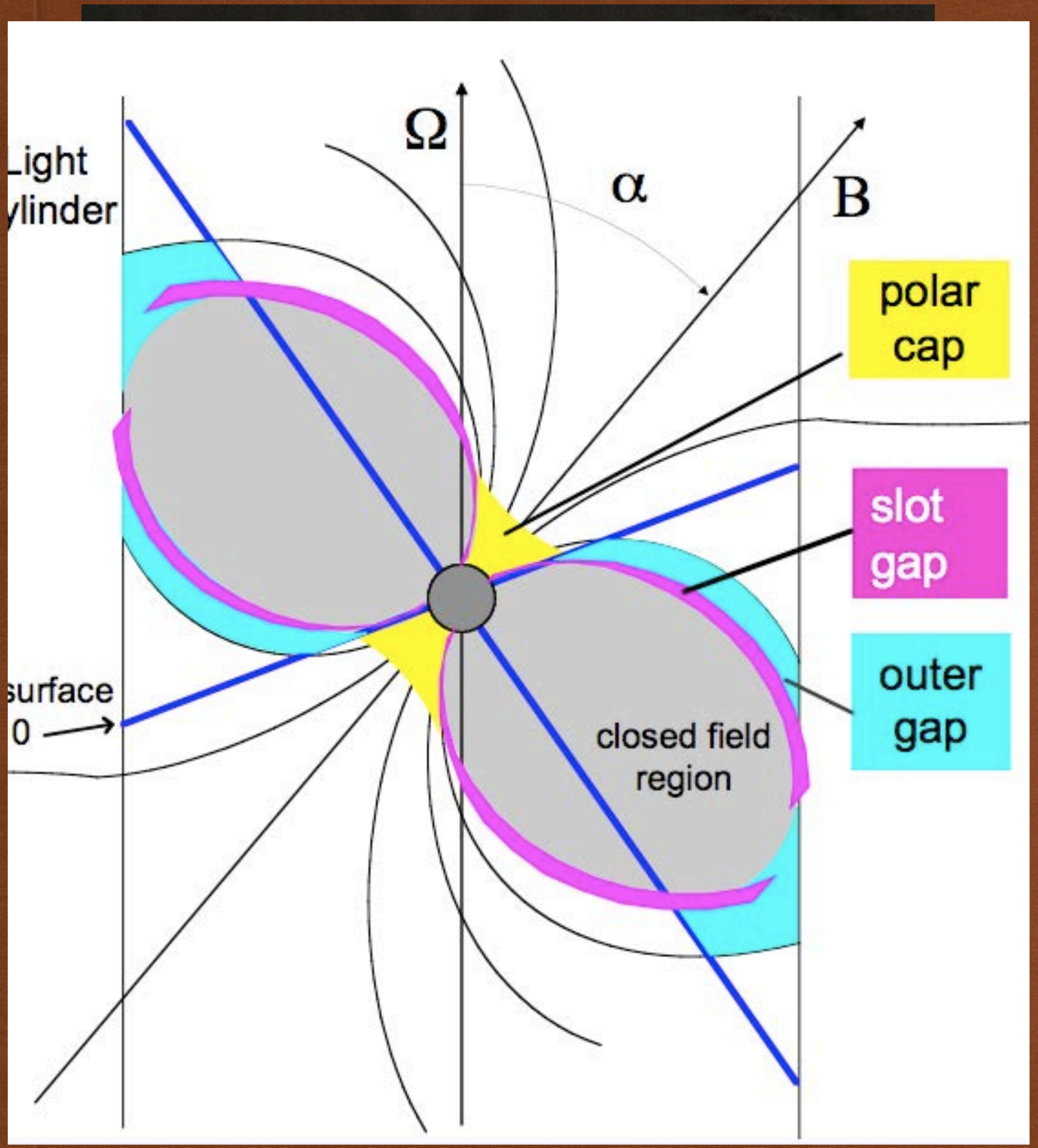
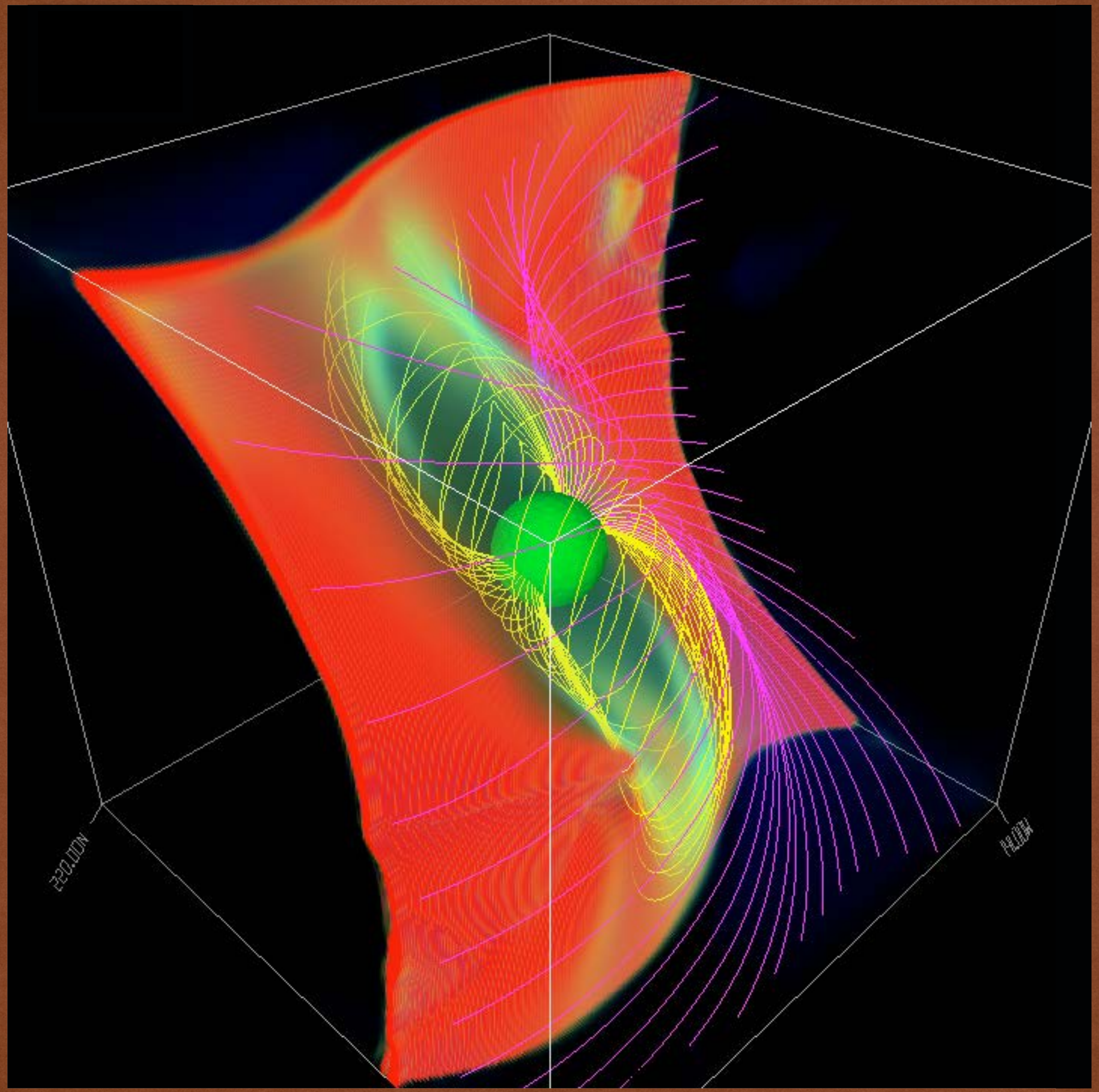
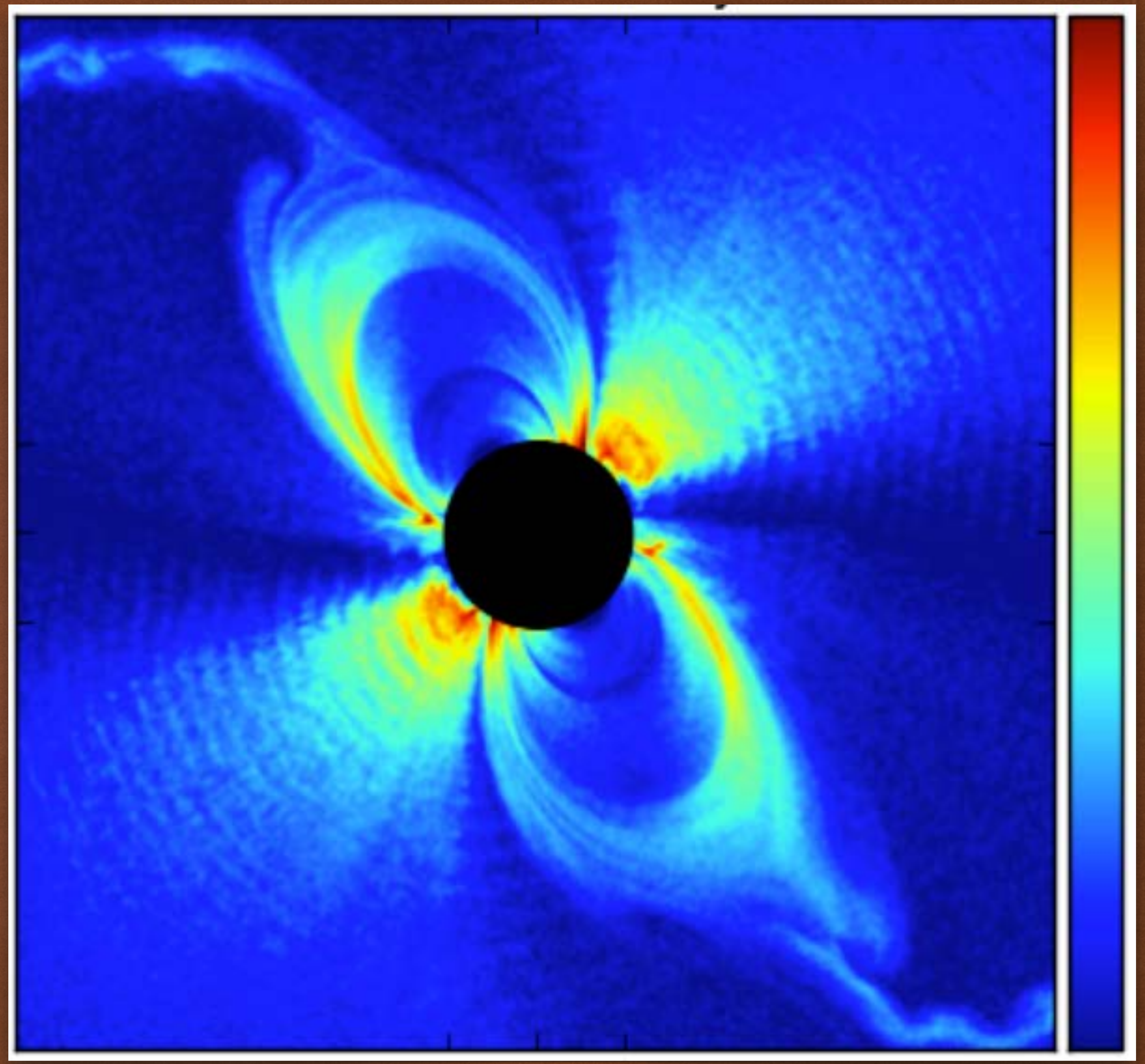
MAGNETOSPHERIC STRUCTURE AND BROADBAND EMISSION IN PULSARS







ANATOLY SPITKOVSKY (PRINCETON)

WITH A. PHILIPPOV, H. HAKOBYAN, B. CERUTTI, X.BAI

OUTLINE

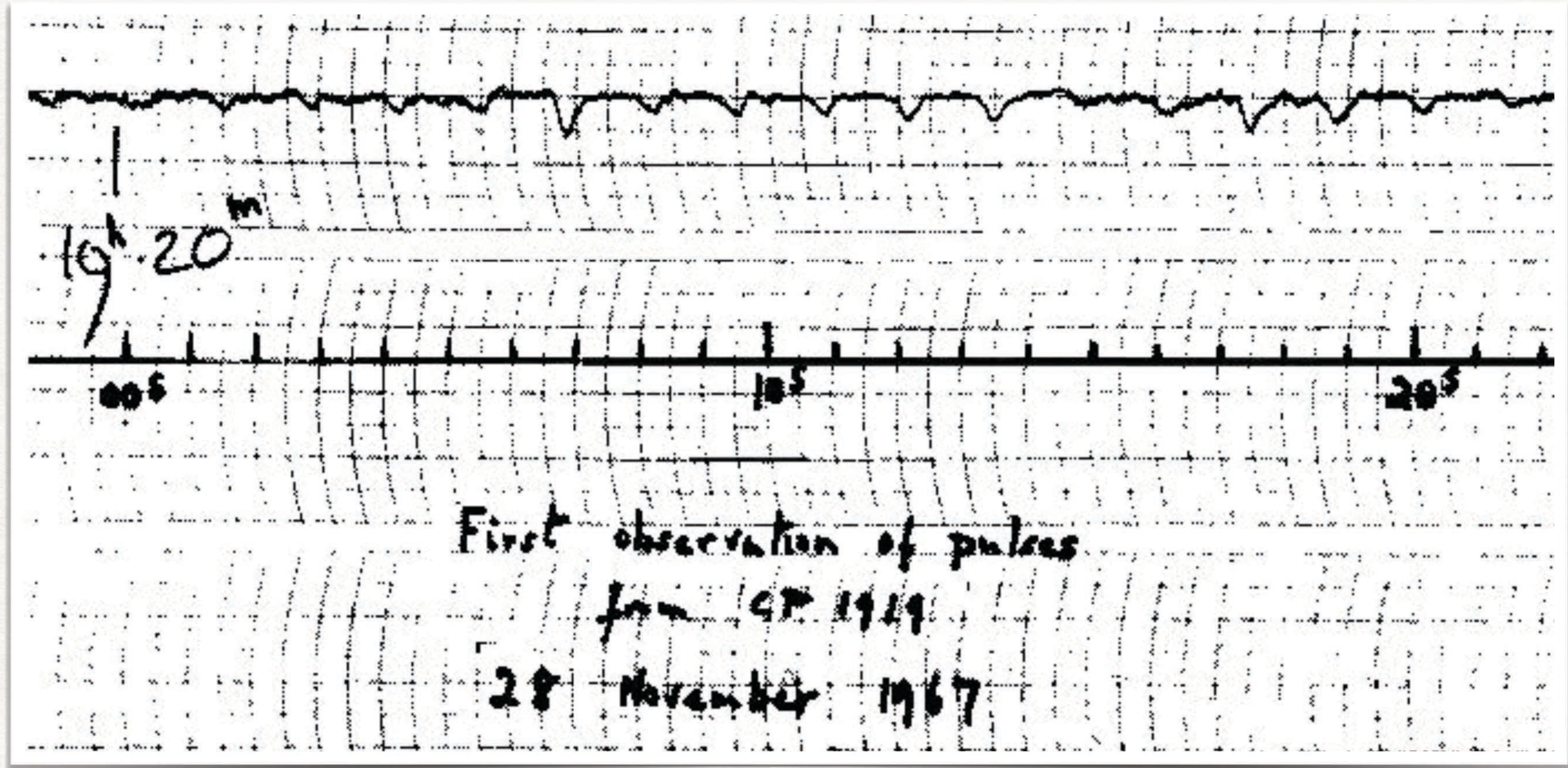
- Pulsars: overview and open questions
- Force-free and kinetic simulations of magnetospheres
- Emission: from gamma-rays to radio
- Example (weird) systems
- Conclusions and outlook

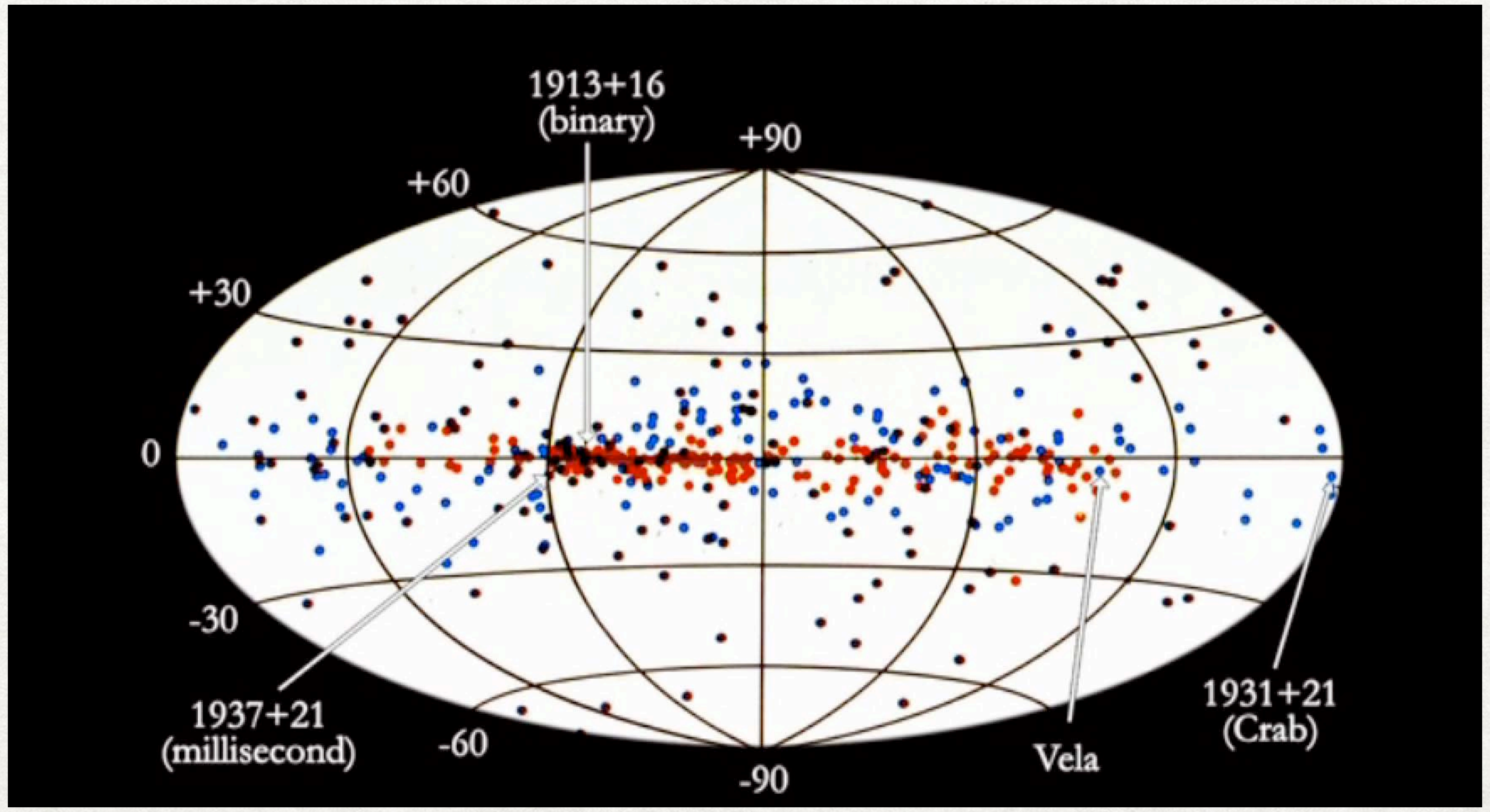
MAIN POINT

Self-consistent models of magnetospheric structure of neutron stars (pulsars) are starting to explain different kinds of pulsed emission.

PULSARS: COSMIC LIGHTHOUSES

Jocelyn Bell-Burnell

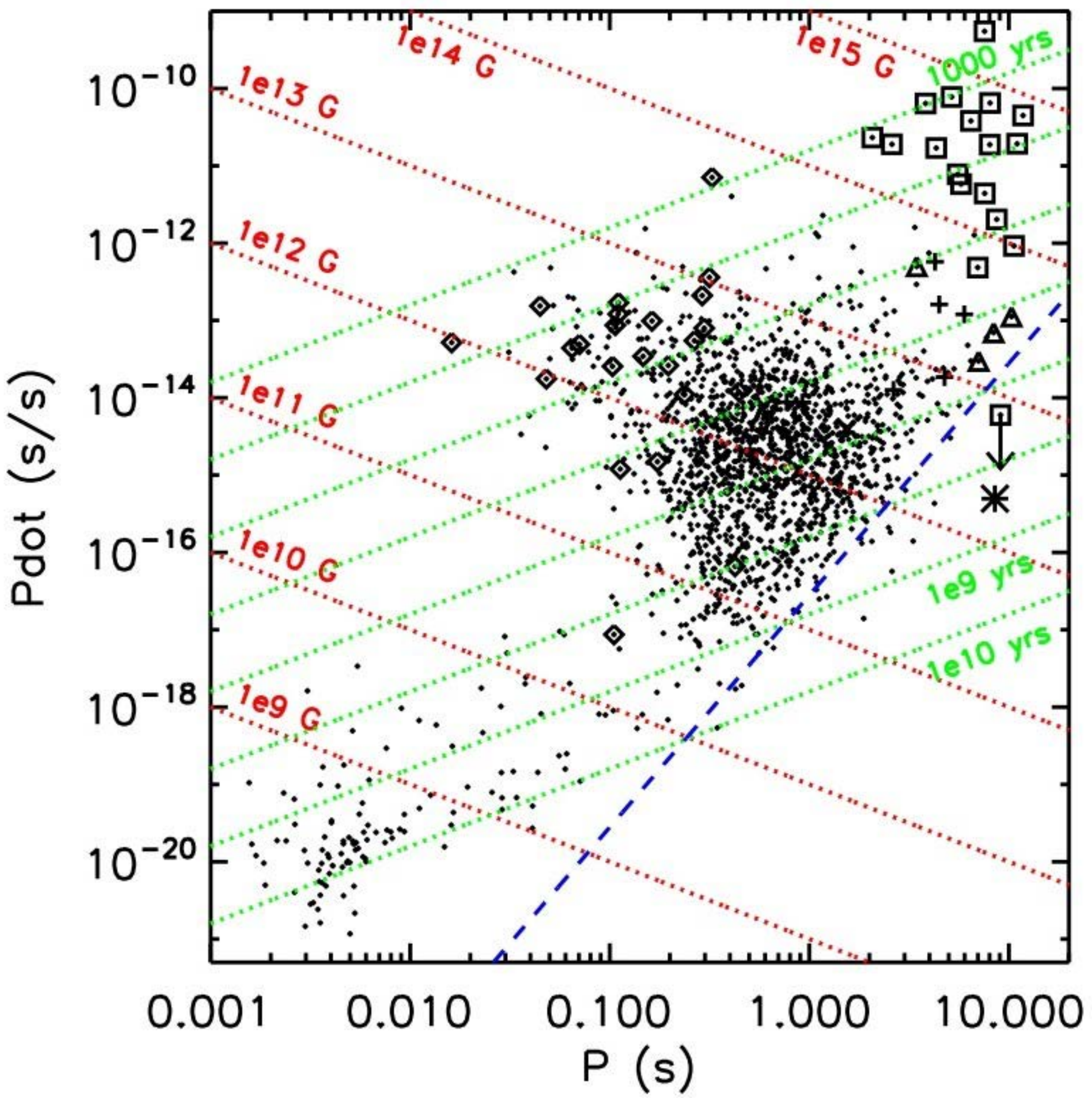




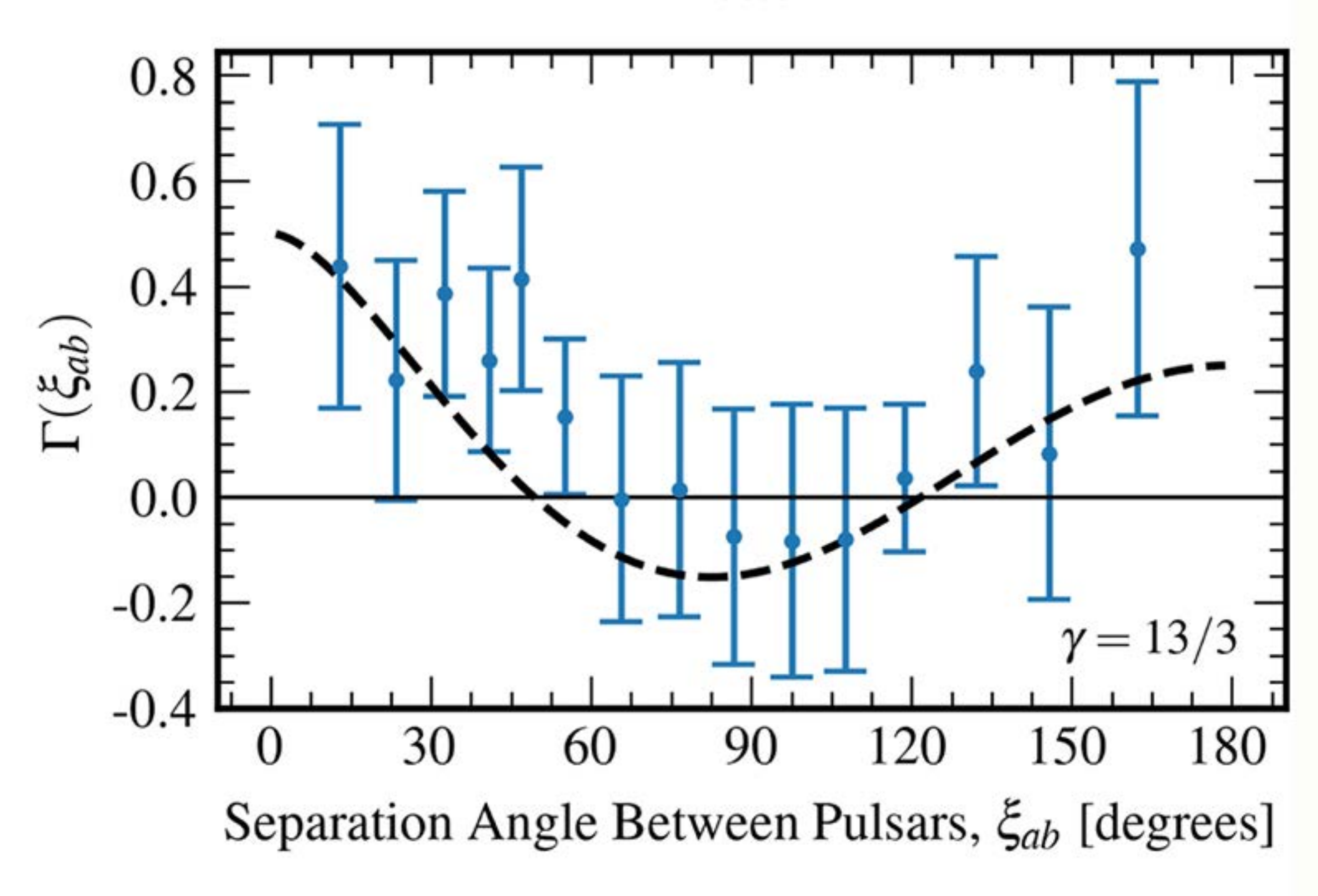
Hewish, Bell et al 1968

PULSARS: A GIFT FOR OBSERVERS

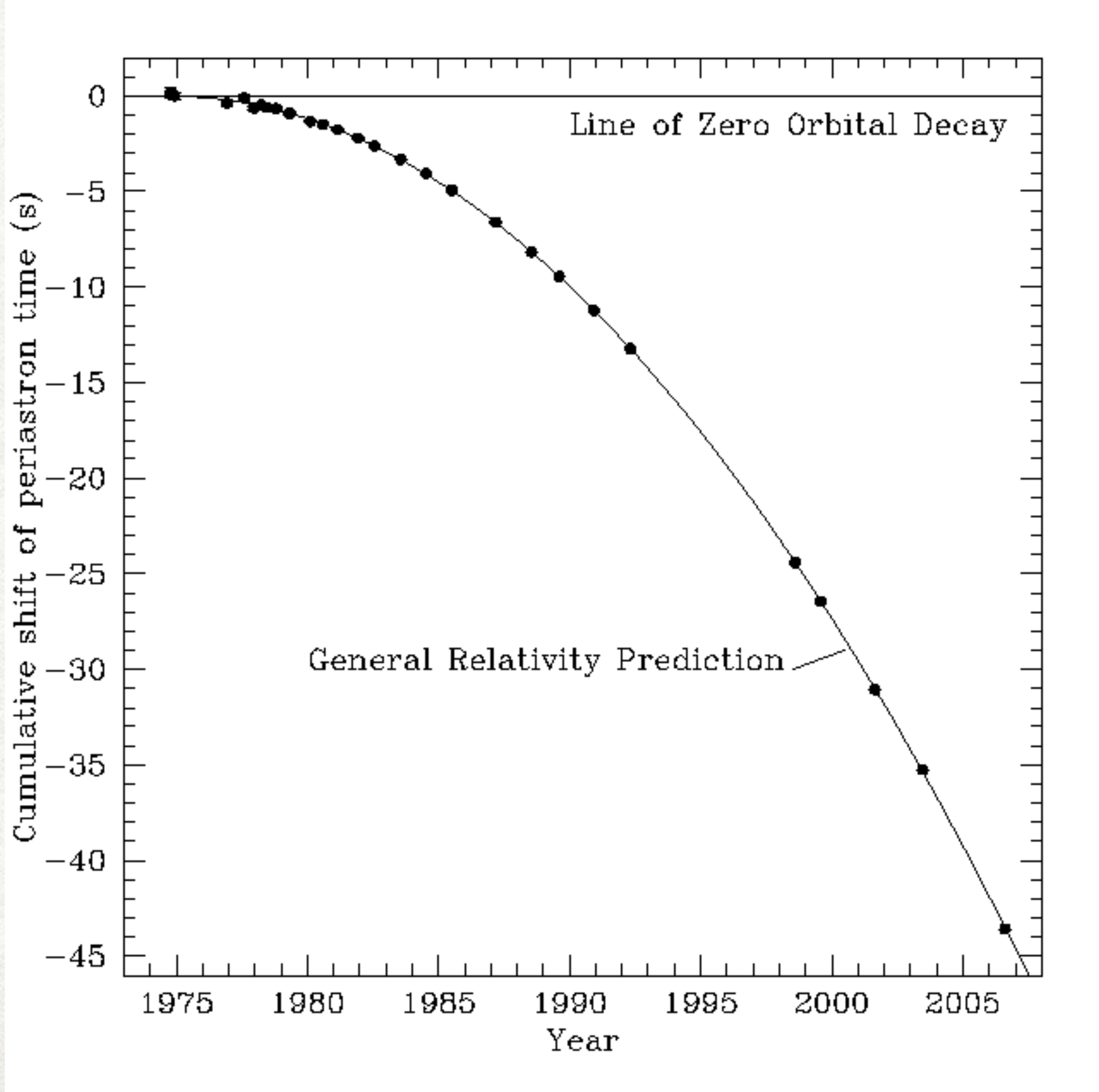
- Radio Pulsars: regular vs ms
- Spin ms — sec, spindown; age: kyr — 10 Gyr
- Probes of interstellar medium
- Amazing clocks: tests of GR
- Hulse-Taylor, Double Pulsar
- New: Nanograv!



>3000 known; all spin down with time

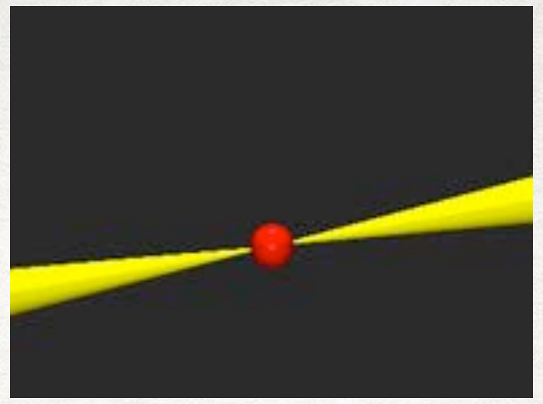


Agazie et al 2023

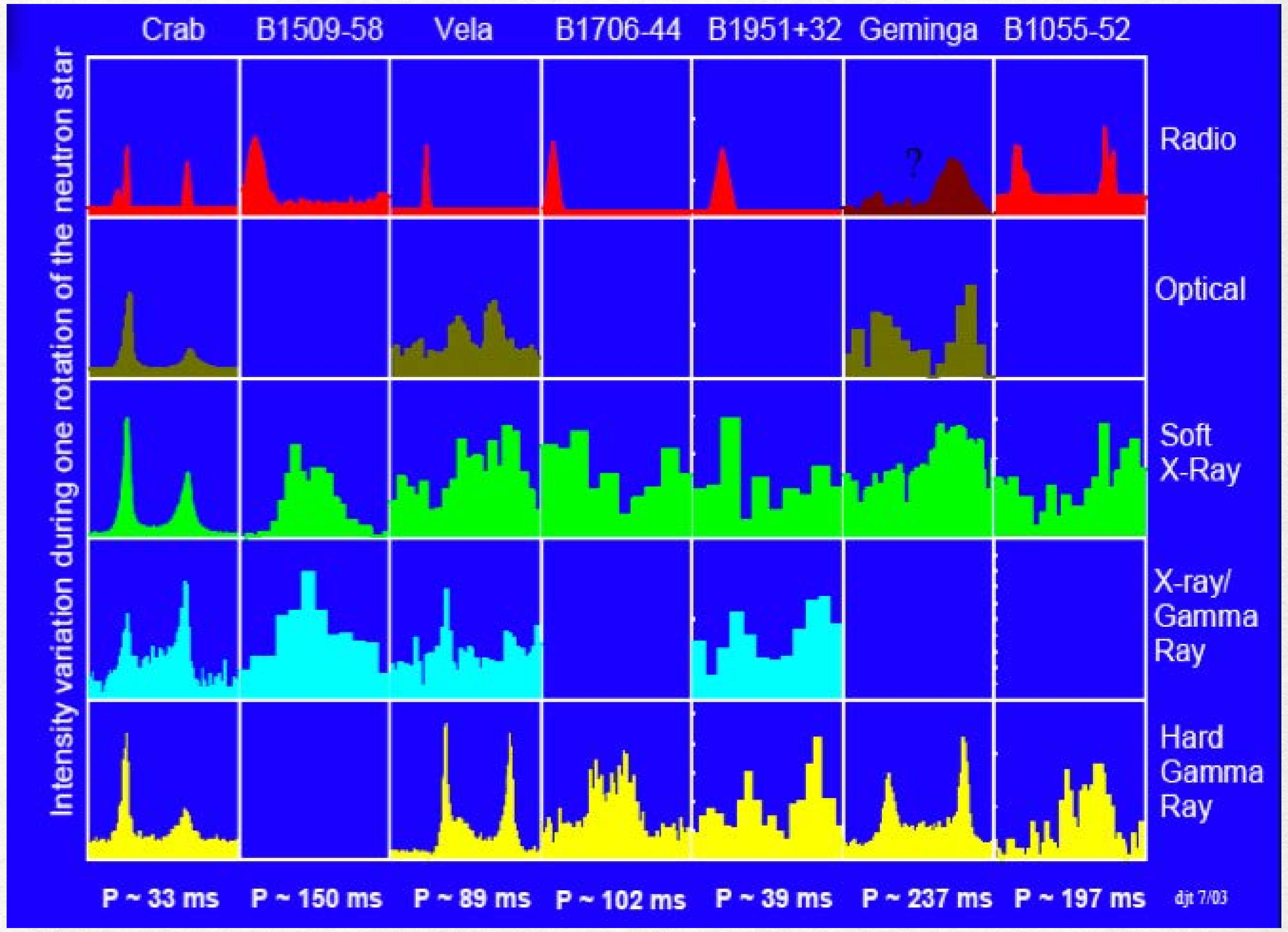


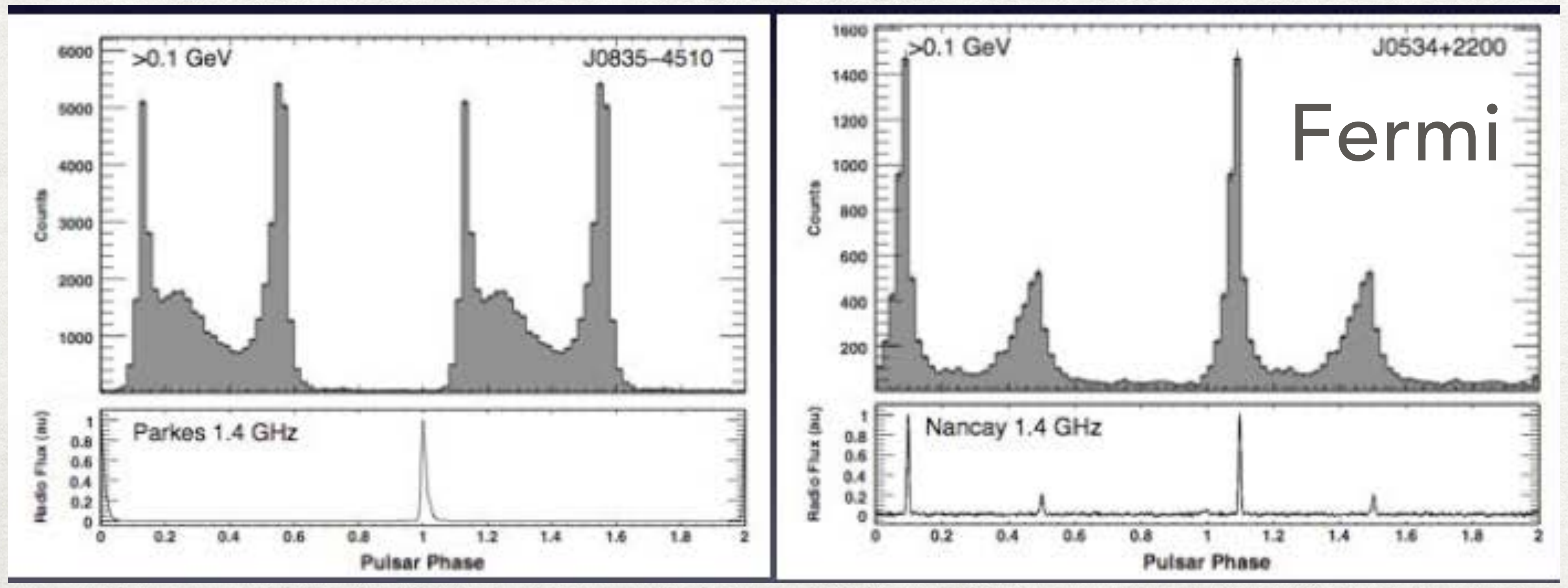
Hulse & Taylor 1974+

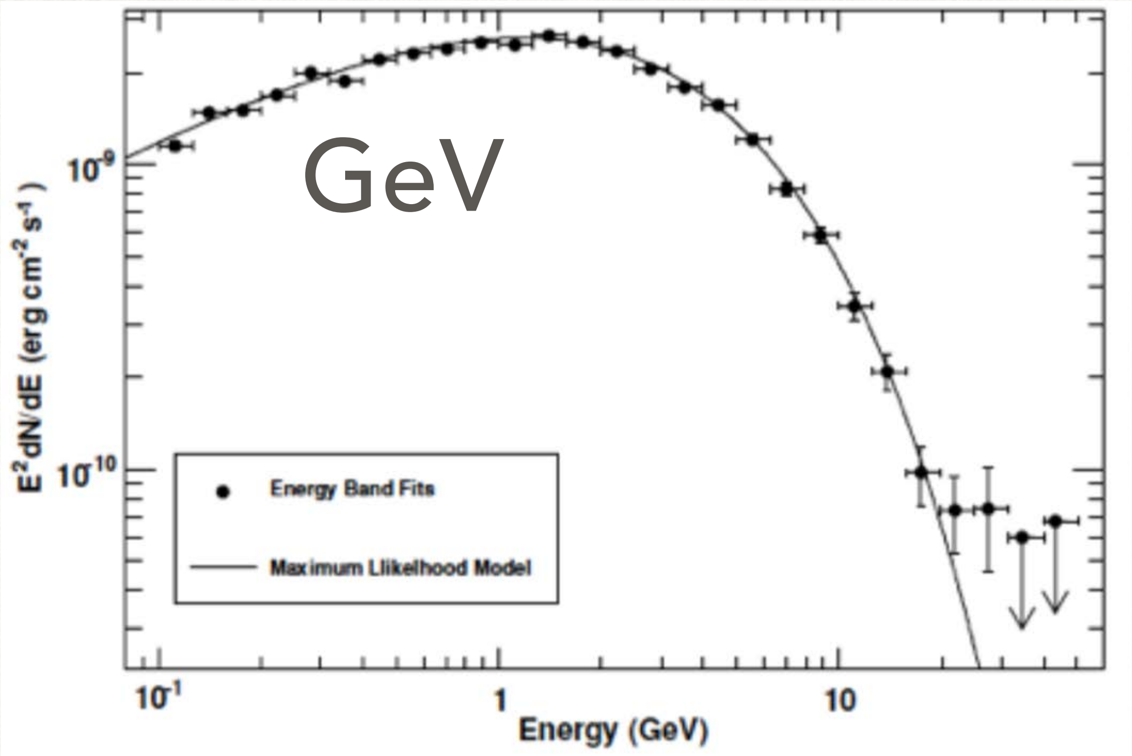
PULSARS: A GIFT THAT KEEPS ON GIVING



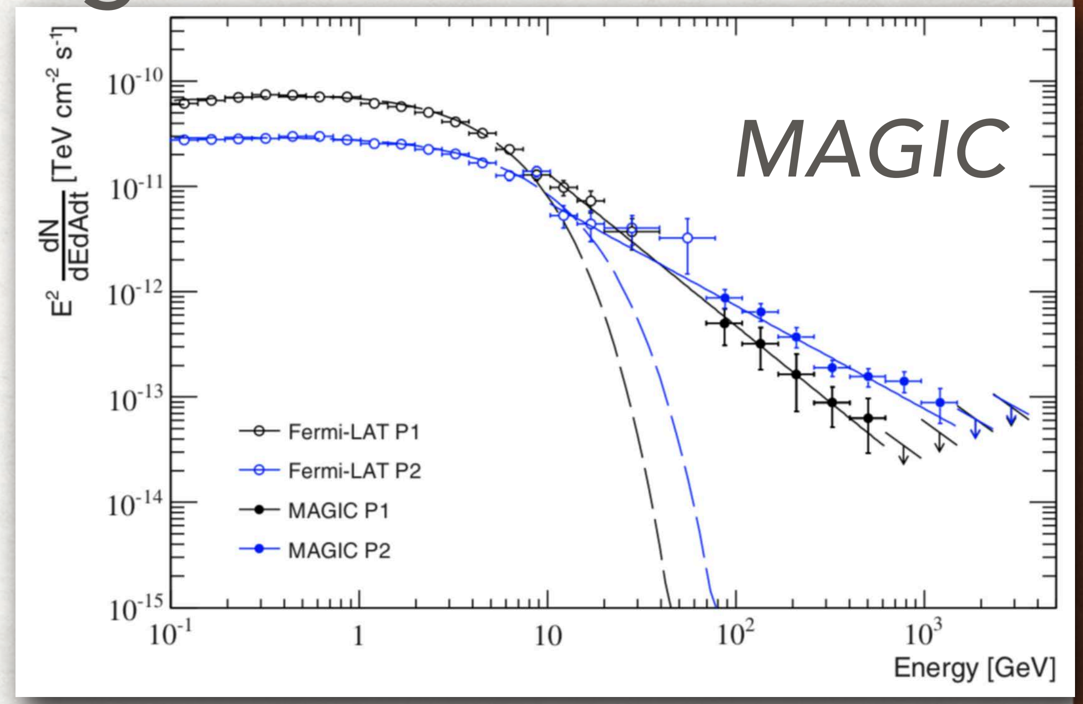
- Rotating magnetized neutron stars:
  - Lose energy to spin-down, 10^{30-38} erg/s
  - Broadband pulsed emitters (radio-g-rays)
  - Spectrum dominated by HE photons (<0.1 Lsd)
  - Pulse morphology changes from radio to g-rays
  - Radio — coherent, complicated phenomenology

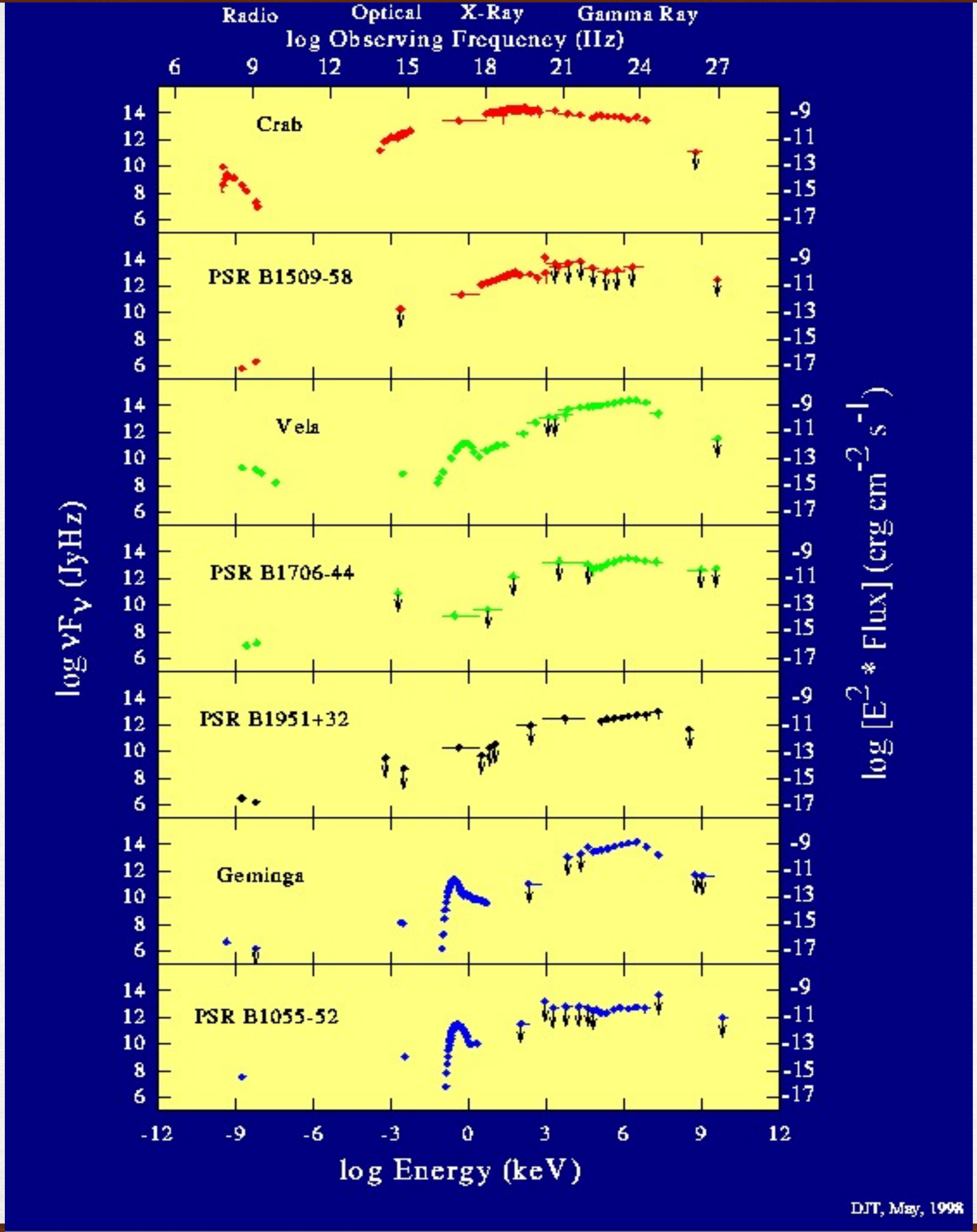






Reaching TeVs:





Broad-band spectra

- *Power peaked in γ-rays*
- *Pulsed emission up to 20+TeV!*
- *High-energy turnover*
- *Increase in hardness with age*
- *Thermal component appears in older pulsars*

OPEN QUESTIONS 59 YEARS LATER

- What is the structure/shape of pulsar magnetosphere?
- How do pulsars spin down?
- Where and what kind of plasma is in the magnetosphere/wind?
- What causes pulsed emission from radio to gamma-rays (coherent vs incoherent)?

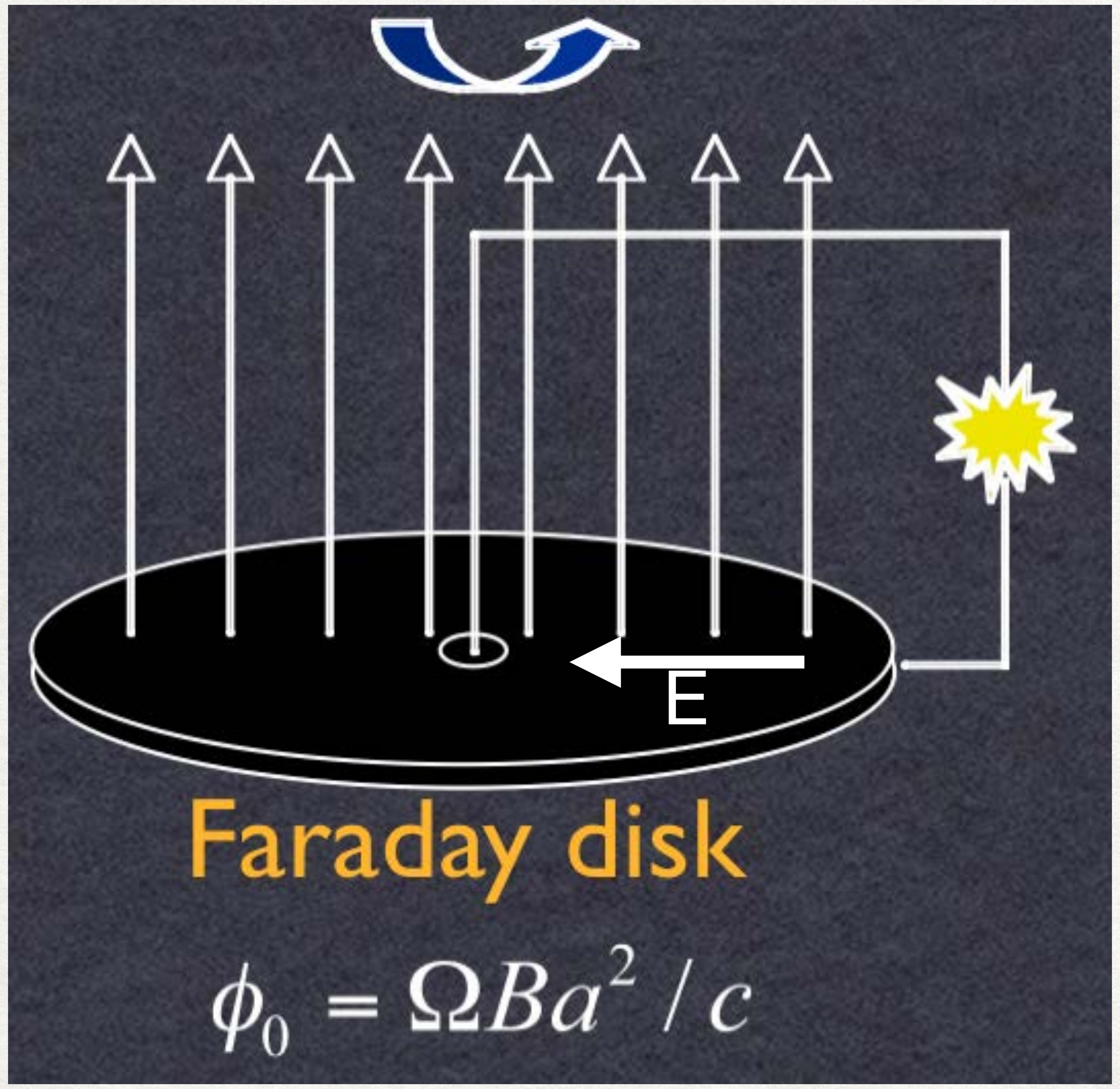
"PULSAR PROBLEM"

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

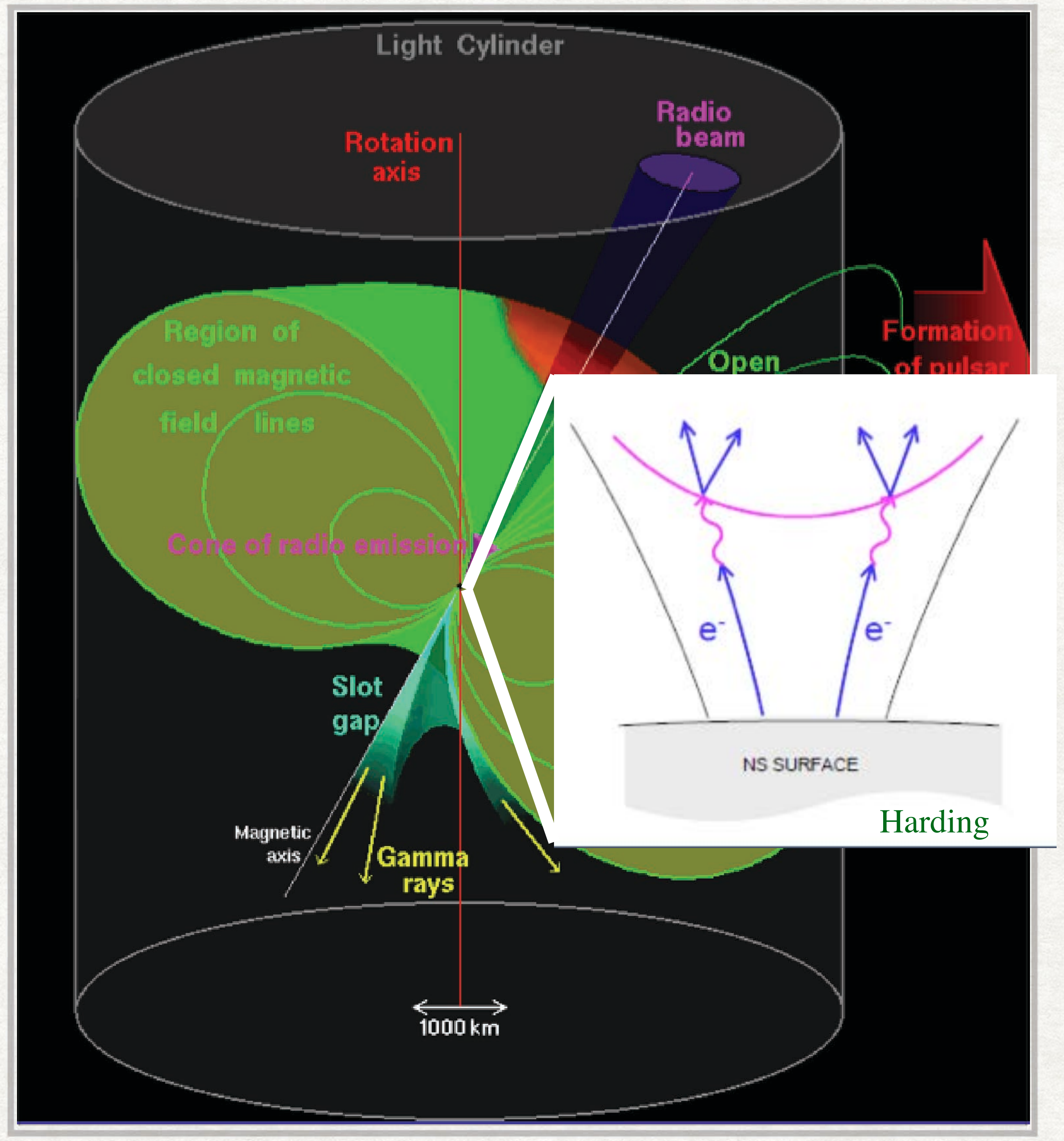
$R_{LC} = \frac{c}{\Omega}$

Goldreich-Julian current

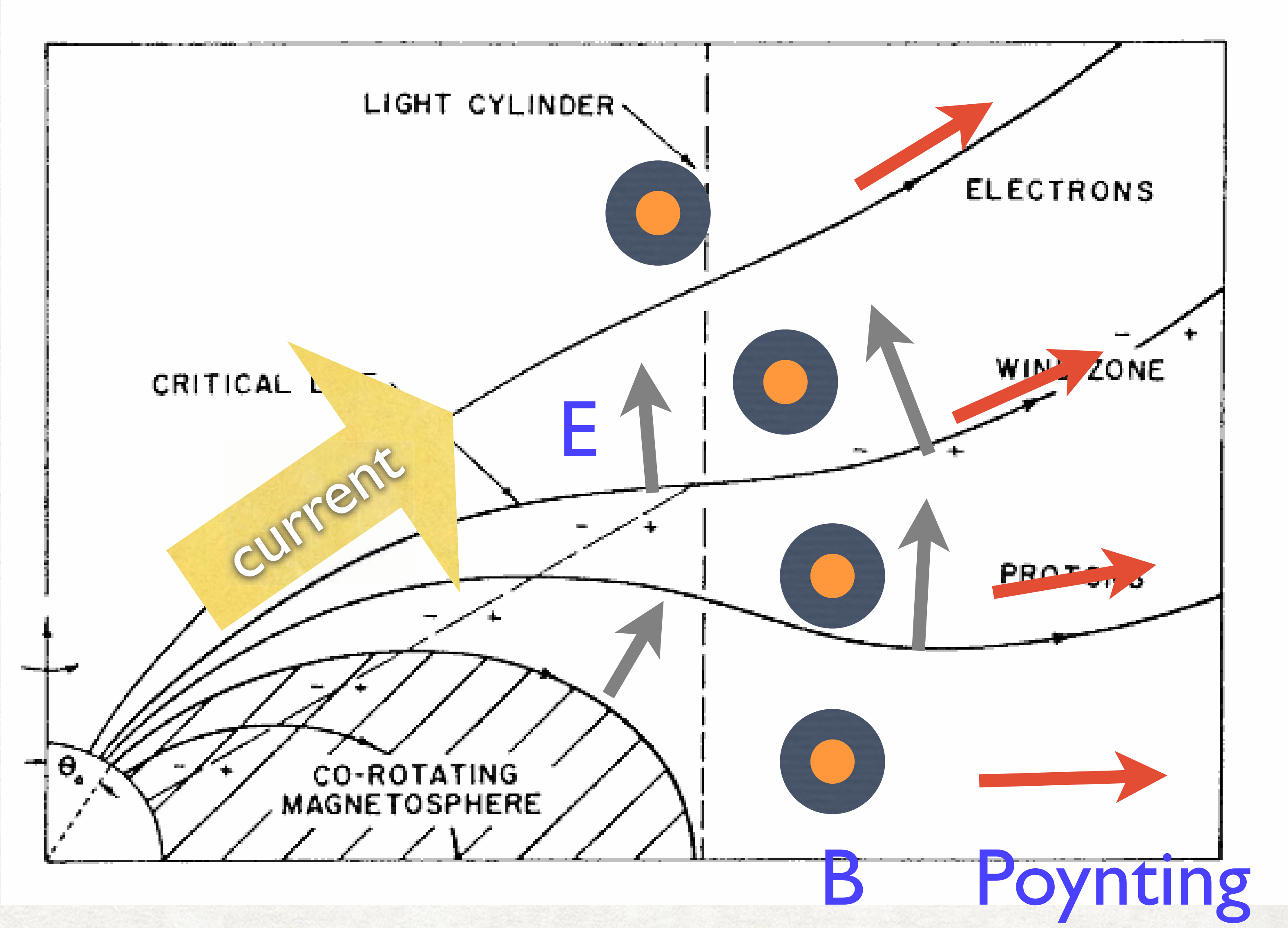
$$j_{GJ} = \rho_{GJ} c = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi}$$



Pole-equator potential



$V \approx \Omega B R^2/c \approx 10^{15} - 10^{19} V$



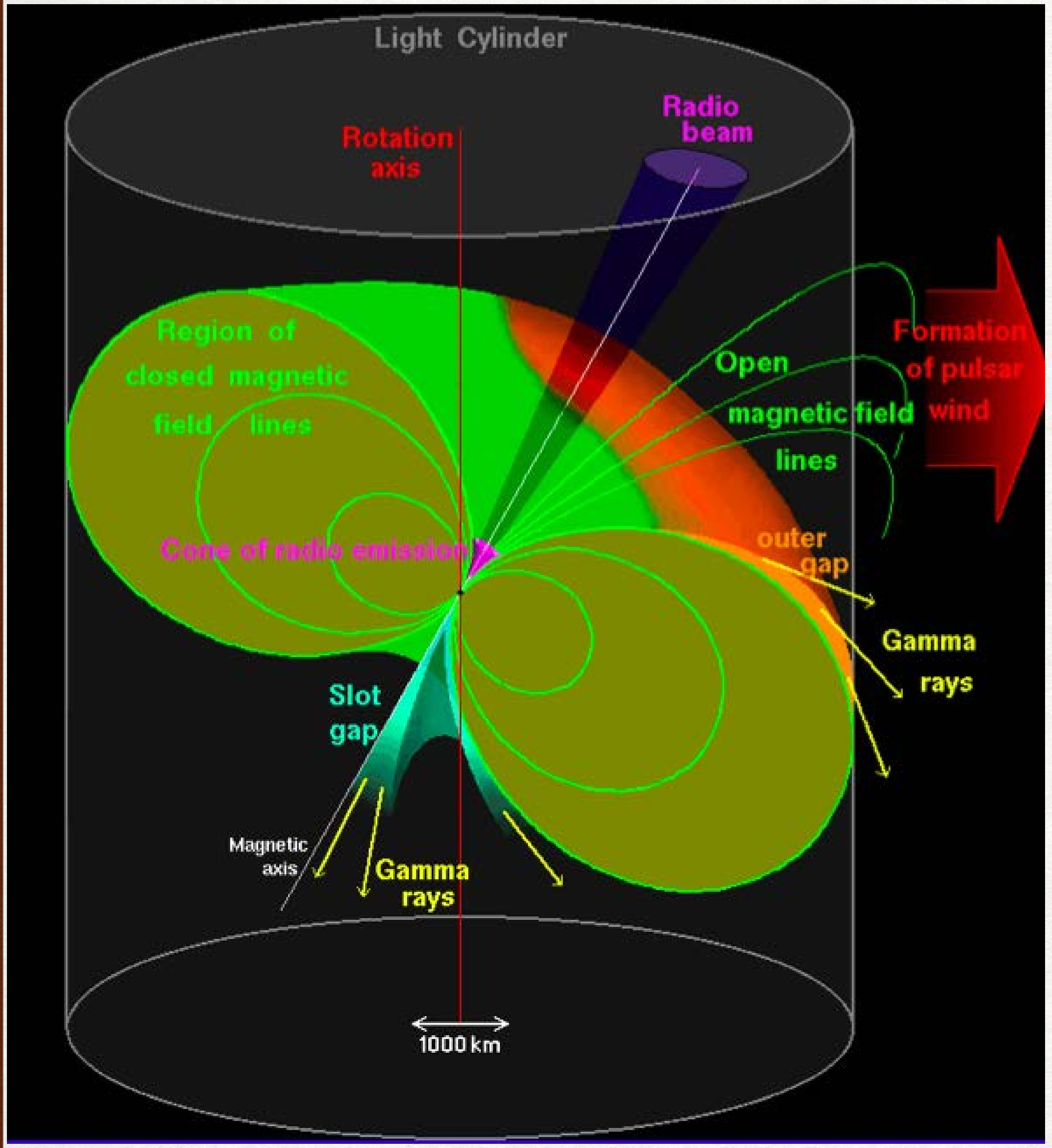
Goldreich & Julian 1969

Current closure is essential

Convert rotational energy into magnetized wind energy.

MAGNETOSPHERIC MODELS

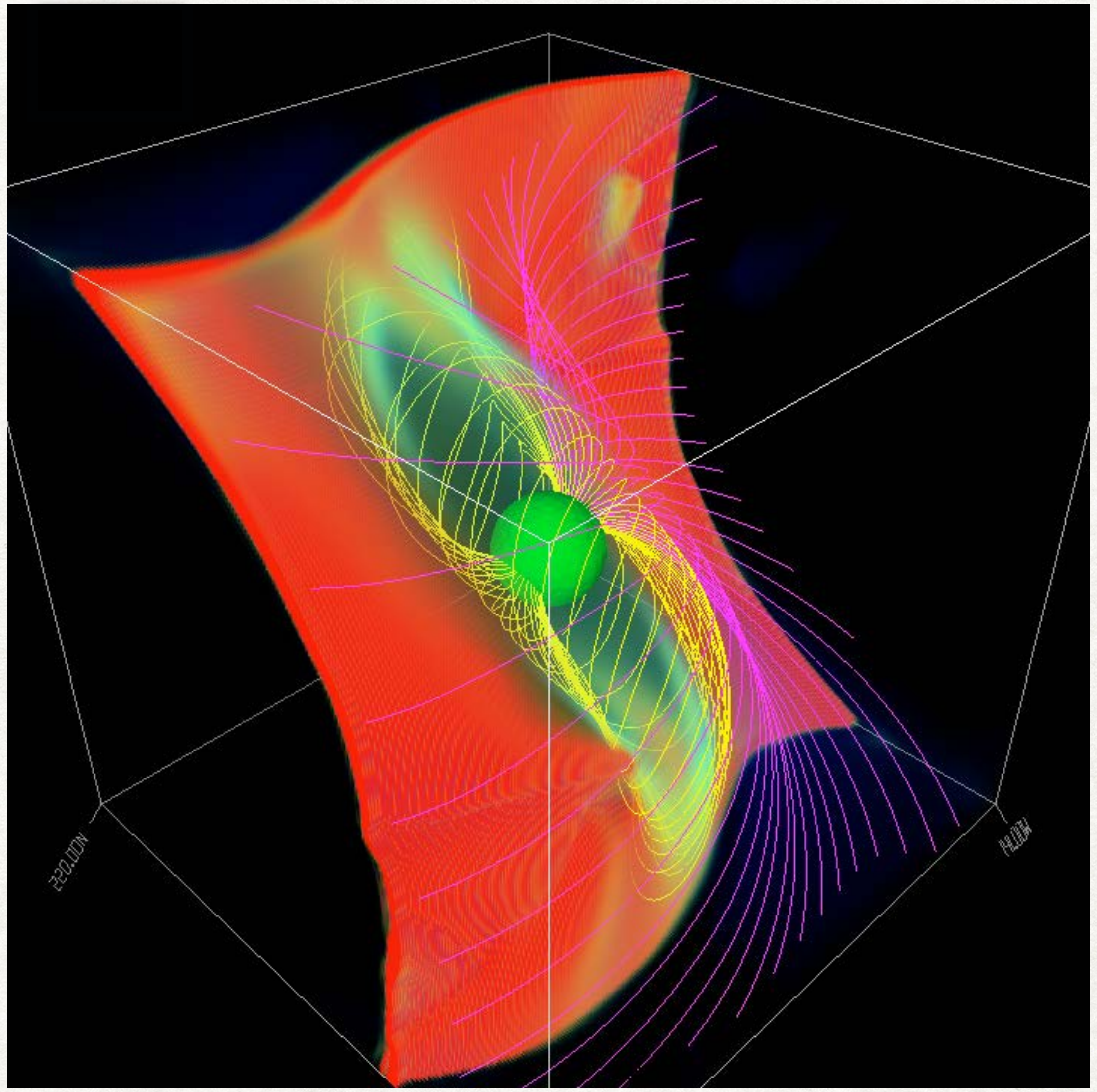
Vacuum



No plasma

1969-present

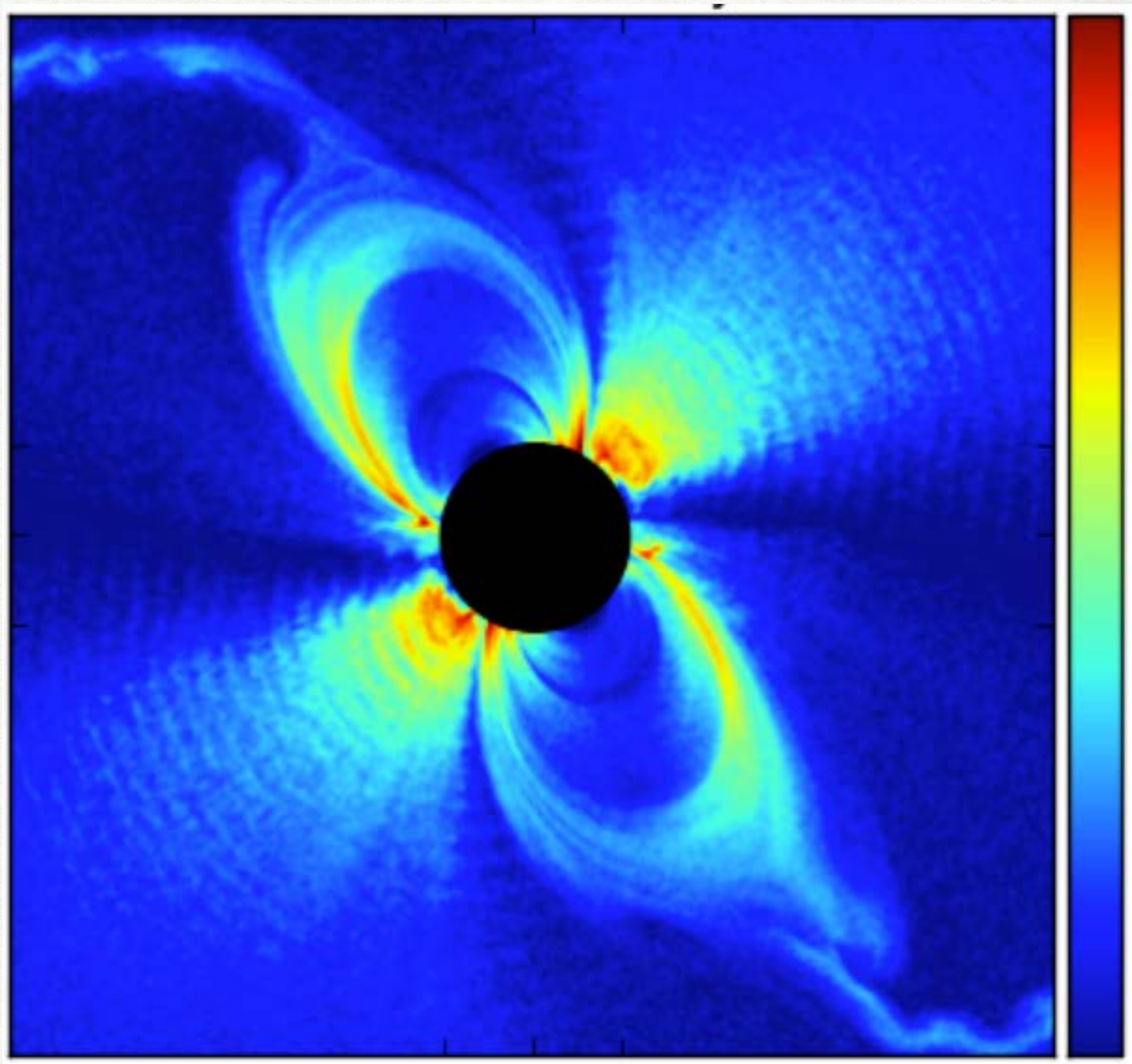
MHD/“force-free”



Abundant plasma everywhere

1999-present

Kinetic



Plasma self-consistently produced

2014-present

PULSAR PROBLEM: FORCE-FREE MAGNETOSPHERE

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

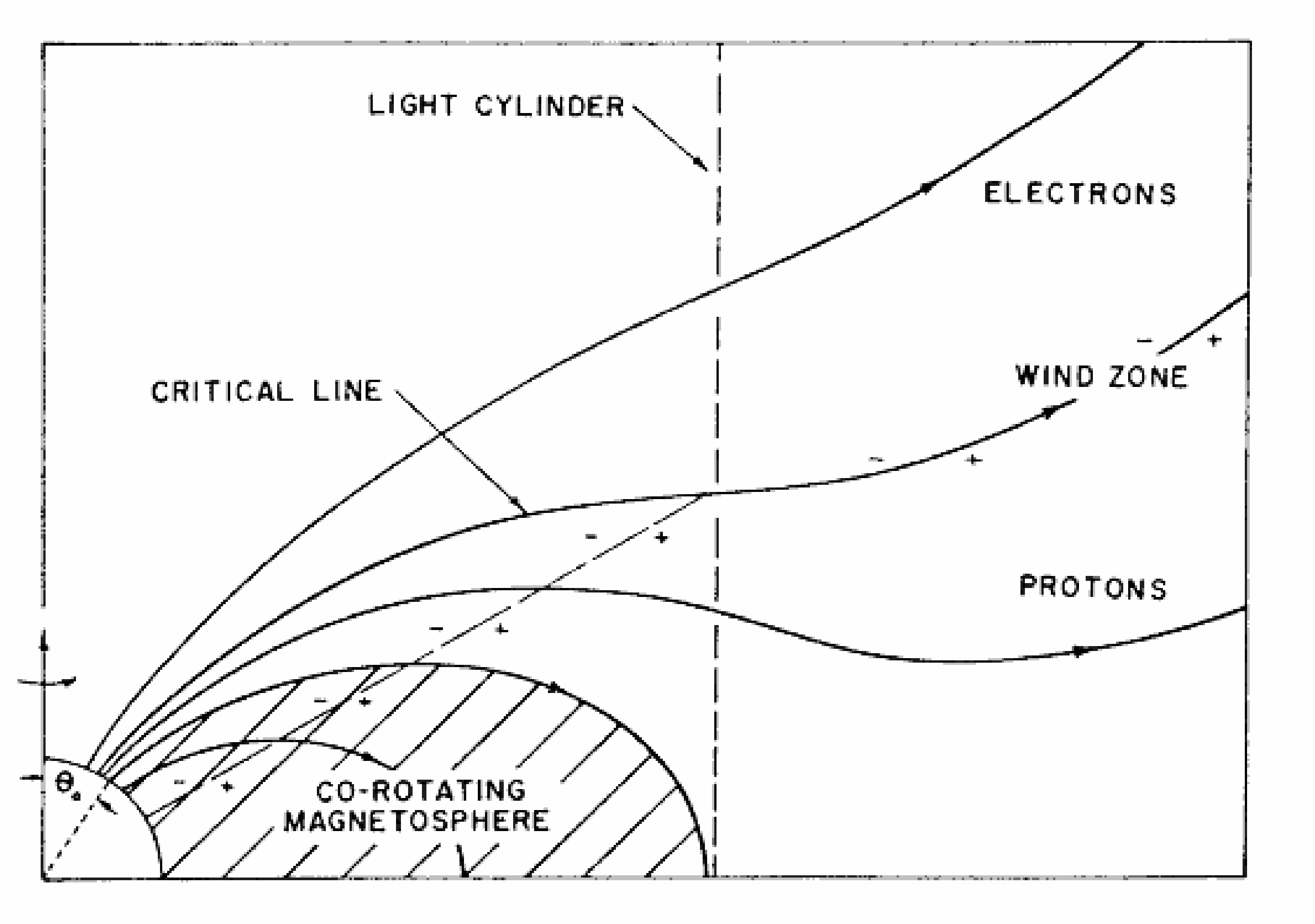
$$\frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} = \boldsymbol{\nabla}\times\boldsymbol{B} - \frac{4\pi}{c}\boldsymbol{j}, \quad \frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla}\times\boldsymbol{E}$$

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

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

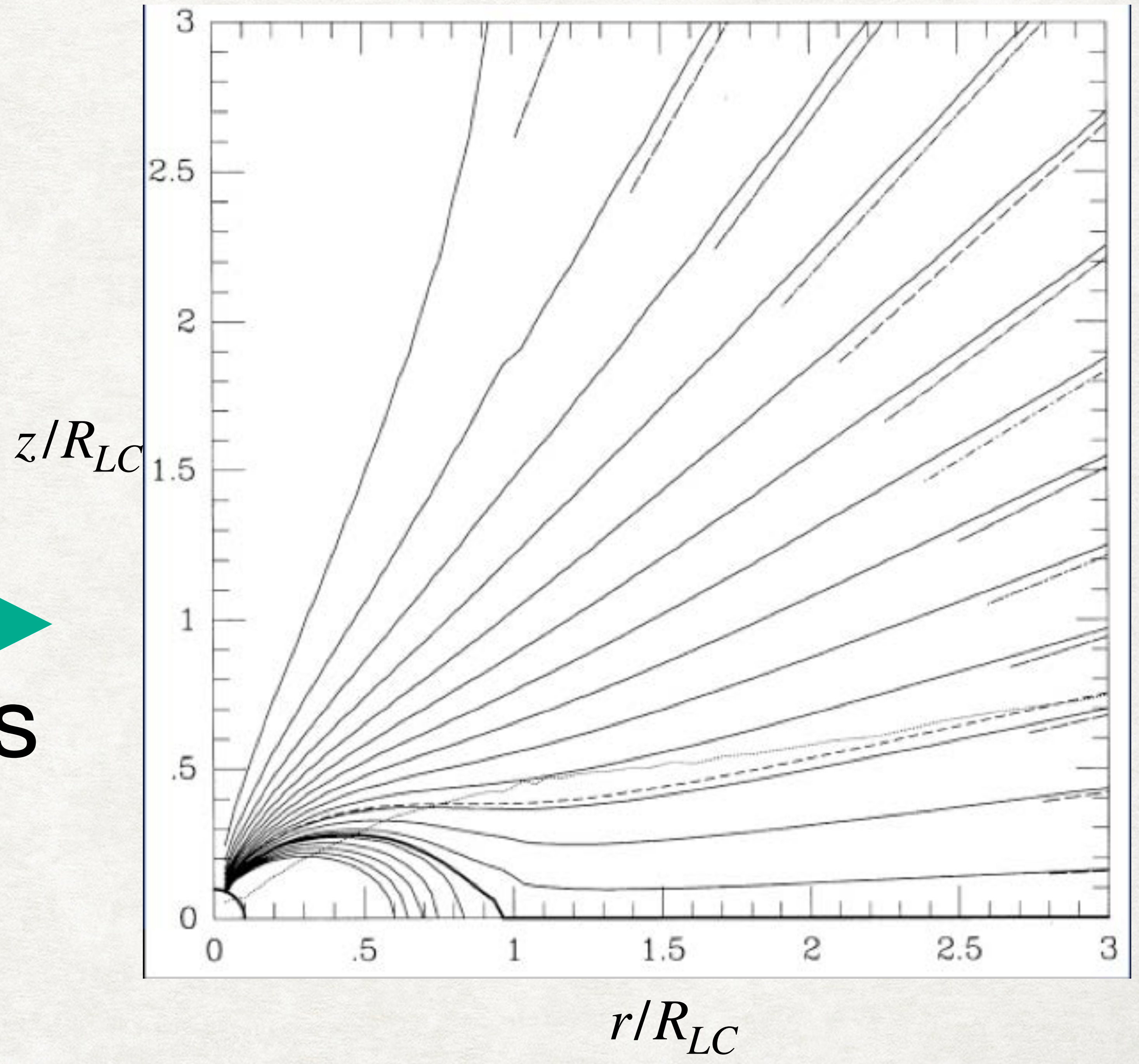
$$\boldsymbol{j} = \frac{c}{4\pi}\boldsymbol{\nabla}\cdot\boldsymbol{E}\,\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2} + \frac{c}{4\pi}\frac{(\boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B} - \boldsymbol{E}\cdot\boldsymbol{\nabla}\times\boldsymbol{E})\boldsymbol{B}}{B^2}$$

- 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



Goldreich & Julian 1969

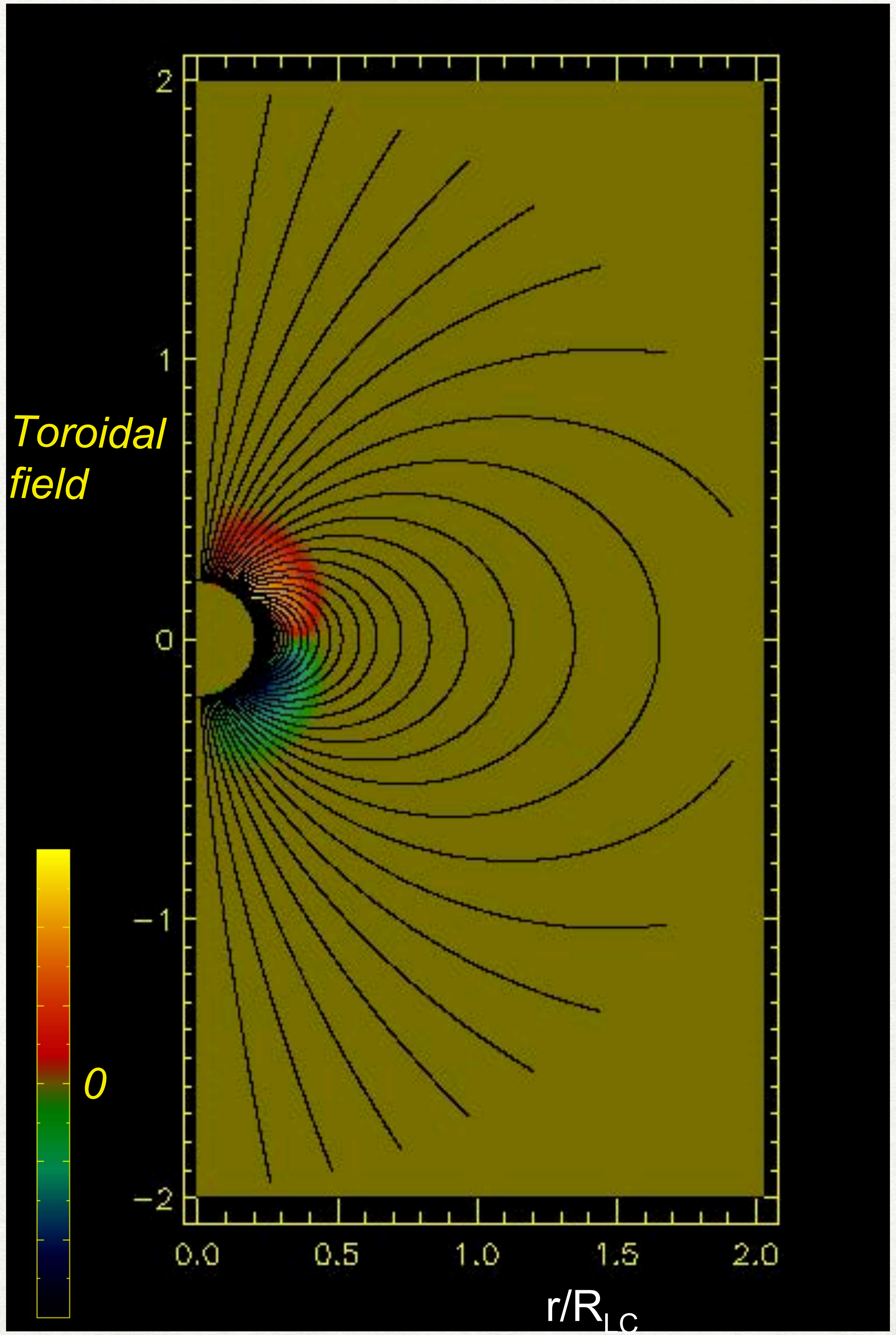
30 years

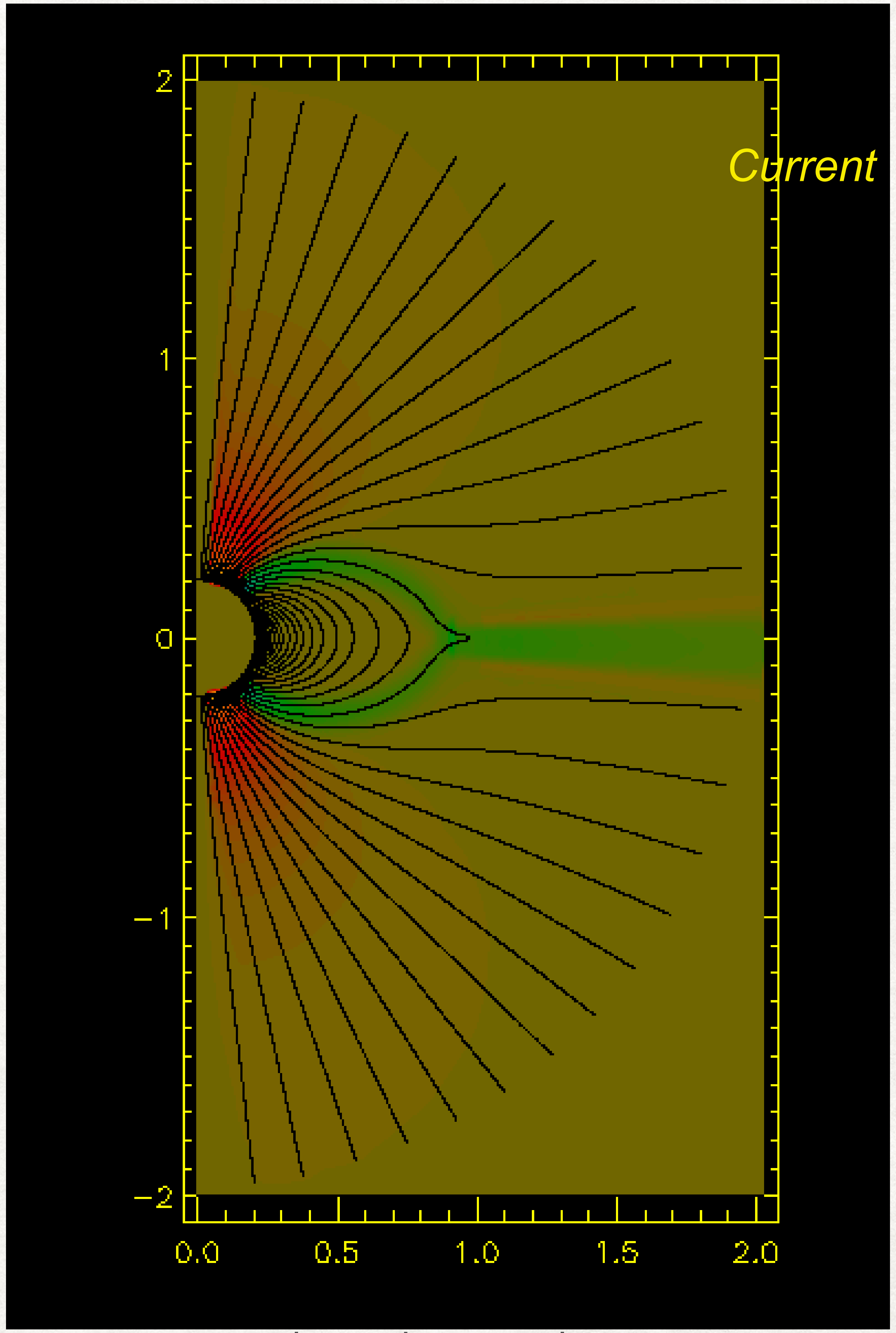


Contopoulos, Kazanas & Fendt 1999

PULSAR PROBLEM: FORCE-FREE MAGNETOSPHERE

- **Force-free** paradigm. Time-dependent solution



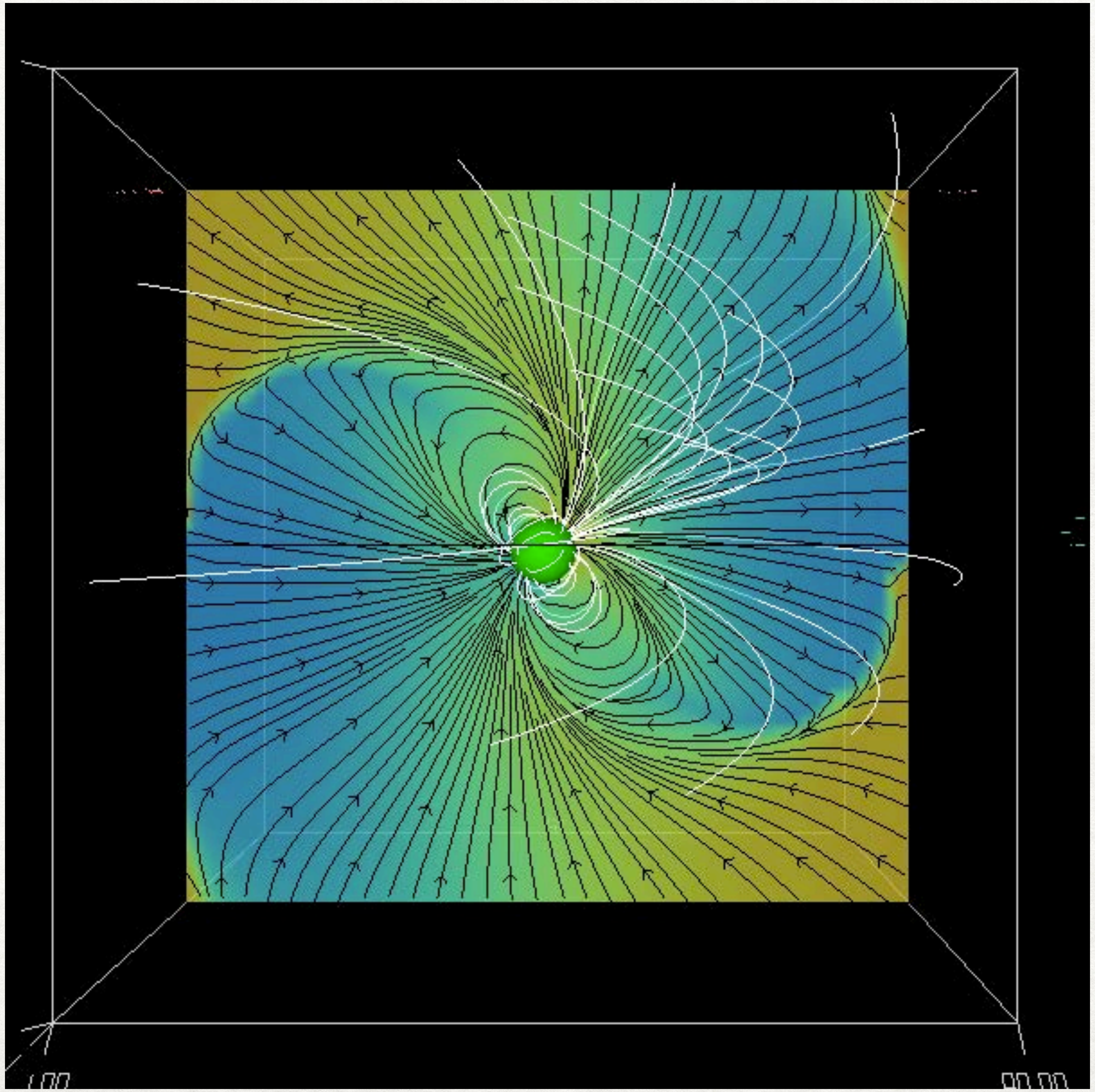


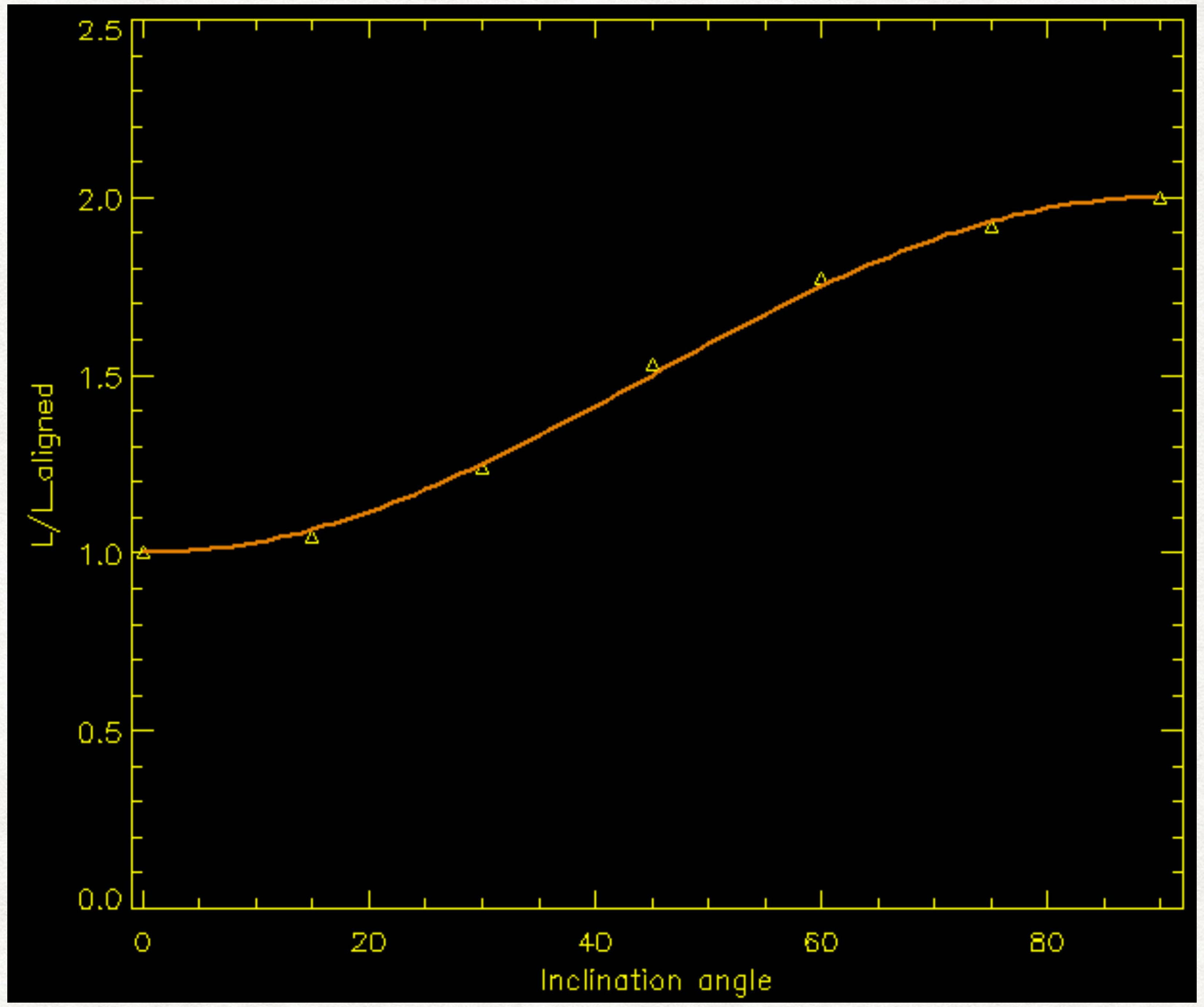
Properties: current sheet, split-monpolar asymptotics; closed-open lines; Y-point

(AS 2006, Timokhin 06, McKinney 06, Kalapotharakis 09, Yu 11, Parfrey 11, Petri 12, Palenzuela 12)

PULSAR PROBLEM: FORCE-FREE MAGNETOSPHERE

- **Force-free** paradigm. Oblique rotator:





Spin down of oblique rotator:

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

AS'06

The difference is large only for nearly aligned rotators

(cf Beskin et al 1993)

PLASMA-FILLED MODELS

Pros:

Allow us to compute global structure of the magnetosphere

Calculate spin-down power

Geometry of emission

Cons:

No acceleration; dissipation is artificial

No radiation

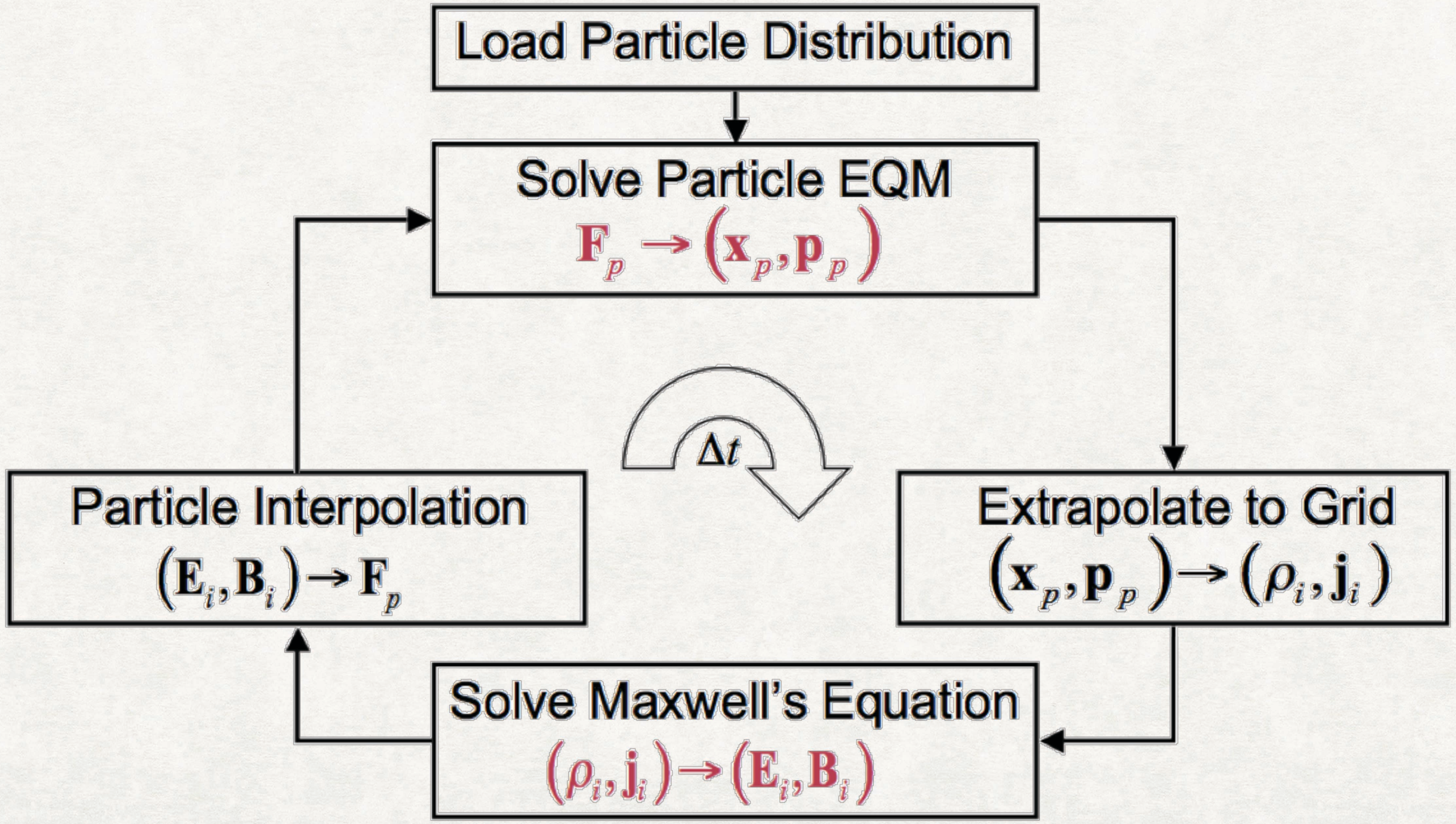
Can we make it more self-consistent? Use particles!

KINETIC METHOD: PARTICLE-IN-CELL (PIC) SIMULATIONS

- Kinetic model: model plasma as particles. We use particle-in-cell (PIC) method

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

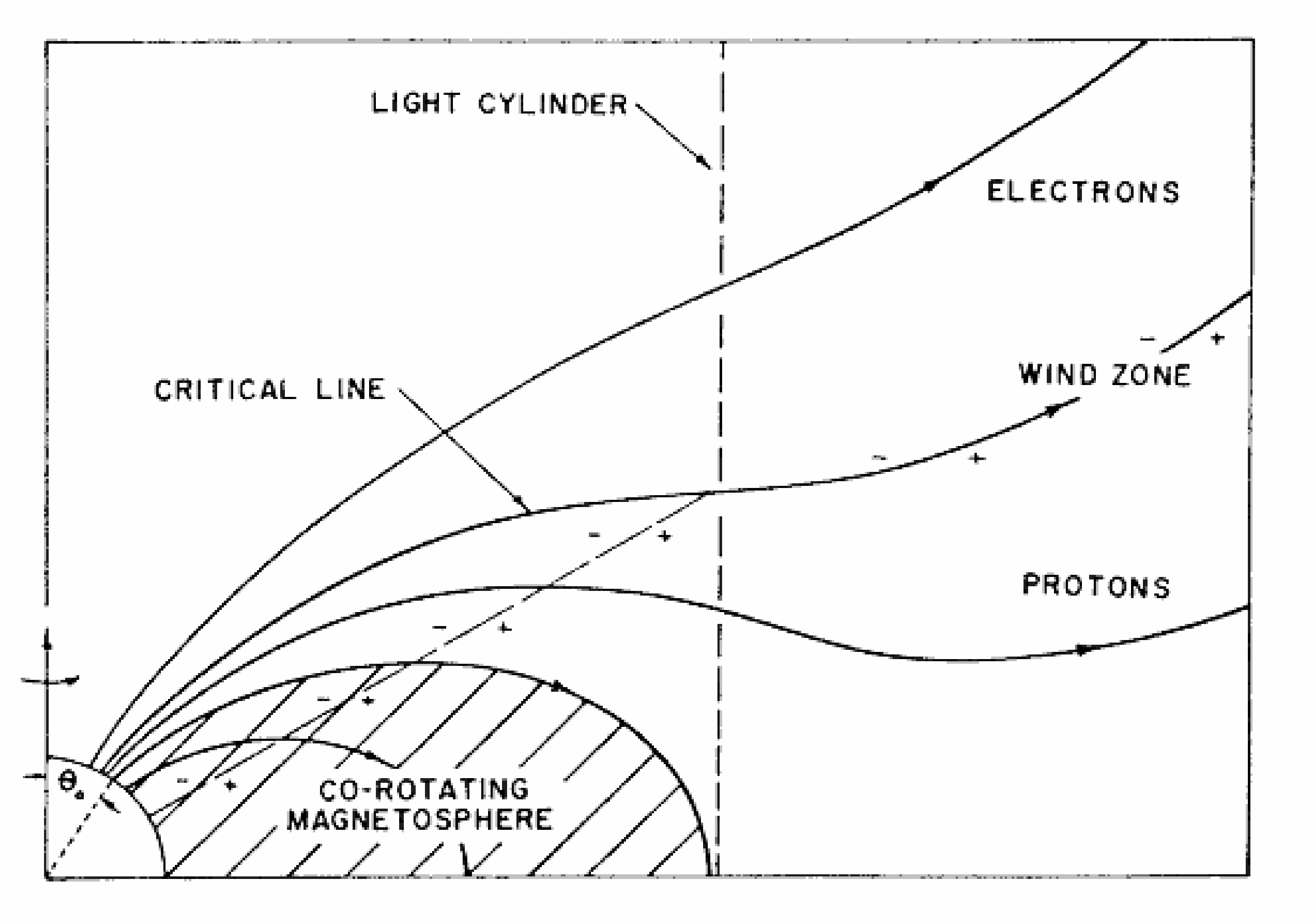
$$\partial B/\partial t = -c(\nabla \times E)\,, \qquad \frac{d}{dt}\gamma m\mathbf{v} = q(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B})$$

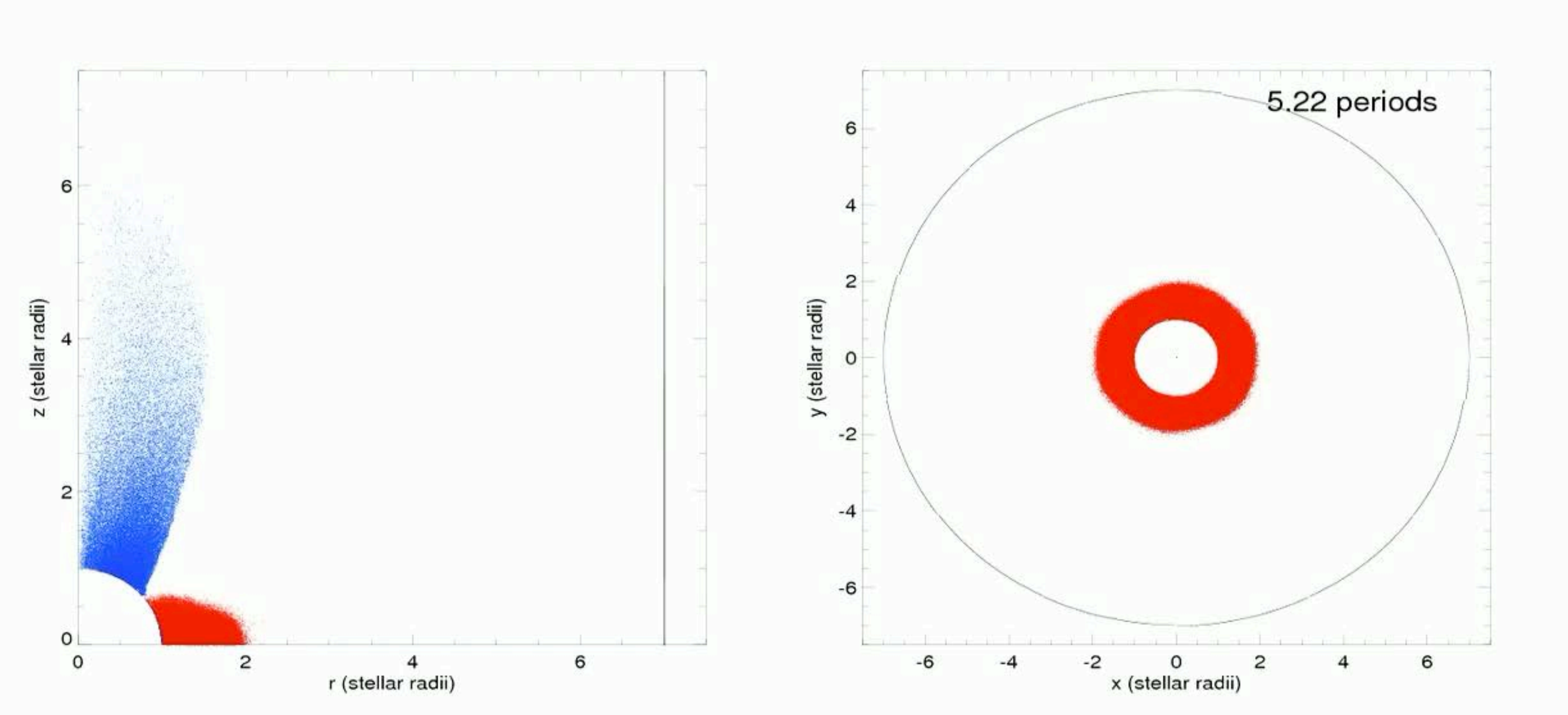


Philippov, Spitkovsky (2014+)
Chen & Beloborodov (2014)
Cerutti, et al. (2016+)
Belyaev (2015)
Kalapotharakos, et al. (2018+)
Cruz+ (2020, 2023)
Hu, & Beloborodov (2021)
Hakobyan+ (2023)
Bransgrove et al (2023)
Benacek+ (2024)

Expensive: can take billions of particles on 2000^3 grids

PIC: NO PAIRS — ELECTROSPHERES



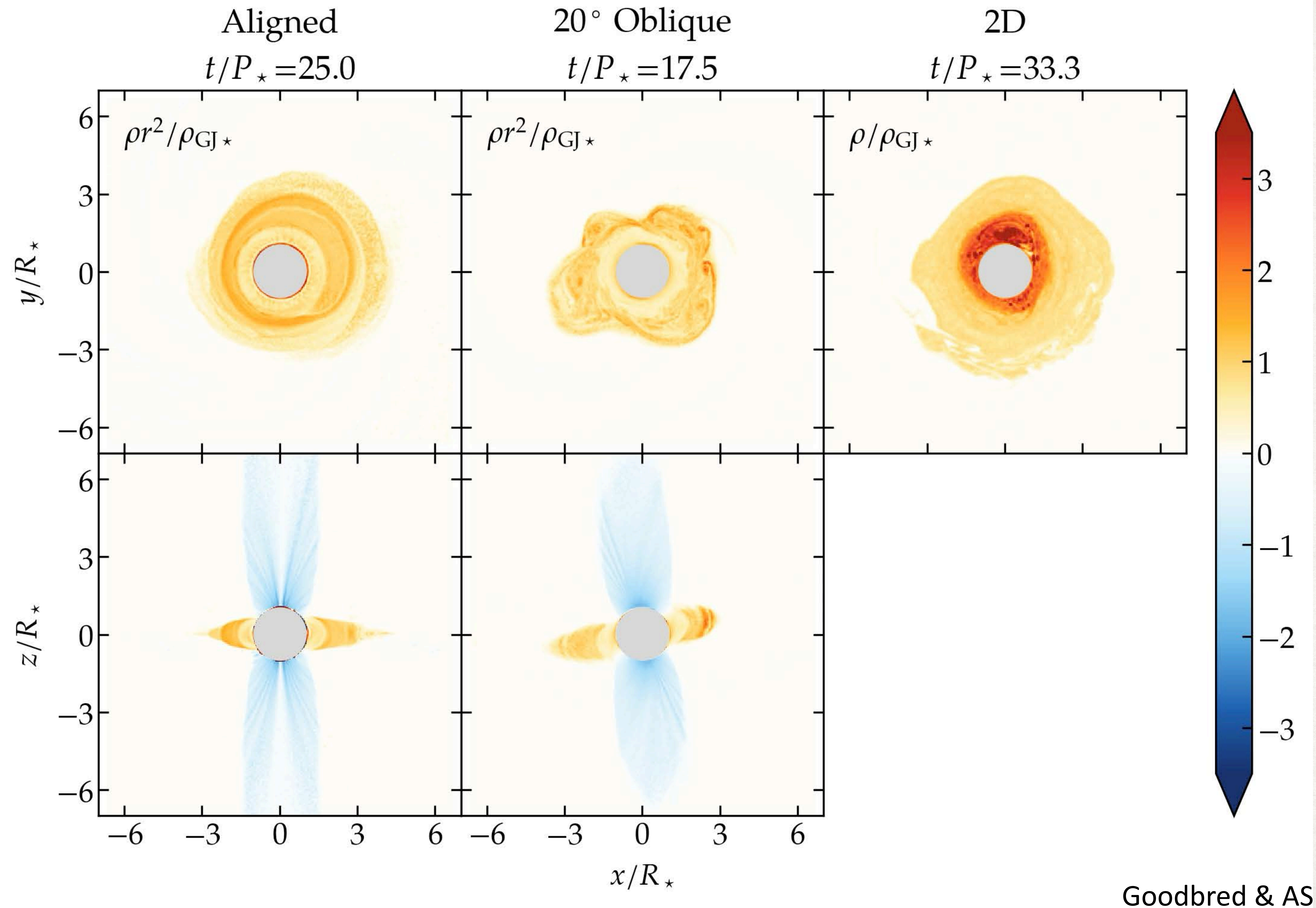


Belyaev & AS in prep

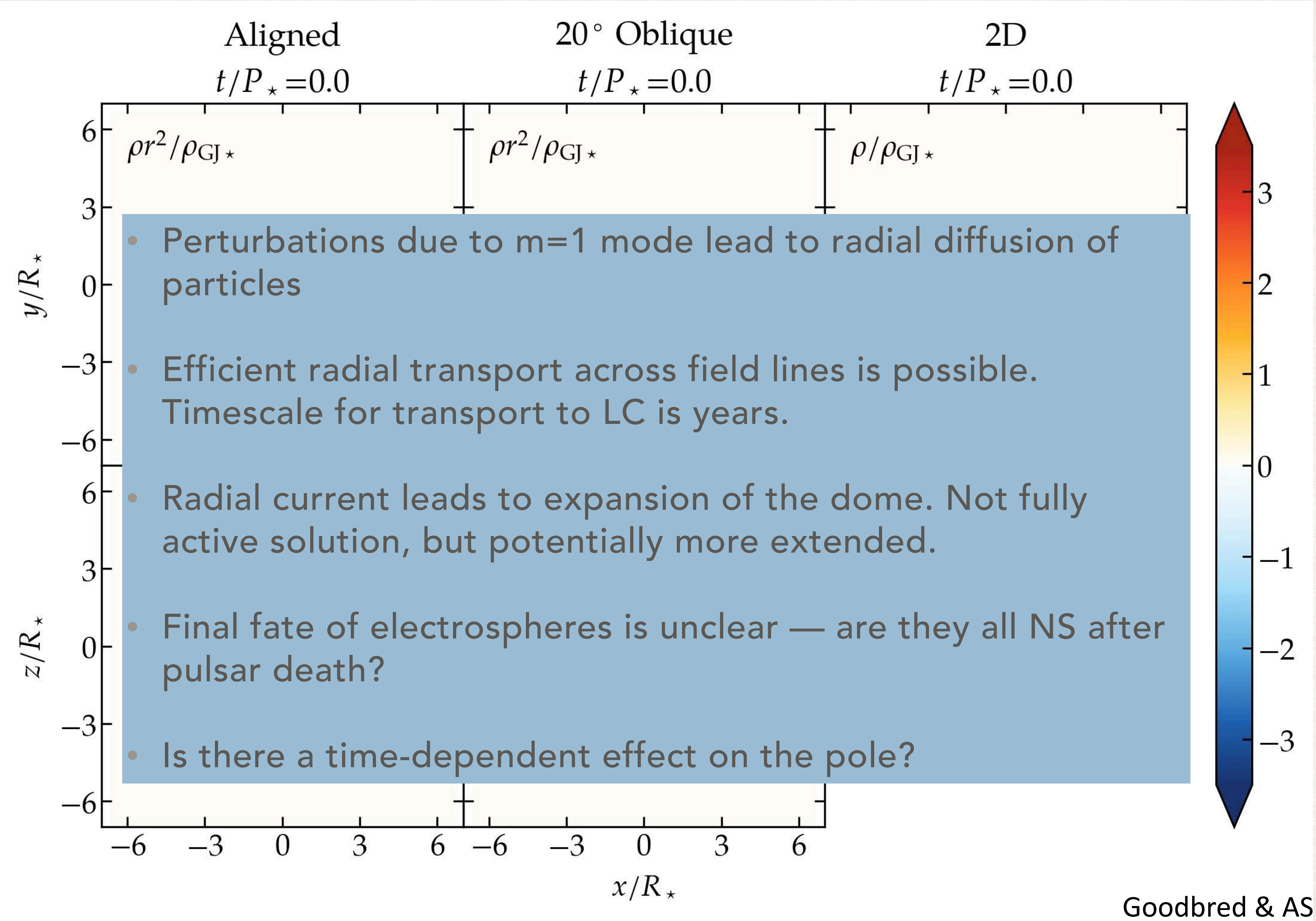
- Null surface traps charge-separated plasma
- Form disk/dome solution — "electrosphere"
- Is this NS beyond death line? No spindown, no radiation? Unscreened fields
- Unstable in 3D to diocotron instability: possible charge transport

Michael et al 84-01

AS & Arons 02;
Petri et al 02-08



Goodbred & AS in prep

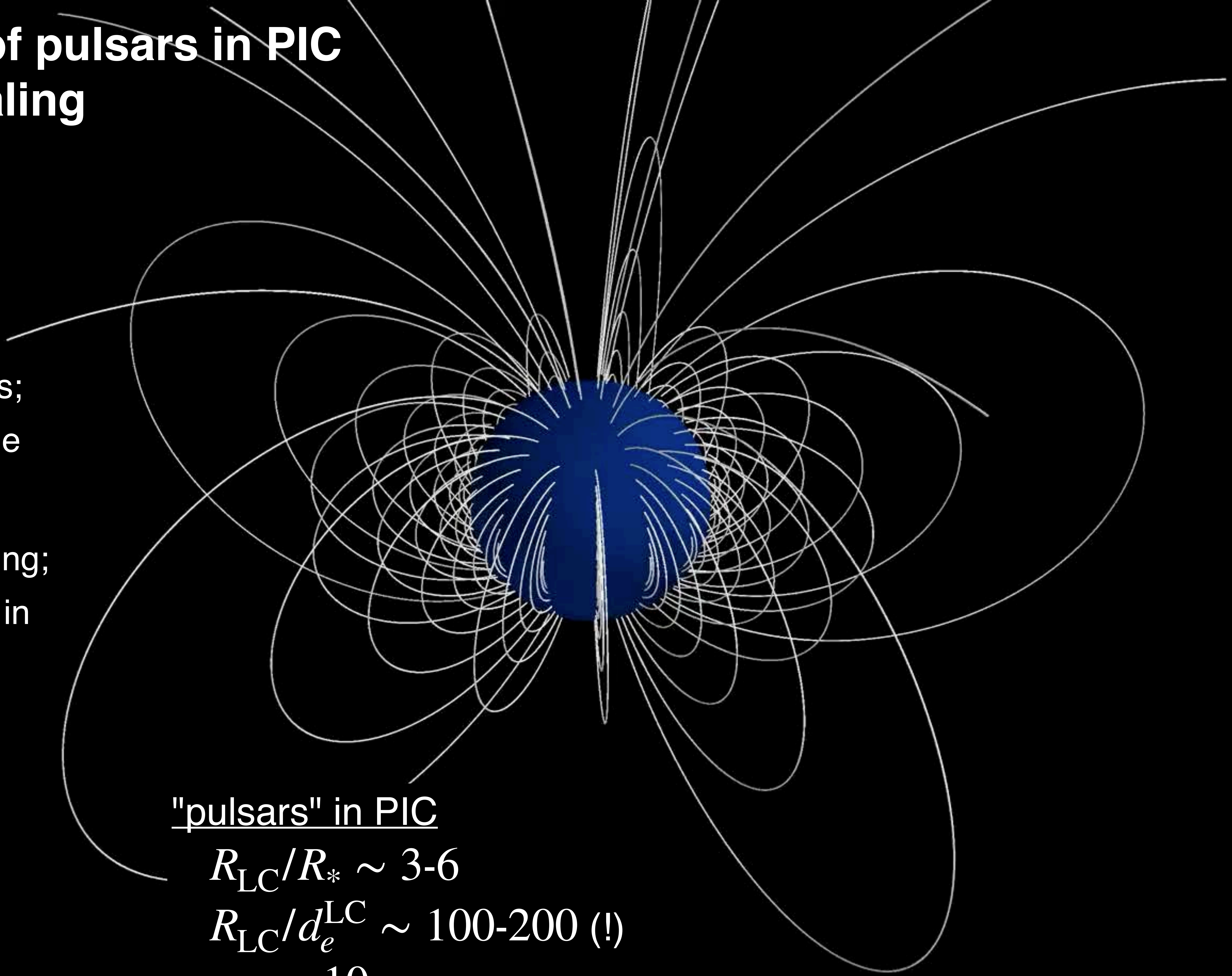


- Perturbations due to m=1 mode lead to radial diffusion of particles
- Efficient radial transport across field lines is possible. Timescale for transport to LC is years.
- Radial current leads to expansion of the dome. Not fully active solution, but potentially more extended.
- Final fate of electrospheres is unclear — are they all NS after pulsar death?
- Is there a time-dependent effect on the pole?

Goodbred & AS in prep

Magnetospheres of pulsars in PIC simulations: rescaling

> $d_e^{\rm LC} \sim 5$ cells
> size of the simulation: 560^3-2500^3 cells



- Initially dipolar ***B***-field (+boundary conditions);
- rotating spherical conductor;
- outflow outer boundaries;
- injection of pairs from the surface or threshold gamma;
- strong synchrotron cooling;
- reduced particle motion in the strong-***B*** regions.

Plasma frequency:

$$\omega_{pe} = \sqrt{\frac{4\pi e^2 n_e}{m_e}}$$

Skin depth:

$$d_e = c/\omega_{pe}$$

<u>real pulsars</u>

$R_{\rm LC}/R_* \gtrsim 100$

$R_{\rm LC}/d_e^{\rm LC} \sim 10^8$

$n_{e^\pm} \sim 10^4$-$10^6\ n_{\rm GJ}$

$\sigma^{\rm LC} = \dfrac{2U_B^{\rm LC}}{\rho_{e^\pm}c^2} \sim 10^4$-$10^6$

<u>"pulsars" in PIC</u>

$R_{\rm LC}/R_* \sim 3$-6

$R_{\rm LC}/d_e^{\rm LC} \sim 100$-$200$ (!)

$n_{e^\pm} \sim 10\ n_{\rm GJ}$

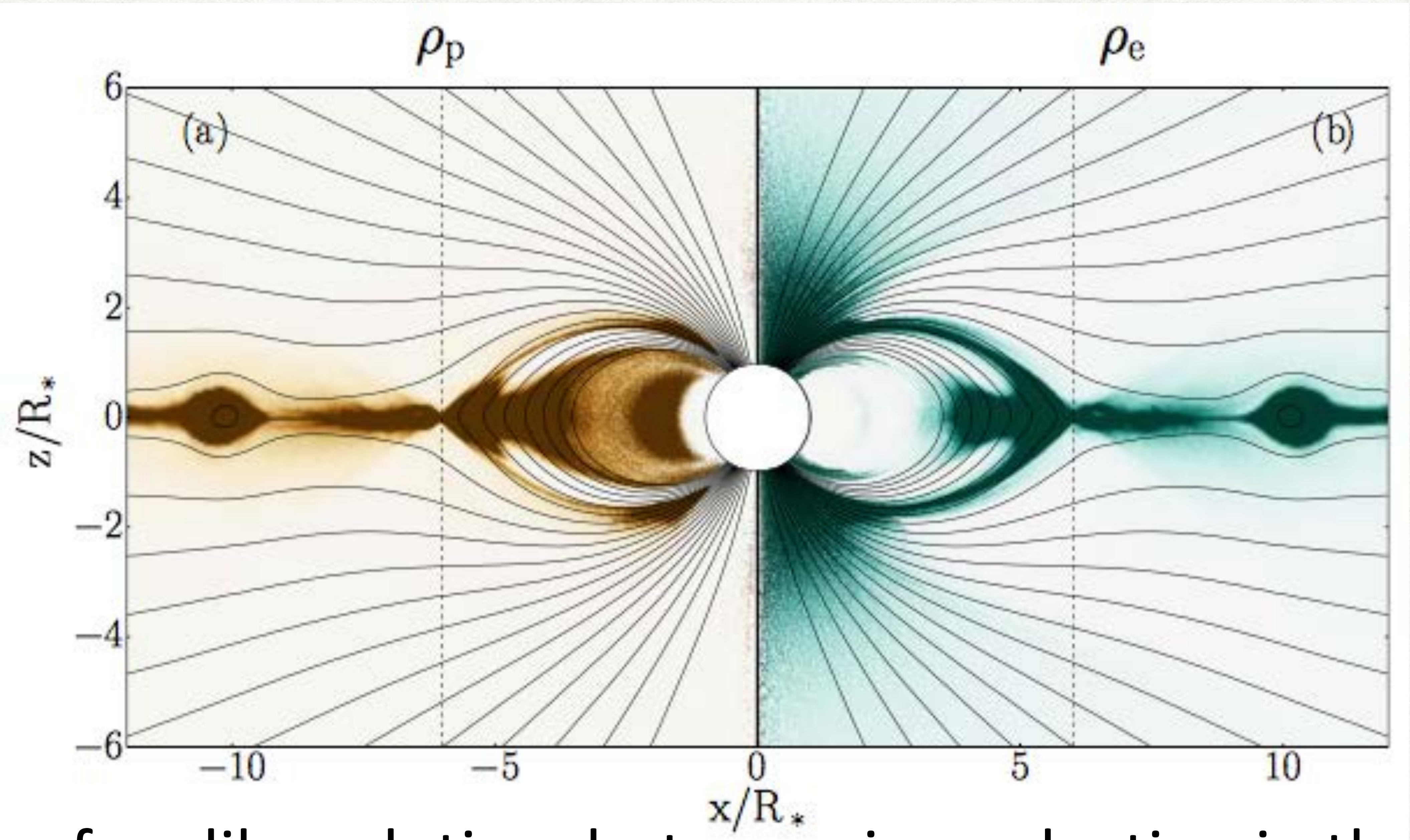
$\sigma^{\rm LC} \sim 10^2$-$10^3$

also see
Philippov, & Spitkovsky (2014-2018)
Cerutti+ (2016), Chen, & Beloborodov (2014)

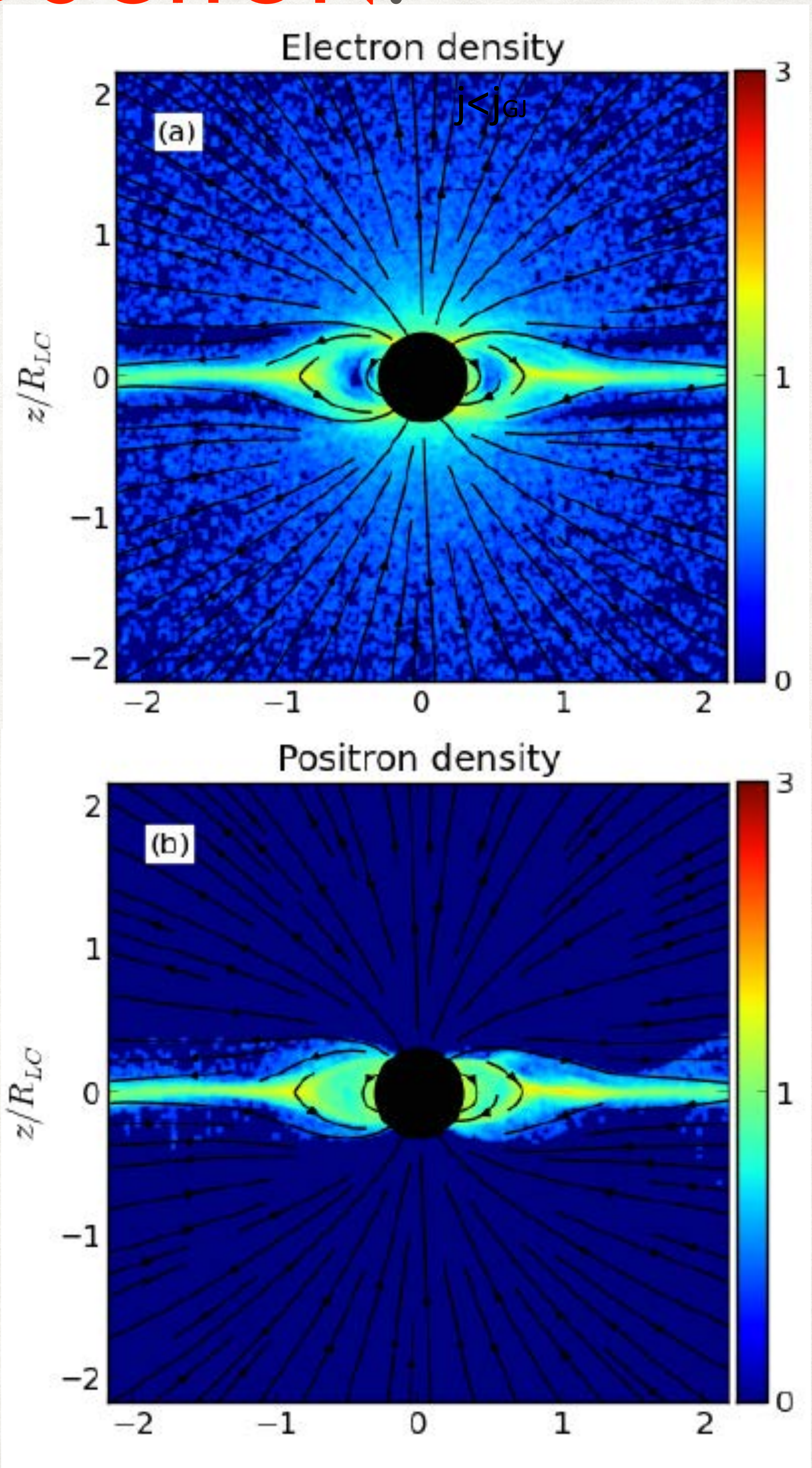
ALIGNED PULSAR WITH PAIR PRODUCTION:

NO DENSE SOLUTIONS!

Add pair production based on threshold energy near the star, or gamma-gamma interaction in the outer magnetosphere



Approaches force-free like solution, but no pair production in the polar region, where the space-charge limited flow does not lead to particle acceleration.

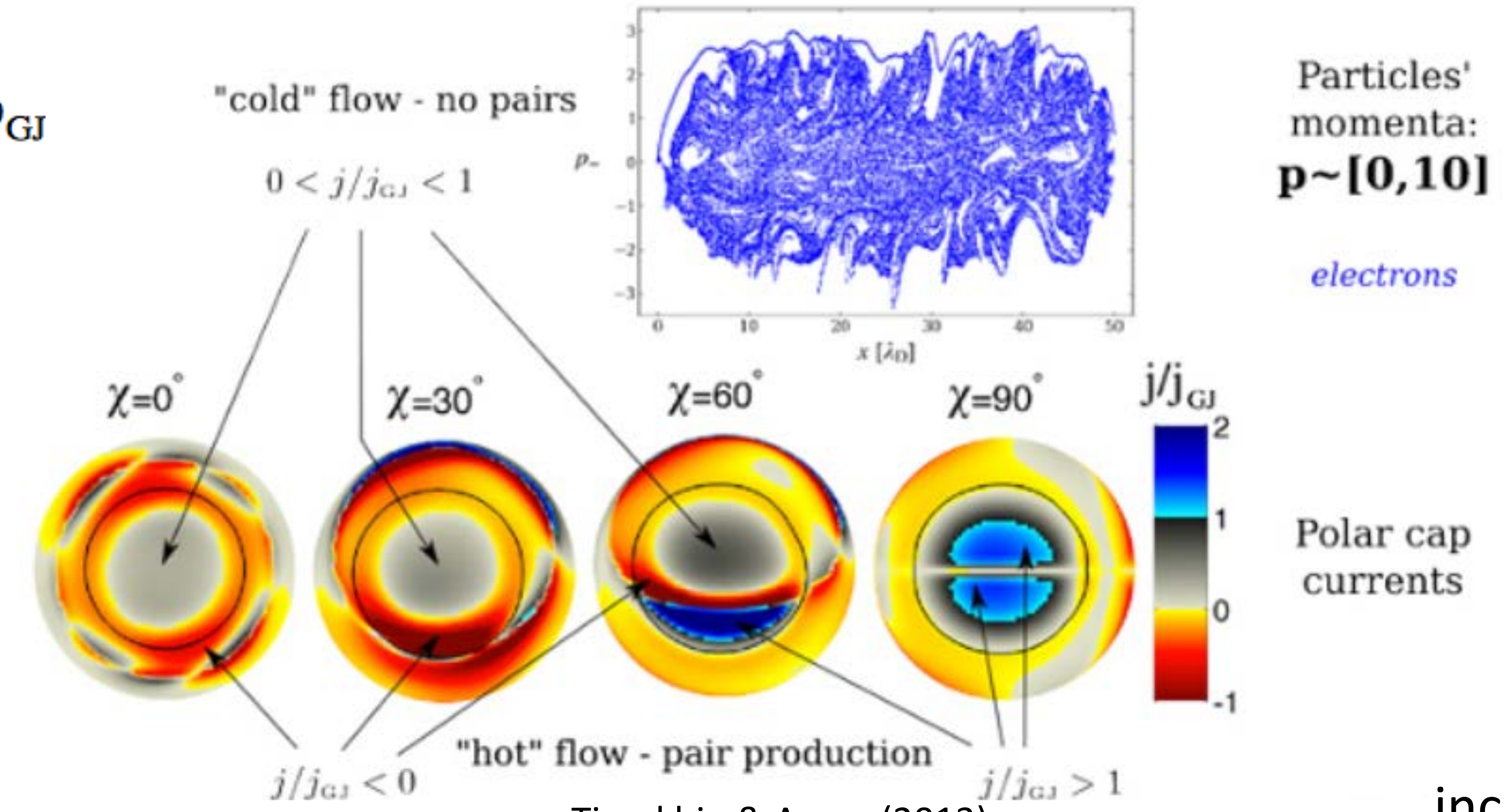


Chen, Beloborodov, ApJ, 2014

Philippov et al., ApJ, 2015a

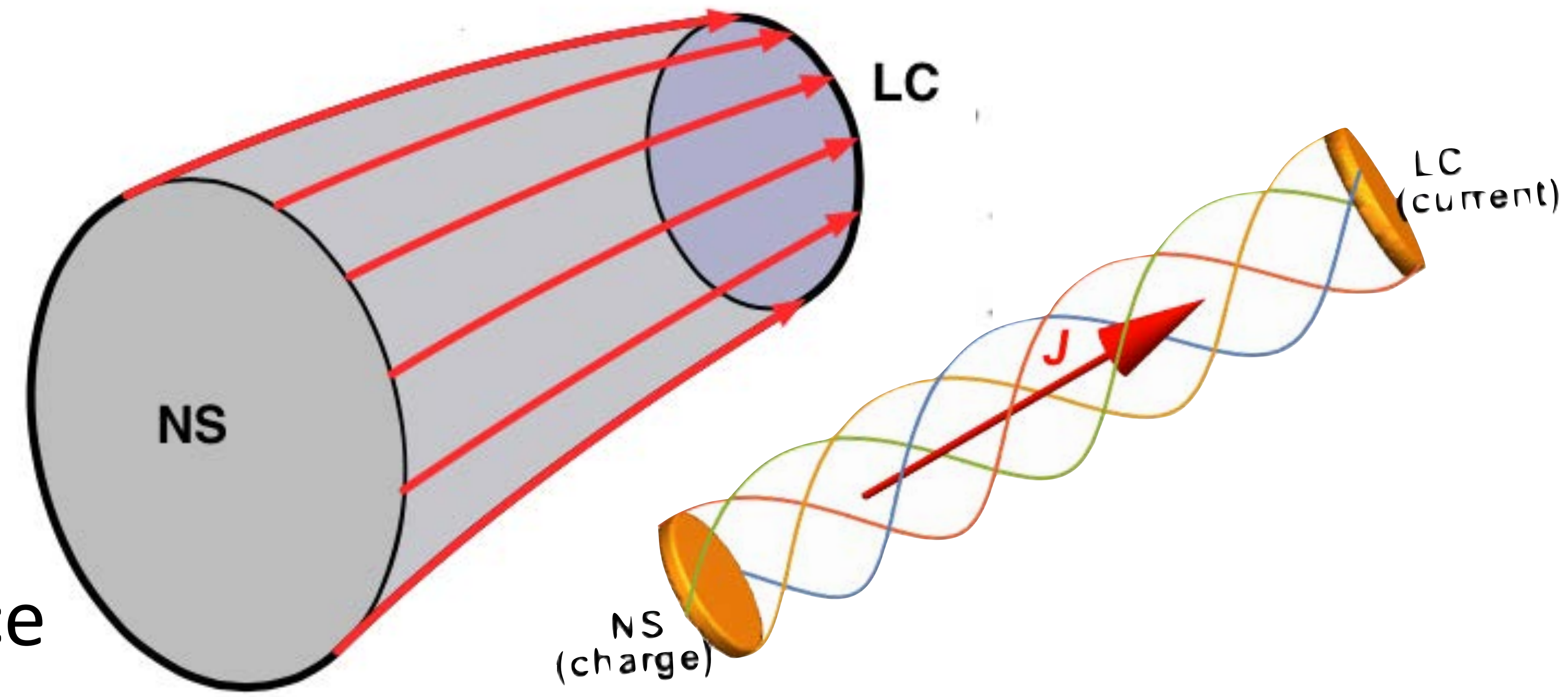
Can we make plasma through discharge?

- 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 (Beloborodov 08).
- Current is set by twist at light cylinder



Timokhin & Arons (2013)

included

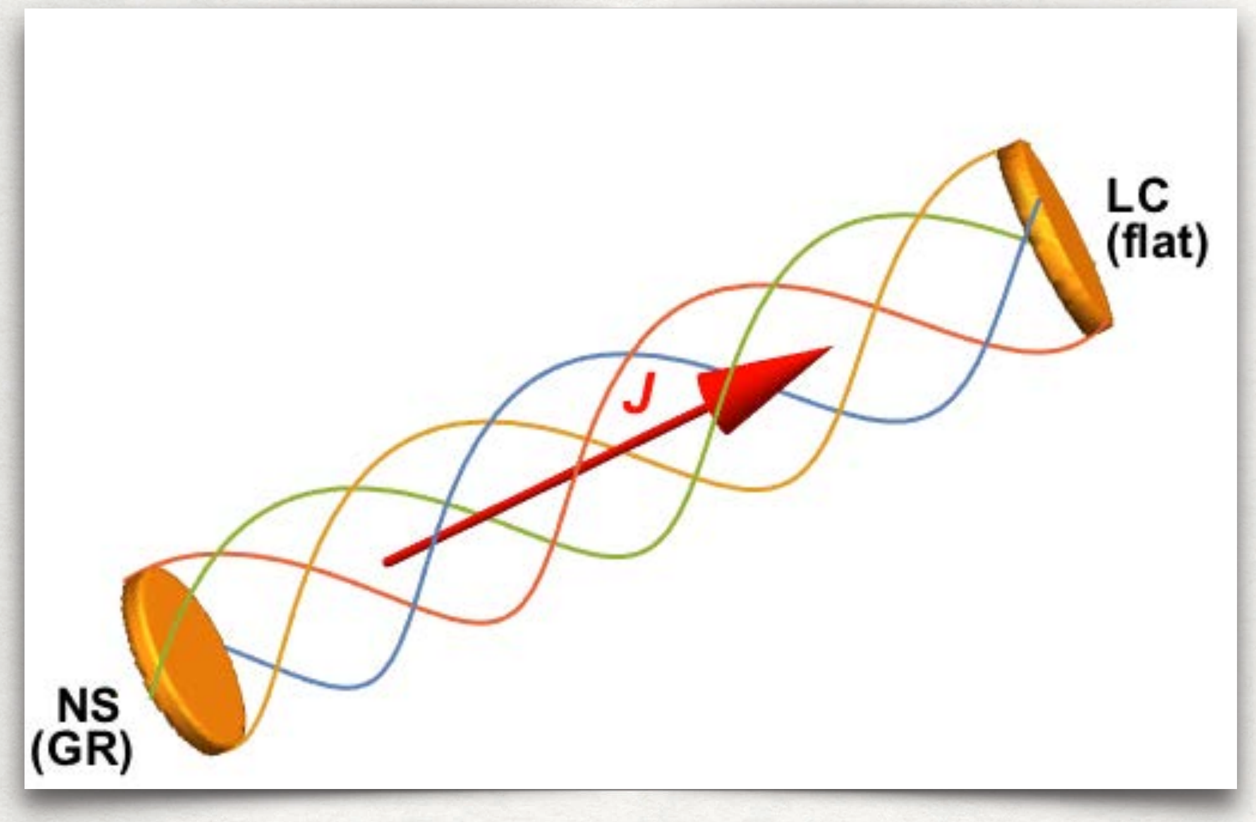


charge source

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



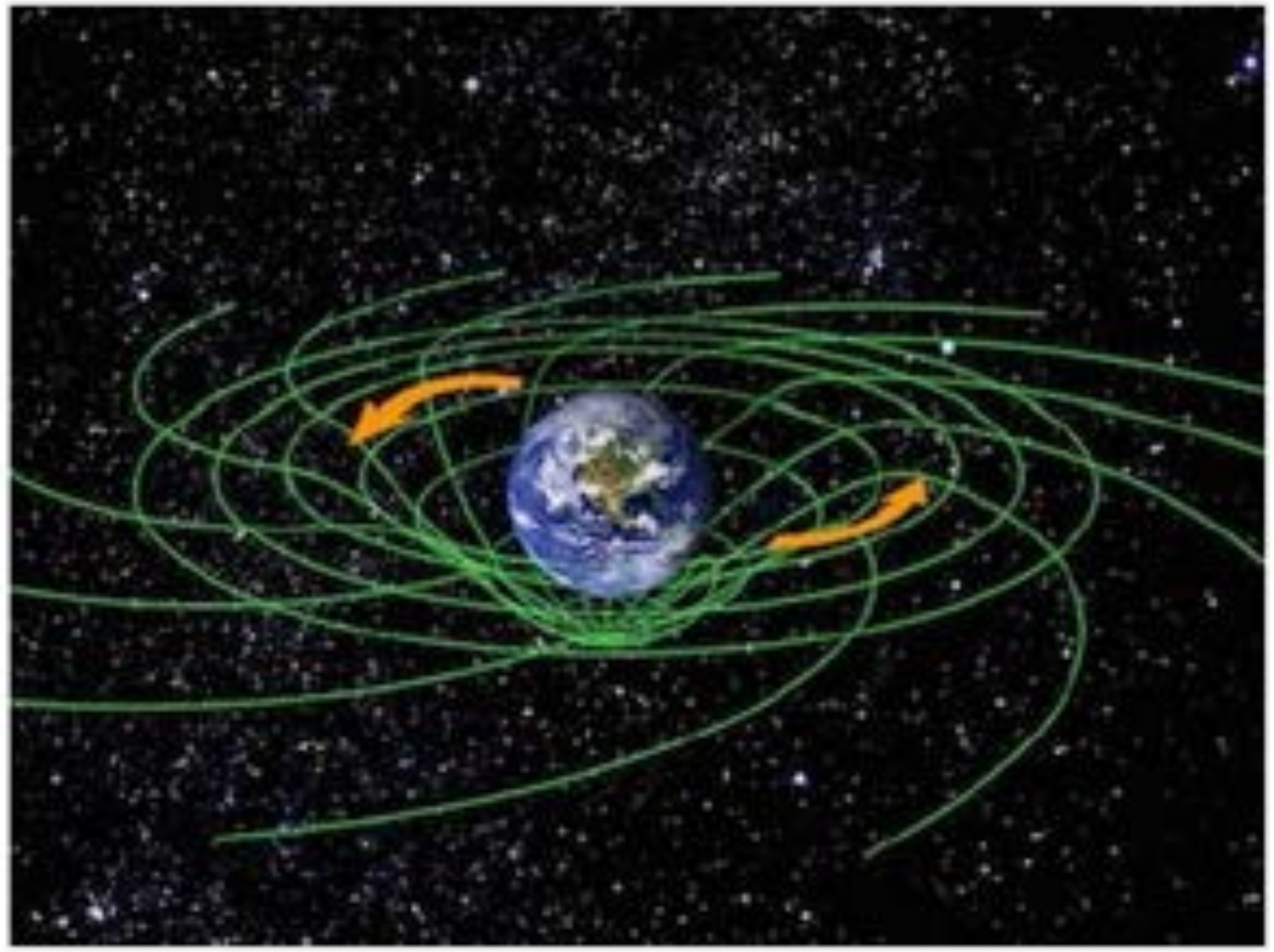
$$\omega_{LT} = \frac{2}{5}\Omega_* \frac{r_s}{R_*}$$

$$\vec{\beta} = \frac{1}{c}\vec{\omega}_{LT} \times \vec{r}$$

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

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

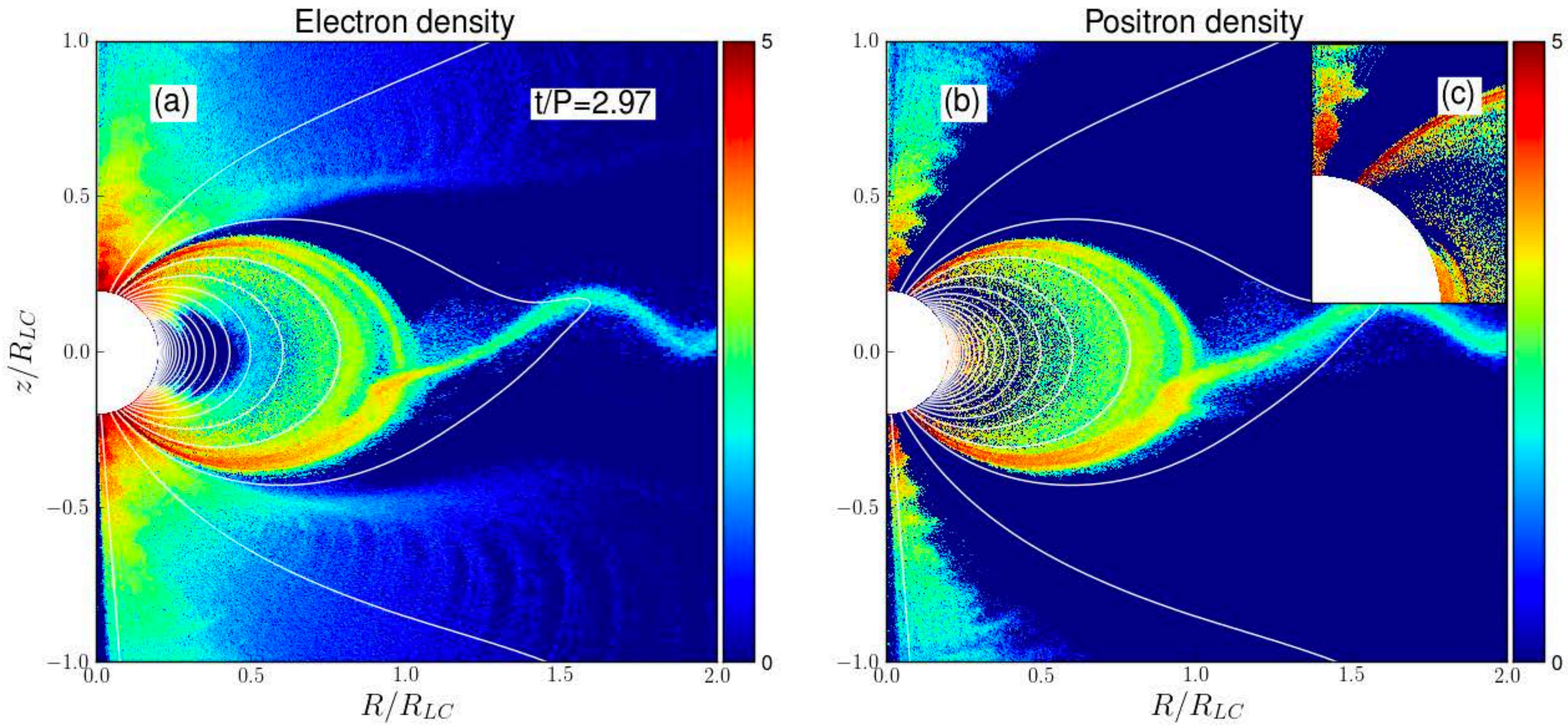
$$\frac{J_{\hat{r}}}{\rho_{GJ} c} \approx \left(\frac{J_{\hat{r}}}{\rho_{GJ} c}\right)_{\text{flat}} \frac{1}{1 - \omega_{LT}/\Omega_*}$$



Lense-Thirring frame dragging

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

PIC: ALIGNED ROTATOR MAGNETOSPHERE



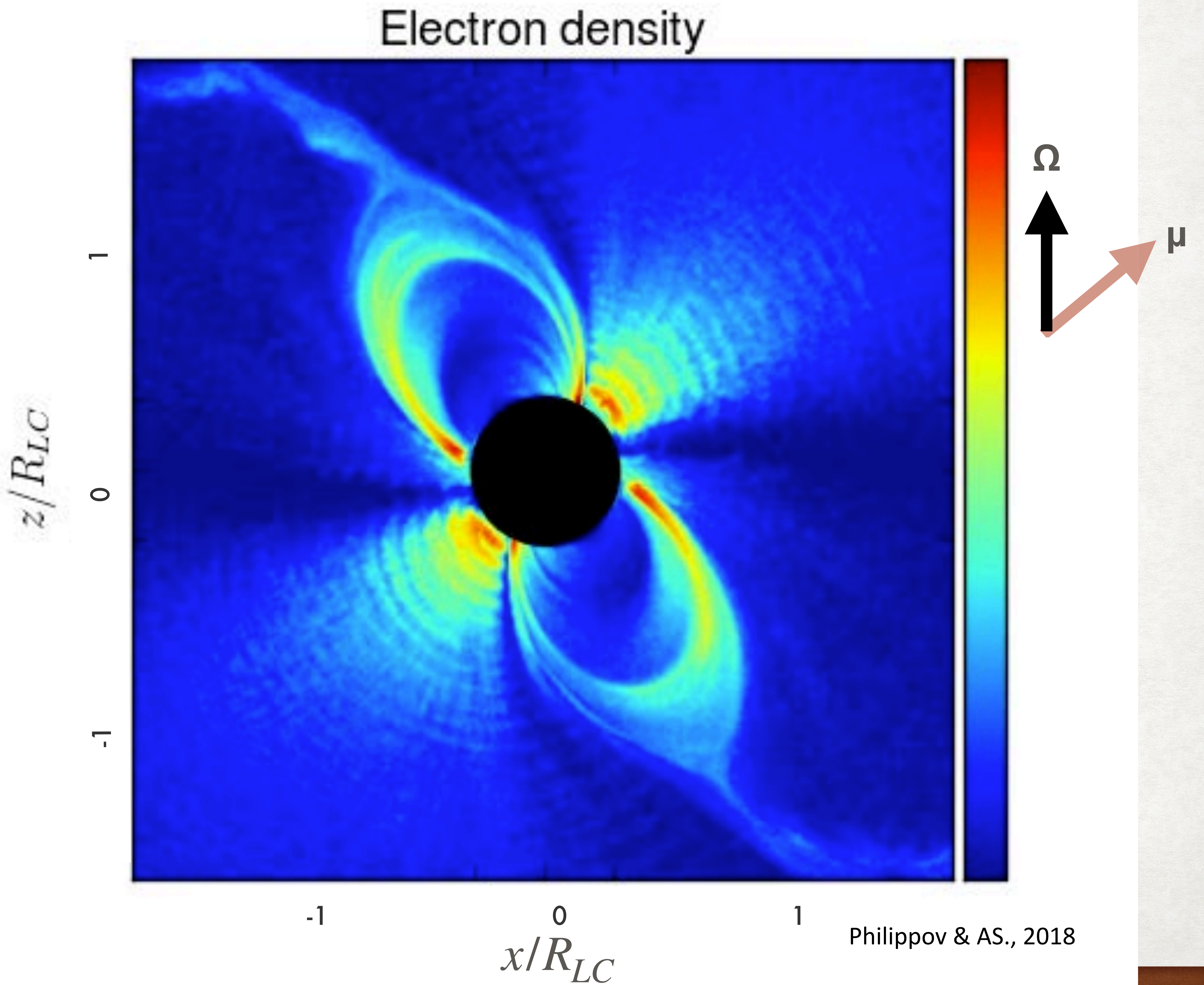
- Polar and current sheet pair production included; effects of general relativity are important near the star

Philippov et al. (2015b)

cf Chen & Beloborodov (2014)

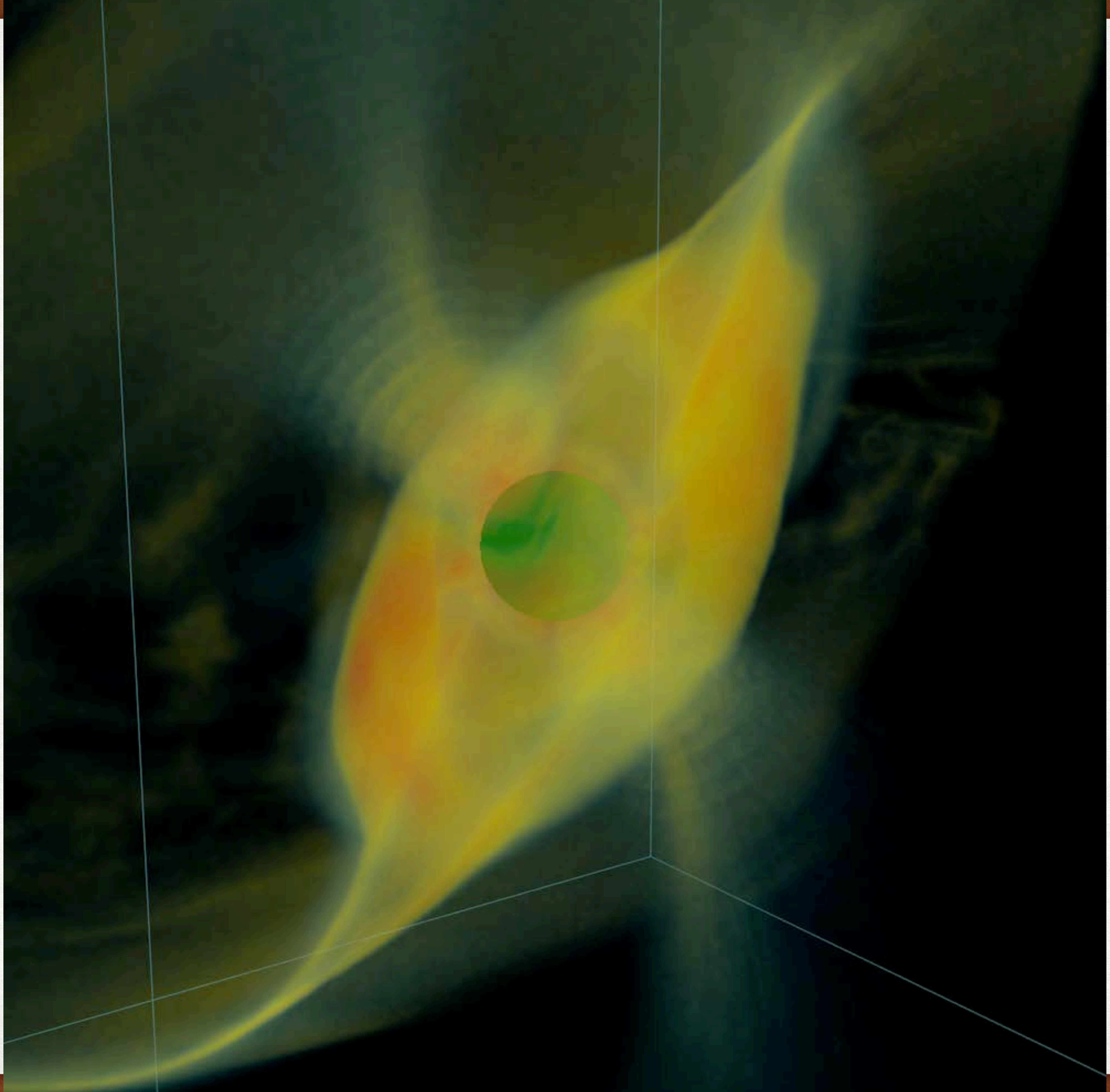
OBLIQUE ROTATOR MAGNETOSPHERE

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

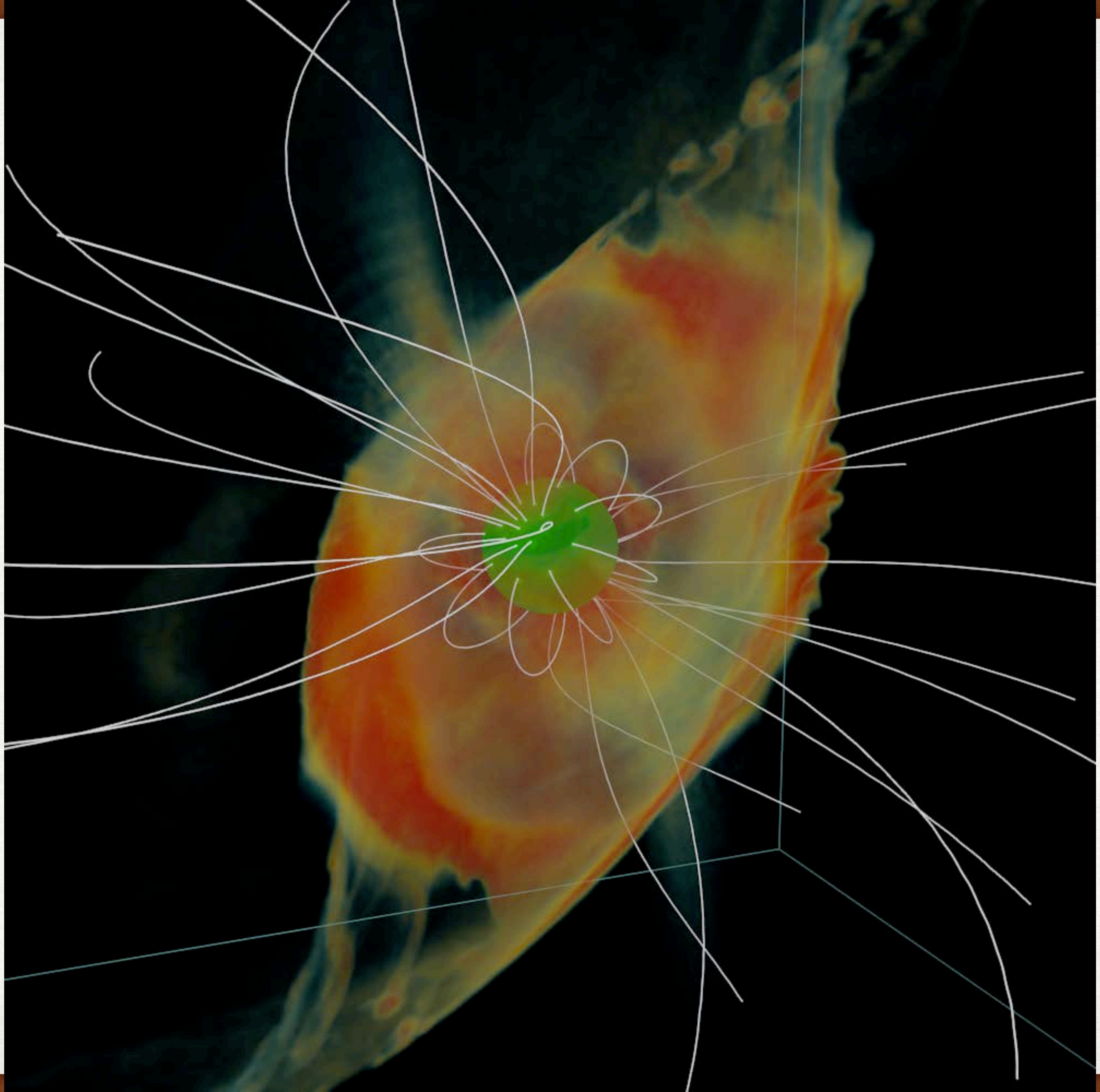


Philippov & AS., 2018

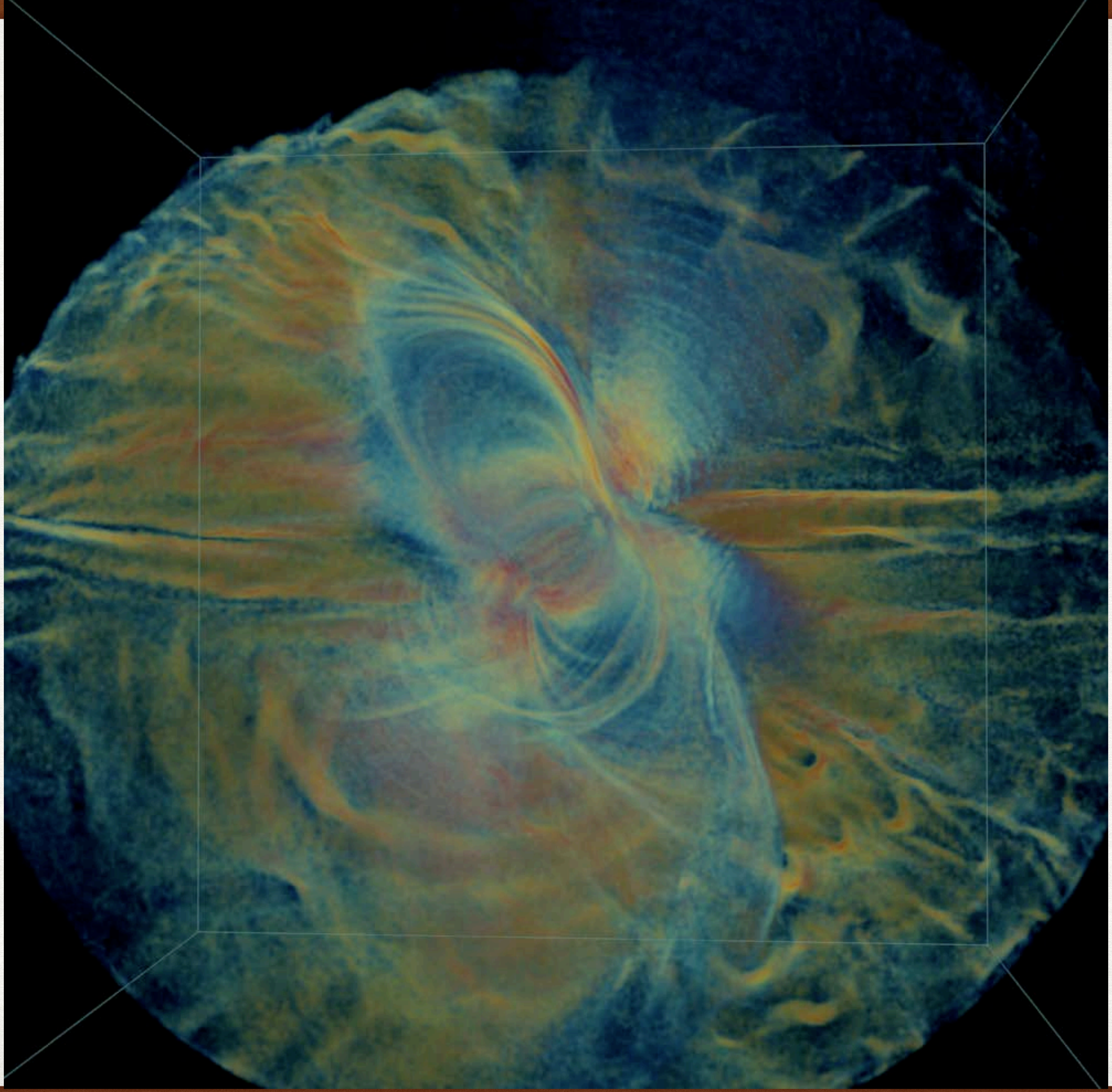
OBLIQUE ROTATOR: PLASMA DENSITY



OBLIQUE ROTATOR: PLASMA DENSITY



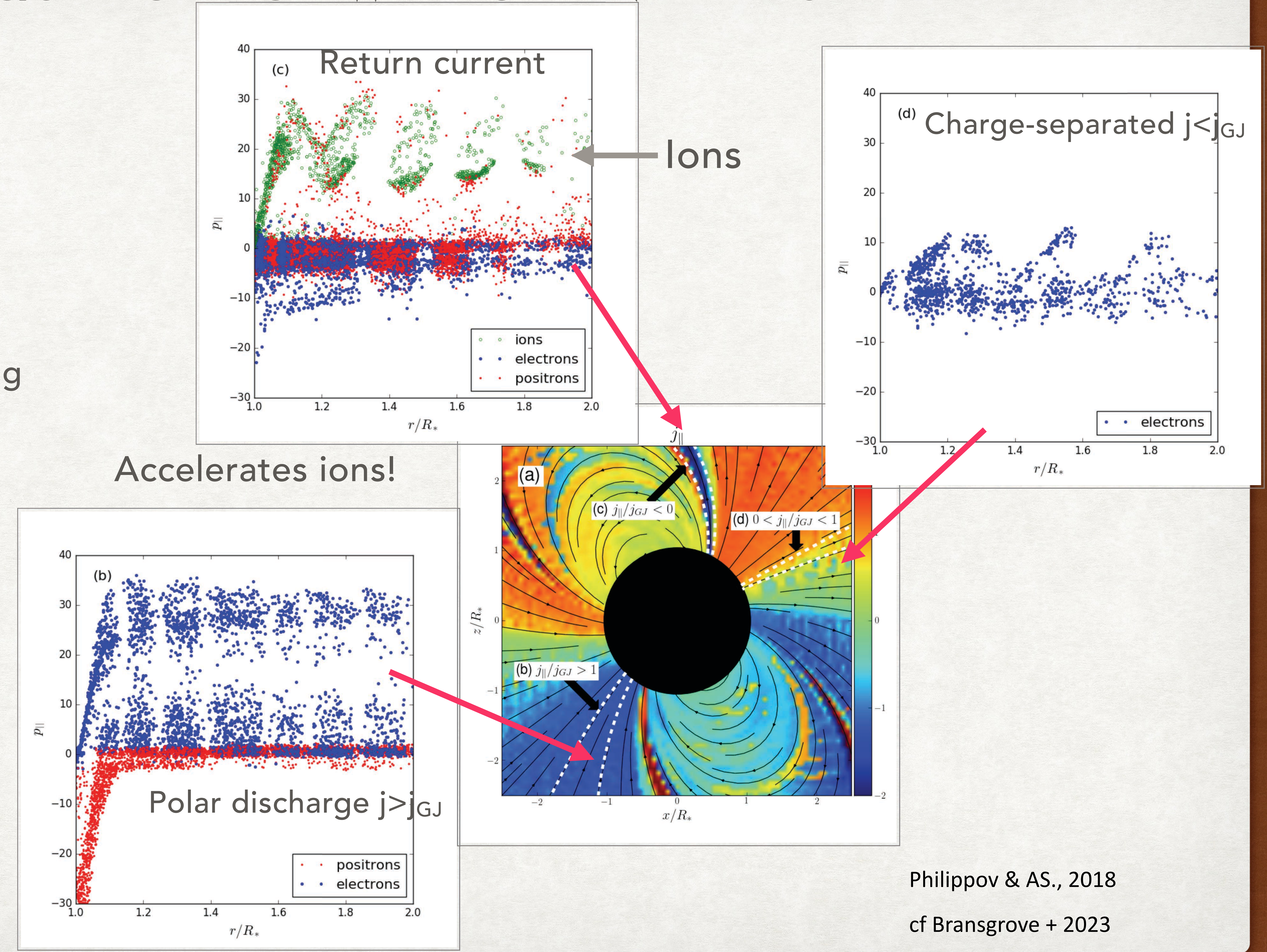
OBLIQUE ROTATOR: CURRENT DENSITY



OBLIQUE ROTATOR WITH GR AND PAIRS

- Counterstreaming is present in polar discharge and in return current region
- Opportunities for maser emission from collective instabilities of counterstreaming distributions
- Also, time-dependent cascade

Momentum space

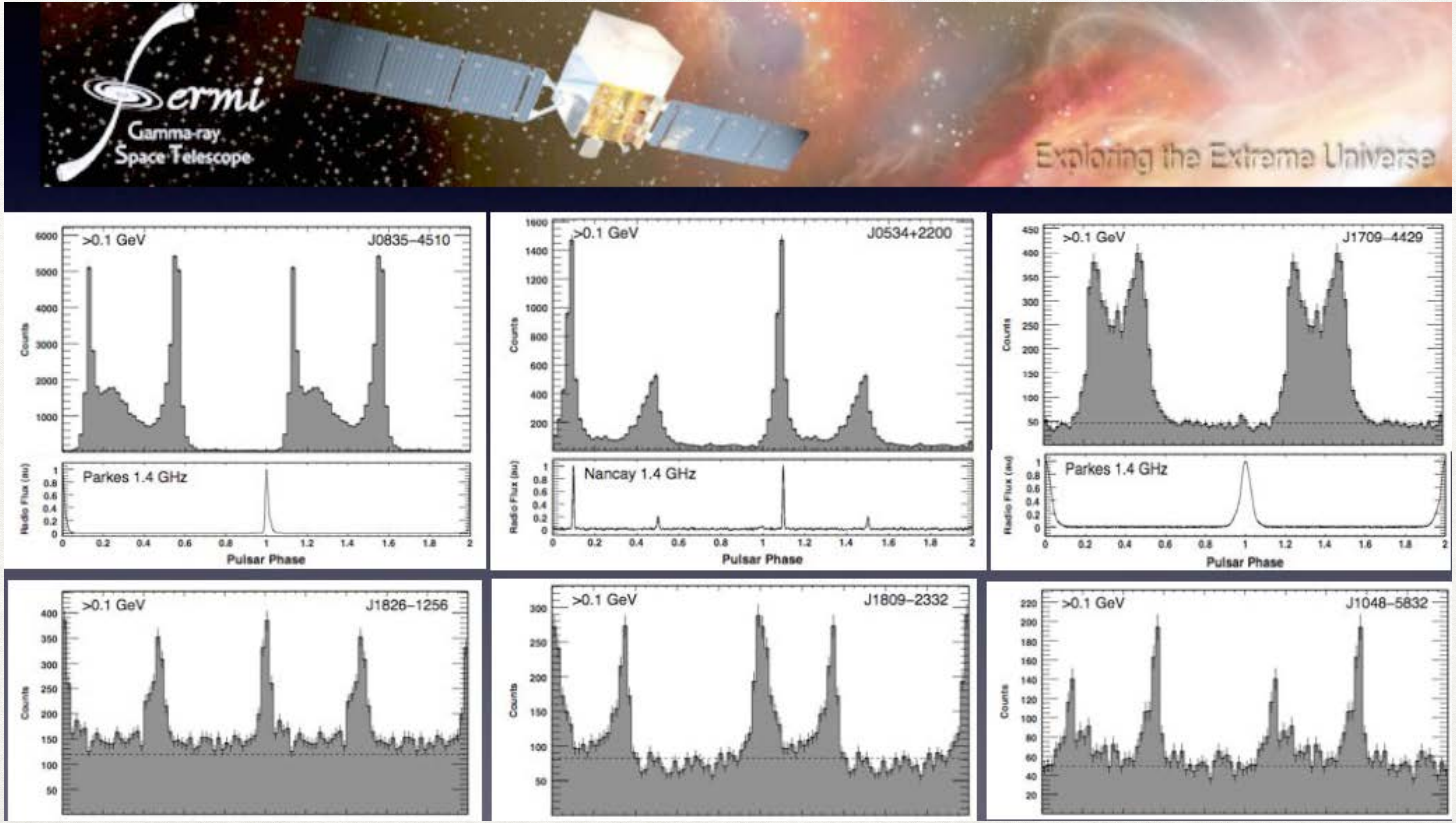


Philippov & AS., 2018

cf Bransgrove + 2023

IMPLICATIONS FOR HIGH-ENERGY EMISSION

We find that current sheet beyond the light cylinder is the source of Fermi ɣ-rays

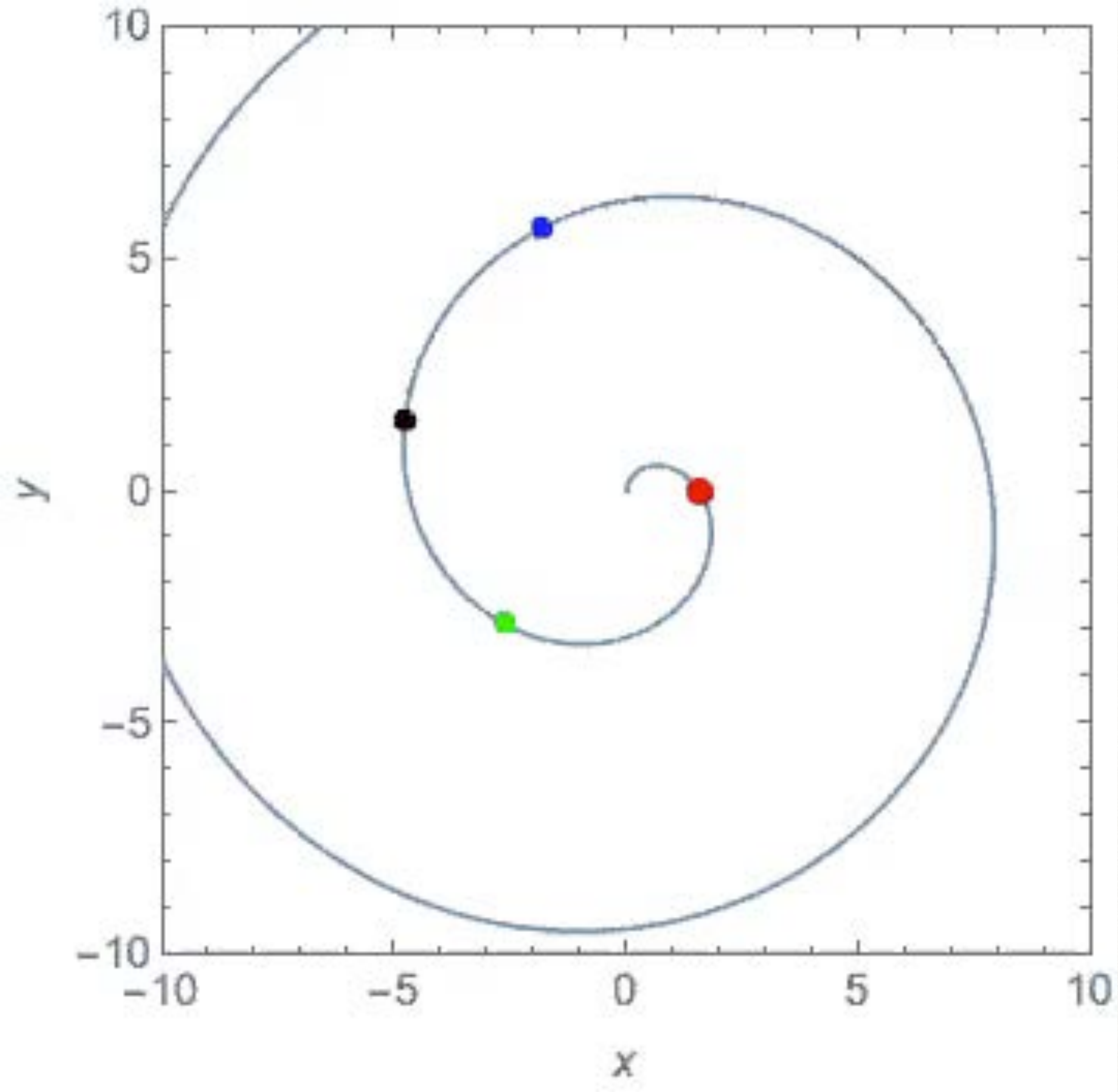


Abdo et al 2010

IMPLICATIONS FOR HIGH-ENERGY EMISSION

We find that current sheet beyond the light cylinder is the source of Fermi ɣ-rays

- Geometry: emission along an Archimedean spiral field arrives in phase — caustic effect (Romani 96, Petri & Kirk 03)
- Emission is beamed along the field lines.
- Field lines that produce double-peaked caustics "hug" the current sheet at and beyond the LC.



Bai & AS, 2010

IMPLICATIONS FOR HIGH-ENERGY EMISSION

We find that current sheet beyond the light cylinder is the source of Fermi ɣ-rays

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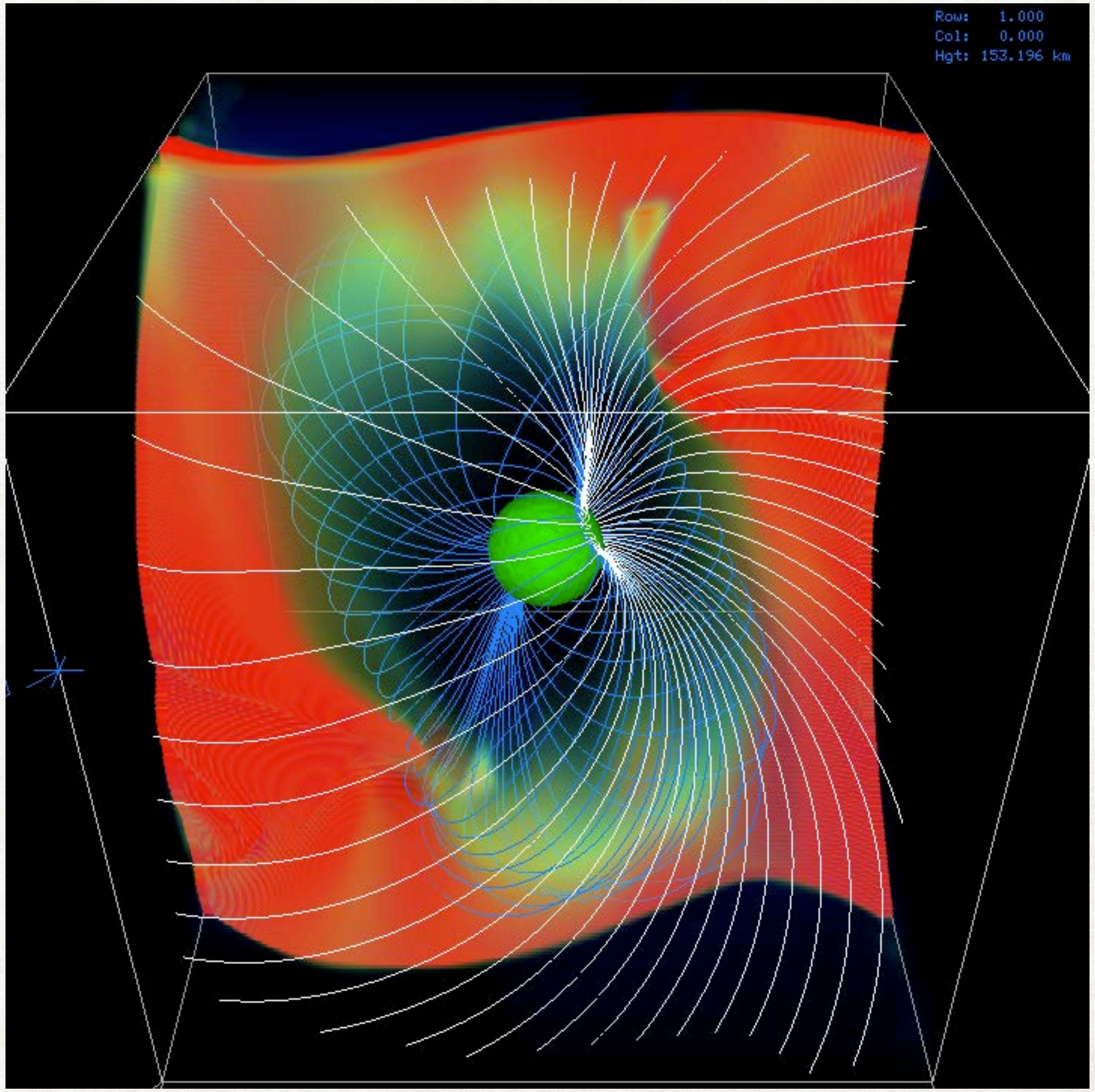
- Emission is beamed along the field lines.
- Field lines that produce double-peaked caustics “hug” the current sheet at and beyond the LC.



Bai & AS, 2010

IMPLICATIONS FOR HIGH-ENERGY EMISSION

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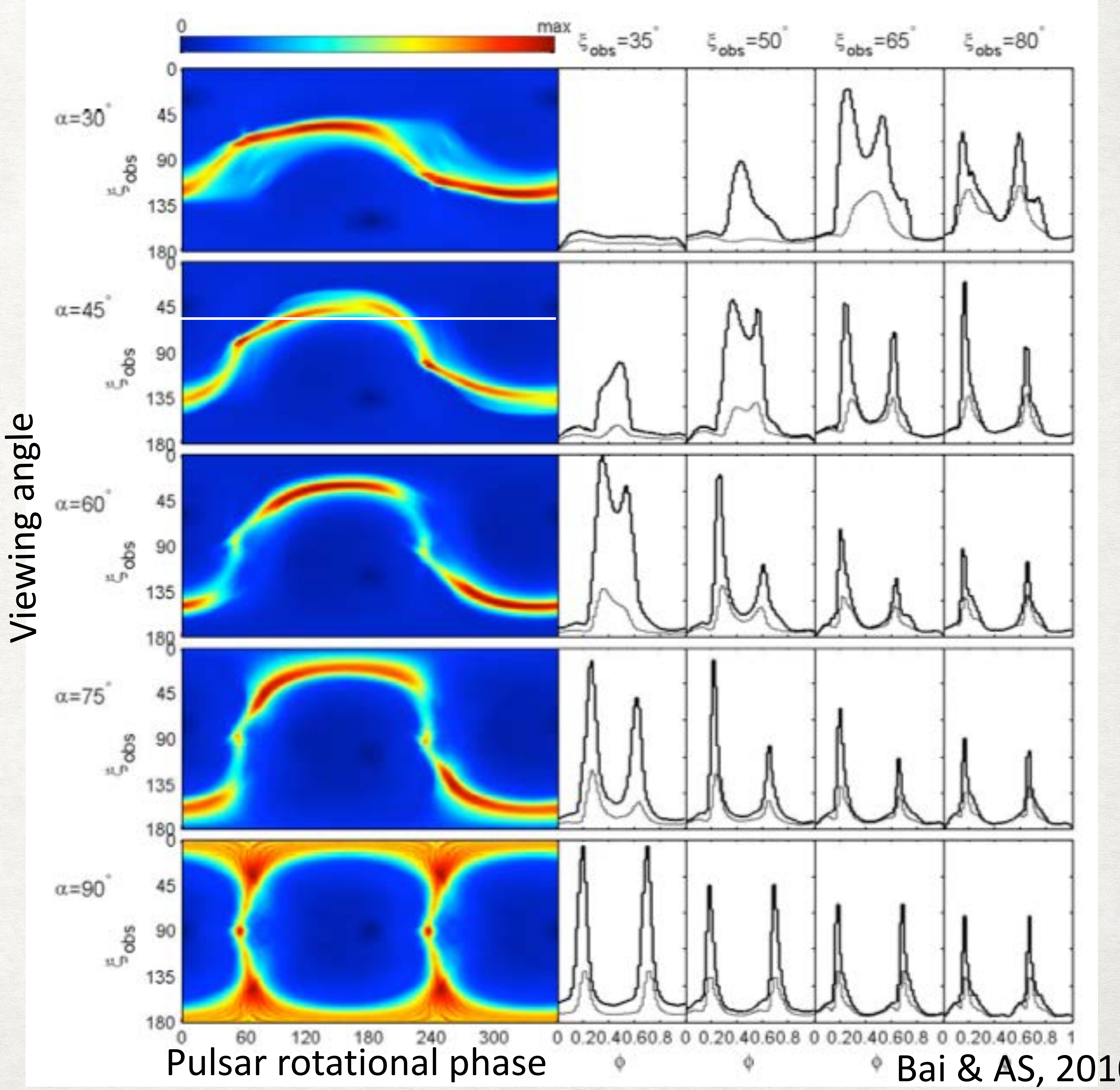
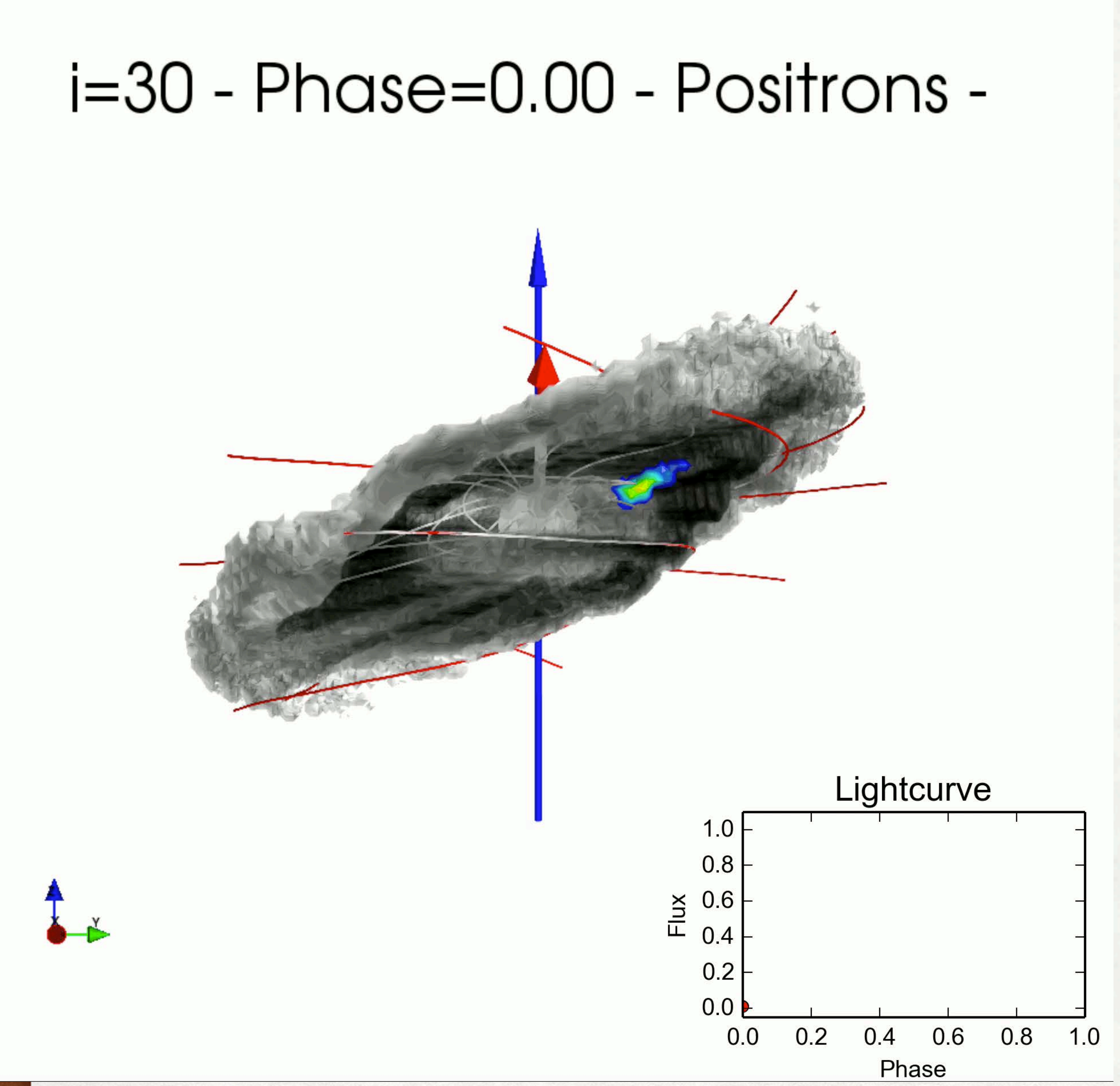


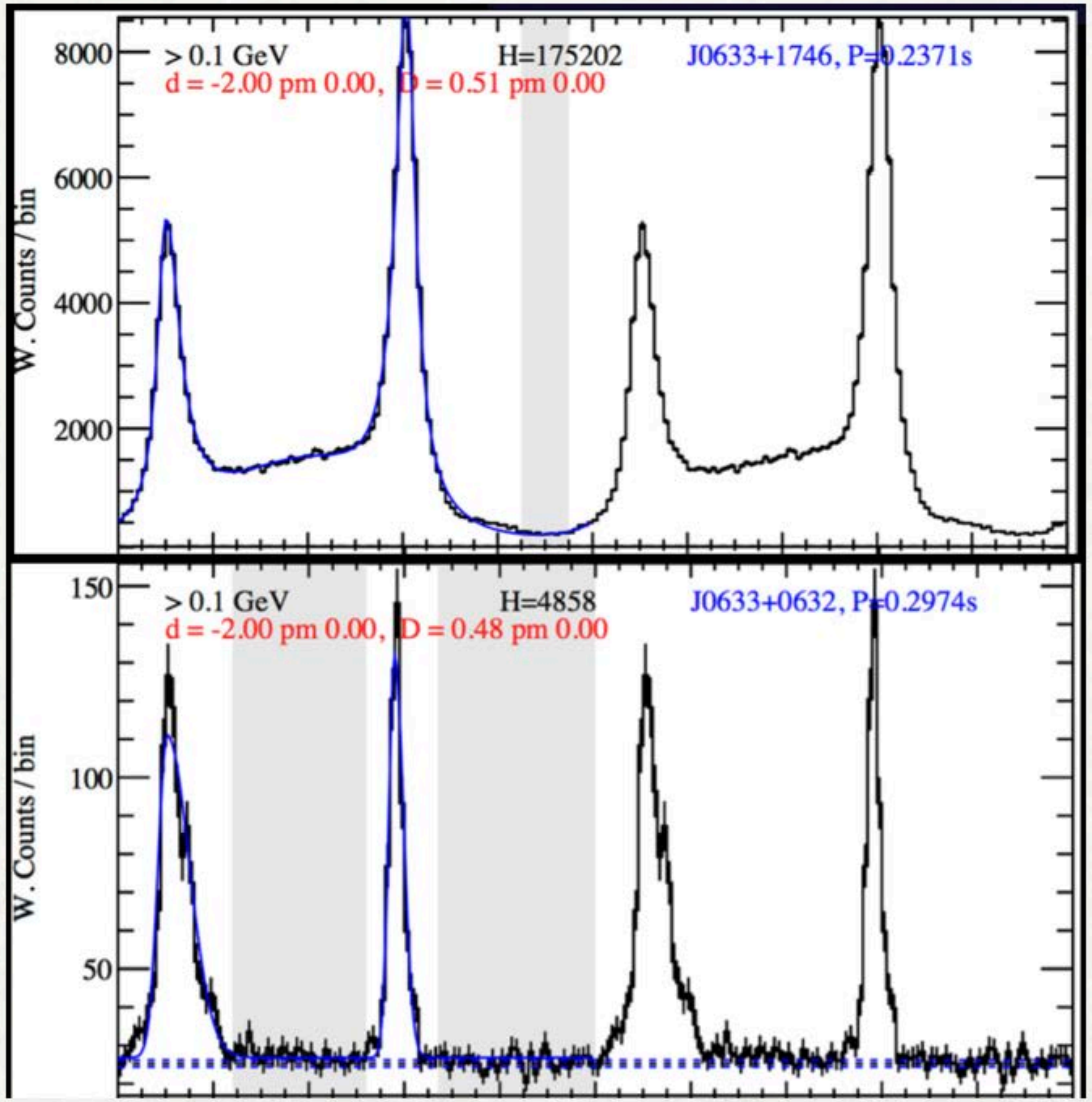
Bai & AS, 2010

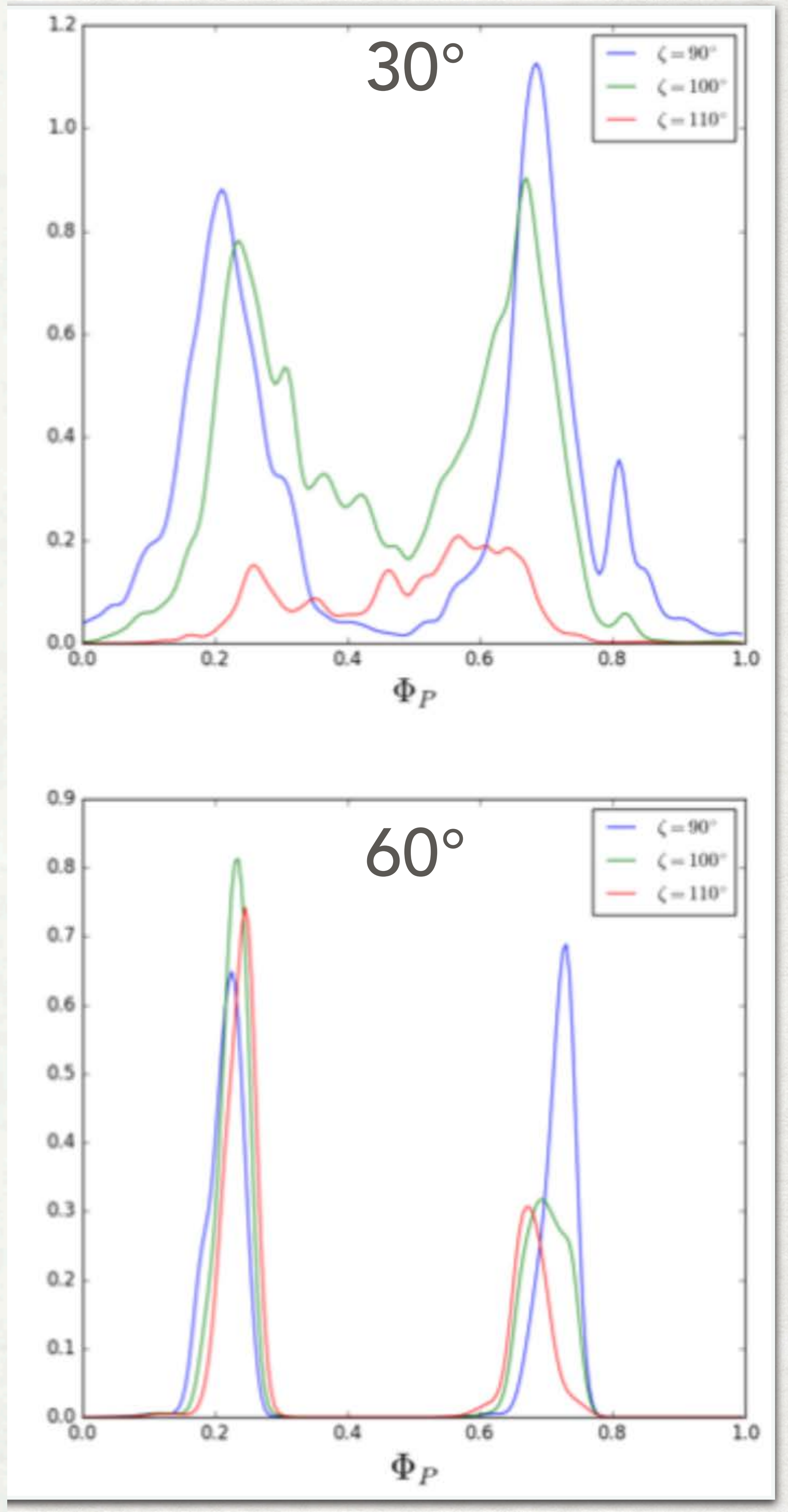
GAMMA-RAY LIGHTCURVES

Self-consistent radiation from PIC simulations



Caustic formation from spiral shape of current sheet





Light Curve

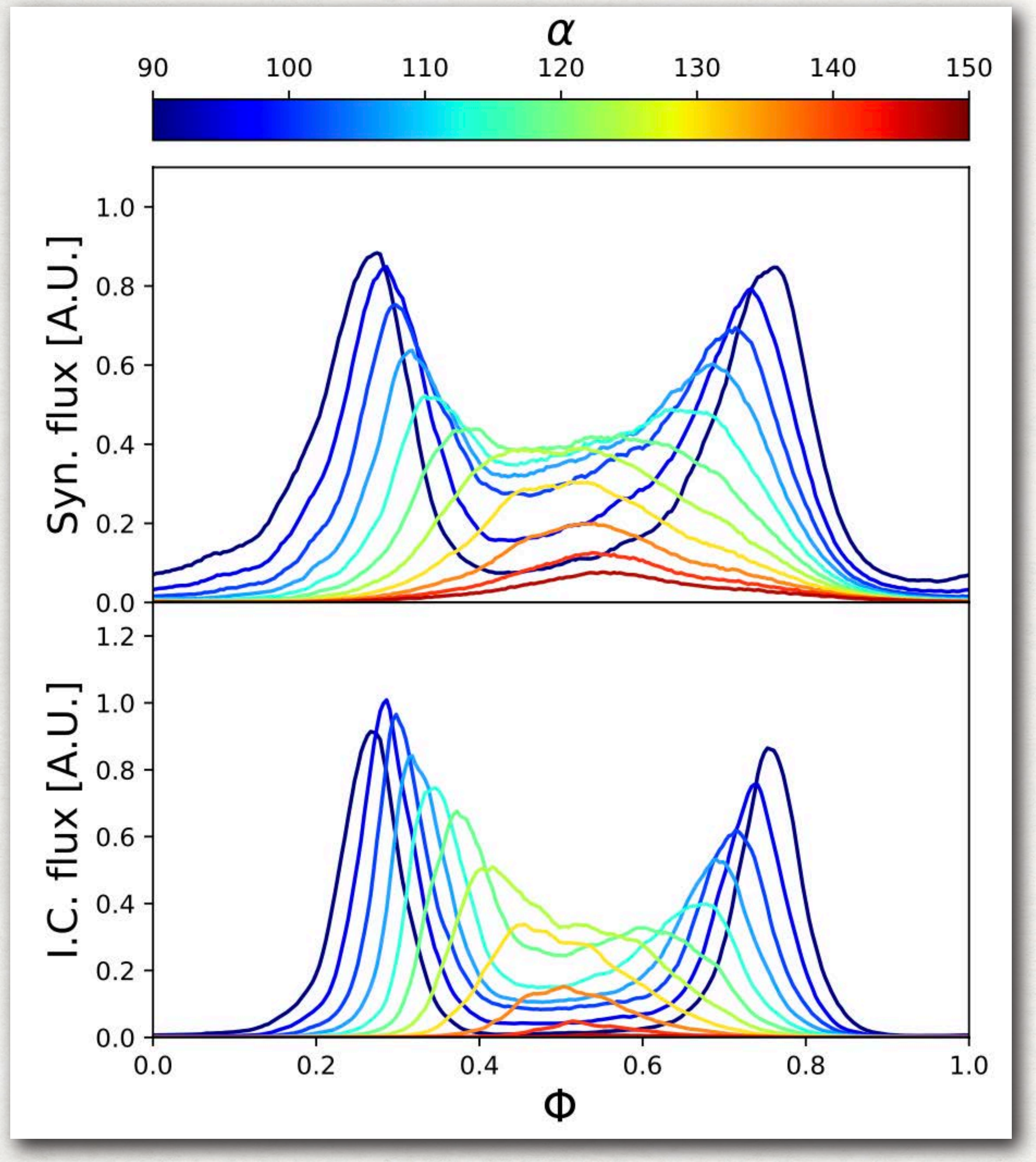
Philippov & AS., 2018

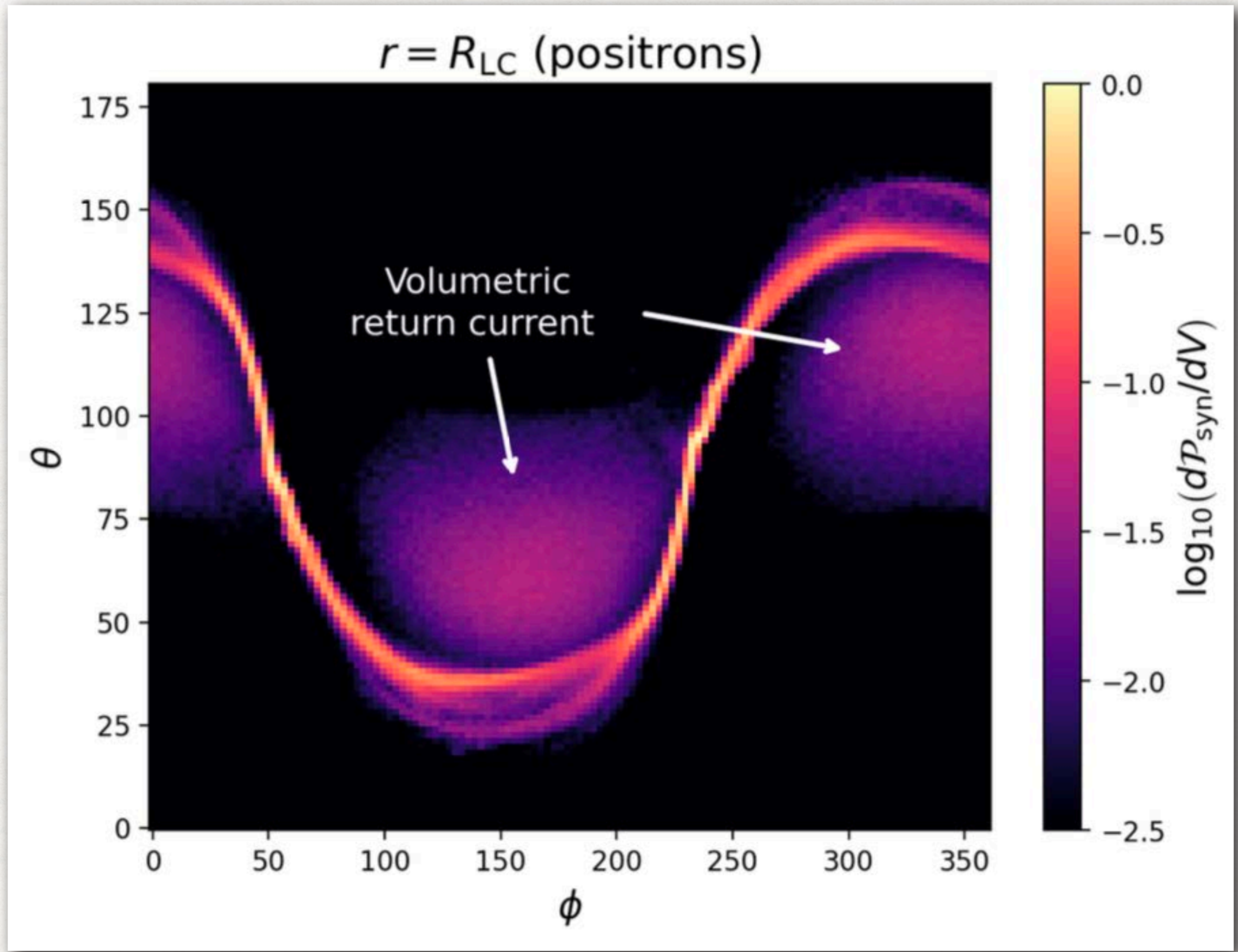
Double-peaked light curves are generic

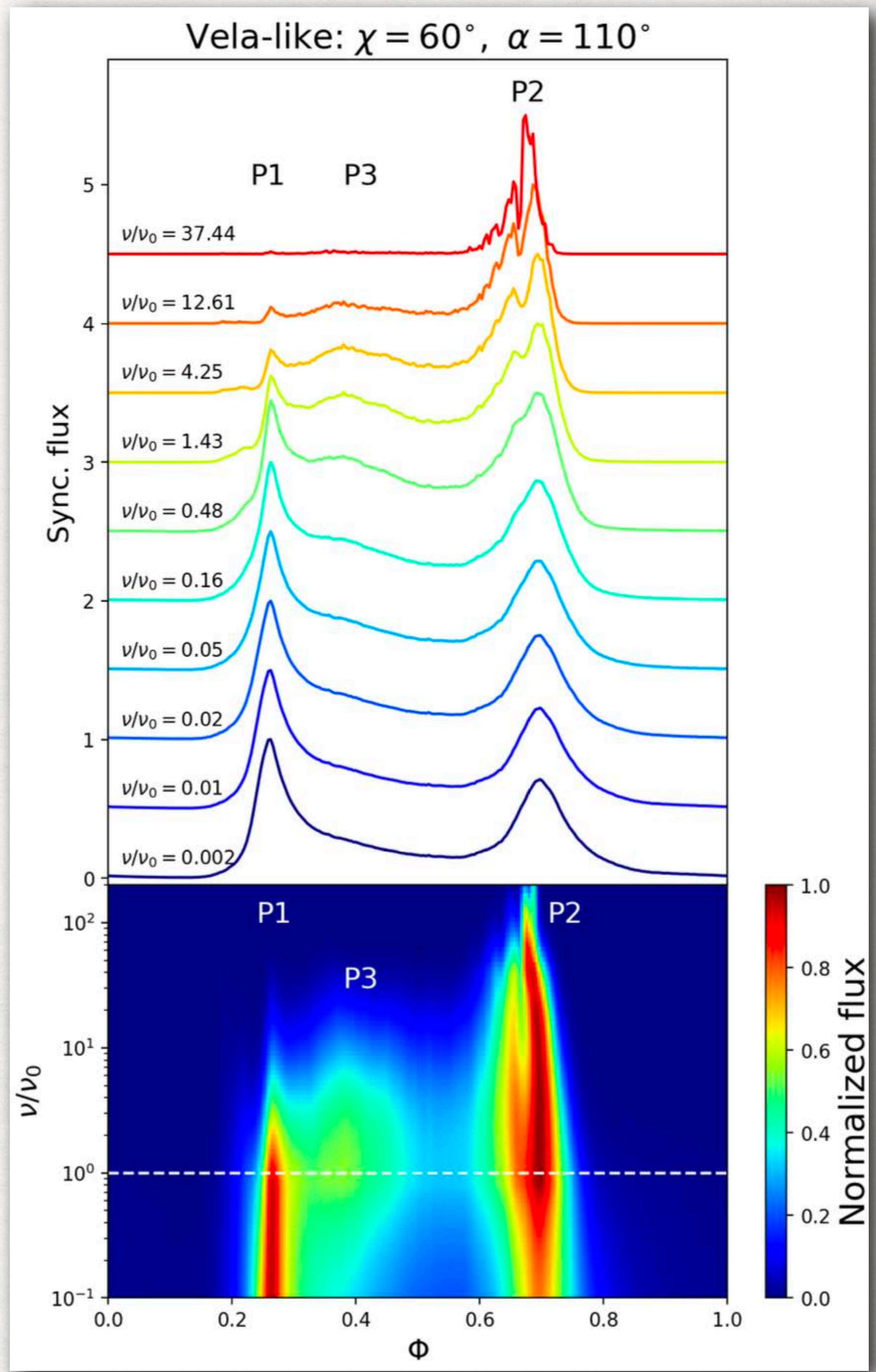
Bridge emission appears for lower obliquity rotators

GAMMA-RAY LIGHTCURVES

Self-consistent radiation from PIC simulations Cerutti+ 2024







Synchrotron and IC flux

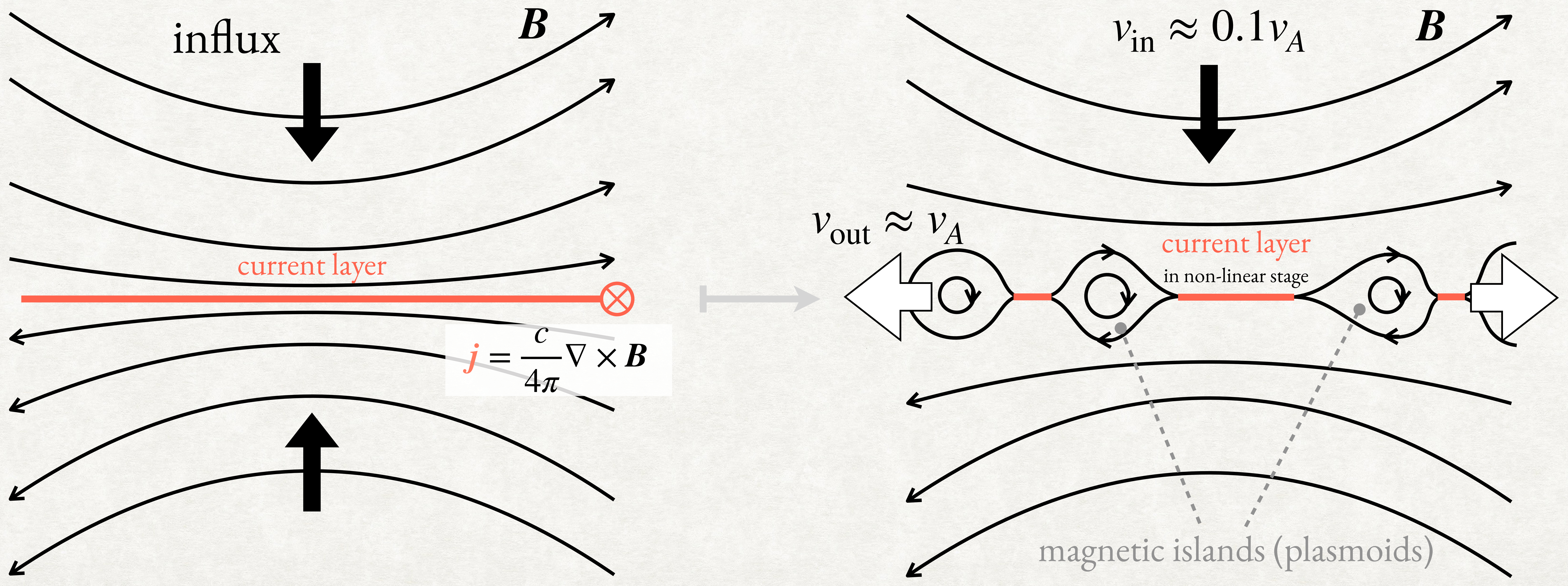
Energy dependent light curve

Appearance of bridge emission from volumetric return current

Cerutti+ 2025

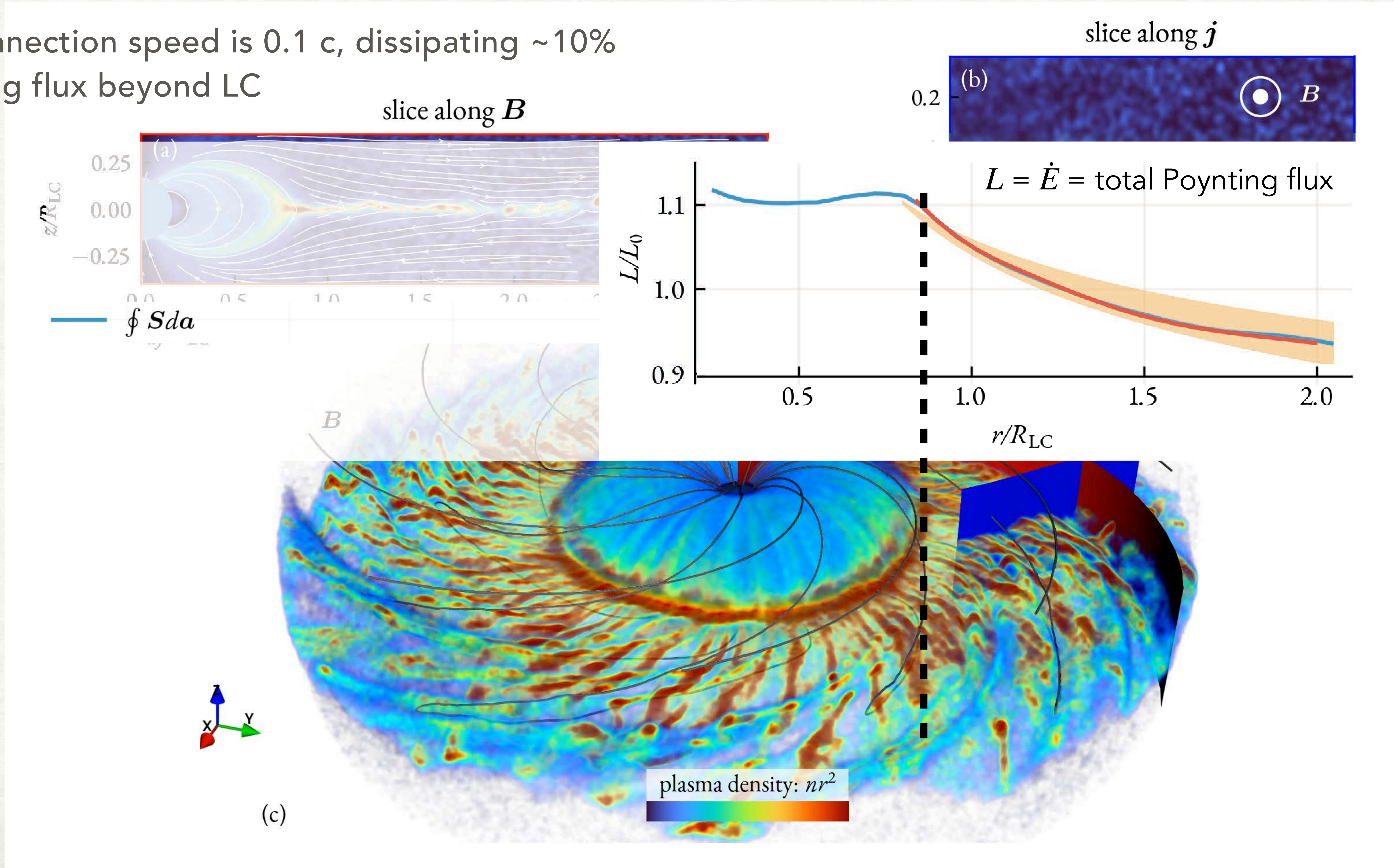
DISSIPATION AND ACCELERATION IN CURRENT SHEET

Collisionless magnetic reconnection in the current sheet accelerates particles

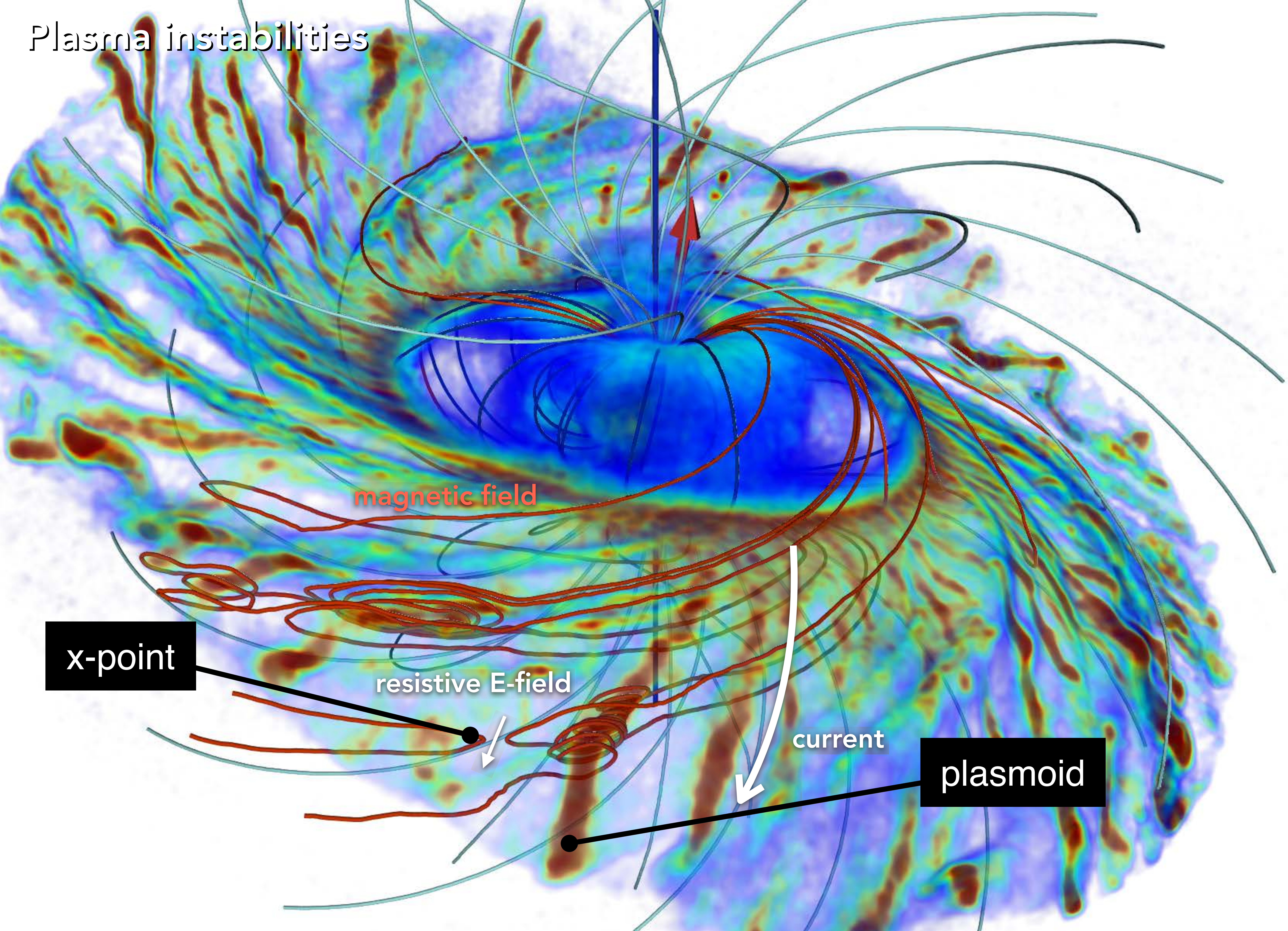


CURRENT SHEET RECONNECTION

Fast reconnection speed is 0.1 c, dissipating ~10% of Poynting flux beyond LC

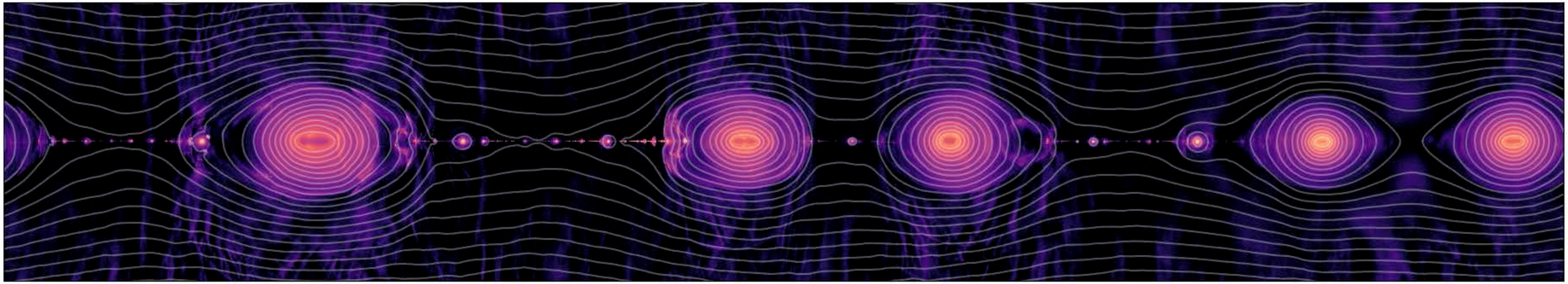


Plasma instabilities



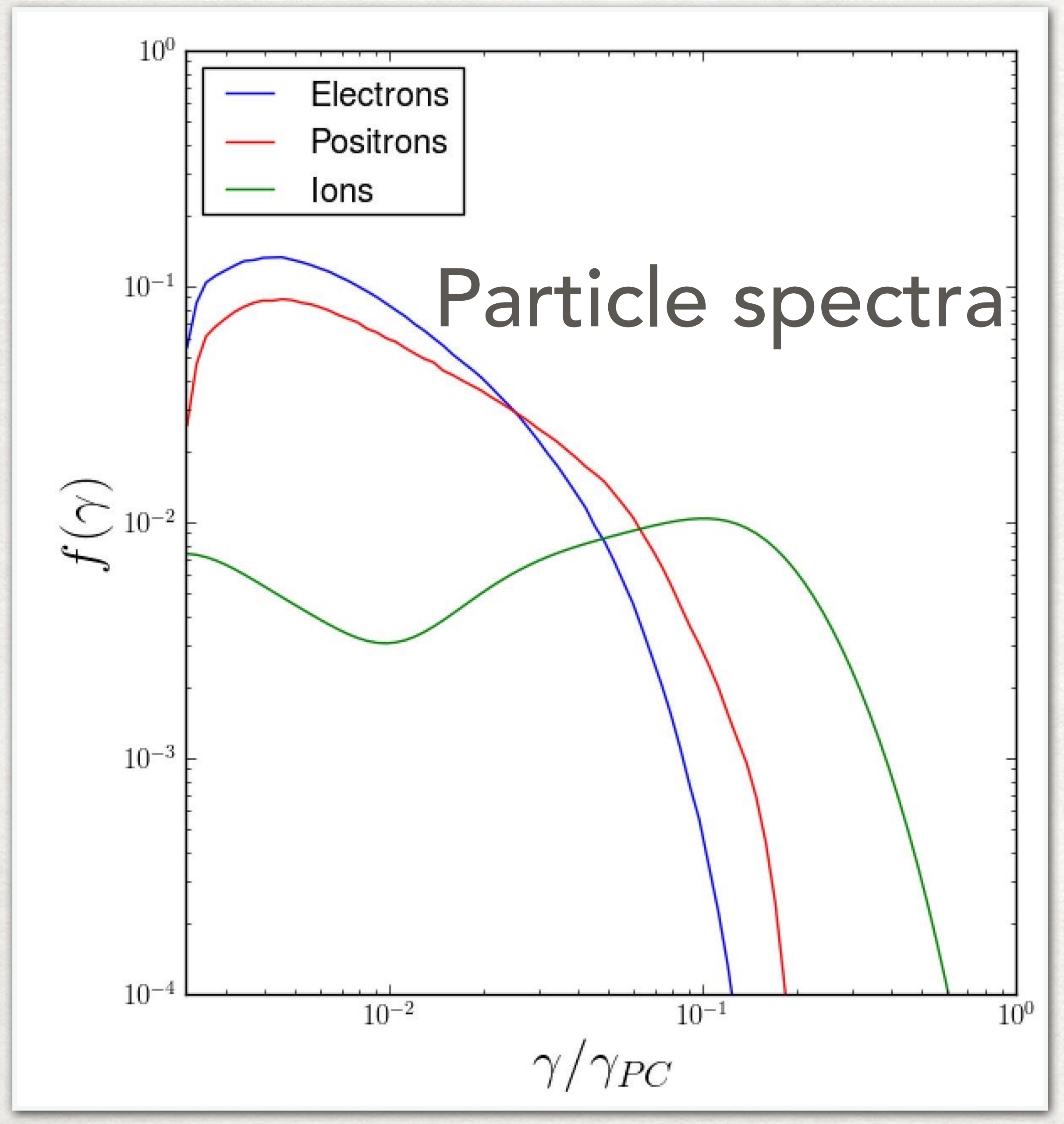
Hakobyan+ 23

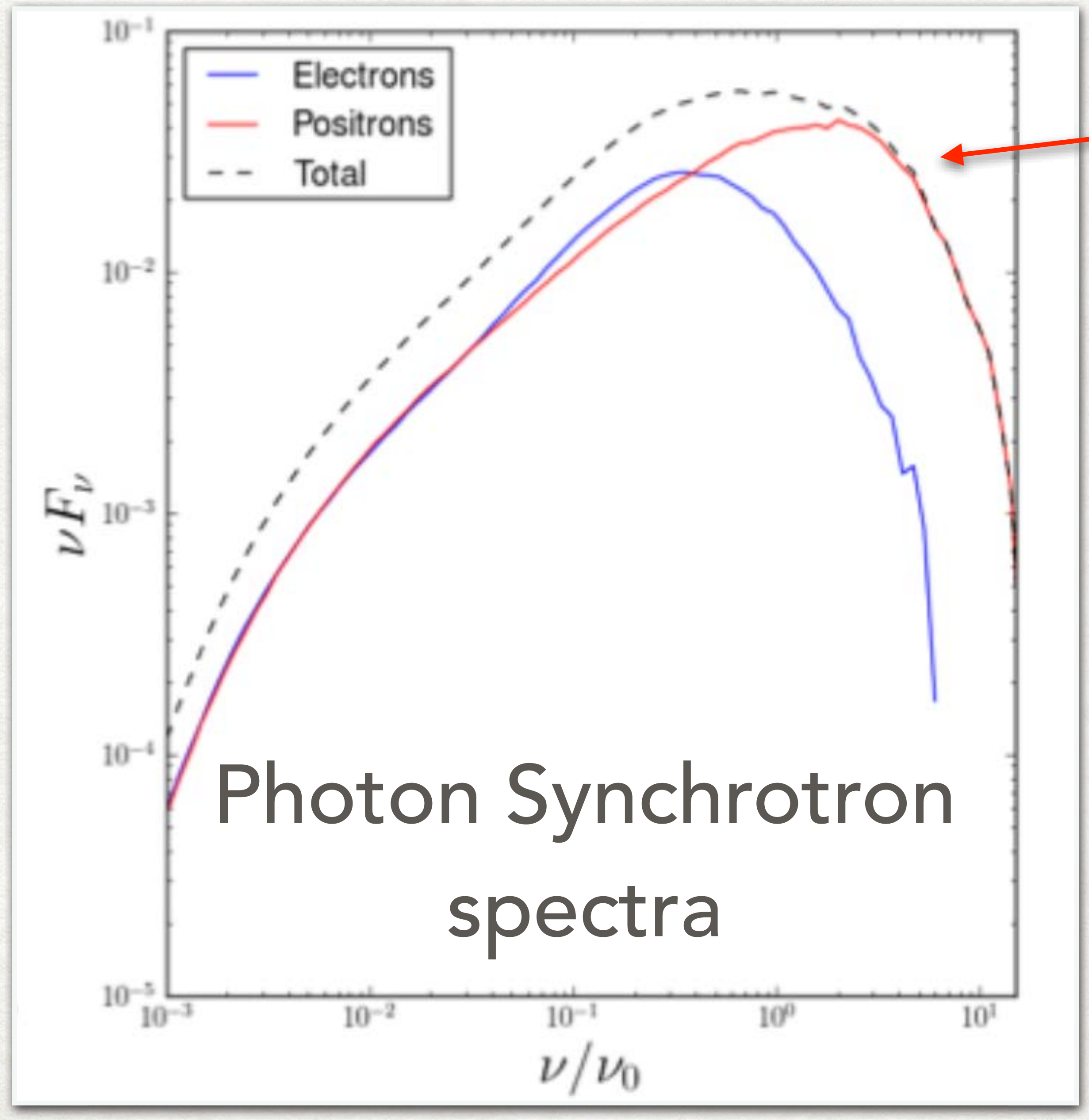
PARTICLE ACCELERATION AND SPECTRA

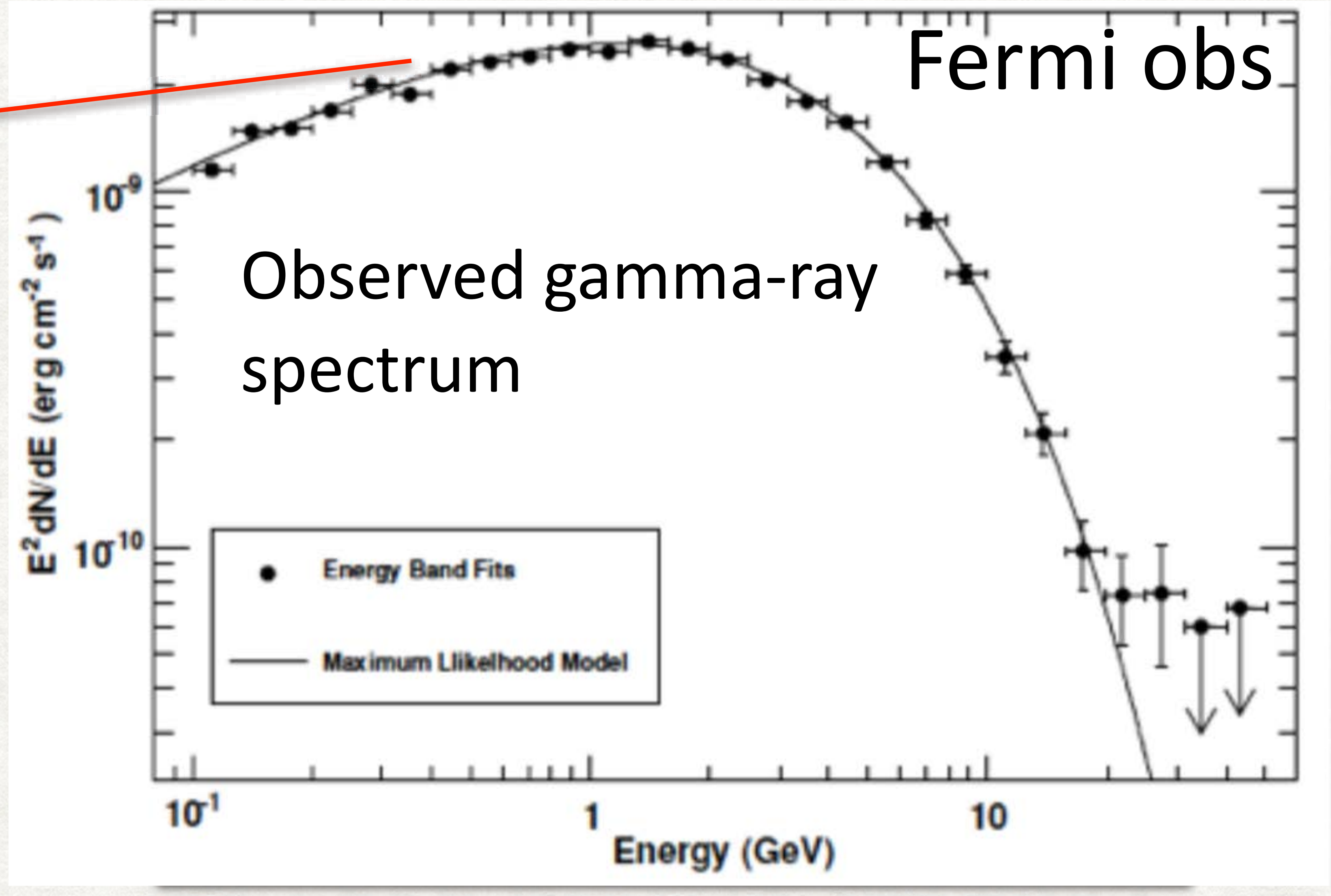


Magnetic reconnection results in particle acceleration

Hakobyan, Philippov, AS 2019

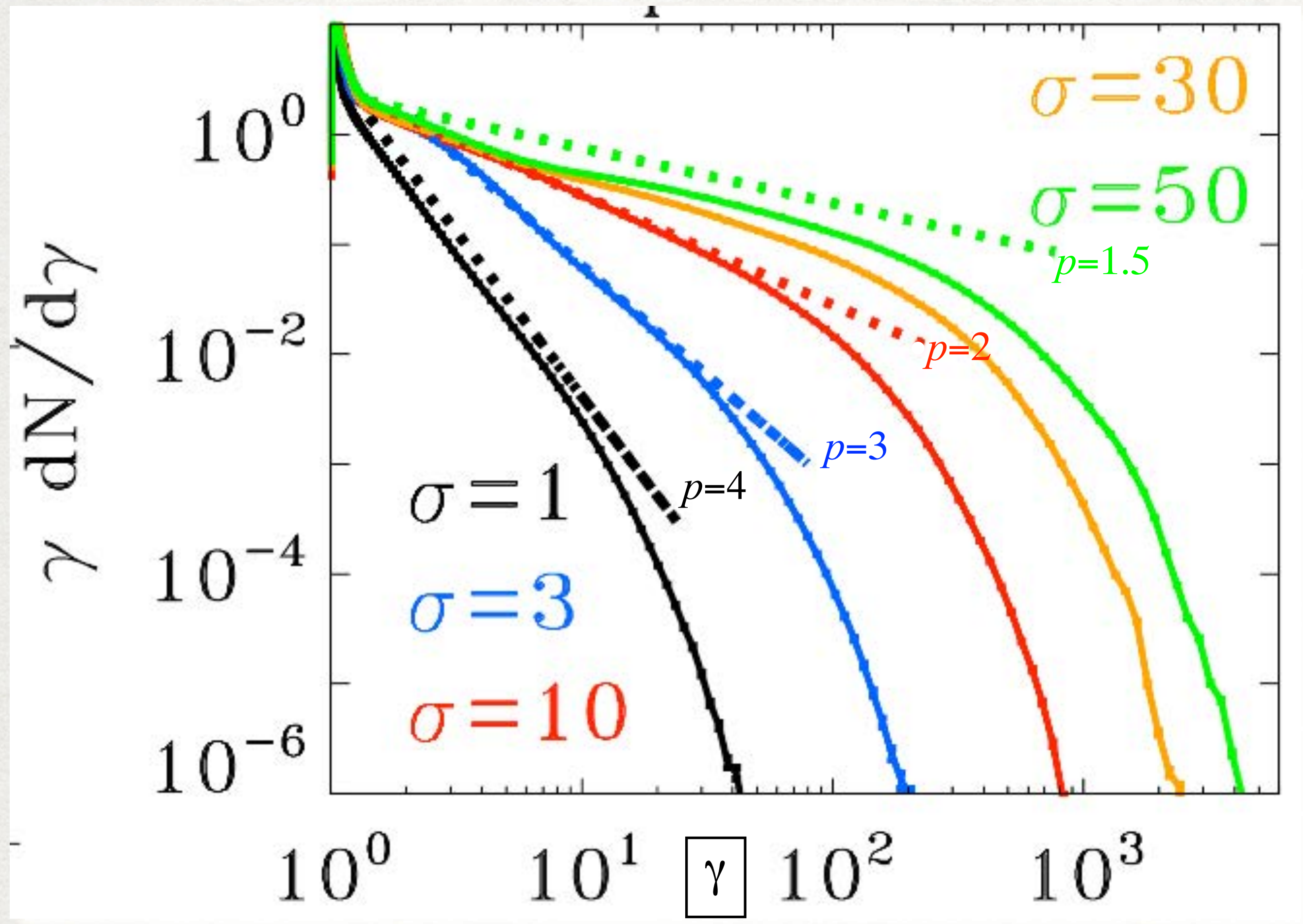






Pair production in the current sheet beyond light cylinder sets the peak emission frequency

PARTICLE ACCELERATION IN RECONNECTION

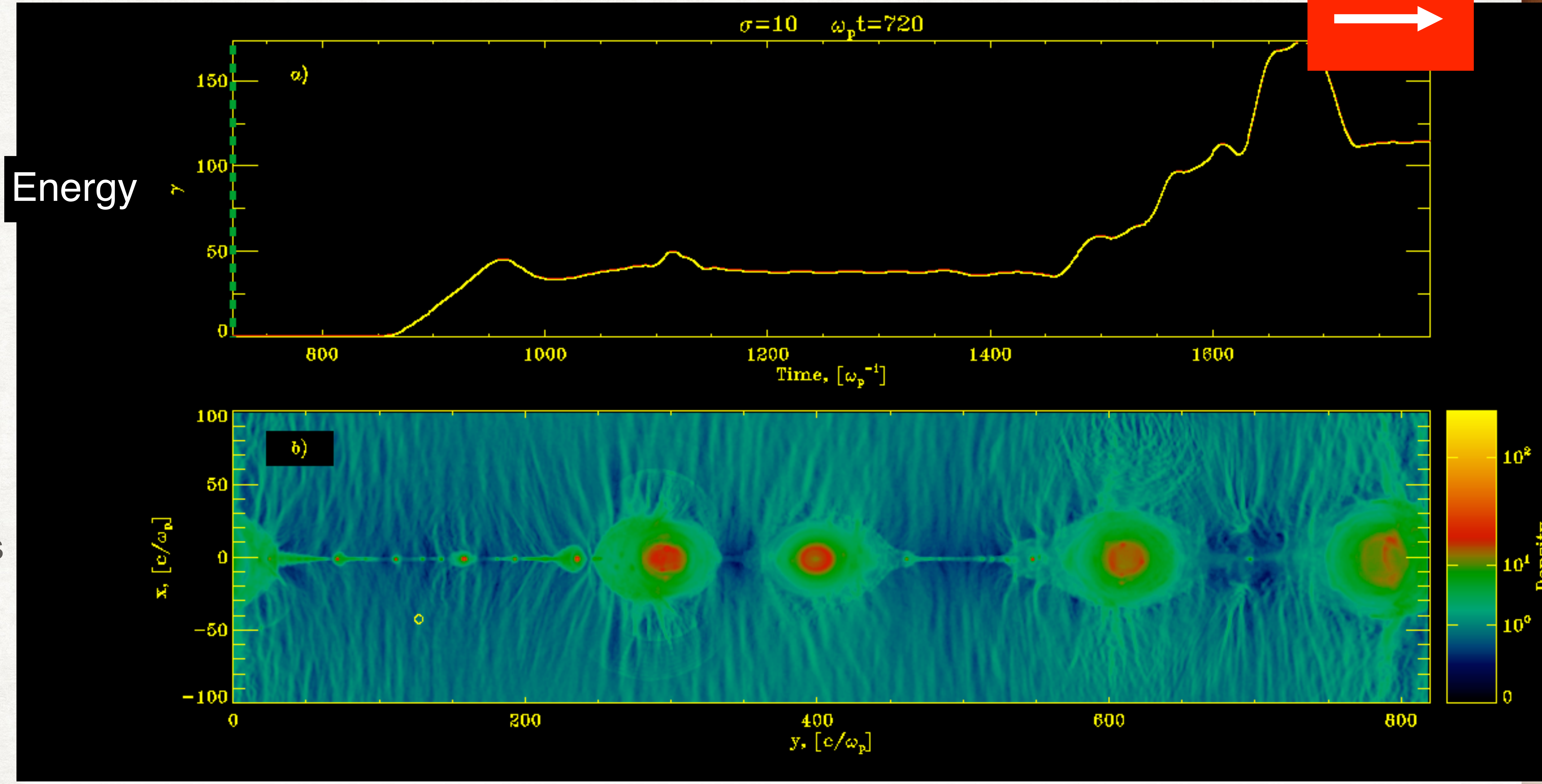


(Sironi & AS 14, Guo et al. 14,
Werner et al. 14)

Relativistic reconnection produces non-thermal tails of accelerated particles, whose power-law slope is harder than *p*=2 for high magnetizations (σ>10), but with max energy limited by a few σ

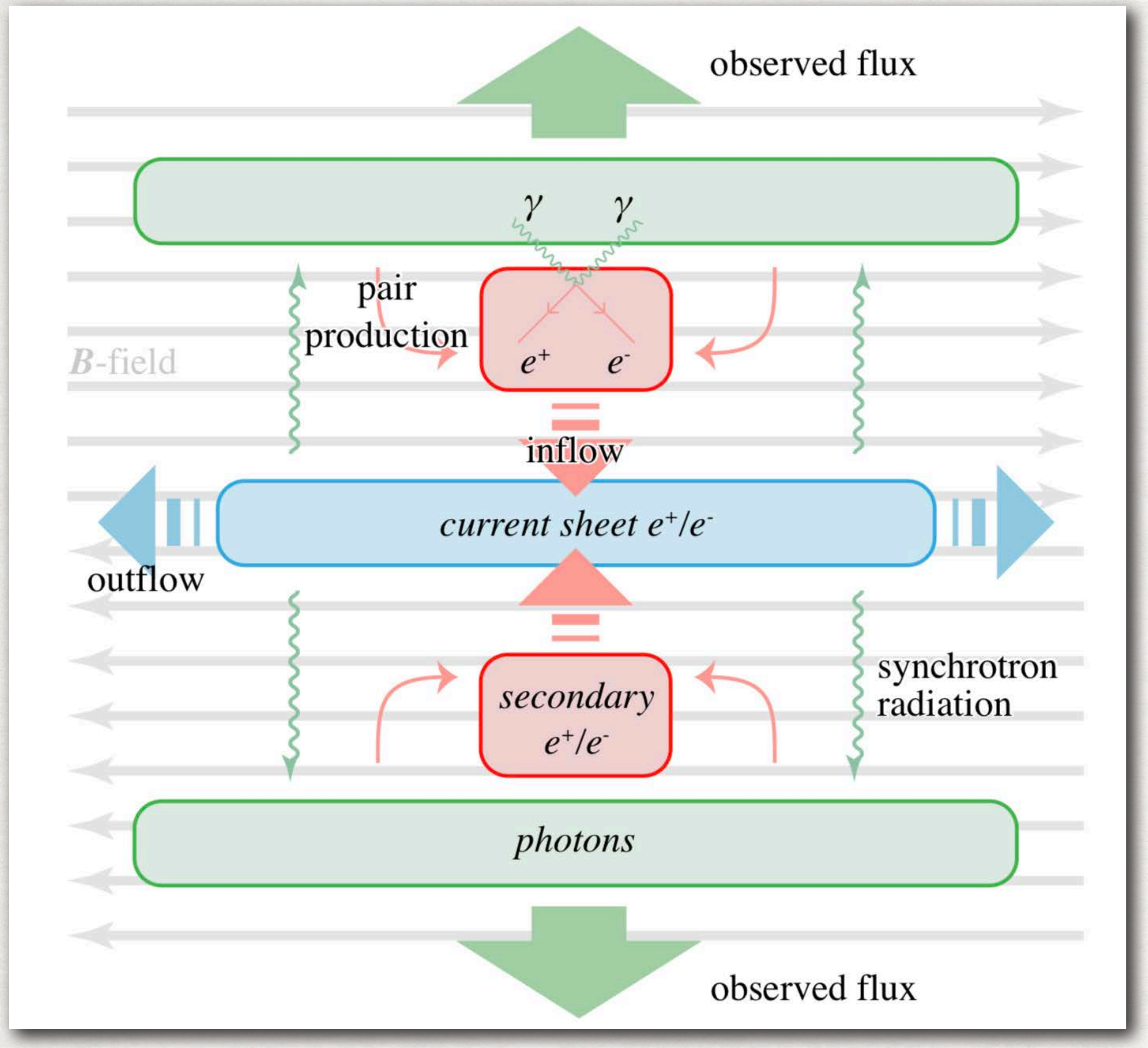
Magnetization:

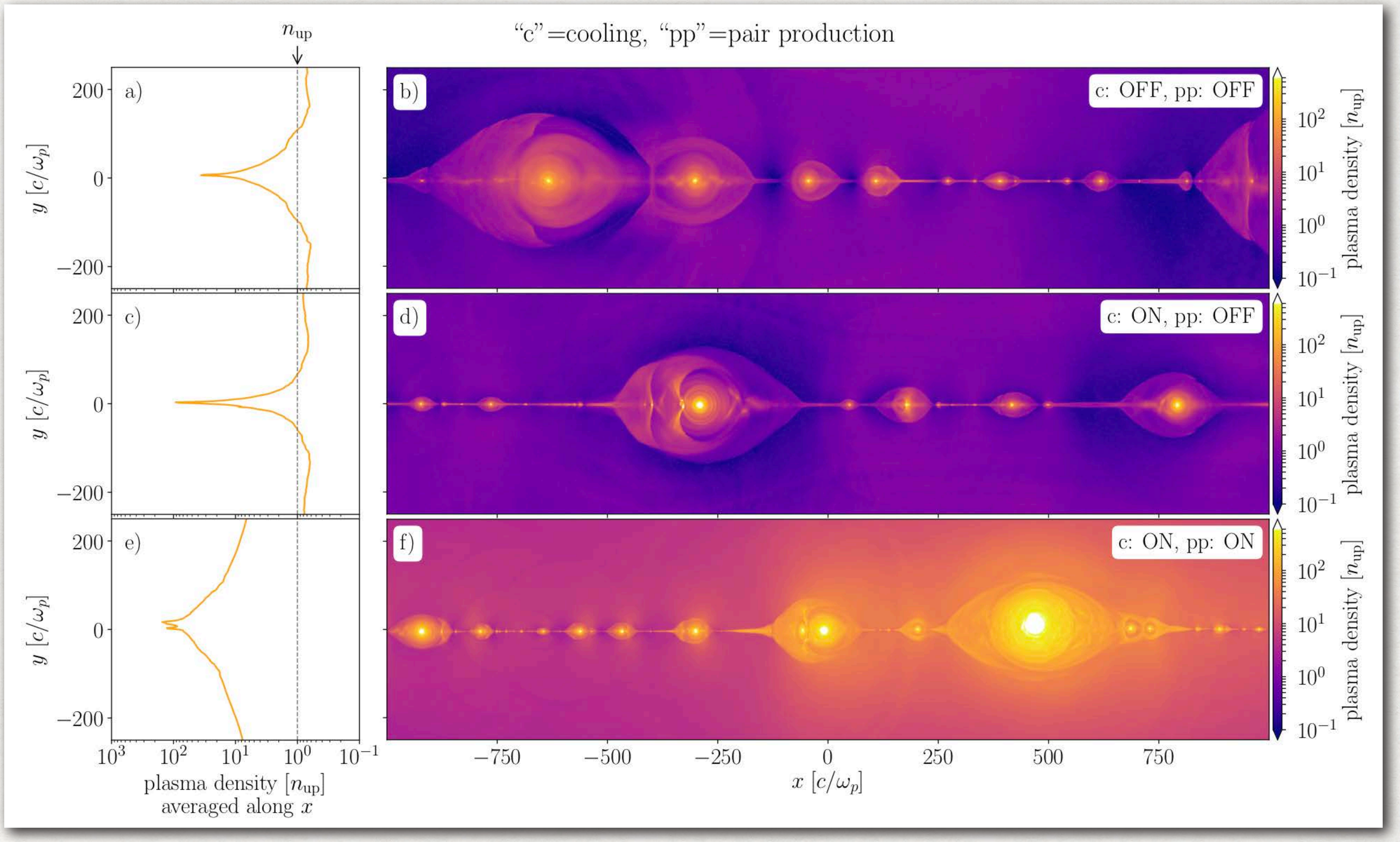
$$\sigma = \frac{B^2}{4\pi n m c^2}$$



Two acceleration phases: 1) at the X-point; 2) in between merging islands

THE ROLE OF RECONNECTION WITH PAIR PRODUCTION IN SETTING CUTOFF ENERGY





Reconnection in the current sheet is the main particle accelerator. Gamma-gamma pair formation can start and increases the pair loading above the sheet, lowering effective magnetization in the sheet.

Particle acceleration follows magnetization, max particle energy is reduced. This results in weaker dependence of maximum gamma-ray energy on the magnetic field at the light cylinder than would be naively expected.

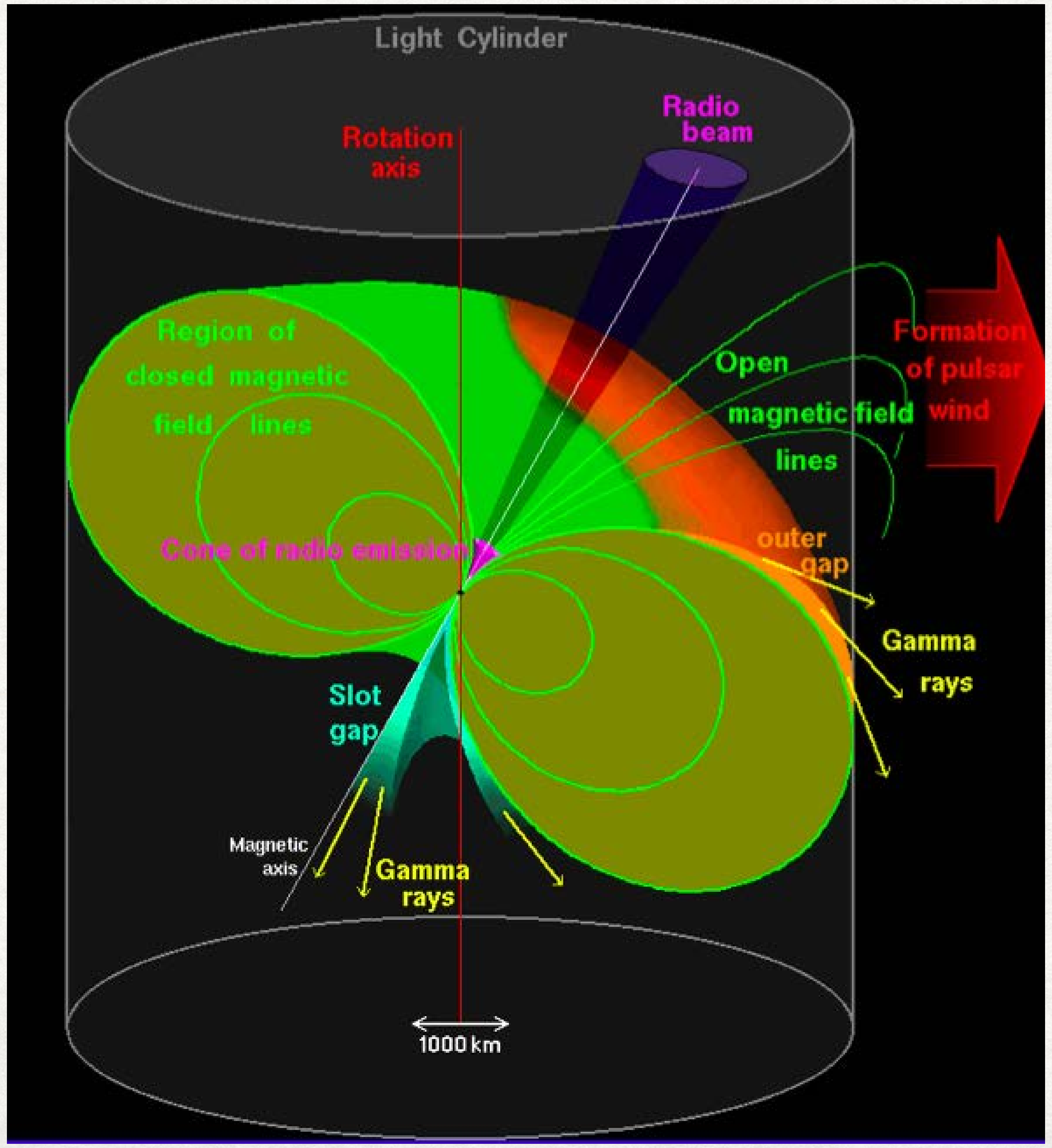
Hakobyan, Philippov, AS 19

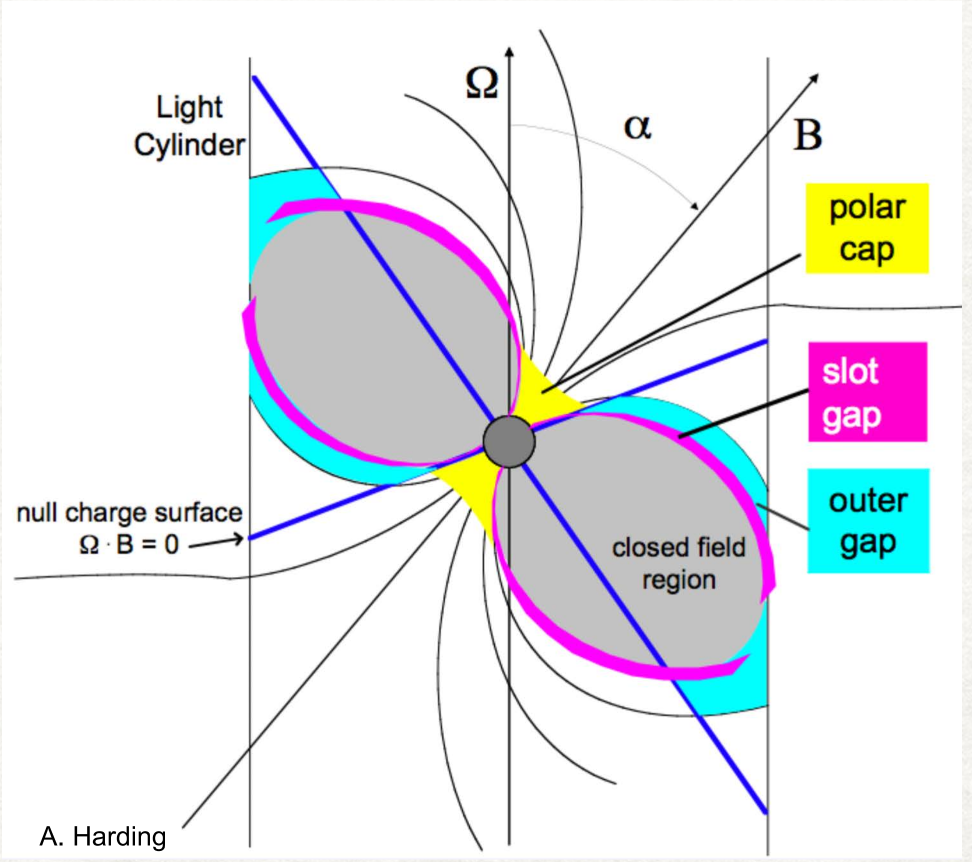
cf: Chen, Uzdensky, Dexter 23 ; Mehlhaff et al 21

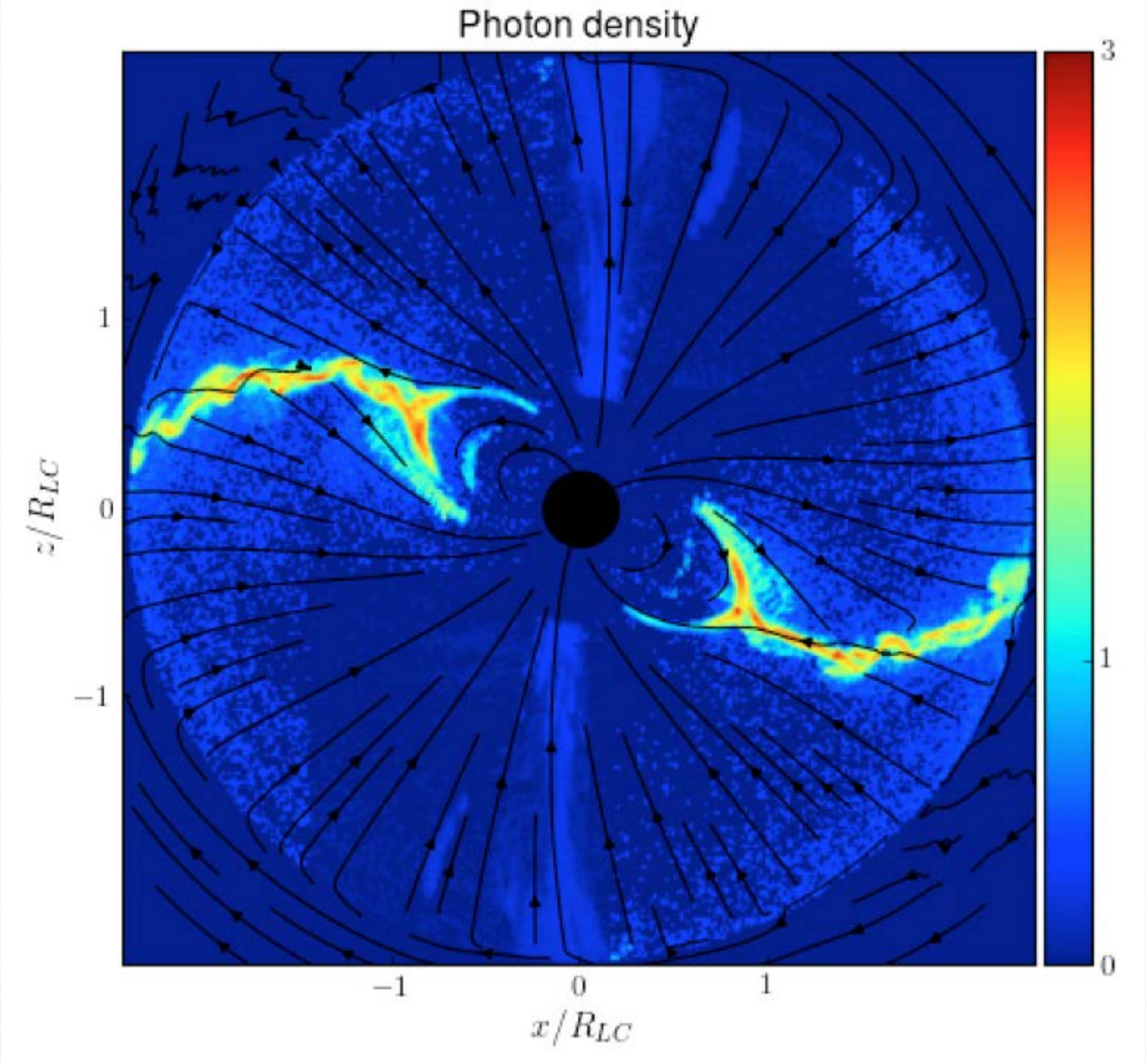
PARADIGM SHIFT ON HIGH-ENERGY EMISSION

High-energy emission is coming from beyond the light cylinder, not from inside. Mechanism: synchrotron radiation from current sheet-accelerated particles + IC for TeV.

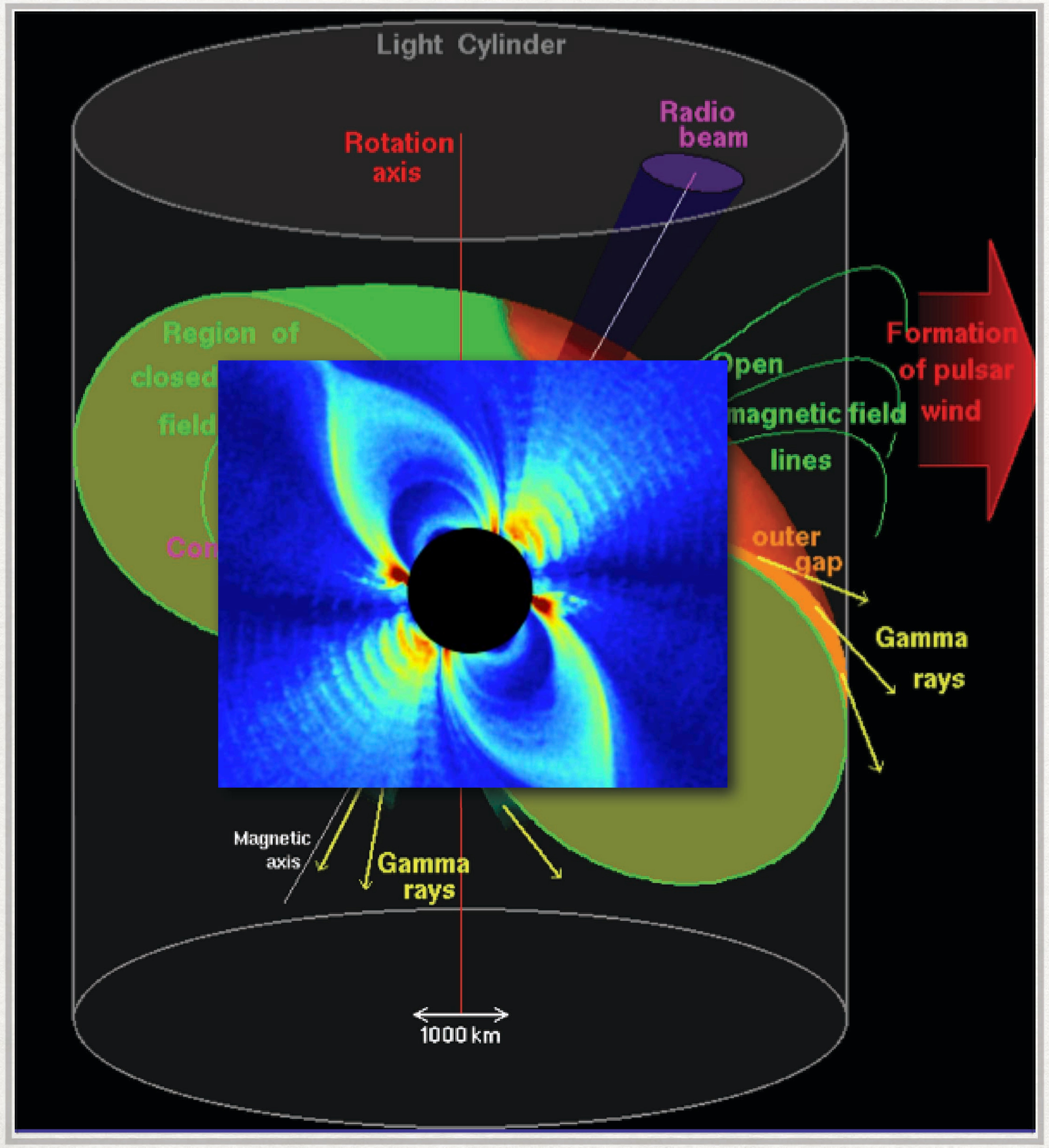
Reconnection is controlling dissipation and acceleration: <10% of spin down. Fraction radiated in gamma-rays depends on pair loading in the current sheet (Hakobyan+ 19, 23).

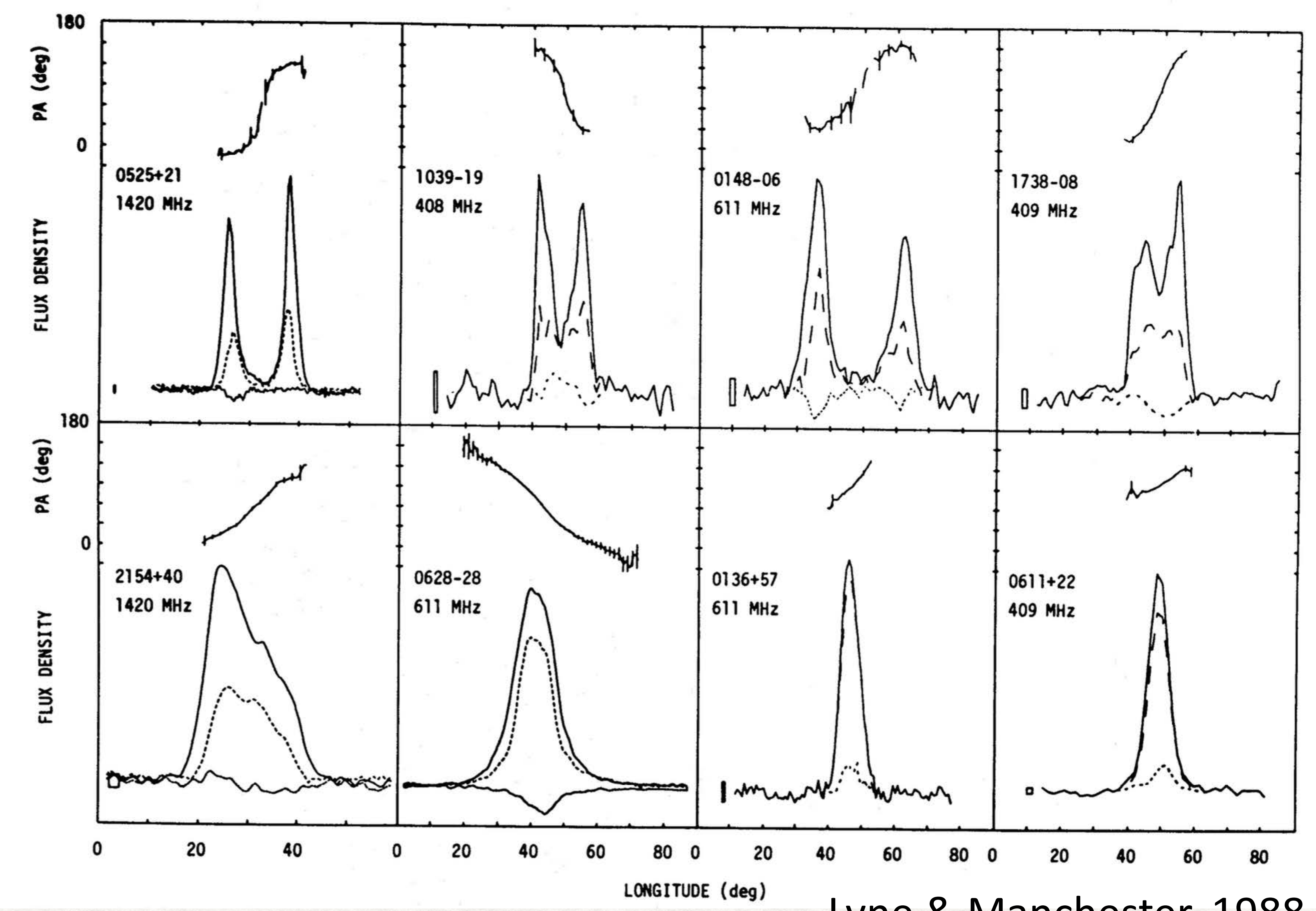






POLAR RADIO EMISSION





Lyne & Manchester, 1988

In most cases see one short pulse per period. Core/cone components. Spectrum: p-law 100Mhz - few GHz

Beam width is related to the polar cap size.

Very high brightness temperature $>10^{21}$K: coherent!

POLAR RADIO EMISSION: IDEAS AND HOPES

Coherent emission needs charges moving in phase

Ideas: Curvature radiation by “bunches” of charge

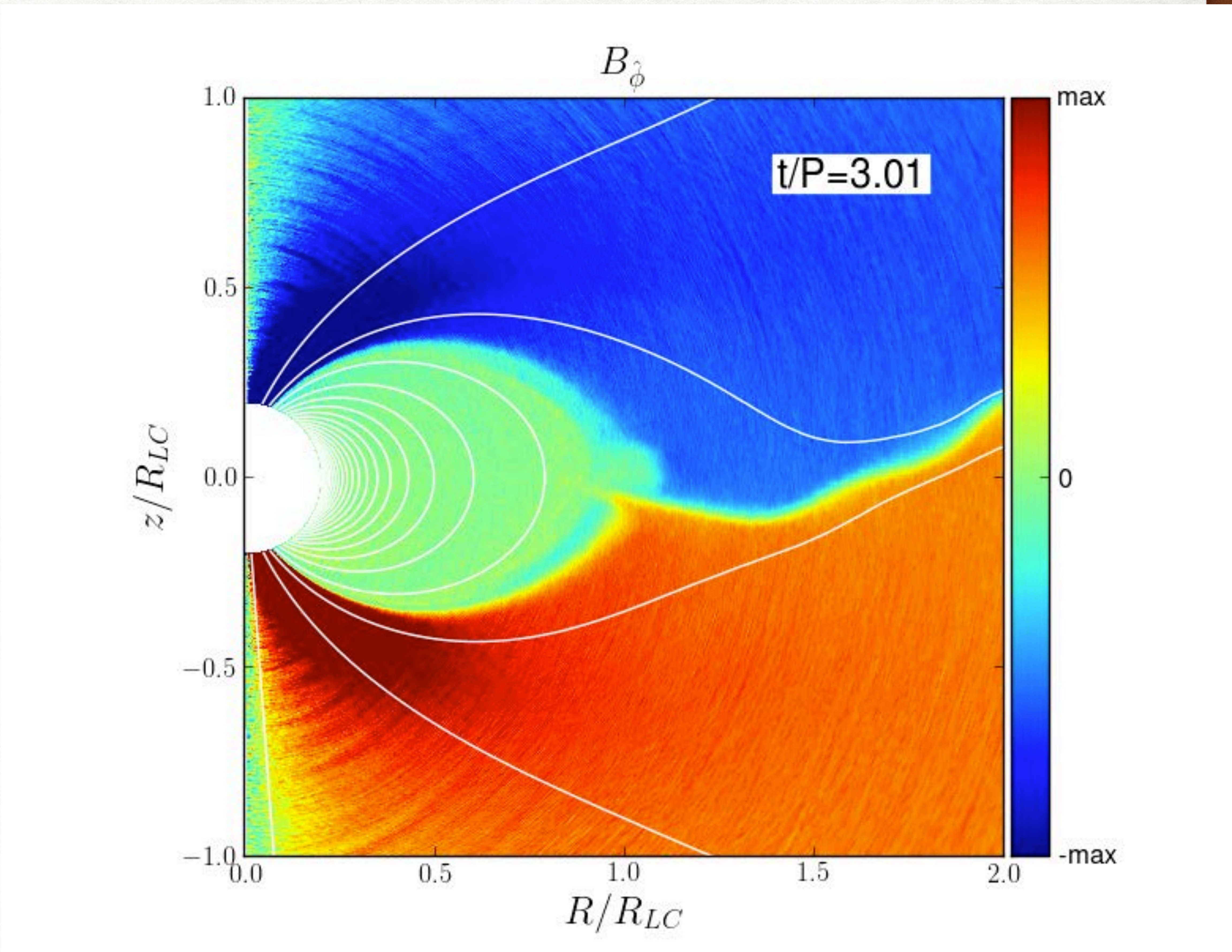
Maser instability amplification

Beam-plasma instability

All have difficulties…

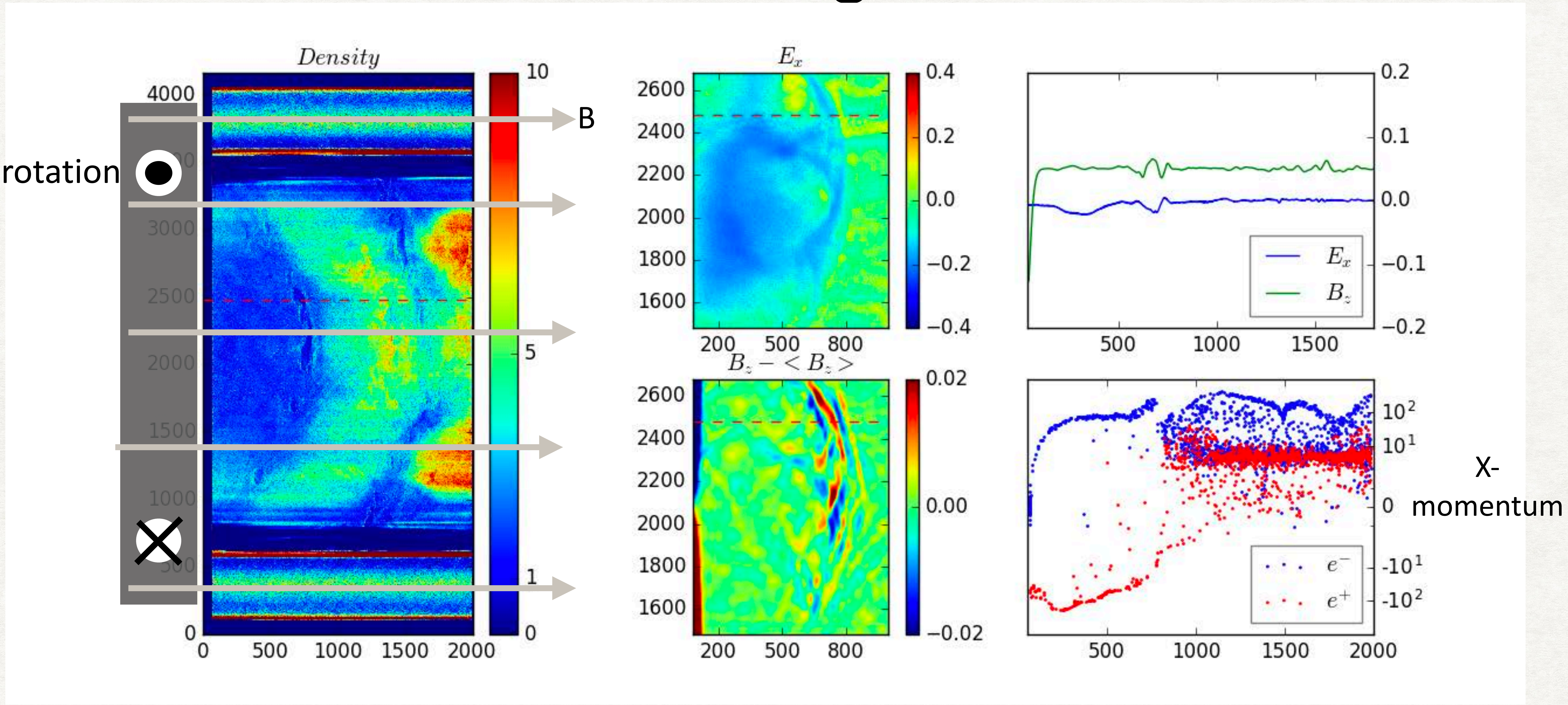
Insight from simulations: the discharge is non-stationary

Waves can be generated in the process of electric field screening by plasma clouds. Can they leave?



Philippov et al., 2015, Beloborodov 08

2D local discharge simulations

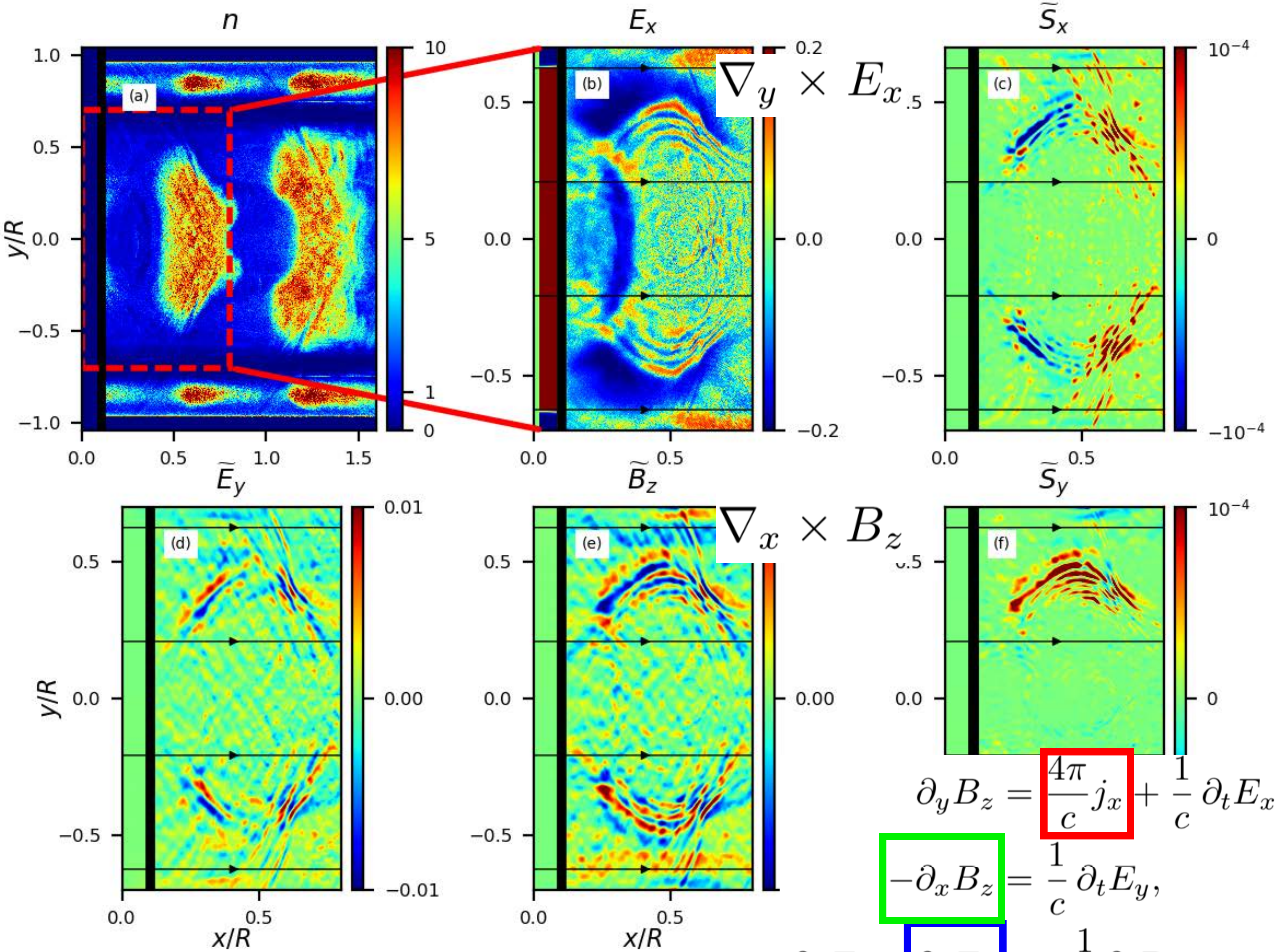


Conducting “rotating” plate on the left, horizontal external B-field, radiation boundary on the right.

Discharges are oblique to the background magnetic field and generate EM waves due to transverse gradients of E field.

Philippov, Timokhin & AS (2020)

Zoom-in

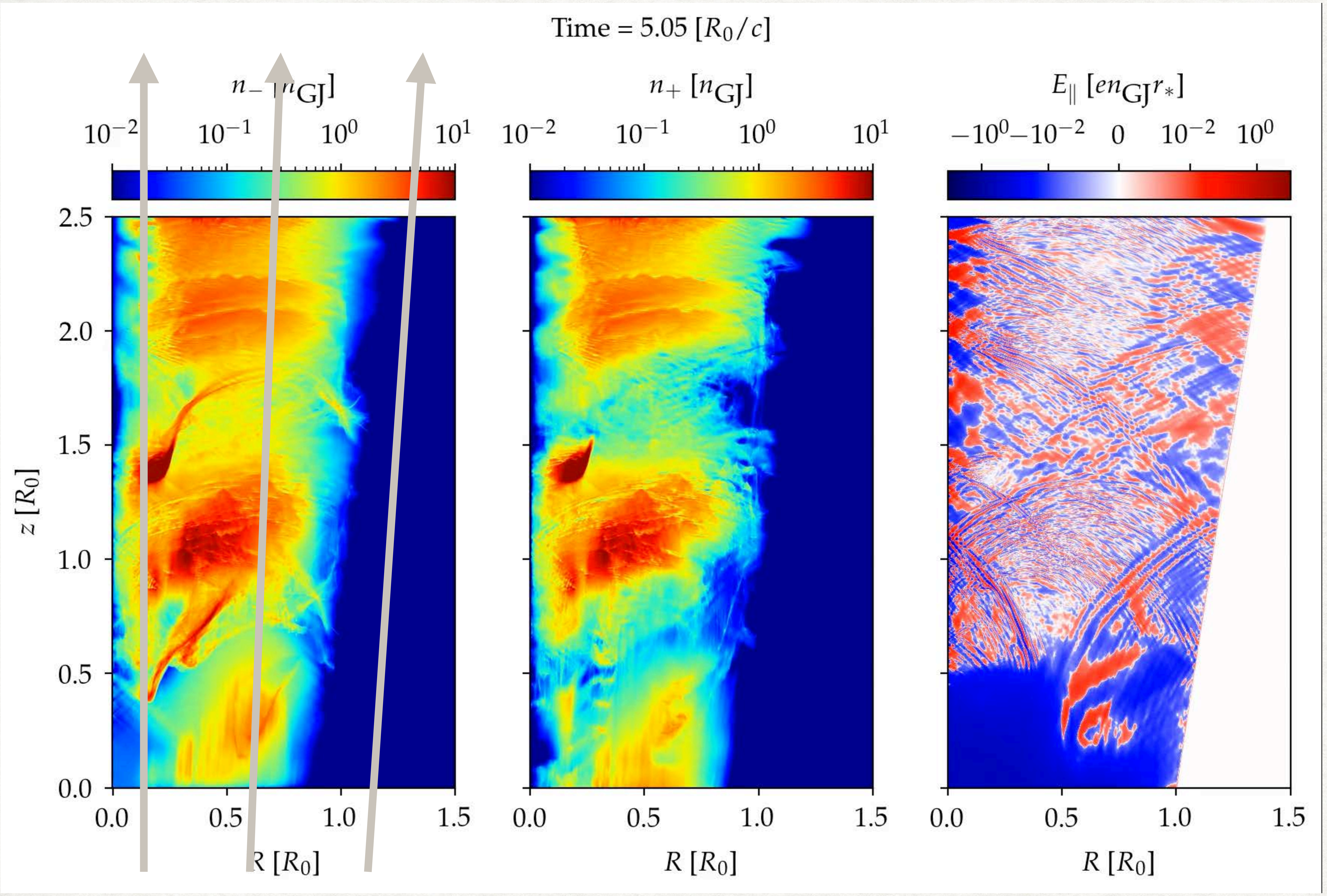


$$\partial_y B_z = \frac{4\pi}{c} j_x + \frac{1}{c}\,\partial_t E_x,$$

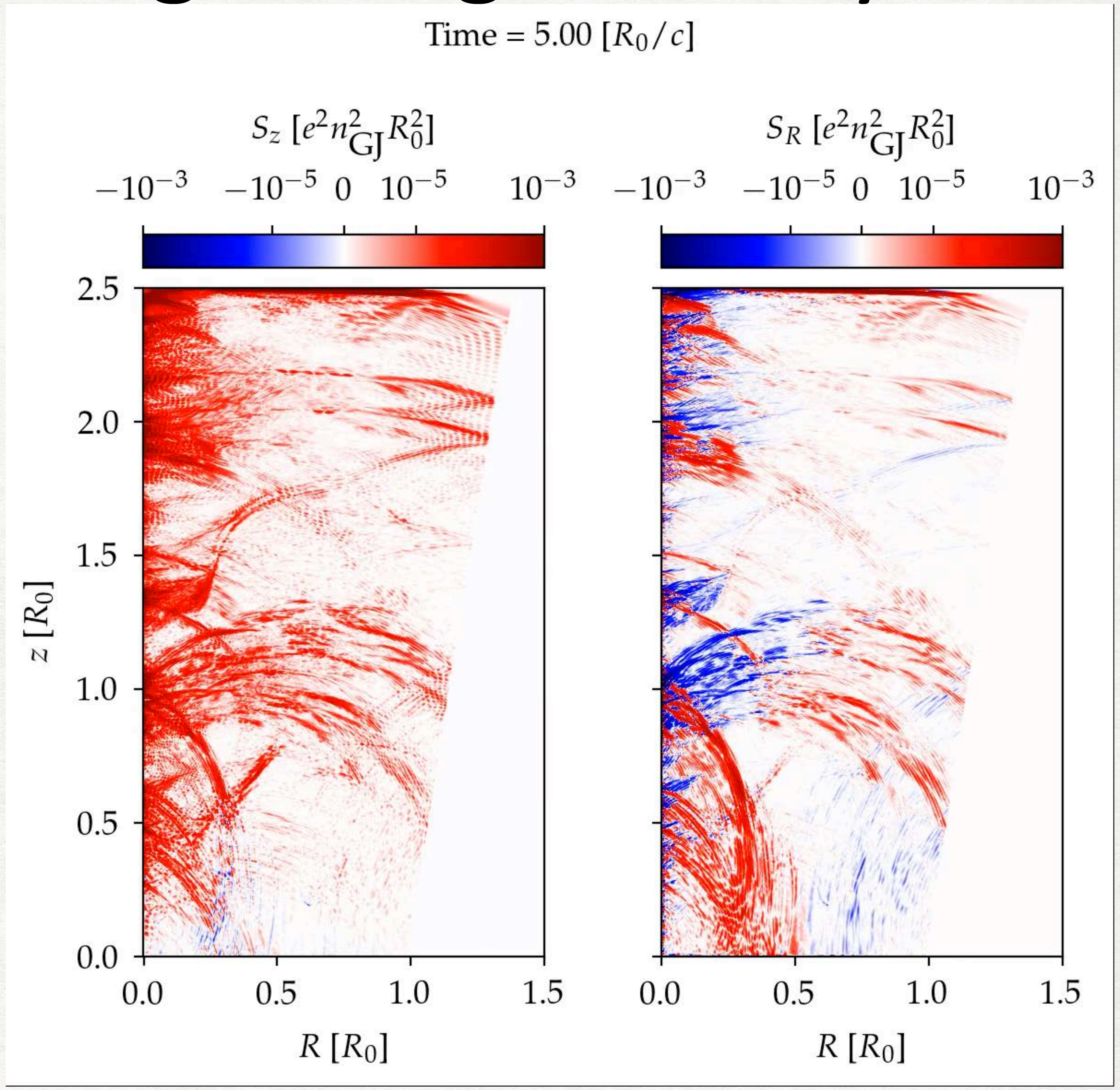
$$-\partial_x B_z = \frac{1}{c}\,\partial_t E_y,$$

$$\partial_x E_y - \partial_y E_x = -\frac{1}{c}\,\partial_t B_z,$$

Pair cascade in more realistic magnetic geometry



Pair density and electric field



Electromagnetic flux

Cruz+ 21

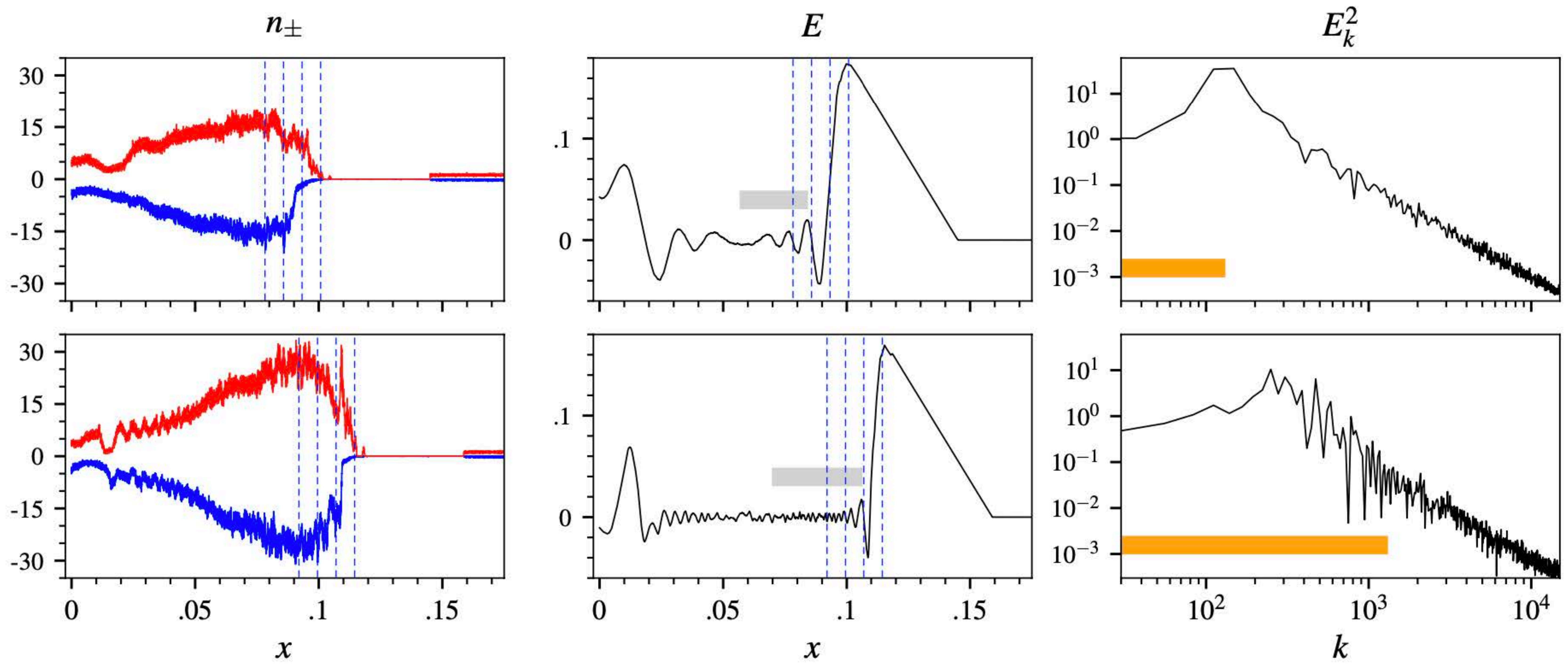
cf Benacek+ 24

Escaping radiation from an intermittent cascade.

Broadband emission set by the plasma frequency span of a growing cloud (in the GHz range).

Nonuniform emission due to variation in pair production across field lines — “core” vs “cone” emission.

1D electrostatic discharge



Clearly a broad-band mechanism. Power cascades to a maximum plasma frequency in the cloud

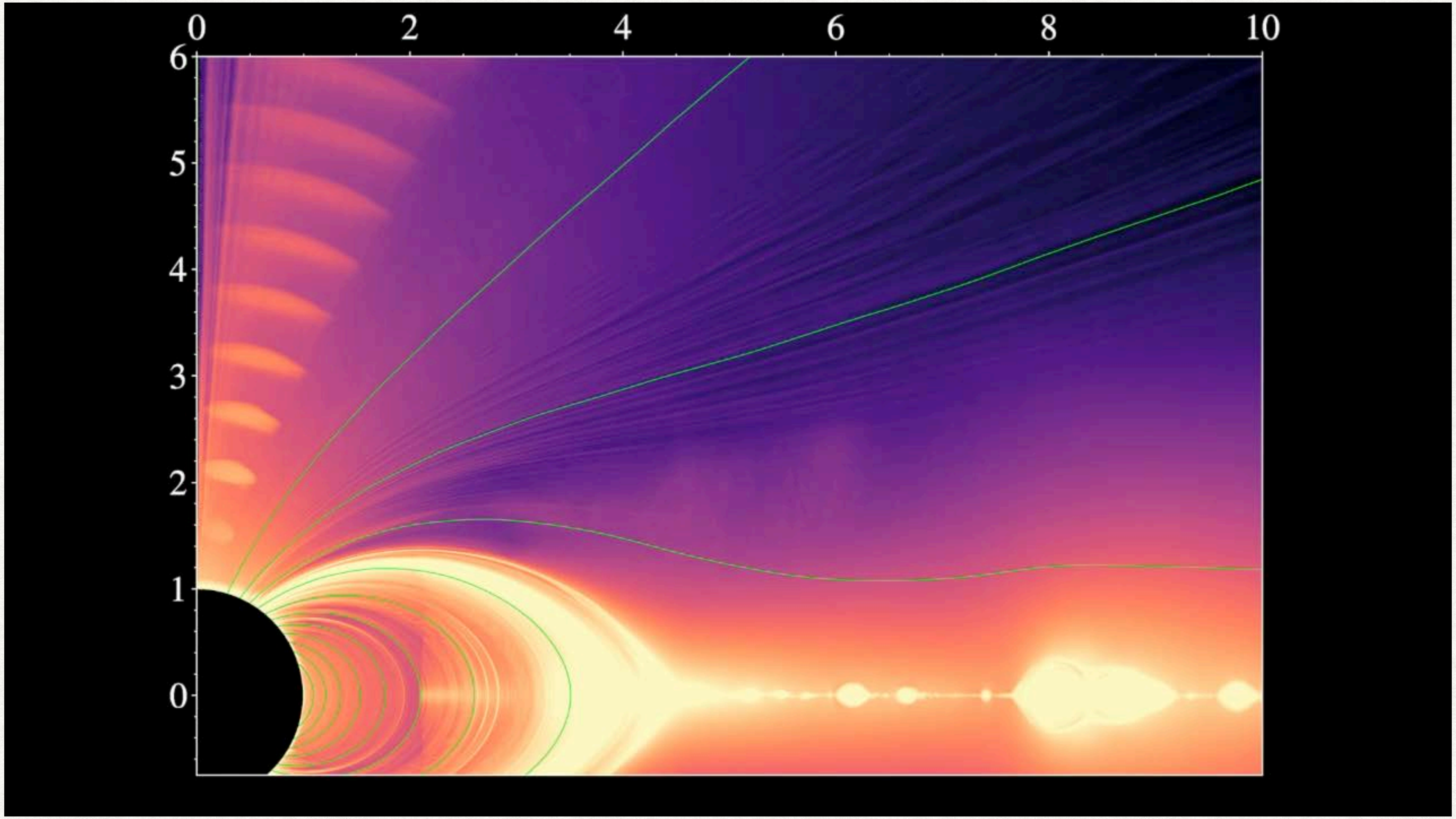
$$\nu \simeq \sqrt{4\pi e^2 \kappa n_{\rm GJ}/\langle\gamma^3\rangle m_e}/2\pi = 26\sqrt{\kappa_5 B_{12}/r^3 P_{0.1}\gamma_{10}^3}\ \mathrm{GHz}$$

Philippov, Timokhin, AS 20

Emission frequency set by screening at plasma frequency

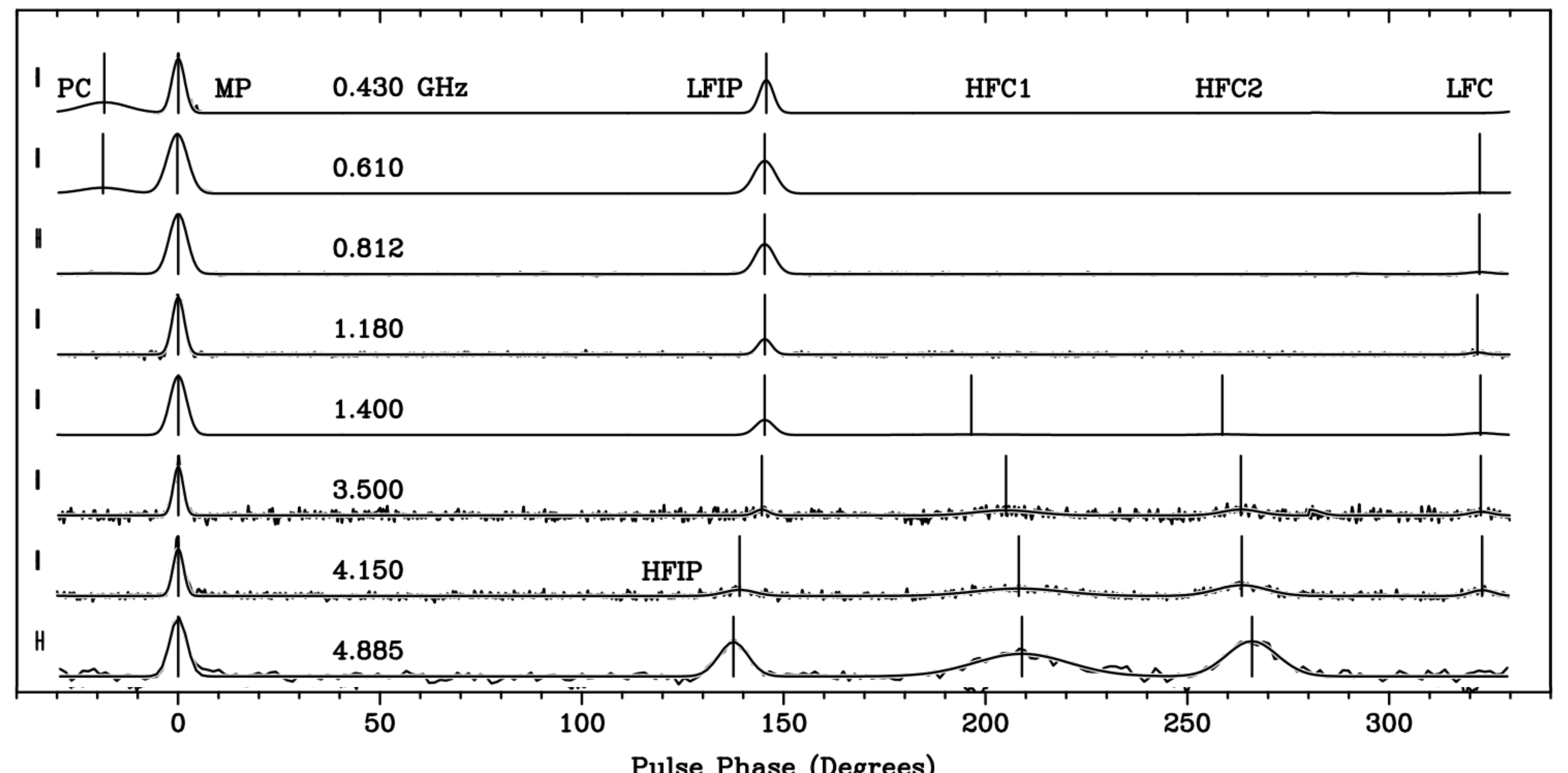
cf: Tolman+ 22

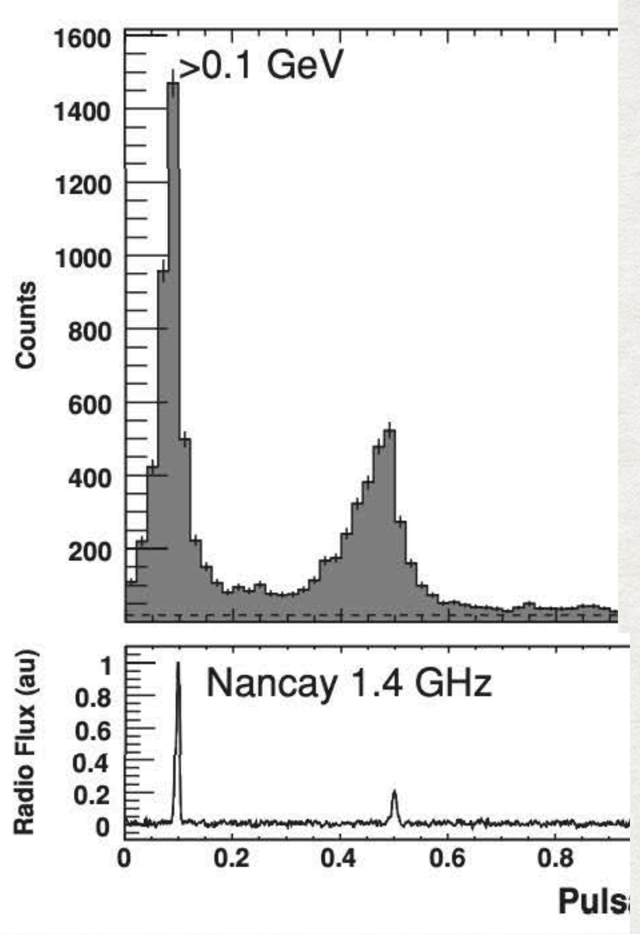
LIVING MAGNETOSPHERE



Bransgrove et al 23

CRAB RADIO EMISSION: OUTER MAGNETOSPHERE

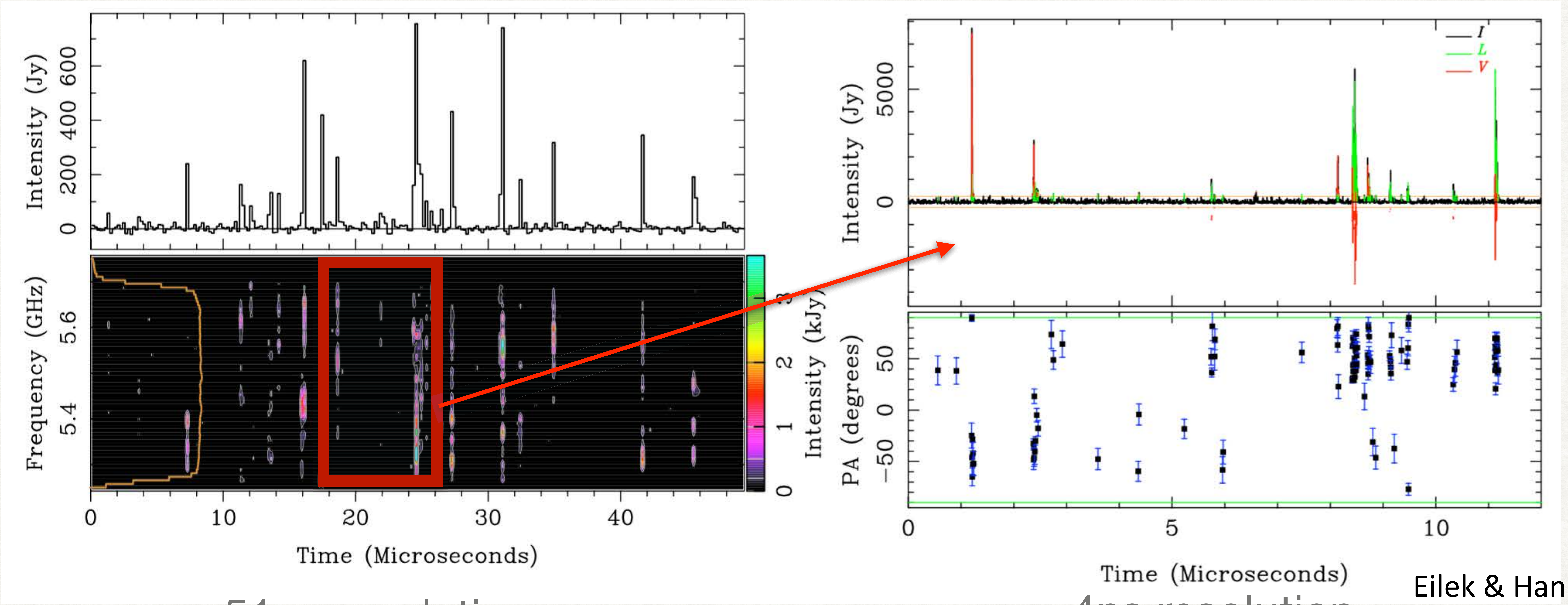




Eilek & Hankins 2016

Main radio pulse and interpulse in Crab have high-energy counterparts, most likely due to emission from outer magnetosphere. “Giant pulses” come in this phase too — very strong pulse with nanosecond substructure.

GIANT PULSES IN CRAB



Eilek & Hankins 2016

51ns resolution

4ns resolution

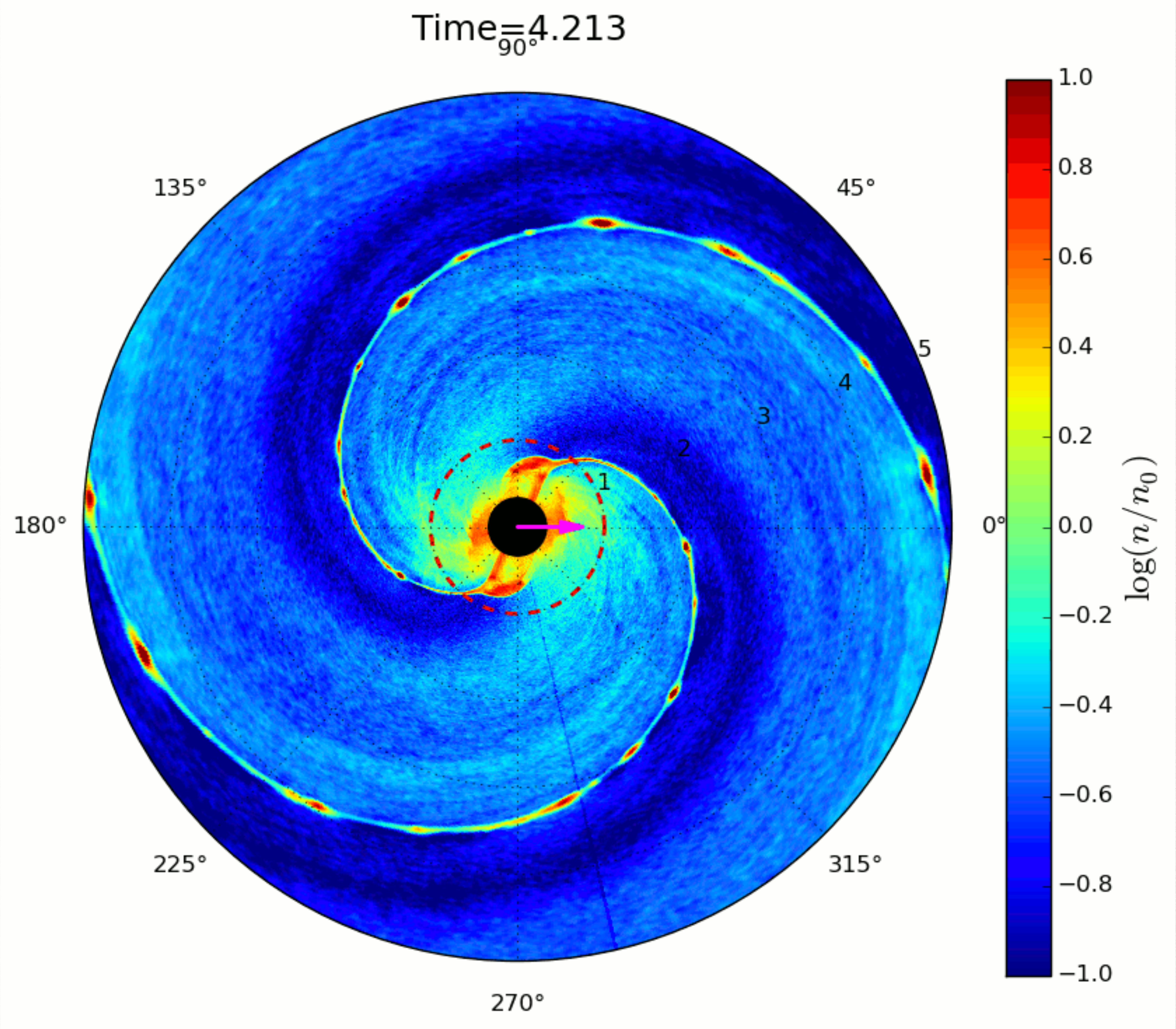
Resolved into nanosecond flashes — nano-shots

Instantaneously very bright, up to 1% of the spin-down power

$\nu_{\rm obs}\delta t \sim O(10)$

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)!
- Duration of pulses set by plasmoid size



Philippov, Uzdensky, AS, Cerutti (2019)

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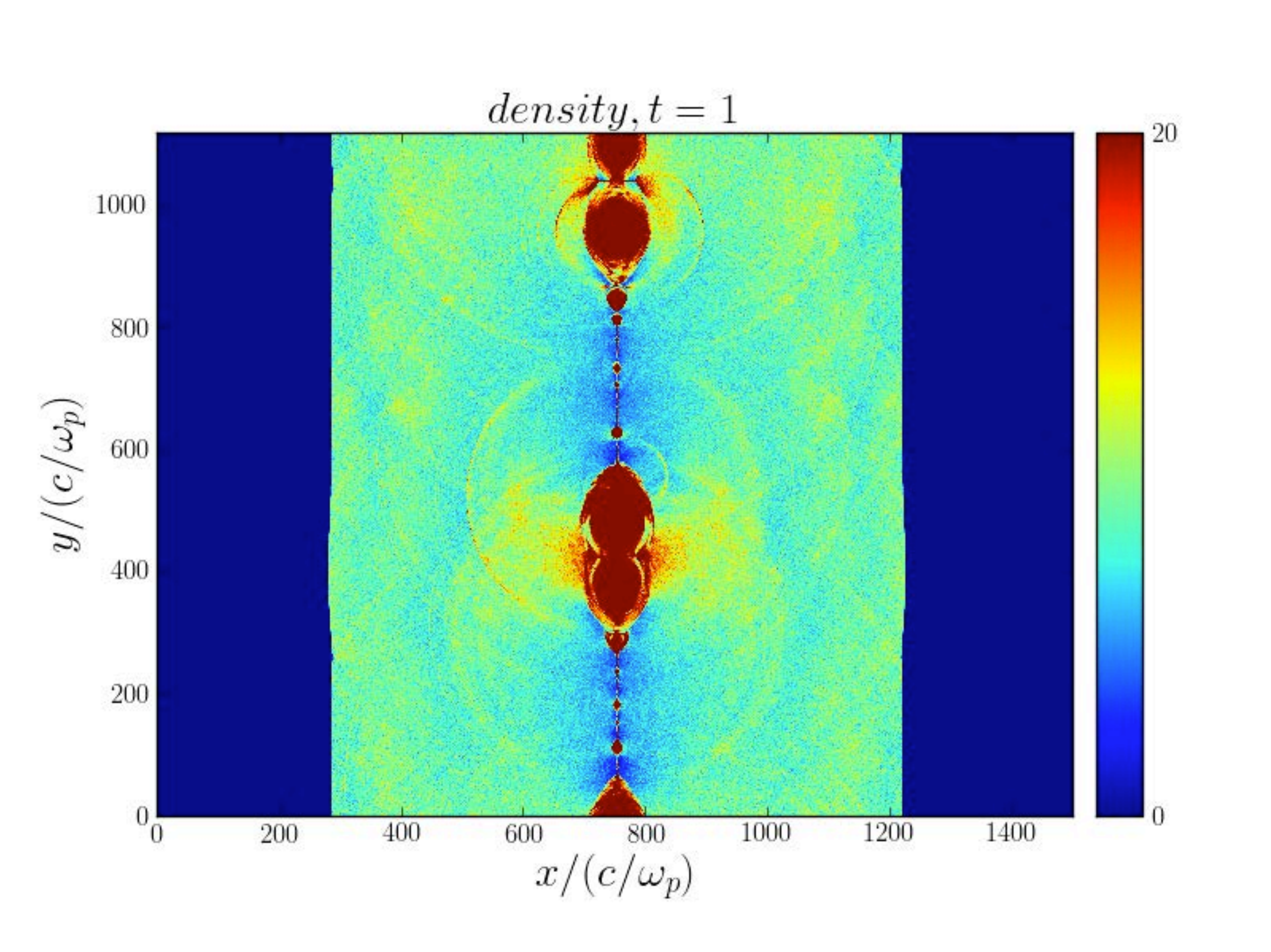

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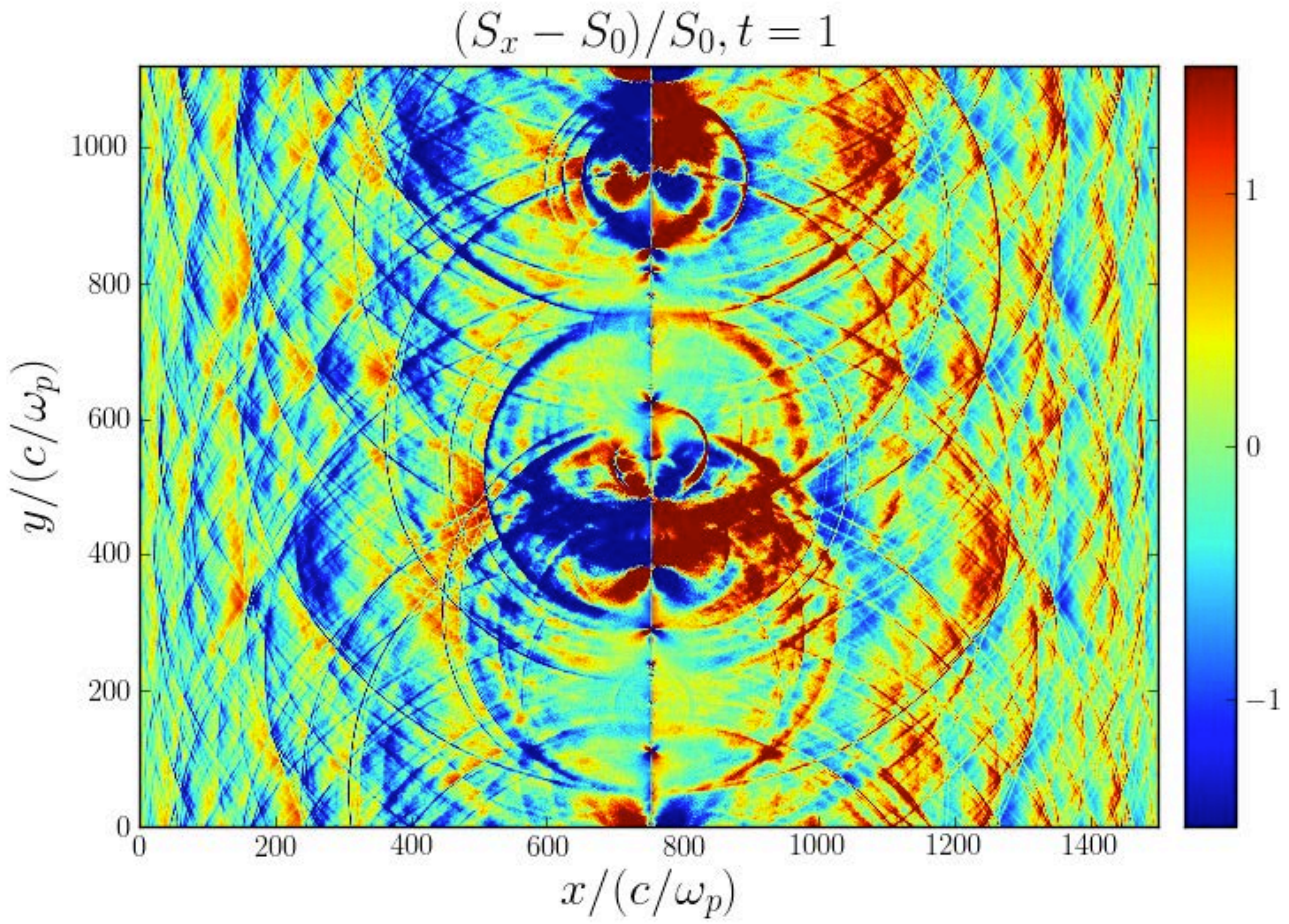
Escaping electromagnetic flux



Philippov, Uzdensky, AS, Cerutti (2019)

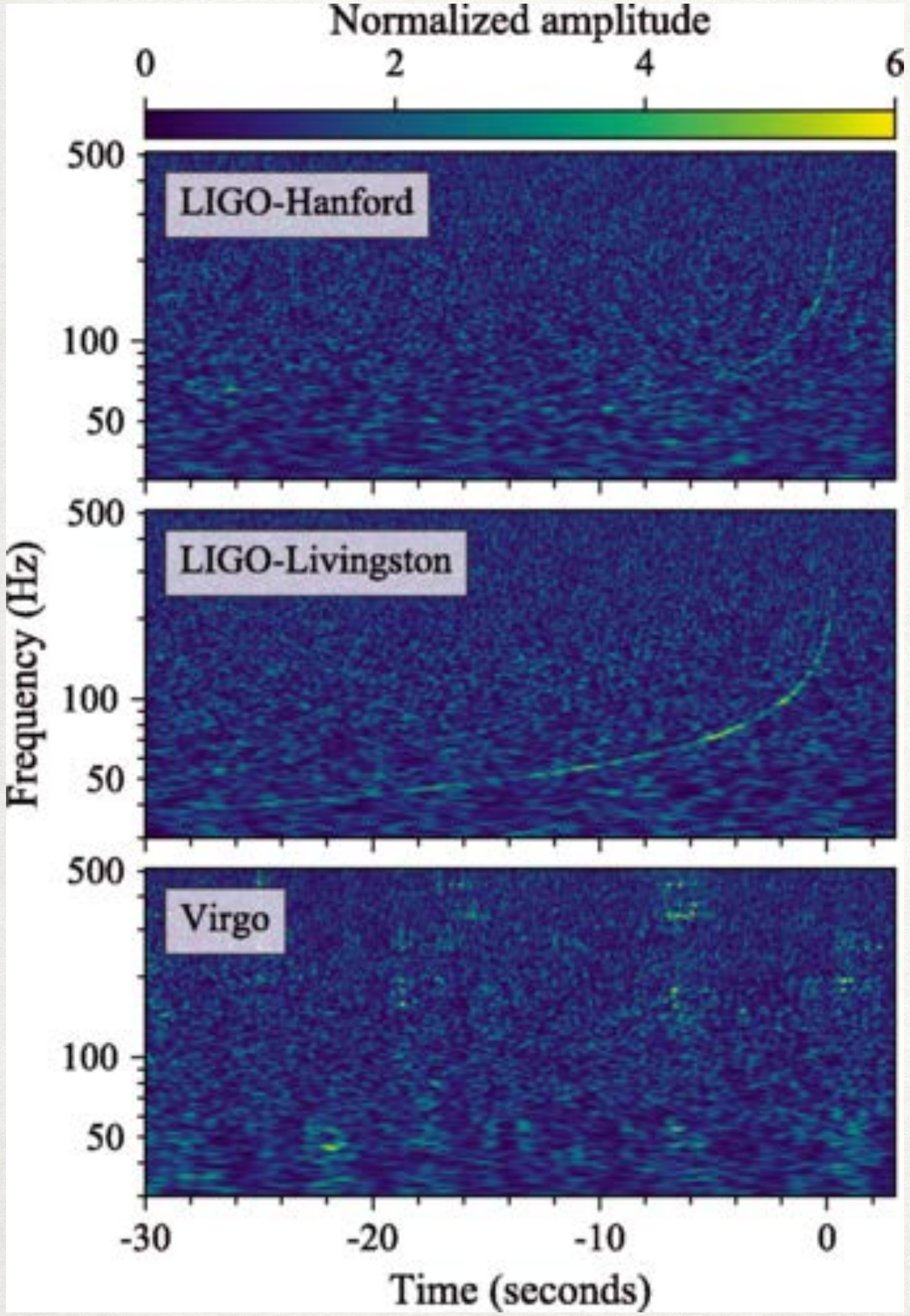
RADIO EMISSION MECHANISM: SUMMARY

- Two kinds of coherent emission: polar cap and outer magnetosphere (giant pulses)
- Polar cap emission is due to intermittent discharges, particularly their non-uniformity transverse to B field. This leads to launching of EM waves (O-modes) which can leave the magnetosphere
- Emission is caused by coherent oscillation of the pair formation front boundary and resulting plasma oscillations in the region of increasing density. This leads to broad frequency spectrum of radiation.
- Outer magnetospheric emission is due to reconnection in the current sheet beyond the light cylinder
- Mergers of plasma islands lead to coherent perturbation of EM fields and results in bursts of radiation of nanosecond duration.

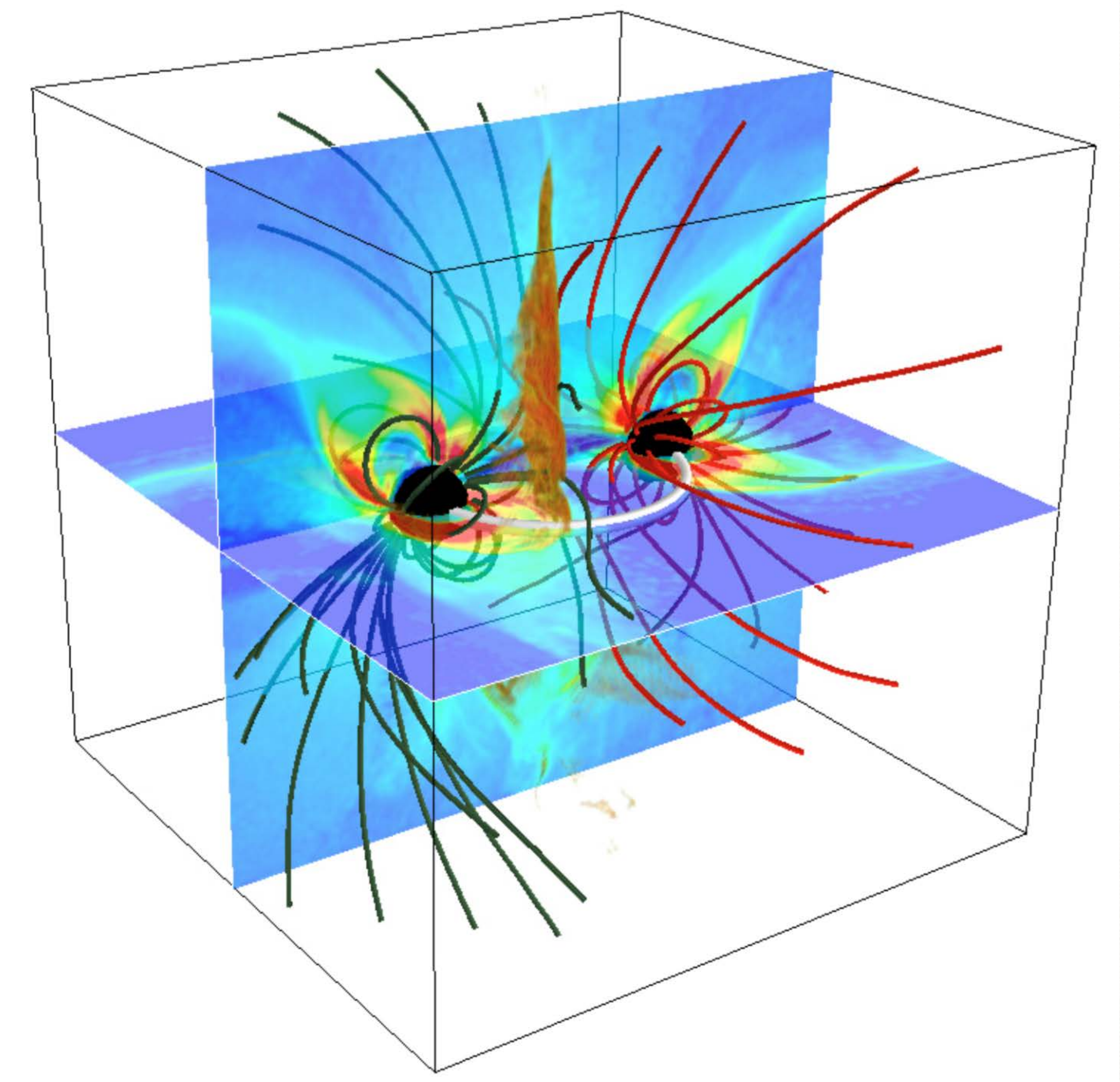
Philippov, Uzdensky, AS, Cerutti (2019); Philippov, Timokhin, AS (2020); Melrose (2021); Lyubarsky (1996)

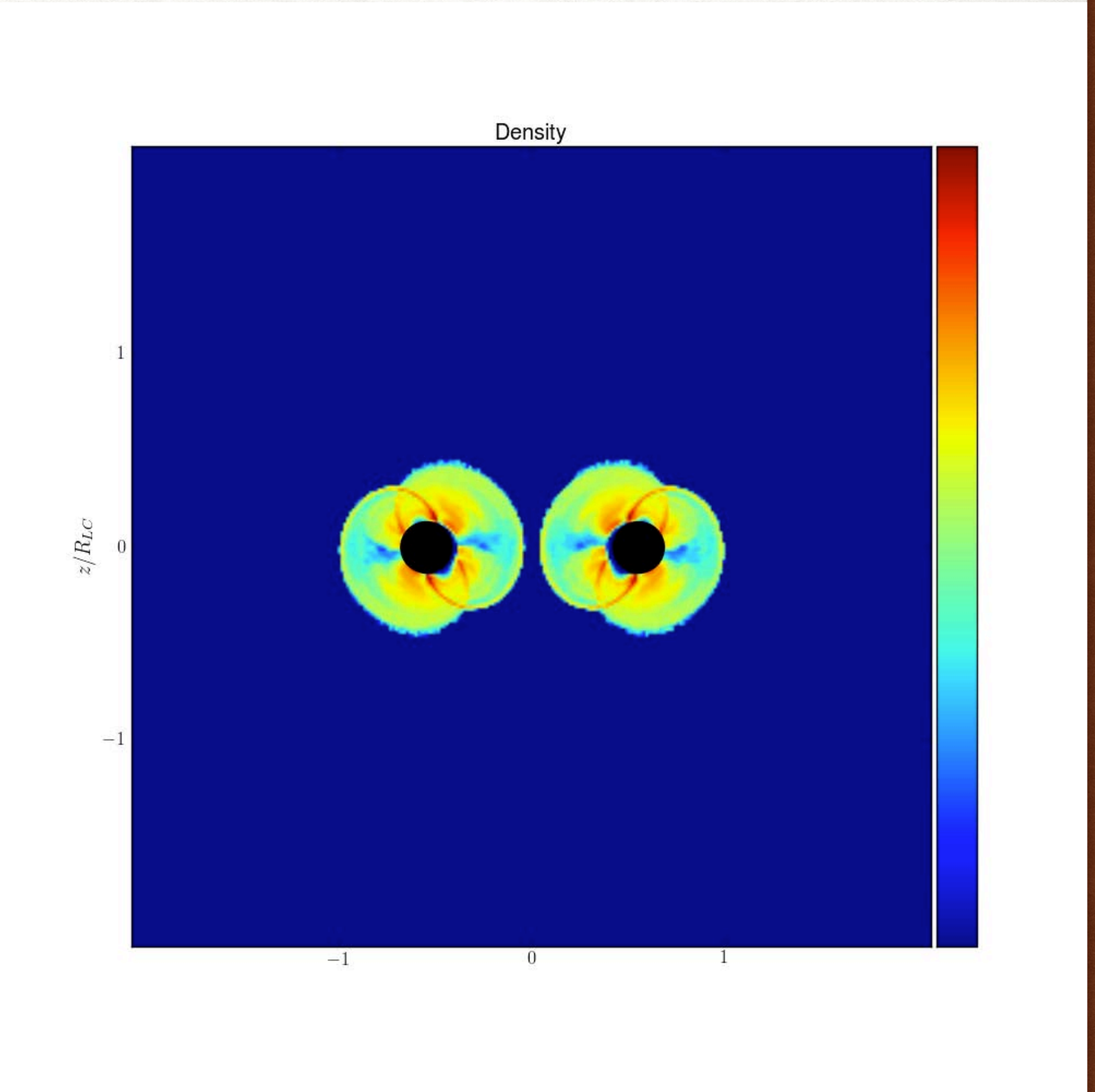
FUTURE APPLICATIONS: MERGERS

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



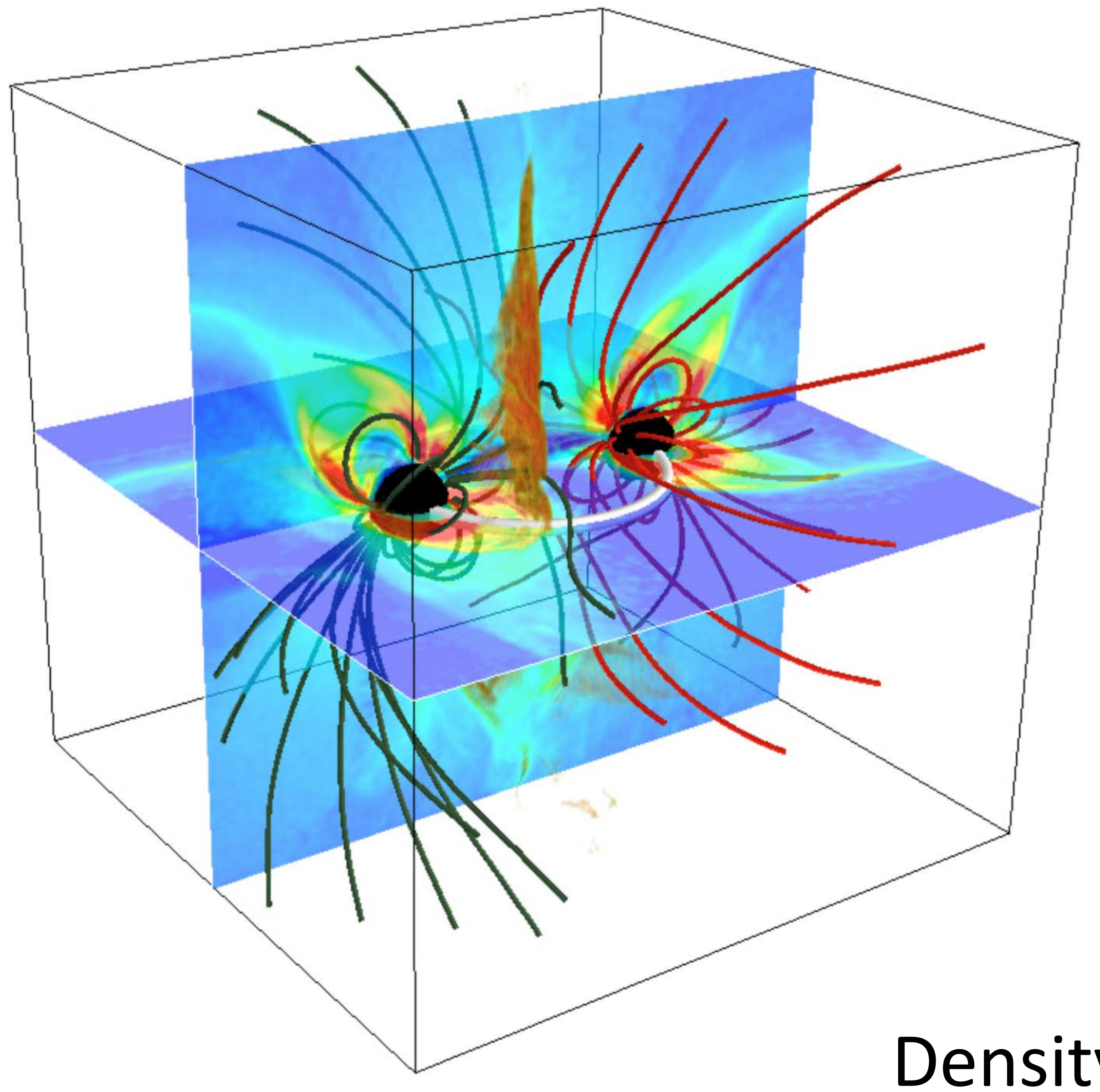
cf: Lyutikov 19; Philippov & Most 23



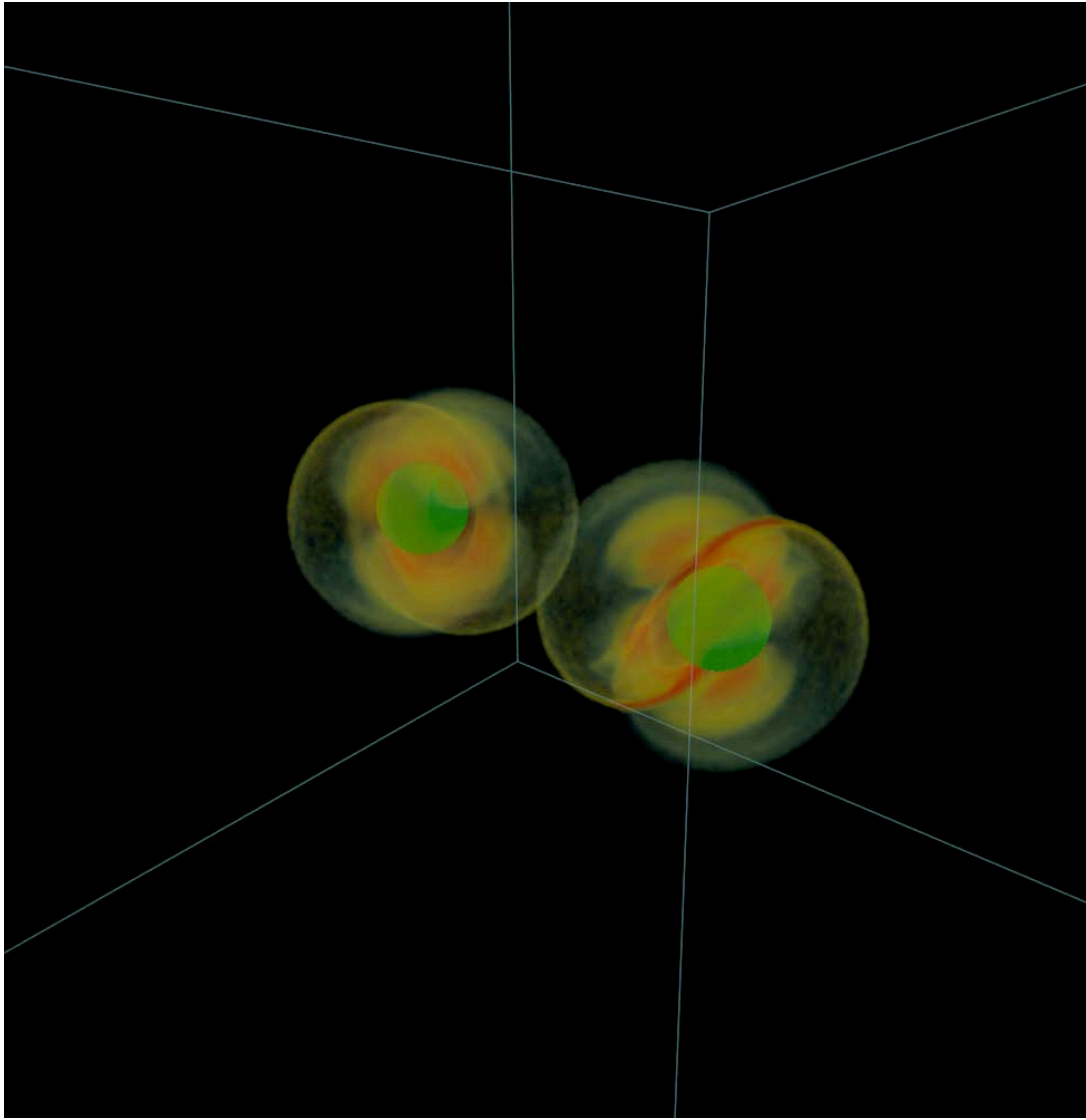


First PIC simulations of binary neutron stars: EM radiative signature?

Precursor EM signals from mergers



Density rendering

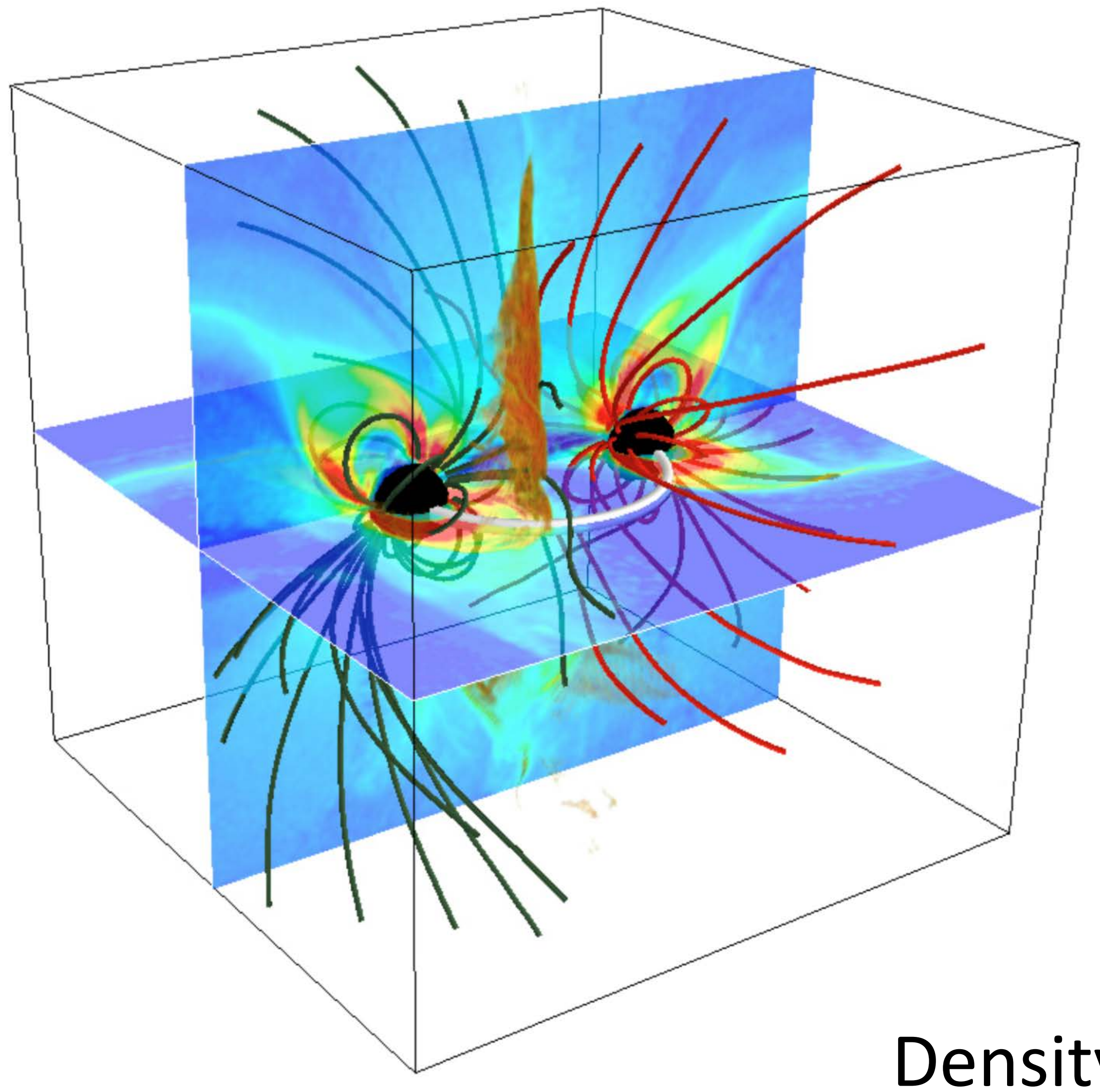


Anti-aligned magnetic moments lead to reconnection between magnetospheres once per rotation of the slowest pulsar. Strong current sheet and particle acceleration occur between magnetospheres

Simulation: Sasha Philippov

Rendering: Hayk Hakobyan

Precursor EM signals from mergers



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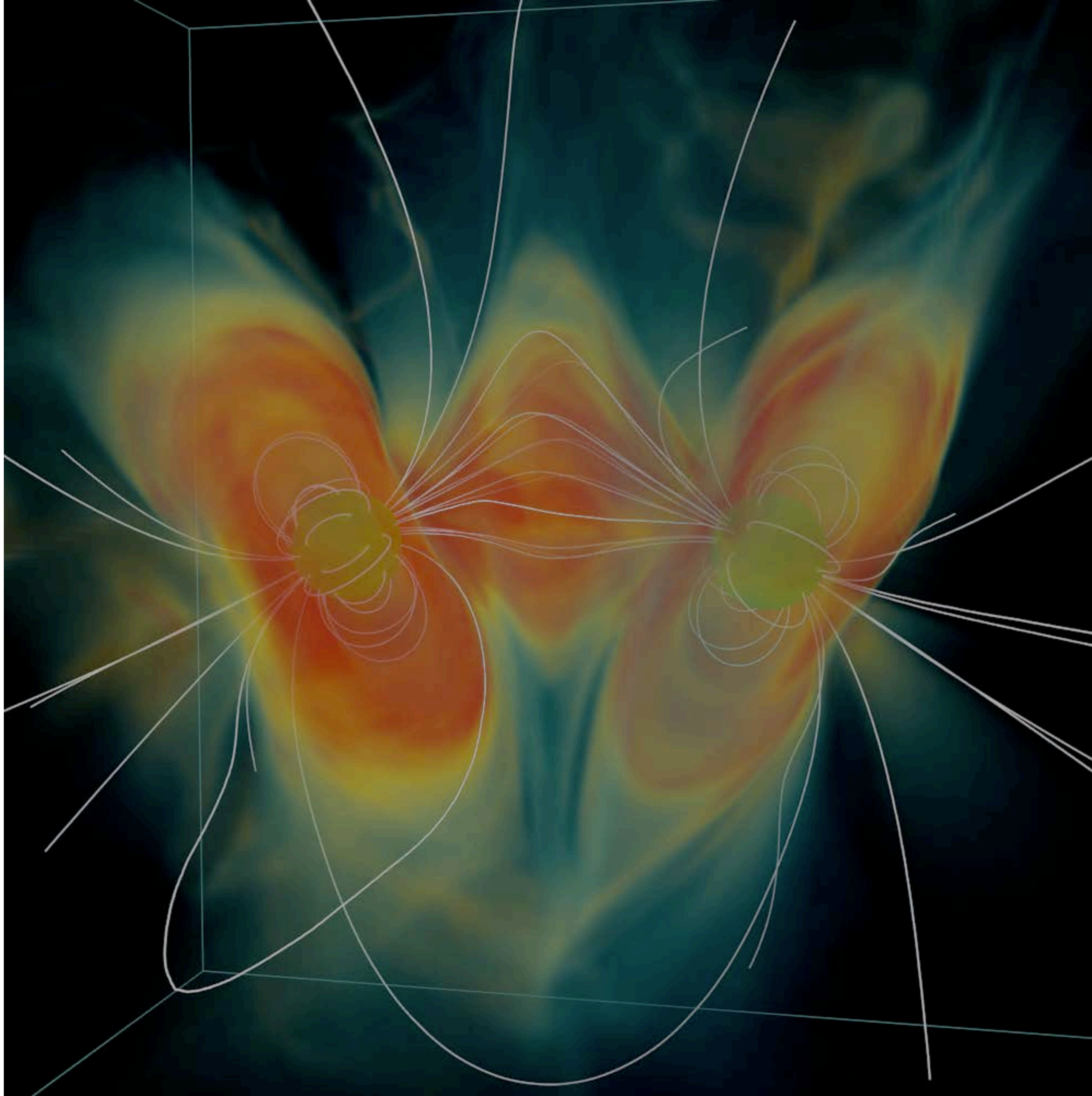

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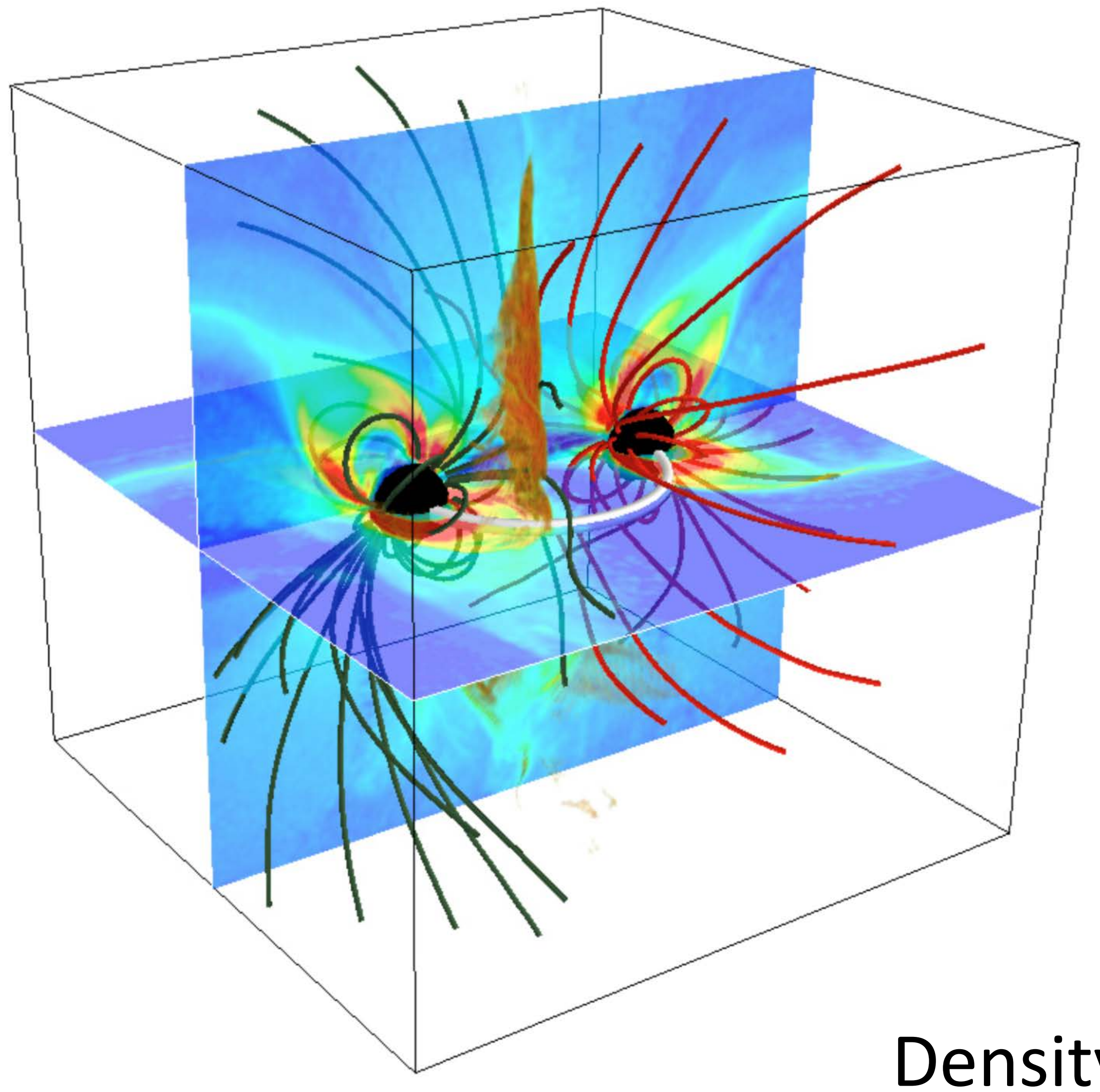

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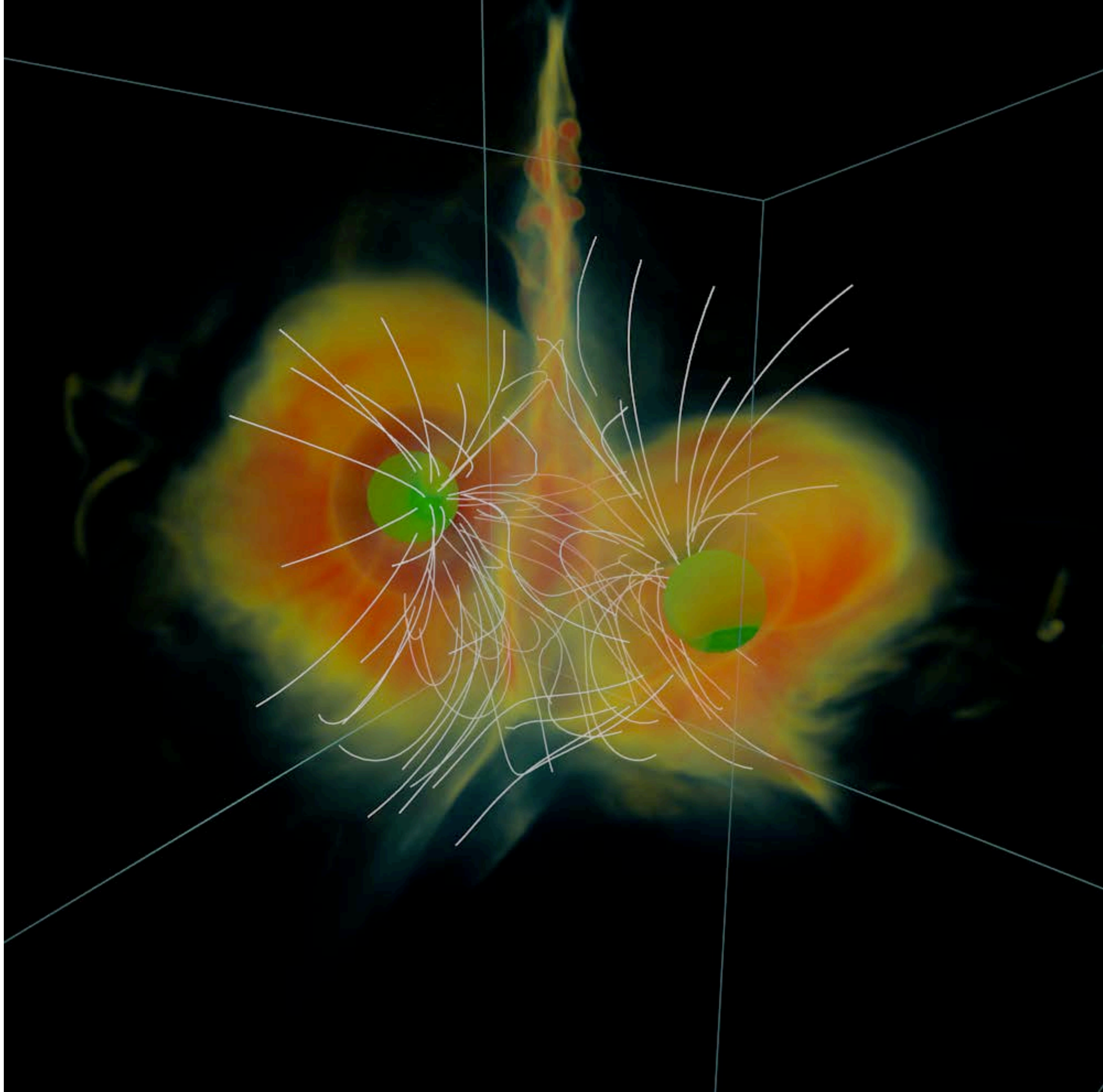

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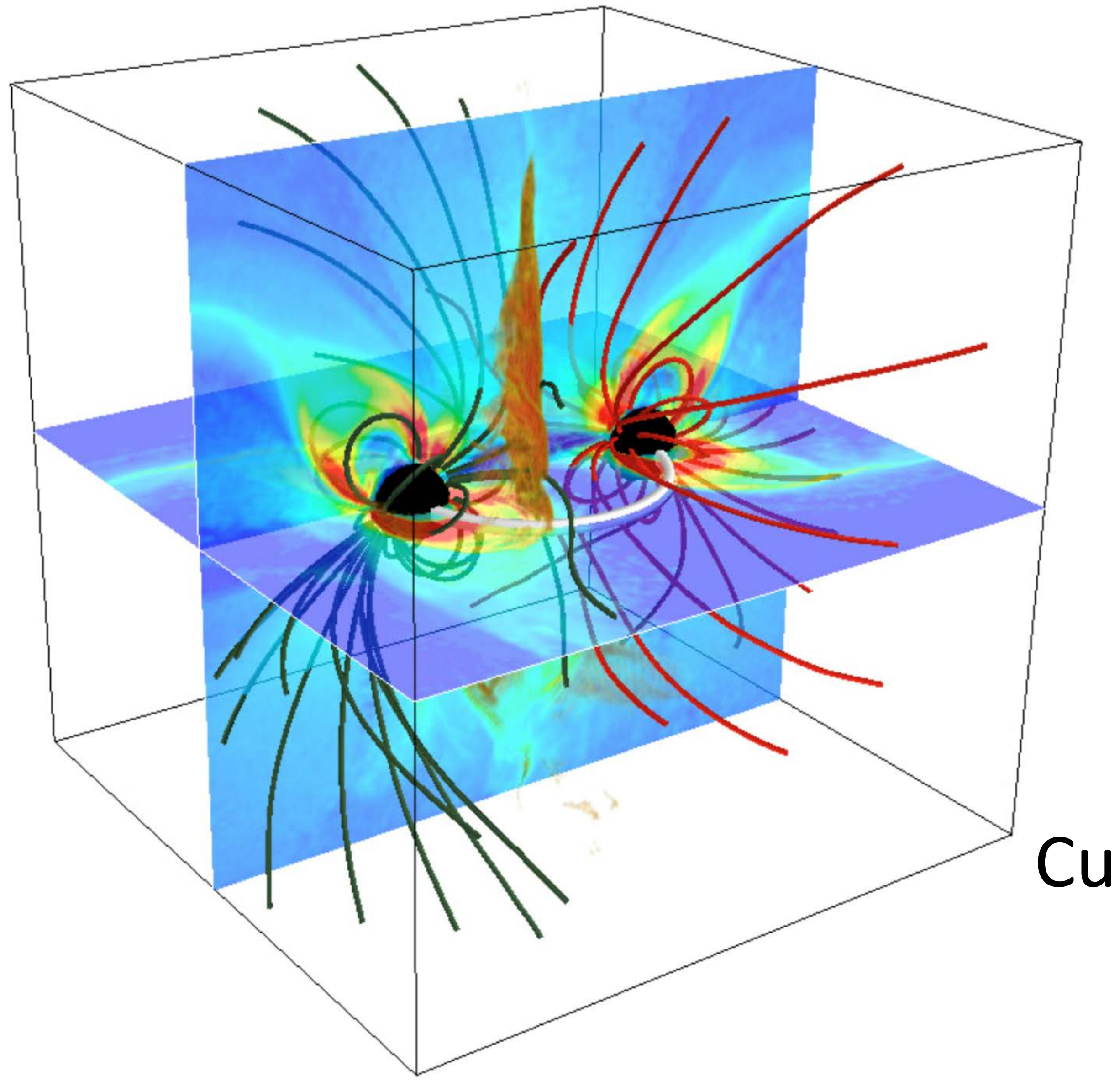

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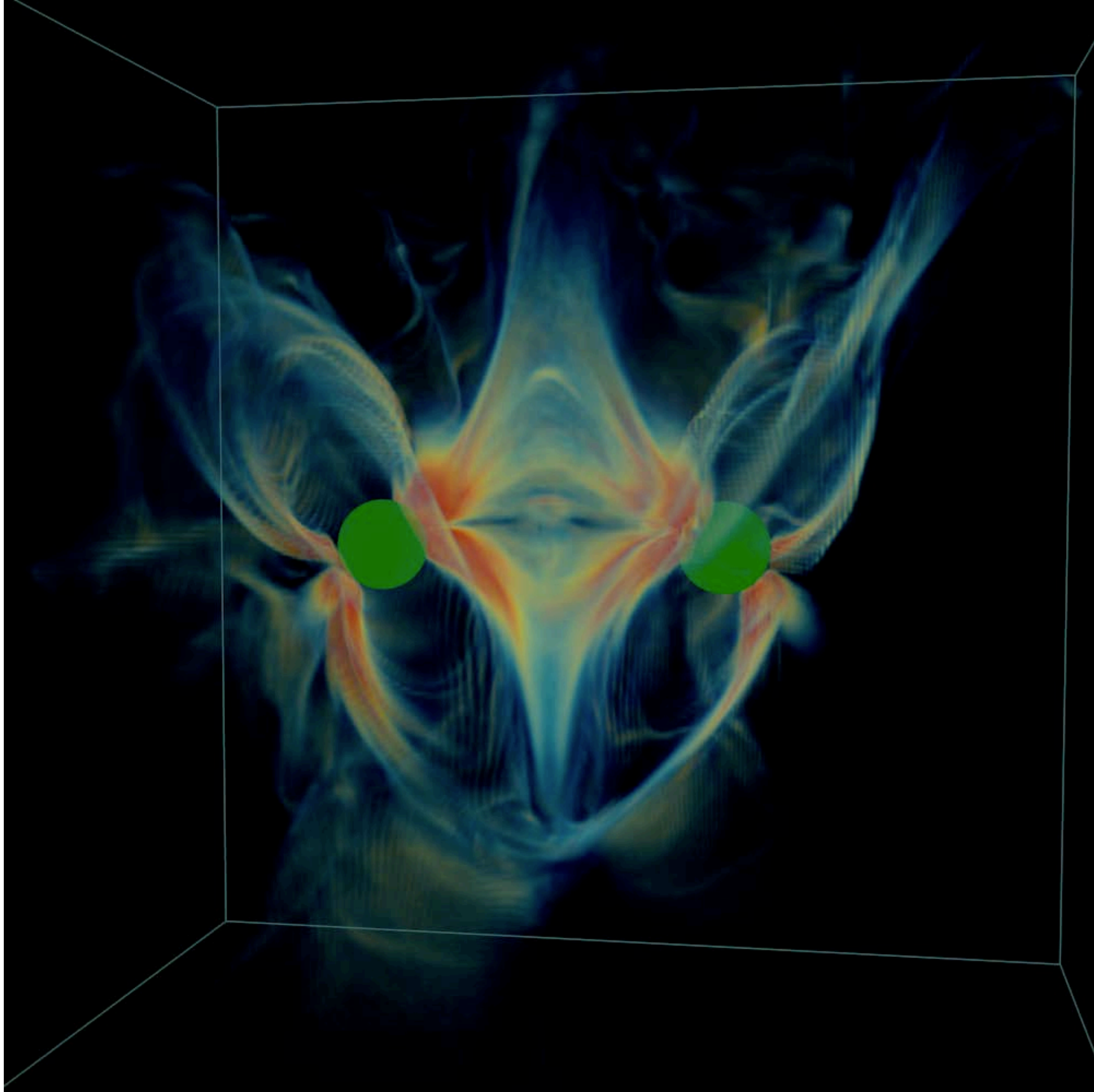

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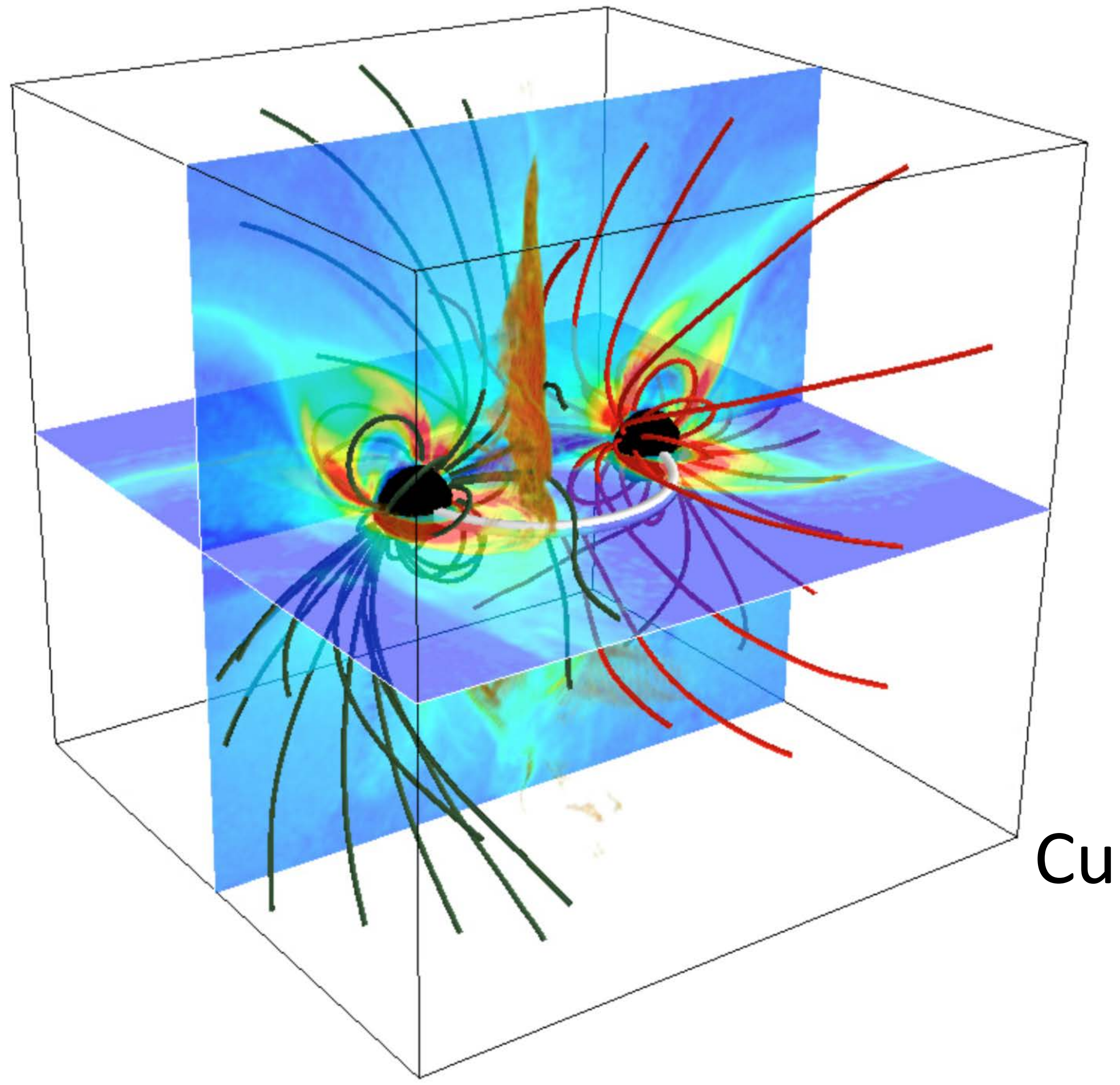

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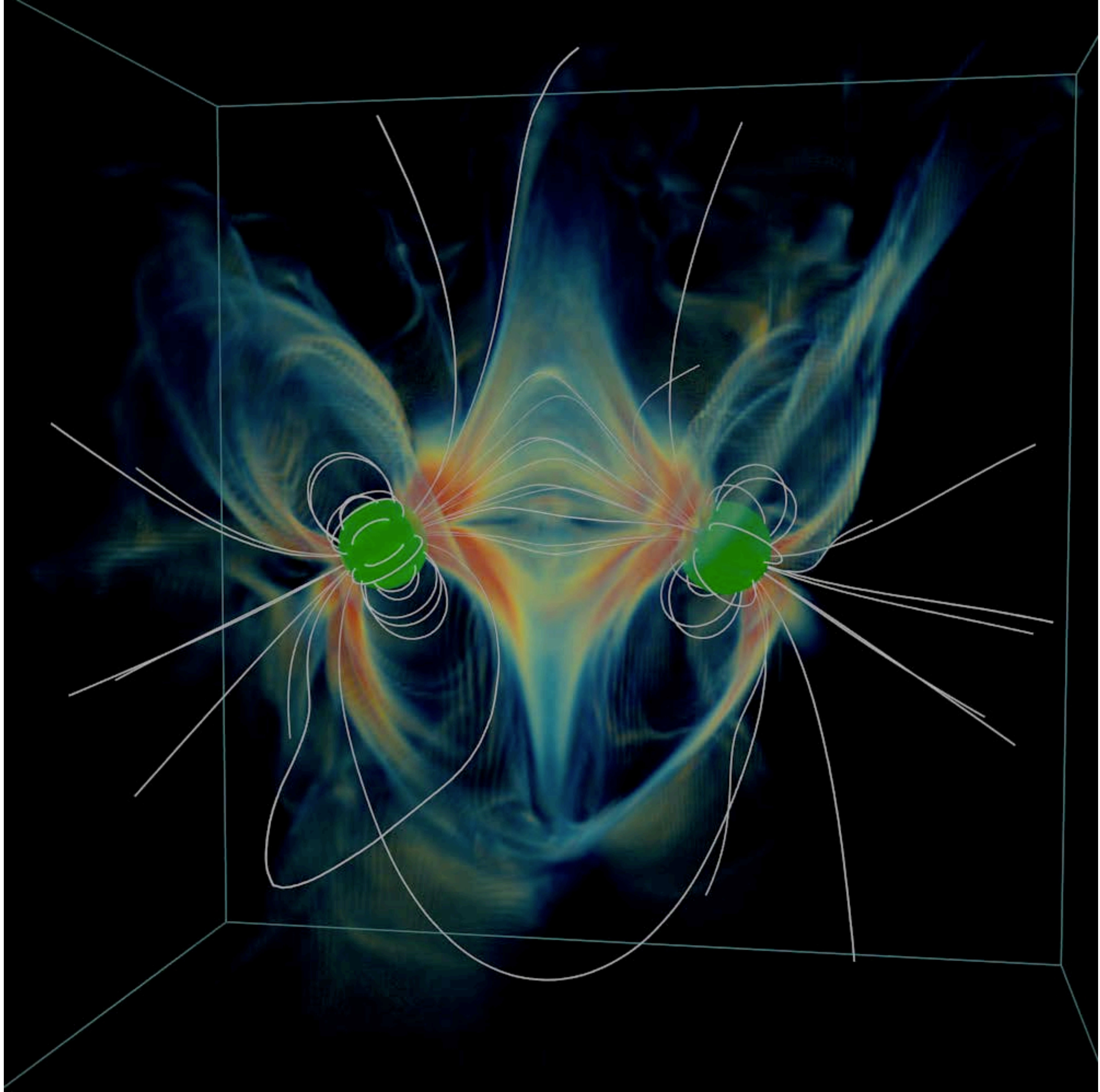

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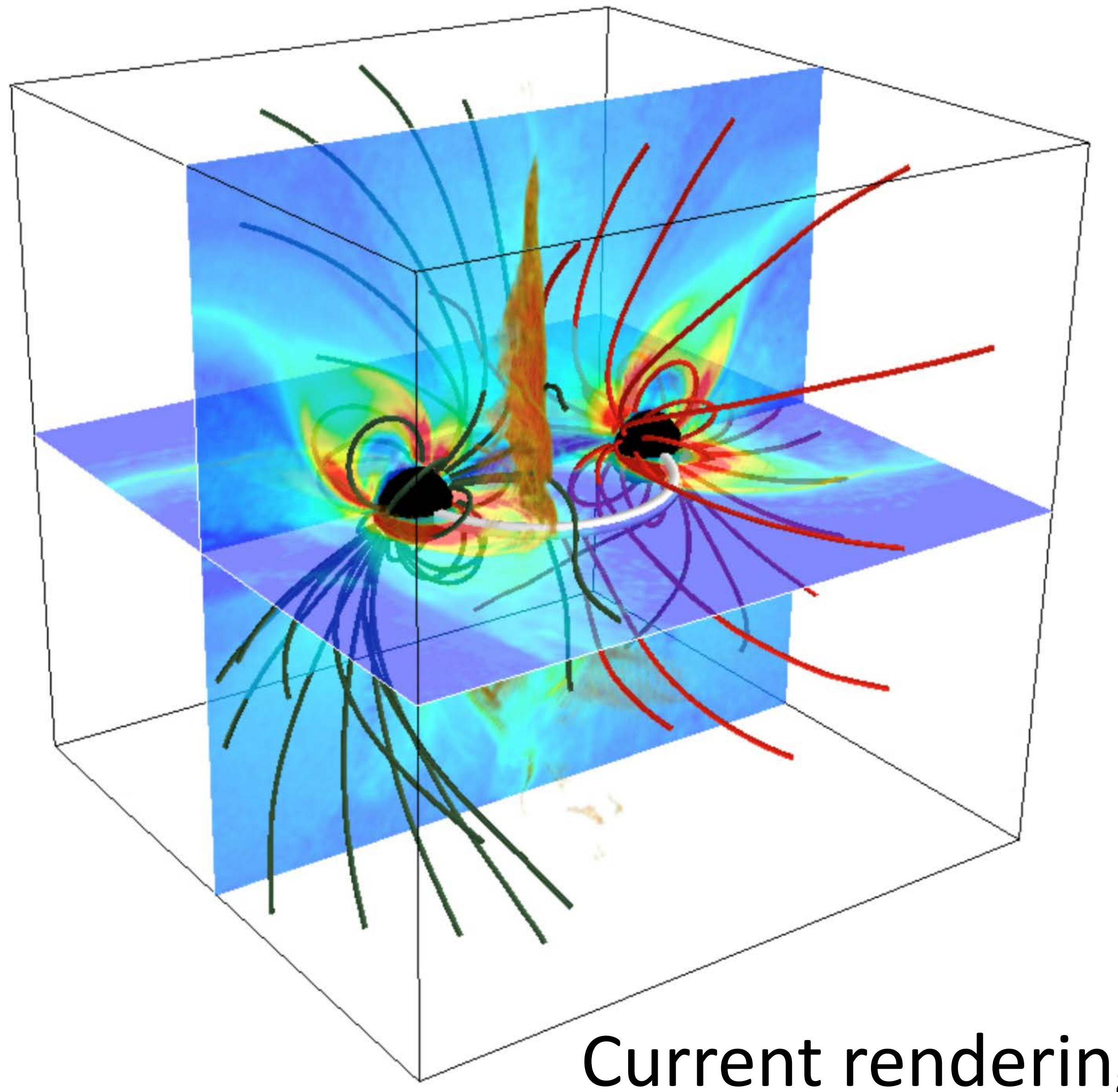
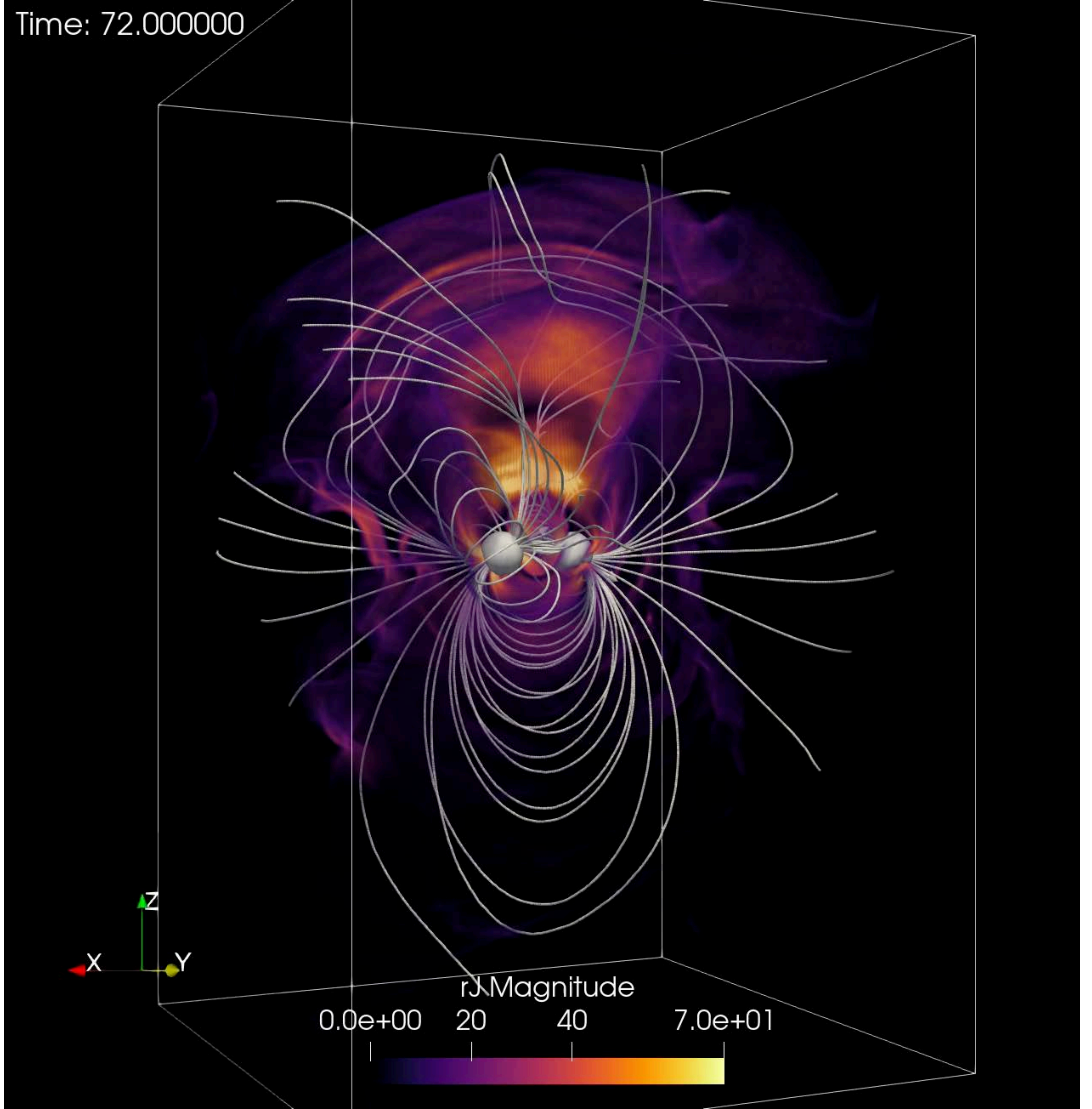


Current rendering

What are the beaming properties during bursts?

At what energy is the emission peaking?

Jasmine Parsons, AS, Philippov, in prep



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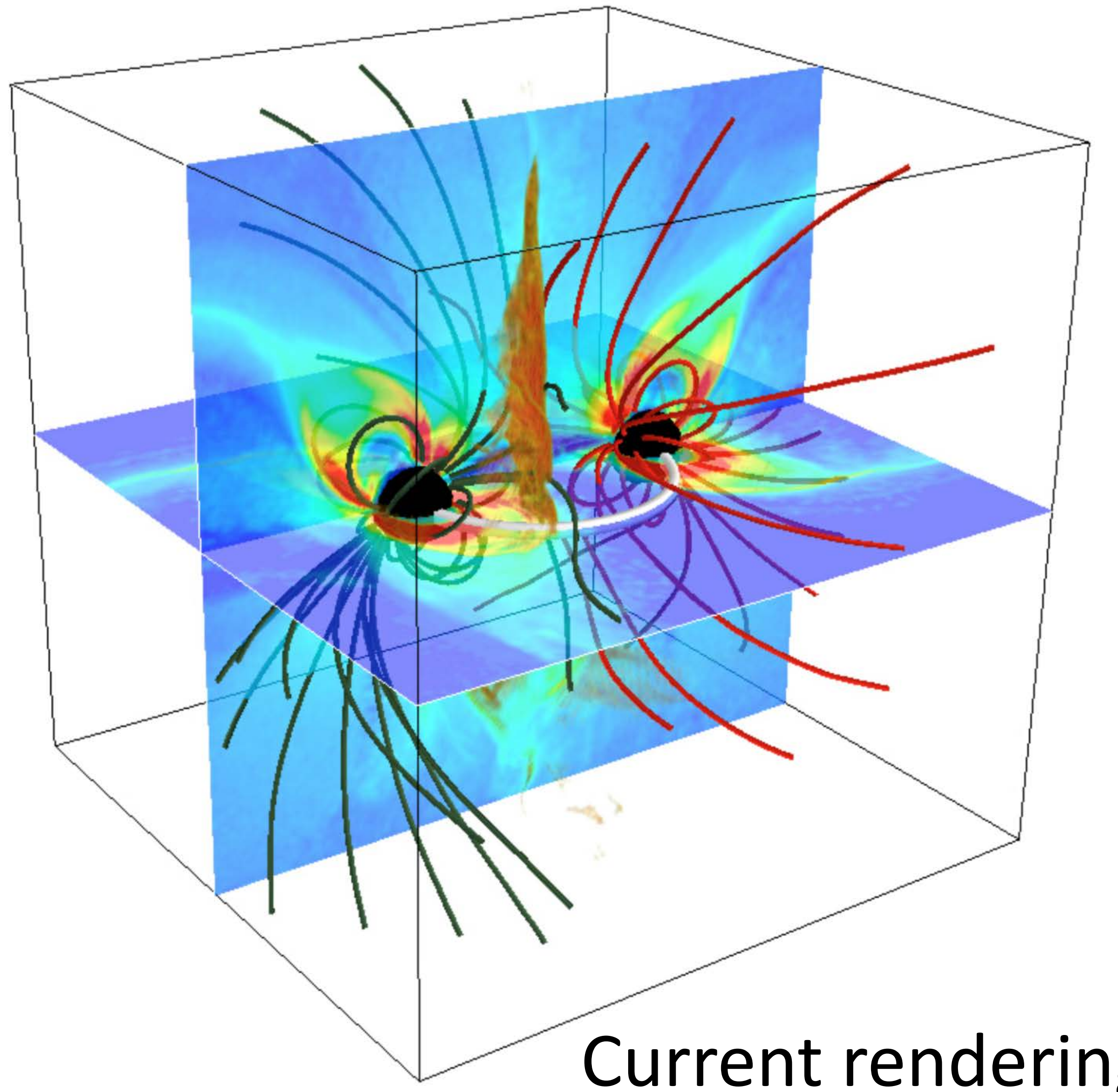
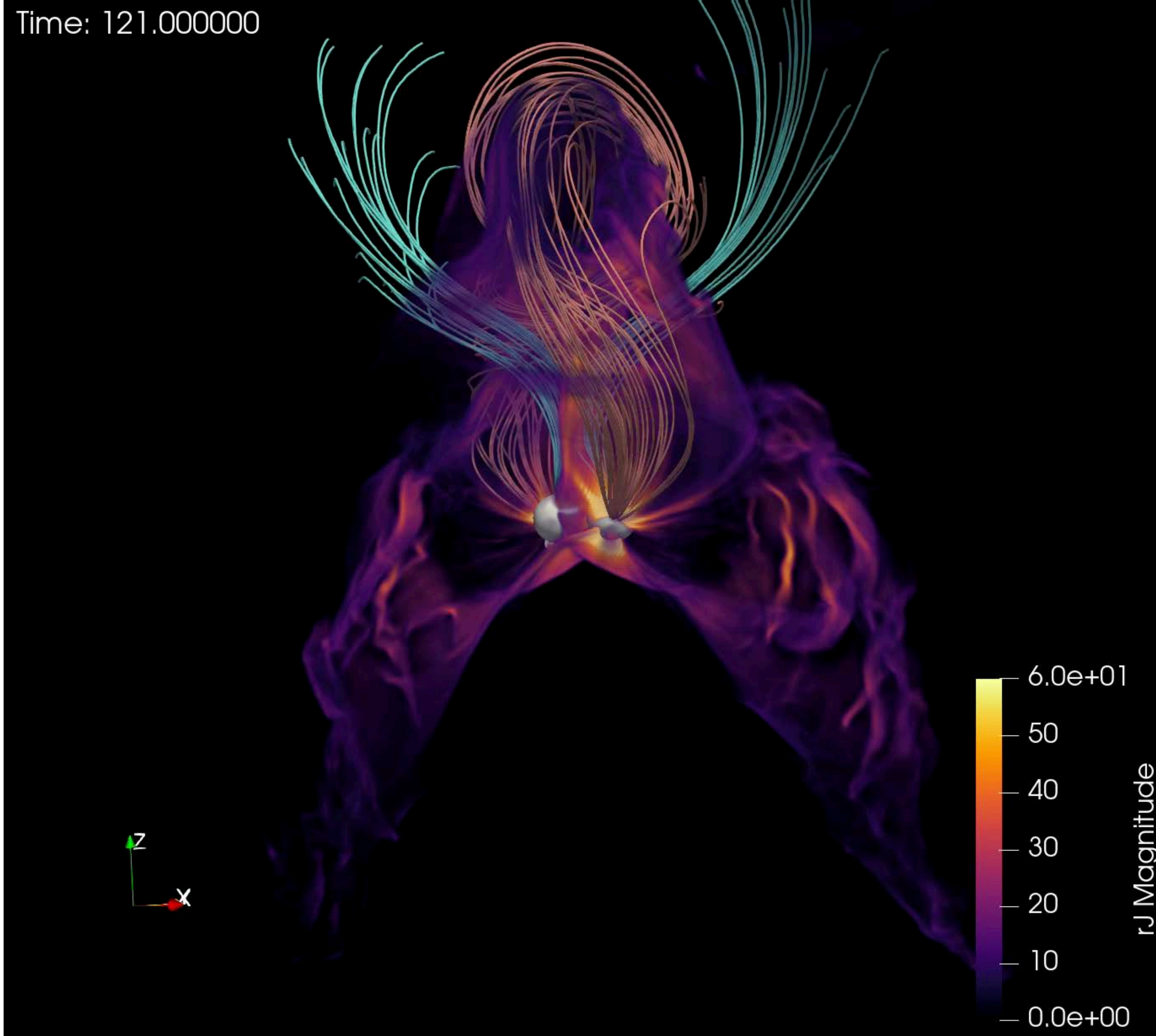


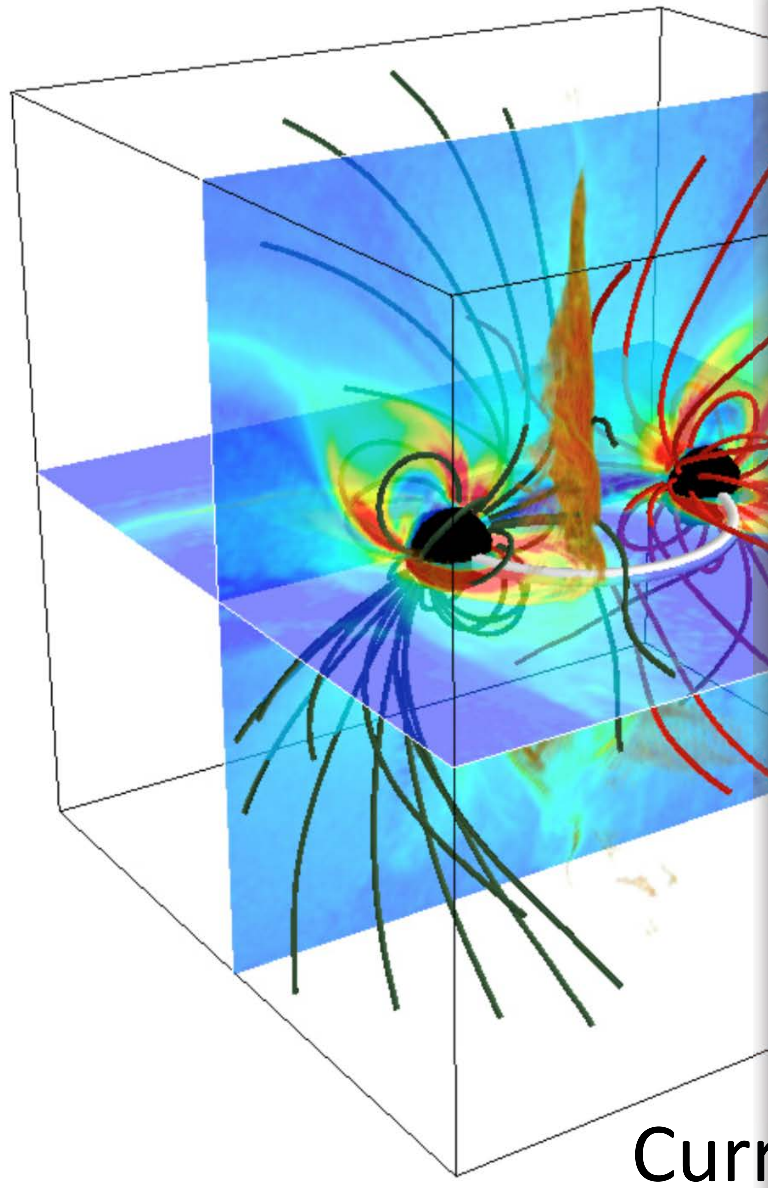
Current rendering

Nontrivial magnetic connection between stars: “bubble” connecting south poles vs “trailing sheet” with reconnection.

Jasmine Parsons, AS, Philippov, in prep



Precursor EM signals from mergers



Curr

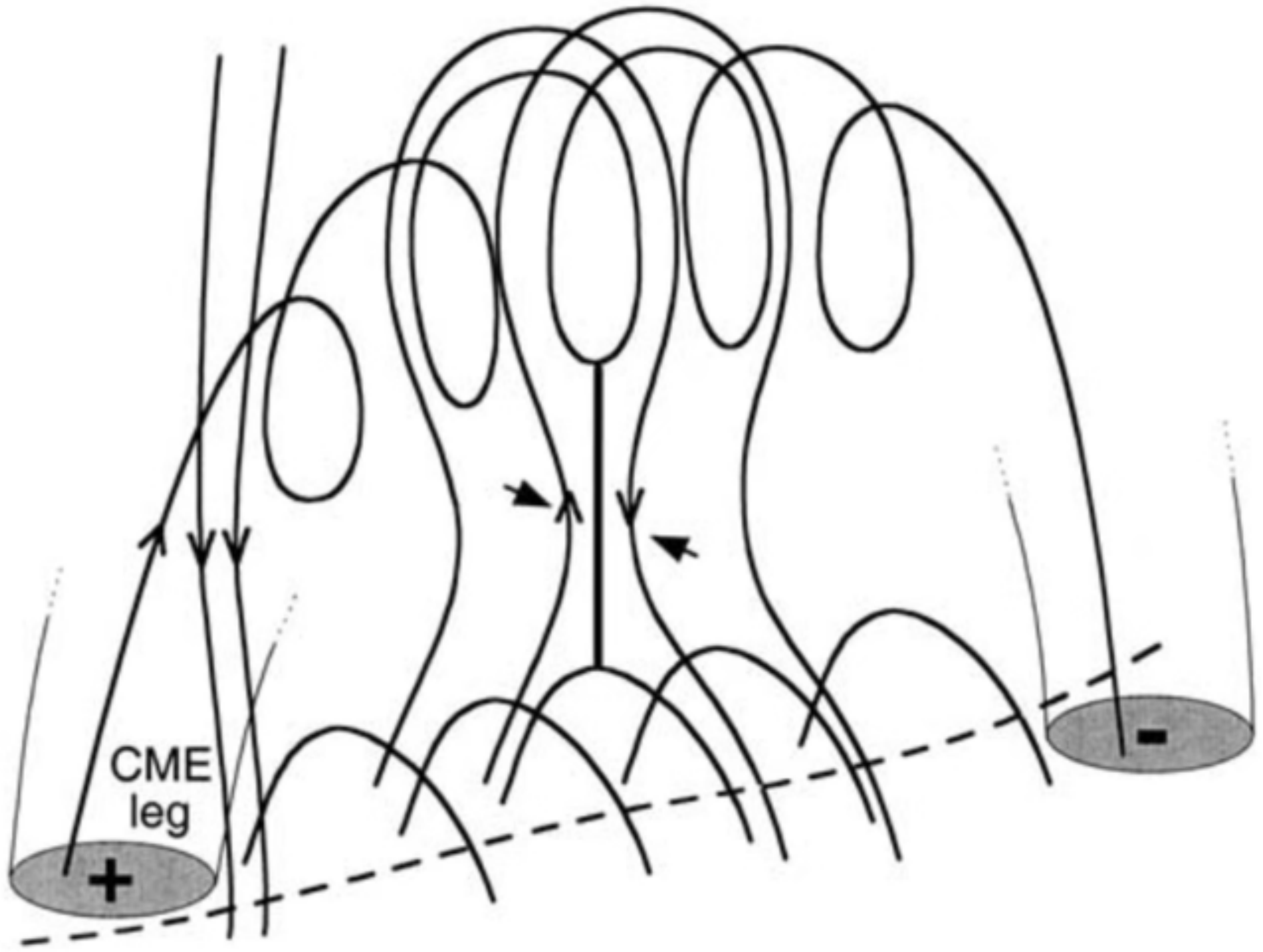
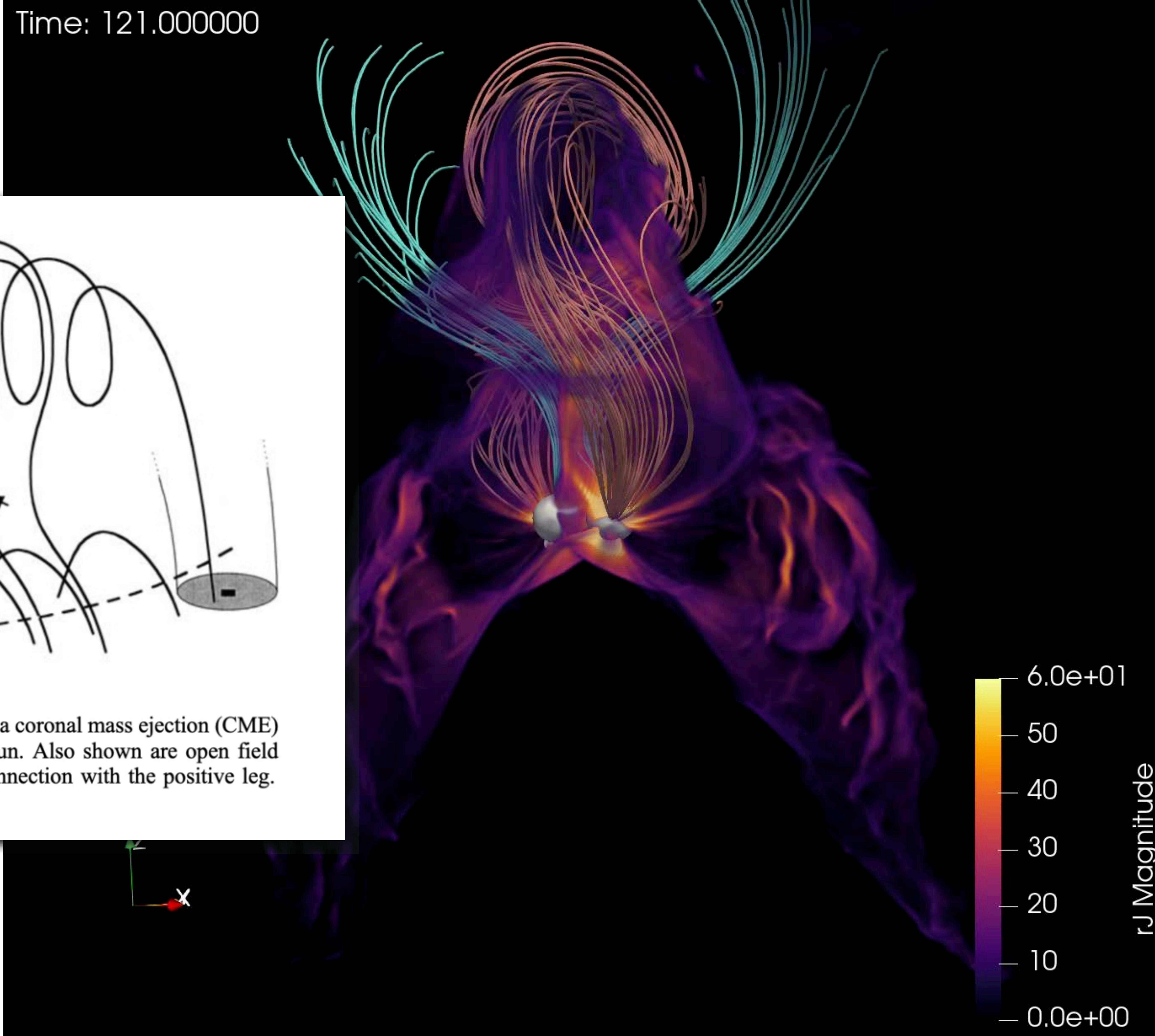
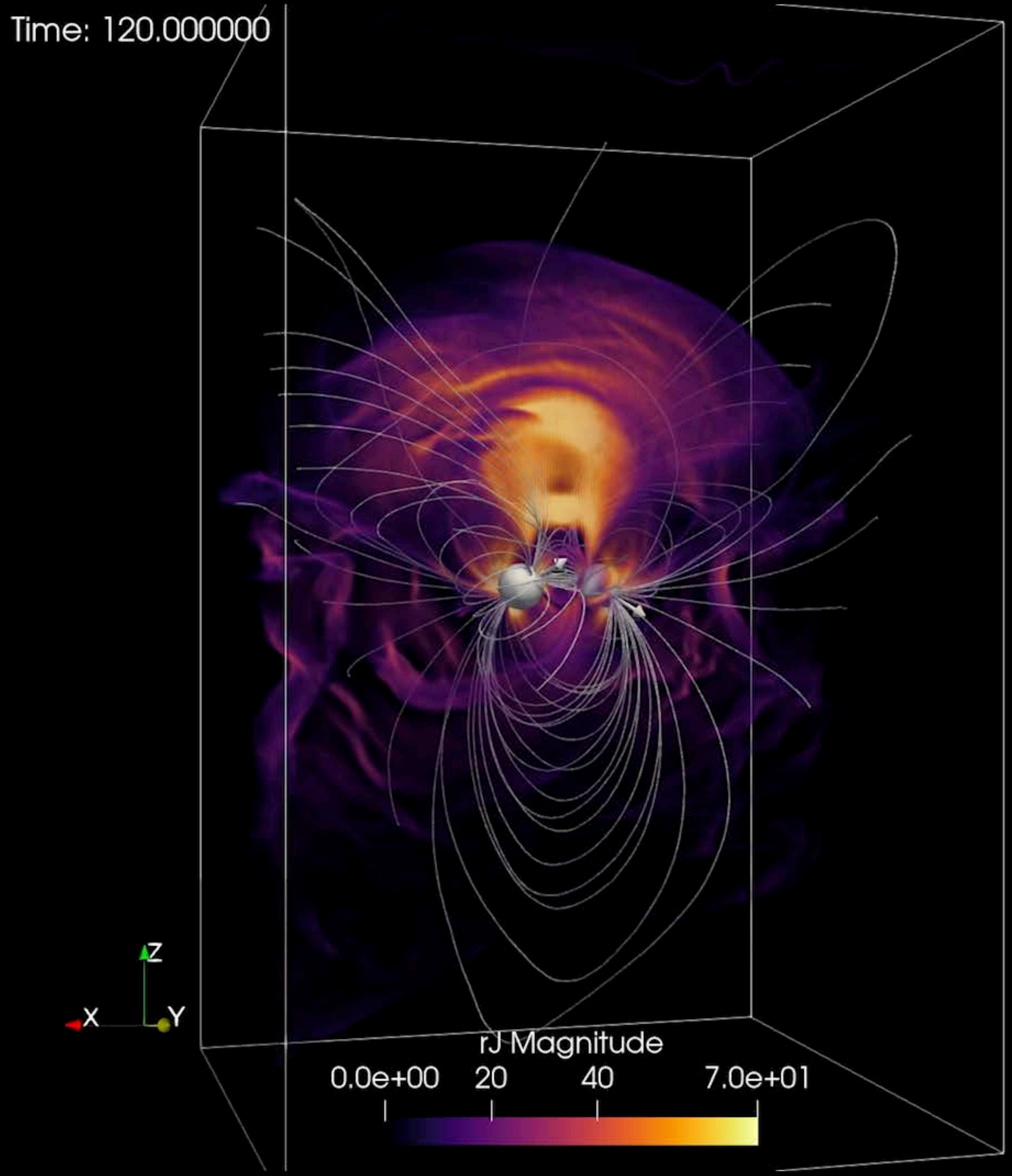


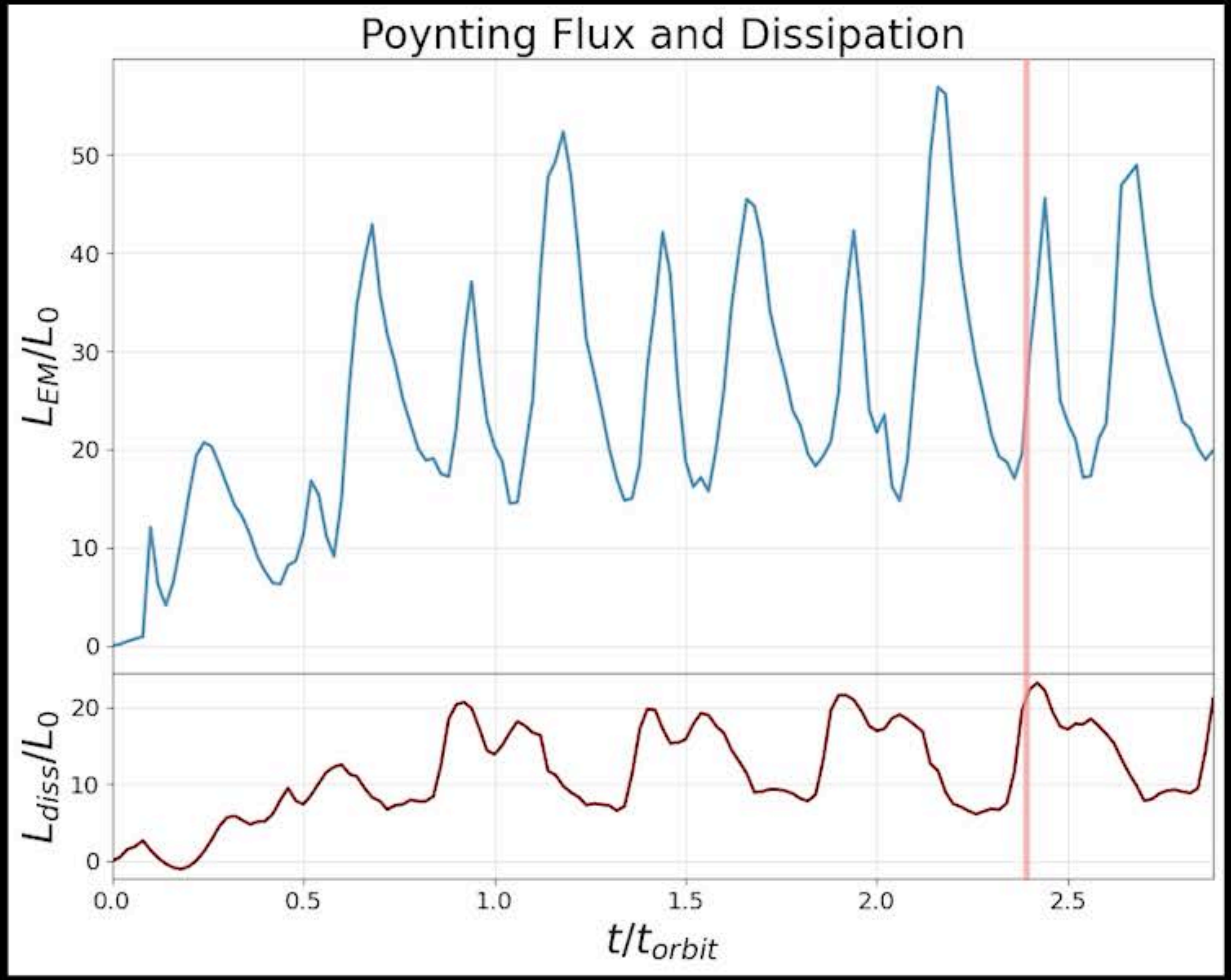
Figure 2. Partial disconnection of a coronal mass ejection (CME) flux rope with legs rooted in the Sun. Also shown are open field lines available for interchange reconnection with the positive leg.



Nontrivial magnetic c
stars: “bubble” conne
“trailing sheet” with

Jasmine Parsons, AS, Philippov, in prep


Time: 120.000000
rJ Magnitude
0.0e+00
20
40
7.0e+01
Z
X
Y


Poynting Flux and Dissipation
L_{EM}/L_0
L_{diss}/L_0
t/t_{orbit}
0
10
20
30
40
50
0.0
0.5
1.0
1.5
2.0
2.5

Precursor EM signals from mergers

Burst of reconnection twice per orbit (period)

Dissipation follows Poynting flux eruptions.

Synchrotron beamed in the polar direction.

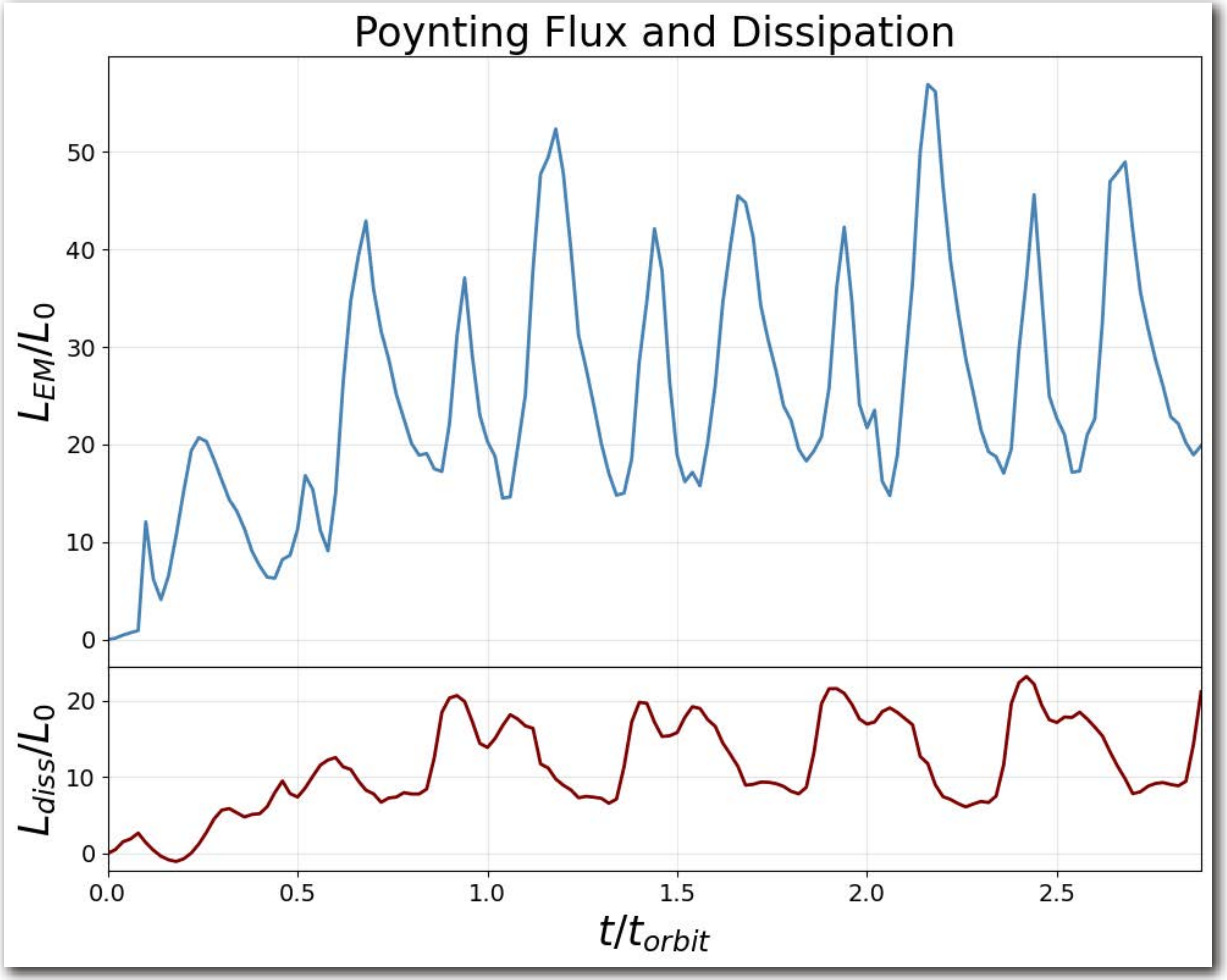
Poynting power for B=2e12G,

orbital frequency ~300Hz: L0 ~ 2x10^42 erg/s

At peak reaches 10^44 erg/s.

Dissipation: 10^43 erg/s.

How does radiation get out?



CONCLUSIONS

- Electrodynamicaly self-consistent, working magnetospheric models with pair formation and radiation are now available using PIC simulations.
- Paradigm change — current sheet beyond light cylinder is an effective particle accelerator and the site of majority of high-energy emission.
- Low altitude radio emission is likely caused by the non-stationary discharge at the polar cap — first signatures of this are seen in local simulations.
- Radio emission associated with gamma-rays (e.g., giant pulses) can also be due to reconnection in the current sheet. Predictions for TeV?
- Time-dependent phenomena can now be addressed, including drifting subpulses, nulling, polarization switches, etc.
- Possibility of ion acceleration in current sheet and precursor emission from merging NSs.