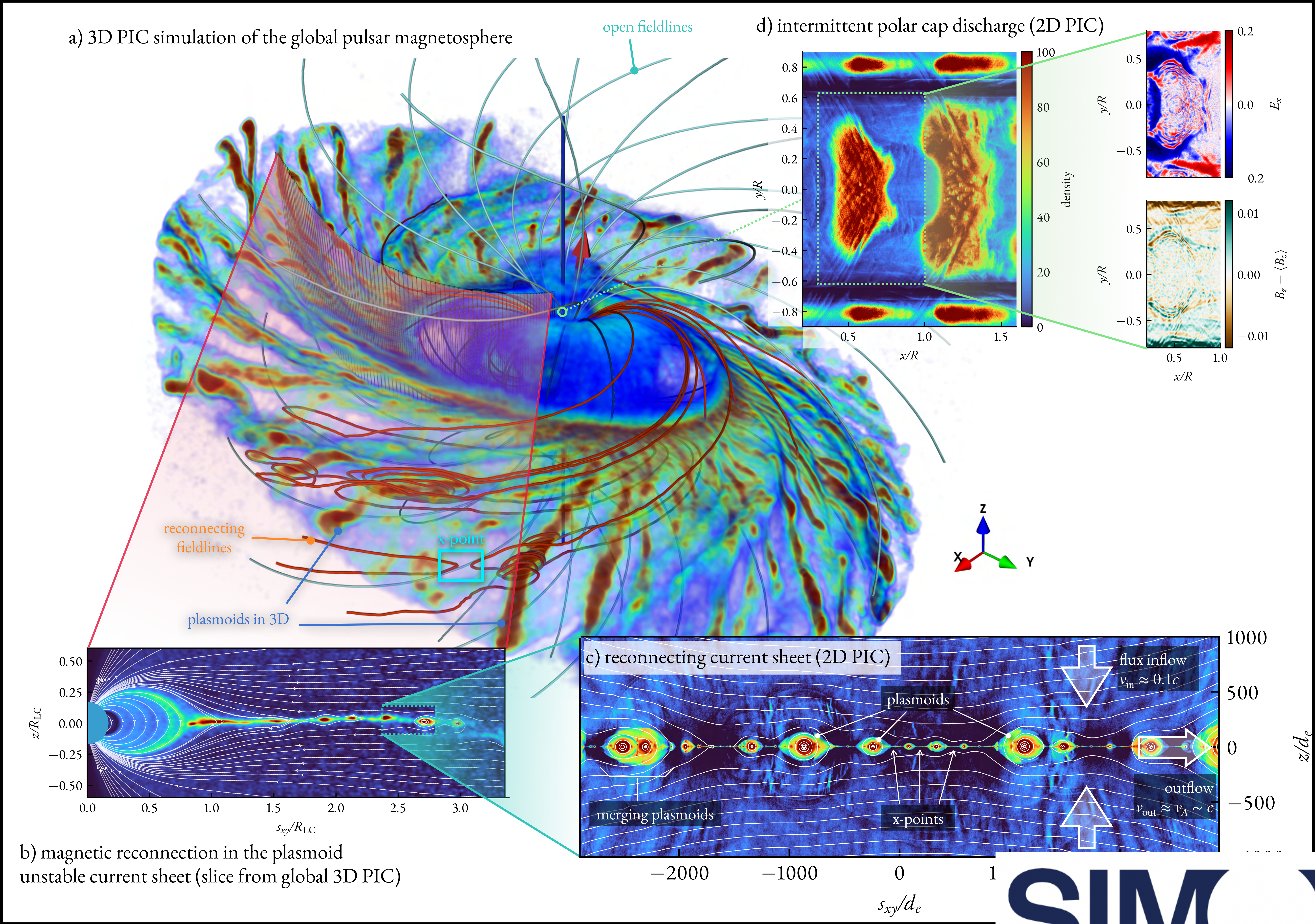
Pulsar magnetospheres and their radiation

Sasha Philippov (Maryland)

with:

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



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

THEORETICAL (AND NUMERICAL) APPROACHES

Force-free electrodynamics

Magnetized plasma without inertia

✓ OK in highly magnetized regions

- breaks when the existence of plasma is not a given, and in reconnection

• typical apps: neutron star magnetospheres, jets

Magnetohydrodynamics

Plasma as an ideal collisional fluid

✓ e.g., no thermal conduction, pressure is same in all directions; OK as a first approximation for global dynamics

- does not describe non-thermal particles

• typical apps: accretion flows

Kinetics

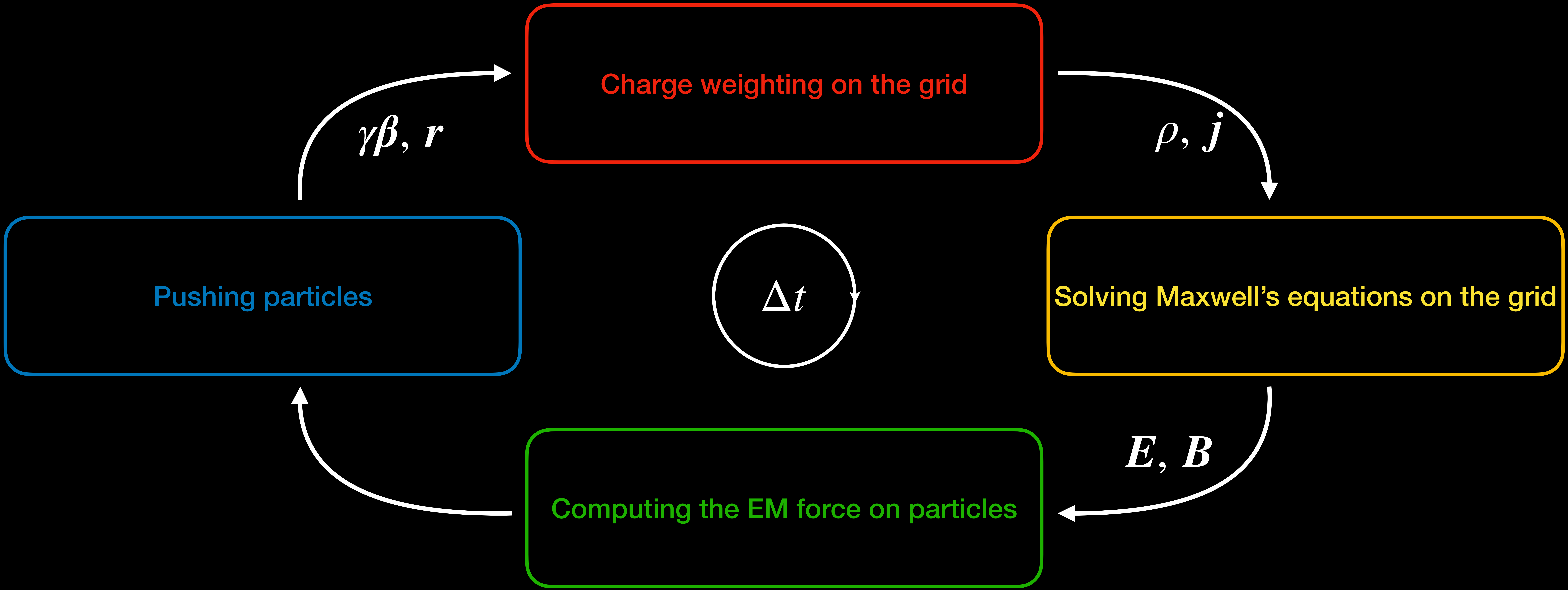
First-principles description for collisionless plasmas

✓ includes non-ideal effects (e.g., pressure is different along and across magnetic field, heat flux), describes particle acceleration

- computationally expensive and usually allows limited dynamic range

• typical apps: plasma instabilities, magnetospheres

PLASMA PHYSICS ON A COMPUTER: (GR)(R)PIC

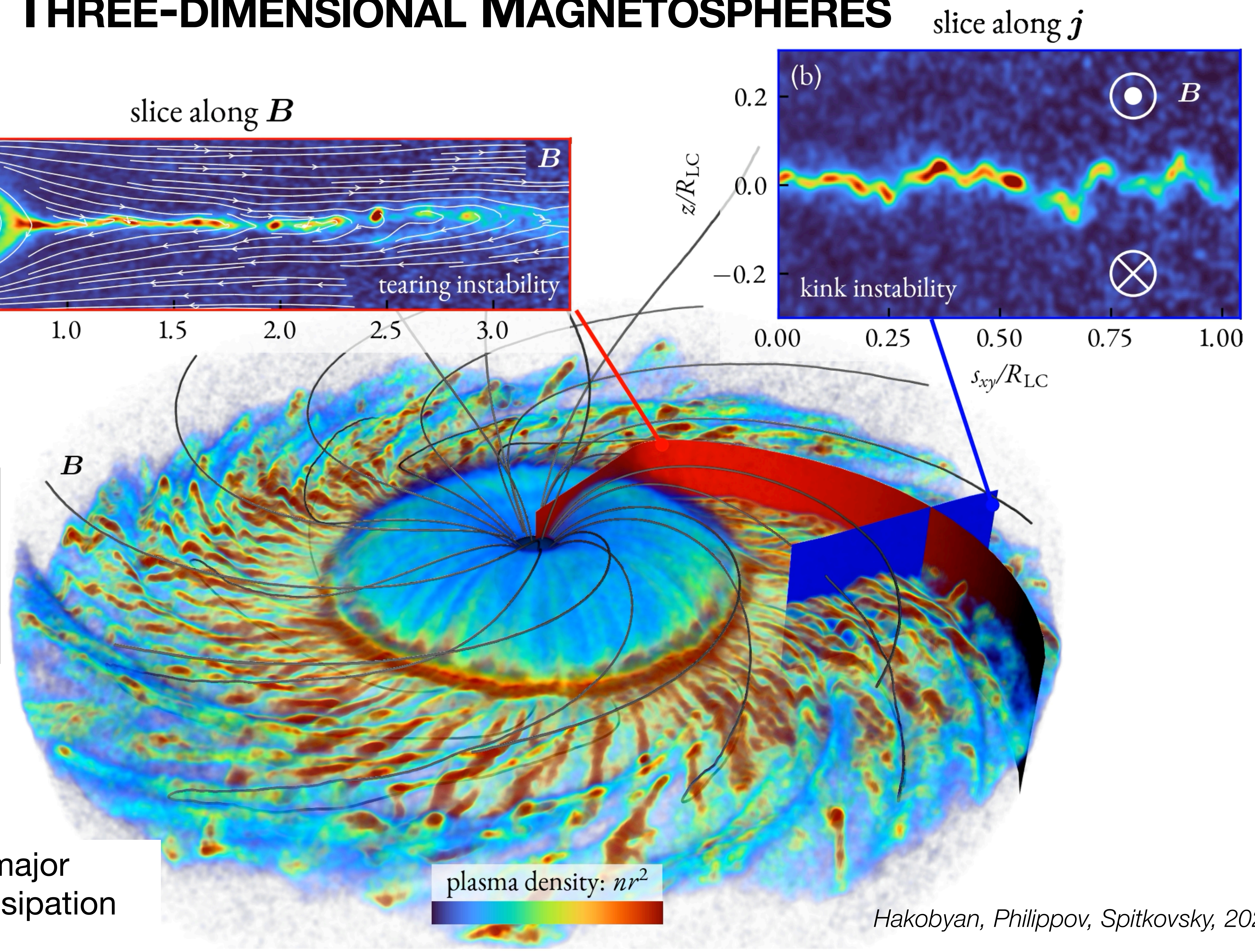


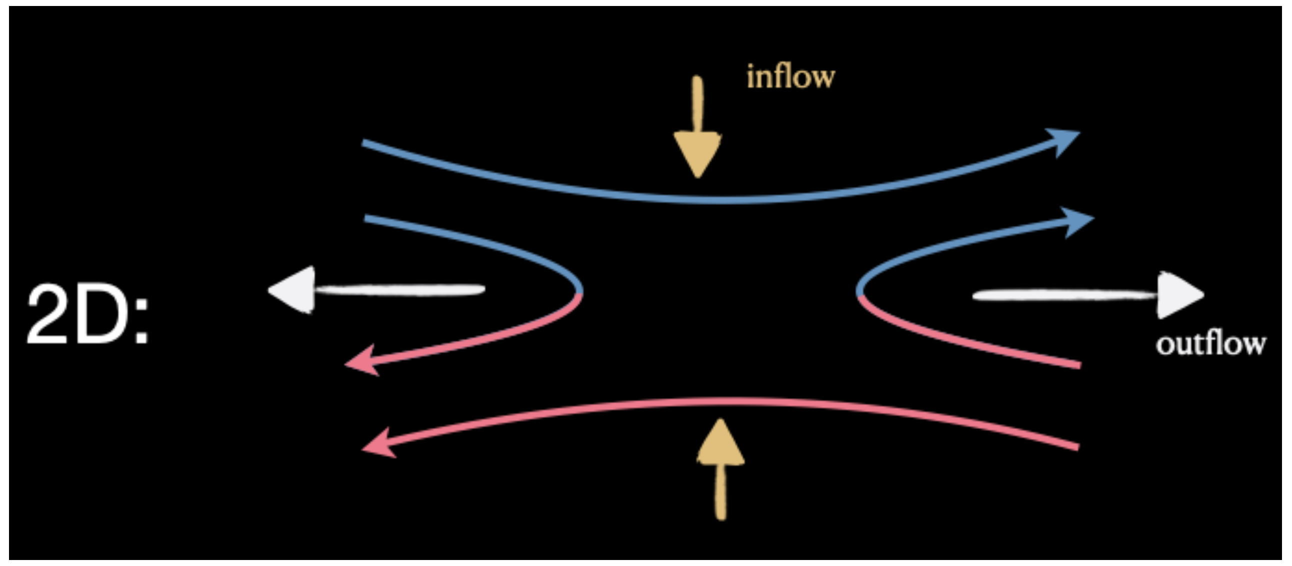
(GR) = general relativistic

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

PIC = particle-in-cell

THREE-DIMENSIONAL MAGNETOSPHERES





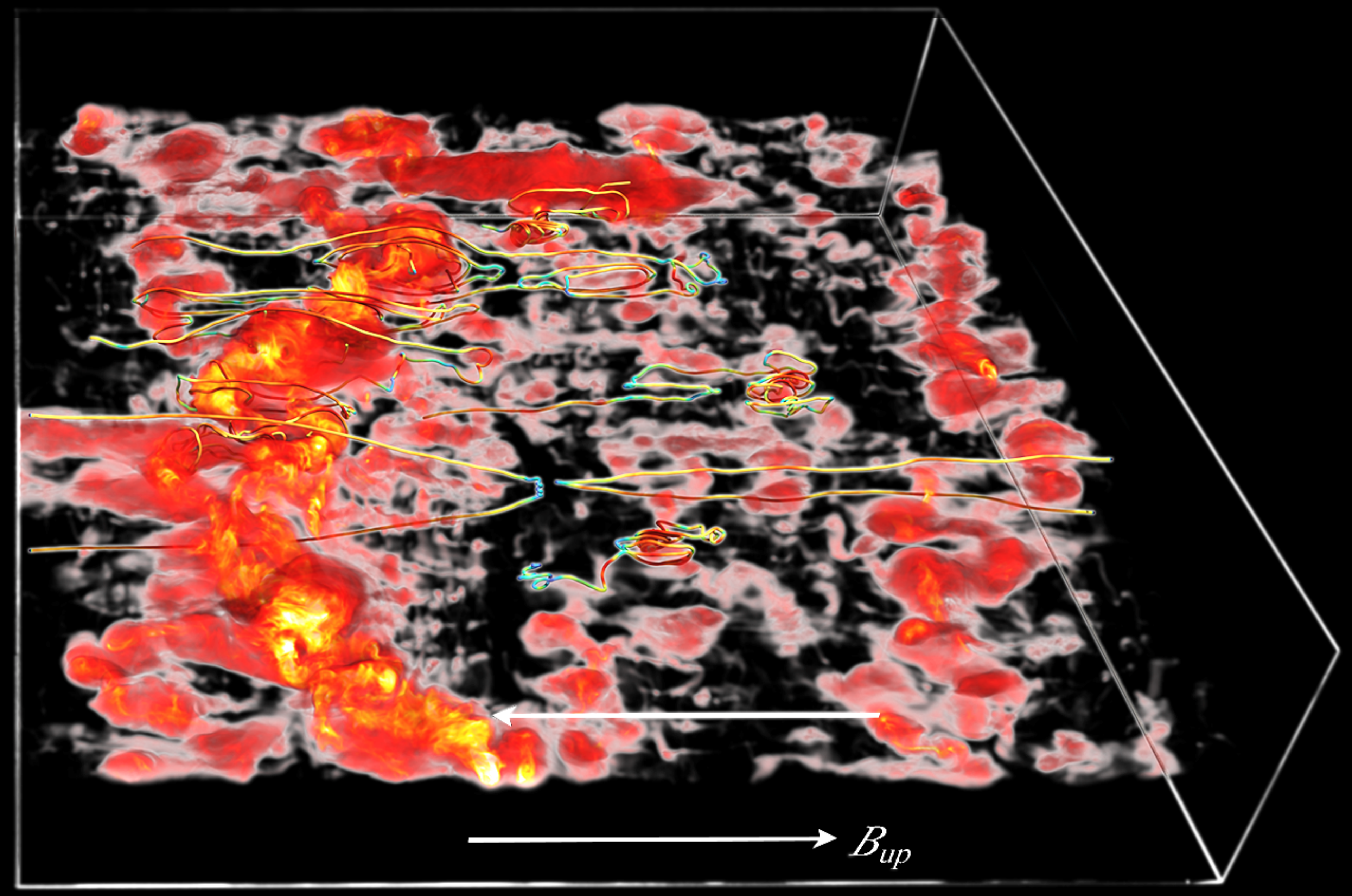
Unstable current sheets are major locations where magnetic dissipation occurs

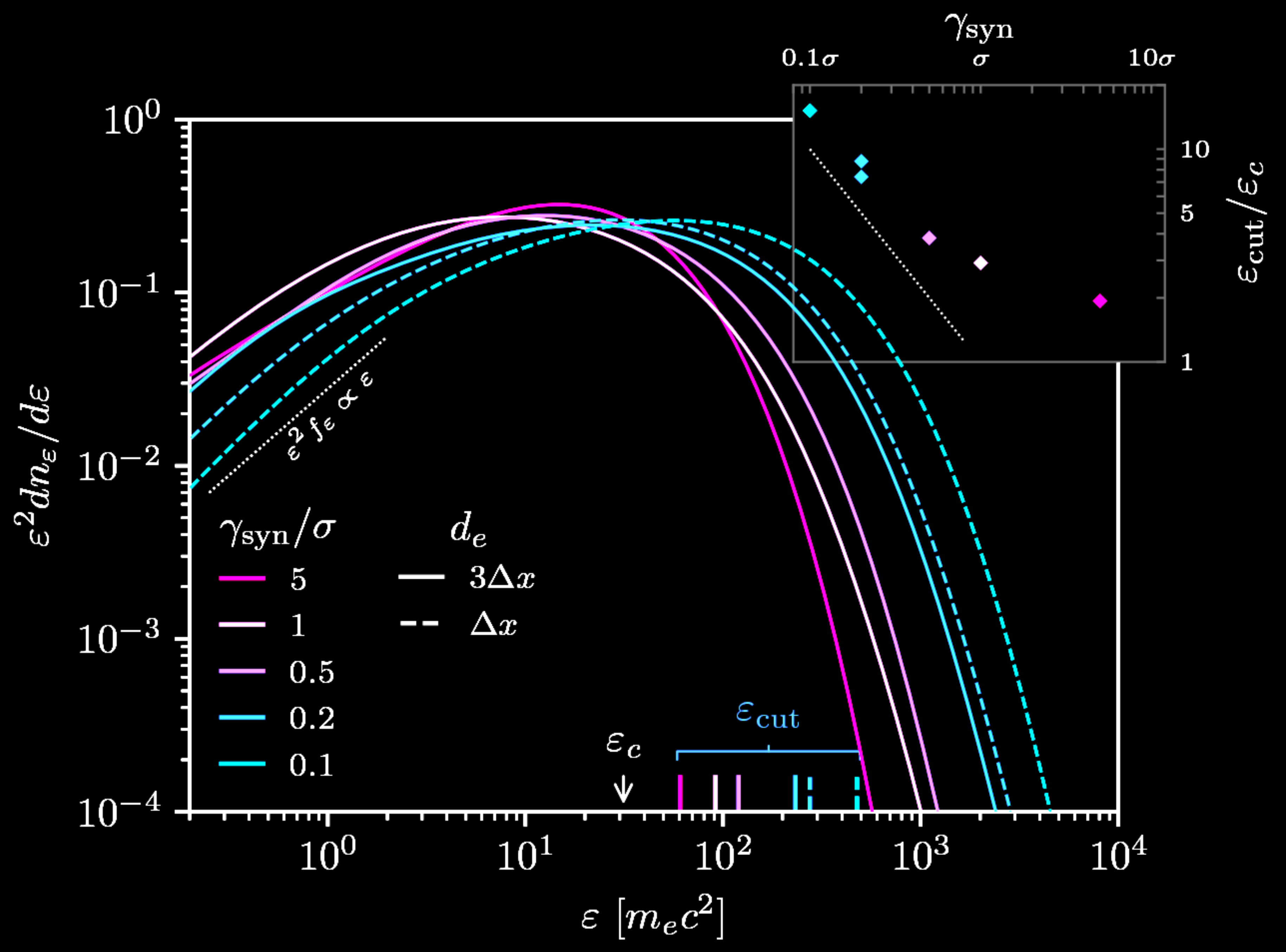
Hakobyan, Philippov, Spitkovsky, 2023 (ApJ)

RECONNECTION IN PULSAR MAGNETOSPHERES

- $B \sim 10^5$ G, $\sigma = B^2/(4\pi\rho_m c^2) \gg 1$
- Reconnection electric field accelerates particles, synchrotron cooling is important on the same timescale
- Pairs accelerate beyond the radiation reaction limit, up to $\gamma \sim \text{few} \times \sigma$
- Highest energy photons are beamed along the upstream magnetic field, consistent with the beaming of GeV lightcurves

$$h\nu_{\max} \approx 16\ \text{MeV} \cdot \left(\sigma/\gamma_{\text{syn}}\right)$$





Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

Reconnection in Pulsar Magnetospheres

Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

Reconnection in Pulsar Magnetospheres

Particle Spectrum

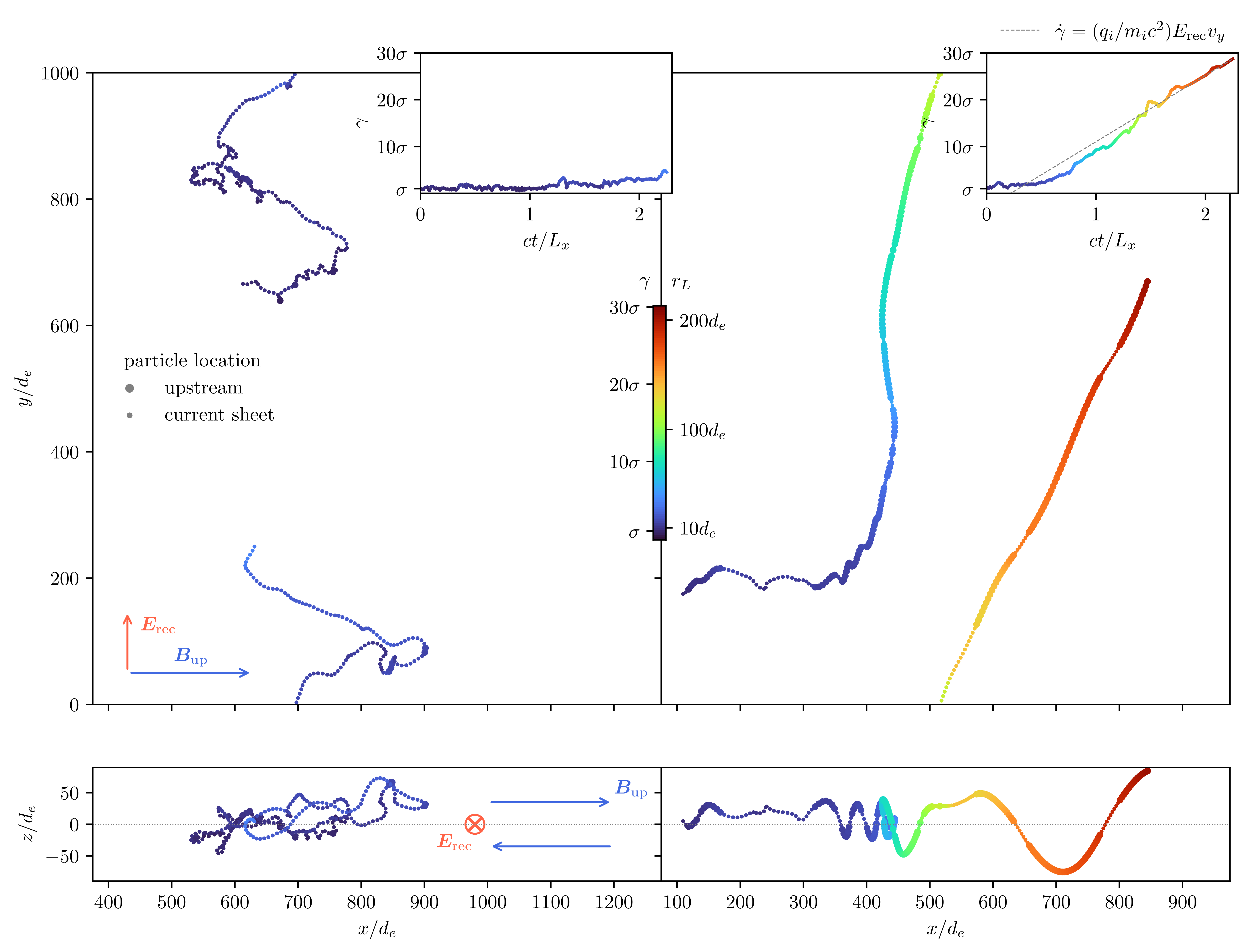
Photon Spectrum

Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

Reconnection in Pulsar Magnetospheres

- $B \sim 10^5$ G, $\sigma = B^2/(4\pi\rho_m c^2) \gg 1$
- Reconnection electric field accelerates particles, synchrotron cooling is important on the same timescale, gives ``burnoff” limit $\gamma_{\rm syn}$
- Pairs accelerate beyond the radiation reaction limit, up to $\gamma \sim \mathrm{few} \times \sigma$
- Highest energy photons are beamed along the upstream magnetic field, consistent with the beaming of GeV lightcurves

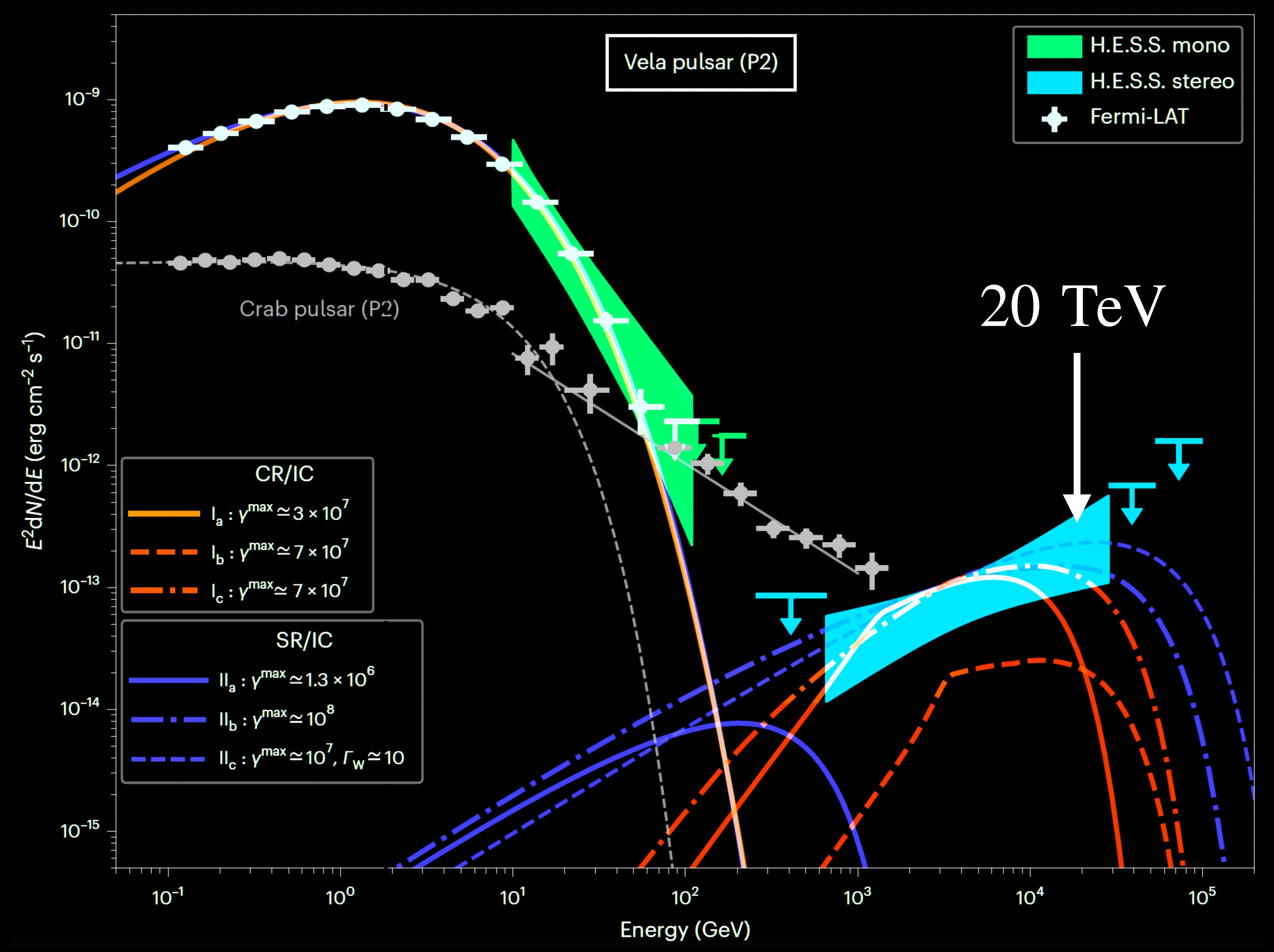
$$h\nu_{\rm max} \approx 16 \text{ MeV} \cdot \left(\sigma/\gamma_{\rm syn}\right)$$



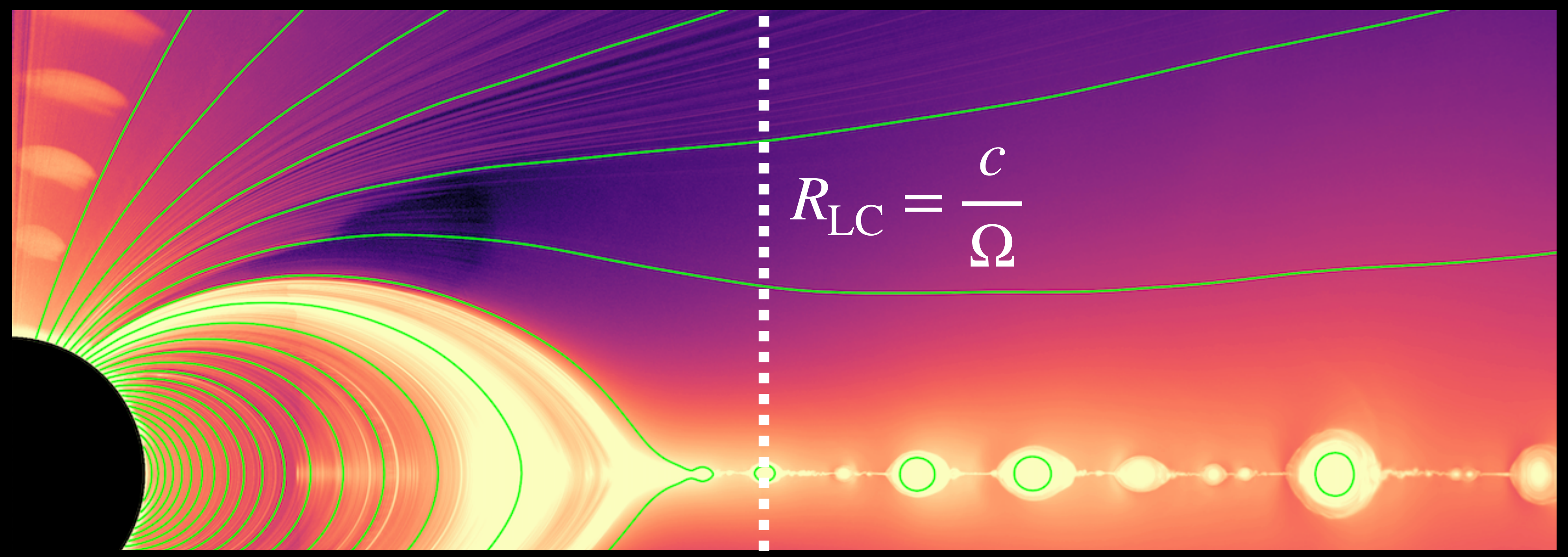
Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

NEW FRONTIER: MULTI-TEV FROM VELA PULSAR [IN PREP]

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



Bransgrove et al, 2023 (ApJL)



$$\gamma_{syn} \approx 10^5 \quad \Rightarrow \quad \sigma \approx \text{few} \times 10^7$$

$$\uparrow$$

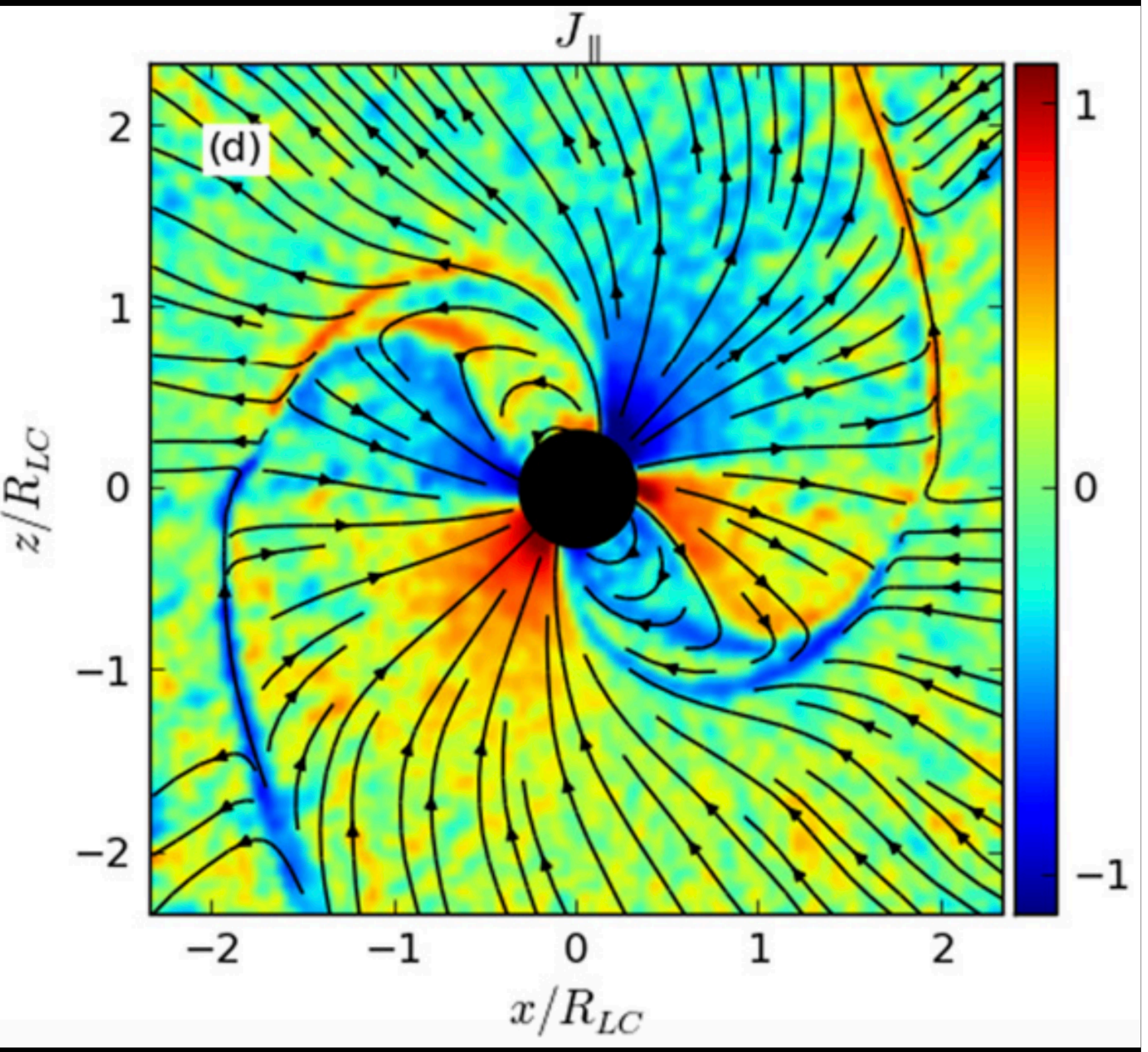
$$\varepsilon_{ph} = 16 \text{ MeV} \cdot \left(\sigma/\gamma_{syn}\right)$$

$$m_e c^2 \gamma_{max} = m_e c^2 \sigma \sim 10 \text{ TeV}$$

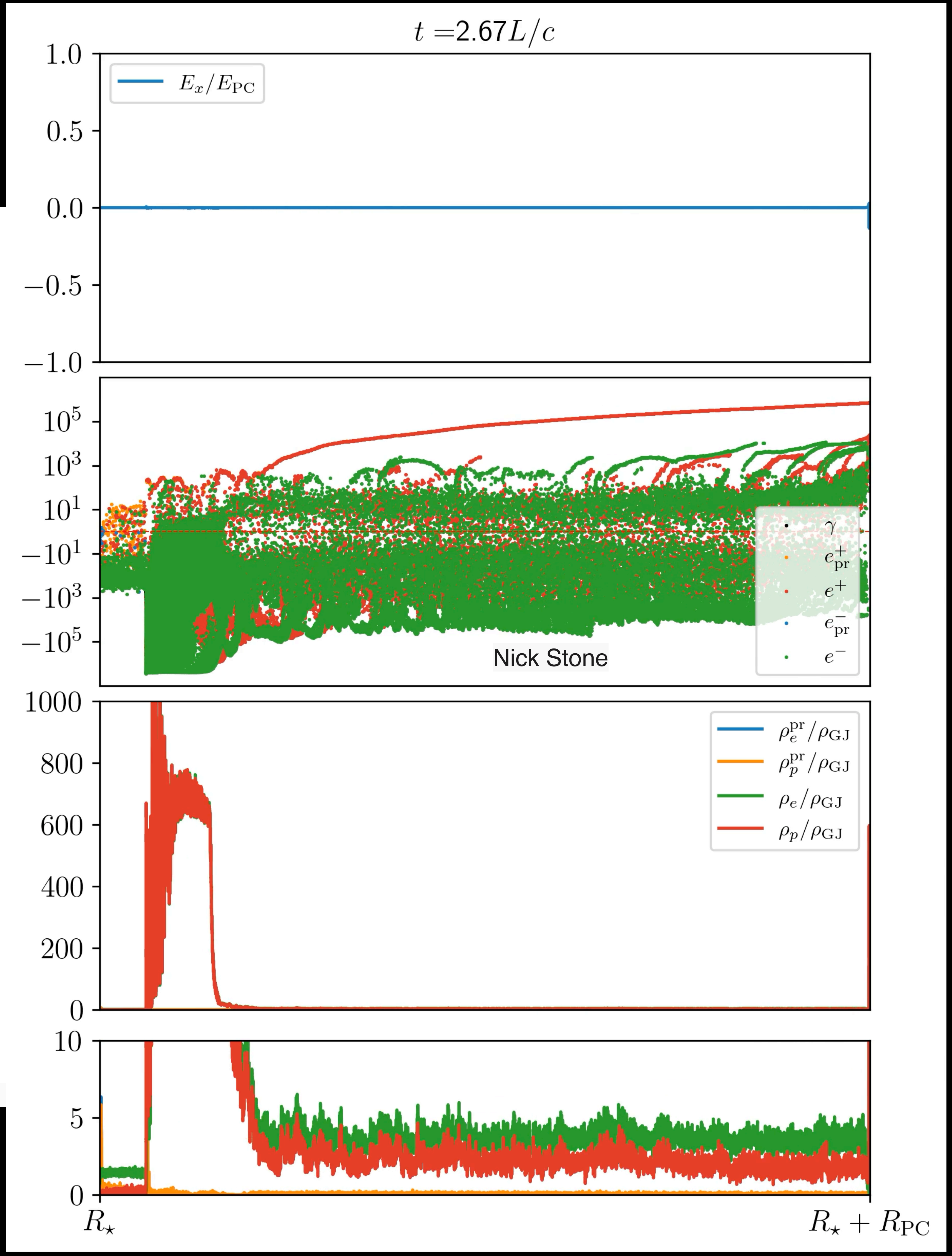
- Pair density is low because "return"-current discharge sends most of the plasma into the star
- Most of the plasma is produced in the current sheet

Prediction: CTA will see moderately energetic γ-ray pulsars as multi-TeV sources

NEW FRONTIER: MULTI-TEV FROM VELA PULSAR [IN PREP]



Philippov et al., 2015 (ApJ)



$$\gamma_{\rm syn} \approx 10^5 \quad \Rightarrow \quad \sigma \approx \text{few} \times 10^7$$

$$\uparrow$$

$$\varepsilon_{\rm ph} = 16\ \text{MeV} \cdot \left(\sigma/\gamma_{\rm syn}\right)$$

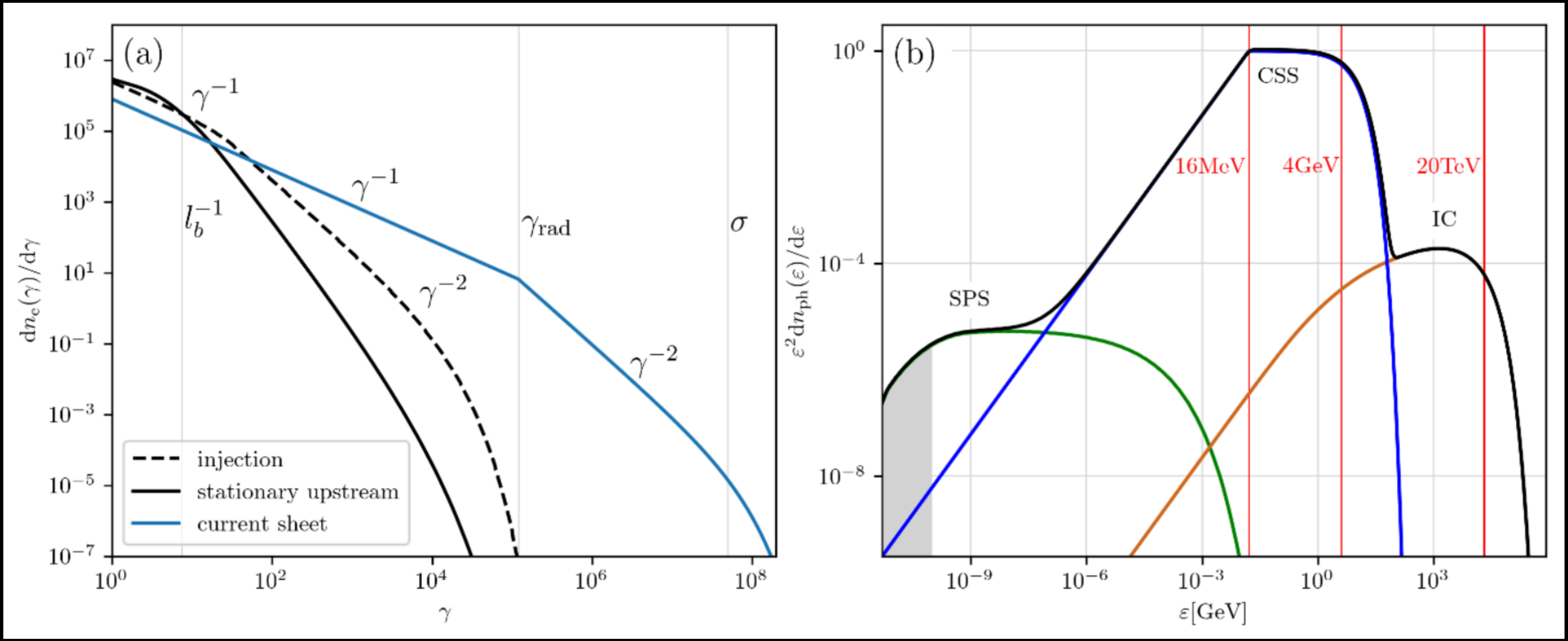
$$m_e c^2 \gamma_{\max} = m_e c^2 \sigma \sim 10\ \text{TeV}$$

- Pair density is low because "return"-current discharge sends most of the plasma into the star
- Most of the plasma is produced in the current sheet

NEW FRONTIER: MULTI-TEV FROM VELA PULSAR [IN PREP]

Particle Spectrum

Photon Spectrum



$$m_e c^2 \gamma_{\max} = m_e c^2 \sigma \sim 10 \text{ TeV}$$

Conclusions

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. Highest energy TeV photons can be produced in the current sheet as well.