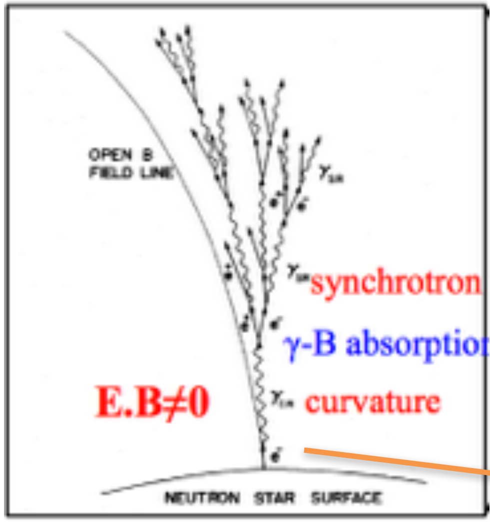
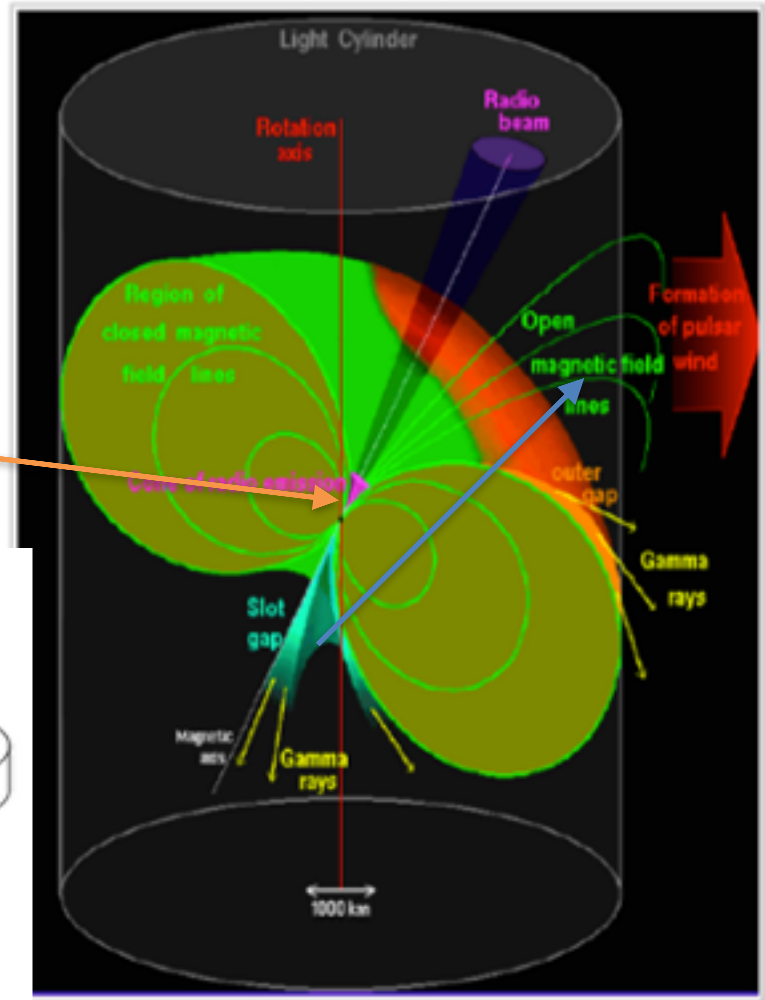
How do pulsars shine?

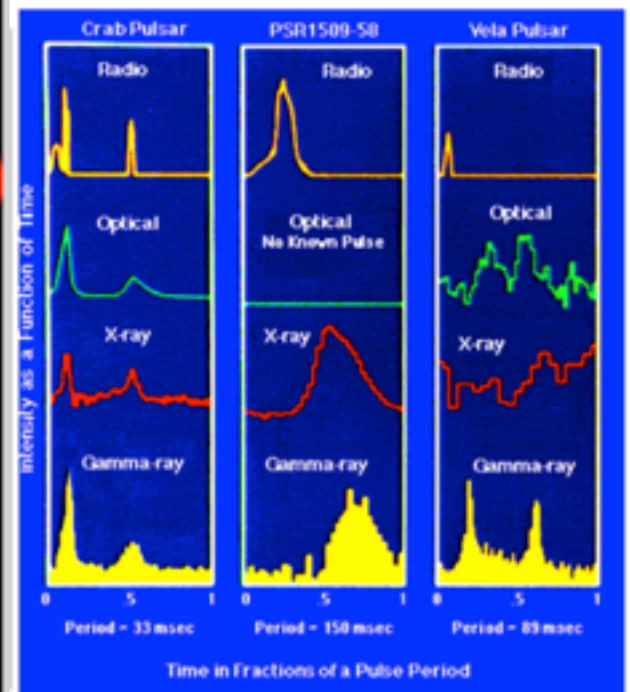
Sasha Philippov
UC Berkeley

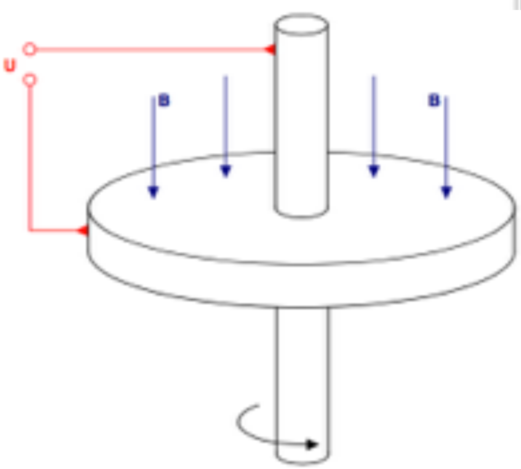
What is a pulsar?

Pair cascade in the polar caps









Unipolar induction

Standard pulsar

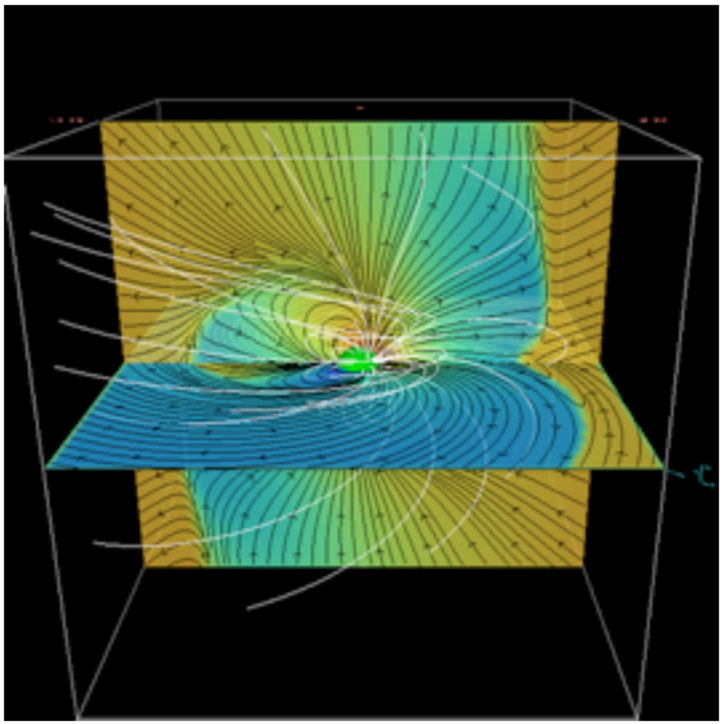
- Force-free paradigm

$$\rho_c\mathbf{E} + \mathbf{j}\times\mathbf{B} = \frac{d(\gamma\rho_m\mathbf{v})}{dt} + \text{pressure}$$

$$\boldsymbol{E}\cdot\boldsymbol{B} = 0$$

$$\boldsymbol{j} = \frac{c}{4\pi}\nabla\cdot\boldsymbol{E}\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2} + \frac{c}{4\pi}\frac{(\boldsymbol{B}\cdot\nabla\times\boldsymbol{B} - \boldsymbol{E}\cdot\nabla\times\boldsymbol{E})\boldsymbol{B}}{B^2}$$

$$\frac{1}{c}\frac{\partial\boldsymbol{E}}{\partial t} = \nabla\times\boldsymbol{B} - \frac{4\pi}{c}\boldsymbol{j}, \quad \frac{1}{c}\frac{\partial\boldsymbol{B}}{\partial t} = -\nabla\times\boldsymbol{E}$$



- Y-point
- Closed/open field lines
- Current sheet
- No pathologies at null surface and LC
- Predicts the spindown law
- Field lines are radial

Oblique: Spitkovsky (2006), Kalapotharakos et al (2009), Petri (2012), Tchekhovskoy et al. (2014) (full MHD)

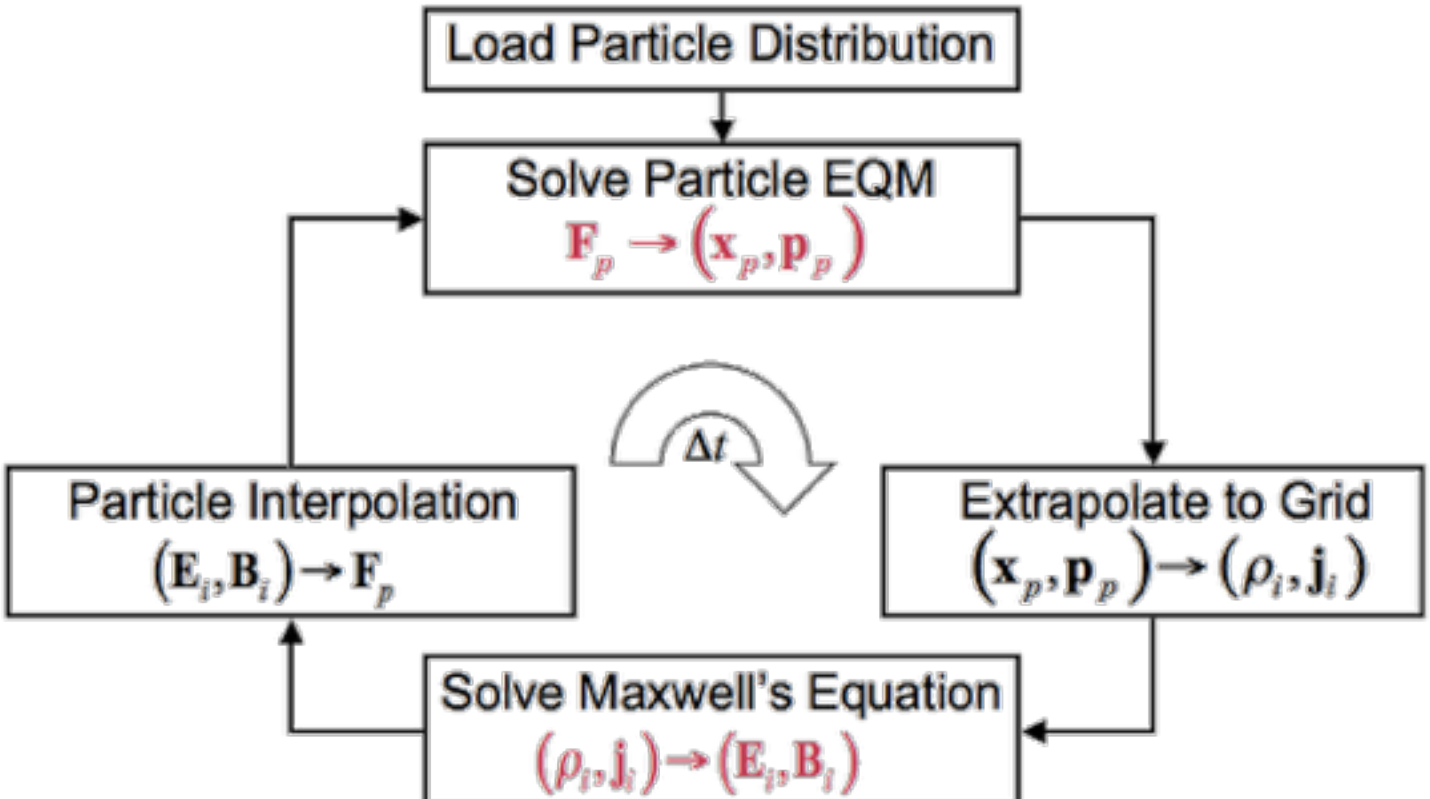
$$L_{\text{pulsar}} = k_1\frac{\mu^2\Omega_*^4}{c^3}(1 + k_2\sin^2\alpha)$$

PIC simulation of magnetospheres I

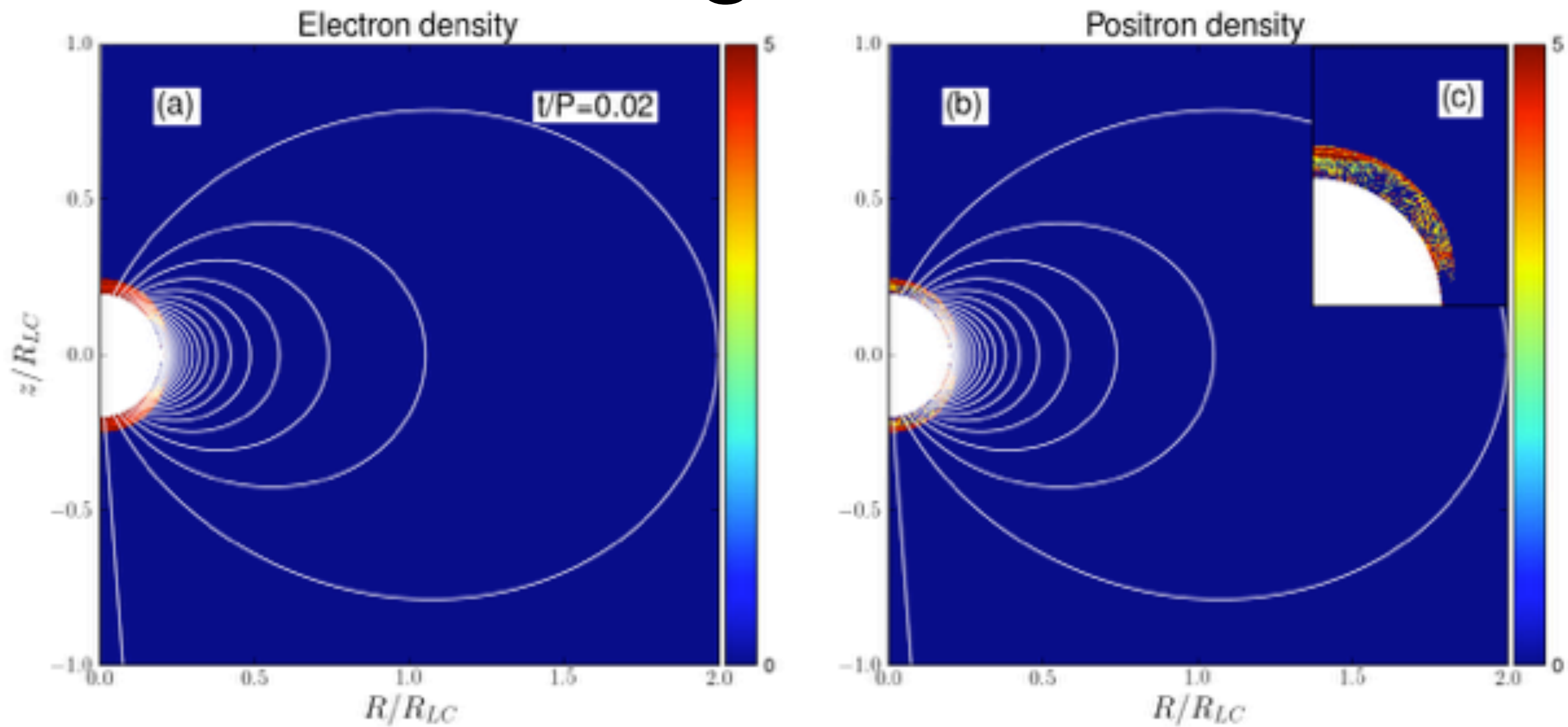
- Core - EM PIC codes TRISTAN-MP (Spitkovsky 2008) and Zeltron (Cerutti et. al., 2014).

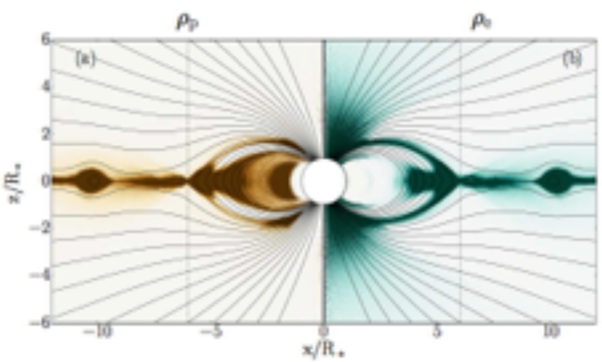
$$\partial E/\partial t = c(\nabla \times B) - 4\pi J\,, \qquad \nabla \cdot E = 4\pi\varrho\,, \quad \nabla \cdot B = 0$$

$$\partial B/\partial t = -c(\nabla \times E)\,, \qquad \frac{d}{dt}\gamma m \mathbf{v} = q(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B})$$



GR aligned rotator





Chen & Beloborodov, ApJ, 2014

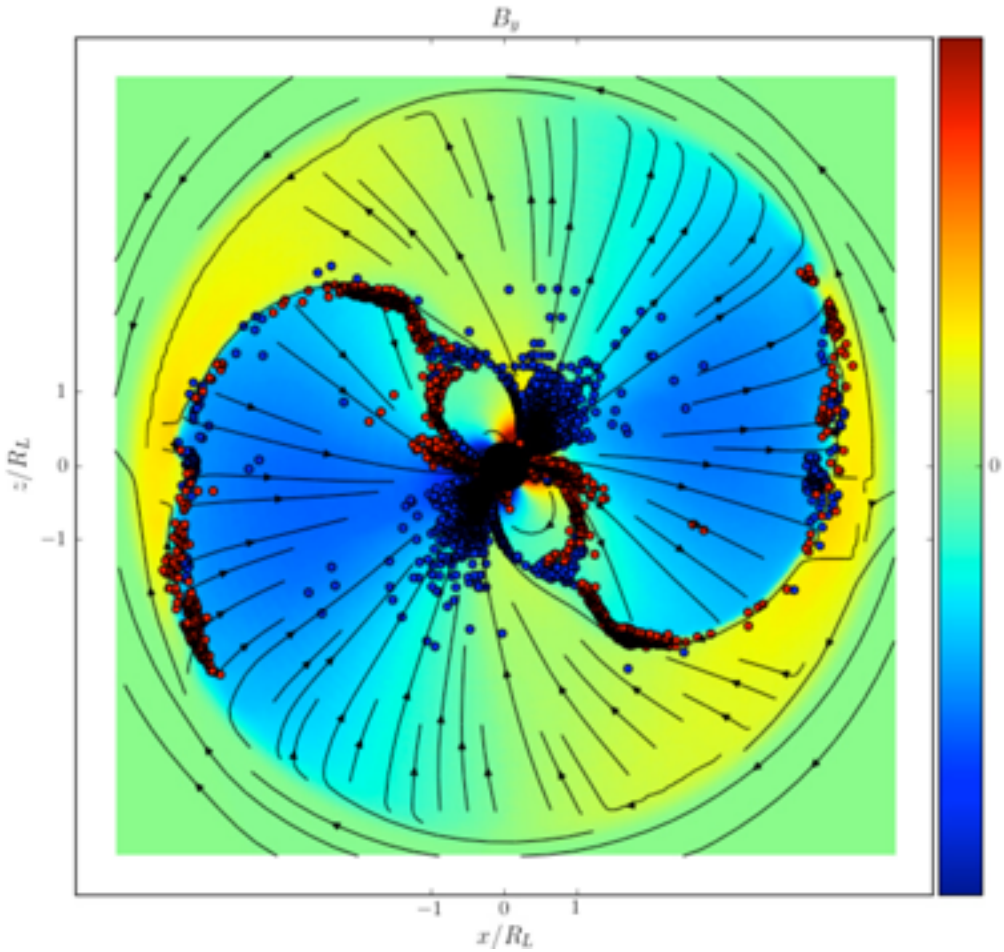
Flat space solution, no pair production

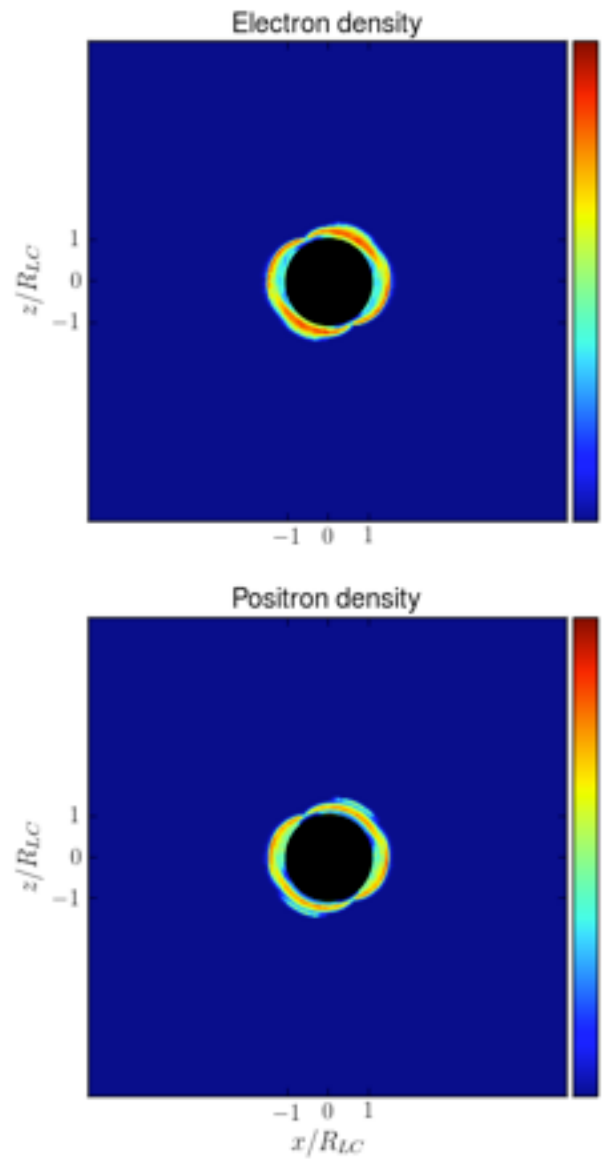
Philippov et al., 2015 ApJ

Feedback from the current sheet on polar cap pair production - implications for the radio variability?

GR oblique models: where does pair formation happen?

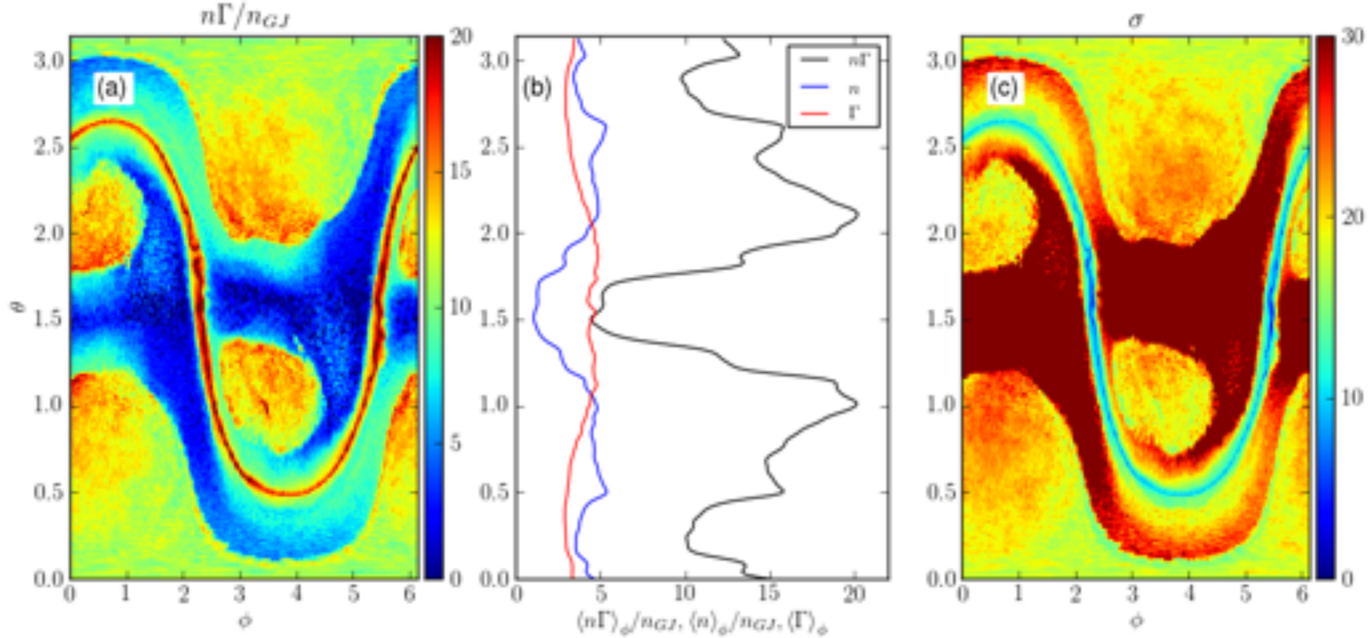
Highlights polar cap, return current layers and the current sheet.





Philippov & Spitkovsky, arxiv July 2017

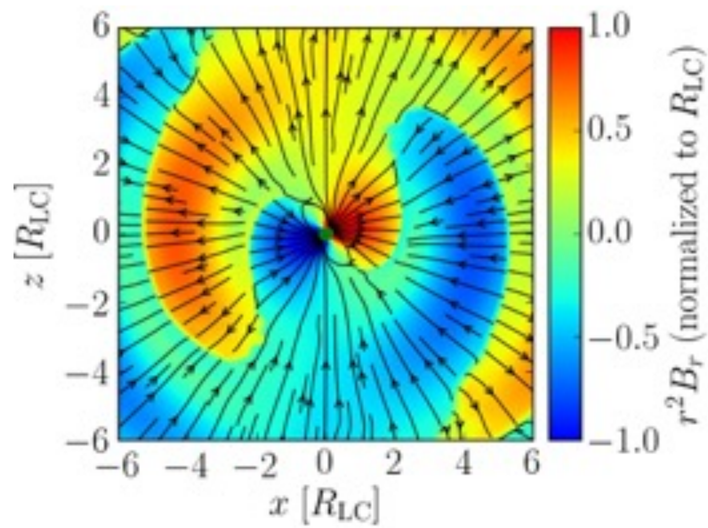
Pulsar Wind



Not exactly a split monopole, has a non-uniform magnetic field with latitude

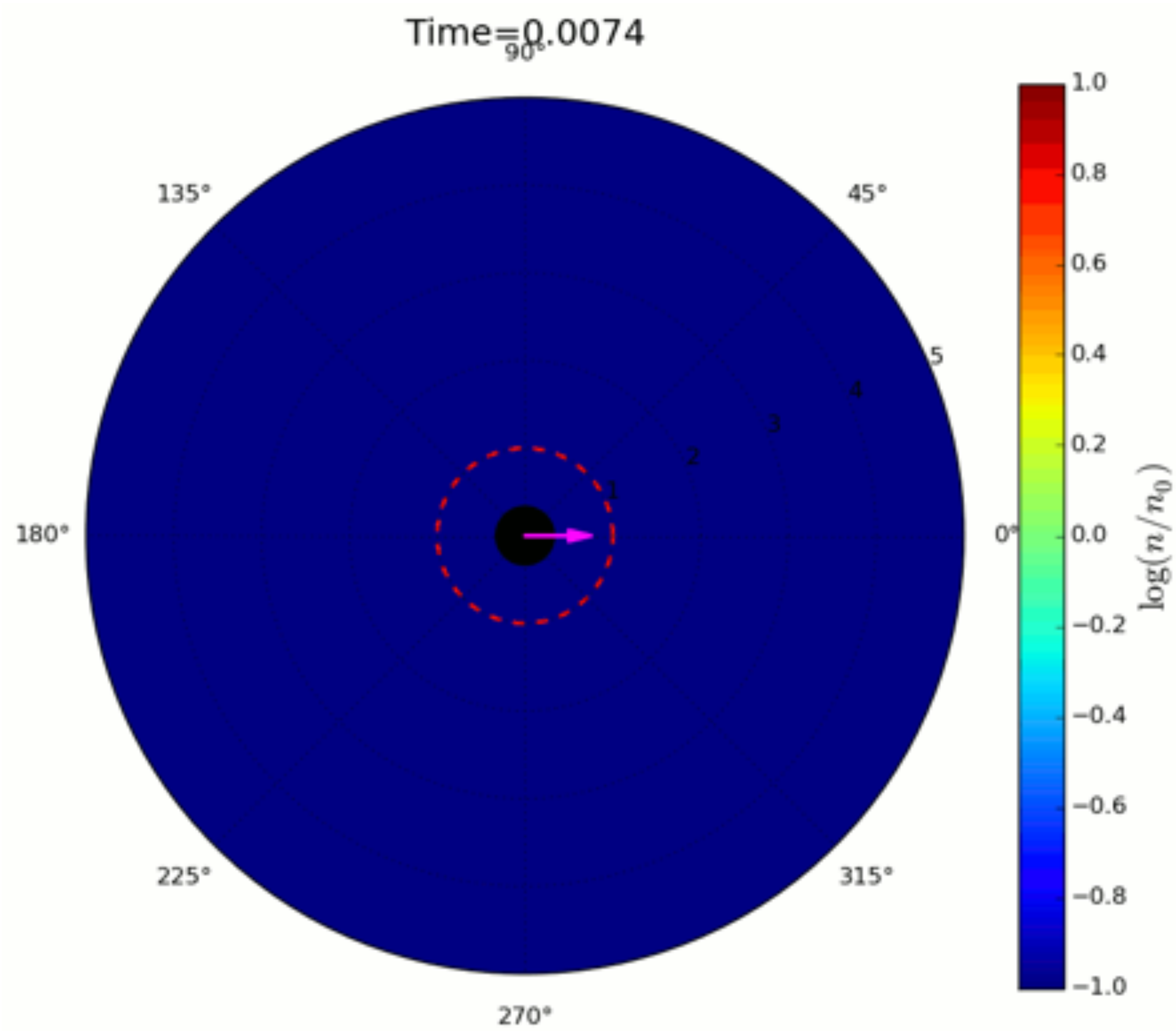
Plasma density is also highly non-uniform with latitude, both in the polar zone and the current sheet wedge

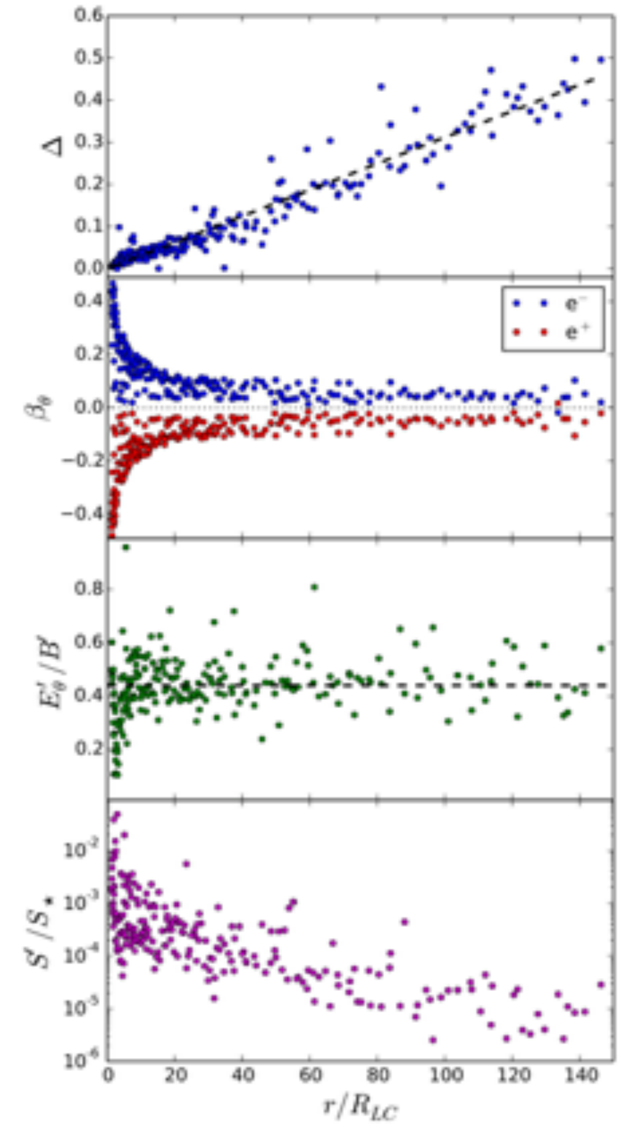
Philippov & Spitkovsky, arxiv July 2017



Tchekhovskoy, Philippov, Spitkovsky, MNRAS, 2016

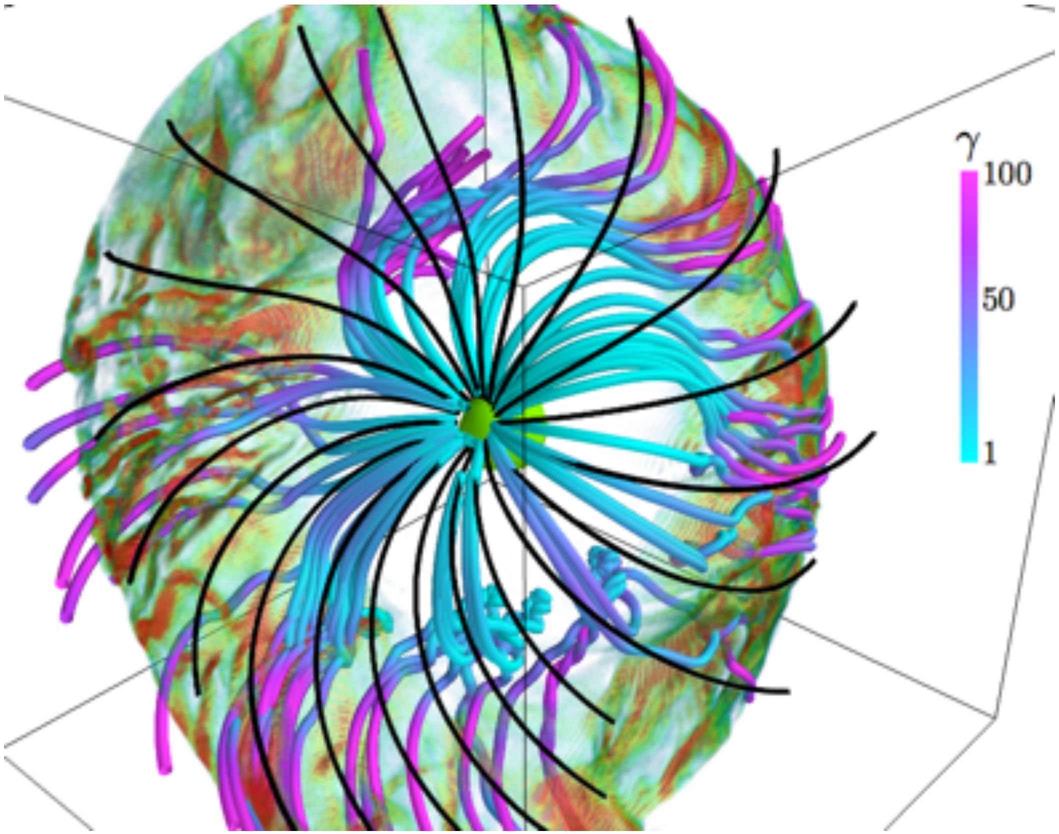
Sheet evolution



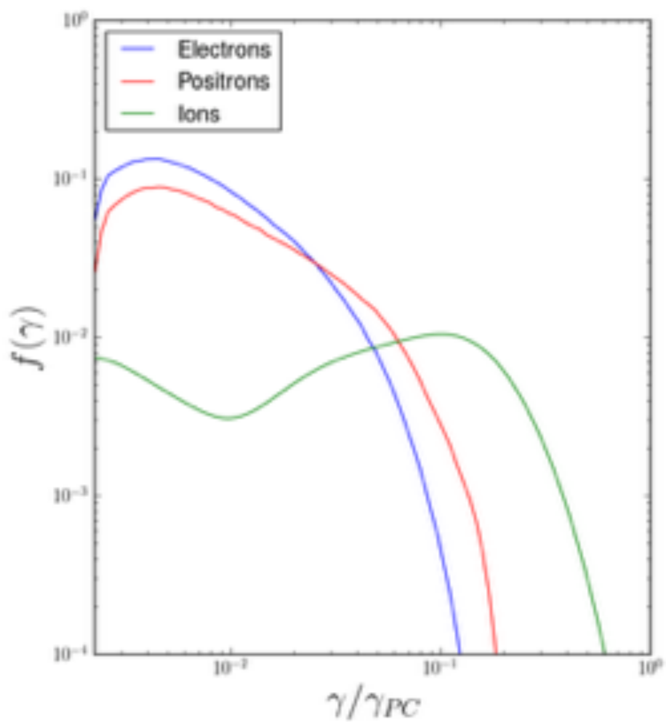


Cerutti & Philippov, in preparation

Energetic ions

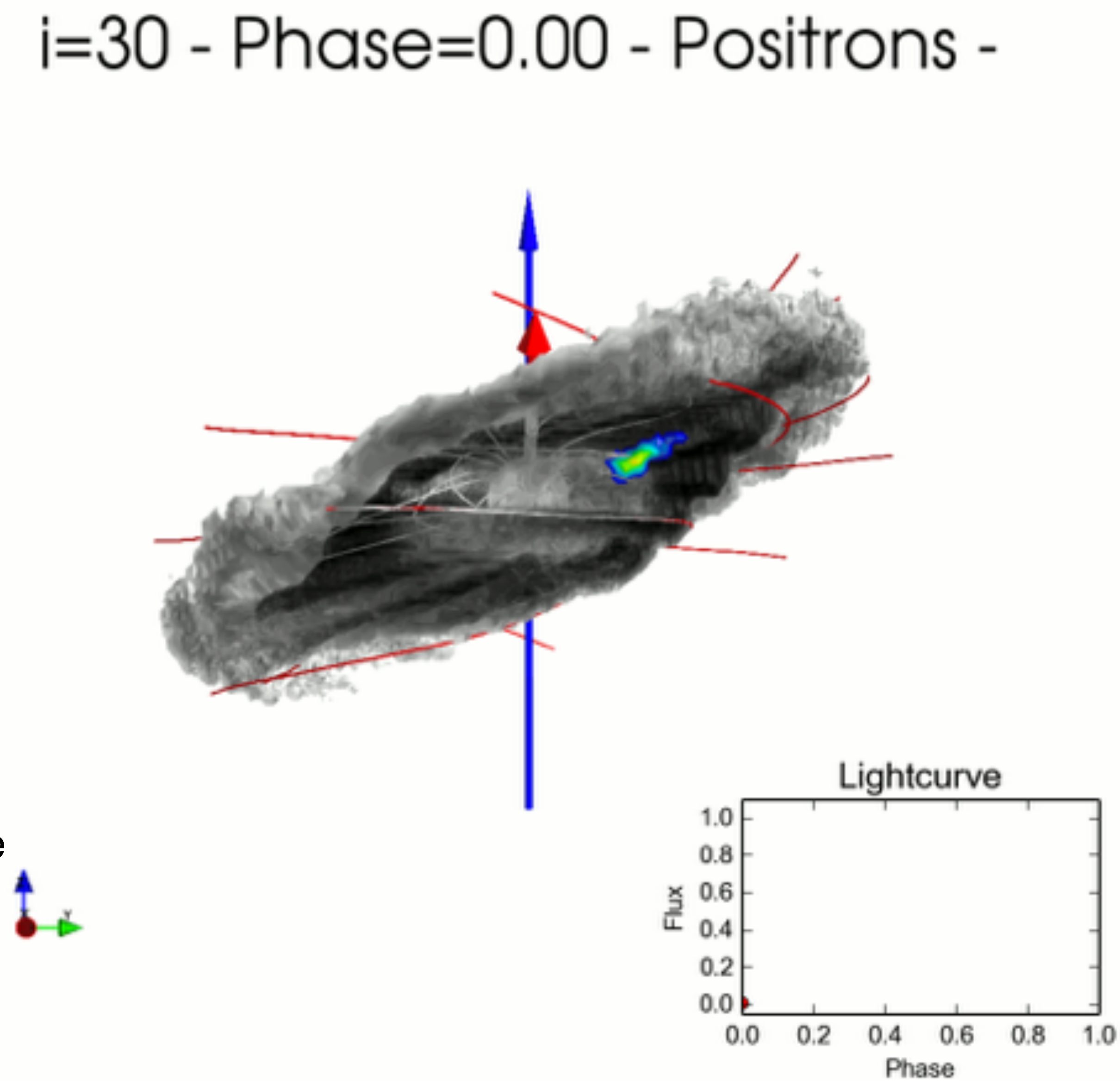


Most energetic particles that are produced in the magnetosphere are ions, extracted from the stellar surface. Gain significant fraction of the open field line voltage. Implications for UHECRs?



Philippov & Spitkovsky, arxiv July 2017

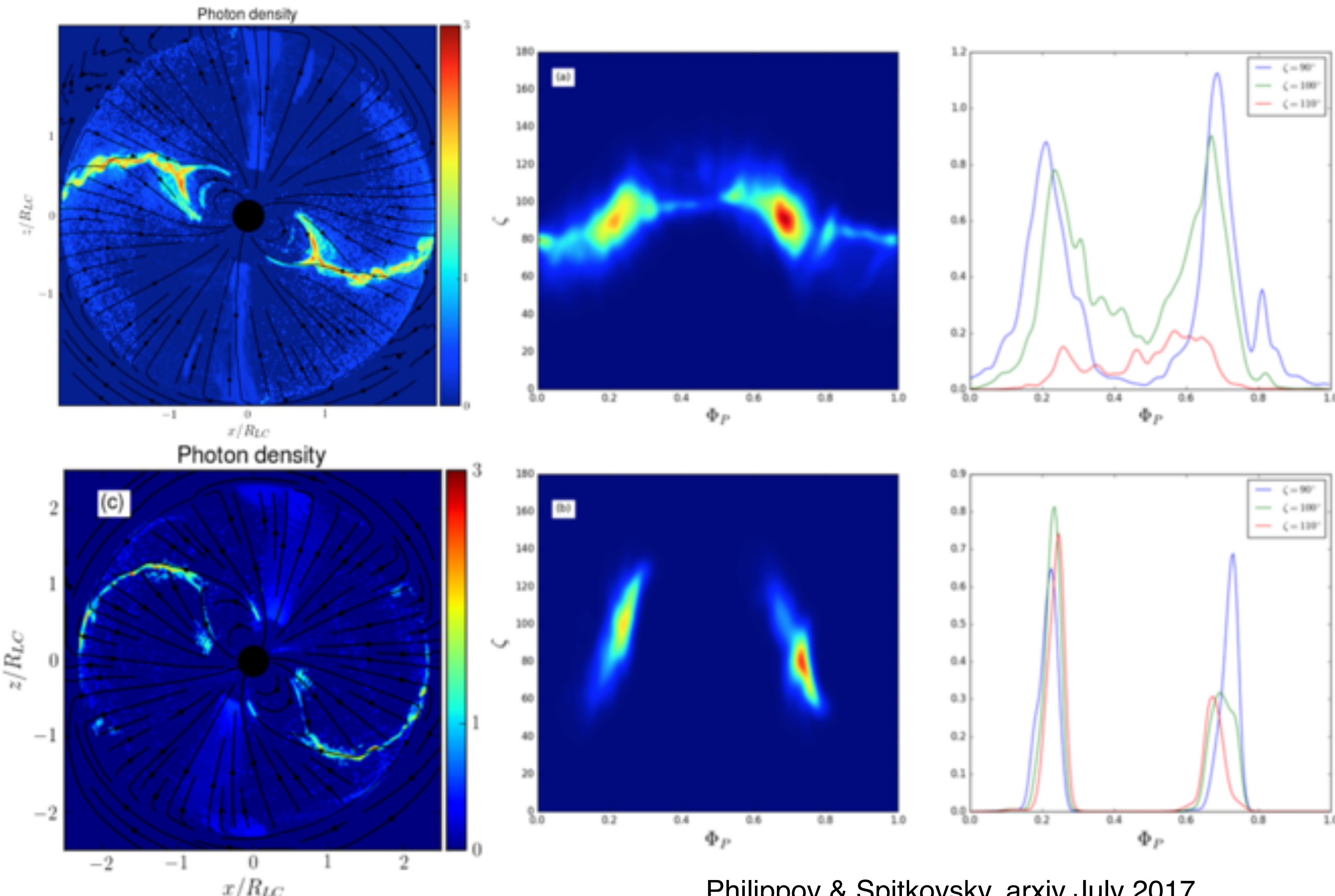
Gamma-ray modeling



- Simulations prefer current sheet as a particle accelerator. Particles radiate synchrotron emission.
- We apply radiative cooling on particles and collect photons.
- Observe caustic emission.
- Neutral injection at the surface.
- Predict gamma-ray efficiencies 1-20% depending on the inclination angle. Higher inclinations are much less dissipative.

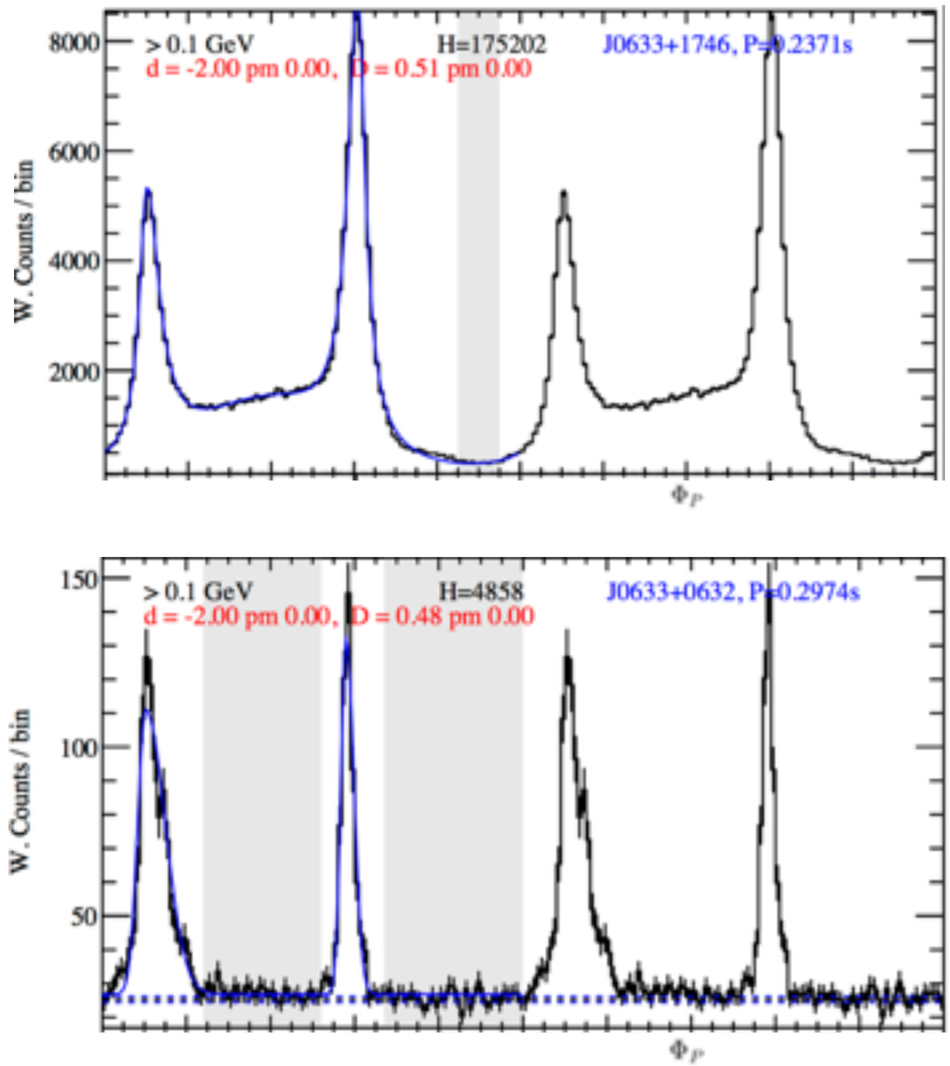
Cerutti, Philippov & Spitkovsky
MNRAS 2016

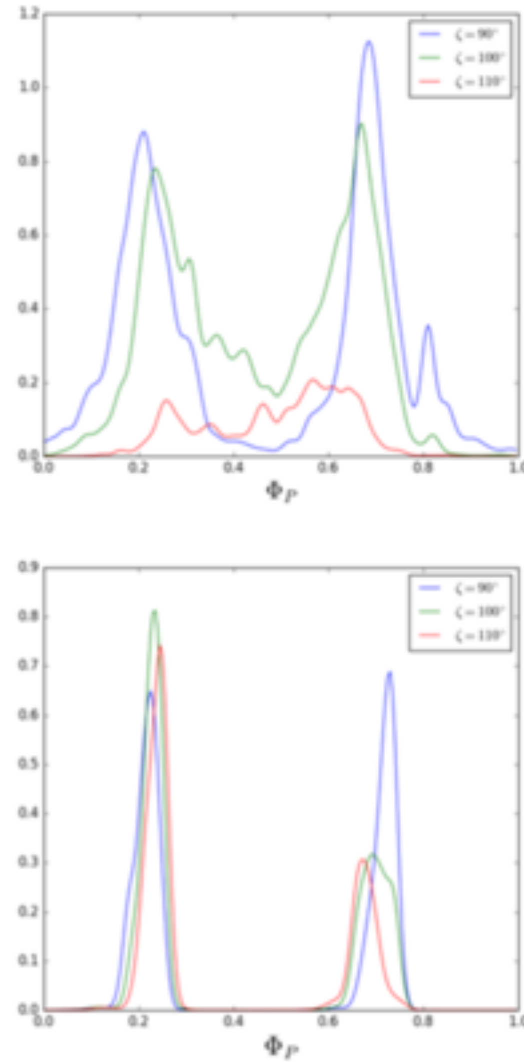
Lightcurves & spectra



Philippov & Spitkovsky, arxiv July 2017

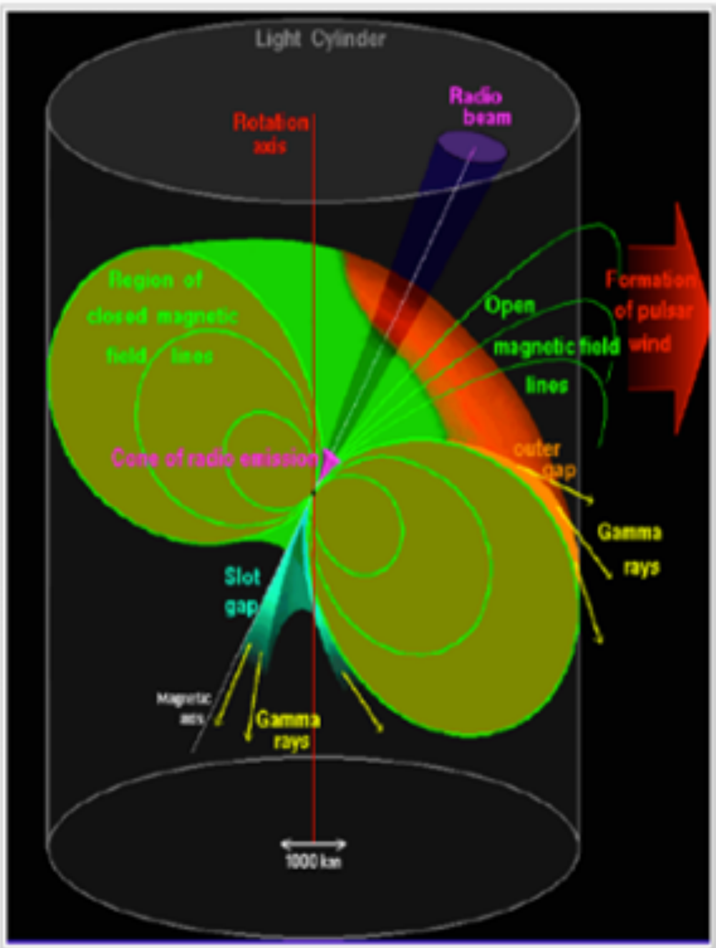
Lightcurves & spectra

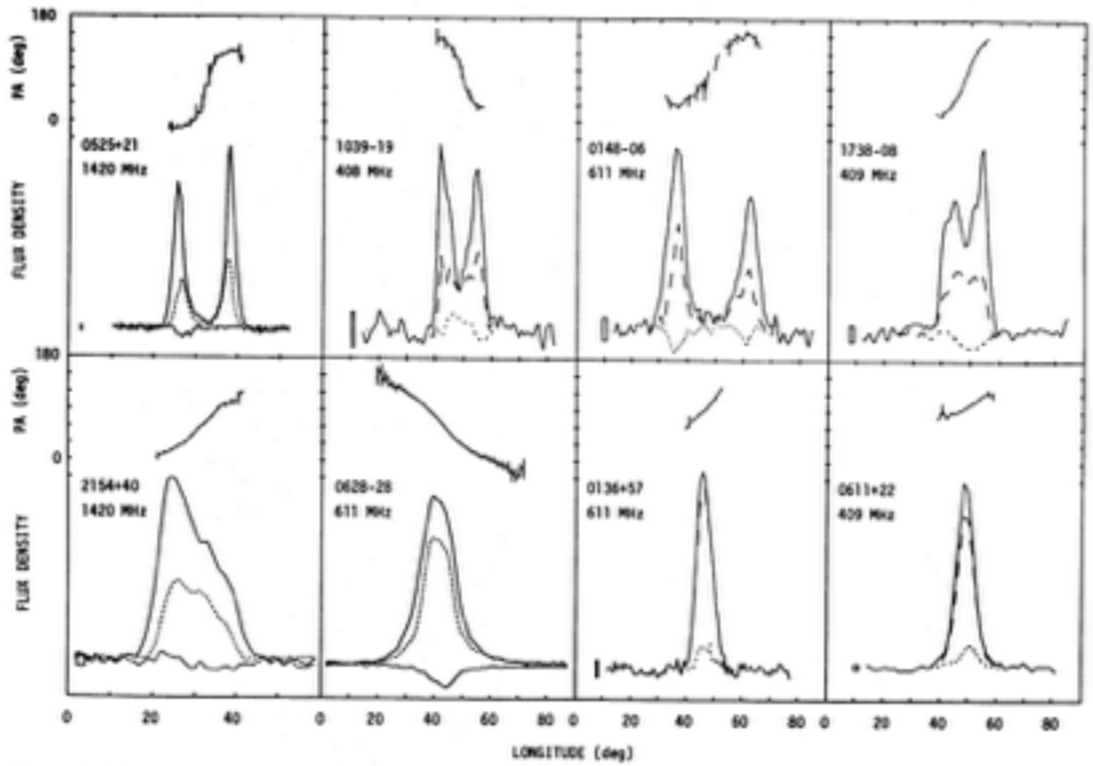




Philippov & Spitkovsky, arxiv July 2017

Polar radio emission





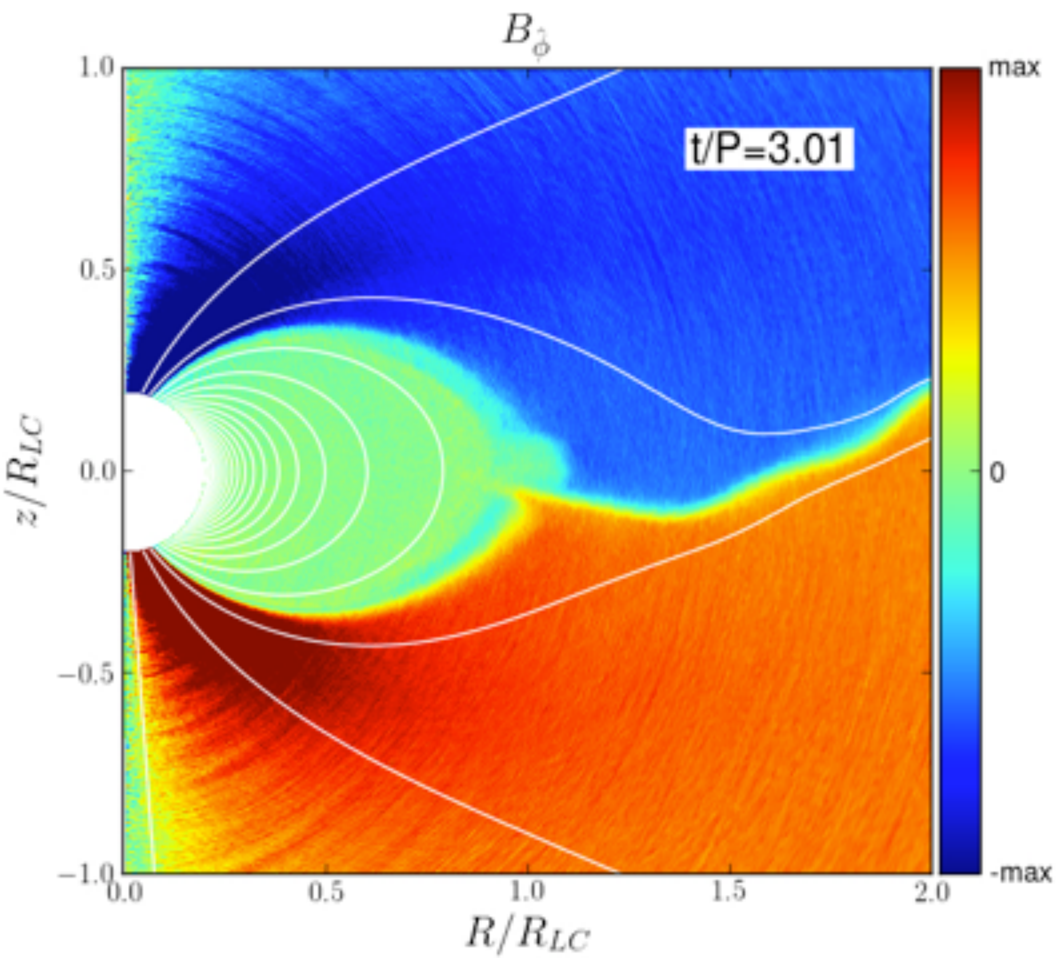
Lyne & Manchester, 1988

In most cases see one short pulse per period.

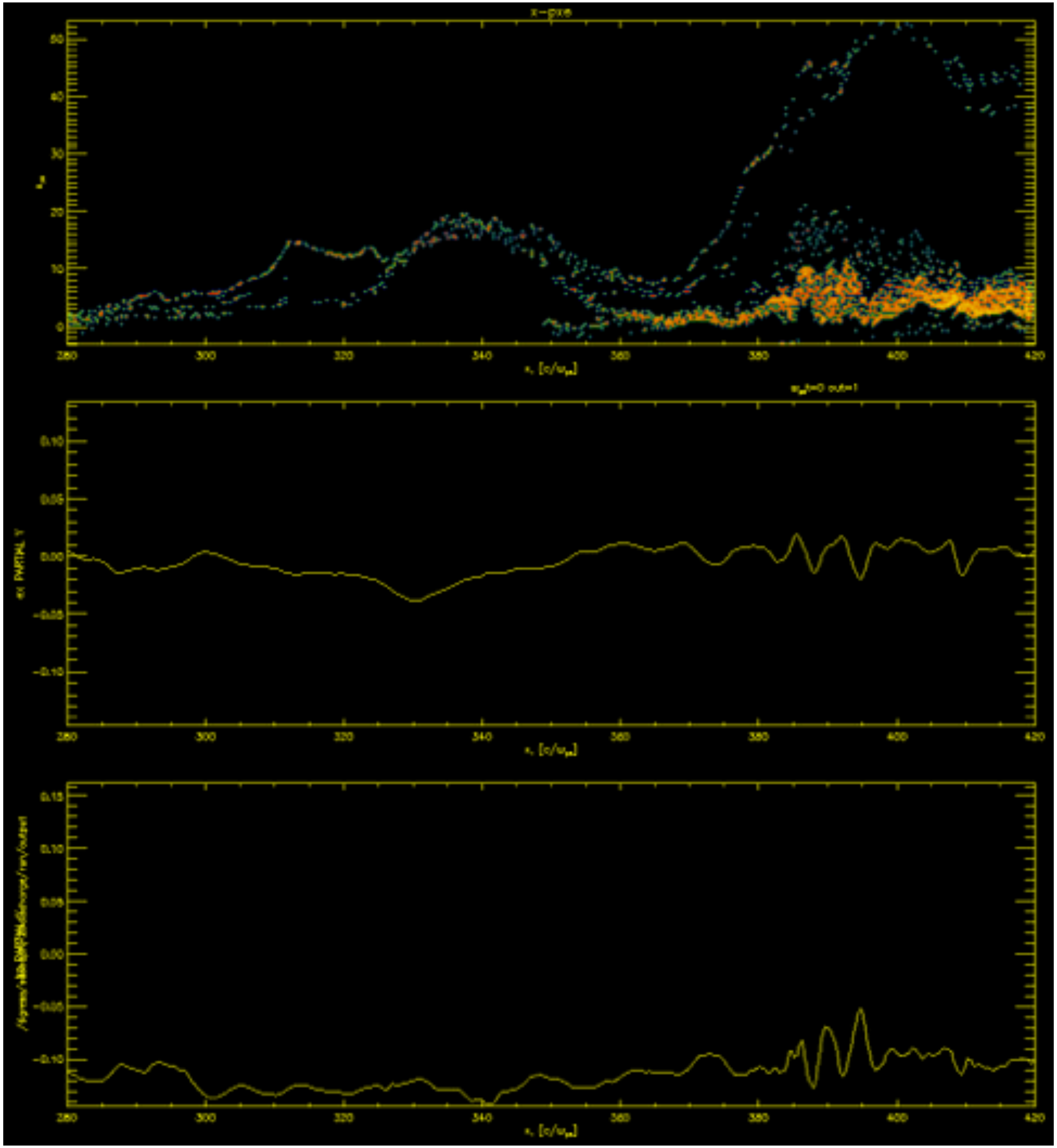
Beam width is related to the polar cap size.

Insight from simulations

- Non-stationary discharge drives waves in the open field zone.
- Waves are generated in the process of electric field screening by plasma clouds. They are driven by collective plasma motions, thus, coherent (see also Beloborodov 2008, Timokhin & Arons 2013)



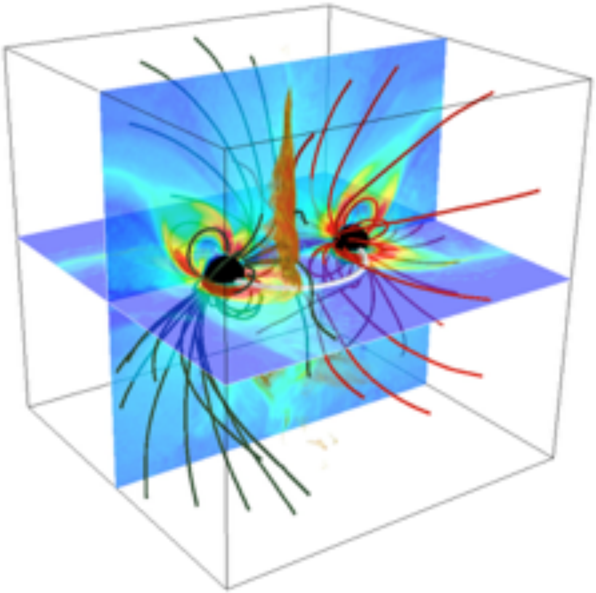
Philippov et al., 2015 ApJ

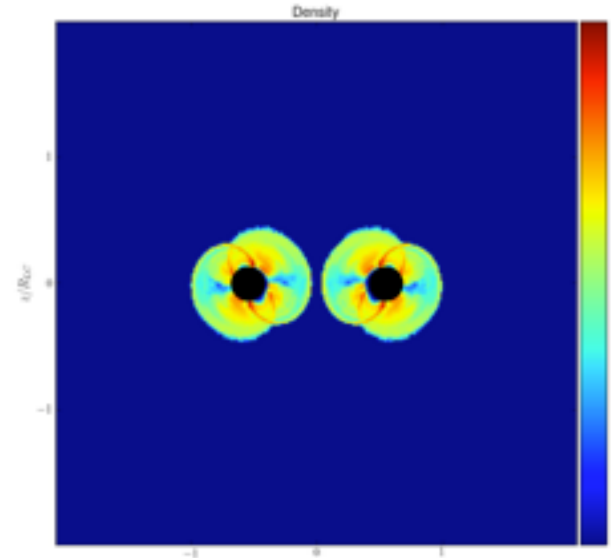


Conclusions

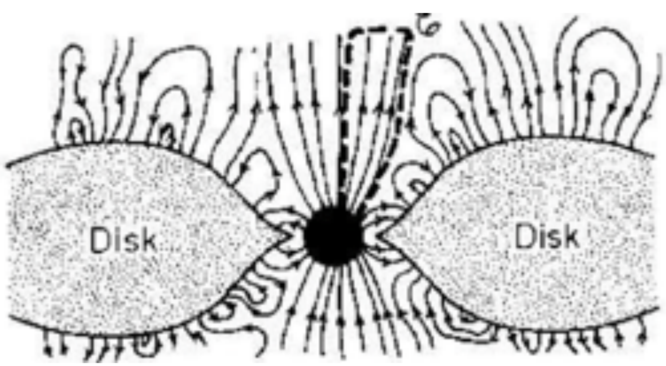
- Origin of pulsar emission has been a puzzle since 1967 - full kinetic simulations are finally addressing this from first principles.
- In flat space, self-consistent kinetic models show that pair cascade does not operate in the polar region for small obliquities, works for >40 degrees.
- General relativity effects are essential in producing discharges in low obliquity pulsars.
- Current sheet is an effective particle accelerator. Particles in the sheet emit powerful gamma-rays mainly via synchrotron mechanism.
- Pulsars are sources of energetic ions. UHECRs?
- Low altitude radio emission is likely caused by the non-stationary discharge at the polar cap.

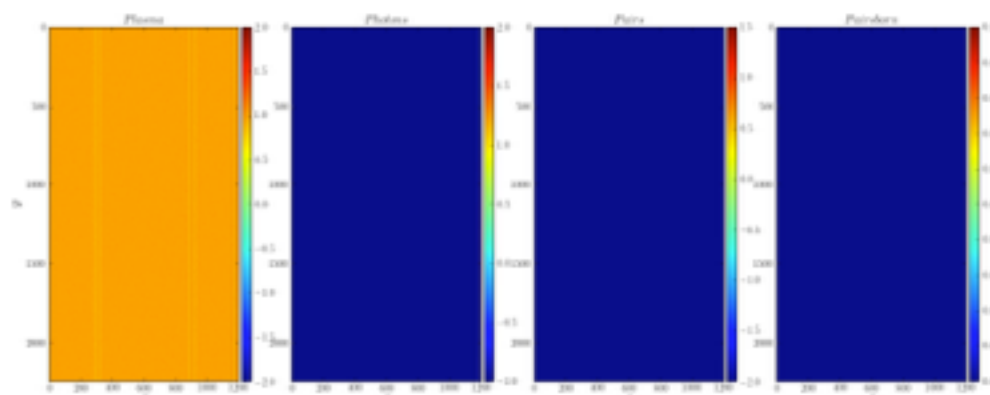
Future applications





First PIC simulations of binary neutron stars: EM radiative signature?





Filling the BH magnetosphere with plasmas, reconnection in coronae of accretion disks near the BH horizon