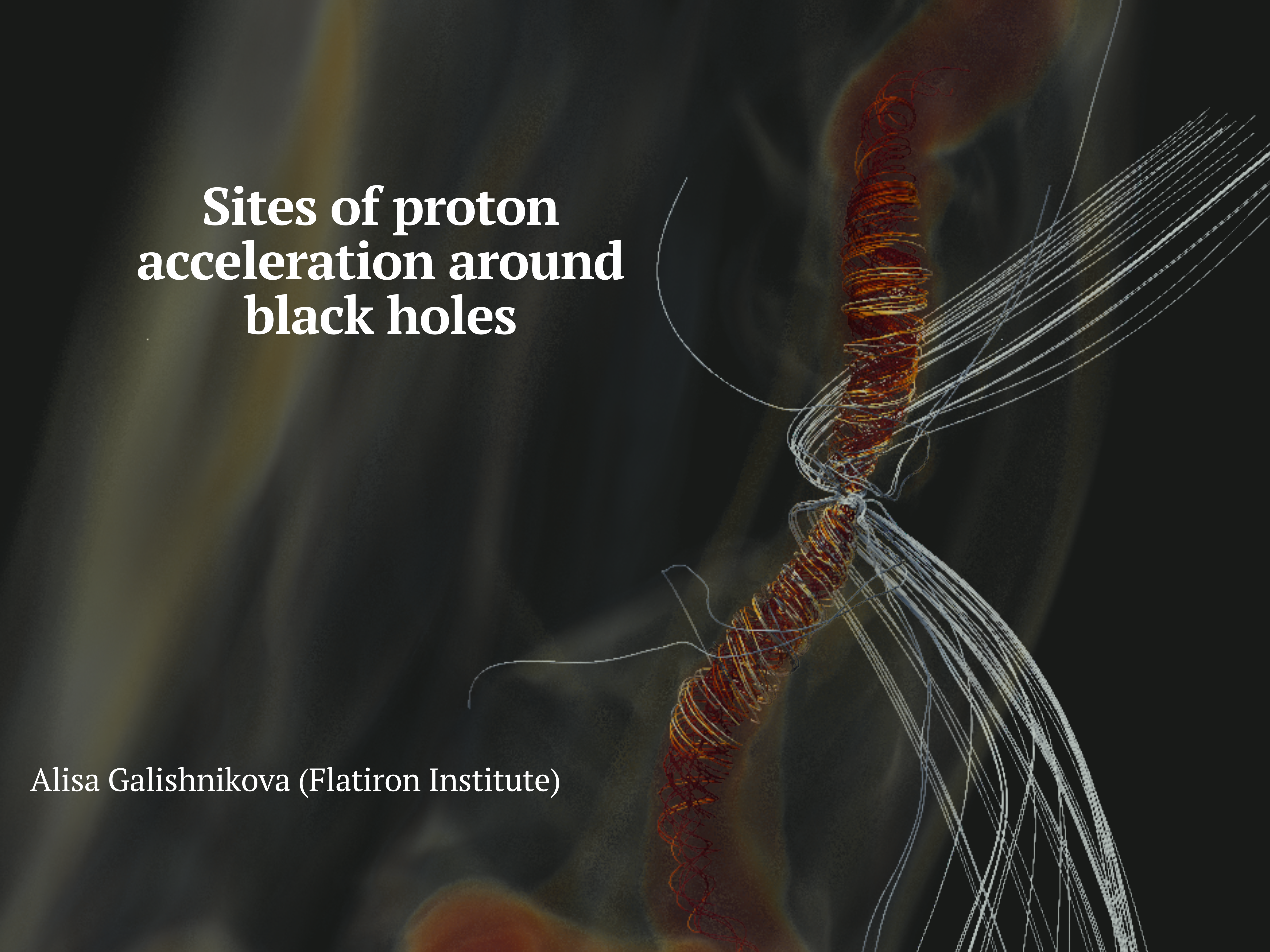
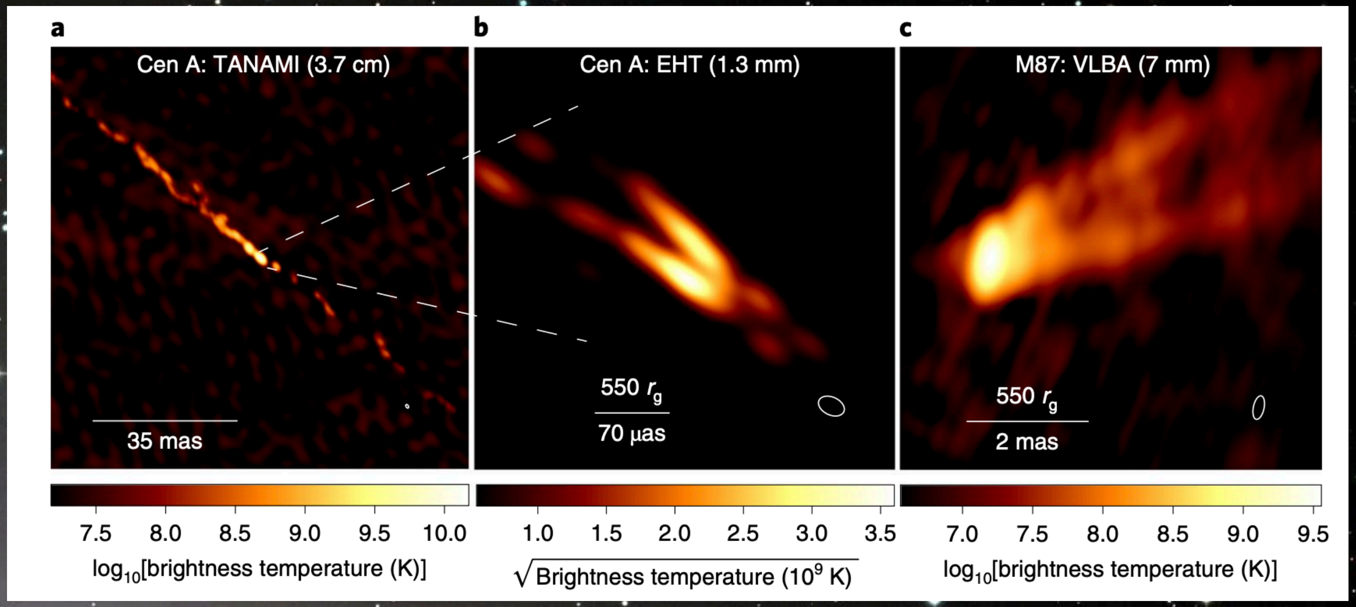
Sites of proton acceleration around black holes



Alisa Galishnikova (Flatiron Institute)

Centaurus A



Event Horizon Telescope

$$M \sim 5 \times 10^7 M_\odot$$

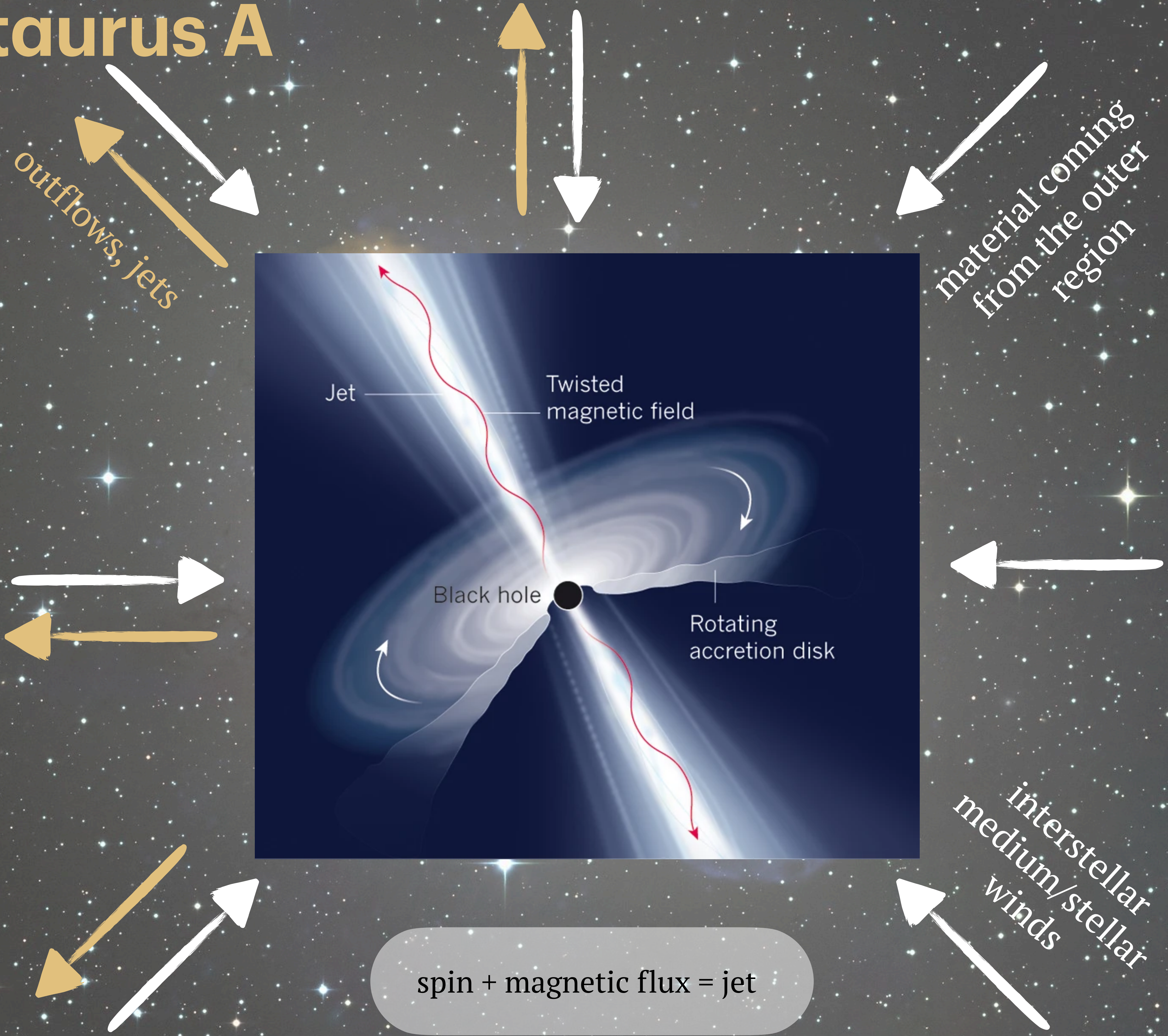
$$r_g = \frac{GM}{c^2} \approx 0.5AU \approx 2 \times 10^{-6} pc$$

Jets and their lobes — out to 100s of kpc

Gabuzda (2014)

ESO/WFI (Optical); MPIfR/ESO/APEX/A. Weiss et al. (Submillimetre); NASA/CXC/CfA/R. Kraft et al. (X-ray)

Centaurus A



outflows, jets

material coming from the outer region

interstellar medium/stellar winds

spin + magnetic flux = jet

Gabuzda (2014)
ESO/WFI (Optical); MPIfR/ESO/APEX/A. Weiss et al. (Submillimetre); NASA/CXC/CfA/R. Kraft et al. (X-ray)

Low luminosity galactic nuclei - M87*

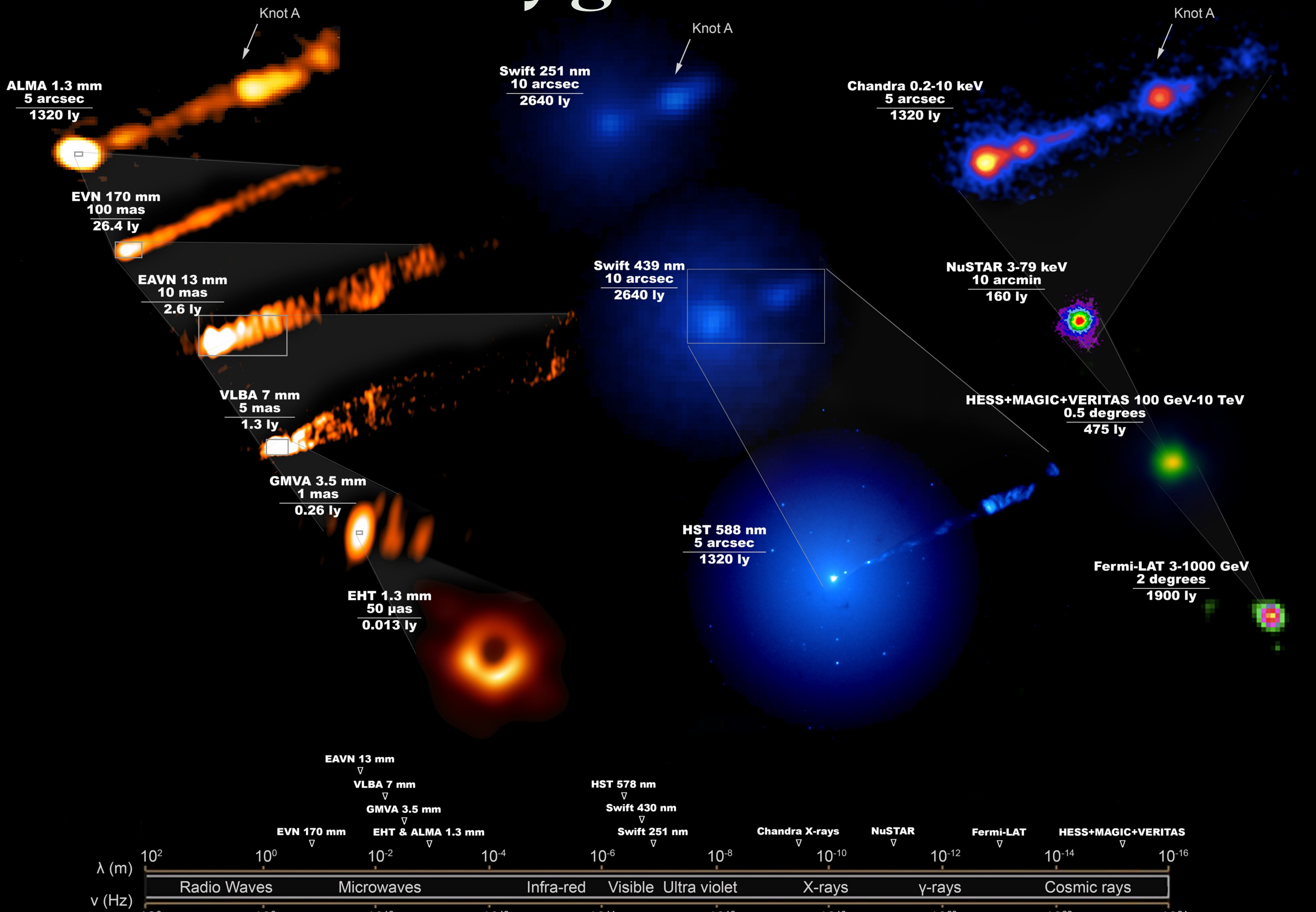
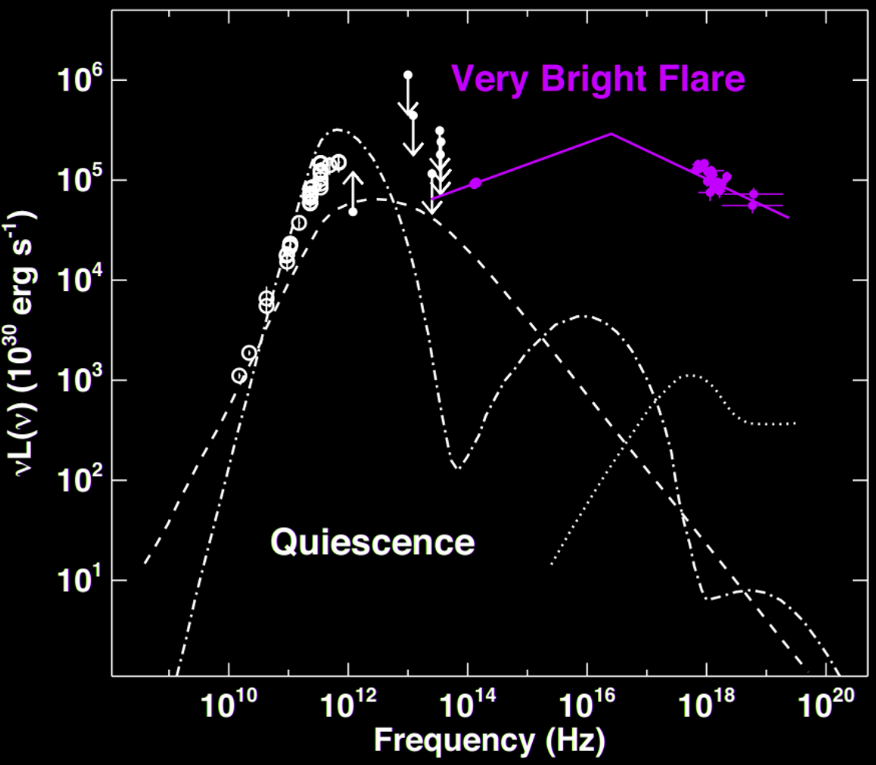


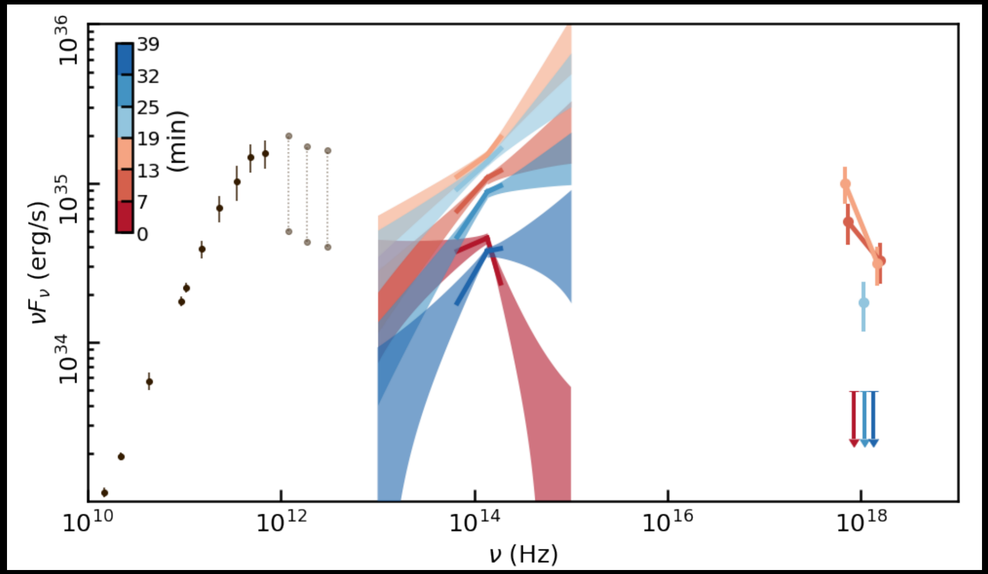
Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

Compact, highly magnetized sources, producing non-thermal emission

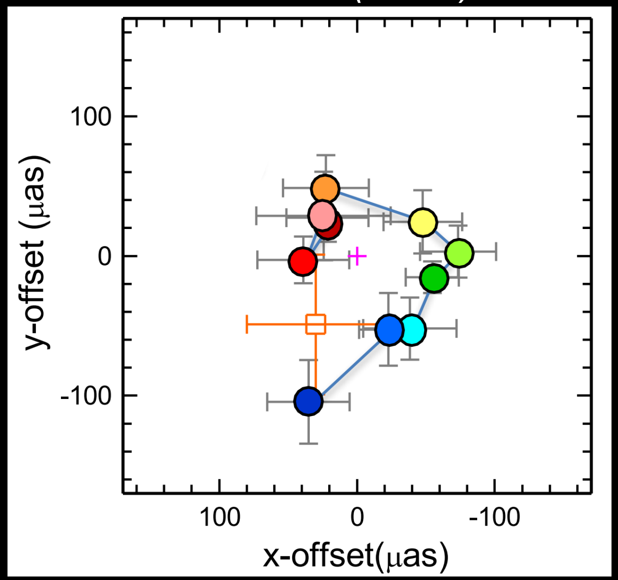
Sgr A* flares by Spitzer: *Ponti+ (2017)*



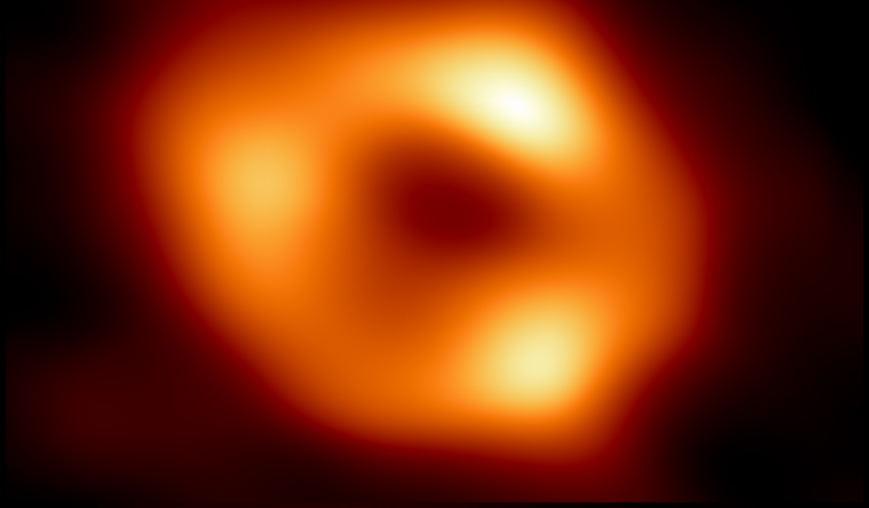
Sgr A* NIR/X-ray flare, *GRAVITY+SWIFT (2021)*



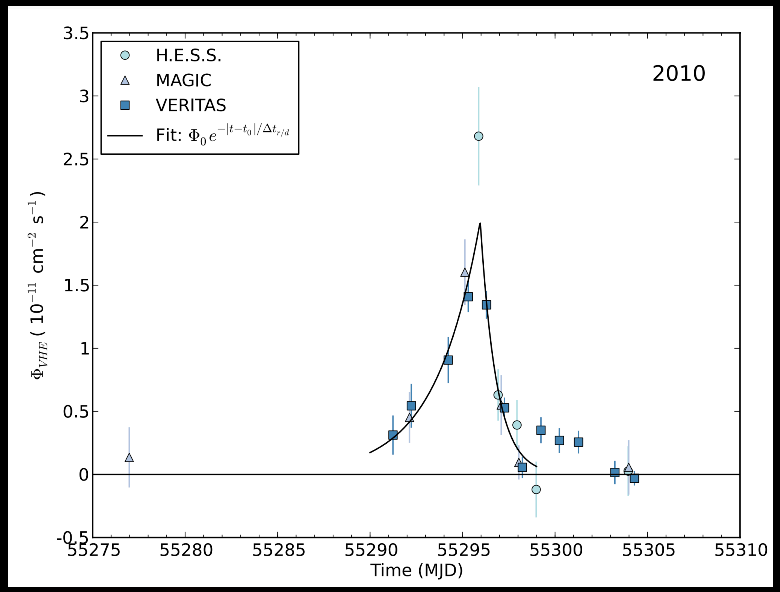
orbiting post-flare “blob”, *GRAVITY (2018)*



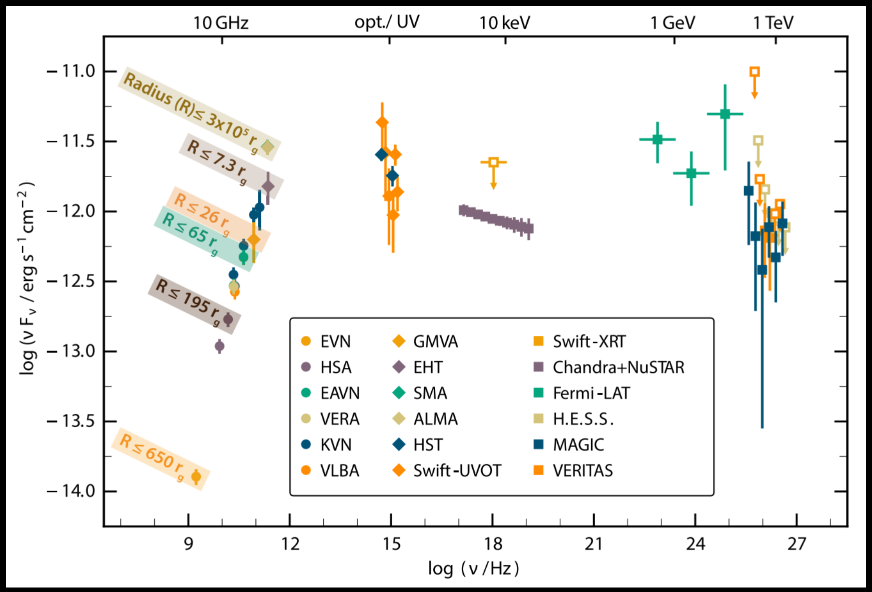
Sgr A* in 230 GHz light by *EHT (2022)*



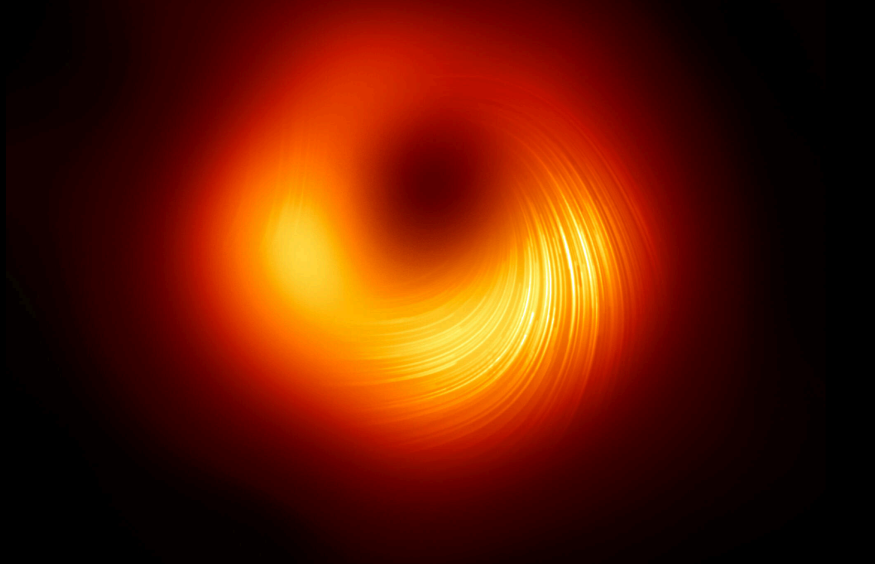
H.E.S.S. + MAGIC + Veritas: Abramowski+ (2012)

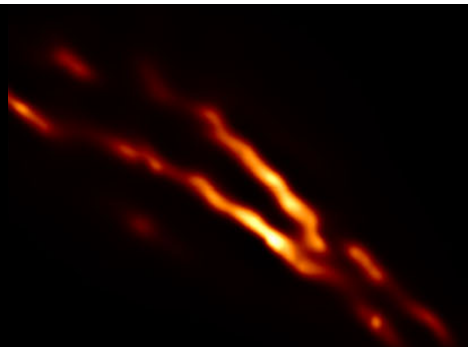


Algaba+ (2021)

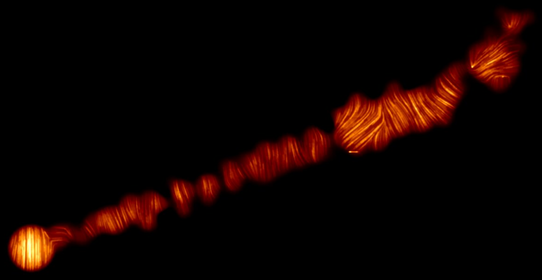


M87* in 230 GHz polarized light by *EHT (2021)*





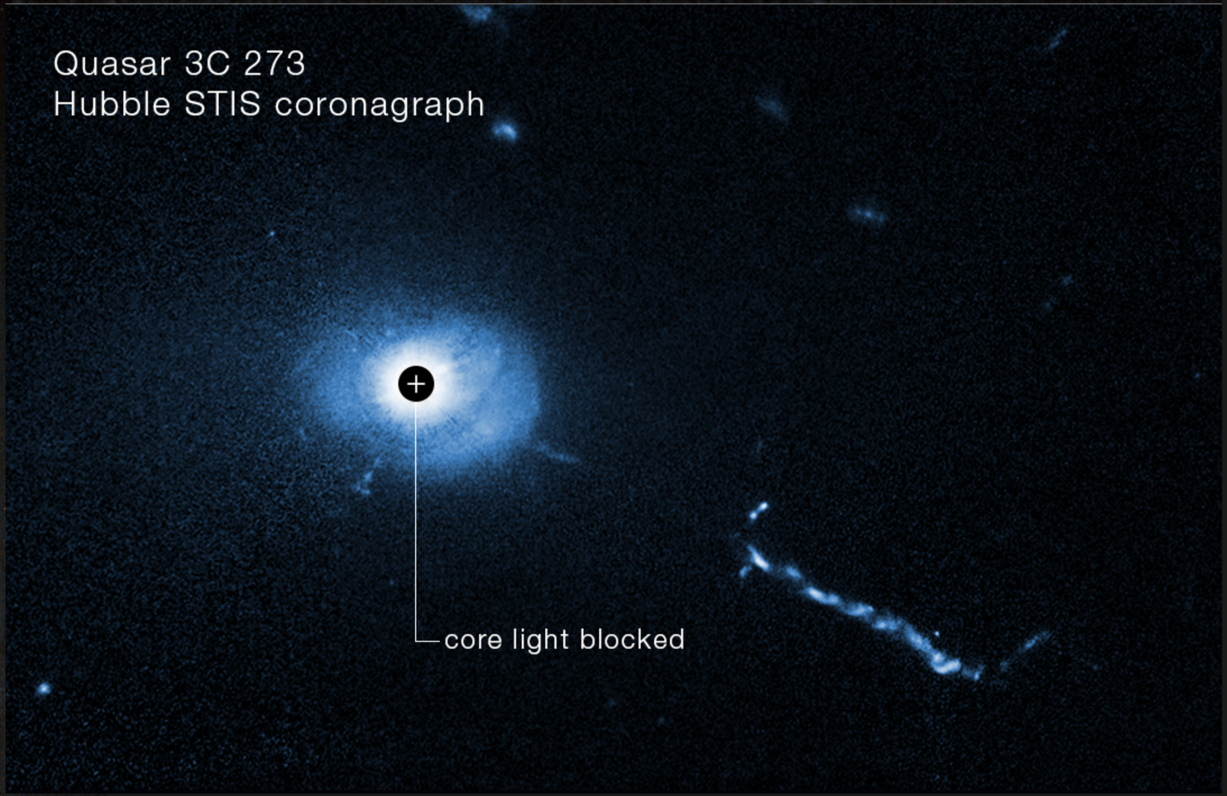
Cen A jet, *EHT (2021)*

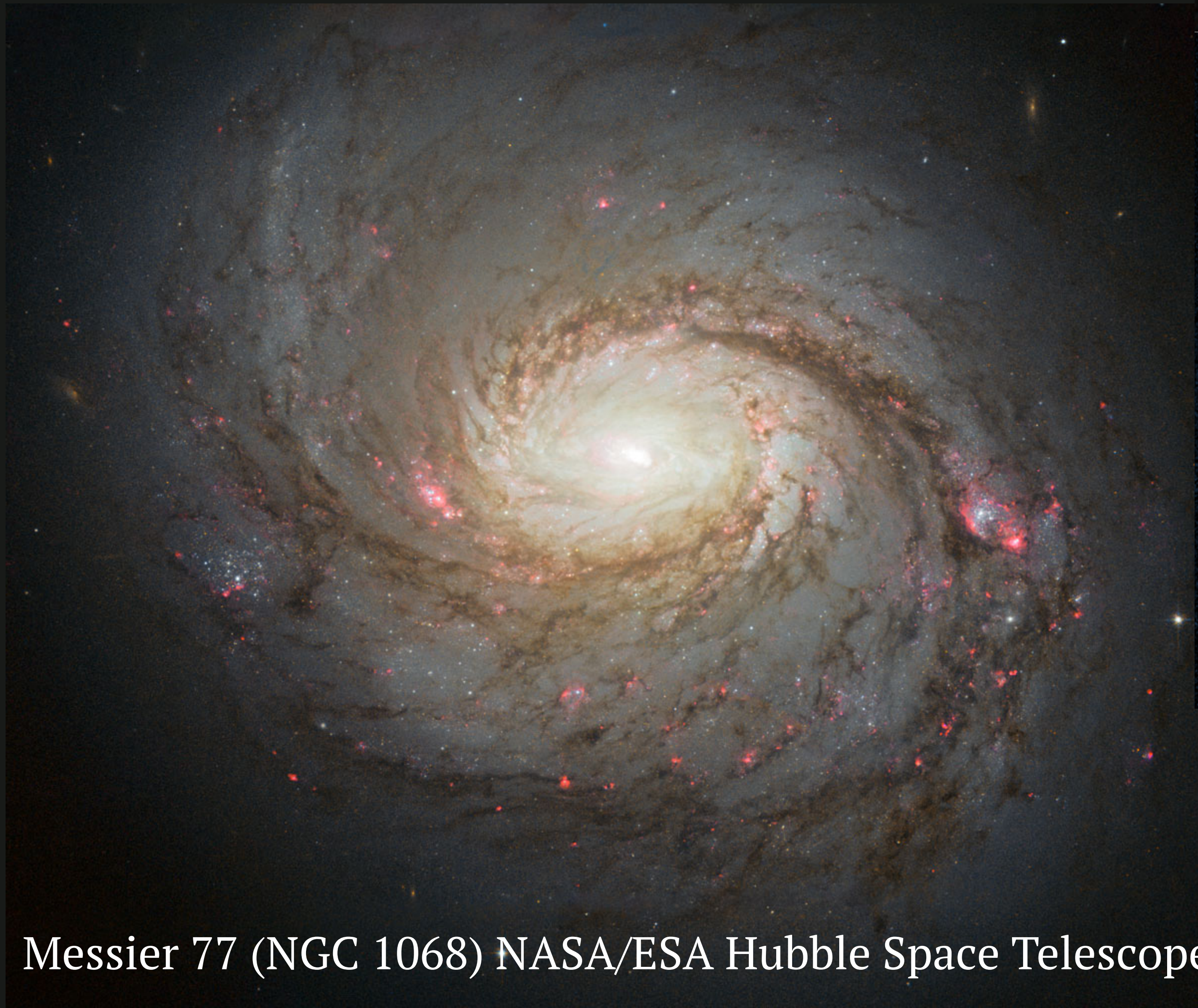


M87* polarized jet, *ALMA (2021)*

Luminous galactic nuclei

The nucleus is bright and can outshine the host galaxy in quasars




Messier 77 (NGC 1068) NASA/ESA Hubble Space Telescope

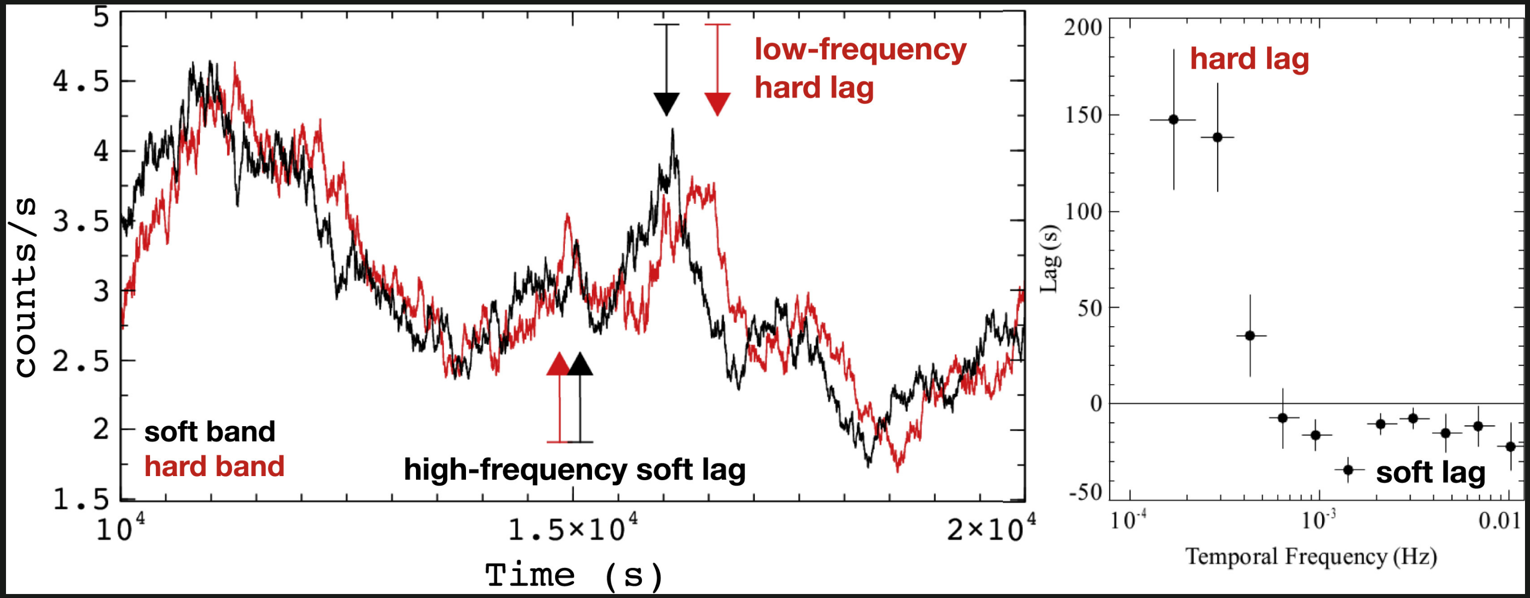
Luminous galactic nuclei

X-rays can get out from innermost of BH vicinity

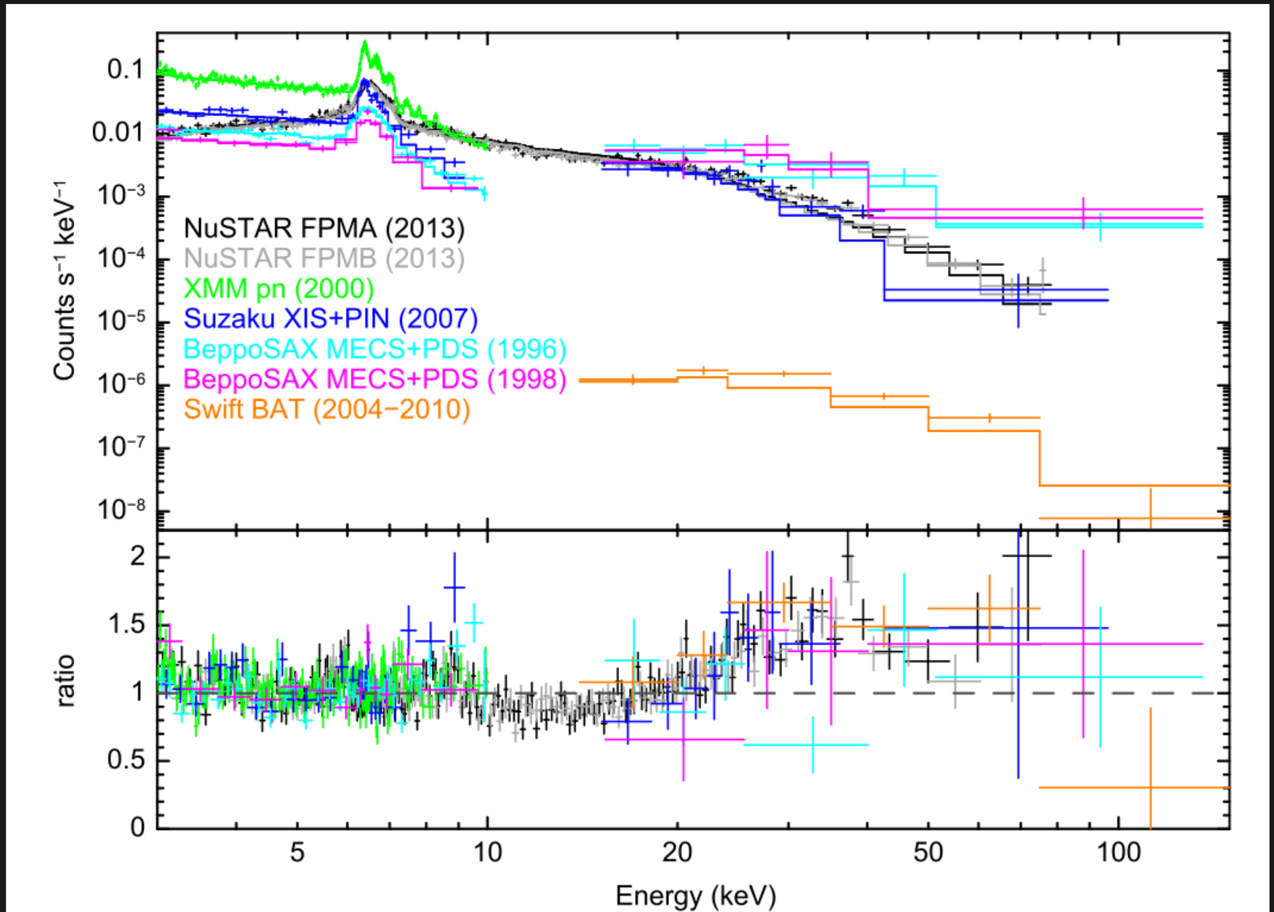
High-energy variability is the main channel to infer the size, geometry, and physics of the innermost engine:

- Changes in the disk —> changes in X-rays
- Reverberation lags

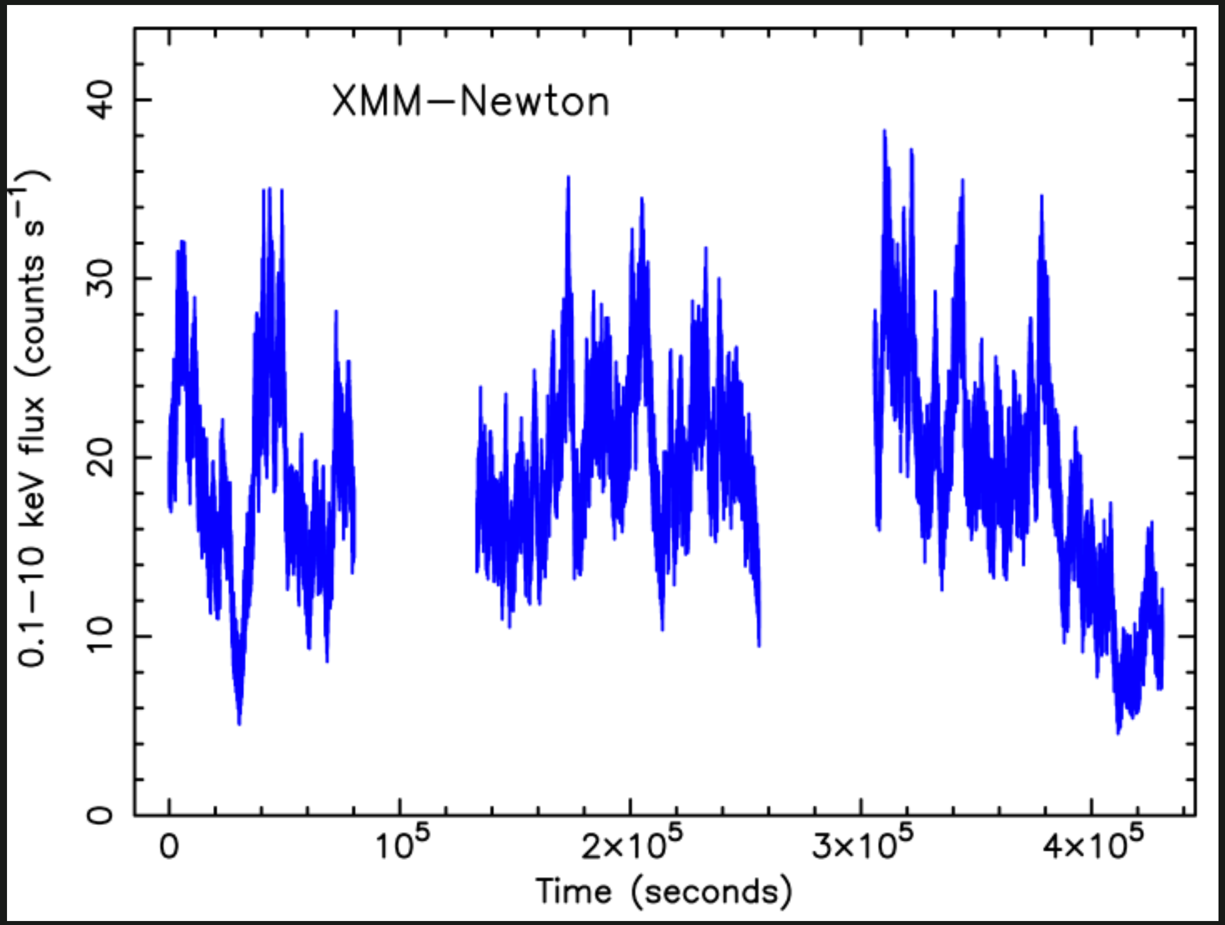
reverberation mapping, Cackett+ (2021)



non-thermal spectrum



variability, McHardy+ (2005)



Accreting is not simple

- Mass at a higher orbit has to fall down
- Material has to shed its angular momentum with time and slowly spiral inward

BUT just the molecular viscosity is not sufficient

—> Magnetorotational instability (Velikhov 1959, Chandrasekhar 1960, Balbus & Hawley 1991)

Magnetic stresses are important!

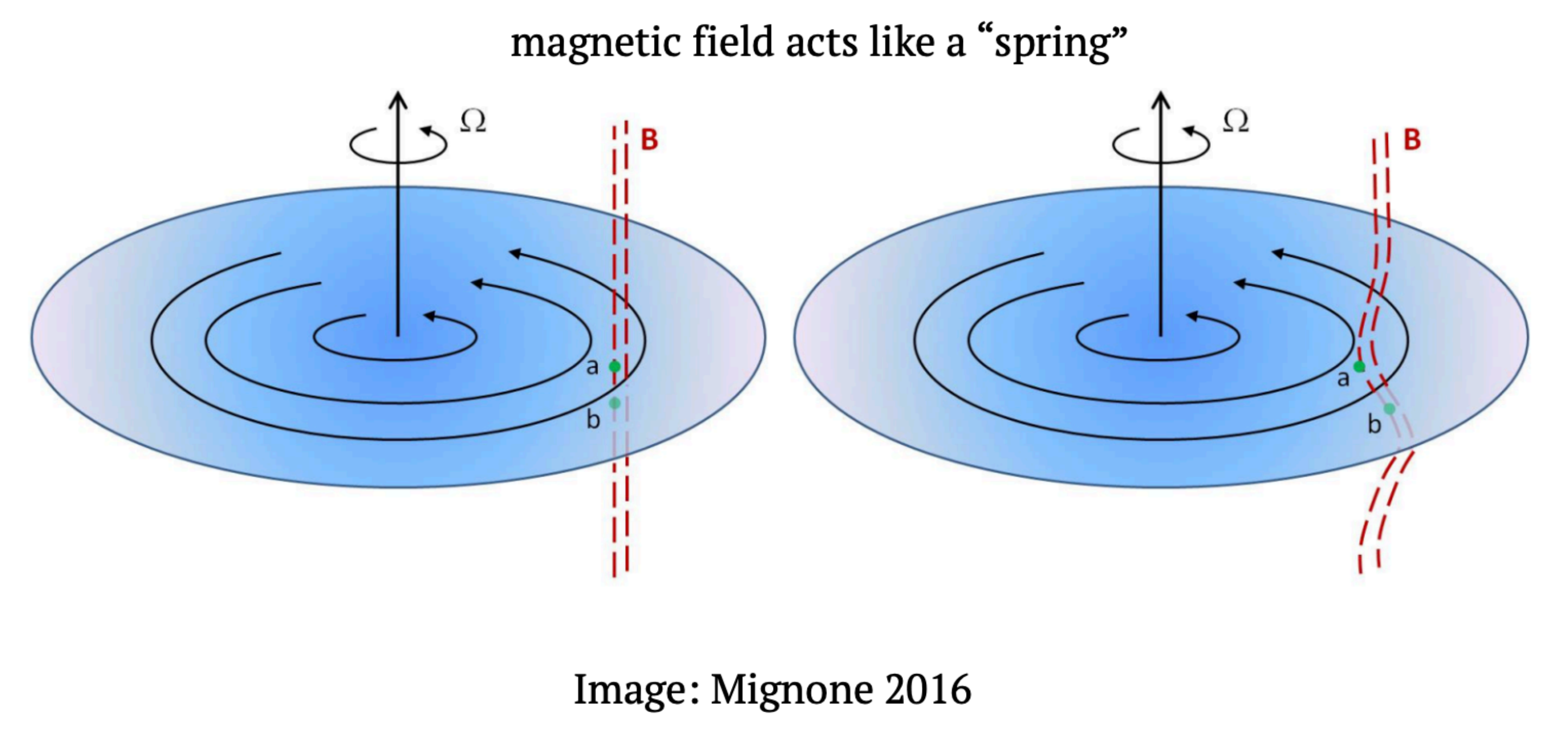


Image: Mignone 2016

The importance of the magnetic field was first noted by Schwartzman (1971)

In spherical inflow of matter: $B^r \propto r^{-2}$

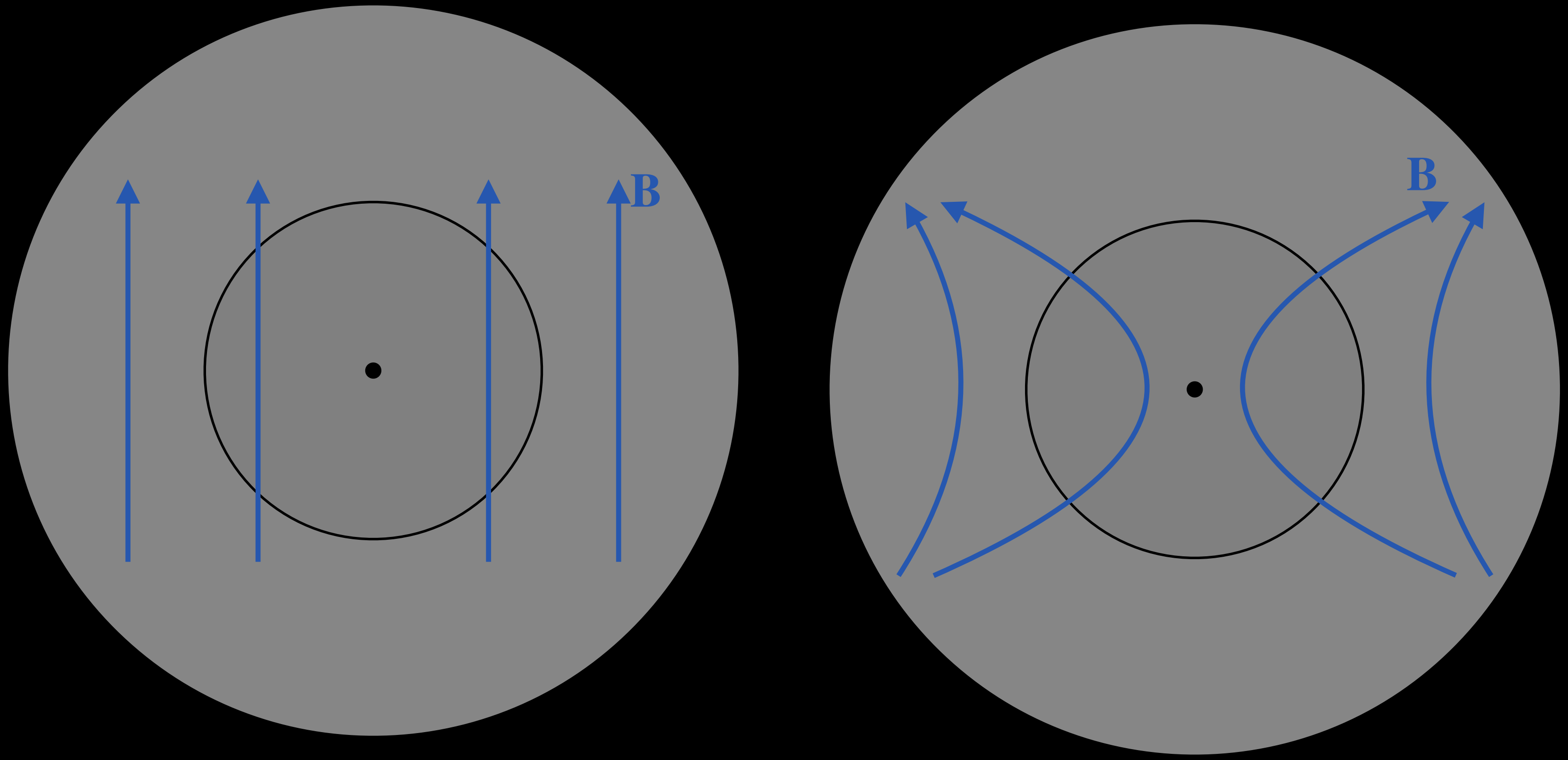
stretching of magnetic field —> inevitably high B:

$$\frac{P_{\text{magnetic}}}{P_{\text{thermal}}} \propto r^{-3/2}$$

Naively, magnetic energy >> thermal energy

but MRI is weak at high magnetic field…

—> non-linear interplay



GRMHD simulations

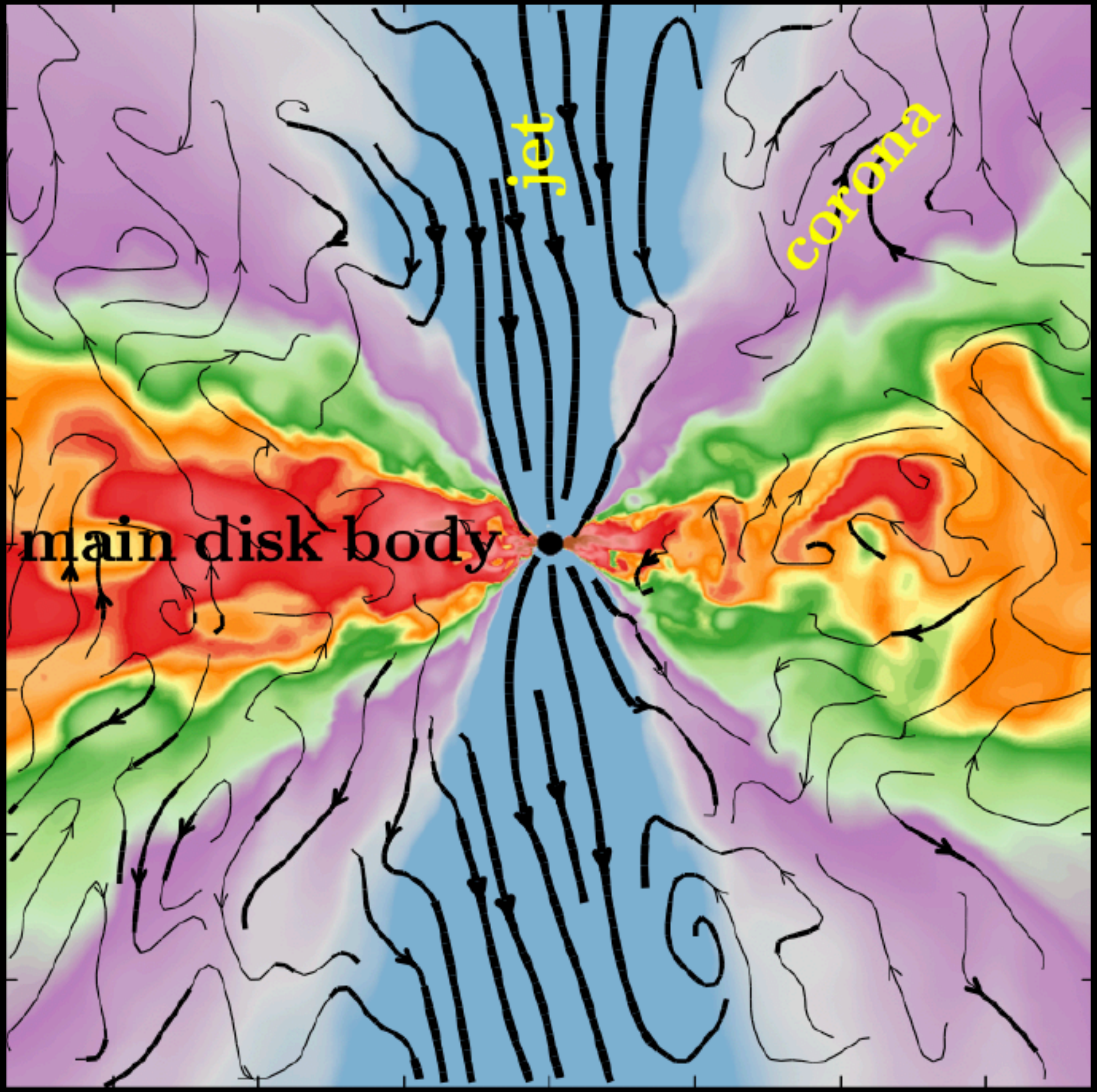
=General Relativistic Magnetohydrodynamics

Magnetohydrodynamics: plasma treated as a conducting magnetized fluid
General Relativity: accounts for strong gravity near the black hole

MHD solves:

- conservation of mass
- conservation of energy-momentum (+EOS)
- Maxwell/MHD induction equations

GRMHD = accreting charged magnetized particles are represented as a magnetized fluid



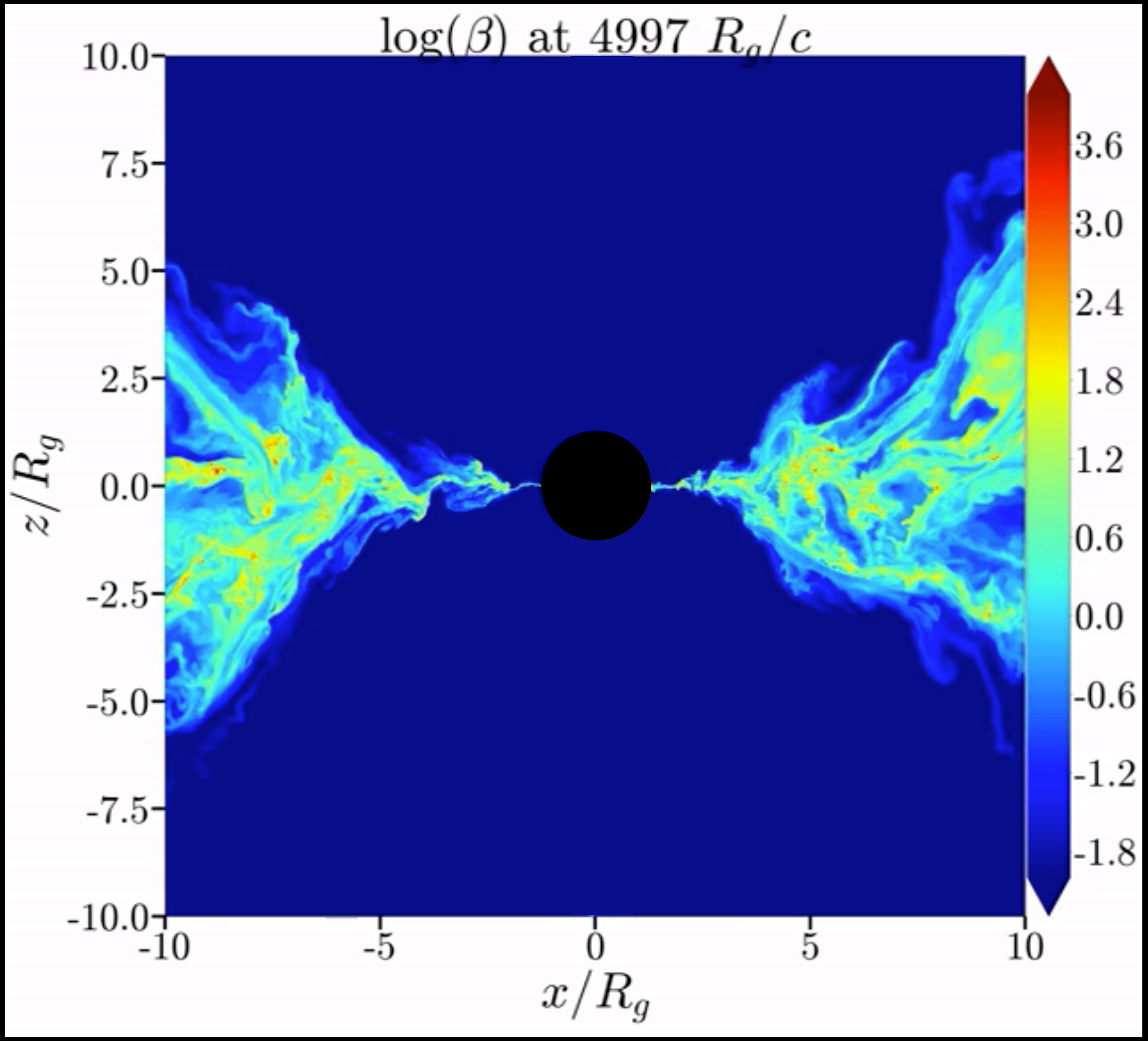
GRMHD simulation (courtesy of Tchekhovskoy)

GRMHD simulations

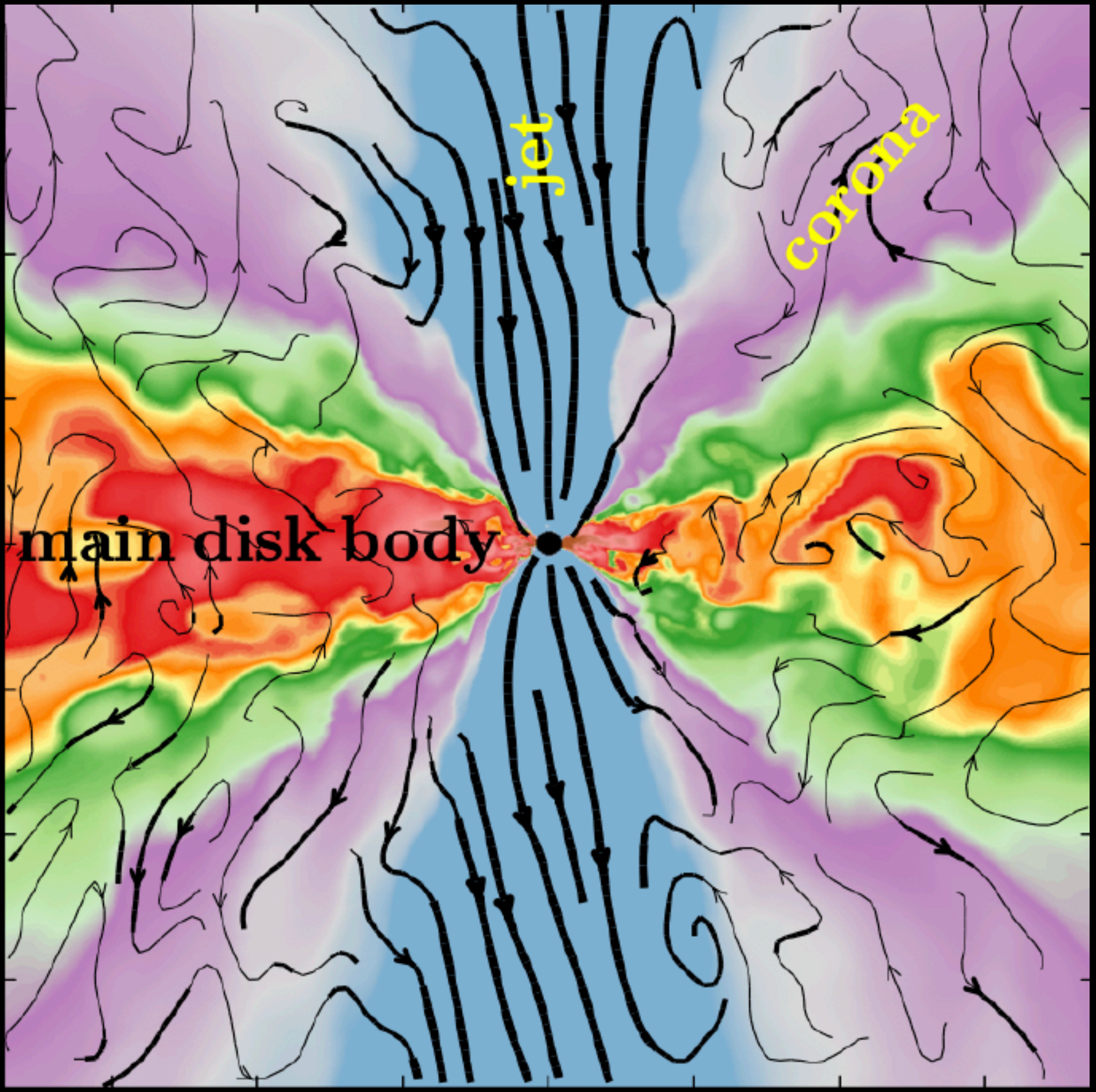
=General Relativistic Magnetohydrodynamics

Magnetohydrodynamics: plasma treated as a conducting magnetized fluid
General Relativity: accounts for strong gravity near the black hole

“Magnetically Arrested Disks” = MAD



GRMHD simulation (Ripperda, Liska+ 2022)

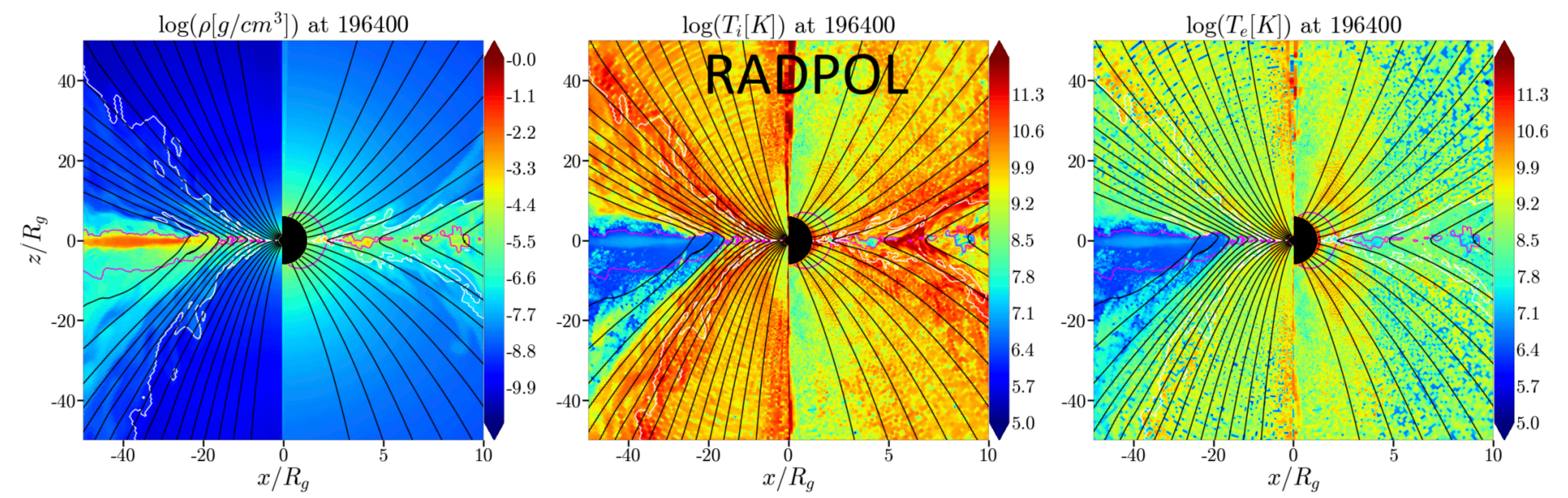


GRMHD simulation (courtesy of Tchekhovskoy)

GRMHD simulations

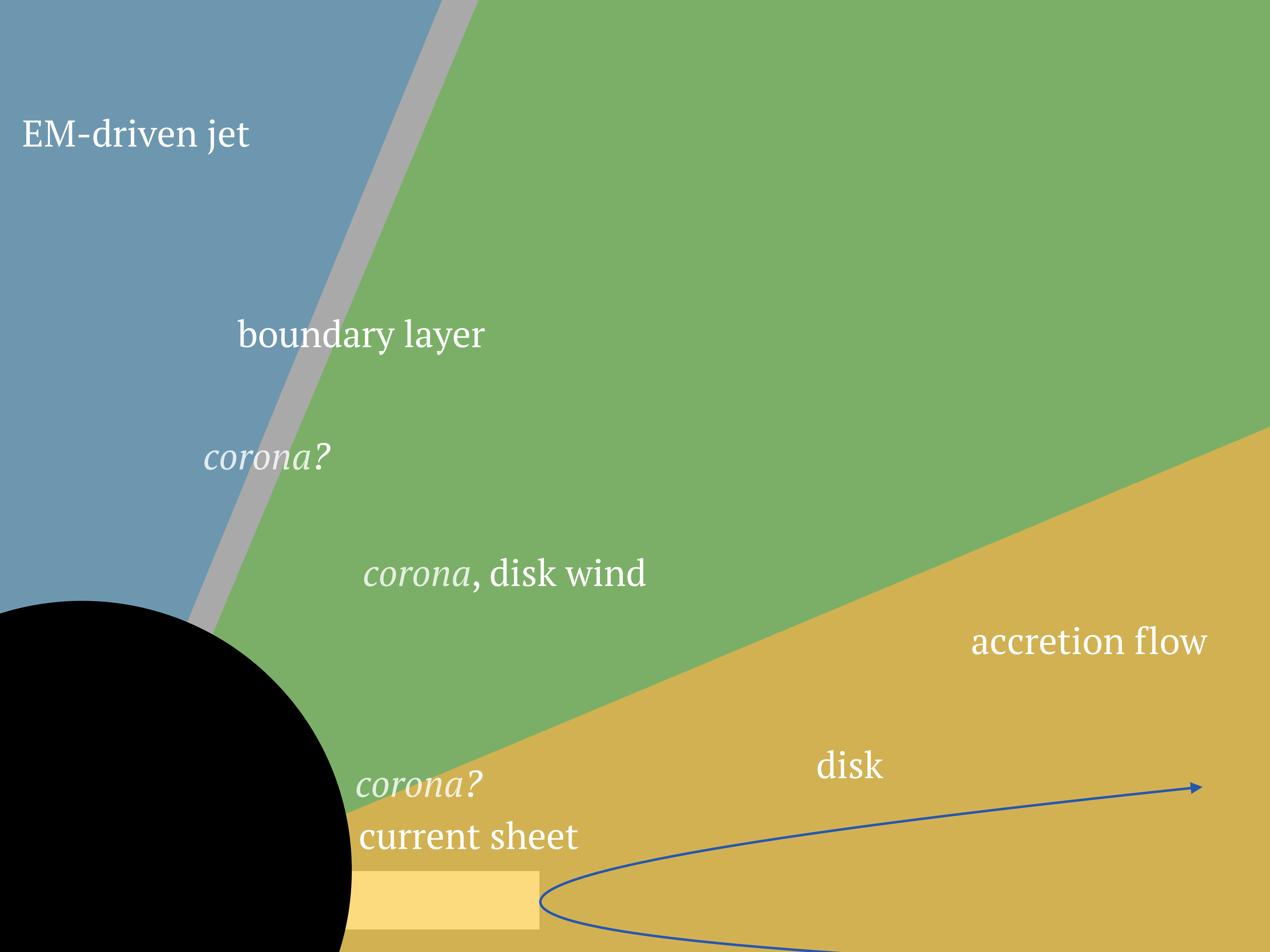
Radiation-transport, two-temperature GRMHD

- A cold, dense, thin *outer* disk
- A hot, dilute, thick MAD-like *inner* flow, with comparable dynamics as in M87*
- Computational challenge: resolve all scales



Liska+ 2022

Thick disks	*Thin disks*
LLAGN, M87, Sgr A*, hard-state XRBs	Seyferts, quasars, soft-state XRBs
• Radiatively inefficient	• Radiatively efficient
• Geometrically thick	• Geometrically thin
• Optically thin	• Optically thick
• Mainly synchrotron/Compton/jet dominated	• Mainly thermal disk emission, optical-UV


EM-driven jet
boundary layer
corona?
corona, disk wind
accretion flow
disk
corona?
current sheet

Therefore, possible acceleration sites in AGNs from global models are (from closest to furthest):

- Inner magnetosphere:
  - current sheet (mostly radiatively inefficient flows)
  - Jet sheath
  - Corona* (radiatively efficient flows)
- Turbulence in accretion disk (but not high energies)
- Shocks; large-scale jet?

P*ossible acceleration processes*:

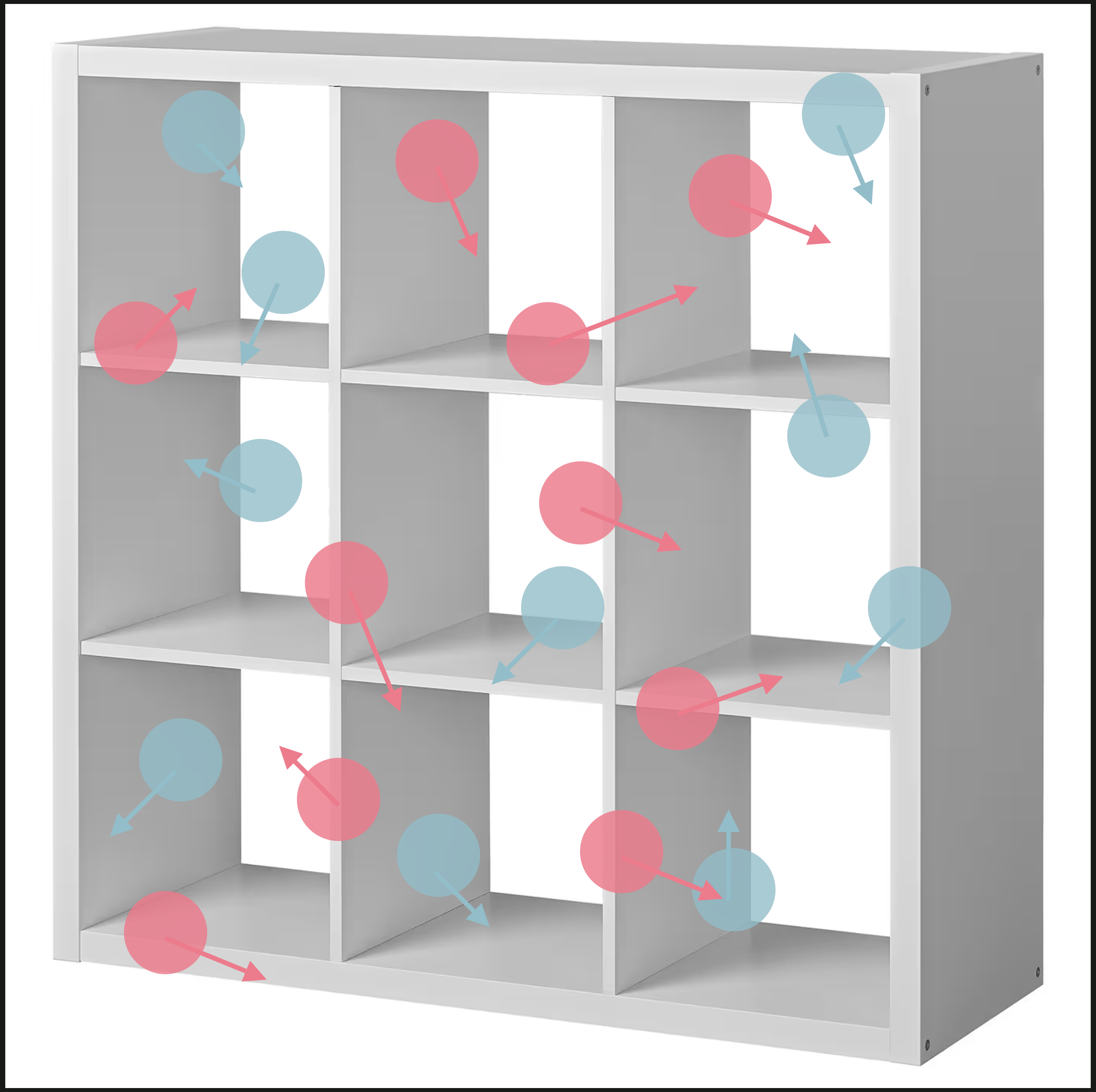
- Turbulence
- Reconnection
- Shocks
- And their combination

*not a spatial location

First-principles approach

Particle-In-Cell = PIC

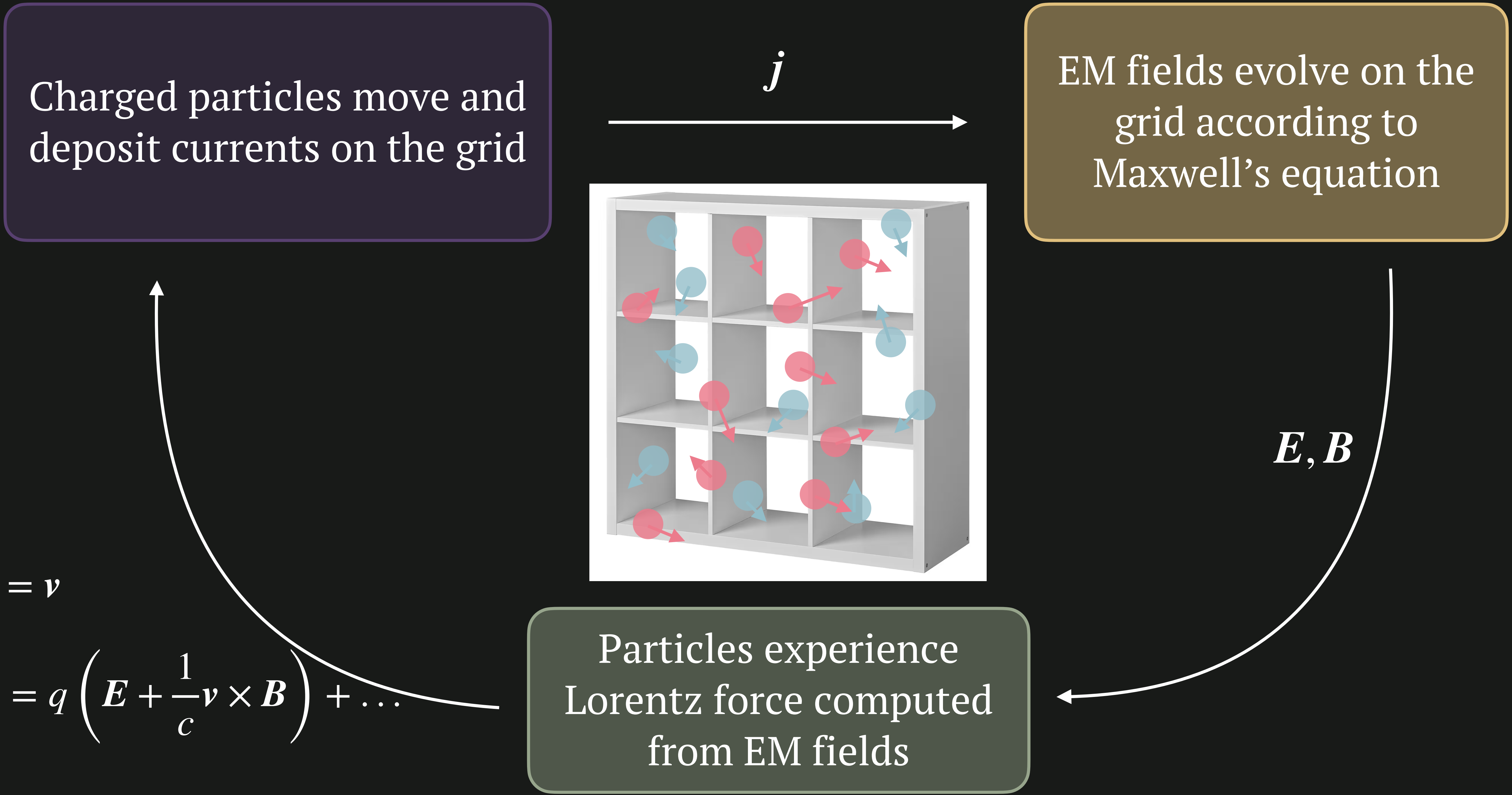
Capturing the interplay of charged particles and magnetic fields



First-principles approach

Particle-In-Cell = PIC

Capturing the interplay of charged particles and magnetic fields



Charged particles move and deposit currents on the grid

$\boldsymbol{j}$

EM fields evolve on the grid according to Maxwell's equation

$\boldsymbol{E}, \boldsymbol{B}$

Particles experience Lorentz force computed from EM fields

$$\frac{d\boldsymbol{r}}{dt} = \boldsymbol{v}$$

$$\frac{d\boldsymbol{p}}{dt} = q\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right) + \dots$$

Computational challenge: need for resolving kinetic plasma scales

First-principles approach

GR Particle-In-Cell = GRPIC

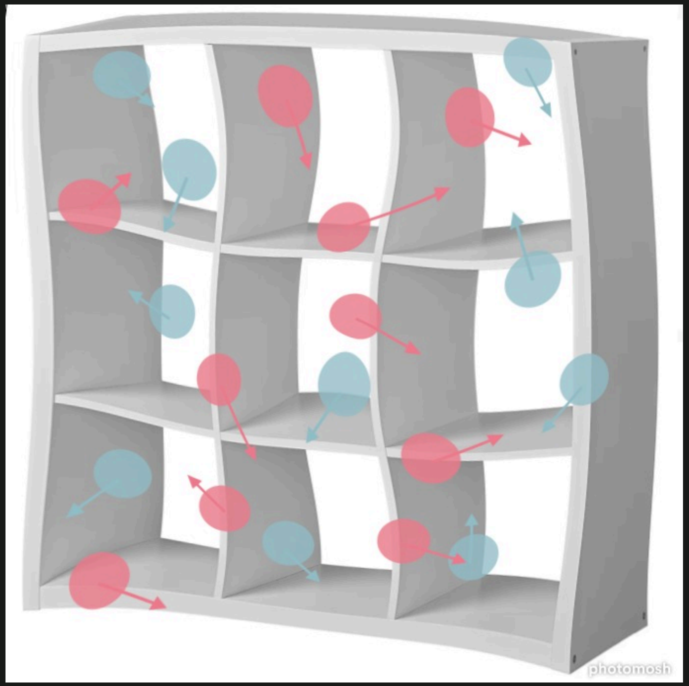
Parfrey+ 2019, Galishnikova+2025

Motivation:

1. low-luminosity systems are collisionless: $\lambda_{mfp} \gg$ system size
2. Non-thermal physics, particle acceleration
3. Multi-fluid plasmas

$$\frac{\mathrm{d}x^i}{\mathrm{d}t} = v^i = \frac{\alpha}{\Gamma}\gamma^{ij}u_j - \beta^i,$$

$$\frac{\mathrm{d}u_i}{\mathrm{d}t} = -\Gamma\partial_i\alpha + u_j\partial_i\beta^j - \frac{\alpha}{2\Gamma}\partial_i(\gamma^{lm})u_l u_m + \frac{\alpha}{m}\mathscr{L}_i$$



$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E},$$

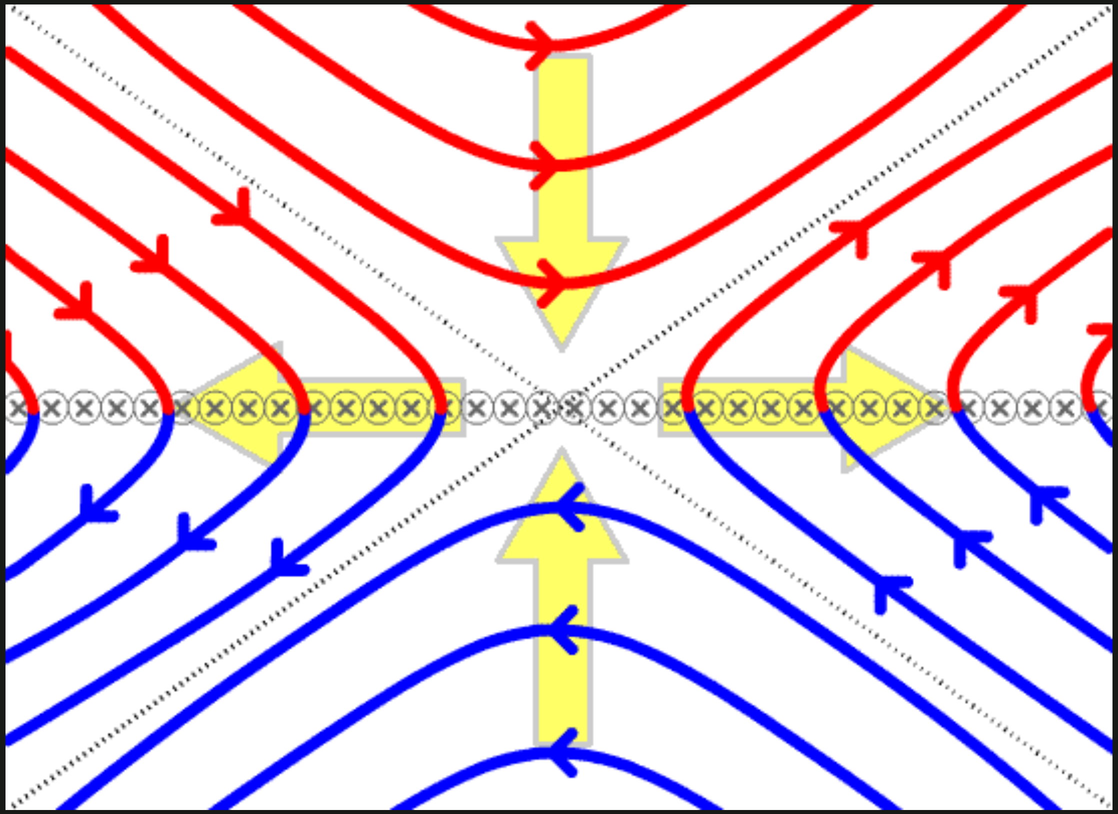
$$\partial_t \mathbf{D} = \nabla \times \mathbf{H} - 4\pi \mathbf{J},$$

where

$$\mathbf{H} = \alpha\mathbf{B} - \beta \times \mathbf{D},\ \mathbf{E} = \alpha\mathbf{D} + \beta \times \mathbf{B}$$

	GRMHD	GRPIC
gas dynamics	✓	✓
large simulations	✓	✗
non-ideal effects	✗	✓

Acceleration mechanism I: Magnetic reconnection

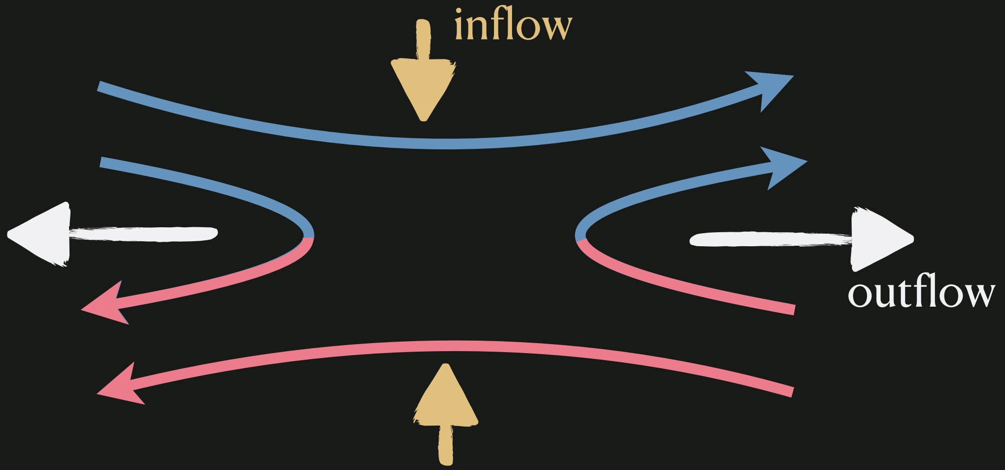


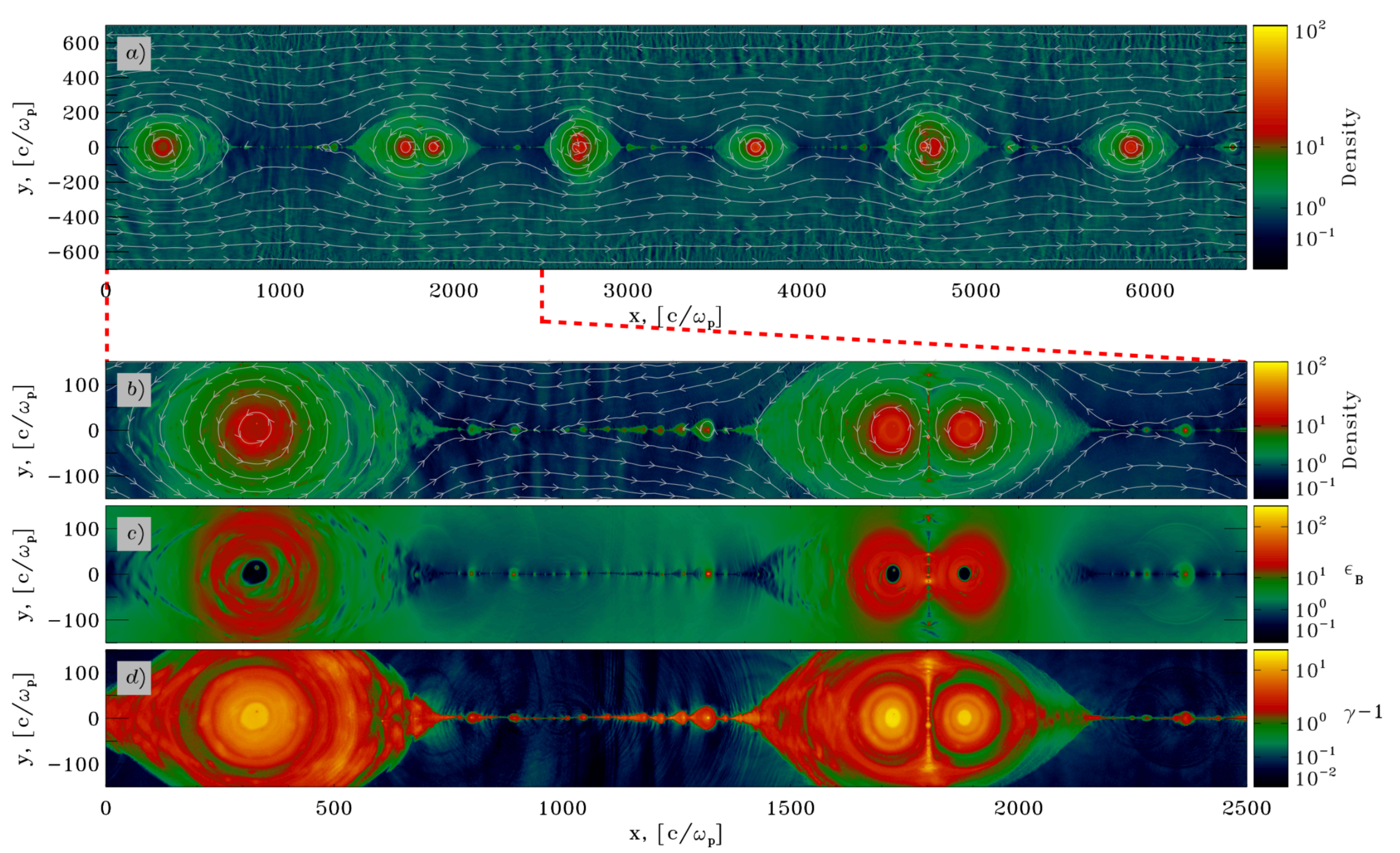
Wikipedia

This is a fast way to turn ordered magnetic energy into hot and nonthermal particles in magnetized plasma.

$$\text{Magnetized: } \sigma = \frac{P_B}{\rho c^2} = \frac{B^2}{4\pi\rho c^2} \gg 1$$

$$\text{Particles are accelerated via } E_{\rm rec} = \frac{v_{\rm in}}{c} B \sim 0.1B$$

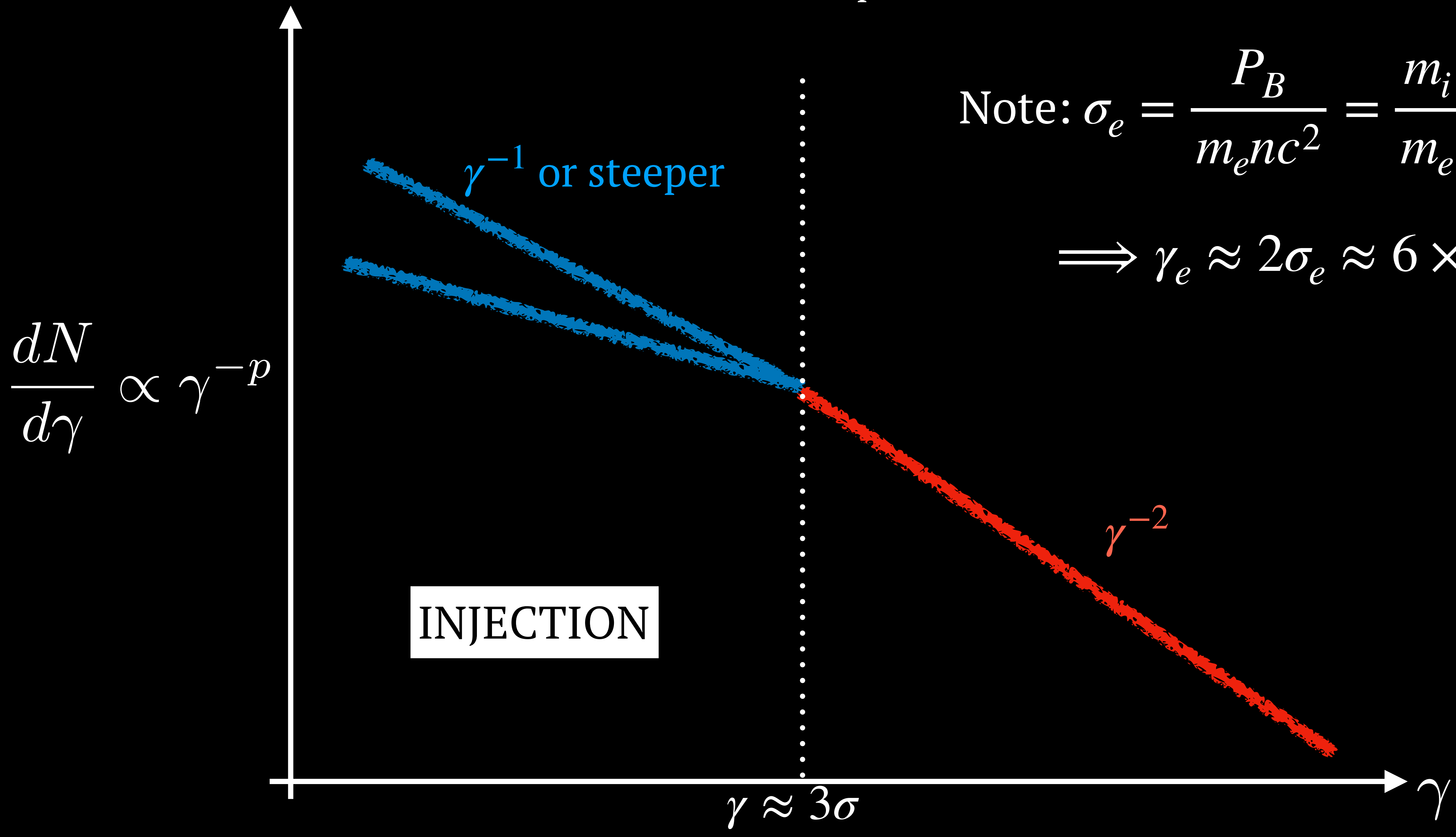




Sironi&Spitkovsky 2014

Acceleration mechanism I: Magnetic reconnection

makes broken power-laws



Note: $\sigma_e = \frac{P_B}{m_e n c^2} = \frac{m_i}{m_e}\sigma_i \approx \frac{m_i}{m_e}\sigma$

$\implies \gamma_e \approx 2\sigma_e \approx 6 \times 10^3 \sigma$

$\gamma \lesssim 2\sigma$:

σ-dependent slopes with $p \gtrsim 1$.

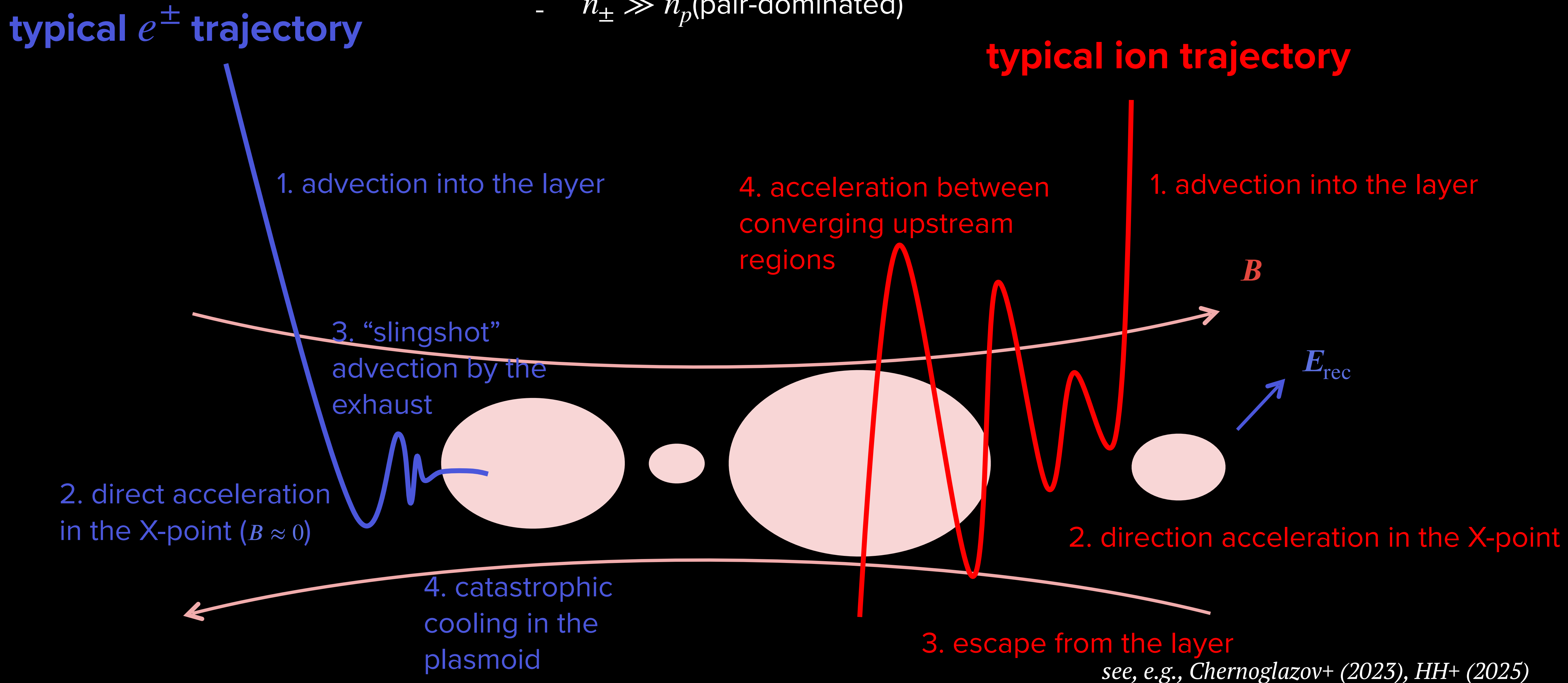
$\gamma \gtrsim 2\sigma$:

3D reconnection leads to a
$\sim$ *σ*-independent slope of *p*~2

Acceleration mechanism I: Magnetic reconnection

$e^{\pm}$plasma reconnection with protons

- strongly cooled $e^{\pm}$
- uncooled protons
- $n_{\pm} \gg n_p$(pair-dominated)



typical $e^{\pm}$ trajectory

1. advection into the layer

2. direct acceleration in the X-point ($B \approx 0$)

3. “slingshot” advection by the exhaust

4. catastrophic cooling in the plasmoid

typical ion trajectory

1. advection into the layer

2. direction acceleration in the X-point

3. escape from the layer

4. acceleration between converging upstream regions

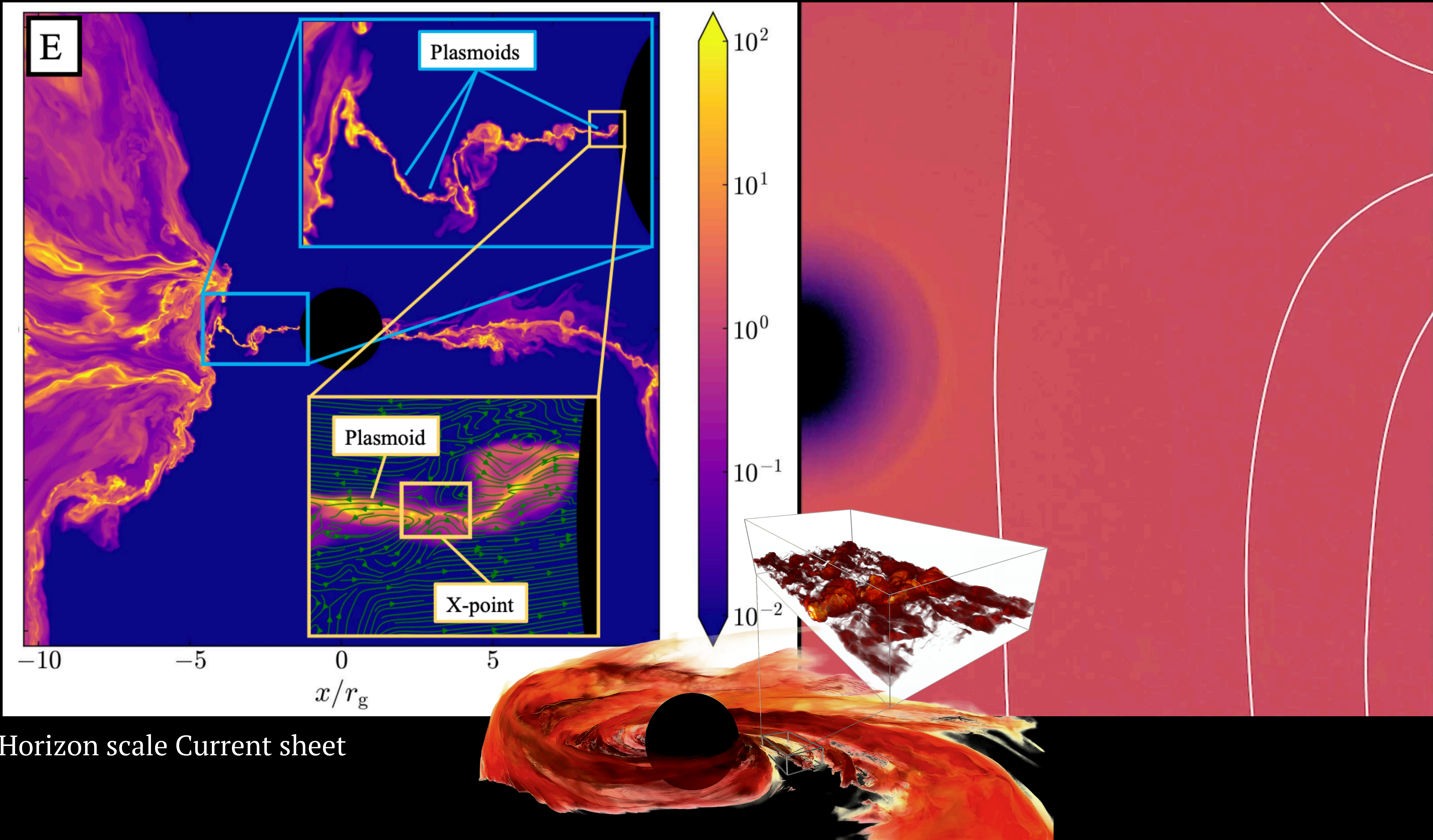
see, e.g., Chernoglazov+ (2023), HH+ (2025)

Acceleration mechanism I: Magnetic reconnection

around black holes

Ripperda+ 2022

Galishnikova+ 2023

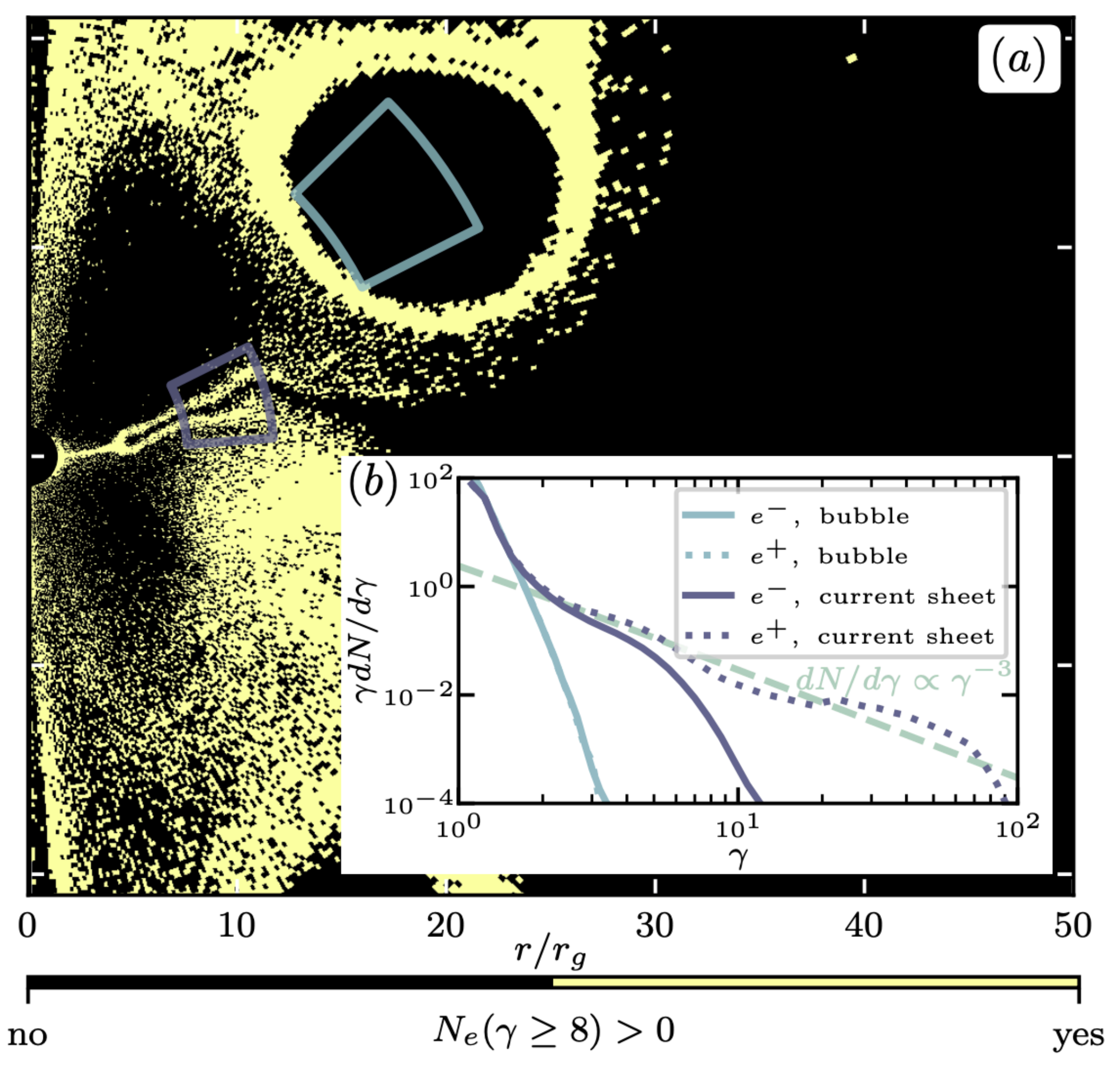


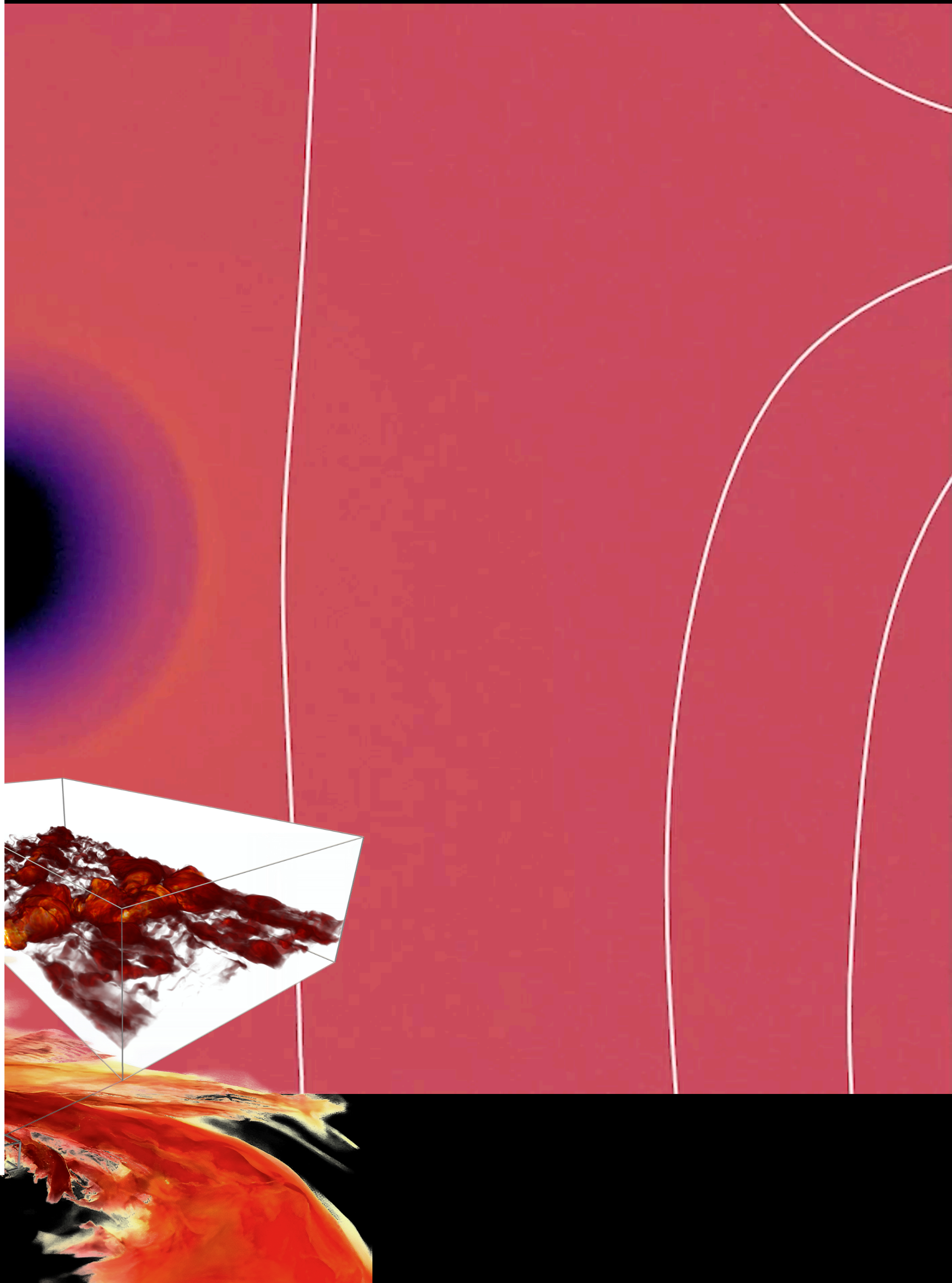
Horizon scale Current sheet

Acceleration mechanism I: Magnetic reconnection

around black holes

Galishnikova+ 2023





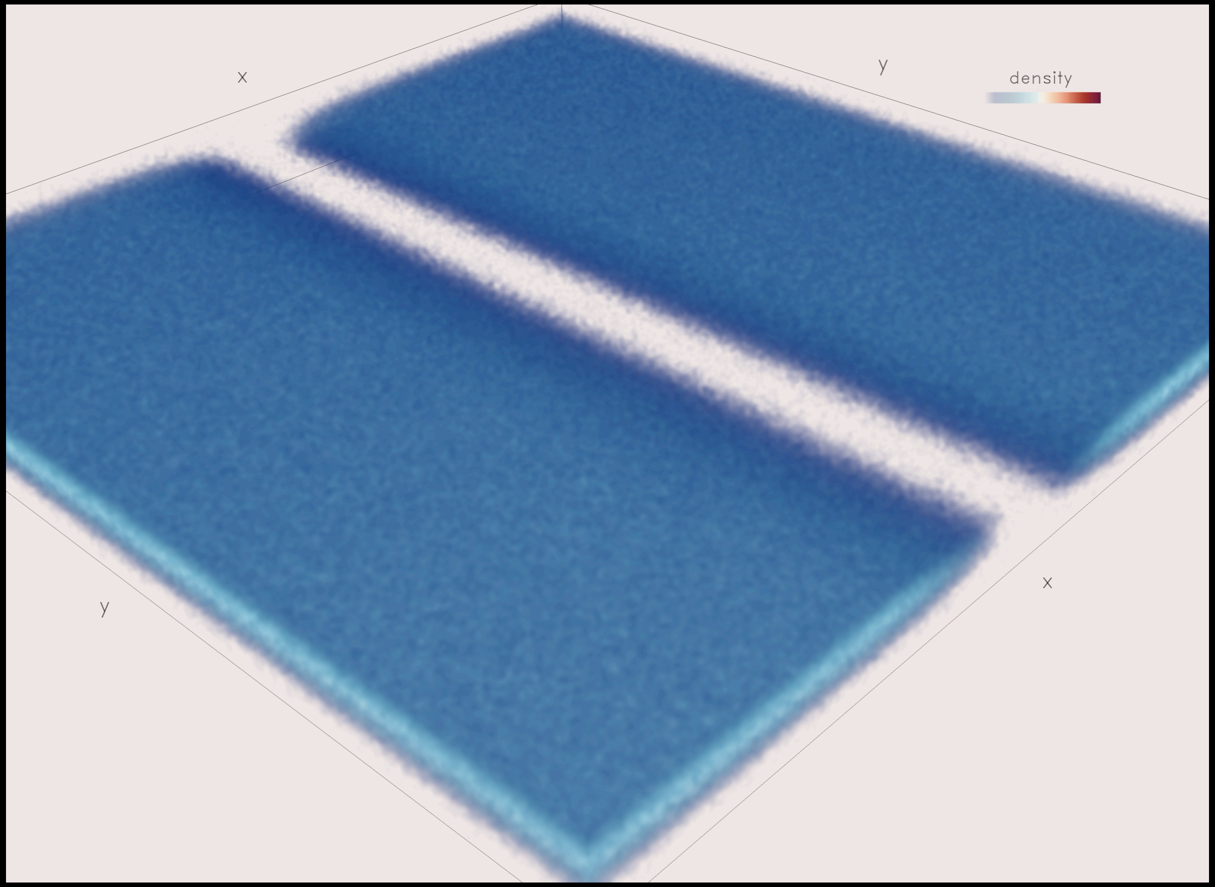
Acceleration mechanism I: Magnetic reconnection

with radiative feedback and QED processes

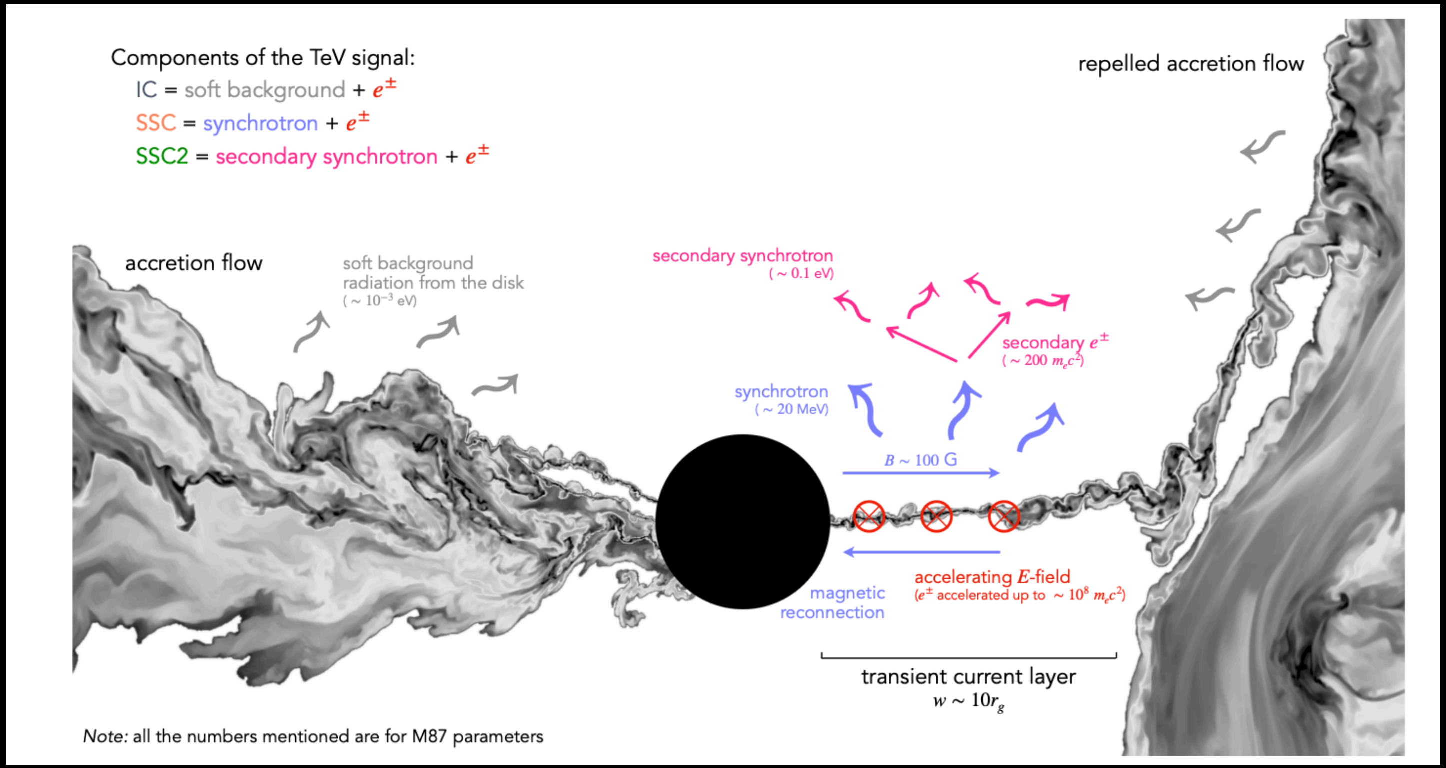
- Photons are EM field! Long-wavelength are automatically resolved on the grid
- High energy emission needs to be treated separately

Examples

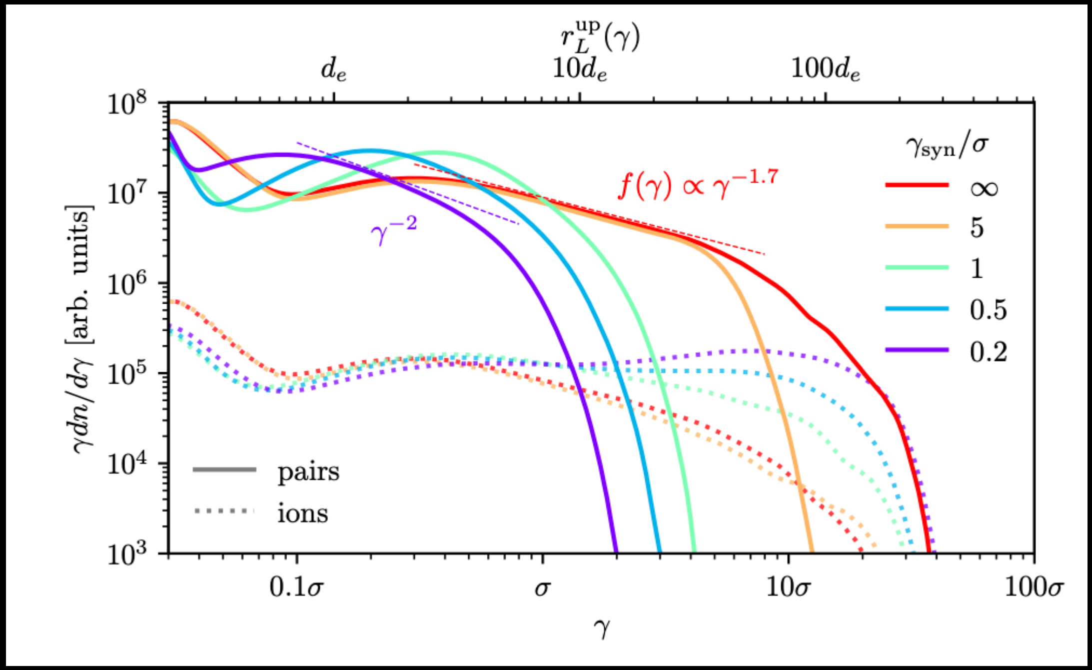
- Single-body: synchrotron, external IC, photon absorption
- Binary: IC scattering, Breit-Wheeler, pair annihilation



Reconnection with synchrotron cooling, Chernoglazov+ 2023

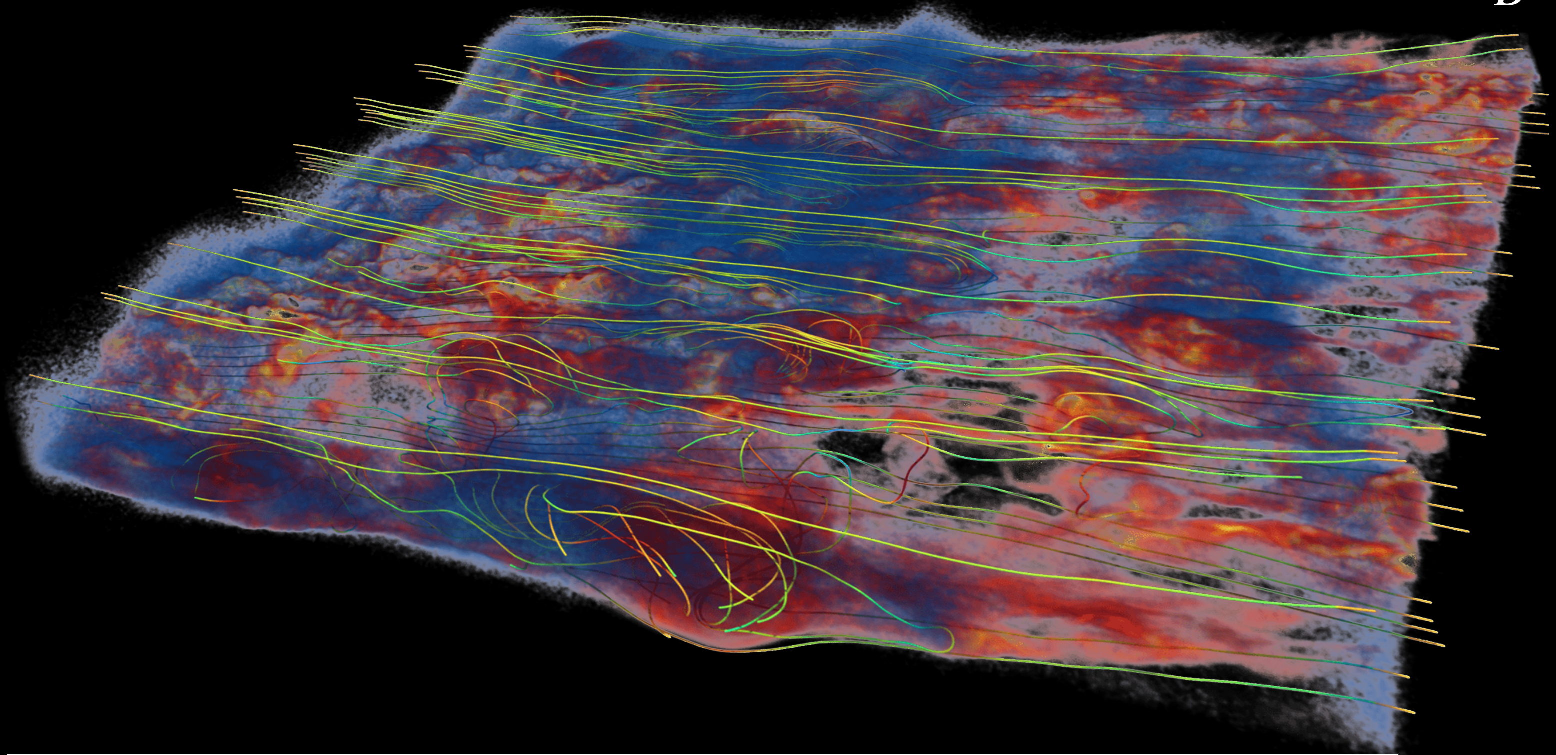


TeV flares from M87*, Hakobyan+ 2023



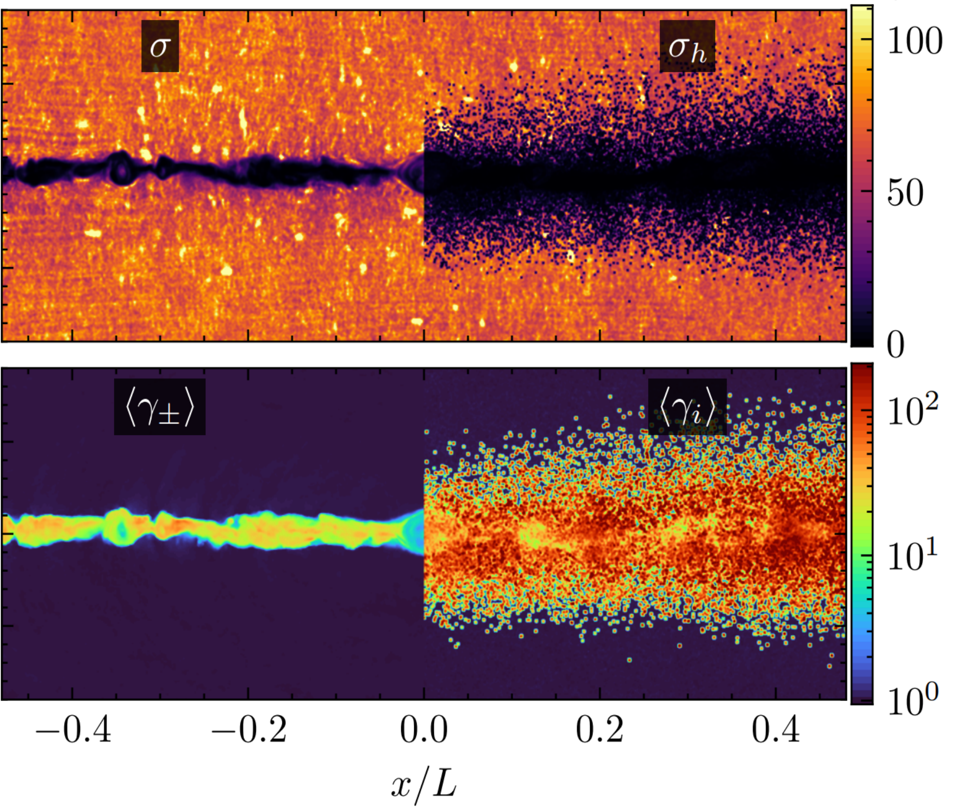
Acceleration mechanism I: Magnetic reconnection

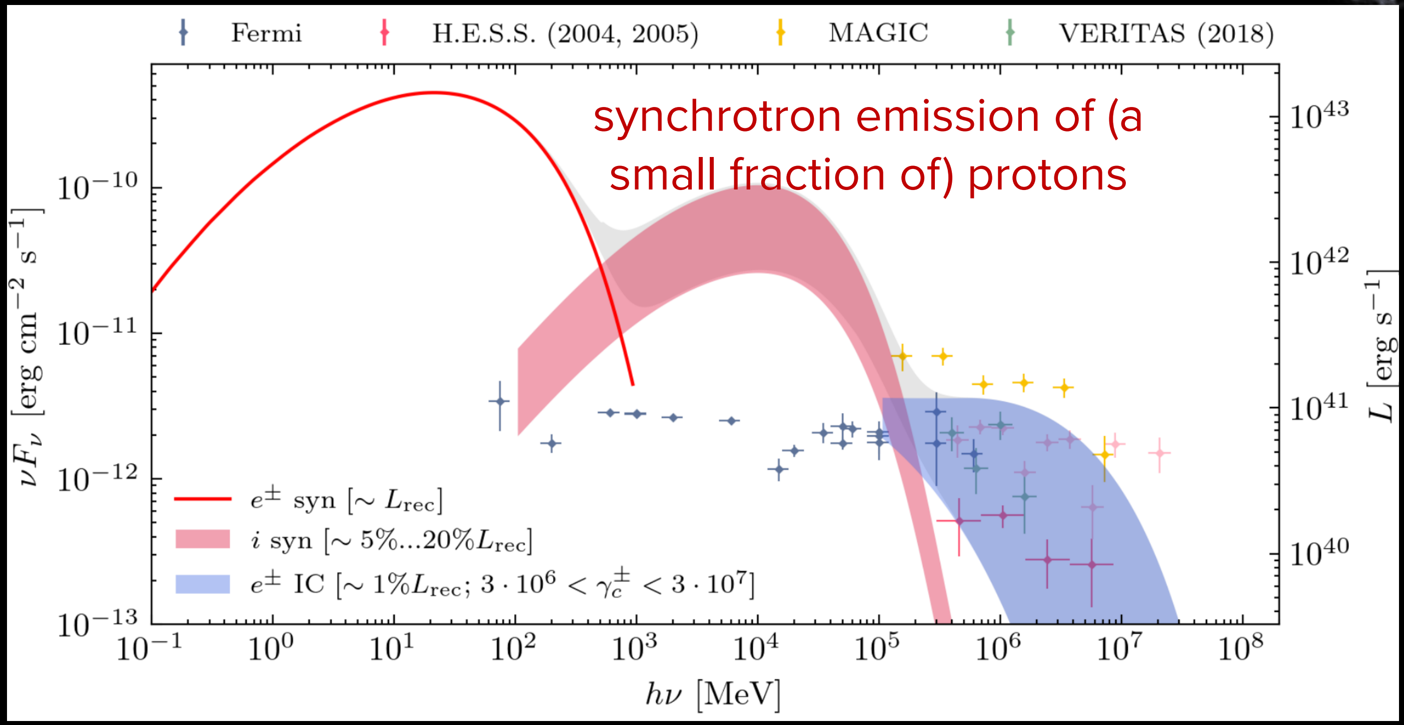
acceleration of ions up to ~equipartition with P_B: $\langle\gamma_i\rangle \sim 0.2\sigma_i = 0.2\dfrac{P_B}{n_i m_i c^2} \gg \sigma$



- strongly cooled $e^\pm$
- uncooled protons
- $n_\pm \gg n_p$ (pair-dominated)

Hakobyan+ 2025





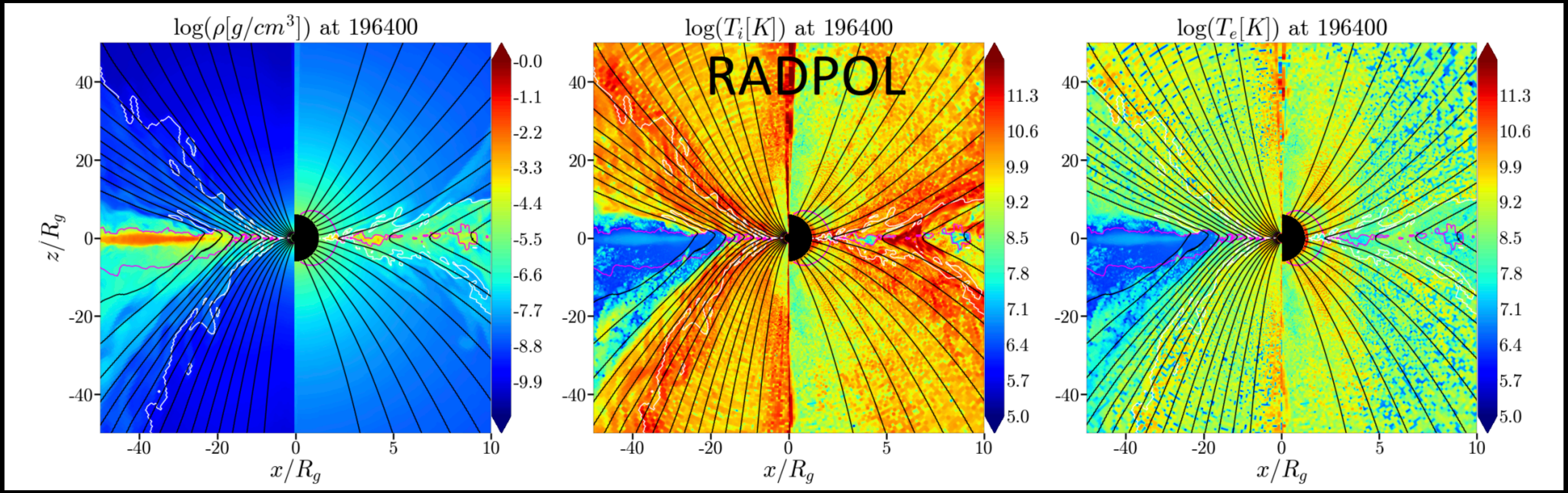
synchrotron emission of (a small fraction of) protons

synchrotron emission of $e^\pm$

inverse-Compton signal from $e^\pm$

However, this picture won’t work for luminous AGNs:

- Reconnection picture might still be relevant, although the environment is much denser
- Very compact magnetized region: fast IC cooling, photon-photon collisions and pair production
- UV background photons



Corona

We know there are hot electrons and IC empirically from X-ray observations but:

1. We don't know where the Comptonizing electrons are located (likely bulk IC since fast cooling regime)

2. The heating mechanism is unclear <— this is important: electrons are light and are cooled, so need an efficient driver

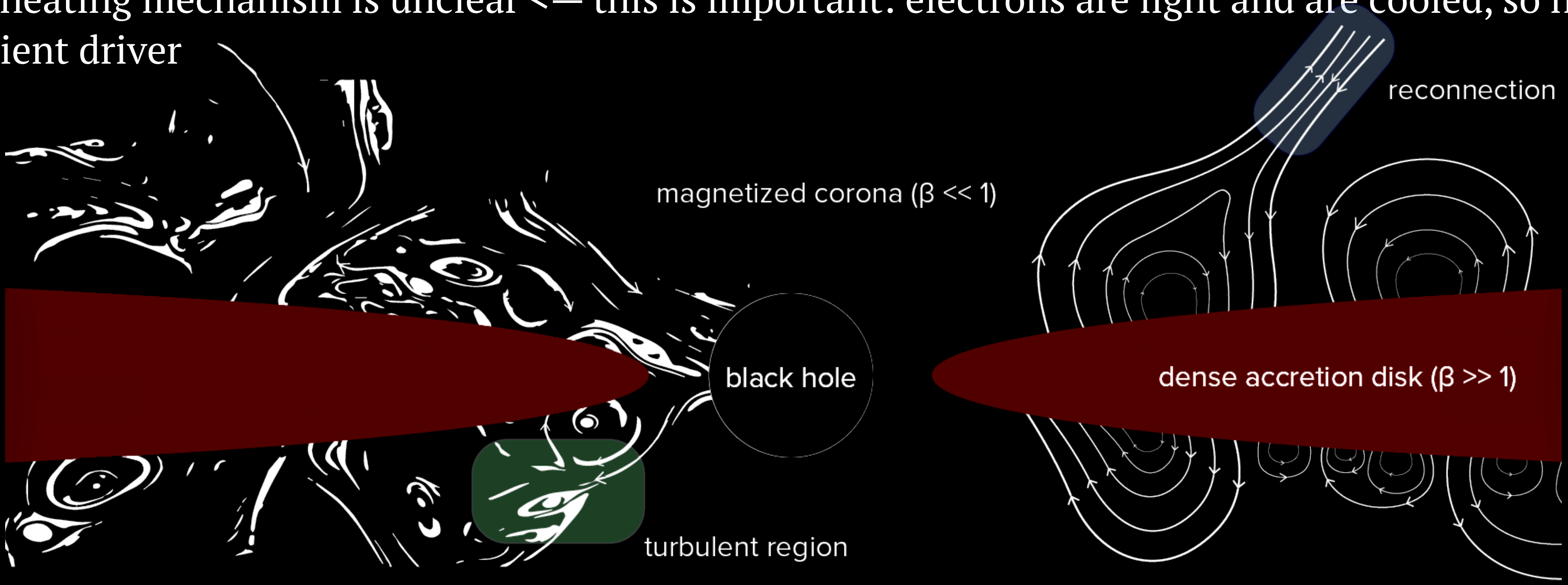
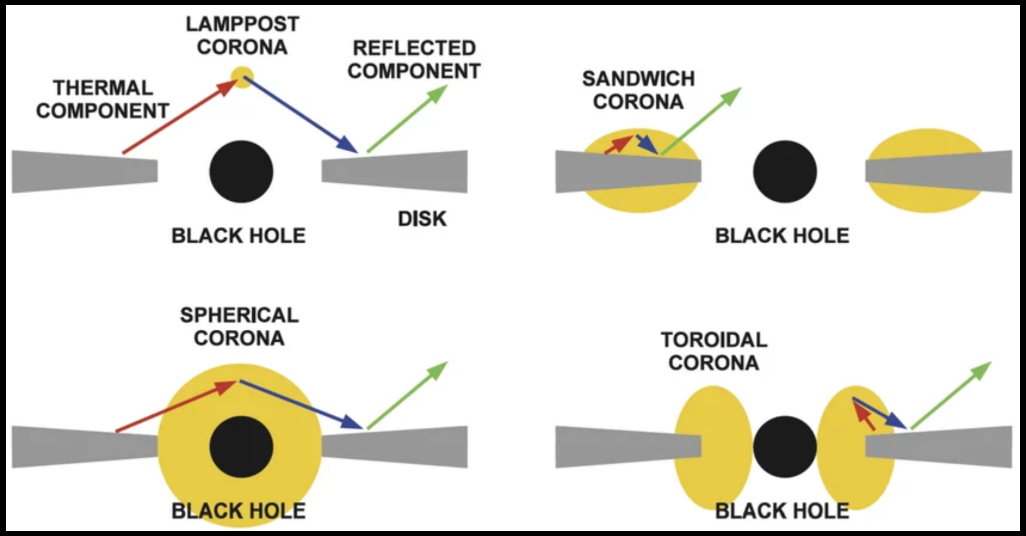


Image by Hakobyan

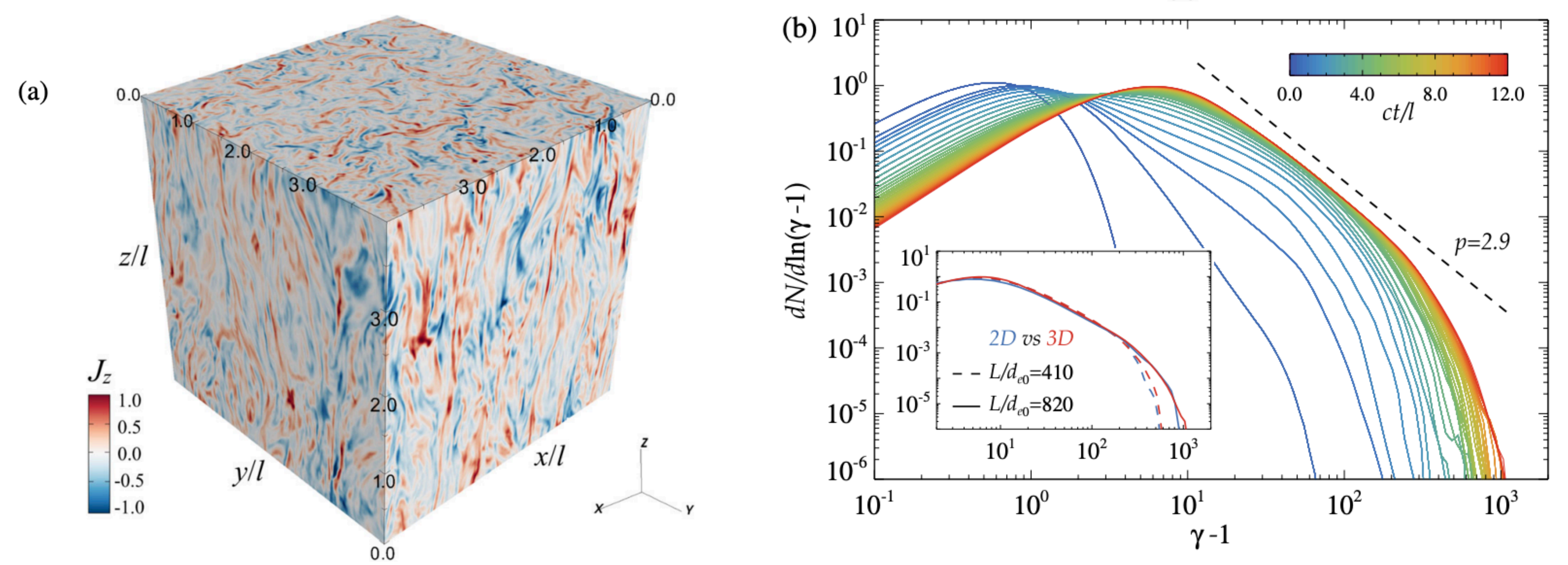


Bambi+ 2021

Acceleration mechanism II: magnetized turbulence

Magnetized kinetic turbulence efficiently produces nonthermal particles and power-law energy spectra (Comisso&Sironi, 2018)

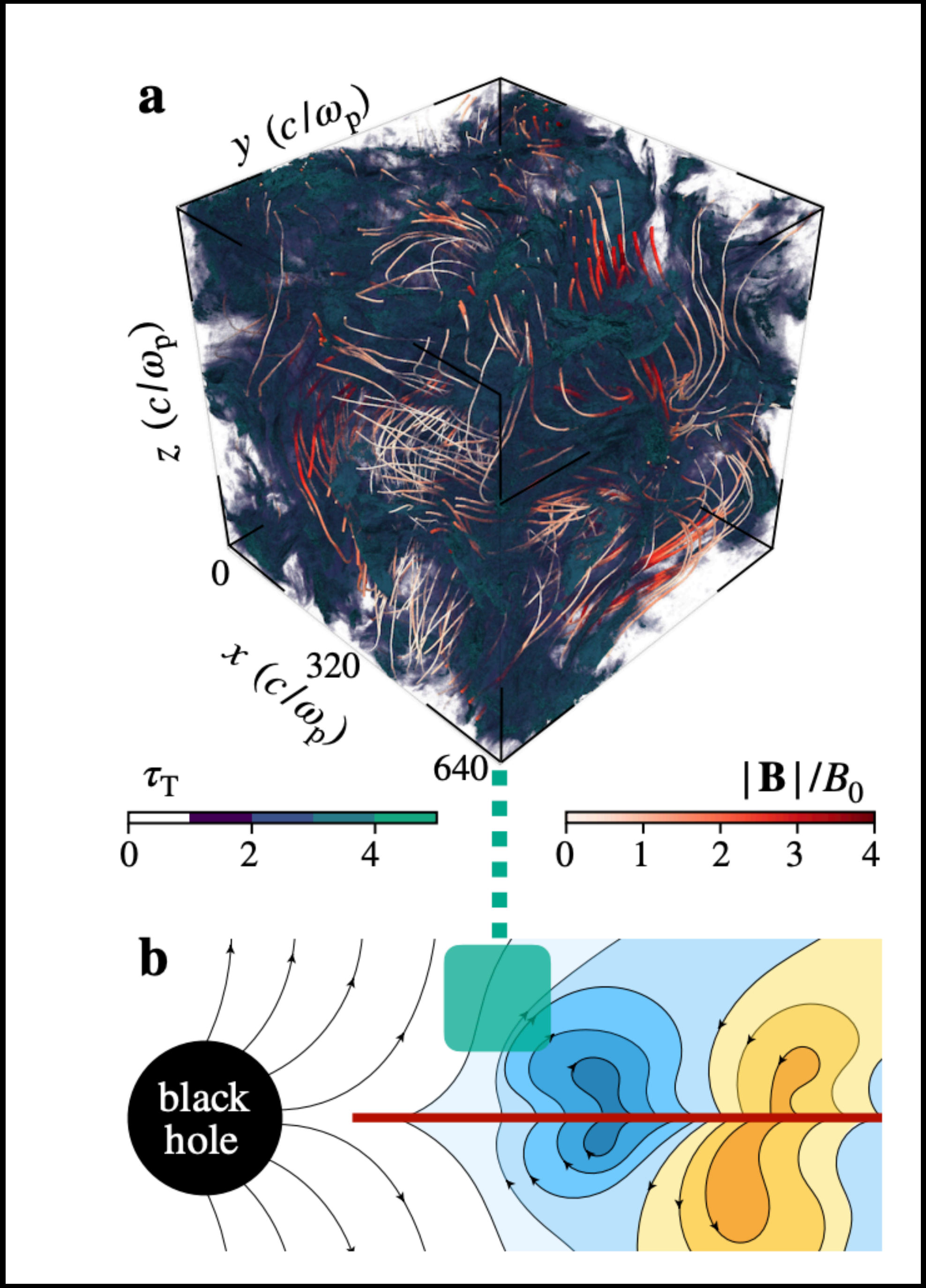
- Injection in reconnection
- Further stochastic acceleration
- Power-law ~ -3



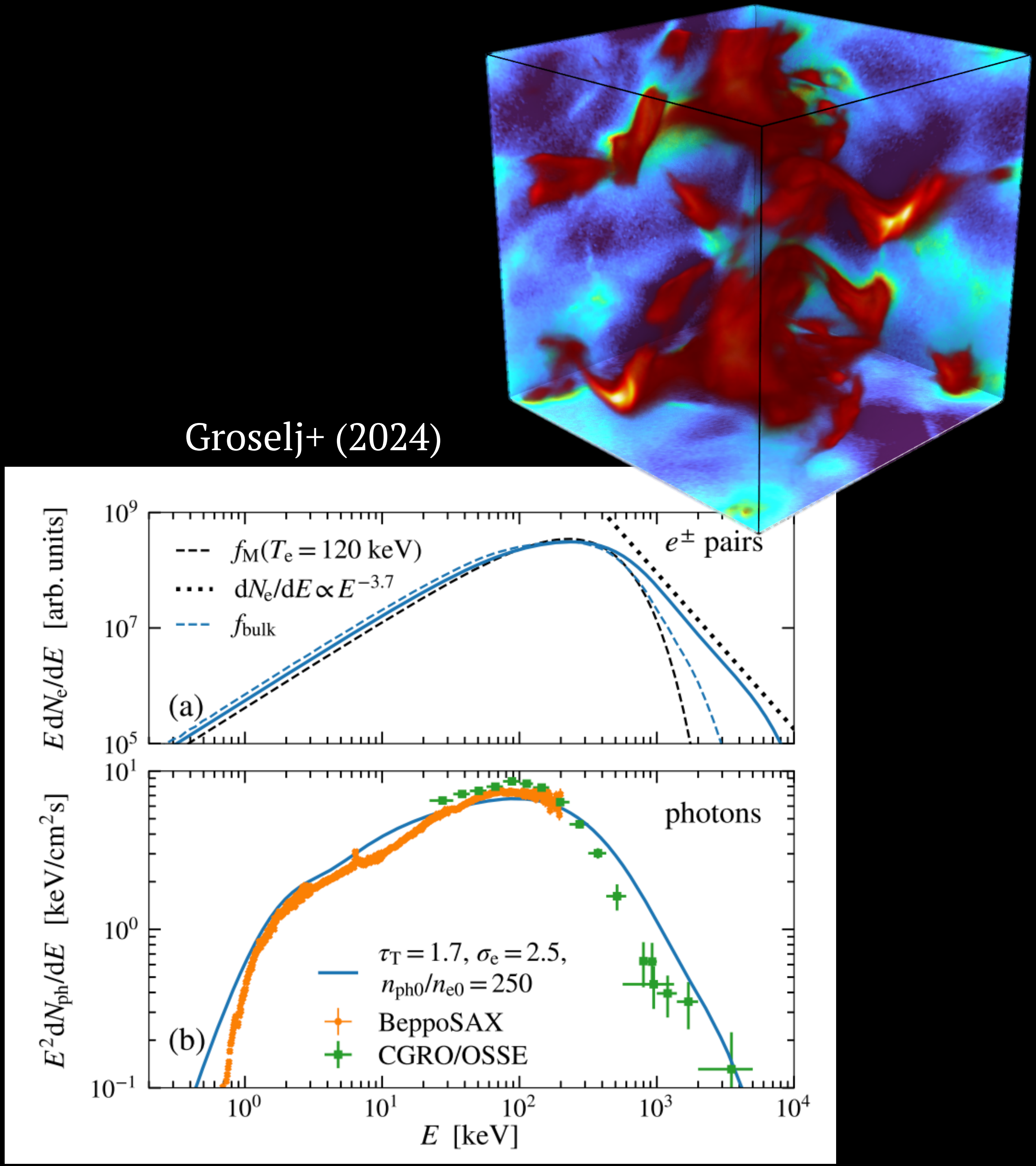
Comisso+ 2019

Acceleration mechanism II: magnetized turbulence

with radiative and QED effects



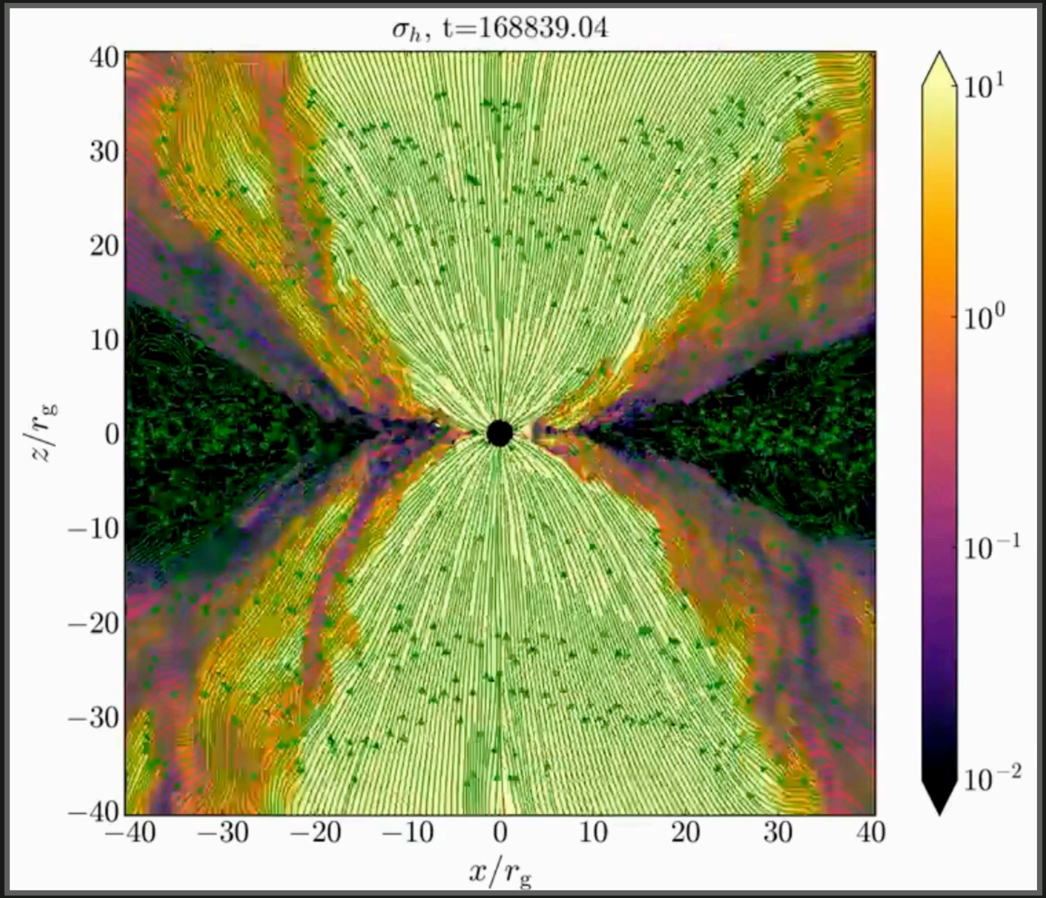
Nättilä+ (2024)



Groselj+ (2024)

Kinetic plasma physics of corona

- self-consistent thermodynamics and feedback is relatively well-understood.
- Kinetic plasma with inverse Compton and gamma-gamma pair production describes the coronal spectra of X-ray binaries in hard state
- However, the global picture is unclear. Global sets, eg, escape rate, ratio of ions to pair, which ultimately set the max energy limits

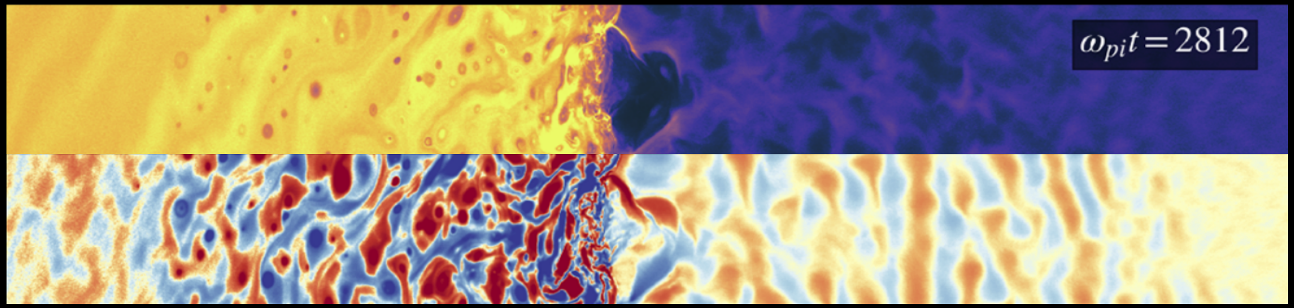


Radiative GRMHD simulation by G. Musoke

Acceleration mechanism III: collisionless shocks

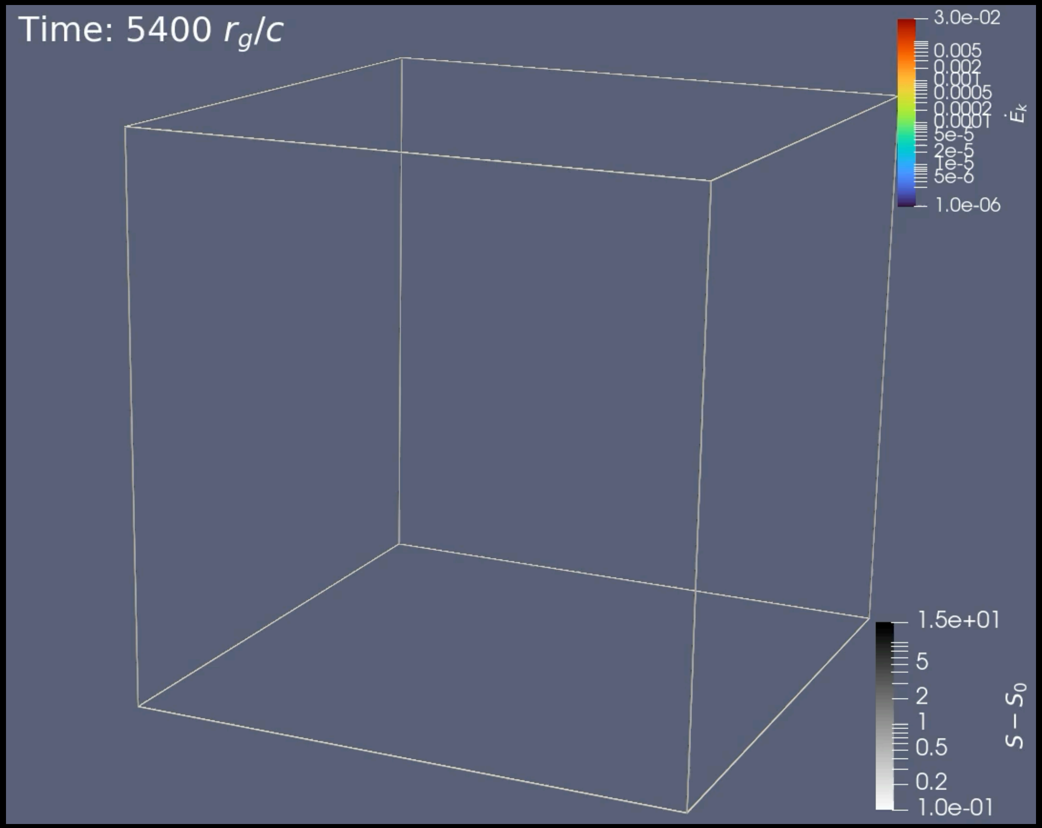
Collisionless shocks in:

- Corona, interplay with reconnection and turbulence
- Jet base, internal jet
- Outflow and feedback shocks



Diffusive shock acceleration (DSA), a first-order Fermi process, in collisionless shocks:

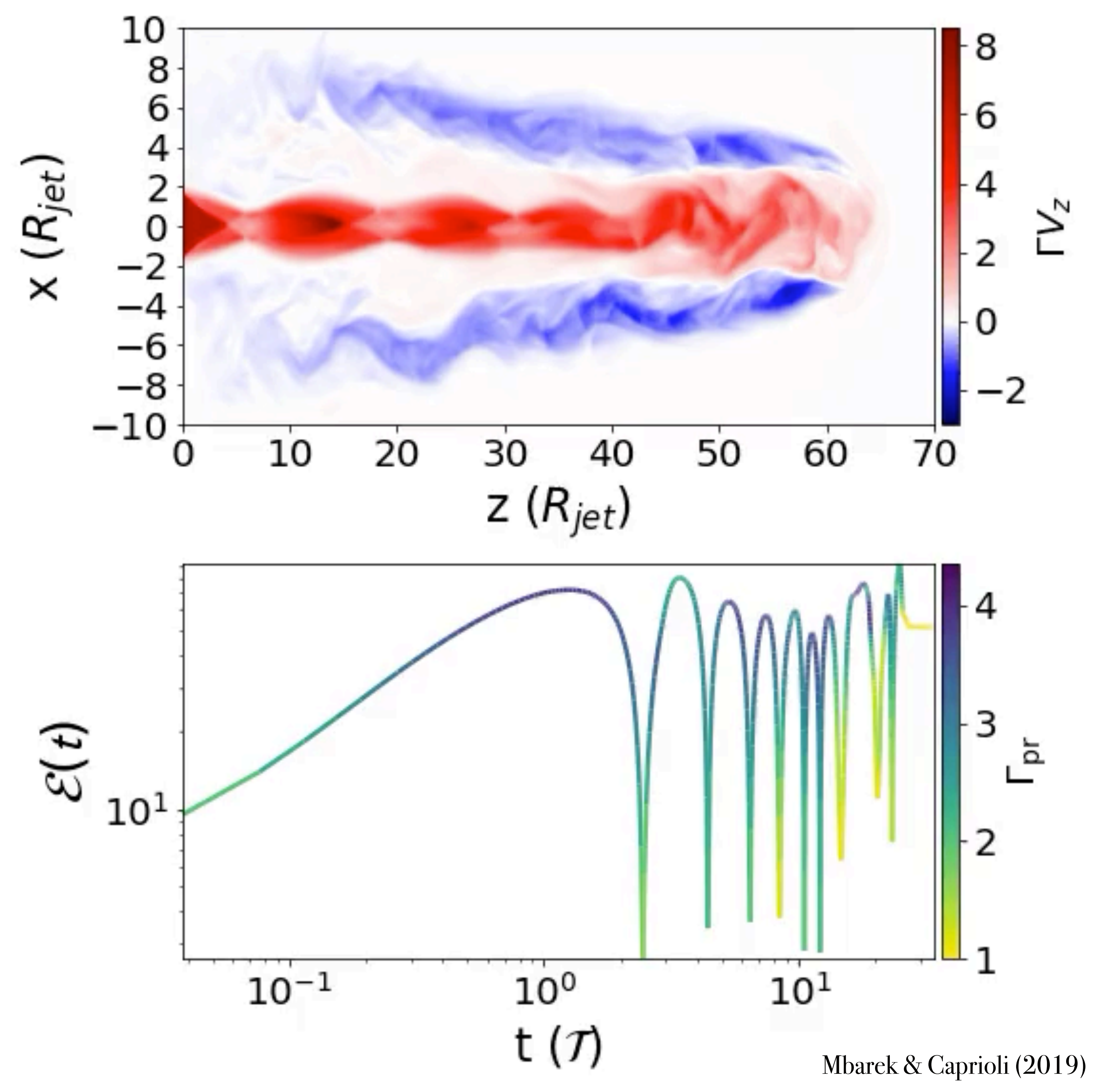
- Effective accelerator of protons
- But still less generic than turbulence and reconnection



Kinetic energy of the outflow

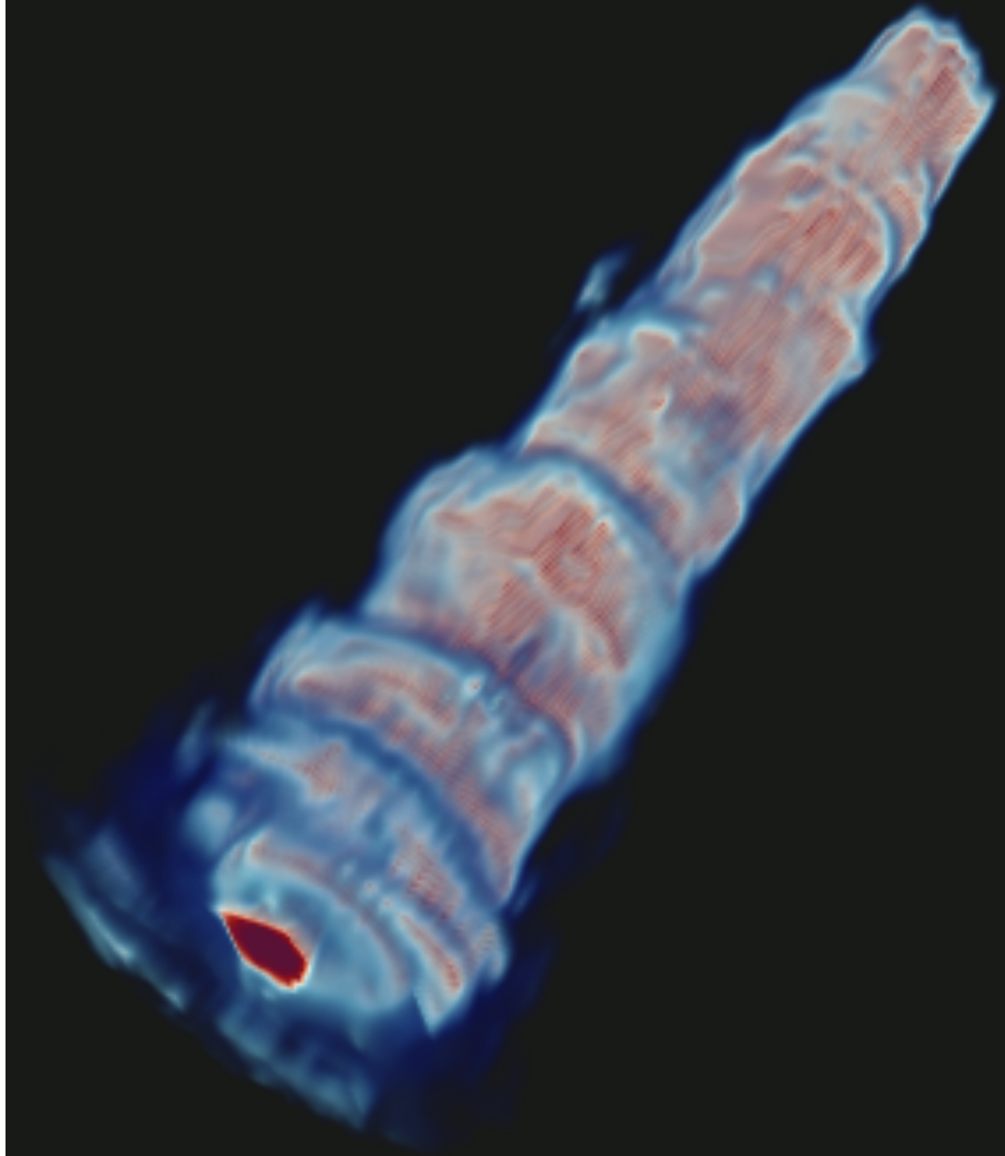
Entropy

Re-acceleration



Mbarek & Caprioli (2019)

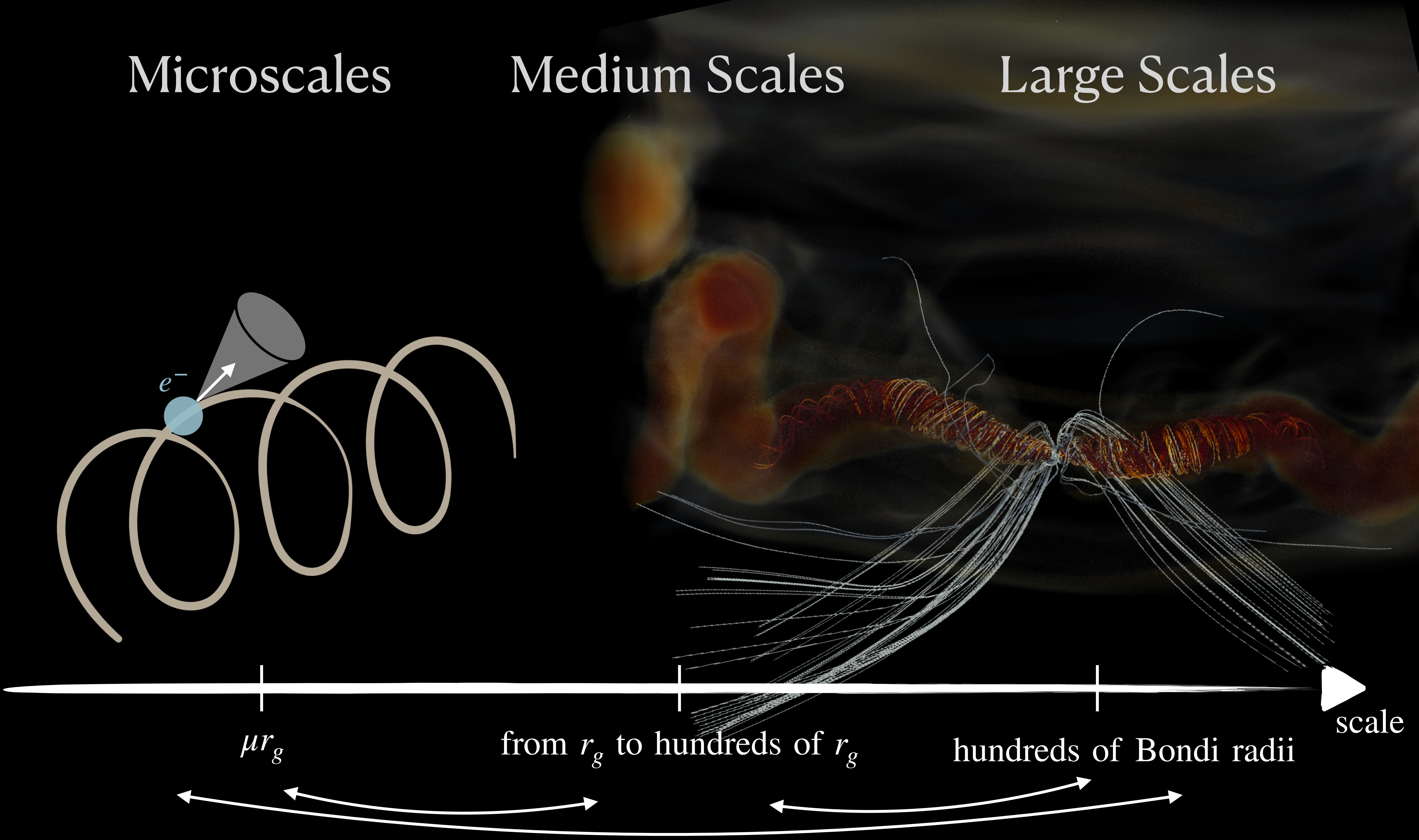
2D slice of Particle trajectory in
MHD jet simulation



Acceleration of pre-injected particles

Mbarek & Caprioli (2021)

Microscales Medium Scales Large Scales



μr_g

from r_g to hundreds of r_g

hundreds of Bondi radii

scales of Larmor radii of particles

scales of the black hole's event horizon up to its sphere of influence, Bondi radius

beyond the Bondi radius

GRMHD identifies candidate acceleration sites while PIC determines microphysical energization and spectra

1. Run global GRMHD to find large scale parameters: magnetization, turbulence, current sheets, jet-disk interfaces, shocks, etc
2. Use local or semi-global PIC kinetic simulations to study particle acceleration in those environments
3. Build subgrid or hybrid prescriptions to map macroscopic flow properties to proton/electron distributions and radiation