The role of Bethe-Heitler pair production in reconnection-driven flares in M87*

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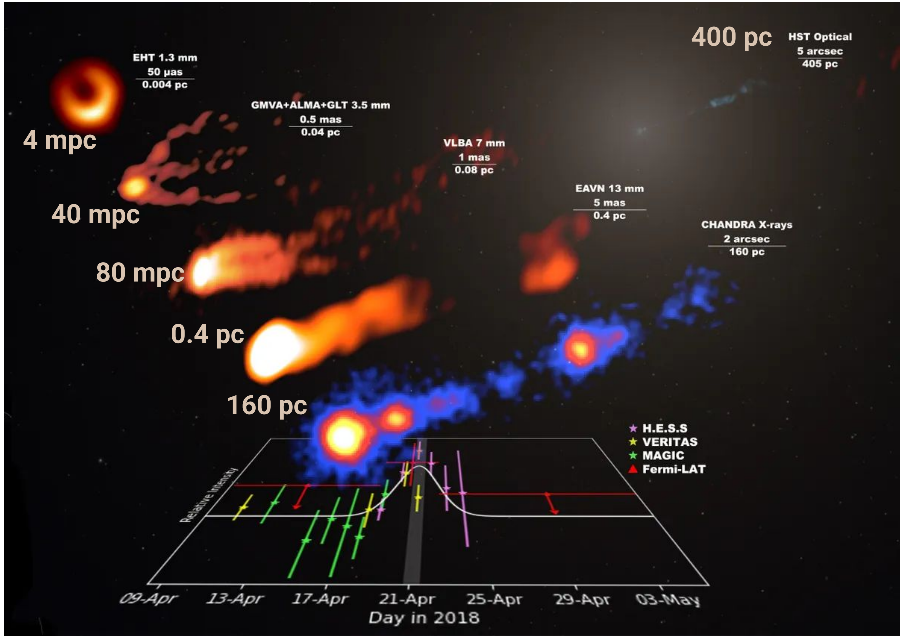
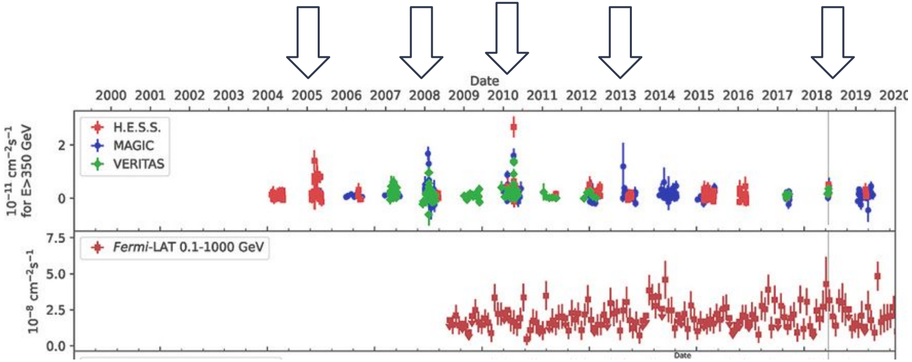
M87*: the heart of an AGN



Credit: EHT Collaboration, Fermi-LAT Collaboration, HESS Collaboration, MAGIC Collaboration, VERITAS Collaboration, EAVN Collaboration

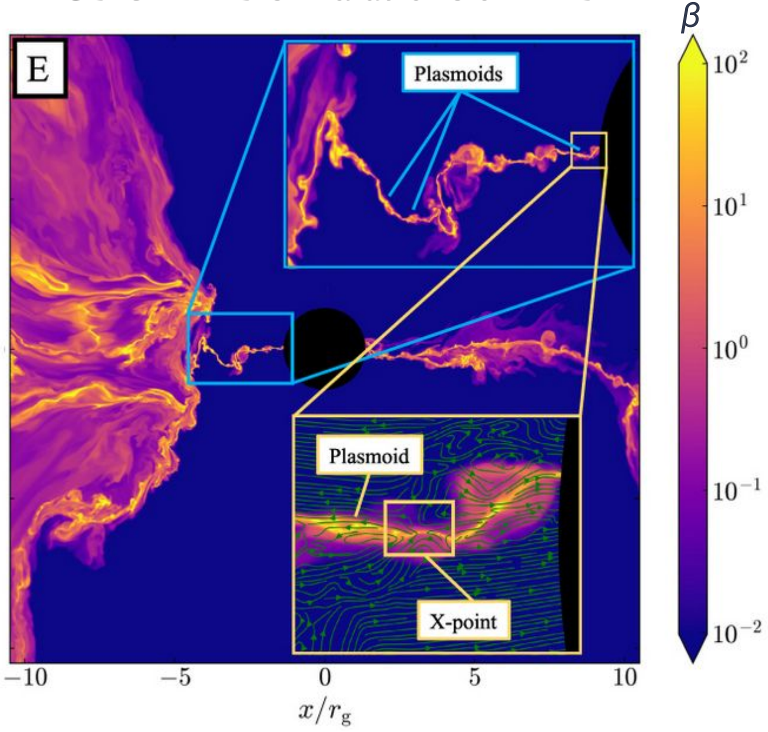
- Misaligned jetted AGN
- Black hole mass: ~6.5 x 10^9 M_{sun}
- Gravitational radius: ~ 10^{15} cm
- Light crossing time of 1 grav. radius: ~ 9 hr



Algaba et al. (2024), A&A

What powers γ-ray flares in M87*?

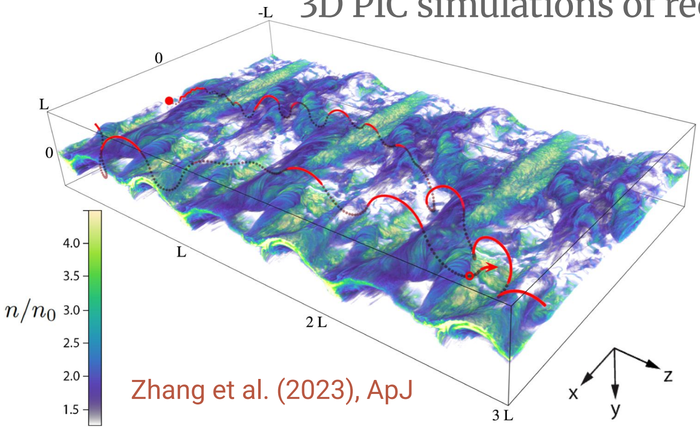
3D GRMHD simulations of MAD



Ripperda et al. (2022), ApJL

1. **Electrostatic gaps**
   (e.g. Levinson 2000; Levinson & Rieger 2011; Chen & Yuan 2020; Crinquand et al. 2020, 2021)
2. **Magnetic reconnection in magnetospheric current sheets**
   (Ripperda et al. 2022; Hakobyan et al. 2023, 2025; Stathopoulos et al. 2024)

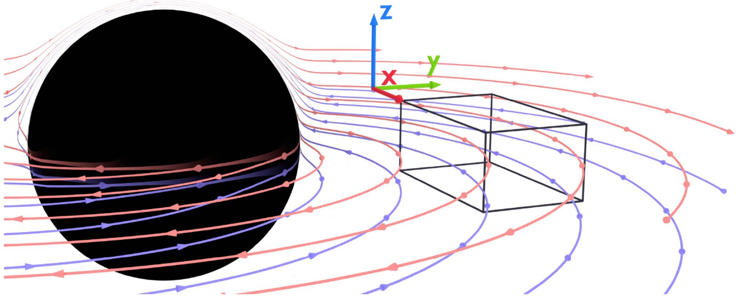
3D PIC simulations of reconnection



Zhang et al. (2023), ApJ

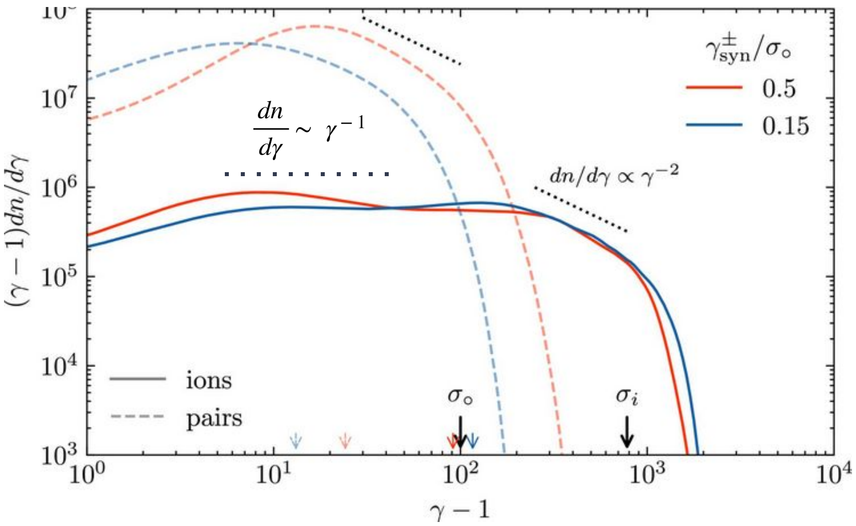
Reconnection in baryon-poor plasmas

3D PIC simulations of relativistic reconnection in pair-proton plasmas



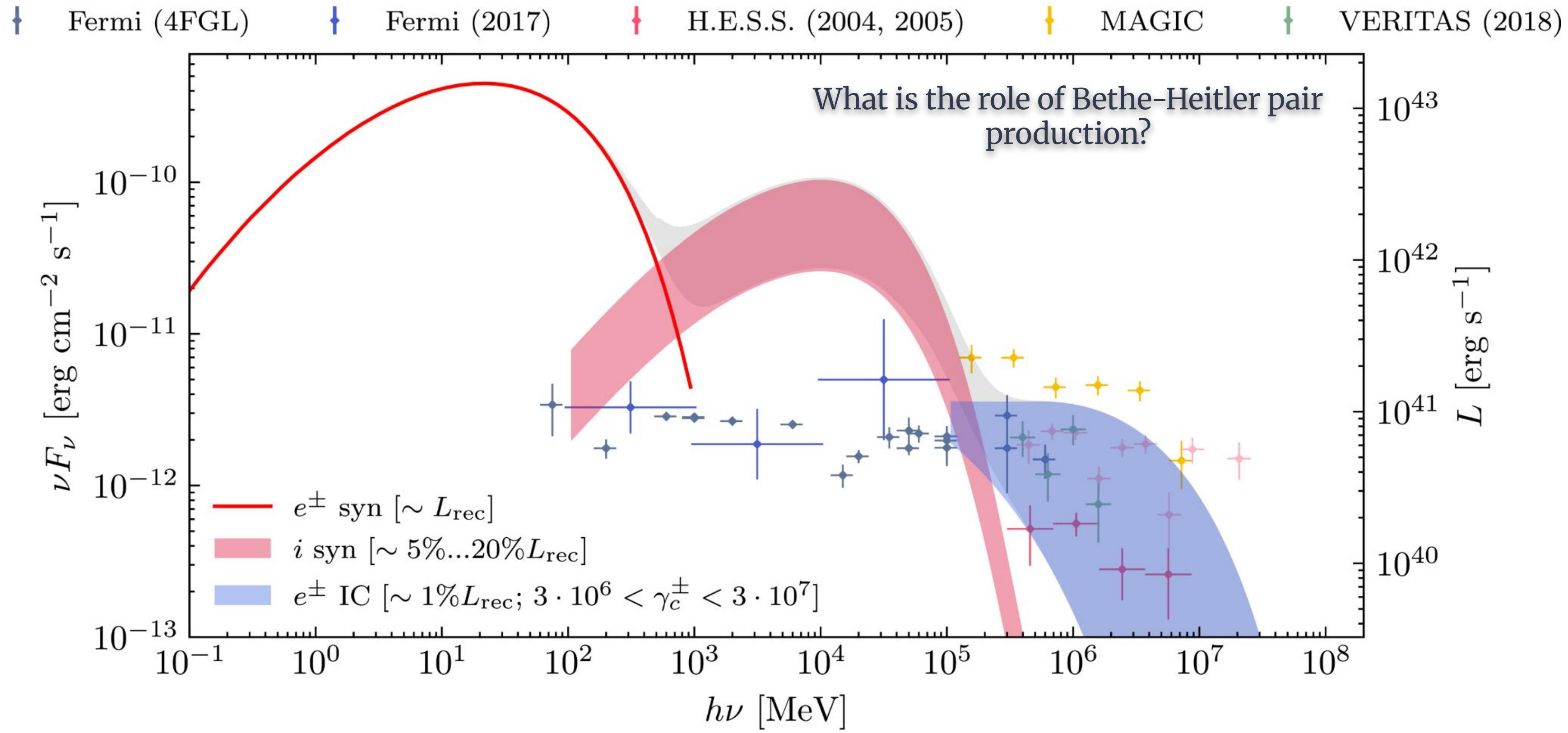
- Zero guide field
- Pairs dominate in number and mass
- Proton number fraction: 5%
- Proton plasma magnetization: $\sigma_p \sim 800$
- Pair plasma magnetization: $\sigma_e \sim 100$

Hakobyan et al. (2025), ApJL



- Proton acceleration due to **(azimuthal) E-field** (demagnetized from layer)
- Protons accelerate into a **broken power-law** distribution
- Proton acceleration not sensitive to pair plasma parameters (as long as $\sigma_p \gg \sigma_e$)

Proton-synchrotron GeV flares



Hakobyan et al. (2025), ApJL

Model

$$L_{rec} = \frac{1}{2}\frac{c\beta_{rec}B^2 r^2}{4\pi}$$

Dissipated Poynting power

$$L_p = \eta_p L_{rec}$$

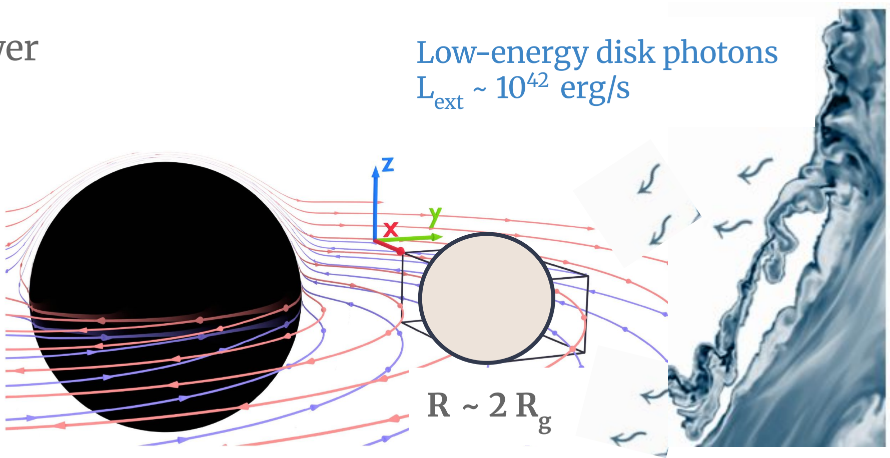
Power transferred to rel protons

$$\frac{dN}{d\gamma} \propto \begin{cases} \gamma^{-1}, \ \gamma \leq \gamma_{br} \\ \gamma^{-2}, \ \gamma_{br} < \gamma \leq \gamma_{rad} \end{cases}$$

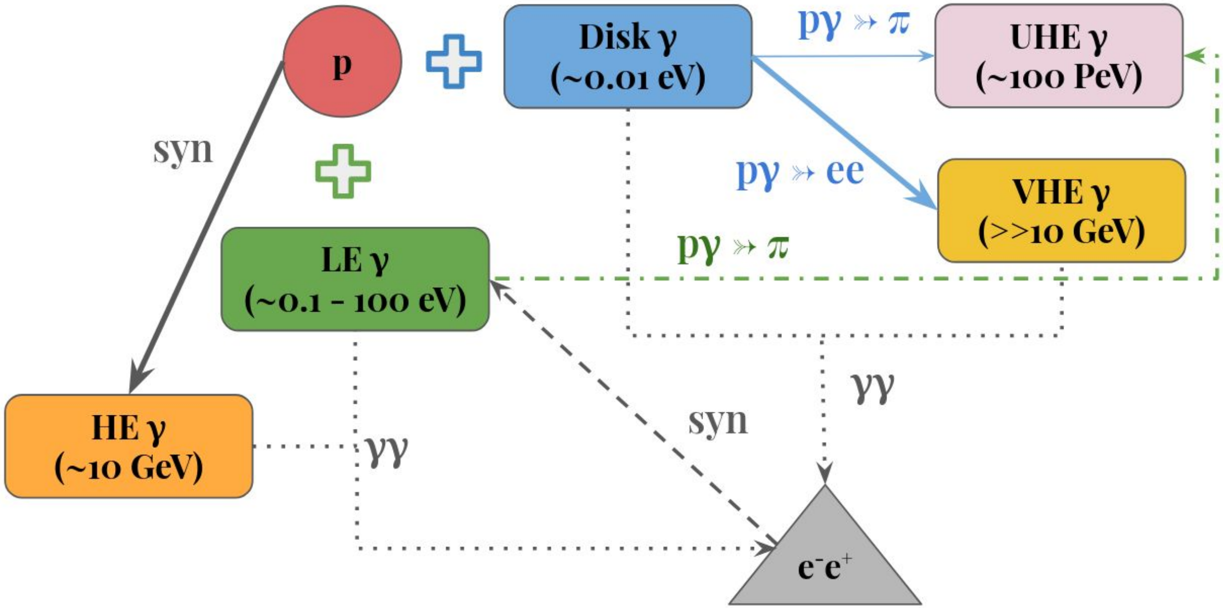
Accelerated proton distribution

$$\gamma_{br} \sim 0.3\,\sigma_p$$

Break Lorentz factor



A network of interactions

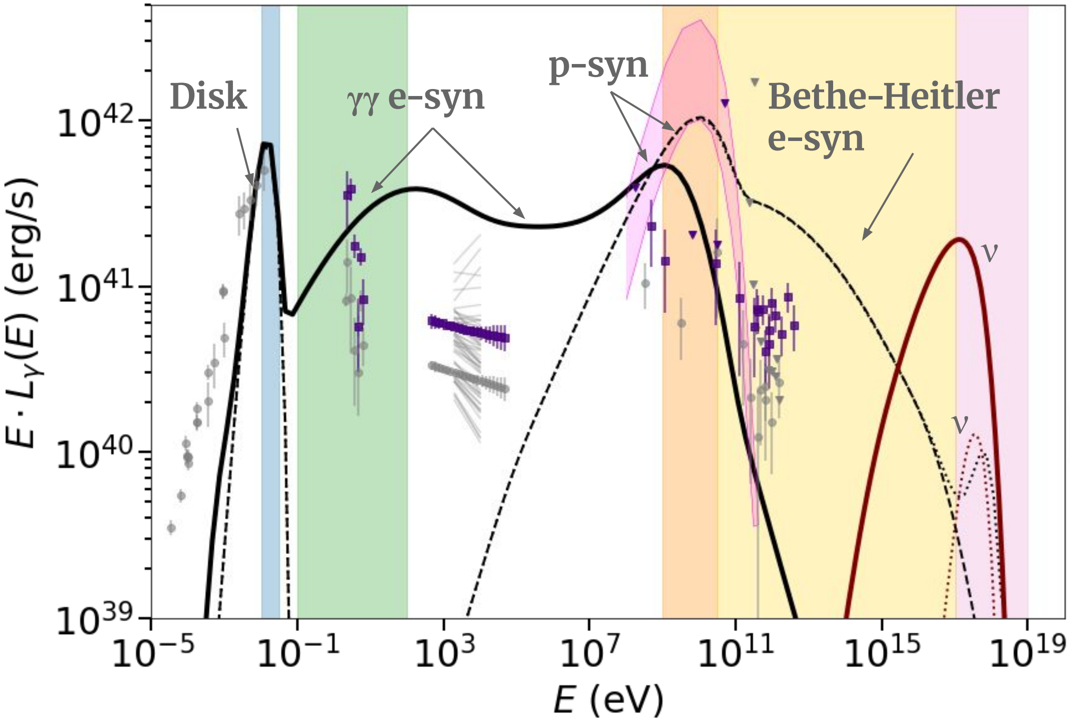


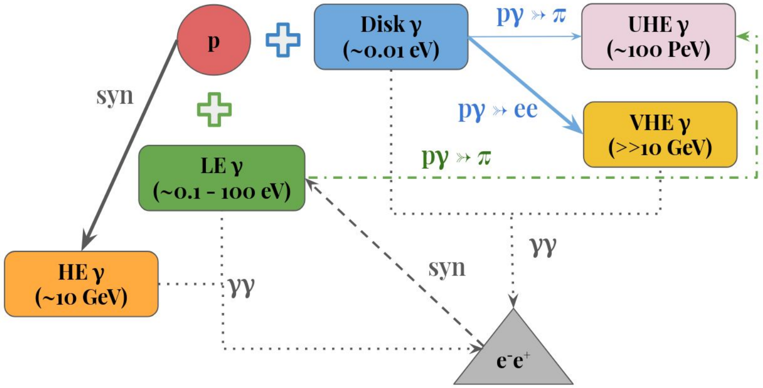
Baseline model parameters

Parameters	Symbol [Units]	Values
	Input	
Black hole mass	M [$M_\odot$]	$10^{9.8}$
Current sheet radius	r [R_g]	10
Reconnection rate	β_{rec}	0.1
Fraction of dissipated power into p	η_p	0.5
Proton plasma magnetization	σ_p	$10^{7.5}$
Upstream magnetic field strength	B [G]	100
External photon luminosity	L_{ext} [erg/s]	10^{42}
External peak photon energy	E_{ext} [eV]	10^{-2}
Dilution factor of ext. photon field	f_d	1
	Derived	
Current sheet effective radius	R [cm]	$10^{15.3}$
Dissipated power	L_{rec} [erg/s]	10^{44}
Relativistic proton power	L_p [erg/s]	$10^{43.7}$
Break proton Lorentz factor	γ_{br}	10^{7}
Max. proton Lorentz factor	$\gamma_{p,rad}$	$10^{9.8}$

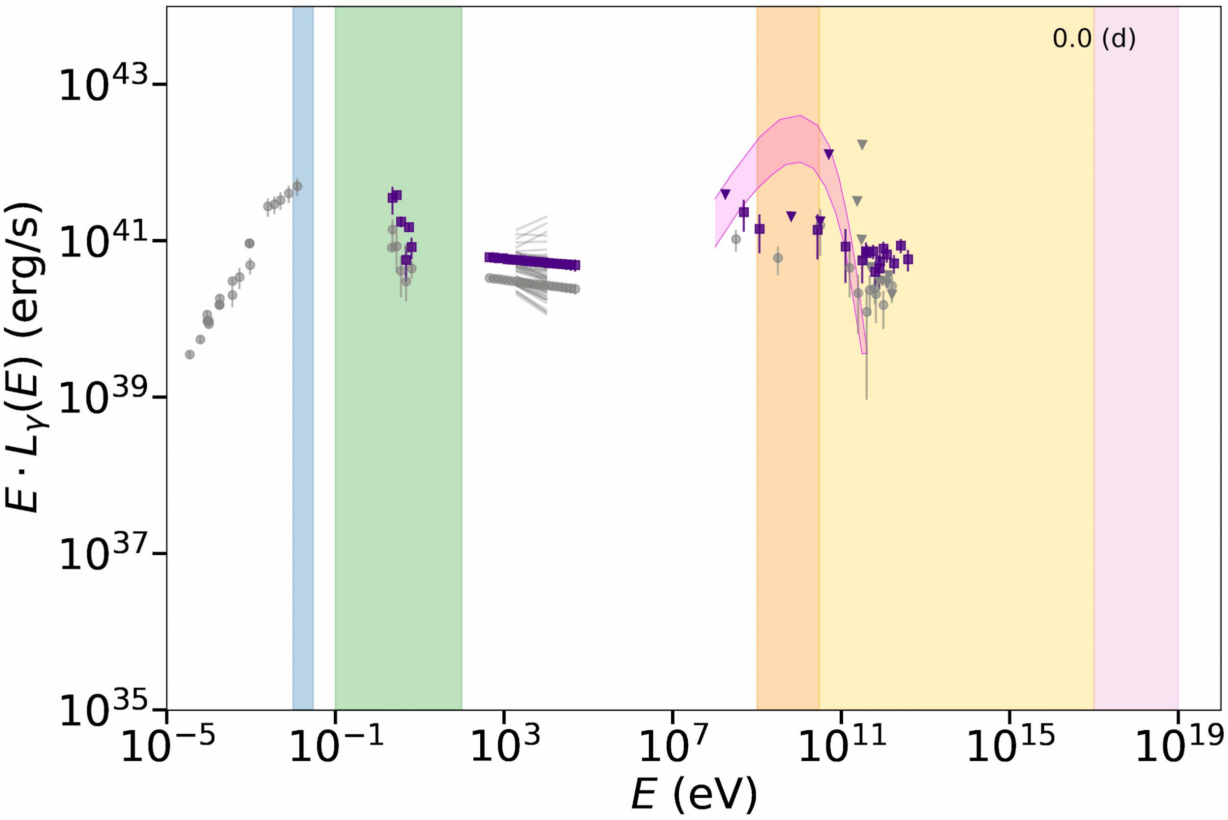
Multi-messenger emission from reconnection flares

Attenuation of Bethe-Heitler e-syn photons → LE photons → attenuation of GeV γ rays → pγ enhancement





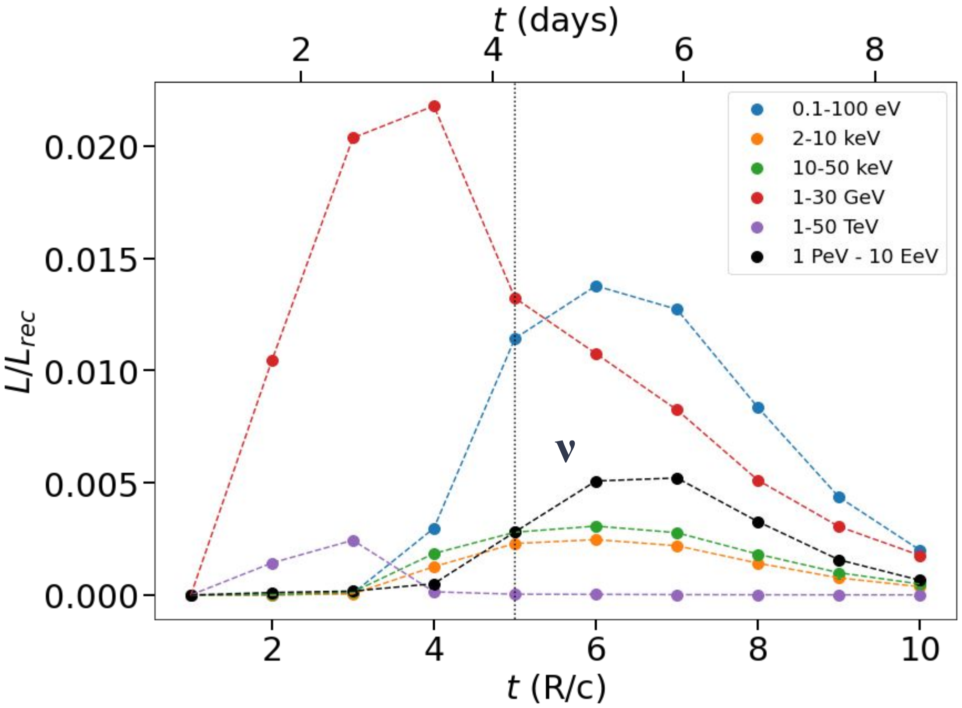
Time-dependent spectra



- Lifetime of layer = duration of proton injection = 5 R/c
- Track evolution for additional 5 R/c

Light curves

$L_{rec} \sim 10^{44}$ erg/s



- Time lags (~ few days) are predicted
  a. TeV
  b. GeV
  c. X-rays/Optical
  d. EeV Neutrinos

- GeV flare with ~ 20-30 % of dissipated power before attenuation kicks in

- Time-lag depends on the size of the reconnection layer

Conclusions

1. Even a small fraction of protons in pair-dominated plasmas can drastically alter the multi-messenger signals of reconnection-driven flares.

2. Bethe-Heitler induced-cascades suppress GeV p-syn emission while enhancing EeV neutrino emission.

3. The EM effects of protons accelerated in magnetospheric current layers of M87* manifest primarily in **baryon-poor regions** with reconnecting guide fields **B ~ 50 - 100 G**, when they receive **>20% of the dissipated power**.

4. **Can we test our model for M87* flares?** Yes! How?

   Triggering ToO observations in X-rays/UV/Optical within ~ 1 day after a TeV flare and monitoring with daily cadence for ~ 10-12 days after the TeV flare.

If you would like to learn more, take a look at our paper:

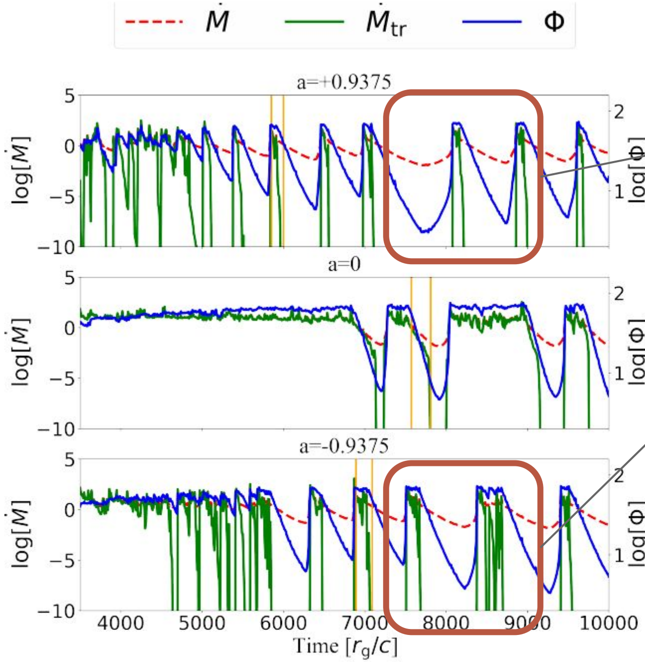
Petropoulou, Karavola, Sironi (2026), accepted in ApJL
https://arxiv.org/abs/2602.23435

Thank you!

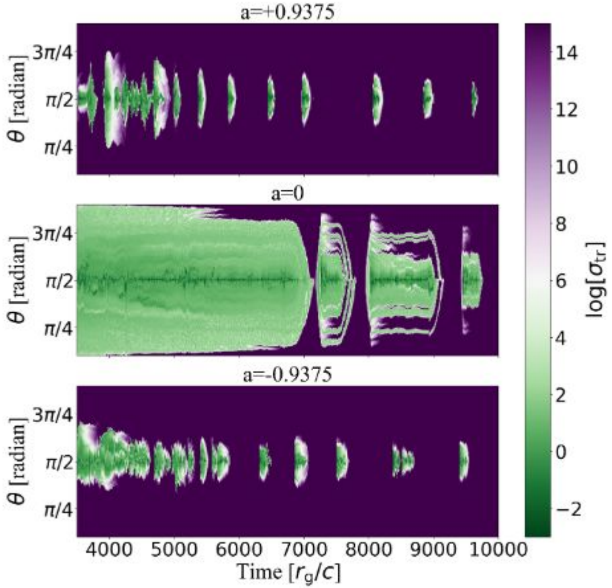
Backup slides

Baryon-poor regions in GRMHD

2D GRMHD simulations of MAD



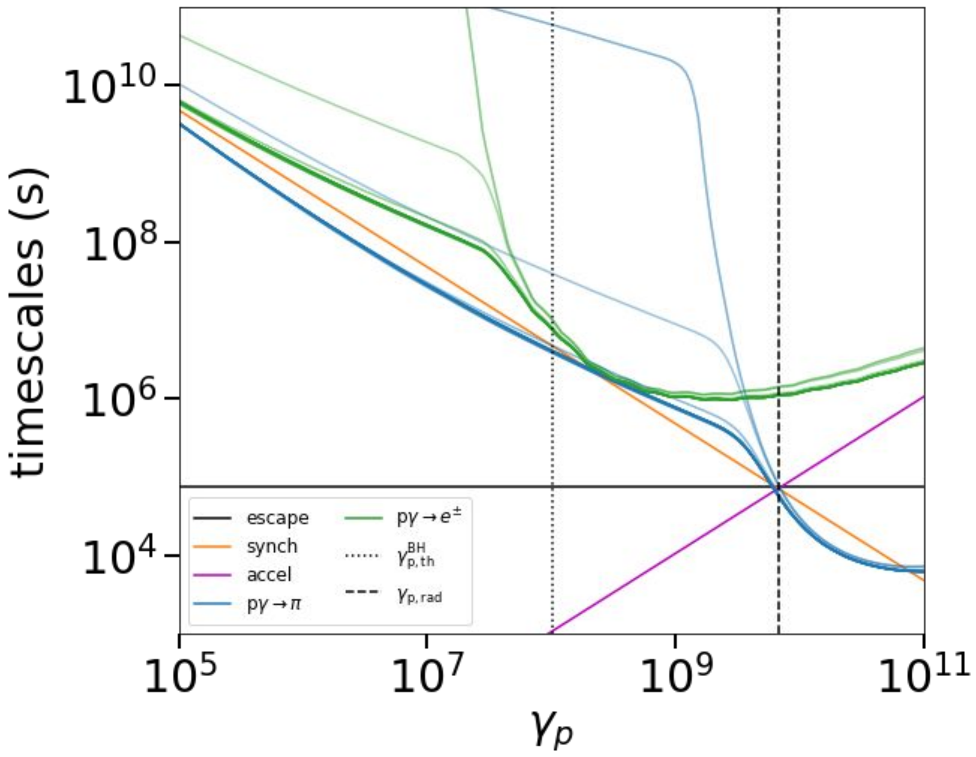
Red lines show more gradual decline due to artificial plasma injection in the MHD simulation



- Baryonic matter from the disk is evacuated intermittently through magnetic flux eruptions (green → white → purple)
- Extended regions (in polar angle) of baryon-poor plasma (purple) are formed

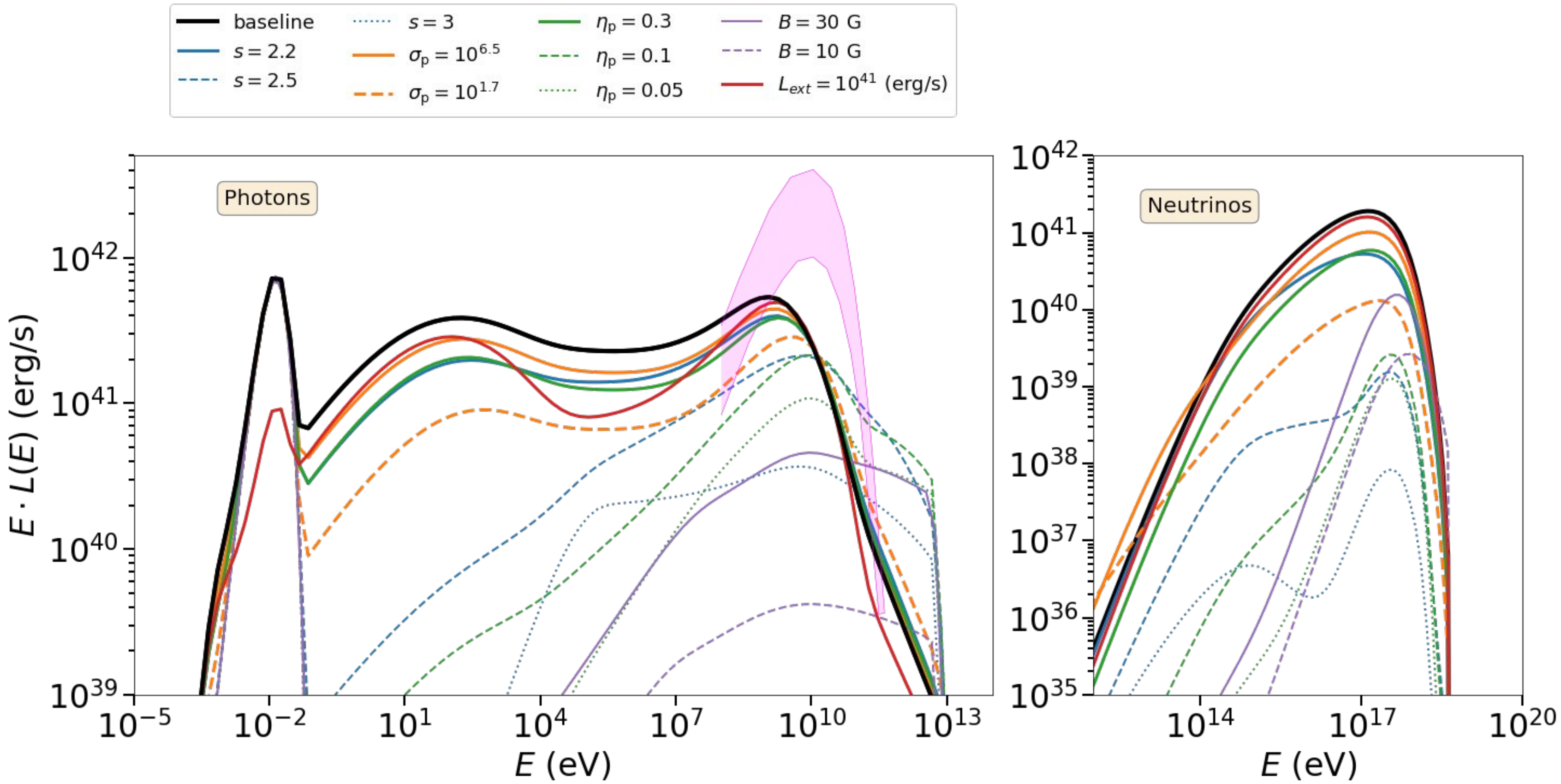
Chow, Sironi, Ripperda, Levinson (in prep)

Proton timescales

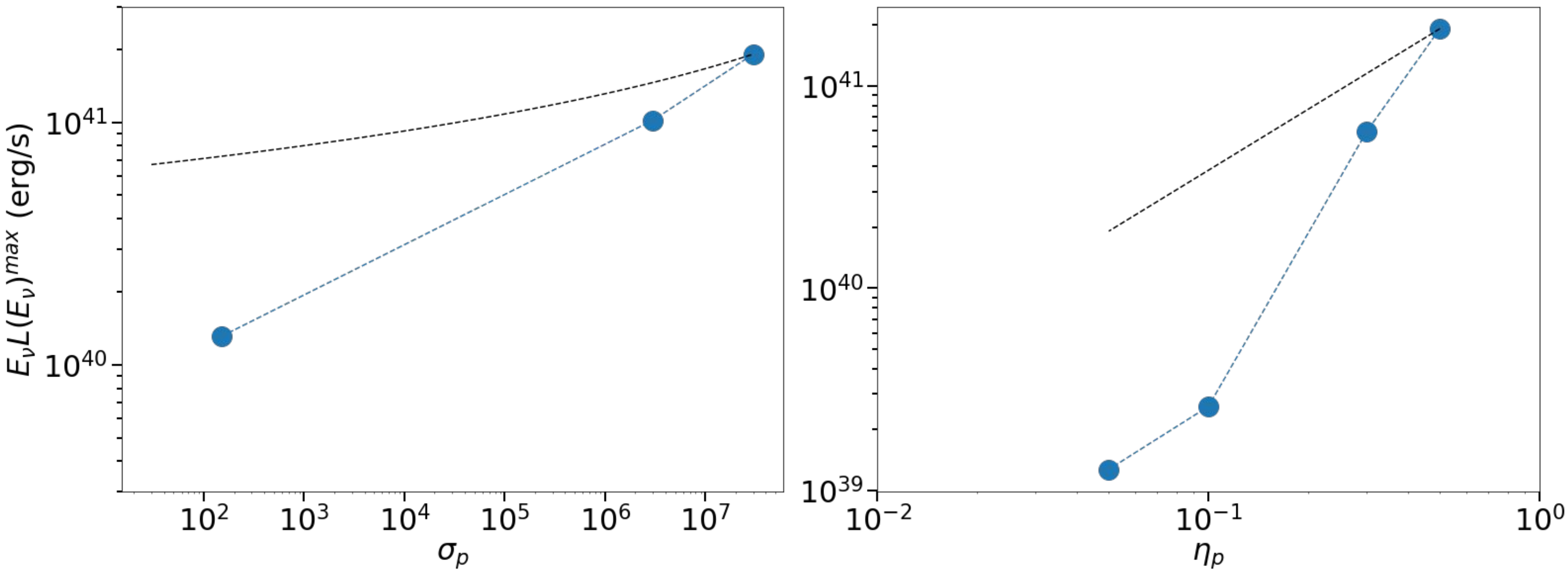


- Temporal evolution shown with light-to-dark colored curves
- Acceleration timescale is fastest → practically instantaneous → modeled with injection term
- Bethe-Heitler energy loss timescale is always longer than escape timescale
- Photopion energy losses become comparable to synchrotron losses close to max proton energy

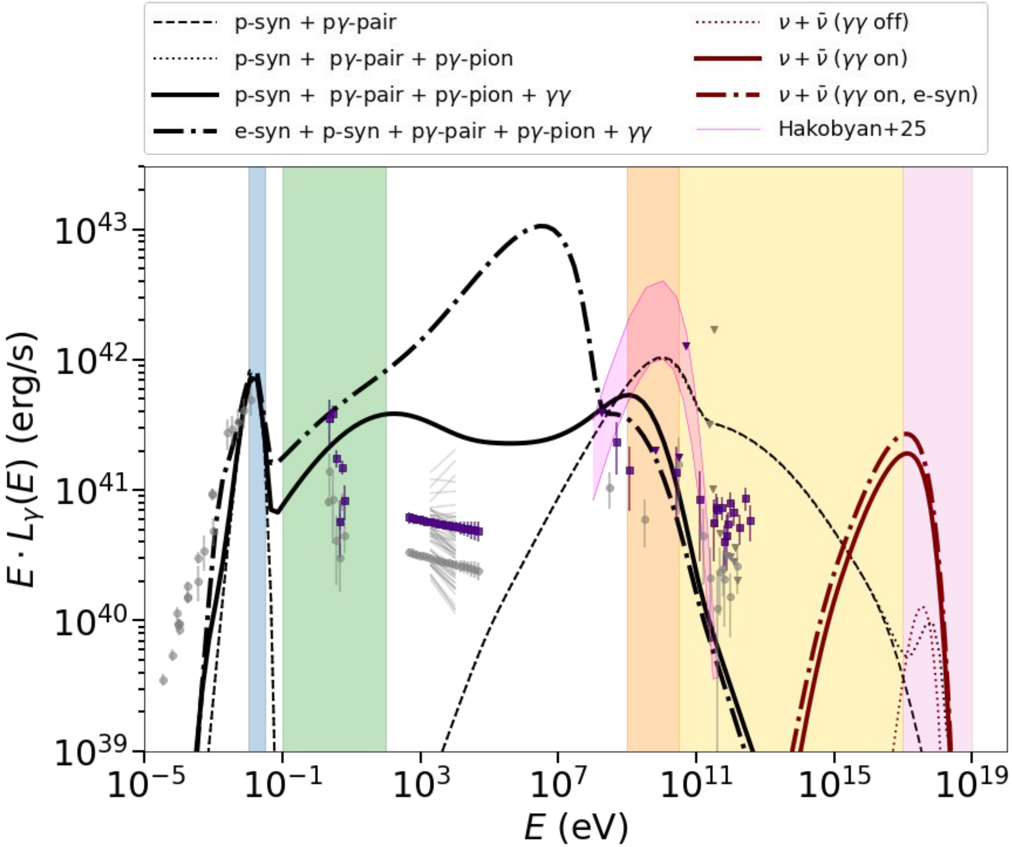
Effects of model parameters



Scalings with model parameters



Effects of primary pairs



$$L_e = \left(1 - \eta_p\right) L_{rec}$$

$$\gamma_{e,\,rad} \approx 10^{6.6} \left(\frac{\beta_{rec,-1}}{B_2}\right)^{\frac{1}{2}} \longrightarrow \sigma_e \gtrsim 10^{6.6}$$

- Primary pairs are accelerated to the synchrotron burnoff limit
- Primary pairs emit syn photons up to few MeV (Hakobyan et al. 2023, Stathopoulos et al. 2024)
- Primary pairs do not alter qualitatively the picture