Outflows, the alpha parameter and GRMHD

based on Narayan, Sądowski, Penna, Kulkarni 2012, MNRAS, in press
and Penna, Sądowski, Kulkarni, Narayan 2012, MNRAS, submitted
in collaboration with Grzegorz Mazur

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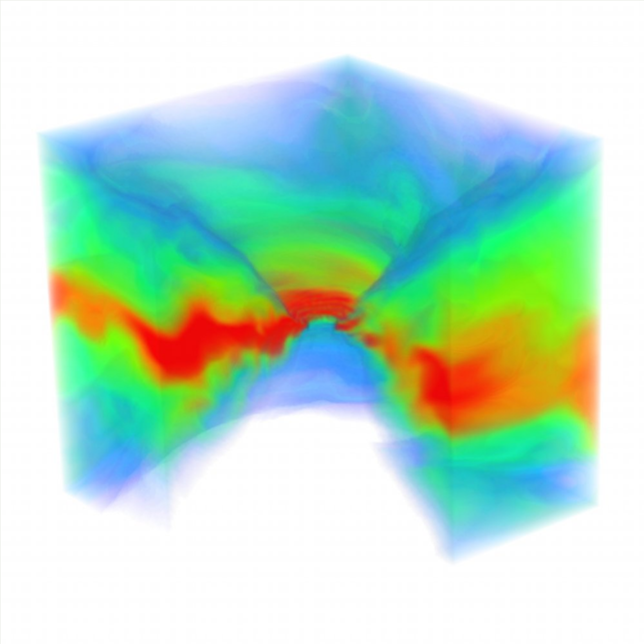
Warsaw, 2012

Outline

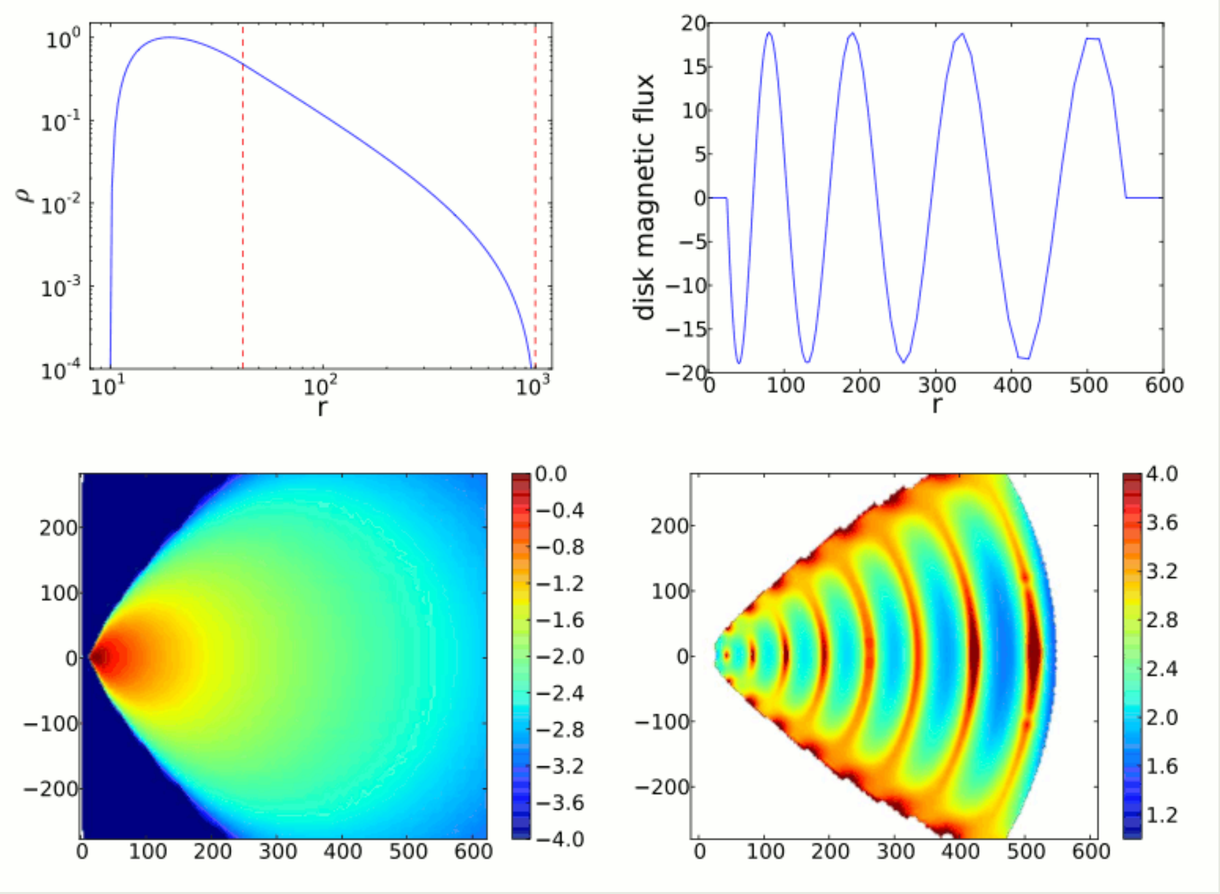
1. GRMHD
2. Outflows
3. Alpha

GRMHD simulations of ADAFs

* 3D conservative relativistic magneto-hydrodynamic code HARM
* MPI parallelized
* 256 x 128 x 64 resolution
* Kerr-Schild coordinates
* no cooling, no radiation
* two modes of accretion: standard (SANE) and magnetically arrested (MAD)
* t=200k GM/c^3 ~ two months on 512 cores

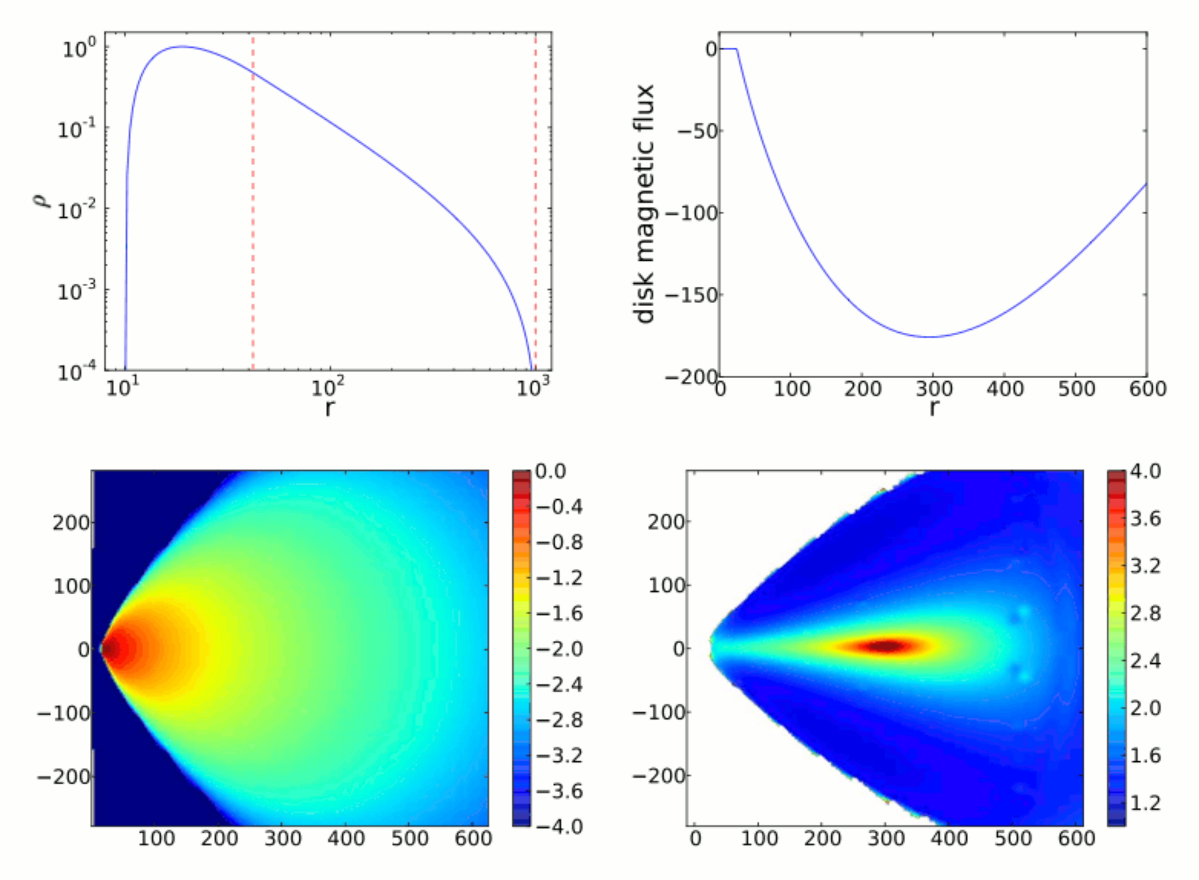


Initial state for the SANE run

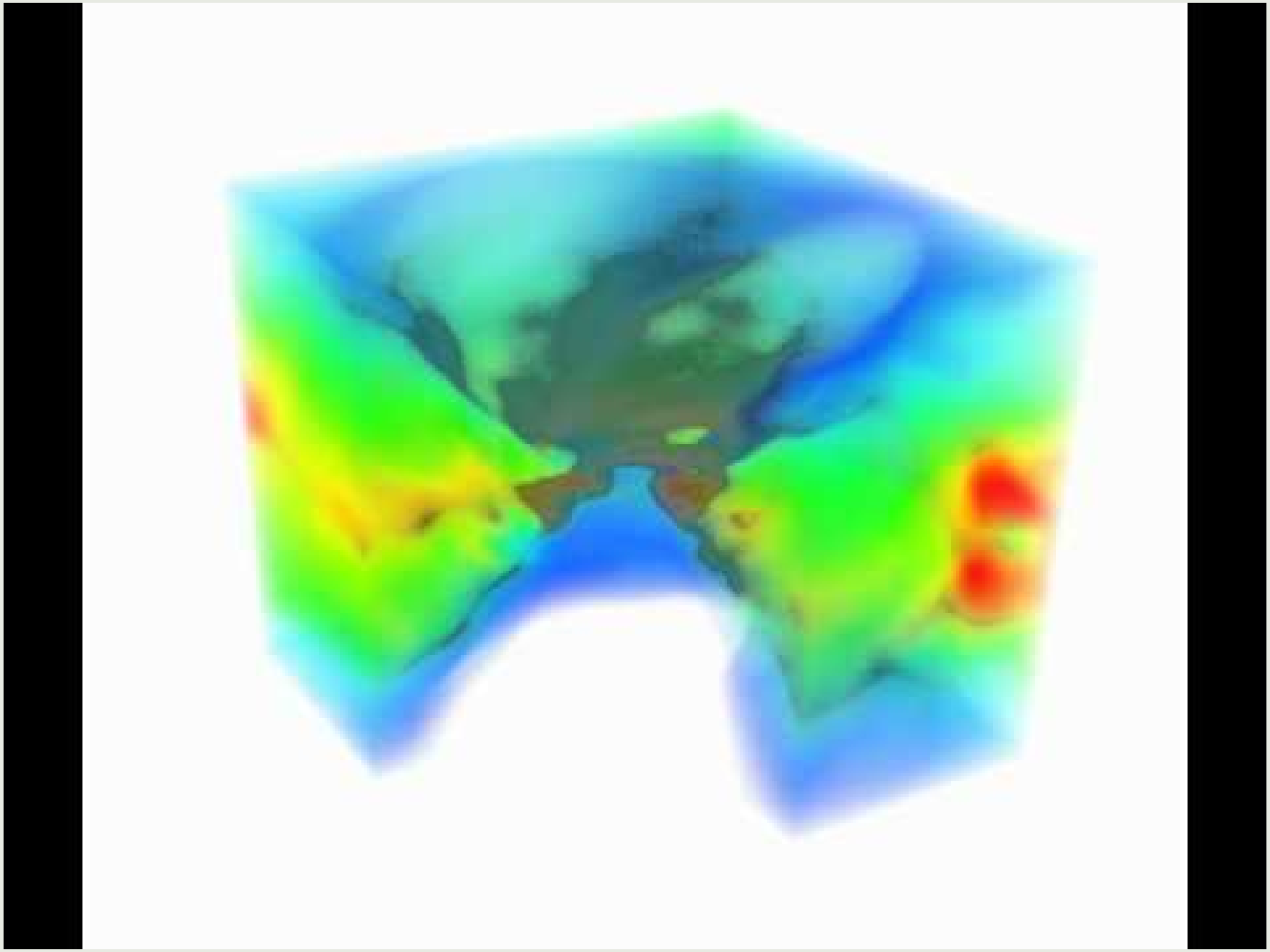


multiple poloidal magnetic loops to ensure small flux through the BH horizon

Initial state for the MAD run

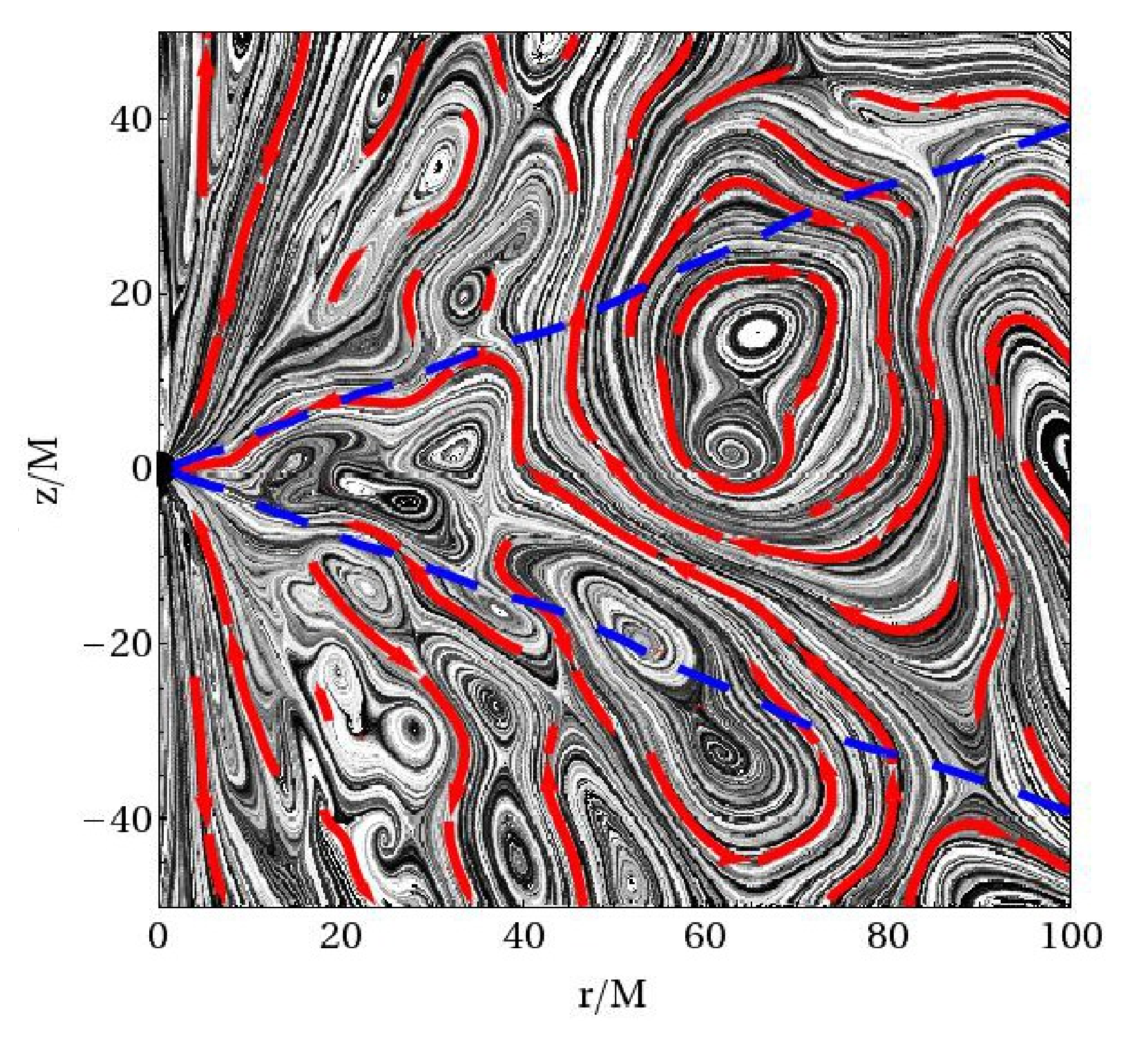


single poloidal magnetic loop results in accumulating flux on the BH horizon leading to the Magnetically Arrested Disk

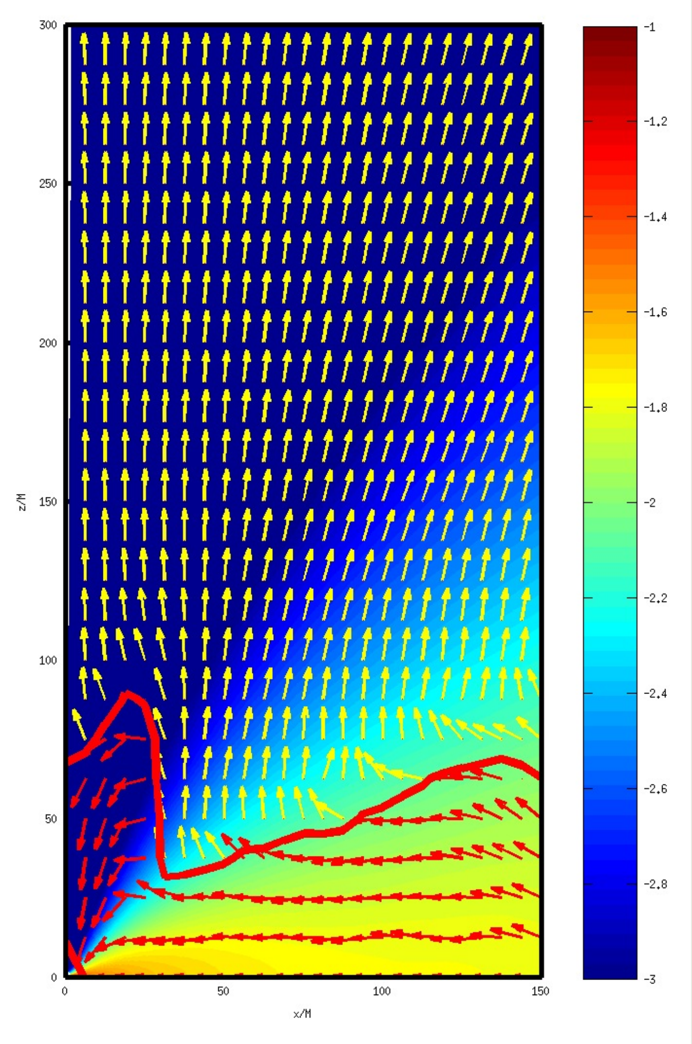


a=0, SANE, colors denote density, proper ray-tracing neglected
credit: Grzegorz Mazur

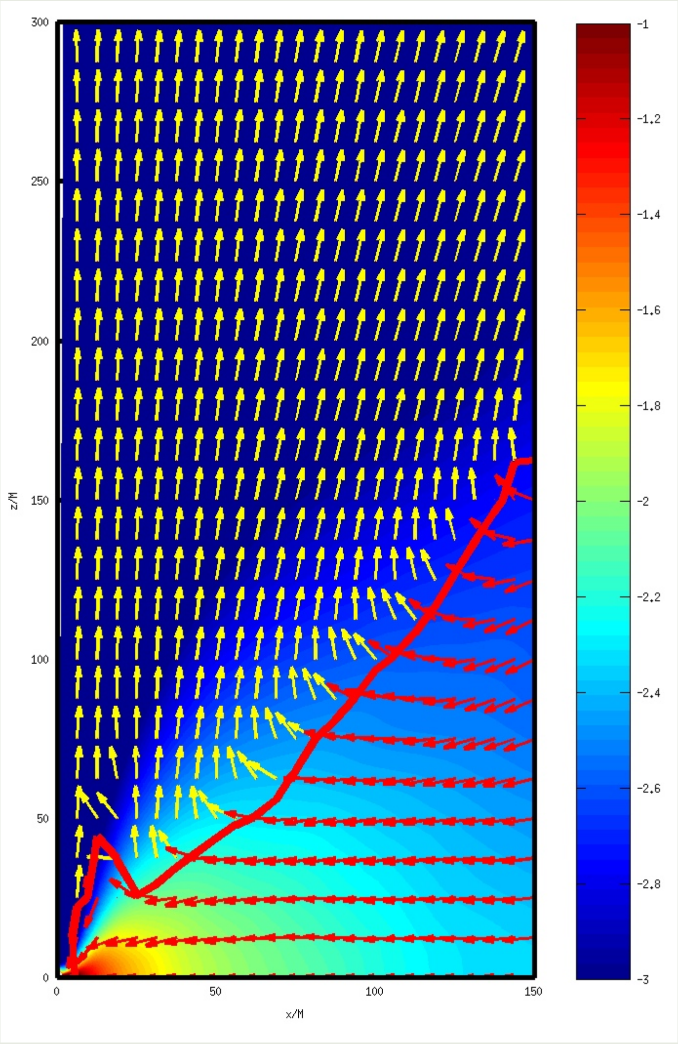
Turbulent flow



Averaged disk structure (t, phi, theta refl.)

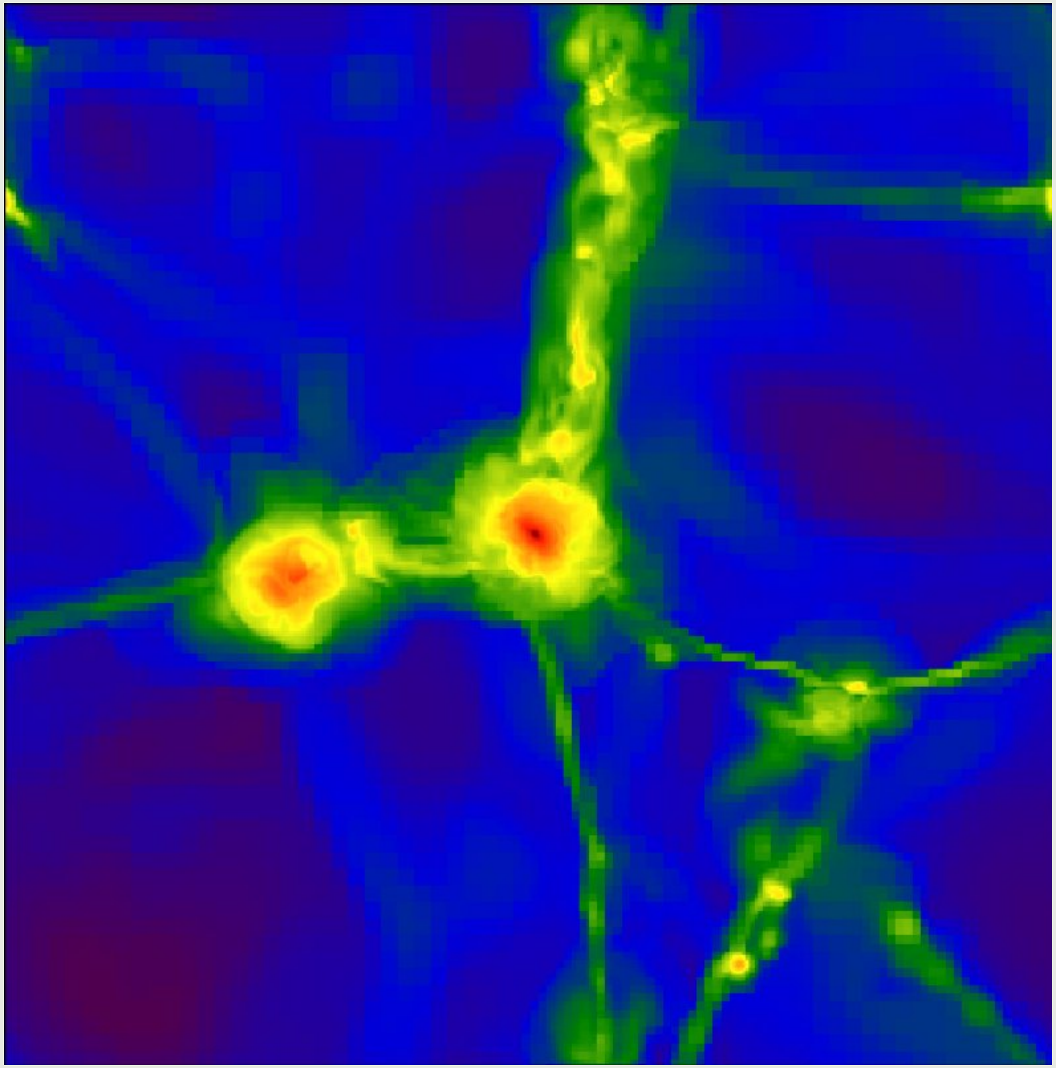


SANE



MAD

Why do we care?



credit: Priyamvada Natarajan's webpage

BH Feedback

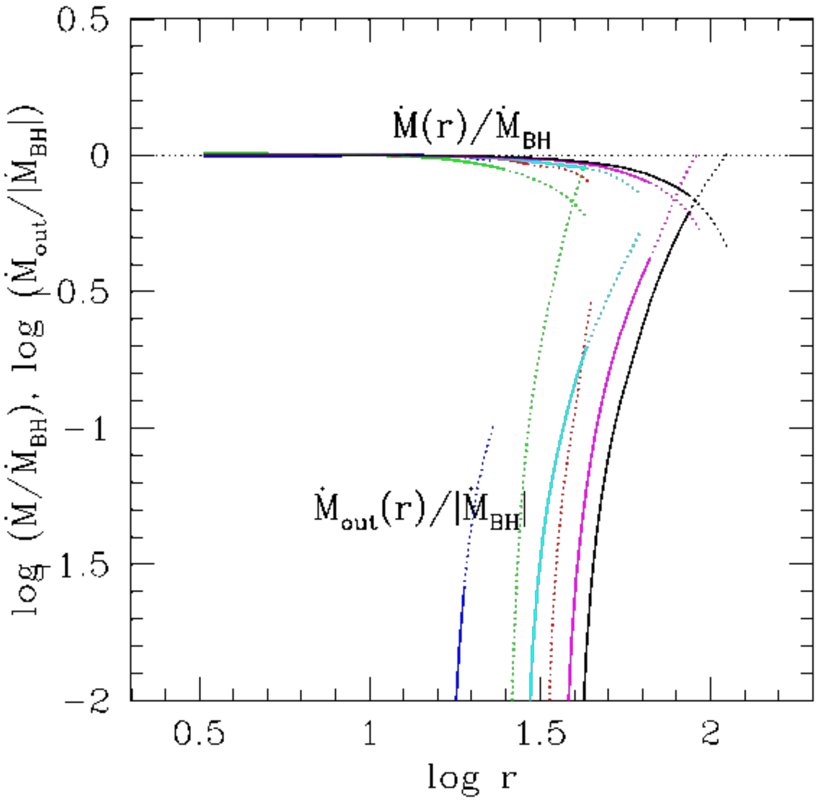
* solves the overcooling problem in galaxy evolution
* leads to M-sigma relation
* ...

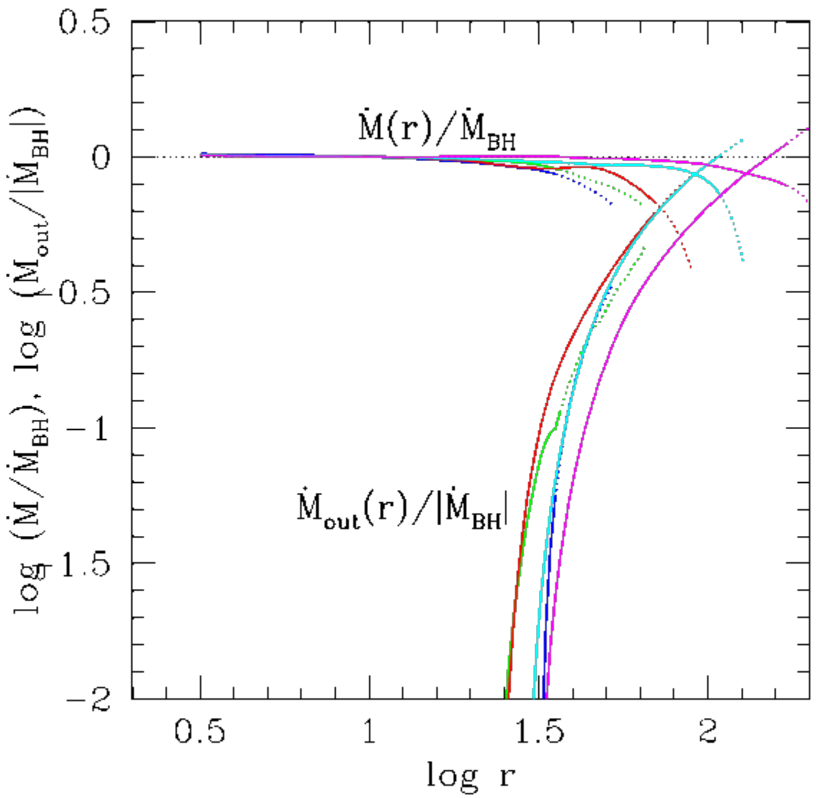
* Sołtan's argument gives eta=~10%
* SPH simulations give constraints
* BH physics under-resolved

2 modes of feedback:
* quasar mode - high mdot
* <u>maintenance mode</u> - low mdot

Outflows in the maintenance mode

SANE **MAD**





$$\mu = \frac{\langle T^p_t \rangle}{\langle \rho u^p \rangle} - 1$$

Outflows in the maintenance mode - conclusions

* The outflows are weak inside r=100M

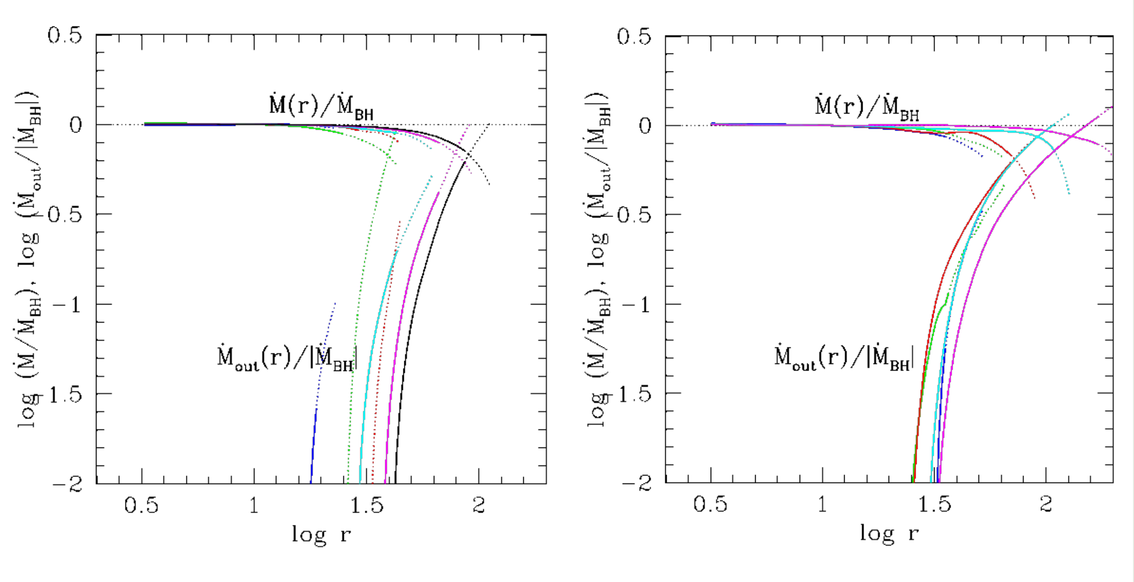
* The mass outflow rate becomes comparable to the net inflow rate at r~90M (SANE) and r~160M (MAD)

* due to unsatisfactory convergence these radii should be considered lower limits

* radial profile of outflows at larger radii cannot be estimated (other studies give Mdot ~ r^(0.5), Yuan+12)

* large fraction of Bondi accretion rate expected to reach BH:

Mdot_BH = 10^-1.5 =
 = 3% Mdot_Bondi



* the effect of BH spin is being investigated

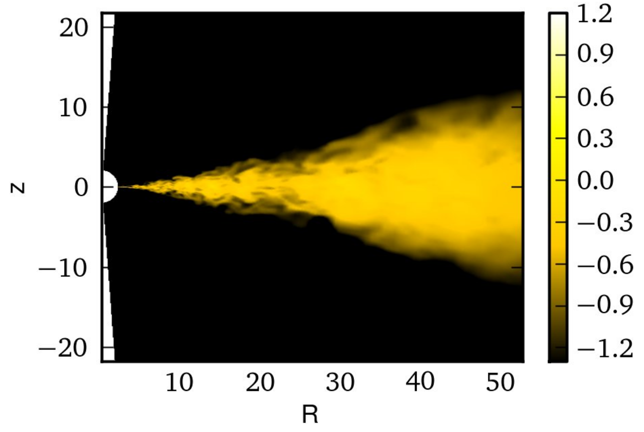
The alpha

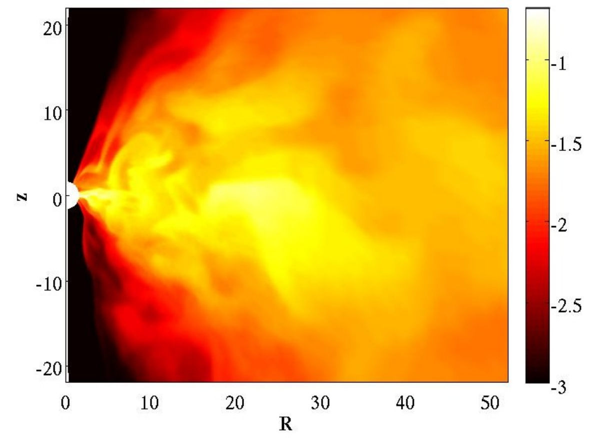
$$T_{\hat{r}\hat{\phi}} = \alpha p$$

$$\alpha = \frac{T^{(\mathrm{rey})}_{\hat{r}\hat{\phi}} + T^{(\mathrm{mag})}_{\hat{r}\hat{\phi}}}{p + b^2/2}.$$

$$T^{(\mathrm{rey})}_{\mu\nu} = (\rho + u) u_\mu u_\nu + p h_{\mu\nu},$$

$$T^{(\mathrm{mag})}_{\mu\nu} = \frac{1}{2}\left(b^2 u_\mu u_\nu + b^2 h_{\mu\nu} - 2 b_\mu b_\nu\right),$$

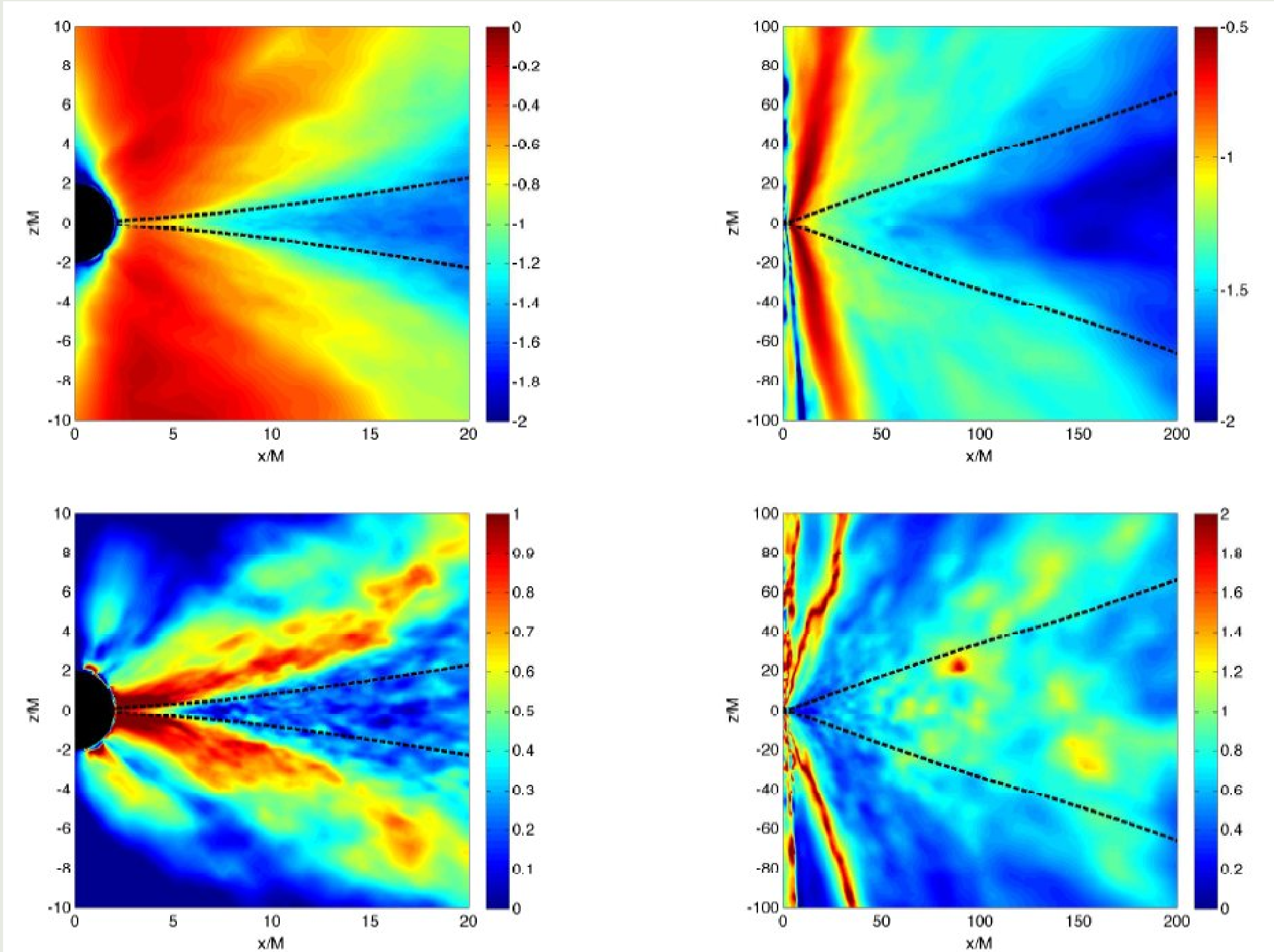




Spatial distributions of alpha

log(alpha)

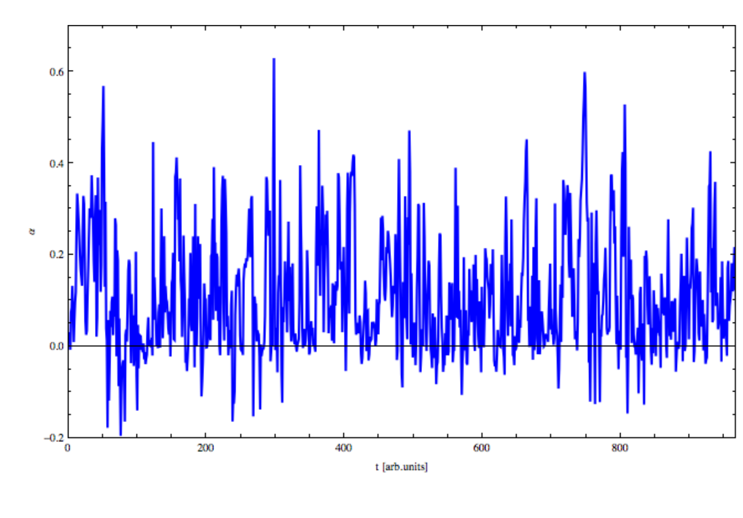
Reynolds/
Maxwell
stress

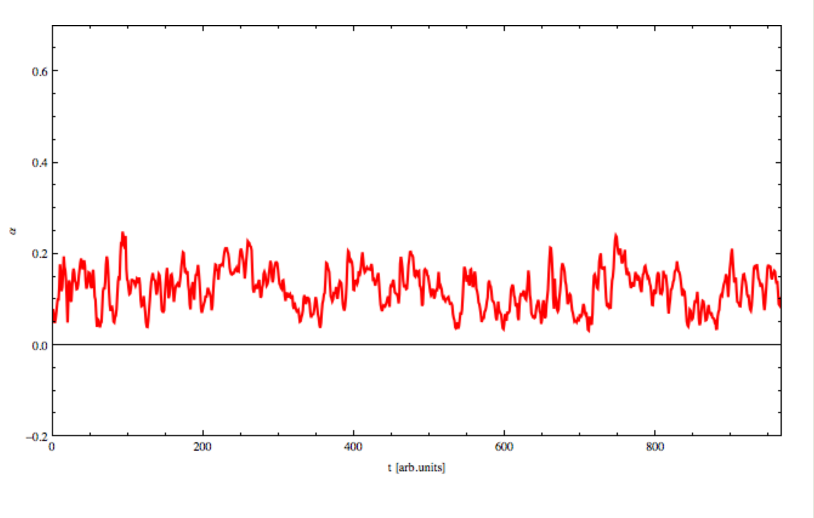


thin disk

ADAF

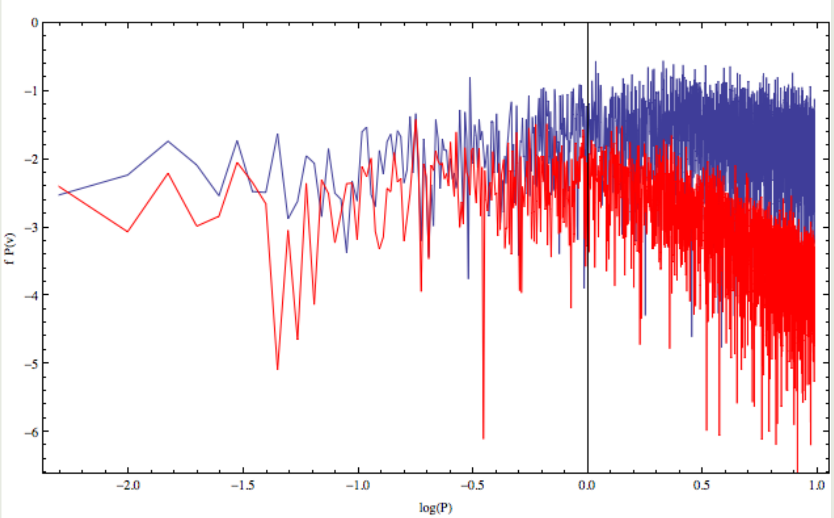
Time variability of alpha in ADAF (a=0, SANE, eq. plane)



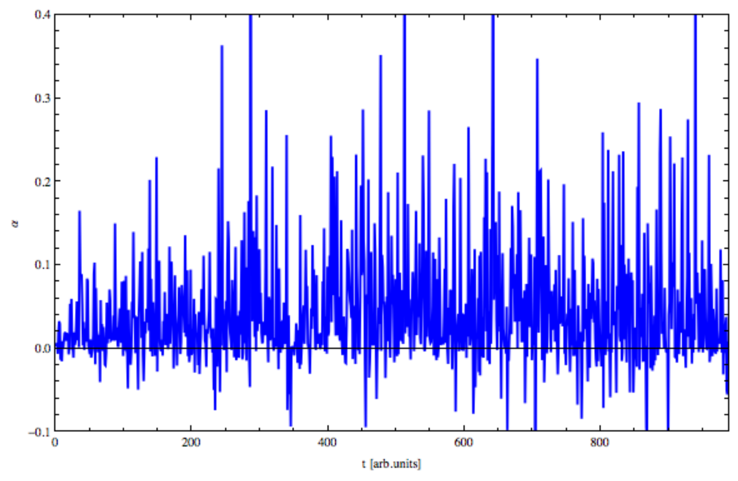


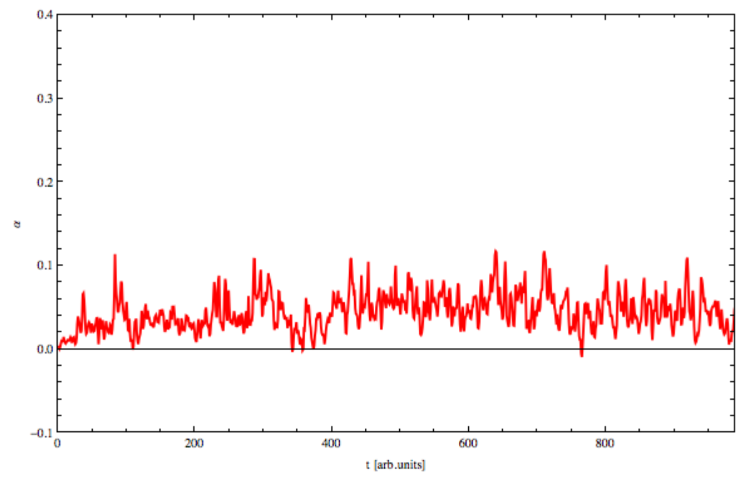
local (fixed lab. coord.)

phi-averaged



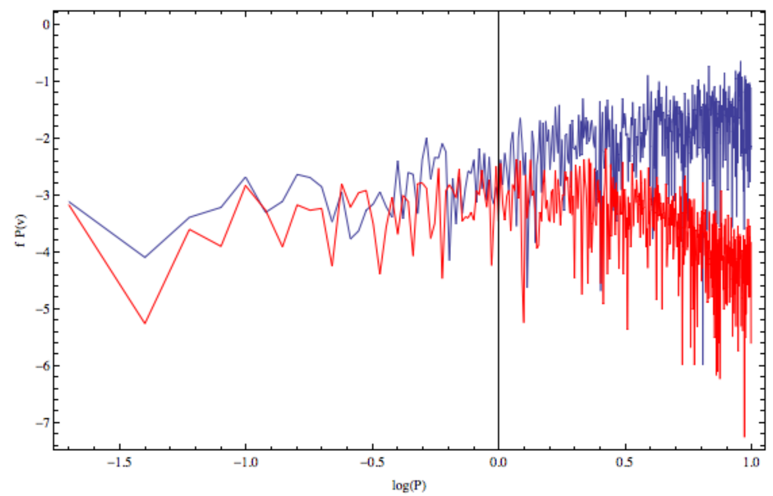
Thin disk (a=0, h/r=0.1, eq. plane, cooling function)



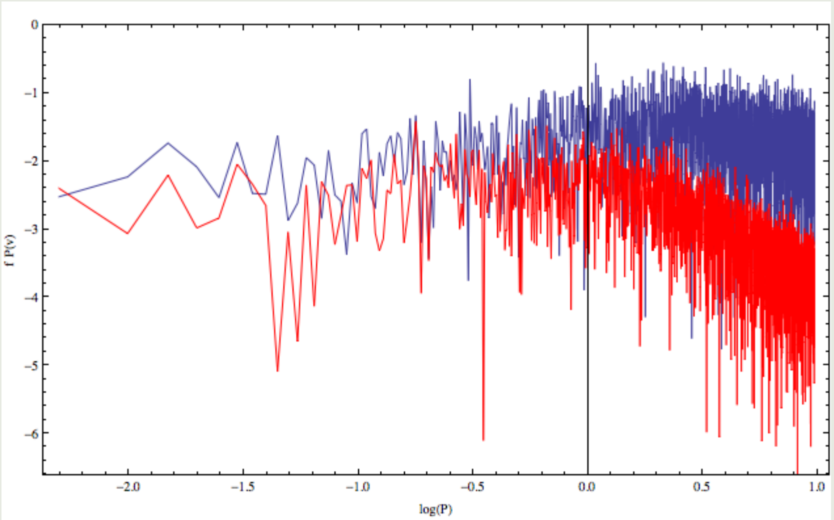


local (fixed lab. coord.)

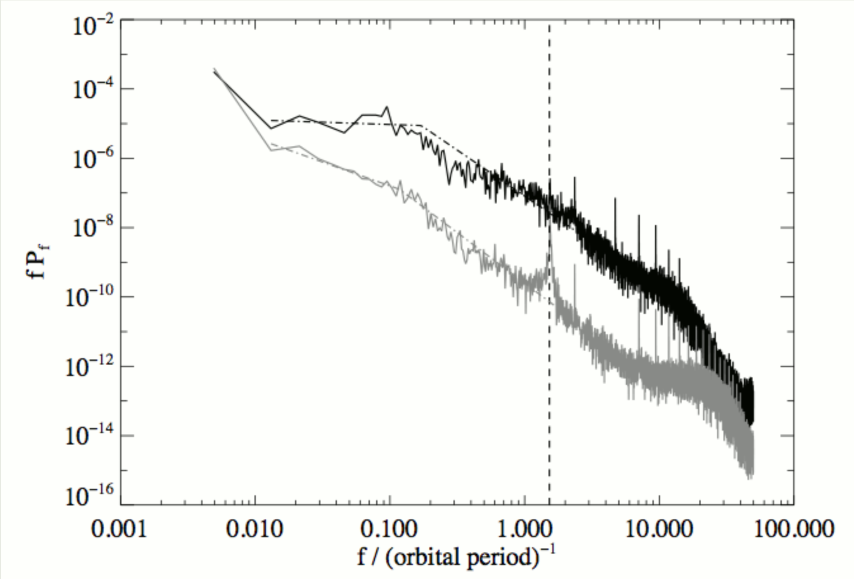
phi-averaged



Power spectrum of alpha variability

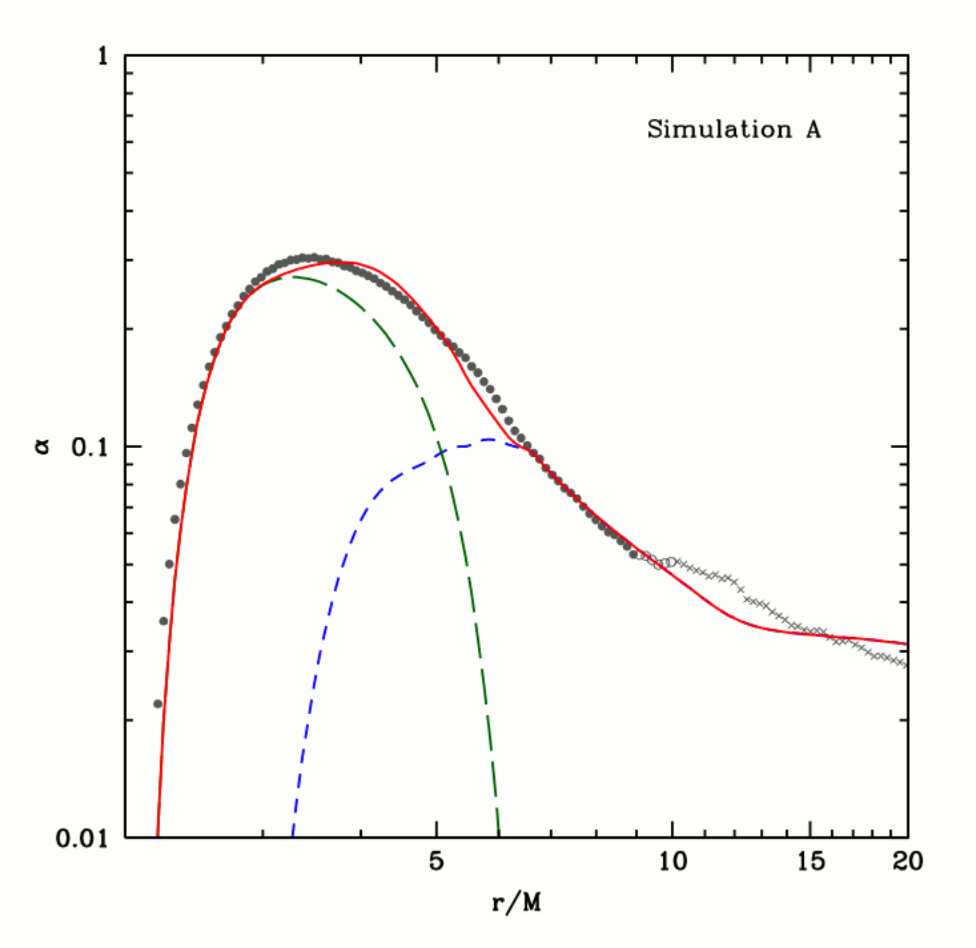


GRMHD



shearing box
thin disk, rad.dominated
(Hirose+08)

Radial profile of alpha



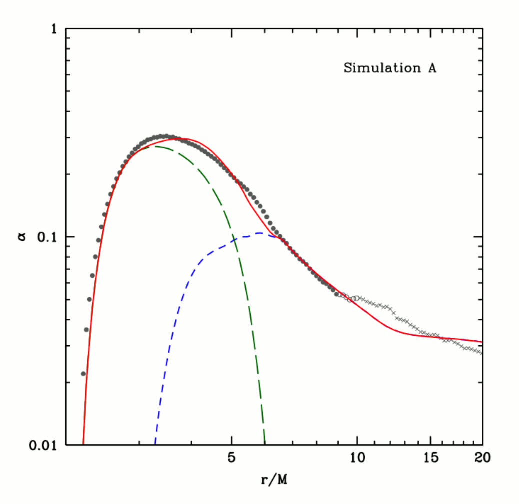
* dots - GRMHD thin disk, h/r=0.1
* lines - analytical model of Penna, Sądowski+12

Radial profile of alpha

turbulent flow: MRI saturation level depends on the local shearing rate q (Abramowicz+96, Pessah+08)

$$\alpha \propto q^n$$

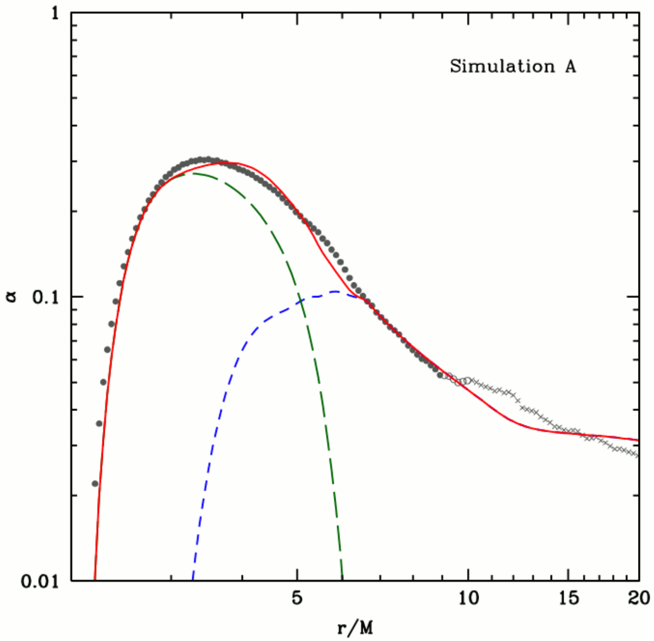
$$q = -2\sigma_{\hat{r}\hat{\phi}}/\Omega = -\gamma^2 \mathcal{A} \frac{d \log \Omega}{d \log r}$$



laminar flow within ISCO:

Gammie (1999) solved for the motion of a fluid with a frozen-in magnetic field as it plunges into a Kerr black hole along the equatorial plane. The inner boundary of the flow is at the event horizon and the outer boundary of the flow is at r_B, where the flow is assumed to have zero radial velocity and Keplerian angular velocity. The governing equations are mass, angular momentum, and energy conservation, and Maxwell's equations. There is no dissipation and the pressure and internal energy of the gas are neglected. The solutions are time-independent, axisymmetric, and vertically averaged. They provide the rest mass density, velocities, and magnetic field of the flow as a function of radius.

Radial profile of alpha



$$\alpha(r) = \alpha_0 \left[\frac{q(r)}{3/2}\right]^n - \alpha_1 \frac{b_{\hat{r}}(r) b_{\hat{\phi}}(r)}{\rho(r)^\Gamma}, \quad (q > 0).$$

Simulation	$M/M_\odot$	a/M	$\dot{M}/\dot{M}_{edd}$	Υ	α_0	α_1	n	r_B
A	10	0	0.5	0.6	0.025	100	6	r_{ISCO}
B	10	0.7	0.2	3	0.025	10	6	r_{ISCO}
C	10	0	0.2	6	0.025	1	6	r_{ISCO}
D	10	0	1	5	0.025	0.5	6	30M
E	10	0.7	1	10	0.025	0.5	6	30M
F	10	0	1	30	0.025	0.1	6	30M

Conclusions

* GRMHD simulations can consistently produce magnetically driven outflows
* simulations converge only up to ~100M
* larger scales available through hydro only (e.g., Yuan+12)
* radiatively driven winds require radiative transfer - so far not done for GR

* GRMHD generates stresses self-consistently
* The alpha parameter varies with time
* Its averaged radial profile may be fitted by two-component analytical model
* Still, radiative transfer required for the proper treatment of thin disks