The Pulsar Sequence

The Fundamental Plane of Gamma-Ray Pulsars: From Observations to PIC Models

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High Energy Phenomena in Relativistic Outflows VII (HEPRO VII)

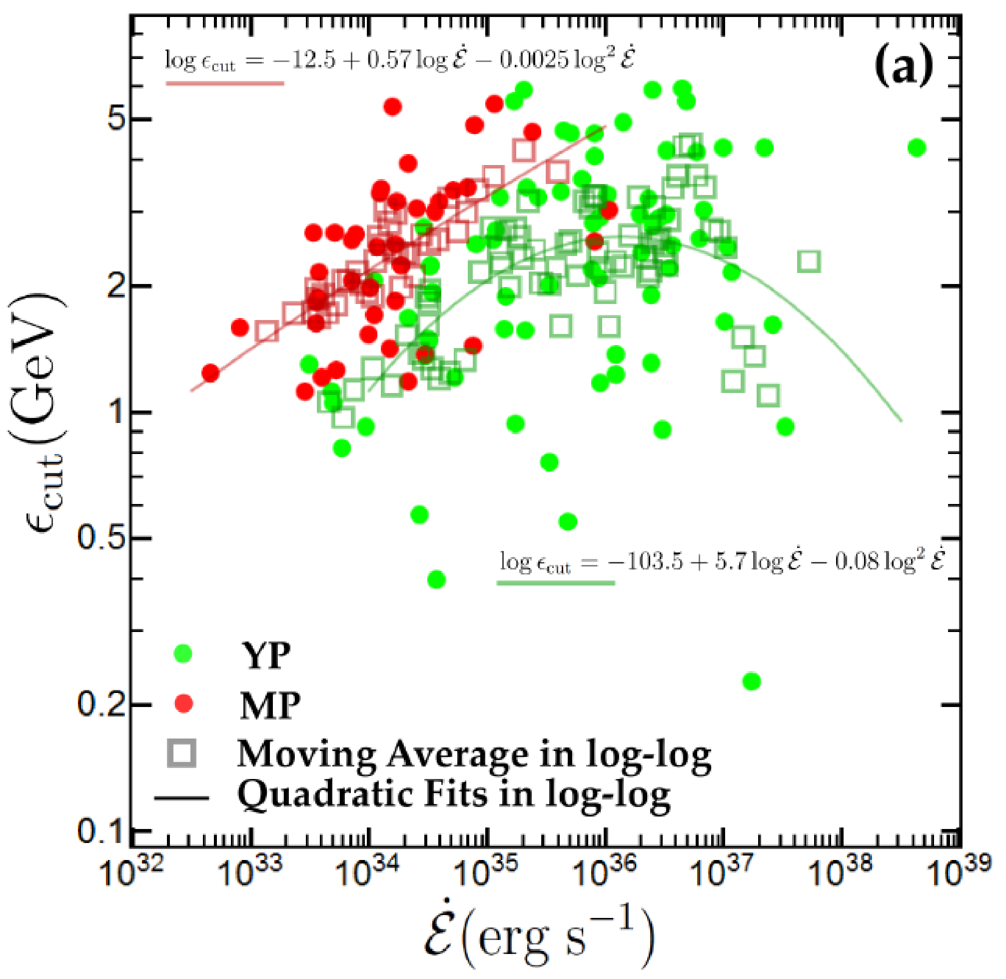
Outline

- Observations (FERMI)
- Orbital exploration CR vs SR
- Fundamental Plane of γ-ray Pulsars
- What PIC Global Models Say
- Summary

Assumptions:
Eq. Cur. Sheet, LC
RRLR

FERMI

$N_p \to \times 30$ $N_p > 230$ (117 in 2PC; Abdo et al. 2013)

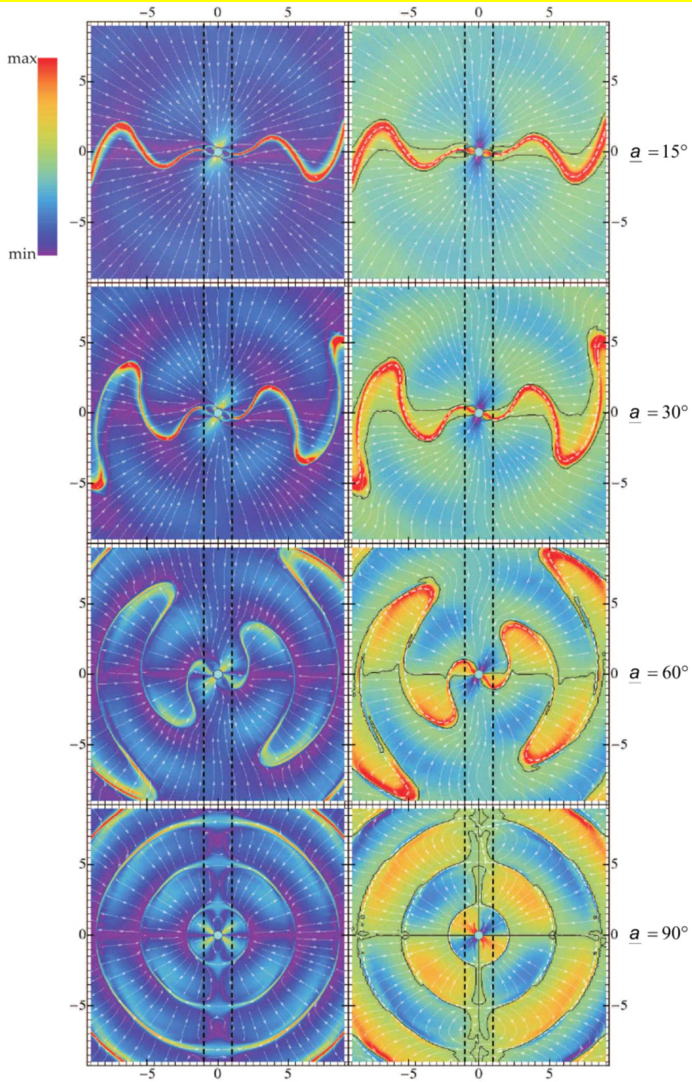


Kalapotharakos et al. (2017)

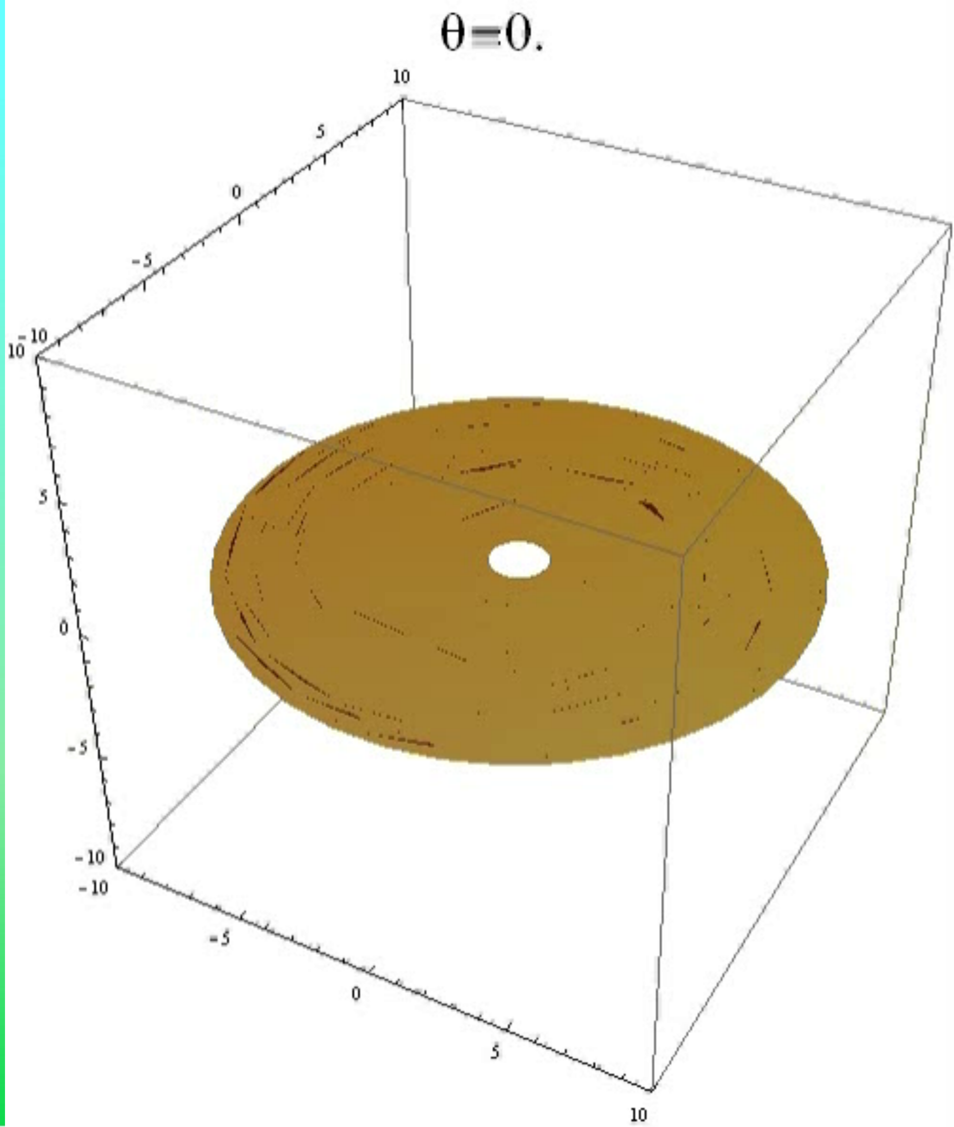
FFE Models

Contopoulos, Kazanas, & Fendt (1999)
Spitkovsky (2006)

Kalapotharakos er al. (2012)

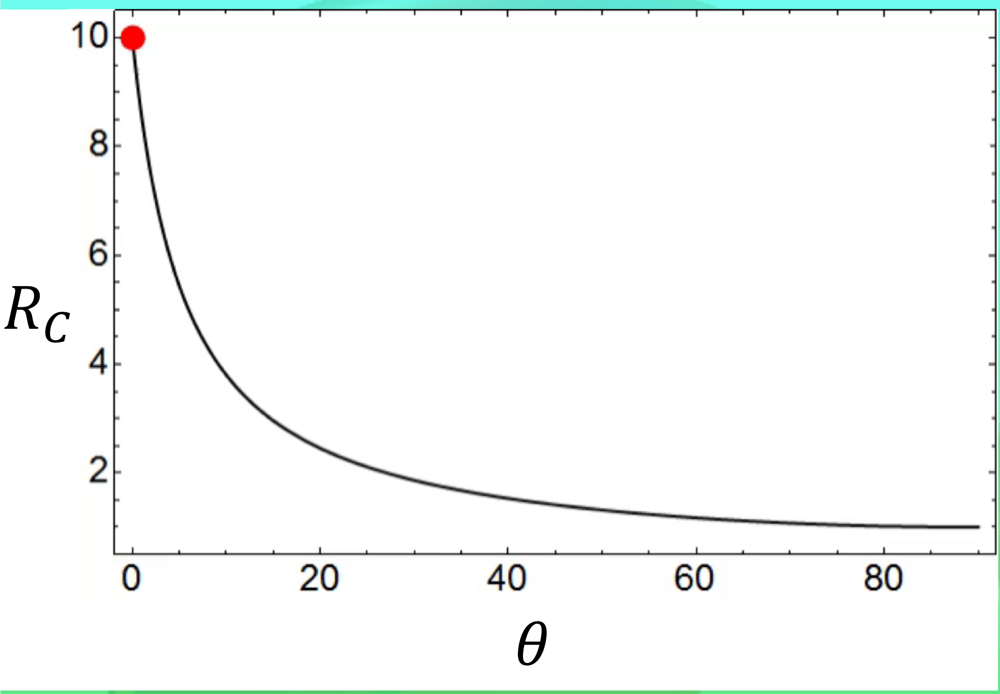


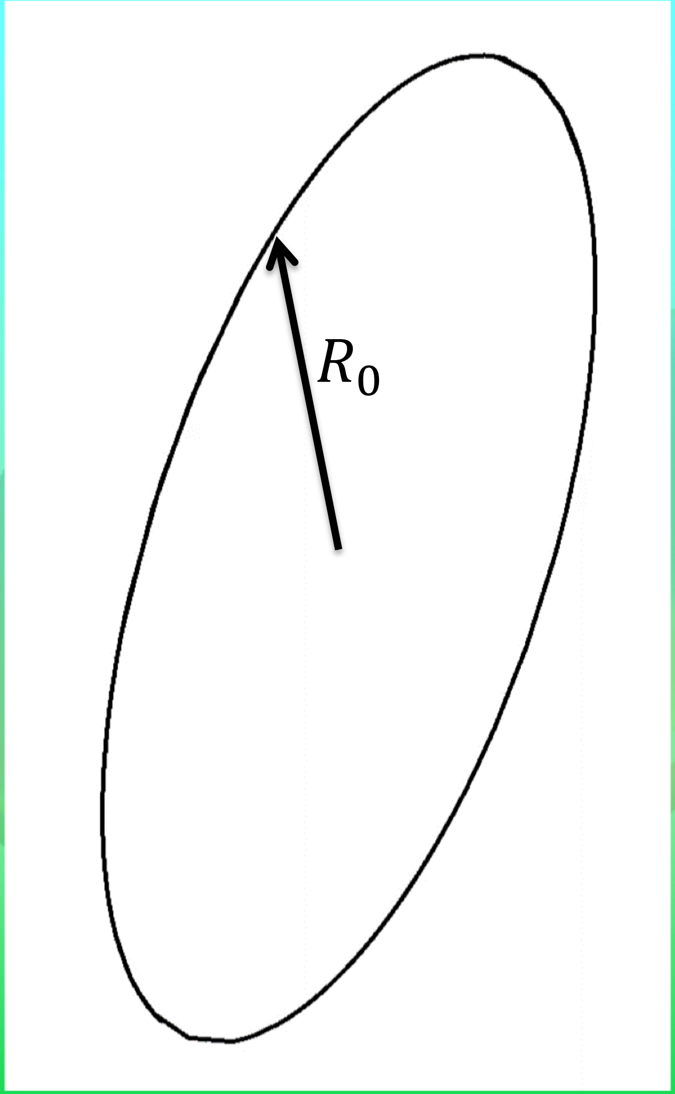
Bogovalov (1999)



Orbital Exploration (SR↔CR)

$\theta = 0.0, \quad R_C = 10.00$





Fundamental Plane (Theory)

Assumptions

1) Radiation Reaction Limit Regime

2) At the ECS near the LC

CR

Kalapotharakos et al. (2019)

$R_C \propto R_{LC} \propto P$

$B_{LC} \propto B_* R_{LC}^{-3} \propto B_* P^{-3}$

$\gamma_L \propto \epsilon^{1/3} P^{1/3}$

$E_{BLC} B_{LC} \propto \gamma_L^4 R_C^{-2}$

$E_{BLC} \propto \epsilon^{4/3} P^{7/3} B_*^{-1}$

$L_{\gamma 1} \propto \epsilon^{4/3} P^{-2/3}$

$\rho_{GJ} \propto B_* P^{-1}$

$\dot{\mathcal{E}} \propto B_*^2 P^{-4}$

$$L_\gamma \propto \epsilon_{cut}^{4/3} B_*^{1/6} \dot{\mathcal{E}}^{5/12}$$

$$\frac{2 q_e^2 \gamma_L^4}{3 m_e c\, R_C^2(\theta)} = \frac{q_e \mathbf{v} \cdot \mathbf{E}}{m_e c^2}$$

$$\epsilon_{cut} = \frac{3}{2} c\hbar \frac{\gamma_L^3}{R_C(\theta)}$$

Fundamental Plane (Theory)

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$R_C \propto r_g \propto \gamma_L B_*^{-1} P^3$

$$L_\gamma \propto \epsilon_{cut} \dot{\mathcal{E}}$$

SR

Fundamental Plane (Observations)

88 Fermi YPs+MPs

$$L_{\gamma(3D)} = 10^{14.2\pm2.3}\,\epsilon_{cut}^{1.18\pm0.24}\,B_*^{0.17\pm0.05}\,\dot{\mathcal{E}}^{0.41\pm0.08}$$

$\epsilon_{cut}(\mathrm{MeV}), B_*(\mathrm{G}), L_\gamma, \dot{\mathcal{E}}(\mathrm{erg/s})$

Fermi data

Kalapotharakos et al. (2019)

$$L_\gamma \propto \epsilon_{cut}^{4/3}\,B_*^{1/6}\,\dot{\mathcal{E}}^{5/12}$$

Theory CR

Fundamental Plane (Observations)

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ϵ_{cut}(MeV), B_*(G), L_γ, $\dot{\mathcal{E}}$(erg/s)

Kalapotharakos et al. (2019)

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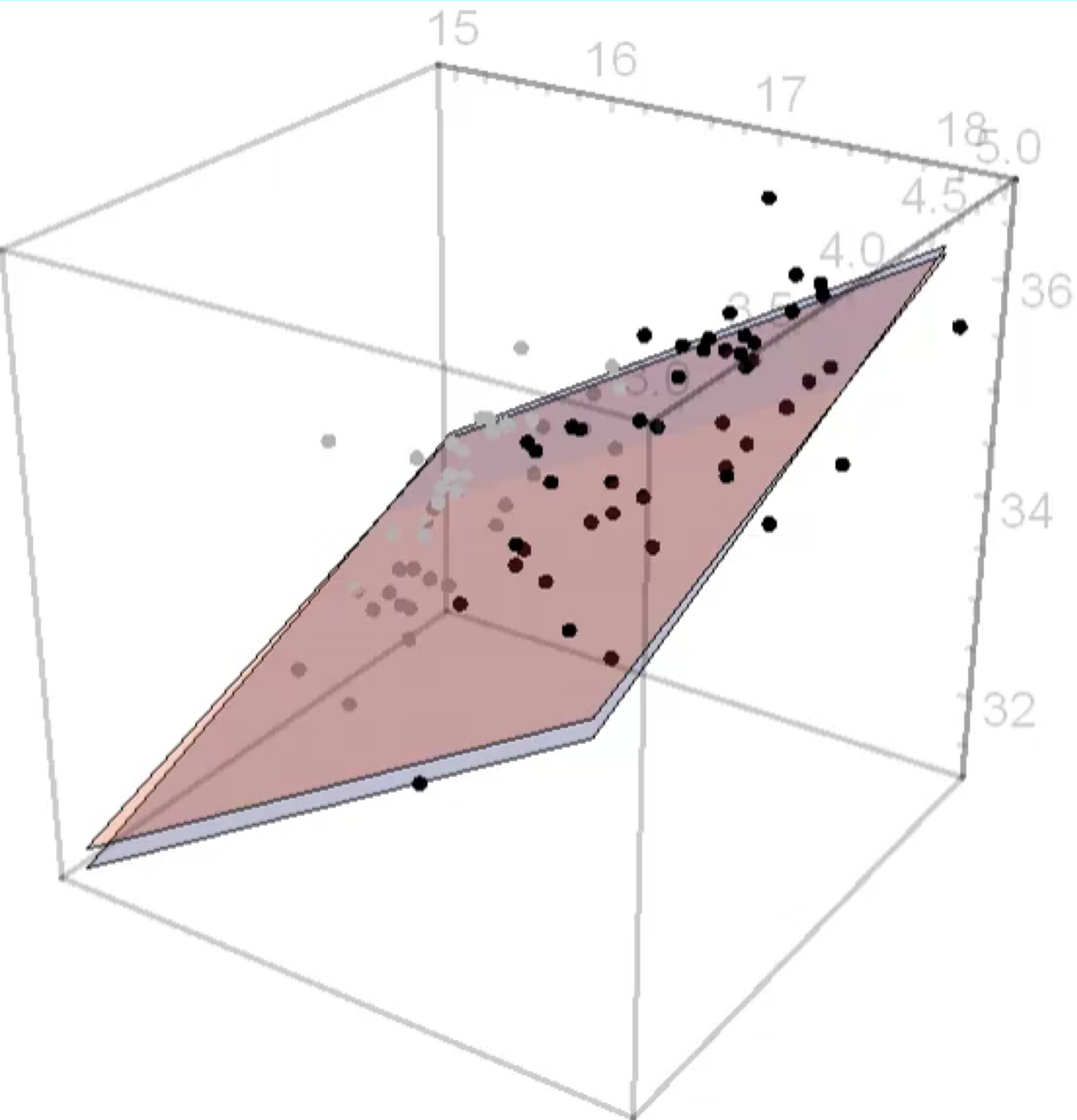
Theory CR

Fundamental Plane (Observations)

4D-space is hard to visualize



$x = B_*^{1/6} \dot{\mathcal{E}}^{5/12}$

$y = \epsilon_{cut}^{4/3}$

$z = L_\gamma$

$z \propto x\, y$
(Theory)

$z \propto x^{0.99}\, y^{0.88}$
(Fermi data)

● Fermi YP

● Fermi MP

Fundamental Plane (Observations)

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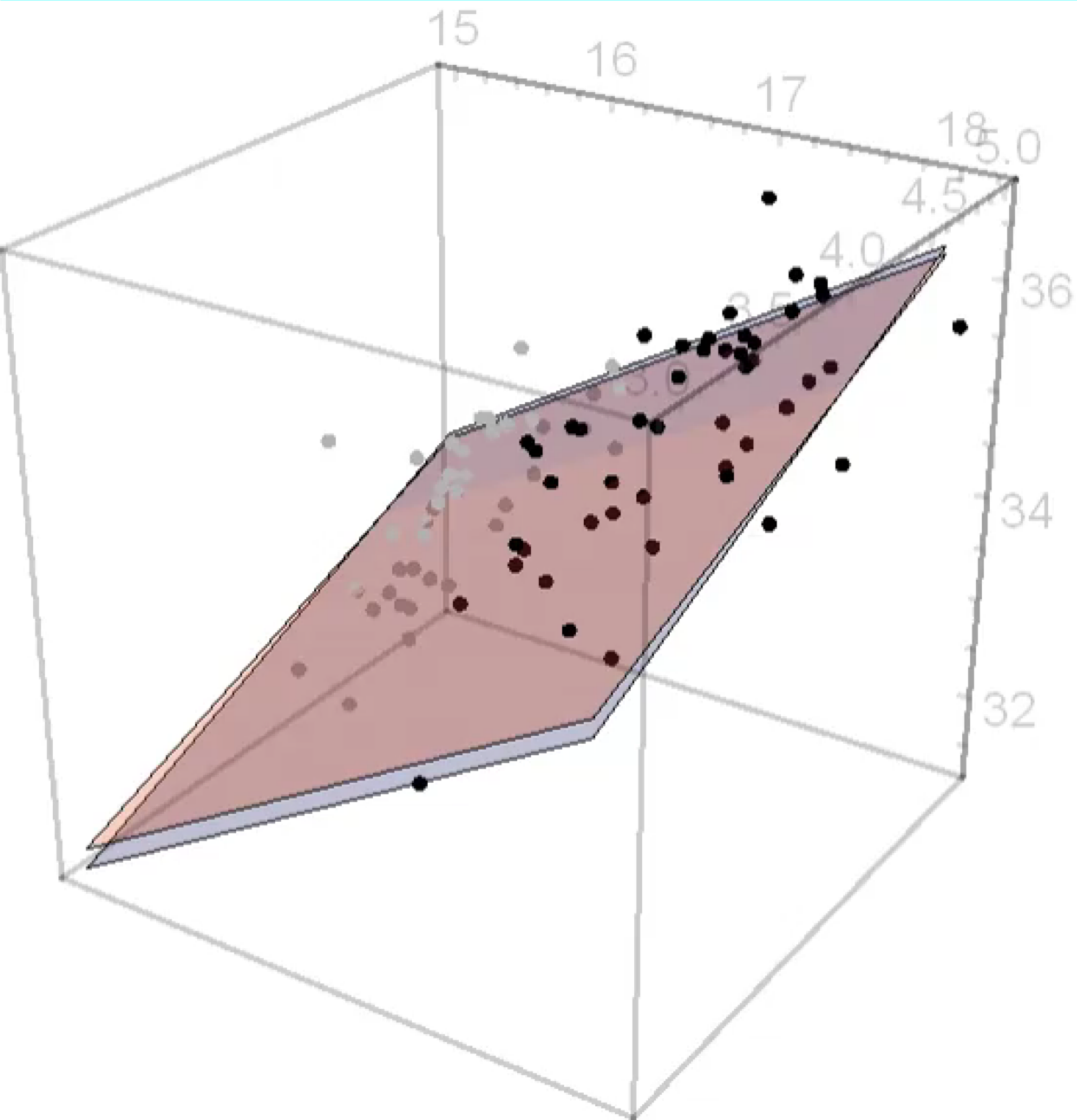

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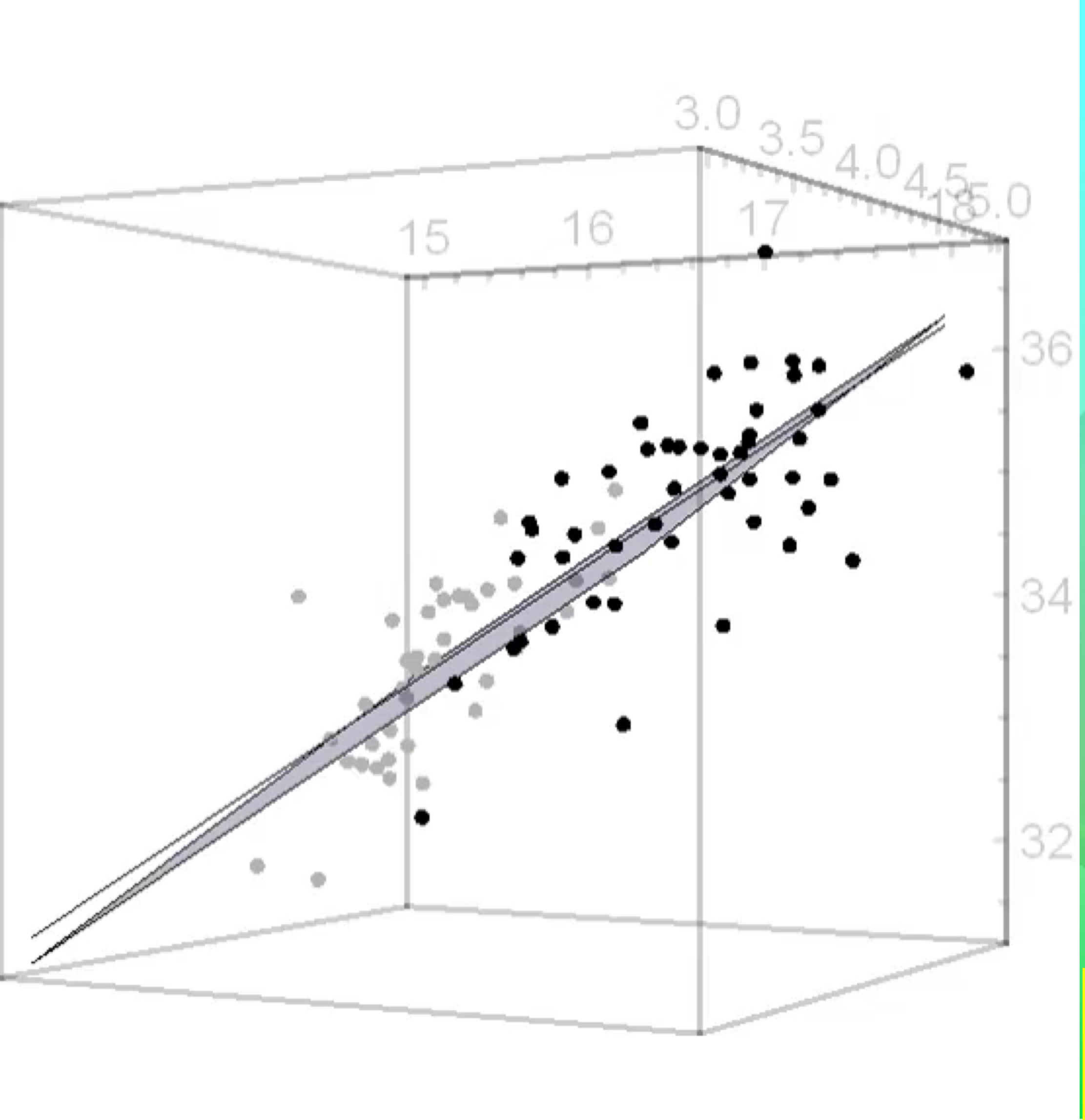

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(Theory)

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(Fermi data)

● Fermi YP

● Fermi MP

3D Kinetic Models (PIC)

Kinetic PIC simulations provide a path to self-consistency.

Field structure & particle distributions are consistent to each other

3D Particle-In-Cell code

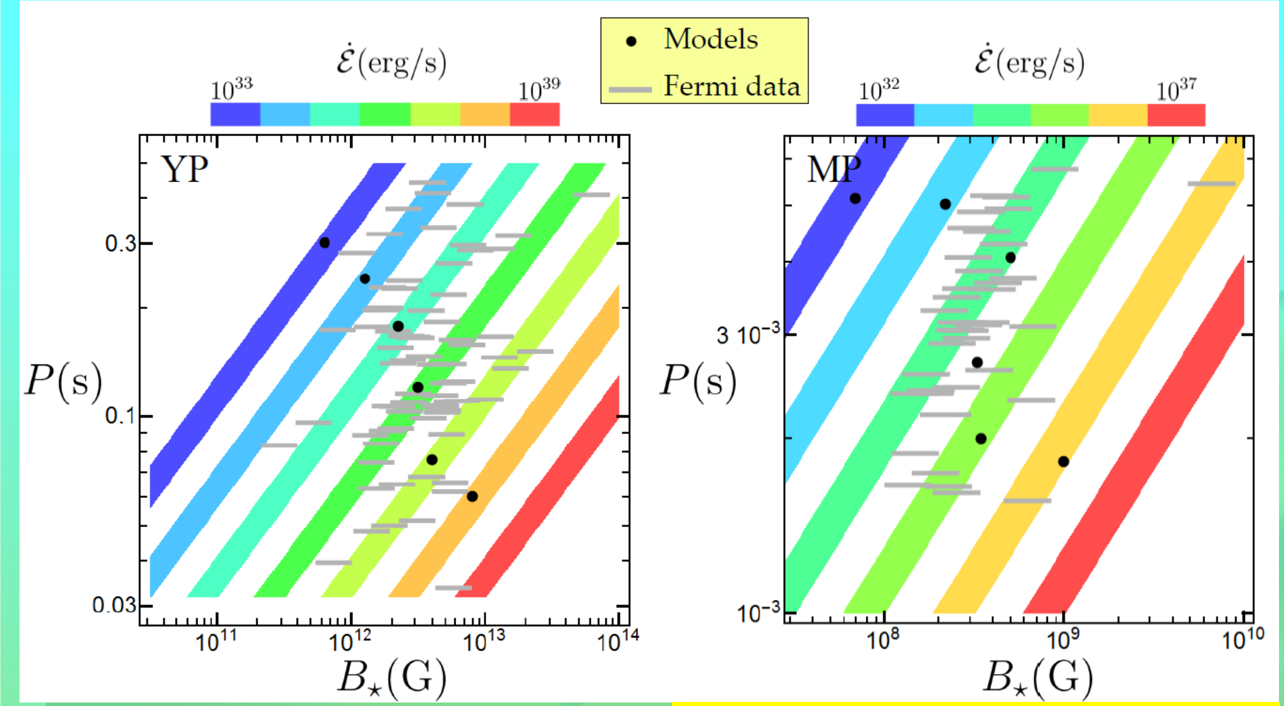
Kalapotharakos et al. (2018)
Brambilla et al. (2018)
Kalapotharakos et al. (2019, in prep)

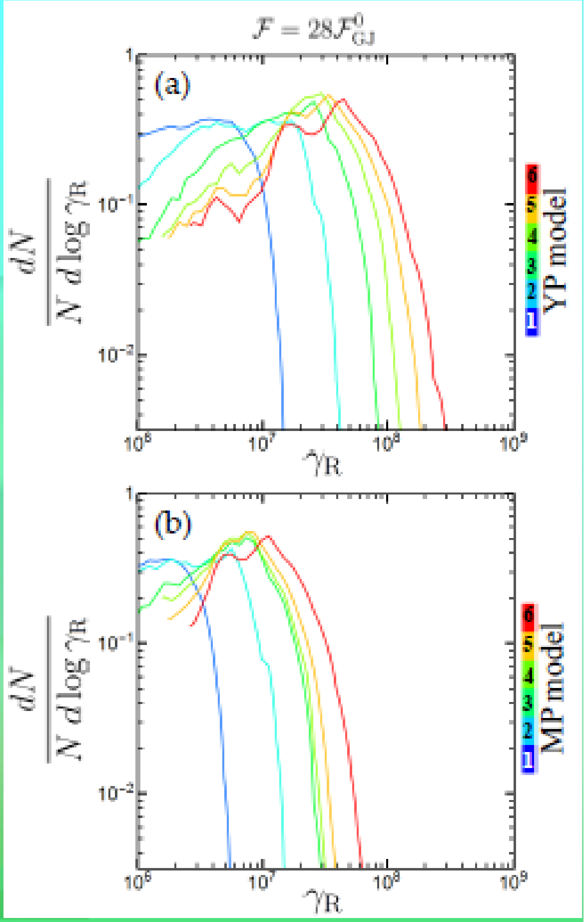
C-3PA

- Cartesian
- Conservative
- Vay's algorithm
- Current Smoothing
- Radiation Reaction Forces
- Load Balancing
- Field Line Dependent Particle Injection

Pleiades & Discover Supercomputers, NASA
~ 4000cpus
$\sim 10^7 - 10^9$ particles

3D Kinetic Models (PIC)

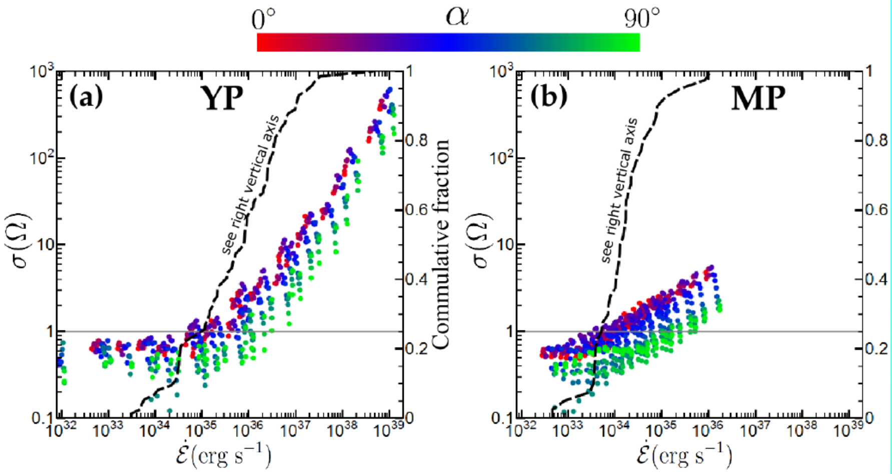




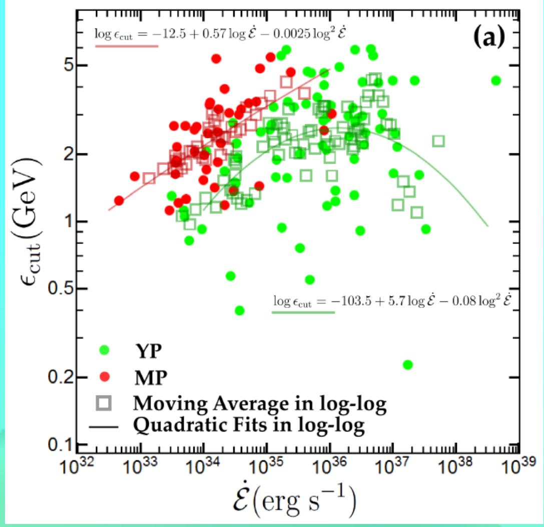
Kalapotharakos et al. (2018)

We scale-up the particle energies assuming realistic B and P values.

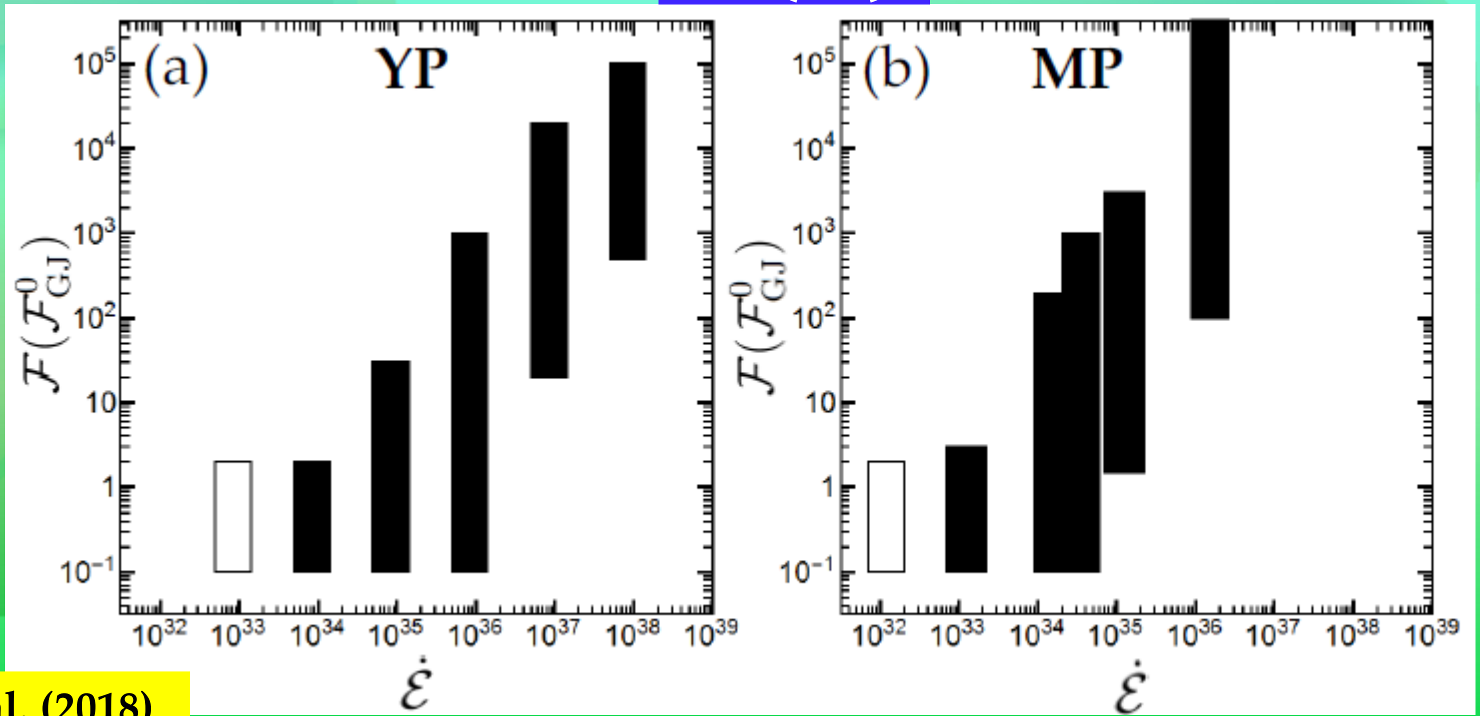
3D Kinetic Models (PIC)



$\sigma(\dot{\mathcal{E}})$



$\mathcal{F}(\dot{\mathcal{E}})$

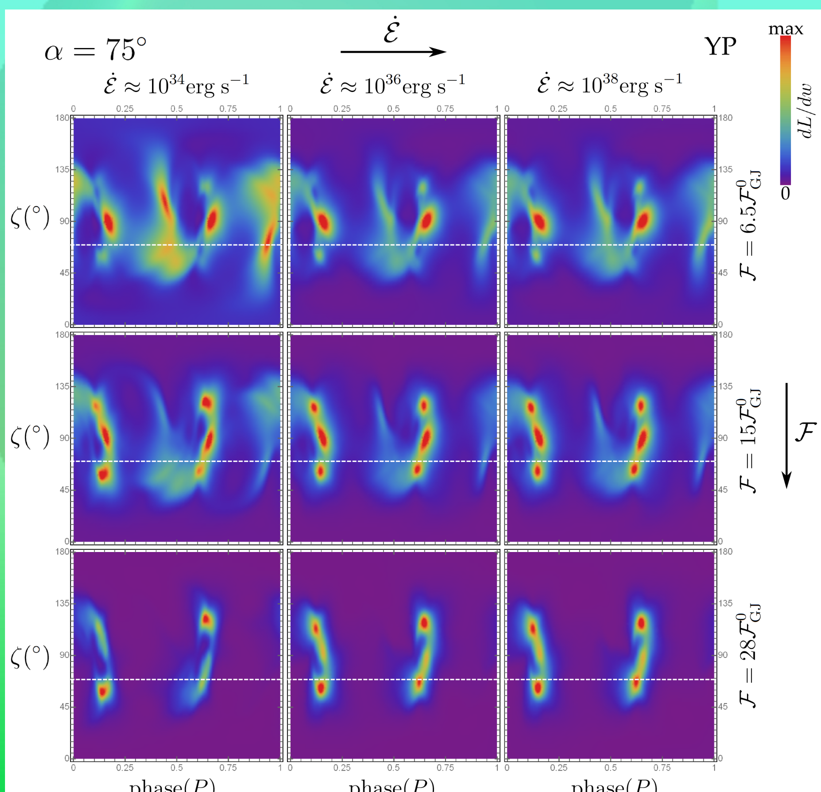


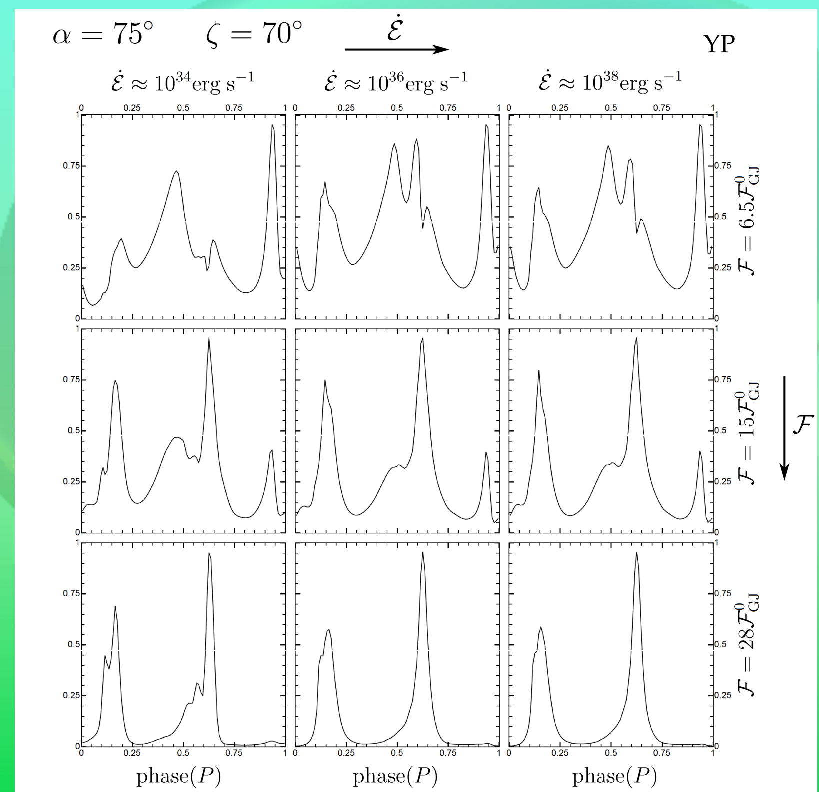
Kalapotharakos et al. (2018)

3D Kinetic Models (PIC)

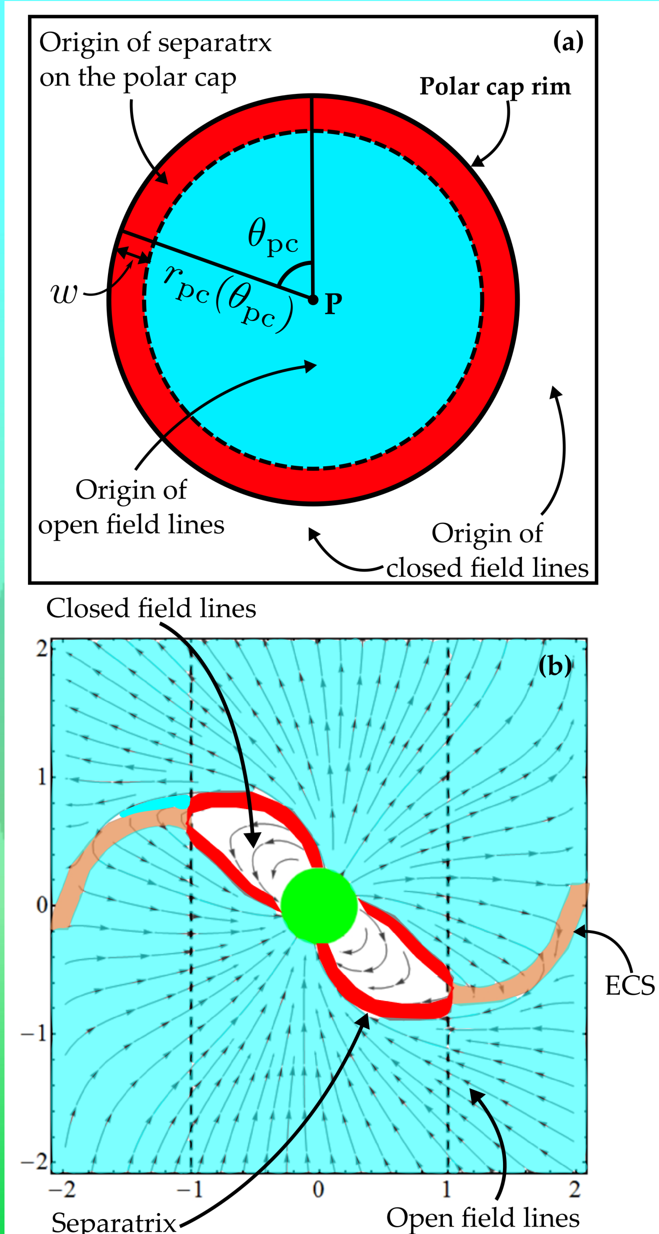
But…

1. The γ-ray light-curves for low $\mathcal{F}$ are messy.
2. Particle-injection regions that regulate the γ-ray emission





3D Kinetic Models (PIC)



Separatrix injection model

The γ-ray pulsar radiation is mainly regulated by

1. **The particle injection rate $\mathcal{F}_s$ along the separatrix**
2. **The width w of the separatrix zone**

Kalapotharakos et al. (in prep.)

Requirements

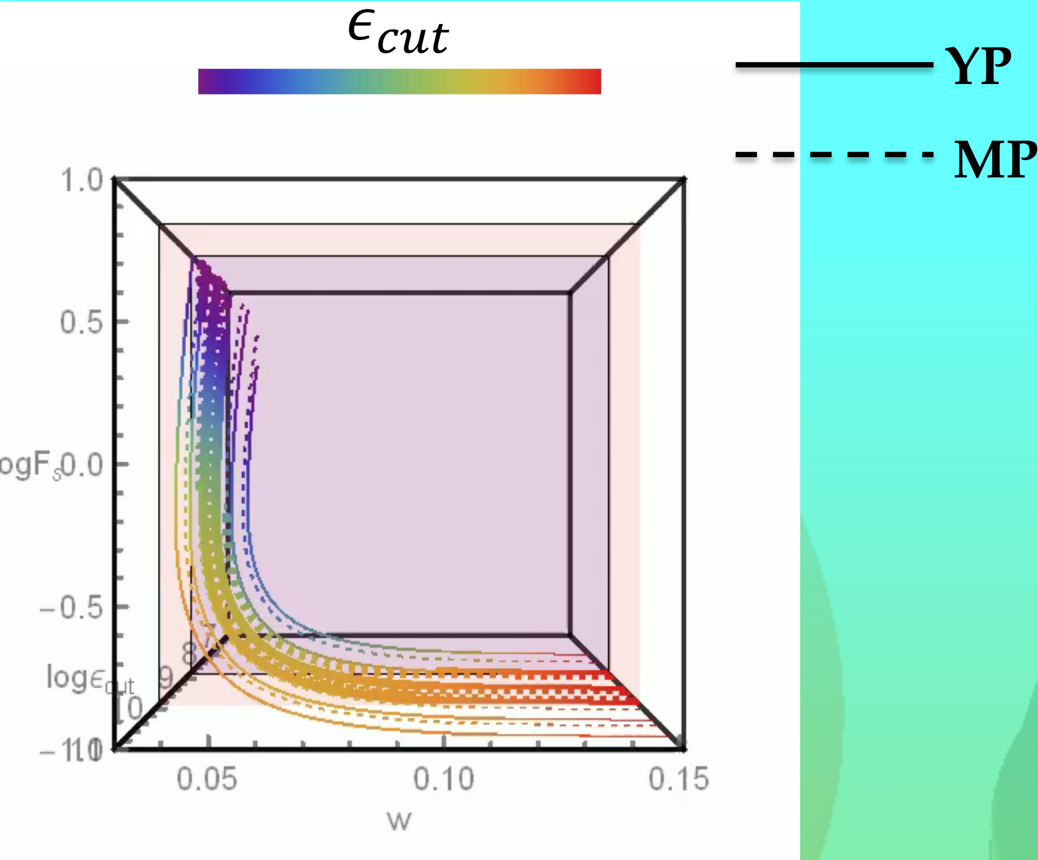
The particle injection rate along the open and the closed field-lines is <u>not very small</u>.

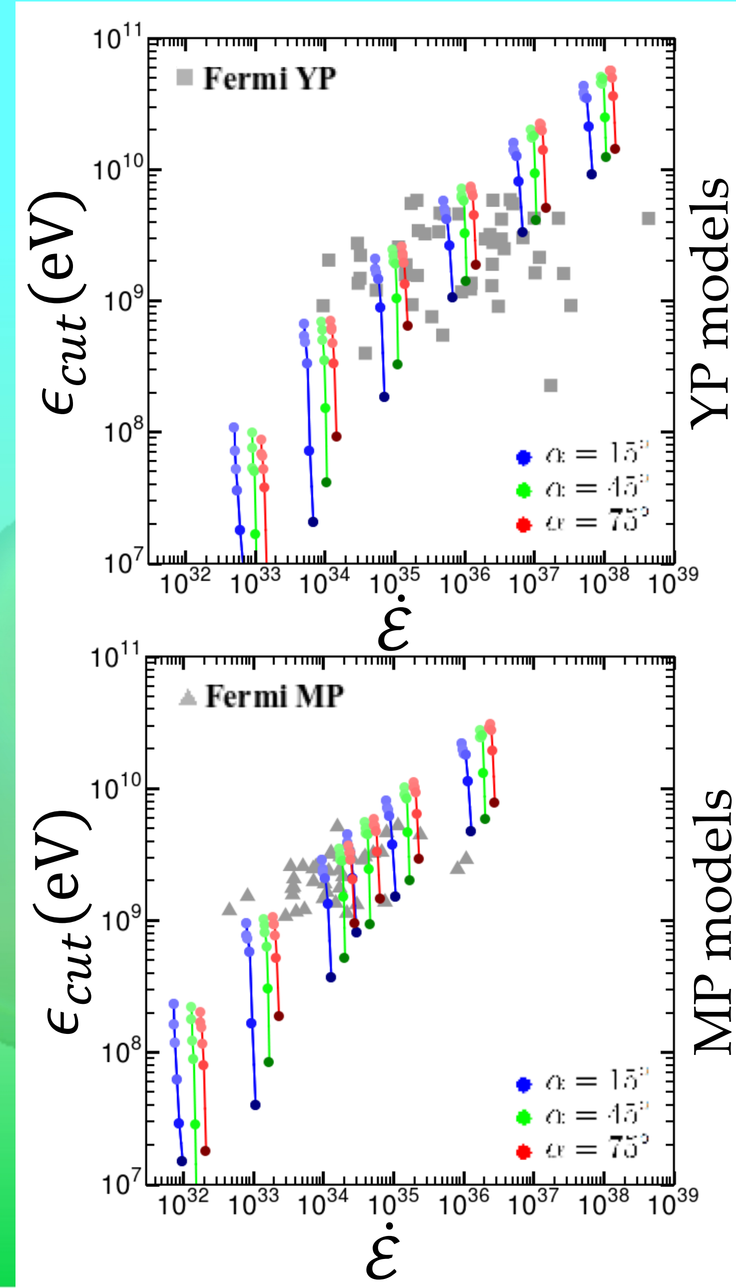
$(> 5\mathcal{F}_{GJ}^{0})$

However, it is <u>not necessary to be high</u>.

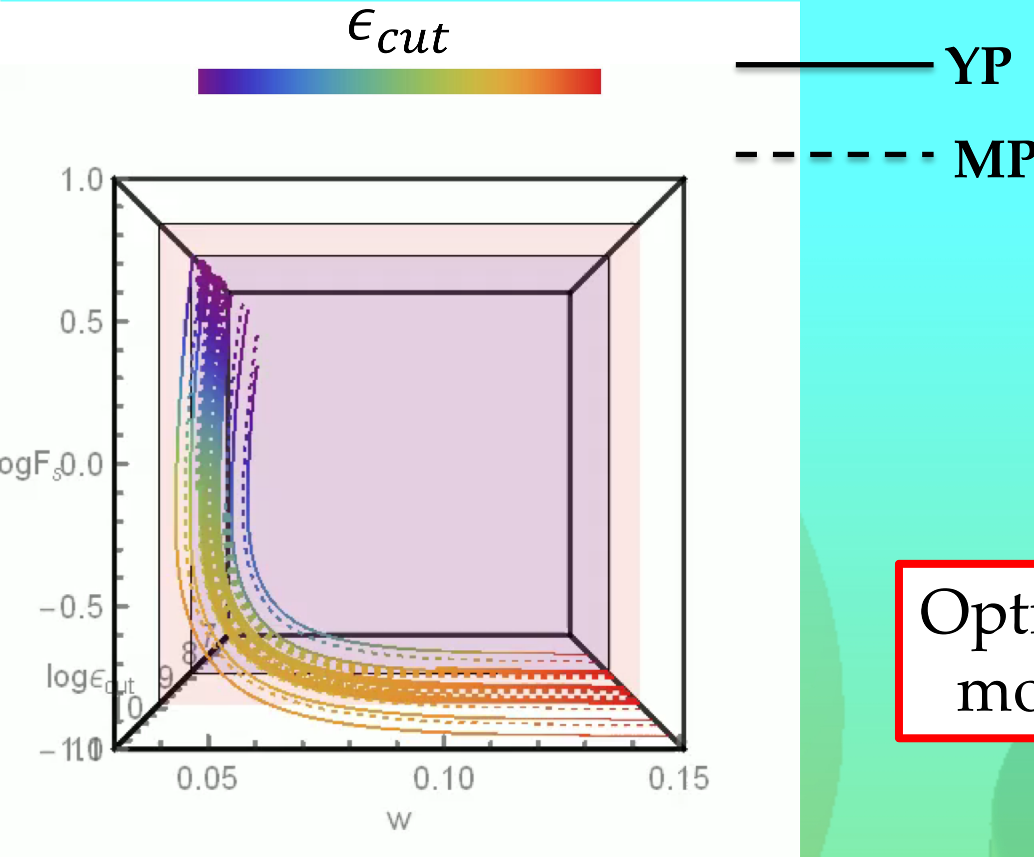
$(< 10\mathcal{F}_{GJ}^{0})$

3D Kinetic Models (PIC)

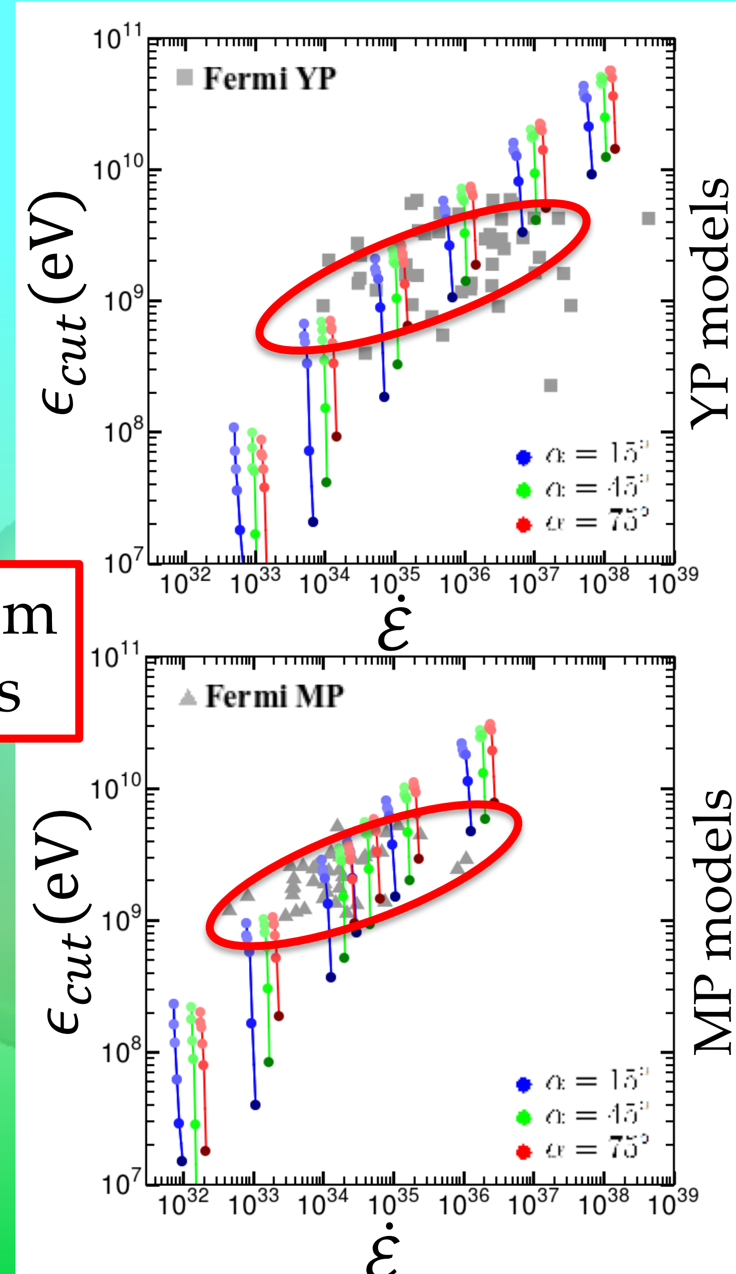




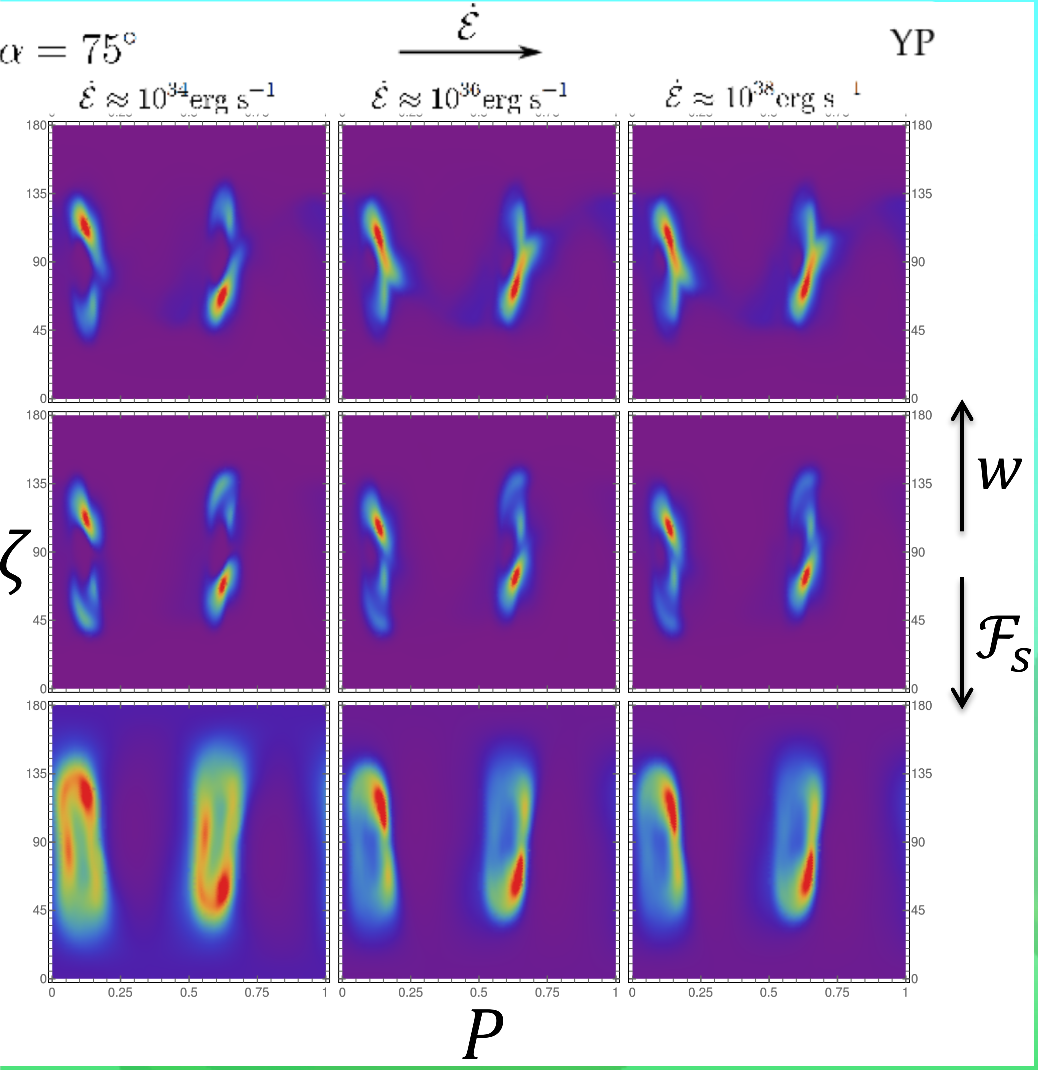
3D Kinetic Models (PIC)

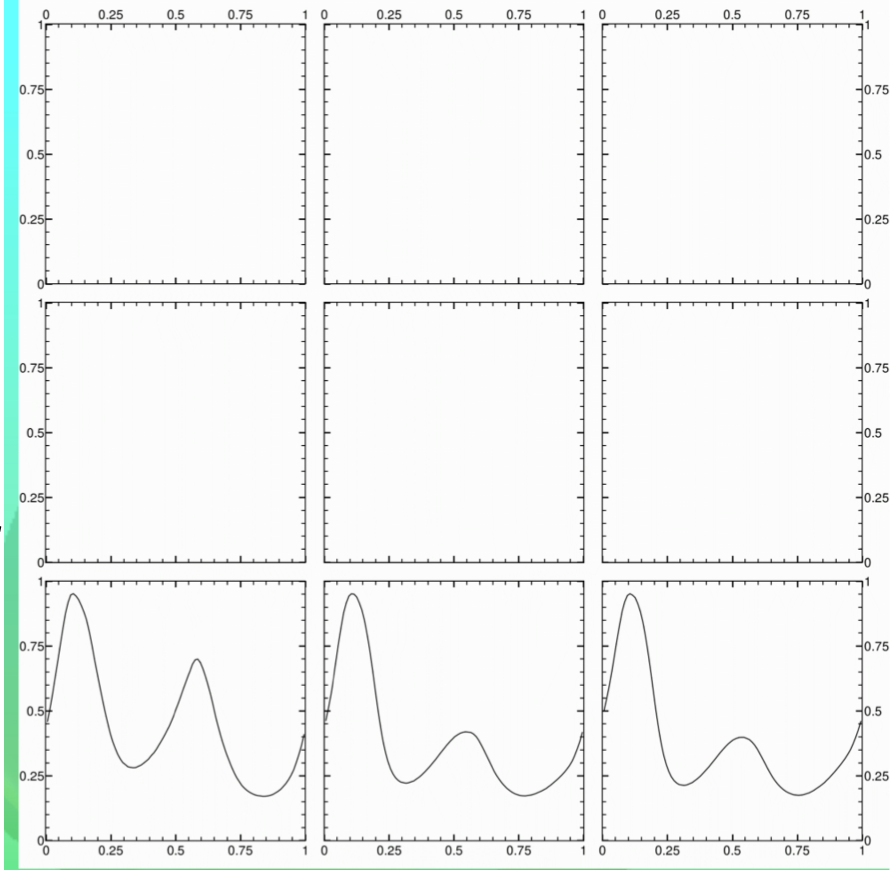


Optimum models



3D Kinetic Models (PIC)





Nice, well defined light-curves similar to those observed by Fermi, for all $\dot{\mathcal{E}}$. They seem able of reproducing the $\delta - \Delta$ correlation.

Fundamental Plane Observations & PIC Models

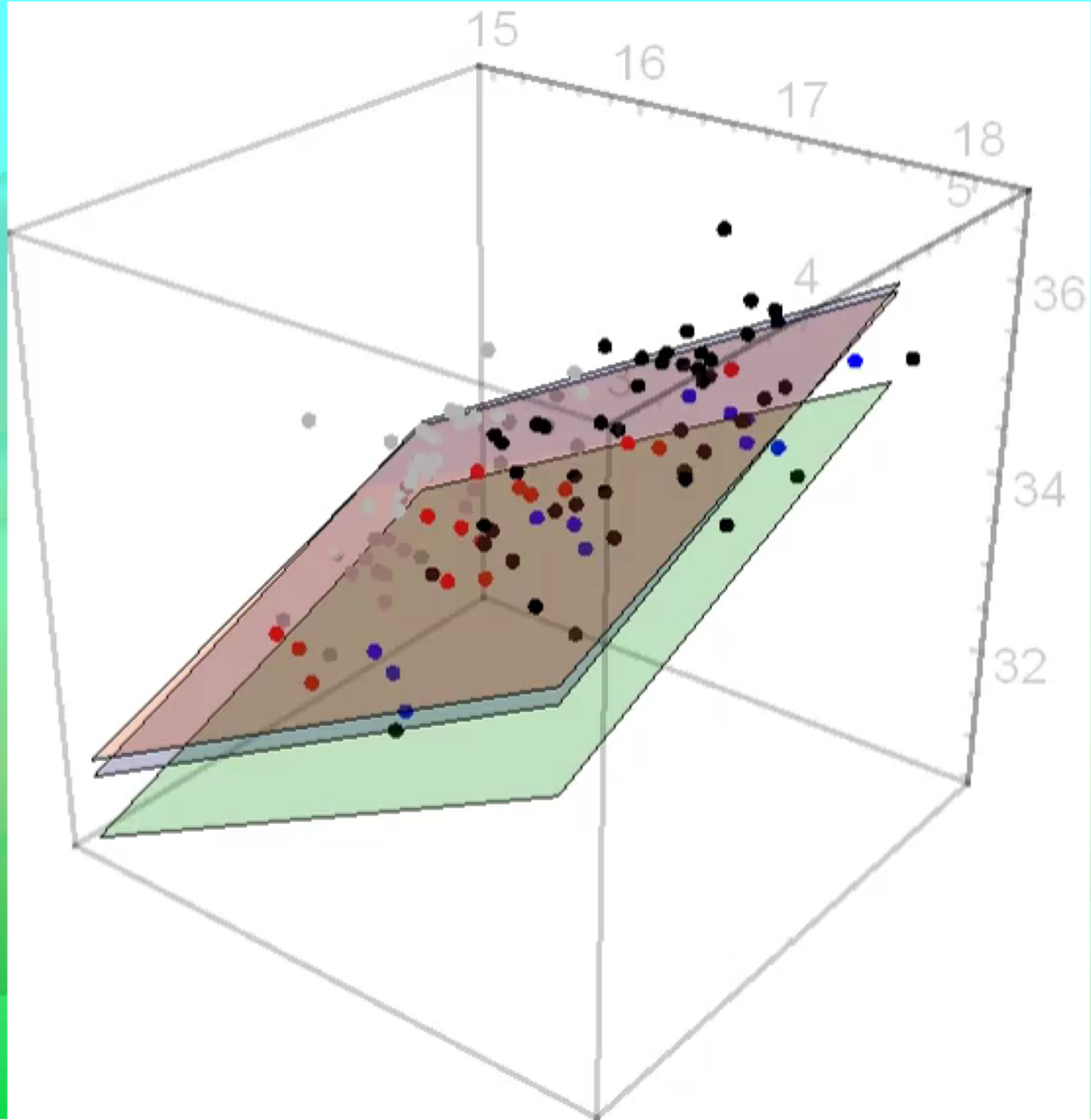
$$L_\gamma \propto \epsilon_{cut}^{1.18\pm0.24}\, B_*^{0.17\pm0.05}\, \dot{\mathcal{E}}^{0.41\pm0.08}$$ **Fermi data**

$$L_\gamma \propto \epsilon_{cut}^{4/3}\, B_*^{1/6}\, \dot{\mathcal{E}}^{5/12}$$ **Theory CR**

$$L_\gamma \propto \epsilon_{cut}^{1.56\pm0.34}\, B_*^{0.20\pm0.04}\, \dot{\mathcal{E}}^{0.29\pm0.11}$$ **PIC Models**

Optimum

Fundamental Plane Observations & PIC Models



- Fermi YP
- Fermi MP

- PIC YP
- PIC MP

$x = B_*^{1/6}\dot{\mathcal{E}}^{5/12}$

$y = \epsilon_{cut}^{4/3}$

$z = L_\gamma$

Fundamental Plane Observations & PIC Models

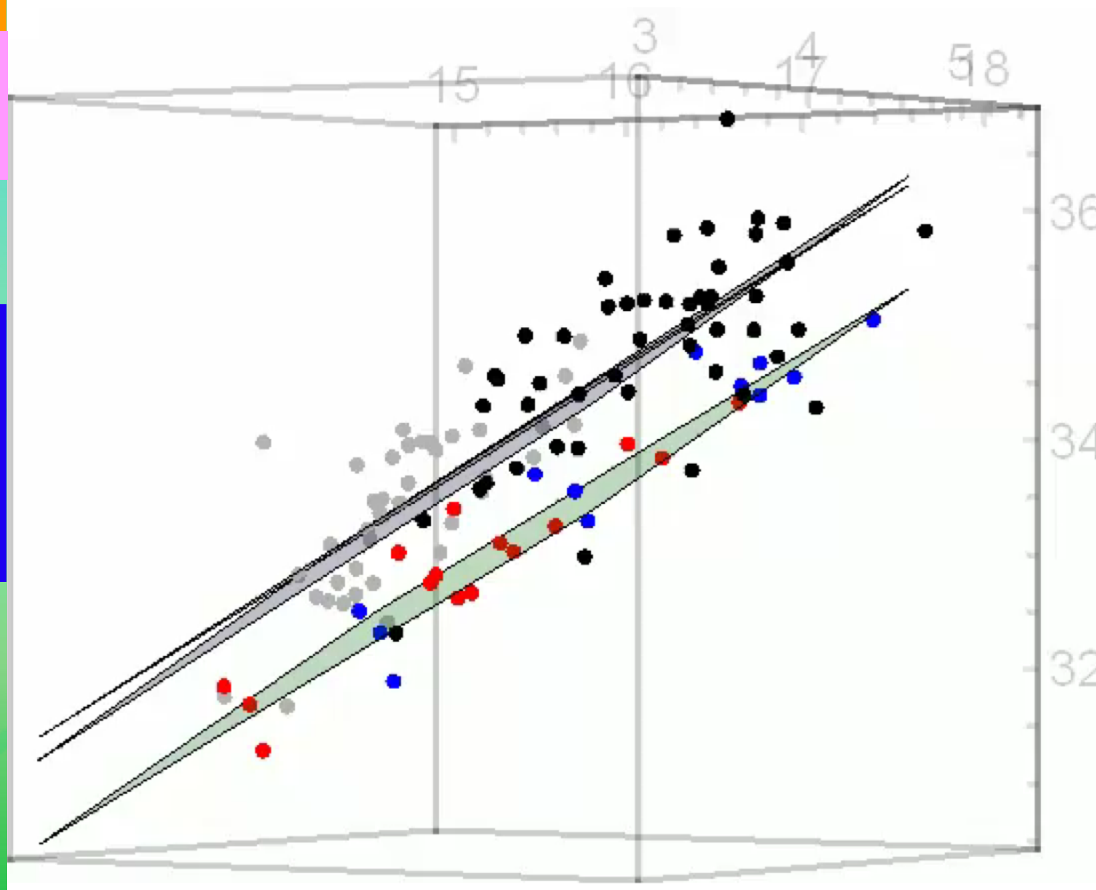
Plane distance ~0.5

Vertical distance ×5

Beaming factor f_Ω

Emission ($r > 2R_{LC}$)

Moment of Inertia, I



● Fermi YP
● Fermi MP

● PIC YP
● PIC MP

$x = B_*^{1/6}\dot{\mathcal{E}}^{5/12}$

$y = \epsilon_{cut}^{4/3}$

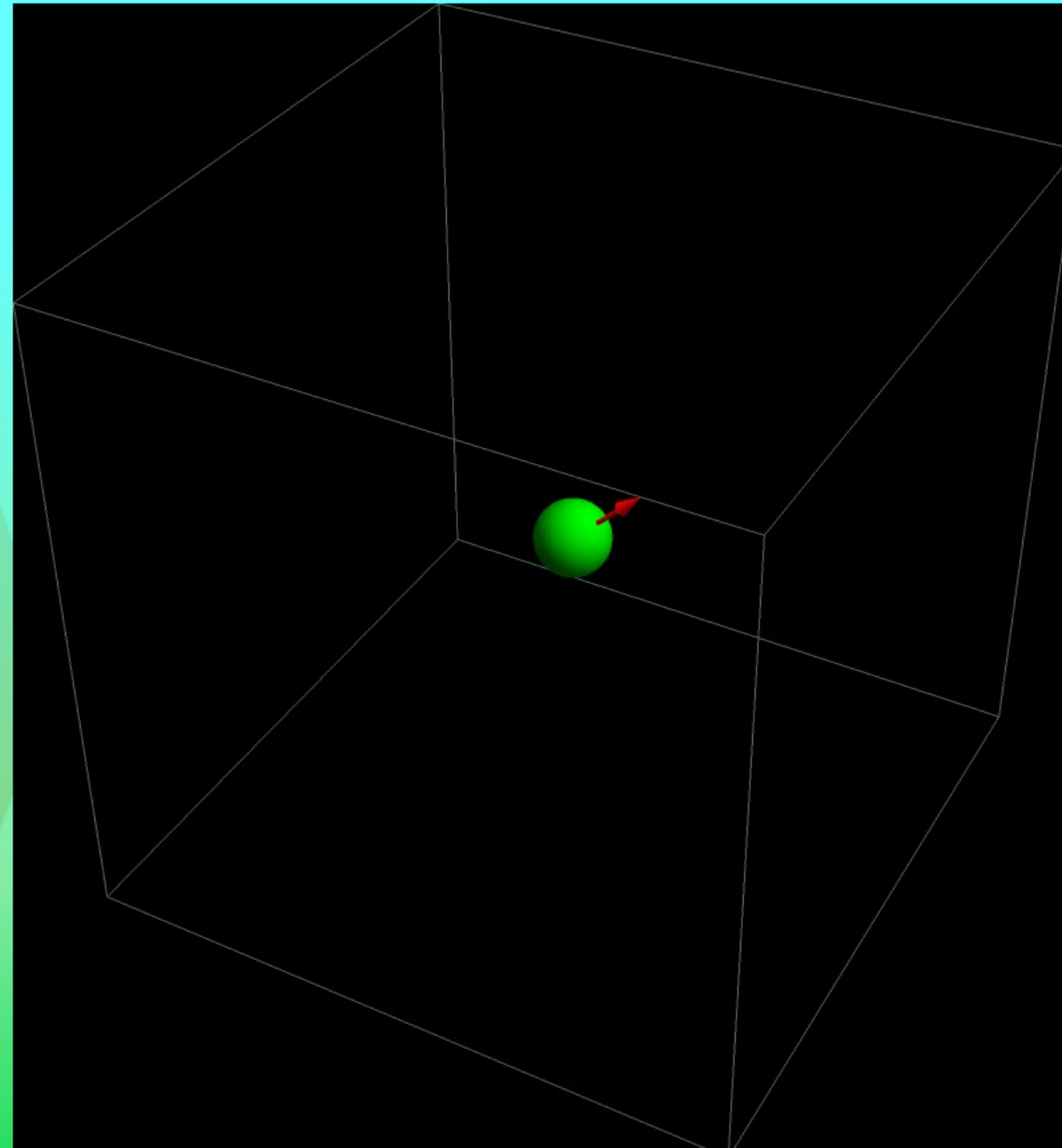
$z = L_\gamma$

3D Kinetic Models (PIC)

Pulsar Theater

Particle injection inside the LC.

Kalapotharakos et al. (in prep.)



CK videos

3D Kinetic Models (PIC)

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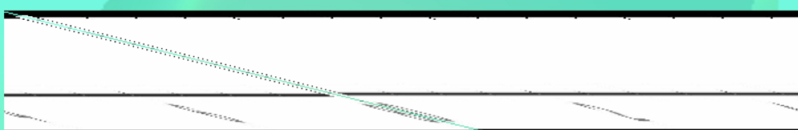
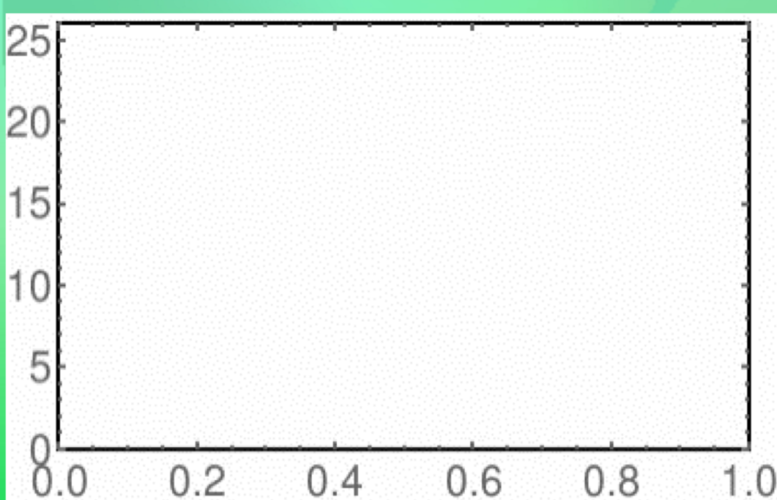
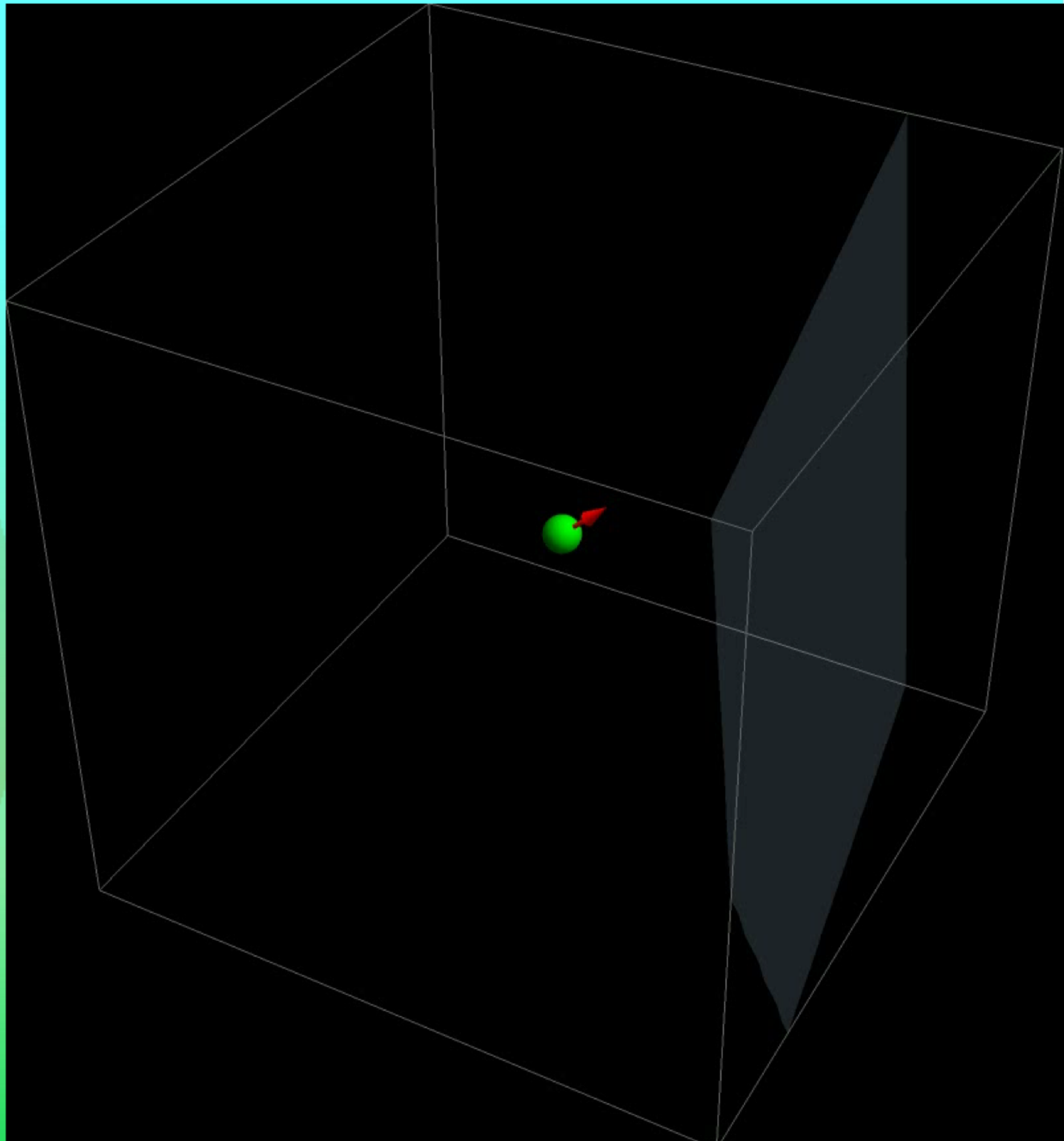






CK videos

Summary

- Fermi data contain an unprecedented level of information that uncovers the mysteries of the pulsar γ-ray emission.

<u>Fundamental Plane</u>

$L_\gamma \propto \epsilon_{cut}^{1.18\pm0.24} B_*^{0.17\pm0.05} \dot{\mathcal{E}}^{0.41\pm0.08}$ **Fermi data**

$L_\gamma \propto \epsilon_{cut}^{4/3} B_*^{1/6} \dot{\mathcal{E}}^{5/12}$ **Theory CR**

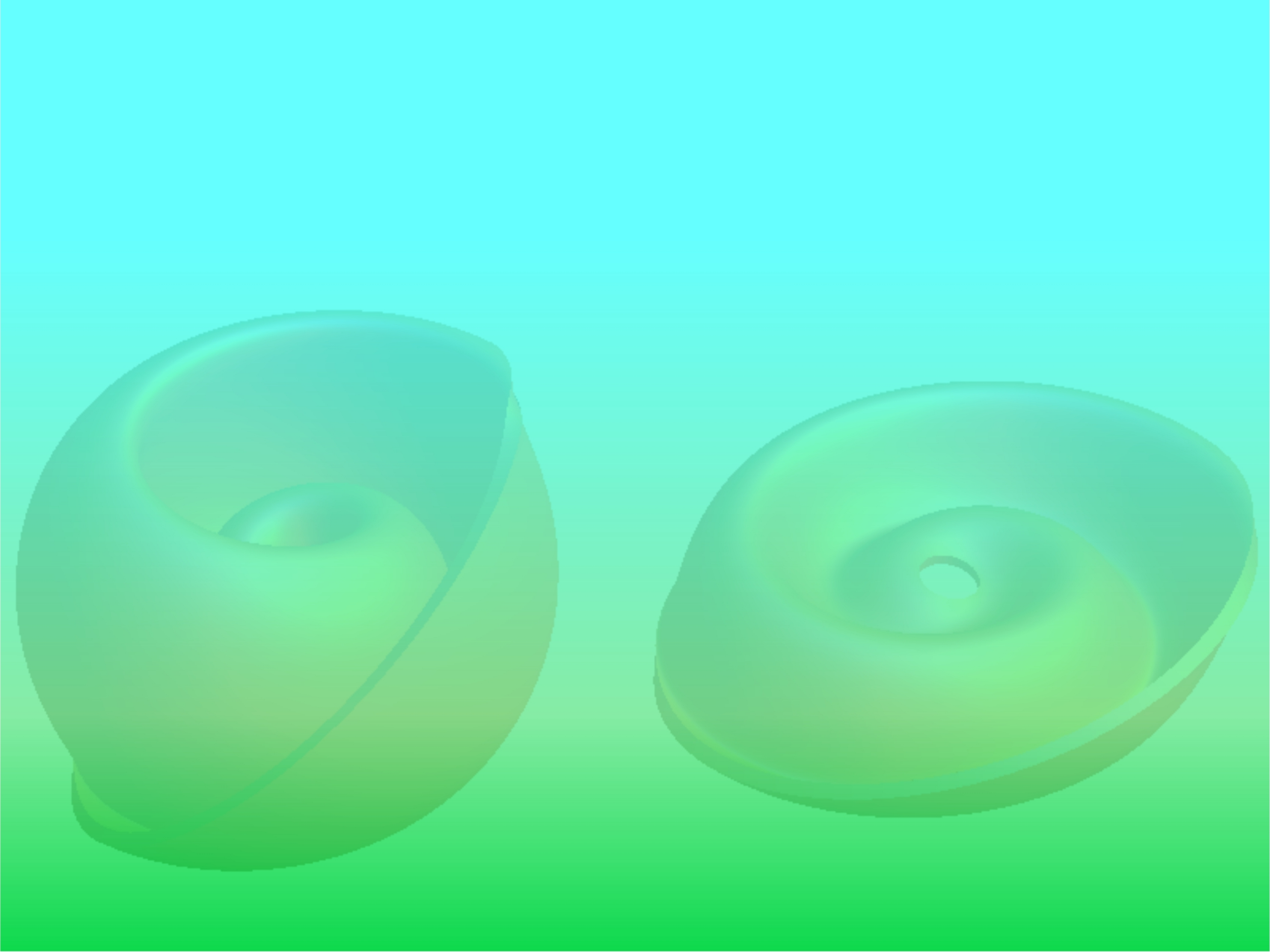
<u>Separatrix Injection Model</u>

- Kinetic PIC models indicate that the particle-injection rate, $\mathcal{F}_s$, in the separatrix region and the width, *w*, of this zone regulate the pulsar emission.

$\sigma(\dot{\mathcal{E}})$ $\mathcal{F}(\dot{\mathcal{E}})$

- Kinetic PIC models follow the FP. The continuation of this study is expected to provide additional constraints deepening even further our understanding.

Thank you!



Q1

Is there any explanation about the observed scattering around the fundamental plane?

Q2

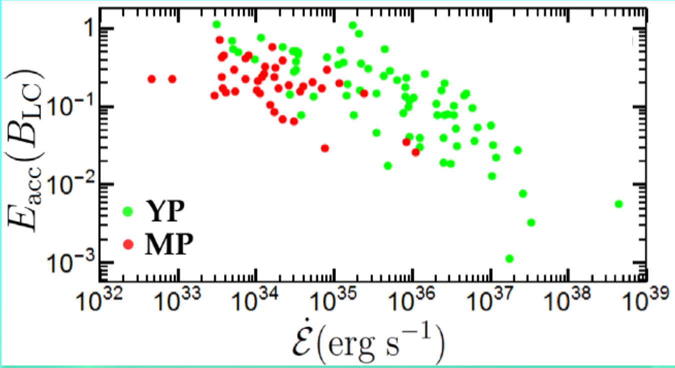
Is there any other prediction other than that of the fundamental plane?

Extras

Fundamental Plane (Observations)

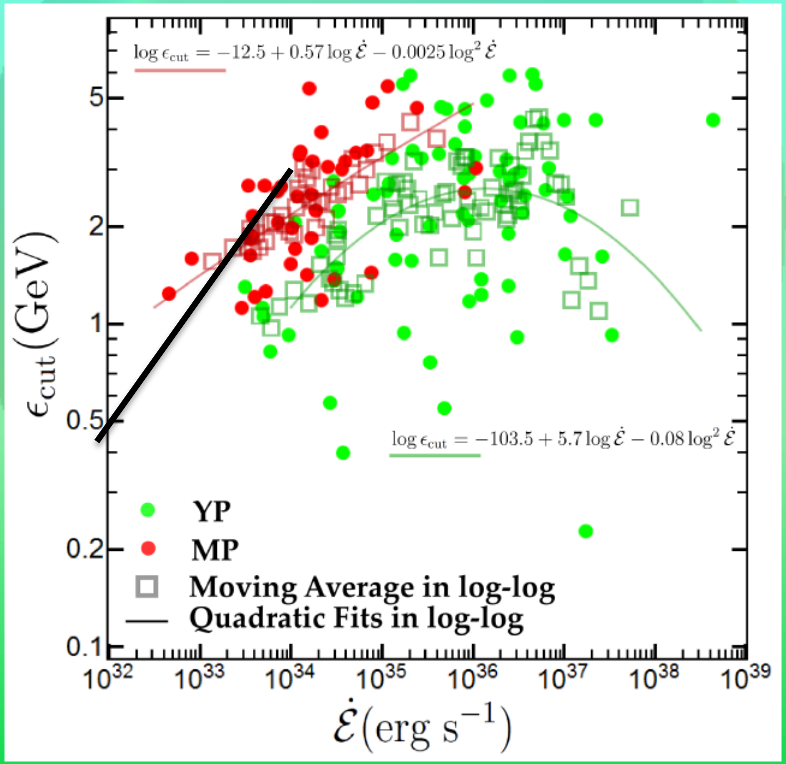
Is that all?

No, it is actually even better



For low $\dot{\mathcal{E}}$, $E_{acc} \propto B_{LC}$

$$\epsilon_{cut} \propto B_*^{-1/8} \dot{\mathcal{E}}^{7/16}$$



$$B_{\star MP} \approx 10^{-4} B_{\star YP}$$

$$\epsilon_{cut_{MP}} \approx 3\epsilon_{cut_{YP}}$$

Viable interpretation of the observed γ-ray pulsar death-line

Better sensitivity in the MeV-band telescope (AMEGO)

VHE pulsed detections

$N_p \to \times 30$ $N_p > 230$ (117 in 2PC; Abdo et al. 2013)

Recent detections by *MAGIC* and *HESSII* of very high energy (VHE) emission from the
Crab (Ansoldi et al. 2016),
Vela (Djannati-Atai et al. 2017), and
Geminga (Lopez et al. 2018)
pulsars imply an additional emission component, and inverse Compton (IC) seems to be the most reasonable candidate (Rudak & Dyks 2017; Harding et al. 2018).

In any case, the multi-TeV photon energies detected imply very high particle energies ($\gamma_L > 10^7$).

3D Kinetic Models (PIC)

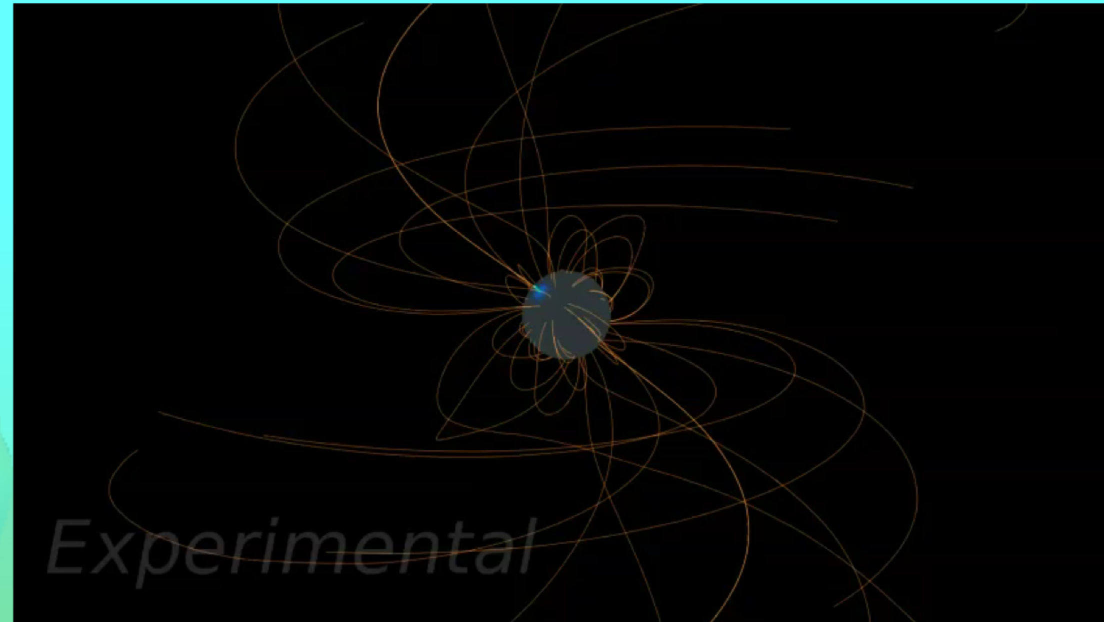
Pulsar Theater

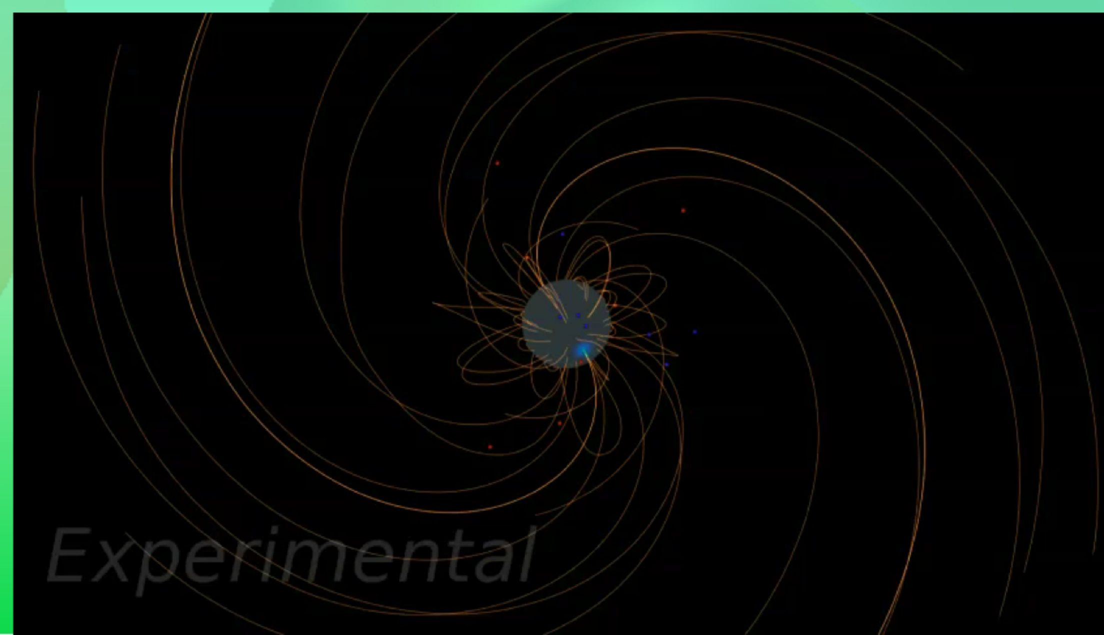
Particle injection near the stellar surface.

Brambilla et al. 2018

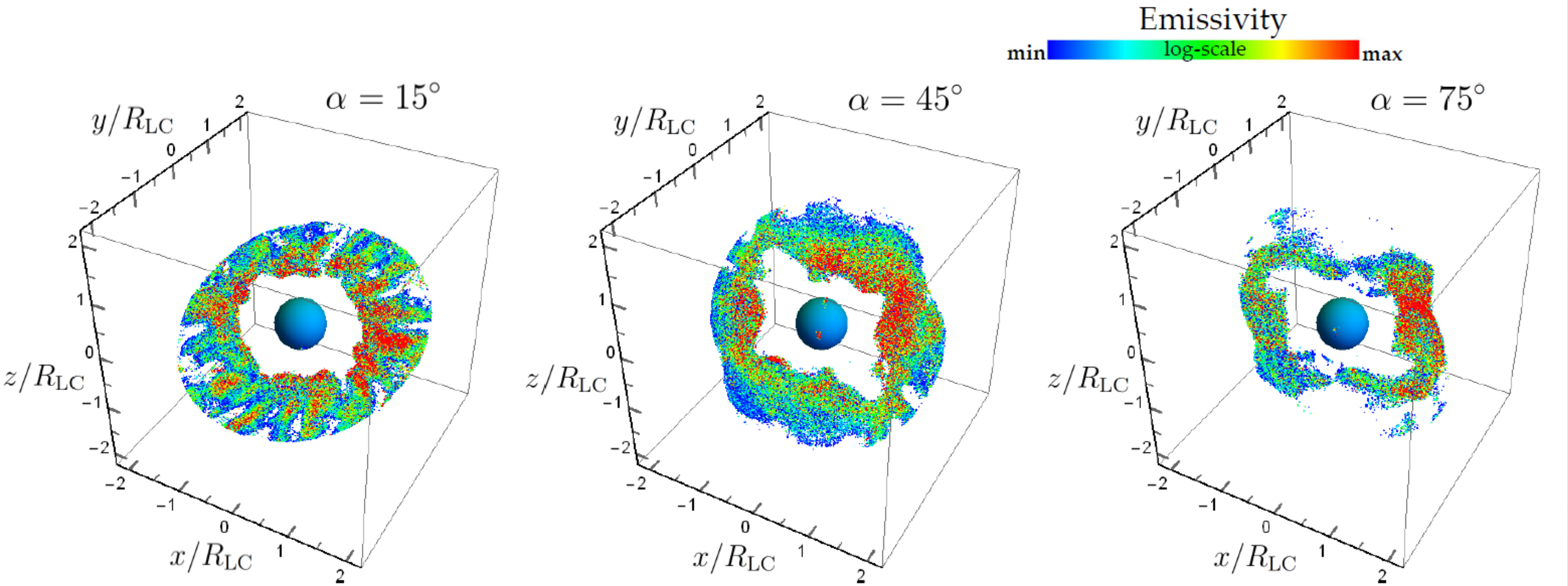
● e^-
● e^+

NASA/GSFC videos





3D Kinetic Models (PIC)



- 95% of the total emission
- Near the equatorial current sheet
- For low α-values closer to the Y-point (LC)
- For high α-values closer to the rotational equator compared to the theoretical extend of the ECS

Fundamental Plane (Observations)

88 Fermi YPs+MPs

$$L_{\gamma(3D)} = 10^{14.2\pm 2.3} \epsilon_{cut}^{1.18\pm 0.24} B_*^{0.17\pm 0.05} \dot{\mathcal{E}}^{0.41\pm 0.08}$$

ϵ_{cut}(MeV), B_*(G), L_γ, $\dot{\mathcal{E}}$(erg/s)

Kalapotharakos et al. (2019)

Fermi data

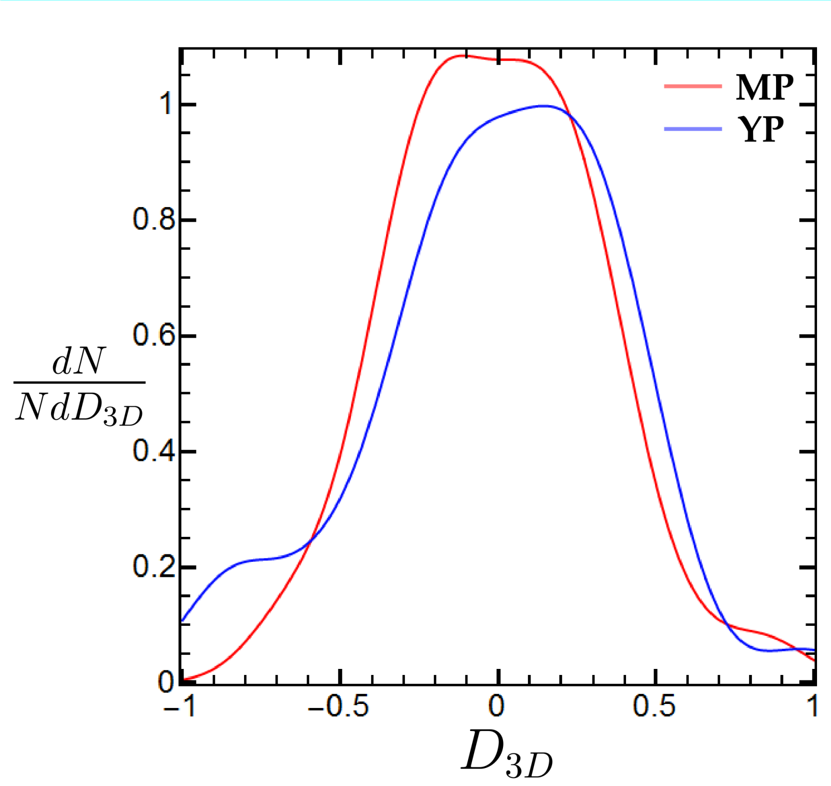
B_*: 4 OoM
$\dot{\mathcal{E}}$: 6 OoM
L_γ: 6 OoM
ϵ_{cut}: < 1 OoM

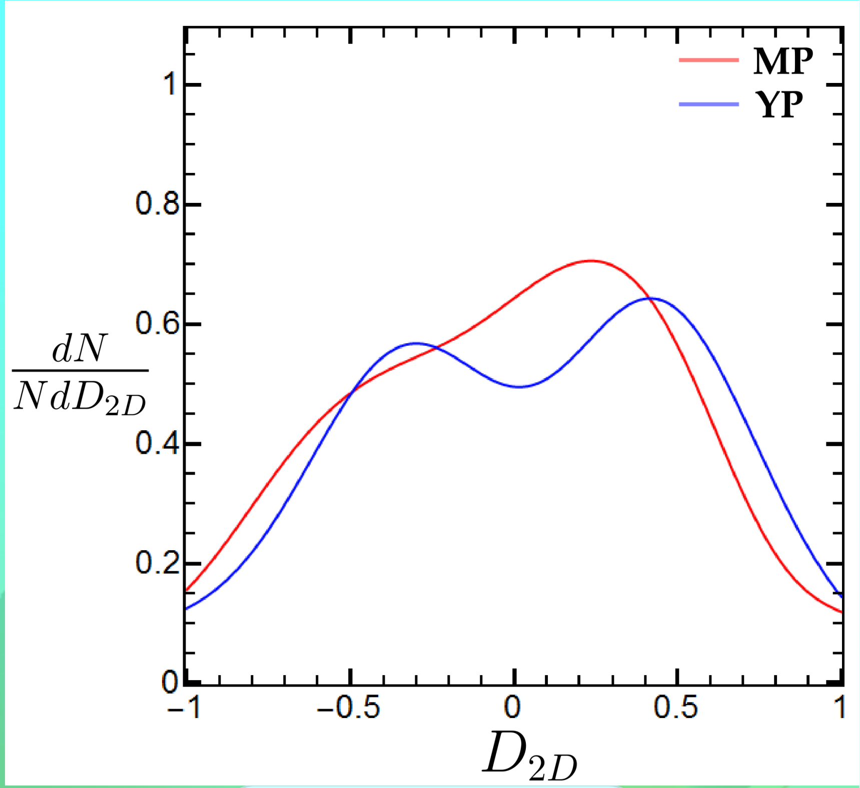
$$L_\gamma \propto \epsilon_{cut}^{4/3} B_*^{1/6} \dot{\mathcal{E}}^{5/12}$$

Theory CR

$$L_{\gamma(2D)} = 10^{15.0\pm 2.6} B_*^{0.11\pm 0.05} \dot{\mathcal{E}}^{0.51\pm 0.09}$$

Fundamental Plane (Observations)





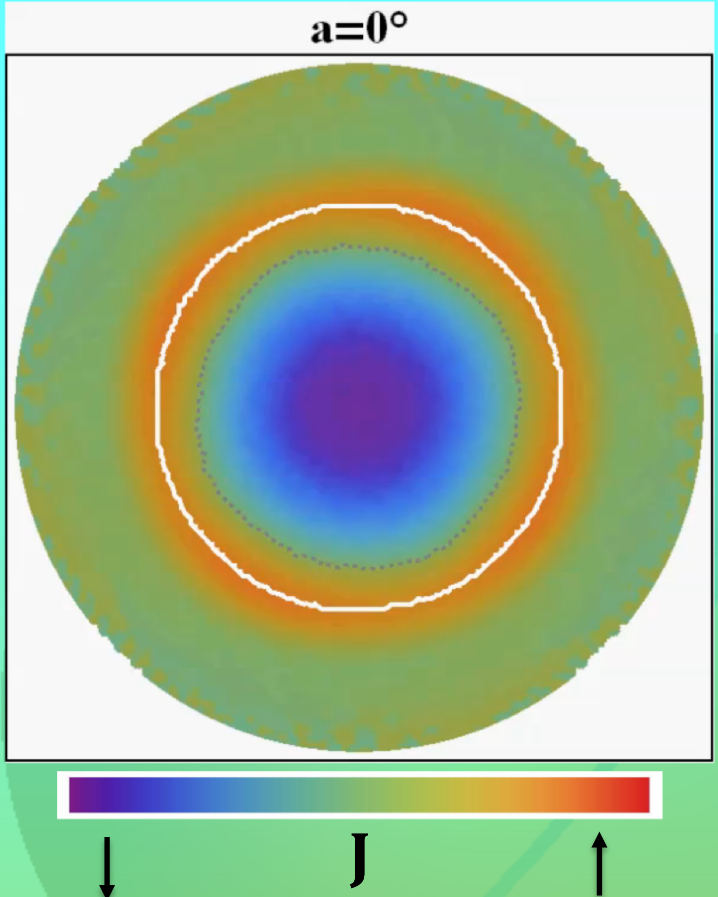
$AIC_{3D} = 159$

$BIC_{3D} = 172$

$AIC_{2D} = 180$

$BIC_{2D} = 189$

3D Kinetic Models (PIC)



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Kalapotharakos et al. (in prep)

Requirements

The particle injection rate along the open and the closed field-lines is <u>not very small</u>.

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However, it is <u>not necessary to be high</u>.

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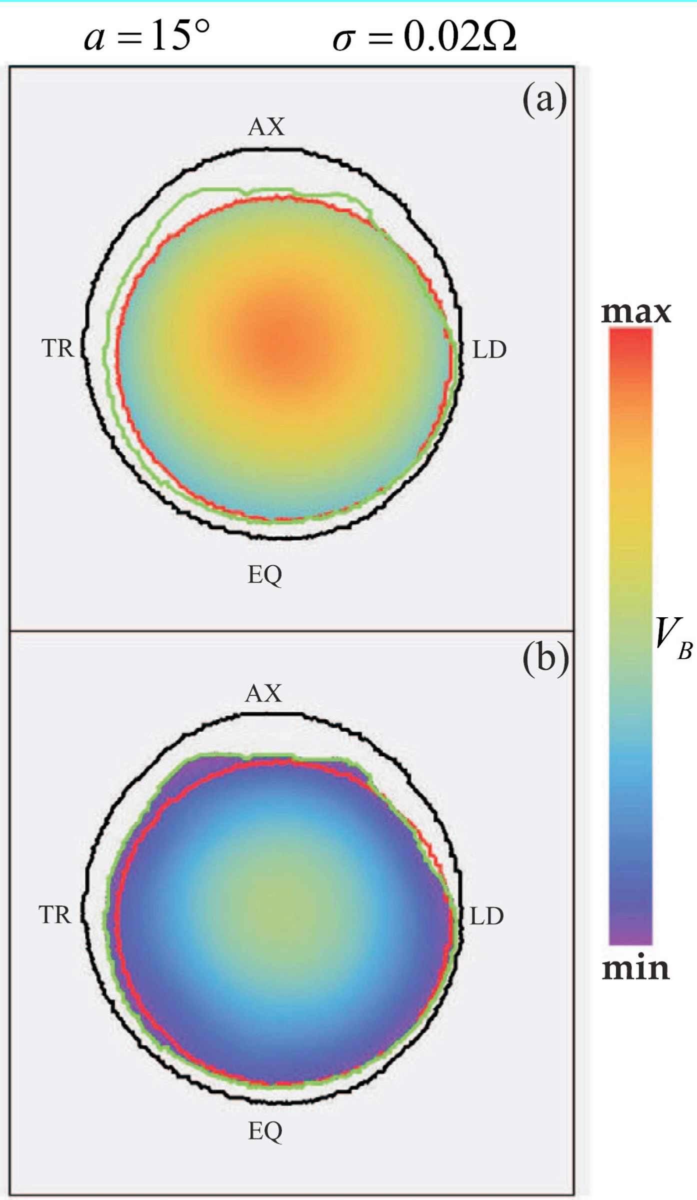

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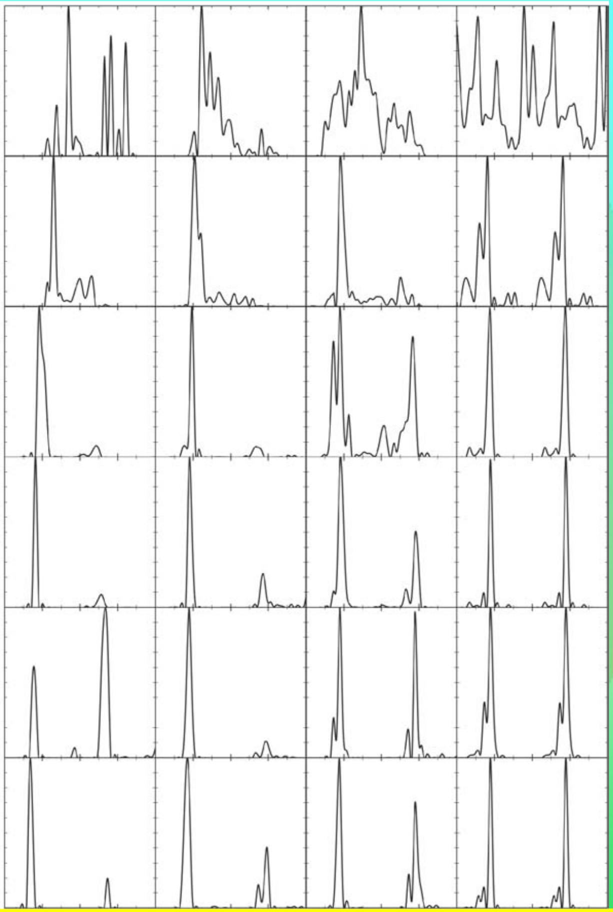
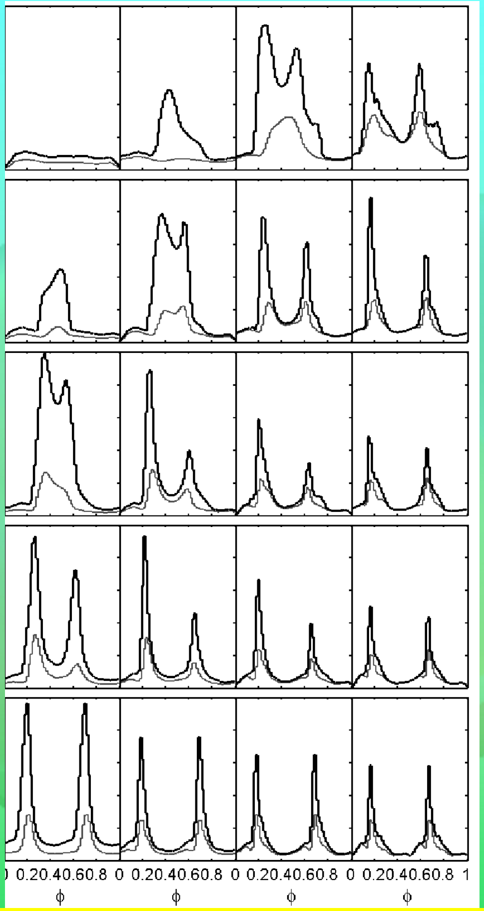
FFE Models

γ-ray light-curves from the region near the equatorial current sheet (ECS)

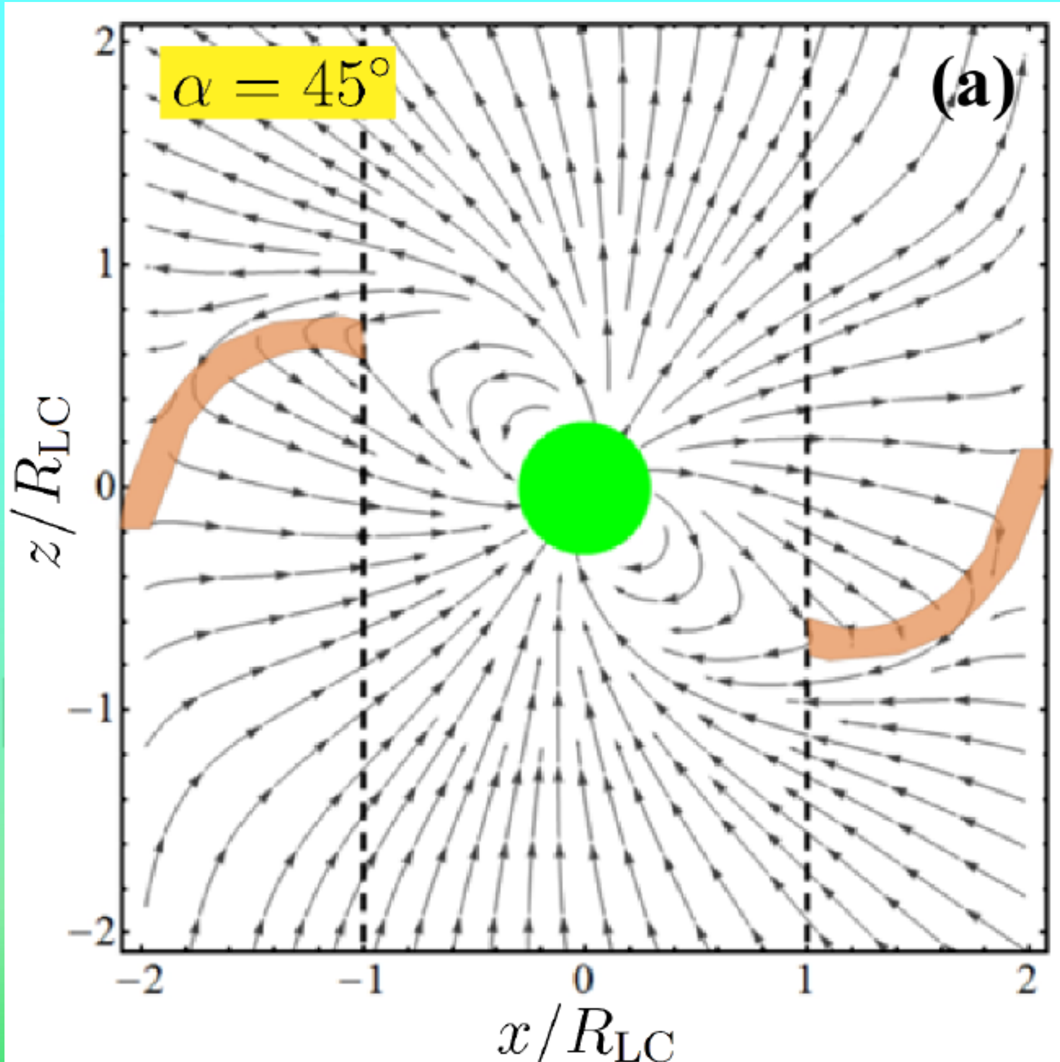


Contopoulos & Kalapotharakos (2010)



Bai & Spitkovsky (2010)

FIDO Models

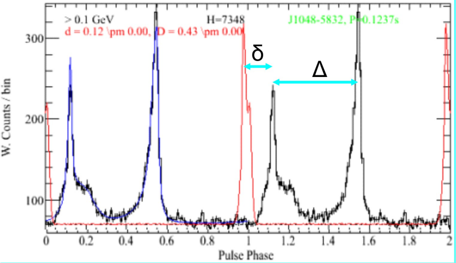


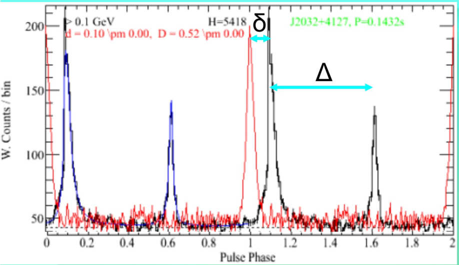
Kalapotharakos et al. (2014, 2017)

FIDO Models
(FFE Inside the Light-Cylinder, Dissipative Outside the Light Cylinder)

σ: conductivity

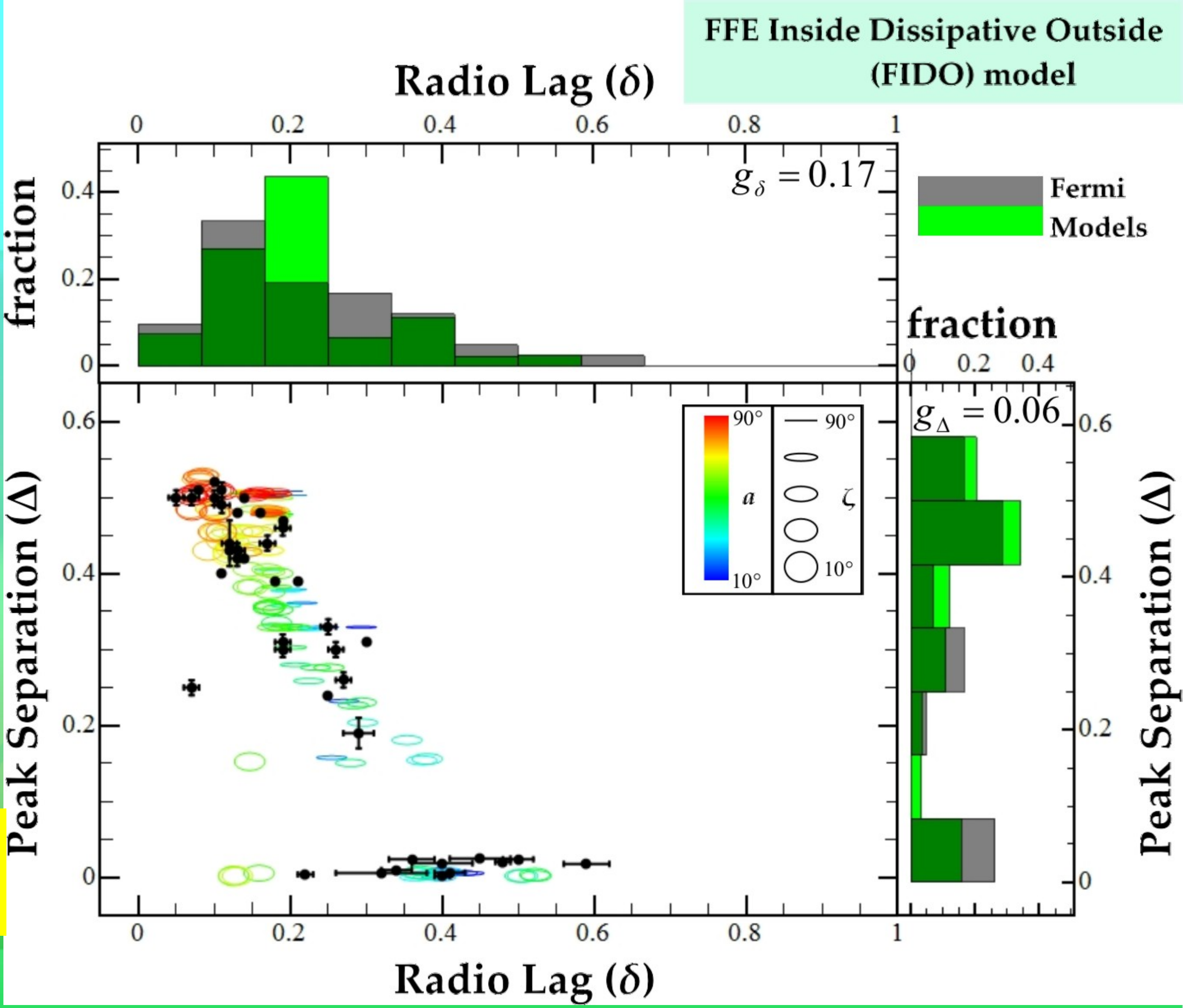
FIDO Models





radio-lag (δ)
vs
peak-separation (Δ)

Test particles
Curvature Radiation

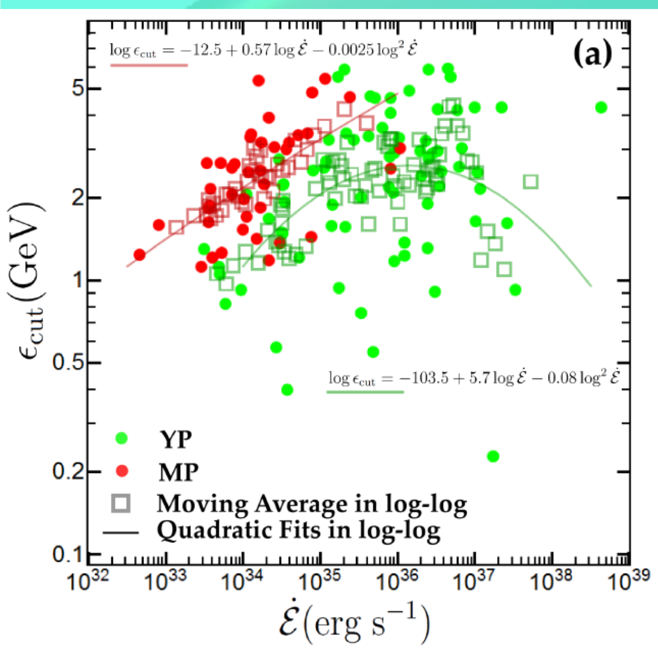


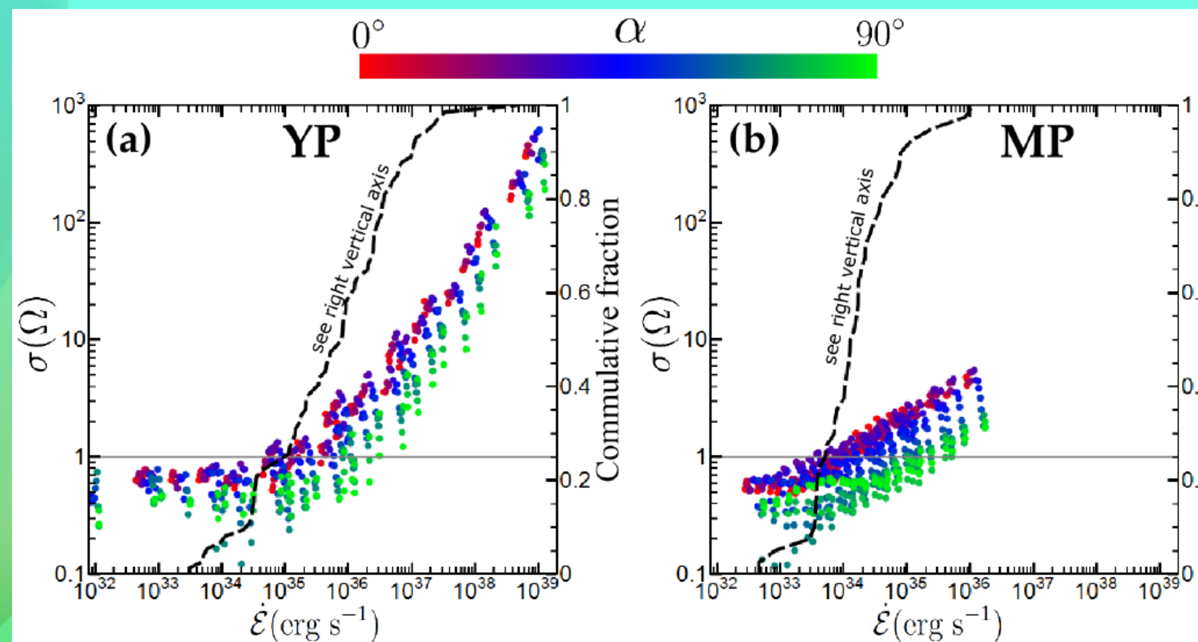
Kalapotharakos et al. (2014)

FIDO Models

The FIDO model allows the calculation of the phase-averaged, phase-resolved spectra and the calculation of the total γ-ray luminosity.

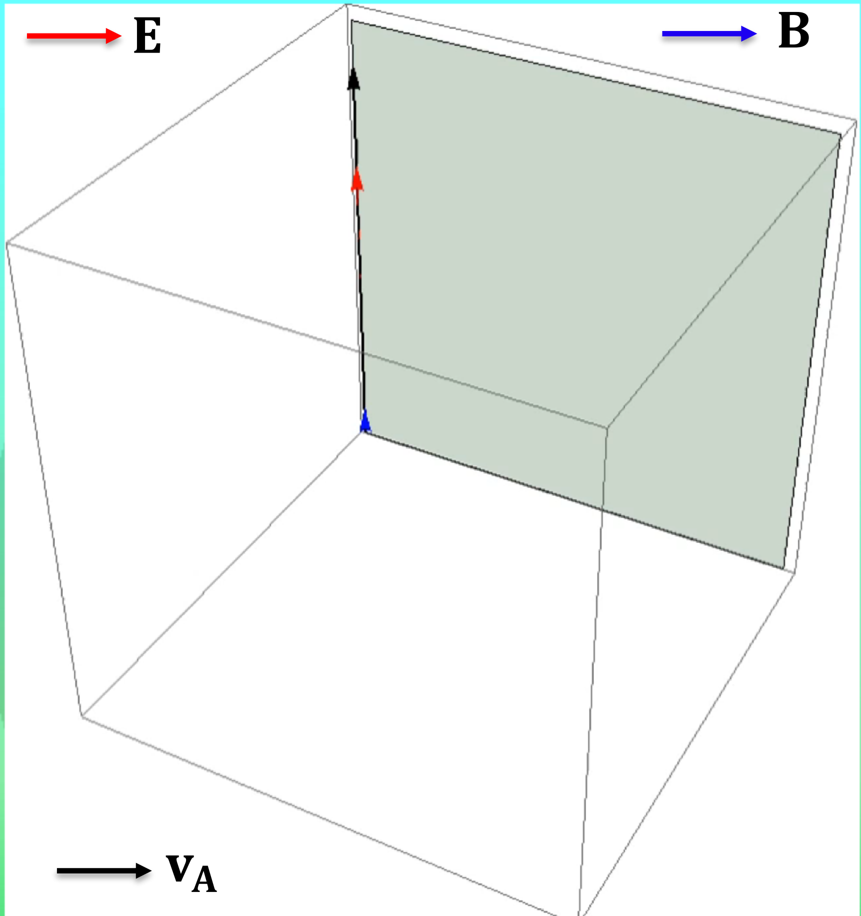
$\sigma(\dot{\mathcal{E}})$





Kalapotharakos et al. (2017)

Orbital Exploration (SR↔CR)

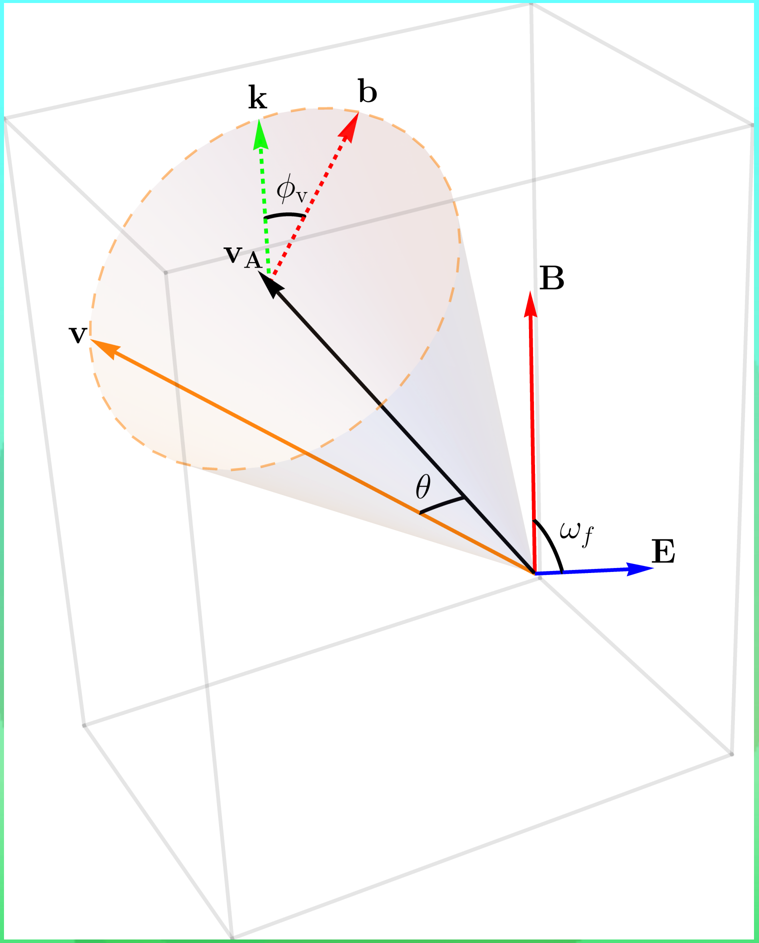


Kalapotharakos et al. (2019)

$$\mathbf{v_A} = \frac{\mathbf{E}\times\mathbf{B} \pm (E_0\mathbf{E} + B_0\mathbf{B})}{E_0^2 + B^2}$$

Aristotelian Electrodynamics
(Gruzinov 2012; Kelner et al. 2015)

Orbital Exploration (SR↔CR)



Kalapotharakos et al. (2019)

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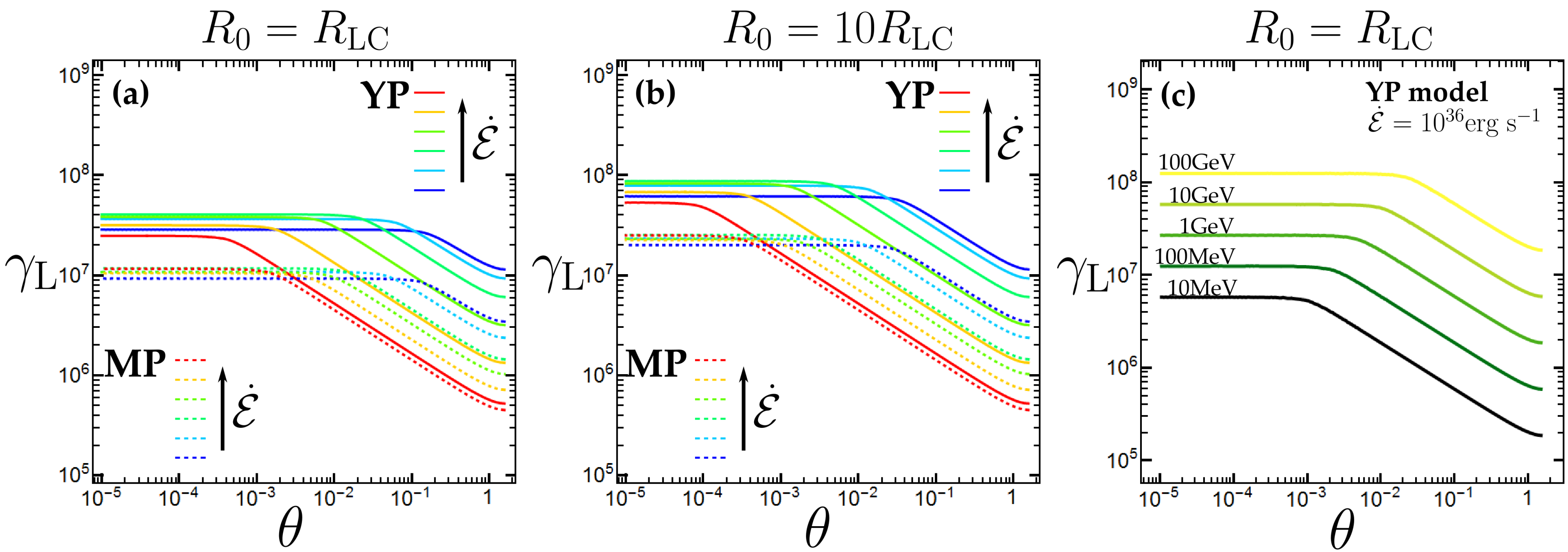
Aristotelian Electrodynamics
(Gruzinov 2012; Kelner et al. 2015)

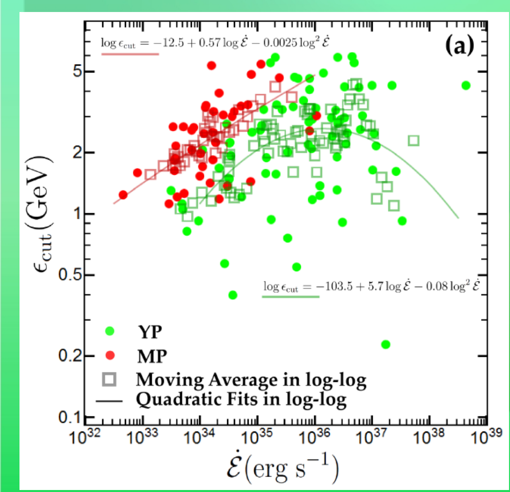
$$R_C = \frac{\gamma_L m_e c^2}{q_e B_{eff}}$$

$$B_{eff} = \sqrt{\left(\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{\mathbf{c}}\right)^2 - \left(\frac{\mathbf{v}\cdot\mathbf{B}}{c}\right)^2}$$

Cerutti et al. 2016

Reverse Engineering





$$\epsilon_{cut} = \frac{3}{2} c\hbar \frac{\gamma_L^3}{R_C(\theta)}$$

Kalapotharakos et al. (2019)

$E, B \sim B_{LC}$

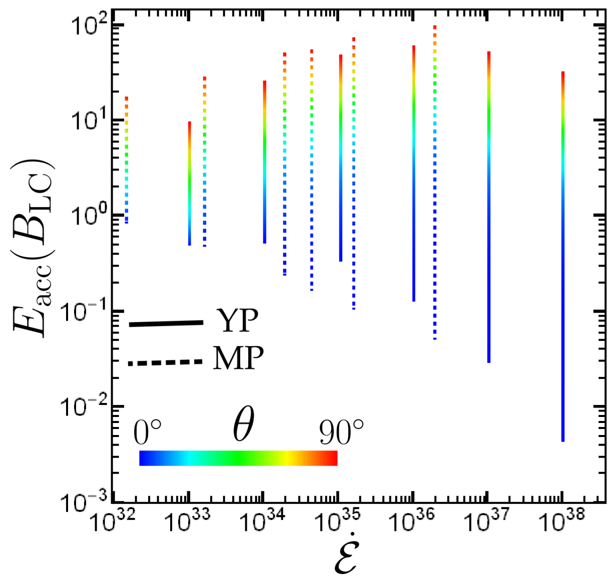
θ decreases:

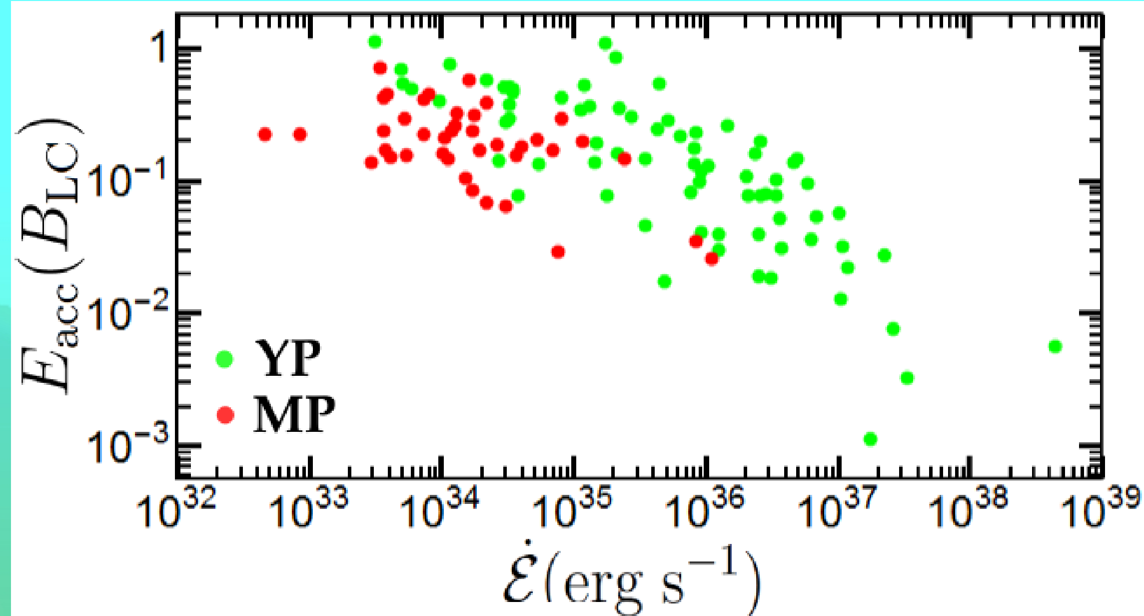
1. Radiation reaction losses
2. Acceleration

***θ* should be sustained by another process (e.g. heating)**

Reverse Engineering

$R_0 = R_{LC}$





Kalapotharakos et al. (2017)

$$\frac{2q_e^2\gamma_L^4}{3m_e c\, R_C(\theta)} = \frac{q_e \mathbf{v}\cdot\mathbf{E}}{m_e c^2}$$

$$\epsilon_{cut} = \frac{3}{2} c\hbar \frac{\gamma_L^3}{R_C(\theta)}$$

Kalapotharakos et al. (2019)

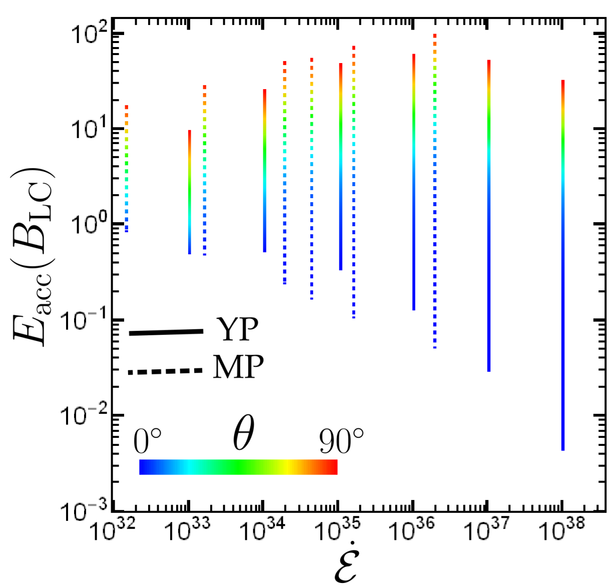
$E_{acc} < B_{LC}$

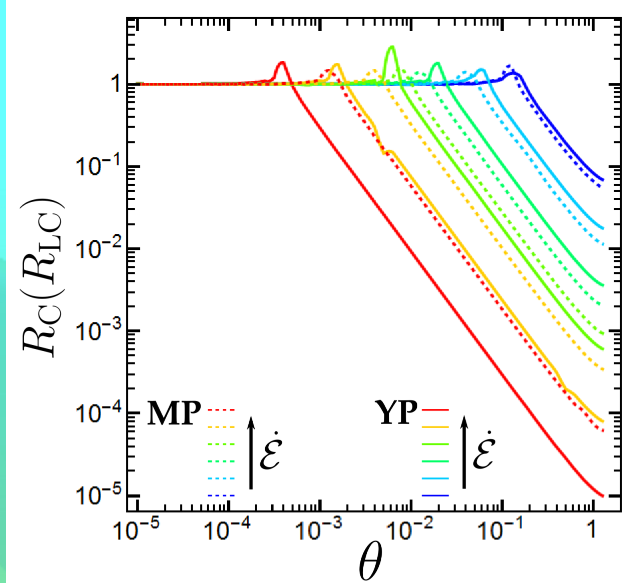
θ decreases:
1. Radiation reaction losses
2. Acceleration

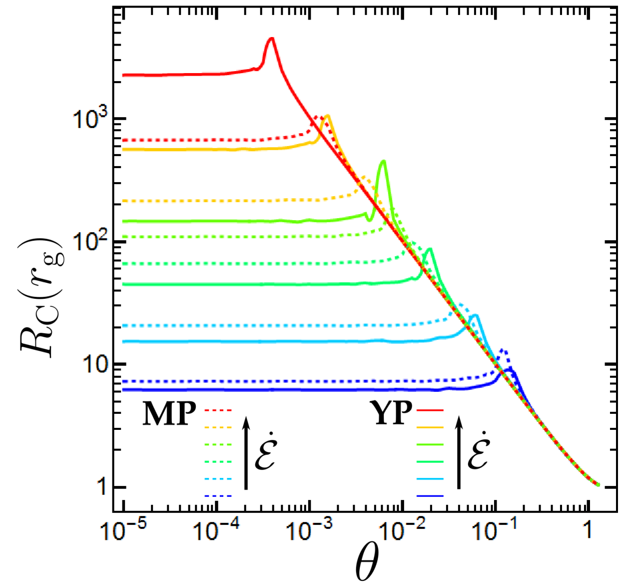
θ should be sustained by another process (e.g. heating)

Reverse Engineering

$R_0 = R_{LC}$







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θ should be sustained by another process (e.g. heating)

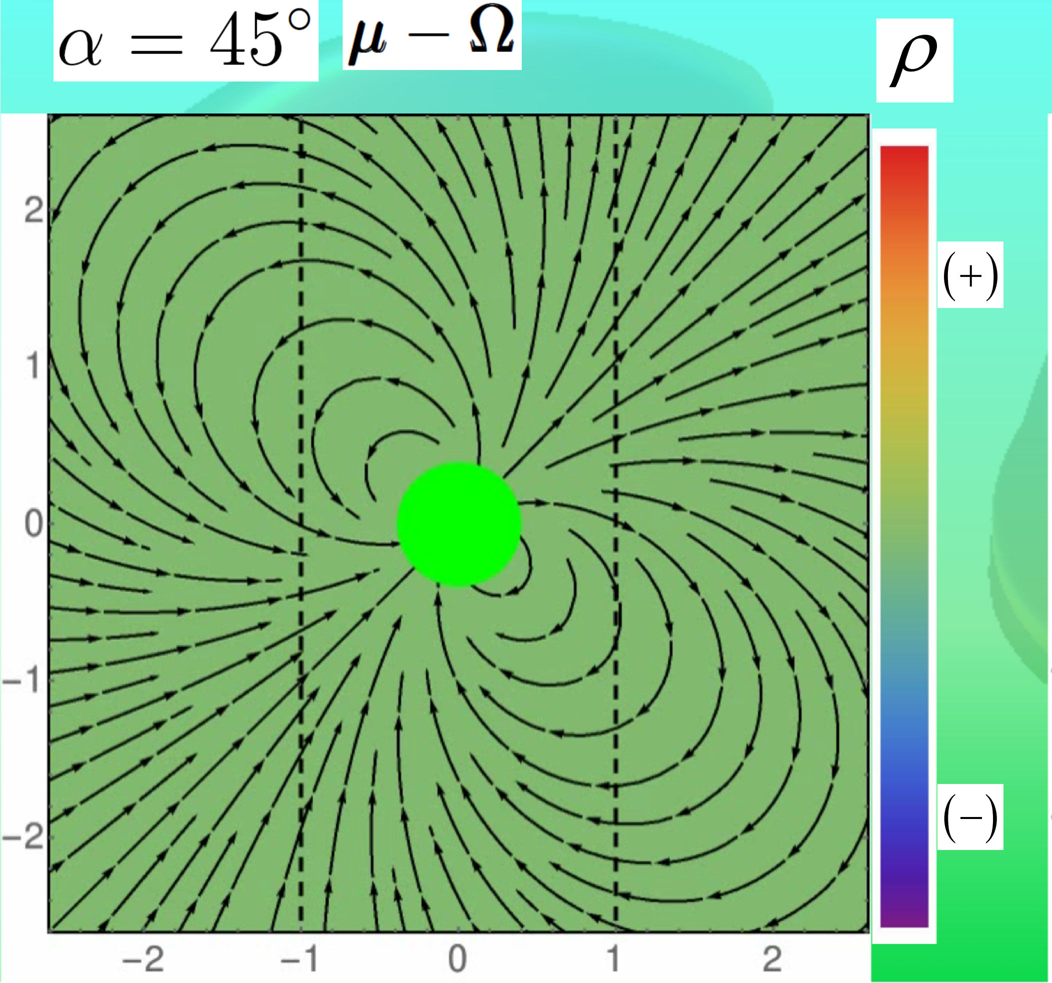
3D Kinetic Models (PIC)

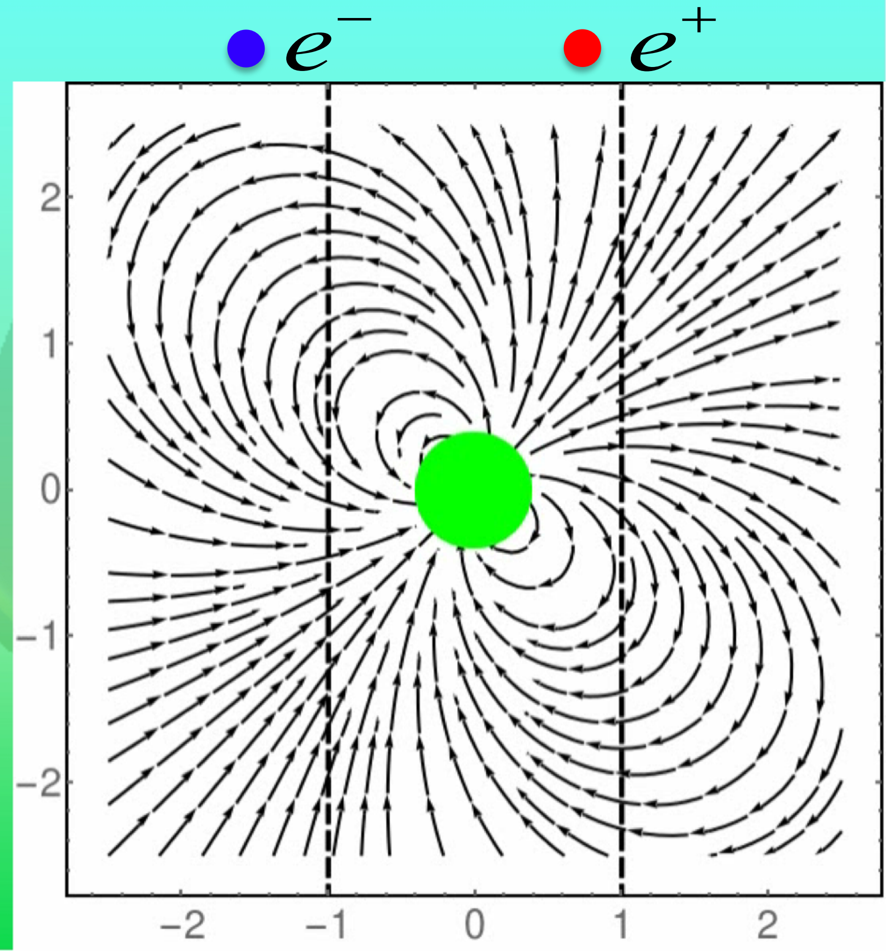
Towards self-consistency:

1) Arbitrary particle injection

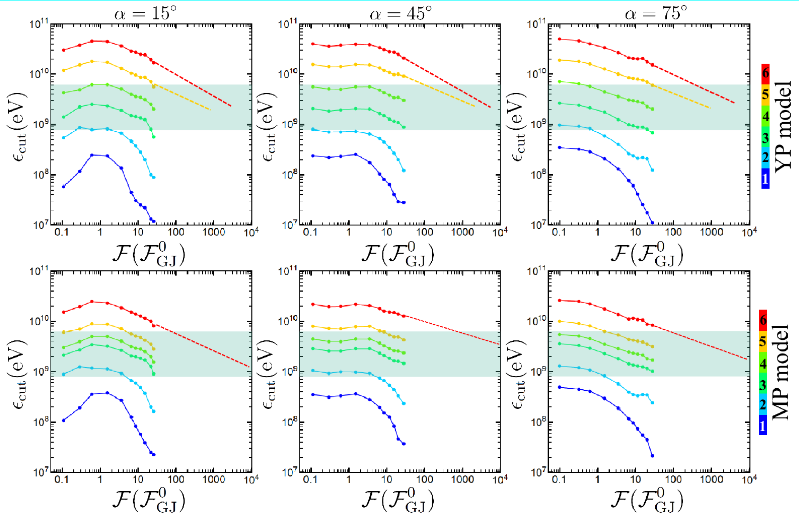
⟶ consistent field structure & particle distribution

$\alpha = 45^\circ$ $\mu - \Omega$

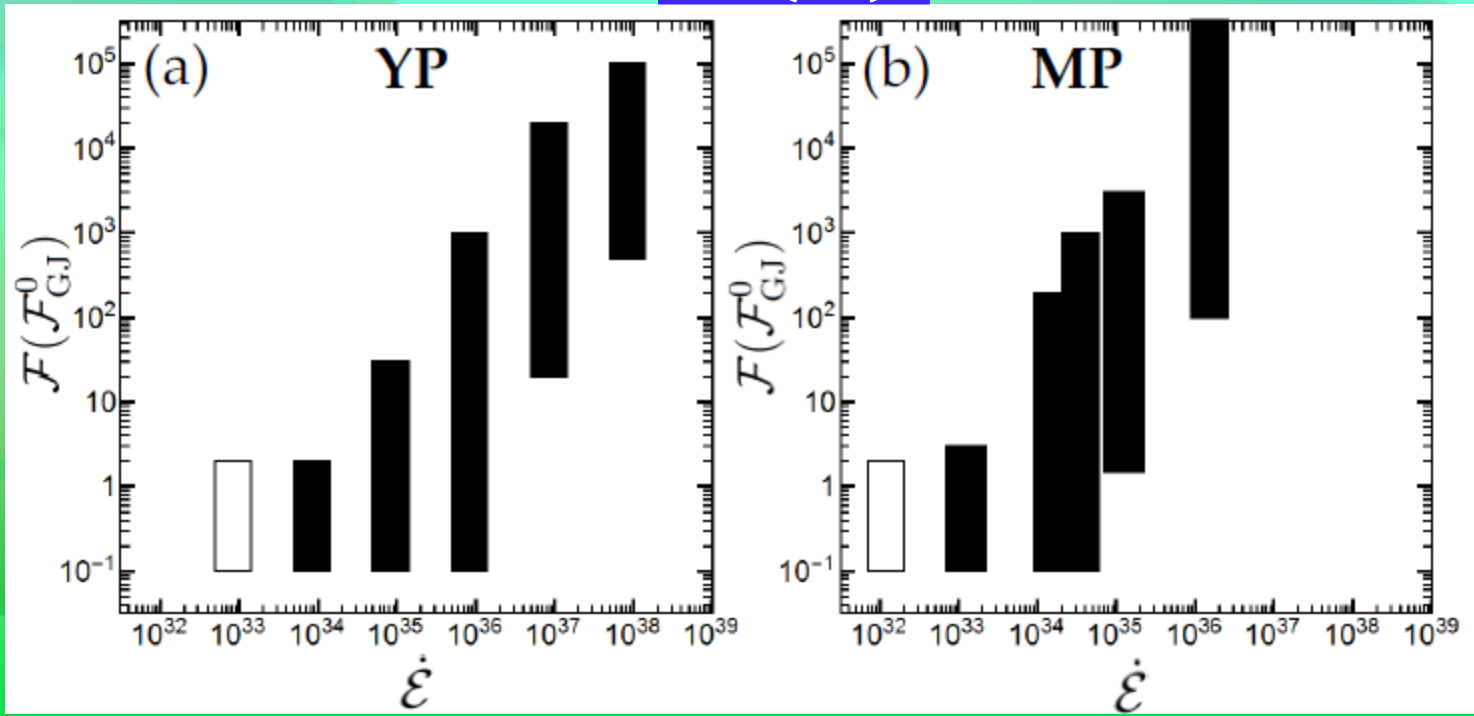




3D Kinetic Models (PIC)

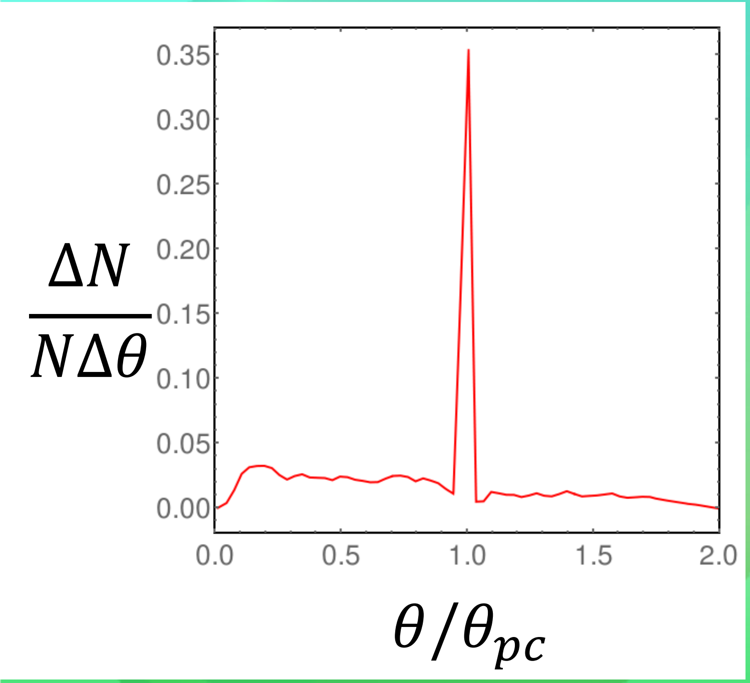


$\mathcal{F}(\dot{\mathcal{E}})$



3D Kinetic Models (PIC)

Separatrix injection model



The γ-ray pulsar radiation is mainly regulated by

1. **The particle injection rate $\mathcal{F}_s$ along the separatrix**
2. **The width w of the separatrix zone**

Kalapotharakos et al. (in prep)

Requirements

The particle injection rate along the open and the closed field-lines is <u>not very small</u>.

($> 5\mathcal{F}_{GJ}^0$)

However, it is <u>not necessary to be high</u>.

($< 10\mathcal{F}_{GJ}^0$)