Planetesimal and planet migration and growth in turbulent discs

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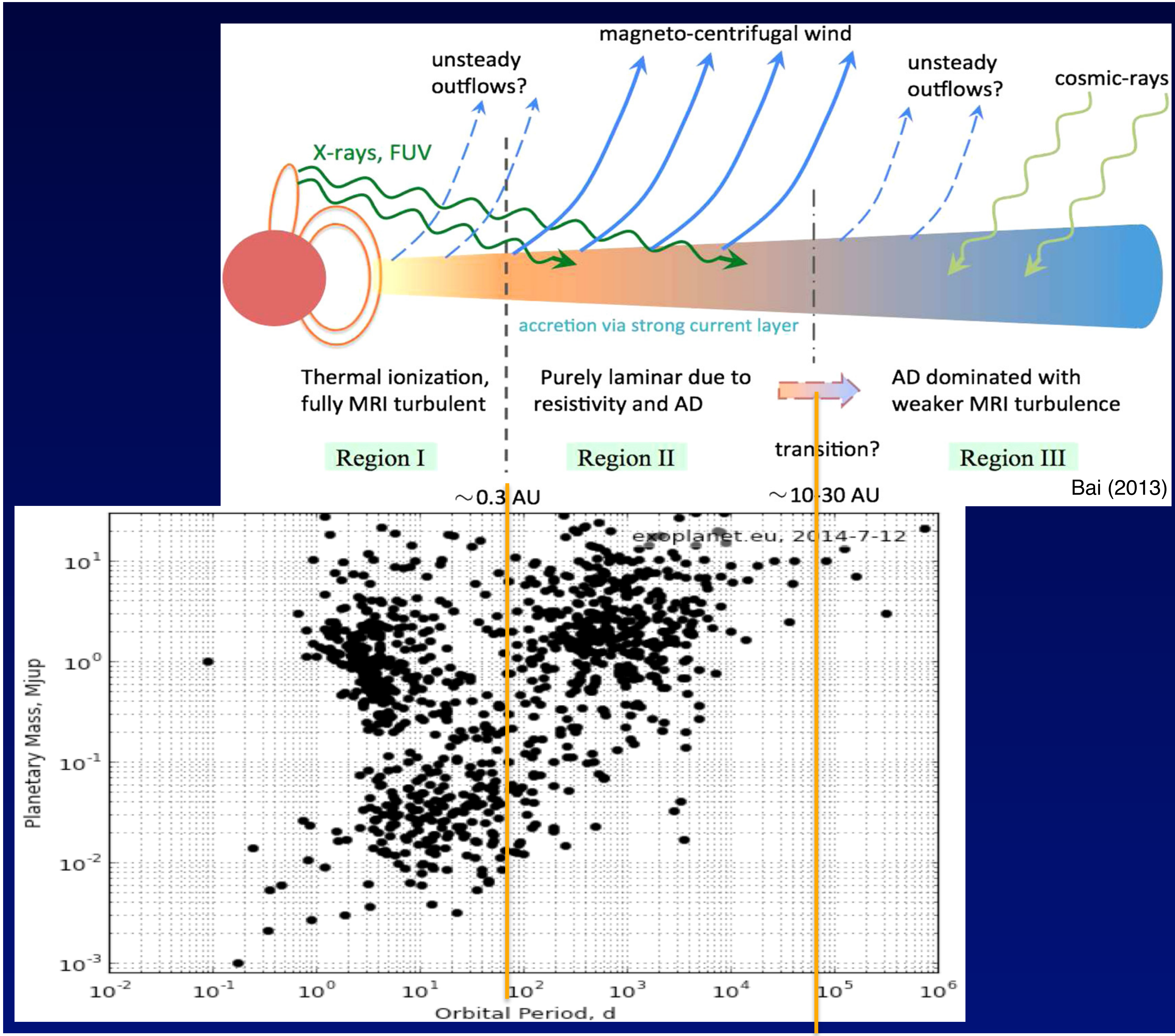
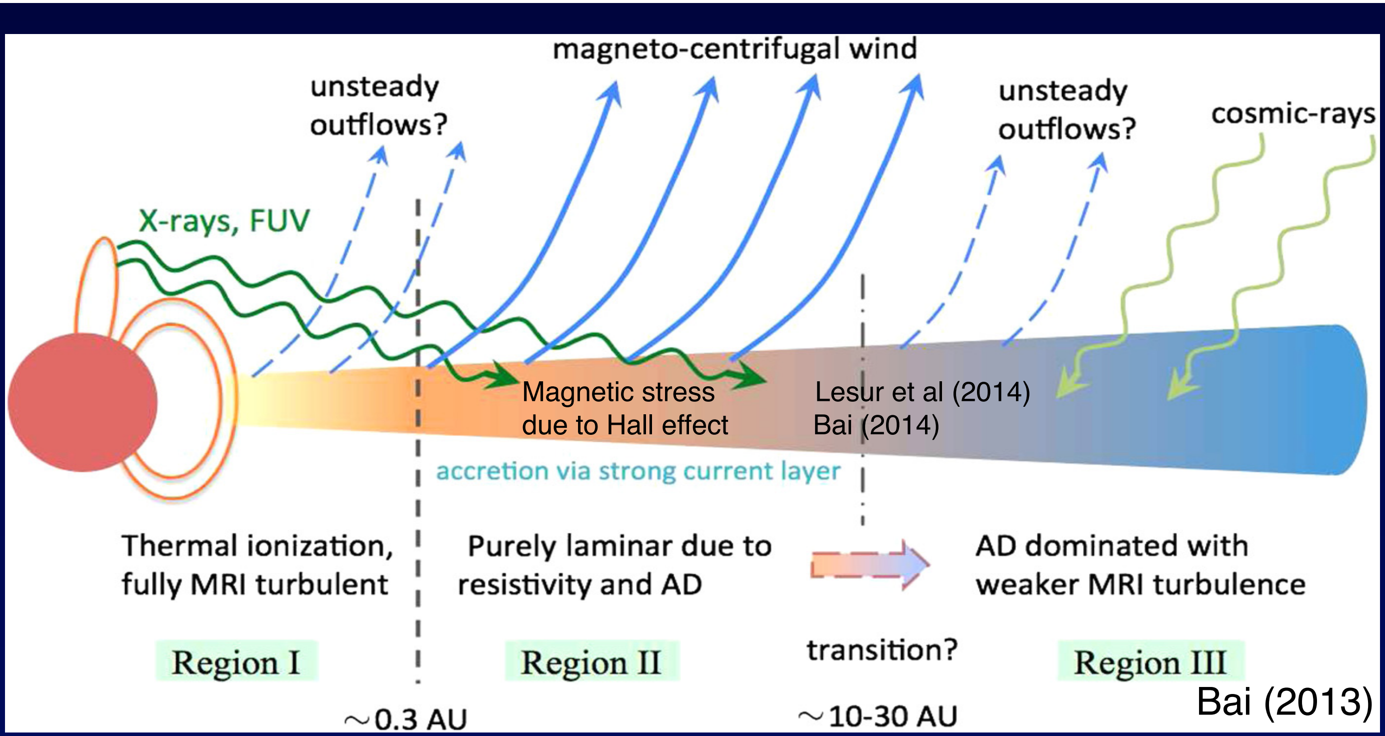
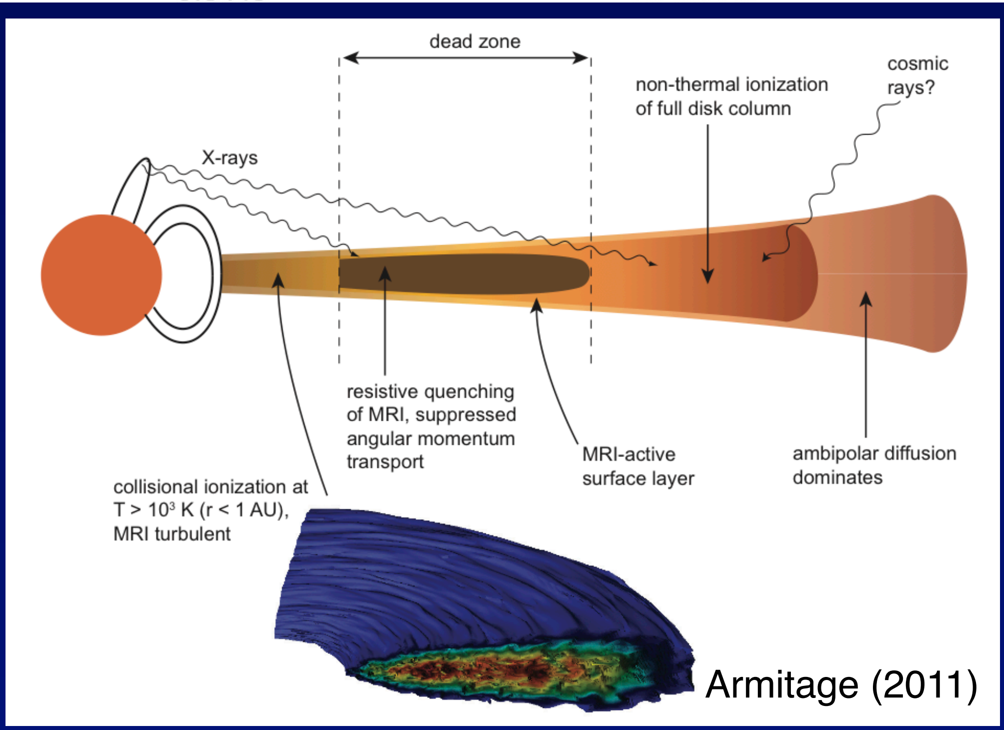

magneto-centrifugal wind
unsteady outflows?
unsteady outflows?
cosmic-rays
X-rays, FUV
accretion via strong current layer
Thermal ionization, fully MRI turbulent
Purely laminar due to resistivity and AD
AD dominated with weaker MRI turbulence
transition?
Region I
Region II
Region III
∼0.3 AU
∼10-30 AU
exoplanet.eu, 2014-7-12
Planetary Mass, Mjup
Orbital Period, d
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}

Bai (2013)



Bai (2013)



Armitage (2011)

Key issues

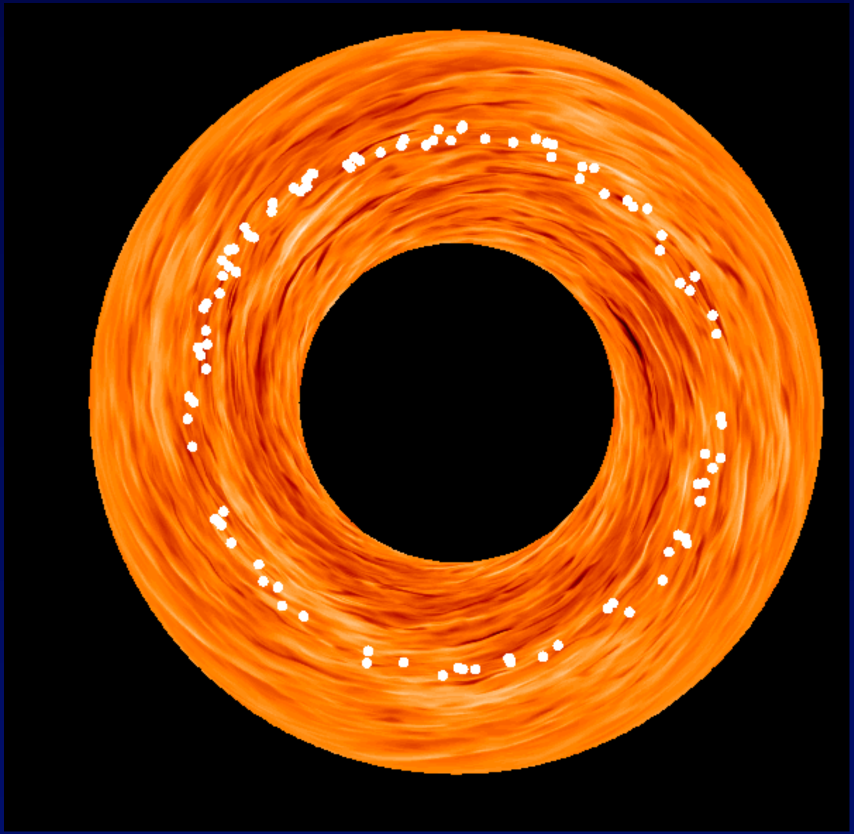
- Planetesimals: how does MRI turbulence and the dead zone affect the dynamical and collisional evolution?

- Low mass planets: how does MRI turbulence and the dead zone affect migration?

Question

- Does a coherent picture emerge that supports current ideas about planet formation?

Planetesimals in turbulent discs



Turbulent density fluctuations generated in the disc by the MRI create a time-varying stochastic gravitational field

i) Turbulence will excite the random velocities of planetesimals
- Implications for the collisional growth/destruction and runaway growth during planet formation

ii) Turbulence will induce radial diffusion
- Implications for the spreading of volatiles across the snow line and radial mixing of asteroid taxonomic types

Nelson & Papaloizou (2004)
Nelson (2005)
Ida, Guillot & Morbidelli (2008)
Nelson & Gressel (2010)
Gressel, Nelson & Turner (2011, 2012)

Shearing box simulations with and without dead zones

Non-ideal MHD shearing box simulations performed using NIRVANA-III (Ziegler 2008)

Initial B-field configuration: net B_z

$$\mathrm{H_2} + h\nu \longrightarrow \mathrm{H_2^+} + \mathrm{e^-}$$
$$\mathrm{H_2^+} + \mathrm{e^-} \longrightarrow \mathrm{H_2}$$
$$\mathrm{H_2^+} + \mathrm{Mg} \longrightarrow \mathrm{H_2} + \mathrm{Mg^+}$$
$$\mathrm{Mg^+} + \mathrm{e^-} \longrightarrow \mathrm{Mg} + h\nu$$

Equilibrium ionisation chemistry including gas-grain interactions (Ilgner & Nelson 2006)

<u>Ionisation sources</u>:

X-rays (Igea & Glassgold 1999)

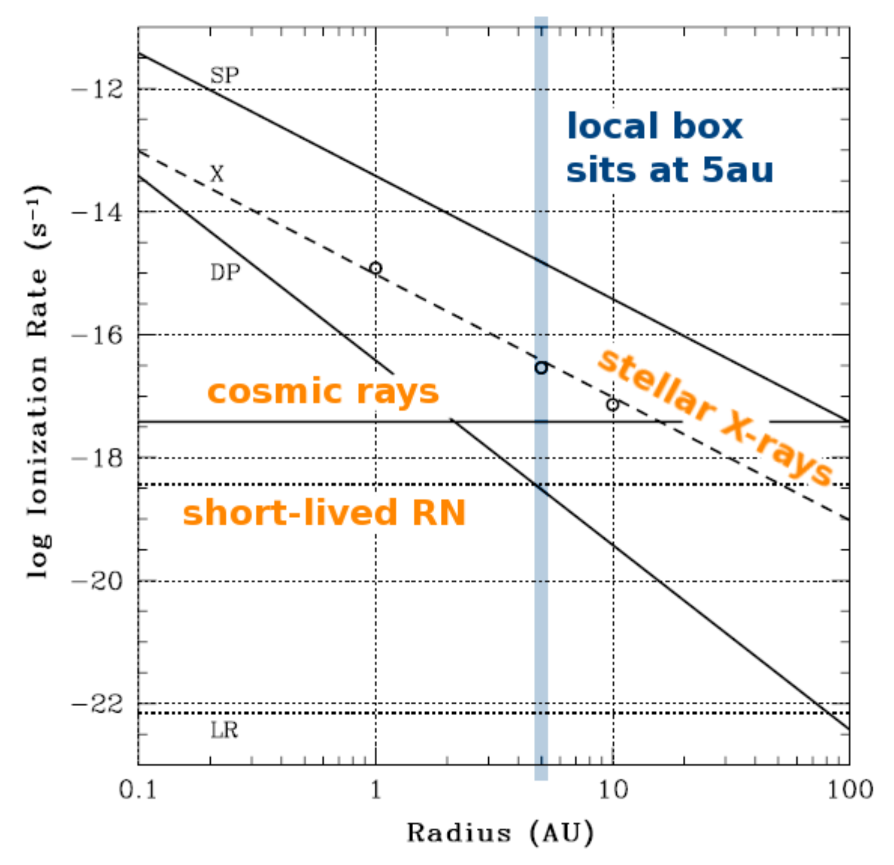
Cosmic rays + radionuclei (Umebayashi & Nakano 1981)

Gas phase $X(e^-)$ ⟶ Ohmic resistivity η

25 planetesimals evolved

R=5 AU, H/R=0.05, T=108 K, Σ=135 g/cm^3

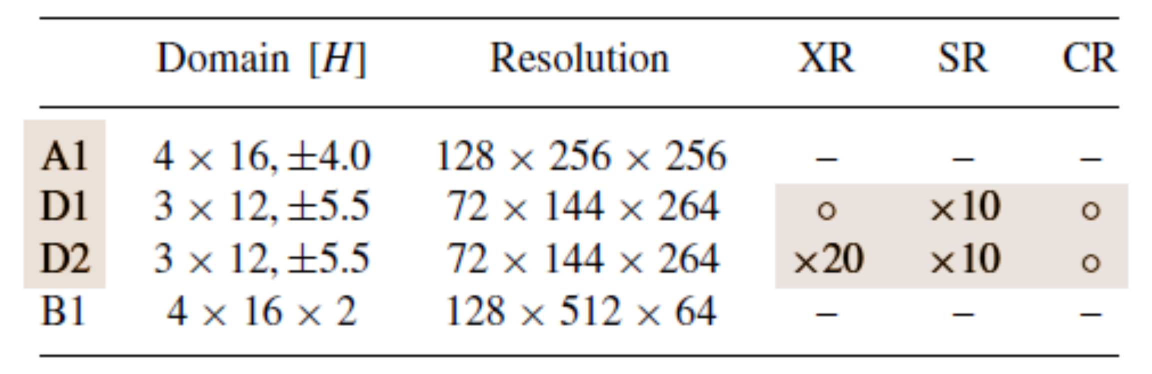
(Gressel, Nelson & Turner 2011,2012)



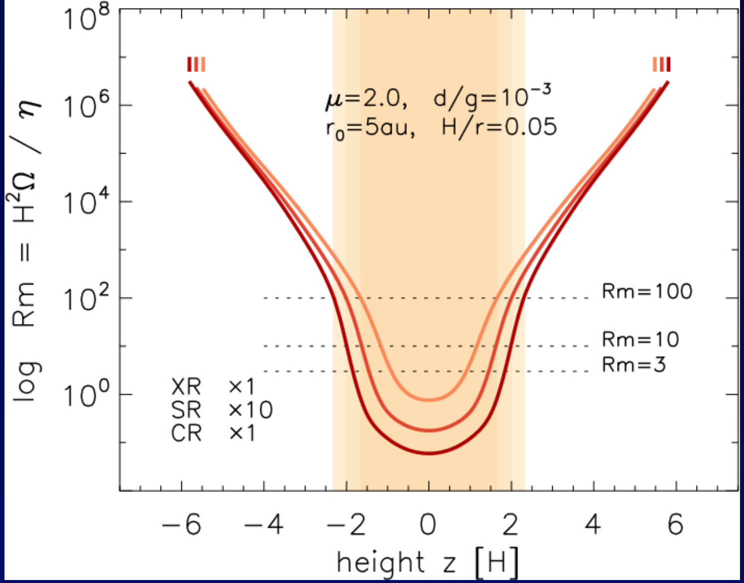
Turner & Drake (2009) fits to X-ray ionisation rates from Igea & Glassgold (1999)

Overview of models

(1) Fully active model.
(2) Dead zone models with varying X-ray ionisation (Gressel, Nelson & Turner 2011):

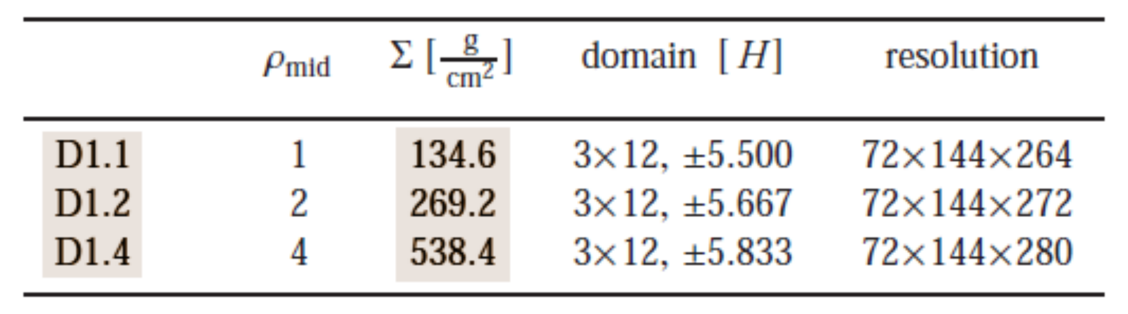


	Domain $[H]$	Resolution	XR	SR	CR
A1	$4 \times 16, \pm 4.0$	$128 \times 256 \times 256$	–	–	–
D1	$3 \times 12, \pm 5.5$	$72 \times 144 \times 264$	∘	×10	∘
D2	$3 \times 12, \pm 5.5$	$72 \times 144 \times 264$	×20	×10	∘
B1	$4 \times 16 \times 2$	$128 \times 512 \times 64$	–	–	–



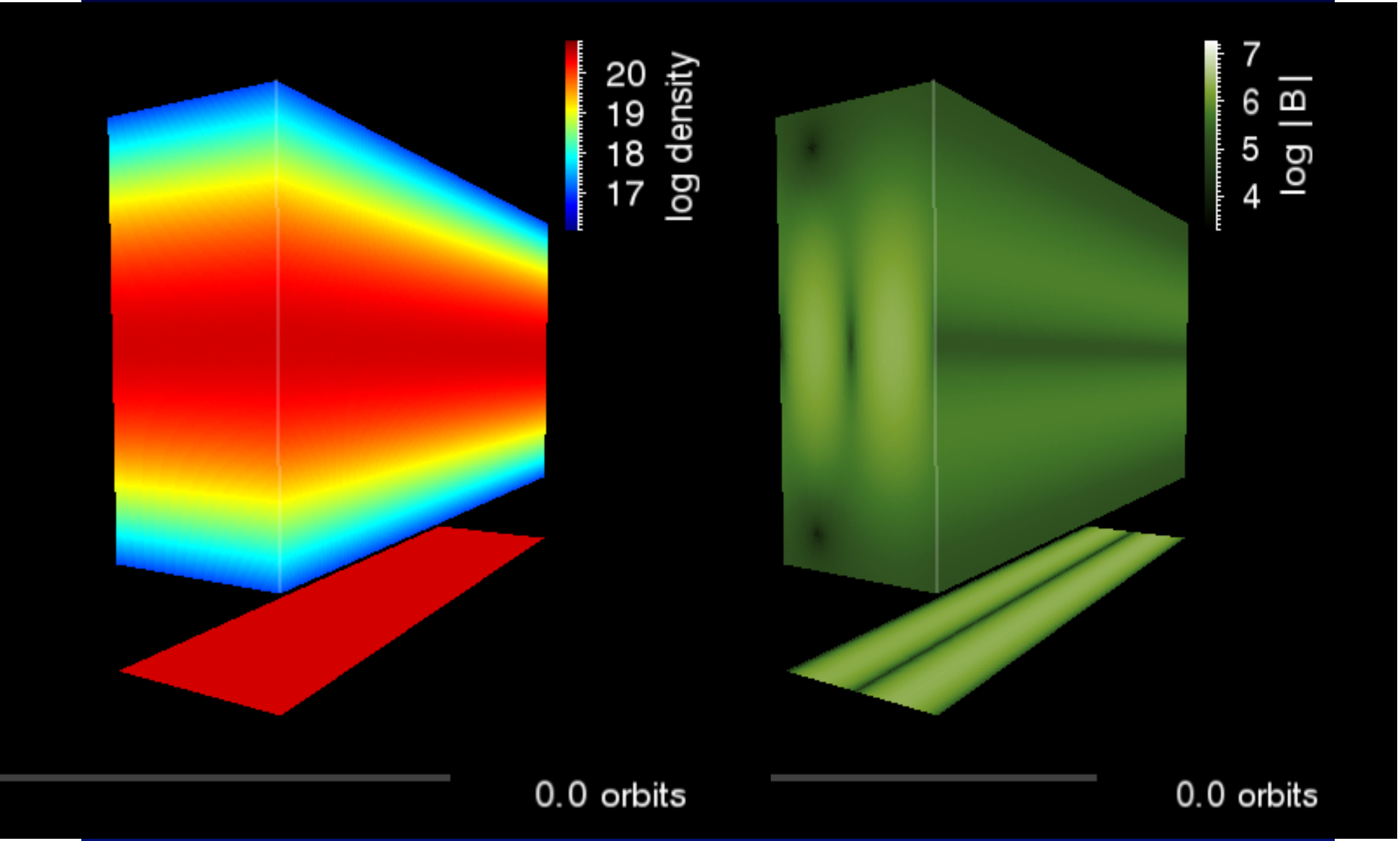
R_m versus height for D1.1, 1.2, 1.4

(3) Dead zone models with varying disc mass:
(Gressel, Nelson & Turner 2012)

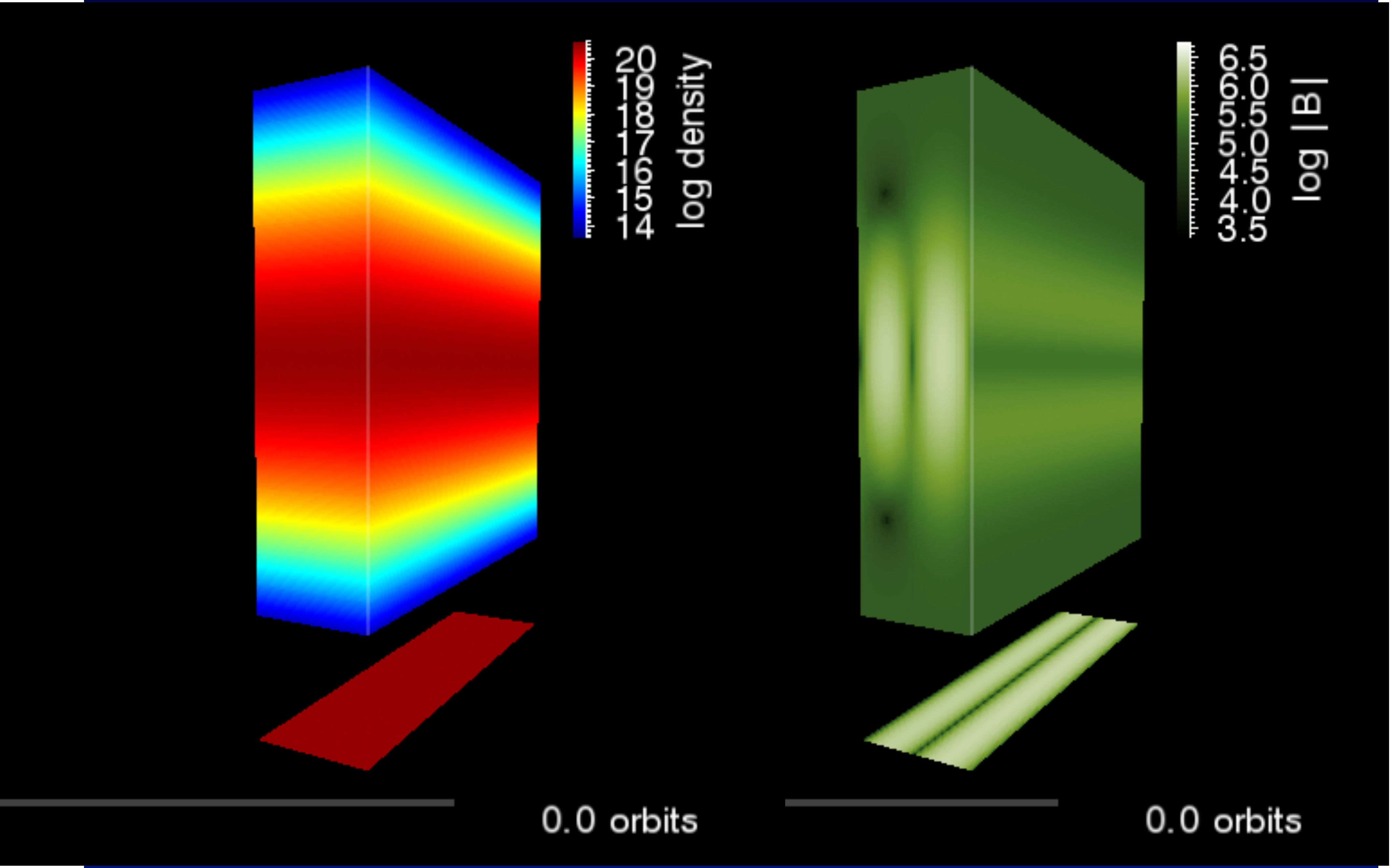


	$\rho_{\rm mid}$	$\Sigma\,[\frac{\rm g}{\rm cm^2}]$	domain $[H]$	resolution
D1.1	1	134.6	$3{\times}12, \pm 5.500$	$72{\times}144{\times}264$
D1.2	2	269.2	$3{\times}12, \pm 5.667$	$72{\times}144{\times}272$
D1.4	4	538.4	$3{\times}12, \pm 5.833$	$72{\times}144{\times}280$

(4) Dead zone models with varying net vertical magnetic field strength:
Models based mainly on model D1.1 with 2.7, 5.4, 10.7, 21.5, 43 mG

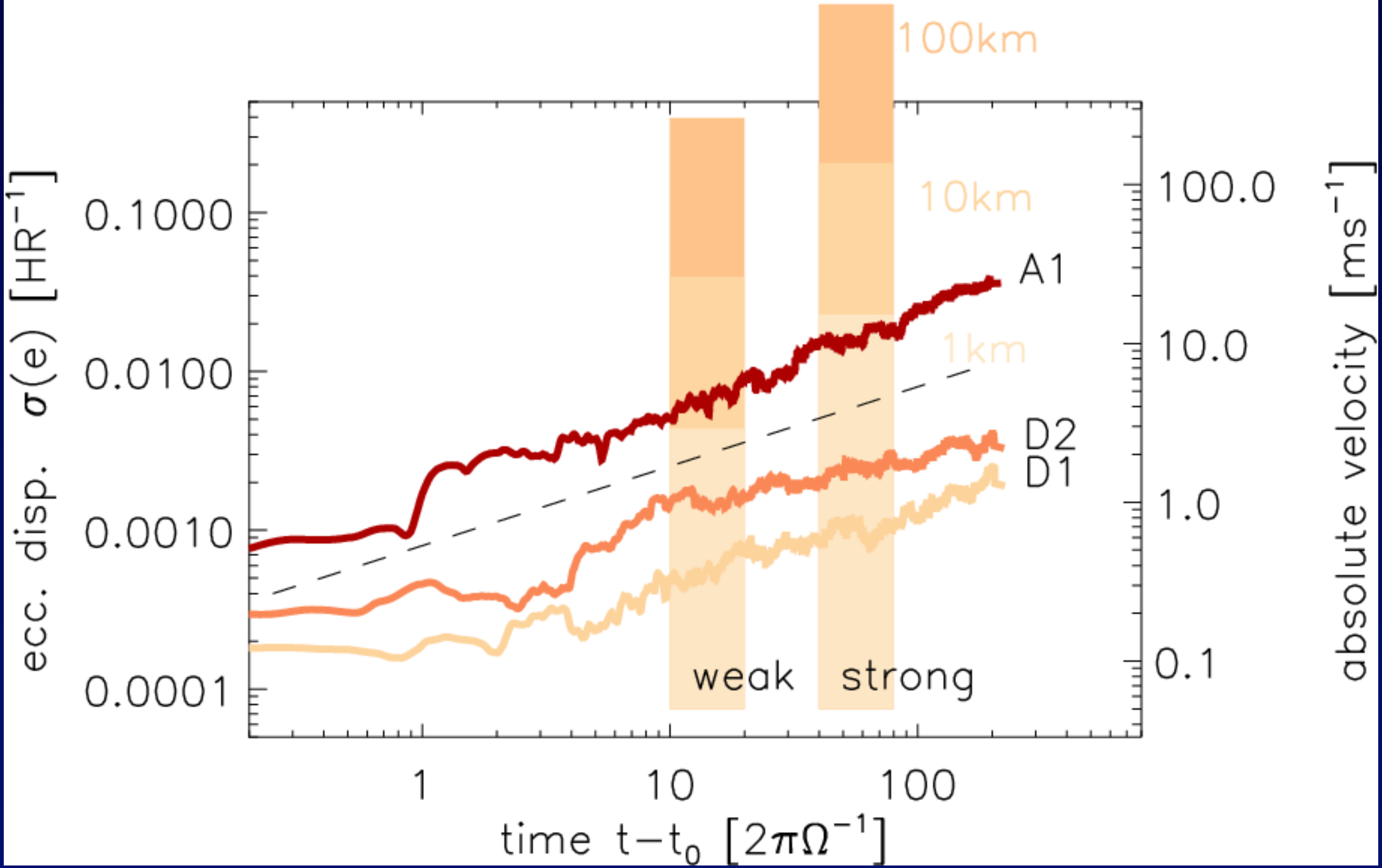


Model A1


20
19
18
17
16
15
14
log density
6.5
6.0
5.5
5.0
4.5
4.0
3.5
log |B|
0.0 orbits
0.0 orbits

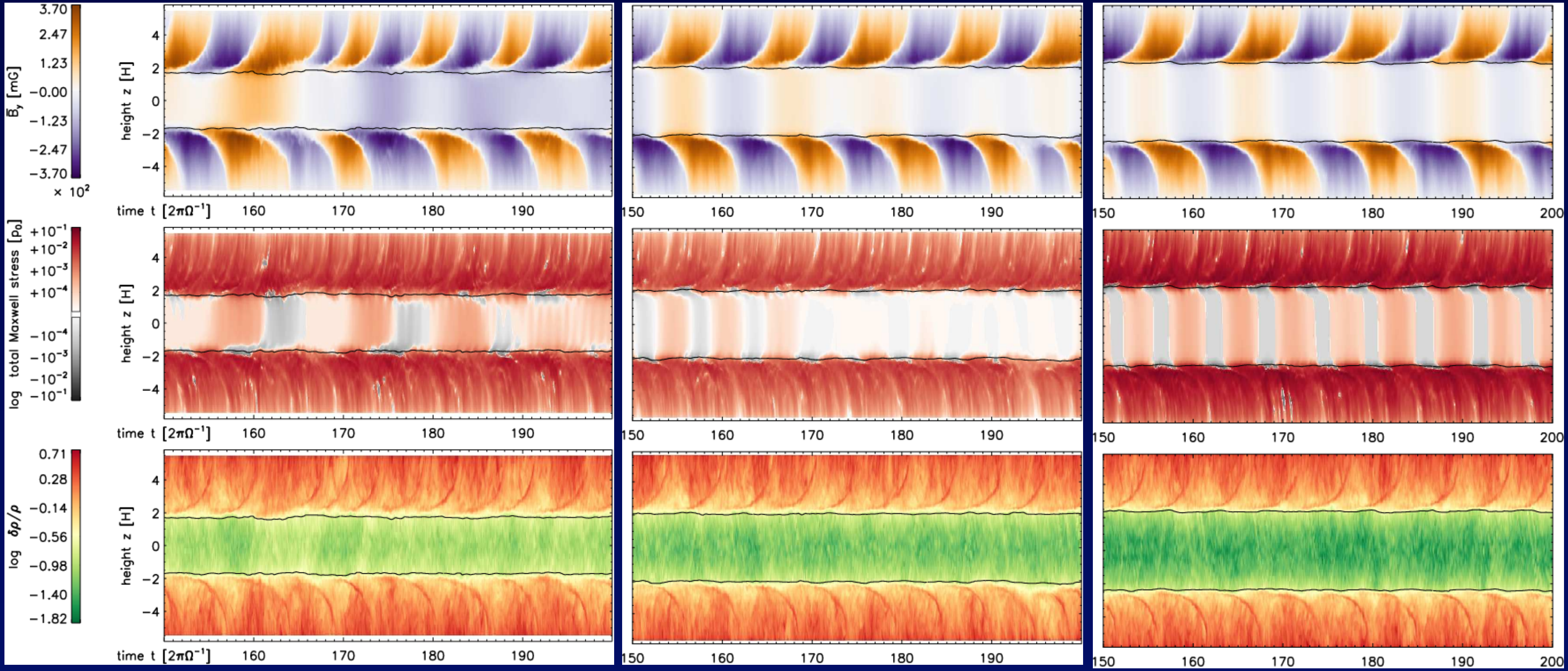
Model D1

Fully active model versus dead zone models



Random velocities in fully active disc (A1) grow ~ 20 x faster than in nominal dead zone model (D1)

Varying the disc mass



Model D1.1

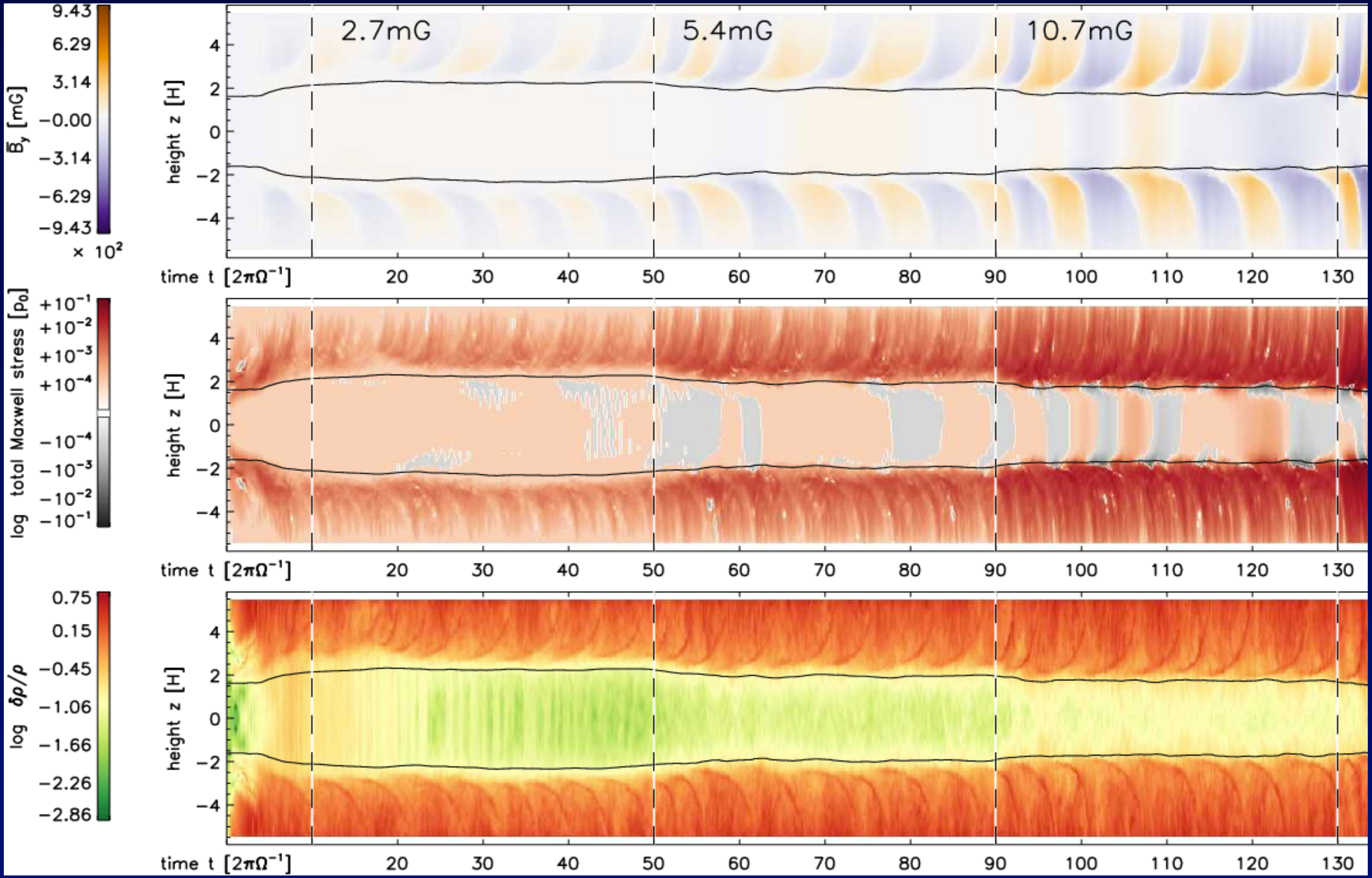
Model D1.2

Model D1.4

$$L_{\mathrm{u}} = \frac{v_{\mathrm{A}}^2}{\Omega \eta}$$

Dead zone boundary occurs where L_u=1

Dependence on magnetic field strength



$$L_\mathrm{u} = \frac{v_\mathrm{A}^2}{\Omega\eta}$$

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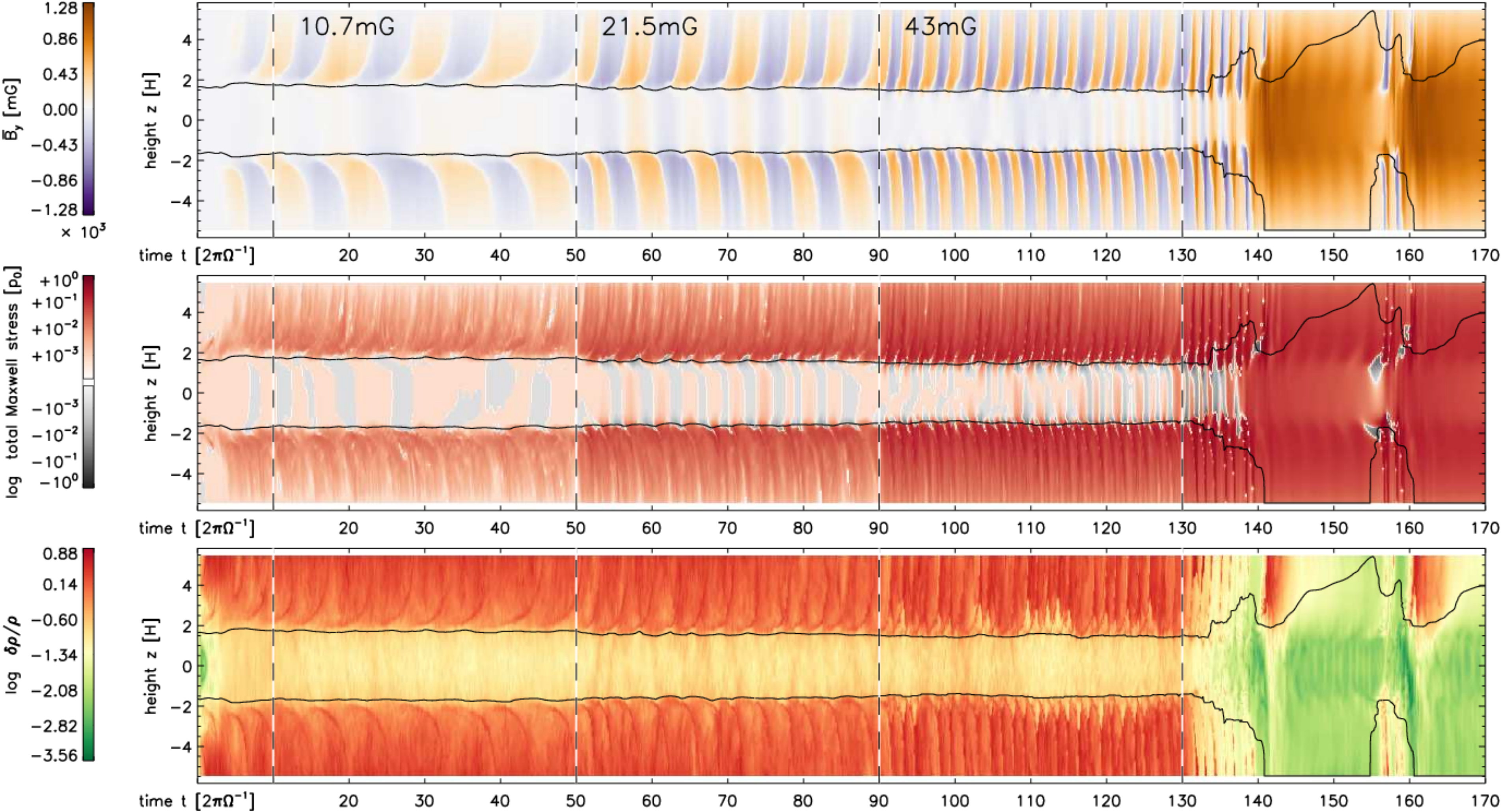
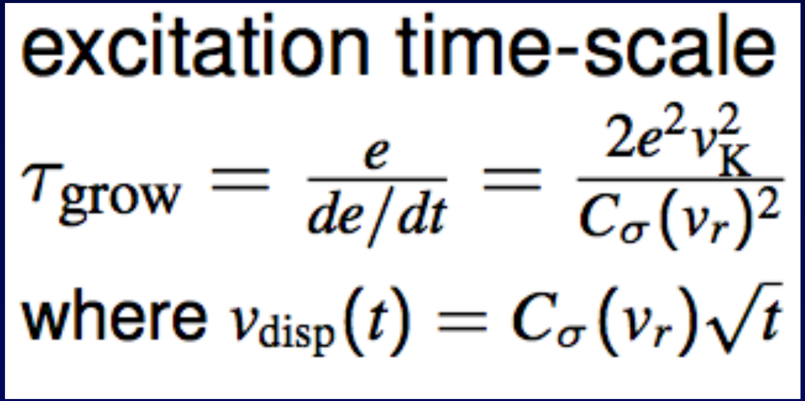
Dependence on magnetic field strength



$$L_{\mathrm{u}} = \frac{v_{\mathrm{A}}^2}{\Omega\eta}$$

Dead zone boundary occurs where L_u=1

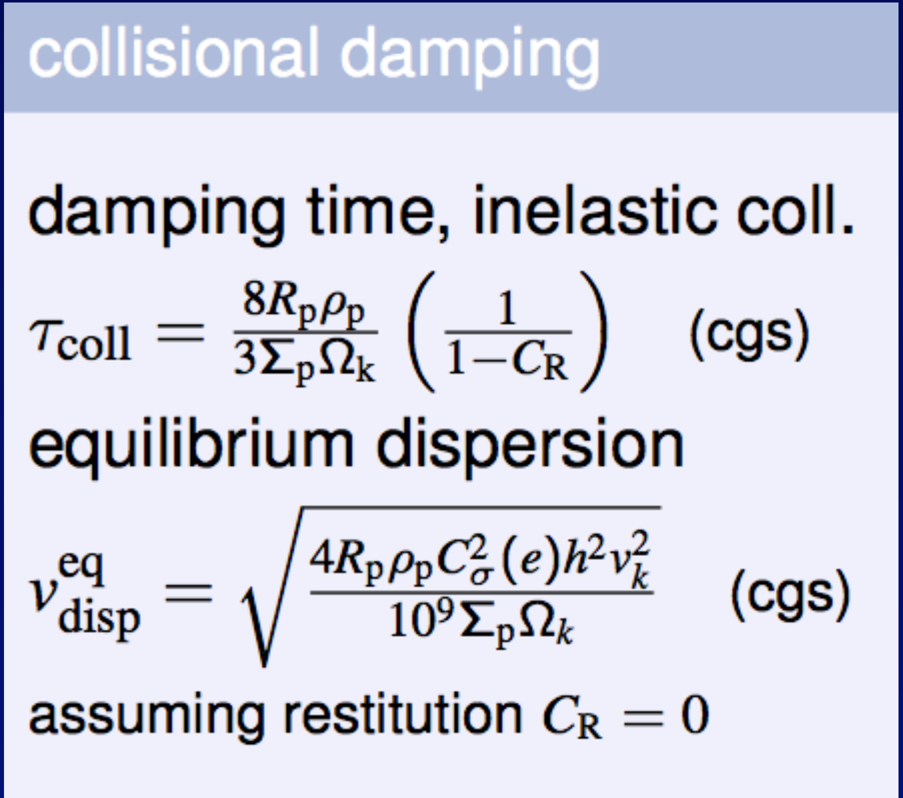
Equilibrium velocity dispersion of planetesimals



excitation time-scale

$$\tau_{\mathrm{grow}} = \frac{e}{de/dt} = \frac{2e^2 v_{\mathrm{K}}^2}{C_\sigma (v_r)^2}$$

where $v_{\mathrm{disp}}(t) = C_\sigma (v_r)\sqrt{t}$



collisional damping

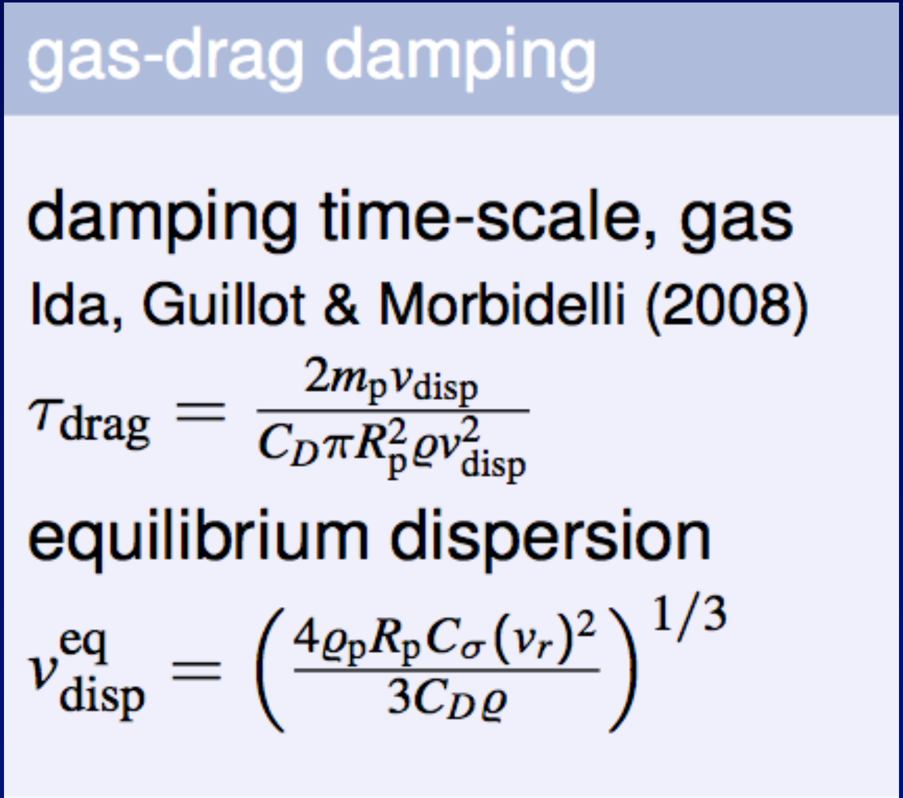
damping time, inelastic coll.

$$\tau_{\mathrm{coll}} = \frac{8R_{\mathrm{p}}\rho_{\mathrm{p}}}{3\Sigma_{\mathrm{p}}\Omega_{\mathrm{k}}}\left(\frac{1}{1-C_{\mathrm{R}}}\right) \quad \text{(cgs)}$$

equilibrium dispersion

$$v_{\mathrm{disp}}^{\mathrm{eq}} = \sqrt{\frac{4R_{\mathrm{p}}\rho_{\mathrm{p}}C_\sigma^2(e)h^2v_k^2}{10^9\Sigma_{\mathrm{p}}\Omega_k}} \quad \text{(cgs)}$$

assuming restitution $C_{\mathrm{R}} = 0$



gas-drag damping

damping time-scale, gas

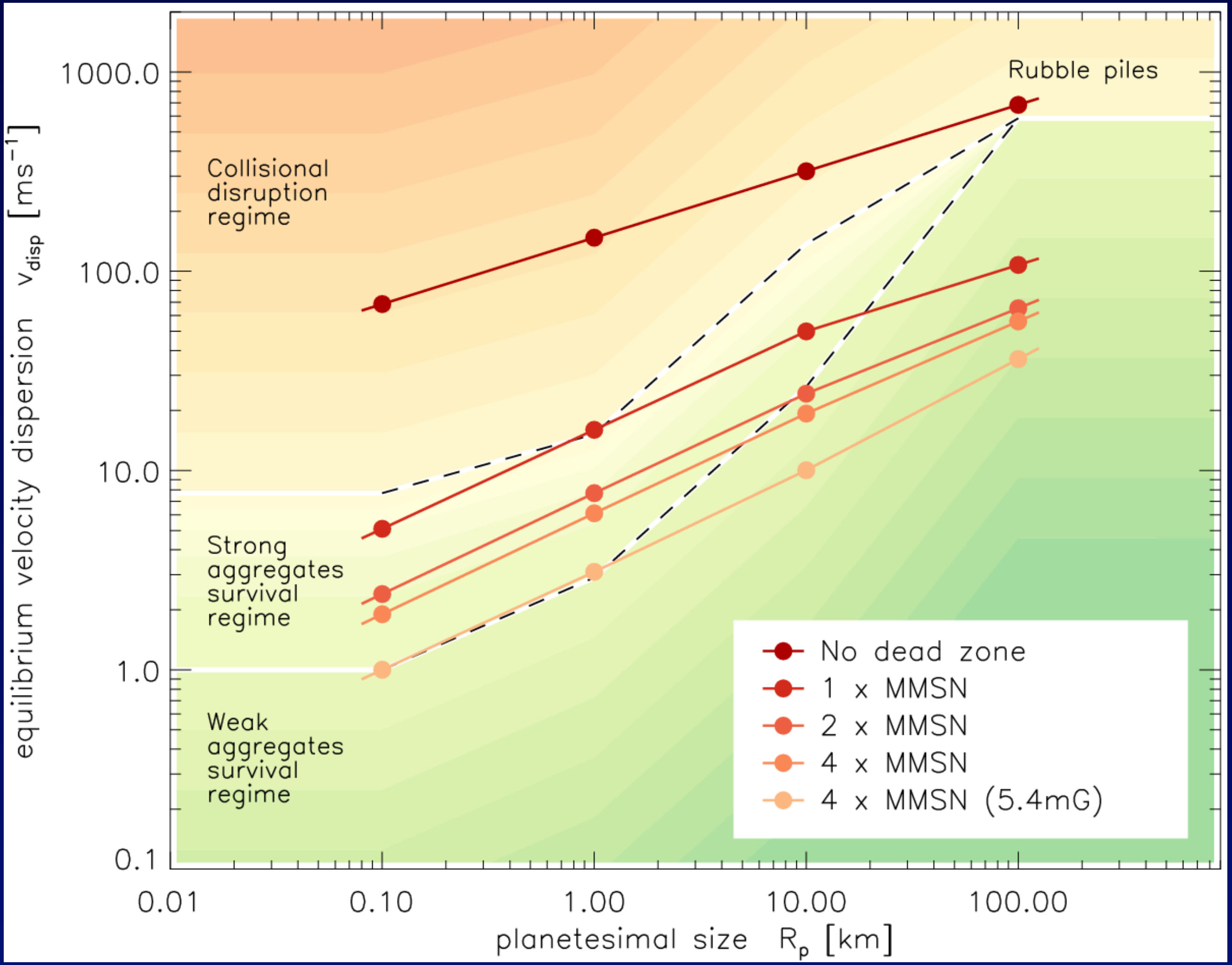
Ida, Guillot & Morbidelli (2008)

$$\tau_{\mathrm{drag}} = \frac{2m_{\mathrm{p}}v_{\mathrm{disp}}}{C_D\pi R_{\mathrm{p}}^2\varrho v_{\mathrm{disp}}^2}$$

equilibrium dispersion

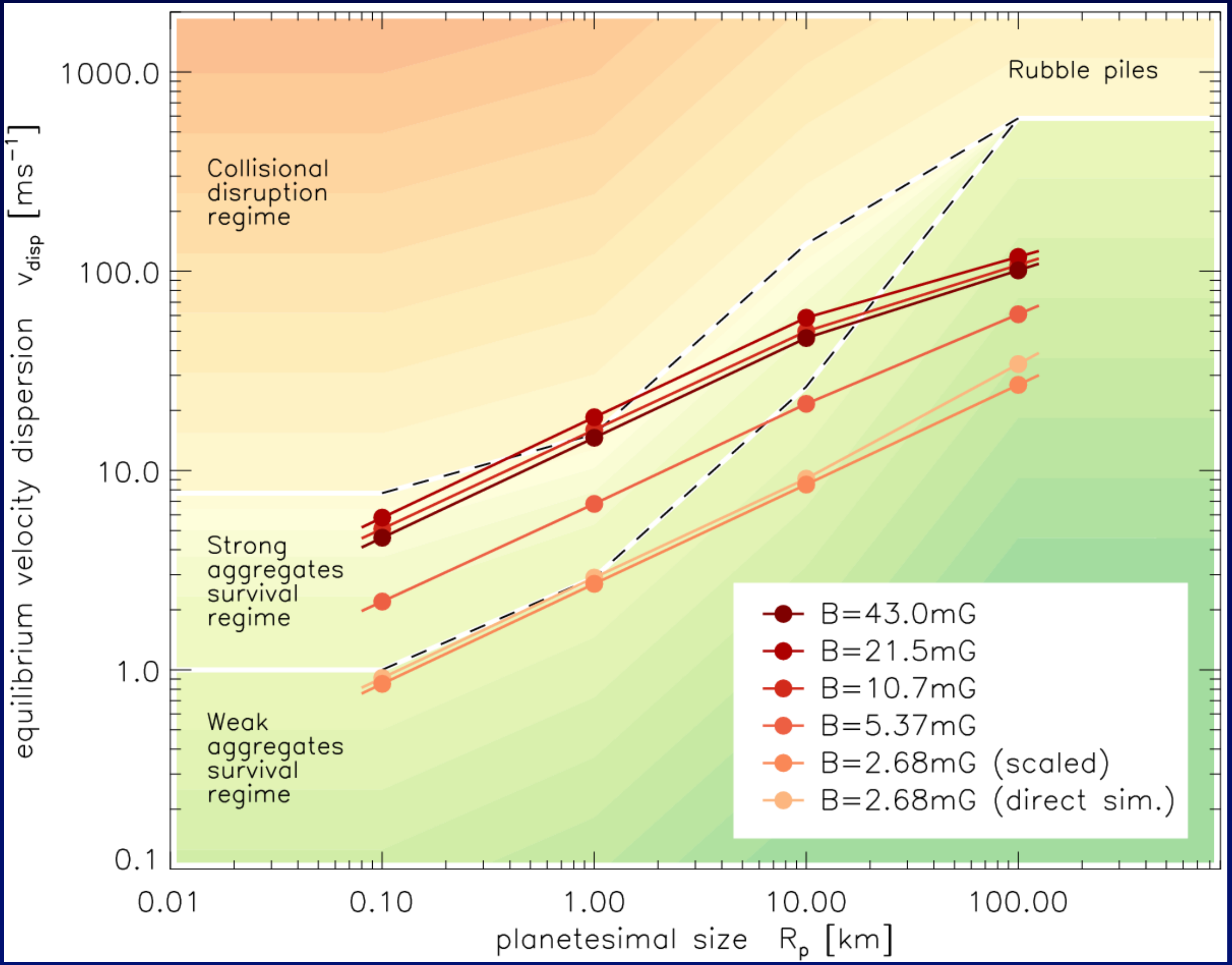
$$v_{\mathrm{disp}}^{\mathrm{eq}} = \left(\frac{4\varrho_{\mathrm{p}}R_{\mathrm{p}}C_\sigma(v_r)^2}{3C_D\varrho}\right)^{1/3}$$

Collisional disruption thresholds – varying disc mass, constant magnetic field strength



Catastrophic disruption velocities from Leinhardt & Stewart (2009)

Constant disc mass, varying magnetic field strength



Conclusion: it is *just* possible to construct a disc model with required mass accretion rate and which allows even weak planetesimals to avoid catastrophic disruption

Implications

- Building icy planetesimals in an incremental growth scenario possible in either a disc with 4 x MMSN and $dm/dt \sim 10^{-8}\ M_{sun}\ yr^{-1}$ or in a MMSN disc with $dm/dt \sim 10^{-9}\ M_{sun}\ yr^{-1}$

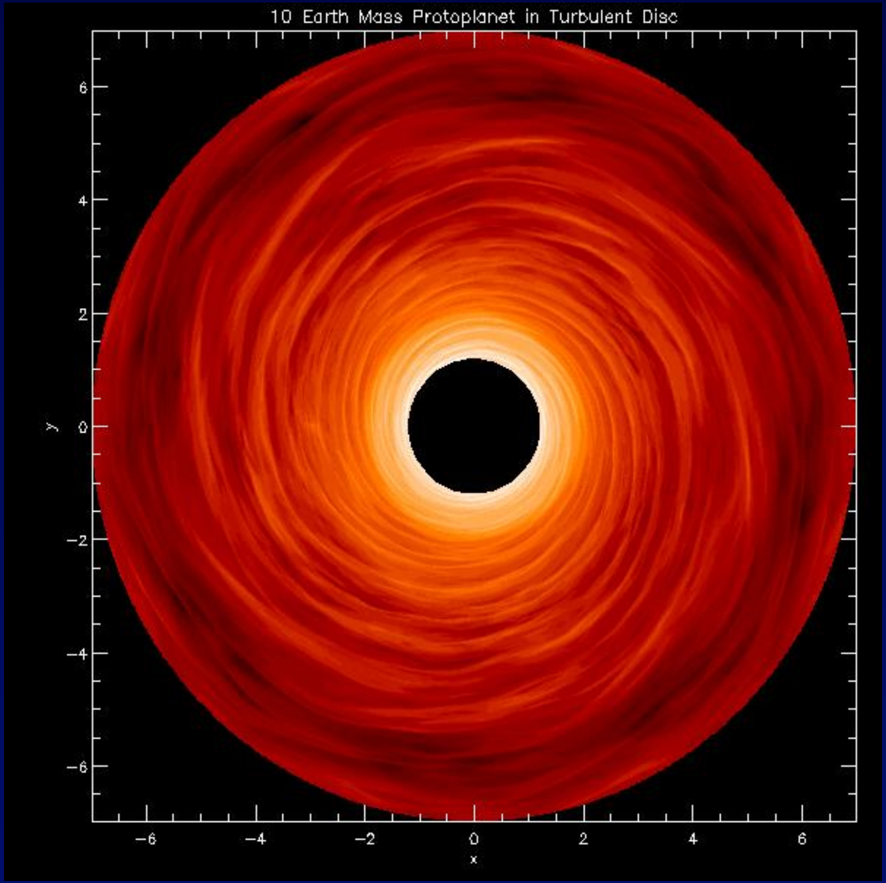
- Prompt formation of 10 km planetesimals leads to delayed runaway growth as $v_{dispersion} \sim 10\ m\ s^{-1}$ in $< 10^5$ years

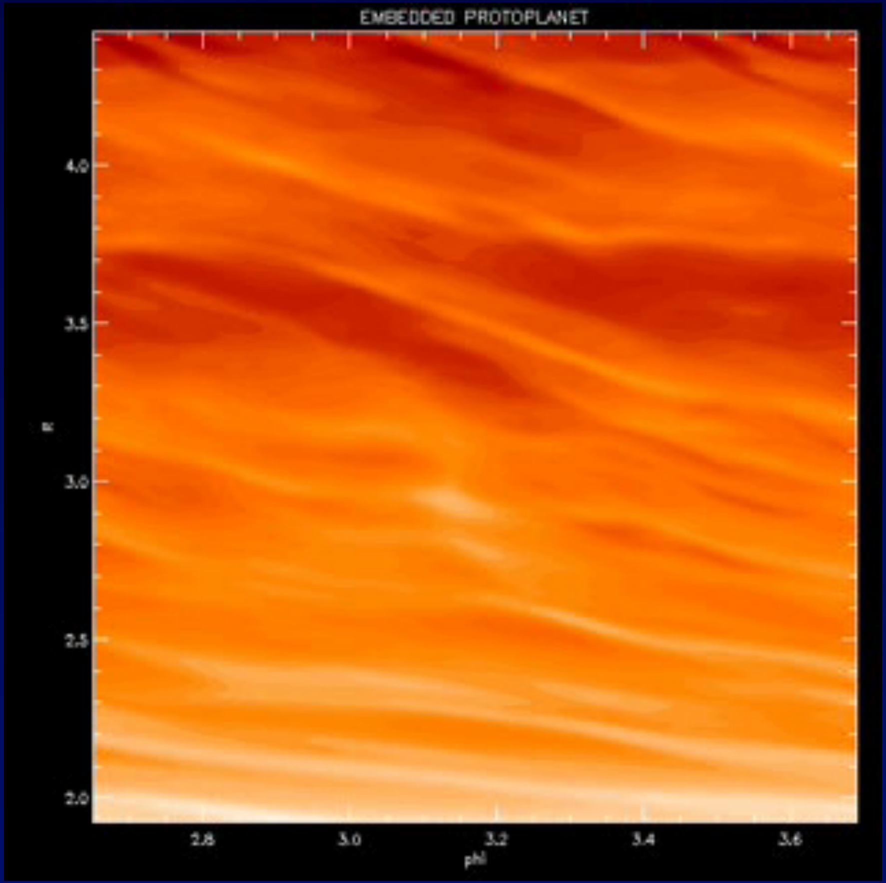
- Prompt formation of 100 km planetesimals leads to immediate runaway growth of these bodies as $v_{dispersion} < v_{esc}$

- Migrating small planetesimals into inner disc regions, as in some *in situ* planet formation scenarios, leads to their rapid collisional destruction

Low mass planets in turbulent discs

Stochastic migration

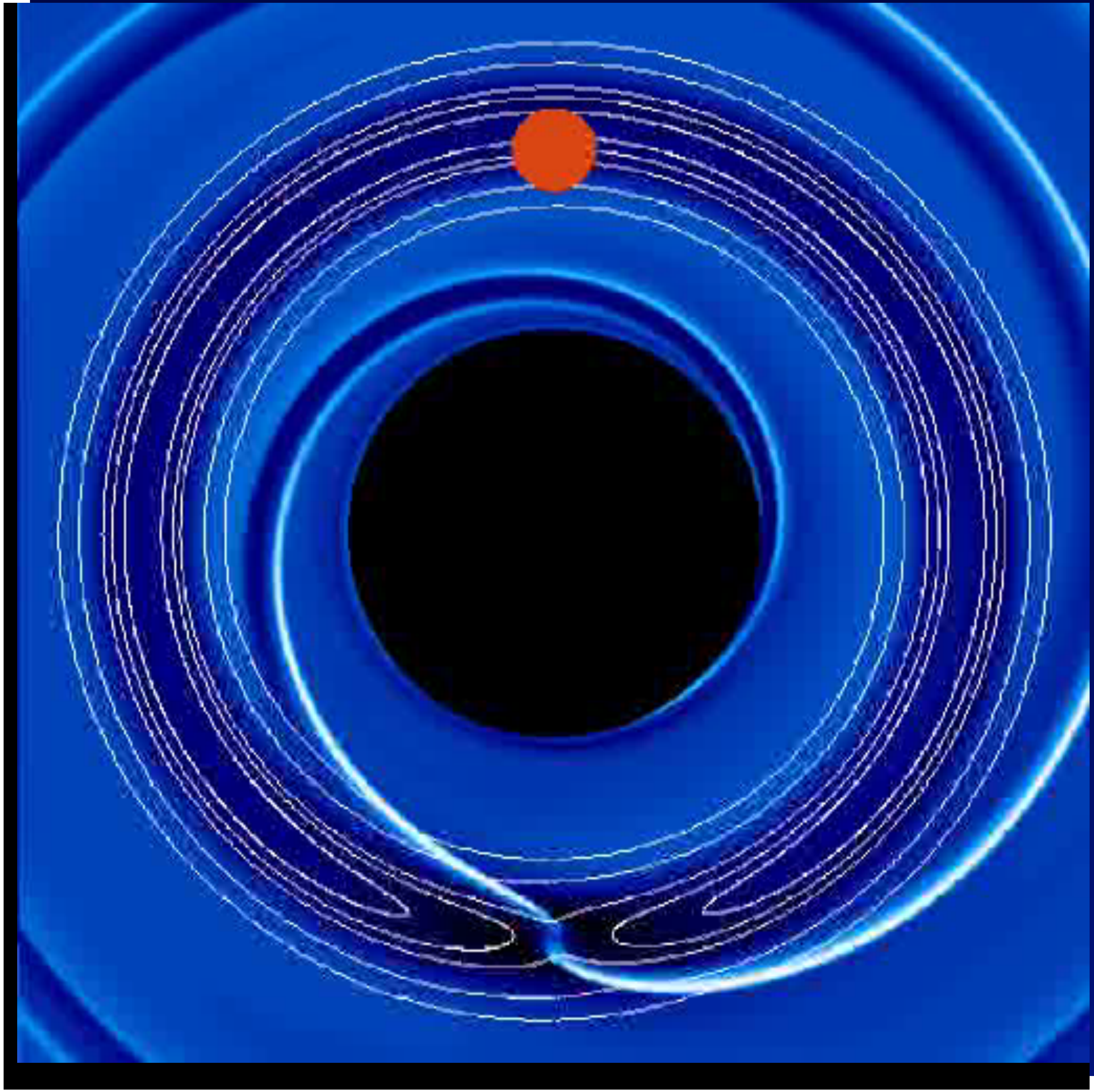




Stochastic migration in a dead zone unlikely to influence or solve type I migration problem

Nelson & Papaloizou (2004)
Papaloizou, Nelson & Snellgrove (2004)
Laughlin, Steinacker & Adams (2004)
Johnson, Goodman & Menou (2006)
Adams & Bloch (2009)

Corotation torques



Corotation torques are driven by vortensity & entropy gradients

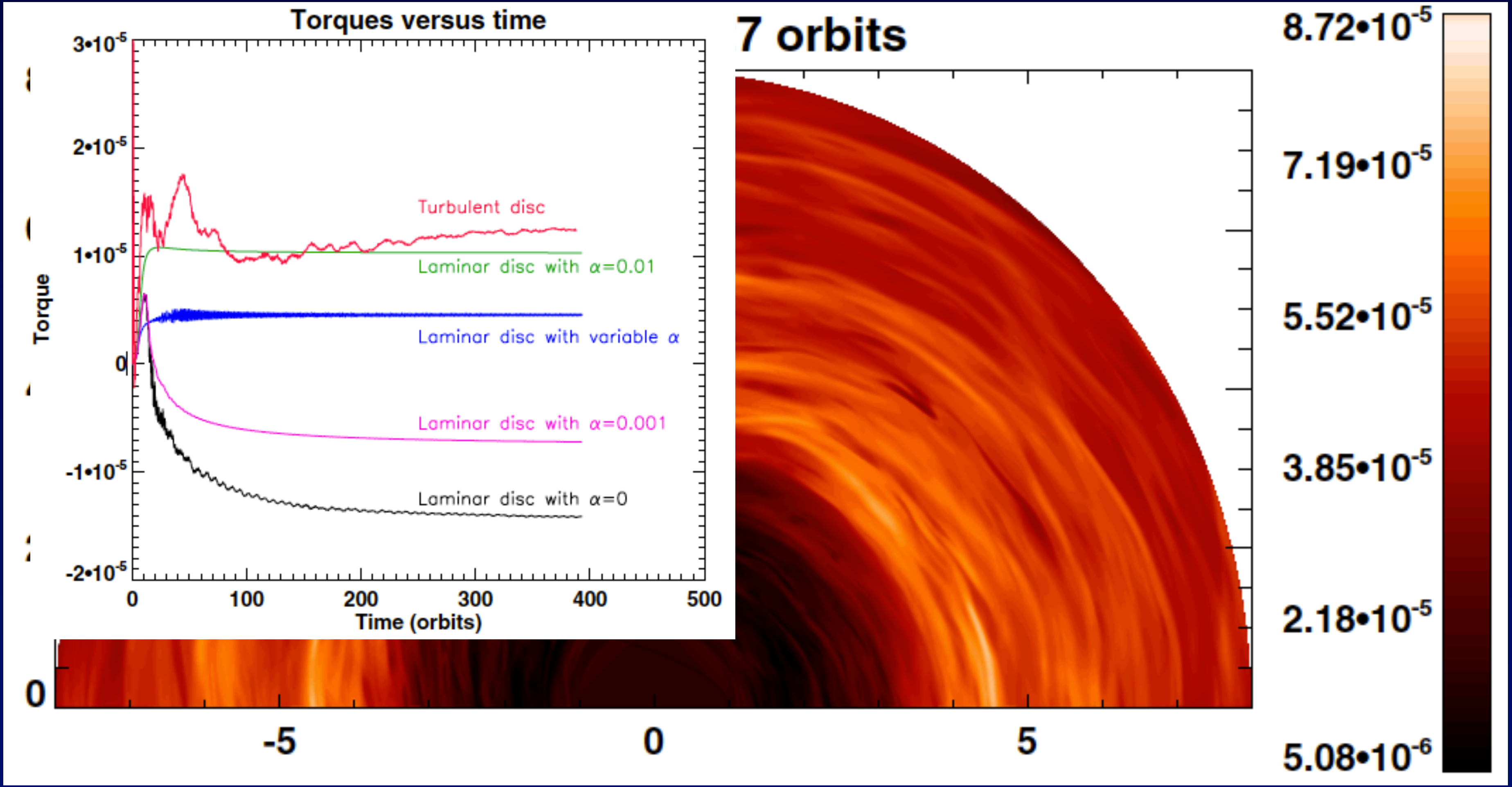
Sustaining corotation torques
➔ require viscous & thermal diffusion times across corotation region ~ horseshoe orbit time
(Paardekooper & Mellema 2007;
Baruteau & Masset 2008;
Pardekooper & Papaloizou 2008)

Note that viscous stresses are required to unsaturate both entropy- and vortensity-related corotation torques

Key questions:

Can fully developed MRI turbulence prevent saturation of corotation torque for low mass planets?
(Baruteau & Lin 2010
Baruteau, Fromang, Nelson, Masset 2011)

Can the Reynolds stress in a dead zone prevent saturation of the corotation torque?
(Nelson, Baruteau, Fromang 2014)



The transition between the fully active region and the dead zone at ~ 0.3 AU may provide a planet trap

Corotation torques in dead zones

- Global simulations of discs with dead zones performed using NIRVANA (Nelson, Baruteau & Fromang 2014)

- Planets with masses $m_p = 5\ M_{earth}$ orbiting at 3 AU

- H/R=0.05

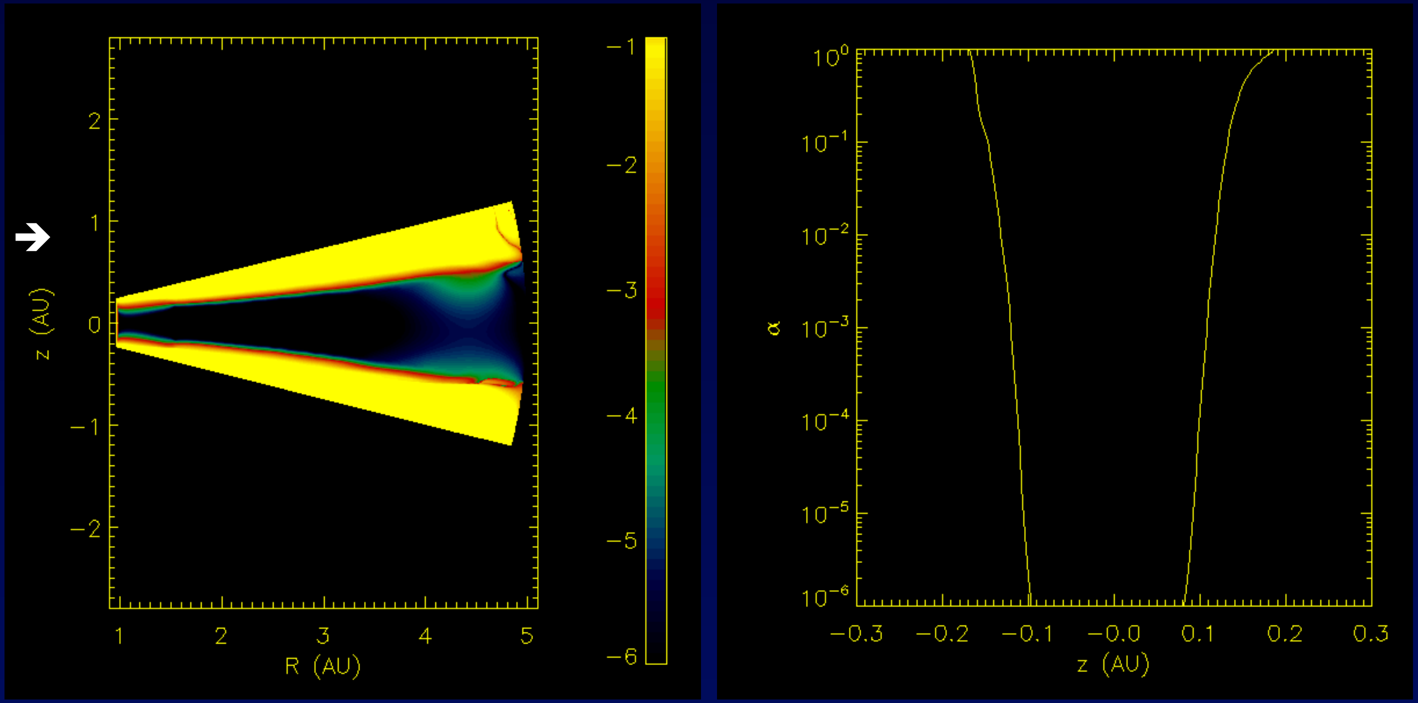
- Disc mass varied between 0.1 – 1 x MMSN to vary dead zone depth

- $\Sigma \sim \Sigma_0\ R^2$ ➔ strong and positive corotation torque

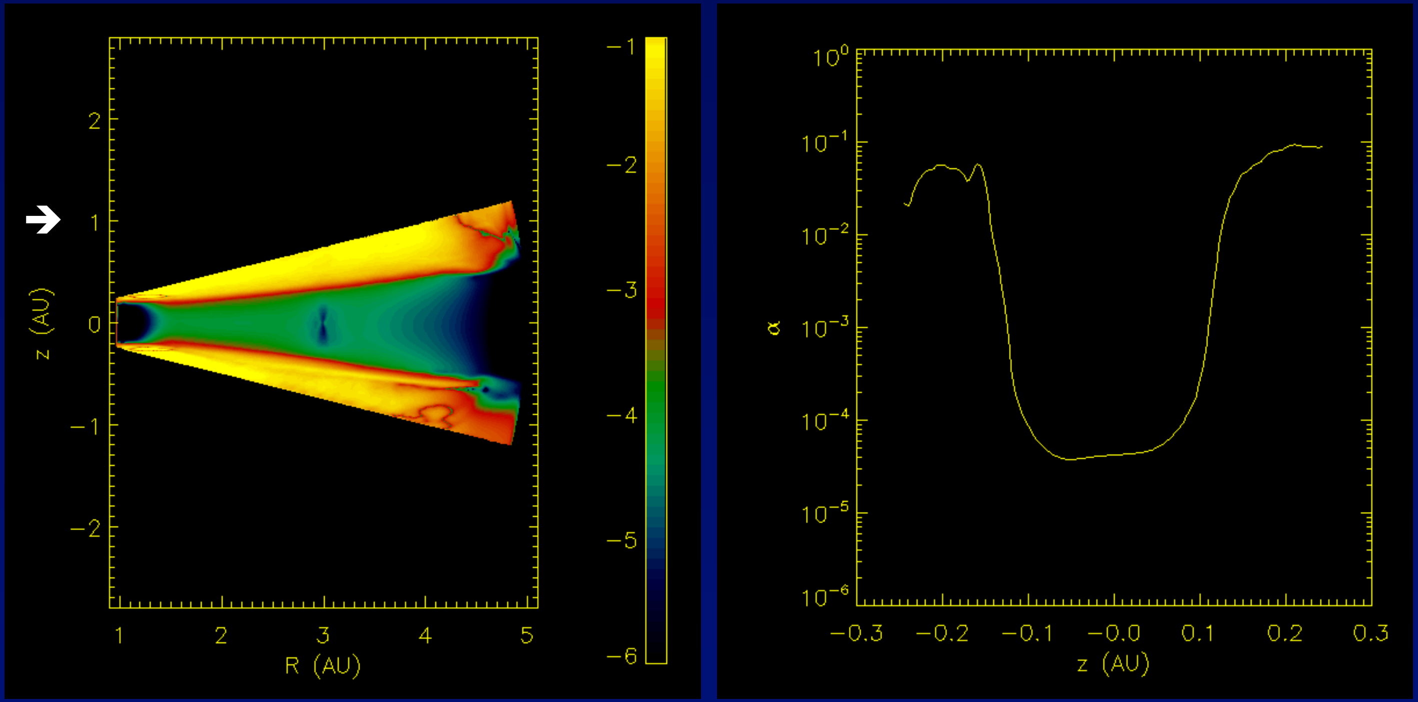
Preventing saturation (prediction!):
$m_p=5\ M_{earth}$ and H/R=0.05 ➔ require $\alpha \sim 10^{-3}$

MMSN

Maxwell stress →

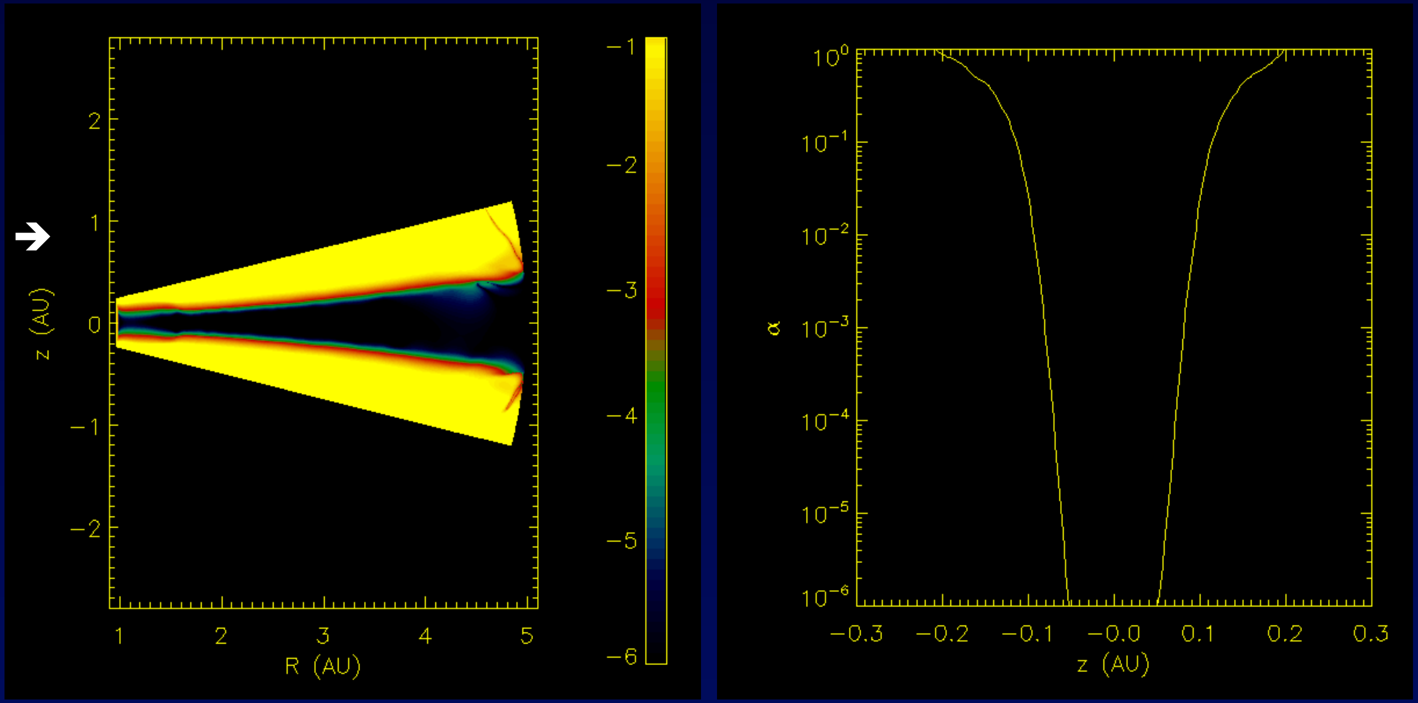


Reynolds stress →

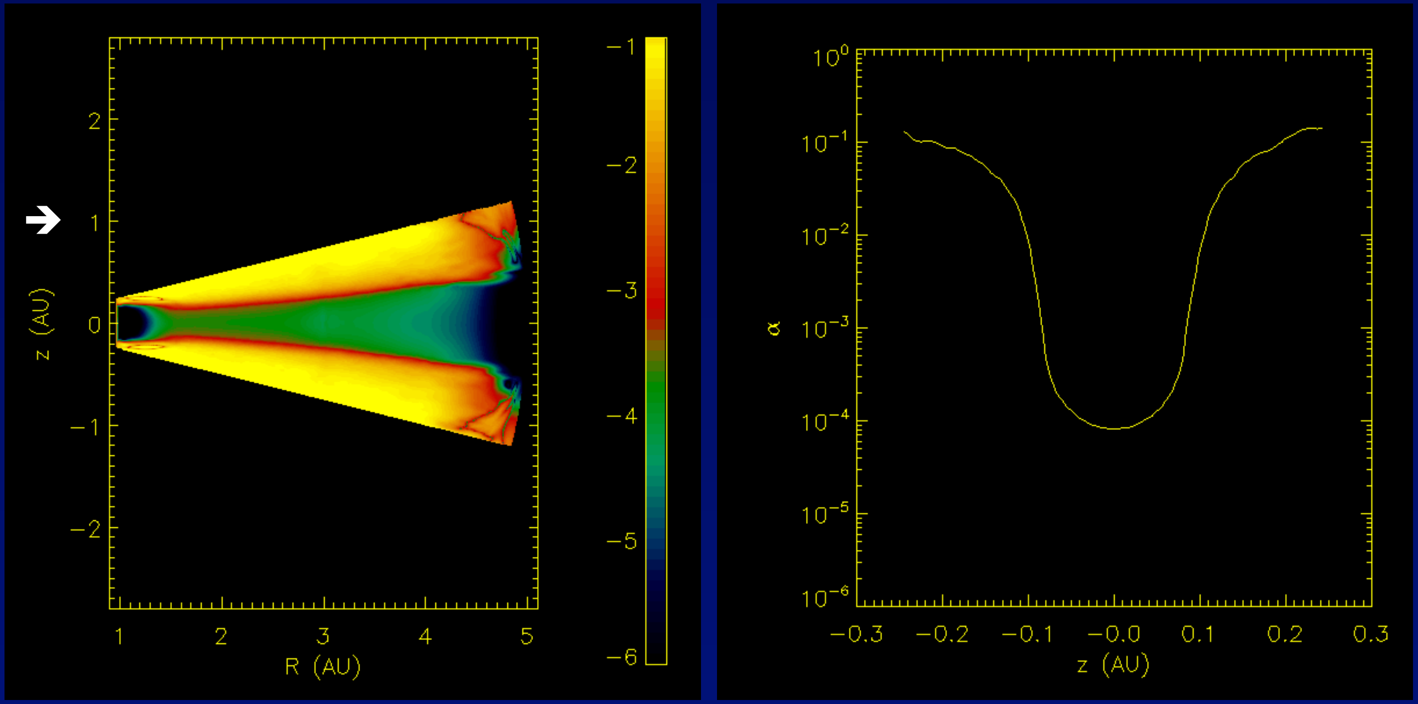


¼ MMSN

Maxwell stress →

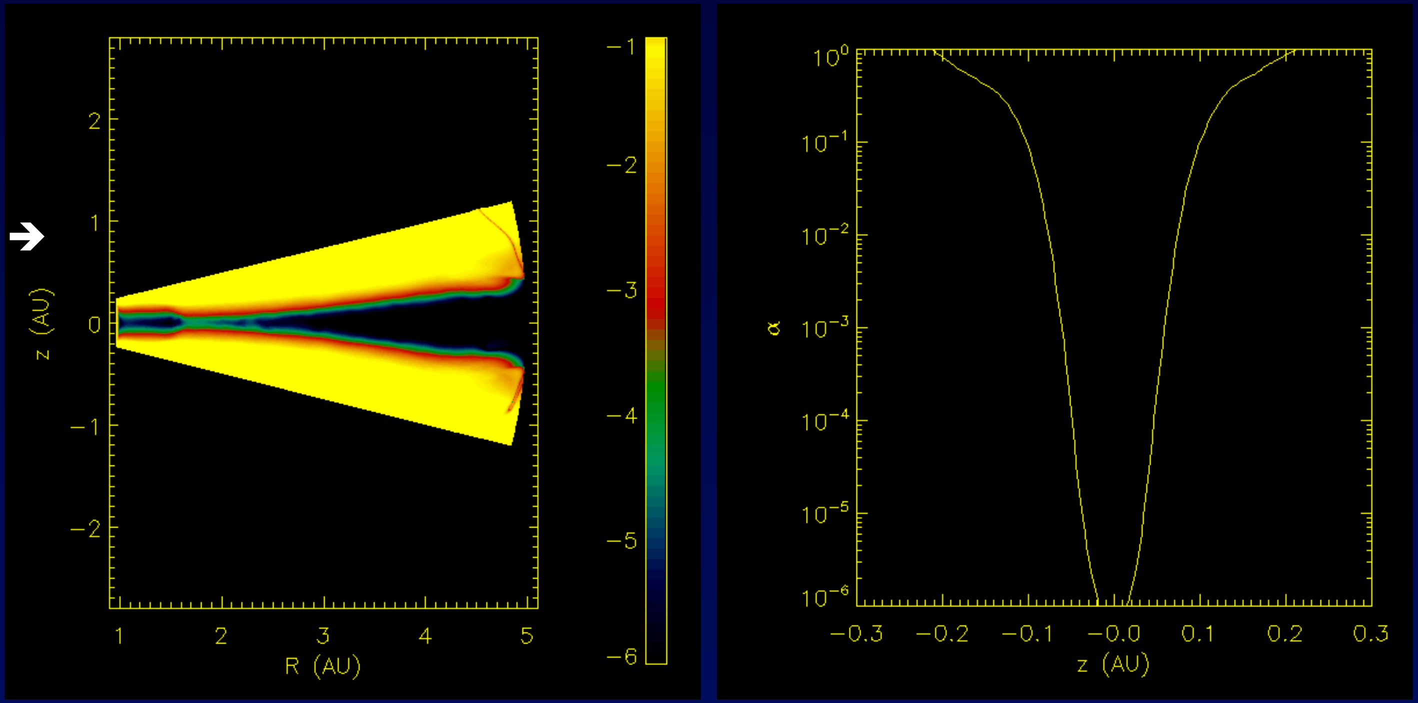


Reynolds stress →

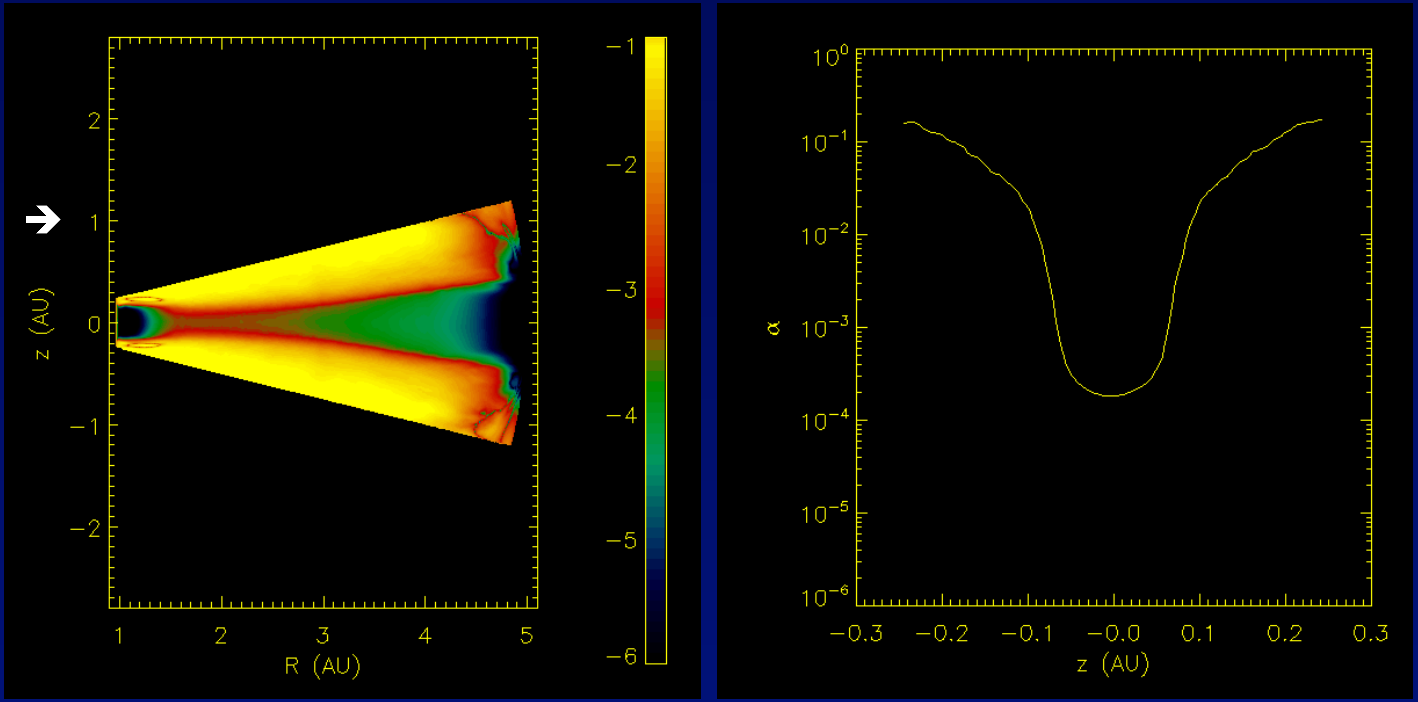


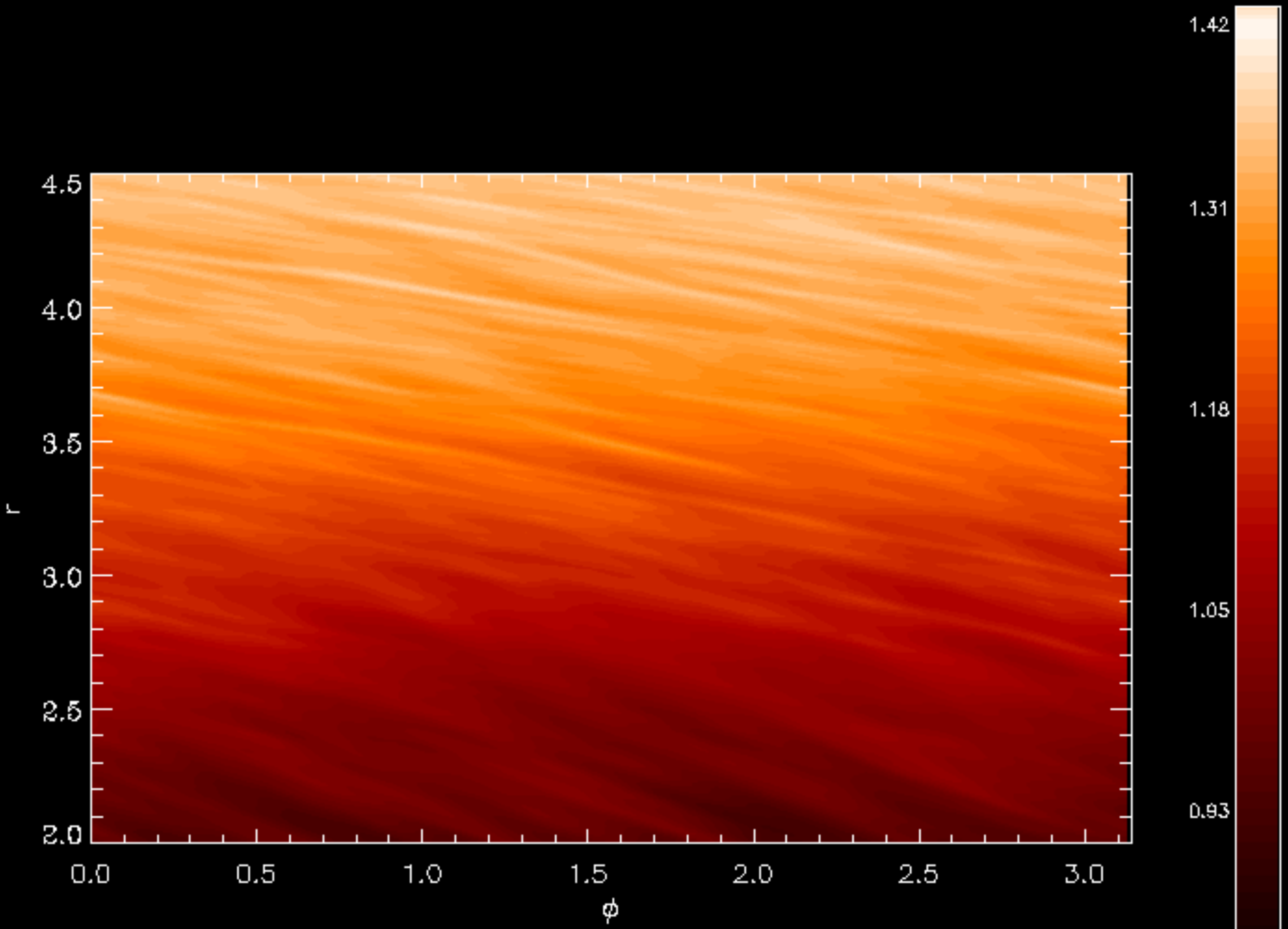
1/10 MMSN

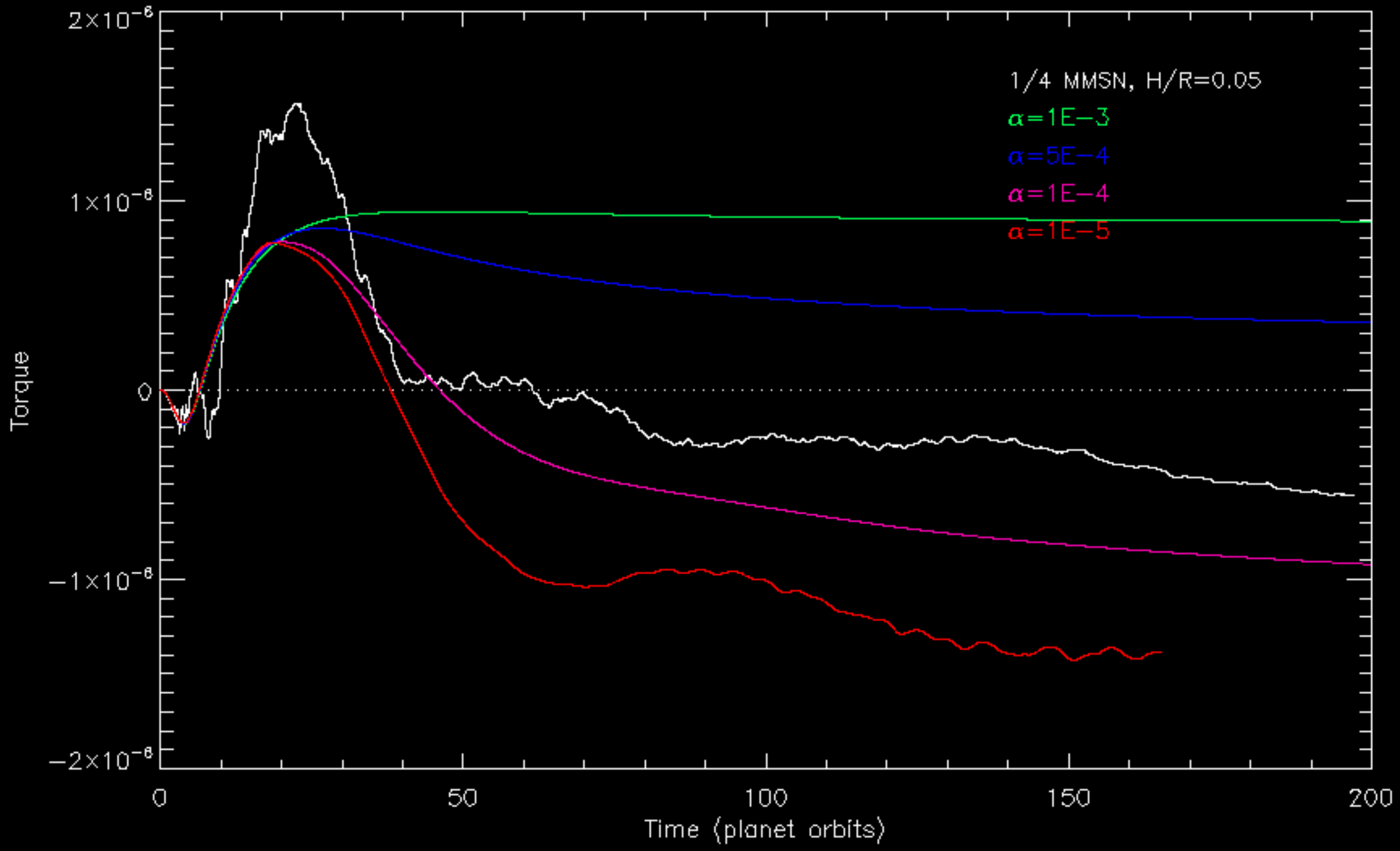
Maxwell stress →



Reynolds stress →




4.5
4.0
3.5
3.0
2.5
2.0
r
0.0
0.5
1.0
1.5
2.0
2.5
3.0
ϕ
1.42
1.31
1.18
1.05
0.93
0.80

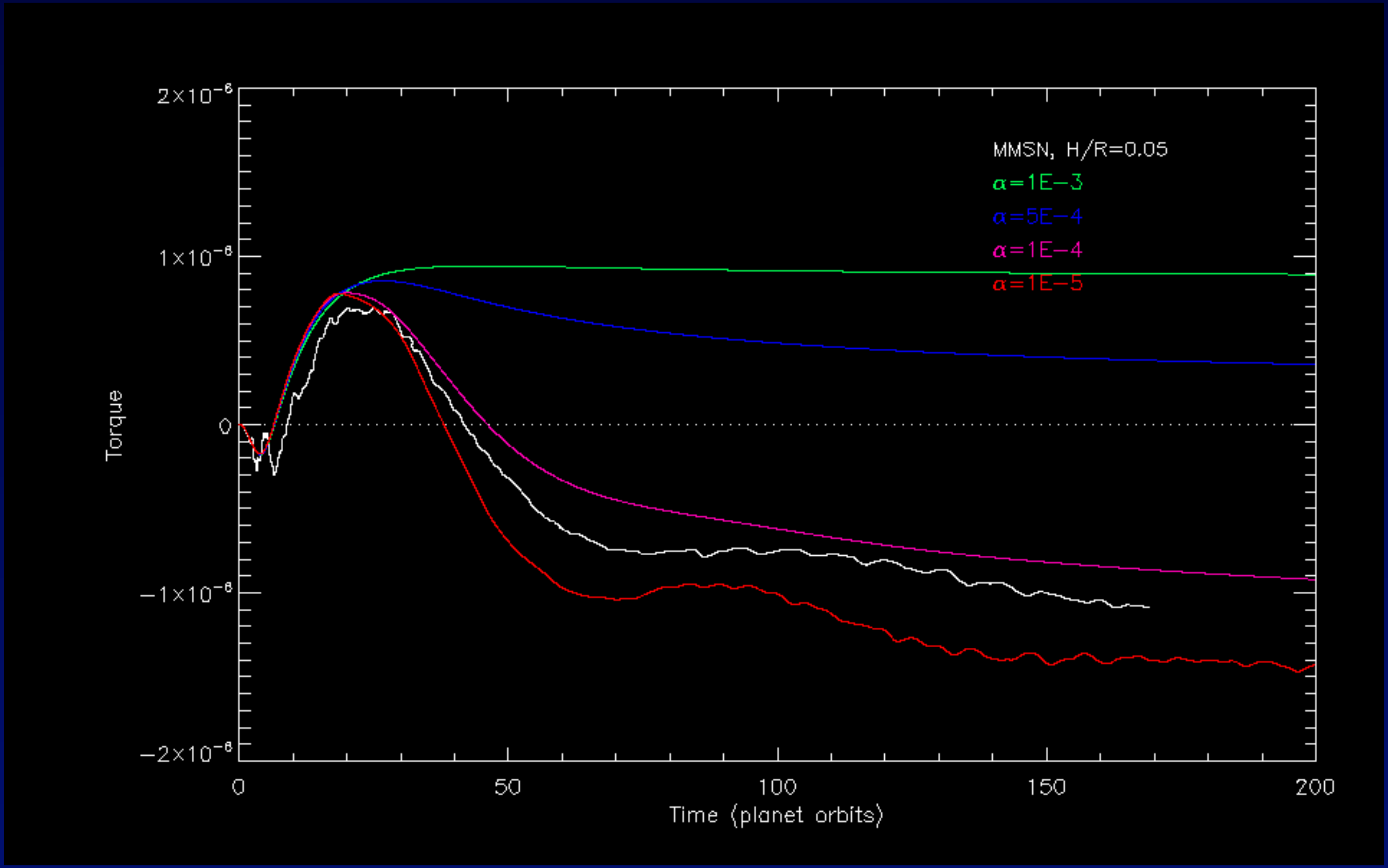


¼ MMSN model

Midplane α ~ $8x10^{-5}$

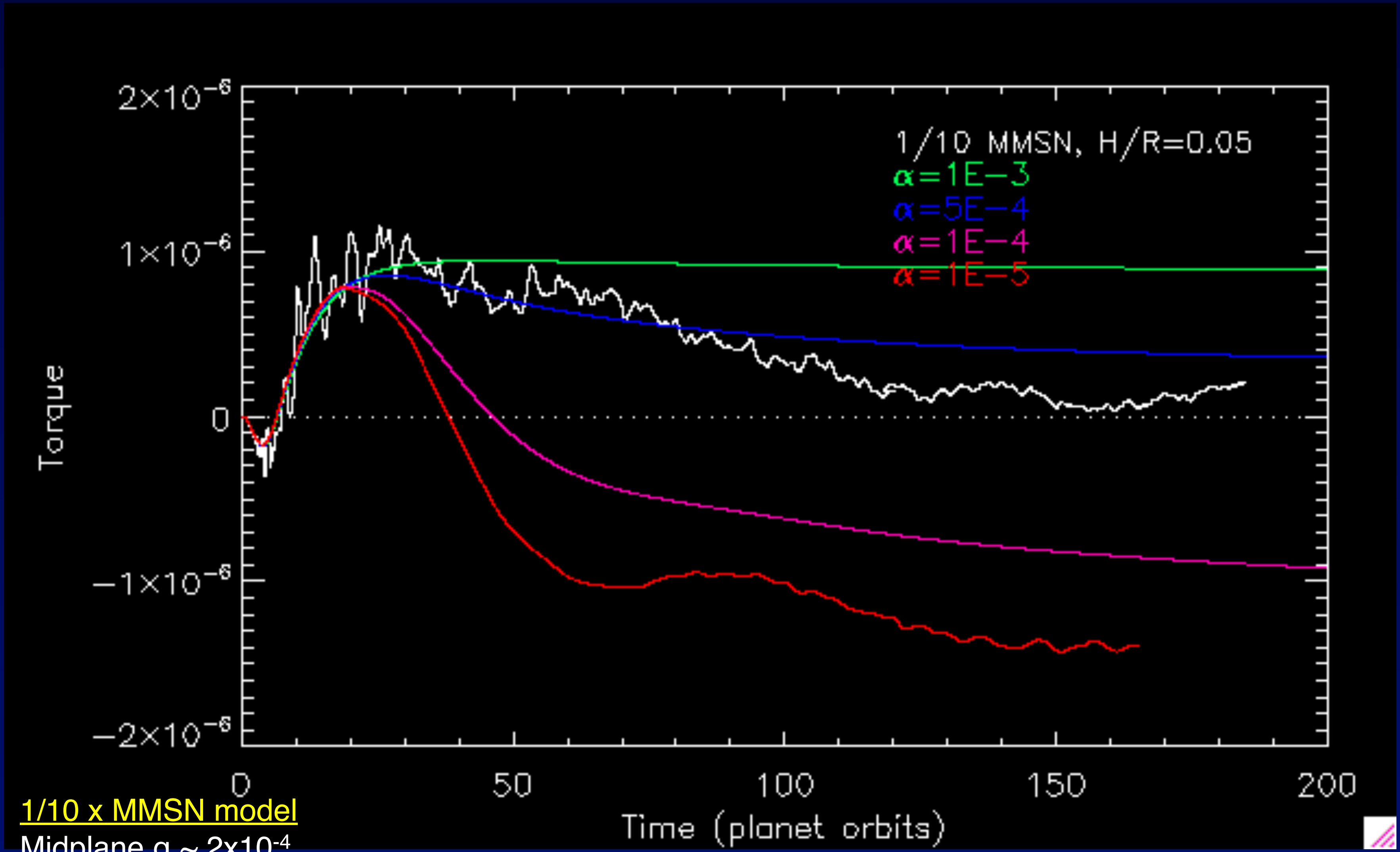
Volume averaged α ~ $5x10^{-4}$

Model evolution corresponds to $10^{-4} \leq \alpha \leq 5x10^{-4}$



MMSN model

Midplane α ~ $3x10^{-5}$
Volume averaged α ~ $8x10^{-5}$
Model evolution corresponds to $10^{-5} \leq \alpha \leq 10^{-4}$



1/10 x MMSN model

Midplane α ~ 2×10^{-4}

Volume averaged α ~ 1.5×10^{-3}

Model evolution corresponds to $10^{-4} \leq \alpha \leq 5 \times 10^{-4}$

Conclusion: cannot prevent saturation of corotation torque for low mass planets in dead zones unless at the end of disc life time ➔ require additional stresses to prevent catastrophic migration

Implications for planet formation

Planetesimals

An incremental planetesimal growth model cannot operate in a disc with fully developed turbulence.

It is only just possible to construct such a model in a ~ MMSN disc with a dead zone.

Prompt formation of 1 - 10 km planetesimals leads to delayed runaway growth, but 100 km planetesimals may undergo immediate runaway growth.

In situ formation models of planets based on rapid inward migration of small planetesimals cannot operate in an inner disc region with fully developed turbulence.

Low mass planets in dead zones

Corotation torques are unsaturated by fully developed MRI turbulence – may operate in disc inner regions

Corotation torques saturate in dead zones of discs with ≥ MMSN masses
➔ rapid inward migration of super-earths and Neptune-mass bodies

Conclusions

Recent models of disc evolution including Hall effect and ambipolar diffusion (Lesur et al 2014; Bai 2014) may allow incremental and prompt planetesimal formation models to operate
– and may allow corotation torques of low mass planets to remain unsaturated.

Caveat: These models predict that discs with be essentially laminar between radii $0.2 \leq R_{disc} \leq 30$ AU. How to maintain population of small grains in disc atmospheres required by SEDs (Dullemond & Dominik 2005)