Gravitational wave emission from turbulent accretion disks around black holes

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Tata Institute of Fundamental Research (ICTS-TIFR), India

Collaborators:

Chen Yuan (IST, Lisbon), Pallavi Bhat (ICTS-TIFR), Vitor Cardoso (NBIA/IST)

Stochastic
Gravitational wave emission from turbulent
Supermassive
accretion disks around black holes

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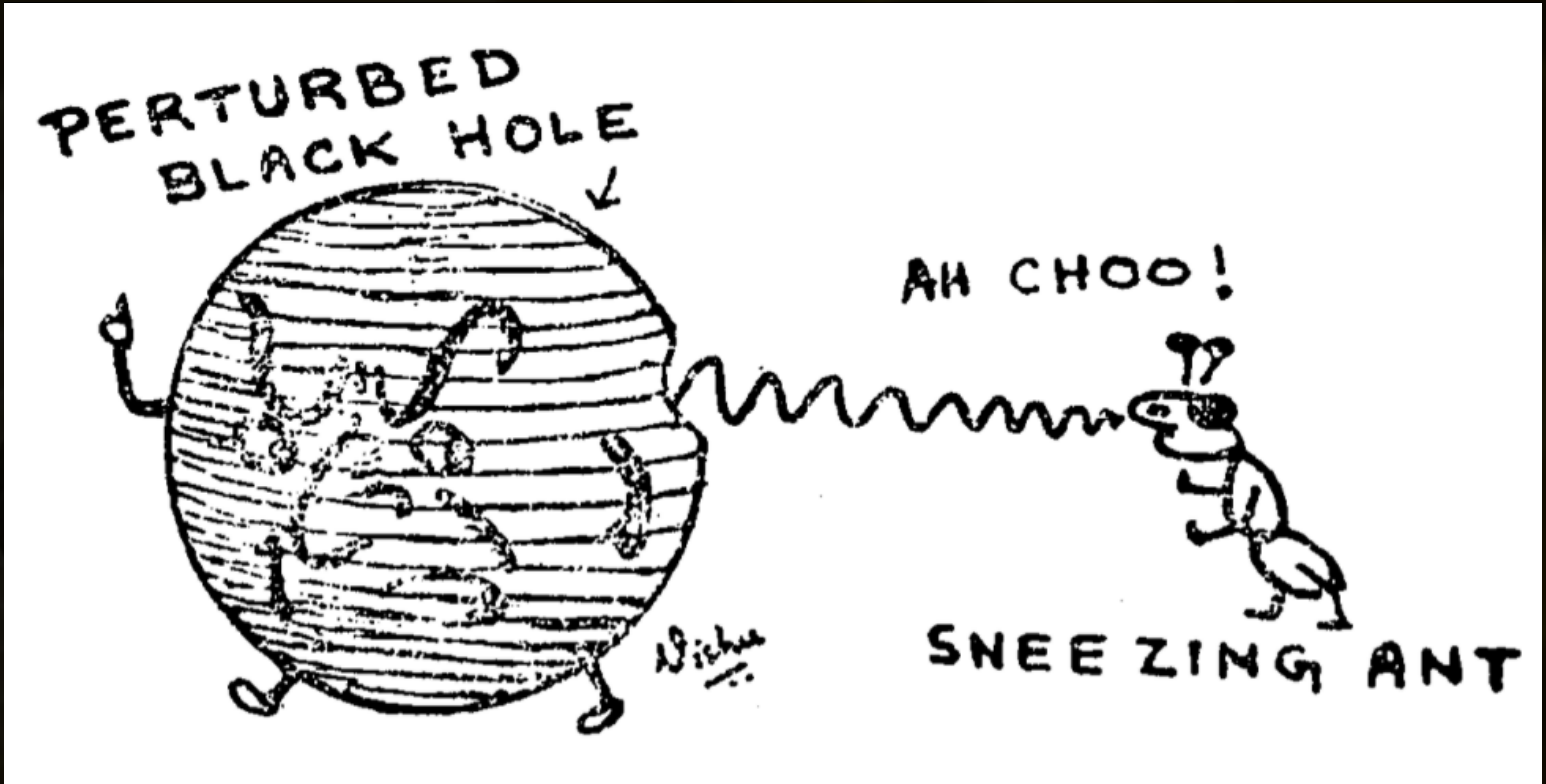
Outline of today's talk:

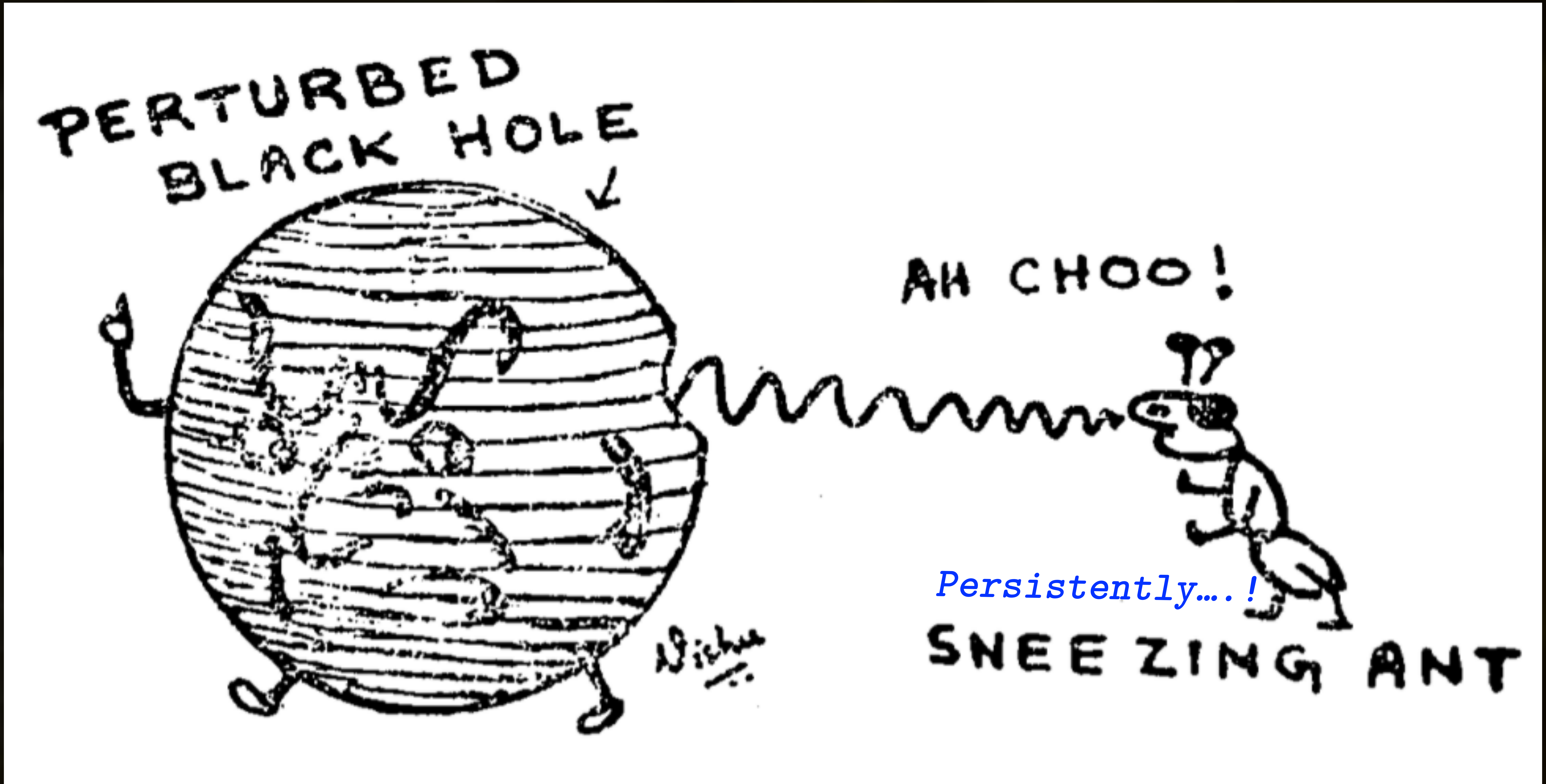
- Motivation
- Turbulent accretion disks: Role of magnetic fields
- Environmental effects on probing quasi-normal ringing
- How does (GR)MHD simulations help?
- Results
- Connecting the dots with our Galactic centre…..! (I will try to somehow…)

Motivation



Credit: C.V. Vishveshwara

Motivation



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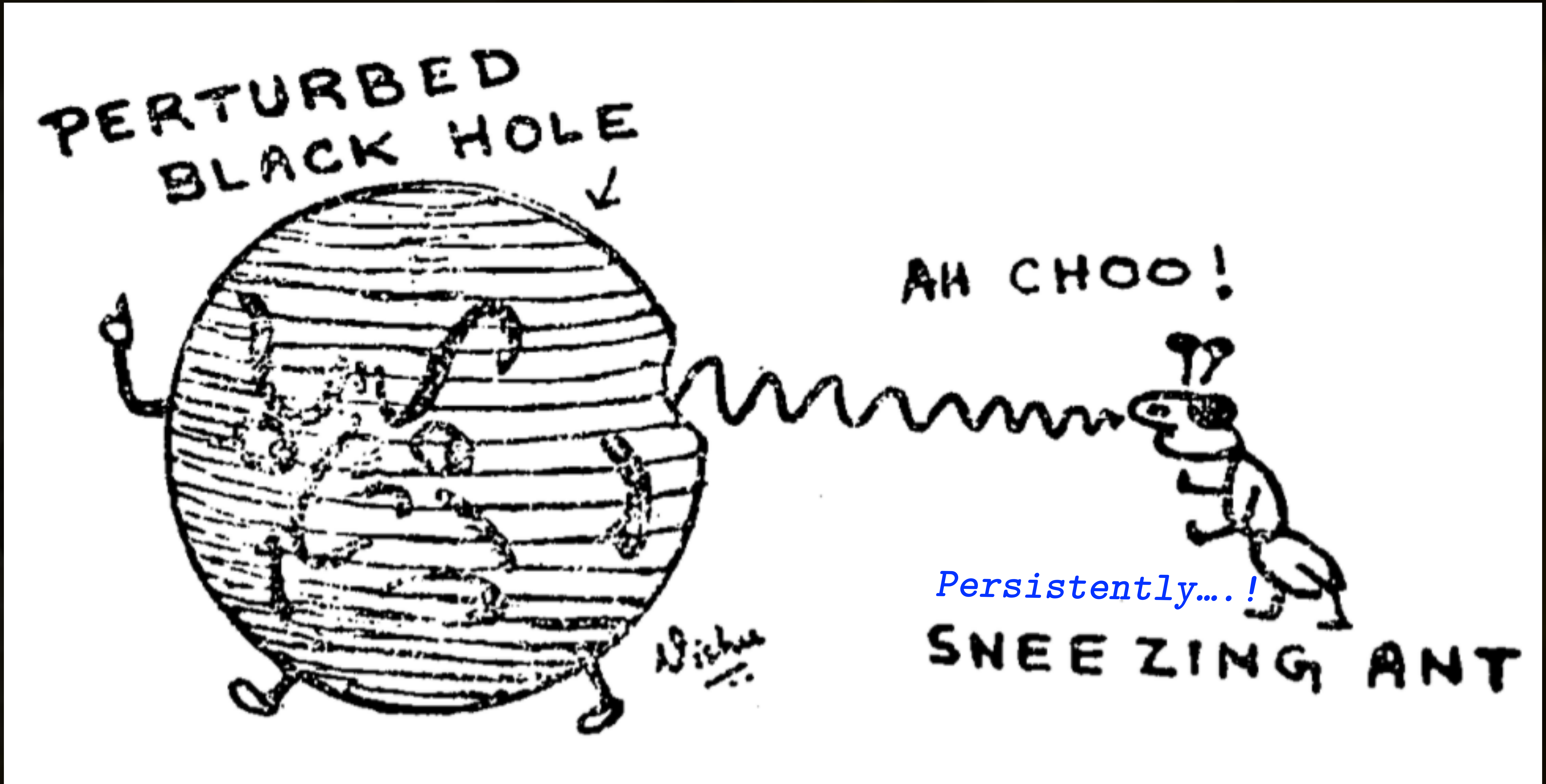
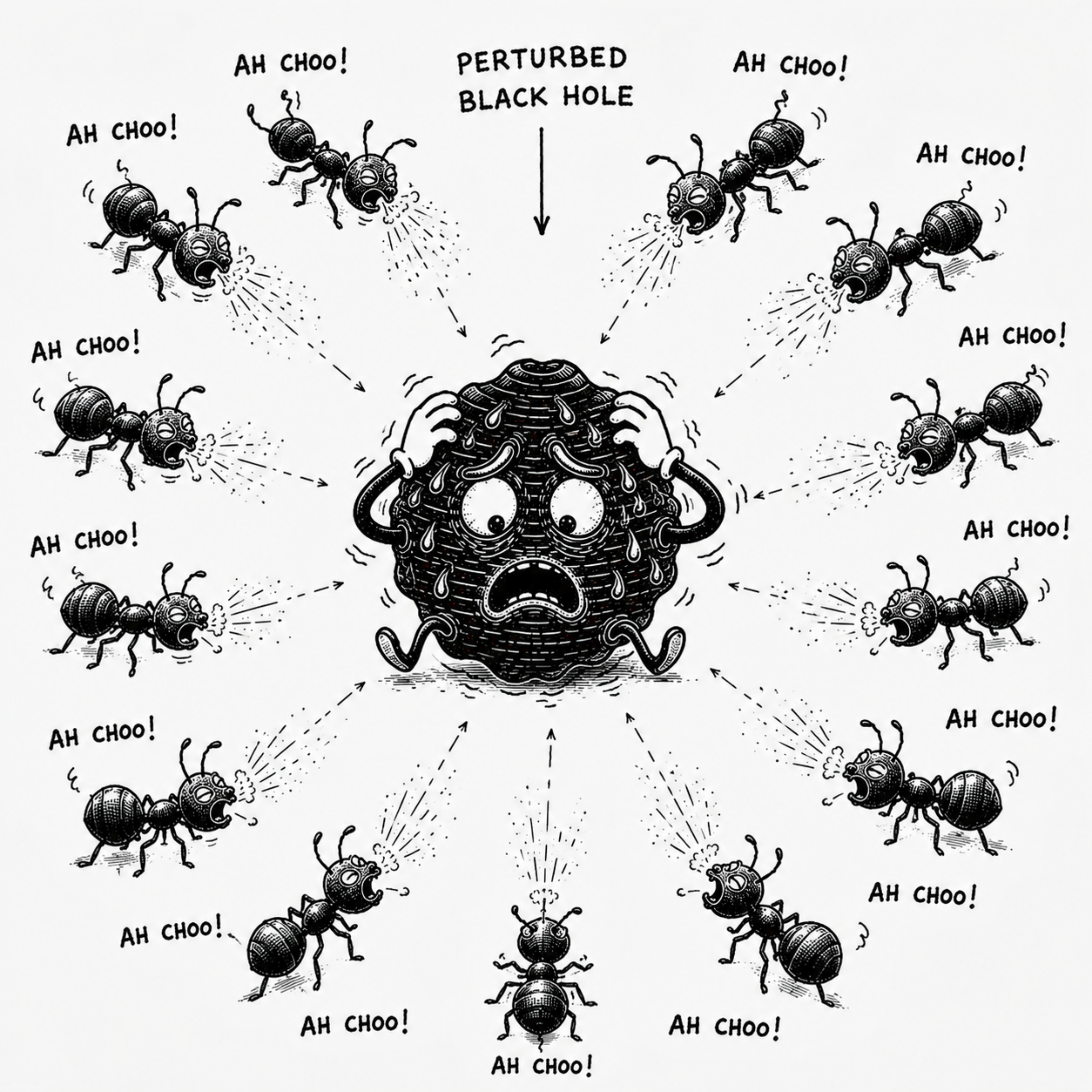


$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \epsilon h_{\mu\nu}; \ |h_{\mu\nu}| \ll 1$$

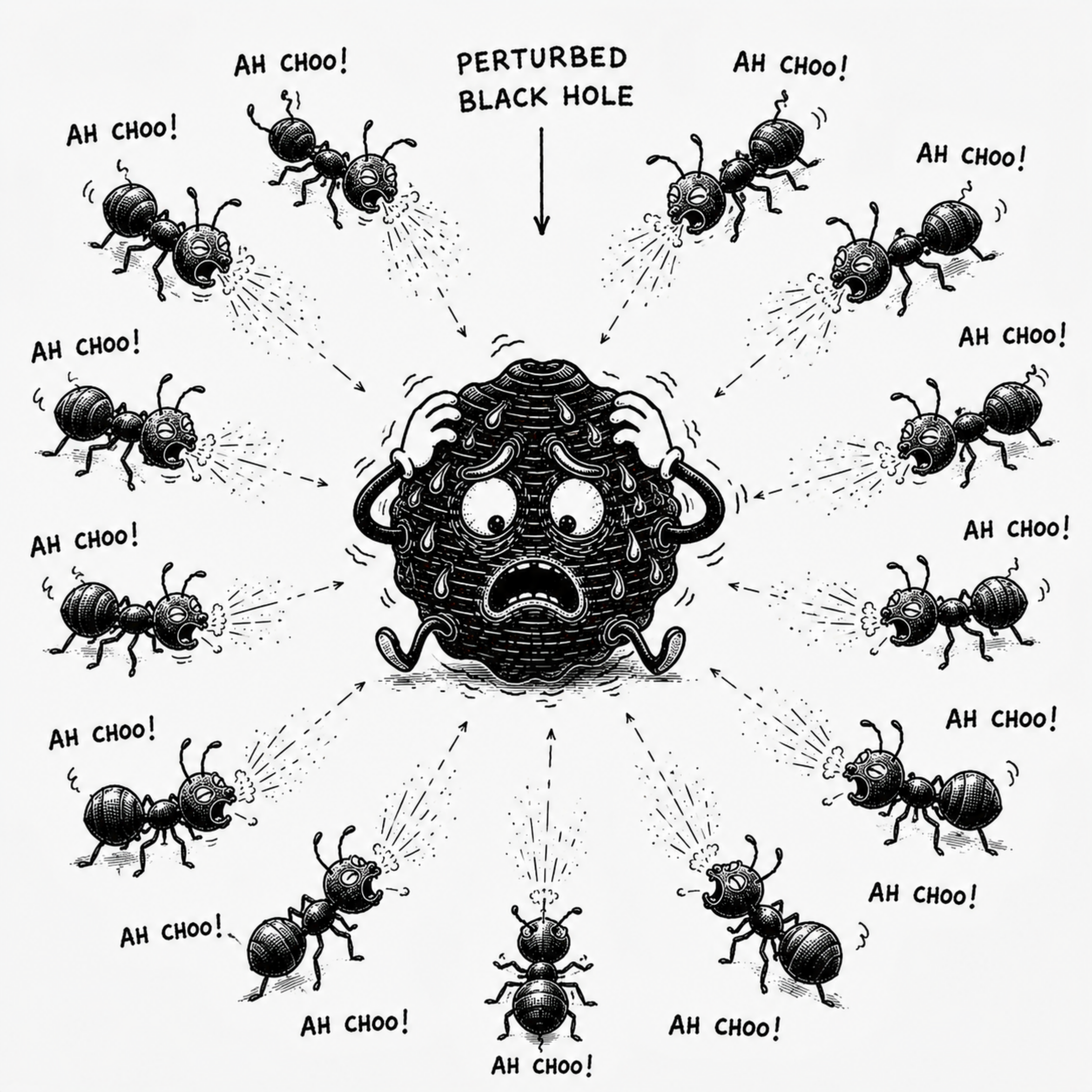
Motivation



$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \epsilon h_{\mu\nu}; \ |h_{\mu\nu}| \ll 1$$

- Persistent stochastic forcing.
- $|h_{\mu\nu}| \ll 1 \to$ linear perturbation theory applies.

Motivation

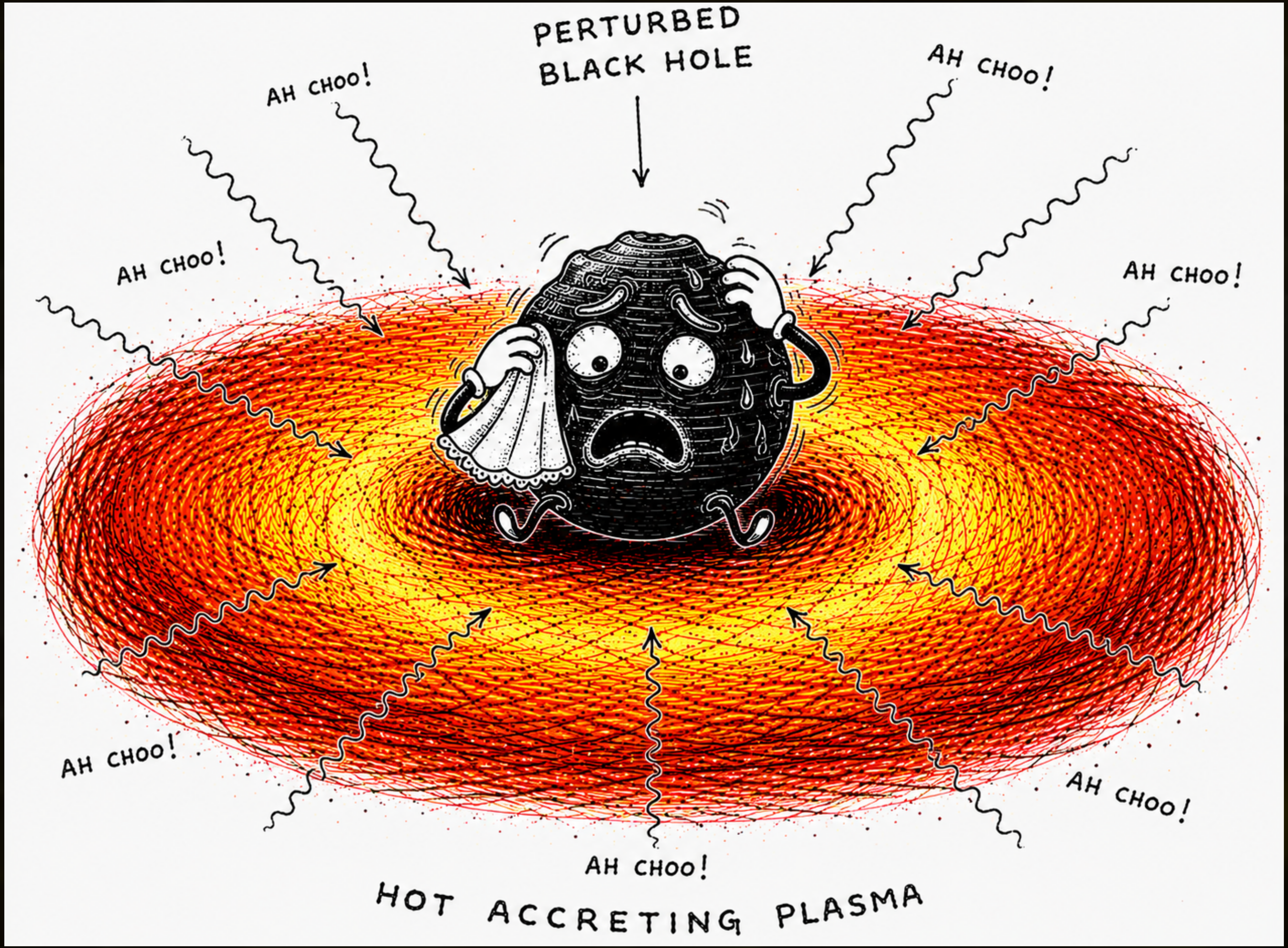


$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \epsilon h_{\mu\nu};\ |h_{\mu\nu}| \ll 1$$

- Persistent stochastic forcing.
- $|h_{\mu\nu}| \ll 1 \rightarrow$ linear perturbation theory applies.

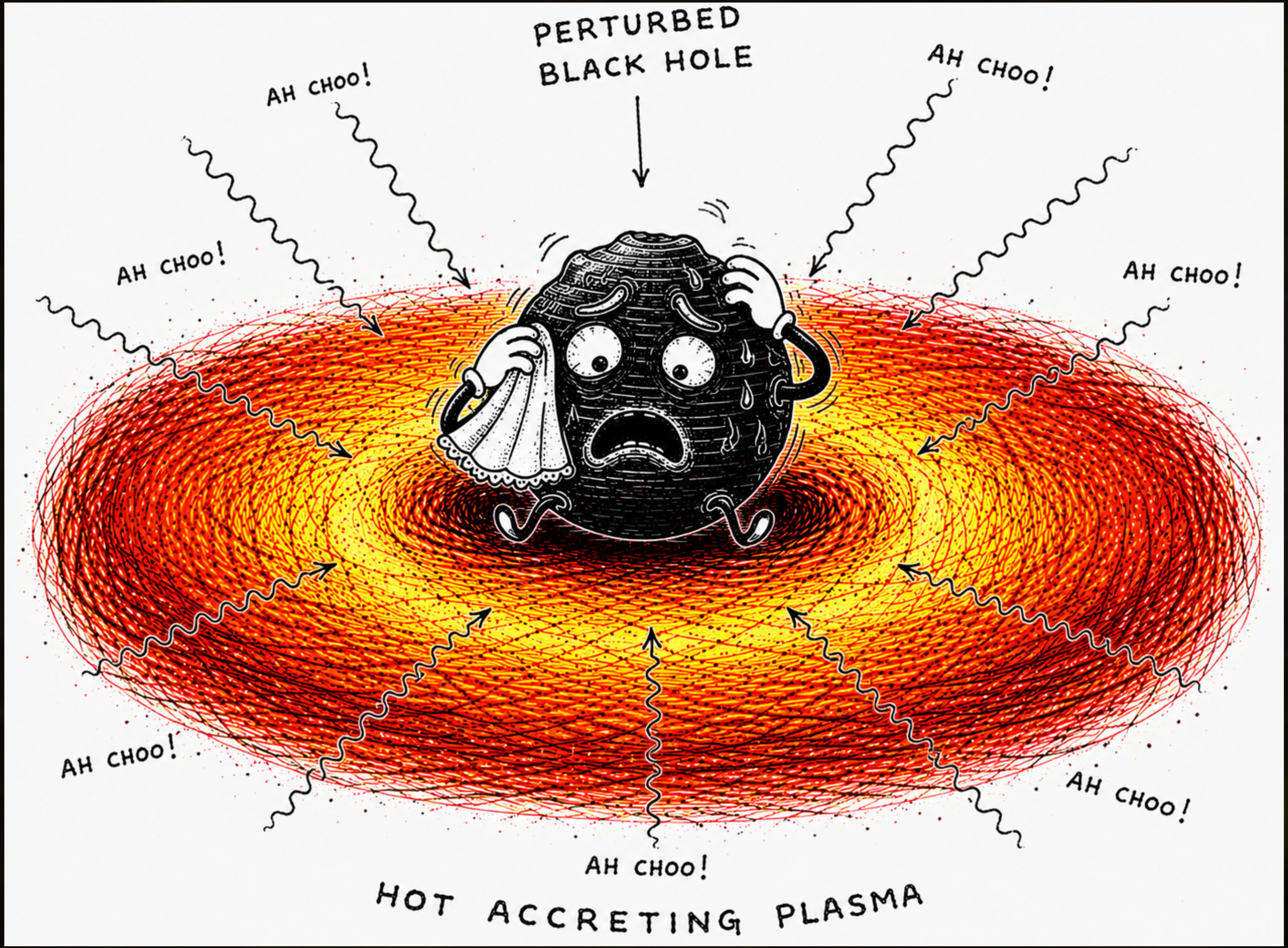
But wait...!

Motivation



PERTURBED BLACK HOLE
AH CHOO!
AH CHOO!
AH CHOO!
AH CHOO!
AH CHOO!
AH CHOO!
AH CHOO!
AH CHOO!
HOT ACCRETING PLASMA

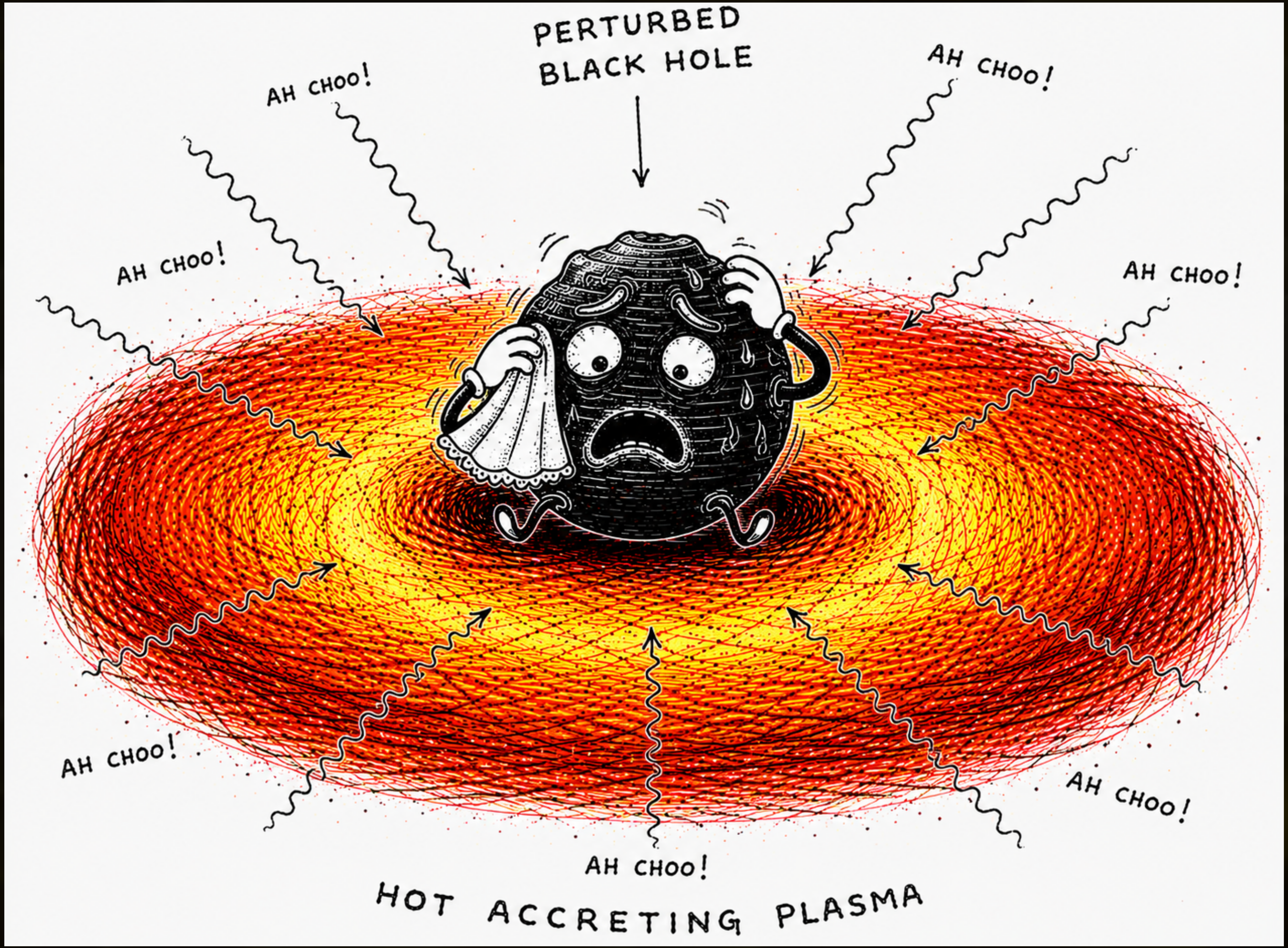
Motivation



Source of

"AH CHOO???"

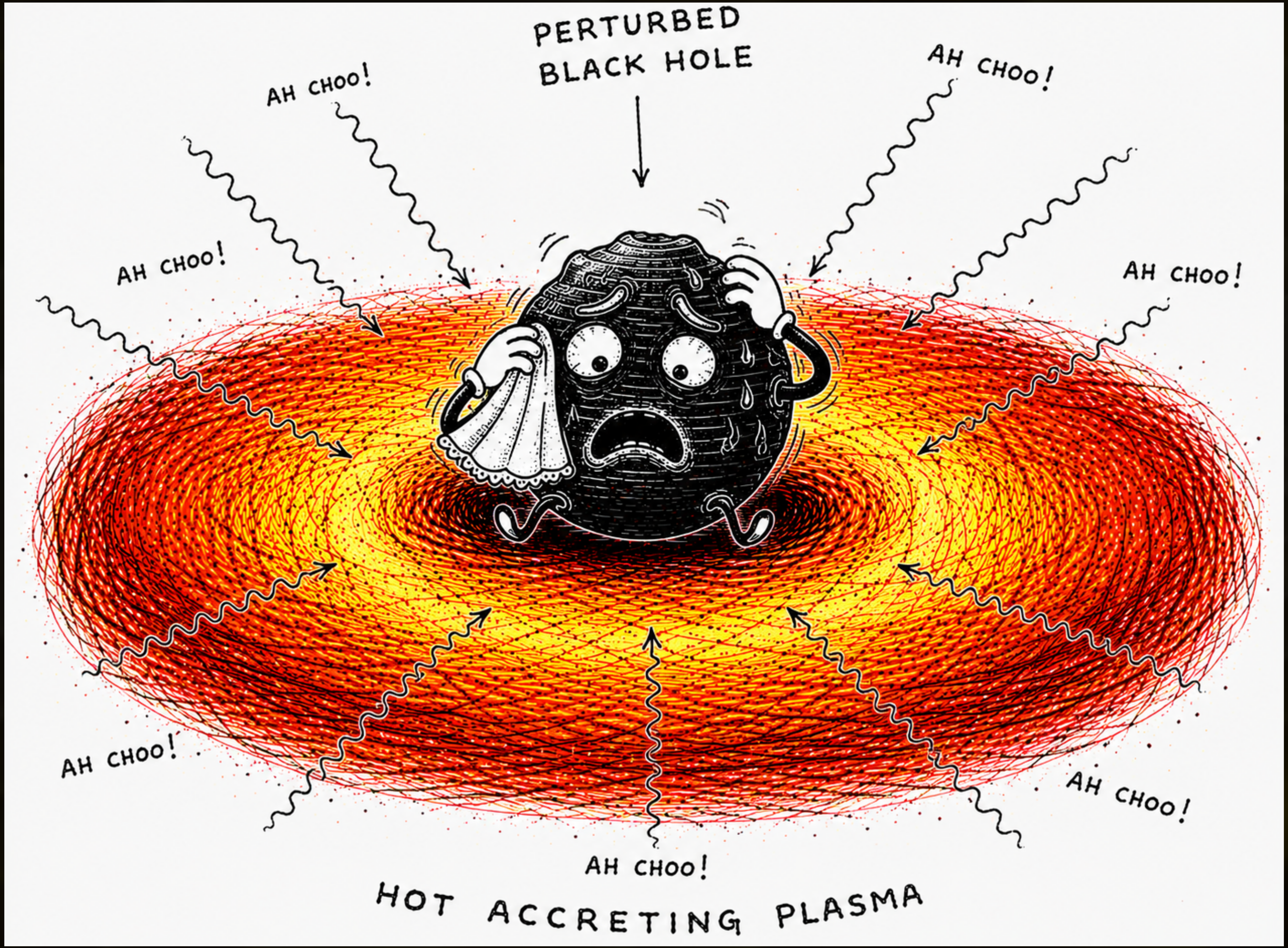
Motivation



"AH CHOO???"

Turbulence within accretion disks

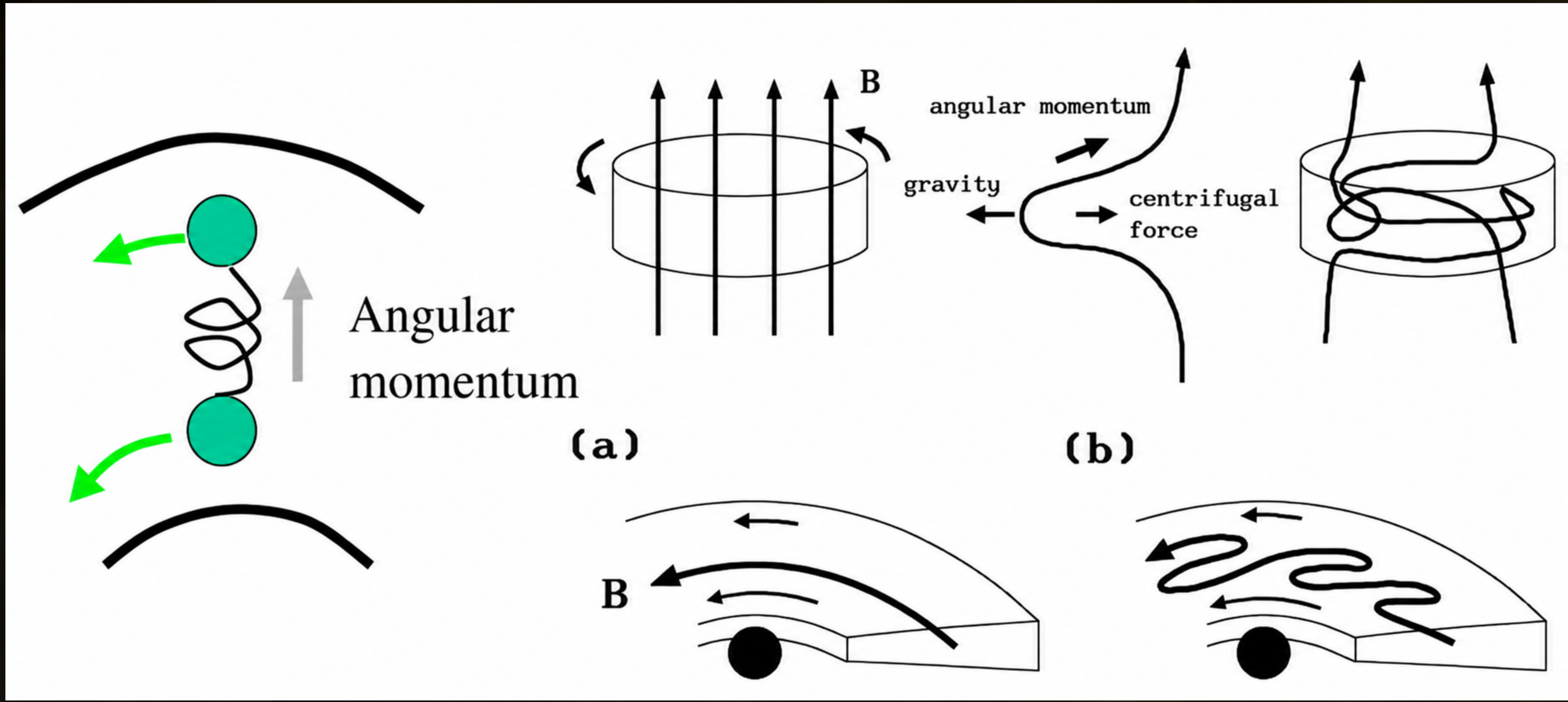
Motivation



"AH CHOO???"

MHD turbulence

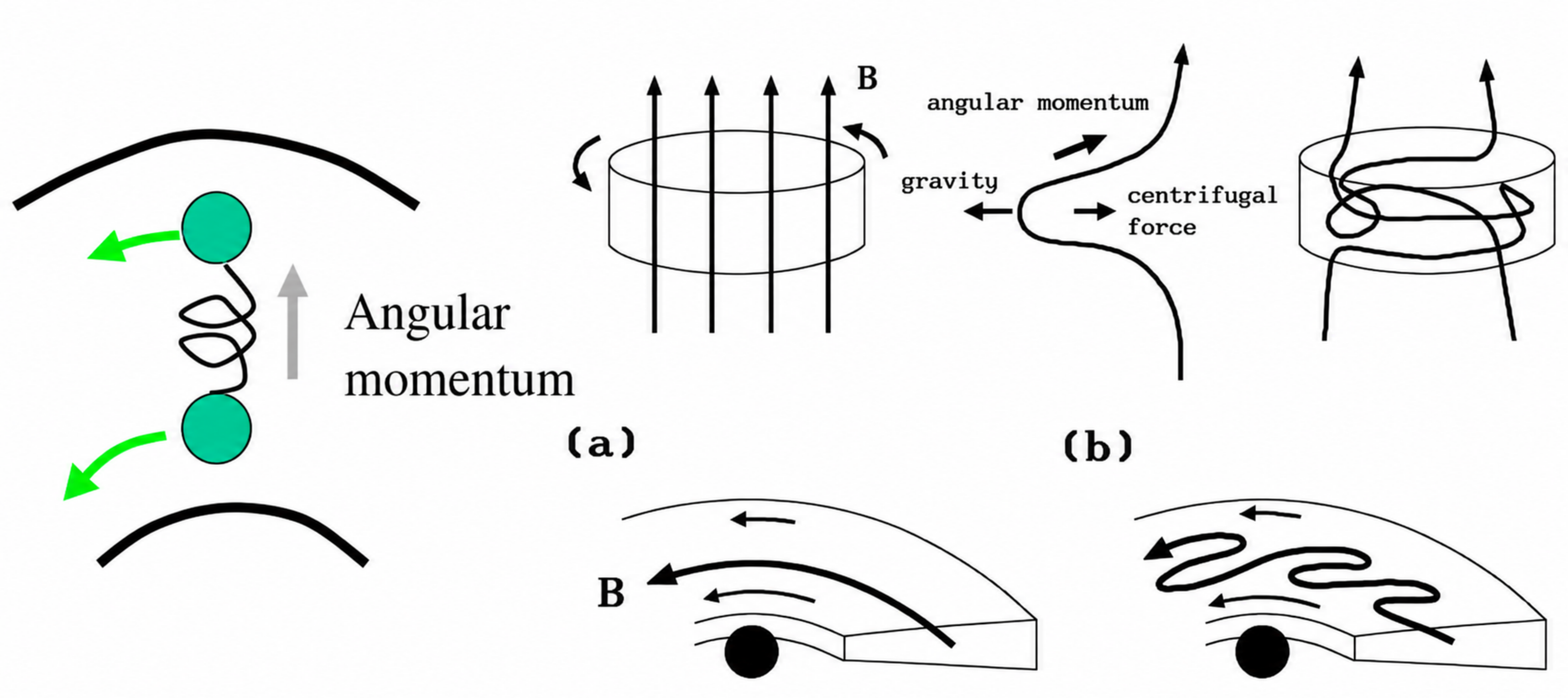
How does MHD Turbulence work?



- Differential rotation ($d\Omega/dr < 0$)
- Weak seed B

Velikov 1959; Chandrasekhar 1960; Balbus & Hawley (1991, 1998); Machida et al. 2006; Mishra et al. 2020

How does MHD Turbulence work?



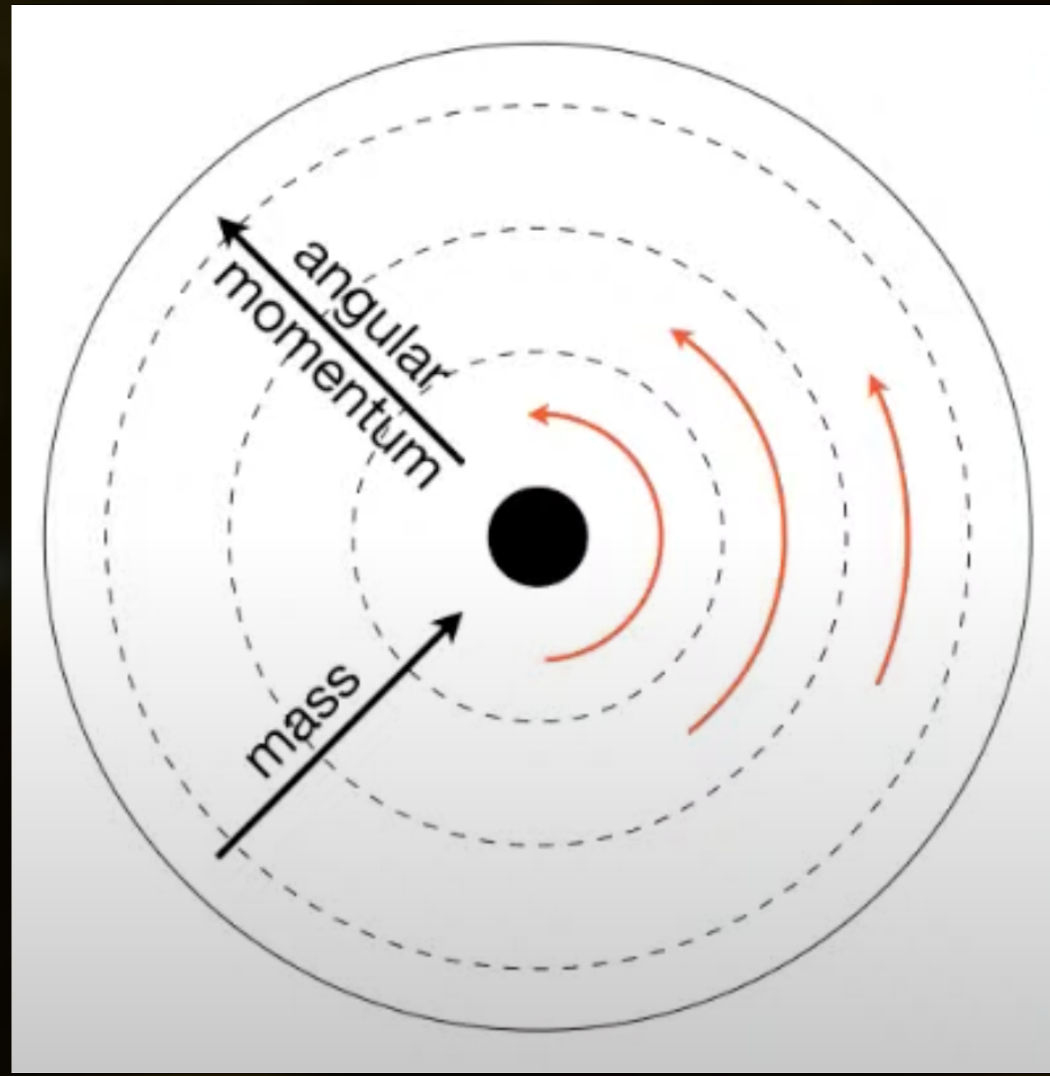
- Differential rotation ($d\Omega/dr < 0$)
- Weak seed B

$$\left.\begin{aligned} \nabla_\mu(\rho u^\mu) &= 0 \\ \nabla_\mu T^\mu_\nu &= 0 \\ \nabla_\mu {}^*F^\mu_\nu &= 0 \end{aligned}\right\}$$

Radial Stress $T_{r\phi} \sim -b_r b_\phi$

Polar Stress $T_{\theta\phi} \sim -b_\theta b_\phi$

Meridional Stress $T_{r\theta} \sim -b_r b_\theta$



Balbus & Hawley (1991, 1998); Machida et al. 2006, Mishra et al. 2020

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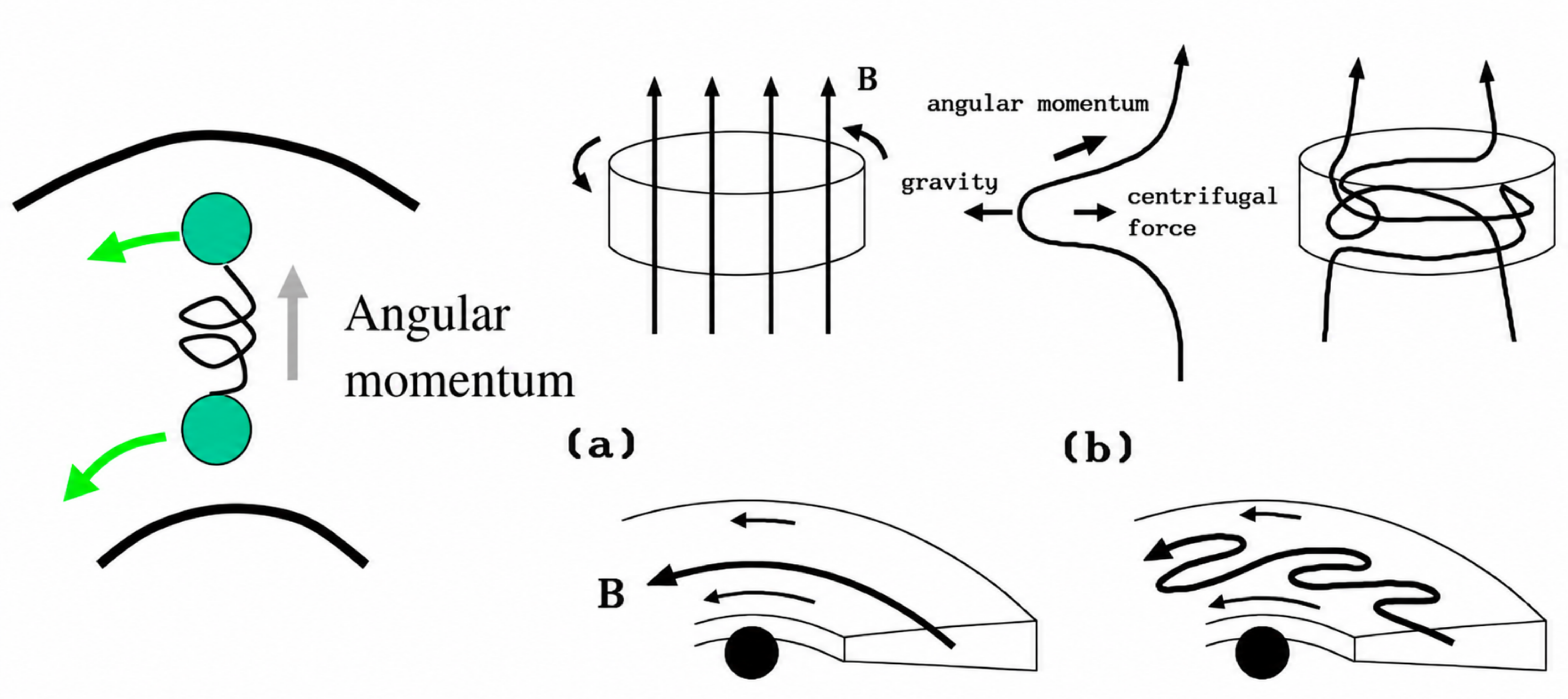

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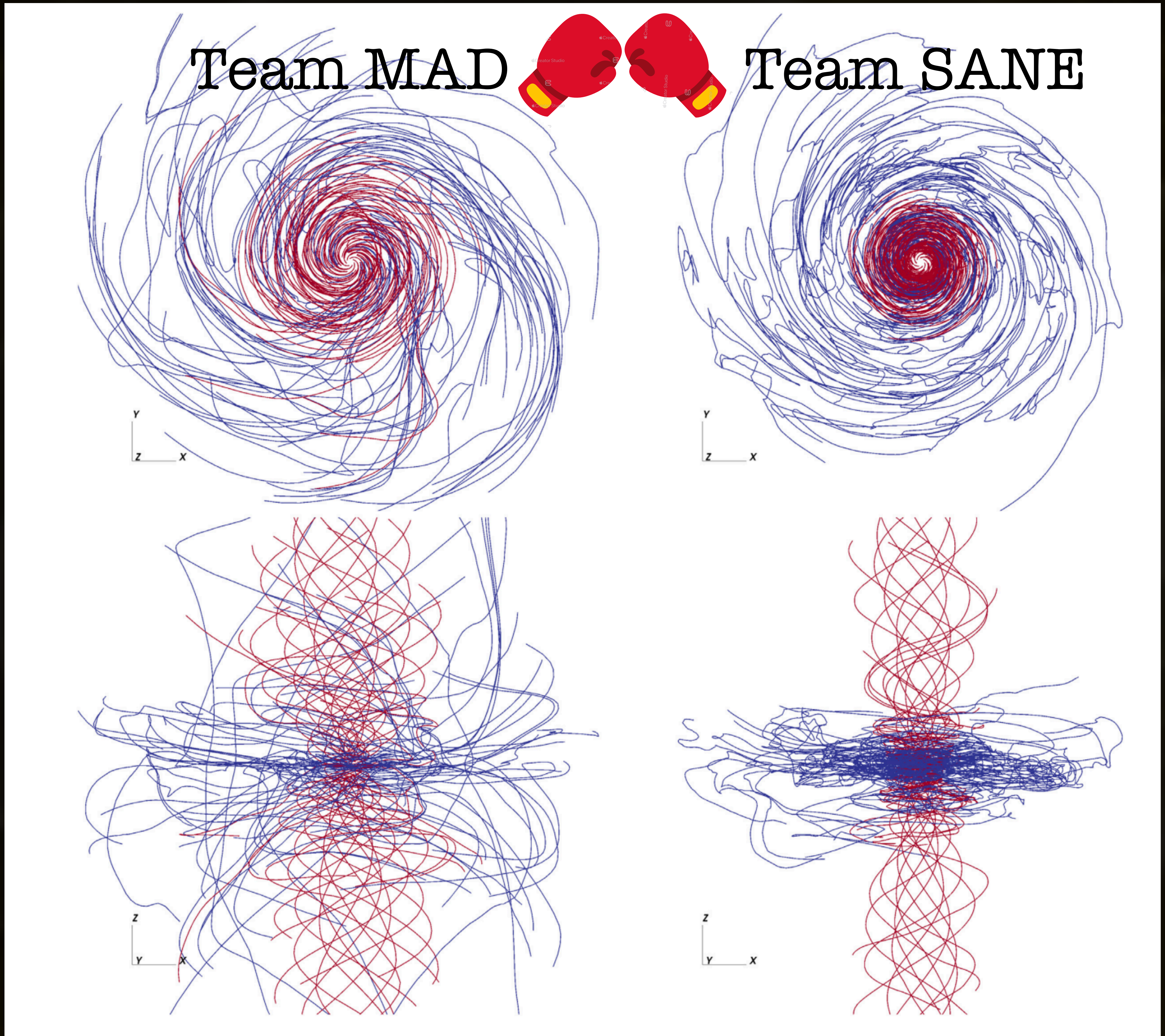
Don't forget about the Reynolds stresses….!

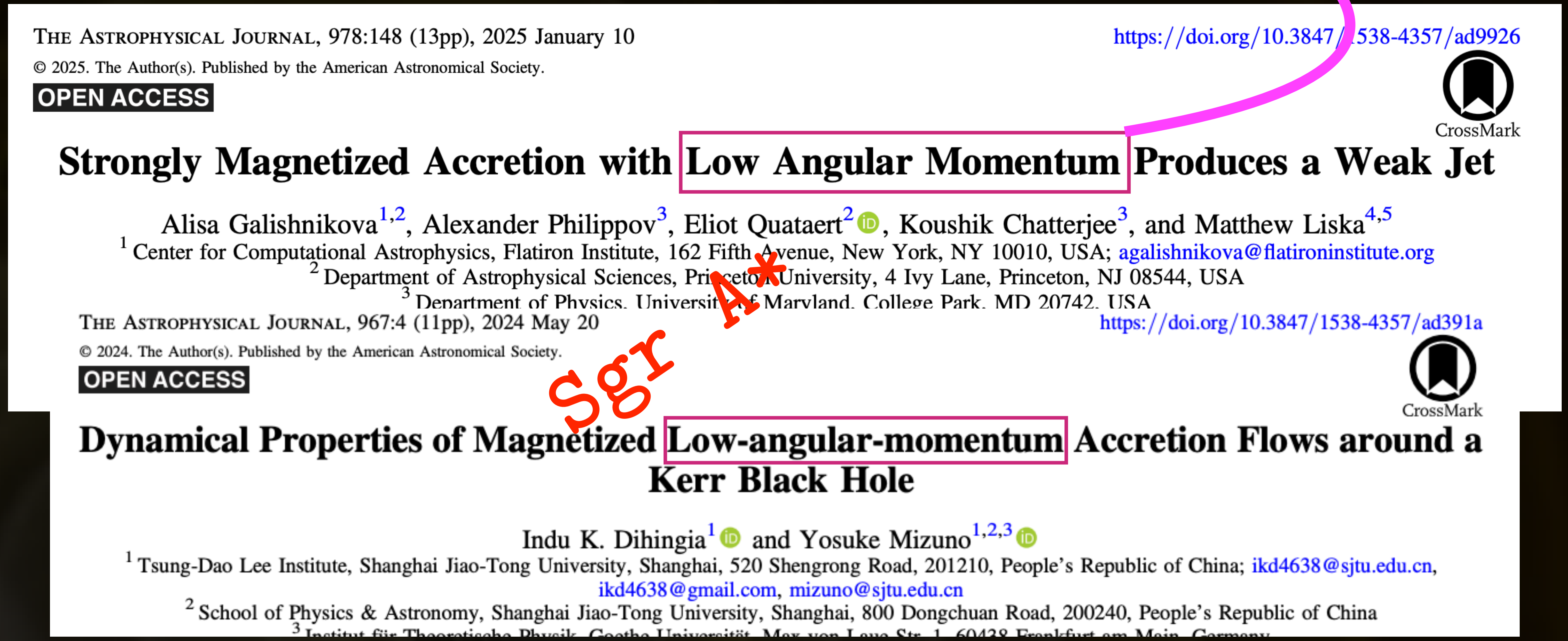
GRMHD simulations…

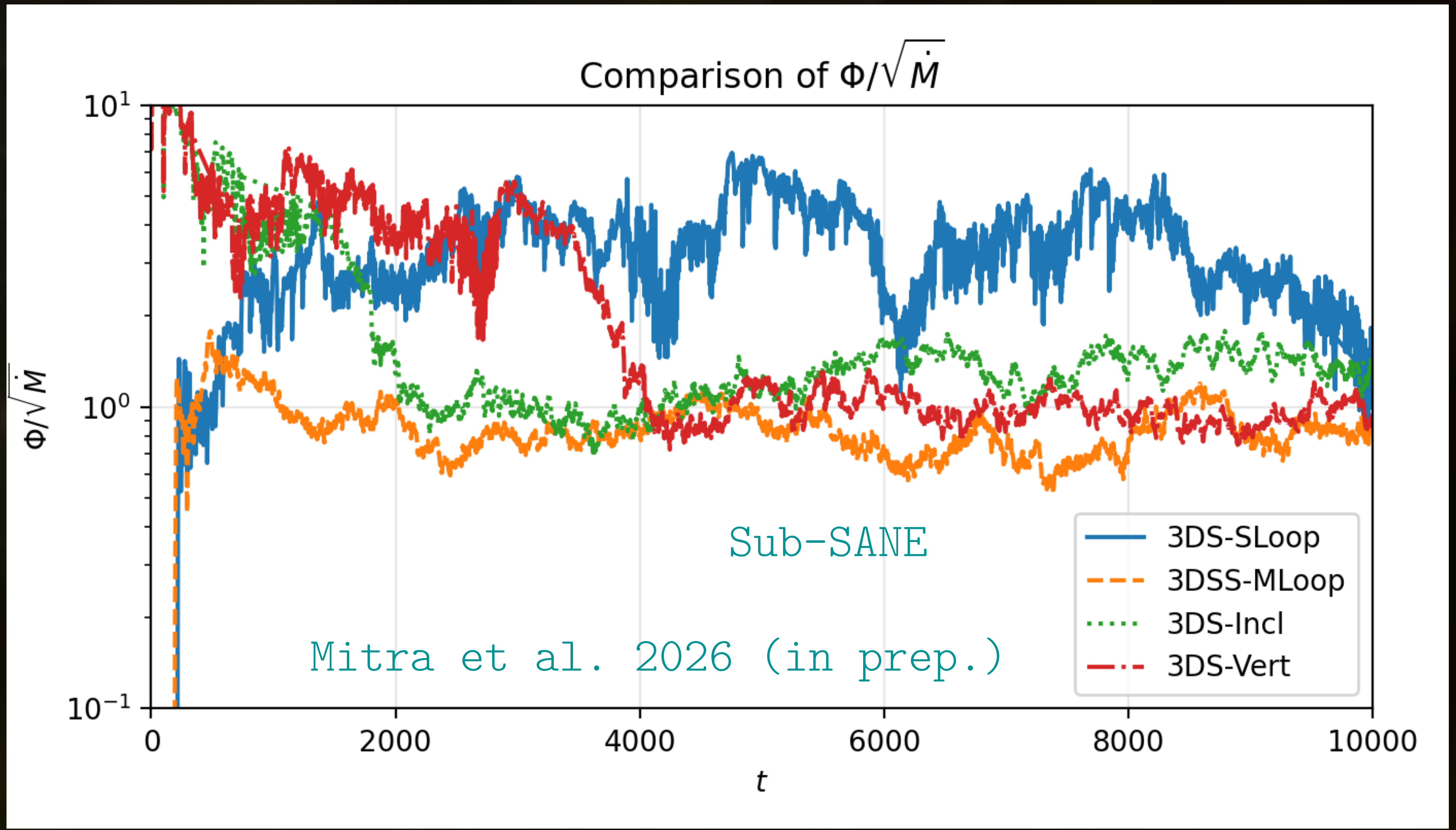
Balbus & Hawley (1991, 1998); Machida et al. 2006, Mishra et al. 2020

Role of GRMHD simulations



Take a look at S56, S22

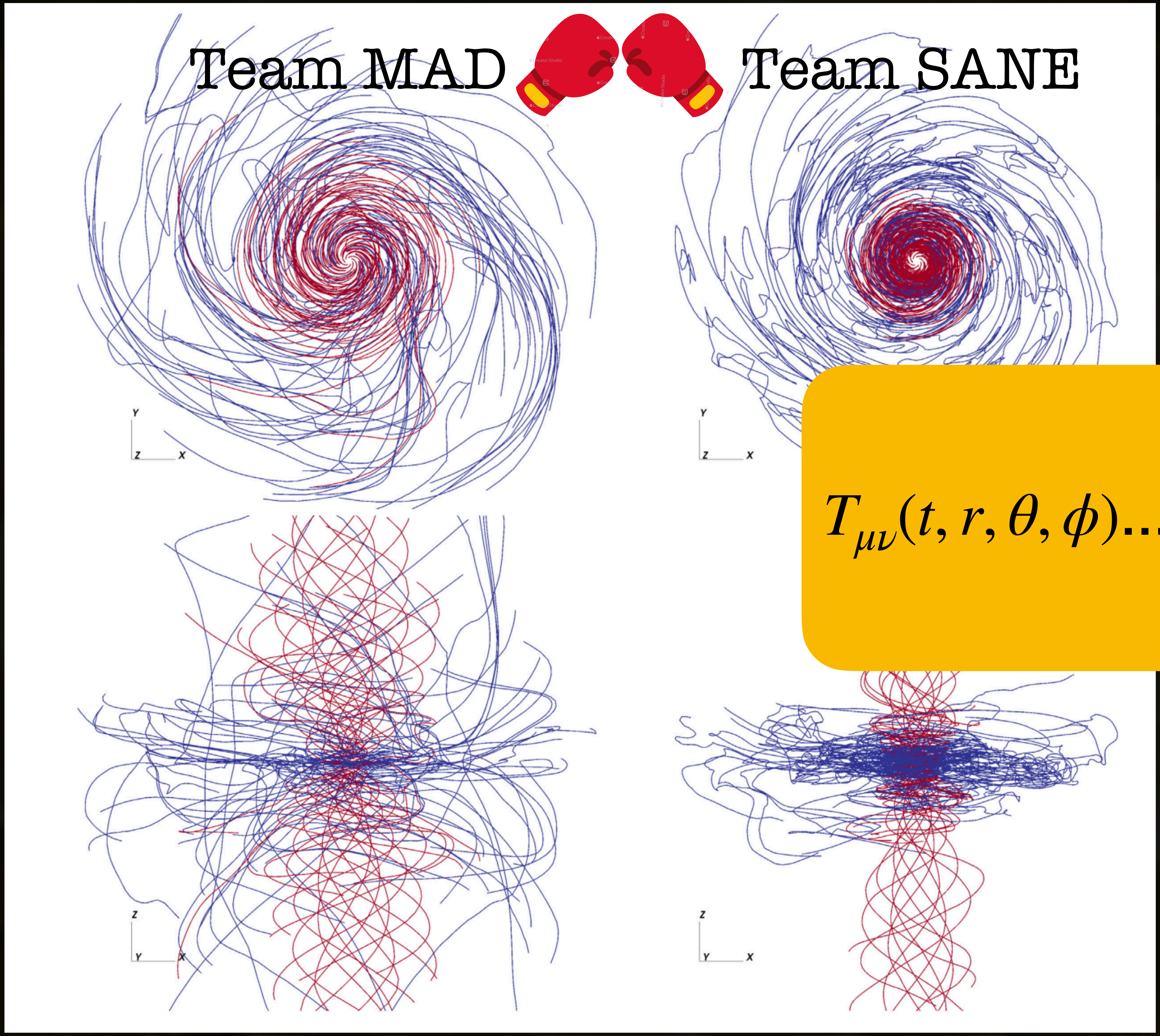


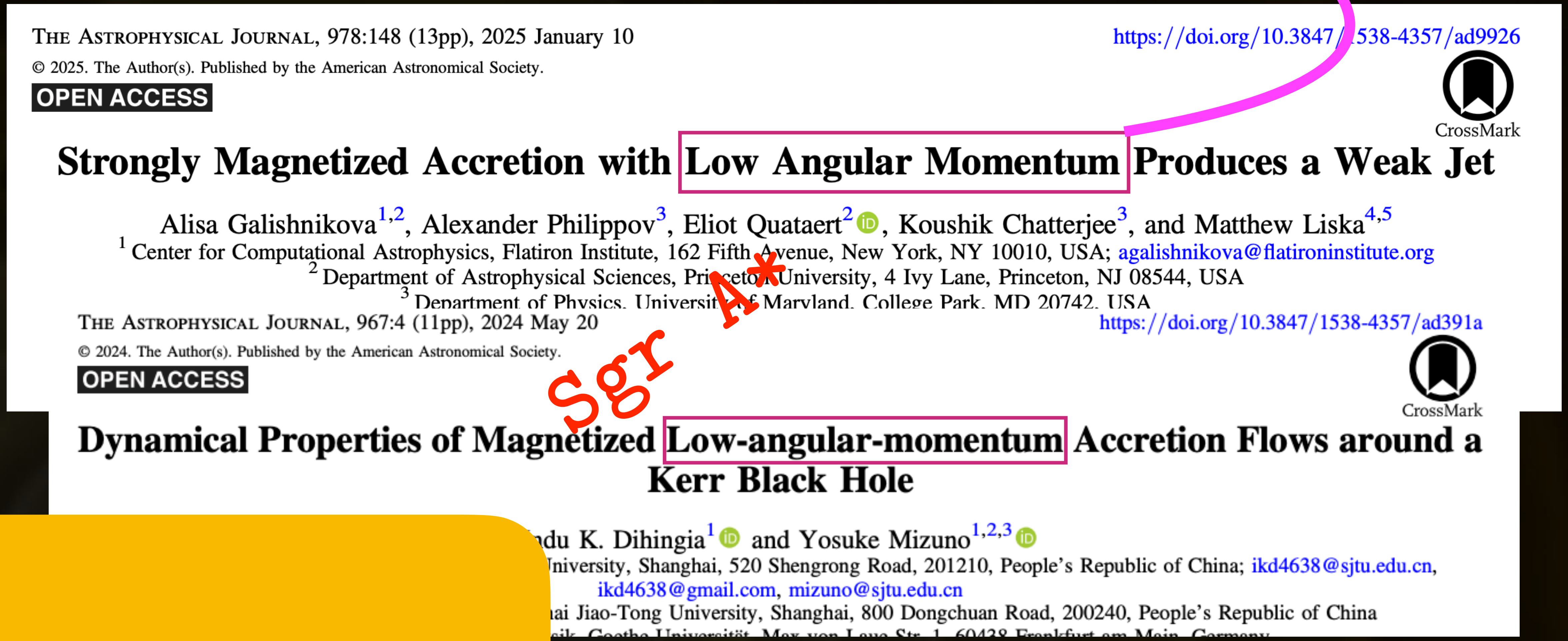


Narayan et al. 2003, Tchekhovskoy et al., 2011, Narayan et al. 2012, Ricarte et al., 2021, Chatterjee & Narayan 2022

Role of GRMHD simulations

Take a look at S56, S22





The Astrophysical Journal, 978:148 (13pp), 2025 January 10
https://doi.org/10.3847/1538-4357/ad9926

Strongly Magnetized Accretion with Low Angular Momentum Produces a Weak Jet

Alisa Galishnikova[1,2], Alexander Philippov[3], Eliot Quataert[2], Koushik Chatterjee[3], and Matthew Liska[4,5]
[1] Center for Computational Astrophysics, Flatiron Institute, 162 Fifth Avenue, New York, NY 10010, USA; agalishnikova@flatironinstitute.org
[2] Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08544, USA
[3] Department of Physics, University of Maryland, College Park, MD 20742, USA

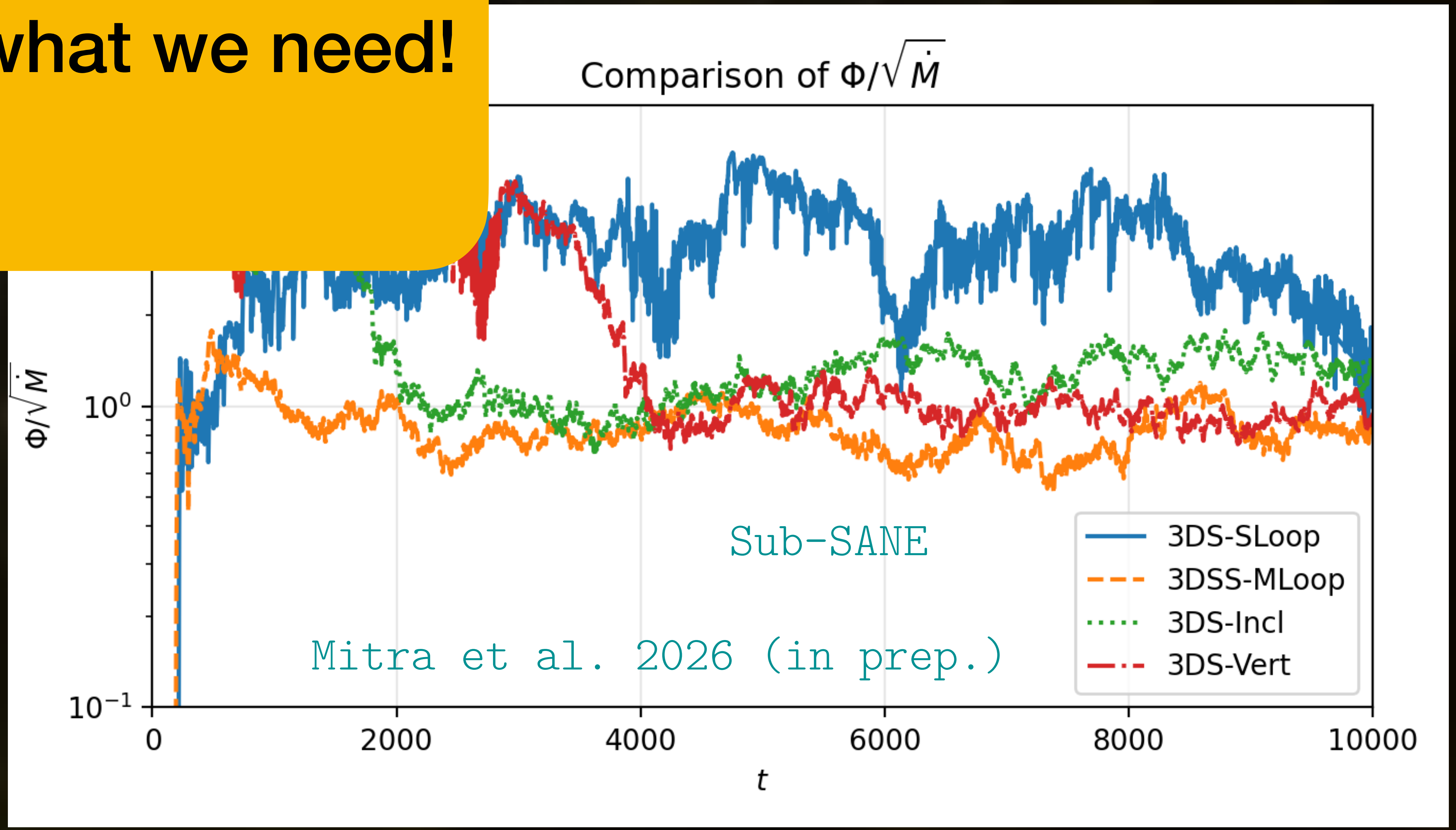
The Astrophysical Journal, 967:4 (11pp), 2024 May 20
https://doi.org/10.3847/1538-4357/ad391a

Dynamical Properties of Magnetized Low-angular-momentum Accretion Flows around a Kerr Black Hole

...du K. Dihingia[1] and Yosuke Mizuno[1,2,3]
...University, Shanghai, 520 Shengrong Road, 201210, People's Republic of China; ikd4638@sjtu.edu.cn, ikd4638@gmail.com, mizuno@sjtu.edu.cn
...ai Jiao-Tong University, Shanghai, 800 Dongchuan Road, 200240, People's Republic of China

Sgr A*

$T_{\mu\nu}(t, r, \theta, \phi)$... is what we need!



Narayan et al. 2003, Tchekhovskoy et al., 2011, Narayan et al. 2012, Ricarte et al., 2021, Chatterjee & Narayan 2022

Where do we connect to GW?

Teukolsky's Master equation…..

$$\Delta^2\partial_r(\Delta^{-1}\partial_r\Psi) - \left[\frac{(r^2+a^2)^2}{\Delta} - a^2\sin^2\theta\right]\partial_{tt}\Psi + 4\left[r - \frac{M(r^2-a^2)}{\Delta} + ia\cos\theta\right]\partial_t\Psi + \frac{1}{\sin\theta}\partial_\theta(\sin\theta\partial_\theta\Psi)$$
$$+ \left[\frac{1}{\sin^2\theta} - \frac{a^2}{\Delta}\right]\partial_{\phi\phi}\Psi - 4\left[\frac{a(r-M)}{\Delta} + \frac{i\cos\theta}{\sin^2\theta}\right]\partial_\phi\Psi - (4\cot^2\theta+2)\Psi - \frac{4Mar}{\Delta}\partial_{t\phi}\Psi = -4\pi\underbrace{(r^2+a^2\cos^2\theta)T}_{\text{Forcing}}$$

$$\Psi = (r - ia\cos\theta)\Psi_4$$

$$\Psi_4 = \frac{1}{2}\left(\frac{\partial^2 h_+}{\partial t^2} - i\frac{\partial^2 h_\times}{\partial t^2}\right)$$

$$T \equiv n^\mu n^\nu T_{\mu\nu} + \ldots +$$

Teukolsky (1972, 1973); Chen et al. 2025; Mitra et al. 2026 (in prep.)

Where do we connect to GW?

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$$+\left[\frac{1}{\sin^2\theta} - \frac{a^2}{\Delta}\right]\partial_{\phi\phi}\Psi - 4\left[\frac{a(r-M)}{\Delta} + \frac{i\cos\theta}{\sin^2\theta}\right]\partial_\phi\Psi - (4\cot^2\theta + 2)\Psi - \frac{4Mar}{\Delta}\partial_{t\phi}\Psi = -4\pi\underbrace{(r^2 + a^2\cos^2\theta)T}_{\text{Forcing}}$$

$$\ddot{x} + 2\gamma\dot{x} + \omega_0^2 x = F(t)$$

$$\Psi = (r - ia\cos\theta)\Psi_4$$

$$\Psi_4 = \frac{1}{2}\left(\frac{\partial^2 h_+}{\partial t^2} - i\frac{\partial^2 h_\times}{\partial t^2}\right)$$

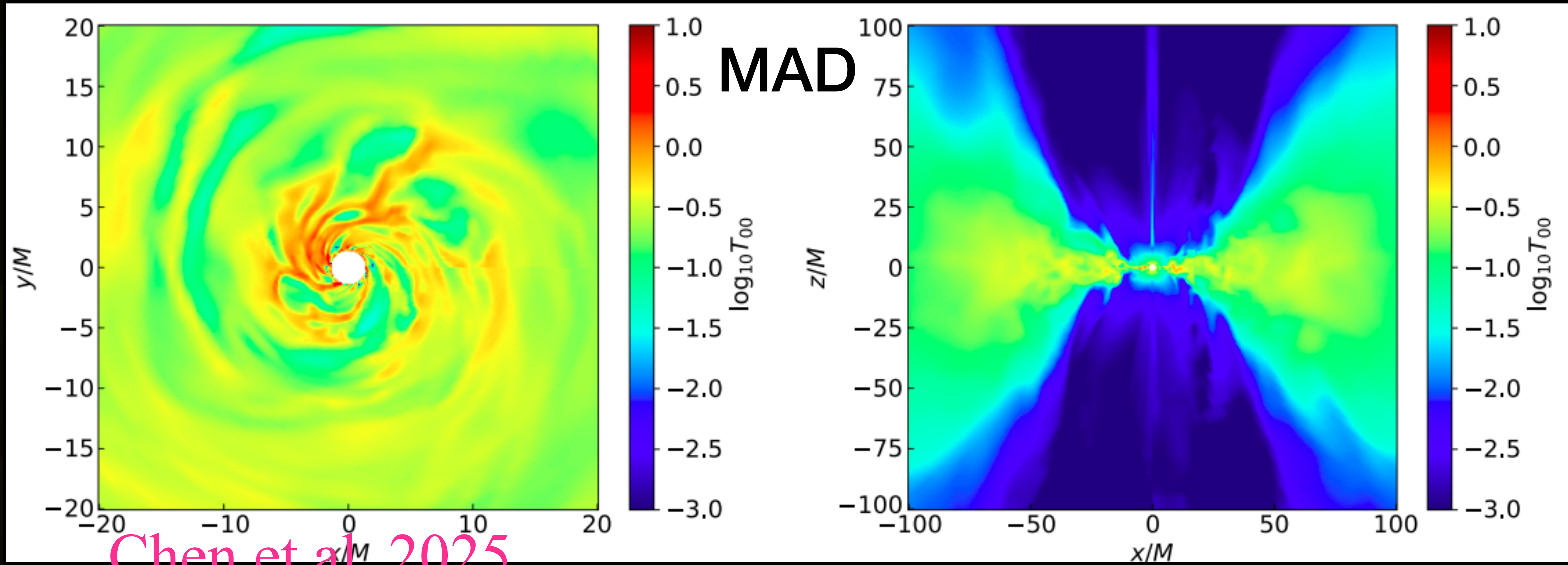
$$T \equiv n^\mu n^\nu T_{\mu\nu} + \ldots +$$

Ringing a Bell—> Bound system —> Normal Modes

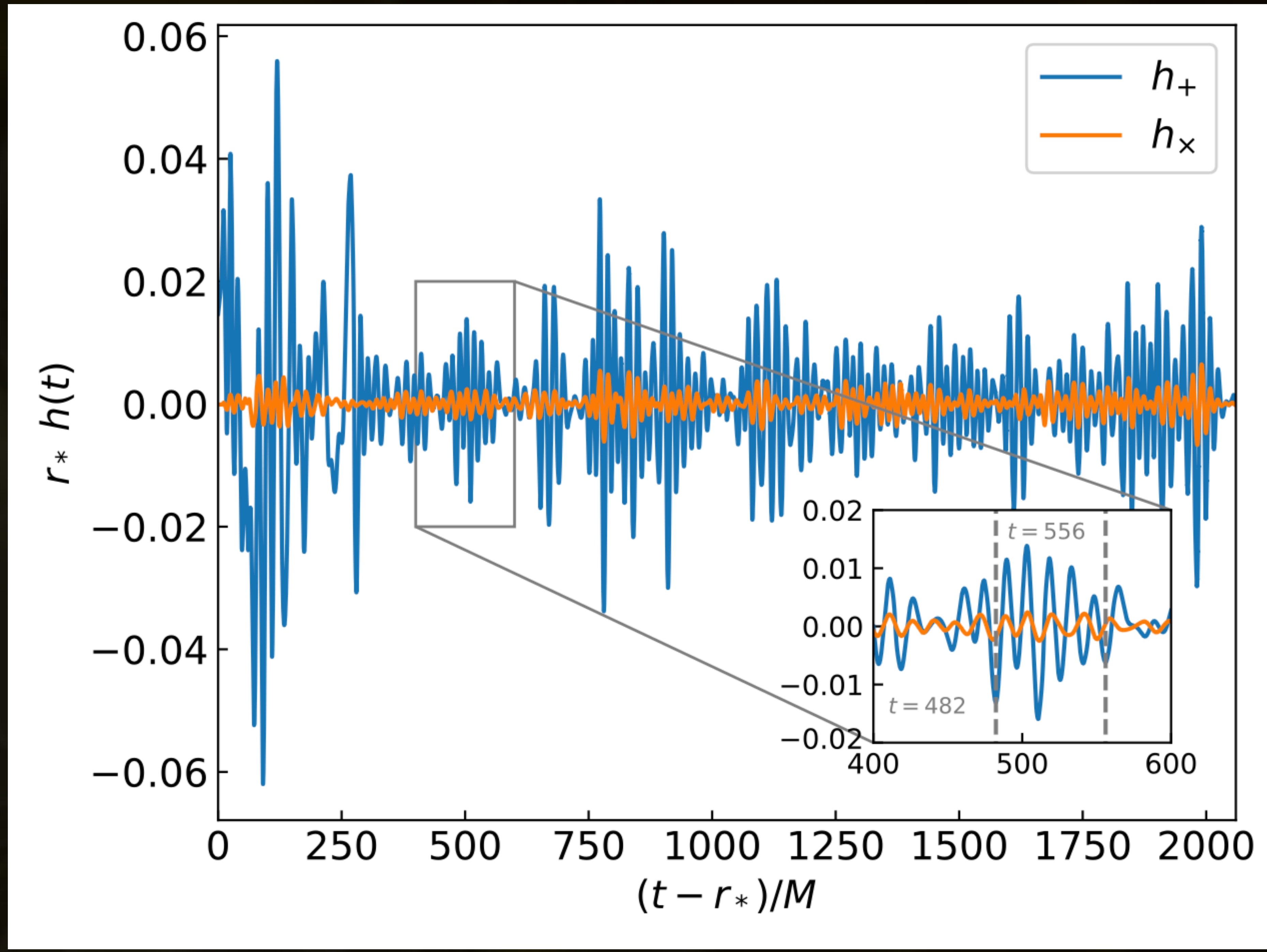
Ringing a BH —> Open system —> Quasi-Normal Modes

Teukolsky (1972, 1973); Mitra et al. 2026 (in prep.)

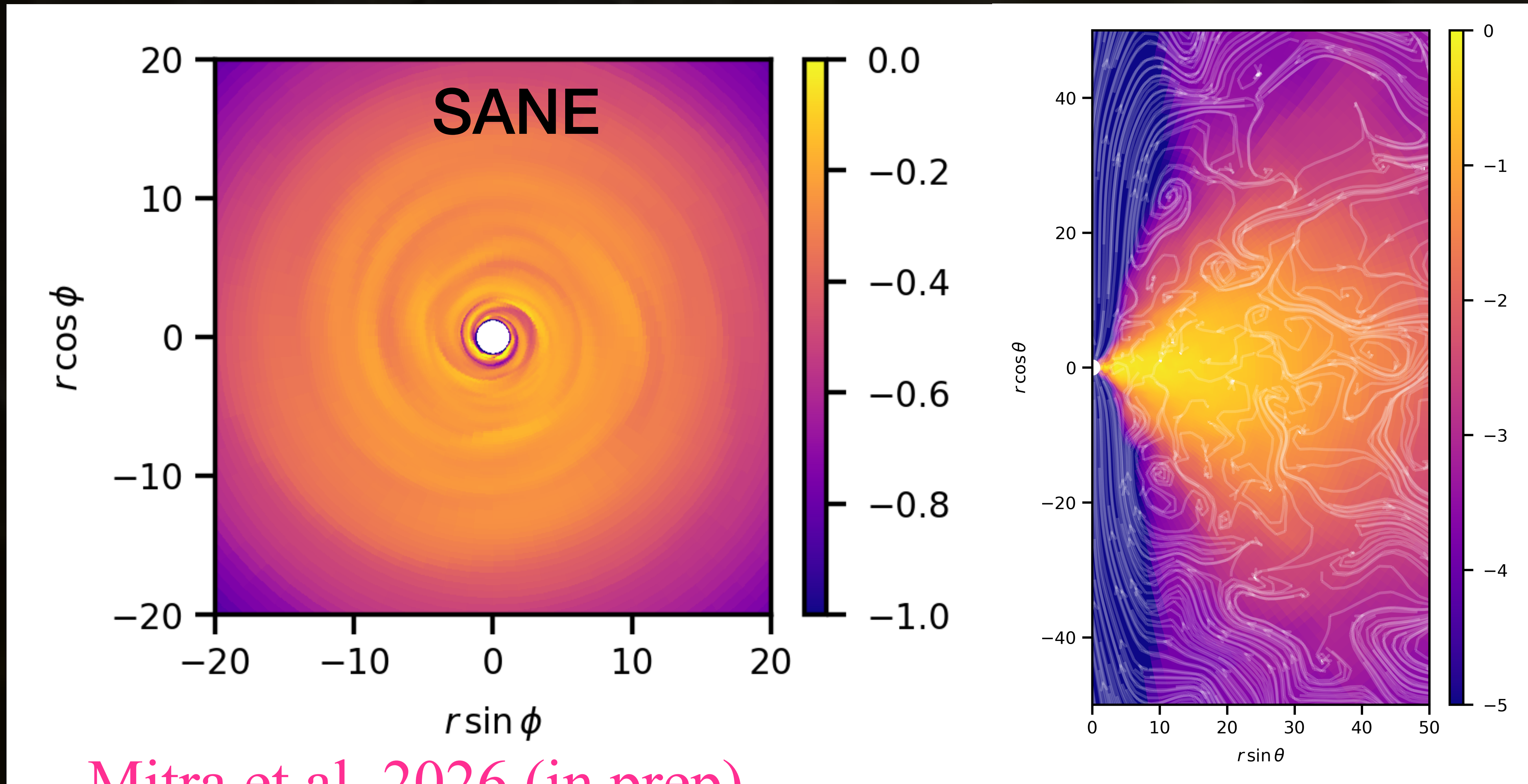
SGWBs from turbulent disks



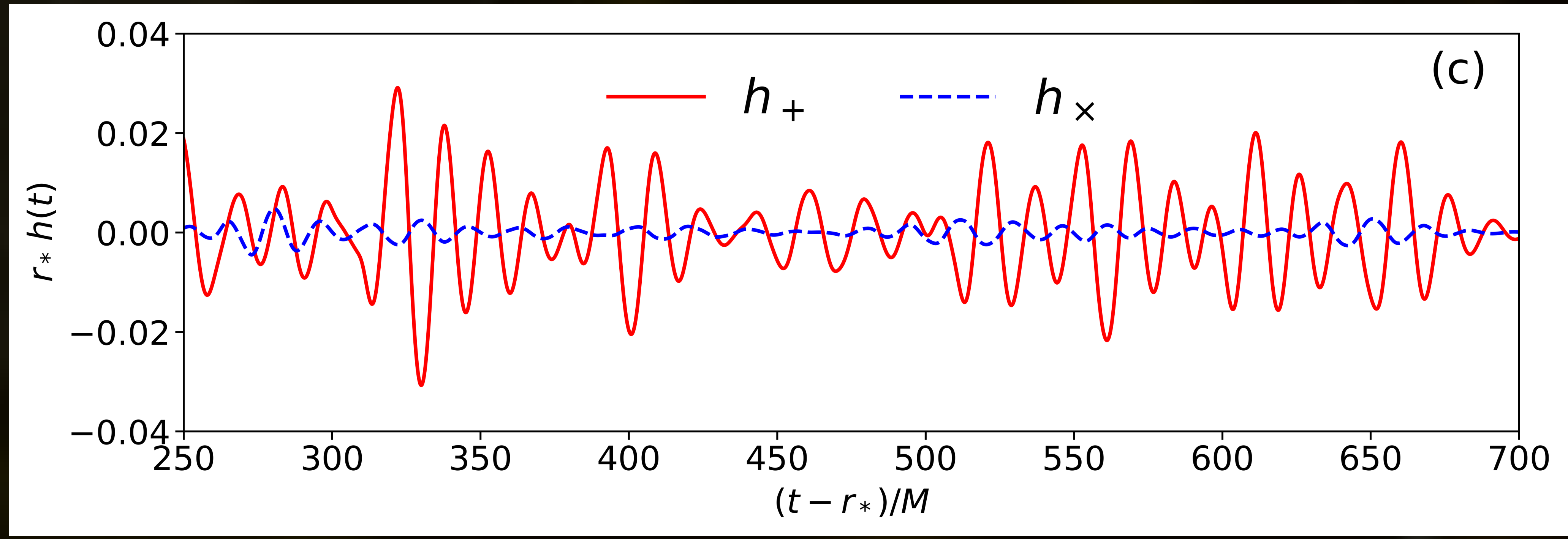
Chen et al. 2025



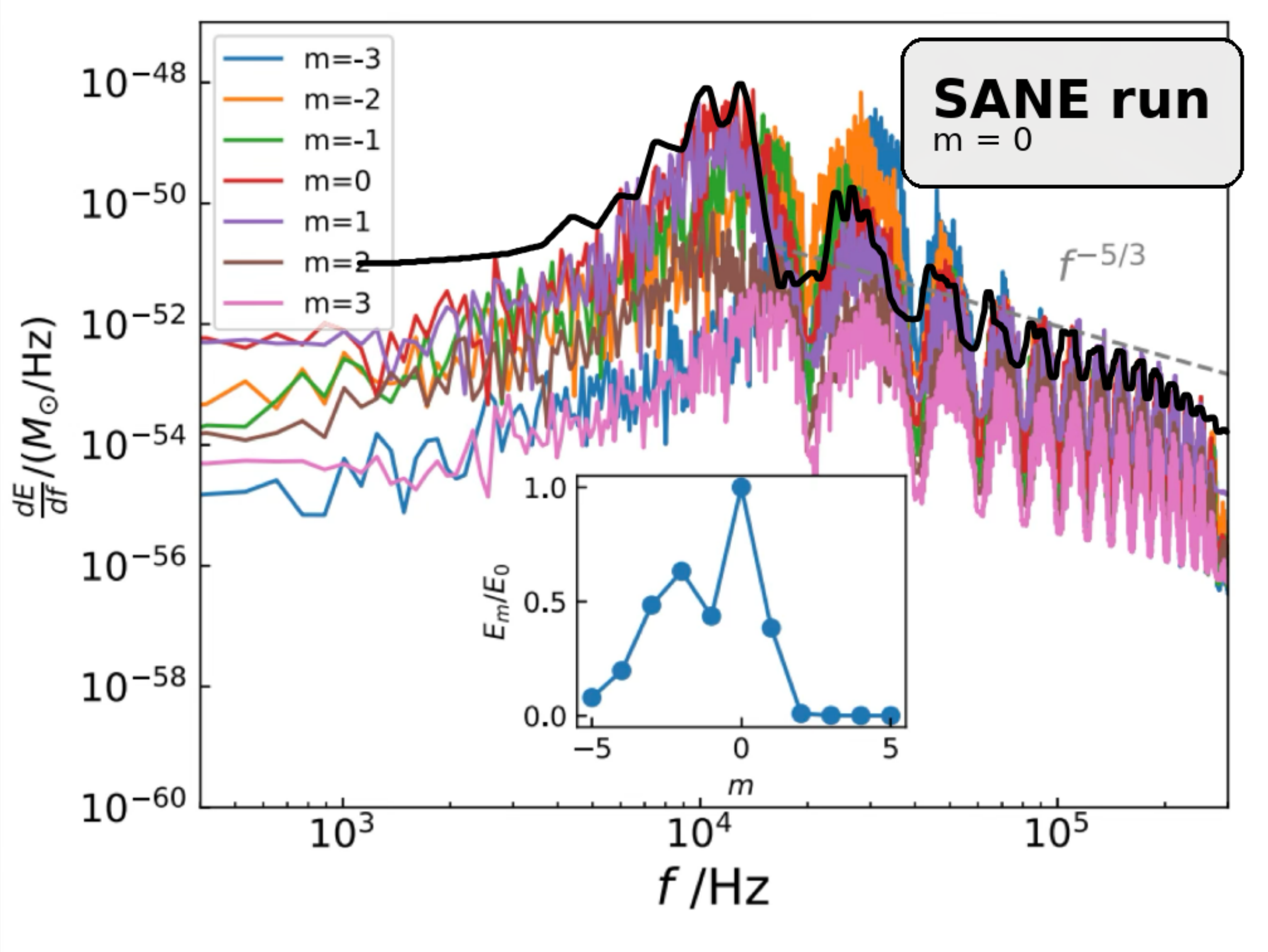
$$M\omega_{\mathrm{QNM}} = 0.42 - 0.0765i$$



Mitra et al. 2026 (in prep)



Energy spectrum of SGWB from turbulent disks….!



$$dE/df \to \Omega_{\rm GW}$$

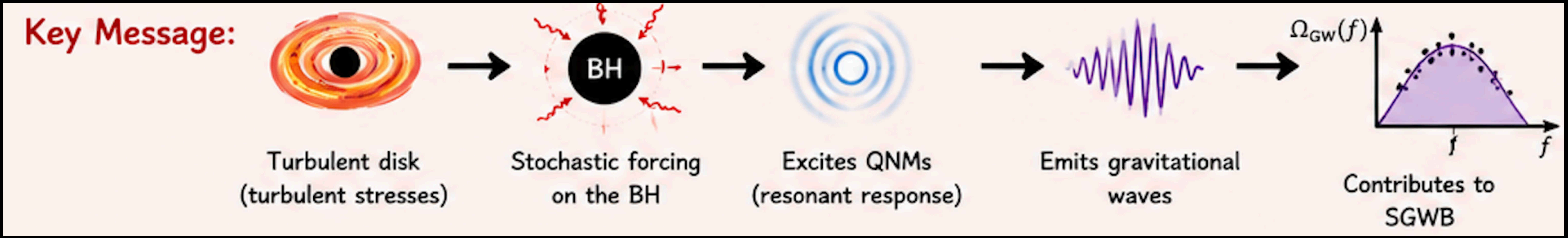
- More results will be out soon….!

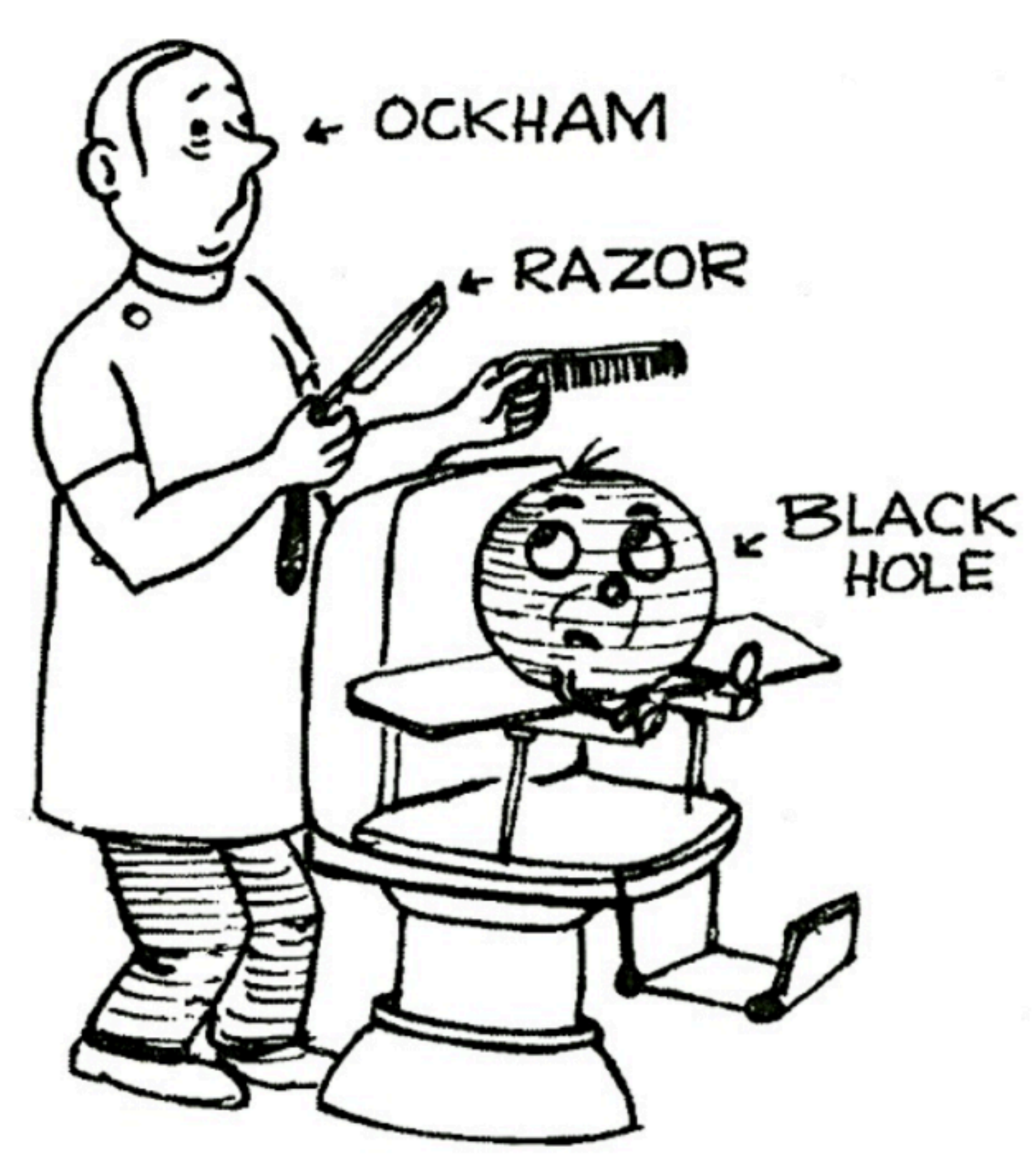
Chen et al. 2025; Mitra et al. 2026 (in prep.)

Summary

- Turbulent Maxwell stresses continuously perturb the black hole. The black hole reacts by ringing in its characteristic quasi-normal modes.

- SGWB will help in constraining the SMBH population models.





Thank You.