TeV Flaring of M87*

powered by magnetic reconnection

Hayk Hakobyan (Columbia/PPPL),
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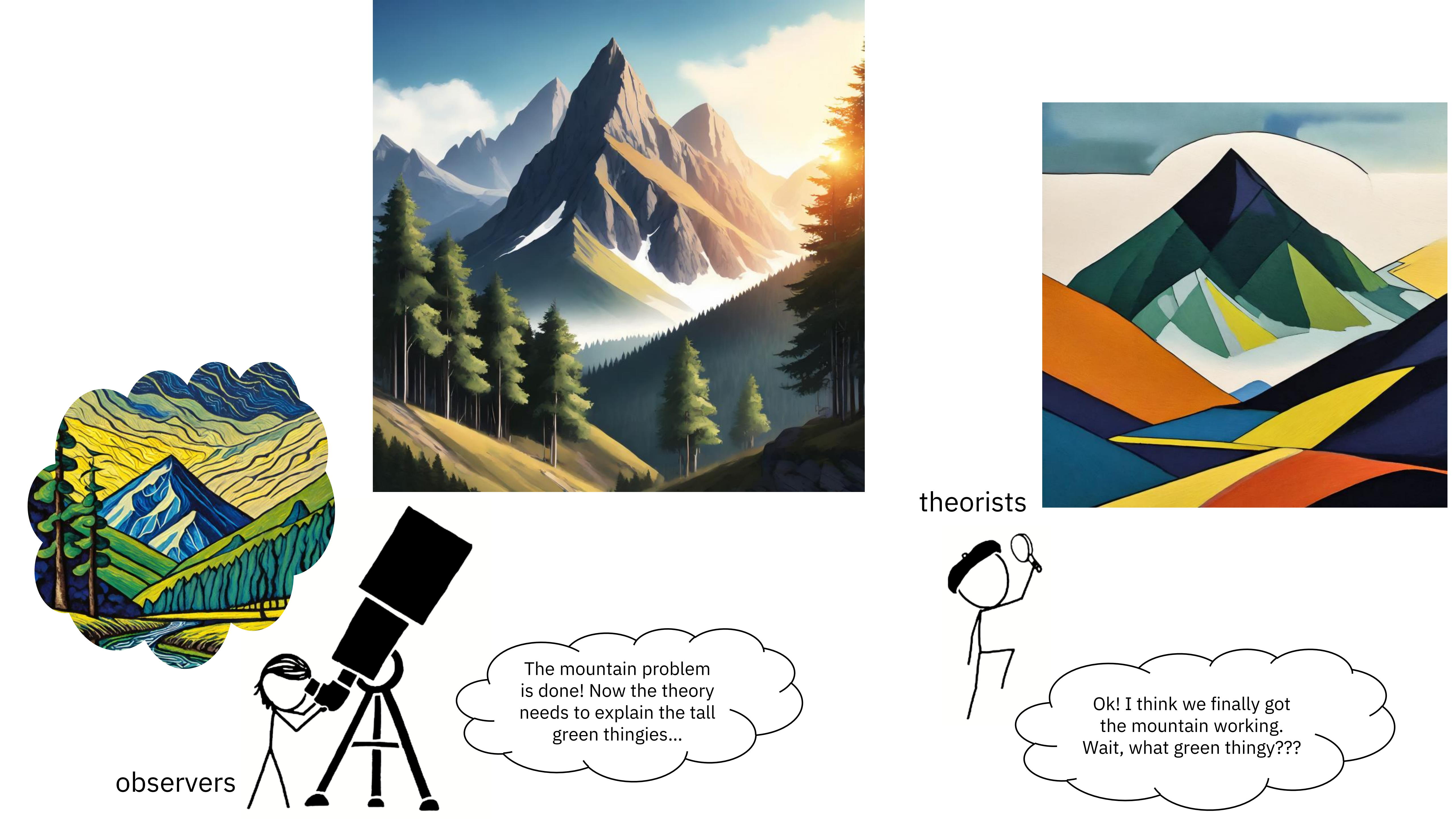
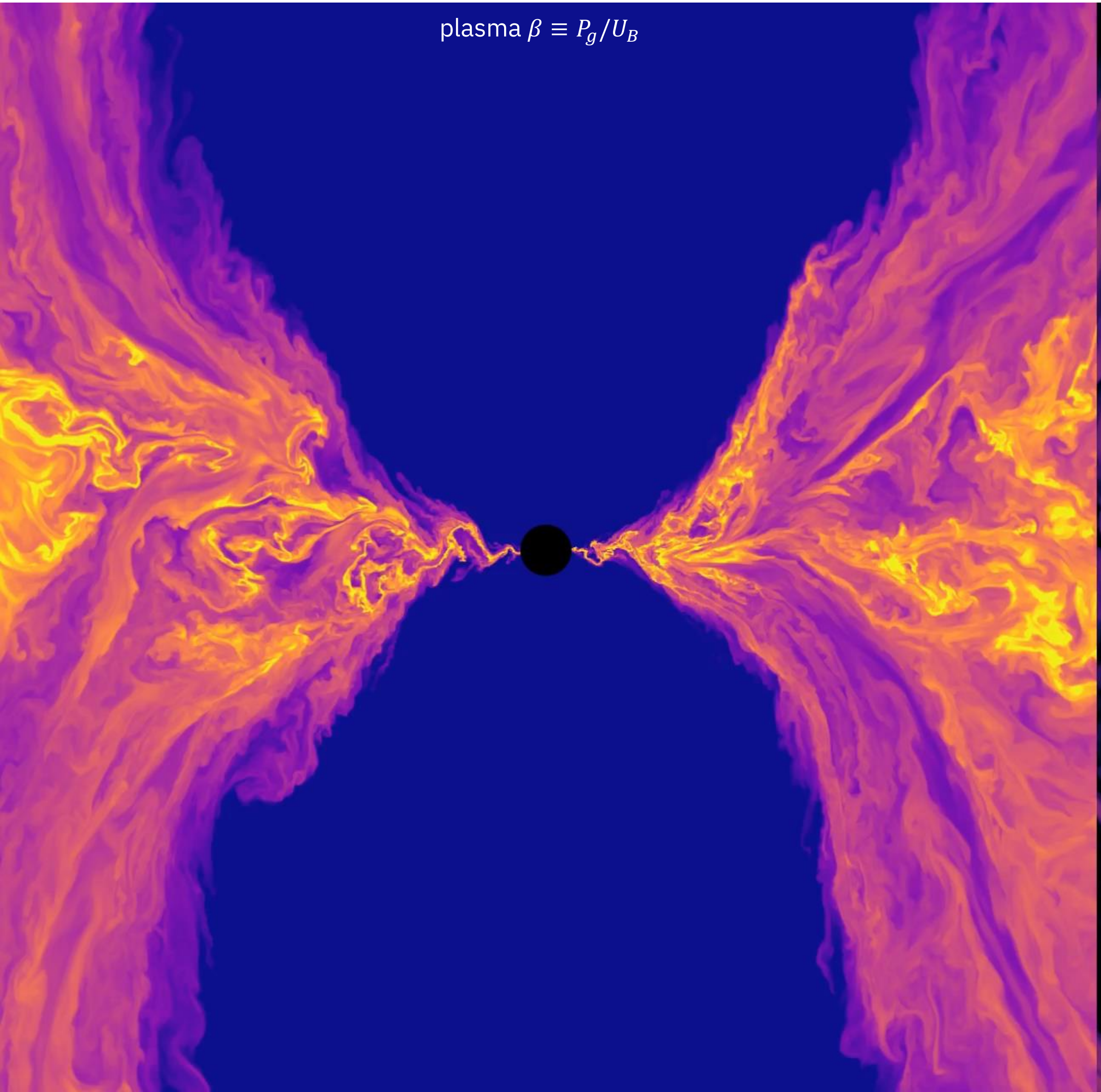
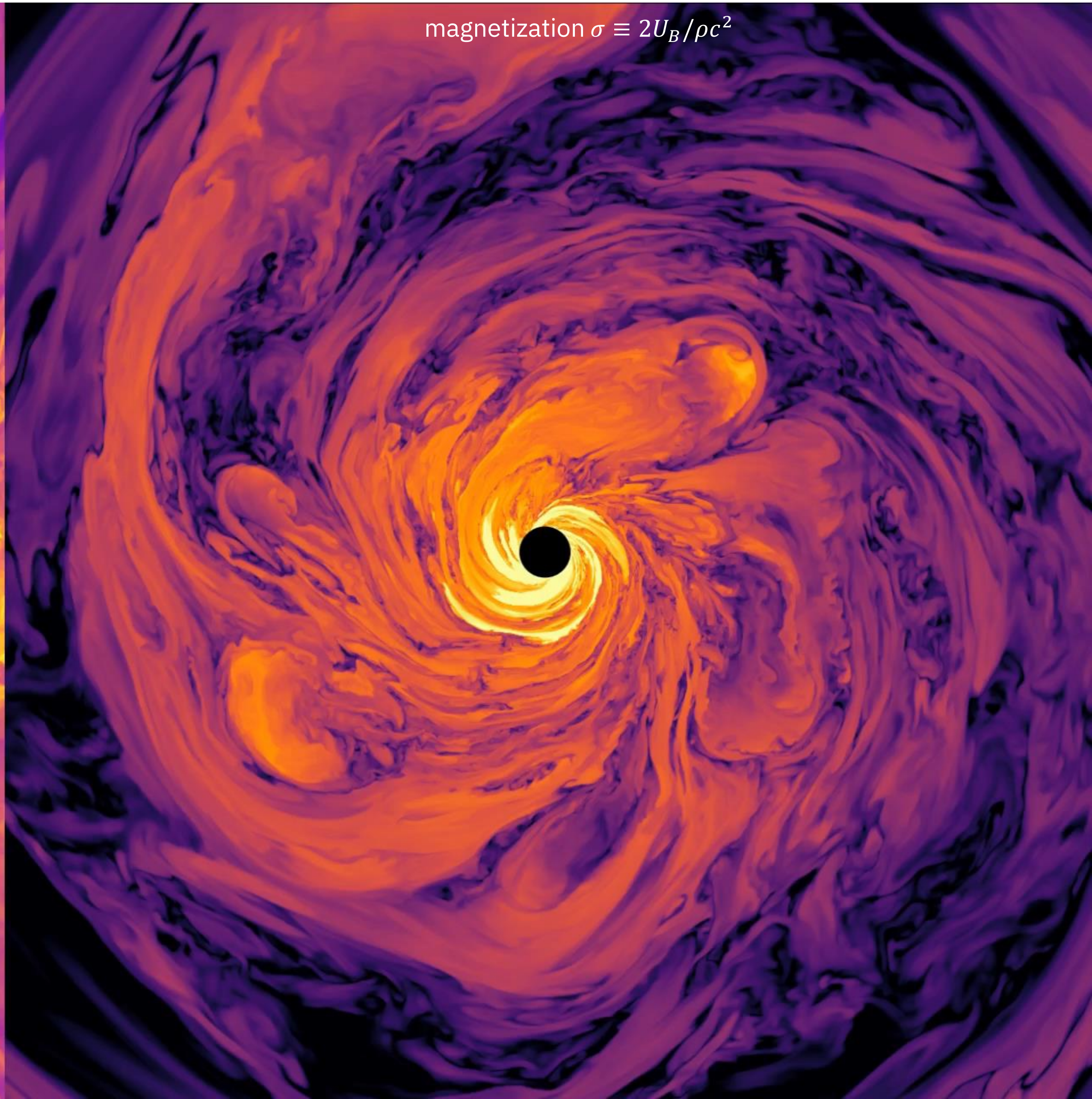

theorists
Ok! I think we finally got the mountain working. Wait, what green thingy???
observers
The mountain problem is done! Now the theory needs to explain the tall green thingies...

GRMHD perspective

Ripperda+ (2022)





GRMHD perspective

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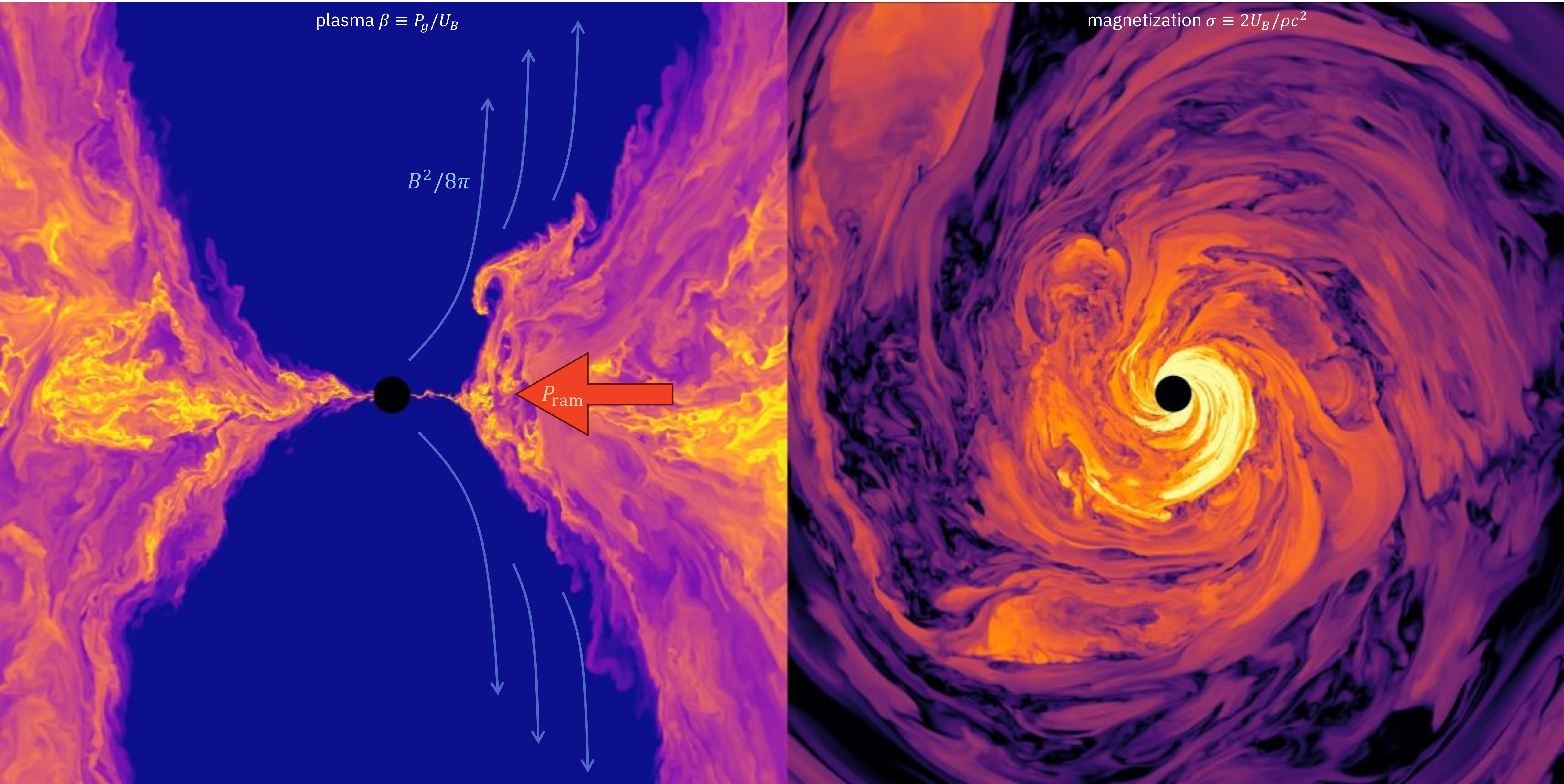

GRMHD perspective

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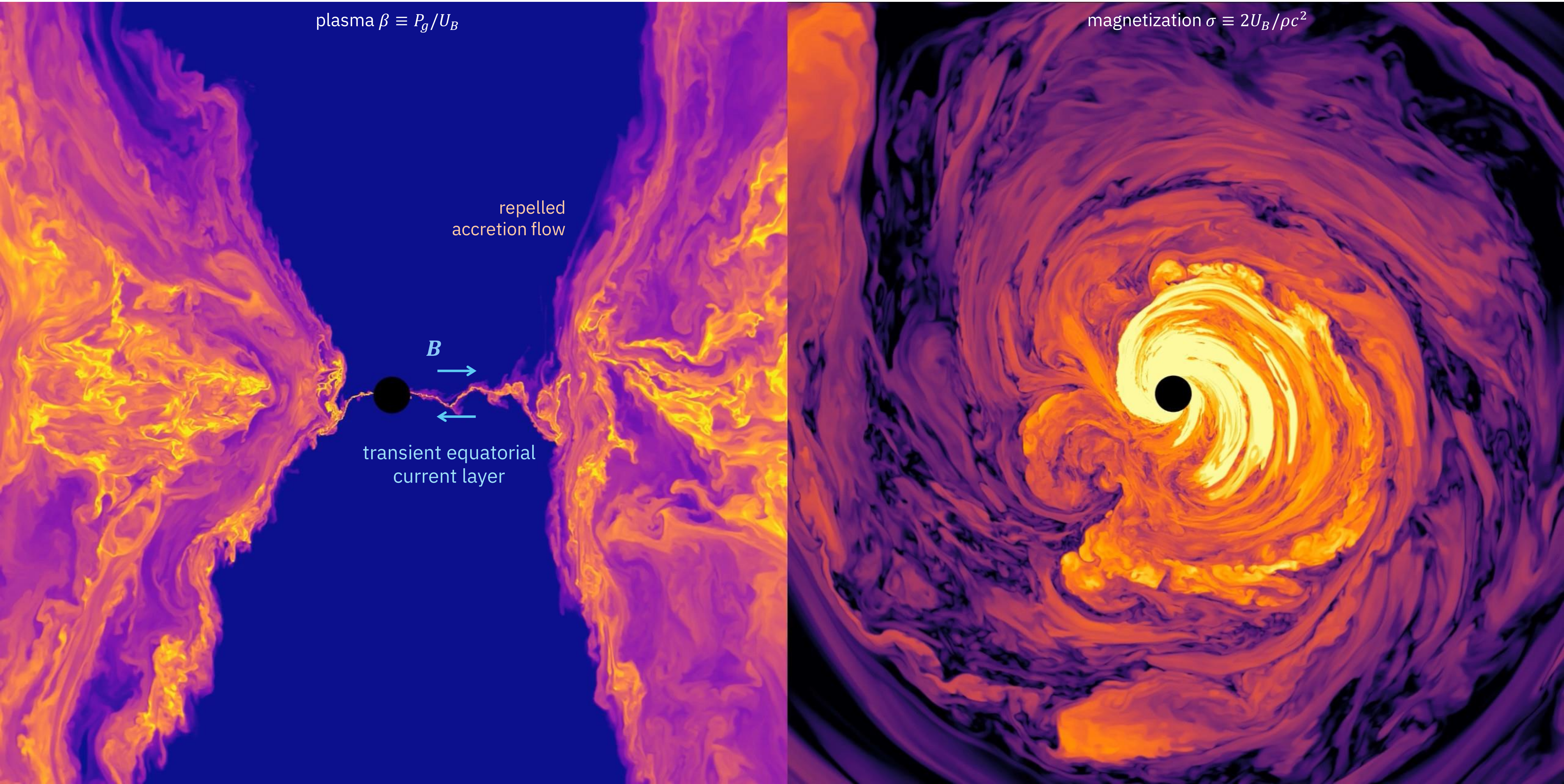

GRMHD perspective

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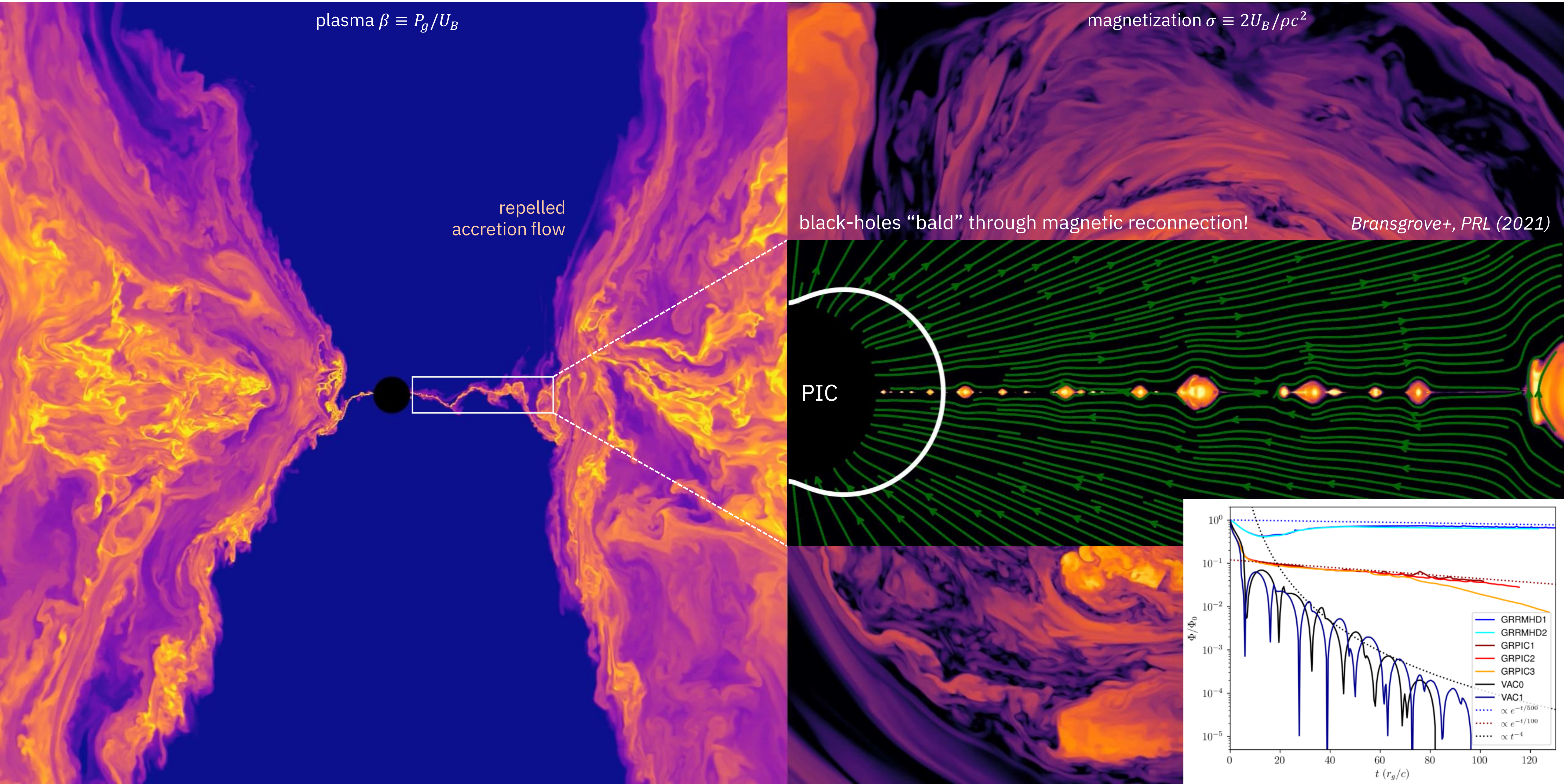
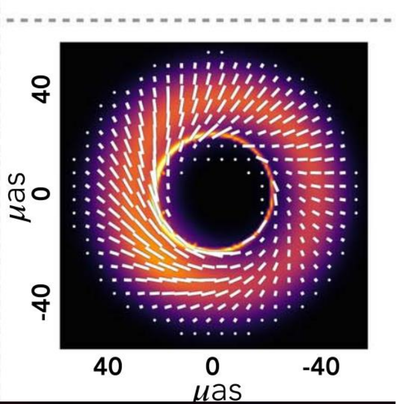


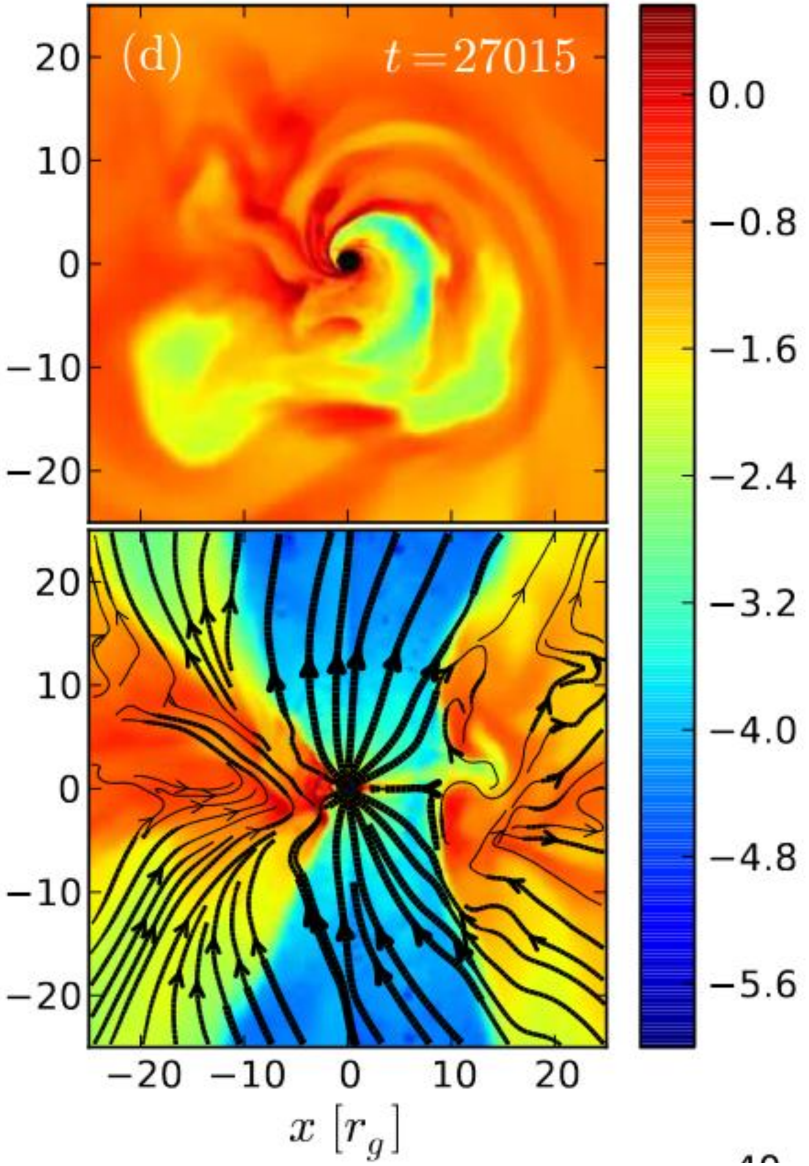
GRMHD perspective

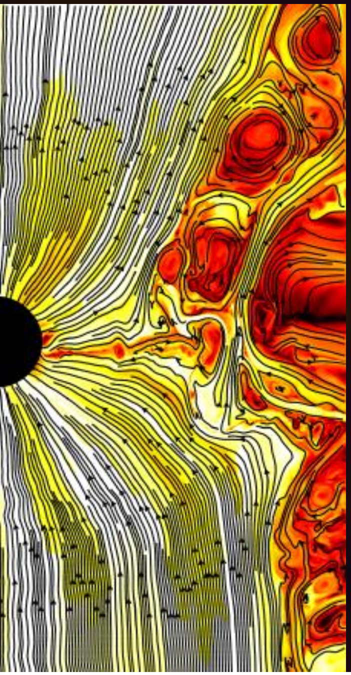
Why did we realize this just now?

1. *M87 polarization ⇒ magnetically arrested accretion state*
2. *Resolution of the simulations:* $\geq (10{,}000)^3$ *effective resolution required*

EHT+ (2021)



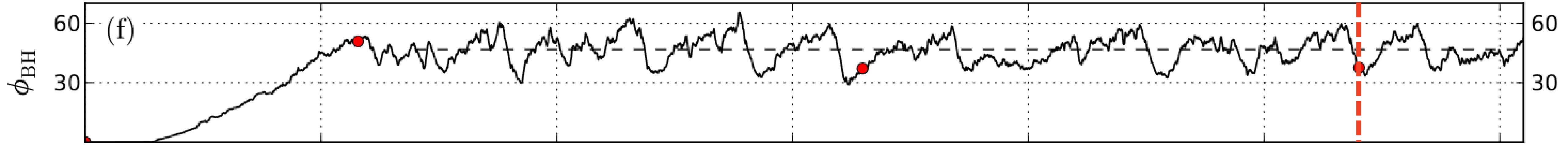




⟸ 2D resistive GRMHD *Ripperda+ (2020)*

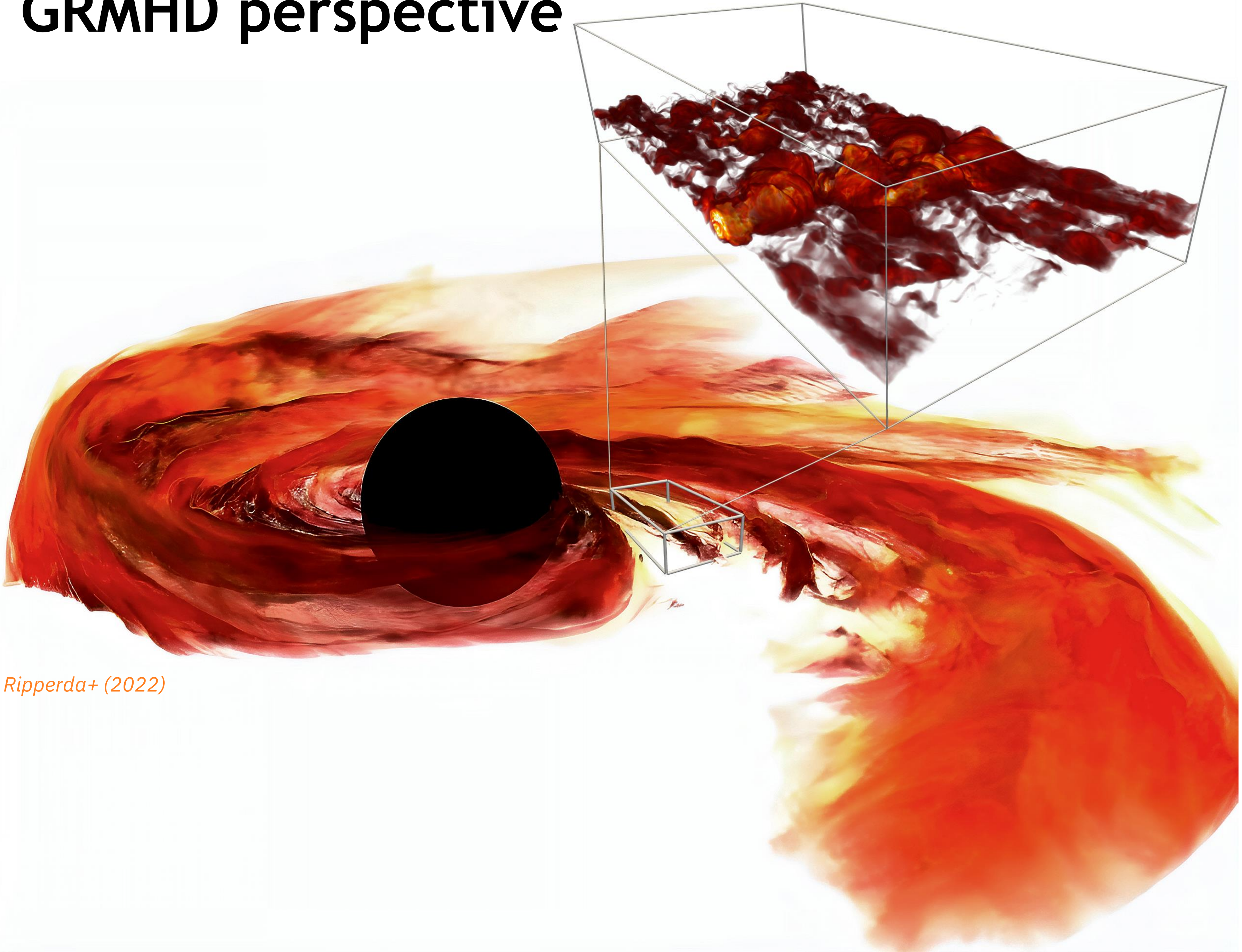
Tchekhovskoy+ (2011) ⇒

⇓



GRMHD perspective

Chernoglazov+ (2023)

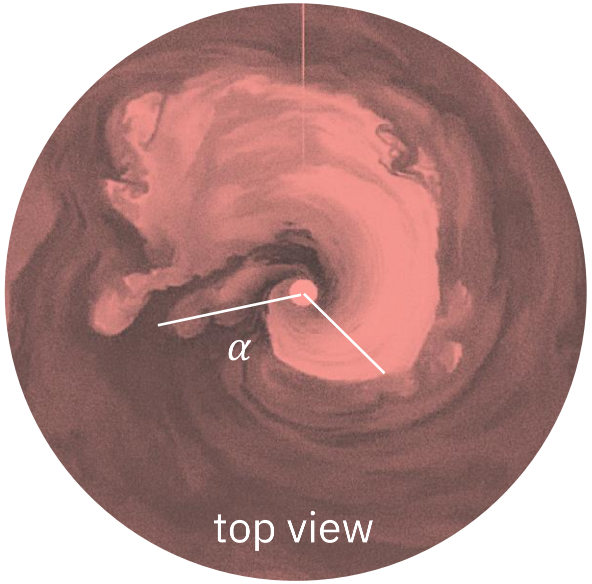


Ripperda+ (2022)

How much energy is dissipated?

$$L_{\rm diss} \sim \underbrace{\frac{\alpha}{2\pi}}_{\text{1-10\%}} \beta_{\rm rec} L_{\rm BZ}$$

$$L_{\rm BZ} = B^2 r_g^2 c/24$$

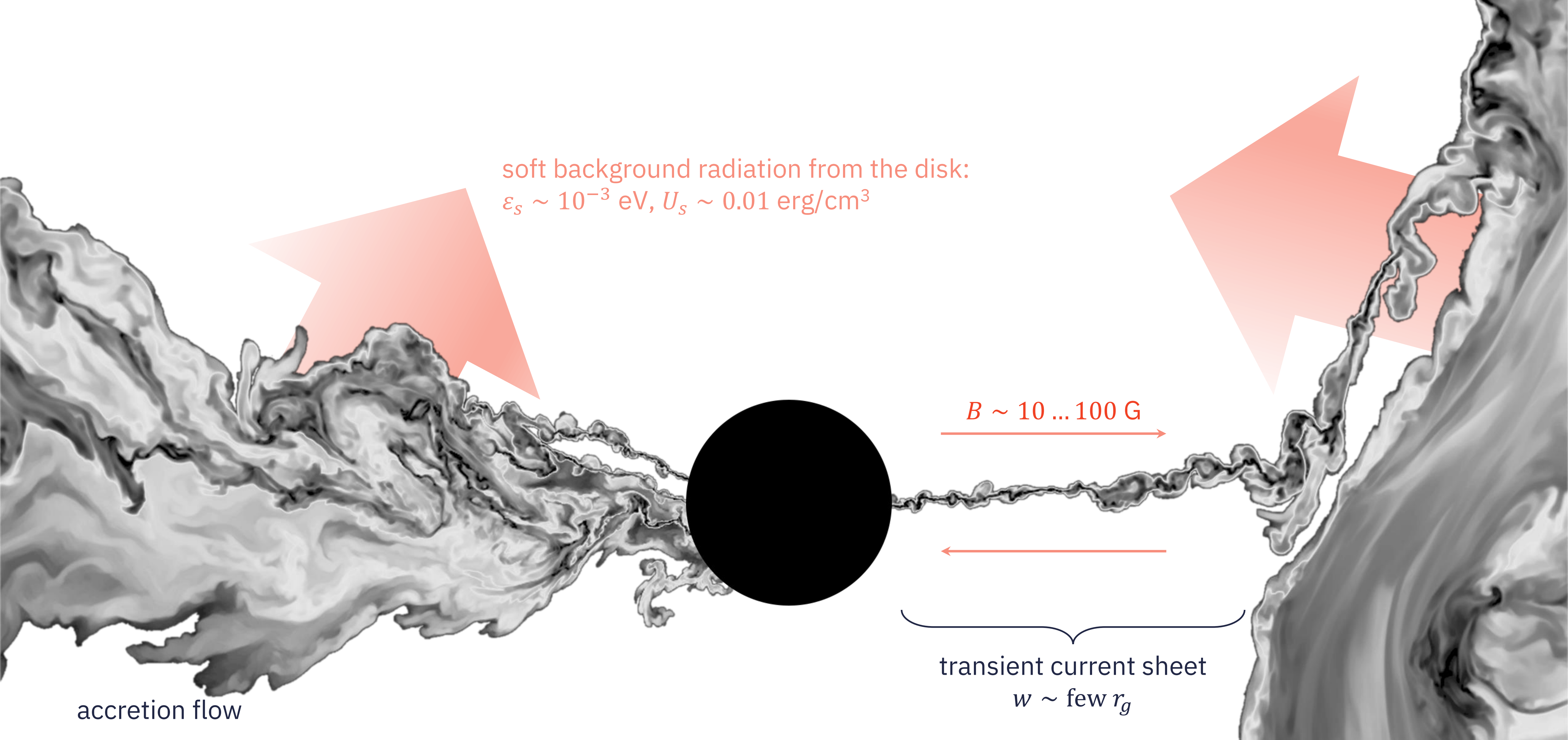


How much of the energy is radiated?

$$l_B = \frac{\sigma_T U_B(\text{few } r_g)}{m_e c^2} \approx \text{few} \Rightarrow t_{\rm cool} \ll r_g/c$$

* $U_B \gg U_s \Rightarrow$ synchrotron is the main radiation mechanism

Kinetic perspective

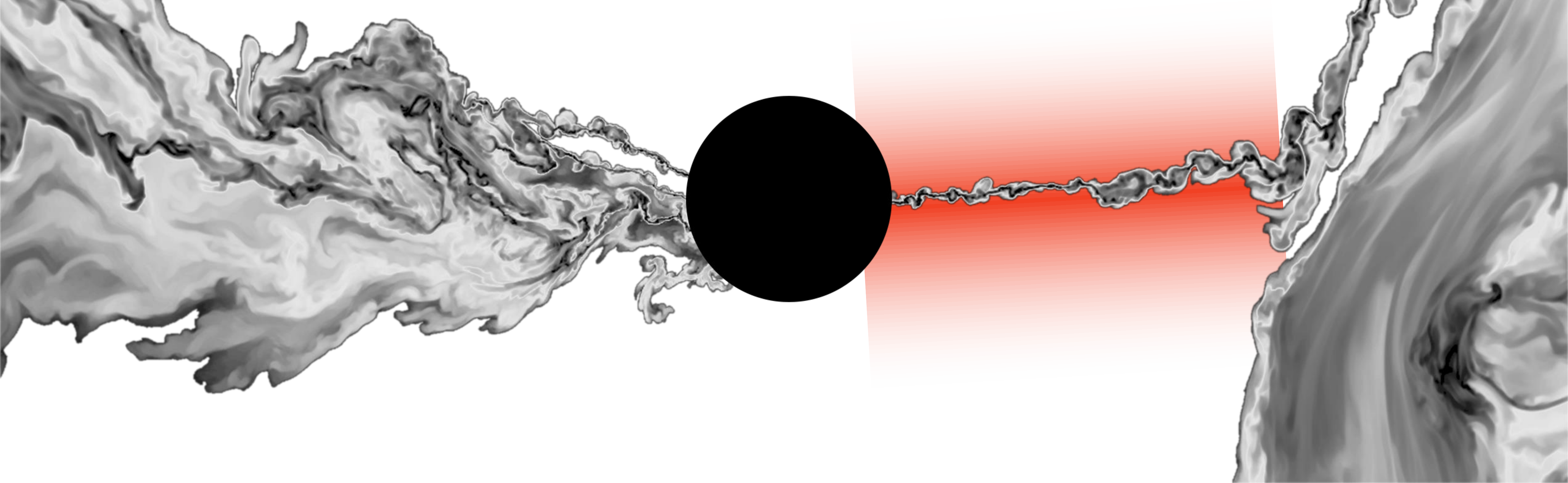


* $U_B \sim 400$ erg/cm$^3 \gg U_s \Rightarrow$ synchrotron is the main radiation mechanism

Kinetic perspective

How much plasma is produced?

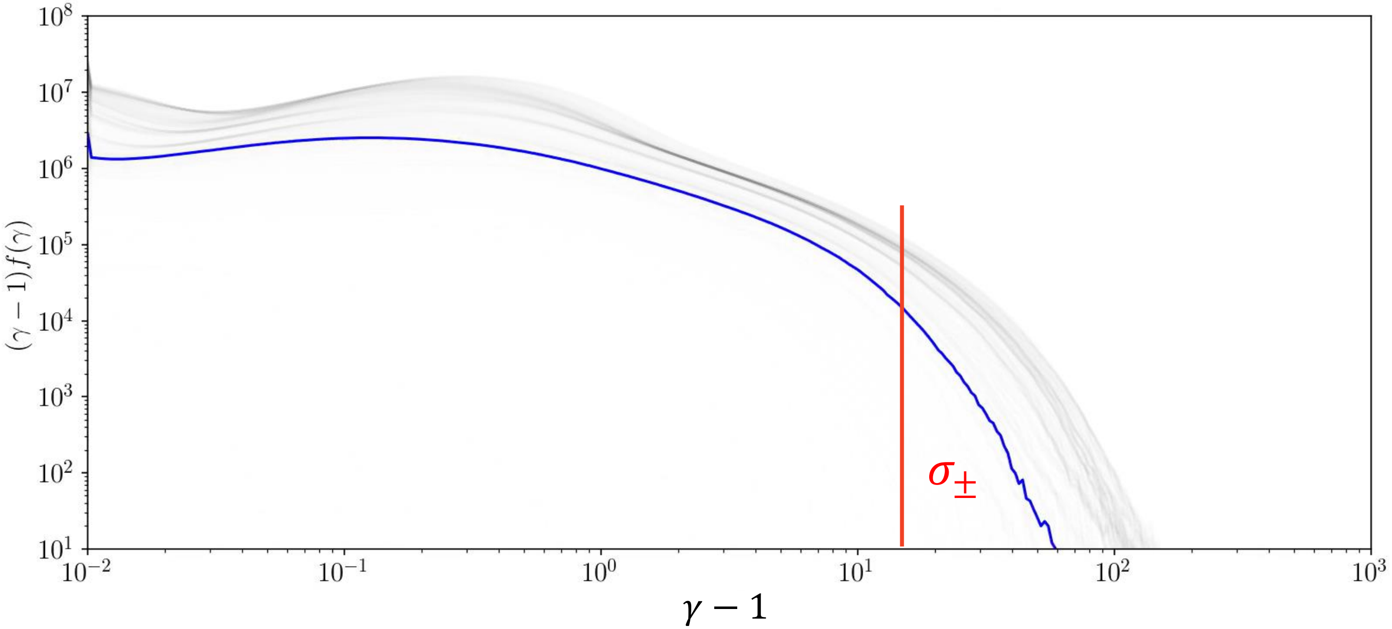
- Relevant quantity to compare with: $\dot{N}_{\rm GJ} = (cL_{\rm BZ})^{1/2}/|e|$ (GJ = Goldreich-Julian, minimum required to the screen $\boldsymbol{E}$-field)
- Two-photon pair production $\varepsilon_1 + \varepsilon_2 \rightarrow e^{\pm}$; optical depth $\tau_{12} \approx 3 f_{\gamma\gamma} \sigma_T L_1/(4\pi w \varepsilon_1) \sim 10^{-4}$
  - L_1 -- “luminosity” of photons with energy ε_1
  - max probability corresponds to $\varepsilon_1 \varepsilon_2 \approx (m_e c^2)^2$
- Total pair-production rate: $\dot{N}_{\pm} \approx \tau_{12} L_2/\varepsilon_2$; take $L_1 L_2 \sim \left(f_{\rm rec} L_{\rm jet}\right)^2$ (justified further)
- Pair multiplicity: $\dot{N}_{\pm}/\dot{N}_{\rm GJ} \approx 10^7$ (by far enough to screen the “gap”)

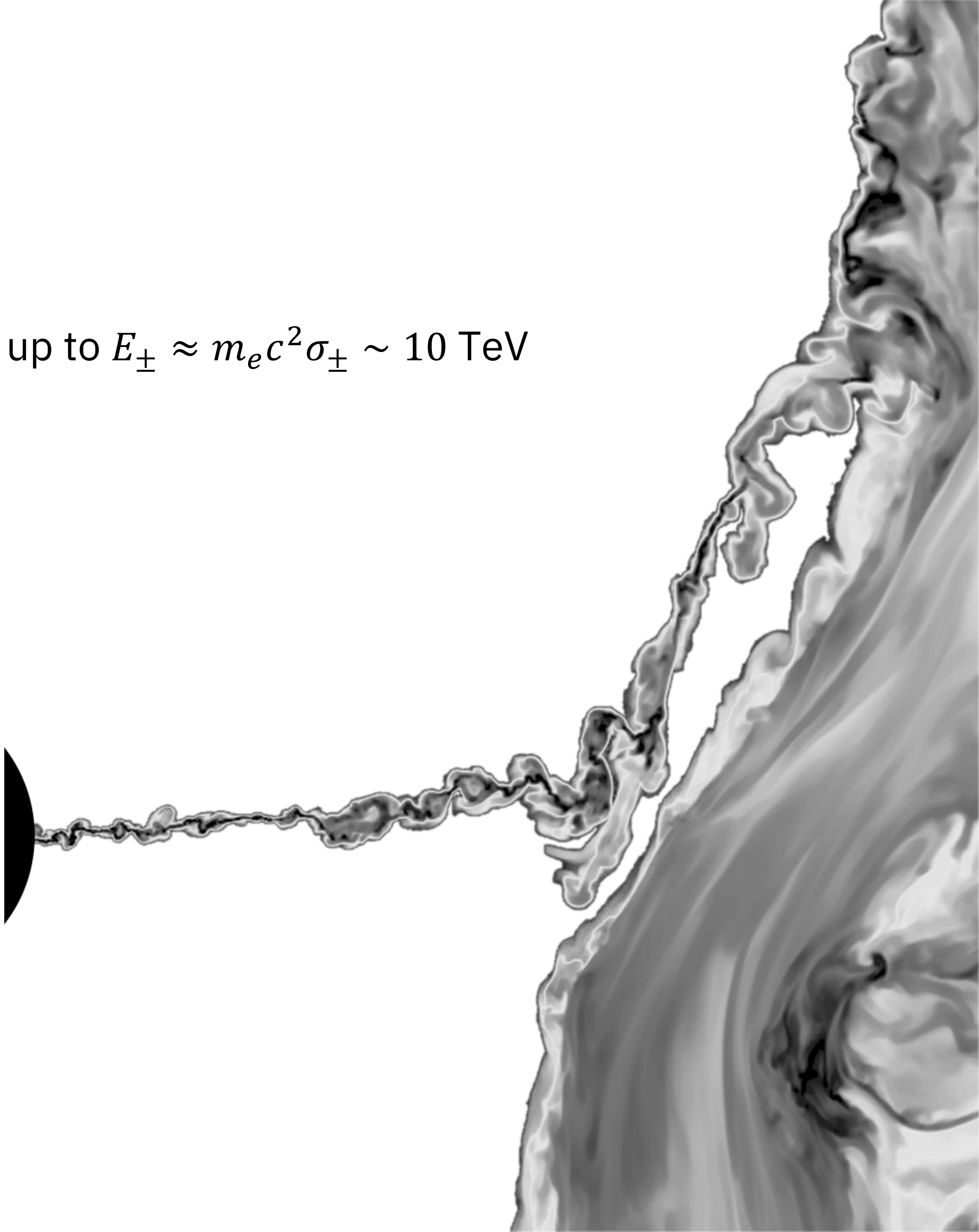


Kinetic perspective

How much are the pairs accelerated?

$$\sigma_\pm \approx \frac{|e|B/m_e c}{2\Omega_{\rm BH}} \frac{\dot{N}_{\rm GJ}}{\dot{N}_\pm} \sim 10^7 \ldots 10^8 \quad \Rightarrow \text{pairs are accelerated up to } E_\pm \approx m_e c^2 \sigma_\pm \sim 10 \text{ TeV}$$





Kinetic perspective

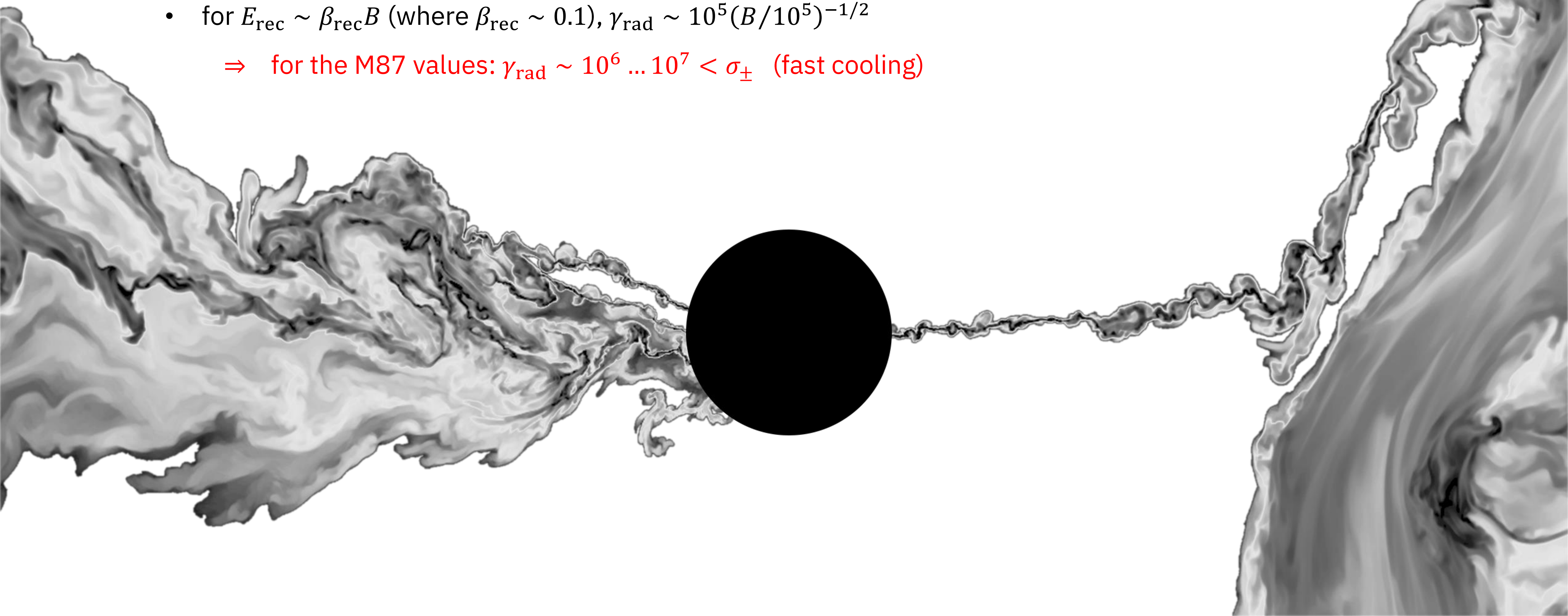
Does synchrotron cooling inhibit acceleration?

- cooling time *vs* acceleration time: $|e|E_{\rm rec}c = 2\sigma_T U_B \gamma_{\rm rad}^2$

  ⇒ $\gamma_{\rm rad}$ = Lorentz factor of particles for which cooling (in upstream field) is as fast as acceleration

- for $E_{\rm rec} \sim \beta_{\rm rec} B$ (where $\beta_{\rm rec} \sim 0.1$), $\gamma_{\rm rad} \sim 10^5 (B/10^5)^{-1/2}$

  ⇒ for the M87 values: $\gamma_{\rm rad} \sim 10^6 \ldots 10^7 < \sigma_\pm$ (fast cooling)



Kinetic perspective

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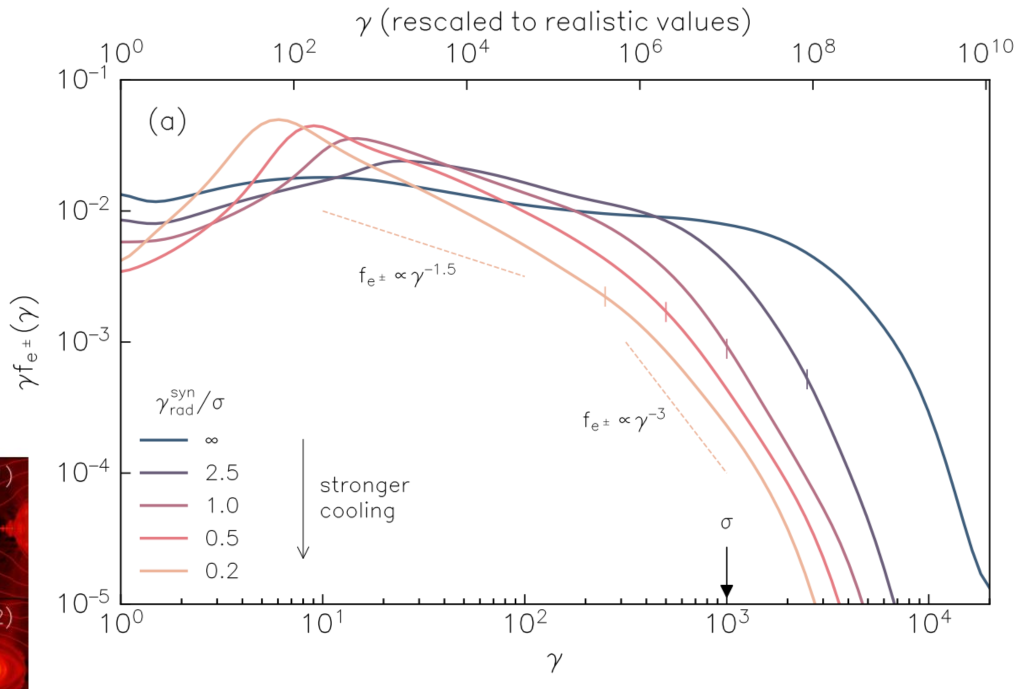
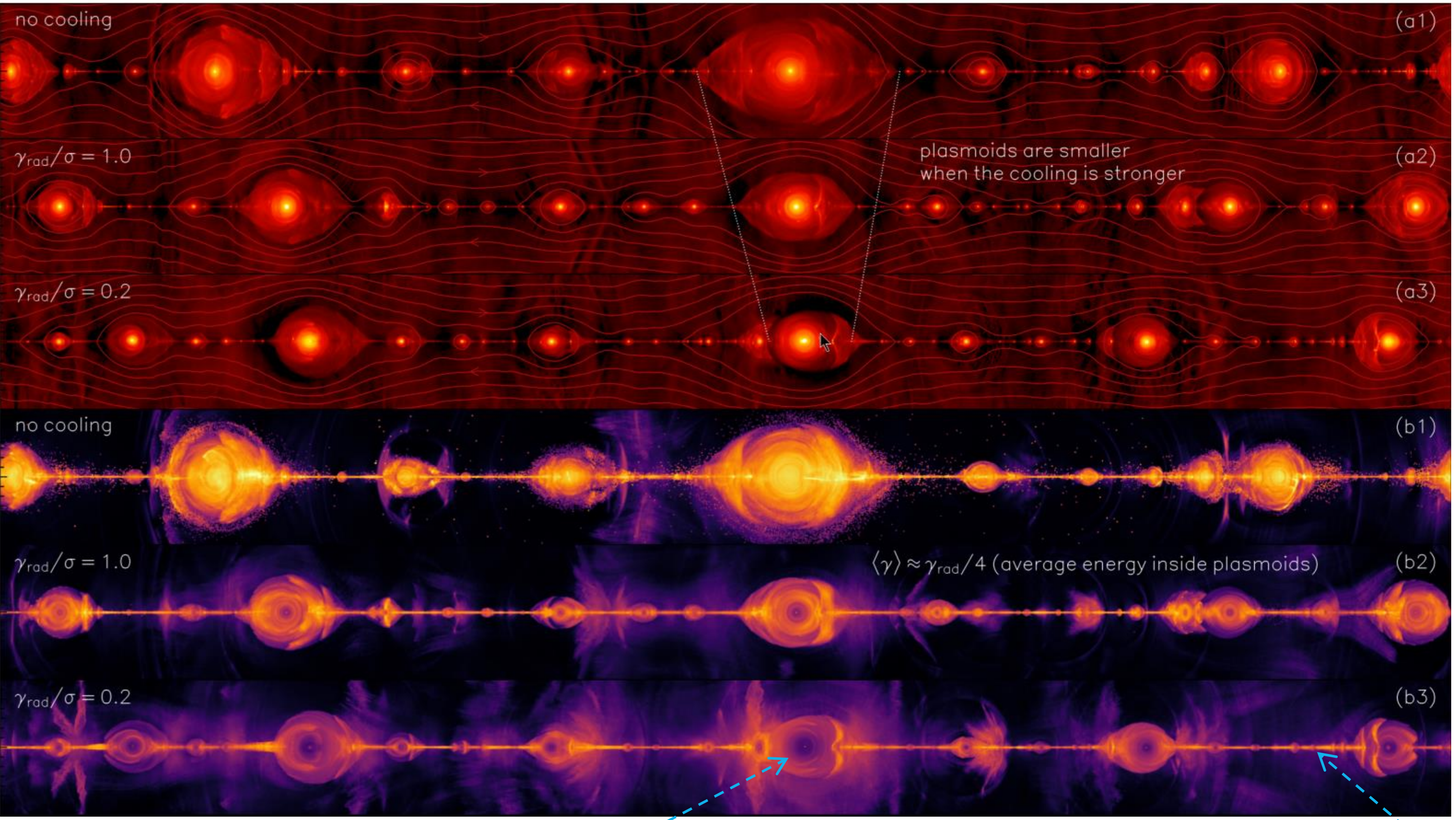


HH+ (2023), also see *Chernoglazov+ (2023)* for 3D



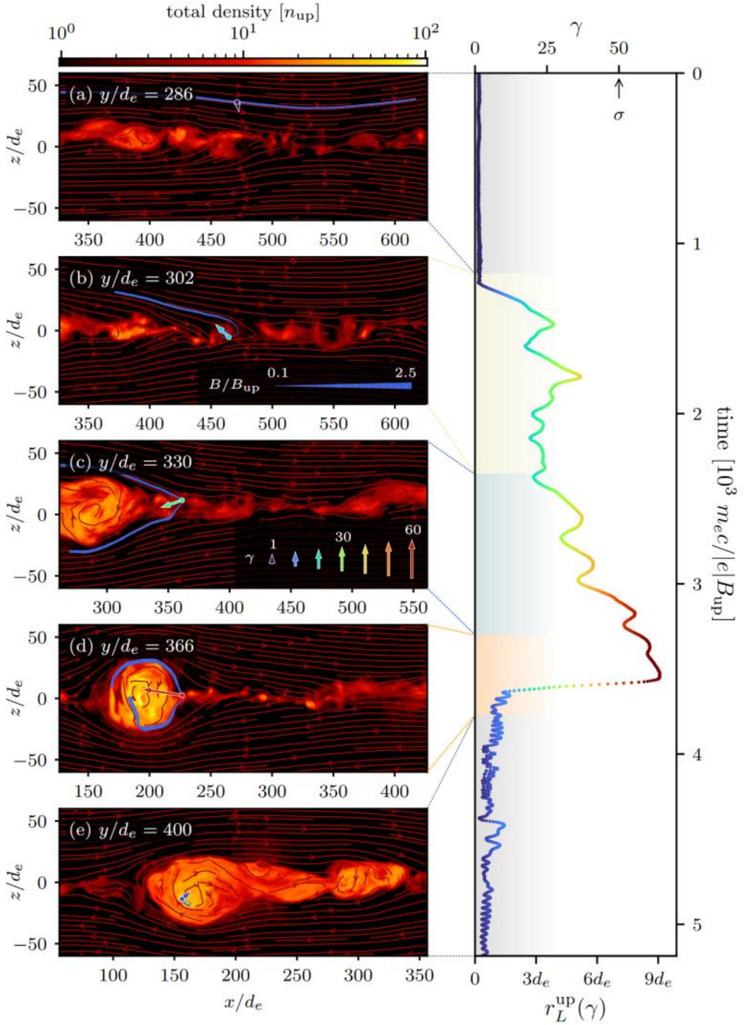
stronger cooling

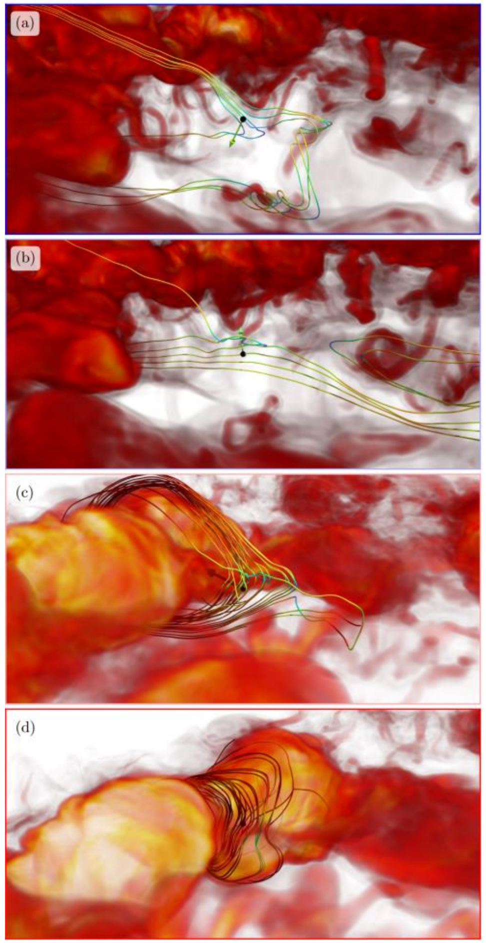
- cooling happens in ***plasmoids***, while the acceleration takes place in ***X-points*** (no B-field ⇒ no cooling)

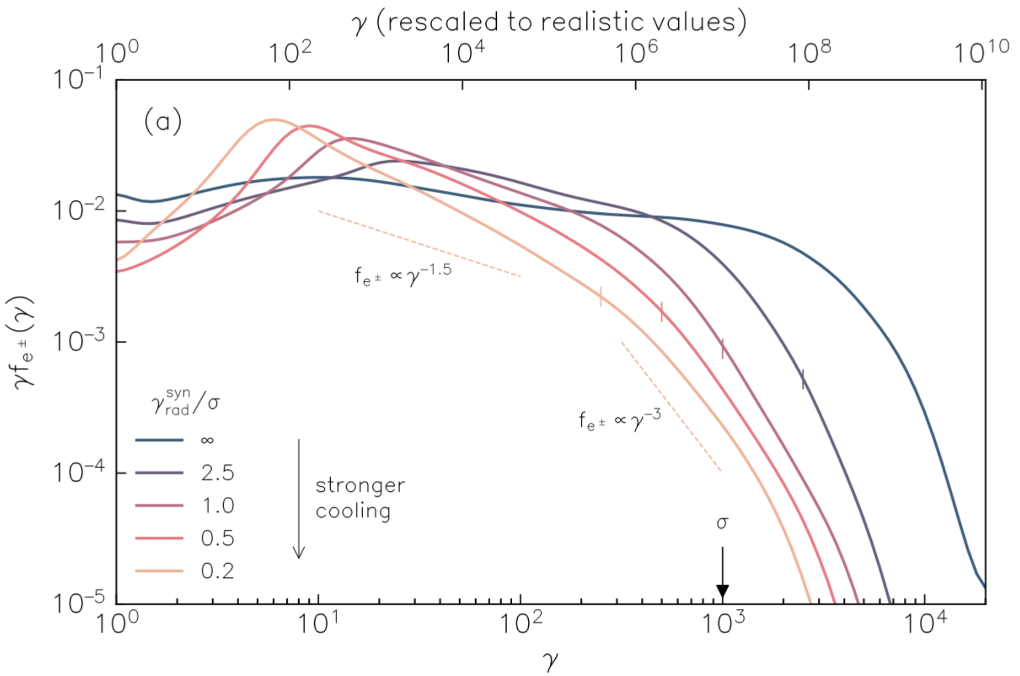
Kinetic perspective

Does synchrotron cooling inhibit acceleration?

- for the M87* values: $\gamma_{\rm rad} \sim 10^6 \dots 10^7 < \sigma_\pm$ (fast cooling)
- further reacceleration is prohibited ($\sigma_\pm$ really is the limit)!





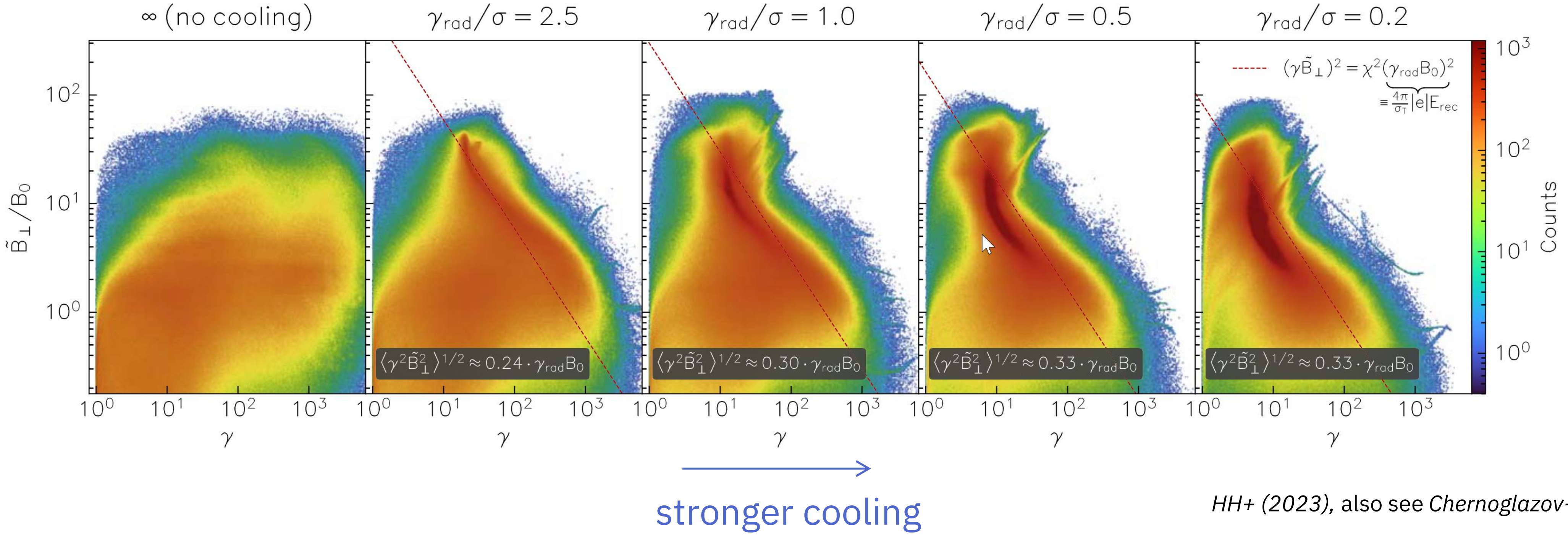


Chernoglazov+ (2023)

Kinetic perspective

What about the emission?

- we have $dn_\pm/d\gamma$, so can we just do $F_\nu \propto \gamma^2 dn_\pm/d\gamma$, where $\nu \propto \gamma^2 B$? (synchrotron)
- ... not really! B-field geometry (pitch angle distribution) matters
- most of the particles (in strong cooling) live on the $\gamma^2 B_\perp^2 \approx \gamma_{\rm rad}^2 B^2$ line (B – background value)



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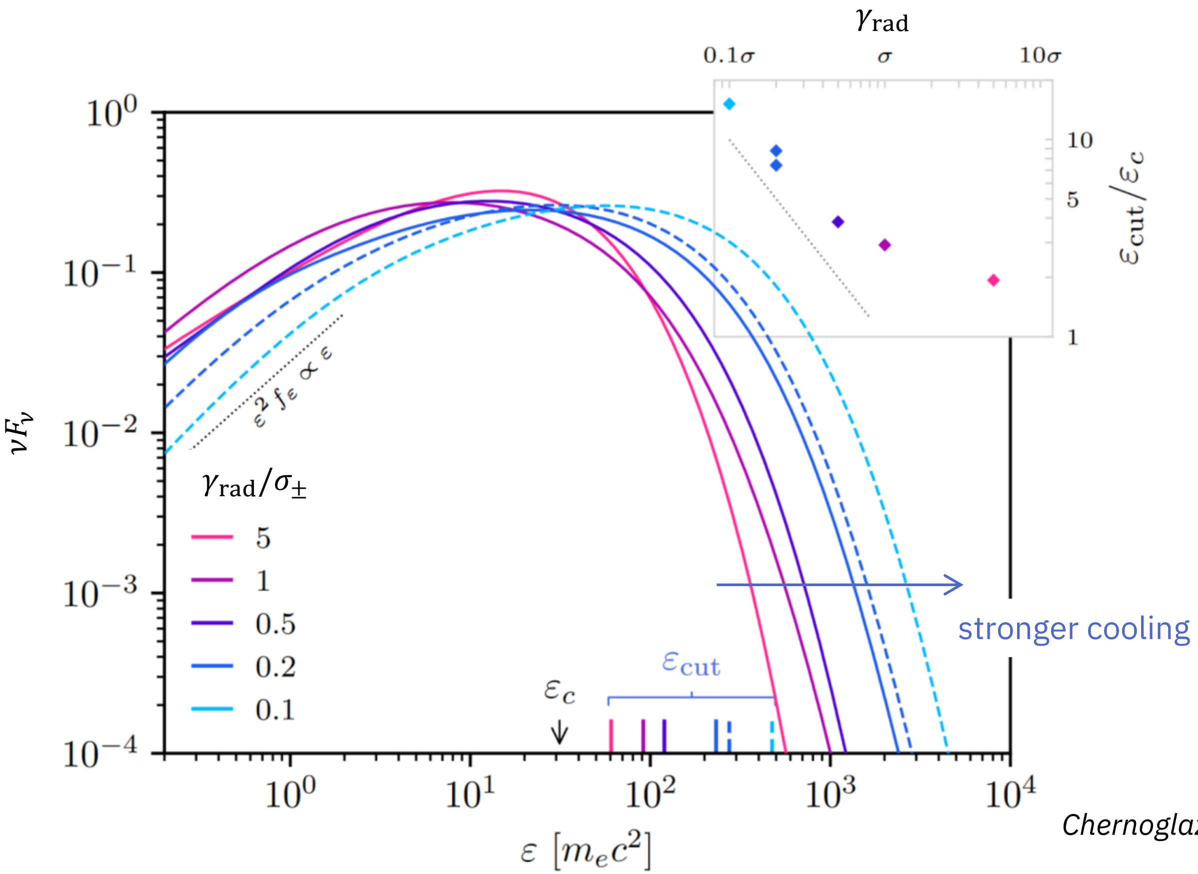


Chernoglazov+ (2023)

- peak (most of the energy flux) is set by $\gamma \sim \gamma_{\rm rad}$:

  $\varepsilon_{\rm peak} \approx \gamma_{\rm rad}^2 (\hbar |e| B/m_e c) \approx 16$ MeV (does not depend on B)

- cutoff determined by $\gamma \sim \sigma_\pm$:

  $\varepsilon_{\rm cut} \approx \sigma_\pm^2 (\hbar |e| B_\perp / m_e c) \approx \varepsilon_{\rm peak}(\sigma_\pm/\gamma_{\rm rad})$

  for the M87* ($\sigma_\pm/\gamma_{\rm rad} \sim 10 \ldots 100$) $\Rightarrow \varepsilon_{\rm cut} \sim$ few GeV

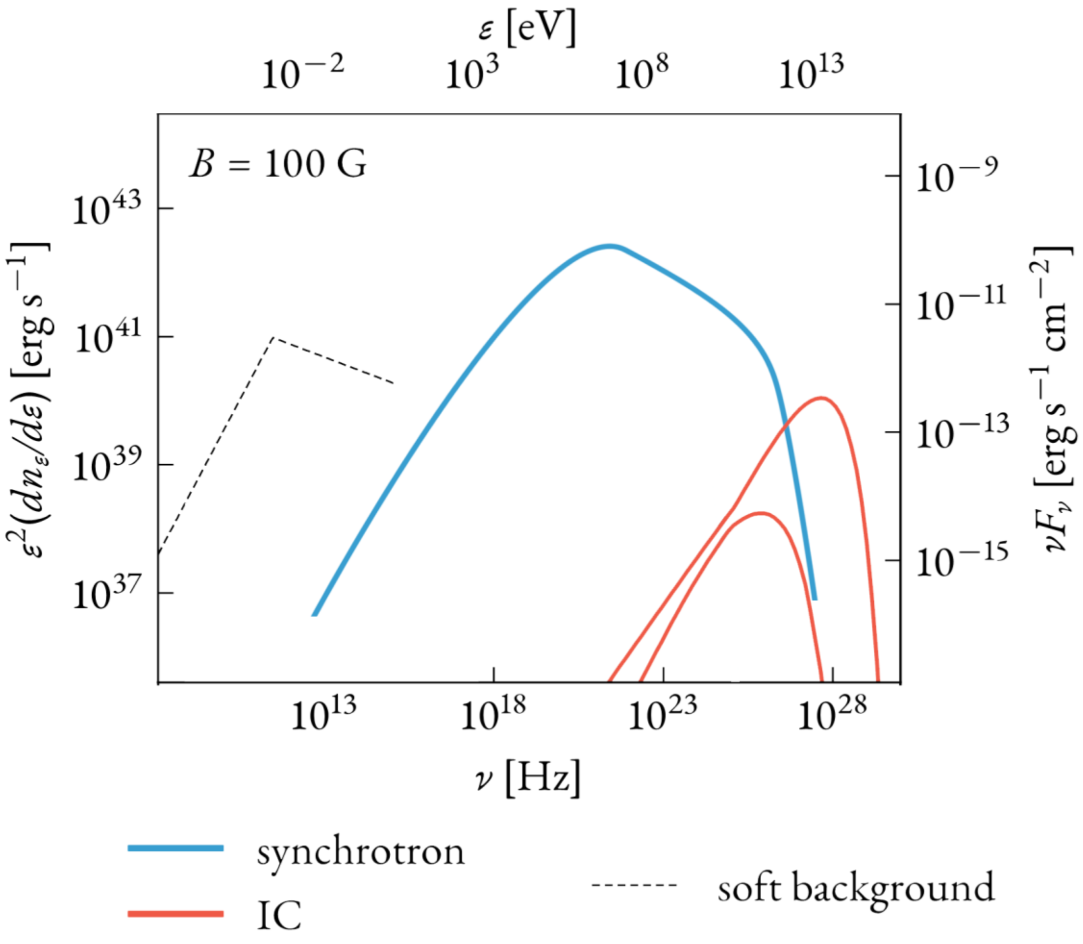
Kinetic perspective

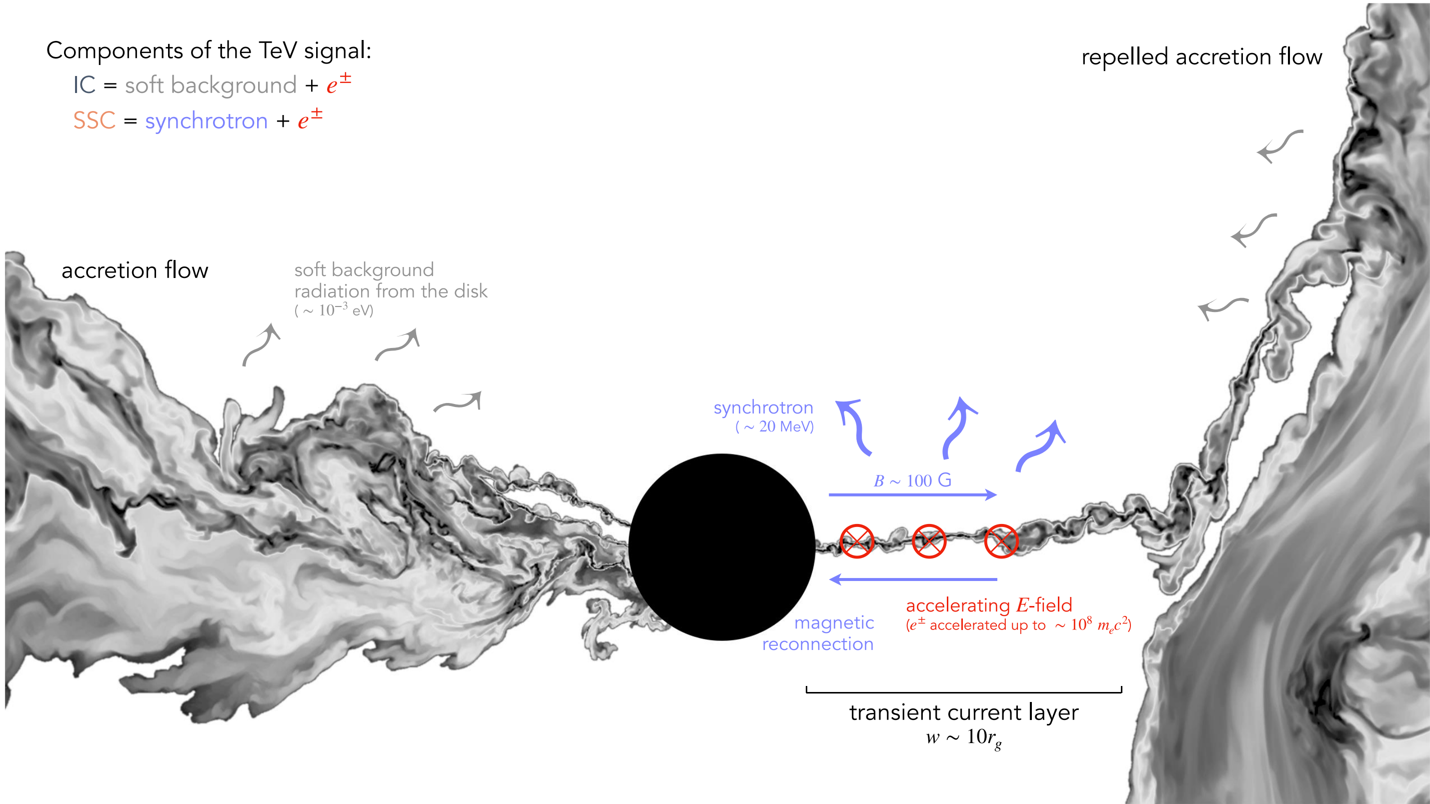
What about the emission?

$$\varepsilon_{\rm peak} \approx \gamma_{\rm rad}^2 (\hbar |e| B / m_e c) \approx 16 \text{ MeV}$$

$$\varepsilon_{\rm cut} \approx \sigma_\pm^2 (\hbar |e| B_\perp / m_e c) \approx \varepsilon_{\rm peak} (\sigma_\pm / \gamma_{\rm rad}) \sim \text{few GeV}$$

- pairs have TeV energies!
- IC of soft background (radio from the disk)
  ⇒ TeV signal @ 0.1 … 1% of BZ power

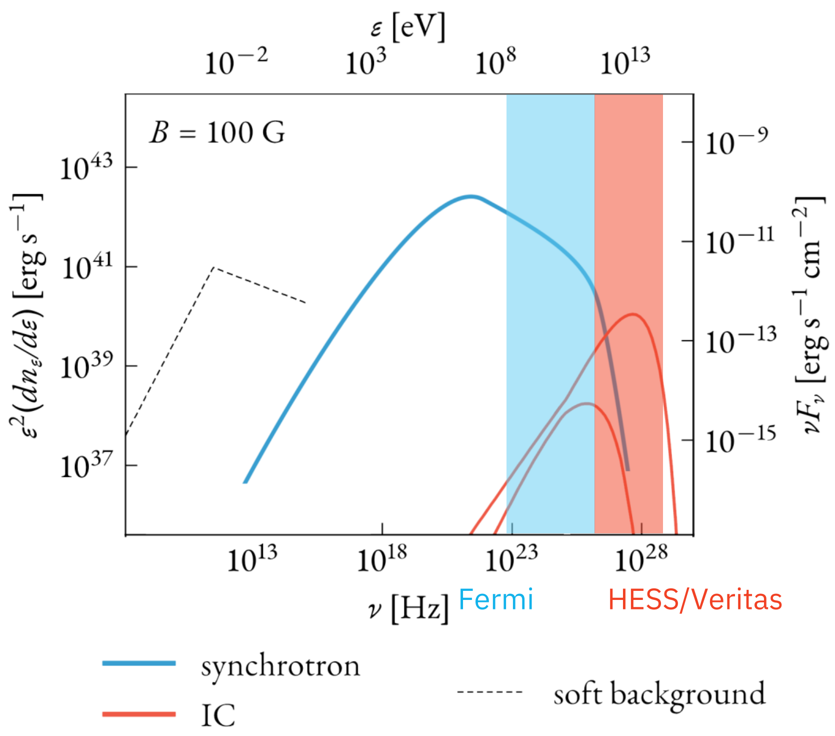




Kinetic perspective

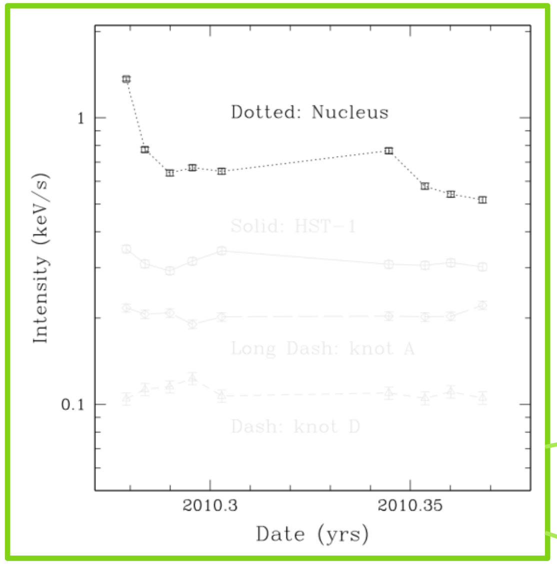
Connection to TeV flares

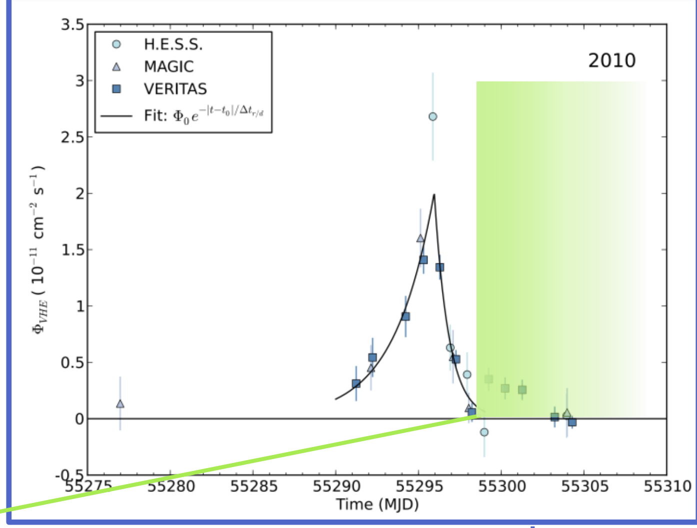
- energy release is fast: $\sim 10\, r_g/c$ (days)
- most of the dissipated energy (fraction of BZ $\sim 10^{43} \ldots 10^{44}$ erg/s) goes to MeV…GeV
- a smaller fraction is scattered to TeV ($10^{40} \ldots 10^{41}$ erg/s)
- duty cycle (repetition period) $\sim 10^3\, r_g/c \sim$ year

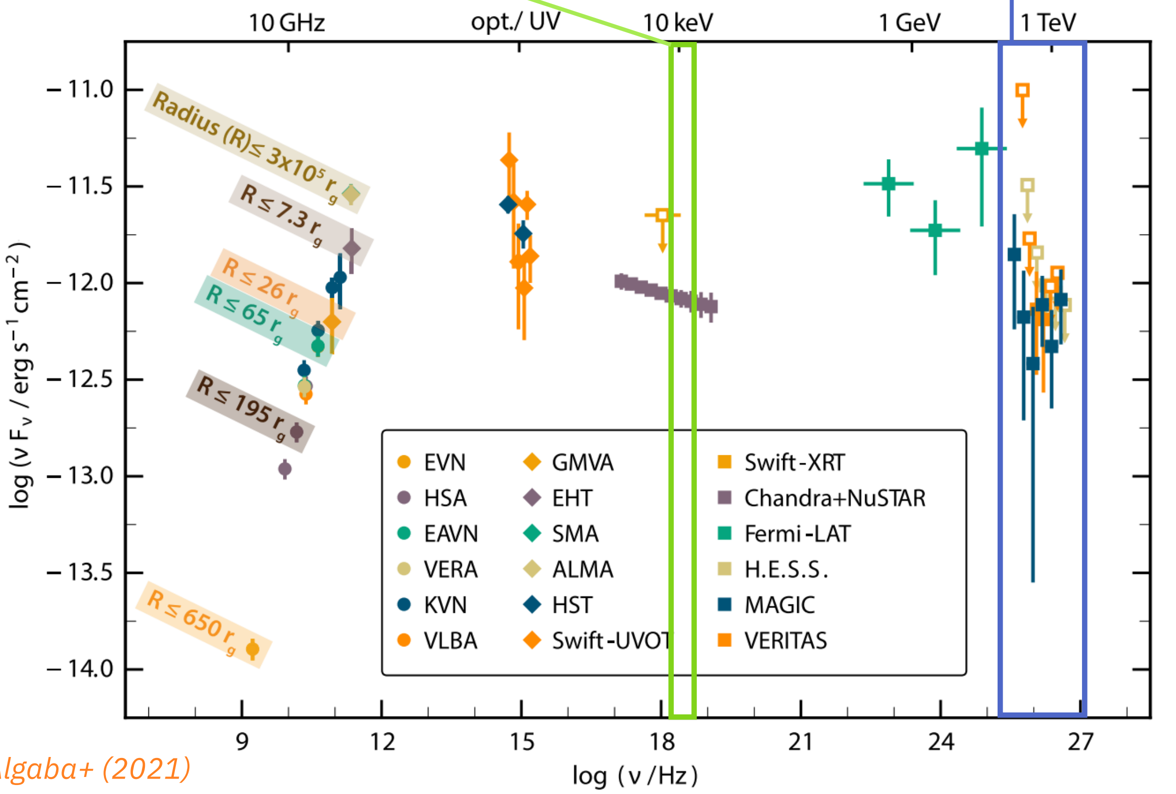


H.E.S.S. + MAGIC + Veritas: Abramowski+ (2012) ⇒

Chandra: Harris+ (2011) ⇒



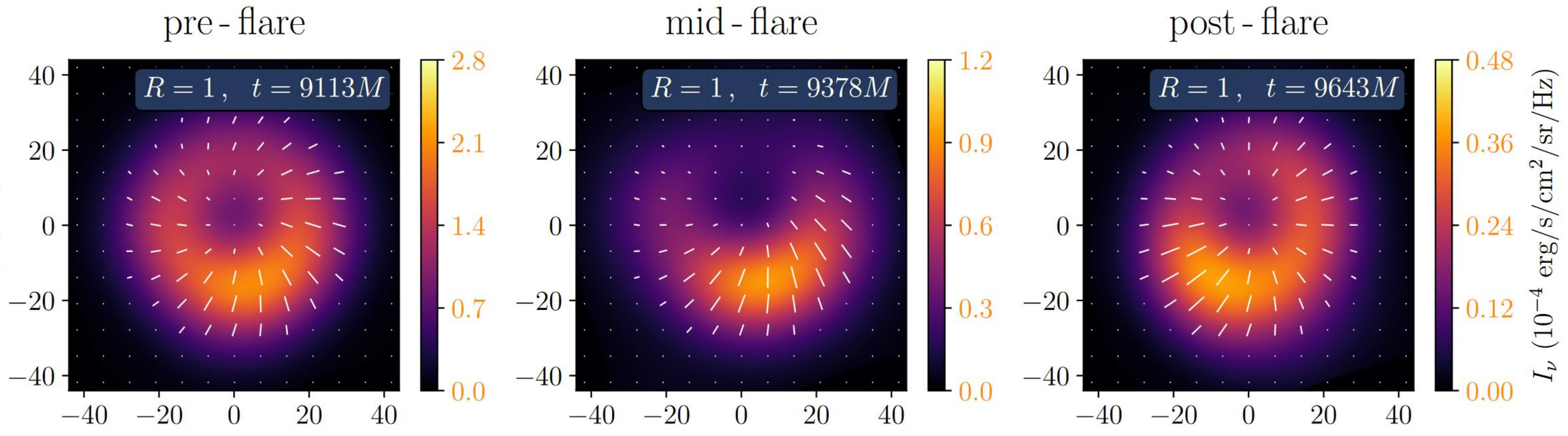




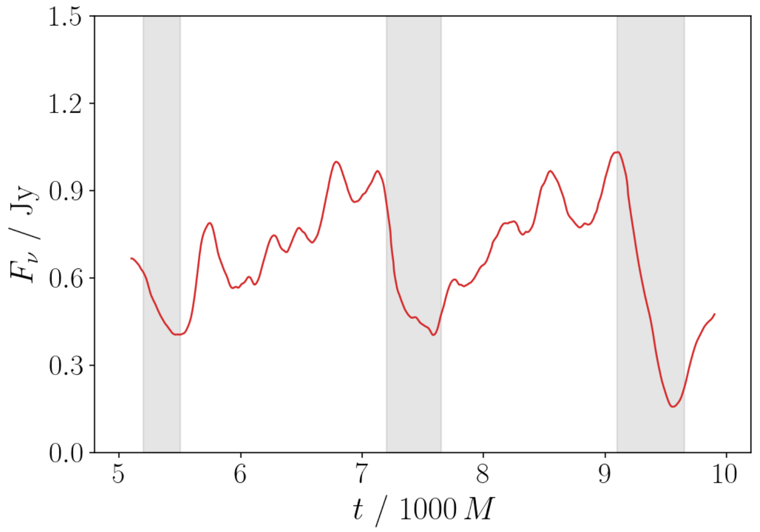
Algaba+ (2021)

Predictions of the model

- Radio dimming coincident with the flare



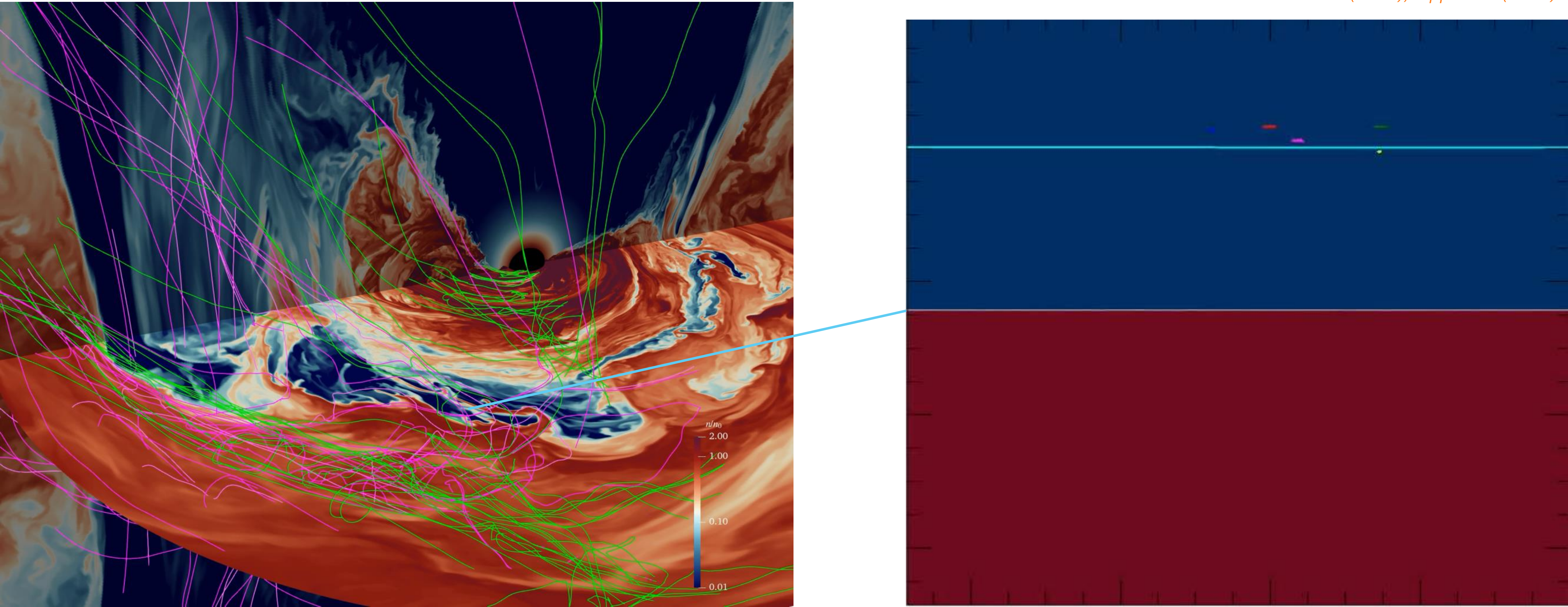
GRMHD post processing (no kinetics): *Jia+ (2023)*



Predictions of the model

- Radio dimming coincident with the flare
- post-flare NIR "hotspots" (presumably observed in Sgr A* by GRAVITY, but not in M87*)

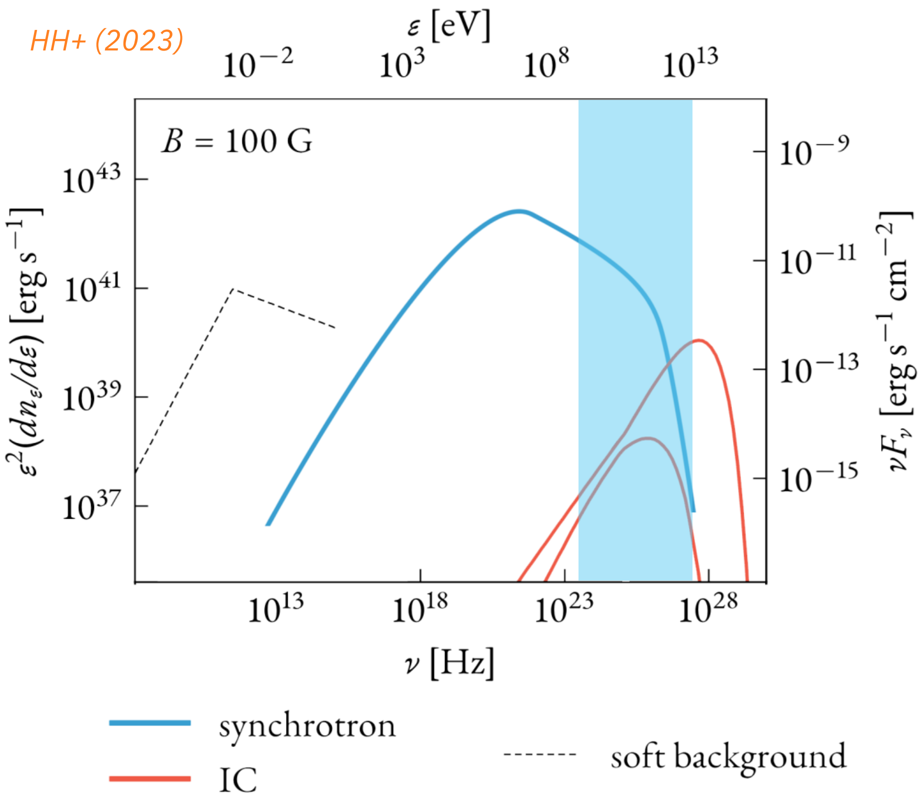
Zhdankin+ (2023), Ripperda+ (2023)



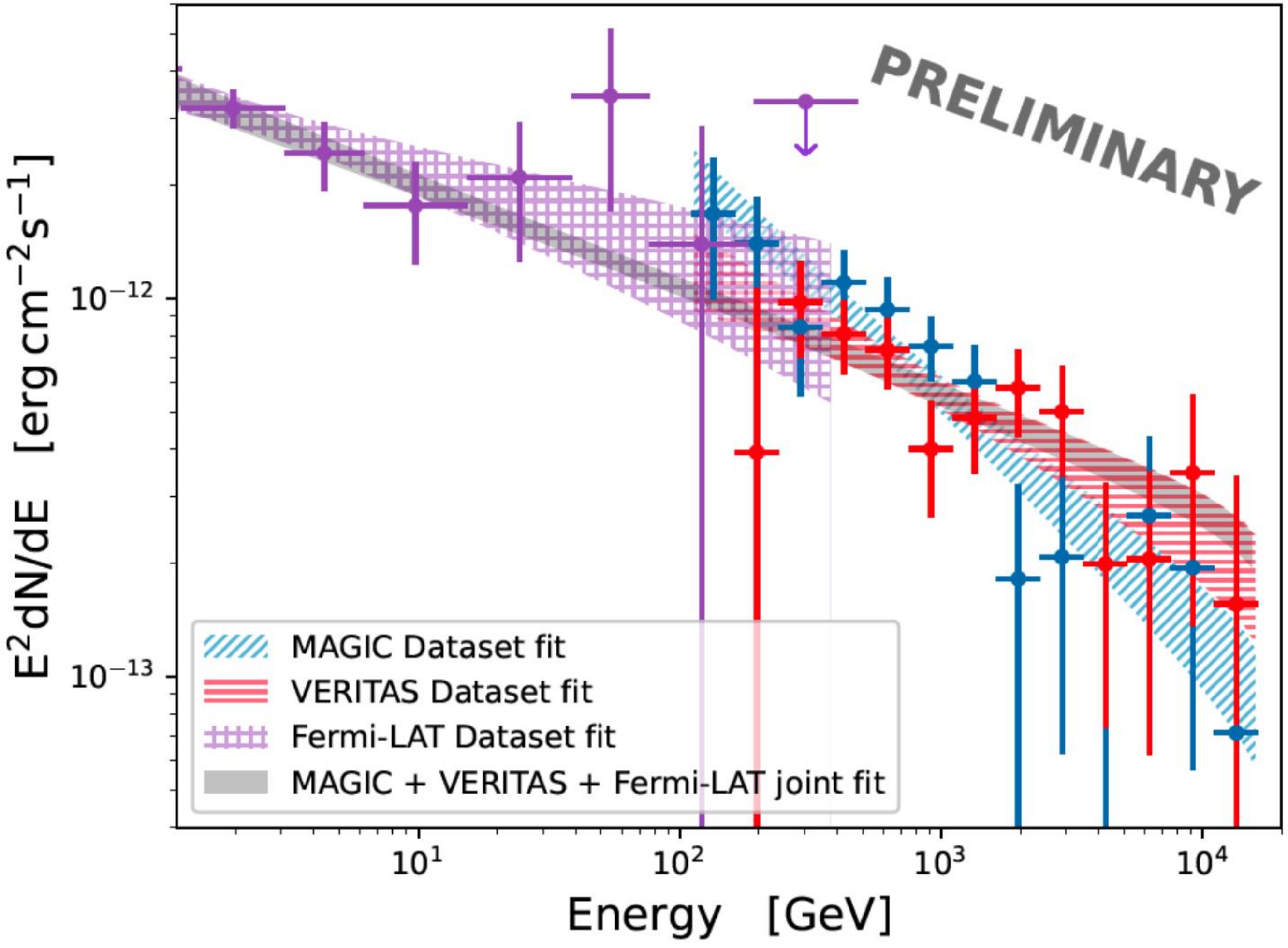
Predictions of the model

- Radio dimming coincident with the flare
- post-flare NIR "hotspots"
- MeV-GeV counterpart

HH+ (2023)

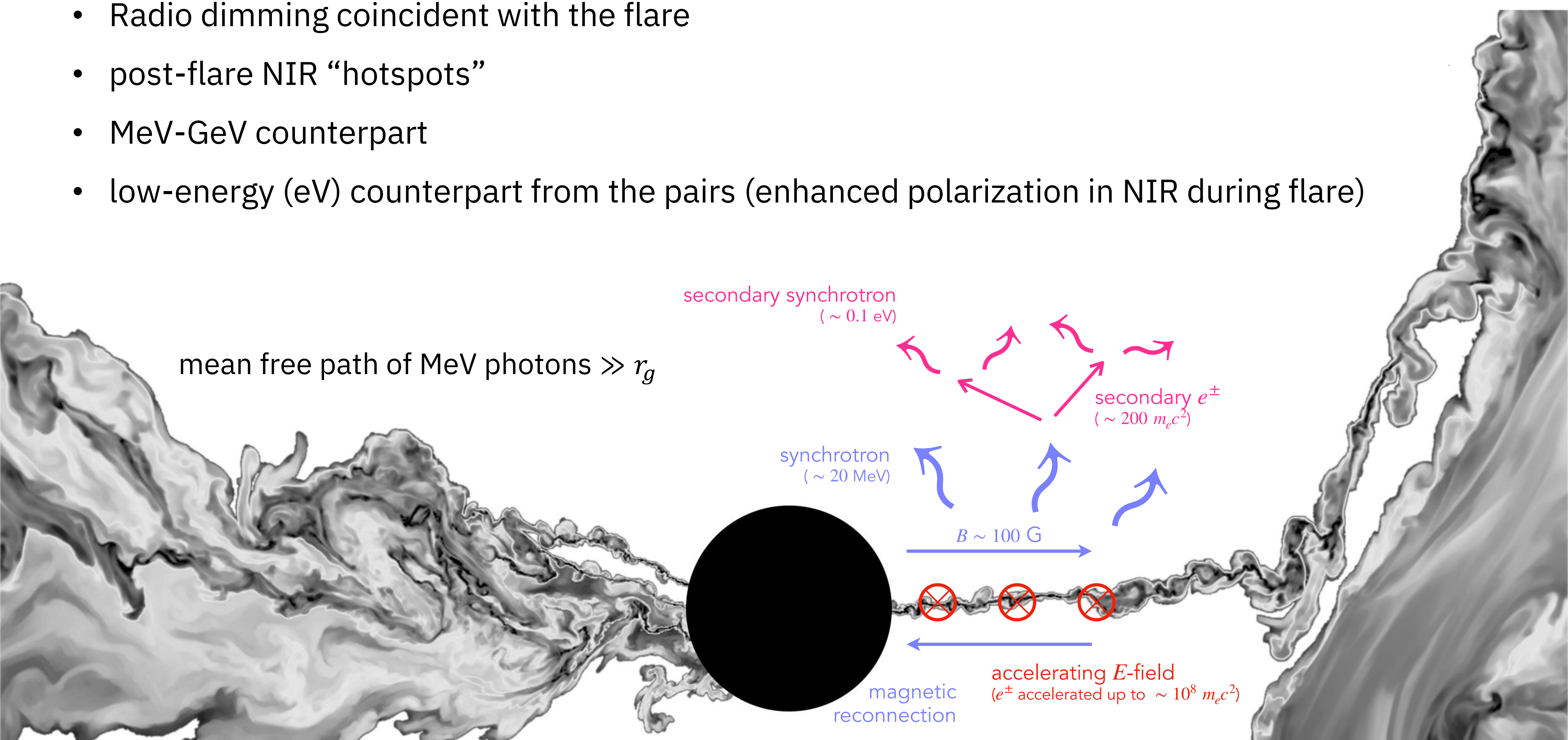


Long timescale accumulation by Fermi + VERITAS + MAGIC: *Molero+ (2023)*
(probably includes both the quiescence & flares)



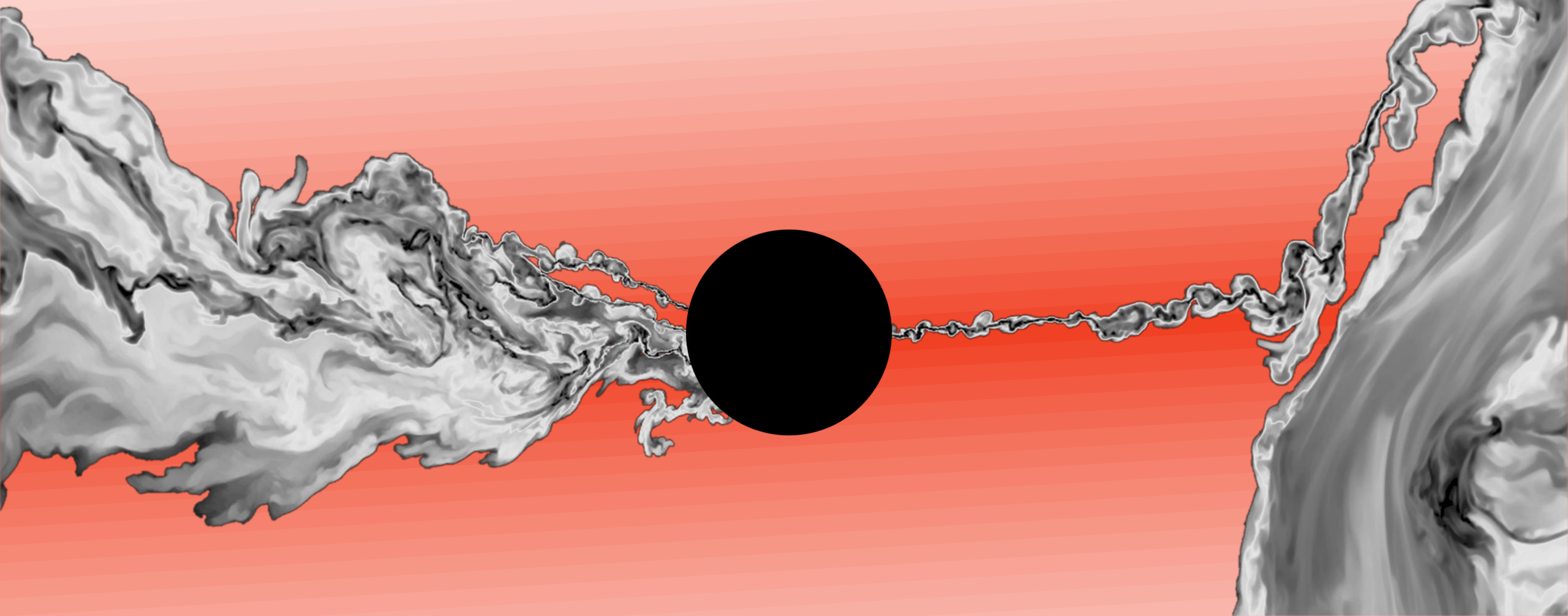
Predictions of the model

- Radio dimming coincident with the flare
- post-flare NIR “hotspots”
- MeV-GeV counterpart
- low-energy (eV) counterpart from the pairs (enhanced polarization in NIR during flare)



Open questions

- Fate of the produced pairs?
  - What fraction populates the jet *vs* disk? Naively, $n_{\pm} \sim n_{\mathrm{disk}}$, so can be dynamically significant.
  - How does the population in the disk affect the polarization signature?



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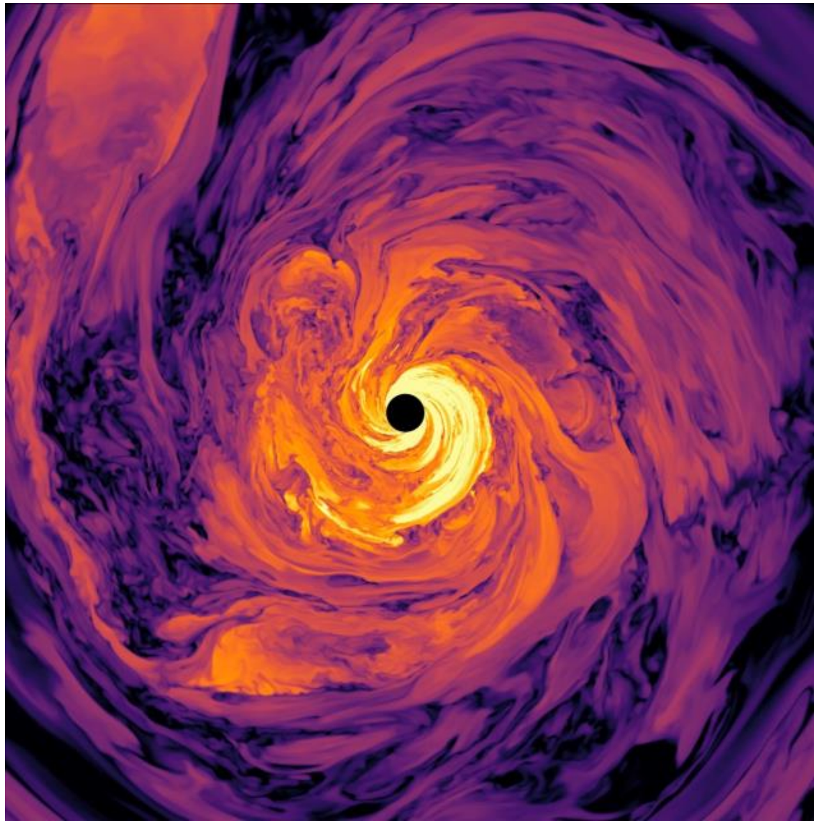
  - More frequent lower luminosity (smaller scale) flares can contribute to quiescent emission in GeV/TeV
  - Constant $e^{\pm}$-pumping to the jet/disk



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  - Constant $e^{\pm}$-pumping to the jet/disk
- How the hell does Sgr A* flare?
  - $l_B \sim 10^{-3}$ & $\tau_{\gamma\gamma} \lll 1$: almost no pairs produced!
  - not observed at MeV/GeV, but strong flaring in NIR & keV

Spitzer: Ponti+ (2017)