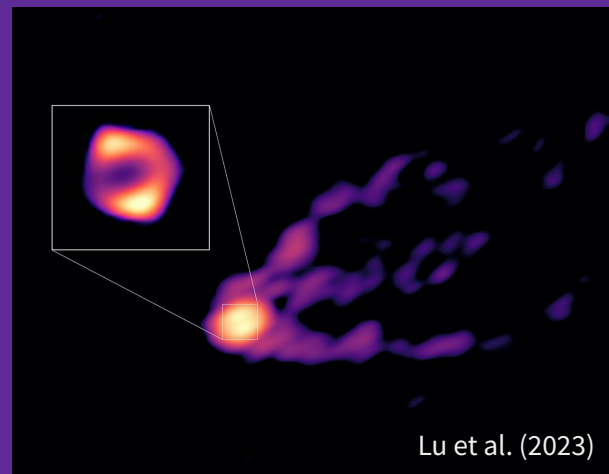


Very high energy flares from M 87

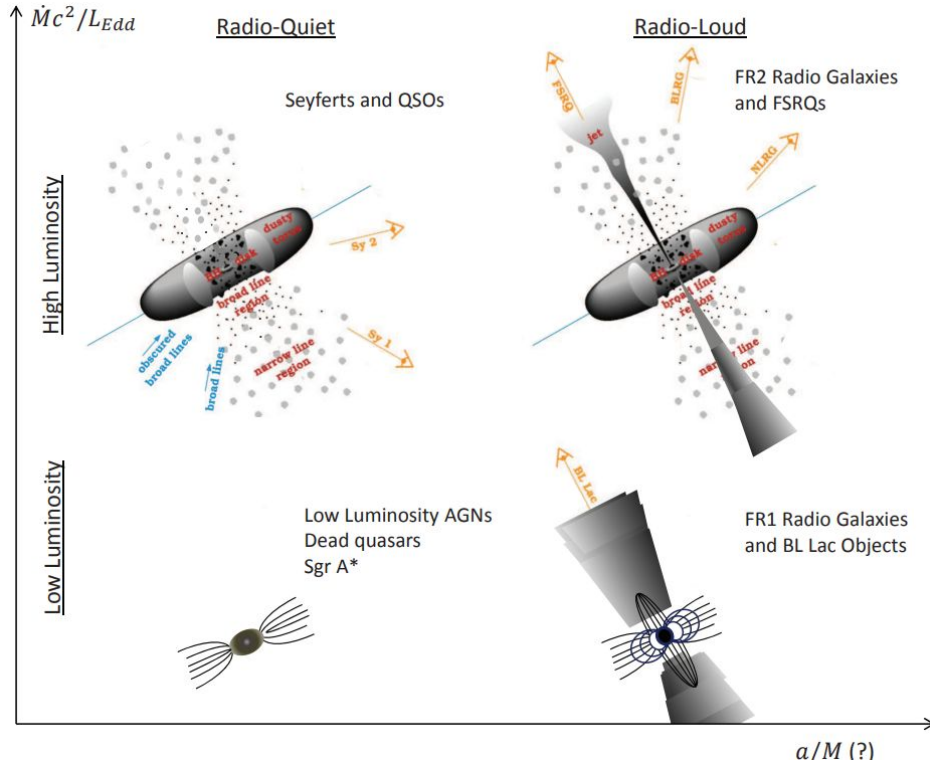
LUX day, 16.06.26

Paloma Thevenet

Supervisors: Andreas Zech (LUX), Frédéric Vincent (LIRA)



Introduction: active galactic nuclei (AGN)



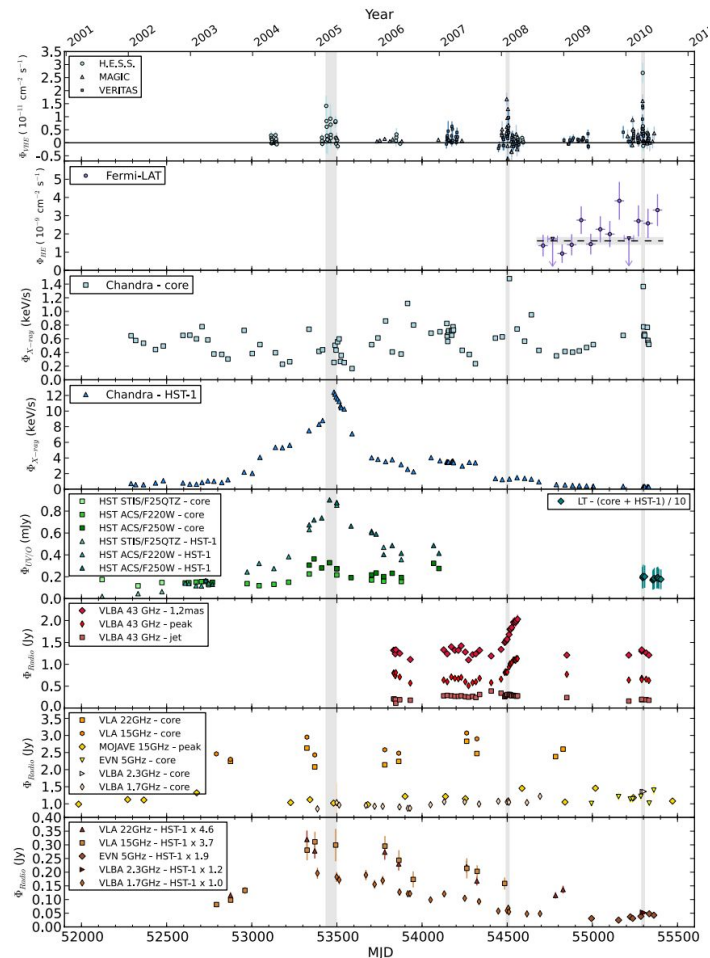
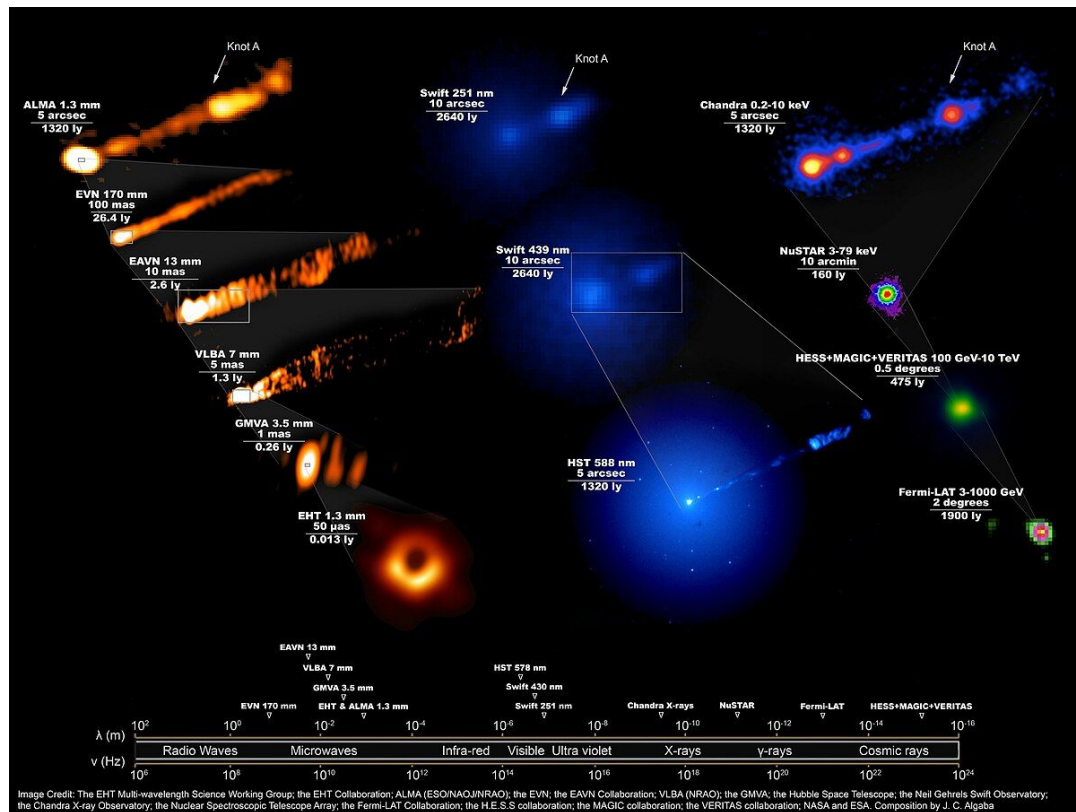
~10% of AGNs are radio loud (RL) and launch a relativistic jet through the Blandford-Znajek (BZ) or Blandford-Payne (BP) mechanism.

We call blazars RL AGNs with jets closely aligned to the line of sight, and radio galaxies those with larger viewing angle.

The main emission from AGN jets is synchrotron radiation, as well as inverse Compton radiation, leading to observations over a large range of wavelengths.

Illustration of an AGN unification model
(Dermer&Giebels+16)

Study of M87 flares



Study of M87 flares: state of the art

- Multiwavelength observations
- Kinetic modeling
- GRMHD simulations
- GRPIC simulations

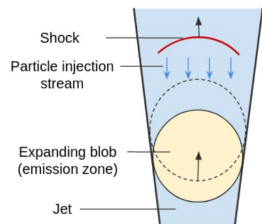
Flare locations/mechanisms proposed:

HST-I	EC starlight photons (e.g. Stawarz+2006)	
Inner Jet (sub-parsec)	leptonic (IC)	decelerating flow (upstream IC) (e.g. Georgopoulos+2005)
		spine-shear (IC interplay) (e.g. Tavecchio+2008)
		multiple SSC components/differential beaming (e.g. Lenain+ 2008)
		reconnection & IC (e.g. Giannios+ 2010)
	hadronic	proton synchrotron & p- γ (e.g. Reimer+ 2004)
		jet-star interactions / pp (e.g. Barkov+ 2012)
		combined lepto-hadronic (e.g. Reynoso+ 2011)
BH vicinity	rotational acceleration & IC (e.g. Rieger & Aharonian 2008)	
	gap-type particle acceleration & IC (e.g. Levinson & Rieger 2011)	

Abramowski+12

Time-dependent kinetic modeling

Objective: use the EMBLEM (Dmytriiev+21) code to reproduce the 2022 flare with a time-dependent SSC modeling, considering Fermi acceleration or magnetic reconnection as flare drivers, occurring downstream or close to the core.



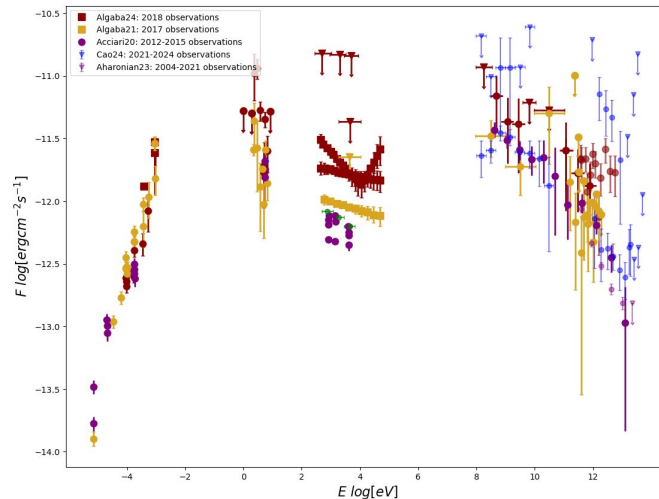
$$\frac{\partial N_e(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma} \left[\underbrace{(b_c(\gamma, t)\gamma^2 + \frac{1}{t_{ad}}\gamma - a(t)\gamma - \frac{2}{\gamma}D_{FII}(\gamma, t))N_e(\gamma, t)}_{\text{Cooling terms}} + \underbrace{\frac{\partial}{\partial \gamma} \left(D_{FII}(\gamma, t) \frac{\partial N_e(\gamma, t)}{\partial \gamma} \right)}_{\text{Acceleration terms}} \right] - \underbrace{N_e(\gamma, t) \left(\frac{1}{t_{esc}} + \frac{3}{t_{ad}} \right)}_{\text{Injection term}} + \underbrace{\dot{Q}_{inj}(\gamma, t)}_{\text{Injection term}}$$

Cooling

- Synchrotron and Inverse Compton: $b_c(\gamma, t)$
- Adiabatic expansion: $t_{ad}(t) = \frac{R(t)}{\beta_{exp}c}$
- Escape: $t_{esc}^{(turb)} = \left(\frac{R_t}{c} \right)^2 \left(\frac{\delta B}{B} \right)^2 \frac{c}{\lambda_{max}} \left(\frac{r_L}{\lambda_{max}} \right)^{q-2}$

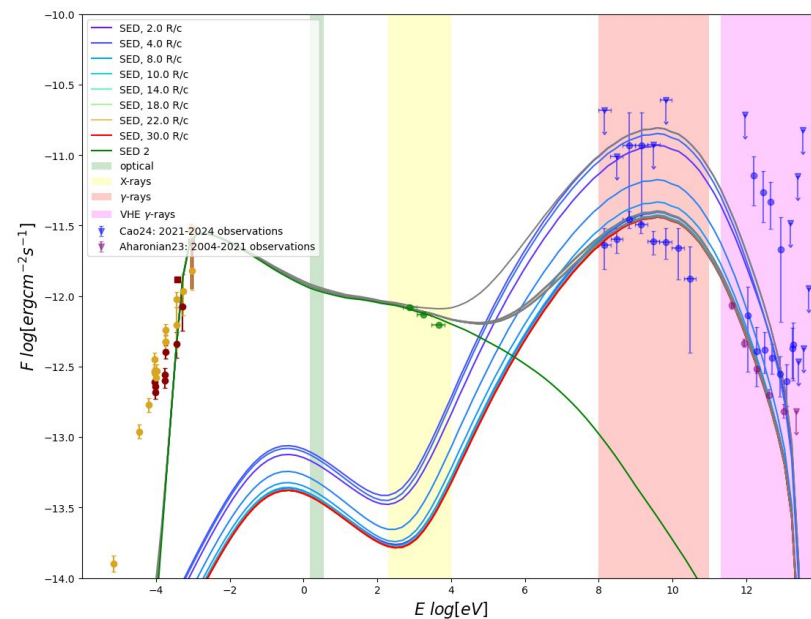
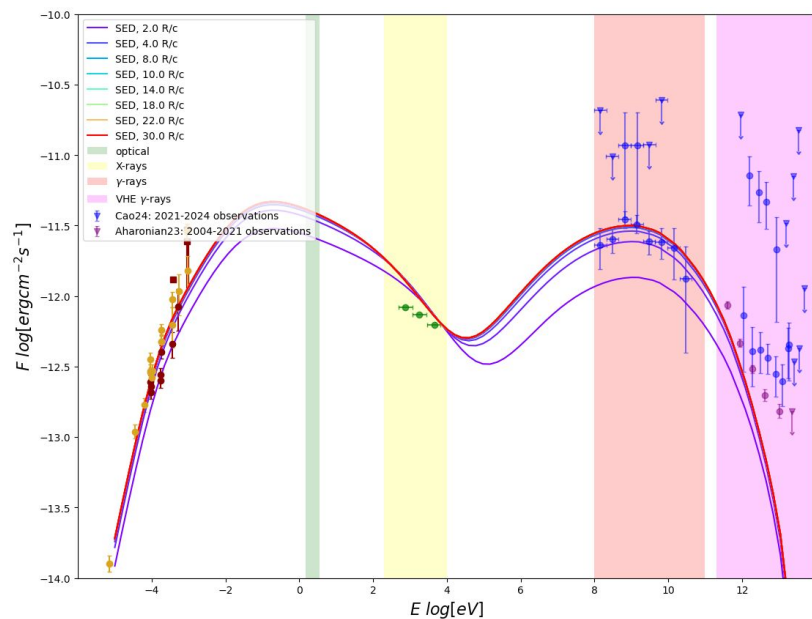
Acceleration

- Fermi I: $a = 1/t_{shock}$, $\dot{Q}(\gamma, t)$
 - Fermi II: $D_{FII}(\gamma, t) = \frac{p^2}{t_{FII}}$
- $$t_{FII} = \frac{1}{\beta_A^2} \left(\frac{\delta B}{B} \right)^{-2} \frac{\lambda_{max}}{c} \left(\frac{r_L}{\lambda_{max}} \right)^{2-q}$$



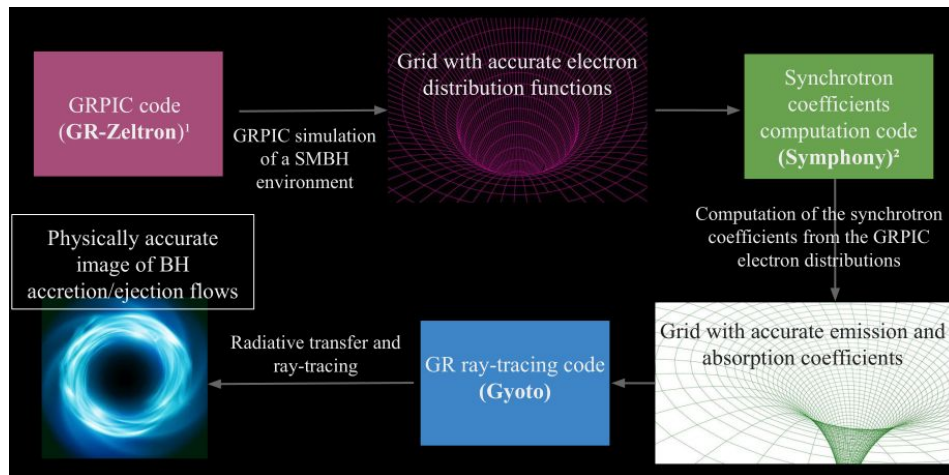
Time-dependent kinetic modeling

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Radiative transfer for GRPIC simulations

Objective: build a pipeline to ray-trace results from GRPIC simulations of BH environments with accurate radiative transfer to produce images of the BH environment and light curves.



1.Parfrey+19

2.Pandya+16

Thank you

Extra: active galactic nuclei (AGN)

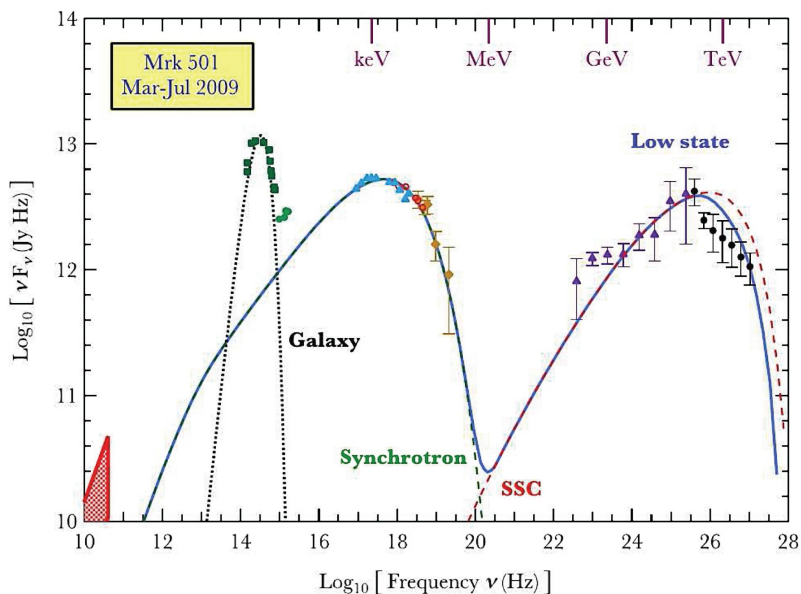


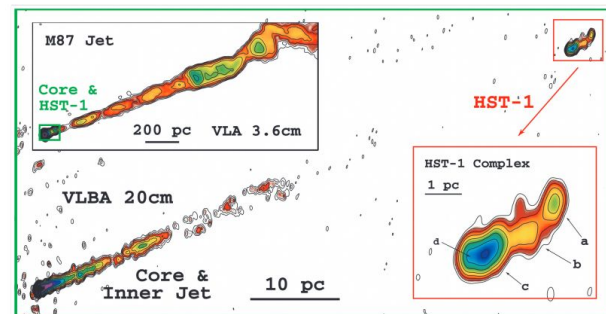
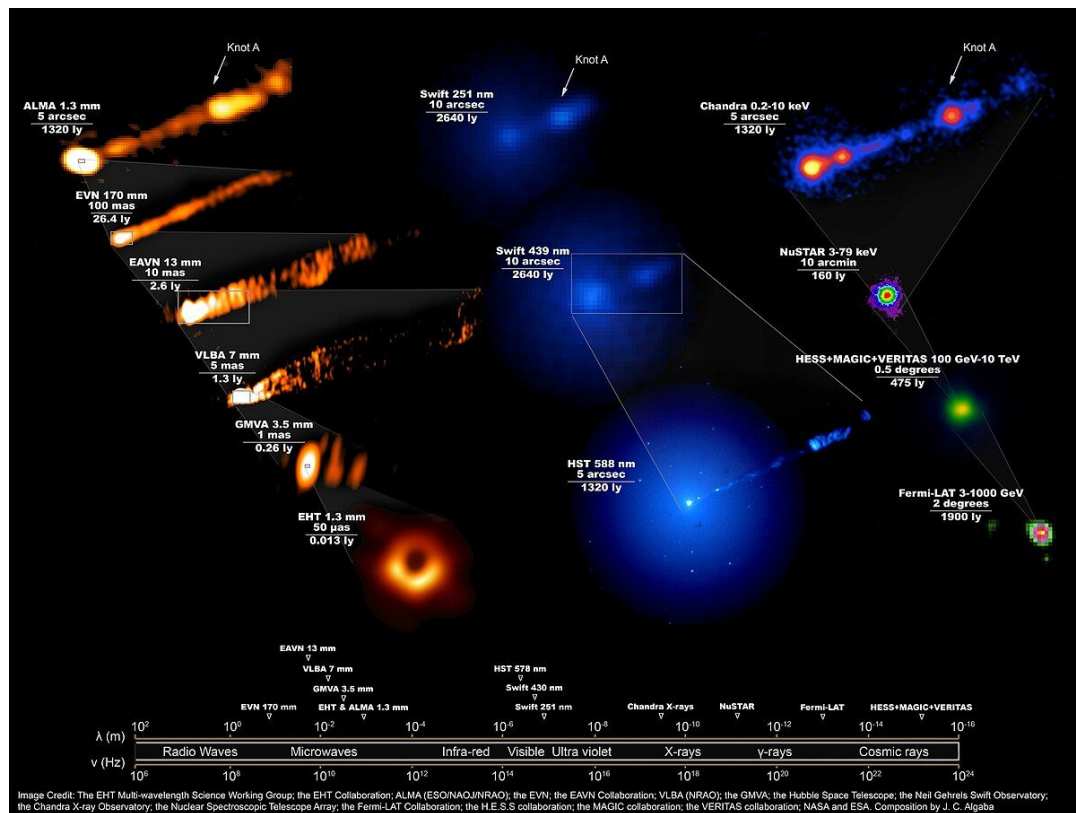
Illustration of a blazar SED (Böttcher+16)

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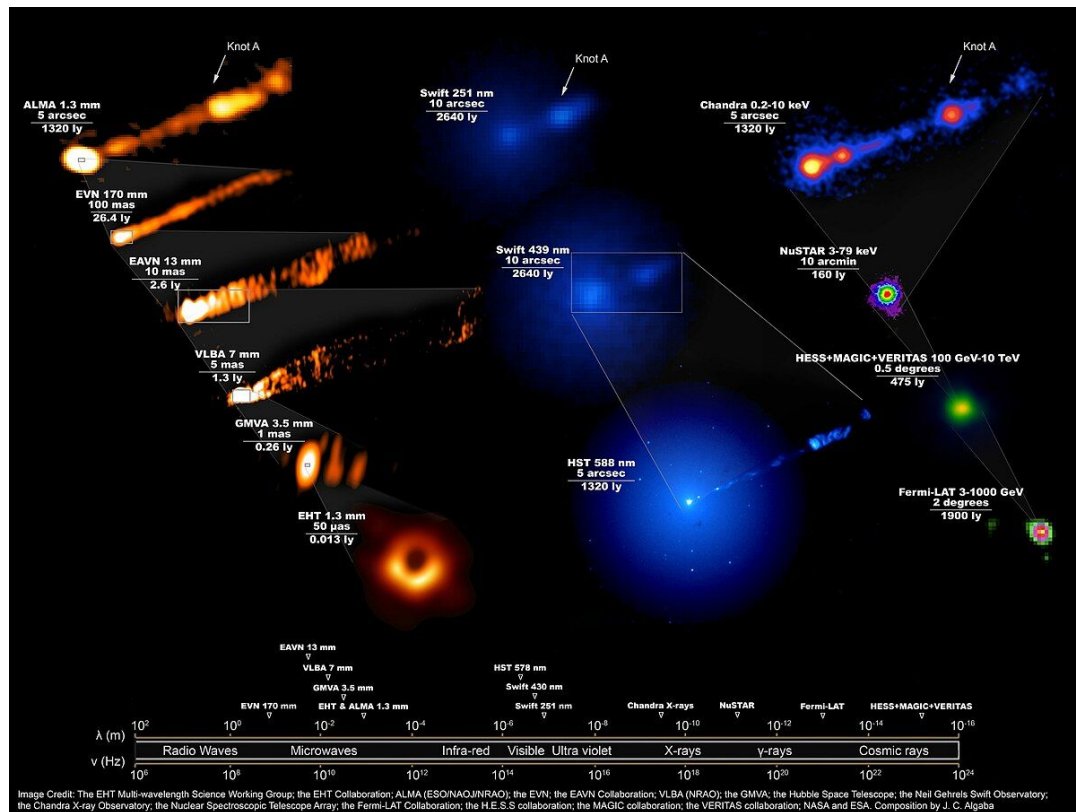
Extra: M 87



Cheung+07

Composite image of the FR I radio galaxy M87

Extra: M 87



M_{BH}

a

$\dot{M}$ (near horizon)

$\dot{M}$ (at Bondi radius)

Φ_{BH}

L_j

$(6 - 7) \times 10^9 M_{\odot}$

likely $\neq 0$

$(3 - 20) \times 10^{-4} M_{\odot} \text{yr}^{-1}$

$\sim 0.2 M_{\odot} \text{yr}^{-1}$

$\sim 10^{33} \text{ G cm}^2$

$\sim 10^{(43-45)} \text{ erg s}^{-1}$

Other observational parameters/quantities

Source distance D

$\sim 16.8 \text{ Mpc}$

Bondi radius r_B

$\sim 220 \text{ pc}$ ($\sim 3.5 \times 10^5 r_s$)

X-ray core luminosity

$\sim 7 \times 10^{40} \text{ erg s}^{-1}$

Core ring diameter (1.3 mm)

$\sim 42 \mu\text{s}$

Core ring diameter (3.5 mm)

$\sim 64 \mu\text{s}$

Jet viewing angle

$\sim 14-20^\circ$

Jet position angle

$\sim 284-292^\circ$ (nominal 288°)

Jet radius ($z < r_B$)

$\propto z^{0.58}$

Jet radius ($z > r_B$)

$\propto z^{1.04}$

Core-shift (1-88 GHz)

$\propto \nu^{-(0.9-1.0)}$

Maximum apparent jet speed

$\sim 6 c$

Maximum $|\text{RM}|$

a few $\times 10^5 \text{ rad m}^{-2}$

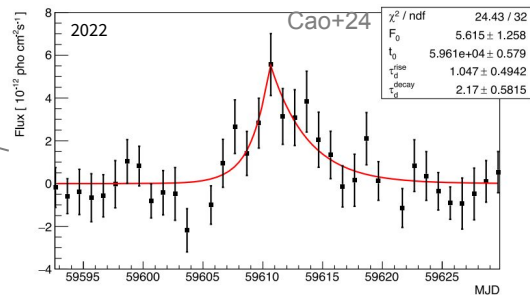
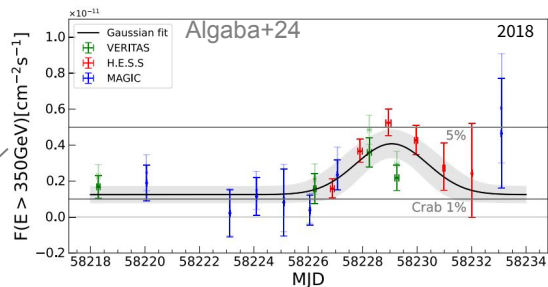
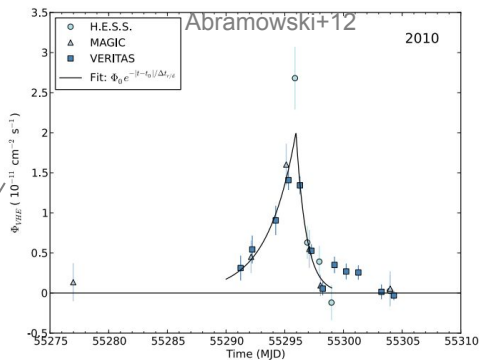
Hada+24

Composite image of the FR I
radio galaxy M87

Extra: study of M87 flares

Table 1: M87 MWL flare observations

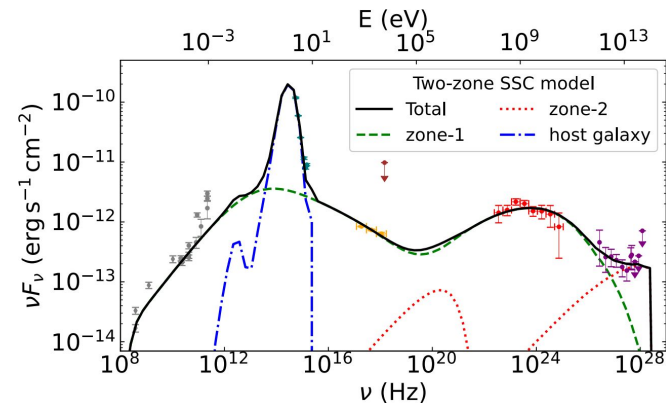
Flare	Band	Instrument	State	t_{rise}	t_{decay}	Subflares	Increase Fact.
2005	Radio	VLA/VLBA	HST-1	years	years	yes	$\sim 30\text{--}50$
	X-ray	Chandra	HST-1	years	years	yes	~ 50
	Optical	HST	HST-1	years	years	yes	~ 90
	VHE	HESS	flare(s)	~ 2	~ 2	yes	$\sim 10\text{--}20$
2008	Radio	VLBA	nucleus	months	-	no	~ 2
	X-ray	Chandra	nucleus	weeks	weeks	yes	~ 2
	VHE	MAG/VER	flare	≤ 1	≤ 1	yes	$\sim 10\text{--}20$
2010	Radio	VLBA	nucleus	-	-	no	~ 1.1
	X-ray	Chandra	nucleus	≤ 2	≤ 2	no	~ 2
	VHE	VER/HESS/MAG	flare	1.69 ± 0.30	0.61 ± 0.08	no	$\sim 10\text{--}20$
2012	Radio	VERA/EVN	nucleus	months	months	-	$\sim 50\text{--}70$
	VHE	VERITAS	elevated	weeks	weeks	-	~ 2
2018	X-ray	Chandra	nucleus	~ 2	~ 5	no	~ 2
	VHE	HESS/MAG/VER	flare	$\sim 1\text{--}2$	$\sim 1\text{--}2$	no	~ 3
2021	VHE	MAGIC	flare?	-	-	-	~ 6
2022	γ -ray	Fermi-LAT	flare?	-	-	-	~ 3.8
	VHE	LHAASO	flare	1.05 ± 0.49	2.17 ± 0.58	no	~ 10



Extra: study of M87 flares

Models for the 2022 LHAASO flare:

- Xue et al. (2025): construct averaged MWL SEDs by combining data from Chandra and Swift-UVOT/XRT covering the same period as the LHAASO detection. Test several radiation mechanisms, including the pp interaction, proton synchrotron emission, and two-zone leptonic model. Only the pion decay gamma rays in pp interactions can interpret the possible hardening at TeV with a one-zone model. The two-zone leptonic model is a viable alternative.



Parameters for Spectral Energy Distribution Fitting with the One-zone SSC+pp Model

Free parameters	R (cm)	B (G)	$L_{e, \text{inj}}$ (erg s ⁻¹)	$\gamma_{e, b}$	$p_{e, 1}$	$p_{e, 2}$	ξ	$\gamma_{p, \text{max}}$	p_p
Values	1.3×10^{18}	9.0×10^{-4}	1.2×10^{43}	4.0×10^4	1.9	3.4	3.5×10^{-3}	6.2×10^5	2.0
Derived/Fixed parameters	Γ	θ_{obs} (deg)	δ_D	$\gamma_{e, \text{min}}$	$\gamma_{e, \text{max}}$	$\gamma_{p, \text{min}}$	χ_p	n_H (cm ⁻³)	f_{pp}
Values	3	15	3.7	1	10^8	1	0.5	4.5×10^2	8.4×10^{-6}

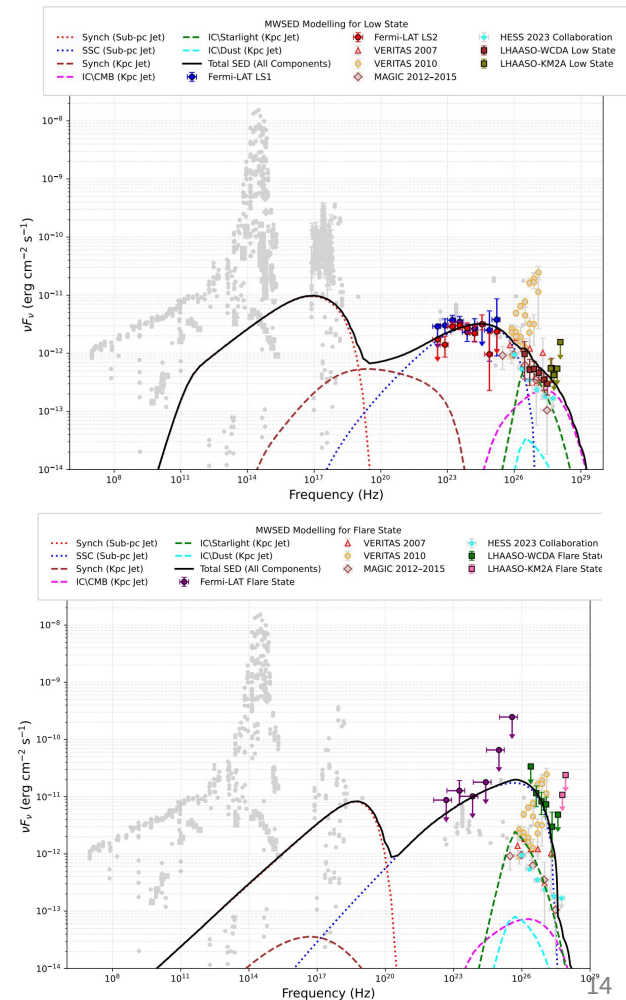
Parameters of the Second Dissipation Zone for Spectral Energy Distribution Fitting with the Two-zone Synchrotron Self-Compton Model

Free parameters	R (cm)	B (G)	$L_{e,\text{inj}}$ (erg s $^{-1}$)	$\gamma_{e,b}$	$p_{e,1}$	
Values	2.7×10^{15} cm	2×10^{-4} G	1×10^{42}	5.0×10^8	2	
Derived/Fixed parameters	Γ	θ_{obs} (deg)	δ_D	$\gamma_{e,\text{min}}$	$\gamma_{e,\text{max}}$	$p_{e,2}$
Values	3	15	3.7	1	$\gamma_{e,b}$	$p_{e,1}$

Extra: study of M87 flares

Models for the 2022 LHAASO flare:

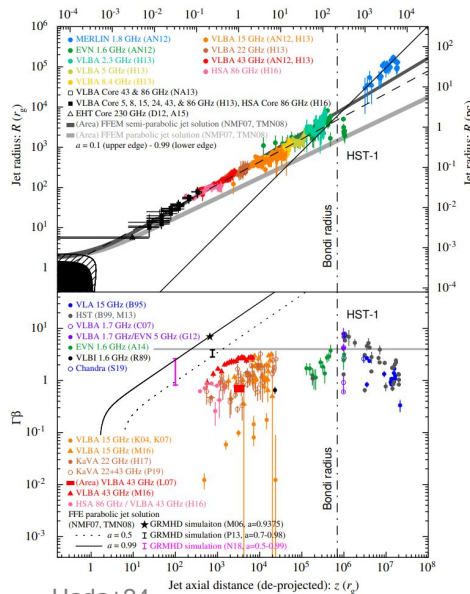
- Xue et al. (2025): construct averaged MWL SEDs by combining data from Chandra and Swift-UVOT/XRT covering the same period as the LHAASO detection. Test several radiation mechanisms, including the pp interaction, proton synchrotron emission, and two-zone leptonic model. Only the pion decay gamma rays in pp interactions can interpret the possible hardening at TeV with a one-zone model. The two-zone leptonic model is a viable alternative.
- Mondal et al. (2026): construct a low-state and high-state SED, modeled independently the two states with an SSC model. The low state gamma-ray flux results from the emissions from the subpc and the kpc scale jets of M87, while the flare state gamma-ray flux is mainly produced in the subpc scale jet.



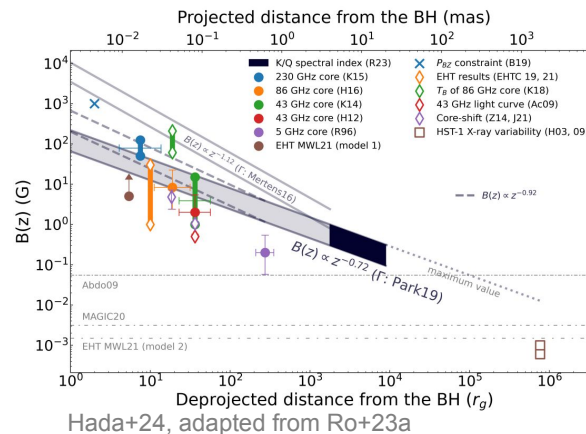
Extra: time-dependent kinetic modeling

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Constraints from observations:

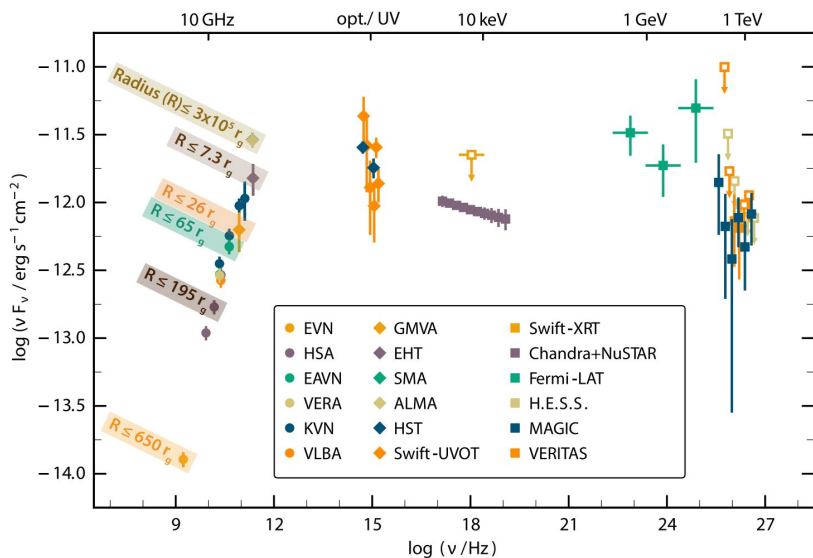


Hada+24

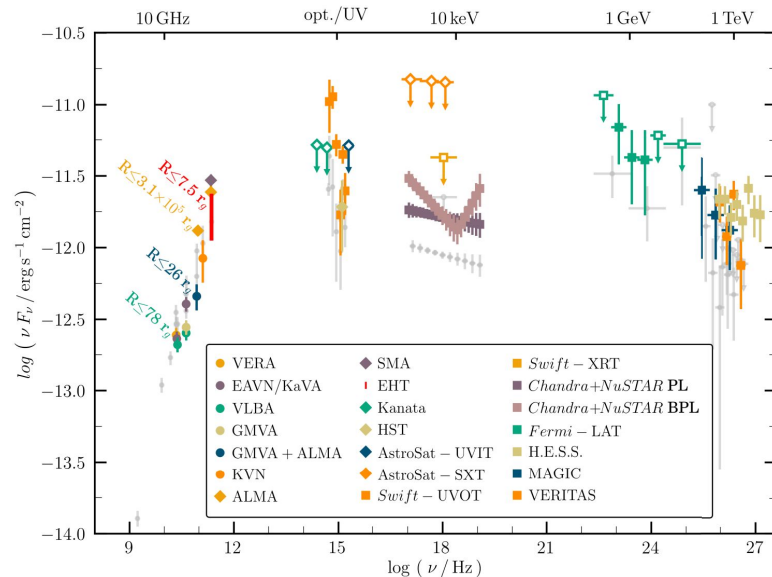


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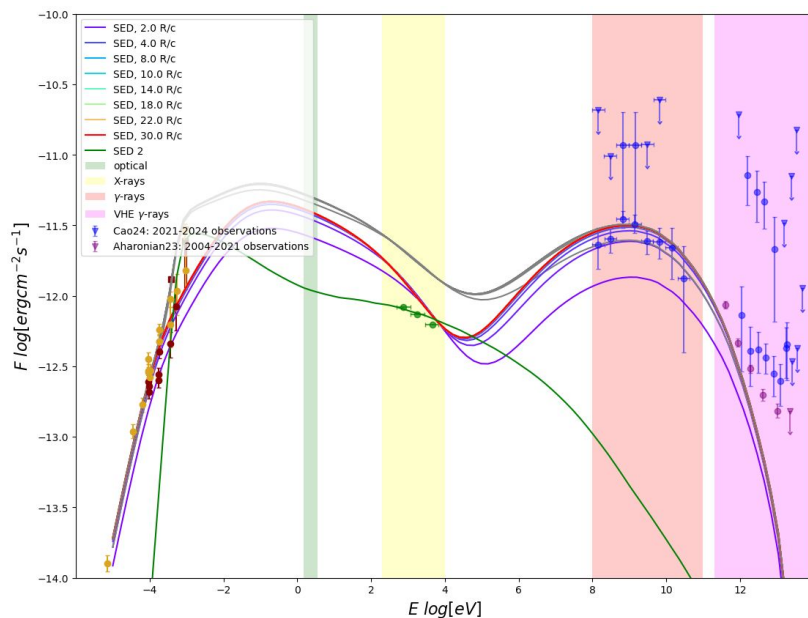
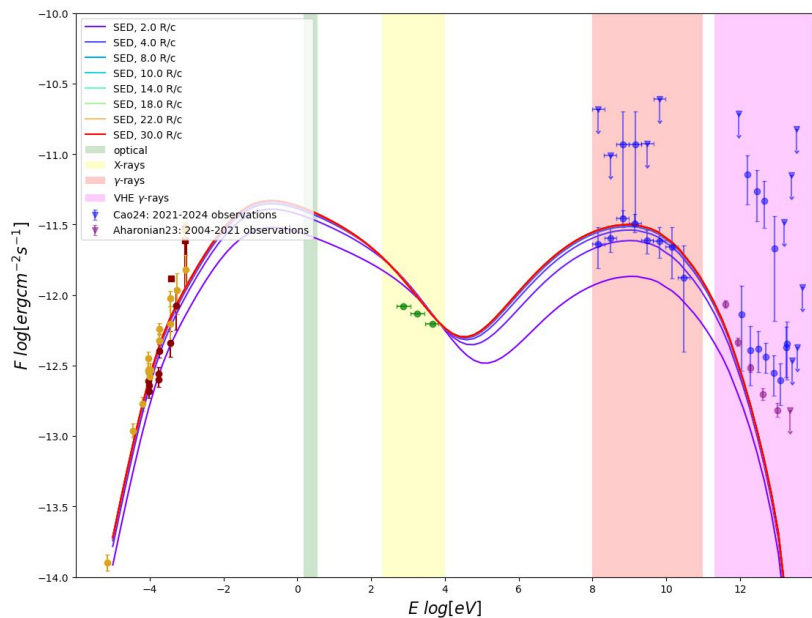
Alga+21



Alga+24

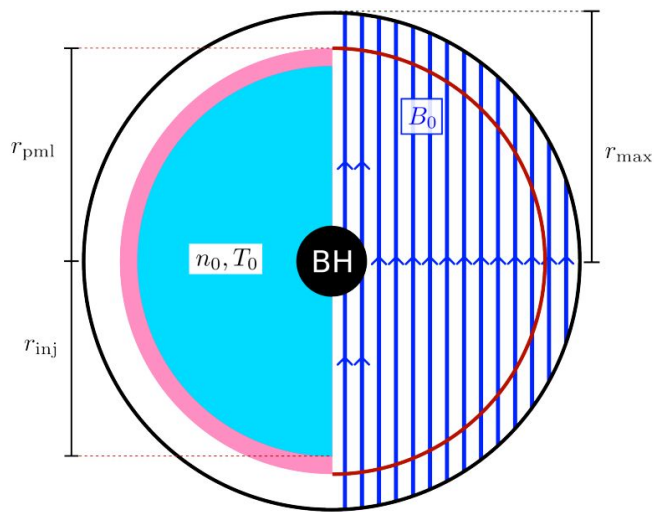
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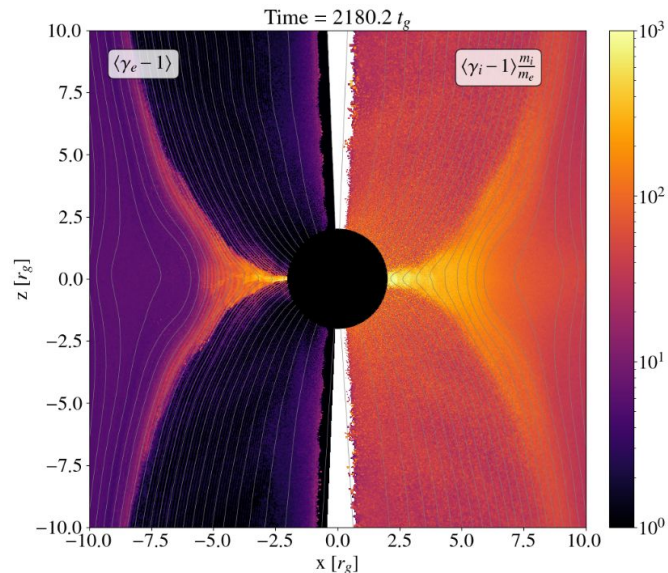


Extra: radiative transfer for GRPIC simulations

Simulation: spherical free-falling accretion onto a SMBH leading to magnetic reconnection events occurring close to the horizon and strong eruption cycles.

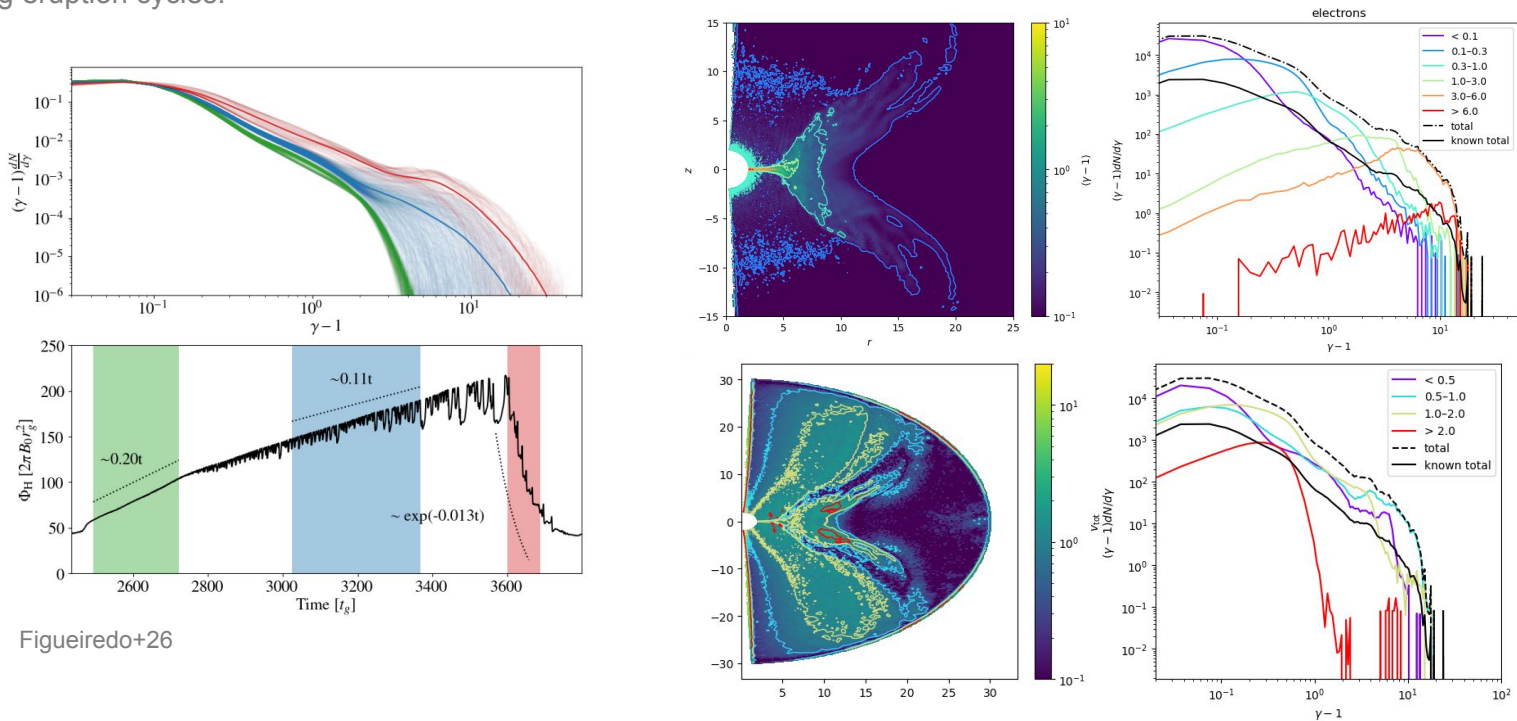


Figueiredo+26



Extra: radiative transfer for GRPIC simulations

Simulation: spherical free-falling accretion onto a SMBH leading to magnetic reconnection events occurring in the current sheet and strong eruption cycles.



Figureirodo+26