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Photon-photon pair production in reconnecting layers from a dynamical perspective

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Context

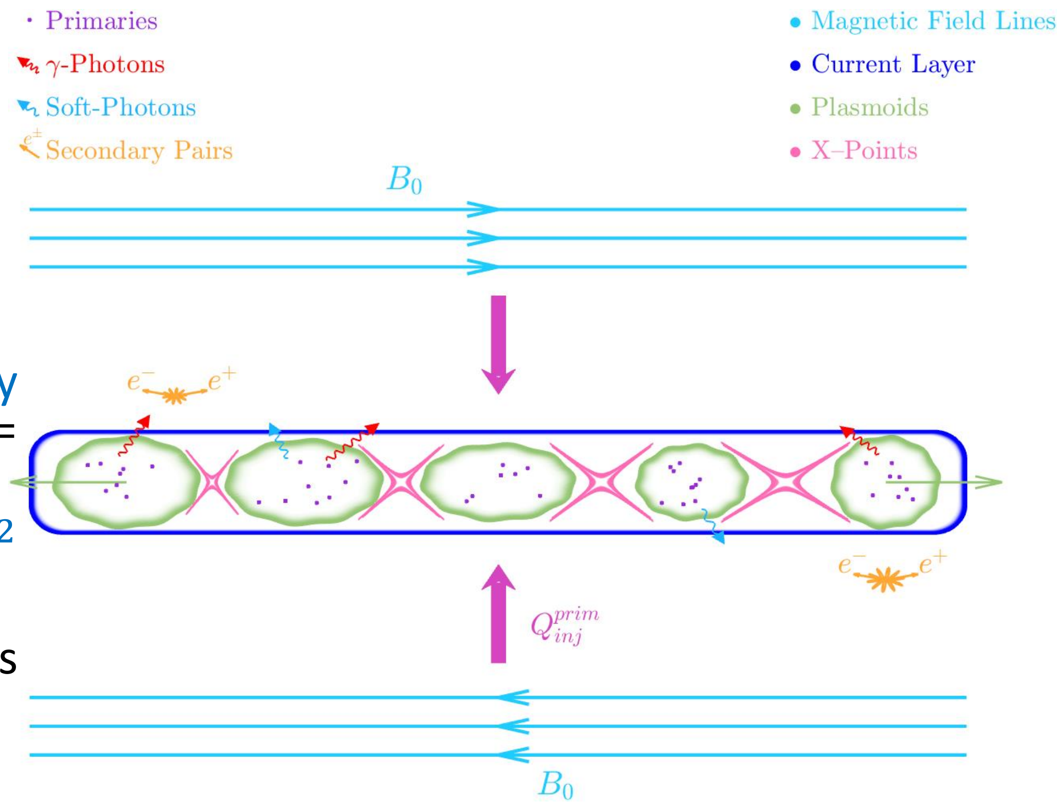
- Pair plasma
- Magnetic reconnection

Continuous cycle – σ dependent

- e^-, e^+ dragged in the current sheet, magnetic energy distributed among the pairs, $\gamma \sim \sigma$, where $\sigma = u_B/2n_\pm m_e c^2$
- Pairs emit synchrotron photons up to energies $\epsilon_\gamma \sim b\sigma^2$ (strong synchrotron cooling)
- $\gamma - \gamma$ interactions create more pairs, magnetization σ is regulated

How does this cycle end?

- System sustains a balanced state, or
- Pair production continues until the system reaches the threshold



Methods

Monoenergetic approach of kinetic equations with three particle populations

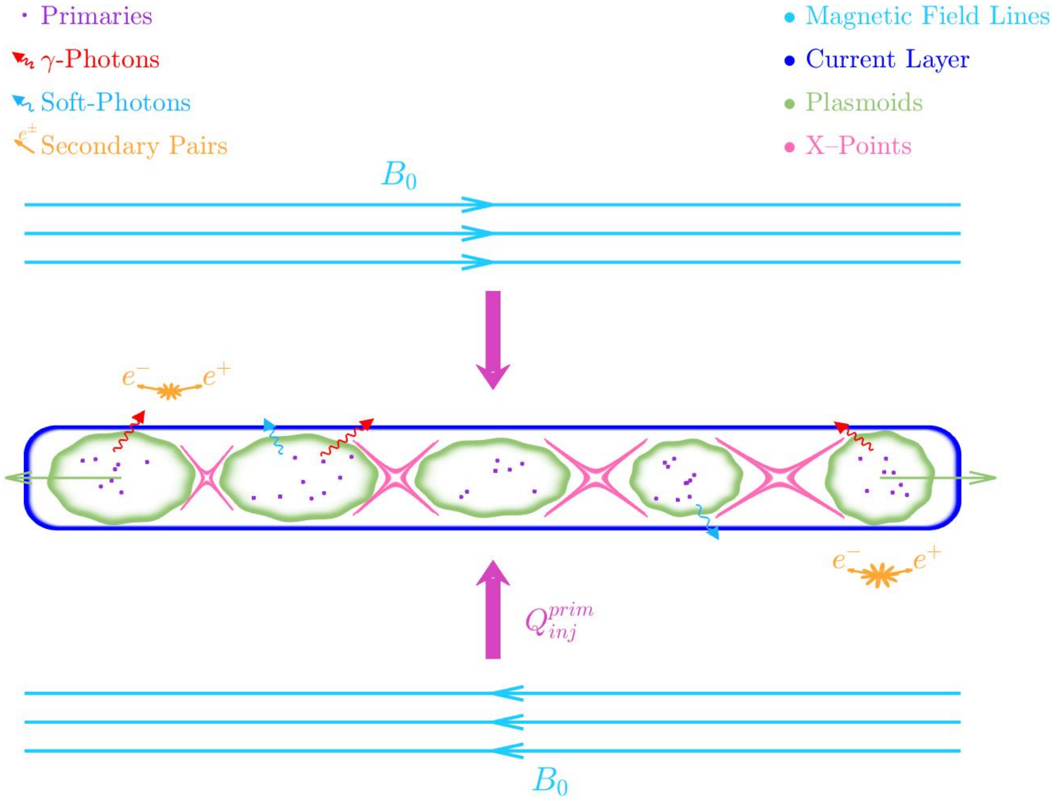
- Primary pairs at $\epsilon_{\text{prim}} = \kappa\sigma$, $\kappa \approx 3-4$[1]
- Photons with $\epsilon_\gamma = b(\kappa\sigma)^2$
- Secondary pairs with $\epsilon_{sec} = b(\kappa\sigma)^2/2$

Linear analysis

- Identify solutions analytically
- Classify their stability

System parameters

- Initial magnetization, σ_0
- Upstream magnetic field, B
- Current sheet length, L



[1] e.g., Chen et al., 2023

Set of ODEs

Primaries: $n_{prim}(\tau)$

Photons: $n_\gamma(\tau)$

Secondaries: $n_{sec}(\tau)$

Magnetization: $\sigma(\tau)$

Catastrophic Synchrotron losses[2]

$$\frac{dn_{prim}(\tau)}{d\tau} = \frac{2 f_{rec} l_B}{\kappa \sigma(\tau)} - \frac{4}{3} l_B \kappa \sigma(\tau) n_{prim}(\tau)$$

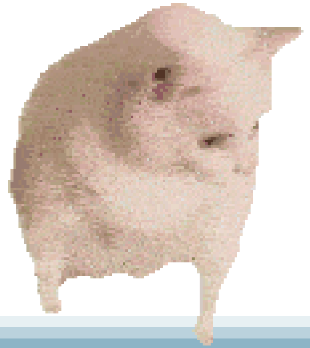
$$\frac{dn_\gamma(\tau)}{d\tau} = \frac{4 l_B}{3b} n_{prim}(\tau) - n_\gamma(\tau) - \frac{1}{3}\left(\frac{\sigma(\tau)}{\sigma_{thr}}\right)^2 n_\gamma^2(\tau) \mathcal{H}(\sigma(\tau) - \sigma_{thr})$$

$\gamma - \gamma$ loss term

$$\frac{dn_{sec}(\tau)}{d\tau} = \frac{2}{3}\left(\frac{\sigma(\tau)}{\sigma_{thr}}\right)^2 n_\gamma^2(\tau) \mathcal{H}(\sigma(\tau) - \sigma_{thr}) - n_{sec}(\tau)$$

$$\sigma(\tau) = \frac{\sigma_0}{1 + \frac{n_{sec}(\tau)}{n_0}}$$

Magnetization regulation via newly created pairs



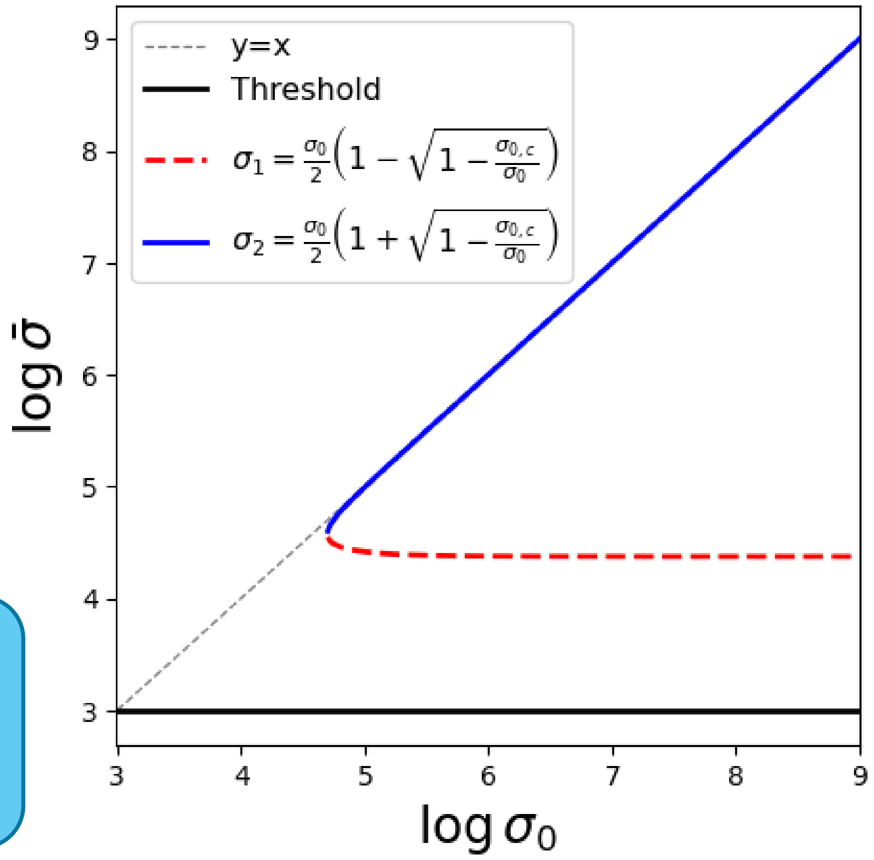
[2] Stawarz & Kirk, 2007

System solutions

We set the derivatives = 0

- Stationary values are denoted with a "‾"
- Heaviside is set = 1, assuming $\bar{\sigma} > \sigma_{thr}$

We find two solutions



Solutions:

$$\sigma_{1,2} = \frac{\sigma_0}{2}\left(1 \pm \sqrt{1 - \frac{\sigma_{0,c}}{\sigma_0}}\right)$$

Critical initial magnetization:

$$\sigma_{0,c} = \frac{3\sqrt{2}}{l_B b \kappa^2}\left(\sqrt{1 + \frac{4\sqrt{2}}{3} f_{rec} l_B} - 1\right)^2$$

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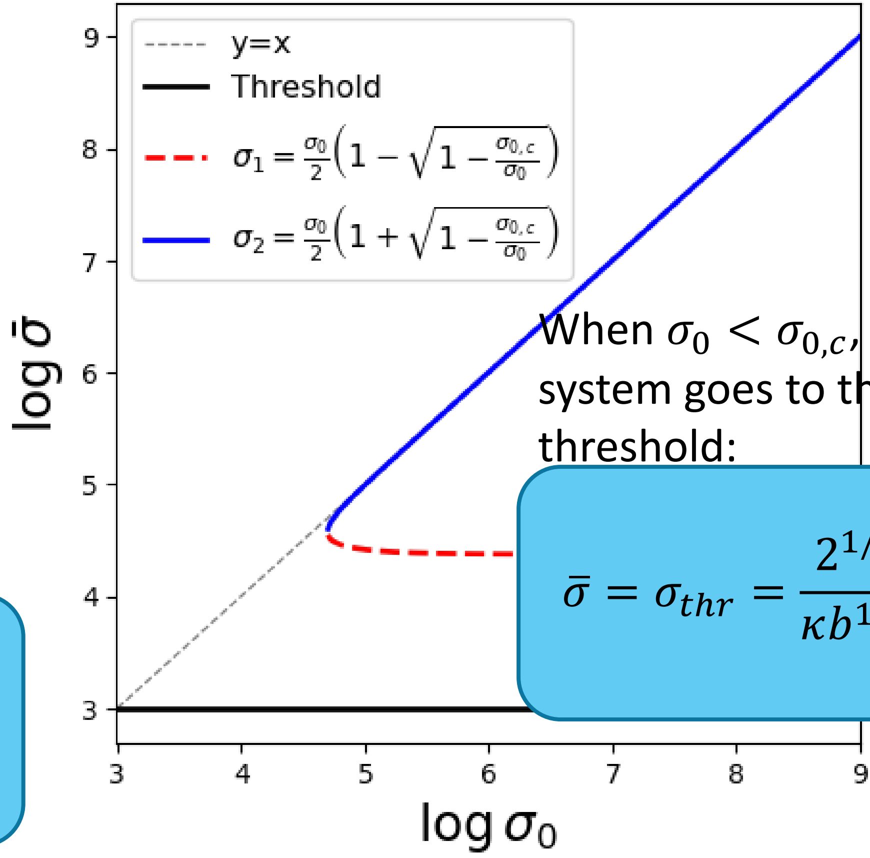


When $\sigma_0 < \sigma_{0,c}$, the system goes to the threshold:

$$\bar{\sigma} = \sigma_{thr} = \frac{2^{1/4}}{\kappa b^{1/2}}$$

Linear analysis – Equilibria classification

Eigenvalue characteristic polynomial:

$$\lambda^3 + \left(\mathcal{R}_{syn} + 3 + c_1\right)\lambda^2 + \left(2\mathcal{R}_{syn} + c_1\mathcal{R}_{syn} + c_1 + 1\right)\lambda + (1 + c_1)\mathcal{R}_{syn} - c_2 = 0$$

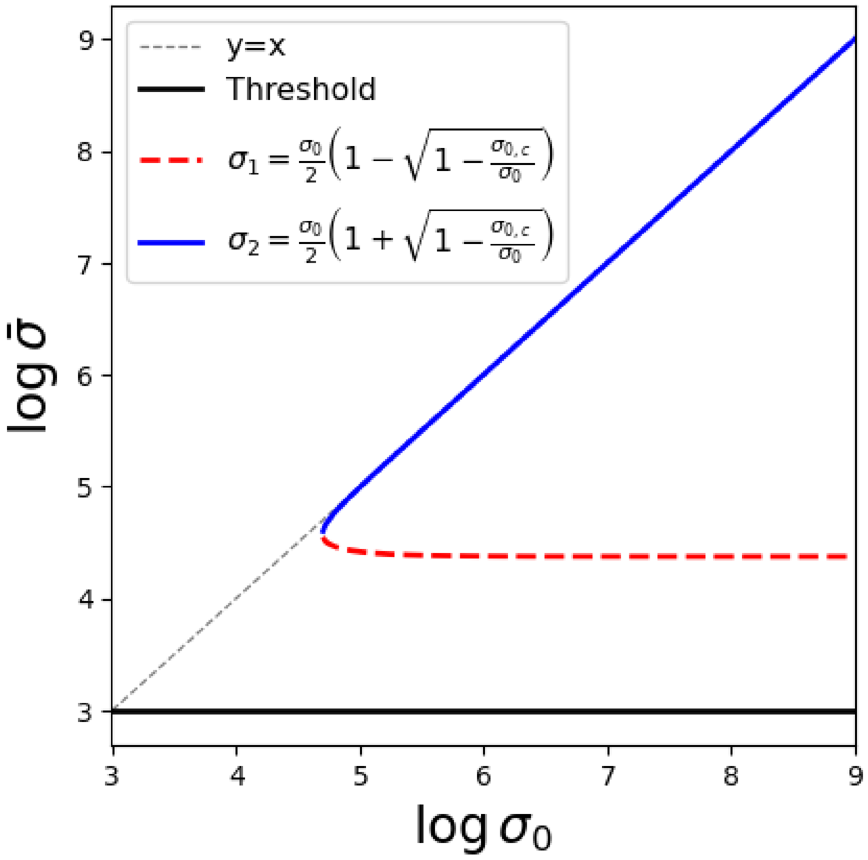
Too complicated to solve analytically

- Although the synchrotron cooling rate R_{syn} is considered large, it is still hard to solve
- $c_1,\ c_2$ depend on the system's parameters
- We rely on a numerical cubic solver

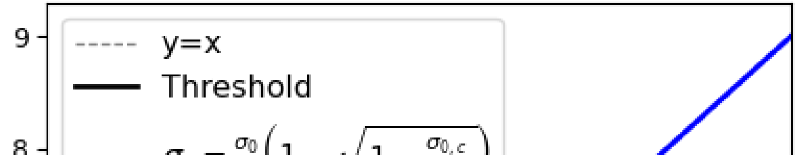
Linear analysis – Equilibria classification

Solution σ_1

- Two negative eigenvalues, one positive $\rightarrow$ saddle point



Linear analysis – Equilibria classification



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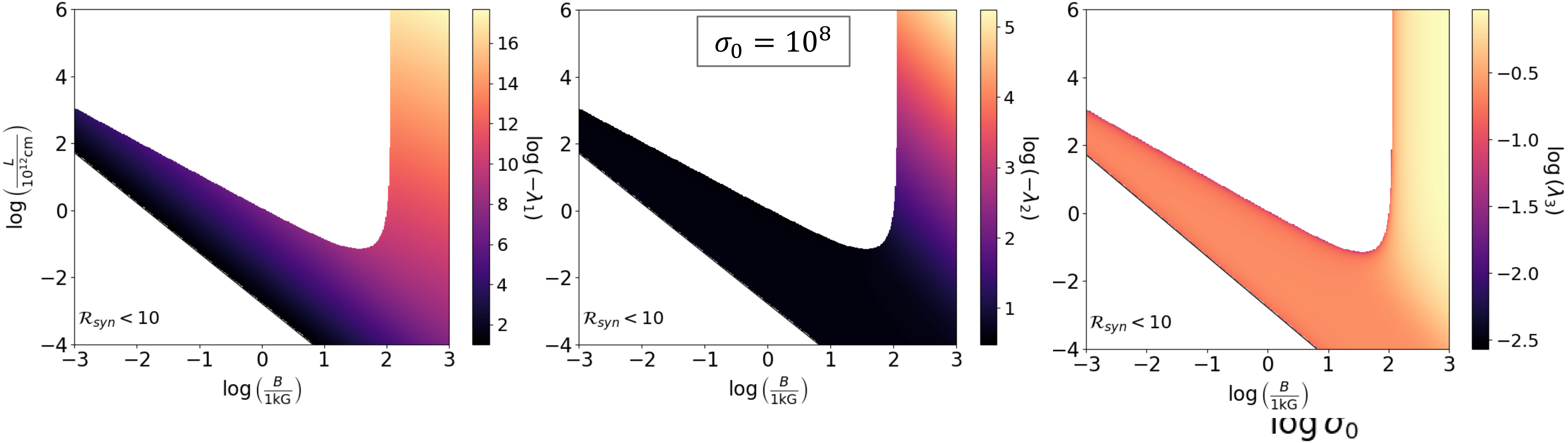


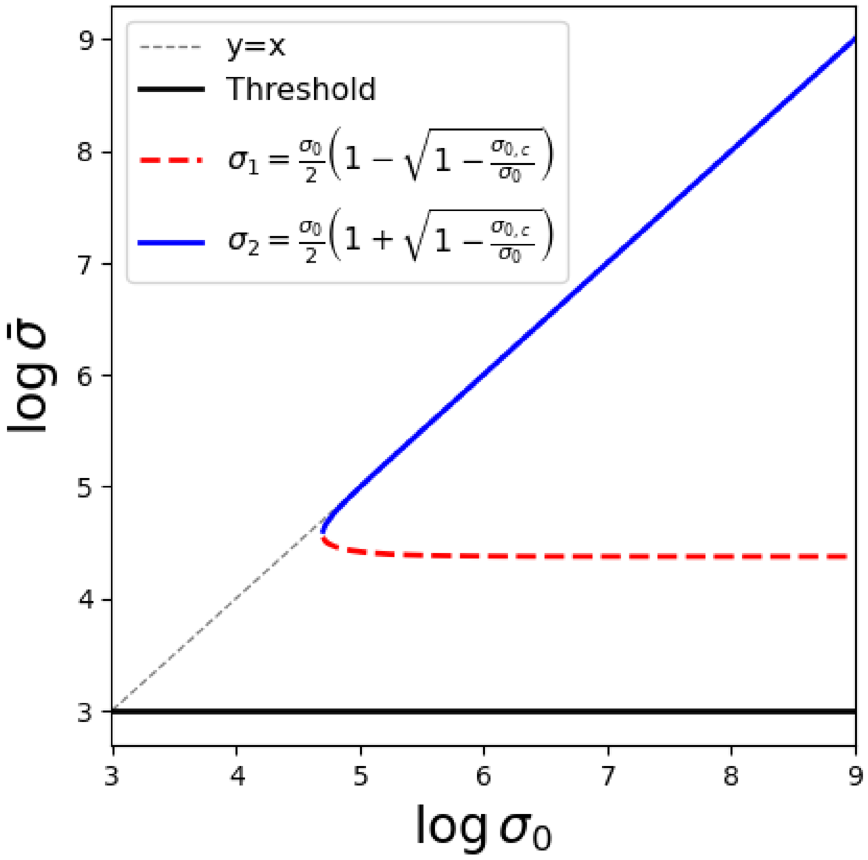
Linear analysis – Equilibria classification

Solution σ_1

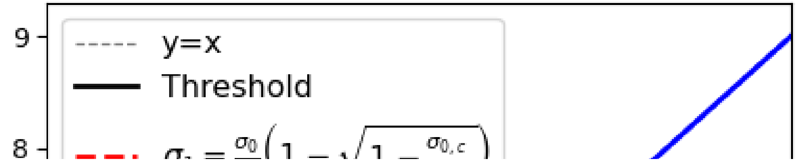
- Two negative eigenvalues, one positive $\rightarrow$ saddle point

Solution σ_2

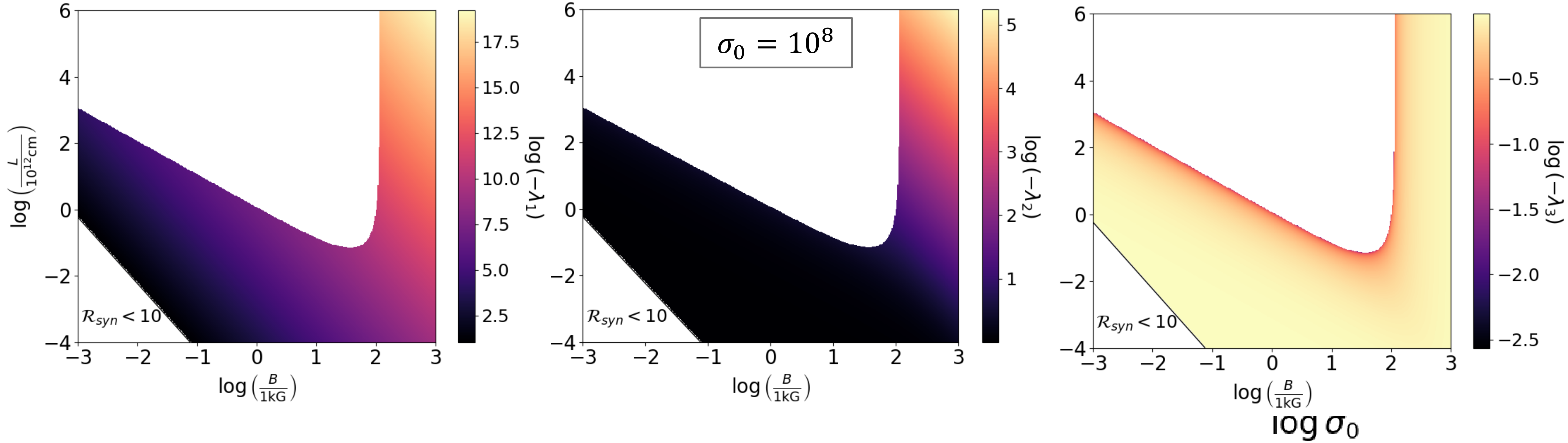
- All three eigenvalues are negative $\rightarrow$ stable point



Linear analysis – Equilibria classification

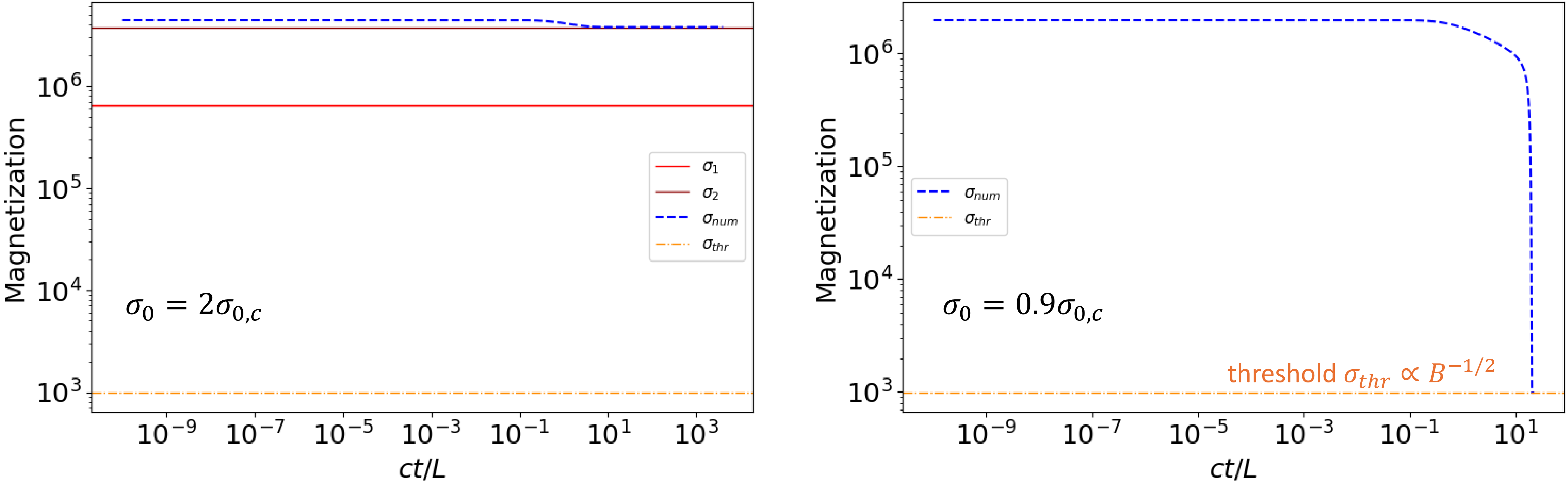


Solution σ_1



Numerical solutions (Crab pulsar LC)

$B \approx 2 \times 10^6 G$
$L \approx 2 \times 10^8 cm$[4]



[4] Uzdensky & Spitkovsky, 2014

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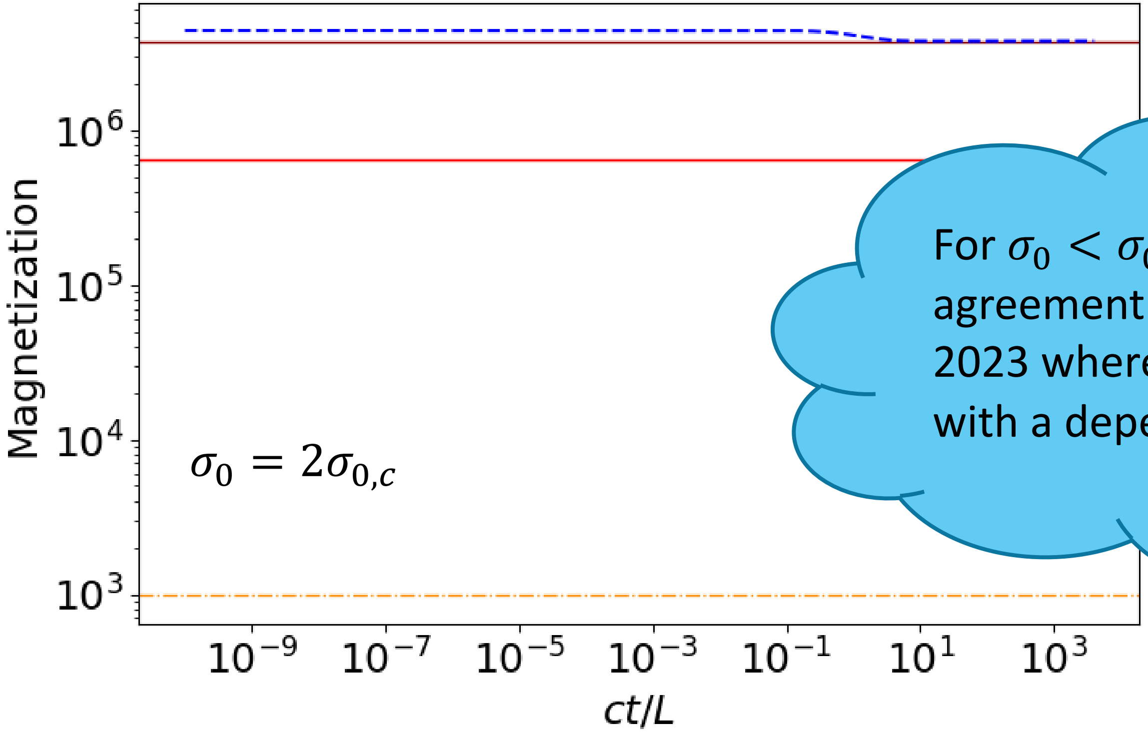
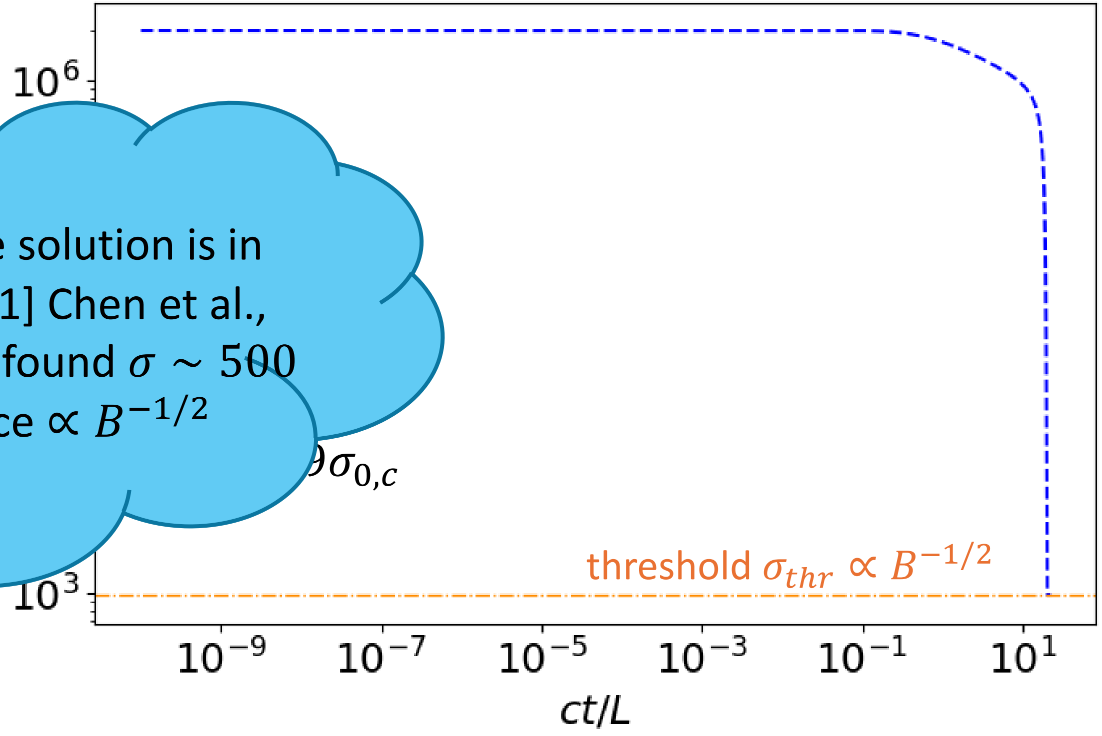


For $\sigma_0 < \sigma_{0,c}$, the solution is in agreement with [1] Chen et al., 2023 where they found $\sigma \sim 500$ with a dependence $\propto B^{-1/2}$



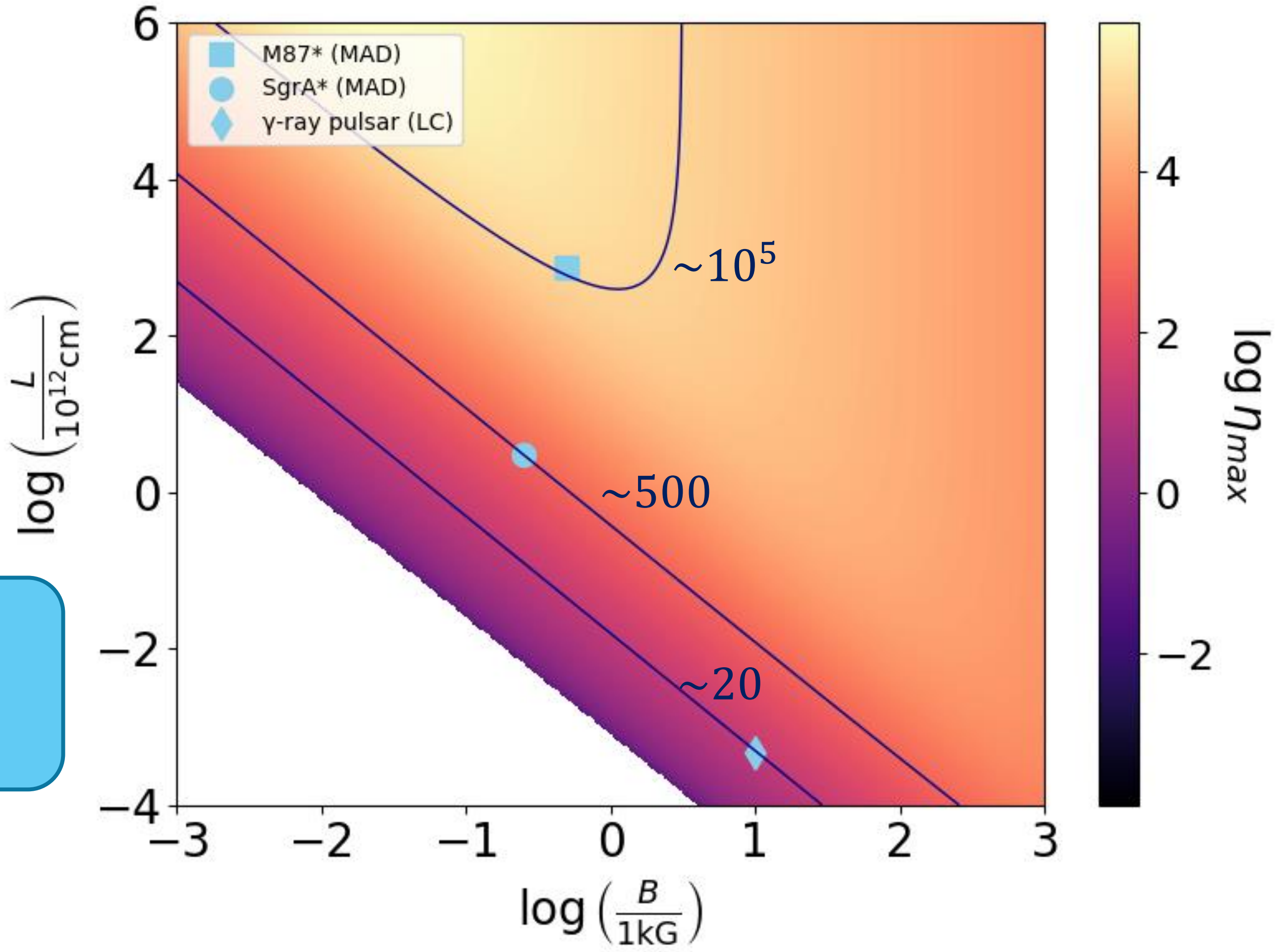
[4] Uzdensky & Spitkovsky, 2014

Pair enrichment

An initial magnetization $\sigma_0 \lesssim \sigma_{0,c}$ leads to the threshold

Maximal pair multiplicity

$$\eta_{max} = \frac{\sigma_{0,c}}{\sigma_{thr}} - 1$$
$$\approx 6 \times 10^6\, \mathcal{B}^{-5/2} \mathcal{L}^{-1} \left(\sqrt{1 + 0.03\mathcal{B}^2\mathcal{L}} - 1\right)^2$$



Conclusions

Using a monoenergetic approach we found two stationary solutions (+ threshold)

- System prefers the stable root $\sigma_2 \sim \sigma_0$ over σ_1

A very high (initial) magnetization ($\sigma_0 > \sigma_{0,c}$) doesn't increase the pairs significantly

- Pair enrichment is limited: $\eta \sim \frac{\sigma_0}{\sigma_2} - 1 \ll 1$

Below critical magnetization, system drops to threshold

- This solution is in agreement with Chen et al., 2023
- Defines a maximal pair multiplicity $\eta_{max} \approx 6 \times 10^6\, \mathcal{B}^{-5/2}\mathcal{L}^{-1}\left(\sqrt{1 + 0.03\mathcal{B}^2\mathcal{L}} - 1\right)^2$

Thank you!

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Questions?

References:

[1] Chen et al., 2023
[2] Stawarz and Kirk, 2007
[3] Filippov A. F., 1988
[4] Uzdensky & Spitkovsky, 2014
[5] Stathopoulos et al., 2024

Backup slide

$$B_{LC} \simeq 3 \times 10^4 G \left(\frac{M_*}{1.4 M_\odot}\right)^{1/2} \left(\frac{R_*}{10km}\right) \left(\frac{\dot{P}}{10^{-13}}\right)^{1/2} \left(\frac{P}{0.1sec}\right)^{-5/2}$$ [4] $L \sim R_{LC}$

$$B_{MAD} \simeq 500G \frac{\dot{m}_{-5}^{1/2} \left(M_9 \eta_{c,-1}\right)^{-1/2}}{f^2(a_s)}$$ [5] $L \sim$ a few R_g

[4] e.g., Uzdensky & Spitkovsky, 2014
[5] Stathopoulos et al., 2024