Broad band spectral modeling of M87 nucleus

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M87 accretion flow

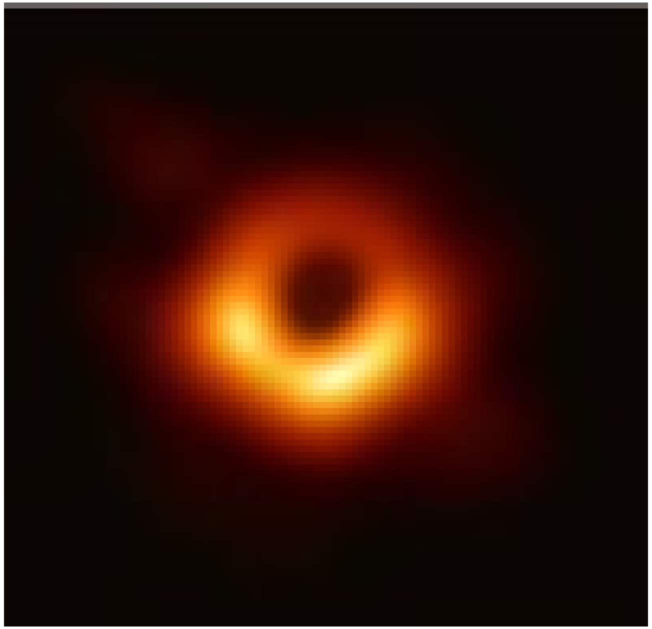


Image of M87 galaxy center, taken by EHT (2019).

Electron temperature of the RIAF affects the photon ring interpretation and should be verified by multiwavelength observations

SMBH horizon region: open questions

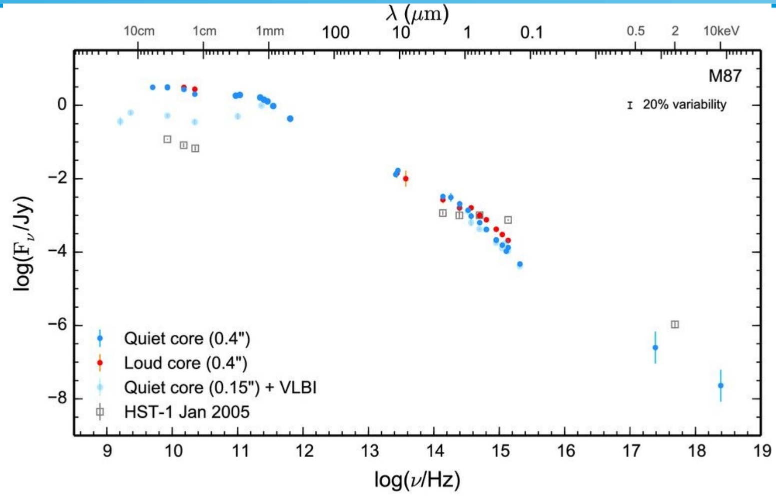
Conference on „Growing Black Holes – Accretion and Mergers", Kathmandu, Nepal, May 2022 (rescheduled from 2020, due to Covid)

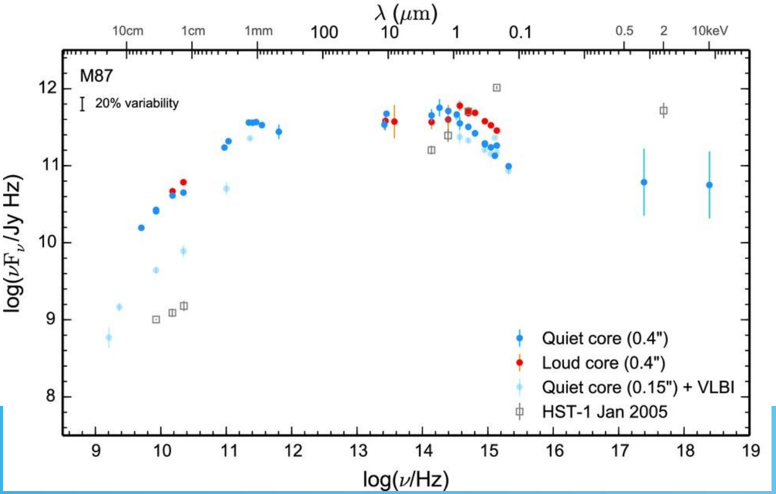
- Spectacular confirmation of the presence of the BH shadow predicted by theory of BH accretion
- We DO SEE radiation emitted by material at the edge of the event horizon just before it falls into the black hole
- But do we understand physical processes taking place in this region.
- Can the huge amount of the observational data from this and other similar objects be used to infer properties of the space-time metric as well as the plasma physics?

Broadband SED of M87 galaxy

- Analytical 1D models failed to explain the broadband SED of M87

- Phenomenological spectral components were incorporated (e.g. Bandyopadhyay et al. 2019)

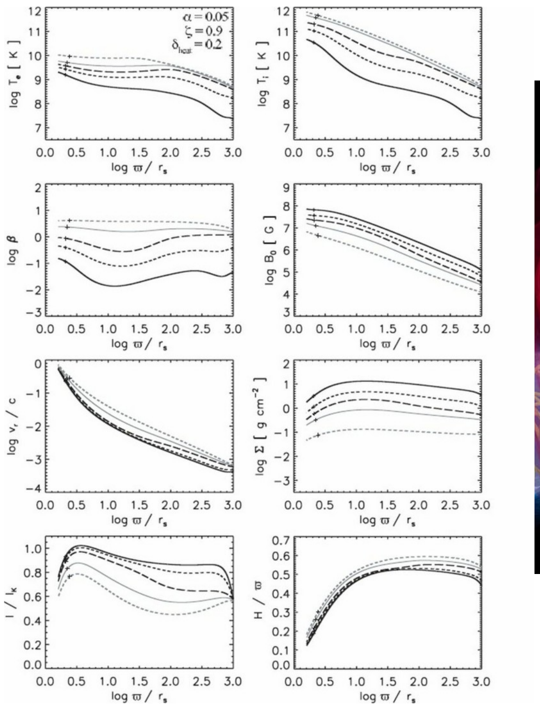




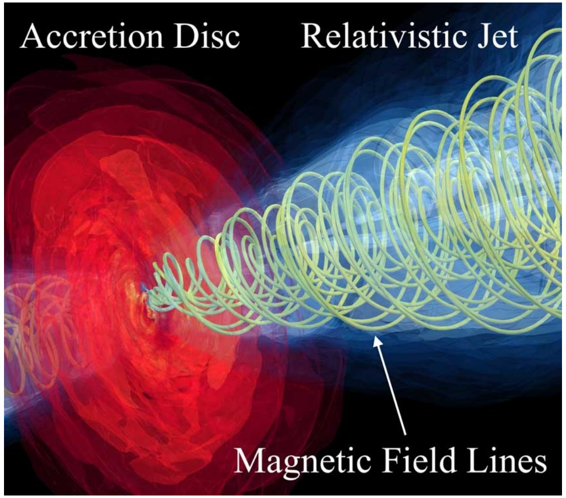
SED measurement of central 32 pc of M87
(Prieto et al. 2016)

Two alternative approaches

- 1. analytical ADAF models (thorough treatment of energy balance but phenomenological description of MHD processes and 1D solutions)
- 2. MHD simulations (crude treatment of energy balance, typically artificial prescription on temperature).
- Both approaches miss some crucial aspects
- We have experience in both MHD simulations and precise modeling of radiative processes. So attempt to make a step toward a more accurate computation of the spectra.



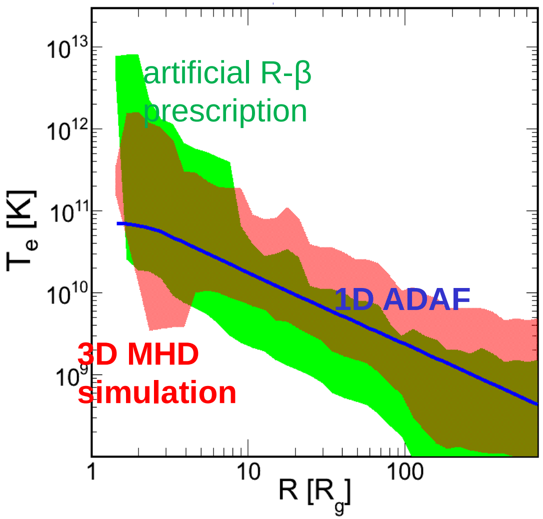
(Narayan et al. 1997)

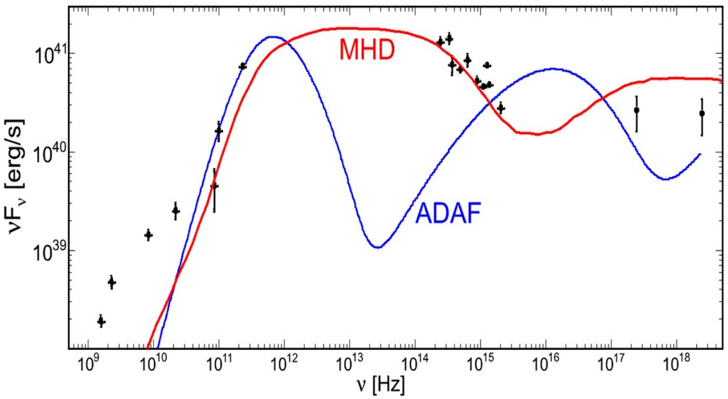


(Cruz-Osorio et al. 2022)

Testing run. Do we need jet?

The need for such a component is not necessarily real. Taking into account inhomogenities of the 3D solution and the related fluctuations of T_e we can explain the spectrum from the mm to X-ray range.





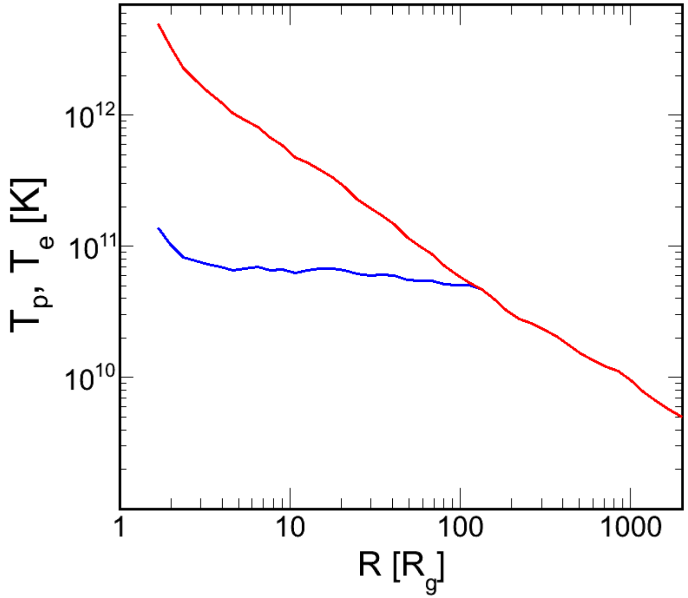
Red spectrum corresponds to the T_e distribution shown by the red shaded region, which corresponds to the same MHD solution as the green one, using T_p/T_e ratio that approximates actual energy balance of electrons

Electron temperature

- We modelled the observed SED of this galaxy, using Monte Carlo code (Niedźwiecki 2005; Niedźwiecki et al. 2012)

- We use T_p from MHD simulation, and calculate the electron temperature

- We want to have constraint $T_e/T_p = 1$ beyond 100 rg
  and
  $T_e = (r/100\ rg)^{0.85}$ within 100 rg



This gives a similar profile to analytic ADAF/RIAF models of electron temperatures distribution and reproduces Te ~ 20 MeV close to the BH horizon

SMBH spectral modeling: problems

1. Electron temperature distribution: crucial quantity.

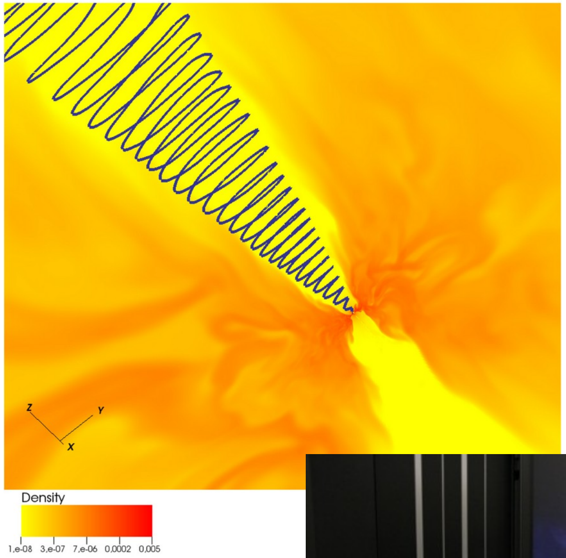
If material is tenuous - we observe radiation produced by electrons. Almost all published spectral predictions based on MHD simulations use the artificial prescription, which gives unphysically large T_e within the central ~3 Rg – where the bulk of the observed synchrotron radiation is produced

2. Corresponding spectra.

The spectrum, corresponding to the 1D ADAF solution, clearly does not match the SED observed from the nucleus. Therefore additional components are postulated – e.g. phenomenological jet contribution – which allow to reconcile the model with the data

Our simulations of MAD disks in AGN

- GR MHD simulations performed with code HARM (Janiuk et al., 2017; 2019)
- Model AGN-HS-100 of (Janiuk & James, 2022)
- Long-time simulations in 3D used as models of MAD disks, addressed to either AGN or GRB central engines
- GR code works with c=G=1 units, so results scale with BH mass, modulo Equation of state
- For AGN case, we chose adiabatic EOS.
- We find disk to be in Magnetically Arrested state.



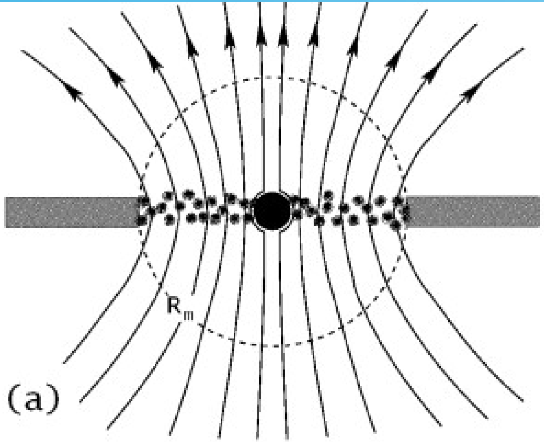
Magnetically Arrested Accretion

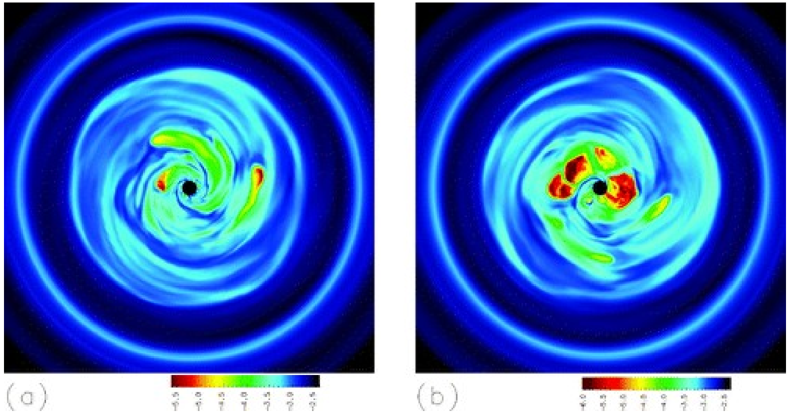
- In the MAD mode, poloidal magnetic field is accumulating close to BH horizon, due to accretion.

- Field is prevented from escape as a result of inward pressure. It cannot fall into black hole either, while only the matter can fall in (Punsly 2001).

- Axisymmetric case: inside magnetospheric radius, R_m, gas accretes as magnetically confined blobs (Narayan, Igumenschev, Abramowicz, 2003).

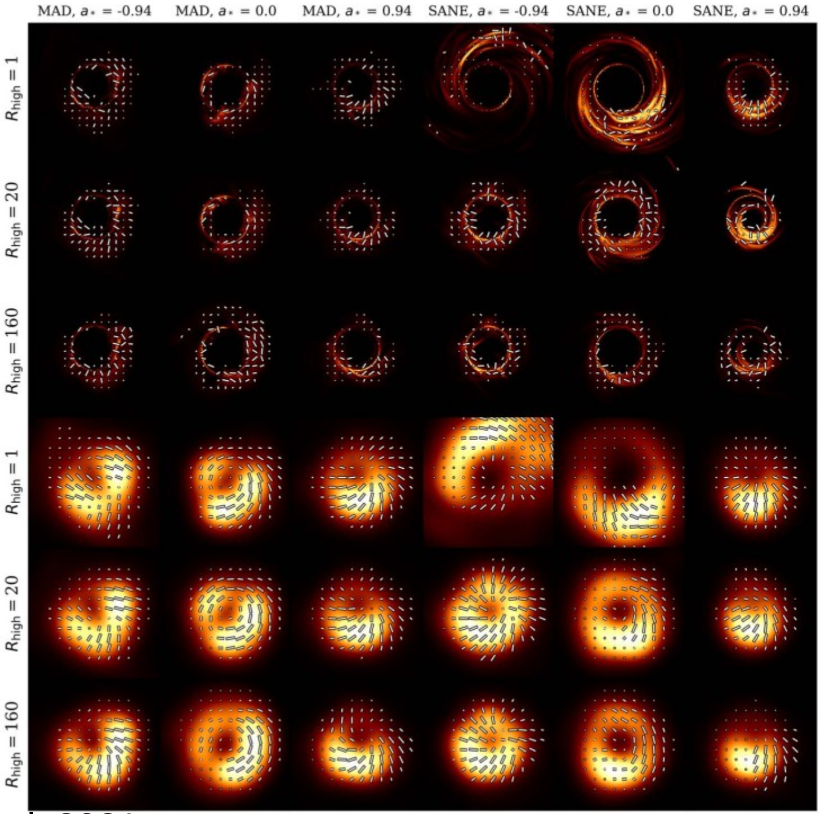
- Non-axisymmetric case: gas forms streams which have to find the way towards the back hole through magnetic reconnections and interchanges (e.g. Igumenshchev 2008)





Application of MAD scenario to M87 image

- Snapshot false-color, blurred images and polarization maps were taken for a subset of the models in the EHT M87 simulation image library
- The models vary with inclination angle and black hole spin vector.
- Physical origin of asymmetric ring shape was interpreted as due to rotation Kerr black hole with high spin.
- Models with MAD are more favored, but image depends on R_{high}/R_{low} value. These are arbitrary free parameters, scaling electron to proton temperature with plasma beta.
- *All models show scrambling in the polarization structure on small scales from internal Faraday rotation, with more pronounced scrambling in models with cooler electrons (larger R_{high} parameter).*



Akiyama et al. 2021

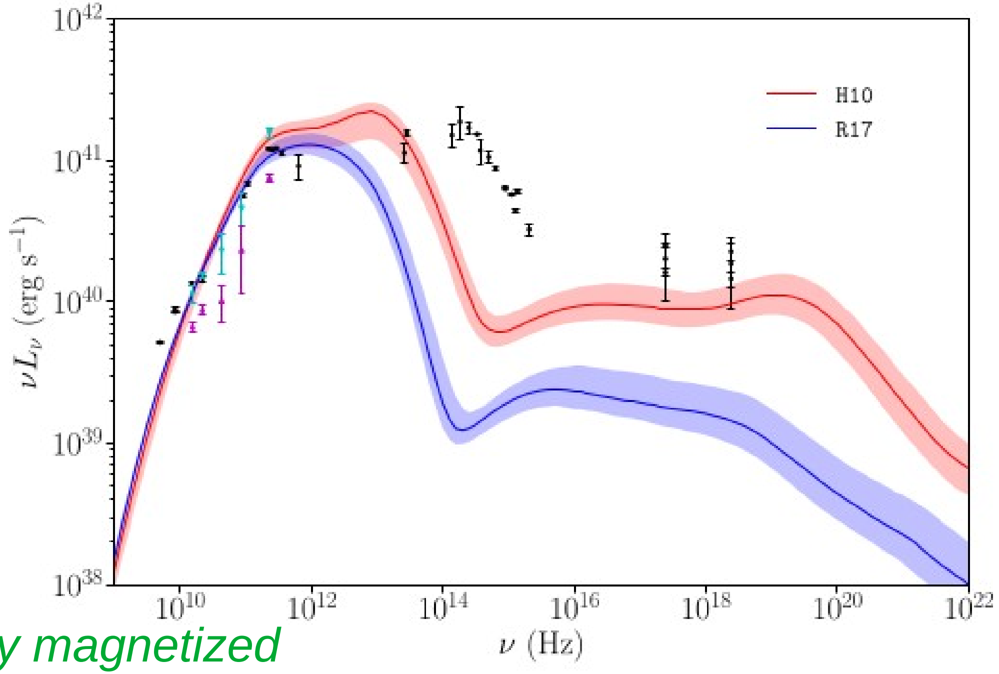
Application of MAD scenario to M87 spectrum

SEDs for the two models for an observer at 17◦ inclination measured from the simulations.

- Spectra were computed from 3D snapshots every 10 t_g, from t = 11 000 to 16 000 $_{tg}$ **after rescaling the density** to approximately match the 0.98 Jy flux density of compact emission at 230 GHz.

- Solid curve shows median spectrum for each model, and the shaded region shows the nominal 1σ time variability.

Two models represent **different electron heating prescriptions** (represented with „delta", being functions of T_e/T_p, and plasma beta)



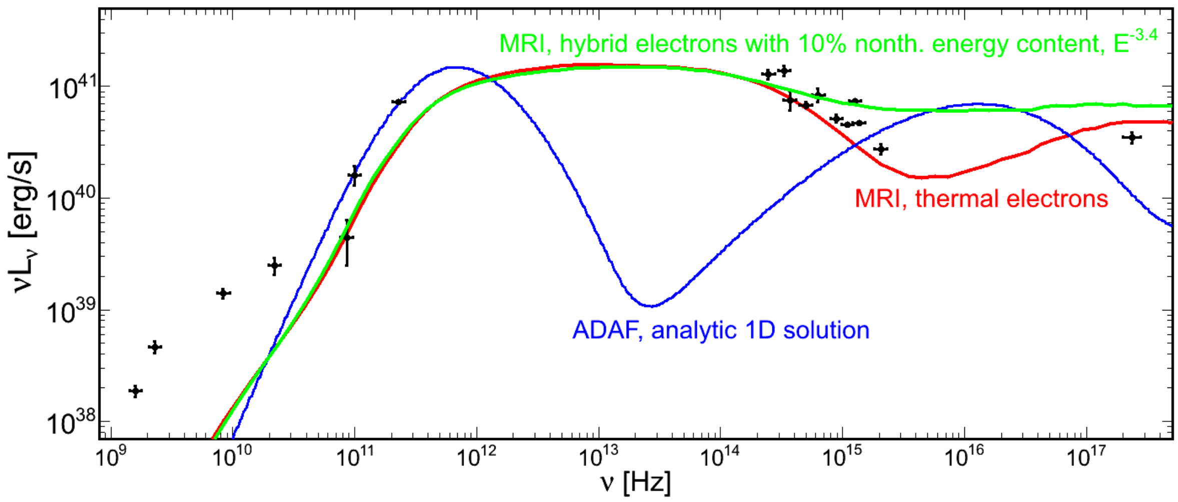
Chael et al. 2019

Spectra fully dominated by strongly magnetized regions in the jet and depend on a rather artificial cut in σ more than on physical parameters

Reproducing the SED

- Synchrotron component matches well the optical/UV part

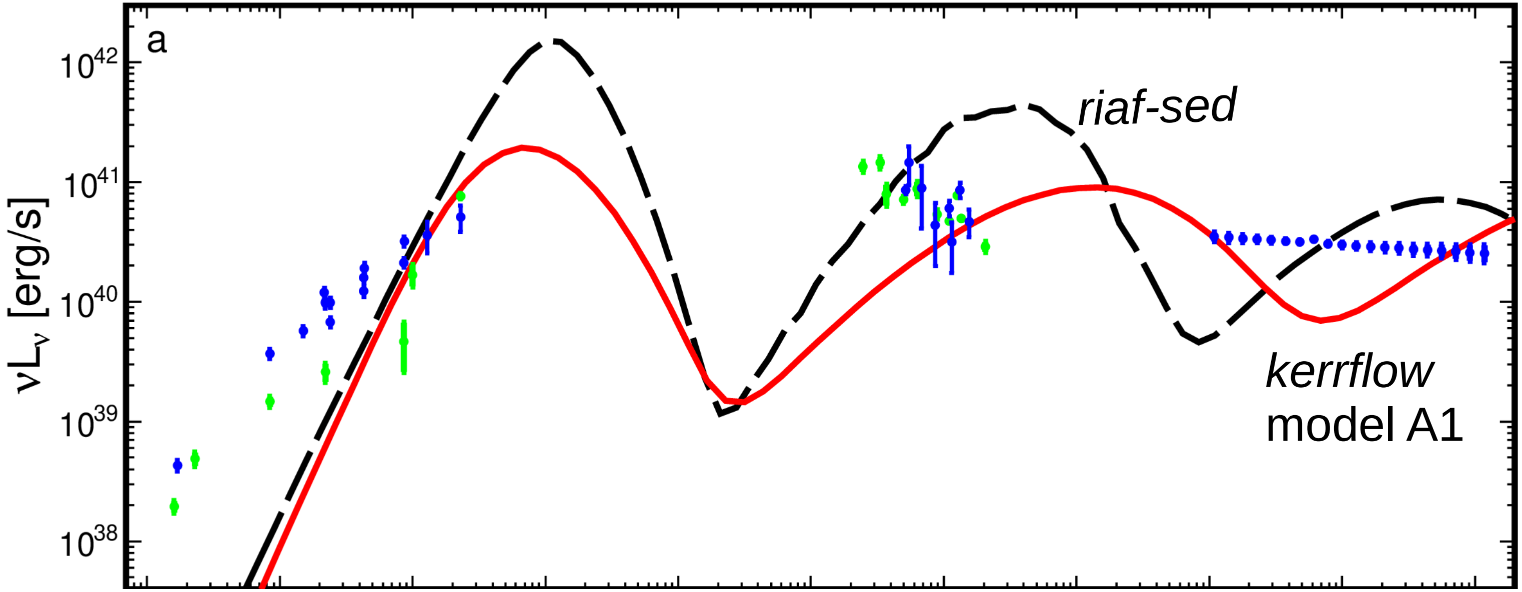
- Hybrid electron distribution (Sironi et al. 2015) with index 3.4, consistent with shock acceleration.



Current best fit model properties

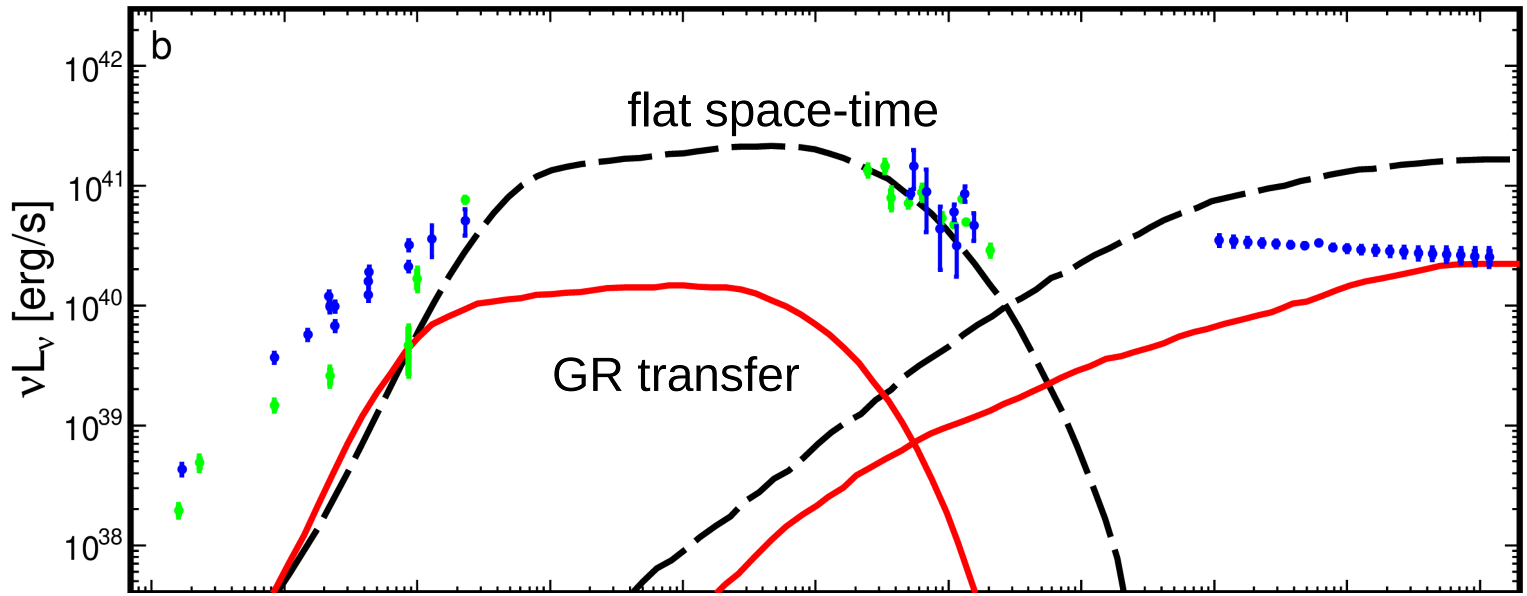
- Synchrotron component reproduces spectra between mm and UV range. Bulk of radiation is produced in region of 2-4 r_g.
- Compton component does not violate X-ray constraints, if accretion rate is low, < 0.01 M_{sun}/yr, and magnetic field relatively strong, beta~1
- X-rays are however reproduced by high energy tail of synchrotron spectrum, if the electron distribution is hybrid, with 5% of non-thermal contribution

Broadband SED from ADAFs



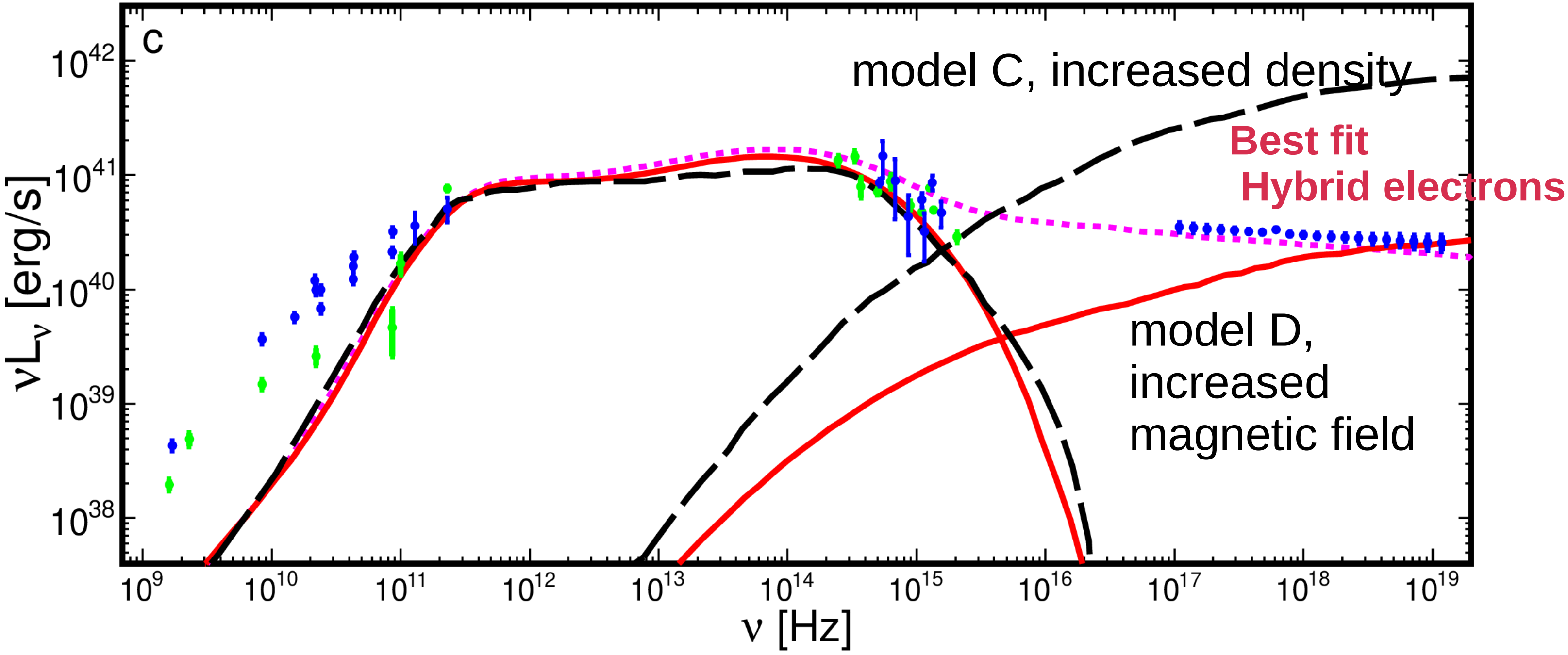
Green points show the highest spatial resolution SED in the quiescent phase of M87* given in Prieto et al. (2016), and the blue points show results of the quasi-simultaneous multi-wavelength campaign in 2017, reported by EHT

Broadband SED from MHD models



Green points show the highest spatial resolution SED in the quiescent phase of M87* given in Prieto et al. (2016), and the blue points show results of the quasi-simultaneous multi-wavelength campaign in 2017, reported by EHT

Broadband SED from MHD, synchrotron fitted to data



Green points show the highest spatial resolution SED in the quiescent phase of M87* given in Prieto et al. (2016), and the blue points show results of the quasi-simultaneous multi-wavelength campaign in 2017, reported by EHT

Summary of parameters

ADAF model	$\dot{m}$ [$\times 10^{-5}$]	β	δ
A1	1	1	0.1
A9	1	9	0.1
MHD model	$\dot{m}$ [$\times 10^{-5}$]	b_{mag}	T_e/T_p
A	3.8	1	0.04
B	25	0.4	0.04
C	35	0.34	0.1
D	7.6	3.9	0.04

Table 1. Parameters of the models. All models assume $M = 6.5 \times 10^9 M_\odot$; the spin parameters $a = 0.9$ in the MHD and $a = 0.95$ in ADAF models.

All models assume BH mass of $6.5\text{x}10^9$ M_{sun}, and inclination angle 17^o.

Niedźwiecki et al. 2024 (ApJ, submitted)

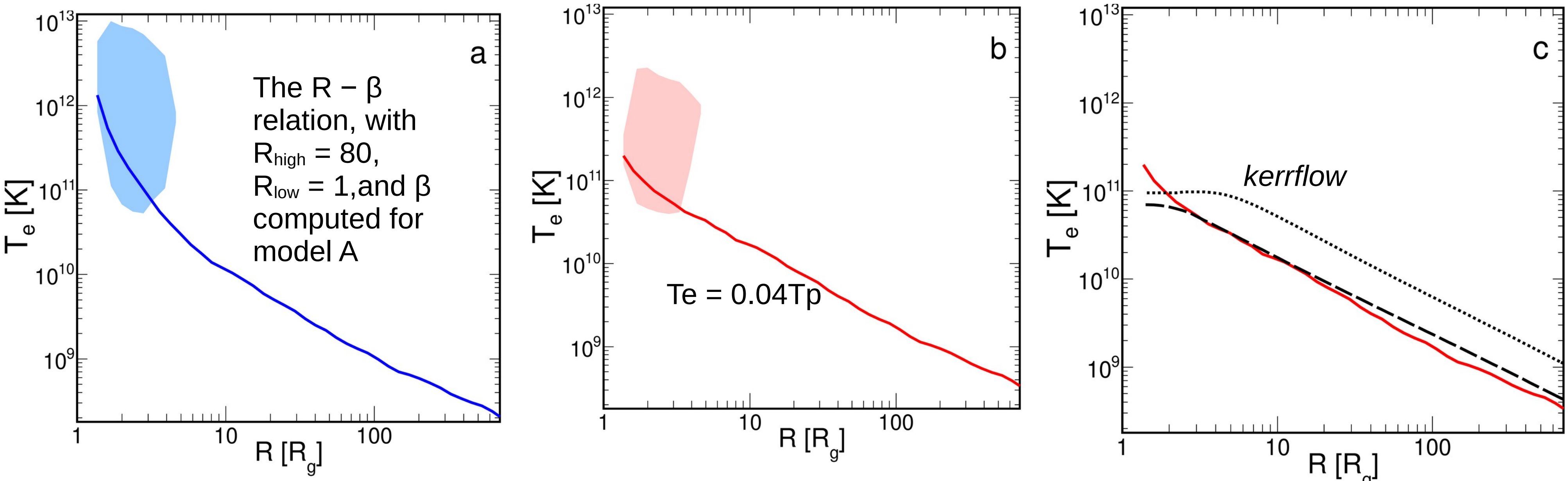
Validation of R-beta prescription

$$R = \frac{T_i}{T_e} = R_{\rm high}\,\frac{\beta^2}{1+\beta^2} + R_{\rm low}\,\frac{1}{1+\beta^2},$$

$$T_e = \frac{2\,m_p u_{\rm gas}}{3\rho k\,(2+R)}.$$

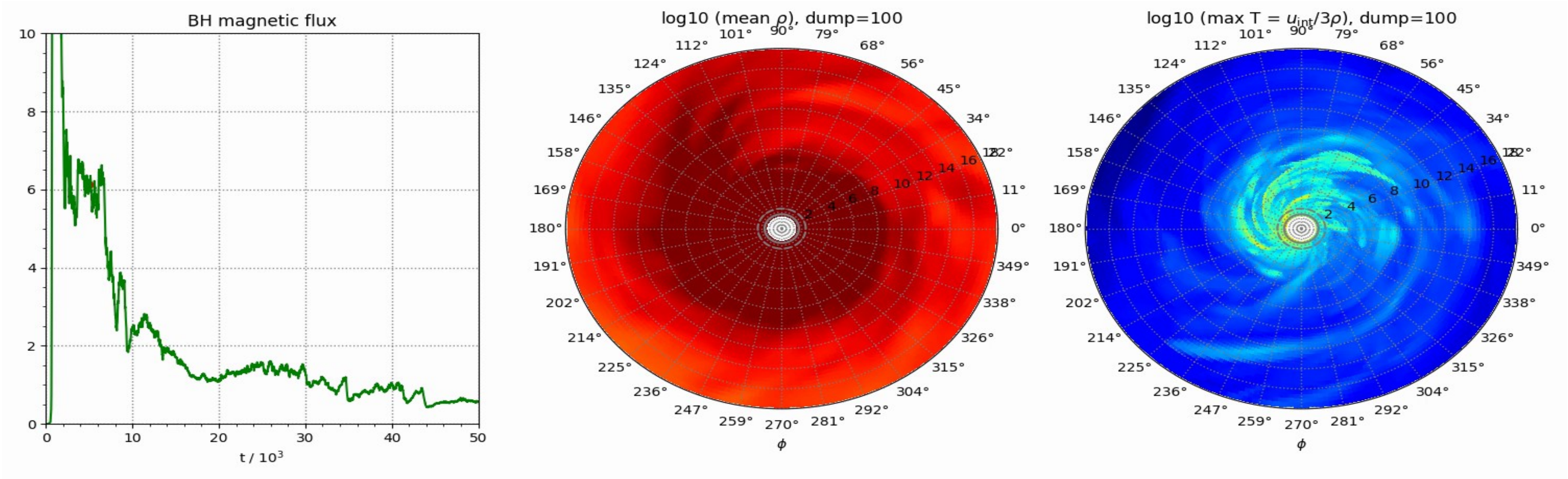
- The R-β prescription tentatively relates the temperature distribution to the efficiency of the electron heating,which increases with plasma magnetisation, as often seen in simulations of electron heating in turbulent or reconnecting plasmas (e.g. Howes 2010; Rowan et al. 2017).
- For Rhigh = 80 and Rlow = 1, which are typical values used in applications of the R-β model, the average $\bar{T}_e$ approaches $\sim 10^{12}$ K at small r (furthermore, in some low-β regions it approaches $\sim 10^{13}$ K).
- This value appears much too high, above the level of $\sim 10^{11}$ K set by the energy balance of electrons in ADAF solutions.
- Synchrotron cooling rate rapidly increases with temperature, $\propto T_e^5$, and keeping electrons at the average Te $\sim 10^{12}$ K would require a heating rate orders of magnitude larger than available accretion power

Validation of R-beta prescription

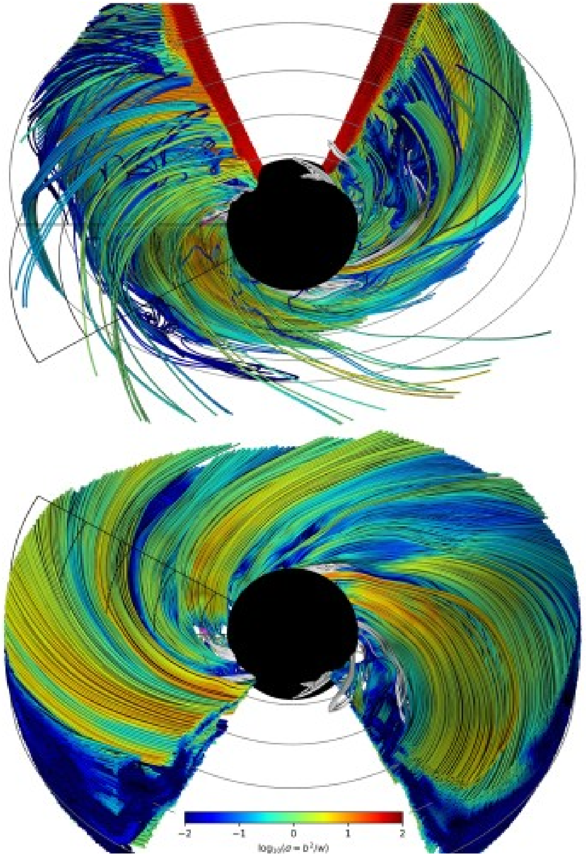


(a) and (b): solid lines show the radial profile of electron temperature obtained by density-weighted spherical averaging in our GRMHD solution, for two prescriptions relating Te to Tp. **Shaded regions** show the range of T_e at which a significant contribution to the synchrotron emission occurs. **(c):** $T_e = 0.04T_p$, the same as in panel (b), T_e profiles in *kerrflow*; dashed line is for model A1 and the dotted line is for δ = 0.3.

Magnetic flux eruptions



Magnetic disconnections and flux eruptions



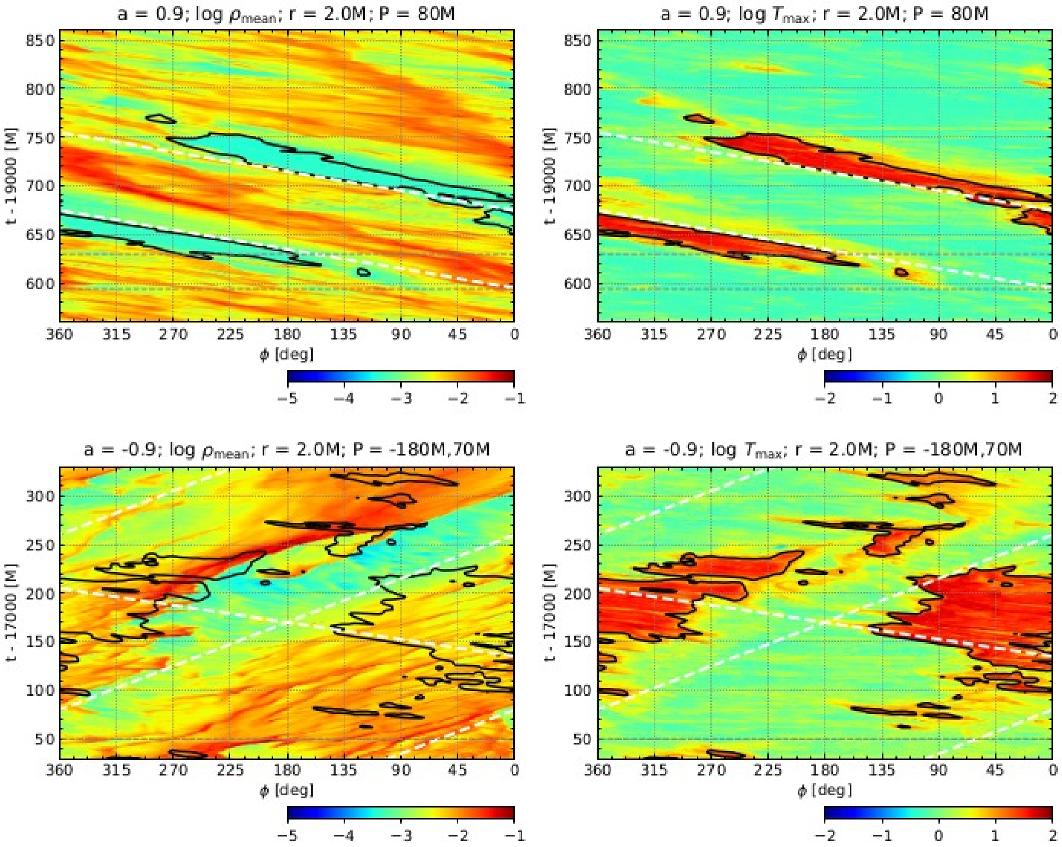
- Magnetic flux eruptions may have various consequences:
  - ejection of magnetic flux tubes orbiting the BH (applied to the VLTI/GRAVITY observations of hotspots orbiting Sgr A*; Dexter et al. 2020; Porth et al. 2021)
  - flares of energetic radiation (Scepi et al. 2022; Hakobyan et al. 2023; Najafi-Ziyazi et al. 2023).
- Eruptions should also be particularly relevant for the substructure and variability of BH crescent images obtained by the EHT Collaboration for M87*

Nalewajko et al. 2024 (A&A, submitted)

Reason for periodic variability in the EHT image

Spacetime diagrams in the (t, φ) coordinates: mean plasma density (left panels) and maximum plasma temperature (right panels), taken over range of θ angle, at fixed radius r = 2M .

- Black contours indicate log10 T_{max} = 1. White dashed lines mark linear rotation trends.
- Upper panels present the prograde a = 0.9 case and lower panels present retrograde a = −0.9 case.
- Both in the time window of magnetic flux eruption.



Conclusions

- We compared radiative properties of two commonly used models of low-luminosity BH systems: one based on the GRMHD simulation and the one using a semi-analytic ADAF description of the two-temperature accretion.
- Spectra based on the GR MHD solution are in a much better agreement with the observed SED. Low radiative efficiency of this model can be compensated by increasing B above the value corresponding to the constant-β scaling of this solution.
- An alternative way to increase the luminosity by increasing either the accretion rate (and hence the density) or the electron temperature results in a significant overprediction of the X-ray flux by the Compton component.
- BH horizon flux eruptions are example of a magnetic avalanche, in which small perturbations trigger events of unpredictable magnitude. May lead to observable effects.

International conferences in exotic places important to bring together Polish scientists and start common projects

Where is the cosmological context?