_\theta \sim B_\phi$

$$L_0 = \iint \Pi_r d^2 S \sim c R_{\rm LC}^2 E_\theta B_\phi \sim c R_{\rm LC}^2 B_{\rm LC}^2$$

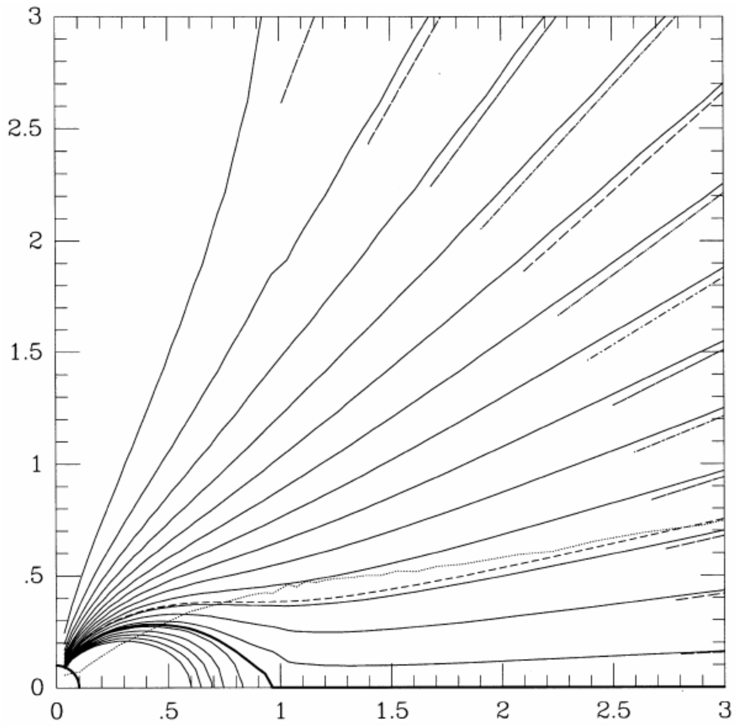
$$B_{\rm LC} \sim \frac{\mu}{R_{\rm LC}^3}$$

$$\boxed{L_0 \sim \frac{\mu^2 \Omega^4}{c^3}}$$

Force-free simulations

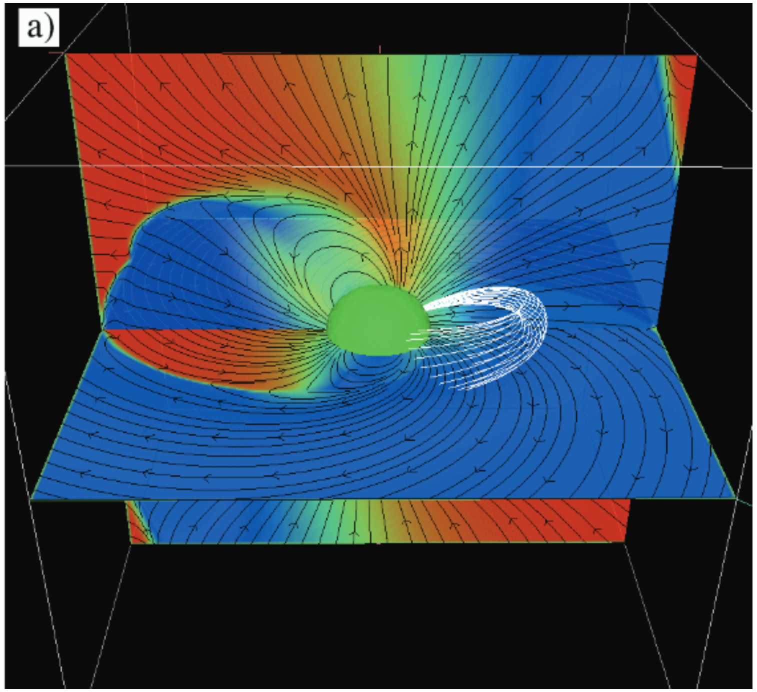
Aligned rotator

[Contopoulos et al. 1999]



Inclined rotator

[Spitkovsky 2006]



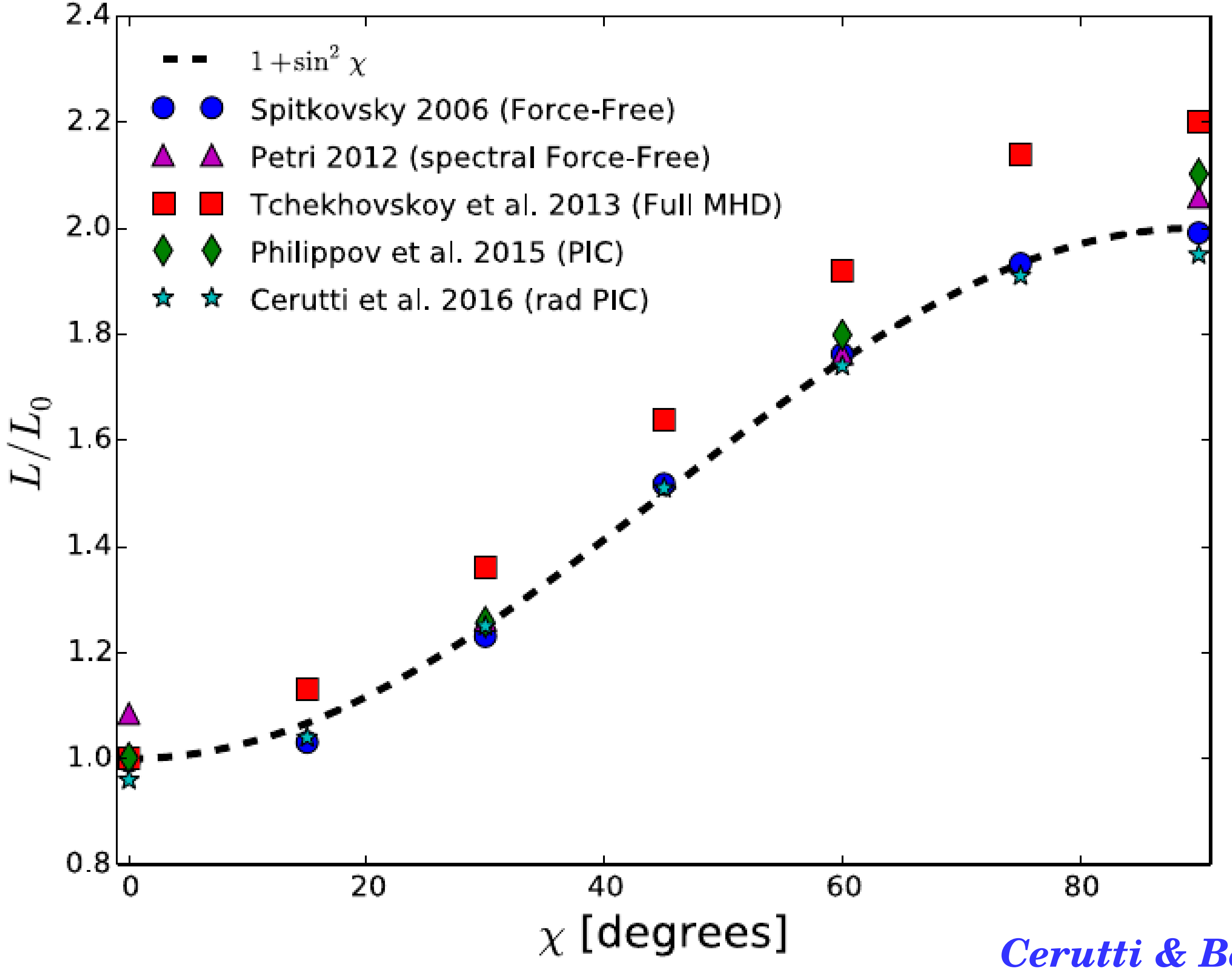
Spindown from simulations

Spitkovsky 2006

$$\boxed{L \approx \frac{\mu^2 \Omega^4}{c^3}(1+\sin^2\chi).}$$

$$L_{\rm dipole} = \frac{2}{3}\frac{\mu^2 \Omega^4}{c^3}\sin^2\chi$$

Aligned magnetosphere do spin down, but very similar to the vacuum formula



Cerutti & Beloborodov 2017

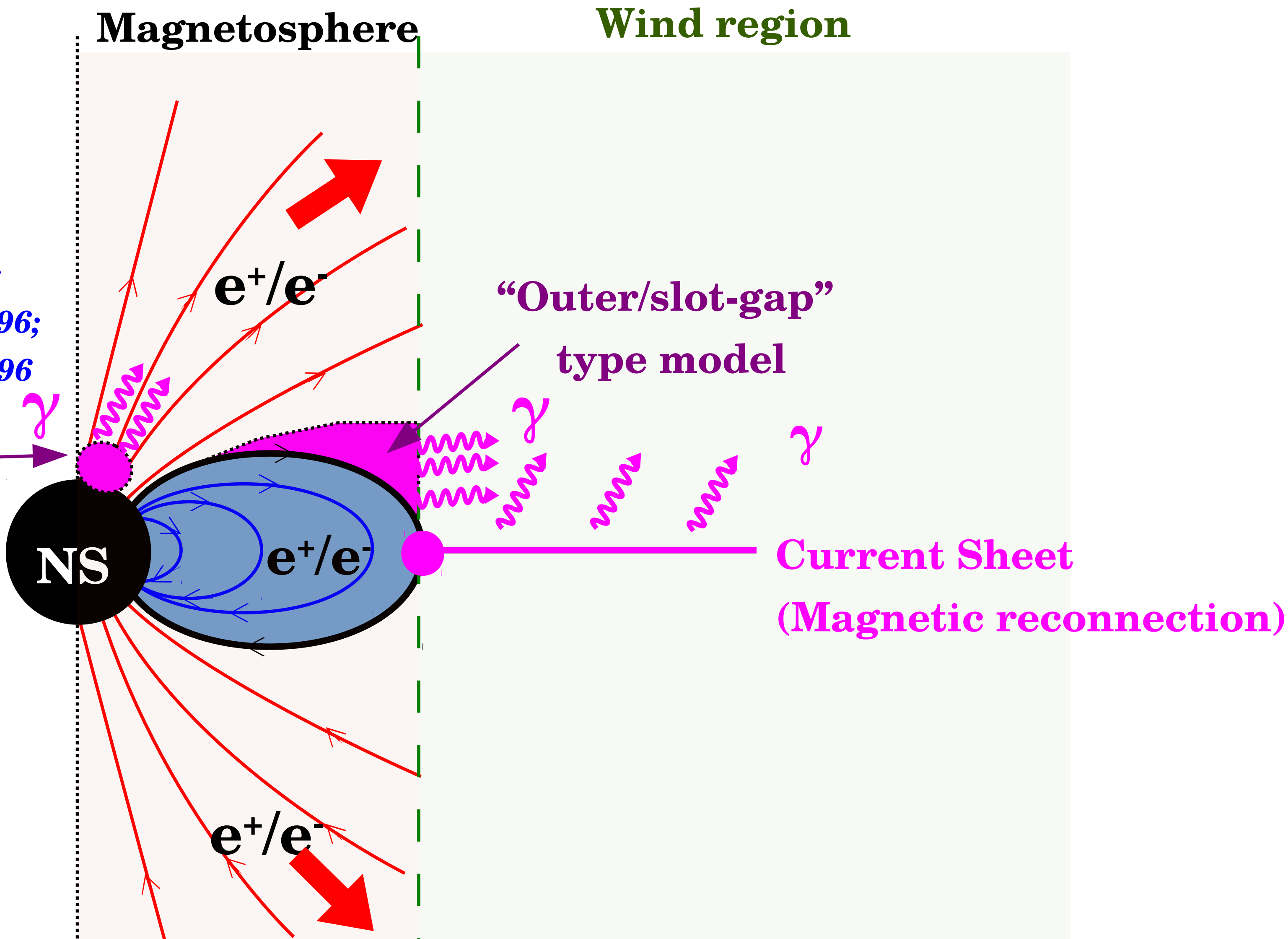
Particle acceleration

Proposed sites for particle acceleration & γ-rays

Acceleration where E.B≠0

γ-ray : curvature or synchrotron radiation

e.g. Arons 1983; Muslimov & Harding 2003; Cheng et al. 1986; Romani 1996; Coroniti 1990 ; Lyubarskii 1996

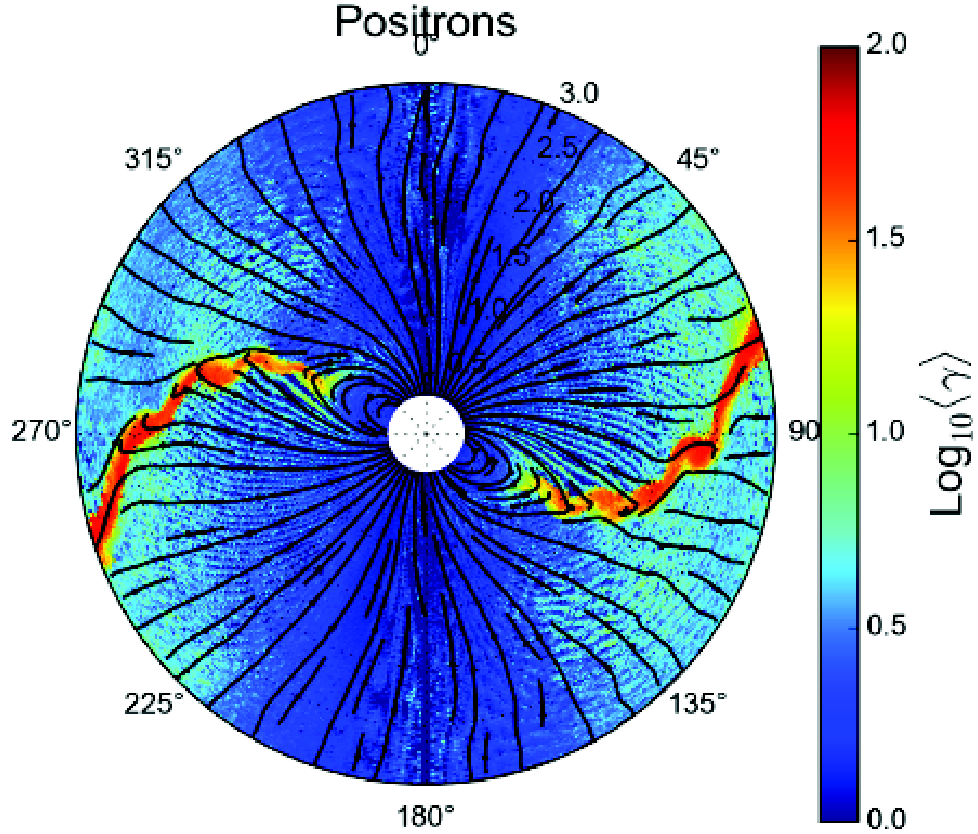


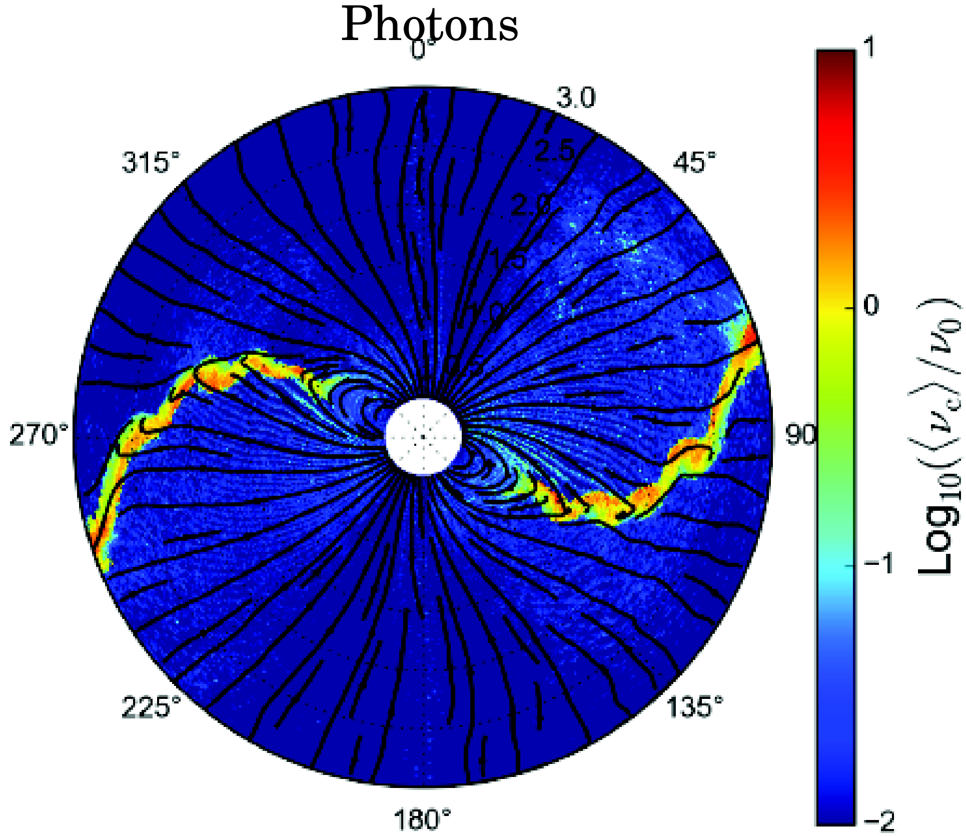
Regions of interest where Force-Free breaks down

=> Kinetic simulations (PIC)

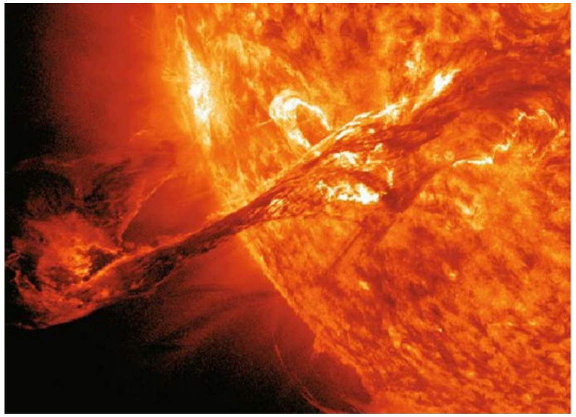
Particle / radiation mean energy (χ=30°)

Cerutti et al. 2016, Philippov & Spitkovsky 2018





Relativistic reconnection

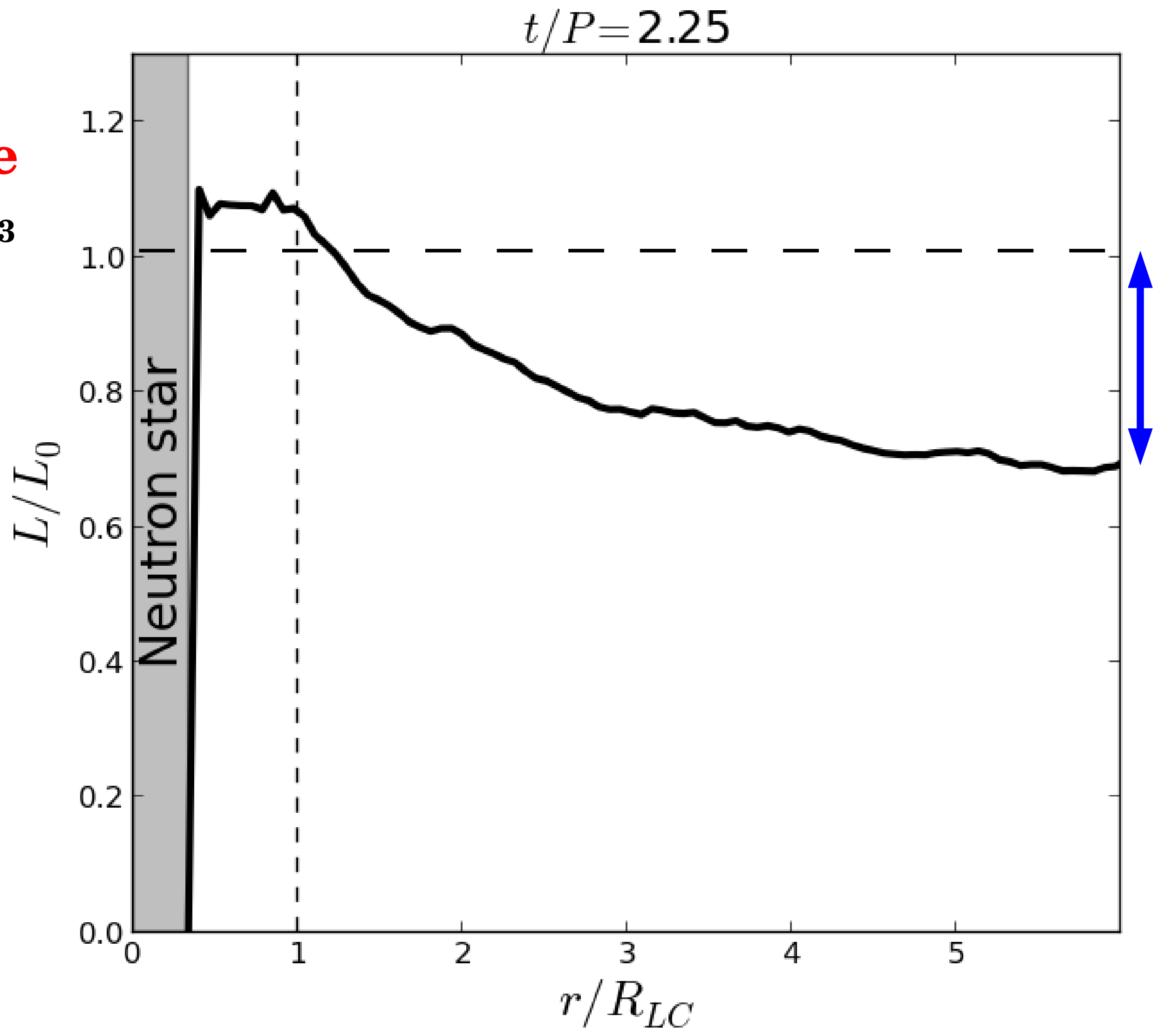


Mostly synchrotron radiation

Pulsar spin down and dissipation

Force-free

$L_0=\mu^2\Omega^4/c^3$



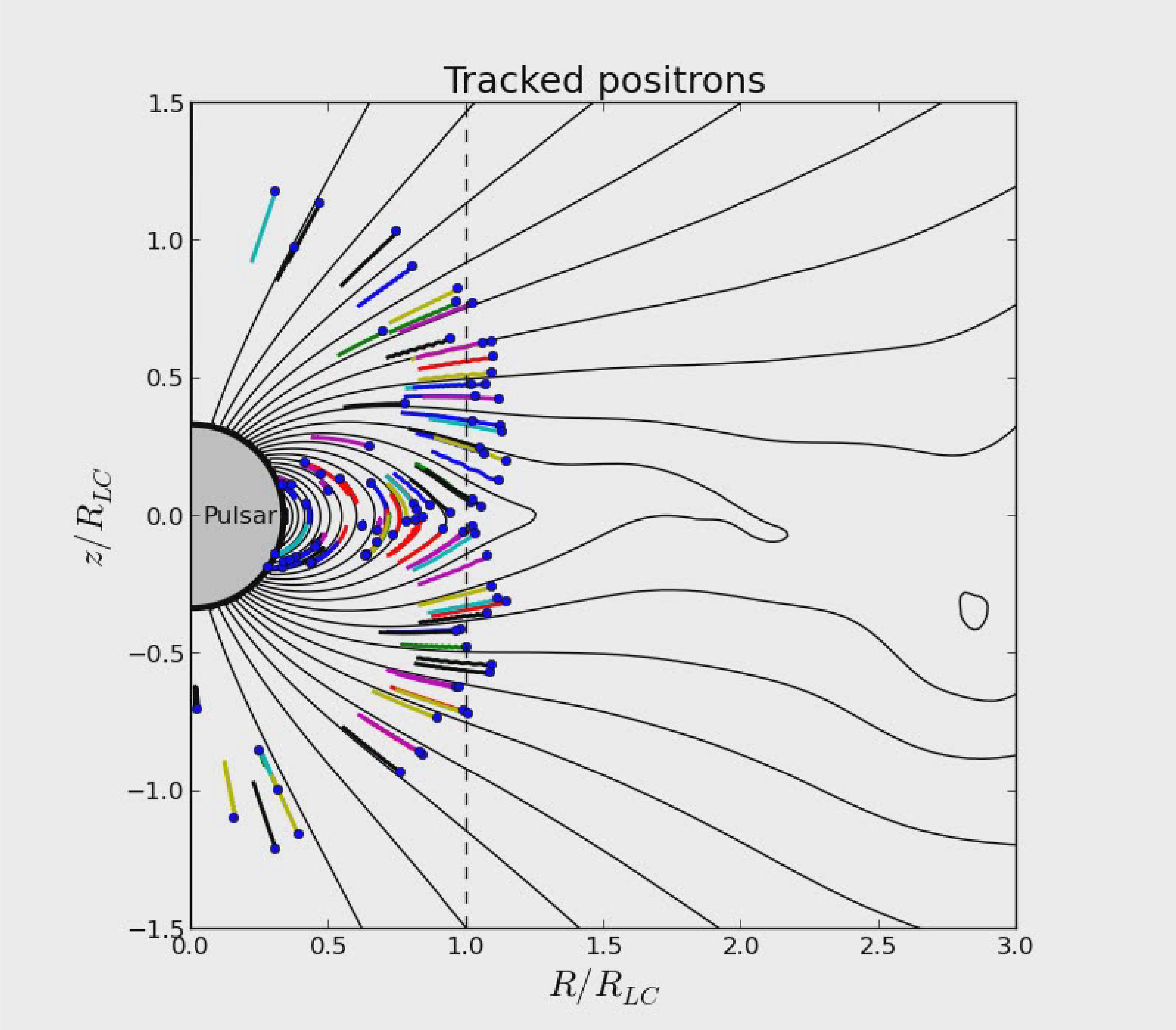
~30% drop

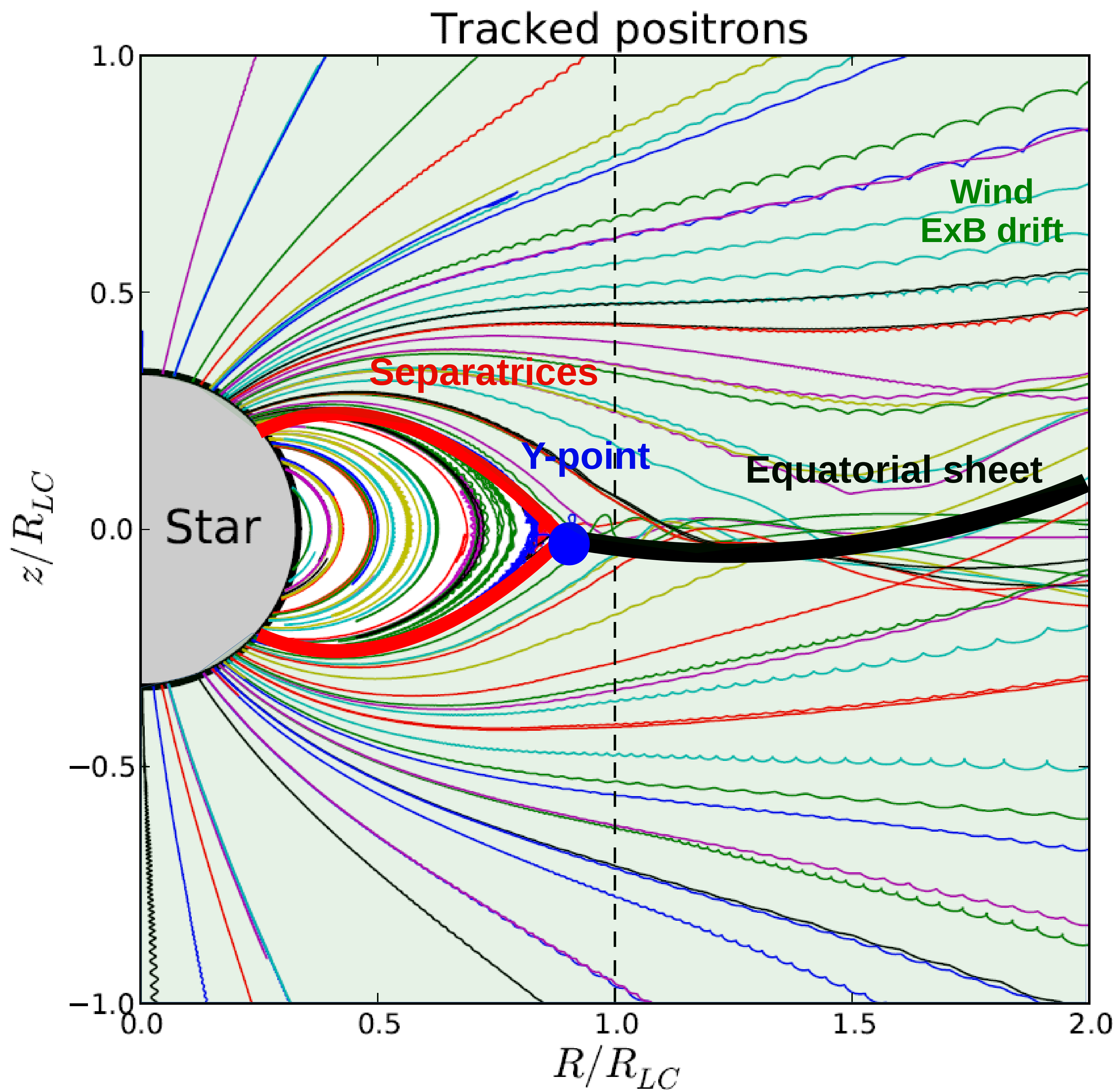
Significant dissipation within a few R_{LC}!

=> Energy transferred to energetic particles and radiation!

Particle acceleration and e$^+$/e$^-$ asymmetry

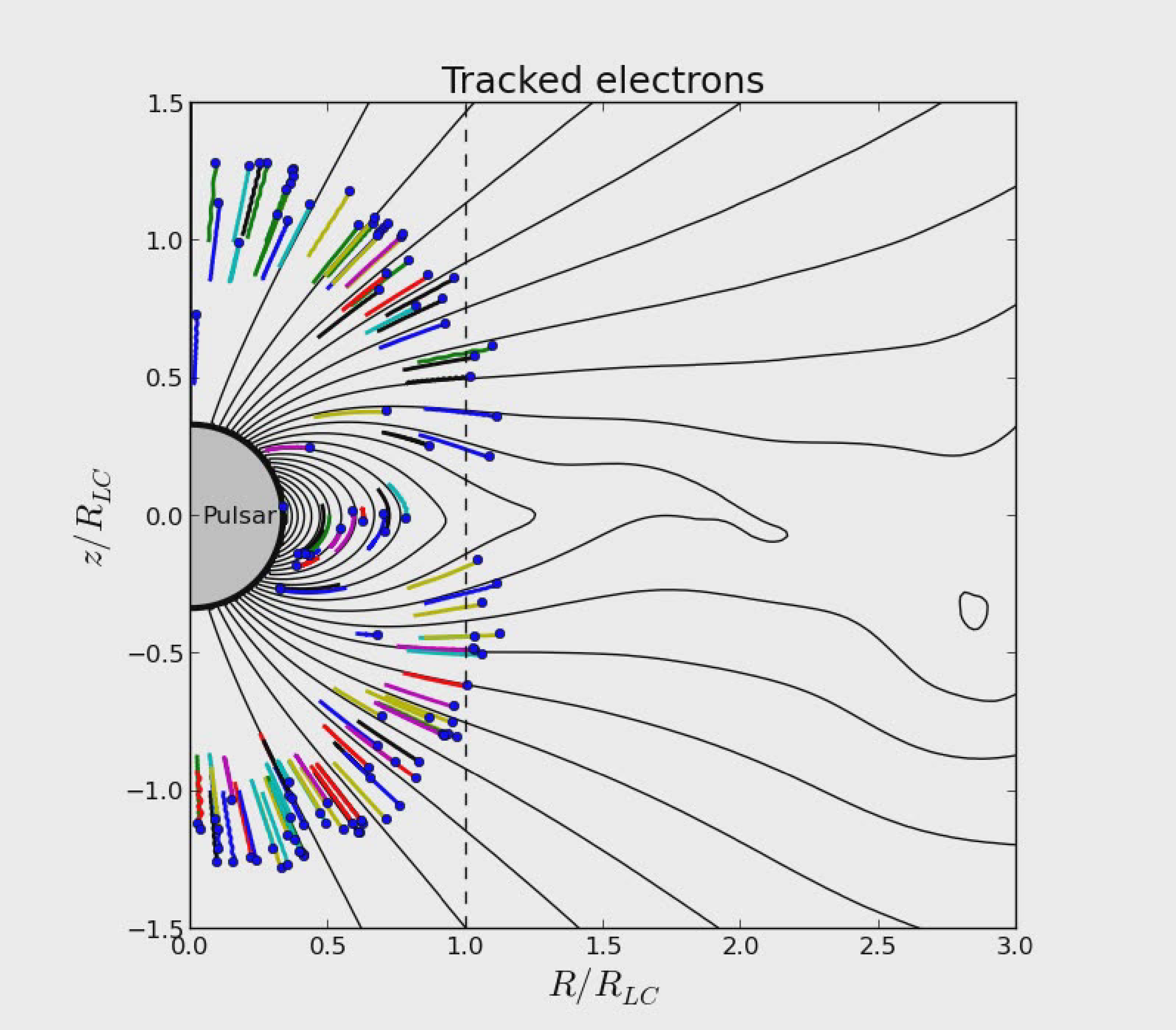
2D




Tracked positrons
Wind
ExB drift
Separatrices
Y-point
Equatorial sheet
Star
z/R_{LC}
R/R_{LC}
1.0
0.5
0.0
−0.5
−1.0
0.0
0.5
1.0
1.5
2.0

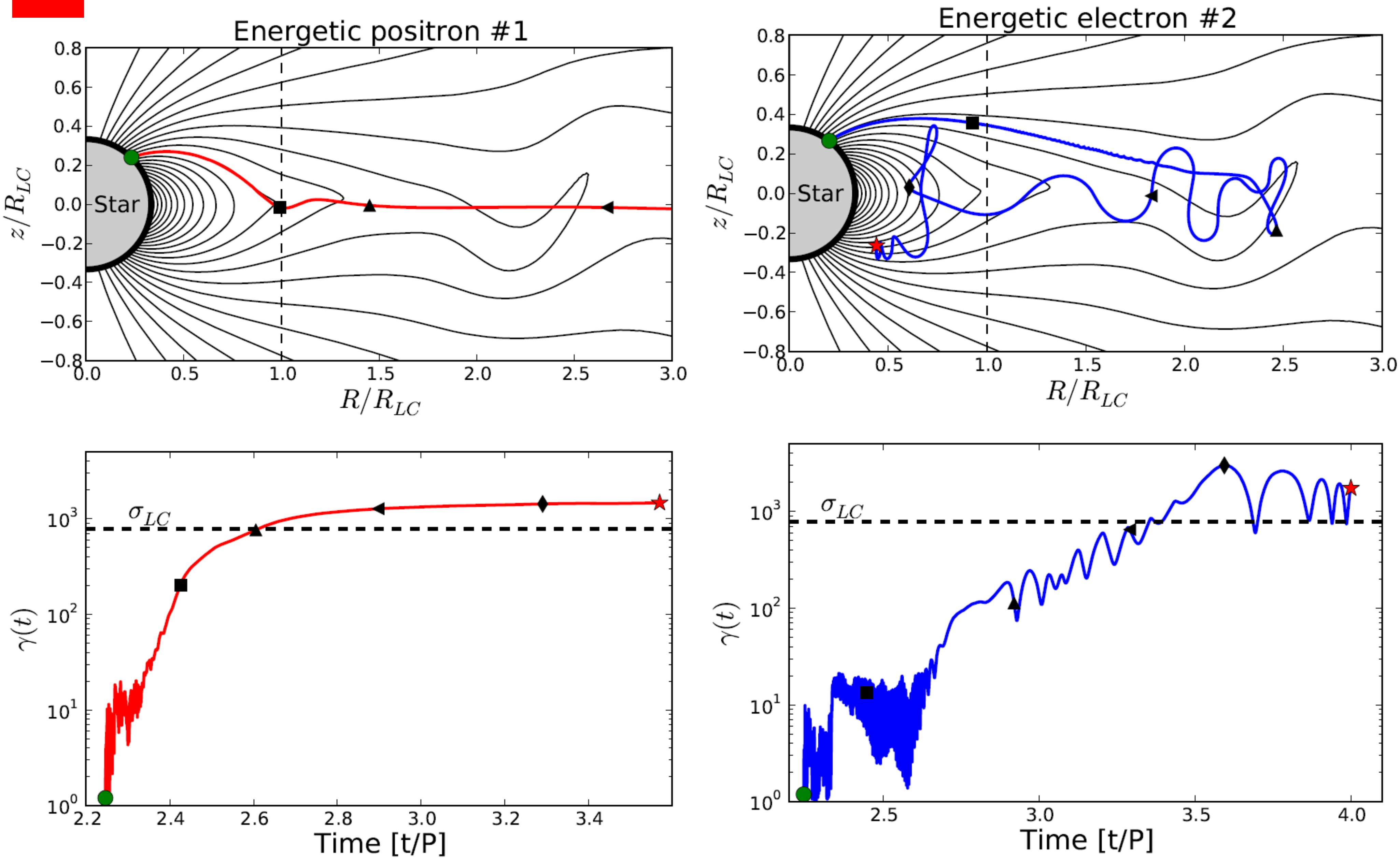
Particle acceleration and e^+/e^- asymmetry

2D



Particle acceleration and e^+/e^- asymmetry

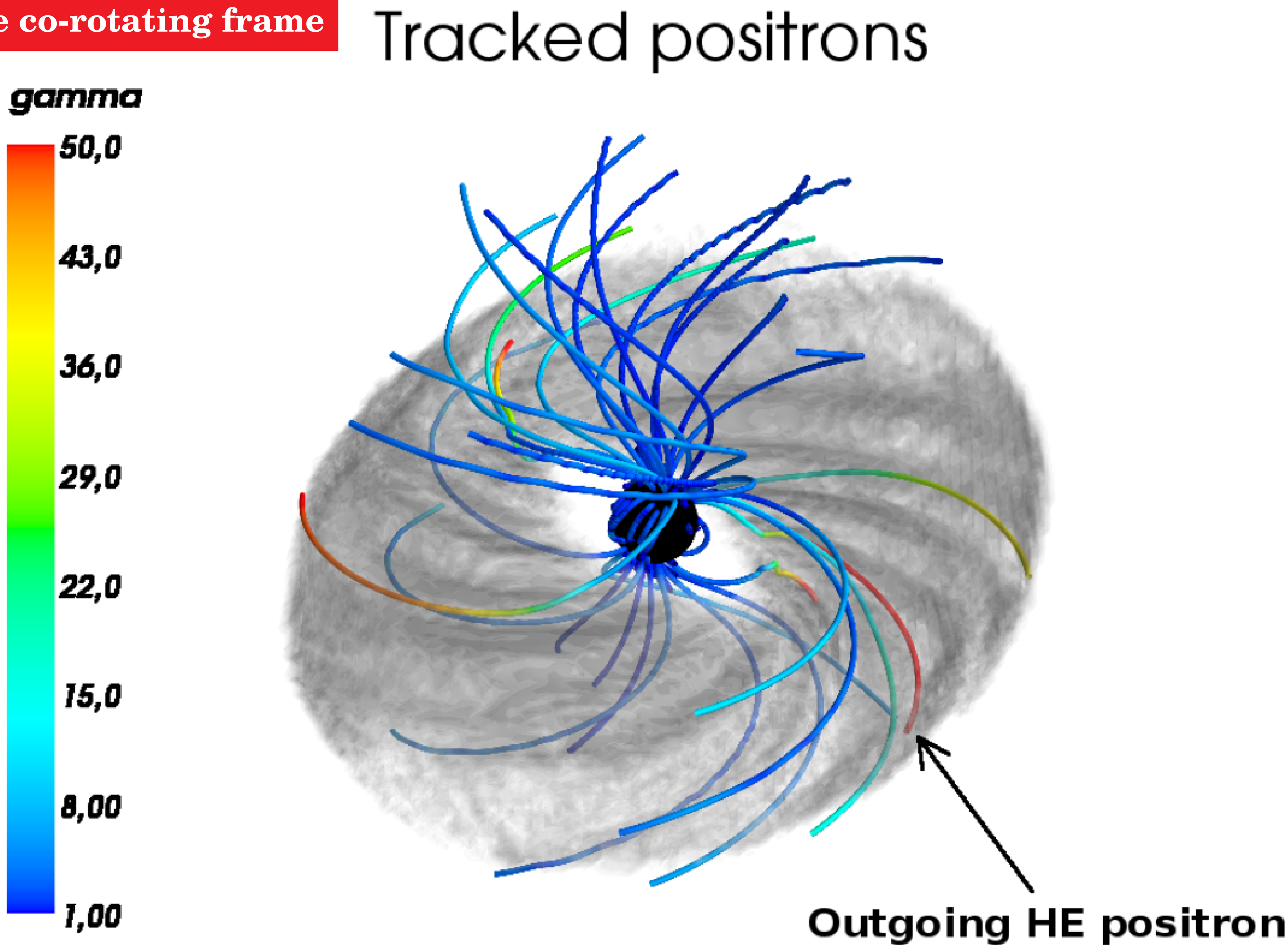
2D



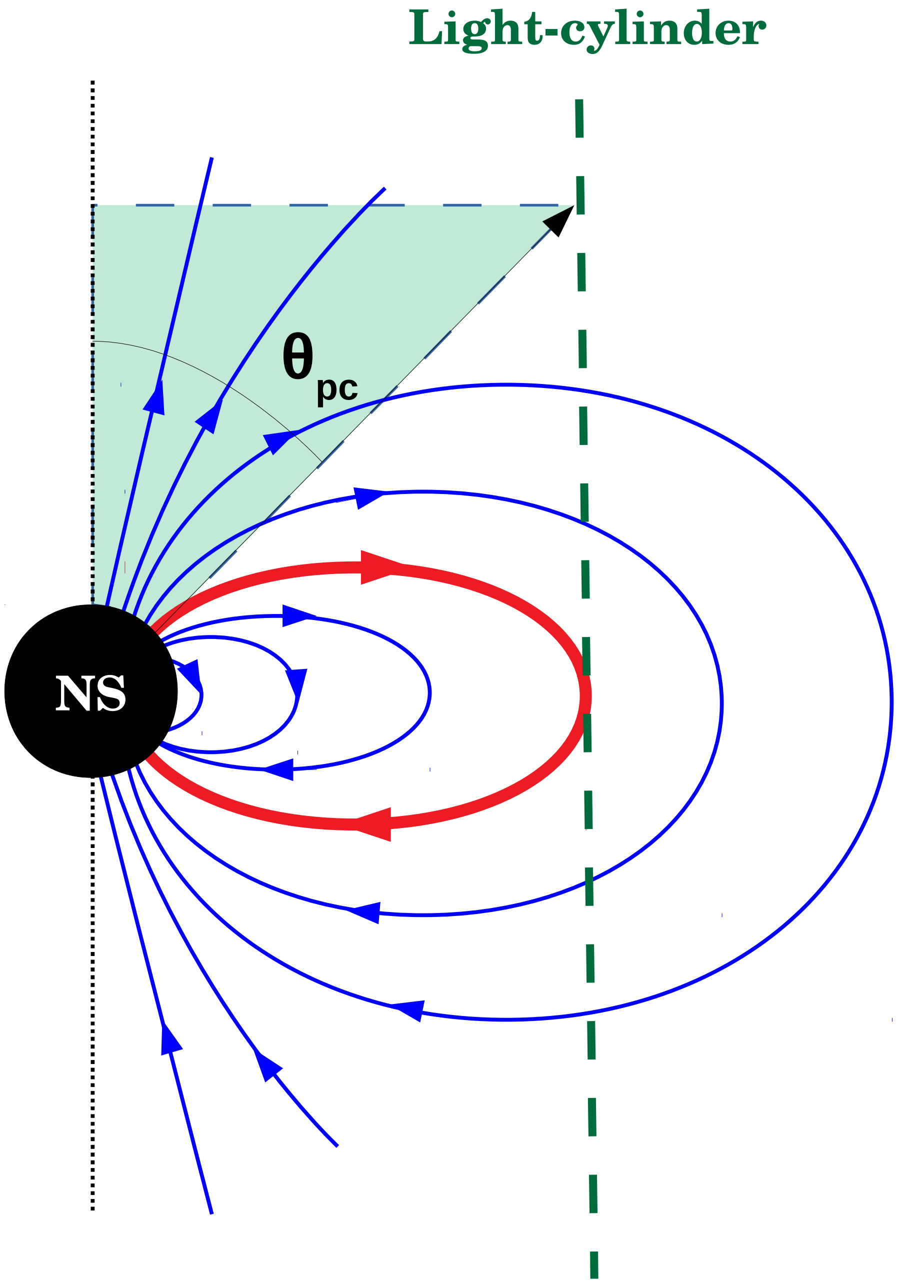
Cerutti et al. 2015

Positron trajectories in oblique pulsar (30°)

In the co-rotating frame



Particle energy estimate



1) Polar-cap size

$$\frac{B_r}{B_\theta} = \frac{dr}{r\,d\theta}$$

$$\int_{R_\star}^{R_{\rm LC}} \frac{dr}{r} = 2\int_{\theta_{\rm pc}}^{\pi/2} \frac{\cos\theta}{\sin\theta}\,d\theta$$

$$\boxed{\sin\theta_{\rm pc} = \sqrt{\frac{R_\star}{R_{\rm LC}}}}$$

2) Vacuum potential drop across the PC

$$\boxed{\Phi_{\rm pc} = \int_0^{\theta_{\rm pc}} E_\theta(R_\star)R_\star\,d\theta = \frac{\mu\Omega^2}{c^2}}$$

3) PIC simulations indicates

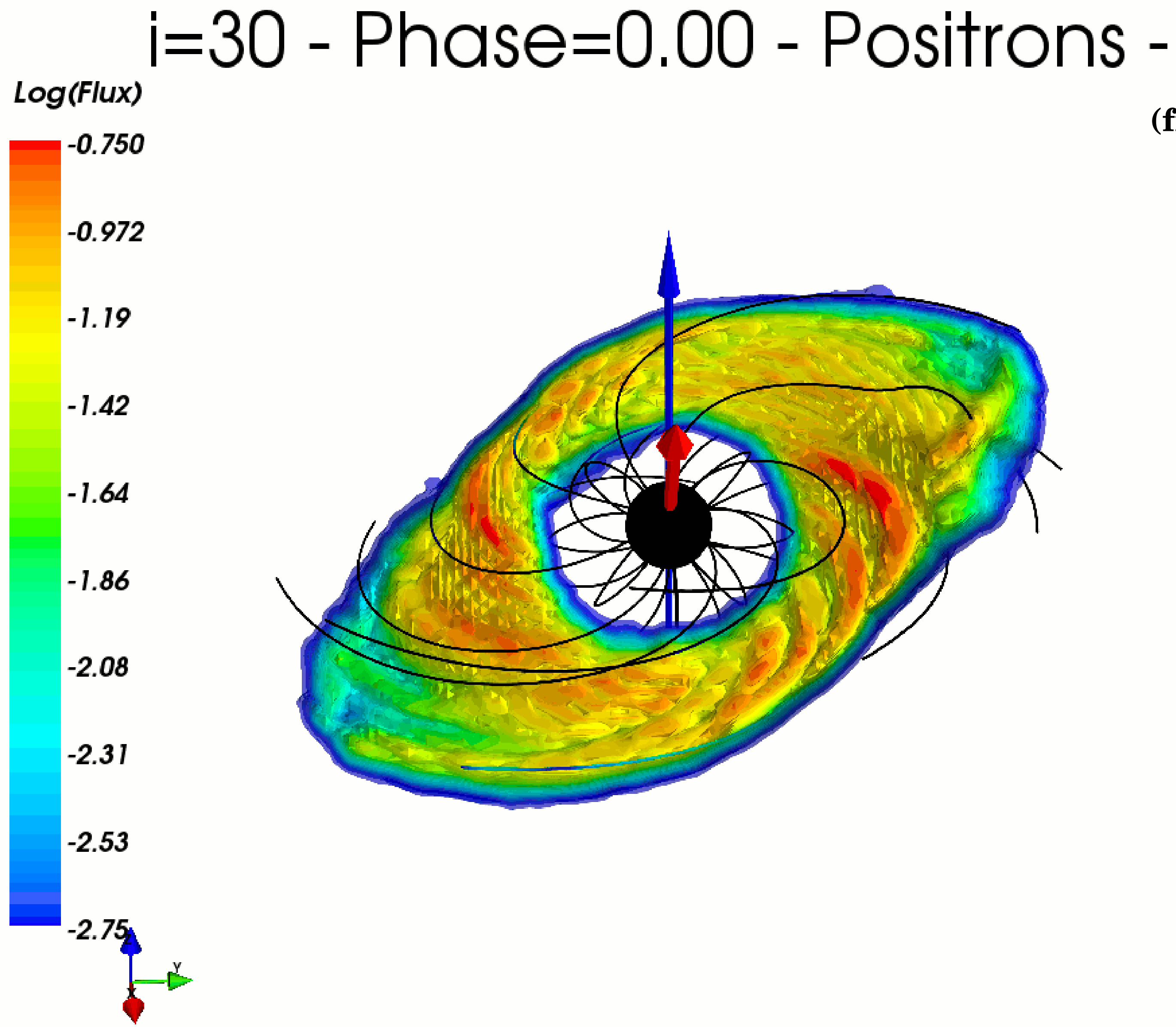
$$\boxed{\gamma \approx \sigma_{\rm LC} \sim \frac{\phi_{\rm pc}}{\kappa\Gamma}}$$

$e\Phi_{pc}/mc^2$

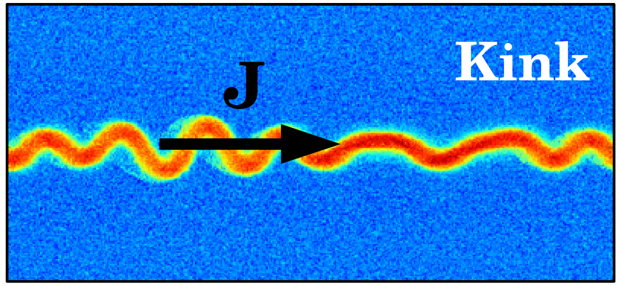
$\kappa = n/n_{GJ}$ (plasma multiplicity)

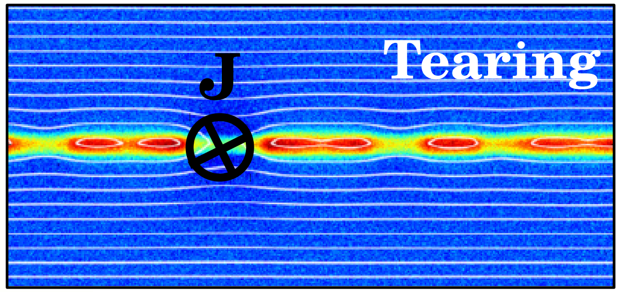
High-energy radiation

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



(from Local reconnection simulations)



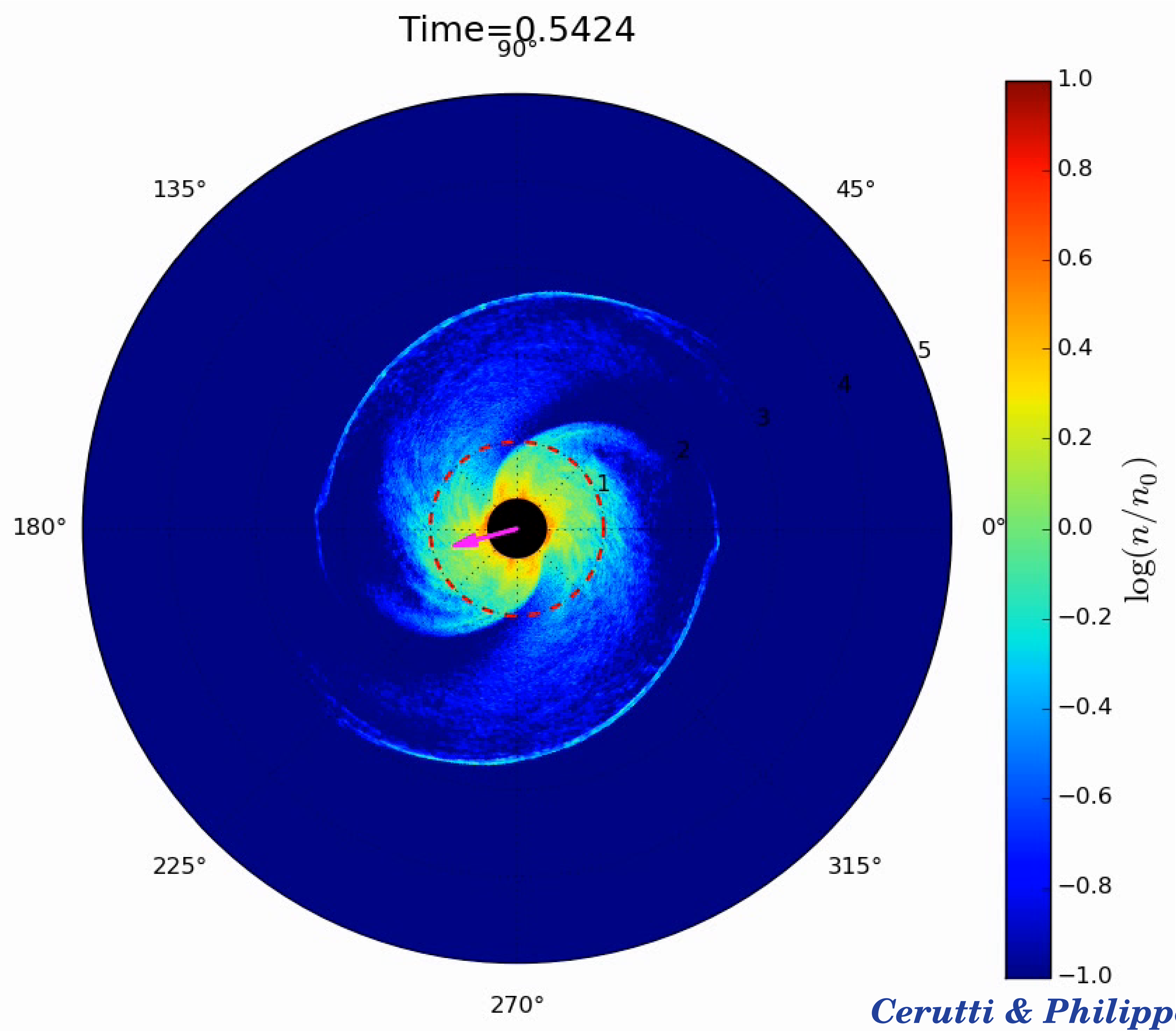


Presence of spatial irregularities due to kinetic instabilities in the sheet

(e.g., kink and tearing modes)

Cerutti et al. 2016

View in the equatorial plane

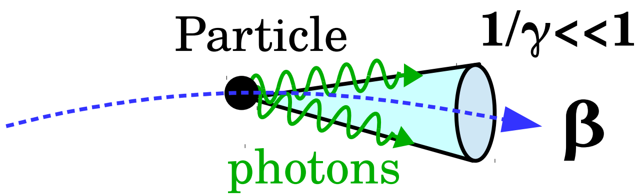


Cerutti & Philippov 2017

<u>Observed</u> high-energy radiation flux ($\nu>\nu_0$, $\chi=0°$)

i=0 - Phase=0.00 - Positrons -

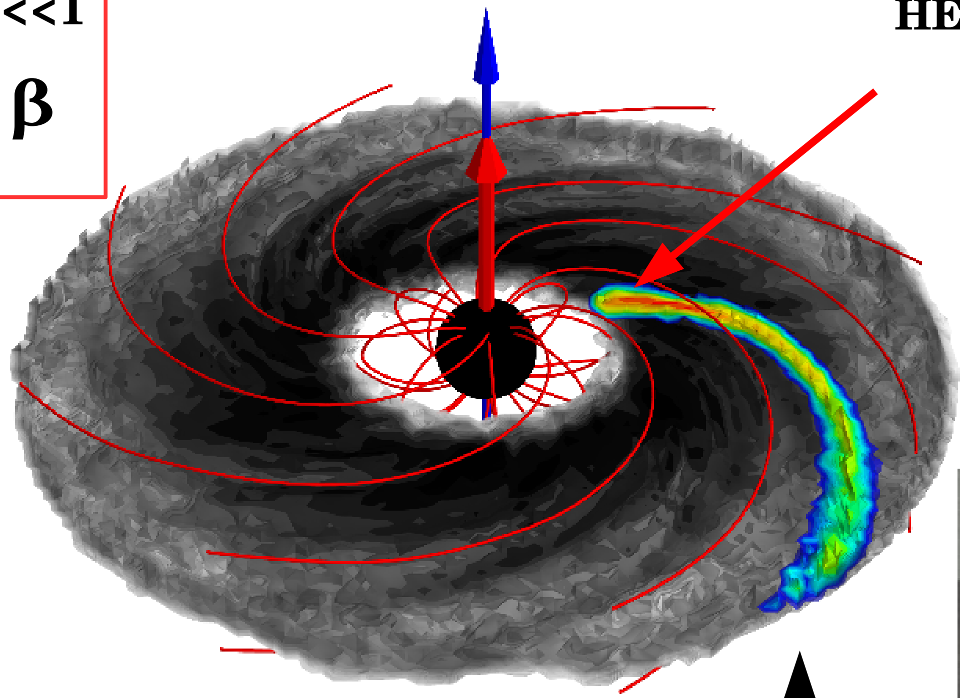
Relativistic beaming



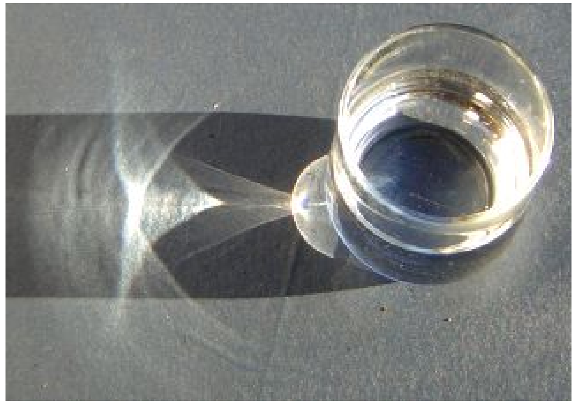
Gray : **Total** flux (all directions)

Color : **Observed** flux

HE flux concentrated close to the light-cylinder



Observer



Spatial extension of the observed emission in the sheet

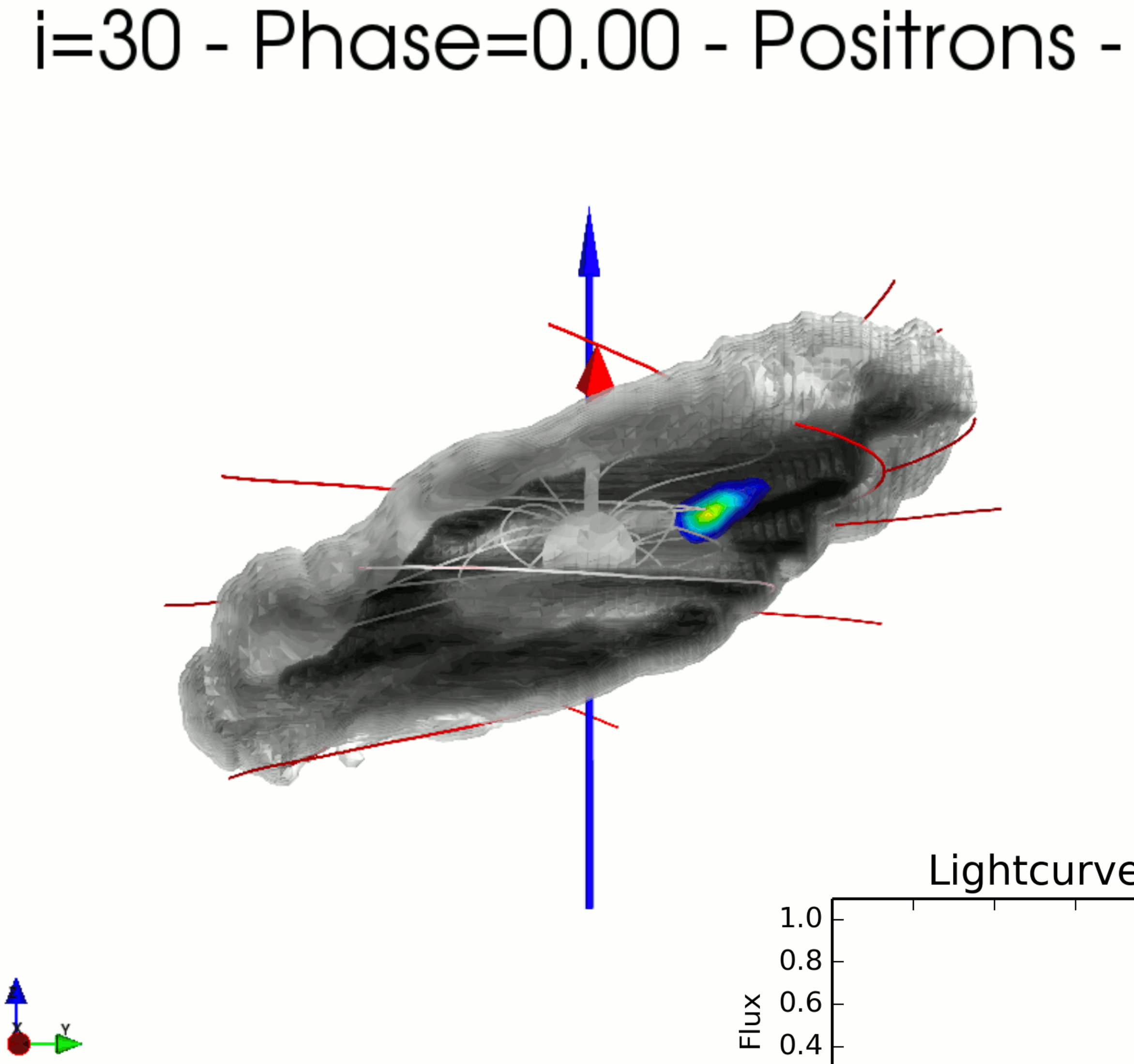
=> Formation of a caustic

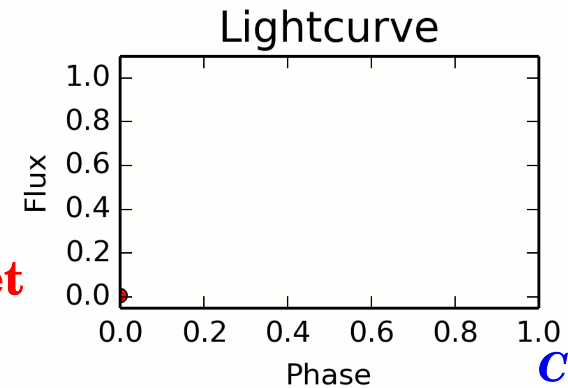
Observed high-energy radiation flux ($\nu > \nu_0$, $\chi = 30°$)

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

Color : **Observed** flux

Light curve shaped by the geometry of the current sheet

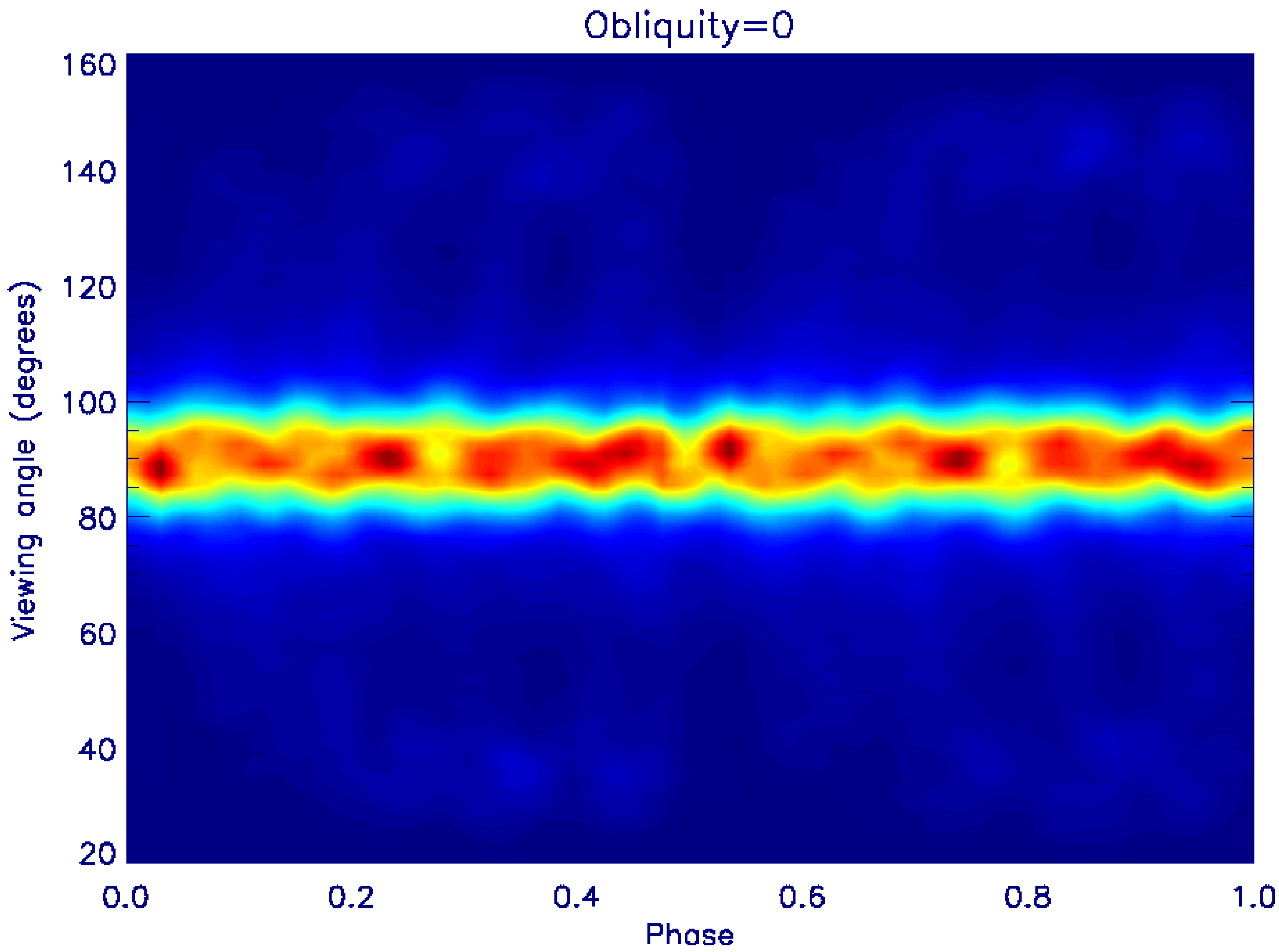




One pulse per crossing of the current sheet

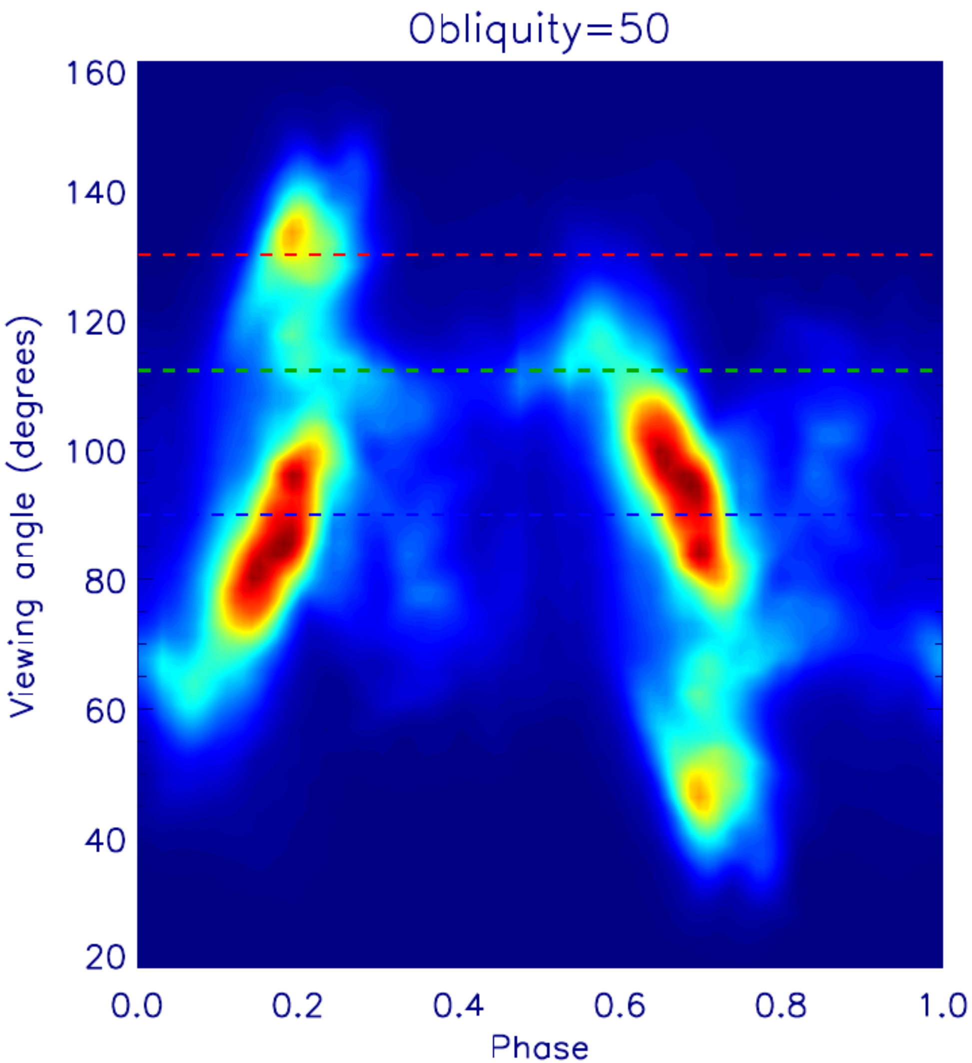
Cerutti et al. 2016

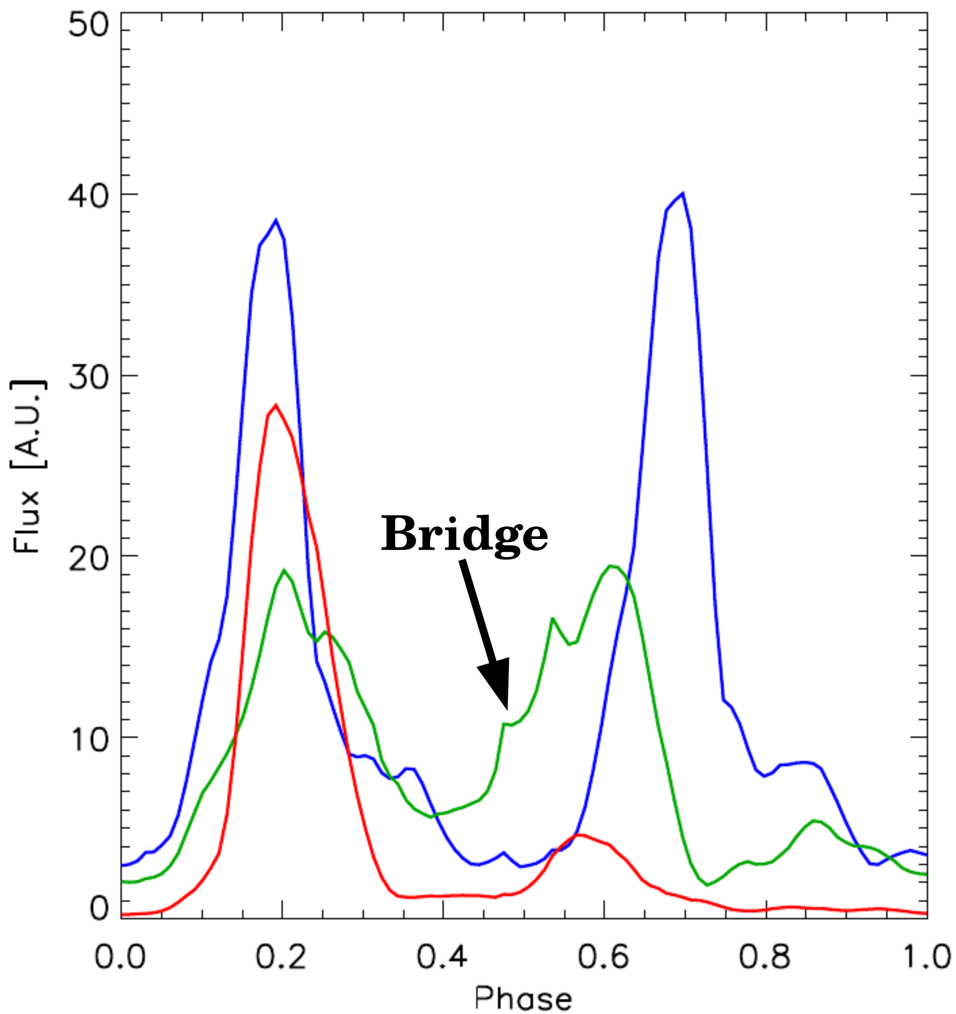
Gamma-ray imprint on the sky



High-energy photons are concentrated within the equatorial regions where most of the spin-down is dissipated.

A few typical lightcurves





Cerutti et al. 2016

Philippov & Spitkovsky 2018

To go further: References & Journal club

- **Reviews**
  - *Arons 1979, 2009, 2012*
  - *Michel 2004*
  - *Kirk et al. 2009*
  - *Spitkovsky 2011*
  - *Beskin et al. 2015*
  - *Pétri 2016*
  - *Cerutti & Beloborodov 2017*

- **Journal club articles:**
  - *Belyaev 2015:* An example of 2D PIC simulations of the aligned pulsar
  - *Philippov et al. 2014*: Force-free torque and pulsar alignment