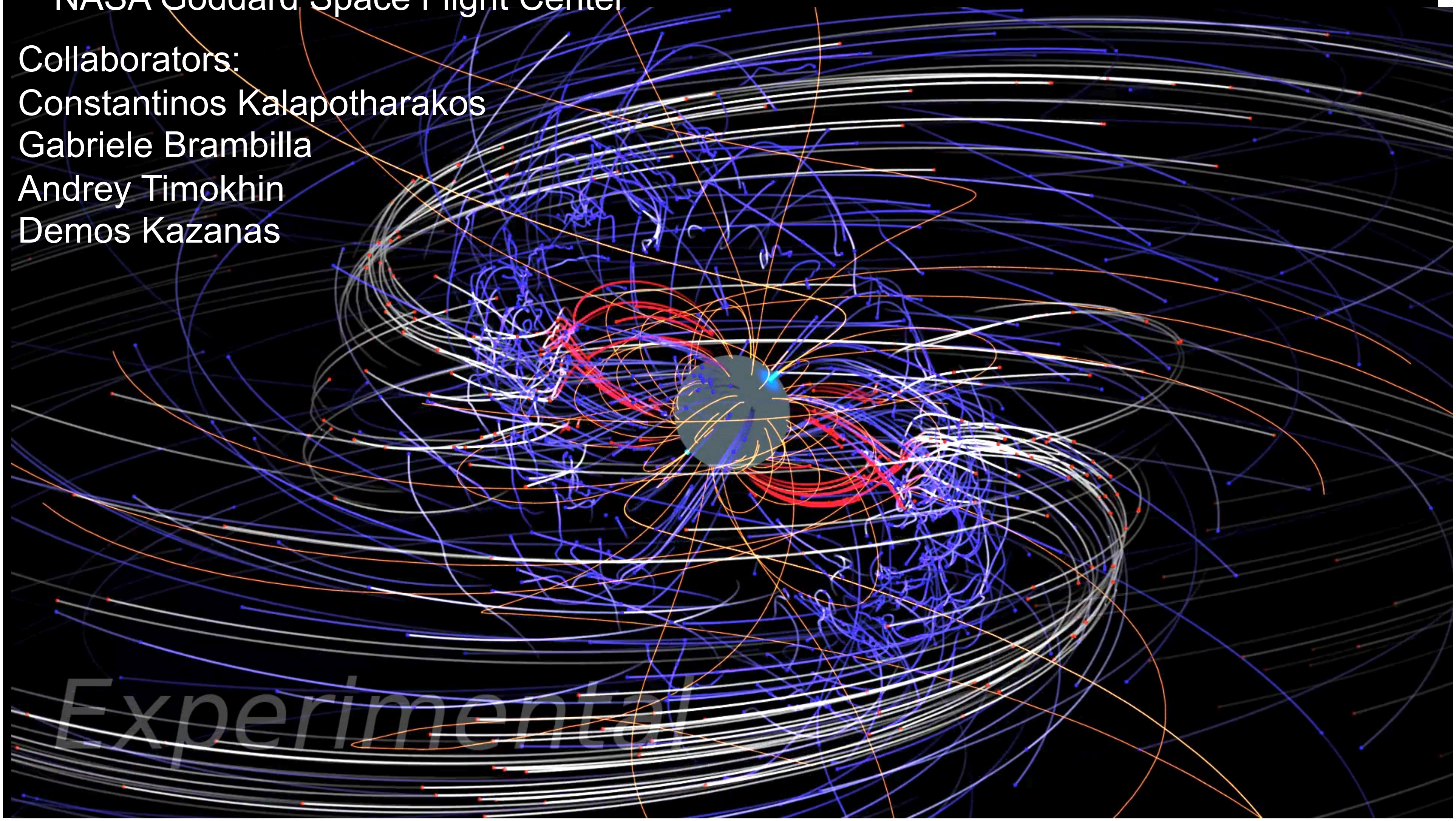
Kinetic Simulations of Pulsar Magnetospheres and High Energy Emission

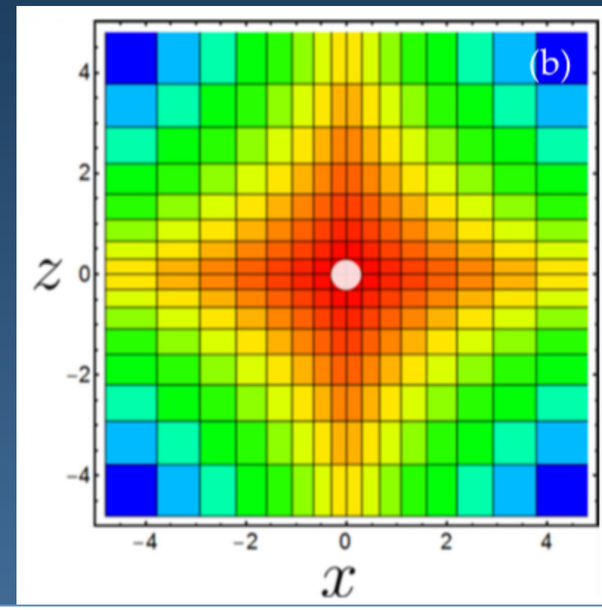
Alice K. Harding
NASA Goddard Space Flight Center

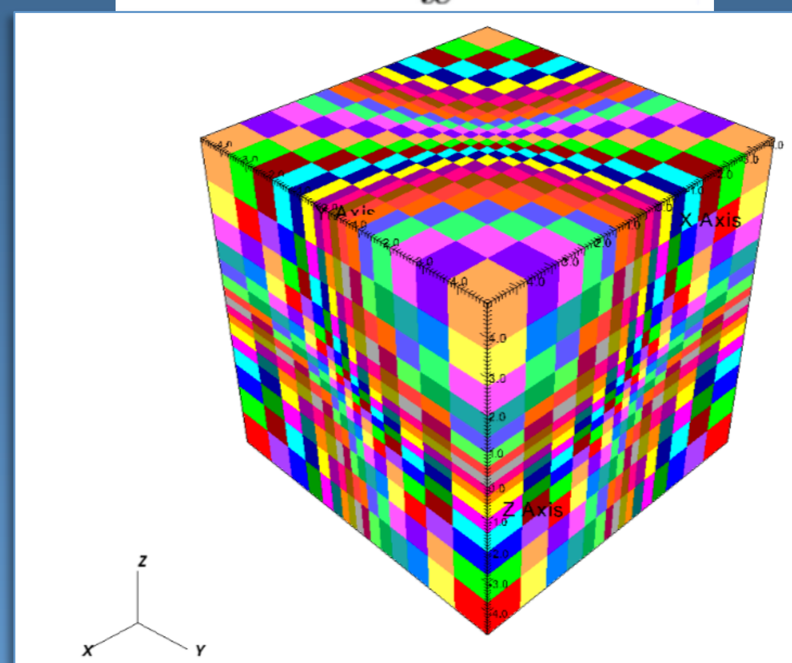


Collaborators:
Constantinos Kalapotharakos
Gabriele Brambilla
Andrey Timokhin
Demos Kazanas

3D Particle-in-Cell code

- 3D Cartesian PIC code written by C. Kalapotharakos
- Particle mover implements Vay's algoritm
- Radiation-reaction forces are included
- Maxwell's Eqns integrated by FDTD on Yee mesh
- Cube with sides 9.6 R_{LC} – PML used at outer boundaries
- Neutron star surface at 0.28 R_{LC} - boundary layer 0.28 – 0.36 R_{LC} enforces force-free E
- Non-uniform computational volume controls CPU load balance
- Surface B <= 10^6 G to maintain high magnetization

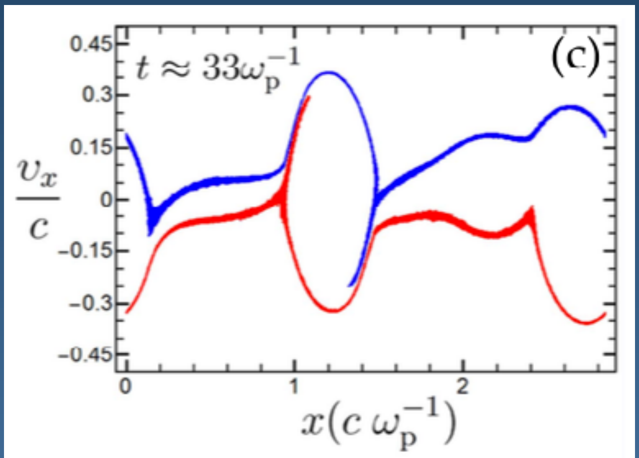


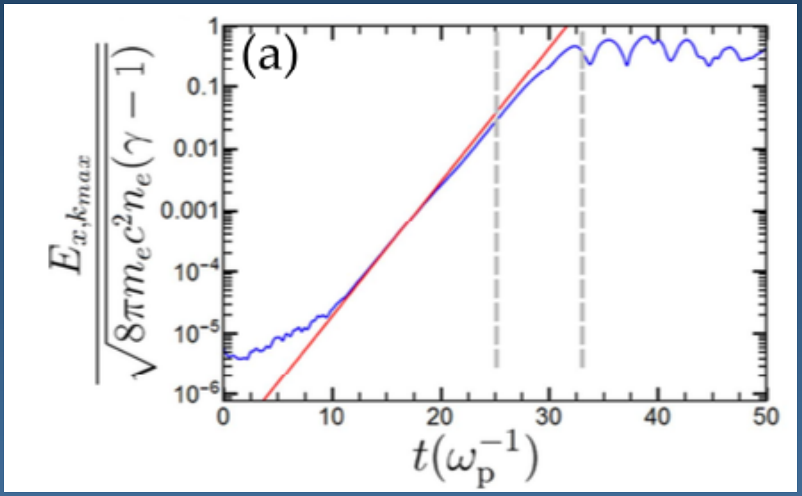


Tests of PIC code

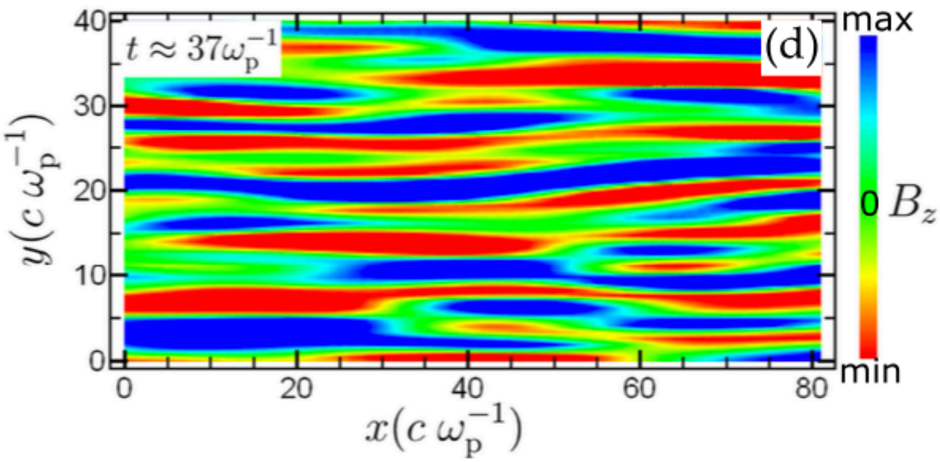
Kalapotharakos et al. 2018

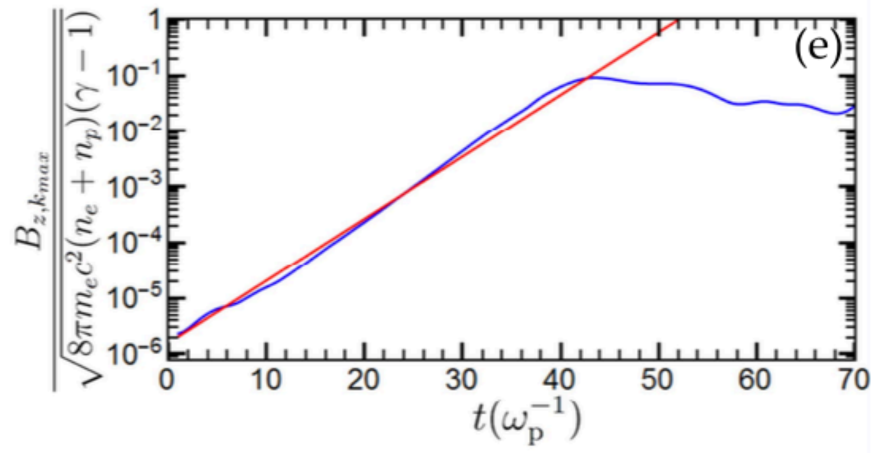
2-stream instability:





Weibel instability:





Pair injection

- Injection in all cells up to r = 2.5 R_{LC}

Inject one pair at rest per time step in each cell where local magnetization is above a value:

$$\sigma_M = \frac{B^2}{8\pi(n_{e^+} + n_{e^-}) m_e c^2}$$

$$\Sigma = \begin{cases} \Sigma_0 \left(\frac{r_s}{r}\right)^3 & \text{if } r \leqslant R_{LC} \\ \Sigma_0 \left(\frac{r_s}{R_{LC}}\right)^3 \frac{R_{LC}}{r} & \text{if } r > R_{LC} \end{cases}$$

where Σ_0 is adjusted to reach a given pair injection rate at the NS r_s

$$F = M\,F_{GJ} = M\,\frac{\Omega B_S A_{PC}}{\pi q_e}, \qquad F_{GJ}^0 = F_{GJ}/\cos\alpha$$

- Injection only near neutron star surface

Inject one pair per time step in only first layers of cells above boundary layer at 0.36 -0.5 R_{LC} when σ_M is above (r_0 = 0.36 R_{LC})

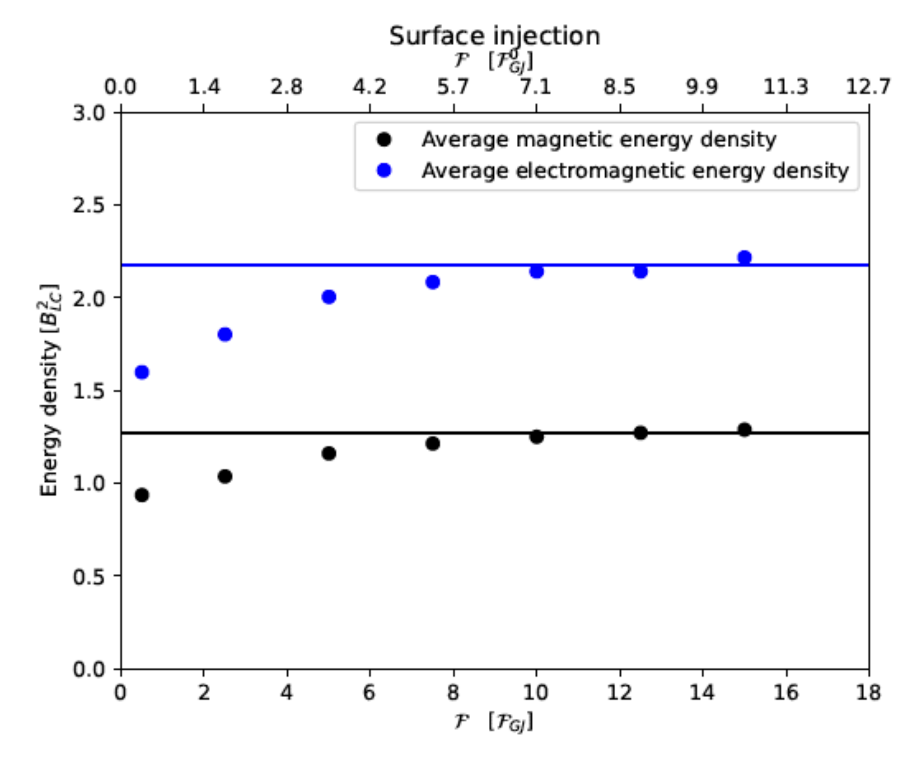
$$\Sigma = \Sigma_0 \left(\frac{r_0}{r}\right)^3$$

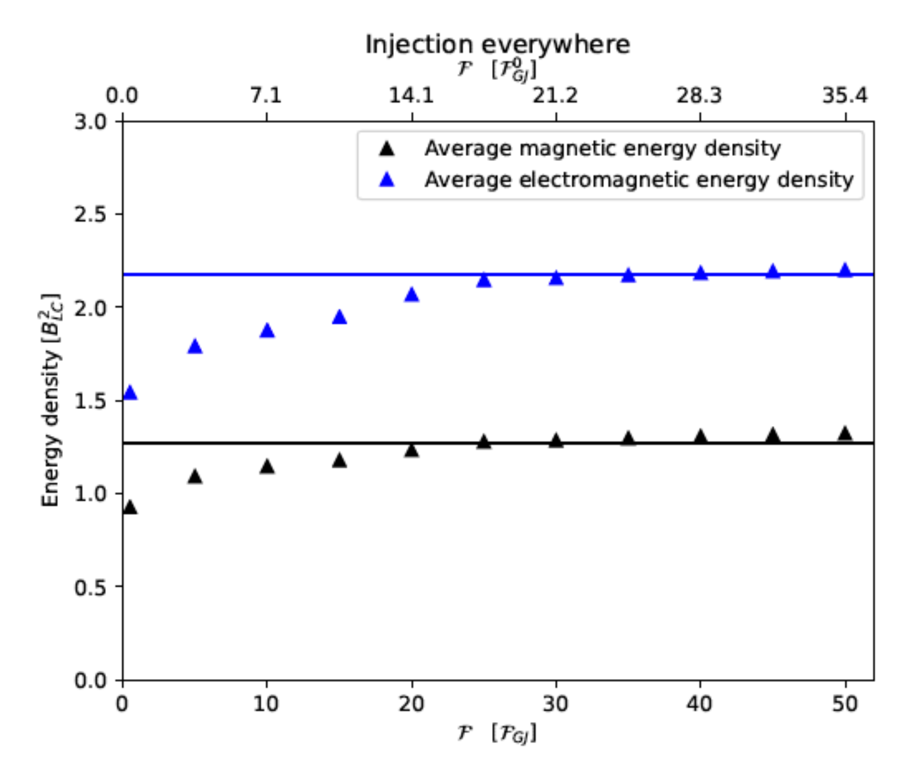
Formation of force-free magnetosphere

Brambilla et al. 2018

Pair injection rate needed to reach average magnetic and electromagnetic energy density of force-free magnetosphere

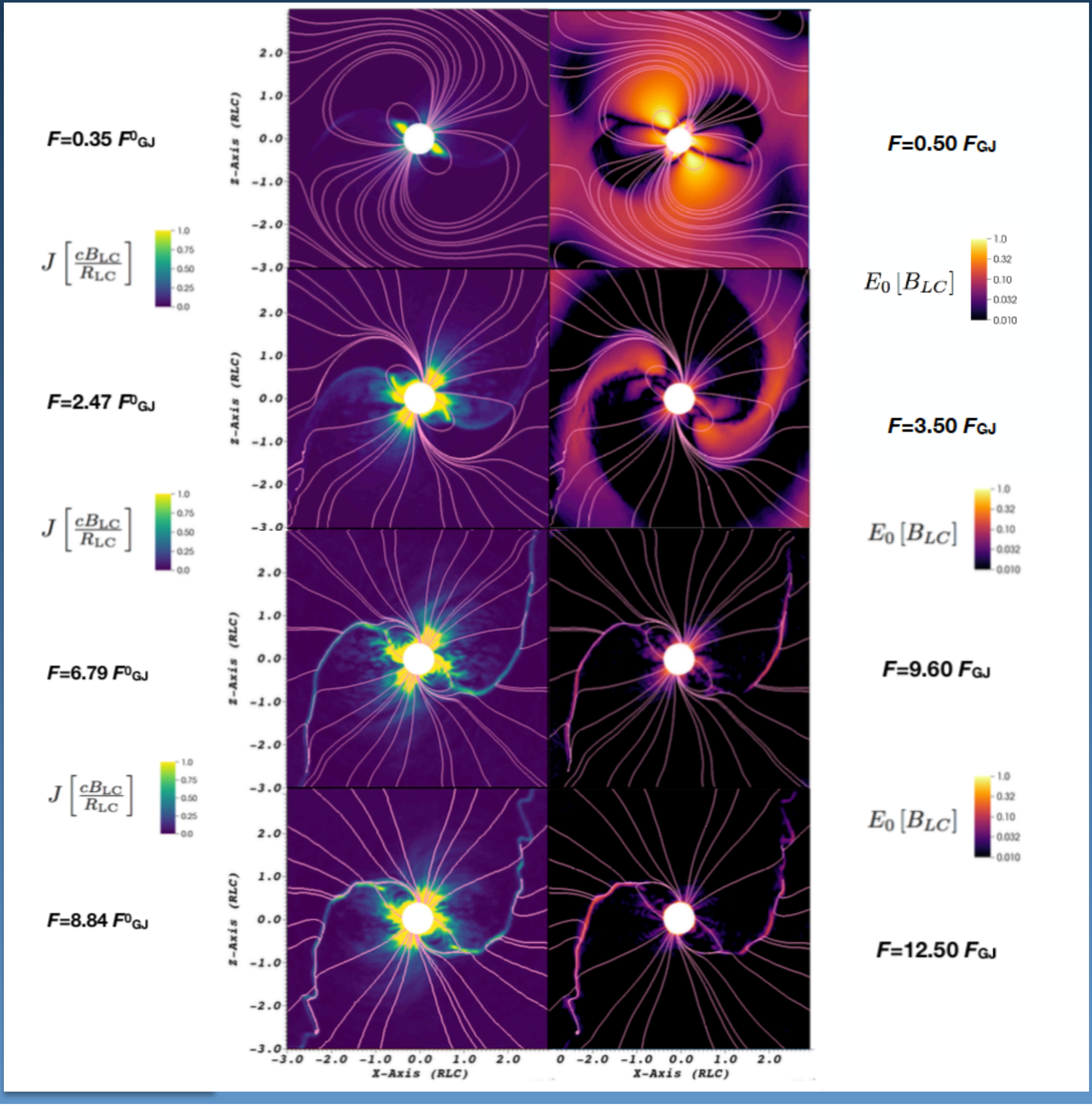
$\alpha = 45^0$





Current and E_0 with injection rate

Brambilla et al. 2018

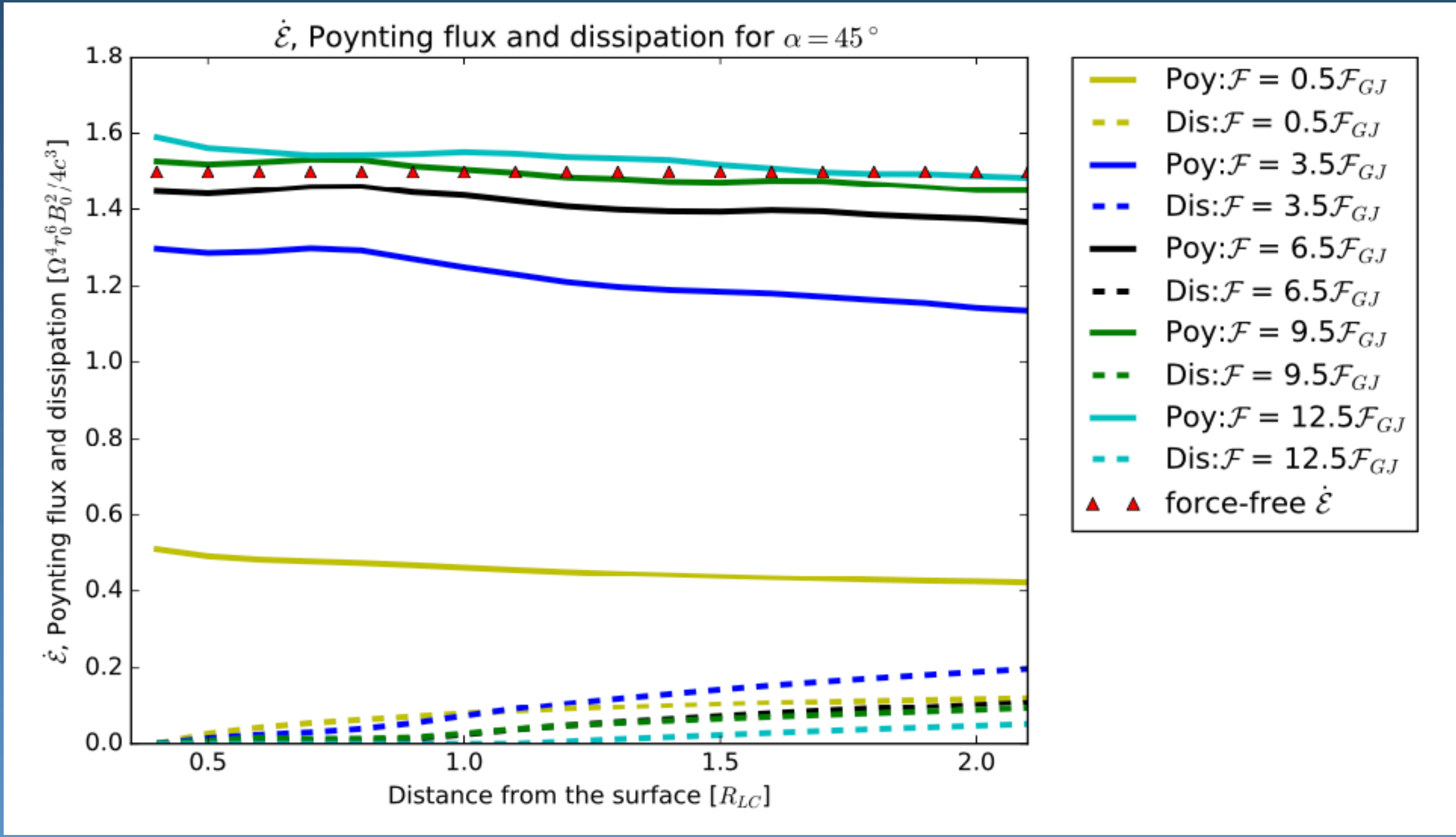


As pair injection rate increases – region of accelerating electric field shrinks to current sheet

Poynting flux and dissipation

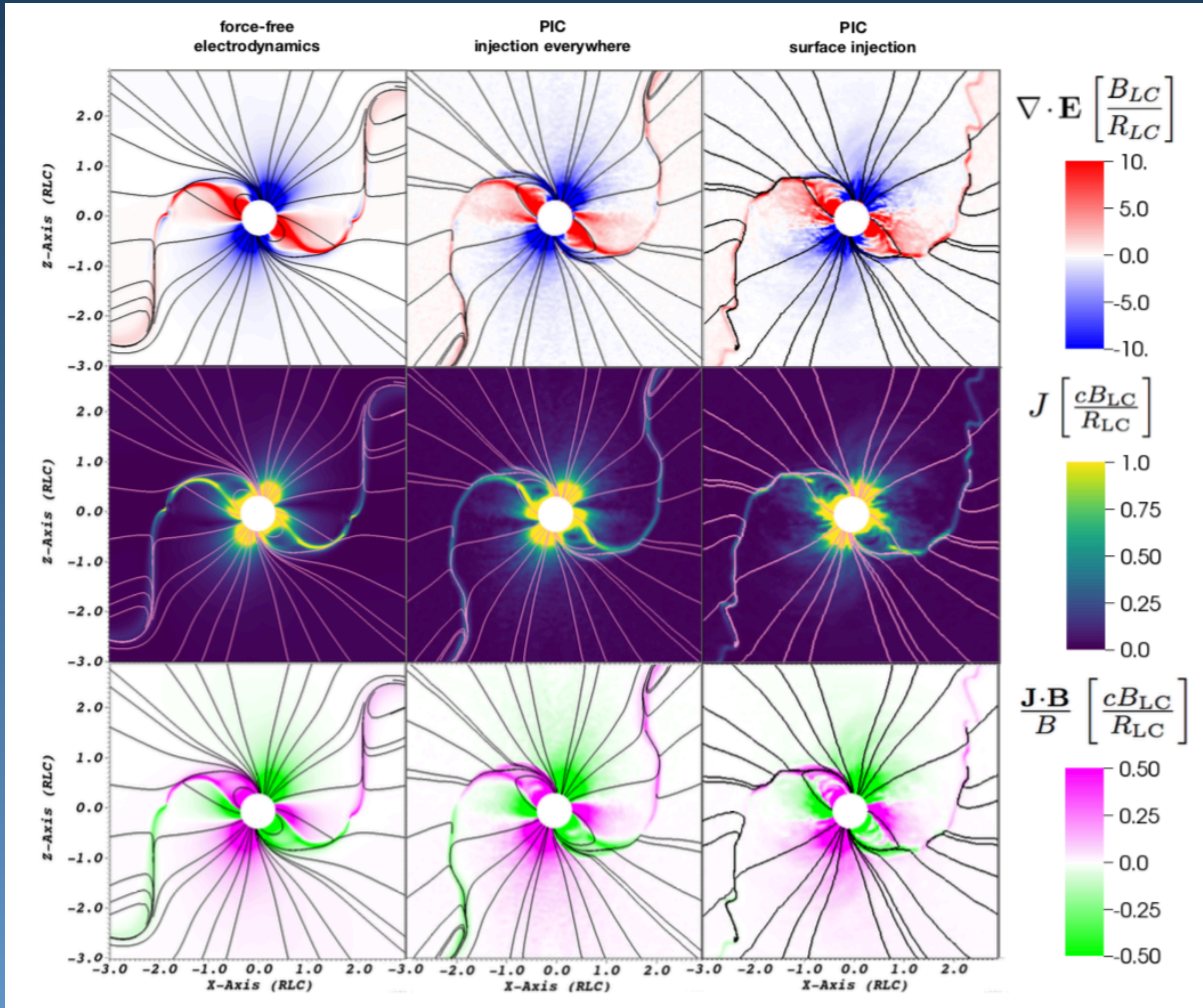
Maximum dissipation 15% at $\mathcal{F} = 3.5\ \mathcal{F}_{GJ}$

Brambilla et al. 2018



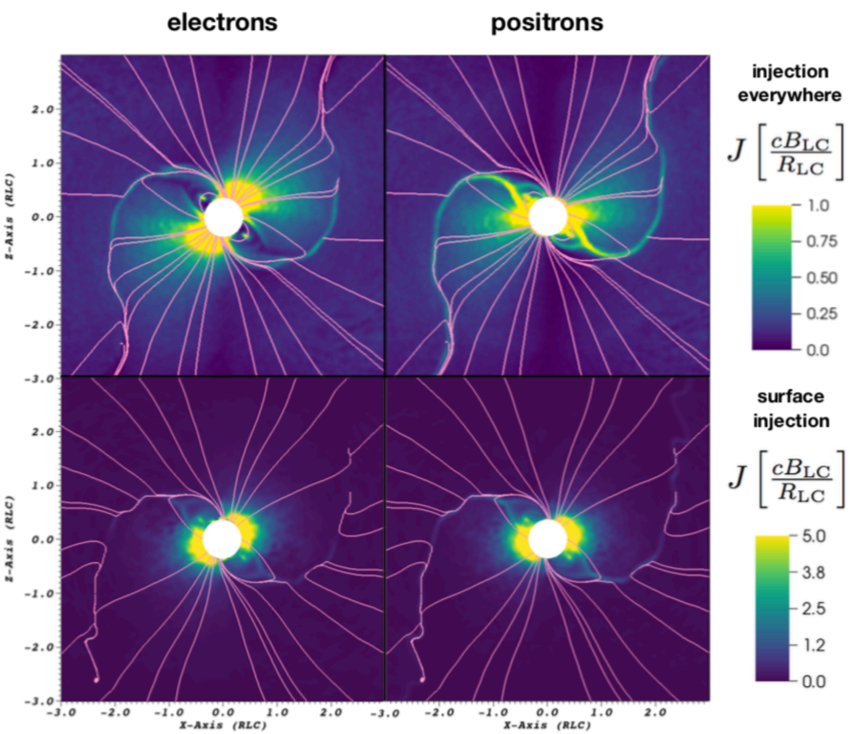
Global vs. surface injection

Brambilla et al. 2018



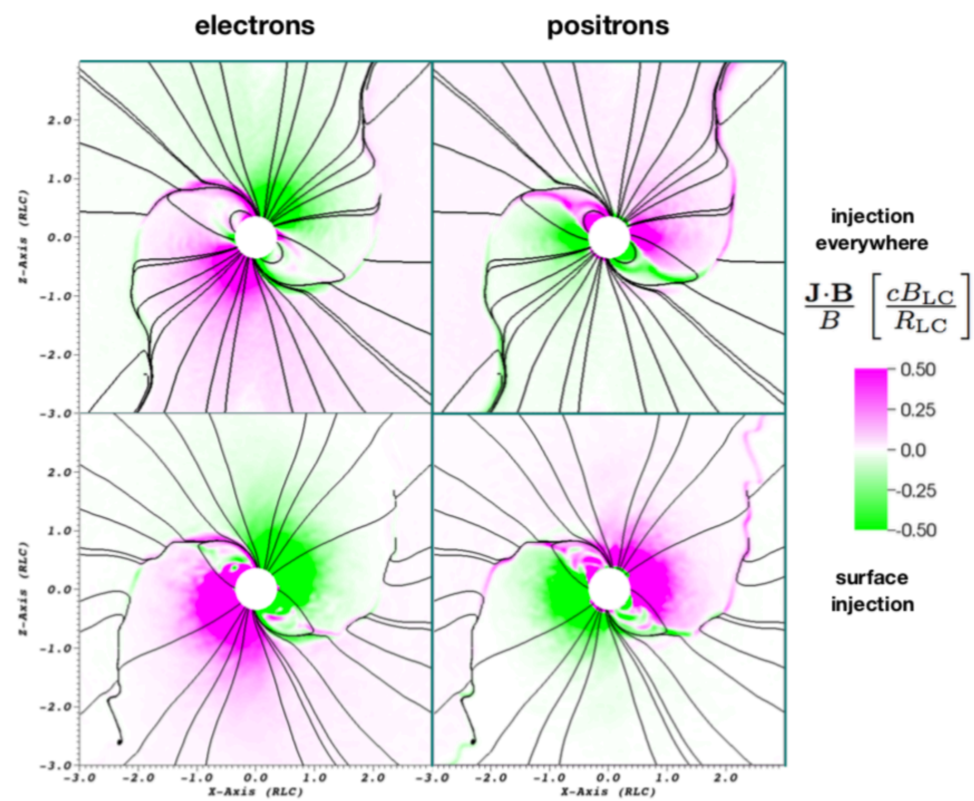
Positron and electron currents

Brambilla et al. 2018



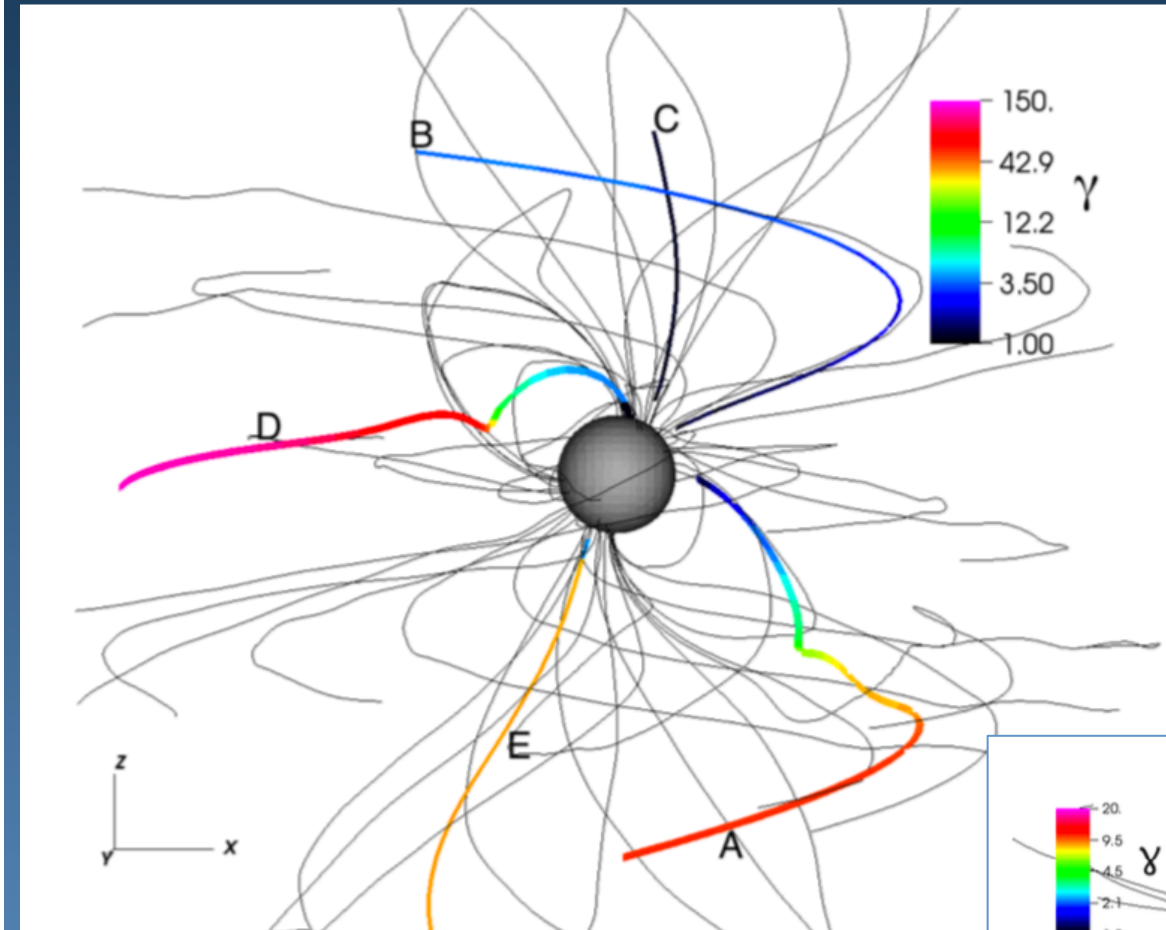
Injection everywhere: e^-/e^+ contribute only to currents in negative/positive charge regions

Surface injection: both e^-/e^+ contribute to currents in all regions



For surface injection e^- and e^+ counter stream only on negative branch of separatrix

Particle trajectories

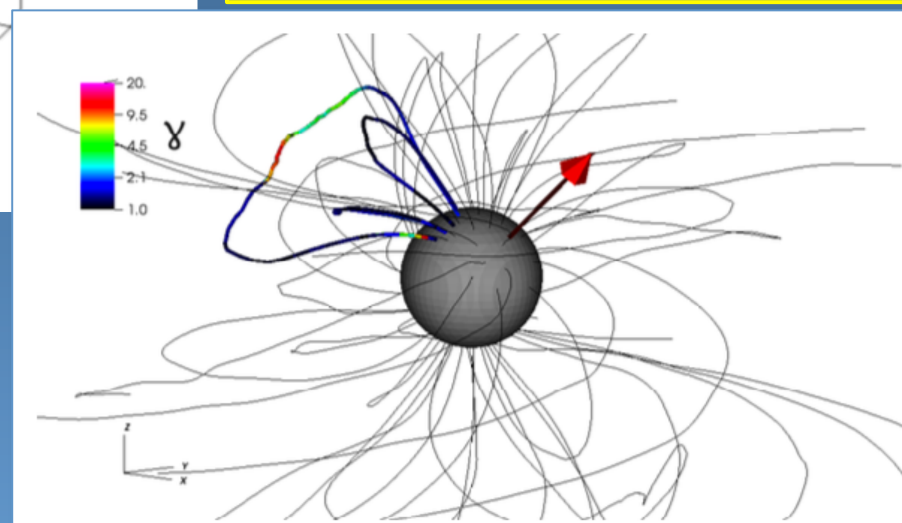


Surface injection

A, D – positrons at Y-point and in current sheet

B, C, E – positrons and electrons flowing out above polar cap

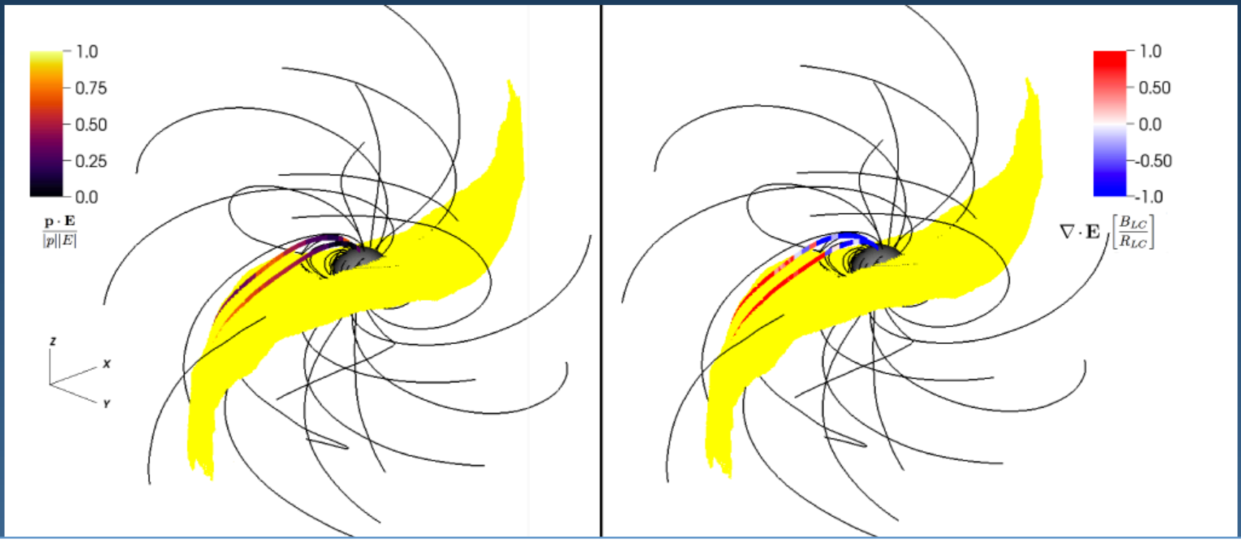
Electrons falling back to the neutron star
(see also Cerutti et al. 2015, Philippov et al. 2017)



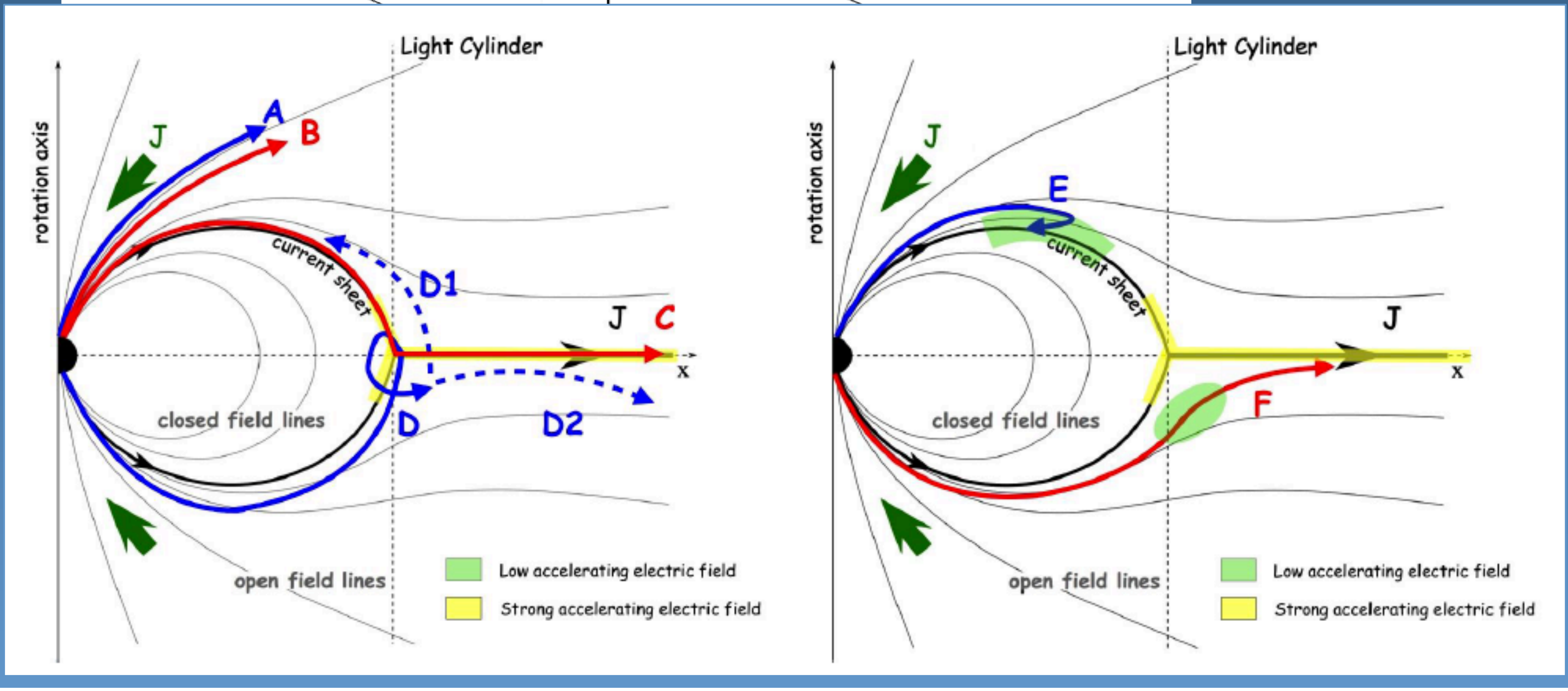
Brambilla et al. 2018

Particle trajectories

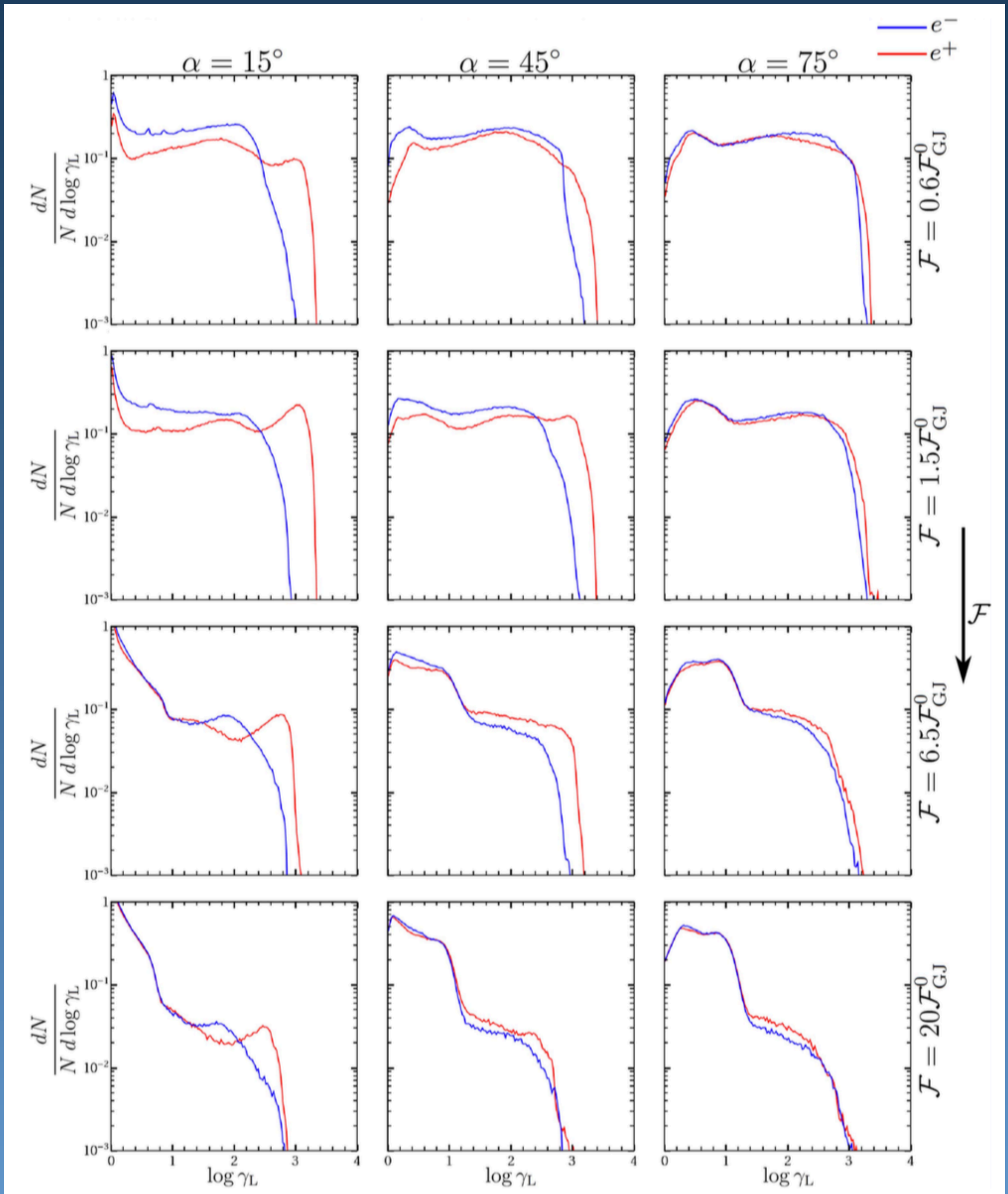
Brambilla et al. 2018



e$^+$ from polar region that cross field lines to enter current sheet



Particle distributions



Low α: mostly positrons at highest energy
High α: both positrons and electrons at highest energy

As injection rate increases: Smaller percentage of particles at highest energy

Kalapotharakos et al. 2018

Accelerating field

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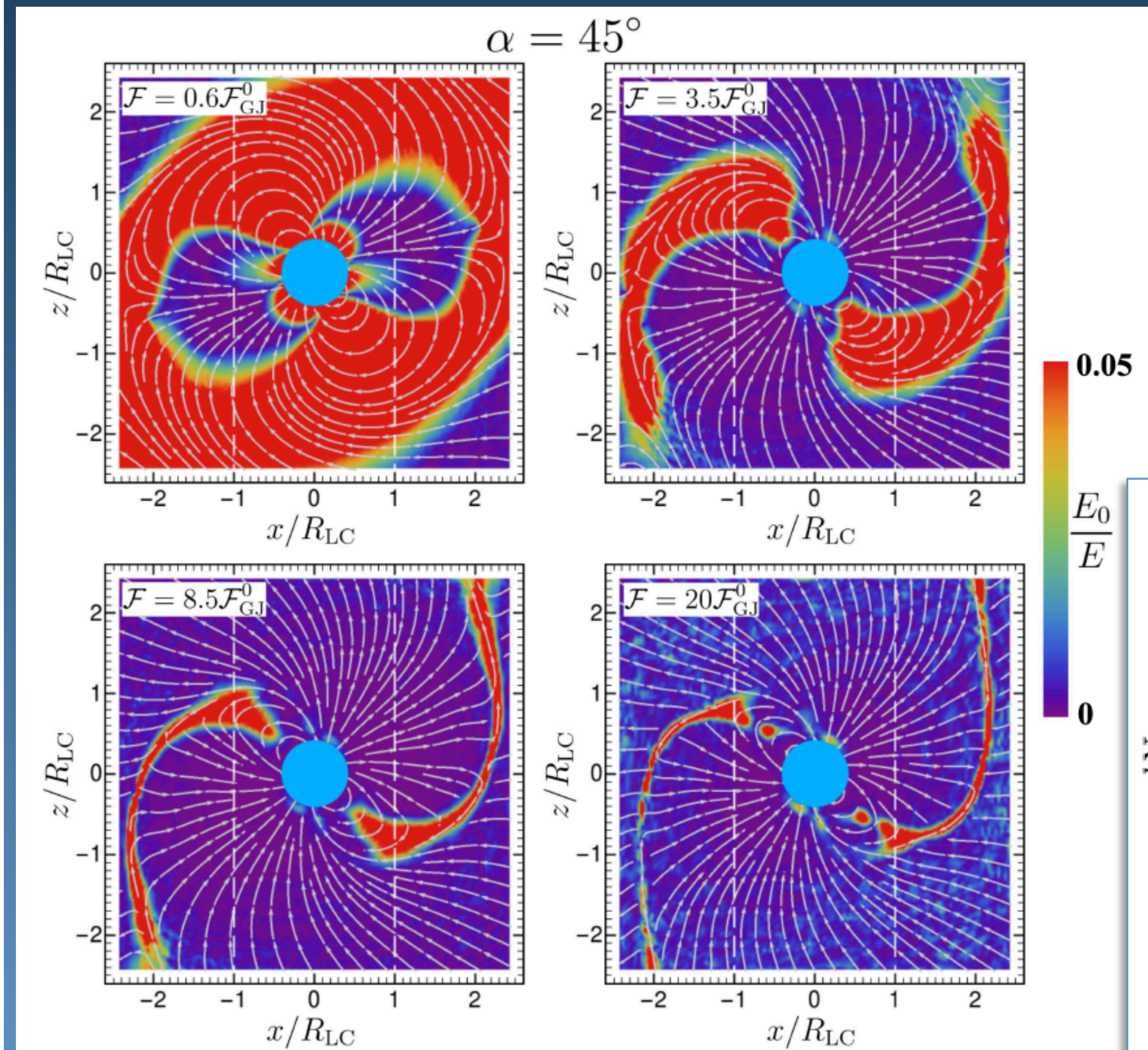
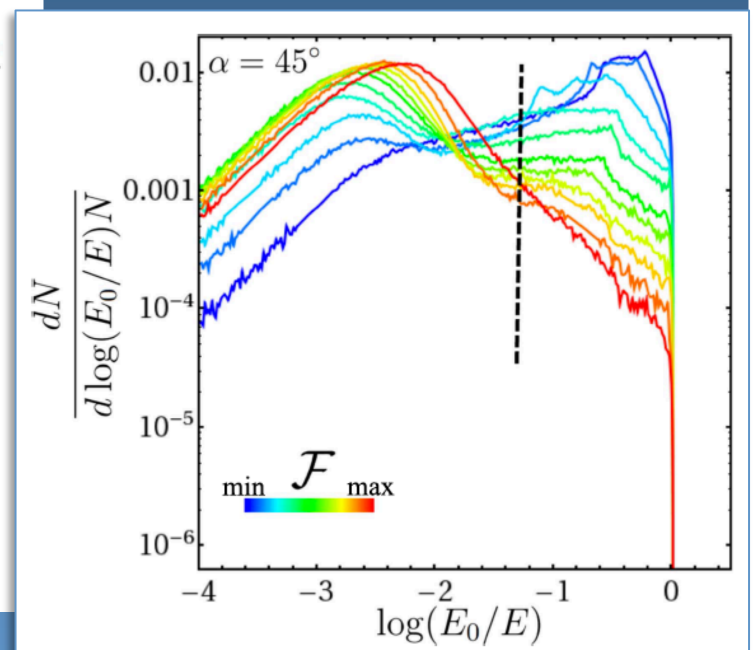


As pair injection rate increases – region of accelerating electric field shrinks to current sheet



Particle acceleration site

Most particle acceleration occurs in and near the current sheet and separatrices

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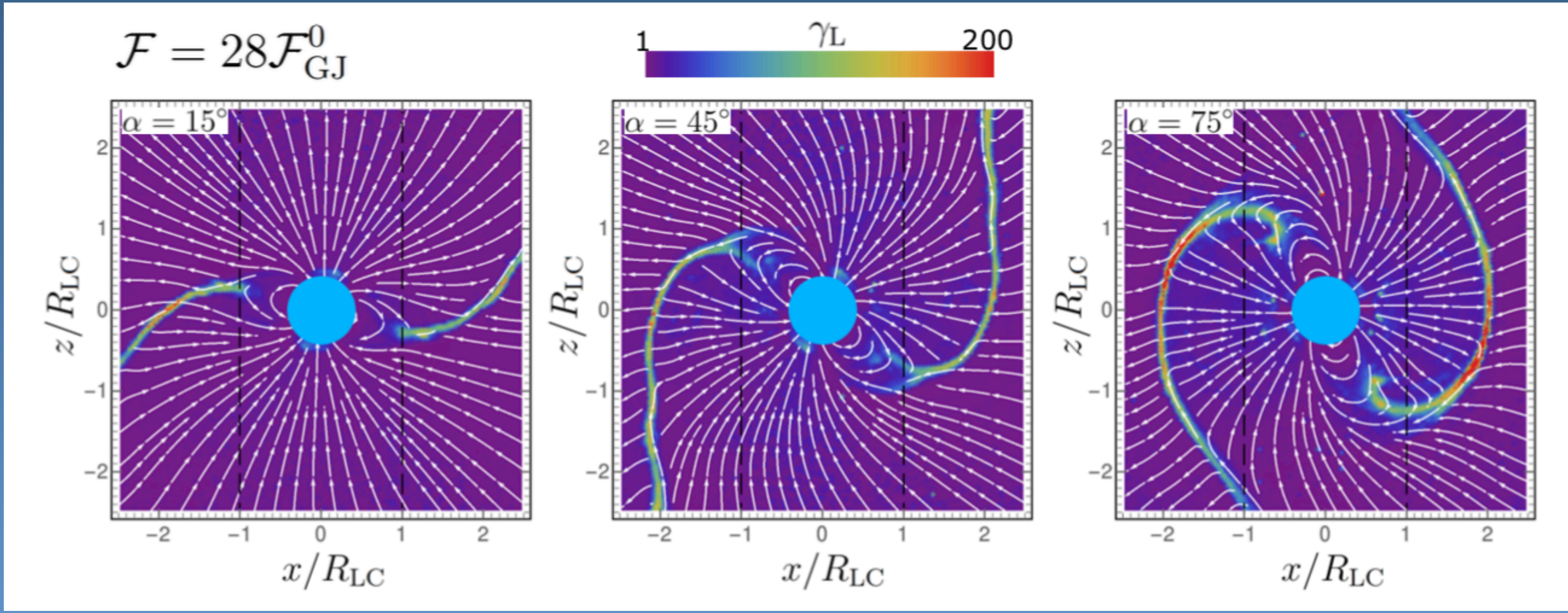


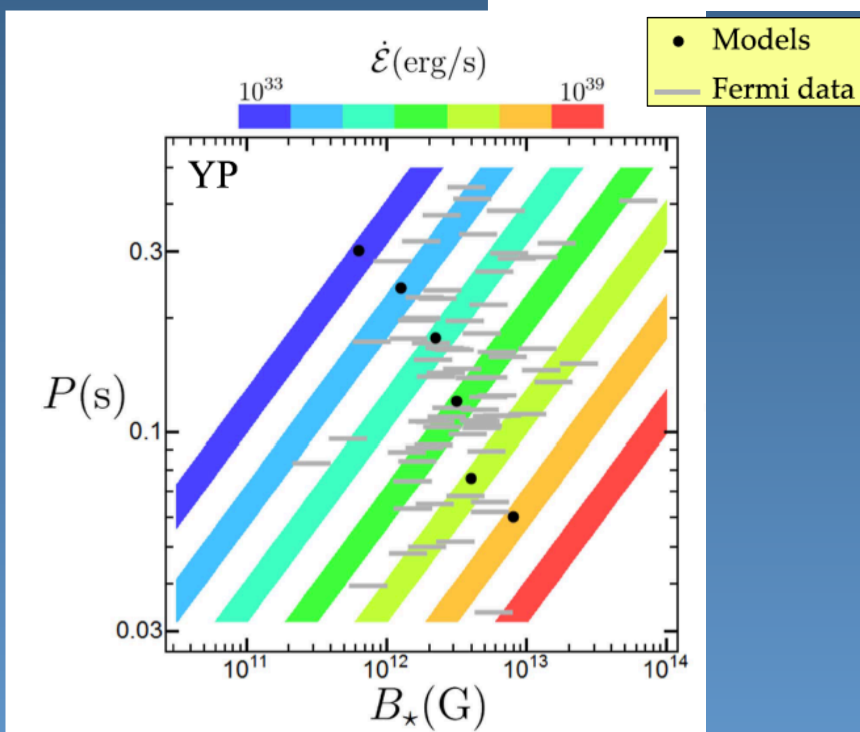
High energy emission

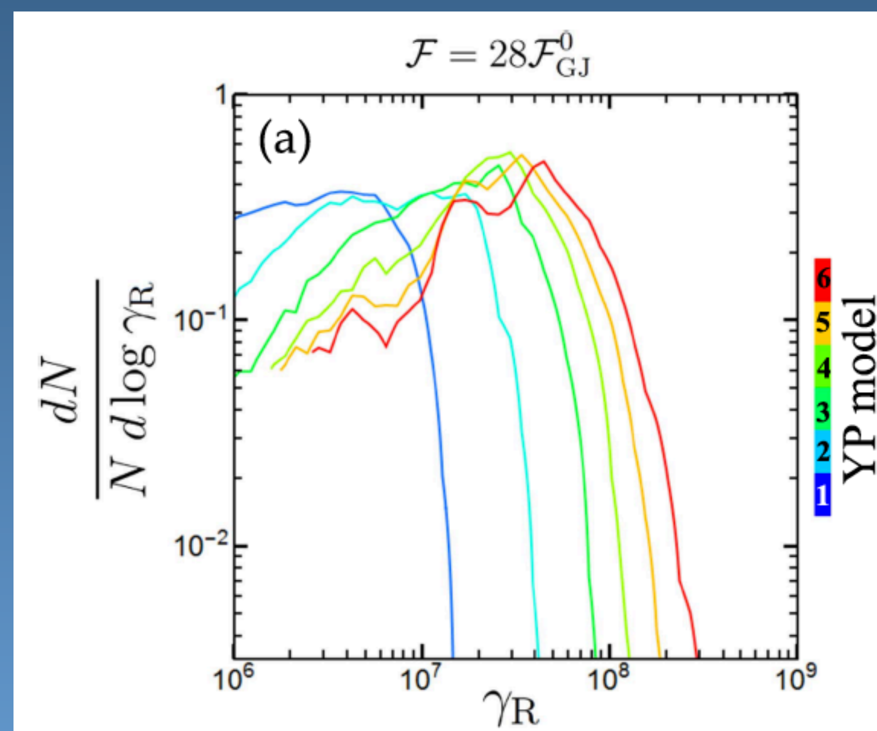
Kalapotharakos et al. 2018

Problem – how to scale maximum PIC energy ($\gamma \sim 10^3$) to maximum energy of real pulsar ($\gamma \sim 10^{7\text{-}8}$)?

Our solution – parallel calculation of particle dynamics with B_0 (and resulting E_0) scaled up to those of real pulsar

$$\frac{d\gamma_R}{dt} = \frac{q_e \boldsymbol{v} \cdot \boldsymbol{E}}{m_e c^2} - \frac{2 q_e^2 \gamma_R^4}{3 R_C^2 m_e c}$$





Spectral cutoff energy

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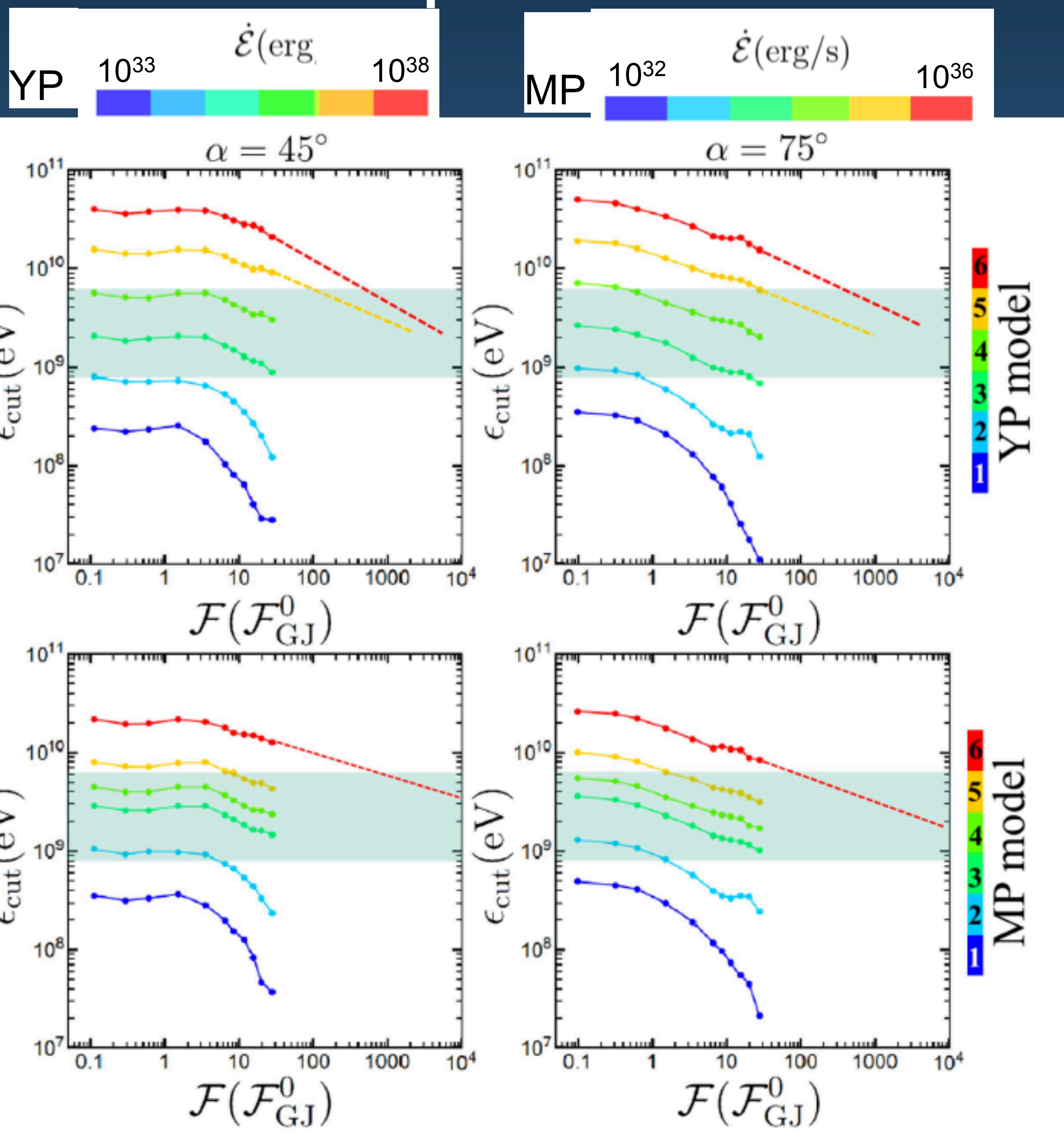
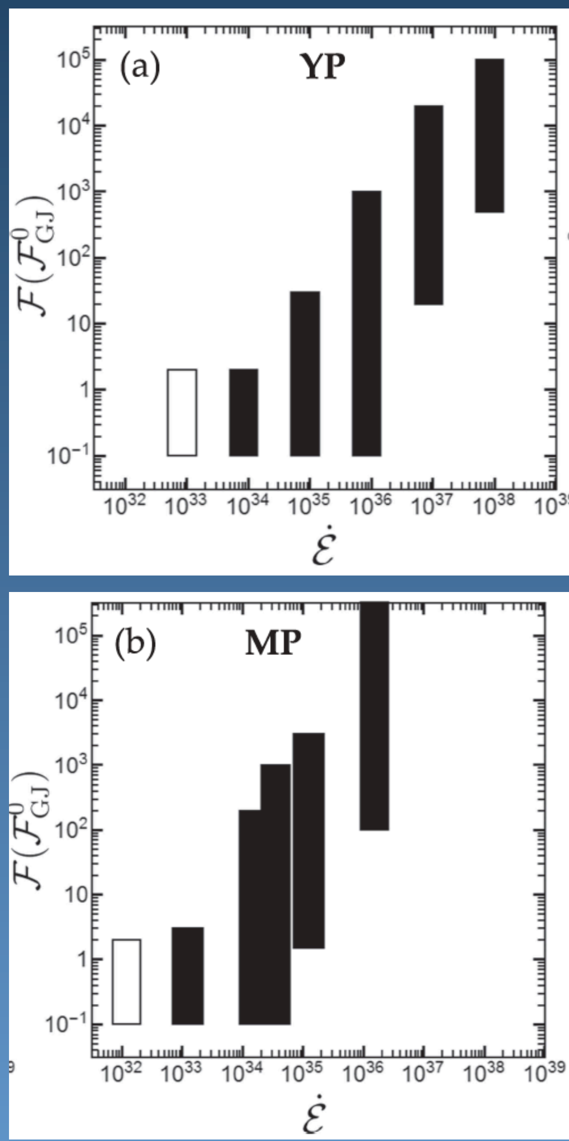
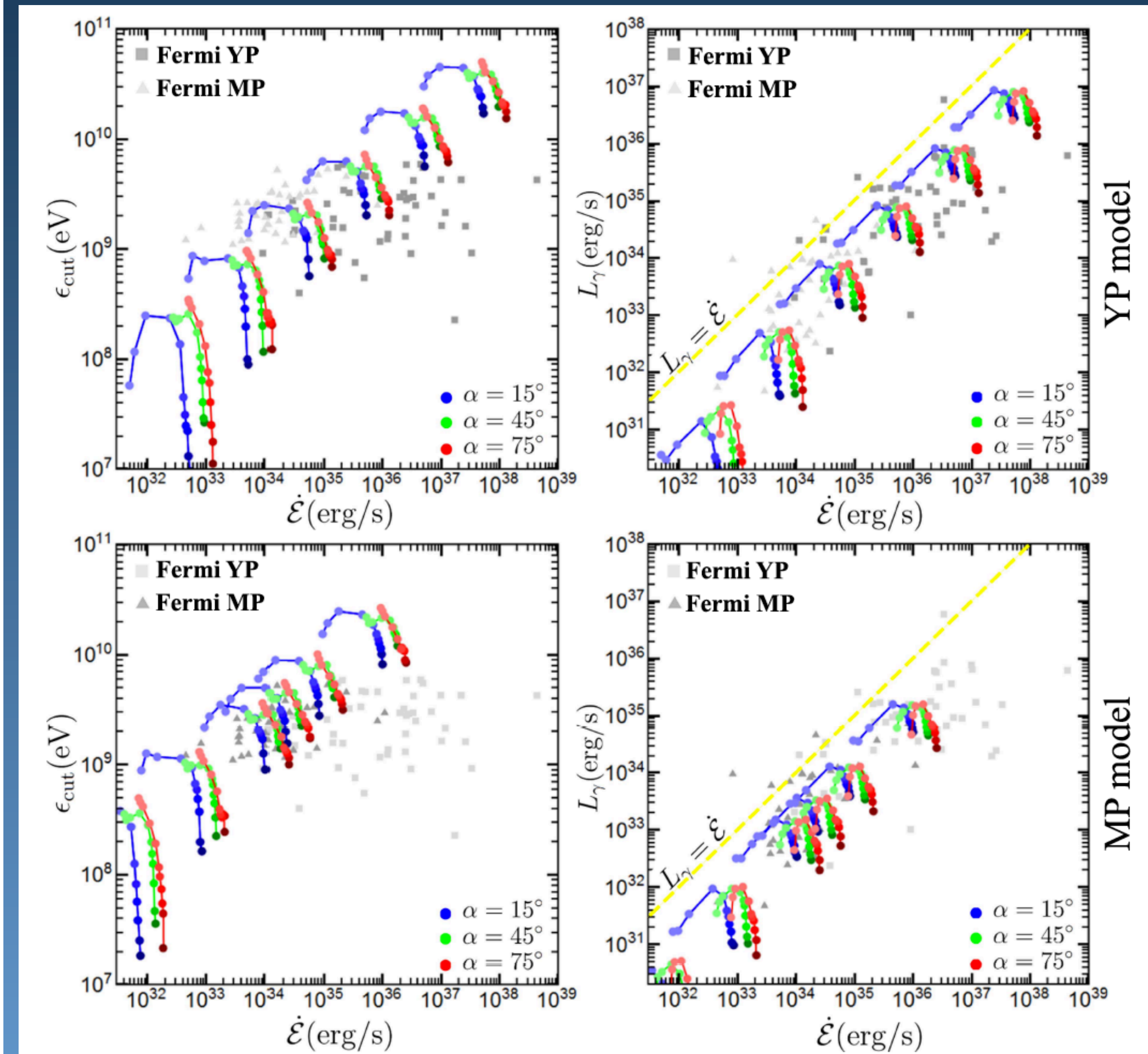




Cutoff energy and luminosity



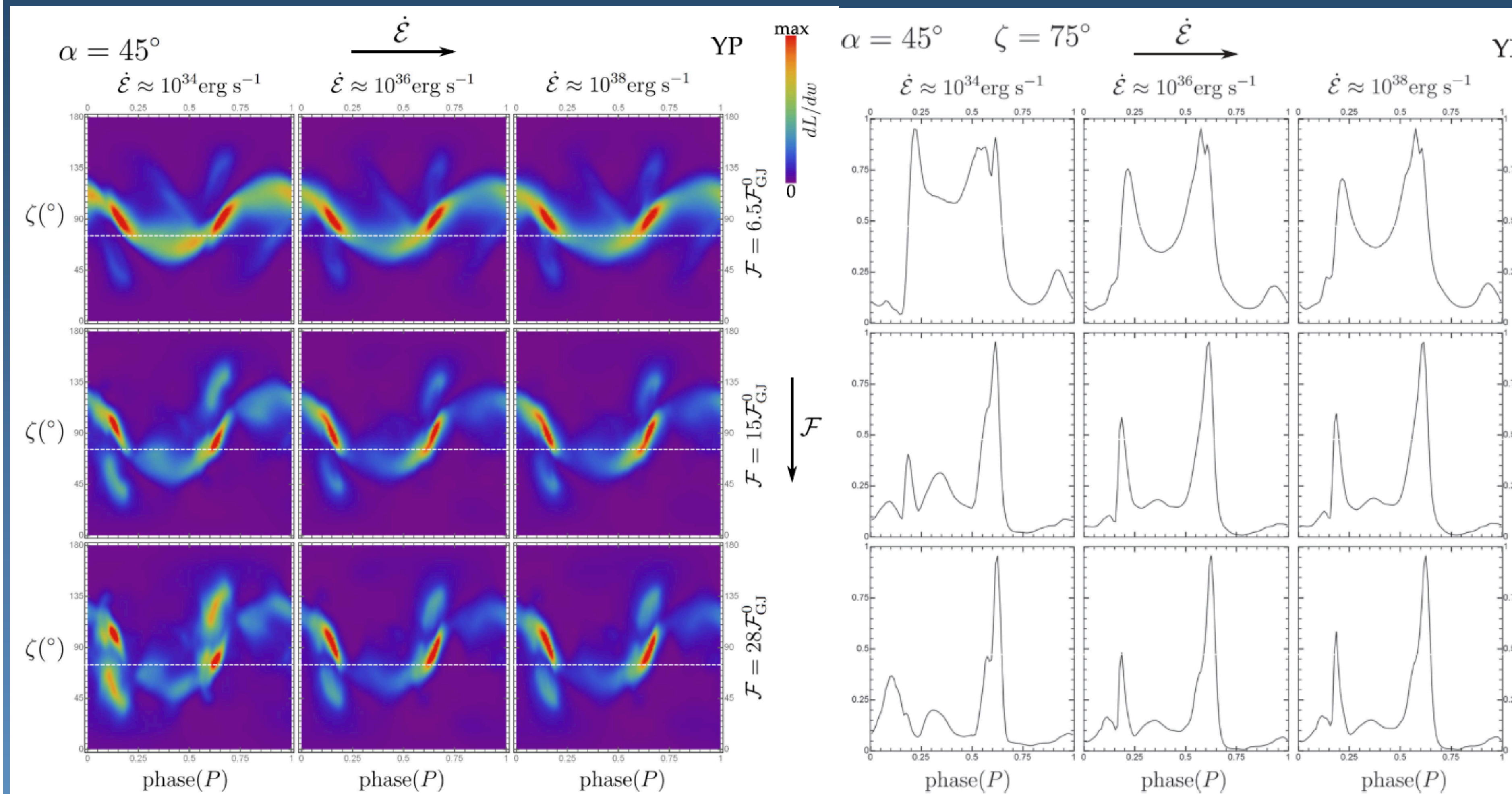
YP with $\dot{\mathcal{E}} < 10^{34}$ erg/s
MP with $\dot{\mathcal{E}} < 10^{33}$ erg/s
produce spectra below Fermi band

No Fermi detection of YP with $L_\gamma < 10^{32}$ erg/s or MP with 10^{31} erg/s

Kalapotharakos et al. 2018

High energy light curves

Kalapotharakos et al. 2018



High energy light curves

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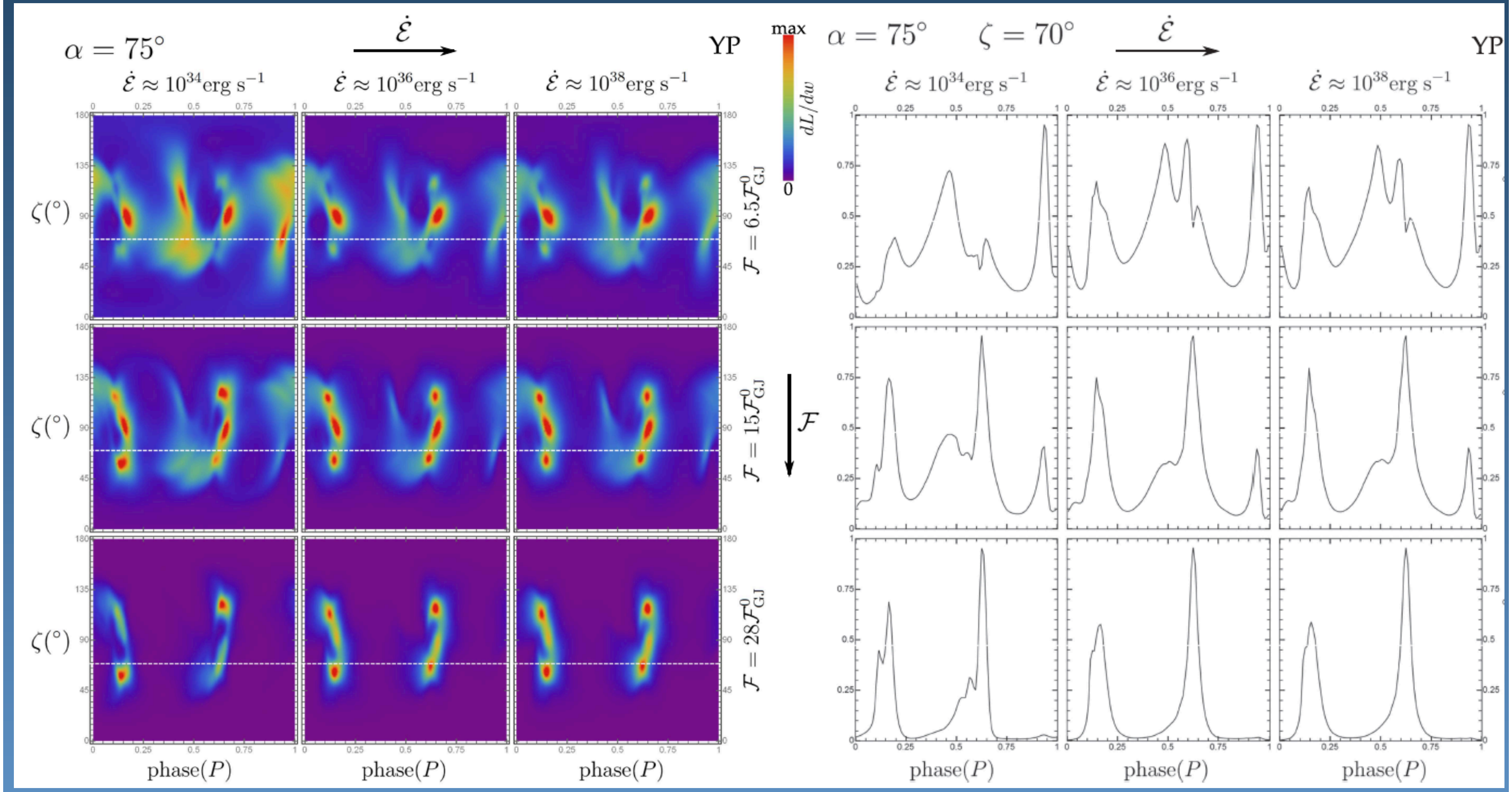

Summary

- Using 3D Cartesian PIC code we simulated pulsar magnetospheres with a range of pair injection rates both from NS surface to 2.5 R_{LC} and only near NS surface
- From near vacuum to near force-free we observe:
  - Pairs screening more parallel E which shrinks toward current sheet
  - Fewer particles are accelerated in smaller E_0
- Electron and positron trajectories show current composition
  - Polar current – outflowing e^- and e^+
  - Return current – outflowing e^+ and returning e^- (some crossing B field)
  - No need for pair production in outer magnetosphere
- Scaled-up particle energies can produce Fermi emission by curvature radiation

Next steps

- Incorporate pair production microphysics - self-consistently?
- Scaling up PIC to real particle energies
- Optical and X-ray emission