Viscous torque in turbulent magnetized AGN accretion disks and its effects on EMRI’s gravitational waves

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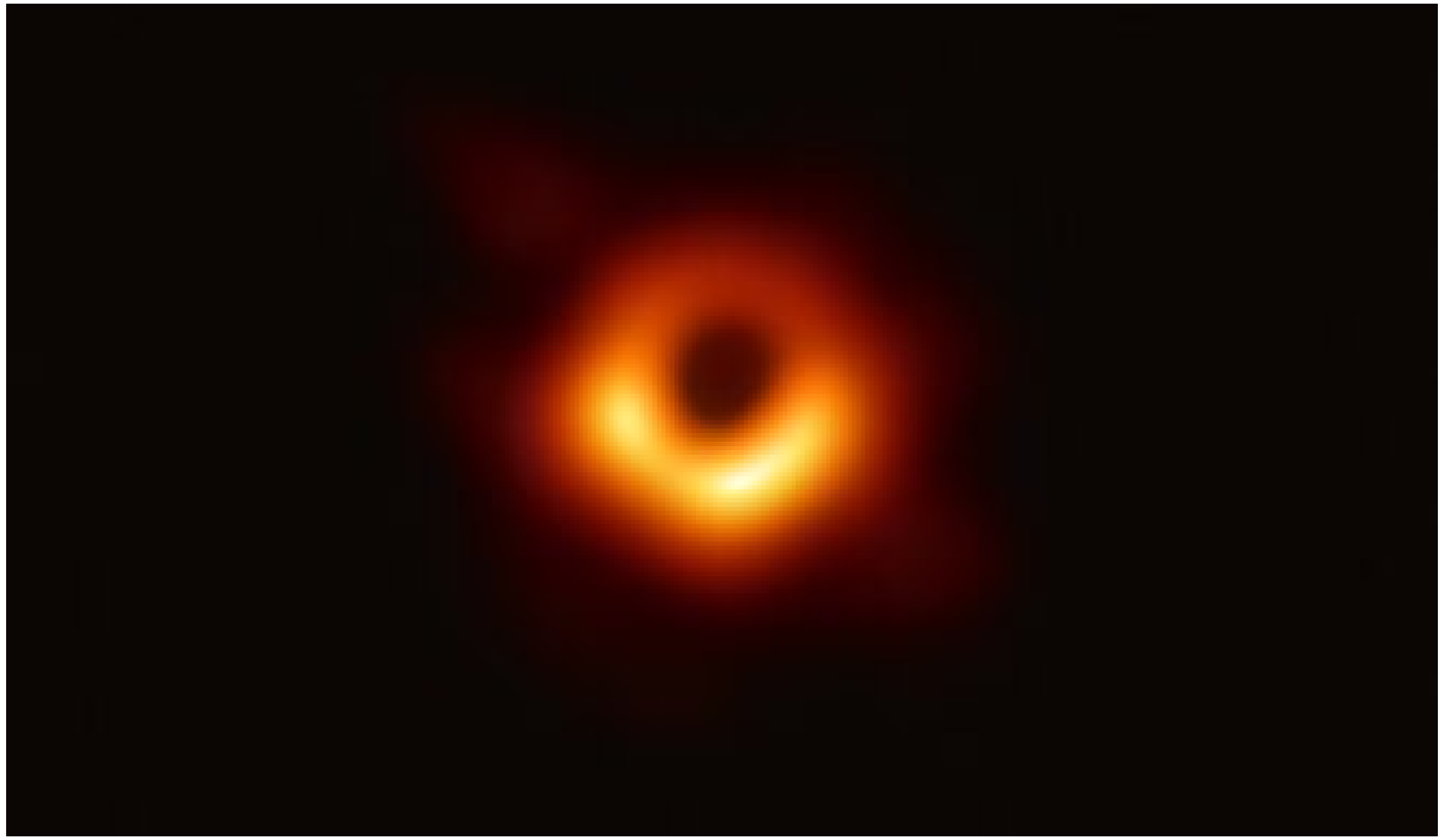
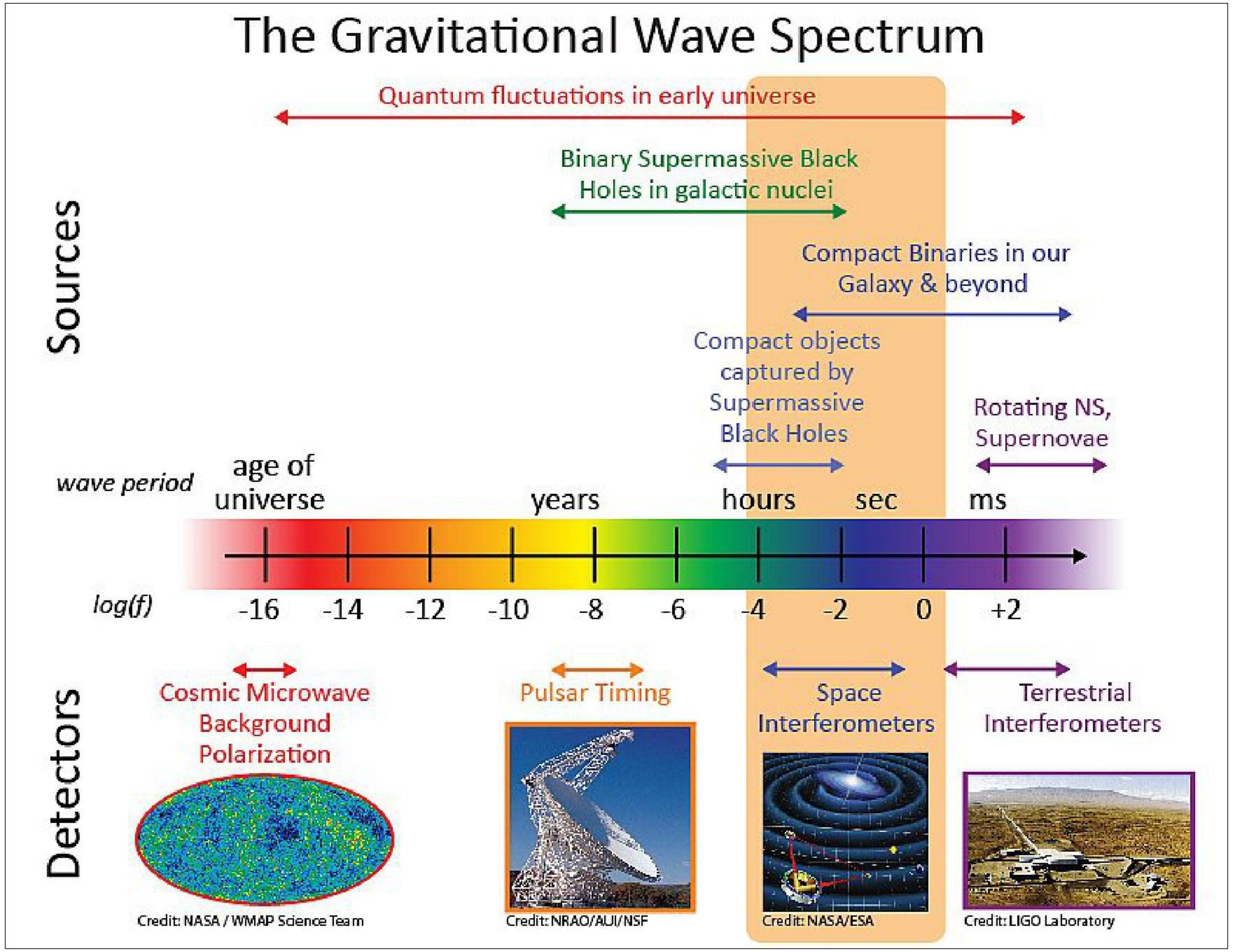
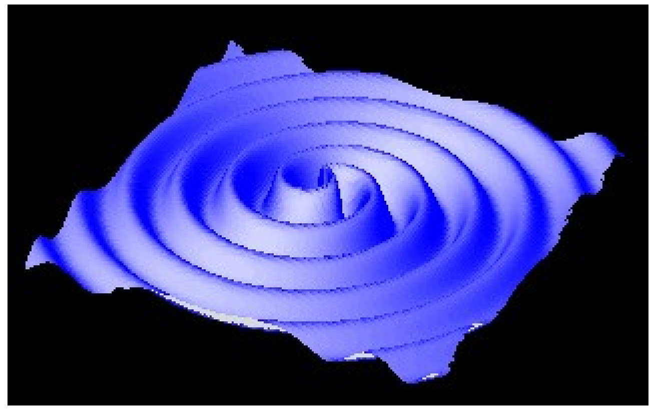


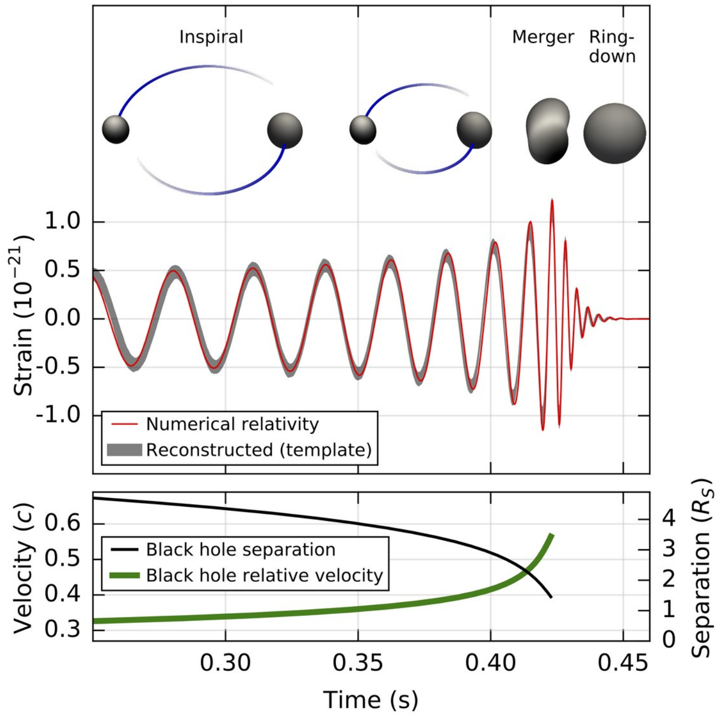
Black hole horizon region in the center of galaxy M87, imaged by Event Horizon Telescope

Active Galactic Nucleus (AGN)

- Brightness of the nucleus is orders of magnitude larger than the light emitted by all stars
- Powered by accretion of gas onto a supermassive black hole







Gravitational waves

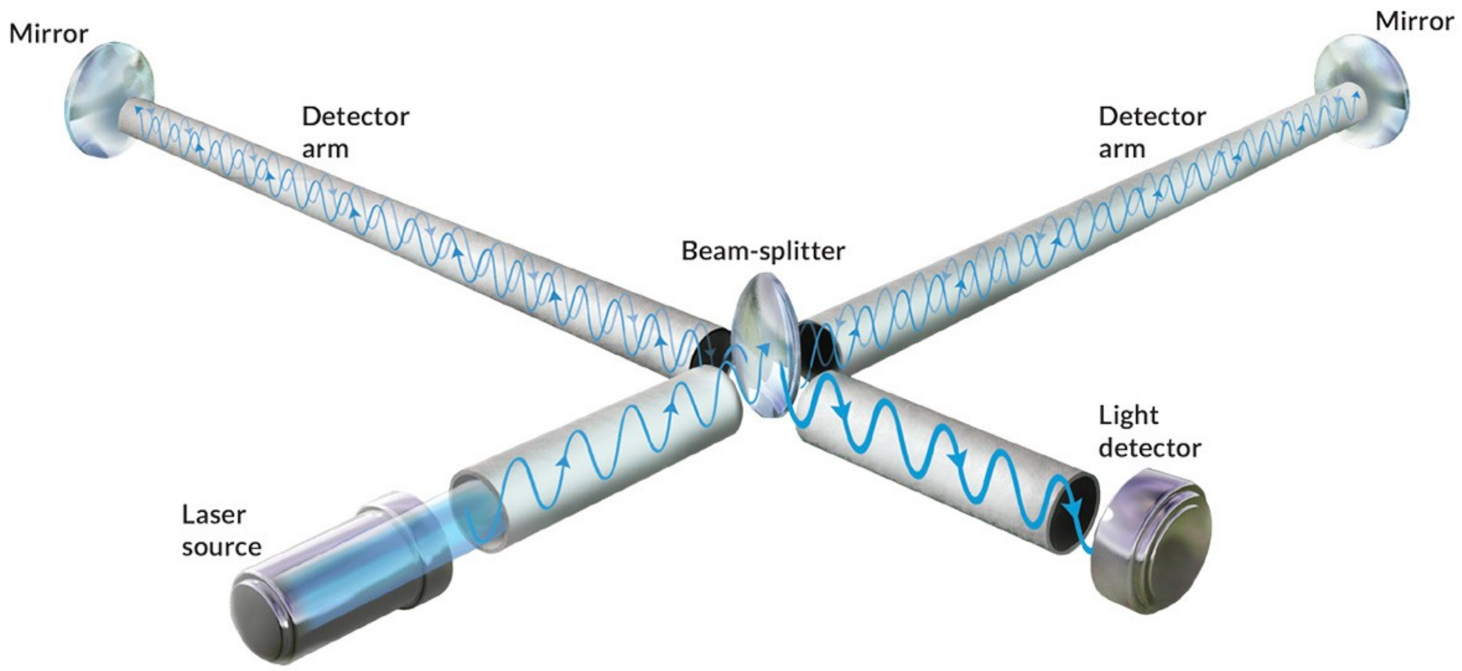
- Transverse deformation of the spacetime curvature, propagating with the speed of light
- Source of gravitational waves is the mass moving with acceleration

Gravitational waves observatories

- **LIGO**: funded by the US National Science Foundation (NSF) in the early 1990's when much of the required technology did not yet exist. Labelled as "high risk, high reward" project. First Detection: **14 September 2015,** binary black hole merger 1.4 billion light years away
- **Virgo**: hosted by the European Gravitational Observatory (EGO) at Cascina, Italy
- **KAGRA** (Japanese LIGO): became operational in February 2020
- **LIGO-India**: Under construction, is expected to be operational by 2030
- Ongoing O4: started May 2023 with LIGO, Virgo and KAGRA

Important milestones

- Nobel Prize in Physics in 2017 for first discovery of the GW (Thorne, Barrish, & Weiss)
- Association with electromagnetic counterpart: merging neutron stars → burst of gamma rays (2017), Kilonova signals (2017, 2021)

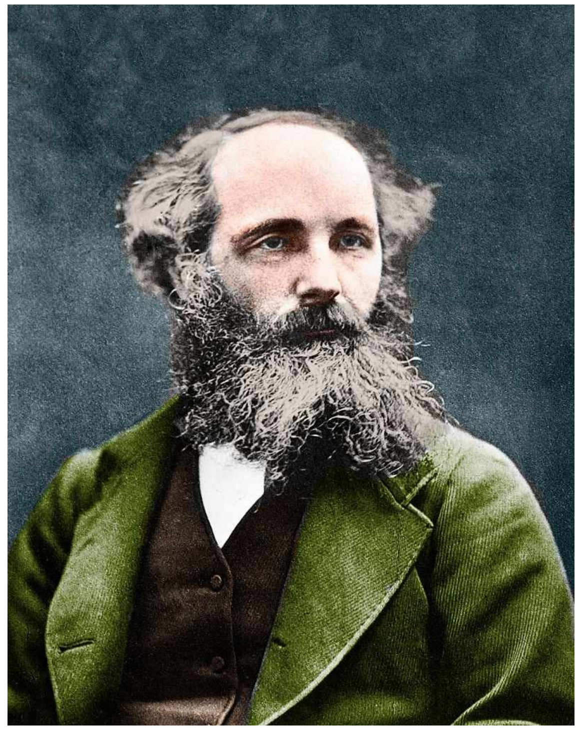


Gas motion in gravitational field of a black hole

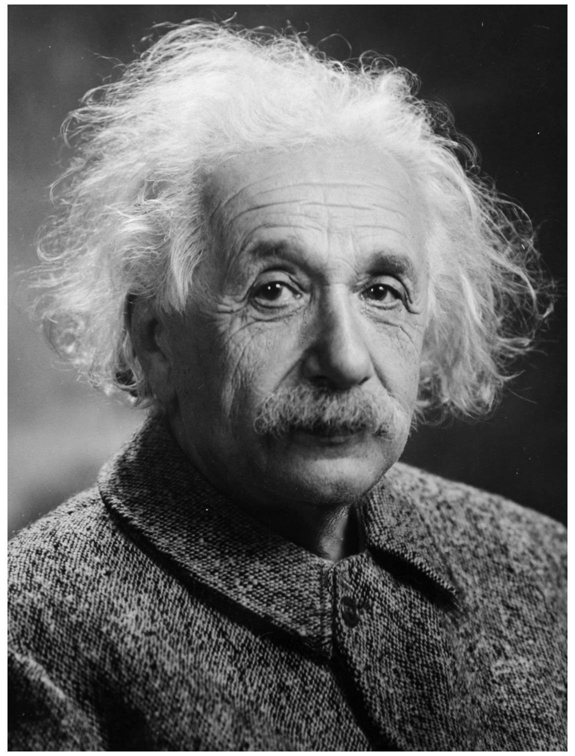
$$(\rho u_\mu)_{;\nu} = 0$$

$$T^\mu_{\nu;\mu} = 0.$$

Leonard Euler



James Maxwell



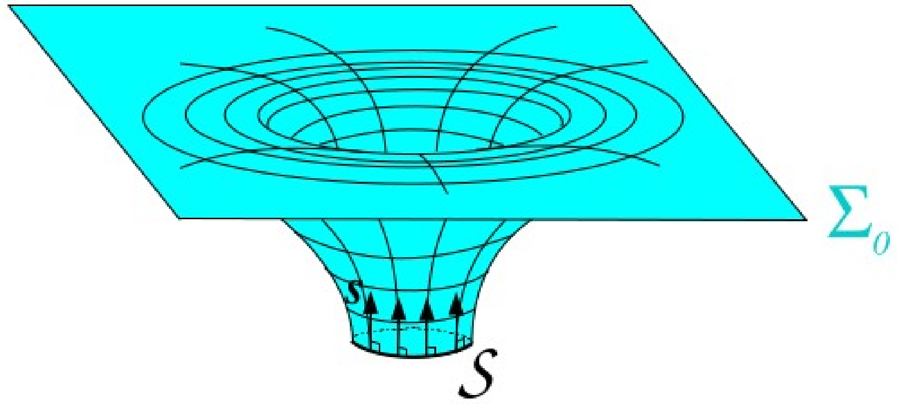
Albert Einstein

$$T_{(m)}{}^{\mu\nu} = \rho\xi u^\mu u^\nu + p g^{\mu\nu}$$

$$T_{(em)}{}^{\mu\nu} = b^\kappa b_\kappa u^\mu u^\nu + \frac{1}{2} b^\kappa b_\kappa g^{\mu\nu} - b^\mu b^\nu$$

$$T^{\mu\nu} = T_{(m)}{}^{\mu\nu} + T_{(em)}{}^{\mu\nu},$$

$$F^{*\mu\nu} = b^\mu u^\nu - b^\nu u^\mu$$



In addition: EOS - equation of state of the gas
Simplest analytical form: adiabatic law.

Ideal MHD – electric field vanishes

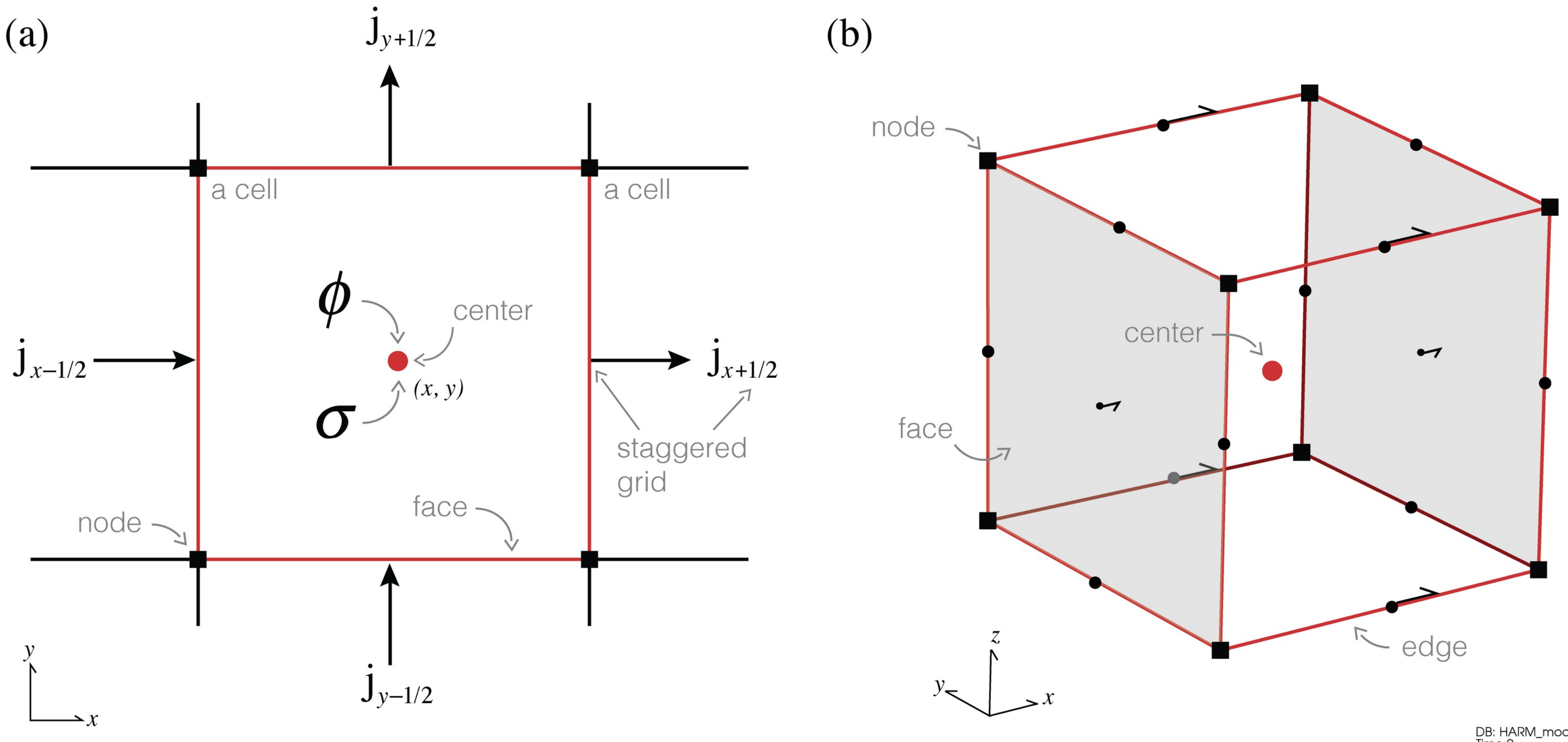
$$F^{*\mu\nu}{}_{;\nu} = 0 \ .$$

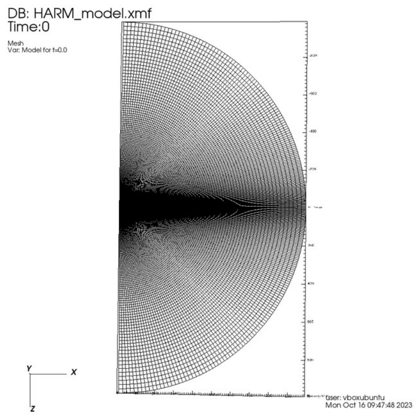
Condition for zero divergence of B field (no magnetic monopoles)

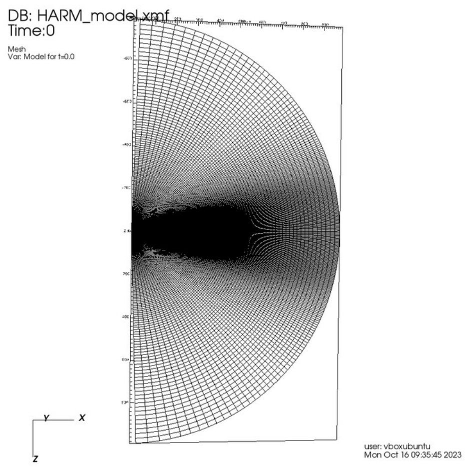
μ, ν = 0,1,2,3

Equations of GR MHD can be written in form:

$$\partial_t \mathbf{U}(\mathbf{P}) = -\partial_i \mathbf{F}^i(\mathbf{P}) + \mathbf{S}(\mathbf{P})$$







- ➔ Discretising equations on the grid
  - Grids non-uniform
- ➔ Finite volume method

Primitive variables have simple physical interpretation **P** and they are used by equation of state.

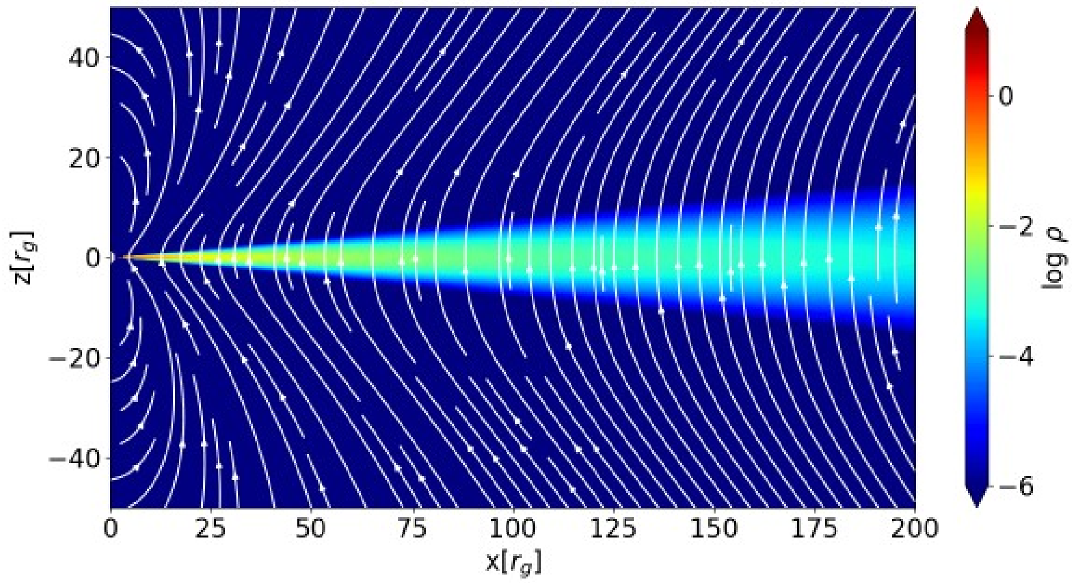
In relativistic MHD, the conserved variables are components of stress-energy tensor.
In each timestep code must invert **P(U)** – 5 nonlinear PDEs

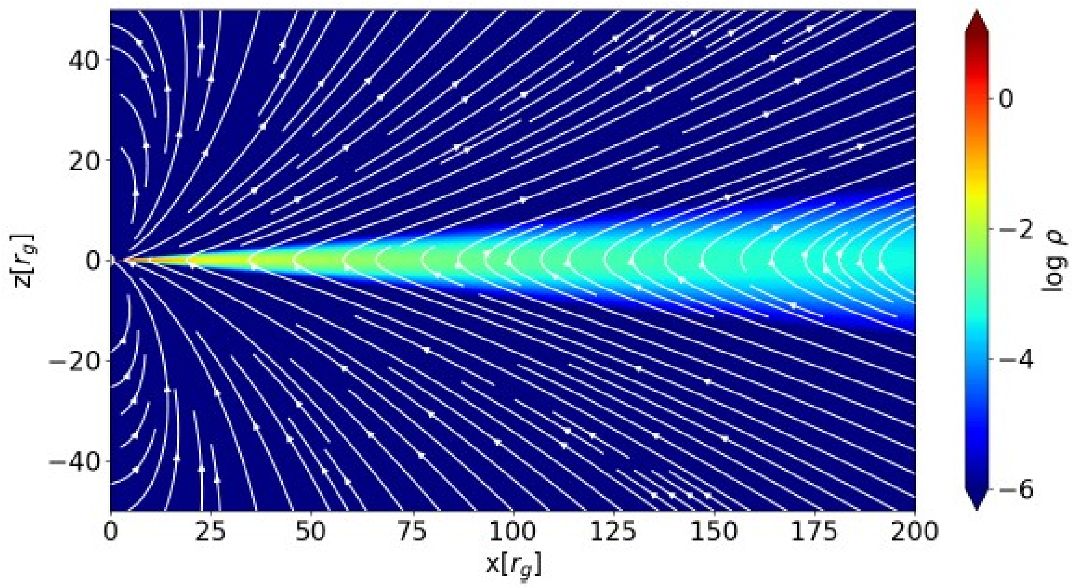
Code HARM-COOL

https://github.com/agnieszkajaniuk/HARM_COOL

- CPU only
- parallelized with MPI
- outputs in ASCII or HDF5
- versions with stationary and evolving Kerr metric
- versions with analytic and tabulated EOS

This project





$$A_\phi = r^{3/4}\frac{m^{5/4}}{(m^2+cos^2\theta)^{5/8}}$$

Problem and Initial Setup

2D models, 1056x528 cells, r_{out} =1000 r_g evolved for t ~ 60000,

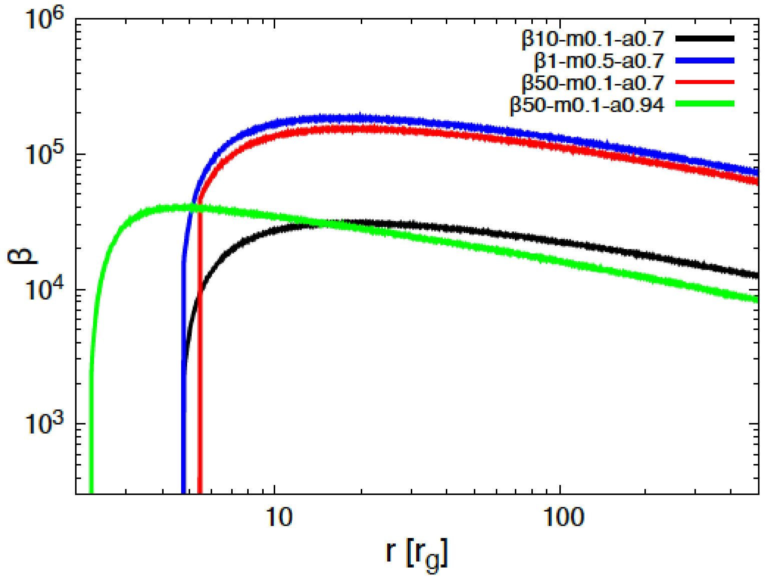
3D model with 288x256x96 cells

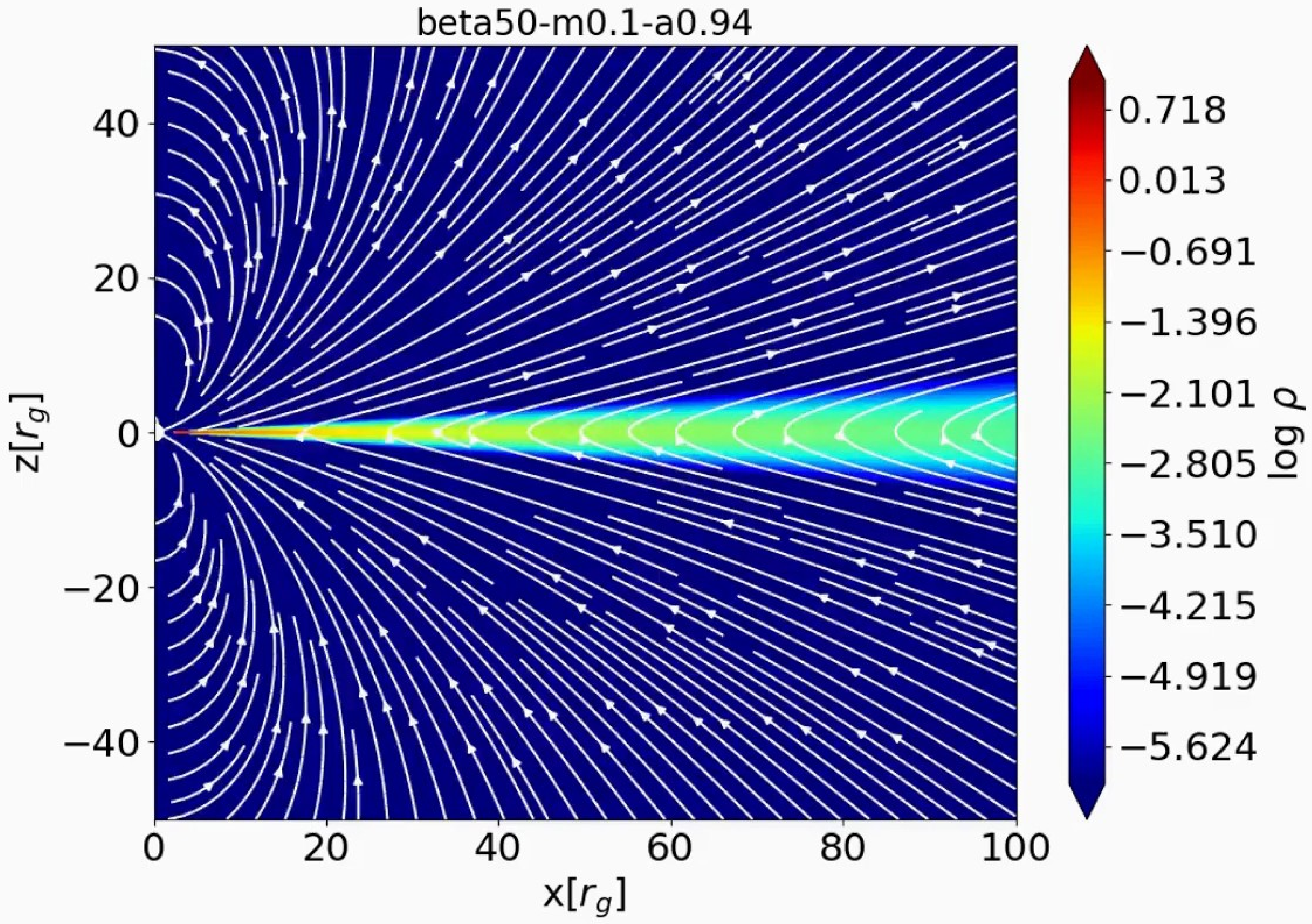
Initial configuration for thin disk, density profile from Dihinigia et al. (2021)

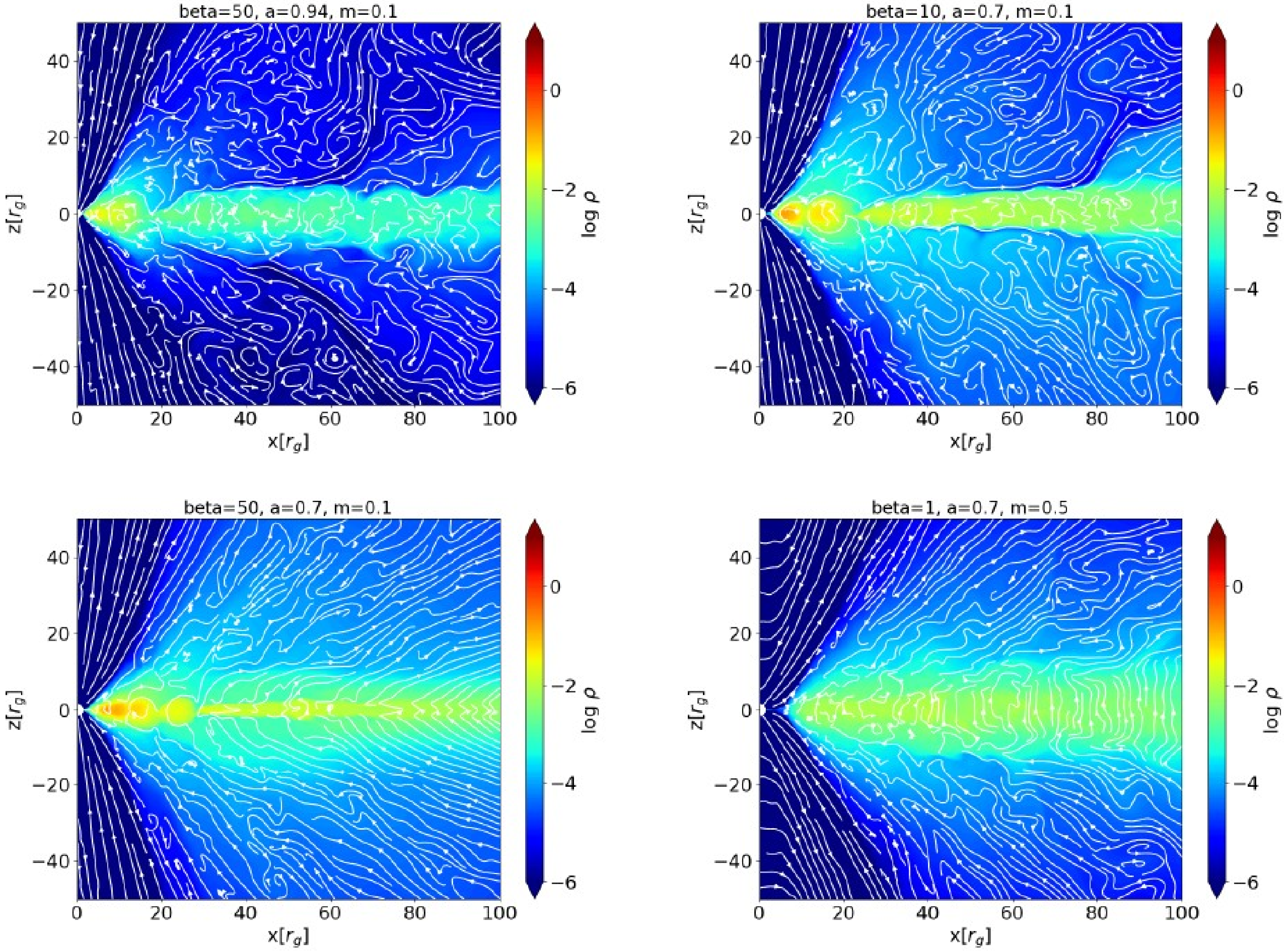
The results are scaled for the central BH mass $10^6\,M_\odot$ and mass ratio q=10^{-3} (the low-mass secondary BH is not included)

case	β	m	BH spin	$\beta_{max,\,eq}$
β1-m0.5-a0.7	1	0.5	0.7	185244
β10-m0.1-a0.7	10	0.1	0.7	31246
β50-m0.1-a0.7	50	0.1	0.7	156000
β50-m0.1-a0.94	50	0.1	0.94	39313

$\beta = P_{gas,max}/P_{B,max}$




beta50-m0.1-a0.94
40
20
0
−20
−40
z[r_g]
0
20
40
60
80
100
x[r_g]
0.718
0.013
−0.691
−1.396
−2.101
−2.805
−3.510
−4.215
−4.919
−5.624
log ρ

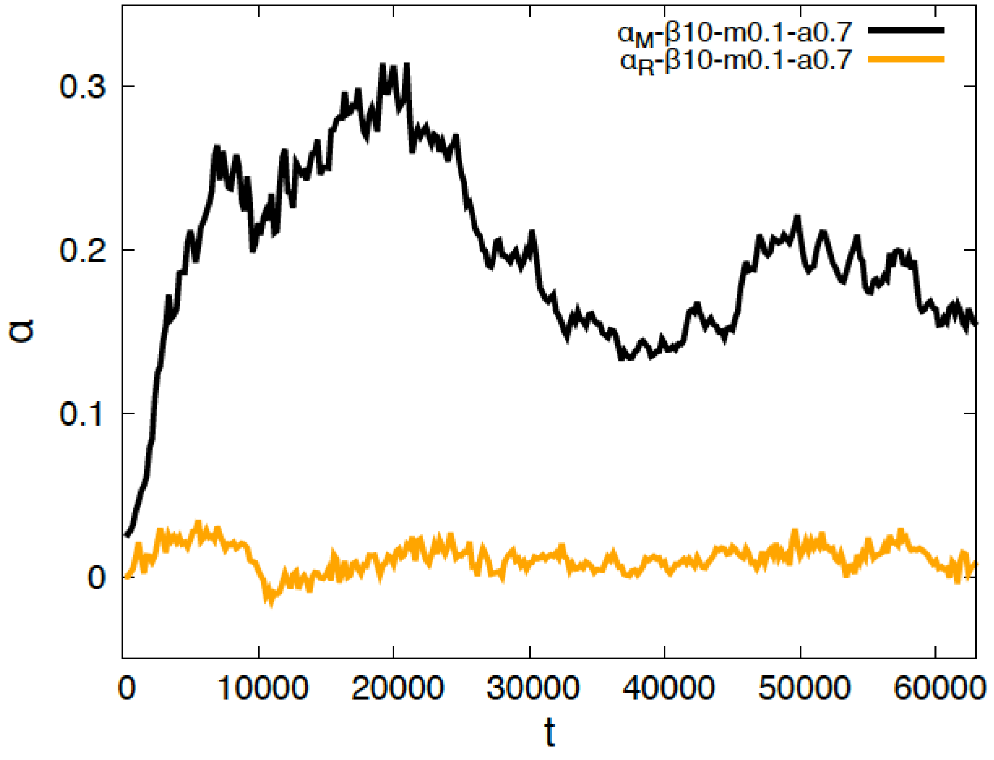


Results

- Magnetically arrested (MAD) state → pauses accretion

$$\Phi_B / \sqrt{\dot{M}} \quad > 15$$

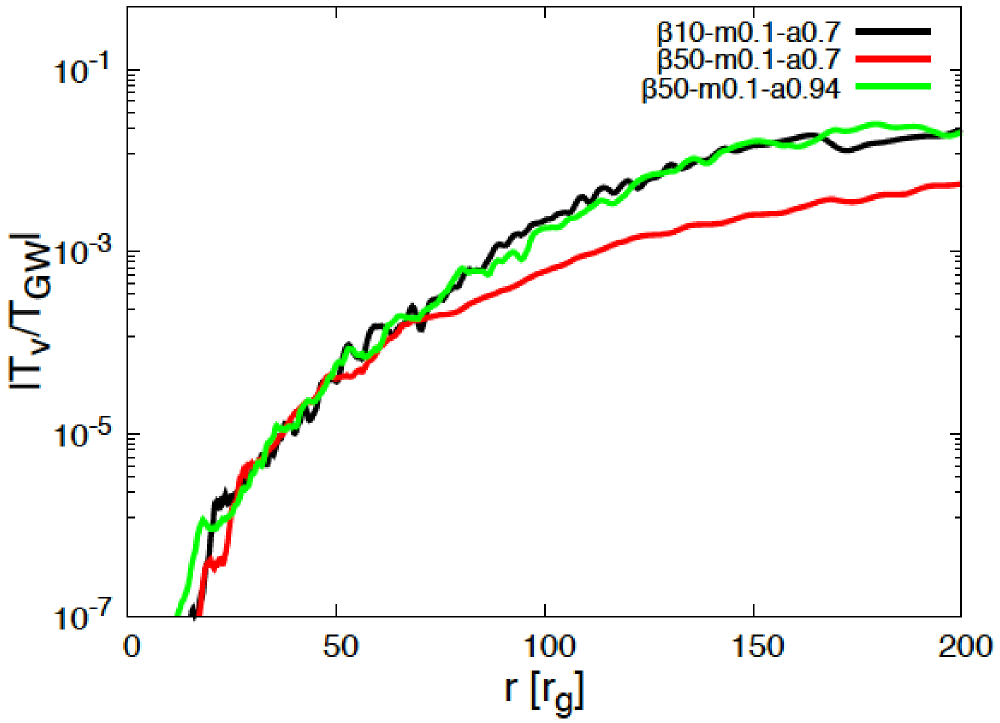
- Turbulent viscosity dominated by Maxwell stress



$$\alpha = \alpha_R + \alpha_M,$$

$$\alpha_R \approx \frac{\rho_0 \delta u_r \delta u_\phi \sqrt{g^{\phi\phi}}}{P_{tot}},$$

$$\alpha_M \approx -\frac{b_r b_\phi \sqrt{g^{\phi\phi}}}{P_{tot}}.$$



Viscous and gravitational wave torques

- GW torque

$$T_{GW} = \frac{1}{2} q M_p r \dot{r}_{GW} \Omega_2,$$

- Viscosity (relativistic approach)

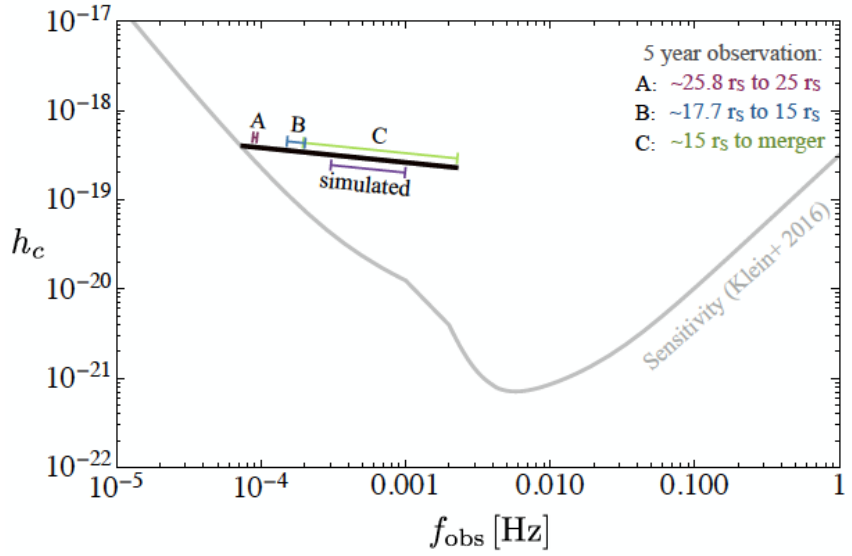
$$T_{\nu,GR} = \dot{M}_{GR} r^2 \Omega_2$$

$$\dot{M}_{GR} = 2\pi \left[\frac{\Gamma}{Q} 3 r^{1/2} \frac{\partial}{\partial r} \left(r^{1/2} \nu \Sigma_{GR} \frac{\mathcal{D}^2}{C} \right) \right],$$

$$\nu = \alpha c_s h$$

Dephasing due to gas

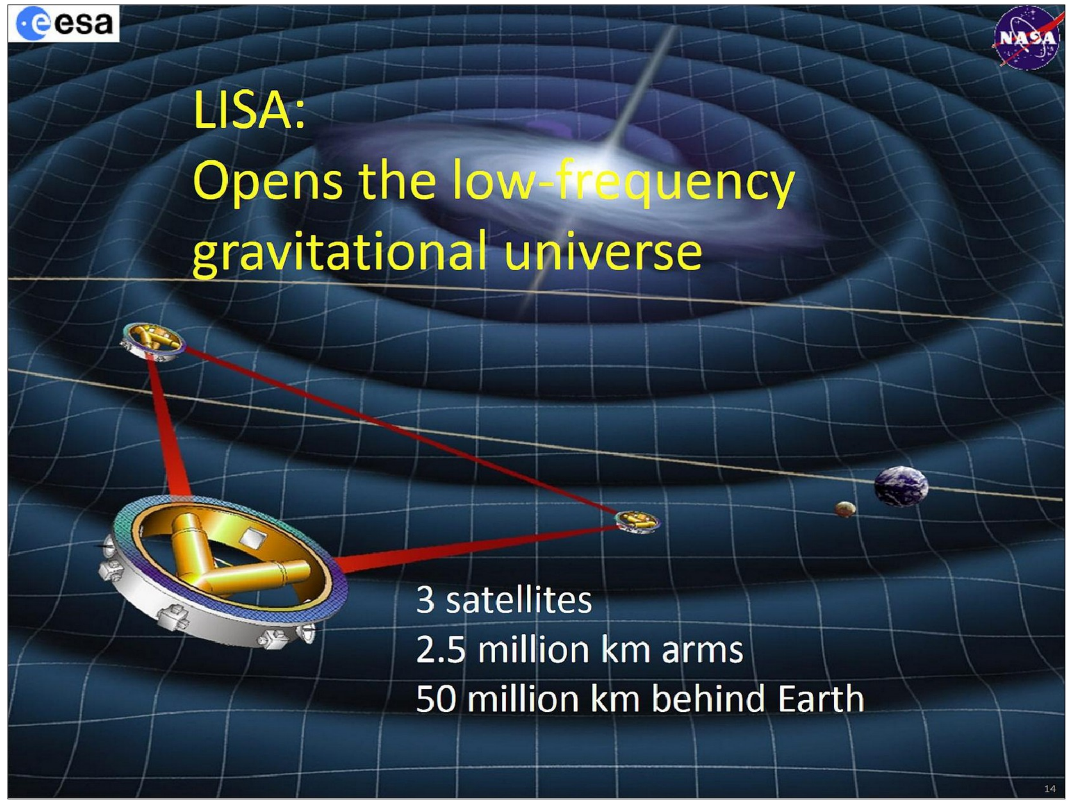
Approximating the GW frequency for a binary with mass ratio 0.001 and $M_p = 10^6 M_\odot$ to be around f ~ 1 mHz, we predict the dephasing would be roughly around ***∼ 10 radian for about 10⁵ inspiral orbits***.



The characteristic strain amplitude of the binary inspiral, for an $M_1 = 10^6 M_\odot$, $M_2 = 10^3 M_\odot$ at redshift z = 1, as a function of the observed GW frequency. (Derdzinski et al. 2019)

Conclusions

- Initial magnetic field configuration plays an important role to trigger and sustain MRI (<u>or</u> supresses MRI and turns the disk into the MAD state)
- We observed the density-weighted, volume-averaged **α** viscosity varies around 0.1− 0.25
- We applied the numerical results from the GRMHD simulations to estimate the viscous torque using 1D GR-Hybrid approach
- Thee time-averaged viscous torque can be as large as $\sim$ 1% of the GW torque for a mass ratio of $q = 10^{-3}$ at radii around $r \sim 100r_g$. This extra torque from the environment appears as **phase shift in the GW signal (~10 radians in 10^5 orbits)**.



TO BE CONTINUED…..

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