Frontier Research Institute for Interdisciplinary Sciences
Tohoku University

Theory of multi-wavelength flares from BH magnetospheres and strategy of joint monitoring observations of M87 with global VLBI, Swift, and CTA

This is not an official project of EHT, but a related project

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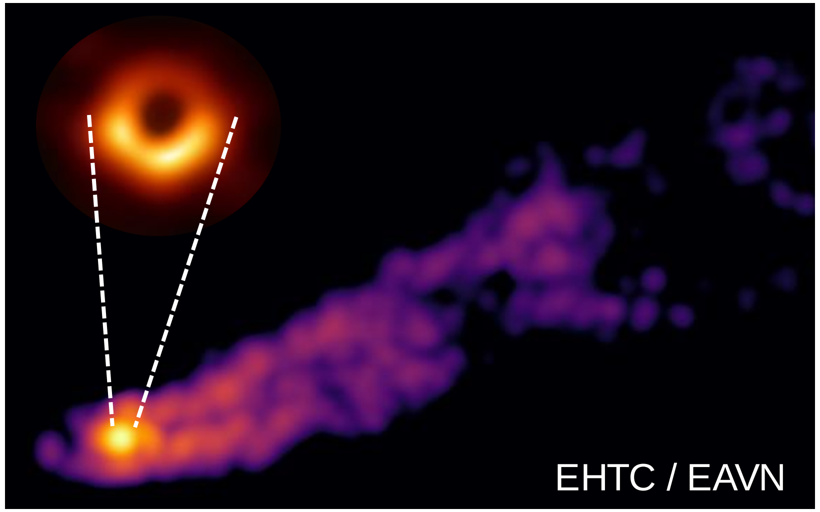
CTA-Japan Workshop @ICRR, Jan 8, 2025



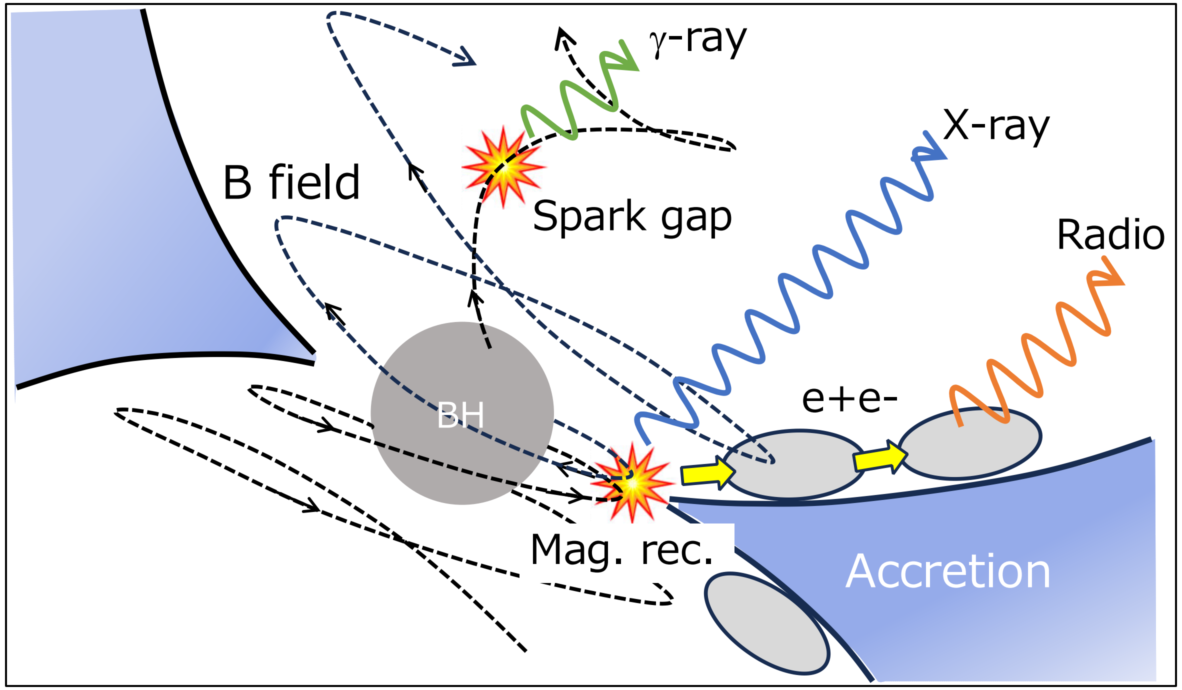
Outline

- Driving mechanism of BH jet & current observational indications

- Our new 86GHz VLBI network
  (cf. Lu, Asada et al. 2023)

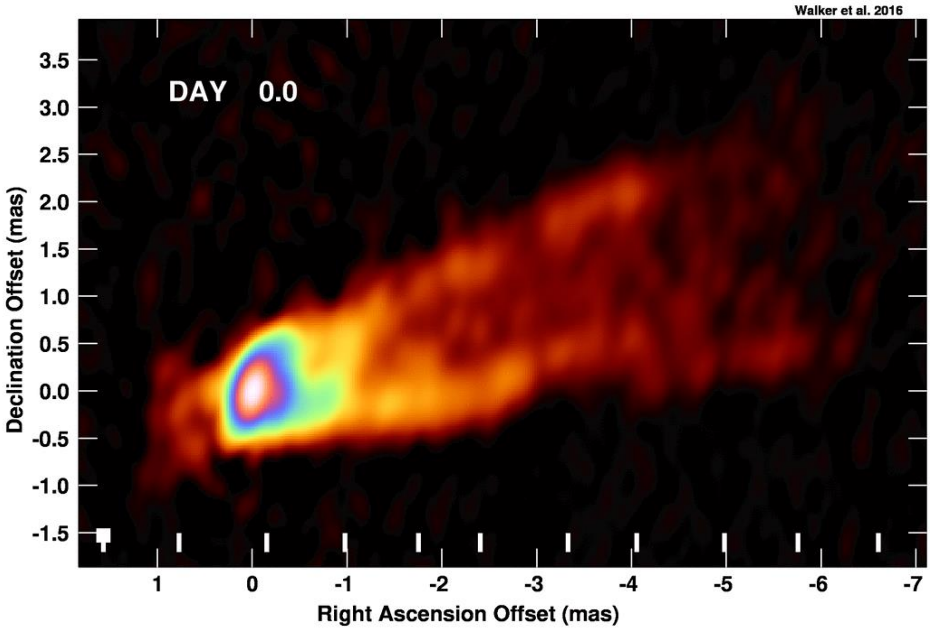
- Recent extremely high-resolution GRMHD simulations and radio features

- Non-thermal effects in BH magnetosphere and X-ray/γ-ray flares
  (Kimura, KT, Noda & Hada 2022; Kisaka, Levinson & KT 2022)

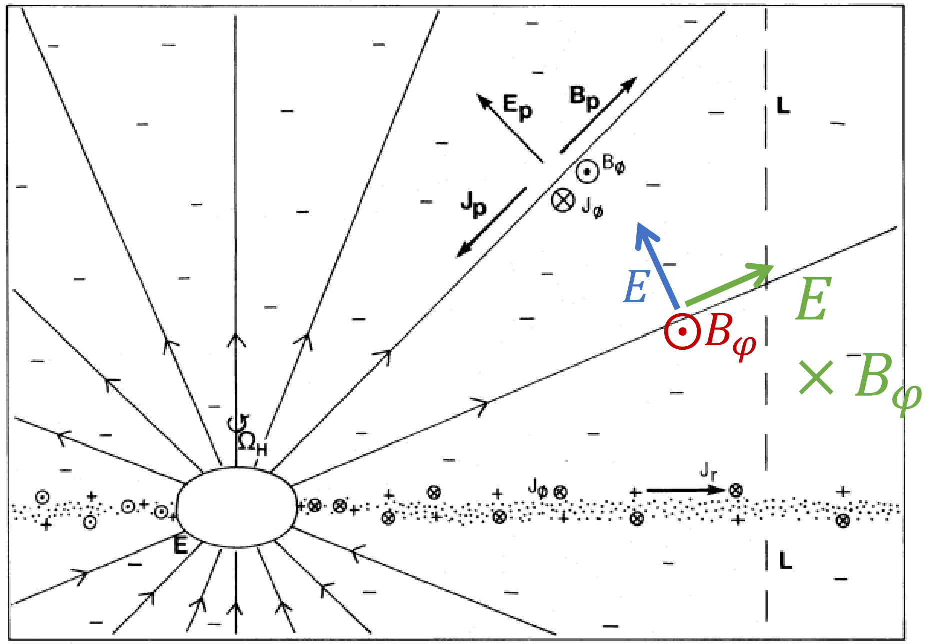


Driving mechanism of black hole jets

43 GHz VLBI observation of M87



BZ process



Steady outward Poynting flux along magnetic field lines threading a rotating BH in magnetically-dominated plasma (magnetosphere)

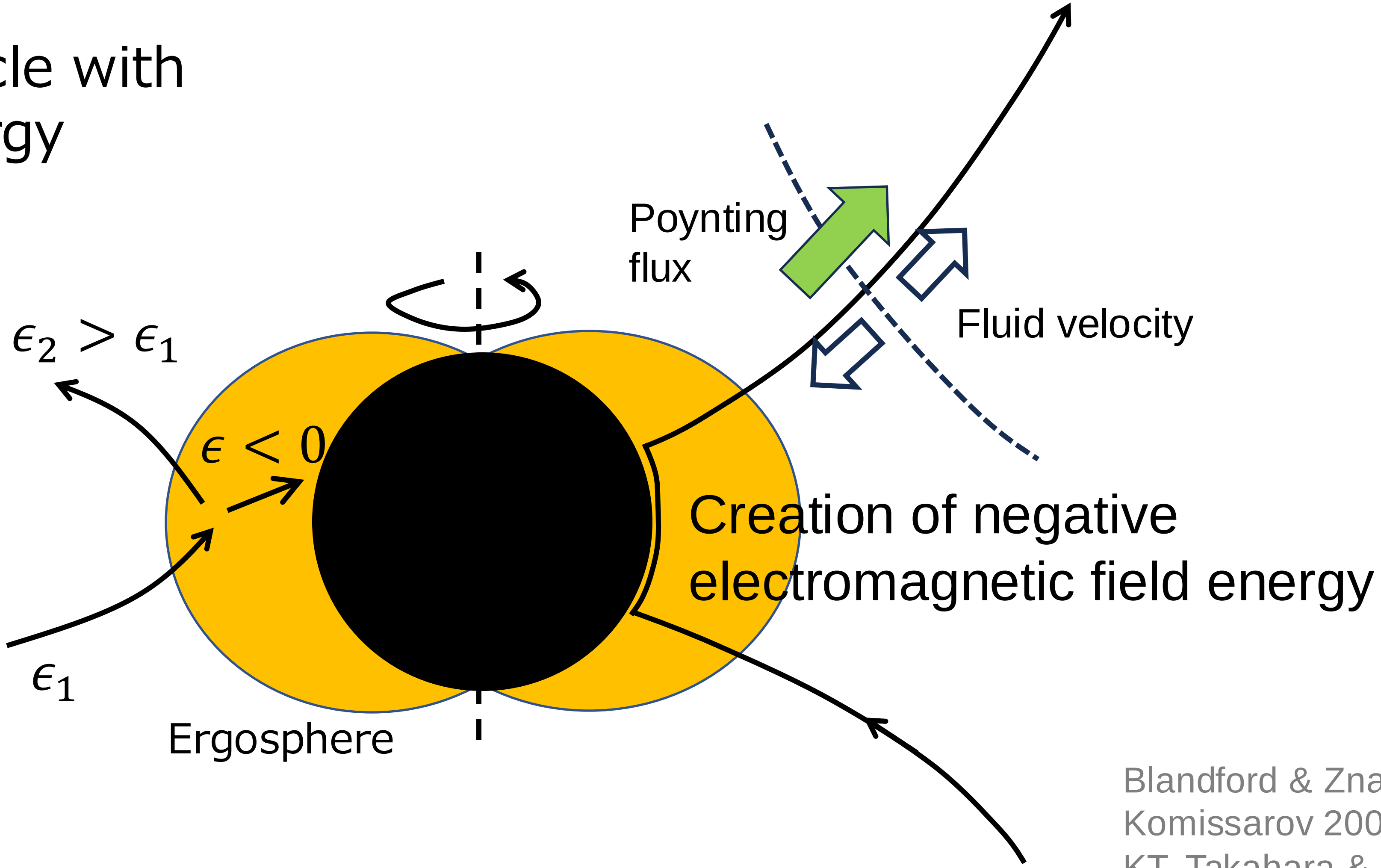
Walker et al. 2016; Blandford & Znajek 1977

Extraction of BH rotational energy

- Mechanical Penrose process:

  Infall of particle with negative energy

- BZ process:

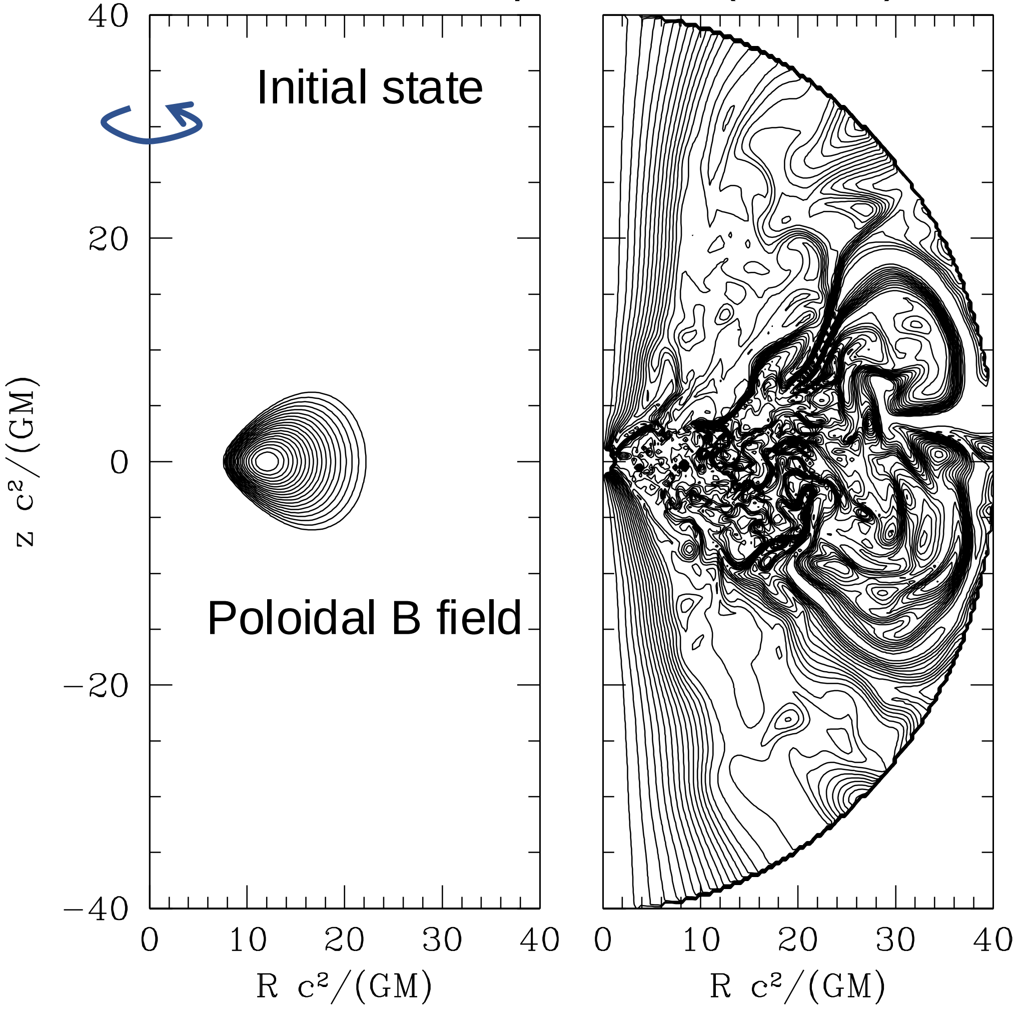


Penrose 1969

Blandford & Znajek 1977;
Komissarov 2009;
KT, Takahara & Nakamura 2024

GRMHD simulations

Fixed Kerr spacetime (a=0.94)

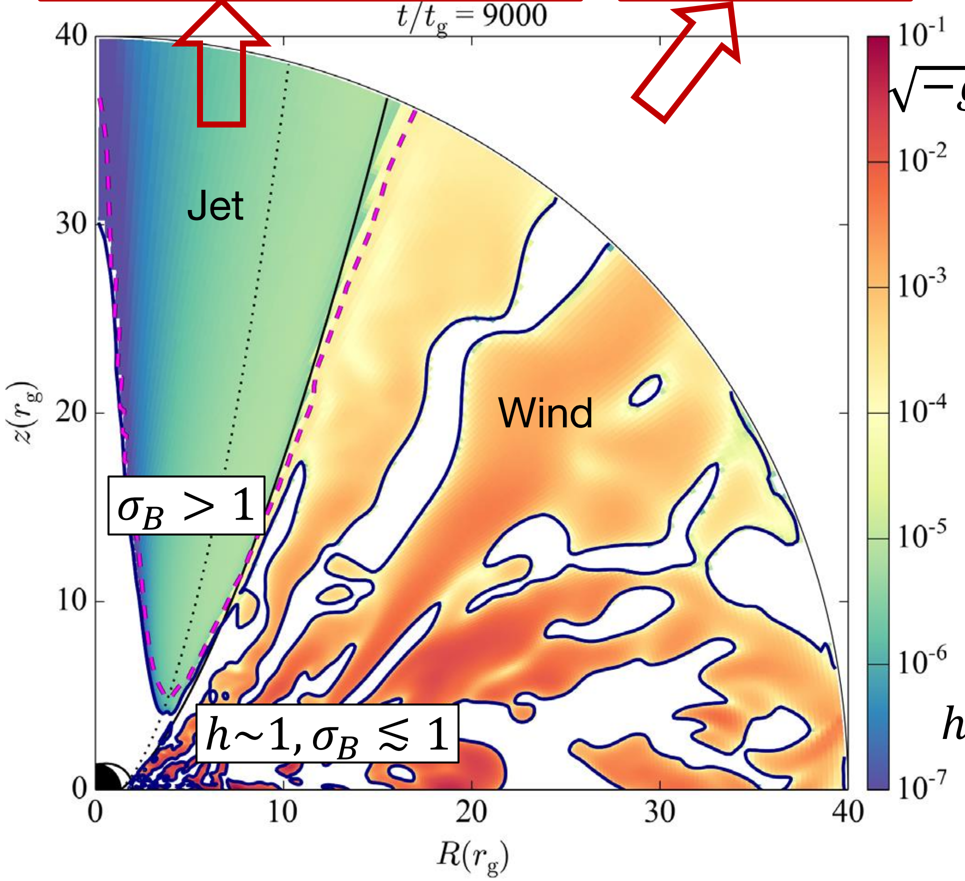


MAGNETOSPHERE

Relativistic speed (radio blobs $v_{app} > c$)

DISK WIND

Non-relativistic

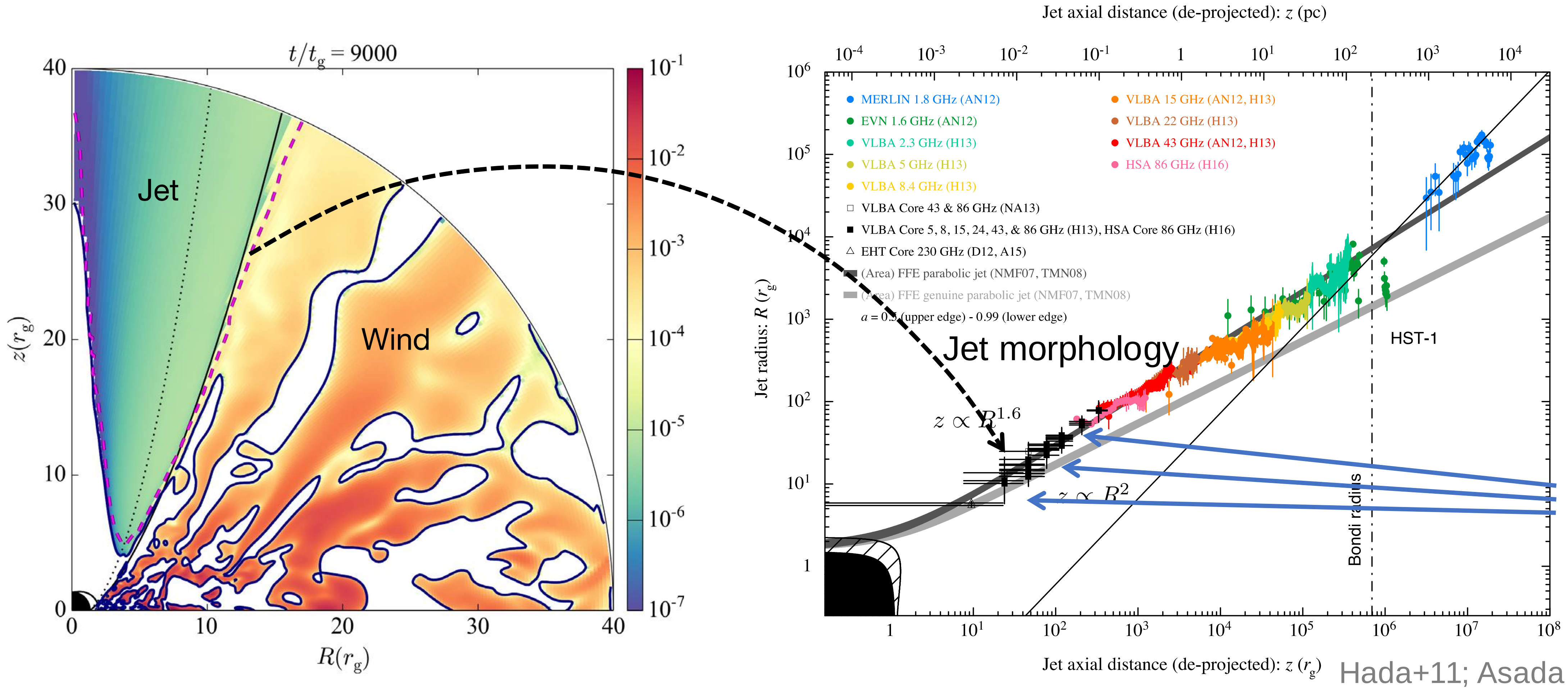


$$\sigma_B = \frac{B^2/4\pi}{\rho c^2}$$

$$h = 1 + \frac{\gamma}{\gamma - 1}\frac{P}{\rho c^2}$$

Blandford & Znajek 1977; Komissarov 01; 04; Koide+02; McKinney & Gammie 04; Barkov & Komissarov 08; Tchekhovskoy+11; Ruiz+12; Contopoulos+13; Takahashi+16; Nakamura, Asada+(KT)18; Porth+19; Liska+20; Ripperda+21

VLBI observations of M87



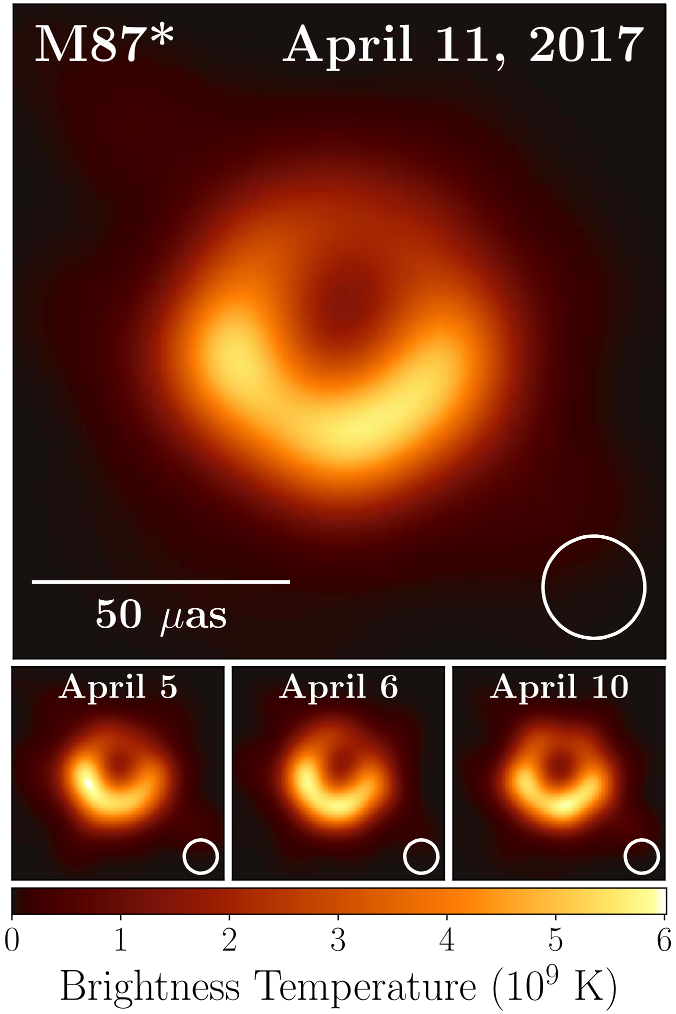
Core shift

$$1 = \tau_{SSA,\nu} \propto n_e B^2 \nu^{-3} L$$

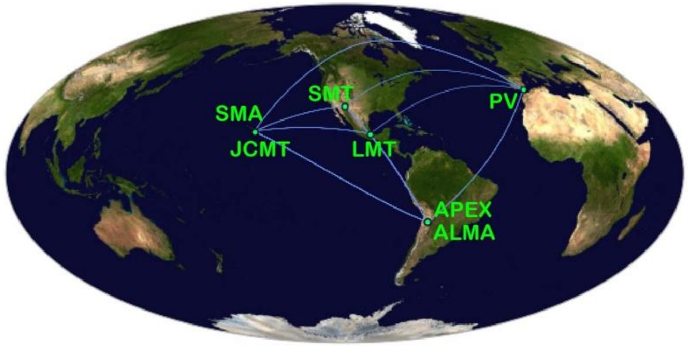
Hada+11; Asada & Nakamura 12; Hada+13; Kino+15; Nakamura+18

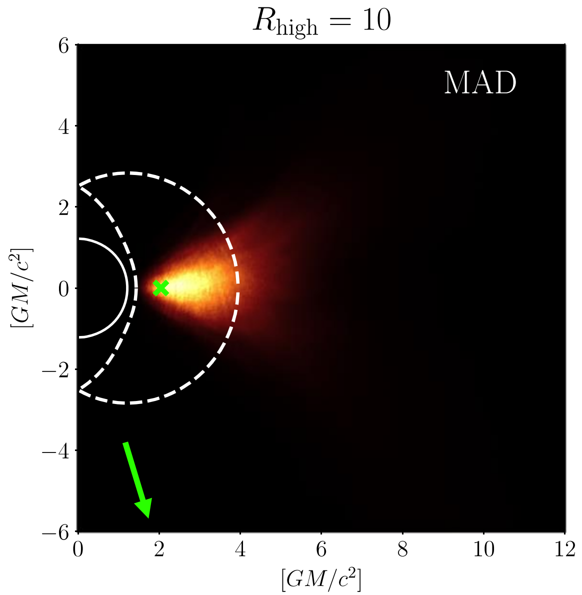
We want to see some kind of more direct evidence of this system (magnetosphere + accretion flow) and BZ process if possible

Event Horizon Telescope

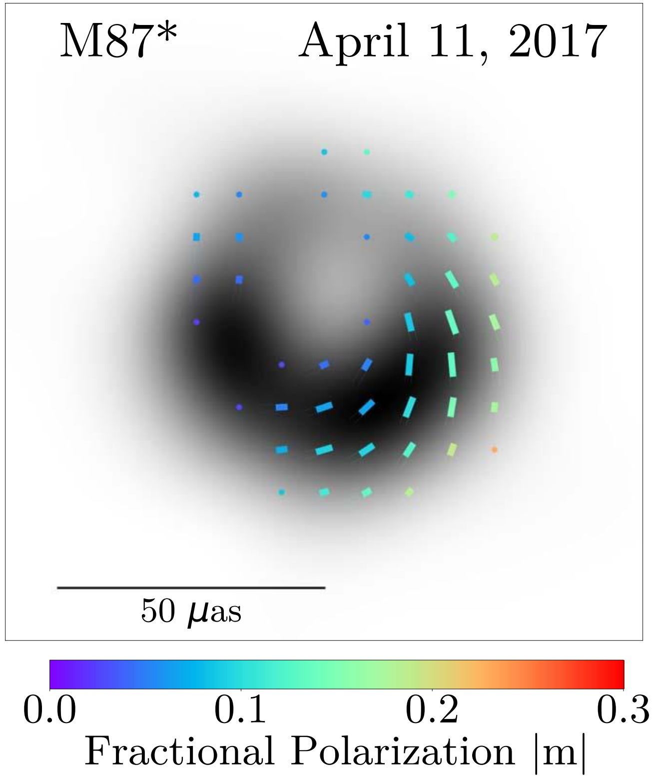


230 GHz VLBI network





Origins of photons that make the ring-like emission in GRMHD simulation

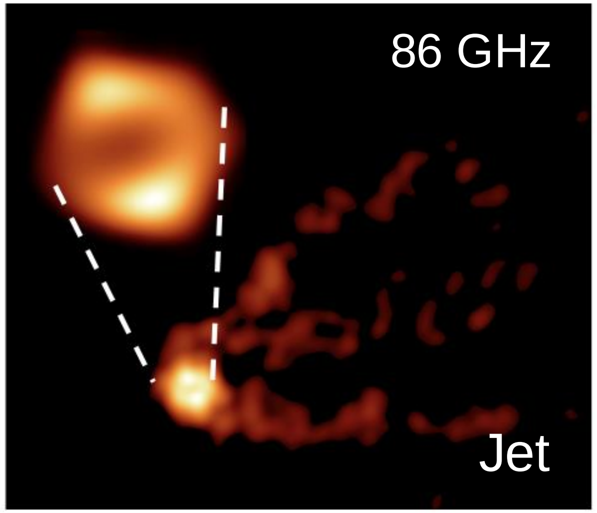


- Optically-thin synchrotron emission
- Linear polarization suggests magnetically arrested disk

EHTC 2019; 2021

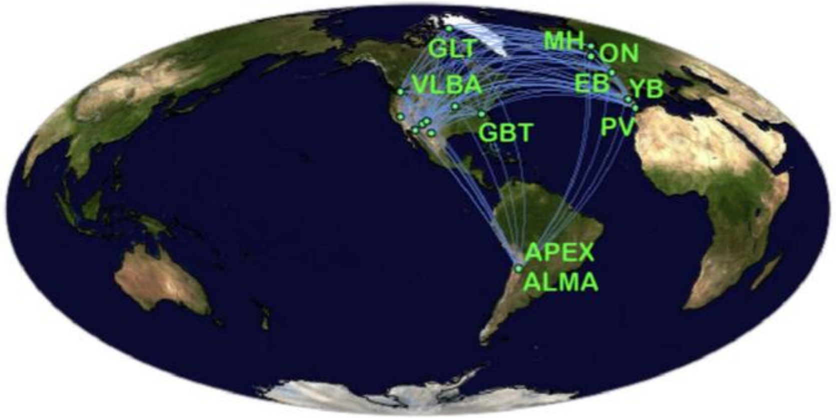
New 86 GHz VLBI network for monitoring M87

A little bit larger ring than EHT observed (230GHz)

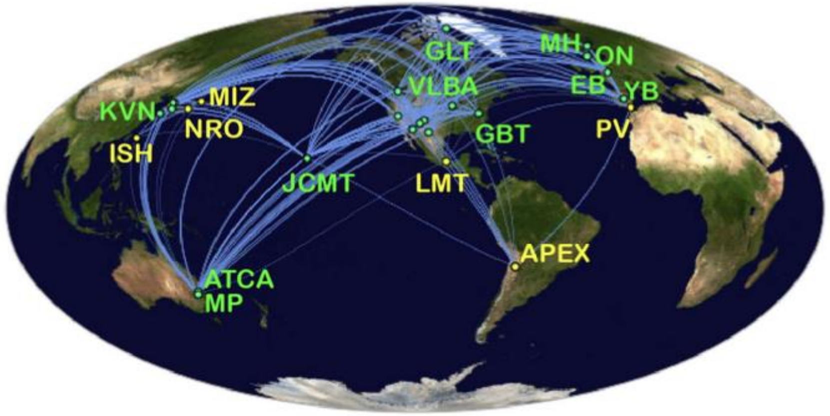


Lu, Asada et al. 2023

2018



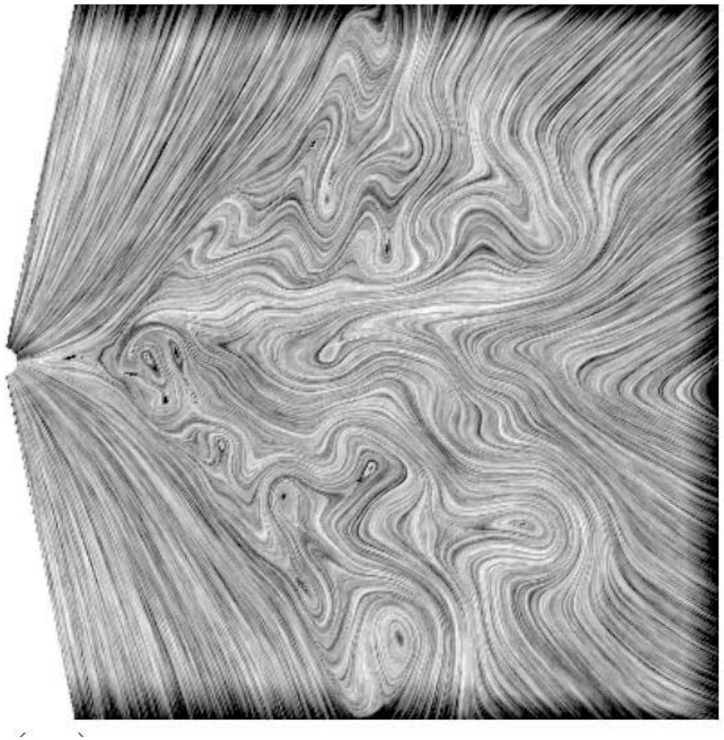
2025 Dec

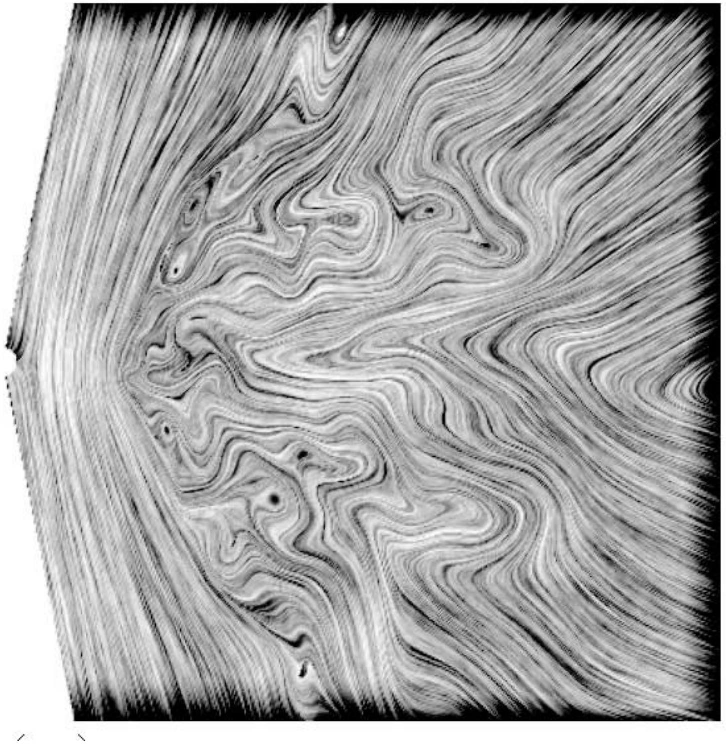


- Multiple observations in a year (Dec - June)
- Without ALMA
- Similar level of angular resolution

Magnetically arrested disks (MADs)

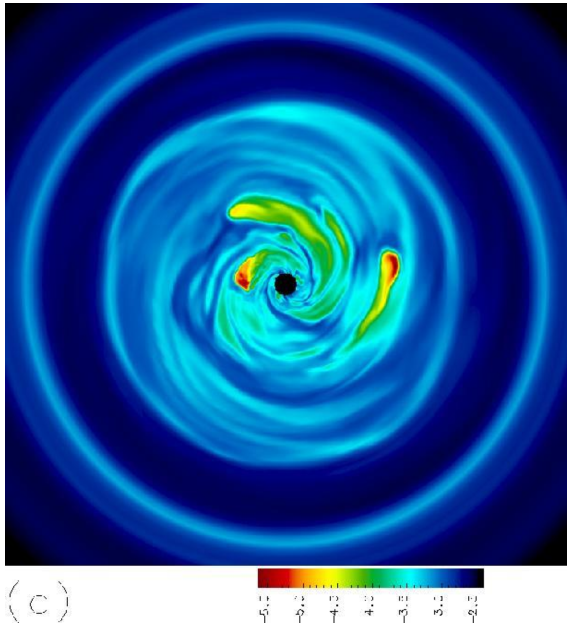
2D Schwarzschild, non-relativistic MHD





Magnetic flux accumulation around the BH halts the accretion

3D



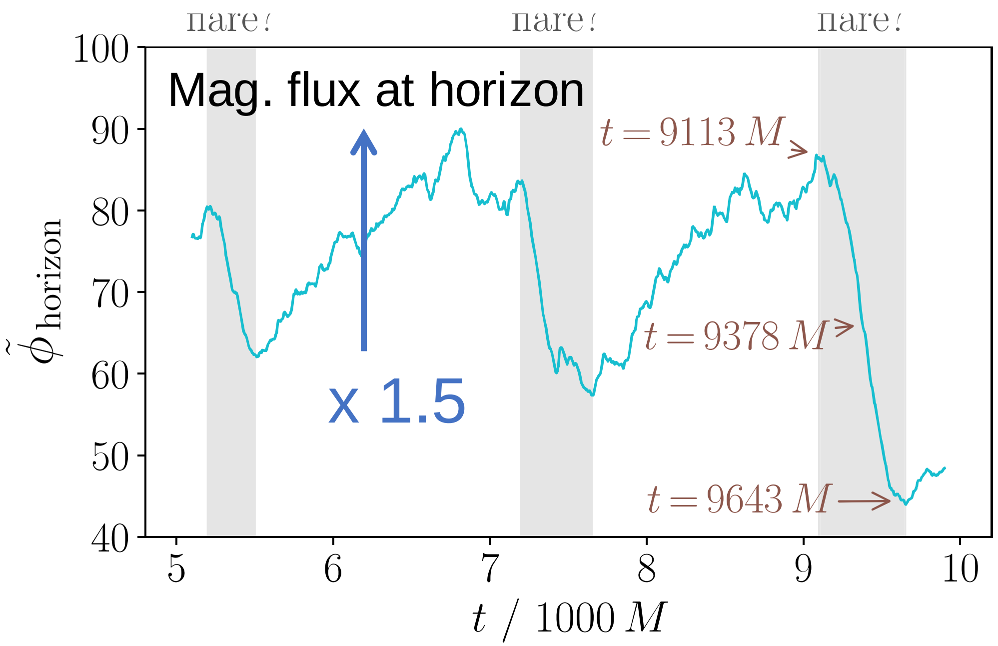
(c)

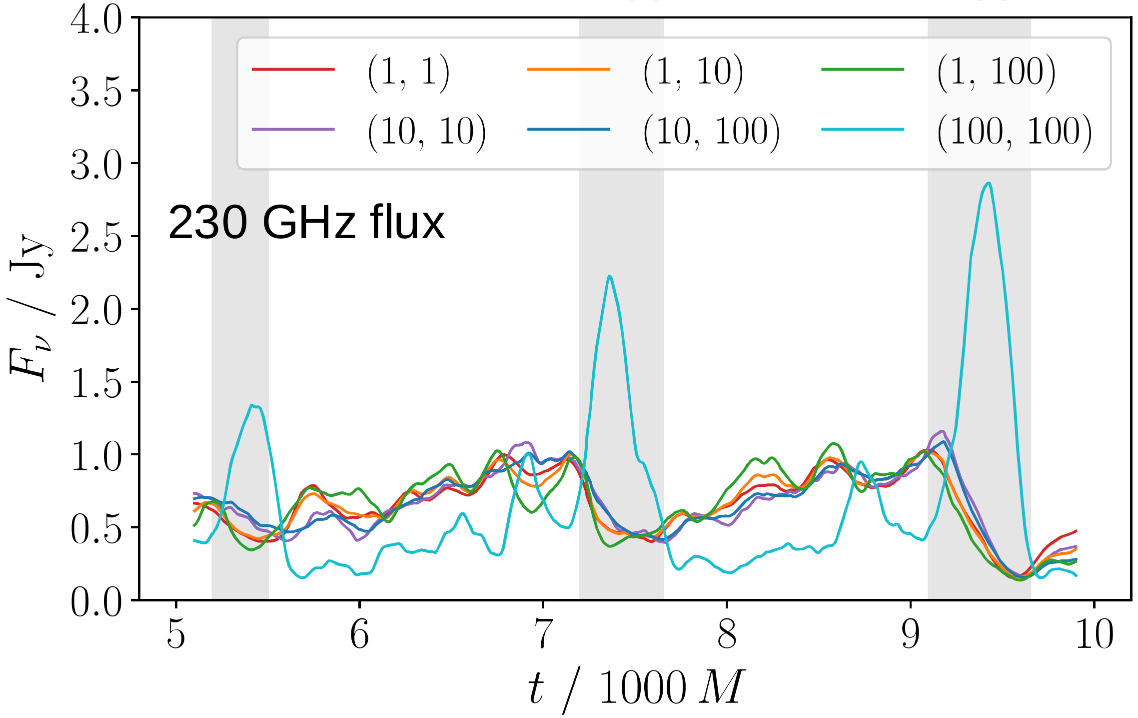
In 3D simulations, Rayleigh-Taylor type instability maintains the accretion

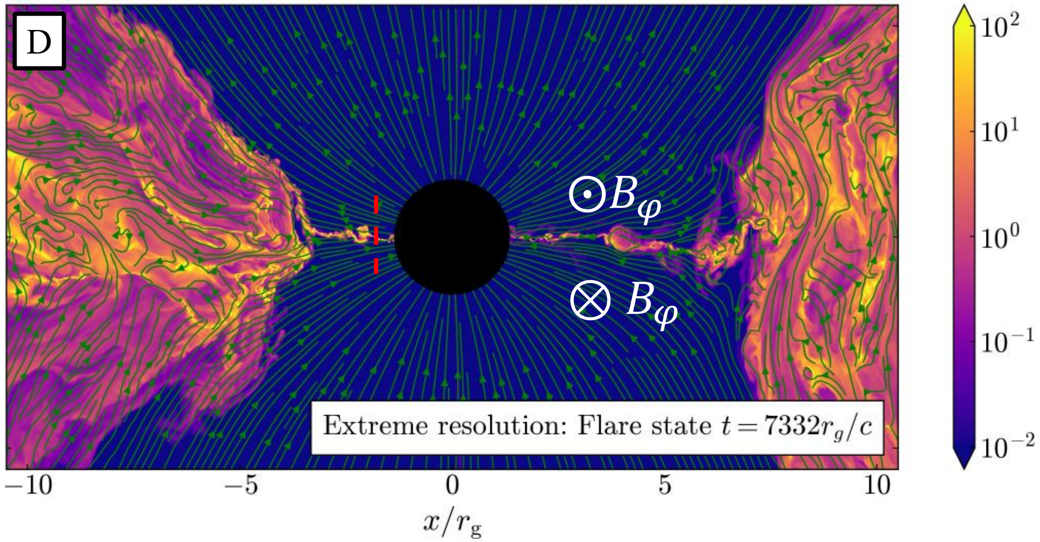
Igumenshchev 2008;
Bisnovatyi-Kogan & Ruzmaikin 1974; Narayan et al. 2003

Extremely high-resolution GRMHD simulations of MADs

Ripperda+22; Jia, Ripperda+23



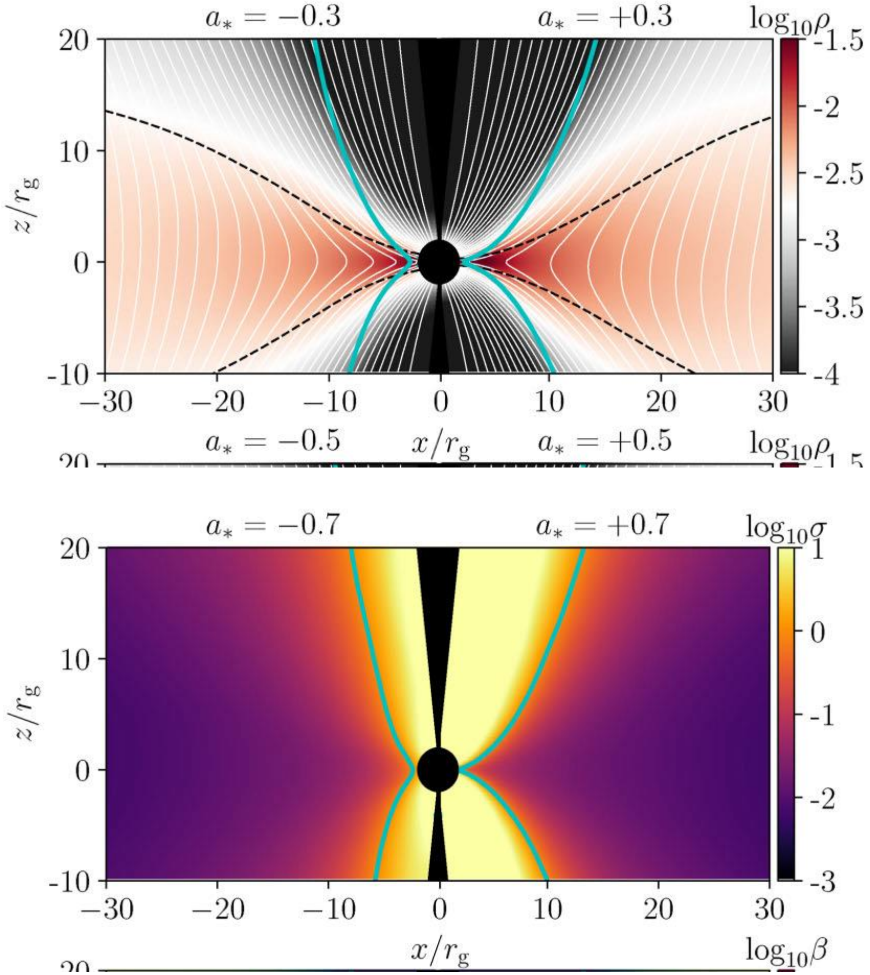




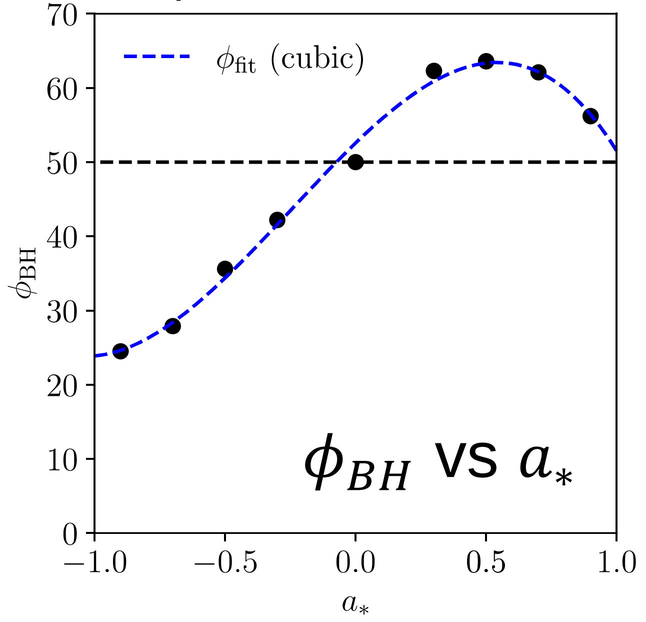
- The non-axisymmetric accretion is associated with mag. flux eruption and mag. reconnection
- Radio flux varies quasi-periodically
- The period is ~ 2 yr for M87

Variation of jet width

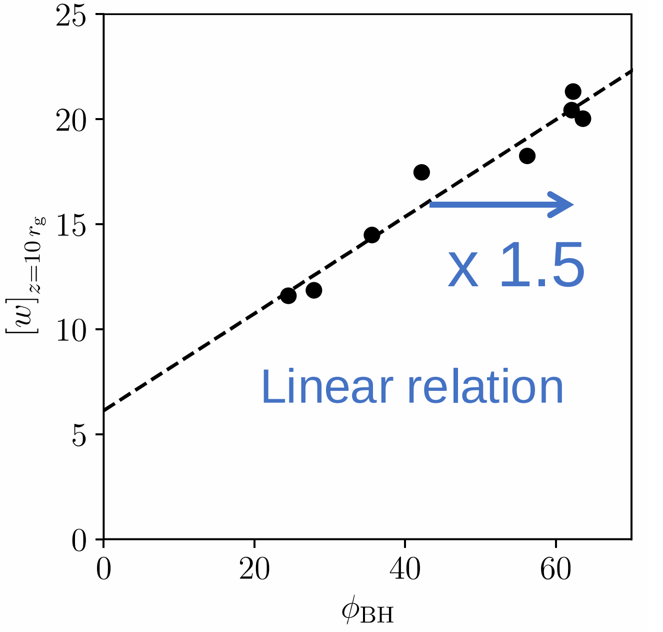
Retrograde   Prograde



Time-averaged mag. Flux vs spin



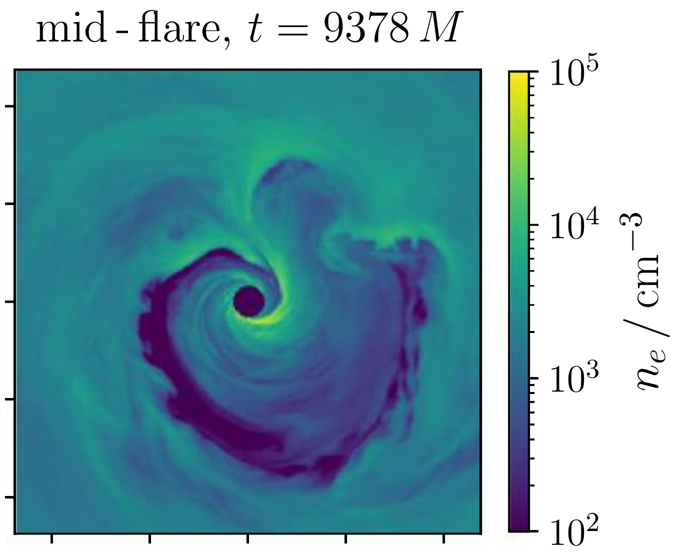
Jet width@10r_g vs mag. flux

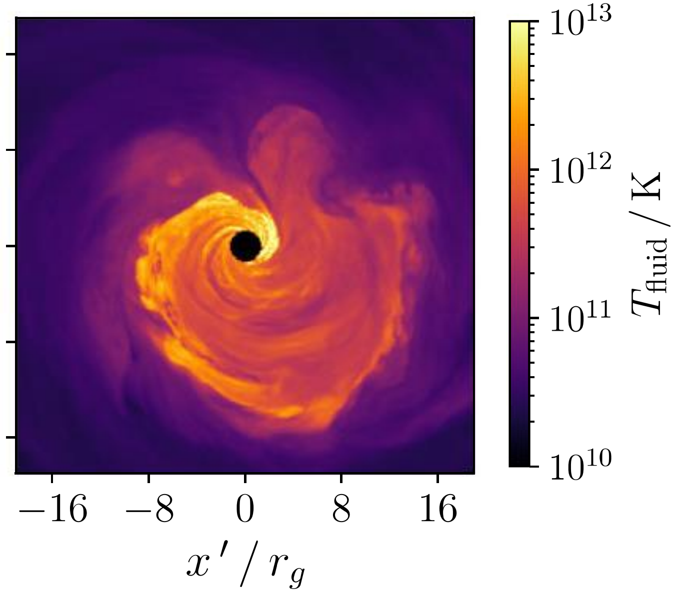


- The magnetosphere (jet) with 1.5 times larger magnetic flux is 1.5 times wider
- This suggests quasi-periodic variation of the jet width

Narayan, Chael et al. 2022

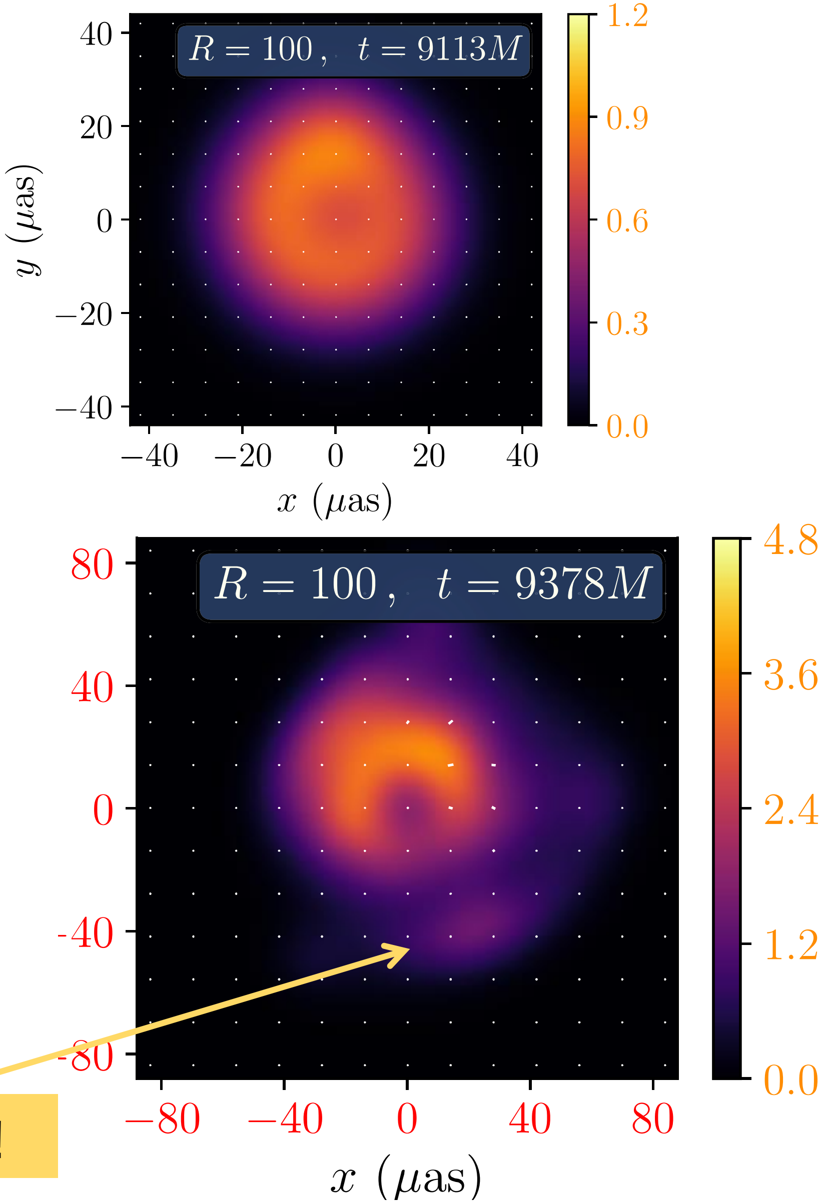
Magnetic reconnection outflow





Magnetic reconnection &
Non-axisymmetric accretion

230 GHz image

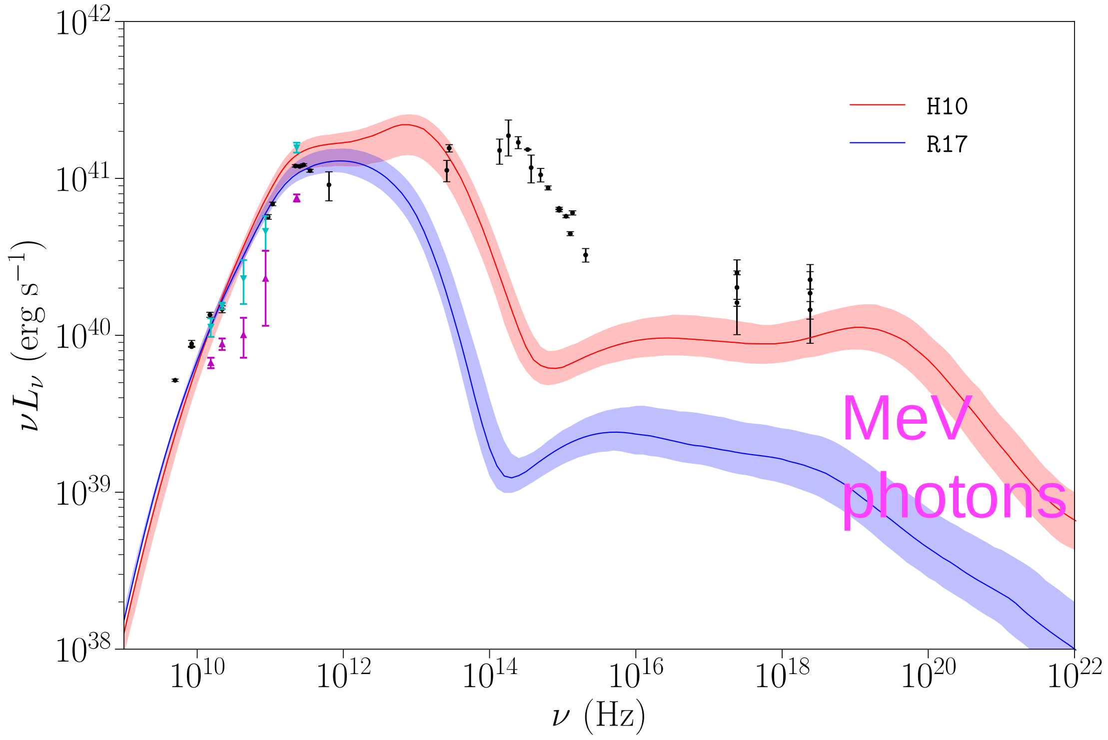


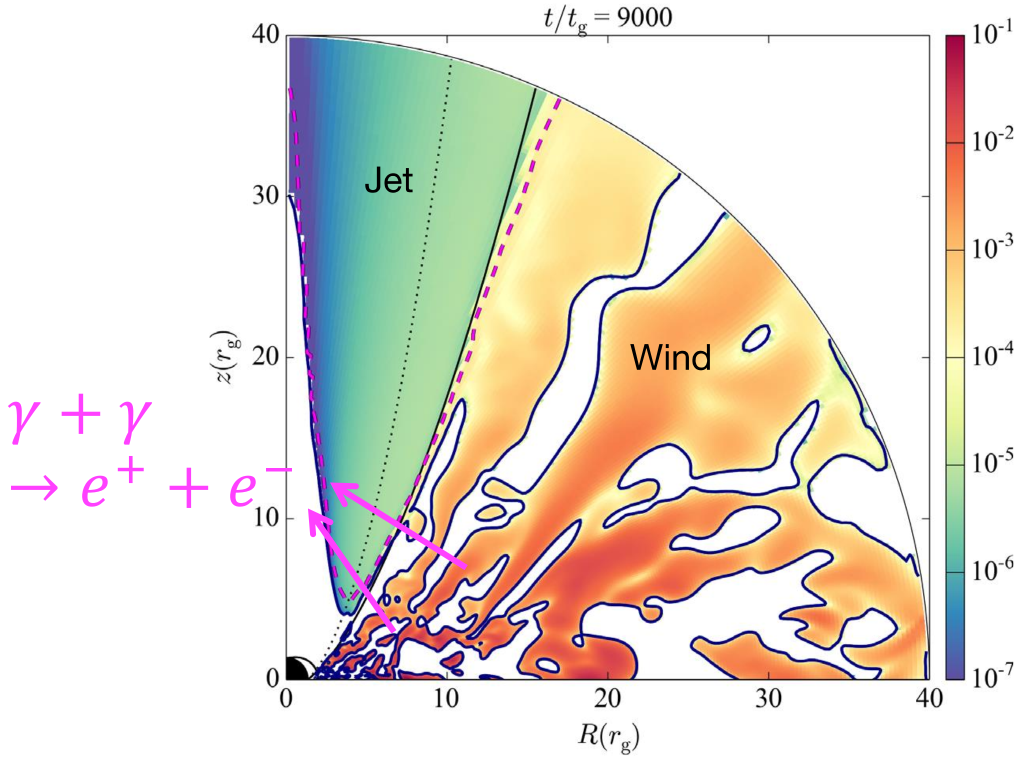
- Magnetic flux eruption with magnetic reconnection produces hot bubble, which may be observable by horizon-scale VLBI

Blob emergence !

Ripperda+22; Jia, Ripperda+23

Plasma density in the magnetosphere





- Pair creation by MeV gamma-rays from $R \sim 10 r_g$

$$n_\pm \sim \sigma_{\gamma\gamma} r_g \left(\frac{L_{\rm MeV}}{4\pi R^2 c\, \epsilon_{\rm MeV}} \right)^2 \sim 2 \times 10^{-5}\ L_{\rm MeV,39}^2 R_1^{-4} M_9^{-3}\ {\rm cm}^{-3}$$

- Charged particle density required for steady outward Poynting flux

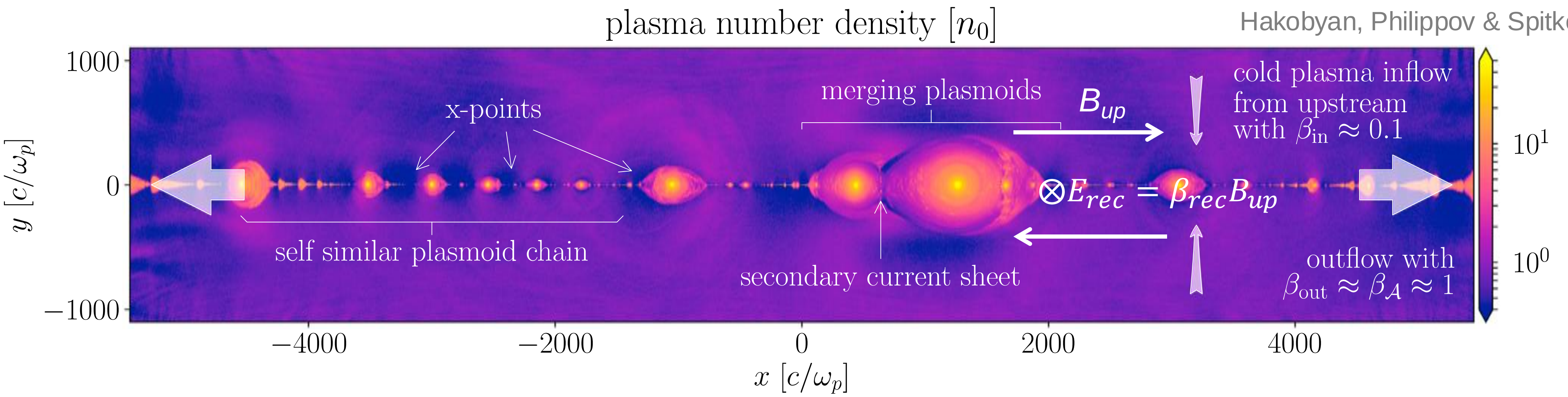
$$n_{\rm GJ} = \frac{\Omega_{\rm F} B}{2\pi e c} \approx \frac{B}{8\pi e r_g} \simeq 5 \times 10^{-5}\ B_2 M_9^{-1}\ {\rm cm}^{-3}$$

$\sigma_{B,GJ} \sim 10^{13}$!!

Levinson & Rieger 11; Kimura & KT 20; Chael+19

High-σ_B magnetic reconnection

Hakobyan, Philippov & Spitkovsky 19



This E-field potentially accelerates particles to $\gamma \gtrsim \sigma_B$, but...

Acceleration

Synchrotron drag

$$|e|E_{\rm rec} = \frac{\sigma_{\rm T}}{6\pi} B_{\rm up}^2 \gamma_{\rm syn}^2$$

$\gamma_{\rm syn} < \sigma_B$

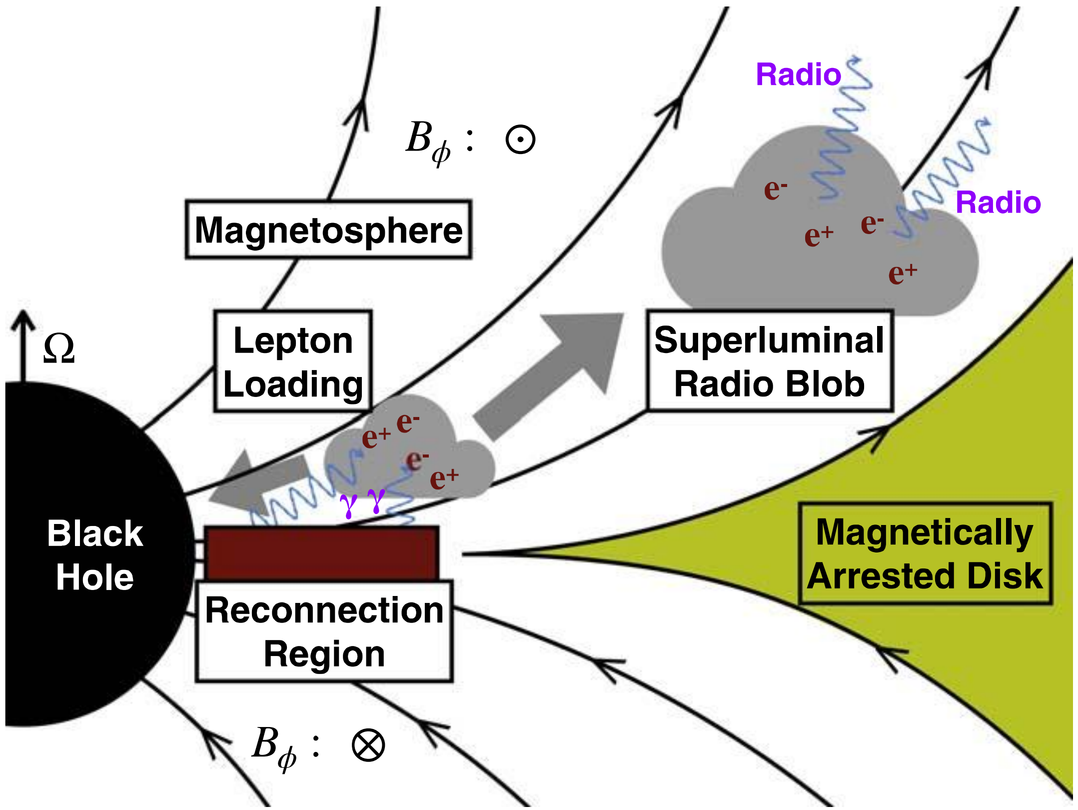
$$E_{\gamma,\rm max} = \frac{heB_{\rm up}\gamma_{\rm syn}^2}{2\pi m_e c} \simeq 16\ \beta_{\rm rec,-1}\ \mathrm{MeV}$$

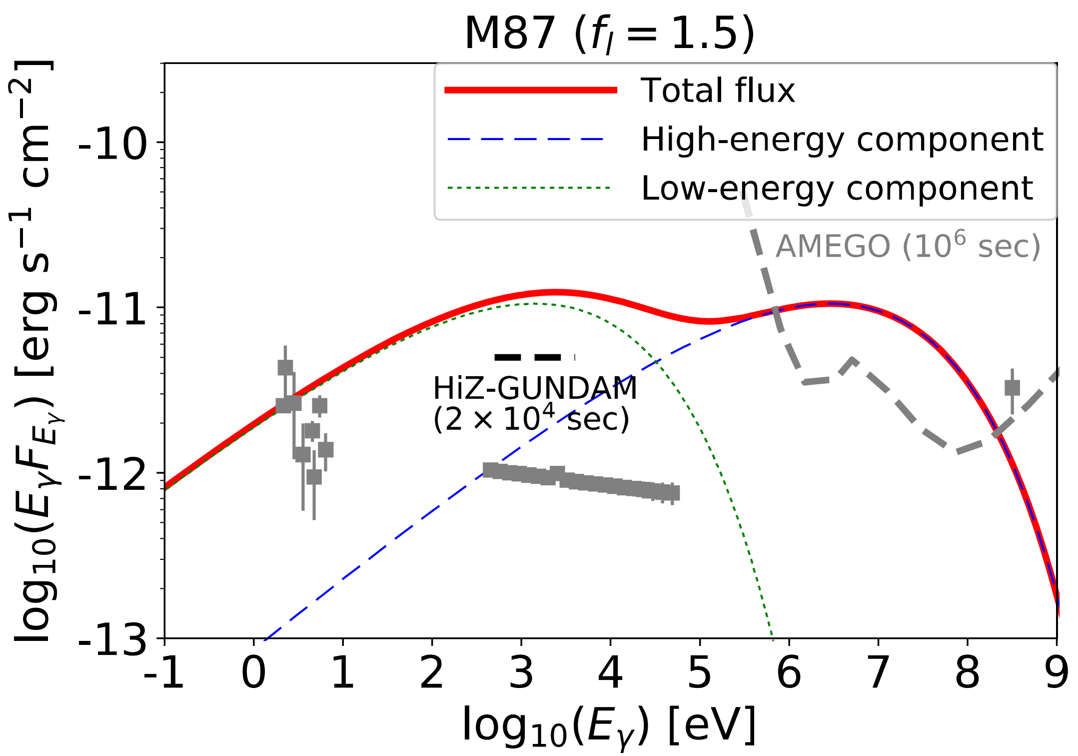
Synchrotron burn-off limit

- Efficient conversion of magnetic energy into MeV photons

e.g. Zenitani & Hoshino 01; Guo+14; 21; Zhang, Sironi & Giannios 21

X-ray flares

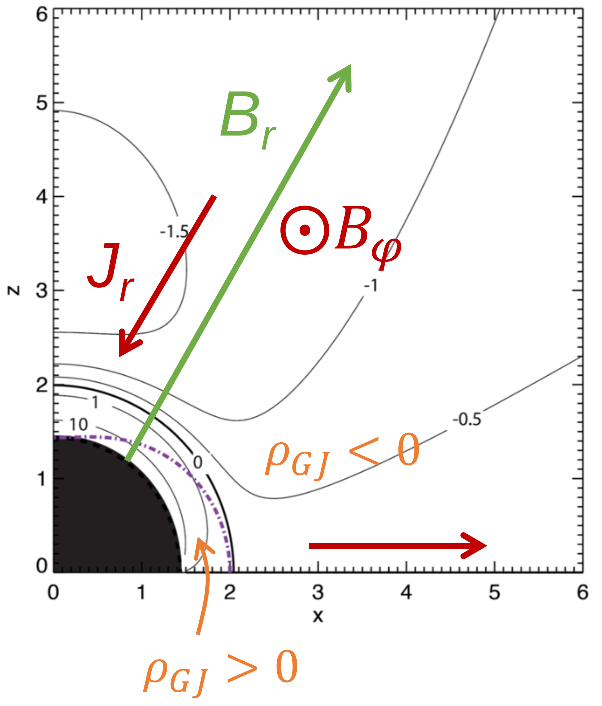


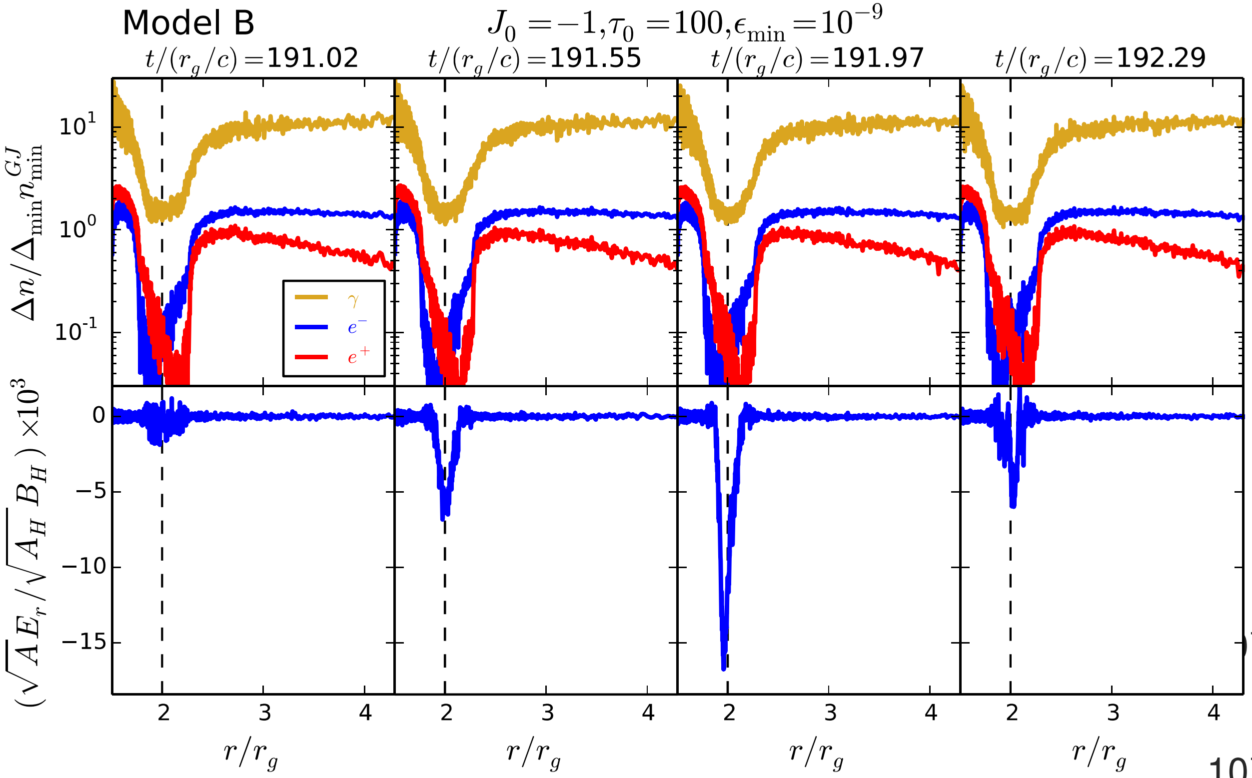


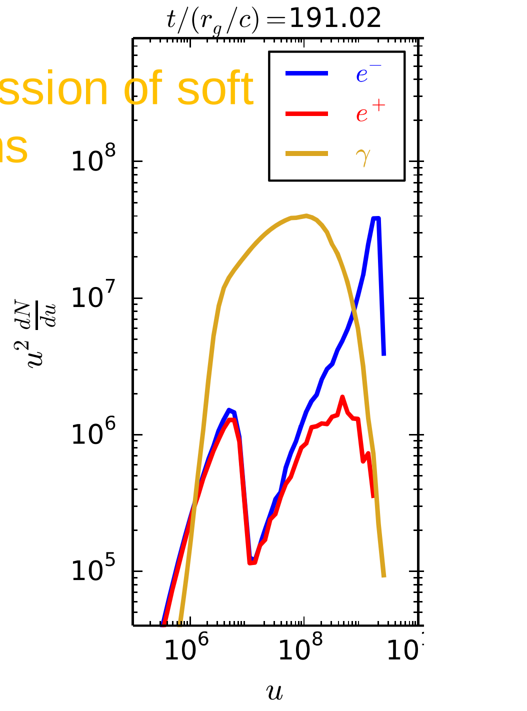
- At the reconnection region, particle acceleration produces large amount of MeV gamma-rays & X-rays, which form e+e- pairs inside the magnetosphere
- The amount of created e+e- pairs is sufficient for superluminal radio blobs

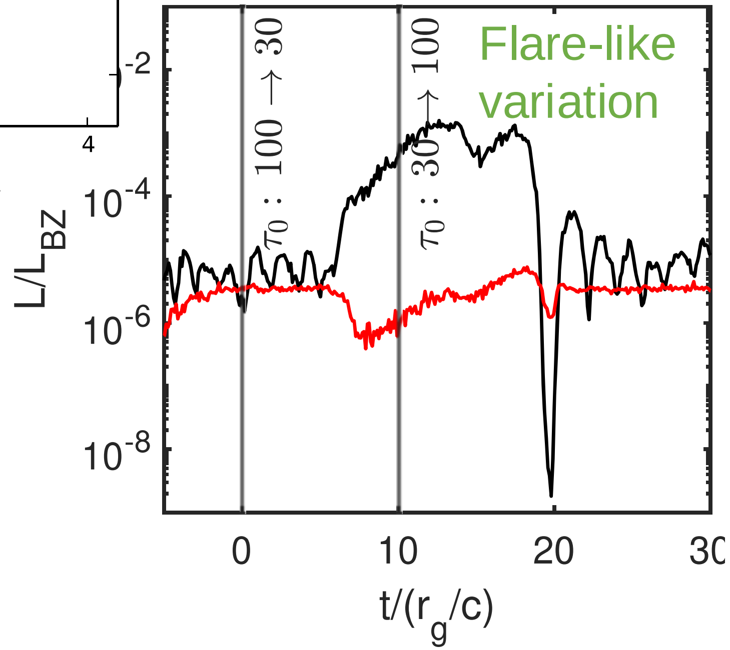
Kimura, KT, Noda & Hada 2022; Chen, Uzdensity & Dexter 2023; Hakobyan et al. 2023

GR-PIC simulations: 1D





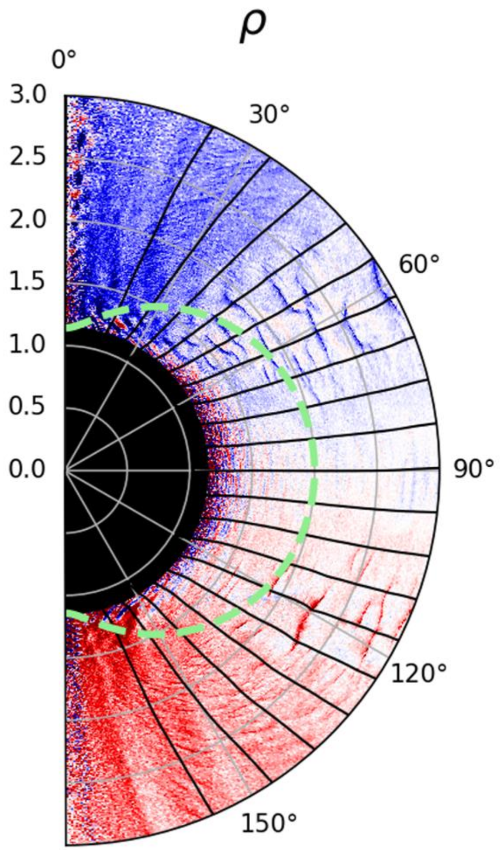


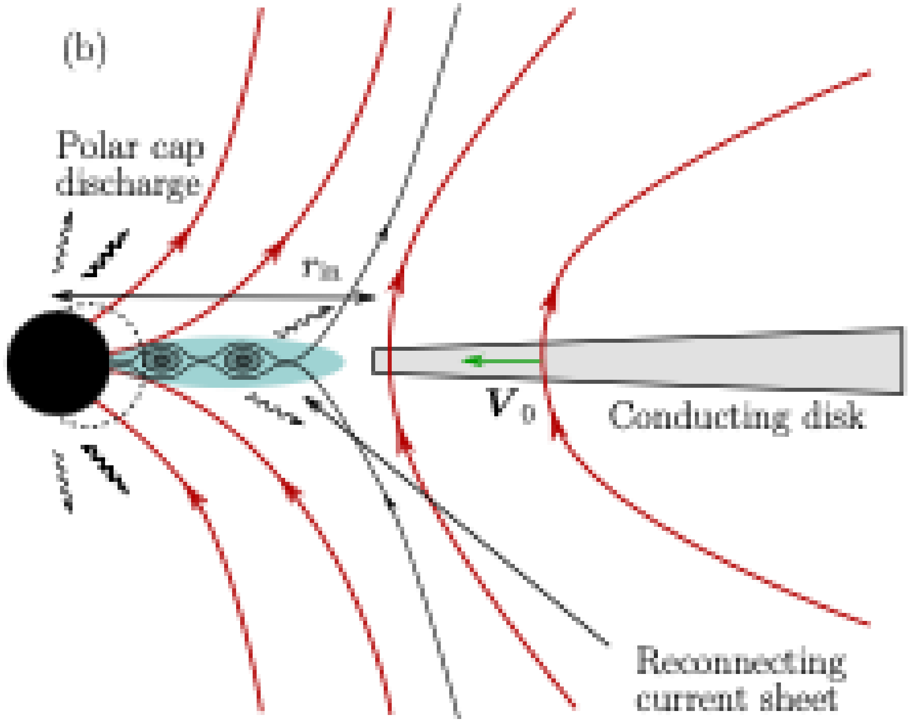


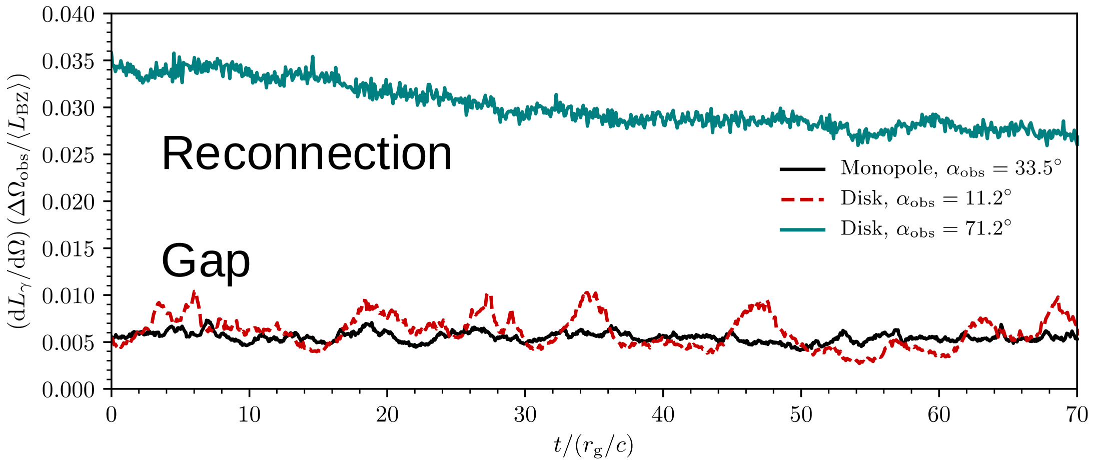
In the low density case, the longitudinal E field develops, which accelerates the leptons to very high energies

Levinson & Segev 17; Levison & Cerutti 18;
Kisaka, Levinson & KT 20, 22; Kin, Kisaka, KT et al. 24

GR-PIC simulations: 2D





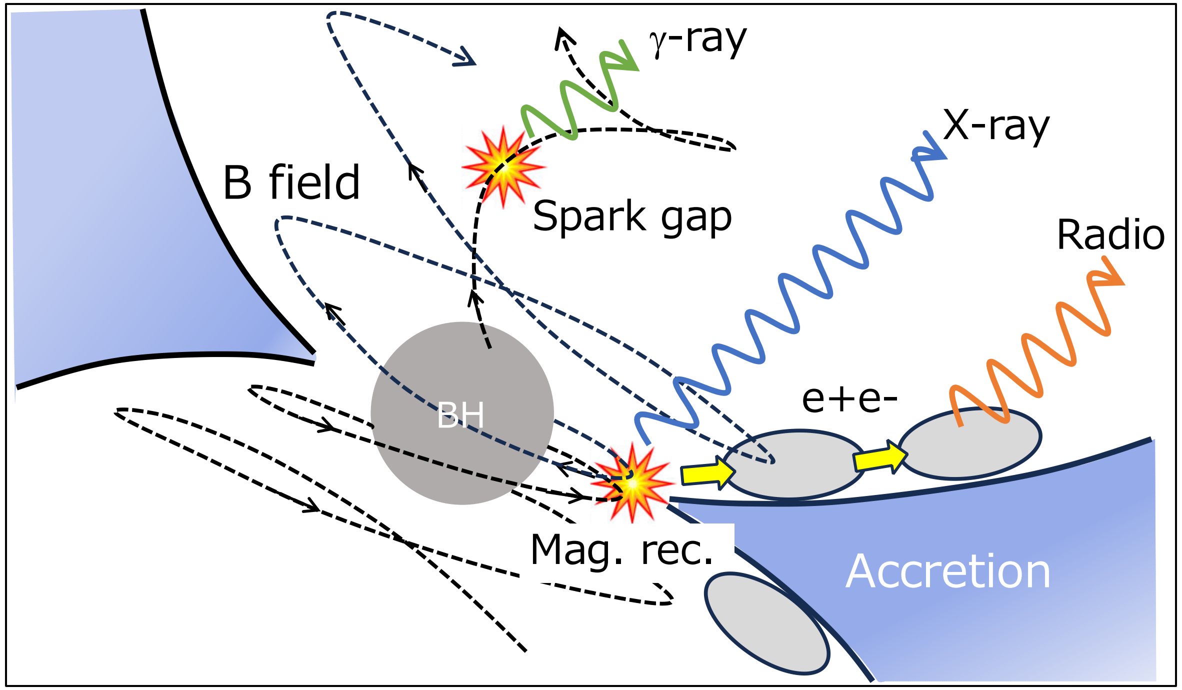


- We are preparing our 2D GR-PIC simulations to investigate relationship between the gap flares and the equatorial reconnection

Crinquand, Cerutti+21

VLBI / X / γ joint monitoring

- If we are lucky enough, we cover the mag. flux eruption phase with our new VLBI network
- We can also monitor it with Swift and CTA
- VLBI cannot send alert



	2025	2026	2027	2028	2029–2030
Theory	GRMHD/GRPIC simulations				Theory-obs Comparison
86 GHz VLBI	Preparation	Obs	Obs	Analysis	
X-ray / VHEγ		Obs	Obs	Analysis	

Summary

- Radio galaxy M87 is the best object for understanding MAD + jet systems and searching evidence of BZ process
- Previous observations suggest that the jet morphology of M87 is consistent with GRMHD simulation results and that its accretion flow is in the MAD state
- Radio flux from M87 MAD and the jet width are expected to be quasi-periodic with about 2 yr timescale
- The magnetic reconnections will result in radio blob ejections, X-ray flares, and also might induce VHE gamma-ray flares
- Those features could be seen in joint monitoring observations with 86 GHz VLBI, Swift and CTA