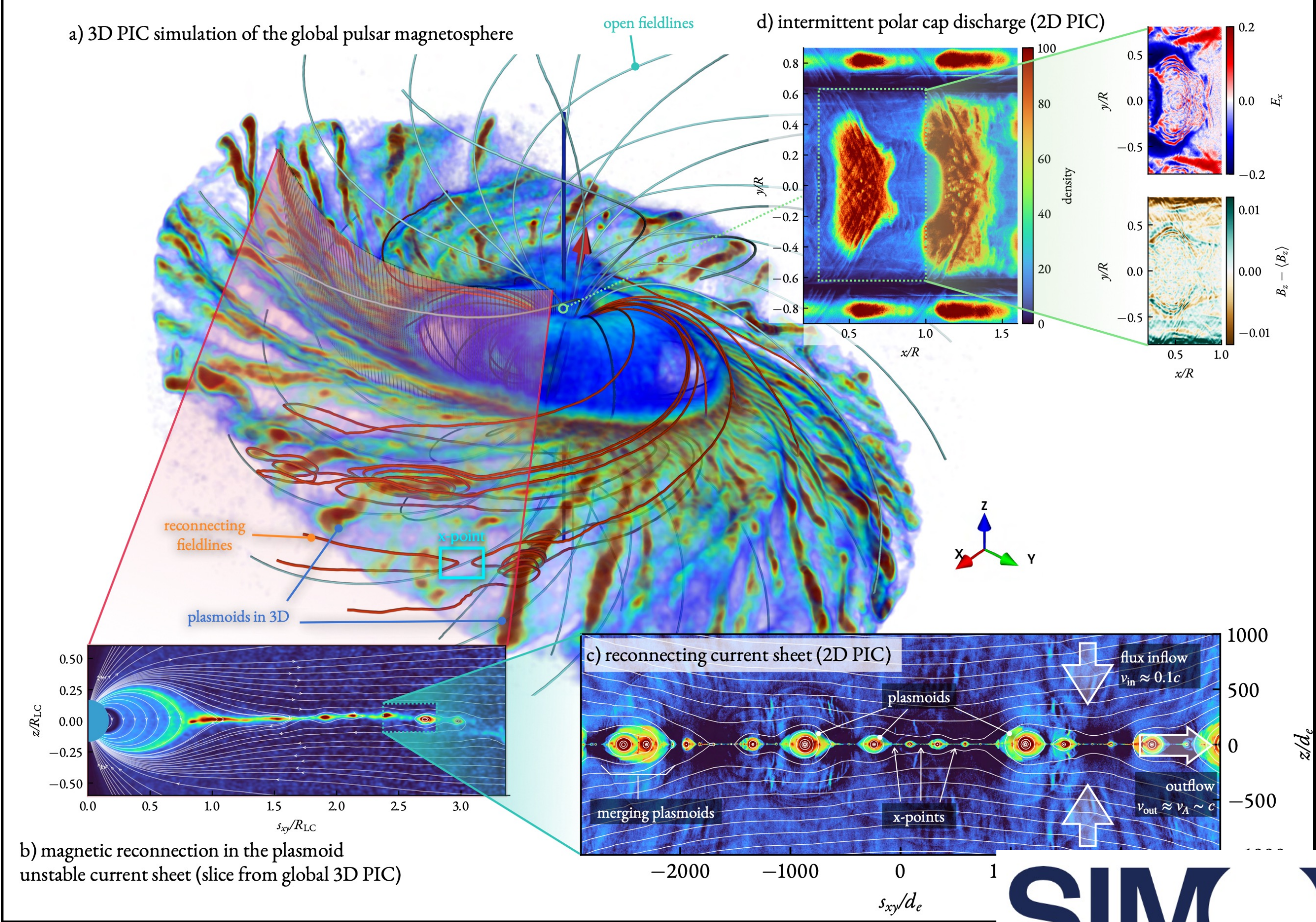


Philippov & Kramer, 2022, Annual Reviews of Astronomy & Astrophysics

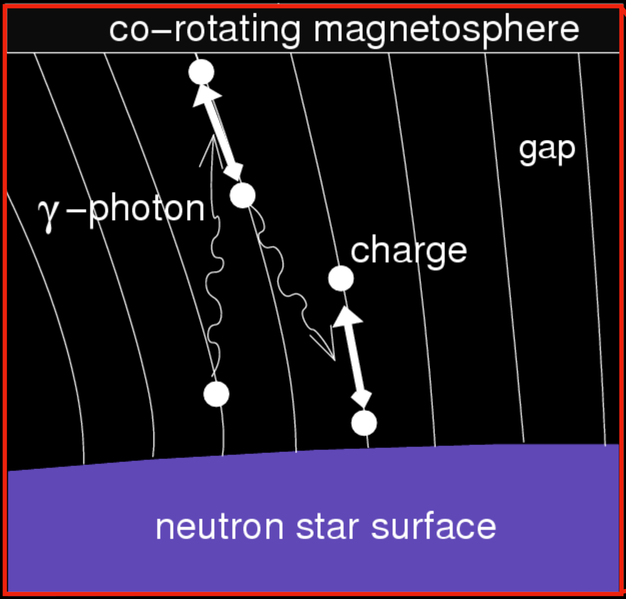
Pulsar magnetospheres and their radiation

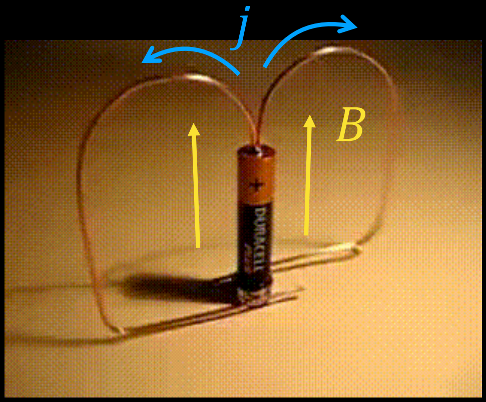
Sasha Philippov (Maryland)

with:

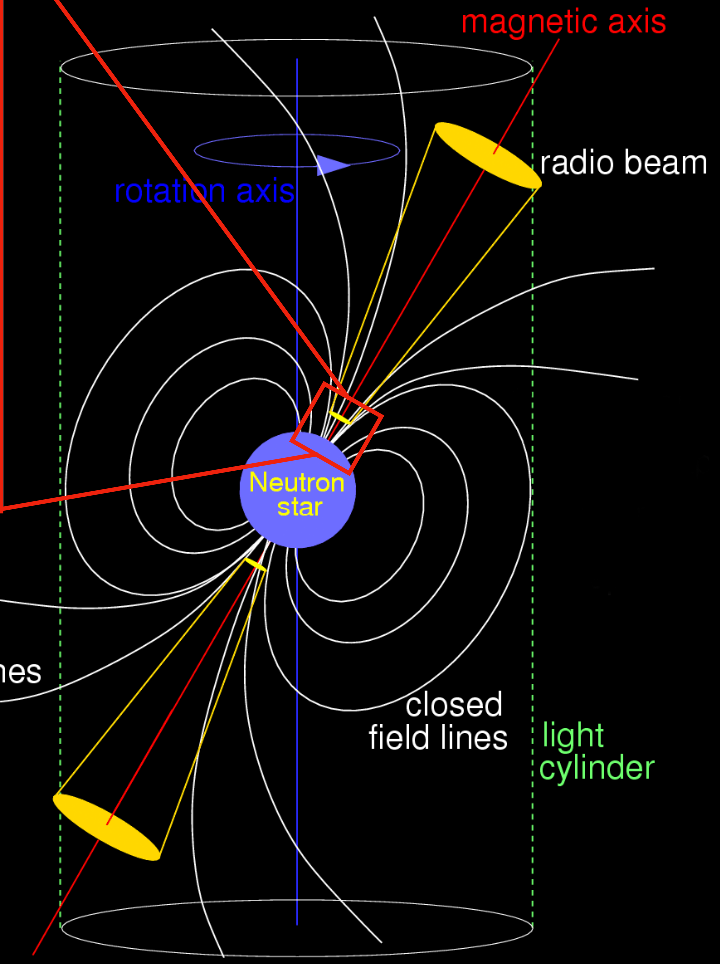
Benoit Cerutti (*Grenoble*)
Sasha Chernoglazov (*Maryland*)
Sam Gralla (*Arizona*)
Hayk Hakobyan *(Columbia)*
Anatoly Spitkovsky (*Princeton)*
Andrey Timokhin (*Zielona Gora*)
Libby Tolman *(IAS, Flatiron)*
Dmitri Uzdensky (*Colorado*)

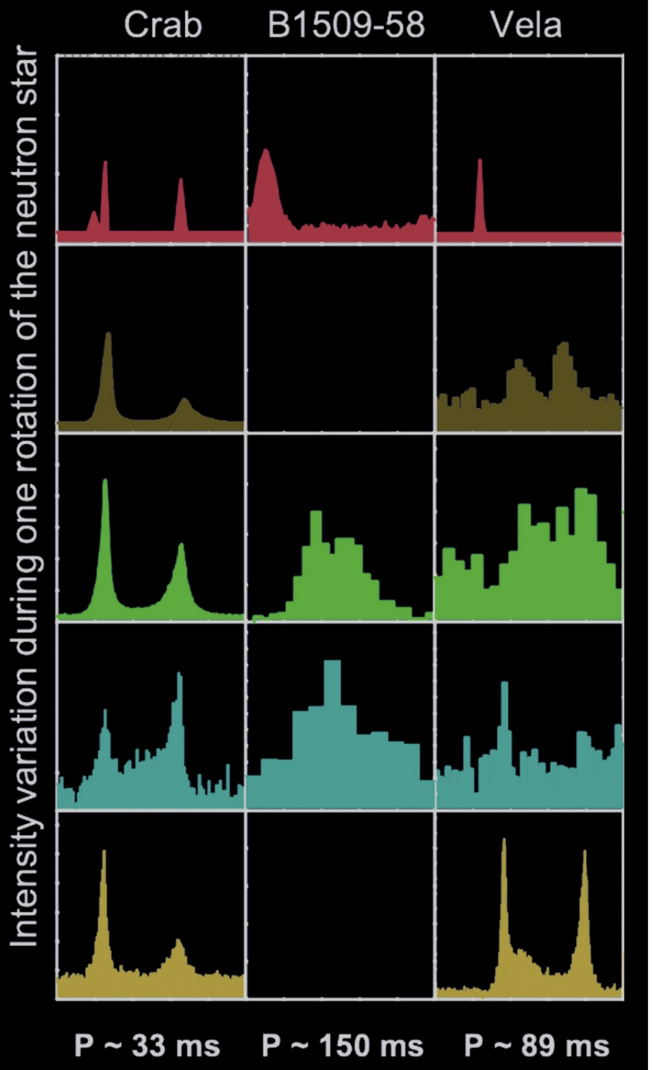
What is a pulsar?





Unipolar induction

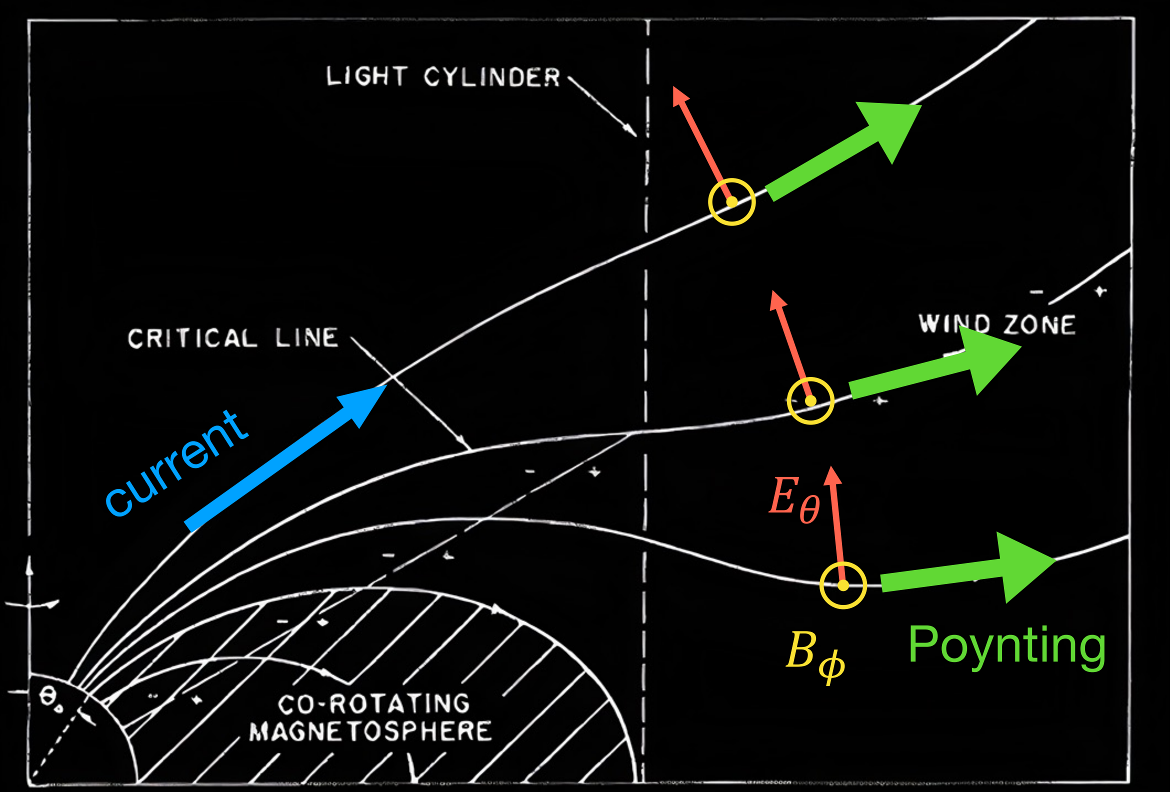




THEORETICAL CARTOON: GJ MODEL

$$\sigma \equiv \frac{B^2/4\pi}{\rho_{\pm}c^2} \gg 1$$

- Corotation electric field
- Sweepback of $\boldsymbol{B}$-field due to poloidal current
- Poynting flux ⇒ electromagnetic energy losses



Goldreich & Julian (1969)

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

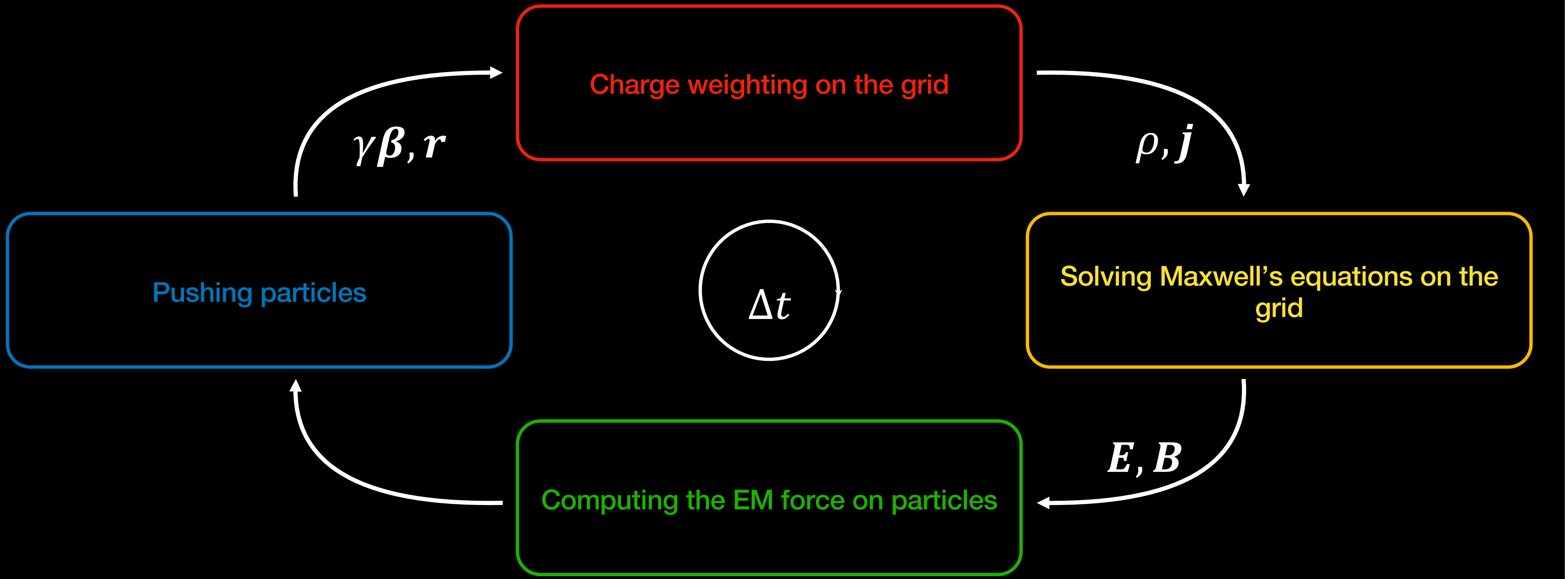
- ✓ e.g., no thermal conduction, pressure is same in all directions; OK as a first approximation for global dynamics
- – does not describe non-thermal particles
- typical apps: accretion flows

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



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

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

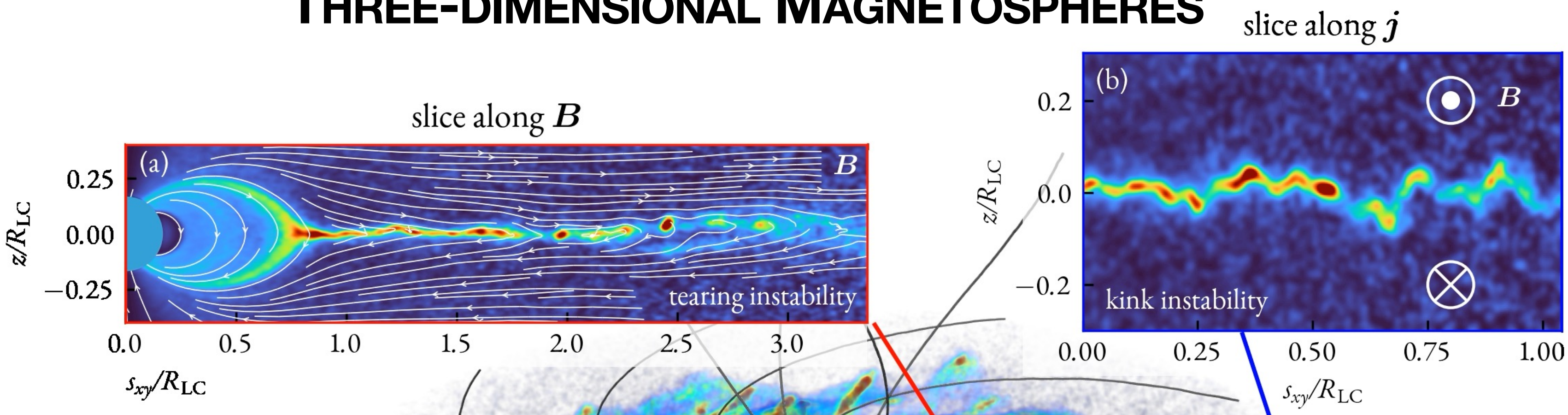
Δt

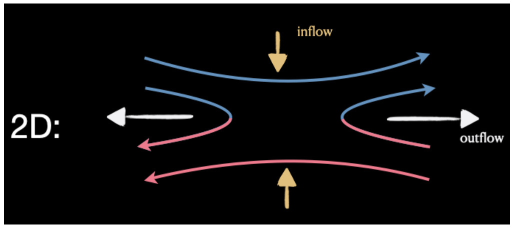
(GR) = general relativistic

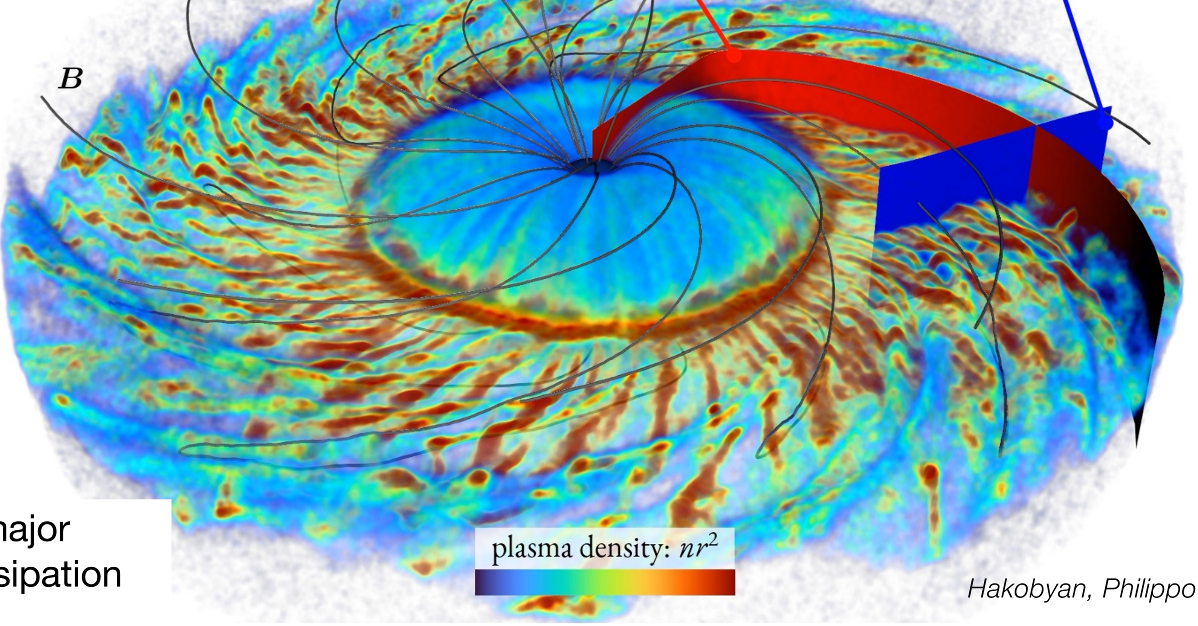
(R) = radiation reaction force, photon emission, multiple pair production mechanisms

PIC = particle-in-cell

THREE-DIMENSIONAL MAGNETOSPHERES



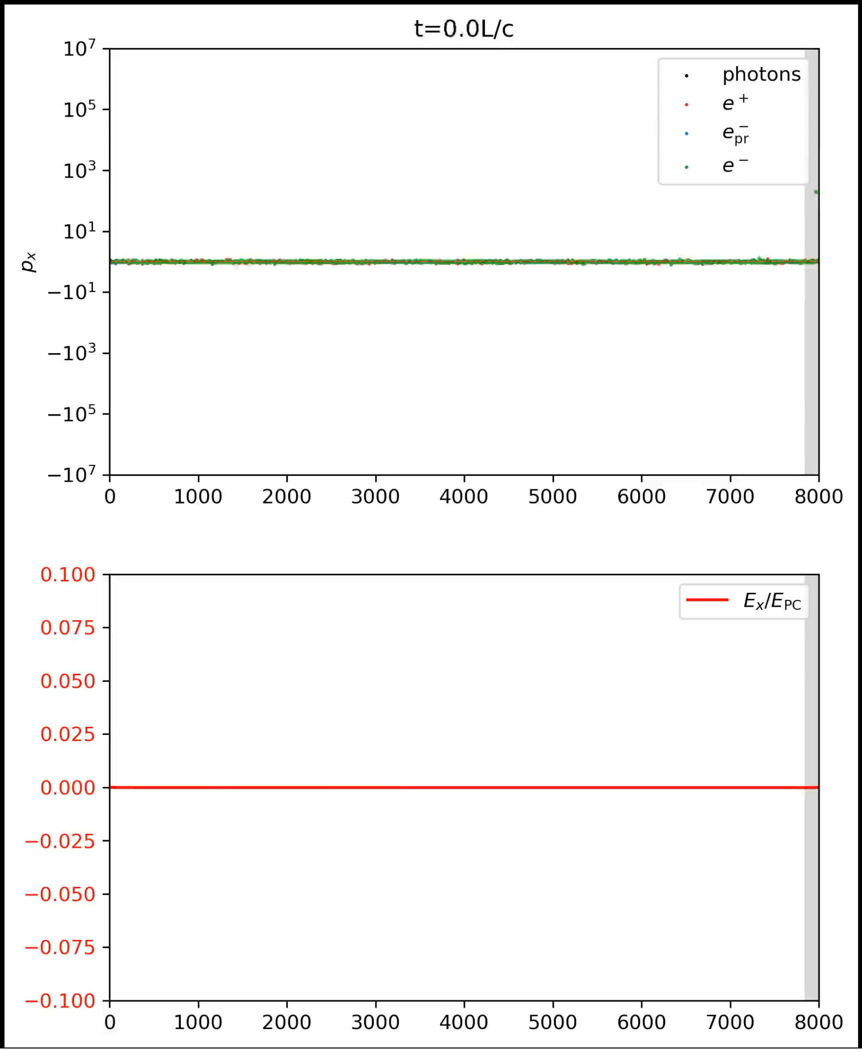




Unstable current sheets are major locations where magnetic dissipation occurs

Hakobyan, Philippov, Spitkovsky, 2023 (ApJ)

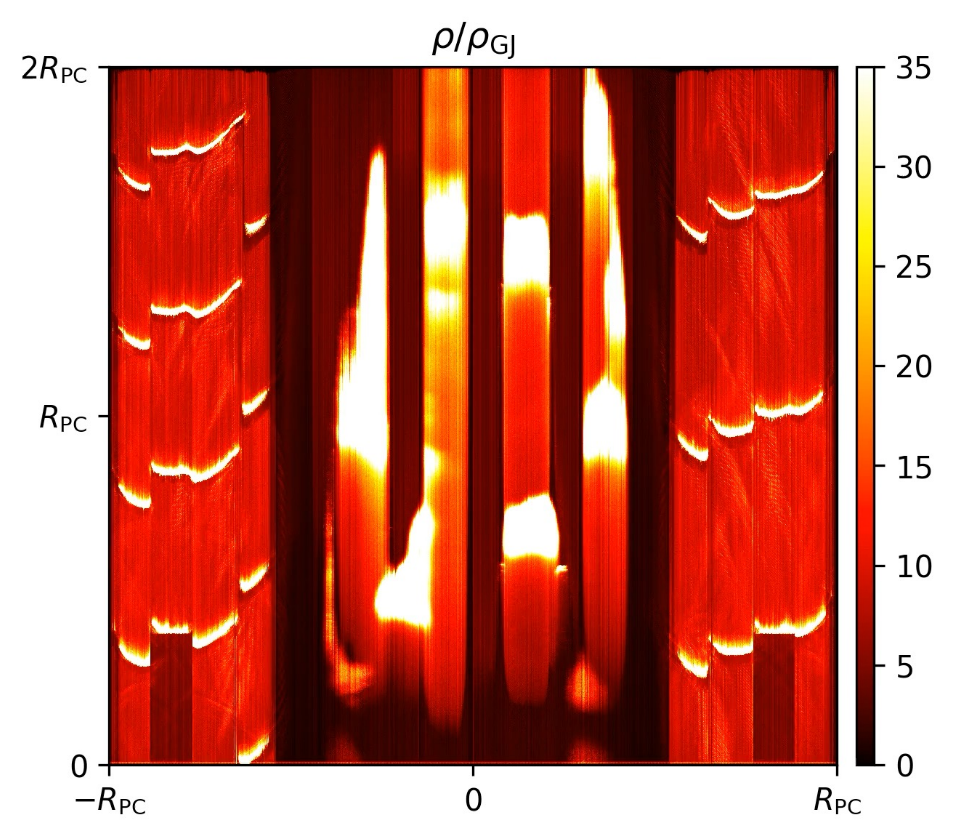
LOCAL SIMULATION OF PAIR DISCHARGE



- Intermittency:
- Gap opening
- Particle acceleration
- Photon emission
- Pair production
- Gap closing
- Outflows
- Gap opening
- Etc.

Chernoglazov, Philippov, Timokhin (2024)

LOCAL SIMULATION OF PAIR DISCHARGE



- Intermittency:
- Gap opening
- Particle acceleration
- Photon emission
- Pair production
- Gap closing
- Outflows
- Gap opening
- Etc.

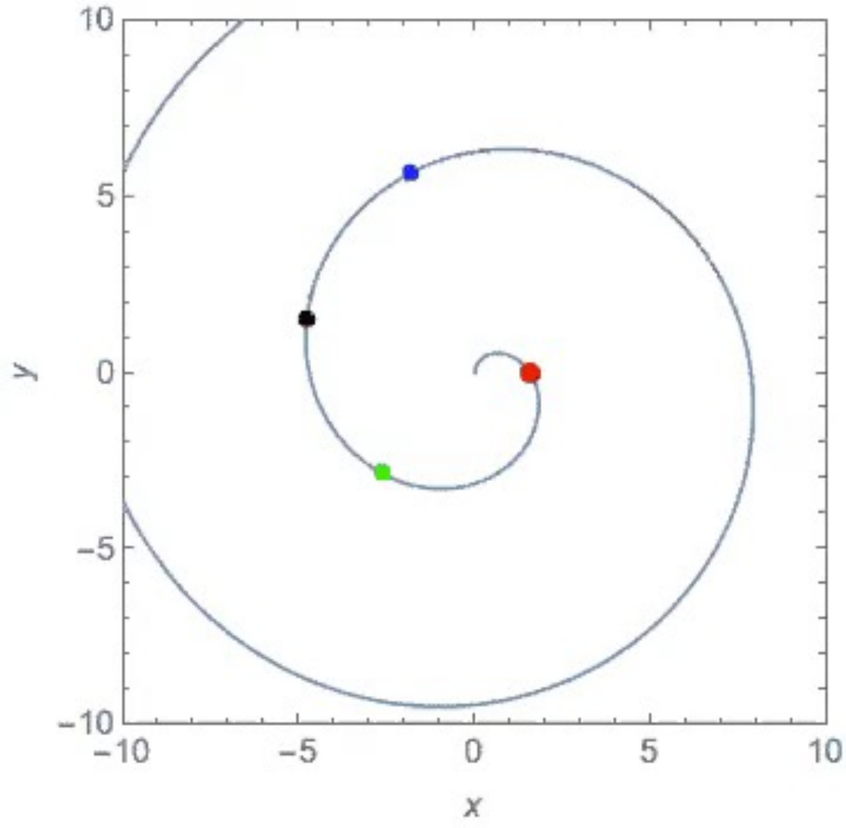
Chernoglazov, Philippov, Timokhin (2024)

Gamma-ray modeling

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

Observe caustic emission.

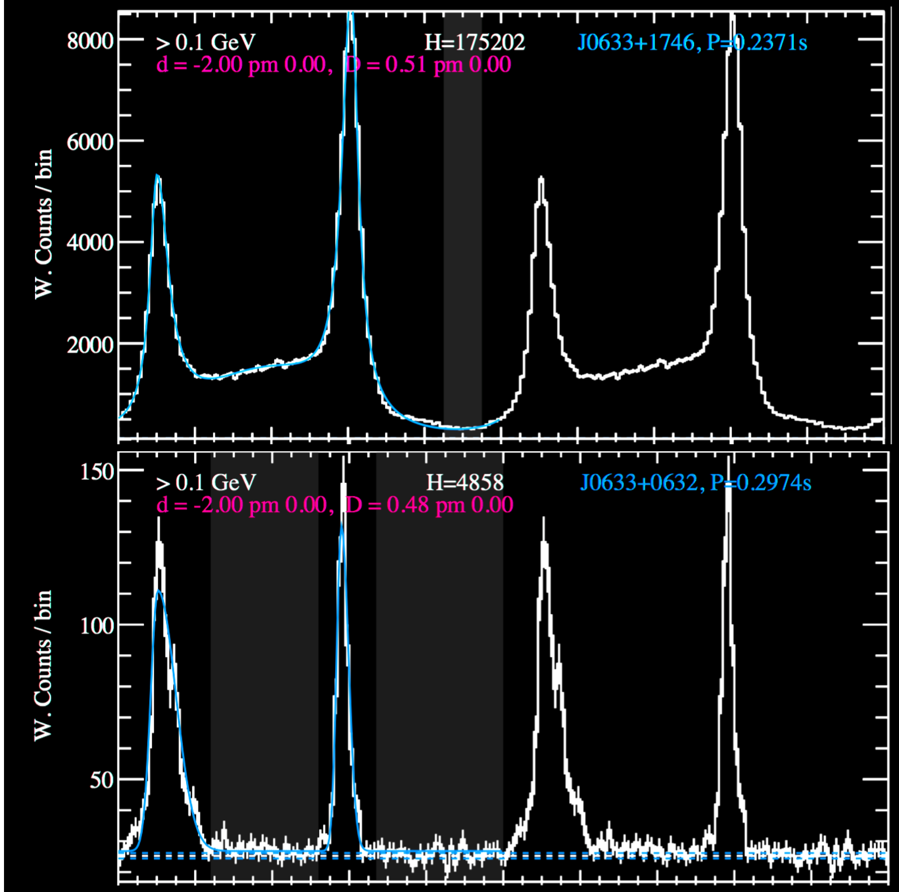
Predict gamma-ray efficiencies 1-20% depending on the inclination angle and pair production efficiency in the sheet. Higher inclinations are less dissipative.

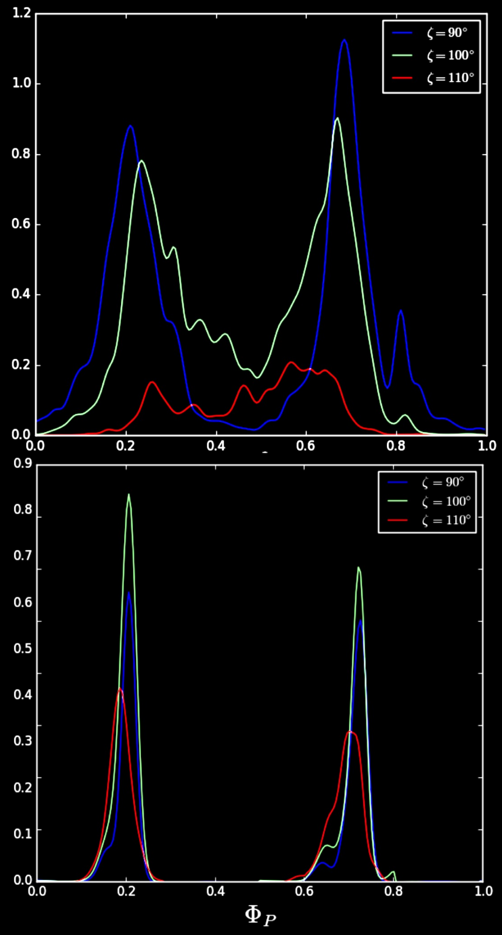


Cerutti, Philippov, Spitkovsky (2016); Philippov, Spitkovsky (2018)

LIGHTCURVES

FERMI





Double-peaked lightcurves are generic

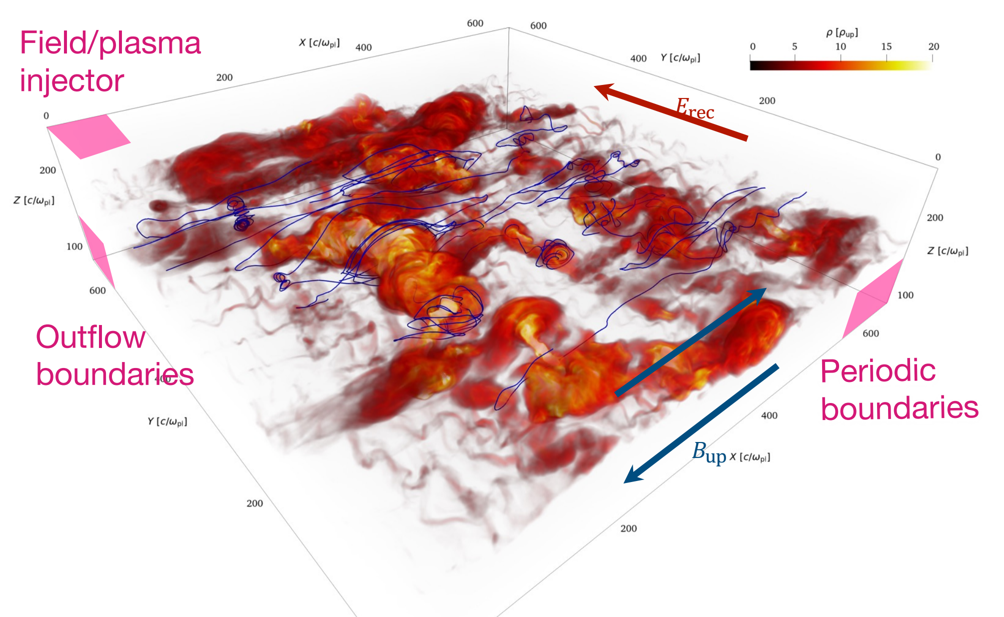
Philippov, Spitkovsky, 2018
(ApJ)

Benoit’s talk on Monday!

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 $\gamma \sim$ few$\times\sigma$
- Highest energy photons are beamed along the upstream magnetic field, consistent with the beaming of GeV lightcurves

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

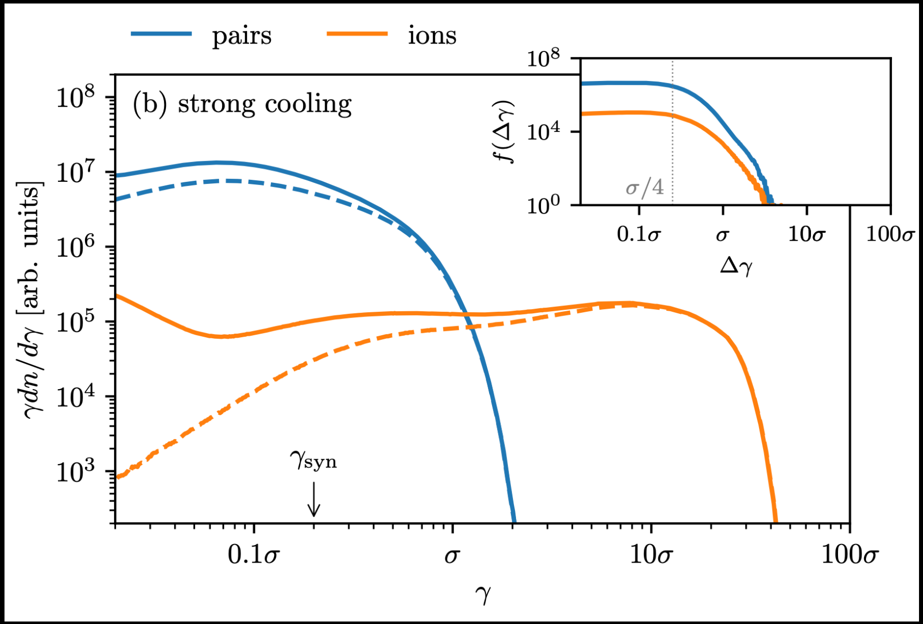


Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

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

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

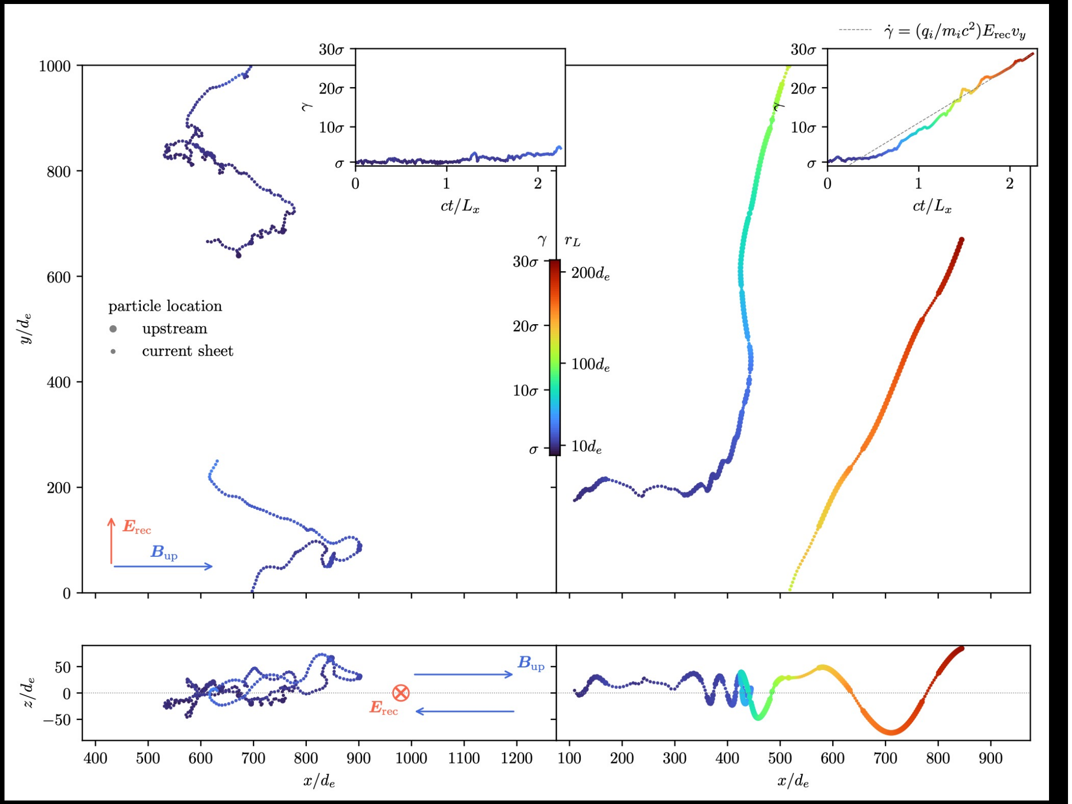


Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

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 γ_{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

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

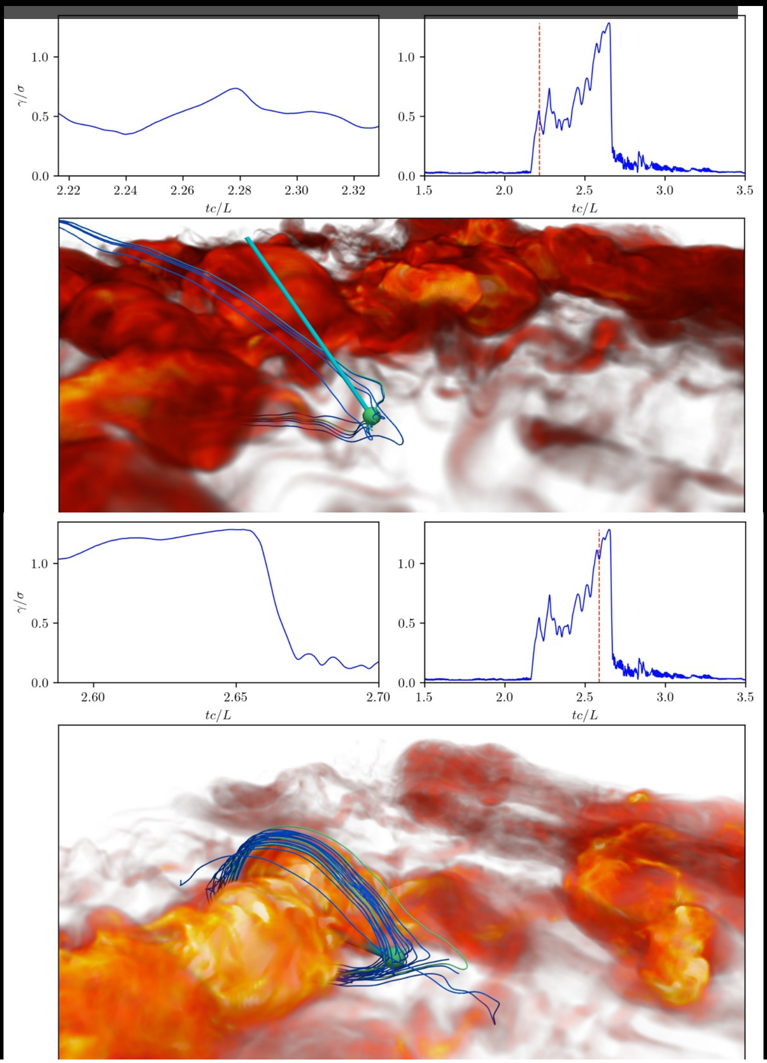


Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

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 γ_{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

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

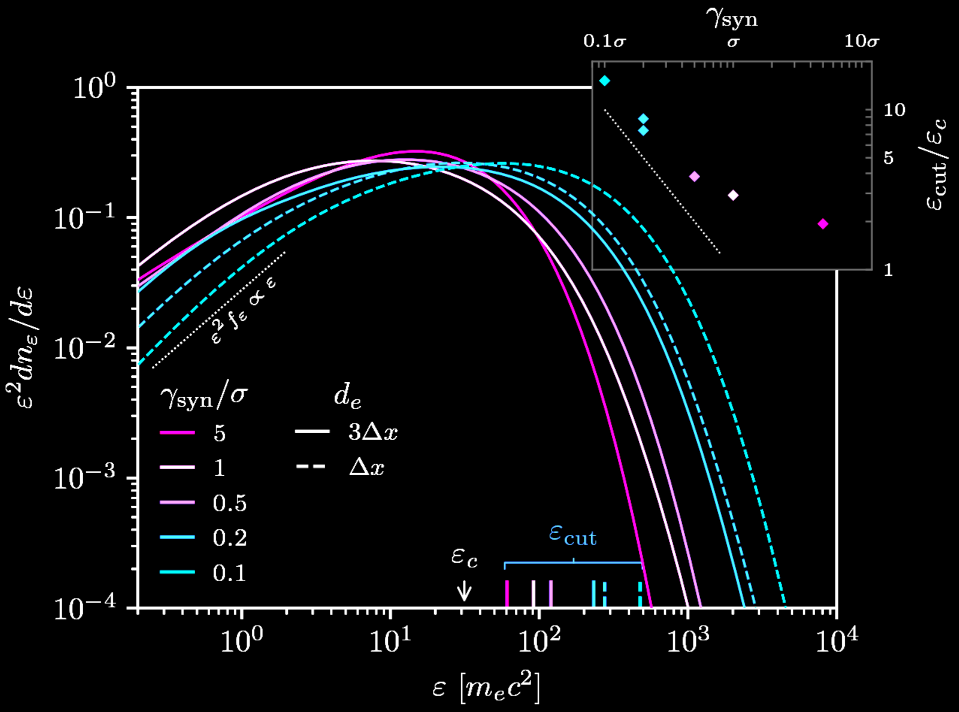


Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

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 $\gamma \sim \text{few}\times\sigma$
- Highest energy photons are beamed along the upstream magnetic field, consistent with the beaming of GeV lightcurves

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

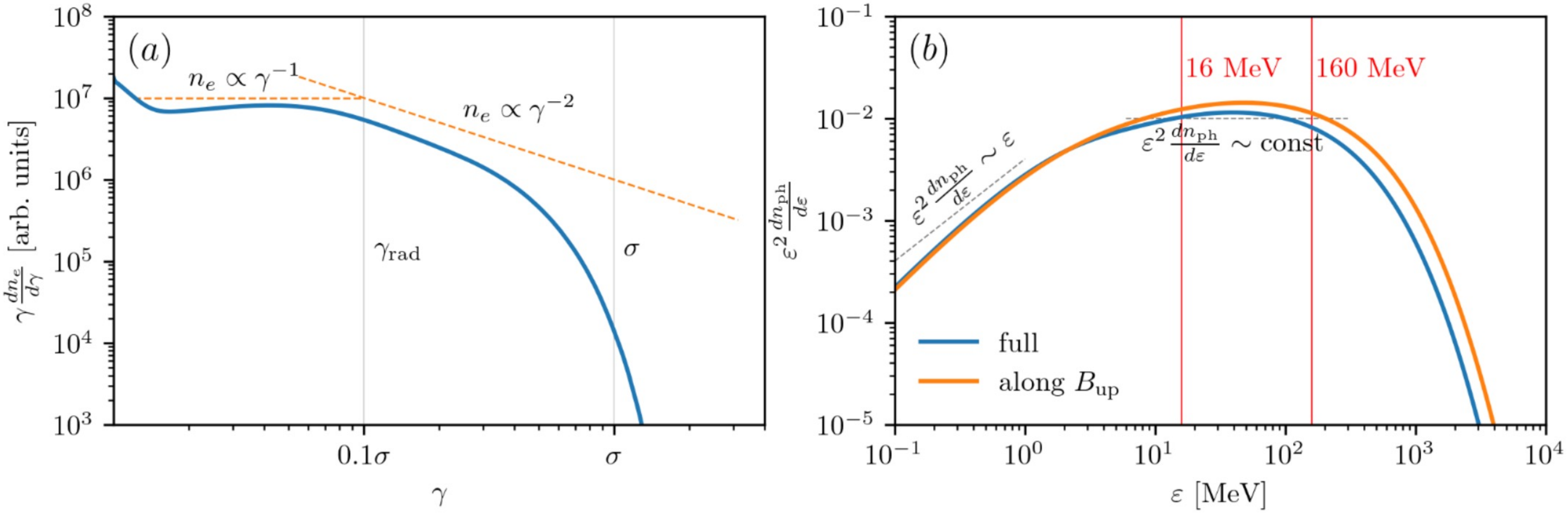


Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

RECONNECTION IN PULSAR MAGNETOSPHERES

Particle Spectrum

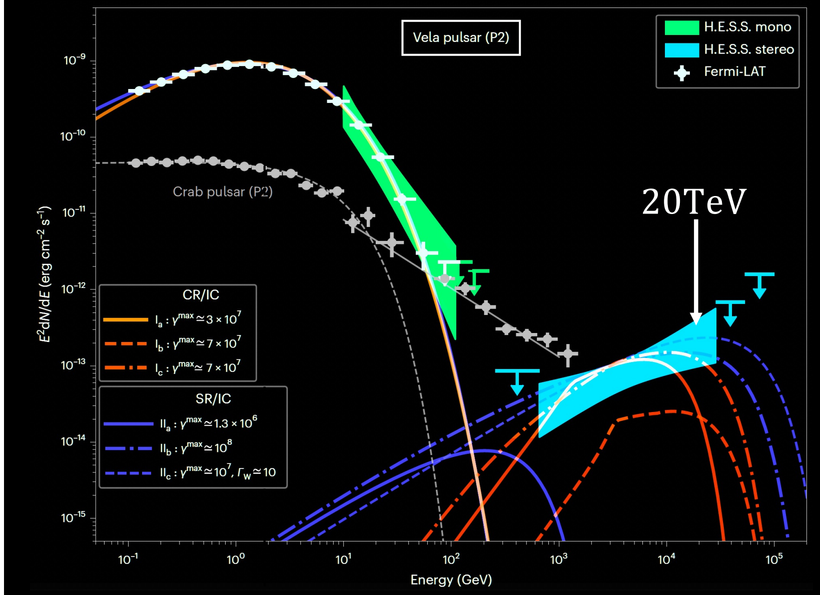
Photon Spectrum



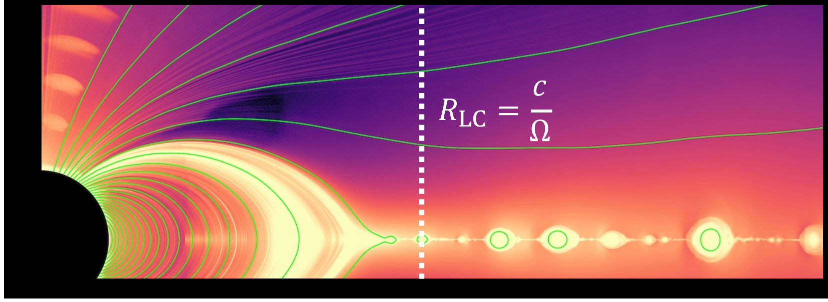
Chernoglazov, Hakobyan, Philippov, 2023 (ApJ)

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

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



Bransgrove et al, 2023 (ApJL)



$$\gamma_{\rm syn} \approx 10^5 \Rightarrow \sigma \approx {\rm few}\times10^7$$

$$\uparrow$$

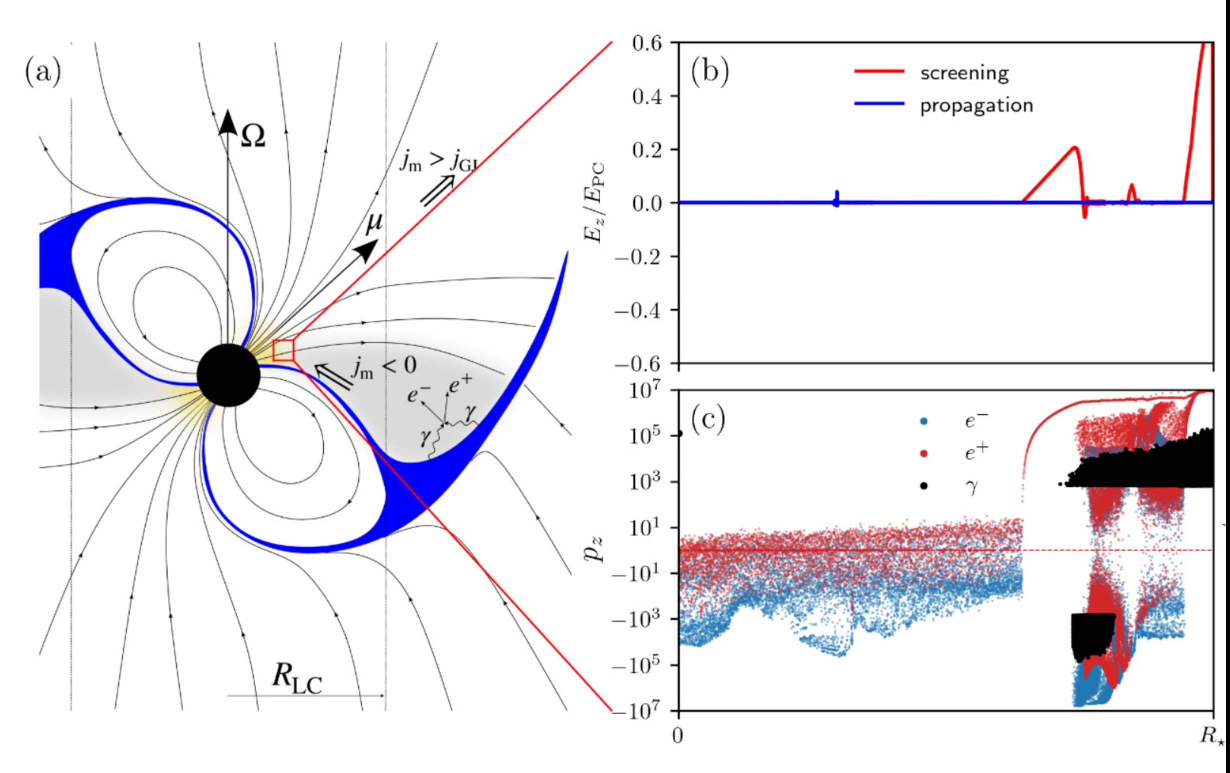
$$\varepsilon_{\rm ph} = 16{\rm MeV}\cdot\left(\sigma/\gamma_{\rm syn}\right)$$

$$\boxed{\begin{array}{c} m_e c^2 \gamma_{\max} = m_e c^2 \sigma \\ \sim 10{\rm TeV} \end{array}}$$

- 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]



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

$$\uparrow$$

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

$$\boxed{\begin{gathered} m_e c^2 \gamma_\mathrm{max} = m_e c^2 \sigma \\ \sim 10\mathrm{TeV} \end{gathered}}$$

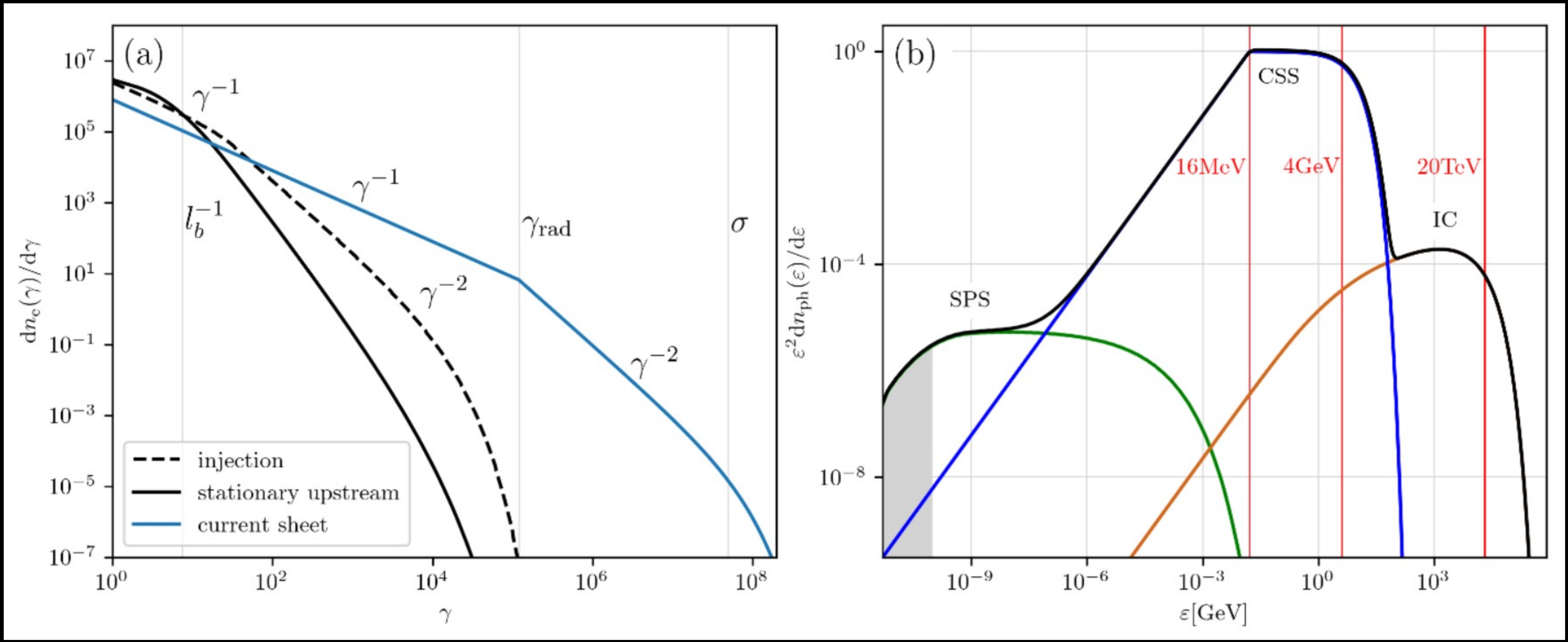
- Pair density is low because "return"-current discharge sends most of the plasma into the star
- Most of the plasma is produced in the current sheet

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

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

Particle Spectrum

Photon Spectrum

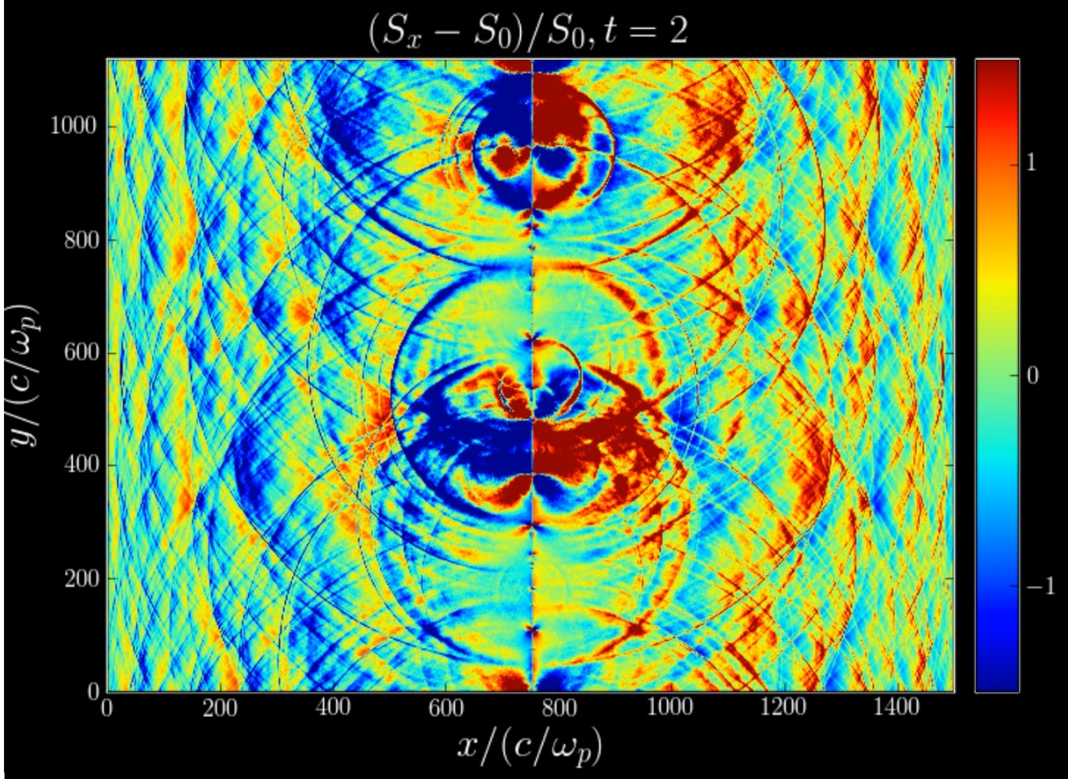


Phase-resolved spectra can probe anisotropy of the particle DF

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

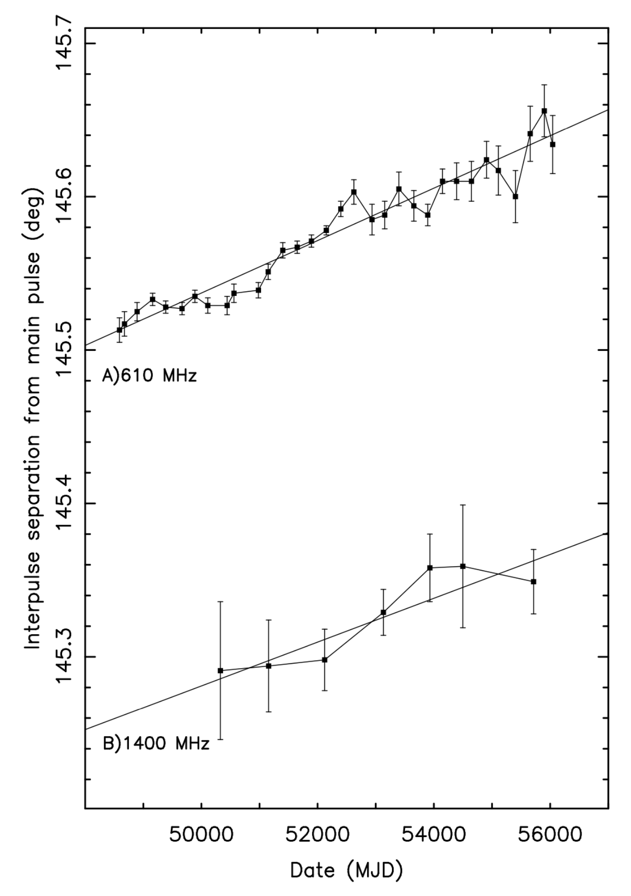
IDEA TO BE TESTED WITH LONG-TERM FERMI DATA

Evidence for the changing magnetic geometry in Crab

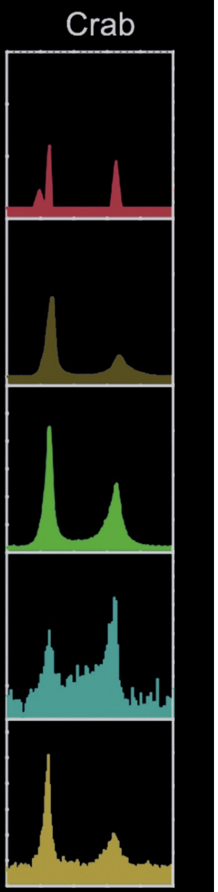


Philippov, Uzdensky, Spitkovsky, Cerutti, 2019 (ApJL)

Potential key for magnetic field evolution in young pulsars



Lyne, Graham-Smith et al., 2013 (Science)



P ~ 33 ms

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. Highest energy TeV photons can be produced in the current sheet as well.
3. Phase-resolved spectra and long-term variability can be very interesting.