How do pulsars shine?

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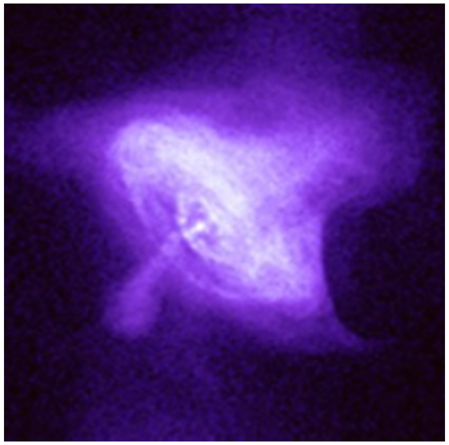
Open questions



- How pulsar magnetosphere works?
    - Nebula observations favor plasma-filled magnetospheres
- How particle acceleration works?
- How pulsars shine?
    - Most of the observable energy comes in gamma-rays

Standard pulsar

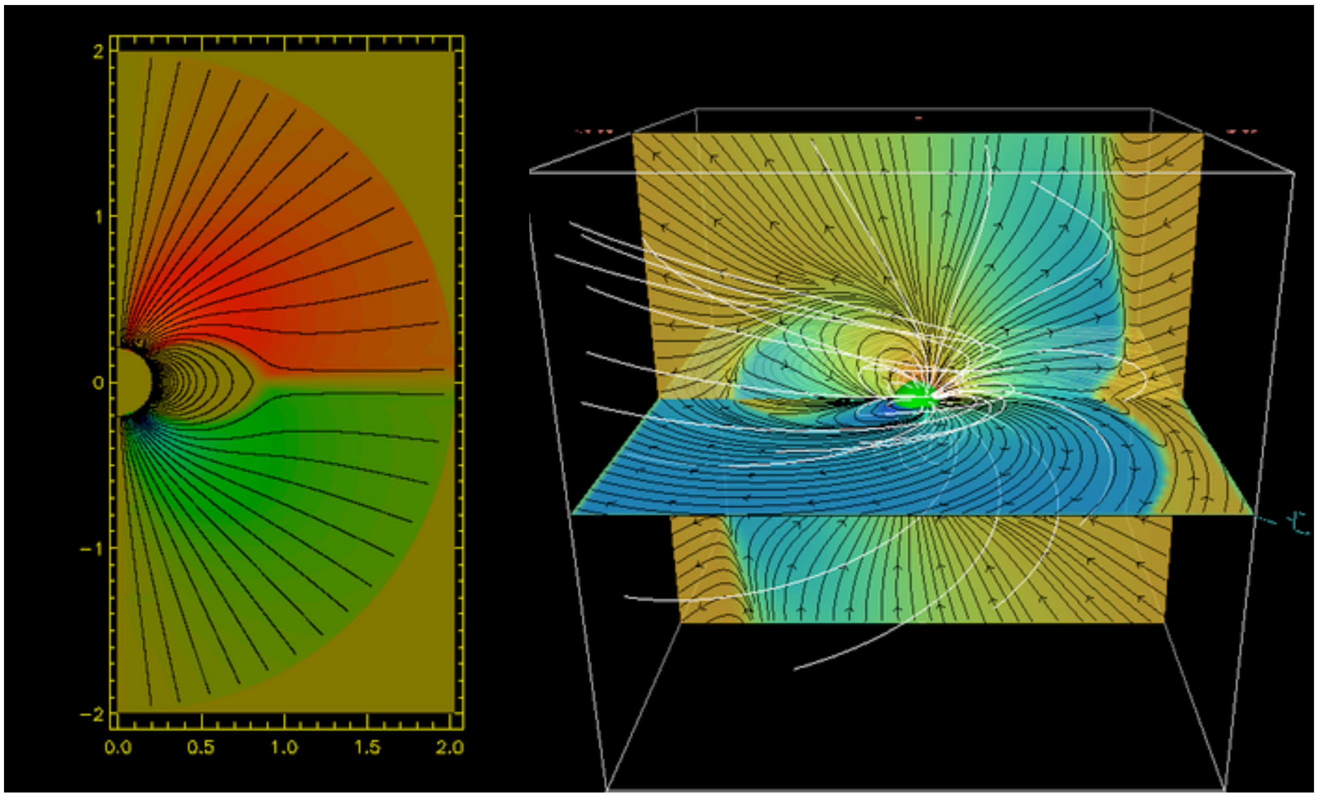
- Force-free paradigm

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

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

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

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



(from Spitkovsky 2006)

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

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

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

What can not be done with MHD?

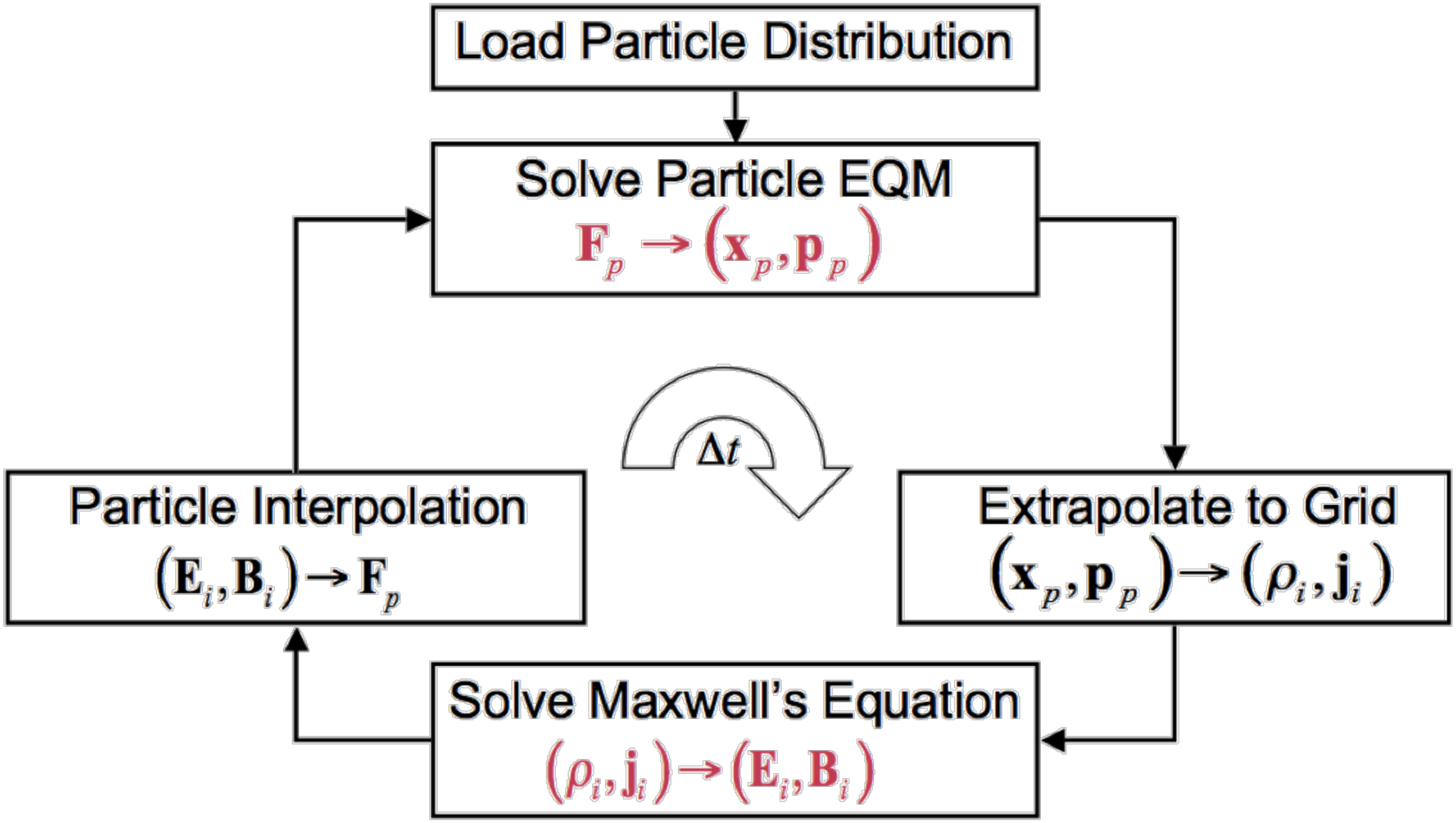
- Are the solutions unique? How magnetospheric plasma is produced?
- How particles are accelerated?
- How non-thermal emission is produced?

ρ_c	$\mathbf{j}$	ρ_m	$\mathbf{T}$	Non-thermal particles	Plasma instabilities
✓	✓	✓	✓	✗	✗

PIC method

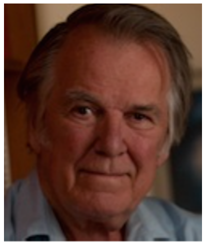
$$\partial E/\partial t = c(\nabla \times B) - 4\pi J\ , \qquad \nabla \cdot E = 4\pi\varrho\ , \quad \nabla \cdot B = 0$$

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



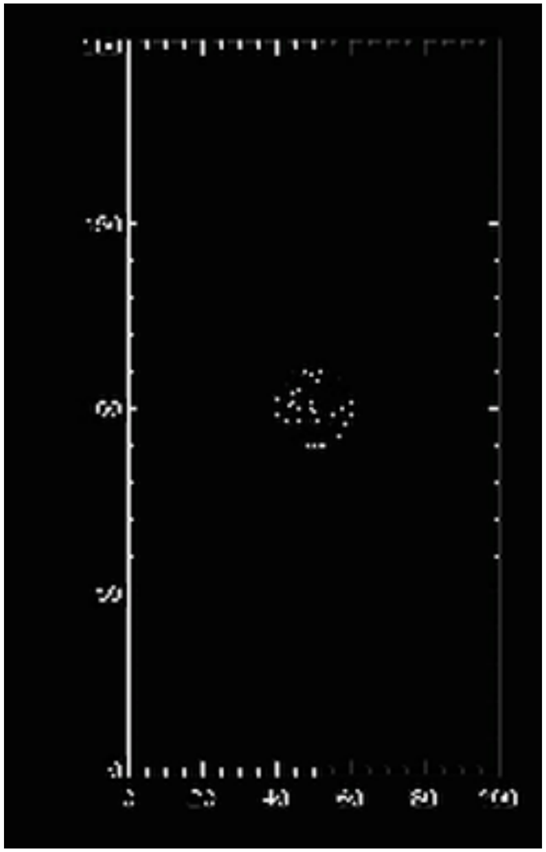
Relativistic version of TRISTAN, Spitkovsky (2003)

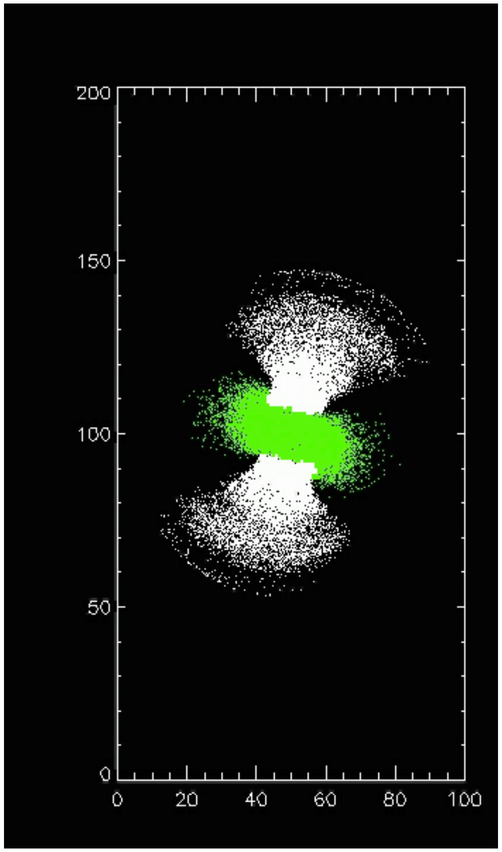
Electrostatically trapped solution



C. Michel

- Only free escape from the surface
- Disk-dome solution
- Almost no outflow and spin-down

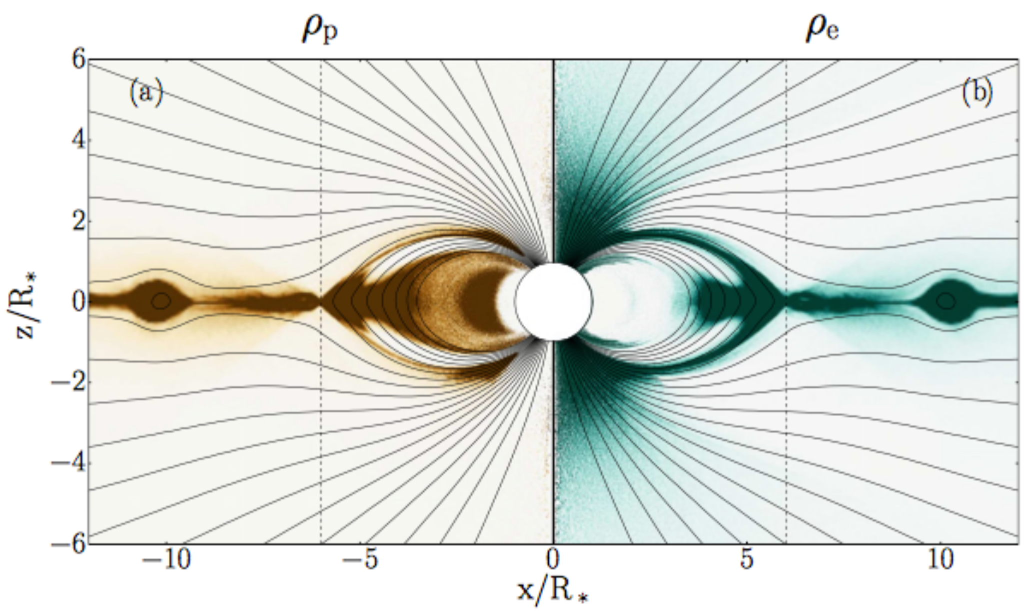




Kraus-Polstorff & Michel, 1985; Spitkovsky & Arons, 2002; Petri et al., 2002; Philippov & Spitkovsky, 2014

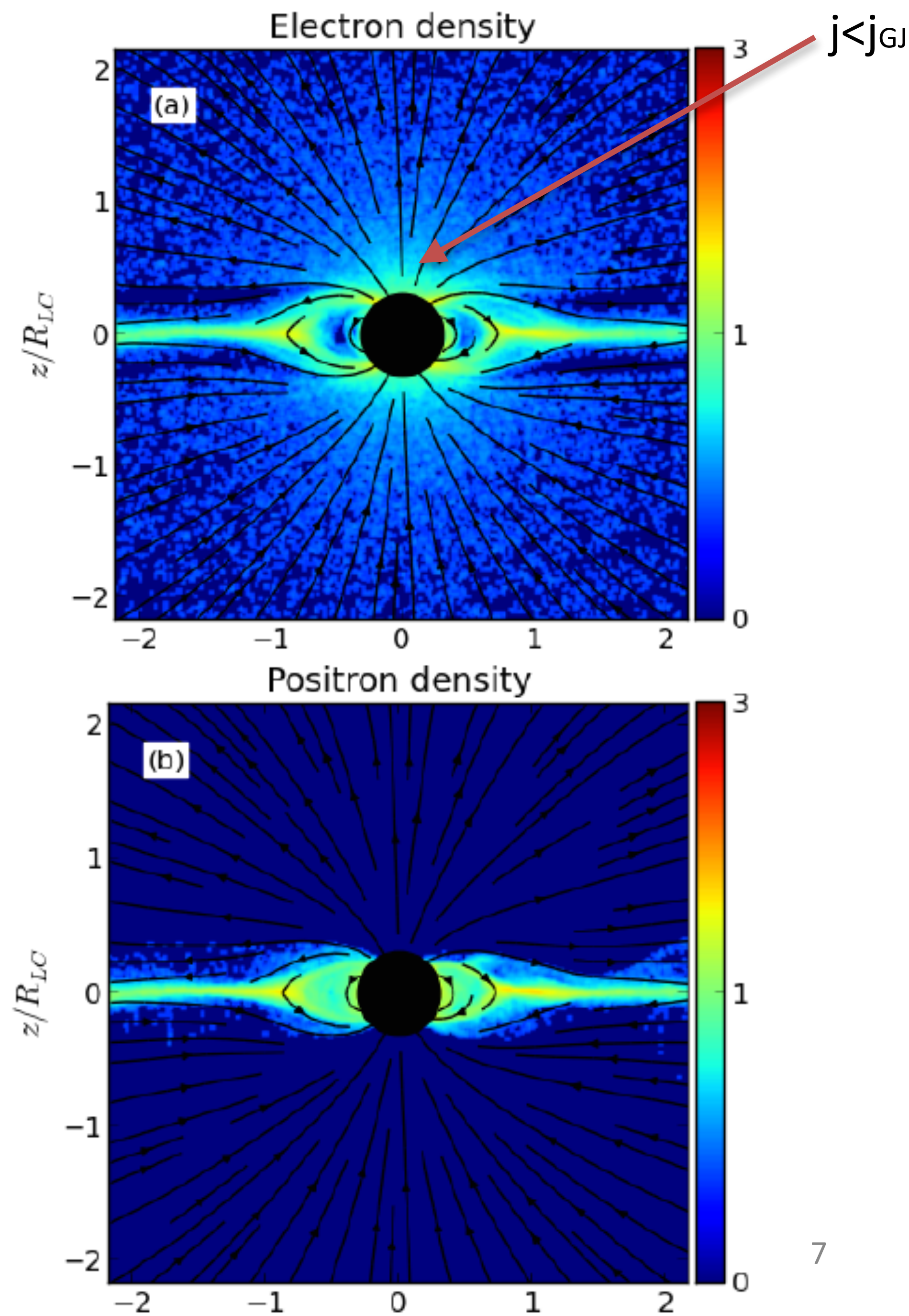
Aligned pulsar with pair production: no dense solutions!

Approaches force-free like solution,
but no pair production in the polar region,
where the space-charge limited flow does not
lead to particle acceleration.



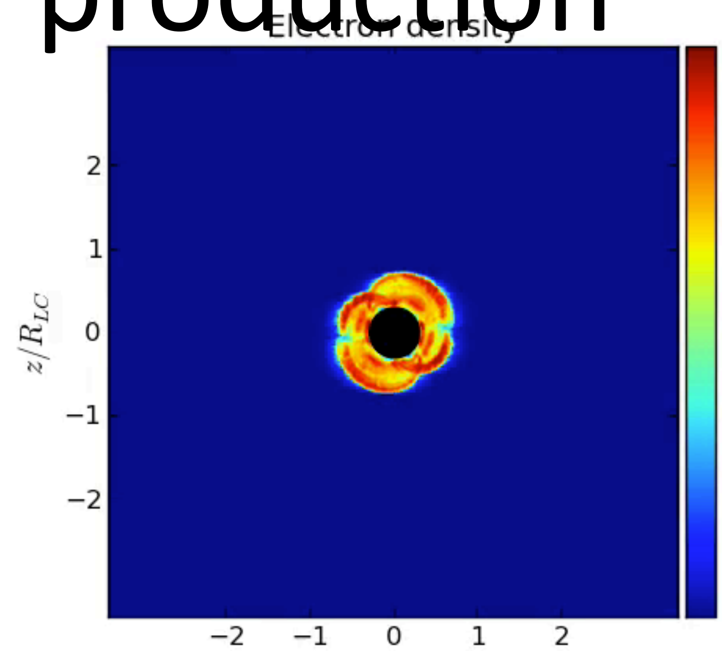
Chen, Beloborodov, ApJ, 2014

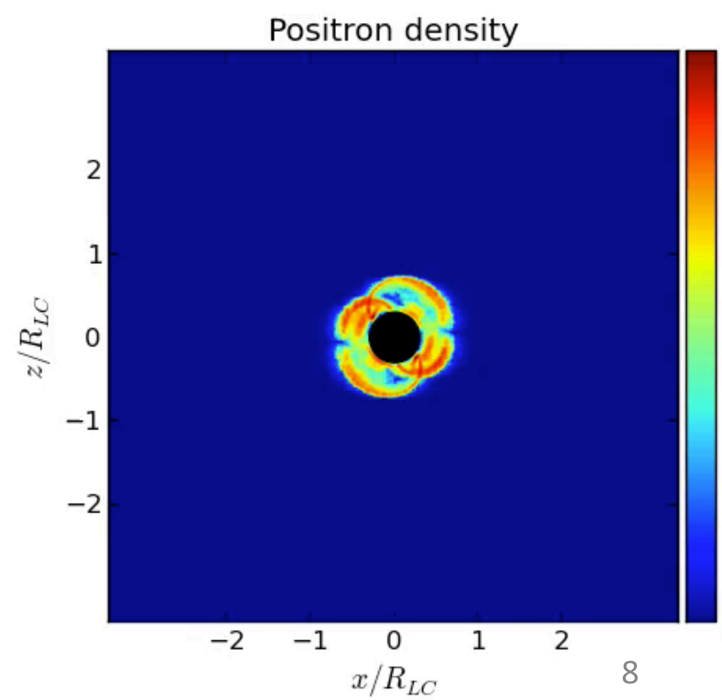
Philippov et al., ApJ, 2015

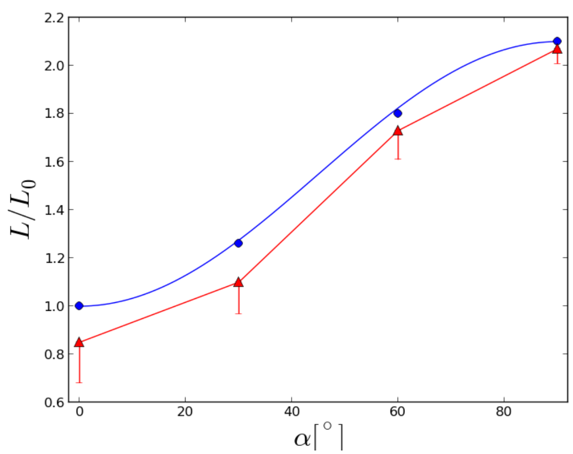


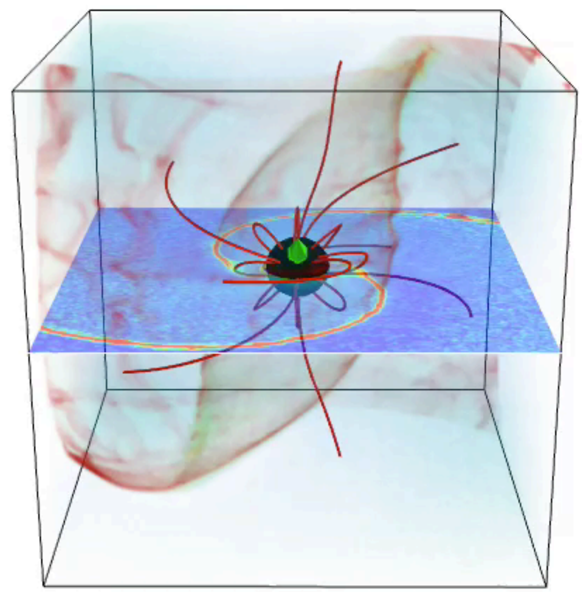
Oblique pulsar with pair production

- Approaches force-free like solution.
- Obliquity does not help in general: pairs are produced only in the part of the polar cap for inclinations larger than 40 deg.
- Dissipation decreases as a function of the inclination angle.





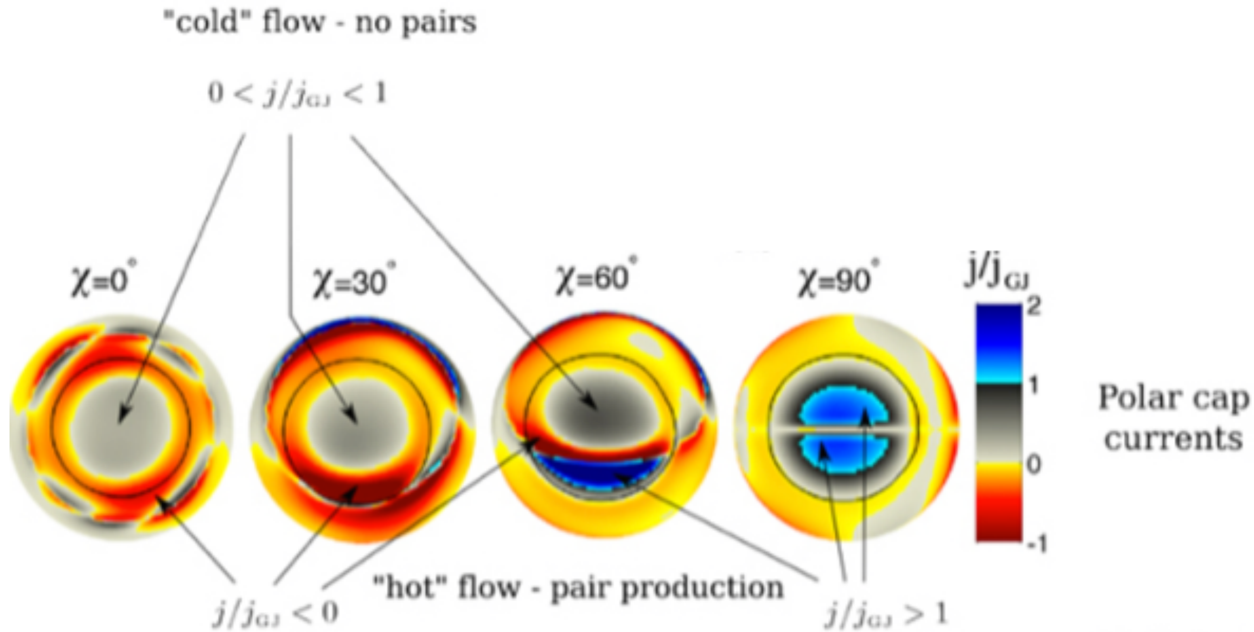




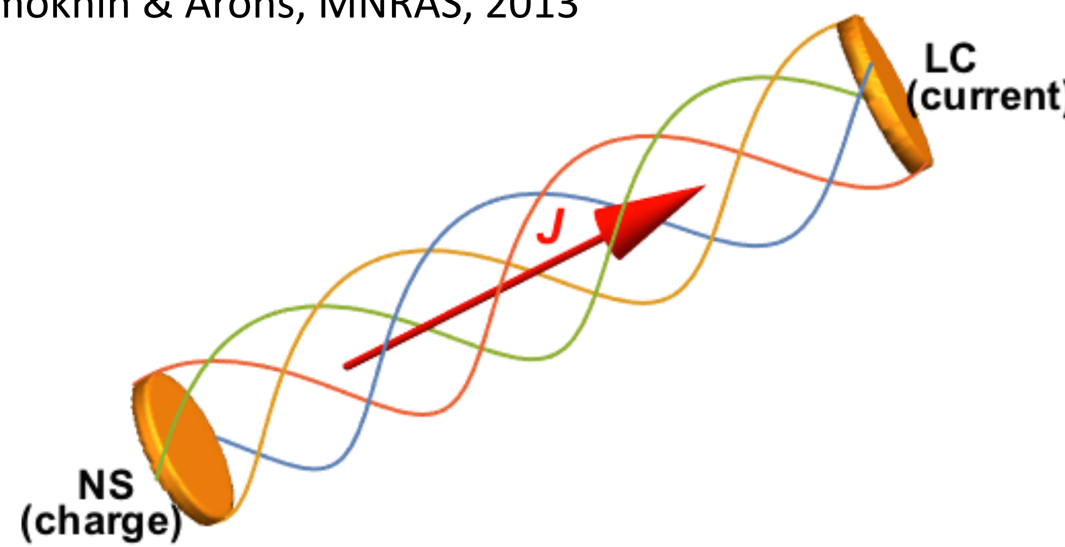
Philippov et al., ApJ, 2015

Discharge operation

- Need to sustain both charge and current density. Key quantity is $j/c\rho_{GJ}$
- If j<charge density*c, charges are advected with non-relativistic velocity
- Current is set by twist of the field lines at LC



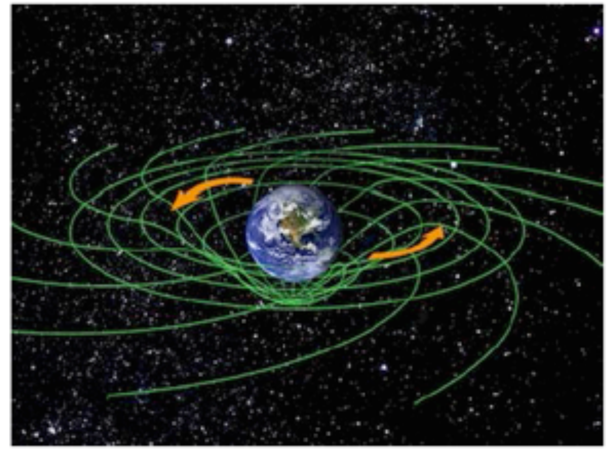
Timokhin & Arons, MNRAS, 2013

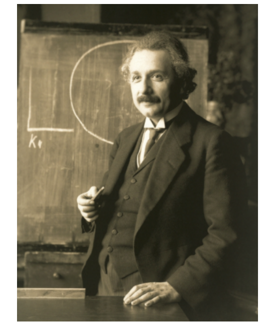


When realistic currents set by global magnetosphere are included in the simulation of polar cap discharge, we find that abundant pair production may not happen for most pulsars! Is this possible?

Prof. Einstein saves the day (1915-2015)!

Problem:
High multiplicity solutions possible only for high inclinations, but radio is observed from pulsars of all obliquities.

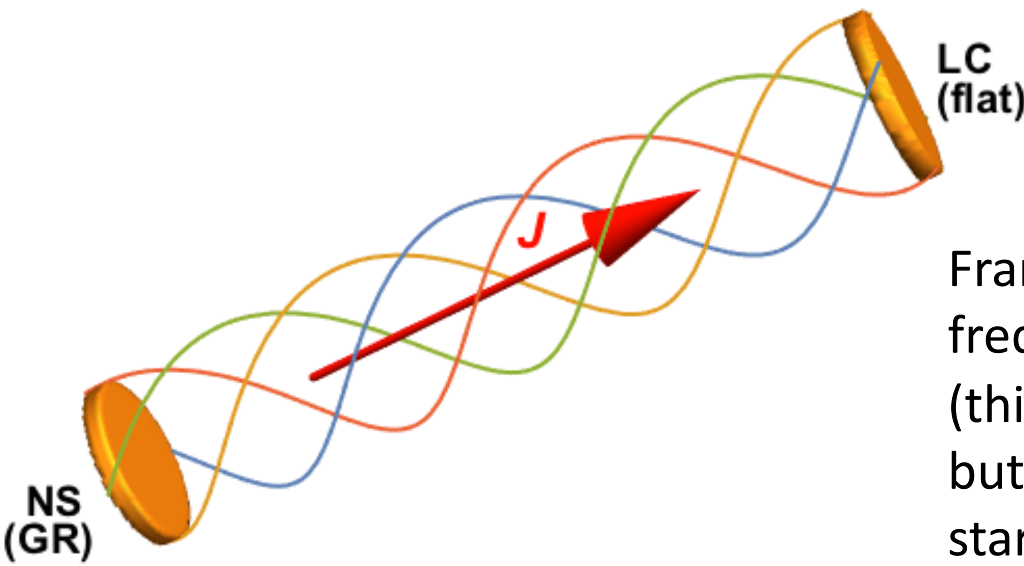




Lense-Thirring frame dragging

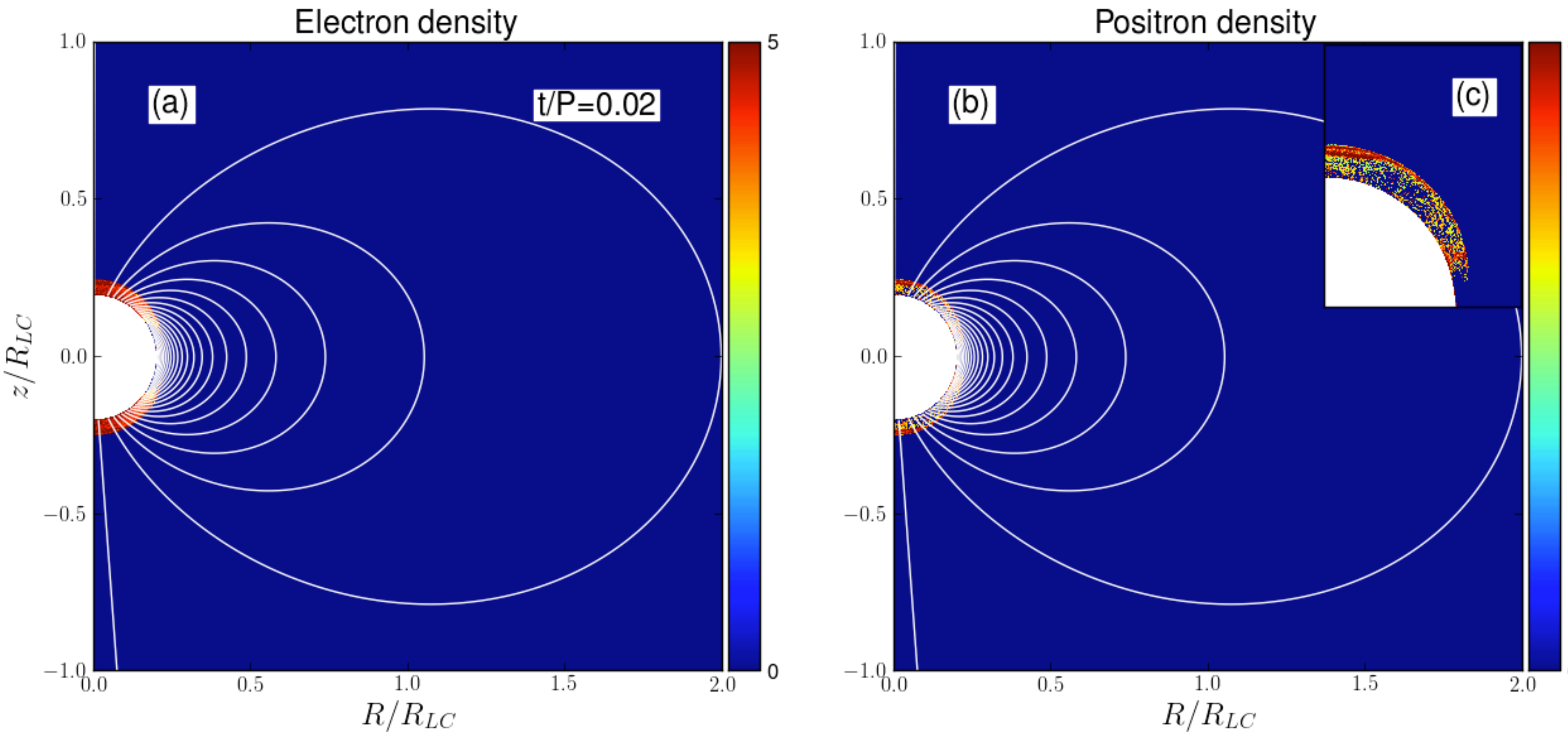
$$\omega_{LT} = \frac{2}{5}\Omega_* \frac{r_s}{R_*}$$

$$\frac{J_{\hat{r}}}{\rho_{GJ}c} \approx \left(\frac{J_{\hat{r}}}{\rho_{GJ}c}\right)_{\text{flat}} \frac{1}{1-\omega_{LT}/\Omega_*}$$

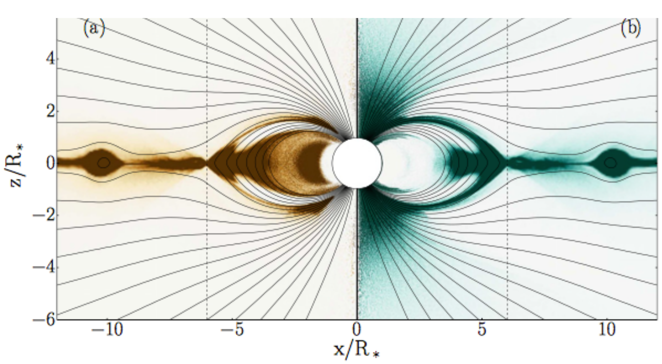


Frame-dragging makes effective rotation frequency of the star smaller close to the star (this lowers the necessary corotation charge), but the rotation is still the same far from the star (this keeps the current the same).

GR aligned rotator



Philippov et. al., 2015, arXiv:1510.01734

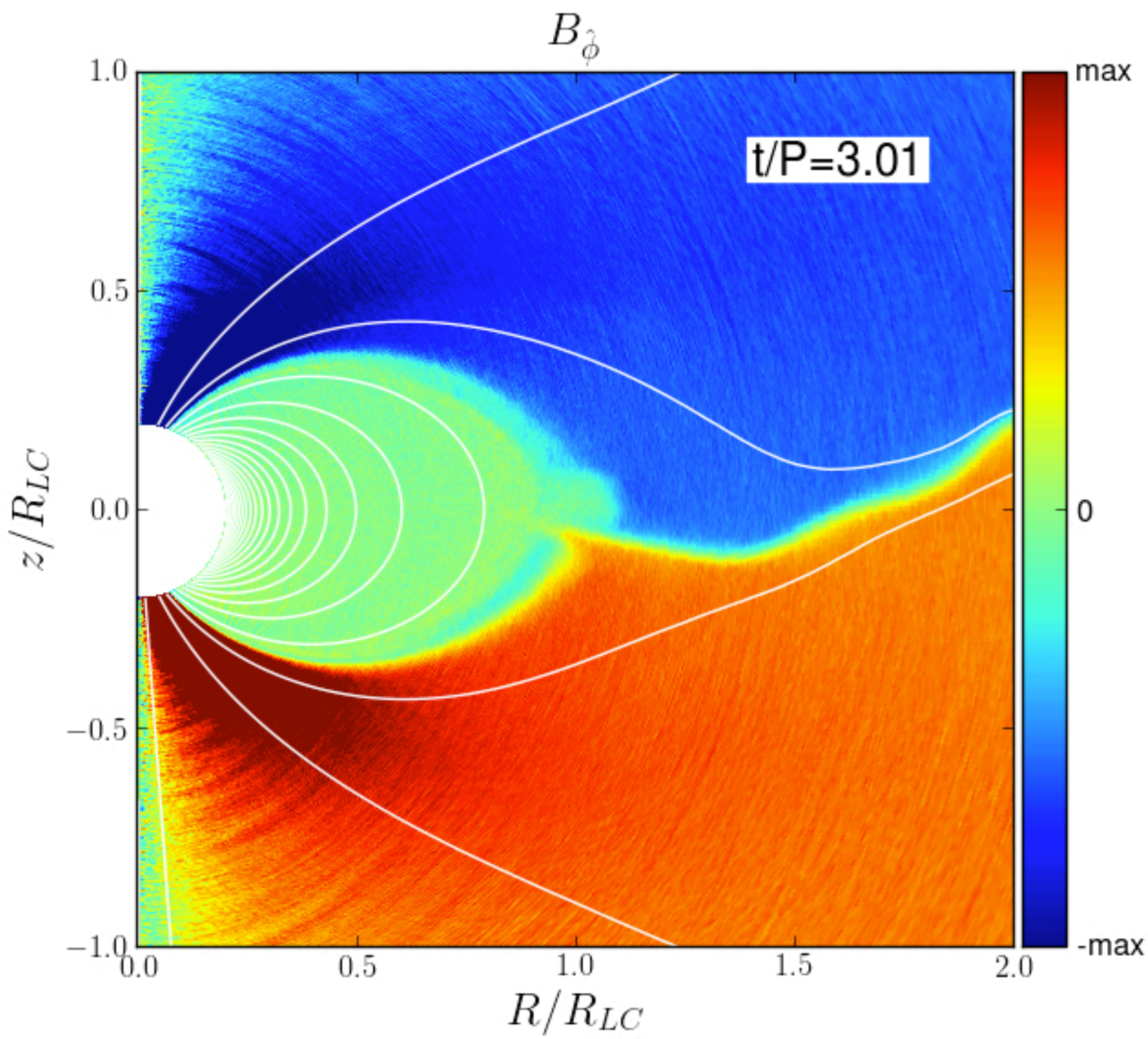


Flat space solution, no pair production

Requires compactness $r_s/R_* \gtrsim 0.5$

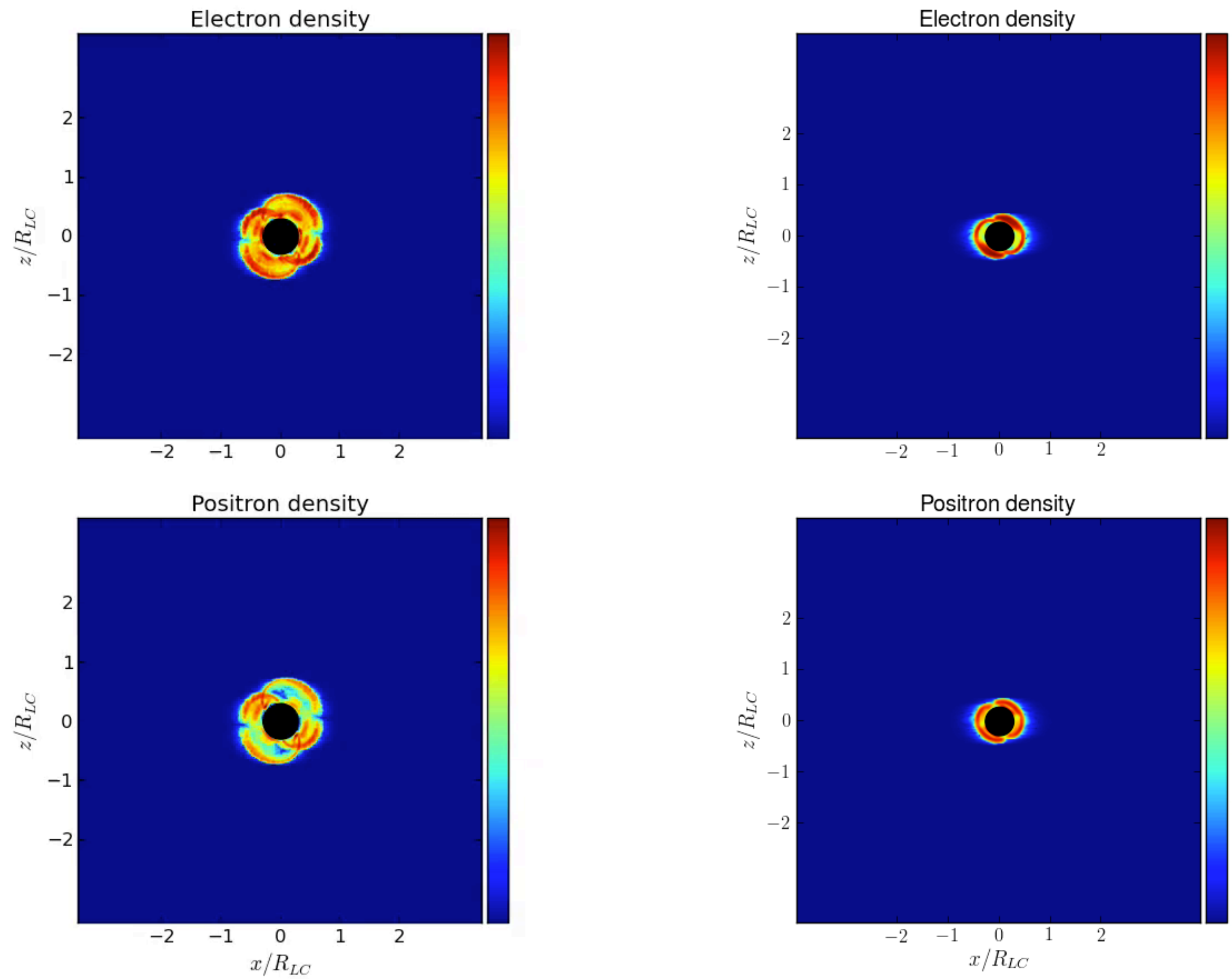
Implications for radio emission

- 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.



Philippov et. al., 2015, arXiv:1510.01734

Flat space vs GR: oblique models



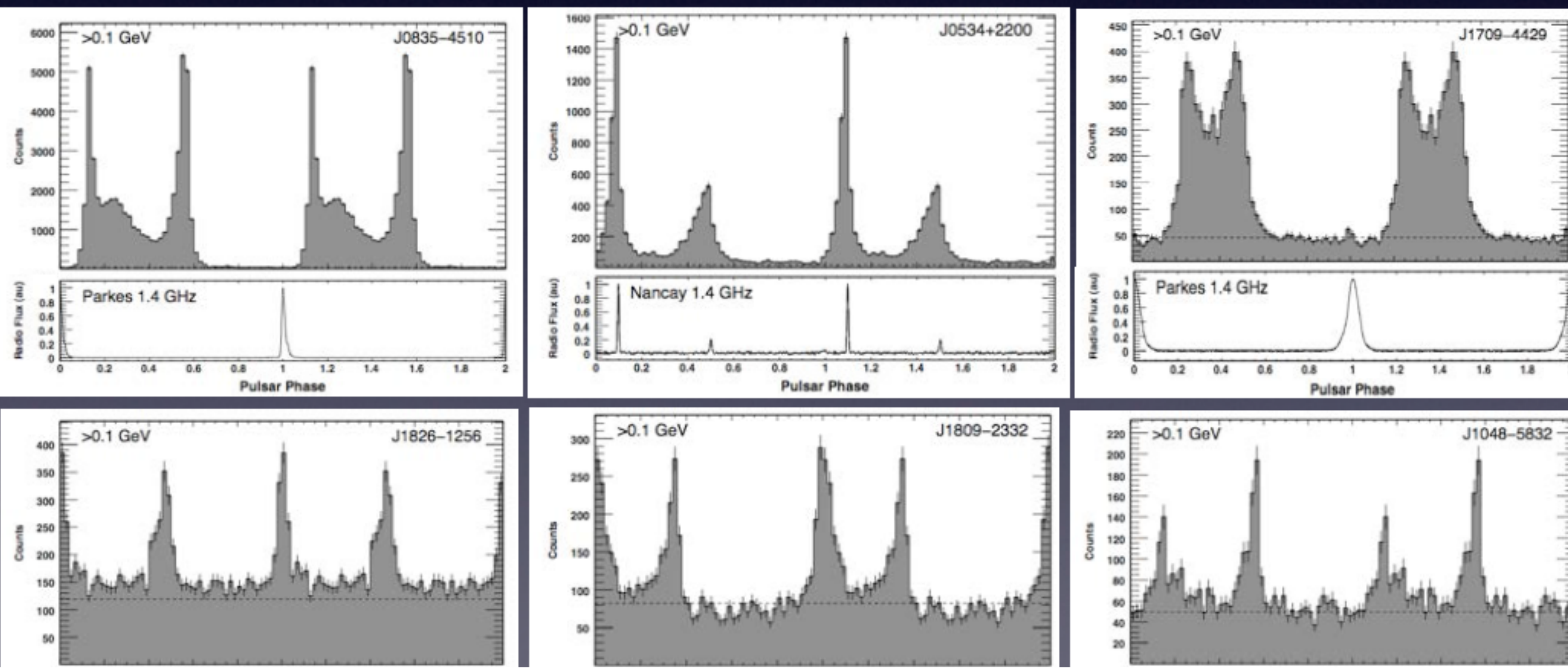
radiative cooling is also included here

Philippov et al., ApJ, 2015

Philippov et al., in preparation

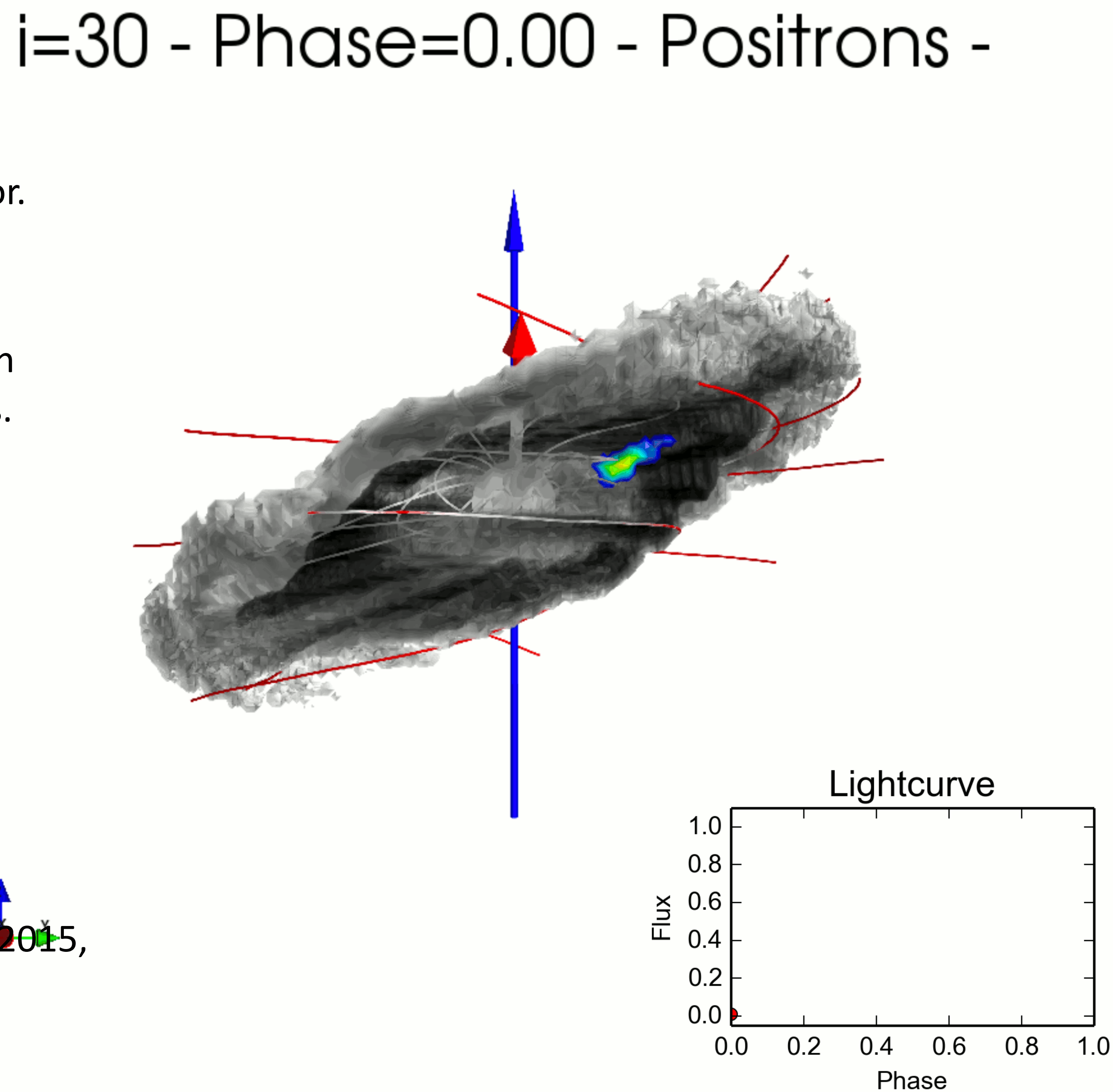
GR helps to establish polar pair cascade for inclined rotators!

Gamma-ray emission from pulsars



Gamma-ray modeling

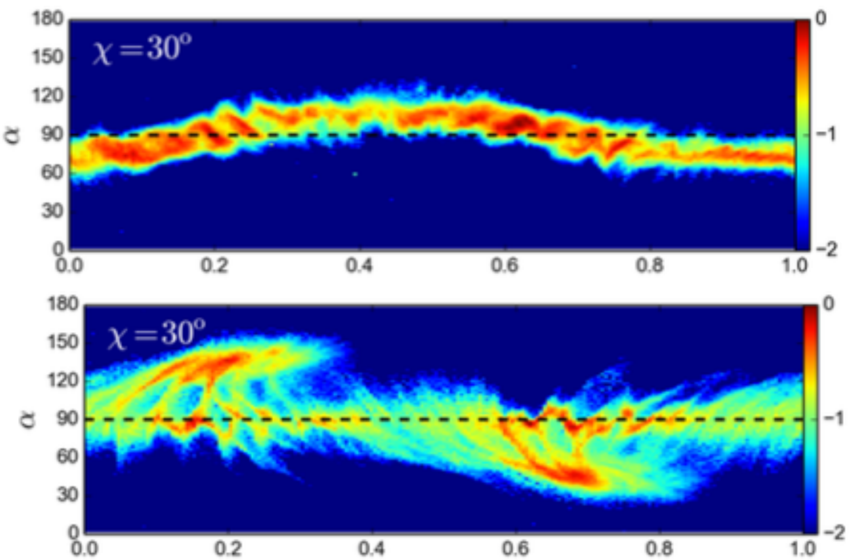
- Simulations prefer current sheet as a particle accelerator. Particles radiate synchrotron radiation.
- We apply radiative cooling on particles and collect photons.
- Observe caustic emission.
- Neutral injection at the surface.

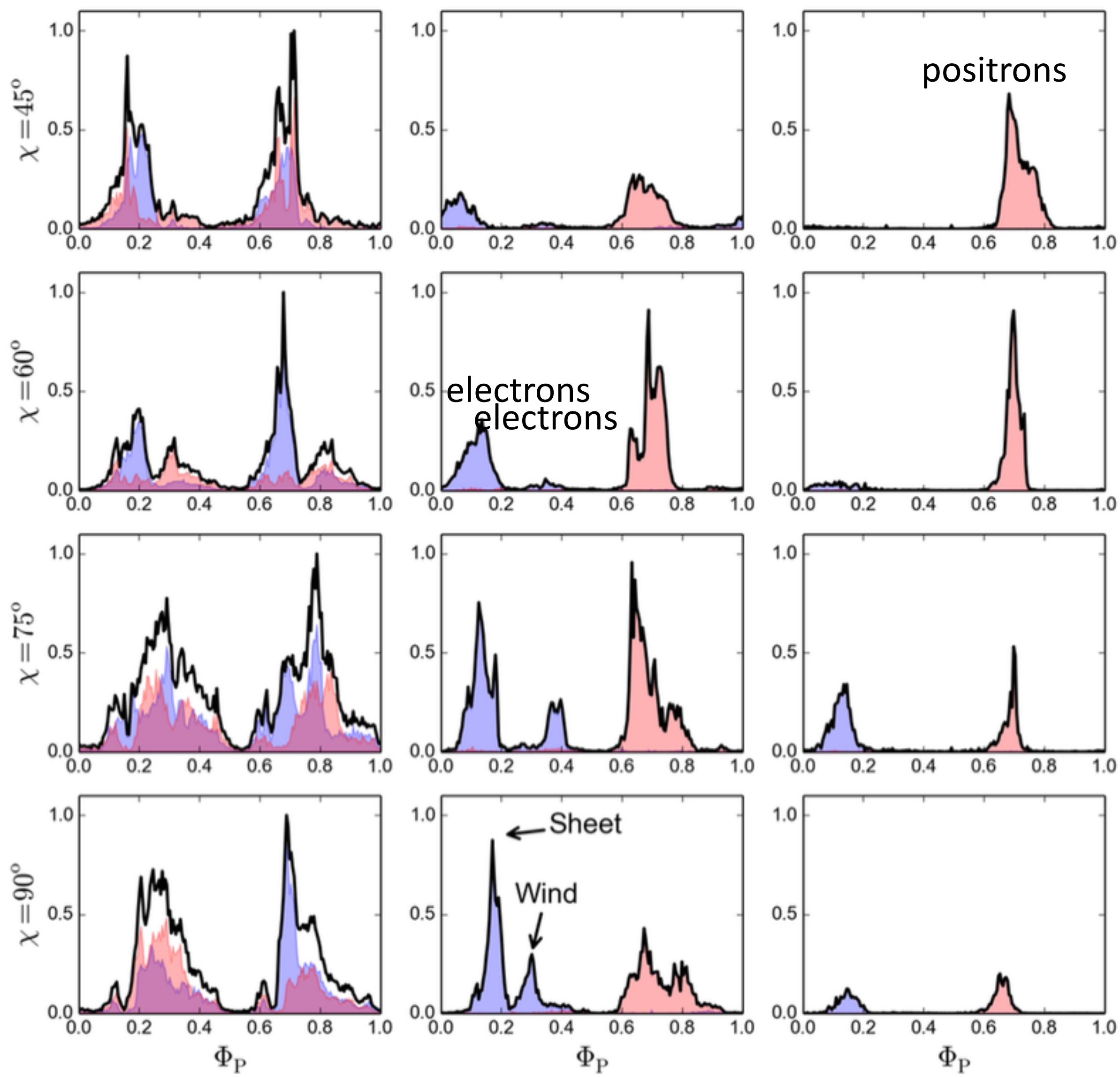


Cerutti, Philippov & Spitkovsky, 2015, arXiv:1511.01785

Lightcurves & spectra

- Caustic emission.
- Current sheet produces usually double peak lightcurves.





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Lightcurves & spectra

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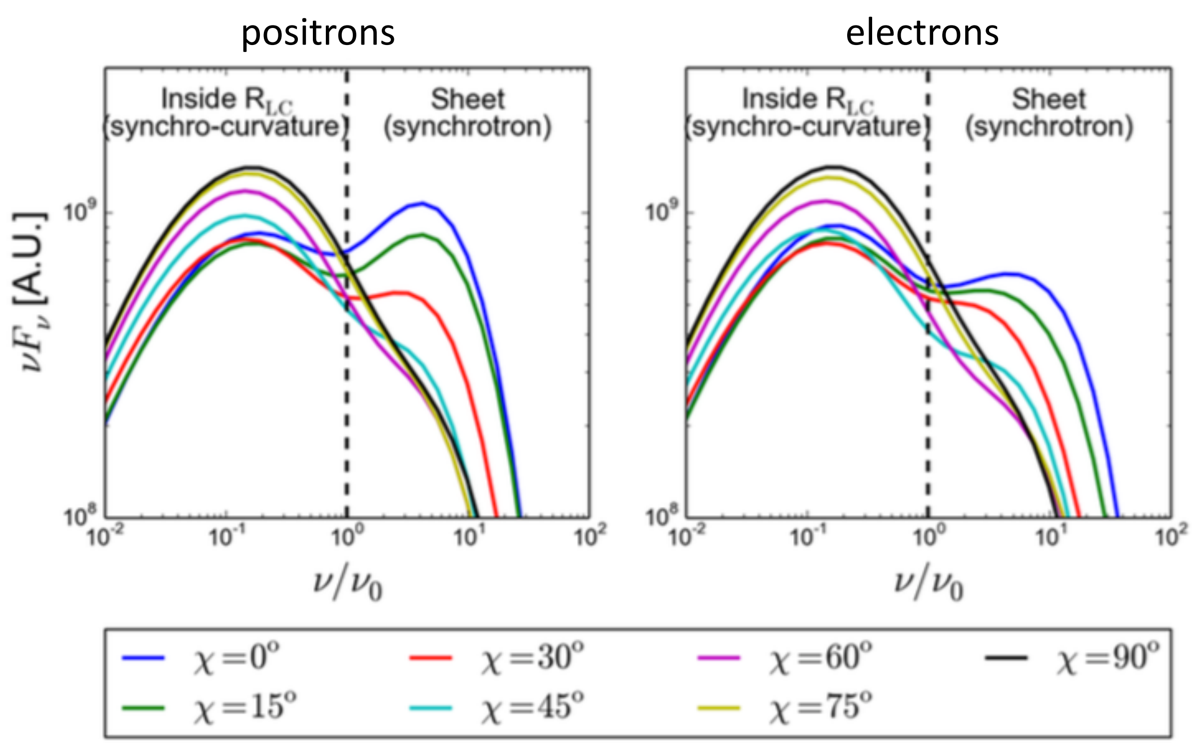
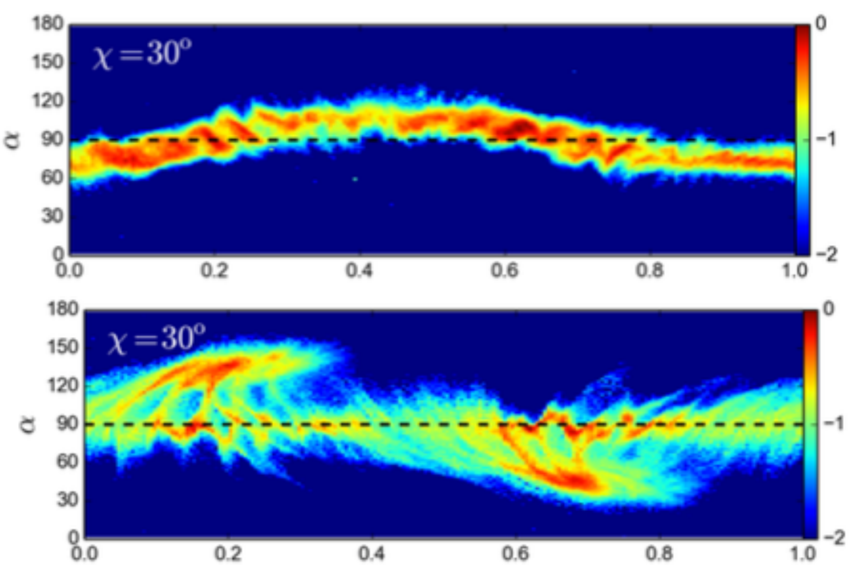
Photon spectra





$\nu_{max} \approx 3e\,(0.1B_{LC})\,\sigma_{LC}^2/4\pi m_e c$ in GeV range!

Cerutti, Philippov & Spitkovsky, 2015, arXiv:1511.01785

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 via synchrotron mechanism.
- Radio emission is caused by the non-stationary discharge at the polar cap - first signatures of this seen in global simulations!