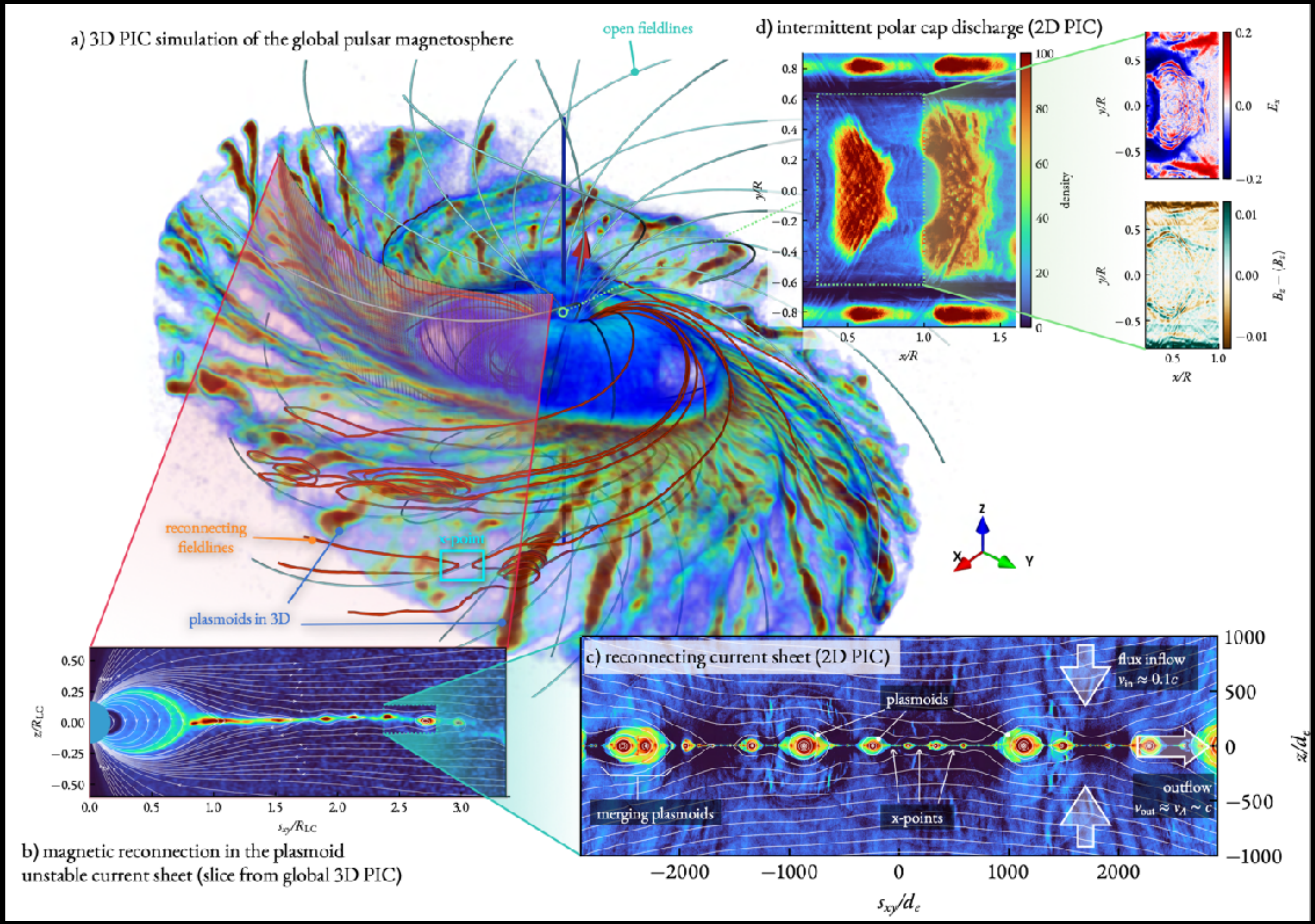
Pulsar magnetospheres and their radiation



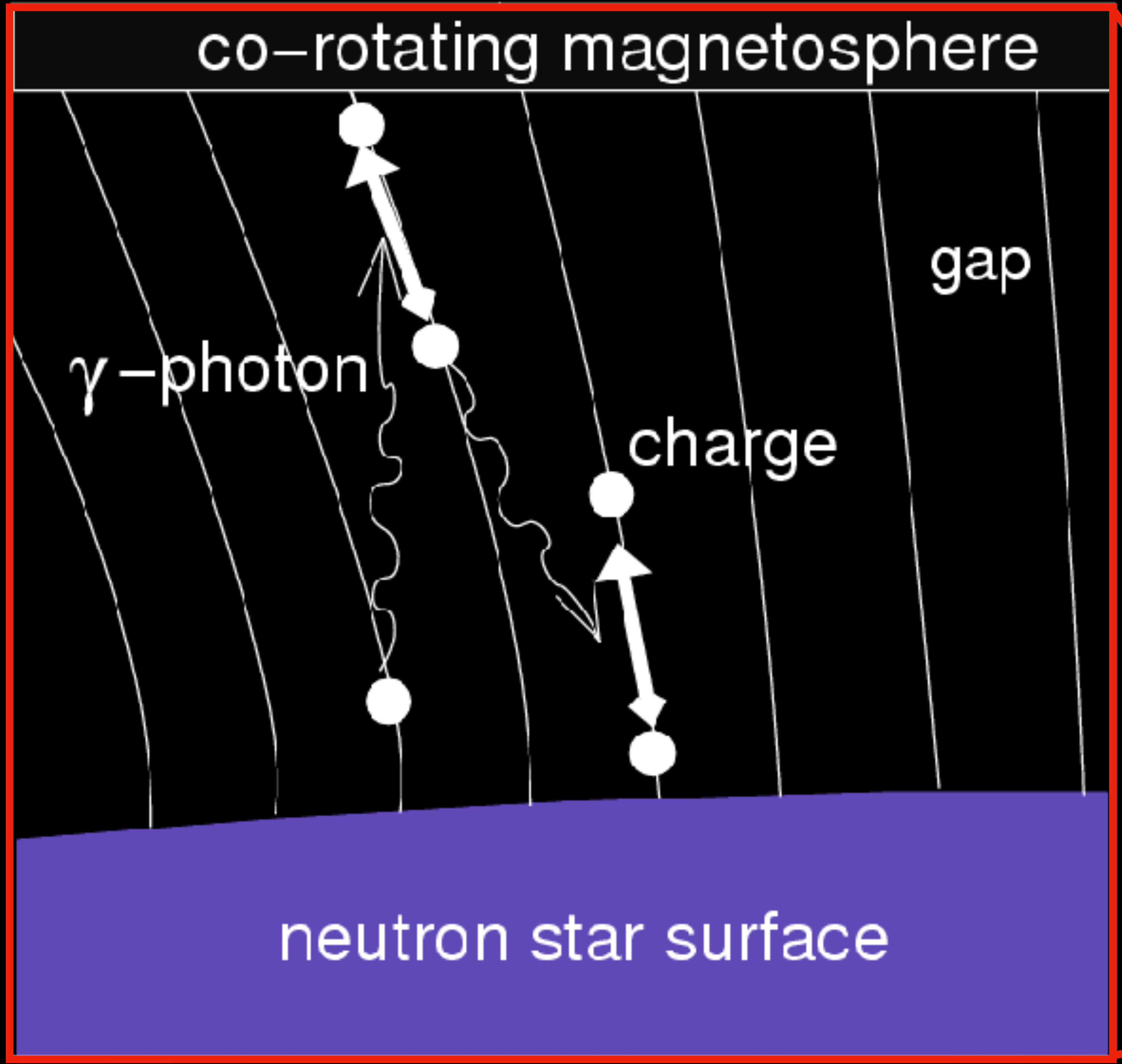
Sasha Philippov (Maryland)

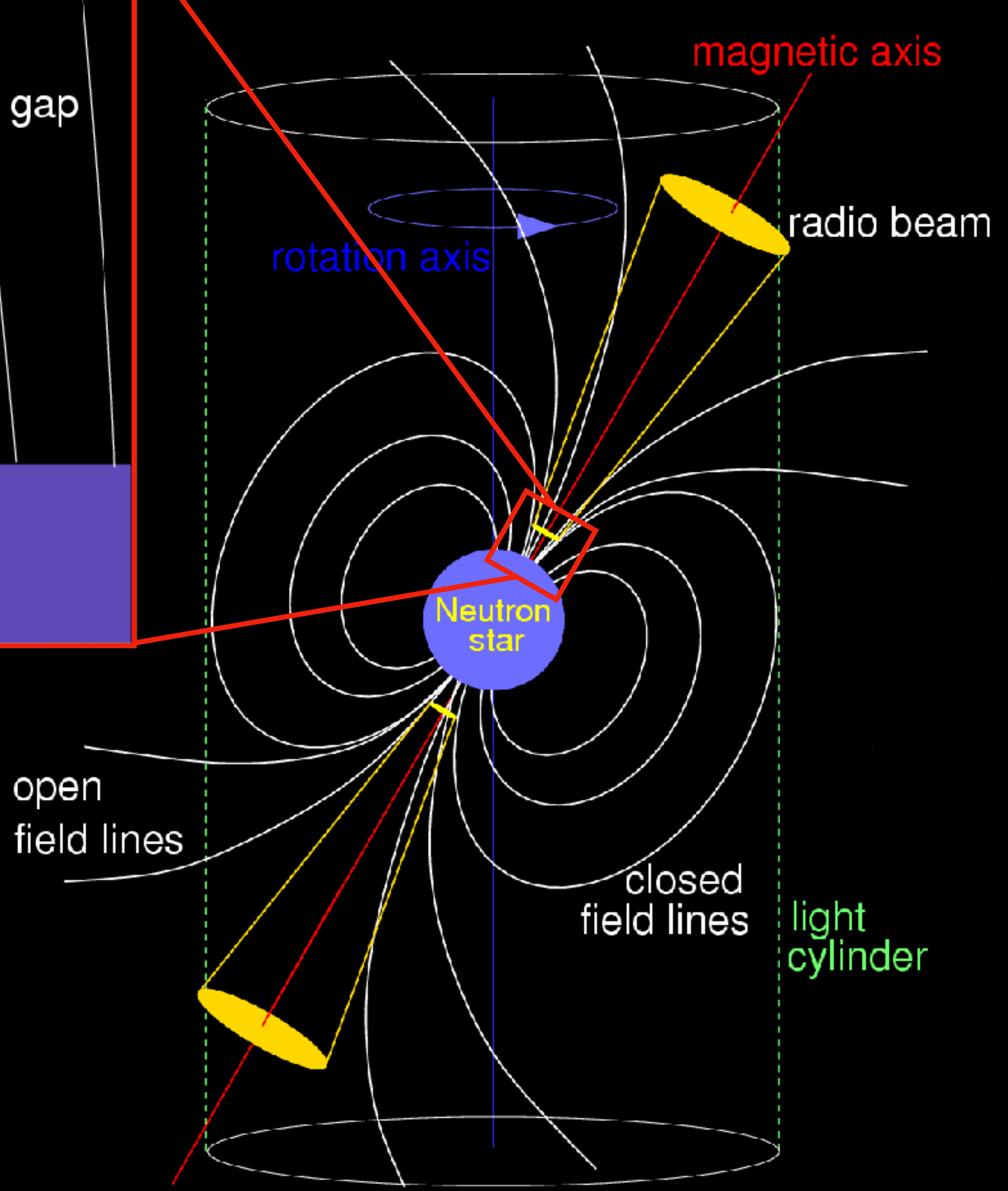
with:

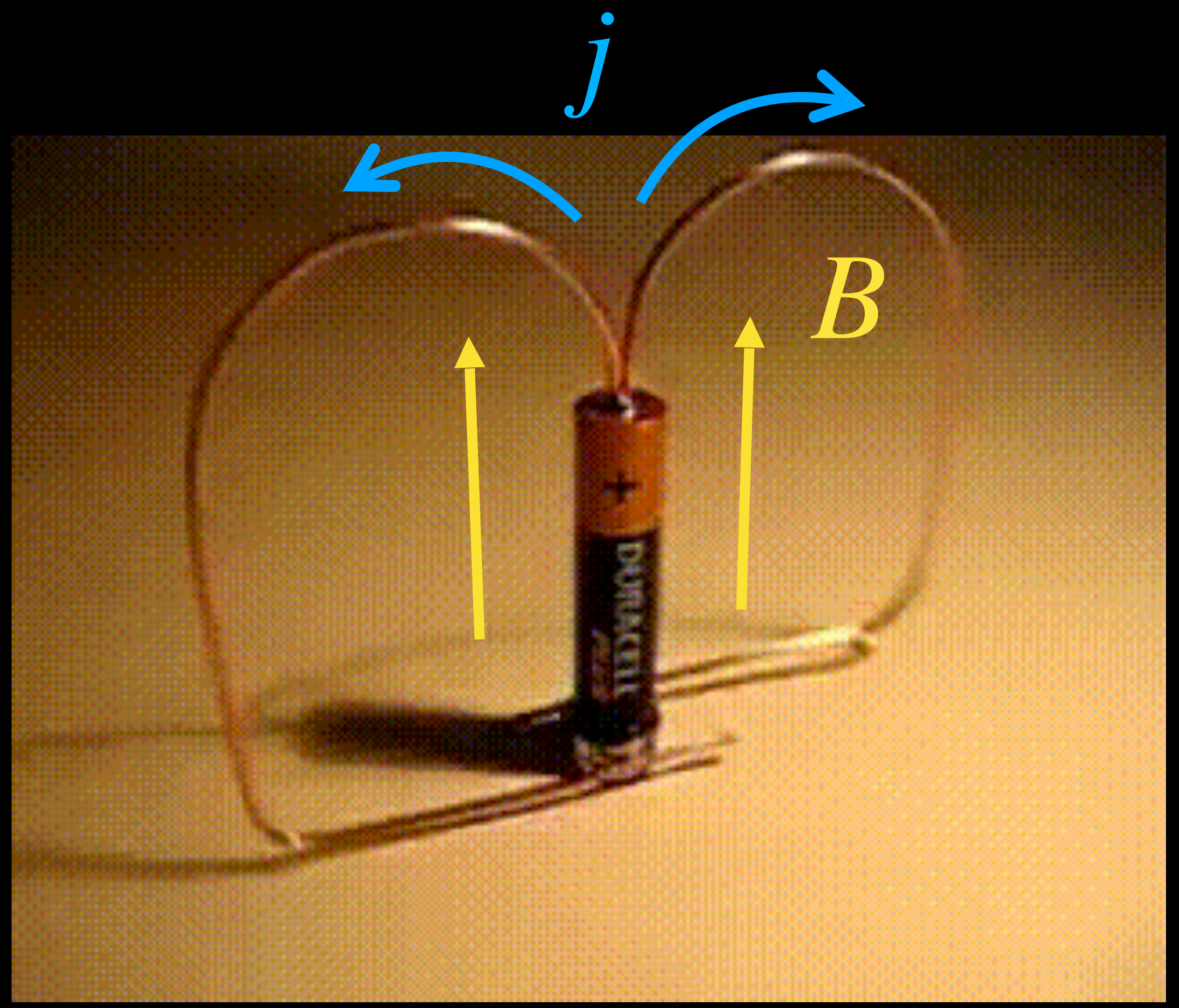
Anatoly Spitkovsky (*Princeton)*
Hayk Hakobyan *(Columbia)*
Benoit Cerutti (*Grenoble, France*)
Sam Gralla (*Arizona*)
Andrey Timokhin (*Zielona Gora, Poland*)
Dmitri Uzdensky (*Colorado*)
Libby Tolman *(IAS, Flatiron)*

Philippov & Kramer, 2022, Annual Reviews of Astronomy & Astrophysics

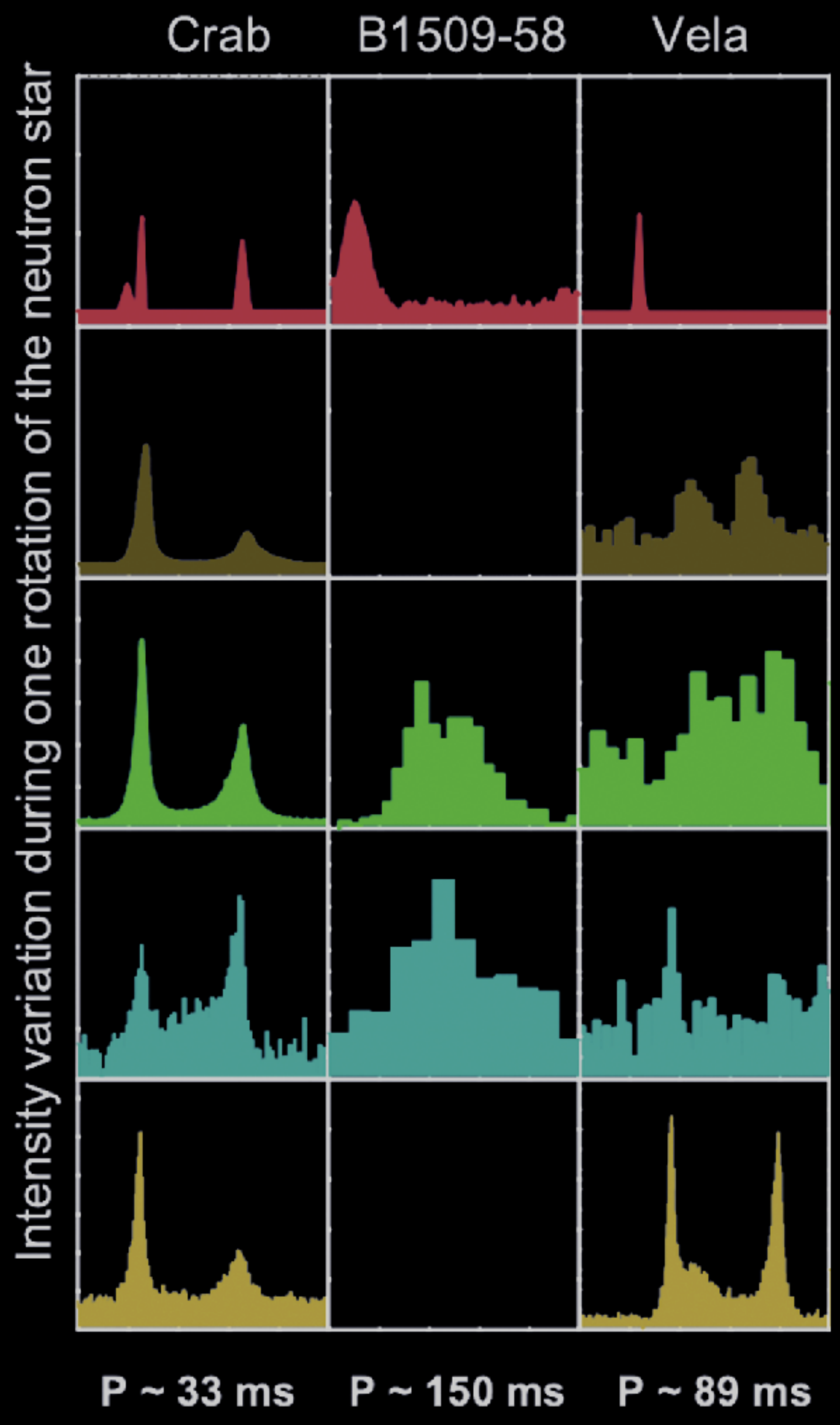
What is a pulsar?







Unipolar induction



Standard pulsar

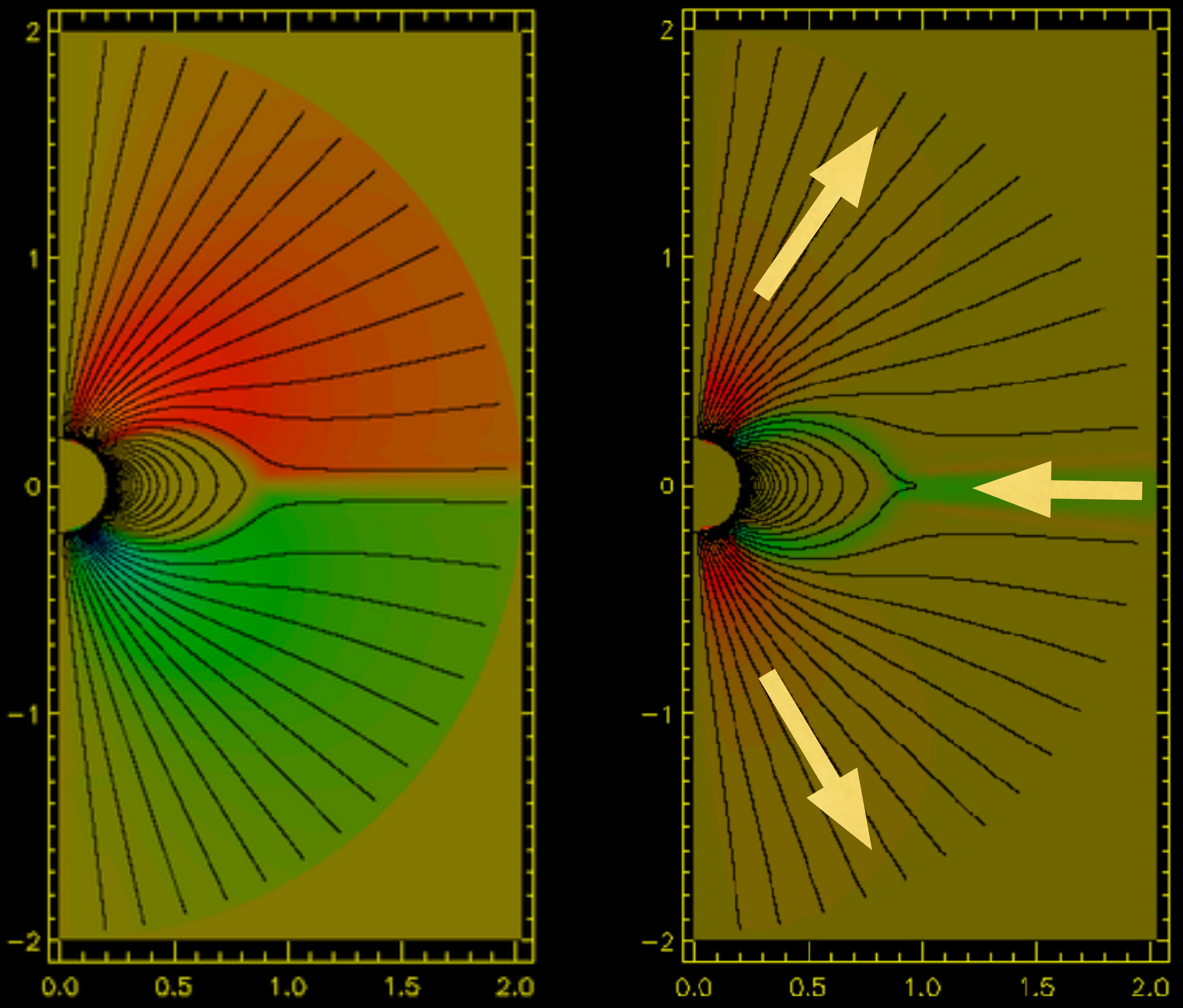
Force-free paradigm:

$$4\pi\rho_c = \nabla \cdot \boldsymbol{E}$$

$$\rho_c \boldsymbol{E} + \boldsymbol{j} \times \boldsymbol{B} = \frac{\mathrm{d}\rho_m \boldsymbol{u}}{\mathrm{d}t} + \text{pressure}, \ \boldsymbol{E} \cdot \boldsymbol{B} = 0 \quad \Rightarrow \quad \boldsymbol{j} = \frac{c}{4\pi} \nabla \cdot \boldsymbol{E} \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} + \frac{c}{4\pi} \frac{(\boldsymbol{B} \cdot \nabla \times \boldsymbol{B} - \boldsymbol{E} \cdot \nabla \times \boldsymbol{E})\boldsymbol{B}}{B^2}$$

+

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



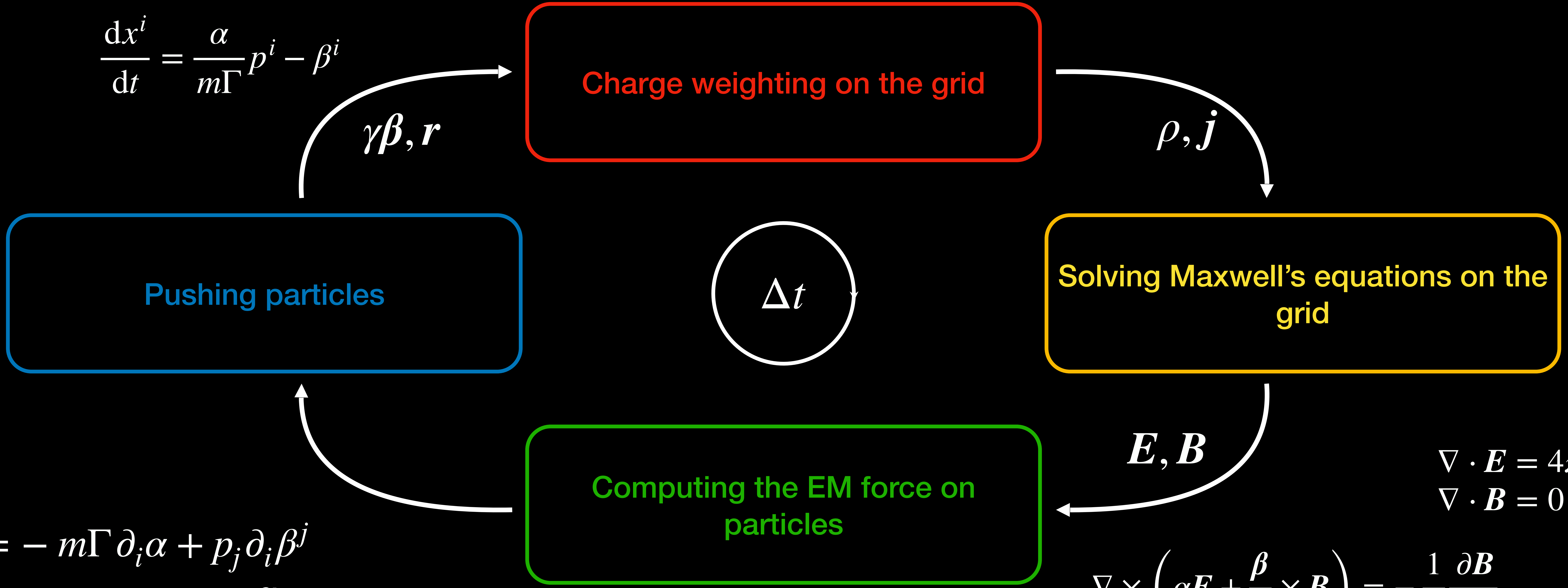
- Y-point;
- closed/open field lines;
- current sheet;
- field lines are asymptotically radial;
- predicts the spindown law:

$$L_{\rm psr} = k_1 \frac{\mu^2 \Omega^4}{c^3}\left(1 + k_2 \sin^2\alpha\right)$$

Contopoulos+ (1999), Spitkovsky (2006), Kalapotharakos (2009), Petri (2012), Tchekhovskoy+ (2014) (MHD)

Plasma Physics on a computer: (GR)(R)PIC

$$\frac{\mathrm{d}x^i}{\mathrm{d}t} = \frac{\alpha}{m\Gamma}p^i - \beta^i$$



$$\nabla \cdot \boldsymbol{E} = 4\pi\rho$$
$$\nabla \cdot \boldsymbol{B} = 0$$

$$\frac{\mathrm{d}p_i}{\mathrm{d}t} = -m\Gamma\,\partial_i\alpha + p_j\partial_i\beta^j - \frac{\alpha}{2\Gamma m}\partial_i\left(\gamma^{lm}\right)p_l p_m + q\left\{\alpha D_i + \epsilon_{ijk}(v^j + \beta^j)B^k\right\}$$

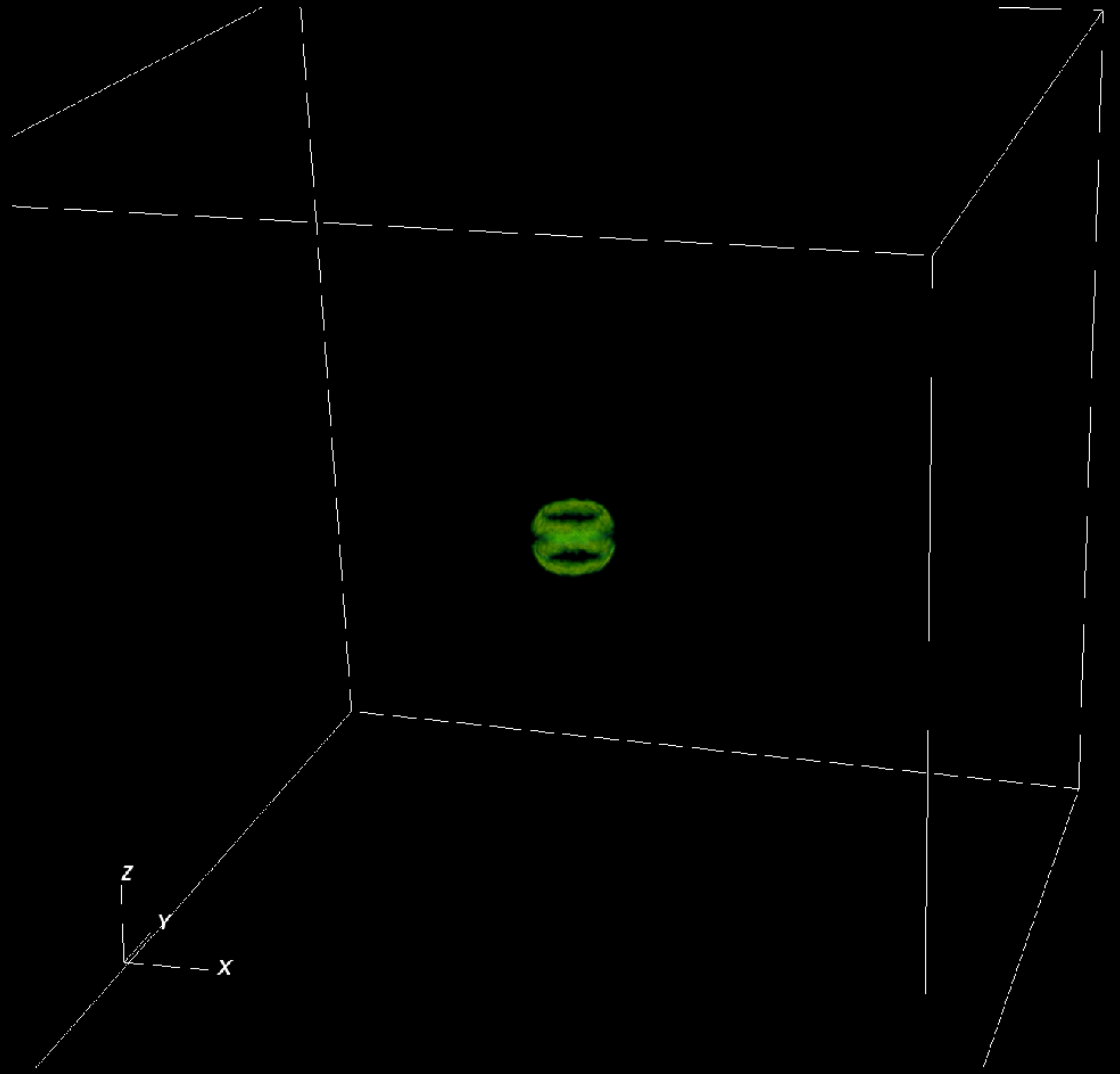
$$\nabla \times \left(\alpha\boldsymbol{E} + \frac{\boldsymbol{\beta}}{c} \times \boldsymbol{B}\right) = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}$$

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

(R) = radiation reaction force, photon emission, multiple pair production mechanisms

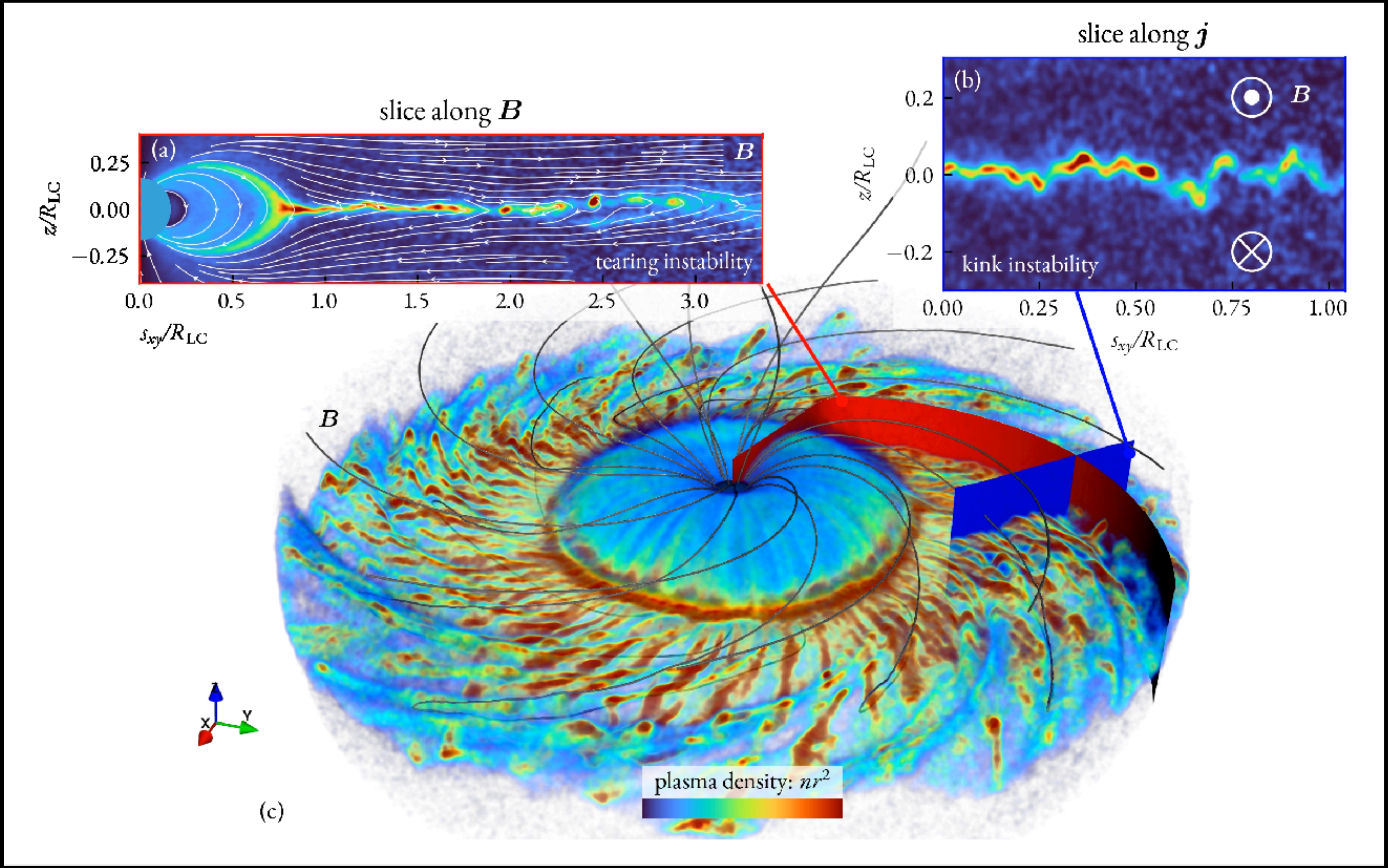
GJ pulsar (no pair production) is dead

- Only free escape from the surface
- Disk-dome solution
- Almost no outflow and spin-down
- Diocotron modes in 3D



Krause-Polstorff, Michel (1985)
Spitkovsky, Arons (2002)
Petri et al. (2002)
Philippov, Spitkovsky (2014)

3D aligned rotator

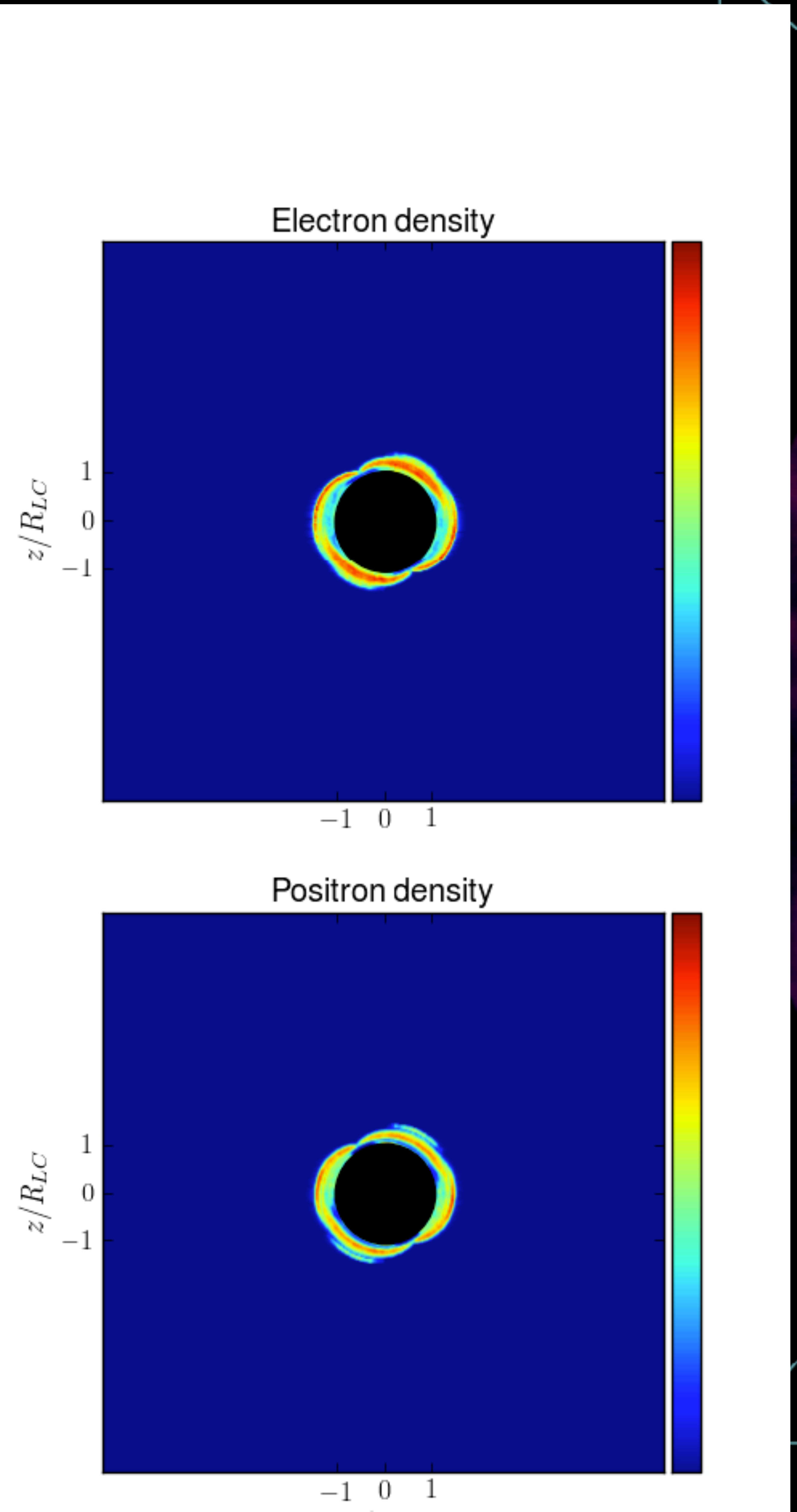


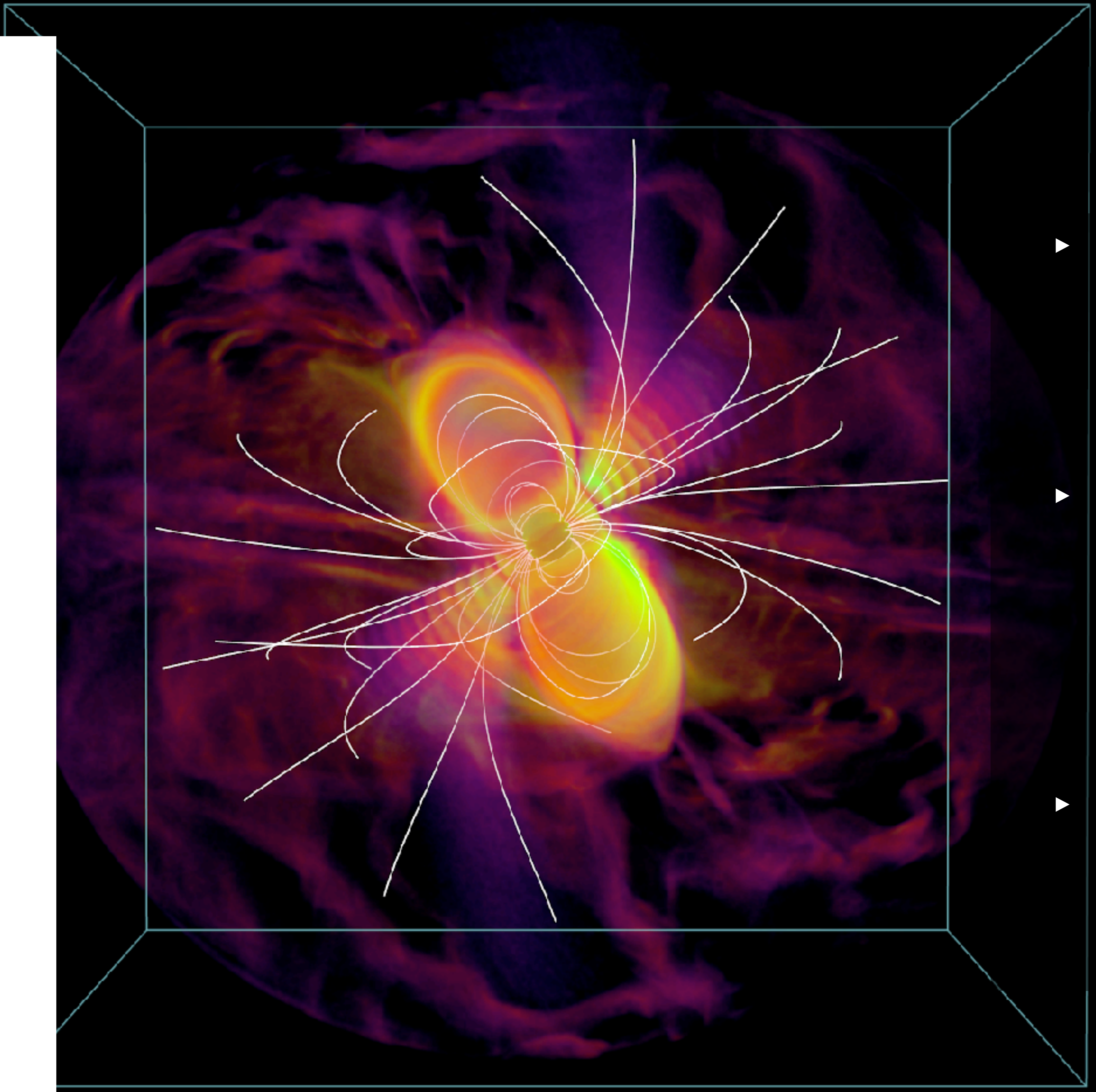
- Non-stationary discharge powers coherent radio emission
- Relativistic magnetic reconnection in the current sheet powers high-energy emission
- Current sheet is unstable to plasmoid (tearing) and drift-kink instabilities

Hakobyan et. al., 2023, ApJ

Oblique rotator

Philippov, Spitkovsky (2018)





- Non-stationary discharge powers coherent radio emission
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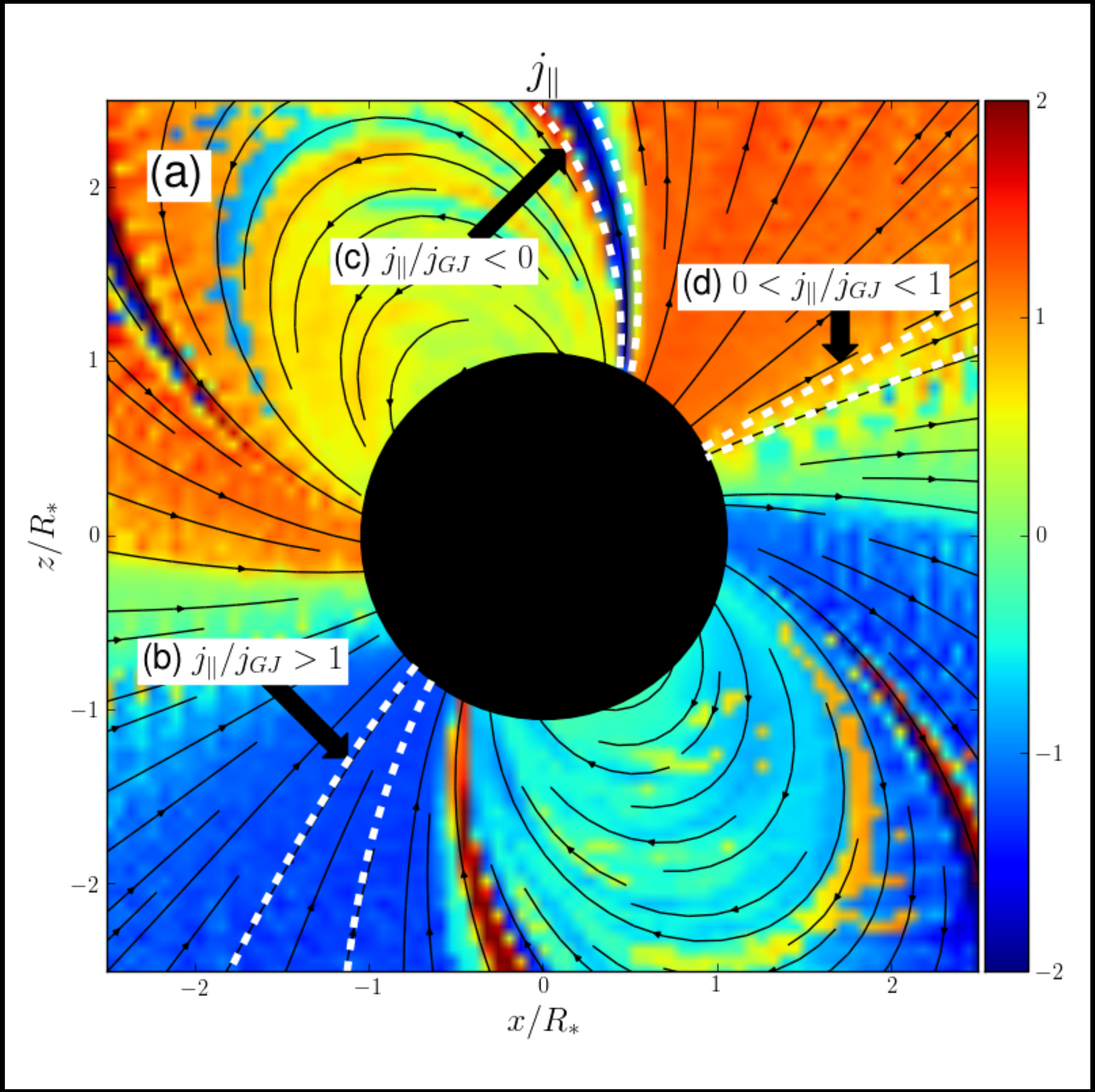
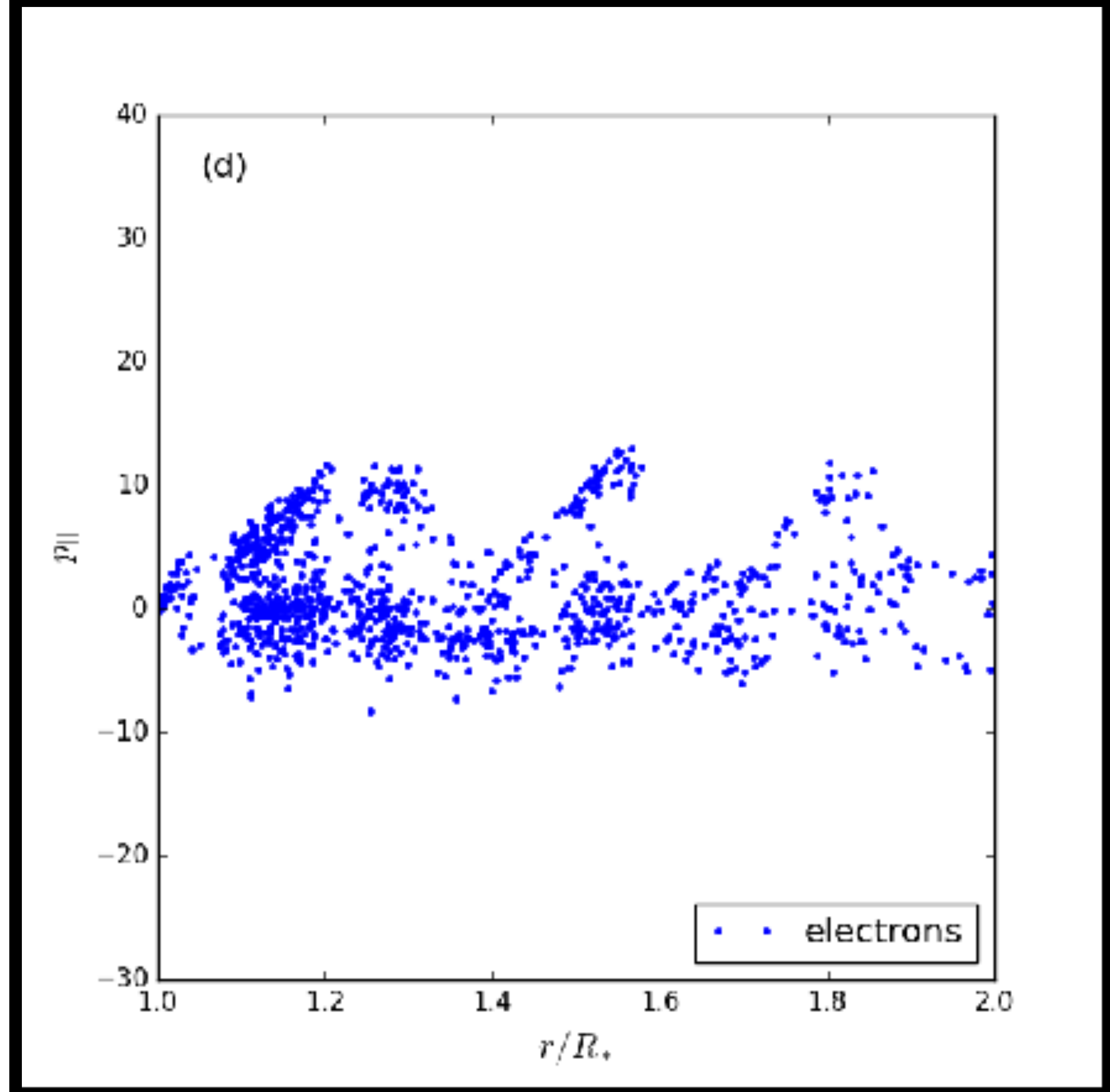
Discharge operation





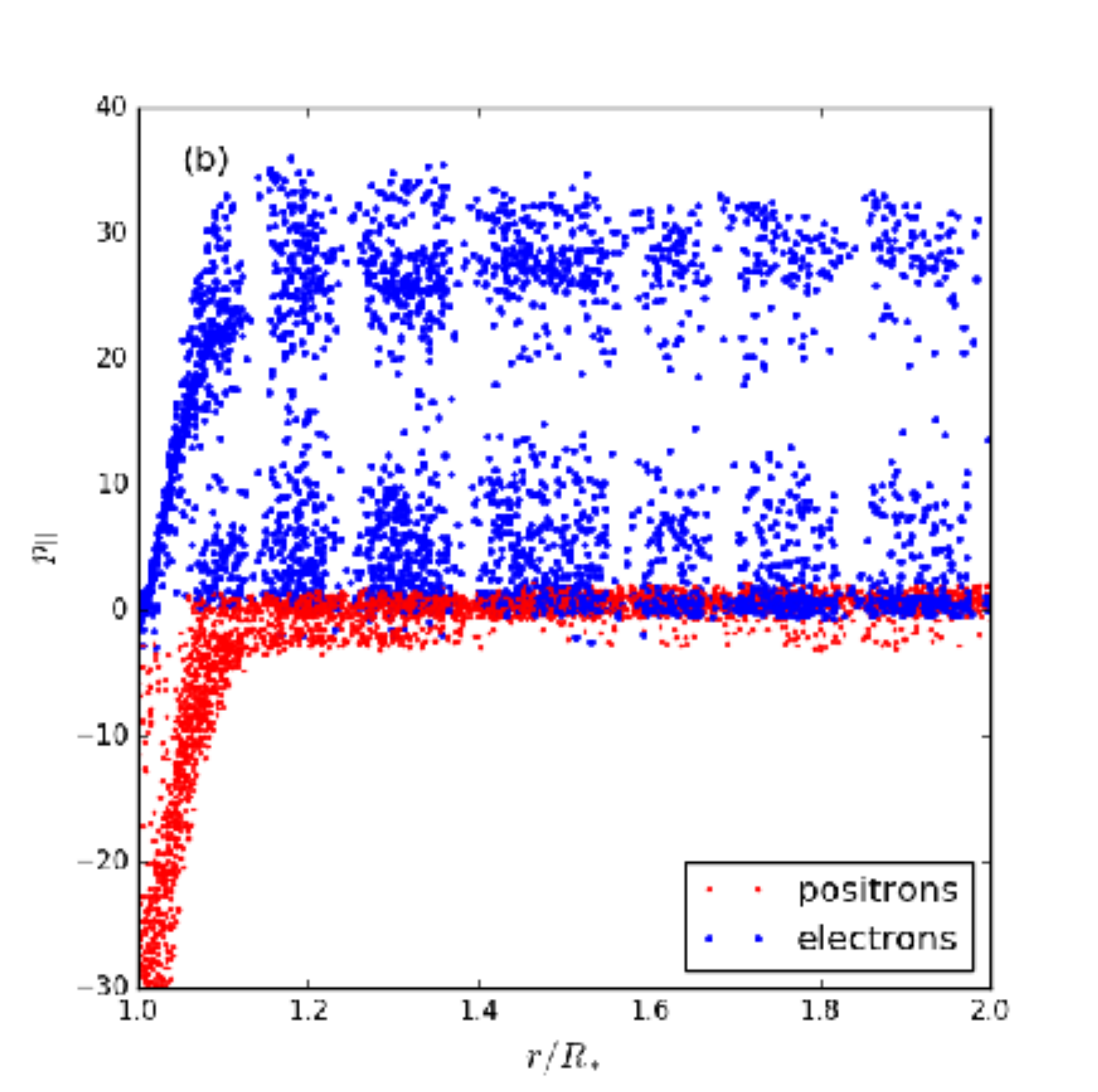
Discharge physics is set by the current. Qualitatively different behaviors co-exist within the polar cap of a general oblique rotator.

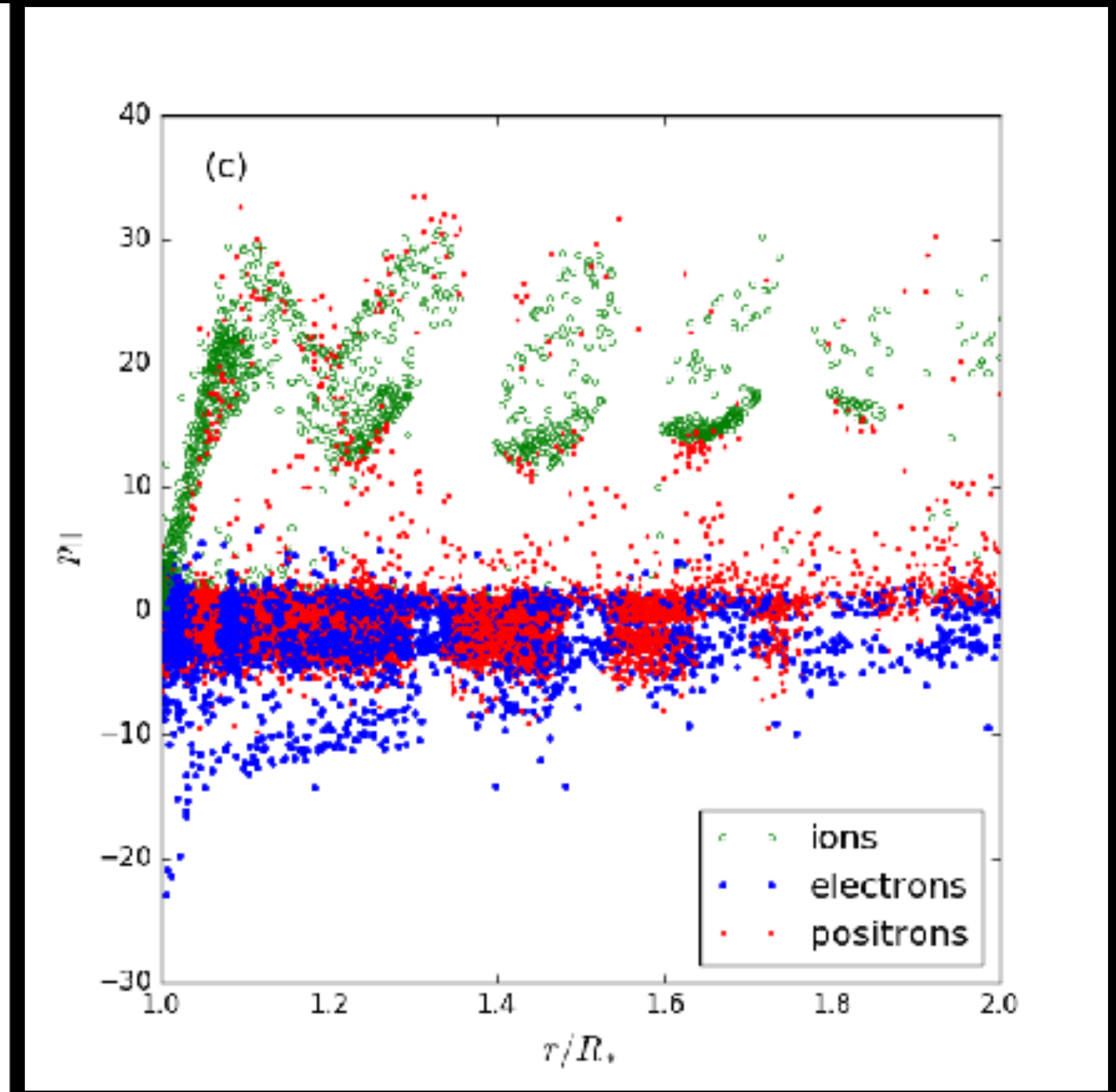
Mestel et al (1985)

Beloborodov (2007)

Timokhin, Arons (2013) in 1D

Philippov, Spitkovsky (2018)



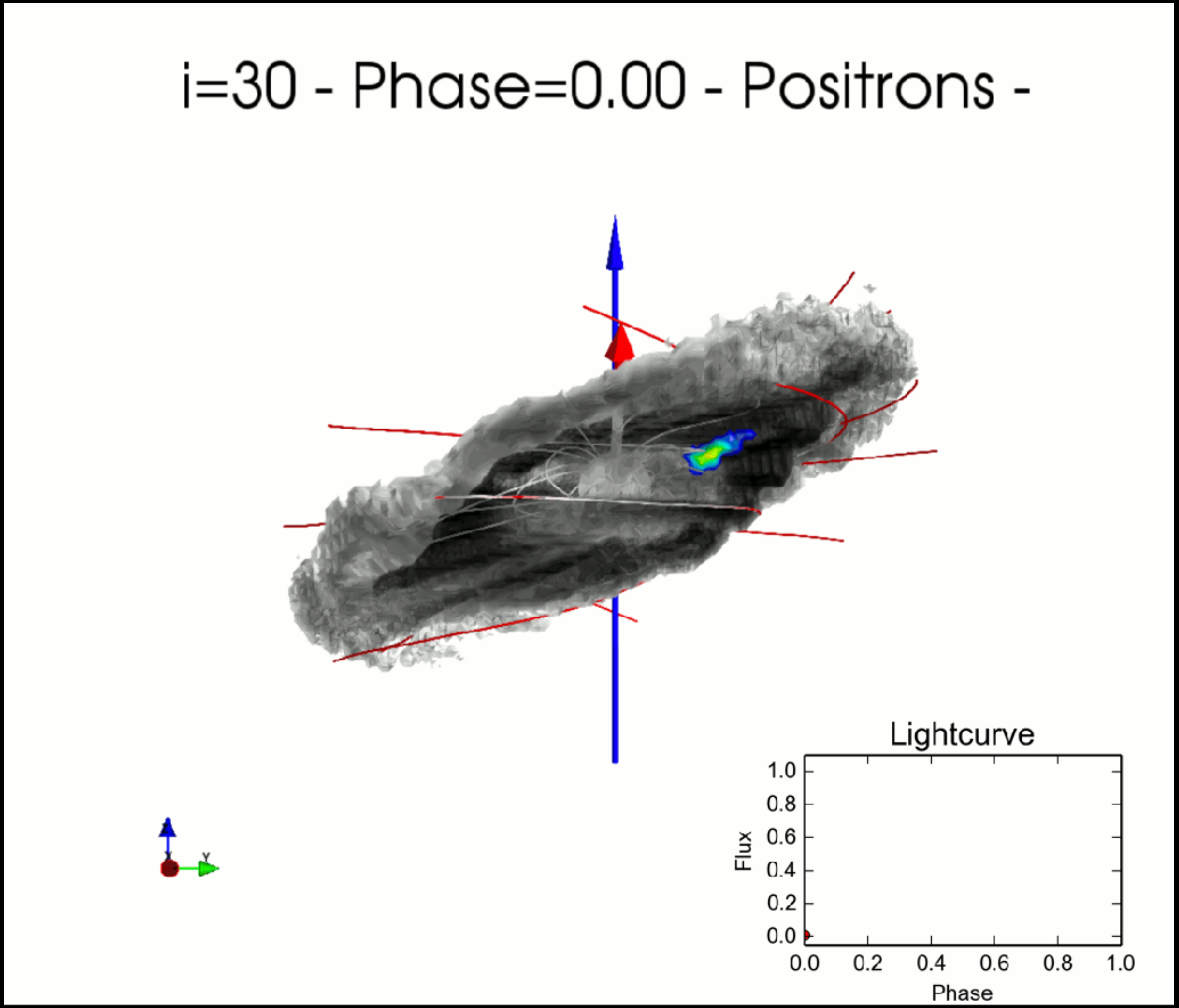


Gamma-ray modeling

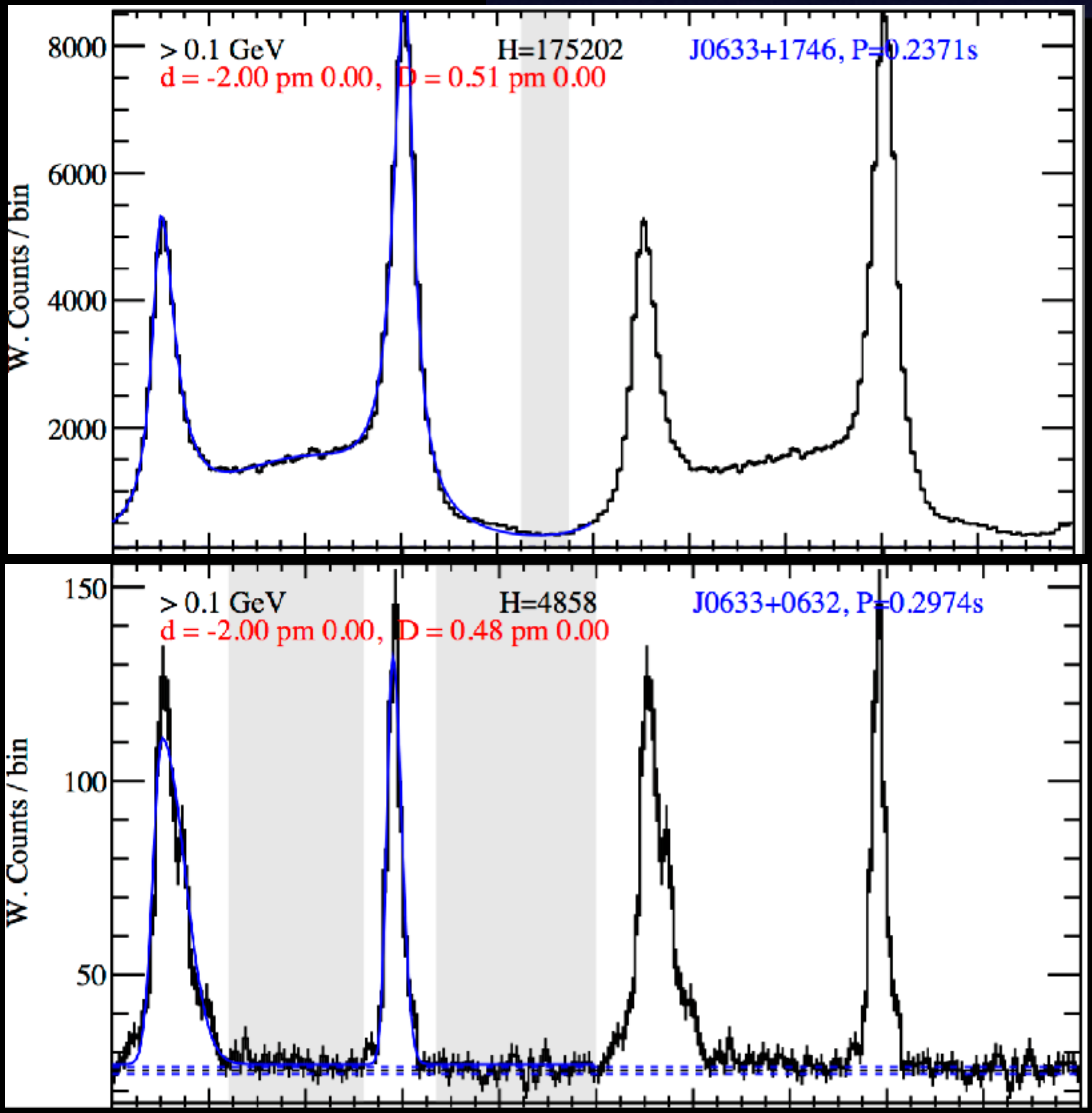
Simulations prefer current sheet as a particle accelerator. Particles radiate synchrotron emission.

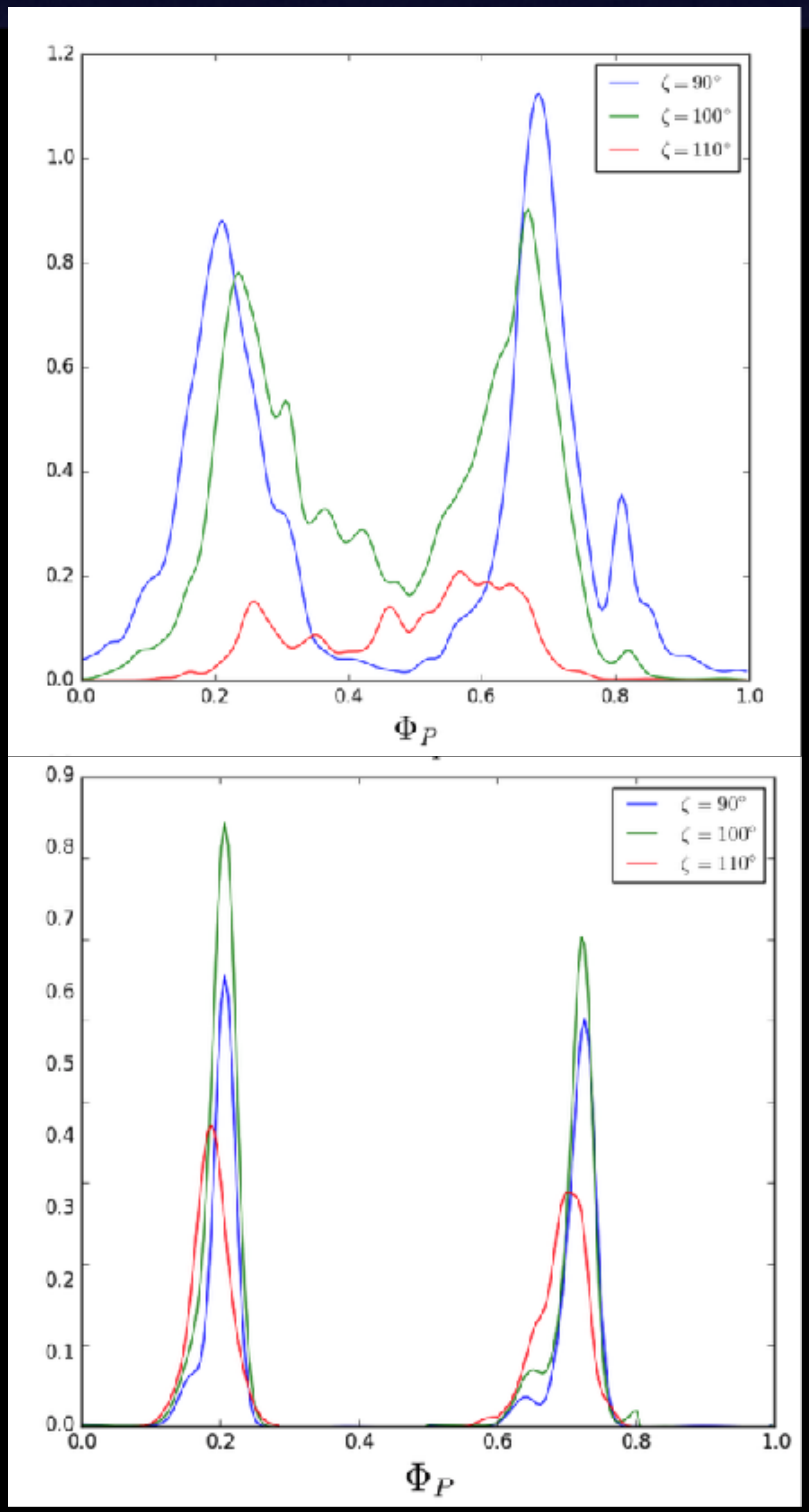
Observe caustic emission.

Predict gamma-ray efficiencies 1-20% depending on the inclination angle and pair production efficiency in the sheet. Higher inclinations are less dissipative.



Cerutti, Philippov, Spitkovsky (2016); Philippov, Spitkovsky (2018)



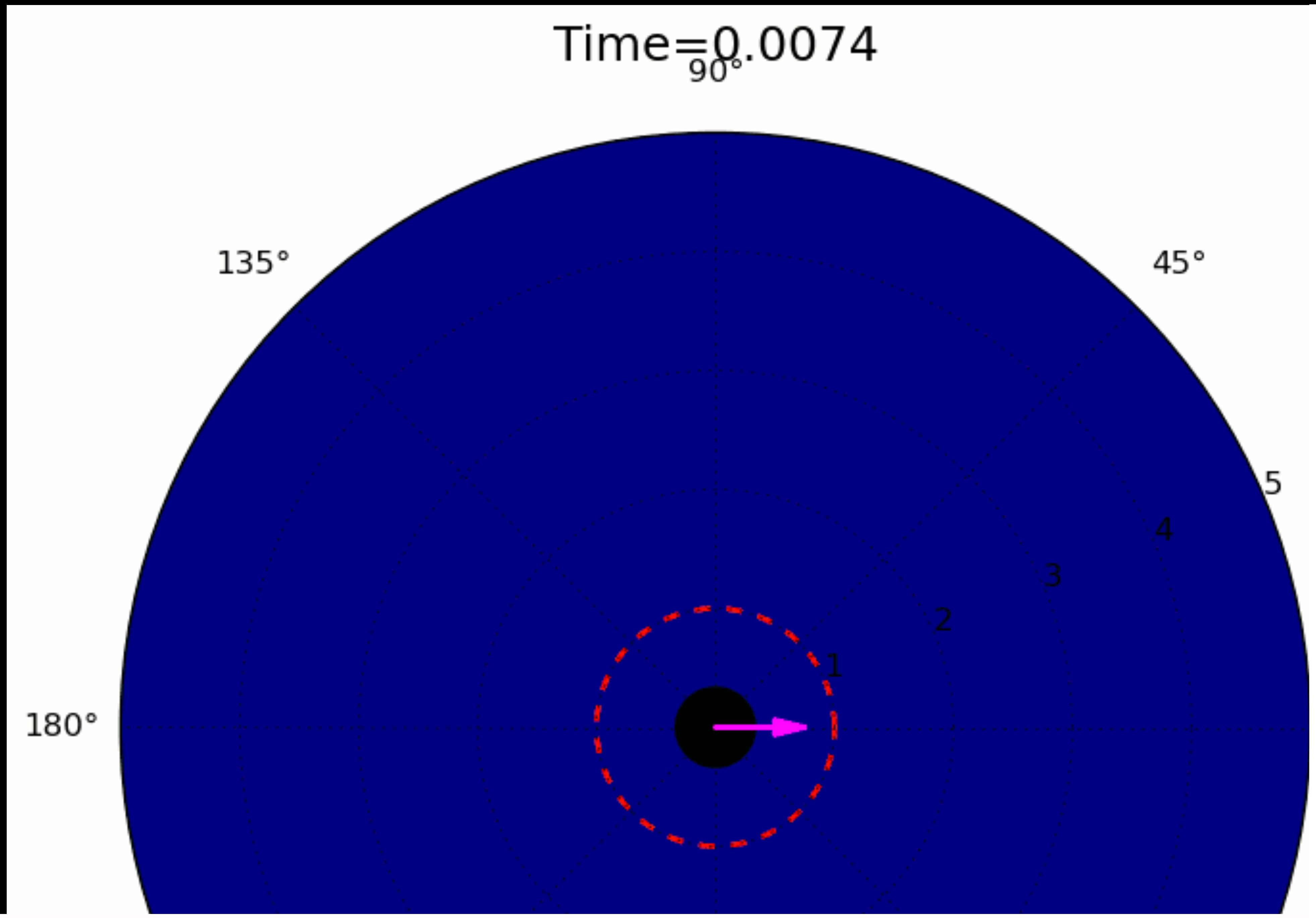


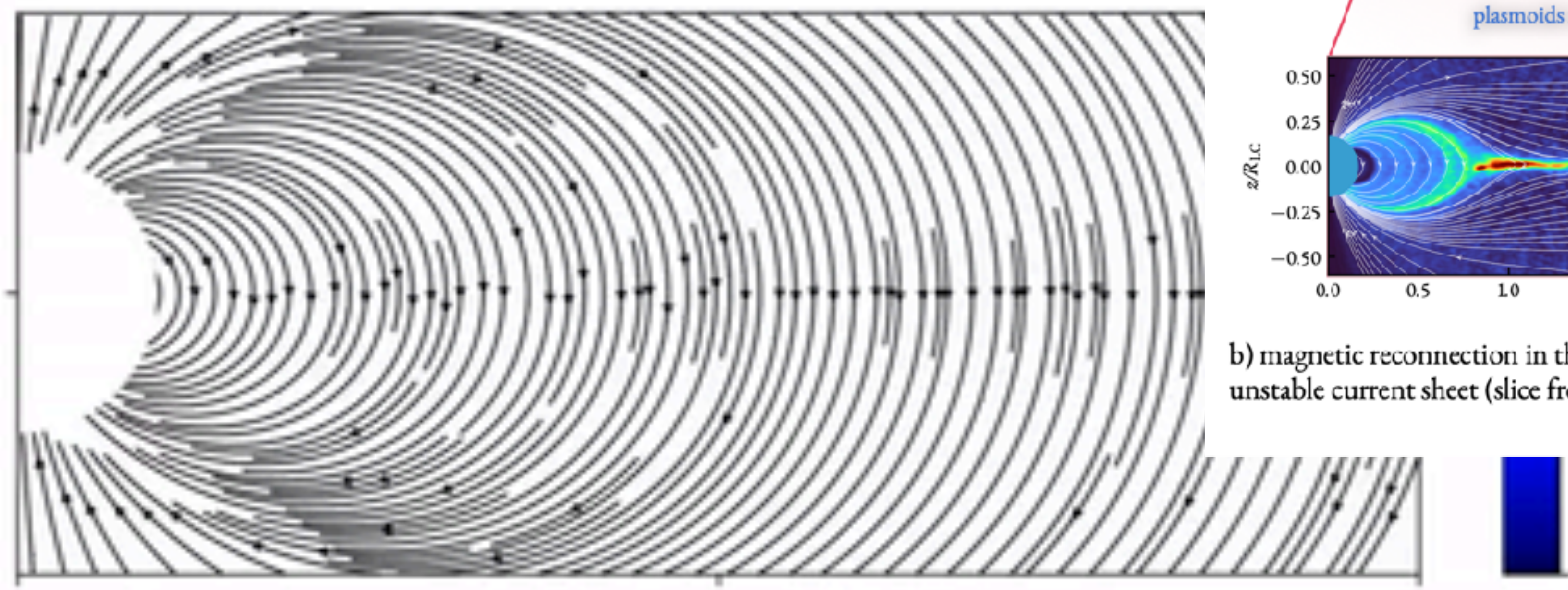
- Double-peaked lightcurves are generic.
- Bridge emission is a feature of lower obliquity rotators in general.

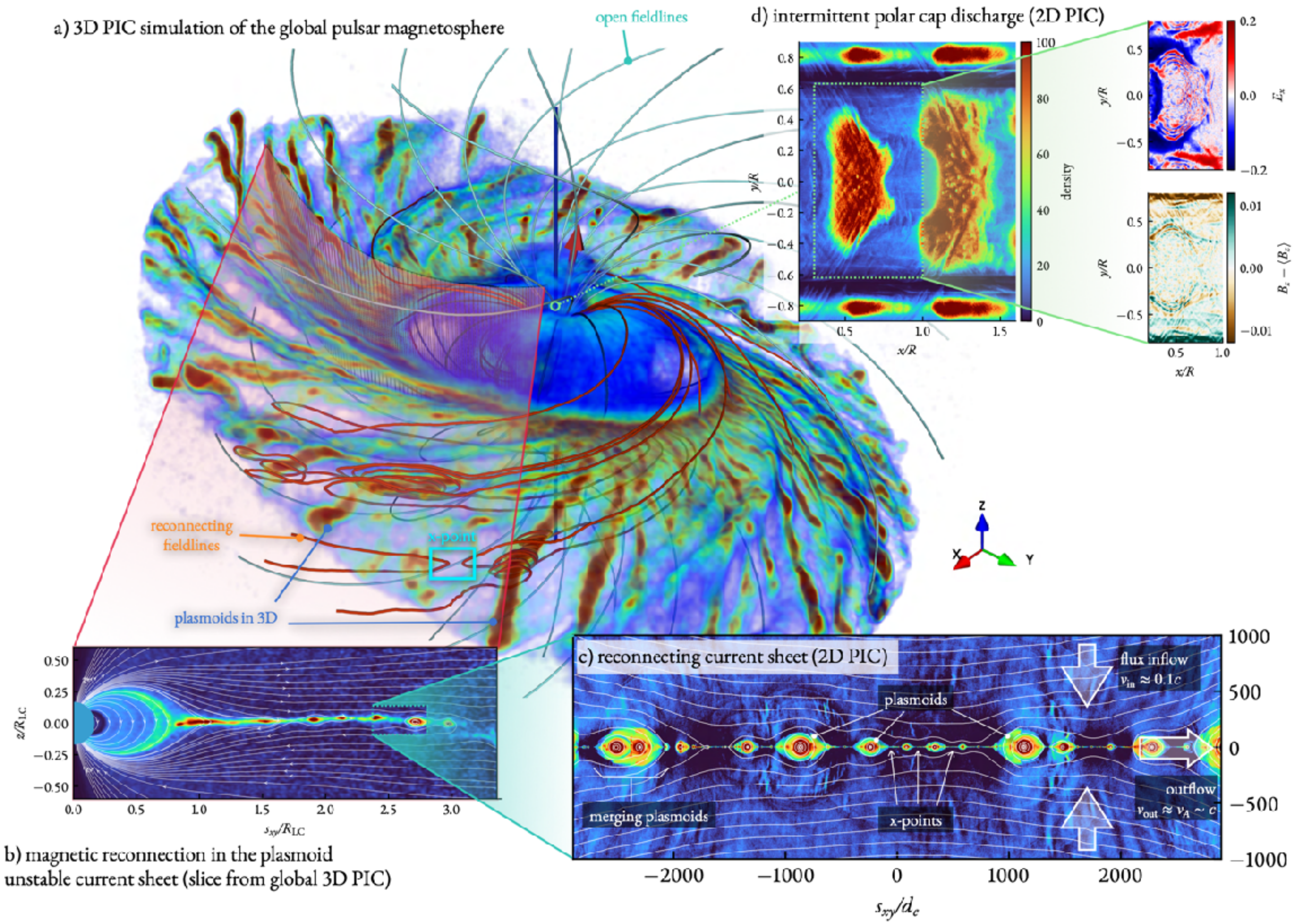
Cerutti, Philippov, Spitkovsky (2016); Philippov, Spitkovsky (2018)

Magnetospheric current sheet in 2D and 3D

Hakobyan et. al., 2022



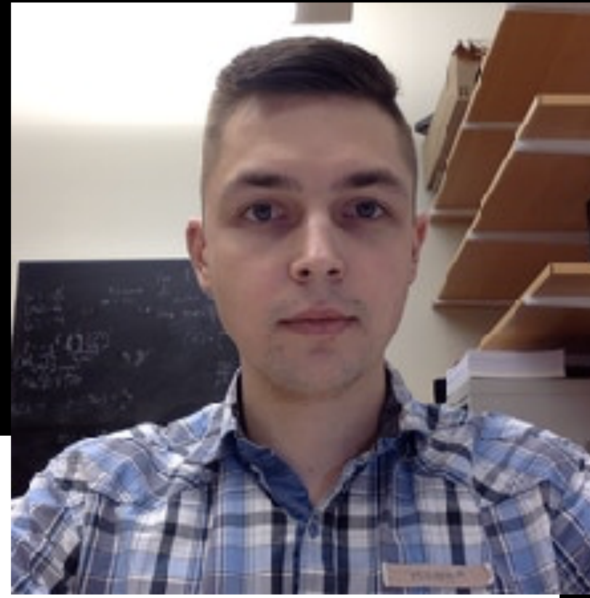




Ripperda et. al., in prep

Philippov, Kramer ARAA (2022)

Reconnection in pulsar magnetospheres



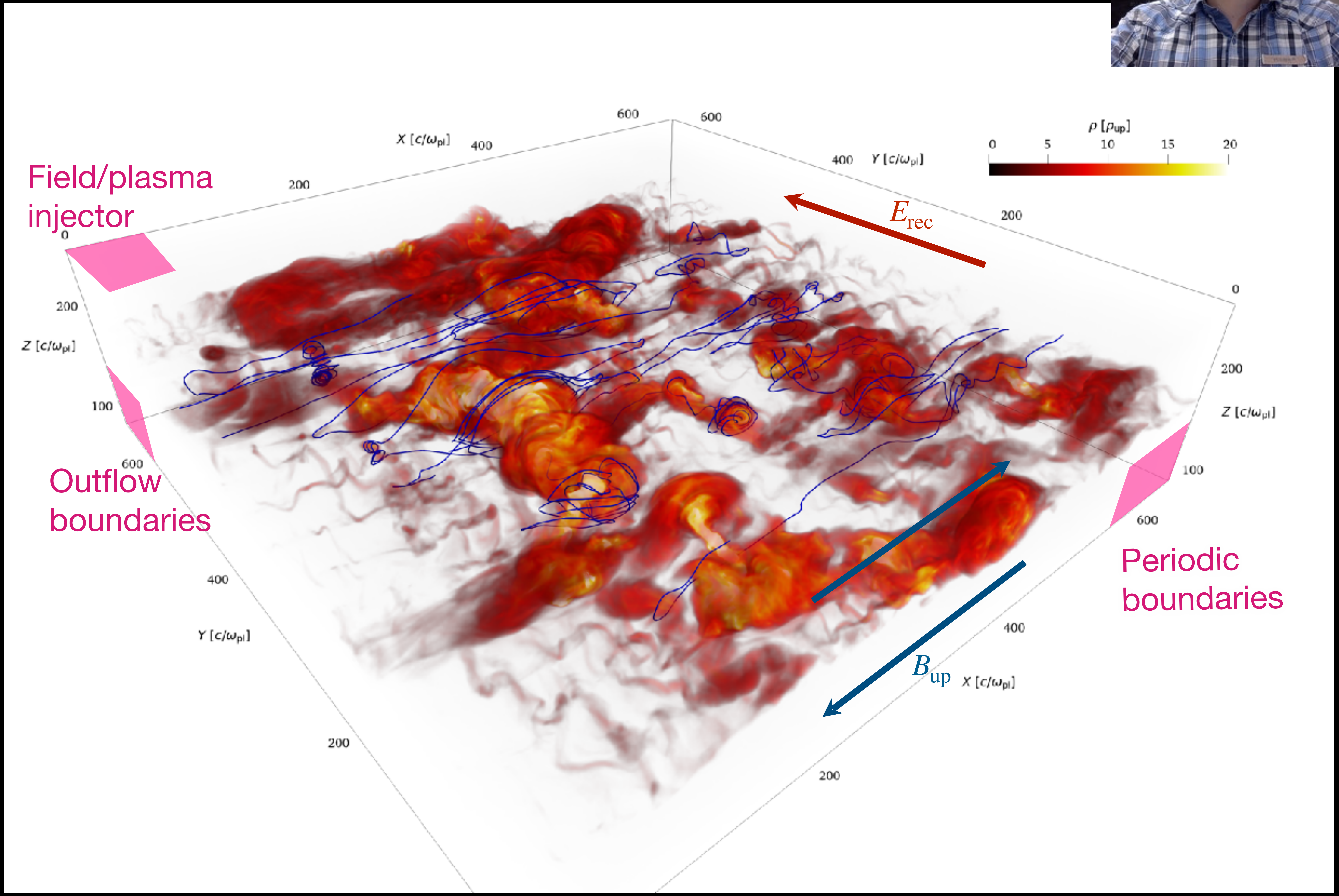
- $B \sim 10^5$ G, $B^2/4\pi \gg \rho c^2$

Synchrotron radiation:

- Reconnection electric field accelerates particles, synchrotron cooling is important on the same timescale.
- They emit a broad photon spectrum, which peaks around GeV energies.

Pair production:

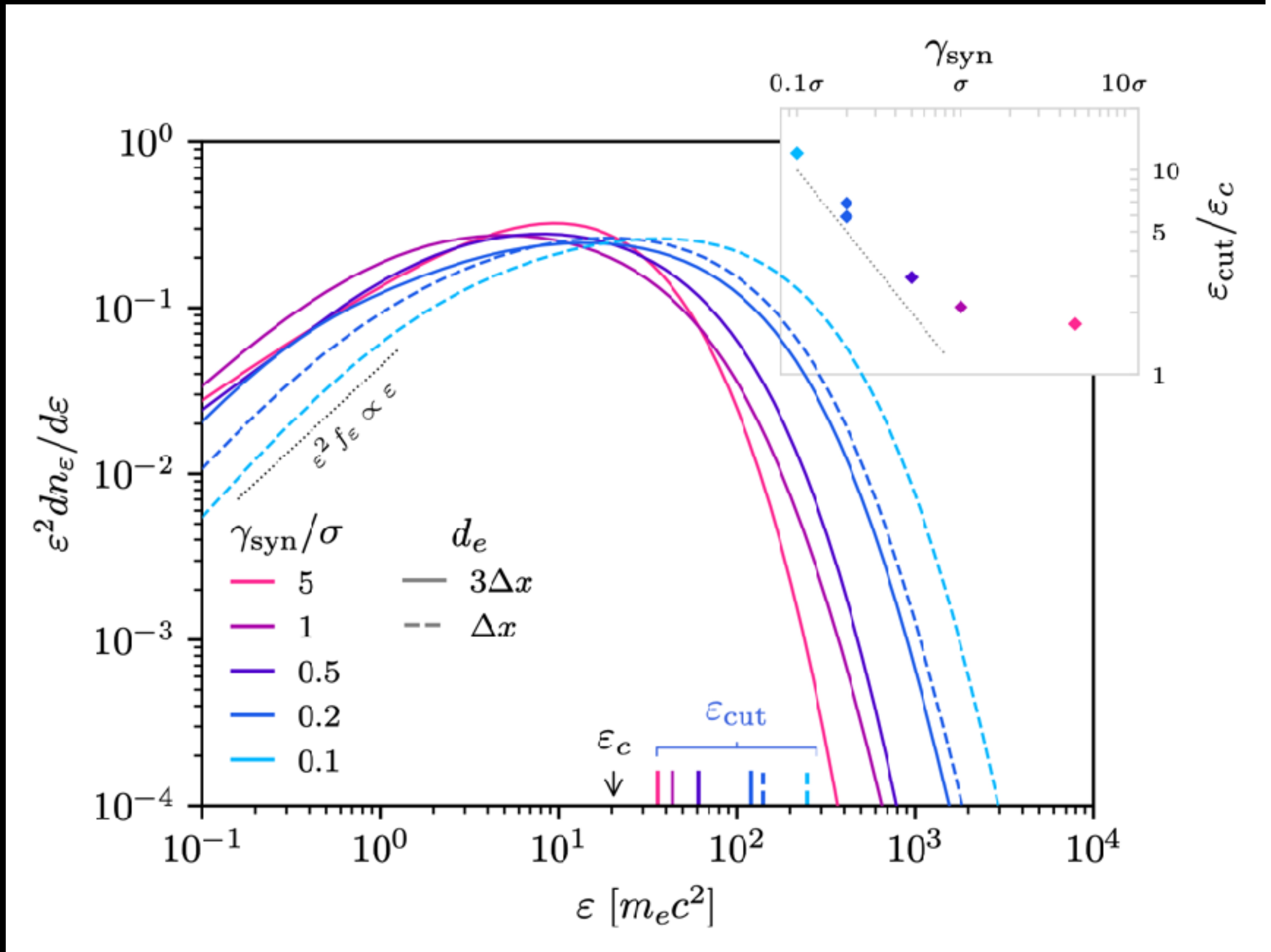
- Pair production by binary collisions of reconnection-produced photons.
- $\tau_{\gamma\gamma} \leq 1$, still produces a lot of pairs to affect the reconnection dynamics (mass loading).

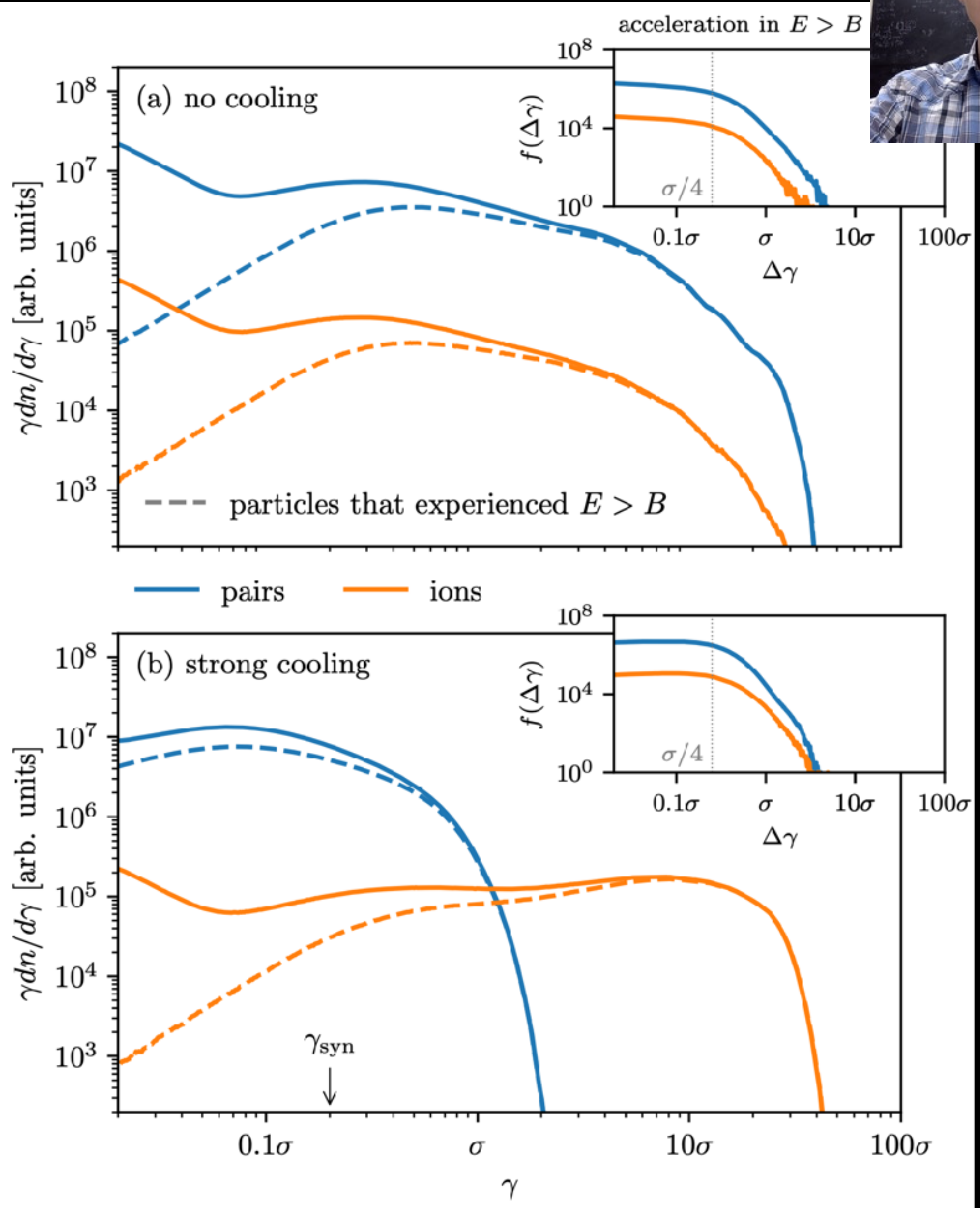


Chernoglazov, Hakobyan, Philippov, 2023, ApJ

Reconnection in pulsar magnetospheres

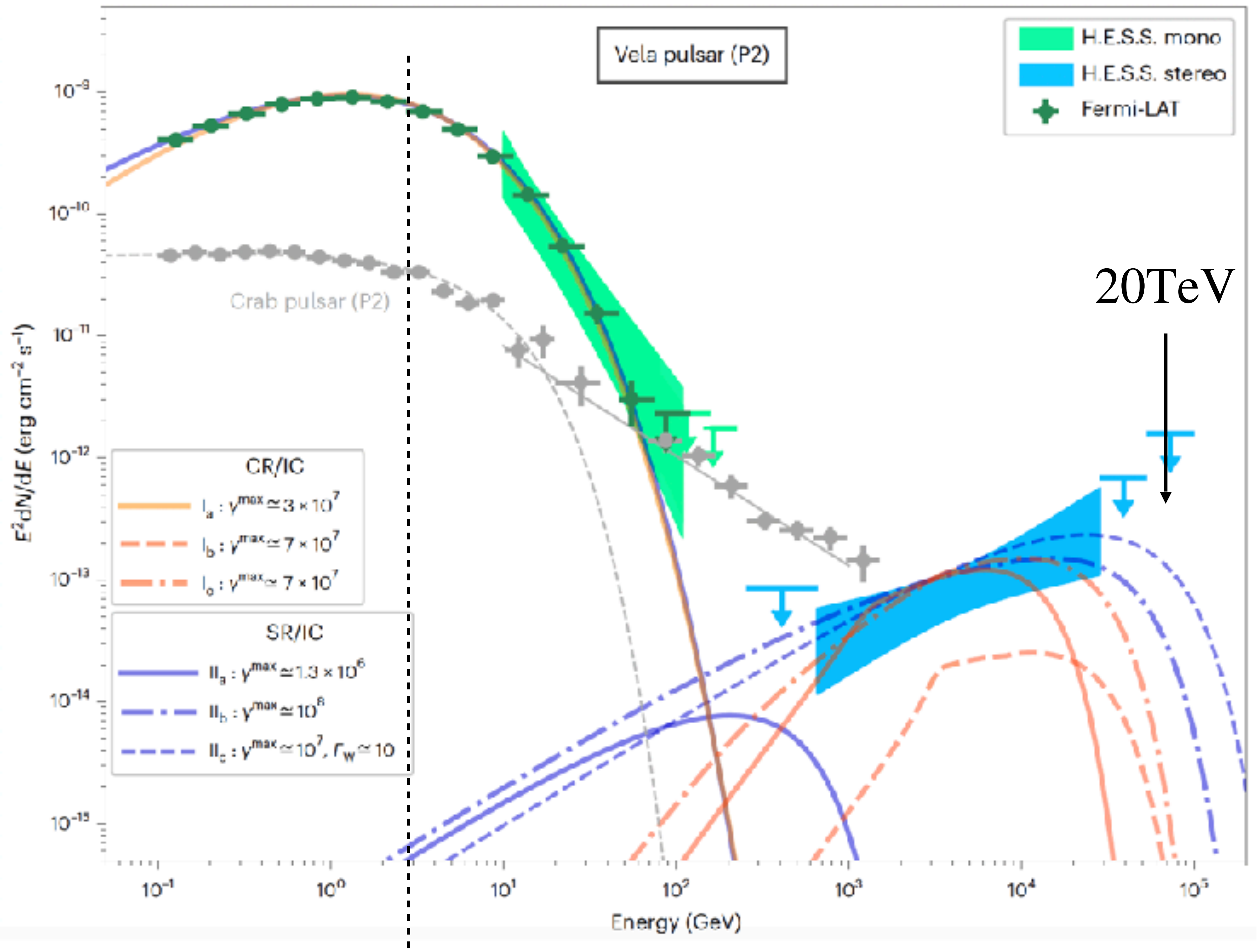
- Lots of high-energy photon flux above the burnoff limit!
- Leptons accelerate beyond the burnoff, but only to about a few sigma. $h\nu_{\max} \approx 16\mathrm{MeV}(\sigma/\gamma_{\mathrm{rad}})$
- Highest energy photons are beamed along the upstream magnetic field, consistent with the beaming of GeV lightcurves.



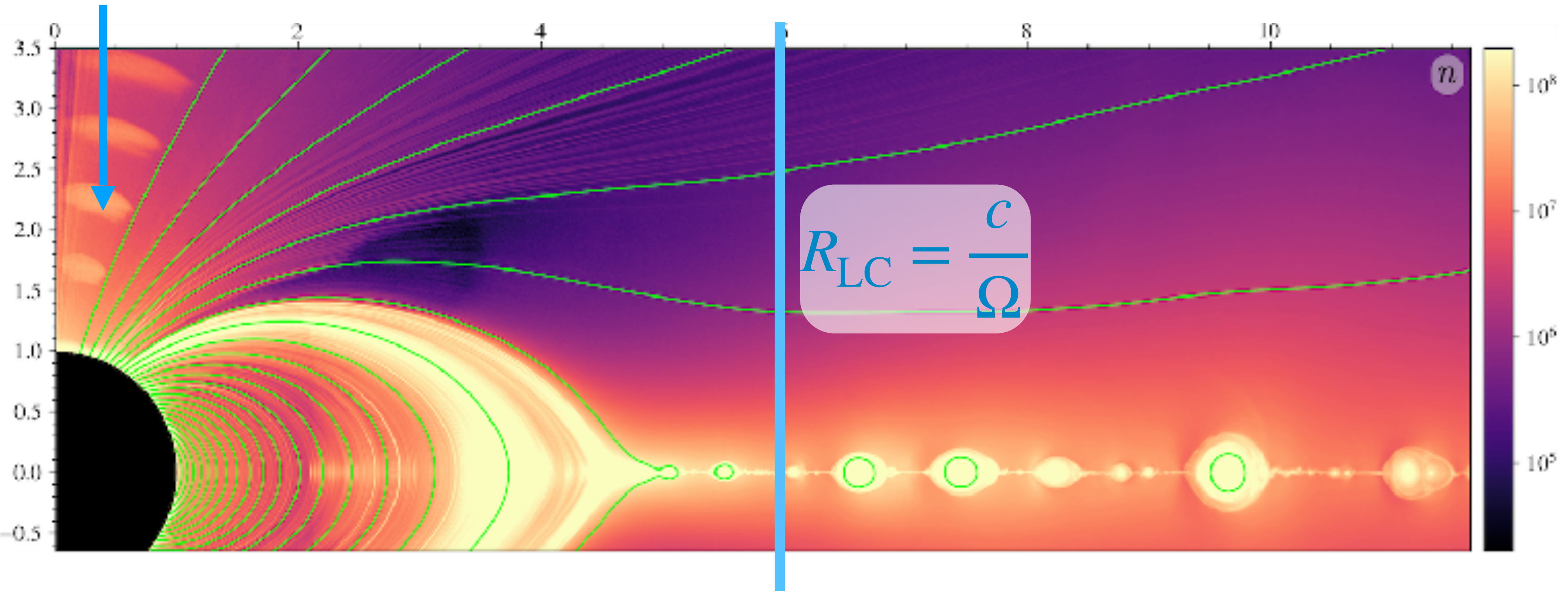


How does this work? Vela pulsar [in prep]

The H.E.S.S. Collaboration, Nature (2023)



Bursts of plasma production



$$\text{Vela}: P = 0.089s, \dot{P} = 1.25 \times 10^{-15} \implies B_\star = 3.3 \times 10^{13} G$$

$$B_{\rm LC} = 7.5 \times 10^4 G$$

$$\gamma_{\rm syn} = 10^5 \rightarrow \sigma \approx 10^7$$

$$\varepsilon_{\rm ph} = 16\text{MeV} \frac{\sigma}{\gamma_{\rm syn}}$$

$$m_e c^2 \gamma_{\max} = m_e c^2 \sigma = \text{fewTeV} \implies \text{IC} \implies \varepsilon_{\rm ph} \approx 10\text{TeV}$$

Suggests starved feeding of the current sheet

$$\gamma_{\rm PC} = \frac{2\pi \rho_{\rm GJ} R_{\rm PC}^2}{m_e c^2} = 3 \times 10^{10}$$

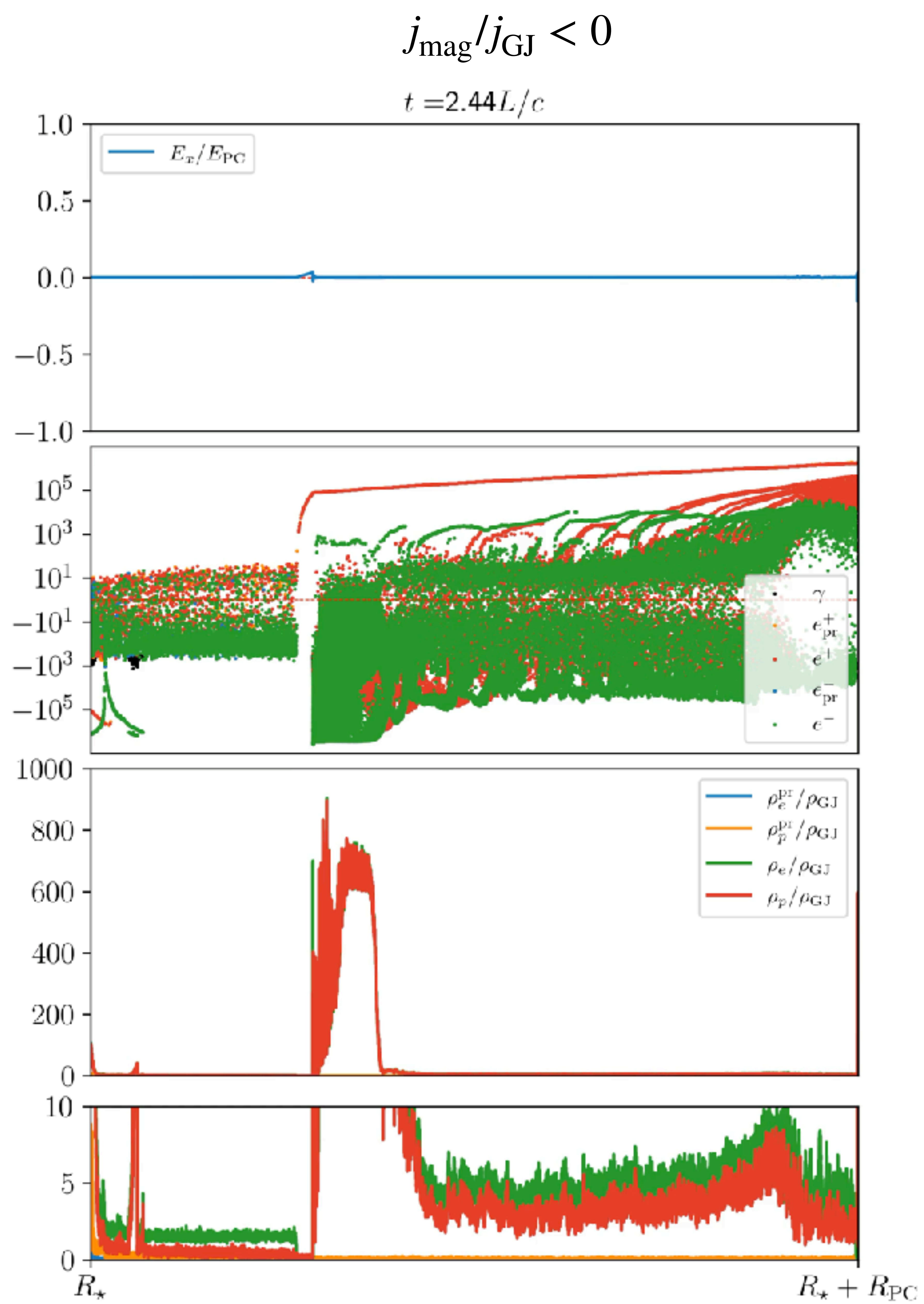
$$\lambda = \frac{n}{n_{\rm GJ}} \approx 10^5 - 10^6$$

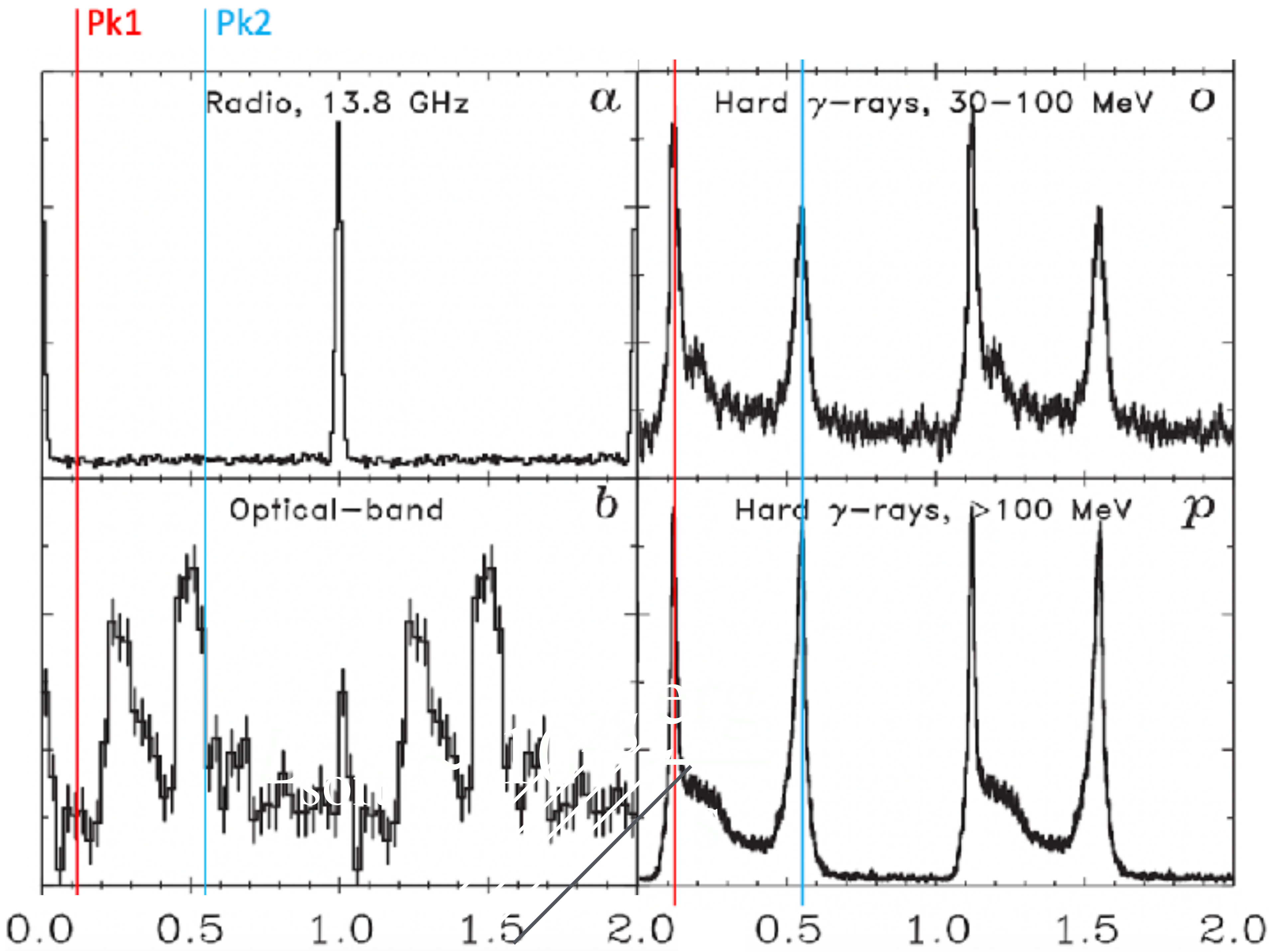
$$\sigma_{\rm expected} = \frac{\gamma_{\rm PC}}{\lambda} \approx 10^5$$

Timokhin+, ApJ (2019)

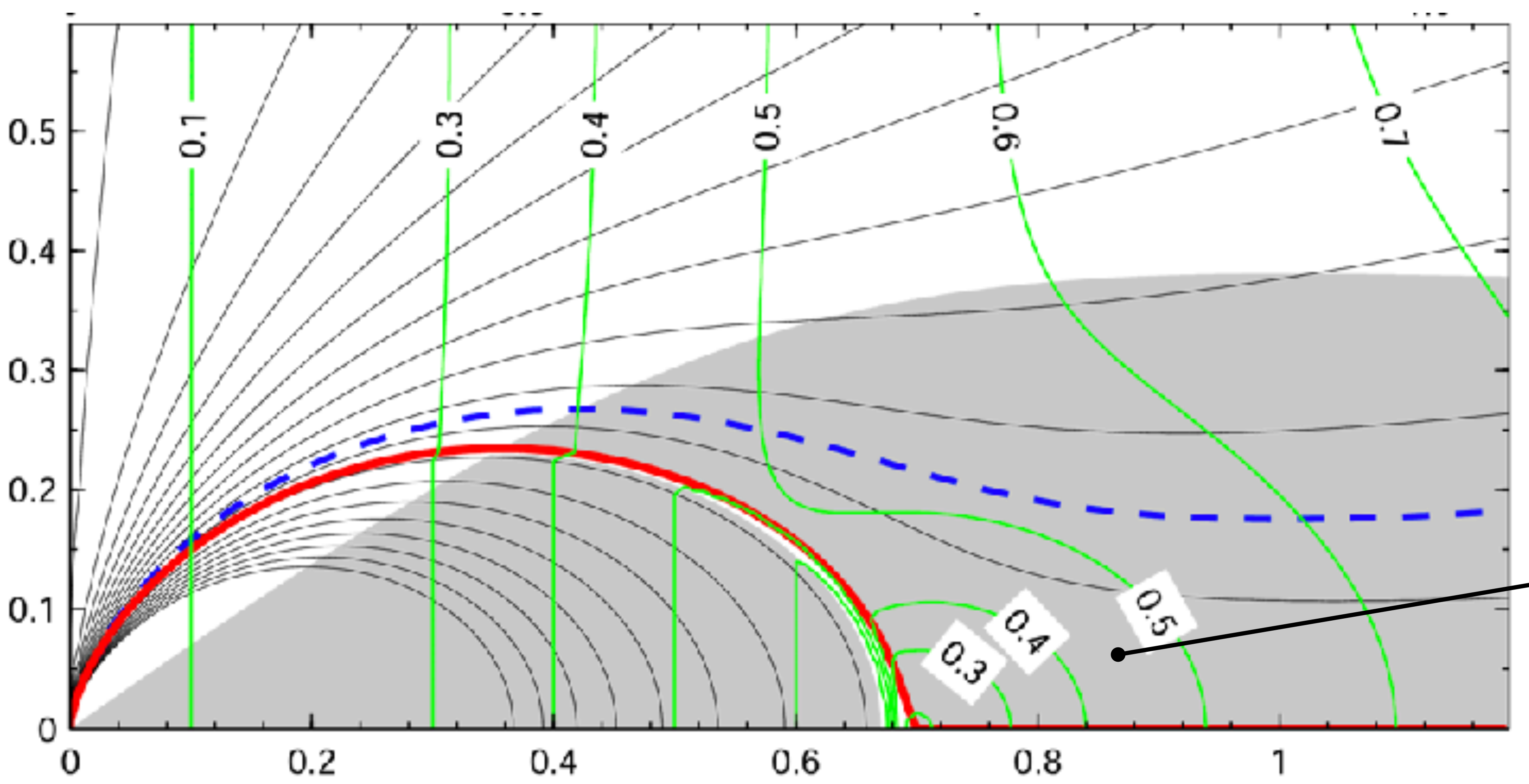
Bransgrove et al, ApJL 2023

Multiplicity for different magnetospheric currents





Kargaltsev O., private communication



$$L_{20\text{TeV}} = 2 \times 10^{30} \frac{\text{erg}}{\text{s}}$$

$$L_{\text{soft}} \sim 10^{28} \frac{\text{erg}}{\text{s}}$$

$$L^{\text{obs}}_{0.6\text{eV}} = 2 \times 10^{28} \frac{\text{erg}}{\text{s}}$$

Field lines carrying return current send only a small fraction of secondary plasma into the magnetosphere

$$\lambda_{\text{outside}} \sim 0.001 - 0.01\lambda$$

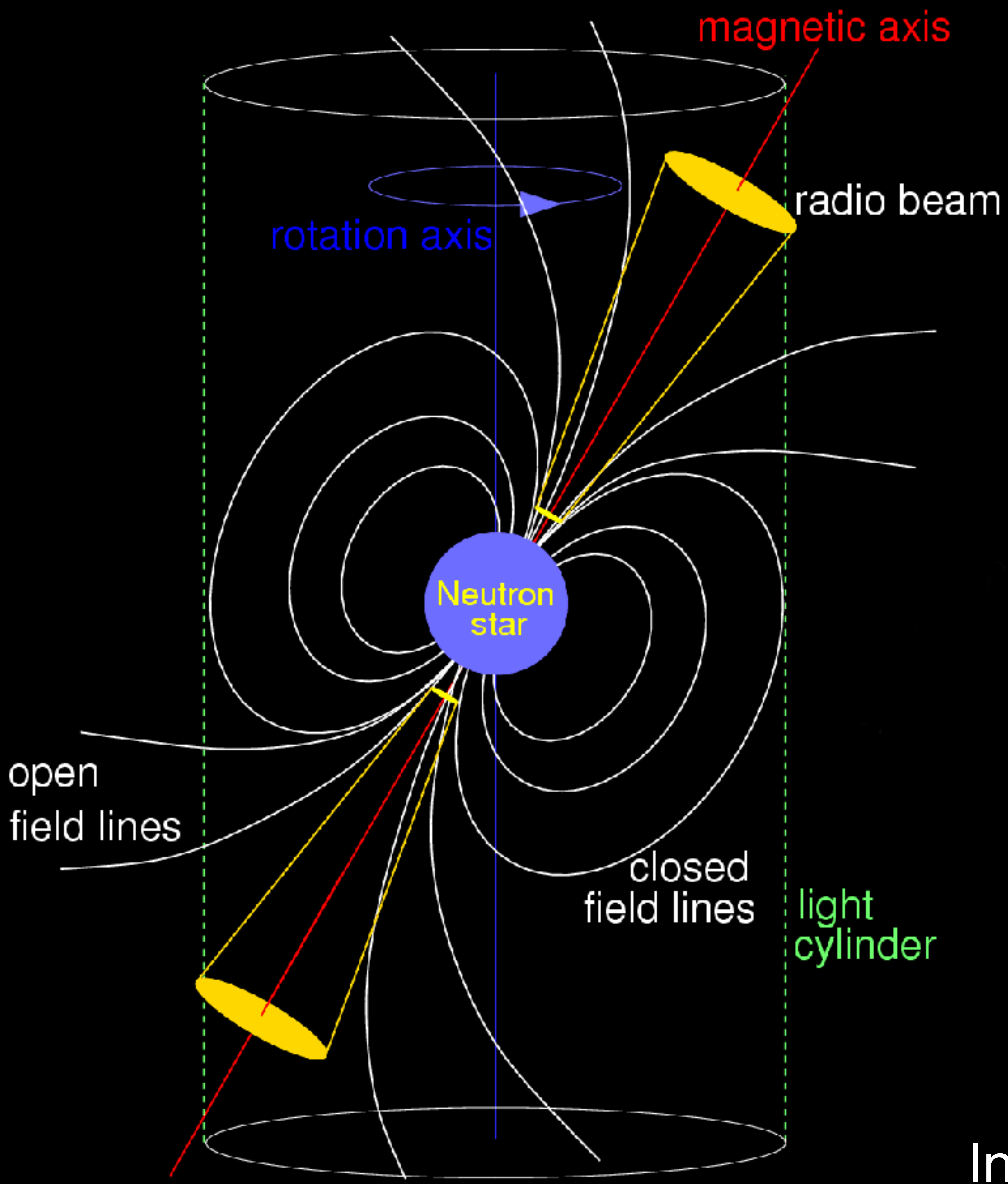
$$\sigma \approx 10^2 - 10^3 \sigma_{\text{expected}} = 10^7 - 10^8$$

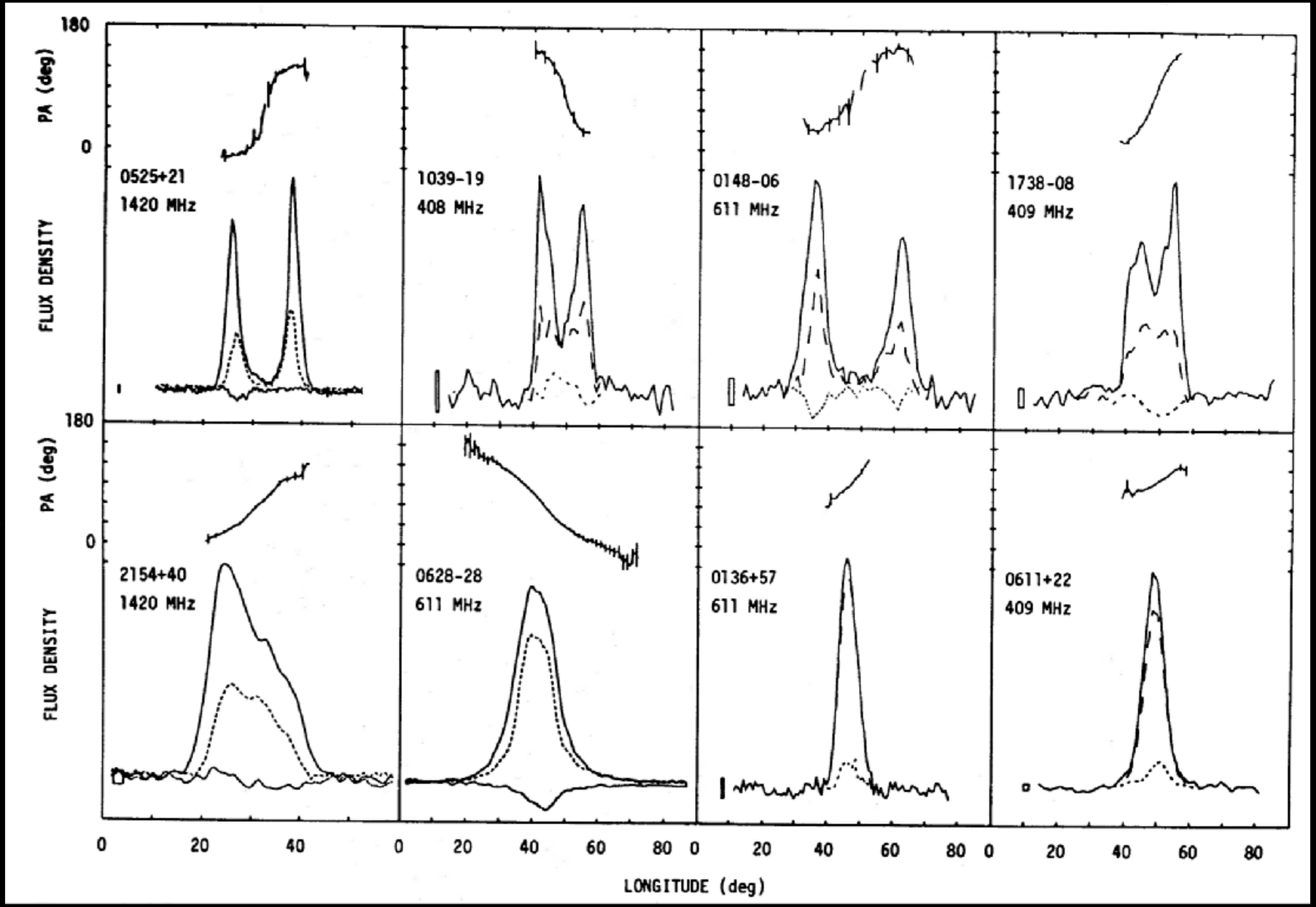
Enough to explain 20 TeV emission

Volumetric return current

Timokhin+, ApJ (2006)

Polar radio emission



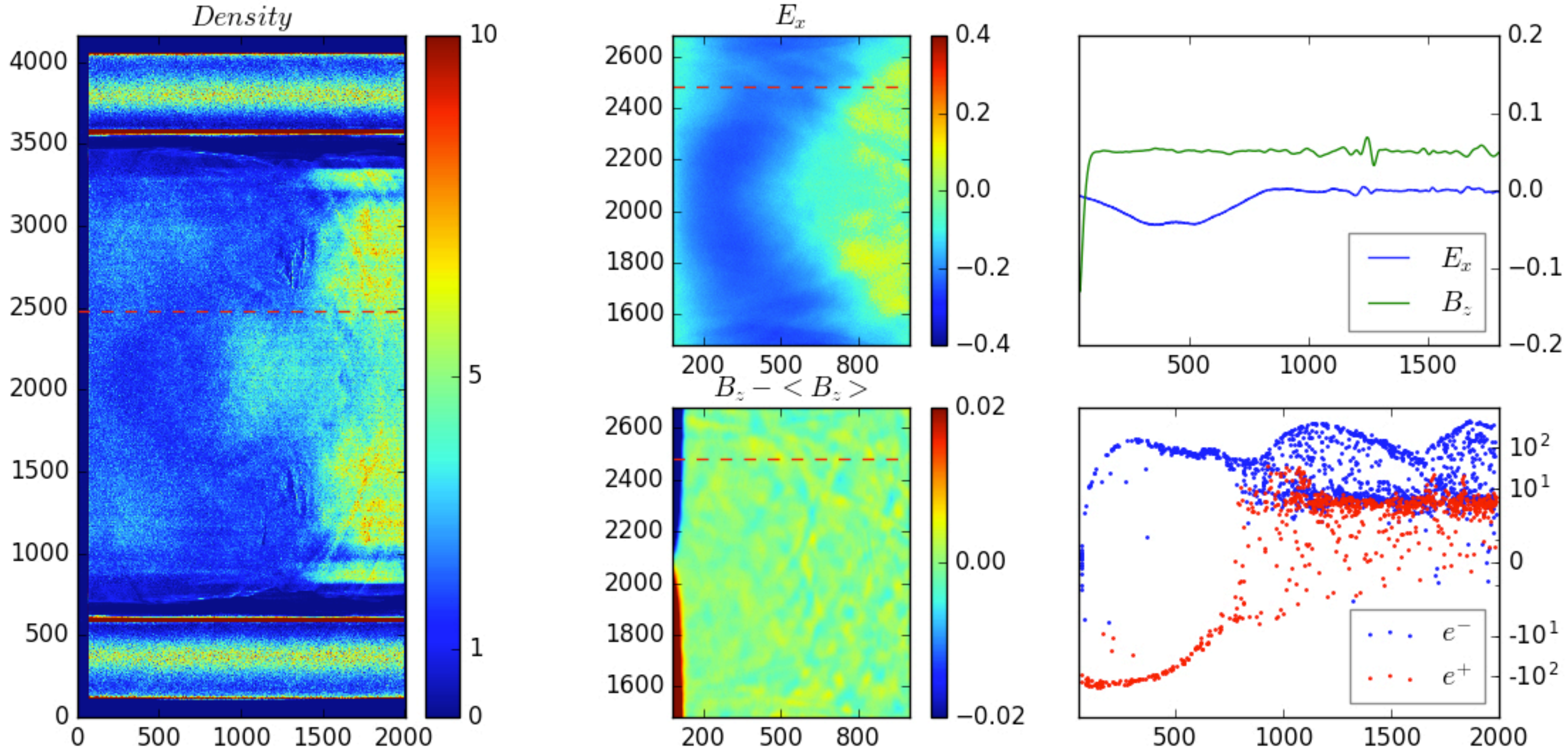


Lyne, Manchester (1988)

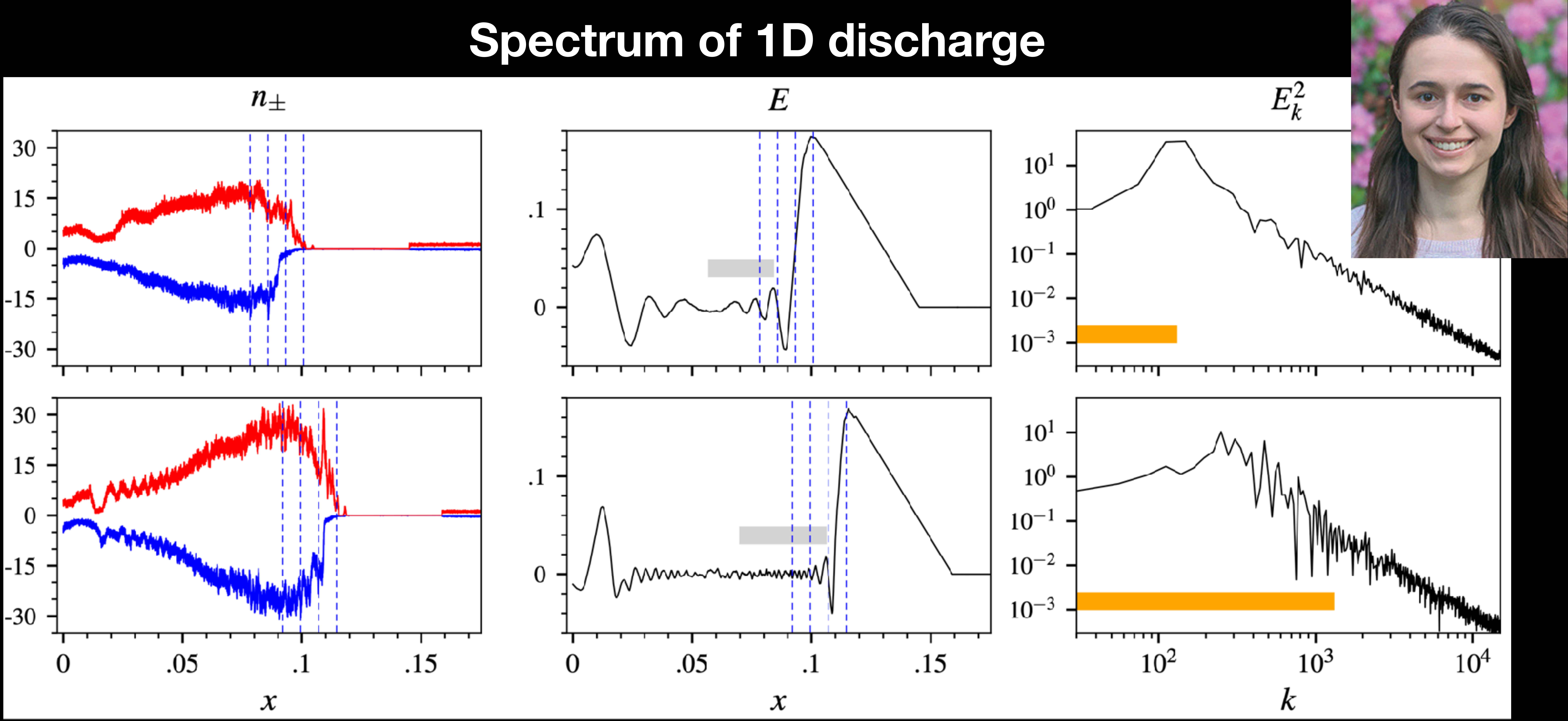
In most cases we see one short pulse per period.
Beam width is related to the polar cap size.

Local simulation of 2D discharge

Philippov, Timokhin, Spitkovsky (2020) PRL



Spectrum of 1D discharge

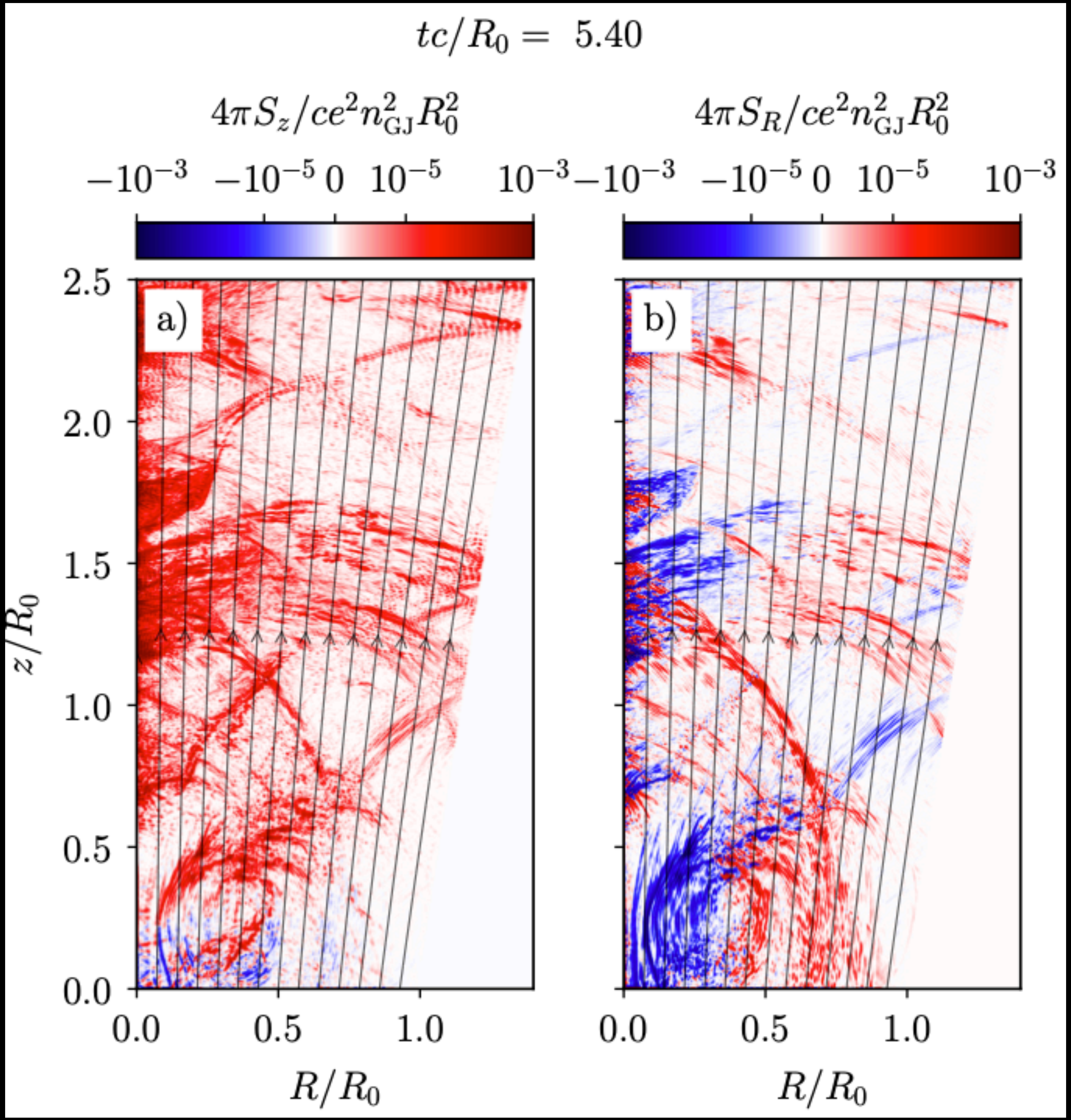


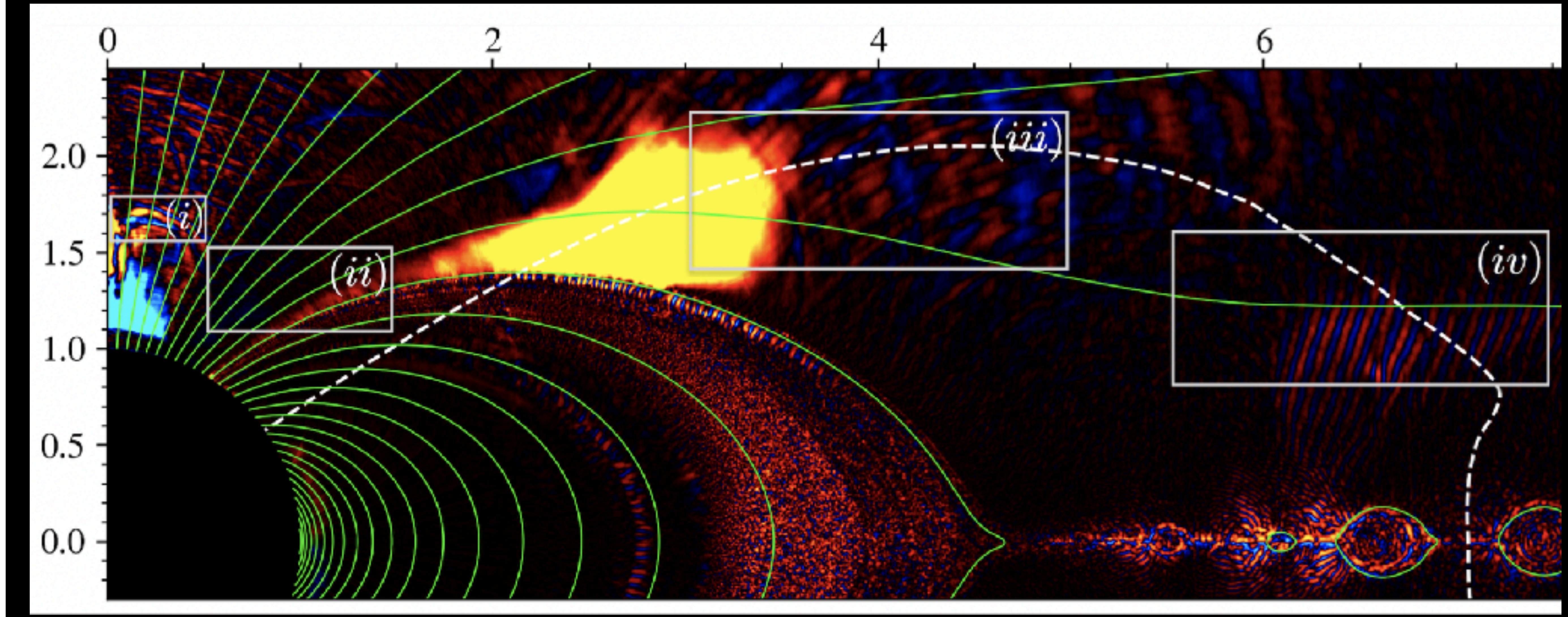
Clearly a broad-band mechanism. Power cascades to a maximum plasma frequency in the cloud.

$$\nu \simeq \sqrt{4\pi e^2 \kappa n_{\rm GJ}/\langle\gamma^3\rangle m_e^3}/2\pi = 26\sqrt{\kappa_5 B_{12}/r^3 P_{0.1}\gamma_{10}^3}\,\text{GHz}$$

Philippov, Timokhin, Spitkovsky (2020) PRL
Tolman, Philippov, Timokhin (2022) ApJL

Confirmation with different codes



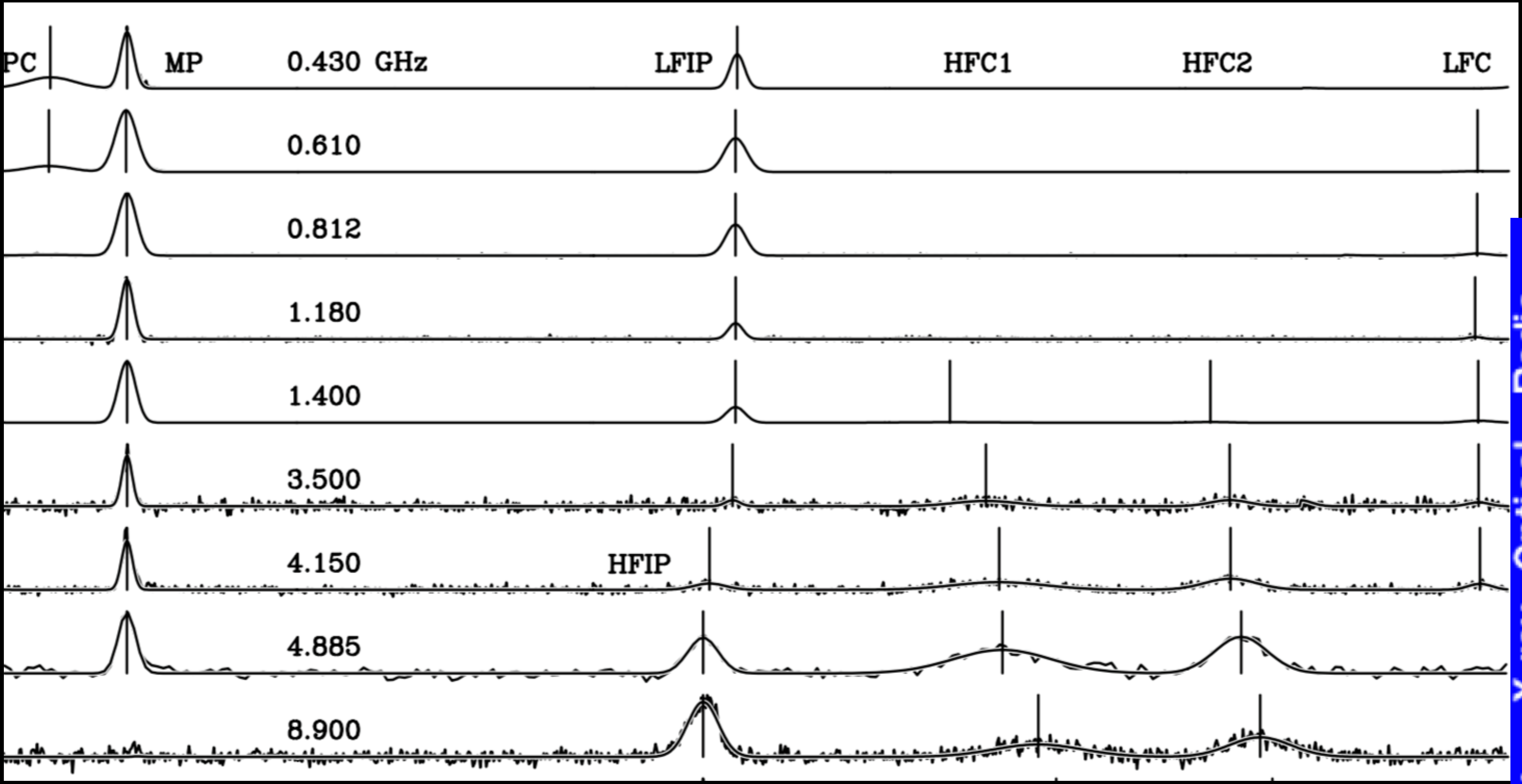


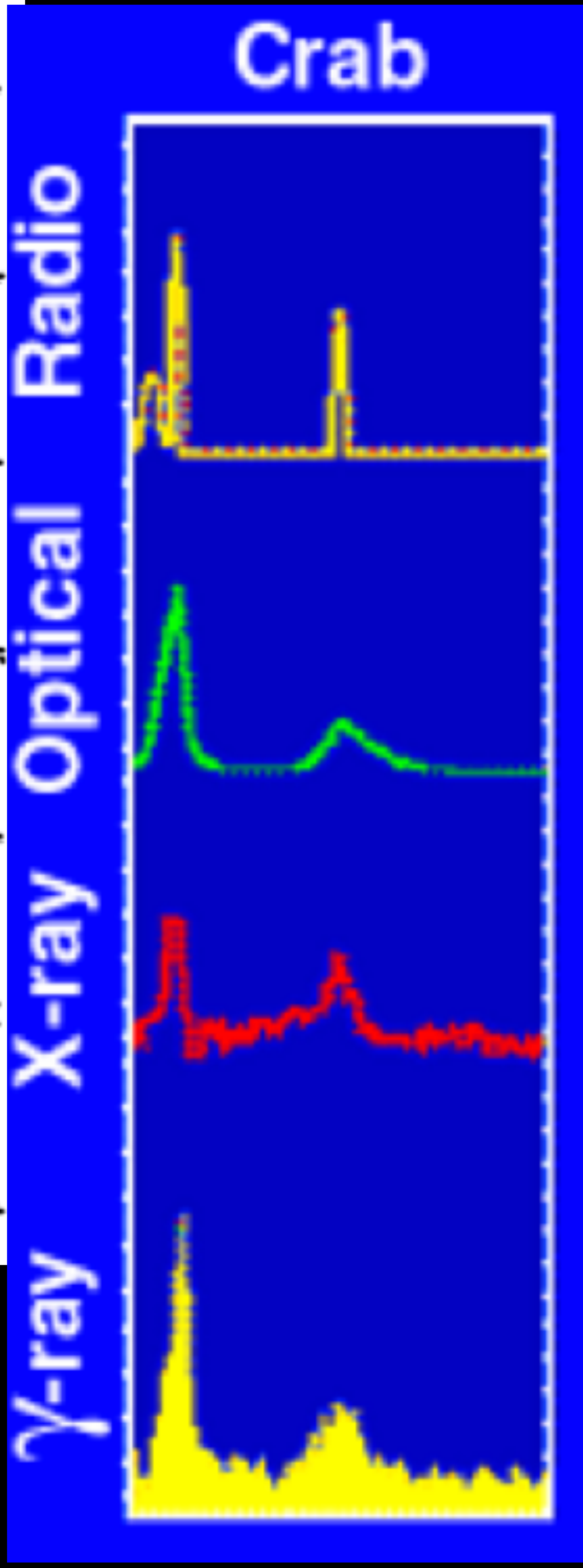
Confirms order-of-magnitude, $10^{-4}L_{sd}$, luminosity

Core-cone geometry of the emission beam

PIC simulations with Osiris & Pigeon

Crab radio emission

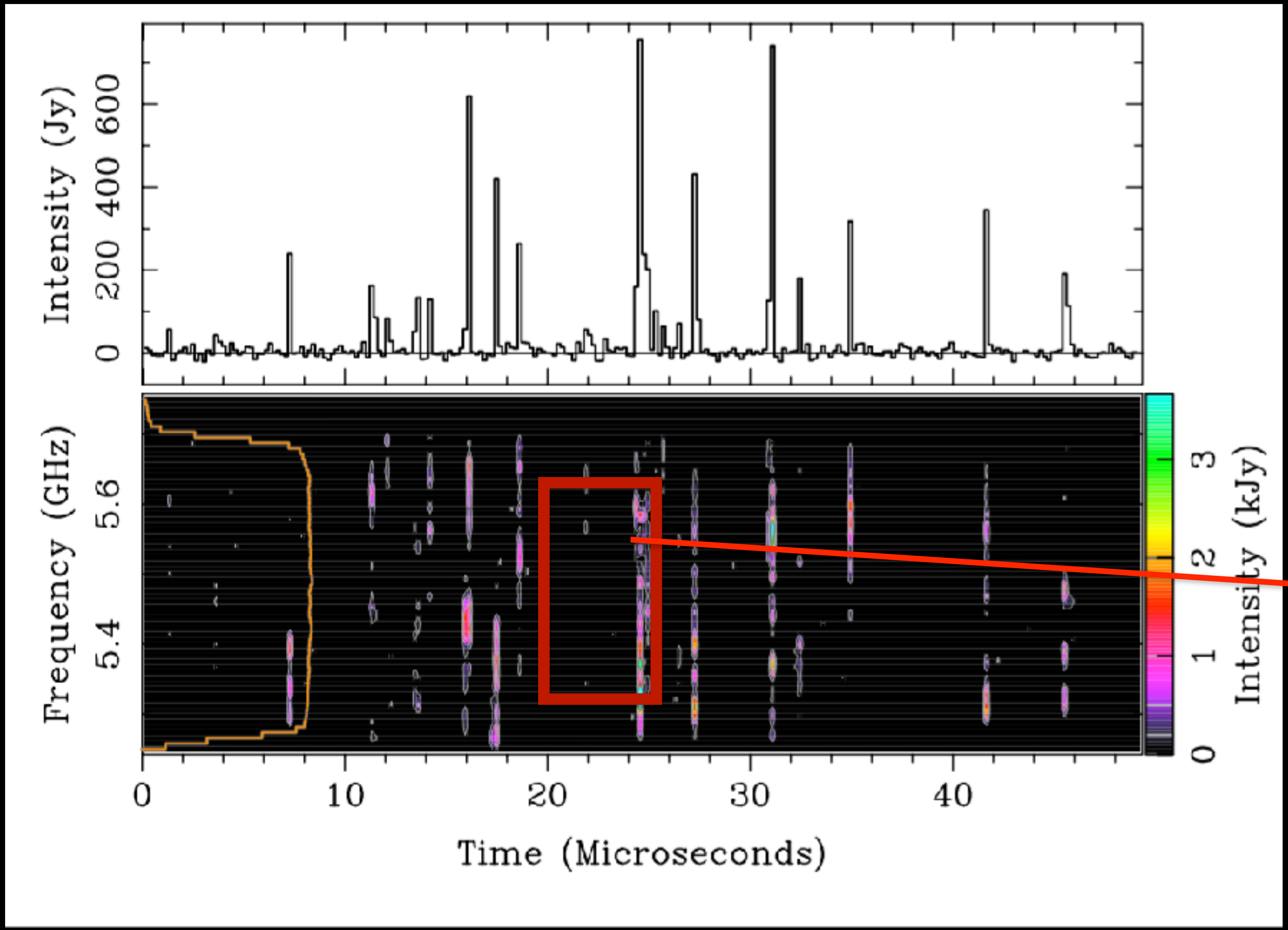


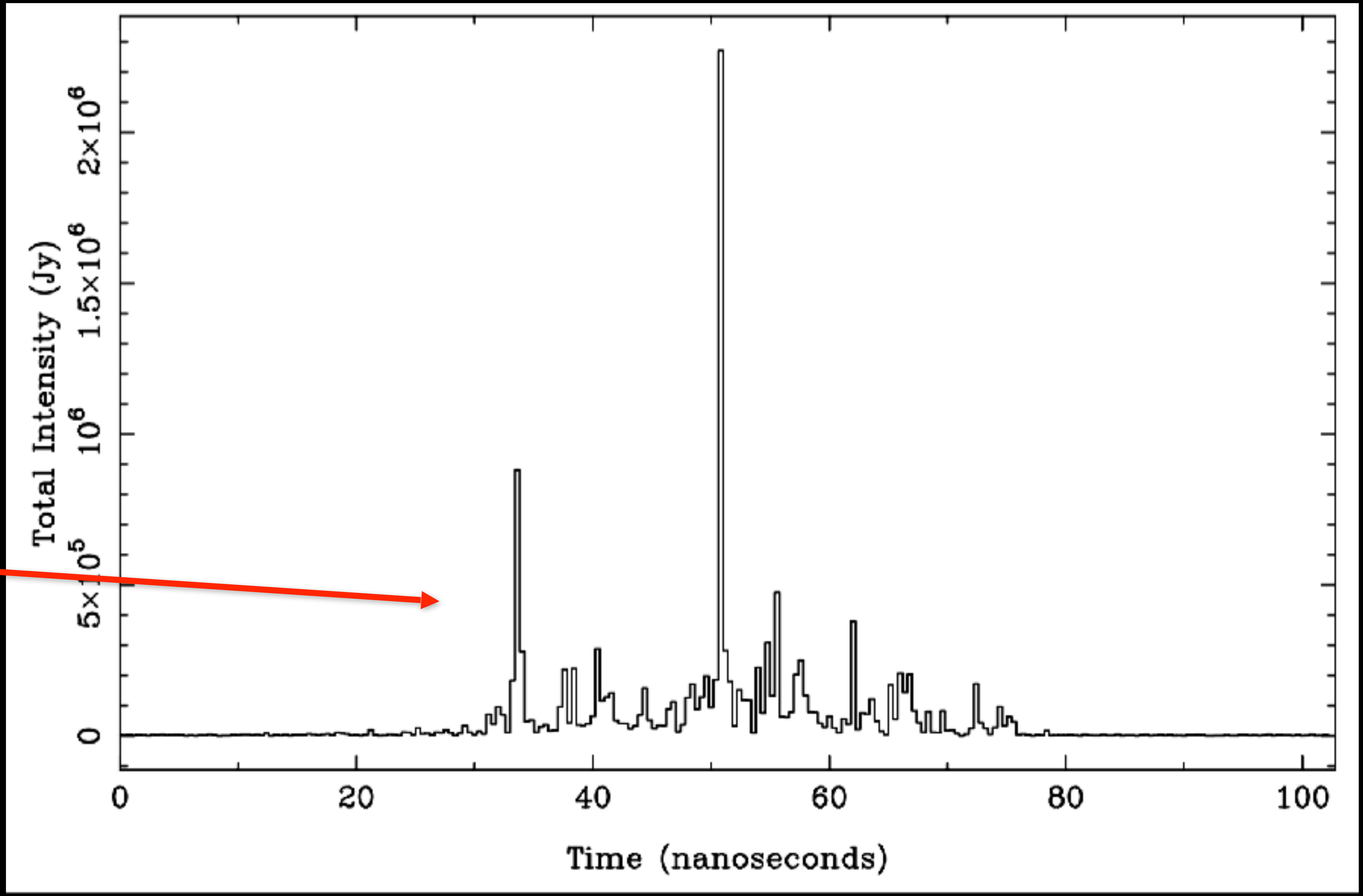


Hankins, Eilek (2016)

MP and IP have high-energy emissioon counter-parts - definetely from the outer magnetosphere.

Giant pulses and nano-shots





51 ns resolution

4 ns resolution

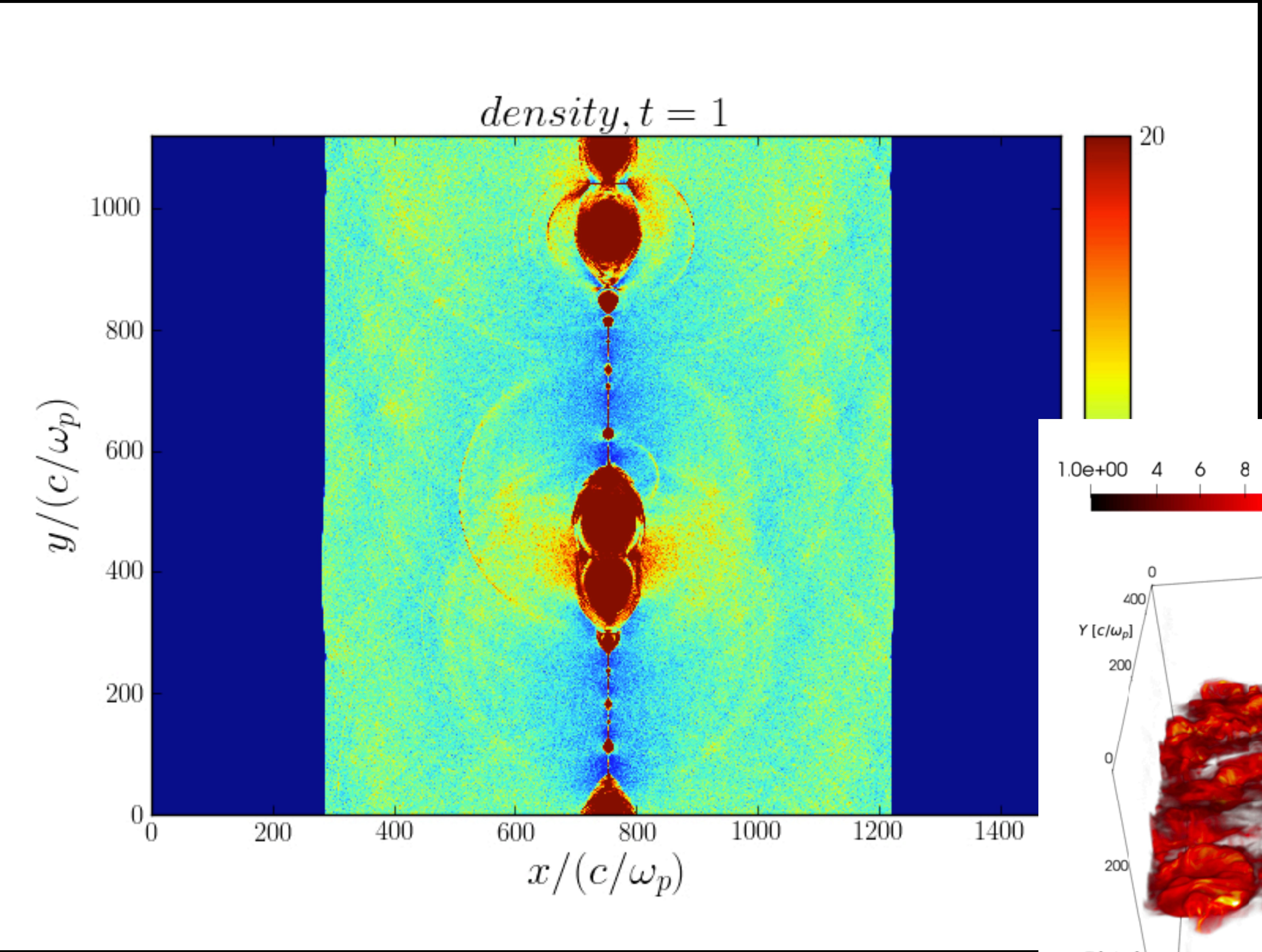
Hankins, Eilek (2016)

Some times resolved into nano-second flashes. Instantaneously very bright, up to few % of the spin-down.

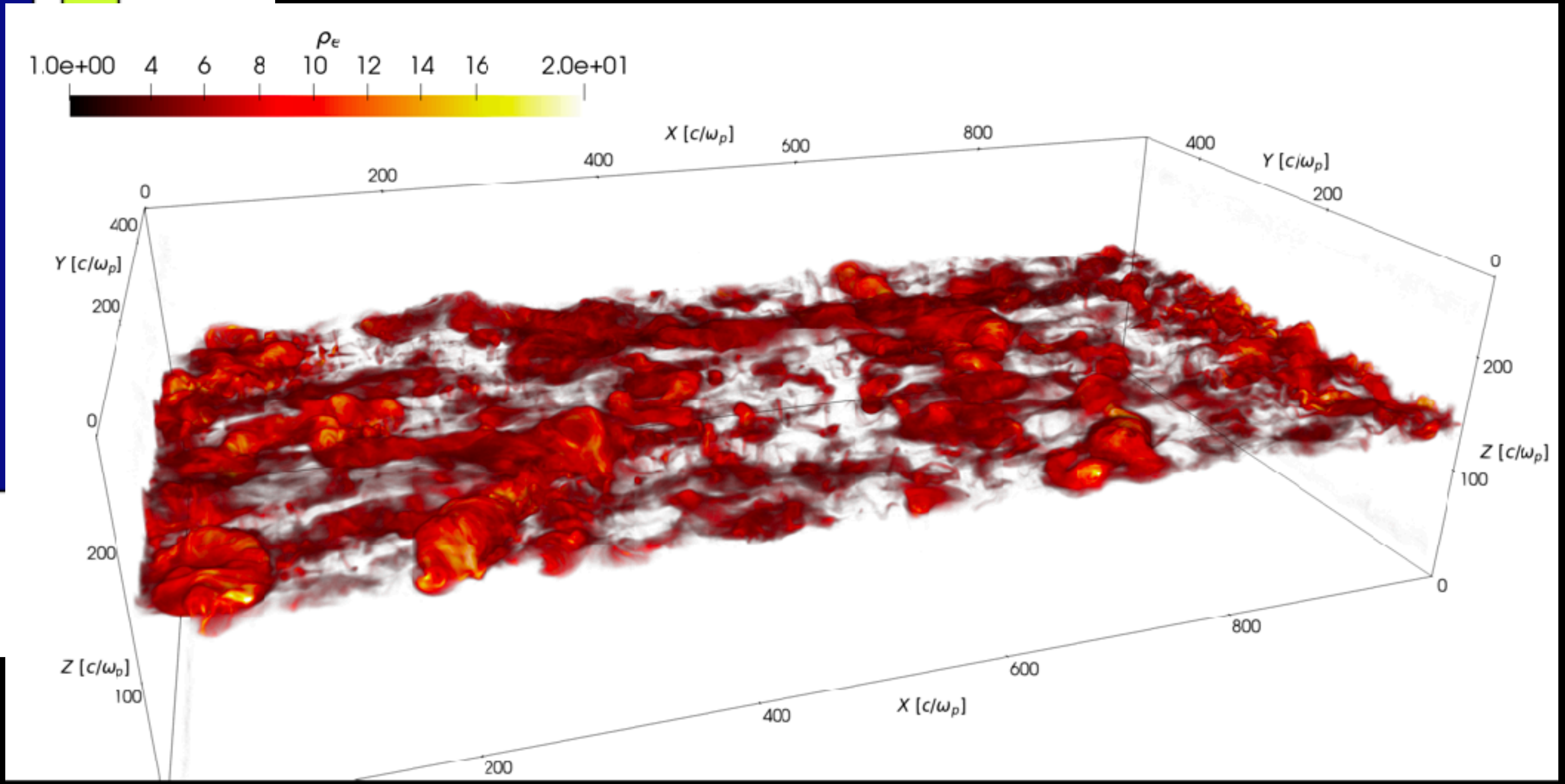
$$\nu_{\rm obs}\delta t \sim \mathcal{O}(10)$$

Giant pulses from reconnection

- Periodic boundary conditions in y, radiative in x.
- Plasma-vacuum interface to look at the escape of waves.
- Current sheet breaks into plasmoids, plasmoids merge.

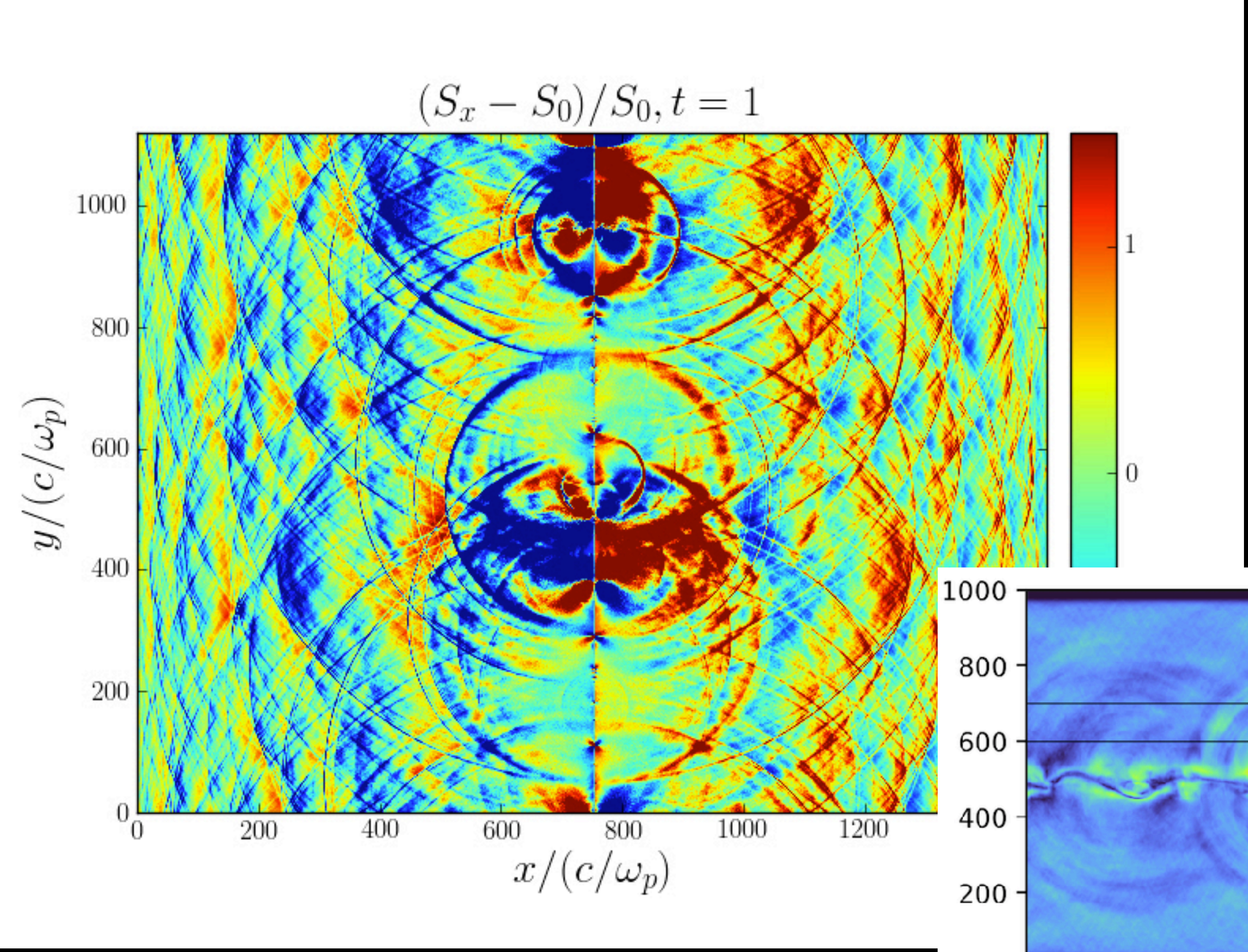


Philippov, Uzdensky, Spitkovsky, Cerutti (2019)

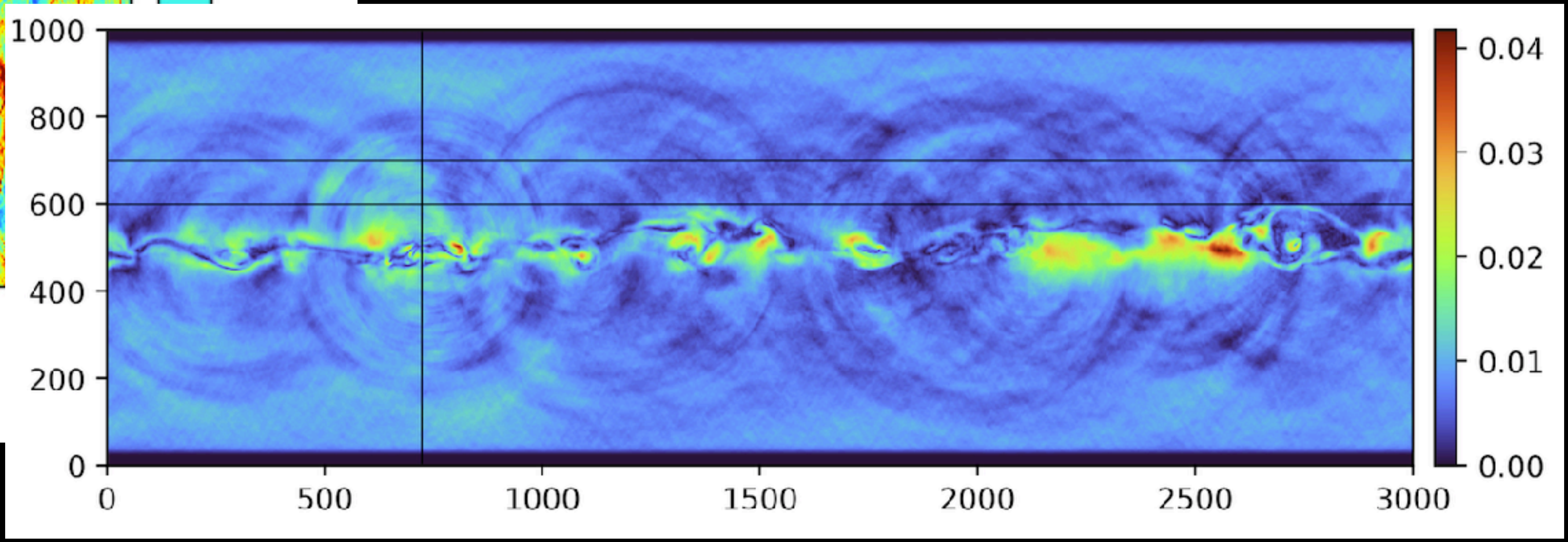


Chernoglazov, Hakobyan, Philippov, 2023

Giant pulses from reconnection



- Periodic boundary conditions in y, outflow in x.
- Plasma-vacuum interface to look at the escape of waves.
- Current sheet breaks into plasmoids, plasmoids merge.



Philippov, Uzdensky, Spitkovsky, Cerutti (2019)

Chernoglazov, Hakobyan, Philippov, in prep

Implications

Energetics:

$$S_{\rm obs} \sim 0.01(\pi d^2)^{-1}(\varepsilon/\tau\nu)\Gamma^3 \sim 10^{-25}\Gamma^3 {\rm erg/cm^2 \cdot sec \cdot Hz} \sim 300{\rm Jy}$$

$$\varepsilon \sim \left(B_{\rm LC}^2/8\pi\right) l^3 \sim 10^{21}{\rm erg}$$

$$T_B \sim S_{\rm obs}c^2/(2k_B\nu^2\delta\Omega) \sim 10^{38}{\rm K}(\Gamma/30)^3$$

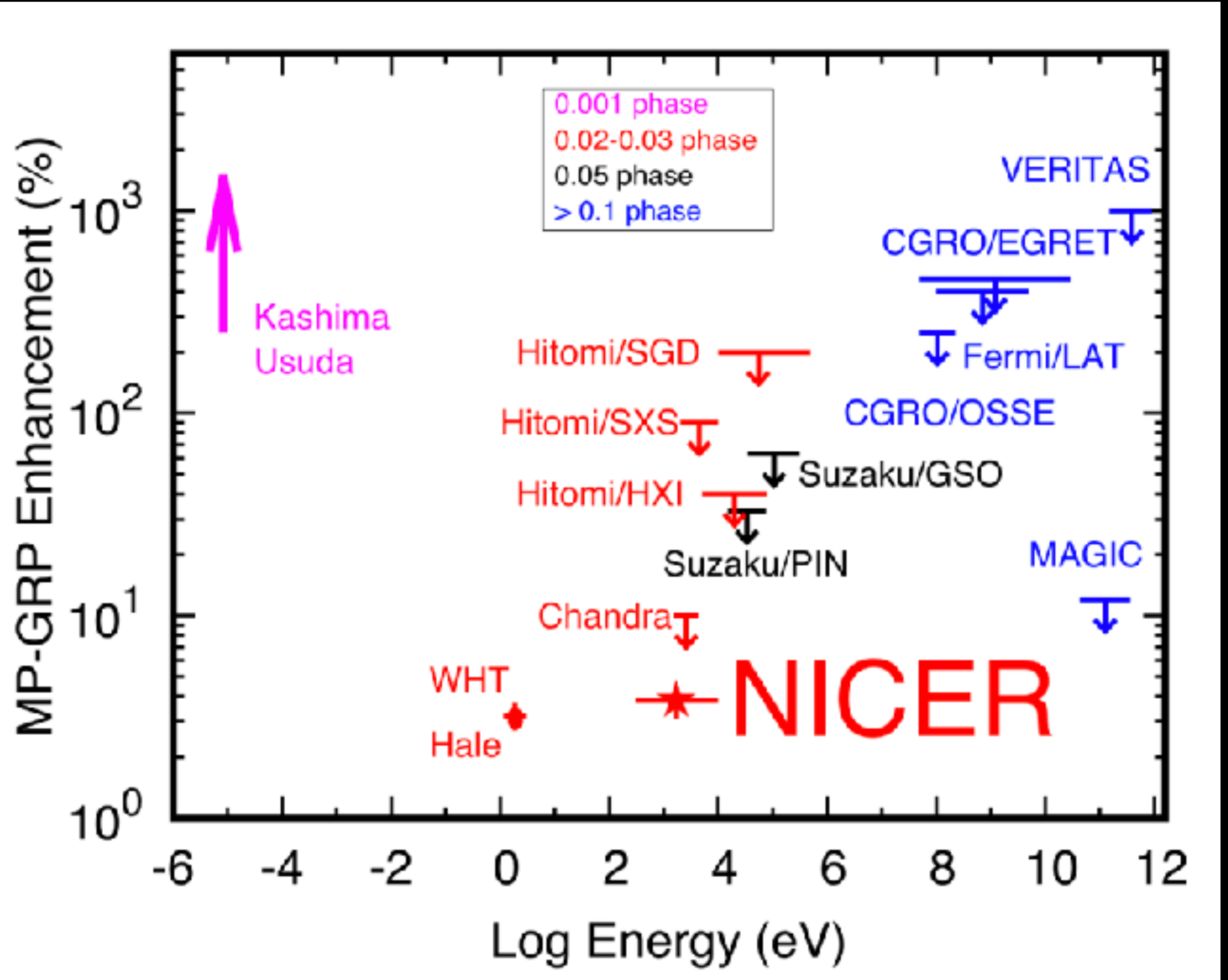
Requires MGs B-field strength at the light cylinder.

Frequency:

$$\delta \sim 1{\rm m}\cdot B_6^{-3/2}, \quad l \sim 10\delta \sim 10{\rm m}$$

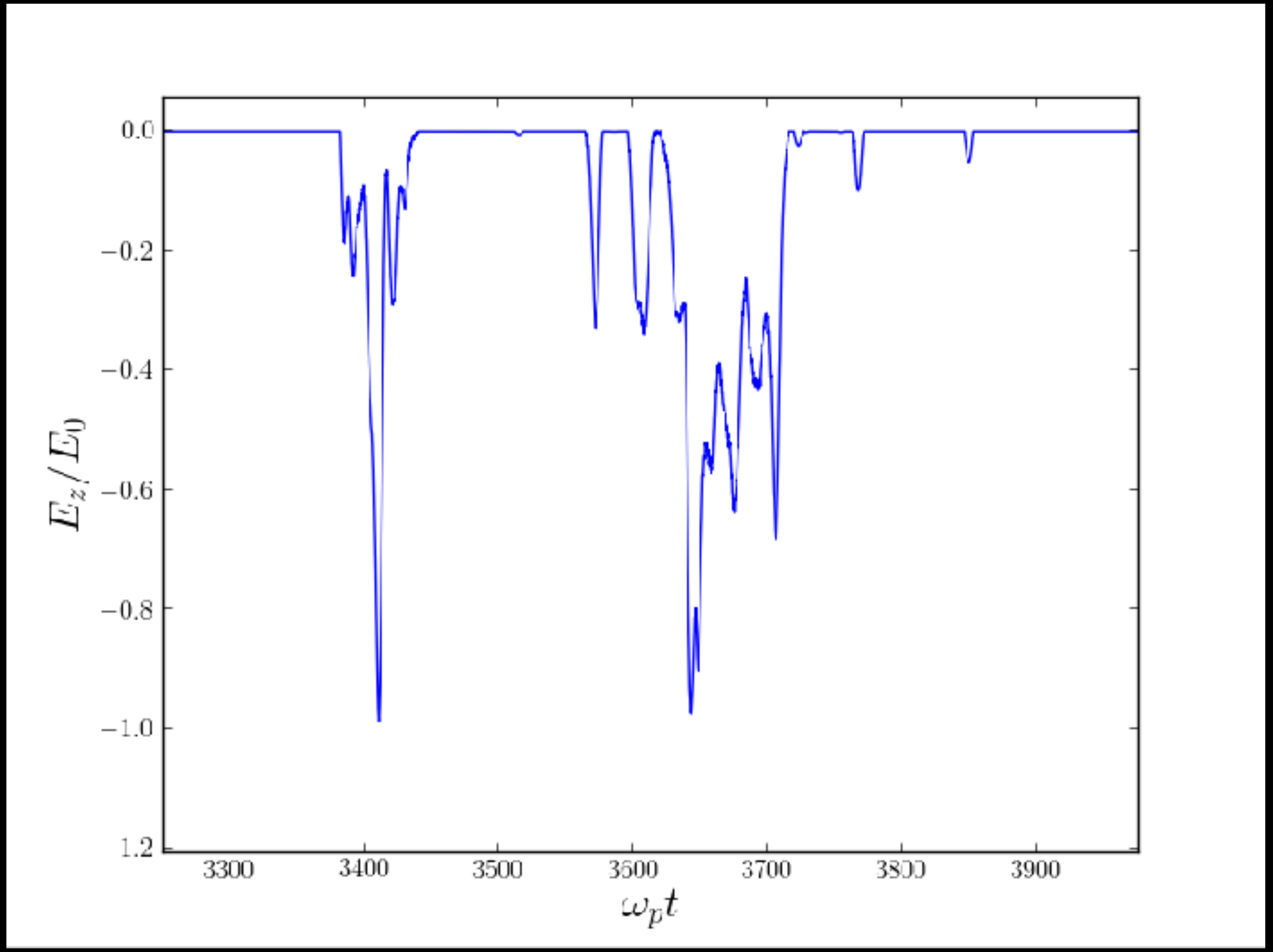
$$\nu \sim c\Gamma/l \sim 1{\rm GHz}\cdot B_6^{3/2}$$

Duration: $\tau \approx 10/\nu$



Few % enhancement of X-ray emission: coincident with GRP arrivals - consistent with plasmoid mergers/ reconnection

Enoto et. al. (2021)



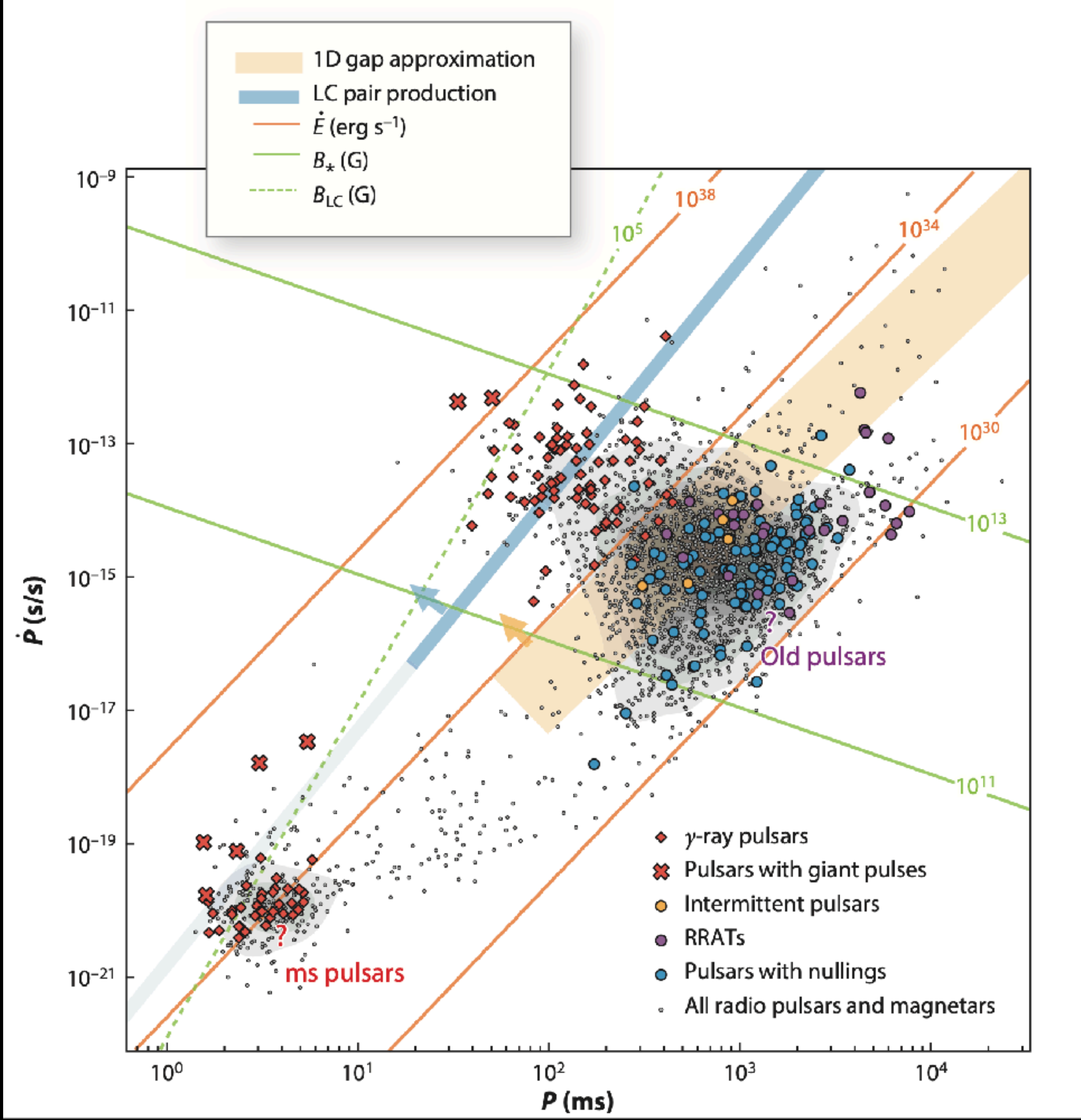
~Five year Future

Pair production in 3D

Old and Millisecond Pulsars

Variability: nulling, thunderstorms, raindrops, drifting subpulses

Other bands: optical, X-ray, etc.



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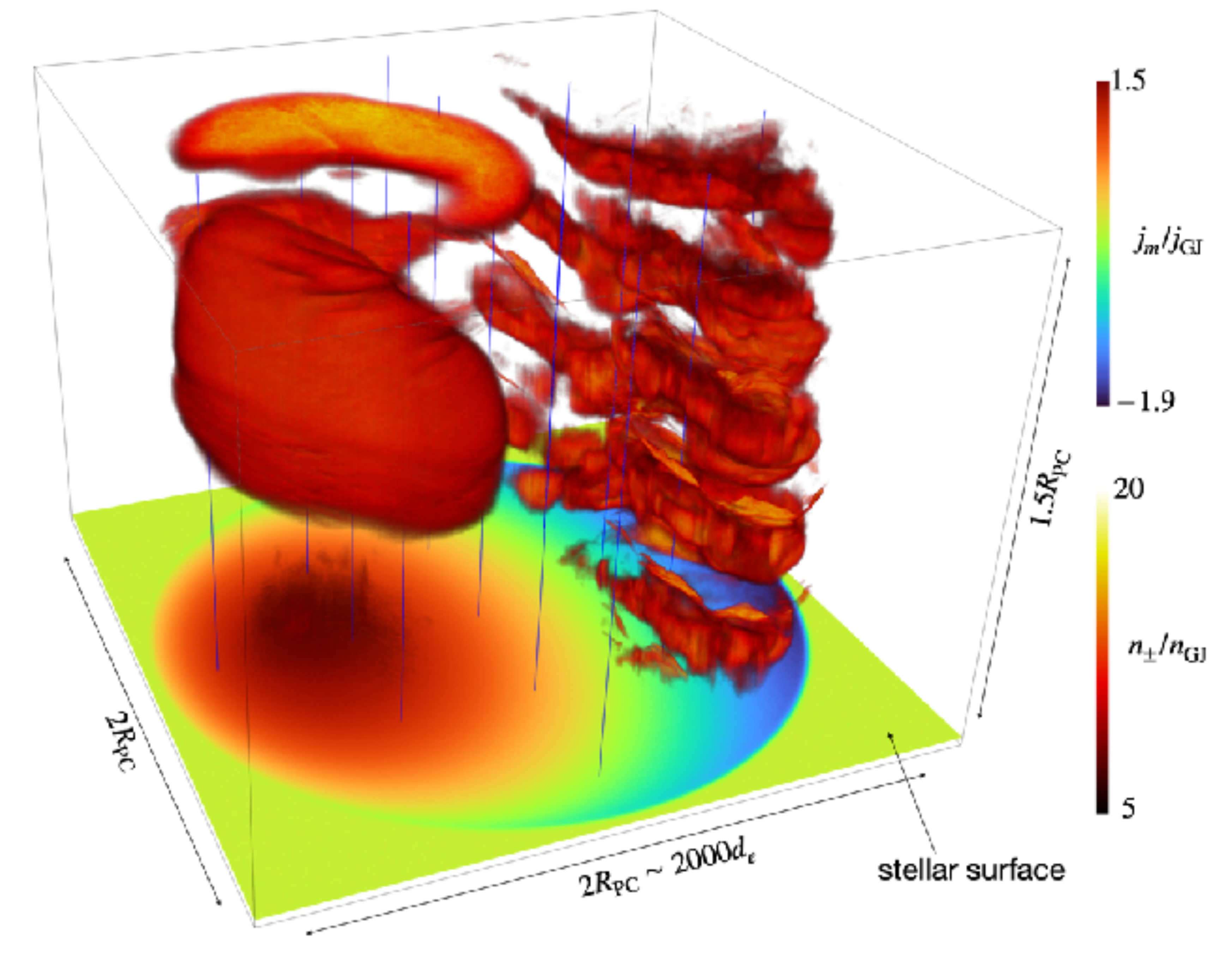
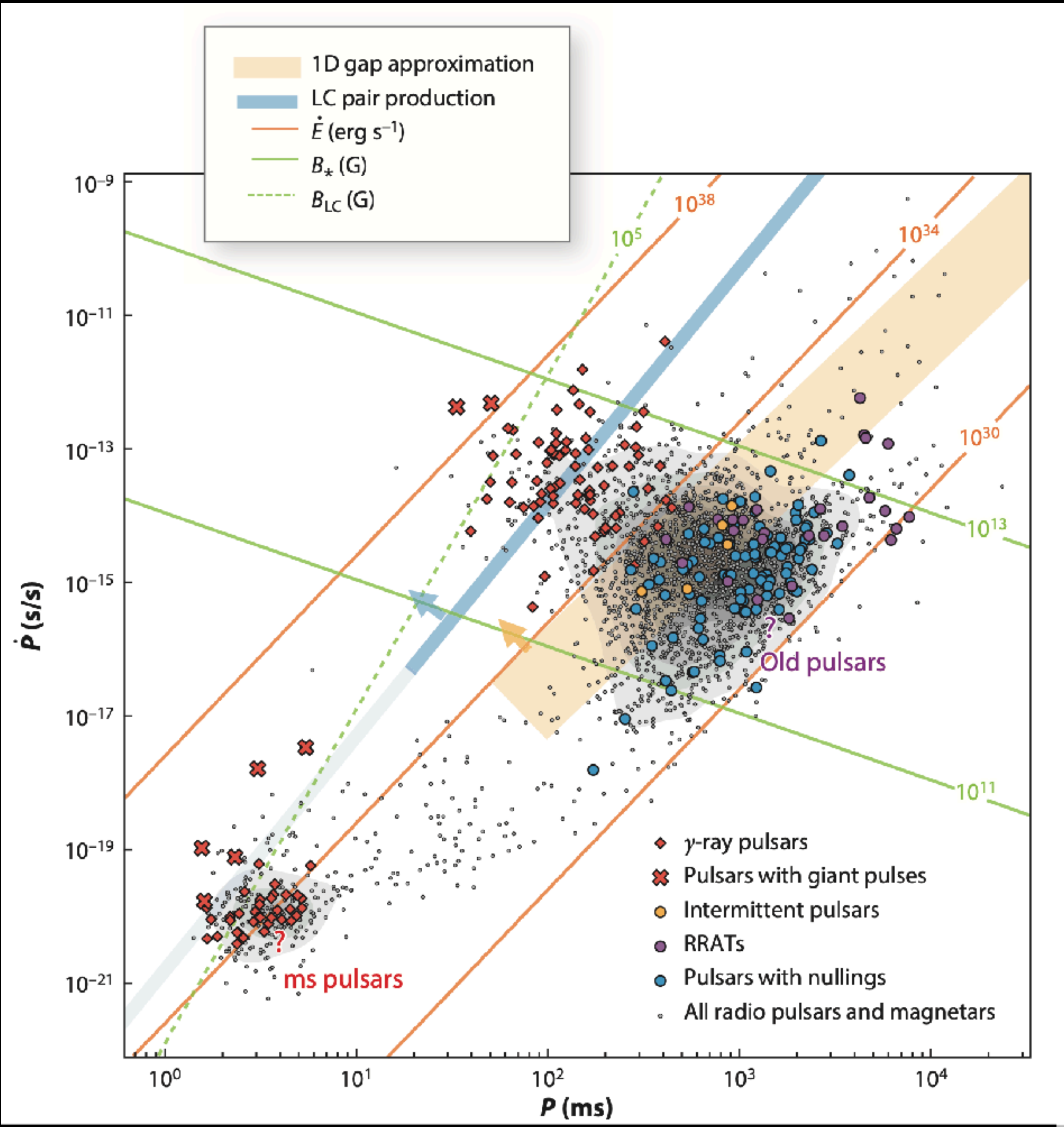
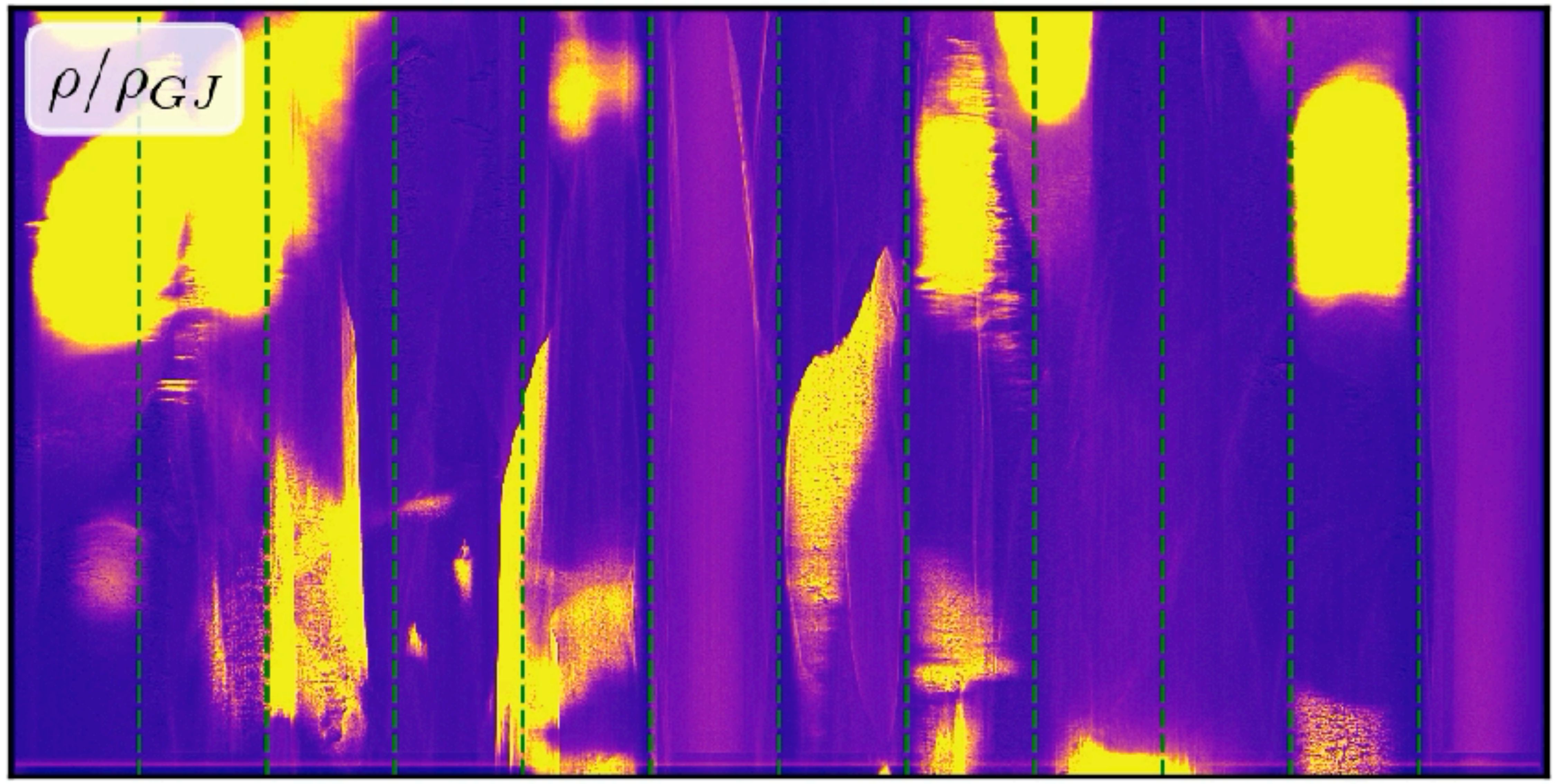
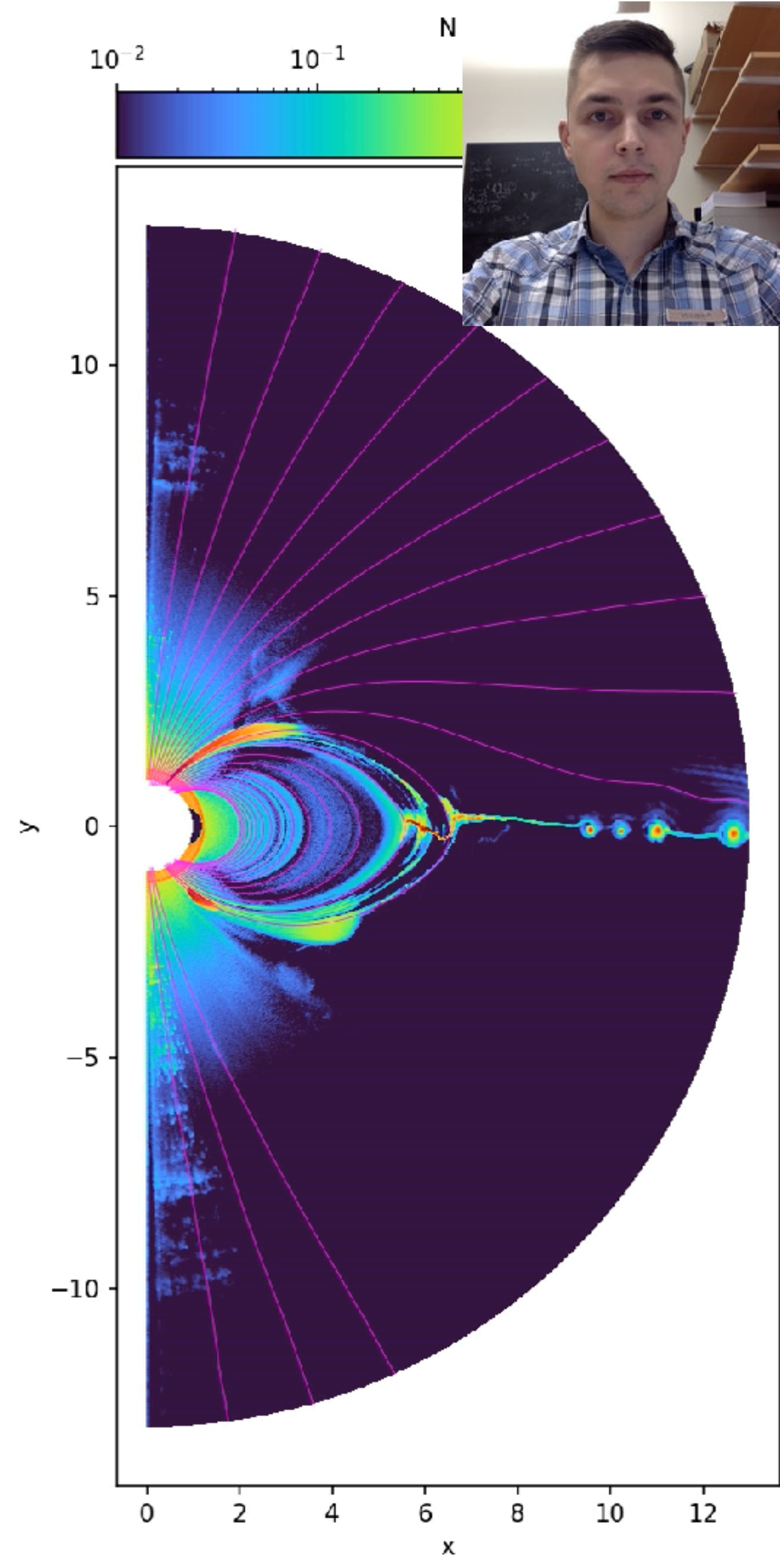
Other bands: optical, X-ray, etc.









Conclusions and outlook

1. Origin of pulsar emission has been a puzzle since 1967 - kinetic plasma simulations are finally addressing this from first principles.

2. Current sheet is an effective particle accelerator. Particles in the sheet emit powerful gamma-ray mainly via synchrotron mechanism.

3. Low altitute radio emission is produced during non-stationary discharge at the polar cap, not a plasma instability in the uniform plasma flow. Giant pulses and nanoshots are powered by plasmoid mergers in the currrent sheet beyond the light cylinder.

4. Radio variability, multi-wavelength aspects are important next steps.