Global Radiation MHD Simulations of AGN Accretion Disks with Realistic Opacity

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Outline

- AGN accretion disks with super-Eddington accretion rates
  - Mechanisms for angular momentum transfer
  - Flow structures
- Compare Accretion Disks in AGNs and X-ray binaries
- AGN Accretion disks with sub-Eddington accretion rates

Motivation

- Super-Eddington Accretion Disks around supermassive black holes
  - Easier to study numerically
  - Relevant for TDEs, growth of black holes in the early universe
- AGN accretion disks are strongly radiation pressure dominated
  - Saturation of MRI in the strongly radiation pressure dominated flow
- Effects of iron opacity

Observational Puzzles for AGNs

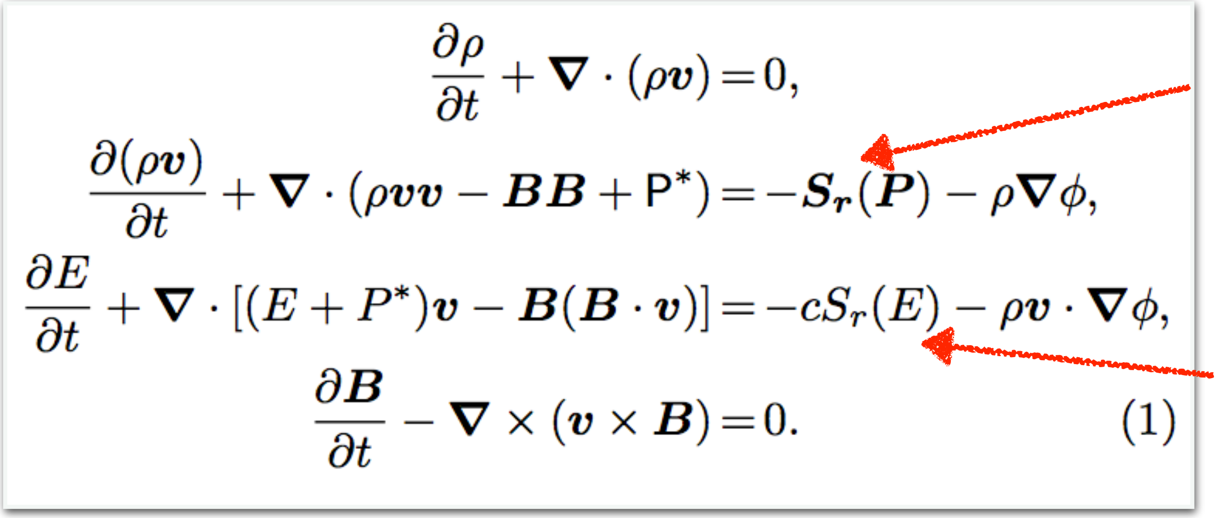
- SED of most AGNs shows a turnover around 1000 A.
- Ultra Fast outflow
- The ionization of lines
- Missing of Lyman Edge
- The observed accretion disk size is systematically larger

Koratkar & Blaes (1999)
Bonning et al. (2007)
Davis et al. (2007)
Morgan et al. (2010)
Edelson et al. (2005)
Higginbottom1 et al. (2014)
Jiang et al. (2017)

The Input Physics

Jiang et al. (2014)

Ideal MHD



$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathsf{P}^*) = -\boldsymbol{S_r}(\boldsymbol{P}) - \rho \boldsymbol{\nabla} \phi,$$

$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot [(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] = -cS_r(E) - \rho \boldsymbol{v} \cdot \boldsymbol{\nabla} \phi,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) = 0. \qquad (1)$$

photon momentum

radiation energy

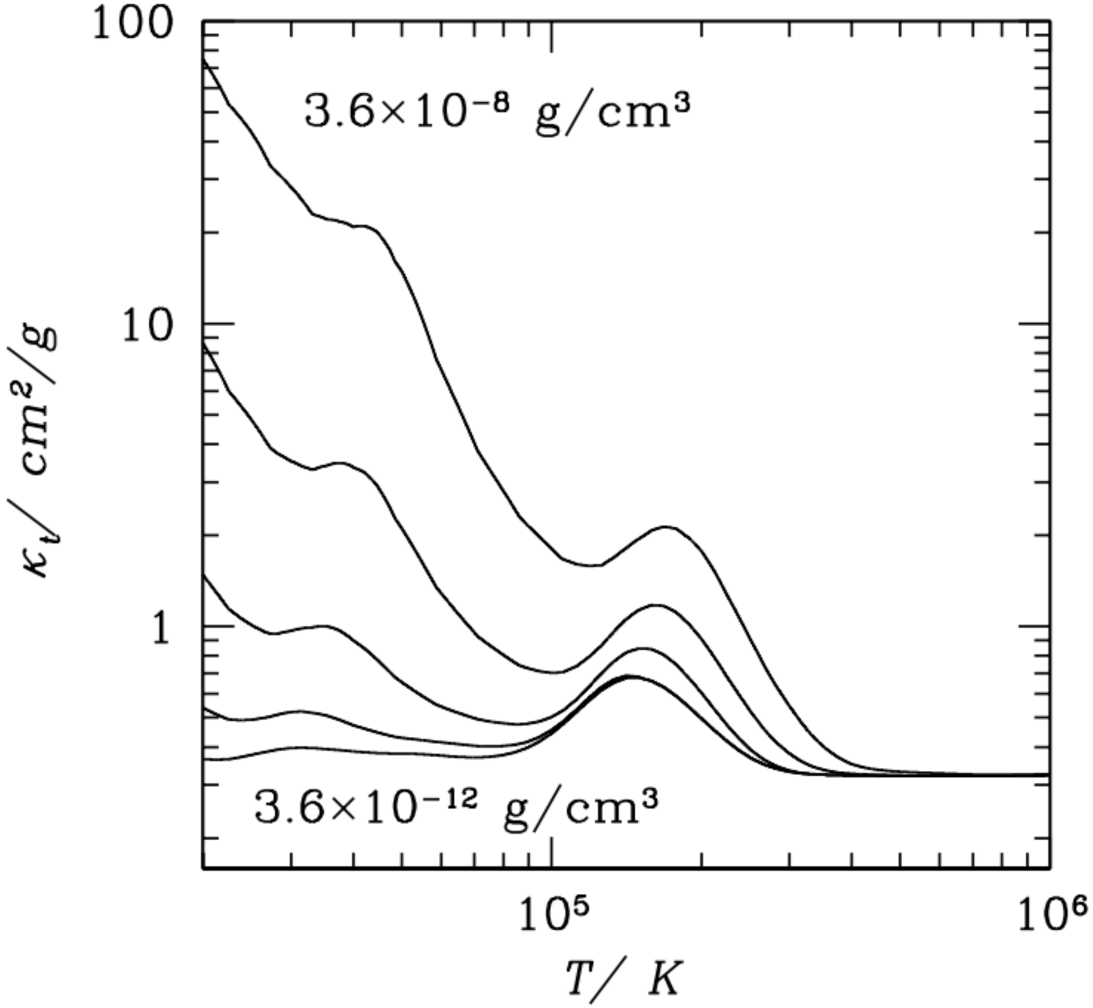
$$\frac{\partial I}{\partial t} + c\boldsymbol{n} \cdot \nabla I = S.$$

Radiative Transfer

$$S = c\rho\kappa_a \left(\frac{a_r T^4}{4\pi} - I_0 \right) + c\rho\kappa_s \left(J_0 - I_0 \right),$$

Lorentz transformation between lab frame and co-moving frame to handle the velocity dependent source terms.

The Opacity

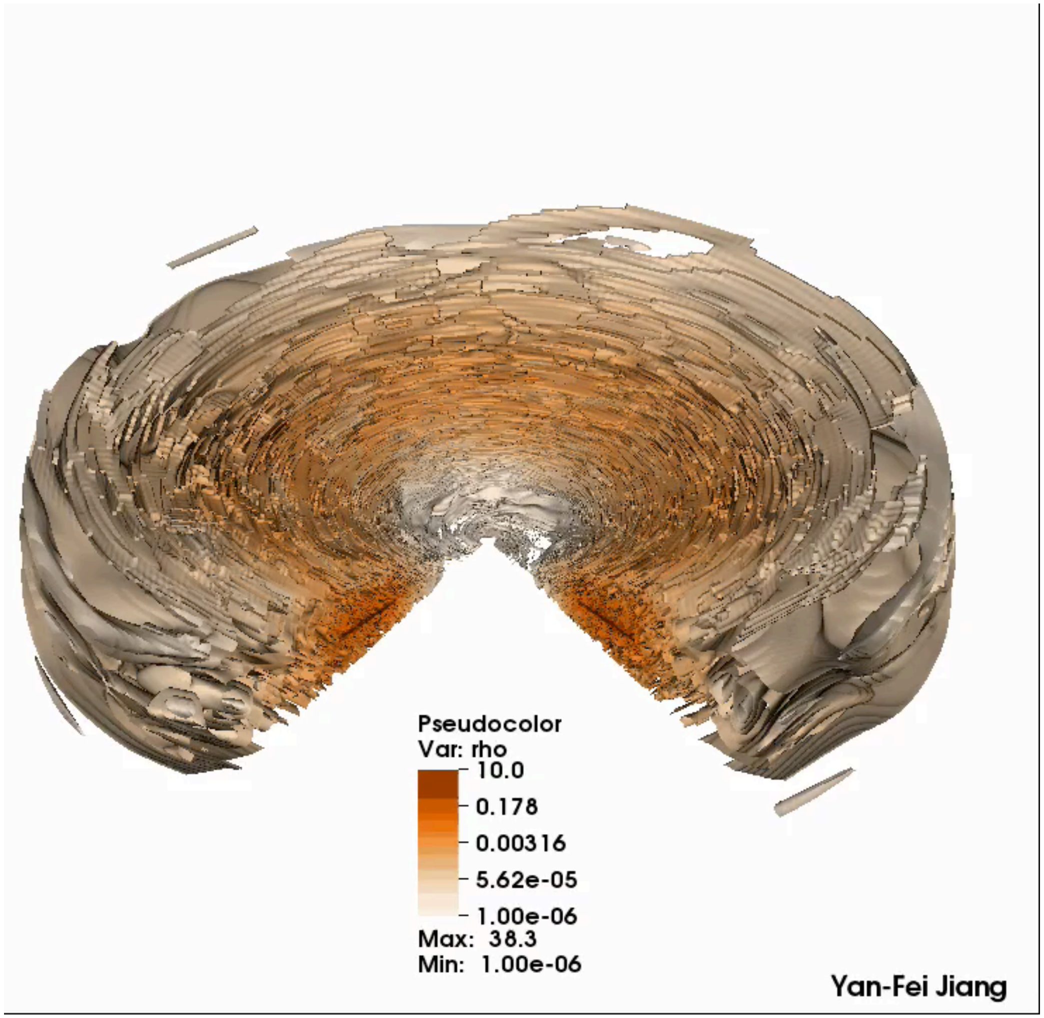


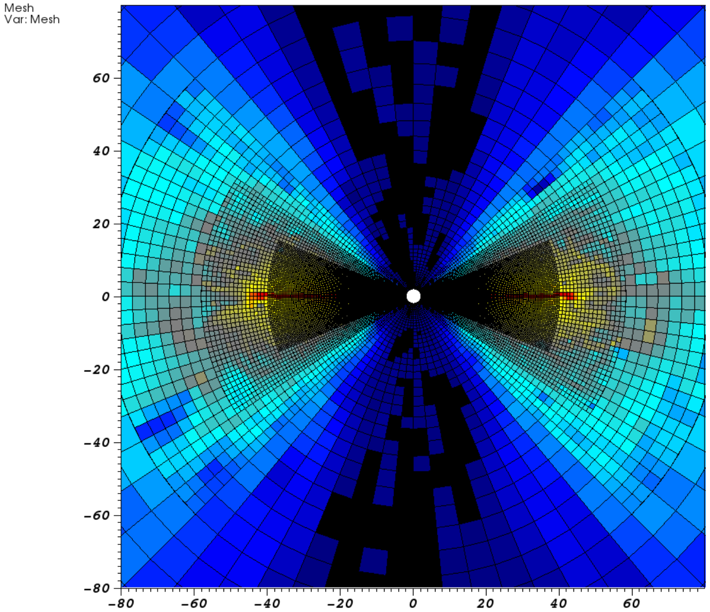
Paxton et al. (2013,2015)
Jiang et al. (2015,2016)

The density and temperature ranges are very similar as in massive star envelopes!

AGN disks with Mesh Refinement in Athena++

Stone et al., in preparation





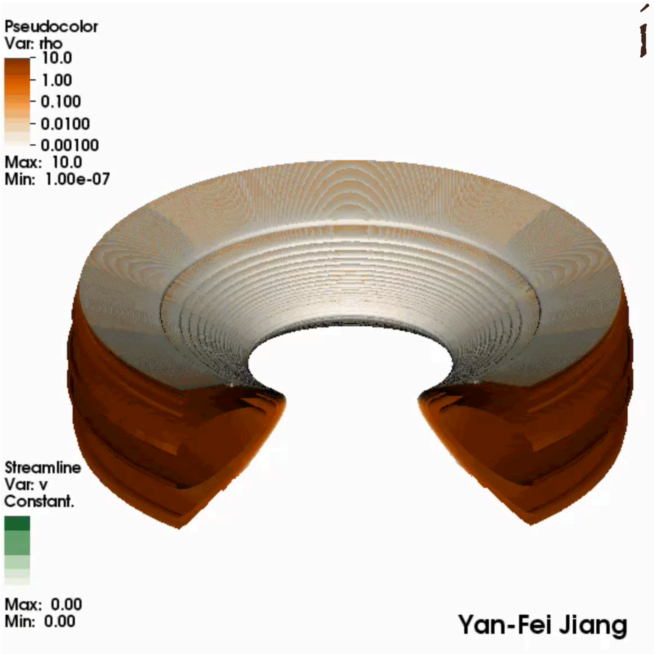
Level 0

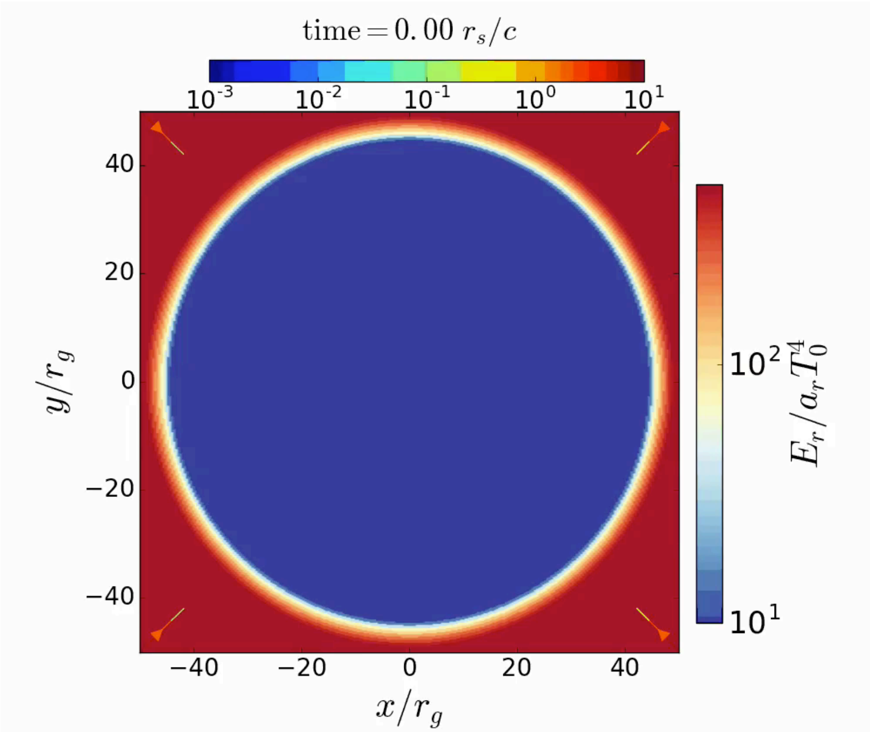
$$N_r \times N_\theta \times N_\phi = 64 \times 32 \times 64$$

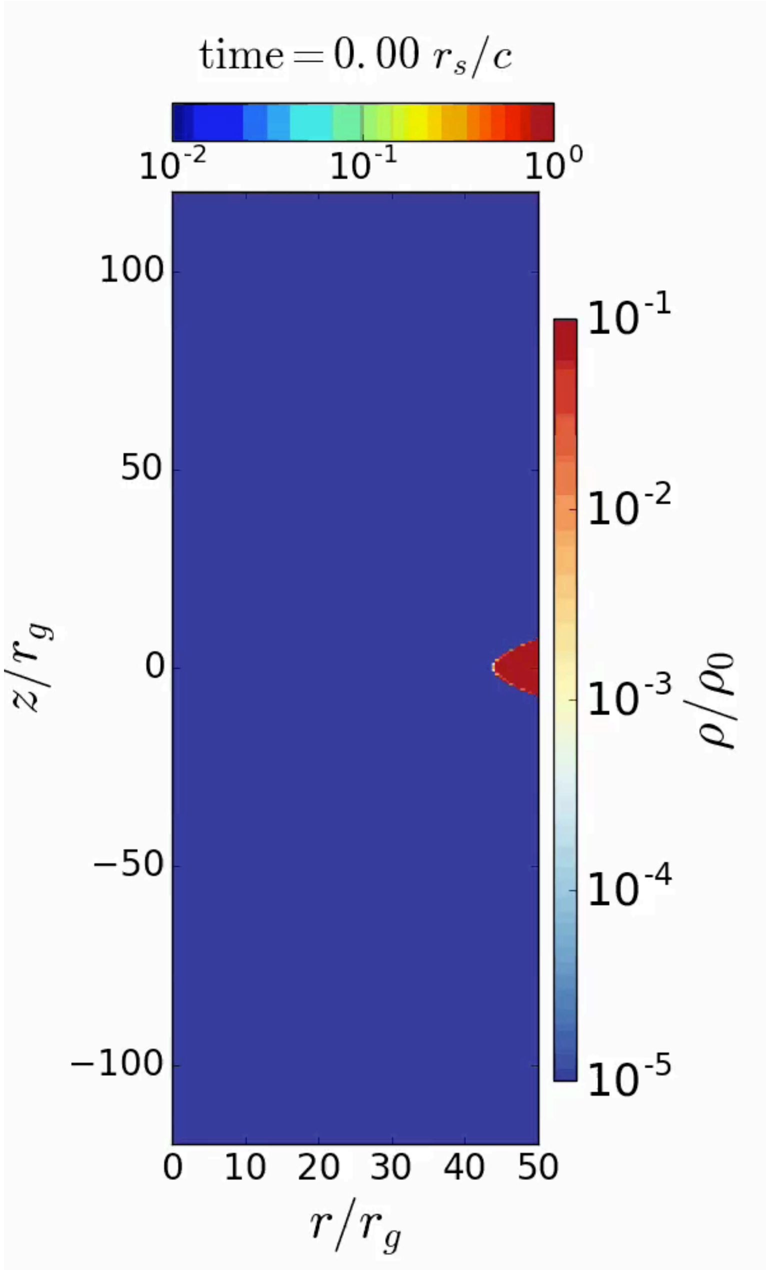
Level 4

$$N_r \times N_\theta \times N_\phi = 1024 \times 512 \times 1024$$

Super-Eddington AGN disks with Mesh Refinement in Athena++



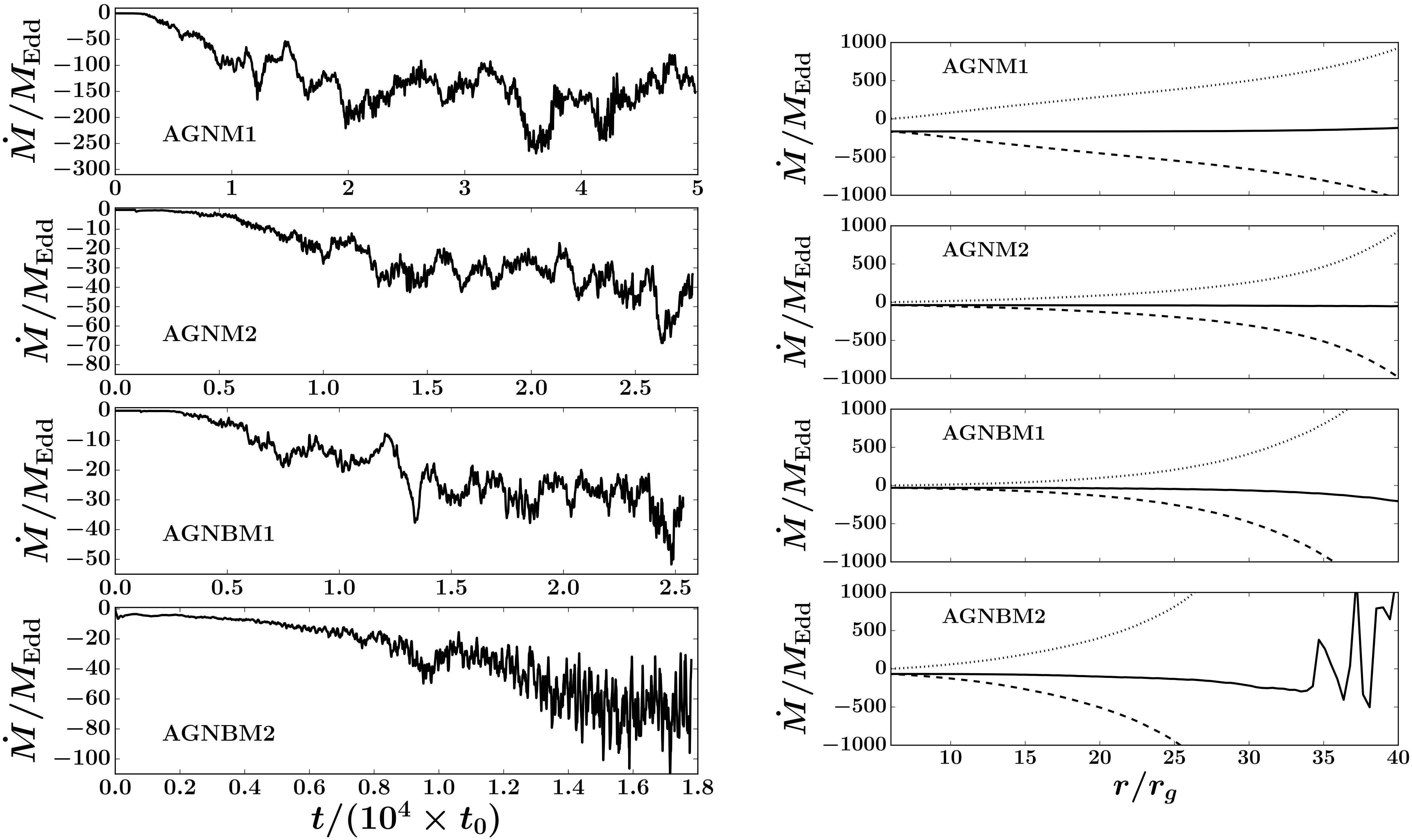




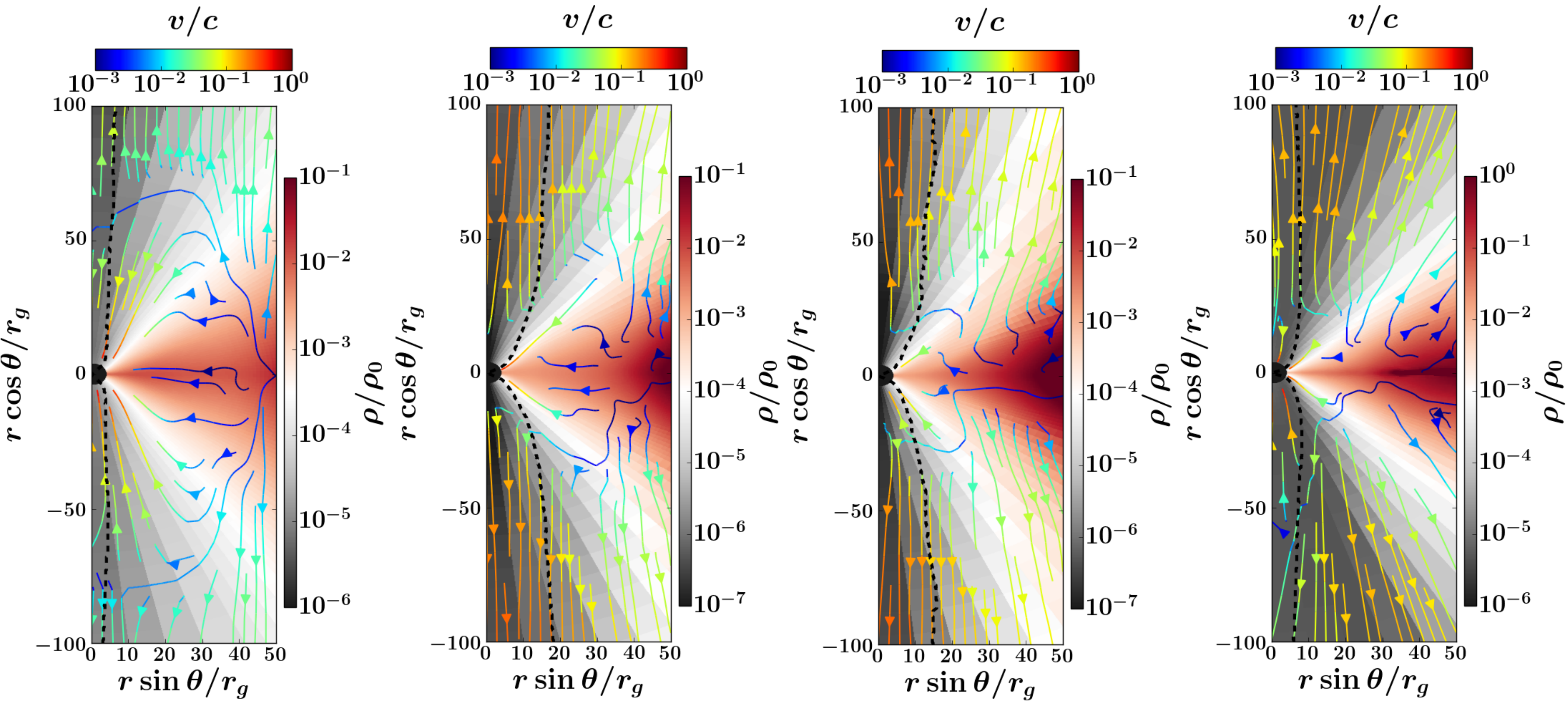
Simulation Parameters

Variables/Units	AGNM1	AGNM2	AGNBM1	AGNBM2
r_i/r_g	80	80	80	50
ρ_i/ρ_0	50	10	10	10
T_i/T_0	12.4	8.4	8.3	8.4
$\Delta r/r$	0.024	0.012	0.012	0.012
$\Delta\theta$	0.024	0.012	0.012	0.012
$\Delta\phi$	0.024	0.012	0.012	0.012
N_n	80	80	80	80
B Loops	Multiple	Multiple	Single	Single

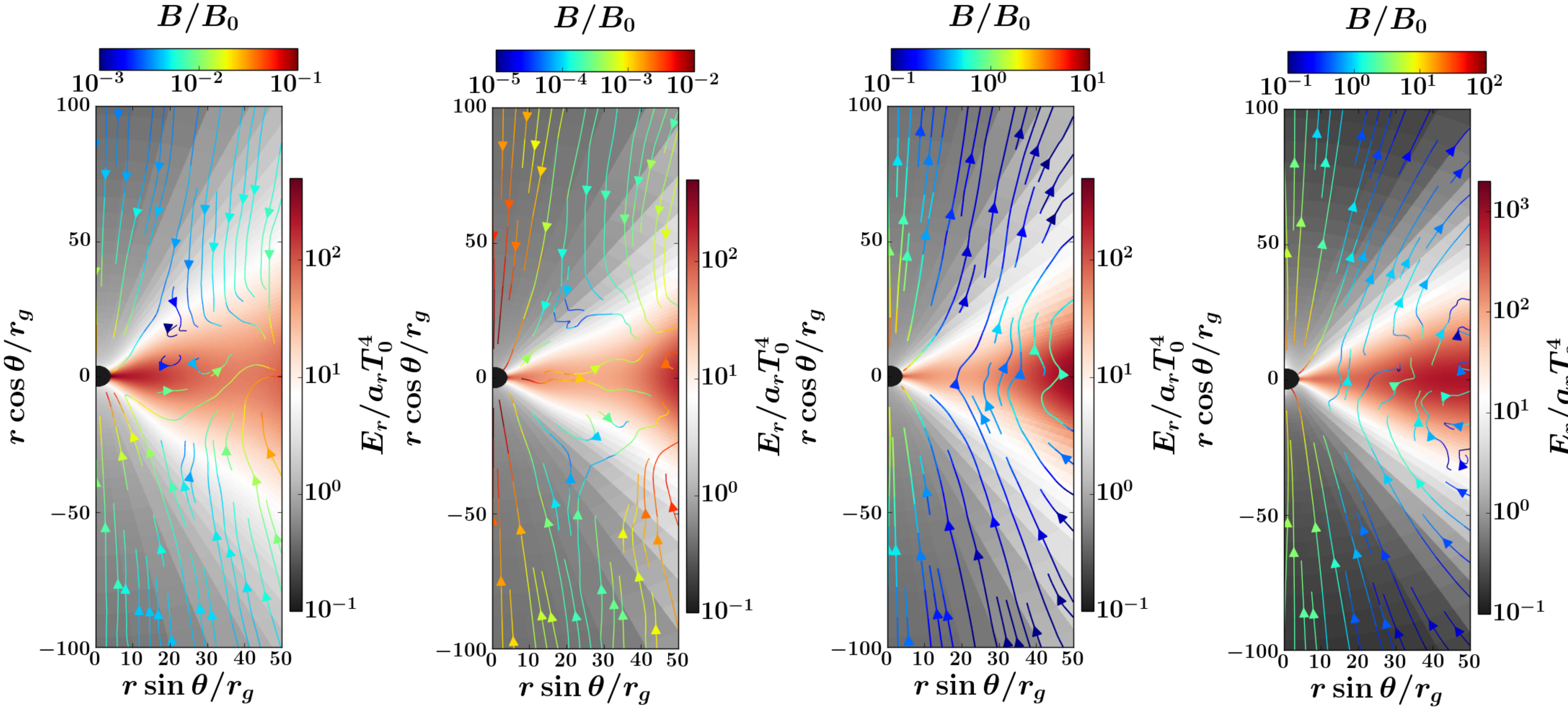
Mass Accretion Rates



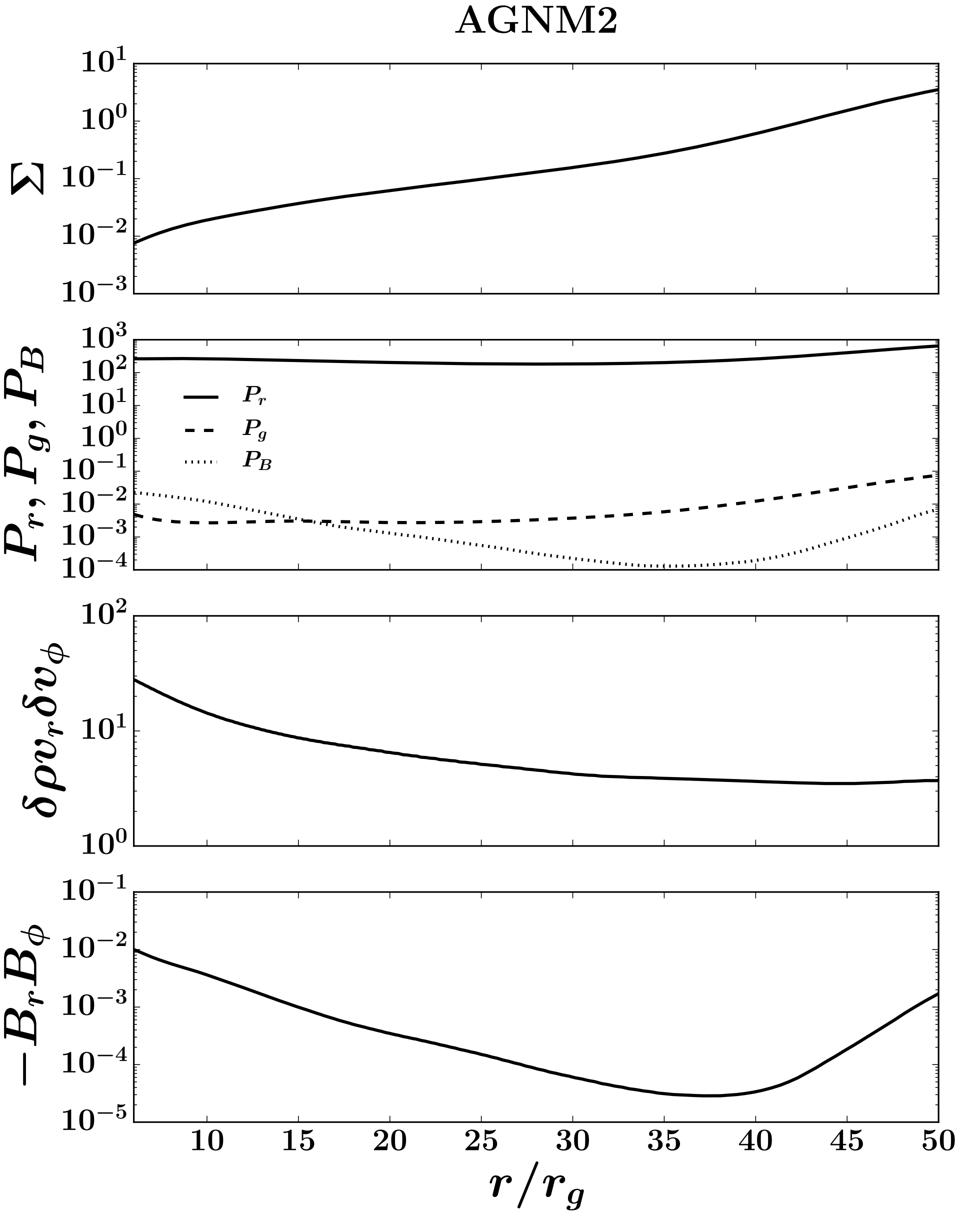
Flow Structures

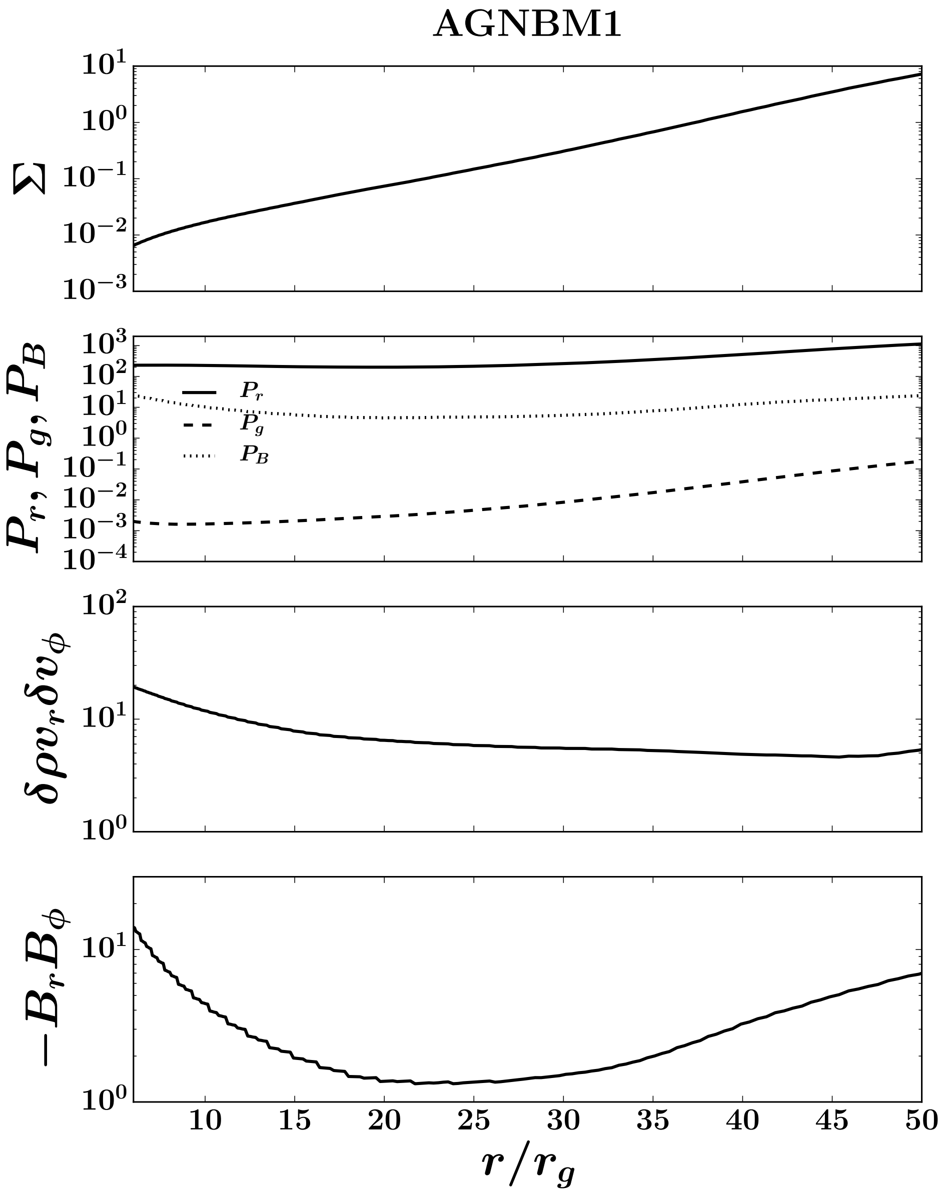


Flow Structures

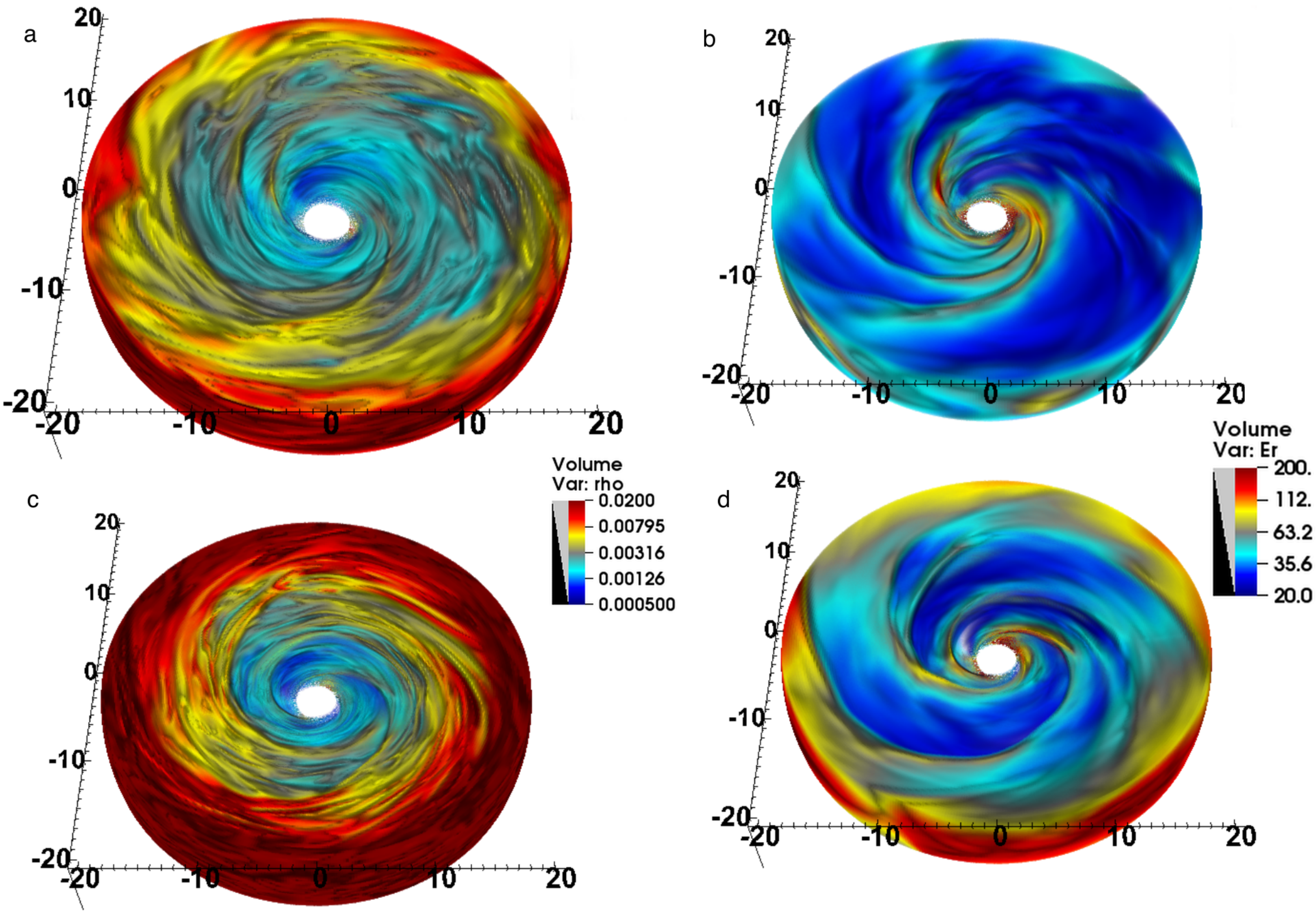


Radial Profiles of the disk





The Density Waves

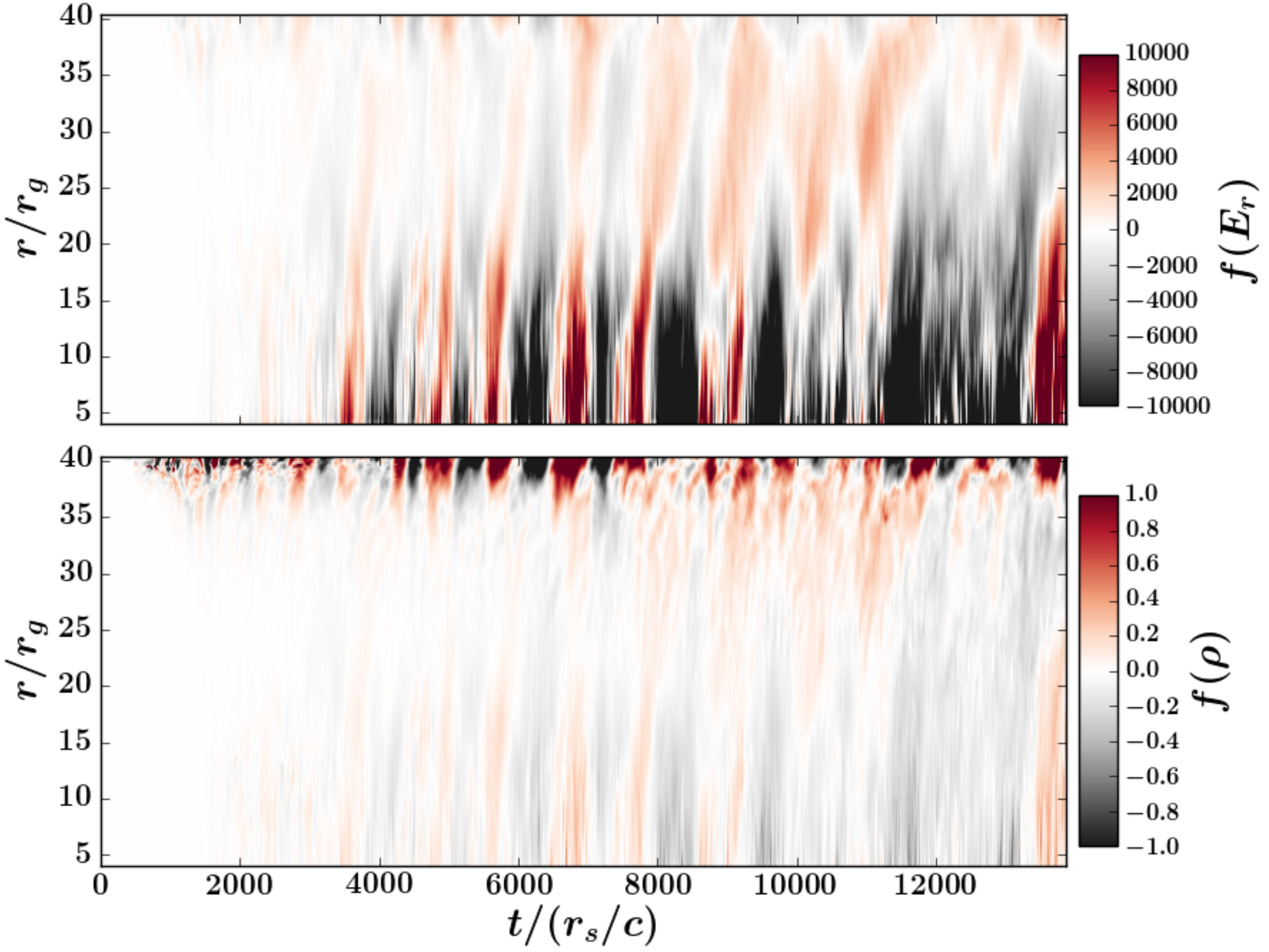


AGNM2

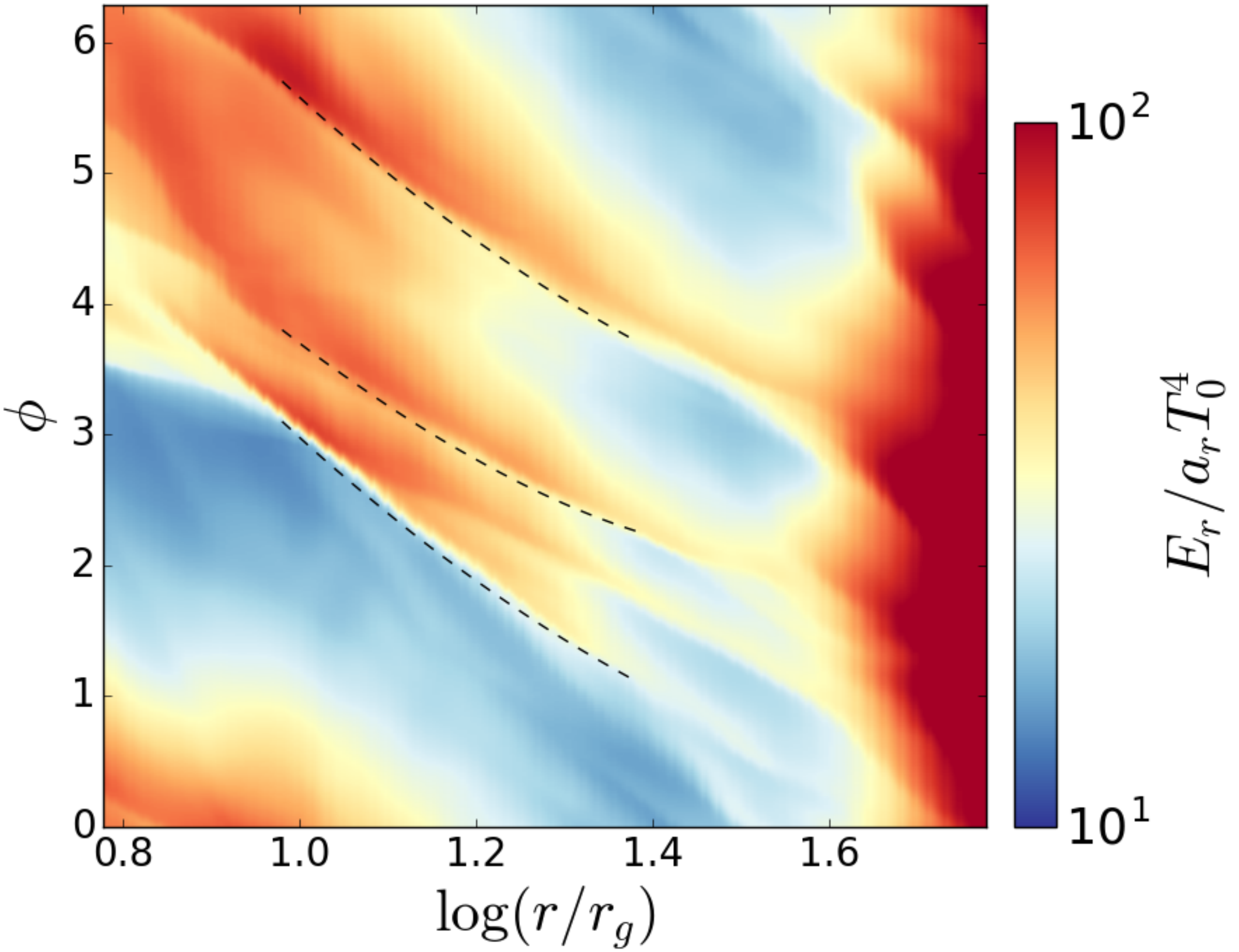
AGNBM1

The Density Waves

m=2

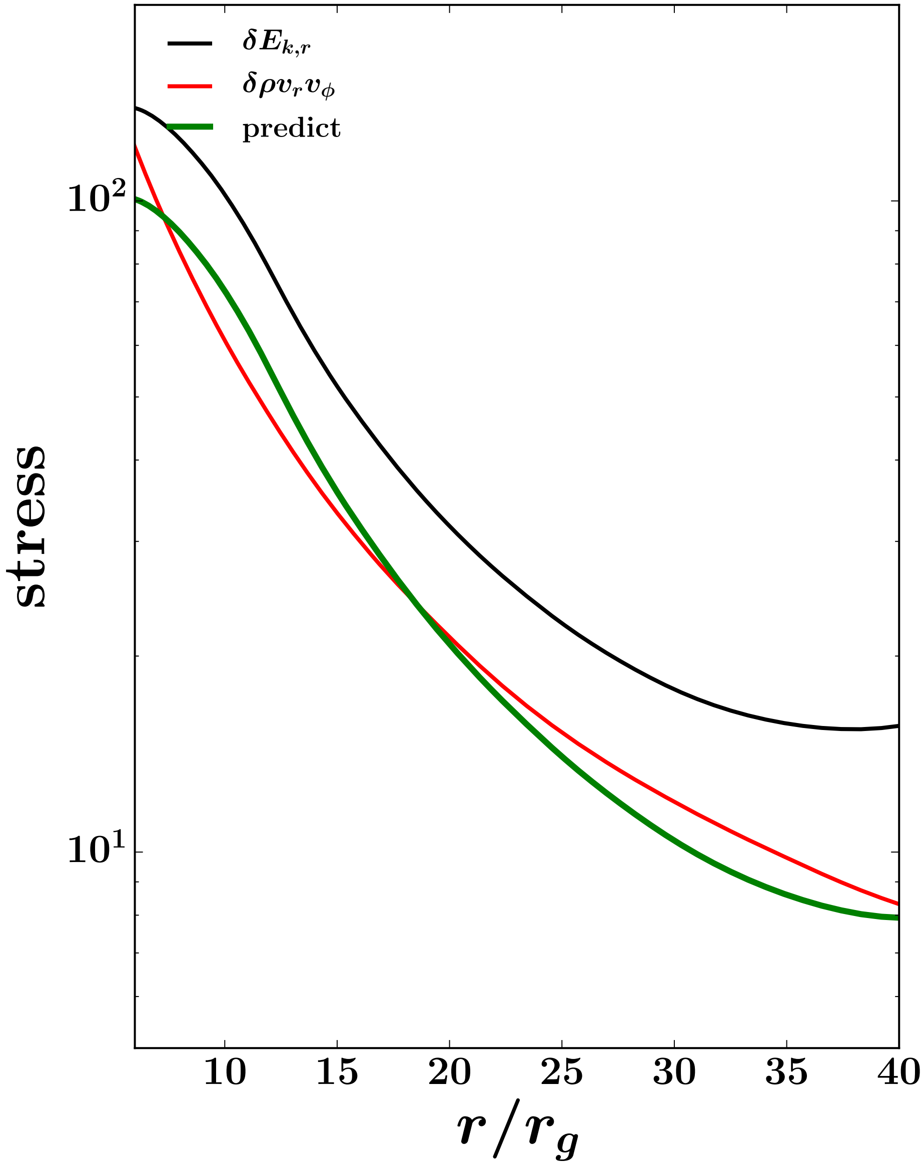


Positions of the Spiral Shock



$$d\phi = -\frac{k_r}{m} dr = -\frac{1}{c_s}\sqrt{(\Omega - \Omega_p)^2 - \kappa^2/m^2 dr}.$$

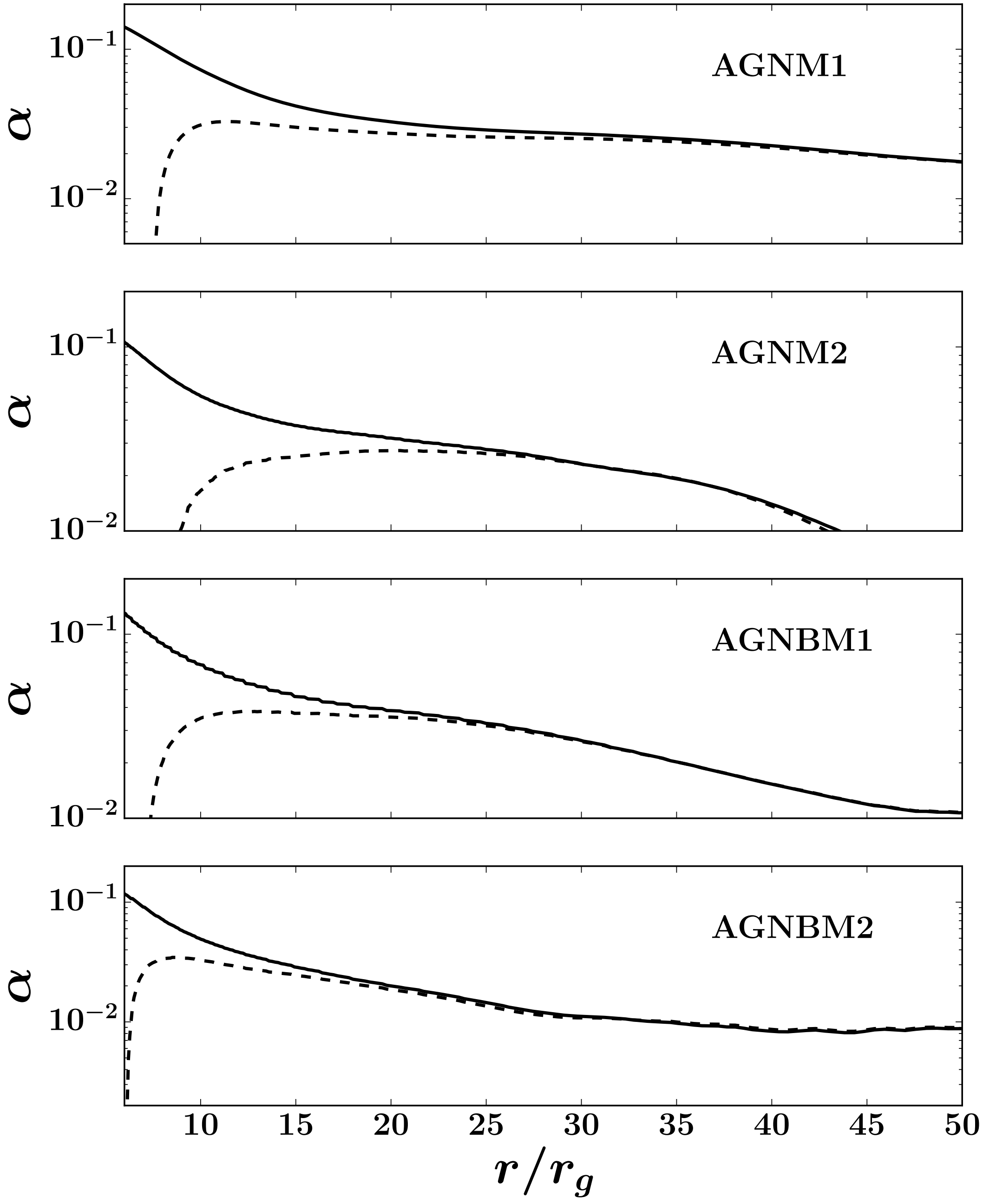
The Reynolds Stress



Balbus (2003)

$$\rho < \delta v_r \delta v_\phi >= m\left(1 - \frac{\kappa^2}{m^2\left(\Omega - \Omega_p\right)^2}\right)\rho < \left(\delta v_r\right)^2 >$$

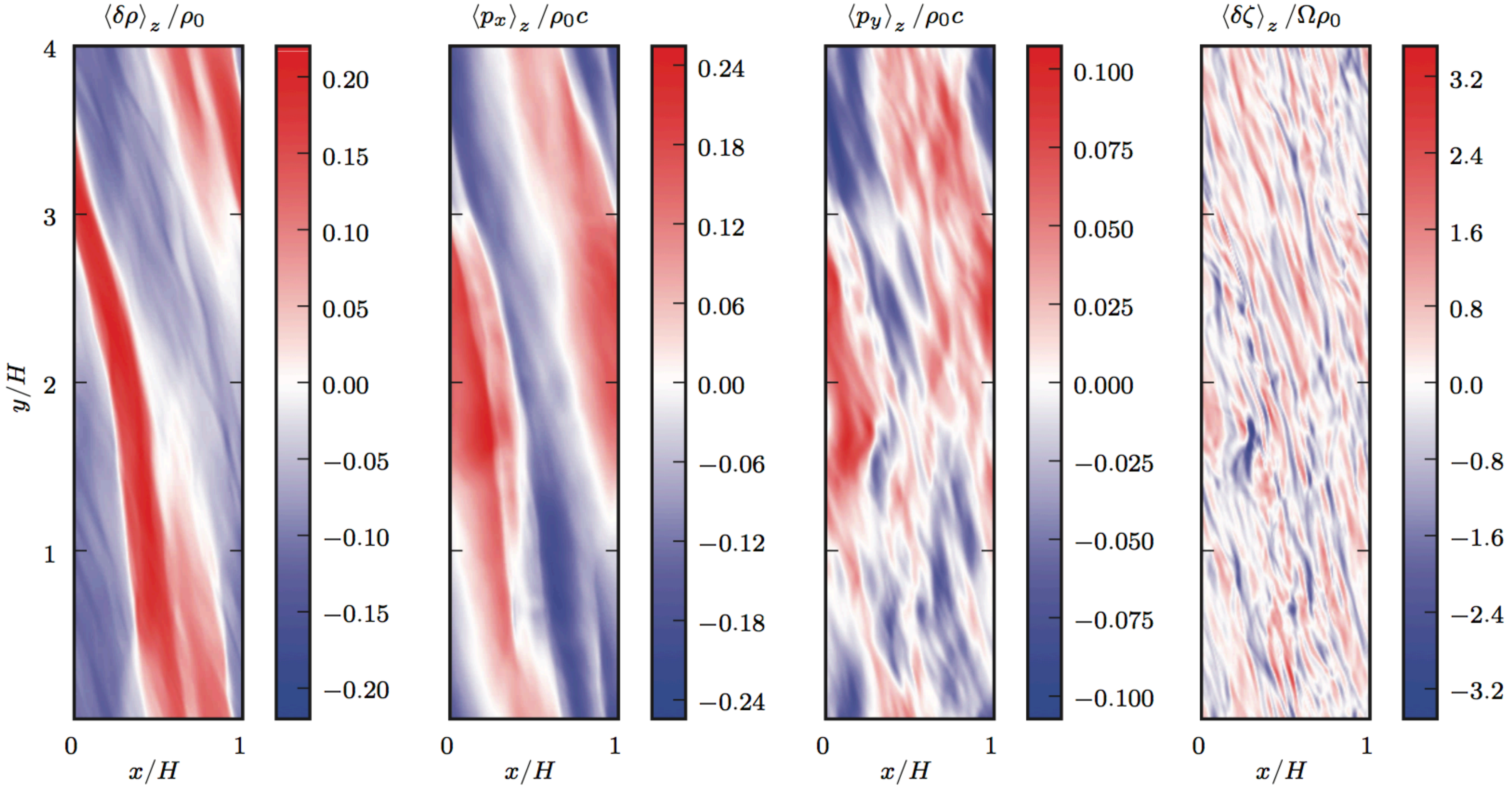
The Effective Alpha



Mechanism for Exciting Density Waves

Heinemann & Papaloizou (2009a,2009b,2012)

- Vortensity can excite density waves



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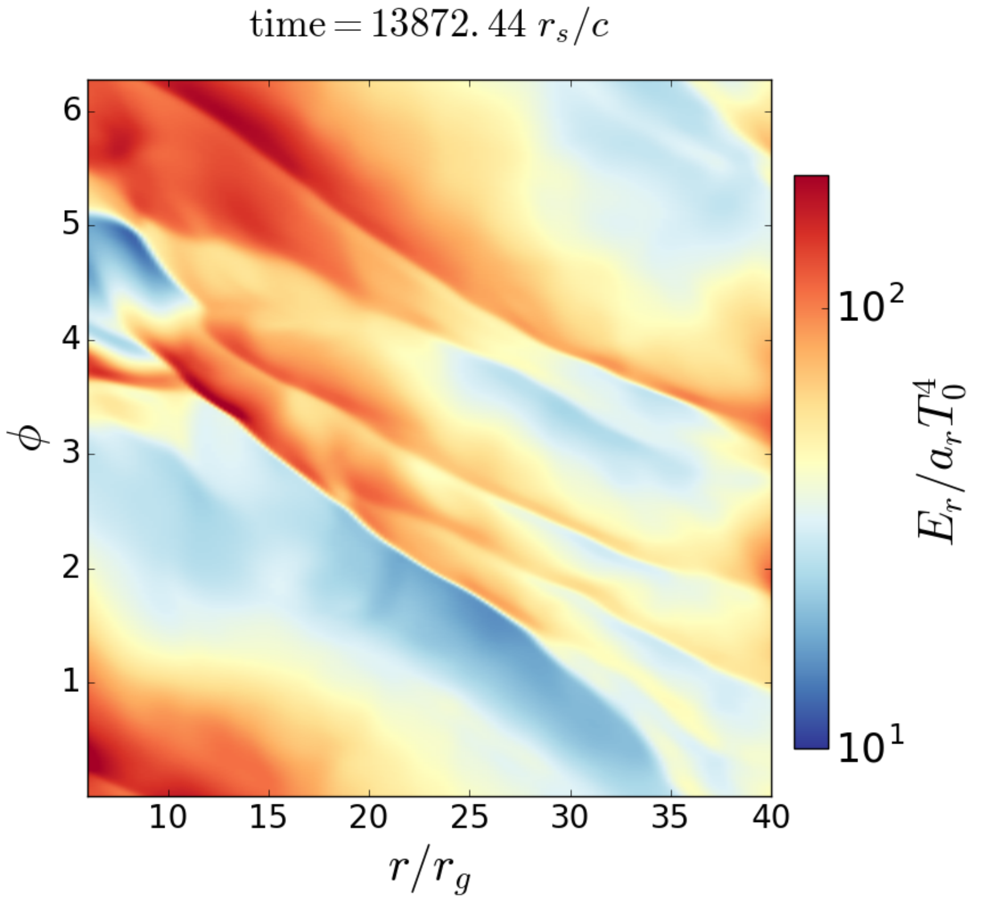
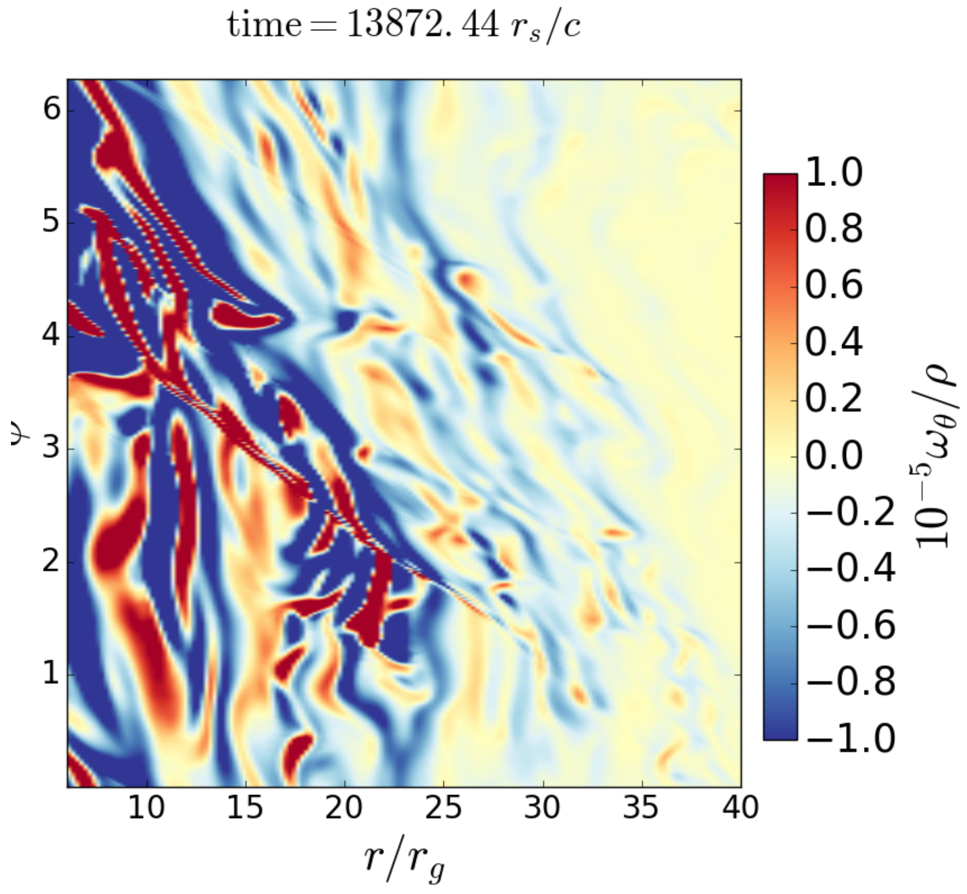




Mechanism for Exciting Density Waves

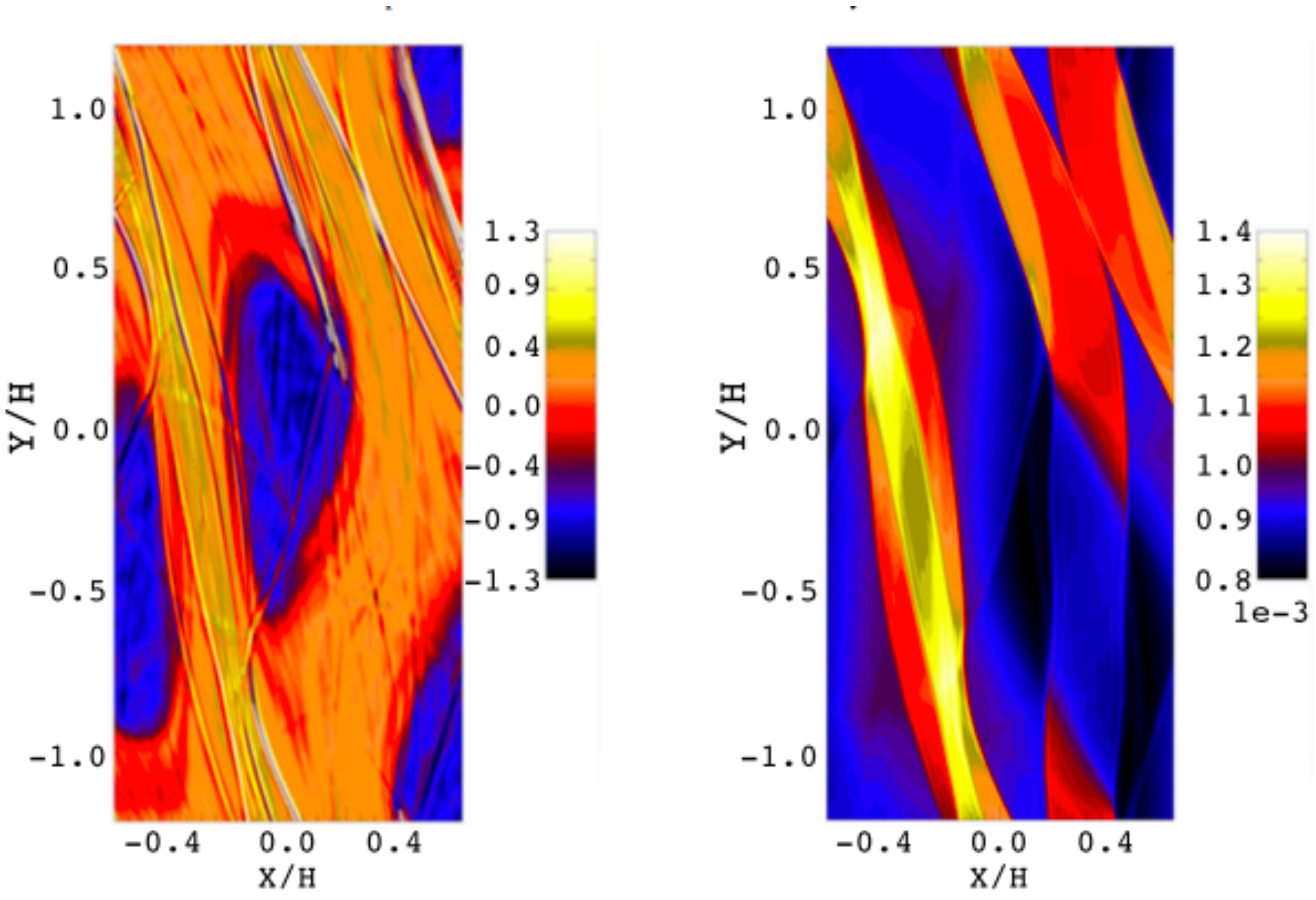
- What generates vorticity

$$
\begin{aligned}
\frac{\partial}{\partial t}\left(\frac{\boldsymbol{\nabla}\times\boldsymbol{v}}{\rho}\right) &= \frac{\omega}{\rho}\cdot\boldsymbol{\nabla}\boldsymbol{v}-\boldsymbol{v}\cdot\boldsymbol{\nabla}\left(\frac{\omega}{\rho}\right)\\
&+\frac{1}{\rho^3}\boldsymbol{\nabla}\rho\times\boldsymbol{\nabla}(P^{*}+P_r)-\frac{1}{\rho^3}\boldsymbol{\nabla}\rho\times\boldsymbol{\nabla}\cdot(\boldsymbol{BB}).
\end{aligned}
$$

  - Maxwell stress
  - Baroclinic term

The Baroclinic Instability

Klahr (2004)
Johnson & Gammie (2005)
Lesur & Papaloizou (2010)

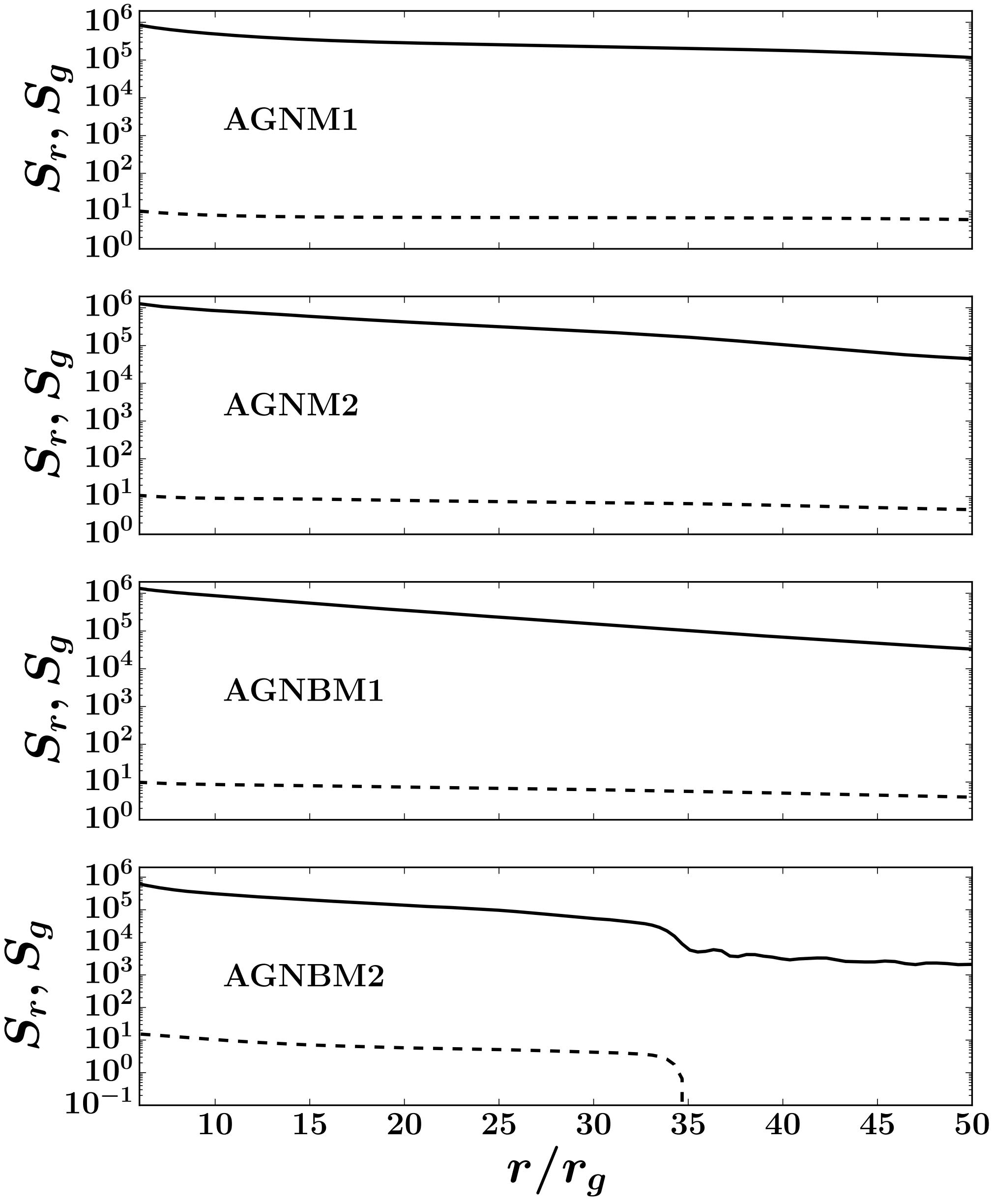


The Baroclinic Instability

Klahr (2004)
Johnson & Gammie (2005)
Lesur & Papaloizou (2010)

- Necessary conditions
  - Large enough amplitude perturbations
  - Entropy decreases with increasing radius

The Baroclinic Instability



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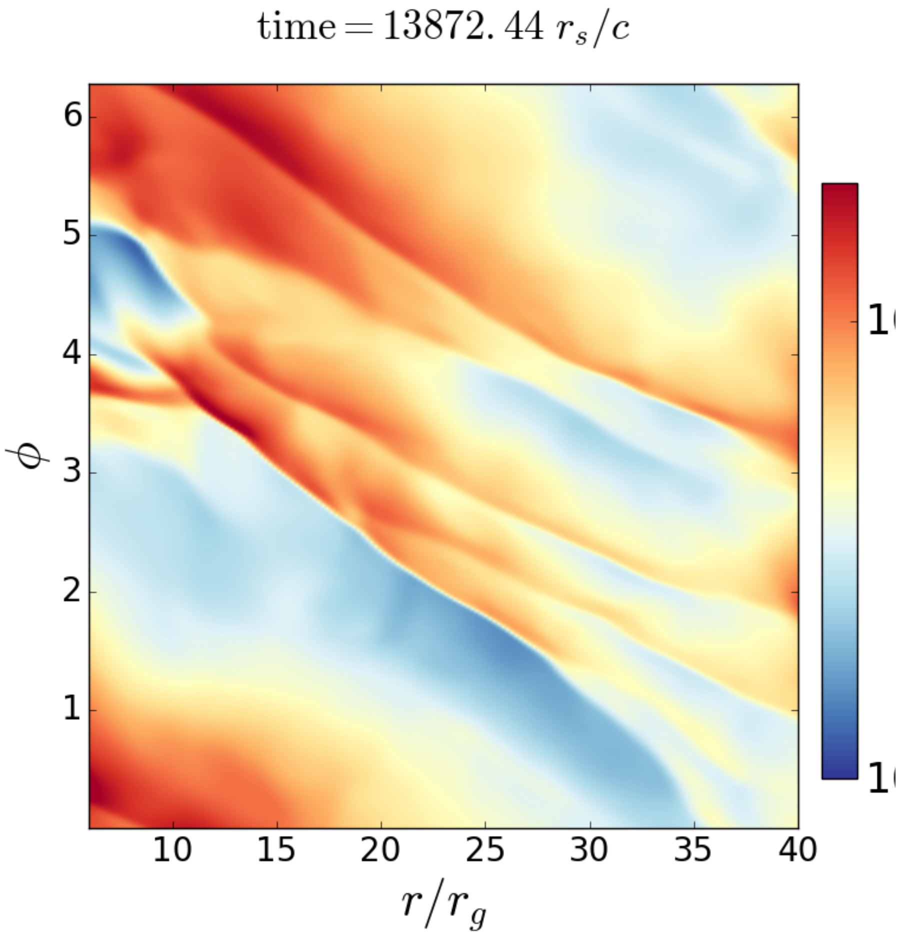
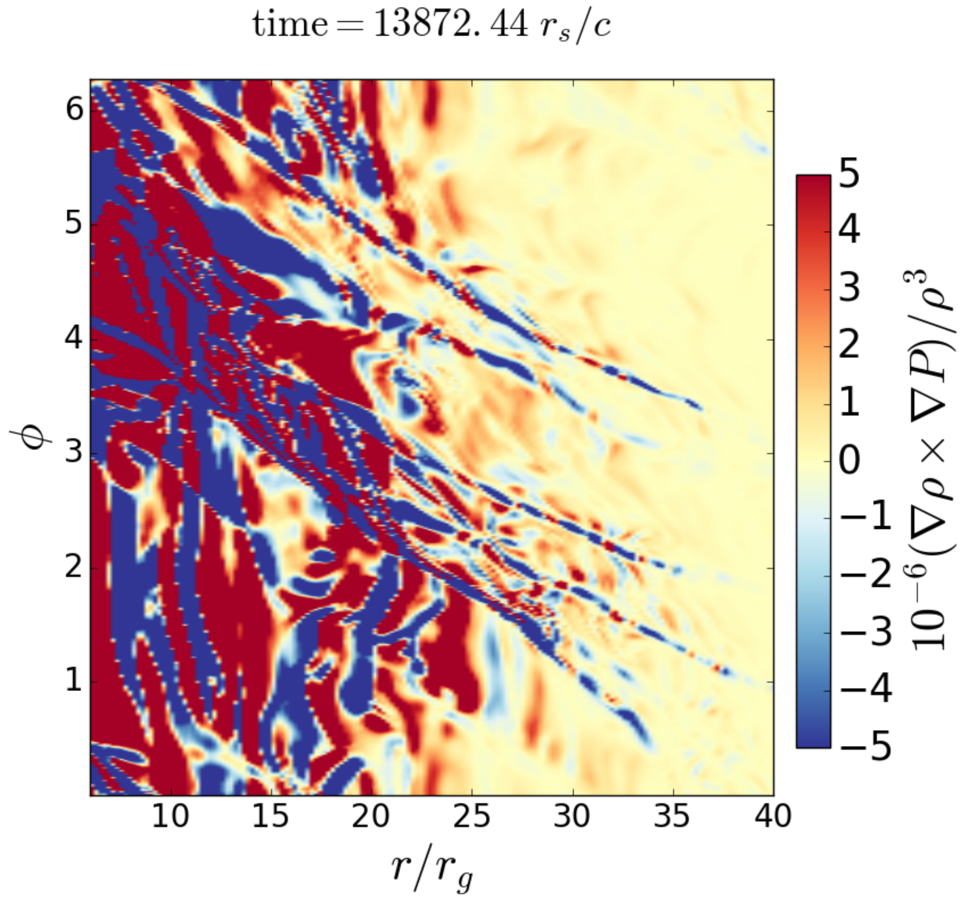
The Baroclinic Terms





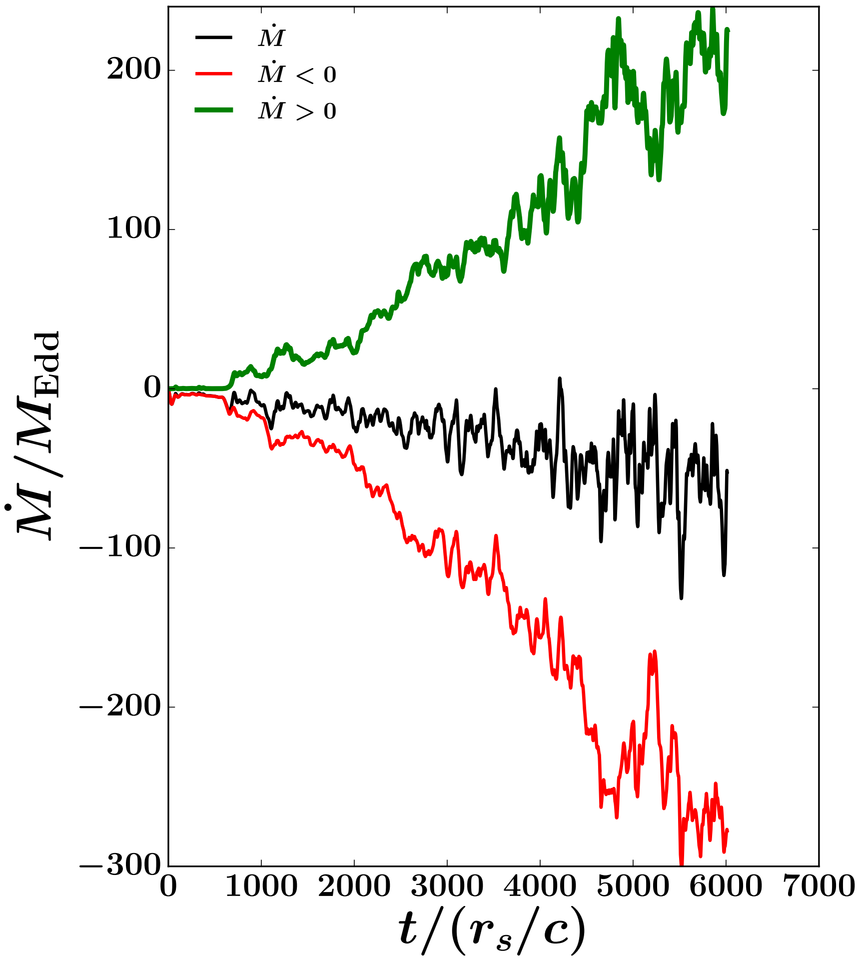
Implications

- Disks driven by spiral shocks may not behave like an alpha disk
- Spectrum of the disk
- Large azimuthal temperature fluctuations in the disk

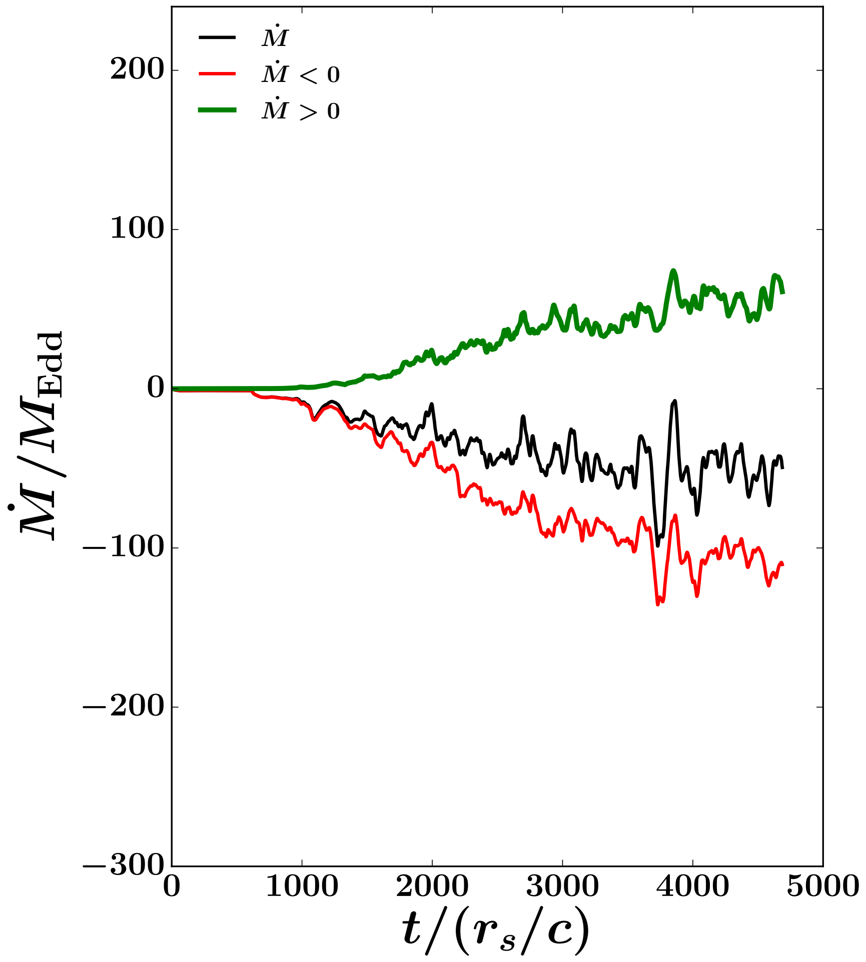
Dexter & Agol (2011)

Compare Accretion Disks in AGNs and X-ray binaries

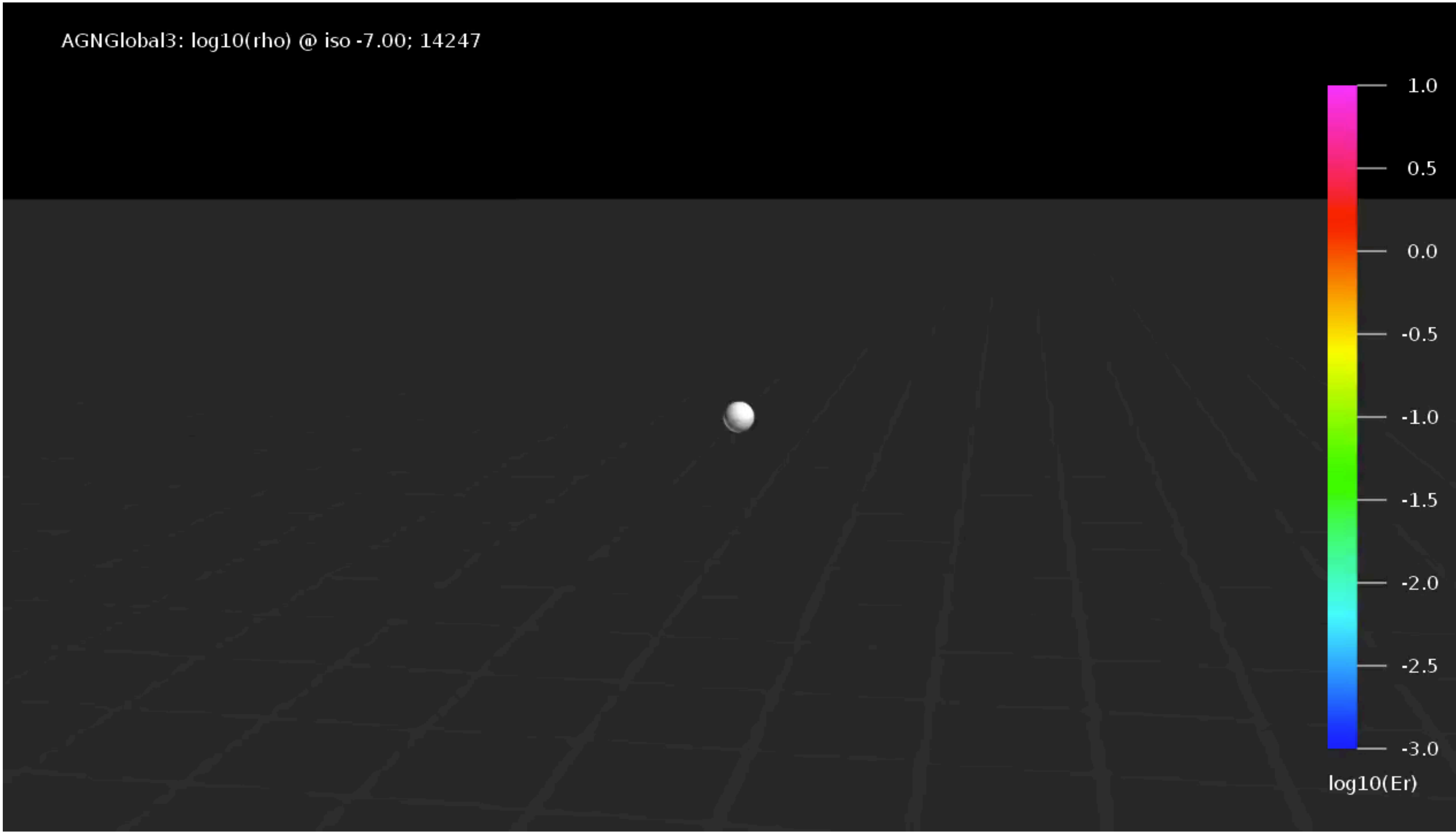
AGN



Stellar Mass Black Hole



Sub-Eddington AGN disks



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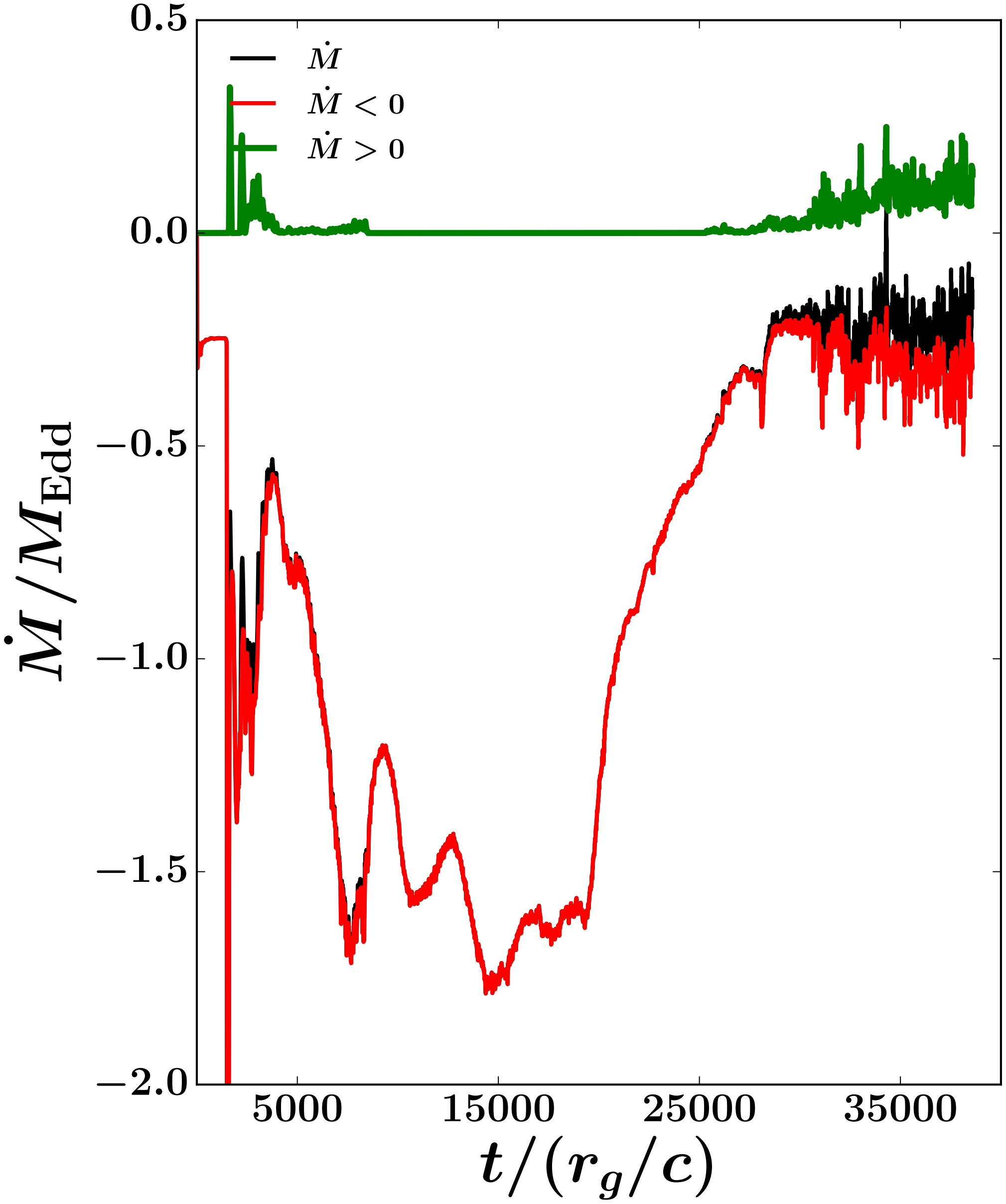
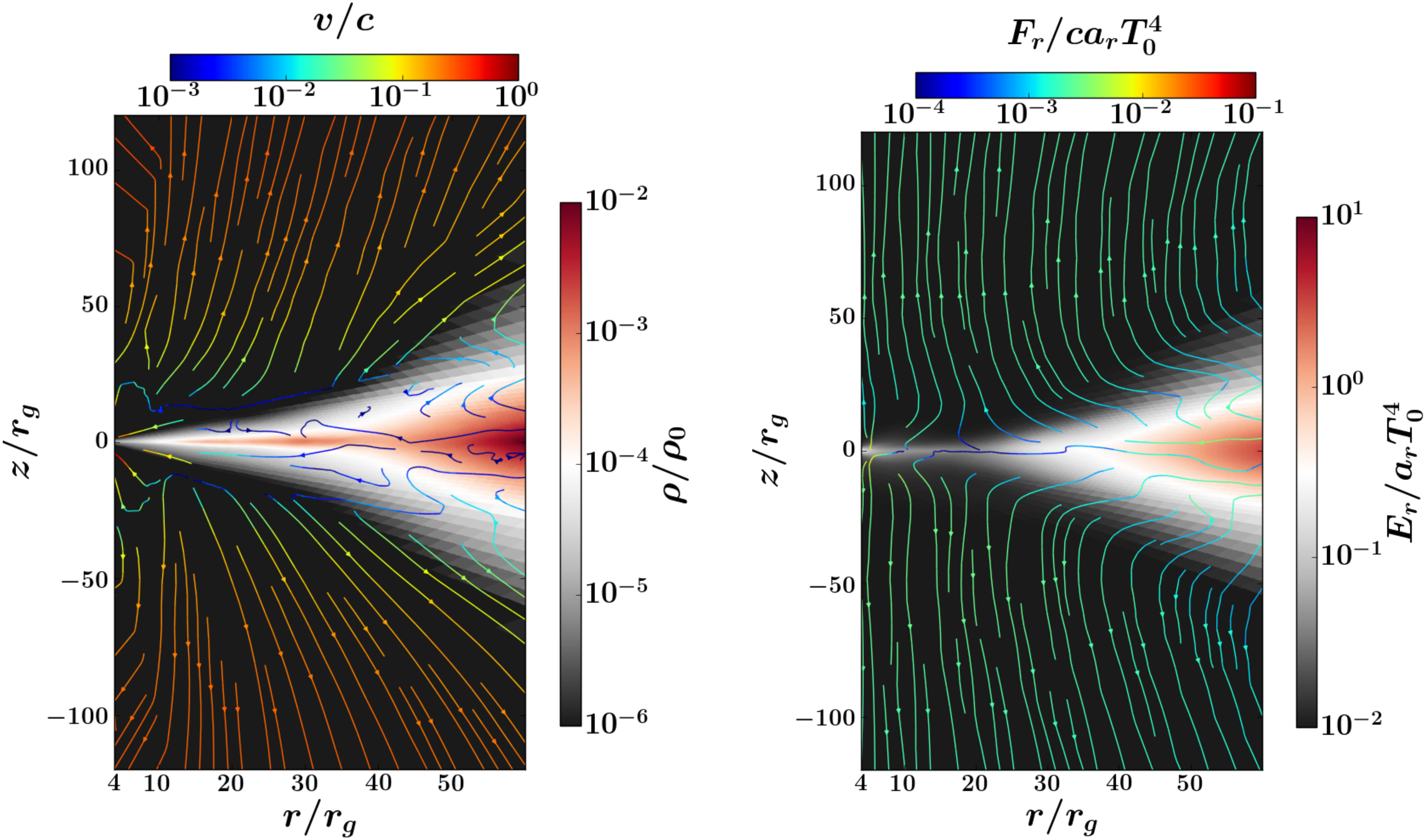
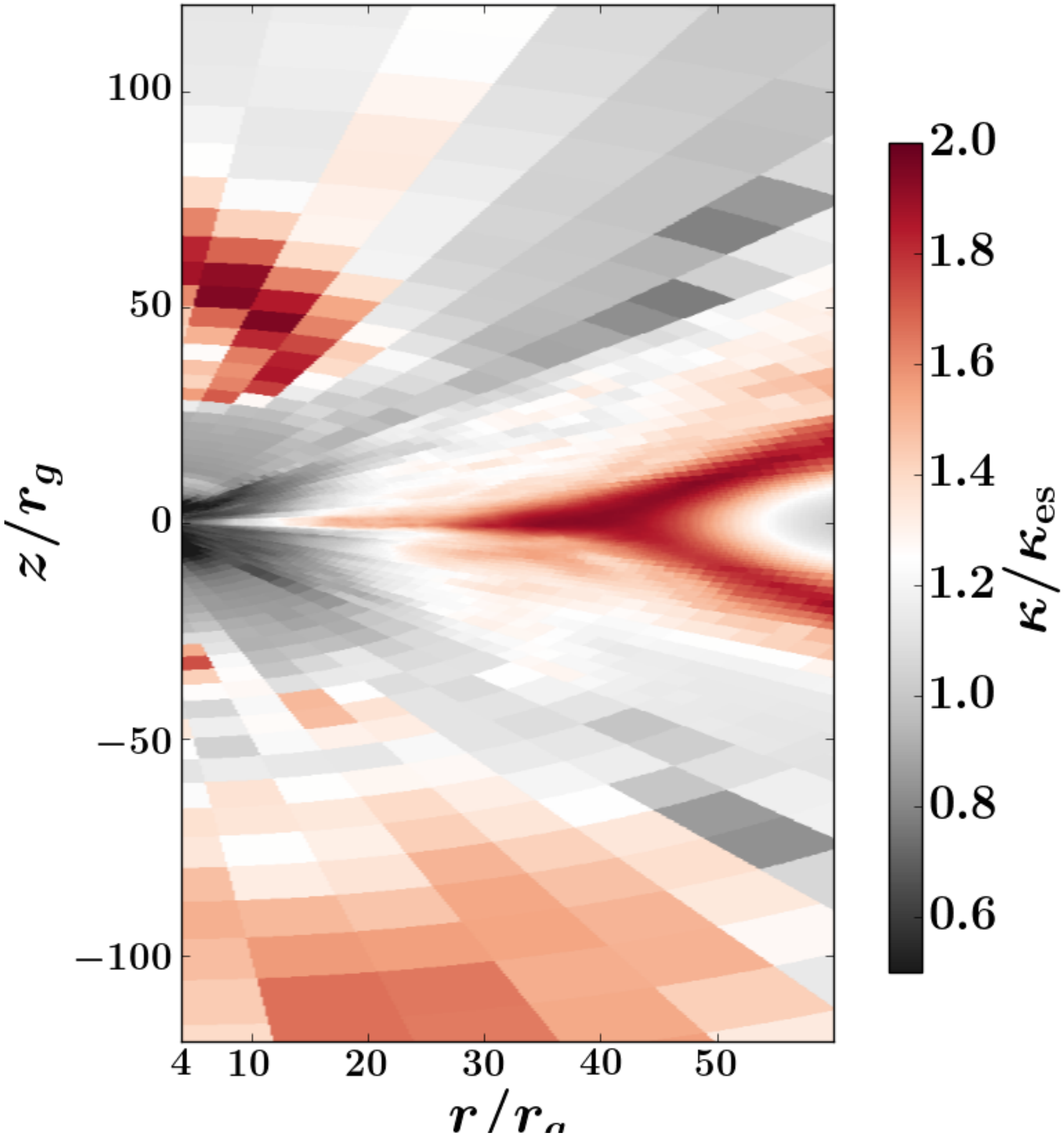


r=10r_g

Sub-Eddington AGN disks



The Opacity



100
50
0
−50
−100
z/r_g
4
10
20
30
40
50
r/r_g
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
$\kappa/\kappa_{\rm es}$

Summary

- 3D Global MHD simulations of black hole accretion disks with self-consistent radiation transfer are doable!
- Density waves excited in AGN disks can dominate the angular momentum transfer and dissipation
- Significant radiation driven outflow in AGN disks