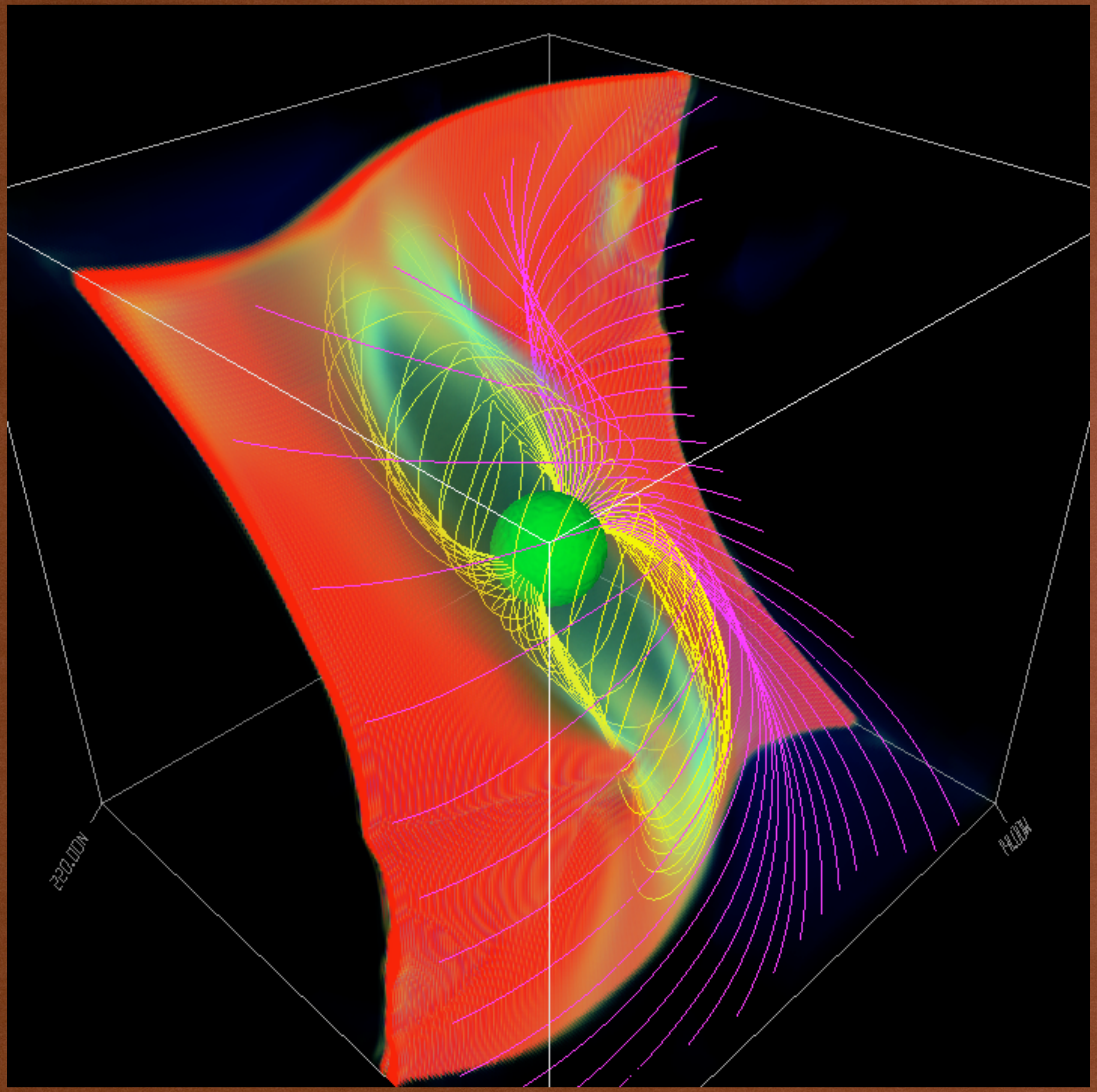
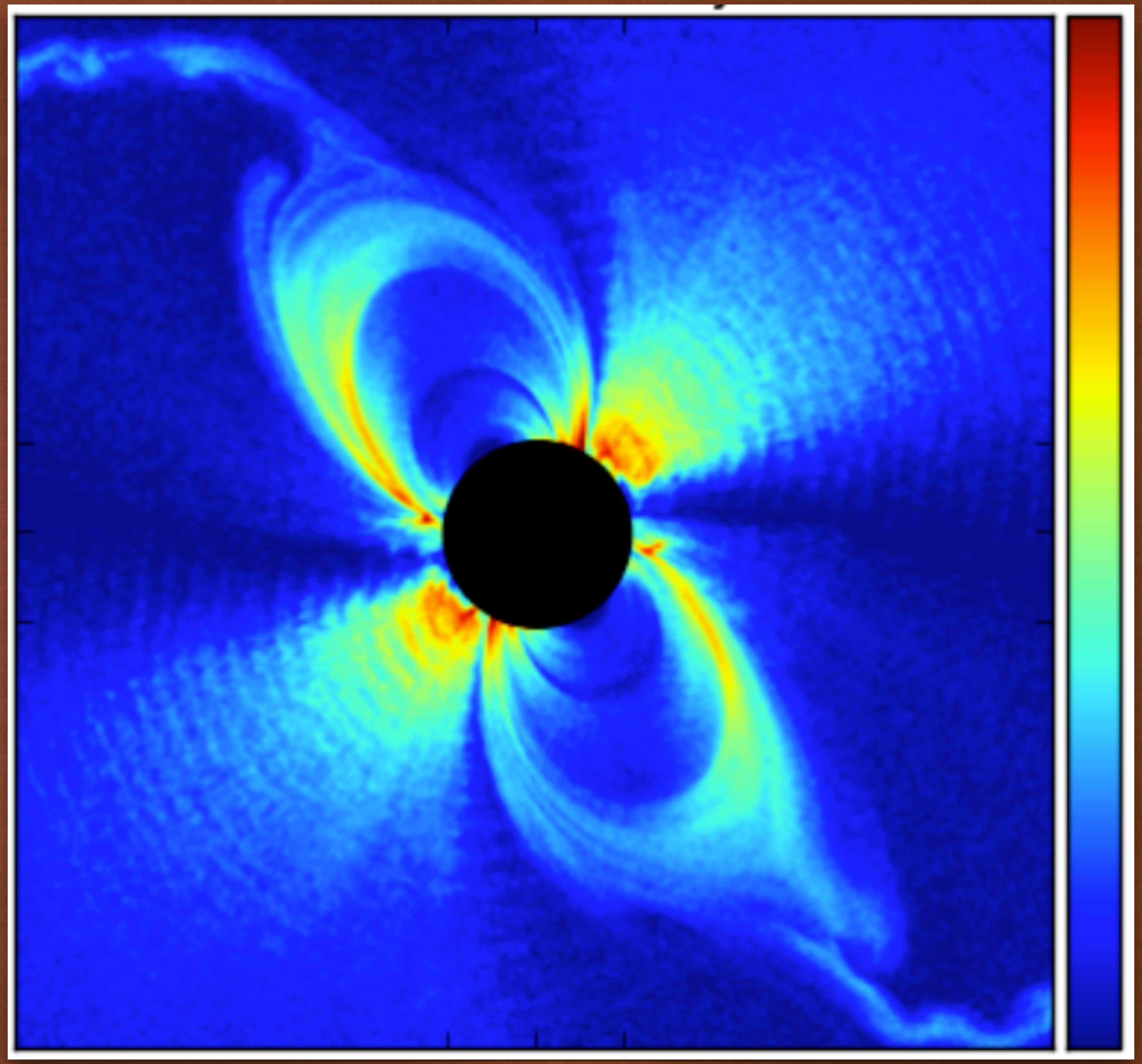
AB-INITIO SIMULATIONS OF MAGNETOSPHERIC STRUCTURE OF PULSARS AND THEIR HIGH ENERGY EMISSION

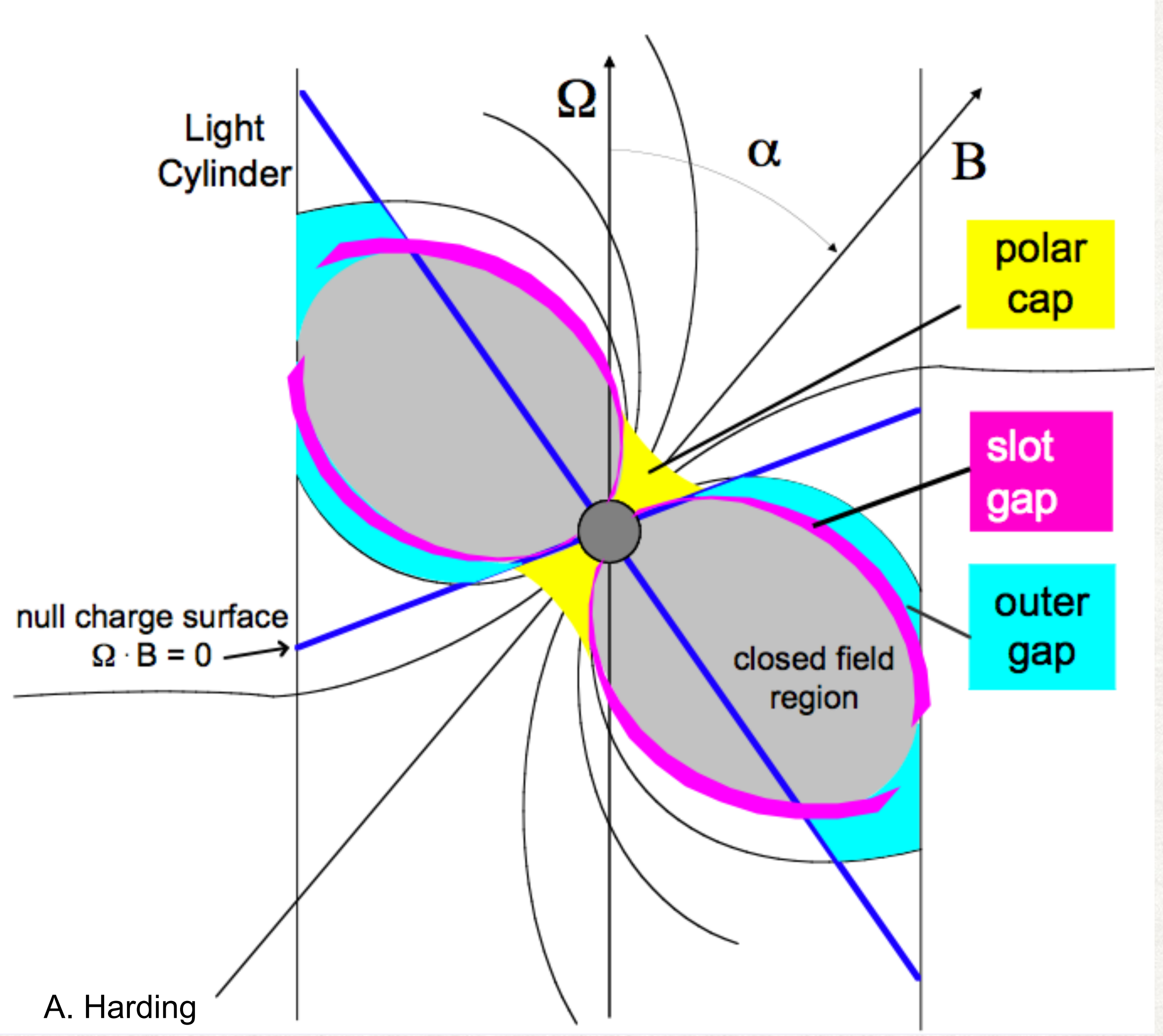


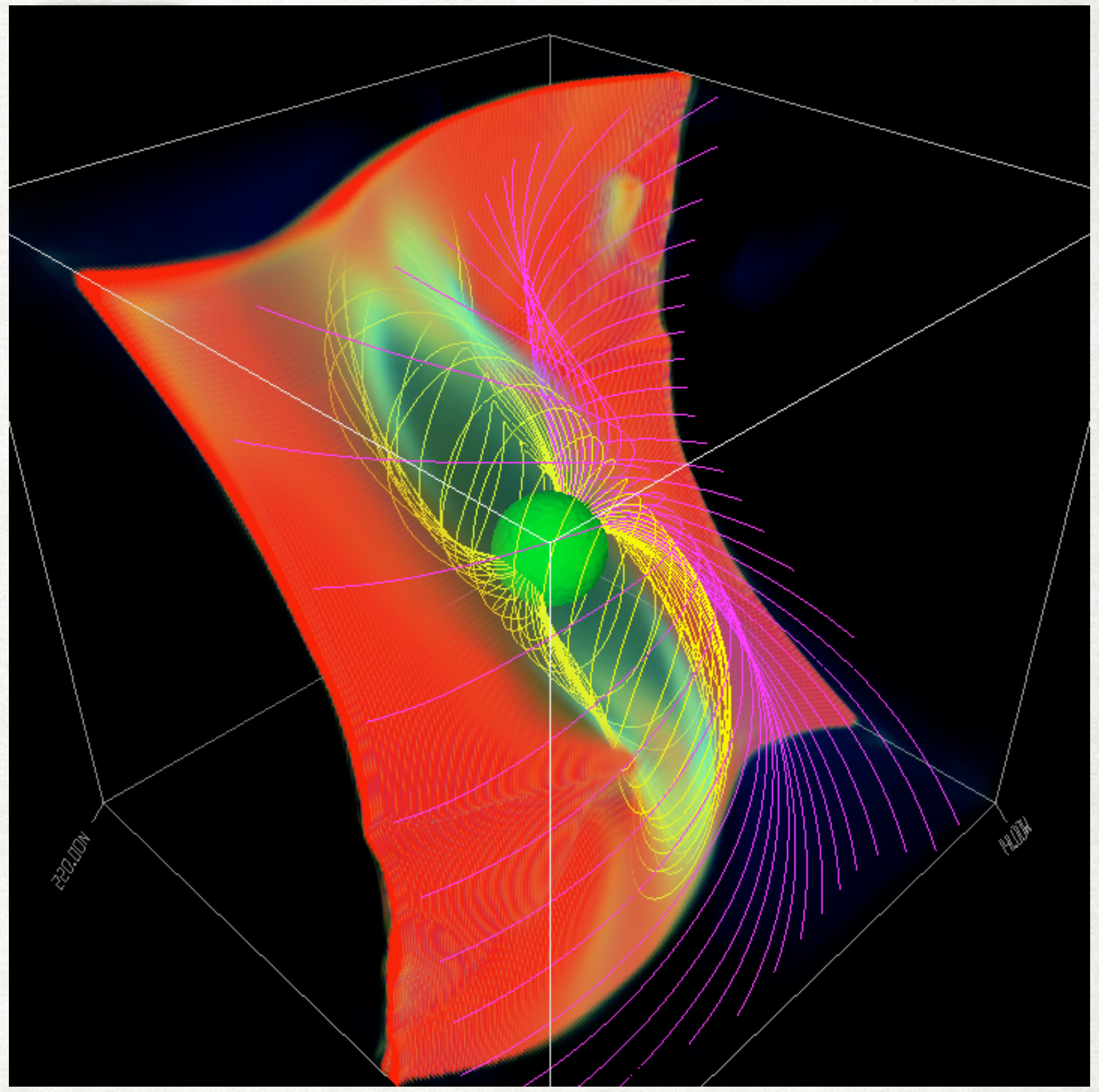


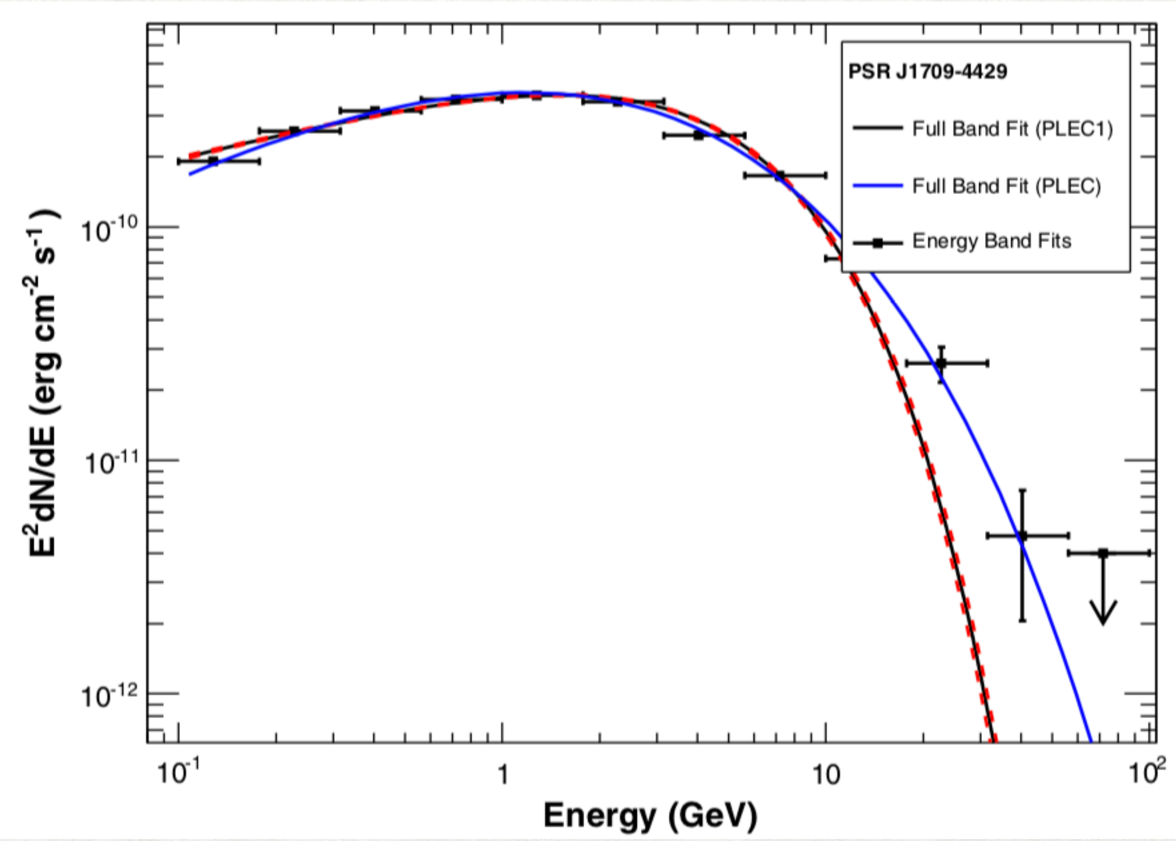
ANATOLY SPITKOVSKY, HAYK HAKOBYAN (PRINCETON)
ALEXANDER PHILIPPOV (FLATIRON INST)

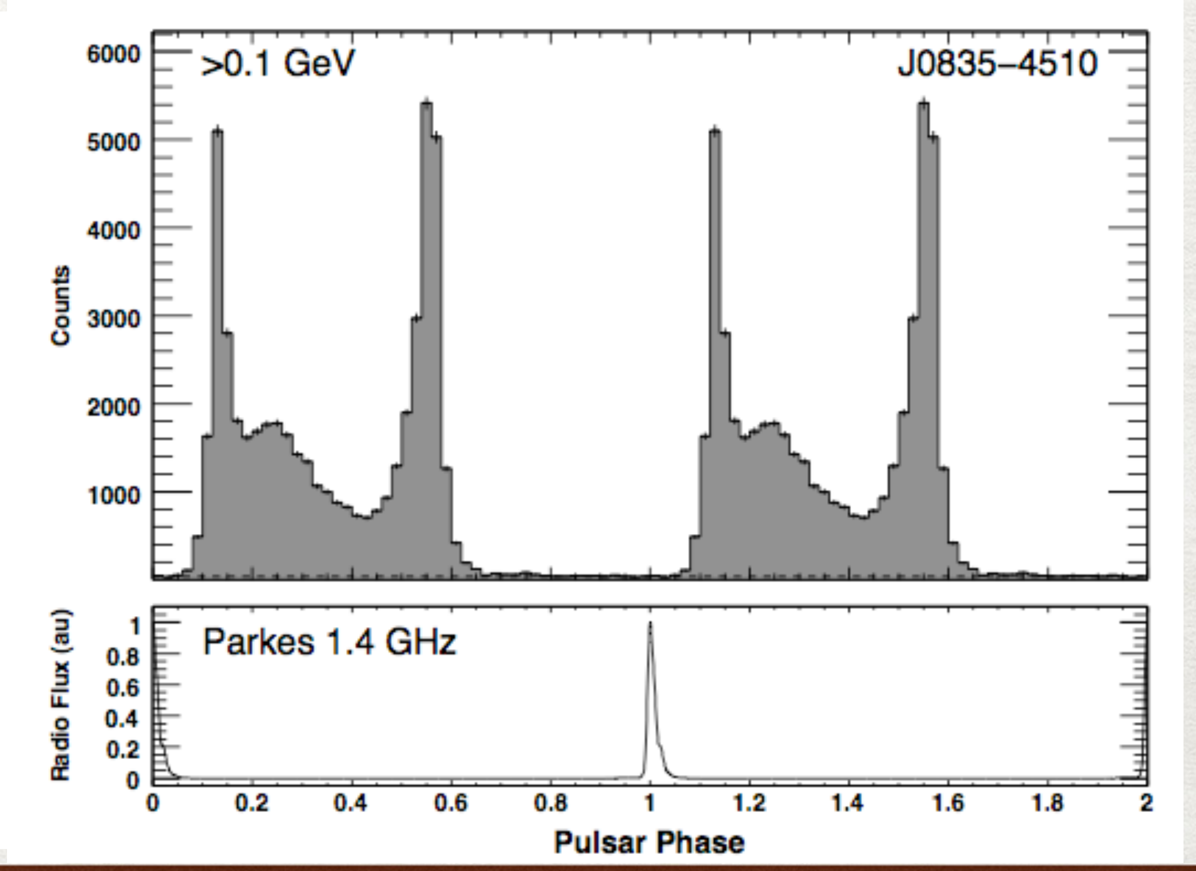
FERMI PULSARS: OPEN QUESTIONS

- Origin of gamma-ray emission: gaps, current sheets, synchrotron, curvature, IC?
- Light curves and spectra
- Luminosity-Edot relation
- Multiwavelength correlations
- What is the magnetospheric structure of pulsars, and how is the plasma supplied?



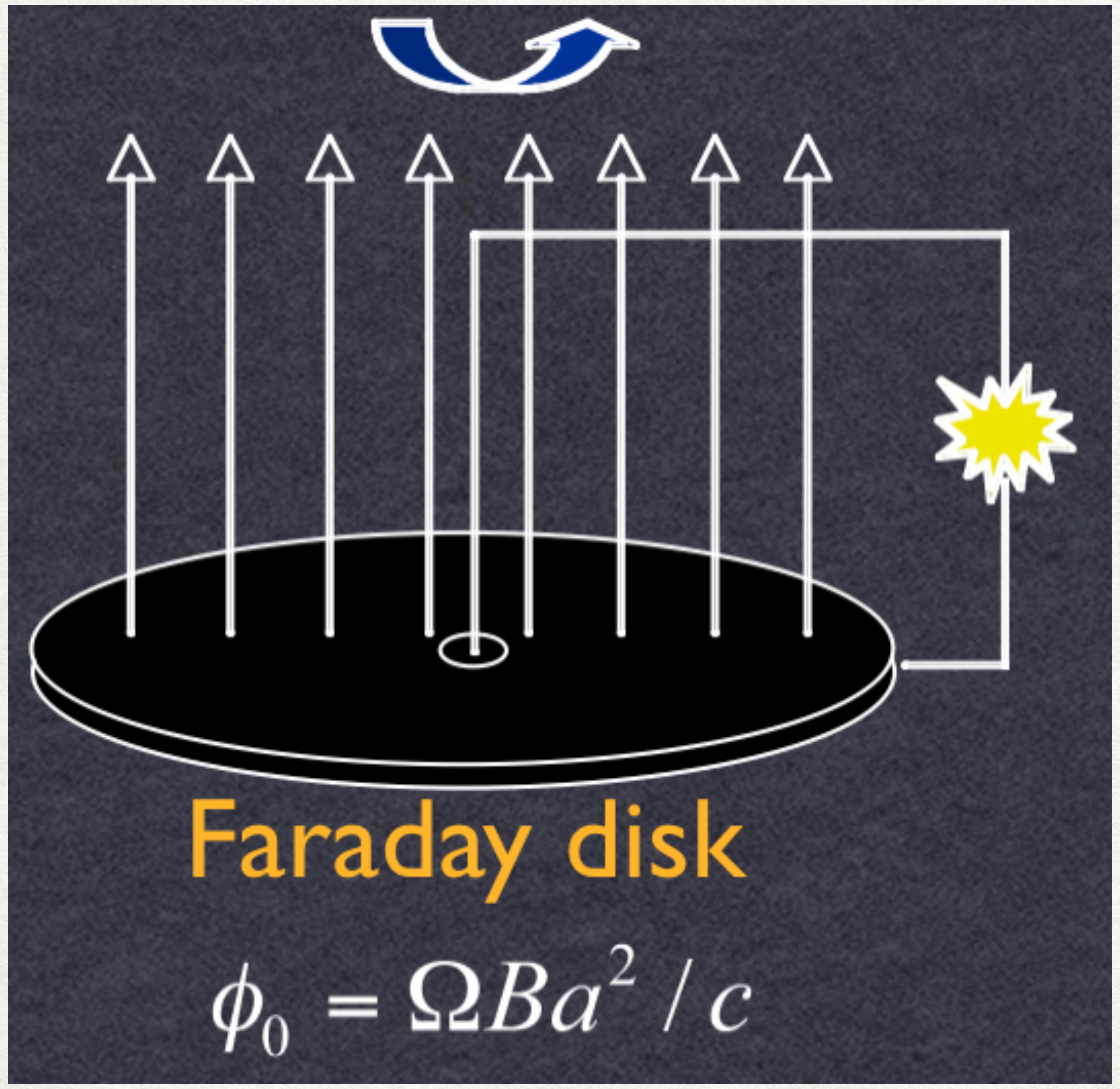




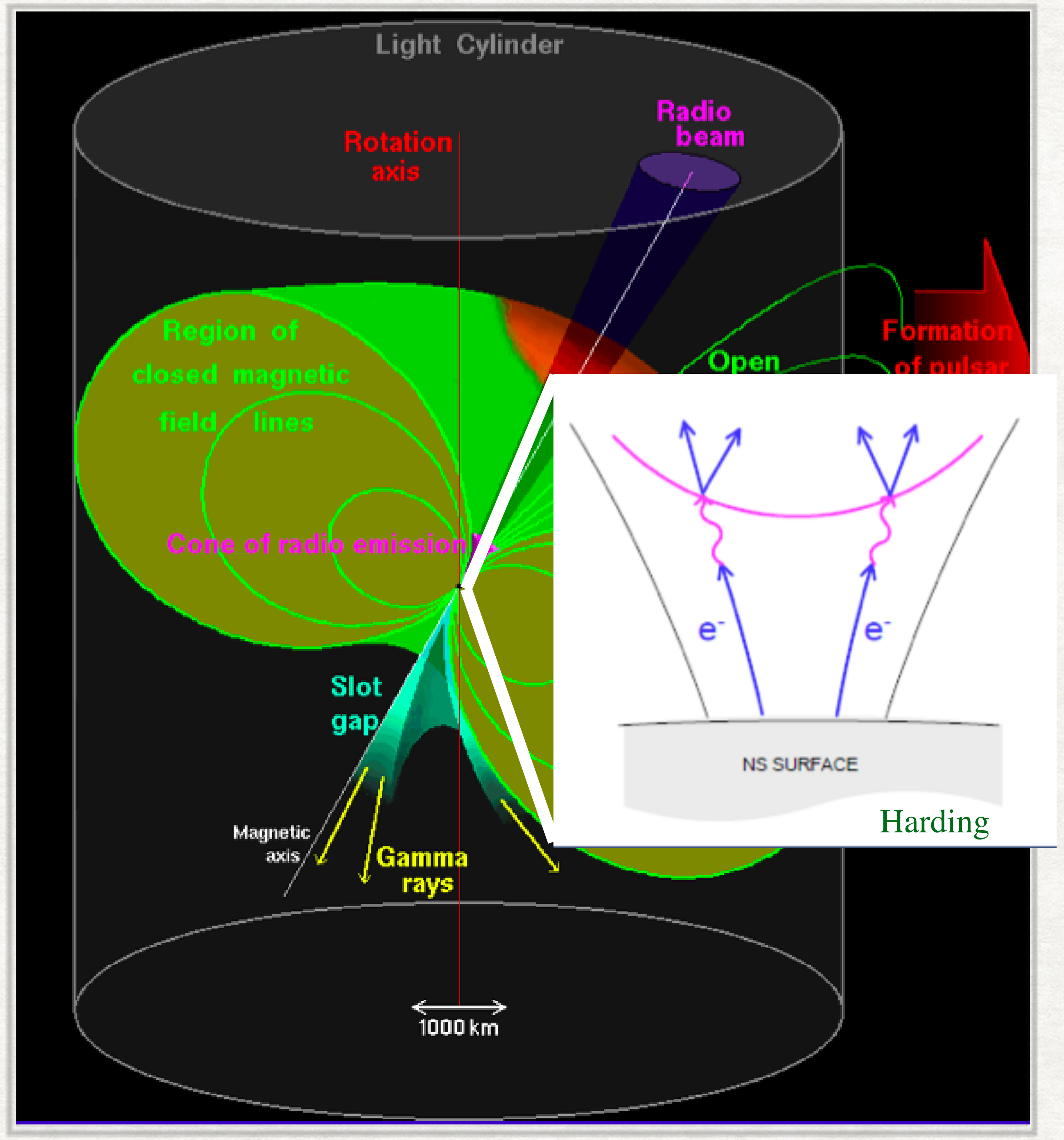


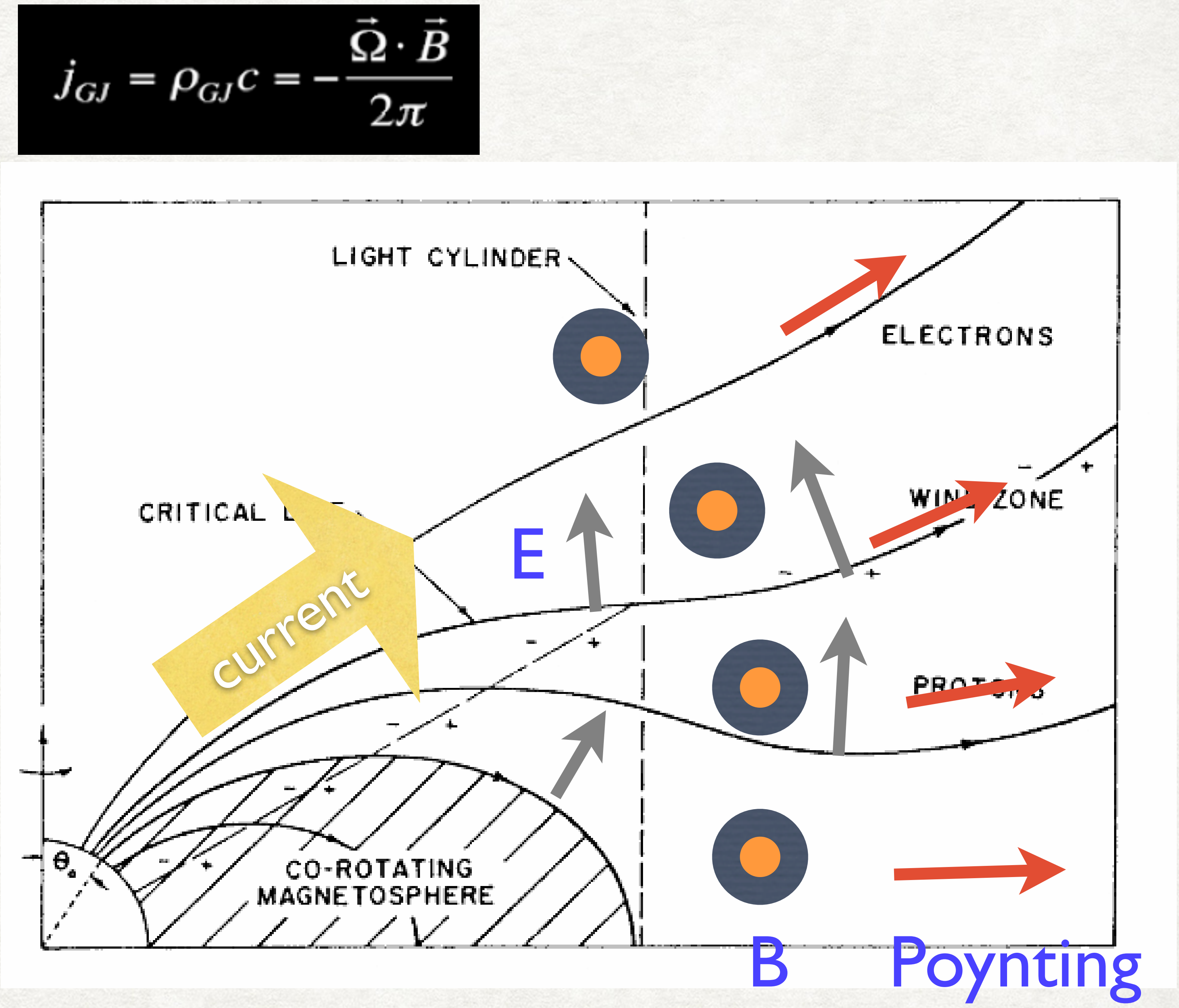
PULSAR PROBLEM: AN OLD CHESTNUT

- What is the magnetospheric structure of a rotating magnetized conducting sphere with small surface work function?



Pole-equator potential





Goldreich & Julian 1969

Current closure is essential

PULSAR PROBLEM: METHODS AND APPROXIMATIONS I

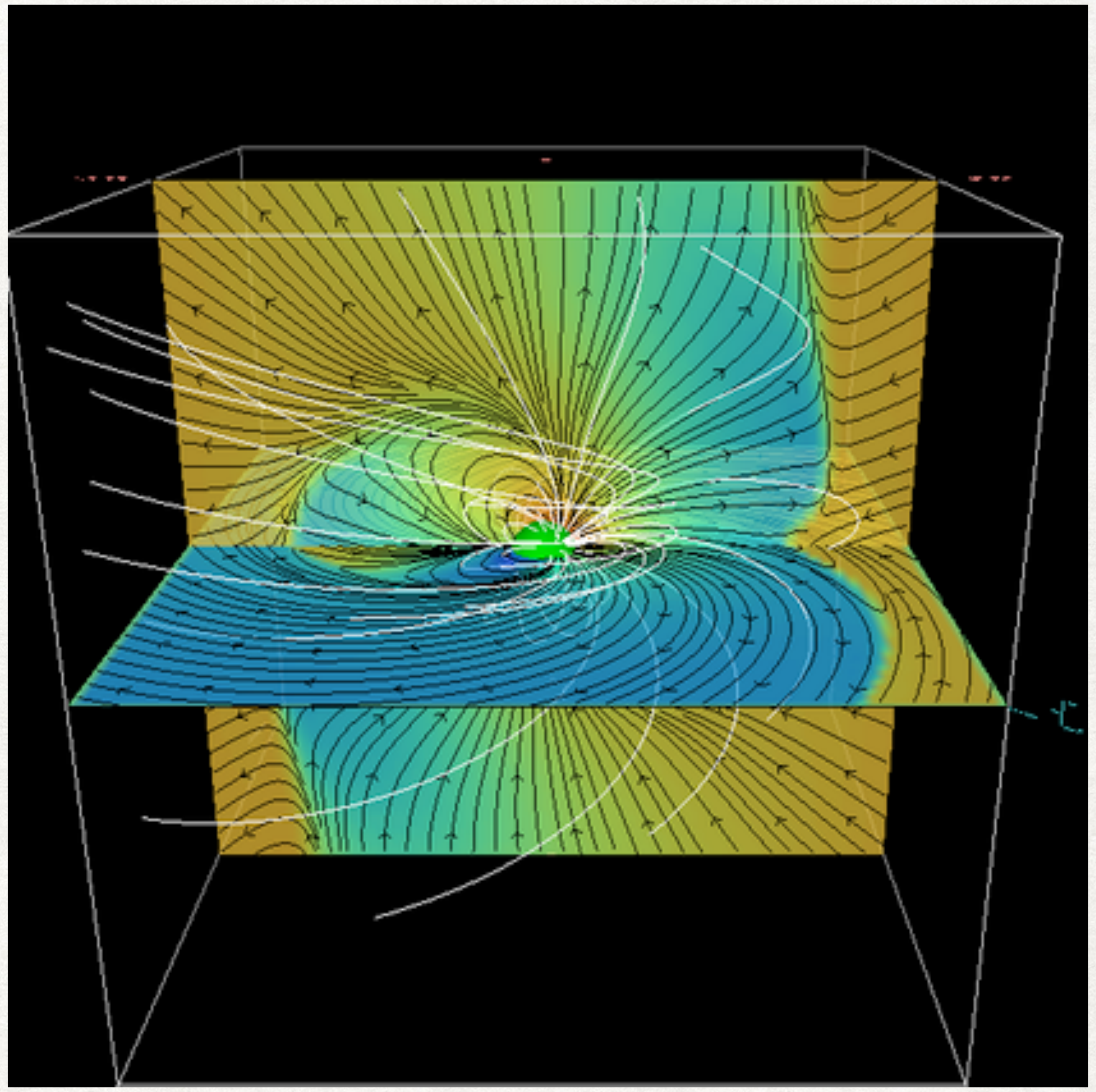
- **Force-free** paradigm. Assume plasma is abundant and light.

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

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

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

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



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

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

- All accelerating fields are shorted out

- Possible to extend to resistive limit (Li et al 2012, Kalapotharakos et al 2012-16)

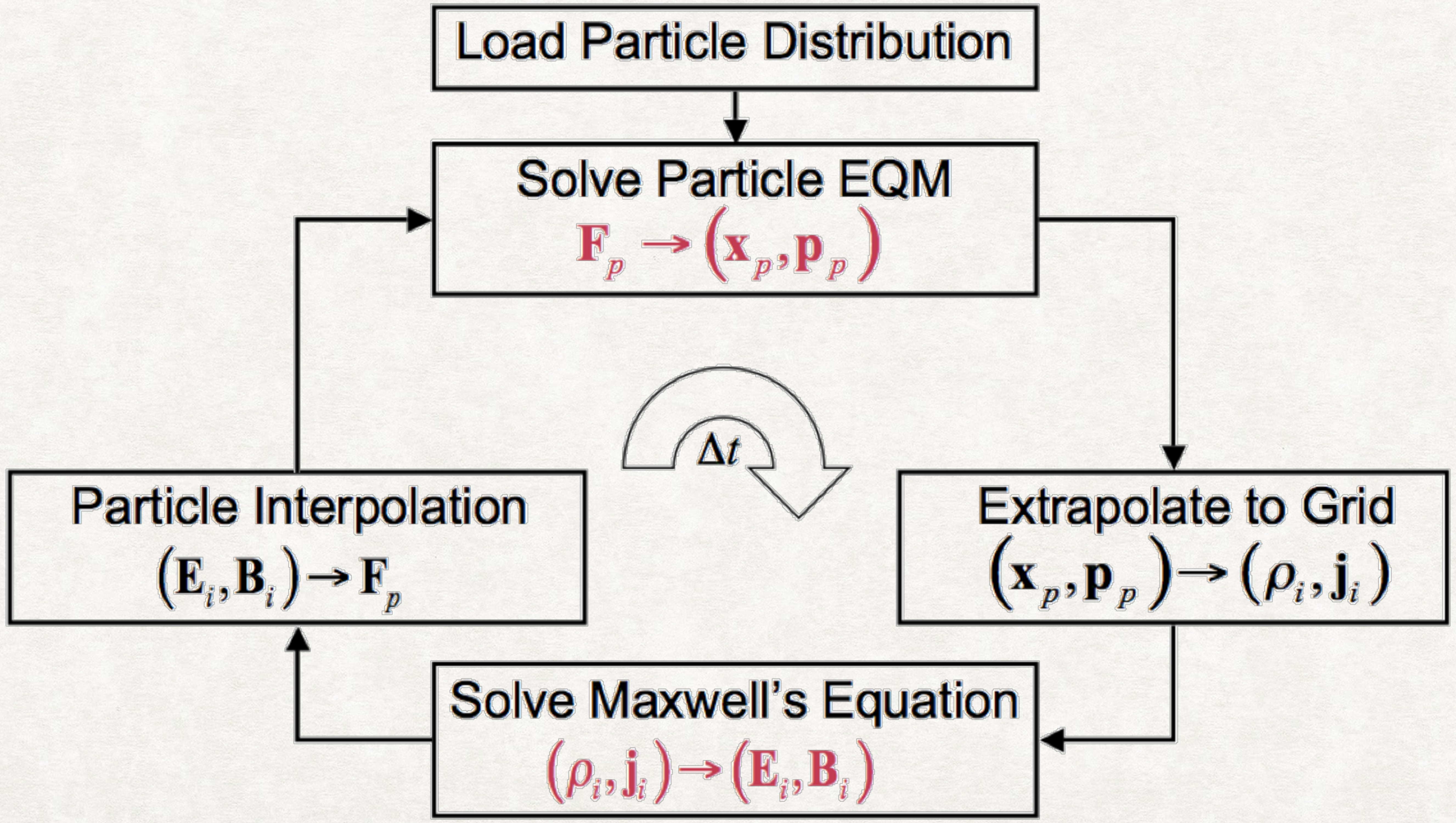
$$\dot{E} = \frac{\mu^2 \Omega^4}{c^3}(1 + \sin^2 \theta)$$

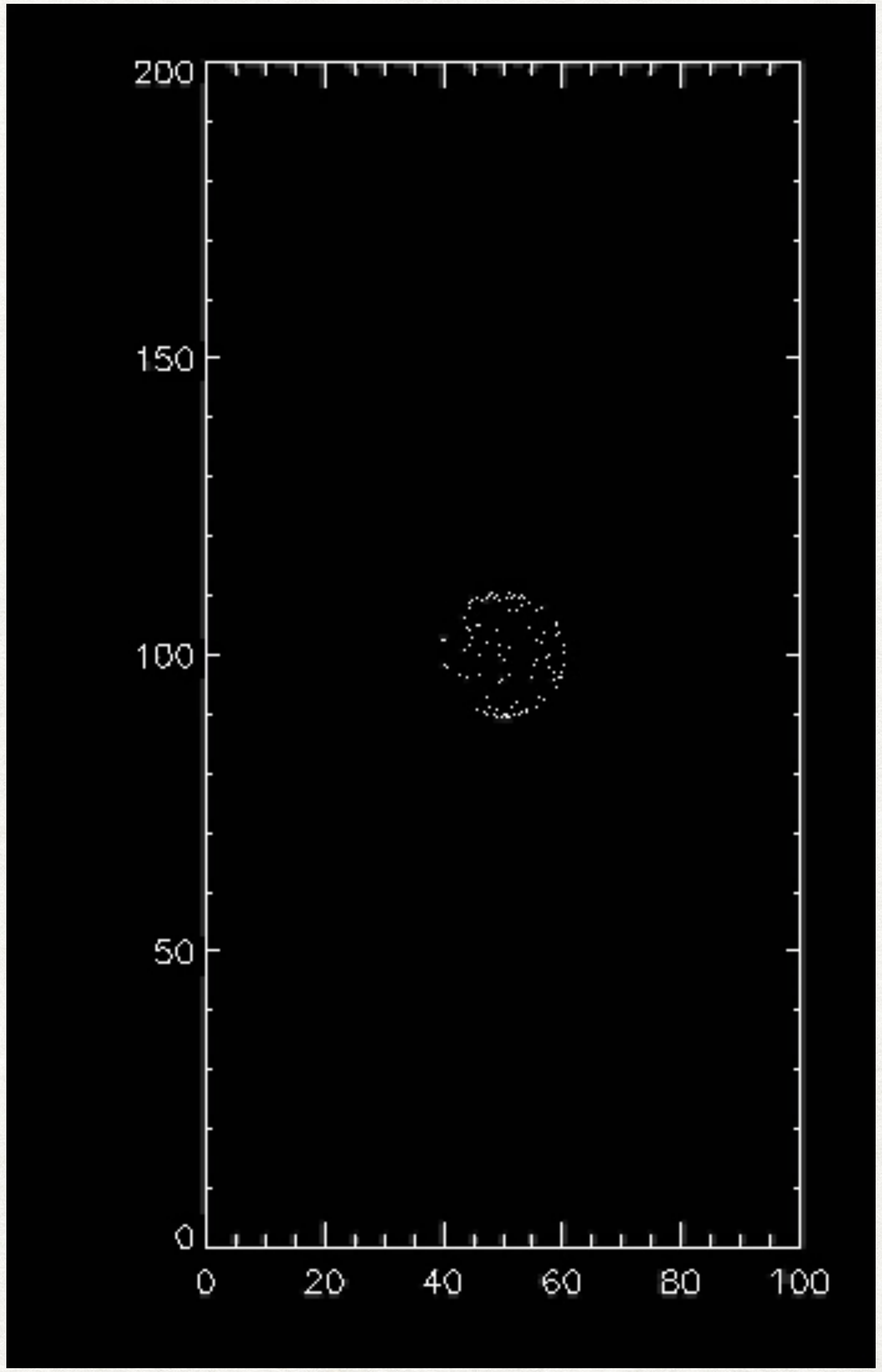
PULSAR PROBLEM: METHODS AND APPROXIMATIONS II

- Kinetic model. Use particle-in-cell (PIC) method

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

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





c.f. Krauss-Polstorff & Michel 1985, Spitkovsky & Arons 2002

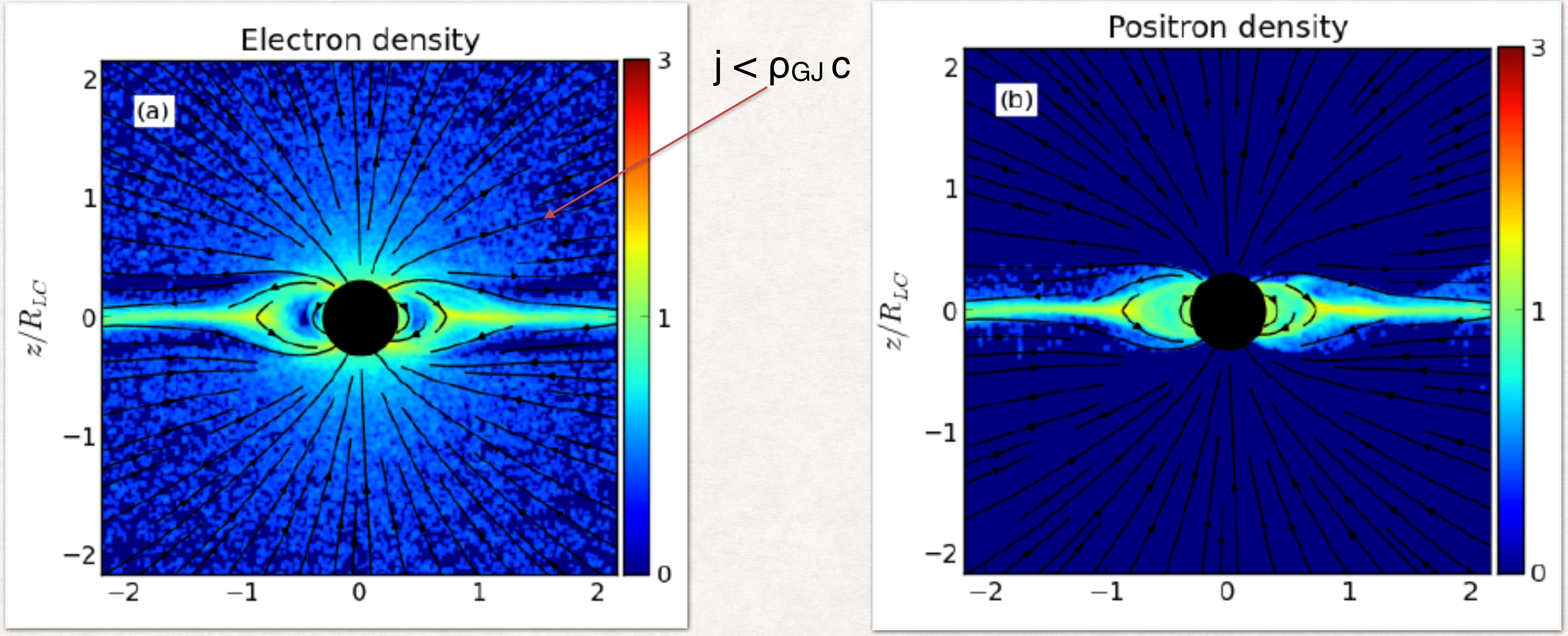
GJ charge-separated solution is dead

Other groups using PIC: Kalapotharakos et al, Chen et al, Belyaev et al

SOLUTIONS WITH PAIR PRODUCTION

- Add pair production with threshold based on particle energy in the inner magnetosphere. Outer magnetosphere: pair production in photon-photon collisions; keep track of photons

$R_*/(c/\omega_p) \approx 30-40 \gg 1$ $\quad R_{LC}/R_* = 3-5$ $\quad \Phi_{PC} = \mu\Omega^2/c^2 \approx 500 \gg \gamma_{\rm threshold} = 40$

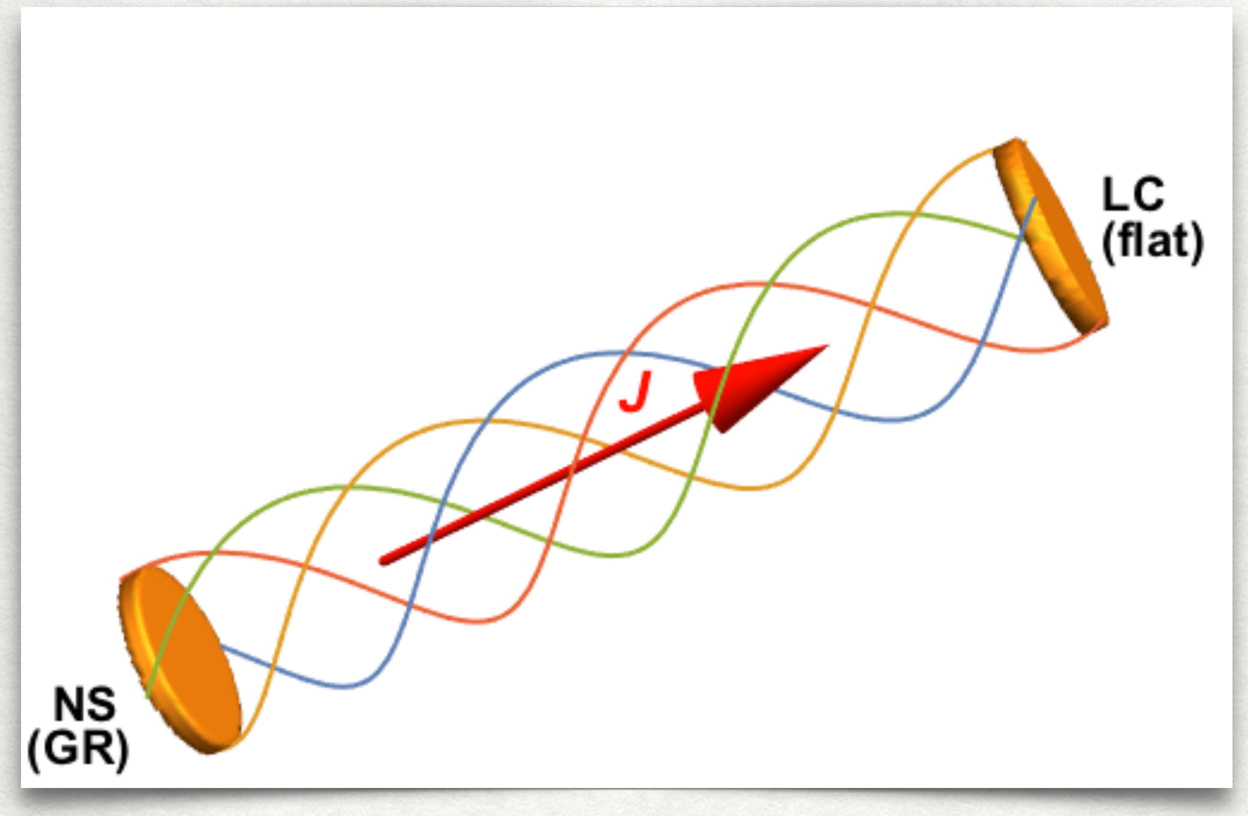


- $j < \rho_{GJ}\, c$ is satisfied by non relativistic outflow of electrons!
- Approaches force-free field solution, but no polar pair production!

Philippov et al. (2015a)
Chen, Beloborodov (2014)

SOLUTION: IT'S A *MASSIVE* ROTATING SPHERICAL CONDUCTOR!

- Add GR frame-dragging effect



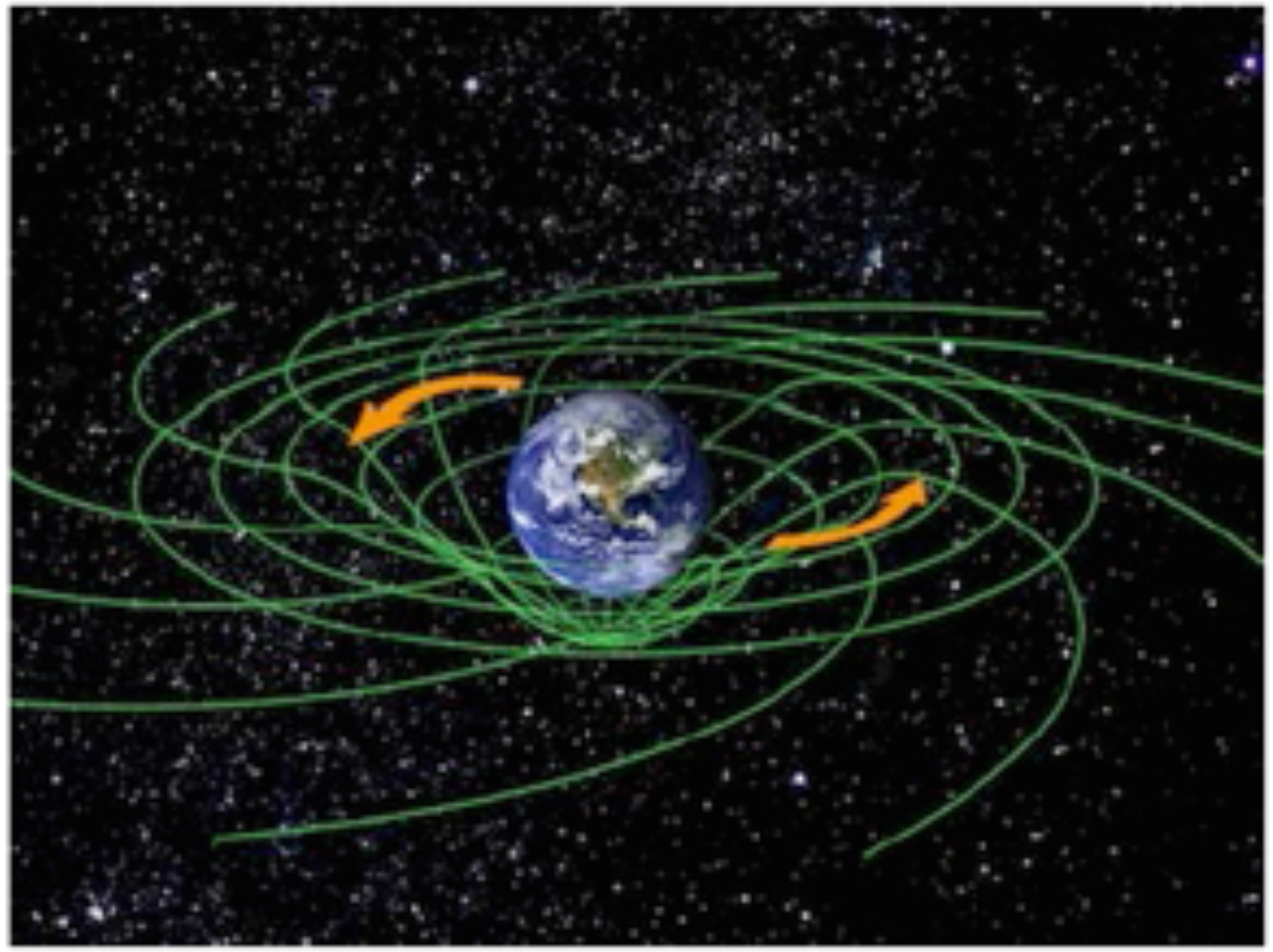
$$\omega_{LT} = \frac{2}{5}\Omega_* \frac{r_s}{R_*}$$

$$\vec{\beta} = \frac{1}{c}\vec{\omega}_{LT} \times \vec{r}$$

$$\nabla \times \left(\alpha \vec{E} + \boxed{\frac{\vec{\beta}}{c} \times \vec{B}}\right) = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t},$$

$$\nabla \times \left(\alpha \vec{B} - \frac{\vec{\beta}}{c} \times \vec{E}\right) = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \alpha \vec{j} - \rho \vec{\beta}.$$

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

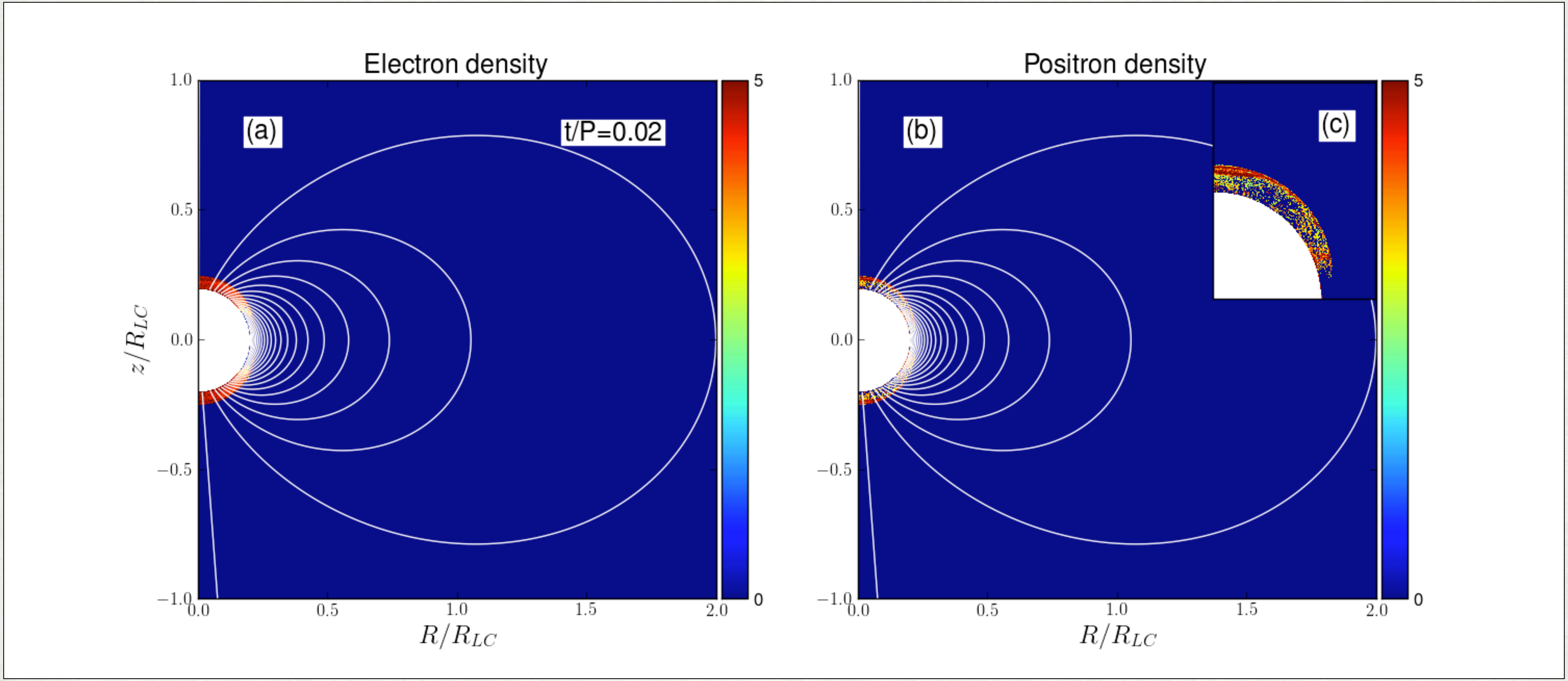


Lense-Thirring frame dragging

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).

Philippov et al. (2015b)
Beskin 1990
Muslimov & Tsygan 1992

ALIGNED ROTATOR WITH GR AND PAIRS



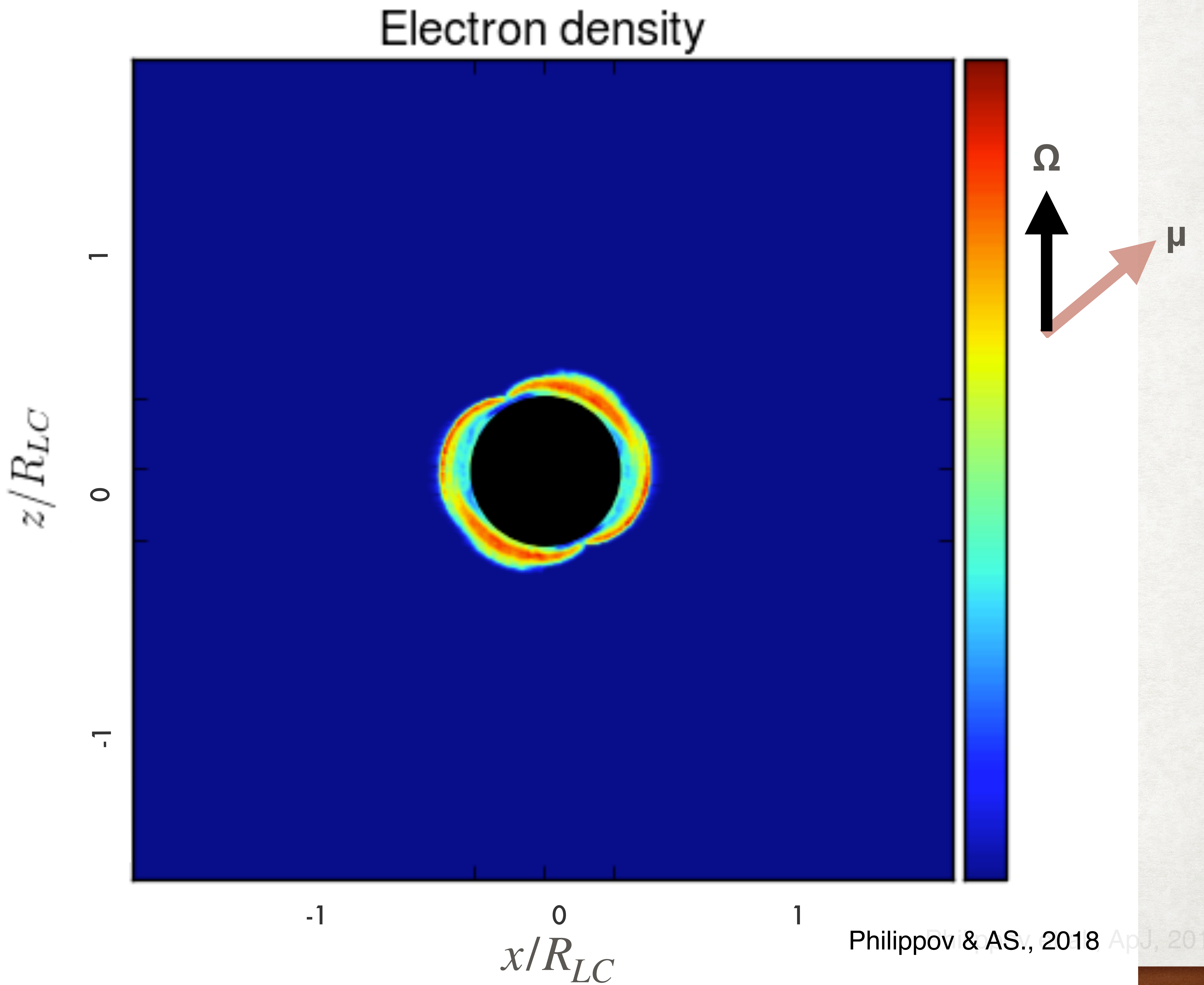
- Polar pair production returns!

Philippov et al. (2015b)

OBLIQUE ROTATOR WITH GR AND PAIRS

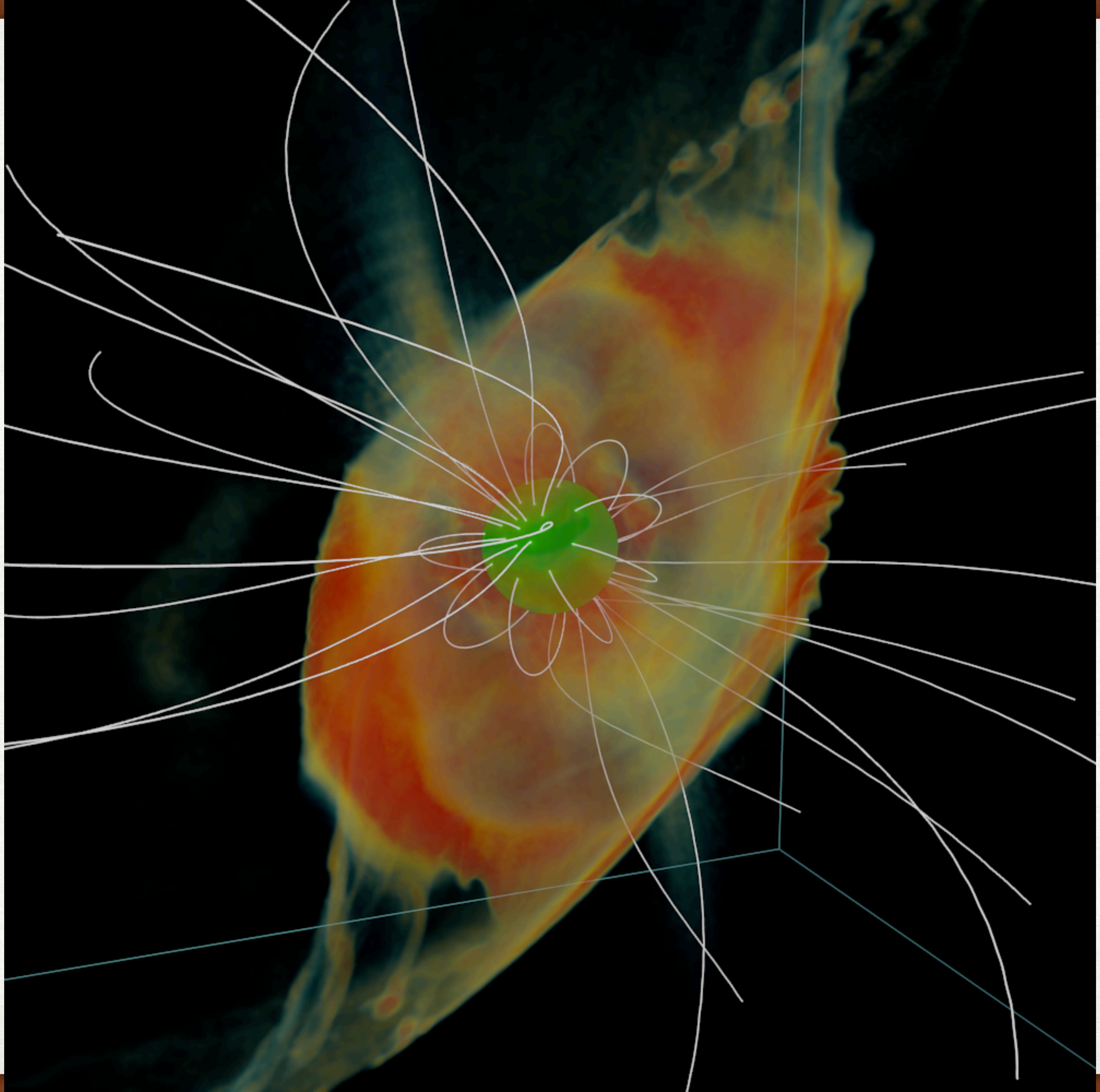
- Pair production happens on the polar cap, in return current layers and in the current sheet beyond LC

- Polar discharge is non-stationary. Electric field screening by advecting plasma clouds generates waves. The plasma motions are collective and coherent — implications for radio emission (see Beloborodov 2008, Timokhin & Arons 2013)



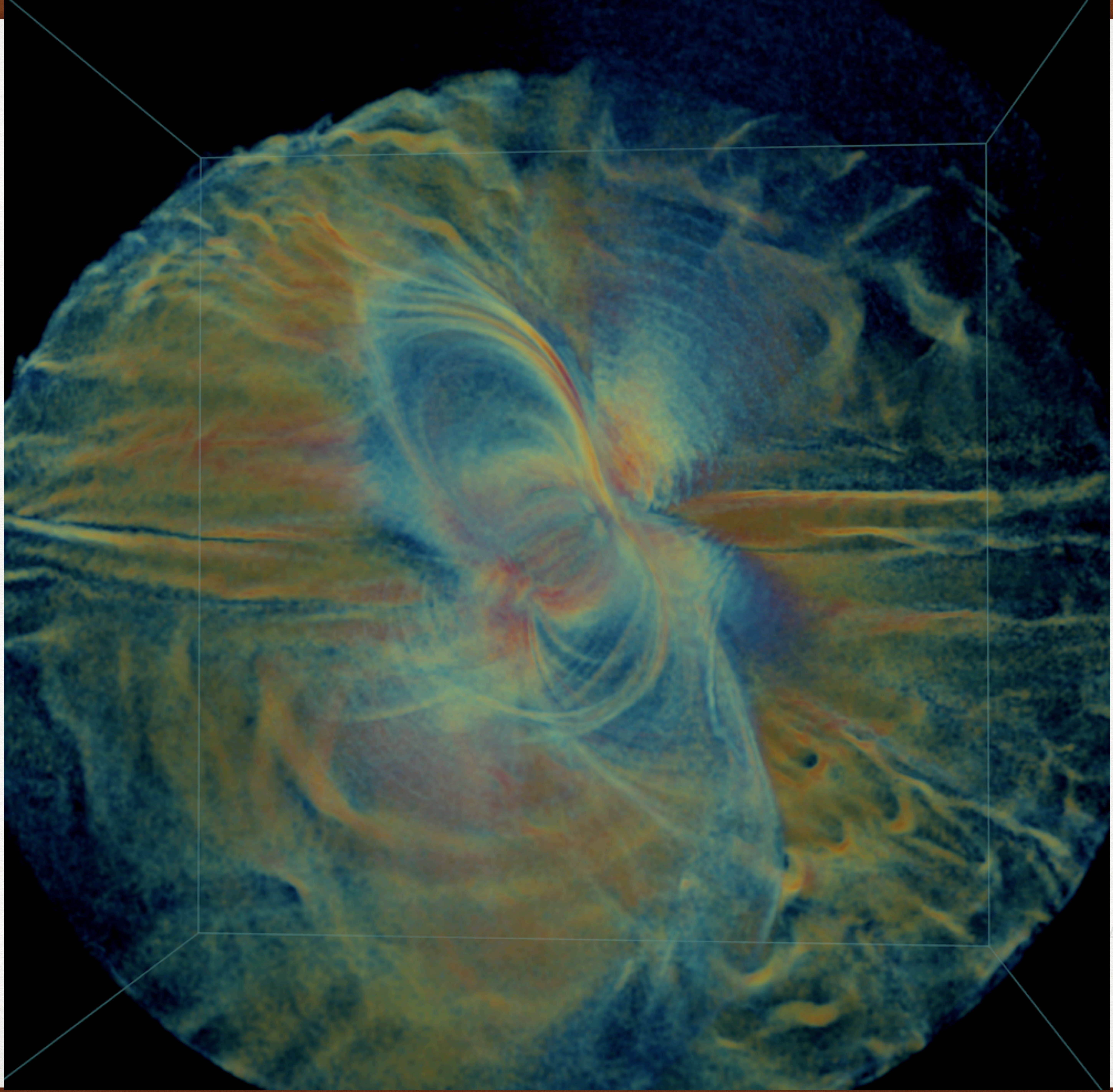
Philippov & AS., 2018

OBLIQUE ROTATOR WITH GR AND PAIRS: PLASMA DENSITY



ApJ, 2016

OBLIQUE ROTATOR WITH GR AND PAIRS: CURRENT DENSITY

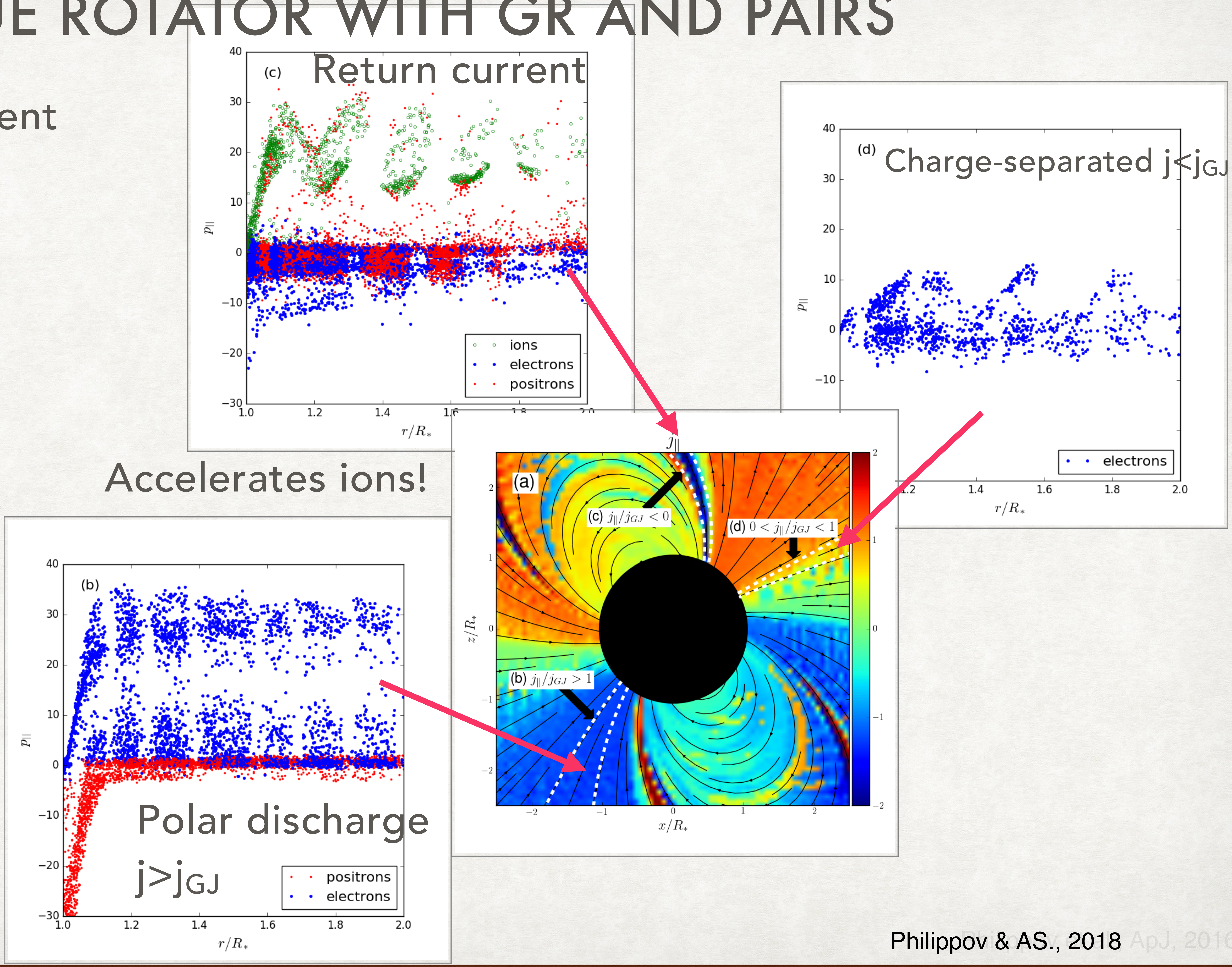


ApJ, 2016

OBLIQUE ROTATOR WITH GR AND PAIRS

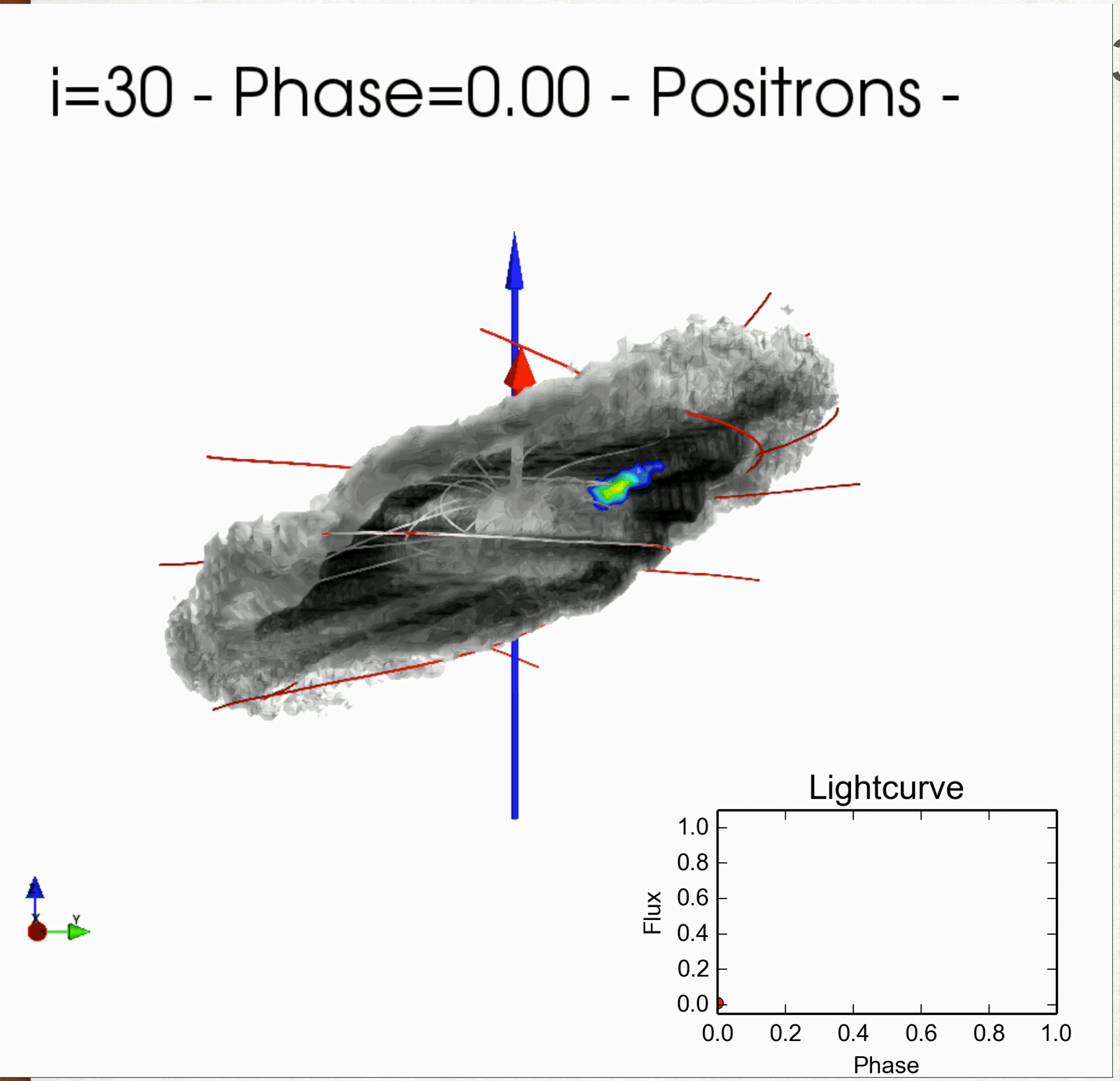
- Counterstreaming is present in polar discharge and in return current
- Opportunities for maser emission from collective instabilities of counterstreaming distributions.

Momentum space

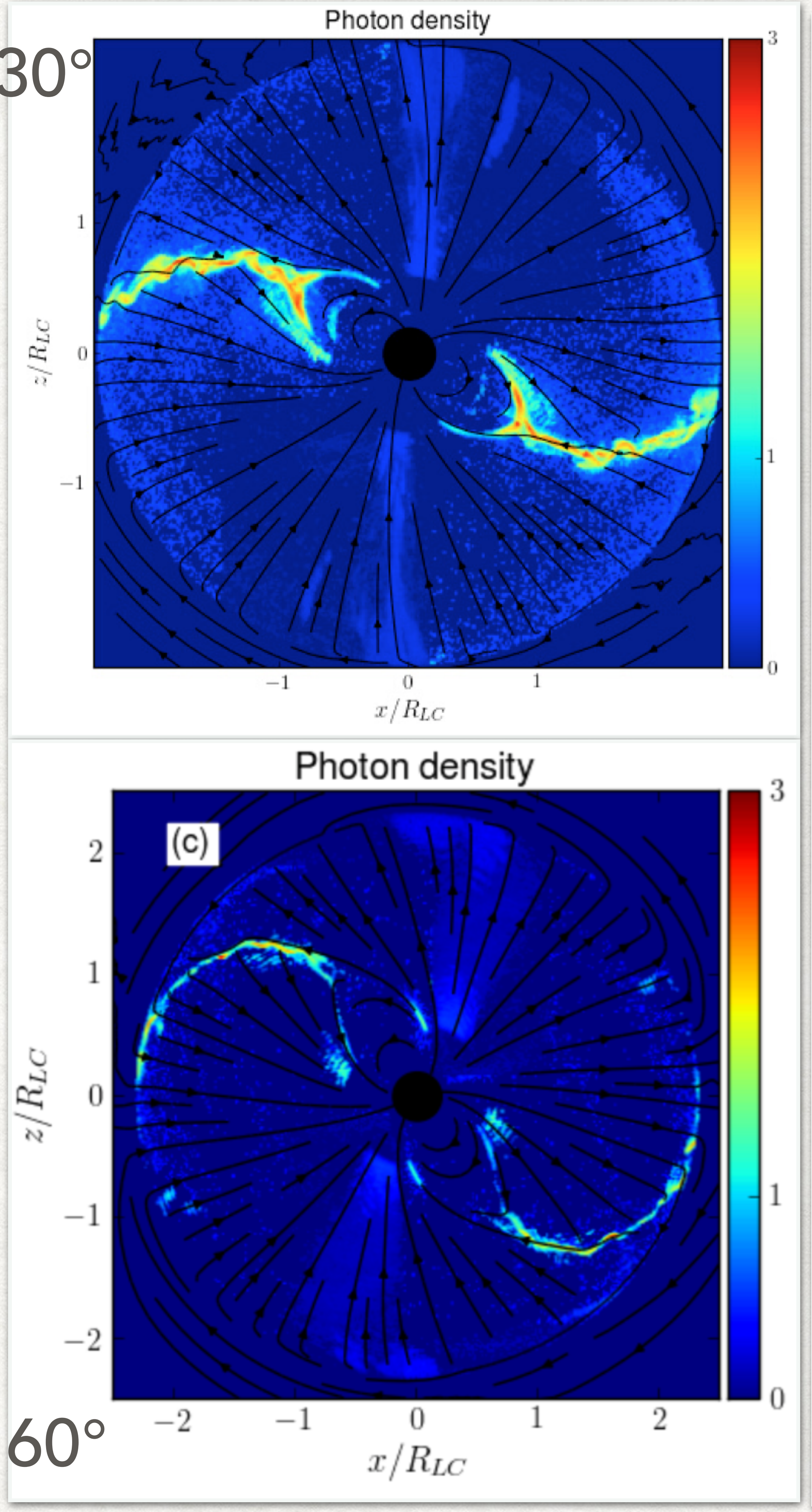


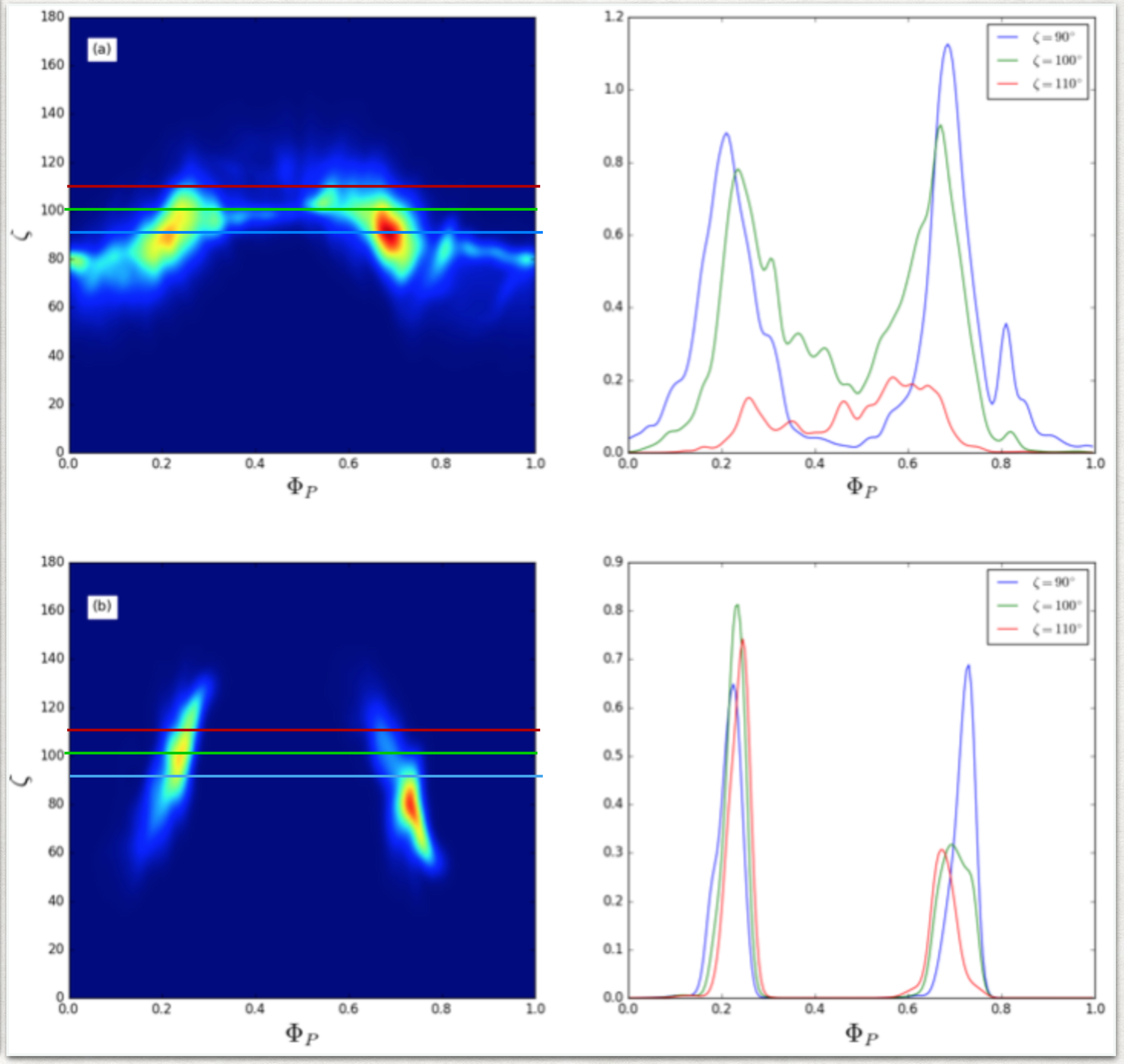
Philippov & AS., 2018

GAMMA-RAY LIGHTCURVES



Caustic formation from spiral shape of current sheet





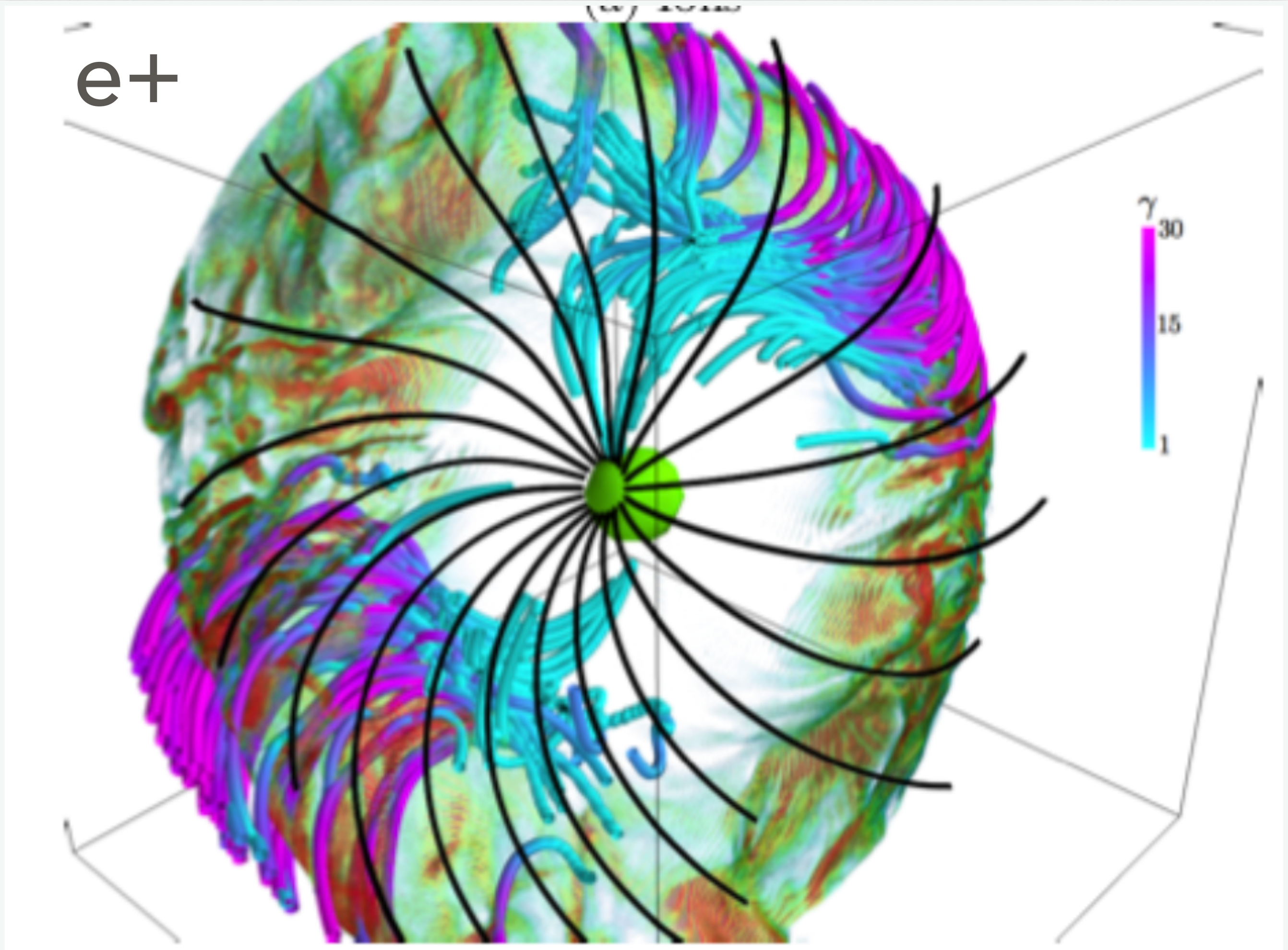
Photon density

Sky map

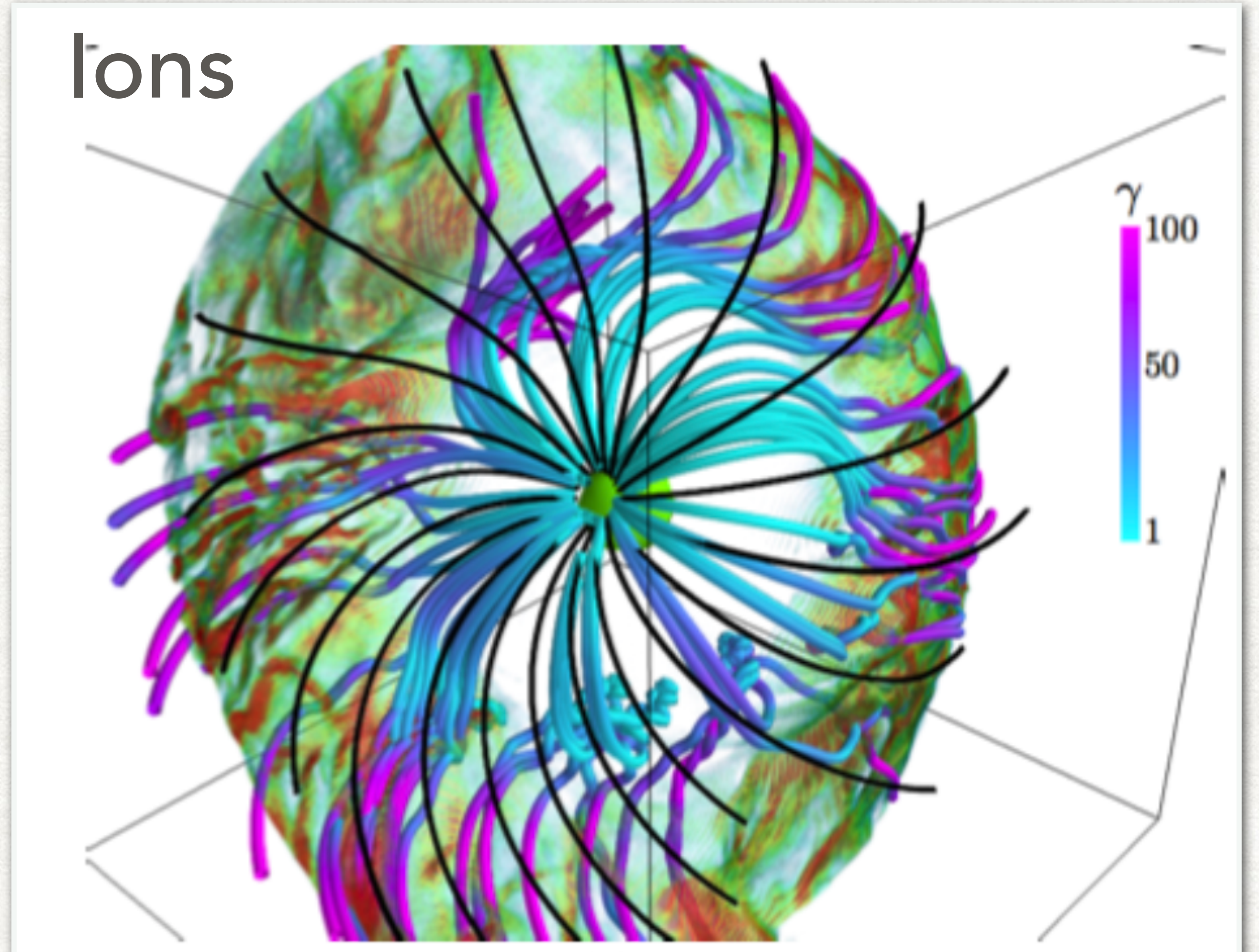
Light Curve

Philippov & AS., 2018; Bai & AS, 2010

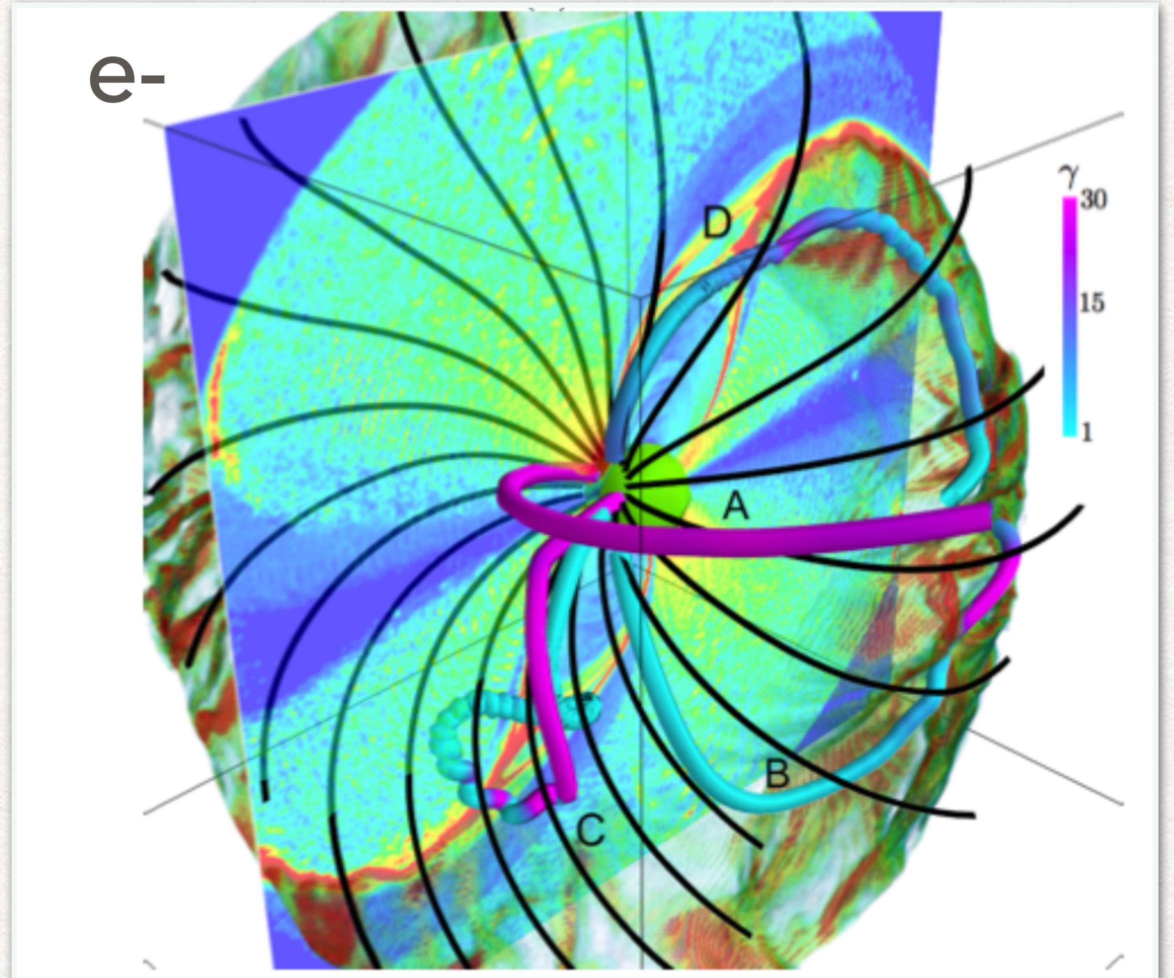
PARTICLE ACCELERATION AND SPECTRA



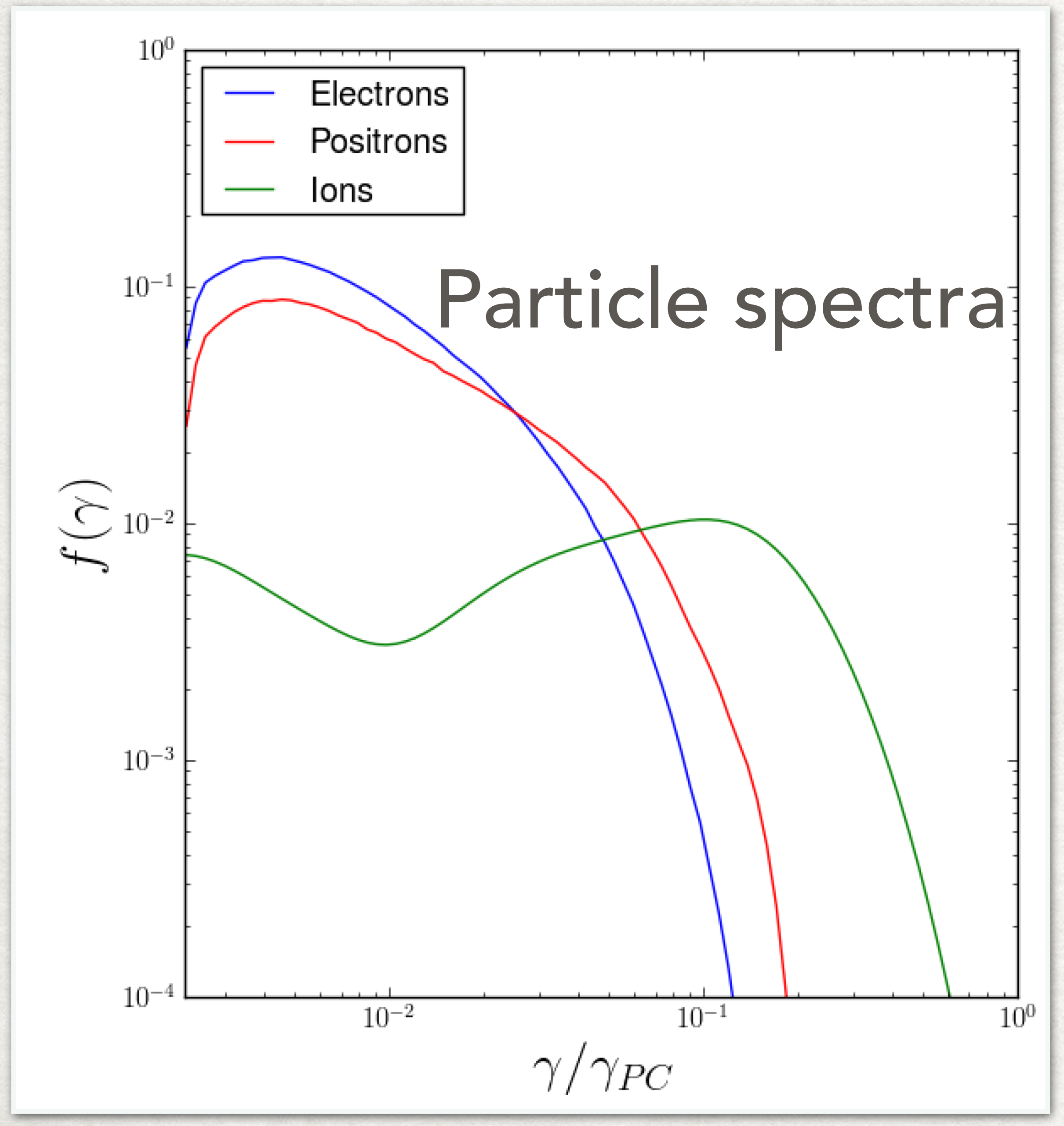
(b) Positrons

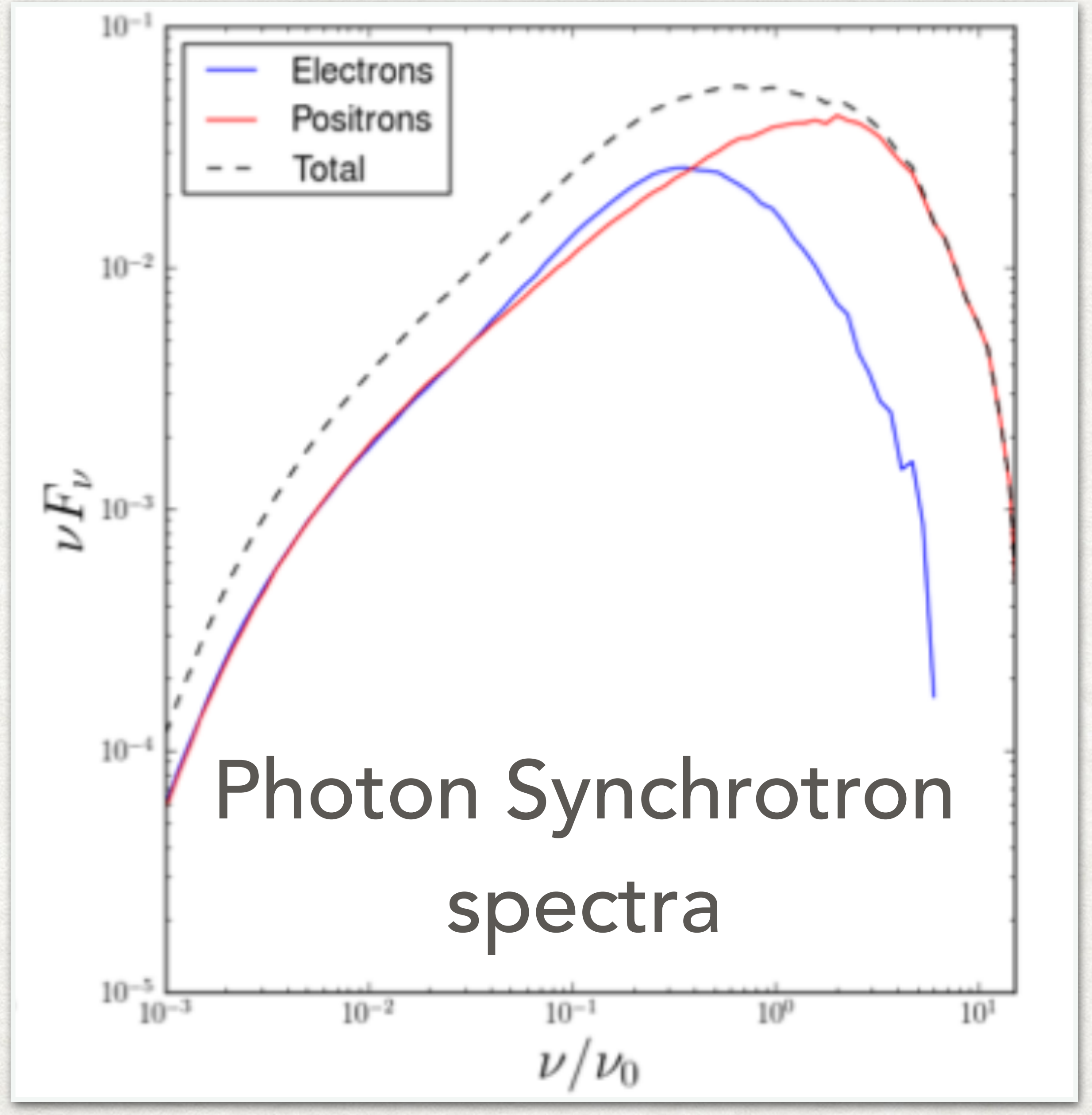


(a) Ions



(c) Electrons





Particles are accelerated in the current sheet during reconnection.

Radiation appears as broad spectral peak.

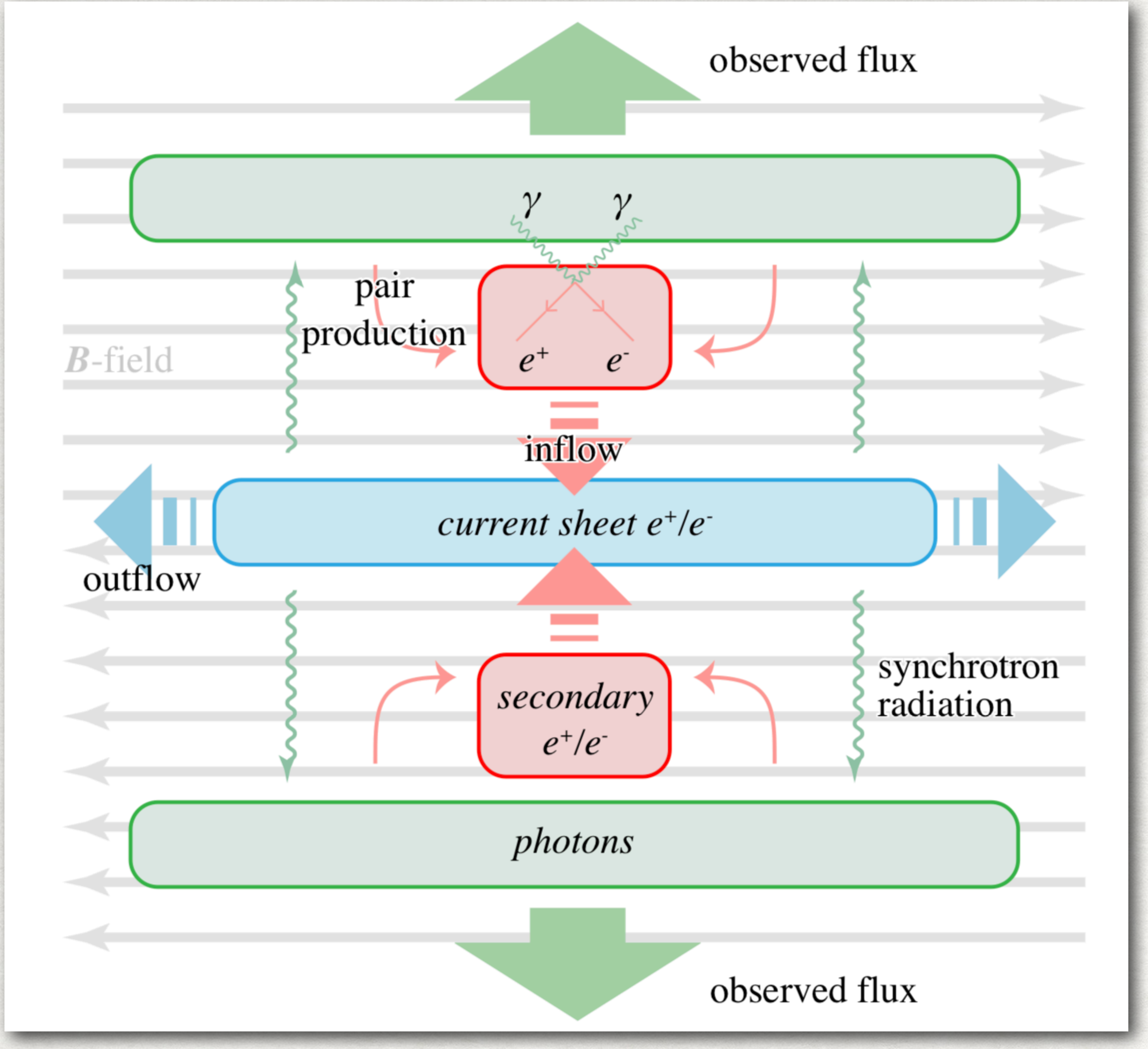
The max frequency is set by magnetization σ_{LC}:

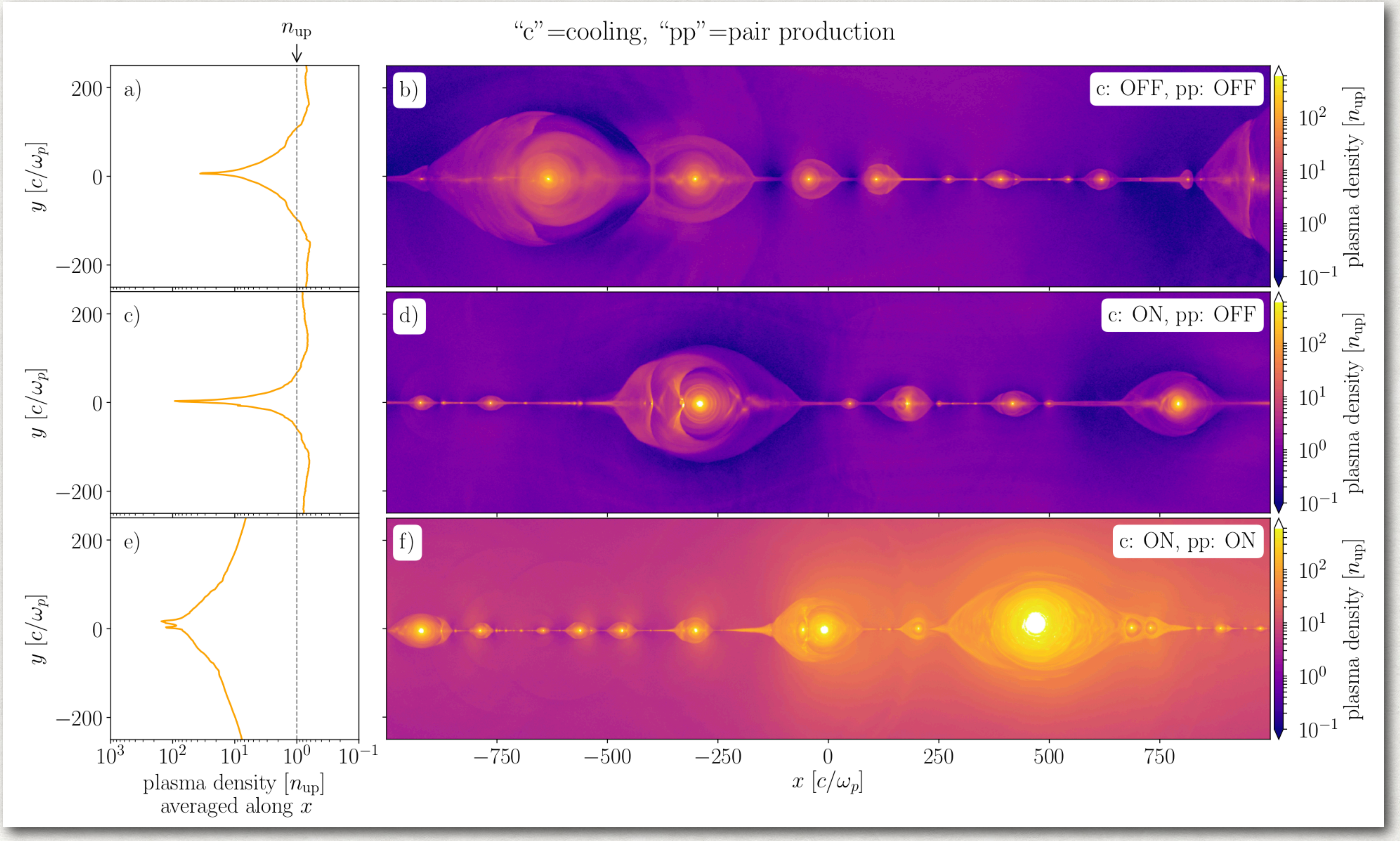
$$\nu_{\max} \approx 3e\,(0.1 B_{\rm LC})\,\sigma_{\rm LC}^2/4\pi m_{\rm e} c$$

Pair production in sheet sets the sigma parameter. Ions gain good fraction of $\Phi_{\rm pc}$

Philippov & AS., 2018

THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING CUTOFF ENERGY

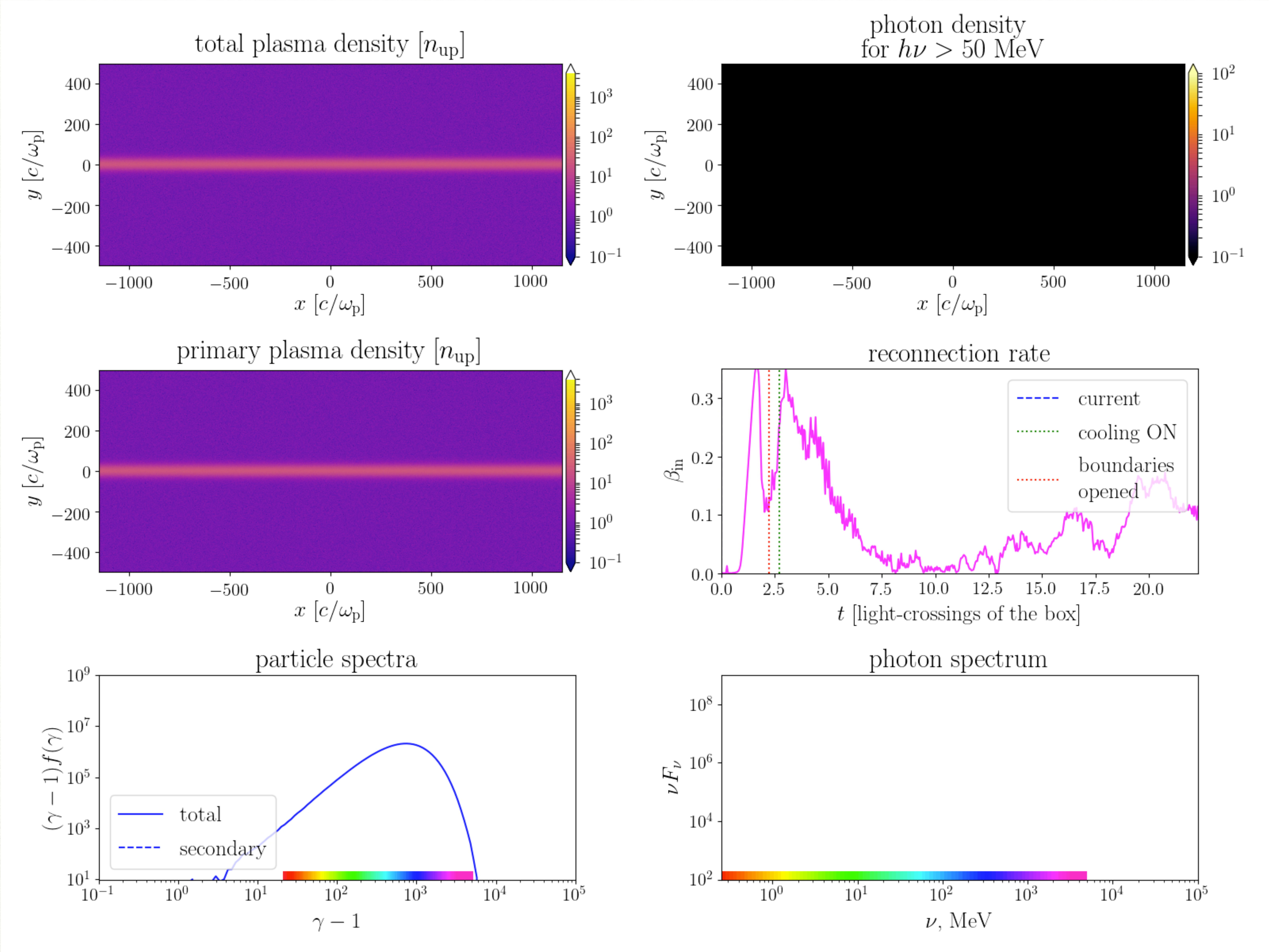




Reconnection in the current sheet is main particle accelerator. Gamma-gamma pair formation can start.
Pair formation increases the pair loading above the sheet, and lowers effective magnetization in the sheet.
Particle acceleration follows magnetization, max particle energy is reduced.

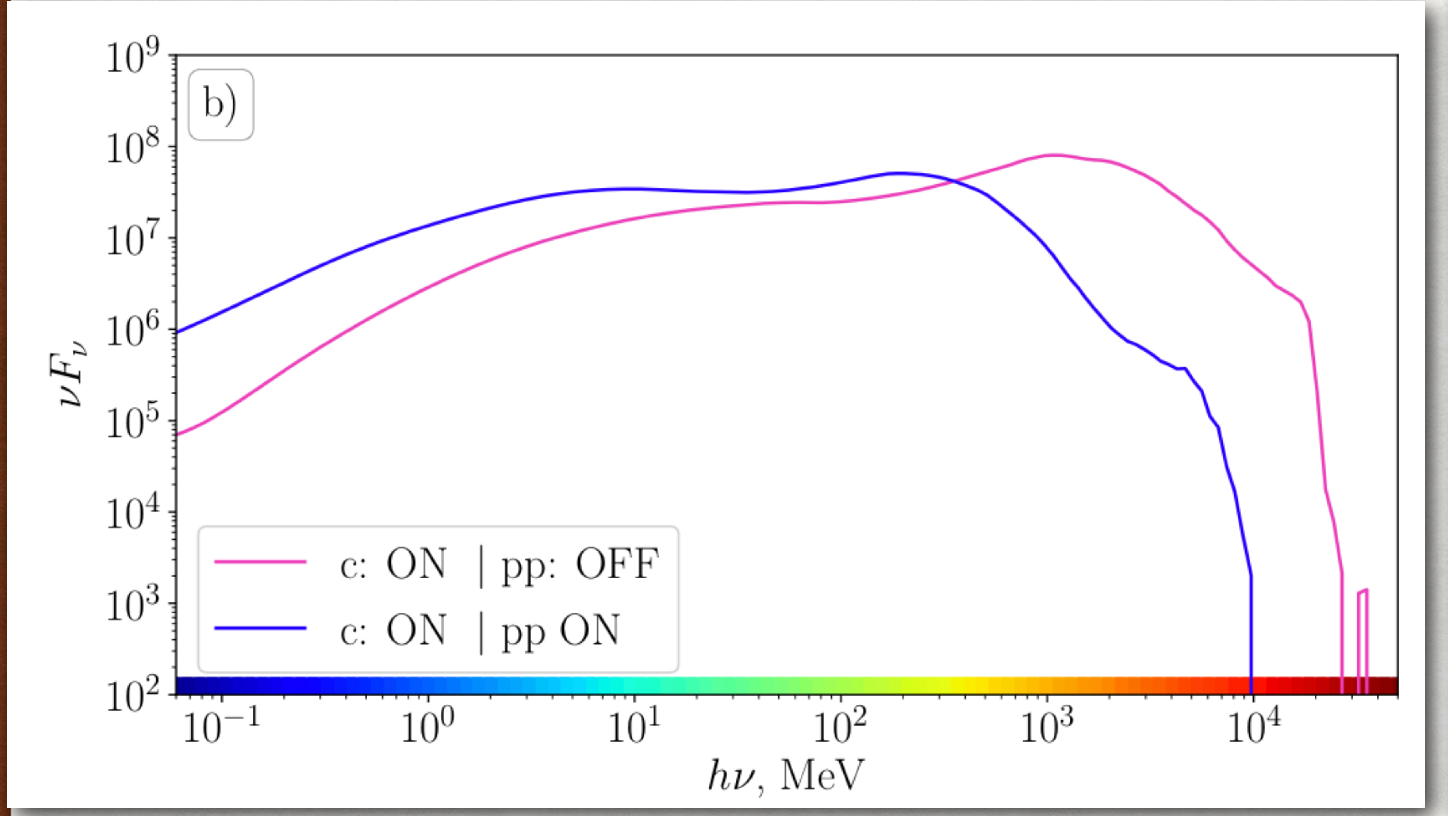
Hakobyan, Philippov, AS 2018

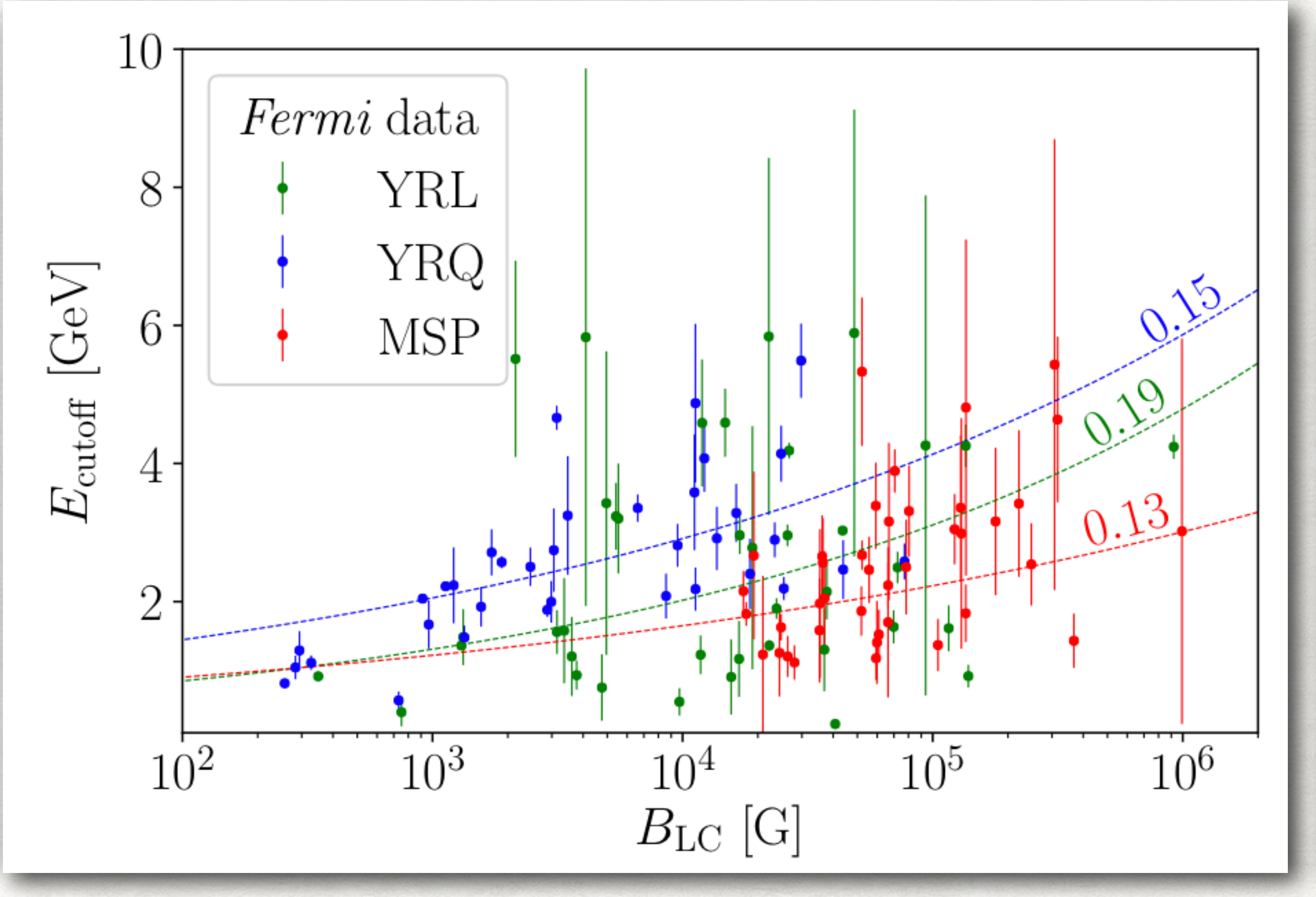
THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING CUTOFF ENERGY

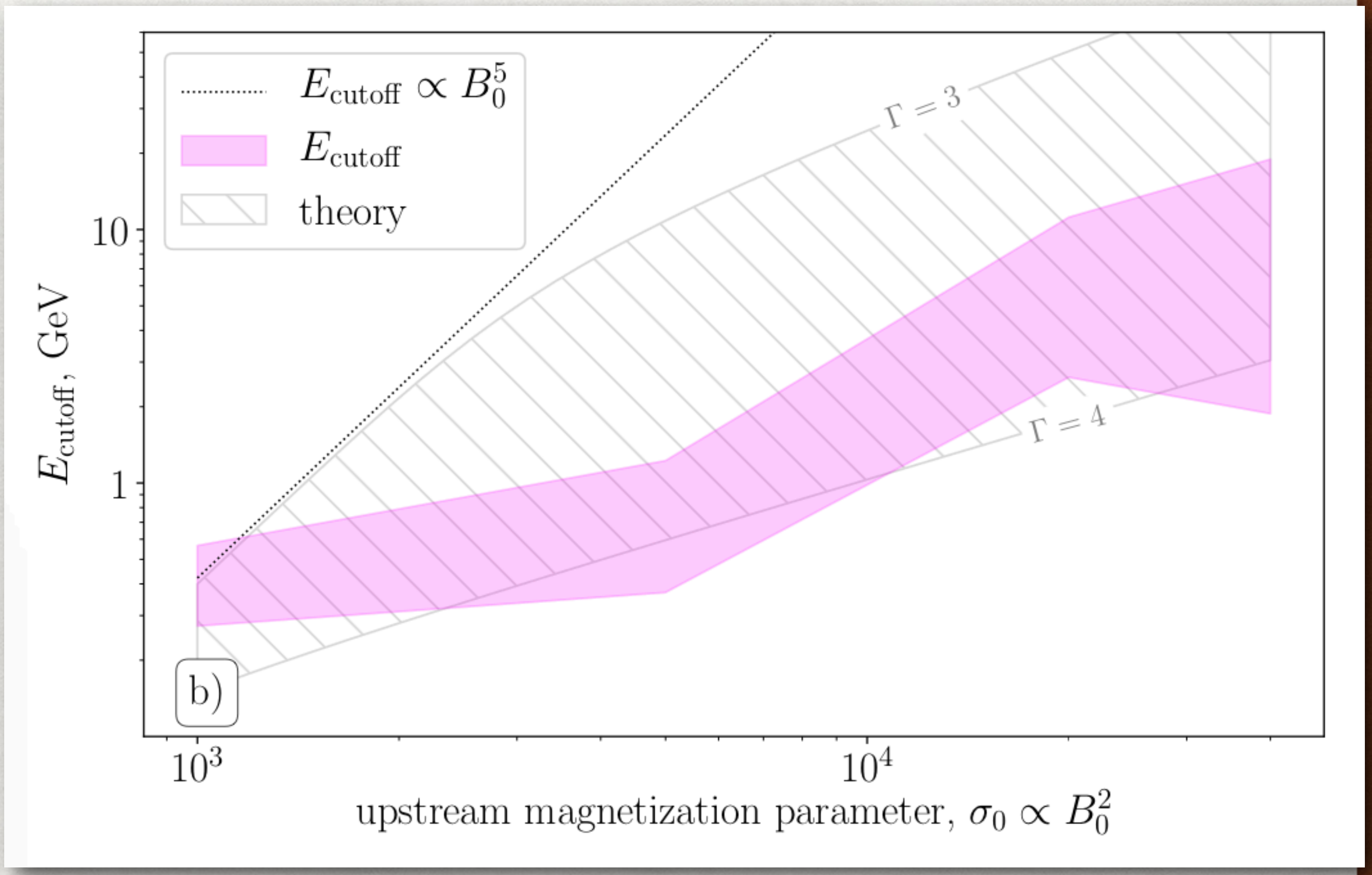


Hakobyan, Philippov, AS 2018

THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING CUTOFF ENERGY







Pair formation increases the pair loading above the sheet, and lowers effective magnetization in the sheet.
Particle acceleration follows magnetization, max particle energy is reduced.
Naively, cutoff energy should be a strong function of B at the LC.

$$\gamma_{\rm cuttoff} \propto \sigma_0 \propto B_0^2, \quad E_{\rm cutoff} \propto \gamma^2_{\rm cuttoff} B_0 \propto B_0^5$$

Pair loading softens the dependence

$$\gamma_{\rm cutoff} \sim \sigma_{\rm LC} \propto B_{\rm LC}^2/\eta n_{\rm GJ}$$

Expect cutoff energy dependence to be between $E_{\rm cutoff} \propto B_{\rm LC}^{1.2}\text{-}B_{\rm LC}^{1.8}$ and $E_{\rm cutoff} \propto B_{\rm LC}^{-0.8}\text{-}B_{\rm LC}^{-0.2}$

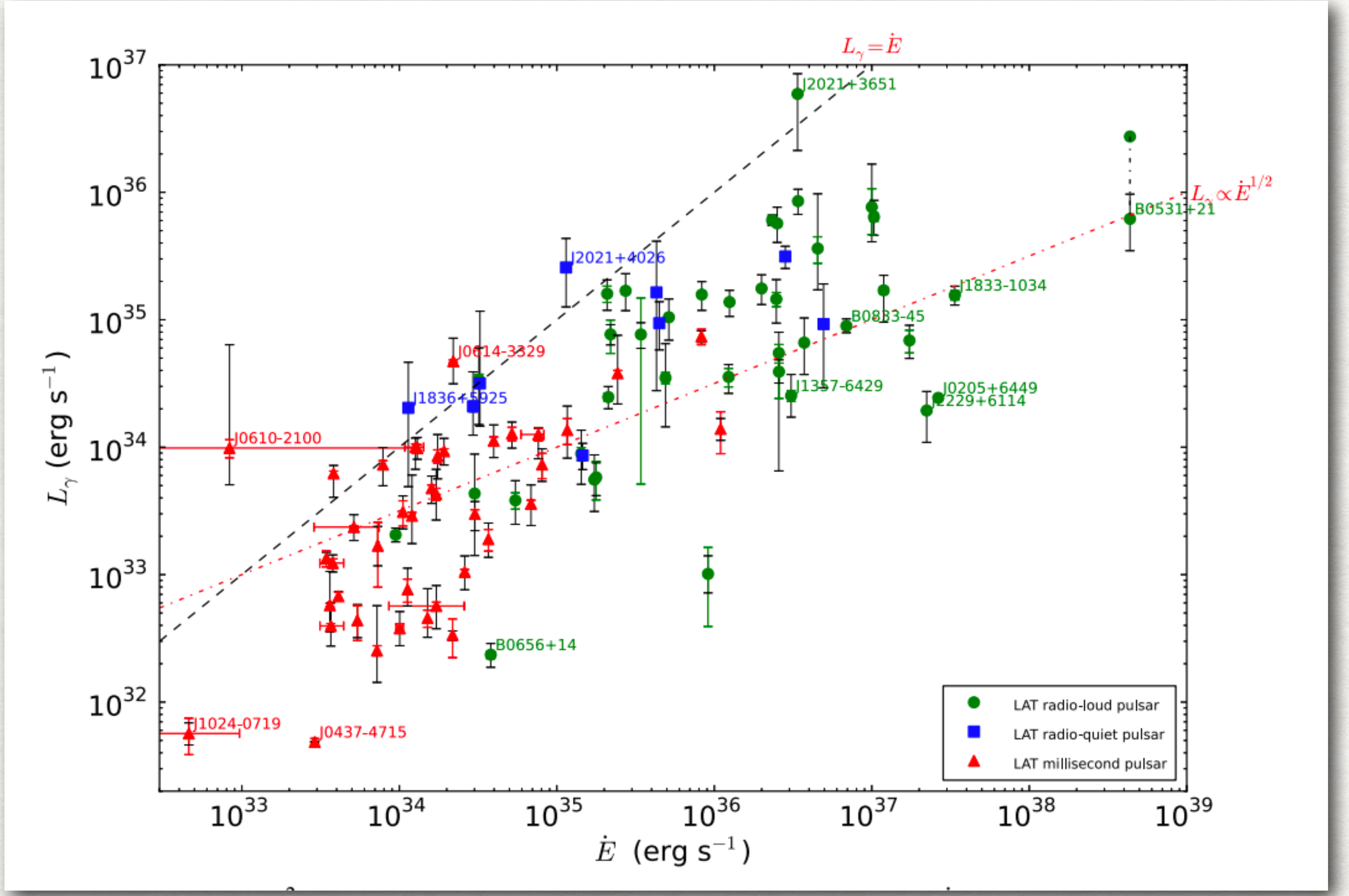
Observed dependence: $E_{\rm cutoff} \propto B_{\rm LC}^{0.1}\text{-}B_{\rm LC}^{0.2}$

Hakobyan, Philippov, AS 2018

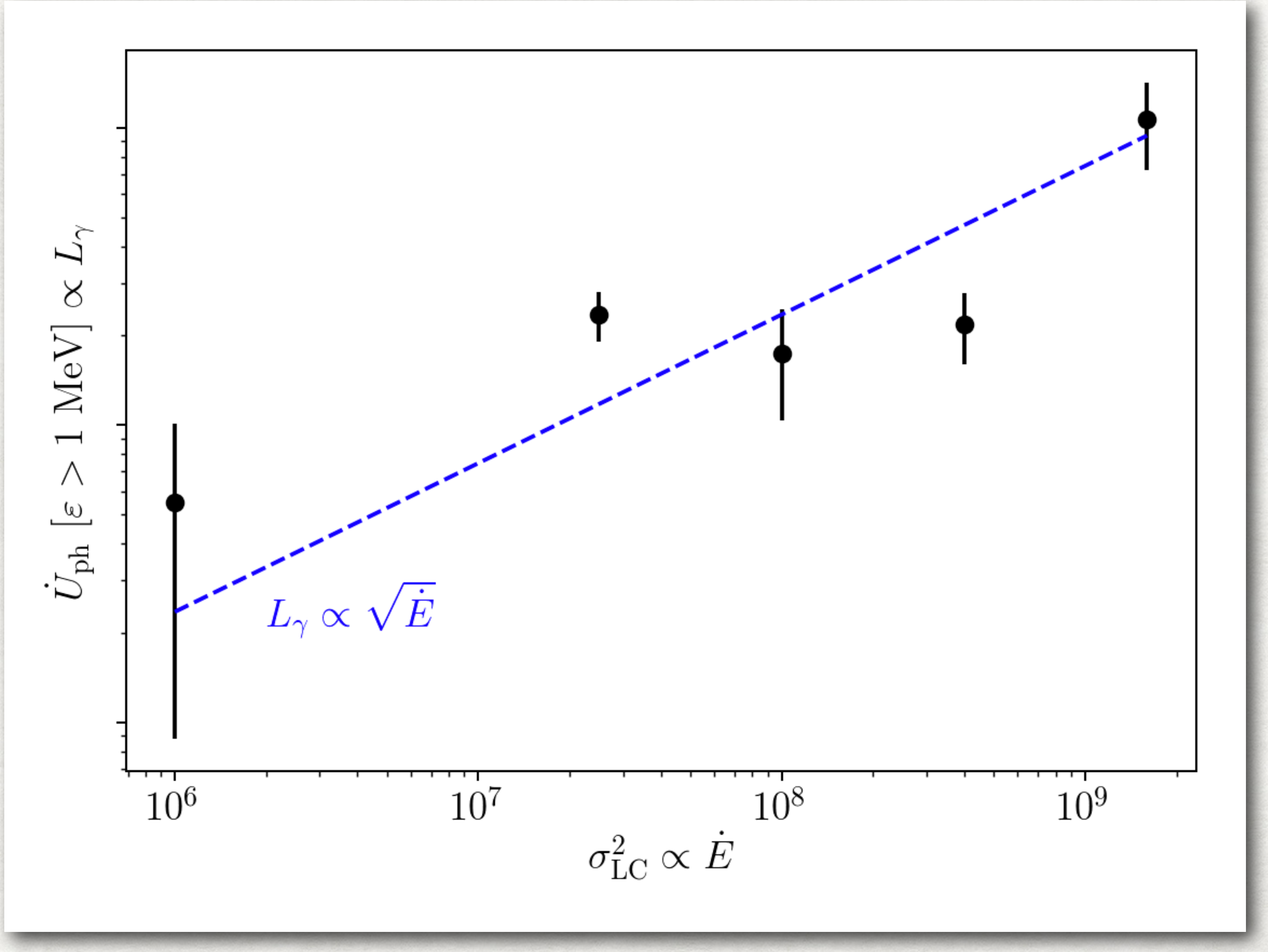
THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING L_γ

Gamma luminosity is larger for aligned rotators than for oblique ones. $L_\gamma/\dot{E}$ varies from 1% for orthogonal rotator to 10% for near aligned. Obliqueness effects can explain the spread in observed values of L_γ. In this regime $L_\gamma \propto \dot{E}$.

Pair formation in the current sheet decreases magnetization and lowers maximum particle energy, and radiative efficiency decreases. Also, reconnection slows down. This leads to slower dependence.



Abdo et al 2013



Philippov et al., ApJ, 2016

CONCLUSIONS

- Electrodynamicaly self-consistent, working magnetospheric models with pair formation and emission are now available using PIC simulations. GR frame-dragging is essential for polar cascades!
- Paradigm change — current sheet beyond LC is effective particle accelerator and the site of majority of high-energy emission. Need global simulations for modeling the right field shape! Forced reconnection with self-consistent pair formation needs to be studied.
- Light curves and spectra are consistent with synchrotron radiation for gamma-ray and below. IC is needed for TeV.
- Pair creation in the current sheet beyond the LC makes the synchrotron cutoff energy to depend weakly on B_{LC}. When pair creation is weak, Lgamma is promotional to Edot. When pair loading is strong, Lgamma scales as sqrt(Edot).
- Radio emission is likely caused by the non-stationary discharge at the polar cap — first signatures of this are seen in global simulations. More on radio and multiwavelength predictions to come!