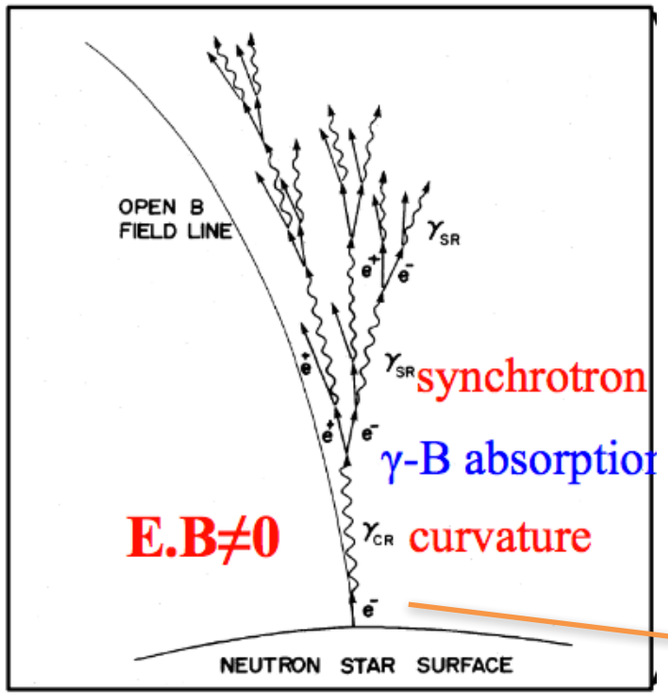
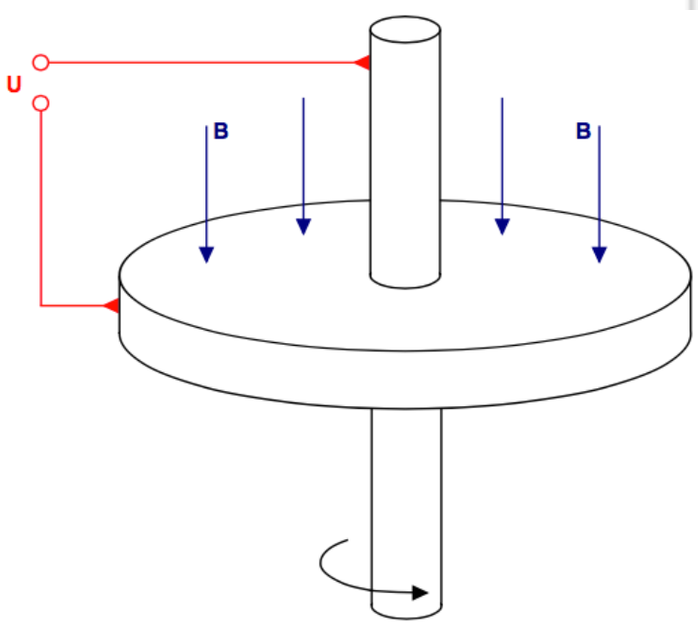
Pulsar magnetospheres and their emission

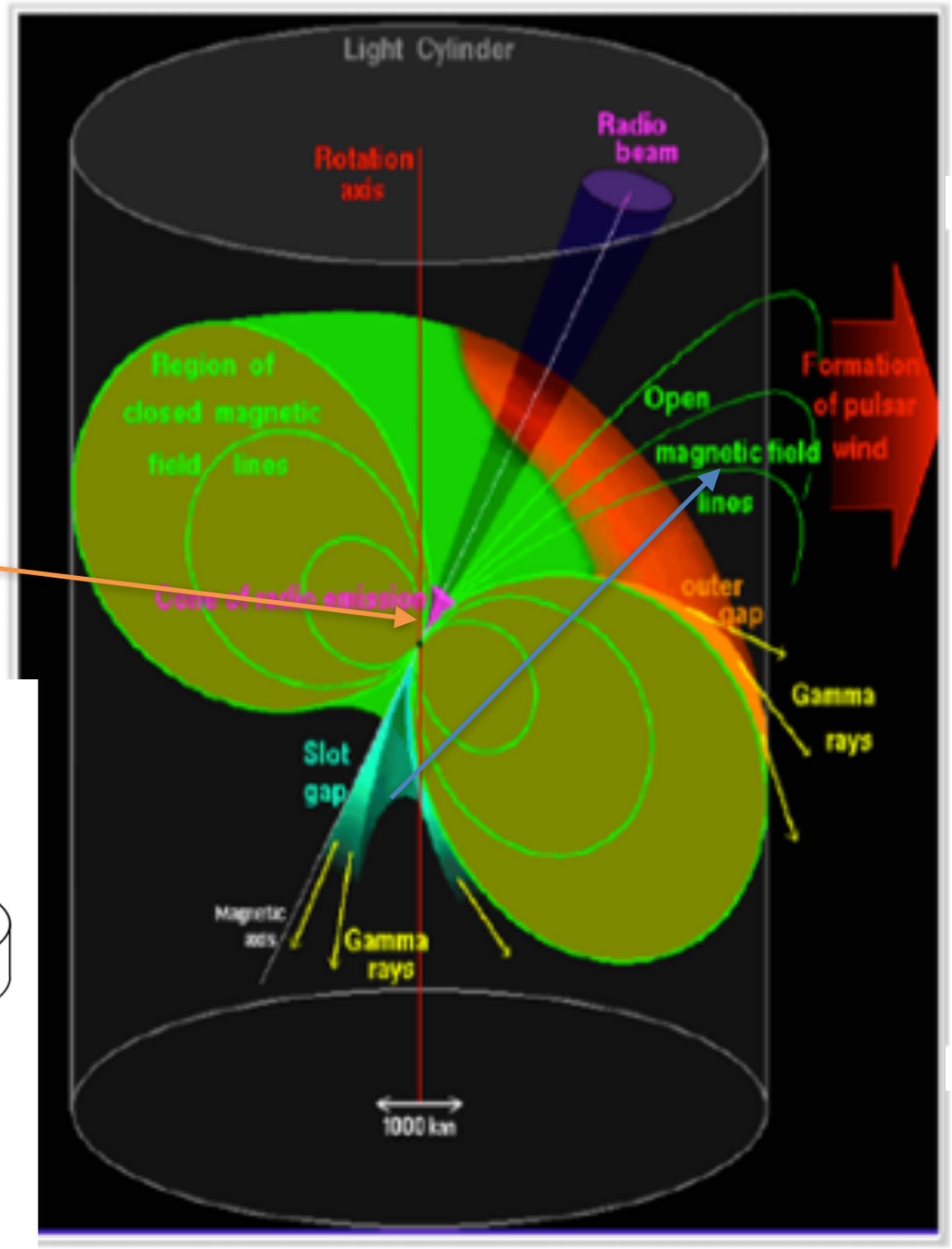
Sasha Philippov (CCA, Flatiron Institute)

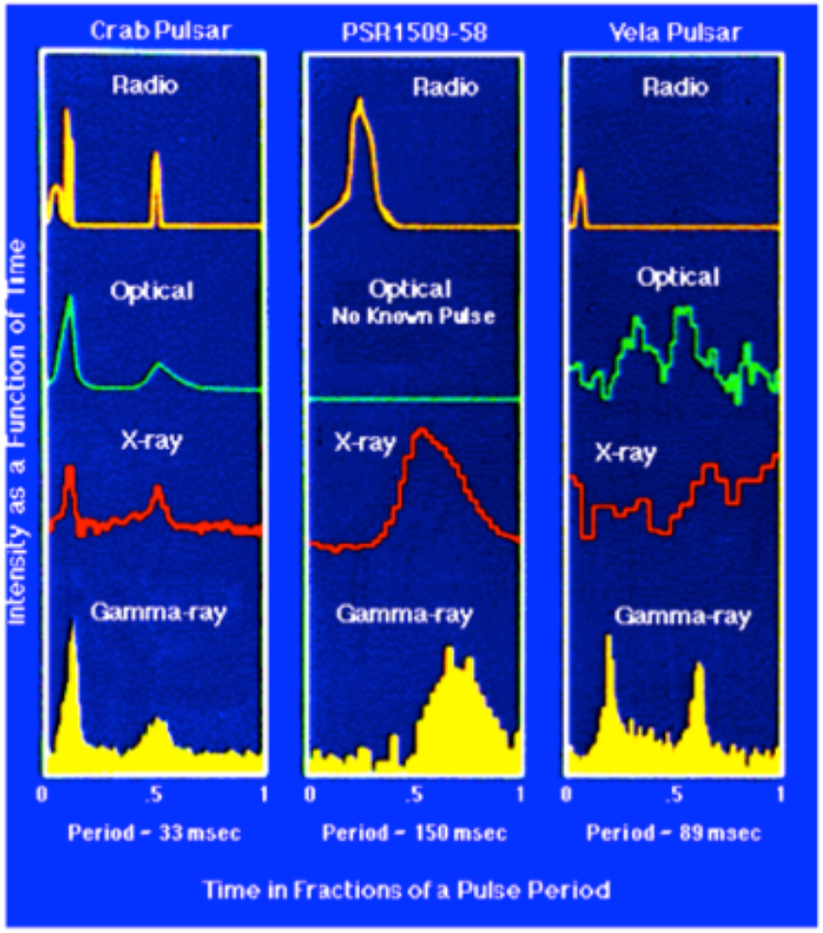
What is a pulsar?

Pair cascade in the polar caps









Unipolar induction

Standard pulsar

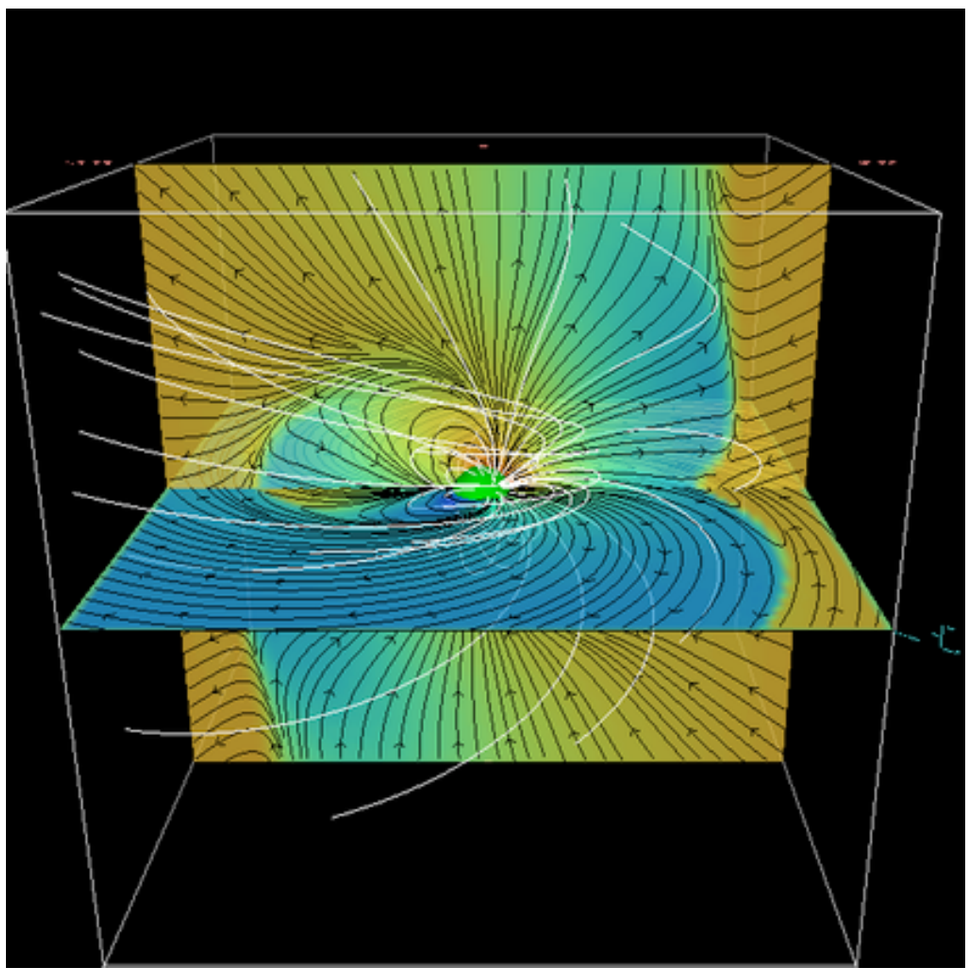
- Force-free paradigm

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

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

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

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



- 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)

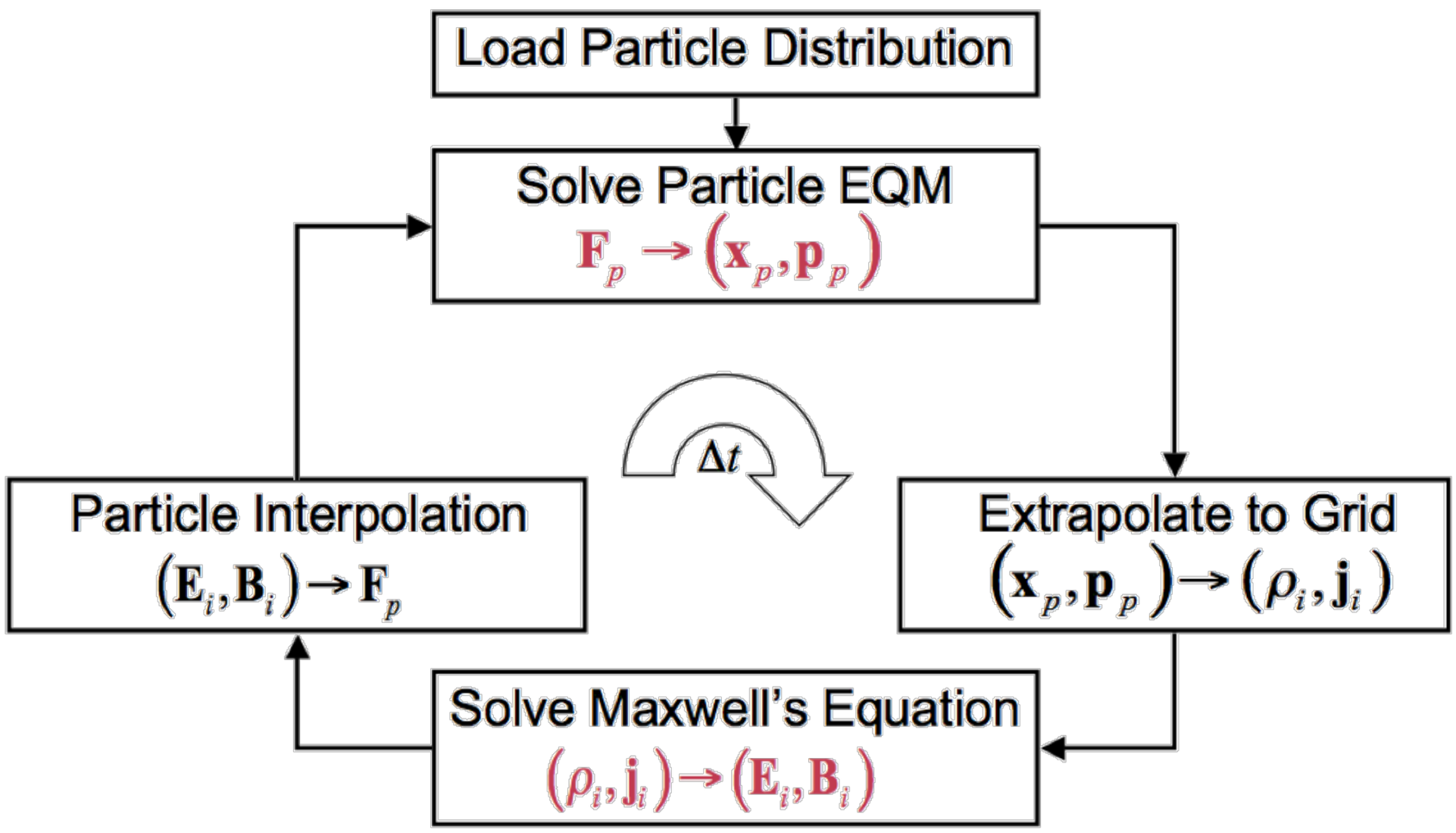
$$L_{\text{pulsar}} = k_1 \frac{\mu^2 \Omega_*^4}{c^3} (1 + k_2 \sin^2 \alpha)$$

PIC simulation of magnetospheres

- Core - EM PIC codes. For compact object magnetospheres, need GR, radiative cooling, pair production and boundary conditions (conductors, atmospheres with particles, etc.)

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

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



PIC simulation of magnetospheres

- 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.

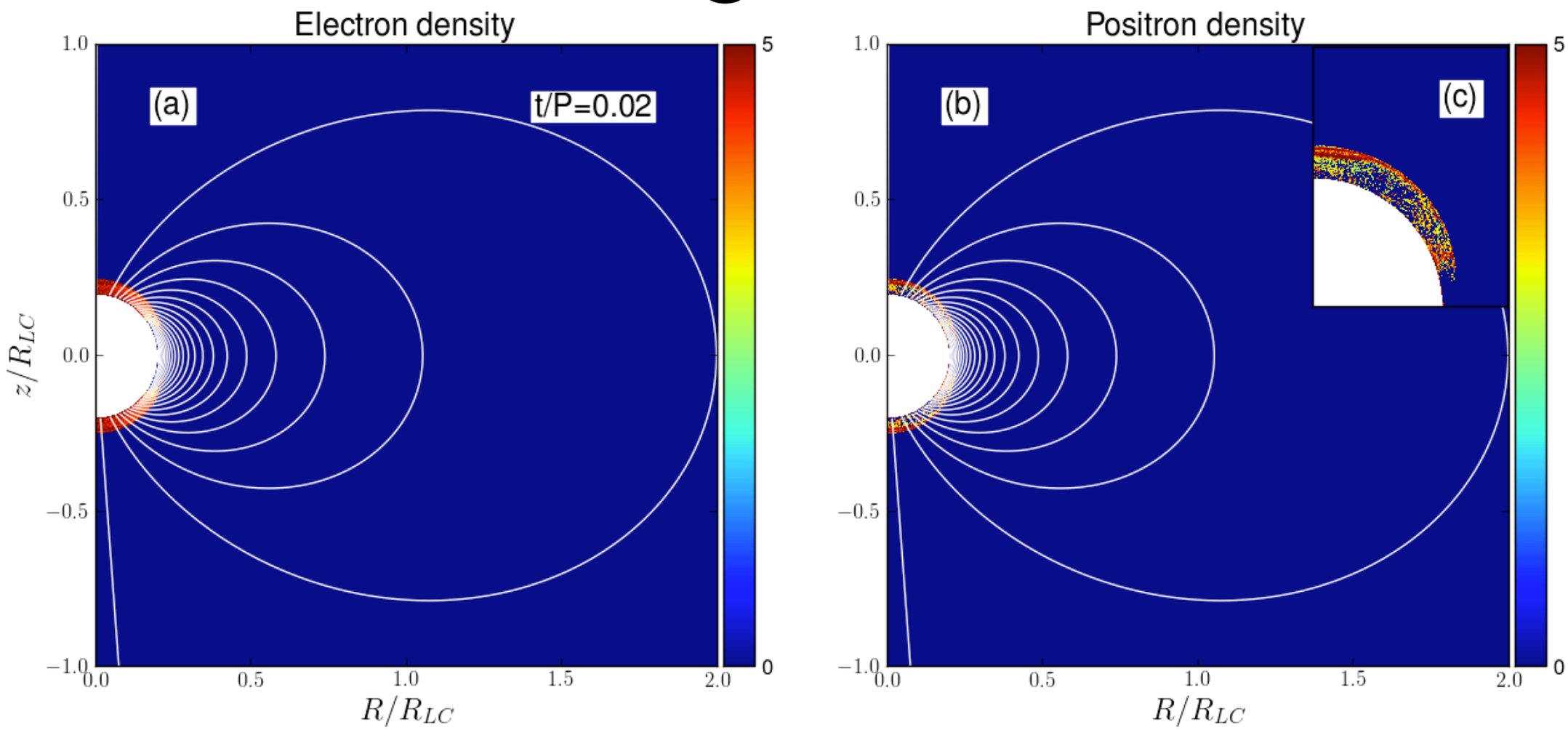
$$\mathbf{g} = \frac{2}{3} r_e^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) \times \mathbf{B} + (\boldsymbol{\beta} \cdot \mathbf{E}) \mathbf{E} \right] - \frac{2}{3} r_e^2 \gamma^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2 \right]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

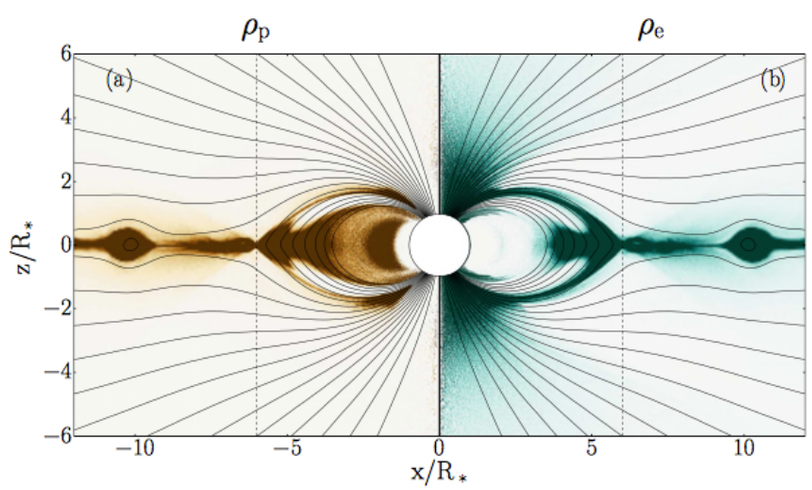
- Pair creation with the threshold based on particle energy in the inner magnetosphere. Outer magnetosphere: pair production in photon-photon collisions, do tracking of high-energy photons.
- Effects of GR: simulations in slowly rotating metric.
- Scales approached:

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

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

GR aligned rotator





Chen & Beloborodov, ApJ, 2014

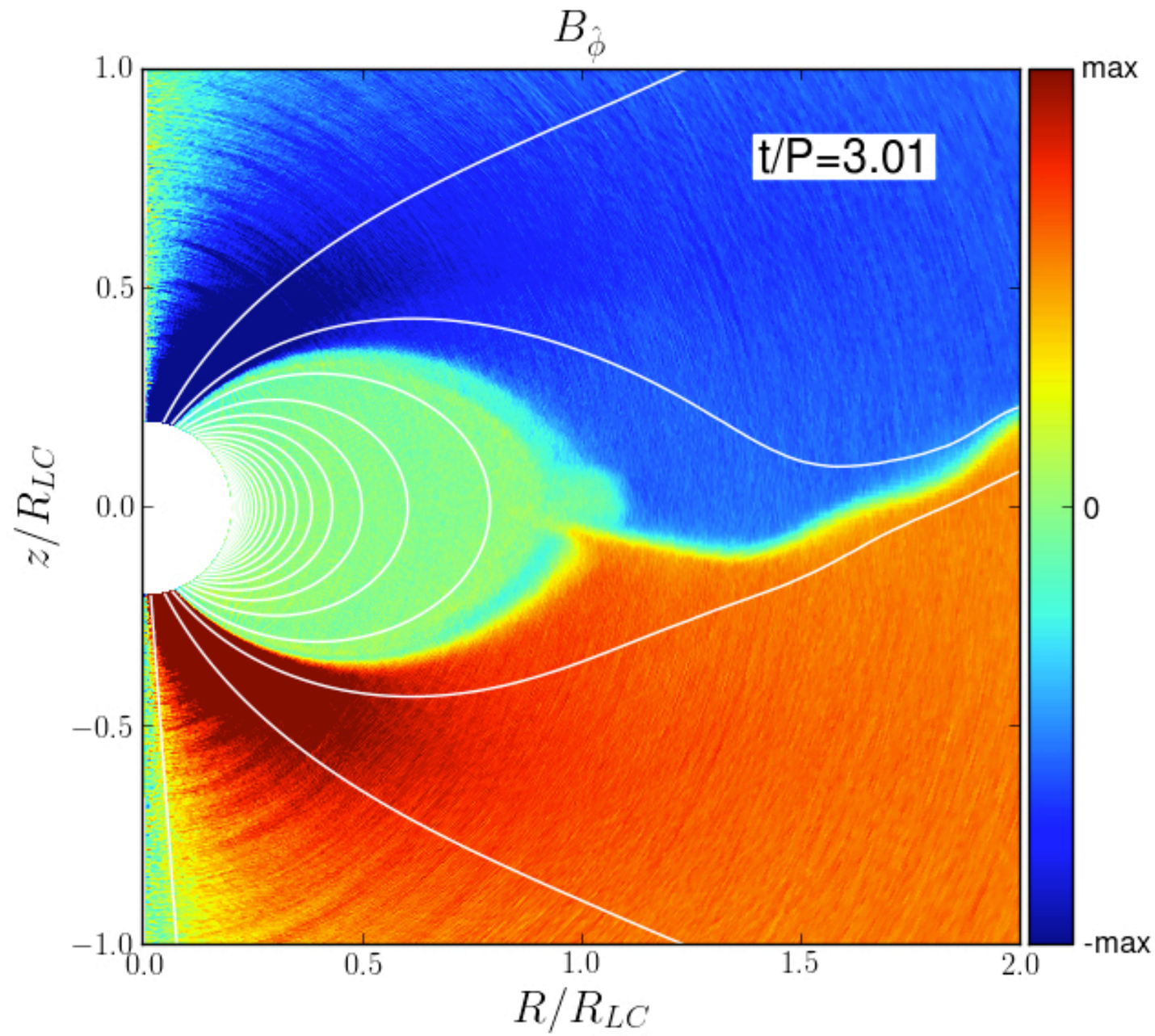
Flat space solution, no pair production

Philippov et al., 2015 ApJ

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

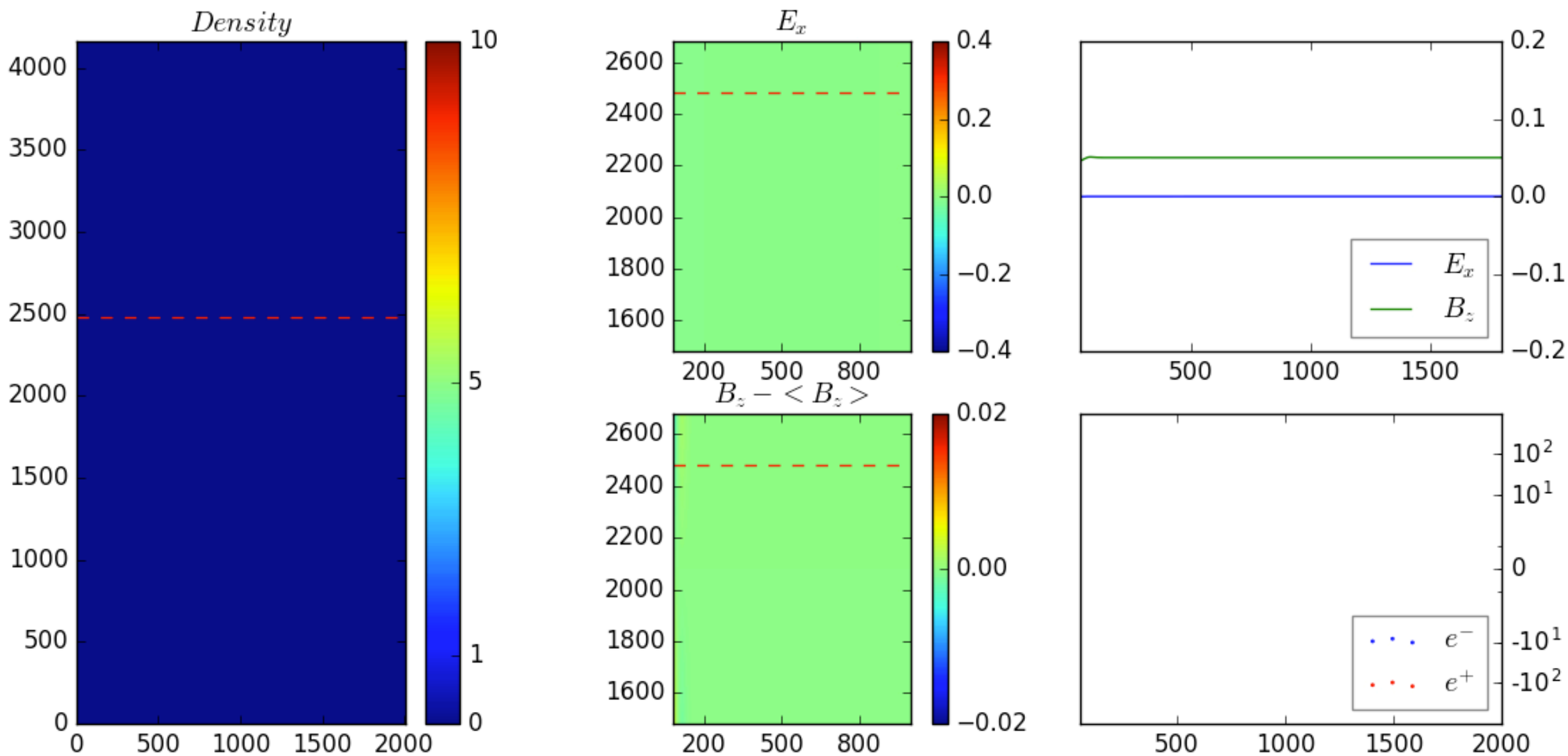
Implications for radio emission

- 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)



Philippov et al., 2015 ApJ

2D local discharge simulations



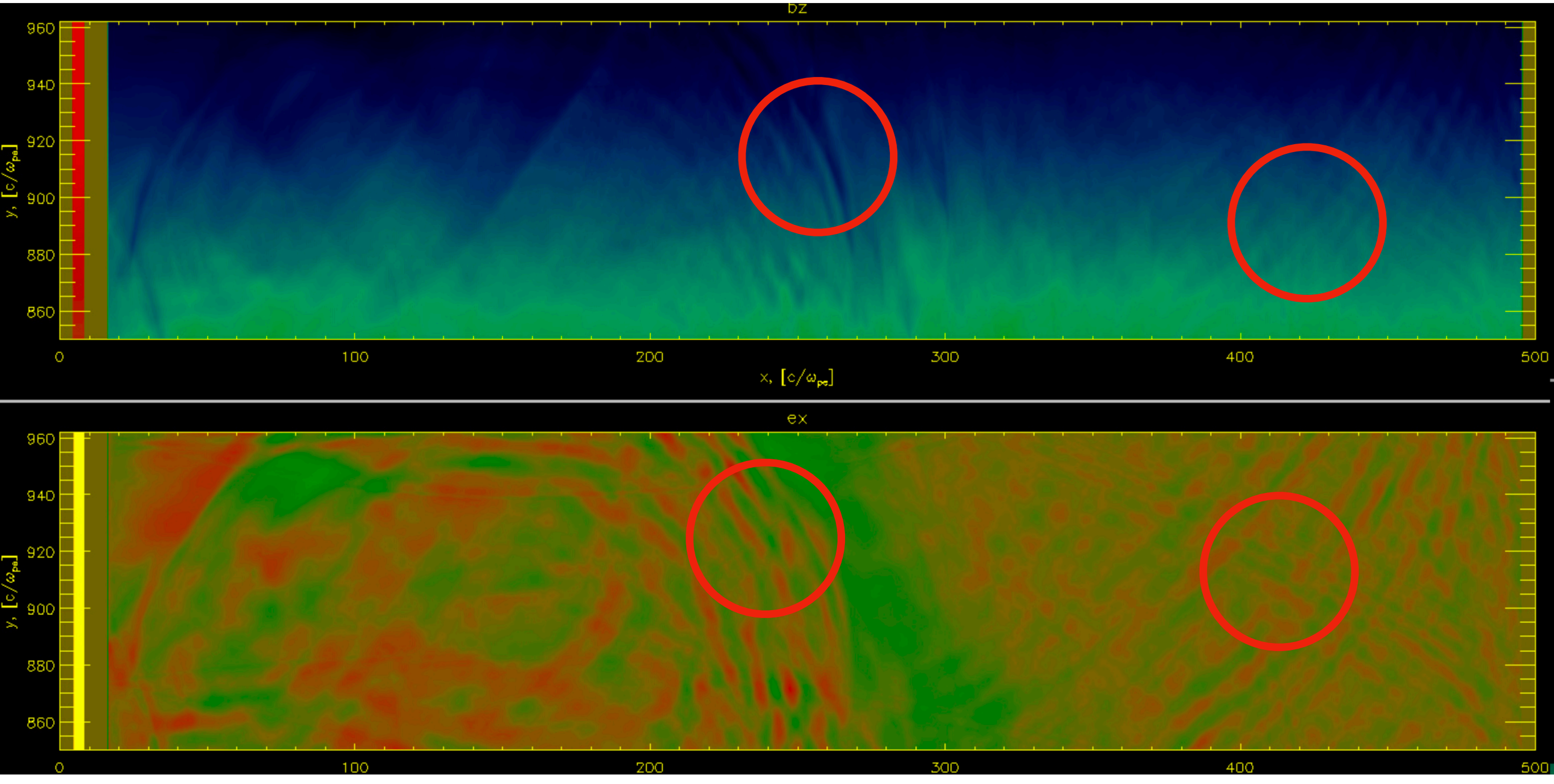
Conducting “rotating” plate on the left, horizontal external B-field, radiation boundary on the right. Frame-dragging prescription is tuned such that the current is super-GJ near the plate, becomes ~GJ at large x. Full EM is included, all the currents and charge densities are driven self-consistently.

Discharges that are oblique to the background magnetic field generate EM waves.

1D: Timokhin & Arons (2013), electrostatic modes

2D: Philippov, Timokhin & Spitkovsky (in preparation)

2D local discharge simulations



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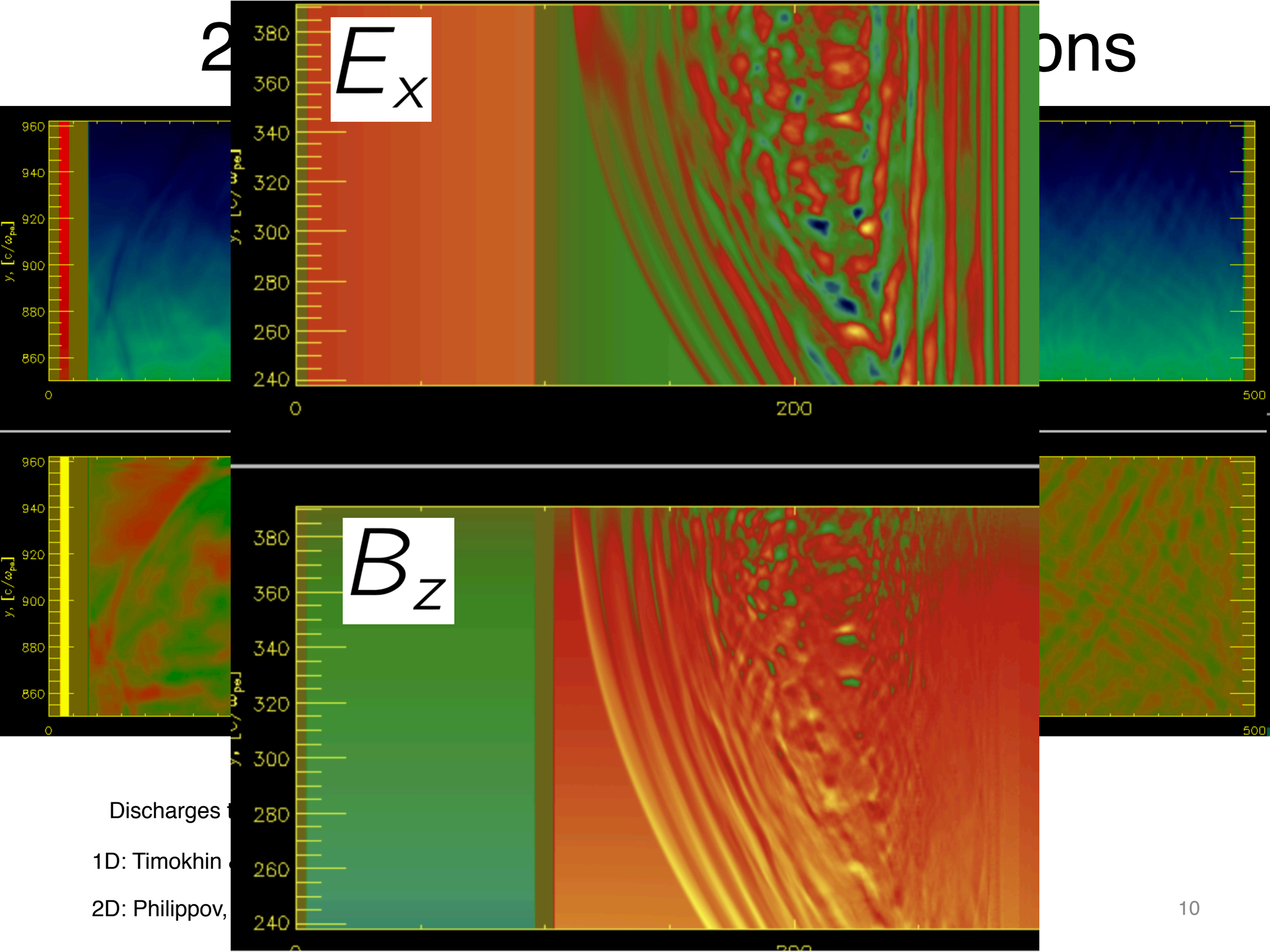
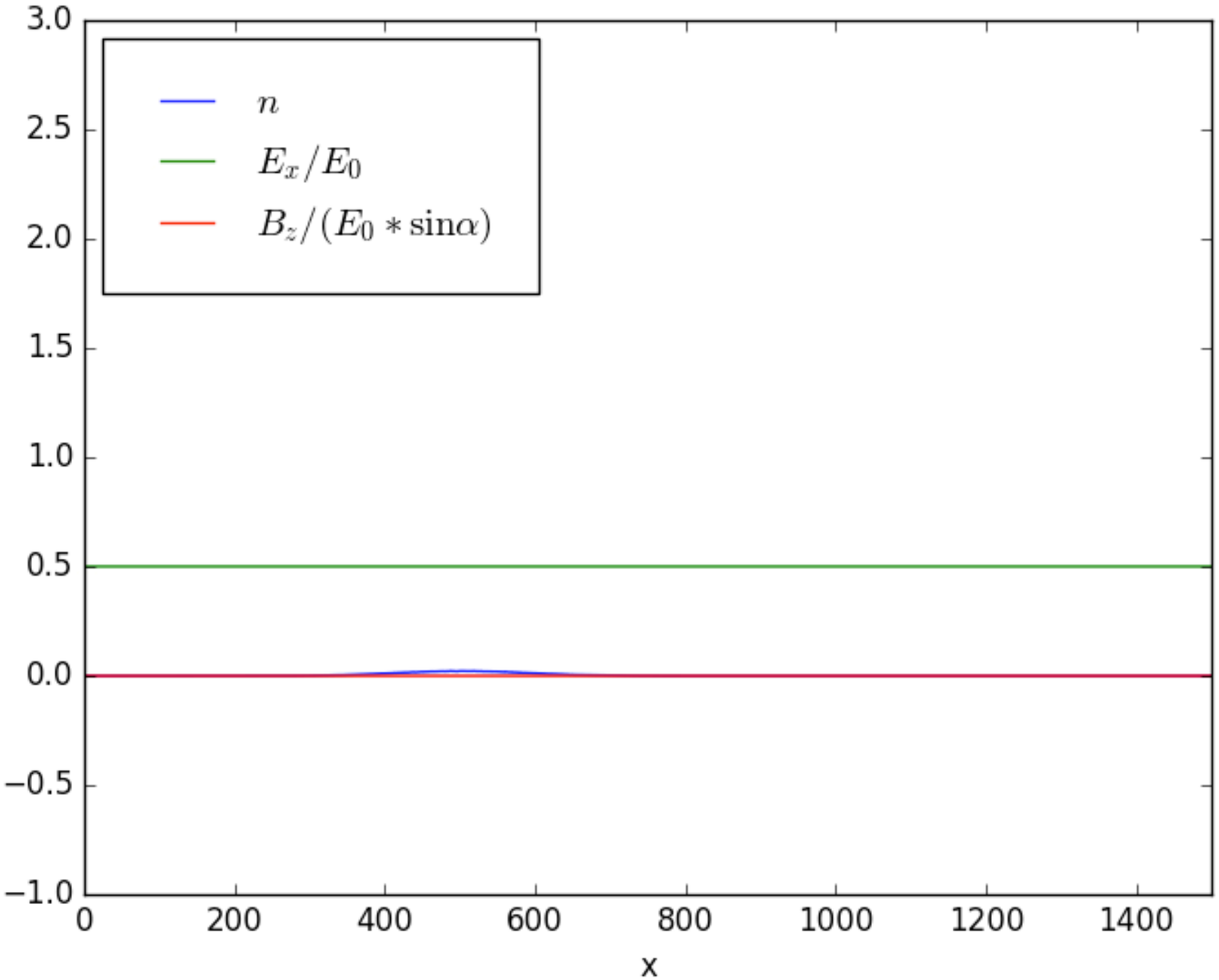


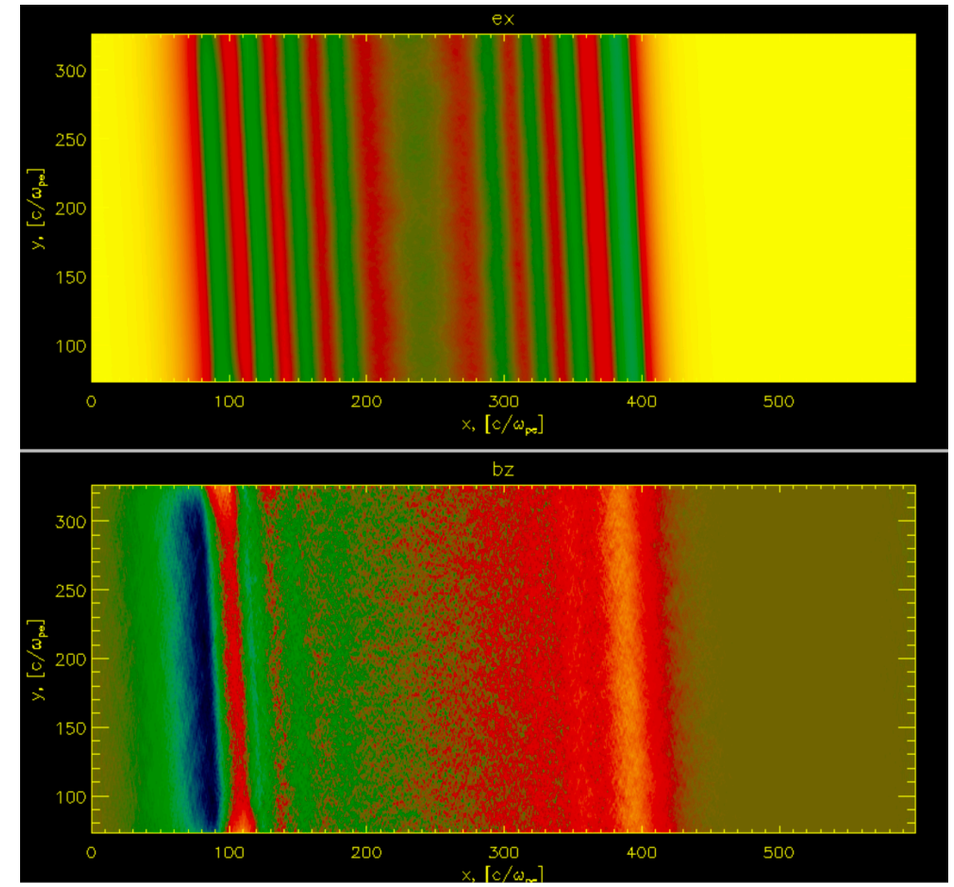
Discharges t

1D: Timokhin

2D: Philippov,

Link to a 1D dispersion relation





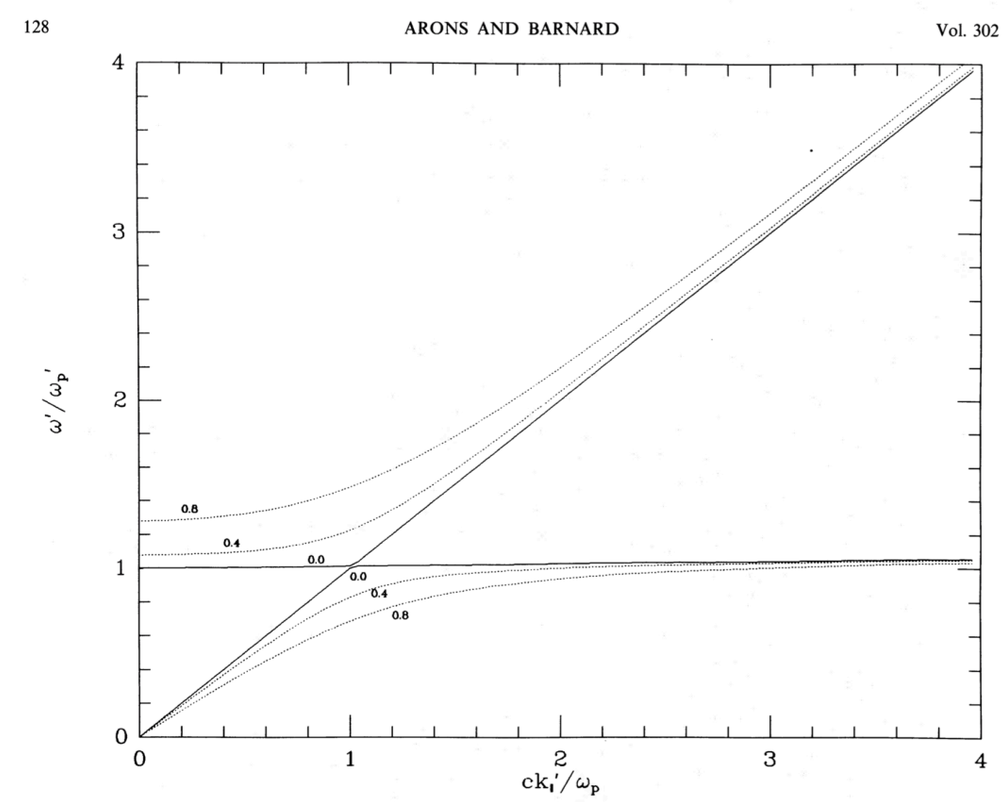


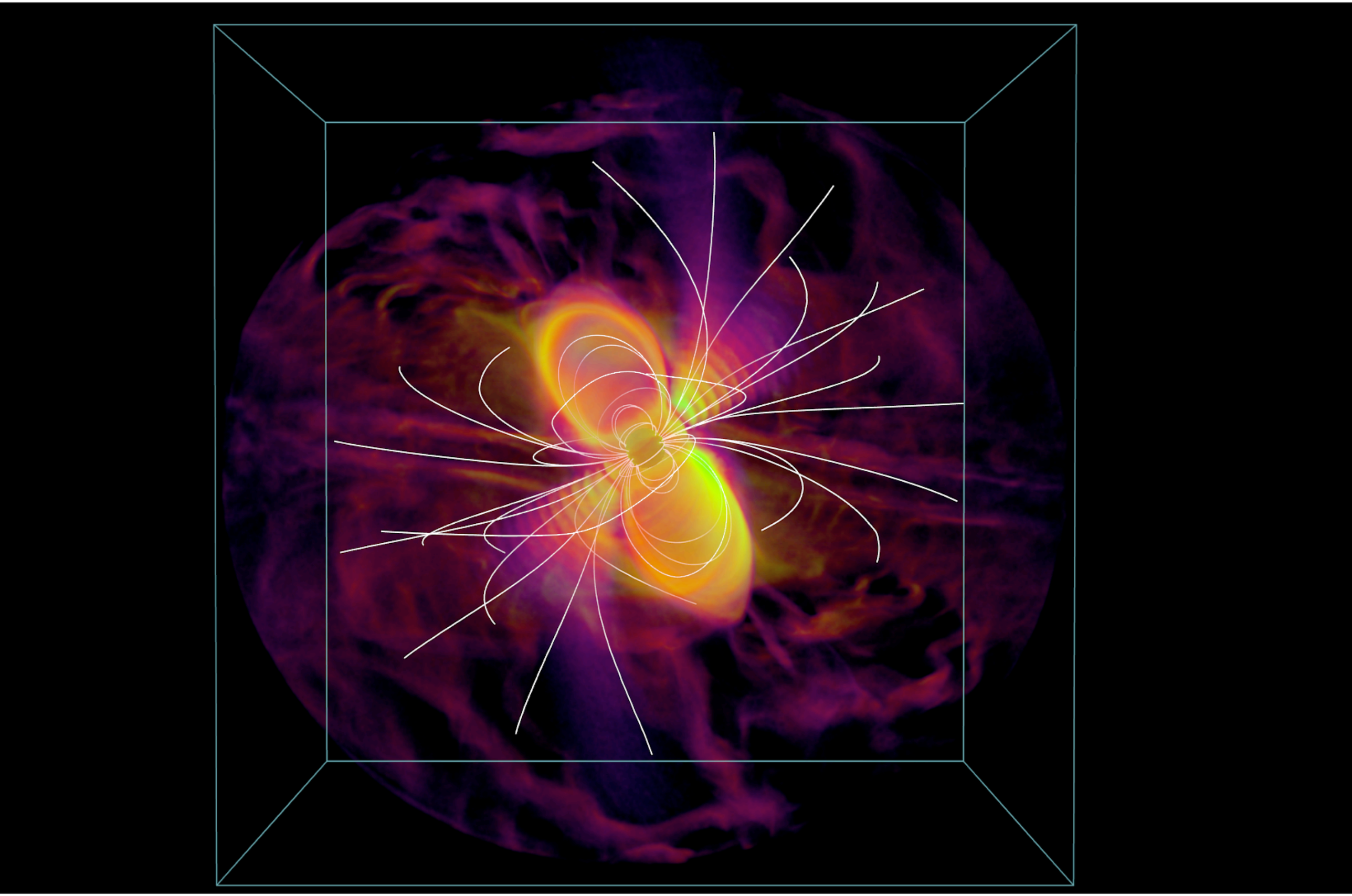
FIG. 1.—Dispersion relation for a cold electron-positron plasma in the rest frame of the plasma. Each curve is for a constant value of $ck'_\perp/\omega'_p$ labeled adjacent to the curve.

Oblique discharge directly excites a superluminal O-mode with non-zero k_perp, which has EM component.

Broad-band emission is produced as pair density increases.

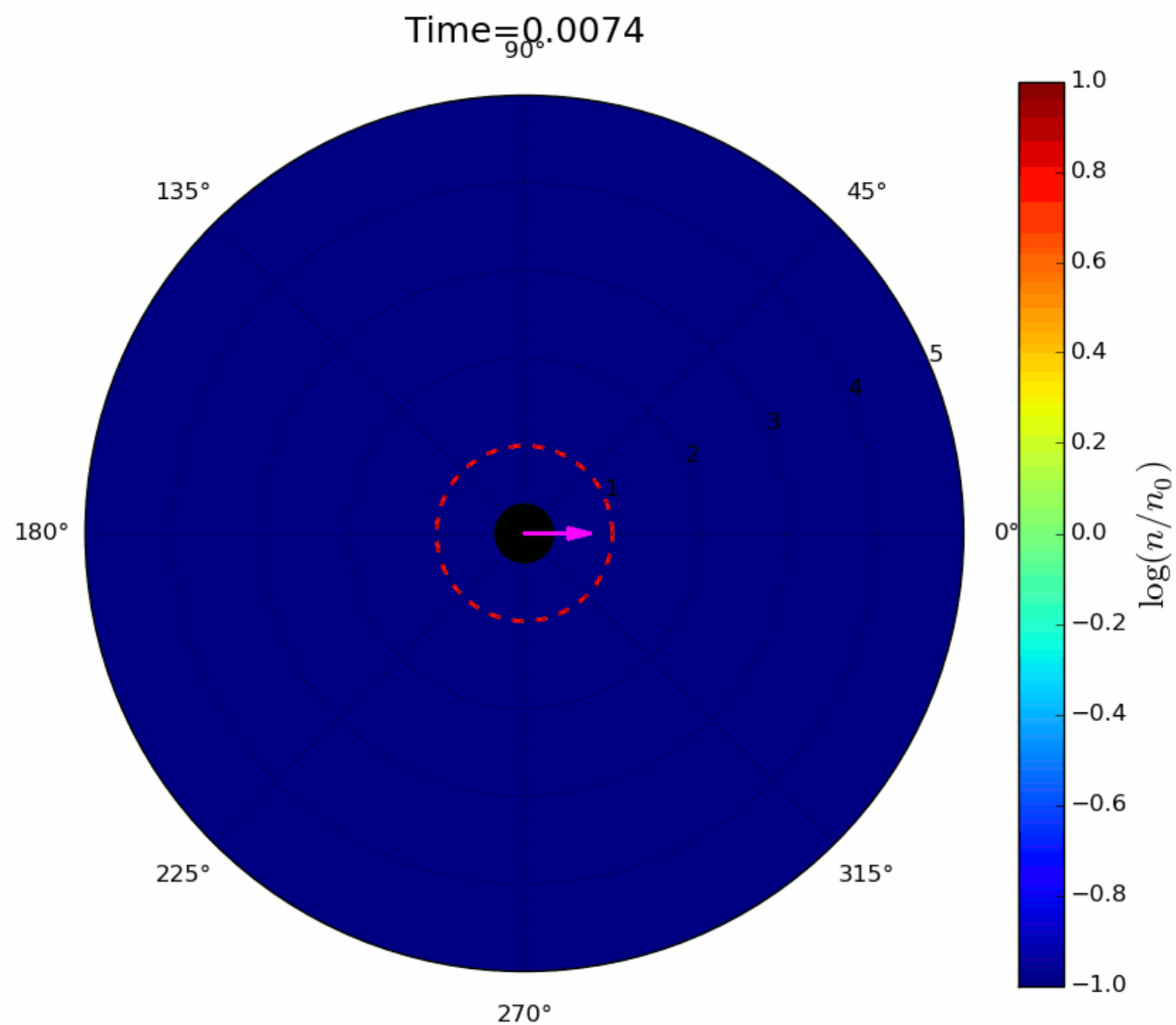
As plasma density drops, these waves should become vacuum EM.

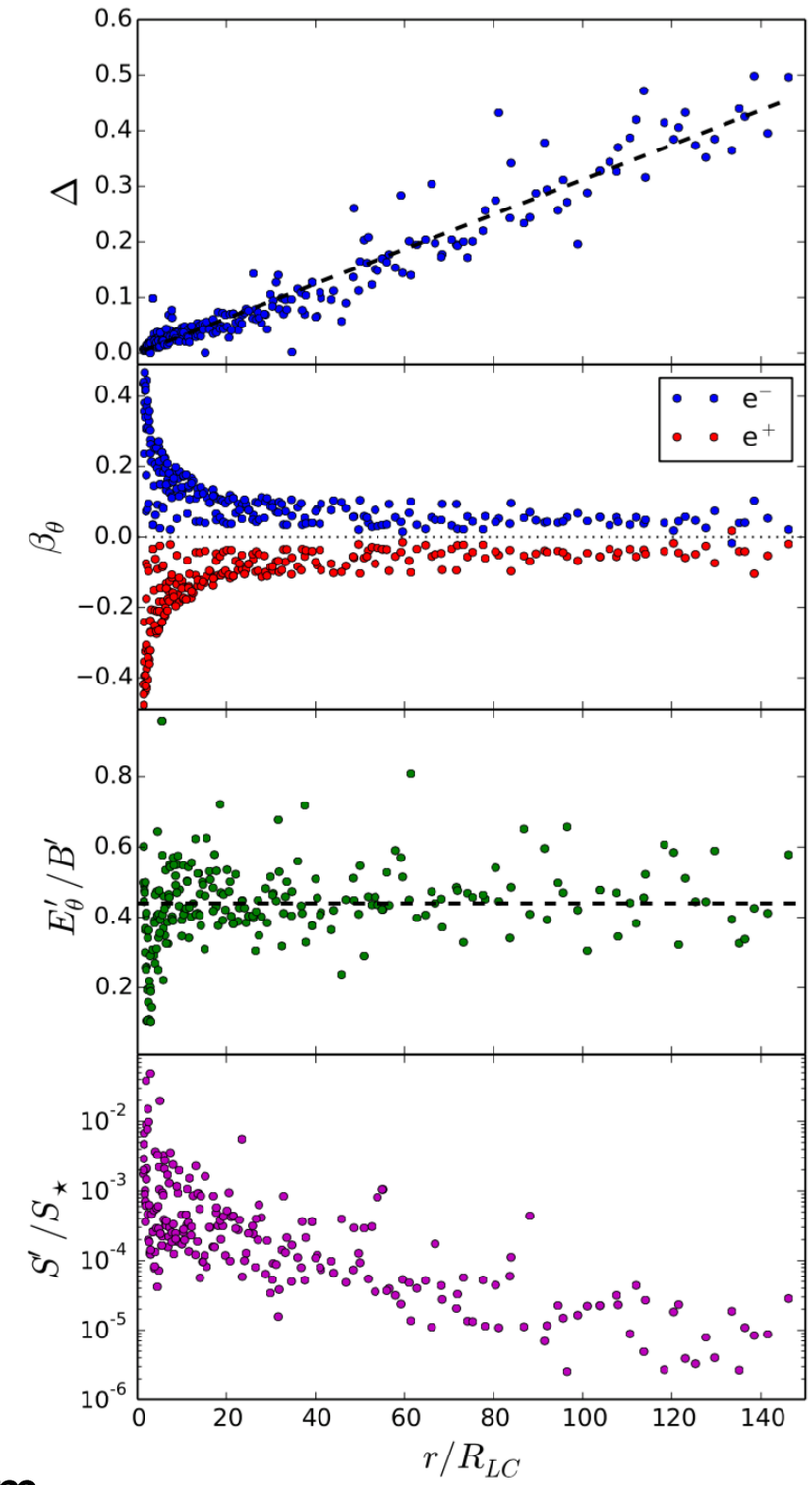
Super-luminal O-mode can not be a result of a streaming instability.



movie by Hayk Hakobyan (Princeton)

Current sheet in 2D





Cerutti & Philippov, 2017

Philippov et al., 2019 - model for radio nanoshots from merging plasmoids

Pulsar Summary

– Global kinetic simulations offer unprecedented insight into how pulsar magnetospheres work

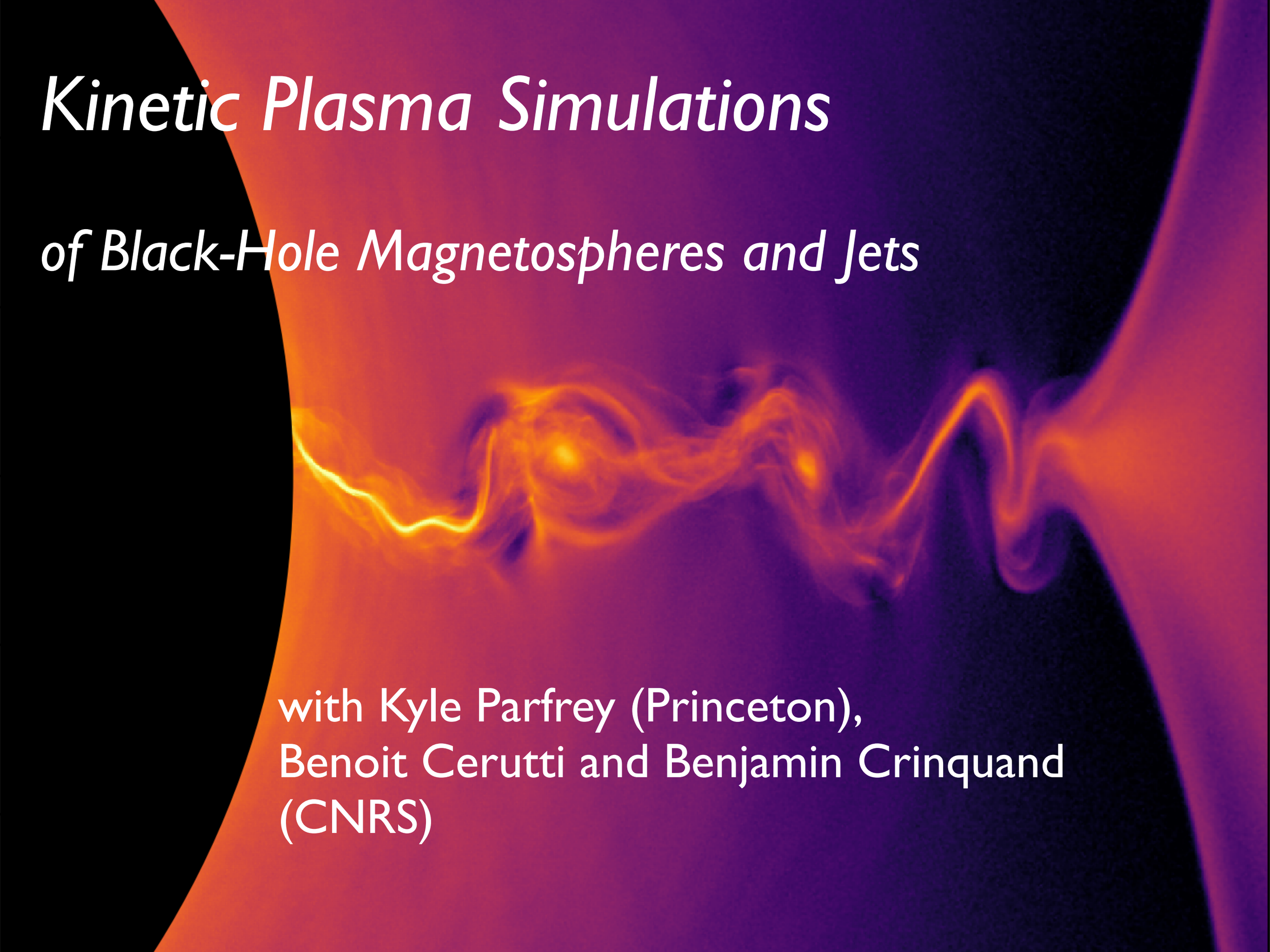
– Radio emission is likely powered by a non-steady discharge and reconnection

Future directions

– Detailed predictions for radio emission

Kinetic Plasma Simulations

of Black-Hole Magnetospheres and Jets



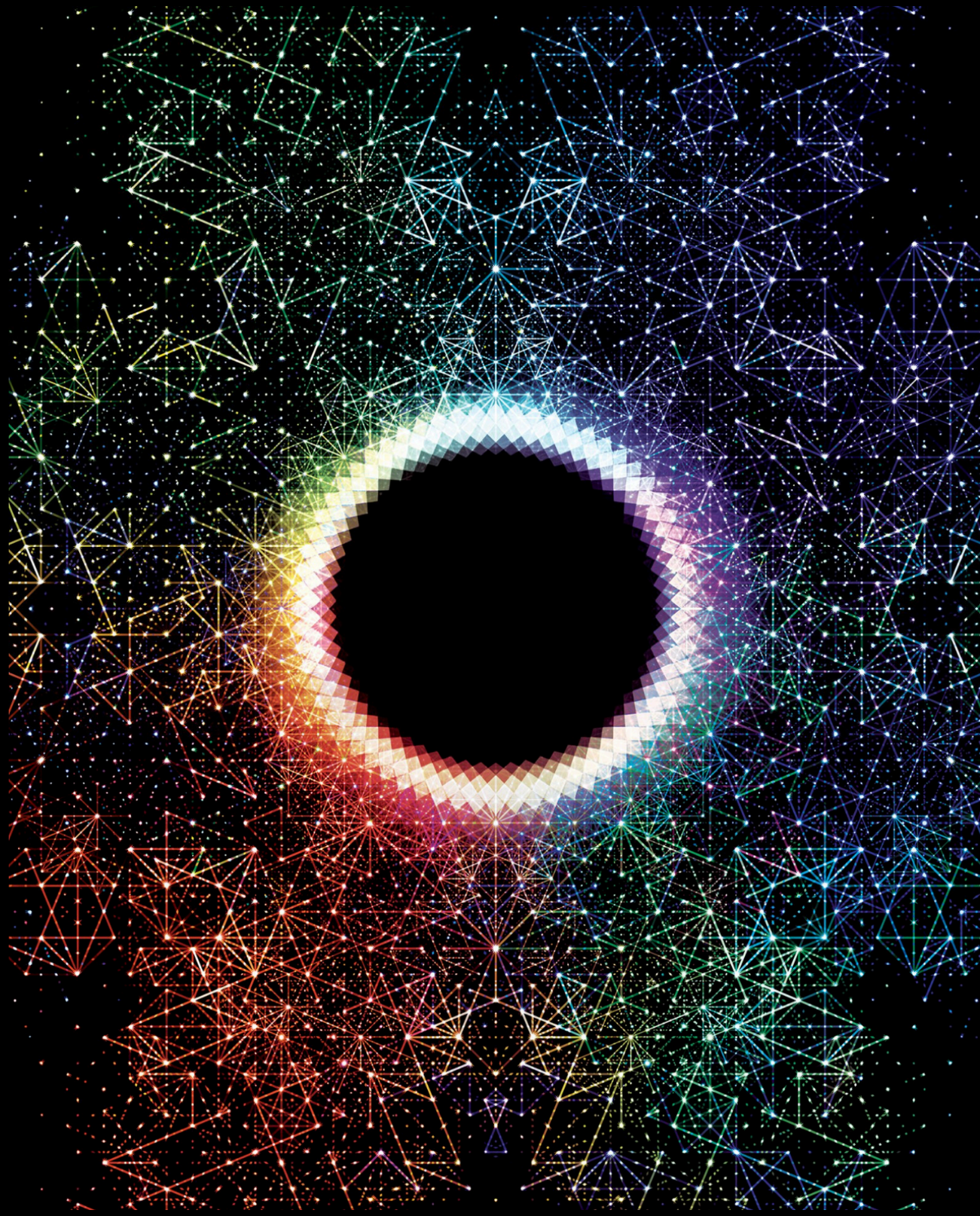
with Kyle Parfrey (Princeton),
Benoit Cerutti and Benjamin Crinquand
(CNRS)

The New York Times Magazine

Account

How Do You Take a Picture of a Black Hole? With a Telescope as Big as the Earth

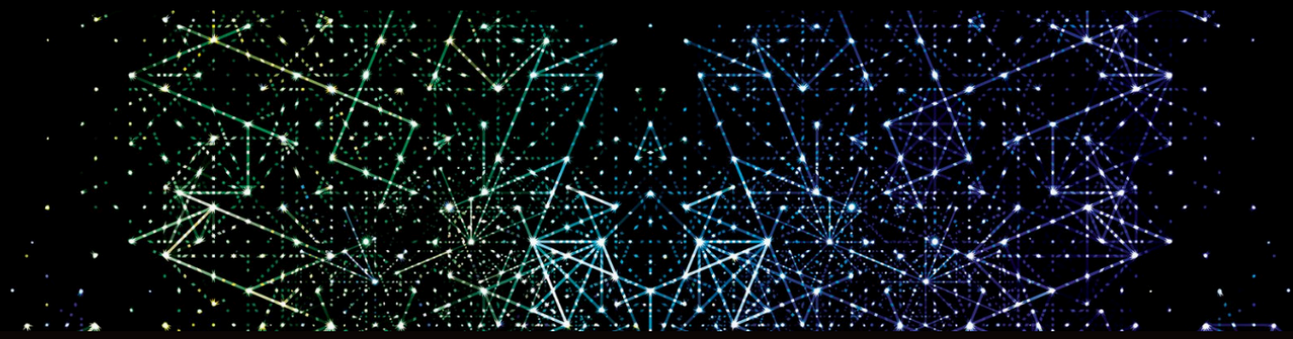
A planet-spanning virtual observatory, years in the making, could change how we think about space, time and the nature of reality. Will it work?



October 4, 2018

The New York Times Magazine

Account



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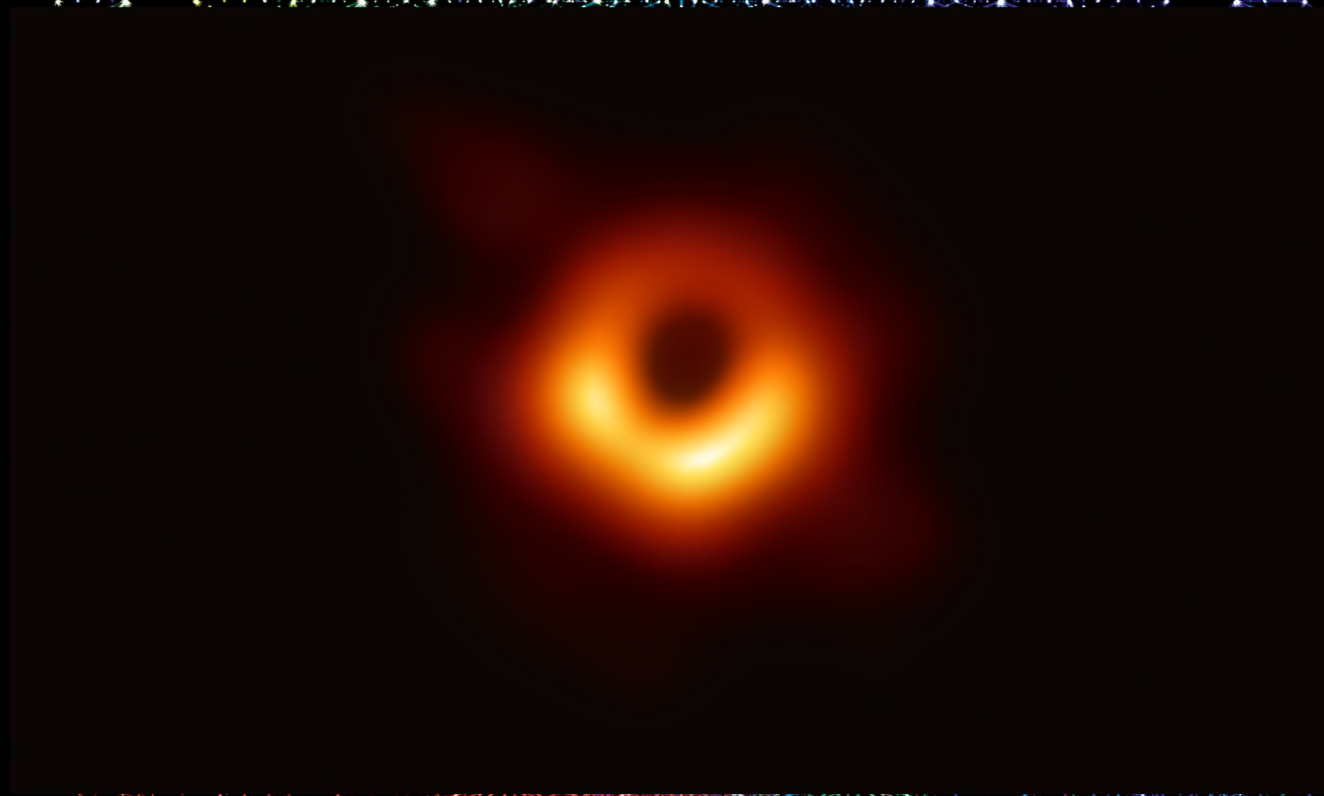
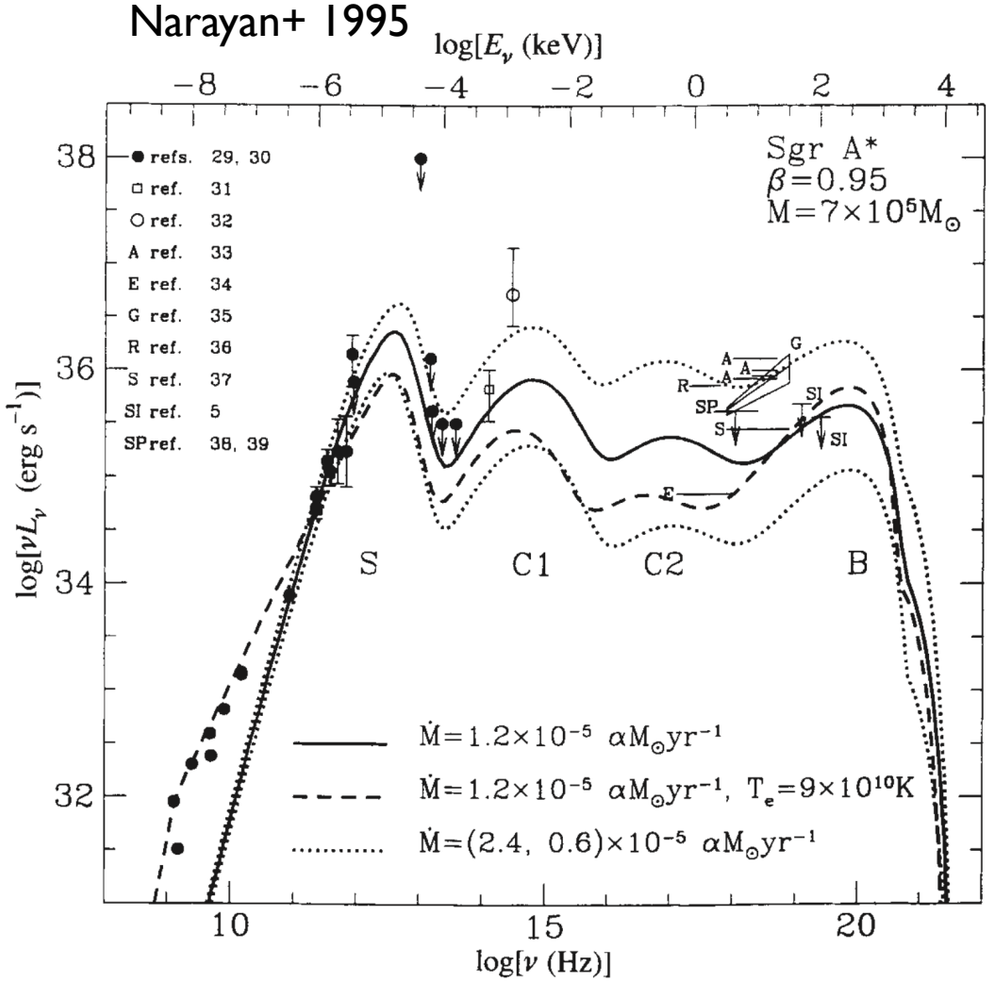


October 4, 2018

Some accretion flows expected to be *collisionless*

At low accretion rate, flow can have ***low-density*** structure where:

Narayan+ 1995



fit of low-density *ADAF* model to Sgr A*

1. Collision mean free path ≫ system scales ~ r_g
2. Collision timescales ≫ accretion timescale

↓

e^- & protons have different *T*,
and generally non-thermal distribution

Holds for

Sgr A* **M87**

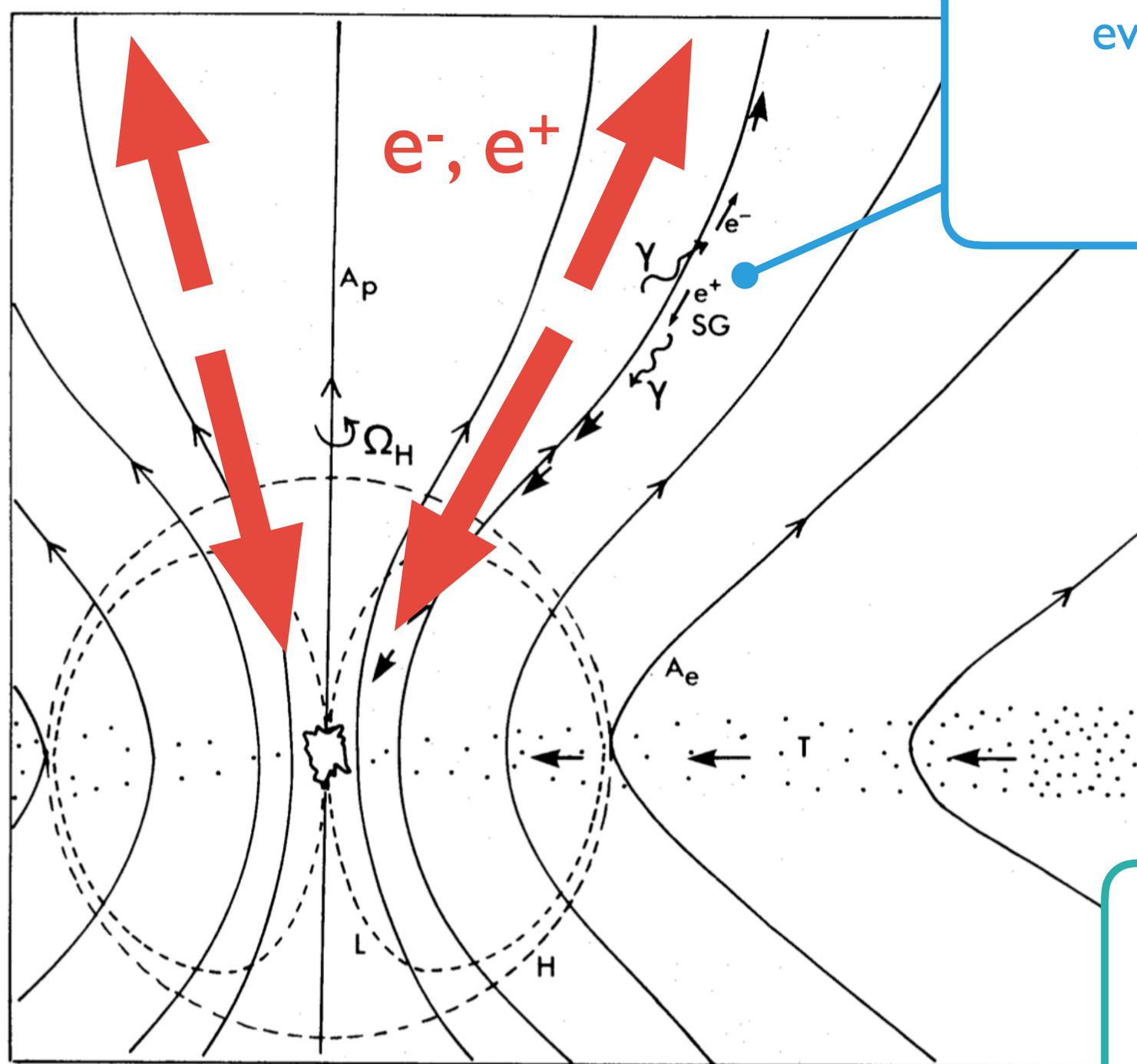
many active galaxies

disc coronae

jets

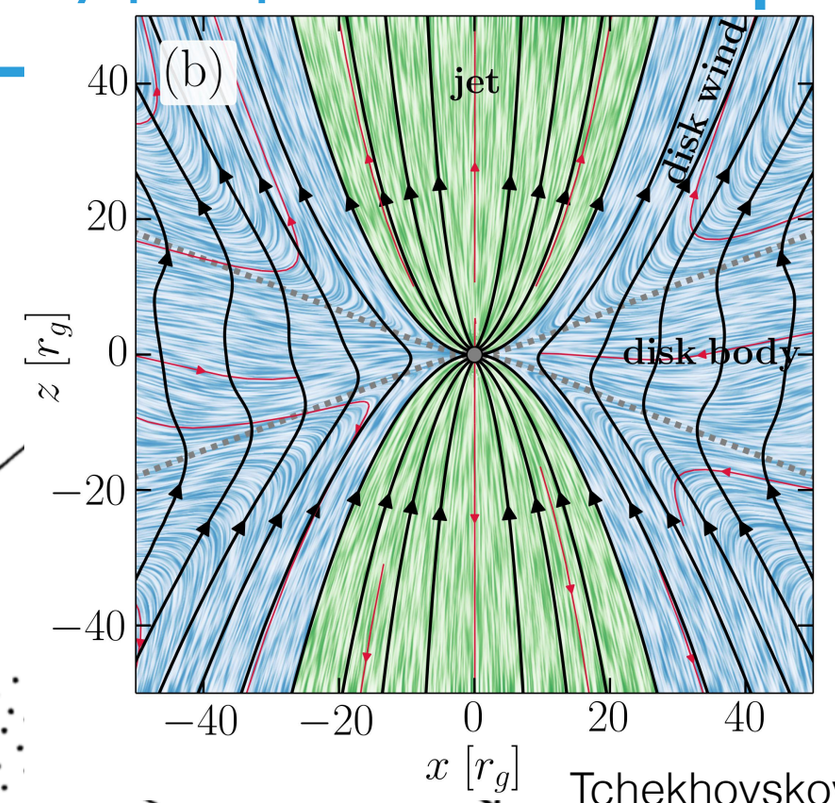
Standard MHD approximation not valid

Jet launching by rotating black holes



Blandford & Znajek 1977

evacuated vacuum "gap"
plasma supplied
by pair production



Tchekhovskoy 2015

MHD cannot predict

gap location
jet density
jet composition
etc.

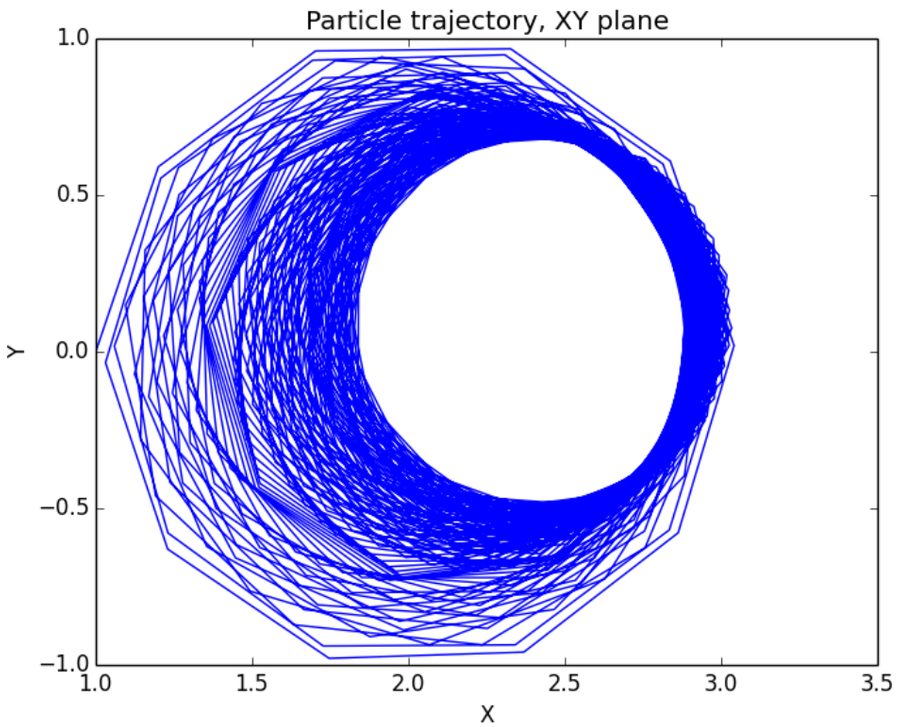
Equations of GRPIC in 3+1

$$\nabla \cdot \boldsymbol{E} = 4\pi\rho,$$
$$\nabla \cdot \boldsymbol{B} = 0,$$
$$\nabla \times \left(\alpha \boldsymbol{E} + \frac{\boldsymbol{\beta}}{c} \times \boldsymbol{B}\right) = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t},$$
$$\nabla \times \left(\alpha \boldsymbol{B} - \frac{\boldsymbol{\beta}}{c} \times \boldsymbol{E}\right) = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} + \alpha \boldsymbol{j} - \rho\boldsymbol{\beta}.$$

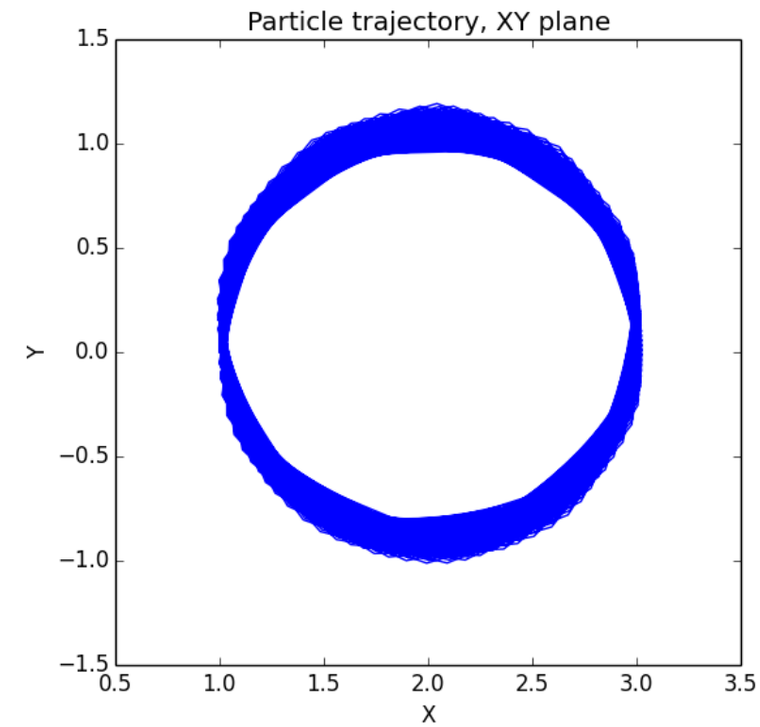
$$\frac{\mathrm{d}x^i}{\mathrm{dt}} = \frac{\alpha}{m\Gamma}p^i - \beta^i$$

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

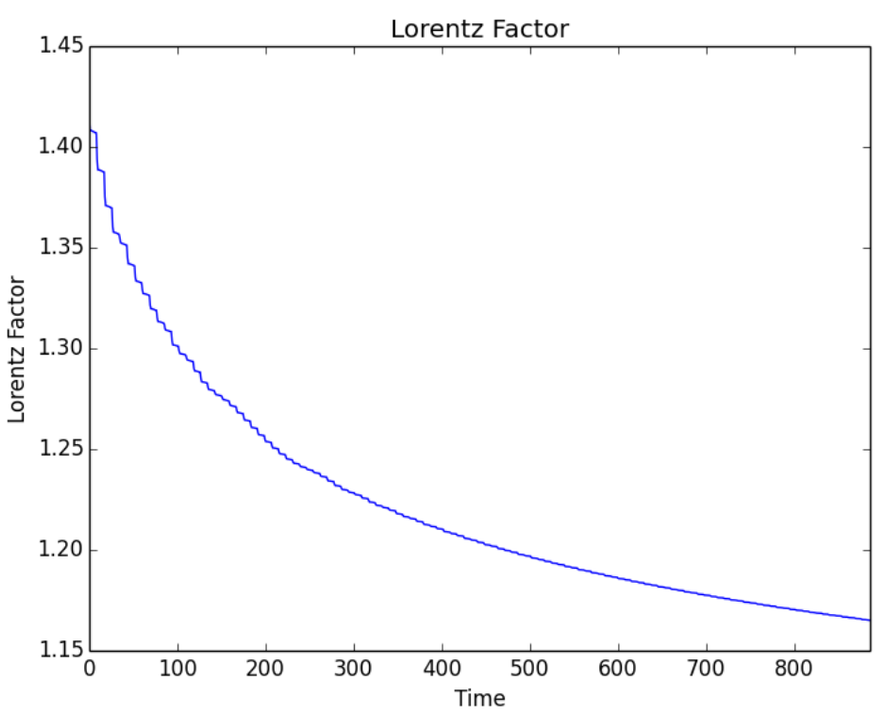
Uniform *B* test



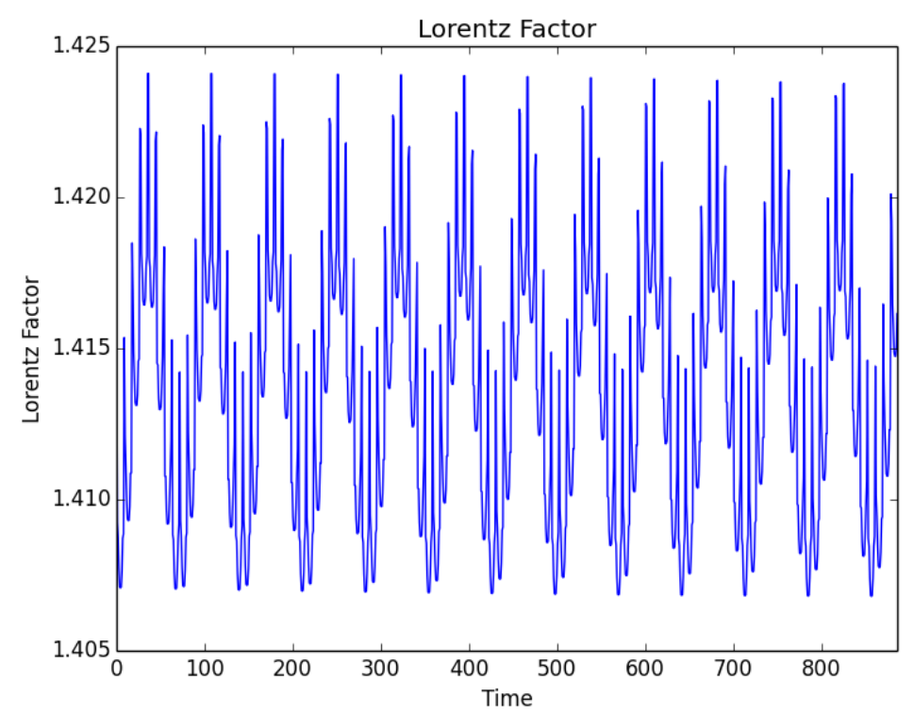
trajectory



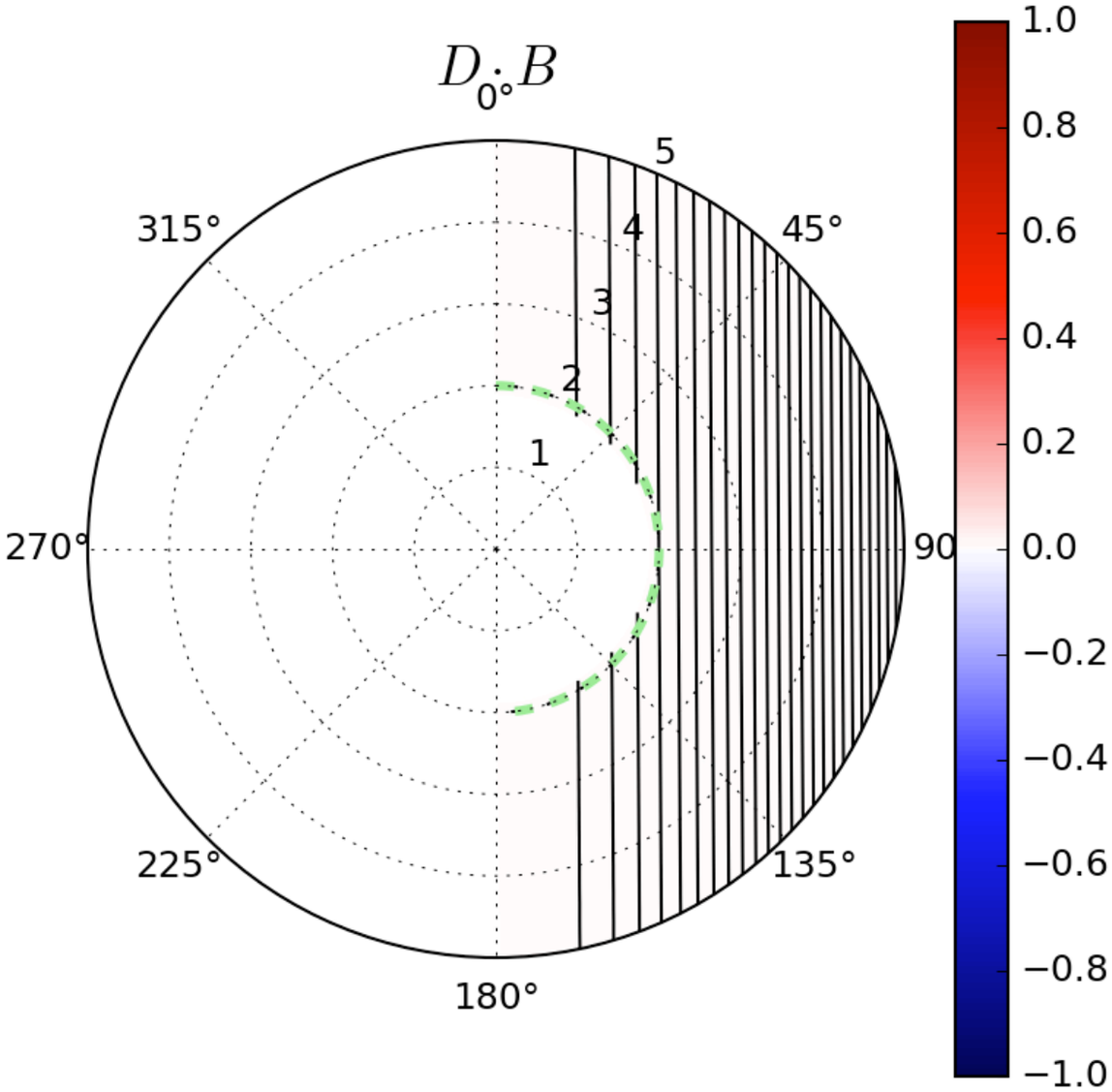
3rd order Runge-Kutta ← integrator for geodesic + move substep → 2nd order implicit midpoint



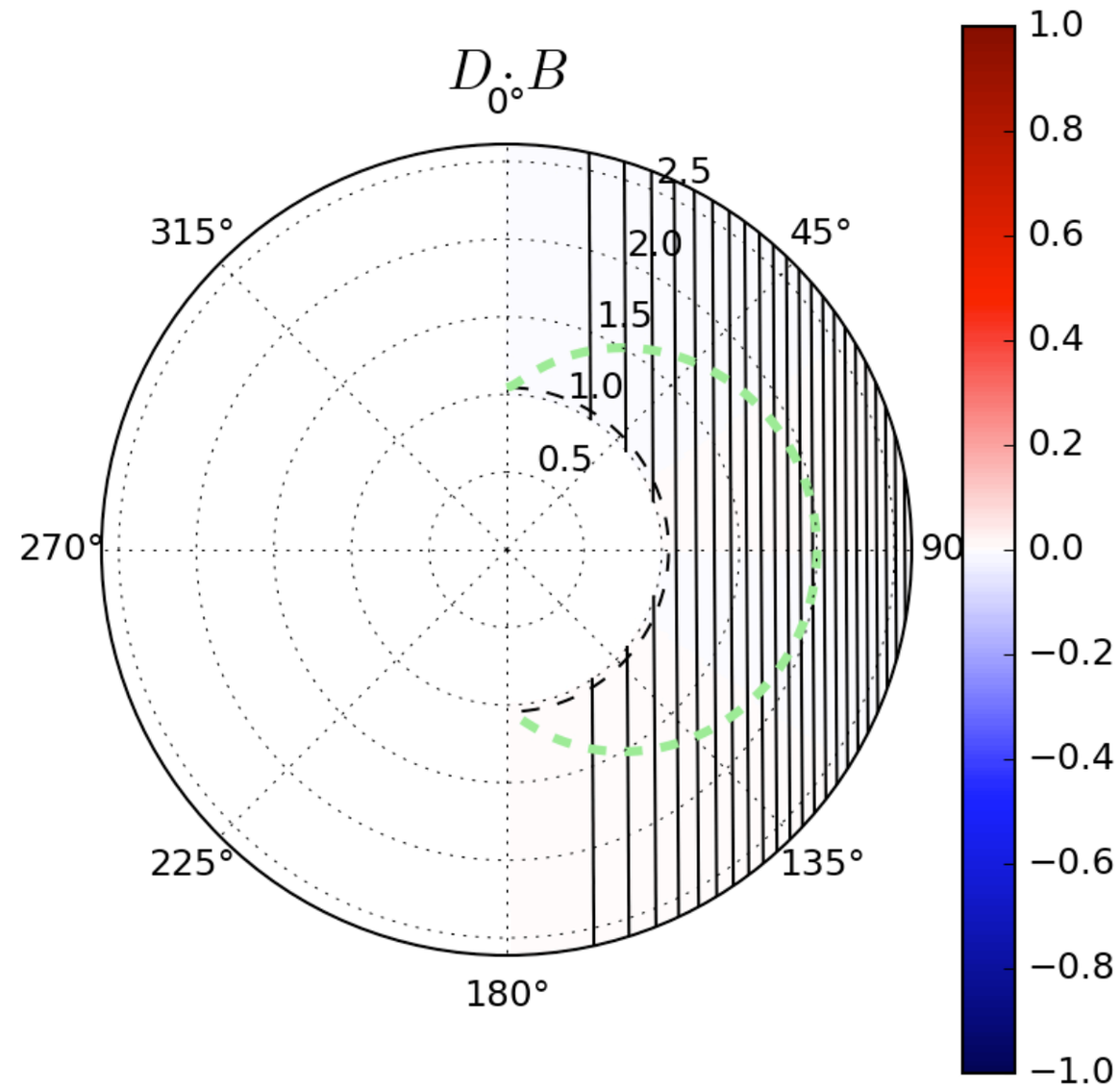
Lorentz factor



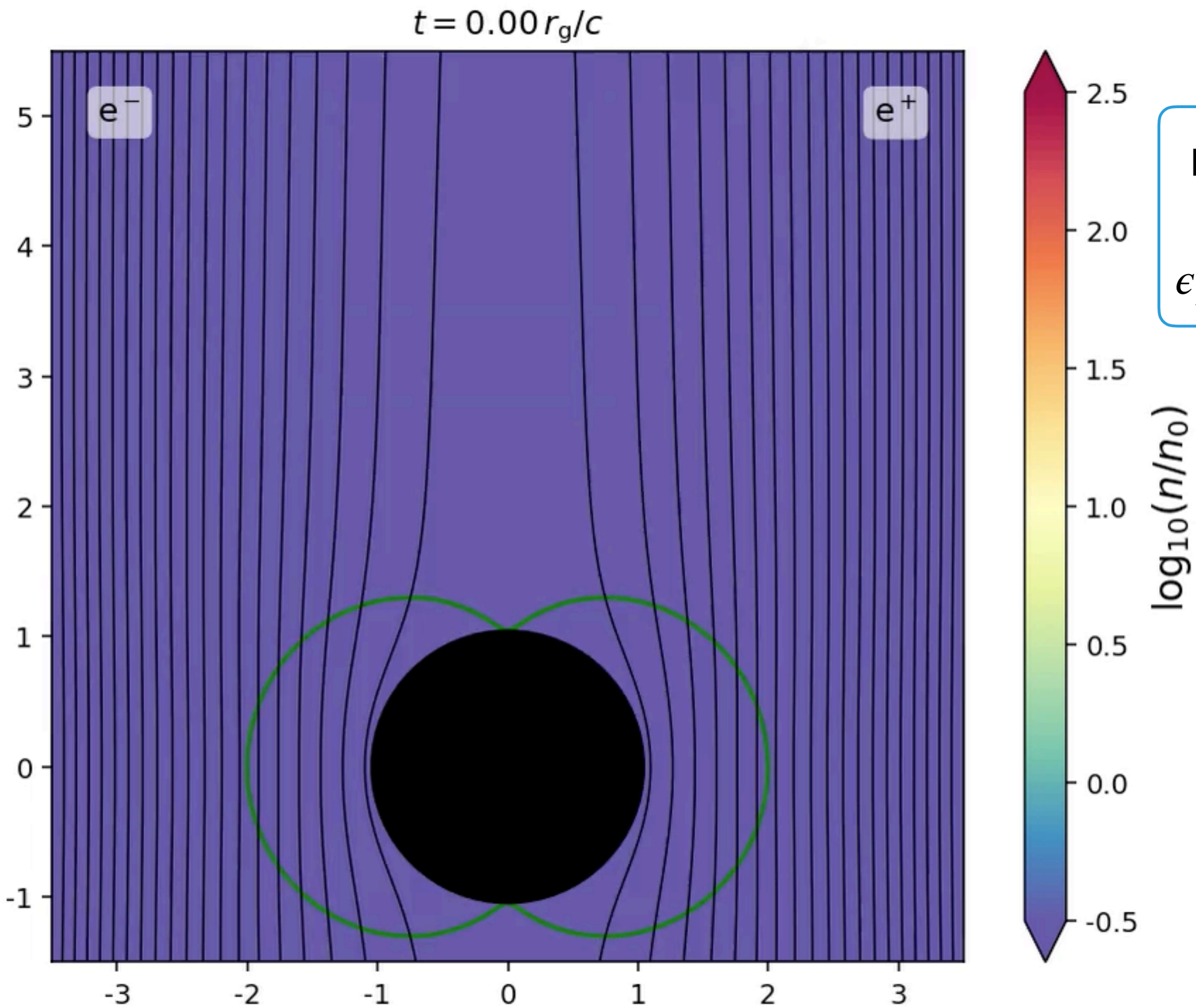
Tests of field solver



Schwarzschild



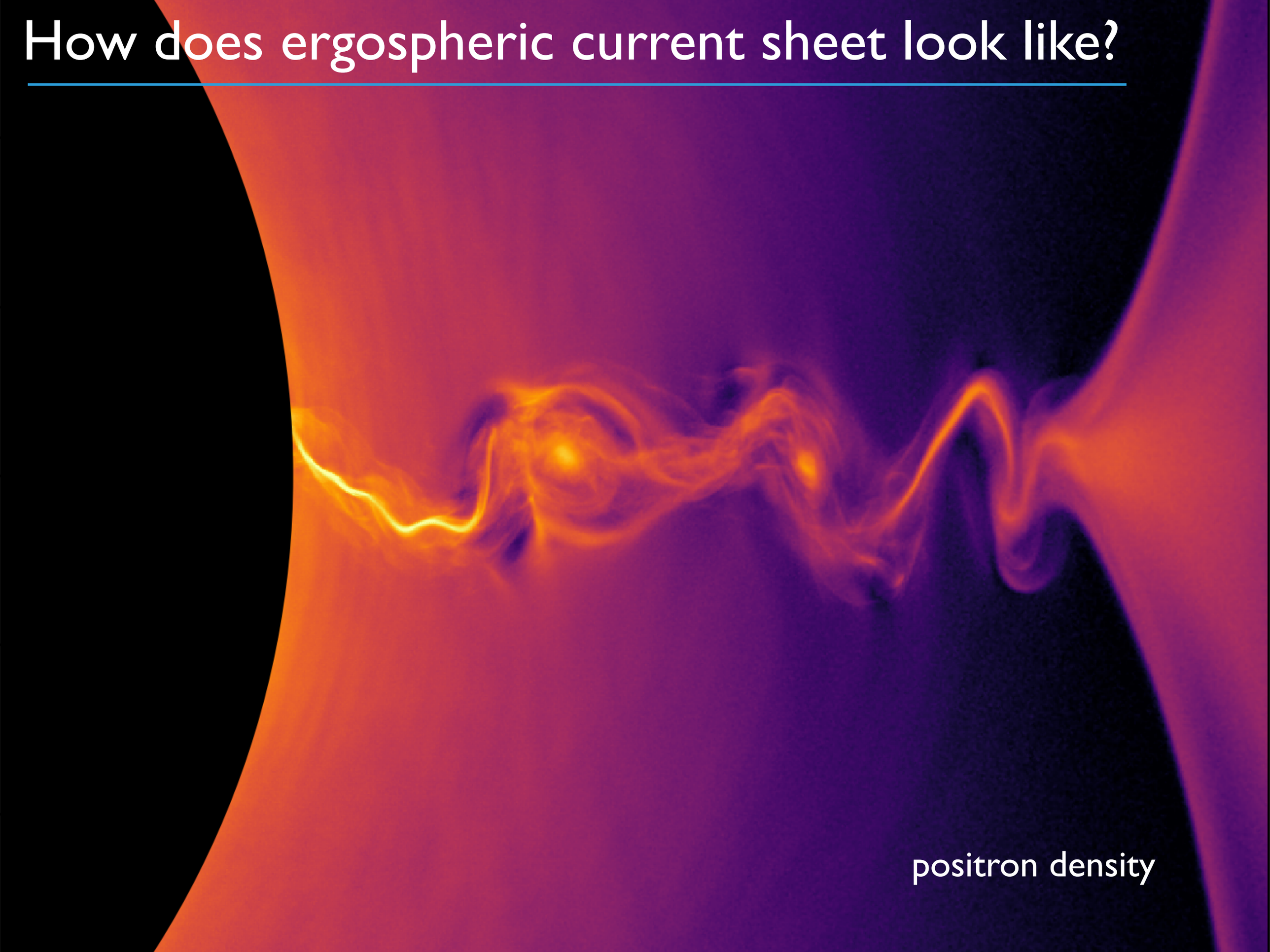
Kerr black hole

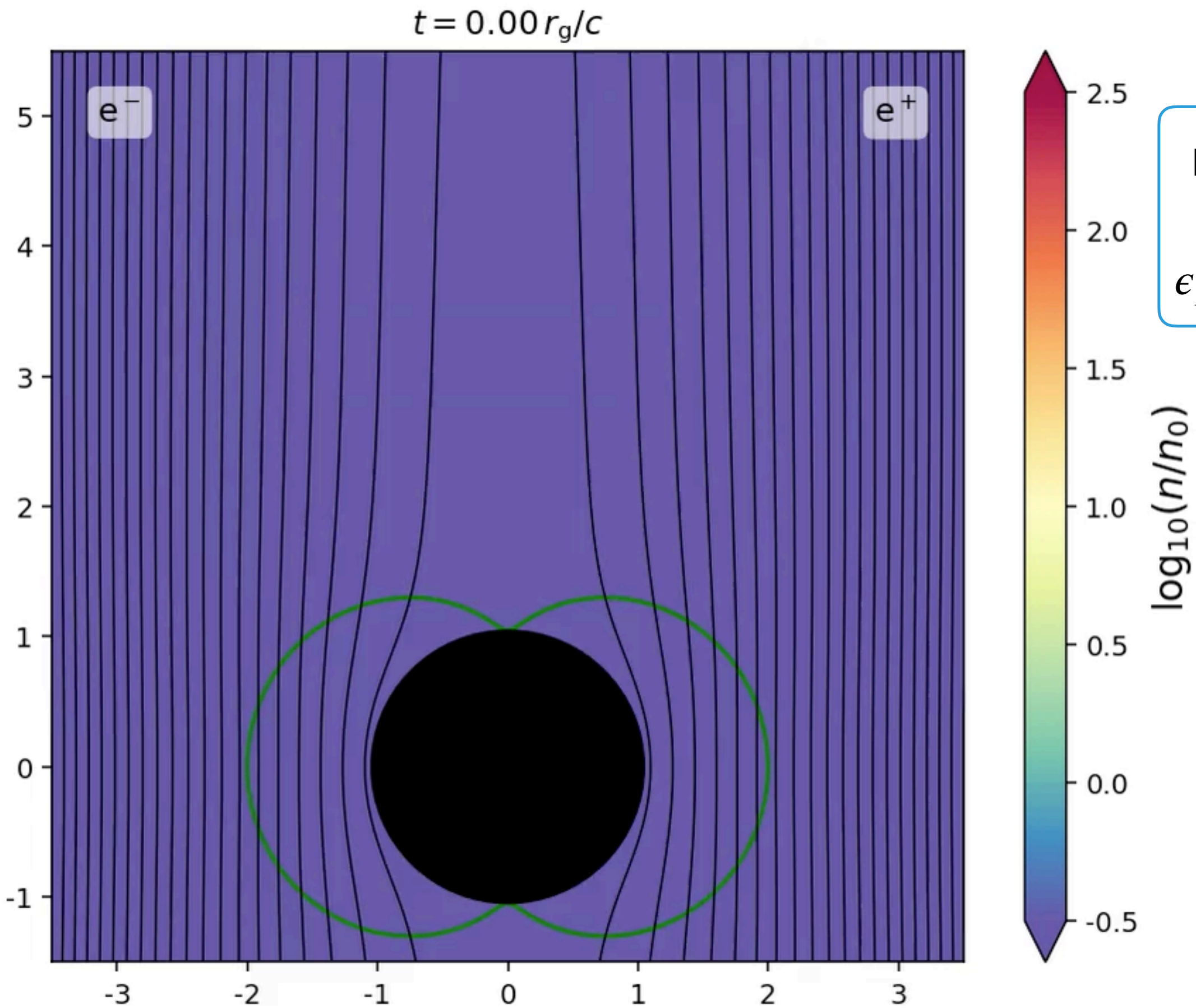


High Plasma Supply

$\epsilon_{D \cdot B} = 10^{-3}$

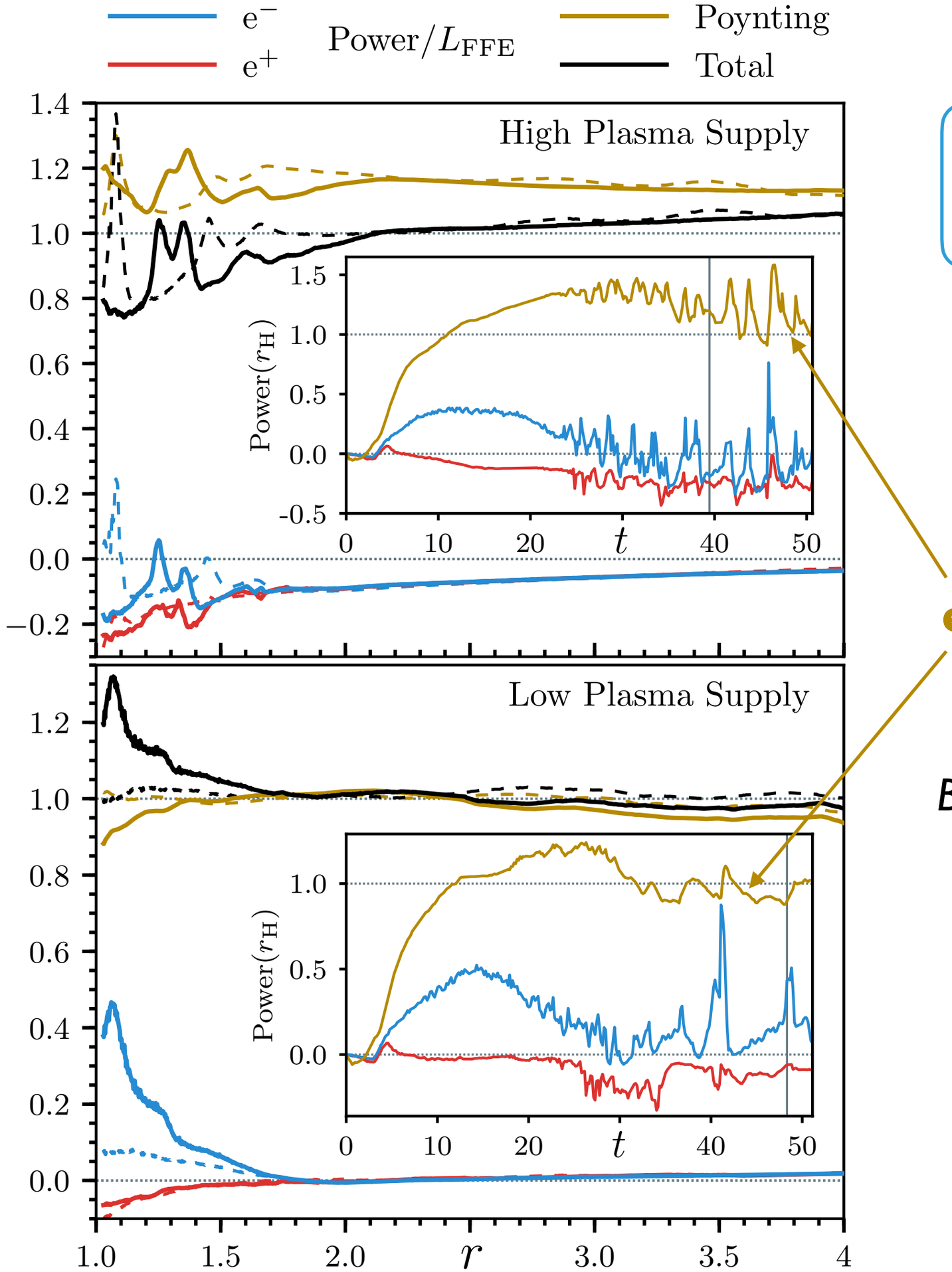
How does ergospheric current sheet look like?





Low Plasma Supply

$\epsilon_{D \cdot B} = 10^{-2}$



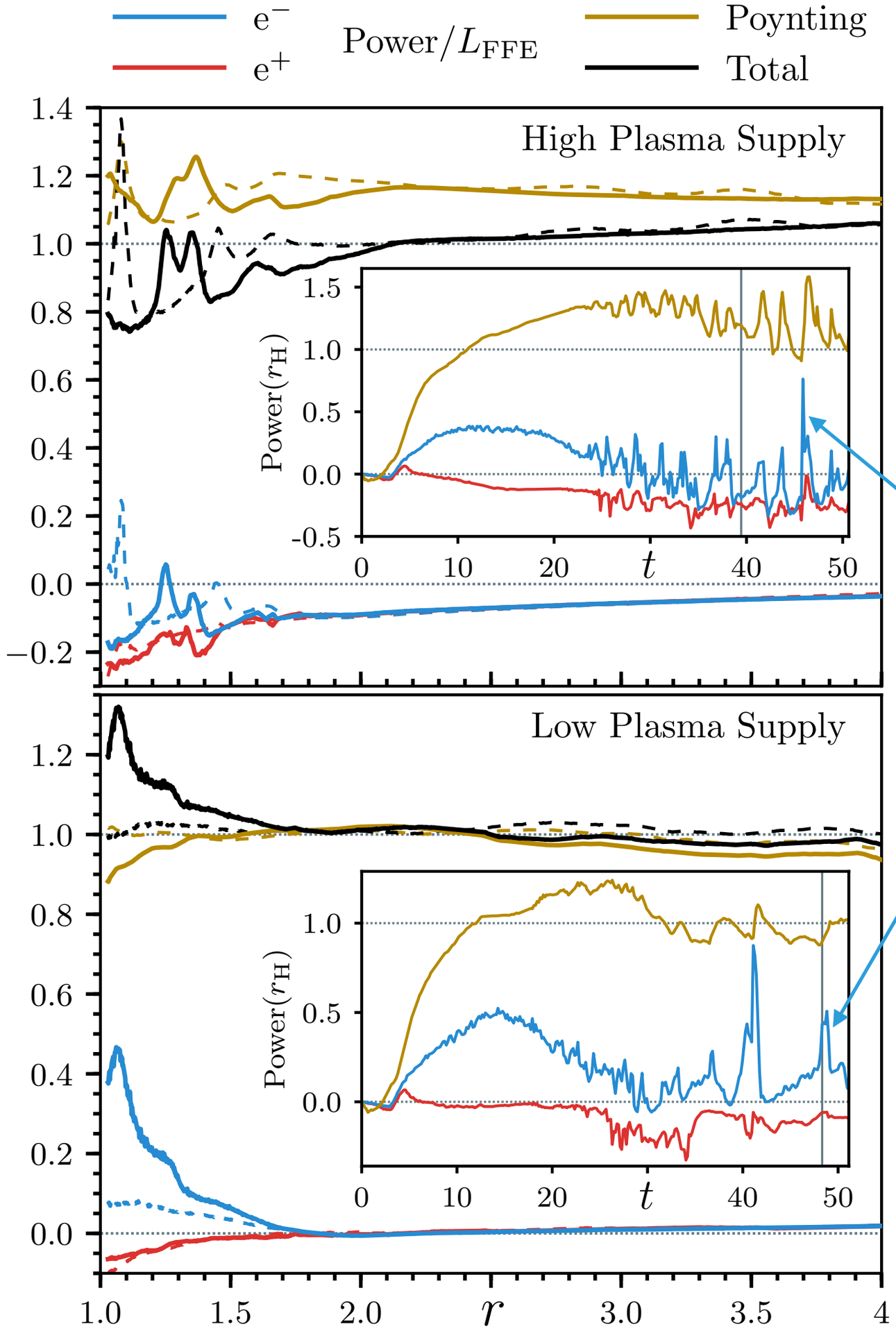
Fluxes of energy at infinity

flux > 0 : energy moving outward

electromagnetic extraction of black hole energy

Blandford-Znajek (1977) mechanism for relativistic jets

Parfrey, Philippov, Cerutti 2019



Fluxes of energy at infinity

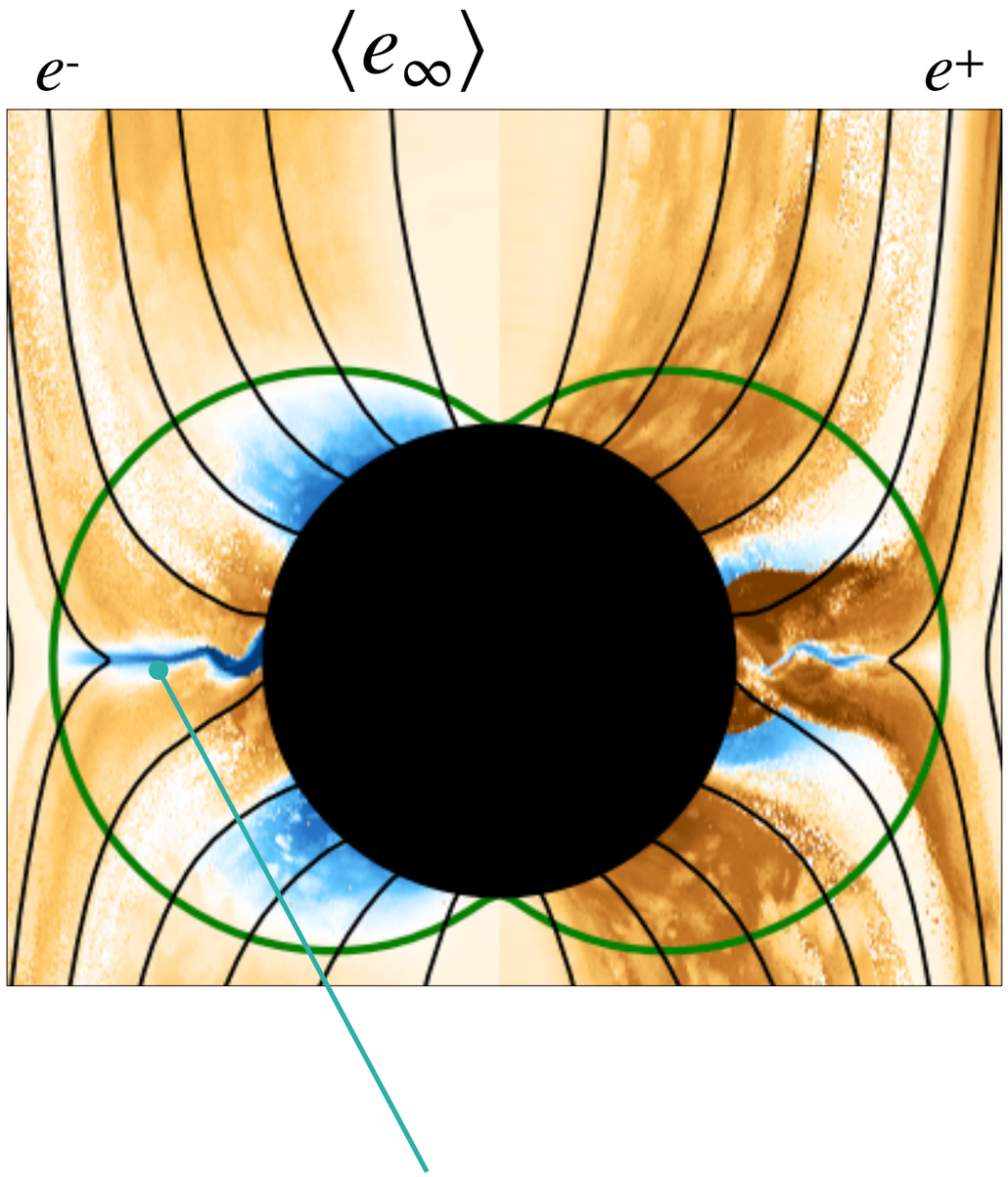
flux > 0 : energy moving outward

extraction of black hole energy by **particles**

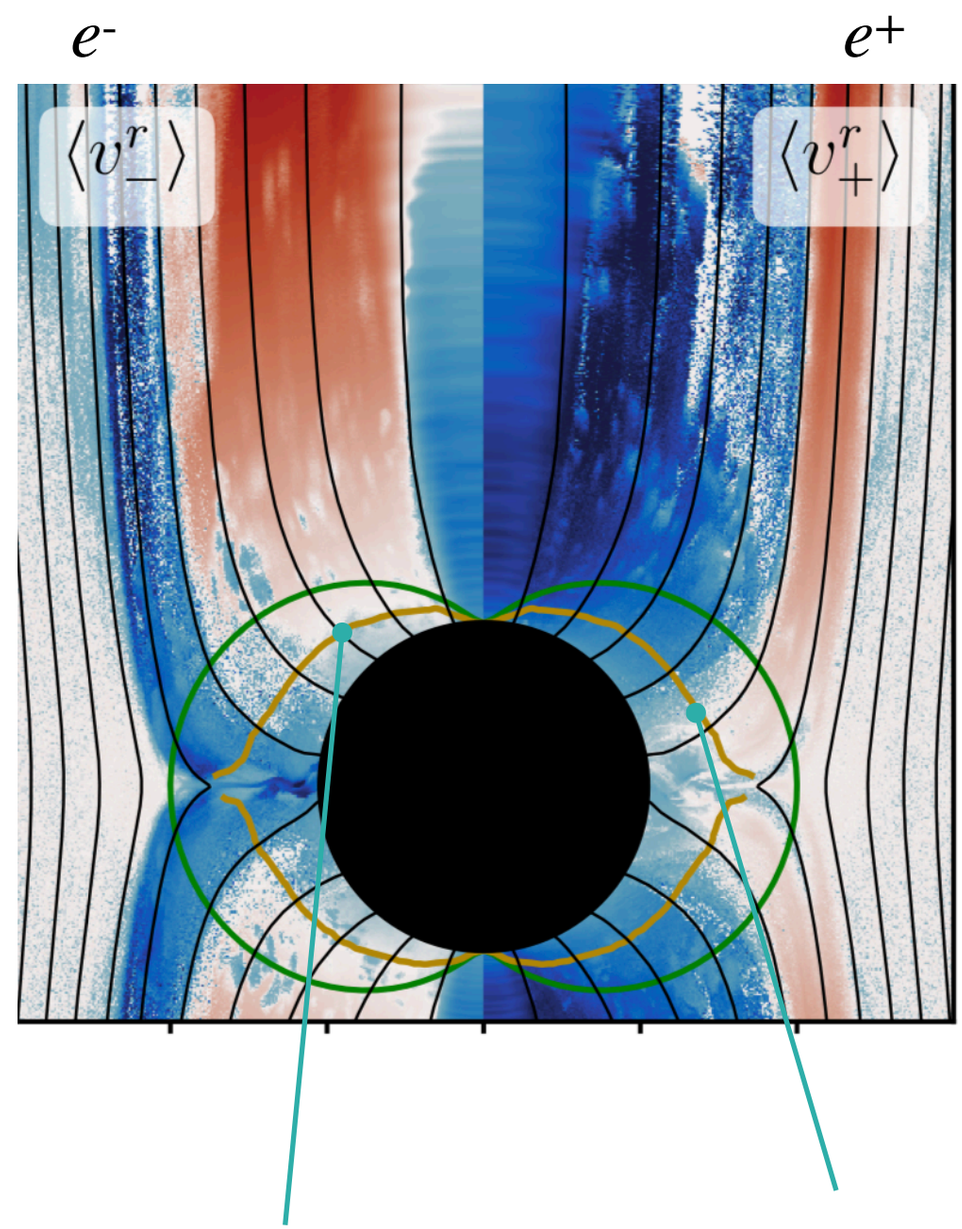
variant of *Penrose (1969) process*

Parfrey, Philippov, Cerutti 2019

Plasma dynamics in the ergosphere



Most "Penrose power" from **current sheet**



Inner light surface separates inflow and outflow for both charge species

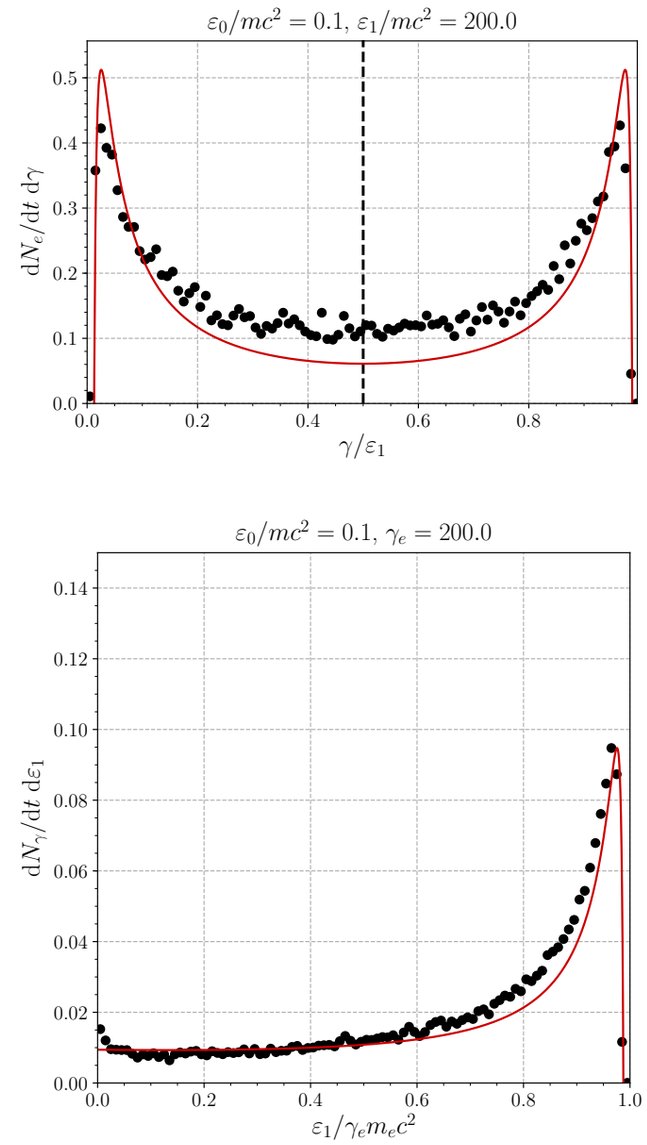
Radiative transfer module

Two radiative processes: IC scattering and $\gamma\gamma$ pair production

- Particles bathed in a soft radiation field (uniform, isotropic, mono-energetic at ε_0)
- High-energy γ photons added as a 3rd species
- γ photons can **pair produce** against soft photons, $e^{\pm}$ can produce γ photons by **scattering** off soft photons
- Uses the complete differential cross sections to determine post-interaction energies
- **Monte-Carlo** algorithm: an interaction occurs if

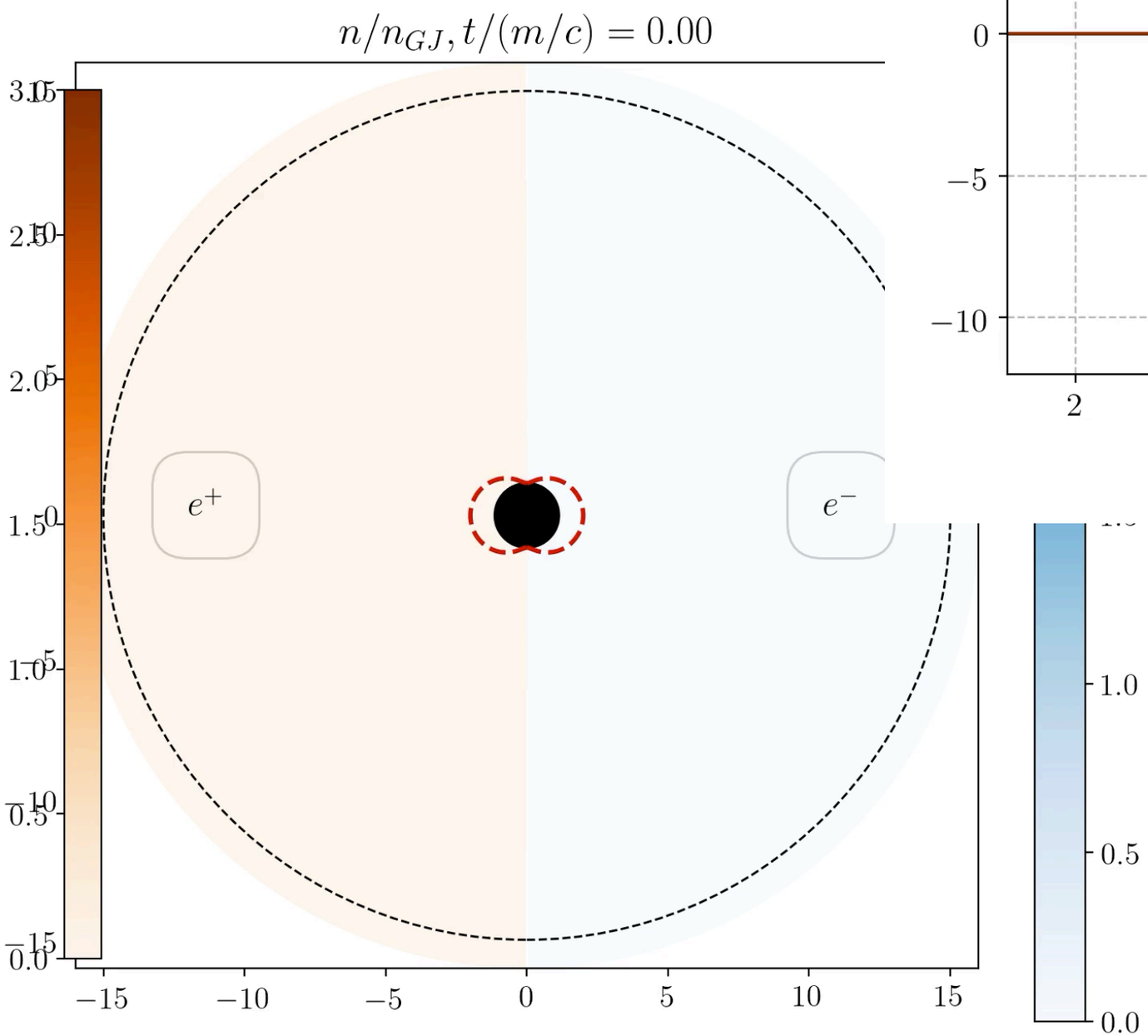
$$p < 1 - e^{-\delta\tau}$$

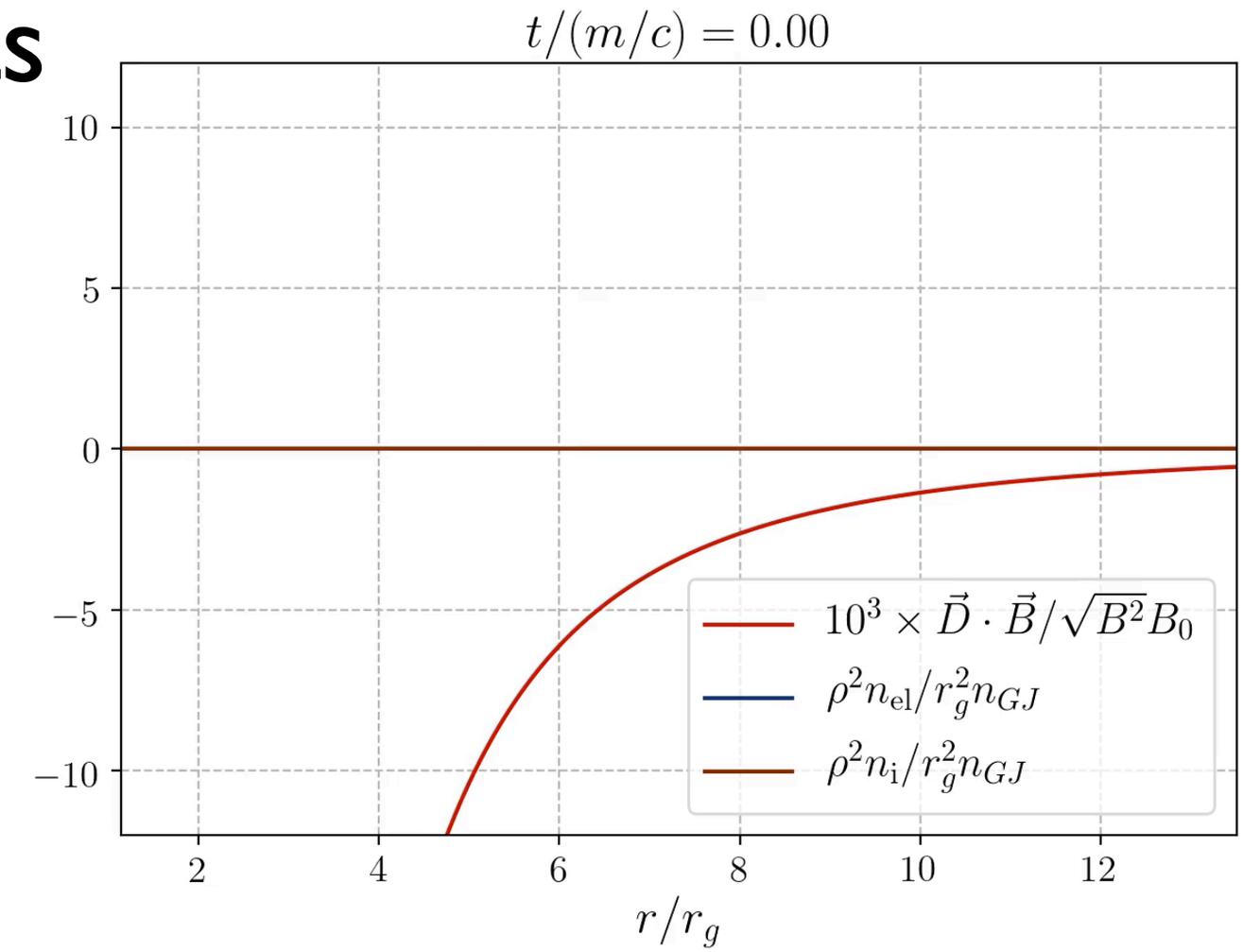
where $p \in [0, 1]$ is a random number and $\delta\tau$ is the optical depth traversed by a particle between two time steps



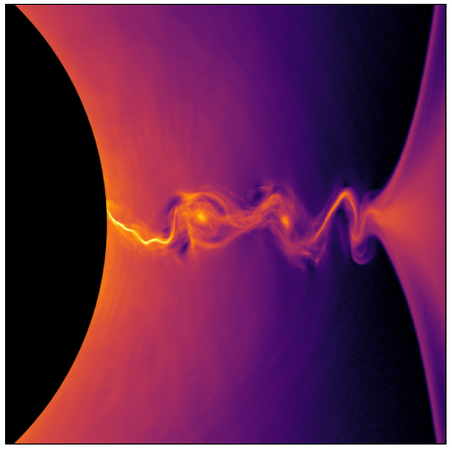
Analytical and simulated spectra from the radiative transfer module

Pair production results





Crinquand et. al., in prep.



Black hole Summary

– First multidimensional collisionless plasma simulations in full GR

– Poynting-flux-dominated jet launching from first principles

– Negative-energy "Penrose" particles in both *jet* and *current sheet*

Future directions

– Add realistic pair-creation physics: where do vacuum gaps form?

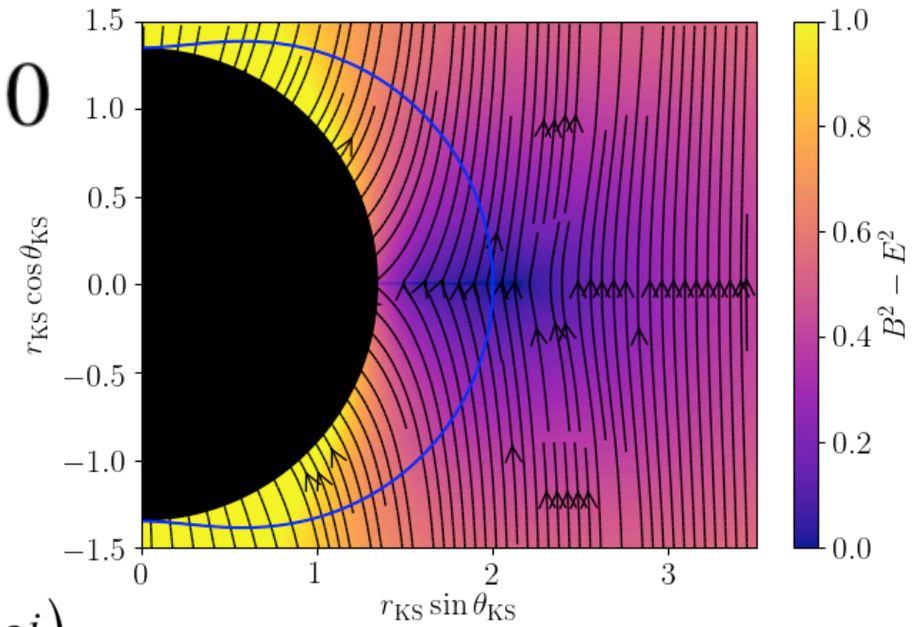
Complete simulation of a collisionless accretion flow

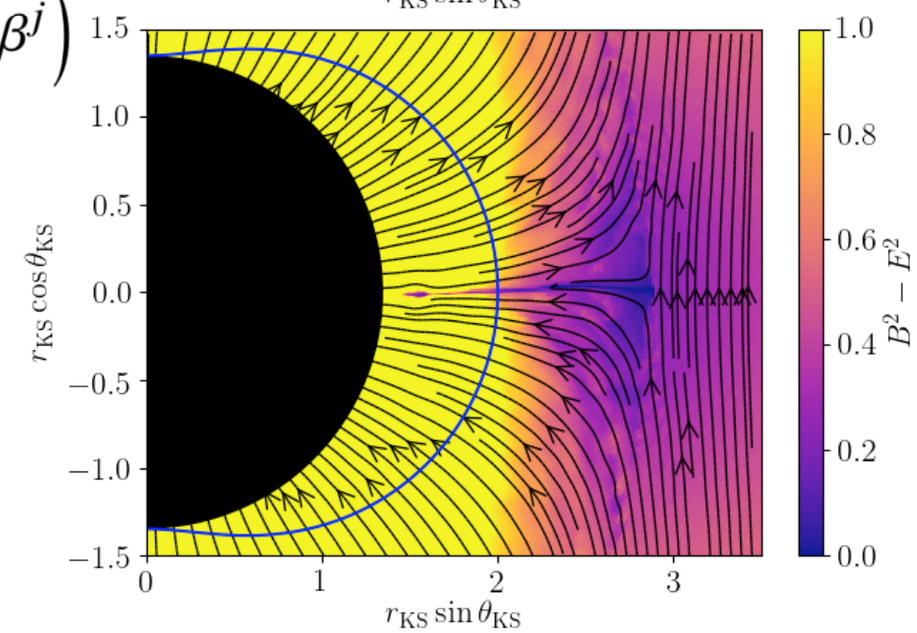
Coupling Force-Free to resistive MHD

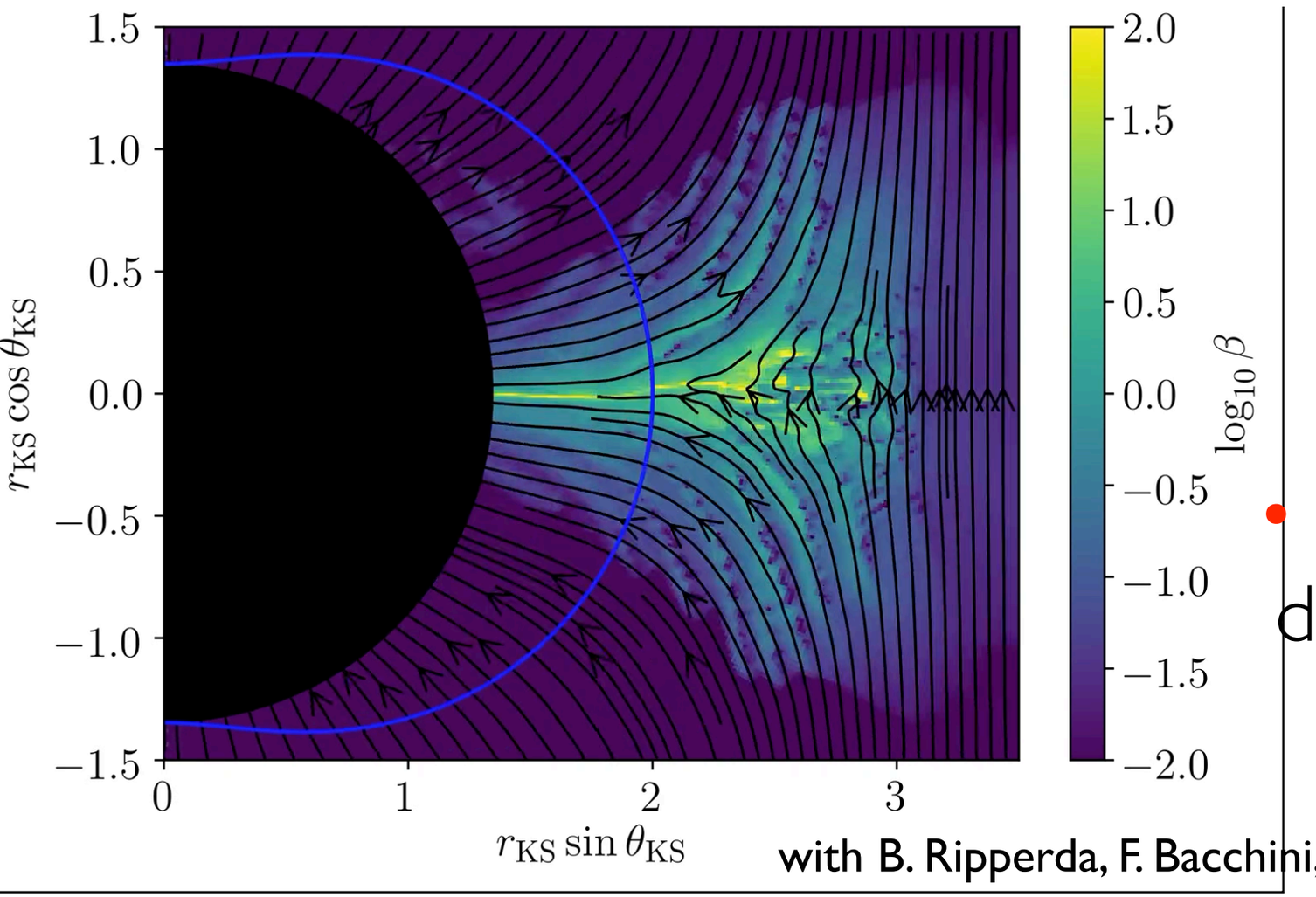
- MHD breaks if magnetization $\sigma \to \infty; \beta \to 0$
- FF breaks in sheets: $\mathbf{E} \cdot \mathbf{B} \neq 0; B^2 - E^2 \lesssim 0$
- Evolve both $\mathbf{E}$ and $\mathbf{B}$ (for MHD and FF):

$$\partial_t \left(\gamma^{1/2} B^j\right) + \partial_i \left[\gamma^{1/2} \left(\beta^j B^i - \beta^i B^j + \gamma^{-1/2} \eta^{ijk} \alpha E_k\right)\right] = 0$$

$$\partial_t \left(\gamma^{1/2} E^j\right) + \partial_i \left[\gamma^{1/2} \left(\beta^j E^i - \beta^i E^j - \gamma^{-1/2} \eta^{ijk} \alpha B_k\right)\right] = -\gamma^{1/2} \left(\alpha J^j - q\beta^j\right)$$







- Coupling purely via current density: $J^i = (1 - v_A^2) J^i_{MHD} + v_A^2 J^i_{FF}$

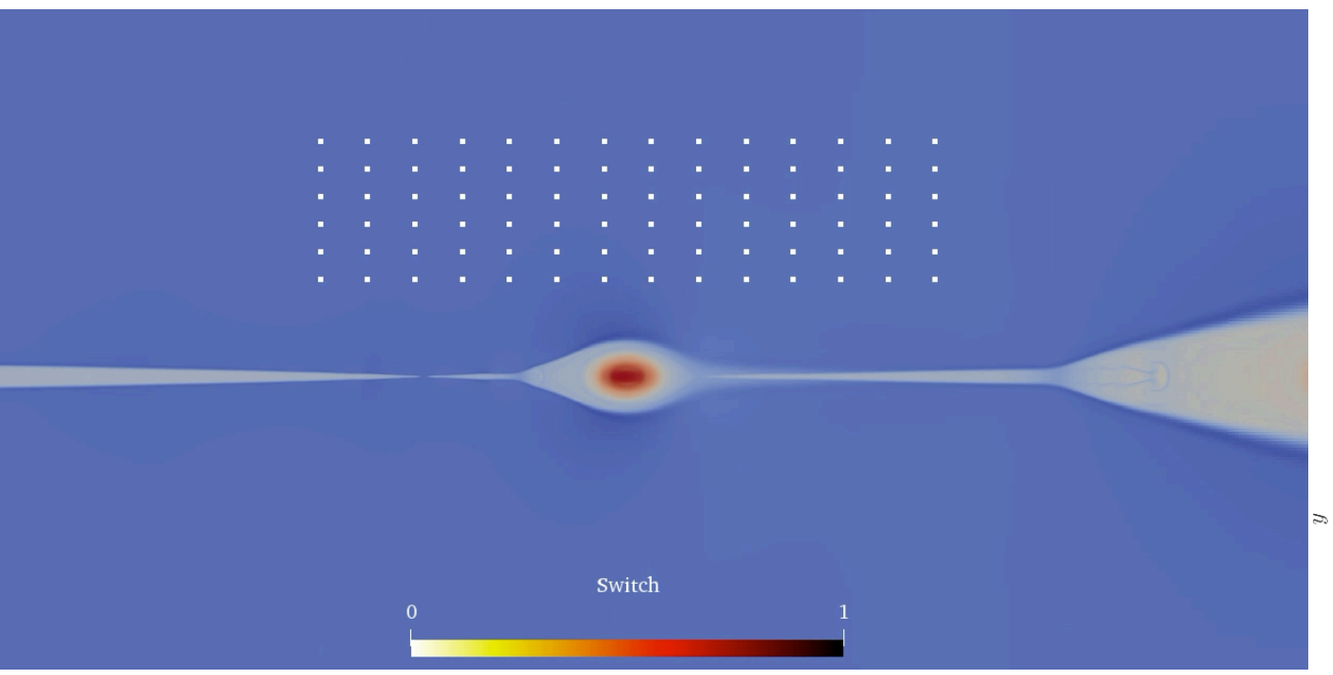
$$v_A^2 = \frac{\sigma}{\sigma + 1} c^2$$

with B. Ripperda, F. Bacchini, E. Most

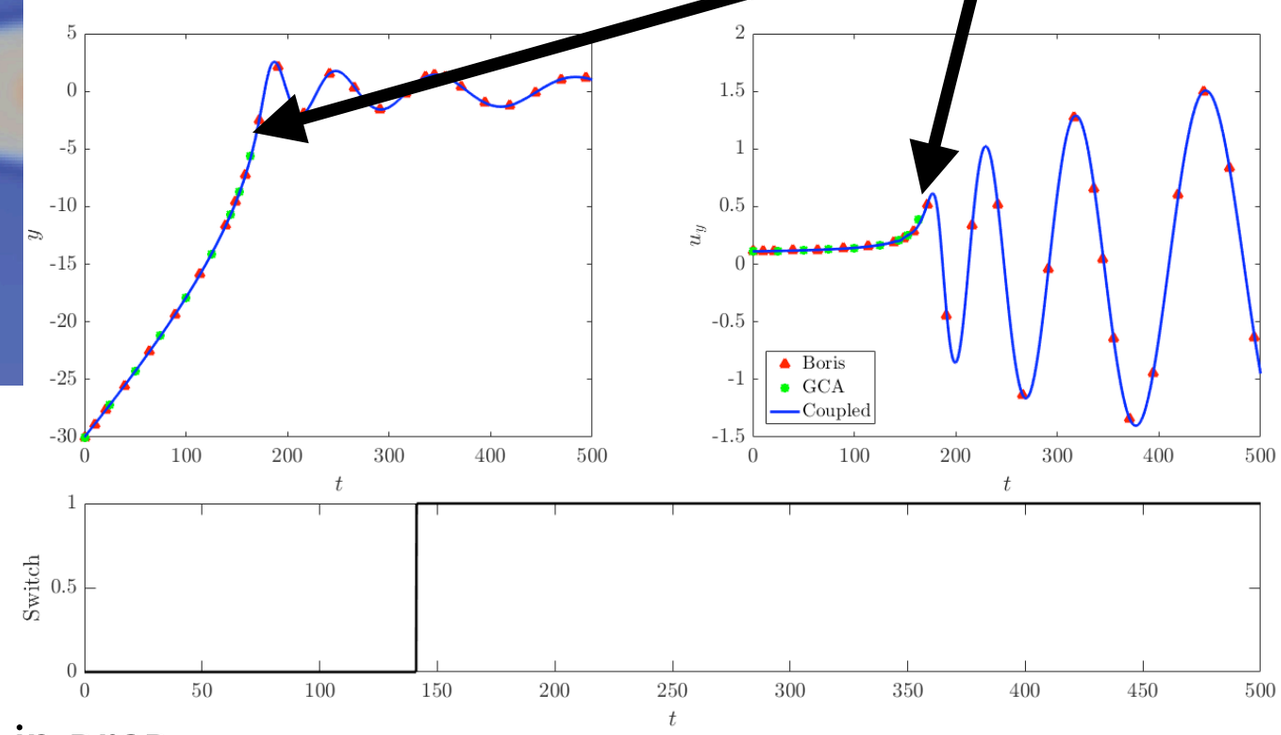
Coupling guiding center to gyrating motion

- Resolving gyroradius $r_L = \frac{\gamma m v_\perp}{|q|B}$ is hard in magnetized plasma
- Guiding center motion is sufficient in the ambient, but breaks in current sheets where $B^2 - E^2 \lesssim 0$ or $\mathbf{B} = 0$

→ Only resolve gyration in interesting regions where $r_L >$ cell size or $B^2 - E^2 \lesssim 0$, else do GCA

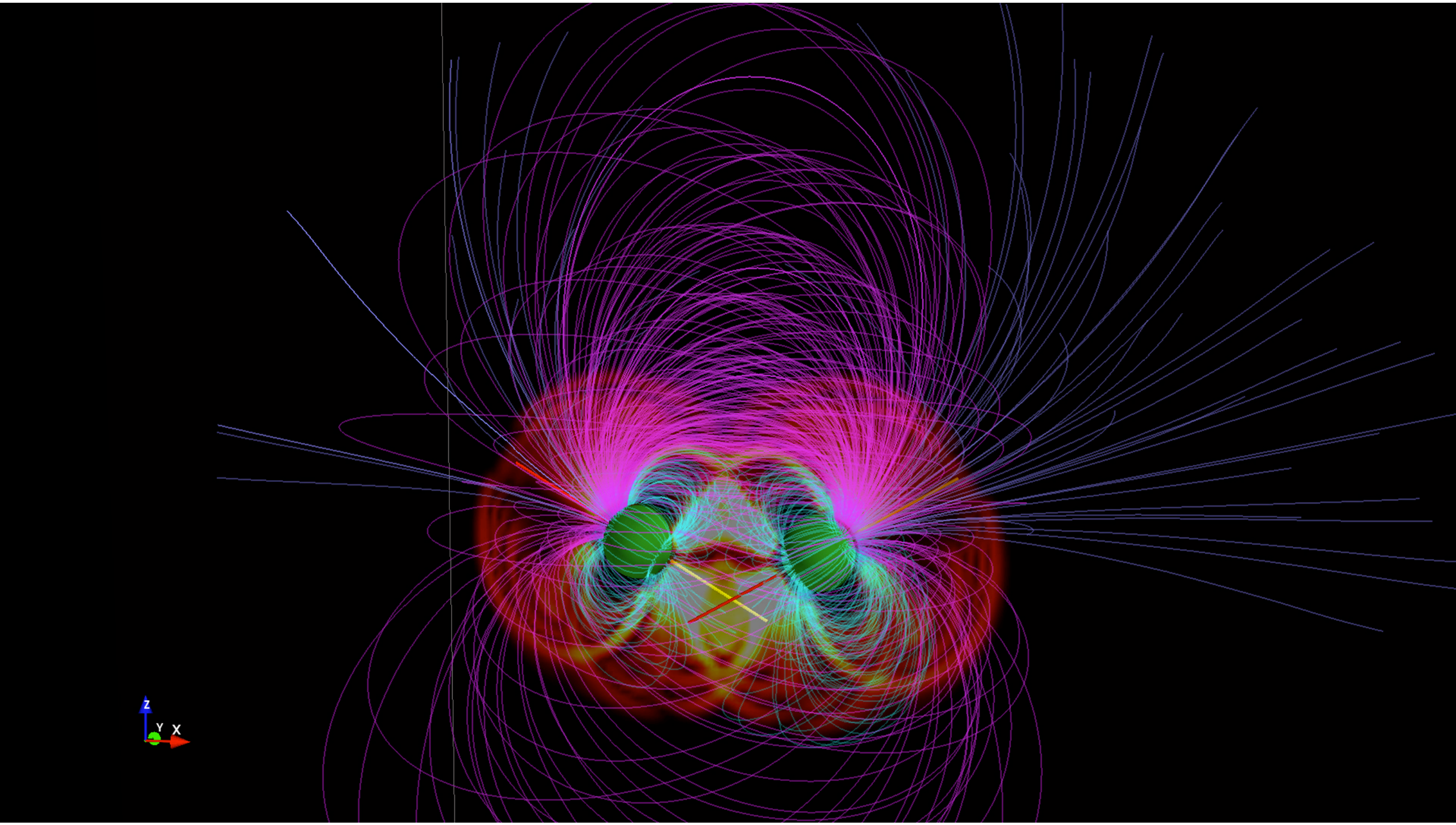


GCA breaks



This works both for test particles in MHD backgrounds as for full kinetic simulations!

Bacchini et. al., in prep.


Z
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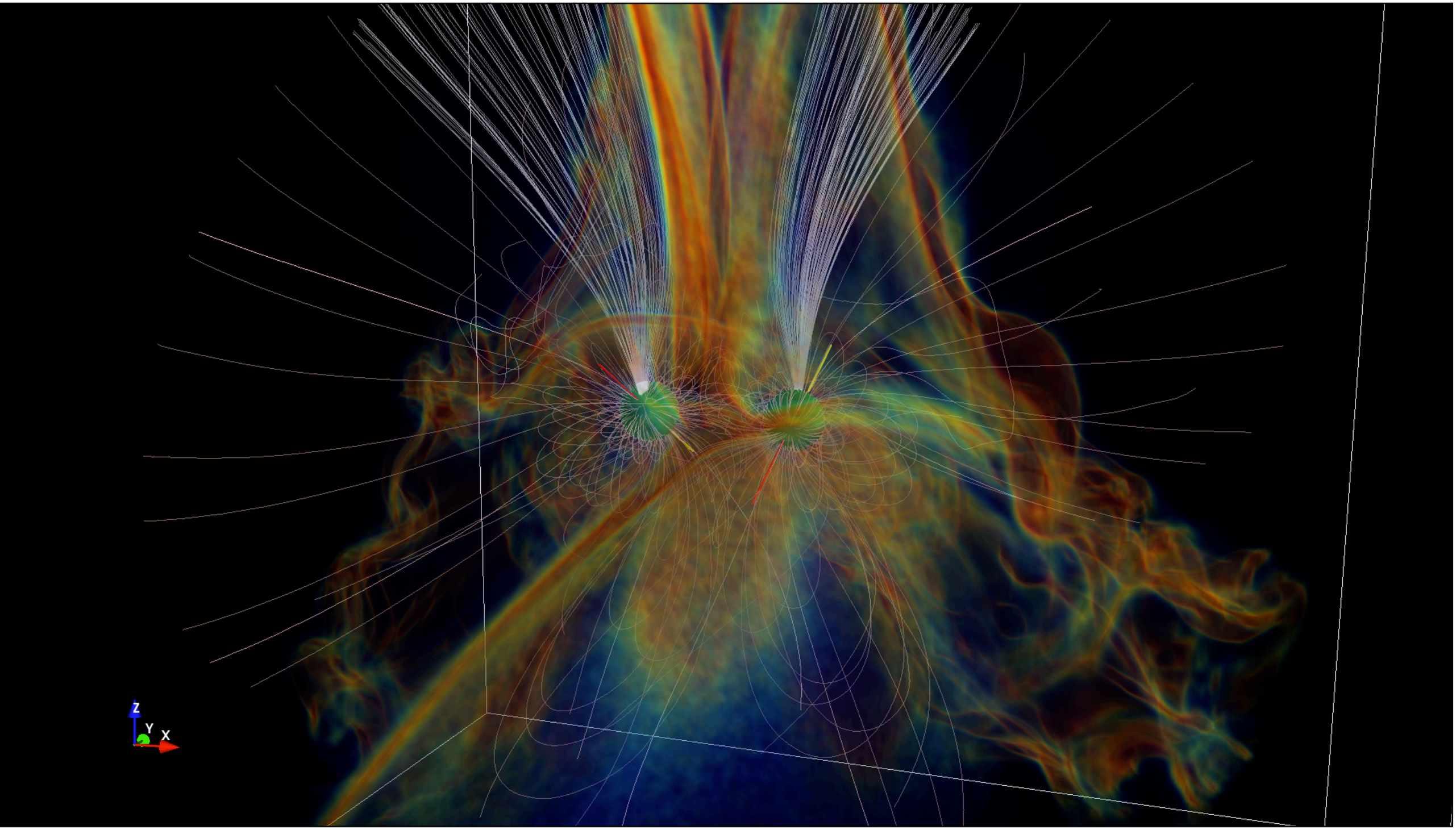
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