# Gamma rays from M87*

Andrzej Niedźwiecki
University of Łódź, Poland

with Michał Szanecki, Sabrina Pizzicato, Yogesh Maharjan, Agnieszka Janiuk

# Introduction: M87

Distance:

$D \approx 16.8 \pm 0.8$ Mpc

Black hole mass:

$M_{BH} \approx 6.5 \times 10^9 M_\odot$ (EHT), $6 \times 10^9 M_\odot$ (stars), $3 \times 10^9 M_\odot$ (gas motion)

Jet:

orientation of the inner part $\theta \sim 17°$,
Doppler factor $\delta \sim 2$ (e.g. Wang & Zhou 2009, Nikonov+ 2003)
(much lower than in blazars: $\delta \sim 10 - 50$)

Core bolometric luminosity:

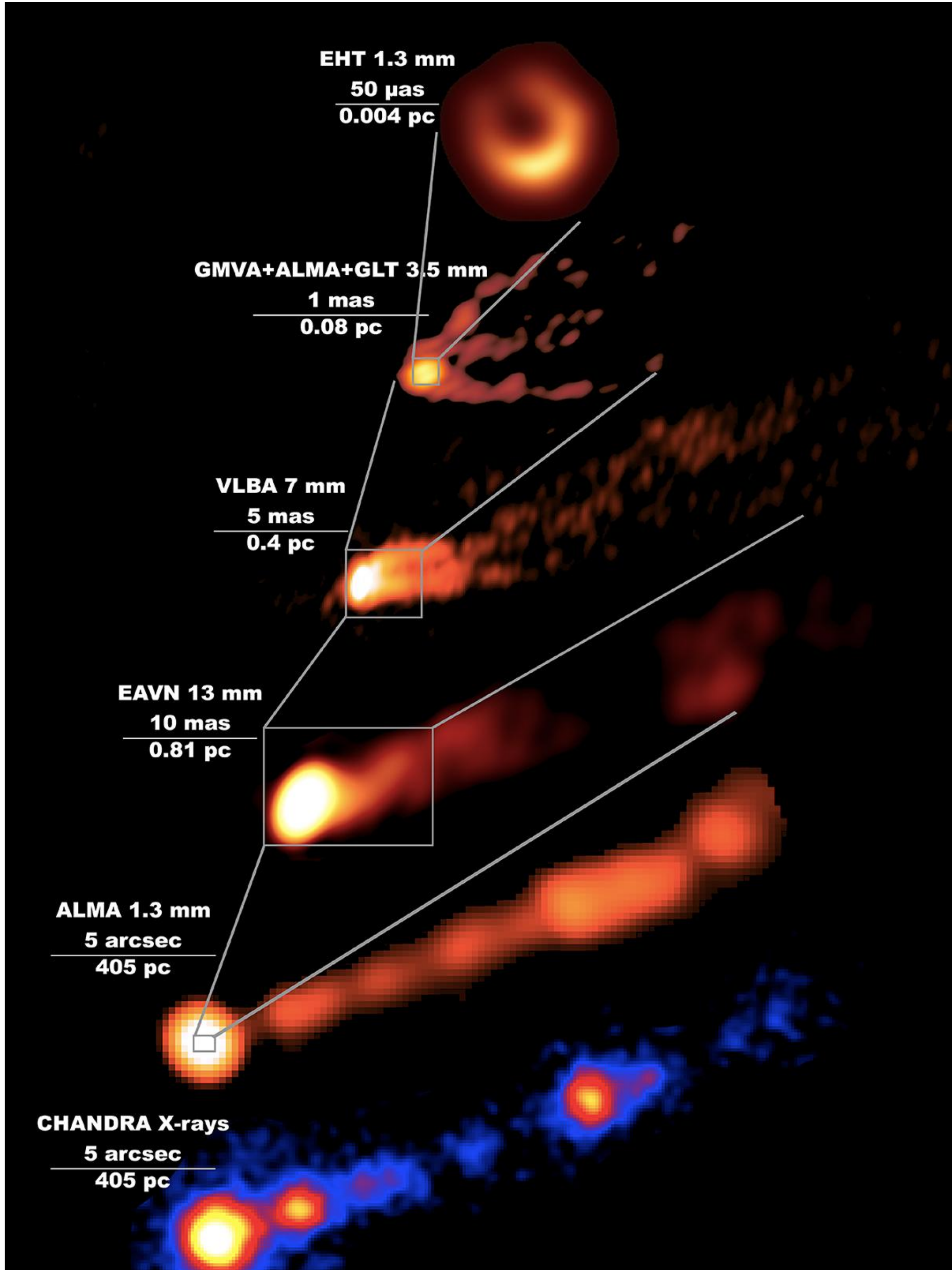
$L \approx 2 \times 10^{42}$ erg/s (e.g. Prieto+ 2016)
(SgrA*: $10^{36}$ ergs/s)

Eddington ratio:

$L/L_{Edd} \approx 5 \times 10^{-6}$
(SgrA*: $3 \times 10^{-9}$)

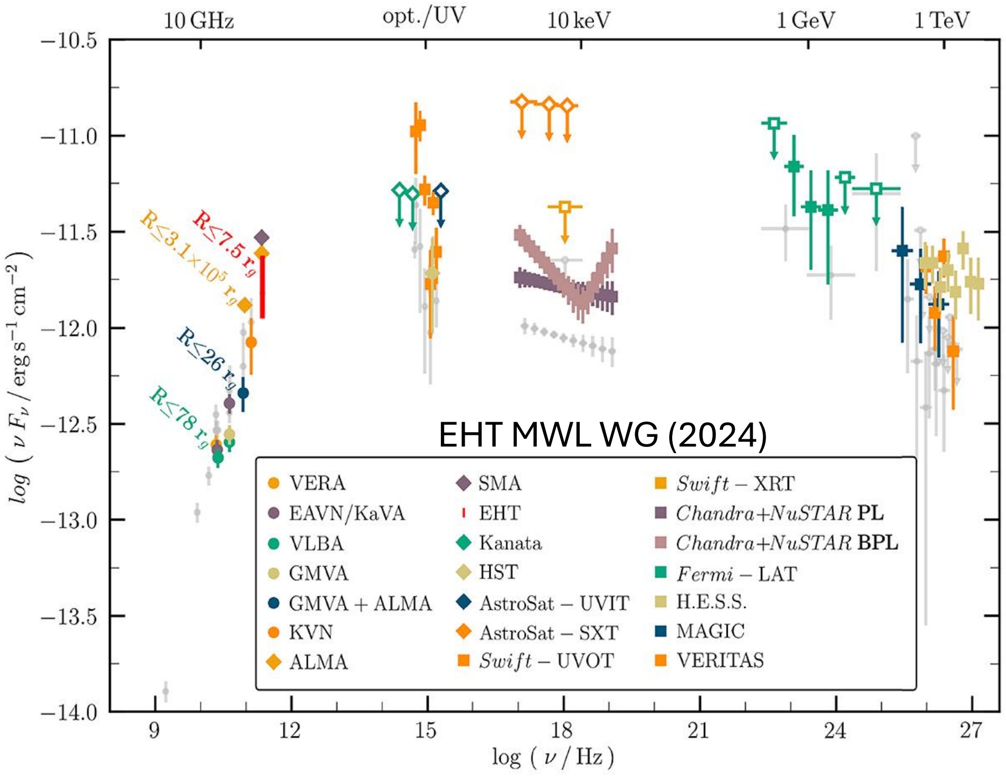
Apparent diameter of BH:

$\theta_{EH} = 2GM_{BH}/(c^2 D) \approx 8$ μas
(SgrA*: 10 μas)




EHT MWL Group (2024)
M87 MWL jet images during the 2018 campaign

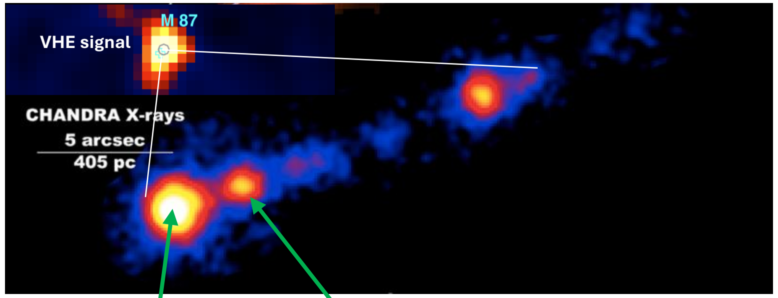
# Introduction: broadband spectrum, gamma-ray flares




SED of M87 contemporaneous with the EHT campaign in April 2018. Grey points represent SED of the 2017 EHT campaign. Different samplings of VHE instruments: MAGIC observations before the $\gamma$-ray flare, VERITAS only partially overlap the flare. All H.E.S.S. observations during the flare and lead to the hardest spectral index. The X-ray spectrum uncertain (despite formally small error bars), hints for hardening above 10 keV

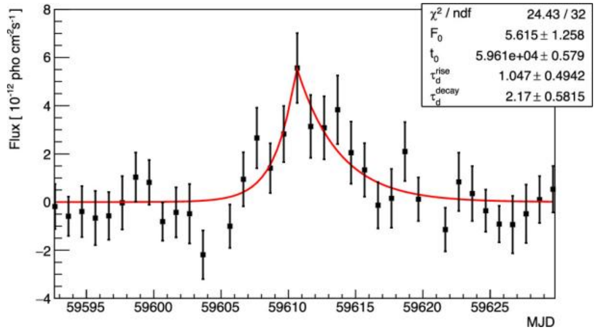
Five significant VHE flares with variability timescales ~1 day: 2005 (Aharonian+ 2006), 2008 (Albert+ 2008), 2010 (Abramowski+ 2012), 2018 (EHT MWL WG 2024), 2022 (Cao+ 2024). Typical peak flux: ~10 × low state flux; in 2018: 3.5 × $F_{\text{low state}}$

Angular resolution of VHE observatories ~ 0.1°




2008
2010
2018

2005 (HST-1, ~70 pc from the center)

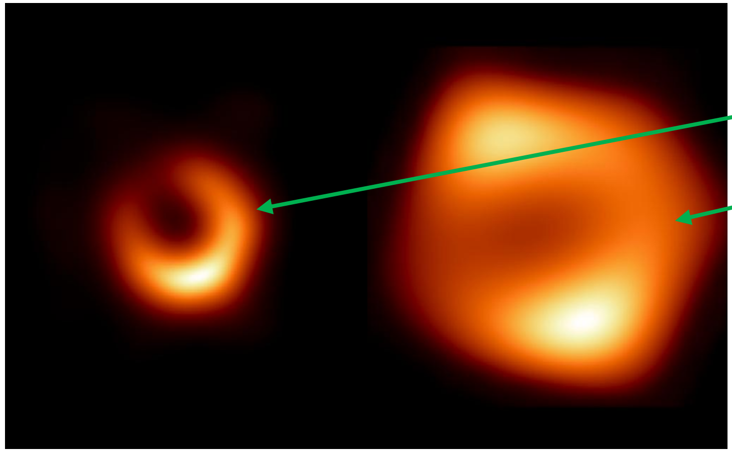


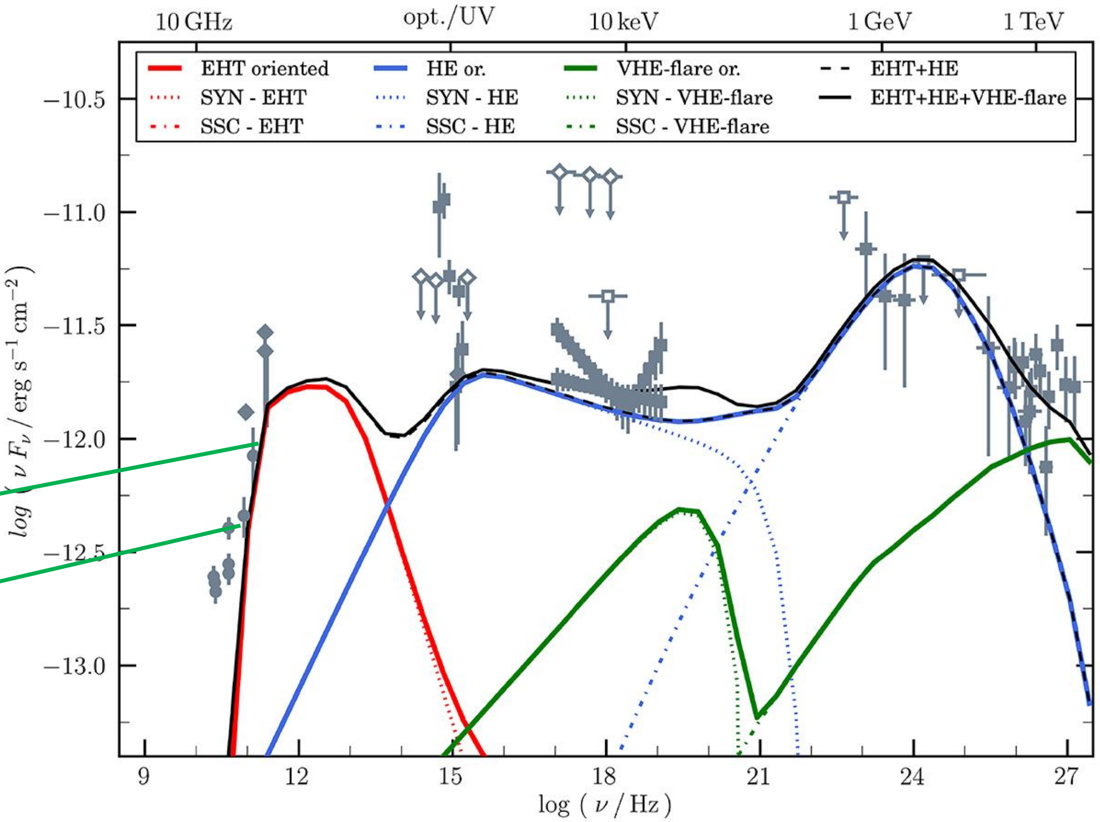

Cao+ 2024: Light curve of the 2022 VHE flare measured by LHAASO.

Isotropic VHE luminosity ~ $4.7 \times 10^{41}$ erg $s^{-1}$

# Introduction: SSC models

Spatially-resolved images of M87* taken in April 2018 by EHT at 1.3 mm (EHT Col 2024) and GMVA+ALMA at 3.5 mm (Lu+ 2023) shown at the same scale. The measured ring diameter, ~42 μas @ 1.3mm and 64 μas @ 3.5mm, implies the size of the emitting region of ~10 $R_g$






SSC model fitted to the broadband SED of M87 for the EHT campaign in April 2018 (EHT MWL WG 2024): stratified jet with electrons described by a PL distribution

Caveats: the plasma is highly self-absorbed at parameters expected in the inner accretion flow (the EHT-oriented component in the SSC fit has similar parameters: $n \sim 10^6$ cm$^{-3}$, $B \sim 5$ G, $R \sim 5R_g$) and the self-absorption is a very efficient mechanism of electron thermalization (e.g. Mahadevan & Quataert 1997). It is then highly unlikely that the low energy part of the spectrum is produced by electrons with a power-law distribution. Notably, such a nonthermal distribution gives a poor match to the observed image morphology (e.g. Lu+ 2023)

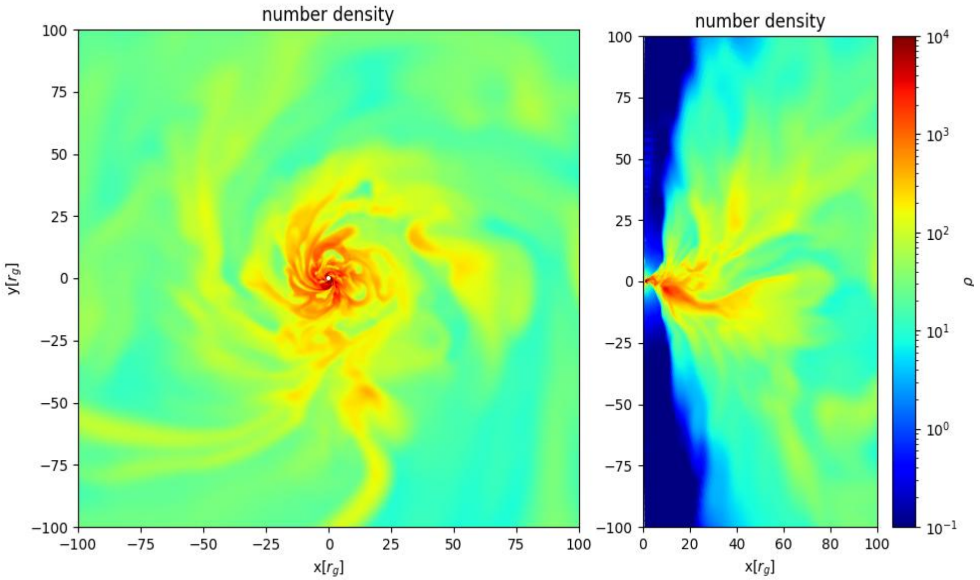
# Model: GRMHD simulations

3D GRMHD simulations (ebhlight, Ryan+ 2015)

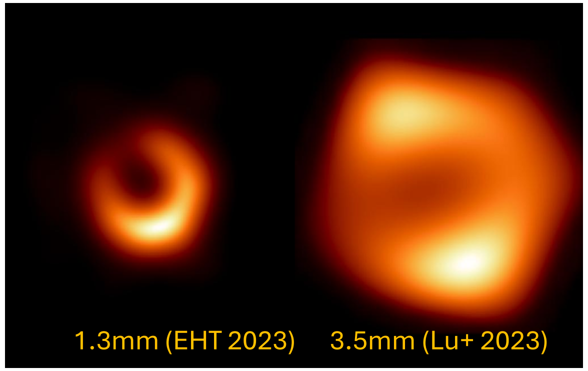
Crucial features of VLBI images (size, brightness temperature) reproduced for BH spin a=0.9, accretion rate ~0.03 $M_\odot$ and electron heating efficiency ~10%

Solutions in the magnetically-arrested state (MAD-ness parameter $\phi_{BH} \sim 20$) producing strong jets (e.g. Narayan+ 2003; Tchekhovskoy+ 2011)
- our solution can account for the jet power estimated for M87 $\sim (10^{43} - 10^{44})$ erg $s^{-1}$ (e.g. Stawarz+ 2006, Bromberg & Levinson 2008)

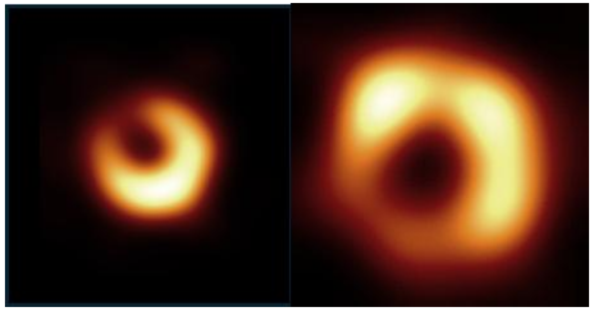
Density distribution, equatorial and vertical cuts:




Observed:




Model:

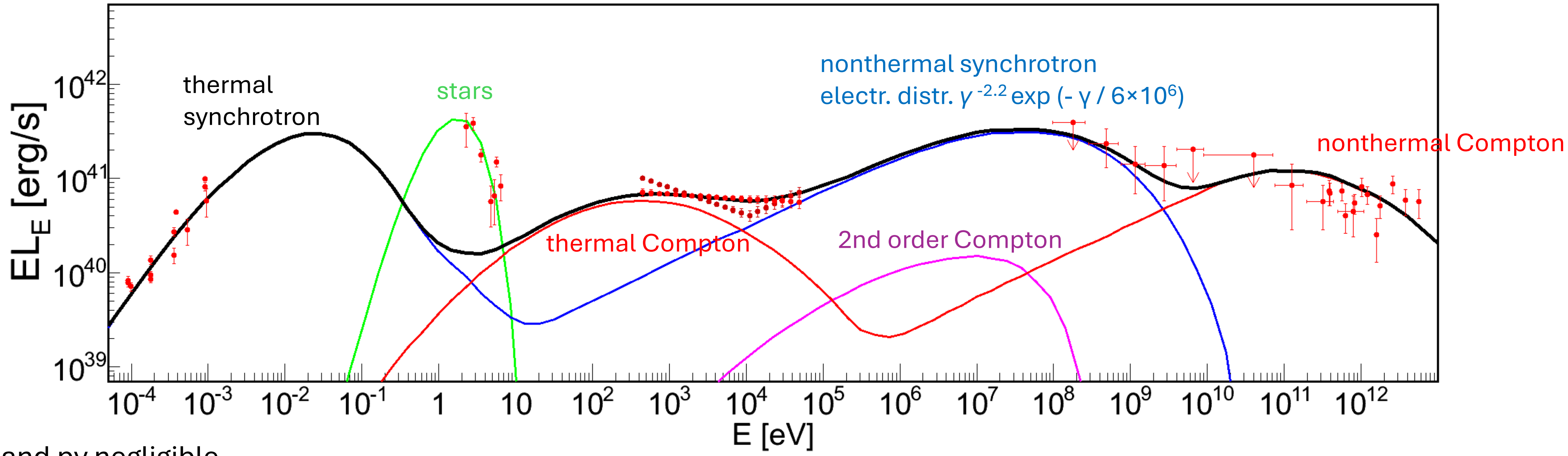


The difference in the appearance at 1.3mm and 3.5mm results from the opacity effects associated with the accretion flow surrounding the SMBH.

Significant contribution to the observed radiation from regions with B ~ 5 – 50 G, $T_e \sim 10^{11} - 10^{12}$ K, n ~ $10^3 - 10^5$ $cm^{-3}$

# Results: fit to the 2018 SED

GRMHD solution + GR Monte Carlo simulation with hybrid electron distribution




pp and pγ negligible

Thermal electrons responsible for the submillimeter and soft X-ray emission

Explaining the GeV and TeV data requires nonthermal electrons with a very hard energy index, p~2.2 (similarly hard electron distribution, p~2.1, found for the HE and VHE components in the SSC fit for the same data)

The high-energy cut-off of the distribution is likely related to the acceleration rate balanced by radiative losses within acceleration region – smooth decline represented here by the exp term rather than sharp cut-off (alternatively, broken PL distribution)

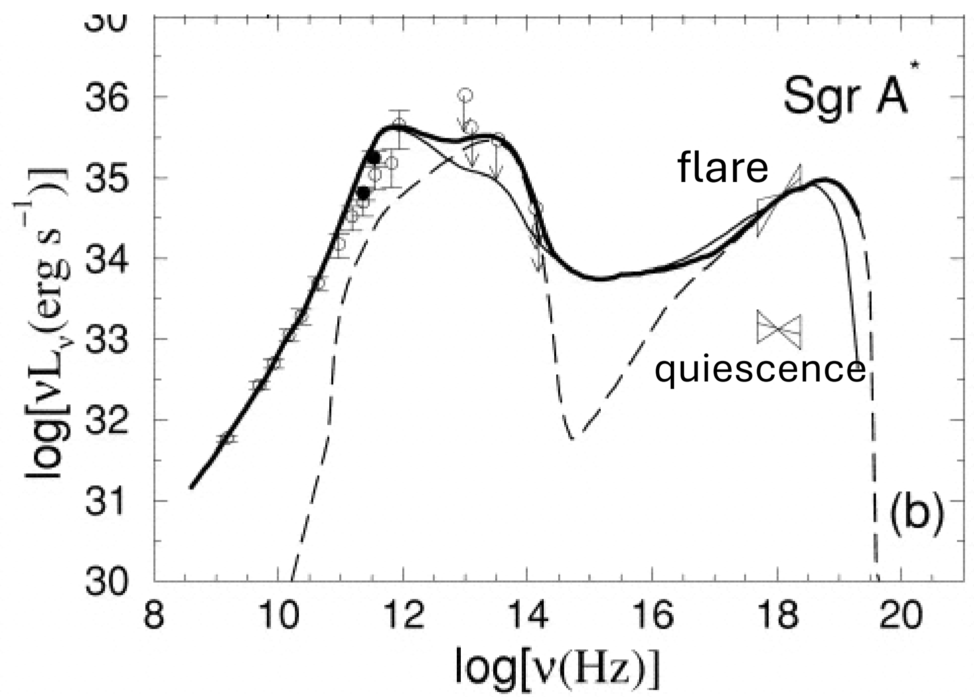
Opt/UV: HST resolution ~0.1 arcsec corresponds to 8 pc and, for a nuclear stellar density of $10^5$ per $pc^3$ (Kormendy & Kennicutt 2004) may include over $10^7$ stars

# Acceleration mechanism. Similarity to Sgr A* flares

An energy index of p~2.2 implies a very hard acceleration index, $s_{acc}$~1.2 (taking into account the synchrotron and IC cooling rates), which can be produced by magnetic reconnection (e.g. Guo+ 2015, Zhang+ 2023)

Episodic magnetic reconnection events found in (extremely high resolution) GRMHD simulations of magnetically arrested accretion flow (Ripperda et al. 2020, 2022)

Sgr A*: X-ray flares occuring roughly once per day (Baganoff et al. 2001, 2003). Explained by emission of nonthermal electrons accelerated with $s_{acc}$~1.2 (Yuan+ 2003):




Gamma-ray signal from Galactic Center region dominated by hadronic interactions in dense ambient gas

# Summary

Self-consistent model for VLBI images and broadband spectrum of M87*. In progres - application to the low state

Better physical motivation than the SSC model of a stratified jet; easier explanation of the TeV emission with IC on the thermal synchrotron bump; single emission site, not two or more

Supports a scenario with magnetic reconnection near the event horizon producing flares observed in the TeV range from M87 and in X-rays from Sgr A*