The viability of NGC 1068 as a neutrino source

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ABSTRACT

This work reports on the dynamics of **tracer particles** added to an environment that simulates the **accretion disk surrounding a black hole**, varying the dynamical regime (MAD or SANE) and the plasma β of the accretion disk. This preliminary investigation is the first step towards the goal of providing insight into the **confinement of high-energy particles in NGC 1068** ([2, 6]), believed to be the **source of the neutrino fluxes measured in [3]**. The accretion disk is evolved according to the equations of **General Relativistic MagnetoHydroDynamic (GRMHD), implemented in the code AthenaK**, a re-implementation of the Athena++ ([8]) code, with the addition of **purely passive particles** ([7, 1]), such that their presence doesn't affect the dynamics of the accretion disk. The confinement properties of energetic particles for the simulated accretion disks are summarized and used to provide **estimates for the escape times of particles** in such accretion disk environment, which is otherwise usually modeled as a free parameter.

FIRST-PRINCIPLE APPROACH

- Accretion disks are magnetized → **Energetic charged particles are scattered** and (potentially) confined.
- Different "level" of magnetization determines **MAD or SANE** accretion regime → How are particles confined in different accretion disks?
- Particular focus on the **properties of the magnetic field** (e.g. particles can also be accelerated by turbulent scattering).
- Use solar-mass black hole as starting point → reference case with **well-resolved particle orbits.**
- Scale-up the simulations to Super-Massive Black Hole → **Gyro-Center Approximation** to deal with scale problem.
- **What ν fluxes could we expect** from a system with the appropriate parameters for NGC 1068?

ICECUBE RESULTS

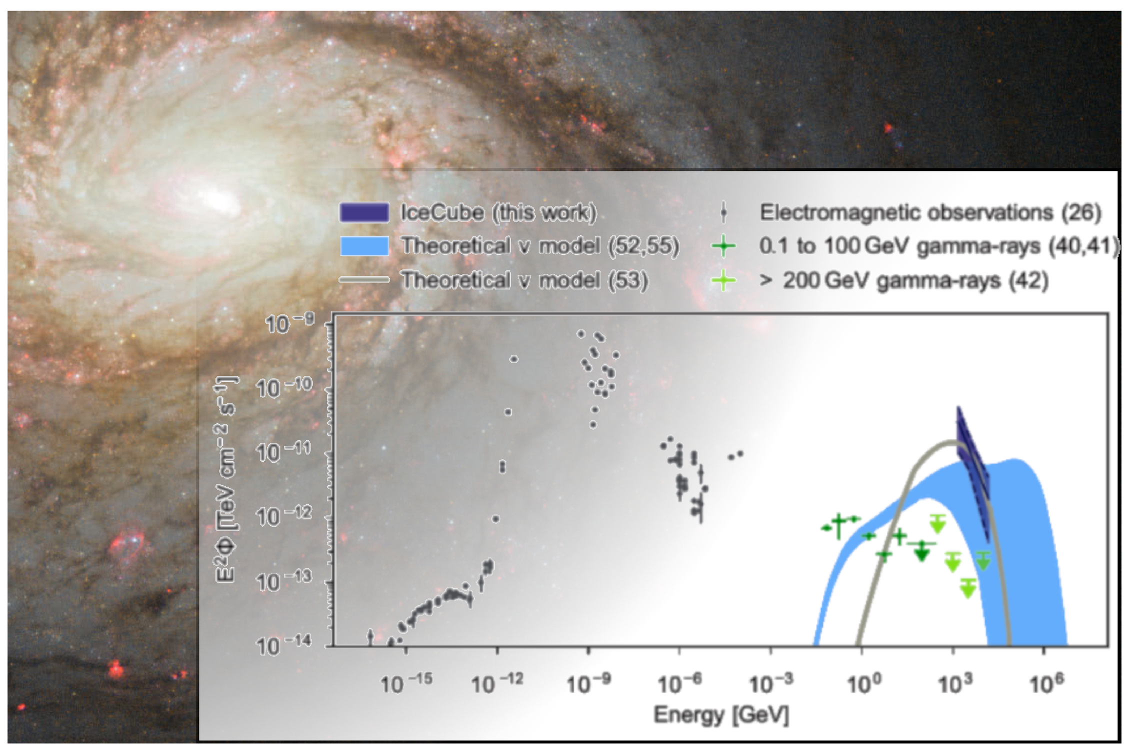

Figure 1: NGC 1068 (Source: NASA/ESA) and IceCube results ([3]).

Multi-wavelength properties of the AGN NGC 1068 allowed to **identify it as one of the sources of extragalactic neutrinos observed by IceCube**.

PRELIMINARY RESULTS

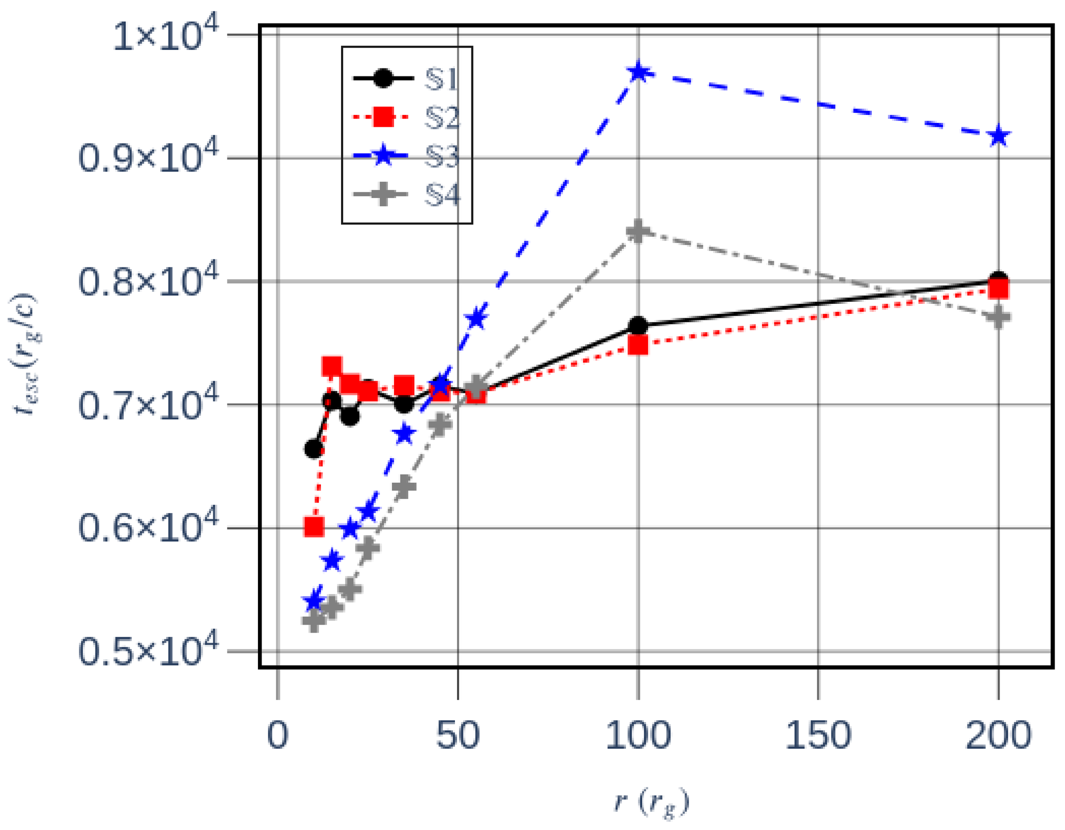

Figure 2: Escape times vs. radius for the MAD cases.

- Different regimes have very different confinement properties over the domain.
- MAD regime is characterized by flaring behaviour → how does this affect particle confinement?

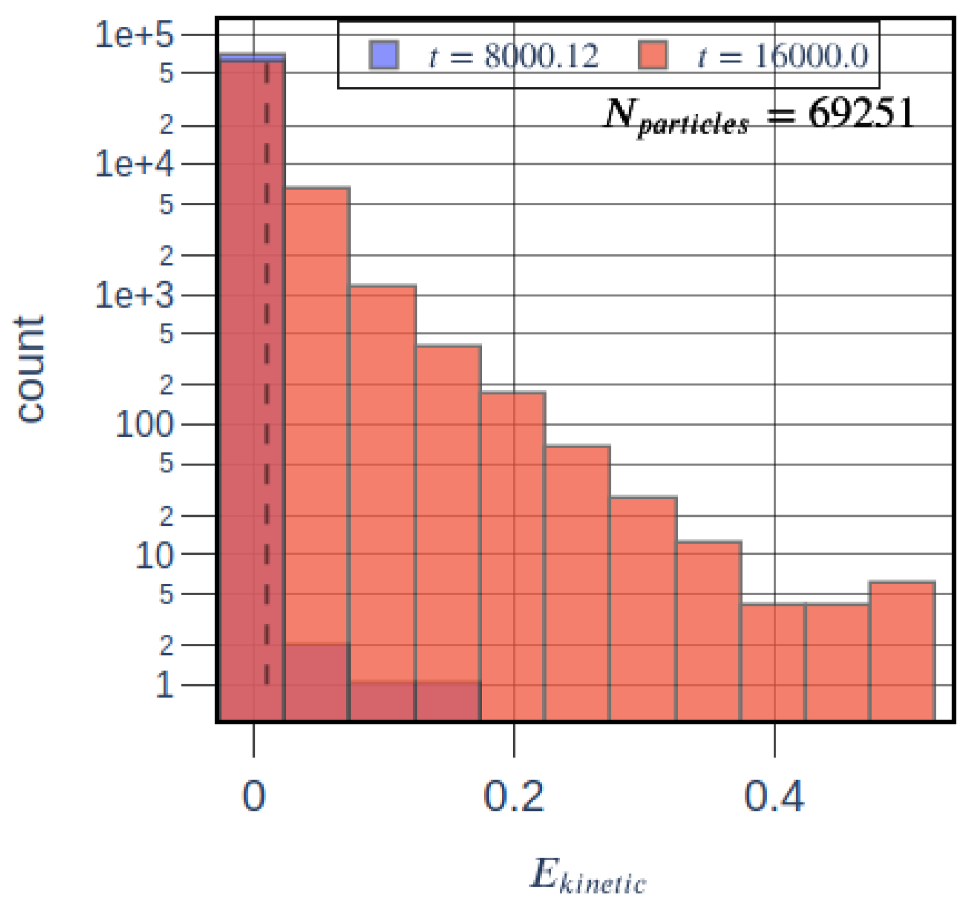

Figure 3: Kinetic energy spectrum over time for $\mathbb{S}1$.

What are the details for turbulent particle acceleration in accretion disks?

EQUATIONS

GRMHD:

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

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

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

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

Particles:

- Gravitational dynamics → iterative method for free-particle Hamiltonian [1]:

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

- Electromagnetic dynamics → explicit Boris steps adapted to GR [7]:

$$\frac{u_i(t+\delta t) - u_i(t)}{\delta t} = \frac{q}{m}\left[E_i(x(t+\frac{1}{2}\delta t)) + \bar{v}_j \times B_k(x(t+\frac{1}{2}\delta t))\right]$$
$$\bar{v}_j = \frac{u_j(t+\delta t) + u_j(t)}{2\Gamma(t+\frac{1}{2}\delta t)} \quad (6)$$

Main focus thus far has been **adding particles to AthenaK**, successor to Athena++ [8].

SIMULATION DETAILS

Accretion disk initialized as a Fishbone-Moncrief [4] torus with poloidal magnetic loops added.

Name	Regime	$\beta^{pl}_{\min}$
$\mathbb{S}1$	MAD	100.0
$\mathbb{S}2$	MAD	10.0
$\mathbb{S}3$	SANE	100.0
$\mathbb{S}4$	SANE	10.0

Particles are initialized at random locations in the domain with (uniformly distributed) energies corresponding to protons with $2\ GeV \leq E_p \leq 8\ GeV$ for application to solar-mass black holes.

Scale problem: can't resolve gyro-motion in NGC 1068.

- $r_g(M = 10^7\ M_\odot) = 1.5 \cdot 10^{10}\ m$
- $\rho_L^{\text{proton}}(E = 1\ PeV, B|_{r=10r_g} = 3\ T) = 7.4 \cdot 10^5\ m$

CONCLUSION AND OUTLOOK

- Modeling **neutrino emission from NGC 1068** requires understanding the confinement properties of its accretion disk with respect to **particles in the energy range** $\mathrm{E} \approx 0.1\mathrm{PeV}$.
- The **magnetic field** of the disk plays a crucial role in the behaviour of the energetic particles.
- System size for a Super Massive Black Hole may require **extension of the method to Gyro-Center Approximation**.
- Correlation of accretion disk dynamics to confinement properties → how does **turbulent acceleration work in accretion disks**? How do **flares** affect confinement?
- Analysis of confinement properties needs to be broken down on a **per-zone** basis, lookig into the "corona" model [5].
- Add **more physics** (radiation transport, diffusive terms...) to the simulations.
- **Can current accretion disk models explain the neutrino emission measured in NGC 1068?**

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