Disc (Magneto)hydrodynamics: Implications for planet formation

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Talk Outline

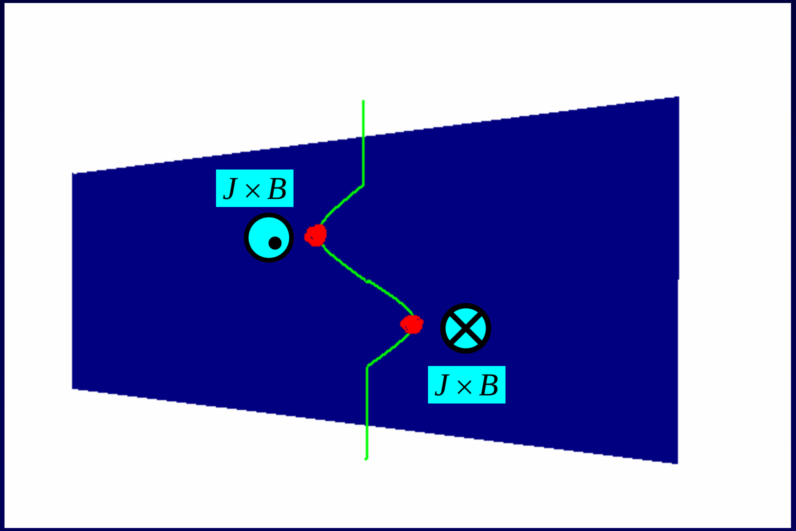
- Models of disc turbulence
- MHD turbulent models
- Planetesimals in turbulent discs
- Low mass planets in turbulent discs
- High mass planets in turbulent discs
- Conclusions and future directions

Hydrodynamic Turbulence

- Keplerian shear flow is linearly stable
- Transient growth of fluctuations may occur (e.g. Mukhopadhyay, Afshordi & Narayan 2004; Umurhan & Regev 2004; Johnson & Gammie 2005)
- Development of turbulence <u>not</u> seen in non linear studies
- Baroclinic instability may lead to turbulence and vortices (Klahr & Bodenheimer 2003)

MHD Turbulence

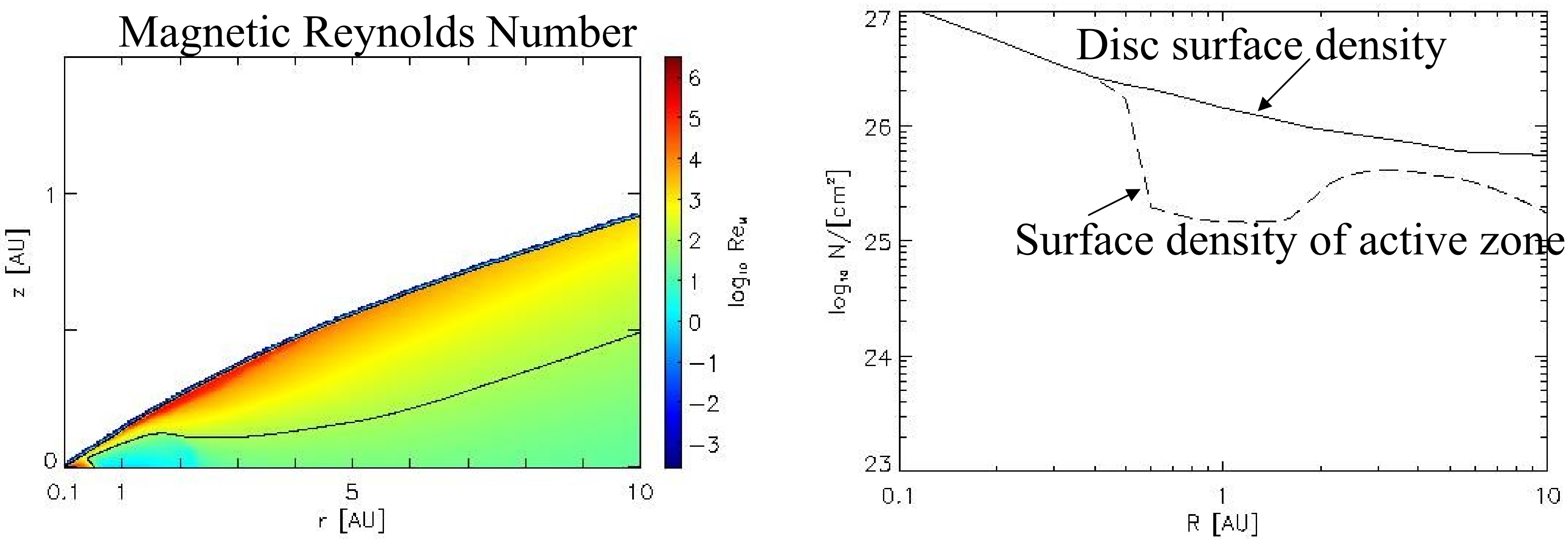
- MRI discovered in context of discs by Balbus & Hawley (1991)
- MRI leads to vigorous turbulence (e.g. Hawley & Balbus 1991; Hawley, Gammie & Balbus 1996)
- Necessary ingredients:
  (i) Weak magnetic field
  (ii) $d\Omega / dR < 0$
  (iii) Sufficient ionisation - $X(e) \sim 10^{-12}$



Magnitude of effective viscosity depends on field topology and strength (e.g. Papaloizou & Steinacker 2002):

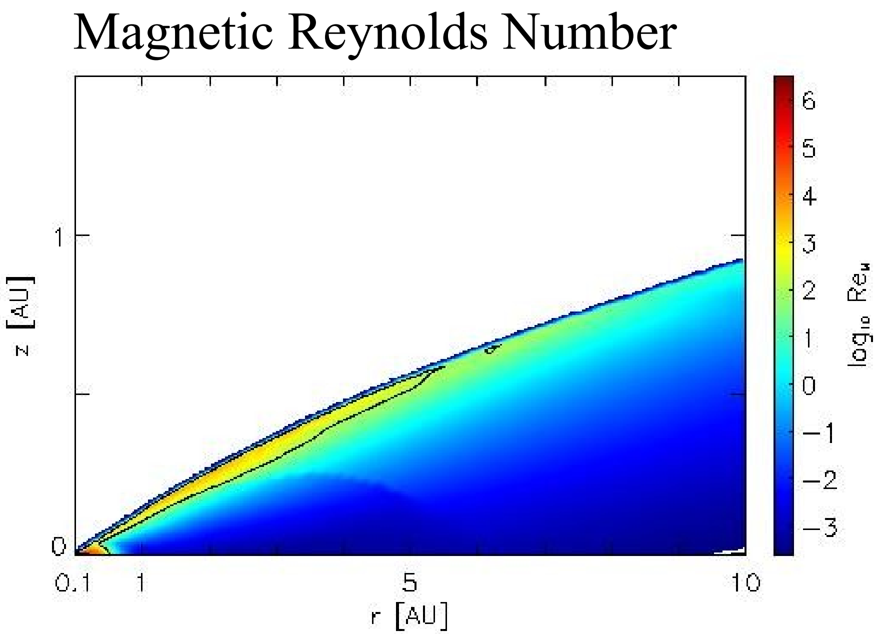
- Zero net flux fields give $\alpha \sim 5 \times 10^{-3}$
- Net flux toroidal fields give $\alpha \sim 0.01 – 0.03$
- Net flux vertical fields give $\alpha \sim 0.1 – 0.2$

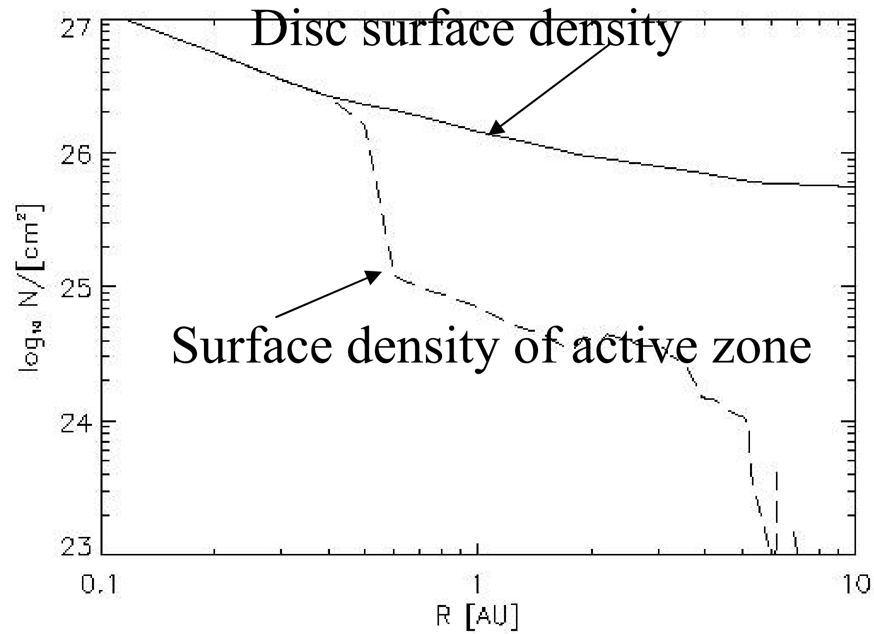
Chemical models used to calculate ionisation fraction in discs:
Gammie (1996); Fromang, Terquem & Balbus (2002); Sano et al (2000); Semenov, Wiebe & Henning (2003); Ilgner & Nelson (2005)



Gas phase chemistry: UMIST network
X-ray ionisation
$X(Mg) \sim 10^{-8}$
Disc model: $dM/dt = 10^{-7} M_{sun}/yr$ $\alpha = 0.01$

Active zones determined by having Magnetic Reynolds number > 100





UMIST network with adsorption + desorption of species onto dust

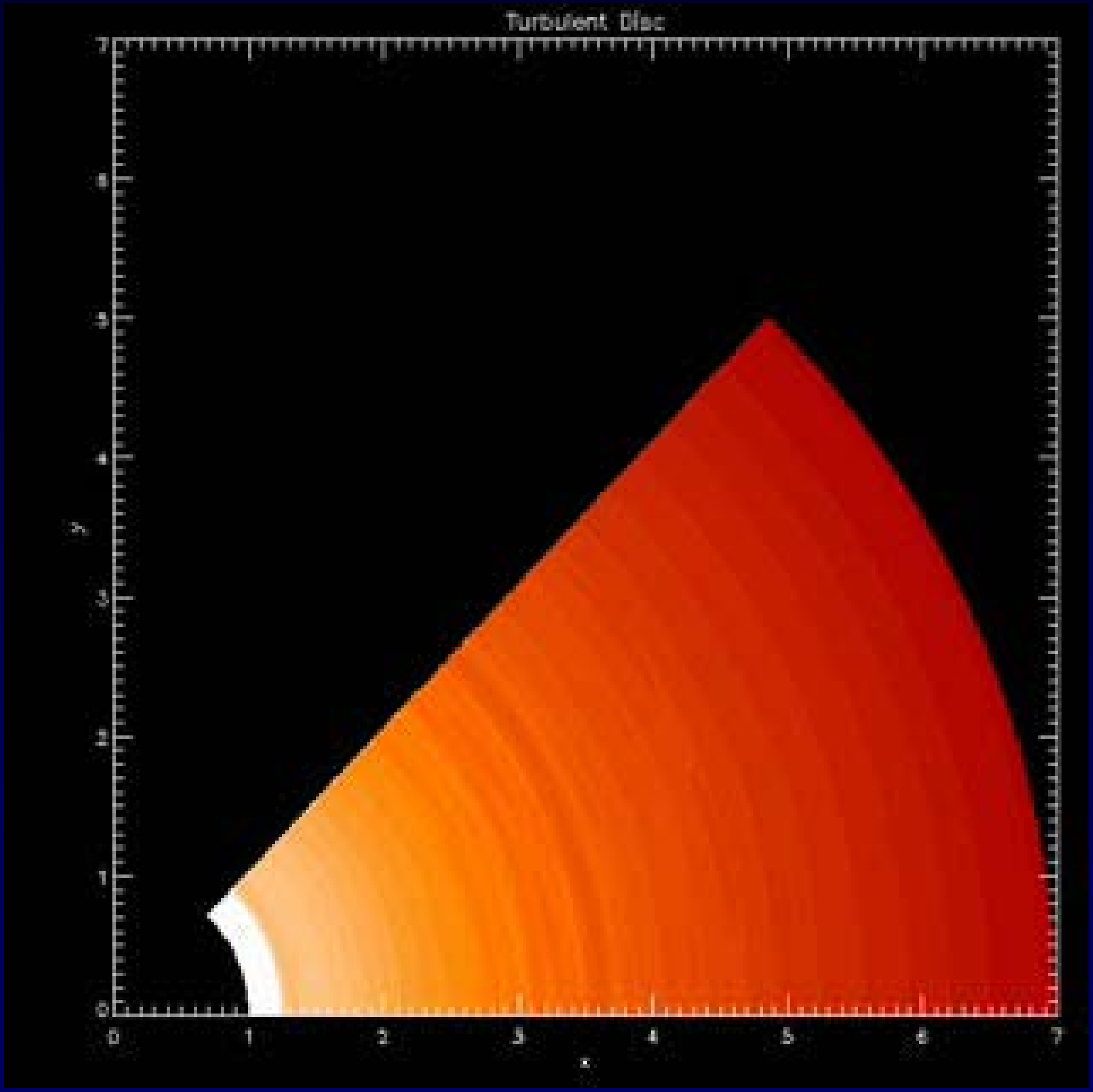
Only ~ 1% of disc mass is magnetically active in planet forming region

To obtain gas phase X(e) $\longrightarrow$ must reduce dust concentration by 10^{-4}

(Note: not a proper dust evolution model !)

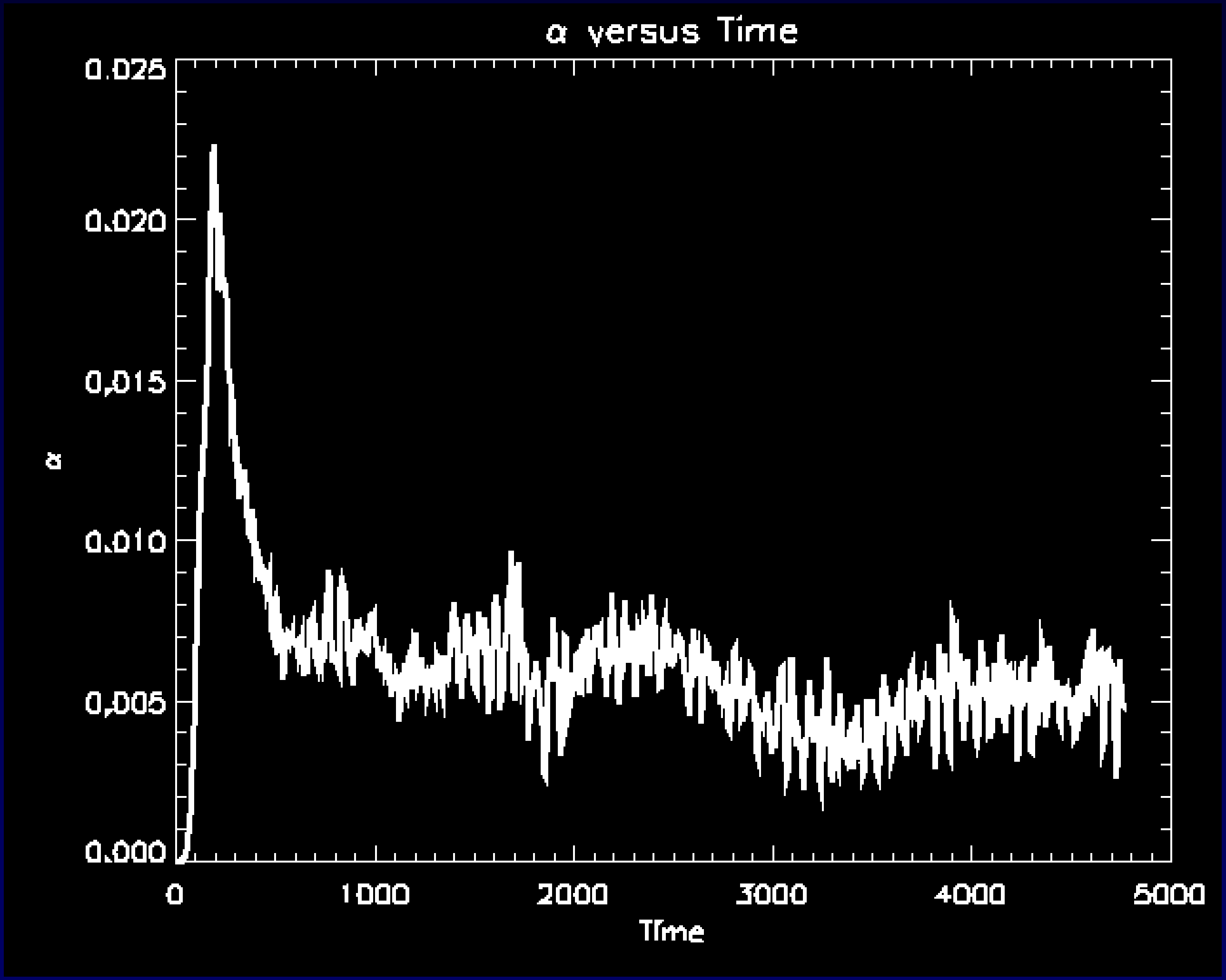
MHD disc models

- Models computed using 3D MHD code NIRVANA run on UKAFF and local beowulf cluster
- Cylindrical discs – no z component of gravity
- Magnetic field – zero net flux (vertical or toroidal) initially distributed in annulus
- Equation of state - locally isothermal
- Disc thickness – H/R=0.07



Animation of turbulent disc model: www.maths.qmul.ac.uk/~rpn

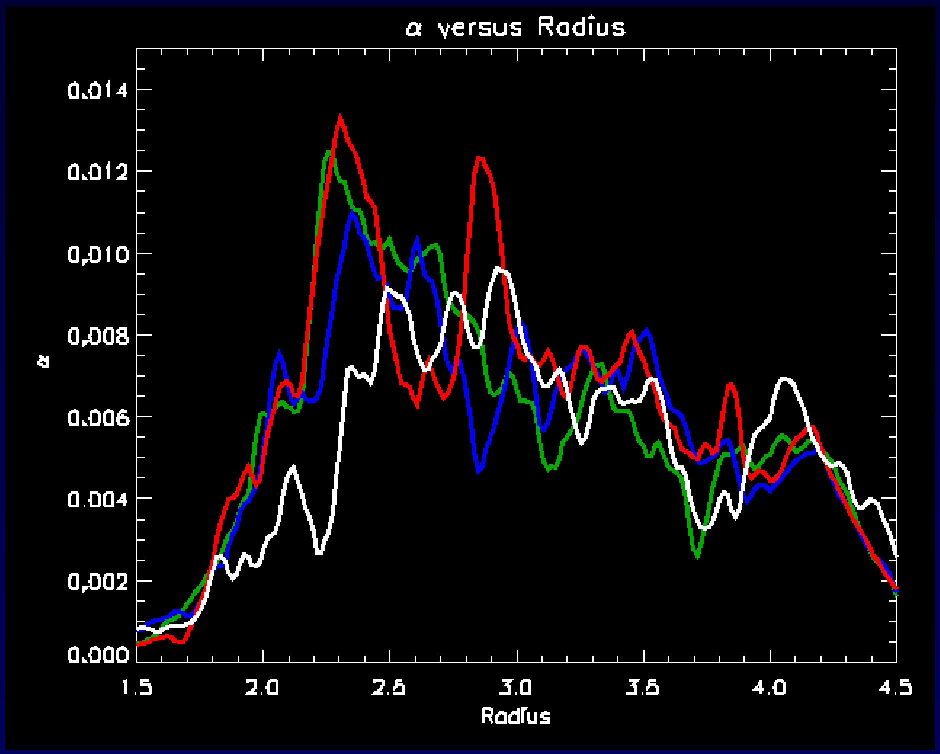
Volume averaged alpha value versus time



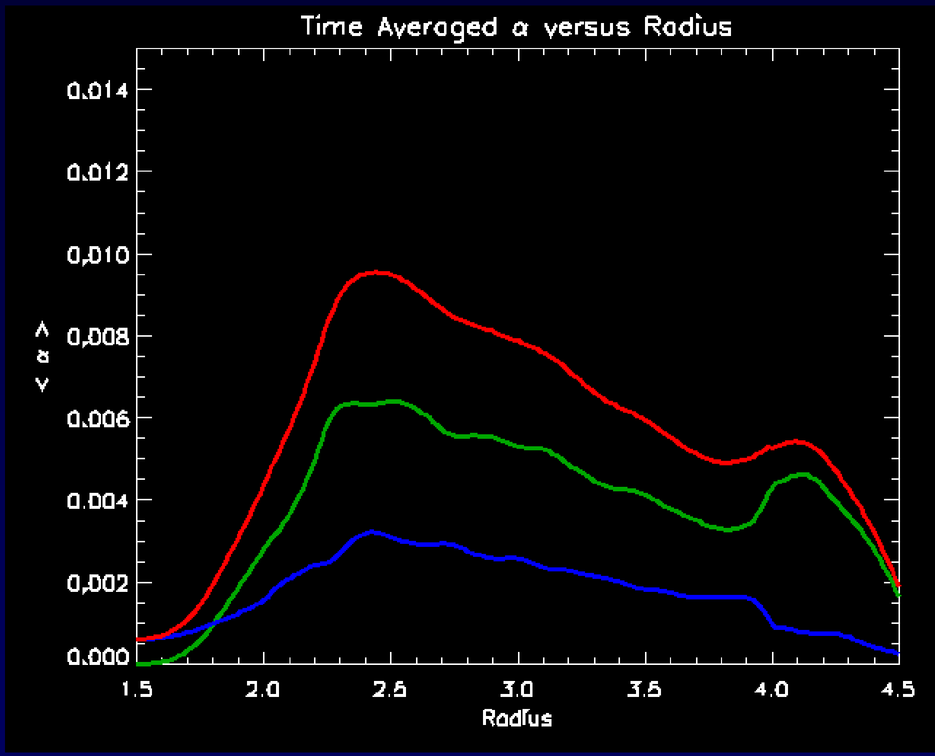
$$T_m = \frac{B_r B_\phi}{4\pi}$$

$$T_R = \rho \delta v_r . \delta v_\phi$$

$$\alpha = \frac{T_R - T_m}{P}$$



Snapshots of radial α distribution



Time averaged α (~ 4 -5 orbits)

Planetesimals in turbulent discs

Planetesimals experience gas drag (e.g. Weidenschilling 1977) and gravitational force due to disc

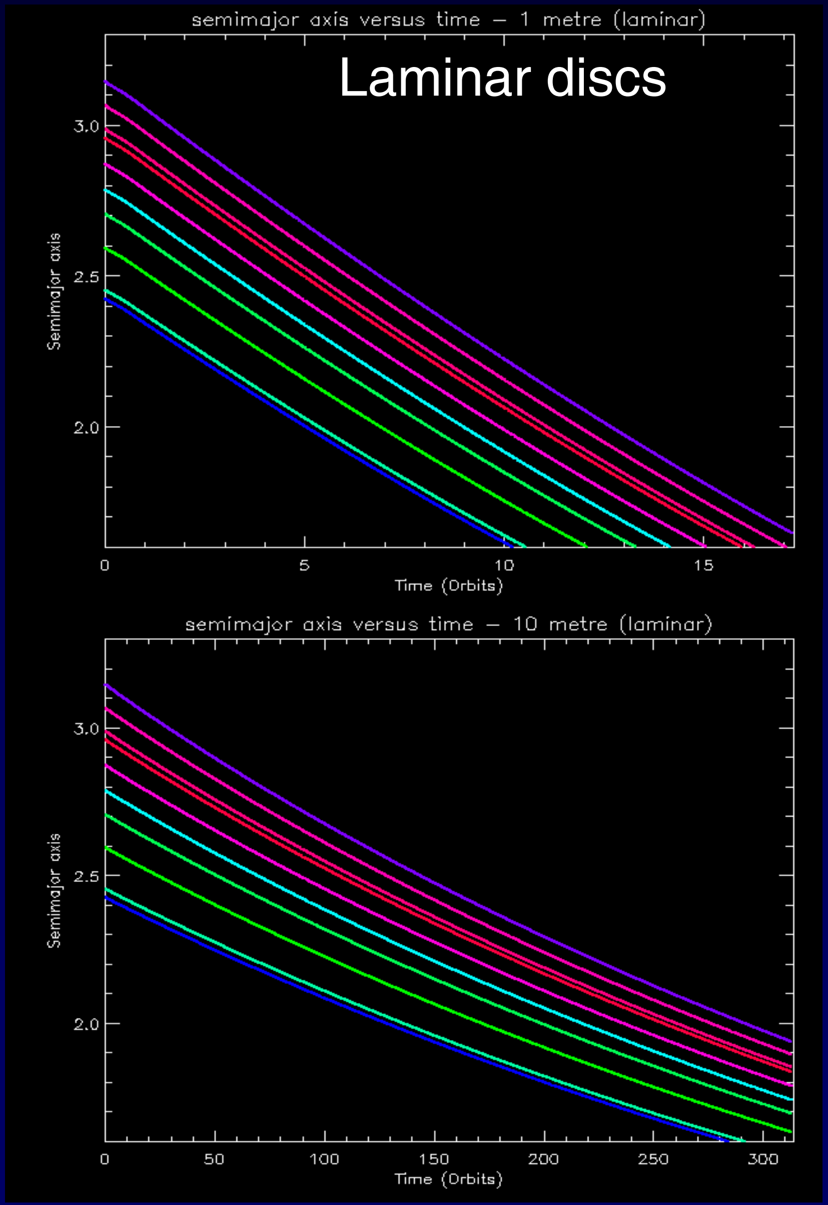
Evolution of 100 planetesimals calculated to examine inward drift and velocity dispersion –treated as particles that experience drag forces
Sizes: 1m – 1km

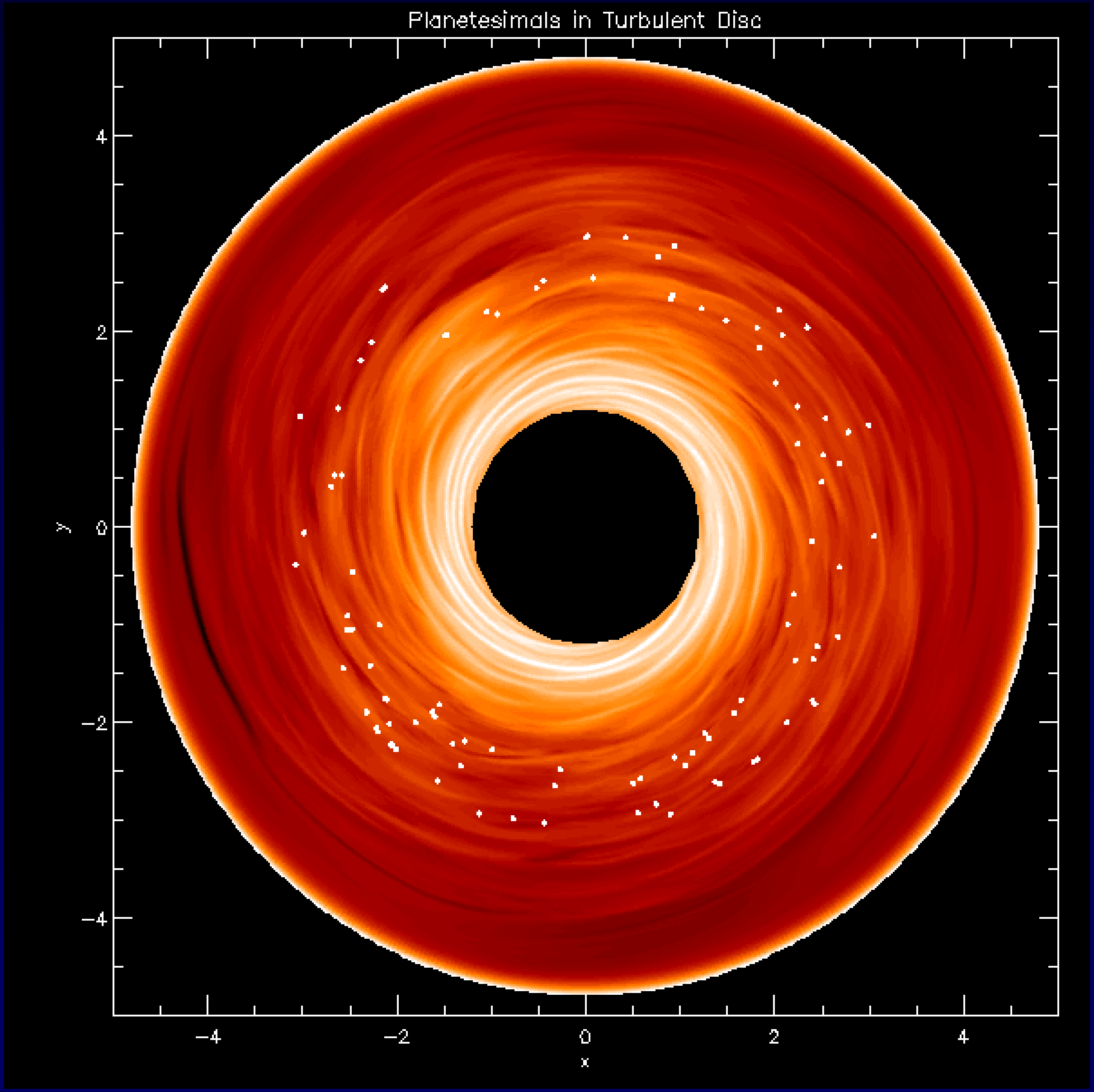
$$\mathbf{F} = C_D \pi a^2 \rho \frac{v^2}{2}$$

$$C_D = 24\mathcal{R}_e \quad \text{for } \mathcal{R}_e < 1$$

$$C_D = 24\mathcal{R}_e^{0.6} \quad \text{for } 1 < \mathcal{R}_e < 800$$

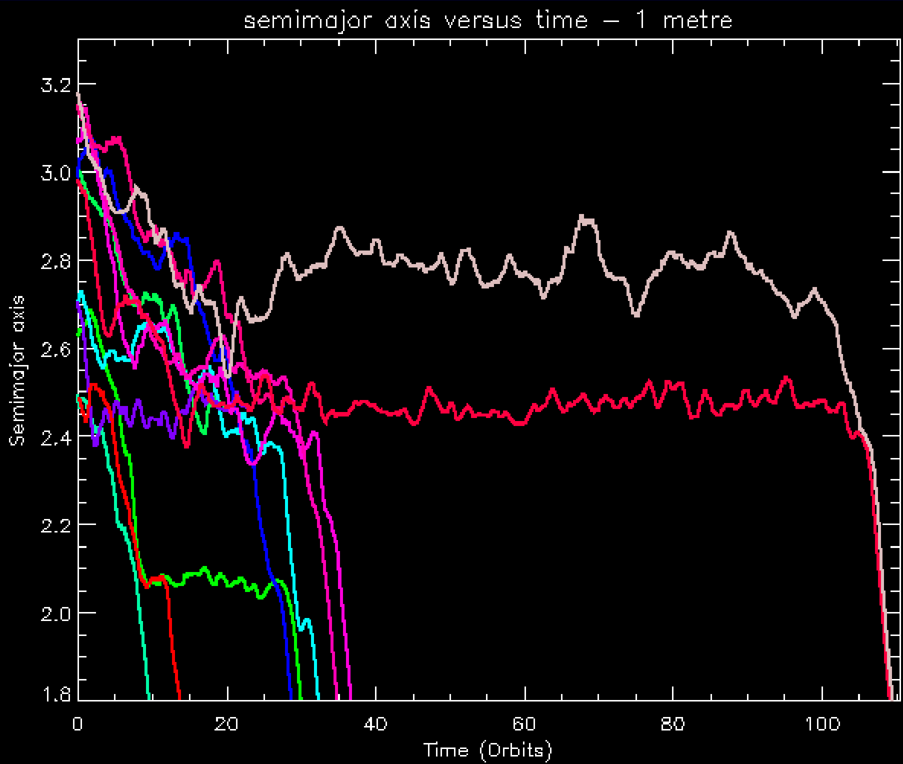
$$C_D = 0.44 \quad \text{for } \mathcal{R}_e > 800$$

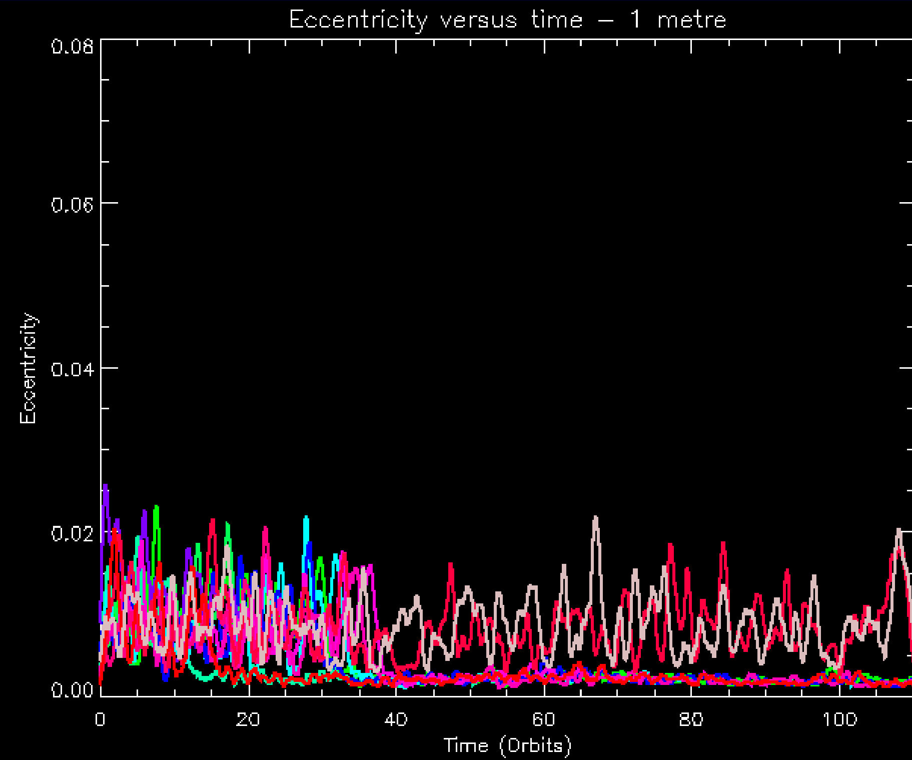




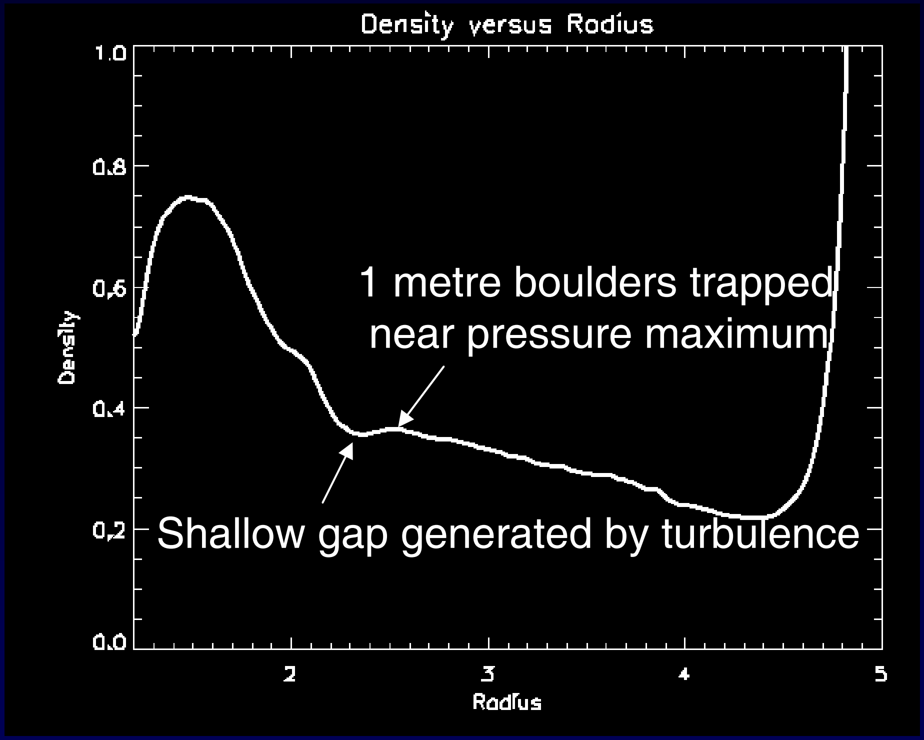
Snapshot of turbulent disc with 100 planetesimals

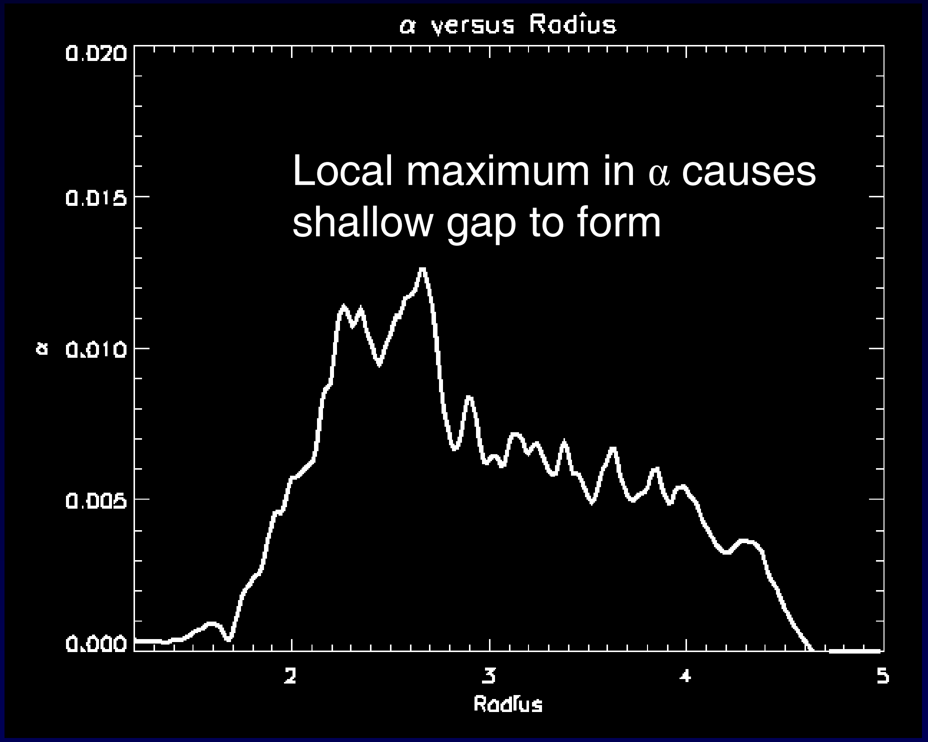
1 metre sized planetesimals



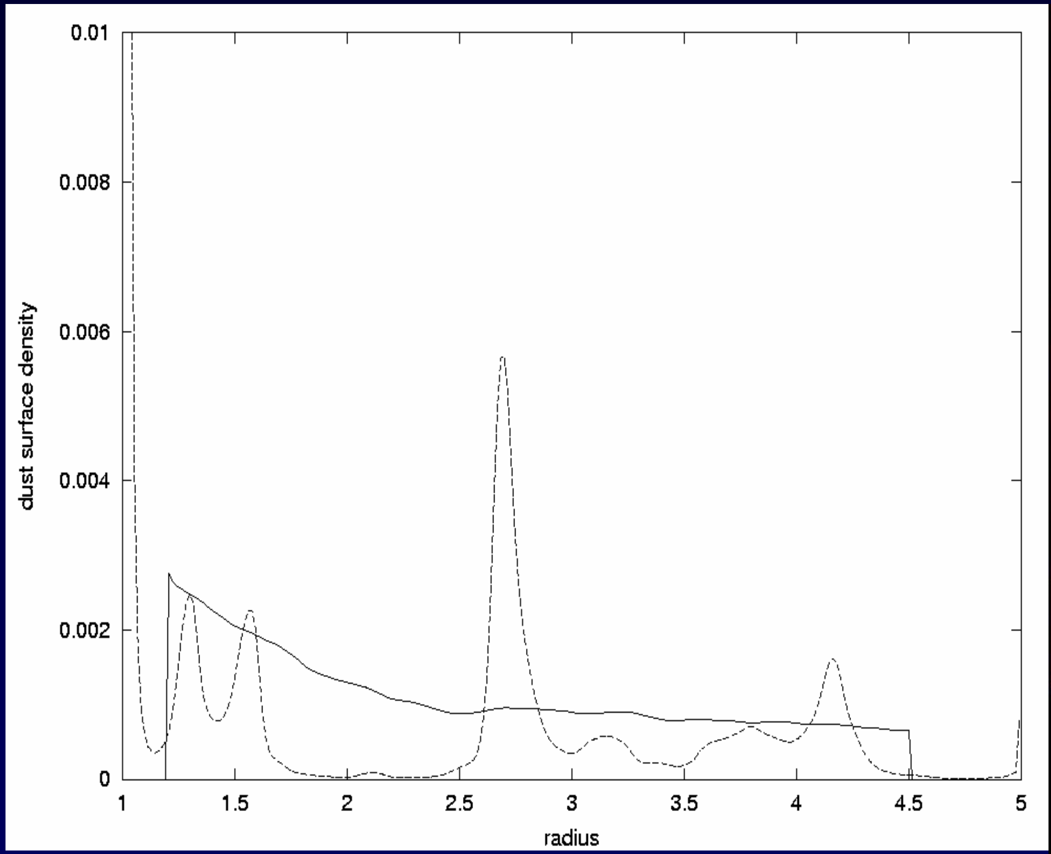


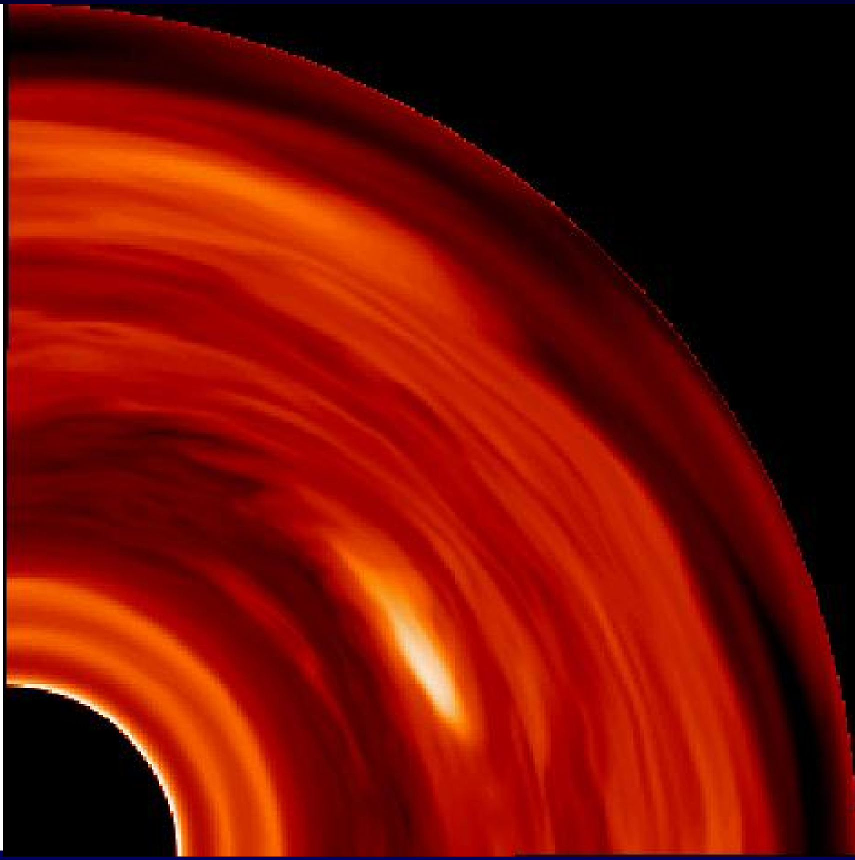
1 metre sized objects migrate in on time scale of ~ 50 orbits (500 years)
Modification of disc surface density causes 1m sized boulders to become trapped and concentrated (see next slide) - 64 out 100 particles trapped
Tight coupling to gas causes large eccentricities – potentially destructive velocity dispersion ?
Neighbouring planetesimals appear to be on very similar orbits… so collisions apparently dominated by Keplerian shear





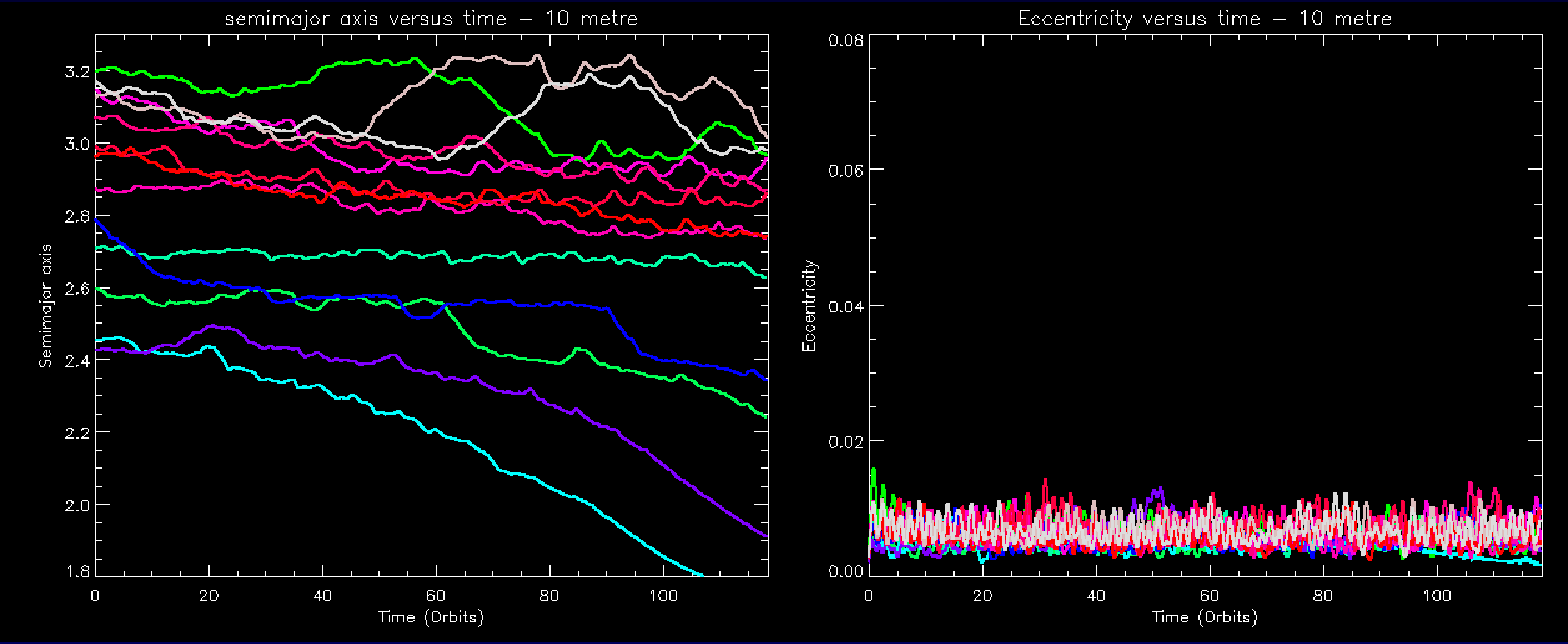
- Surface density is modified by variations in effective α generated by turbulence
- Region centred around r ~ 2.4 forms shallow gap
- For pressure gradient $dP/dr < 0$ gas orbits at sub-Keplerian velocities
- For pressure gradient $dP/dr > 0$ gas orbits at super-Keplerian velocites
  - 1 m sized boulders get trapped at edge of gaps generated by turbulence
- Concentration of boulders may enhance planetesimal growth rate





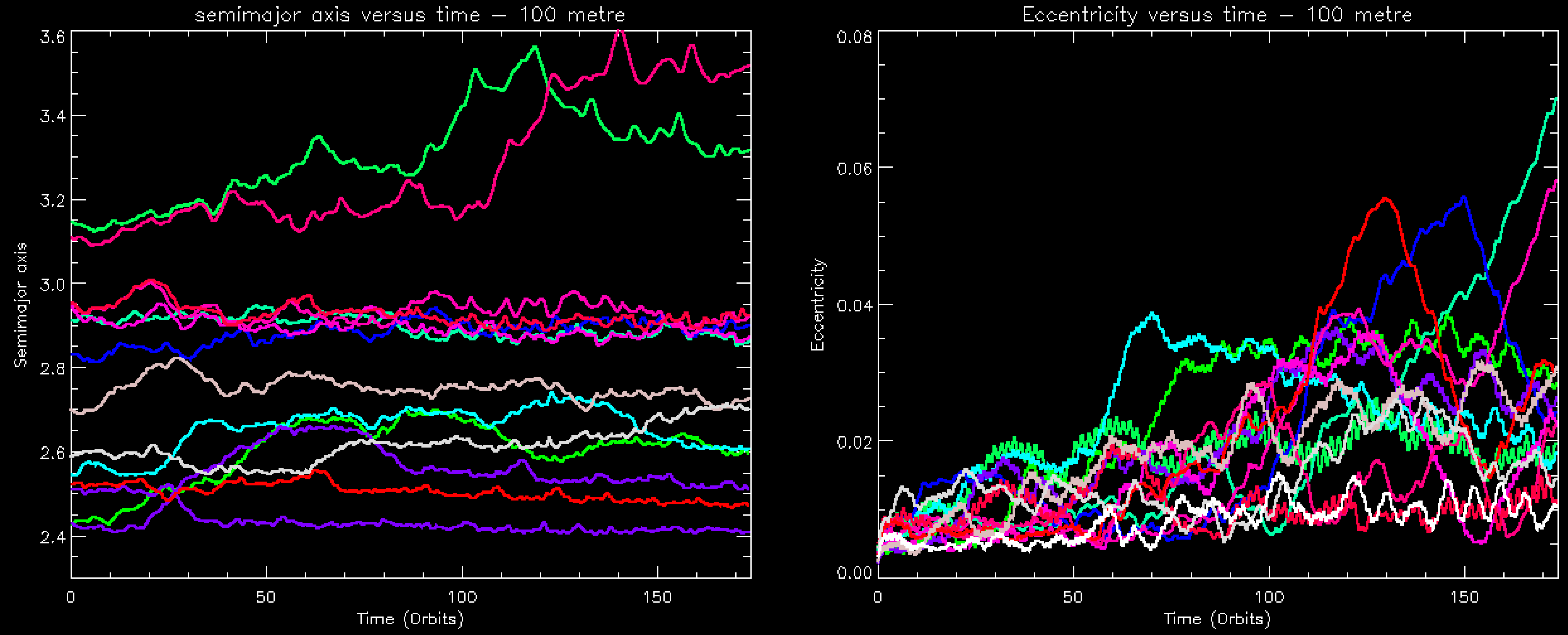
- Similar results are obtained using a two-fluid description of solids and gas
- Left slide shows enhancement in solid density due to trapping at shallow gap edge generated by turbulence – This plot is for 1 m sized objects
- Right slide shows image of density of solids in disc with a solids enhancement feature observed at edge of shallow gap

10 metre sized planetesimals



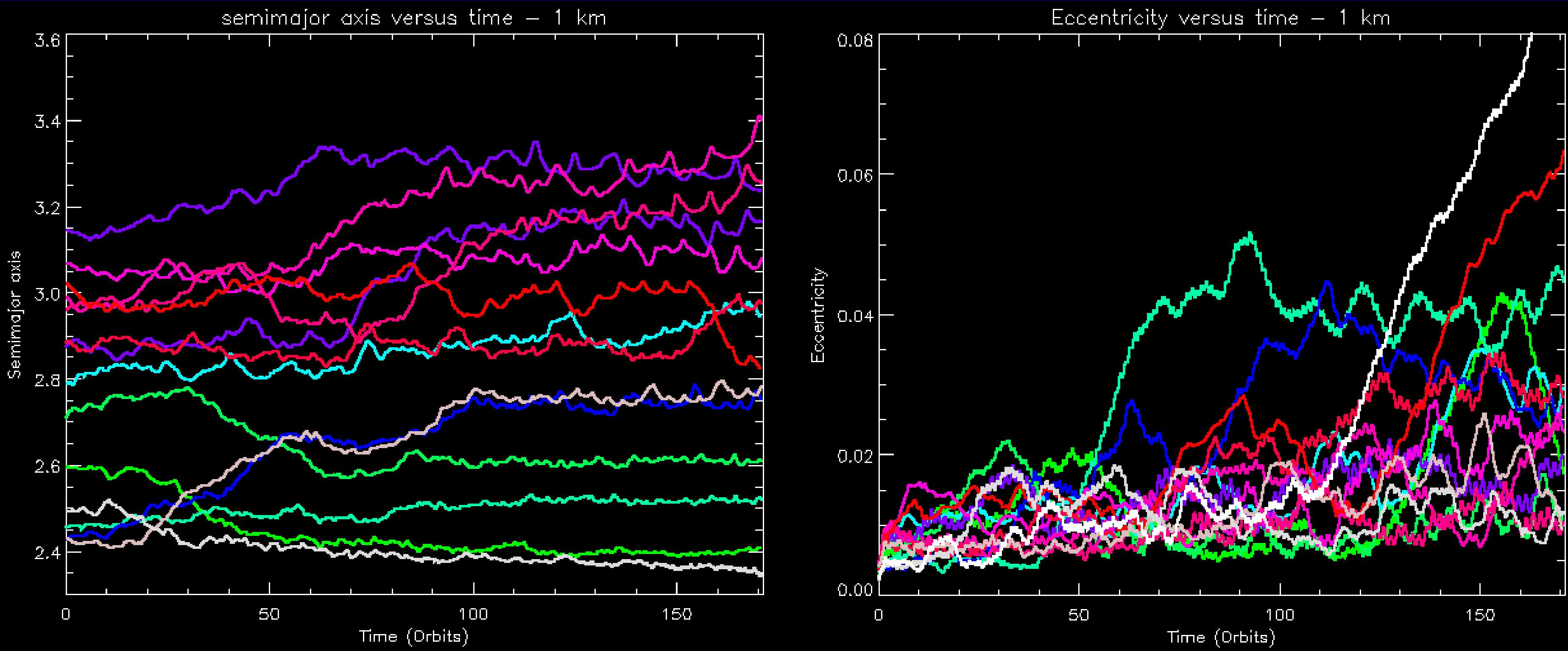
- Most 10 m size boulders drift inward on time scale of ~ few thousand years – a few drift in more slowly
- Velocity dispersion remains quite small – coupling too weak to allow individual fluctuations in gas velocity to determine velocity dispersion
- Danger of destructive collisions: $e=0.01 \longrightarrow \langle v \rangle \sim 0.12$ km/s at 5 AU
- Icy 10 m sized bodies fragment with $\langle v \rangle \sim 0.25$ km/s (Benz & Asphaug 1999)

100 metre sized planetesimals



- 100 m sized objects dominated by fluctuations in disc gravity which dominates over influence of gas drag
- Instead of inward drift undergo `random walk'
- Icy 100m sized objects fragment if <v> ~ 0.12 km/s
- Velocity dispersion <v> ~ 0.24 km/s for e=0.02 at 5 AU
- Destructive collisions likely

1 km sized planetesimals

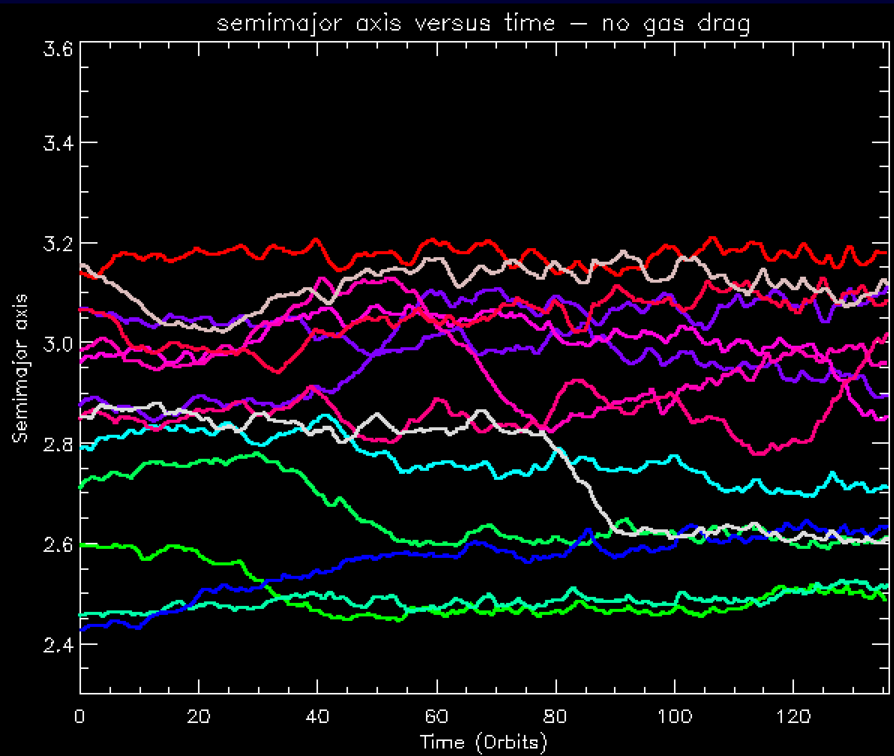


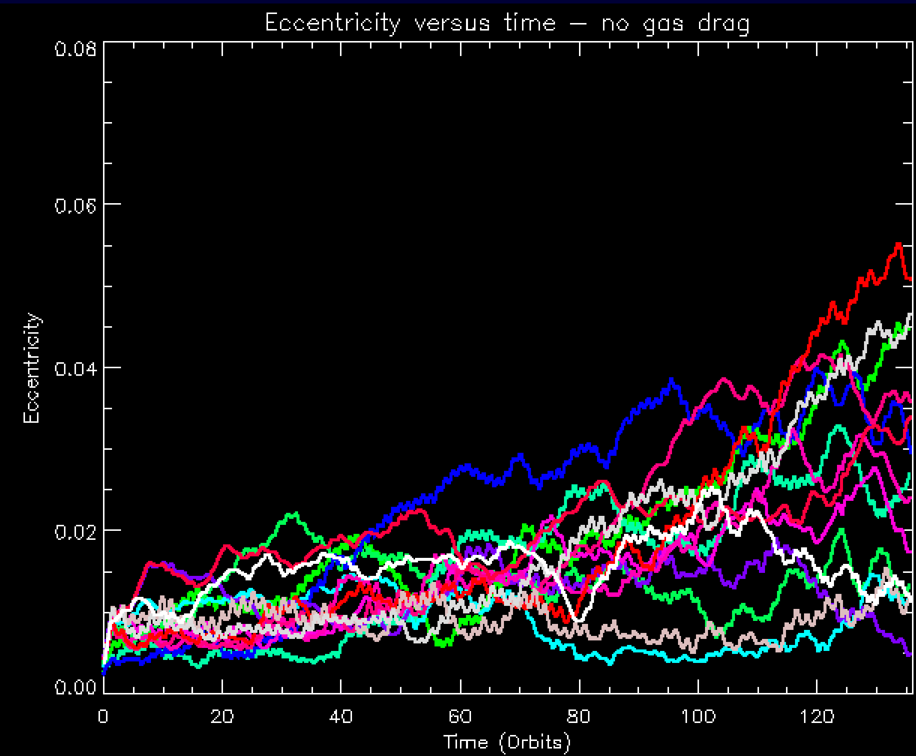
<u>Results similar to 100 metre sized objects:</u>

1 km sized planetesimals undergo random walk

Velocity dispersion quite large – possible destructive collisions and slow-down of runaway growth ?

Gas drag switched off

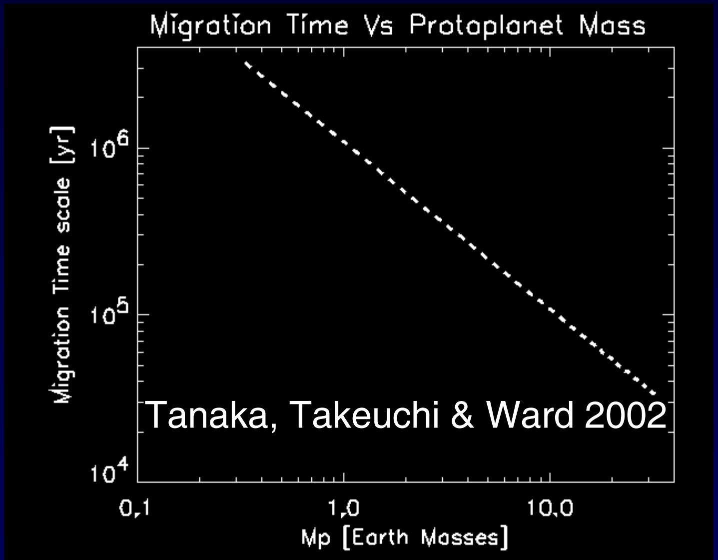


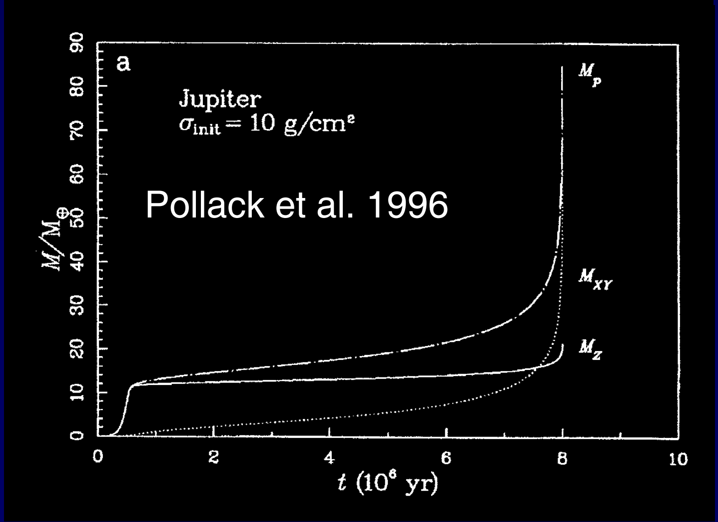


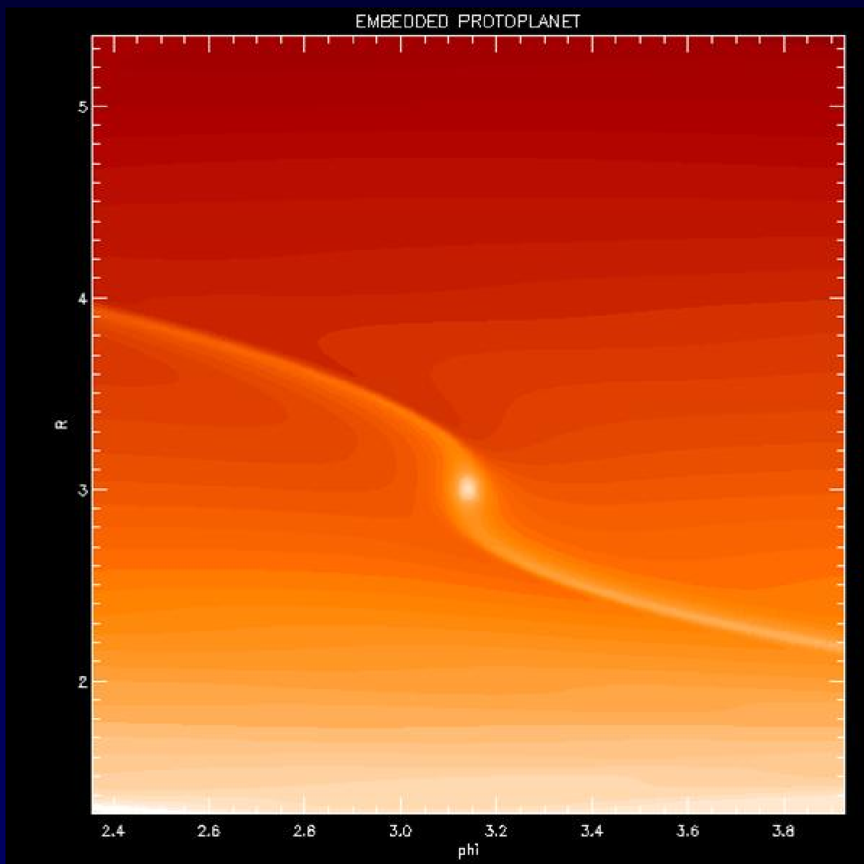
Results similar to 100m and 1 km sized objects showing importance of fluctuations in gravitational potential generated by disc turbulence

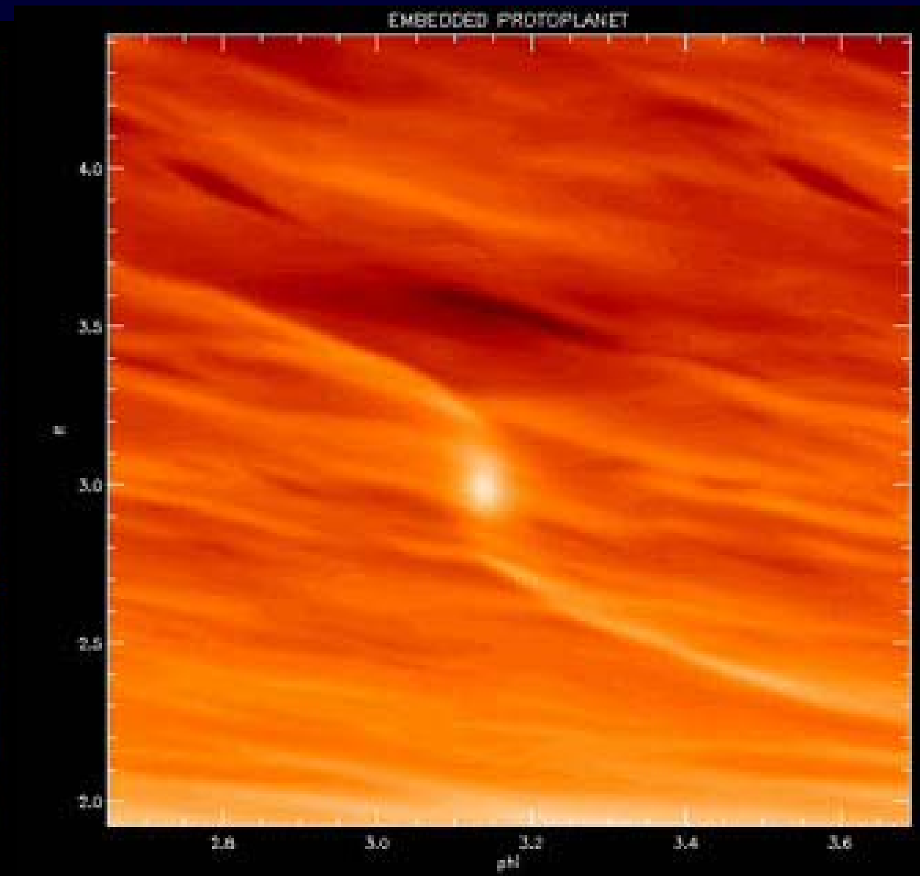
Low mass protoplanets

- Type I migration time < gas accretion time
- Consider orbital evolution of: m_p=1,3,5,10,30 Earth mass planets
- Question: what is effect of turbulence on type I migration ?

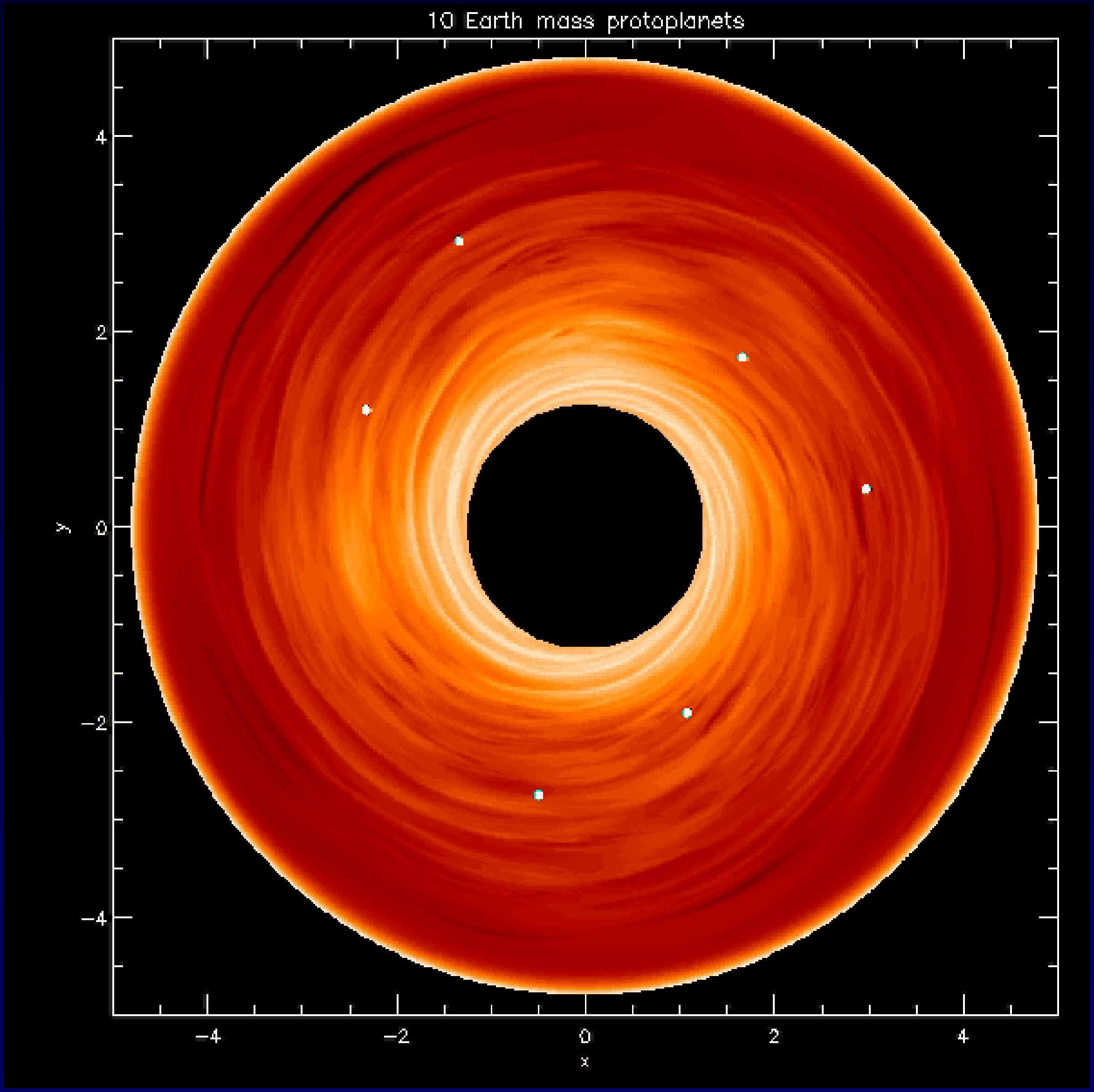




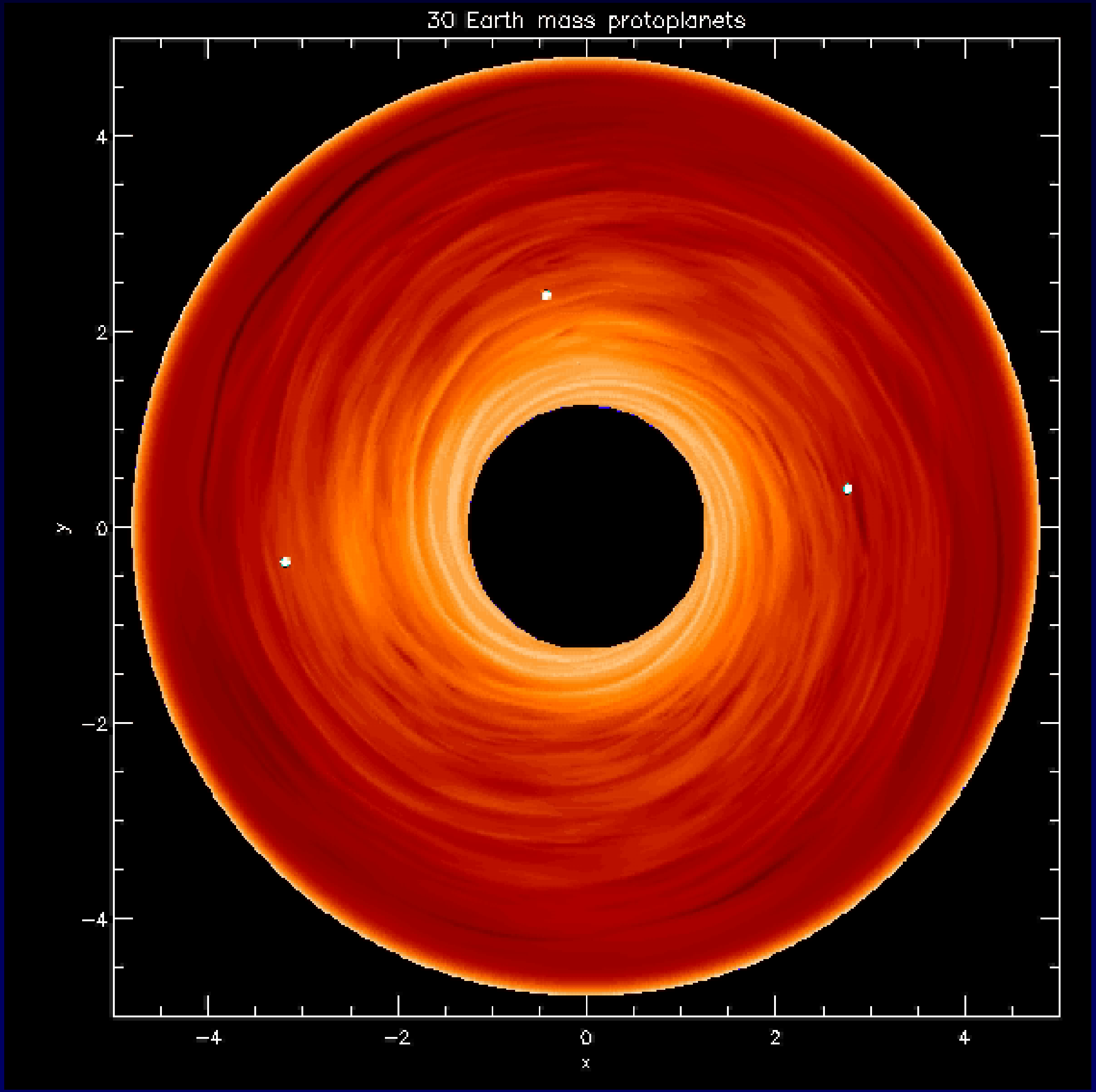




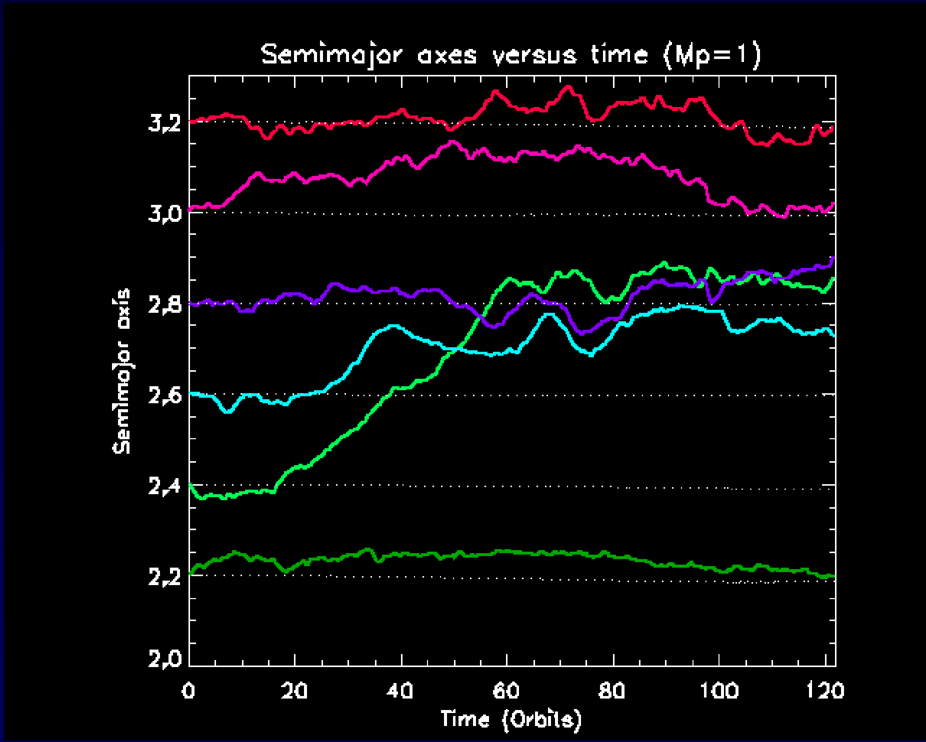
Mp=30 Earth masses – turbulent fluctuations ~ spiral wakes

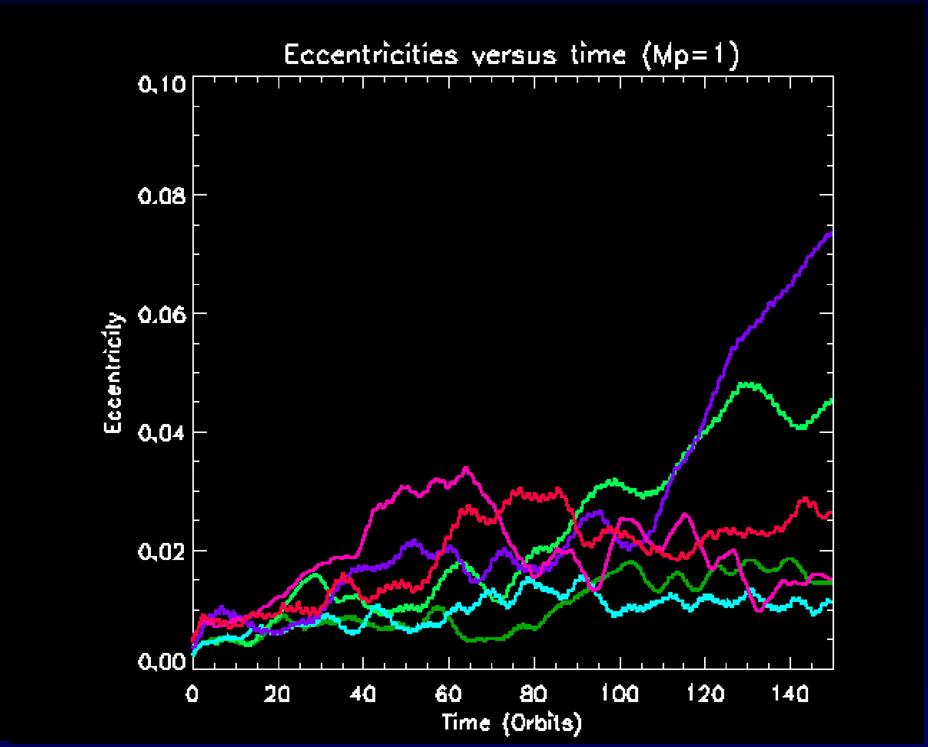


mp=10 Earth masses

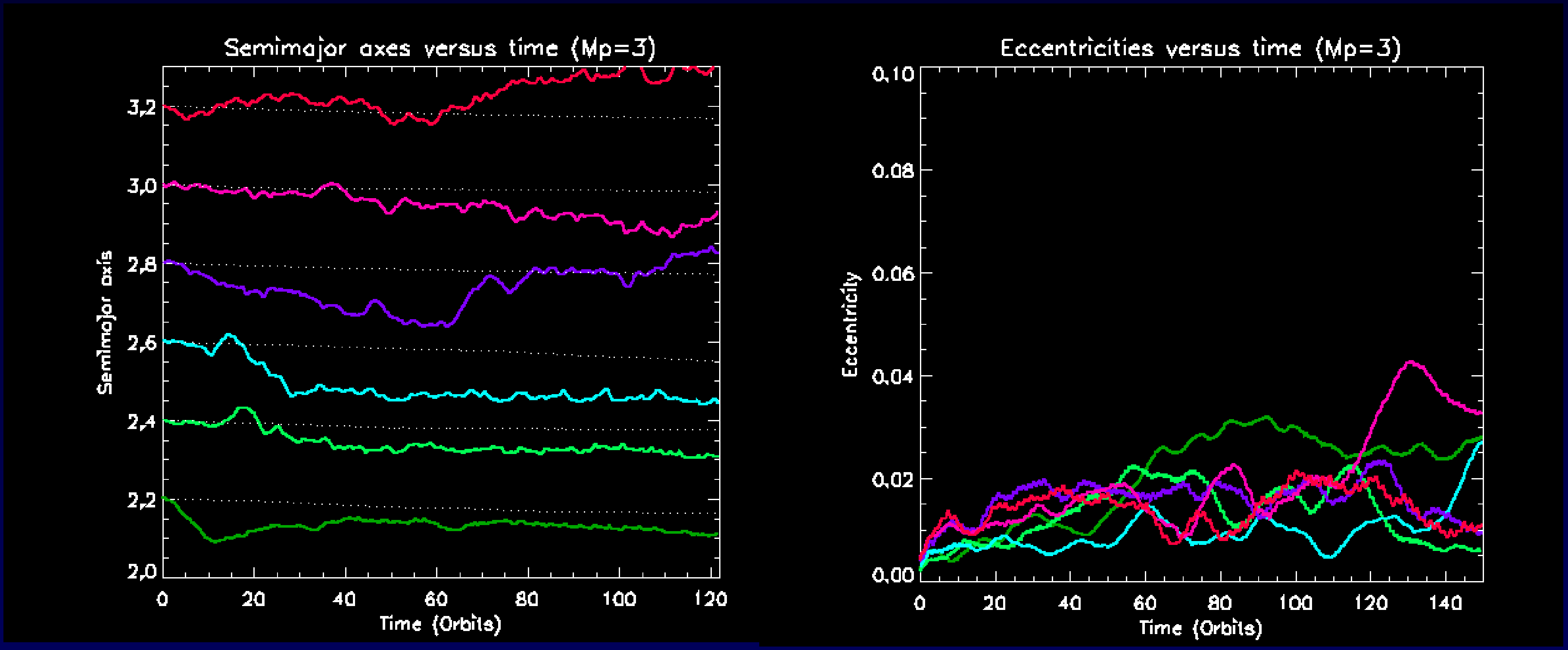


mp=30 Earth masses

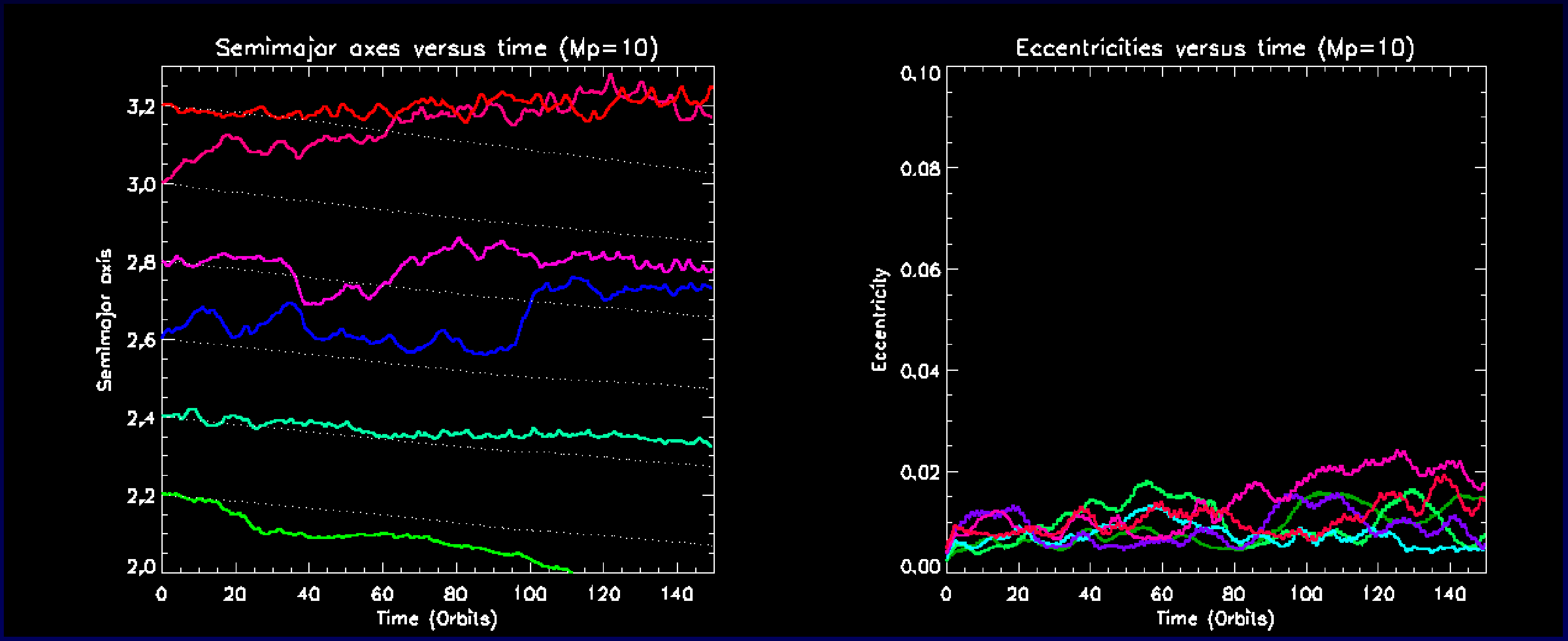




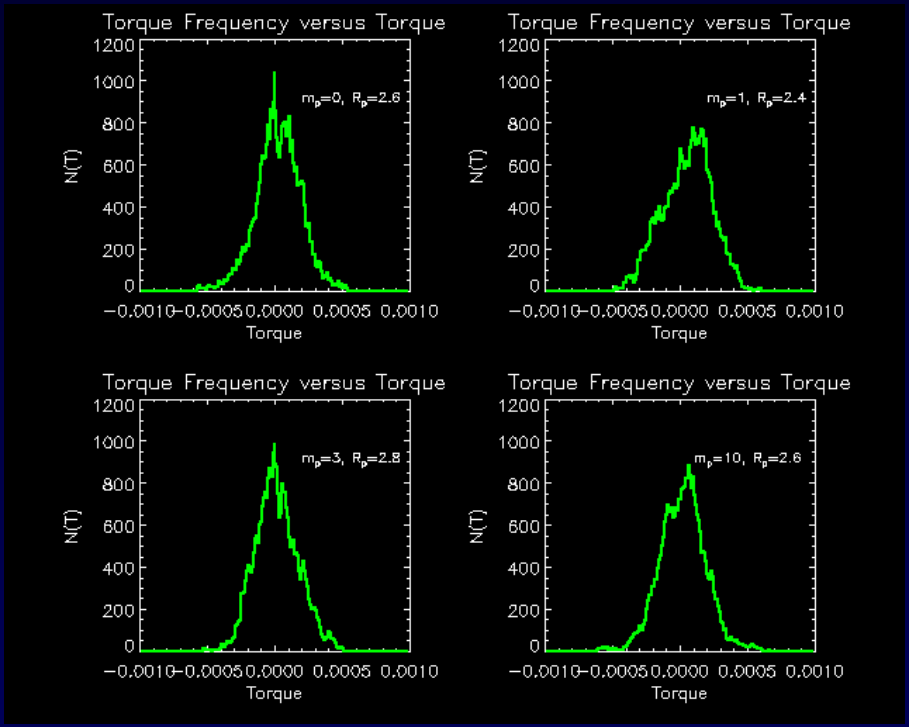
Mp = 1 Earth mass

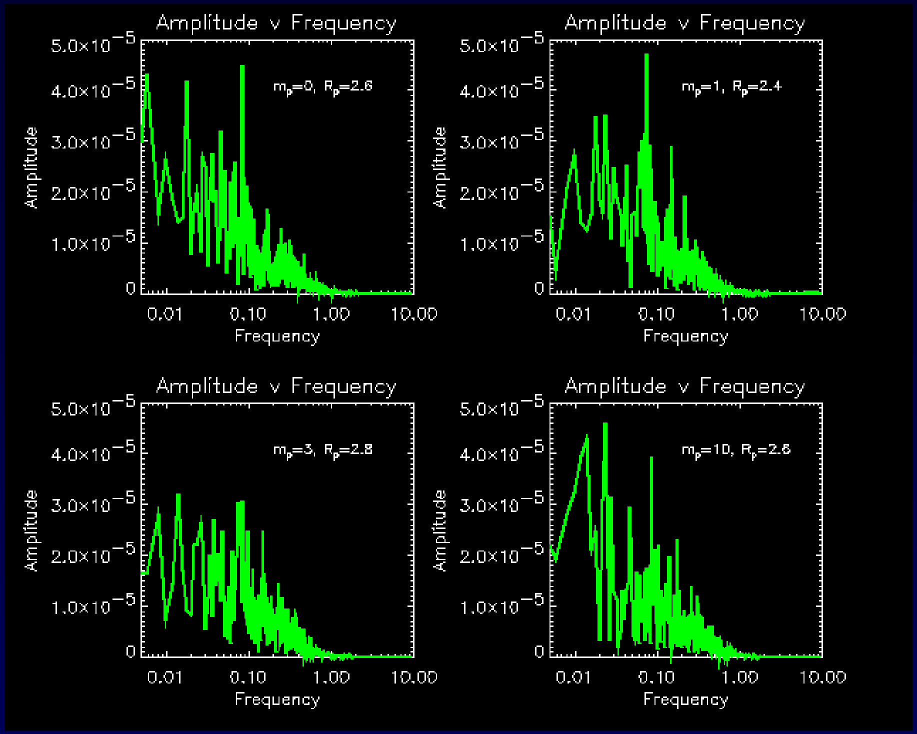


Mp = 3 Earth masses



Mp = 10 Earth masses





Torque Distributions ⟶ σ

$$\overline{T} = \langle T \rangle + \frac{\sigma}{\sqrt{t}}$$

Power spectrum – shows torques have temporal variations as long as run time of simulations

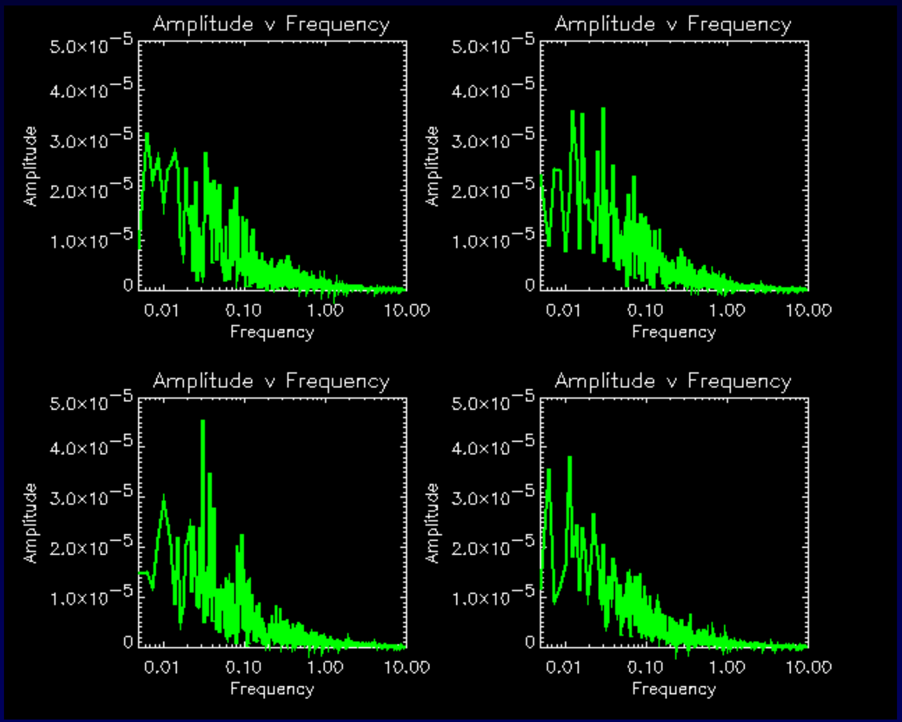
Naïve application suggests inward migration should be obtained mp=10

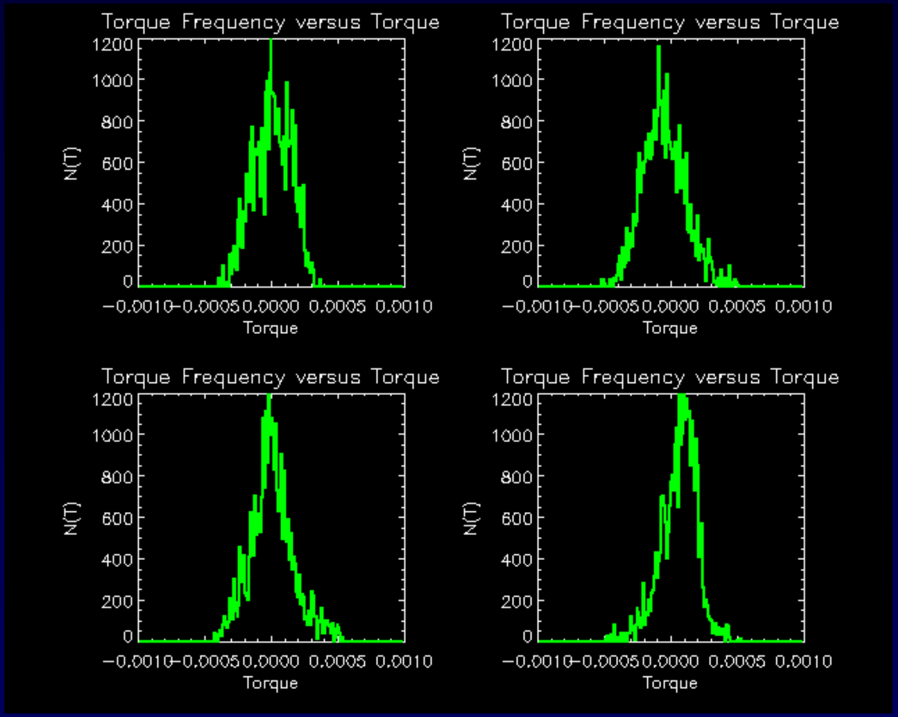
Long term evolution

- Simple estimates of migration time of planetesimals using random walk model indicate $t_{mig} \sim 1$ Myr
- For low mass protoplanets main question is: can stochastic migration overcome type I migration ?
- Use simple model of stochastic migration + type I migration to investigate this using N-body integrations

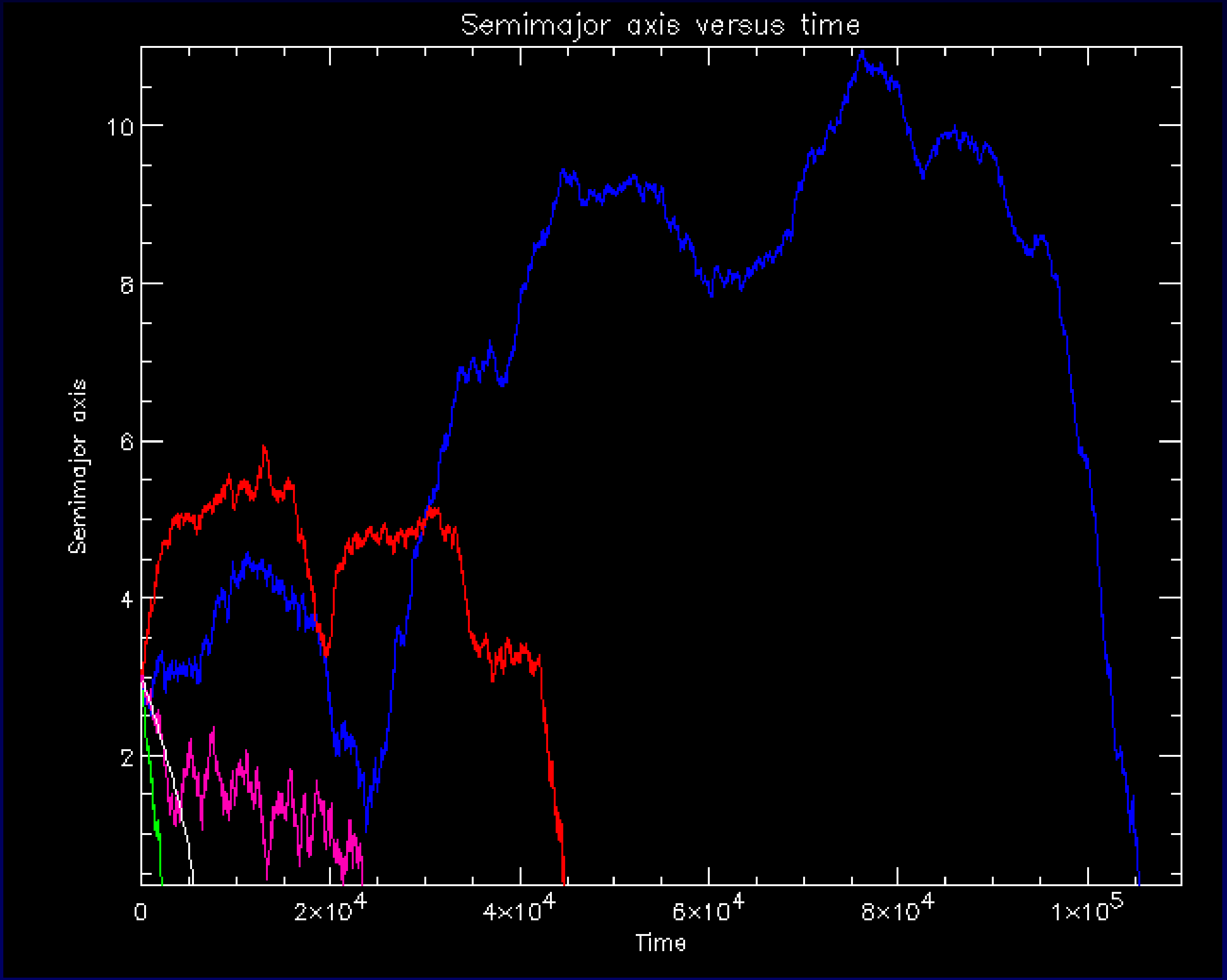
Simple model

- Time evolution of stochastic torques given by $T(t) = \sum_{i=1}^{10} T_i(t_i)$ where each component varies on a different time scale, and has amplitude drawn from Gaussian distribution
- Type I torques included using standard formulae
- Question: can such a model have torque distribution and power spectrum similar to MHD simulations, and provide long term survival of low mass protoplanets





Power spectra and torque distributions similar to full MHD simulation

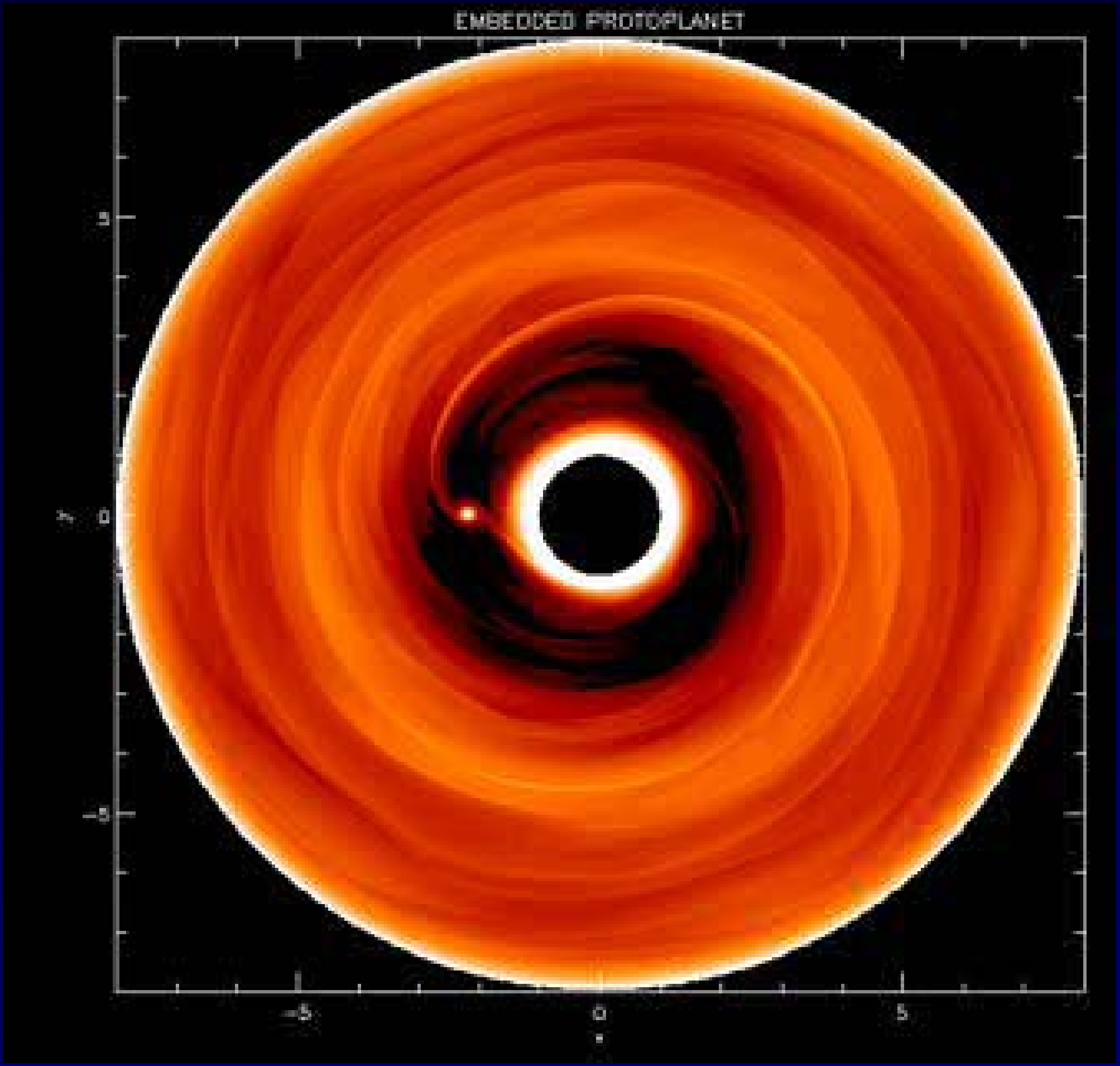


Possible long term outcome:
distribution of migration times – with longer times leading to planet survival

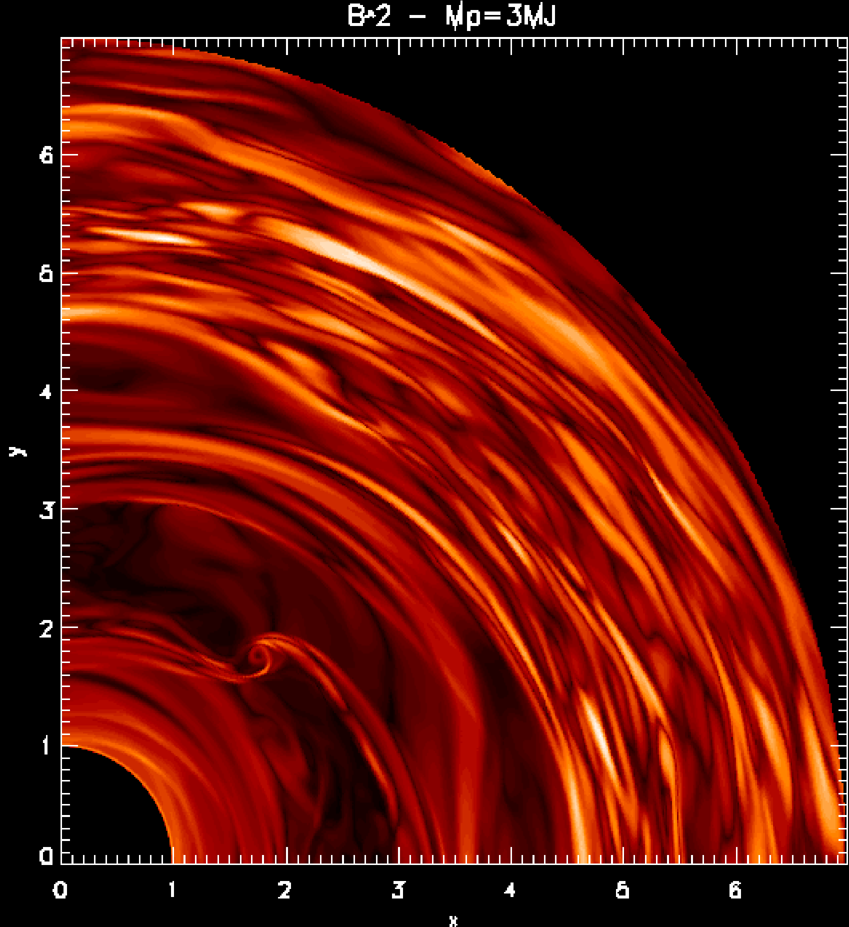
High Mass Protoplanets

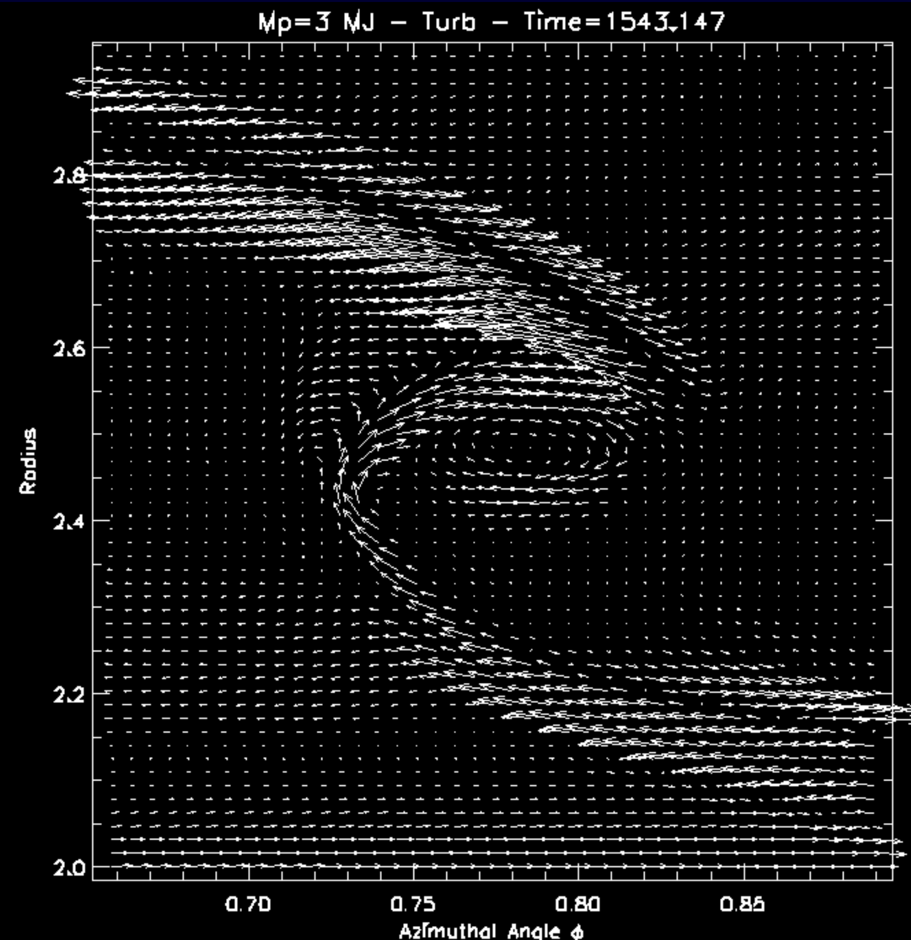
- 5 and 3 $M_{Jupiter}$ protoplanets
- $H/R=0.1, 0.07$
- $\alpha \sim 0.005, 0.007$

Papaloizou & Nelson (2003)
Nelson & Papaloizou (2003)
Winters, Balbus & Hawley (2003)

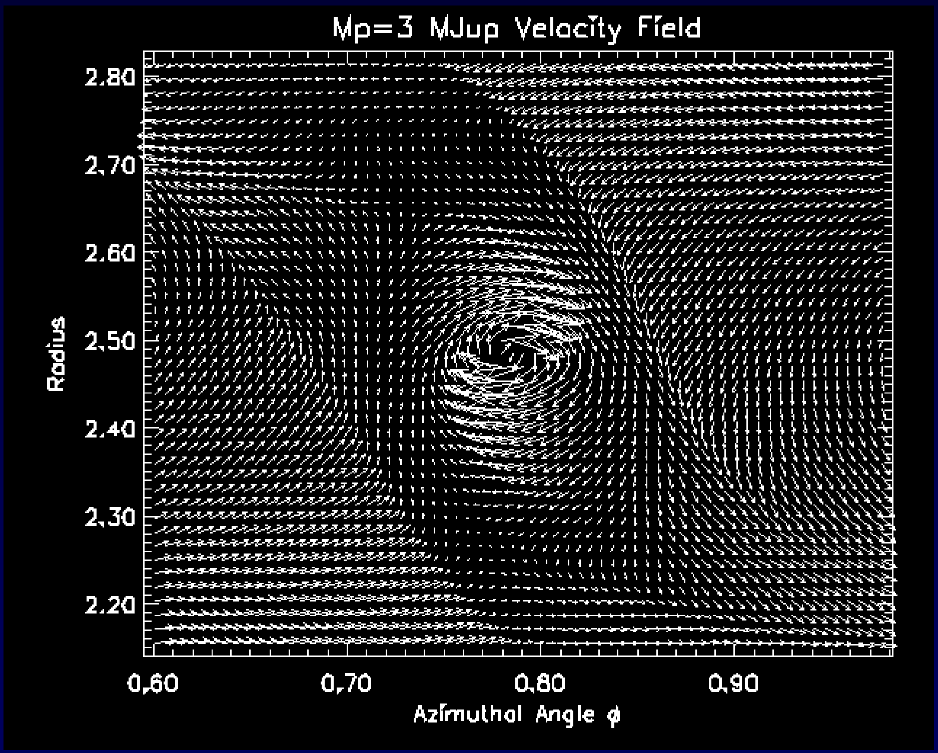


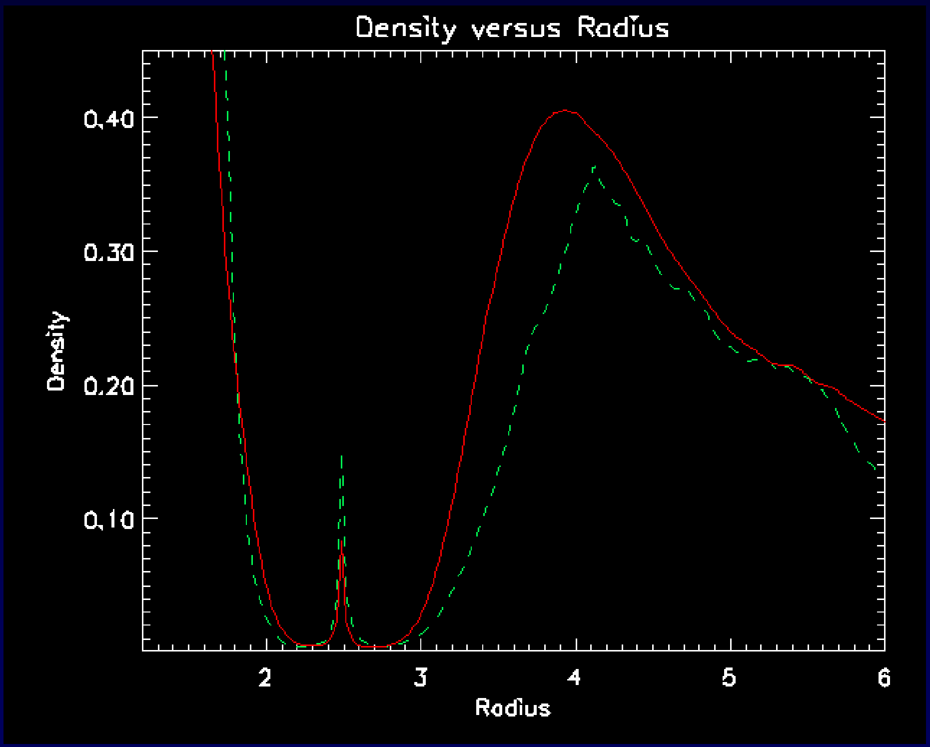
Turbulent disc with giant protoplanet – migrates in ~ 10^5 yr





Magnetic field lines link between protostellar disc and circumplanetary disc





- More accretion occurs in magnetic run when rotationally supported circumplanetary disc is formed
  - Magnetic braking of circumplanetary disc ?
  - Allows higher mass accretion ?

Conclusions & future directions

1. Turbulence may help planetesimal growth by concentrating 1 metre sized objects at gap edges
2. Turbulence may also inhibit growth by inducing destructive collisions and decreasing runaway growth rates due to increasing velocity dispersion
3. Type I migration may be inhibited for some planetary embryos by turbulence
4. Evolution of massive planets similar to that found in laminar discs

<u>Future directions:</u>

1. Vertically stratified models
2. Resistivity – incorporate simple chemistry + ionisation sources
3. Evolution of solids in turbulent discs: – sticking rates of grains
   -- settling of grains to midplane
4. Equation of state + radiative transfer
5. Examine long term orbital evolution of planets