MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Dynamics of energetic particles in the vicinity of Black Holes

TOK/MHD Retreat 2025

PLASMA ASTRO

Daniele Villa

The fundamental problem

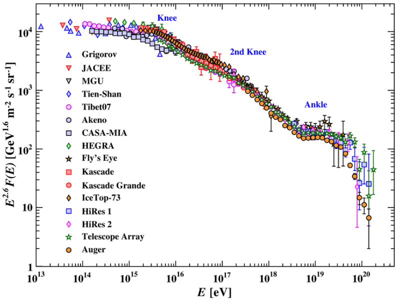

Figure: Source: CERN Document Server.

- Mechanism that **accelerates particles to** $\sim$ **EeV** $=$ **10^{18}eV** energies unknown $\rightarrow$ must be of **extragalactic origin**.
- Such particles offer a **window into remote and extreme environments**.
- **Black holes** “contain” huge amounts of energy $\rightarrow$ if transferred to particles these could easily reach high energies.
- Understanding the **large-scale environment around black holes**.

Active Galactic Nuclei

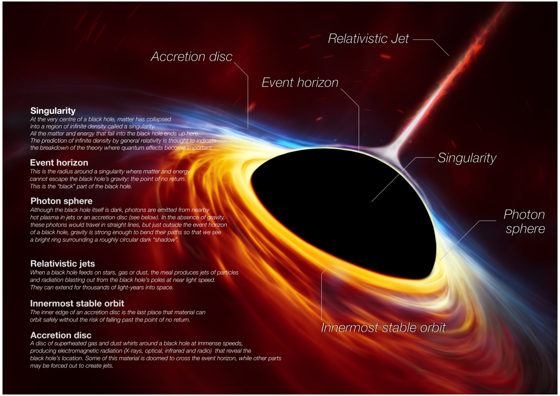

Figure: Source: ESO.

Active Galactic Nuclei

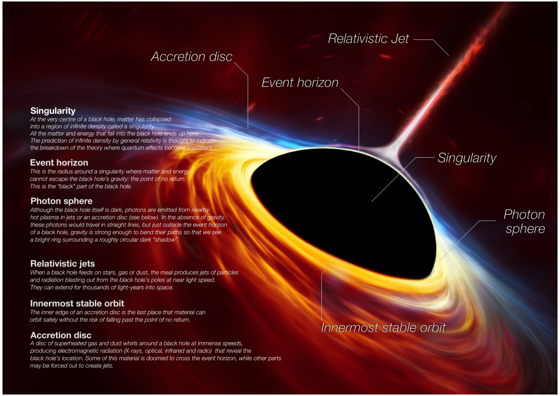

Figure: Source: ESO.

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Active Galactic Nuclei

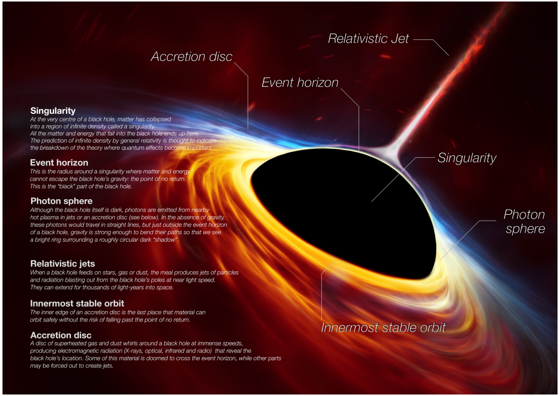


Figure: Source: ESO.

- **Central black hole** $\rightarrow$ Supermassive ($M \geq 10^6 M_\odot$), often spinning
- **Accretion Disk** $\rightarrow$ Matter captured by the gravitational well of the black hole $\rightarrow$ magnetized turbulent fluid

Active Galactic Nuclei

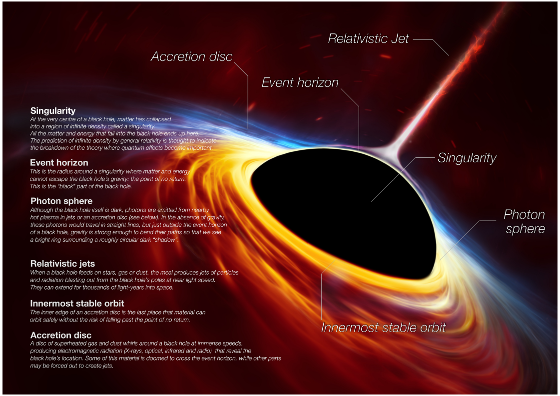


Figure: Source: ESO.

- **Central black hole** $\rightarrow$ Supermassive ($M \geq 10^6 M_\odot$), often spinning
- **Accretion Disk** $\rightarrow$ Matter captured by the gravitational well of the black hole $\rightarrow$ magnetized turbulent fluid
- **Relativistic Jet** $\rightarrow$ Strongly accelerated (and strongly magnetized) outflow of matter

General Relativistic MHD

Ideal system of equations *(Y. Mizuno and L. Rezzolla, 2024, arXiv:2404.13824)*

$$\partial_t\left(\sqrt{\gamma}D\right) + \partial_i\left(\sqrt{\gamma}D(\alpha v^i - \beta^i)\right) = 0 \quad (1)$$

$$\partial_t\left(\sqrt{\gamma}S_j\right) + \partial_i\left(\sqrt{\gamma}(\alpha W^i_j - \beta^i S_j)\right) = \frac{1}{2}\sqrt{-g}T^{\mu\nu}\partial_j T_{\mu\nu} \quad (2)$$

$$\partial_t\left(\sqrt{\gamma}U\right) + \partial_i\left(\sqrt{\gamma}(\alpha S^i - U\beta^i)\right) = -\sqrt{-g}T^{\mu\nu}\nabla_\mu n_\nu \quad (3)$$

$$\partial_t\left(\sqrt{\gamma}B^j\right) + \partial_i\left(\sqrt{\gamma}B^j(\alpha v^i - \beta^i) - \sqrt{\gamma}B^i(\alpha v^j - \beta^j)\right) = 0 \quad (4)$$

Code: AthenaK *(J. M. Stone et al., 2024, arXiv:2409.16053)* (KOKKOS for parallel hybrid-architecture execution, i.e. multi-gpu support).

Adding particles in AthenaK

Development of a new physics module for AthenaK that allows single particle dynamics. Currently only **tracer/passive particles**.

Gravitational dynamics $\rightarrow$ iterative method for the free-particle Hamiltonian *(F. Bacchini et al., 2019, The Astrophysical Journal Supplement Series, 240, 2.)*:

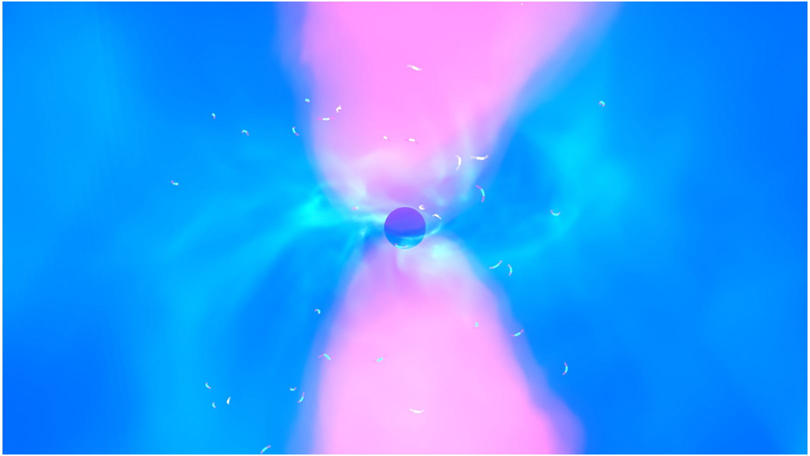
$$\mathcal{H}(x^i, u_i) = \alpha(\gamma^{jk}(x^i)\, u_j u_k + \epsilon)^{1/2} - \beta^j(x^i)\, u_j \tag{5}$$

Electromagnetic dynamics $\rightarrow$ explicit Boris steps adapted to GR *(B. Ripperda et al., 2018, The Astrophysical Journal Supplement Series, 235, 1.)*

$$\frac{u_i(t+\delta t) - u_i(t)}{\delta t} = \frac{q}{m}(E_i(x(t+\frac{1}{2}\delta t)) + \bar{v}_j \times B_k(x(t+\frac{1}{2}\delta t))) \qquad \bar{v}_j = \frac{u_j(t+\delta t) + u_j(t)}{2\Gamma(t+\frac{1}{2}\delta t)} \tag{6}$$

Main hurdle at the moment is finding appropriate parameters for system of interest.

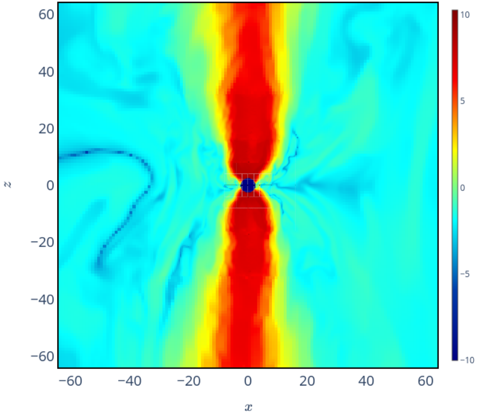
What does this “look like”?



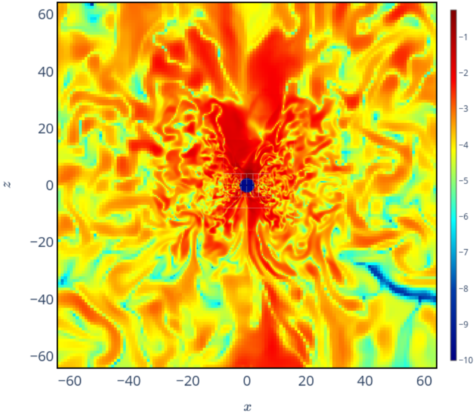
Accretion Disk Regimes

View **IN** the disk plane

MAD $a = 0.99$ $\log_{10}(\sigma)$



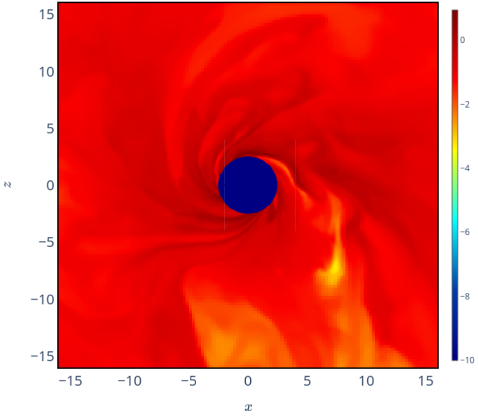
SANE $a = 0.99$ $\log_{10}(\sigma)$



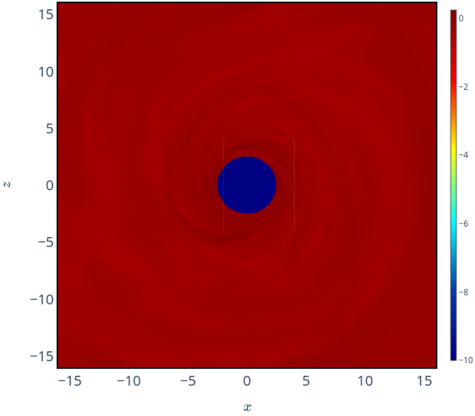
Accretion Disk Regimes

View **PERPENDICULAR TO** the disk plane

MAD $a = 0.99$ $\log_{10}(n)$

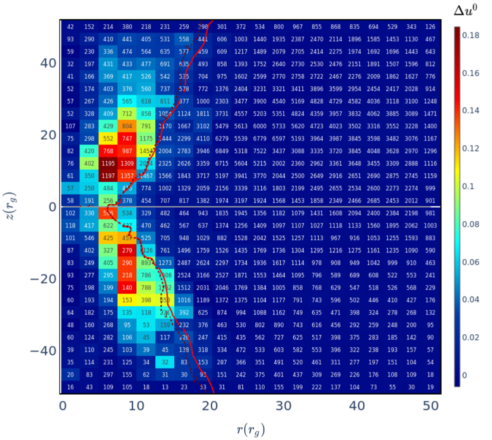


SANE $a = 0.99$ $\log_{10}(n)$

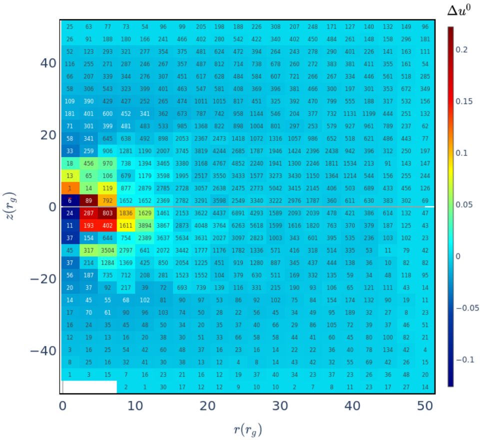


Average Particle Dynamics

MAD $a = 0.99$ $\quad < \Delta u^0 >$

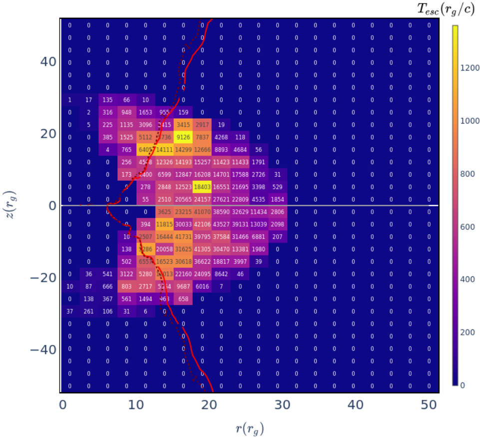


SANE $a = 0.99$ $\quad < \Delta u^0 >$

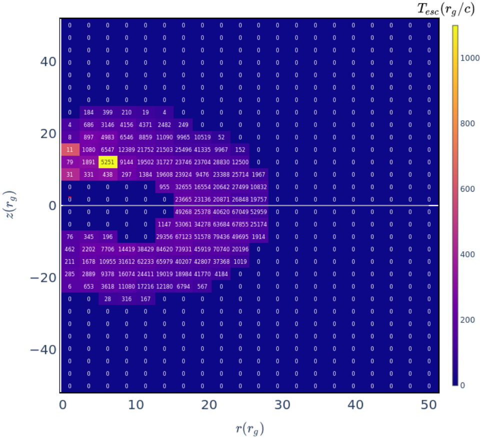


Average Particle Dynamics

MAD $a = 0.99$ $\quad < \tau^{max}_{esc,out} >$

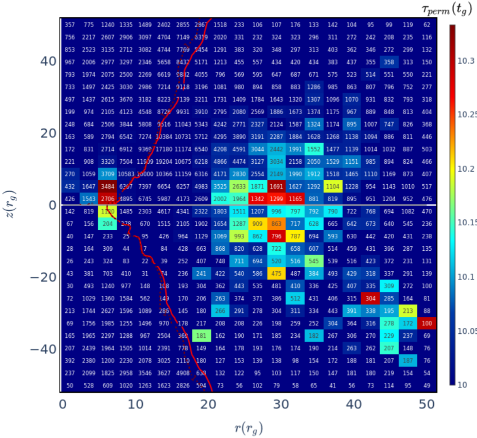


SANE $a = 0.99$ $\quad < \tau^{max}_{esc,out} >$

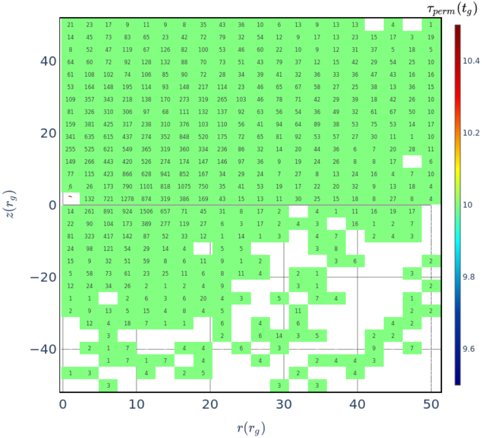


Average Particle Dynamics

MAD $a = 0.99$ $< \tau_{trap} >$

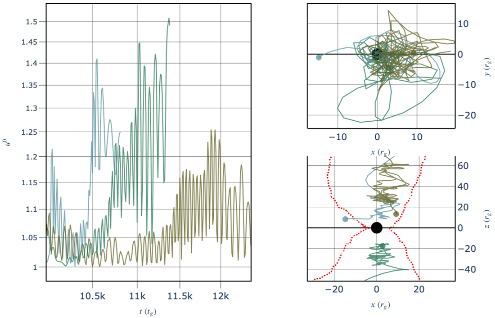


SANE $a = 0.99$ $< \tau_{trap} >$

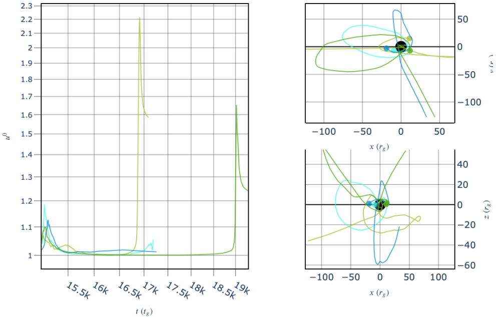


Individual Particle Dynamics

MAD $a = 0.99$



SANE $a = 0.99$



Outlook and future developments

- Use **particle pusher that evolves equations in Gyro-Center Approximation** to deal with system scale $\rightarrow$ Implemented, ongoing validation.

- Assess whether **current models of Accretion Disks are satisfactory** to explain neutrino emission from NGC 1068
  - Extend to **local resistivity** model.
  - Include **cooling and possibly radiation transport** in GRMHD simulations.

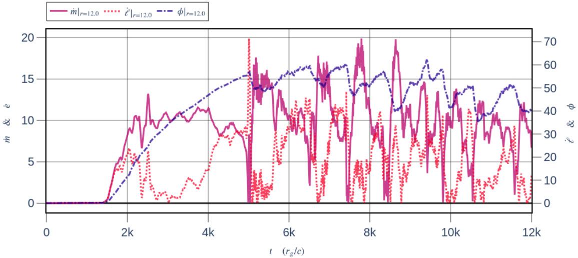
- Study the properties of **turbulence in GRMHD**.

- Study the **AGN NGC 1068 as a potential neutrino source**, trying to provide a first-principle explanation for the results from IceCube *(IceCube Collaboration, 2022, Science, 378, 6619.)*

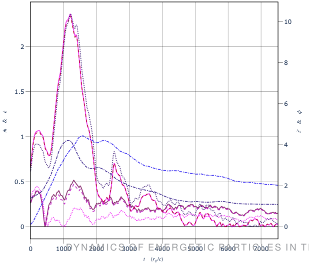
Extra slides

Accretion Disk Regimes

MAD regime



SANE regime



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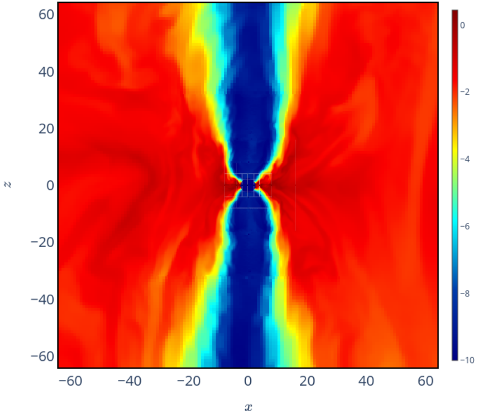

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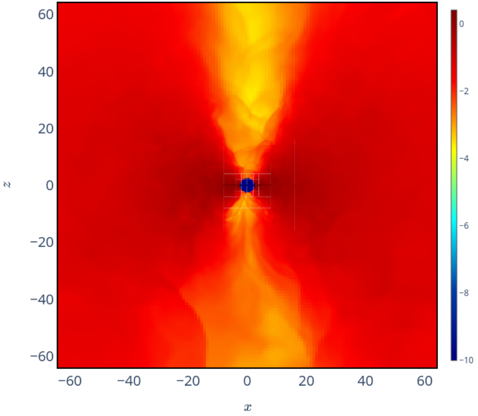
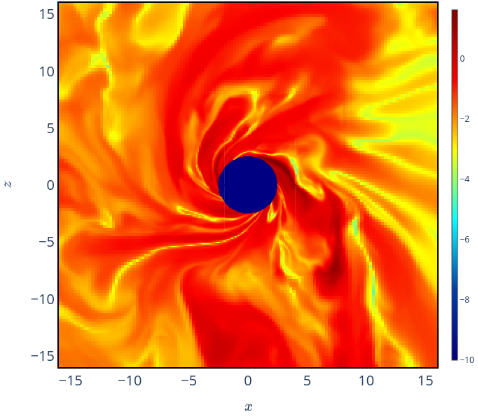


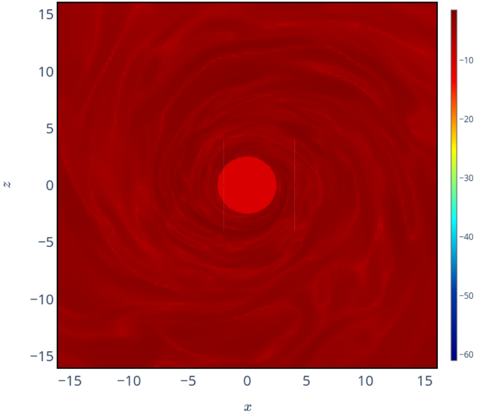
Accretion Disk Regimes

View **PERPENDICULAR TO** the disk plane

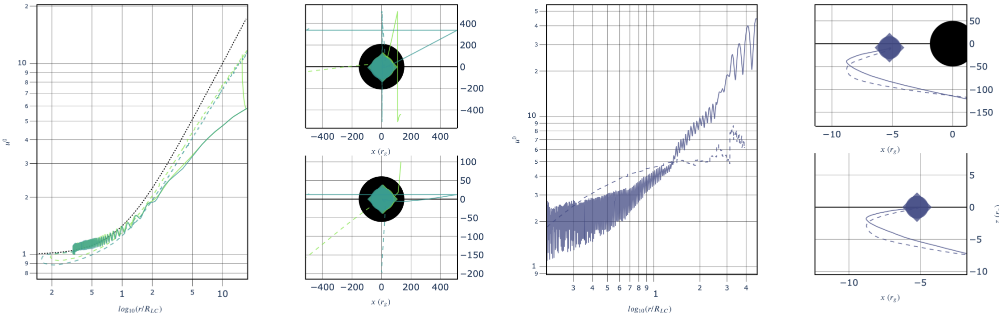
MAD $a = 0.99$ $\log_{10}(\sigma)$



SANE $a = 0.99$ $\log_{10}(\sigma)$



GCA vs Kinetic



Comparison of individual particle dynamics in MAD and SANE cases

Neutrino Measurements At IceCube

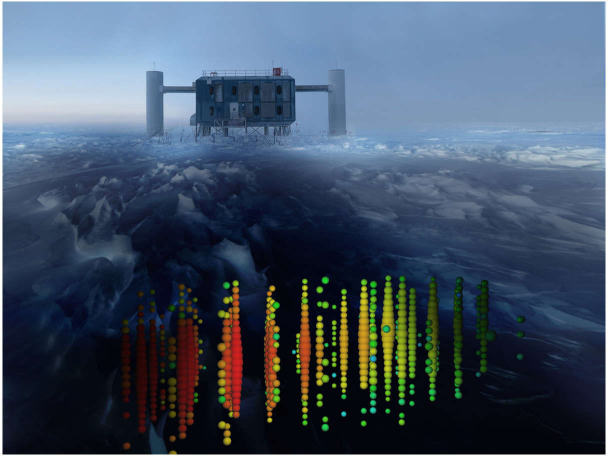


Figure: The IceCube Observatory.

Neutrino Measurements At IceCube

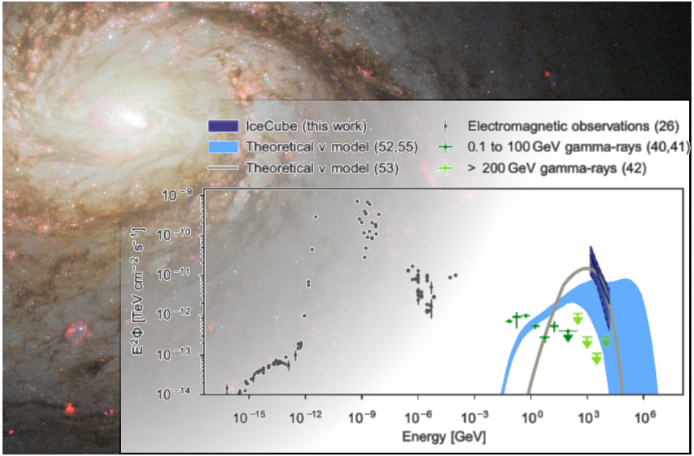


Figure: The Galaxy NGC 1068 has been identified as the source of the neutrino flux *(IceCube Collaboration, 2022, Science, 378,6619)*.

Investigation methods

System spans several orders of magnitude:

- The Accretion Disk can extend for **thousands of $\mathbf{r_g} = \frac{\mathbf{GM}}{\mathbf{c^2}}$** away from the Black Hole
- **Turbulence** develops on sub-r_g scales
- Recent efforts *(B. Ripperda et al., 2019, The Astrophysical Journal Supplement Series, 244, 1 – B. Ripperda et al., 2022, The Astrophysical Journal Letters, 924, 2.)* even attempt to **resolve the resistive scale** near the Black Hole $\rightarrow$ magnetic reconnection

The system is described using **General Relativistic MHD (GRMHD)**:

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The system is described using **General Relativistic MHD (GRMHD)**:

$$\nabla_\mu(\rho u^\mu) = 0 \quad (7)$$

$$\nabla_\mu(T^\mu_\nu) = 0 \quad (8)$$

$$\nabla_\mu({}^*F^\mu_\nu) = 0 \quad (9)$$

Accretion Disk Evolution

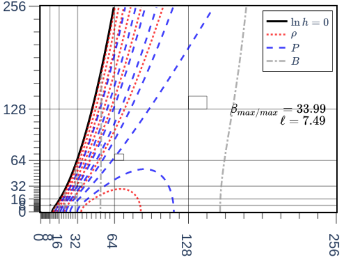
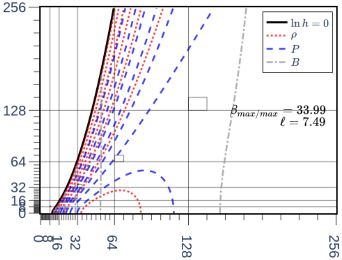


Figure: *(L.G. Fishbone and V. Moncrief, 1976, The Astrophysical Journal, 207.)*

Initial condition is **hydrodynamic** solution → Add “dynamically negligible” poloidal magnetic field → Accreted magnetic flux determines regime (MAD vs. SANE) *(Y. Mizuno, 2022, Universe, 8, 2.)*.

Accretion Disk Evolution



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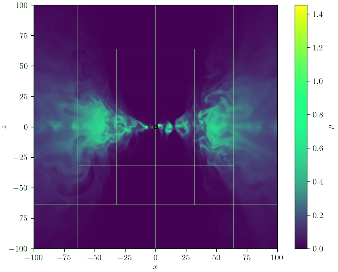

Figure: Density of the magnetized fluid around the Black Hole. View in the equatorial plane.

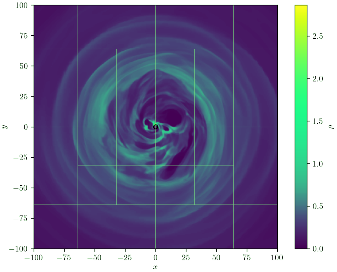

Figure: Density of the magnetized fluid around the Black Hole. View perpendicular to the equatorial plane.

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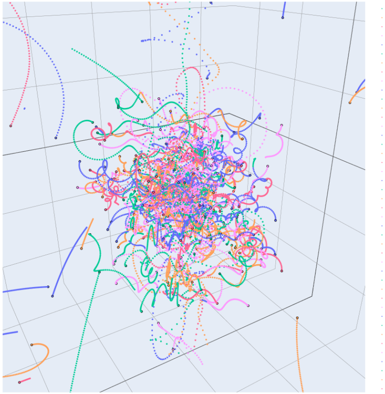
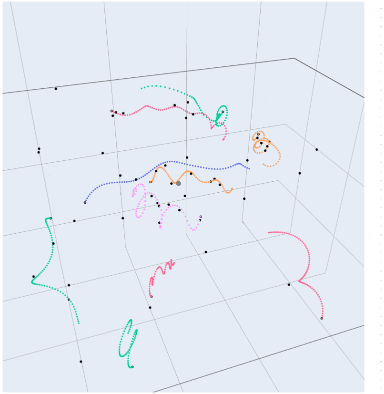
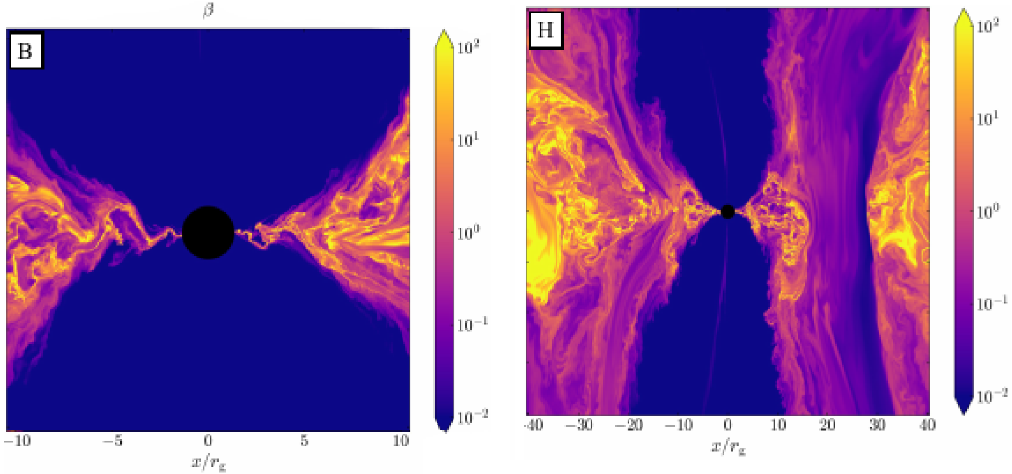
Adding particles





Particle trajectories in a MAD accretion disk.

Accretion Disk Evolution



Figures from Ripperda et al., 2022: resistive GRMHD

AthenaK Performance Scaling

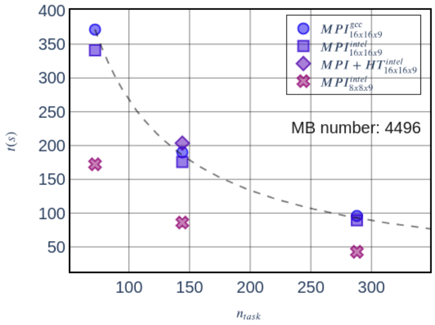


Figure: Performance scaling on CPU

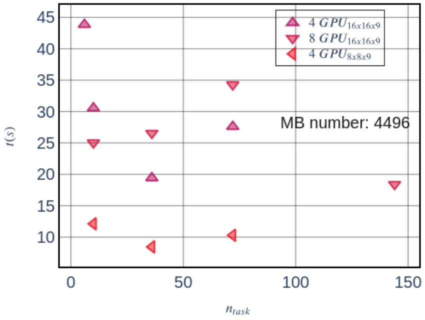


Figure: Performance scaling on GPU

AthenaK Performance Scaling

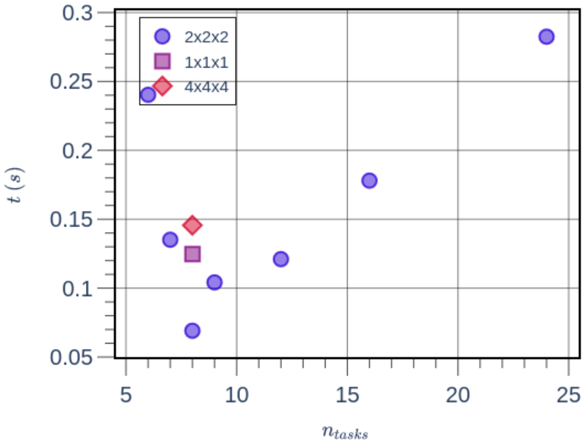


Figure: Performance scaling on GPU depending on domain setup.

Validation of particles in AthenaK

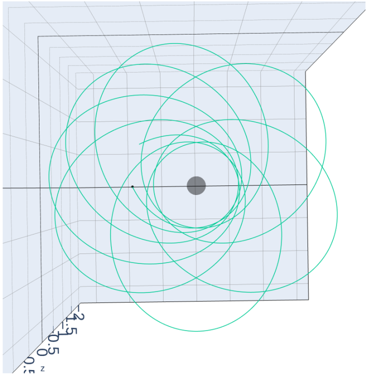


Figure: Precessing orbits in Schwarzschild (non-rotating black hole) spacetime.

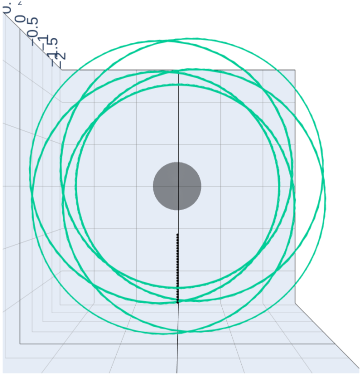


Figure: Closed orbits in Kerr (rotating black hole) spacetime.

Energy conservation properties of the algorithm

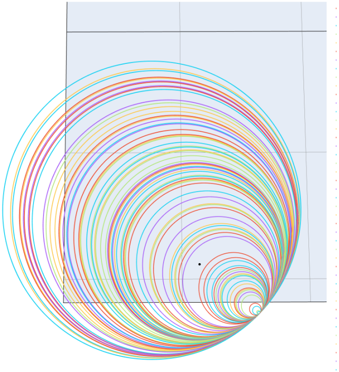


Figure: Larmor orbits in uniform magnetic field.

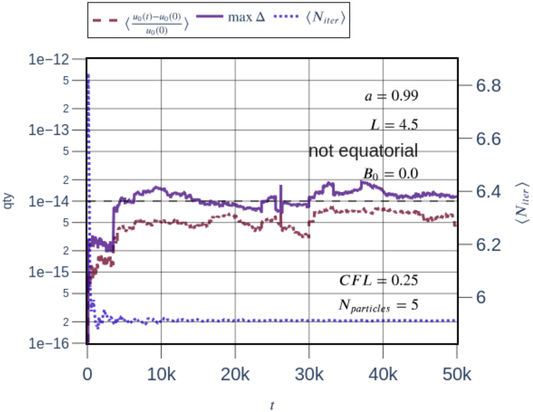


Figure: Energy conservation of the Hamiltonian scheme for gravitational dynamics.

Accretion Disk Evolution