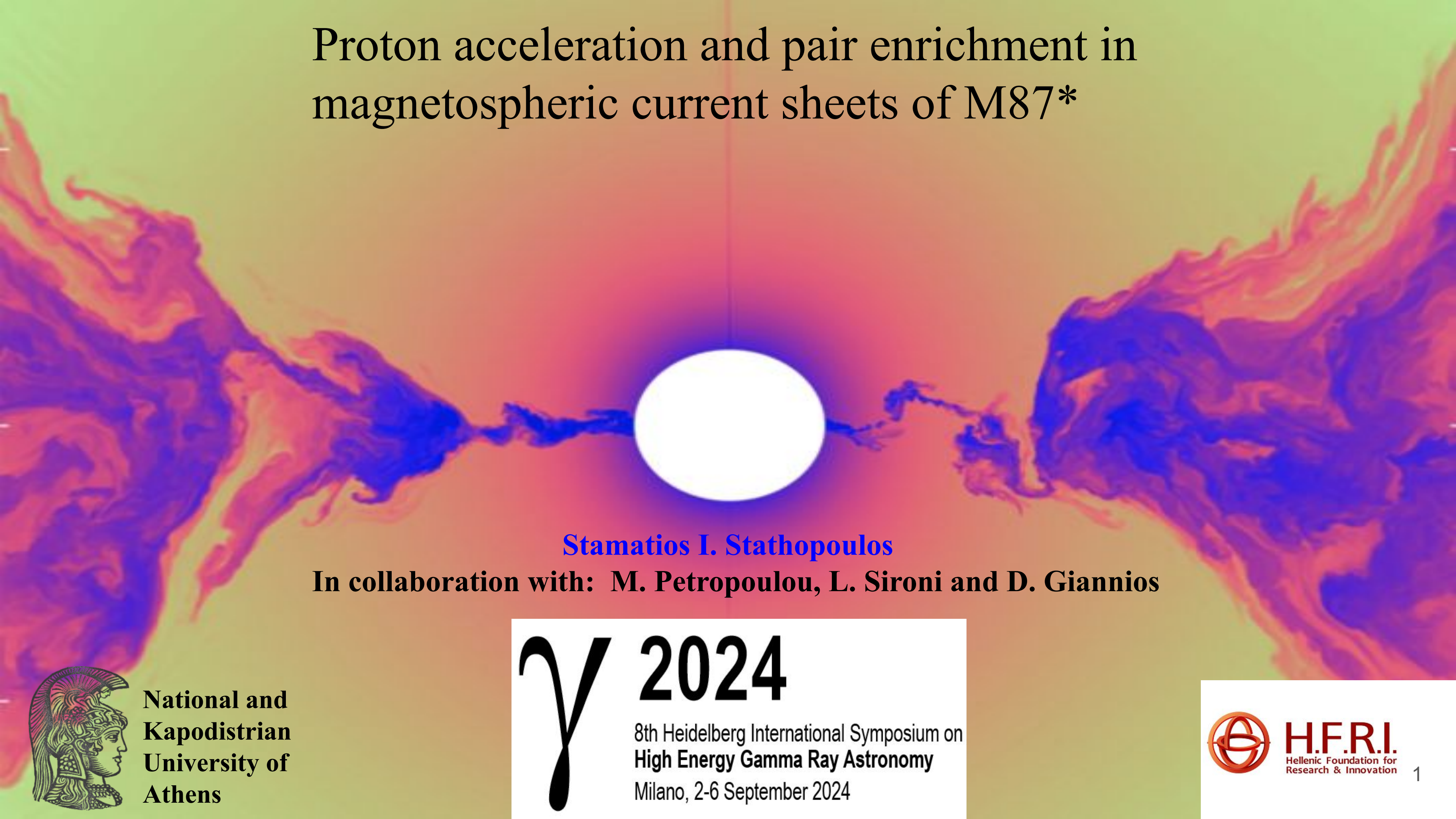

Proton acceleration and pair enrichment in magnetospheric current sheets of M87*

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In collaboration with: M. Petropoulou, L. Sironi and D. Giannios

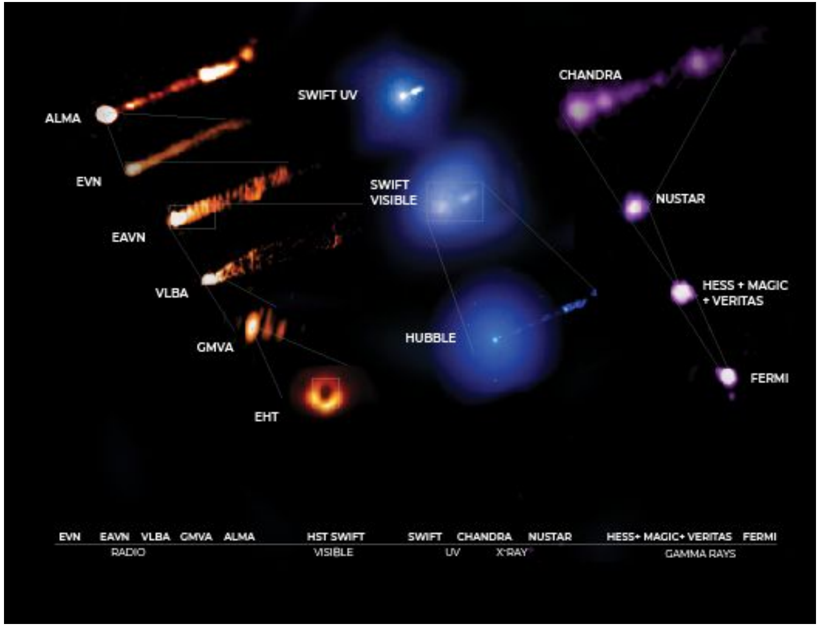
γ 2024

8th Heidelberg International Symposium on
High Energy Gamma Ray Astronomy
Milano, 2-6 September 2024

National and Kapodistrian University of Athens

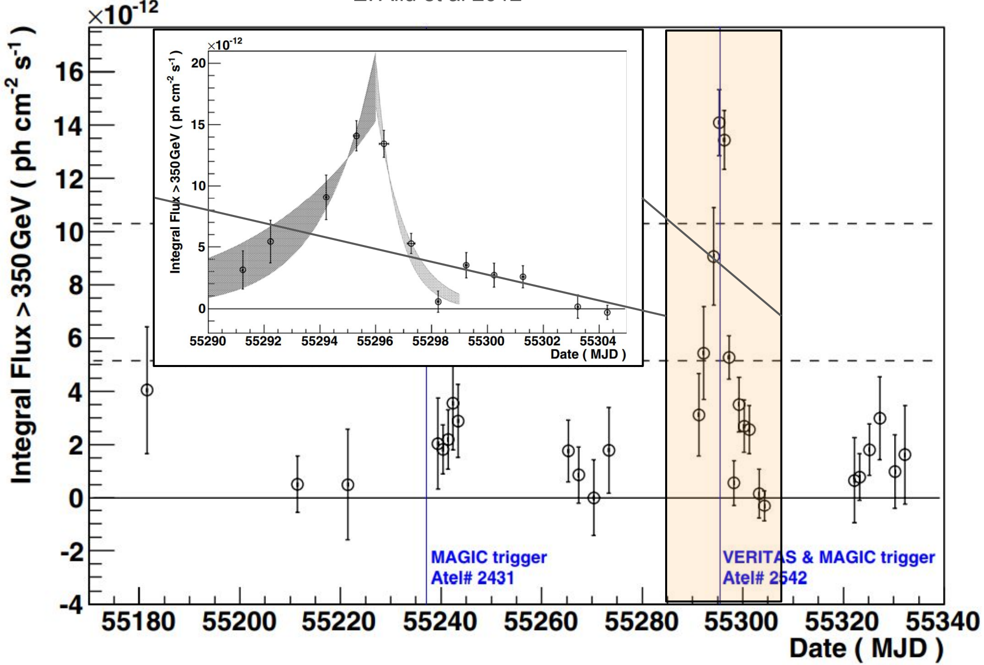
H.F.R.I.
Hellenic Foundation for Research & Innovation

M87* Emission & Variability



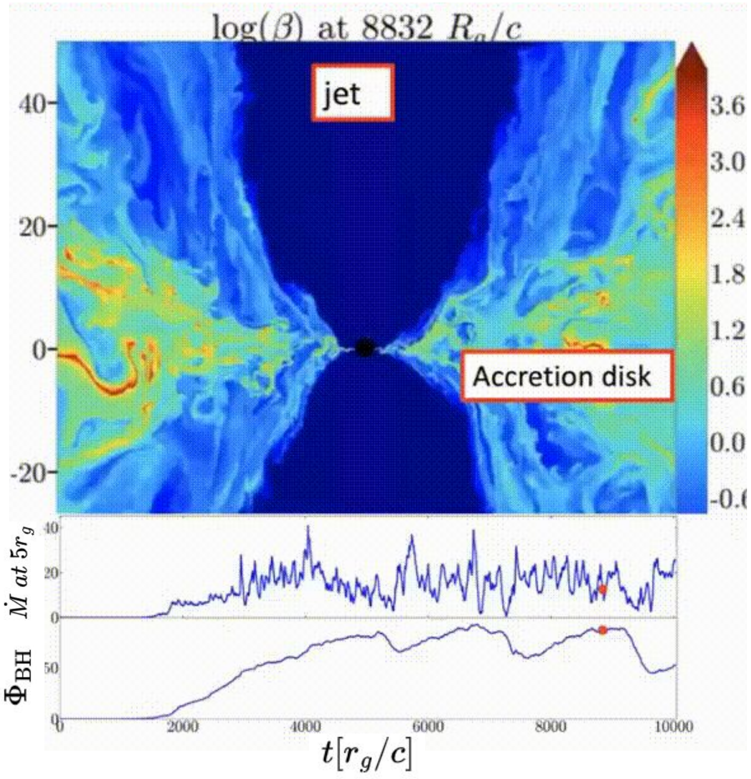
Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA.

E. Aliu et al 2012



1. Variability: Δt~1-3 d~R_g/c
2. Non-thermal emission suggests particle acceleration
3. EHT obs: Magnetically arrested state

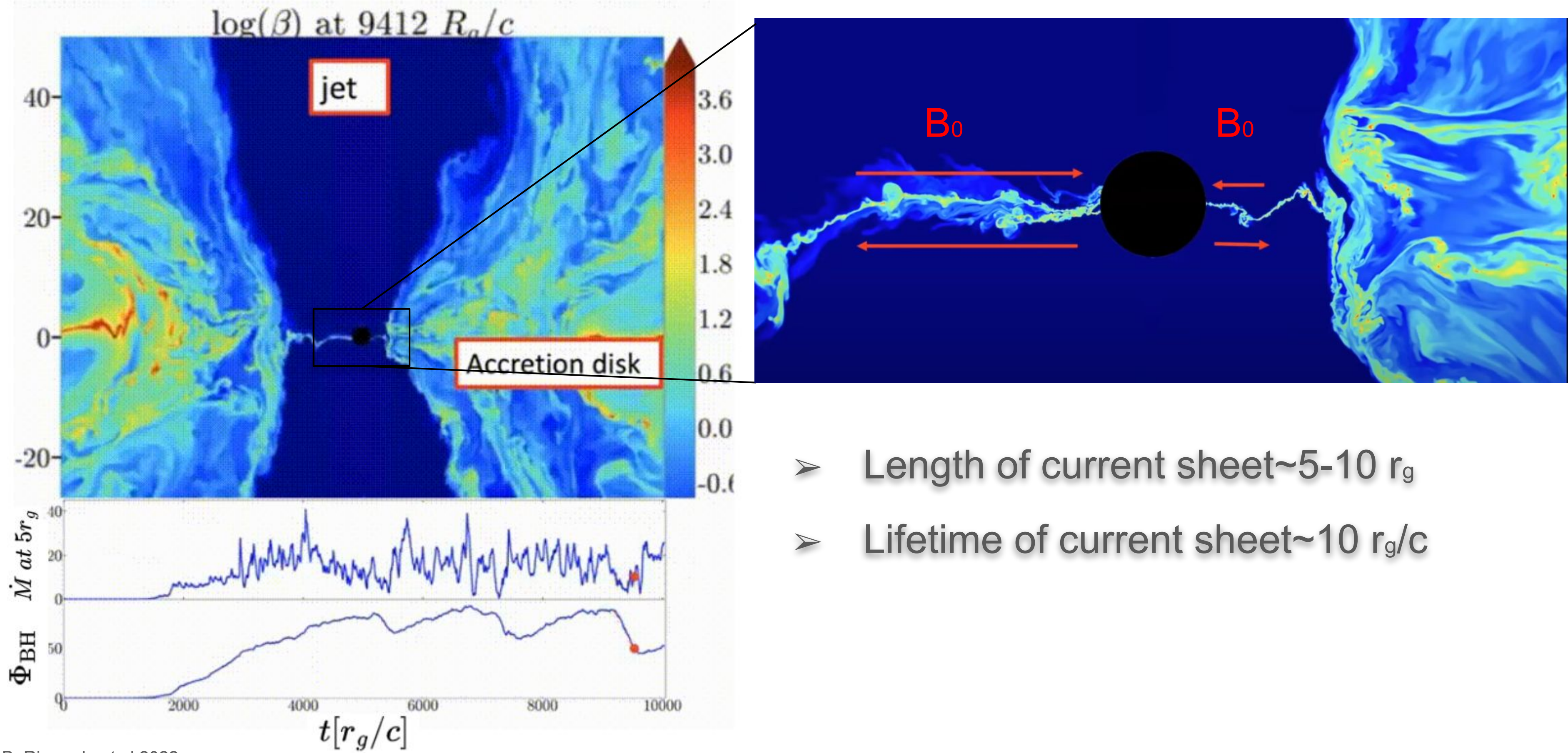
M87* Results from 3D GRMHD simulations



1. Accumulation of magnetic flux in the horizon.
2. Magnetic force balances the inward gravitational force.
3. Periodic eruptions of magnetic flux from the SMBH into the disk.
4. These eruptions are associated with magnetic reconnection (equatorial current sheet).

B. Ripperda et al 2022

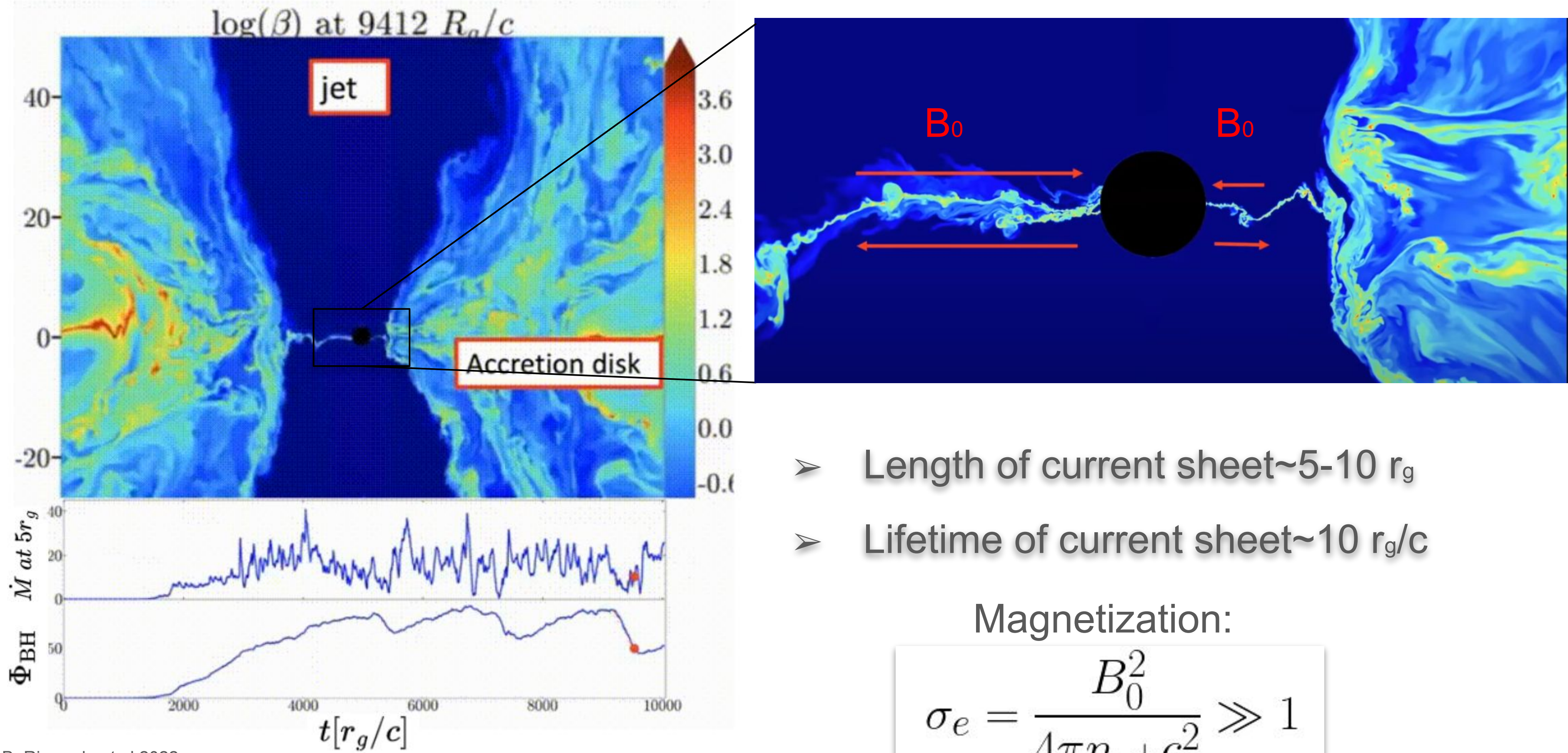
M87* Results from GRMHD simulations



- Length of current sheet~5-10 r_g
- Lifetime of current sheet~10 r_g/c

B. Ripperda et al 2022

M87* Results from GRMHD simulations



B. Ripperda et al 2022

- Length of current sheet~5-10 r_g
- Lifetime of current sheet~10 r_g/c

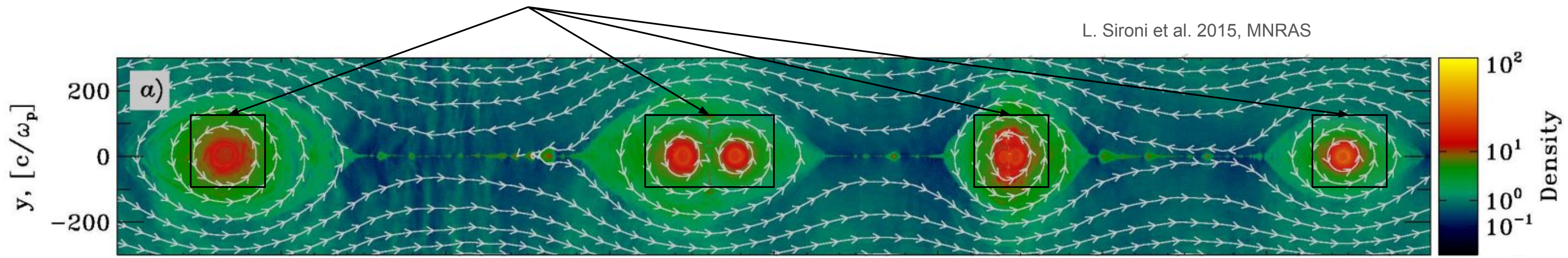
Magnetization:

$$\sigma_e = \frac{B_0^2}{4\pi n_{e\pm} c^2} \gg 1$$

Magnetic reconnection in 2D (PIC simulations)

Reconnection layer tears up into plasmoids

L. Sironi et al. 2015, MNRAS



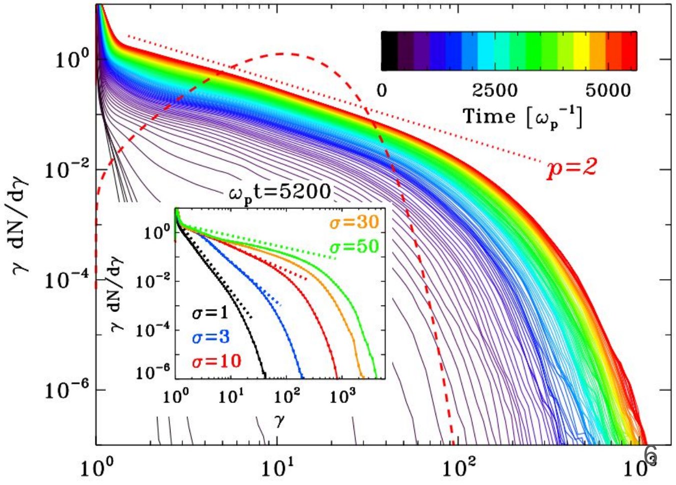
Plasmoids advect and merge with other plasmoids

Pairs accelerate to power law distributions up to $\gamma \sim \sigma_e$

Acceleration in regions with non ideal electric field

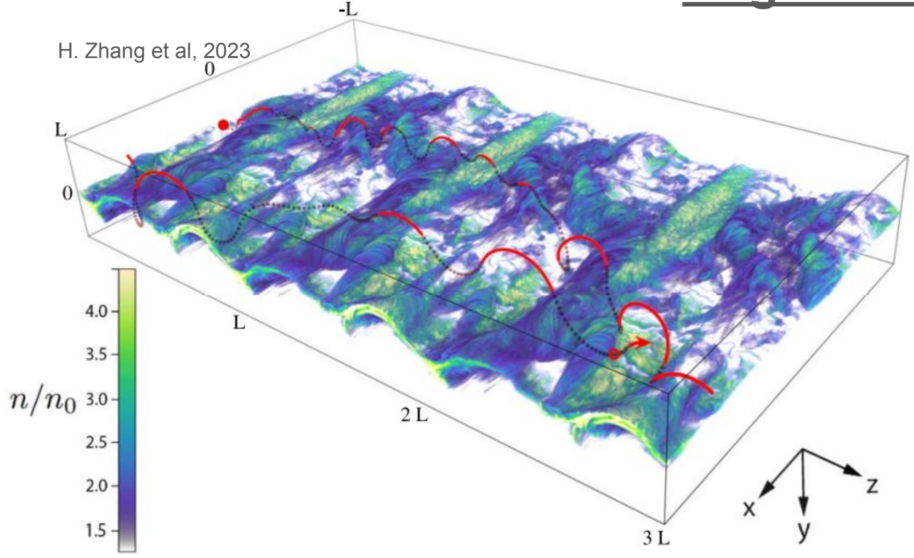
$$E \neq -\frac{v}{c} \times B$$

or curvature-drift a.o.



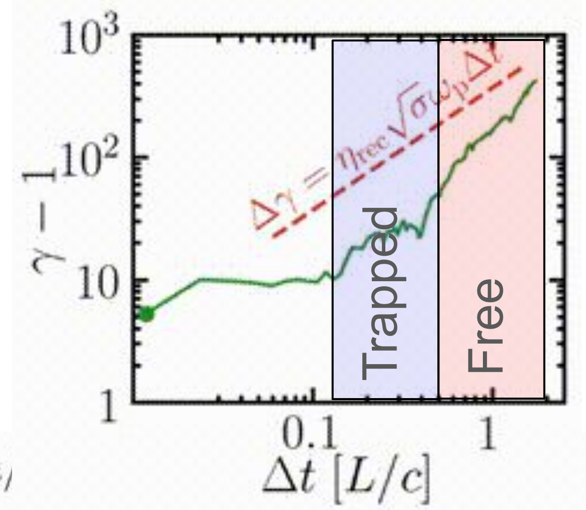
Sironi & Spitkovsky, 2014

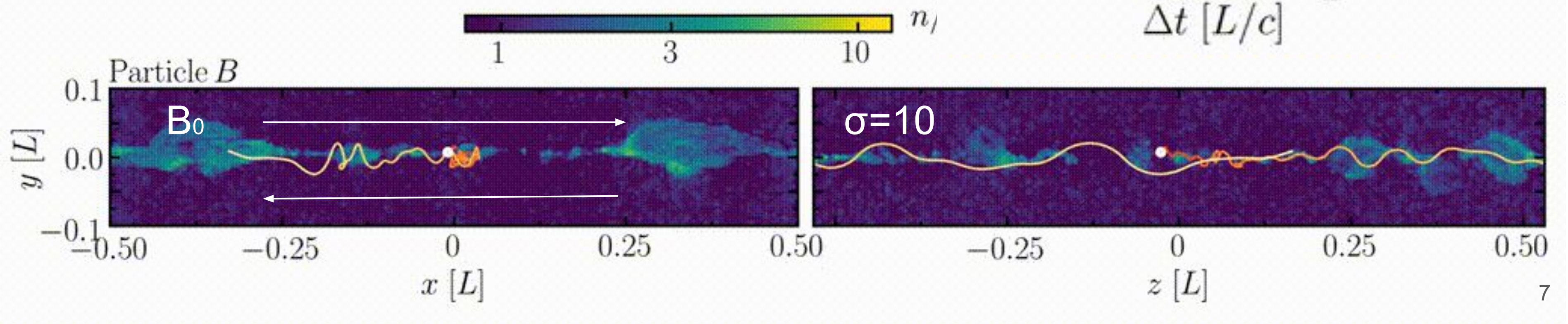
Magnetic reconnection in 3D



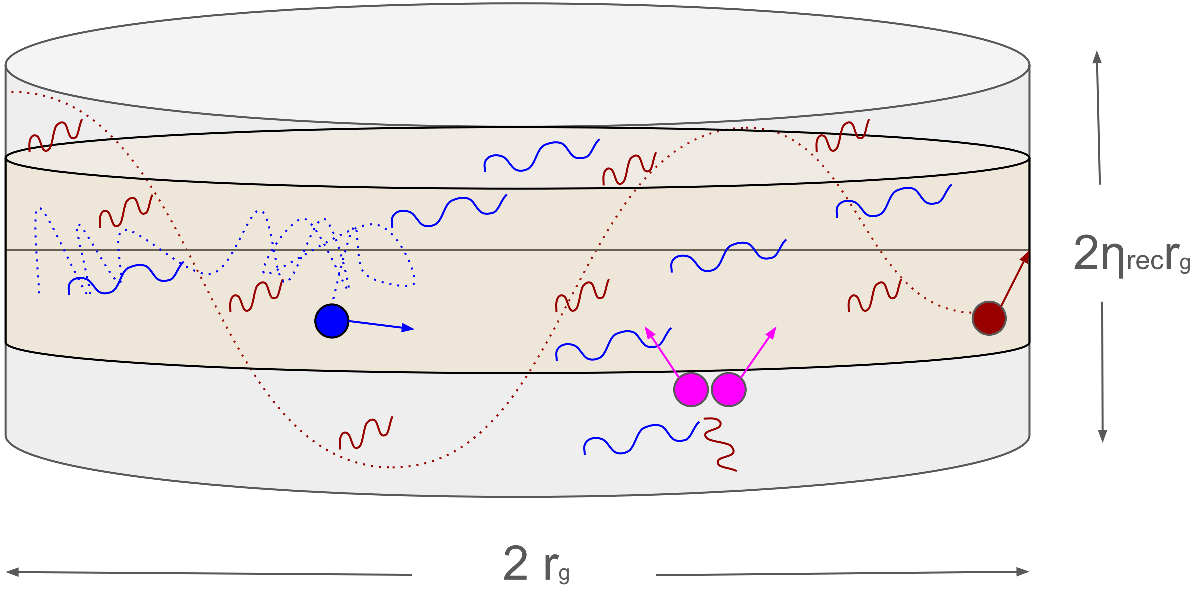
H. Zhang et al, 2021

Particles can accelerate beyond γ~σ in the upstream electric field





Current sheet of M87* (Model description)



Free parameters

- Accretion rate: $\dot{m} \in [10^{-6}, 10^{-5}]$
- Pair magnetization: $\sigma_e \in [10, 10^6]$

Assumption

MAD regime: $\phi_{BH} = \Phi_{BH}/\sqrt{\dot{M} c r_g^2} \simeq 50$

$$B_0 \simeq 5 \cdot 10^2\ \mathrm{G}\ \frac{\dot{m}_{-5}^{1/2}(M_9 \eta_{c,-1})^{-1/2}}{f^2(a_s)}$$

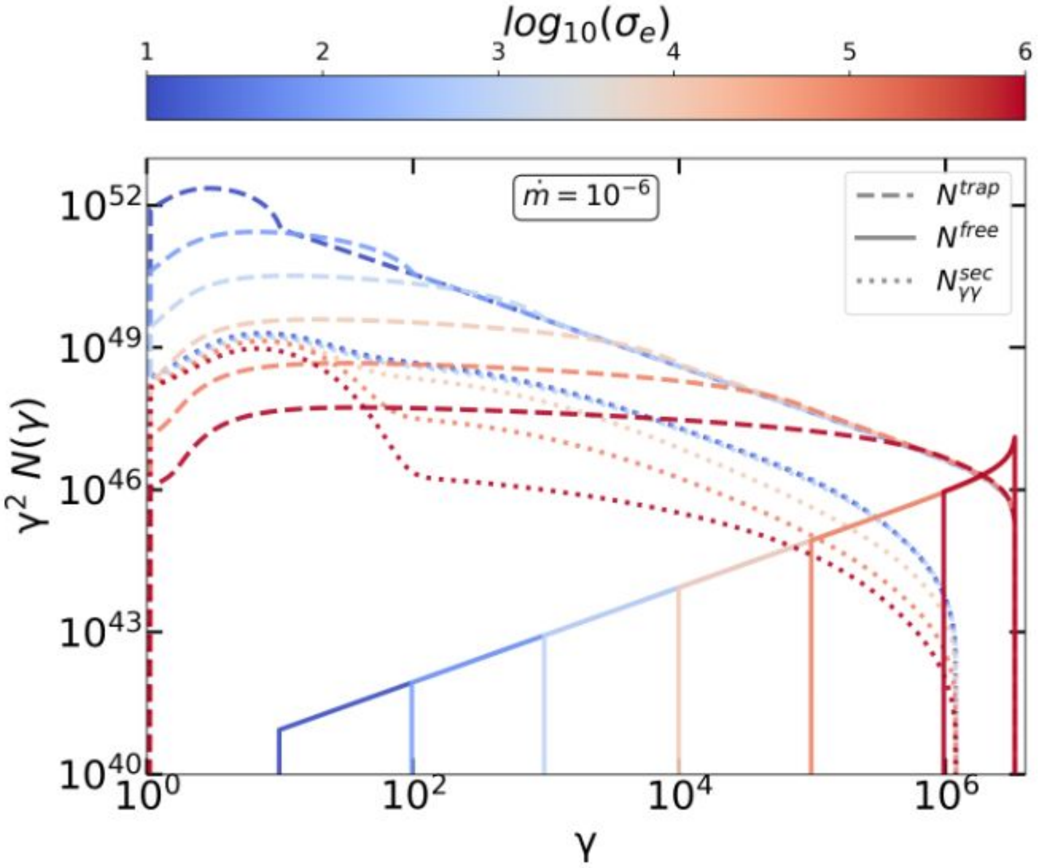
Pairs distribution in the current sheet M87*

Pair & photon distributions were calculated using **LeHaMoC**

Free pairs: Accelerated in the upstream region from $\sigma_e<\gamma<\gamma_{rad}$. (solid)

Trapped pairs: Accelerated in the downstream region from non ideal E $1<\gamma<\sigma_e$ or escaped from the upstream region. (dashed)

Secondary pairs: Produced from $\gamma\gamma$ absorption. (dotted)



Stathopoulos et al. 2024, arXiv:2406.01211

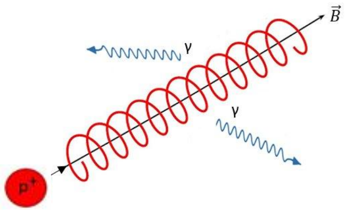
Proton acceleration in M87* current sheets

Maximum available energy in the current sheet:

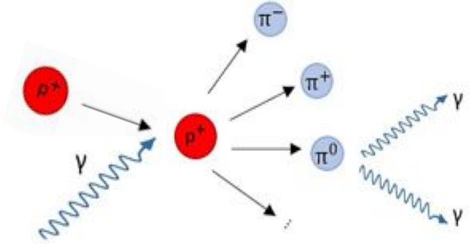
$$E_{\rm p,max}^{\rm (acc)} \simeq \underbrace{e\eta_{\rm rec}B_0 l}_{E_{rec}} \simeq 4\ {\rm EeV}\ \frac{\eta_{\rm rec,-1}(\dot{m}_{-5}M_9)^{1/2}\mathcal{R}_0\eta_{\rm c,-1}^{-1/2}}{f^2(a_{\rm s})}$$

Protons lose energy from

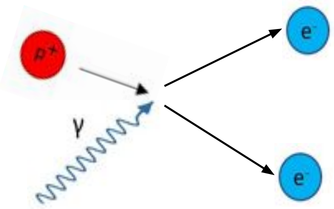
Synchrotron



Photopion



Bethe-Heitler



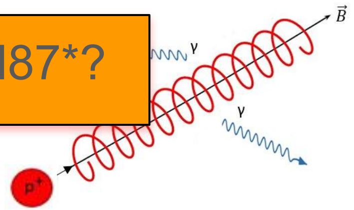
Proton acceleration in M87* current sheets

Maximum available energy in the current sheet:

$$E_{\mathrm{p,max}}^{(\mathrm{acc})} \simeq \underbrace{e\eta_{\mathrm{rec}}B_0 l}_{E_{\mathrm{rec}}} \simeq 4\ \mathrm{EeV}\ \frac{\eta_{\mathrm{rec},-1}(\dot{m}_{-5}M_9)^{1/2}\mathcal{R}_0\eta_{\mathrm{c},-1}^{-1/2}}{f^2(a_{\mathrm{s}})}$$

What are the target photon fields in M87*?

Protons lose energy from



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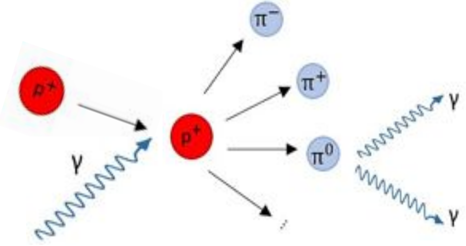
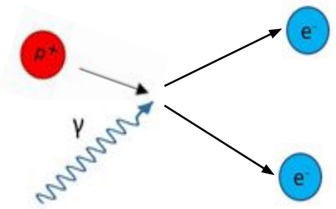


Bethe-Heitler

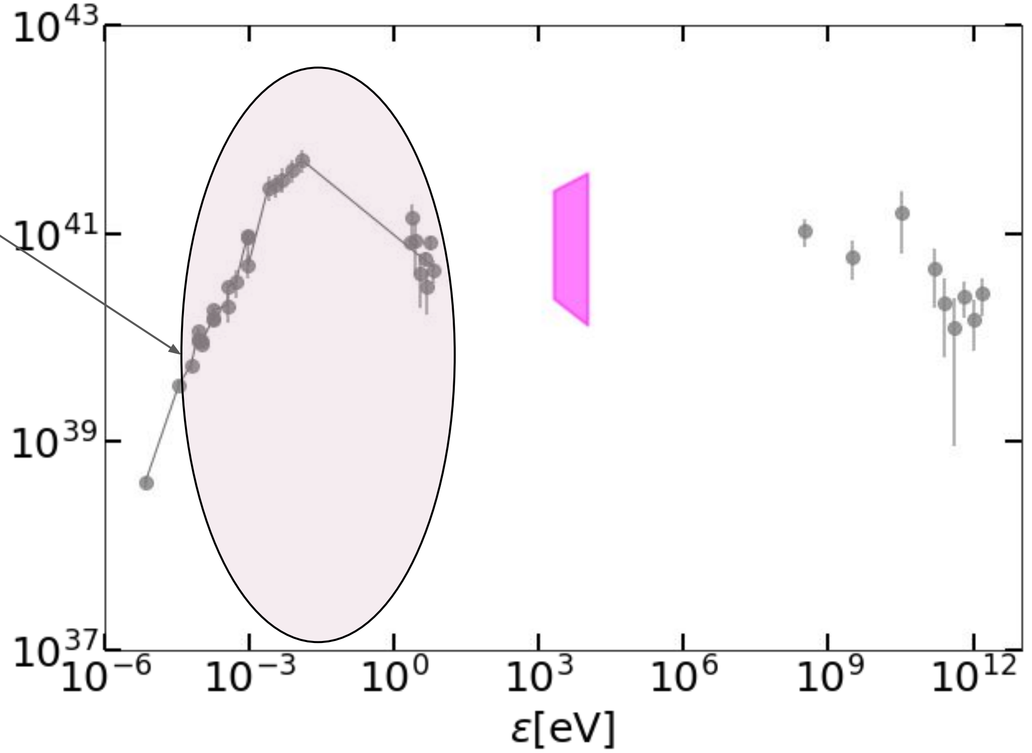


Proton acceleration M87* (photon fields)

Disk photon field

Synchrotron emission from thermal electrons

Emission from $R < 7r_g$



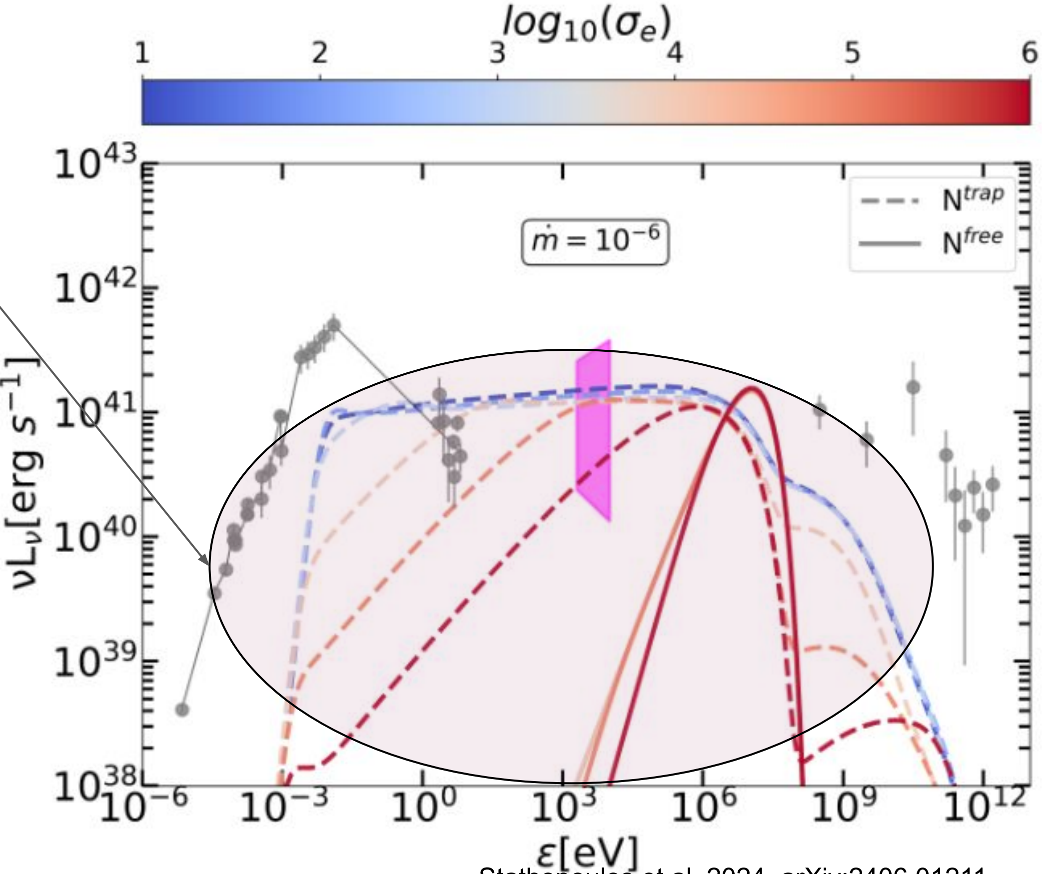
Proton acceleration M87* (photon fields)

Non-thermal photon field

Low energy targets <eV depend on σ_e

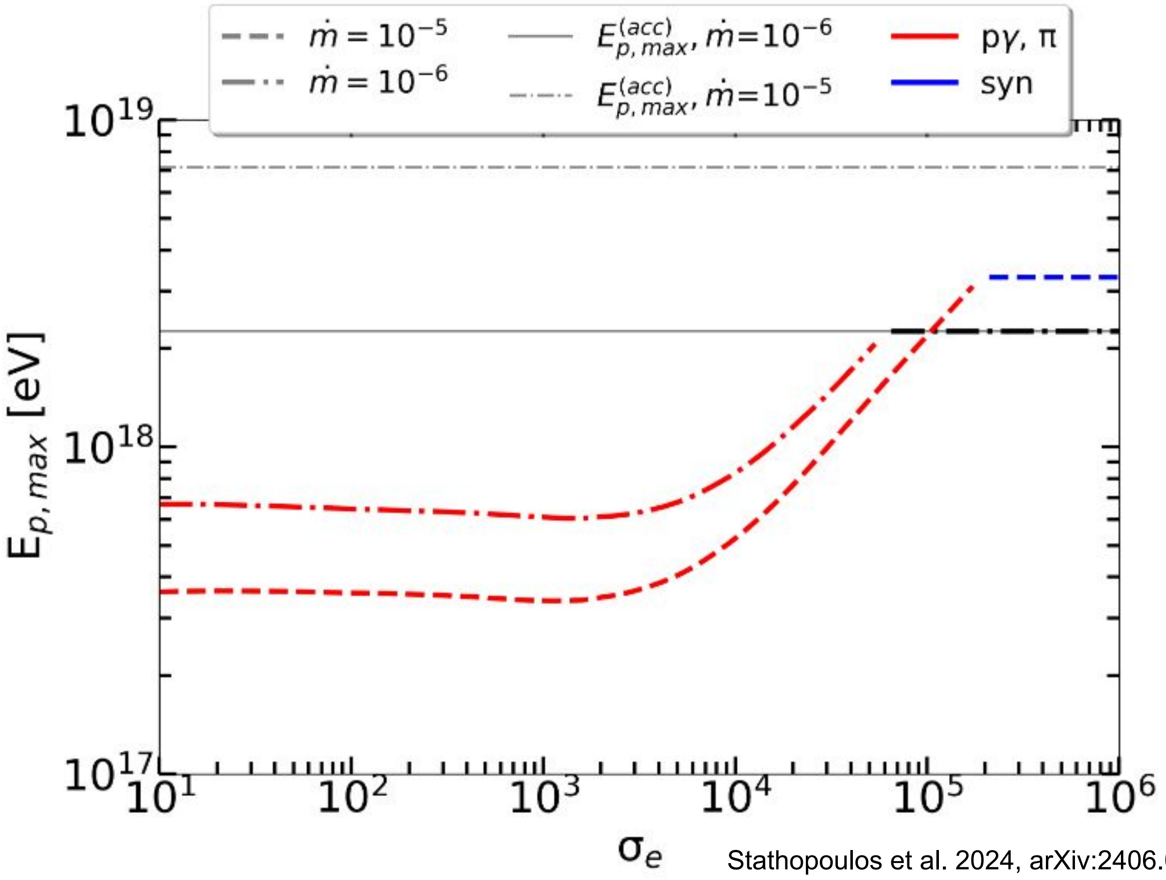
Free pairs emit synchrotron photons in the burn-off limit ~10 MeV

IC emission is minimal compared to the synchrotron emission (depends on σ_e)



Stathopoulos et al. 2024, arXiv:2406.01211

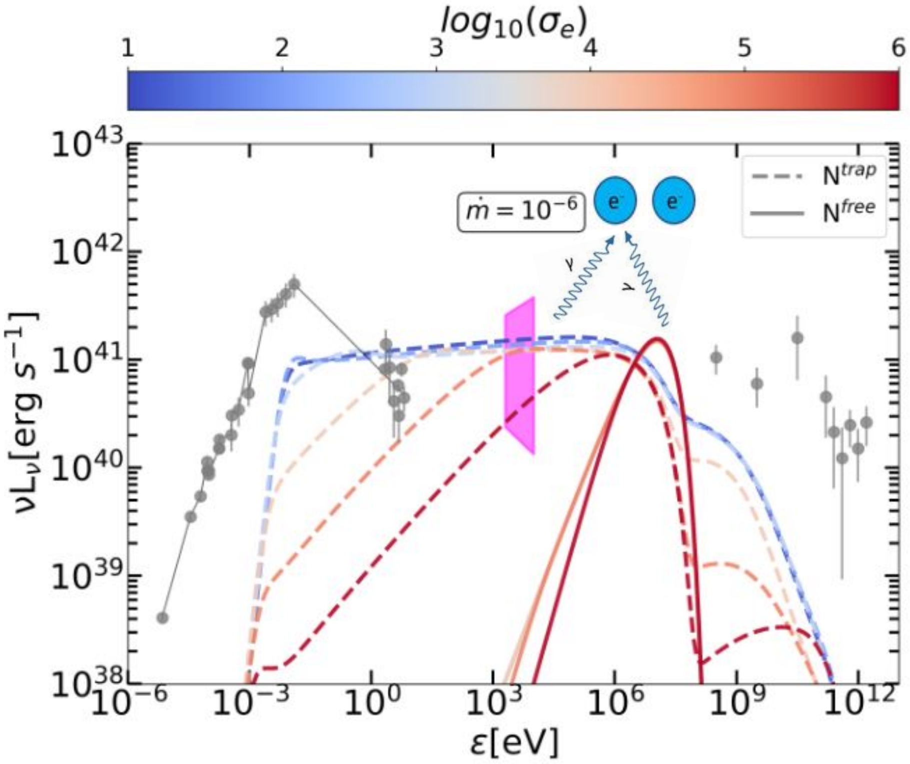
Maximum energy of protons in M87*



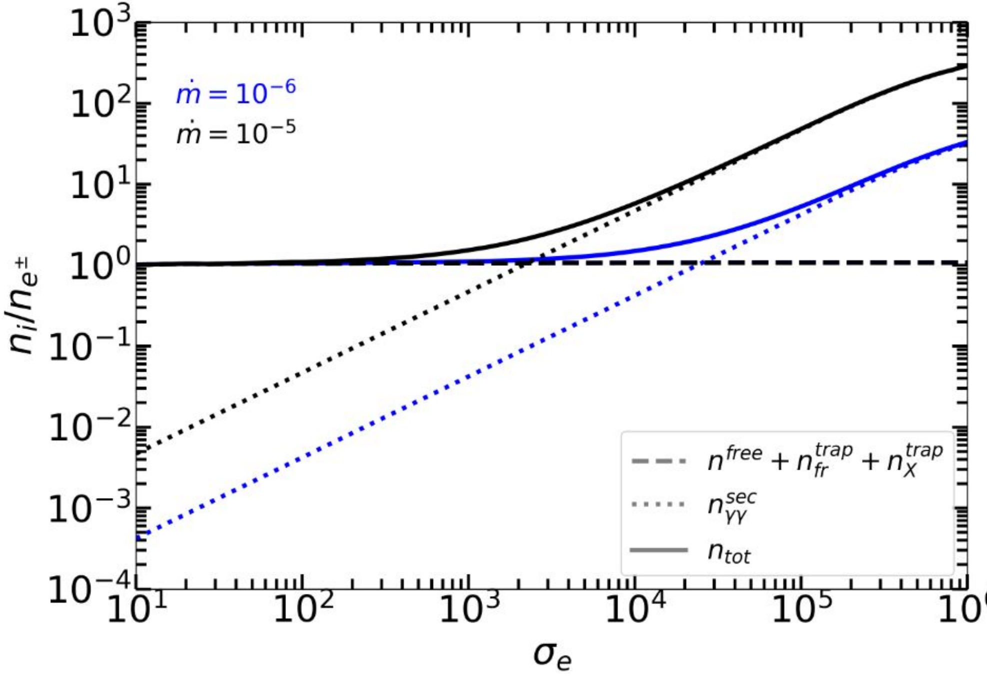
Stathopoulos et al. 2024, arXiv:2406.01211

Pair enrichment in M87*

10 MeV photons produced from the free pairs can be absorbed from lower energy photons



$$\sigma_e = \frac{B_0^2}{4\pi n_{e^\pm} c^2}$$



Stathopoulos et al. 2024, arXiv:2406.01211

Conclusions

- Proton acceleration ~EeV energies
- Pair enrichment - σ_e modification
- X-ray and MeV flares in magnetospheric currents sheets M87*

Future plans

- Include a proton population in the current sheet (motivated by PIC simulations).
- Account for anisotropic effects in the pair distributions.
- Provide a more accurate calculation of pair production (geometric effects).

Thank you !

Backup slides

Model description (Injection of particles)

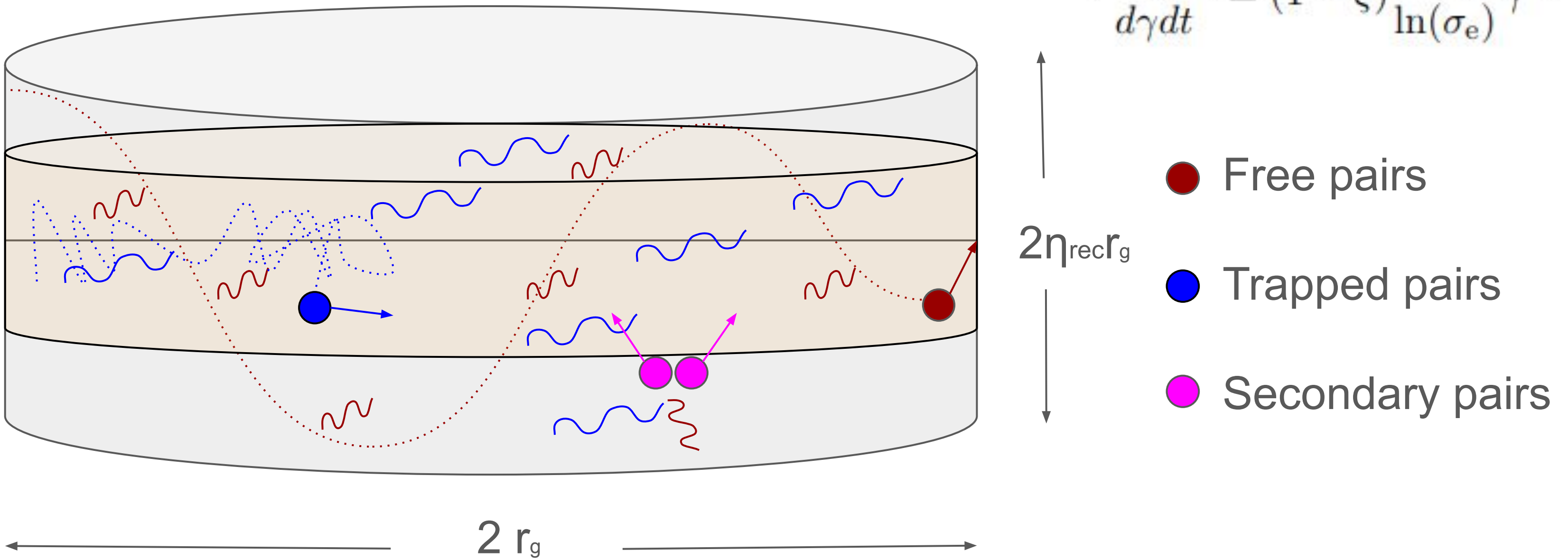
$$Q^{\rm tot}_{\rm e,inj} = 2 n_{\rm e\pm} \eta_{\rm rec} c A$$

$$\eta_{\rm rec} = v_{\rm rec}/c \sim 0.06$$

$$\frac{\partial N^{\rm free}}{\partial t} + \frac{\partial}{\partial \gamma}\left((\dot{\gamma}_{\rm acc} + \dot{\gamma}_{\rm syn}) N^{\rm free} \right) + \frac{N^{\rm free}}{t^{\rm fr}_{\rm esc}(\gamma)} = \zeta Q^{\rm tot}_{\rm e,inj} \delta(\gamma - \gamma_{\rm inj}),$$

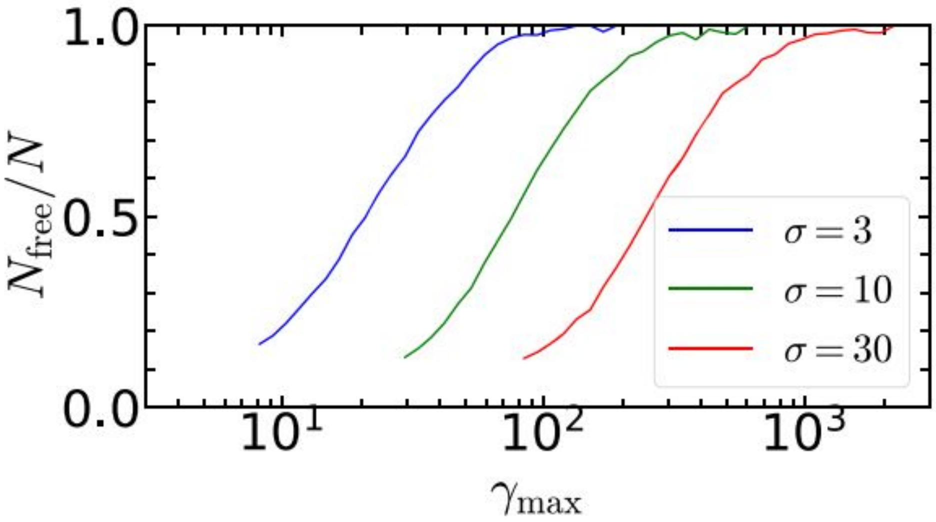
$$\frac{dN^{\rm trap}_{\rm fr}}{d\gamma dt} \simeq \frac{1}{t^{\rm fr}_{\rm esc}(\gamma)} \frac{dN^{\rm free}}{d\gamma} \simeq Q^{\rm free}_{\rm e,inj} \gamma_{\rm inj} \gamma^{-2}$$

$$\frac{dN^{\rm trap}_{\rm X}}{d\gamma dt} = (1-\zeta) \frac{Q^{\rm tot}_{\rm e,inj}}{\ln(\sigma_{\rm e})} \gamma^{-1}$$



Fraction of free to trapped pairs

H. Zhang et al, 2023



Around 20-30% of the pairs with $\gamma \sim \sigma_e$ are in the free phase of acceleration.

$$N^{\rm free}(\gamma) = \zeta Q^{\rm tot}_{\rm e,inj} \gamma^{-1} t_{\rm acc}(\gamma),\ \gamma \geq \gamma_{\rm inj}$$

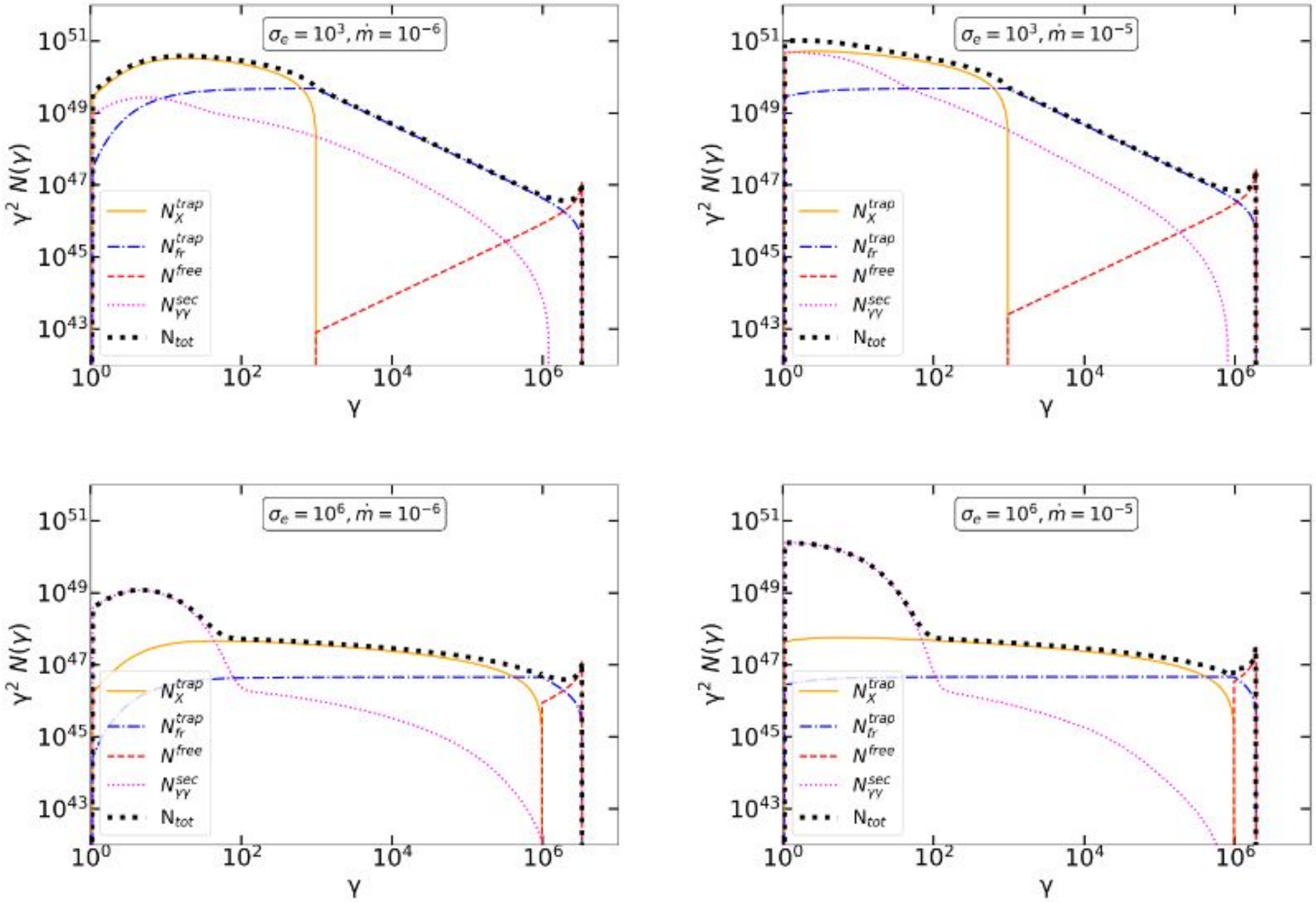
$$N^{\rm trap}_{\rm fr}(\gamma) = \zeta Q^{\rm tot}_{\rm e,inj} \gamma^{-2} \gamma_{\rm inj} t_{\rm adv},\ \gamma \geq \gamma_{\rm inj}$$

$$N^{\rm trap}_{\rm X}(\gamma) = (1-\zeta) \frac{Q^{\rm tot}_{\rm e,inj}}{\ln(\sigma_{\rm e})} \gamma^{-1} t_{\rm adv},\ \gamma \leq \gamma_{\rm inj}$$

$$\xi \equiv \frac{\left[\gamma N^{\rm free}(\gamma) + \gamma N^{\rm trap}_{\rm fr}(\gamma)\right]_{\gamma=\gamma_{\rm inj}}}{\left[\gamma N_{\rm tot}(\gamma)\right]_{\gamma=\gamma_{\rm inj}}}$$

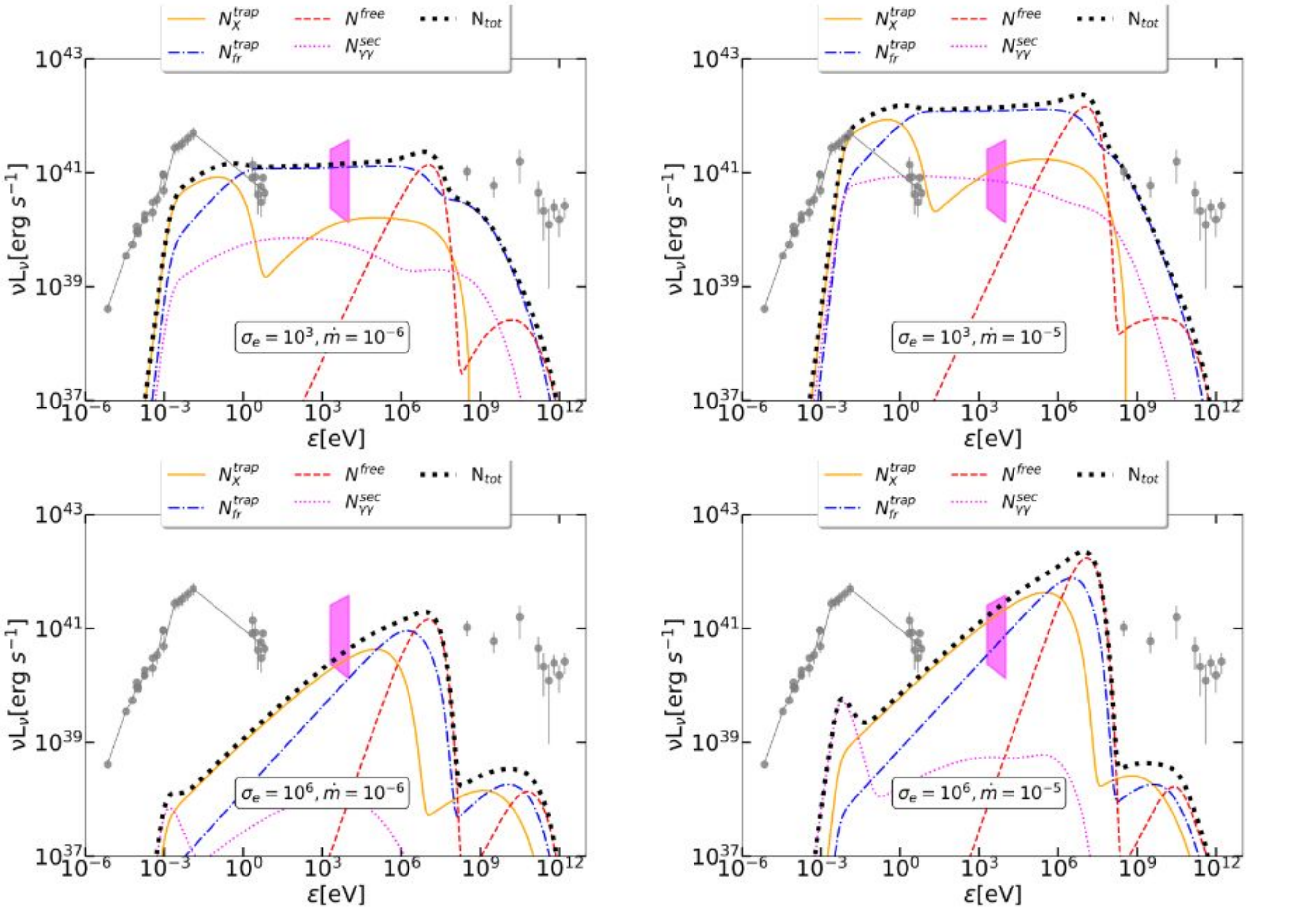
Stathopoulos et al. 2024, arXiv:2406.01211

Pair spectrum

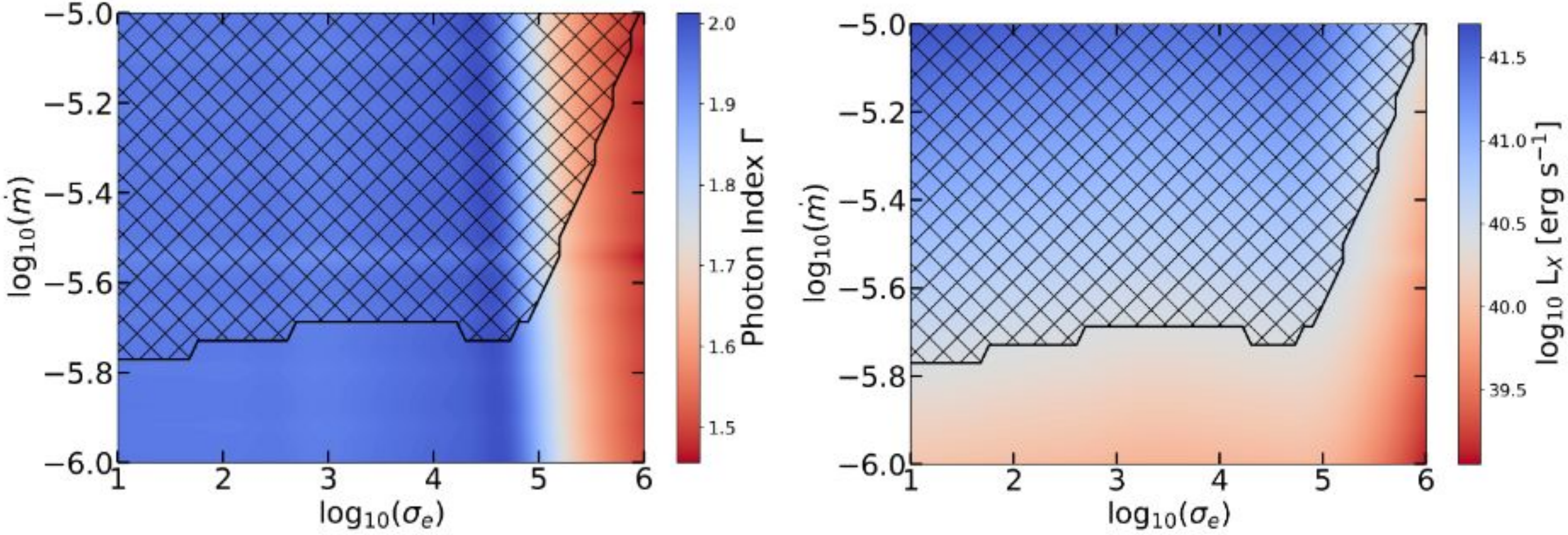


Photon spectrum

Stathopoulos et al. 2024, arXiv:2406.01211



Model parameters vs X-ray observations

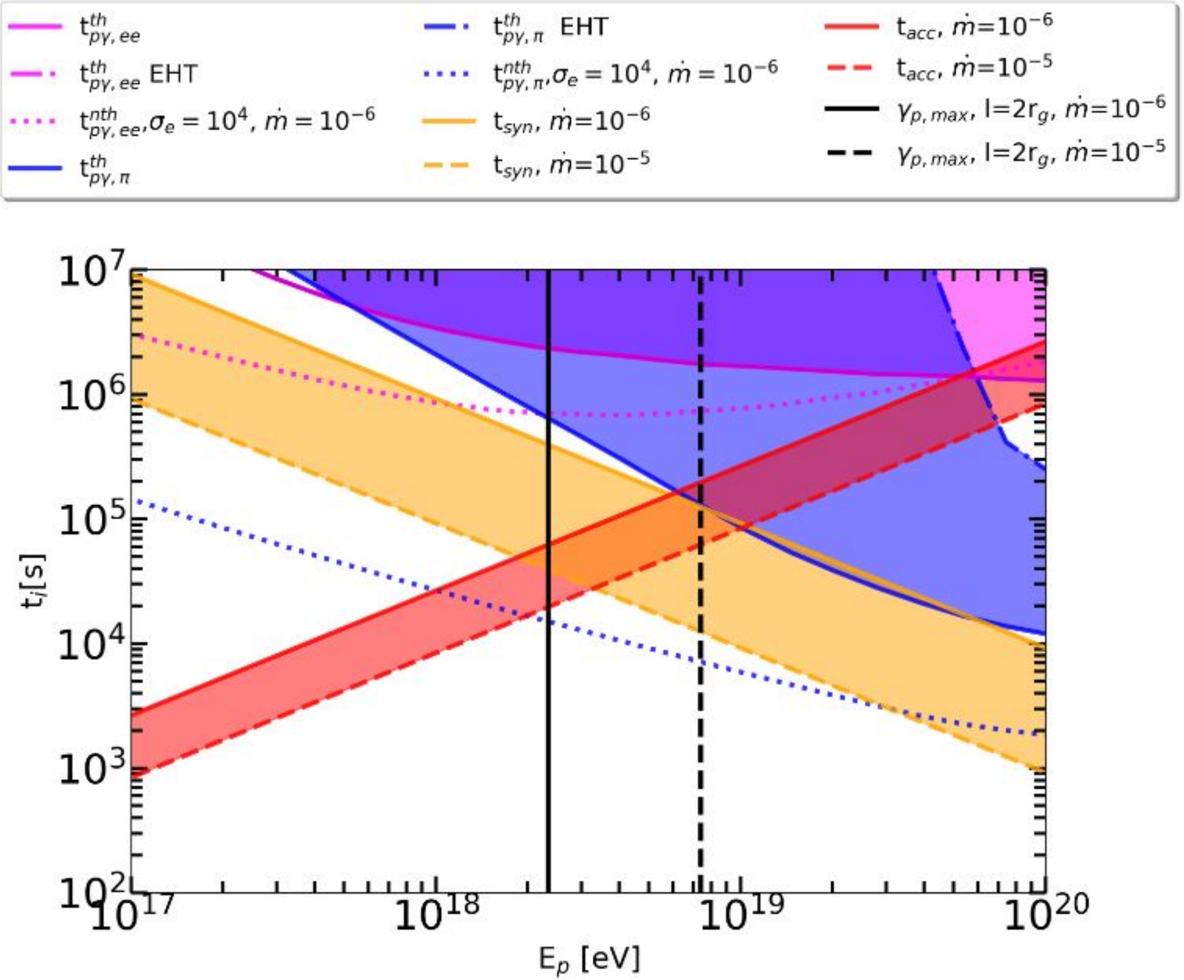


Low accretion rates and high magnetizations are favored

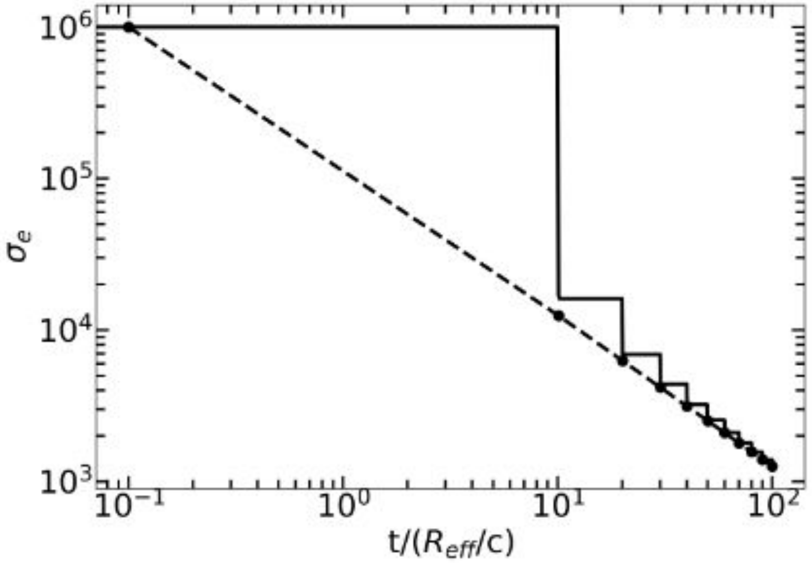
Stathopoulos et al. 2024, arXiv:2406.01211

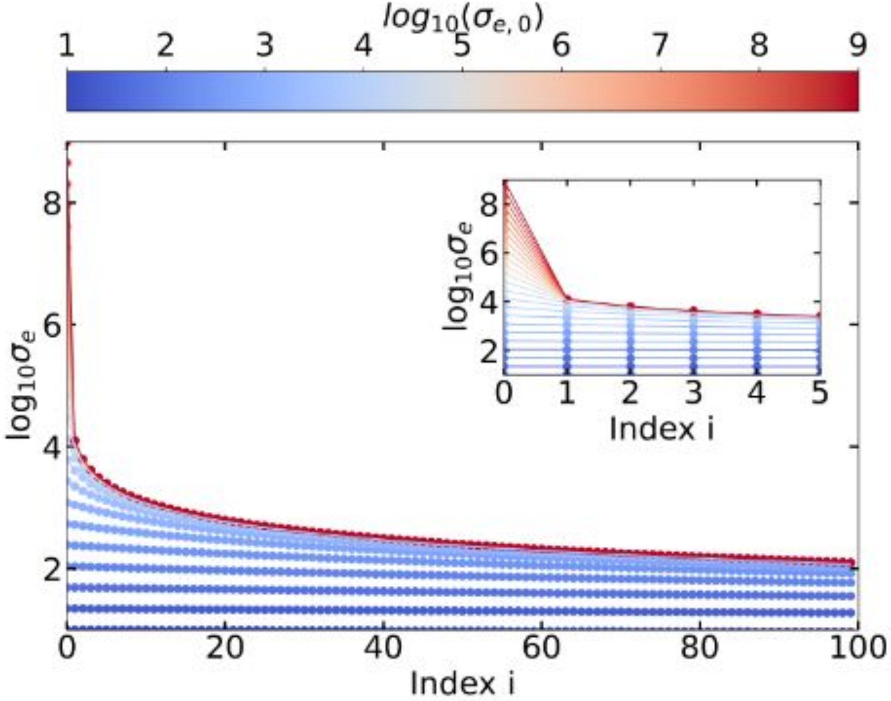
Stathopoulos et al. 2024, arXiv:2406.01211

Proton timescales



Pair enrichment and σ_e modification





Stathopoulos et al. 2024, arXiv:2406.01211

Maximum energy of protons in SgrA*

$$M = 4\ 10^6 M_\odot$$
$$\dot{m} \in (10^{-8}, 10^{-7}) EHT$$

$$E_{p,\max}^{(\mathrm{Sgr\ A^*})} \simeq \frac{e\eta_{rec}B_0 l}{m_p c^2} \simeq 8\ \mathrm{PeV}\ \frac{\eta_{rec,-1}(\dot{m}_{-8} M_{Sgr\ A^*})^{1/2} \mathcal{R}_0 \eta_{c,-1}^{-1/2}}{f^2(a_s)}$$