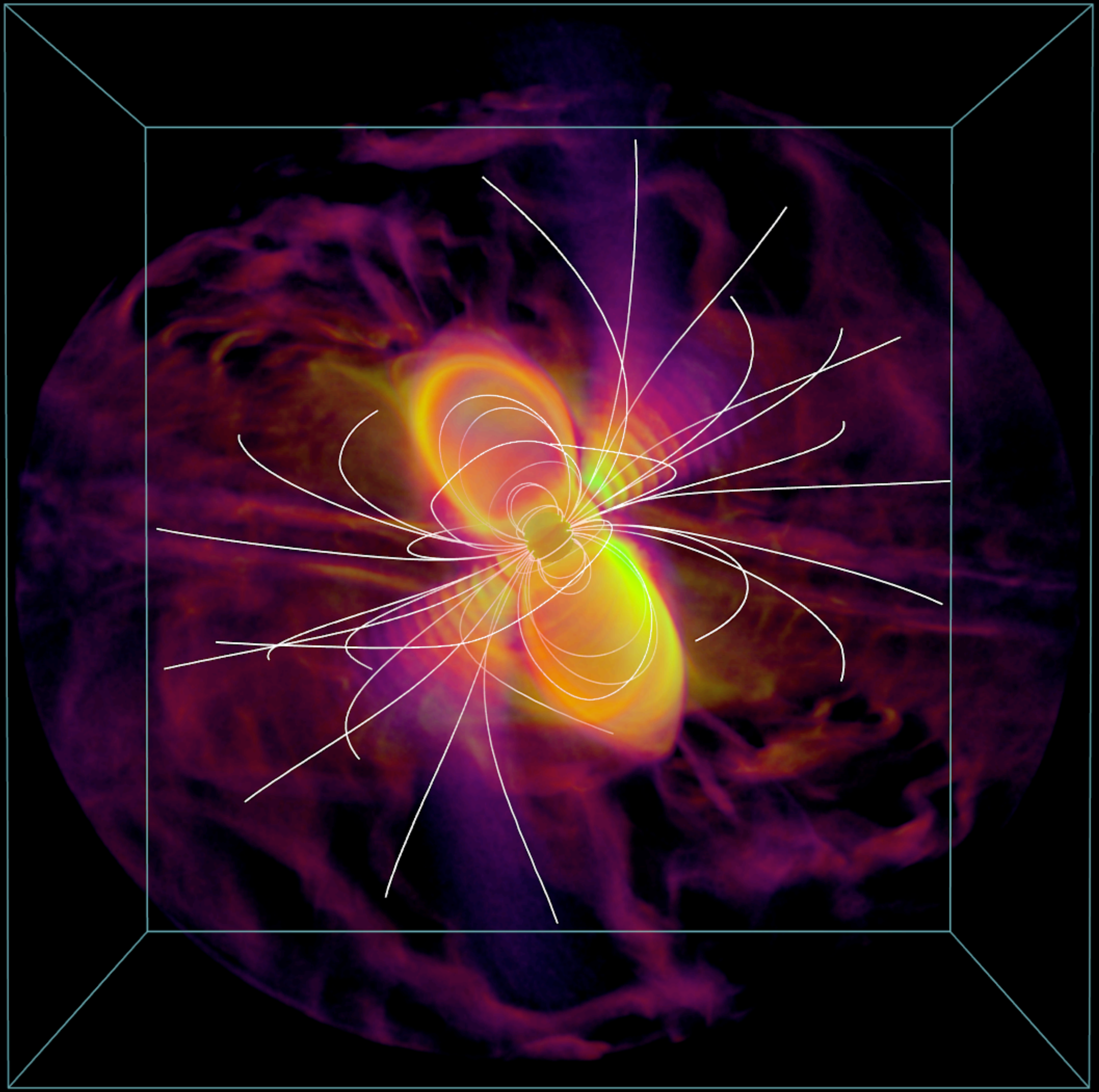


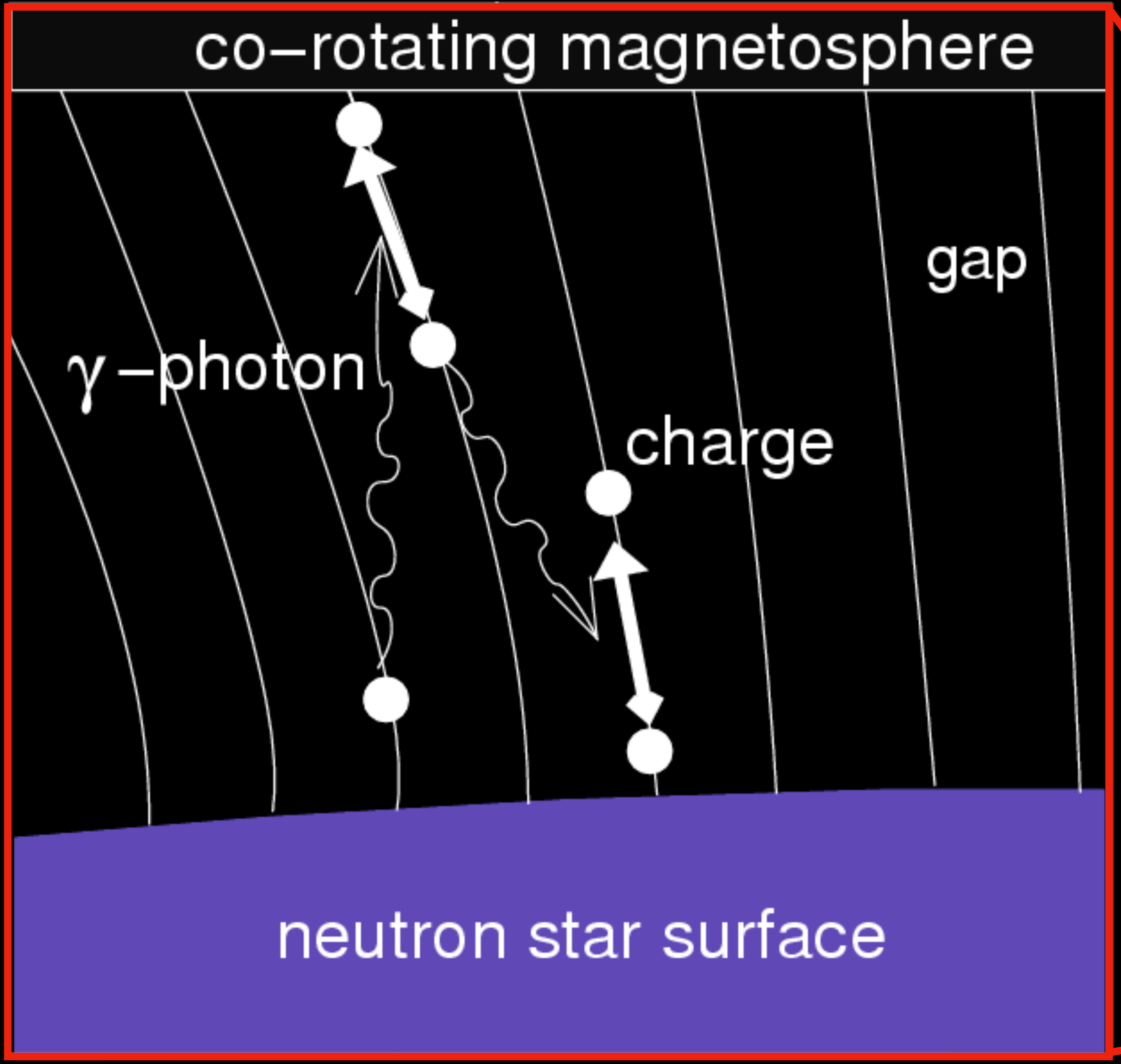
Physical processes in magnetospheres of pulsars and black holes

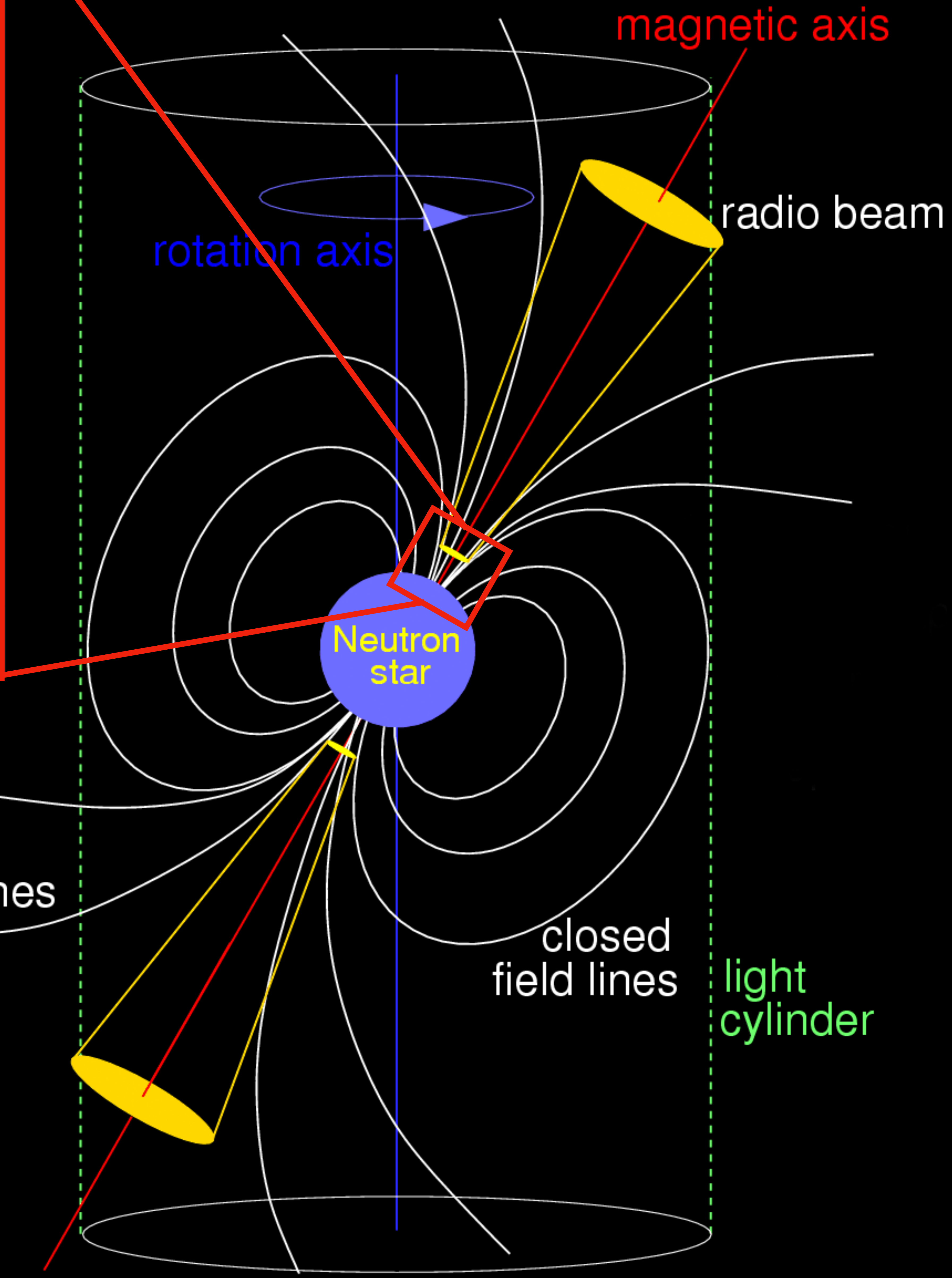
Sasha Philippov (U Maryland)

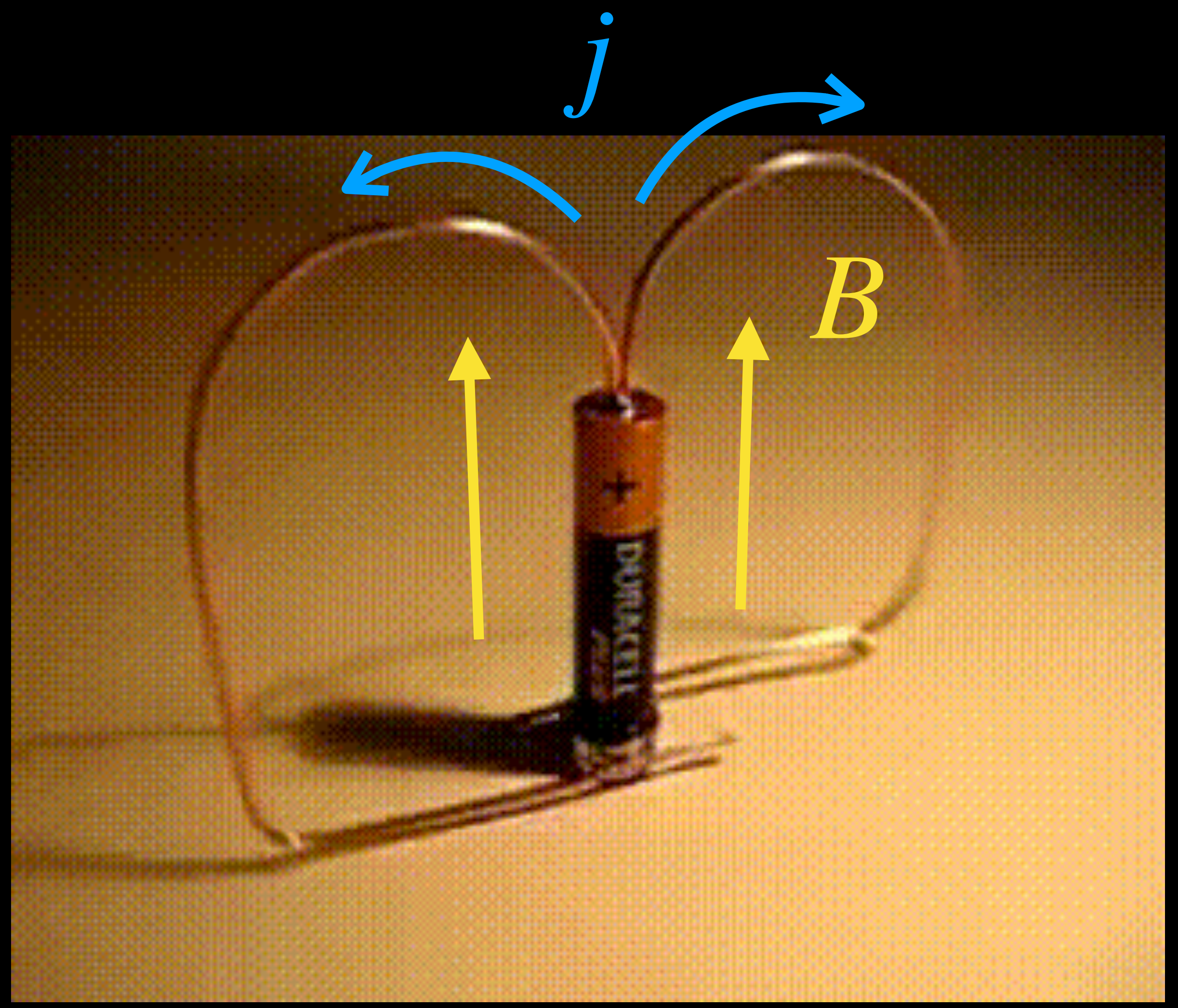
with:

Ashley Bransgrove (Princeton)
Benoit Cerutti (Grenoble, France)
Koushik Chattarjee (Harvard)
Sasha Chernoglazov (Maryland)
Benjamin Crinquand (Princeton)
Hayk Hakobyan (Columbia)
Amir Levinson (Tel Aviv, Israel)
Matthew Liska (Georgia Tech)
Jens Mahlmann (Columbia)
Bart Ripperda (CITA)
Anatoly Spitkovsky (Princeton)
Libby Tolman (Flatiron)
Andrey Timokhin (Zielona Gora, Poland)
Dmitri Uzdensky (Colorado)
Yajie Yuan (University of Washington, St Louis)

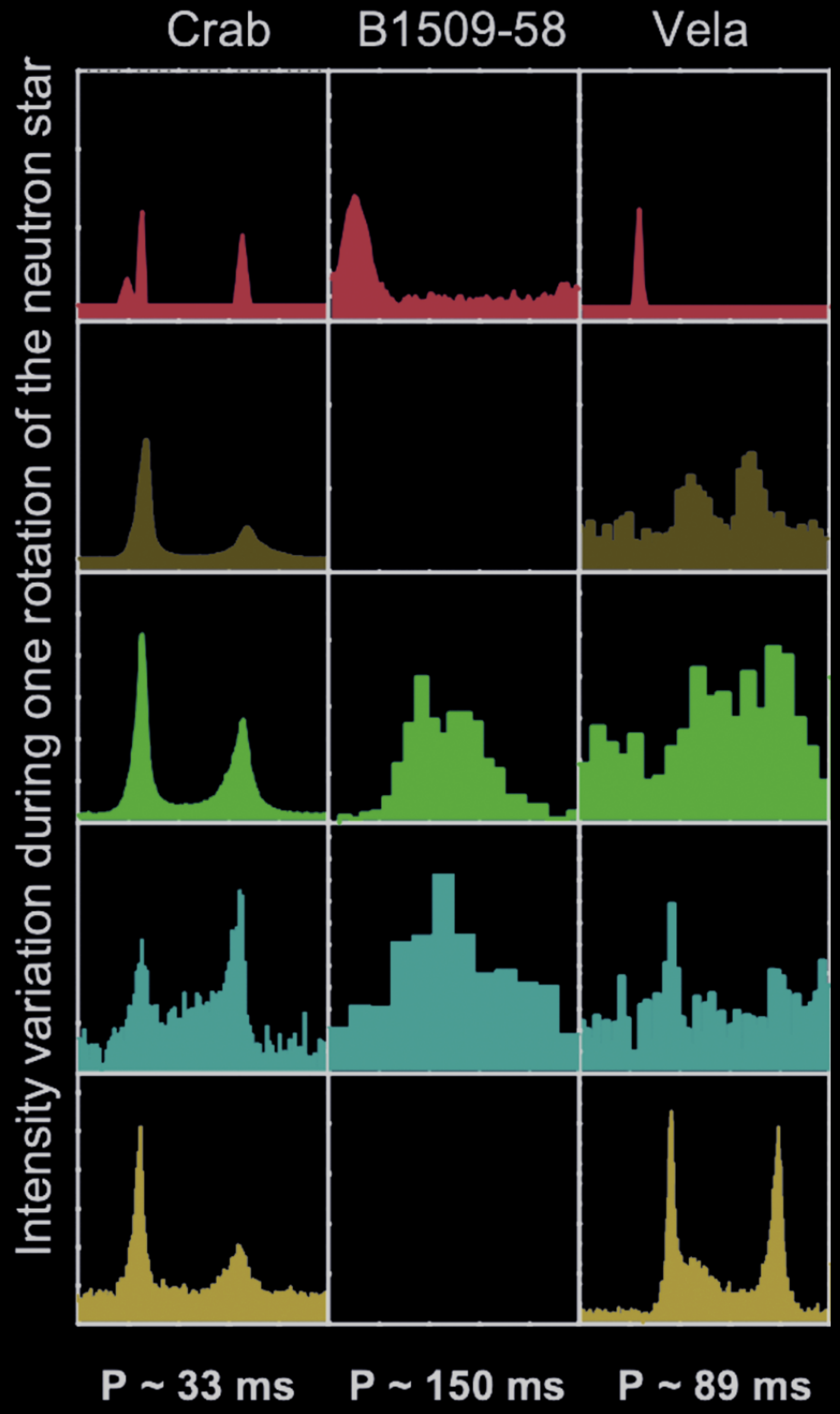
What is a pulsar?



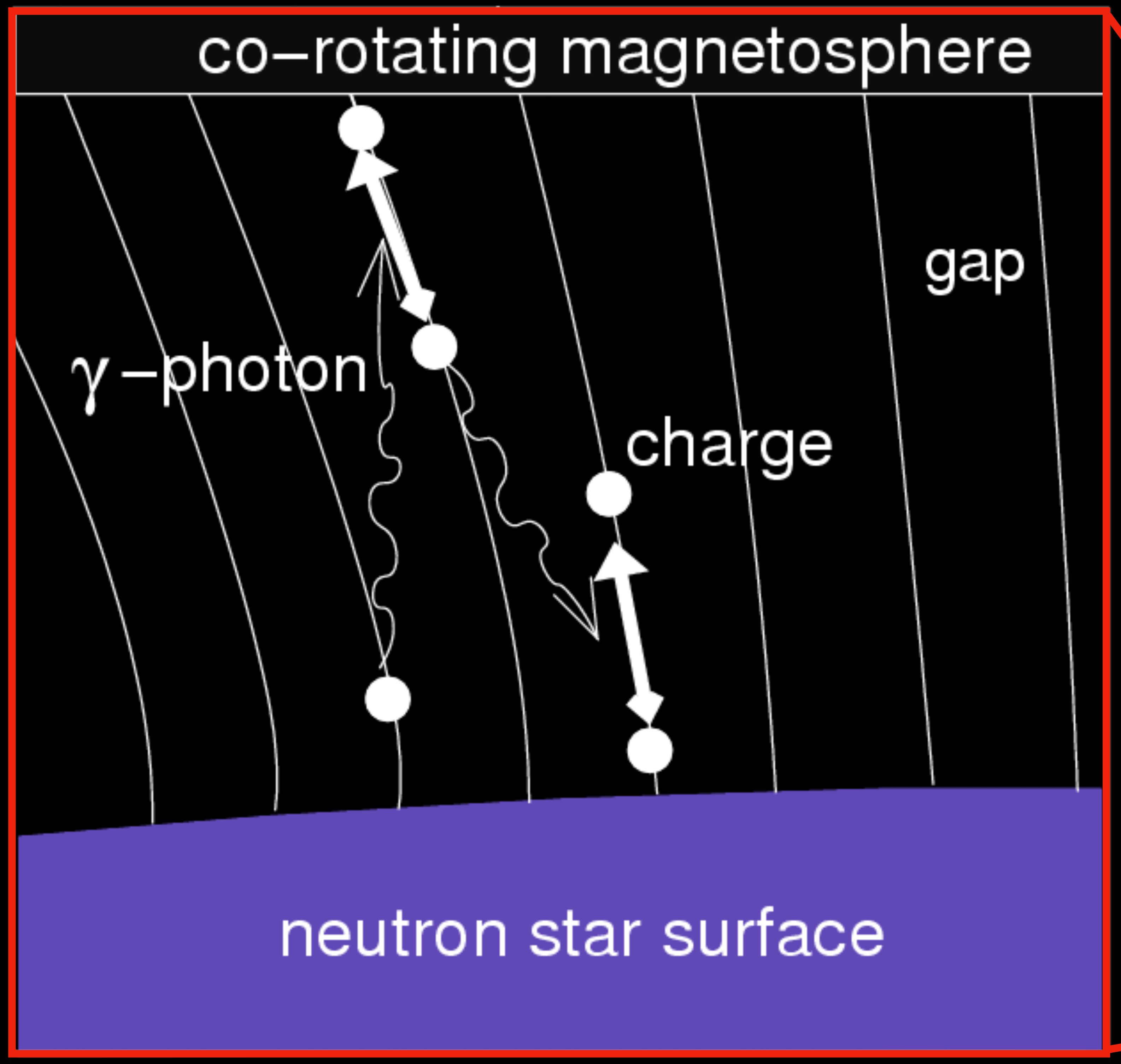


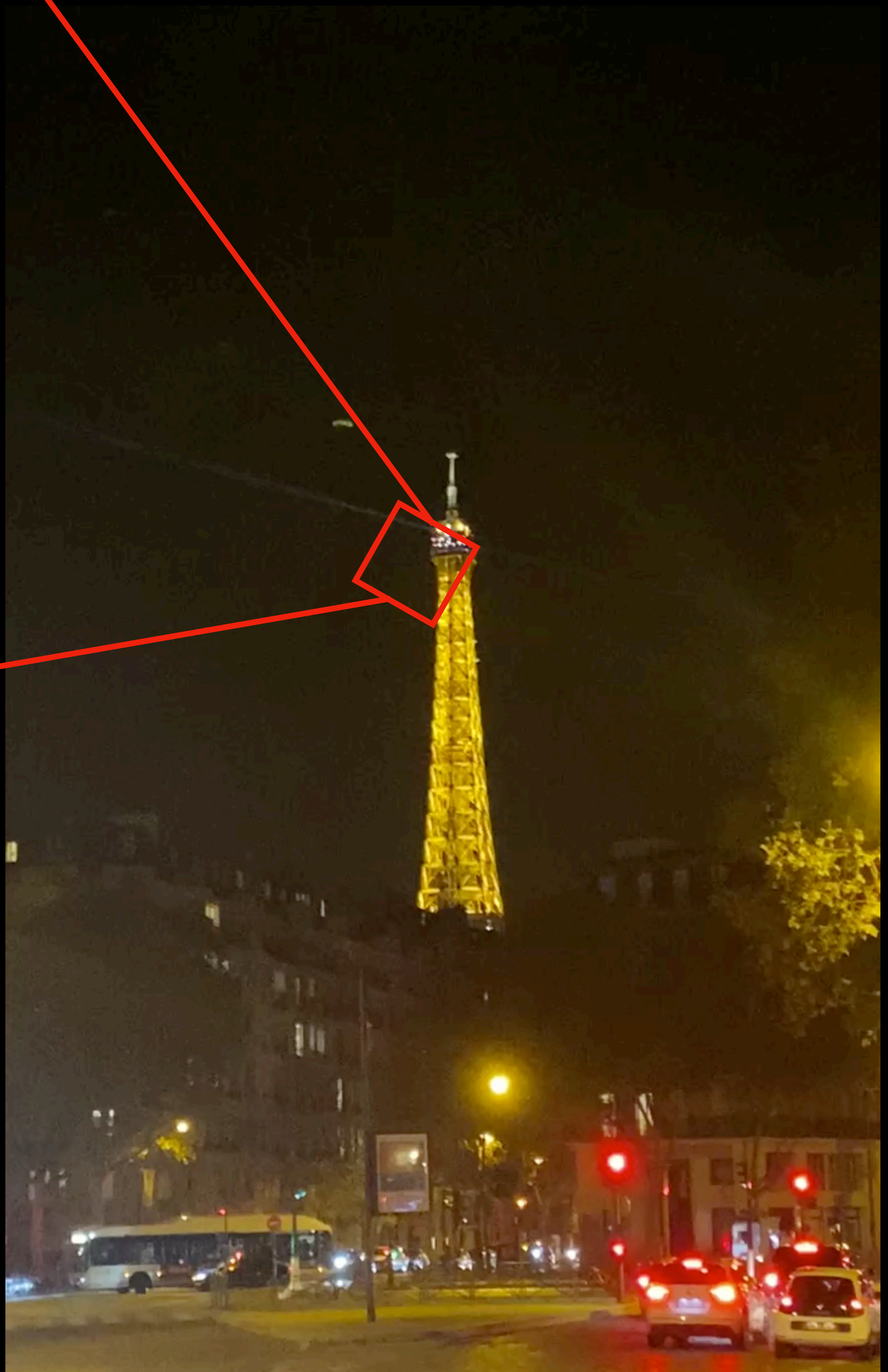


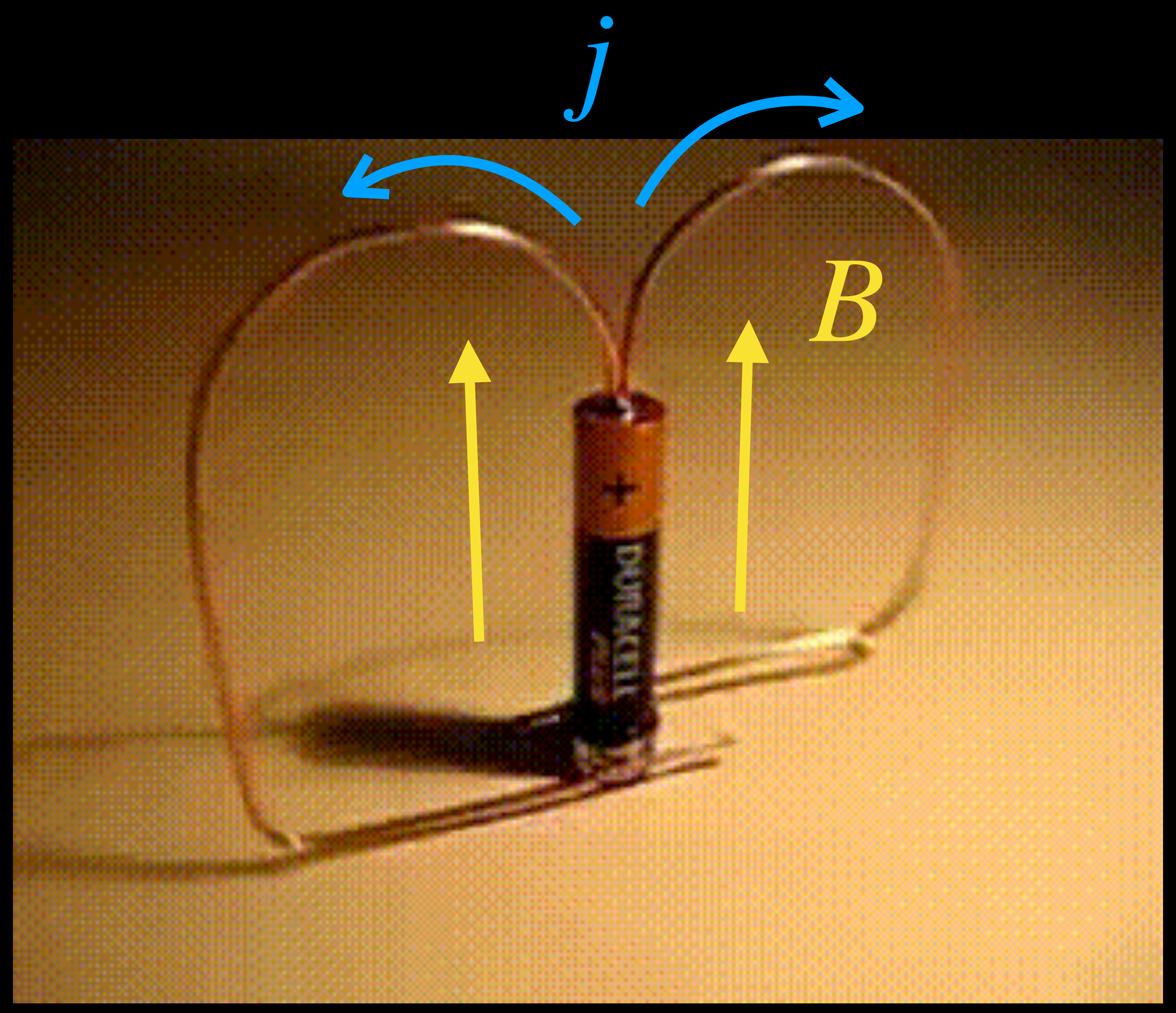
Unipolar induction



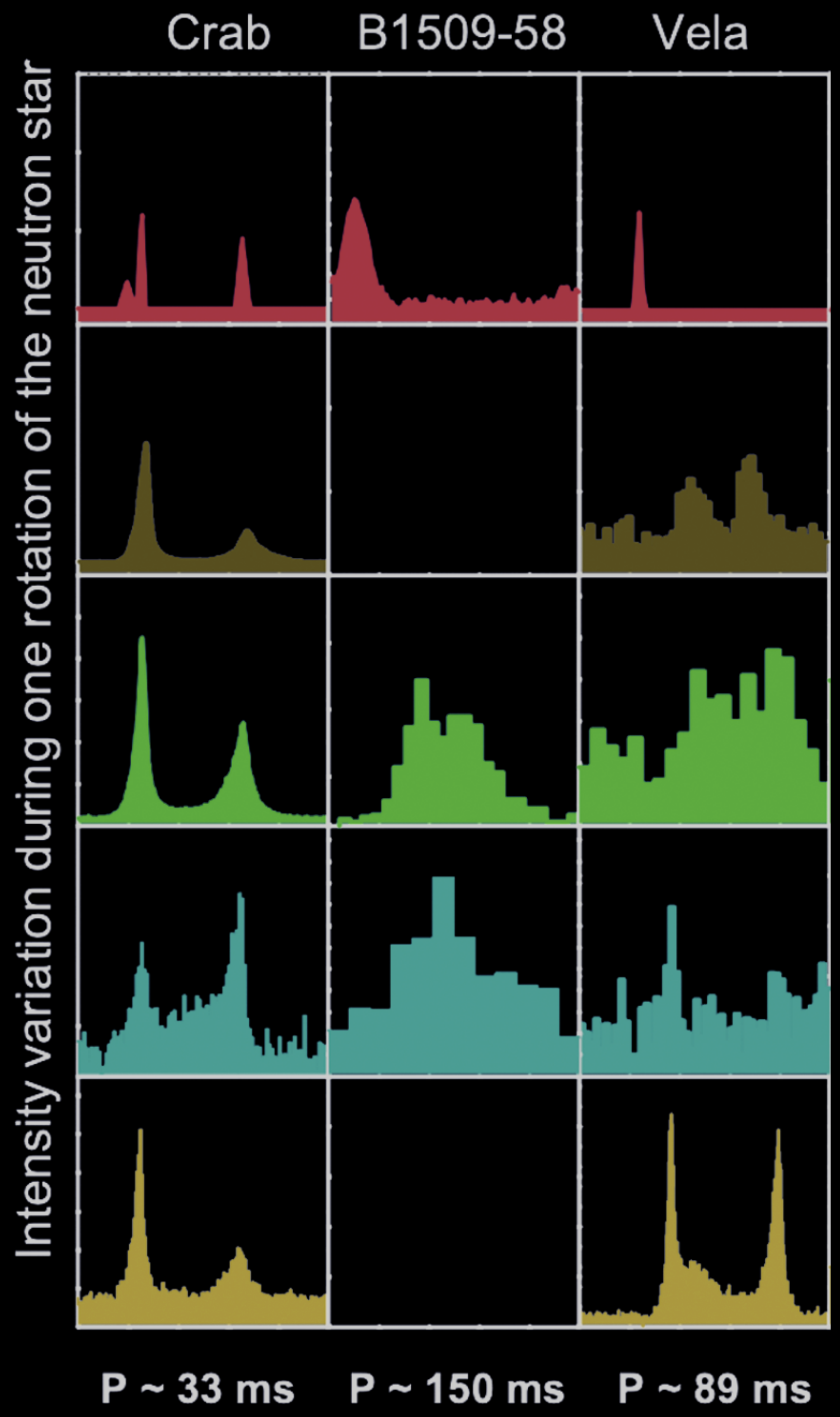
What is a pulsar?







Unipolar induction

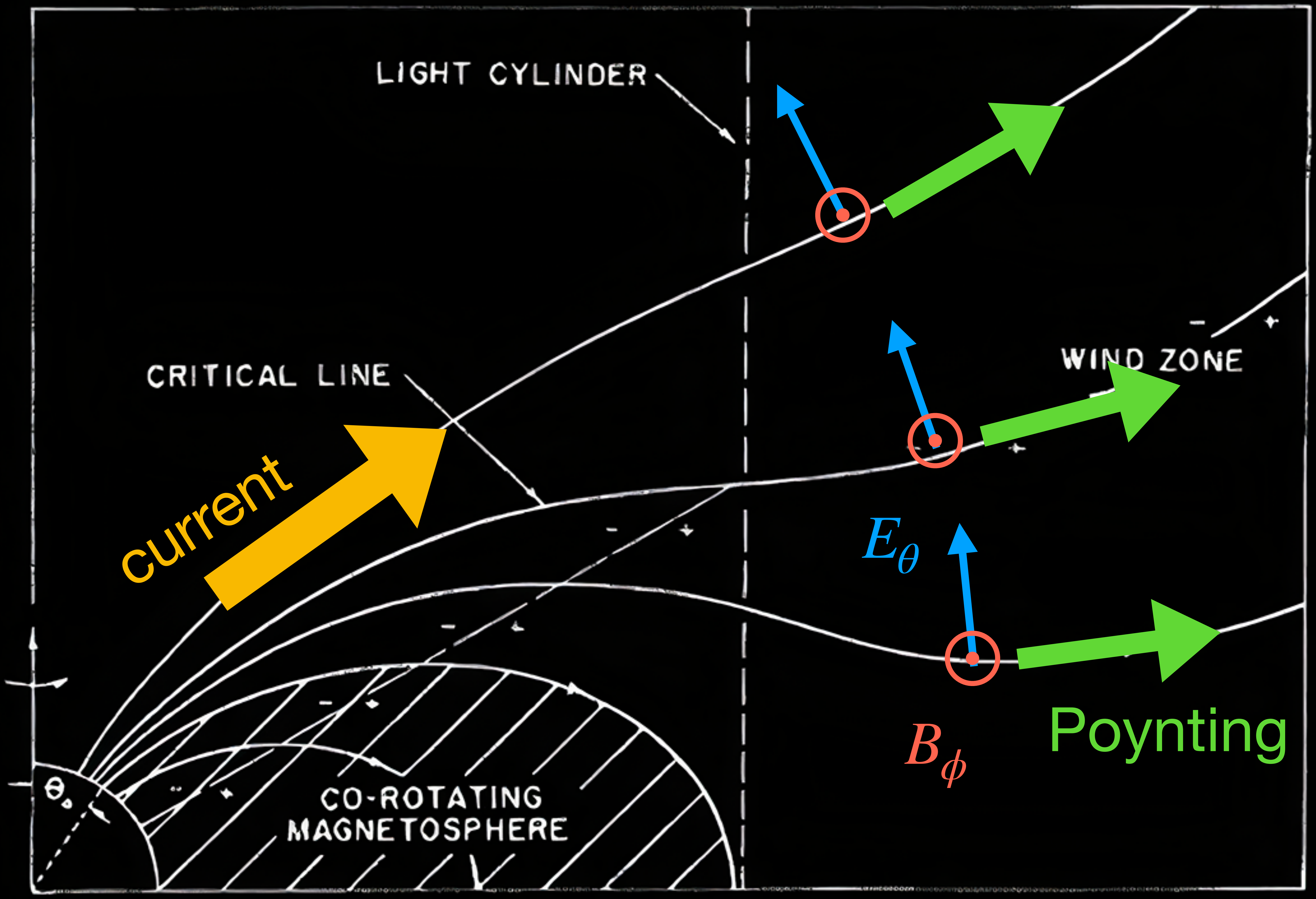


Theoretical cartoon: GJ model

- corotation electric field: $\boldsymbol{E} + \dfrac{\boldsymbol{\Omega} \times \boldsymbol{r}}{c} \times \boldsymbol{B} = 0$;
- sweepback of $\boldsymbol{B}$-field due to poloidal current;
- poynting flux: $\boldsymbol{E} \times \boldsymbol{B}$;
- electromagnetic energy losses.

$$\sigma = B^2/(4\pi\rho c^2) \gg 1$$

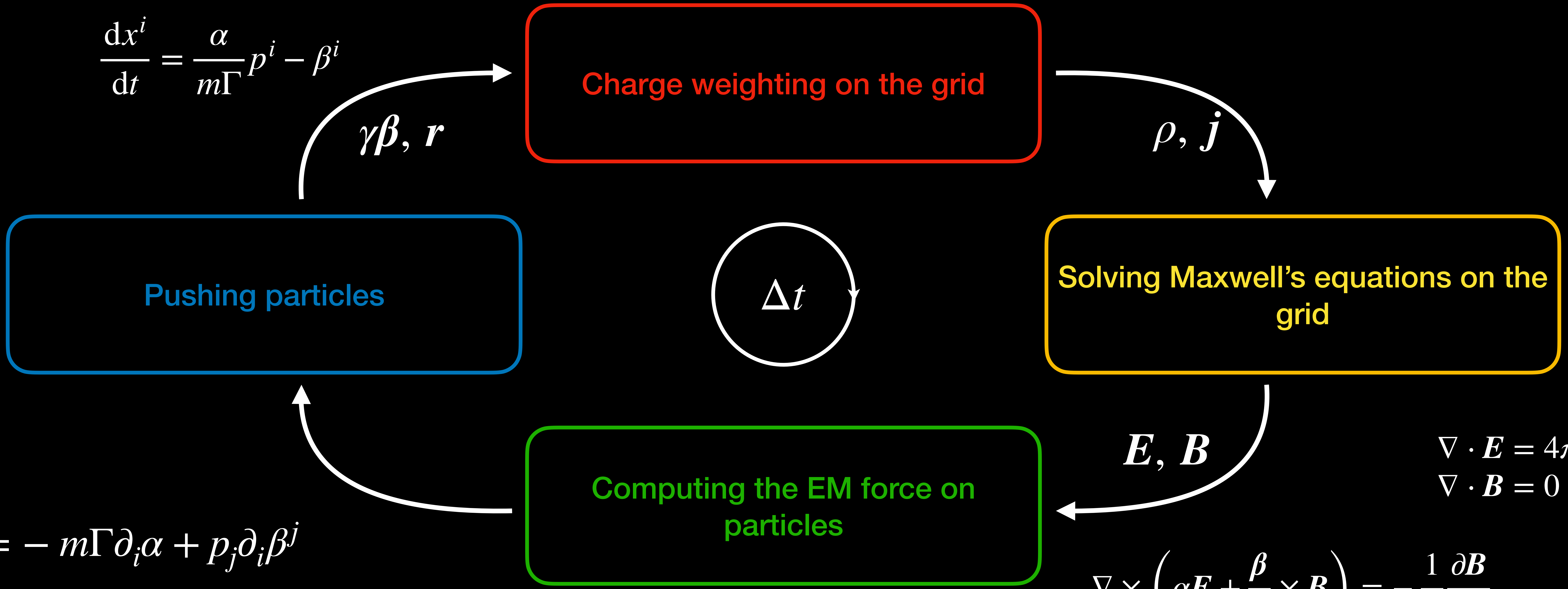
$$\rho_{\rm GJ} = -\frac{\boldsymbol{\Omega} \cdot \boldsymbol{B}}{2\pi c}$$



Goldreich & Julian (1969)

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

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



Charge weighting on the grid

$\rho,\, \boldsymbol{j}$

Solving Maxwell's equations on the grid

$\boldsymbol{E},\, \boldsymbol{B}$

Computing the EM force on particles

Pushing particles

$\gamma\boldsymbol{\beta},\, \boldsymbol{r}$

Δt

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

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

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

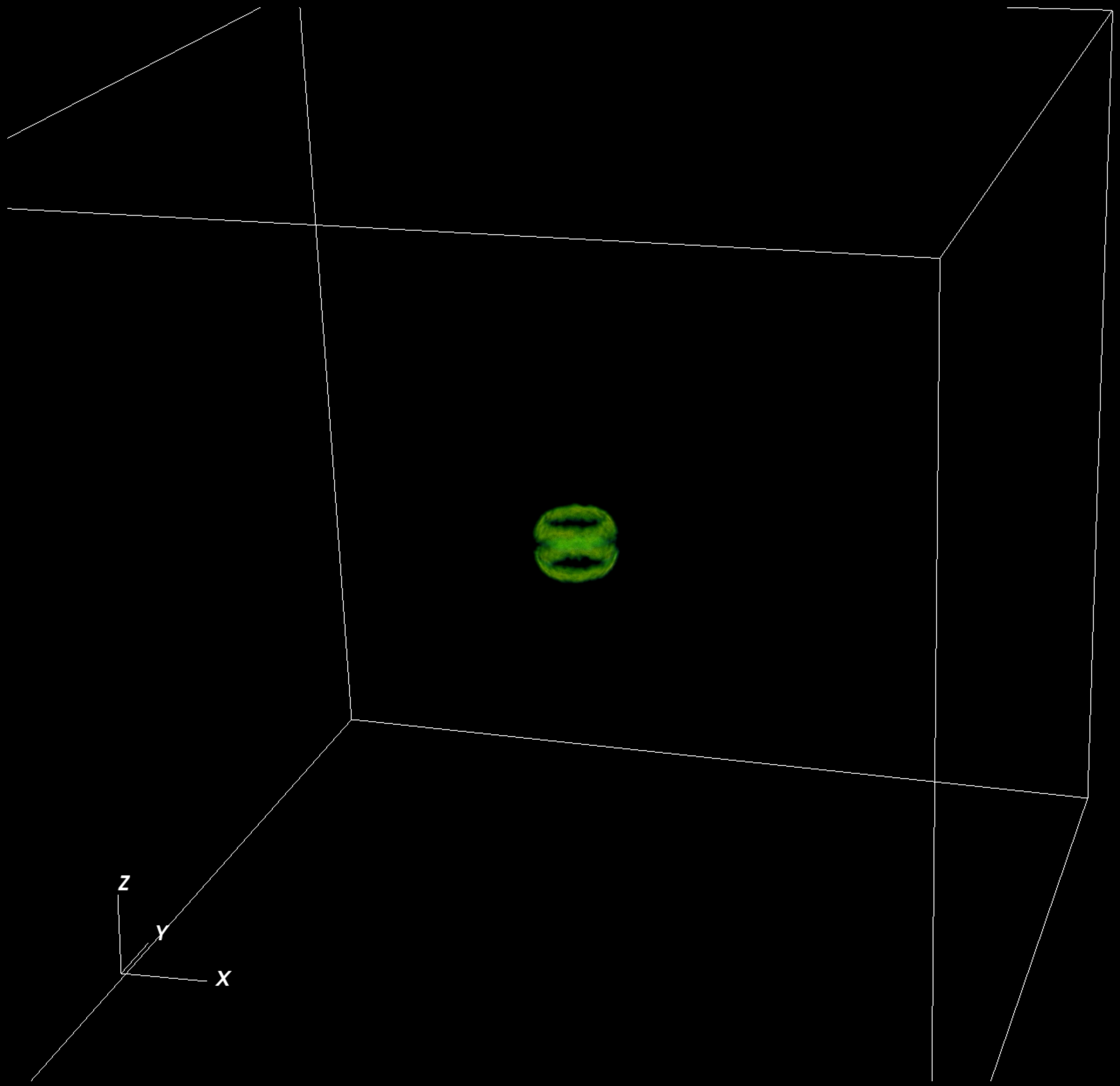
$$\nabla \times \left(\alpha \boldsymbol{B} - \frac{\boldsymbol{\beta}}{c} \times \boldsymbol{E} \right) = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} + \alpha \boldsymbol{j} - \rho\boldsymbol{\beta}$$

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

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

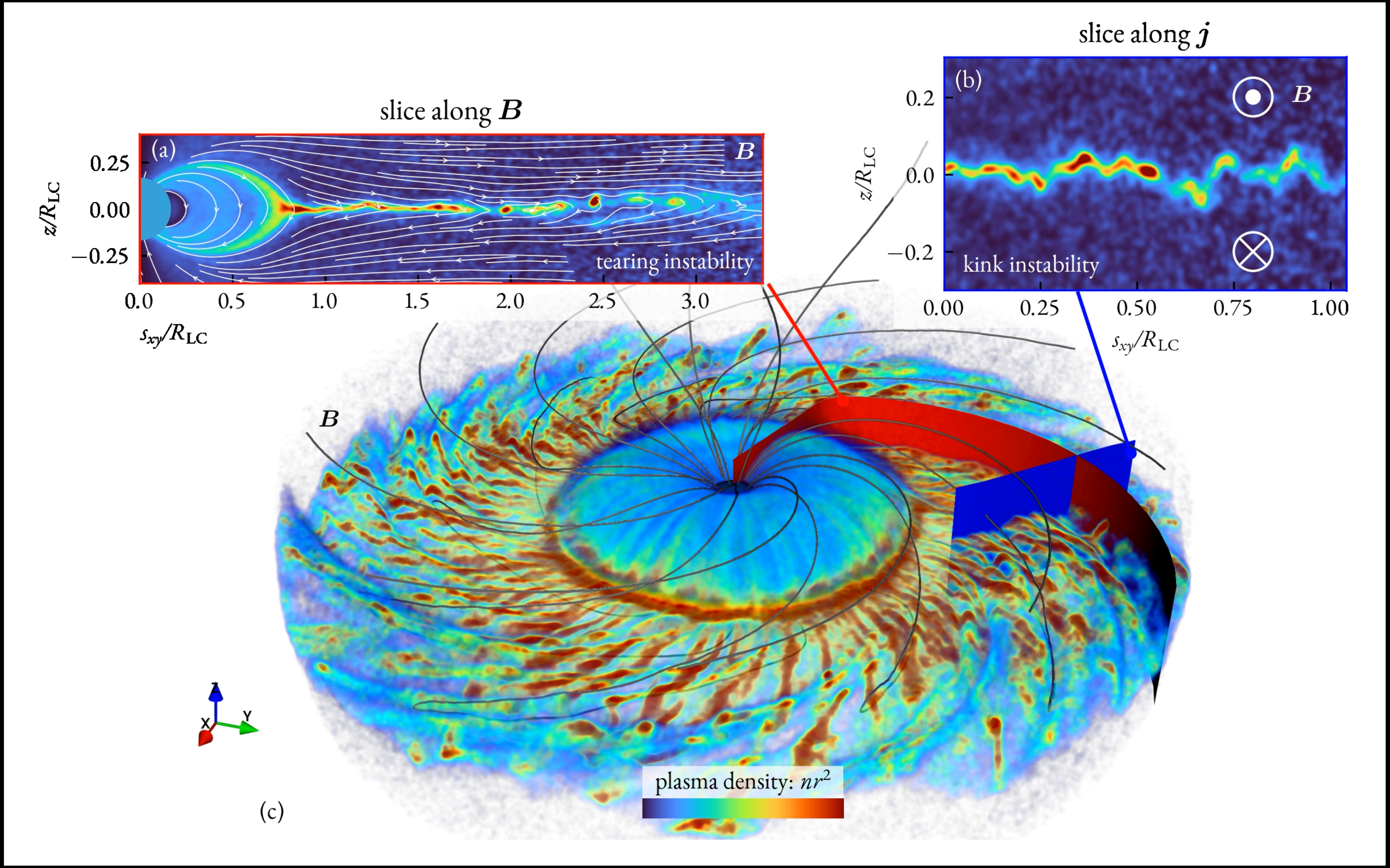
GJ pulsar (no pair production) is dead

- 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



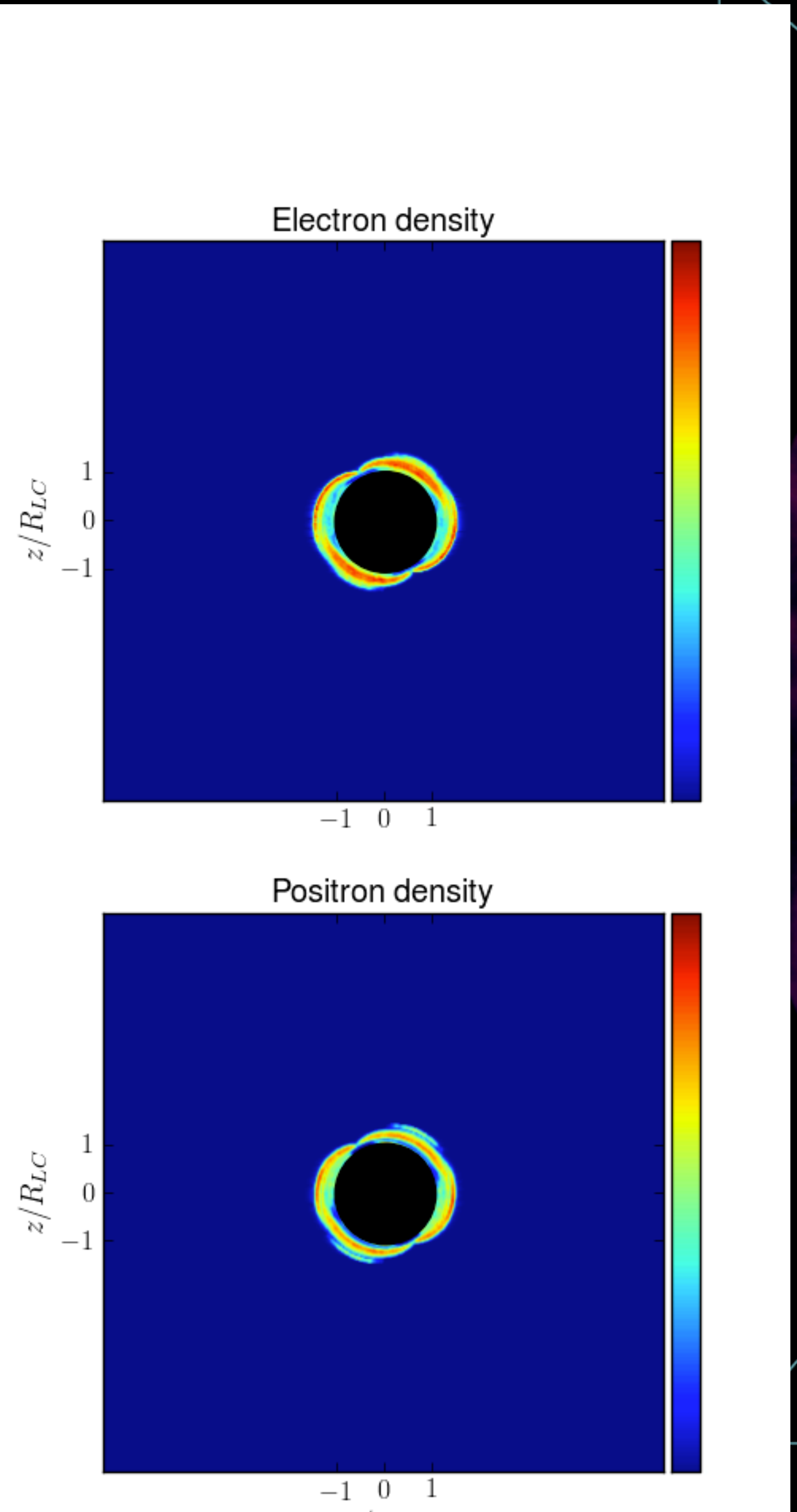
- Non-stationary discharge powers coherent radio emission

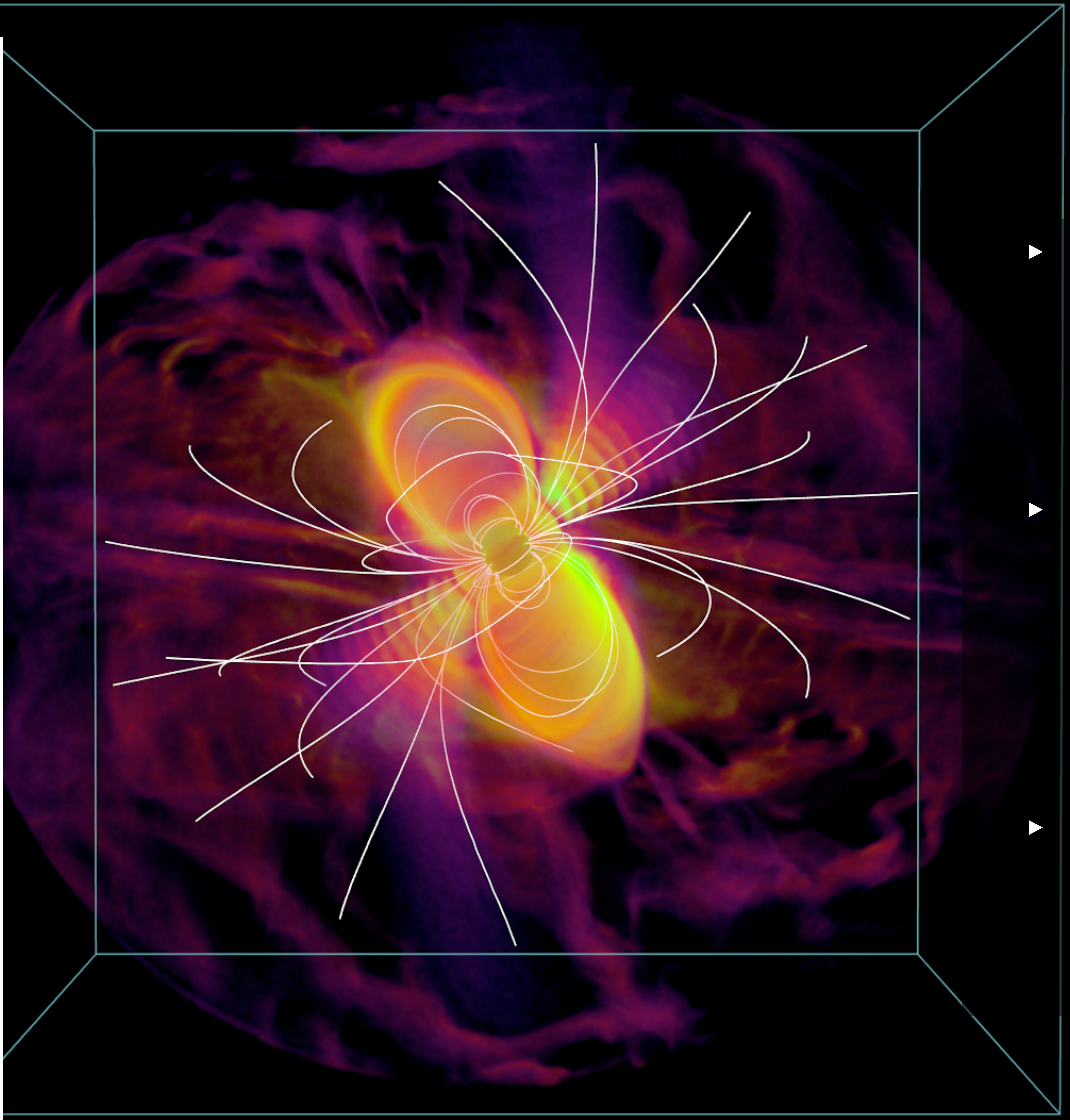
- Relativistic magnetic reconnection in the current sheet powers high-energy emission

- Current sheet is unstable to plasmoid (tearing) and drift-kink instabilities

Hakobyan et. al., 2023, ApJ

(GR) Oblique rotator with pair production





Philippov, Spitkovsky (2018)

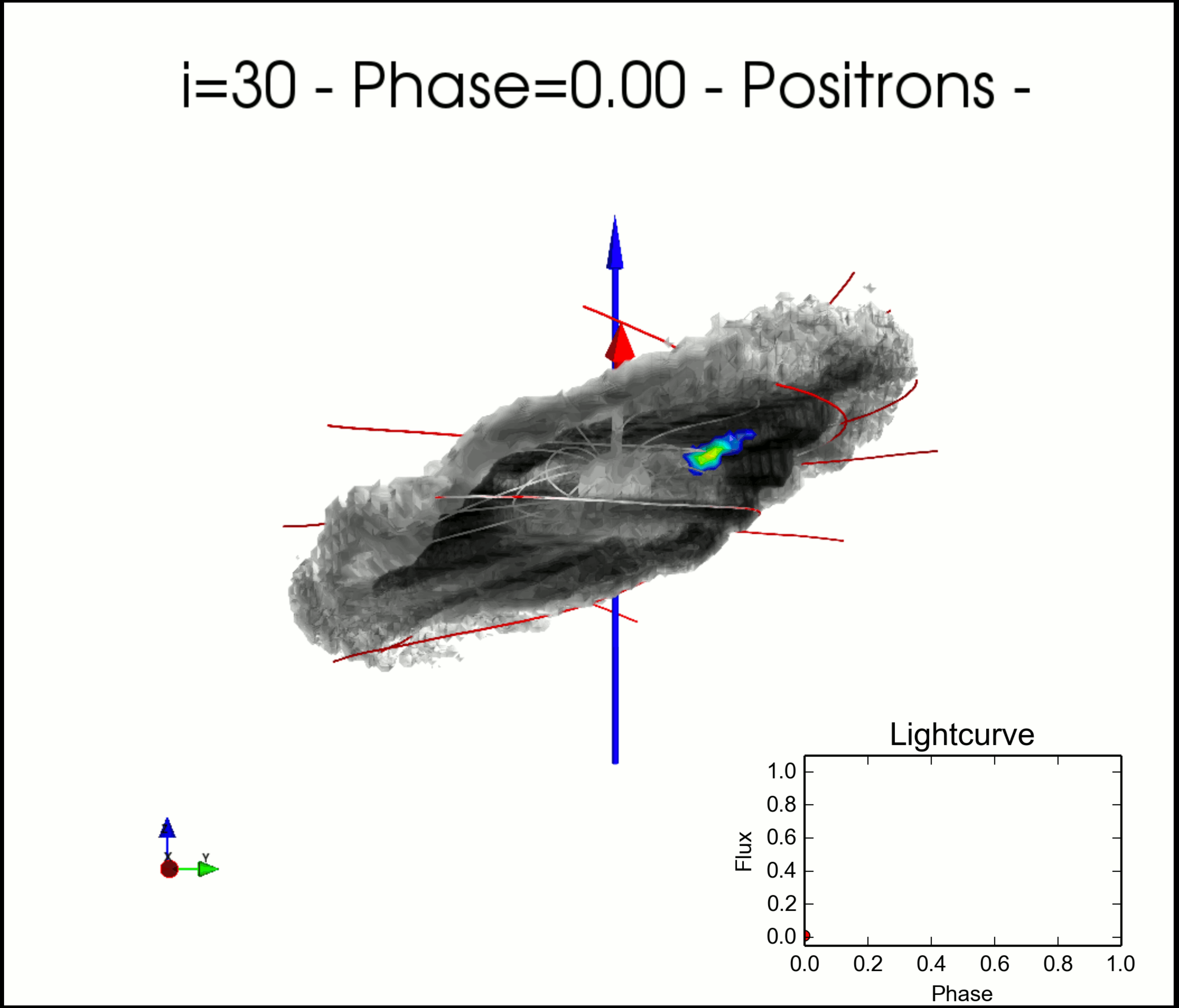
- Non-stationary discharge powers coherent radio emission
- Relativistic magnetic reconnection in the current sheet powers high-energy emission
- Current sheet is unstable to plasmoid (tearing) and drift-kink instabilities

Gamma-ray modeling

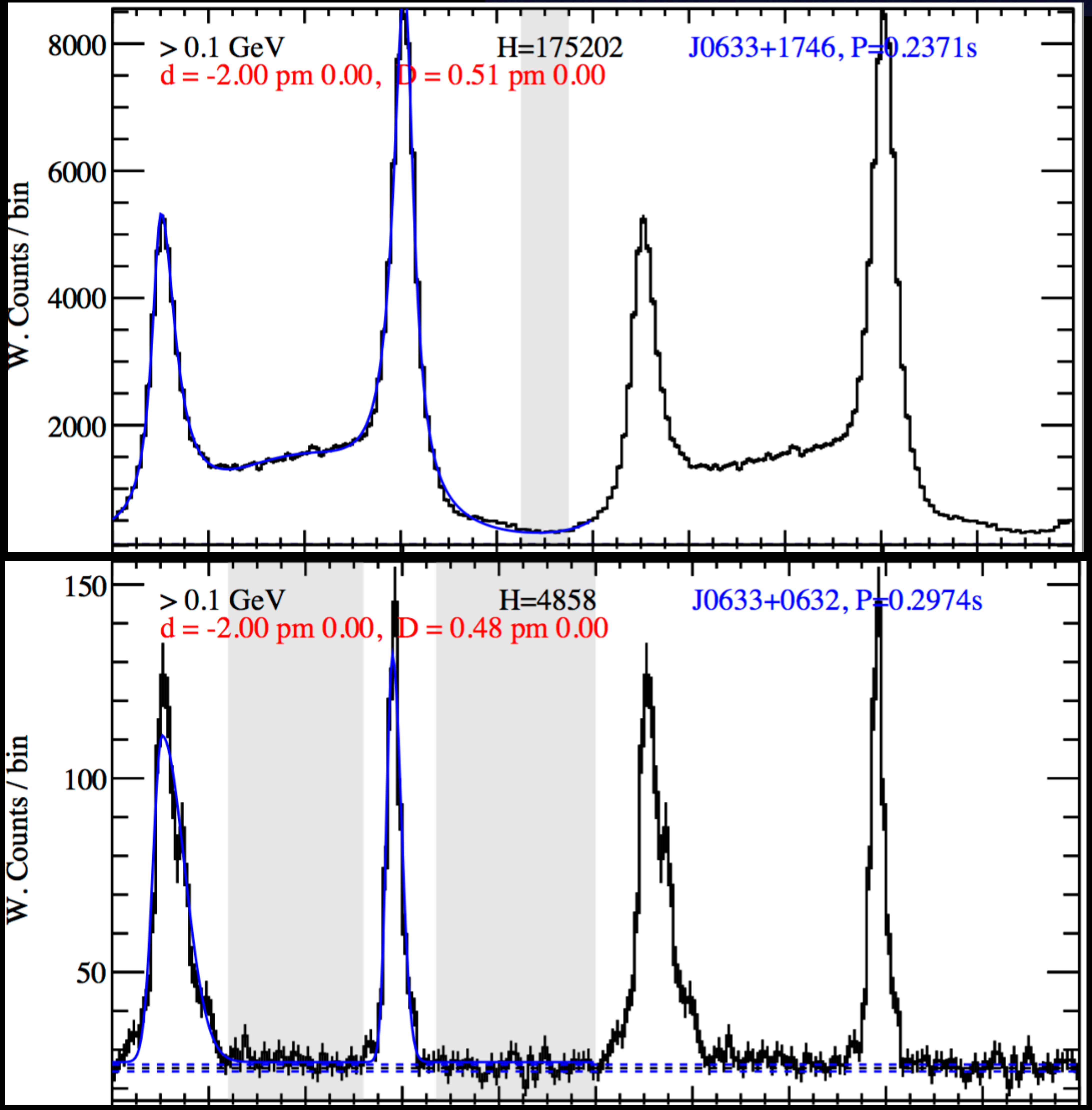
Simulations prefer current sheet as a particle accelerator. Particles radiate synchrotron emission.

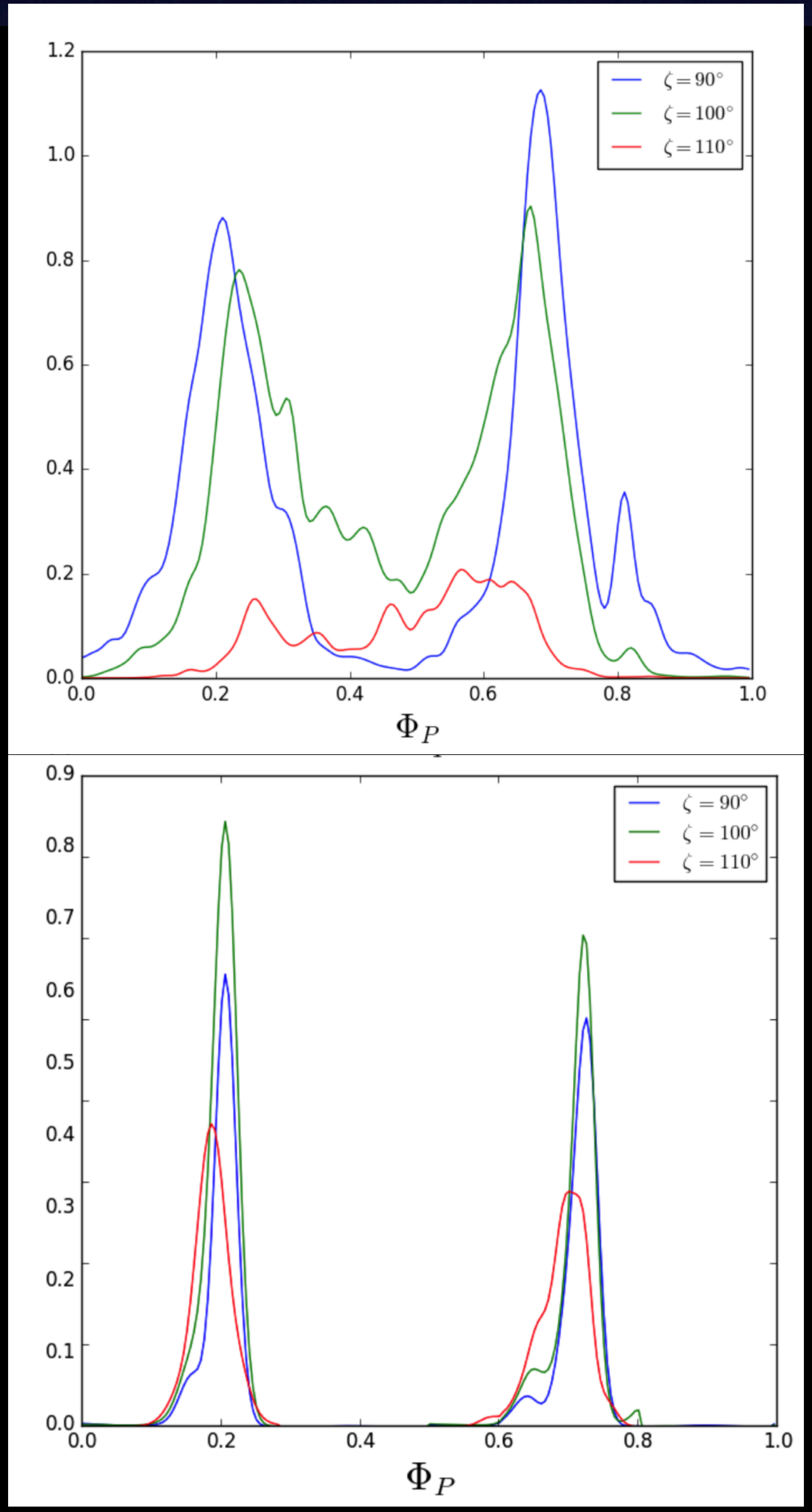
Observe caustic emission.

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)



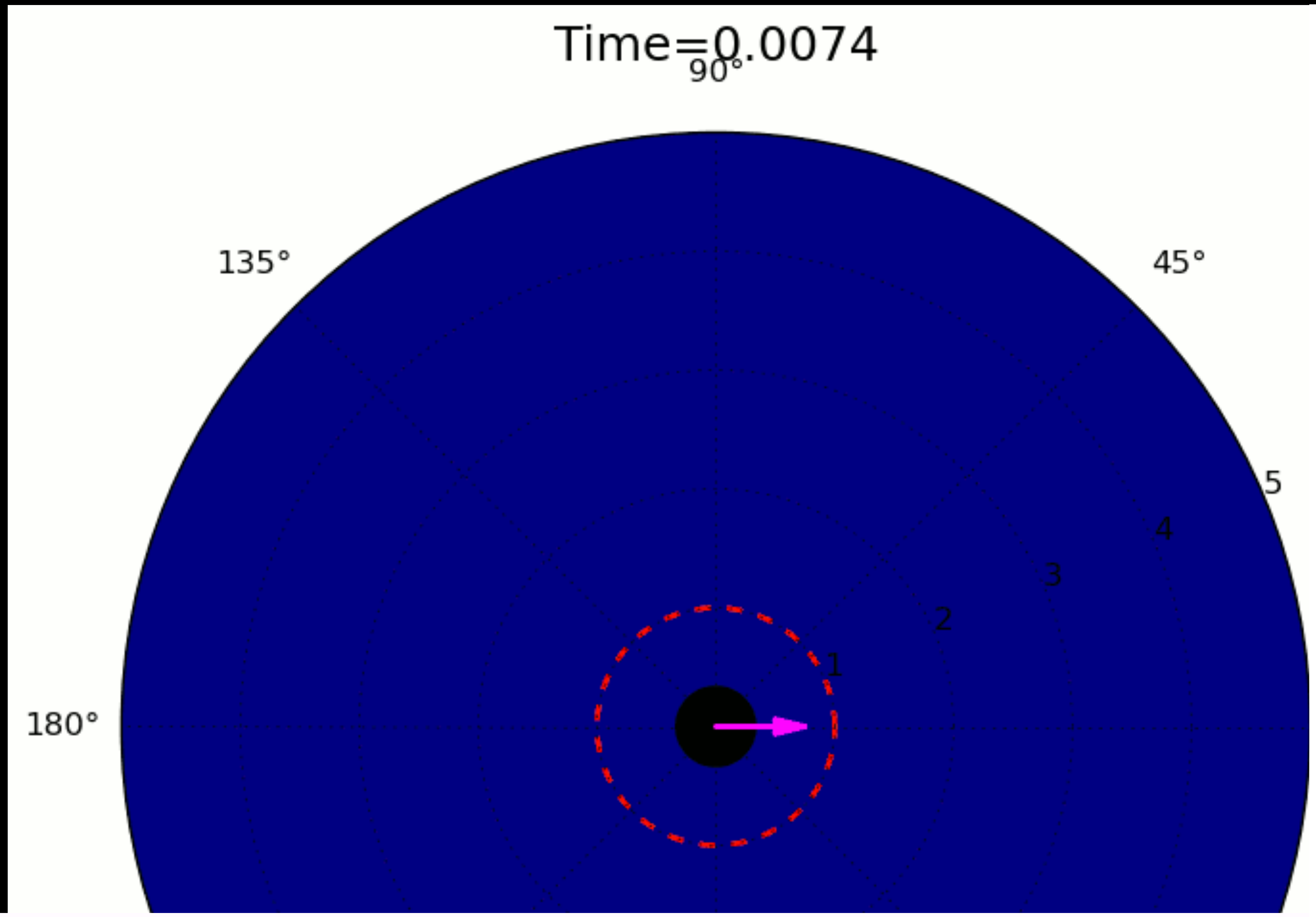


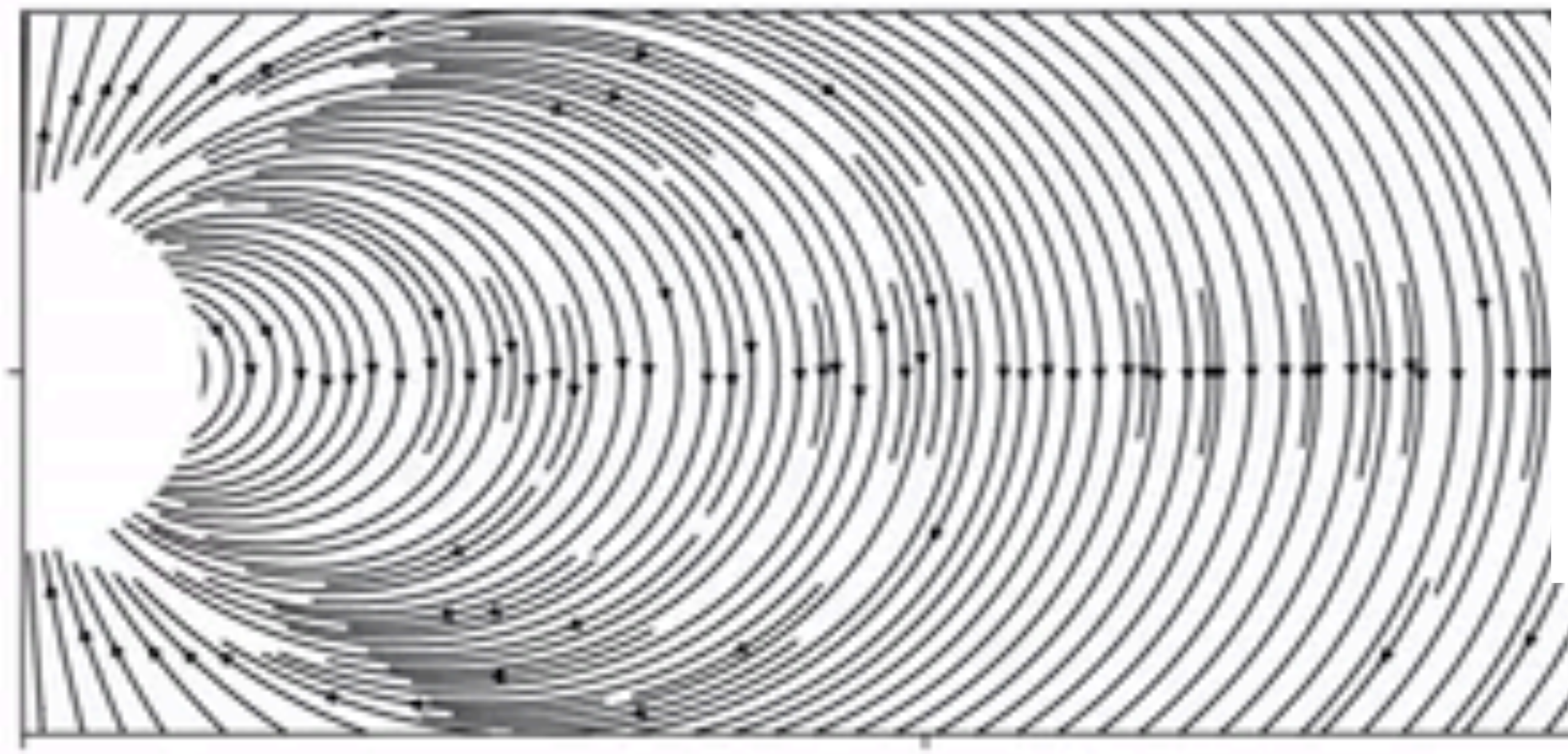
- Double-peaked lightcurves are generic.
- Bridge emission is a feature of lower obliquity rotators in general.

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

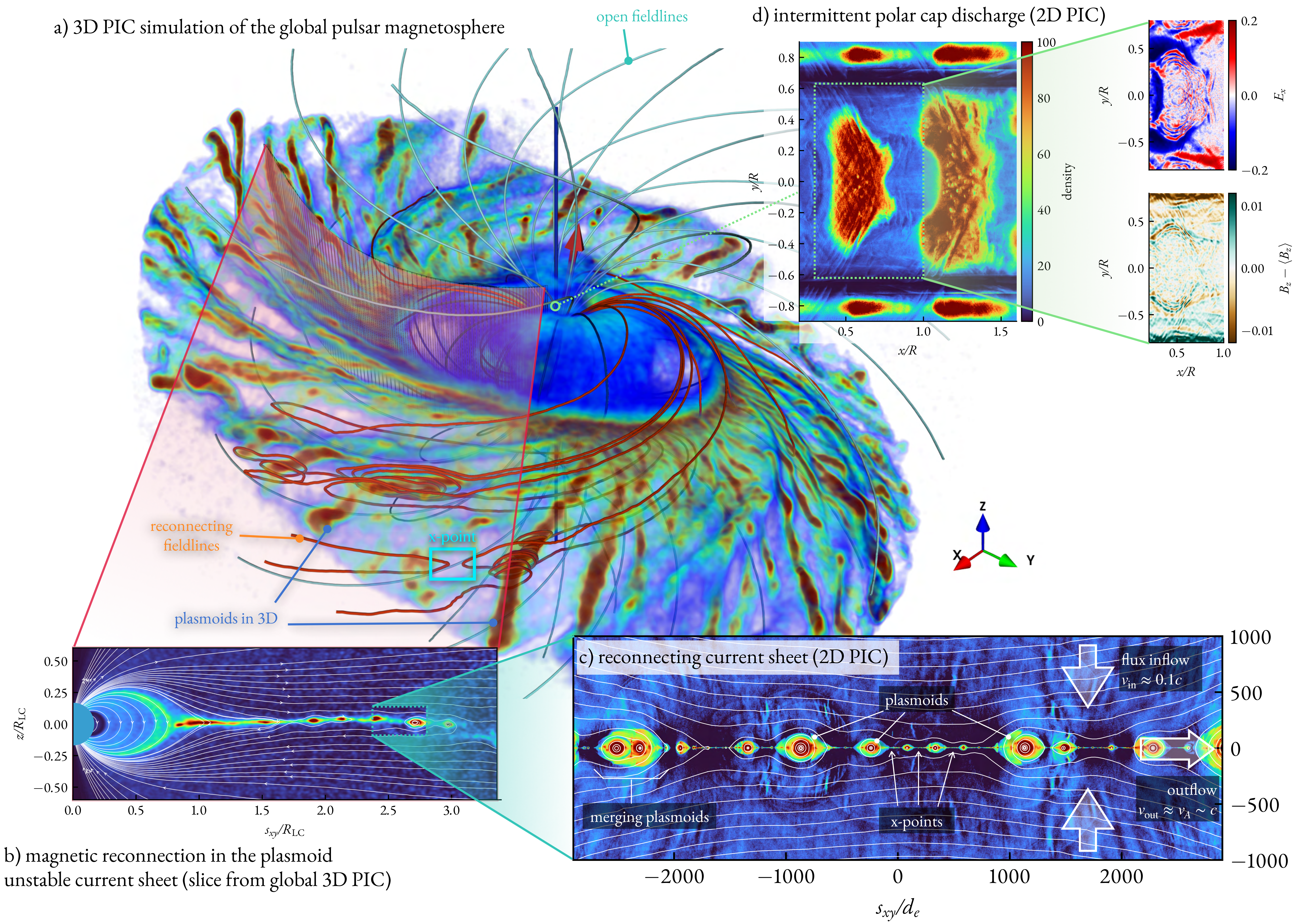
Magnetospheric current sheet in 2D and 3D

Hakobyan et. al., 2022





Ripperda et. al., in prep



a) 3D PIC simulation of the global pulsar magnetosphere

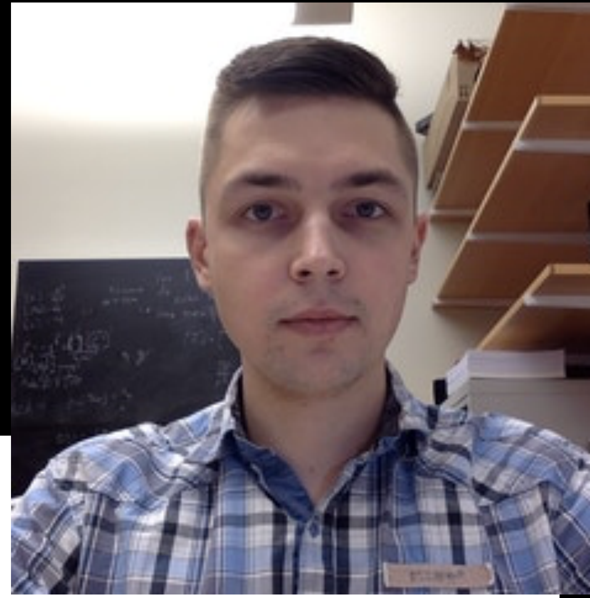
b) magnetic reconnection in the plasmoid unstable current sheet (slice from global 3D PIC)

c) reconnecting current sheet (2D PIC)

d) intermittent polar cap discharge (2D PIC)

Philippov, Kramer ARAA (2022)

Reconnection in pulsar magnetospheres



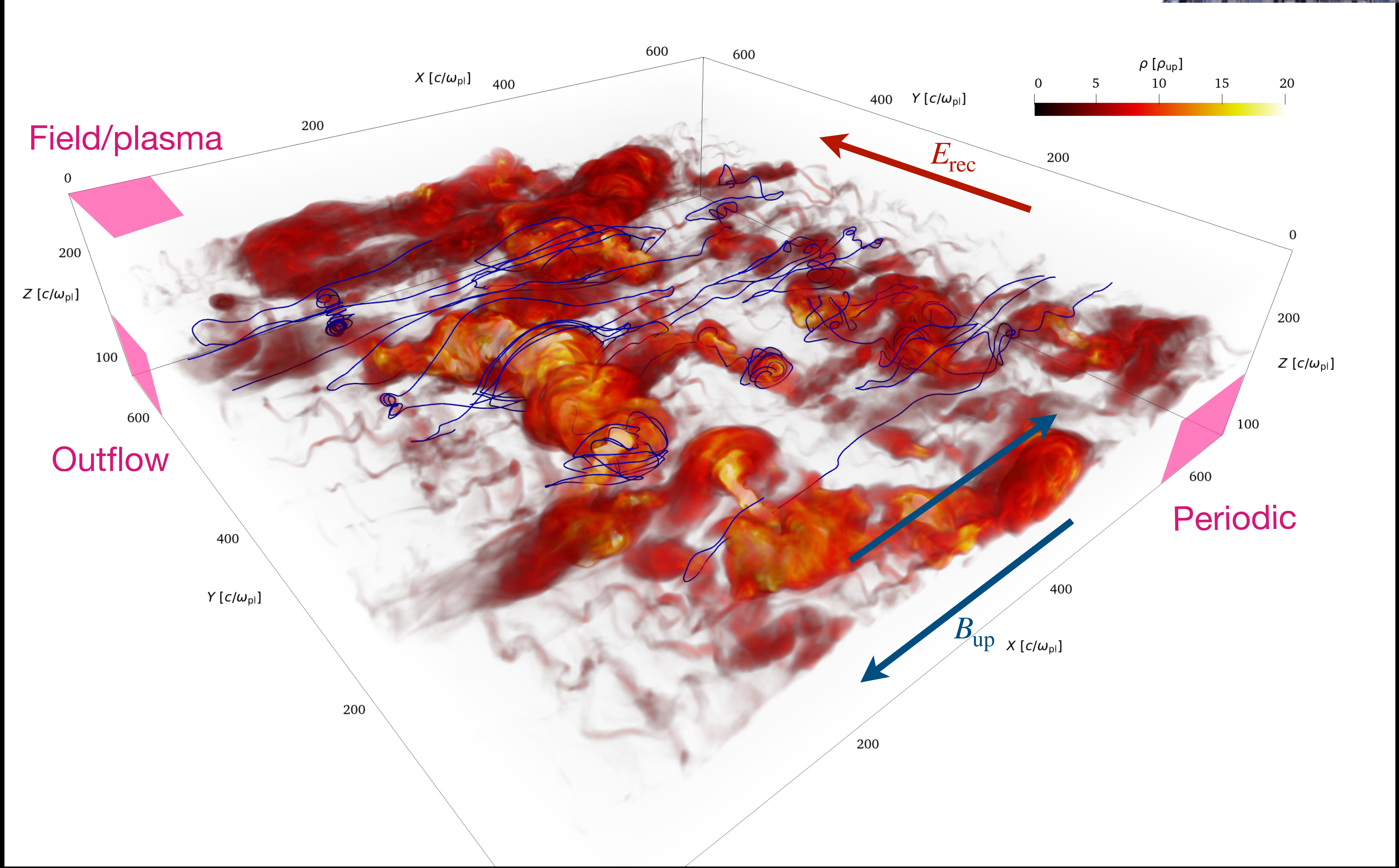
- $B \sim 10^5$ G, $B^2/4\pi \gg \rho c^2$

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:

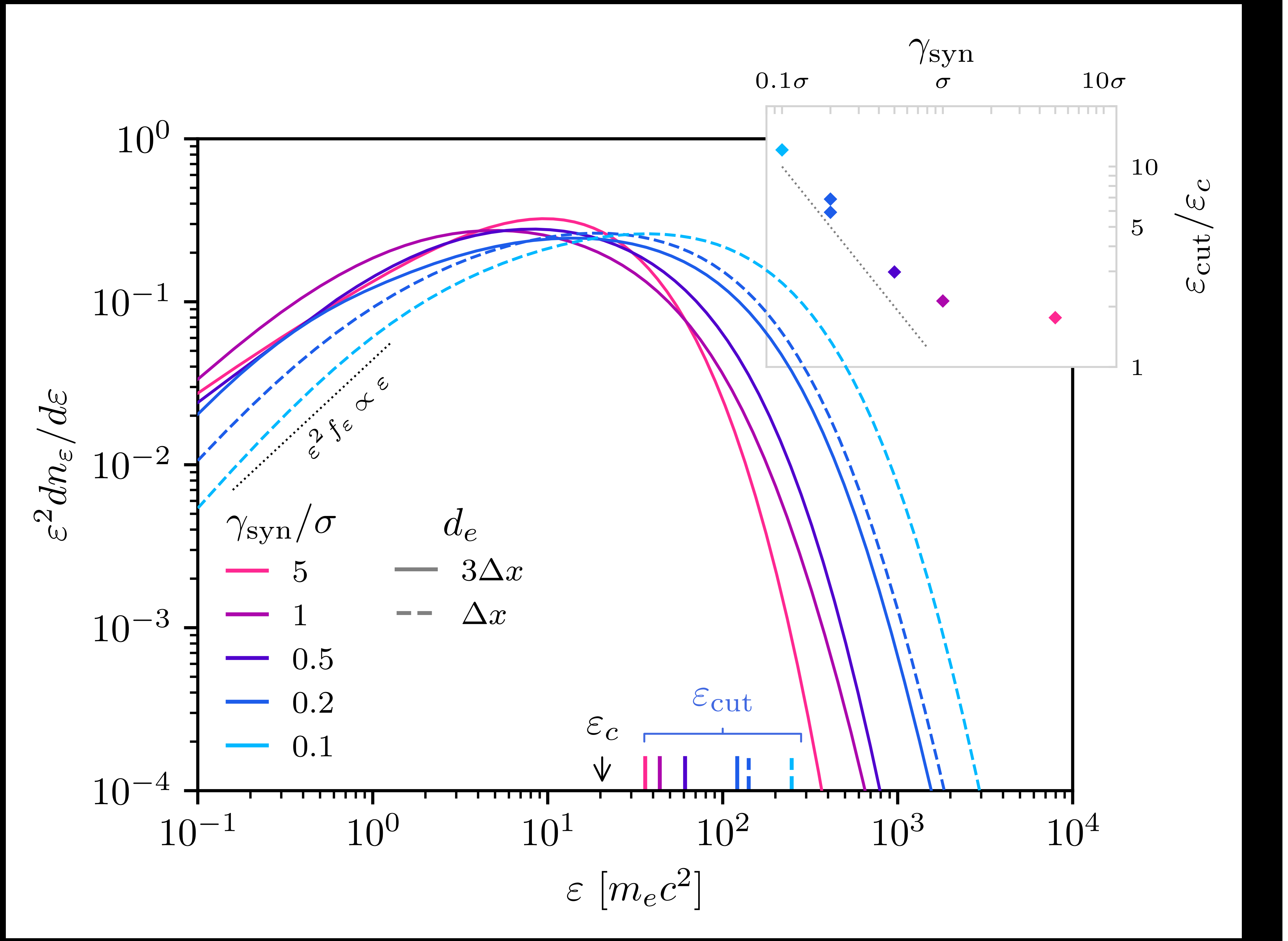
- Pair production by binary collisions of reconnection-produced photons.
- $\tau_{\gamma\gamma} \leq 1$, still produces a lot of pairs to affect the reconnection dynamics (mass loading).

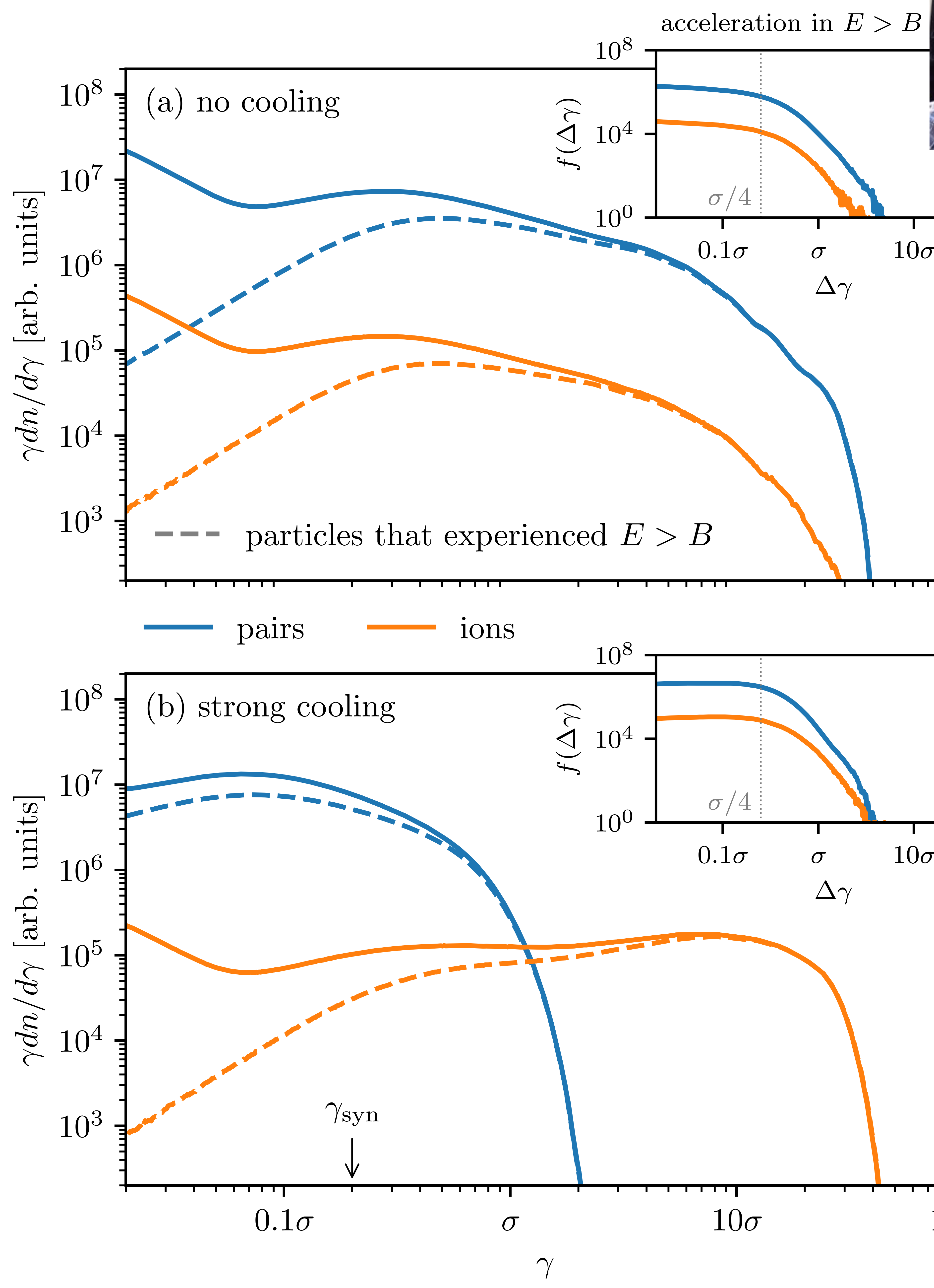


Chernoglazov, Hakobyan, Philippov, 2023, ApJ

Reconnection in pulsar magnetospheres

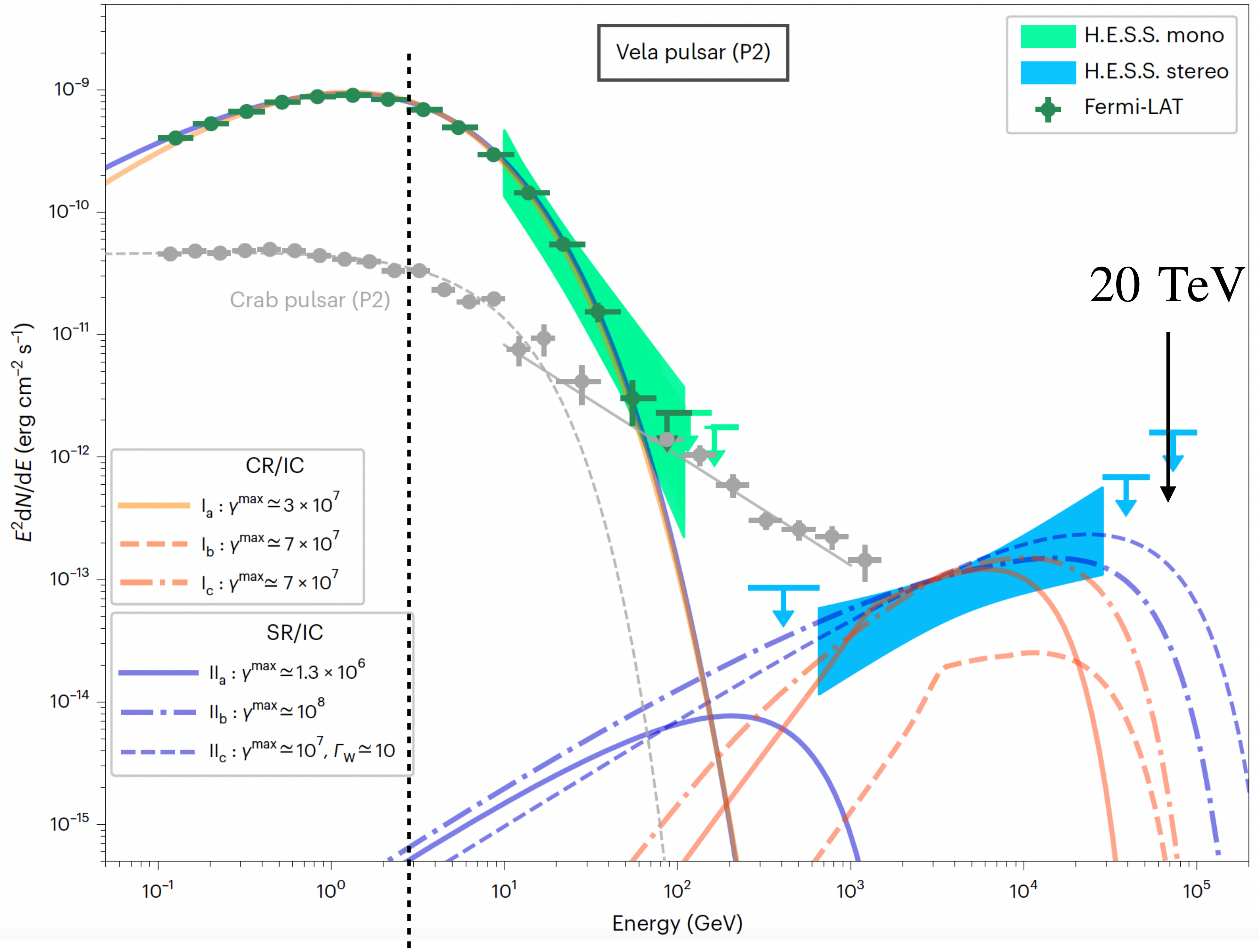
- Lots of high-energy photon flux above the burnoff limit!
- Leptons accelerate beyond the burnoff, but only to about a few sigma. $h\nu_{\max} \approx 16\mathrm{MeV}(\sigma/\gamma_{\mathrm{rad}})$
- Highest energy photons are beamed along the upstream magnetic field, consistent with the beaming of GeV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



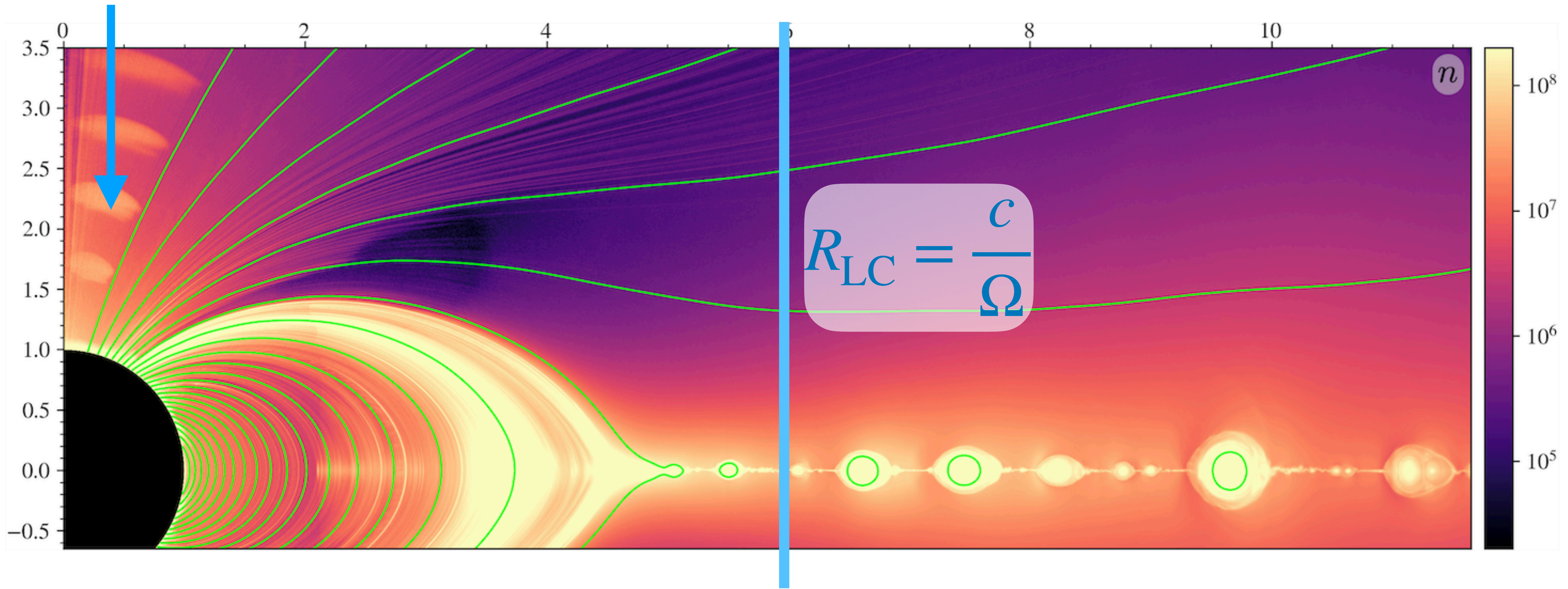


How does this work? Vela pulsar

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



Bursts of plasma production



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

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

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

$$\uparrow$$

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

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

But…

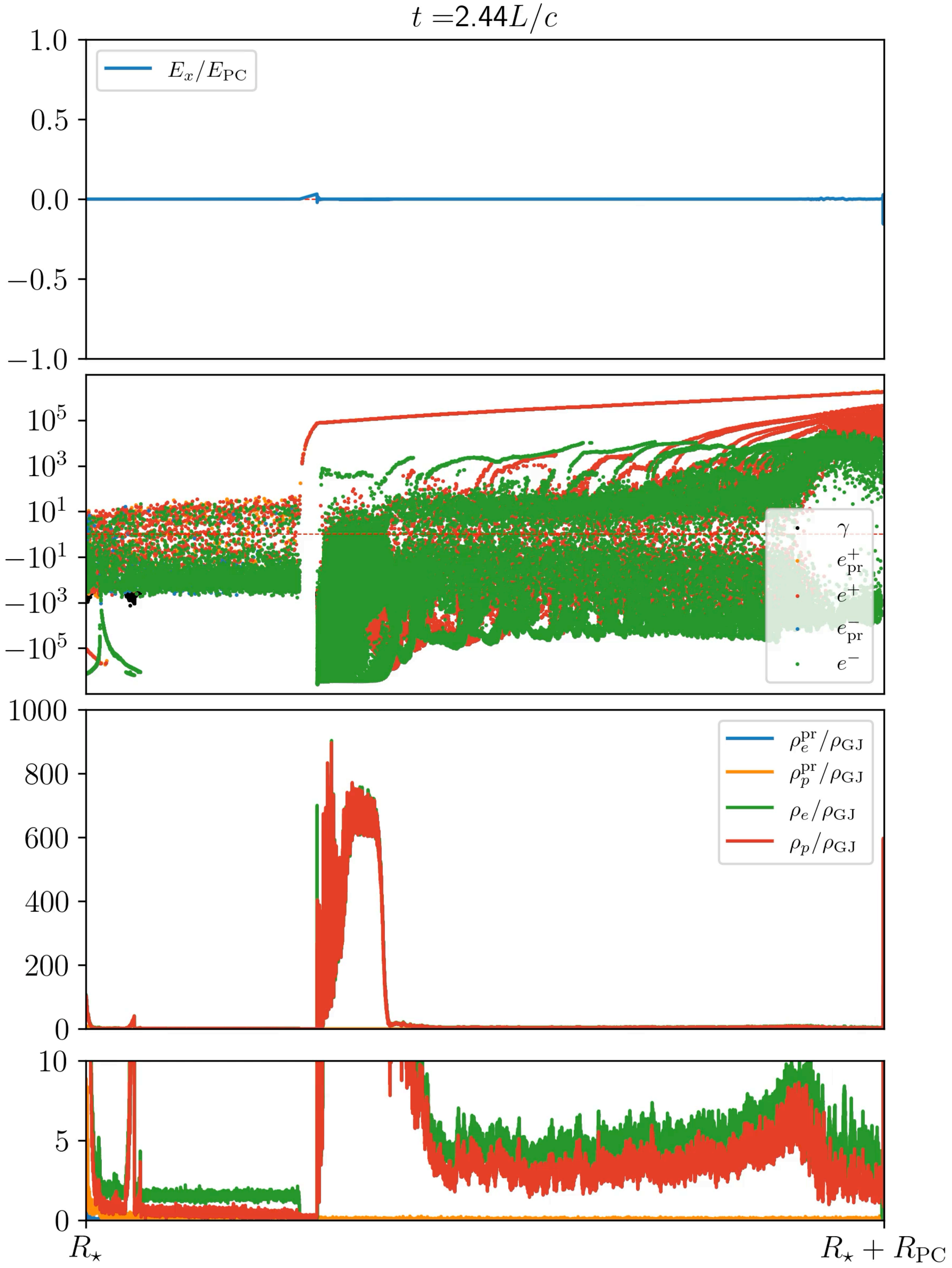
$$\left.\begin{aligned} \gamma_{\rm PC} &= \frac{2\pi \rho_{\rm GJ} R_{\rm PC}^2}{m_e c^2} = 3 \times 10^{10} \\ \lambda &= \frac{n}{n_{\rm GJ}} \approx 10^5 - 10^6 \end{aligned}\right\} \sigma_{\rm expected} = \frac{\gamma_{\rm PC}}{\lambda} \approx 10^5$$

Timokhin+, ApJ (2019)

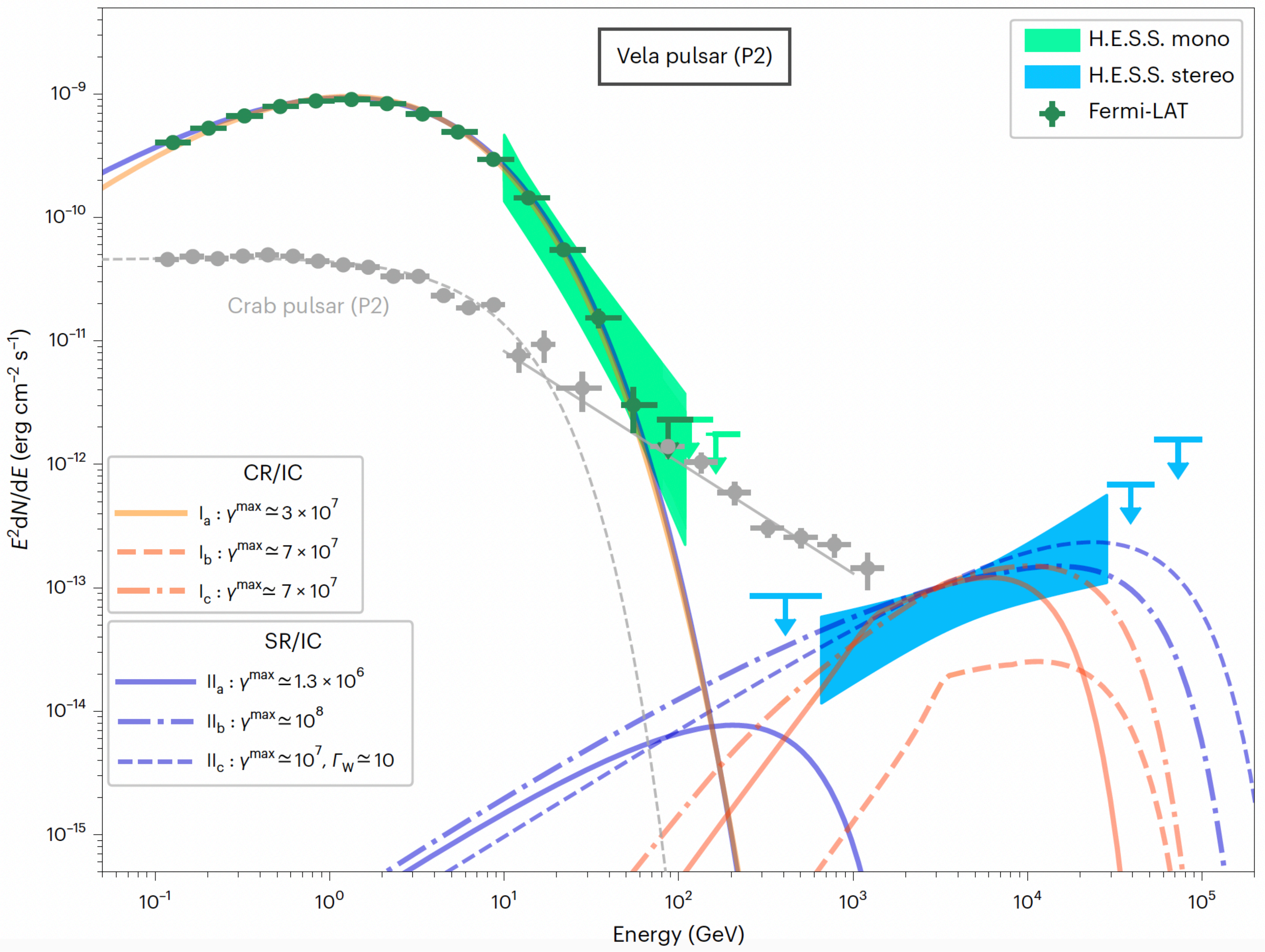
Bransgrove et al, ApJL 2023

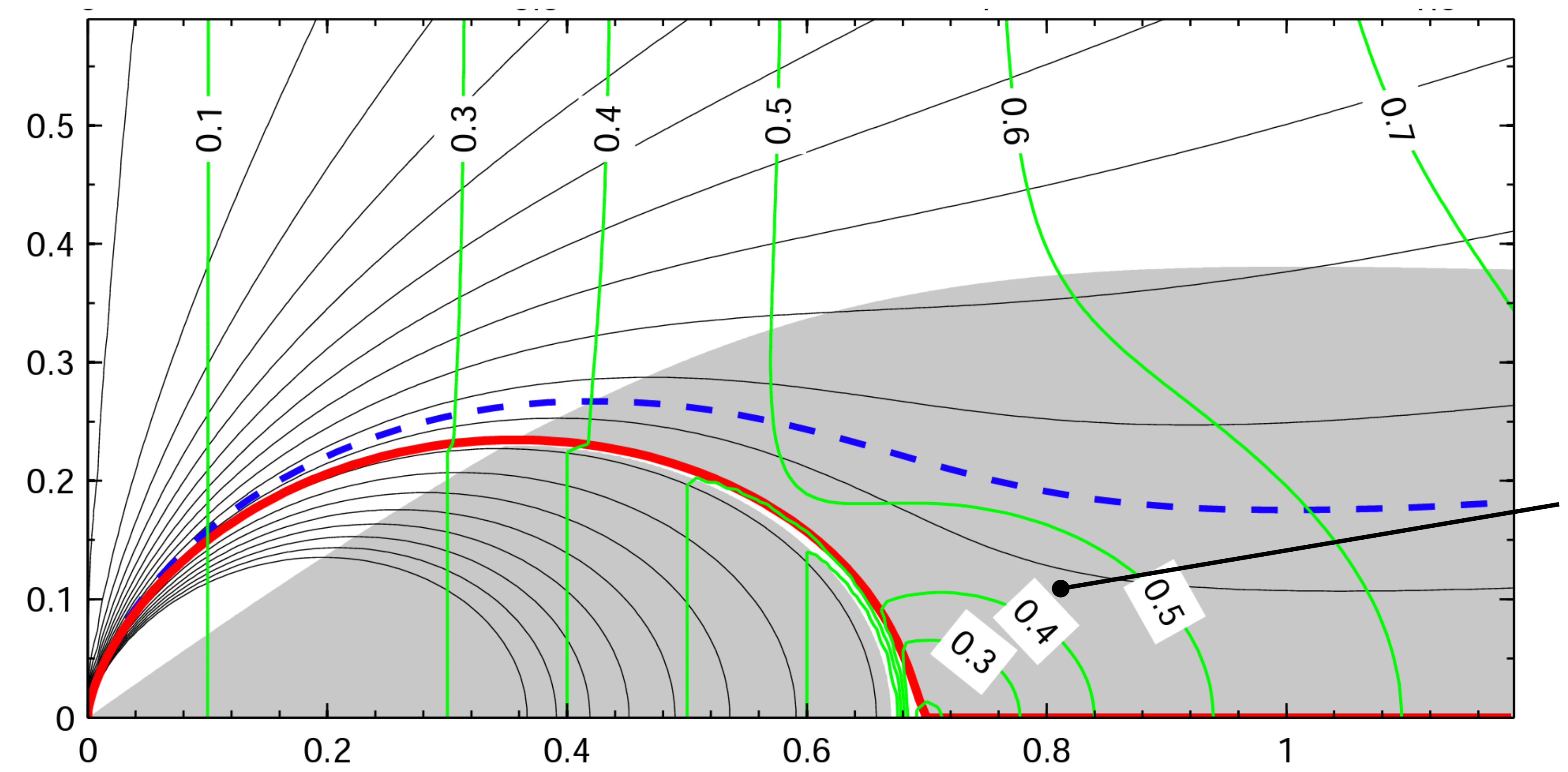
Multiplicity for different magnetospheric currents

$j_{\rm mag}/j_{\rm GJ} < 0$



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





Volumetric return current

Timokhin+, ApJ (2006)

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

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

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

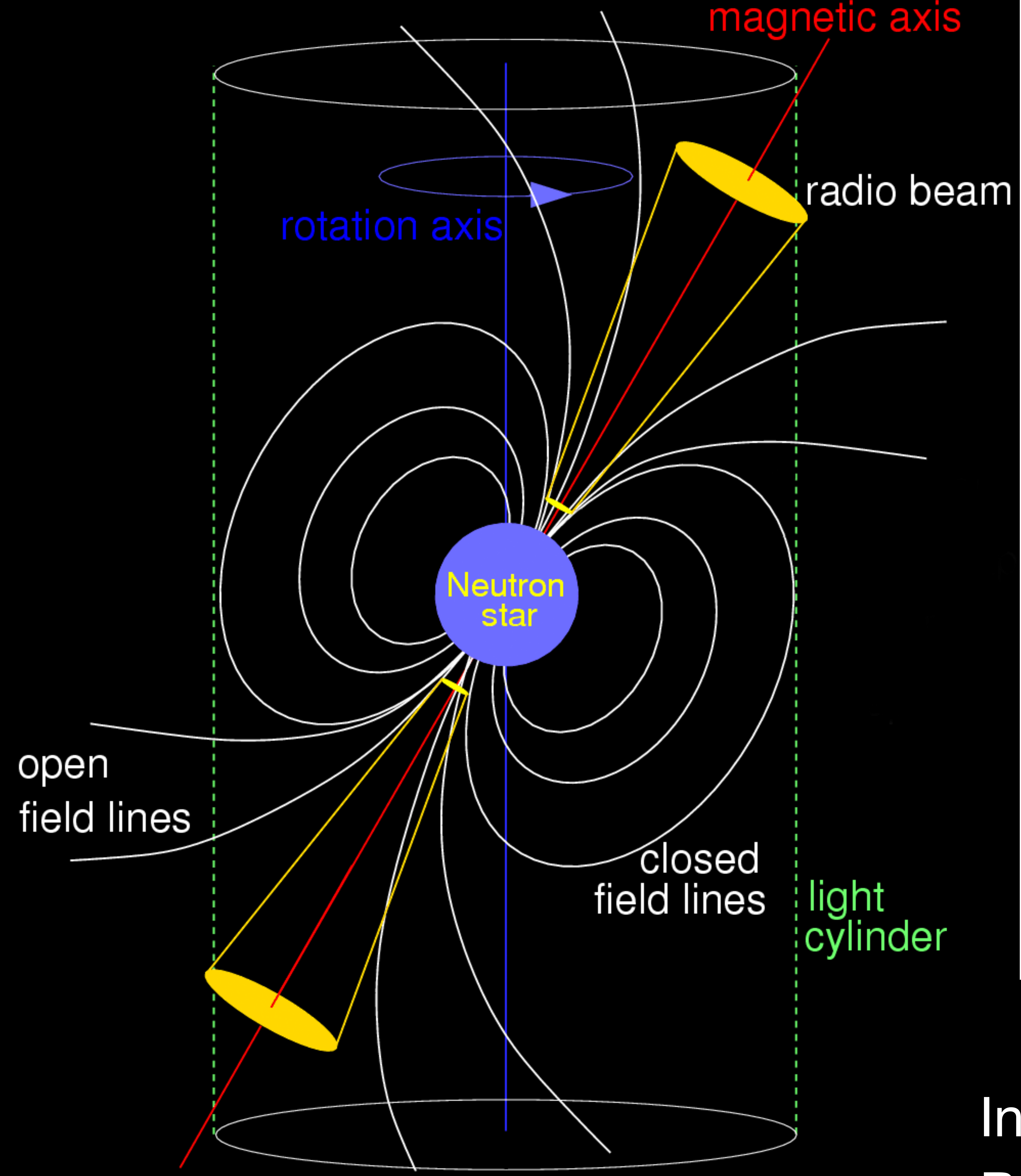
Field lines carrying return current send only a small fraction of secondary plasma into the magnetosphere

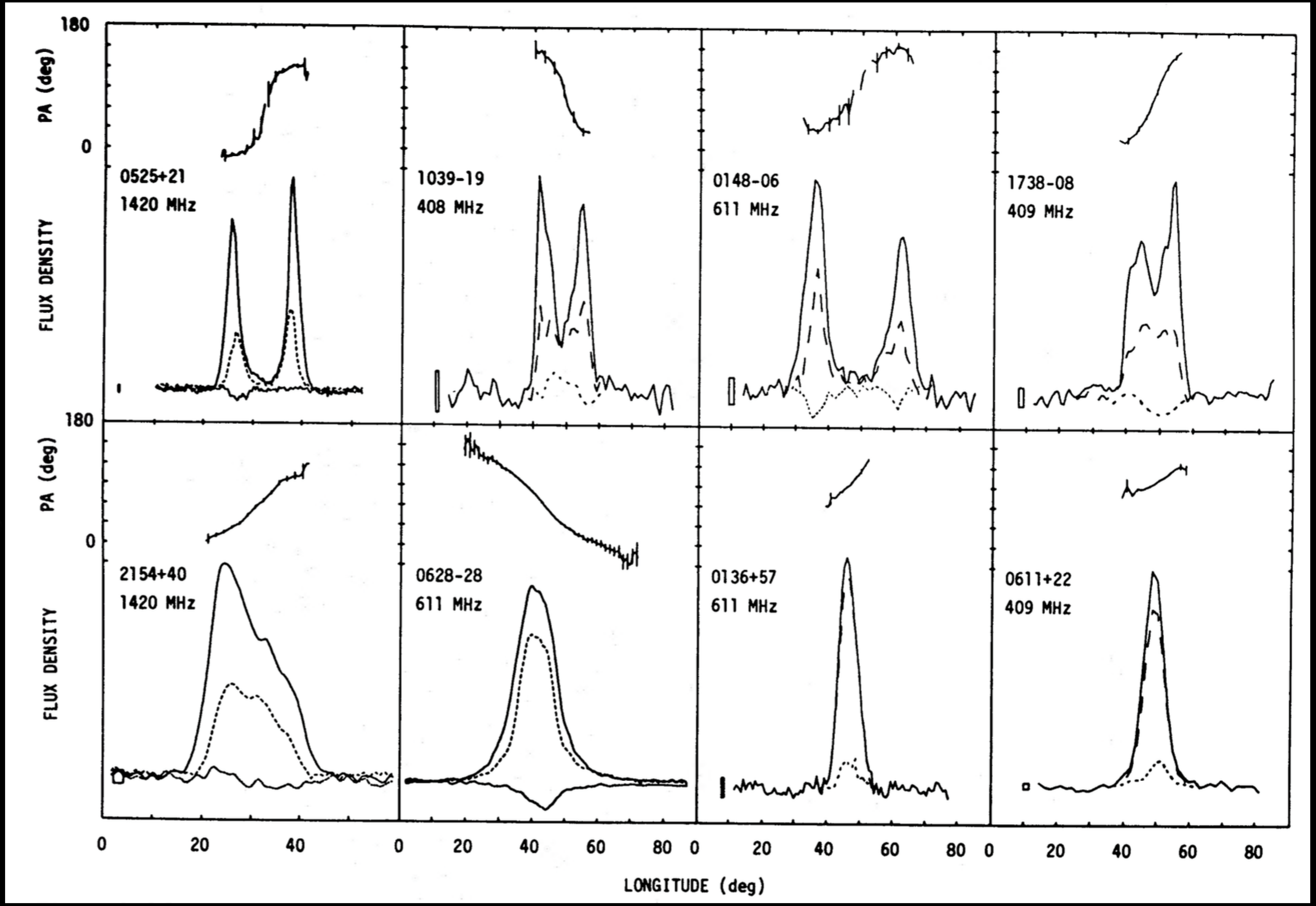
$$\lambda_{\rm outside} \sim 0.001 - 0.01\lambda$$

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

Enough to explain 20 TeV emission

Polar radio emission





Lyne, Manchester (1988)

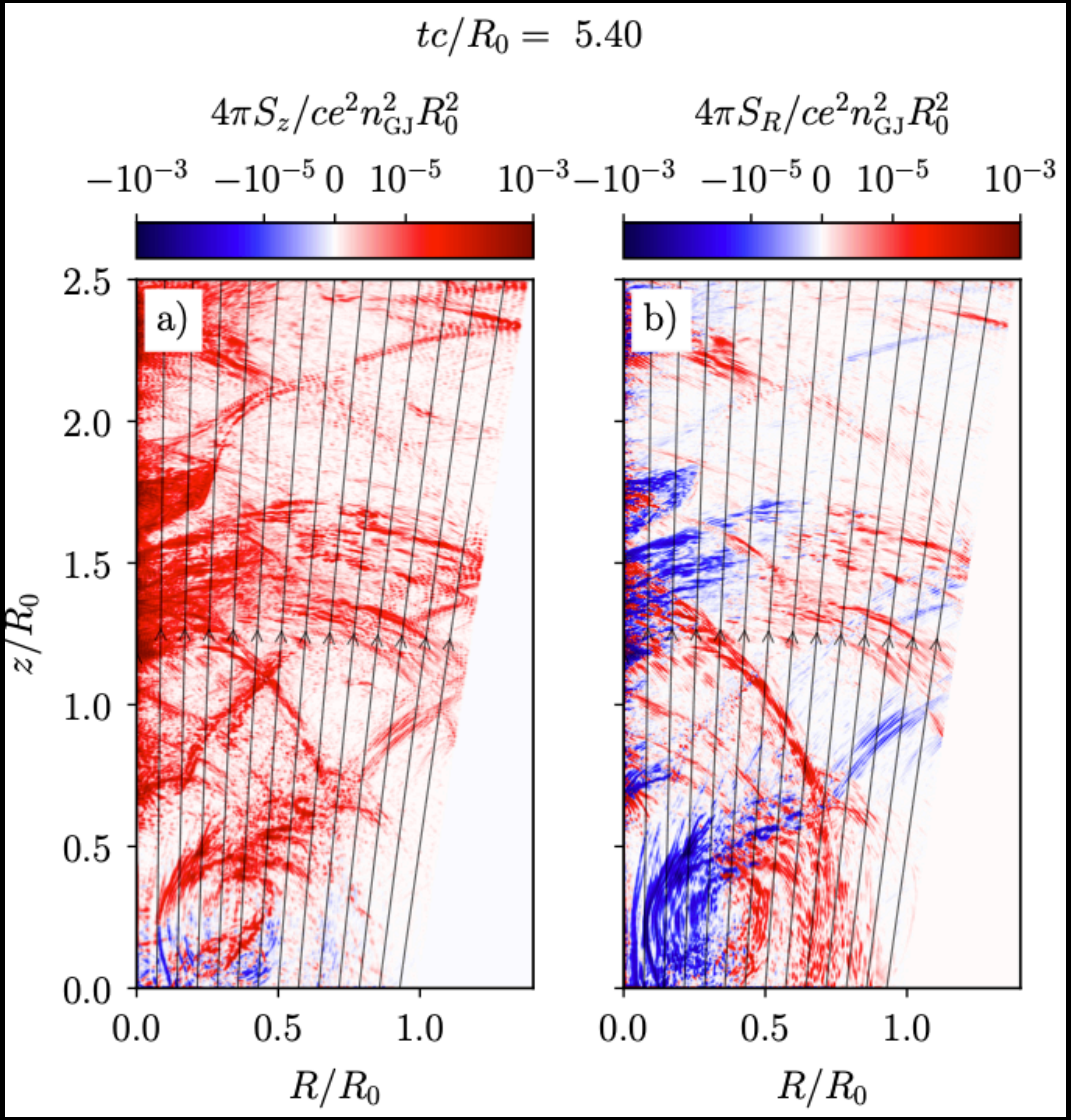
In most cases we see one short pulse per period.

Beam width is related to the polar cap size.

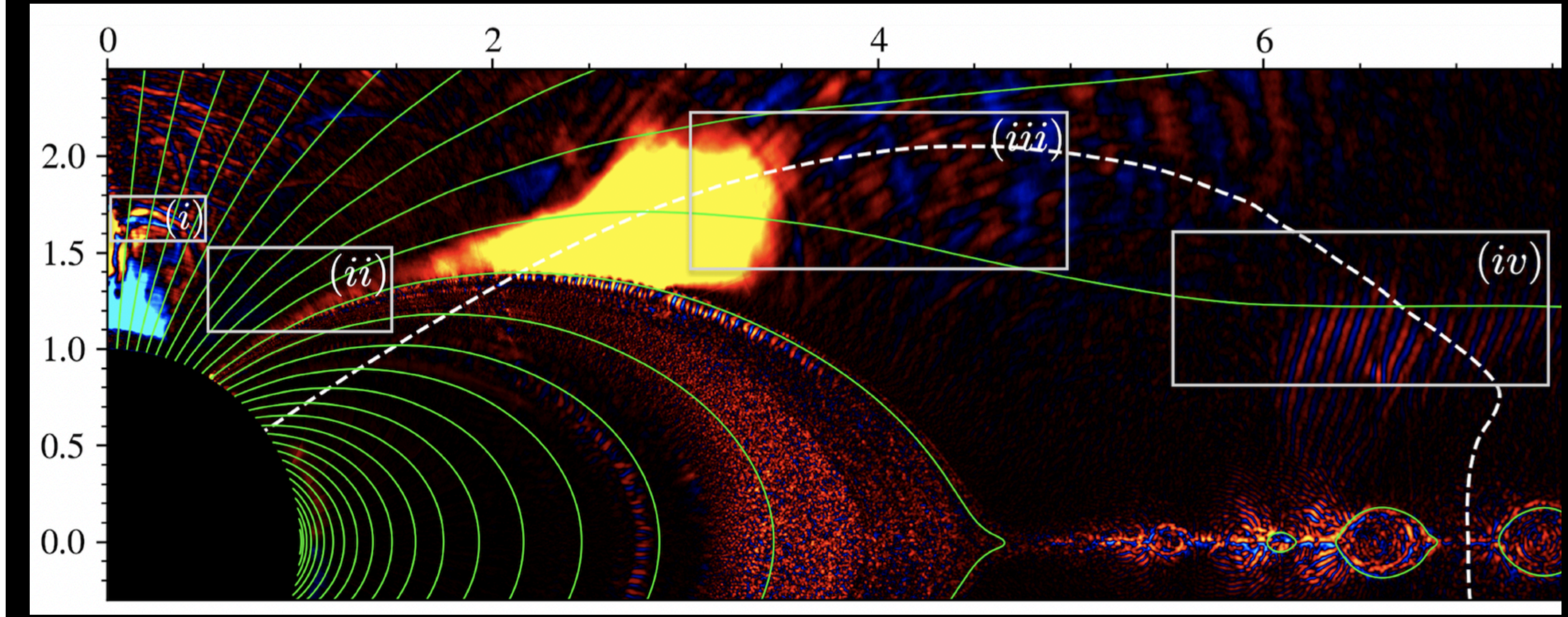
Local simulation of 2D discharge

Philippov, Timokhin, Spitkovsky (2020) PRL

Confirmation with different codes



Cruz et. al., (2021) ApJL

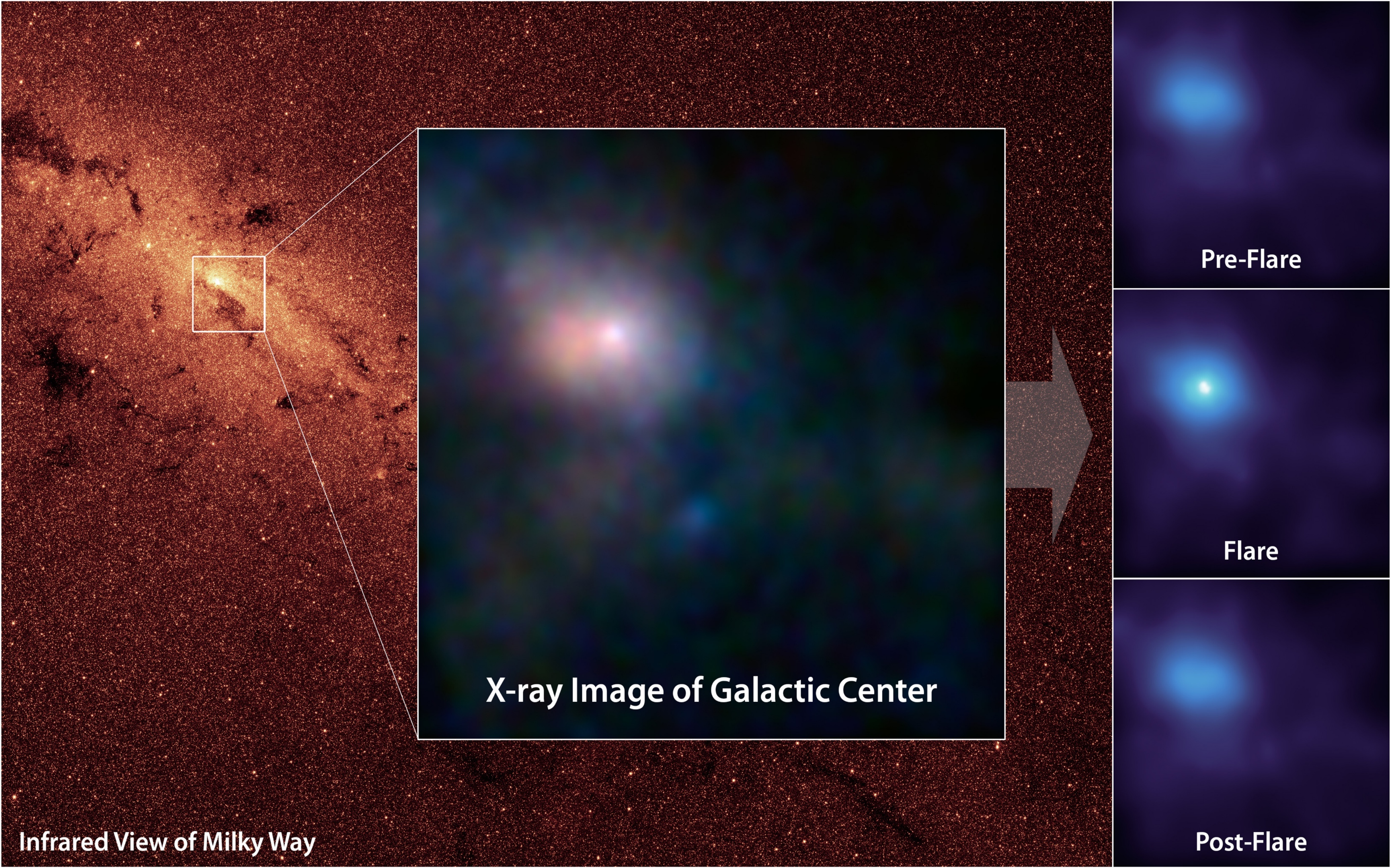


Bransgrove et. al., 2023, ApJL

Confirms order-of-magnitude luminosity
Core-cone geometry of the emission beam

PIC simulations with Osiris & Pigeon

SgrA* and M87(*)



conditions imply macroscopically collisionless,
but strongly magnetized plasma

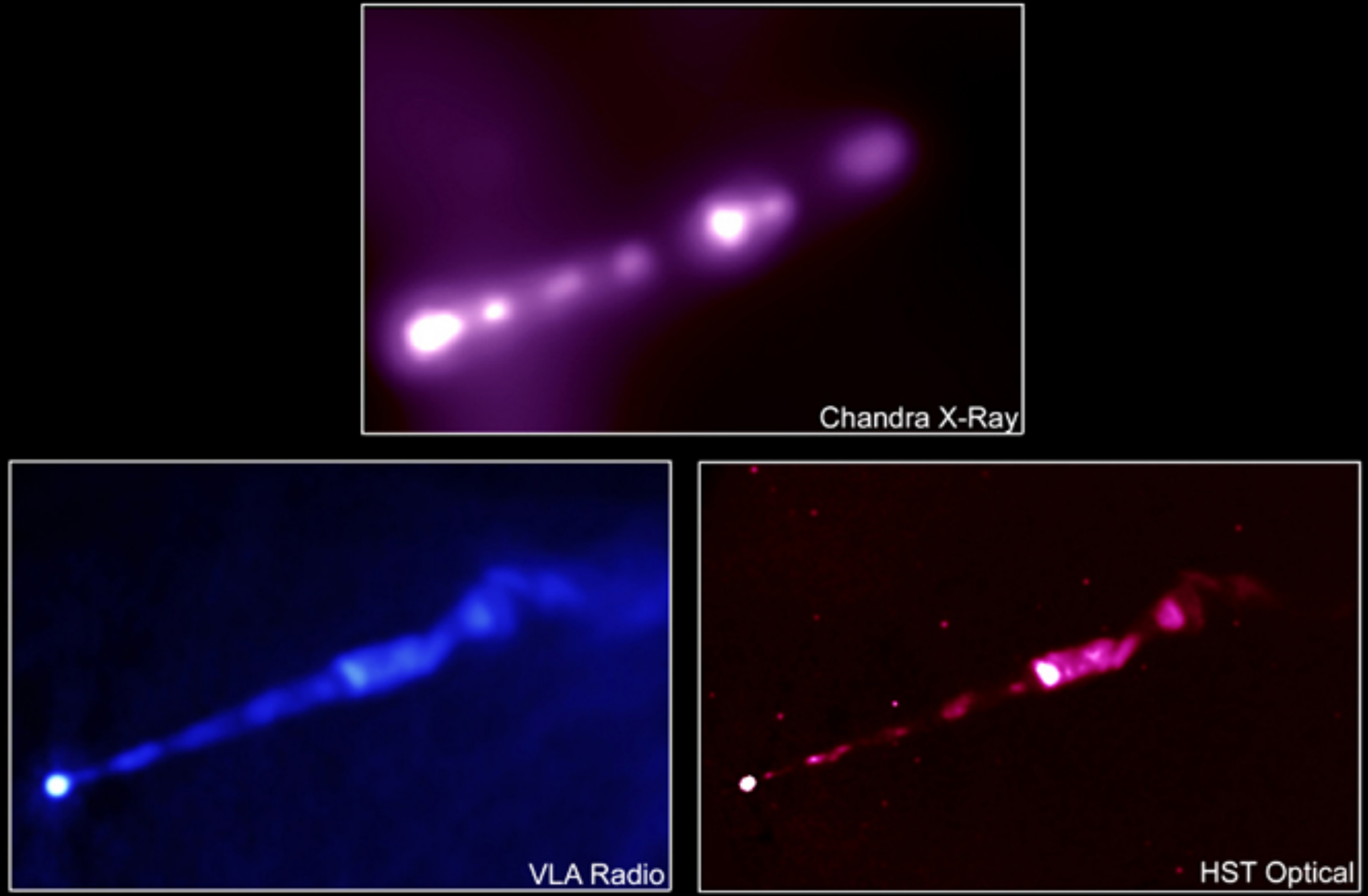
large-scale jet is observed for M87

Multi-wavelength flares (NIR/X-ray for SgrA*, TeV for M87)

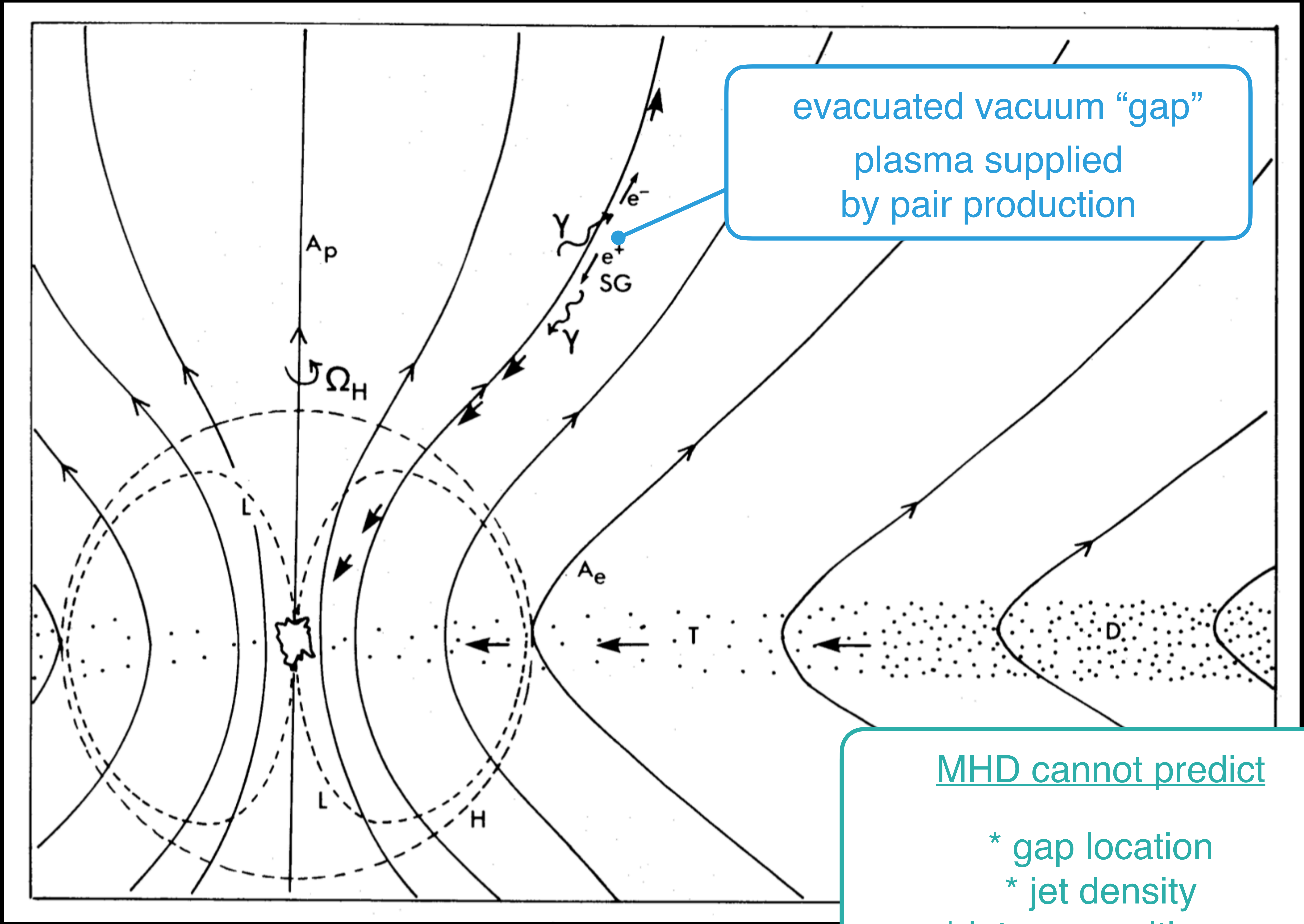
$$B \sim 10\mathrm{G}$$

$$n_e \sim 3 \cdot 10^4 \mathrm{cm}^{-3}$$

$$T_e \sim 1\mathrm{MeV}$$



Theoretical cartoon: Plasmas around black holes



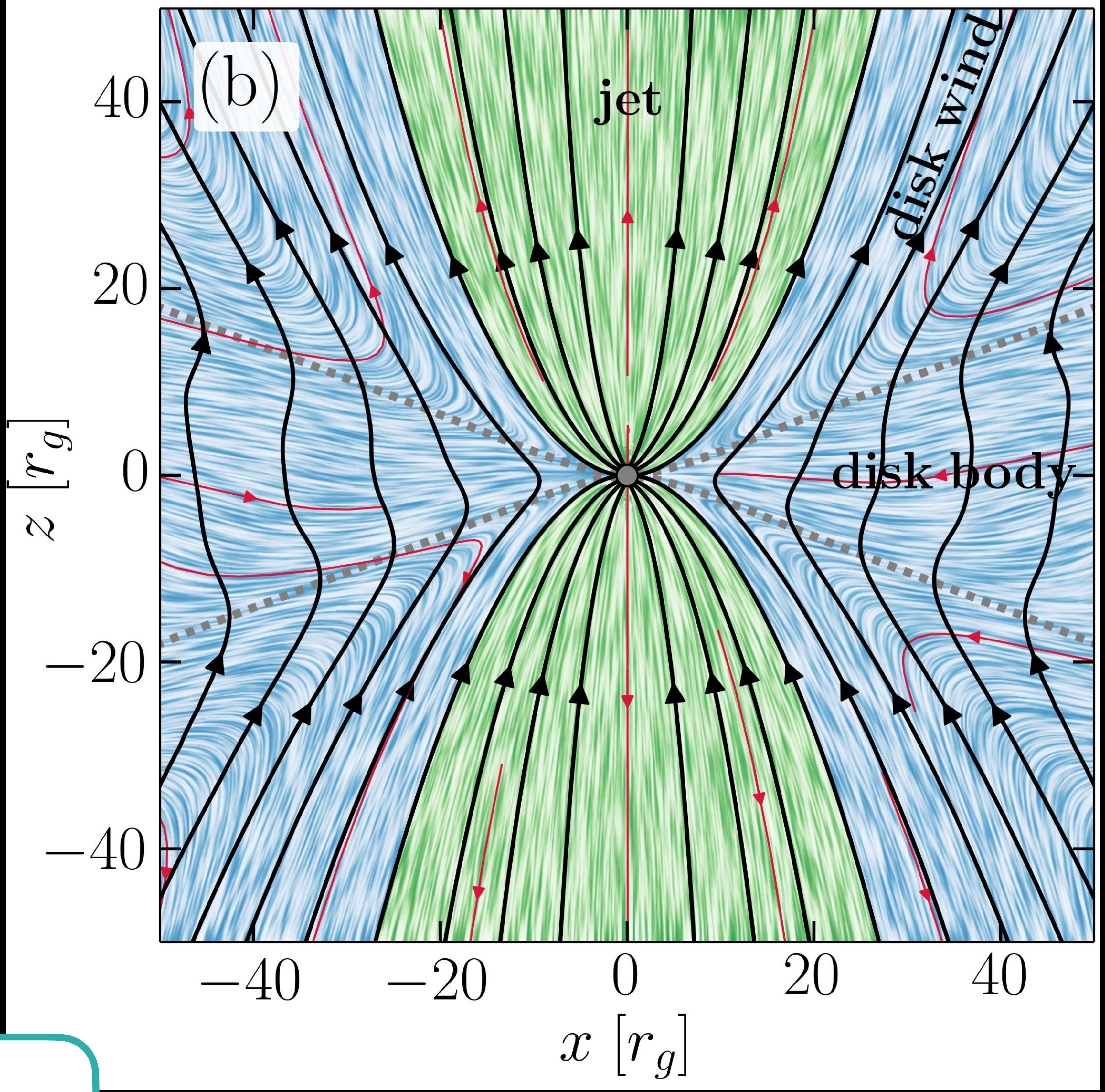
evacuated vacuum “gap”
plasma supplied
by pair production

MHD cannot predict

- gap location
- jet density
- jet composition ...

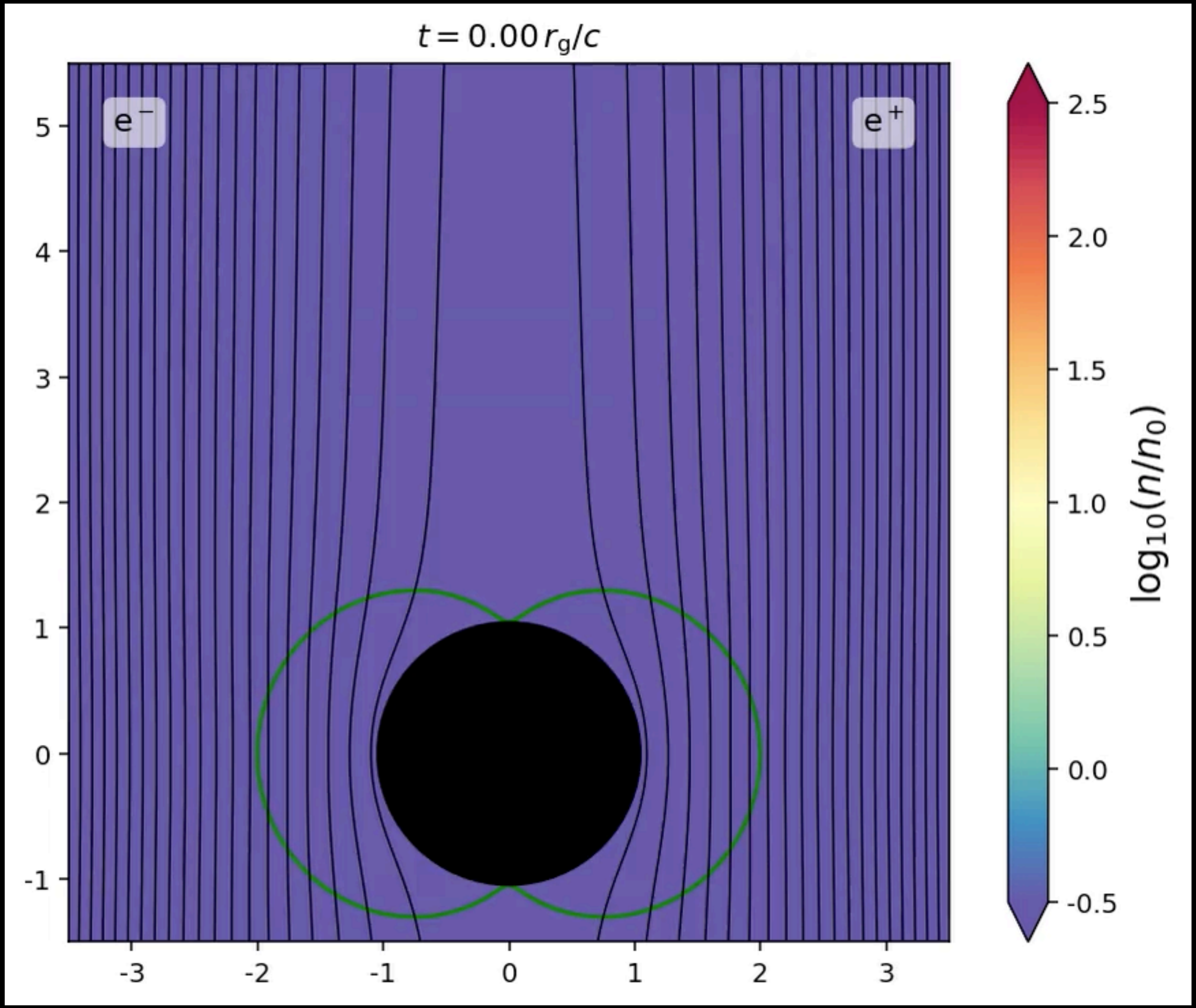
Blandford, Znajek, 1977

State-of-the-art MHD (fluid) model

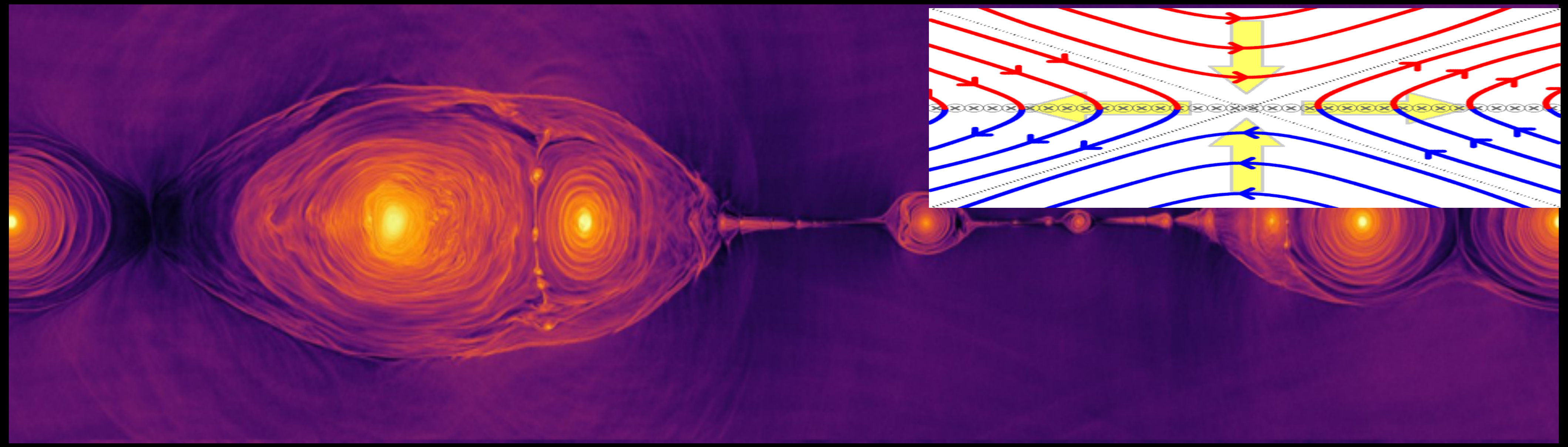


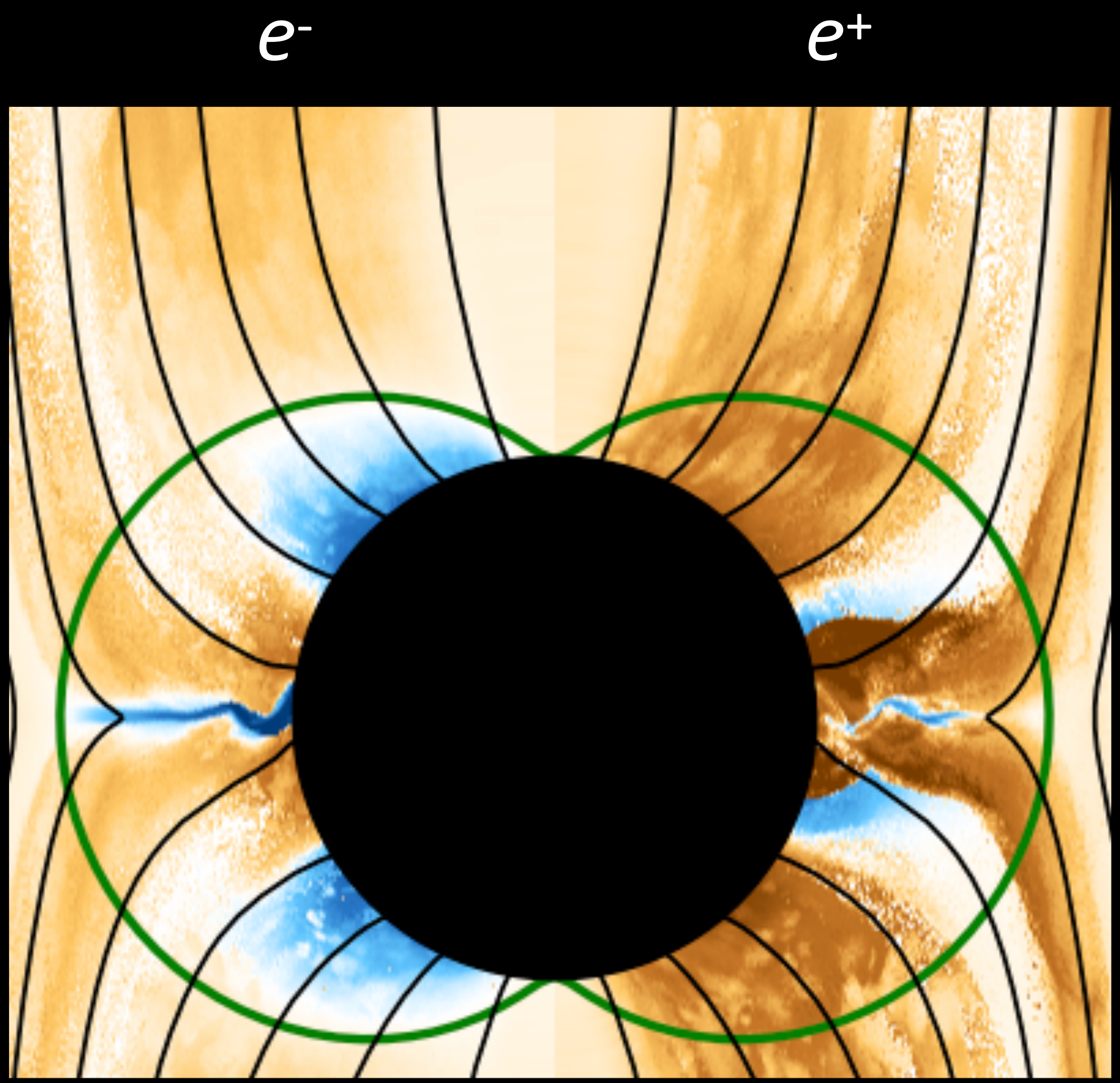
Tchekhovskoy, 2015

First GR kinetic simulation of jet launching



Parfrey, Philippov, Cerutti, cover of PRL, 2019

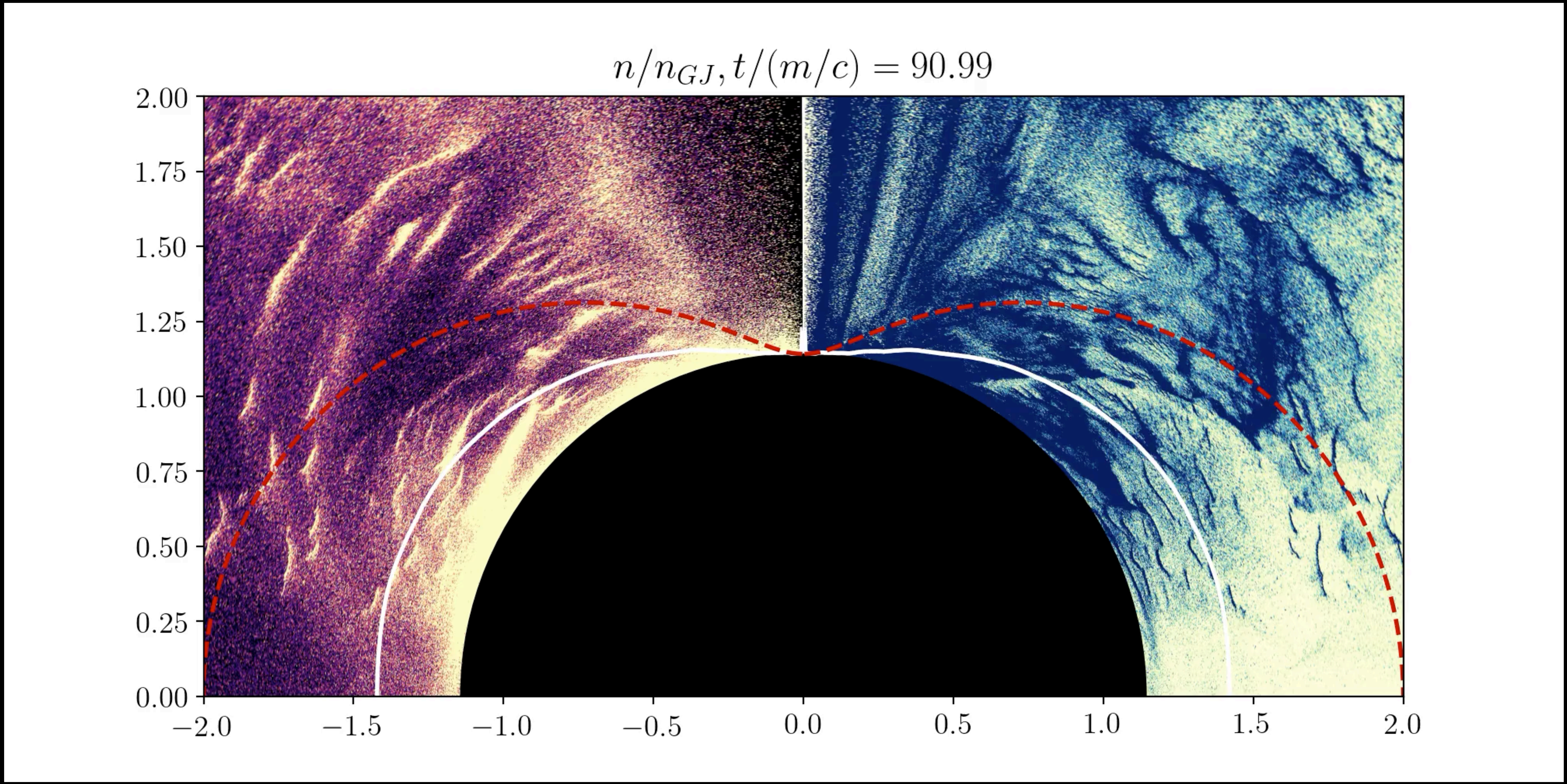




Penrose-like process of
energy extraction in the current sheet

analytics by Comisso, Asenjo, PRD, 2021

Anti-matter production: QED lightning near the EH



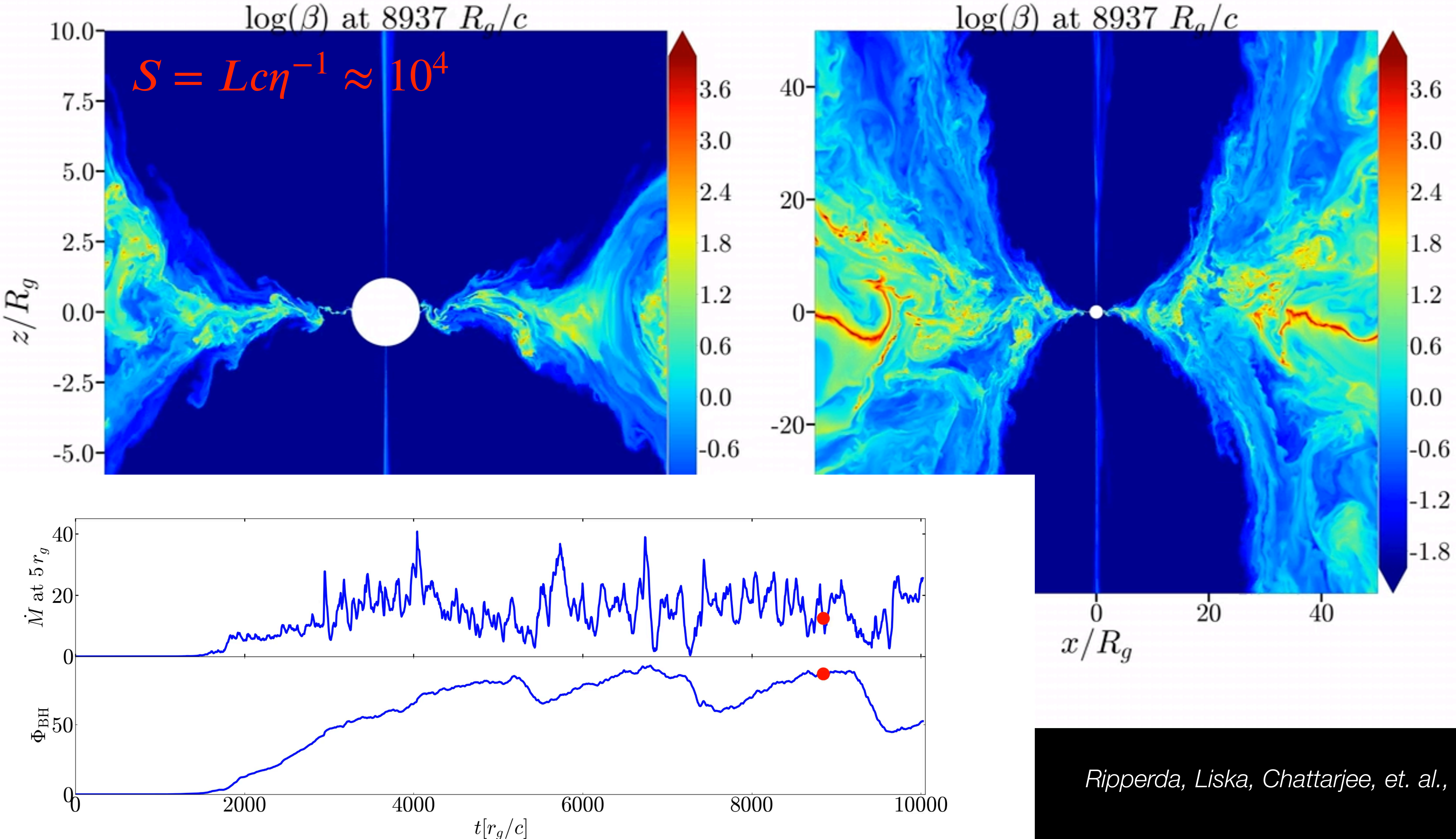
Solves the problem of plasma creation in jets. Intrinsic discharge intermittency is probably not sufficient to explain large TeV flares from M87.

Three-dimensional GR PIC simulations are still challenging….

Crinquand, Cerutti, Philippov, et. al., PRL, 2020

Cerutti, Levinson, Yuan, Chen, etc.

Large Flares: Magnetic Reconnection near the EH


$S = Lc\eta^{-1} \approx 10^4$

Ripperda, Liska, Chattarjee, et. al., 2022, ApJL

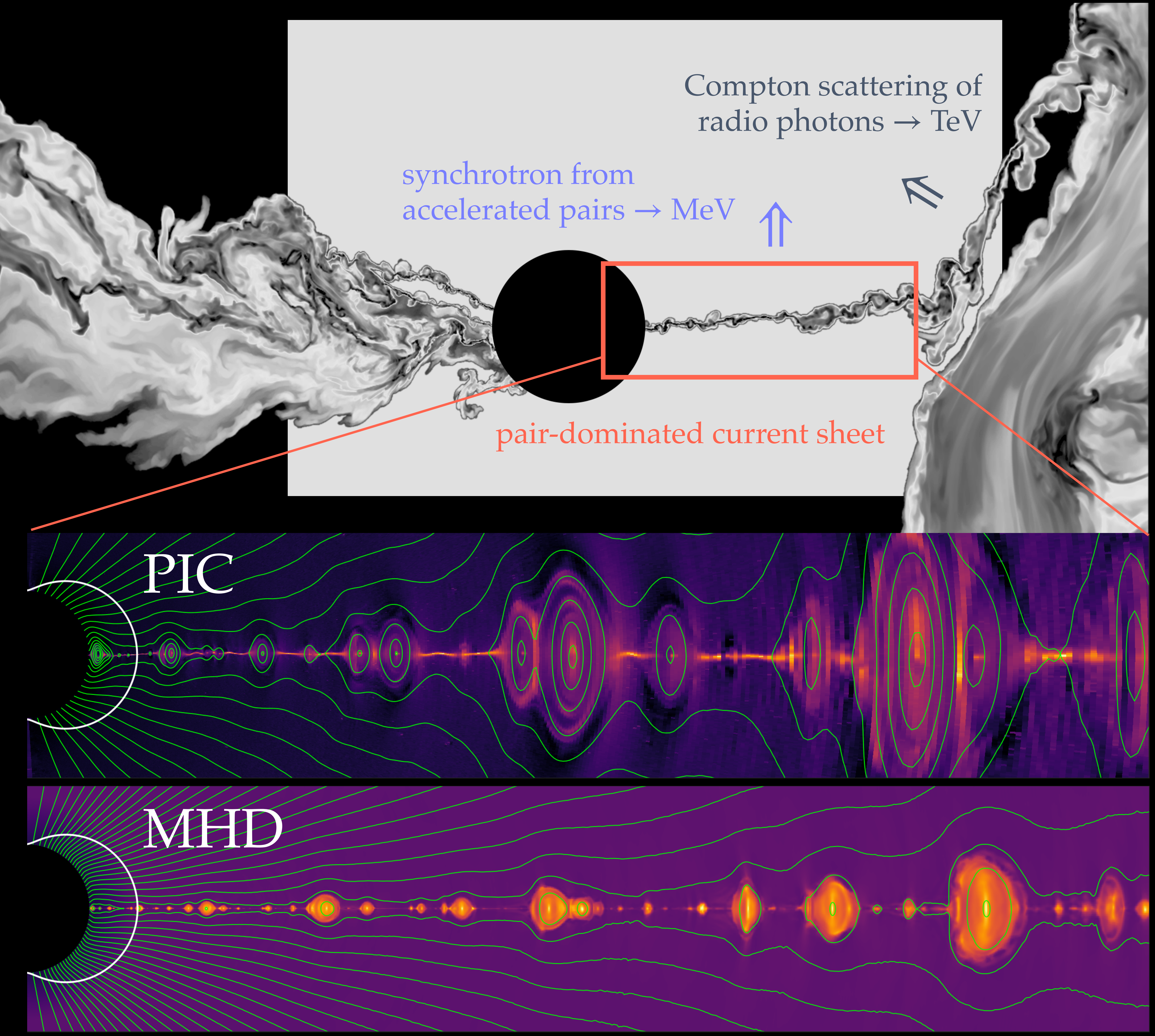
Toy model: “Balding” black hole

(First proposed by Lyutikov, 2011, PRD)

Bransgrove, Ripperda, Philippov, 2021, cover of PRL

The time for magnetic flux to escape the event horizon is controlled by the plasma physics of magnetic reconnection

Regime of radiative reconnection



$B \sim 10^2$ G, $B^2/4\pi \gg \rho c^2$, $\sigma \sim 10^7$

Inverse Compton radiation:

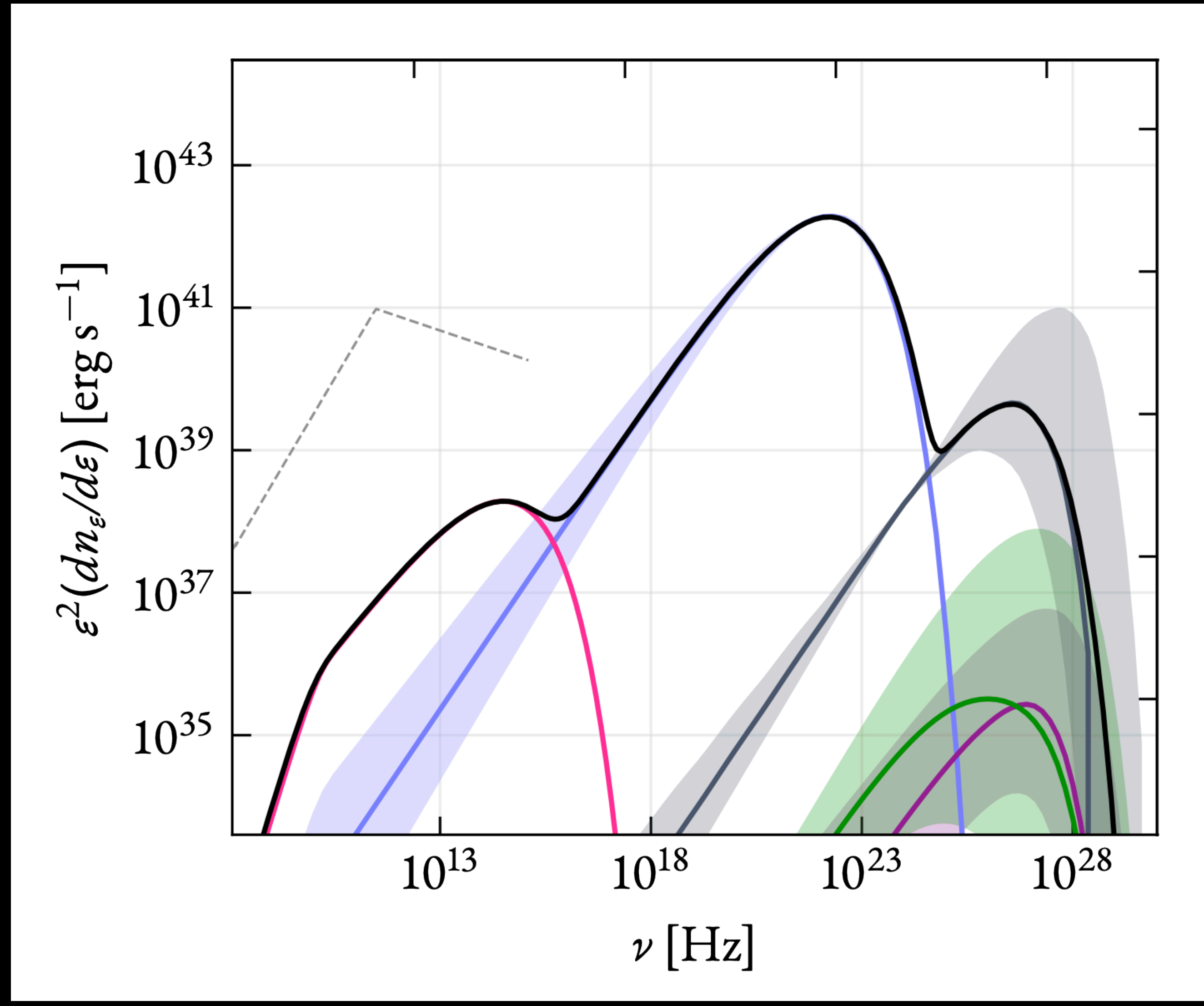
- $t_{\rm acc} \ll t_{\rm IC} \ll L/c \;\Rightarrow$ moderate IC drag compared to acceleration, but important on dynamical timescales

Synchrotron cooling:

- $t_{\rm acc} \sim t_{\rm sync} \;\Rightarrow$ synchrotron cooling affects particle acceleration

Pair production:

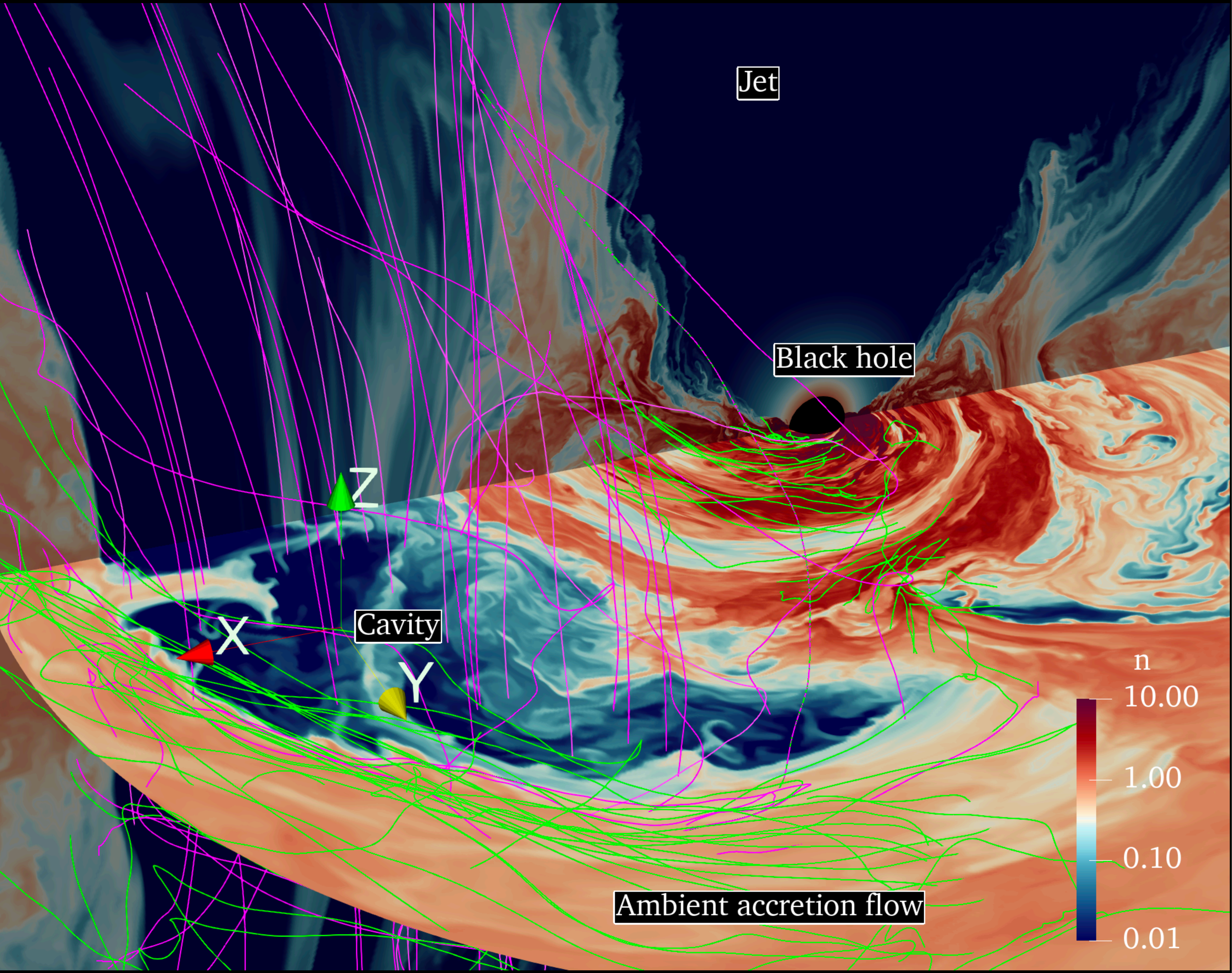
- plasma density is dominated by $e^{\pm}$ pairs
- $\tau_{\gamma\gamma} \ll 1$, annihilation ($\gamma\gamma \leftrightarrow e^{\pm}$) is not important (but important in X-ray binaries)

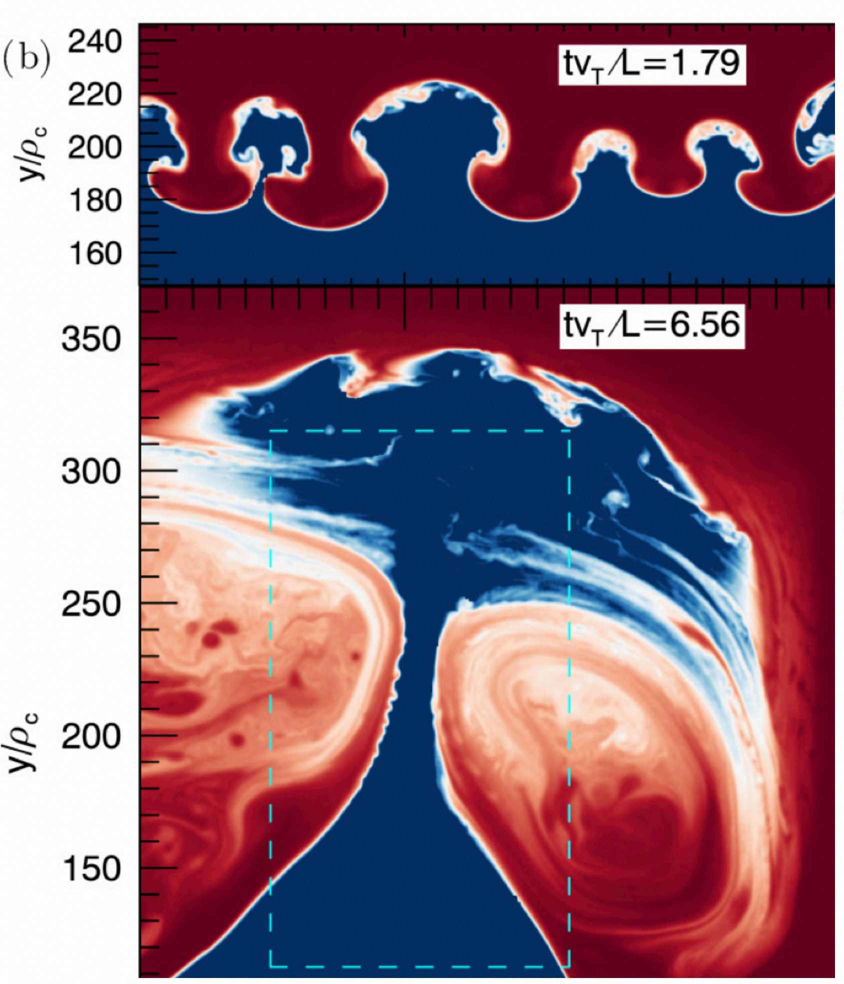


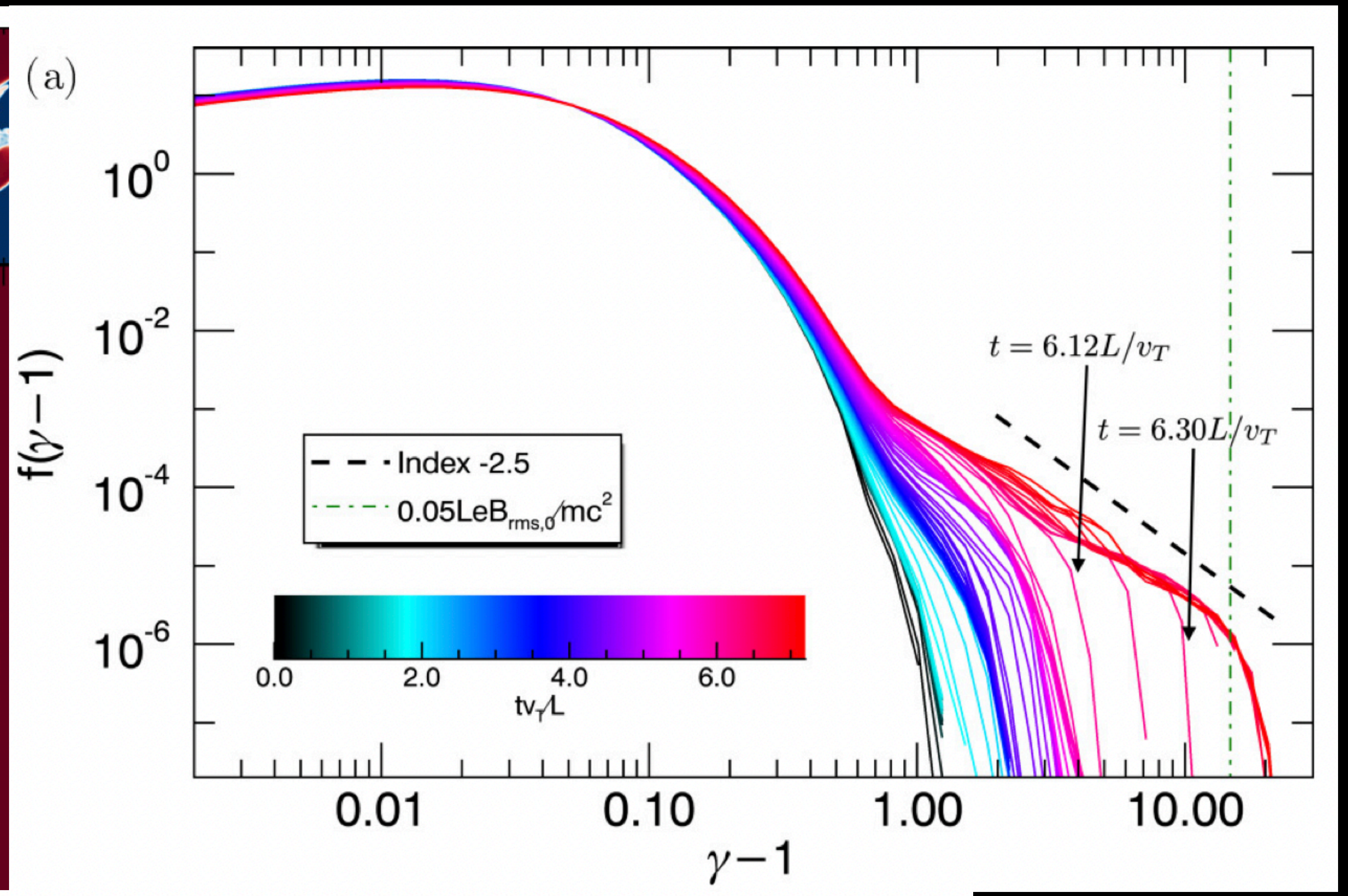
Ripperda et. al. (2022)
Bransgrove, Ripperda, Philippov (2021)

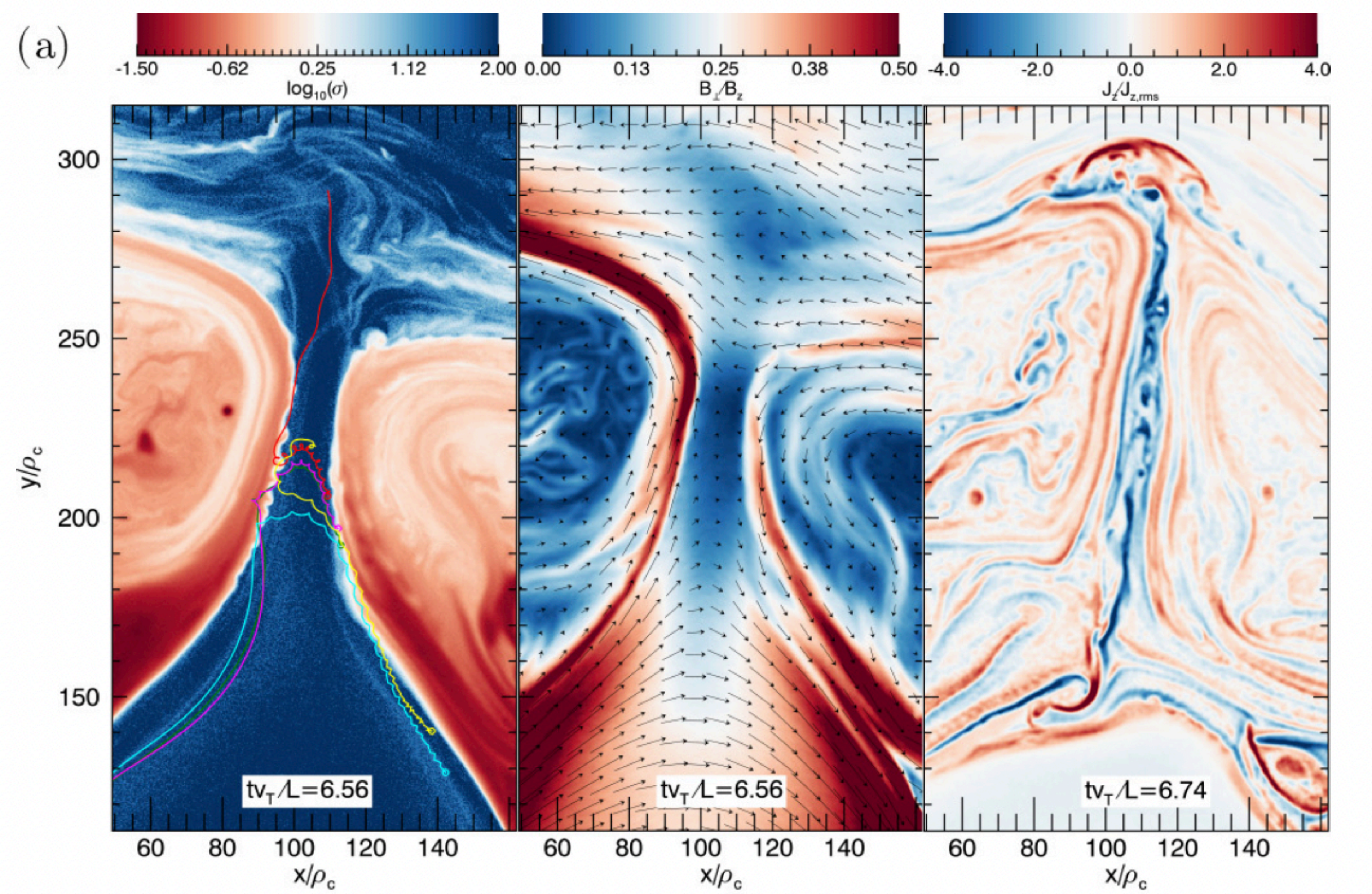
Hakobyan et. al., 2023, ApJL

GRAVITY hotspot?







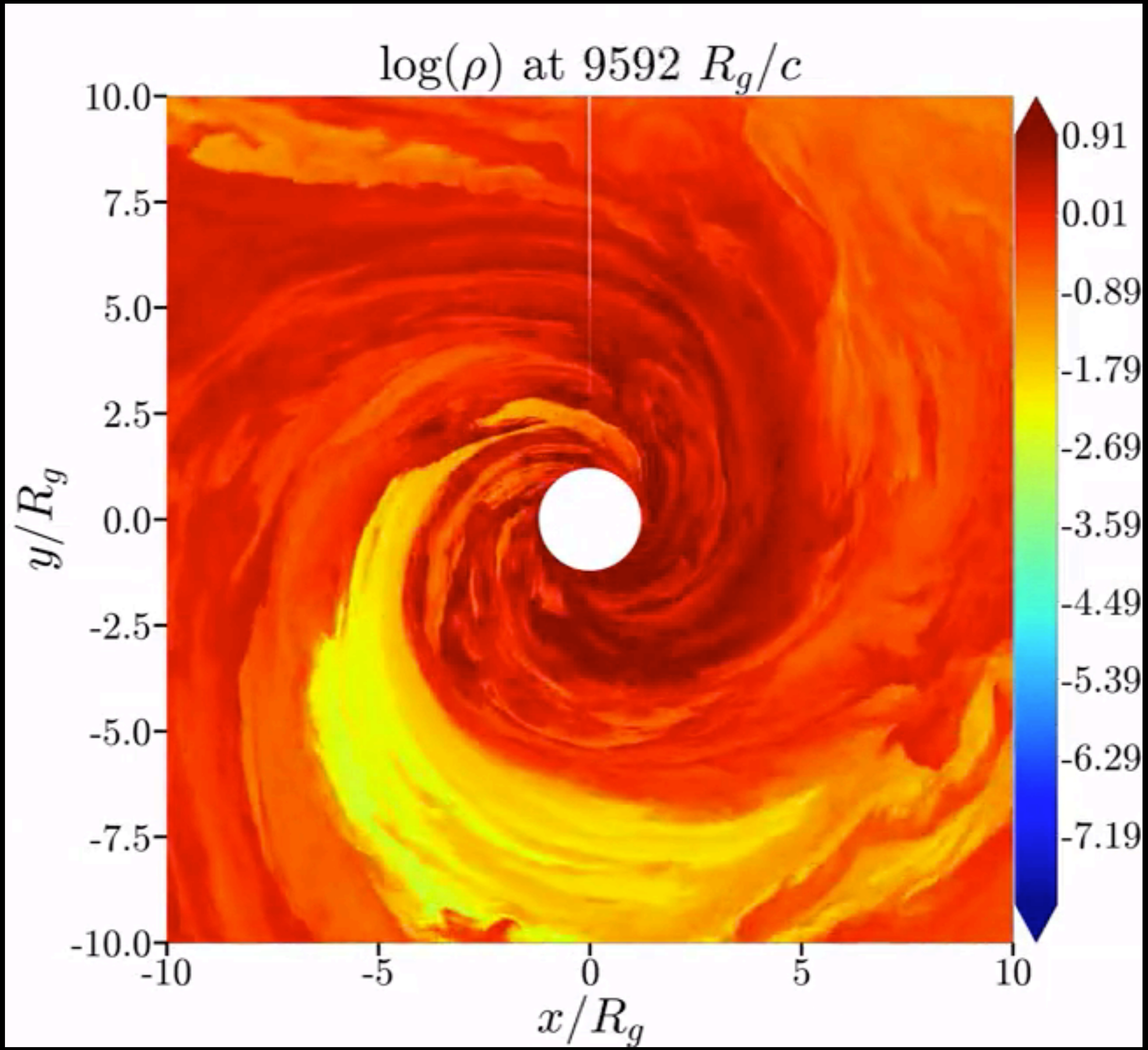


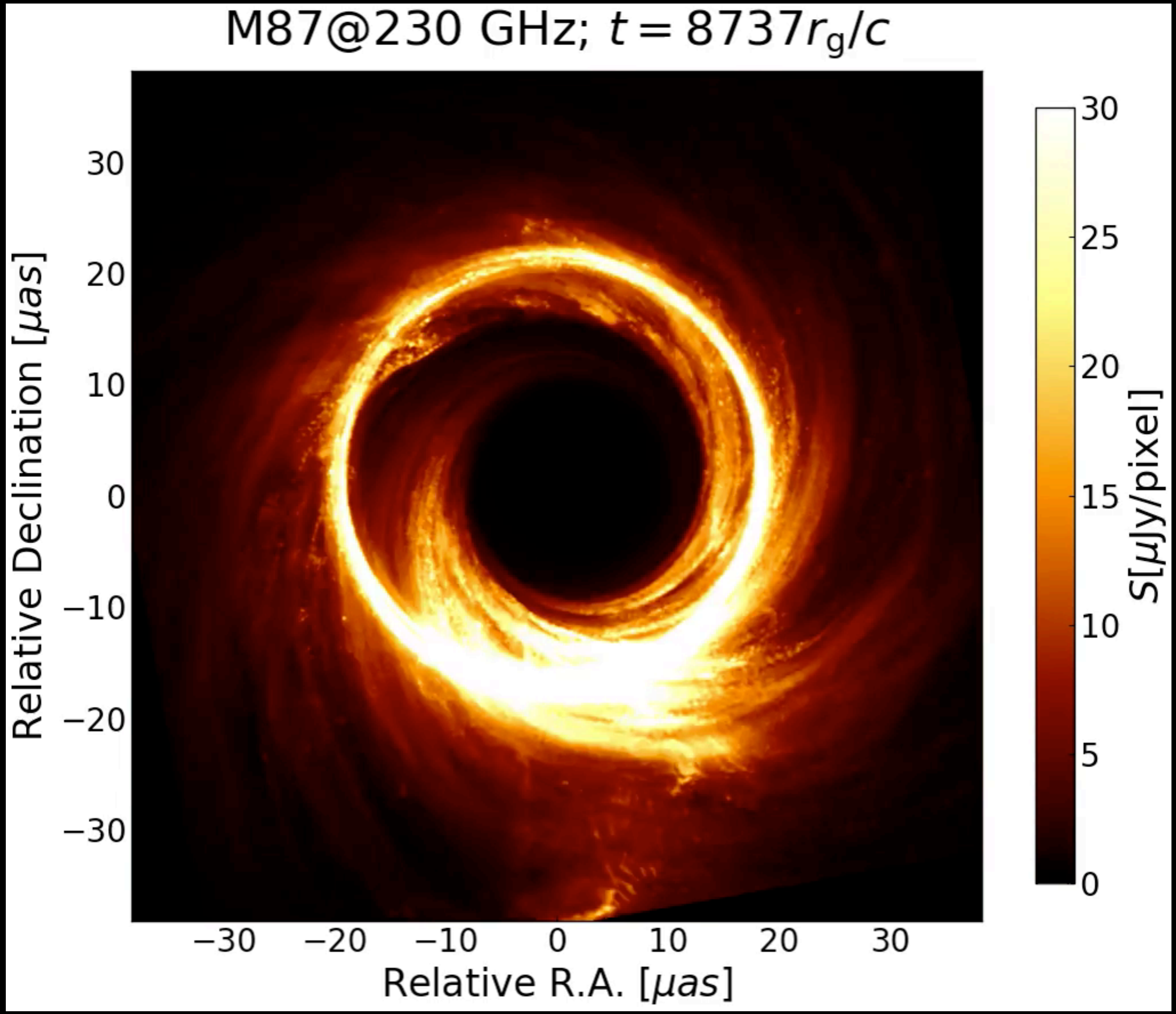
Exhaust of the reconnection layer; likely filled with non-thermal particles; quasi-vertical magnetic field; mixed with the disk via RT instabilities in about one orbit.

Ripperda, Liska, Chattarjee, et. al., 2022, ApJL

Zhdankin et al., 2023, PRR

Brightness dips in EHT imaging



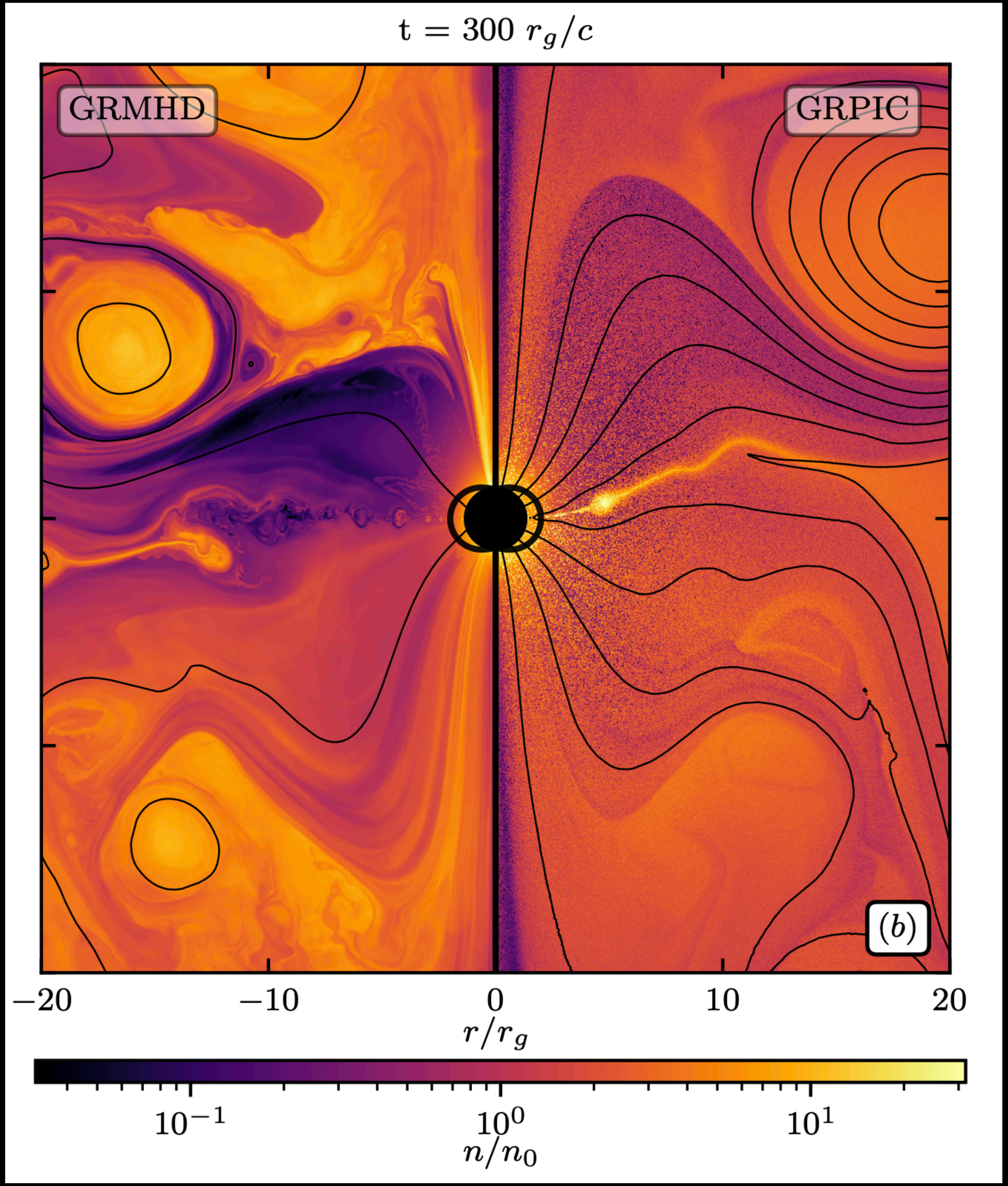


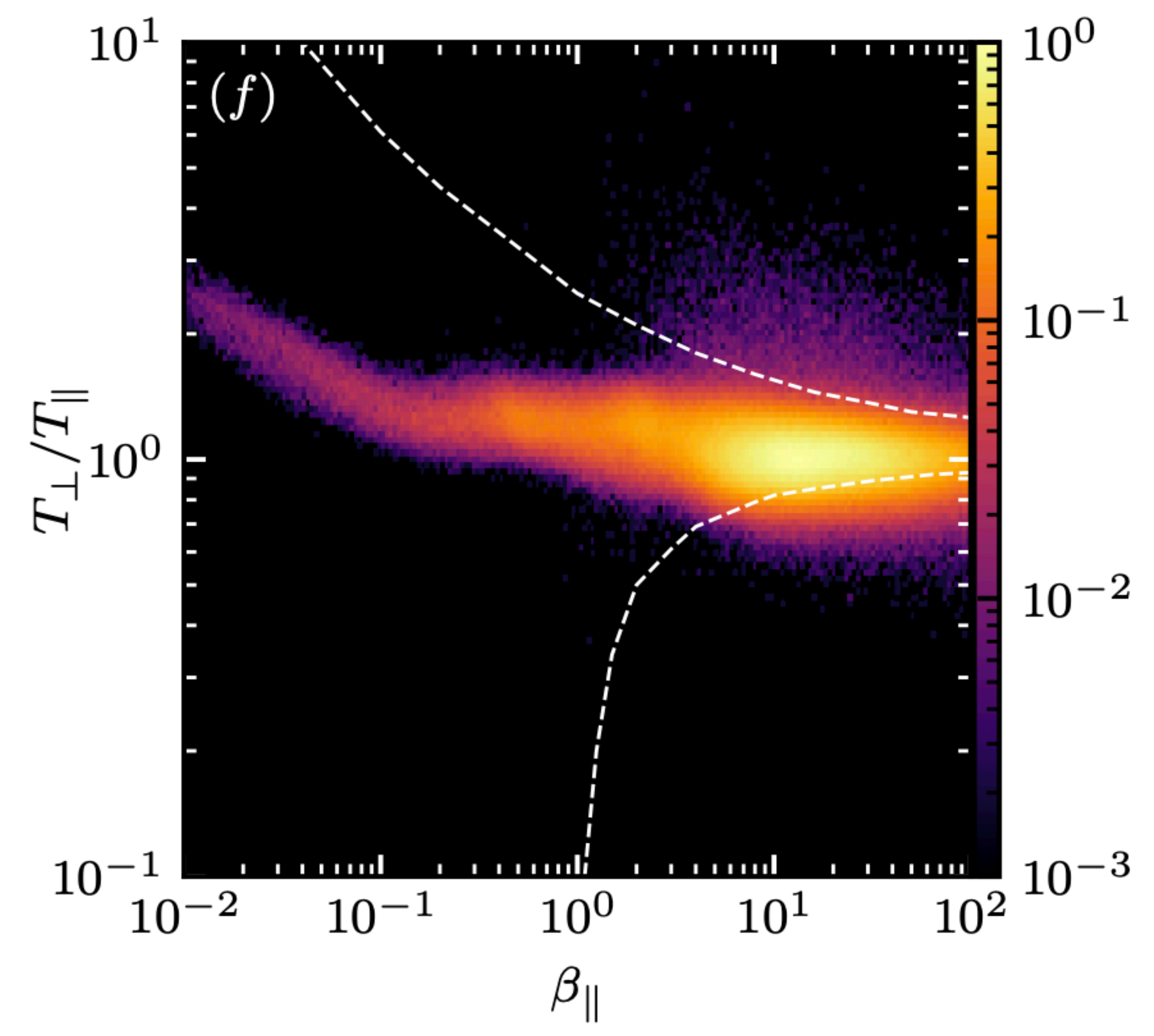
ngEHT can test this picture if observations can sample both the quiescence and flare; AND if observed signatures are different (prediction: dimming of the radio image).

He et. al., MNRAS, 2023

Movie by Koushik Chatterjee

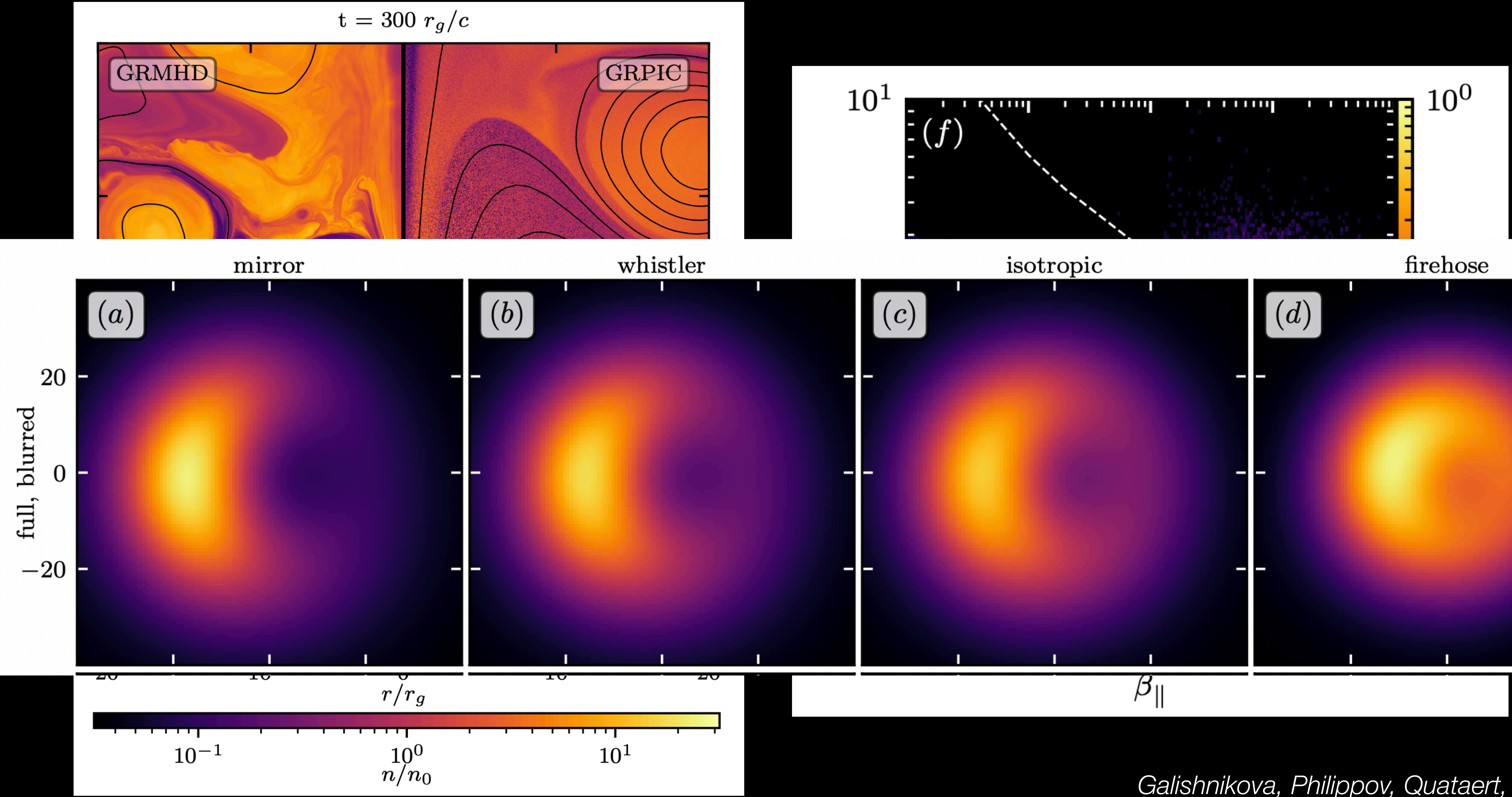
Glimpse into the future





Galishnikova, Philippov, Quataert et. al., 2023, cover of PRL

Glimpse into the future



Galishnikova, Philippov, Quataert, 2023, ApJ

Conclusions

1. Origin of pulsar emission has been a puzzle since 1967 - kinetic plasma simulations are finally addressing this from first principles. Accelerated particles in the current sheet emit powerful gamma-ray mainly via synchrotron mechanism. Low altitute radio emission is produced during non-stationary discharge at the polar cap, not a plasma instability in the stationary plasma flow.

2. Magnetically arrested accretion flows onto SgrA* and black hole in M87 are intermittent, and are accompanied by low accretion rate episodes driven by the expulsion of magnetic flux. These events can power multi-wavelength flares and show up as dimming of the horizon-scale radio image.

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The Principal Investigators and Co-Principal Investigators collaborating on SCEECS are Roger Blandford, Stanford, Director (rdb3@stanford.edu), Sasha Philippov, Maryland, Deputy Director (sashaph@umd.edu), Richard Anantua, U Texas, San Antonio, (richard.anantua@utsa.edu), Matt Caplan, Illinois State (mecapl1@ilstu.edu), Katerina Chatziioannou, Caltech, (kchatziioannou@caltech.edu), Ke Fang (kefang@physics.wisc.edu) and Ellen Zweibel (egzweibel@wis.edu), U. Wisconsin, Sam Gralla, Arizona, (sgralla@email.arizona.edu), Yuri Levin (yl3470@columbia.edu) and Lorenzo Sironi (lsironi@astro.columbia.edu), Columbia, Amir Levinson, Tel Aviv, (levinson@tauex.tau.ac.il), Tsvi Piran, Hebrew University, (tsvi.piran@mail.huji.ac.il), Anatoly Spitkovsky, Princeton (anatoly@astro.princeton.edu), Chris Thompson, CITA, (thompson@cita.utoronto.ca), and Yajie Yuan, Washington University at St Louis (yajiey@wustl.edu). Applications made in response to this advertisement, as well as those made through the institutions of collaborating investigators that designate SCEECS, will be considered by the entire collaboration.

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