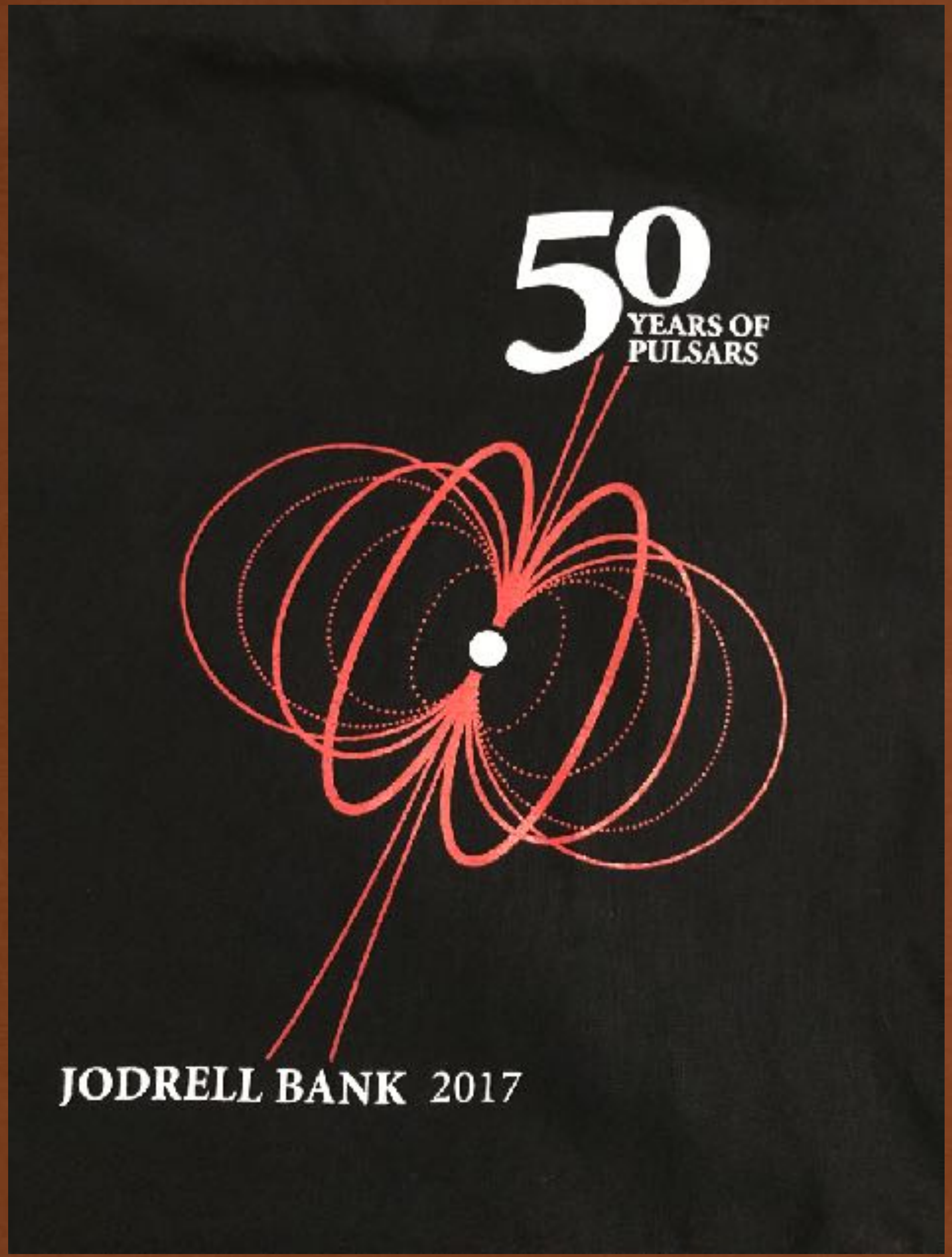
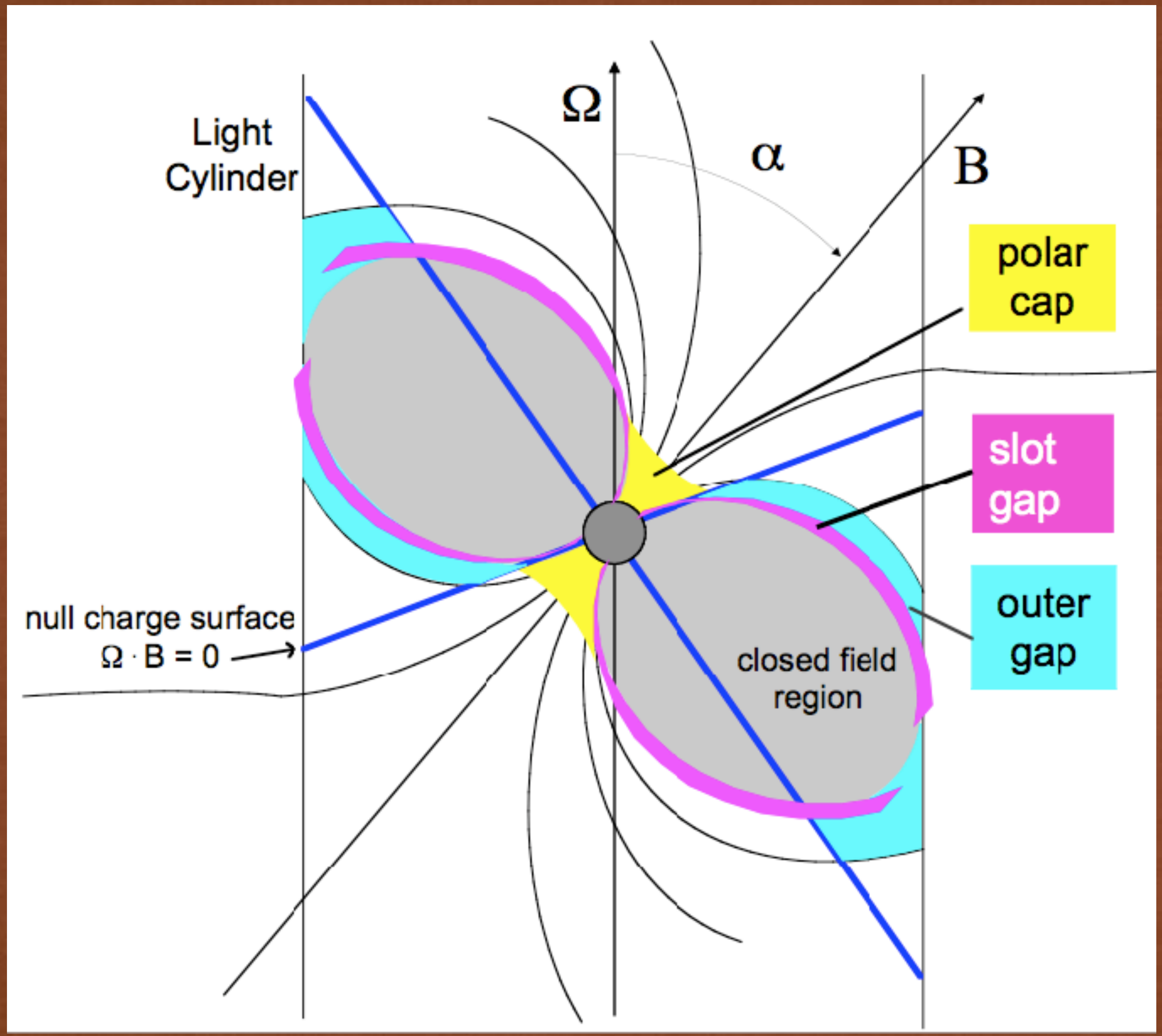
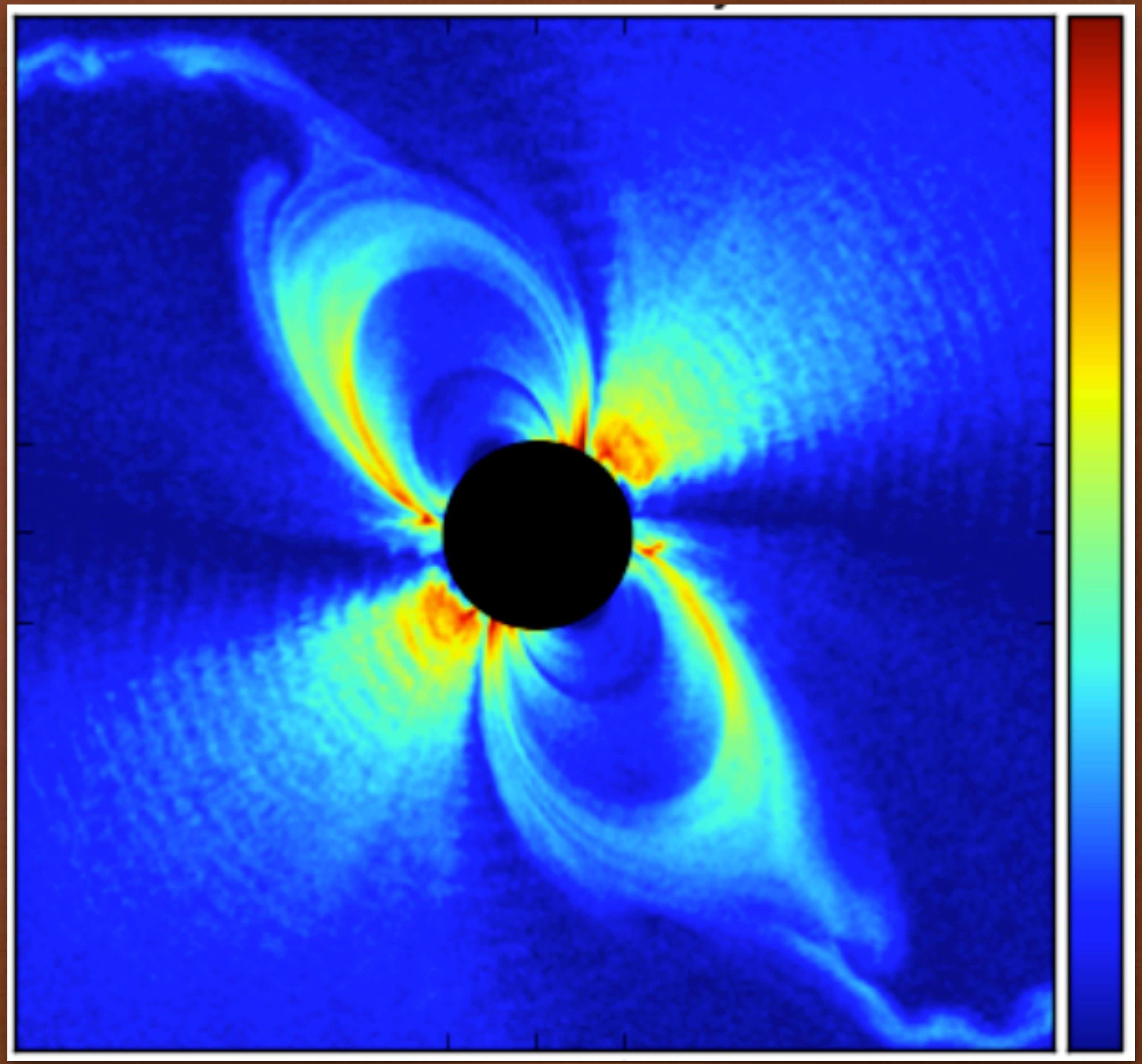
PULSARS: A GIFT THAT KEEPS ON GIVING



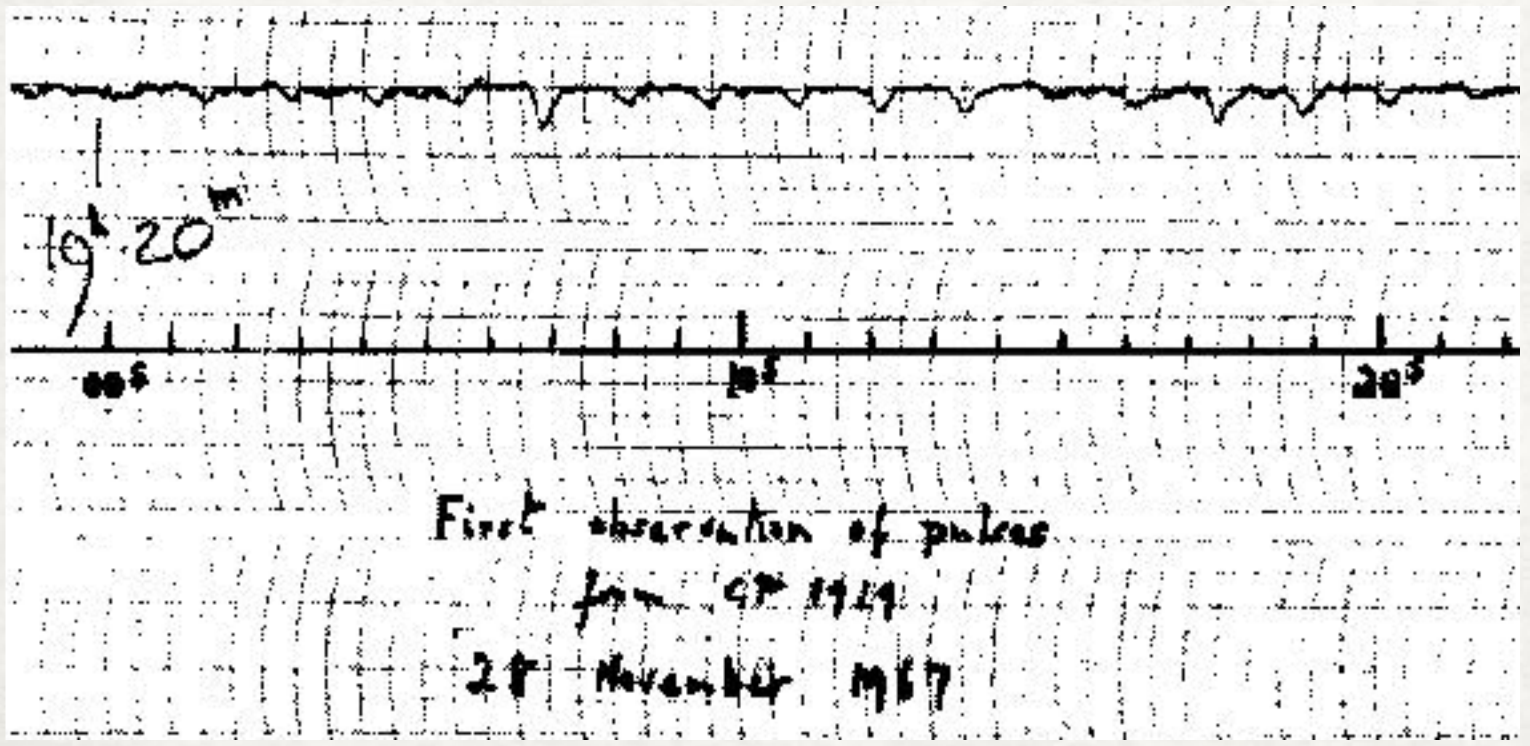


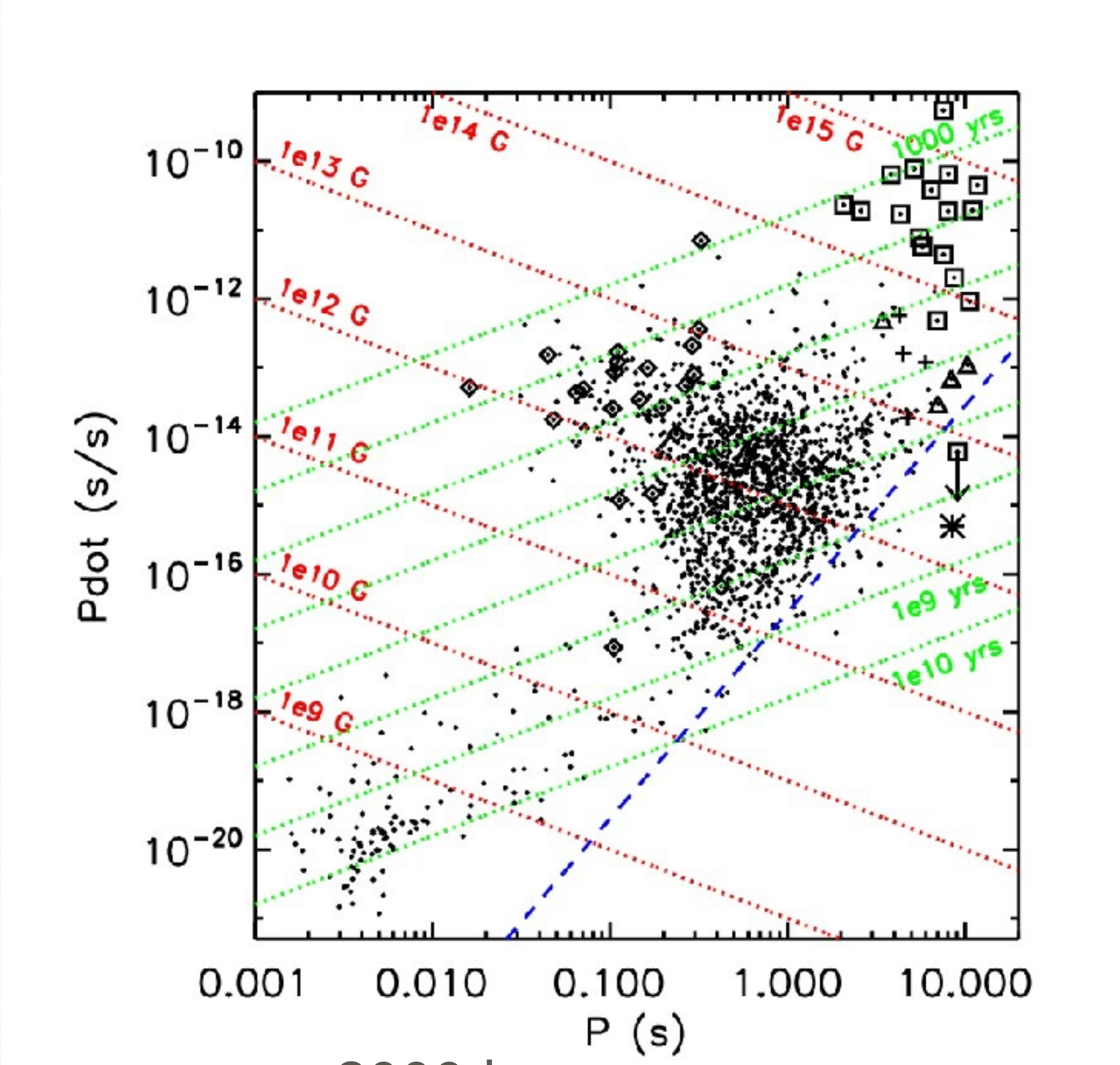


ANATOLY SPITKOVSKY (PRINCETON)
WITH A. PHILIPPOV, B. CERUTTI, H. HAKOBYAN, J. LI, X.BAI

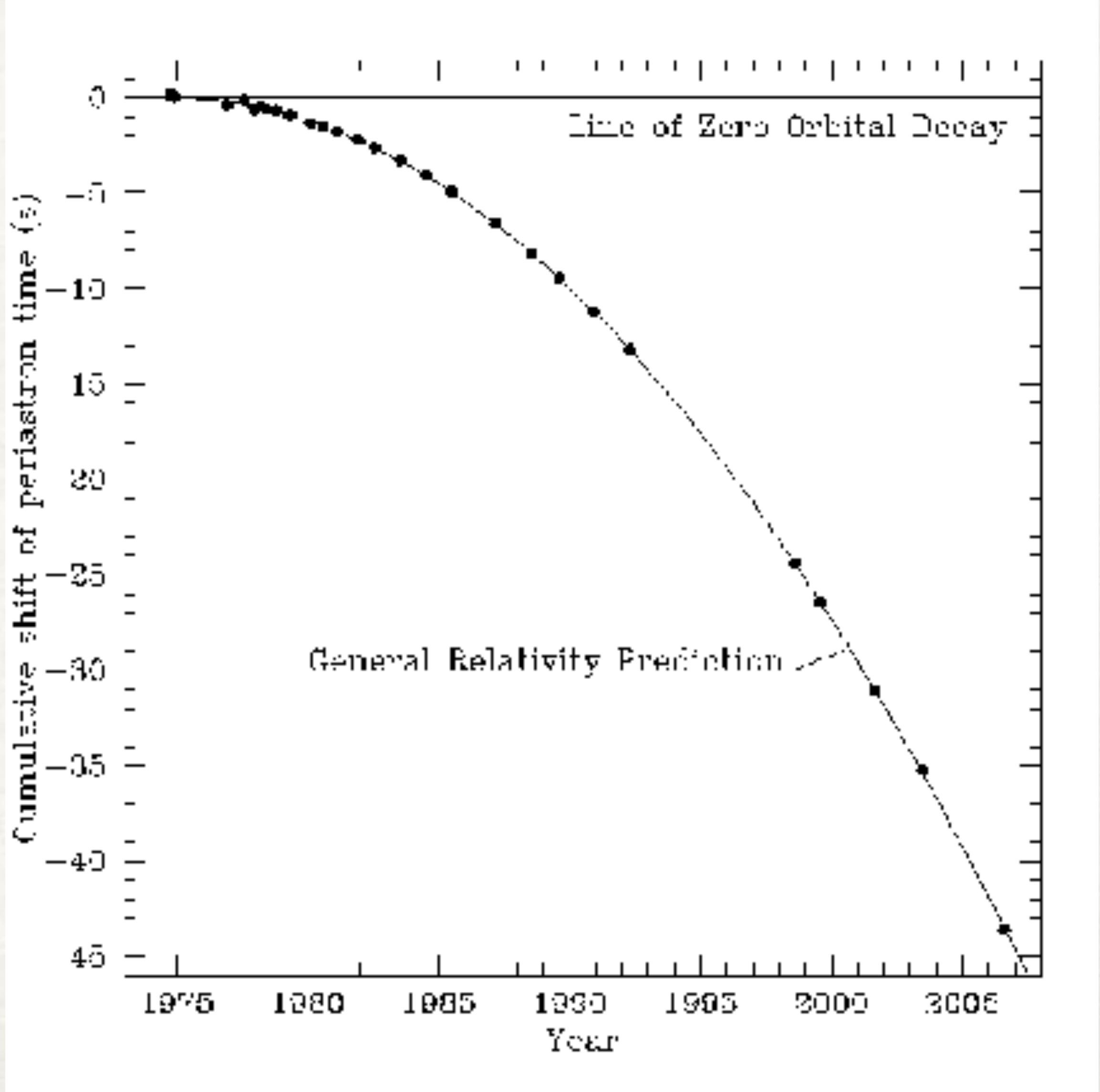
PULSARS: A GIFT FOR OBSERVERS

- Rotating magnetized neutron stars in their many incarnations:
- Radio Pulsars: regular vs ms
- Amazing clocks: tests of GR
- Hulse-Taylor, Double Pulsar
- upcoming: Nanograv



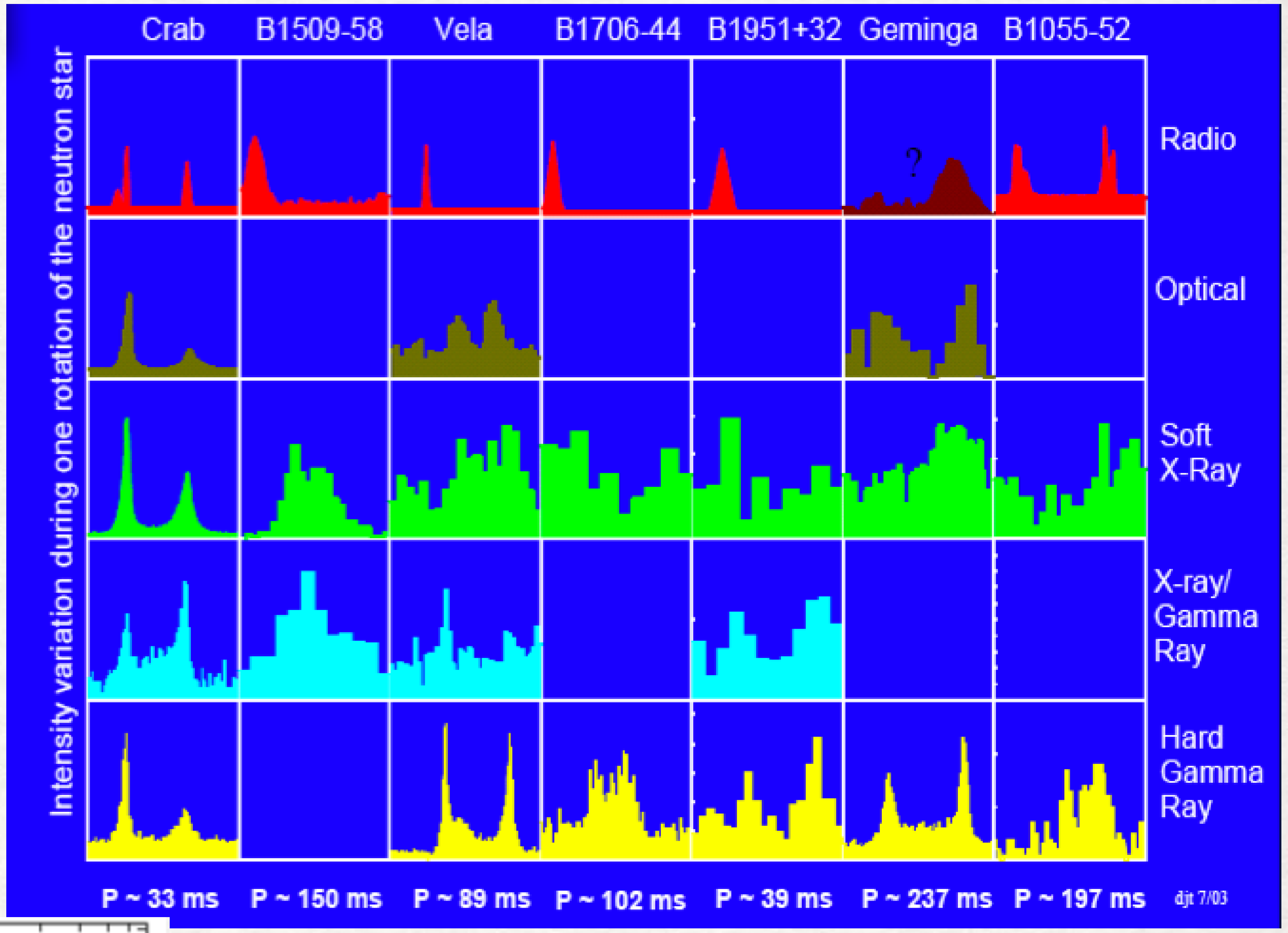


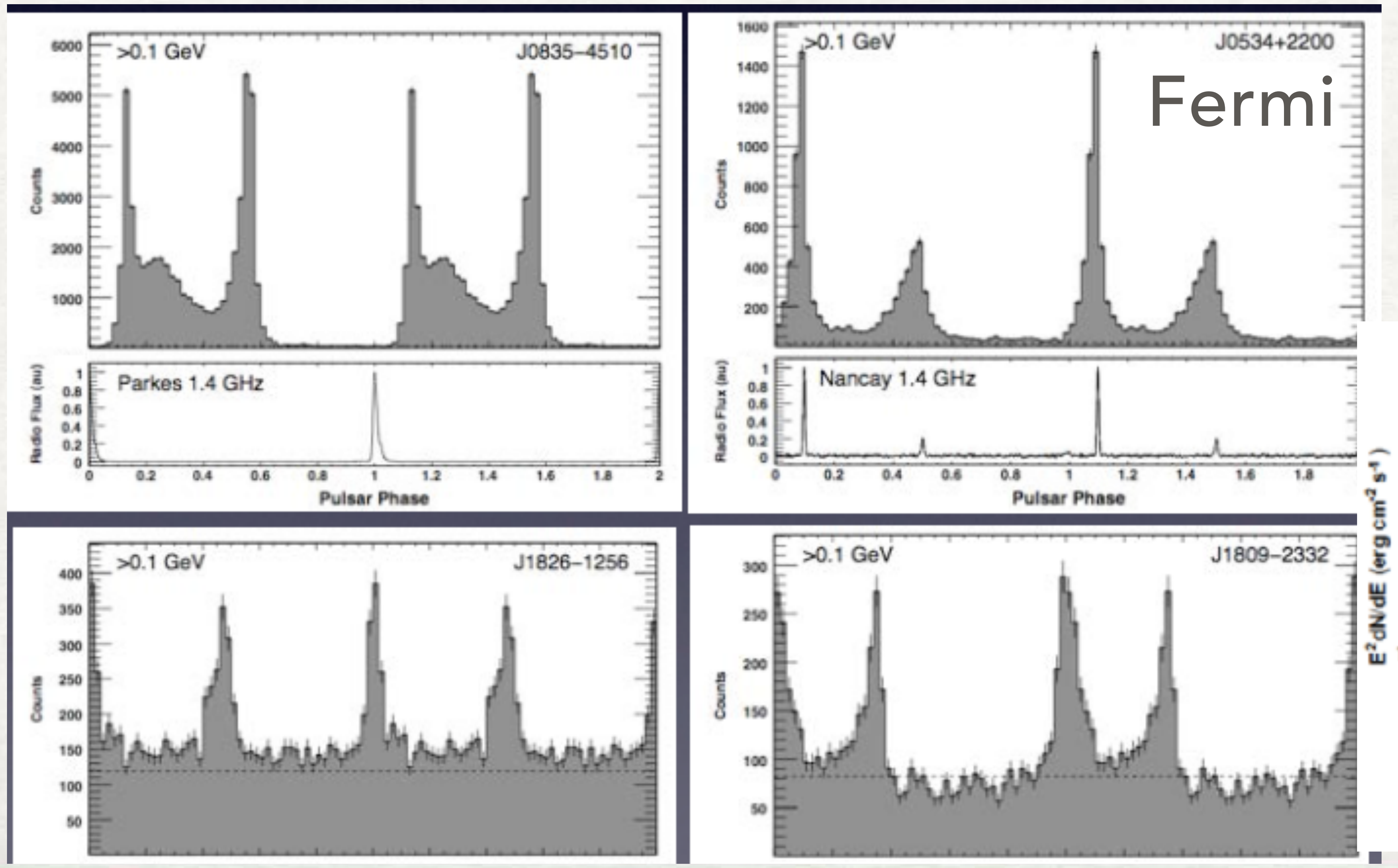
> 2000 known

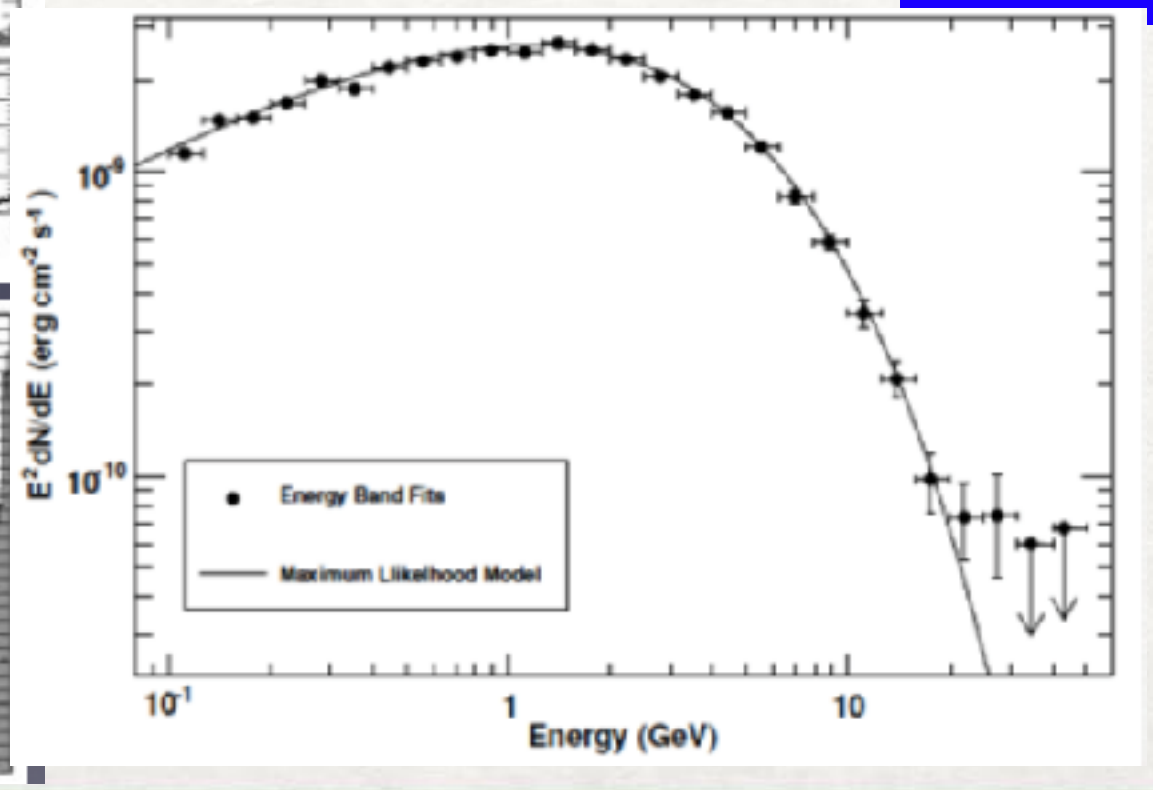


PULSARS: A GIFT FOR OBSERVERS

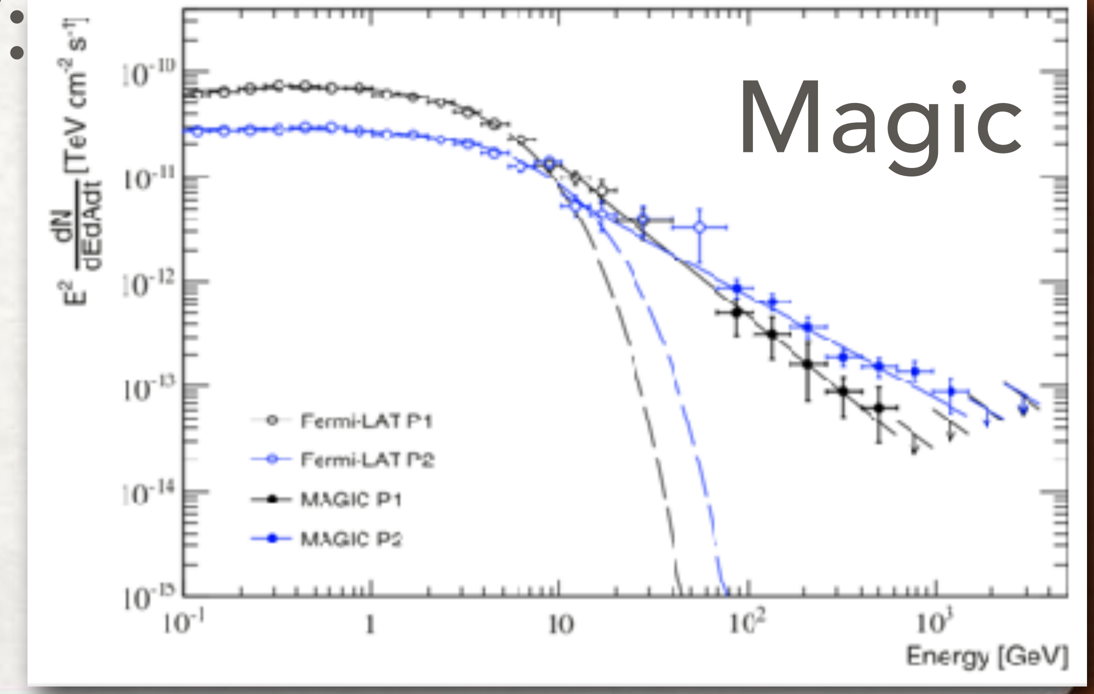
- Rotating magnetized neutron stars in their many incarnations:
- Broadband pulsed emitters
- Went from 7 to 230 gamma-ray emitting pulsars in 10 years of Fermi, including radio-quiet and radio-loud discoveries







Reaching TeV:

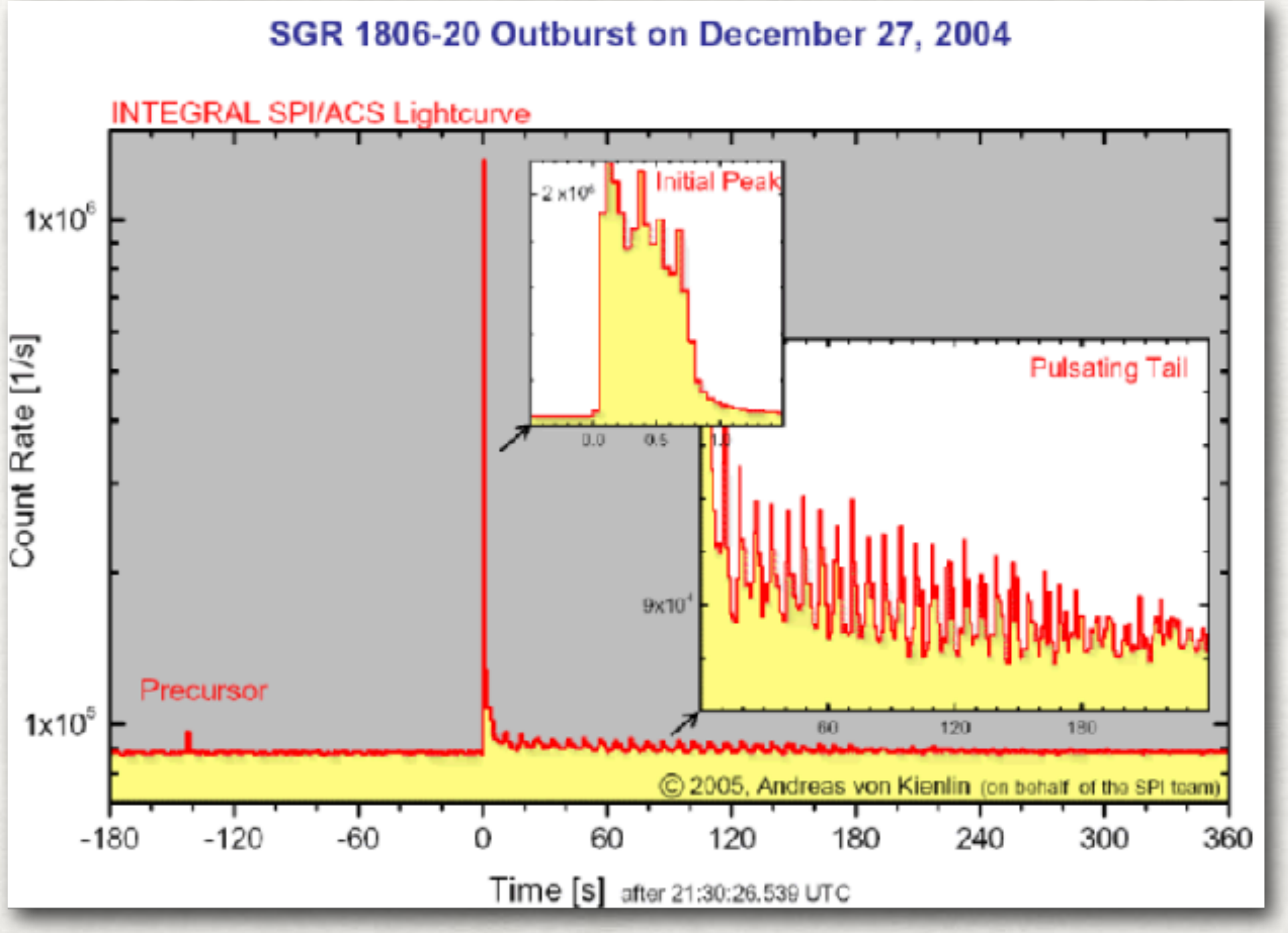


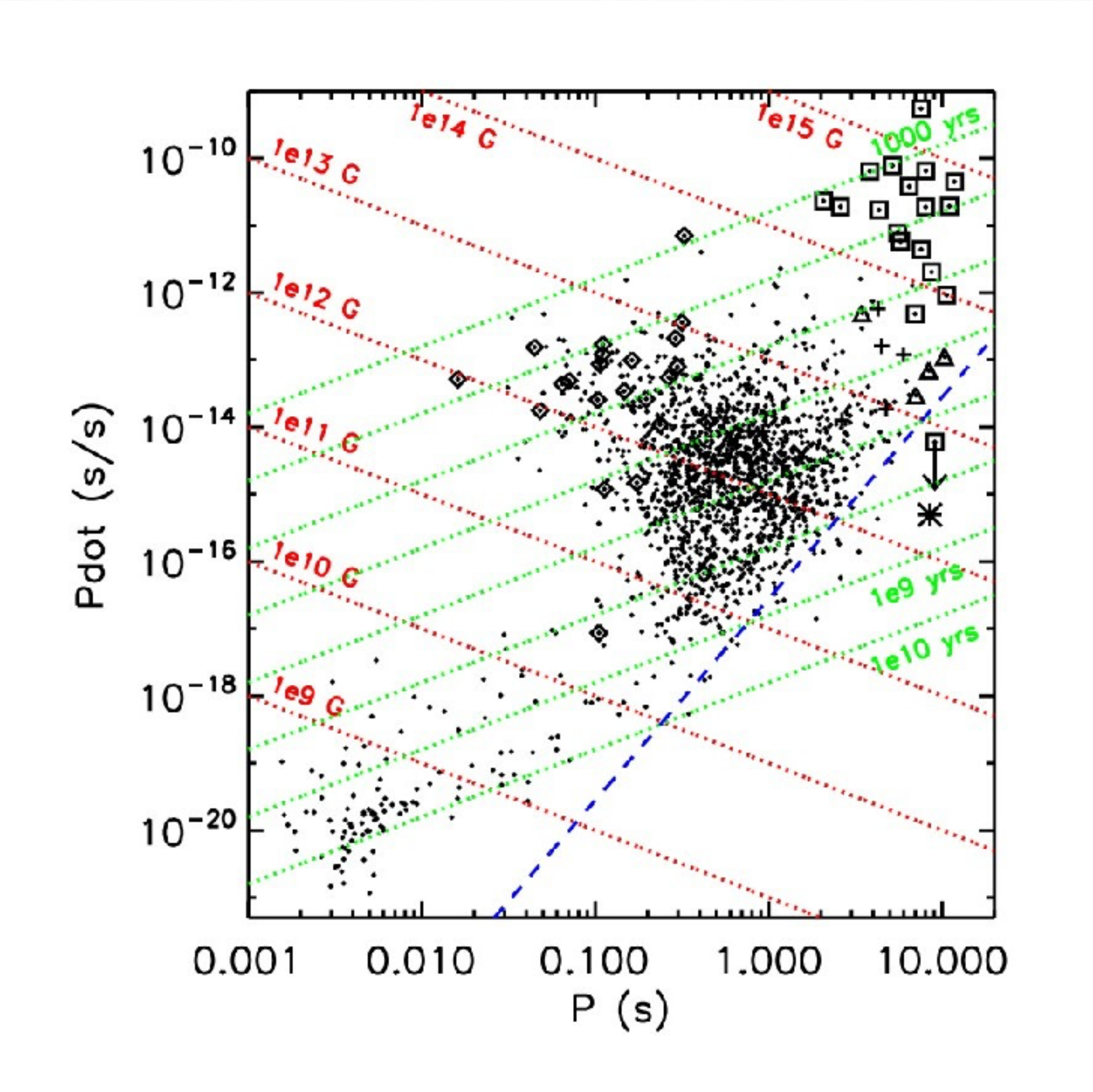
PULSARS: A GIFT FOR OBSERVERS

- Rotating magnetized neutron stars in their many incarnations:

- Exotic and transient objects

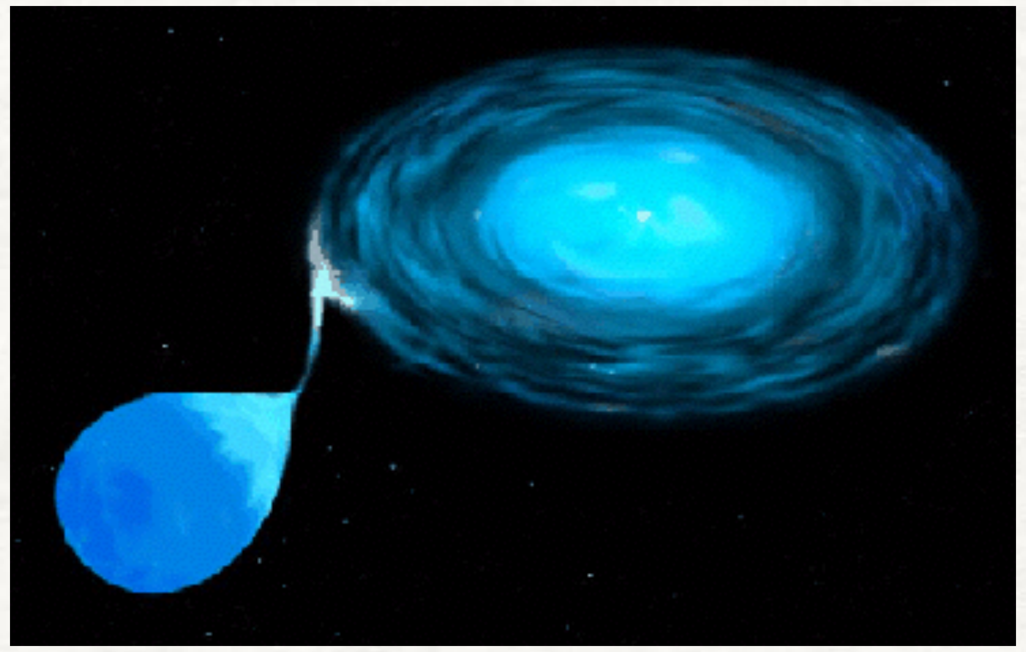
- Magnetars, SGRs, AXPs: $B>10^{14}$G; energy release larger than spin down energy — powered by magnetic energy dissipation

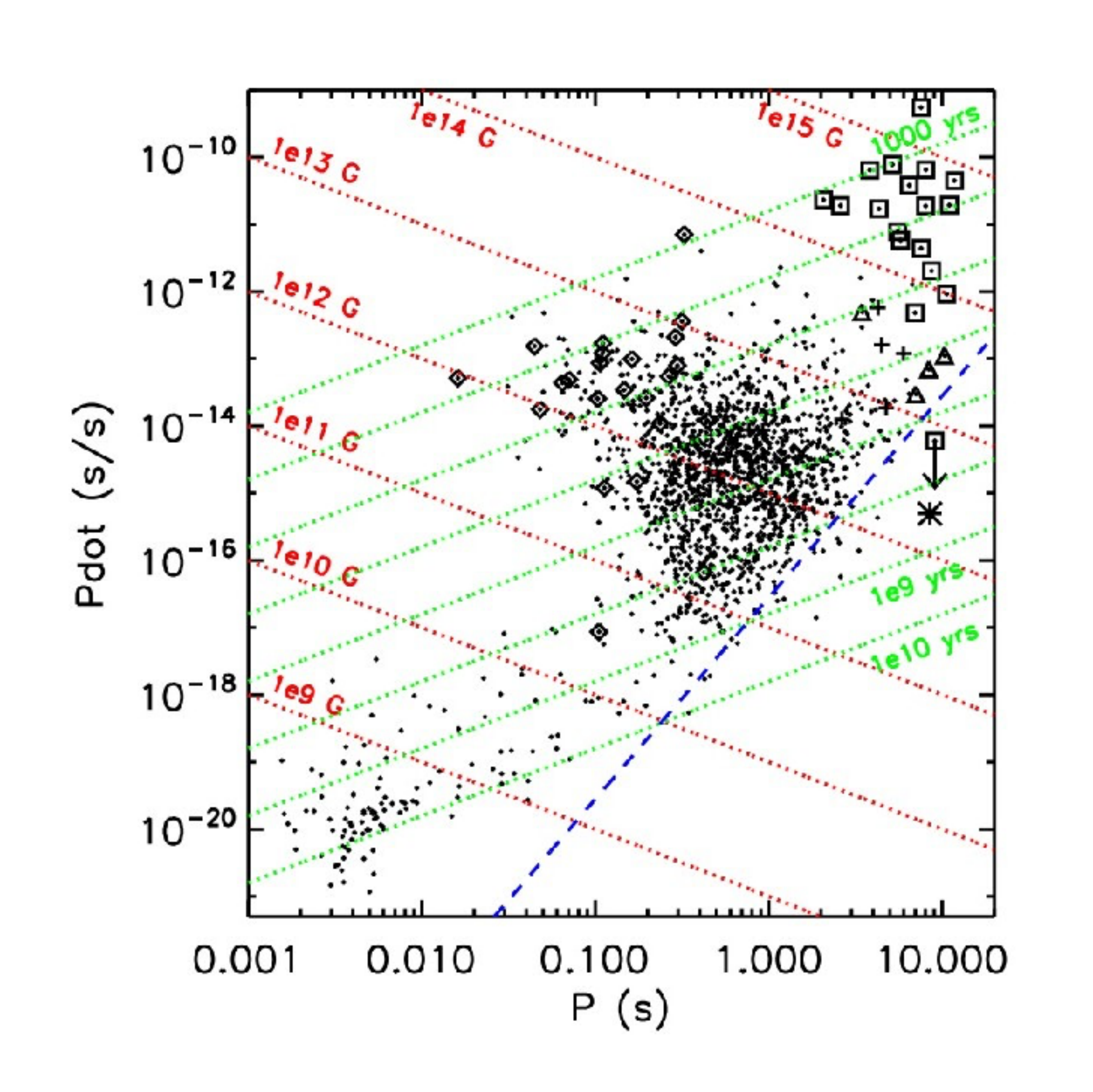




PULSARS: A GIFT FOR OBSERVERS

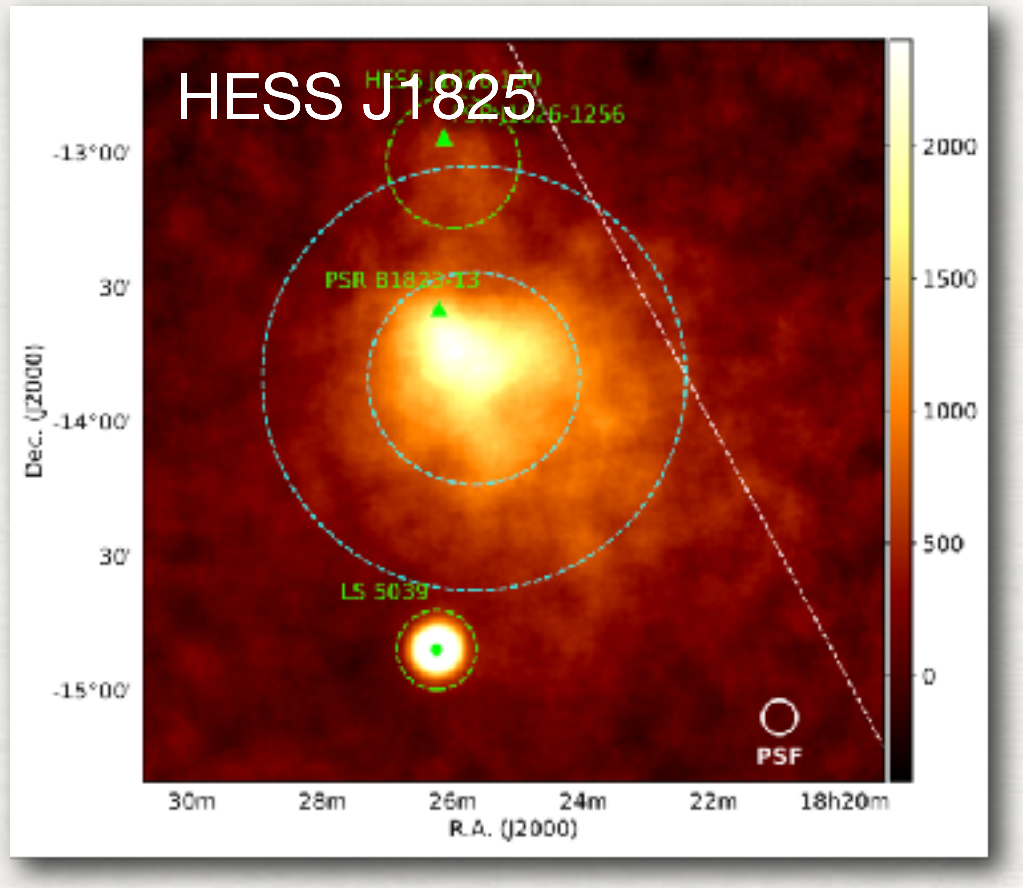
- Rotating magnetized neutron stars in their many incarnations
- Binary and accreting sources:
- HMXB, LMXB
- Transitional MSPs
- “Spiders”: black widows and redbacks
- Gamma-ray emitting binaries
- Thermal emission from polar caps of ms psrs (soon NICER results)

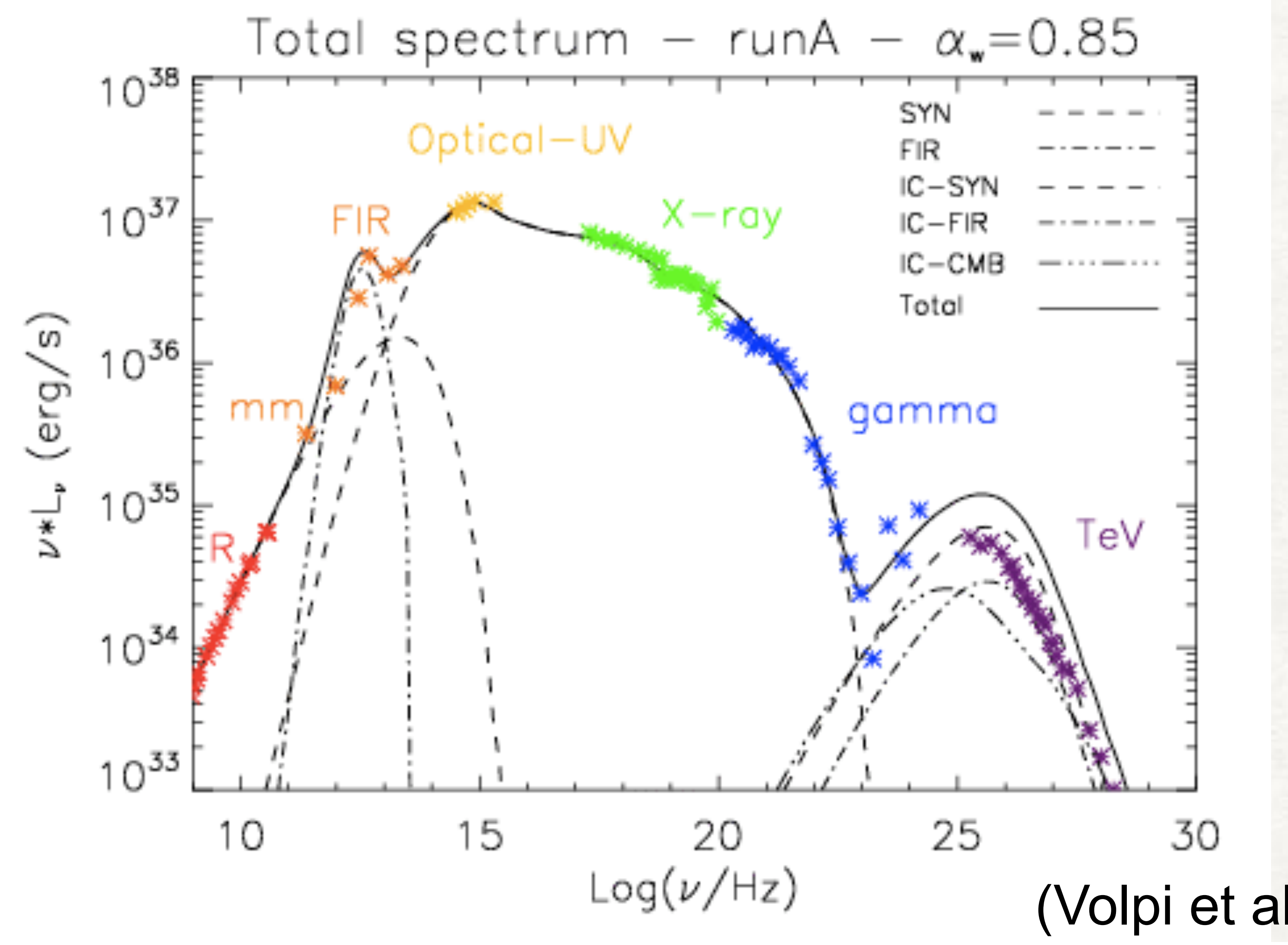




PULSARS: A GIFT FOR OBSERVERS

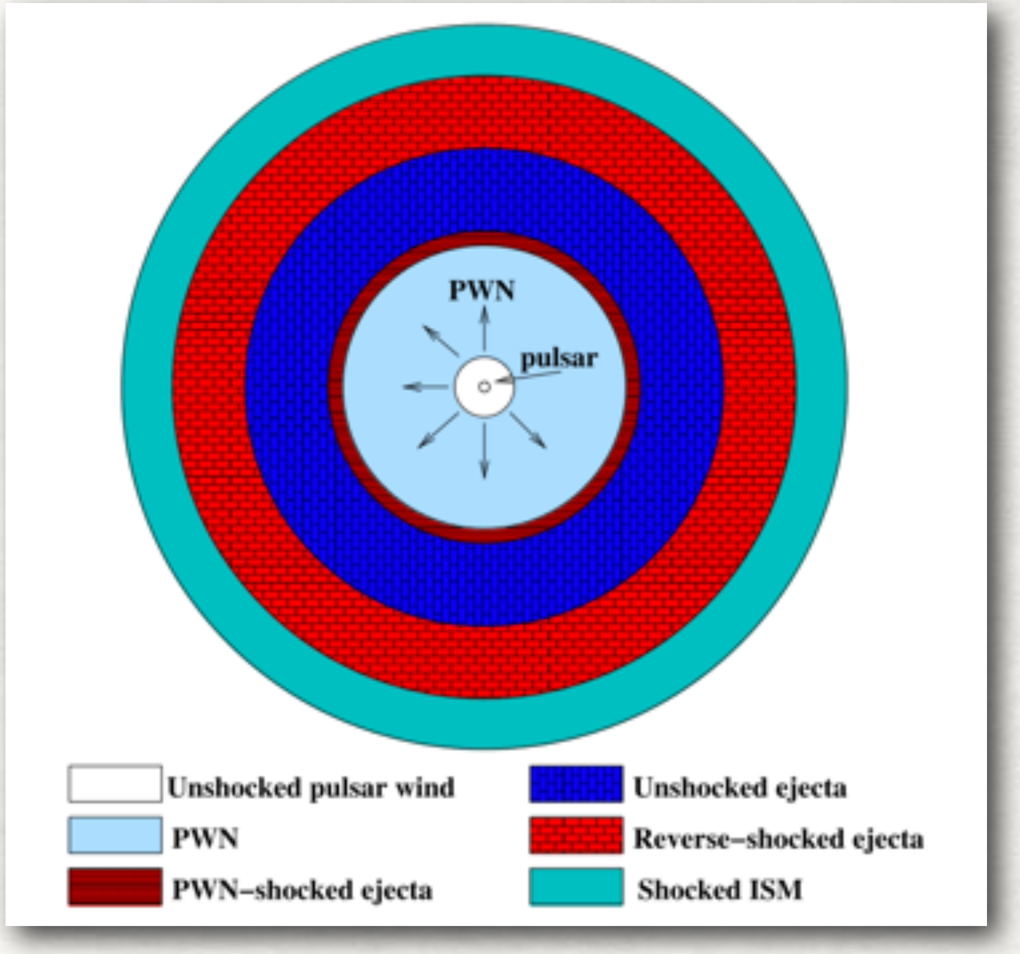
- Rotating magnetized neutron stars in their many incarnations:
- Pulsar wind nebulae

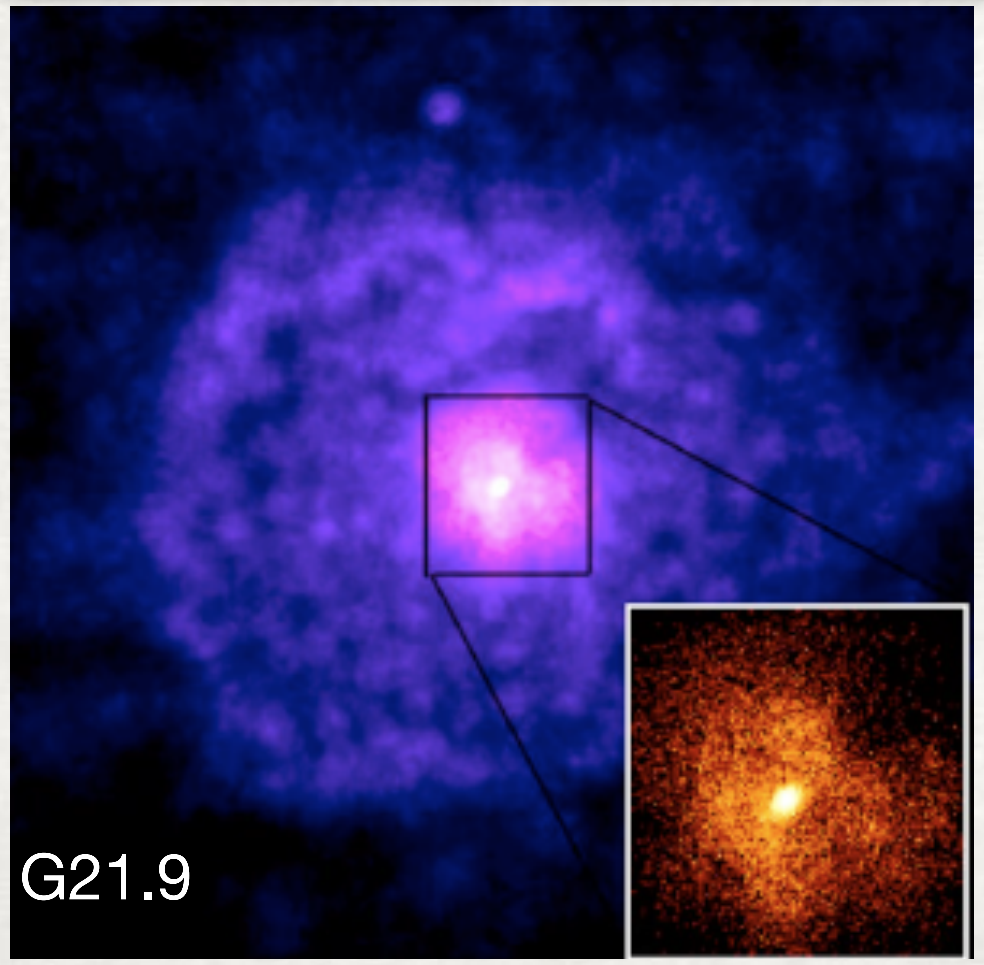


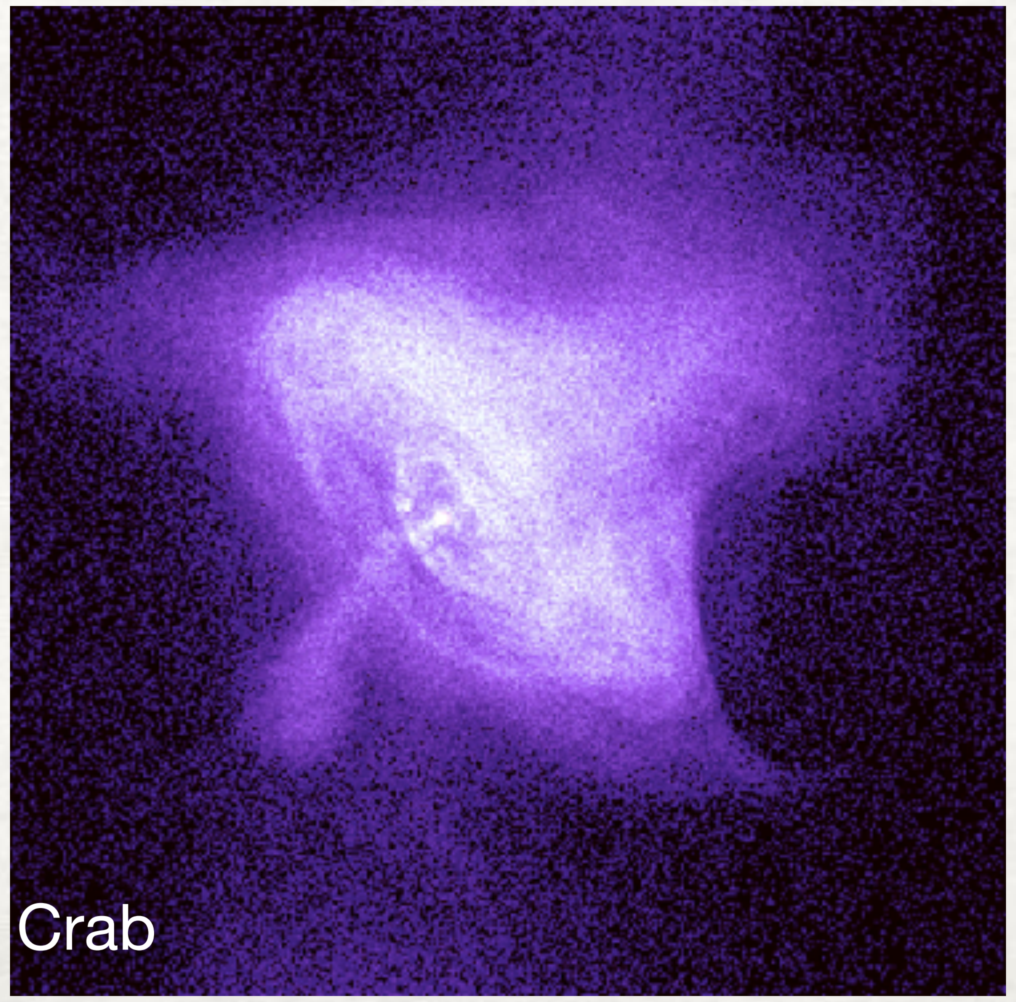


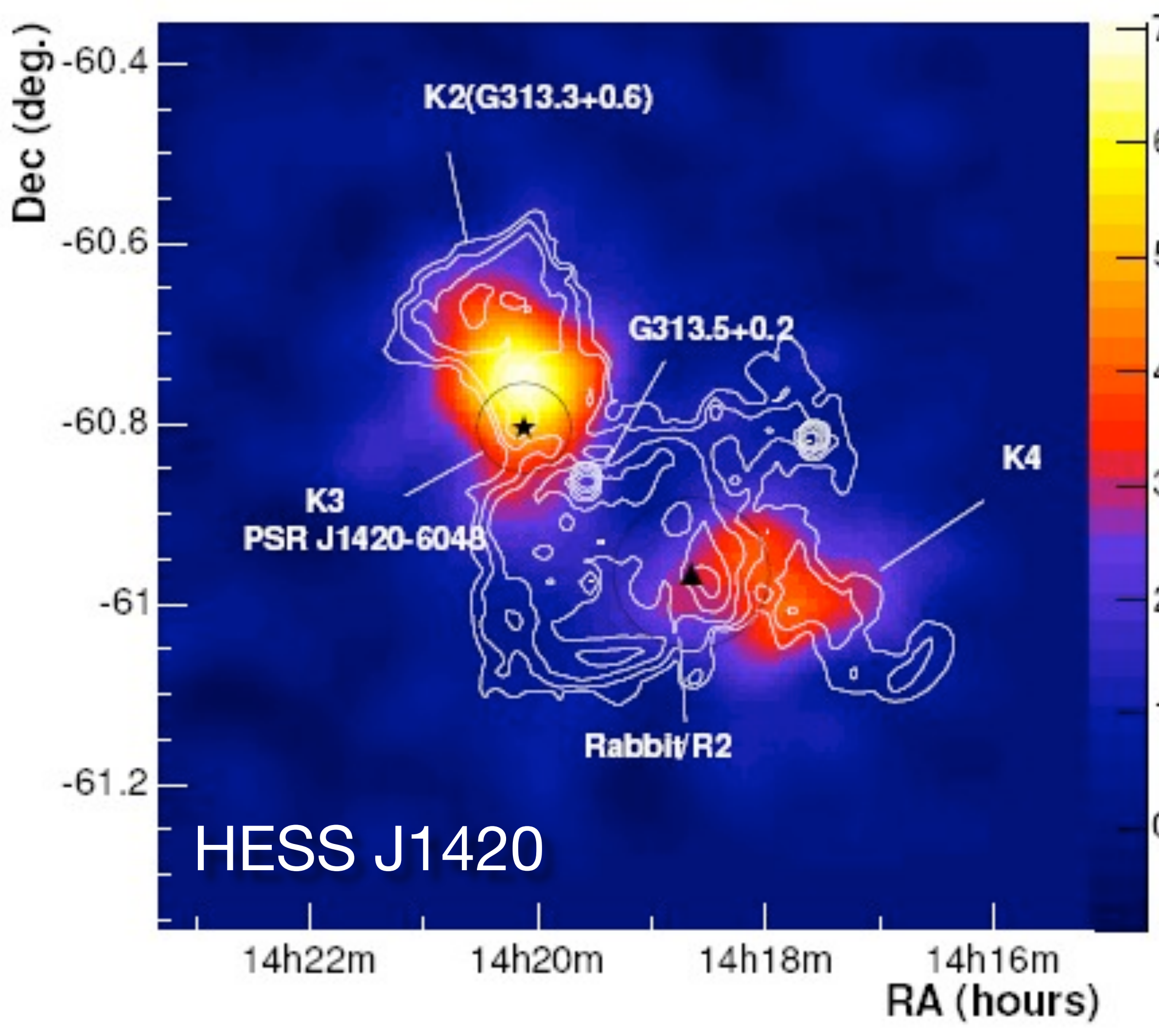
(Volpi et al 09)

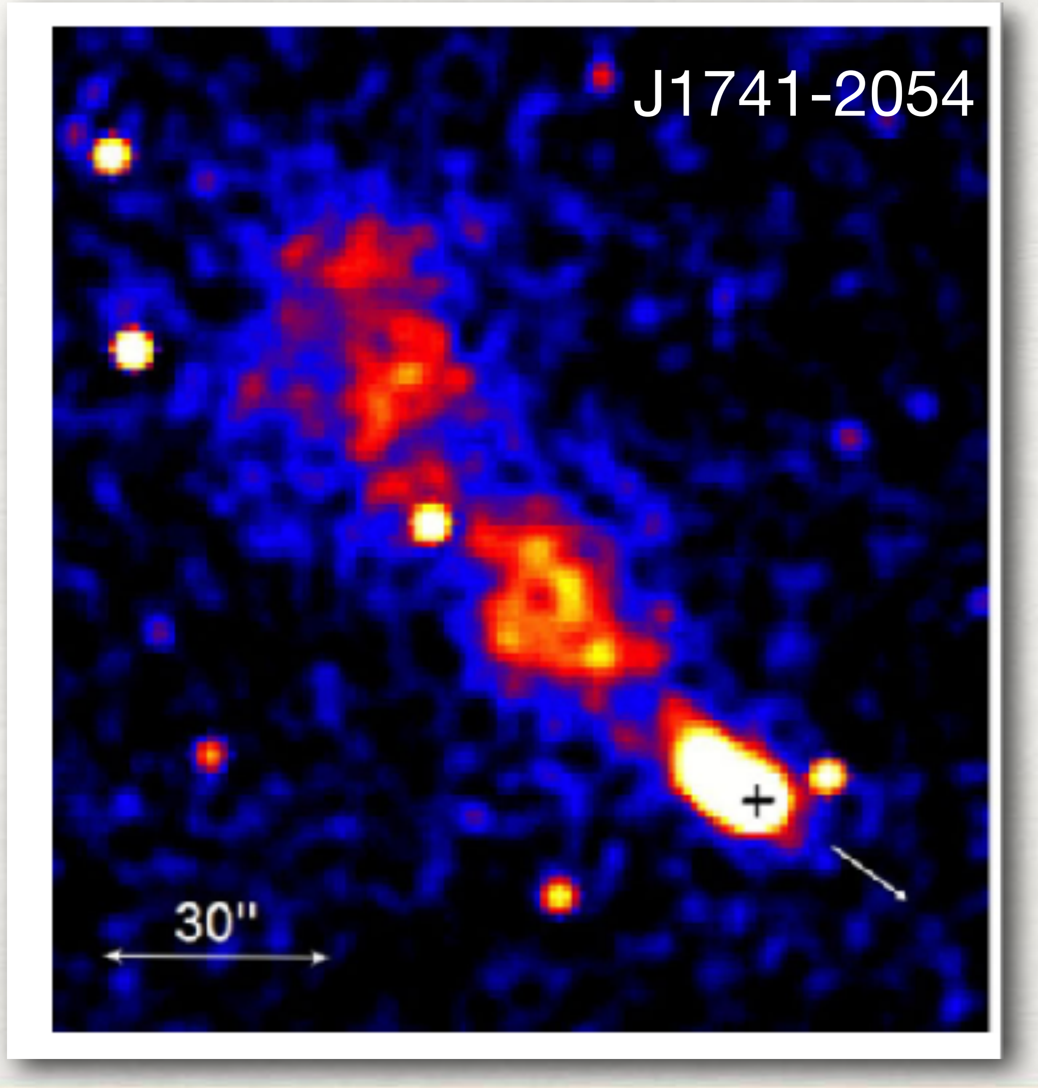
Major source for CTA





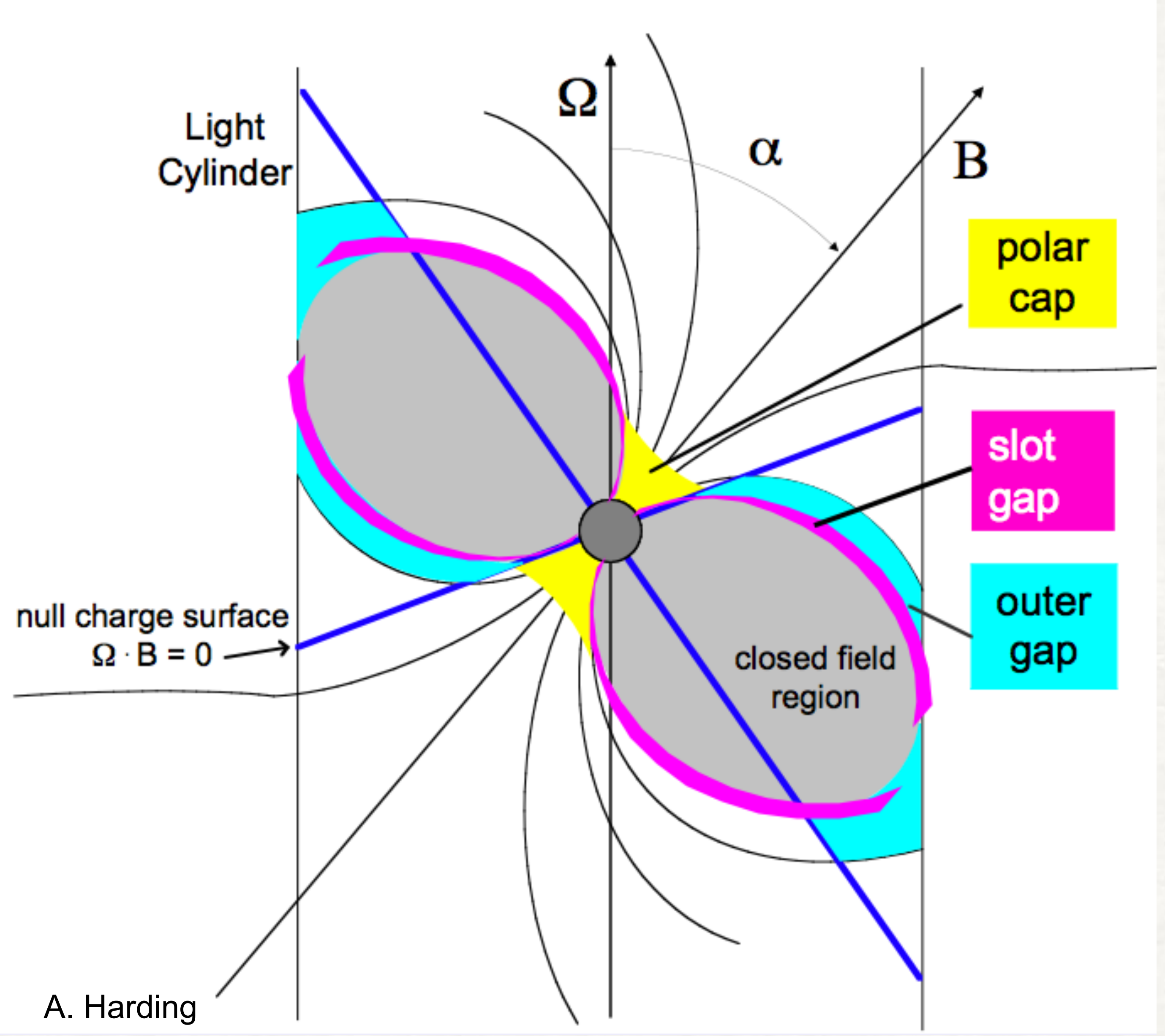


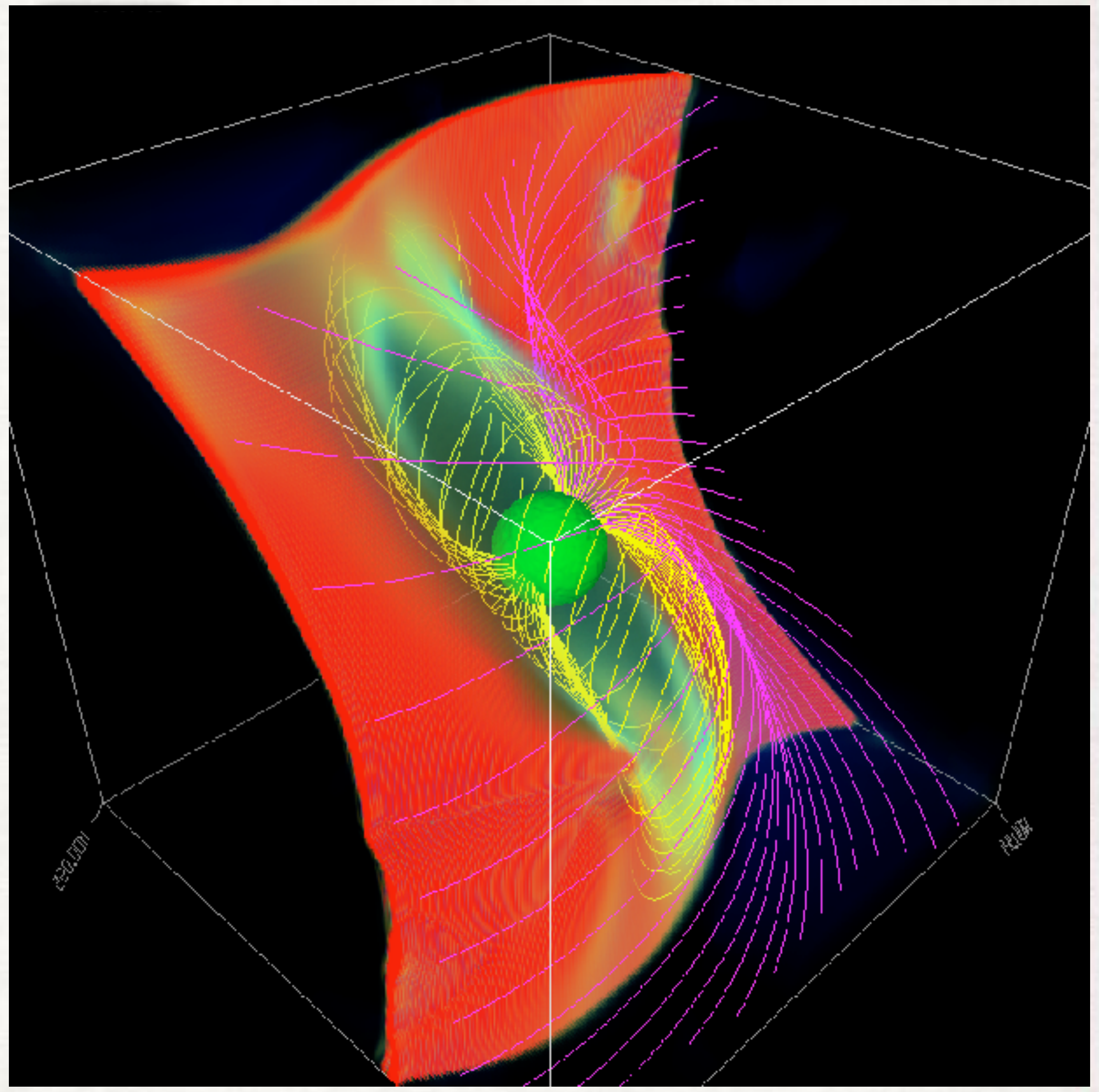


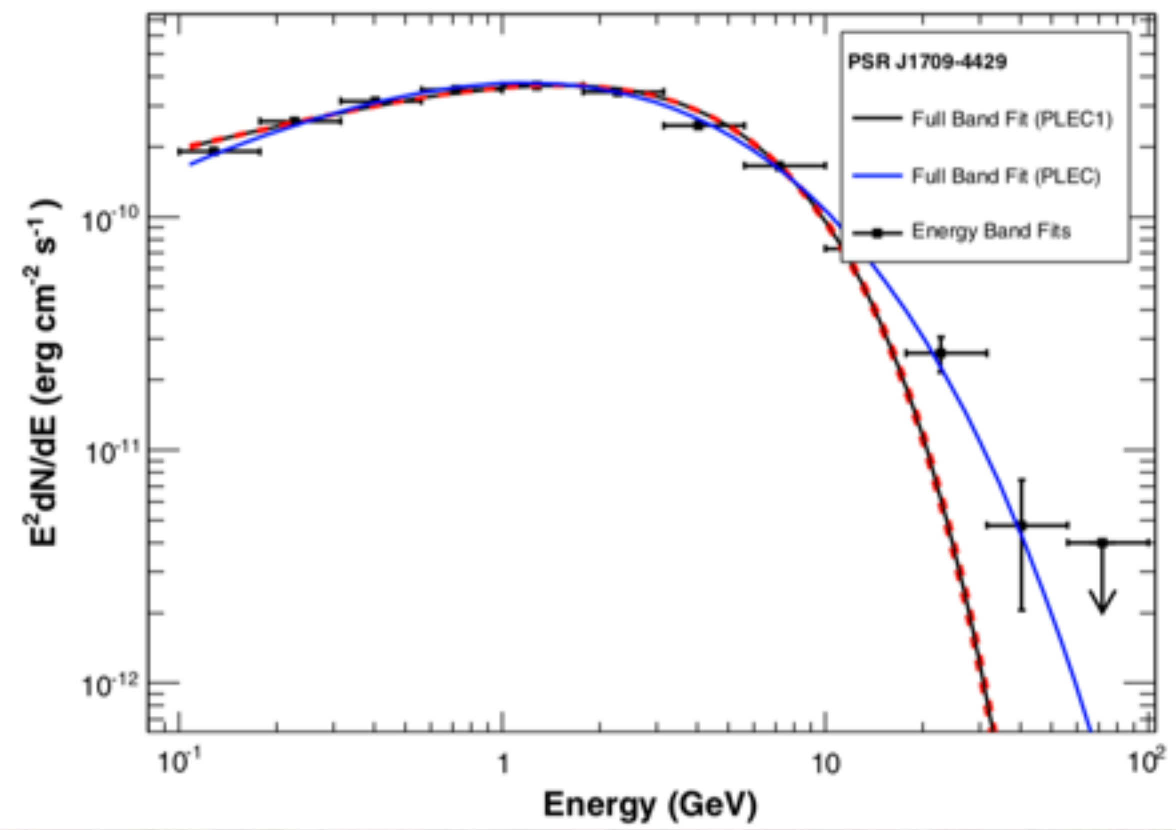


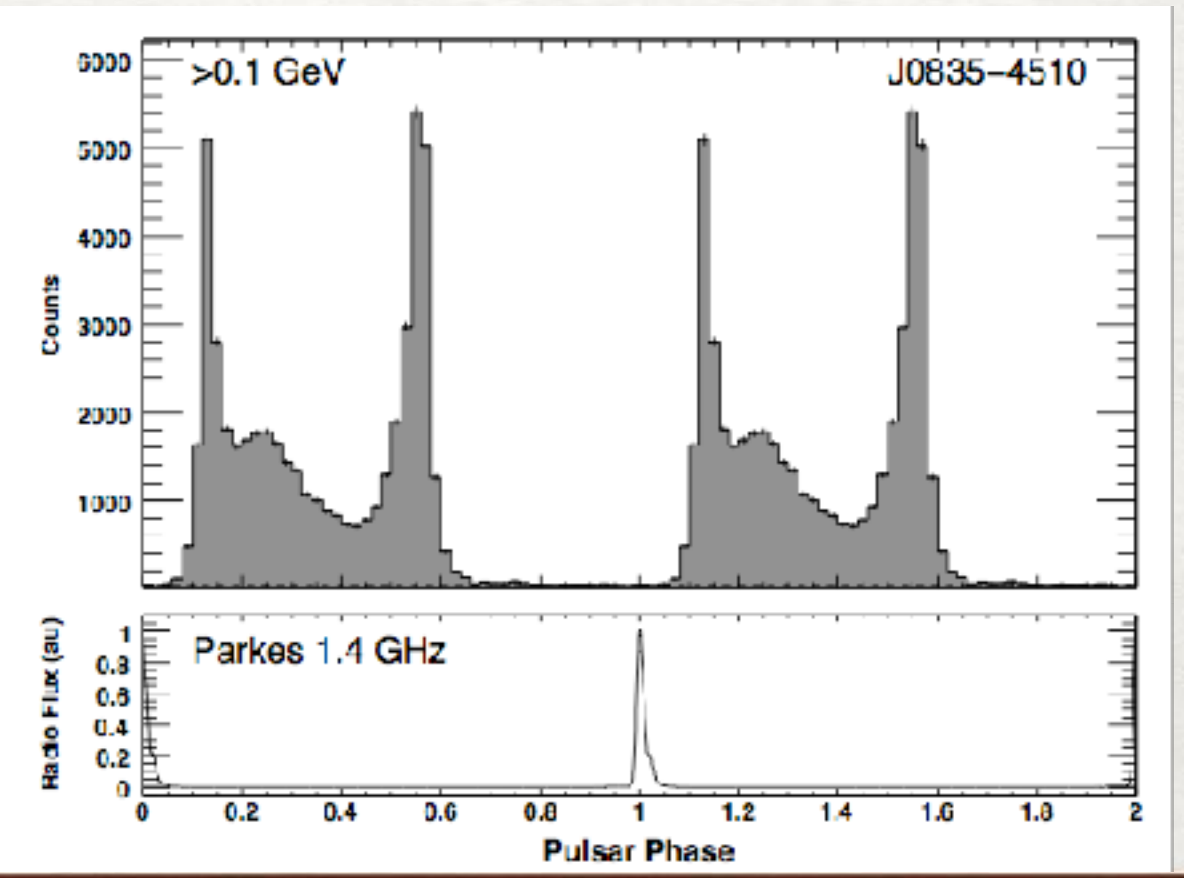
PULSARS: A GIFT FOR THEORISTS

- Playground of high B field, strong gravity, fast rotation, QED, and plasma physics: theorist's dream!
- Origin of gamma-ray emission: gaps, current sheets, synchrotron, curvature, IC?
- Light curves and spectra
- Origin of radio emission (coherent!)
- Luminosity-Edot relation
- Multiwavelength correlations
- What are the properties of the wind?
- What is the magnetospheric structure of pulsars, and how is the plasma supplied?



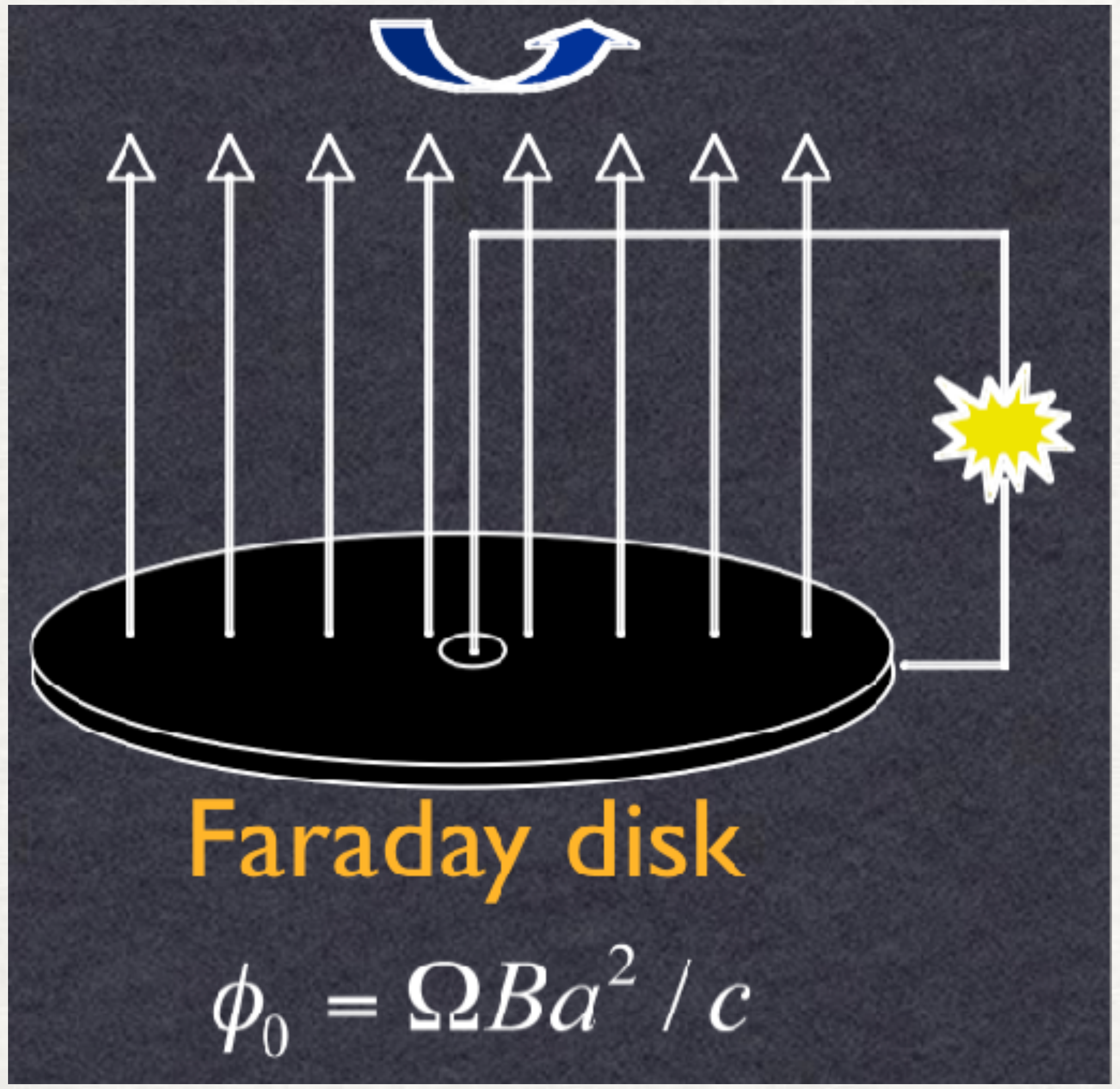




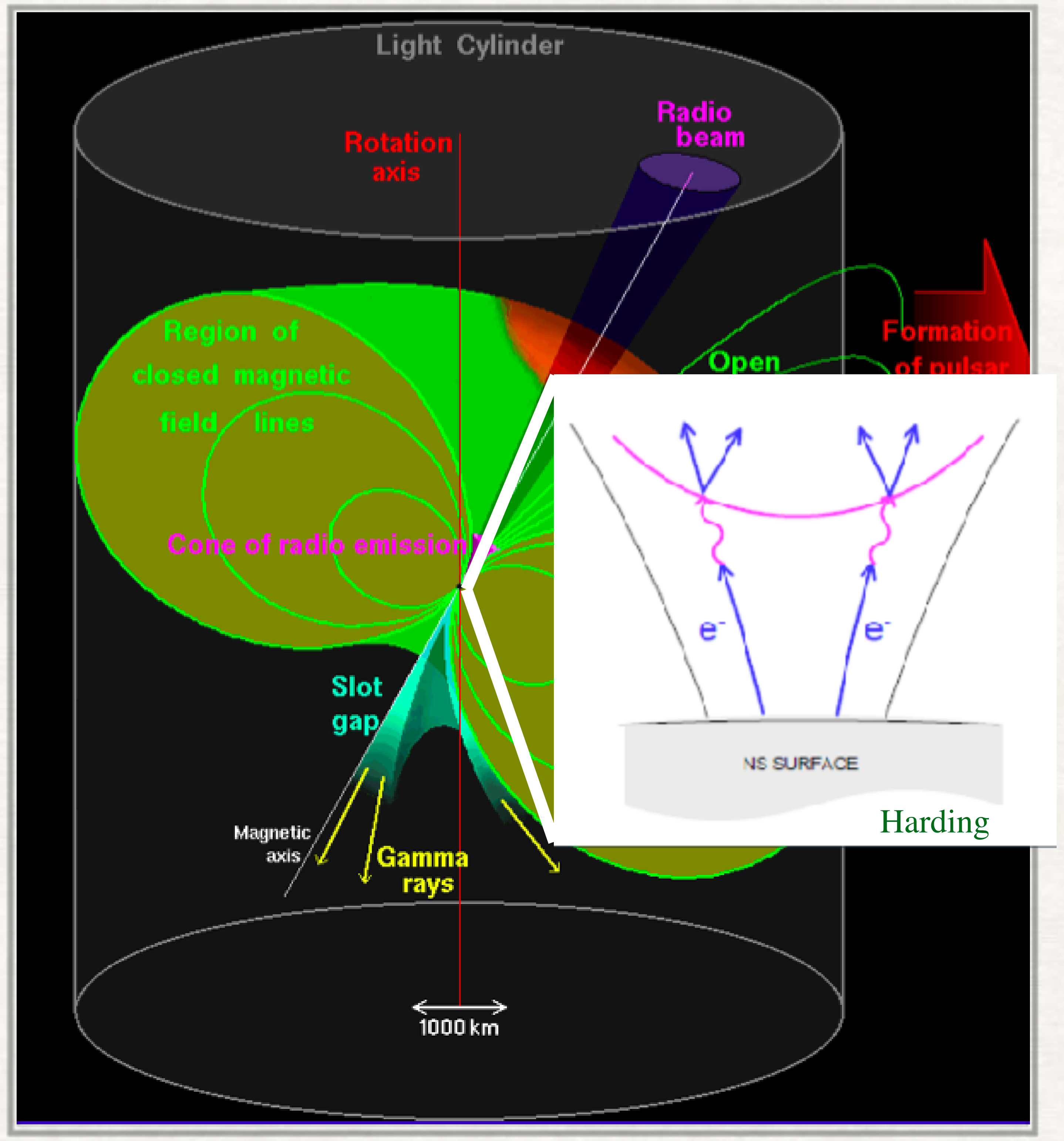


PULSAR PROBLEM: AN OLD CHESTNUT

- What is the magnetospheric structure of a rotating magnetized conducting sphere with small surface work function?

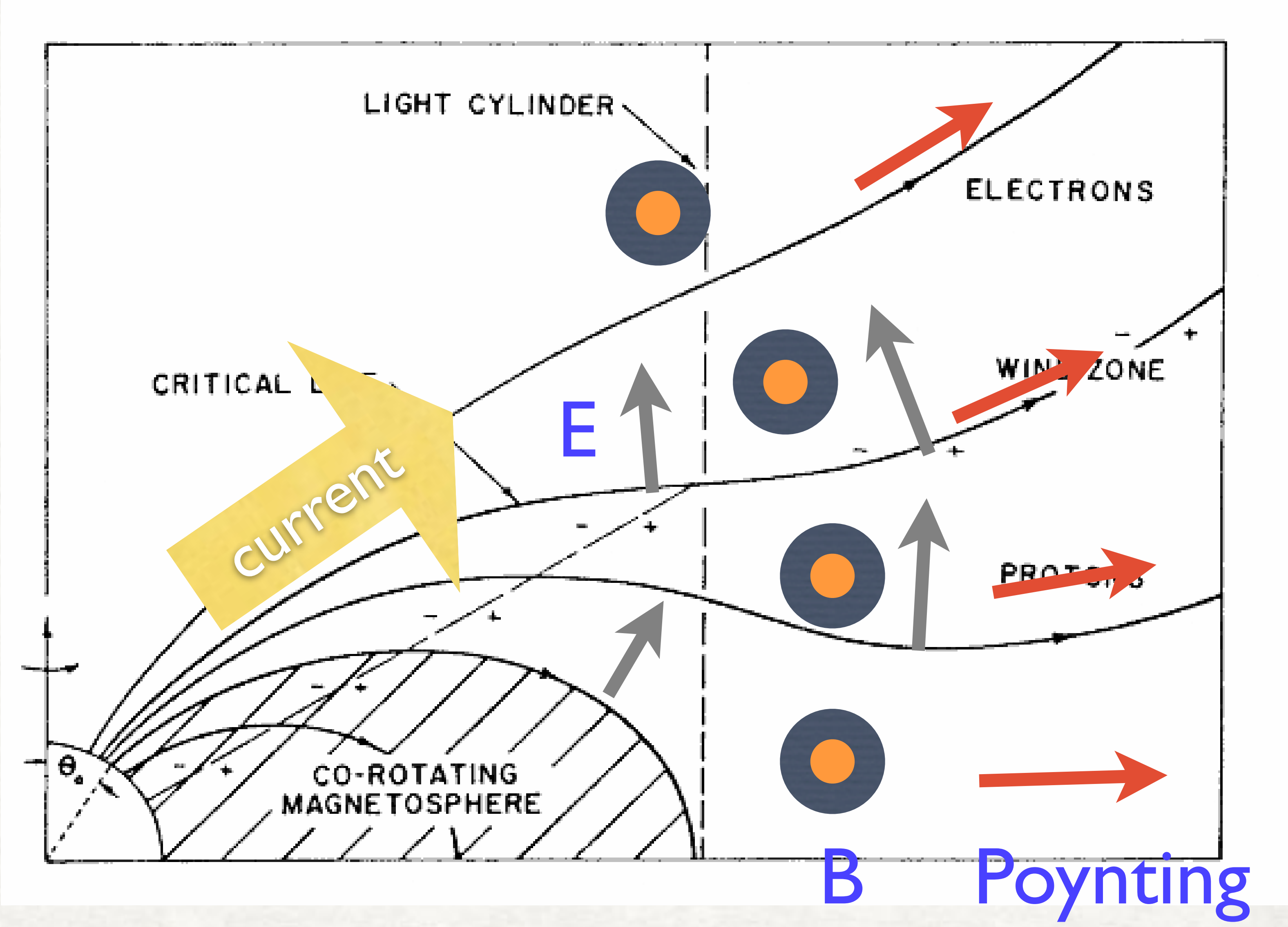


Pole-equator potential



Goldreich-Julian current

$$j_{GJ} = \rho_{GJ} c = -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi}$$



Goldreich & Julian 1969

Convert rotational energy into magnetized wind energy. Current closure is essential.

PULSAR PROBLEM: METHODS AND APPROXIMATIONS I

- **Force-free** paradigm. Assume plasma is abundant and light.

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

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

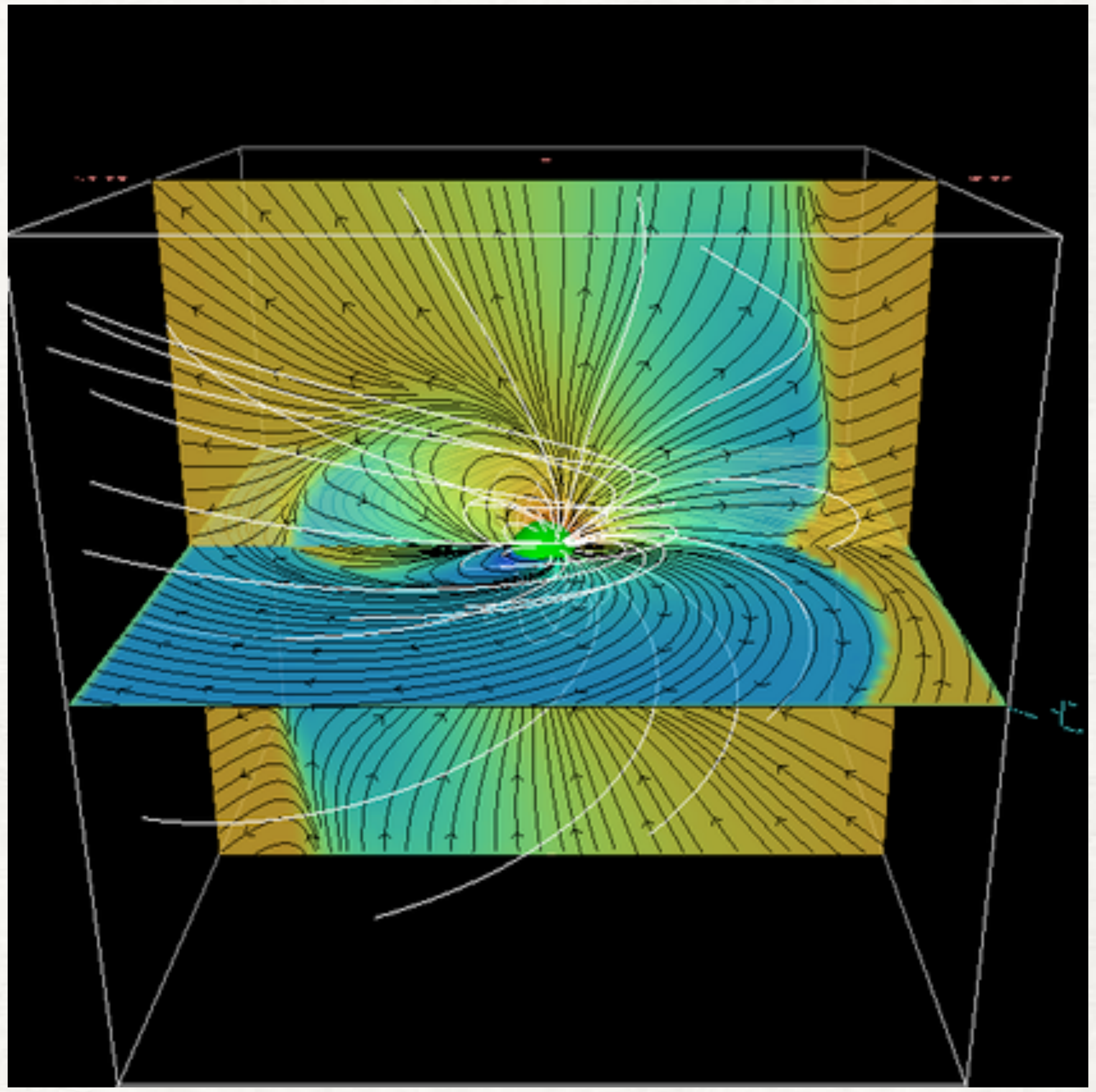
$$\boldsymbol{E} \cdot \boldsymbol{B} = 0$$

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

- Solution properties:
  - Y-point
  - Closed/open field lines
  - Current sheet
  - No pathologies at null surface and LC
  - Predicts the spindown law
  - Field lines are asymptotically radial

- All accelerating fields are shorted out

- Possible to extend to resistive limit (Li et al 2012, Kalapotharakos et al 2012-16)



Oblique: Spitkovsky (2006), Kalapotharakos et al (2009), Petri (2012), Tchekhovskoy et al. (2014) (full MHD)

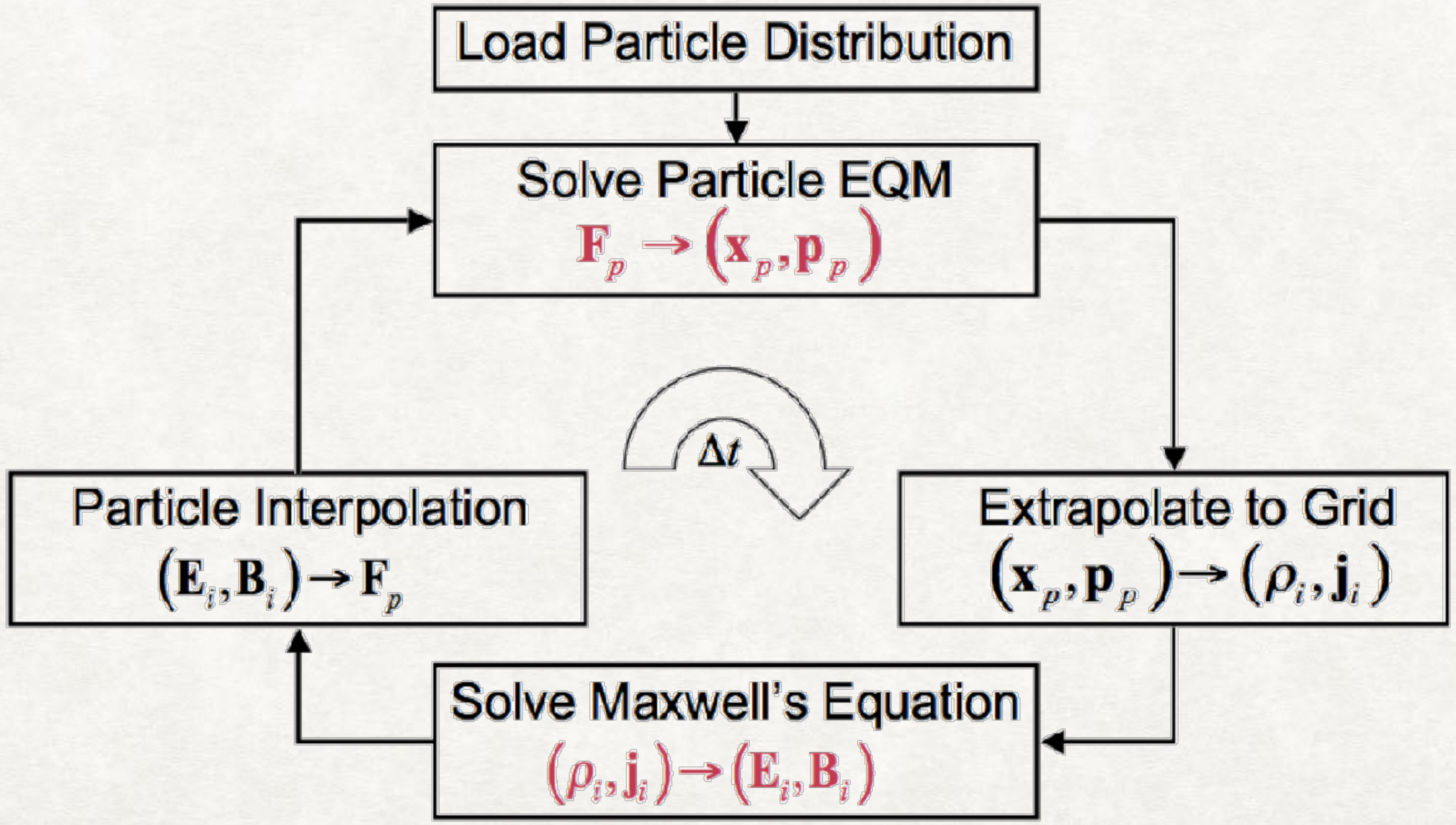
$$\dot{E} = \frac{\mu^2 \Omega^4}{c^3}(1 + \sin^2 \theta)$$

PULSAR PROBLEM: METHODS AND APPROXIMATIONS II

- Kinetic model. Use particle-in-cell (PIC) method

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

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

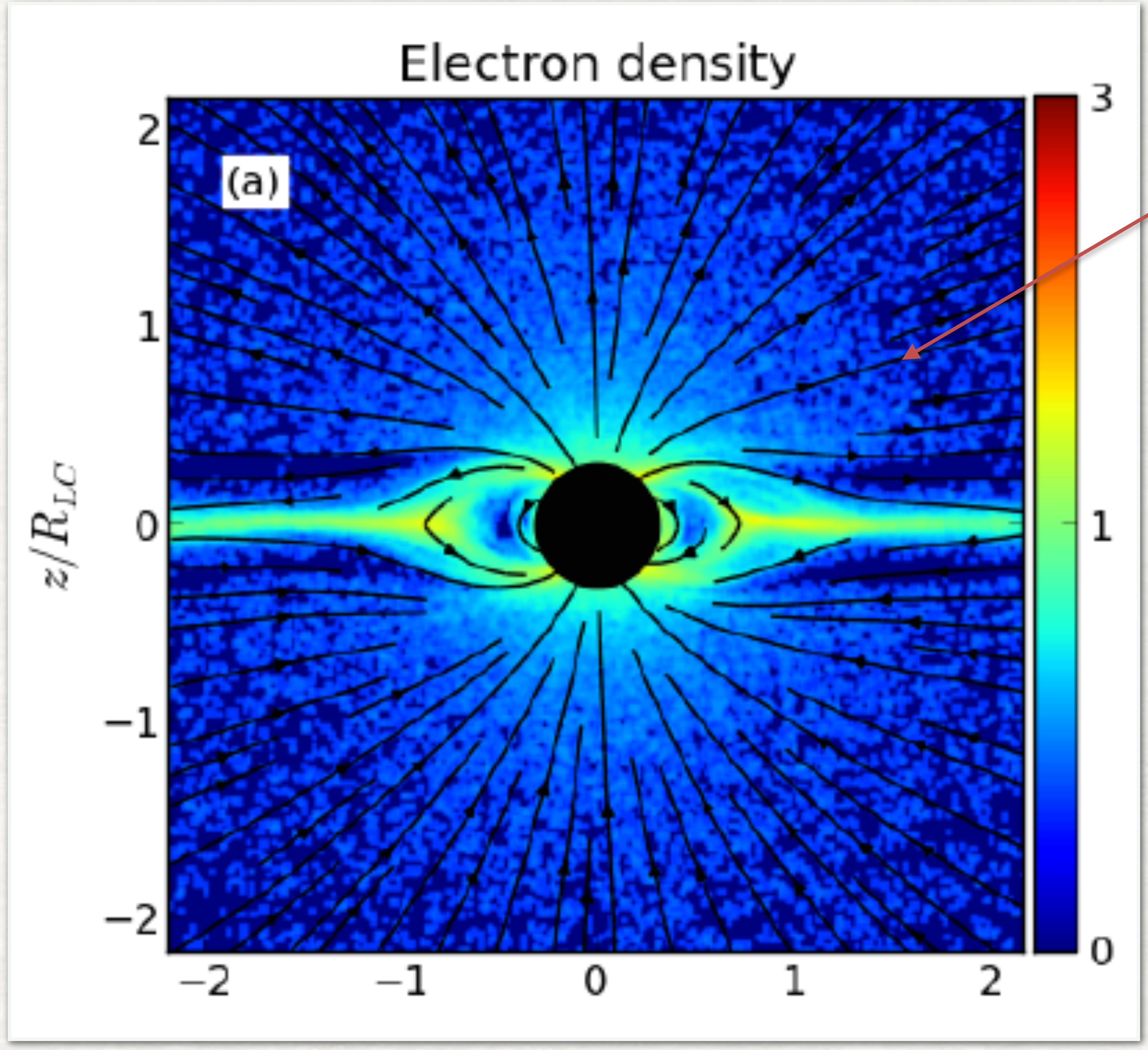


Other groups using PIC: Kalapotharakos et al, Chen et al, Belyaev et al

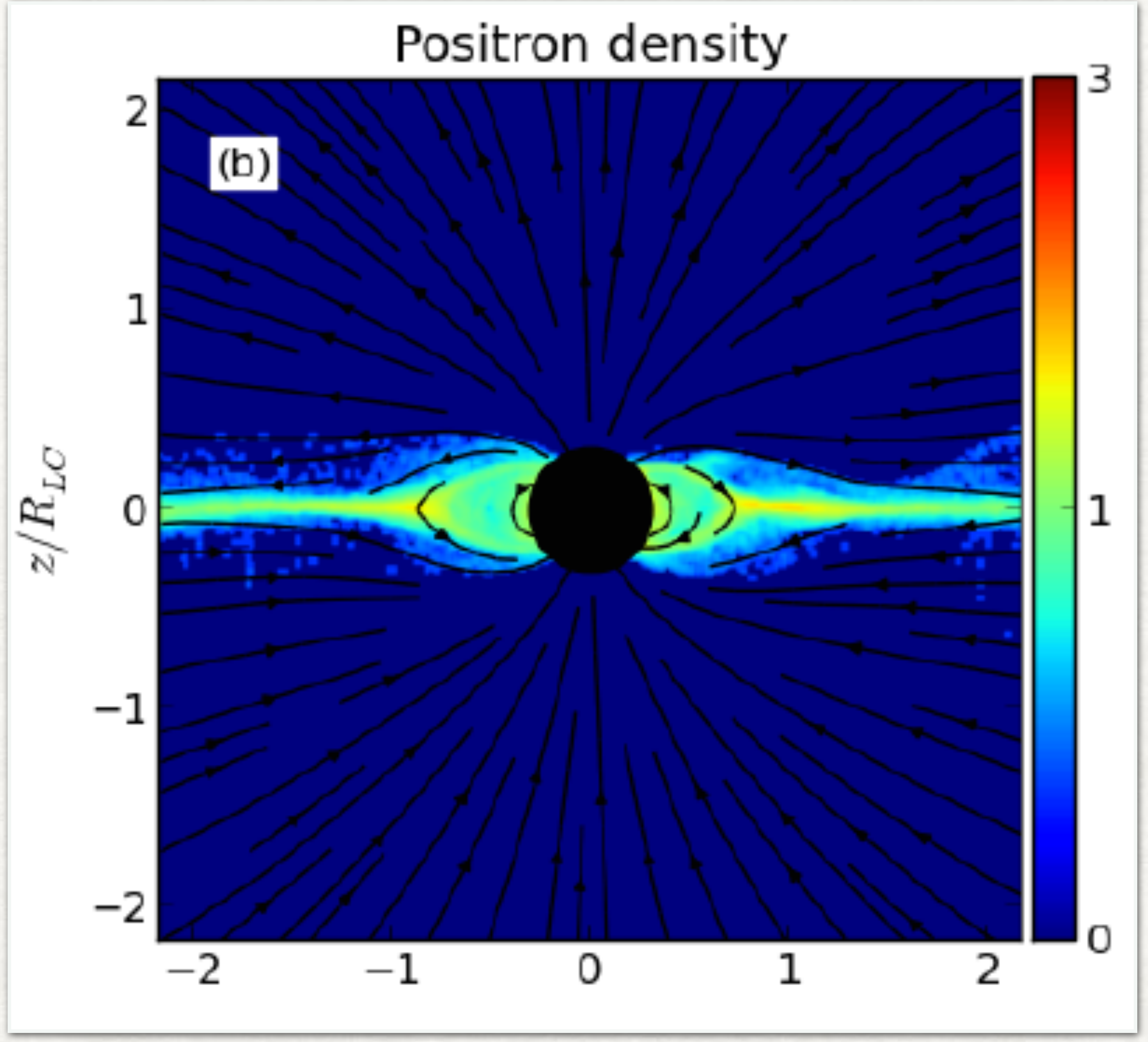
SOLUTIONS WITH PAIR PRODUCTION

- Add pair production with threshold based on particle energy in the inner magnetosphere. Outer magnetosphere: pair production from photon-photon collisions

$R_*/(c/\omega_p) \approx 30 - 40 \gg 1$ $\quad R_{LC}/R_* = 3 - 5$ $\quad \Phi_{PC} = \mu\Omega^2/c^2 \approx 500 \gg \gamma_{\mathrm{threshold}} = 40$



$j < \rho_{GJ}\, c$

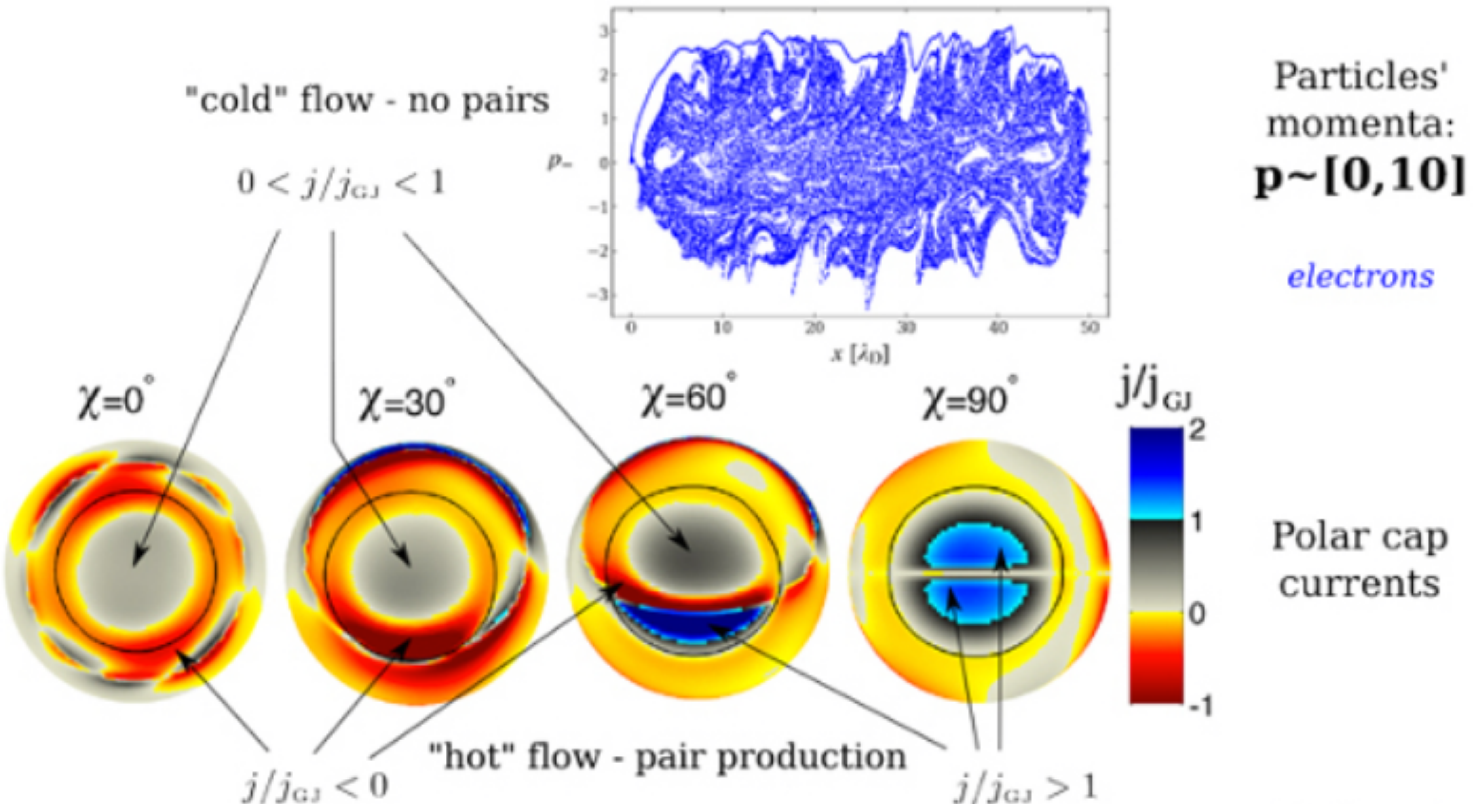


- $j < \rho_{GJ}\, c$ is satisfied by non relativistic outflow of electrons!
- Approaches force-free field solution, but no polar pair production!

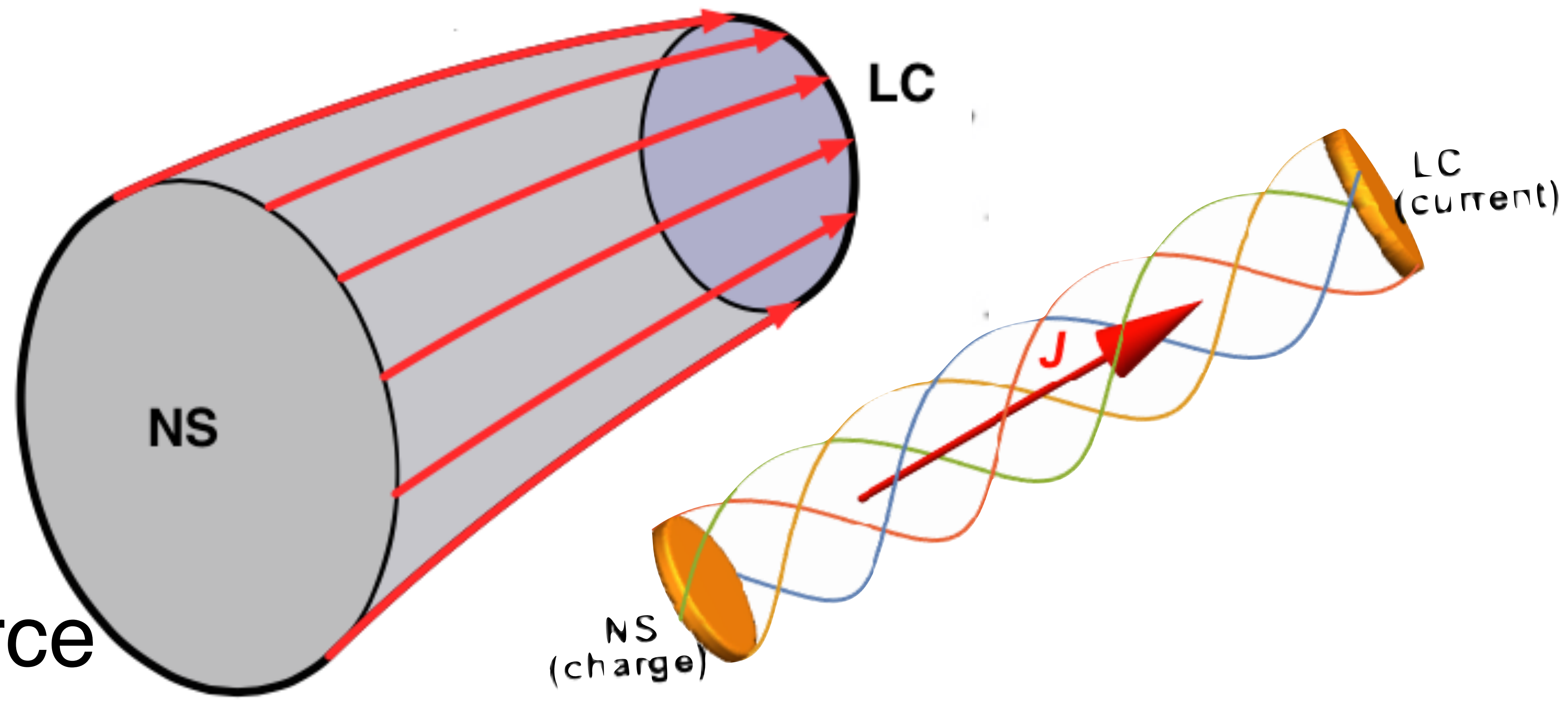
Philippov et al. (2015a)
Chen, Beloborodov (2014)

When can we make plasma through discharge?

- Need to sustain both charge and current density. Key quantity is $j/c\rho_{GJ}$
- If current is < c*charge density, the electric fields are screened by non-relativistic flow of particles extracted from the NS surface.
- Current is set by twist at light cylinder



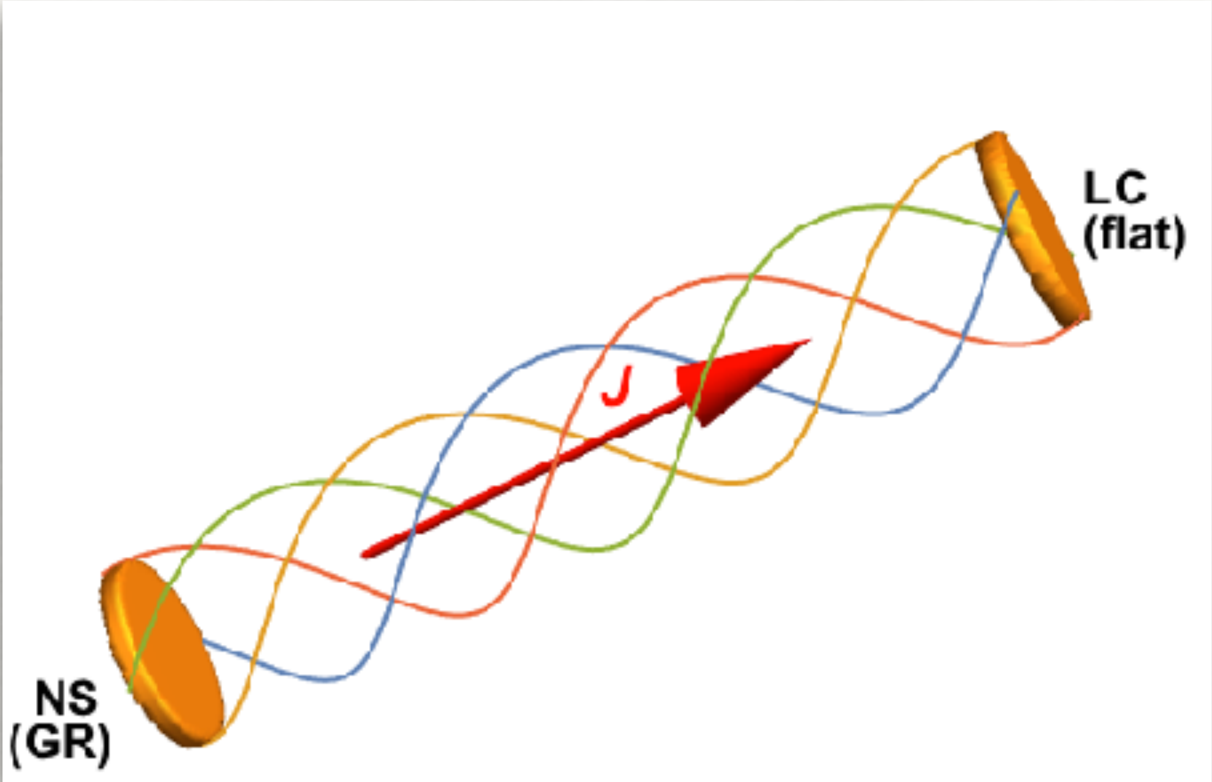
Timokhin & Arons (2013)



When realistic currents (set by global magnetosphere) are included in the simulation of polar cap discharge, we find that abundant pair production may not happen for most pulsars, as the required current is provided by advection of one sign of charge! Is this possible?

SOLUTION: IT'S A *MASSIVE* ROTATING SPHERICAL CONDUCTOR!

- Add GR frame-dragging effect

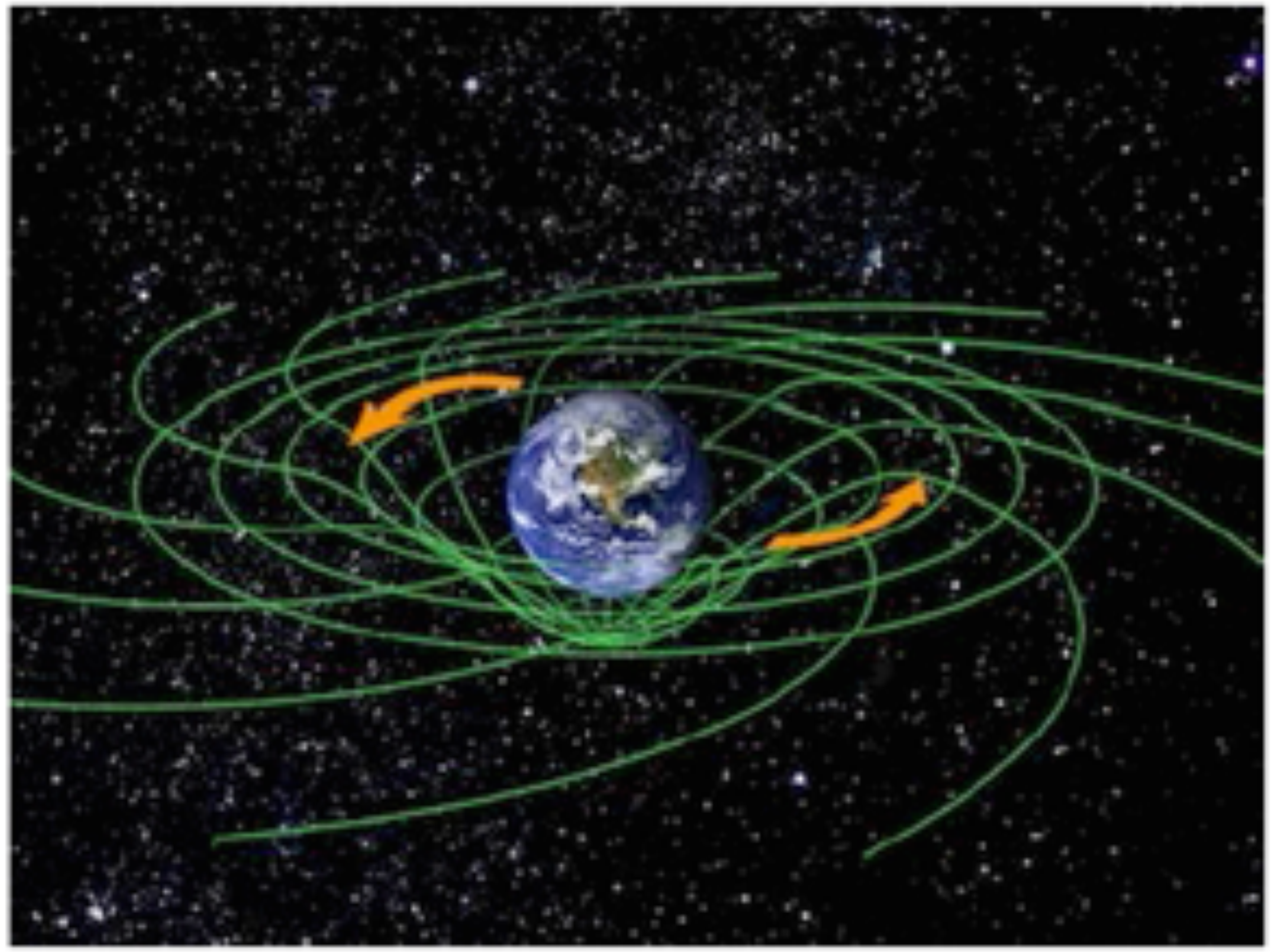


$$\omega_{LT} = \frac{2}{5}\Omega_* \frac{r_s}{R_*} \qquad \vec{\beta} = \frac{1}{c}\vec{\omega}_{LT} \times \vec{r}$$

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

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

$$\frac{J_{\hat{r}}}{\rho_{GJ} c} \approx \left(\frac{J_{\hat{r}}}{\rho_{GJ} c}\right)_{\text{flat}} \frac{1}{1 - \omega_{LT}/\Omega_*}$$

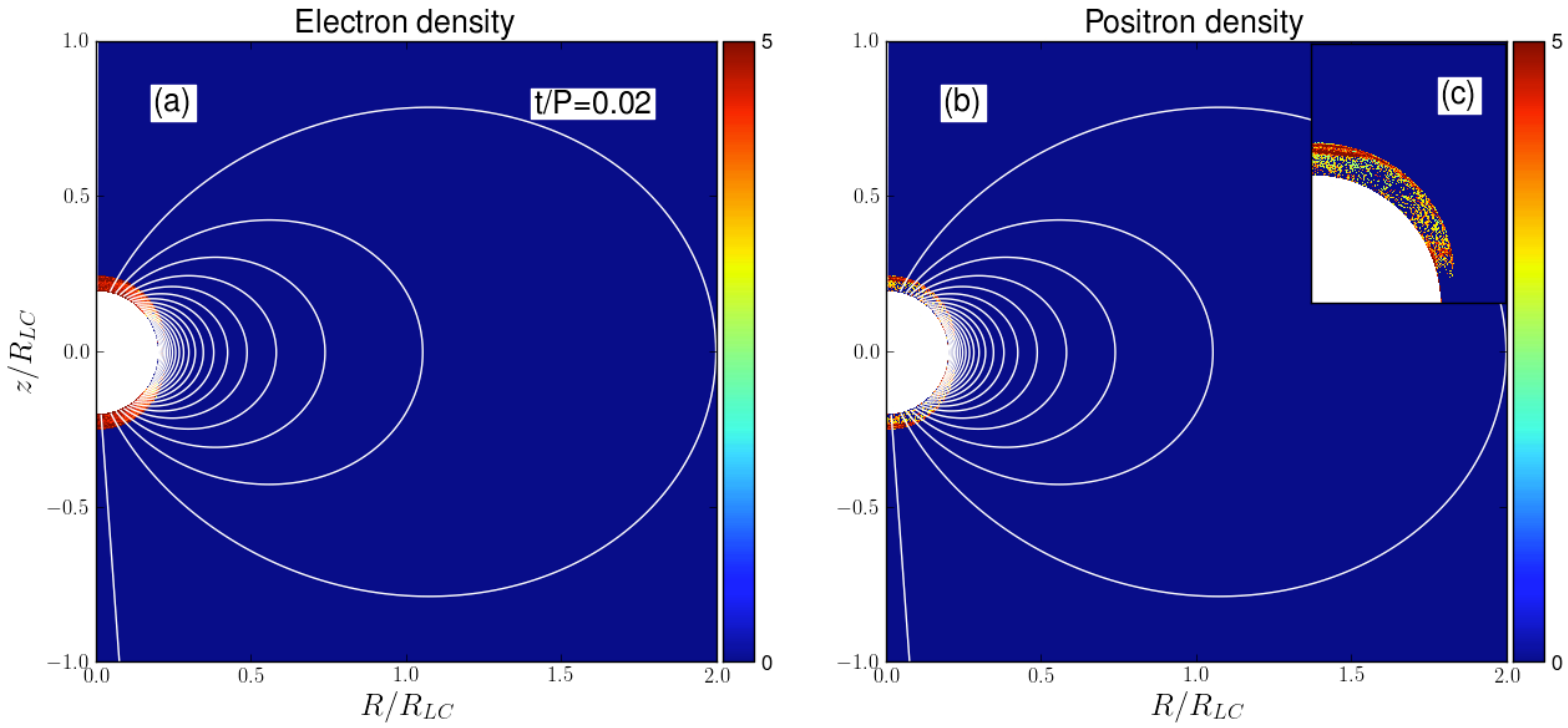


Lense-Thirring frame dragging

Frame-dragging makes effective rotation frequency of the star smaller close to the star (this lowers the necessary corotation charge), but the rotation is still the same far from the star (this keeps the current the same).

Philippov et al. (2015b)
Beskin 1990
Muslimov & Tsygan 1992

ALIGNED ROTATOR WITH GR AND PAIRS



- Polar pair production returns!

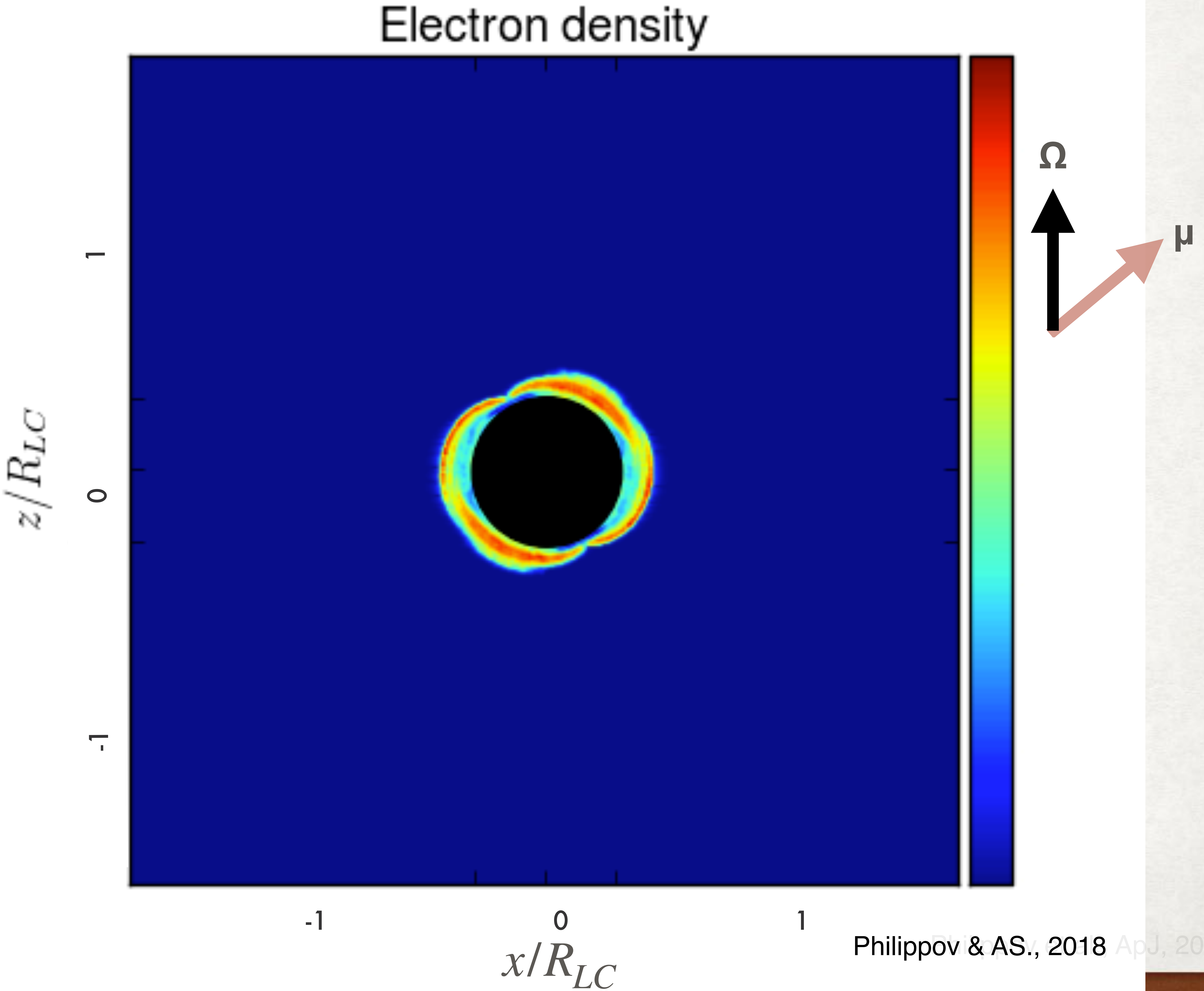
Philippov et al. (2015b)

OBLIQUE ROTATOR WITH GR AND PAIRS

- Pair production happens on the polar cap, in return current layers and in the current sheet beyond LC

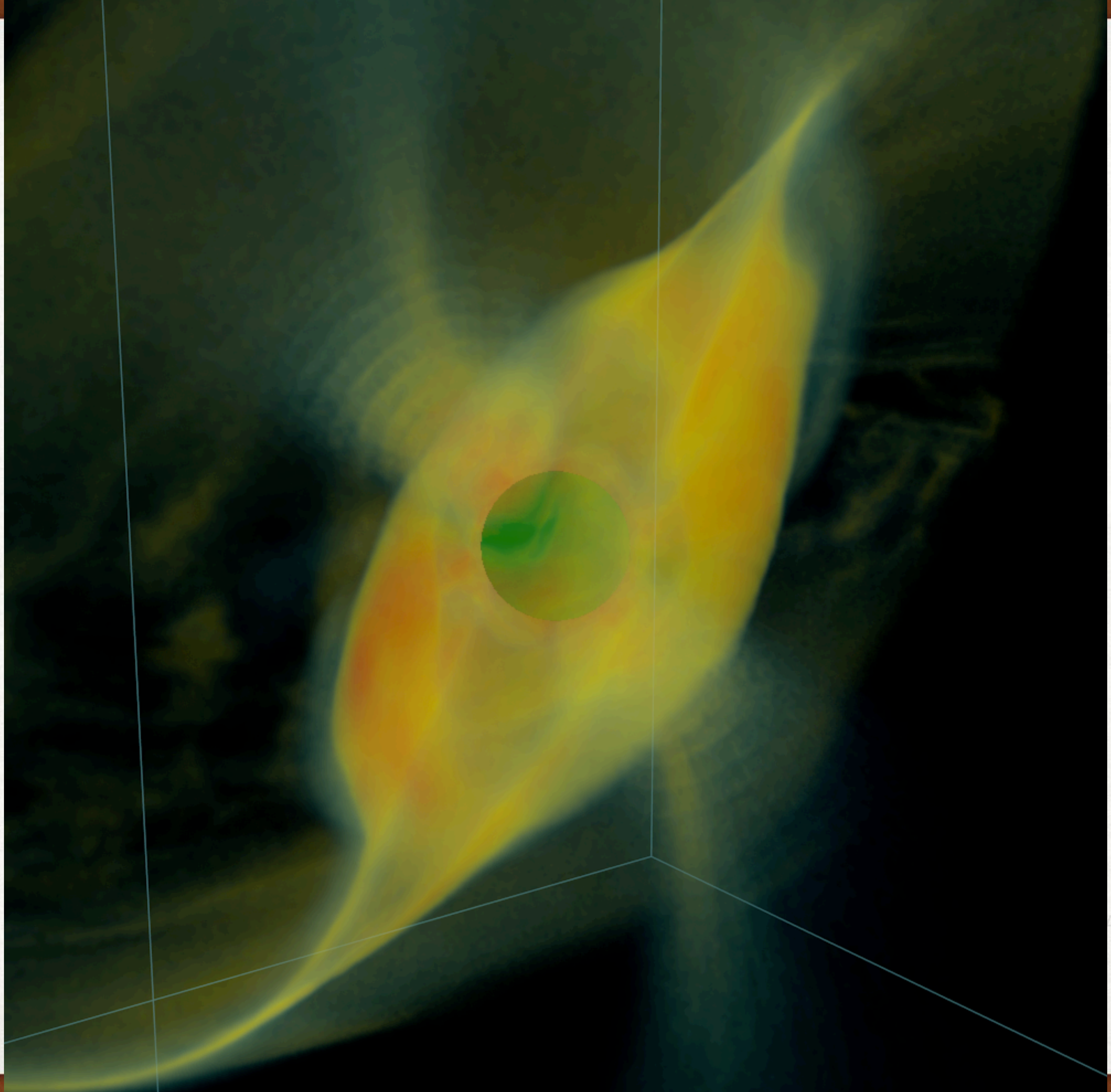
- Polar discharge is non-stationary. Electric field screening by advecting plasma clouds generates waves. The plasma motions are collective and coherent — implications for radio emission (see Beloborodov 2008, Timokhin & Arons 2013)

- Reconnection in current sheet



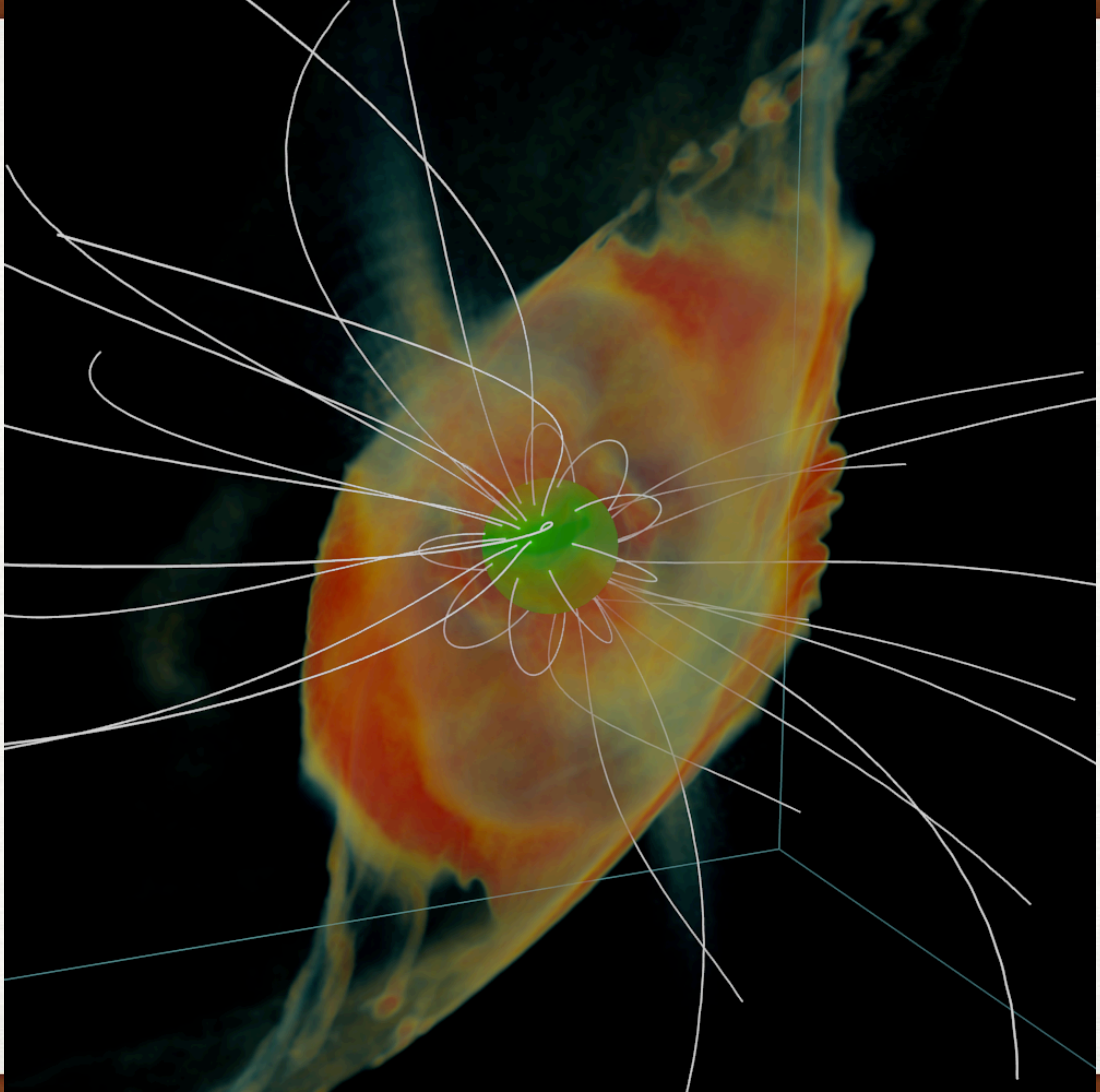
Philippov & AS., 2018

OBLIQUE ROTATOR WITH GR AND PAIRS: PLASMA DENSITY



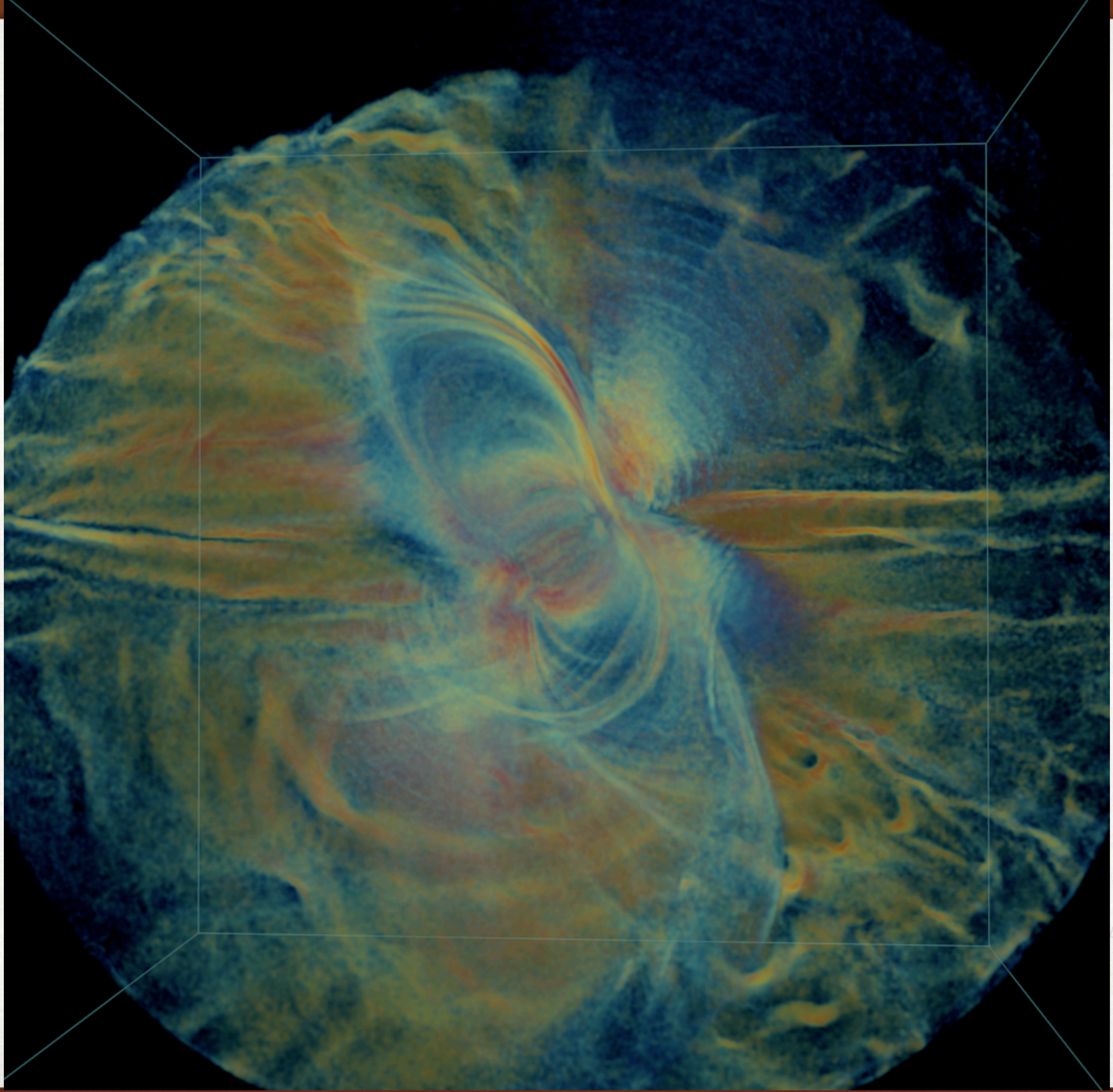
ApJ, 2016

OBLIQUE ROTATOR WITH GR AND PAIRS: PLASMA DENSITY



ApJ, 2016

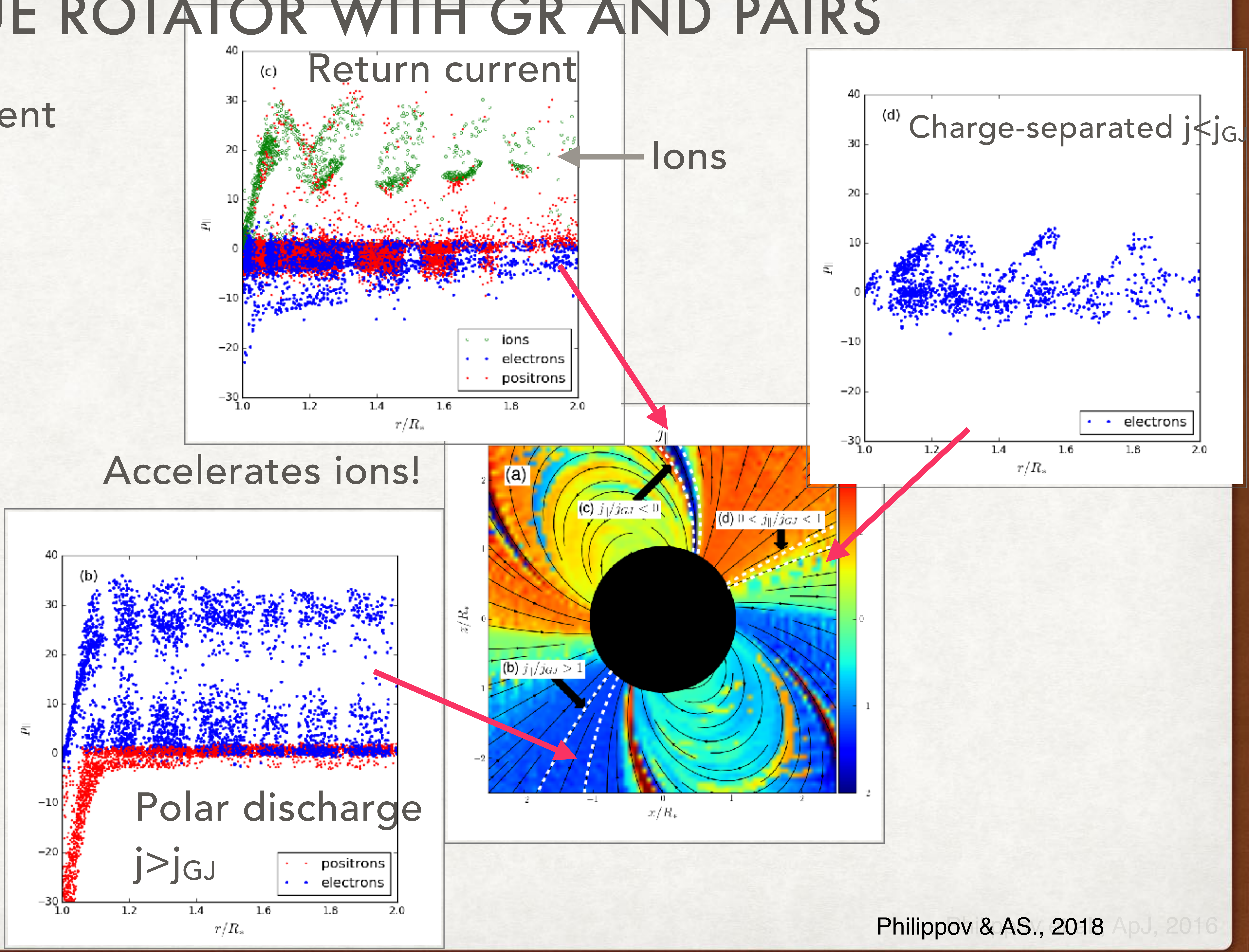
OBLIQUE ROTATOR WITH GR AND PAIRS: CURRENT DENSITY



ApJ, 2016

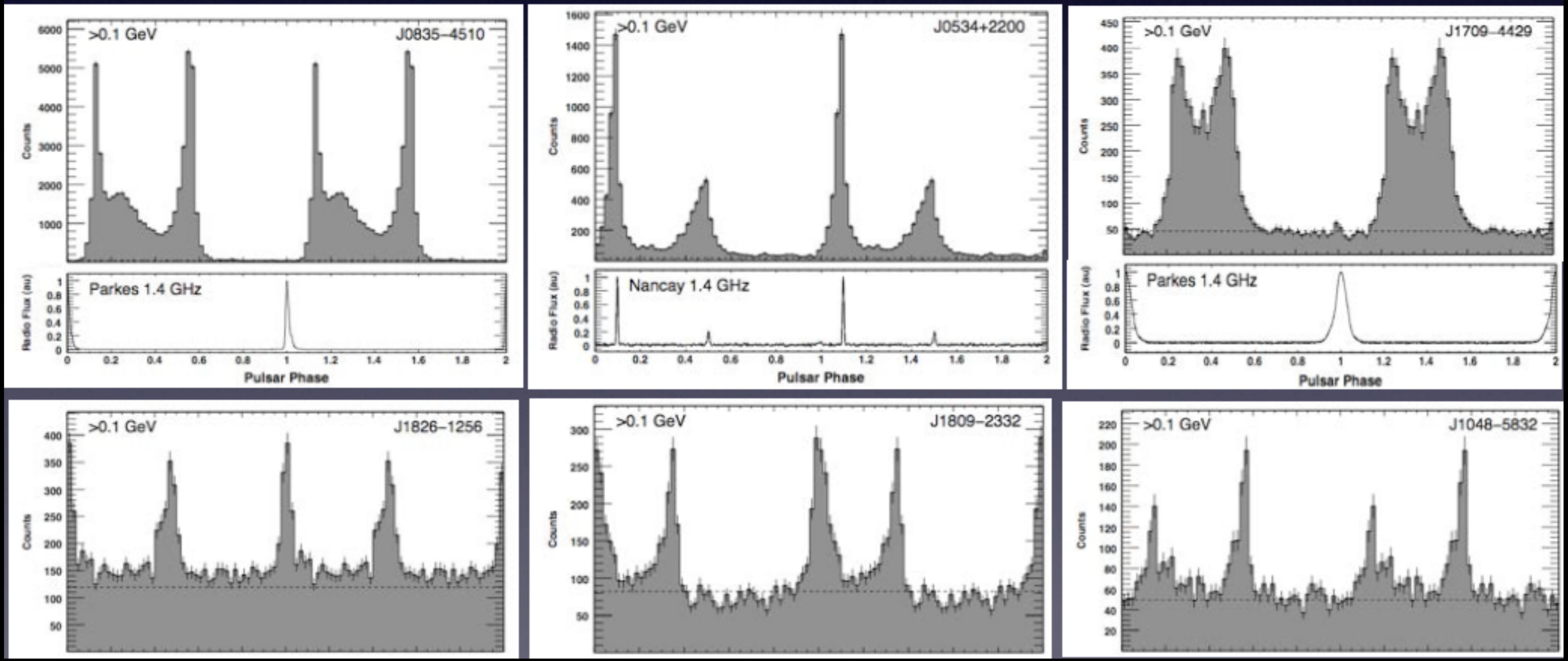
OBLIQUE ROTATOR WITH GR AND PAIRS

- Counterstreaming is present in polar discharge and in return current
- Opportunities for maser emission from collective instabilities of counterstreaming distributions.



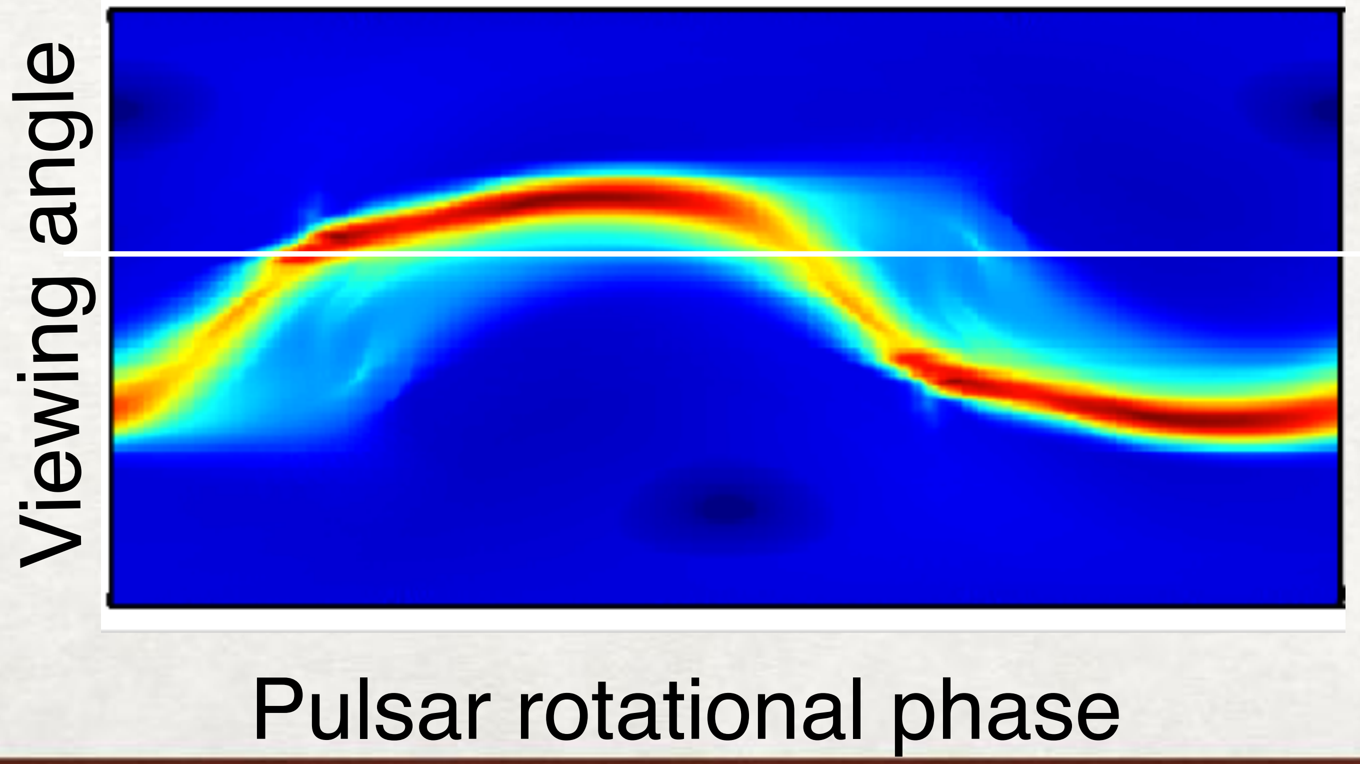
Philippov & AS., 2018

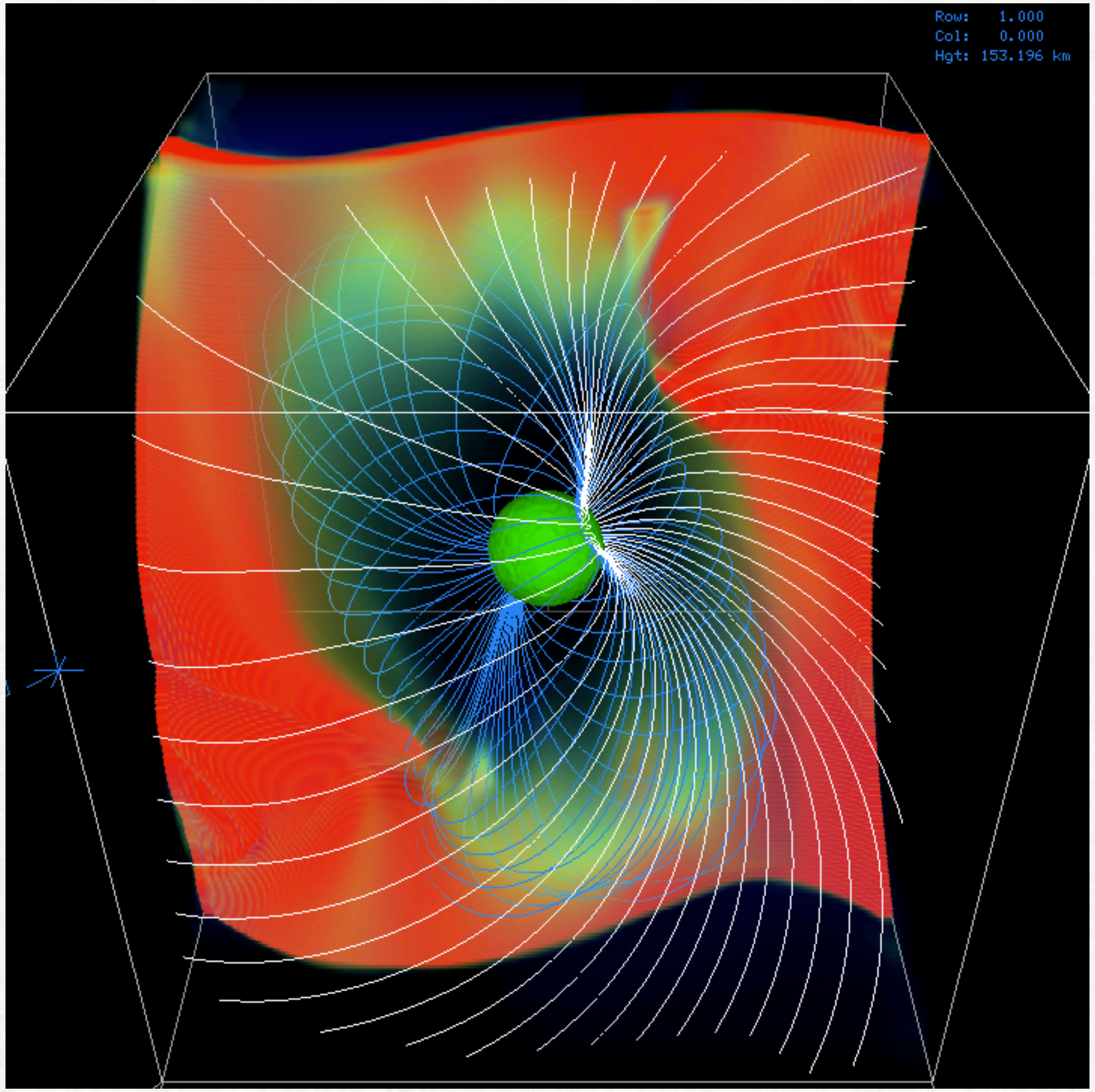
Gamma-ray emission from pulsars



PREVIOUS MODELING IN FORCE-FREE

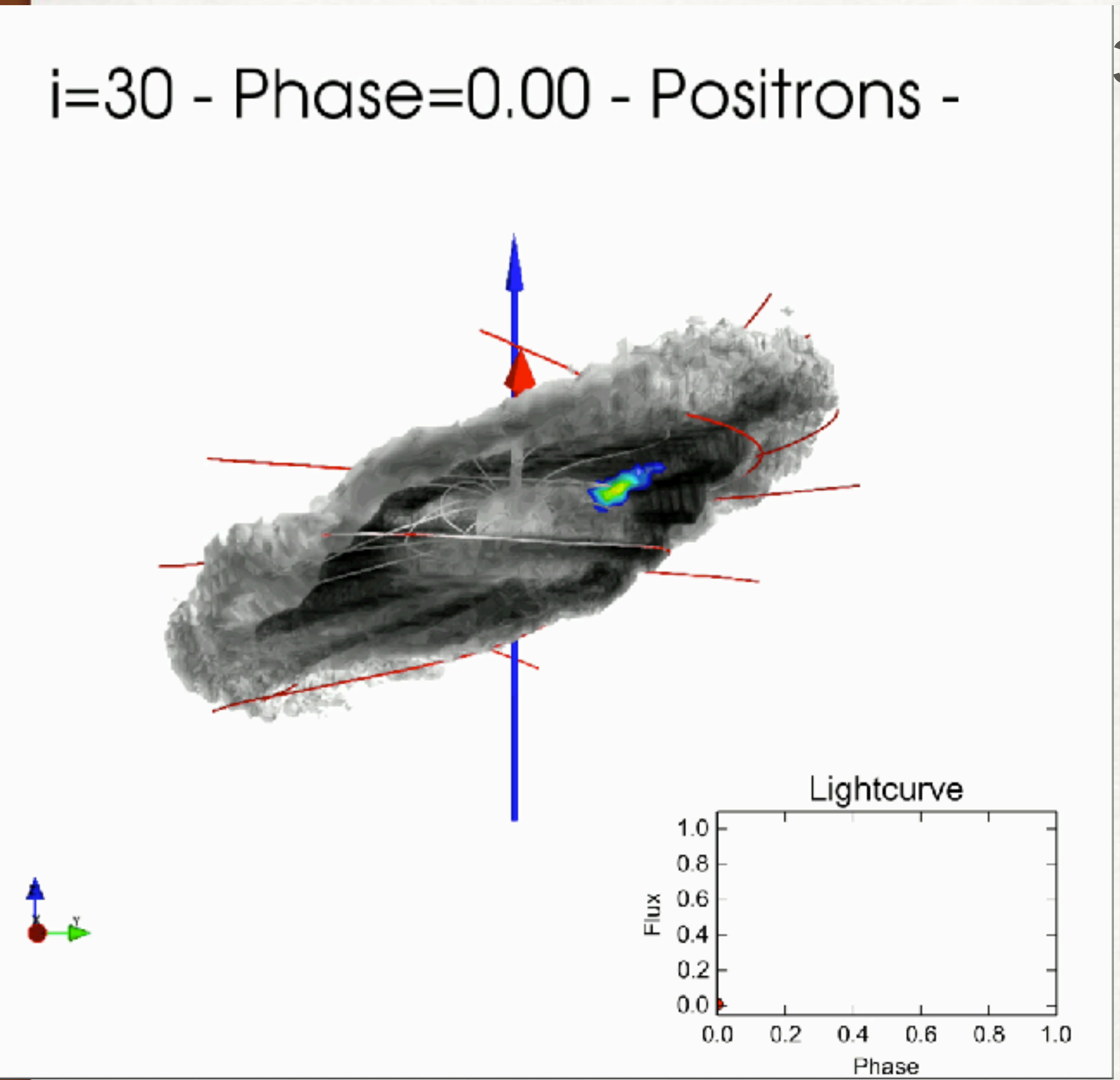
- Observe caustic emission, when light from a given field line arrives in phase.
- Emission is assumed along the field lines.
- Field lines that produce best force-free caustics seem to "hug" the current sheet at and beyond the LC.



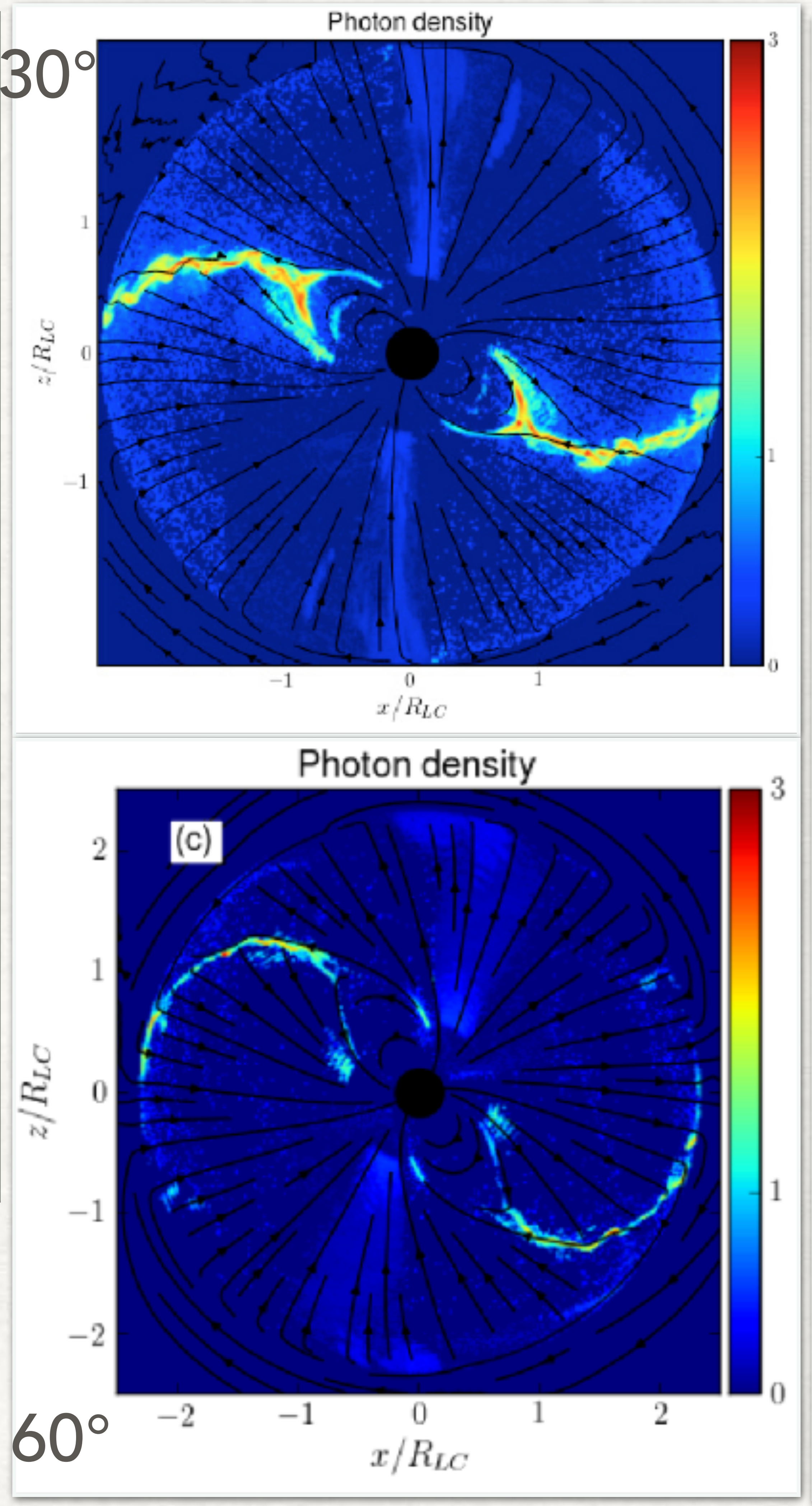


Bai & AS, 2010

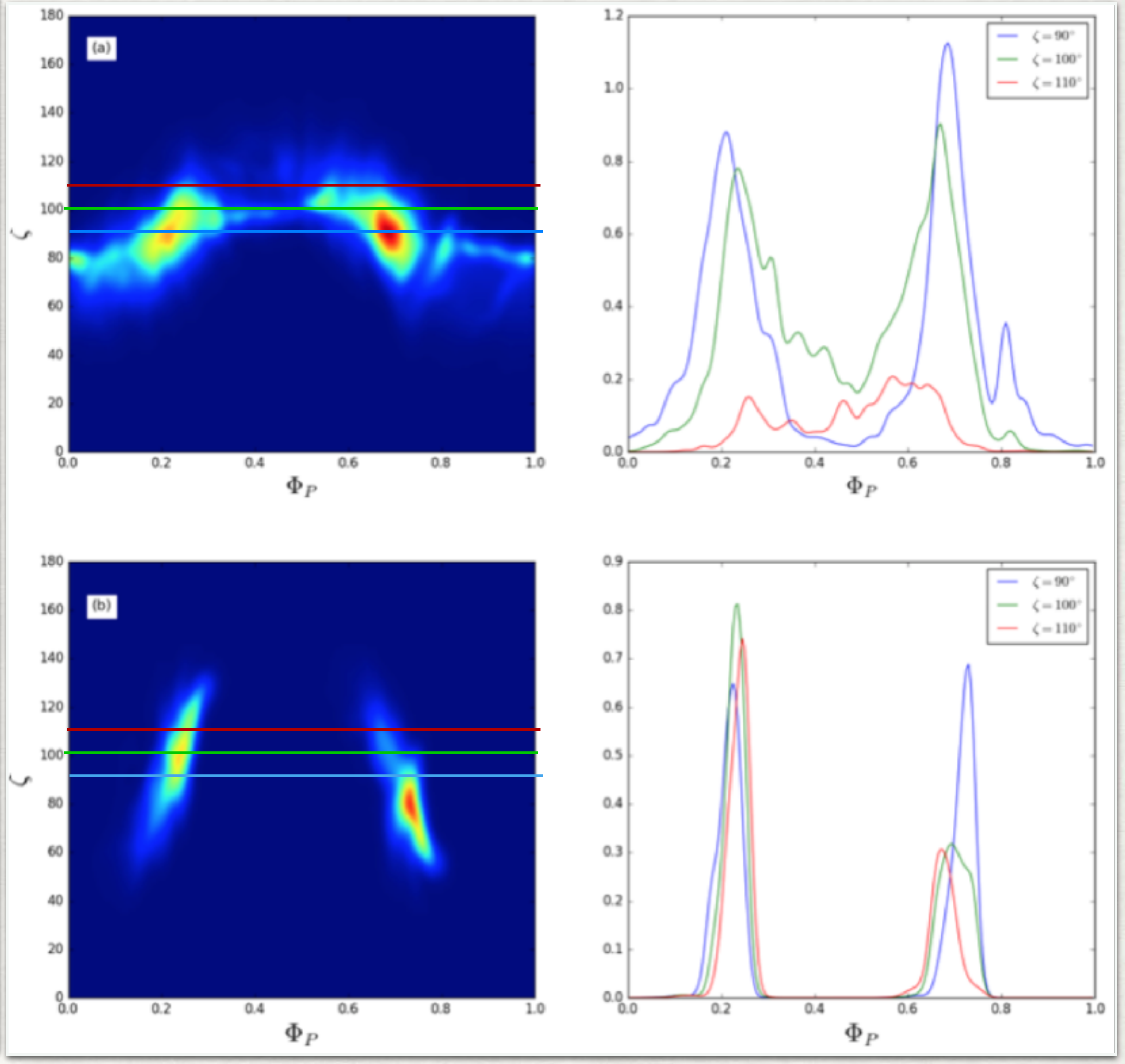
GAMMA-RAY LIGHTCURVES FROM PIC SIMULATIONS



Caustic formation from spiral shape of current sheet



Photon density

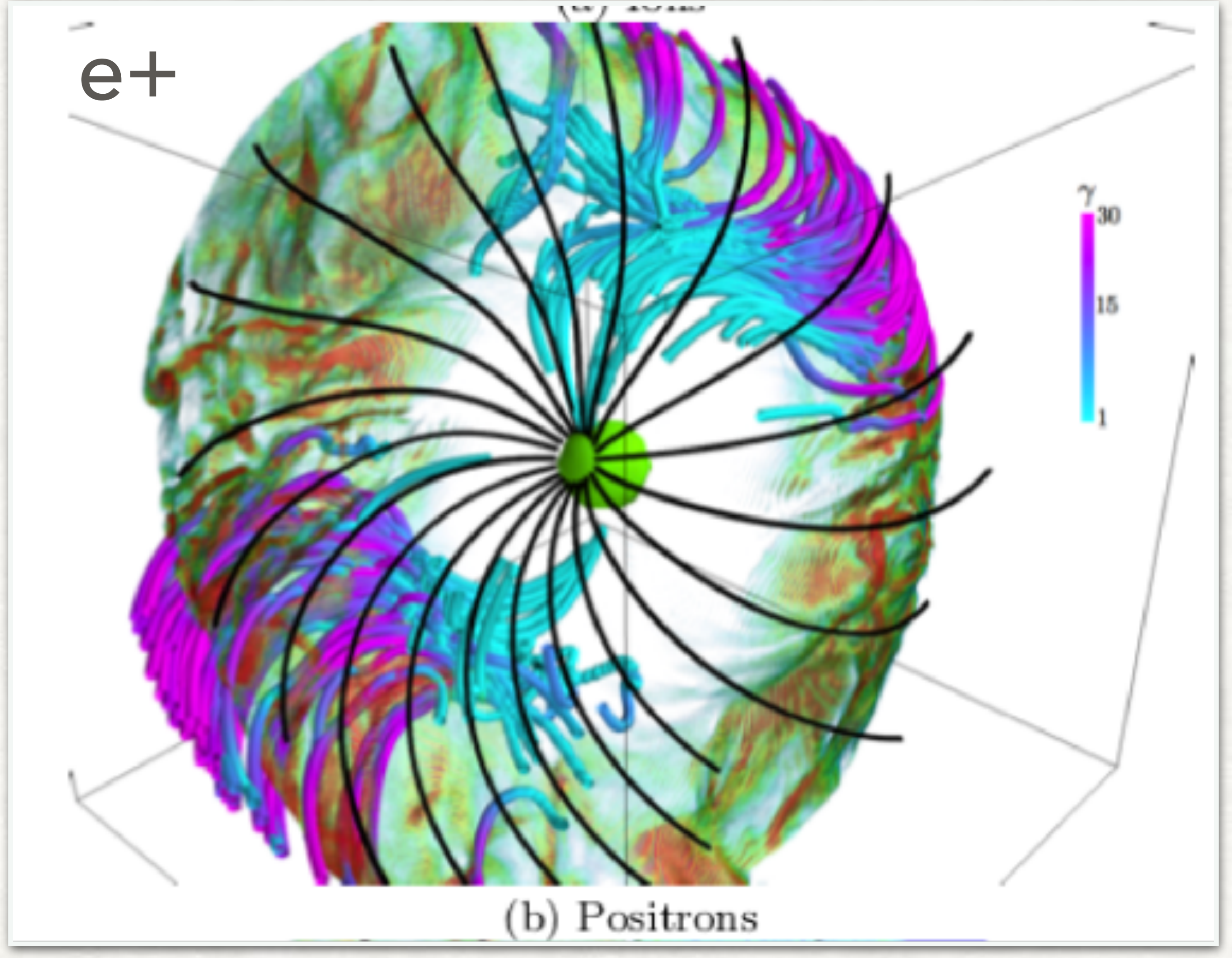


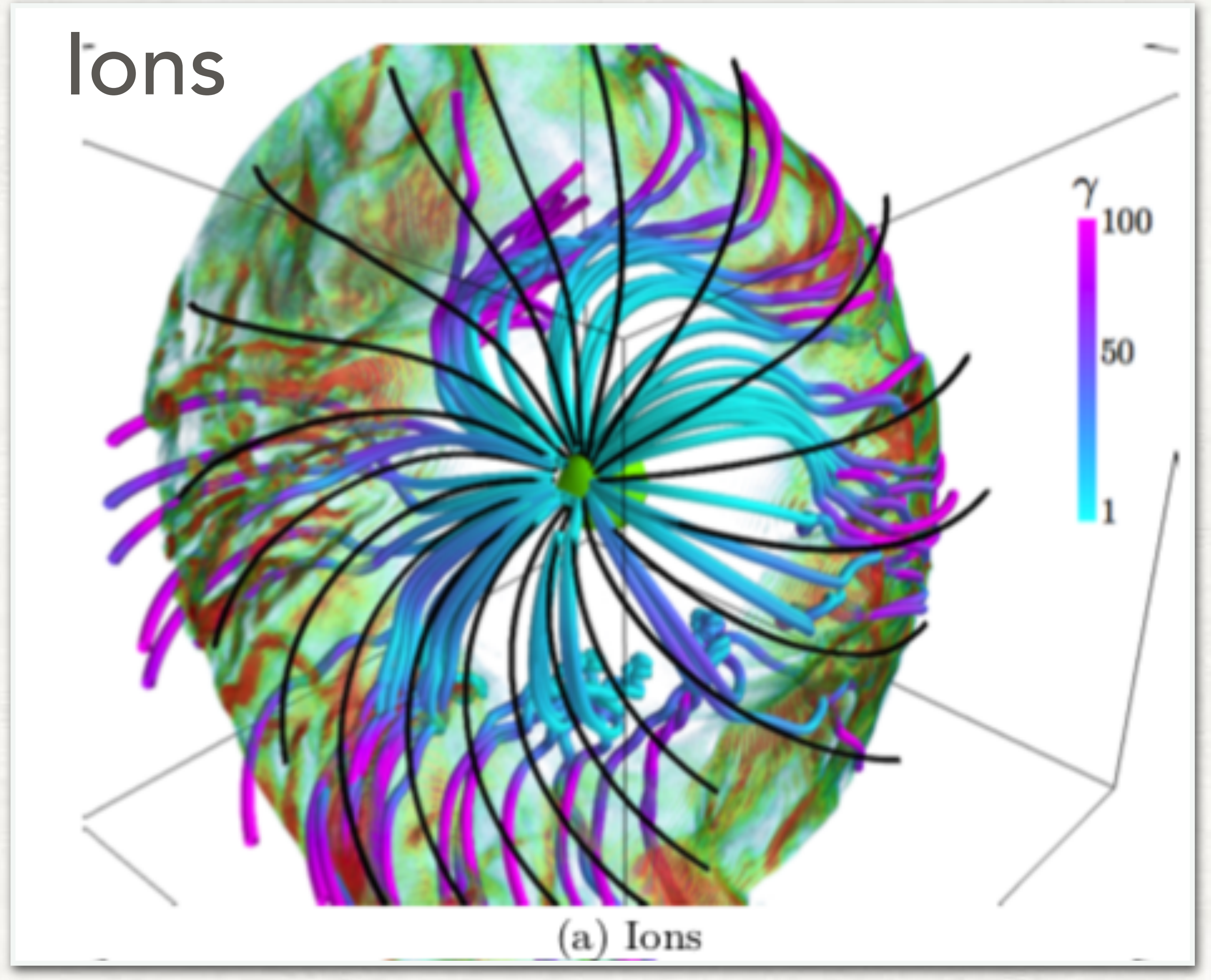
Sky map

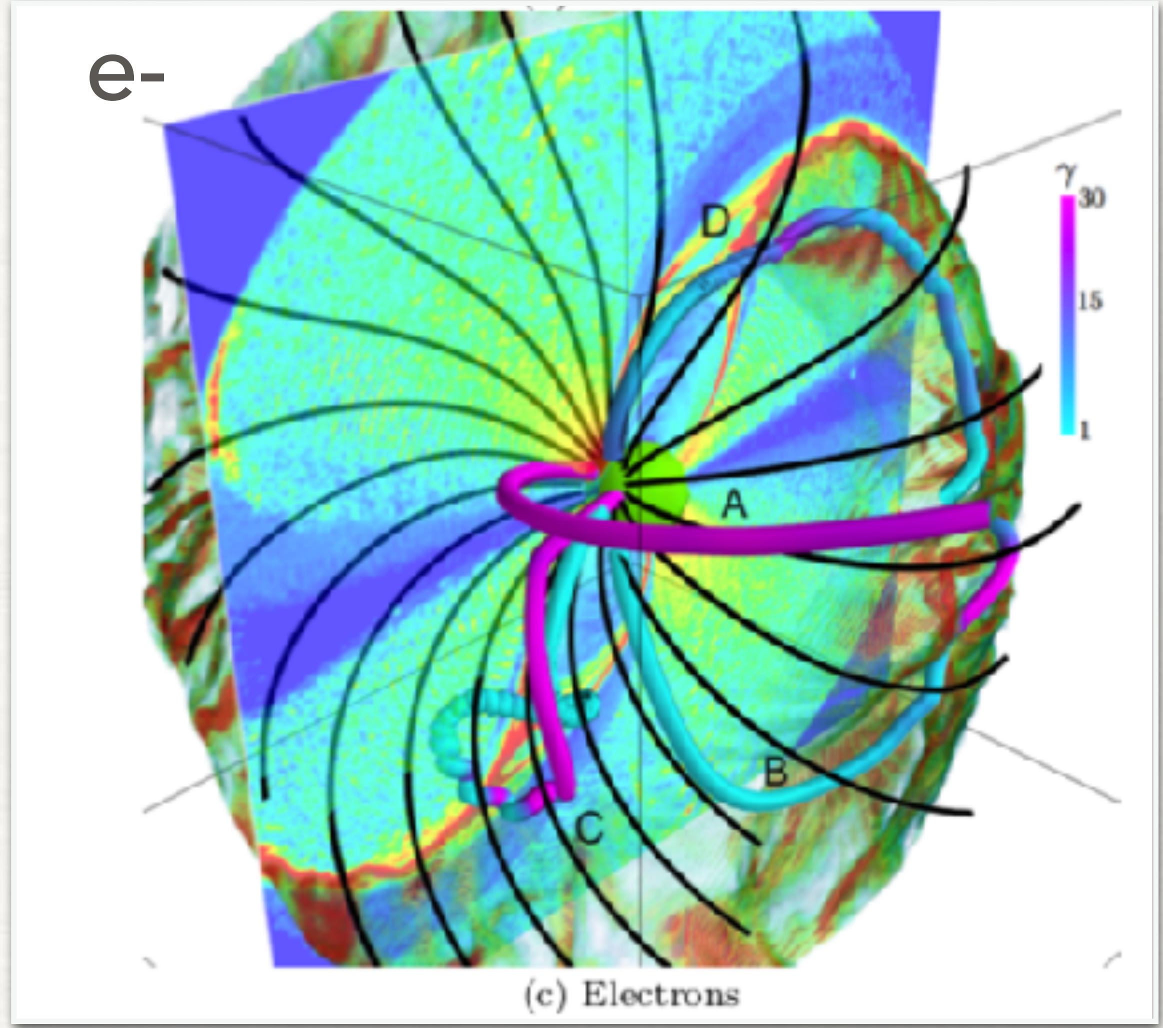
Light Curve

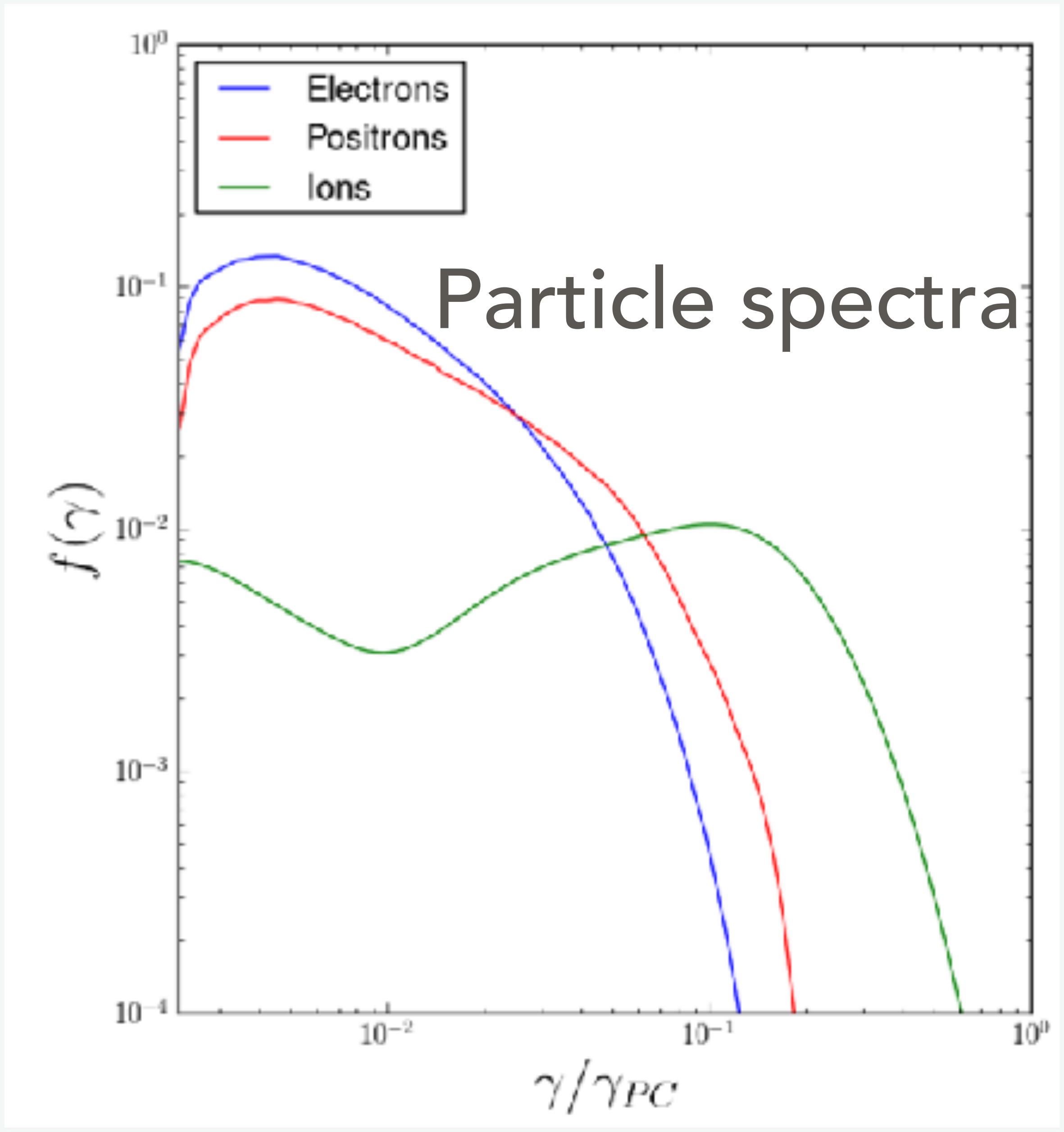
Philippov & AS., 2018; Bai & AS, 2010

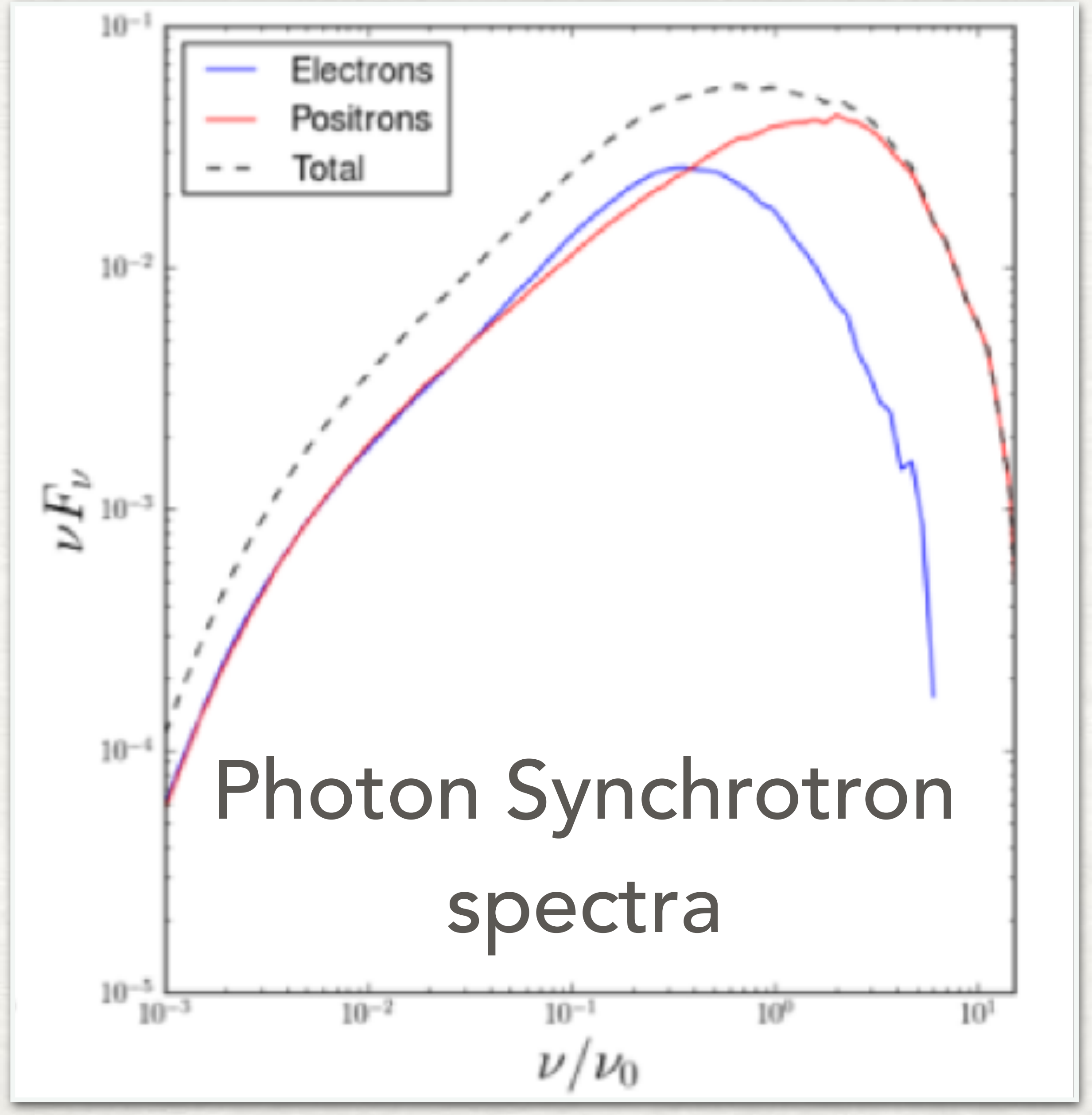
PARTICLE ACCELERATION AND SPECTRA











Particles are accelerated in the current sheet during reconnection.

Radiation appears as broad spectral peak.

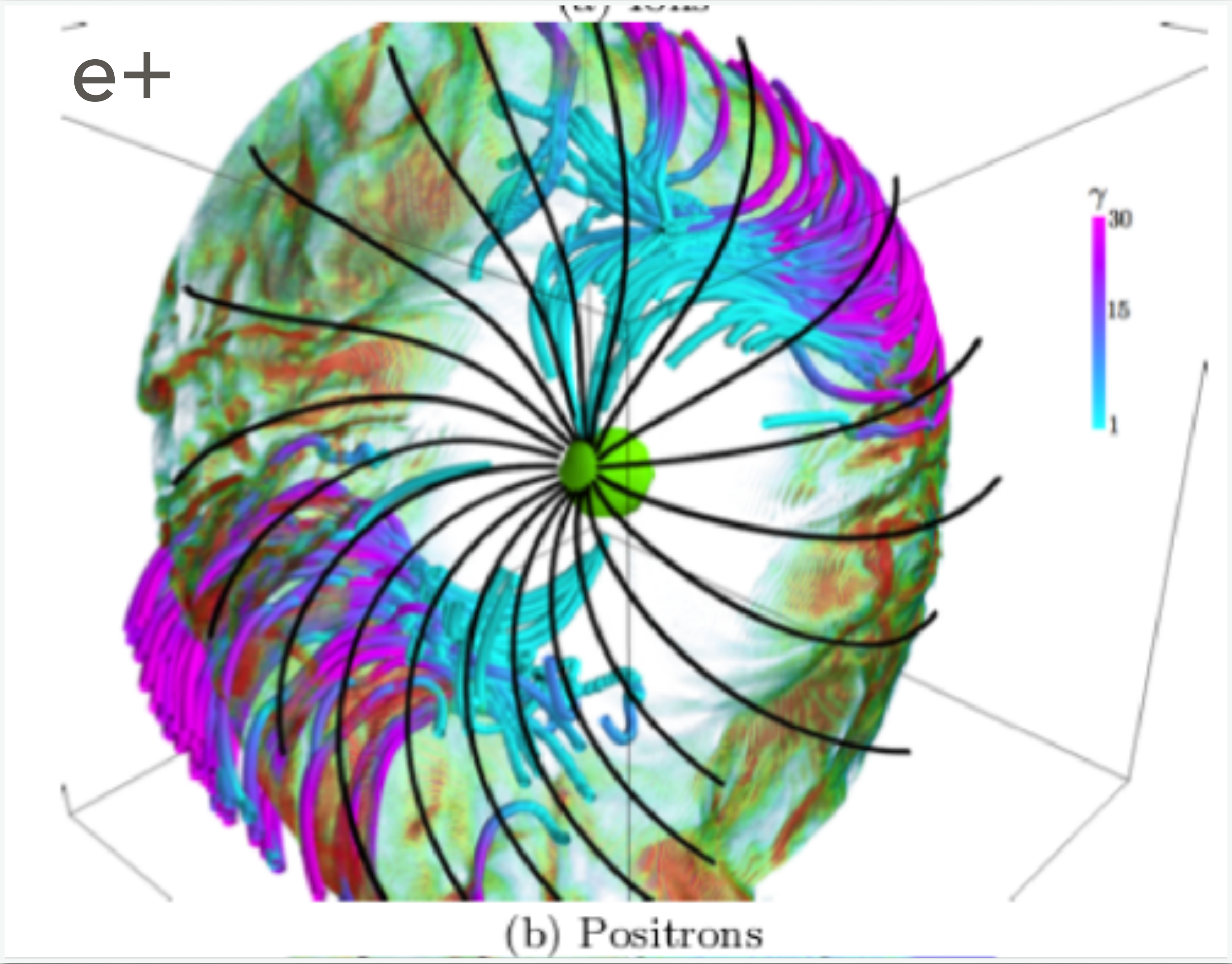
The max frequency is set by magnetization σ_{LC}:

$$\nu_{\max} \approx 3e\,(0.1 B_{\rm LC})\,\sigma_{\rm LC}^2/4\pi m_e c$$

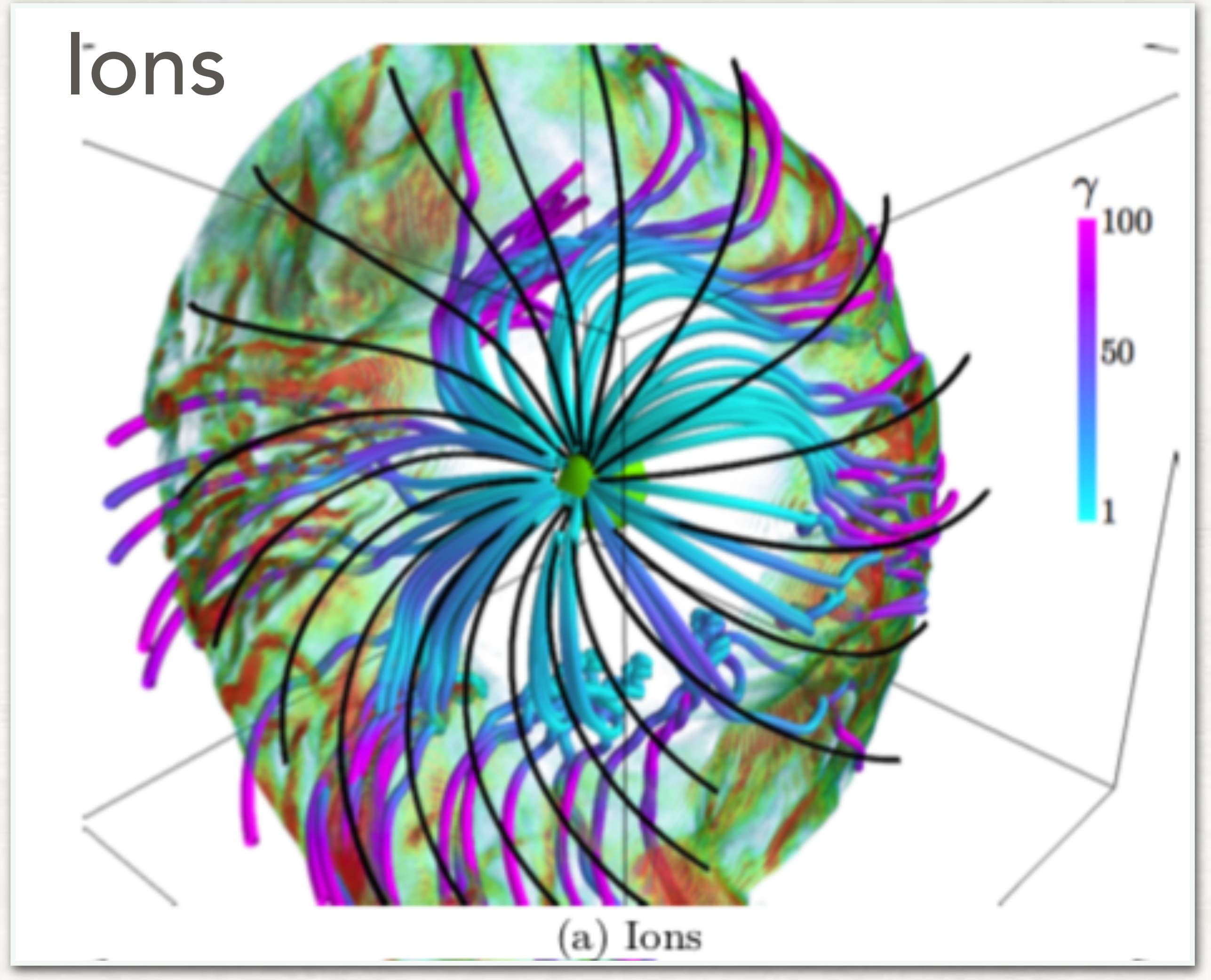
Pair production in sheet sets the sigma parameter. Ions gain good fraction of Φ_{pc}

Philippov & AS., 2018

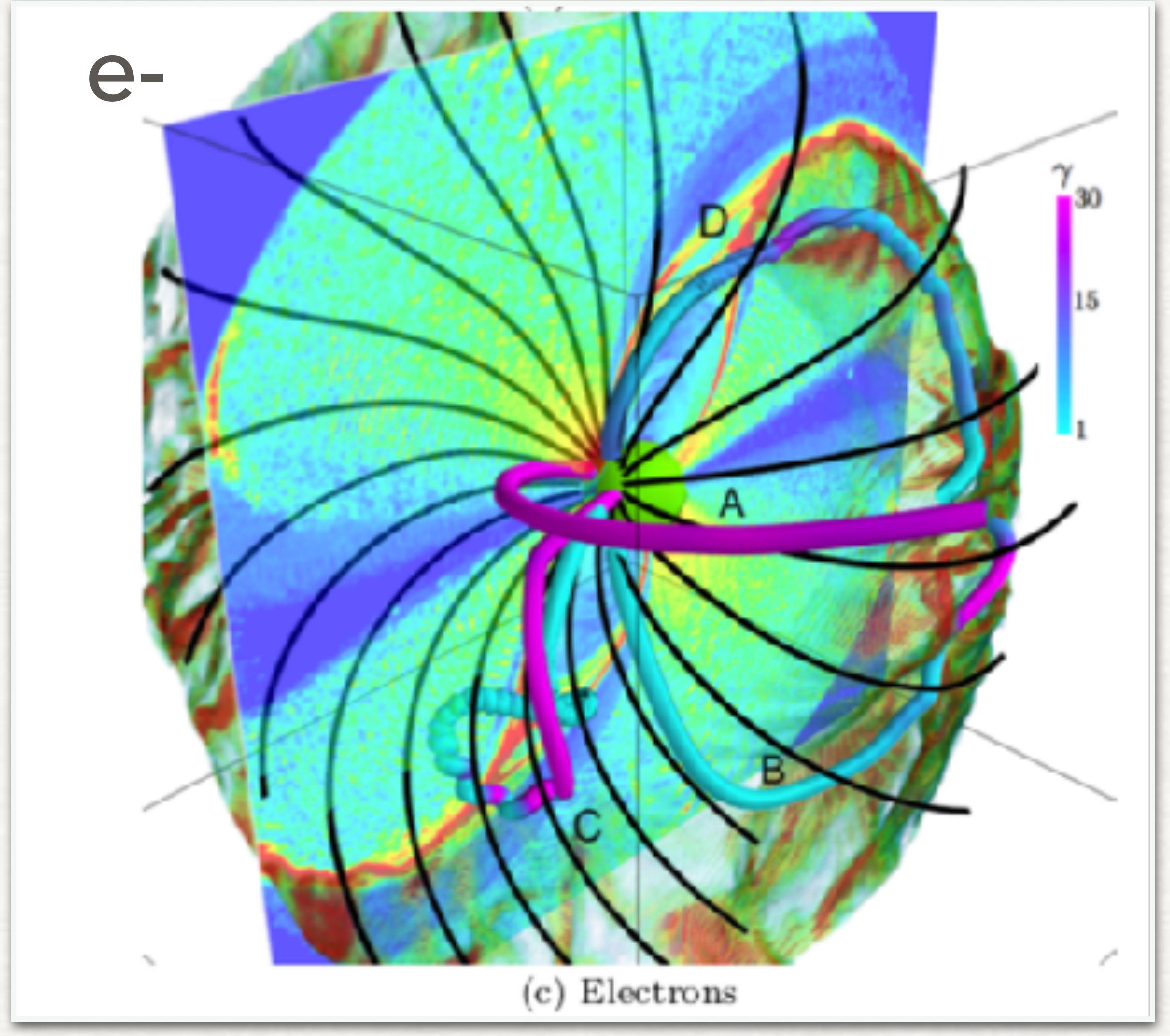
PARTICLE ACCELERATION AND SPECTRA



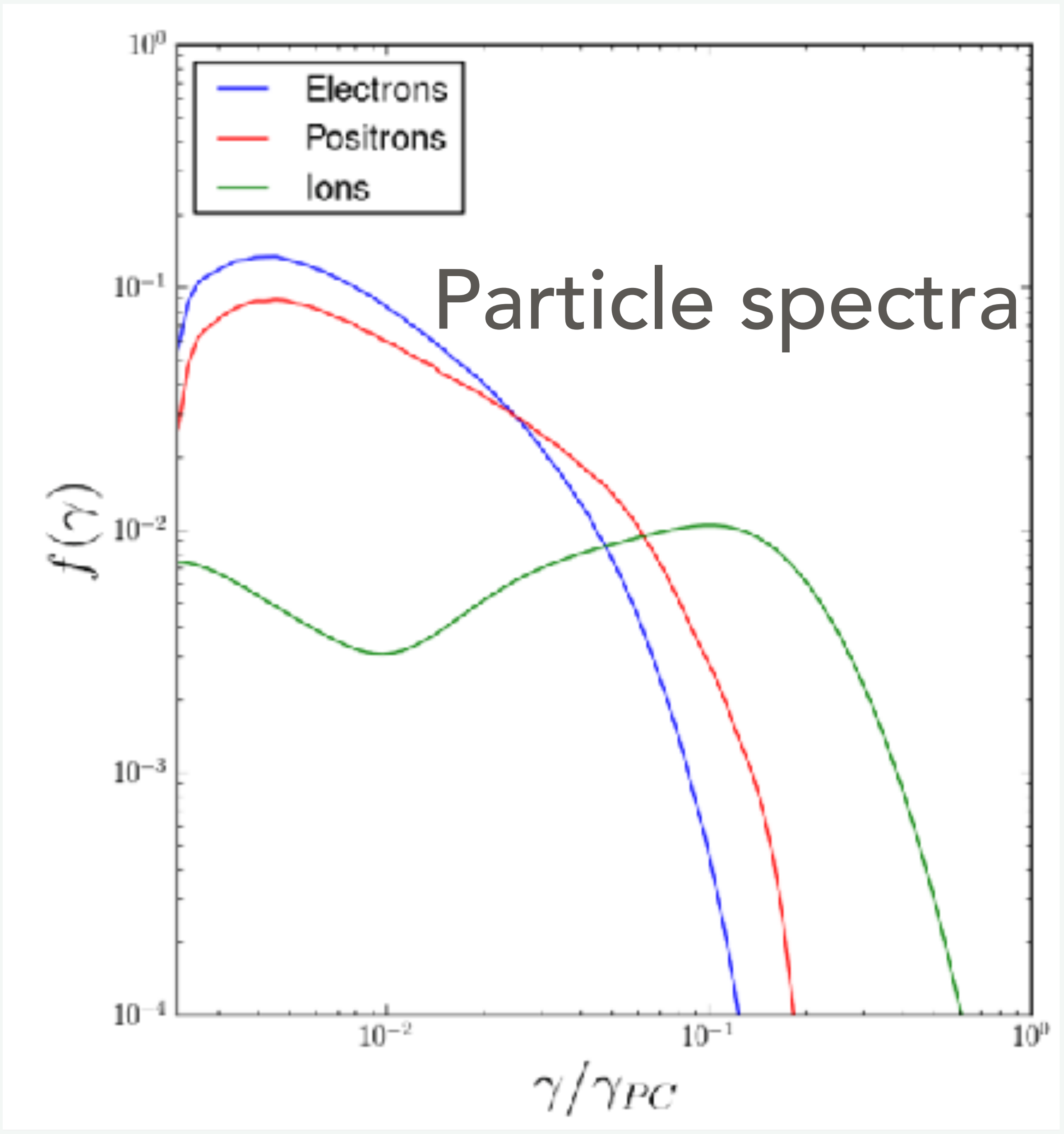
(b) Positrons

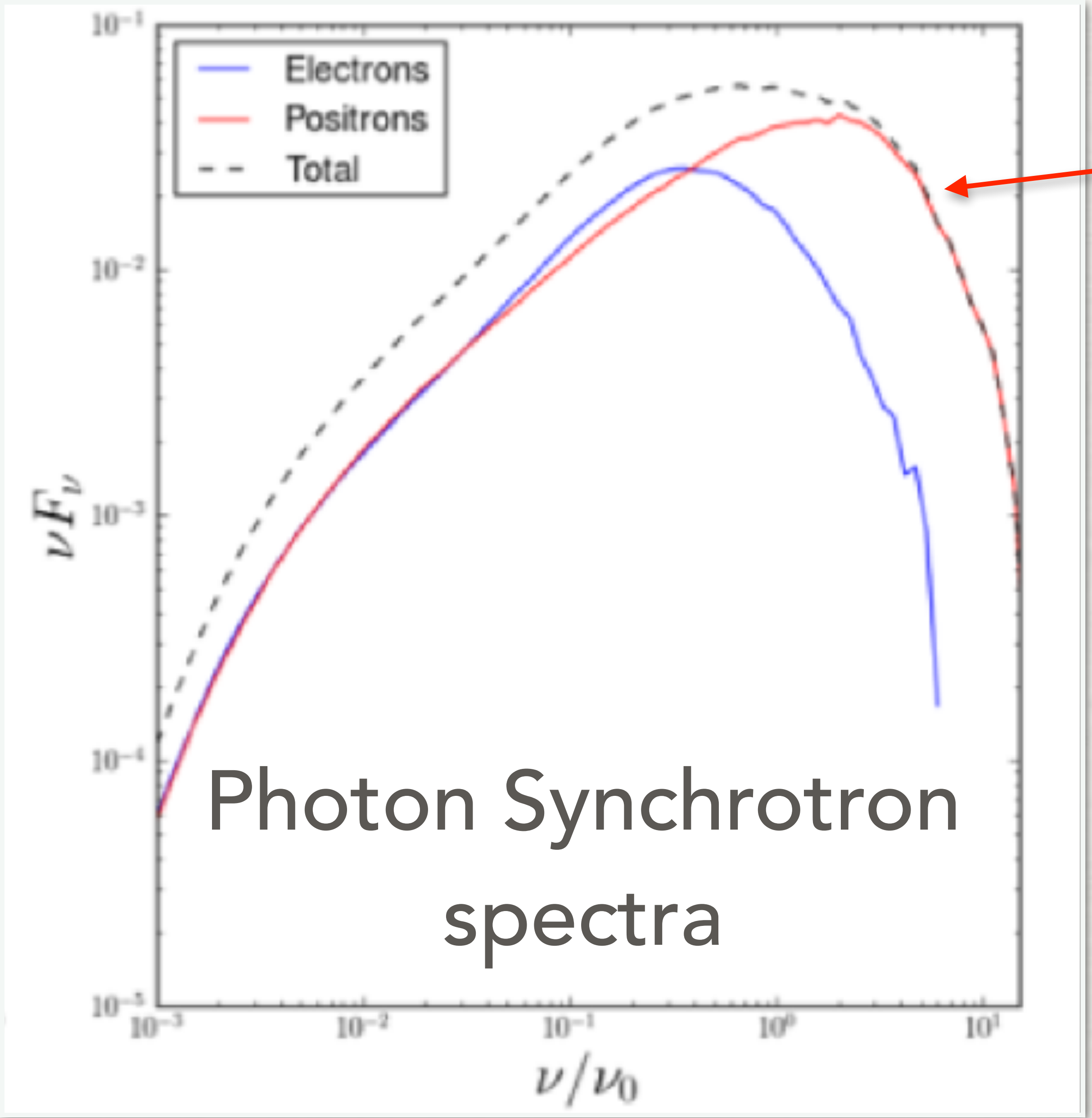


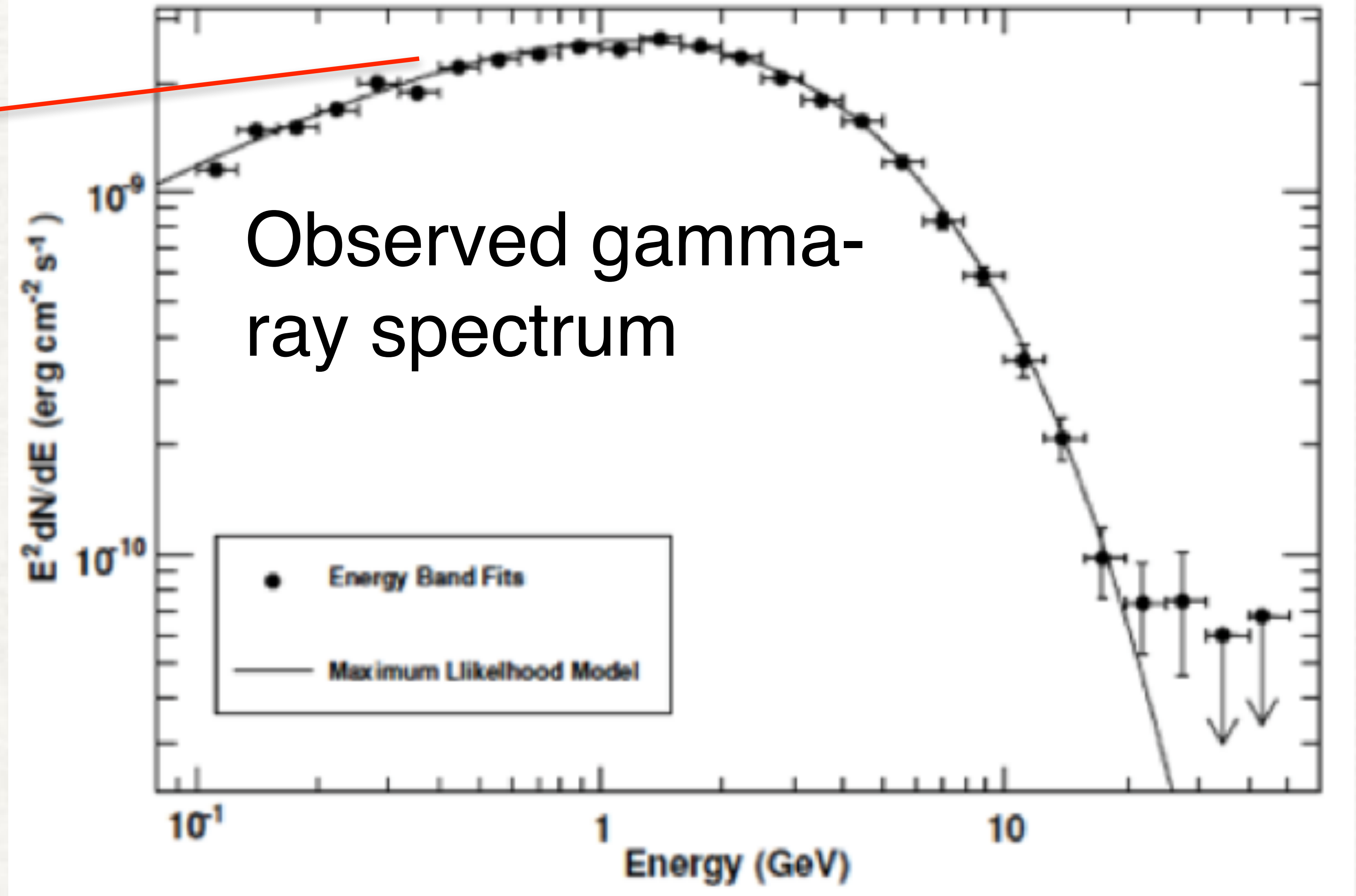
(a) Ions



(c) Electrons





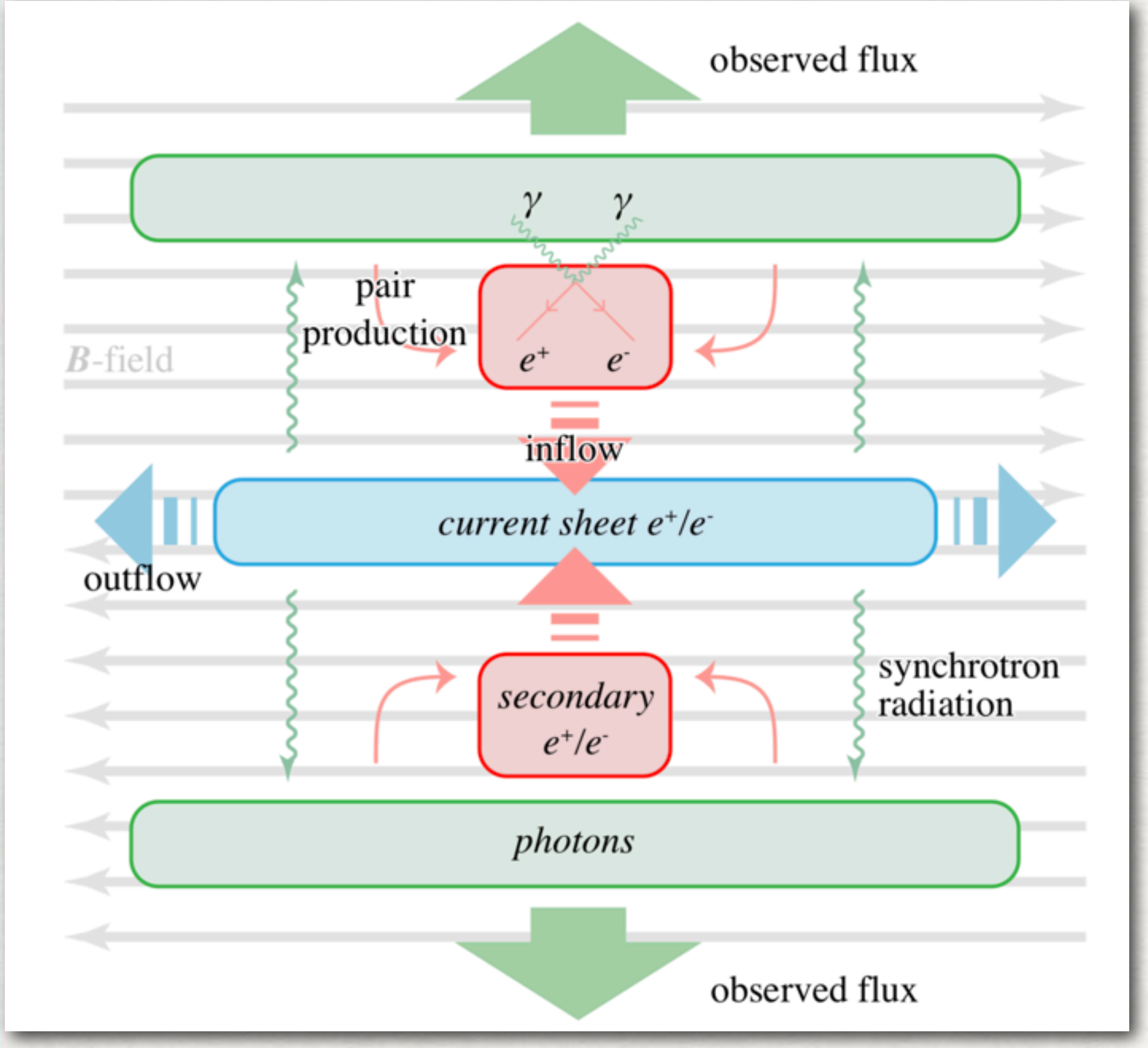


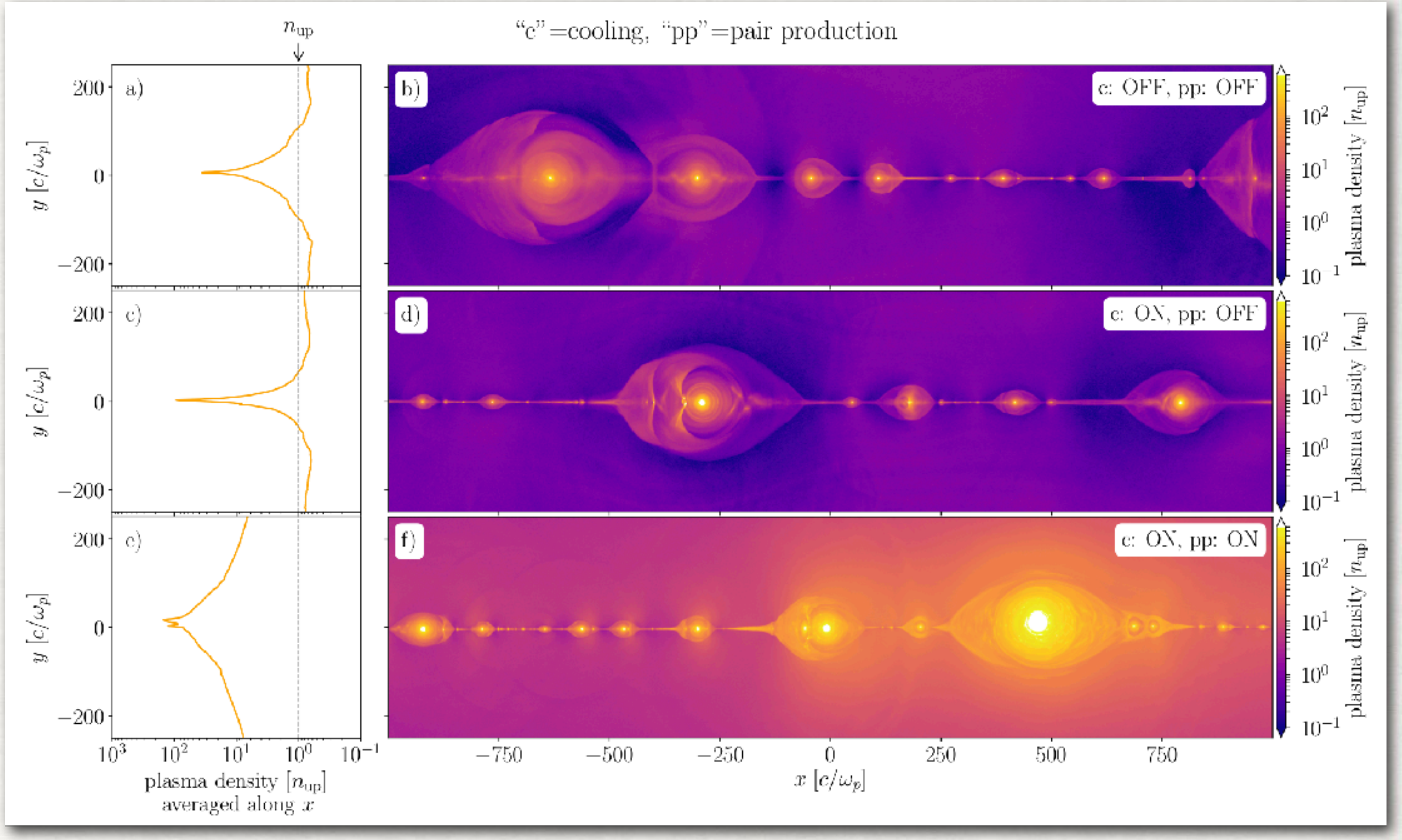
$m_e c$

Pair production at LC sets the peak emission frequency

Philippov et al., ApJ, 2016

THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING CUTOFF ENERGY

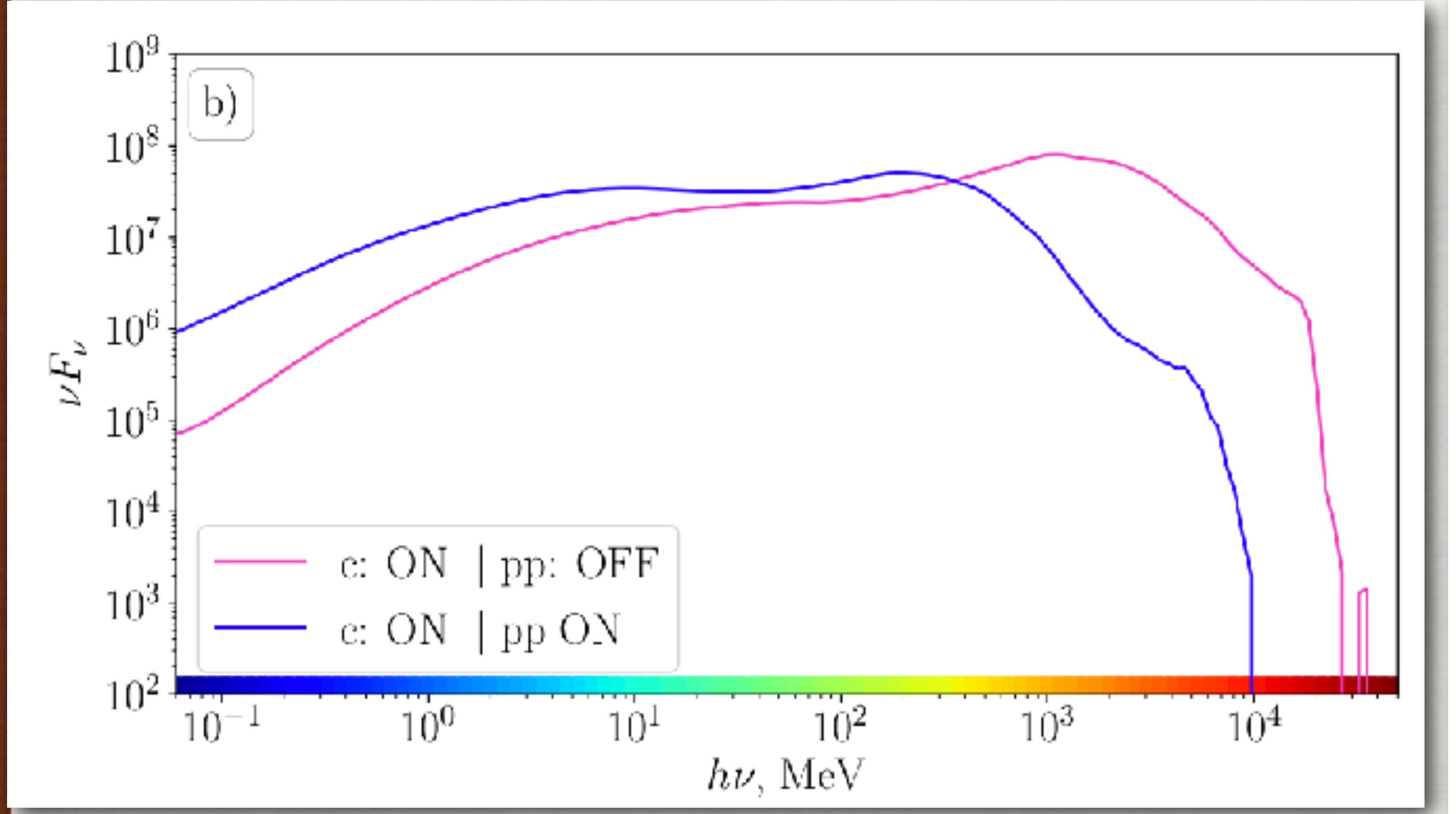


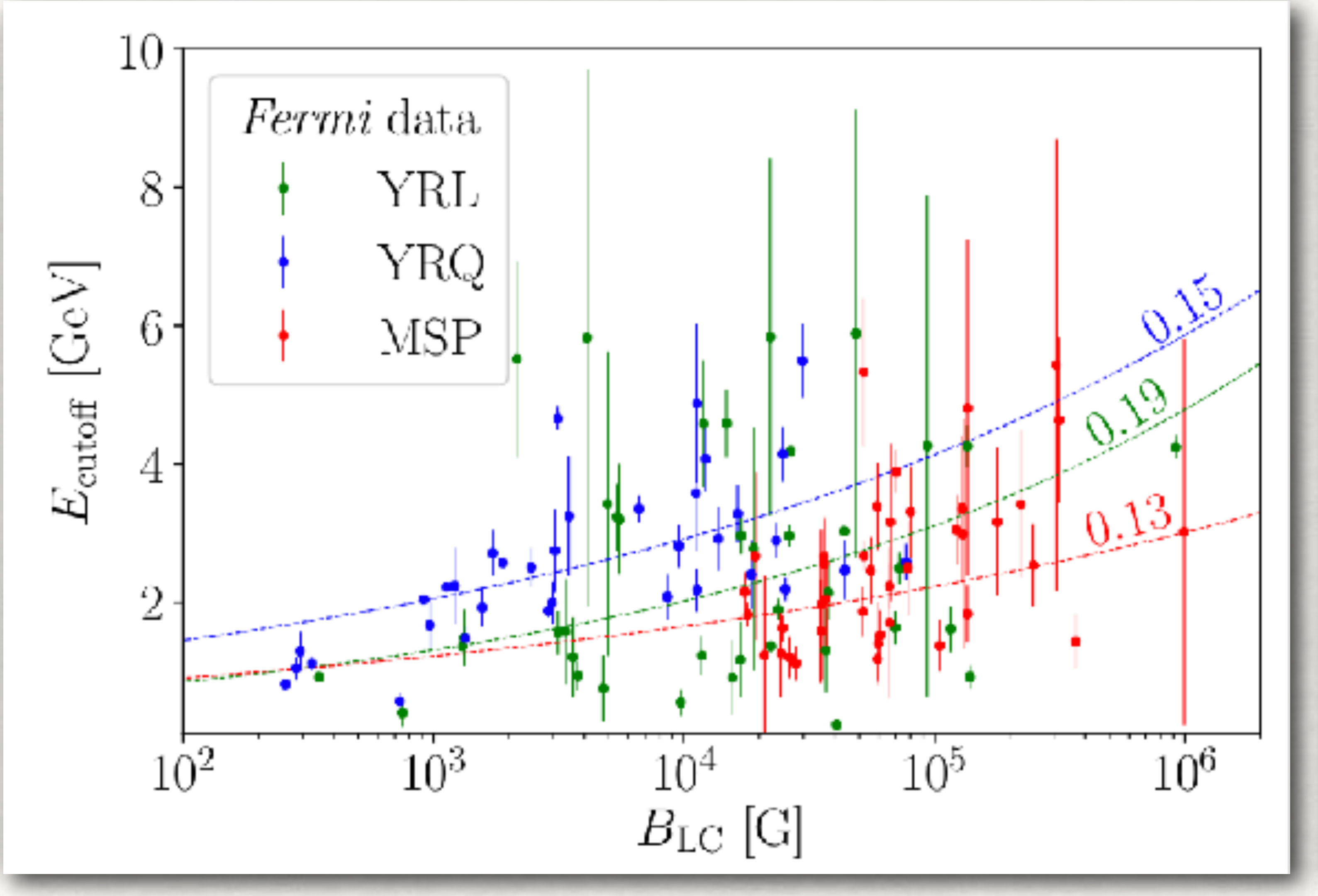


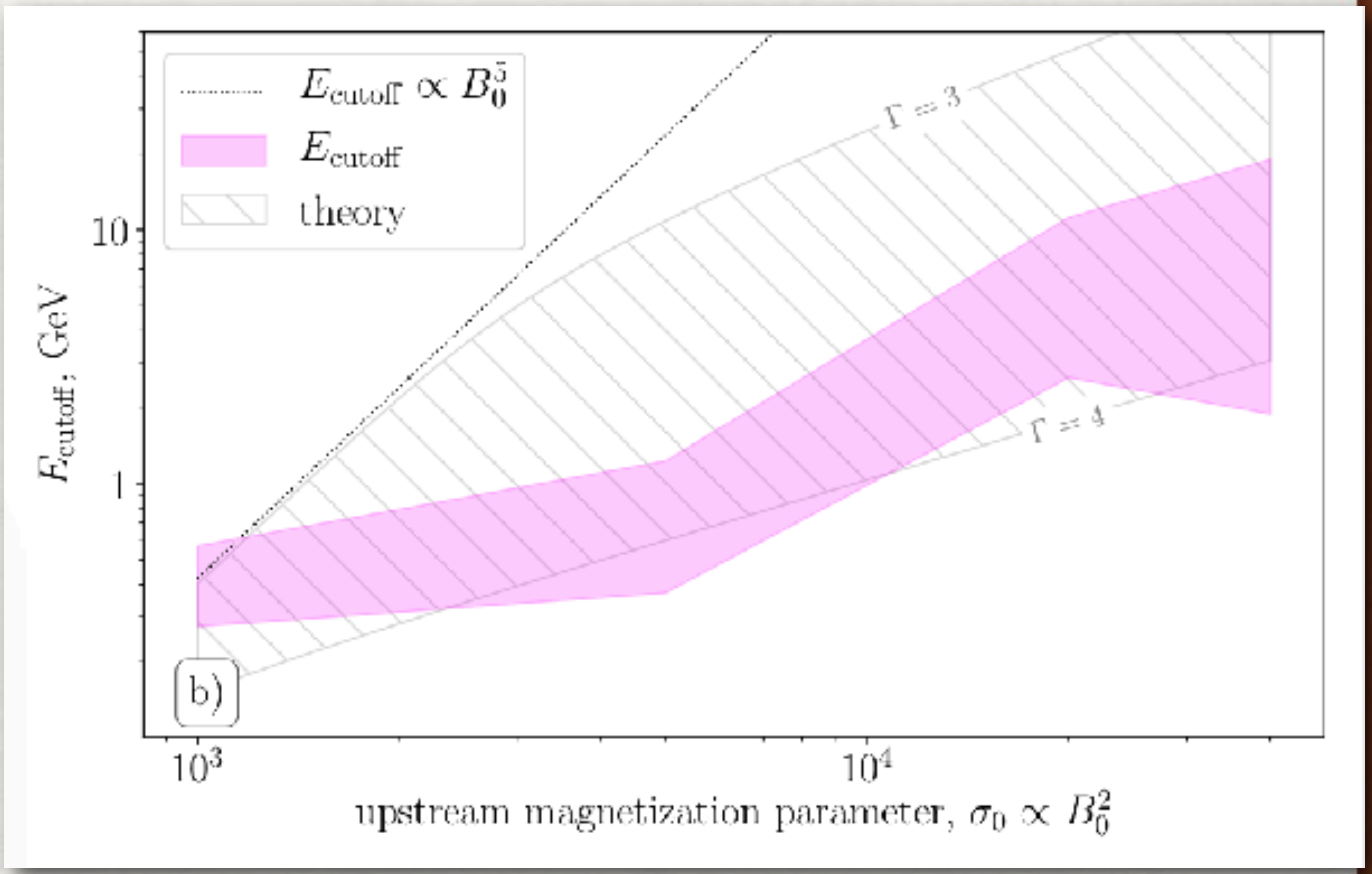
Reconnection in the current sheet is main particle accelerator. Gamma-gamma pair formation can start.
Pair formation increases the pair loading above the sheet, and lowers effective magnetization in the sheet.
Particle acceleration follows magnetization, max particle energy is reduced.

Hakobyan, Philippov, AS 2018

THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING CUTOFF ENERGY







Pair formation increases the pair loading above the sheet, and lowers effective magnetization in the sheet.
Particle acceleration follows magnetization, max particle energy is reduced. Synchrotron emission.
Naively, cutoff energy should be a strong function of B at the LC.

$$\gamma_{\rm cuttoff} \propto \sigma_0 \propto B_0^2; \quad E_{\rm cutoff} \propto \gamma_{\rm cuttoff}^2 B_0 \propto B_0^5$$

Pair loading softens the dependence

$$\gamma_{\rm cutoff} \sim \sigma_{\rm LC} \propto B_{\rm LC}^2/\eta n_{\rm GJ}$$

Expect cutoff energy dependence to be between $E_{\rm cutoff} \propto B_{\rm LC}^{1.2}\text{-}B_{\rm LC}^{1.8}$ and $E_{\rm cutoff} \propto B_{\rm LC}^{-0.8}\text{-}B_{\rm LC}^{-0.2}$

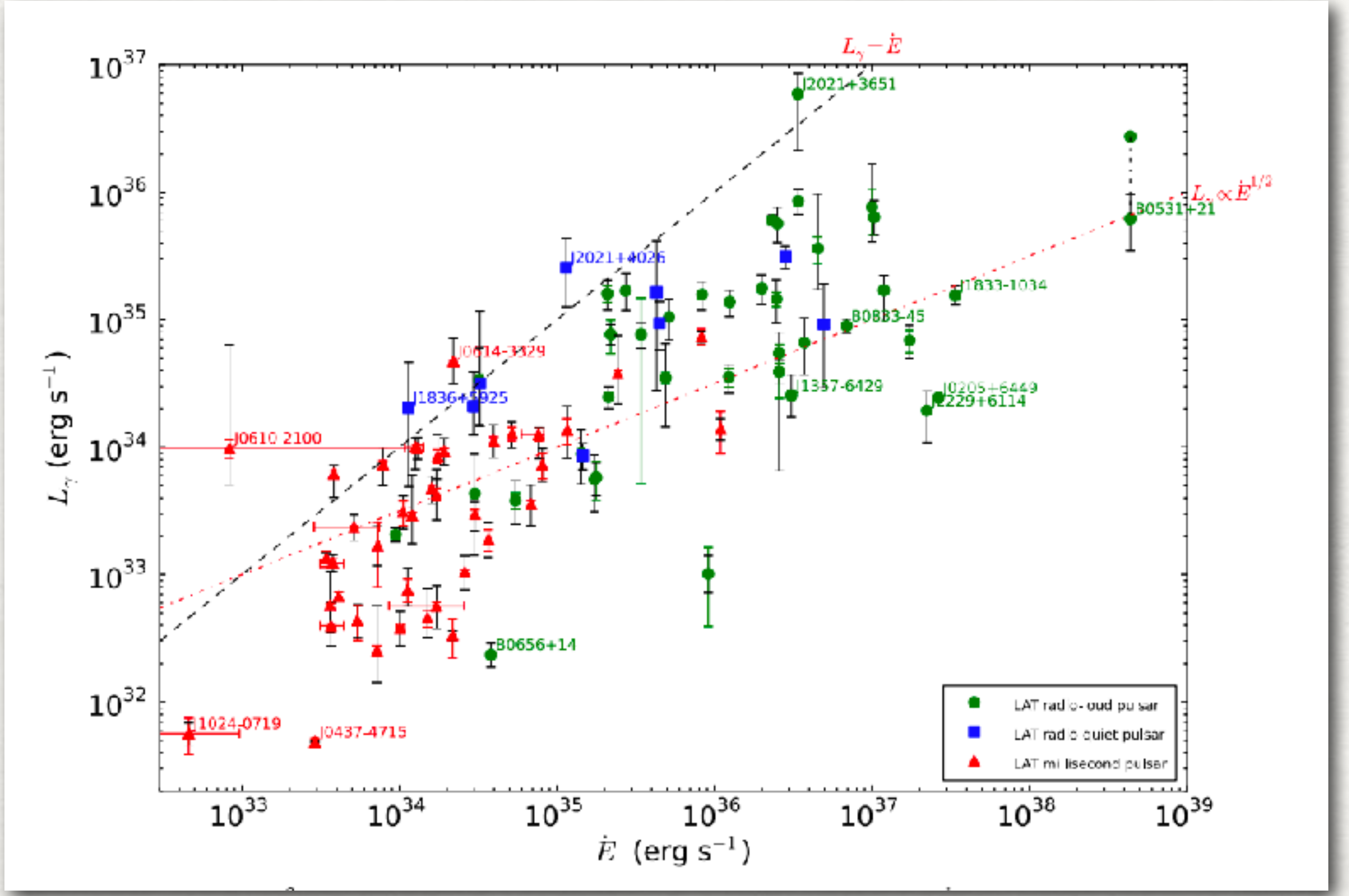
Observed dependence: $E_{\rm cutoff} \propto B_{\rm LC}^{0.1}\text{-}B_{\rm LC}^{0.2}$

Hakobyan, Philippov, AS 2018

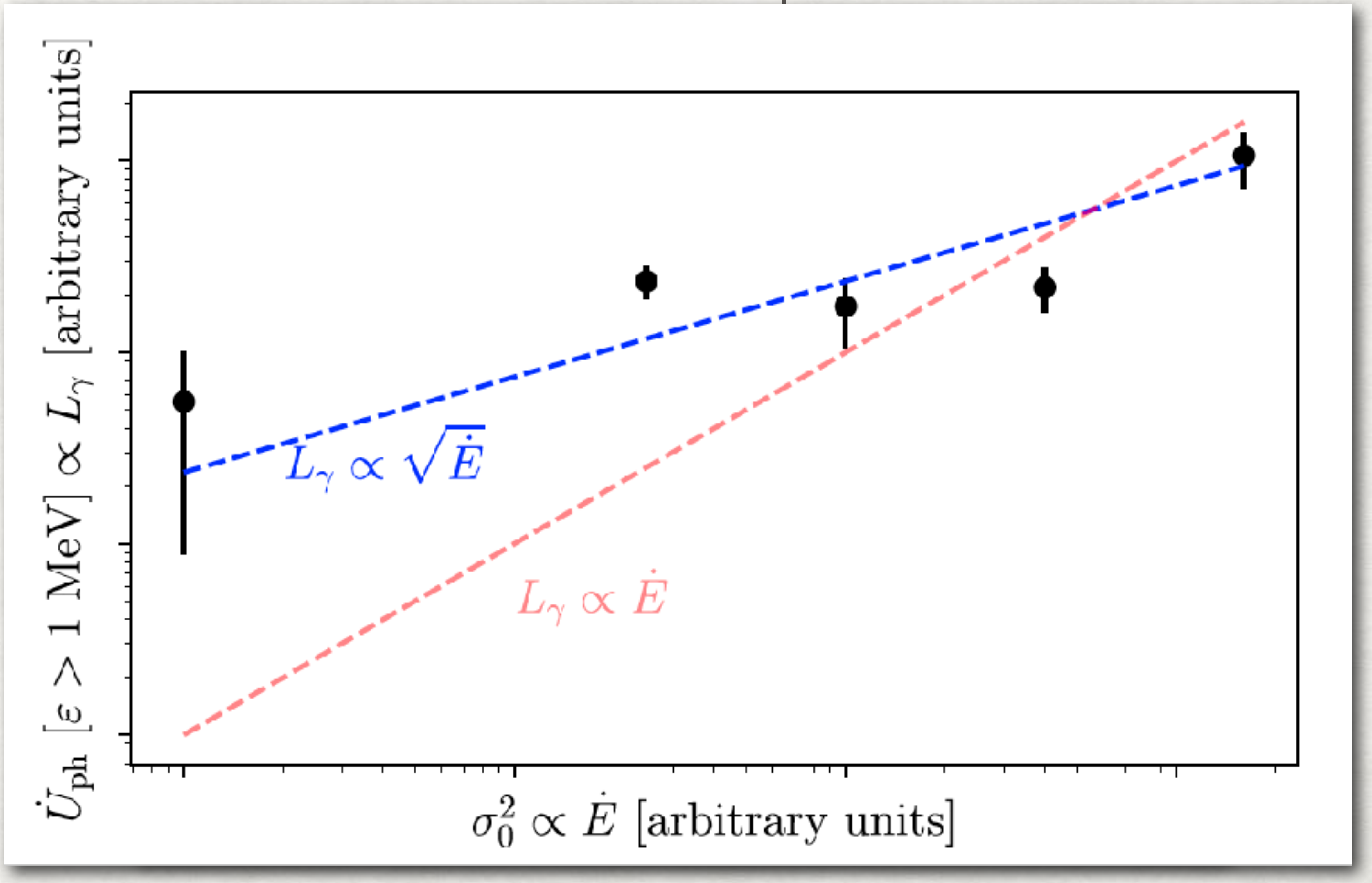
THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING L_γ

Gamma luminosity is larger for aligned rotators than for oblique ones. $L_\gamma/\dot{E}$ varies from 1% for orthogonal rotator to 10% for near aligned. Obliqueness effects can explain the spread in observed values of L_γ . In this regime $L_\gamma \propto \dot{E}$. Another model: curvature emission cf: Kalapotharakos et al 2019

Pair formation in the current sheet decreases magnetization and lowers maximum particle energy, and radiative efficiency decreases. Also, reconnection slows down. This leads to slower Edot dependence.



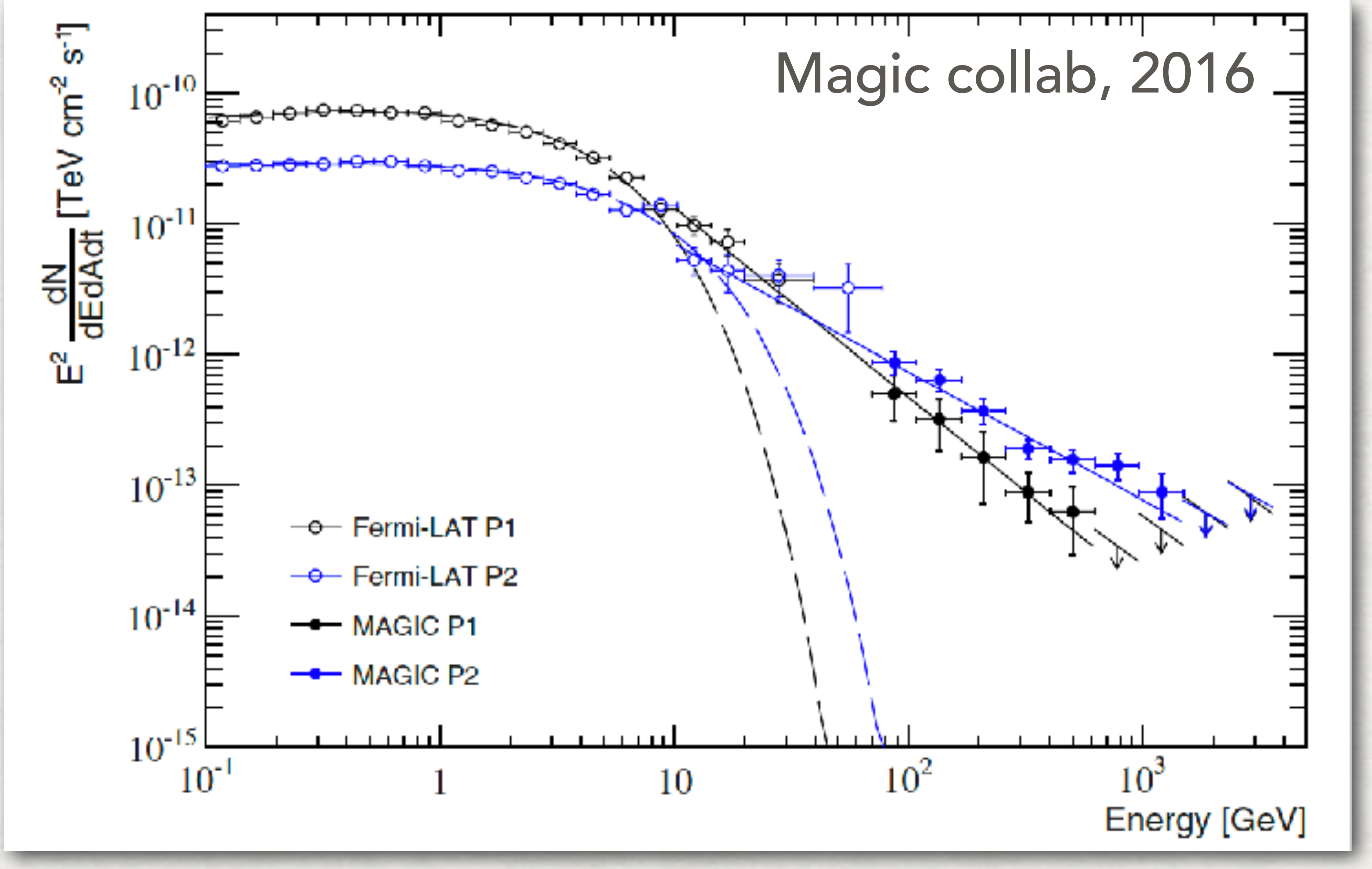
Abdo et al 2013

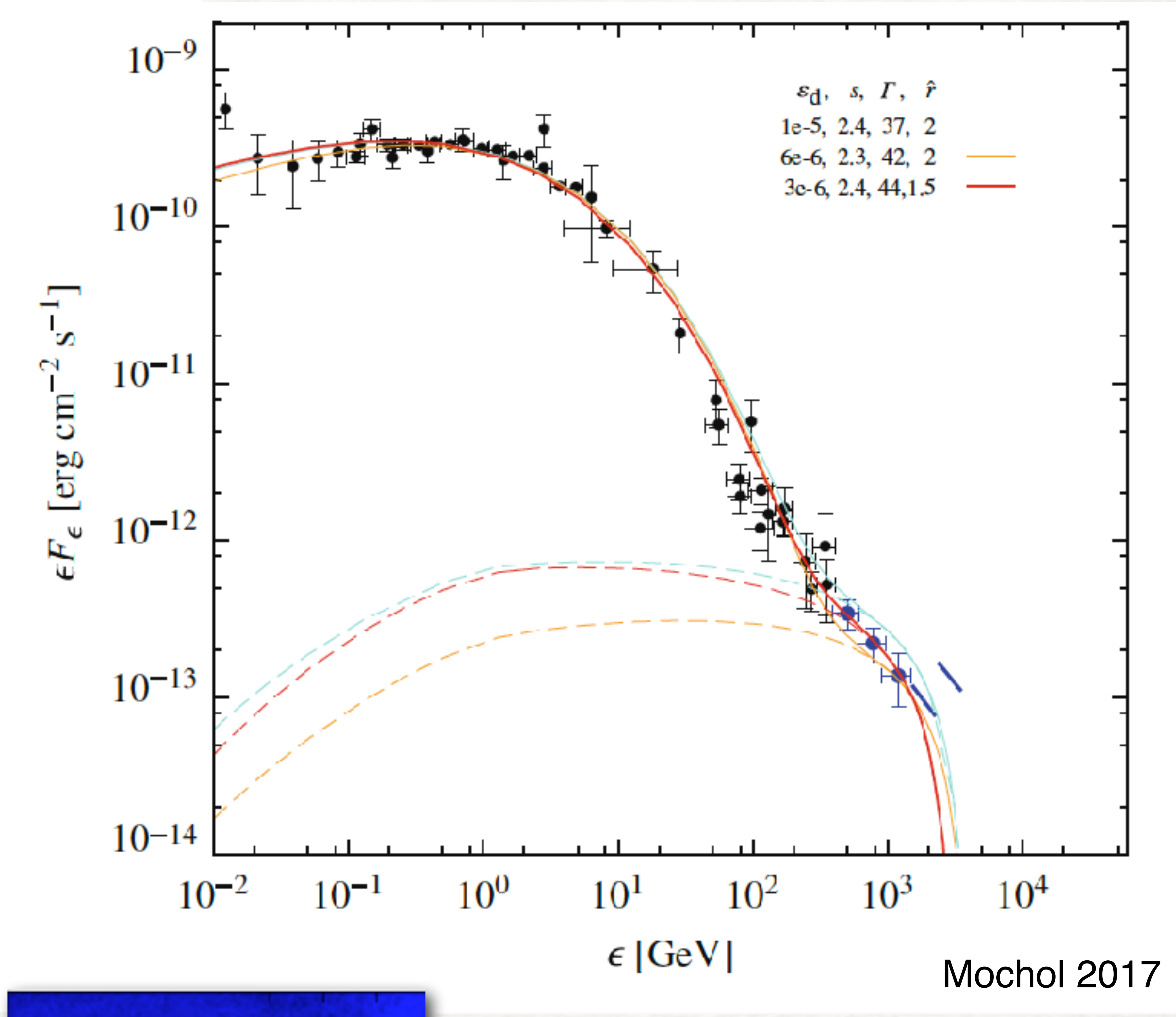


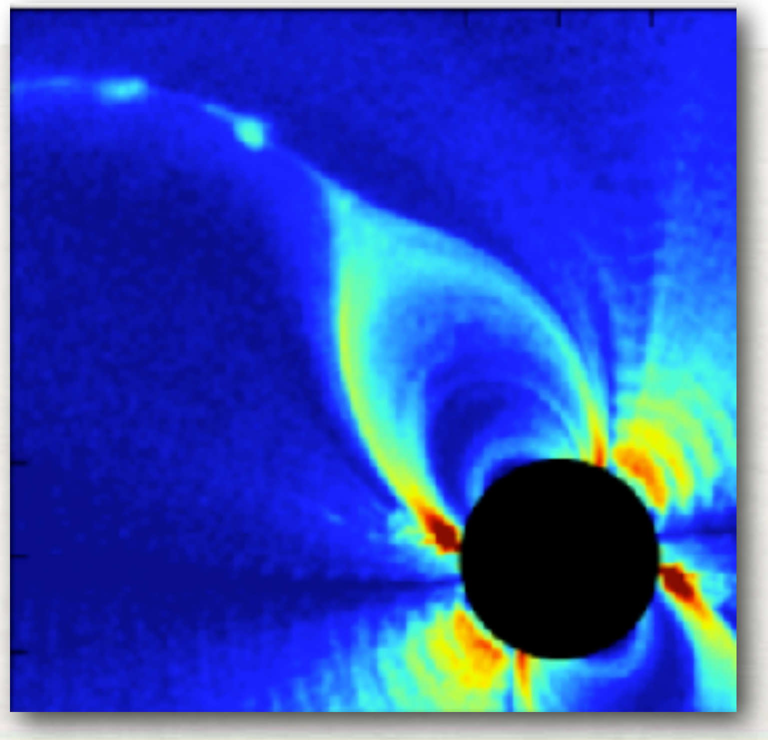
Hakobyan, Philippov, AS 2018

PULSED TEV EMISSION

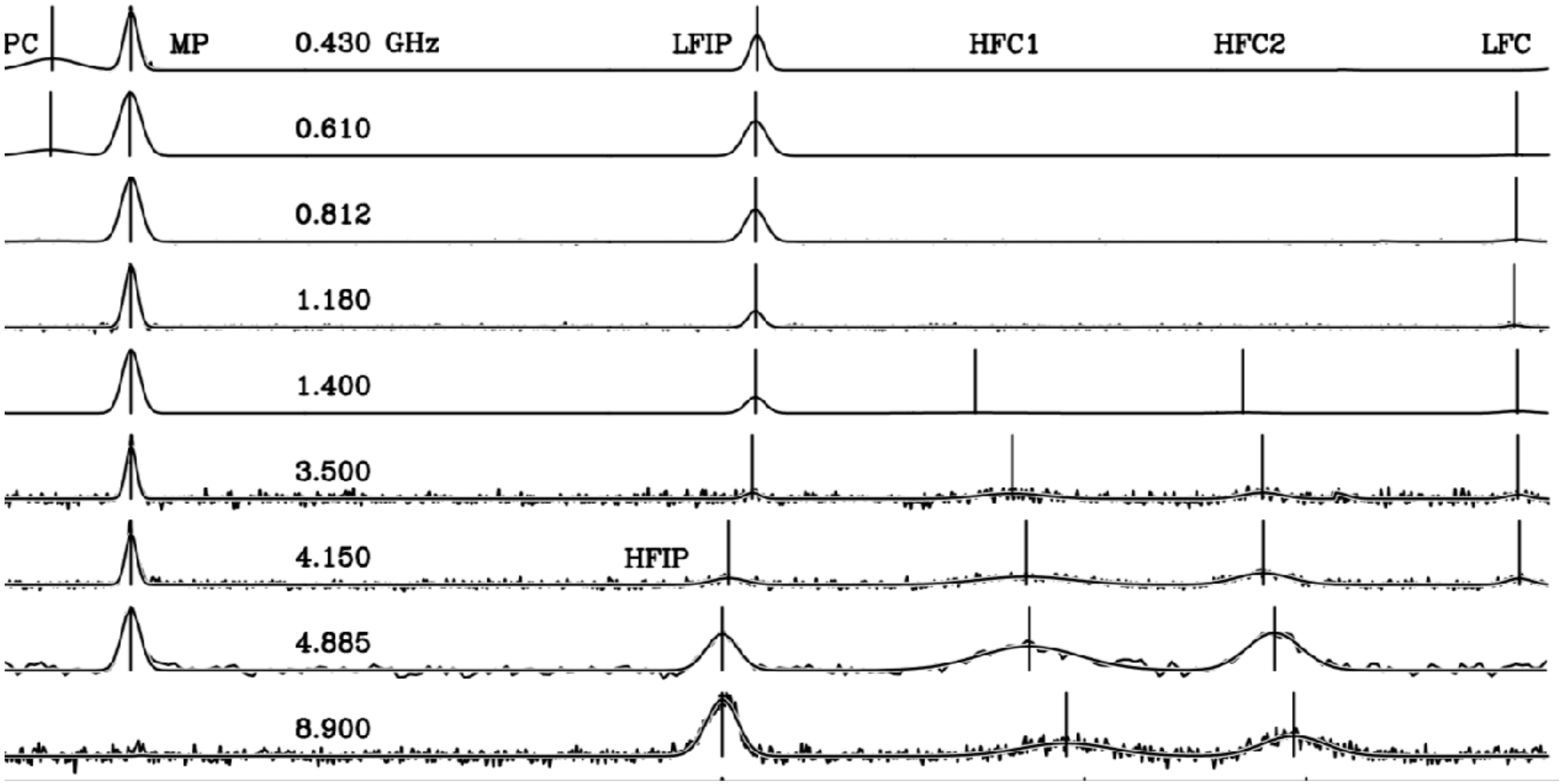
- IACT detection of pulsed TeV: new component or IC?
- Direct IC would imply particles with gamma~10^7 in the current sheet — hard to obtain in reconnection without direct Ell acceleration (Harding et al 18).
- SSC of current-sheet accelerated particles +doppler boost due to bulk wind motion (Mochol 17) is more natural. More modeling needs to be done!

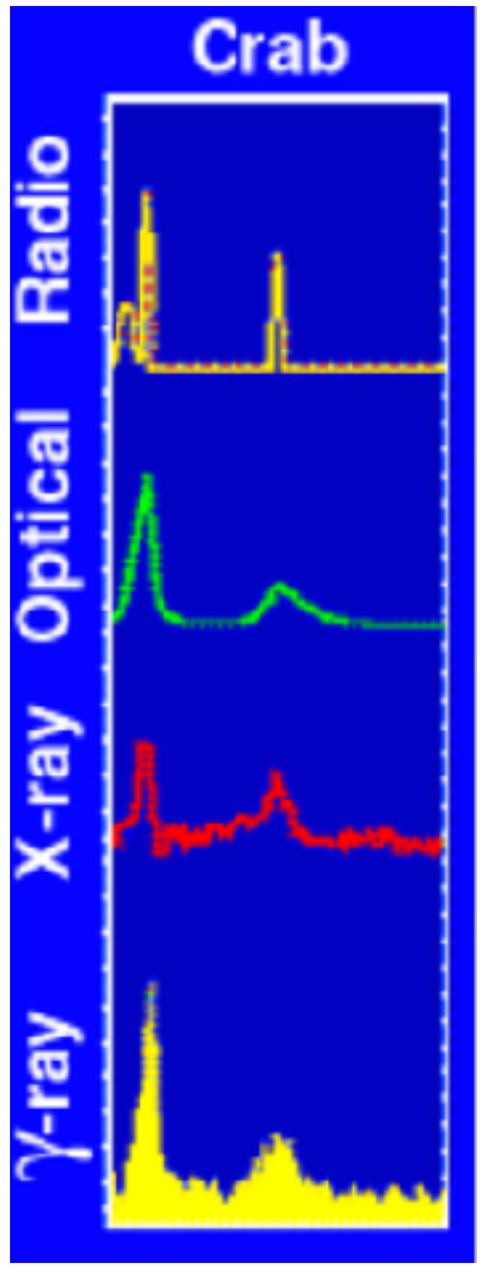






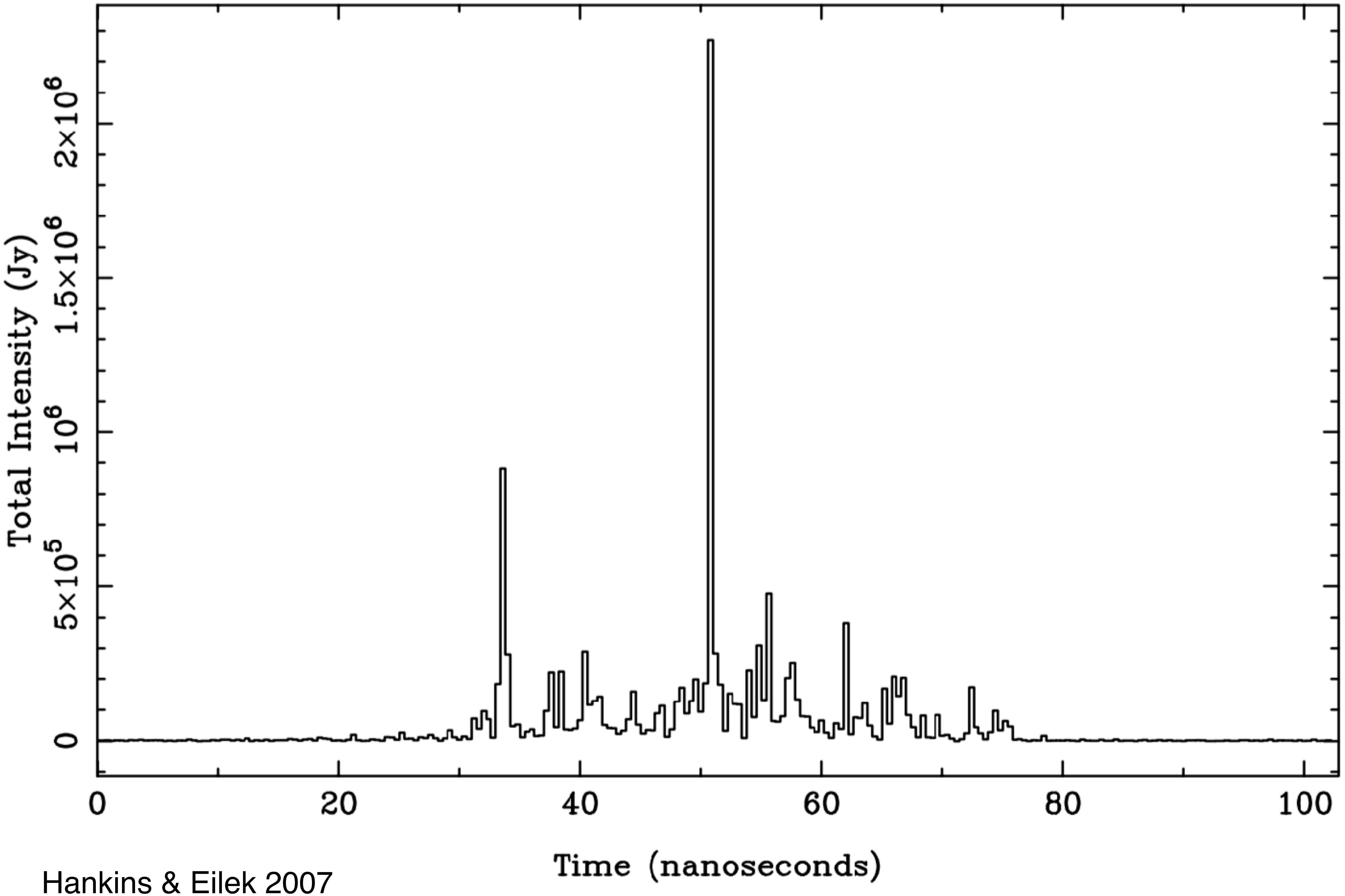
Related: Crab radio from outer magnetosphere





MP and IP have high-energy counter-parts, definitely emission from outer magnetosphere

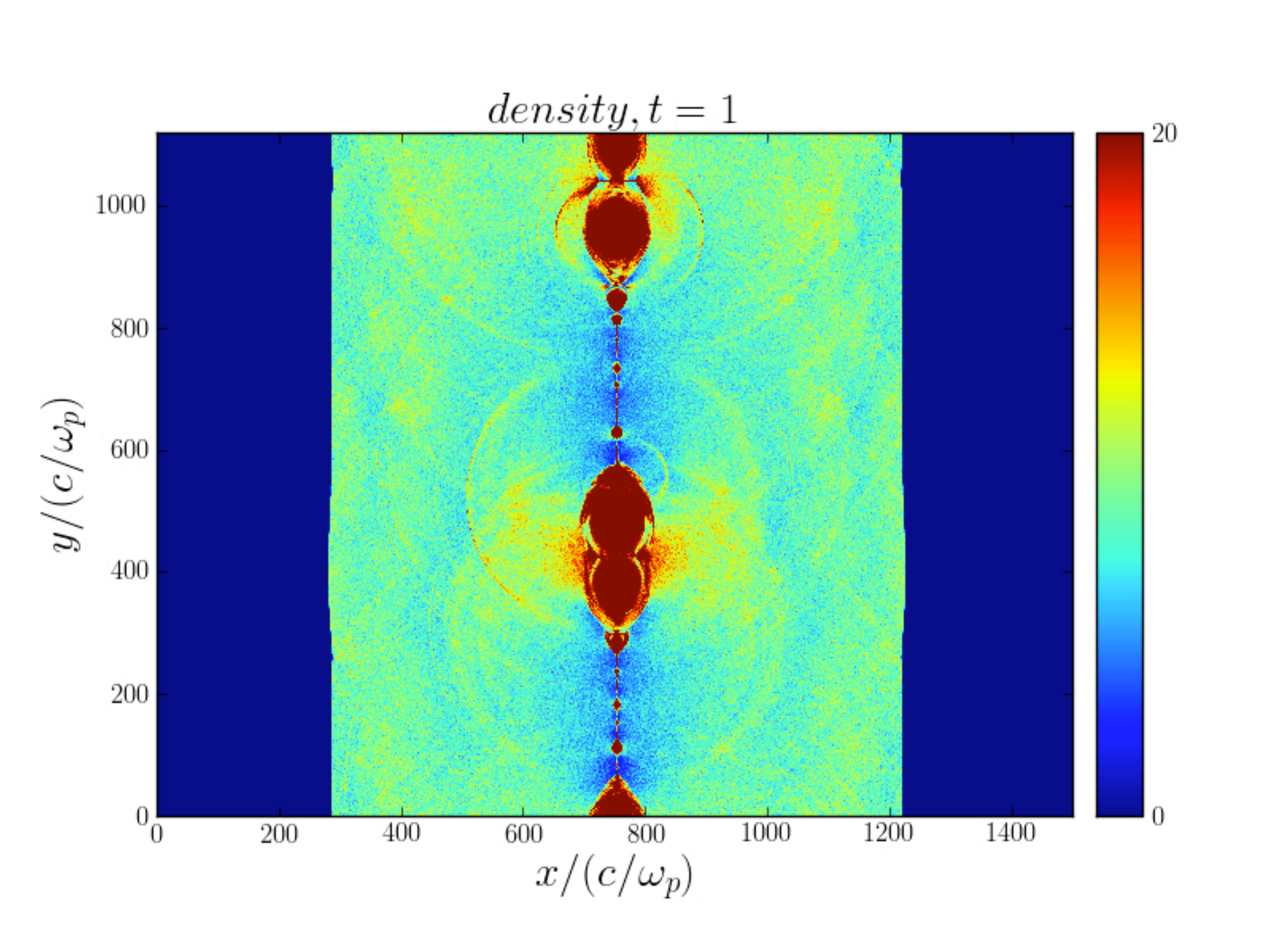
Hankins & Eilek 2016



Hankins & Eilek 2007

GIANT PULSES: COHERENT EMISSION FROM RECONNECTION

- Current sheet breaks into a plasmoid chain.
- Plasmoids merge.
- EM pulses are produced, leave the box freely
- 0.2% of the reconnection power (~0.0001% of the spin-down luminosity) goes into waves at high magnetizations
- Instantaneously, these pulses can be very bright ~ 10% of the reconnection Poynting flux (0.5% of the spin-down)!



Philippov, Uzdensky, AS, Cerutti (2019)

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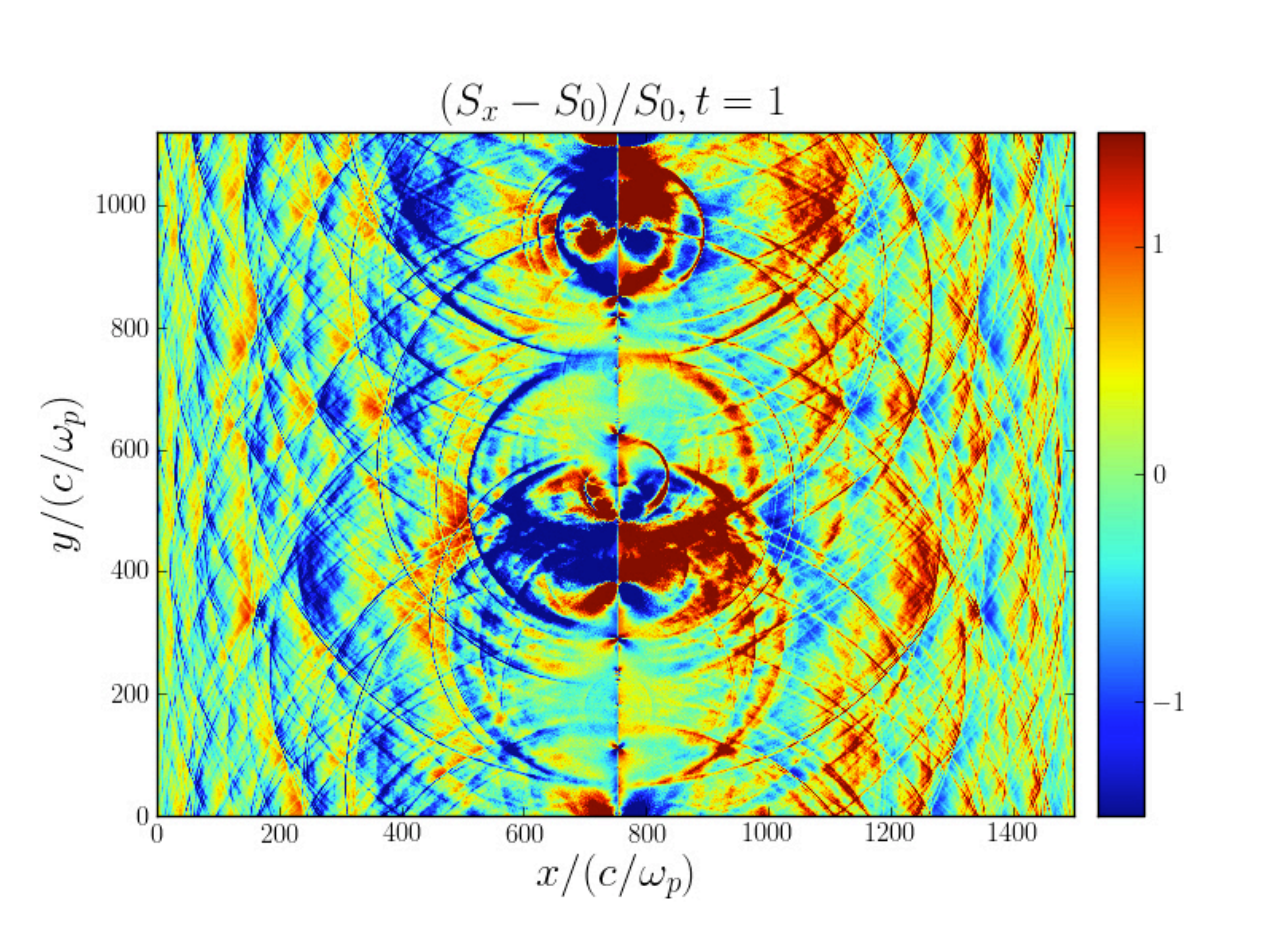
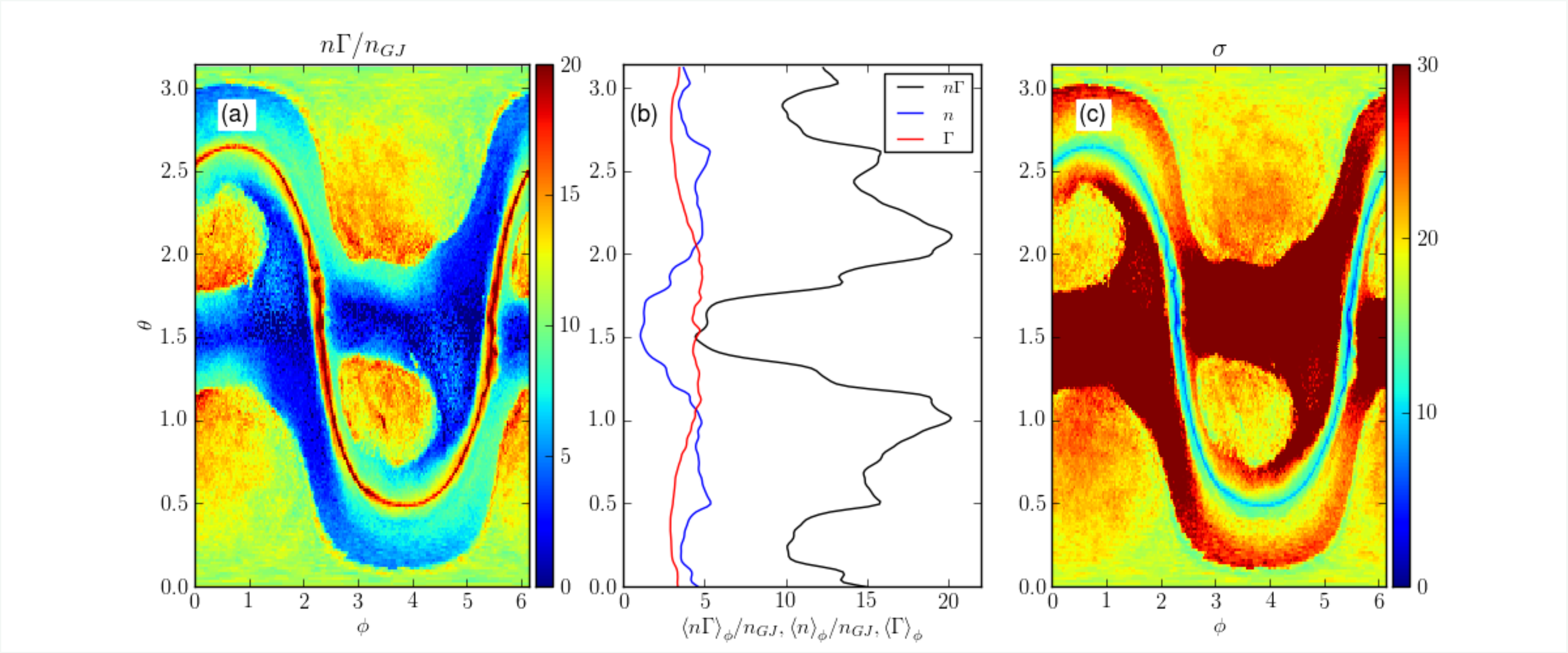


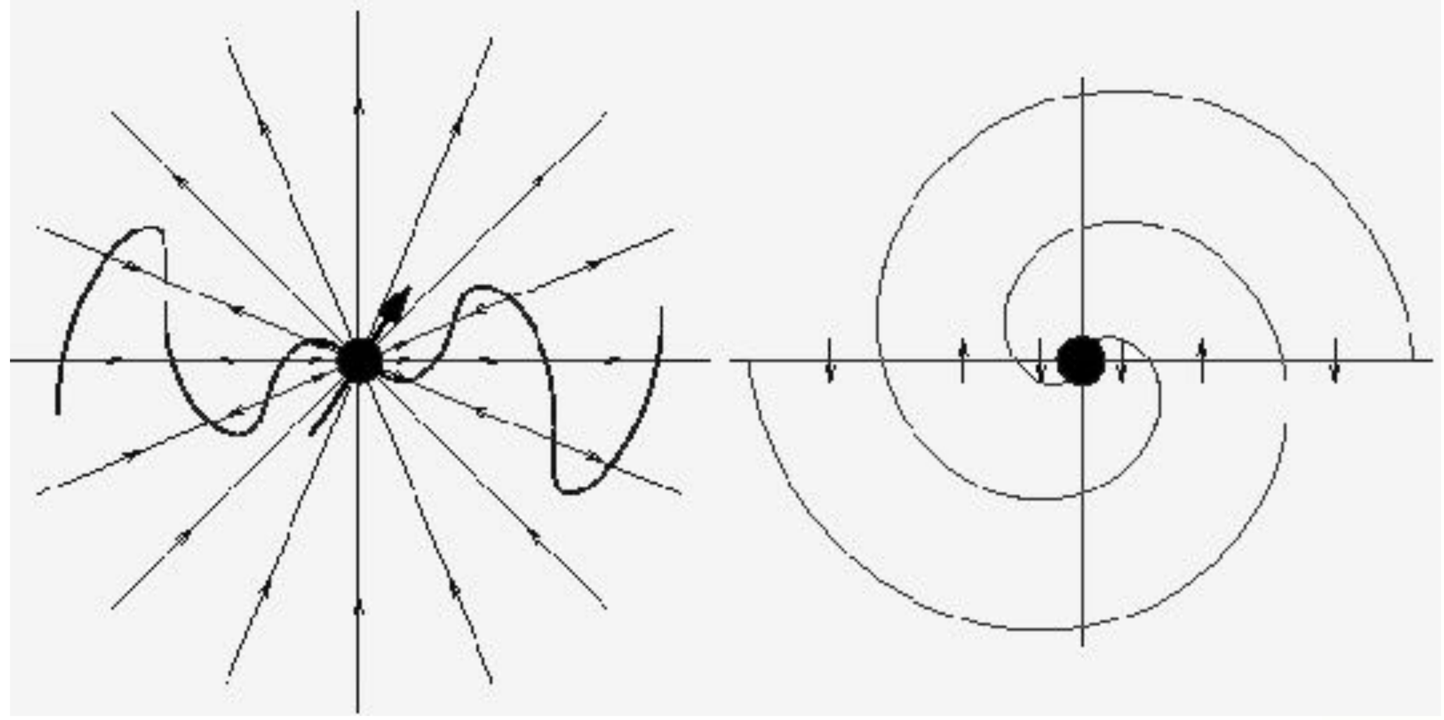
Philippov, Uzdensky, AS, Cerutti (2019)

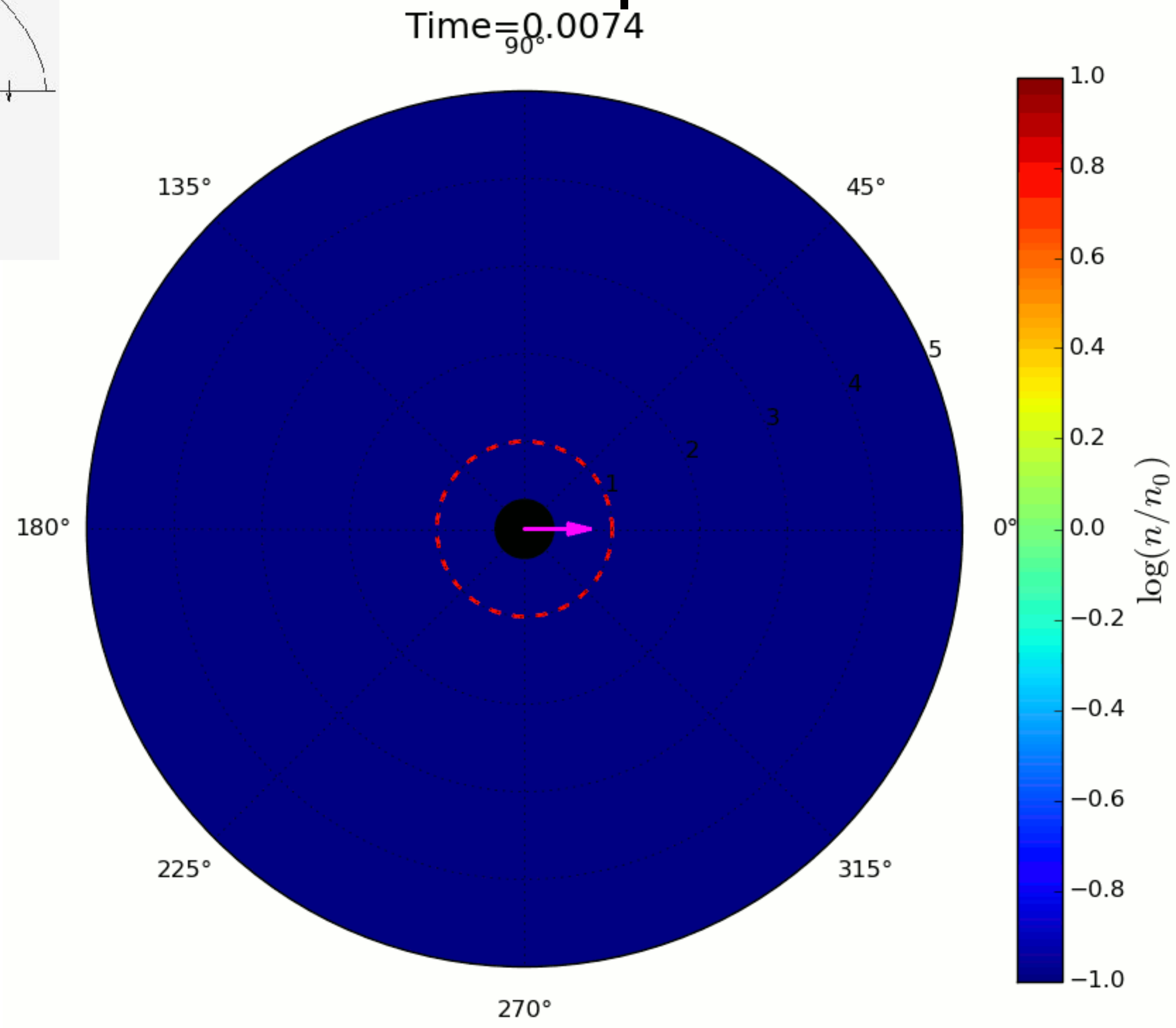
PULSAR WIND:



- Plasma density is non-uniform with latitude, both in the polar zone and in the current sheet wedge
- Magnetic field is not exactly a split monopole, nonuniform with latitude; $S \propto \sin^4\theta$

Evolution of pulsar wind

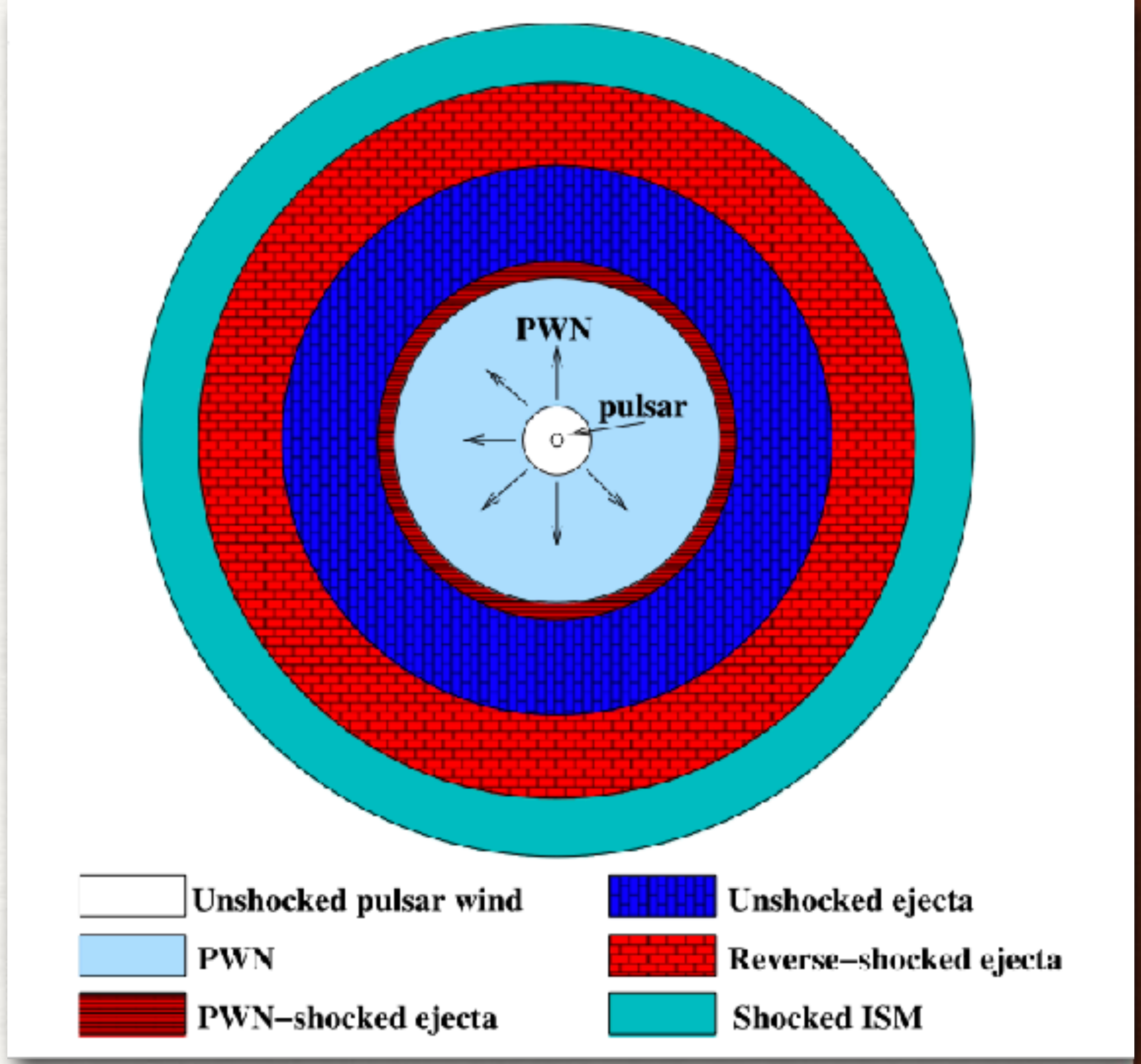


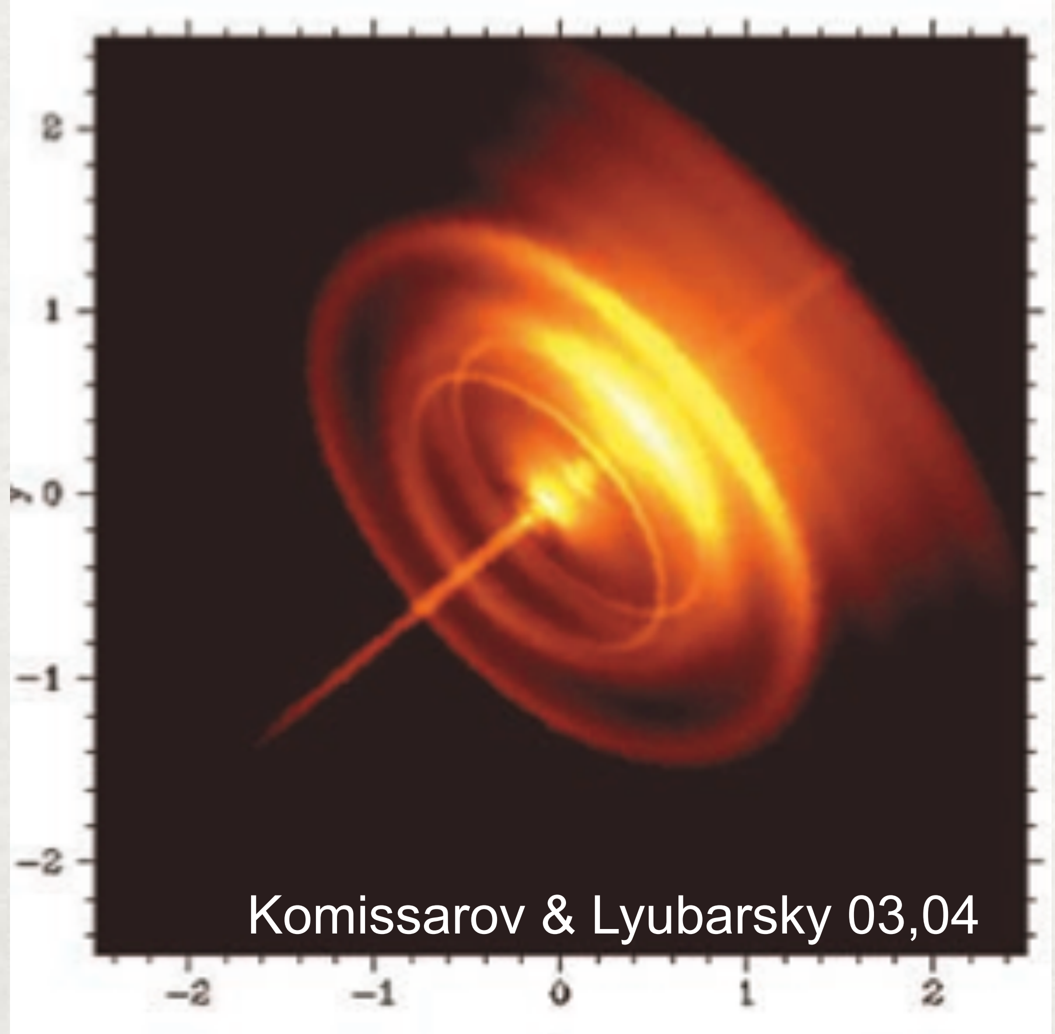


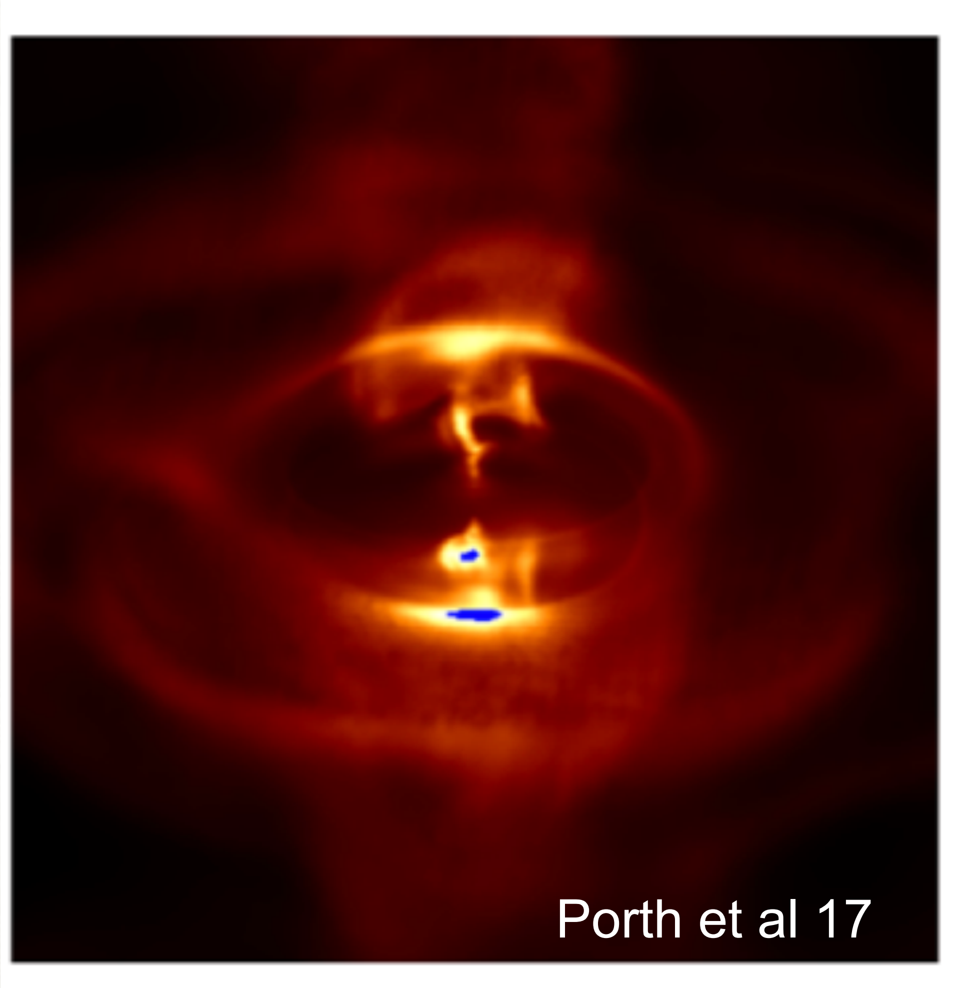
The "striped wind" has alternating fields which can reconnect. Evolution on large scale suggests that it can be reconnected before the wind arrives at the nebula (Cerutti & Philippov 2017): may explain why pulsar winds are more weakly magnetized than expected ("sigma" problem)

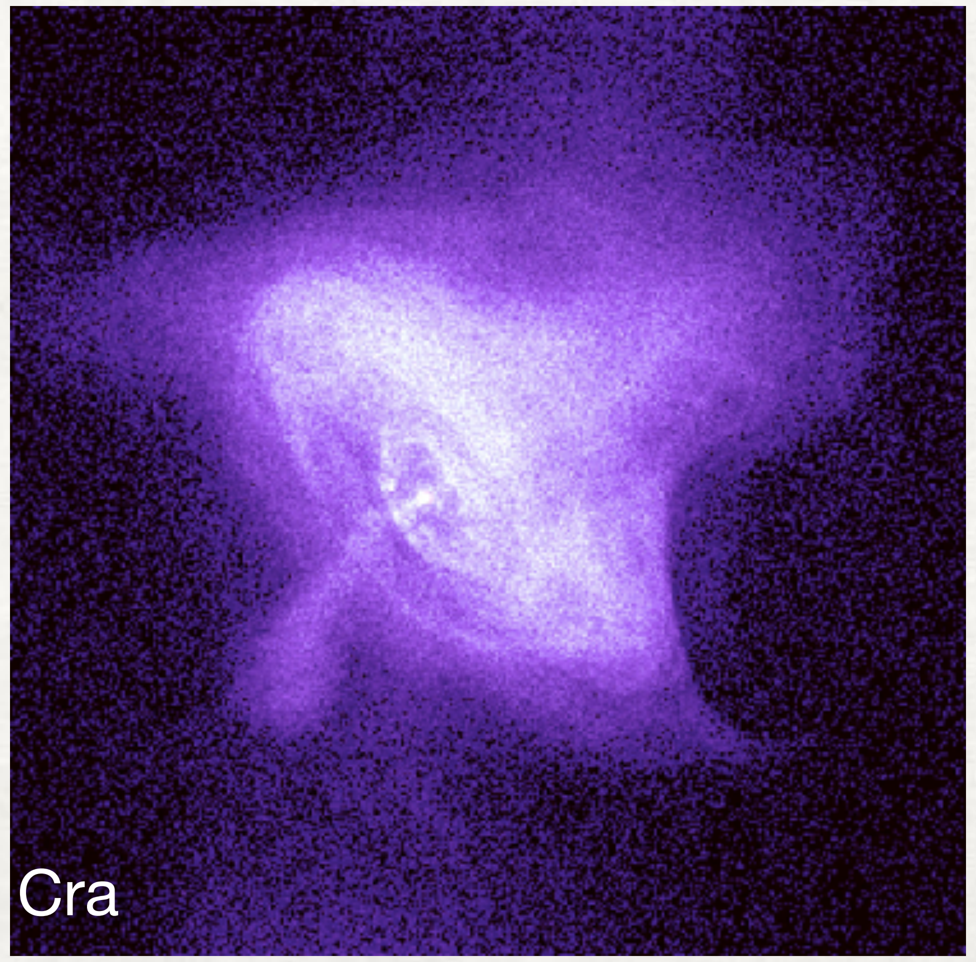
PULSAR WIND NEBULAE

- Transport and deposition of pulsar wind into nebula is important. MHD modeling implies low magnetization at shock, sigma ~ 0.001-0.1, gamma ~ 10^6.
- Magnetization is conserved in ideal MHD, so need non-ideal processes (e.g., reconnection) to convert field.
- Also, wind is latitude-dependent, so different magnetization may come at different latitudes.
- Hoop stress collimates the "jet" post shock.
- Emission: synchrotron, SSC, IC.









How are particles accelerated to multi-TeV energies? Shock? Reconnection?

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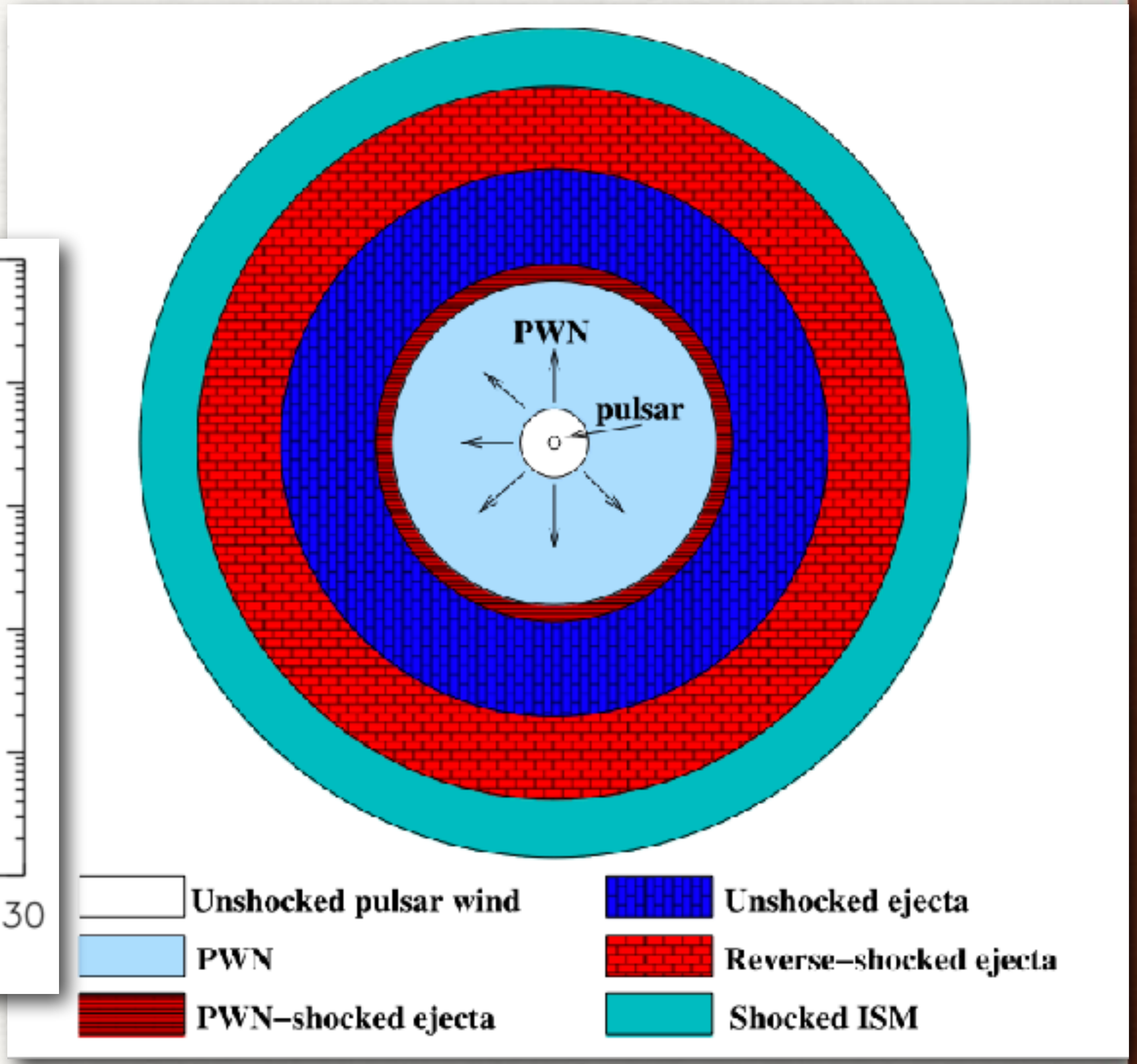
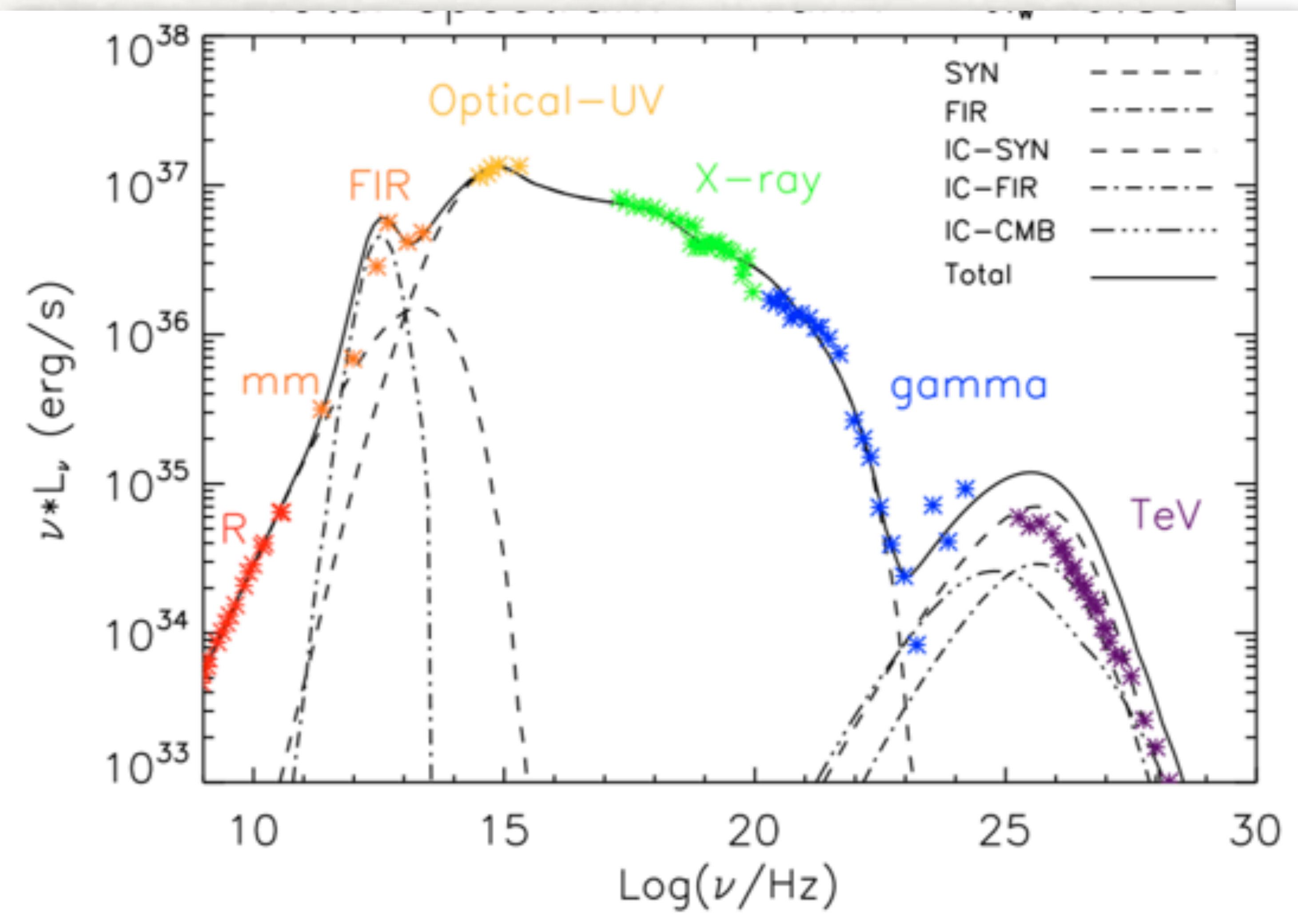
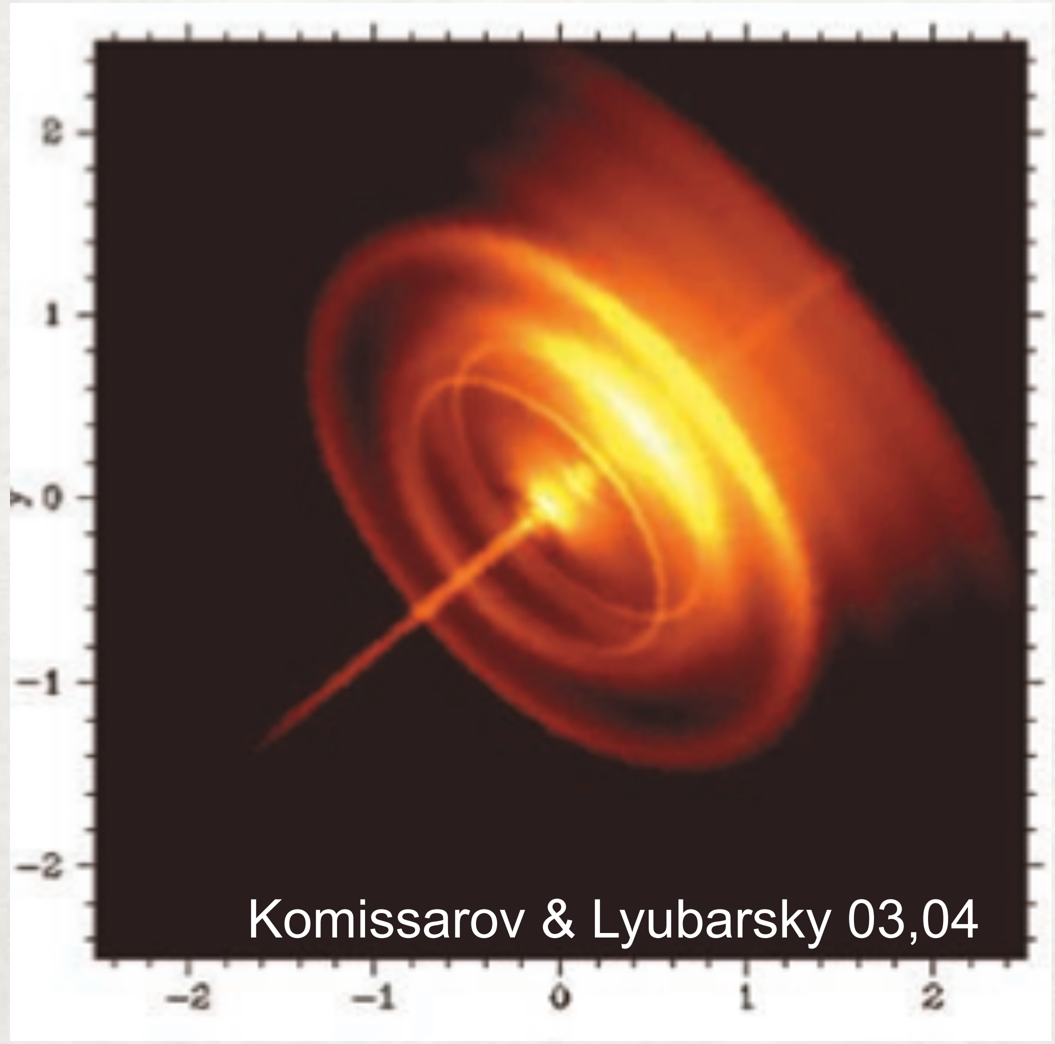
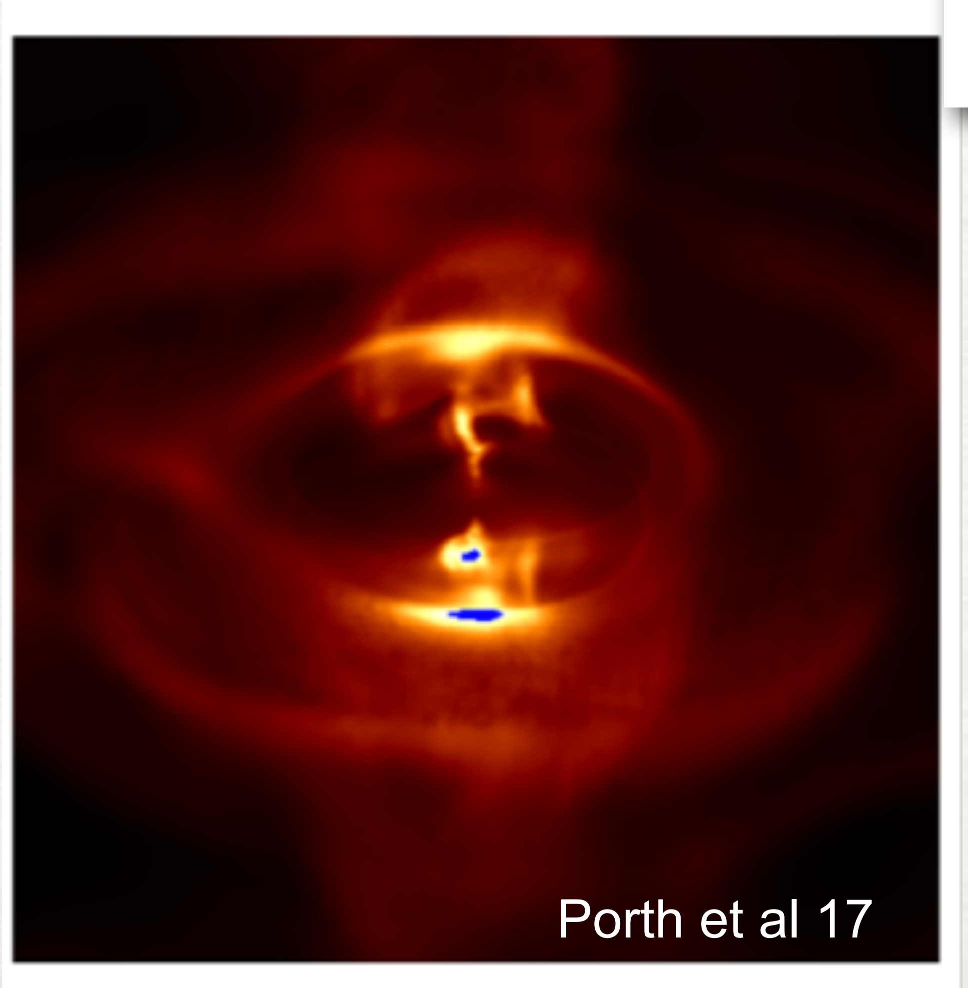
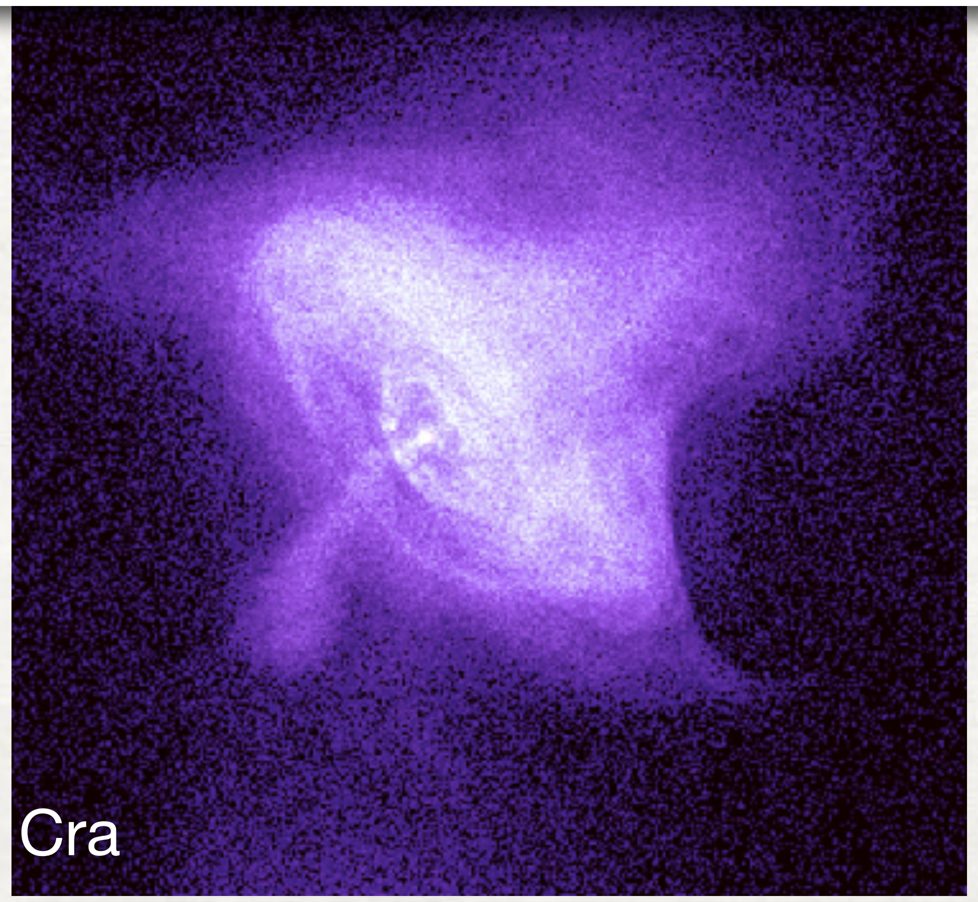





Komissarov & Lyubarsky 03,04


Porth et al 17

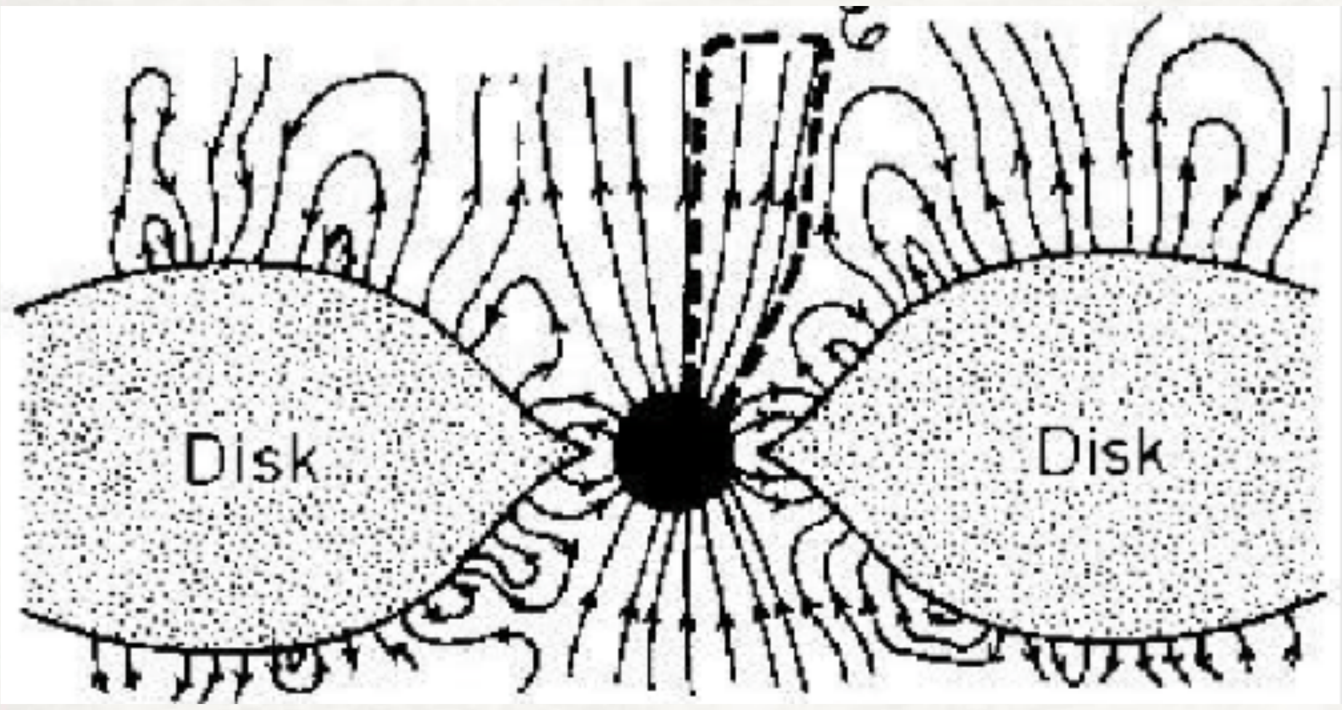

Cra

How are particles accelerated to multi-TeV energies? Shock? Reconnection?

CONCLUSIONS

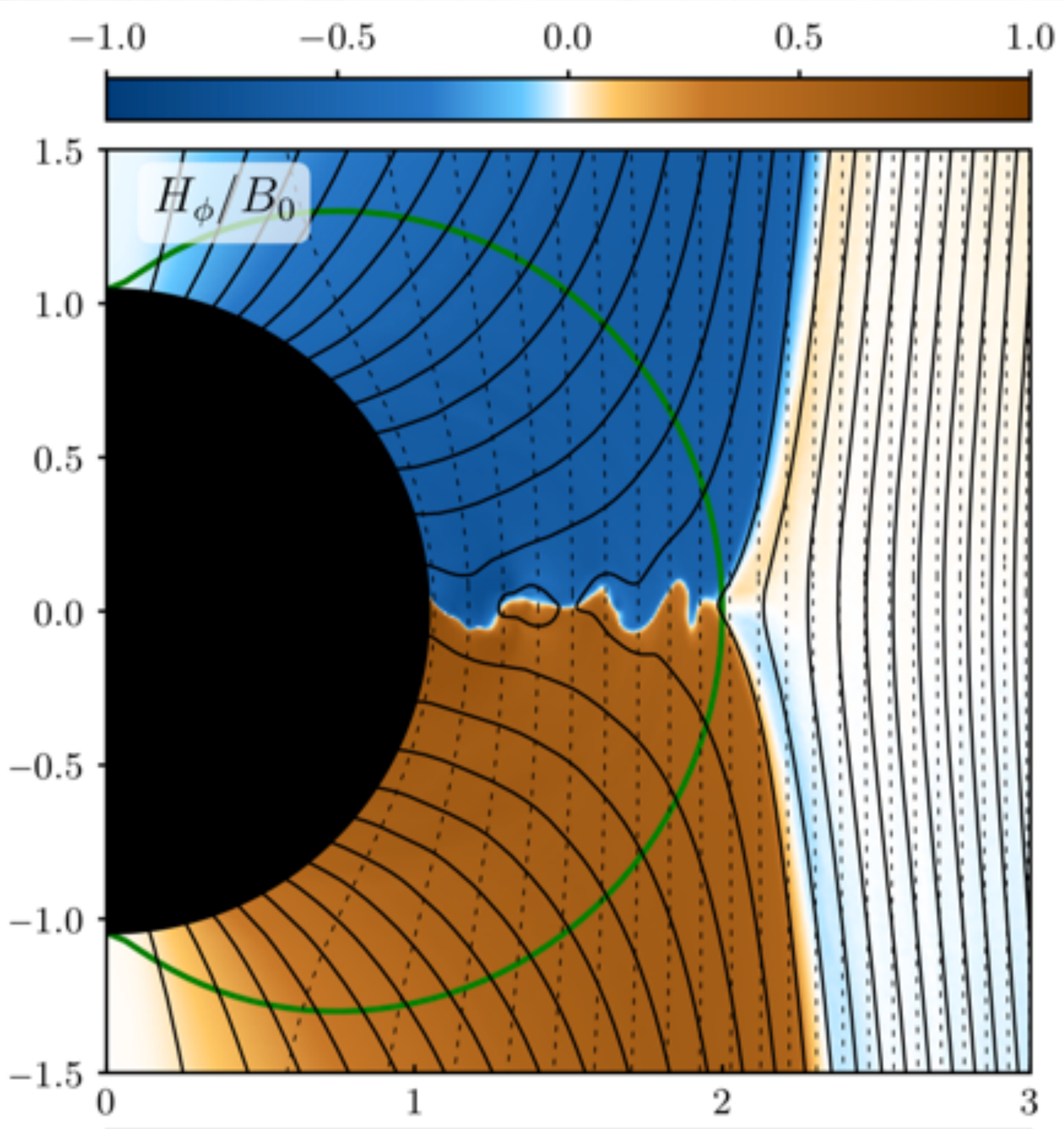
- Electrodynamicaly self-consistent, working magnetospheric models with pair formation and emission are now available using PIC simulations. GR frame-dragging is essential for polar cascades!
- Paradigm change — current sheet beyond LC is effective particle accelerator and the site of majority of high-energy emission. Outer gaps are out. Reconnection with self-consistent pair formation needs to be studied.
- Light curves and spectra are consistent with synchrotron radiation for gamma-ray and below. IC or SSC is needed for TeV.
- Pair creation in the current sheet beyond the LC makes the synchrotron cutoff energy to depend weakly on B_{LC}. When pair creation is weak, Lgamma is proportional to Edot. When pair loading is strong, Lgamma scales as sqrt(Edot).
- Radio emission is likely caused by the non-stationary discharge at the polar cap — first signatures of this are seen in global simulations. More on radio and multiwavelength predictions to come!
- Nebular magnetization, shock acceleration and particle diffusion are not fully understood yet. CTA observations will provide unique constraints on models.

FUTURE APPLICATIONS: ACCRETION AND MERGERS

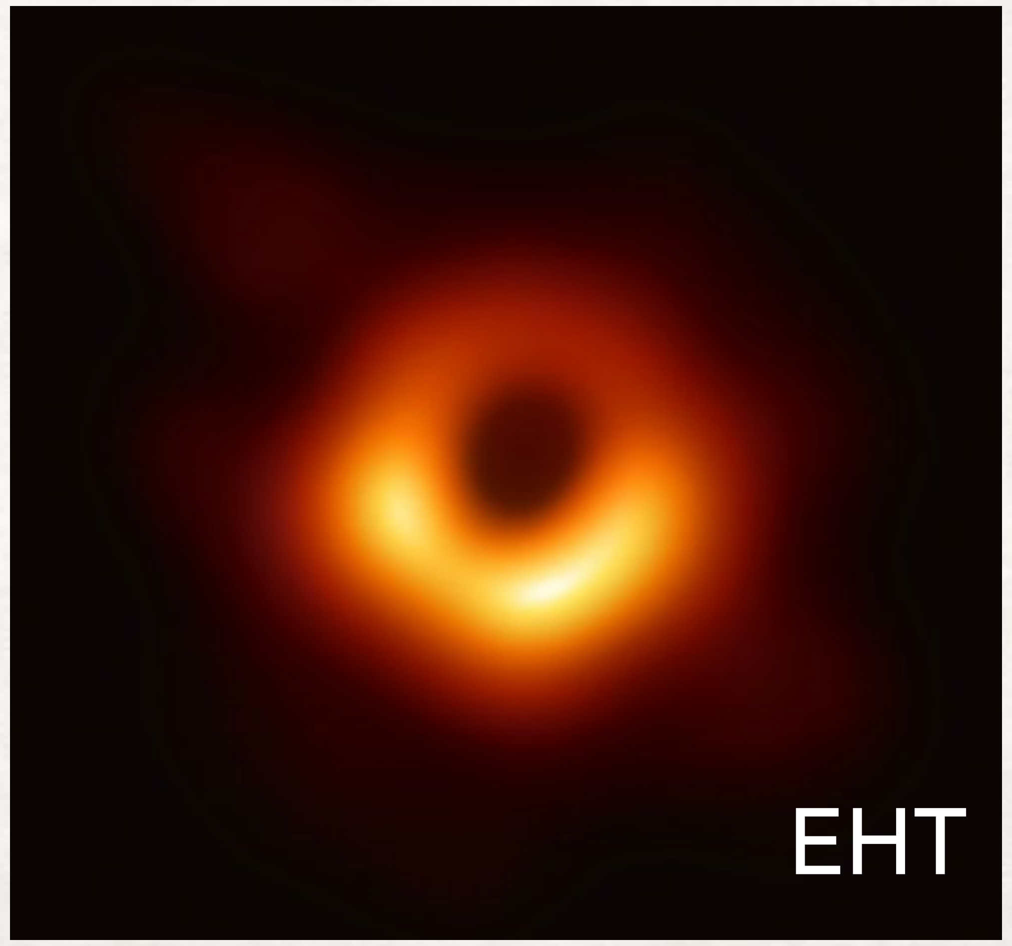


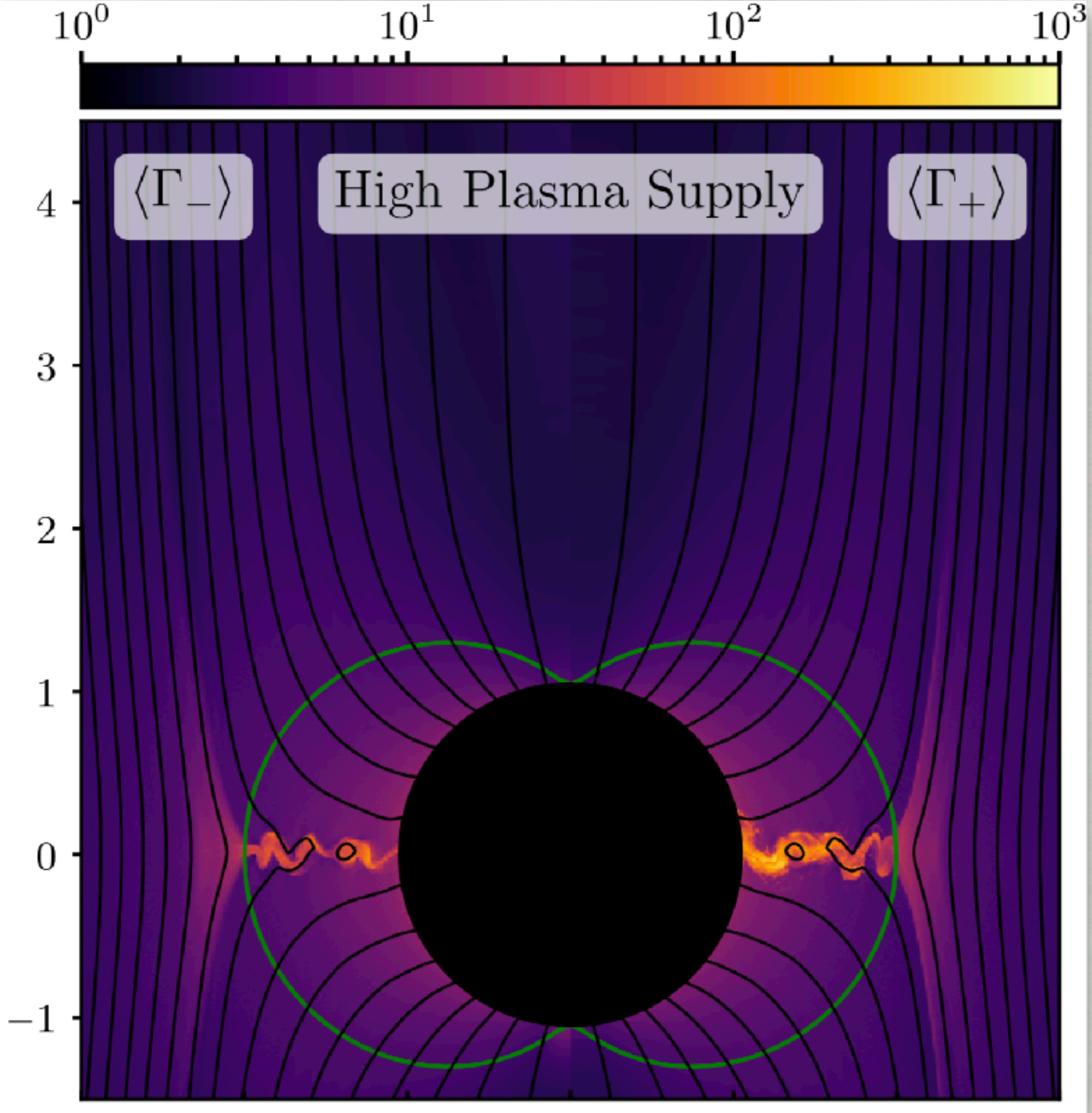
Filling the BH magnetosphere with plasmas, reconnection in accretion disks near the BH horizon can now be addressed with methods developed for pulsars.

GR-PIC simulations show current structure and particle acceleration.



Poloidal and toroidal field in the ergosphere

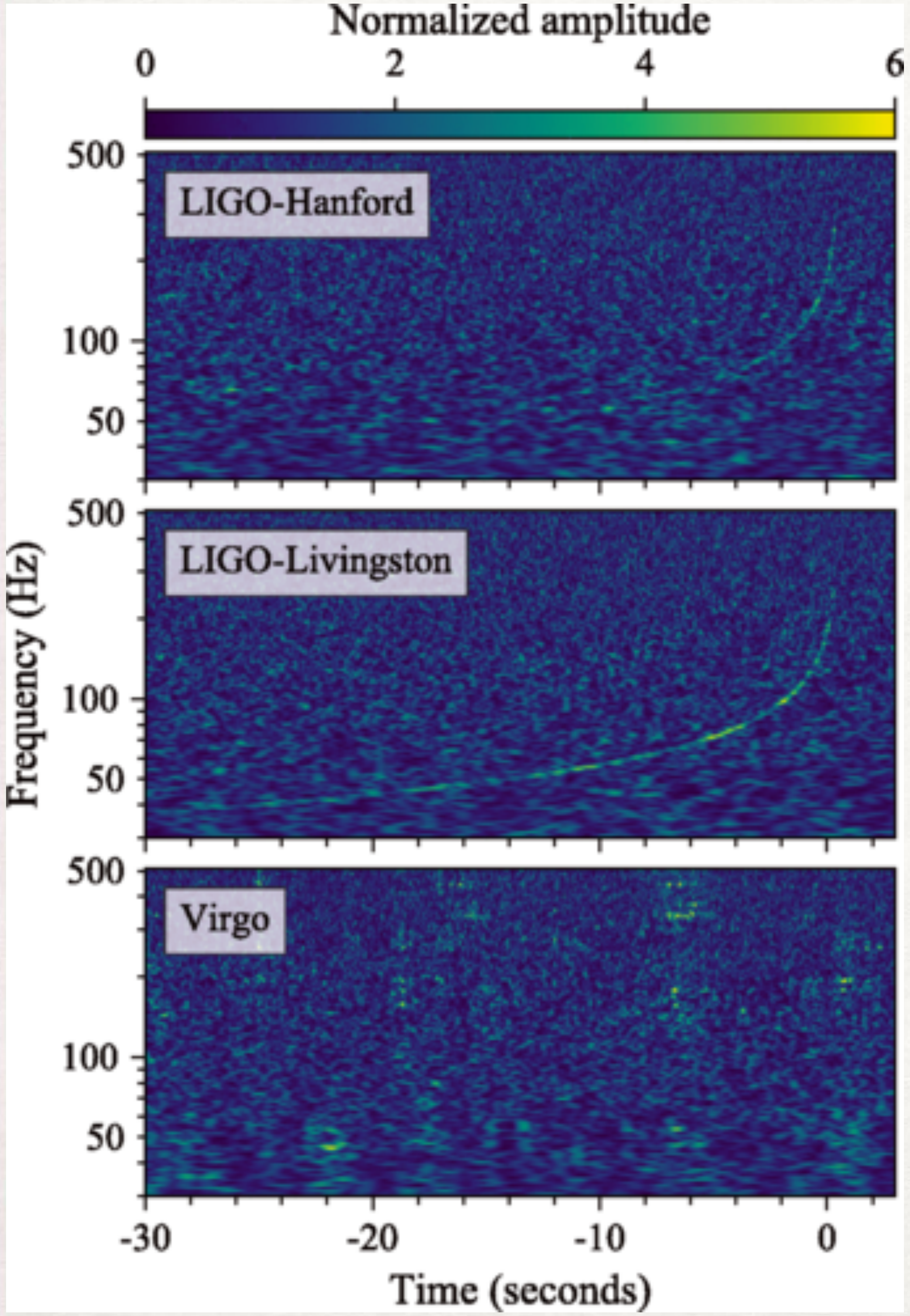


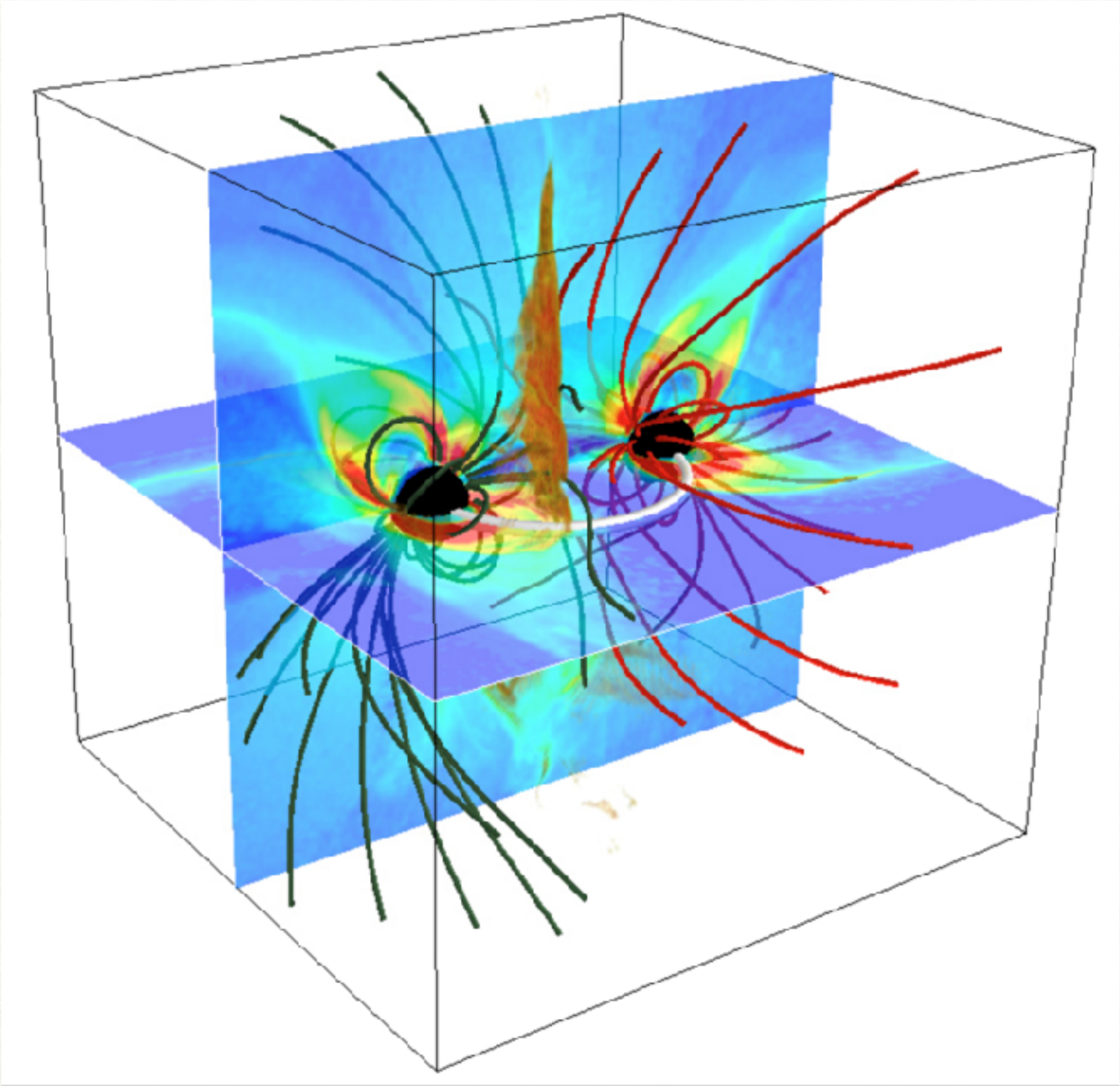


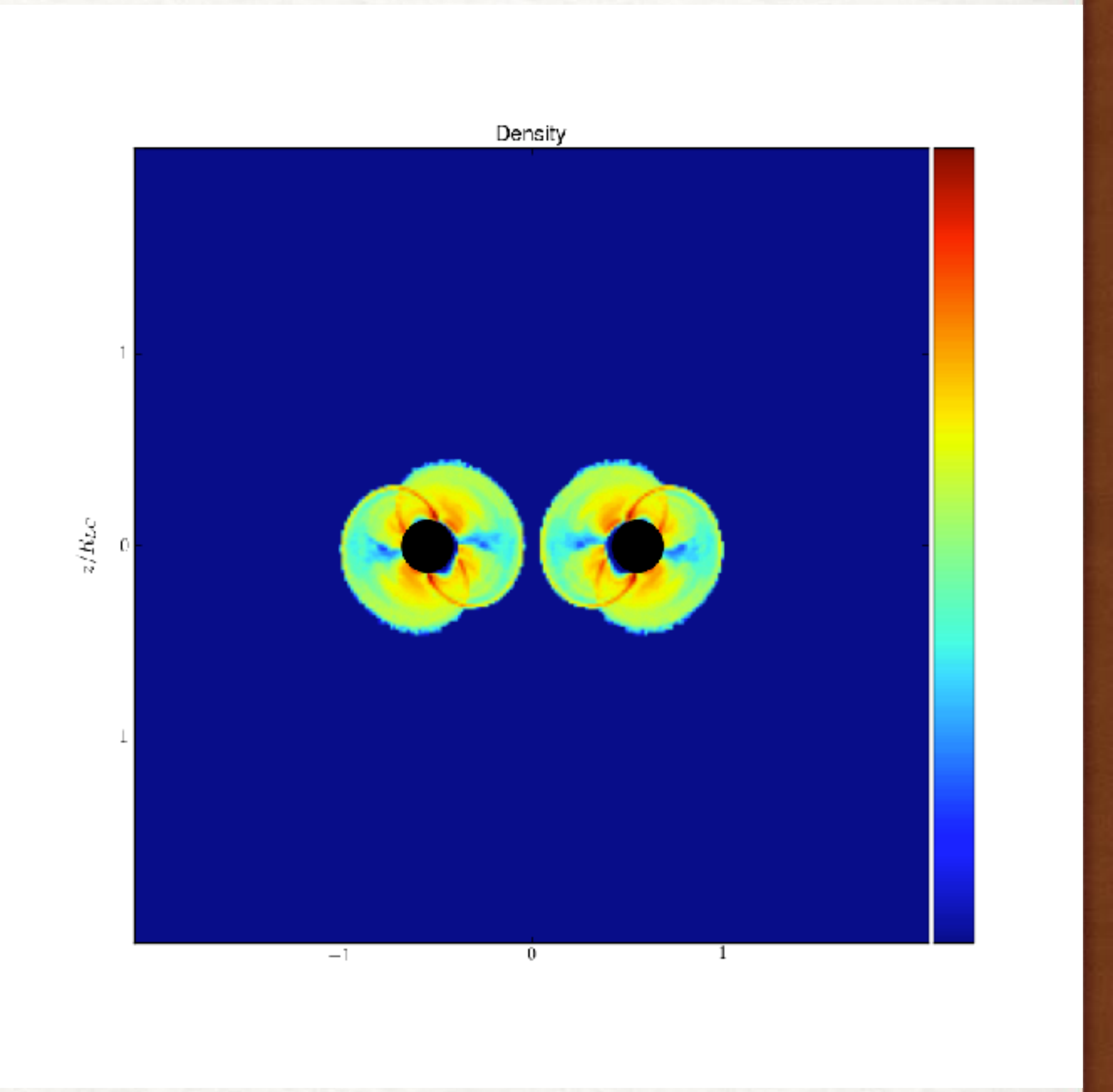
Parfrey, Philippov, Cerutti 2019

FUTURE APPLICATIONS: ACCRETION AND MERGERS

GW170817: Neutron star merger event. What if the merging neutron stars had magnetospheres?

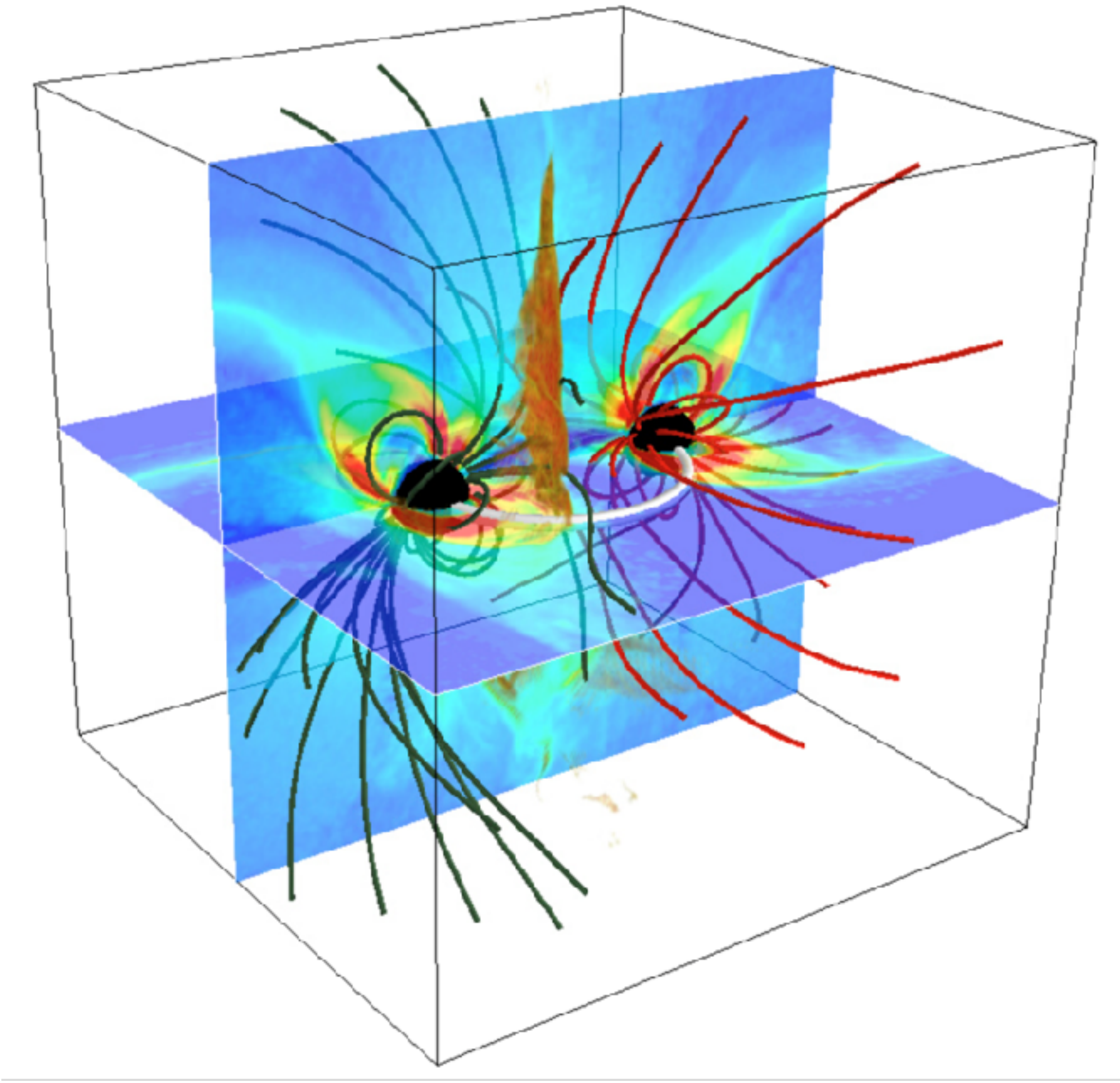


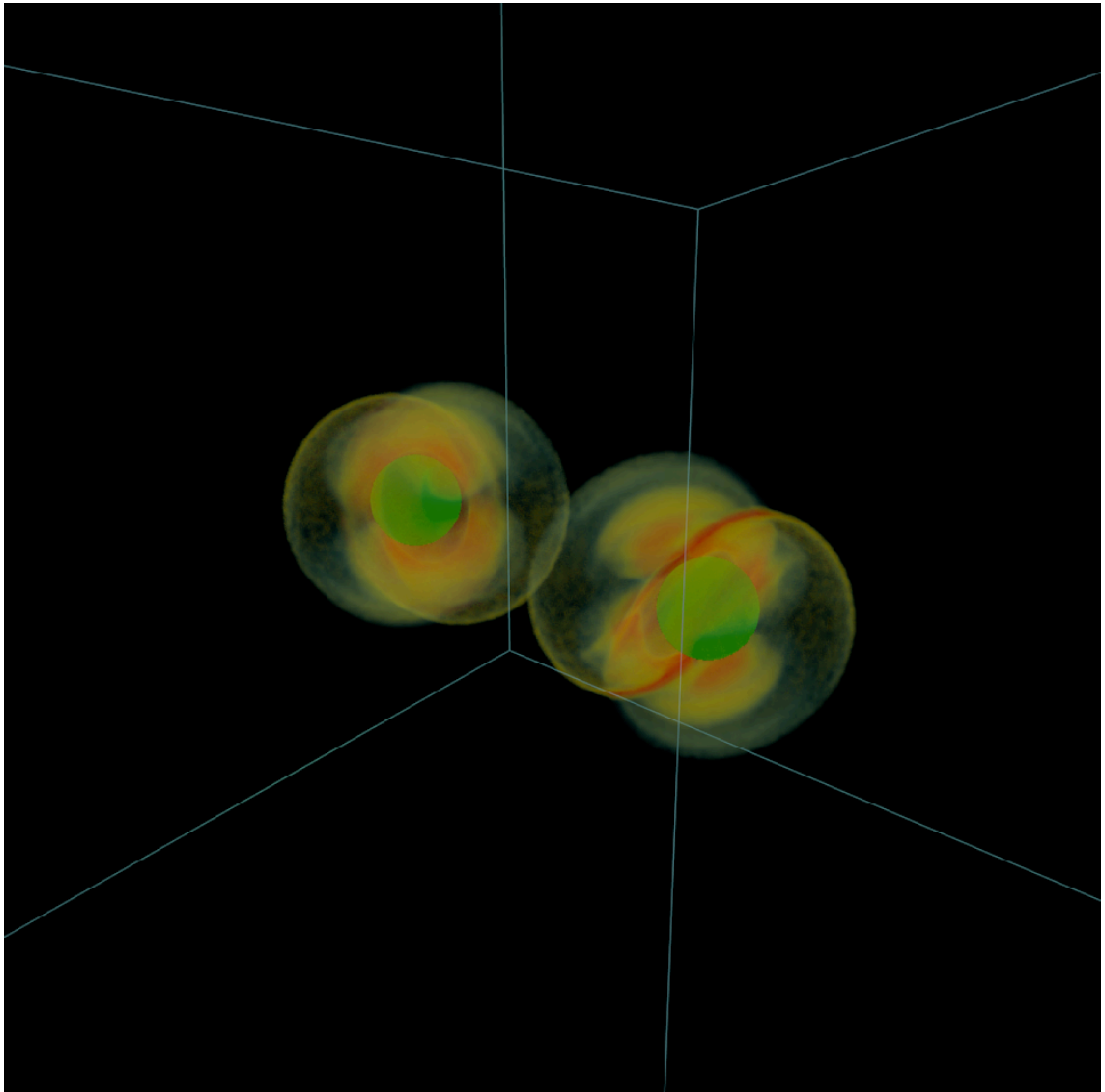




First PIC simulations of binary neutron stars: EM radiative signature?

Precursor EM signals from mergers





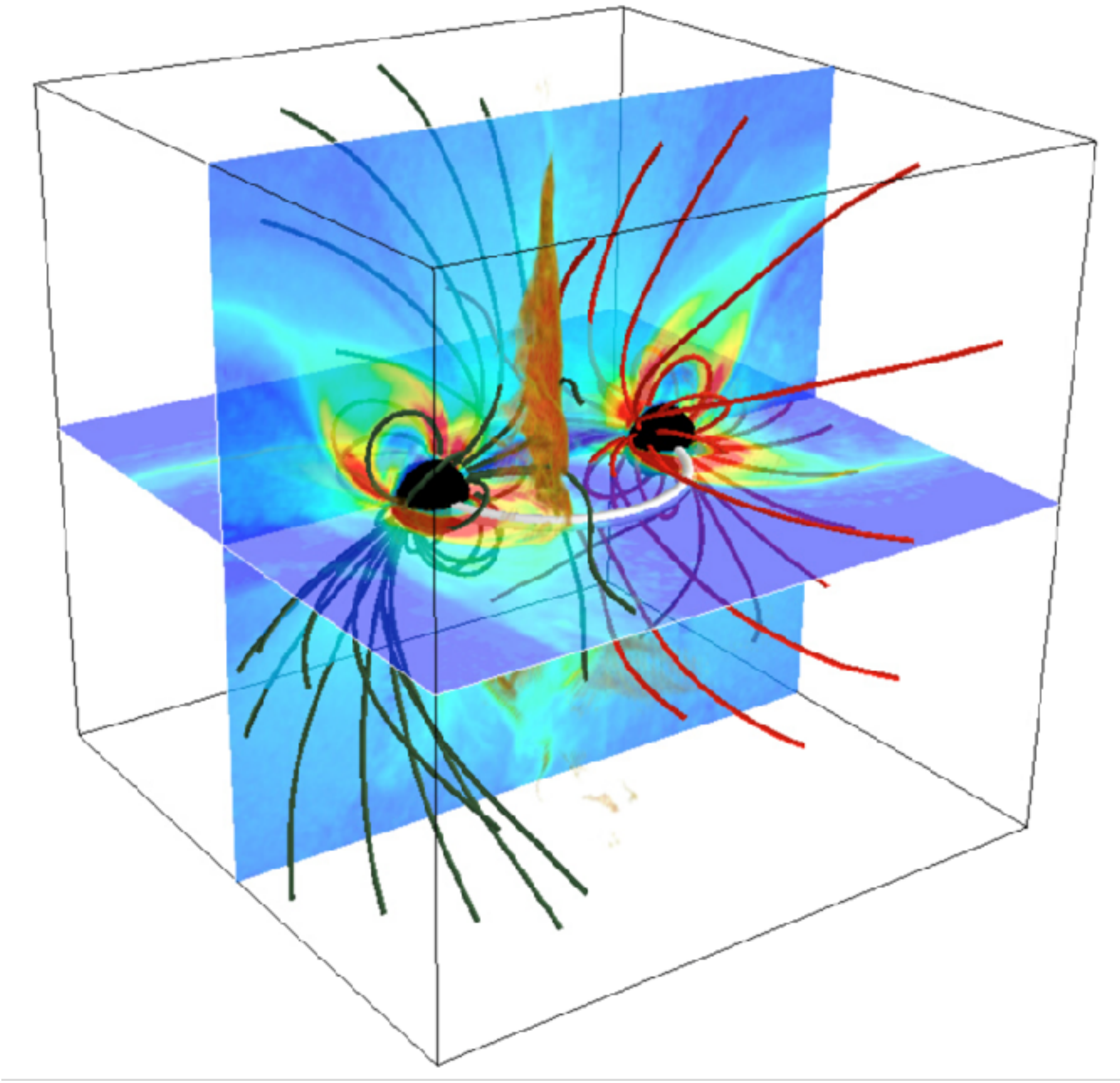
Density rendering

Anti-aligned magnetic moments lead to reconnection between magnetospheres once per rotation of the slowest pulsar. Strong current sheet and particle acceleration occur between magnetospheres

Simulation: Sasha Philippov

Rendering: Hayk Hakobyan

Precursor EM signals



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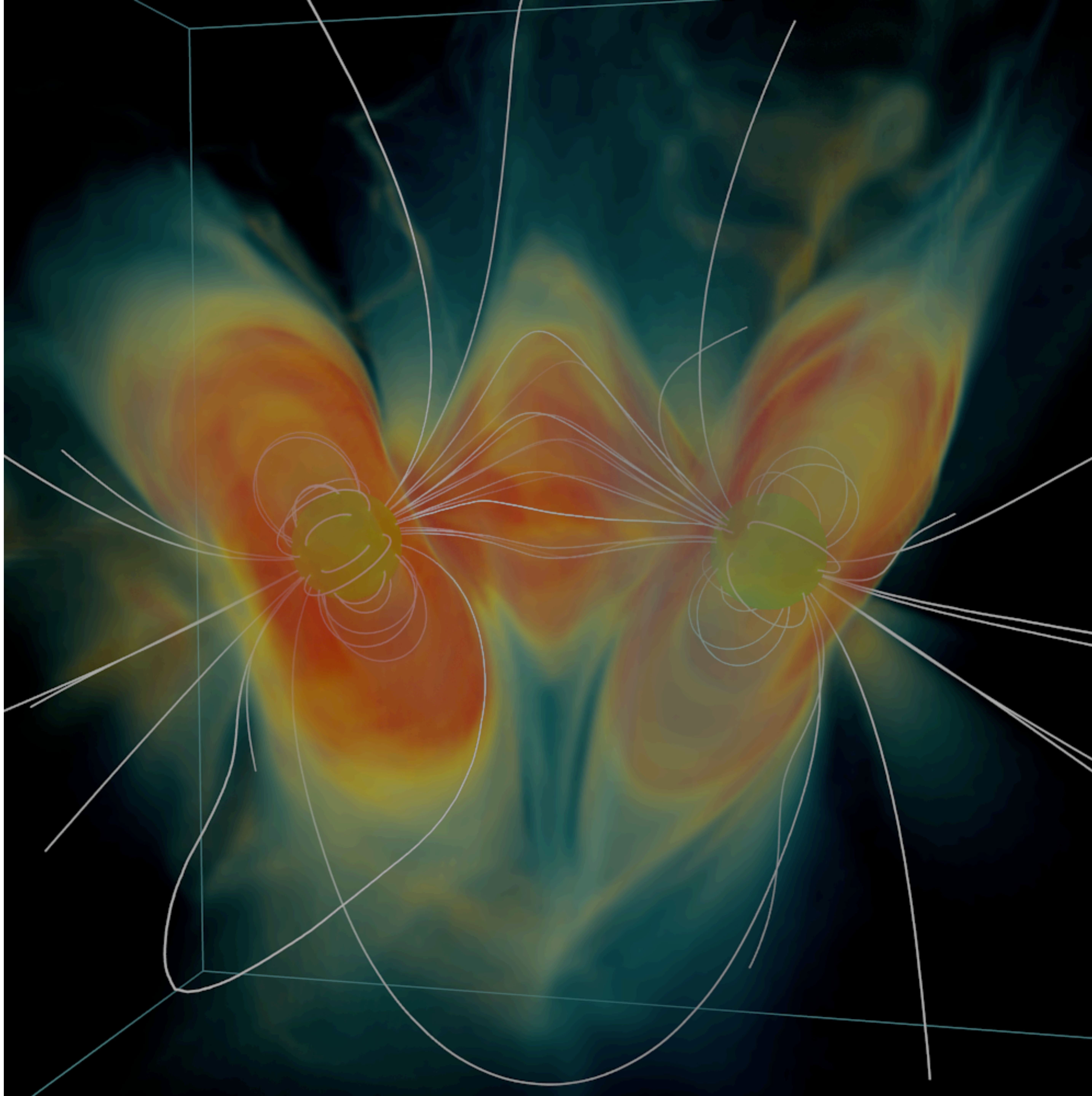

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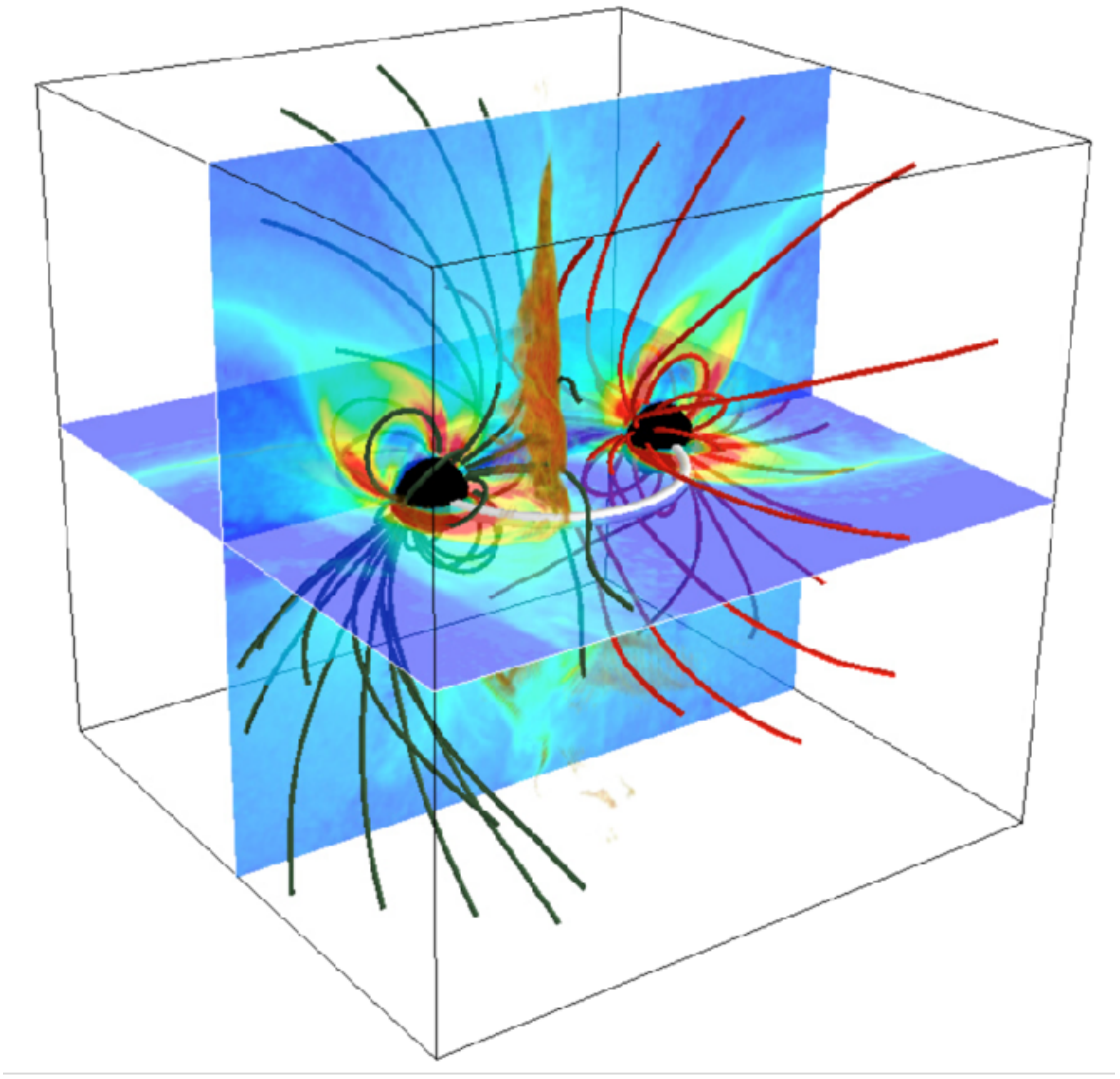

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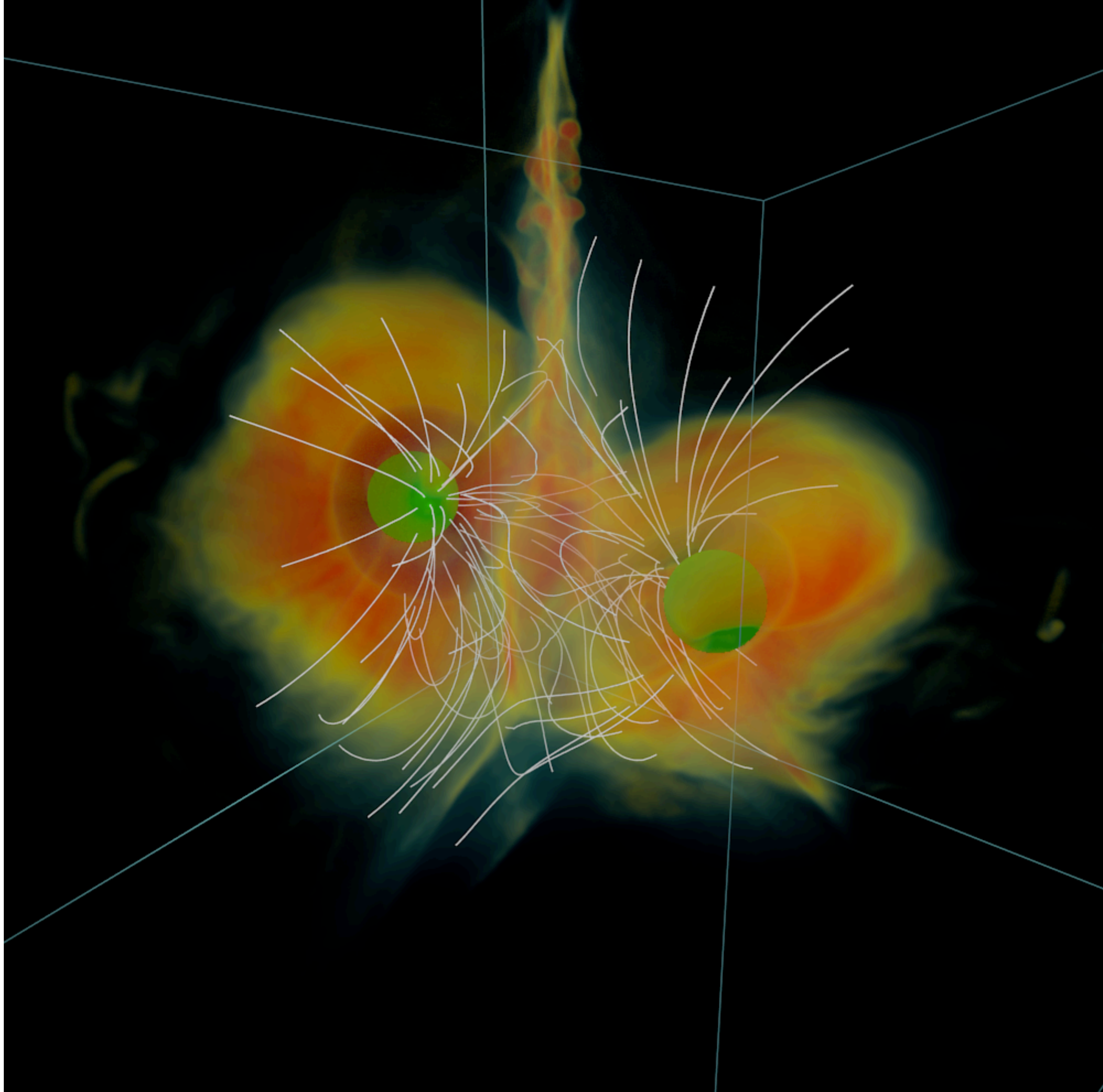

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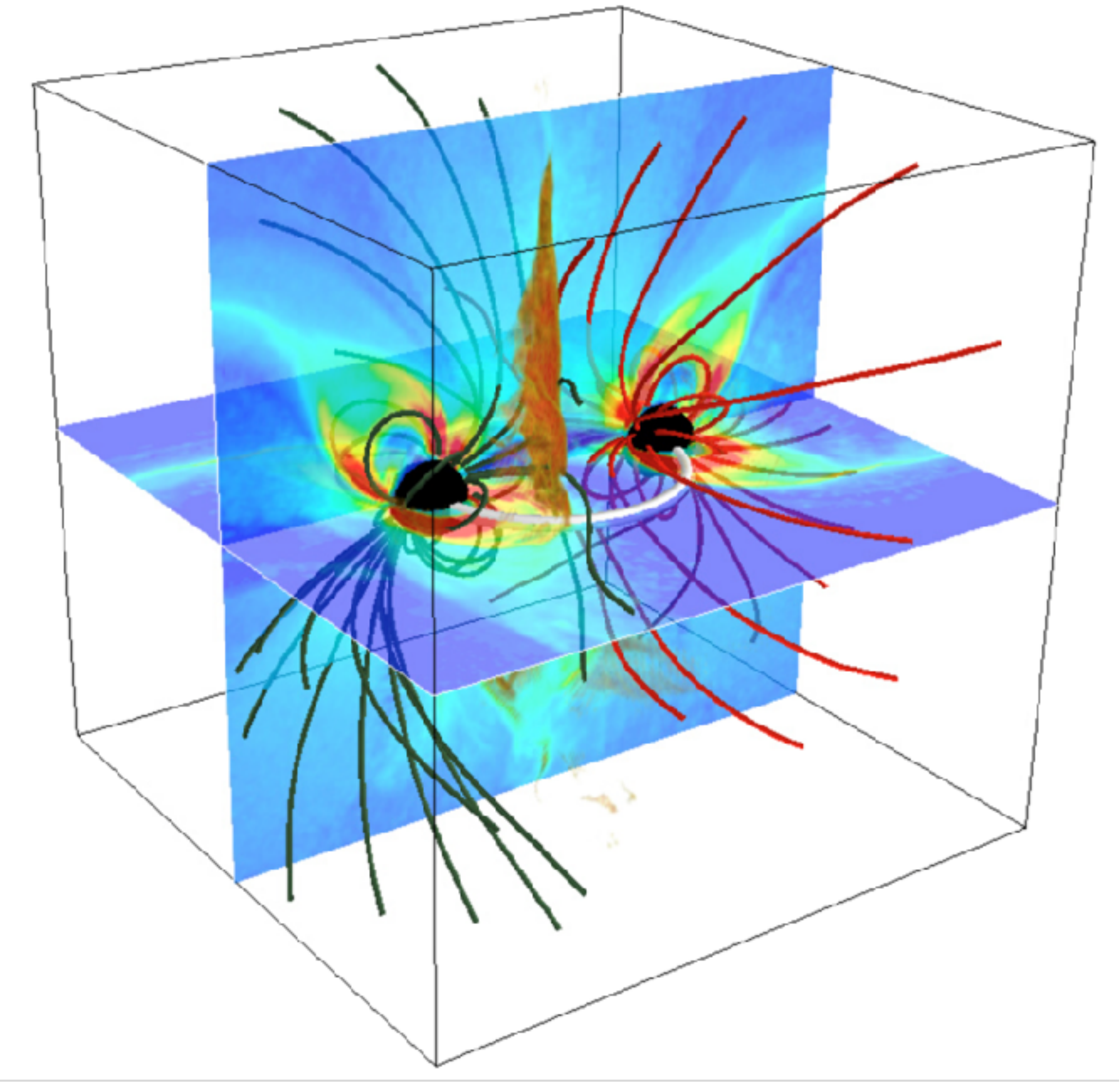
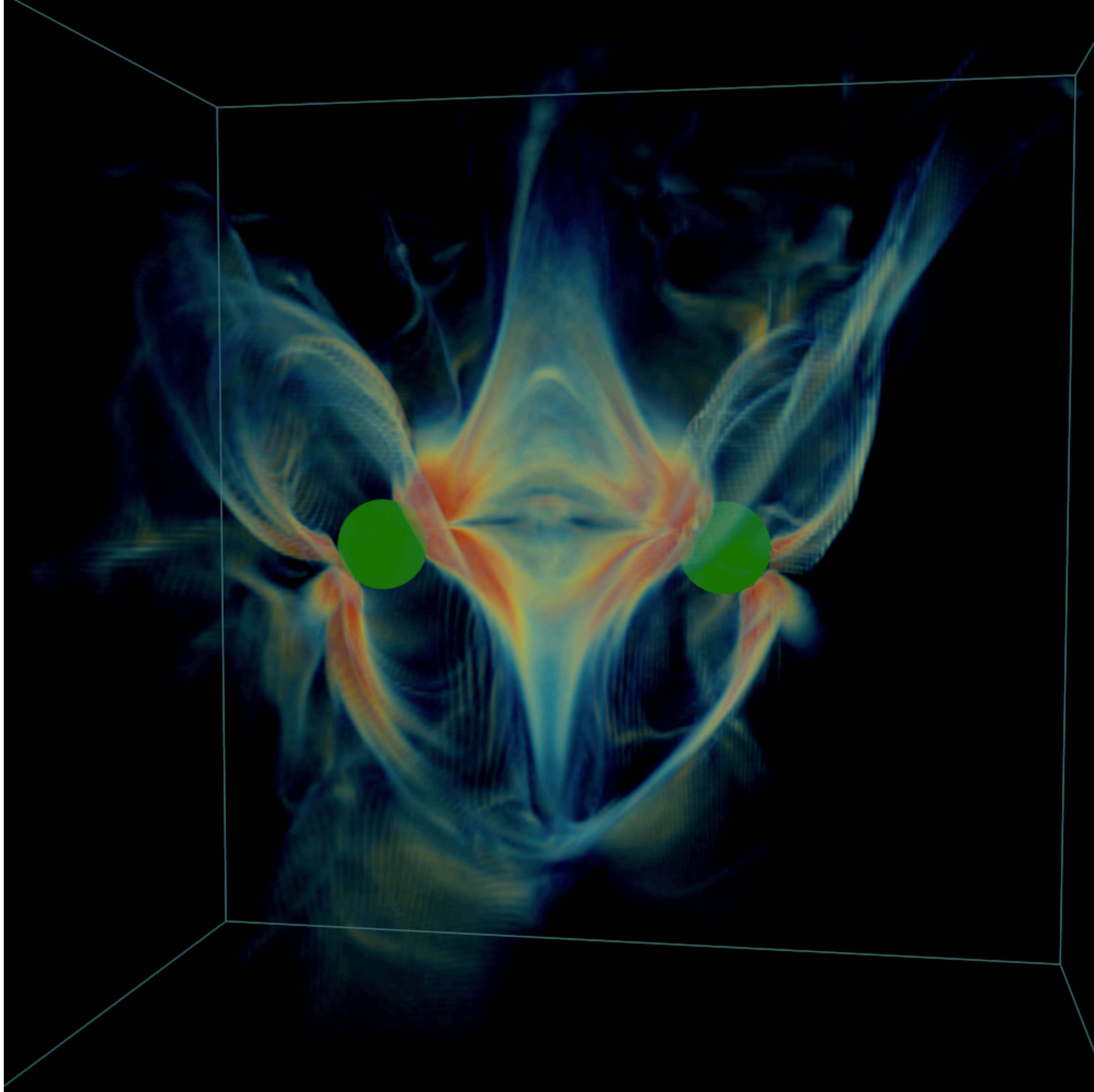


Current rendering



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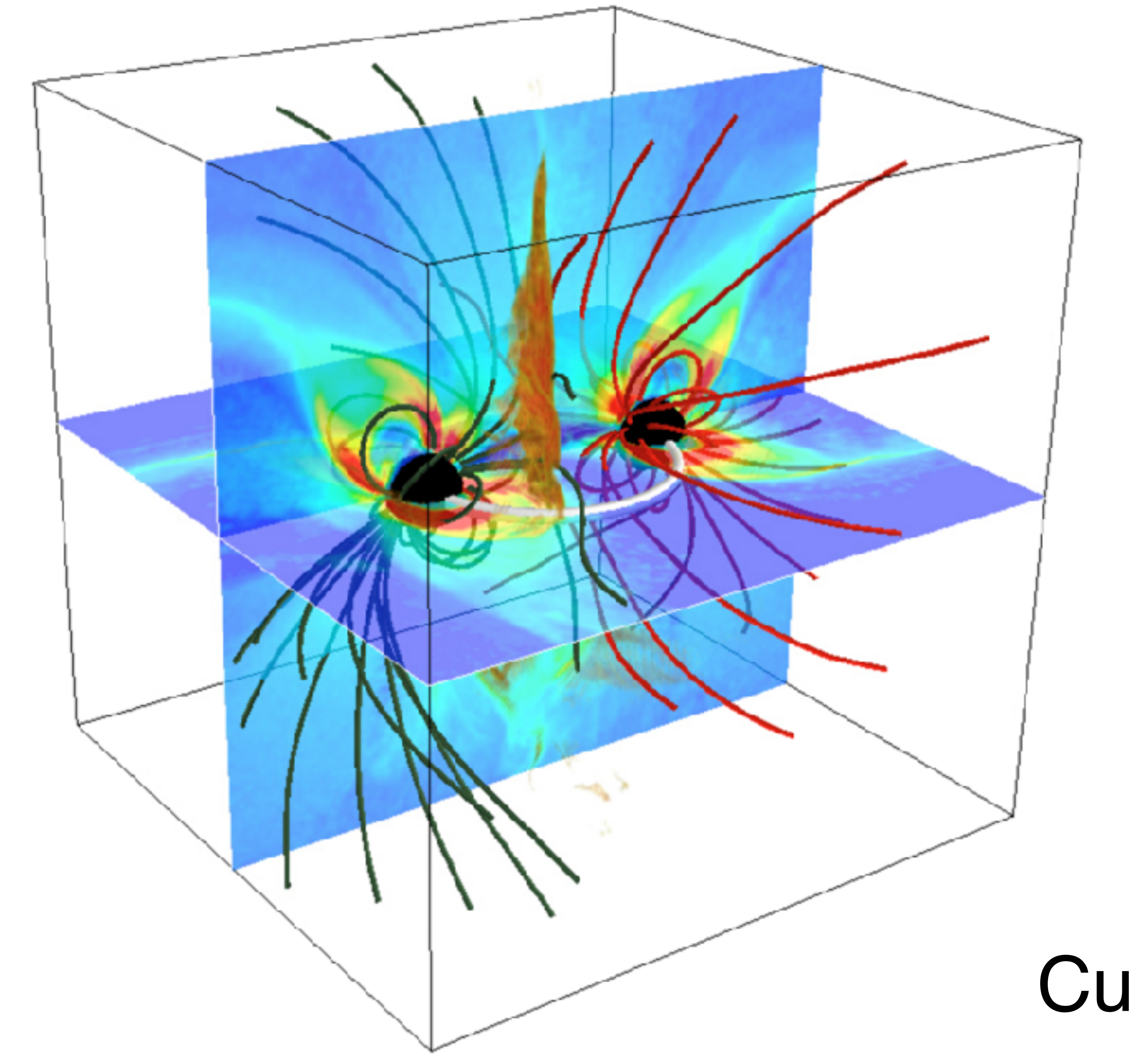

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