Title: How do pulsars shine?

Date: Jan 26, 2017 01:00 PM

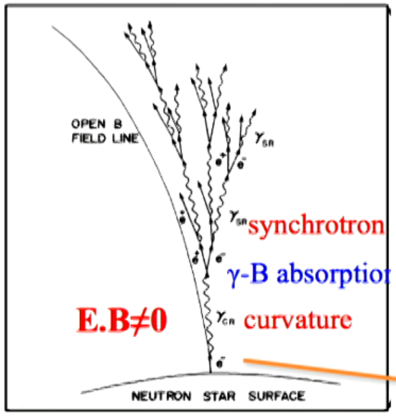
URL: http://pirsa.org/17010067

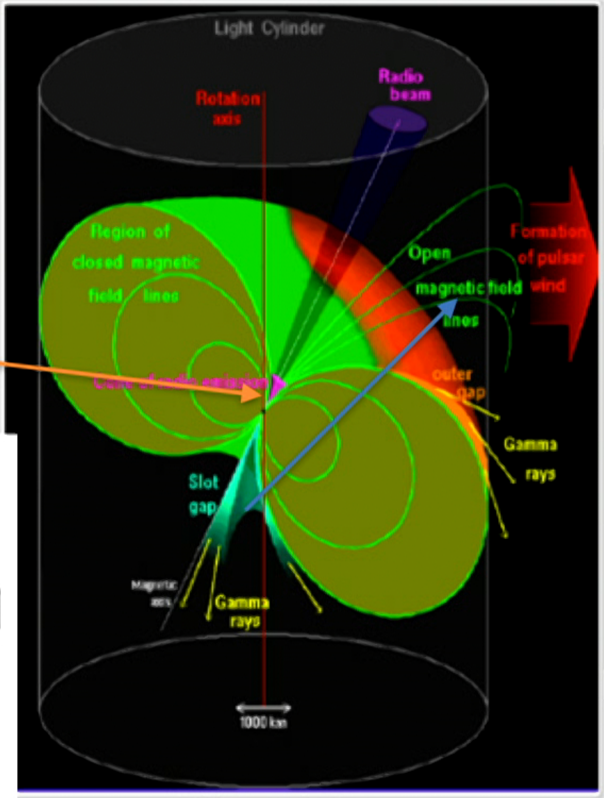
Abstract: <p>The modeling of pulsar radio and gamma-ray emission suggests that in order to interpret the observations one needs to understand the field geometry and the plasma state in the emission region. In recent years, significant progress has been achieved in understanding the magnetospheric structure in the limit of abundant plasma supply. However, the very presence of dense plasma everywhere in the magnetosphere is not obvious. Even the region where the observed emission is produced is subject to debate. To address this from first principles, we constructed global kinetic simulations of pulsar magnetospheres using relativistic Particle-in-Cell codes, which capture the physics of plasma production and particle acceleration. In this talk I will describe how plasma is produced in magnetospheres of pulsars. I will present modeling of high-energy lightcurves, calculated self-consistently from particle motion in the pulsar magnetosphere. I will also show evidence that observed radio emission is powered by non-stationary discharge at the polar cap.</p>

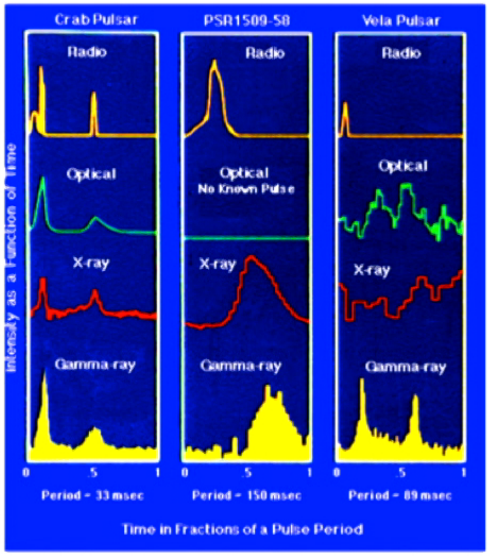

eley)
1

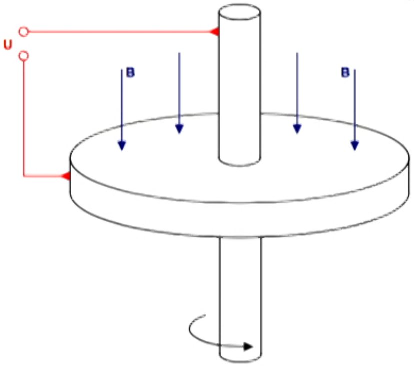
What is a pulsar?

Pair cascade in the polar caps



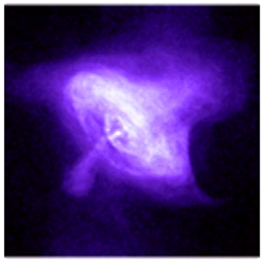






Unipolar induction

Open questions:

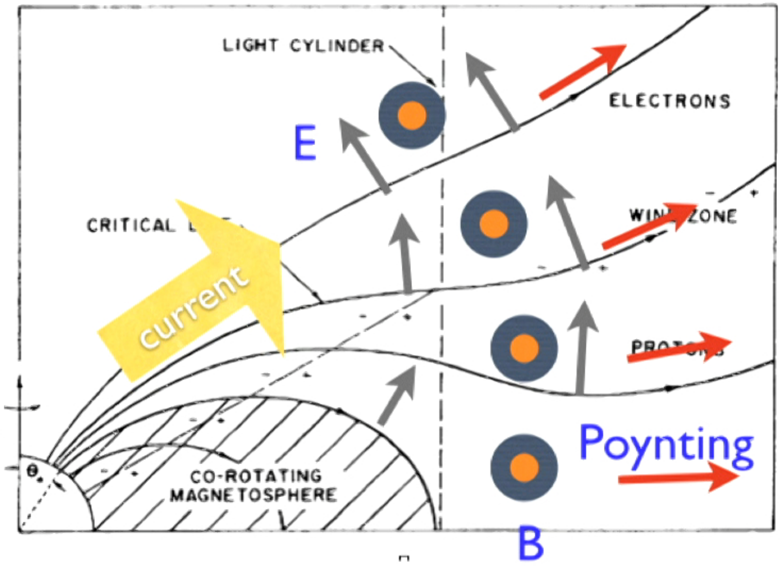


- How pulsar magnetosphere works?
  - Nebula observations favor plasma-filled magnetospheres
- How particle acceleration works?
- How pulsars shine?
  - Most of the observable energy comes in gamma-rays
- How pulsars evolve?

Magnetospheric cartoon

$$\rho_{GJ} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c}$$

- Corotation electric field
- Sweepback of B field due to poloidal current
- ExB -> Poynting flux
- Electromagnetic energy loss



Goldreich & Julian, 1969

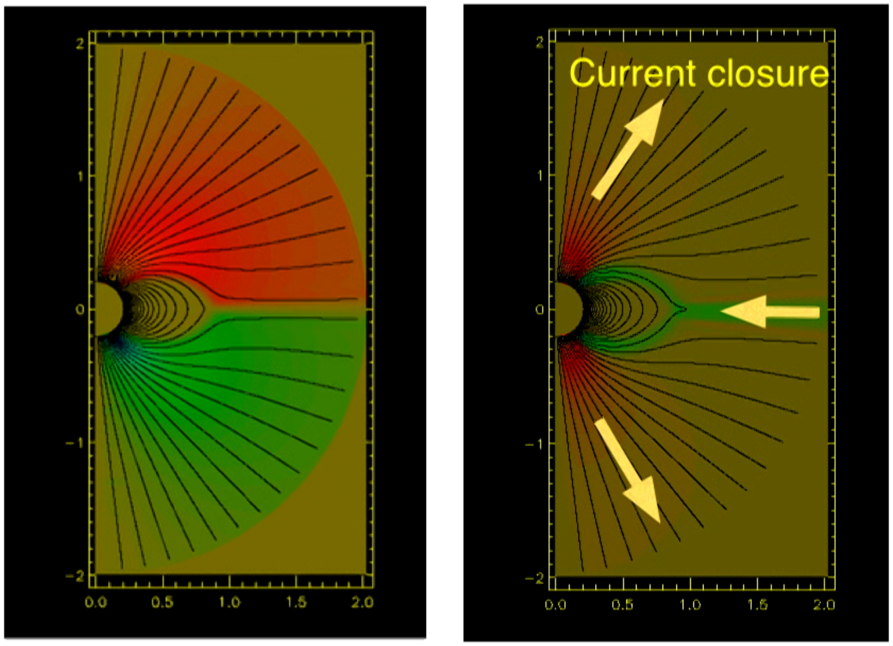
Standard pulsar

- Force-free paradigm

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

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

$$\boldsymbol{j} = \frac{c}{4\pi}\boldsymbol{\nabla}\cdot\boldsymbol{E}\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2} + \frac{c}{4\pi}\frac{(\boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B} - \boldsymbol{E}\cdot\boldsymbol{\nabla}\times\boldsymbol{E})\boldsymbol{B}}{B^2} \qquad \frac{1}{c}\frac{\partial\boldsymbol{E}}{\partial t} = \boldsymbol{\nabla}\times\boldsymbol{B} - \frac{4\pi}{c}\boldsymbol{j}, \quad \frac{1}{c}\frac{\partial\boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla}\times\boldsymbol{E}$$



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

(from Spitkovsky 2006)

Standard pulsar

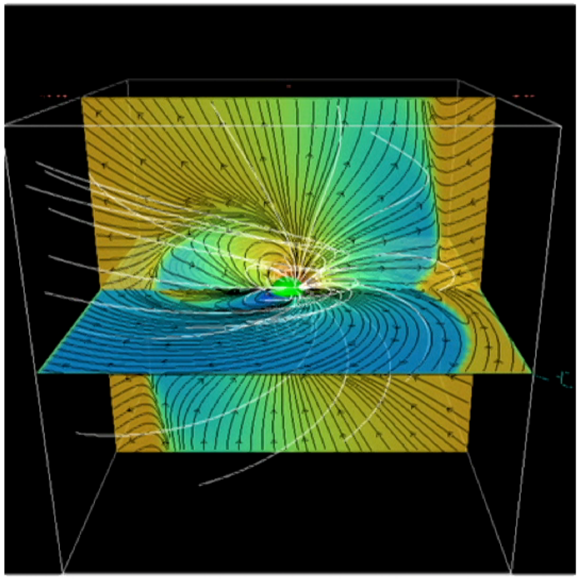
- Force-free paradigm

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

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

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

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



- 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)

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

Standard pulsar

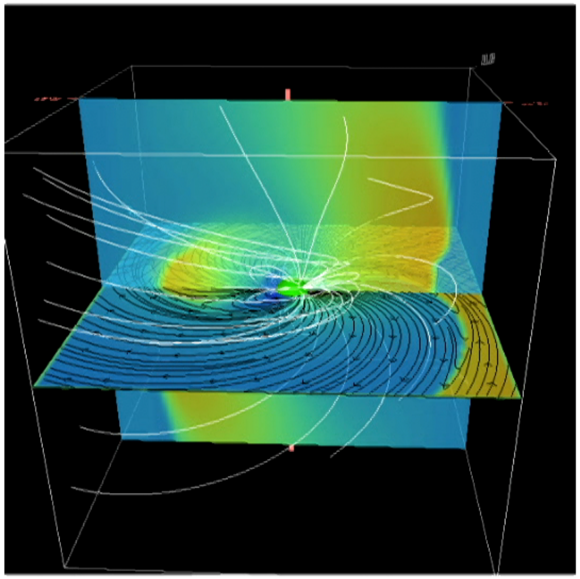
- Force-free paradigm

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

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

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

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



- 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)

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

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?

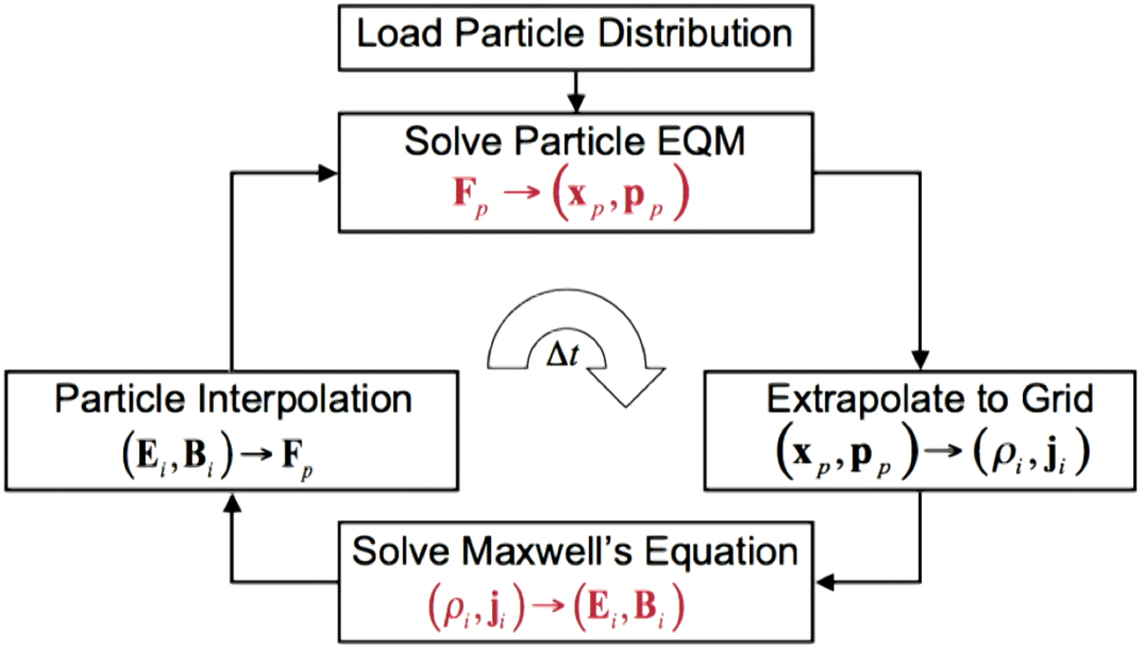
ρ_c	$\mathbf{j}$	ρ_m	T	Non-thermal particles	Plasma instabilities
✓	✓	✓	✓	✗	✗

PIC simulation of magnetospheres I

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

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

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



Load Particle Distribution

Solve Particle EQM

$\mathbf{F}_p \rightarrow (\mathbf{x}_p, \mathbf{p}_p)$

Δt

Extrapolate to Grid

$(\mathbf{x}_p, \mathbf{p}_p) \rightarrow (\rho_i, \mathbf{j}_i)$

Solve Maxwell's Equation

$(\rho_i, \mathbf{j}_i) \rightarrow (\mathbf{E}_i, \mathbf{B}_i)$

Particle Interpolation

$(\mathbf{E}_i, \mathbf{B}_i) \rightarrow \mathbf{F}_p$

PIC simulation of magnetospheres II

- Core - EM PIC codes TRISTAN-MP (Spitkovsky 2008) and Zeltron (Cerutti et. al., 2014).
- Conducting BC at the stellar surface, “absorbing layer” BC at the outer edge. Provide free escape of particles (both electrons and ions) from the surface.
- Radiative cooling is implemented for particle motion. To get correct cooling rates, need to resolve Larmor gyrations in time.

$$\mathbf{g} = \frac{2}{3} r_e^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) \times \mathbf{B} + (\boldsymbol{\beta} \cdot \mathbf{E}) \mathbf{E} \right] - \frac{2}{3} r_e^2 \gamma^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2 \right] \boldsymbol{\beta}$$

- Pair creation with the threshold based on particle energy in the inner magnetosphere. Outer magnetosphere: pair production in photon-photon collisions, do tracking of high-energy photons.
- Effects of GR: simulations in slowly rotating metric.
- Scales approached:

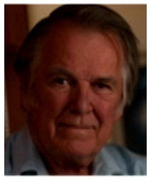
$$R_*/(c/\omega_p) \approx 30 - 40 \gg 1 \qquad R_{LC}/R_* = 3 - 5$$

$$\Phi_{PC} = \mu\Omega^2/c^2 \approx 500 \gg \gamma_{\mathrm{threshold}} = 40$$

Jump-starting the pulsar: regimes of plasma supply

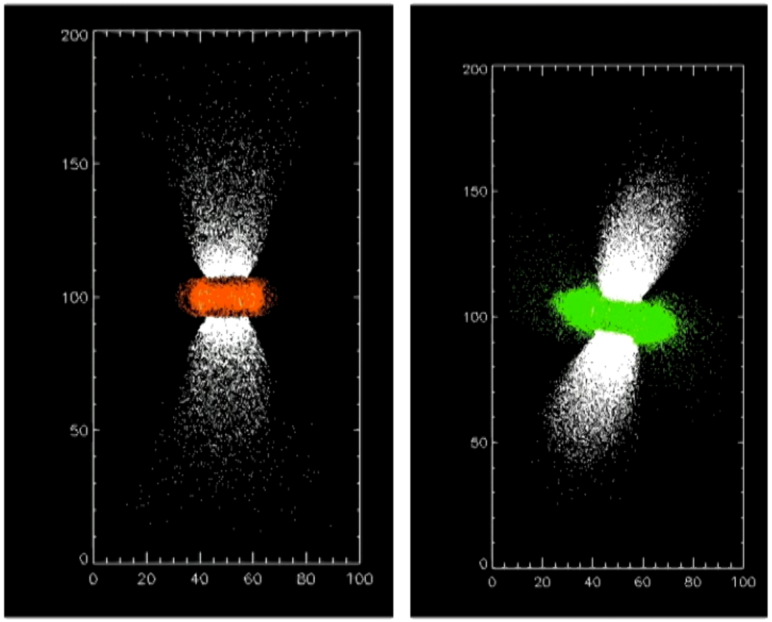
- Availability of plasma supply and whether magnetosphere is filled with plasma can determine the properties of spindown and radiation. We tried:
  - Free particle escape from the surface without pair production.
  - Free particle escape with volumetric or surface injection.
  - Free escape with pair production: aligned and oblique rotators.
  - Modifications of pair supply in GR.

Electrostatically trapped solution



C. Michel

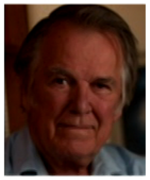
- Only free escape from the surface
- Disk-dome solution
- Almost no outflow and spin-down



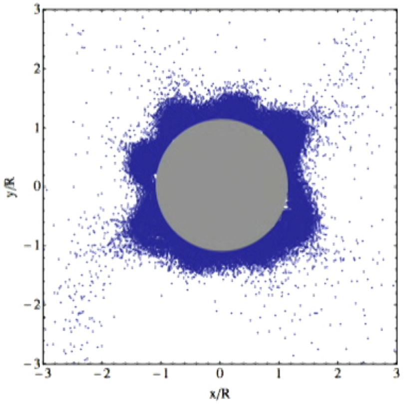
Kraus-Polstorff & Michel, 1985; Spitkovsky & Arons, 2002; Petri et al., 2002; Philippov & Spitkovsky, 2014

Extremes: plasma supply from the star

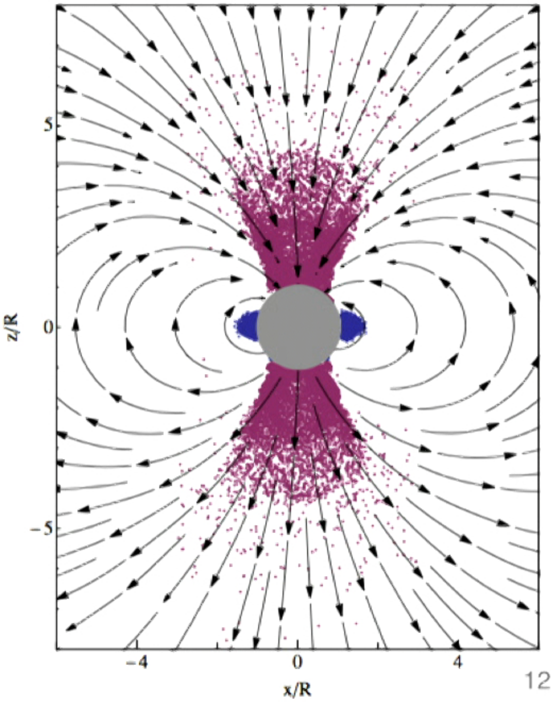
- Disk-dome solution (Kraus-Polstorff, Michel, 1985) (Spitkovsky, Arons, 2002)
- Disk is unstable to the diocotron instability
- Almost no outflow



C. Michel

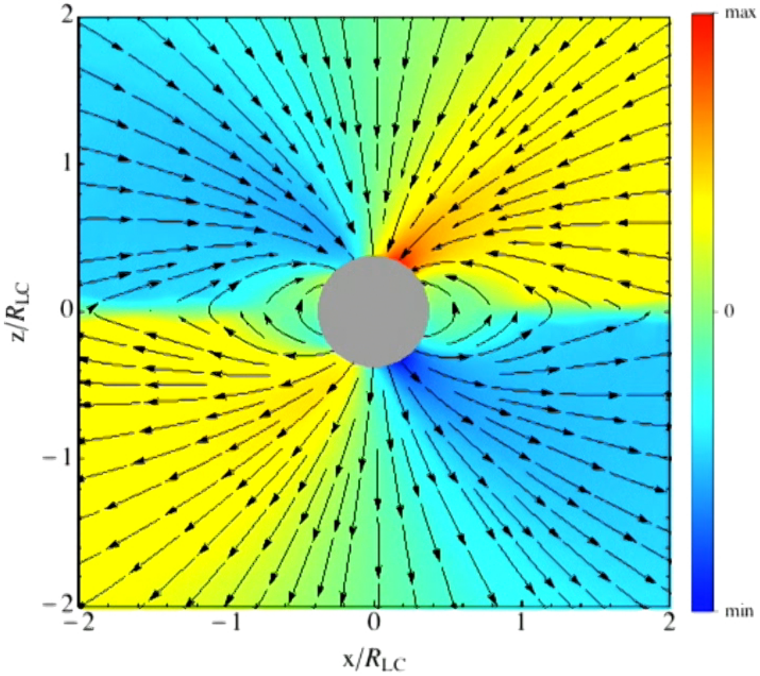


Philippov & Spitkovsky, ApJ, 2014



Volumetric pair supply in the aligned magnetosphere

- Approaches force-free
- Self-consistent current sheet
- 15% of Poynting flux is dissipated within $2R_{LC.}$
- Observed drift-kink instability of the current sheet.
- Particles are accelerated up to $\boldsymbol{\sigma}_{\mathbf{LC}}$ energies.

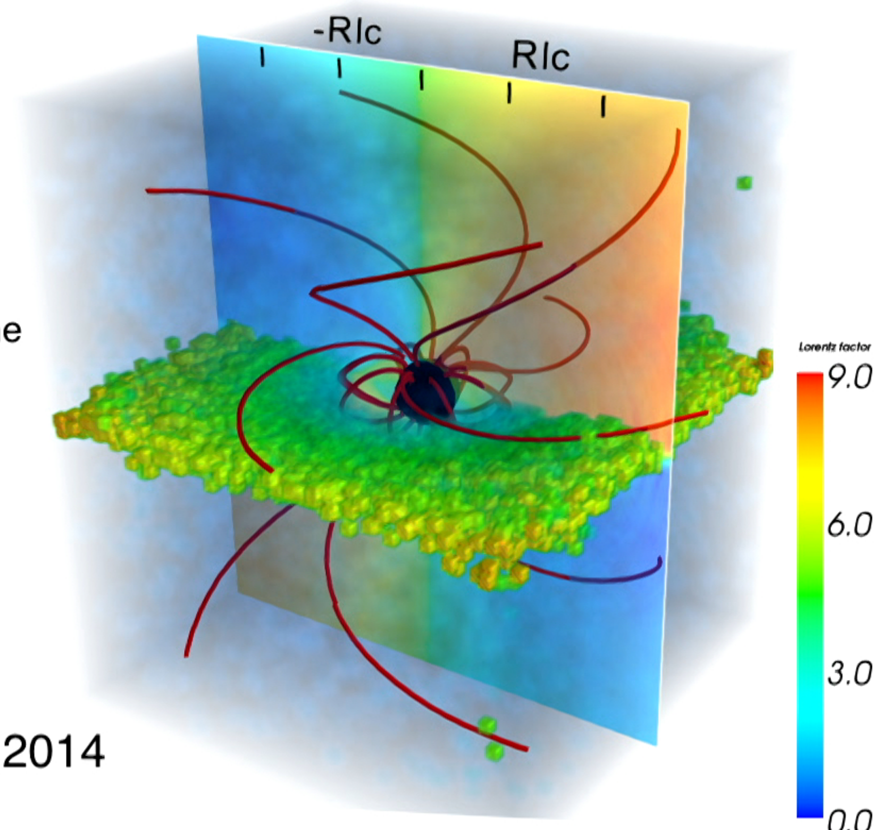


Philippov & Spitkovsky, ApJ, 2014

Sasha Philippov

Volumetric pair supply in the aligned magnetosphere

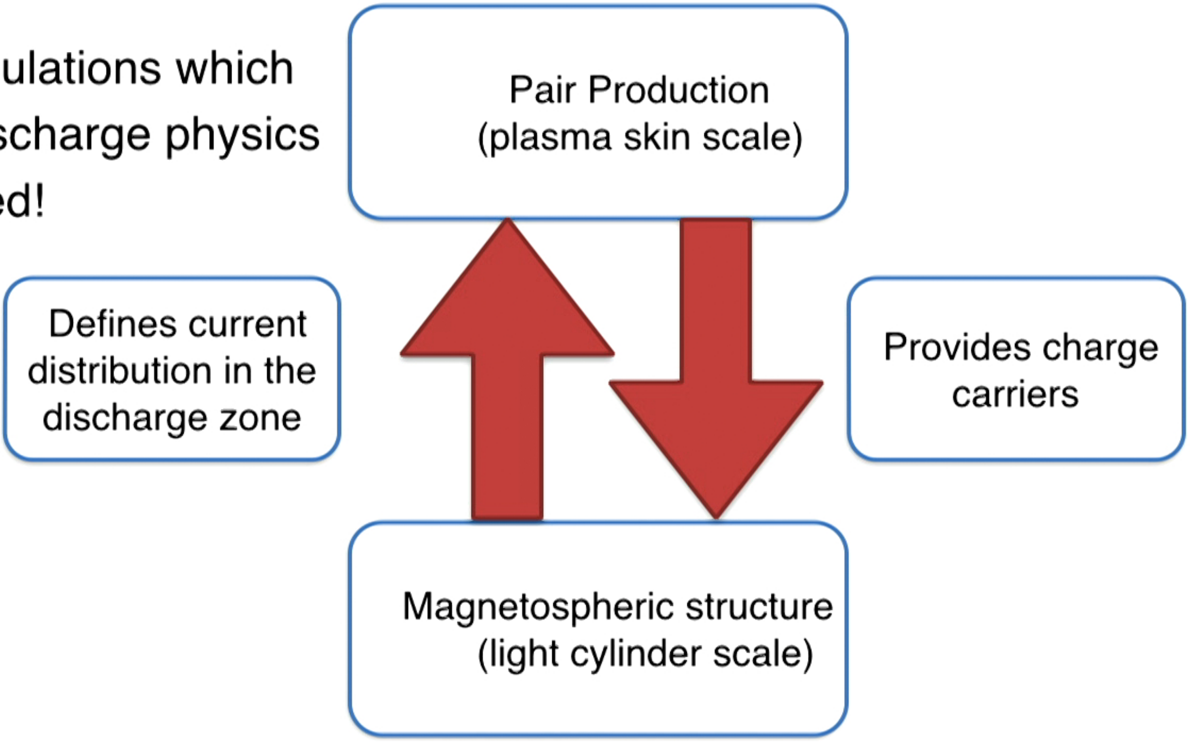
- Approaches force-free
- Self-consistent current sheet
- 15% of Poynting flux is dissipated within $2R_{LC.}$
- Observed drift-kink instability of the current sheet.
- Particles are accelerated up $\boldsymbol{\sigma}_{\mathrm{LC}}$ energies.



Philippov & Spitkovsky, ApJ, 2014

Magnetosphere is a self-regulated system

Global simulations which capture discharge physics are required!



Pair Production (plasma skin scale)

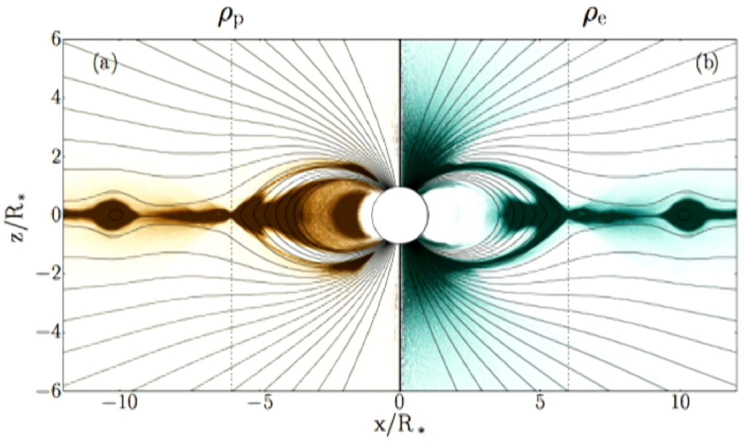
Defines current distribution in the discharge zone

Provides charge carriers

Magnetospheric structure (light cylinder scale)

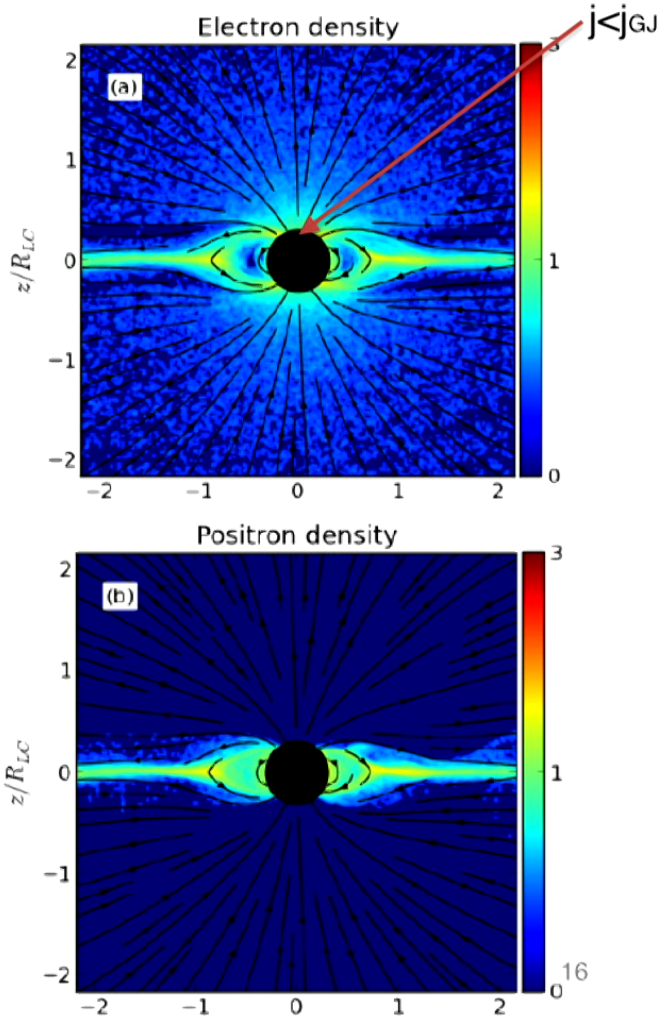
Aligned pulsar with pair production

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. Outer magnetosphere pair production is required to drive an active circuit.



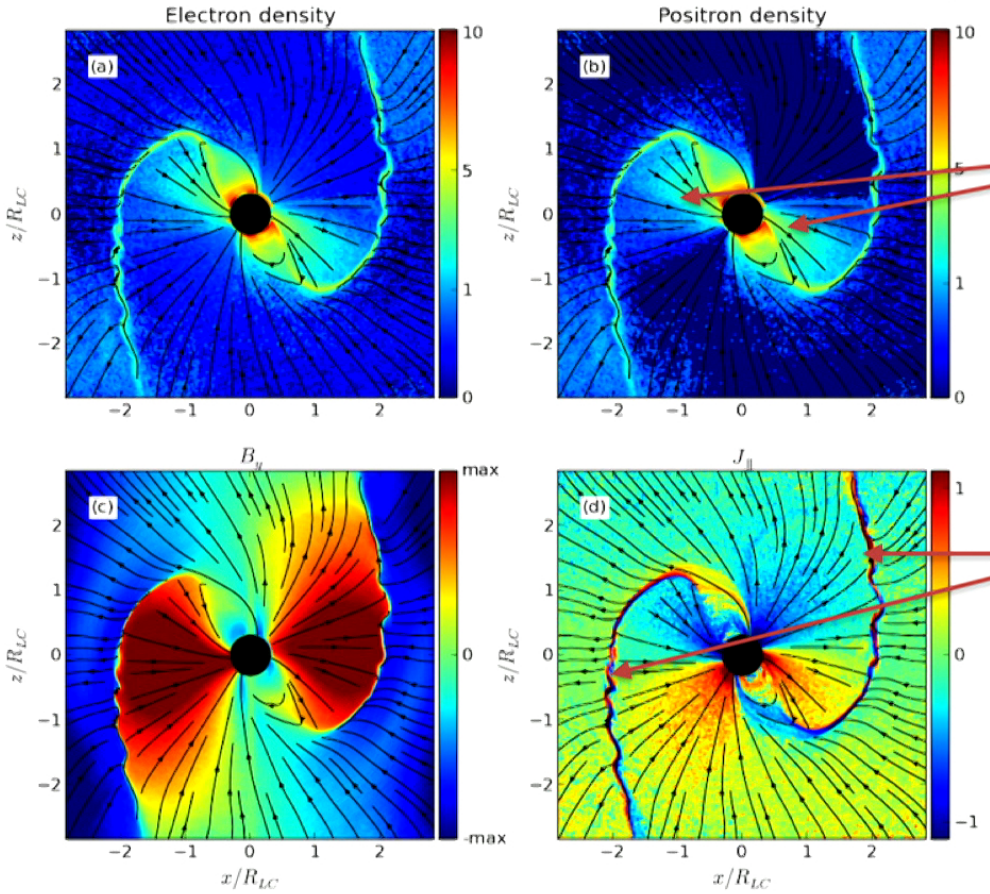
Chen, Beloborodov, ApJ, 2014

Philippov et al., ApJ, 2015



Oblique pulsar with pair production

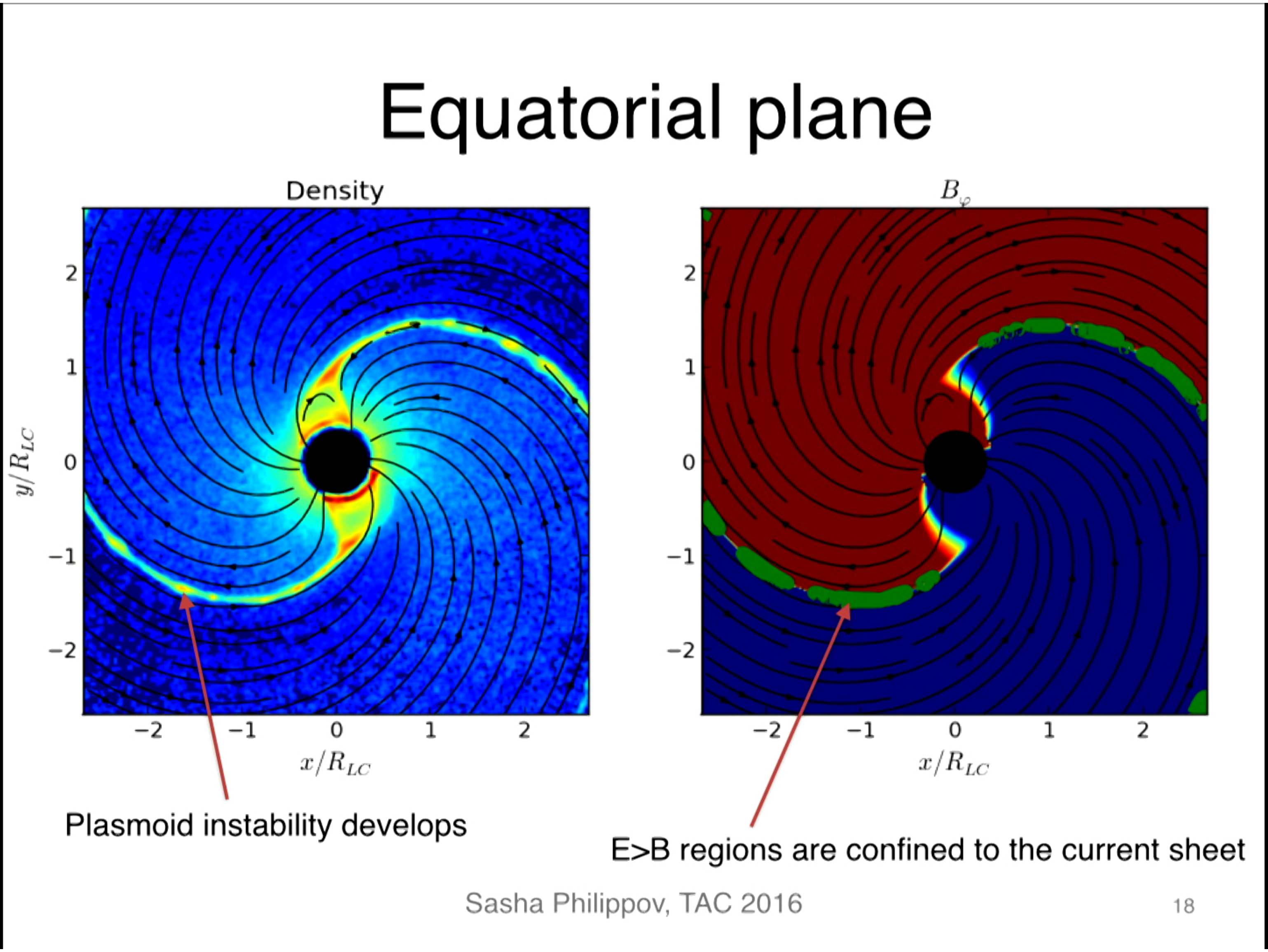
Philippov et al., ApJ, 2015



j>jGJ

Drift-kink instability

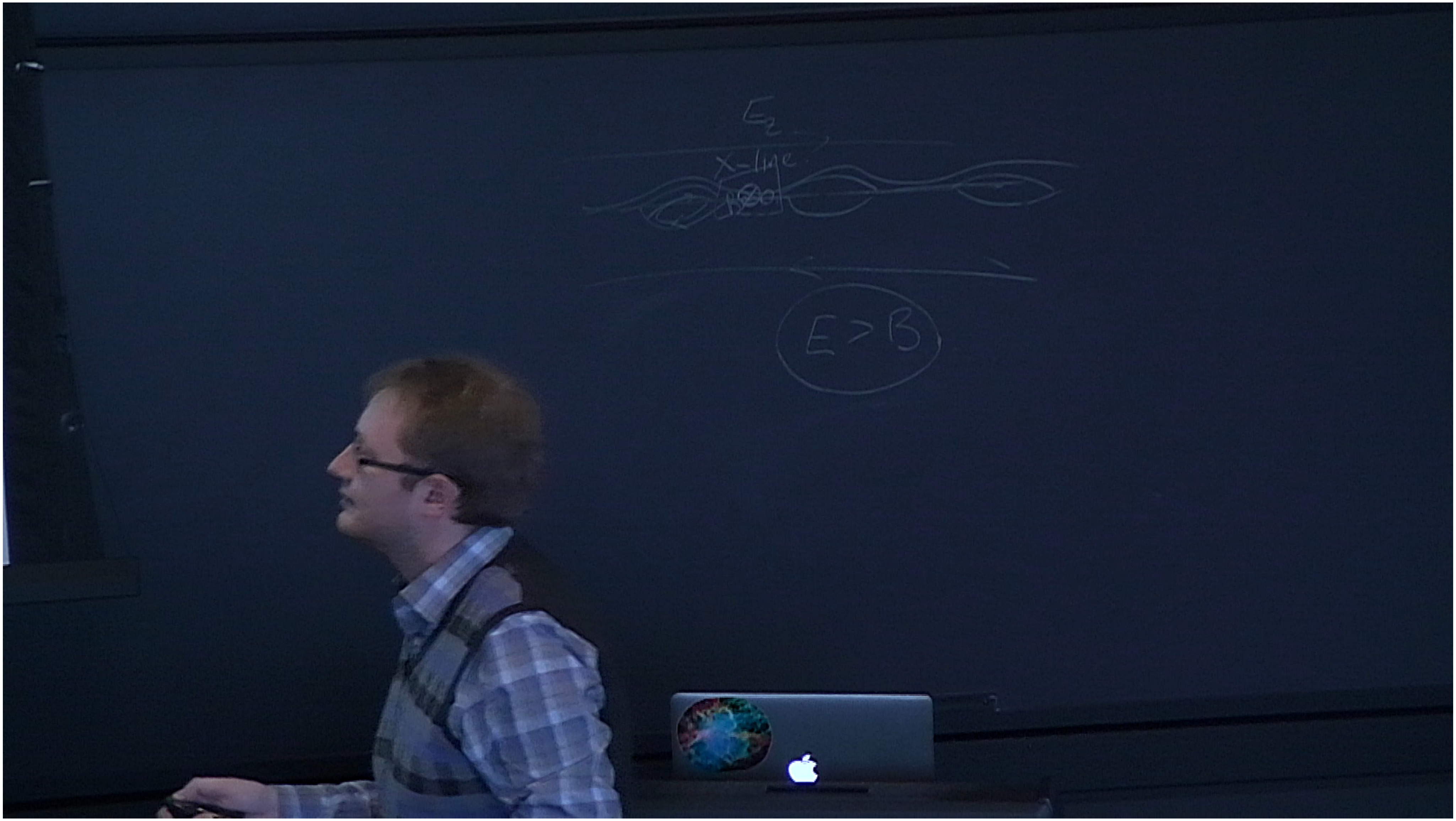
$$\sigma = \frac{B^2}{4\pi n_e m_e c^2} \gg 1$$

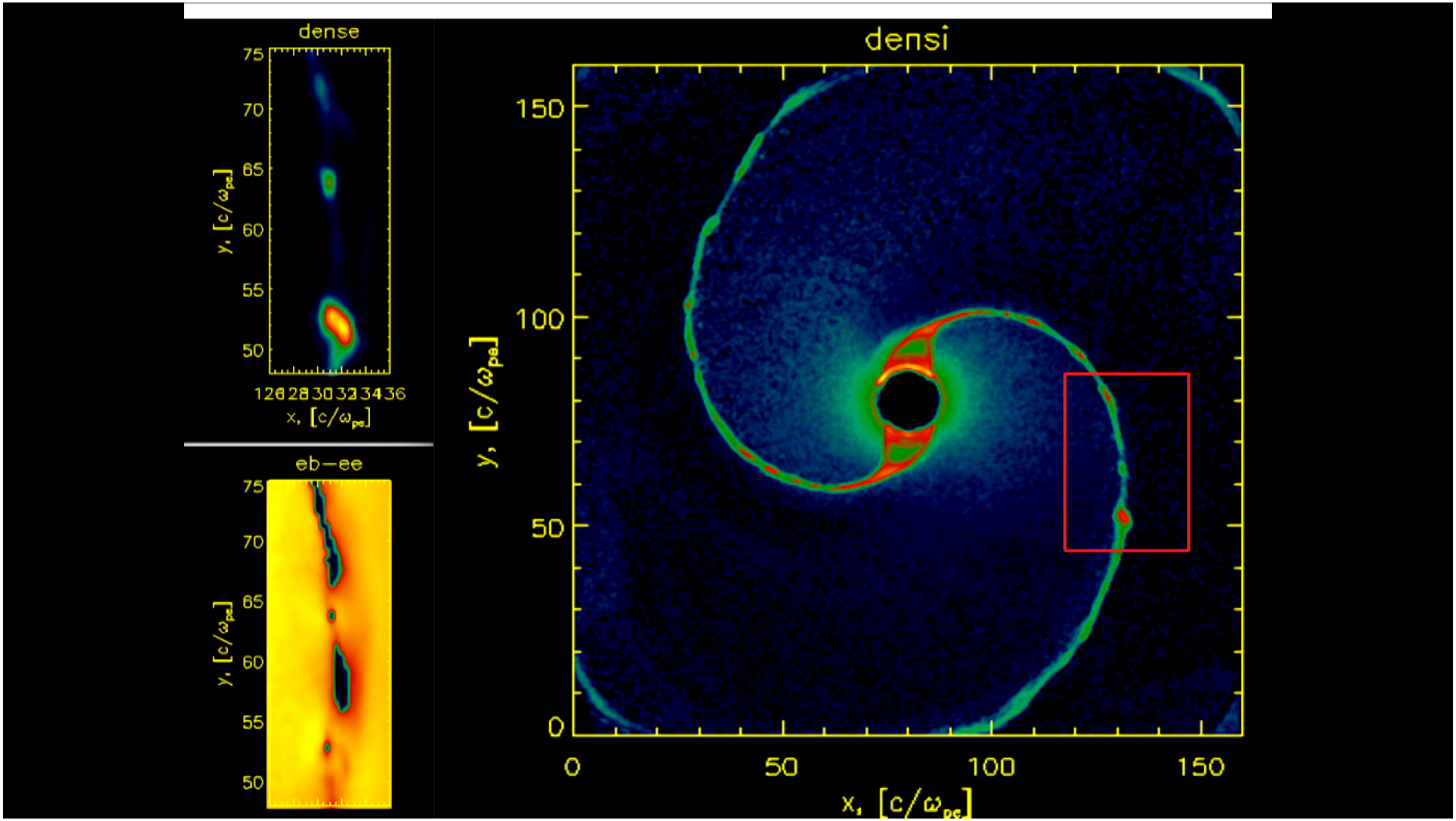


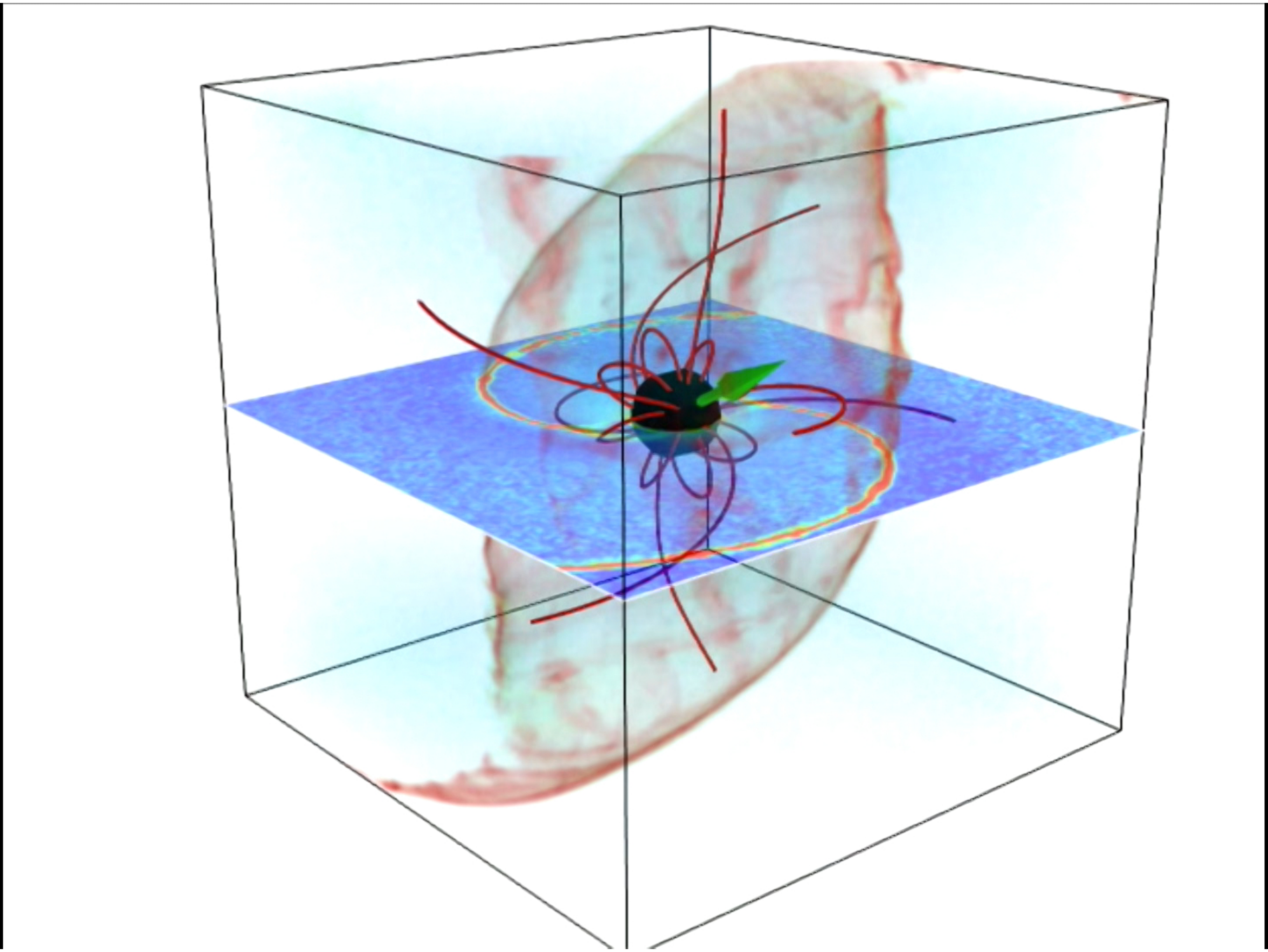
Equatorial plane

Plasmoid instability develops

E>B regions are confined to the current sheet


E_z
x-line
$B \approx 0$
$E > B$

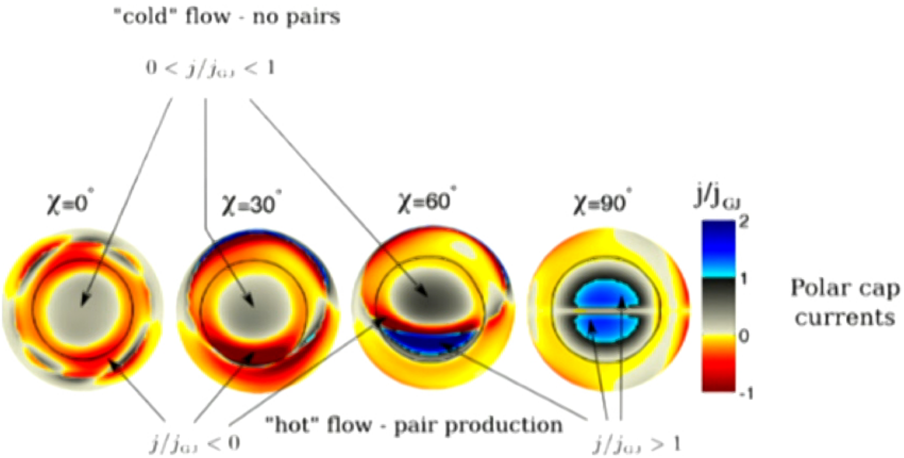

dense
75
70
65
60
55
50
y, [c/ωpe]
26 28 30 32 34 36
x, [c/ωpe]
eb−ee
75
70
65
60
55
50
y, [c/ωpe]
densi
150
100
50
0
y, [c/ωpe]
0
50
100
150
x, [c/ωpe]



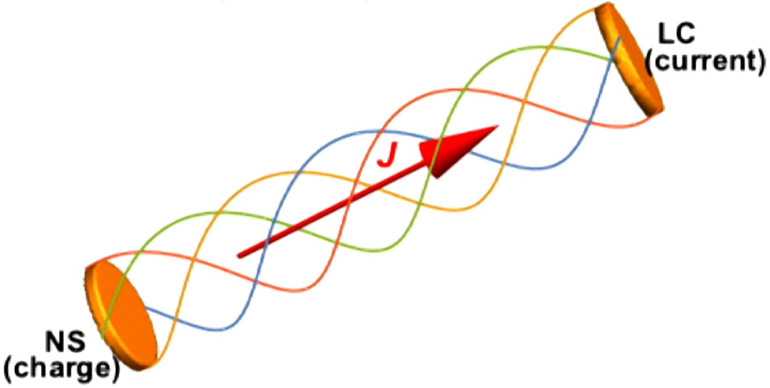
Discharge operation

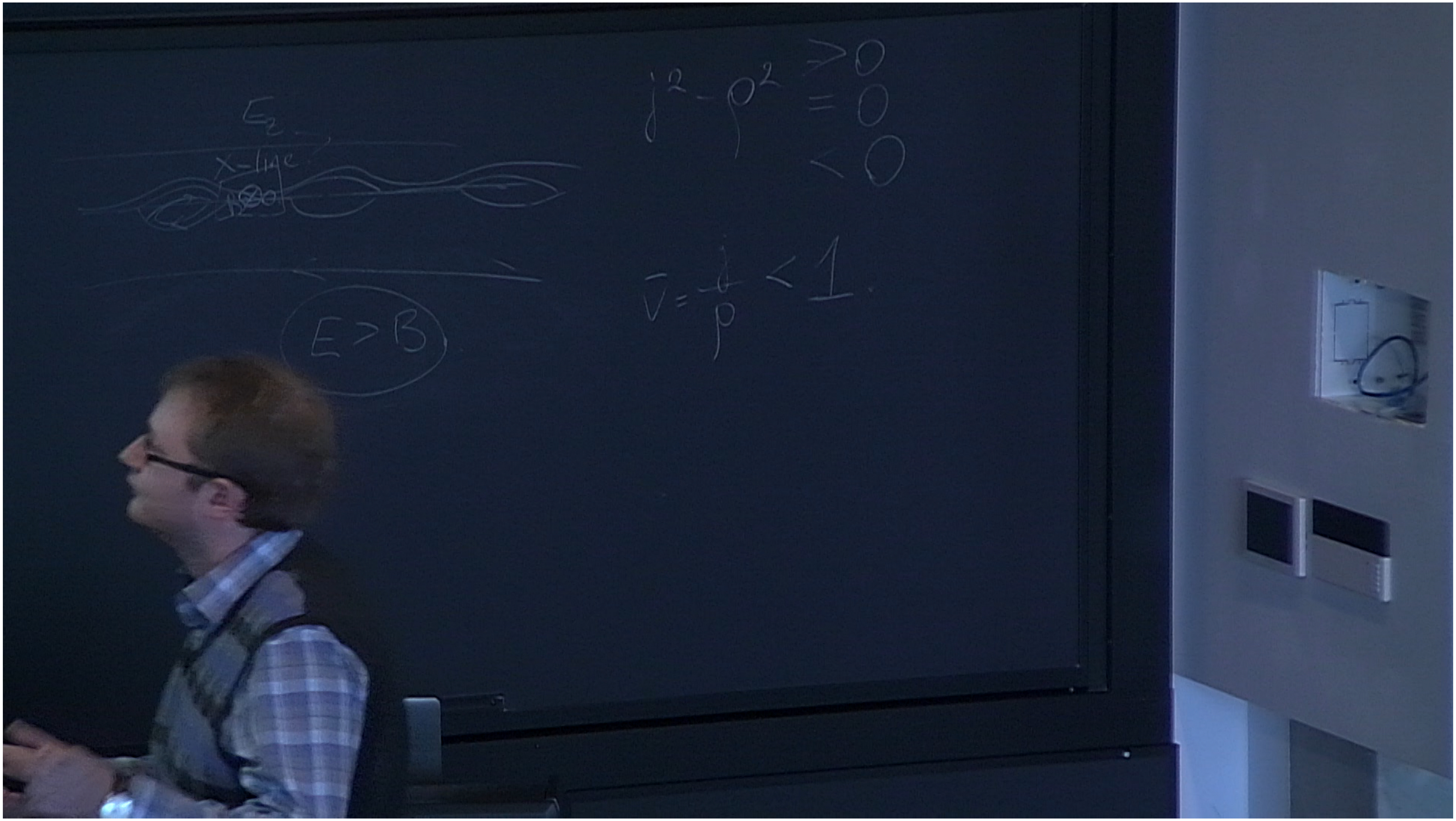
- Need to sustain both charge and current density. Key quantity is $j/c\rho_{\mathrm{GJ}}$
- If j<charge density*c, charges are advected with non-relativistic velocity
- Current is set by twist of the field lines at LC

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?



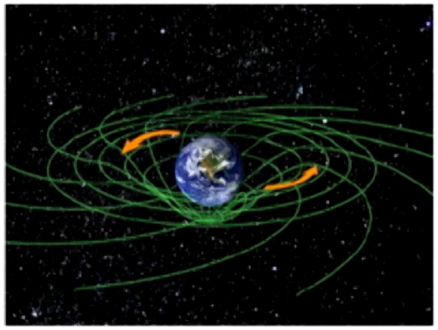
Timokhin & Arons, MNRAS, 2013

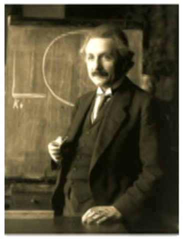



E_z
X-line
$E > B$
$j^2 - \rho^2 \geq 0$
$= 0$
< 0
$\bar{v} = \frac{j}{\rho} < 1$

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.



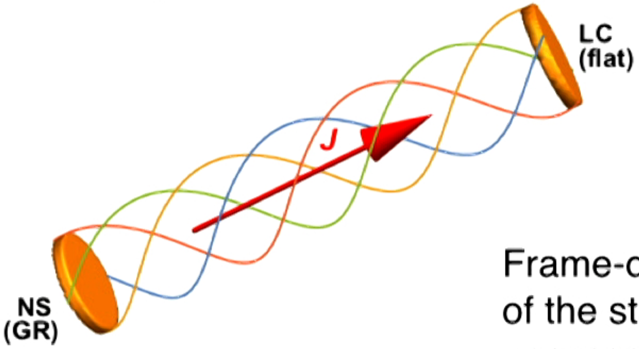


Lense-Thirring frame dragging

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

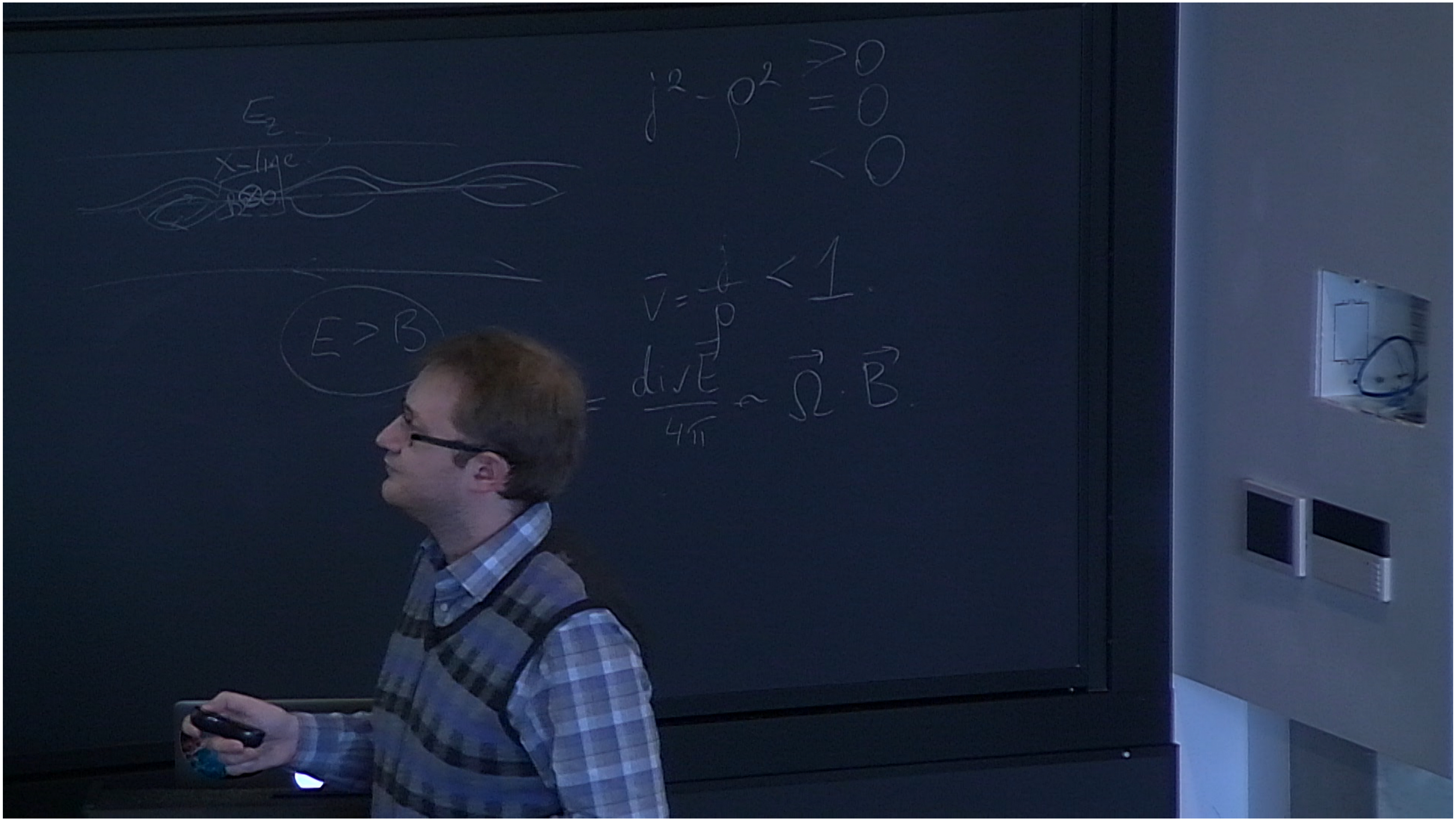
$$\nabla \times \left(\alpha \vec{E} + \boxed{\frac{\vec{\beta}}{c} \times \vec{B}}\right) = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t},$$

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



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). Beskin 1990, Muslimov & Tsygan 1992

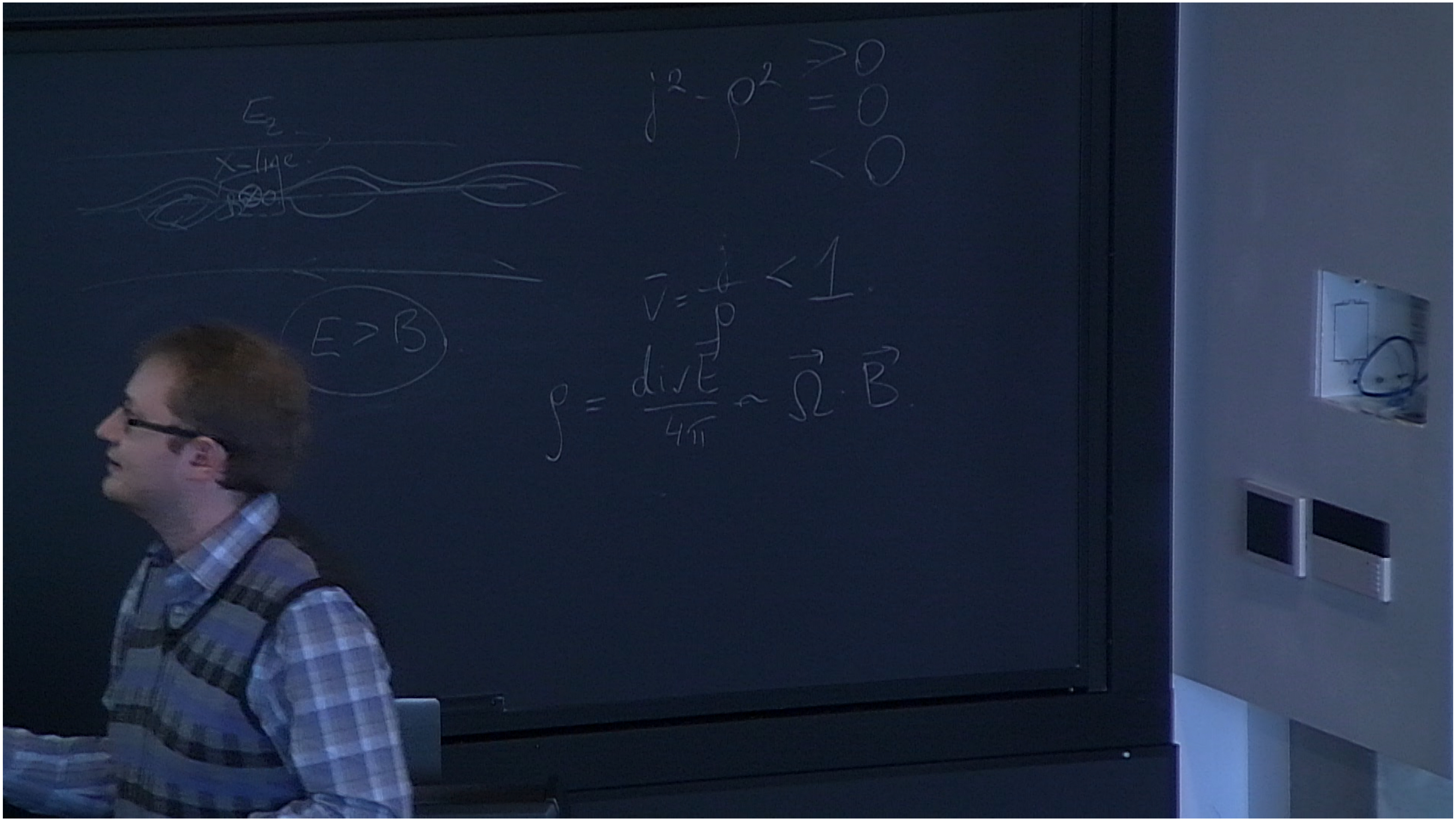
$$\frac{J_{\hat{r}}}{\rho_{GJ}c} \approx \left(\frac{J_{\hat{r}}}{\rho_{GJ}c}\right)_{\text{flat}} \frac{1}{1 - \omega_{LT}/\Omega_*}$$



$$j^2 - \rho^2 \begin{array}{l} > 0 \\ = 0 \\ < 0 \end{array}$$

$$\bar{v} = \frac{j}{\rho} < 1.$$

$$\rho = \frac{\mathrm{div}\, \vec{E}}{4\pi} \sim \vec{\Omega} \cdot \vec{B}.$$



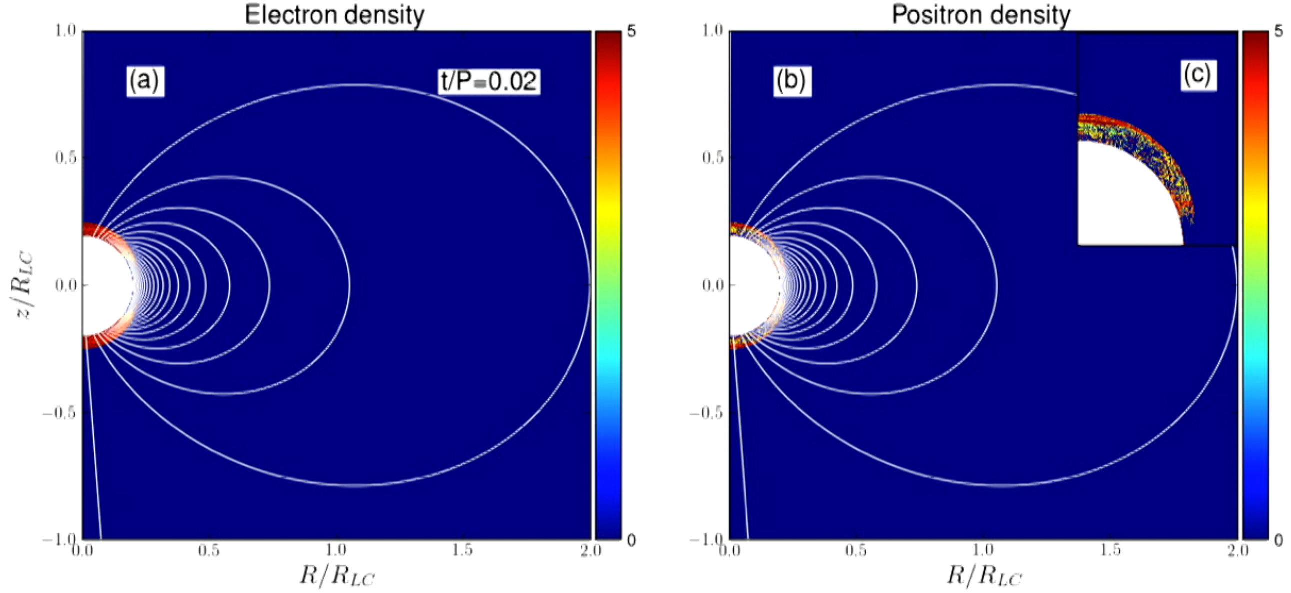
$$\boxed{E > B}$$

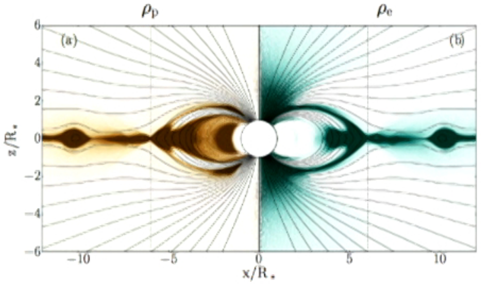
$$j^2 - \rho^2 \begin{array}{l} > 0 \\ = 0 \\ < 0 \end{array}$$

$$\bar{v} = \frac{j}{\rho} < 1$$

$$\rho = \frac{\operatorname{div} \vec{E}}{4\pi} \sim \vec{\Omega} \cdot \vec{B}$$

GR aligned rotator





Chen & Beloborodov, ApJ, 2014

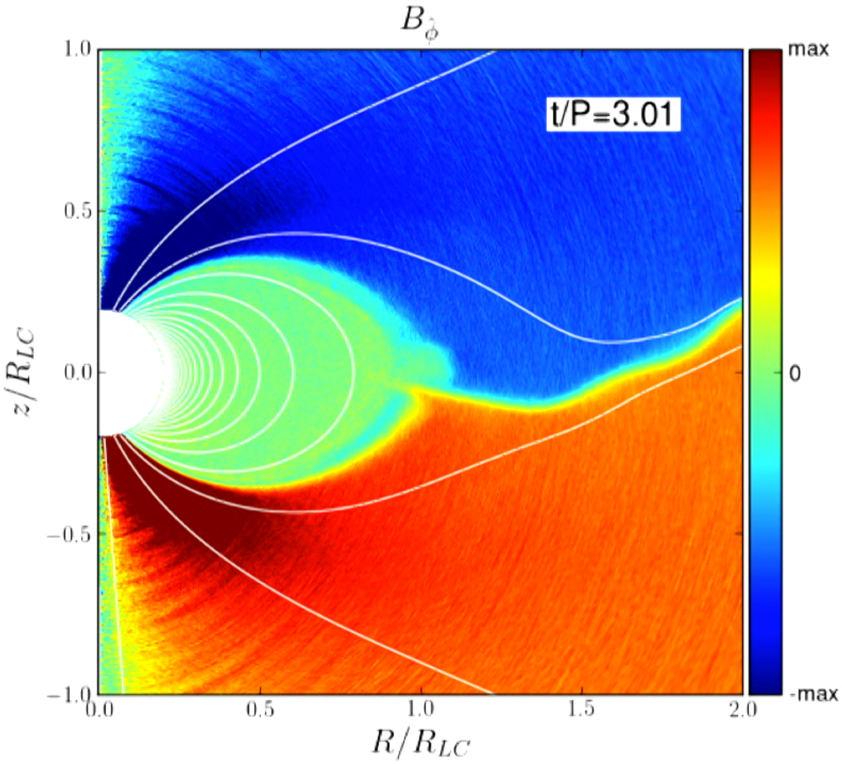
Flat space solution, no pair production

Philippov et al., 2015 ApJ

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

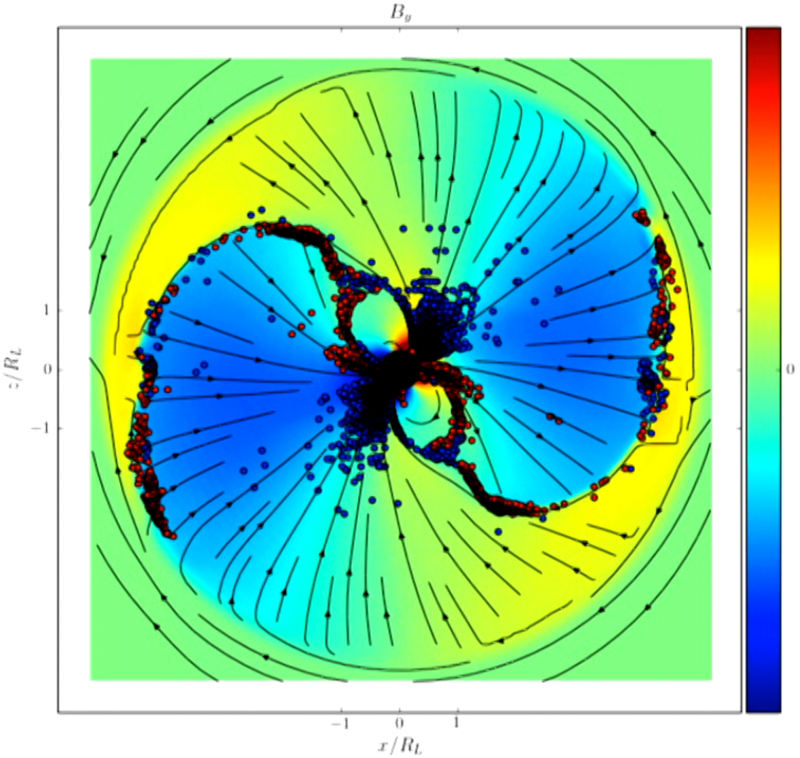
Implications for radio emission

- 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 (see also Beloborodov 2008, Timokhin & Arons 2013)



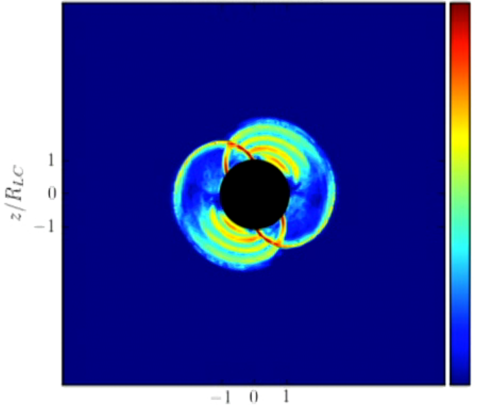
GR oblique models: where pair formation happens?

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

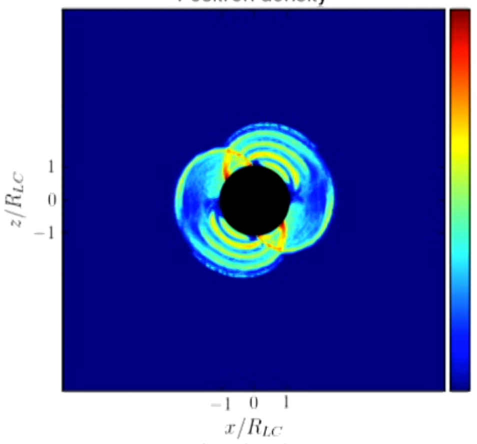


Philippov & Spitkovsky, in preparation

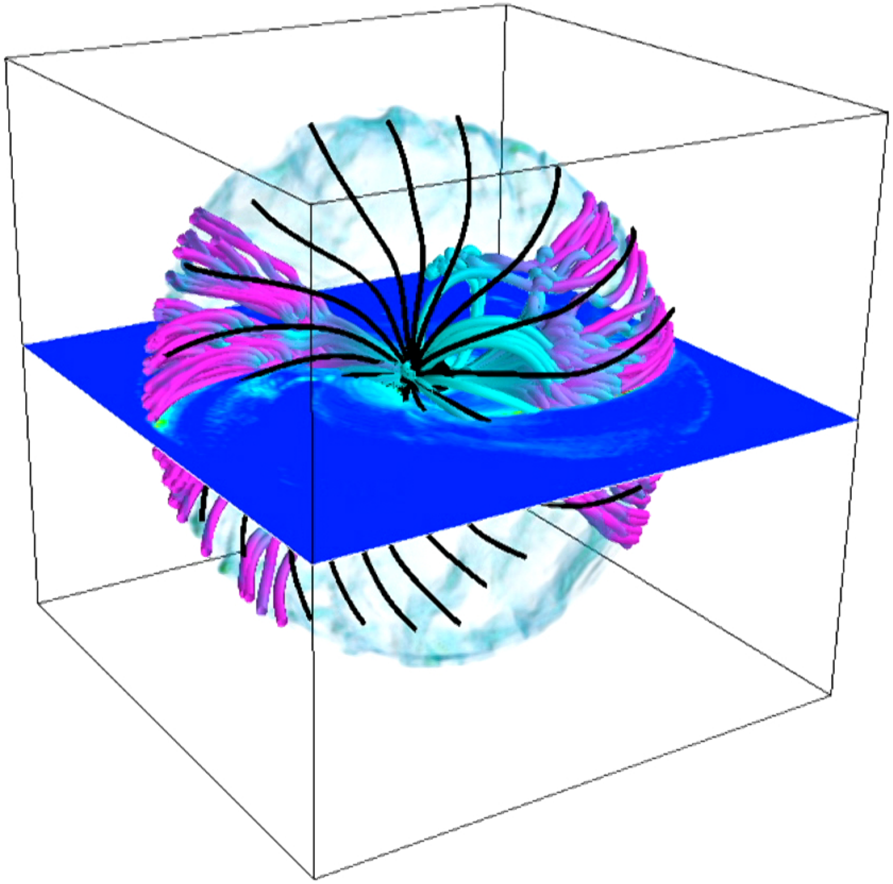
Electron density



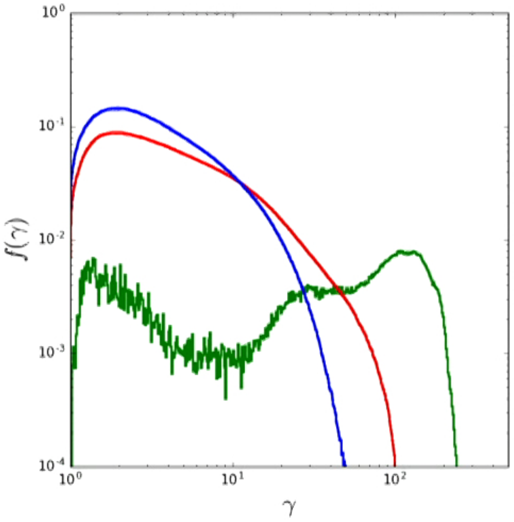
Positron density



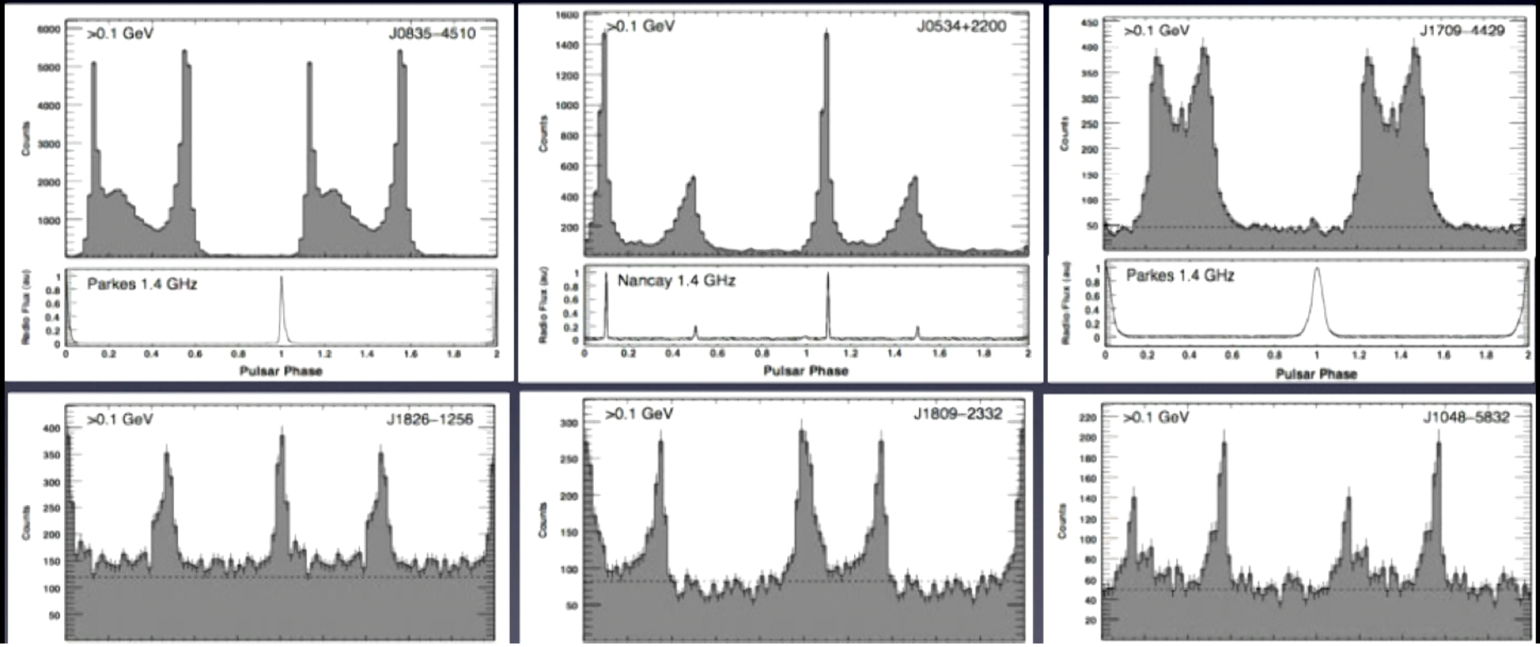
Energetic ions

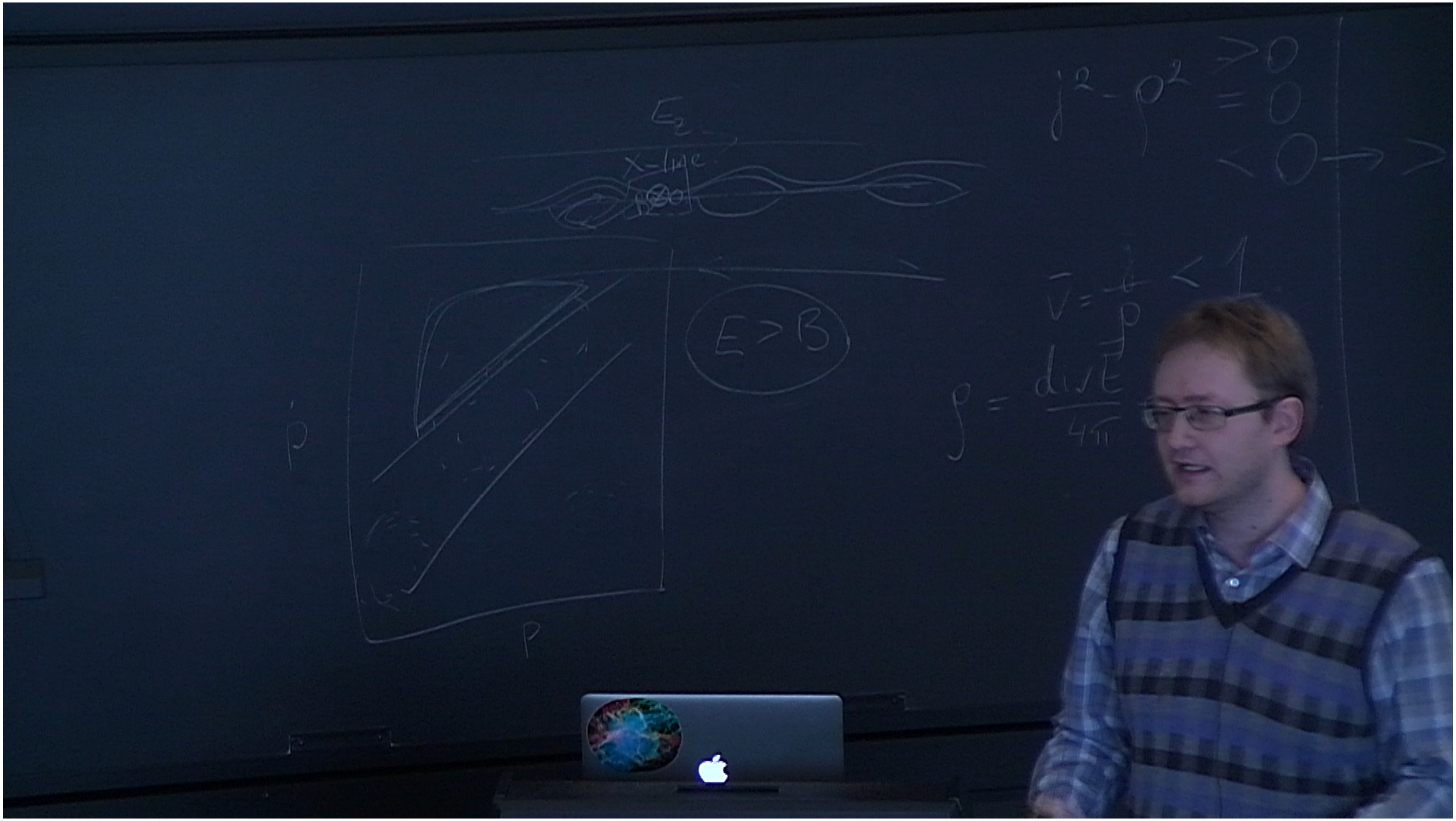


Most energetic particles that are produced in the magnetosphere are ions, extracted from the stellar surface. Gain up to 10% of the open field line voltage. Implications for UHECRs?



Gamma-ray emission from pulsars

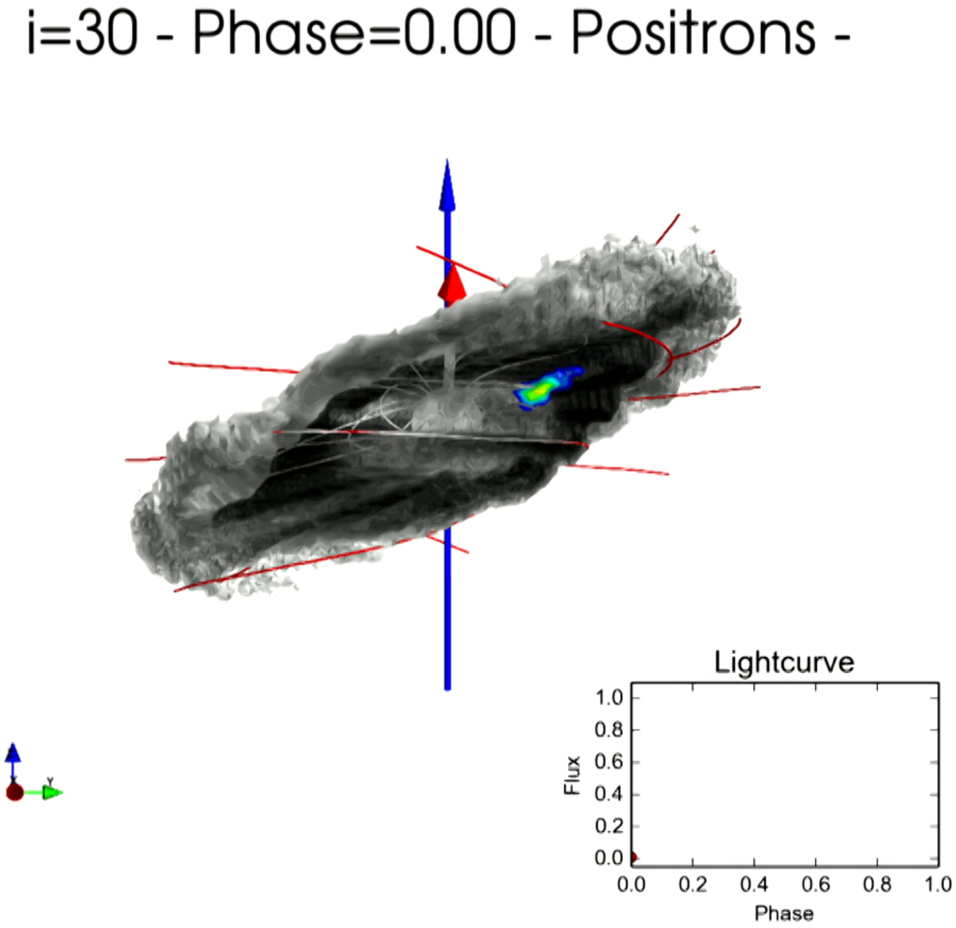



E_z
x-line
B
E > B
$\dot{p}$
p
$j^2 - \rho^2 > 0$
$= 0$
$< 0 \rightarrow >$
$\bar{v} = \frac{j}{\rho} < 1$
$\rho = \frac{\mathrm{div}\, E}{4\pi}$

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.

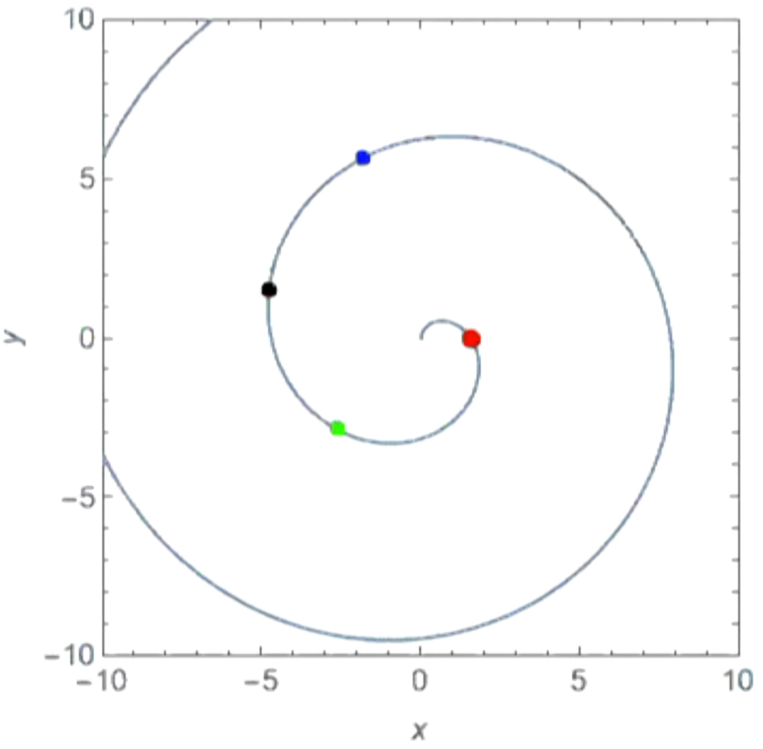
Cerutti, Philippov & Spitkovsky
MNRAS 2016



Gamma-ray modeling

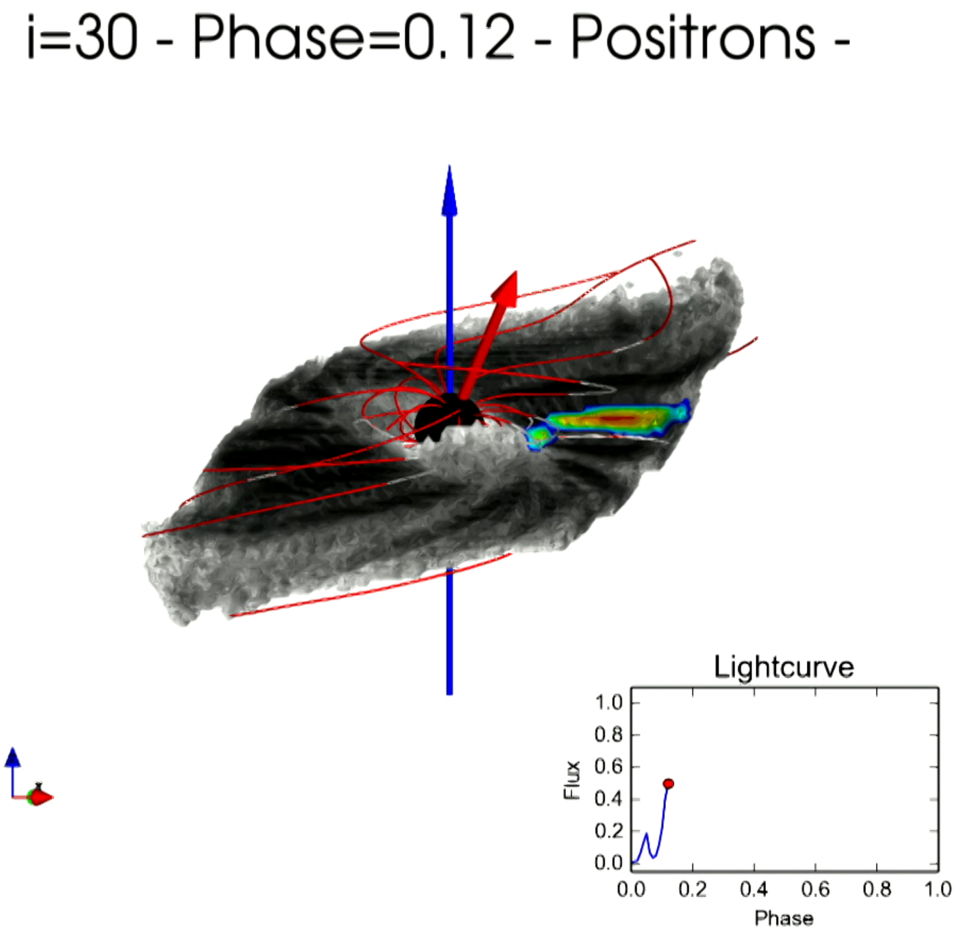
- Simulations prefer current sheet as a particle accelerator. Particles radiate synchrotron radiation.
- We apply radiative cooling on particles and collect photons.
- Observe caustic emission.
- Predict gamma-ray efficiencies 1-20% depending on the inclination angle. Higher inclinations are much less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

Cerutti, Philippov & Spitkovsky
MNRAS 2016



Gamma-ray modeling

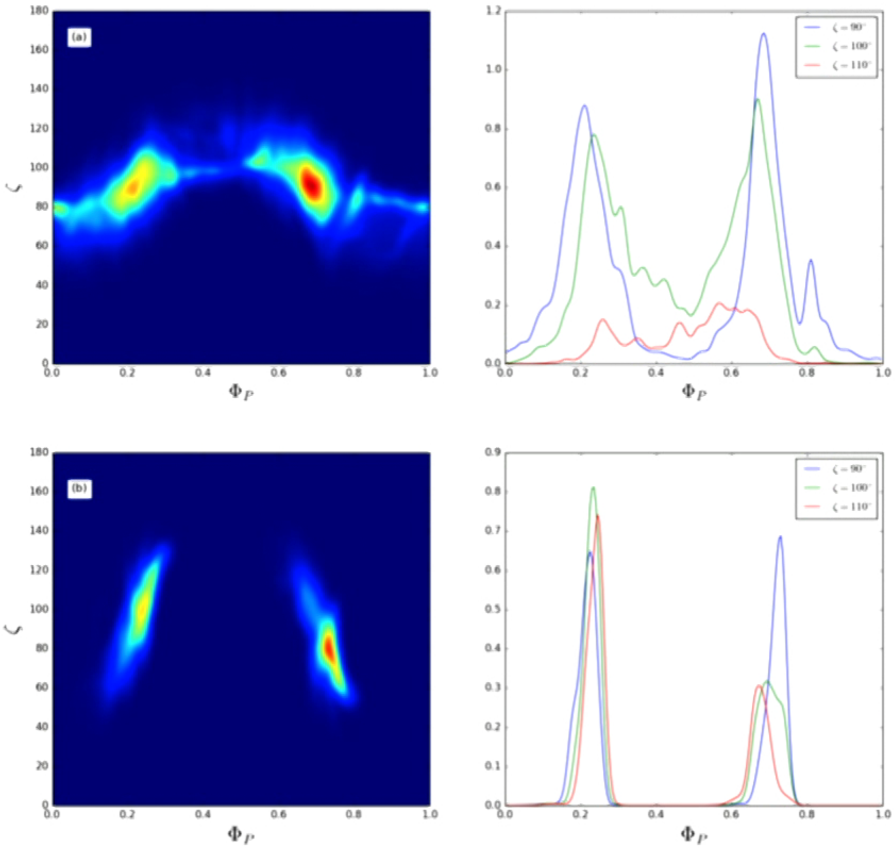
- Simulations prefer current sheet as a particle accelerator. Particles radiate synchrotron emission.
- We apply radiative cooling on particles and collect photons.
- Observe caustic emission.
- Neutral injection at the surface.
- Predict gamma-ray efficiencies 1-20% depending on the inclination angle.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



Cerutti, Philippov & Spitkovsky
MNRAS 2016

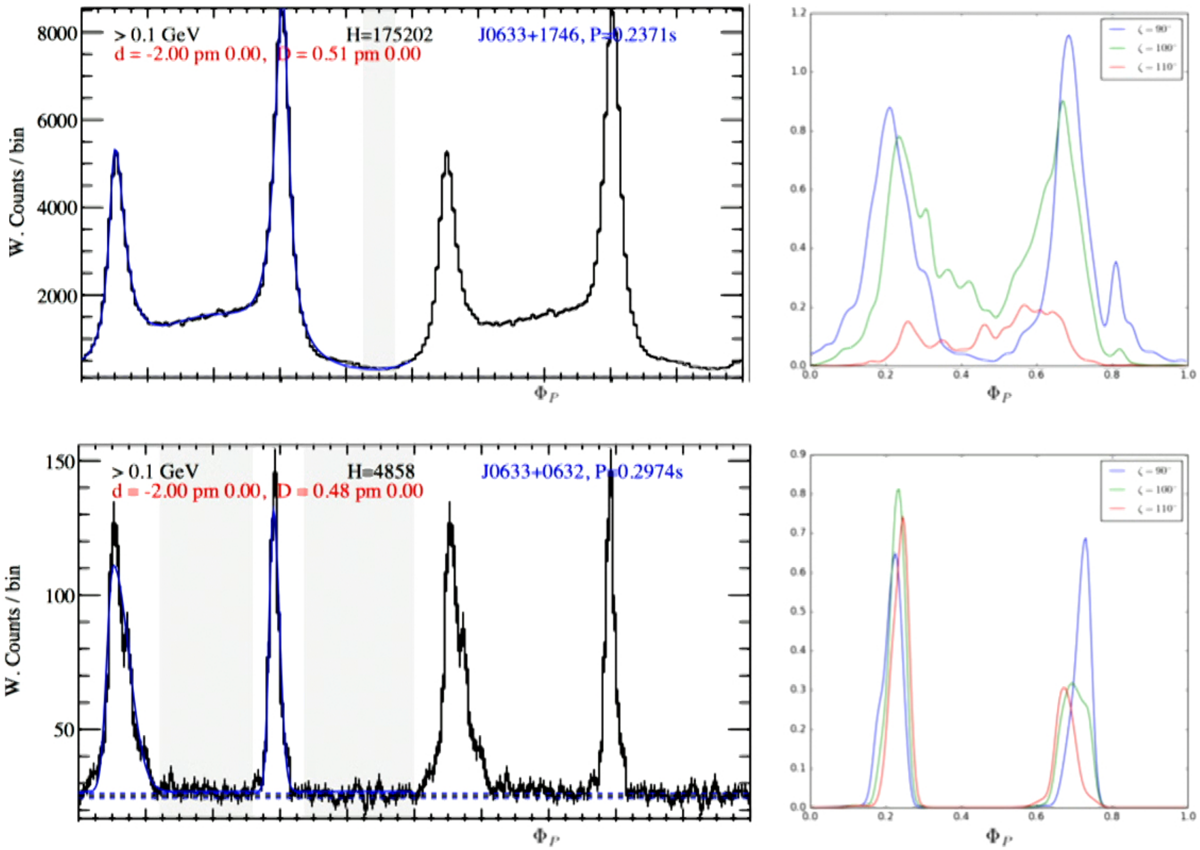
Lightcurves & spectra

- Observe caustic emission.
- Get a two-peak light-curve,with significant bridge emission for low inclination angles.



Philippov & Spitkovsky, in preparation

Lightcurves & spectra

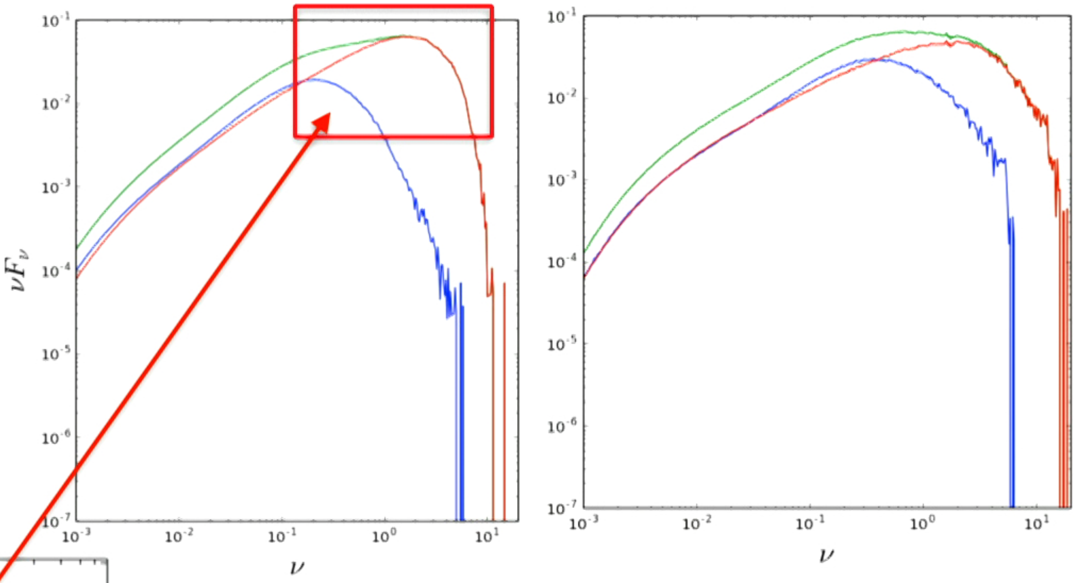


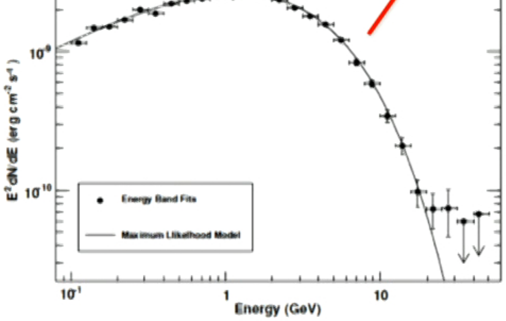
Philippov & Spitkovsky, in preparation

Lightcurves & spectra

- Particle acceleration is not limited by synchrotron cooling.
- Easily produce photons higher than the burnoff limit.

Photon spectra

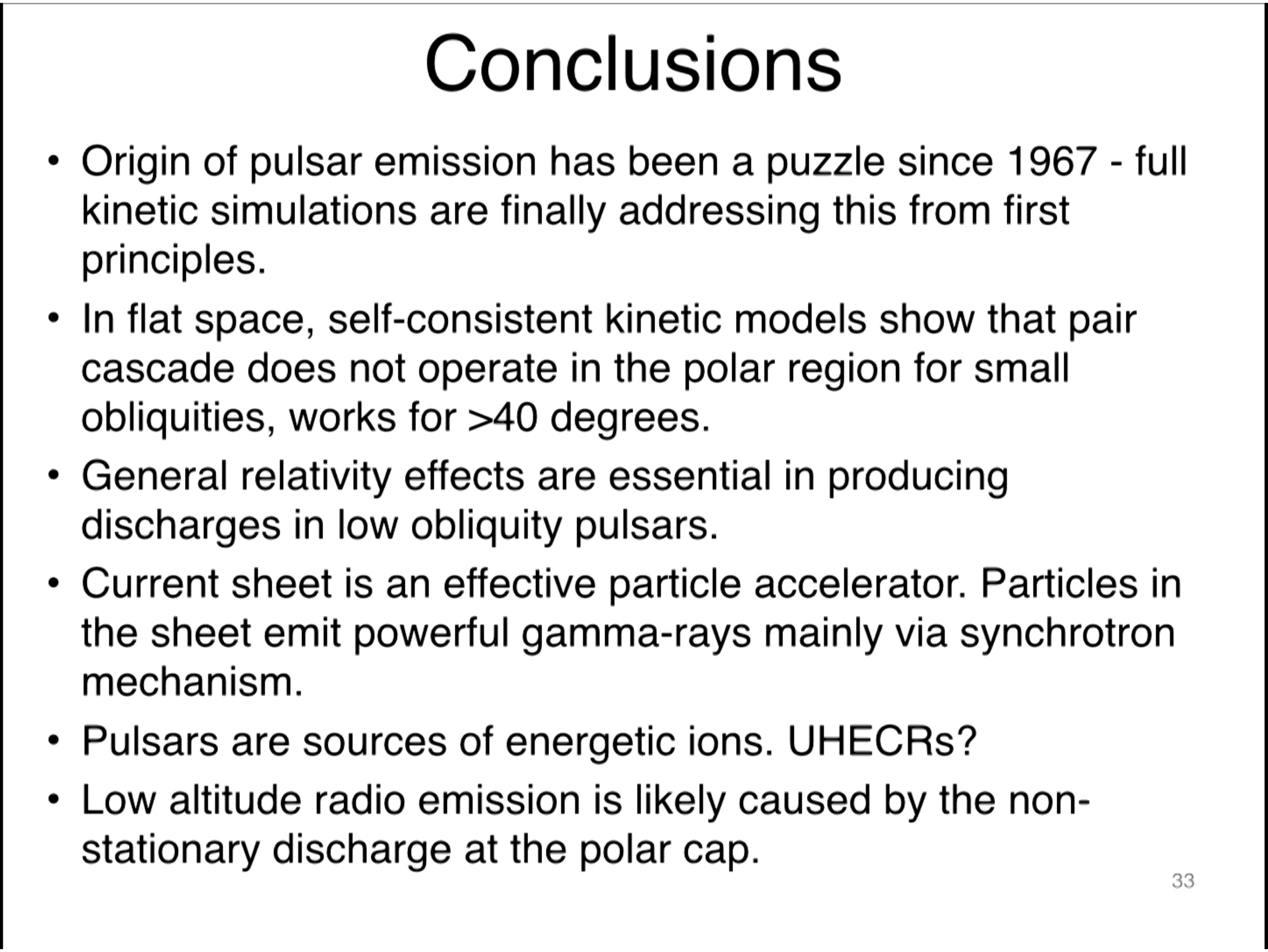




$$\nu_{\max} \approx 3e\,(0.1 B_{\rm LC})\,\sigma_{\rm LC}^2/4\pi m_e c$$

Pair production sets the sigma parameter.

Lyubarsky 1996
Philippov & Spitkovsky, in preparation



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.