Simulations vs. Observations

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Outline

- **Observations**
  The Fermi Era (Success Requirements)
- **Macroscopic Global Models**
- **Kinetic PIC Models**
- **Interpreting the Observations:**
  Fundamental Plane of γ-ray Pulsars
- **Conclusions**

Technical Details

Guidance

Constraints

Understanding

Simplicity

Challenges

Chronological Order
Motivation
Development of Ideas

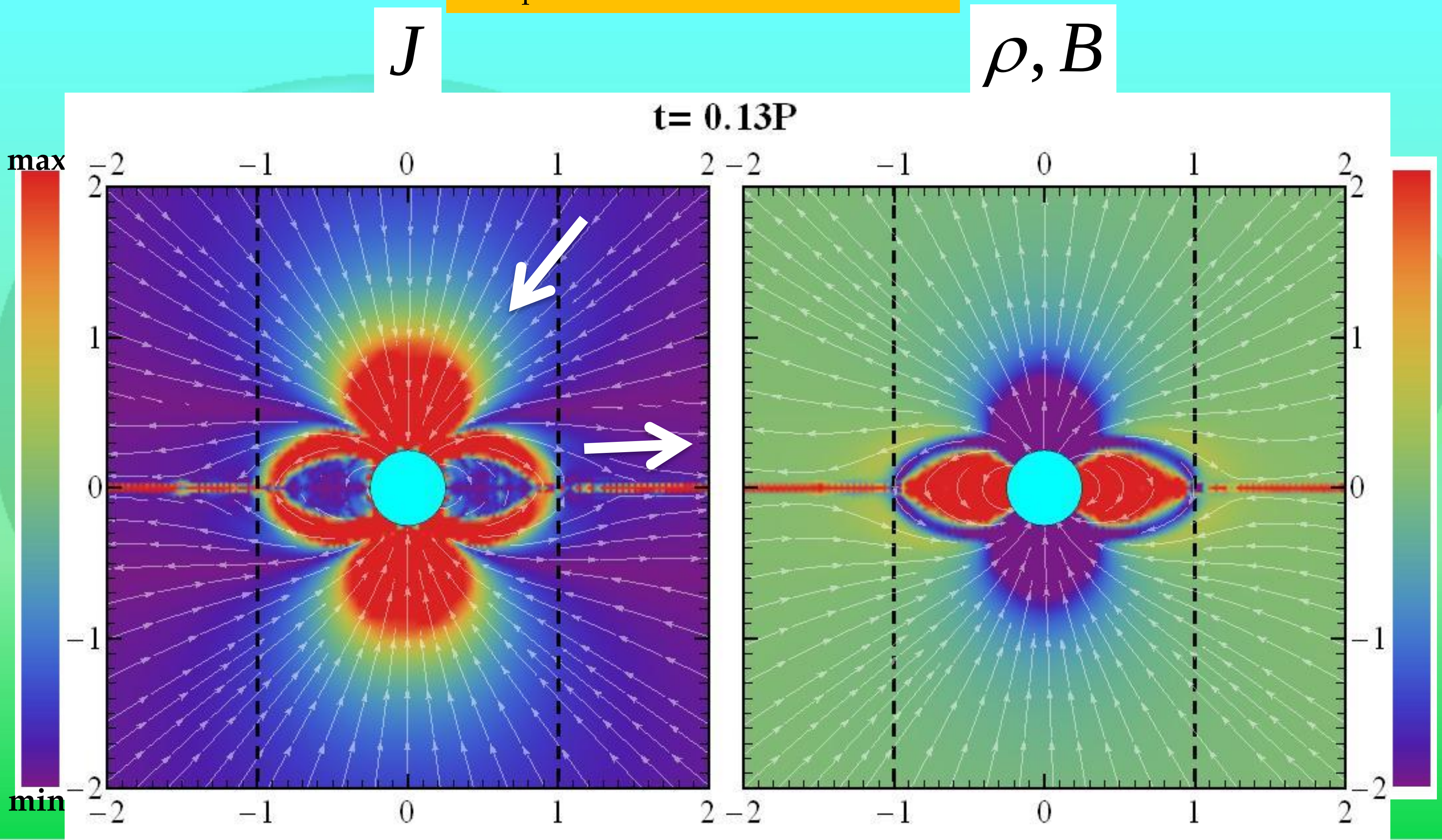
FFE Solutions

Contopoulos, Kazanas, & Fendt (1999)

Spitkovsky (2006)

$\alpha = 0^\circ$

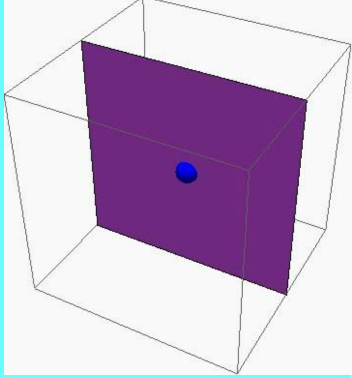
Kalapotharakos & Contopoulos 2009
Kalapotharakos et al. 2012

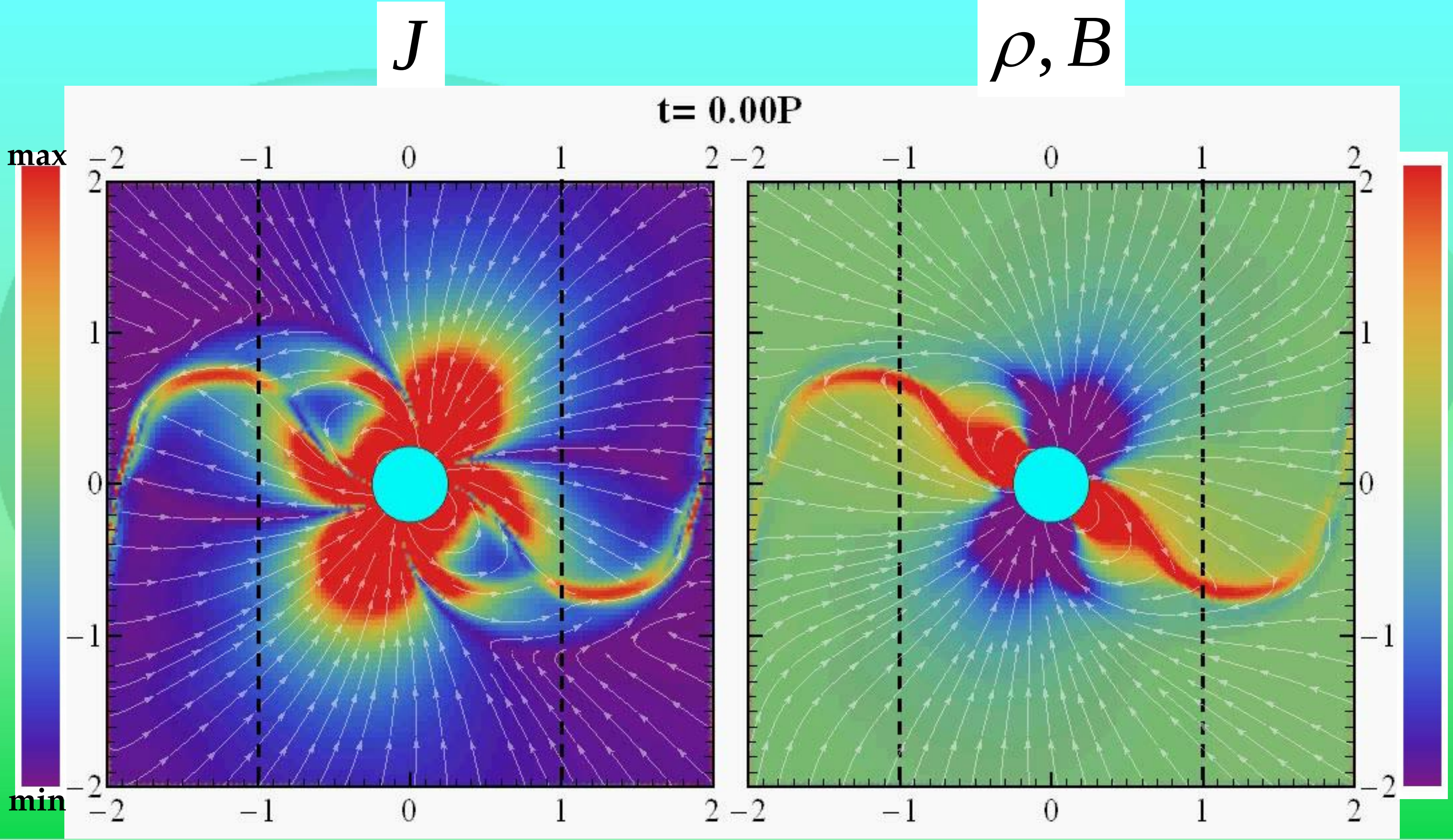


FFE Solutions

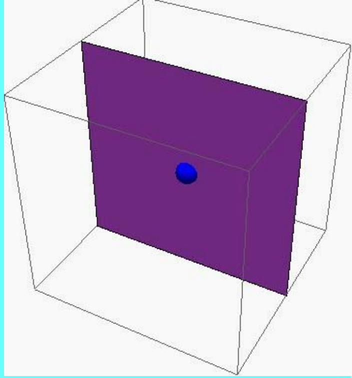
$\alpha = 45°$

Kalapotharakos & Contopoulos 2009
Kalapotharakos et al. 2012





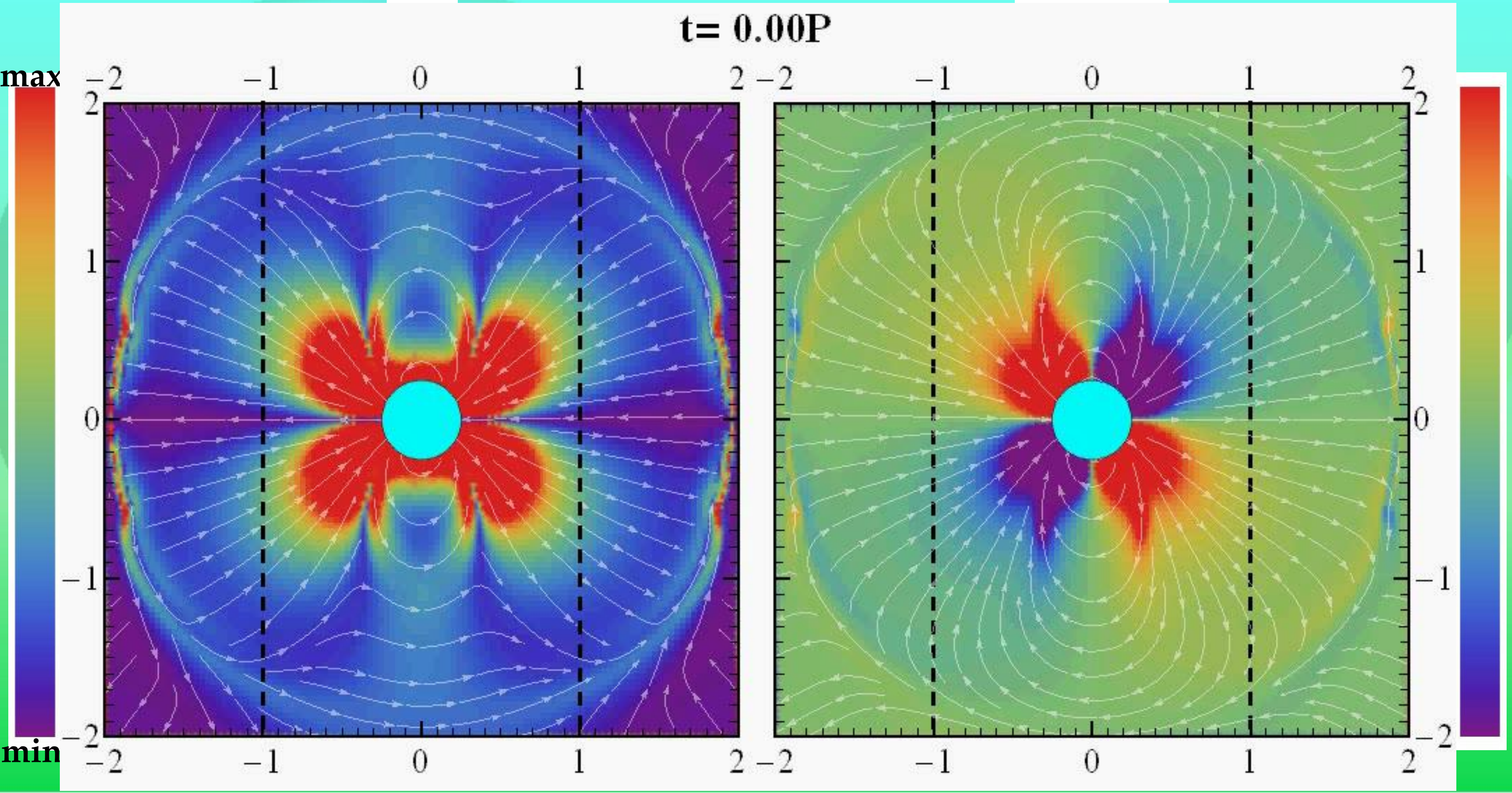
FFE Solutions



$$\alpha = 90^\circ$$

Kalapotharakos & Contopoulos 2009
Kalapotharakos et al. 2012

J ρ, B



FFE Solutions

Spin down rate

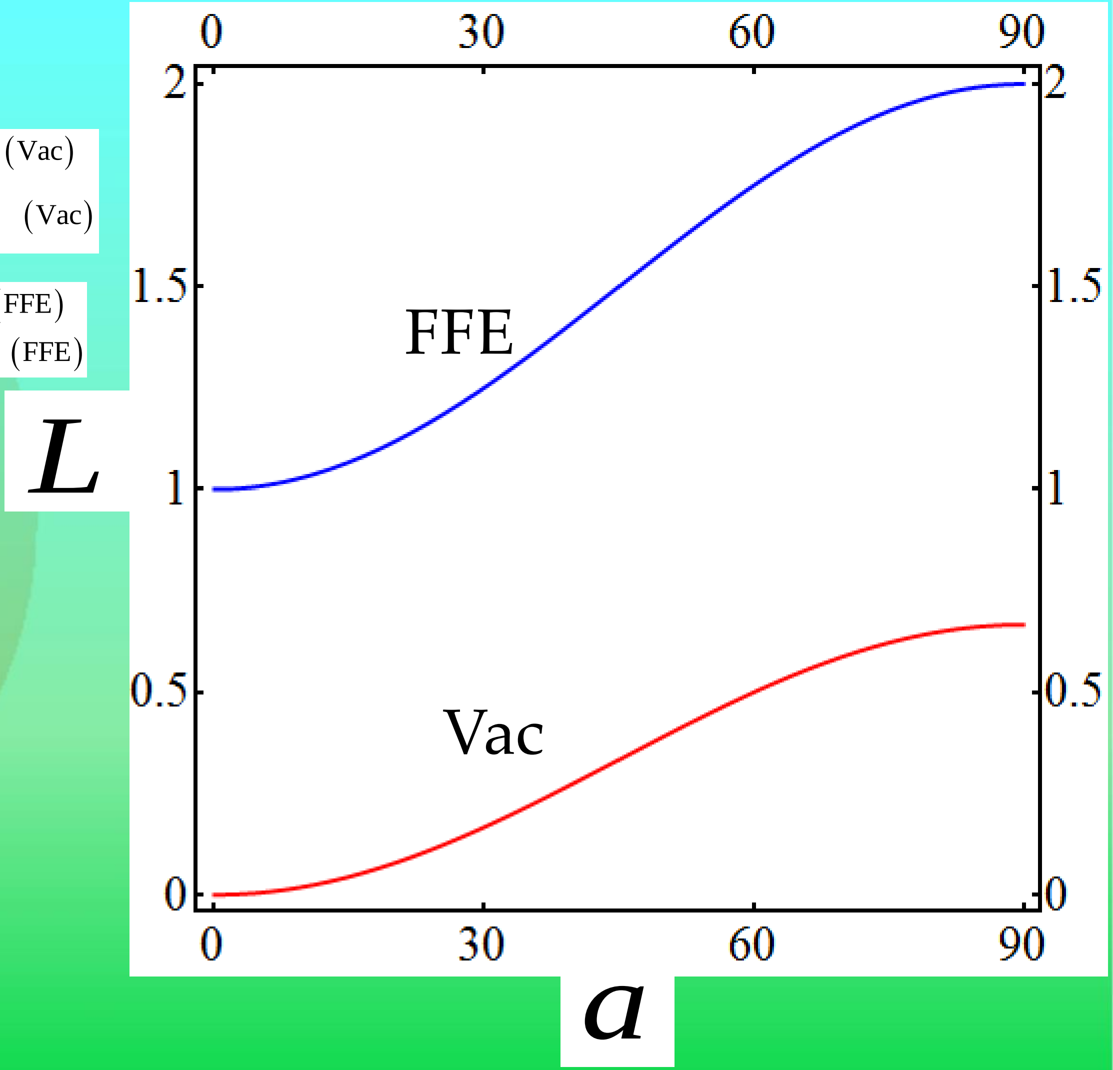
$$L = \begin{cases} \dfrac{2}{3}\dfrac{\mu^2\Omega^4}{c^3}\sin^2 a & \text{Vac} \\ \dfrac{\mu^2\Omega^4}{c^3}(1+\sin^2 a) & \text{FFE} \end{cases}$$

$L(0°)=0 \quad (\text{Vac})$

$L(90°)=\frac{2}{3} \quad (\text{Vac})$

$L(0°)=1 \quad (\text{FFE})$

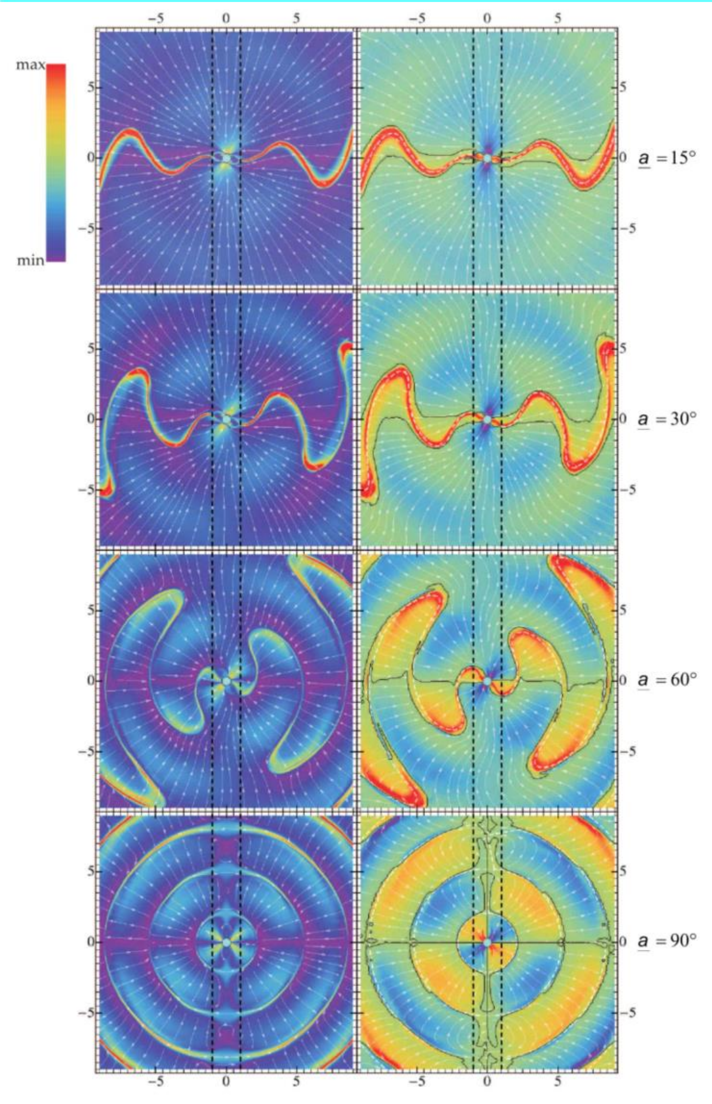
$L(90°)=2 \quad (\text{FFE})$



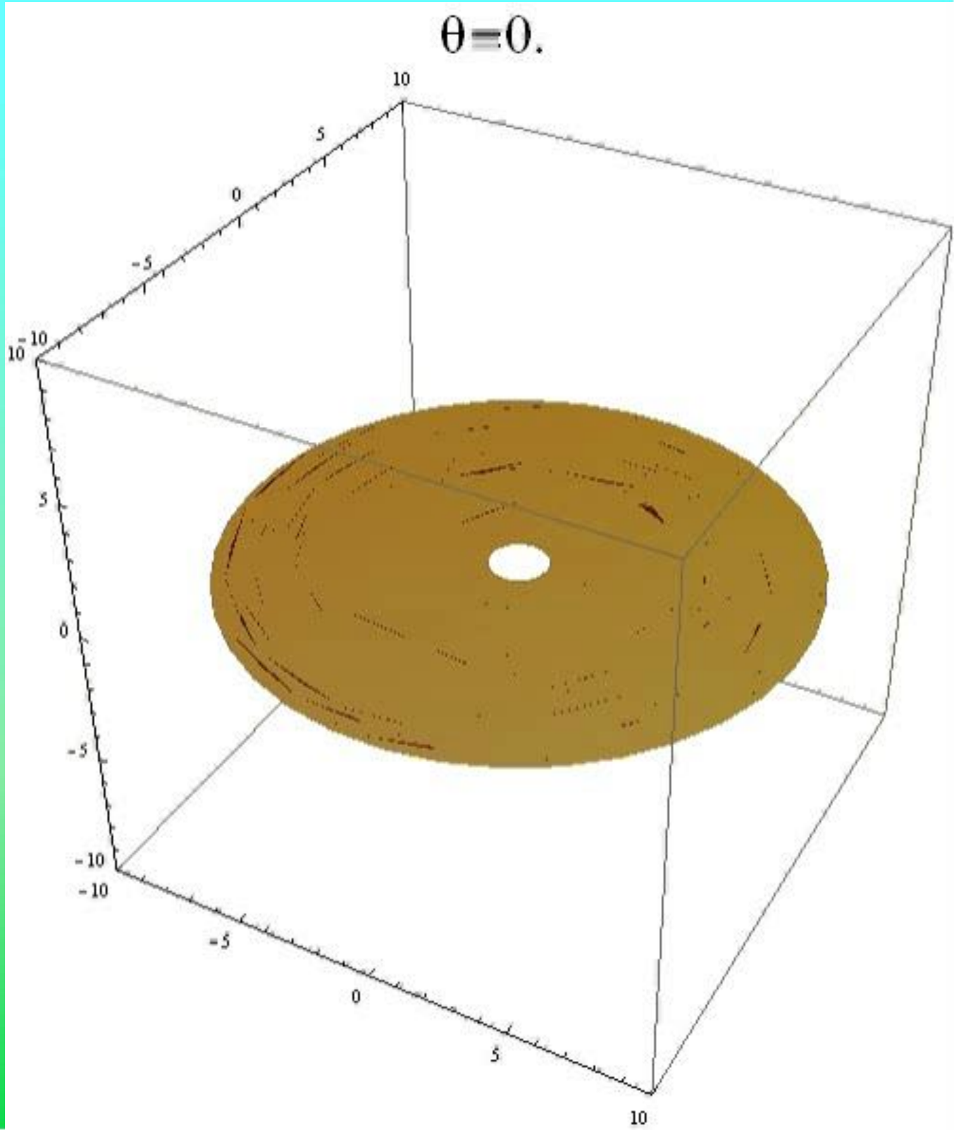
Spitkovsky 2006
Kalapotharakos & Contopoulos 2009
Tchekhovskoy et al. 2013

FFE Solutions

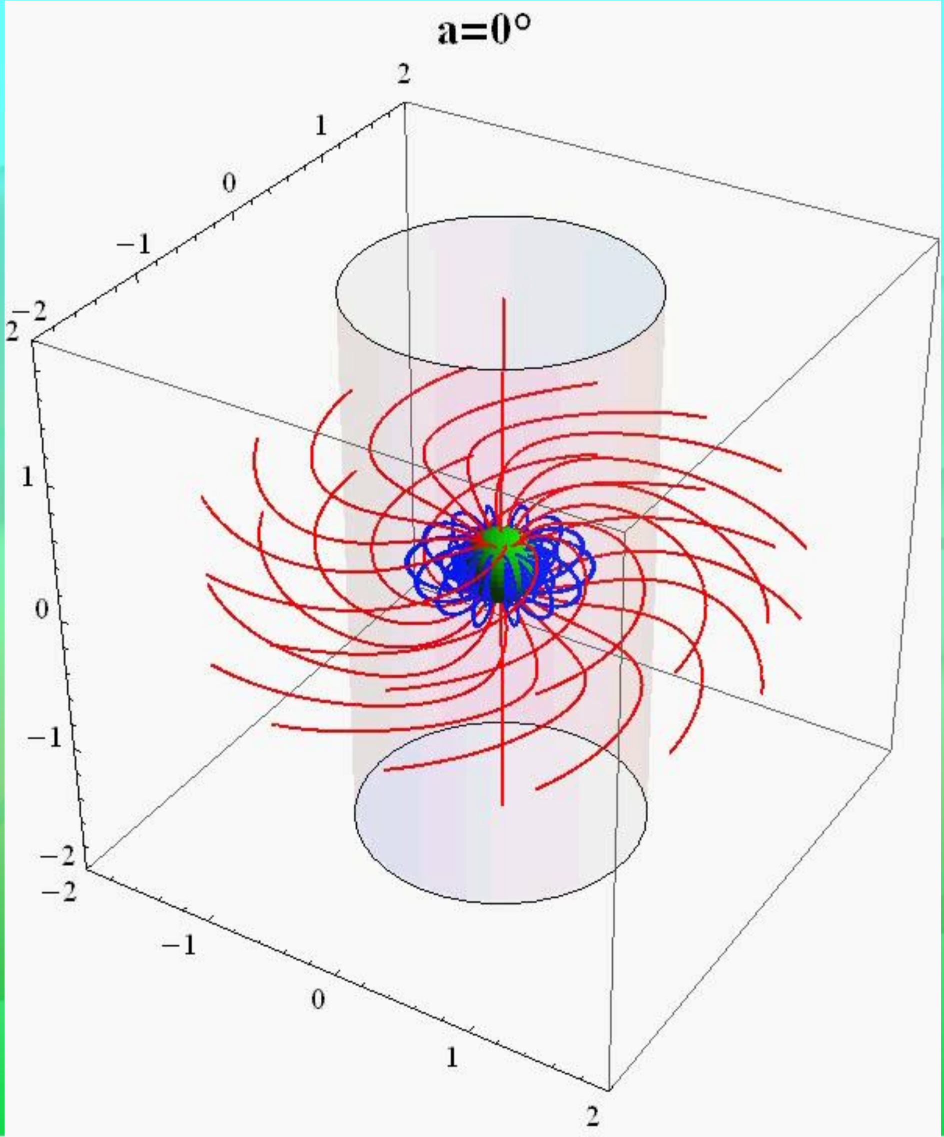
Kalapotharakos et al. (2012)



Bogovalov (1999)

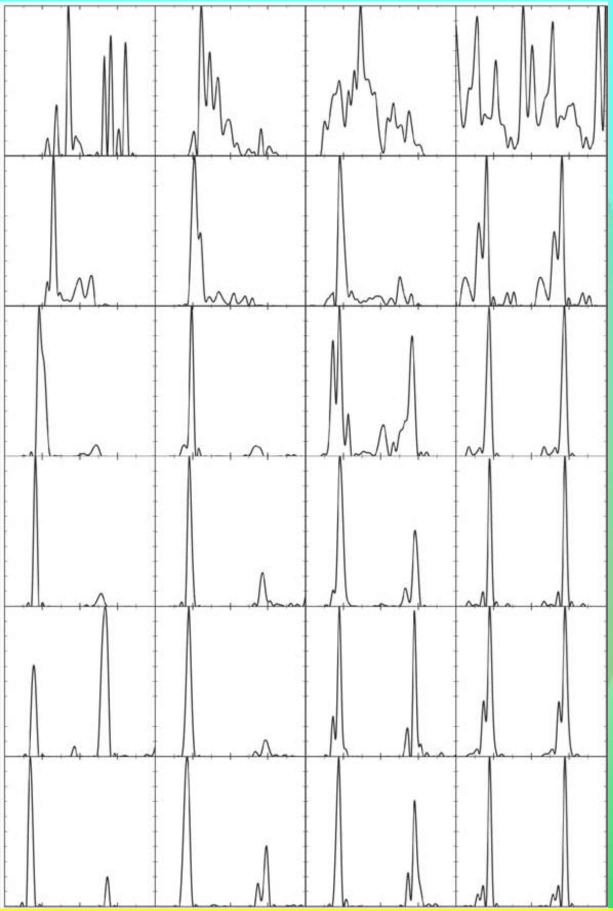


FFE Solutions

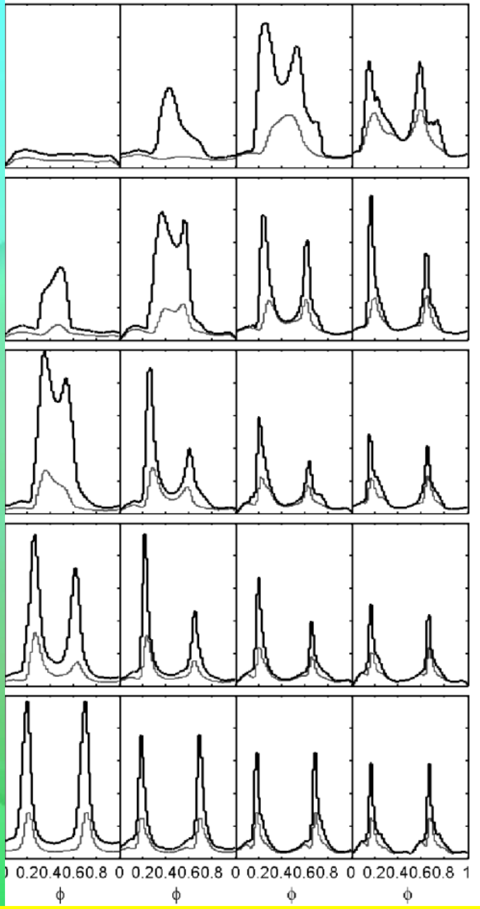


FFE Models

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



Contopoulos & Kalapotharakos (2010)



Bai & Spitkovsky (2010)

The Problem

VRD

- $\rho=0$
- $E_{||}\neq0$

FFE

- $\rho\neq0$
- $E_{||}=0$

Cannot be observed!

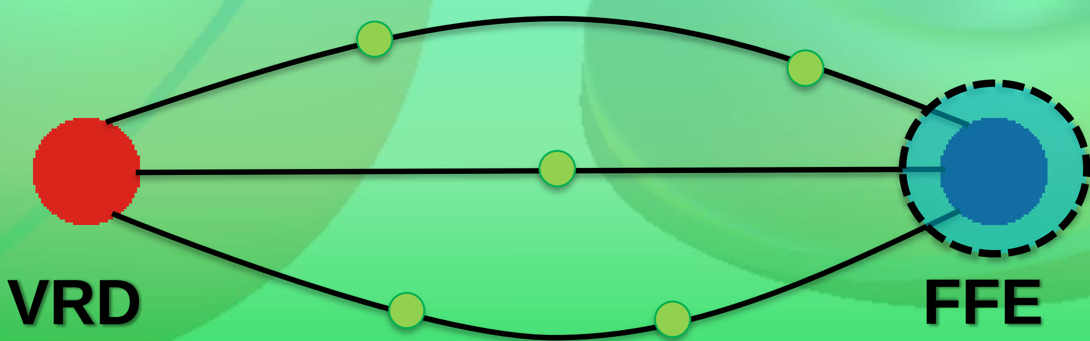
I don't know how many "Pulsars" follow *exactly* these solutions (VRD or FFE) but I *definitely* know that none of the observed ones does.

The Problem

VRD
- $\rho=0$
- $E_{\|}\neq 0$

FFE
- $\rho\neq 0$
- $E_{\|}=0$

Cannot be observed!



Dissipative Solutions

$$\mathbf{J} = c\rho\frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{c}{4\pi}\frac{\mathbf{B}\cdot\nabla\times\mathbf{B} - \mathbf{E}\cdot\nabla\times\mathbf{E}}{B^2}\mathbf{B}$$

FFE

$$\mathbf{J} = c\rho\frac{\mathbf{E}\times\mathbf{B}}{E_0^2 + B^2} + \sigma E_{\parallel}$$

Kalapotharakos et al. (2012, 2014)

$$\mathbf{J} = \frac{c\rho\mathbf{E}\times\mathbf{B} + (c^2\rho^2 + \gamma^2\sigma^2 E_0^2)^{1/2}(B_0\mathbf{B} + E_0\mathbf{E})}{B^2 + E_0^2}$$

Gruzinov (2007, 2008)

$$\mathbf{J} = \frac{c\rho\mathbf{E}\times\mathbf{B} + \gamma\sigma(B_0\mathbf{B} + E_0\mathbf{E})}{B^2 + E_0^2}$$

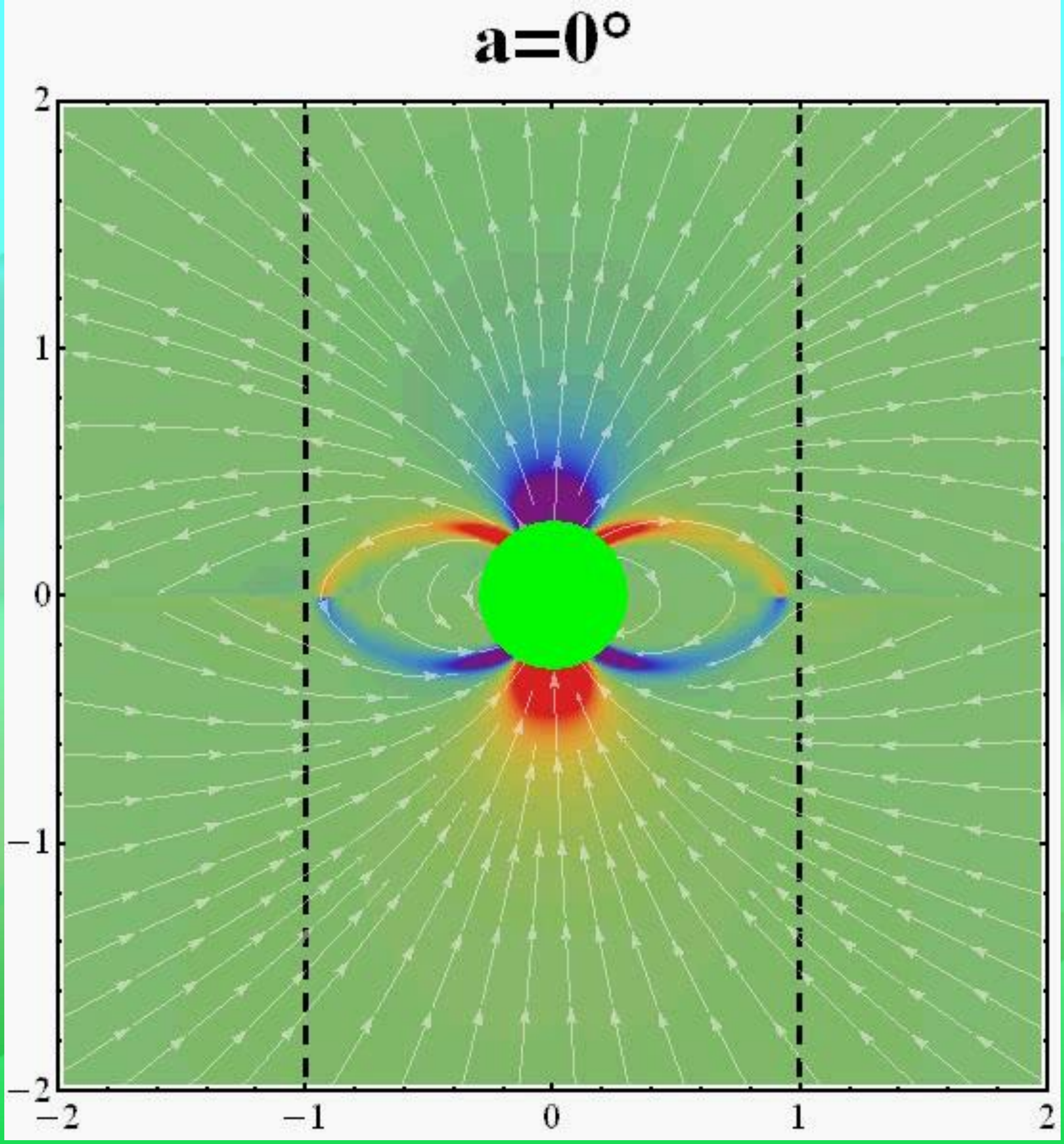
Li et al. (2012)

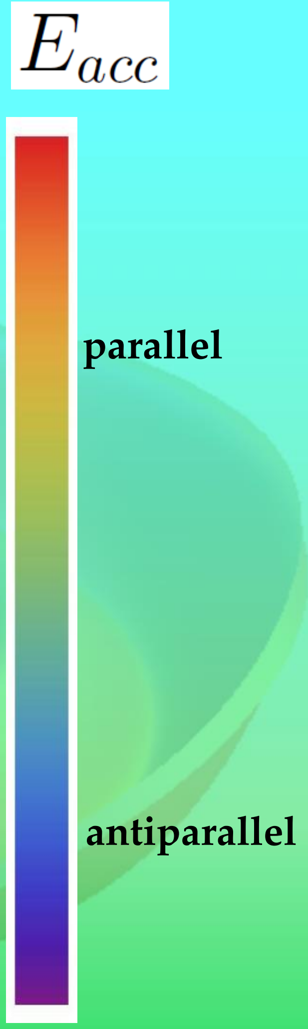
σ: 0 $\longrightarrow$ ∞

VRD $\longrightarrow$ FFE

Dissipative Solutions

Very high σ near FFE





Modeling γ-ray emission
curvature radiation

We consider trajectories

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

$v = c$

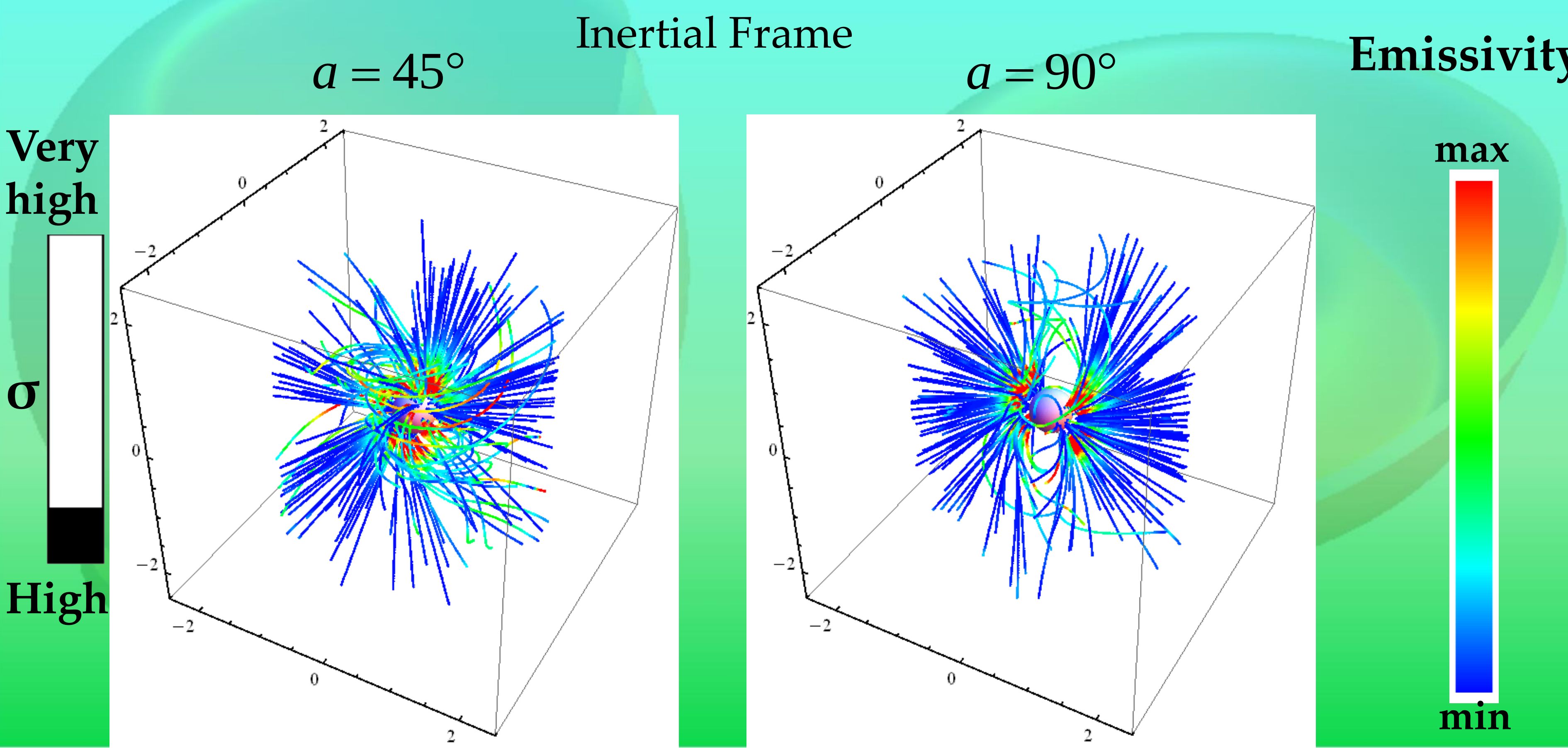
motion outwards

Aristotelian Electrodynamics
Gruzinov (2013)

$$\frac{d\gamma_L}{dt} = \frac{q_e c E_{\rm acc}}{m_e c^2} - \frac{2 q_e^2 \gamma_L^4}{3 R_C^2 m_e c}$$

Curvature Radiation

Radiation, Light Curves, Pulses

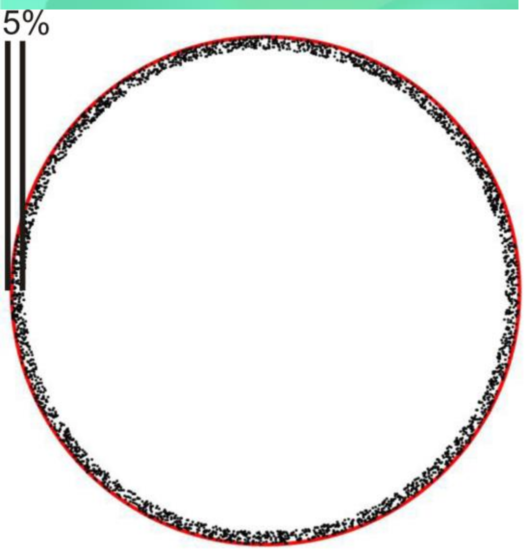


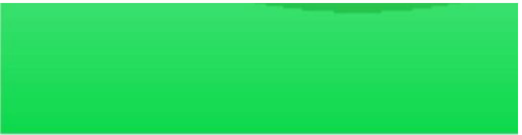
Radiation, Light Curves, Pulses
Comparison with Observations

Contopoulos & Kalapothrakos (2010)

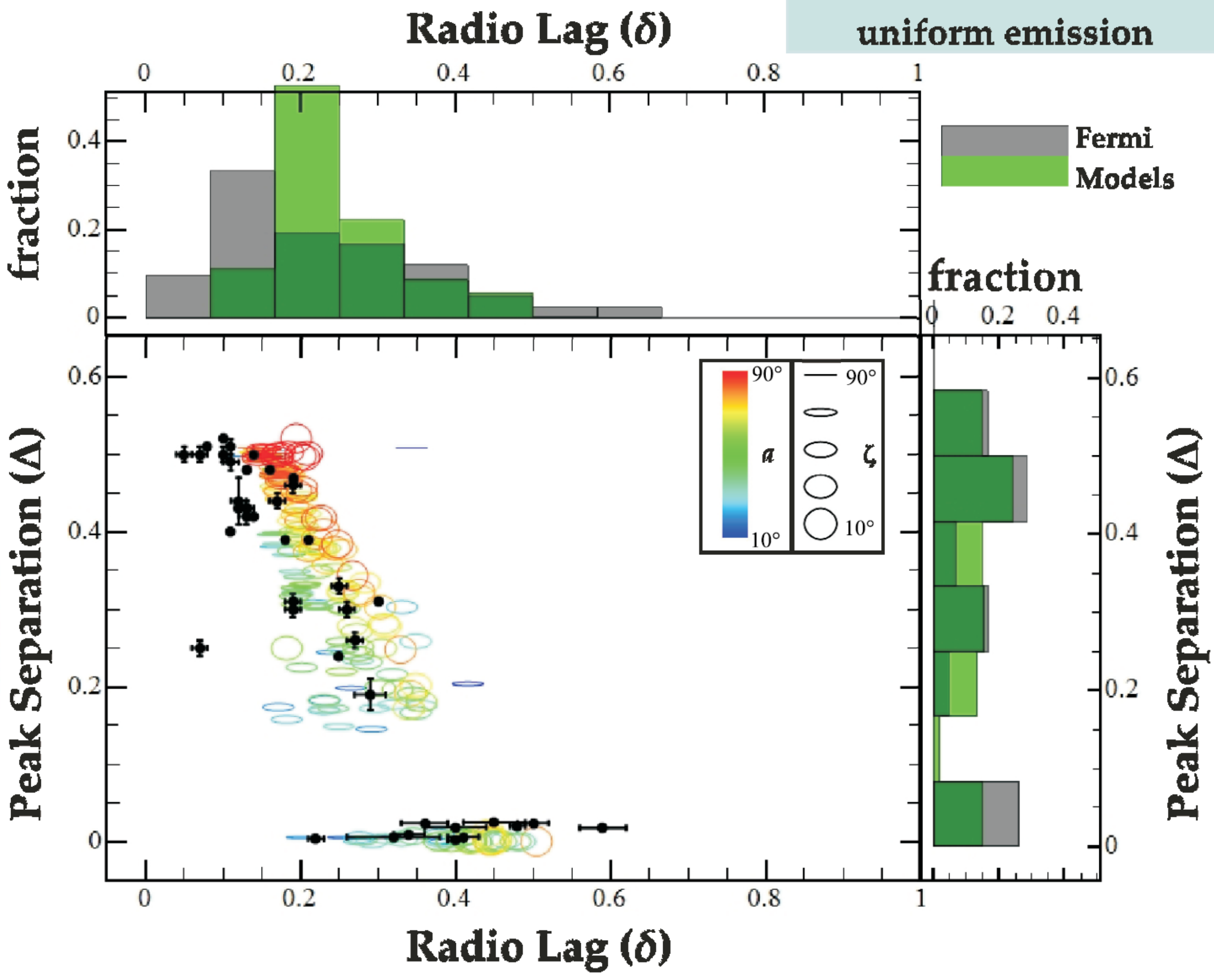
Bai & Spitkovsky (2010)

Arka & Dubus (2013)

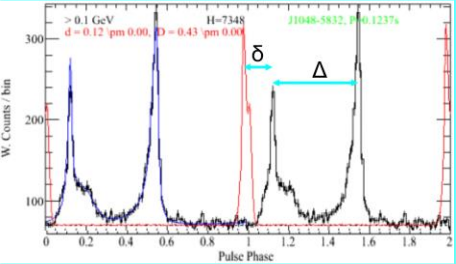


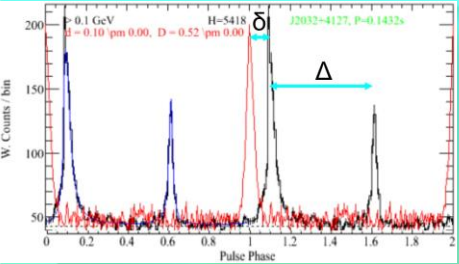


Current Sheet model
uniform emission



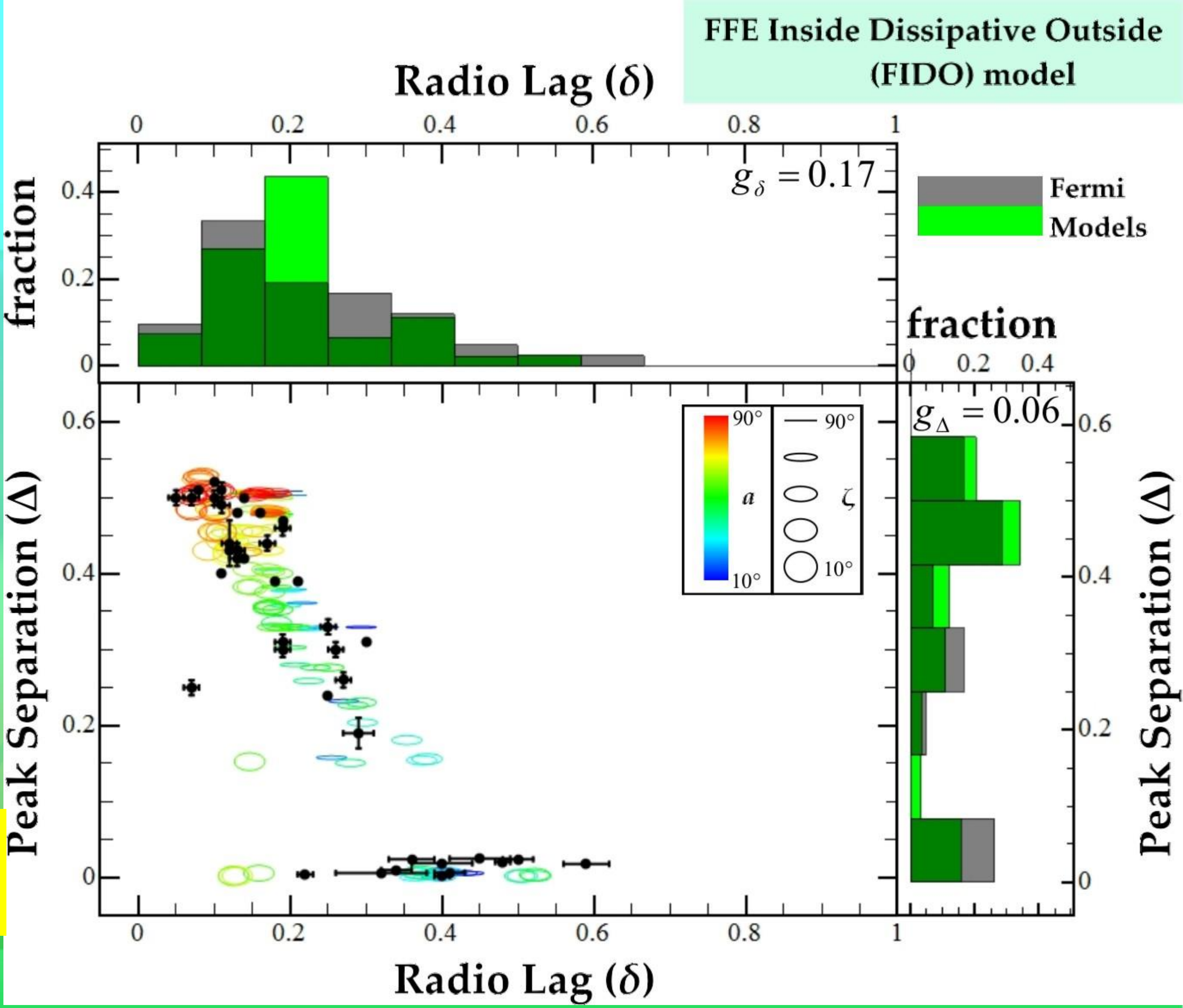
FIDO Models





radio-lag (δ)
vs
peak-separation (Δ)

Test particles
Curvature Radiation



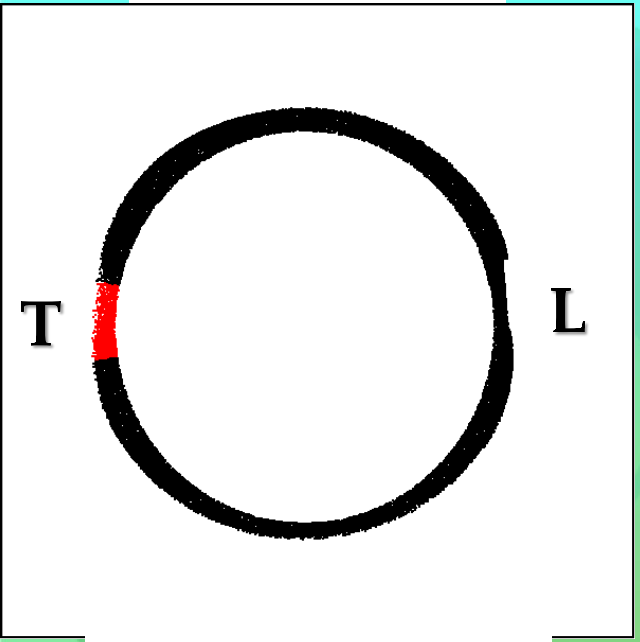
Kalapotharakos et al. (2014)

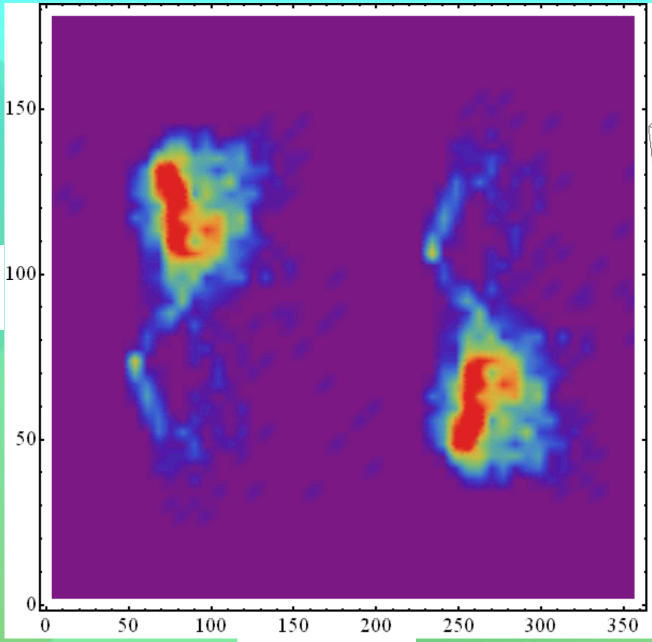
Radiation, Light Curves, Pulses

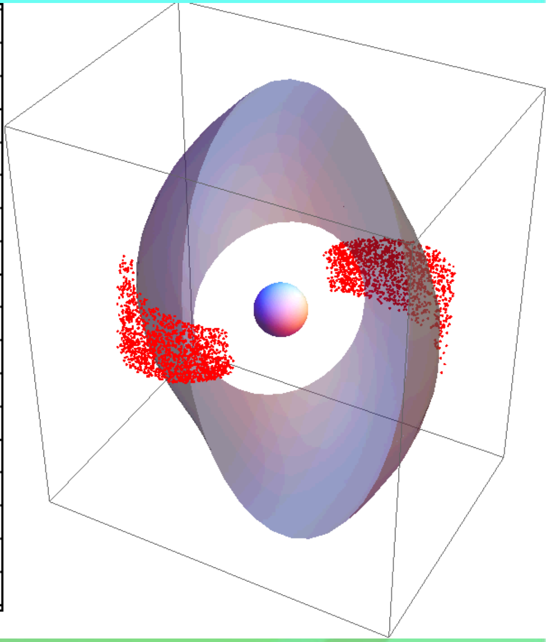
Physical Light Curves

Comparison with Observations

$a = 75°$







Radiation, Light Curves, Pulses

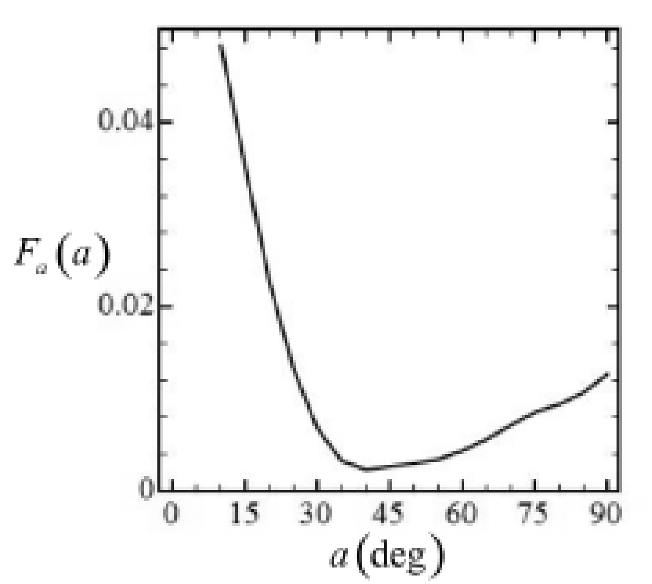
Physical Light Curves

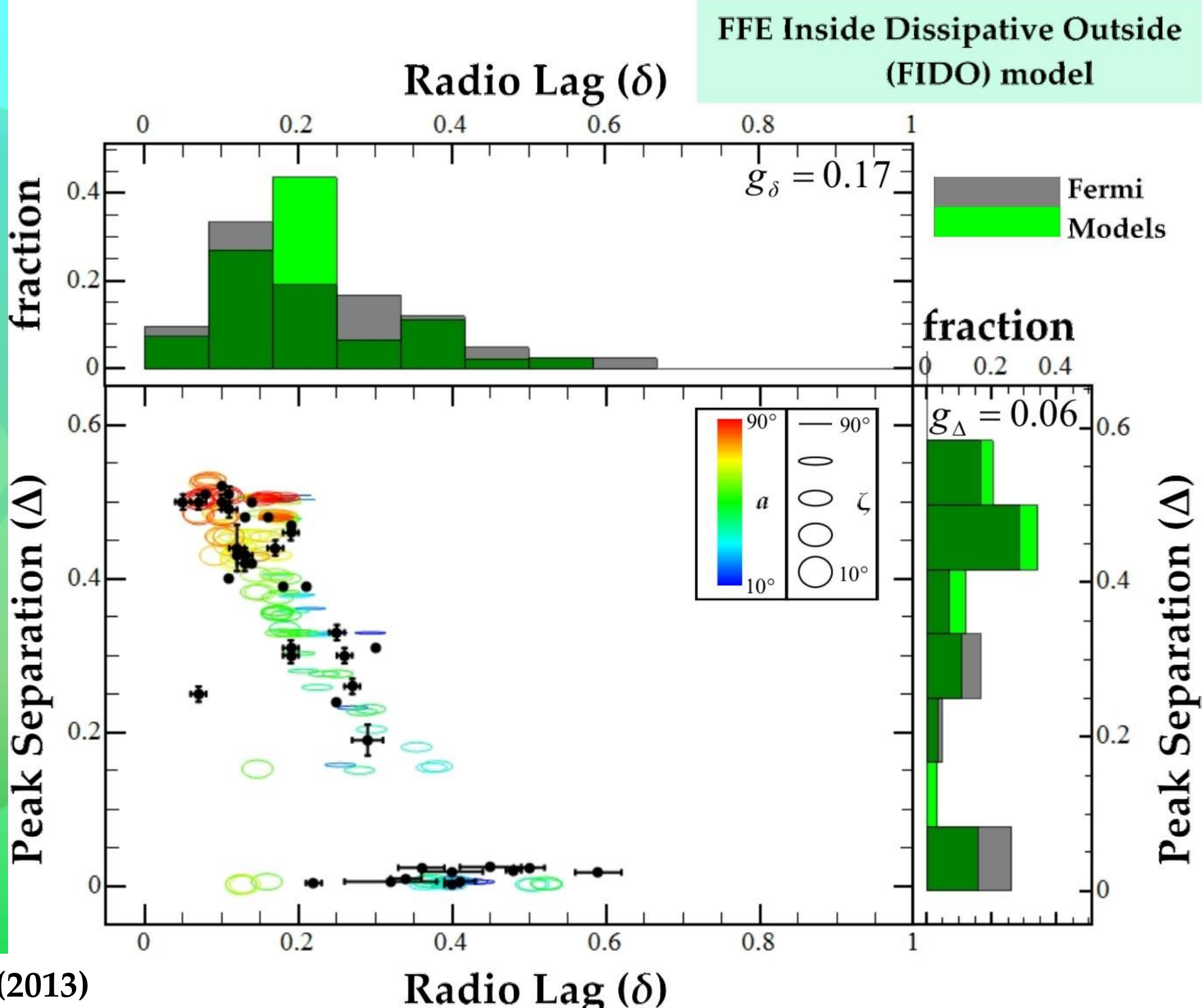
Steven Kenyon
Devin Hahne
GSFC, NASA

3D Printing Technology

Radiation, Light Curves, Pulses

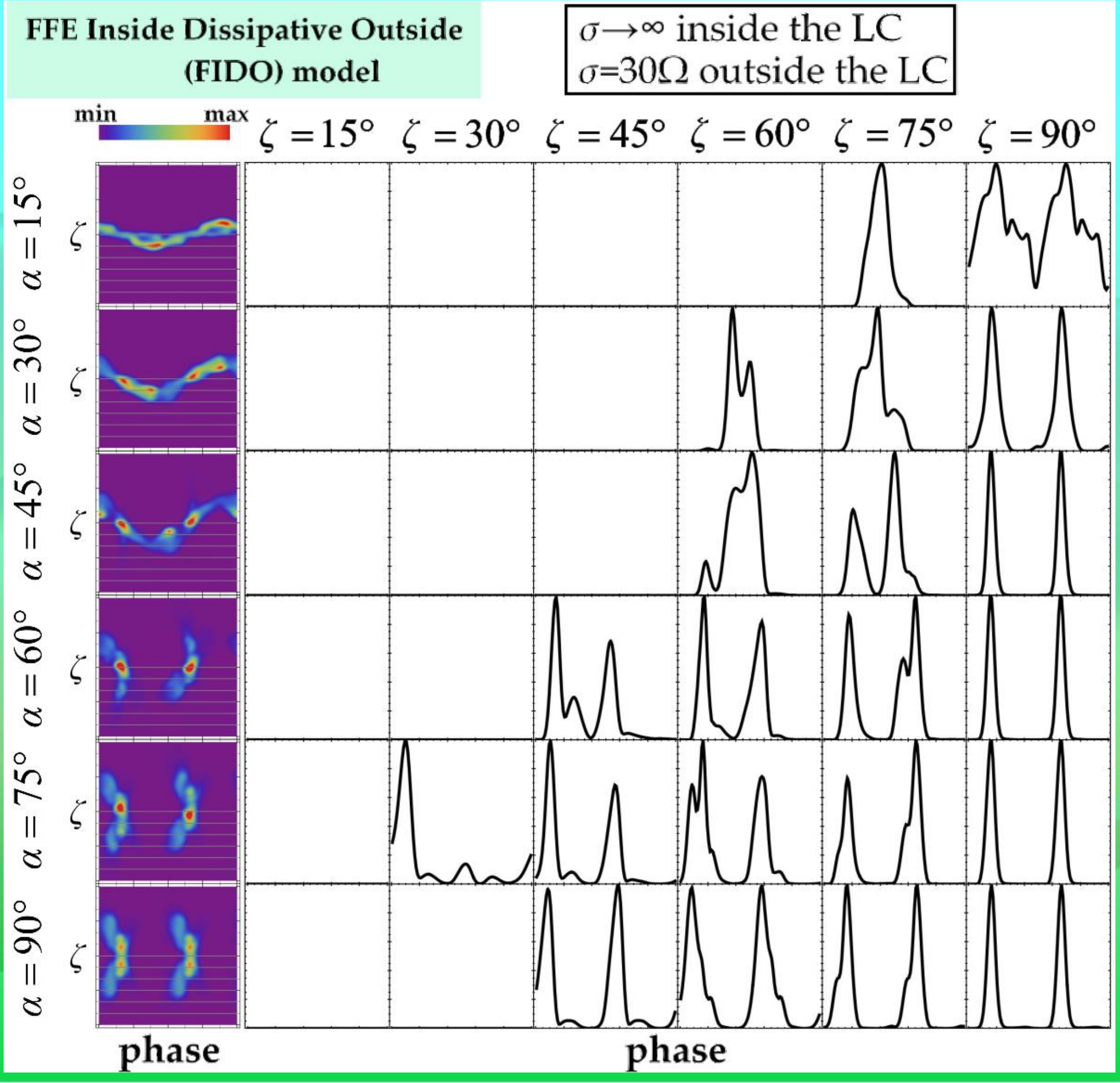
FIDO Models (FFE Inside the Light-Cylinde, Dissipative Outside the Light Cylinder)





Kalapotharakos, Harding & Kazanas (2013)

FIDO Models



FFE Inside Dissipative Outside (FIDO) model
$\sigma\rightarrow\infty$ inside the LC
σ=30Ω outside the LC
min
max
$\zeta = 15°$
$\zeta = 30°$
$\zeta = 45°$
$\zeta = 60°$
$\zeta = 75°$
$\zeta = 90°$
$\alpha = 15°$
$\alpha = 30°$
$\alpha = 45°$
$\alpha = 60°$
$\alpha = 75°$
$\alpha = 90°$
ζ
phase
phase

FERMI

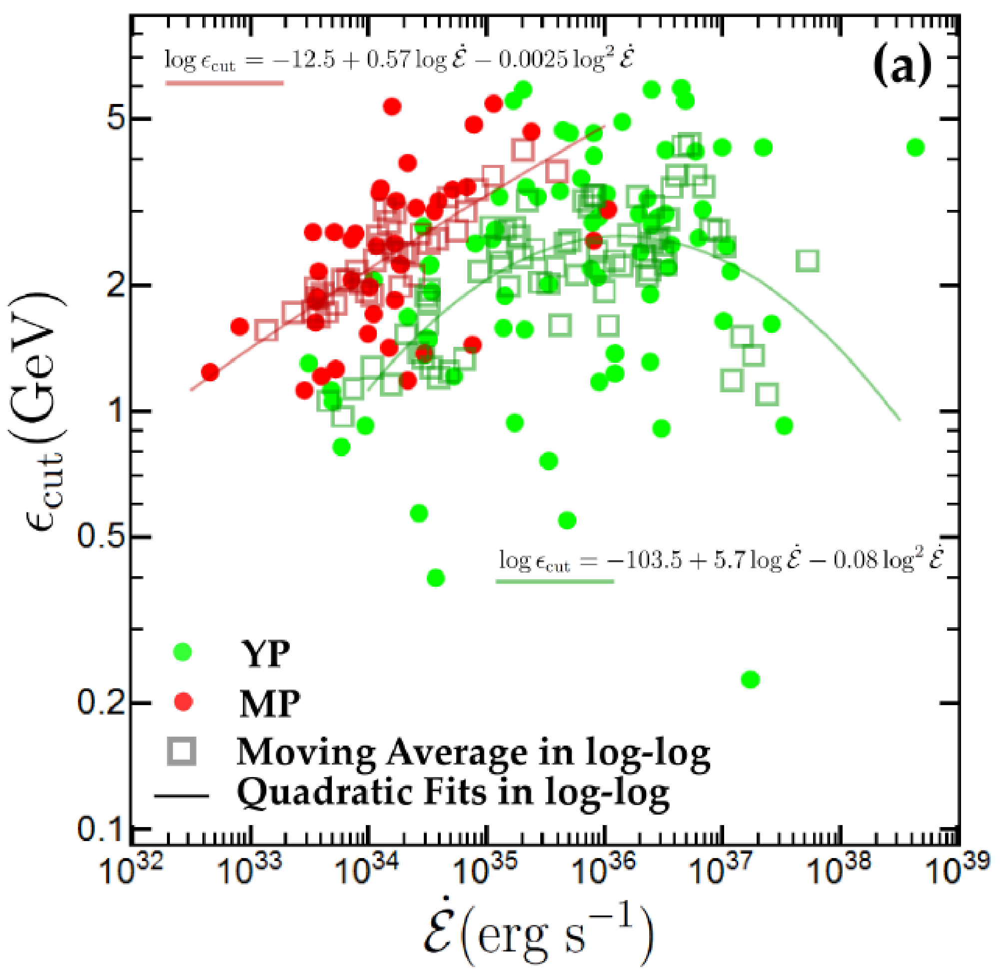
ϵ_{cut} vs. L_γ

- Small range
- Reliable

- Large range
- Large spread
- Large uncertainties

FERMI

2PC; Abdo et al. 2013)



Kalapotharakos et al. (2017)

FERMI

Fermi ϵ_{cut} values under simple assumptions provide a unique insight through the determination of the E_{acc}.

Assumptions

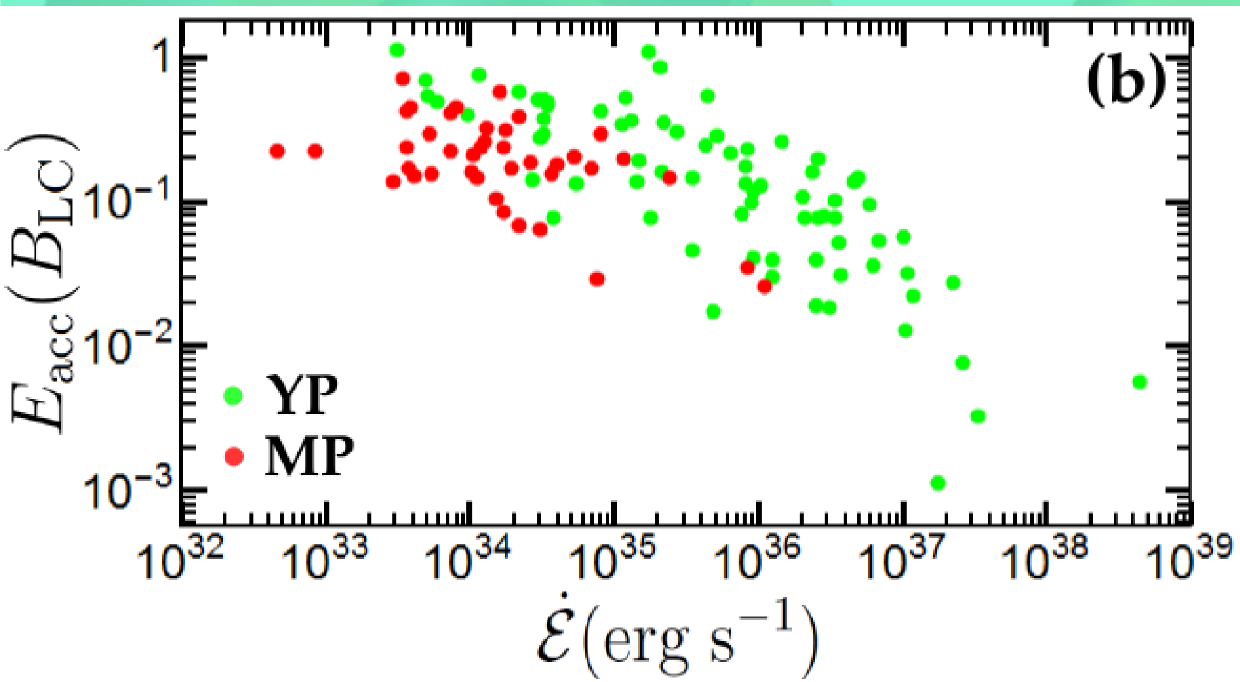
1) CR, Radiation Reaction Limit Regime

2) At the ECS near the LC

$$0 = \frac{d\gamma_L}{dt} = \frac{q_e c E_{\rm acc}}{m_e c^2} - \frac{2 q_e^2 \gamma_L^4}{3 R_C^2 m_e c}$$

$$E_{\rm cut} = \frac{3}{2} c\hbar \frac{\gamma_L^3}{R_C}$$

$f\, B_{LC}$



Simplicity

Kalapotharakos et al. (2017)

FERMI

Assumptions

Fermi ϵ_{cut} values under simple assumptions provide a unique insight through the determination of the E_{acc}.

1) CR, Radiation Reaction Limit Regime

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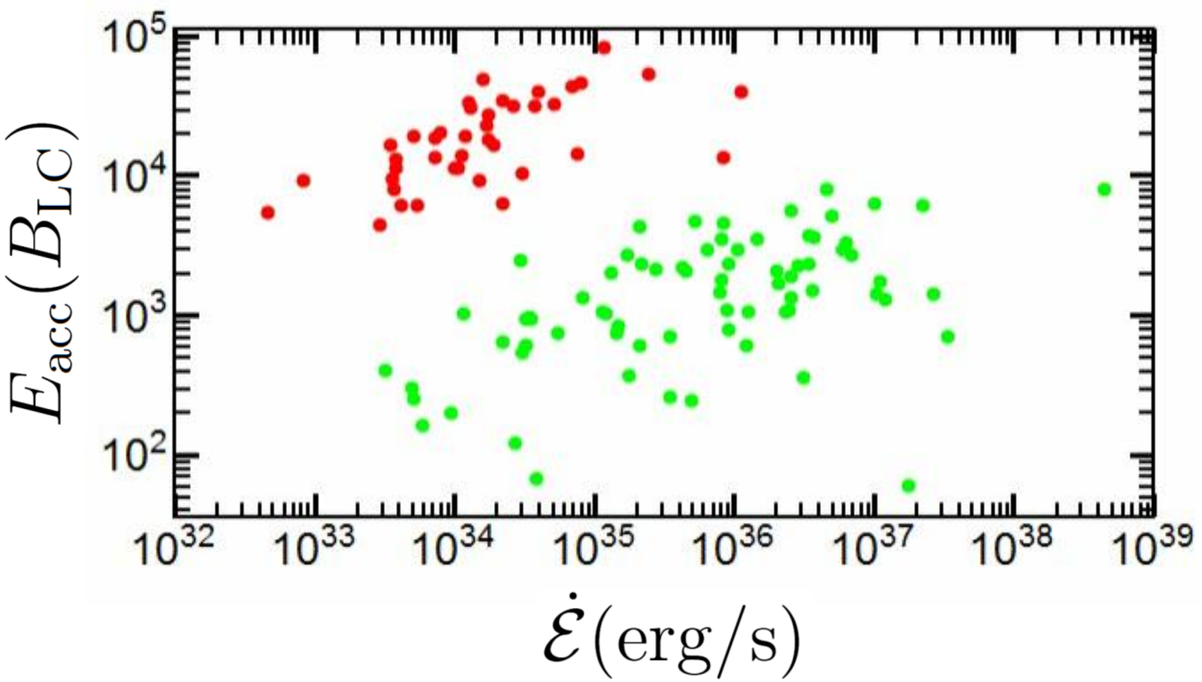
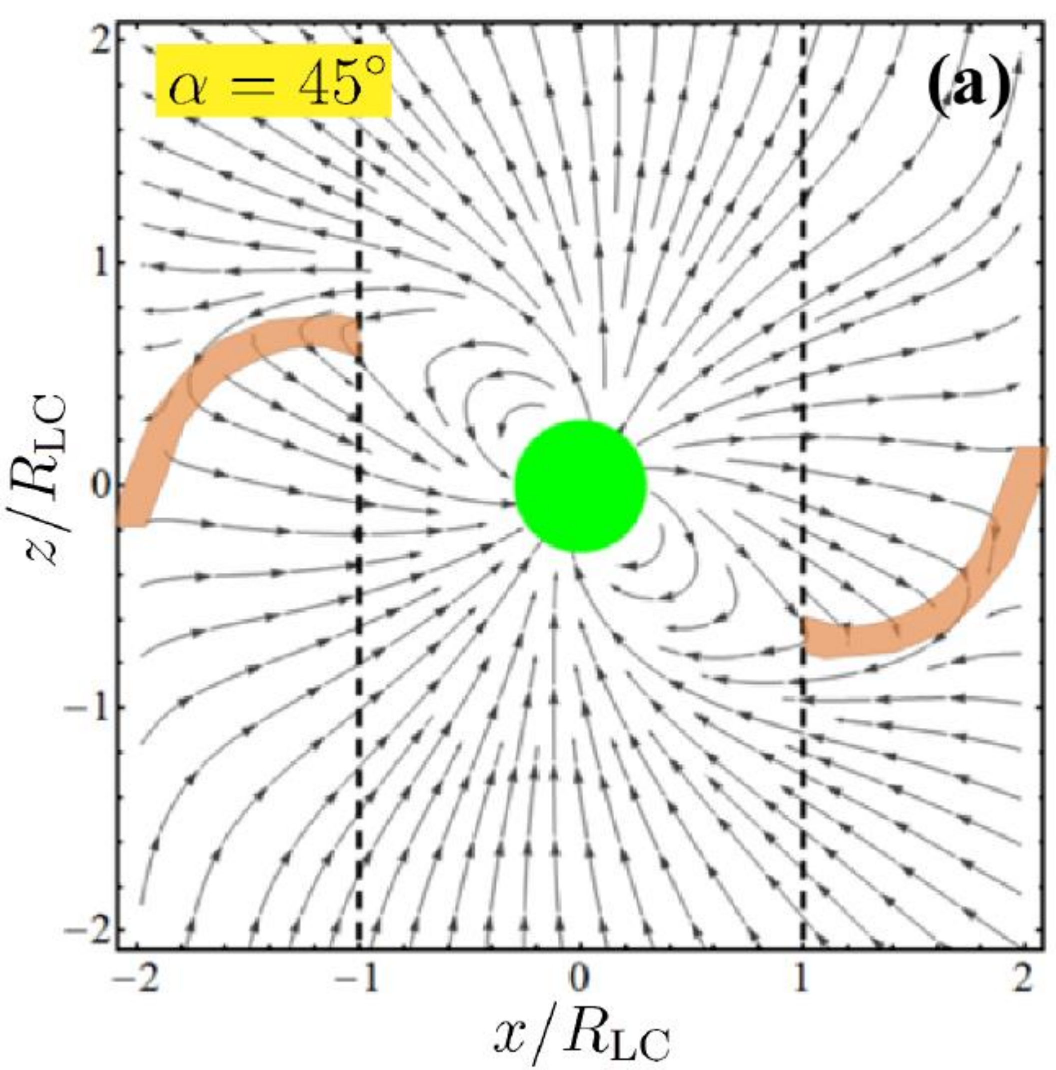


Simplicity

Kalapotharakos et al. (2017)

FIDO Models



Kalapotharakos et al. (2014, 2017)

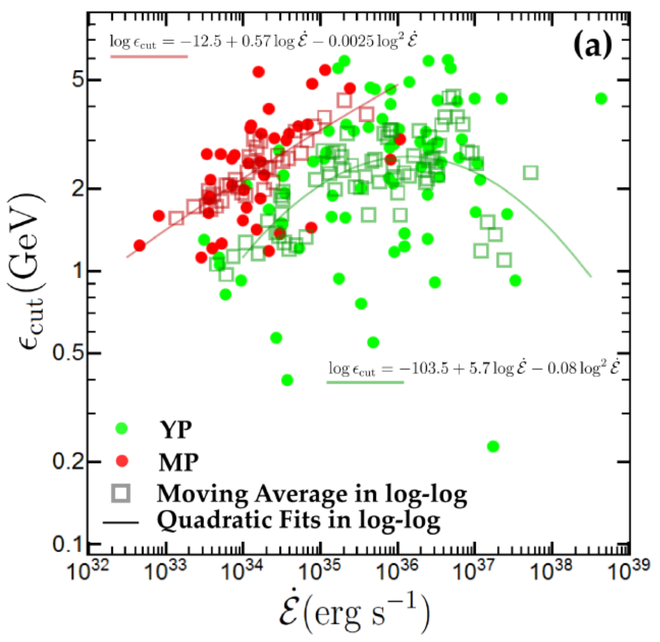
FIDO Models
(FFE Inside the Light-Cylinder, Dissipative Outside the Light Cylinder)

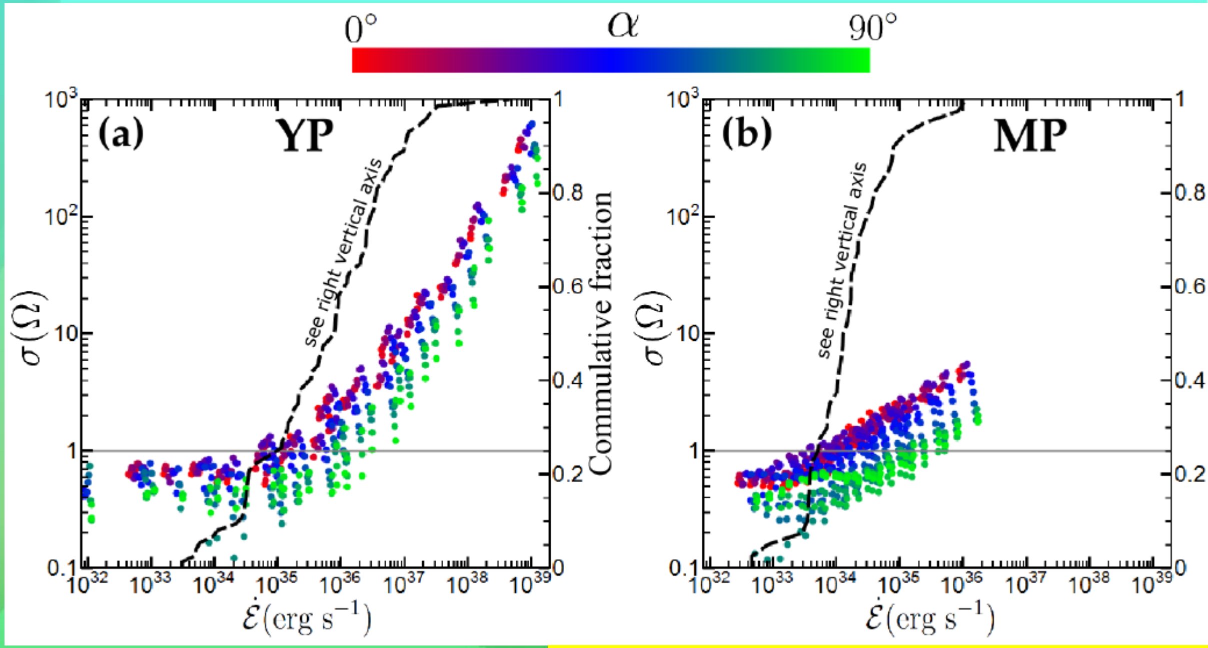
σ: conductivity

FIDO Models

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

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



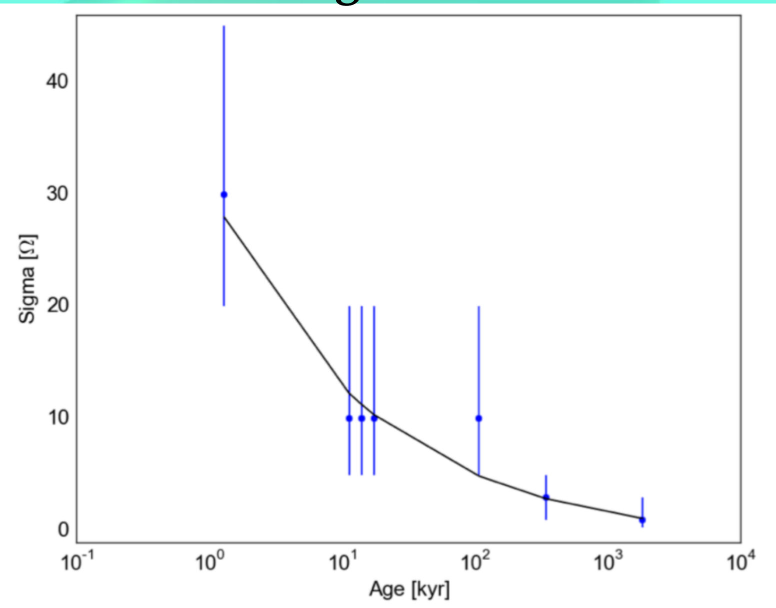


Kalapotharakos et al. (2017)

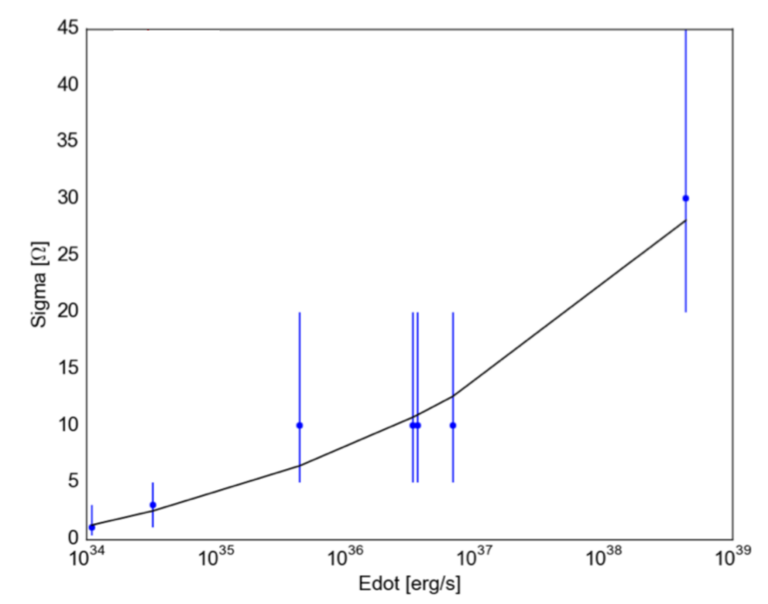
FIDO model - Spectral properties

The σ values that best describe each of the 8 bright pulsars (with published phase-resolved spectra) show an increase with the spin down rate$(\dot{E})$ and a decrease with the pulsar age, expected if pair cascades are providing the magnetosphere conductivity (σ).

Age vs **σ**



Spin-down rate vs **σ**



Brambilla et al. 2015

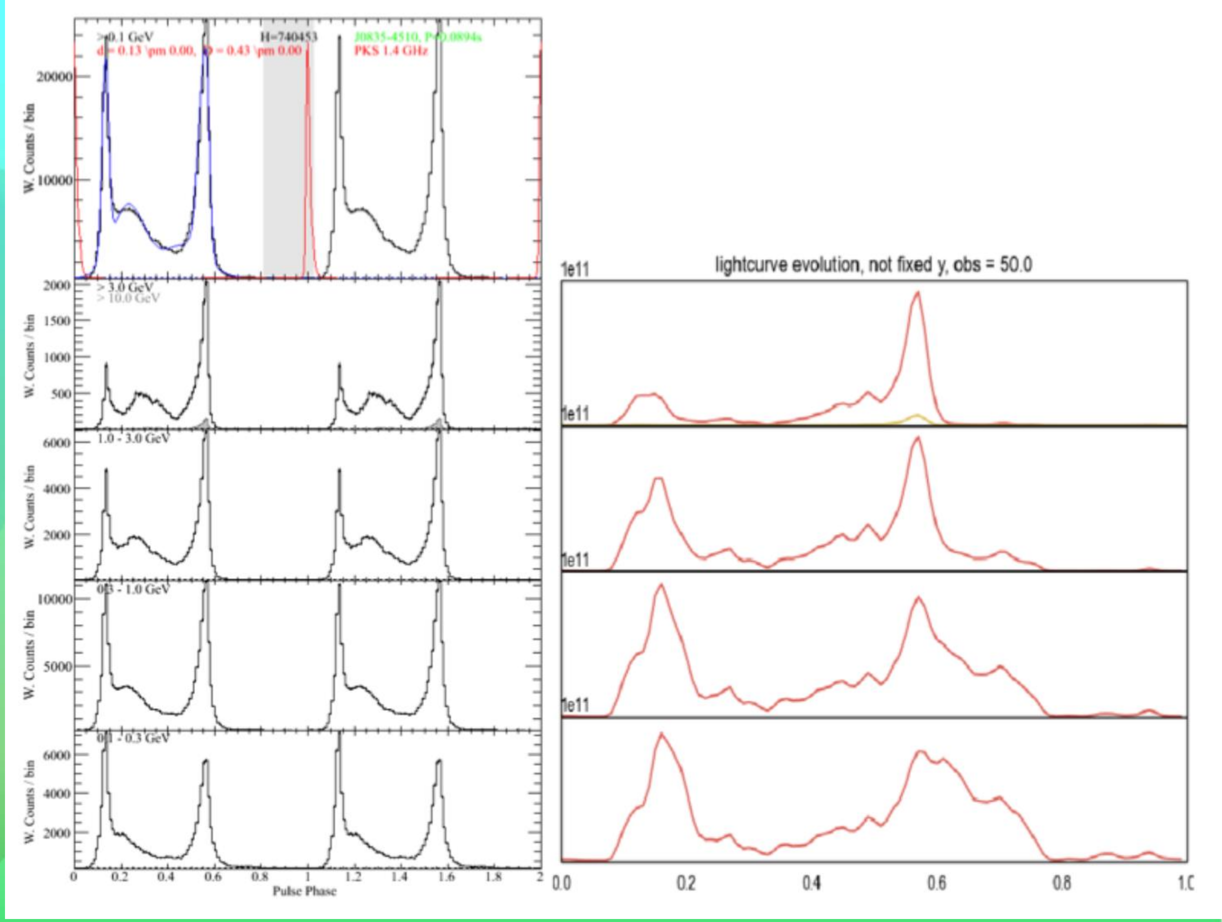
FIDO Models

Vela

Light-curve energy evolution

observations, 2PC

model



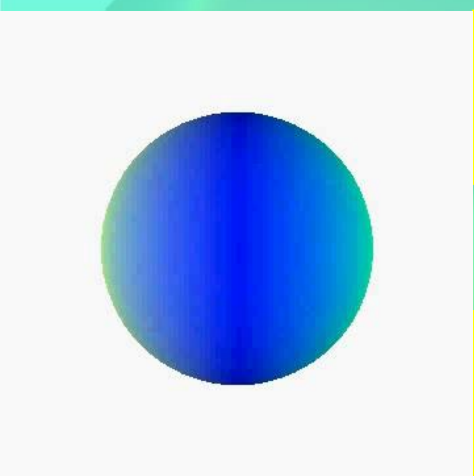
The evolution of the model light-curves with energy is similar to the observed one.

Brambilla et al. 2015

3D Kinetic Models (PIC)

Macroscopic models guided by observations become successful providing unique insight

The fields and the particles are still treated separately. Not Self-Consistent!



Huge EM Fields

charge acceleration

pair creation triggering

Particle distribution

tends to kill the E_{acc}

Rotating Magnet

What we observe is the result of this sensitive balance

3D Kinetic Models (PIC)

Kinetic PIC simulations provide a path to self-consistency.

Field structure & particle distributions are consistent with each other

Philippov & Spitkovsky 2014, 2017
Chen & Beloborodov 2014
Cerutti et al. 2015, 2016
Philippov et al. 2015, 2016
Belyaev 2015a,b, 2016

3D Particle-In-Cell code

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

C-3PA

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

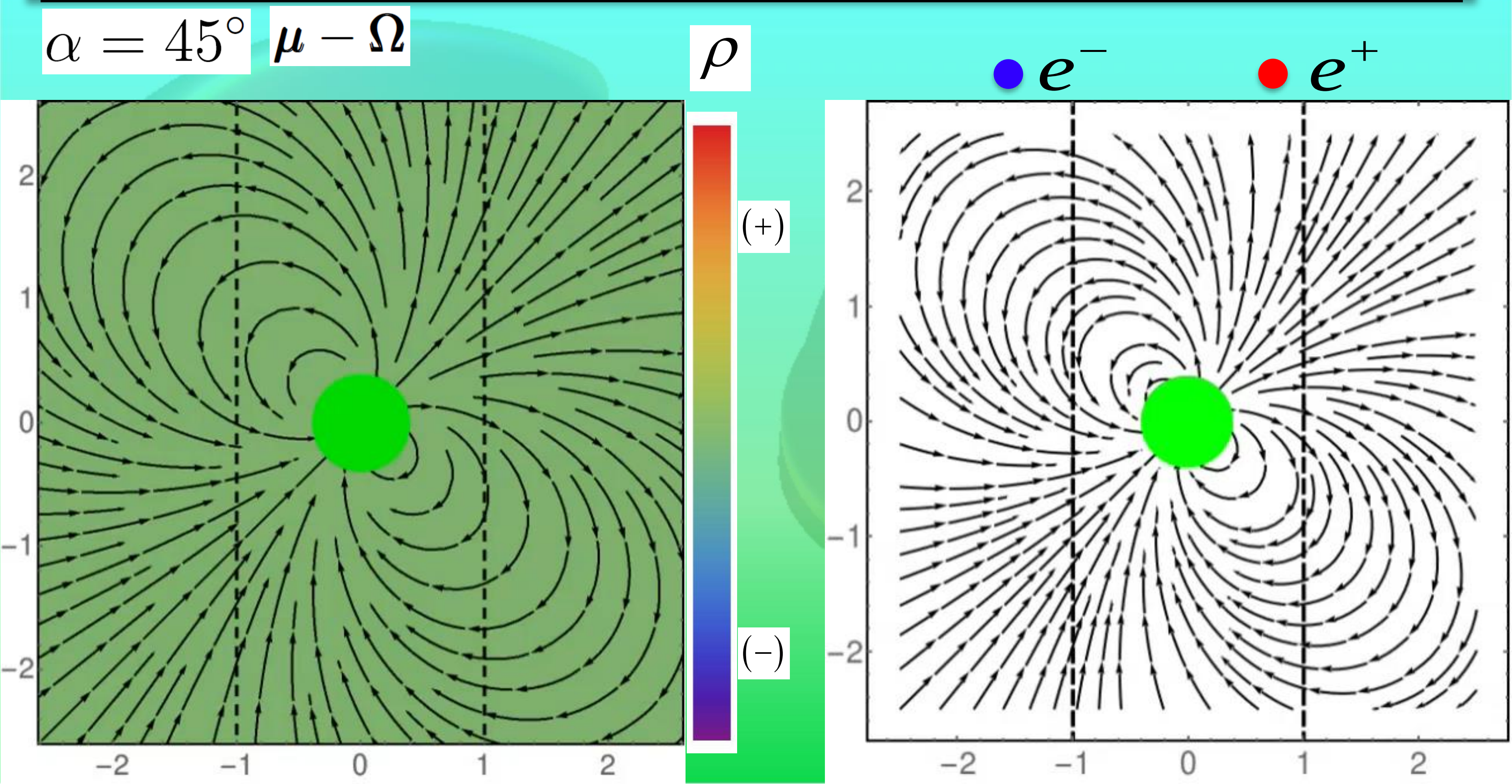
- **Cartesian**
- **Conservative**
- **Vay's algorithm**
- **Current Smoothing**
- **Radiation Reaction Forces**
- **Load Balancing**
- **Field Line Dependent Particle Injection**

3D Kinetic Models (PIC)

Towards self-consistency:

1) Arbitrary particle injection

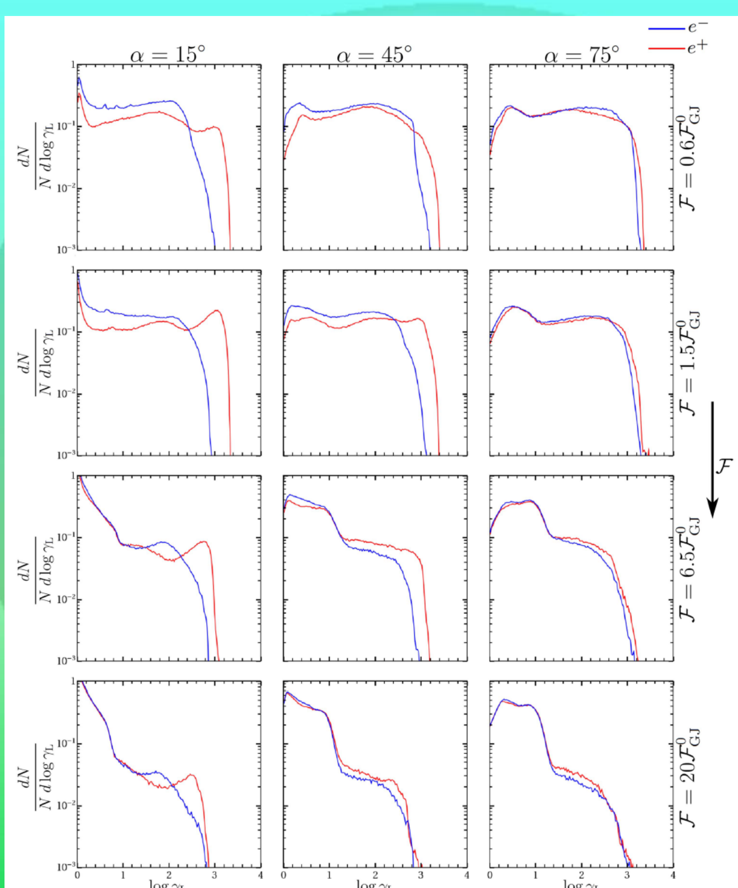
$\longrightarrow$ consistent field structure & particle distribution



3D Kinetic Models (PIC)

Is this treatment relevant to reality?

$$B_\star = 10^5 - 10^6 G$$



Kalapotharakos et al. (2018)

- ➢Radiation reaction forces have no effect on the particle energies
- ➢Gyromotion remains intact

$$\mathbf{F}_{\mathbf{rr}} = \frac{2q_e^3\gamma}{3m_ec^3}\left[\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{E} + \frac{\mathbf{v}}{c}\times\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{B}\right] + \frac{2q_e^4}{3m_e^2c^4}\left[\mathbf{E}\times\mathbf{B} + \mathbf{B}\times\left(\mathbf{B}\times\frac{\mathbf{v}}{\mathbf{c}}\right) + \mathbf{E}\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)\right] - \frac{2q_e^4\gamma^2}{3m_e^2c^5}\mathbf{v}\left[\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)^2 - \left(\mathbf{E}\cdot\frac{\mathbf{v}}{c}\right)^2\right]$$

Landau & Lifshitz 1987

3D Kinetic Models (PIC)

Is this treatment relevant to reality?

$$\dot{\gamma} \propto B^2\gamma^2$$

$$t_{sc} = \frac{\gamma}{\dot{\gamma}} \propto B^{-2}\gamma^{-1}$$

$\dot{\mathcal{E}}$ (erg/s)	10^{33}	10^{34}	10^{35}	10^{36}	10^{37}	10^{38}
γ_{pc}	9×10^7	3×10^8	9×10^8	3×10^9	9×10^9	3×10^{10}
t_{sc-LC}(P)	4×10^{-4}	1×10^{-5}	2×10^{-7}	5×10^{-9}	1×10^{-10}	3×10^{-12}
γ_{SR-LC}	1.2×10^7	1×10^7	6×10^6	3×10^6	1×10^6	5×10^5
t_{sc-LC}(P)	3×10^{-3}	3×10^{-4}	3×10^{-5}	5×10^{-6}	1×10^{-6}	2×10^{-7}
γ_{2500}	330	80	17	2.5	1.3	1.05

3D Kinetic Models (PIC)

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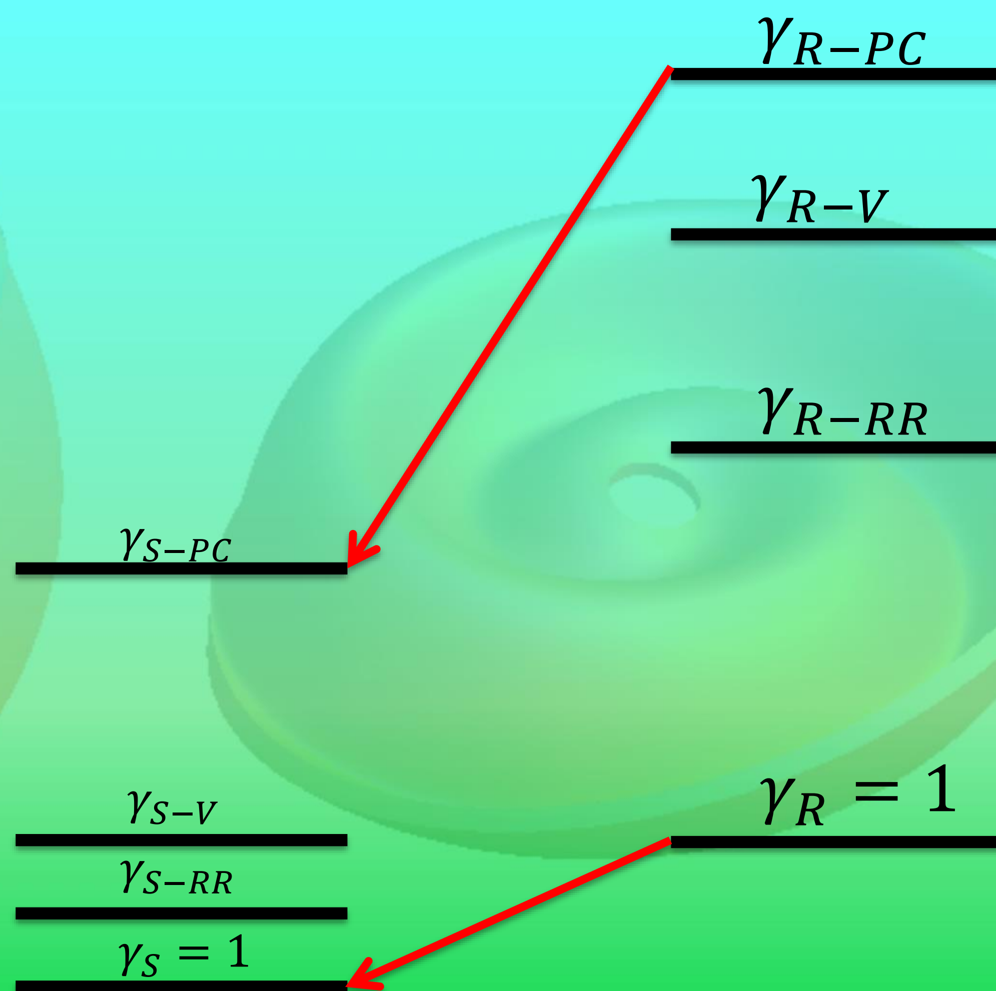


3D Kinetic Models (PIC)

Is this treatment relevant to reality?

$$\dot{\gamma} \propto B^2\gamma^2$$

$$t_{sc} = \frac{\gamma}{\dot{\gamma}} \propto B^{-2}\gamma^{-1}$$

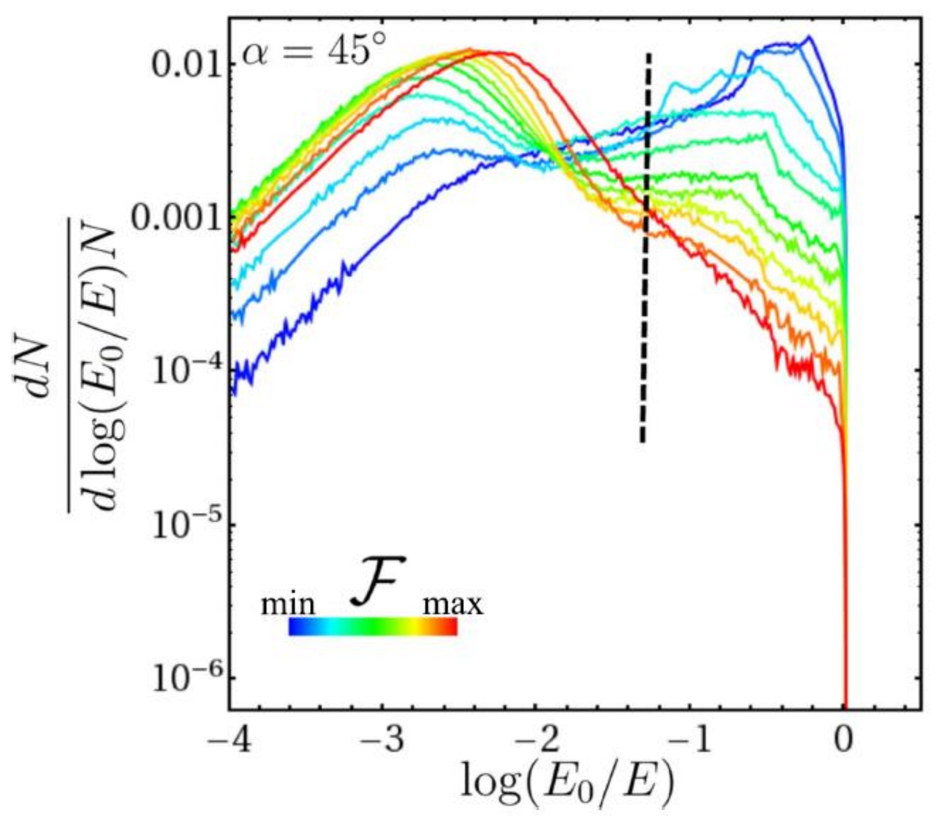
CK calculations:
Cerutti et al. 2016
$\dot{\mathcal{E}} \approx 10^{31}$erg/s

$\dot{\mathcal{E}}$ (erg/s)	10^{33}	10^{34}	10^{35}	10^{36}	10^{37}	10^{38}
γ_{pc}	9×10^{7}	3×10^{8}	9×10^{8}	3×10^{9}	9×10^{9}	3×10^{10}
t_{sc-LC}(P)	4×10^{-4}	1×10^{-5}	2×10^{-7}	5×10^{-9}	1×10^{-10}	3×10^{-12}
γ_{SR-LC}	1.2×10^{7}	1×10^{7}	6×10^{6}	3×10^{6}	1×10^{6}	5×10^{5}
t_{sc-LC}(P)	3×10^{-3}	3×10^{-4}	3×10^{-5}	5×10^{-6}	1×10^{-6}	2×10^{-7}
γ_{2500}	330	80	17	2.5	1.3	1.05

3D Kinetic Models (PIC)

Is this treatment relevant to reality?

Something must be relevant…



Kalapotharakos et al. (2018)

$\mathbf{J} \cdot \mathbf{E}$ should be trusted

$\mathbf{J}$ is trusted

Task:
Find the reliable $E_{acc} \stackrel{\text{def}}{=} E_0$

Calculation of realistic particle energies

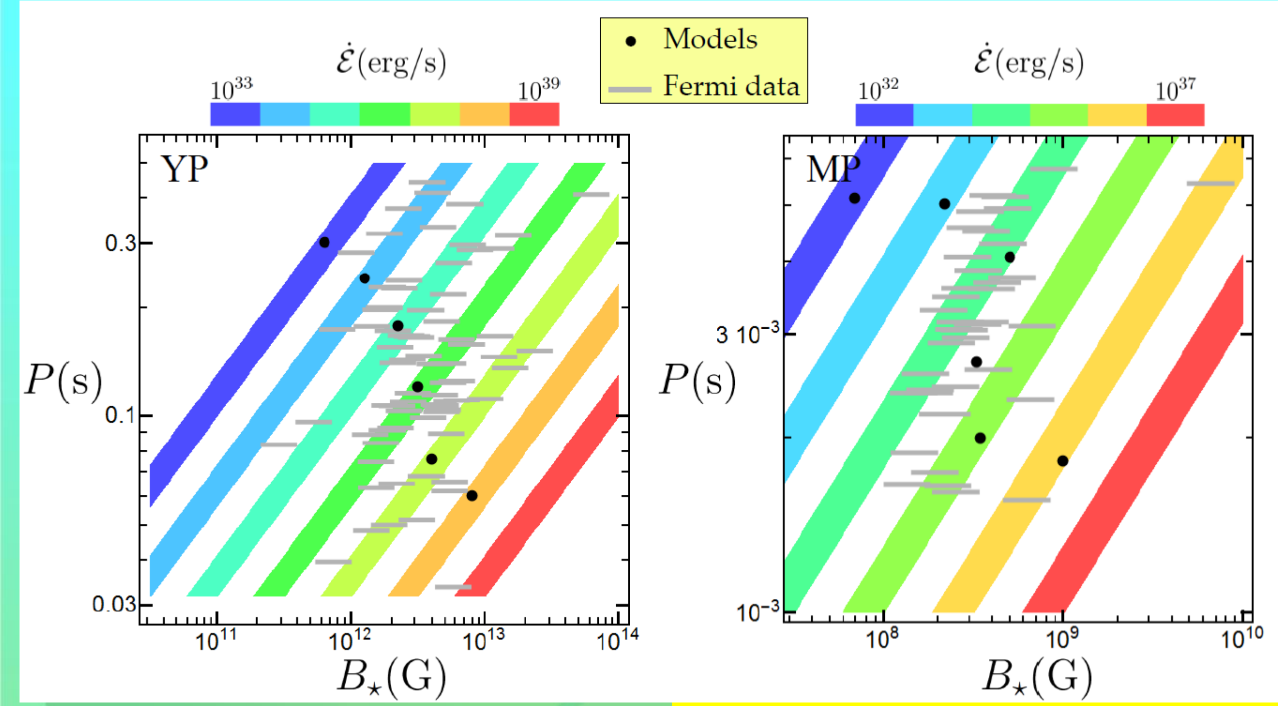
Choose realistic

$B_\star, P$

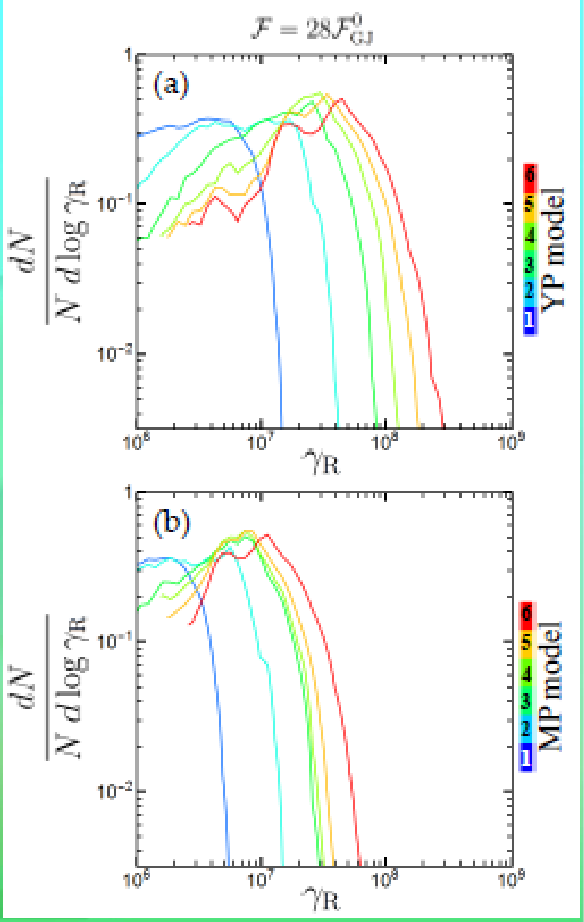
Rescale fields and length scales

$$\frac{d\gamma_L}{dt} = \frac{q_e c E_{\rm acc}}{m_e c^2} - \frac{2q_e^2\gamma_L^4}{3R_C^2 m_e c}$$

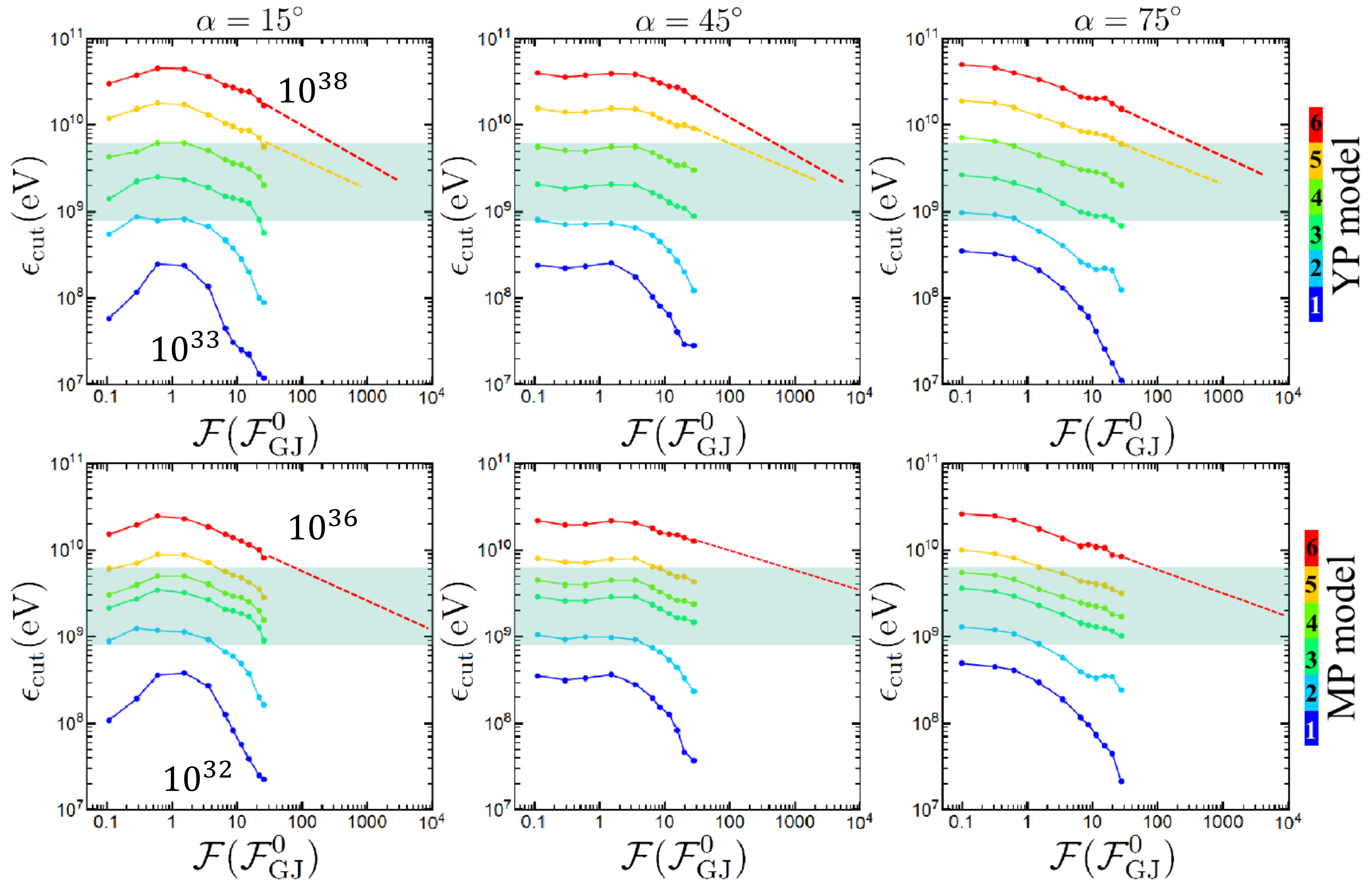
3D Kinetic Models (PIC)



Kalapotharakos et al. (2018)

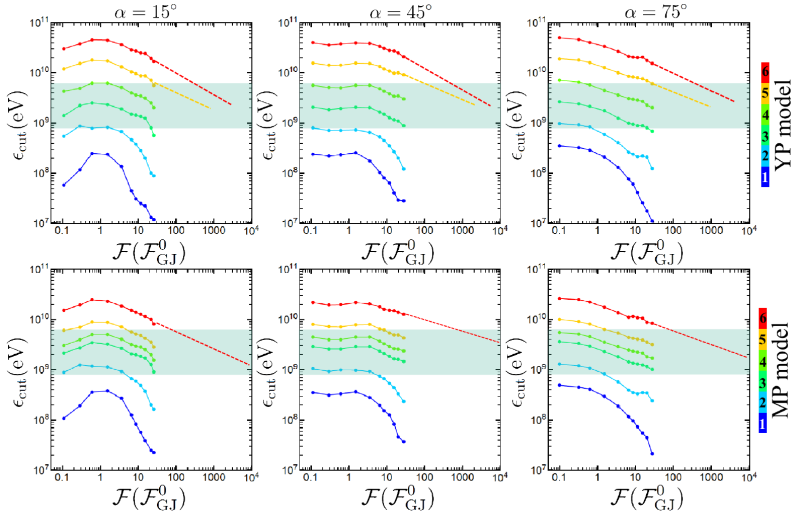


3D Kinetic Models (PIC)



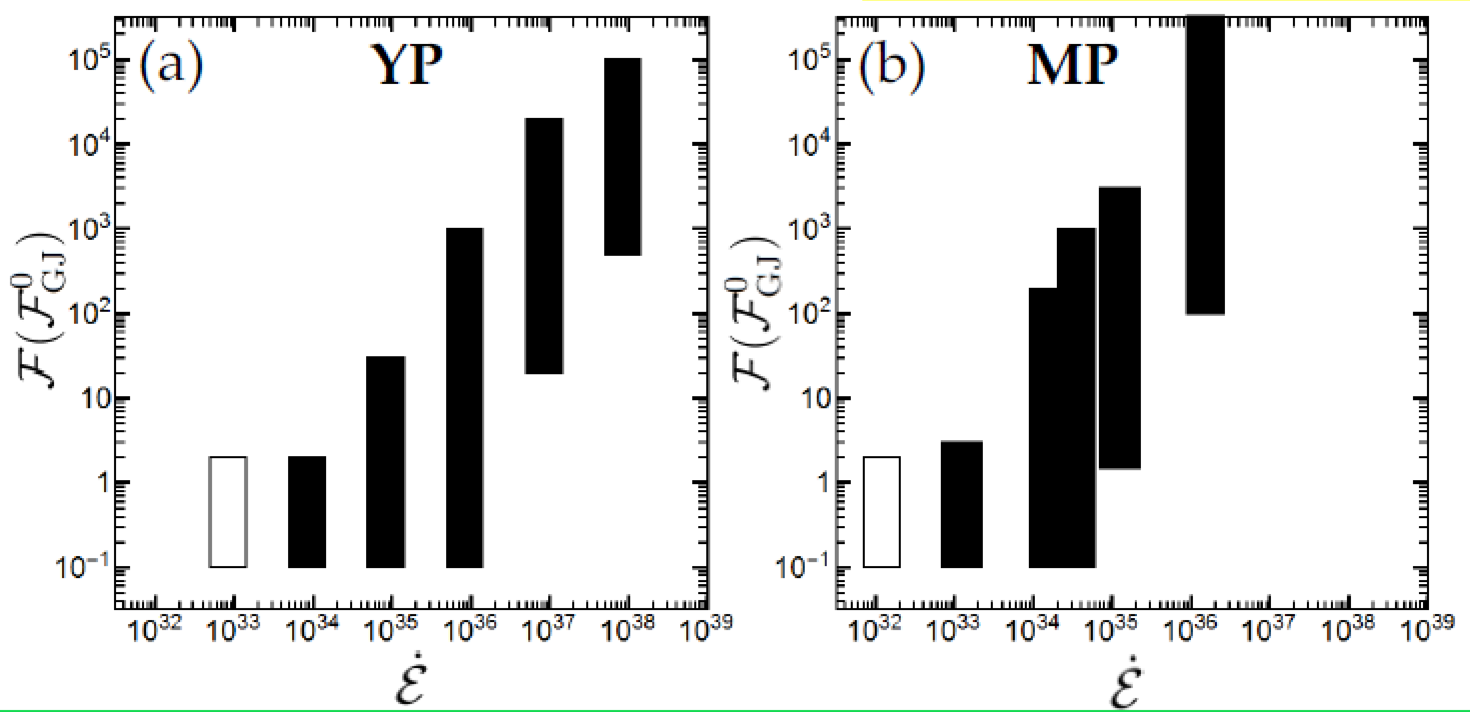
Kalapotharakos et al. (2018)

3D Kinetic Models (PIC)

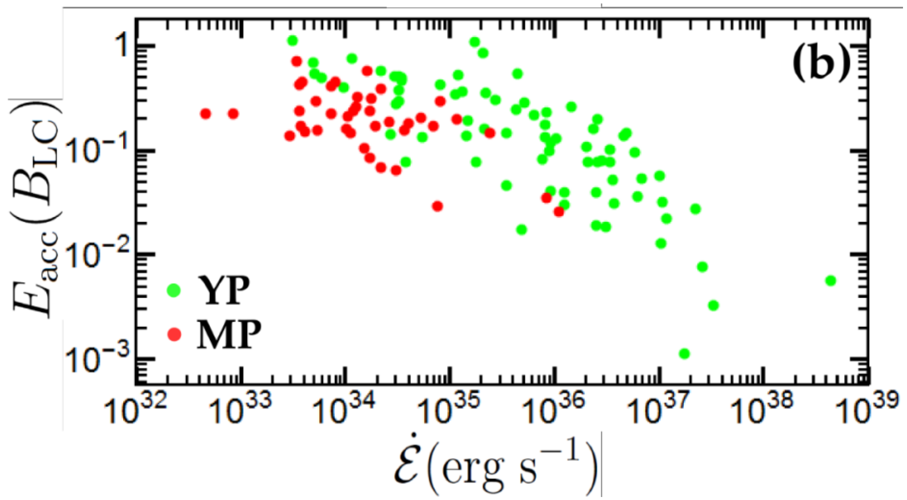


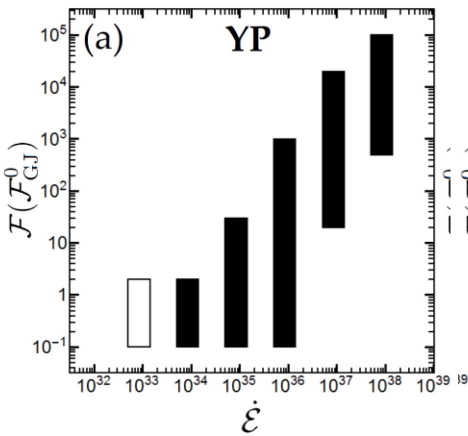
$\mathcal{F}(\dot{\mathcal{E}})$

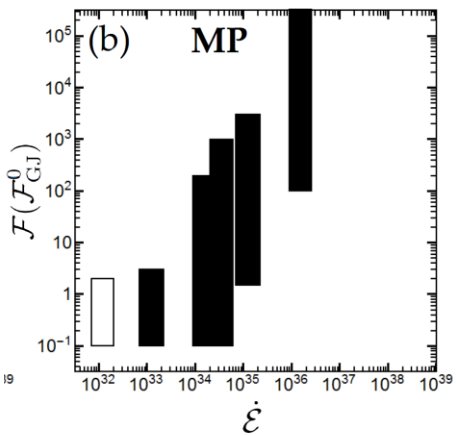
Kalapotharakos et al. (2018)

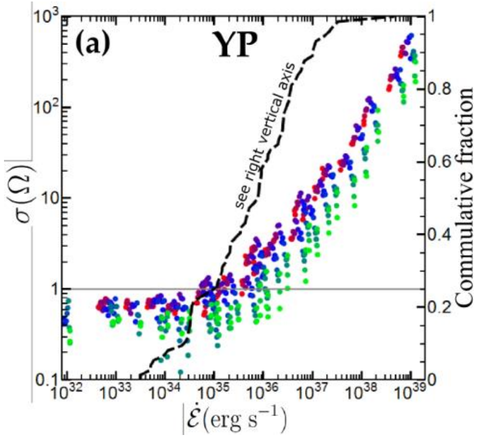


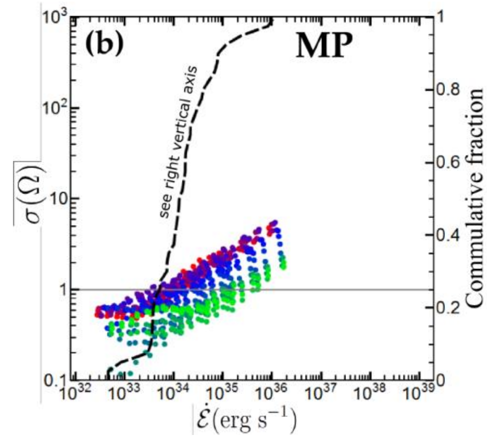
Summary - Future steps



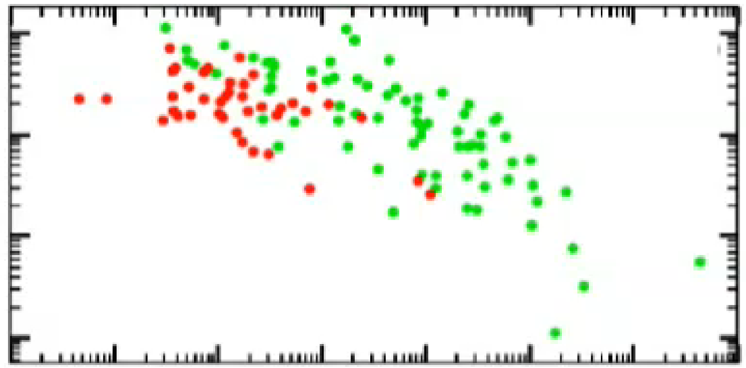


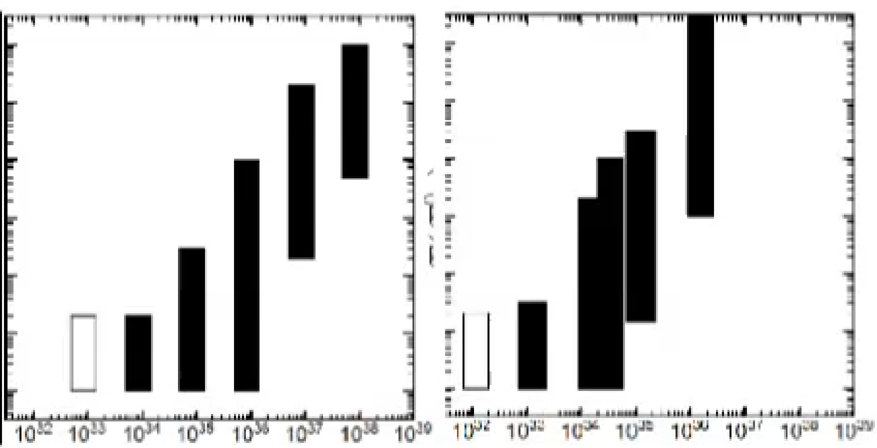


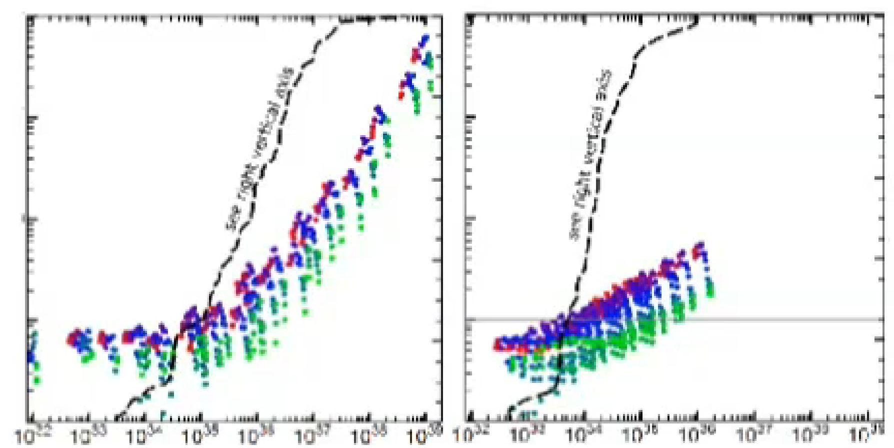




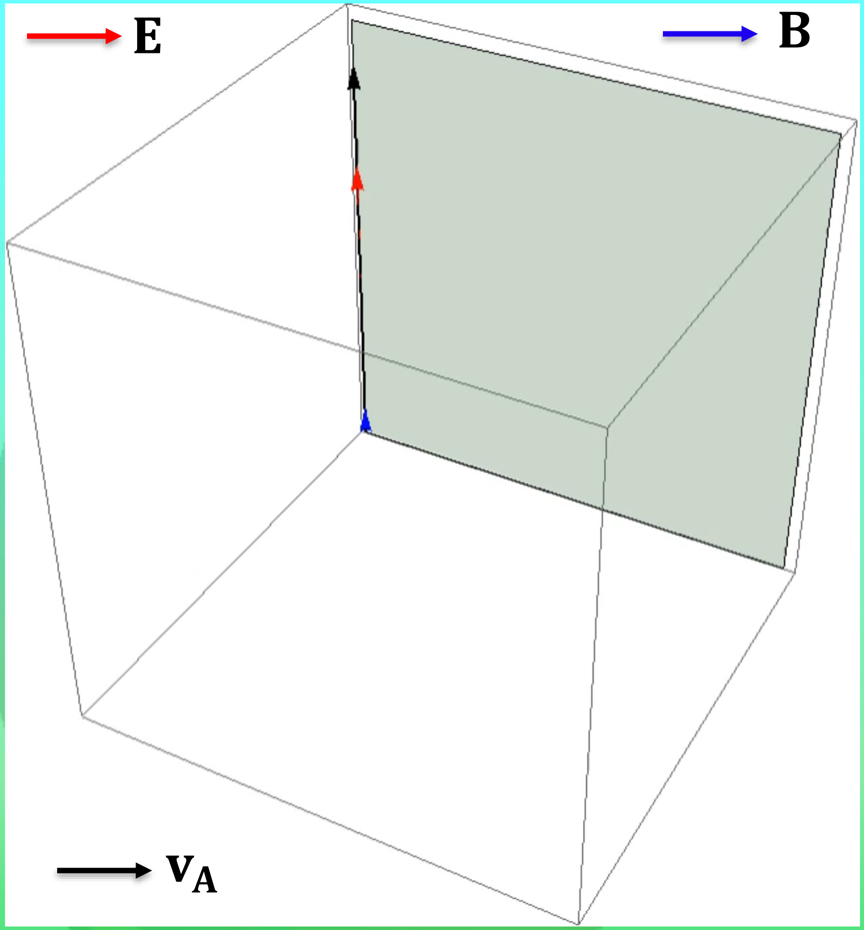
Summary - Future steps







Orbital Exploration (SR↔CR)



Kalapotharakos et al. (2019)

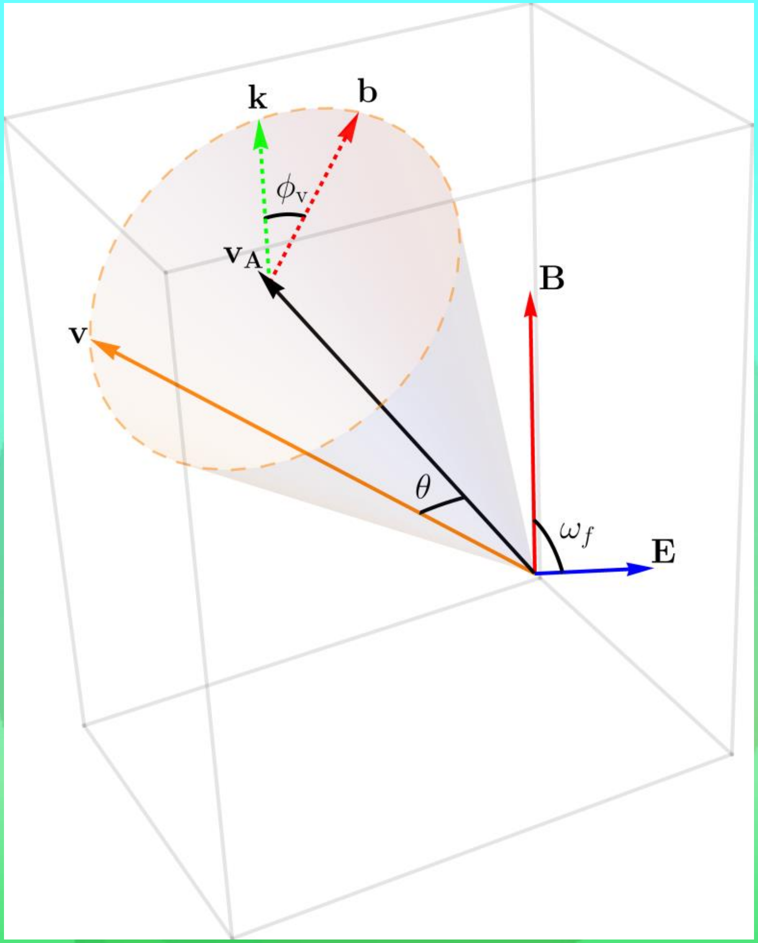
$$\mathbf{v}_{\mathrm{A}} = \frac{\mathbf{E}\times\mathbf{B} \pm (E_0\mathbf{E} + B_0\mathbf{B})}{E_0^2 + B^2}$$

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

Debate

Princeton Group	Goddard Group
Synchrotron Radiation	Curvature Radiation

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)

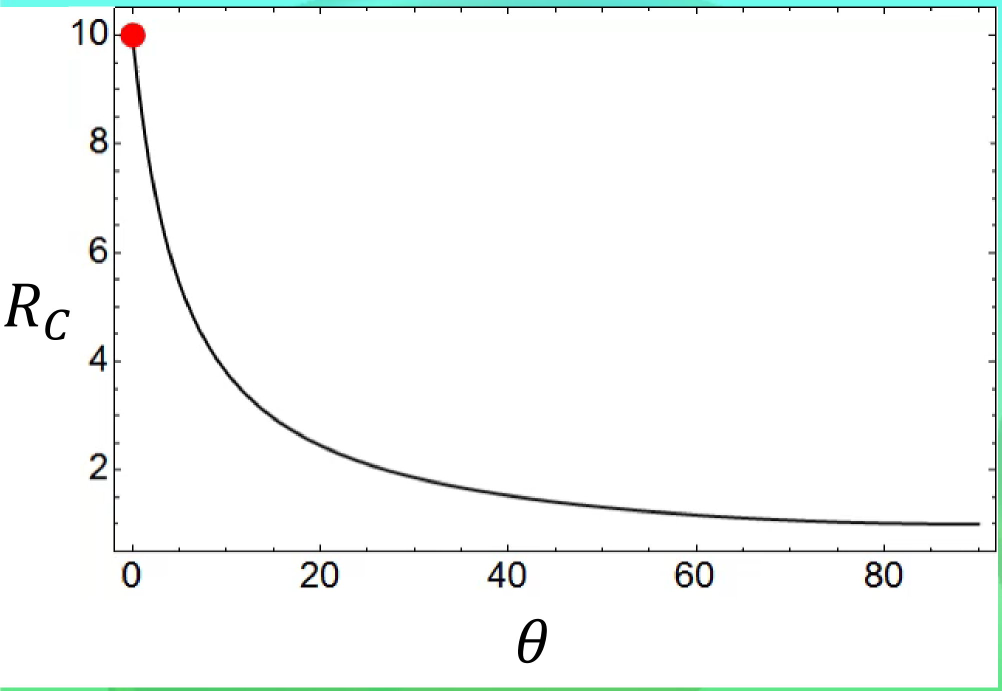
$$R_C = \frac{\gamma_L m_e c^2}{q_e B_{eff}}$$

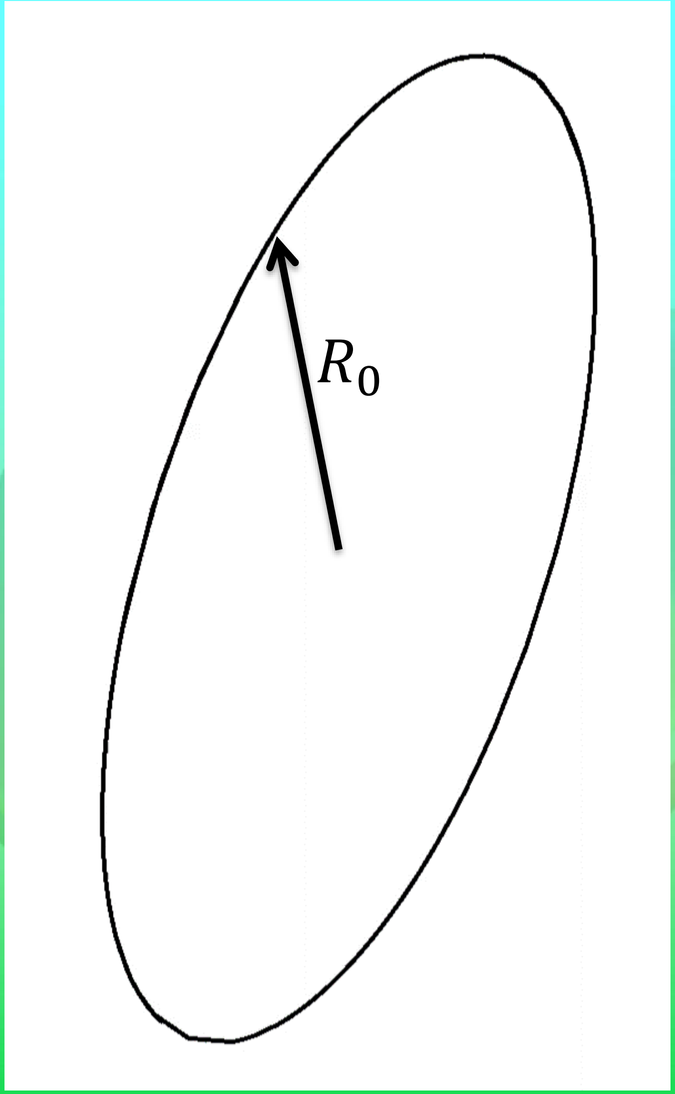
$$B_{eff} = \sqrt{\left(\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{\mathbf{c}}\right)^2 - \left(\frac{\mathbf{v}\cdot\mathbf{E}}{c}\right)^2}$$

Cerutti et al. 2016

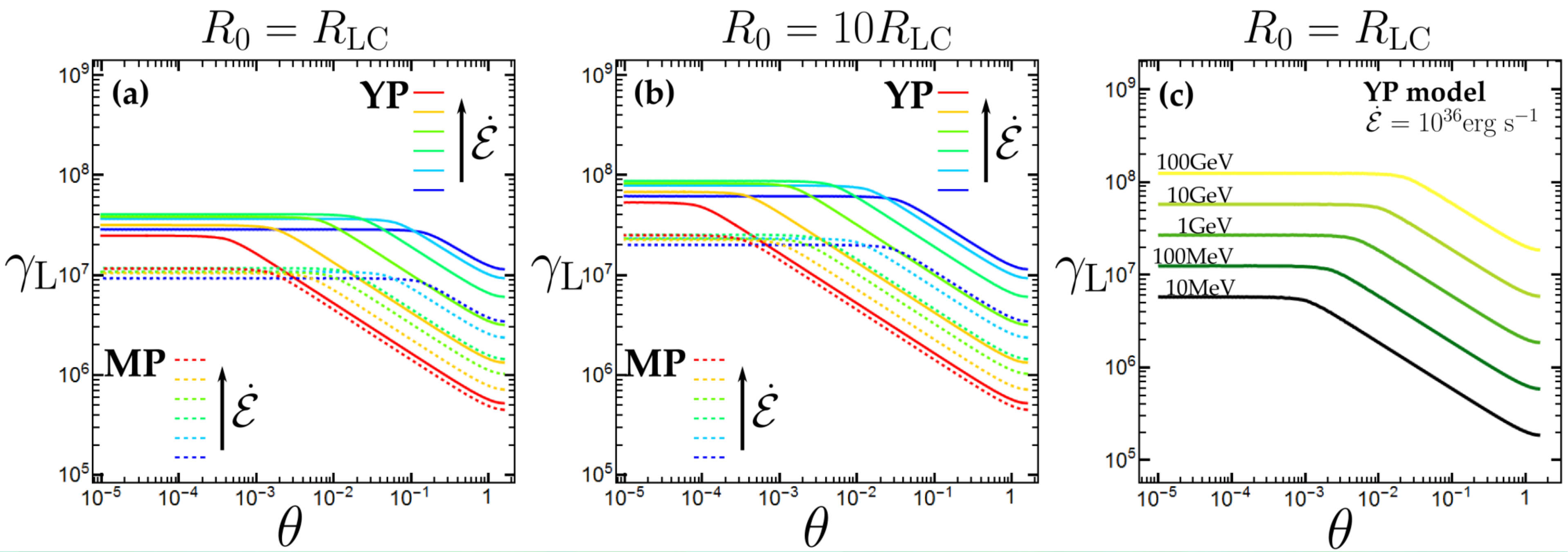
Orbital Exploration (SR↔CR)

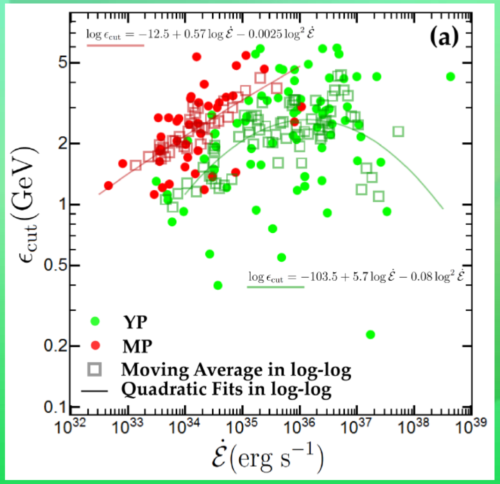
θ= 0.0, R_C= 10.00





Reverse Engineering





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

Kalapotharakos et al. (2019)

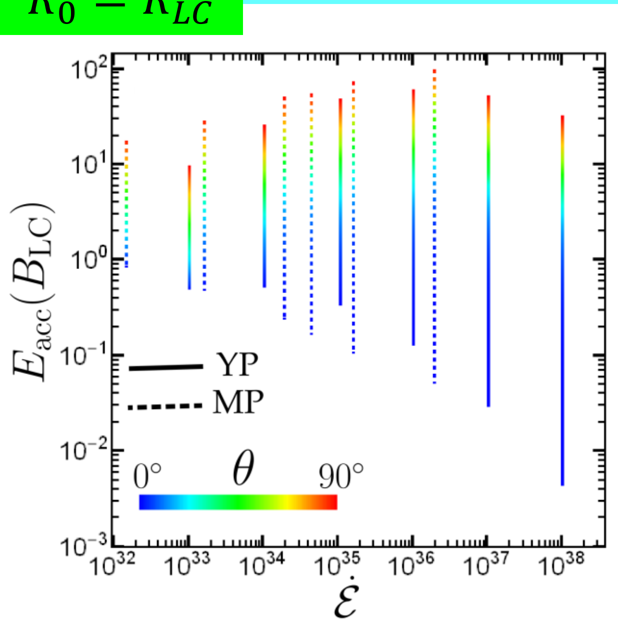
$E, B \sim B_{LC}$

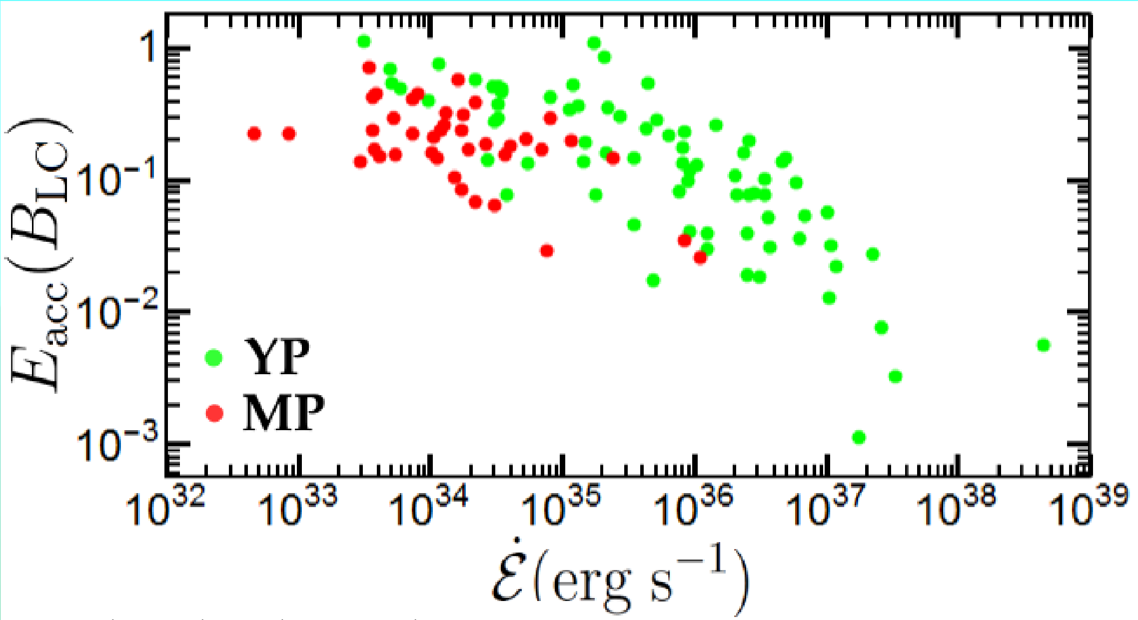
θ decreases:
1. Radiation reaction losses
2. Acceleration

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

Reverse Engineering

$R_0 = R_{LC}$





Kalapotharakos et al. (2017)

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

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Kalapotharakos et al. (2019)

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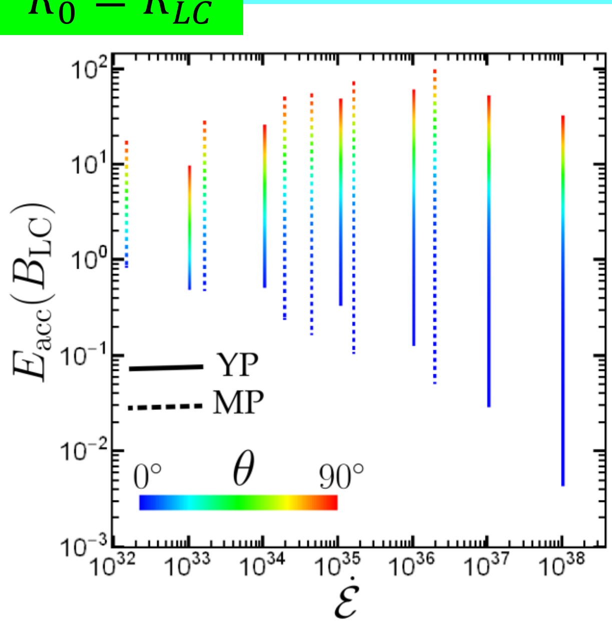

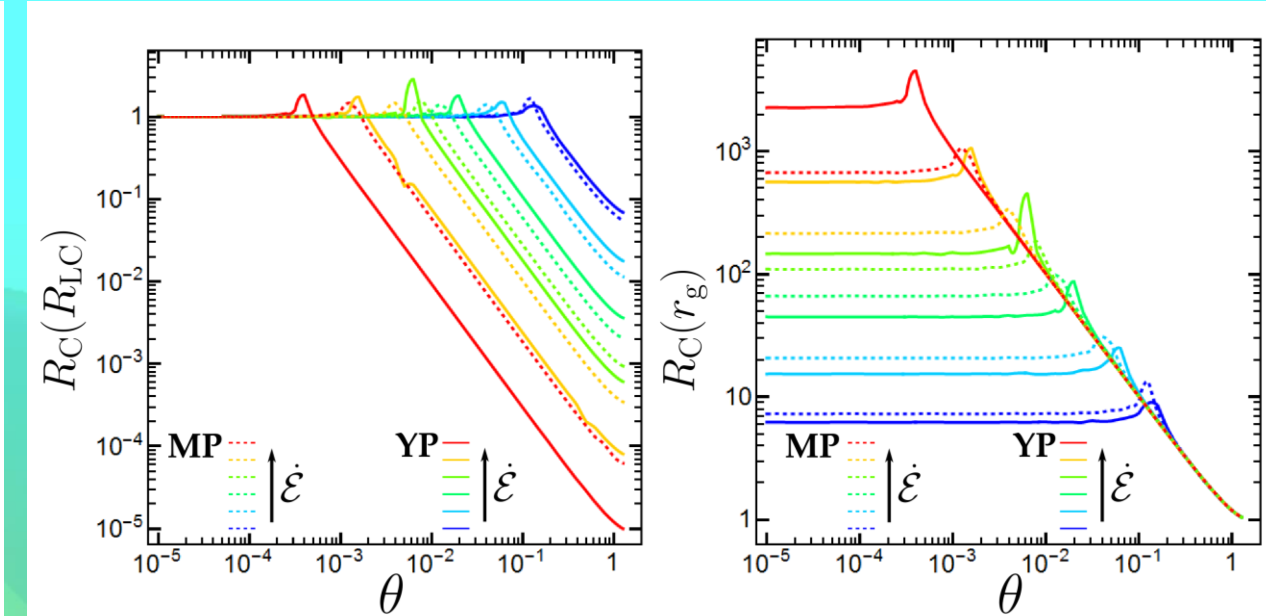

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Fundamental Plane (Theory)

Assumptions

1) Radiation Reaction Limit Regime

2) At the ECS near the LC

CR

Kalapotharakos et al. (2019)

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

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

$\gamma_L \propto \epsilon_{cut}^{1/3} P^{1/3}$

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

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

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

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

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

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

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

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

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

SR

Fundamental Plane (Observations)

88 Fermi YPs+MPs

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

Fermi data

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

Kalapotharakos et al. (2019)

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

Theory CR

Fundamental Plane (Observations)

88 Fermi YPs+MPs

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Fermi data

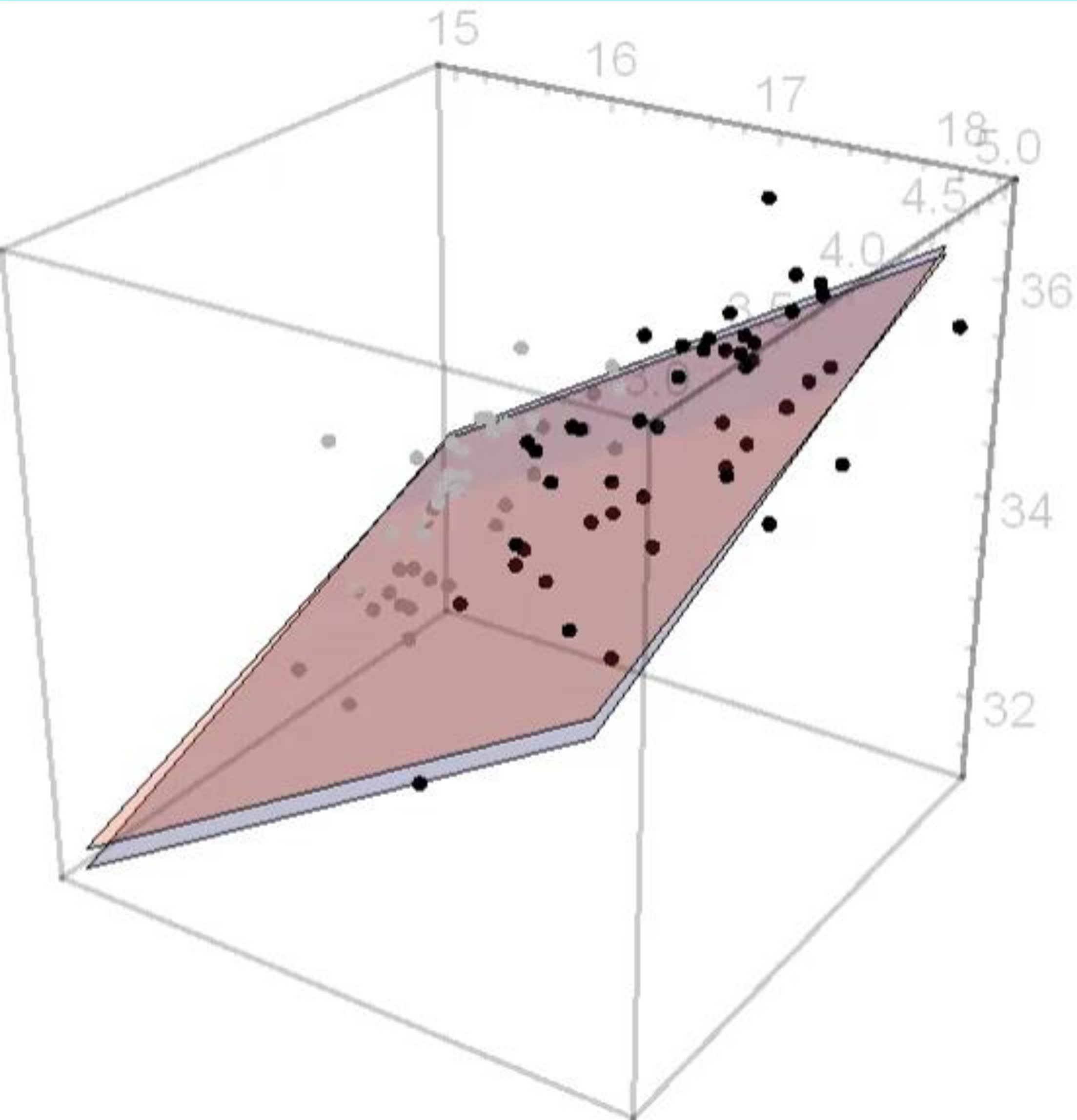
Kalapotharakos et al. (2019)

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

Theory CR

Fundamental Plane (Observations)

4D-space is hard to visualize



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

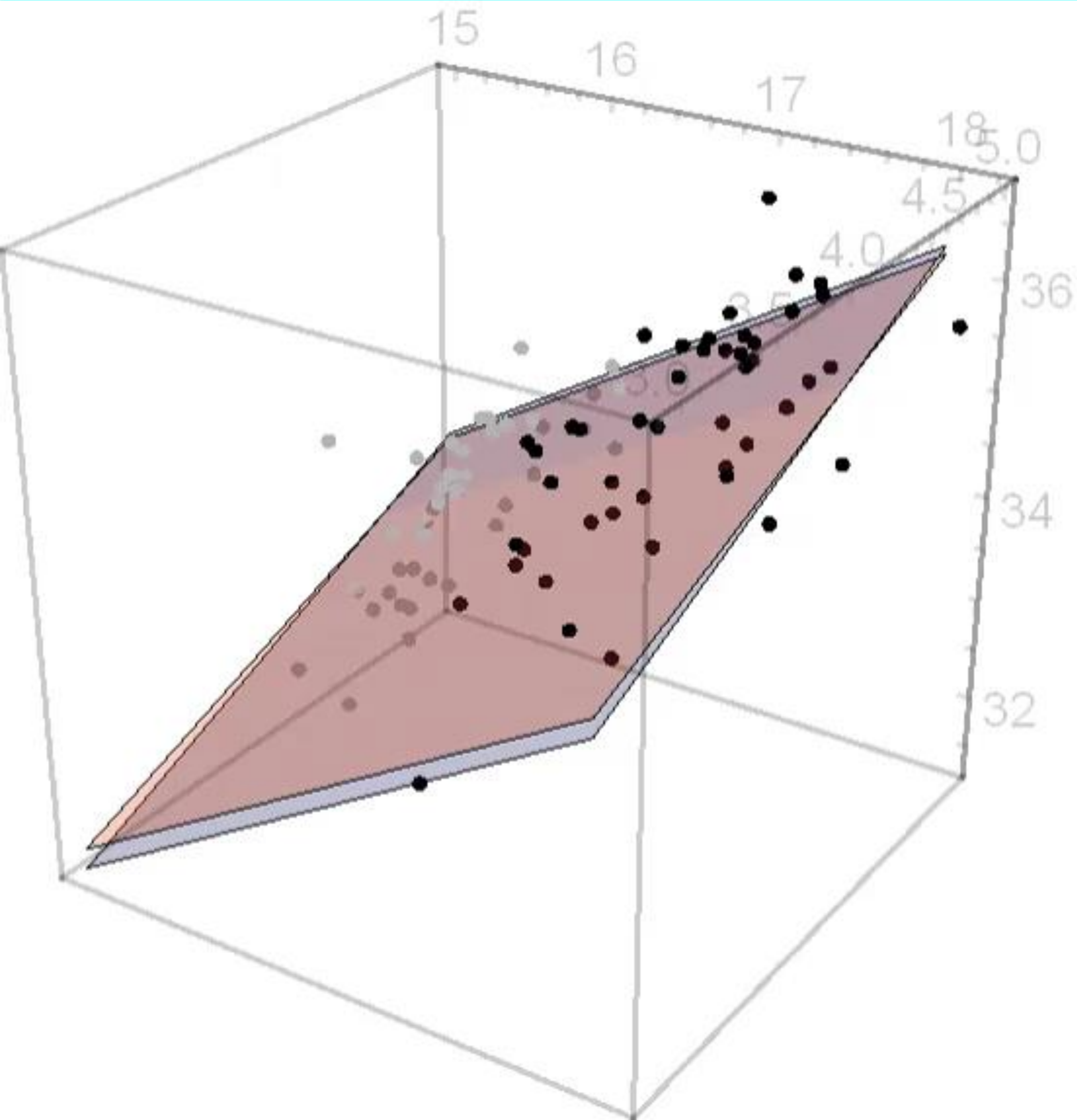
$z \propto x\, y$
(Theory)

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

● Fermi YP
● Fermi MP

Fundamental Plane (Observations)

4D-space is hard to visualize



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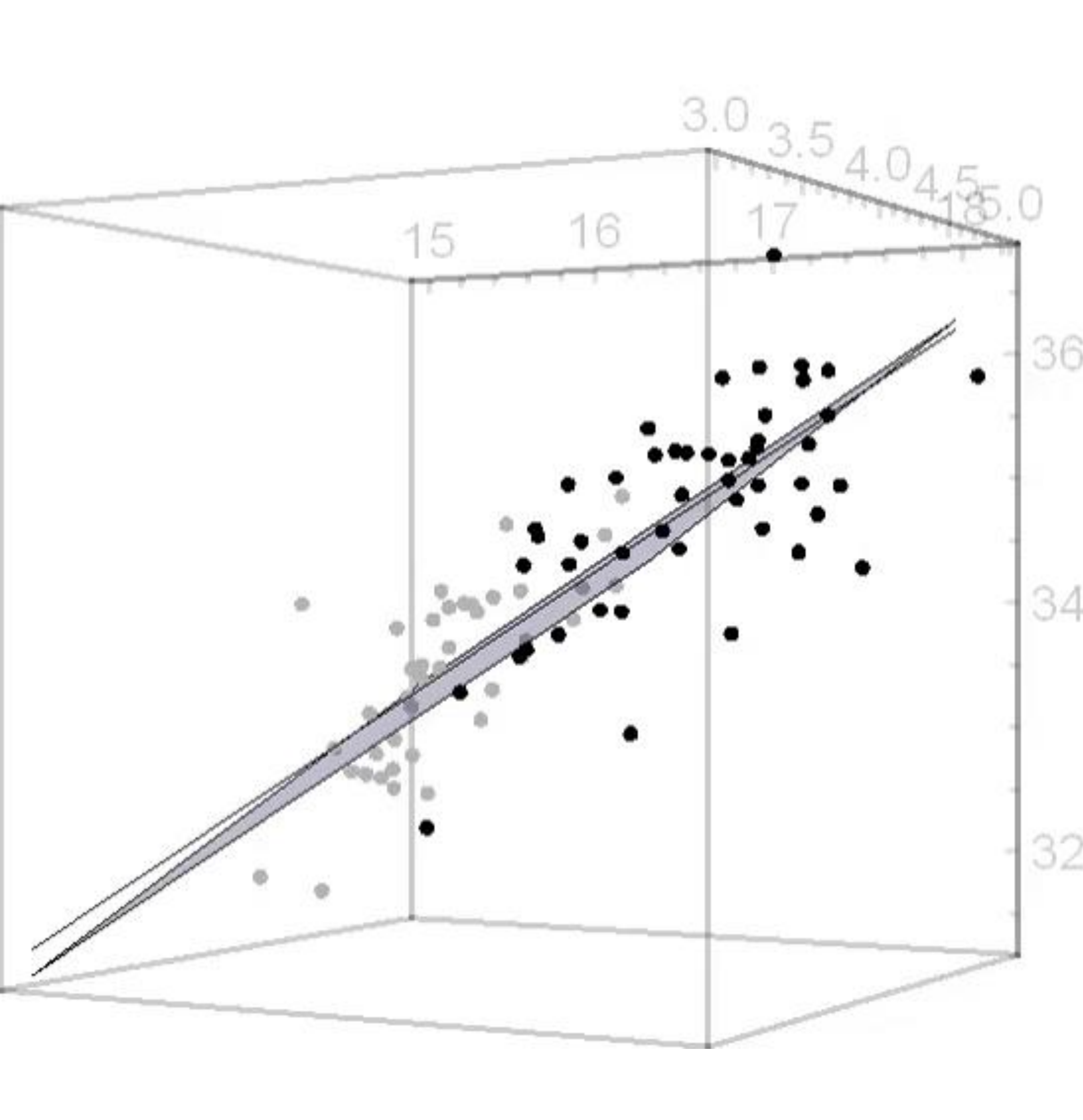
● Fermi YP
● Fermi MP

Fundamental Plane (Observations)

4D-space is hard to visualize



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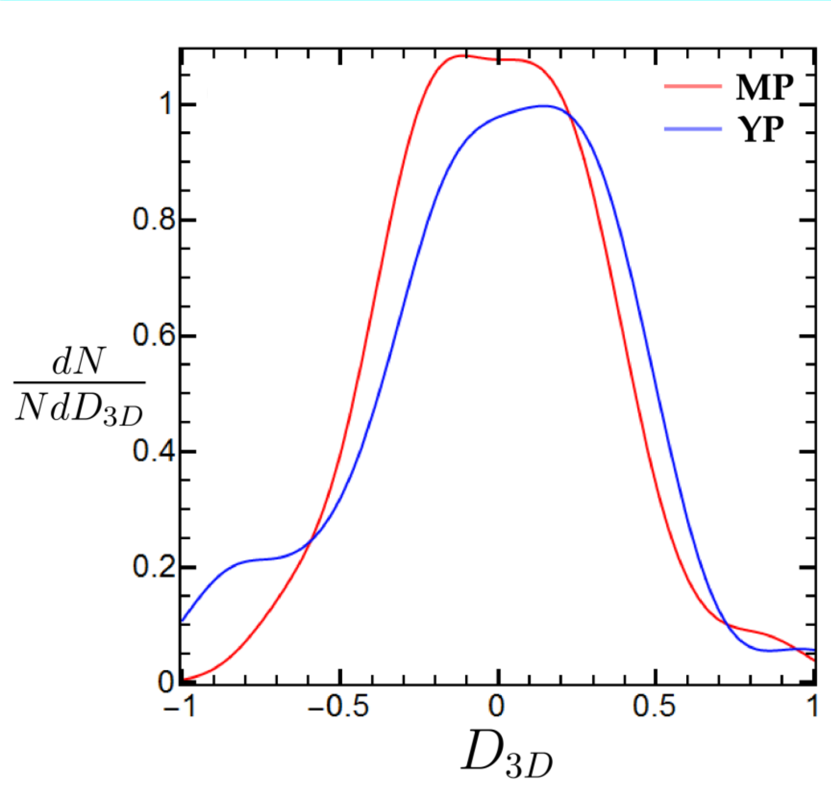
(Theory)

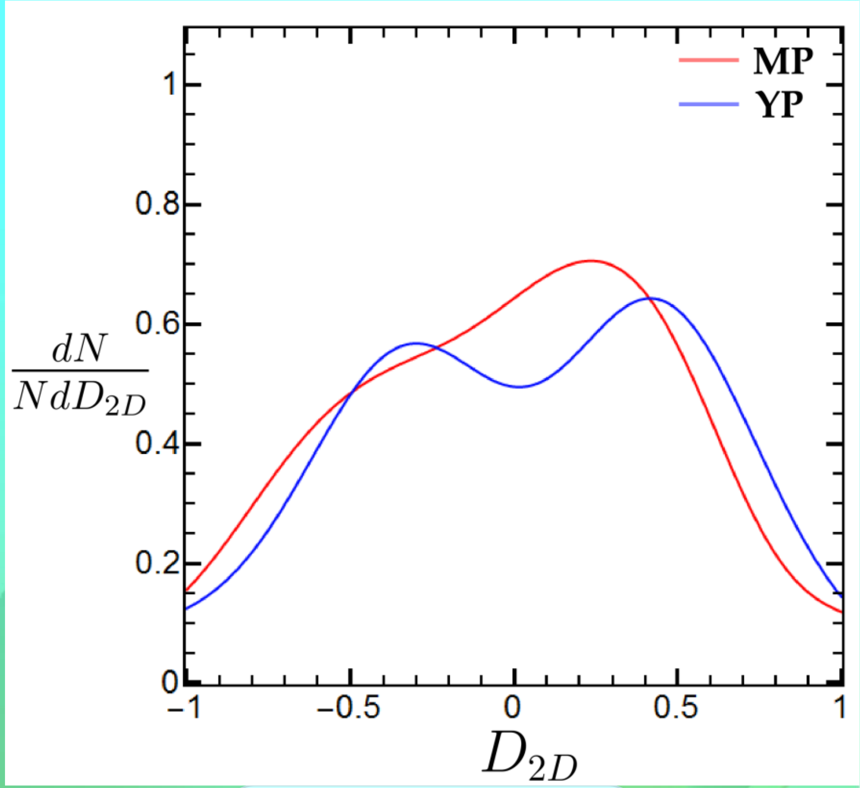
$z \propto x^{0.99}\,y^{0.88}$
(Fermi data)

- ● Fermi YP
- ● Fermi MP

Fundamental Plane (Observations)



$$AIC_{3D} = 159$$
$$BIC_{3D} = 172$$

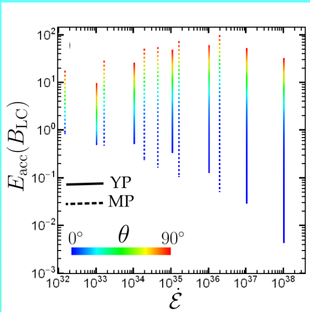


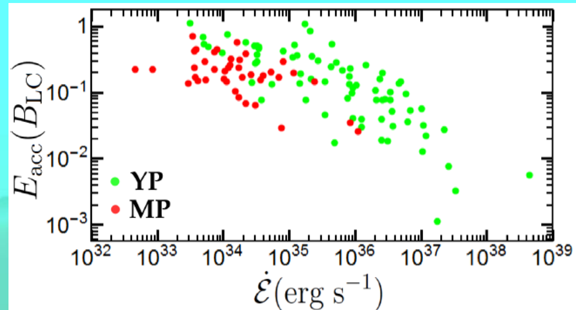
$$AIC_{2D} = 180$$
$$BIC_{2D} = 189$$

Fundamental Plane (Observations)

Is that all?

No, it is actually even better

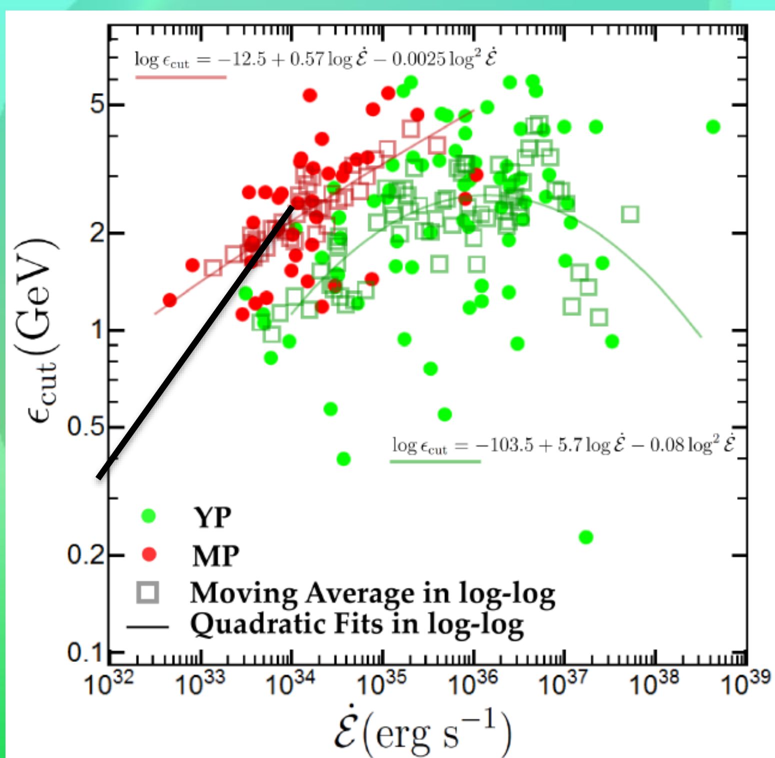




For low $\dot{\mathcal{E}}$, $E_{acc} \propto B_{LC}$

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

Kalapotharakos et al. (2019)



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

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

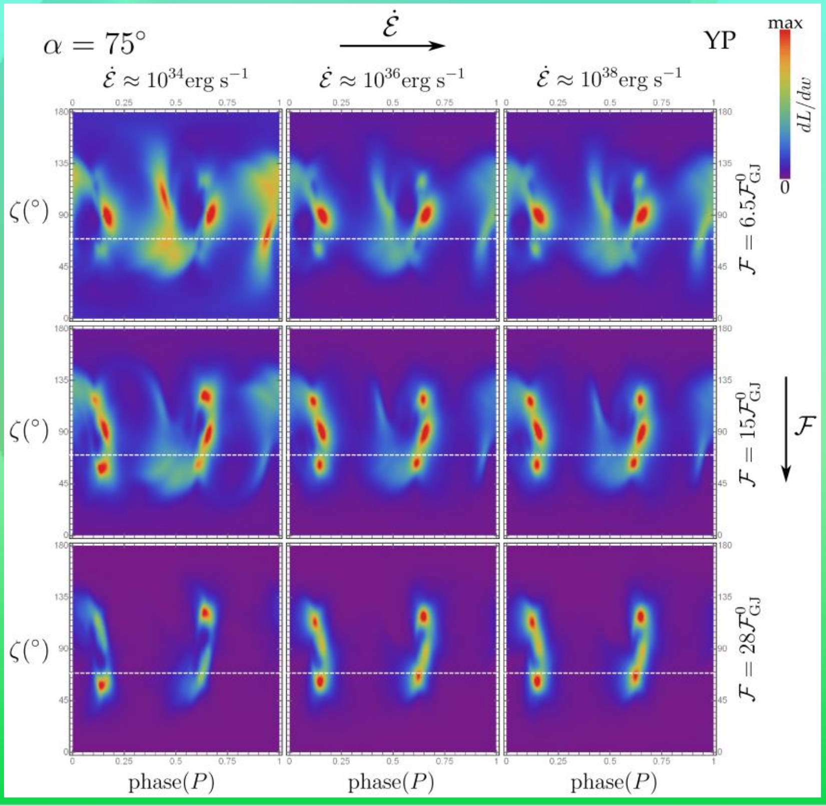
Viable interpretation of the observed γ-ray pulsar death-line

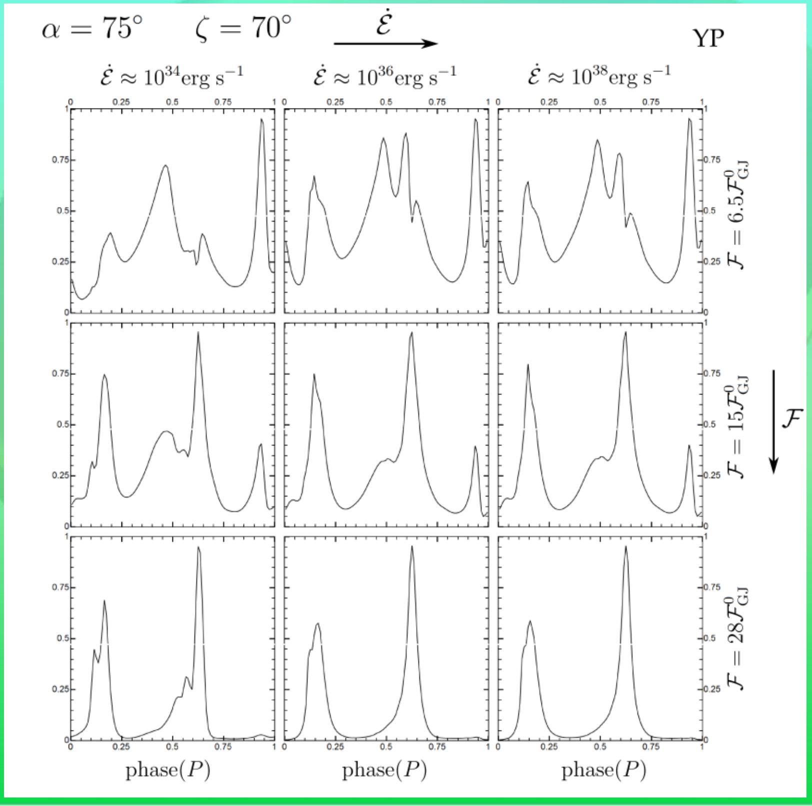
Better sensitivity in the MeV-band telescope (AMEGO)

3D Kinetic Models (PIC)

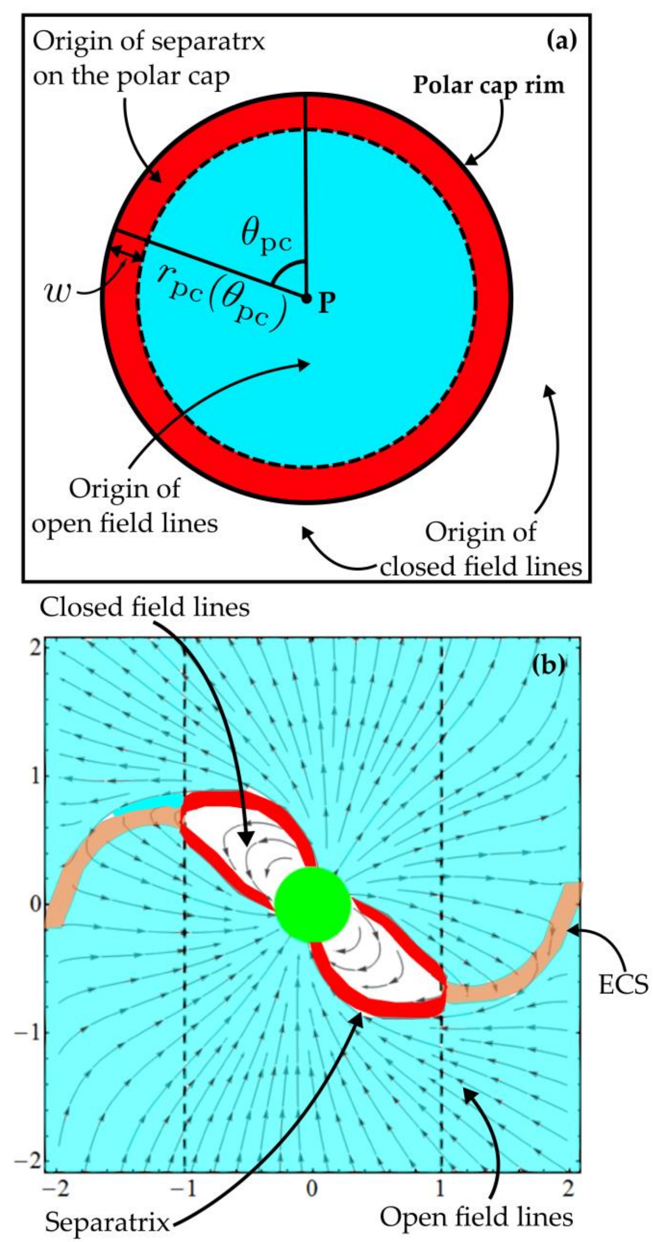
But…

1. The γ-ray light-curves for low $\mathcal{F}$ are messy.
2. For high $\dot{\mathcal{E}}$ an extrapolation has to be used.
3. 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

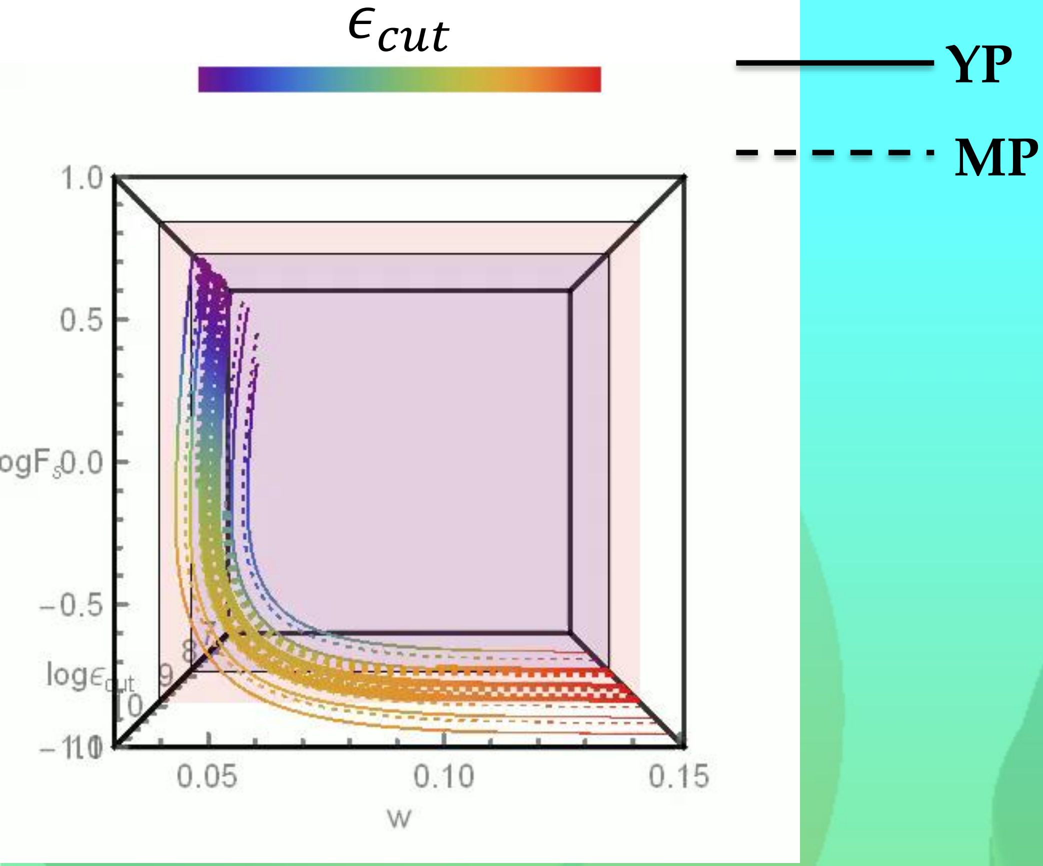
The particle injection rate along the open and the closed field-lines is <u>not very small</u>.

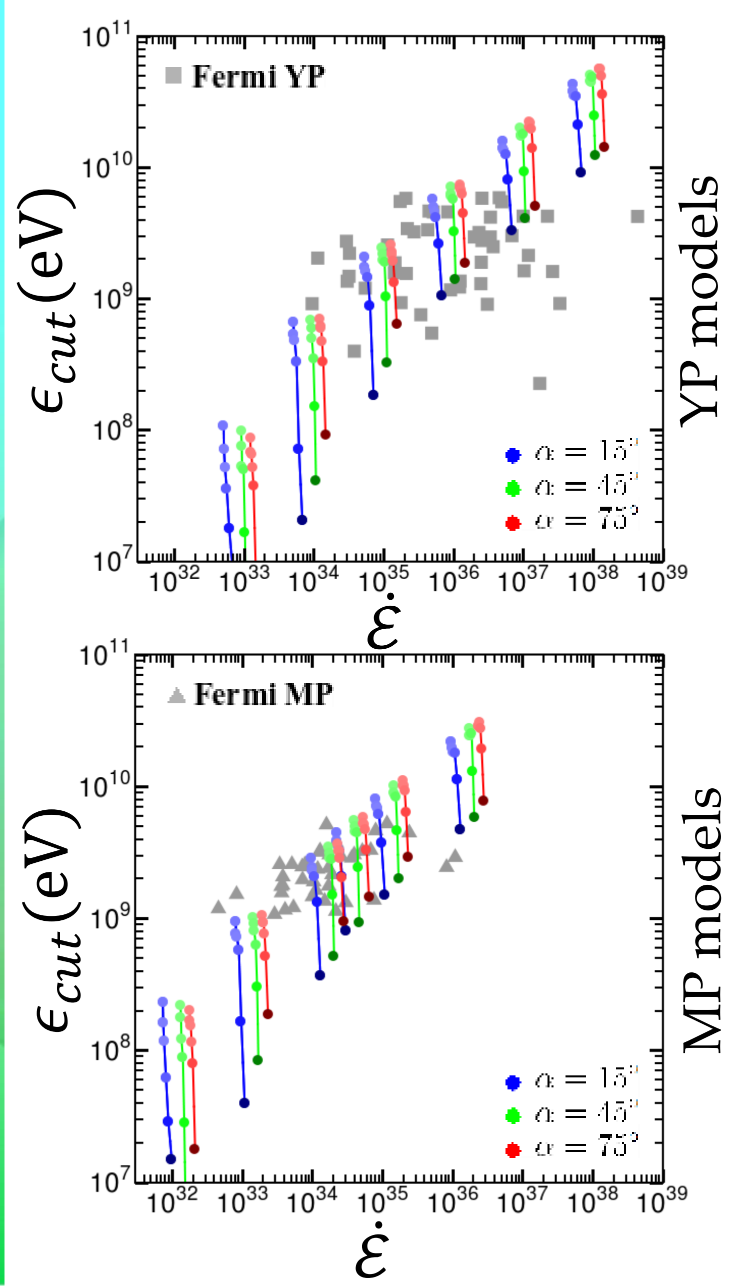
$(> 5\mathcal{F}_{GJ}^{0})$

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

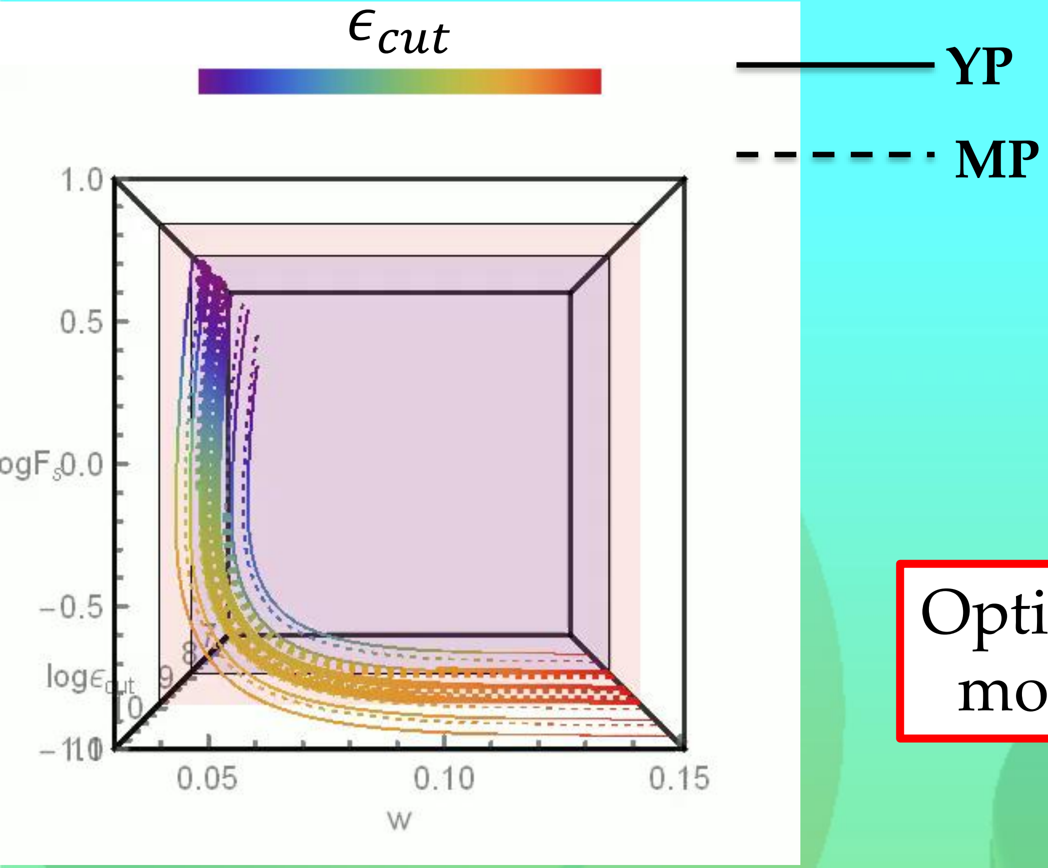
$(< 10\mathcal{F}_{GJ}^{0})$

3D Kinetic Models (PIC)

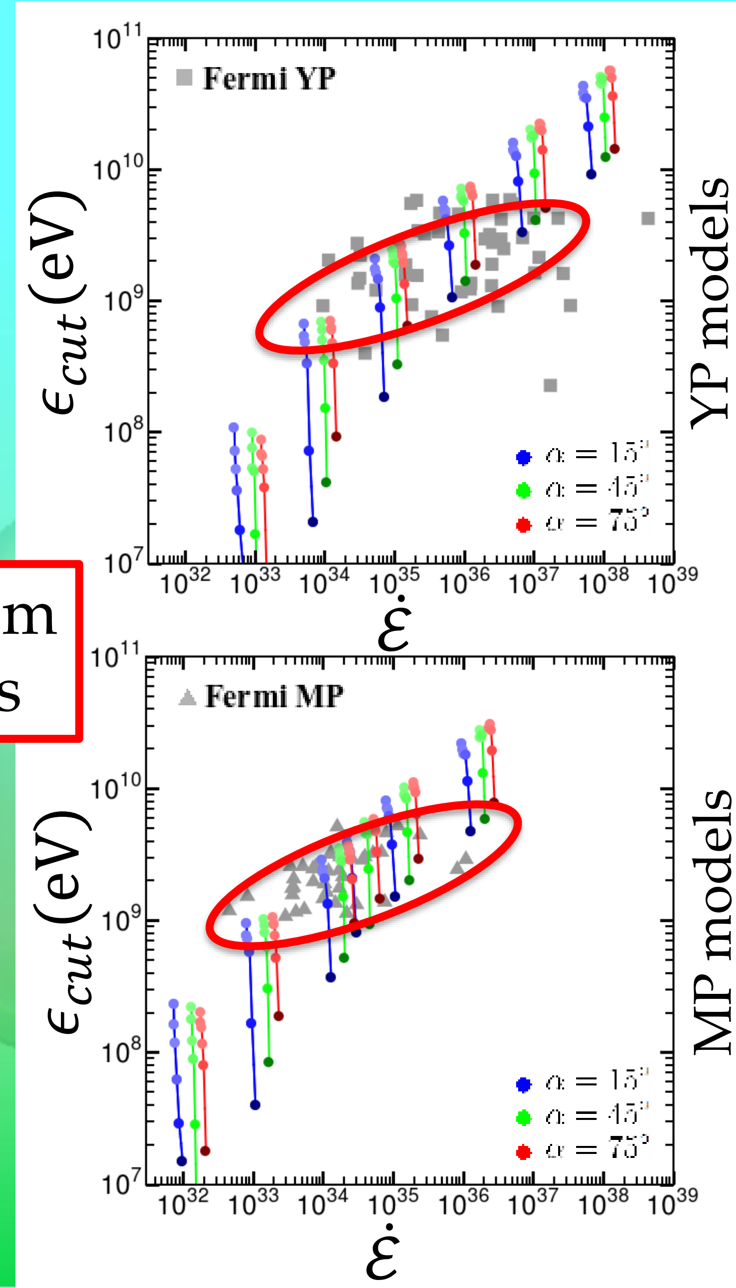




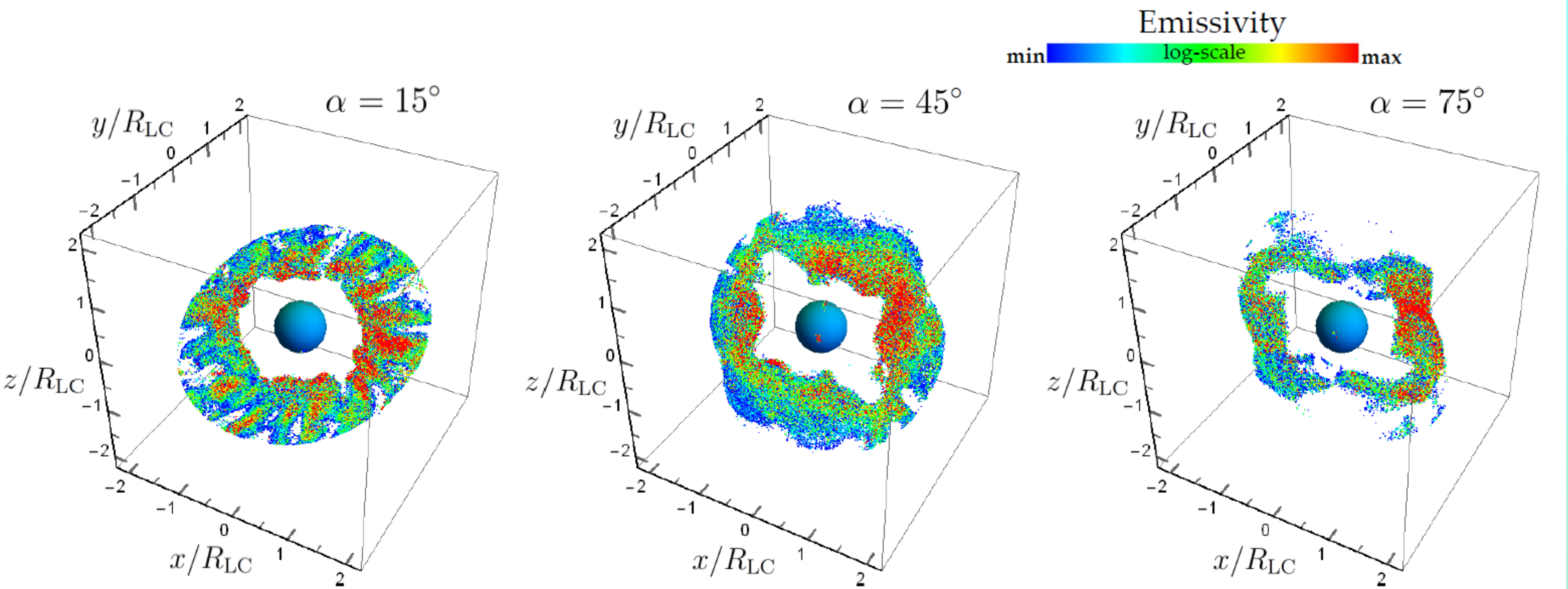
3D Kinetic Models (PIC)



Optimum models

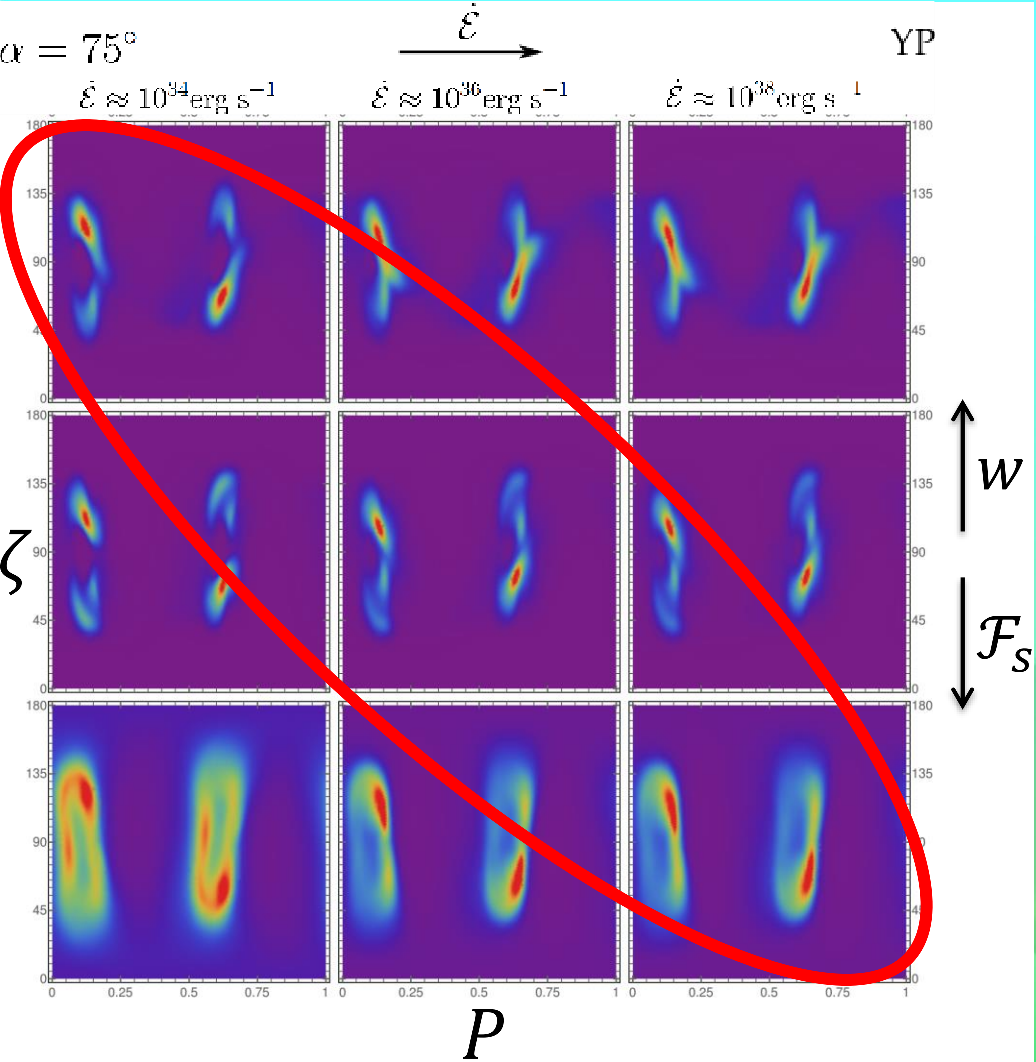


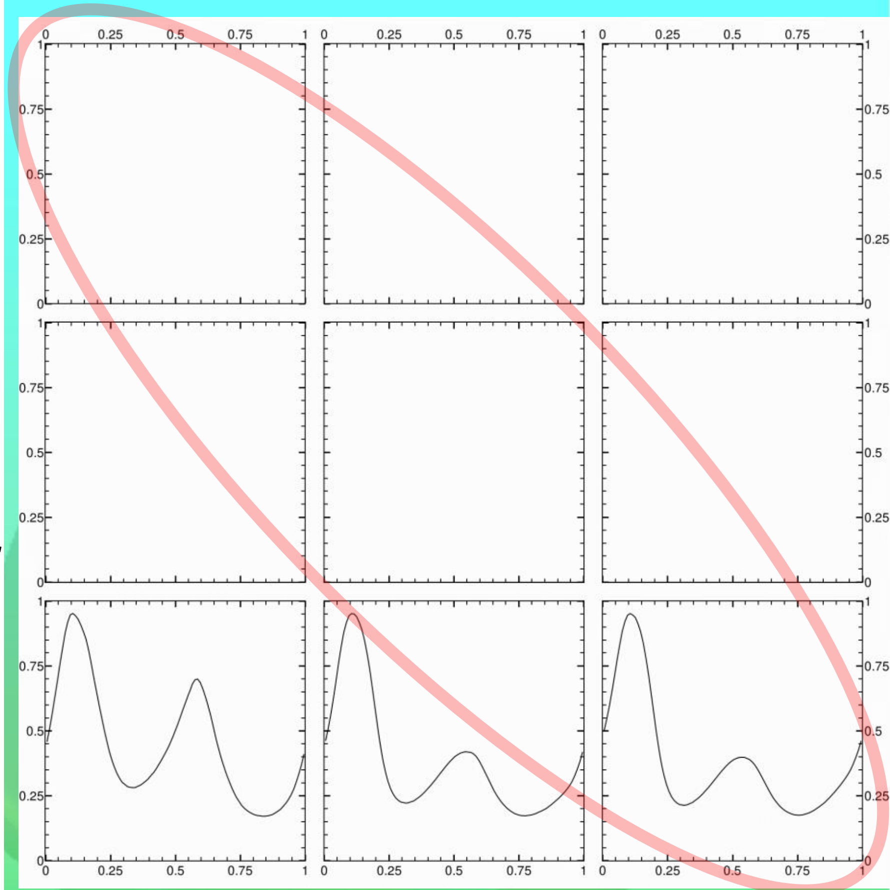
3D Kinetic Models (PIC)



- 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

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

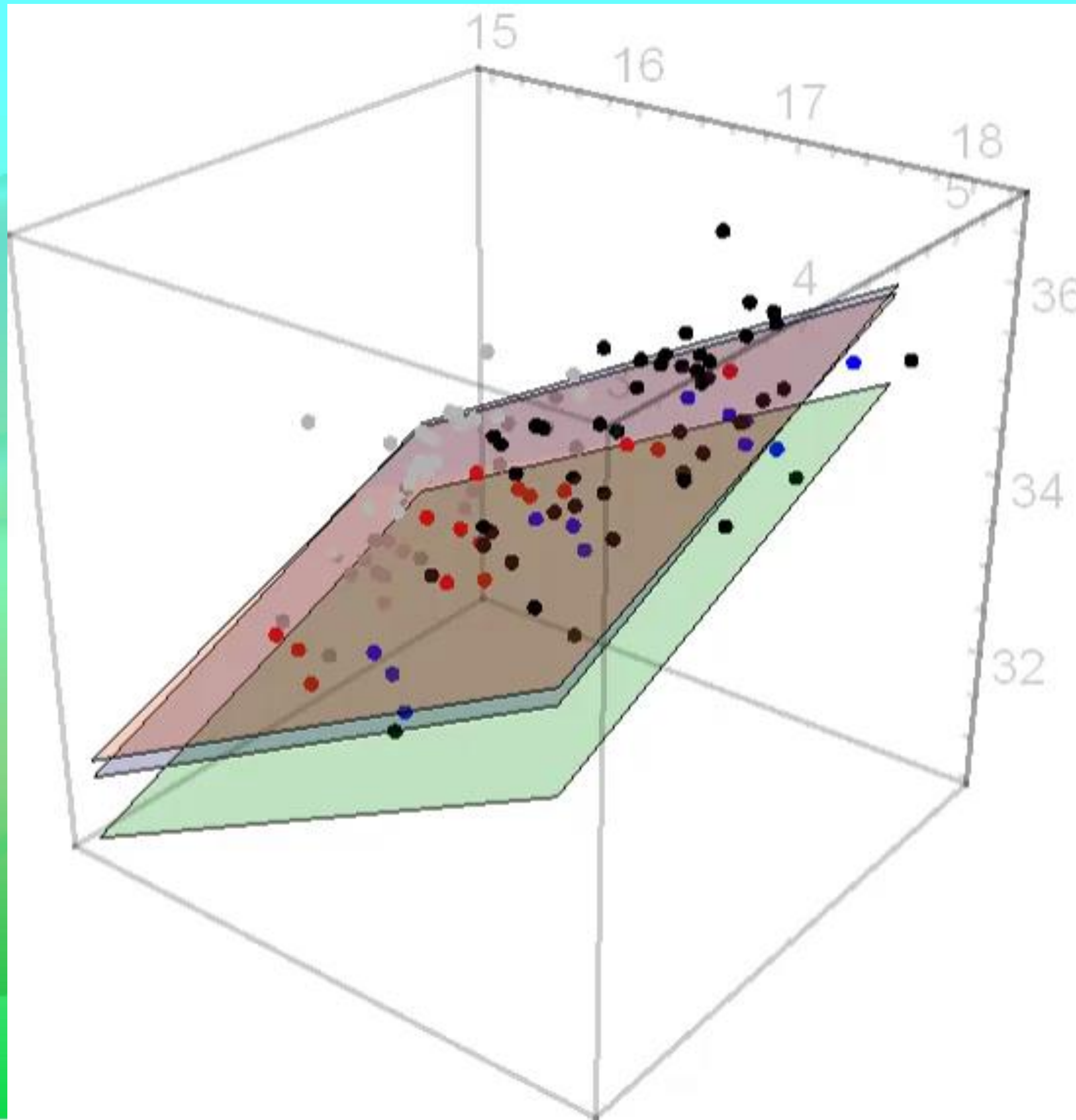
$L_\gamma \propto \epsilon_{cut}^{1.18\pm0.24}\, B_*^{0.17\pm0.05}\, \dot{\mathcal{E}}^{0.41\pm0.08}$ **Fermi data**

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

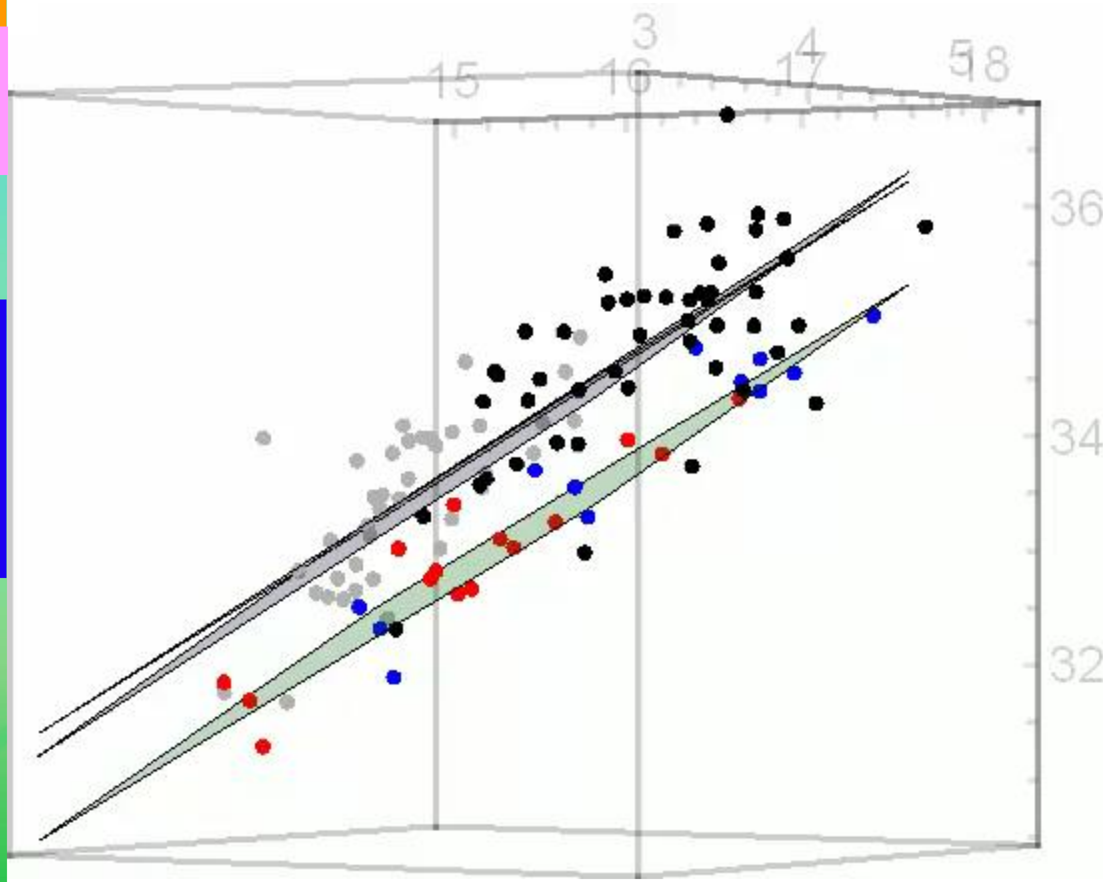
Plane distance ~0.5

Vertical distance $\times$ 5

Beaming factor f_b

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

Moment of Inertia, I



● Fermi YP

● Fermi MP

● PIC YP

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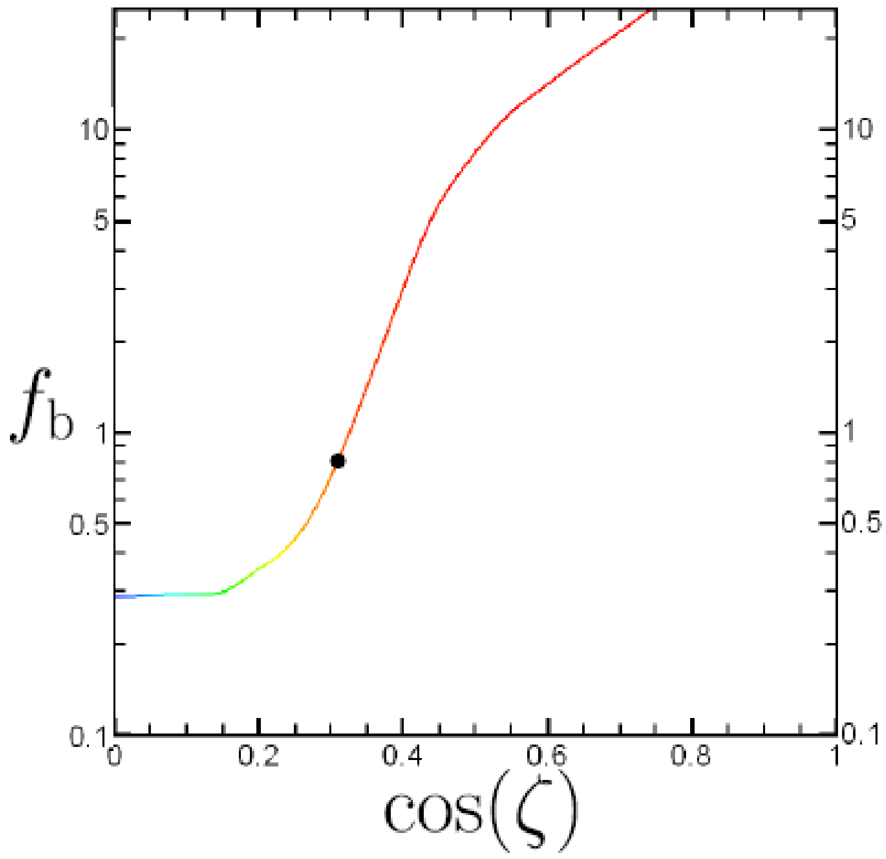


● Fermi YP

● Fermi MP

● PIC YP

● PIC MP

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

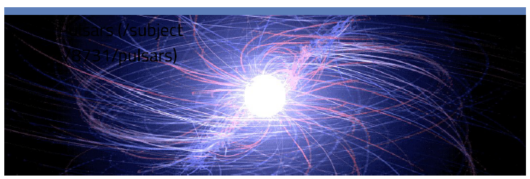
3D Kinetic Models (PIC)

Pulsar Theater

Particle injection near the stellar surface.

Brambilla et al. 2018

NASA/GSFC videos



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Oct. 10, 2018

'Pulsar in a Box' Reveals Surprising Picture of a Neutron Star's Surroundings

An international team of scientists studying what amounts to a computer-simulated "pulsar in a box" are gaining a more detailed understanding of the complex, high-energy environment around spinning neutron stars, also called pulsars. The model traces the paths of charged particles in magnetic and electric fields near the neutron star, revealing behaviors that may help explain how pulsars emit gamma-ray and radio pulses with ultraprecise timing.

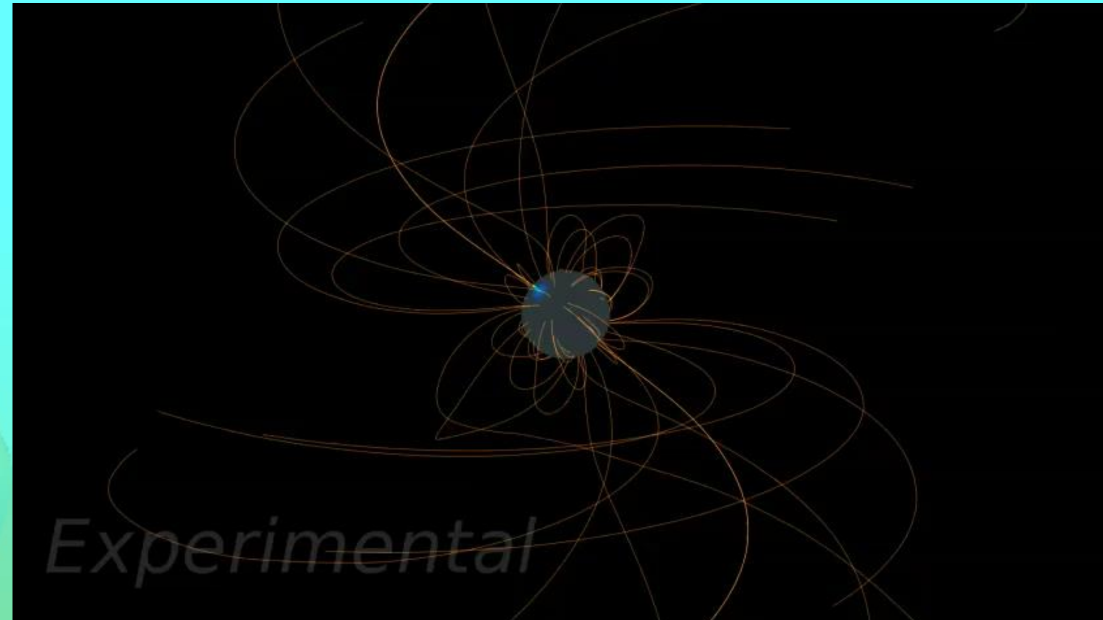
"Efforts to understand how pulsars do what they do began as soon as they were discovered in 1967, and we're still working on it," said Gabriele Brambilla, an astrophysicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland, and the University of Milan who led a study of the recent simulation. "Even with the computational power available today, tracking the physics of particles in the extreme environment of a pulsar is a considerable challenge."

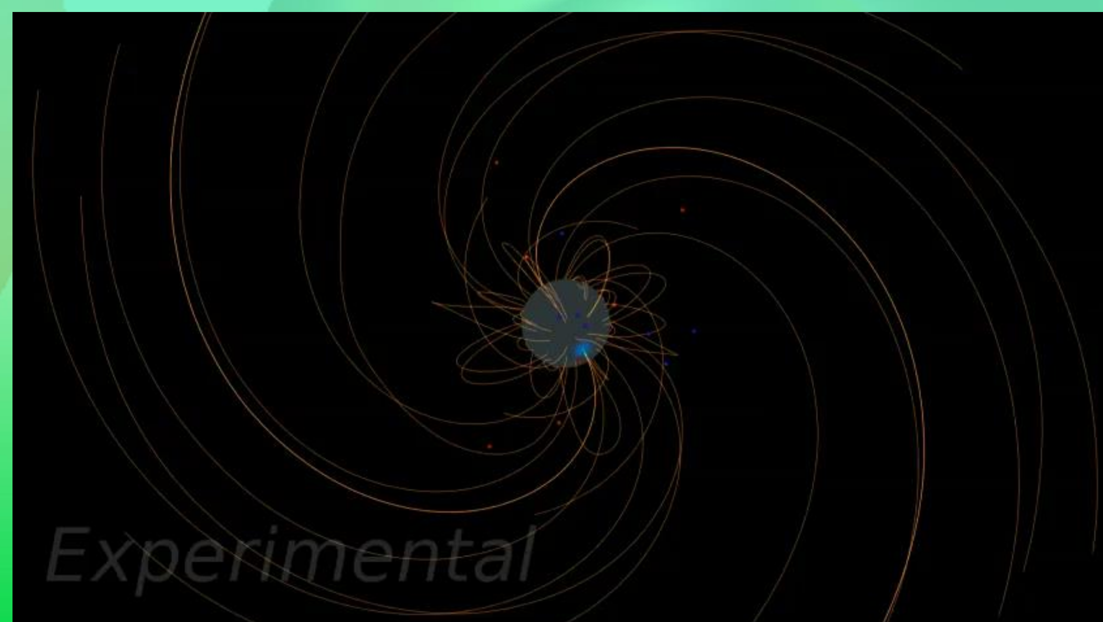
A pulsar is the crushed core of a massive star that ran out of fuel, collapsed under its own weight and exploded as a supernova. Gravity forces more mass than the Sun's into a ball no wider than Manhattan Island in New York City while also revving up its rotation and strengthening its magnetic field. Pulsars can spin thousands of times a second and wield the strongest magnetic fields known.

https://www.nasa.gov/feature/goddard/2018/pulsar-in-a-box-reveals-surprising-picture-of-a-neutron-star-s-surroundings

● e^-

● e^+



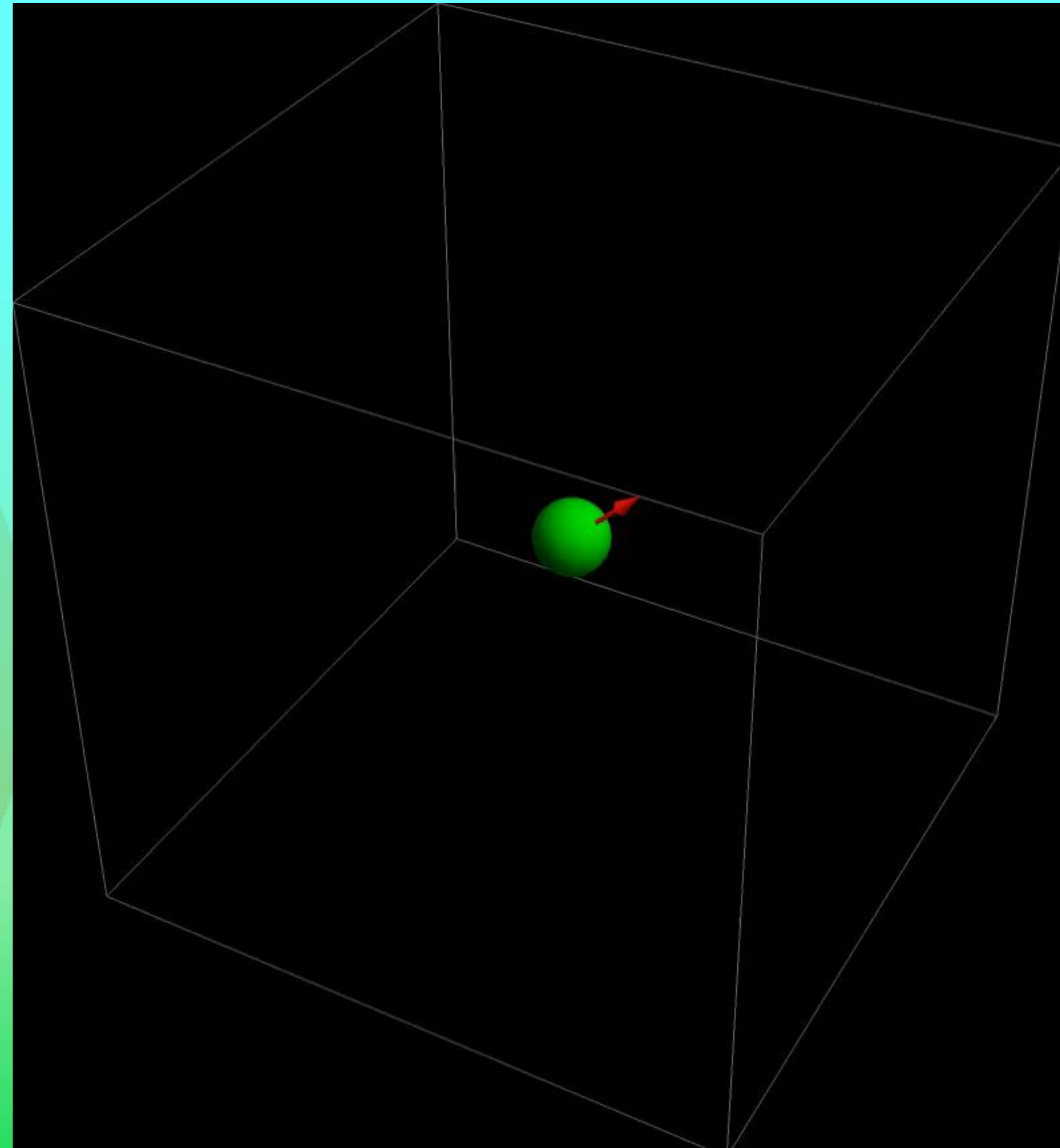


3D Kinetic Models (PIC)

Pulsar Theater

Particle injection inside the LC.

Kalapotharakos et al. (in prep.)



CK videos

3D Kinetic Models (PIC)

Pulsar Theater

Particle injection
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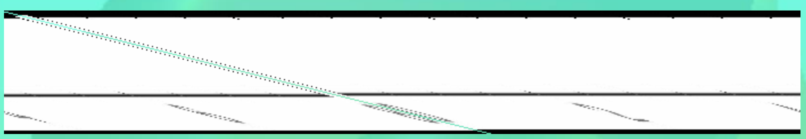
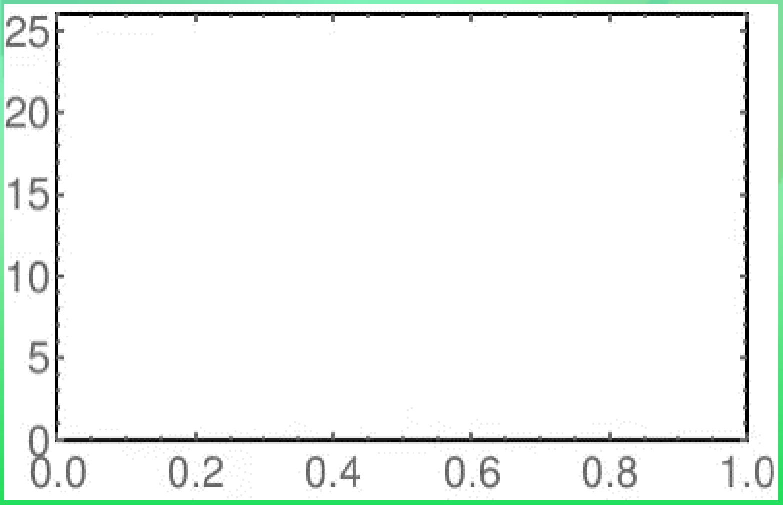
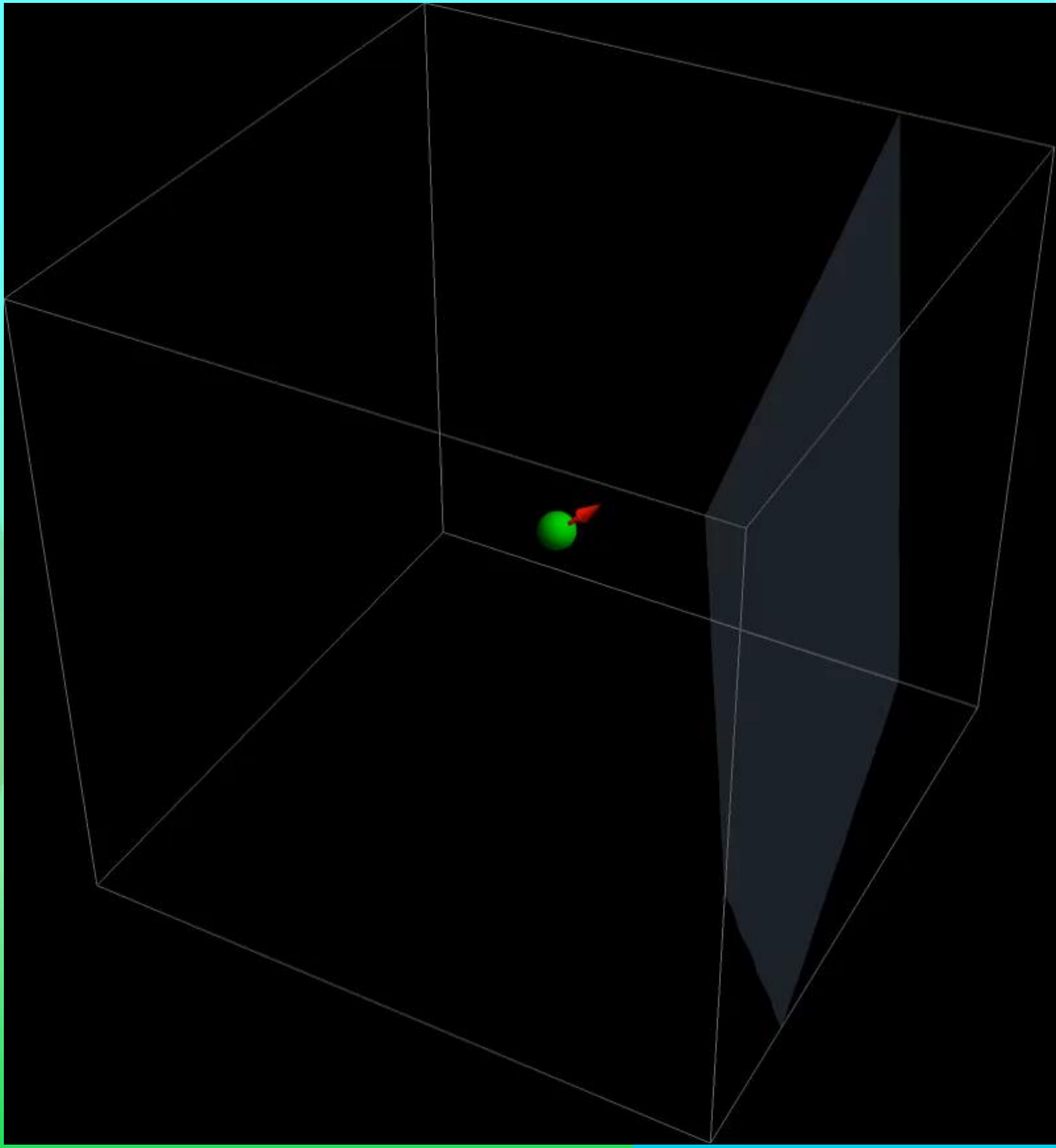






CK videos

Conclusions

- **Key point:** The advantageous interaction between models and observations.
- Different model approaches converge leading to a deeper understanding and a continuously advancing reproduction of a broader and broader spectrum of the observed phenomenology.
- Simple theoretical considerations lead to an advanced interpret-tation of the observations (e.g., FP).

Even though our models are powerful, the connection, between the microphysics of pair-production and the more macroscopic view our models provide, is missing.

Most importantly what is missing is a quantified behavior of these mechanisms that hopefully support our successful global macroscopic and PIC models.

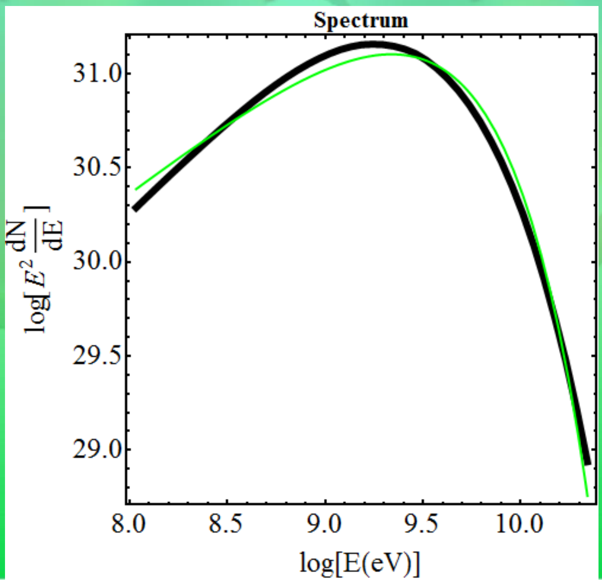
Conclusions

- **Key point:** The advantageous interaction between models and observations.
- Different model approaches converge leading to a deeper understanding and a continuously improved reproduction of a broader and broader spectrum of the observed phenomenology.
- Simple theoretical considerations lead to an advanced interpretation of the observations (e.g., FP).

Our models also do not reproduce the spectral index vs. spin-down power correlation.

Idea!

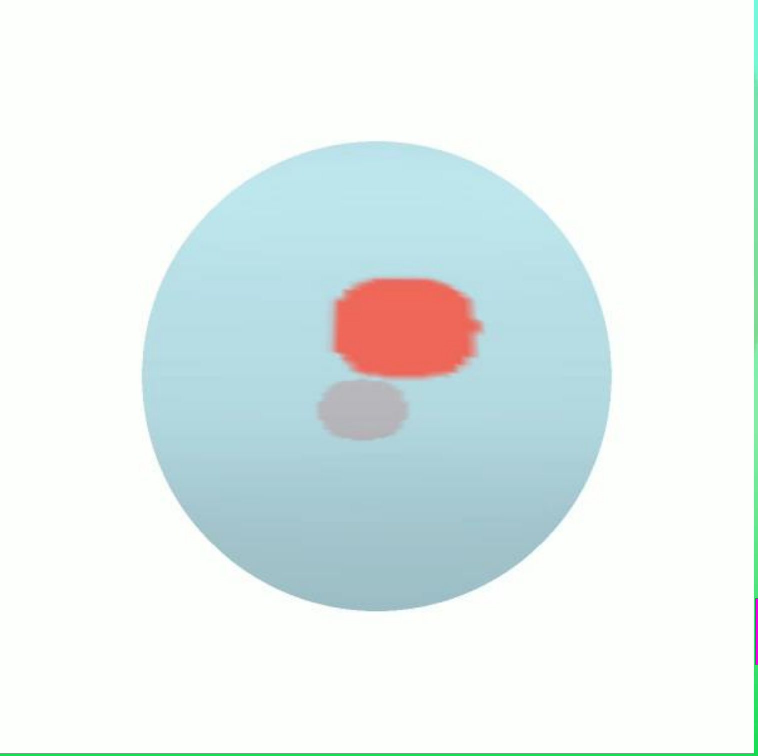
SR CR IC

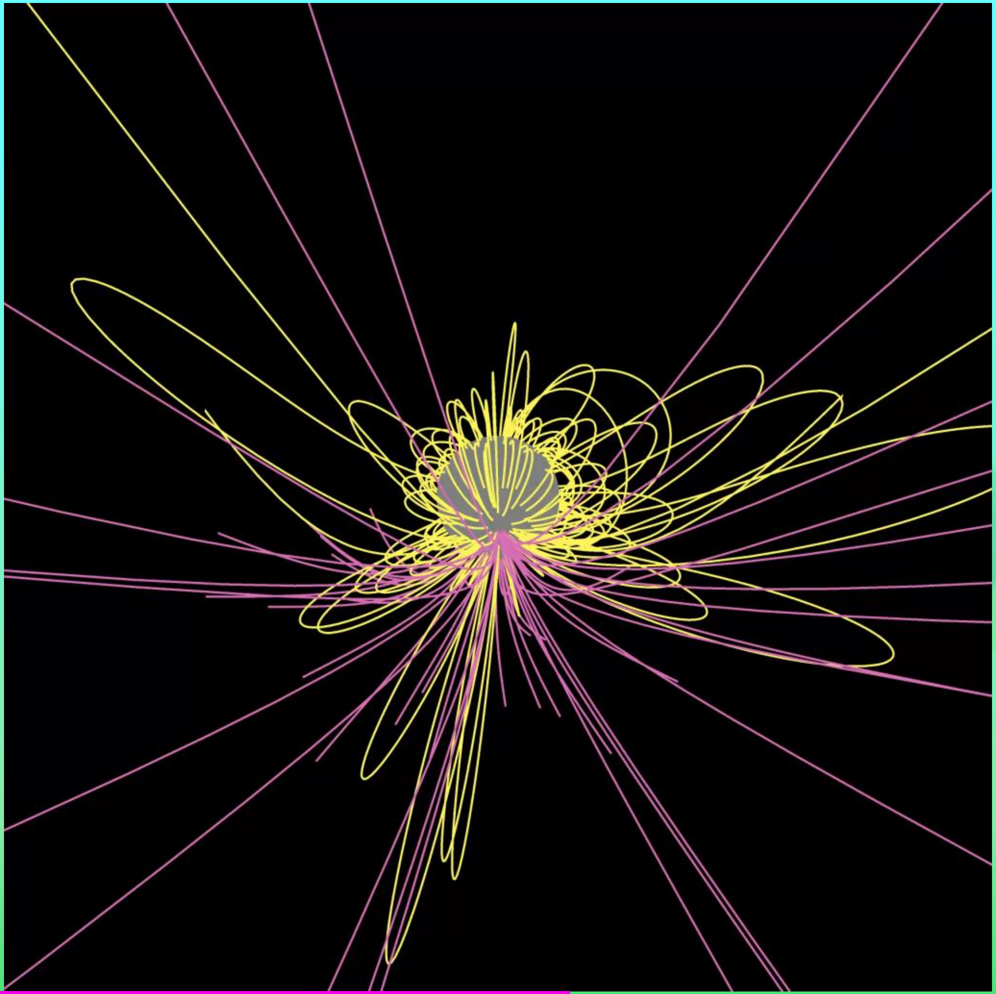


Torres 2018, Torres et al. 2019

More Complexity? *NICER* observations

NICER data indicate that the magnetic field structure deviates considerably from the dipolar one





Off-center Dipole + Quadrupole

Kalapotharakos et al. (in prep.)

Thank you!