MHD simulations of planet-disk interaction

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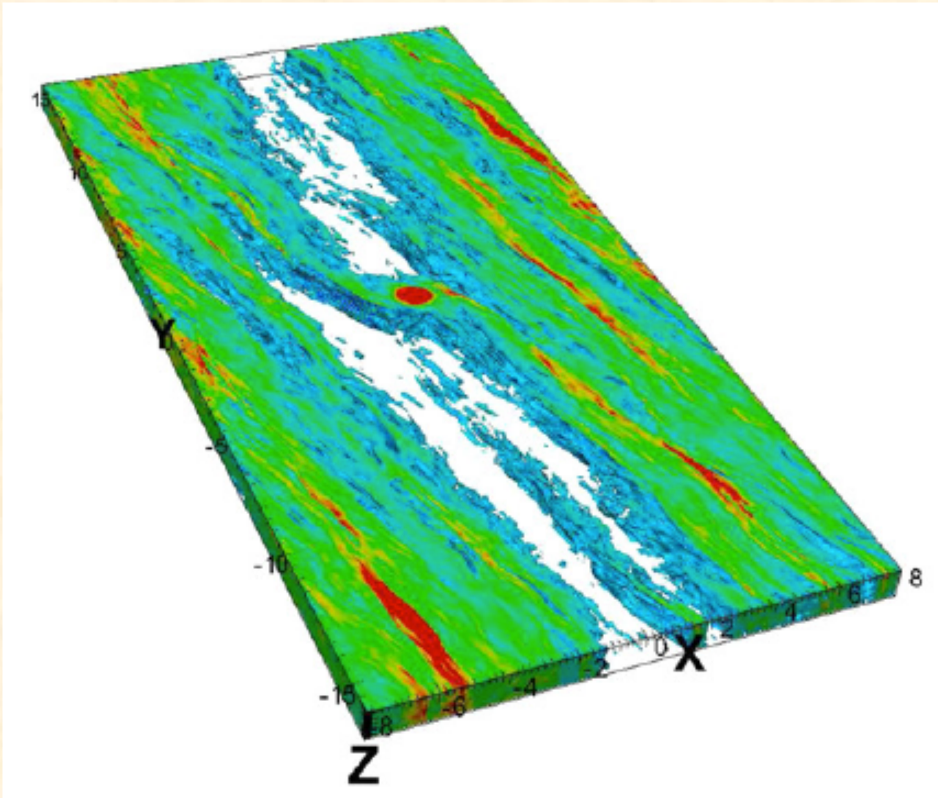
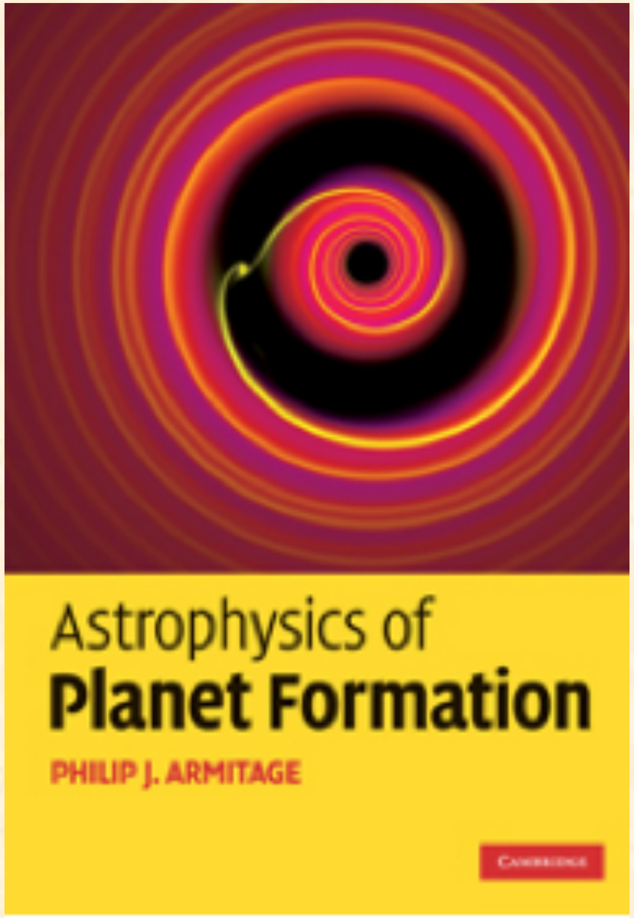


Introduction

Planets excite density waves in gaseous disks.

Such waves can lead to angular momentum exchange between planet and disk. This can lead to planet migration.



Deposition of angular momentum in disk can open gaps, which can then strongly affect planet growth and migration.

(see also review by Kley & Nelson 2012)

Gap opening criteria

Thermal criterion:

Hill radius of planet must exceed disk scale height.

This requires M > M_{th}

$$M_{\rm th} = C_s^3/(G\Omega_p)$$

$$\approx 12\left(\frac{C_s}{1\ \mathrm{km\ s^{-1}}}\right)^3\left(\frac{r_p}{1\ \mathrm{AU}}\right)^{3/4} M_\oplus$$

Viscous criterion:

Torque on gas from planet must exceed viscous effects.

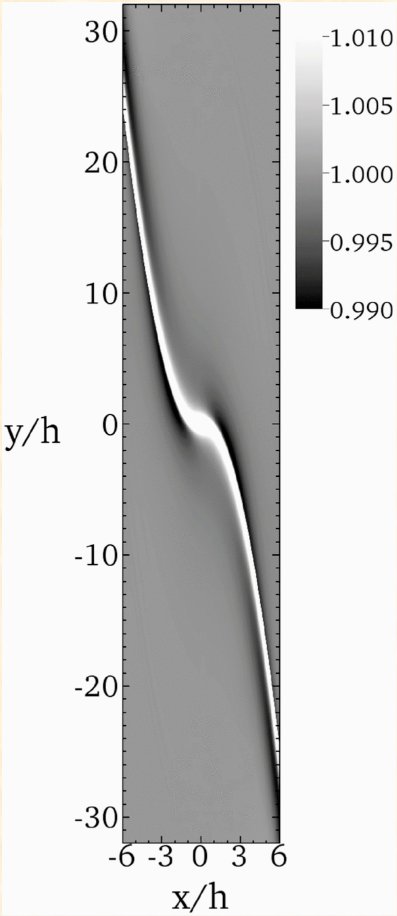
Can be used to place an upper limit on planet mass for a given α

$$M_p > M_{\rm th}\left(\frac{\alpha}{0.043}\frac{a}{h}\right)^{1/2}$$

But PPDs are not viscous (although they may be turbulent).

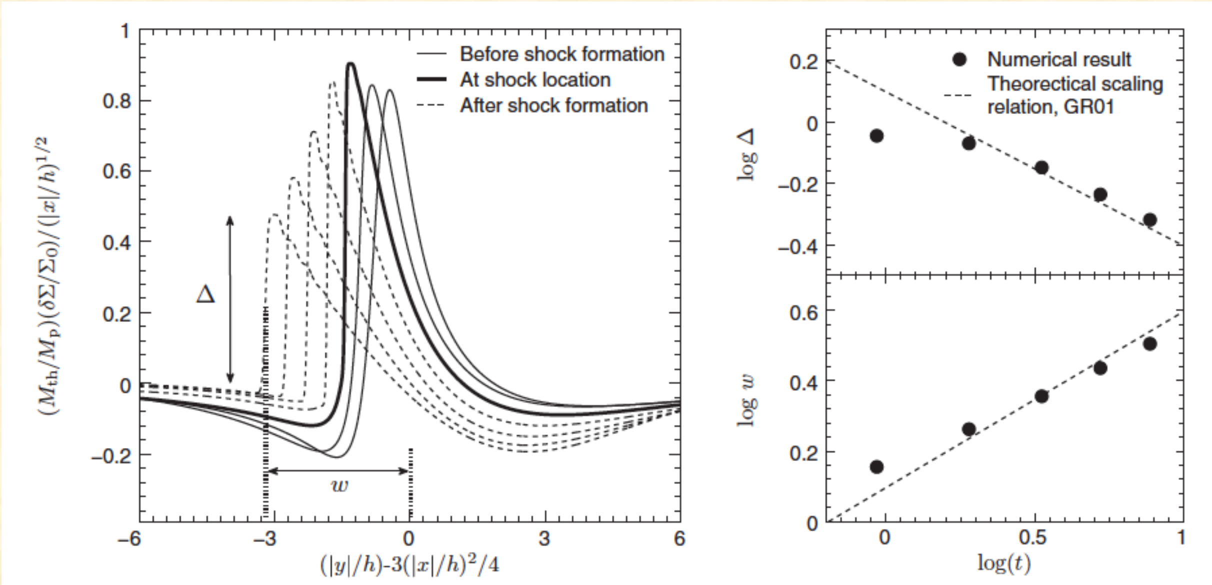
Linear density waves launched by low-mass planets ($M < M_{th}$) steepen into shocks and open gaps in an inviscid disk

(Goodman & Rafikov 2001; Dong et al 2009; Muto et al 2010)



Shock-formation occurs at a distance:

$$|x| \approx 0.93 \left(\frac{5(\gamma+1)M_p}{12M_t} \right)^{-2/5} H$$

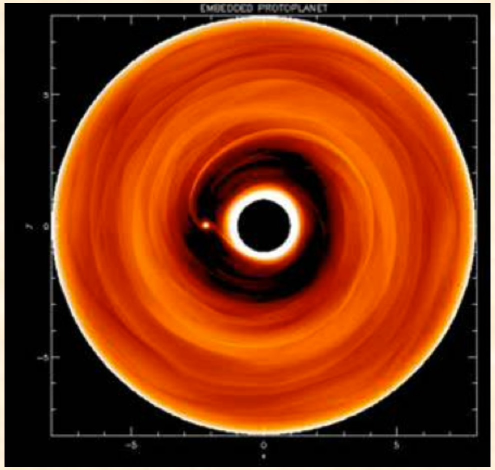


Caveat: gap opening timescale is so long planet migration must be included (Ward 1997; Rafikov 2002a;b ; Li et al 2009)

Previous studies of gap opening in turbulent MHD disks

Gap opening by both high and low mass planets in MRI turbulence studied by a variety of authors:

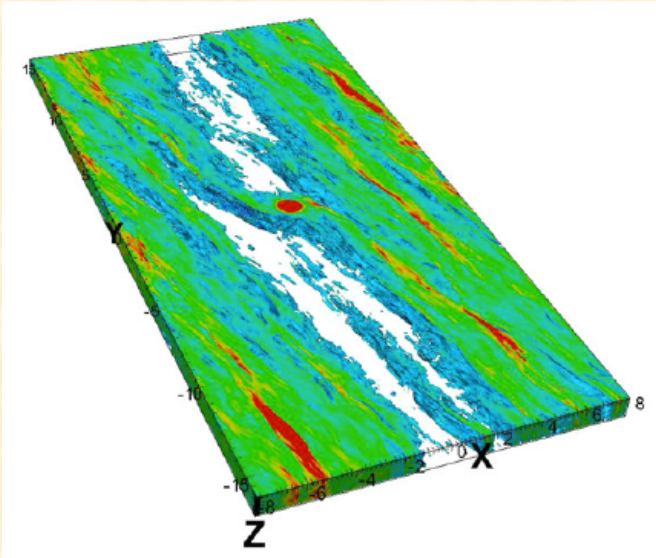
Winters et al 2003; Nelson & Papaloizou 2003; Papaloizou et al 2004; Uribe et al 2011; Baruteau et al. 2001; Gressel et al 2013



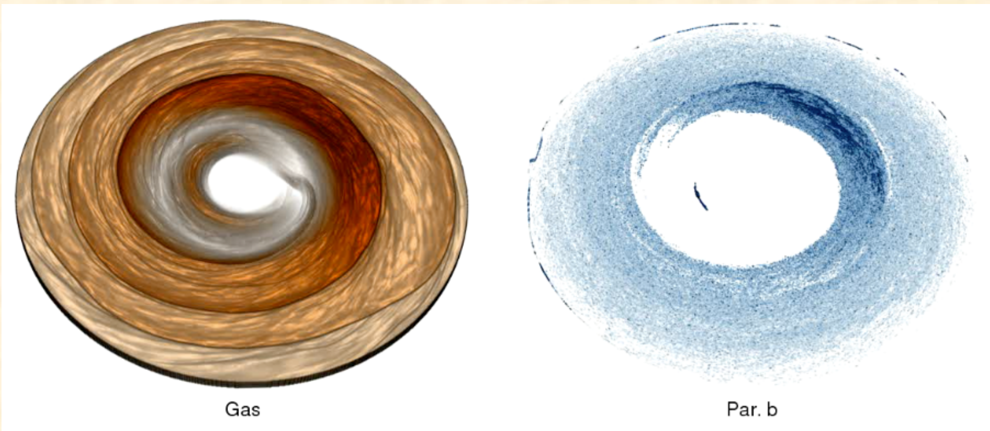
Nelson & Papaloizou 2003

Most previous work has used toroidal or no-net flux.

Our results are spread over two talks



This talk: high-resolution shearing box simulations of gap opening in ideal MHD using net vertical flux.



Next talk (Zhu): global non-ideal MHD simulations including particles

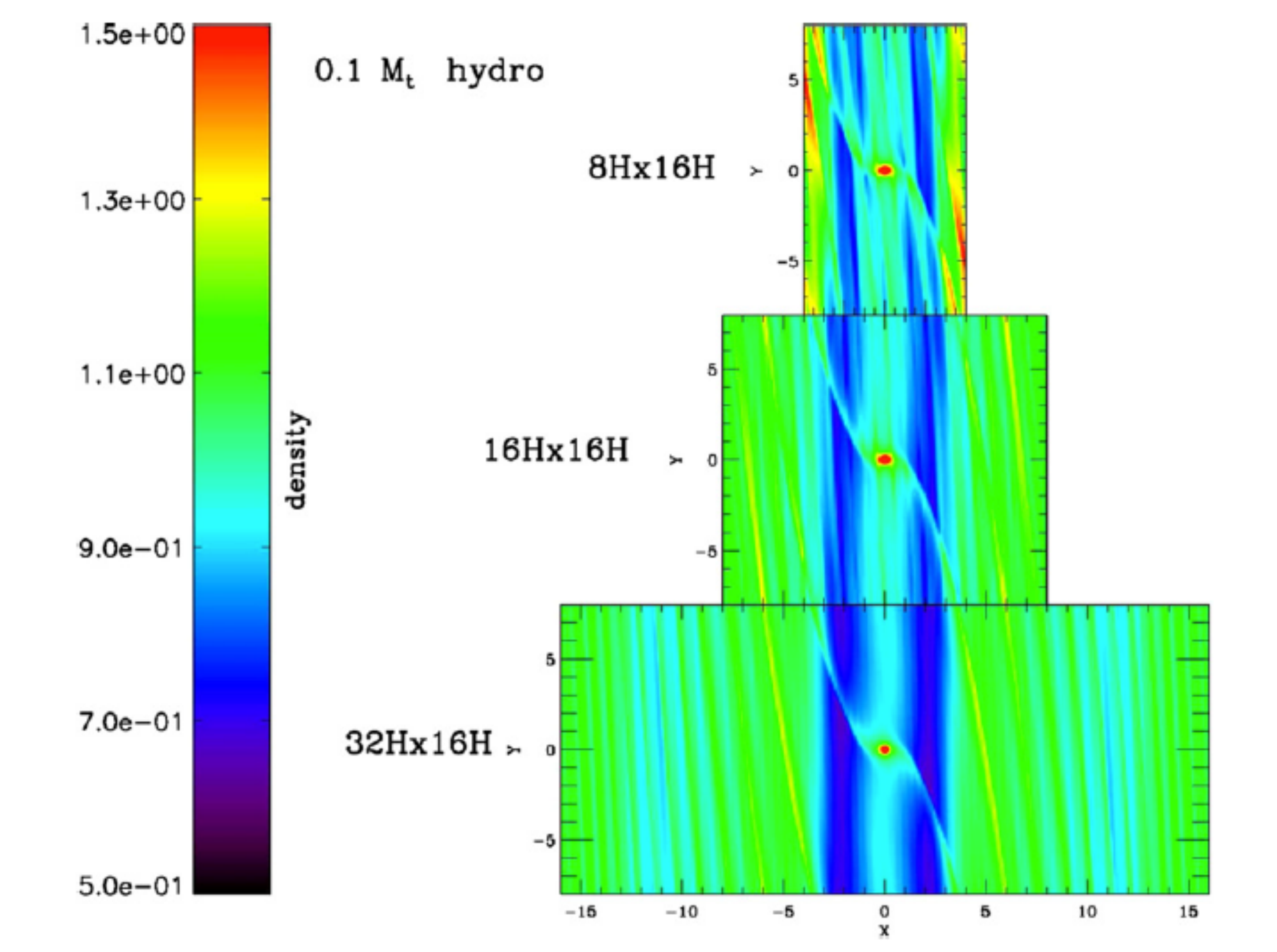
3D ideal-MHD simulations

Zhu, Stone & Rafikov 2013

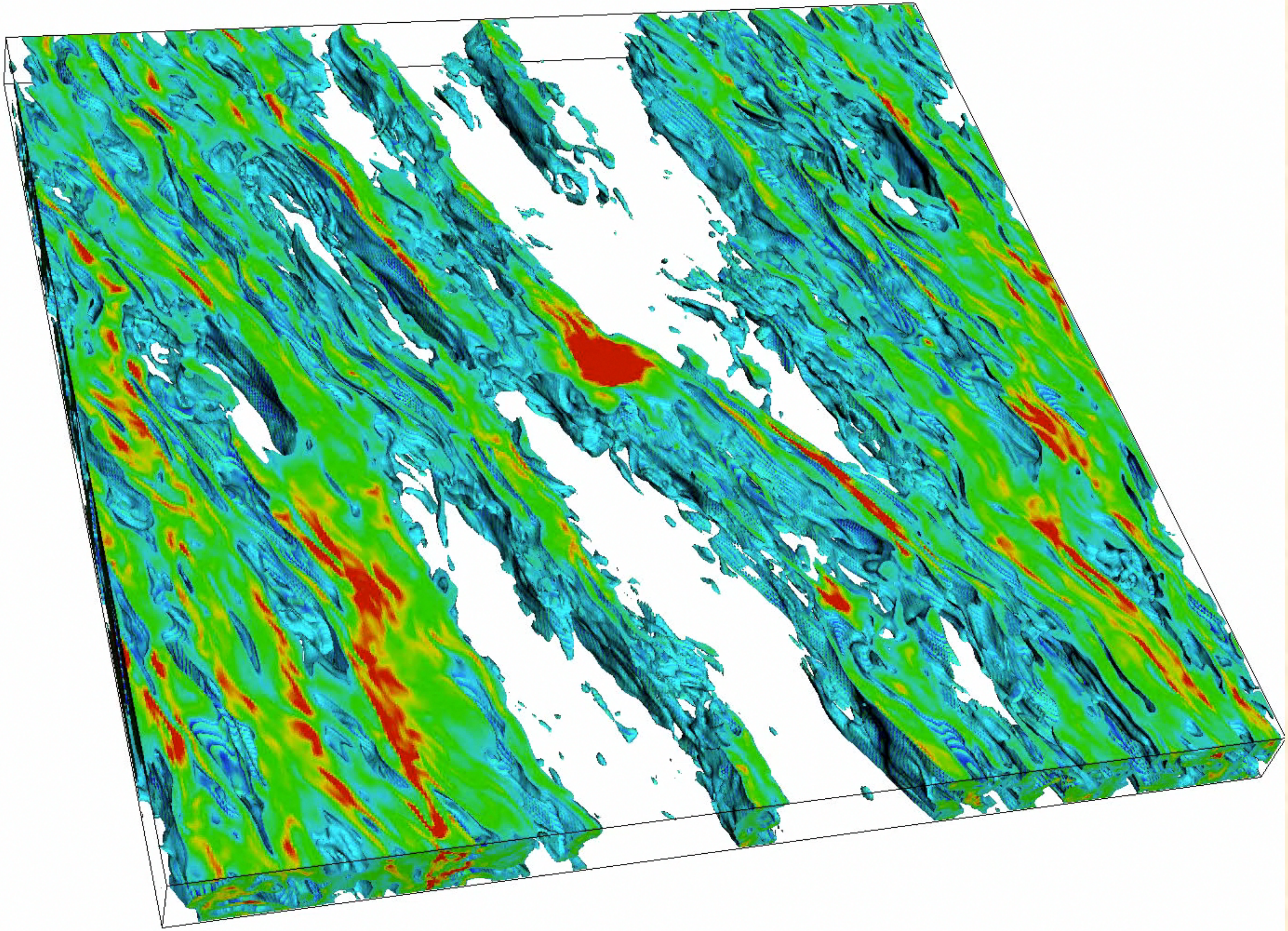
MHD Models (Unstratified 3D; $X = 16\ H$, $Z = 1\ H$)

Case Name	Planet Mass (M_t)	Run Time $2\pi/\Omega$	Net Field Geometry	Initial Field β_0	Stress $\langle\alpha\rangle$
		$Y = 16\ H$			
B400	0	200	Vertical	400	0.18
M01B400	0.1	400	Vertical	400	0.17
M03B400	0.3	246	Vertical	400	0.17
M03B1600	0.3	264	Vertical	1600	0.085
M10B400	1	258	Vertical	400	0.17
M10B1600	1	225	Vertical	1600	0.081
M30B400	3	258	Vertical	400	0.12
		$Y = 32\ H$			
M10B1600b	1	138	Vertical	1600	0.084

Testing how large a box is needed

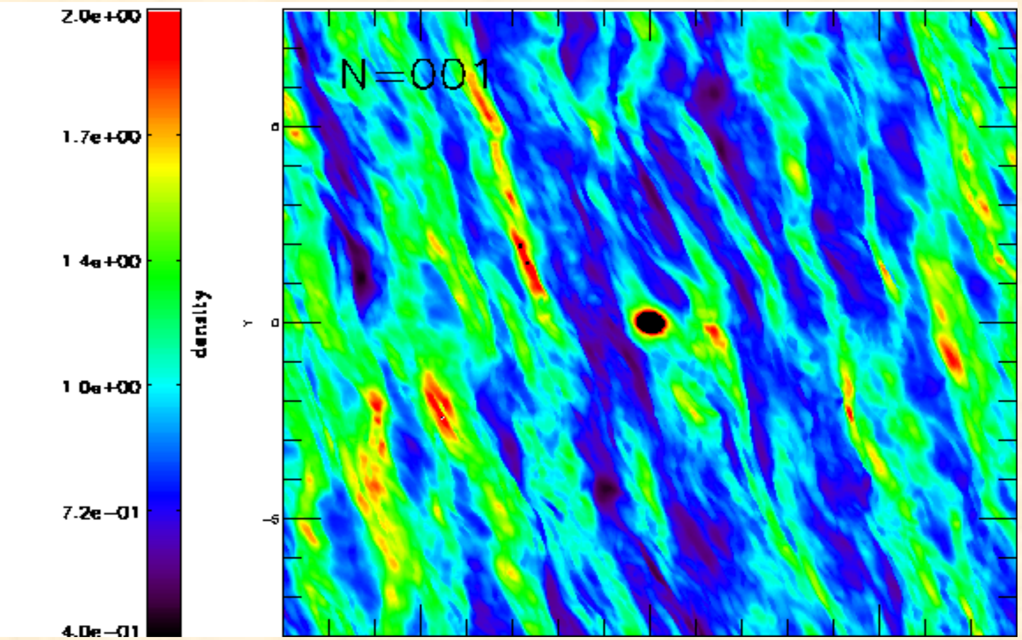


Density isocontours: thermal mass ($M \sim 0.1M_J$) planet in MRI turbulence

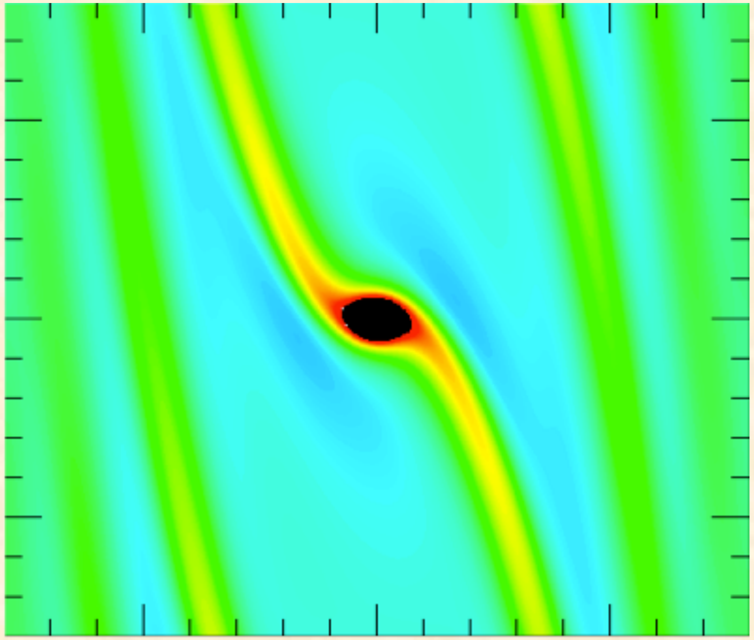


Comparison of wake ($M = M_{th}$).

Plots of surface density



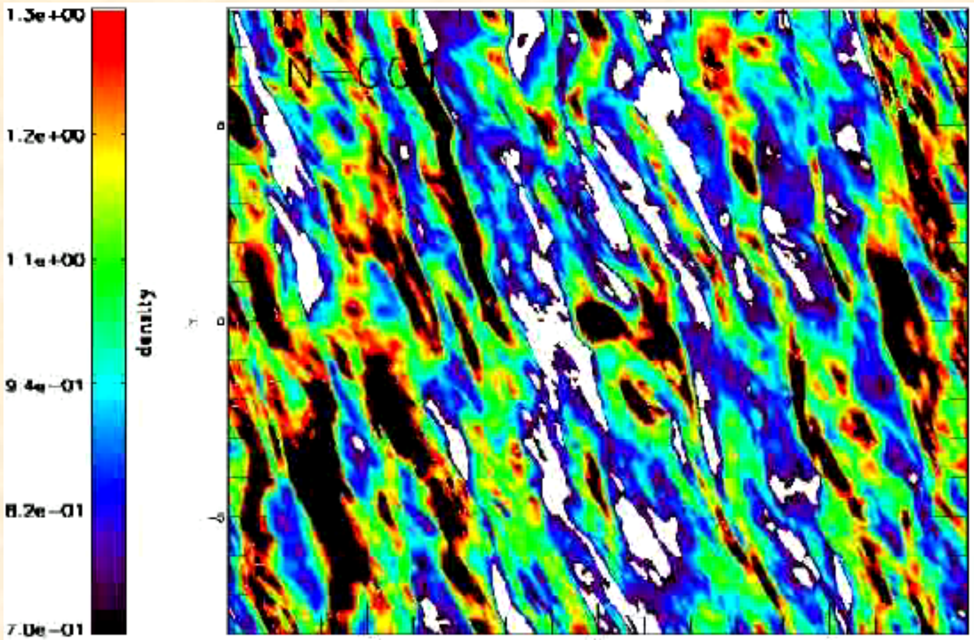
Turbulent MHD disk

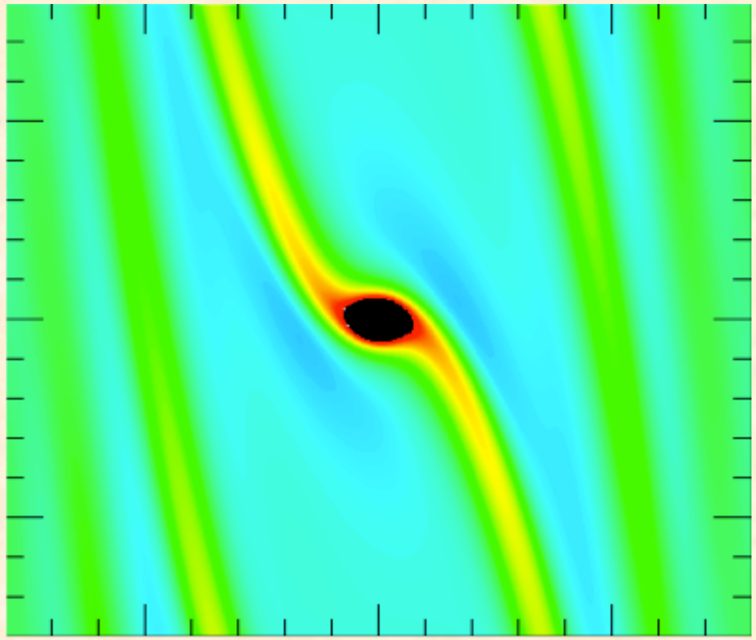


Viscous hydrodynamic disk
Same α as MHD

Comparison of wake ($M = M_{th}$).

Plots of surface density



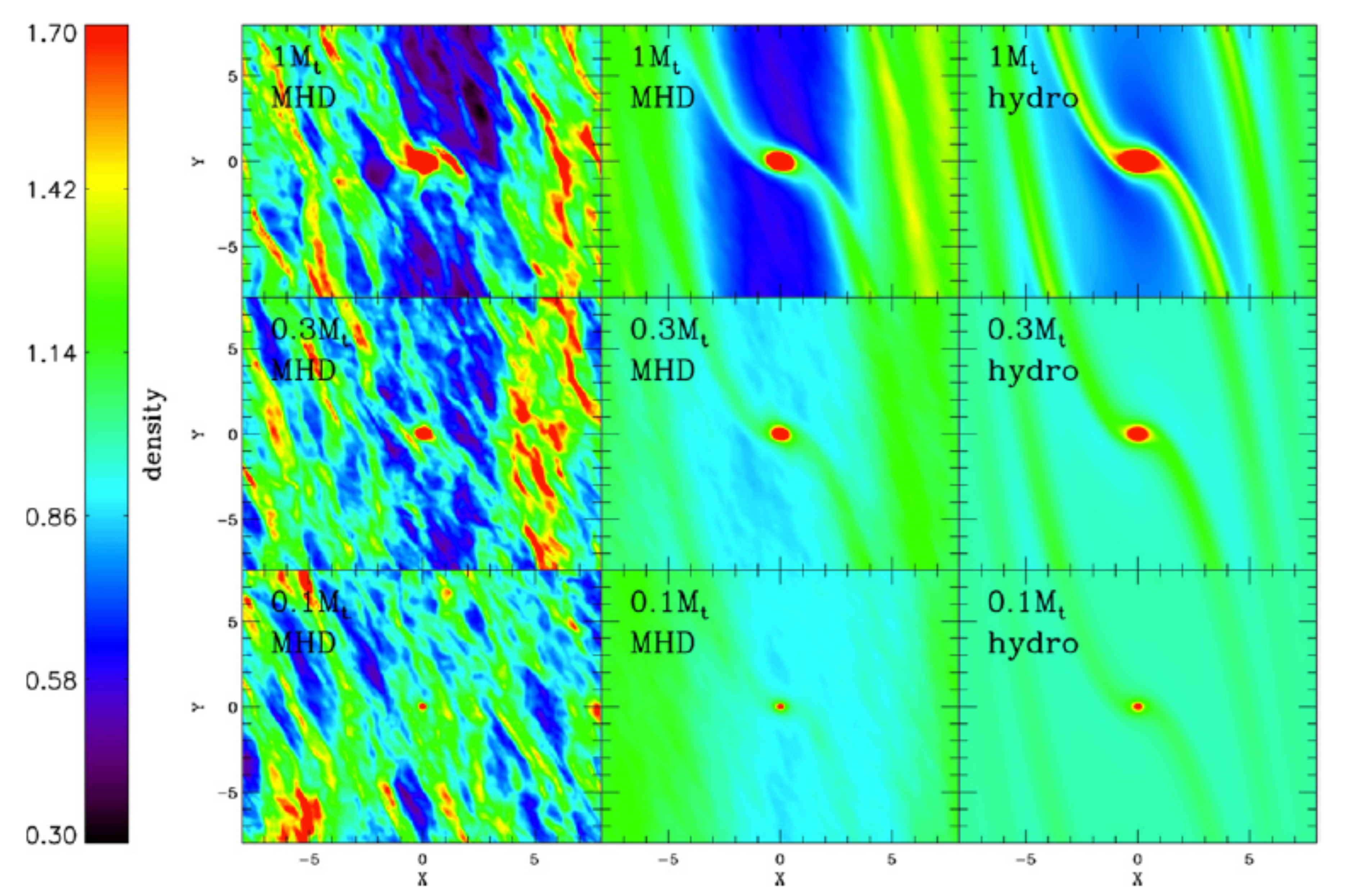


Turbulent MHD disk Viscous Hydrodynamic disk

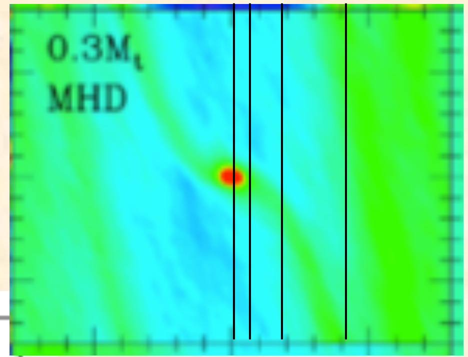
Time averaging reveals wake!

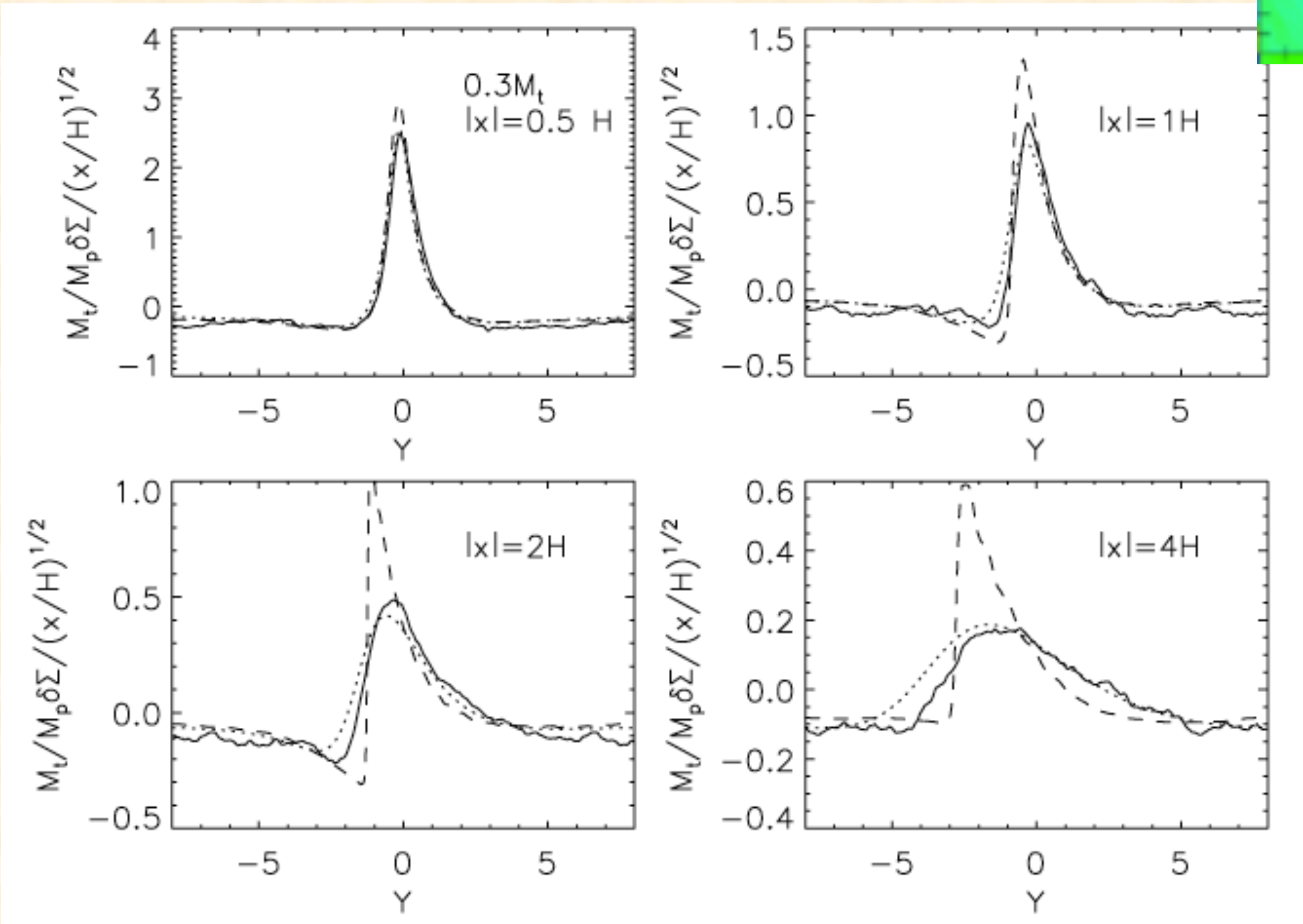
Profiles of gap and wake substantially different than α-disk model.

Gaps even with low-mass planets



Time-averaged radial profiles of density along different radial slices

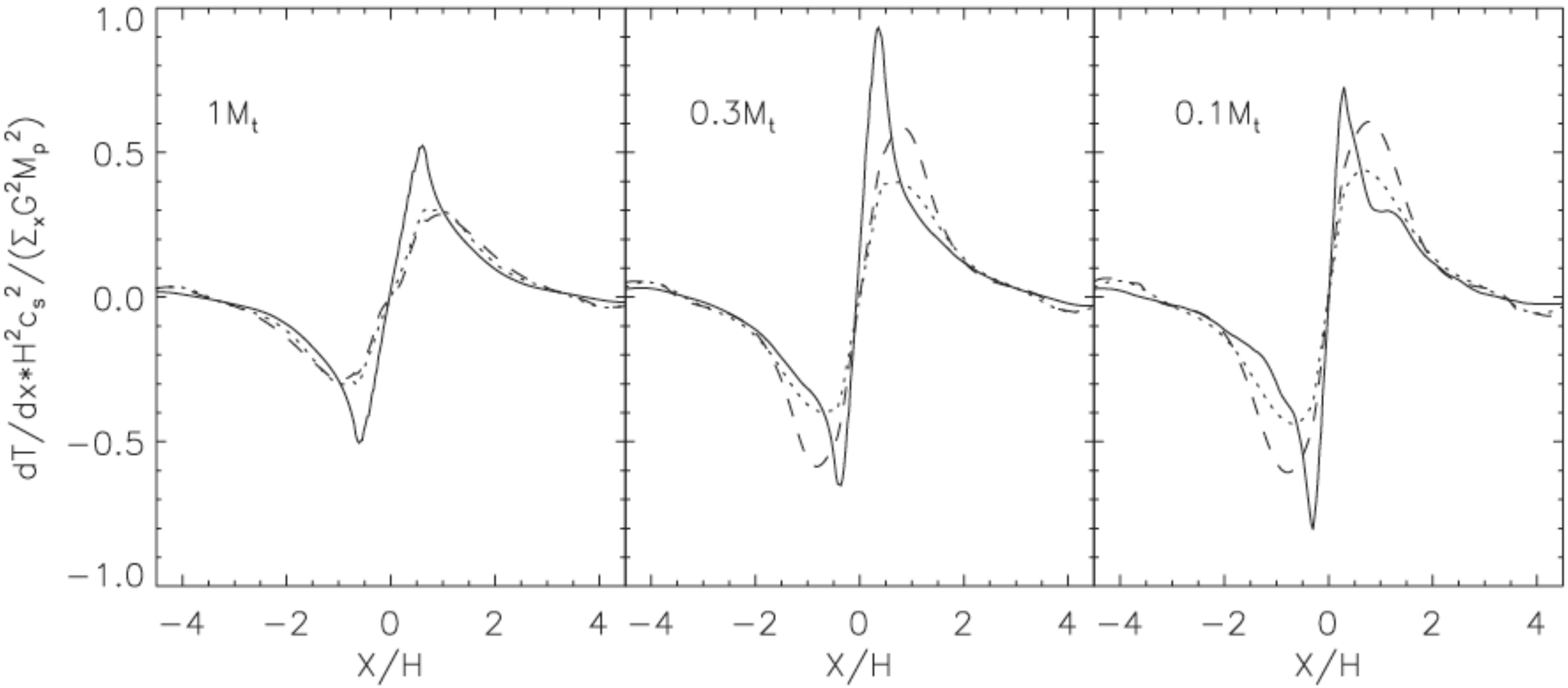




dashed = inviscid hydro
dotted = viscous hydro
solid = MHD

Density profiles in reasonable agreement with viscous hydro solution

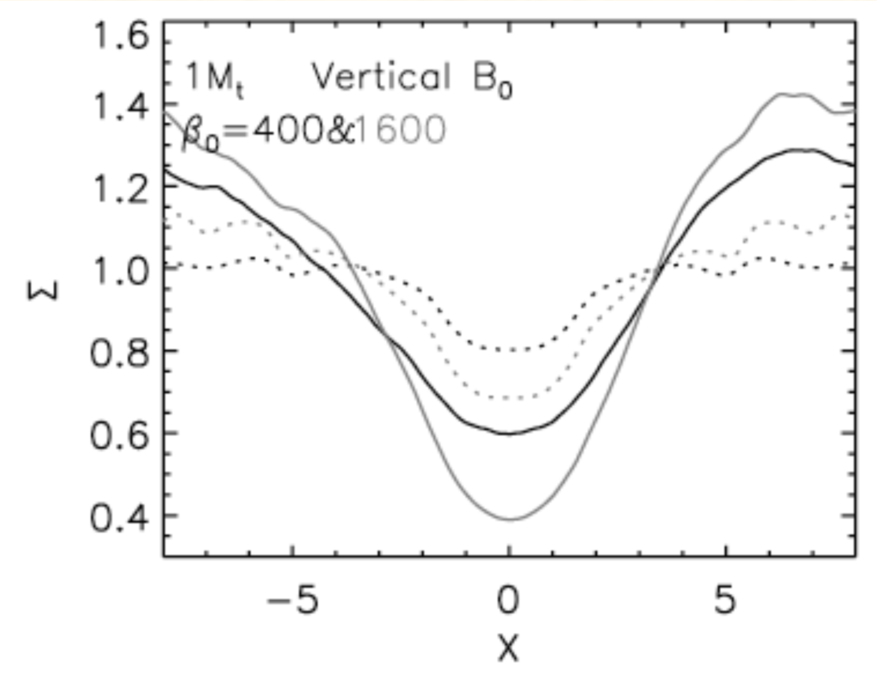
But profiles of torque density $\left\langle \frac{dT}{dx} \right\rangle = -\int \Sigma \frac{\partial \phi}{\partial y} dy$ different in MHD compared to viscous hydro

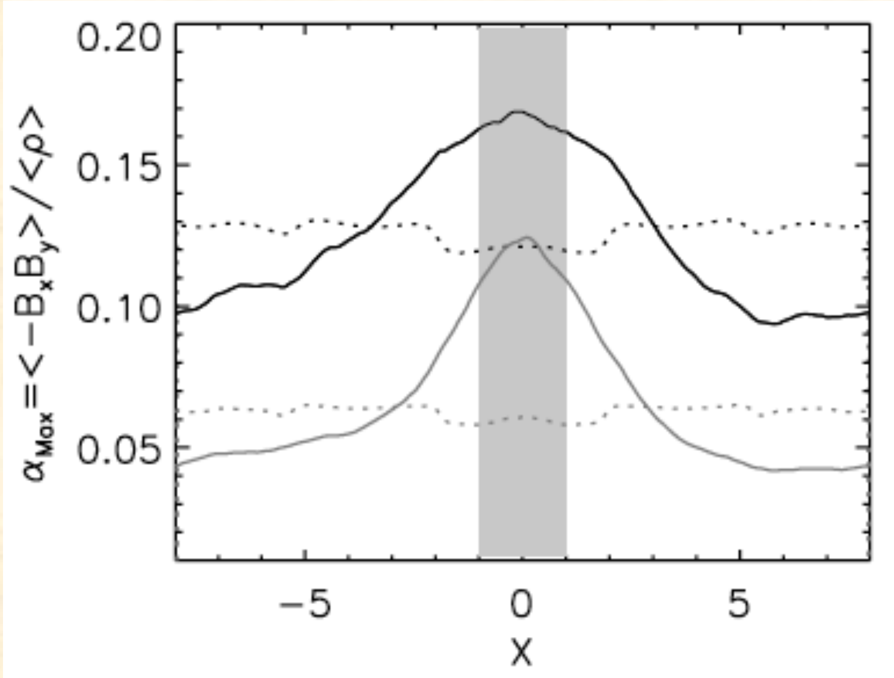


dashed = inviscid hydro
dotted = viscous hydro
solid = MHD

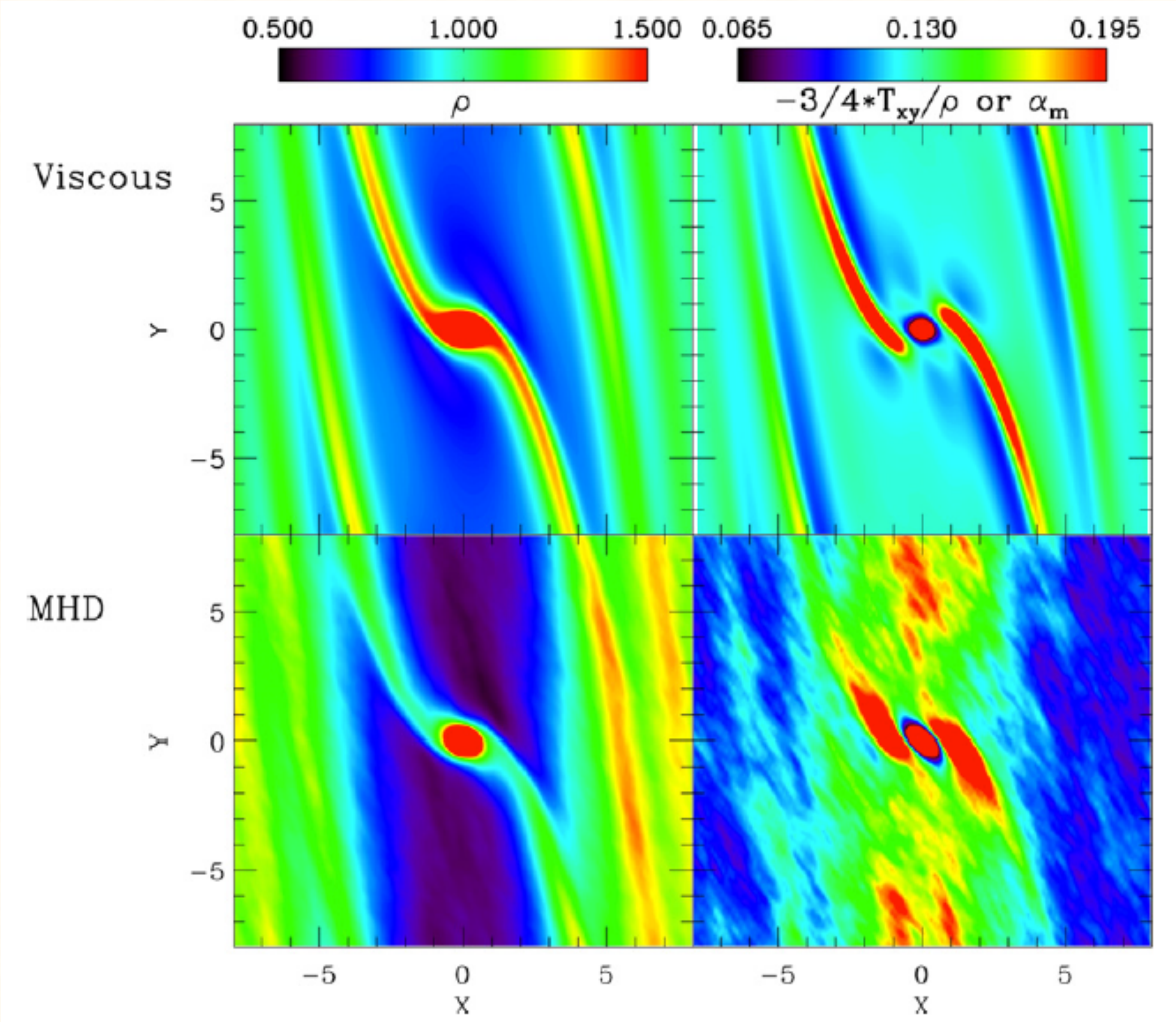
Gaps in MHD are wider and deeper

dotted = viscous hydro
solid = MHD





In MHD effective α peaks in gap region

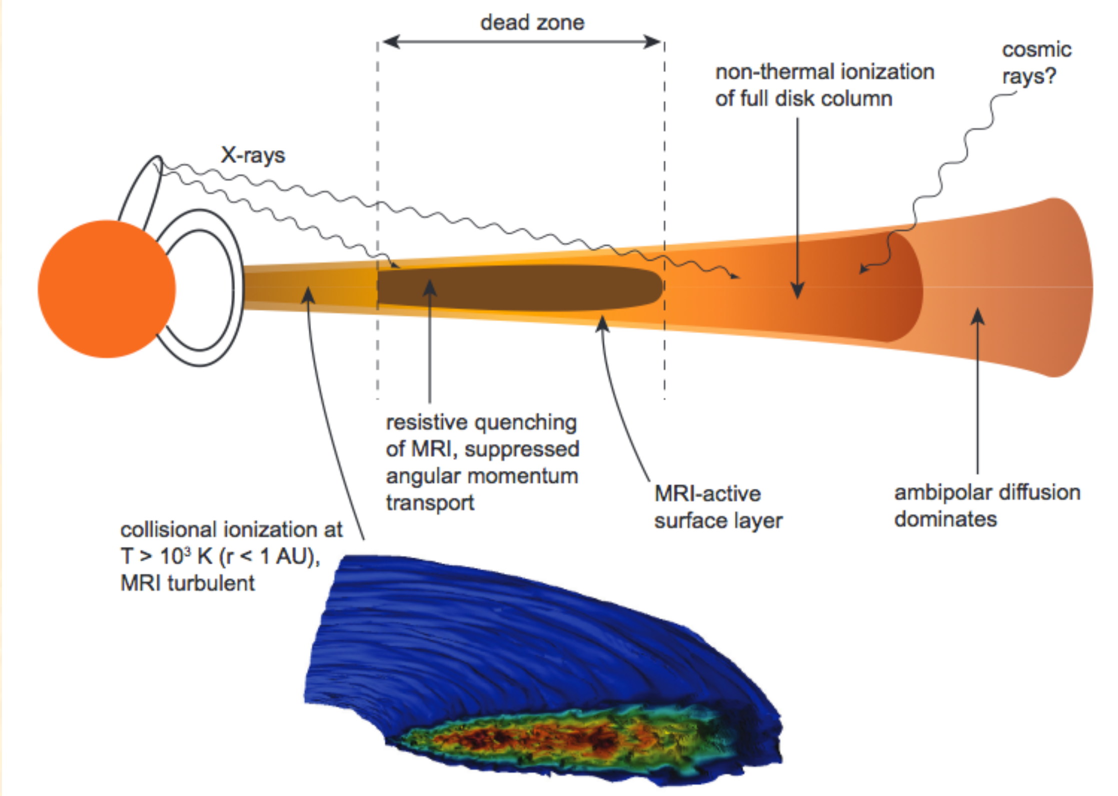


α

α_m

Viscous hydro models require using non-constant α across gap

Towards more realistic vertically-stratified models

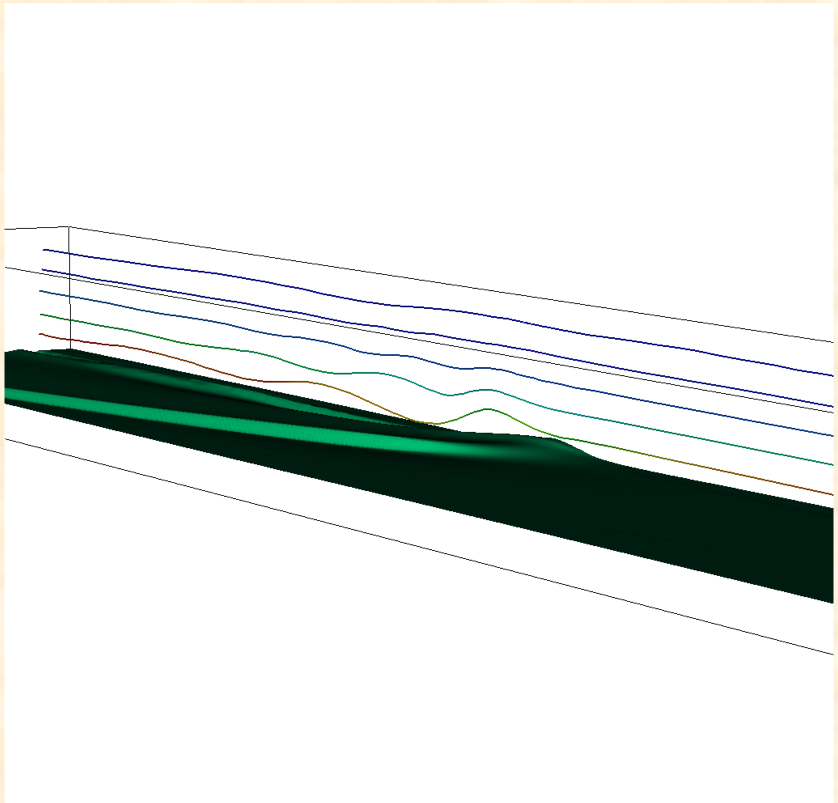


Eventually would like to include non-ideal MHD, thermodynamics, etc. (as in O. Gressel's talk)

But to start, simply consider vertically stratified disks with non-isothermal EOS

In 3D stratified disk with realistic equation of state, planet at midplane launches gravity waves.

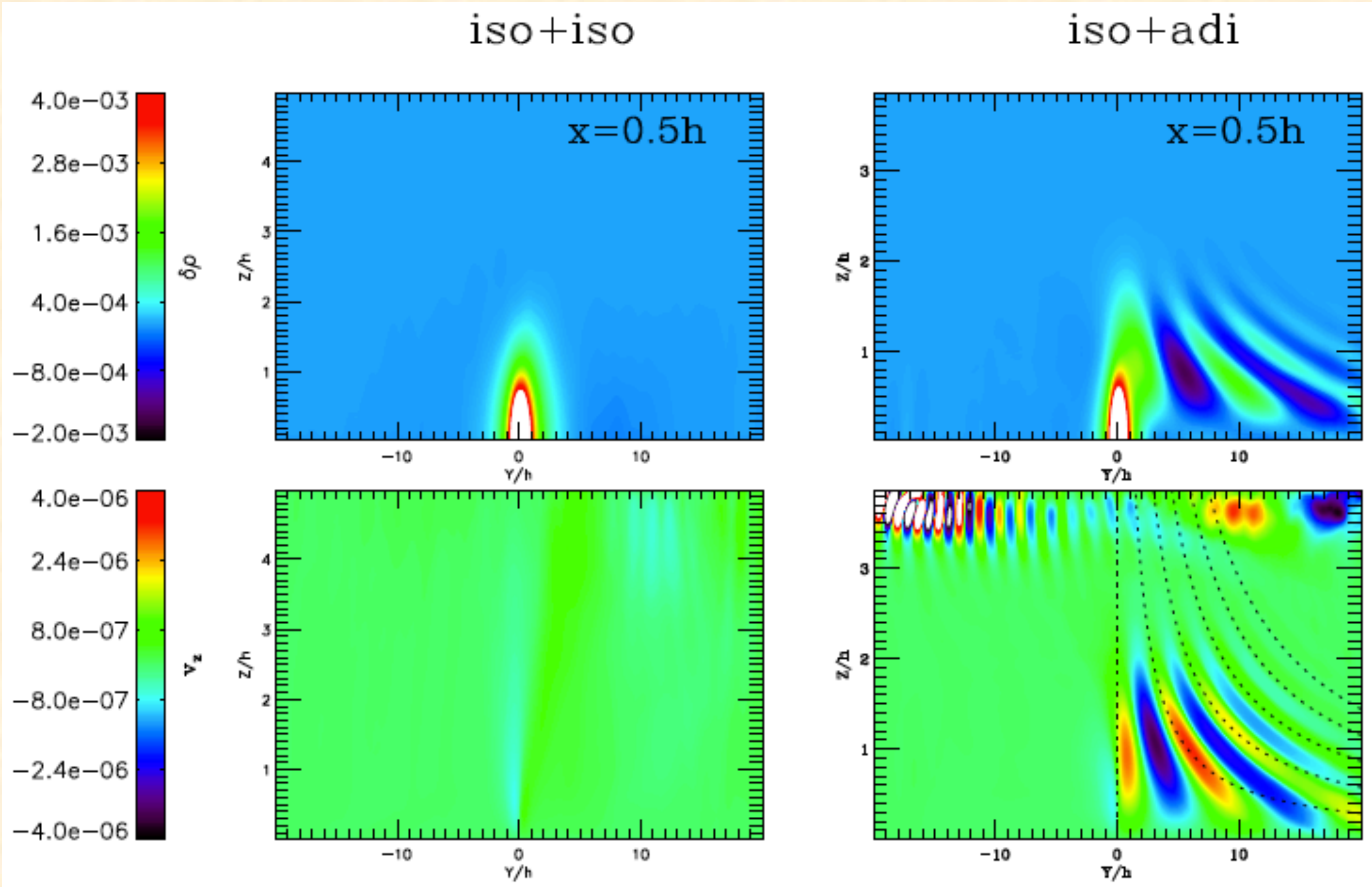
Isosurface of density



Fluid streamlines. Flow similar to “wind over mountains”.

Capturing gravity waves requires non-isothermal EOS.

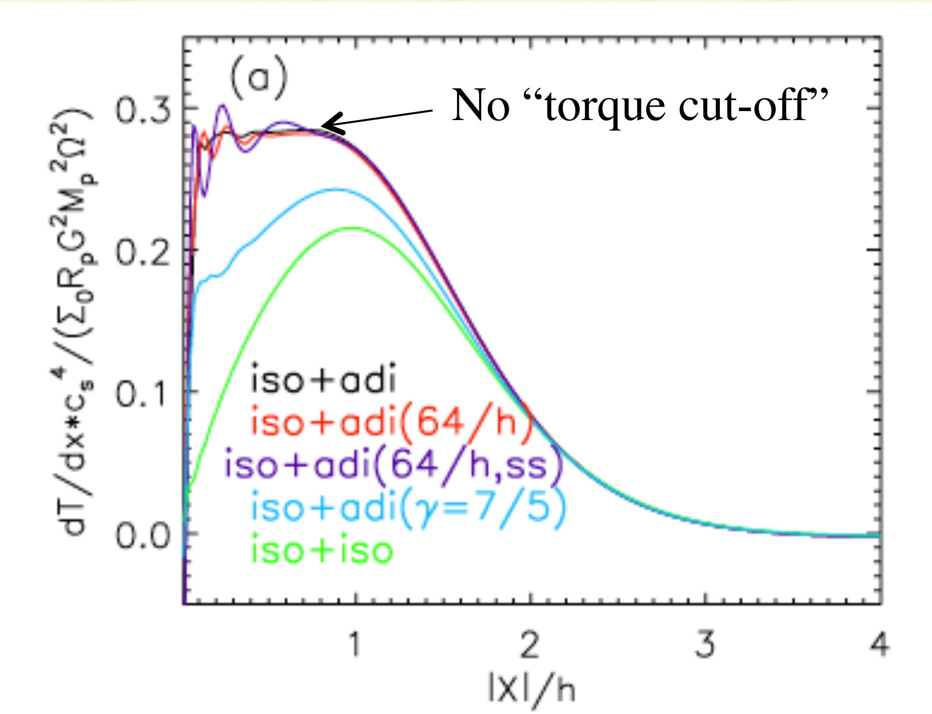
Slices in X-Z plane



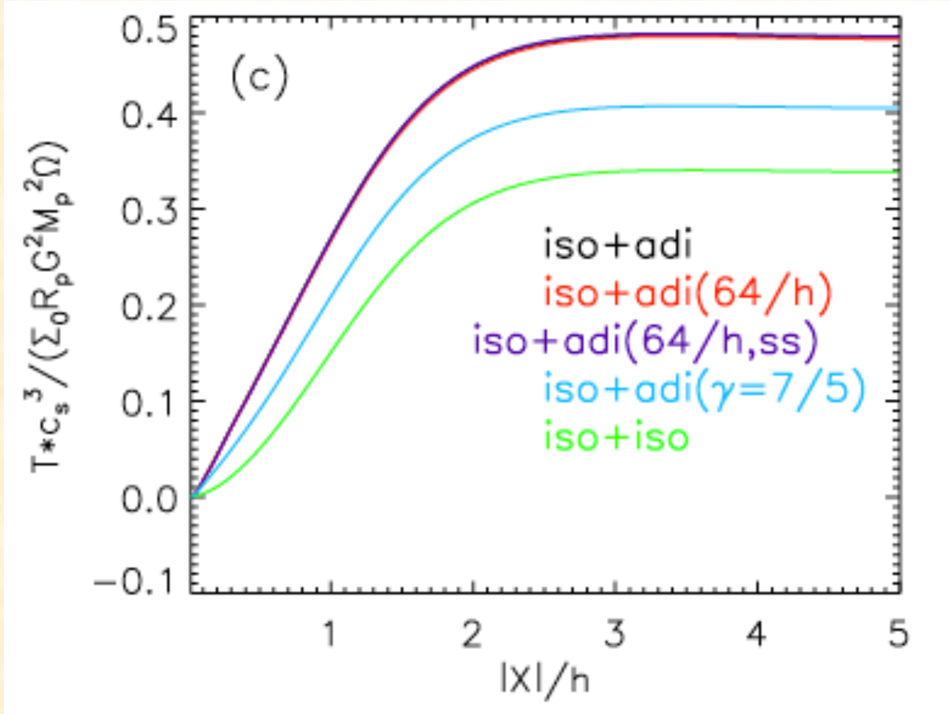
Density perturbation

Velocity perturbation

Remarkably, these gravity waves can produce significant torque that may modify planet migration. Zhu, Stone, & Rafikov 2012



Torque density



Integrated torque

See Lubow & Zhu (2014) for analytic model.

There will likely be more surprises in non-ideal MHD models…

Summary

- Low mass planets can open gaps. The thermal criterion does not apply.
- In MHD, the viscous criteria must be suitably modified.
- Details of planet-disk interaction differ in MHD compared to viscous hydrodynamics.
- Buoyancy waves are a new source of angular momentum exchange between planet and disk.
- *Much remains to be done to explore different non-ideal MHD regimes*.