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Turbulence-assisted planetary growth

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Ph.D. Thesis defense

Planet Formation

Planetesimal Hypothesis (Safronov 1969)

From dust to boulders

μm -> m: Electromagnetic forces cause sticking

m -> km: ***HOW????***

From planetesimals to protoplanets

km -> 1000 km: Gravity

From protoplanets to planets

Rocky Planets: Protoplanets collide

Gas Giants: Attract gaseous envelope

From meter to kilometer

Growth barrier

- through EM?

They don't stick, they break

Gentle Collisions

- through Gravity?

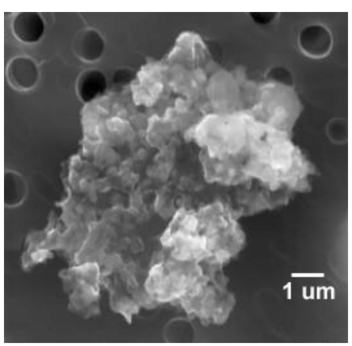
They aren't massive enough

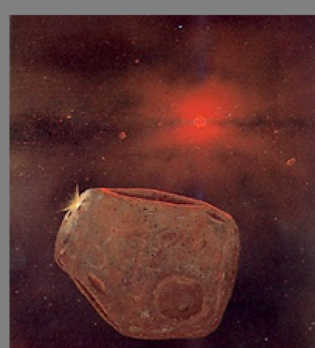
High number density

Timescale barrier

They migrate quite fast

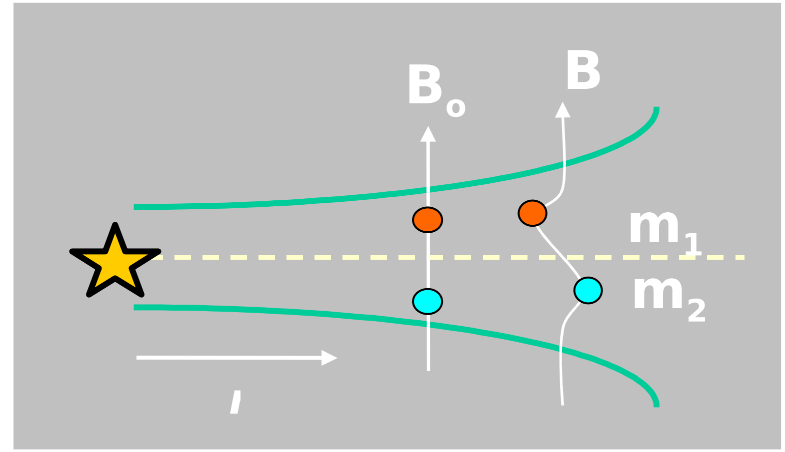
Stopping Mechanism





Turbulent Disk Models

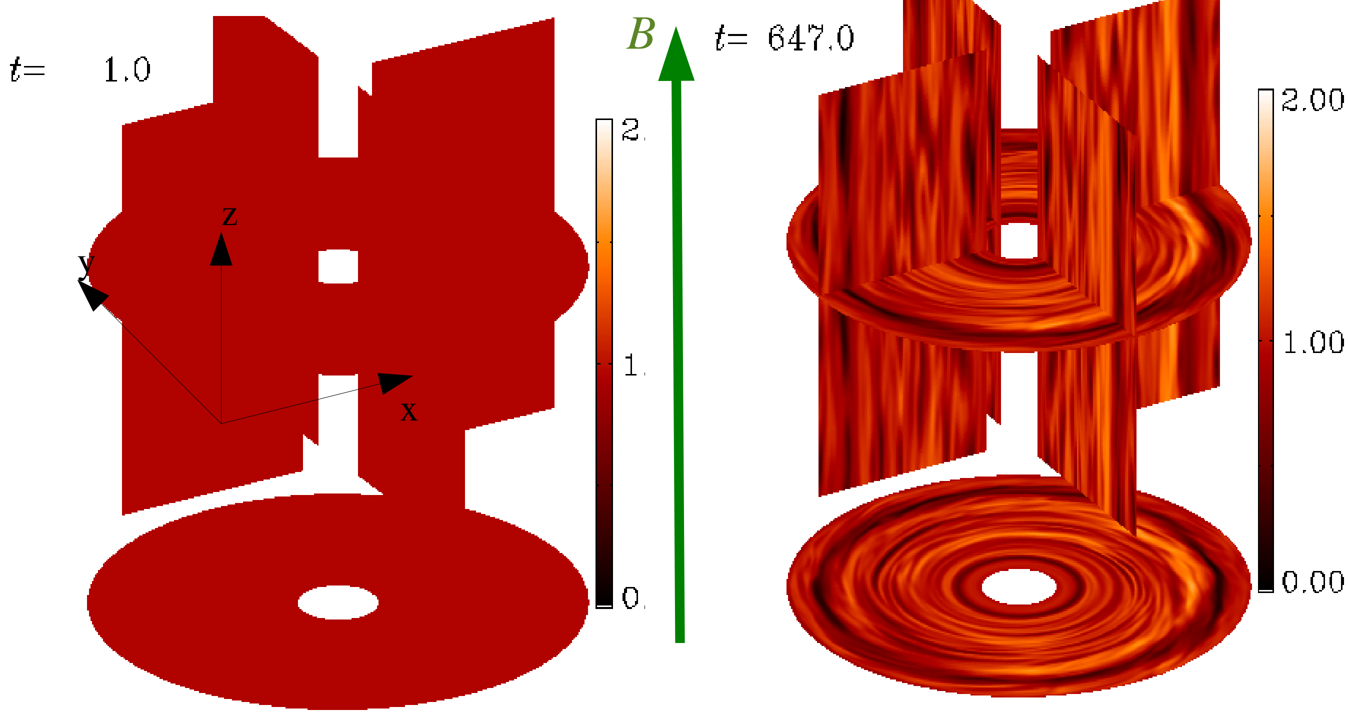
Accretion disks are unstable to the Magneto-Rotational Instability (MRI). The turbulence that ensues is the best candidate to explain accretion
(Balbus and Hawley 1991)



Build-up of magnetic tension:

- tries to restore equilibirum (*resists streching*)
- tries to enforce rigid rotation (*resists shear*)

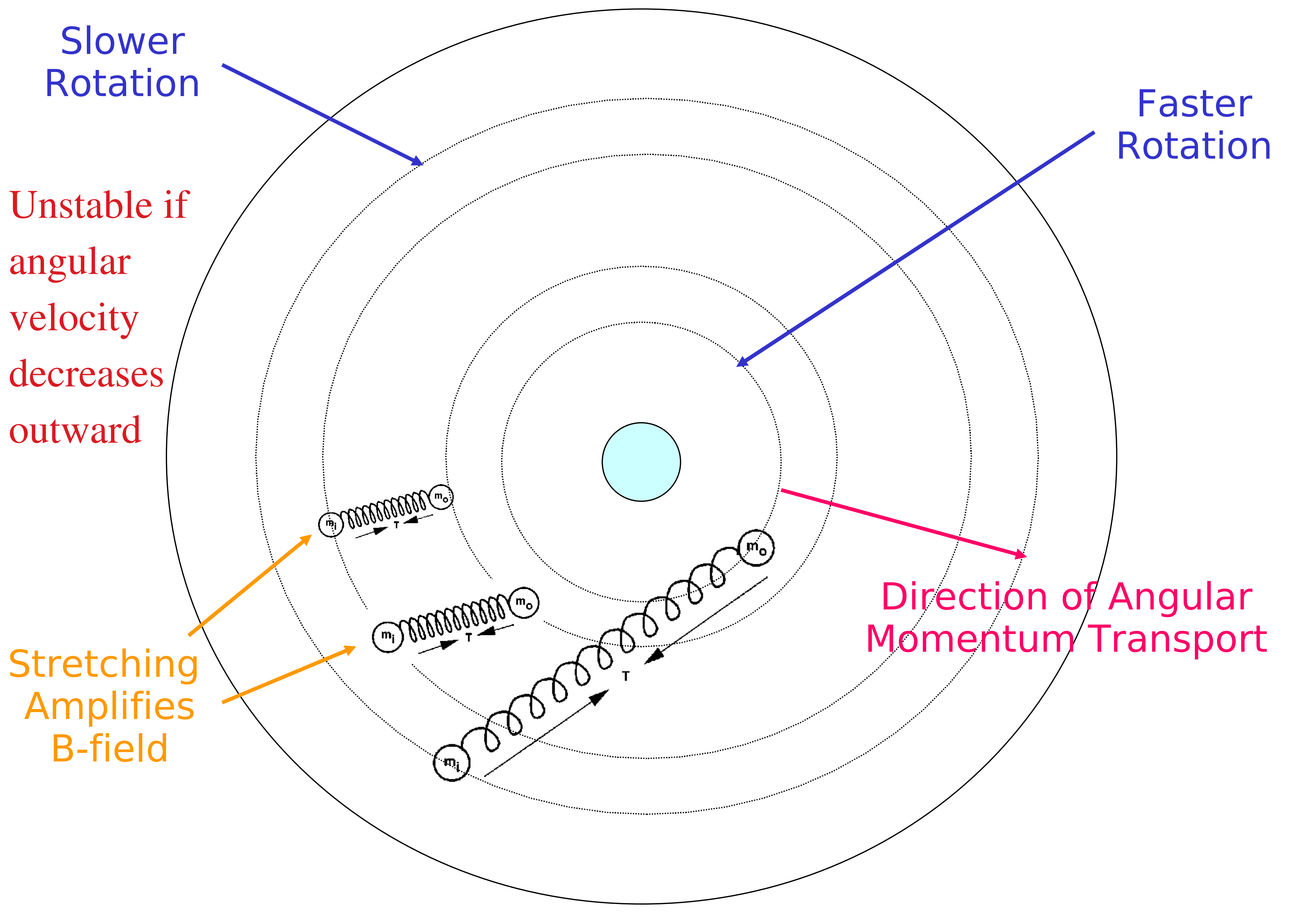
Density Evolution



Color code: **Density**

Time unit = $(2\text{pi}/T_{\text{Jup}})$ = **1.6 yr**

Density unit = **2×10^{-11} g/cm^3**


Slower Rotation
Faster Rotation
Unstable if angular velocity decreases outward
Direction of Angular Momentum Transport
Stretching Amplifies B-field
m_i
m_o
T

Solids in a turbulent disk

Gas $\frac{D\boldsymbol{u}}{Dt} = -\nabla\Phi - \rho^{-1}\nabla p$

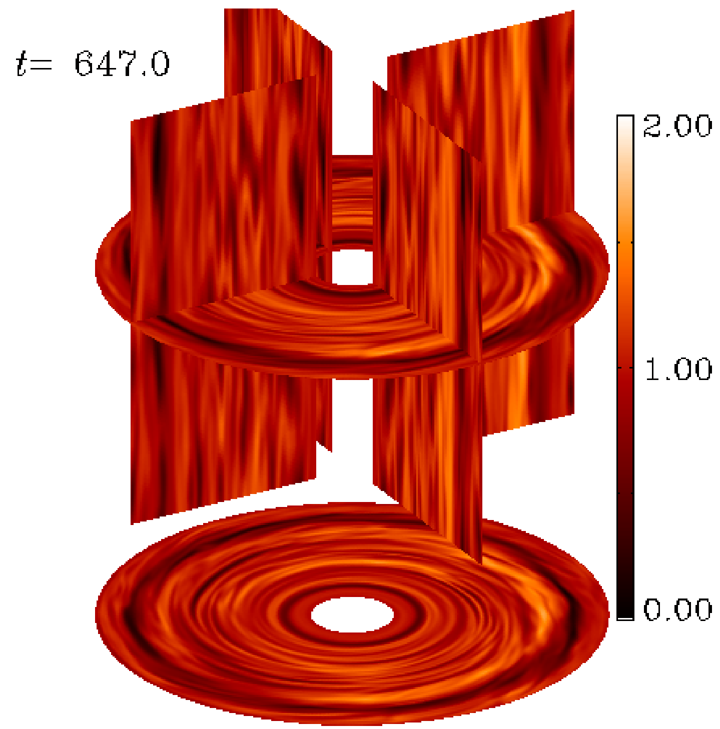
Solids $\frac{d\boldsymbol{w}}{dt} = -\nabla\Phi - \frac{(\boldsymbol{w}-\boldsymbol{u})}{\tau}$

$\boldsymbol{V} = \boldsymbol{u} - \boldsymbol{w}$

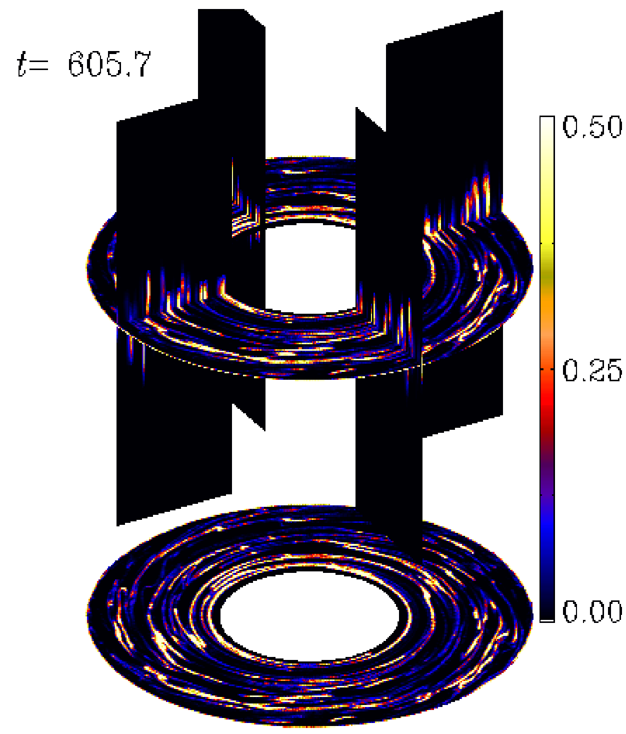
$\frac{D\boldsymbol{V}}{Dt} \approx \rho^{-1}\nabla p + \frac{\boldsymbol{V}}{\tau}$

Instantaneously, the drag force pushes the solids *towards* the pressure gradient

Gas

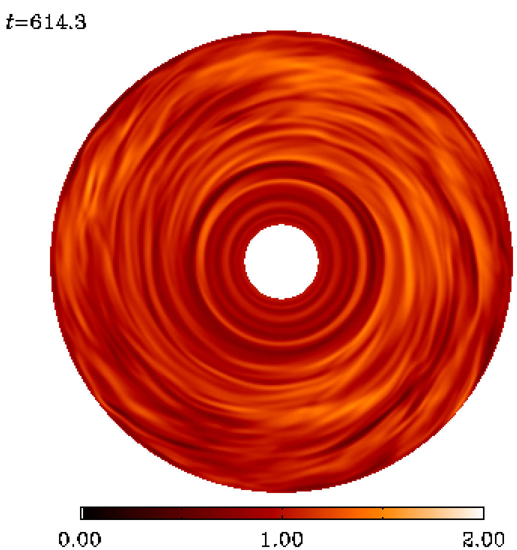


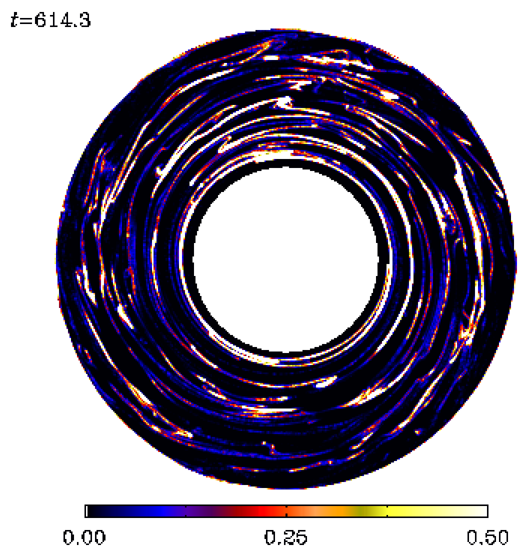
Solids



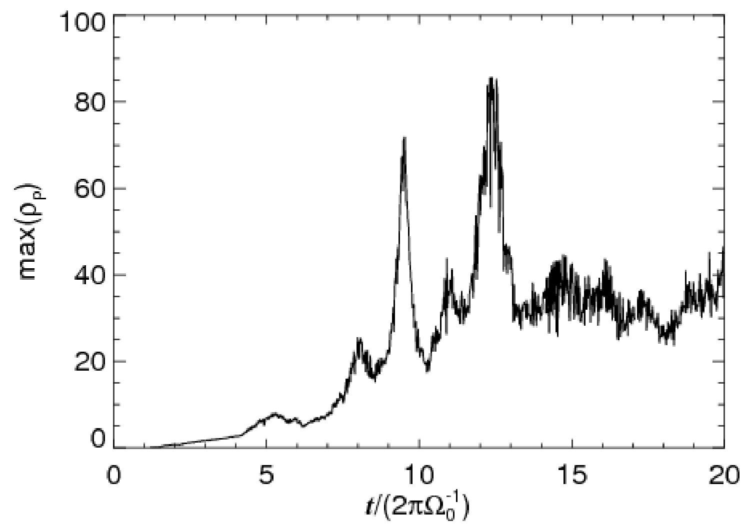
Intense Clumping!!

Solids in a turbulent disk





Intense Clumping!!



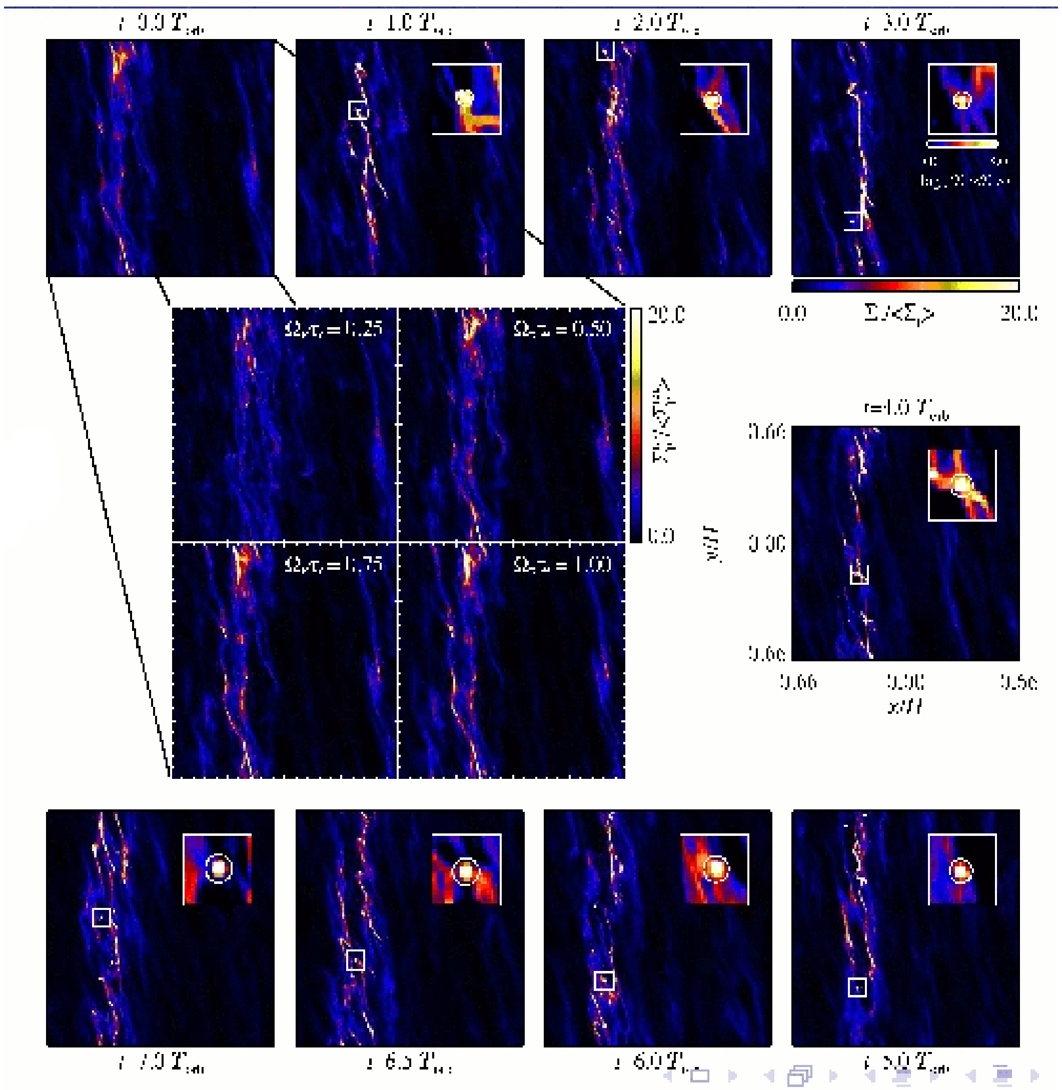
-Turbulent eddies are very efficient particle traps

-Correlation between gas and solids density maxima

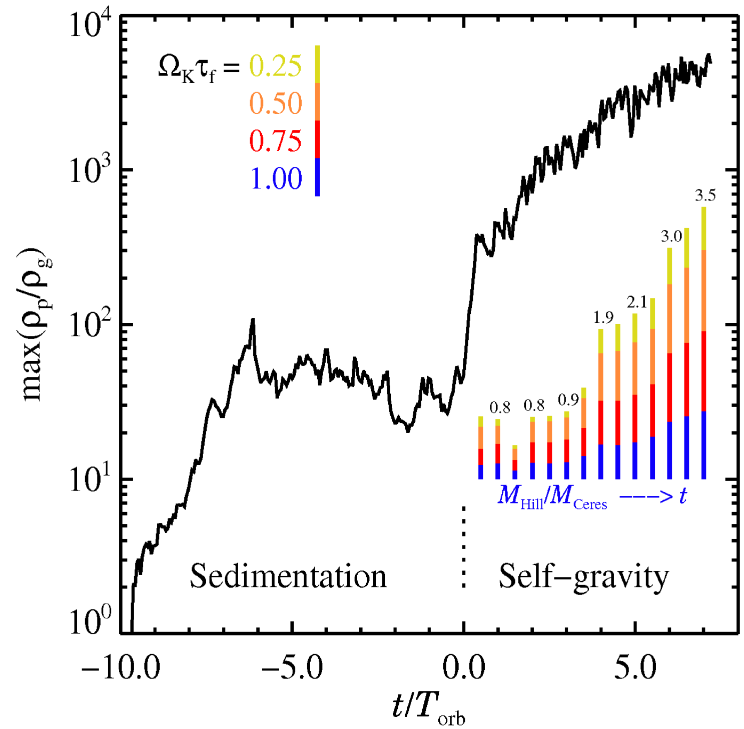
>3 orders of magnitude increase in the solids-to-gas ratio.

Including Self-Gravity: Gravitational Collapse into Dwarf Planets

Local model: MRI plus self-gravity

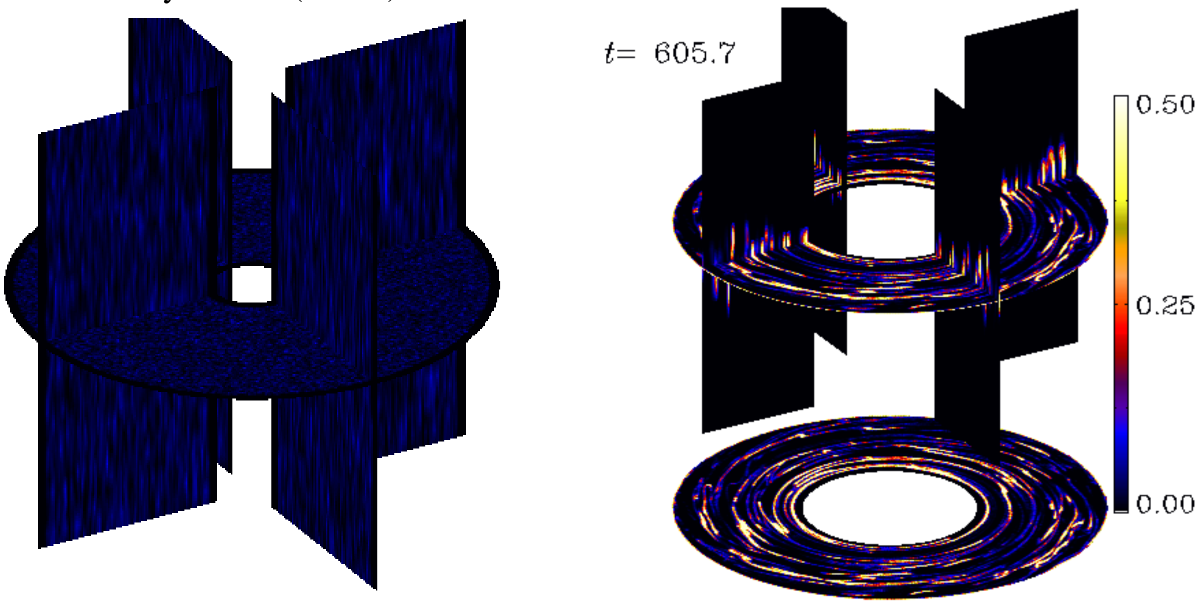


Source: Johansen et al. (2007)



Breaching the meter size barrier
by a giant leap

Source: Lyra et al. (2008a)

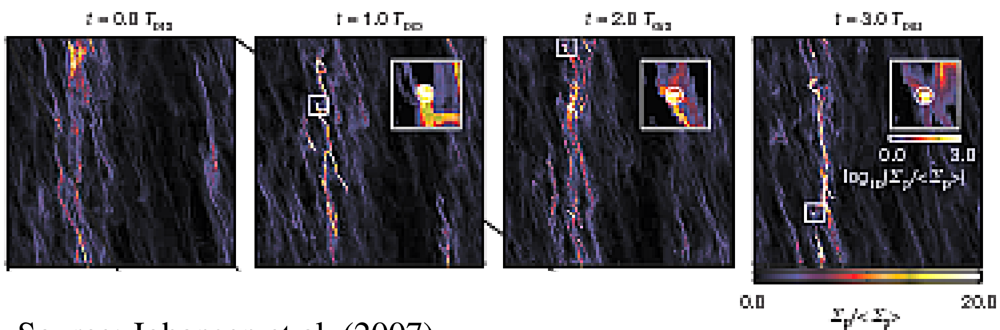


Gentle Collisions ***NOT OK***

Turbulence provides

High number density **OK**

Stopping Mechanism **OK**



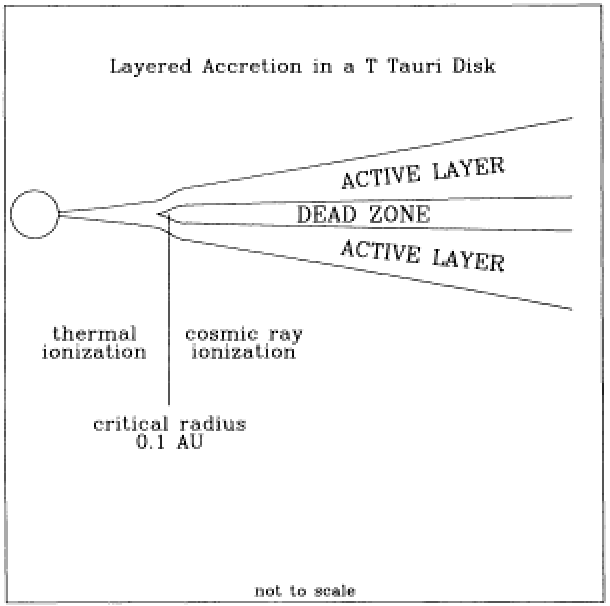
Source: Johansen et al. (2007)

The Dead Zone

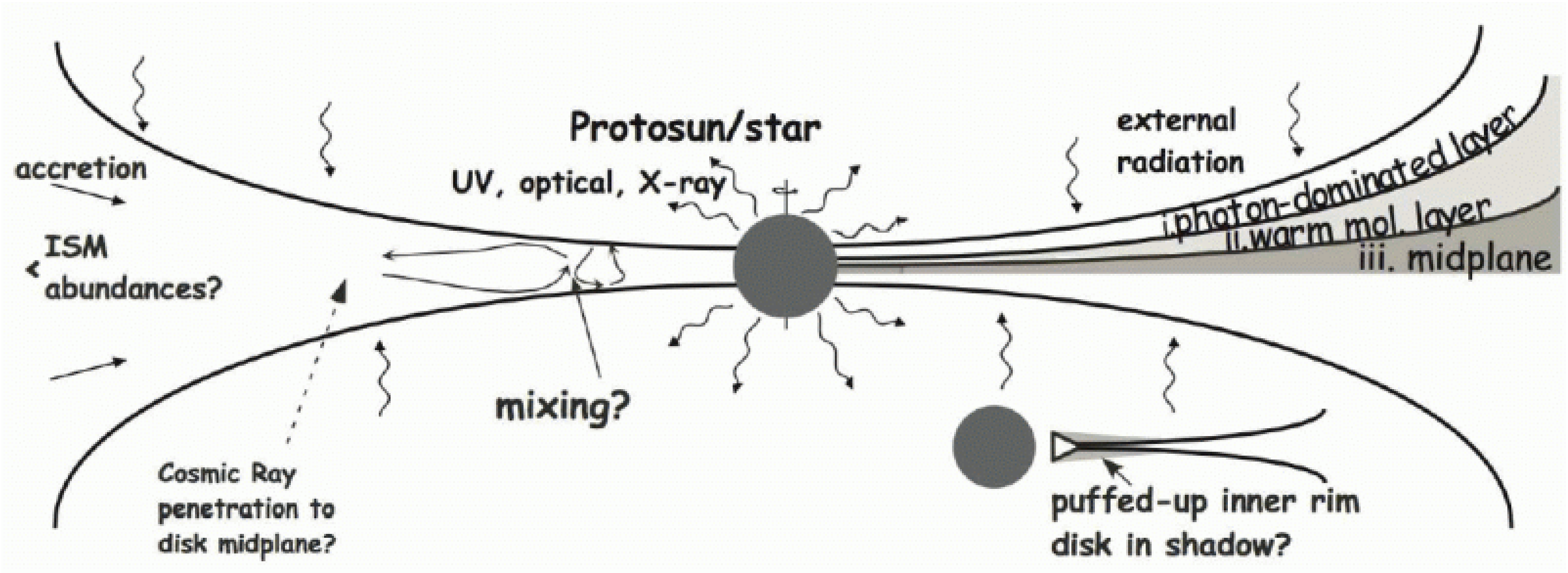
Midplane is

- too **dense** (no cosmic ray ionization)
- too **cold** (no thermal ionization)

No ionization, no MRI turbulence...



Source: Gammie et al. (1996)



The Dead Zone is a spiky business

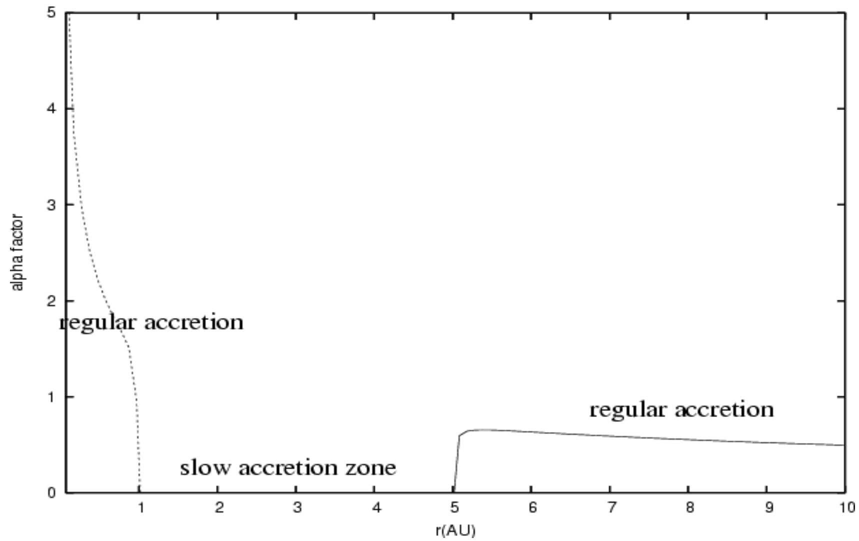
Vlad L. says:

One step back, two steps forward!

If you trust your quality....

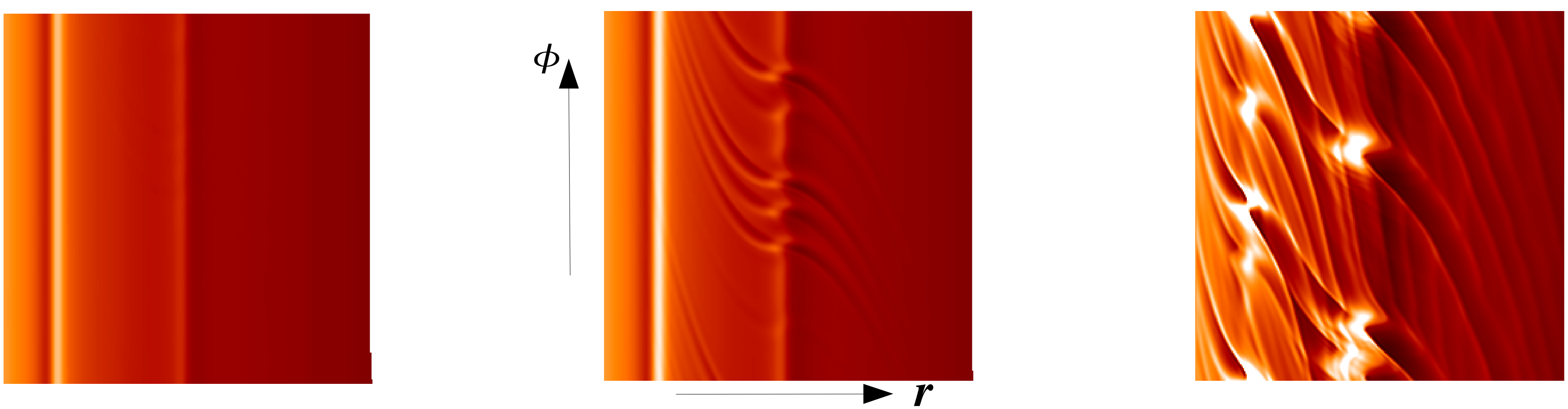
... you can dare to be ugly!

A simple Dead Zone model



Alpha-disk with viscosity jumps

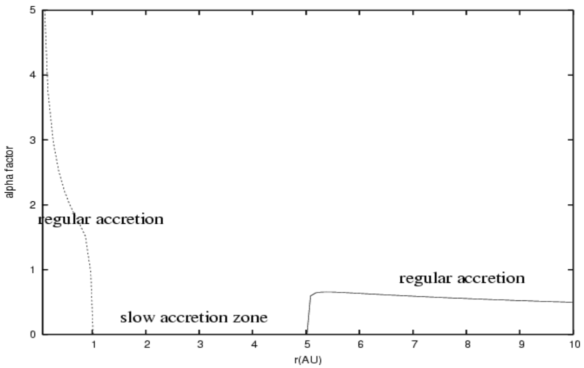
Source: Varniere & Tagger (2006)



Inflow discontinuity triggers the Rossby wave instability (RWI)... ...that saturates into vortices

Source: Lyra et al. (2008b)

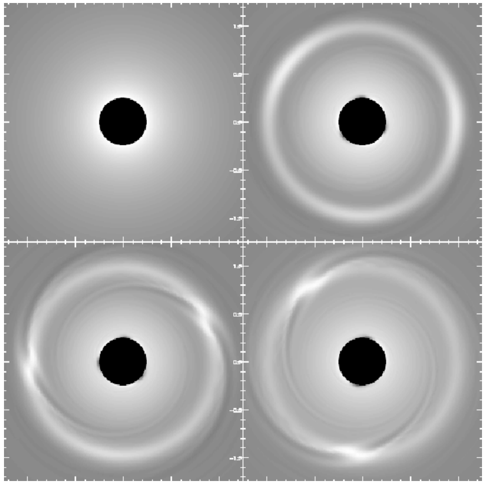
A simple Dead Zone model with particles



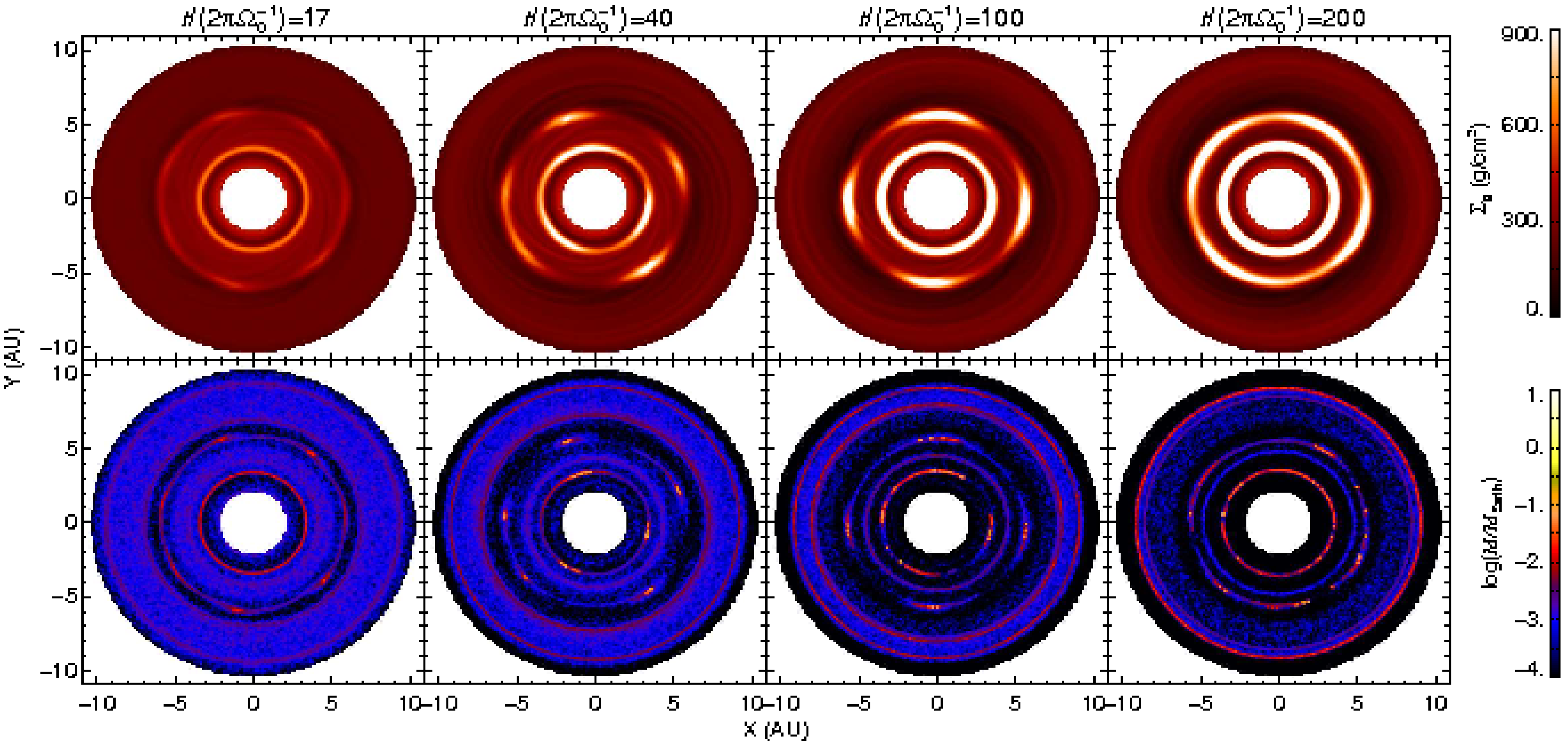
Alpha-disk with viscosity jumps

Inflow discontinuity triggers the RWI

When including particles and solving for their potential...

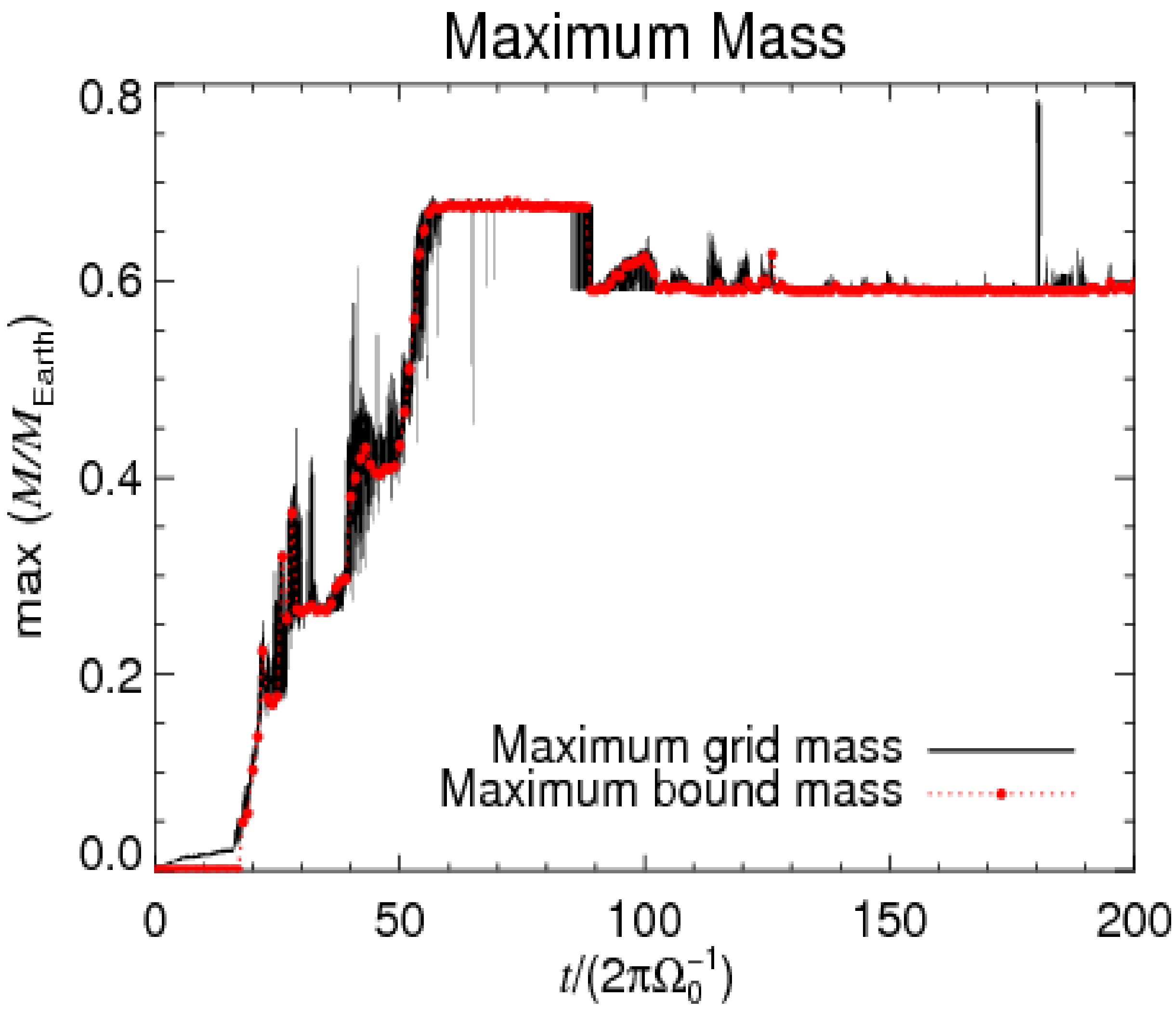


Source: Varniere & Tagger (2006)

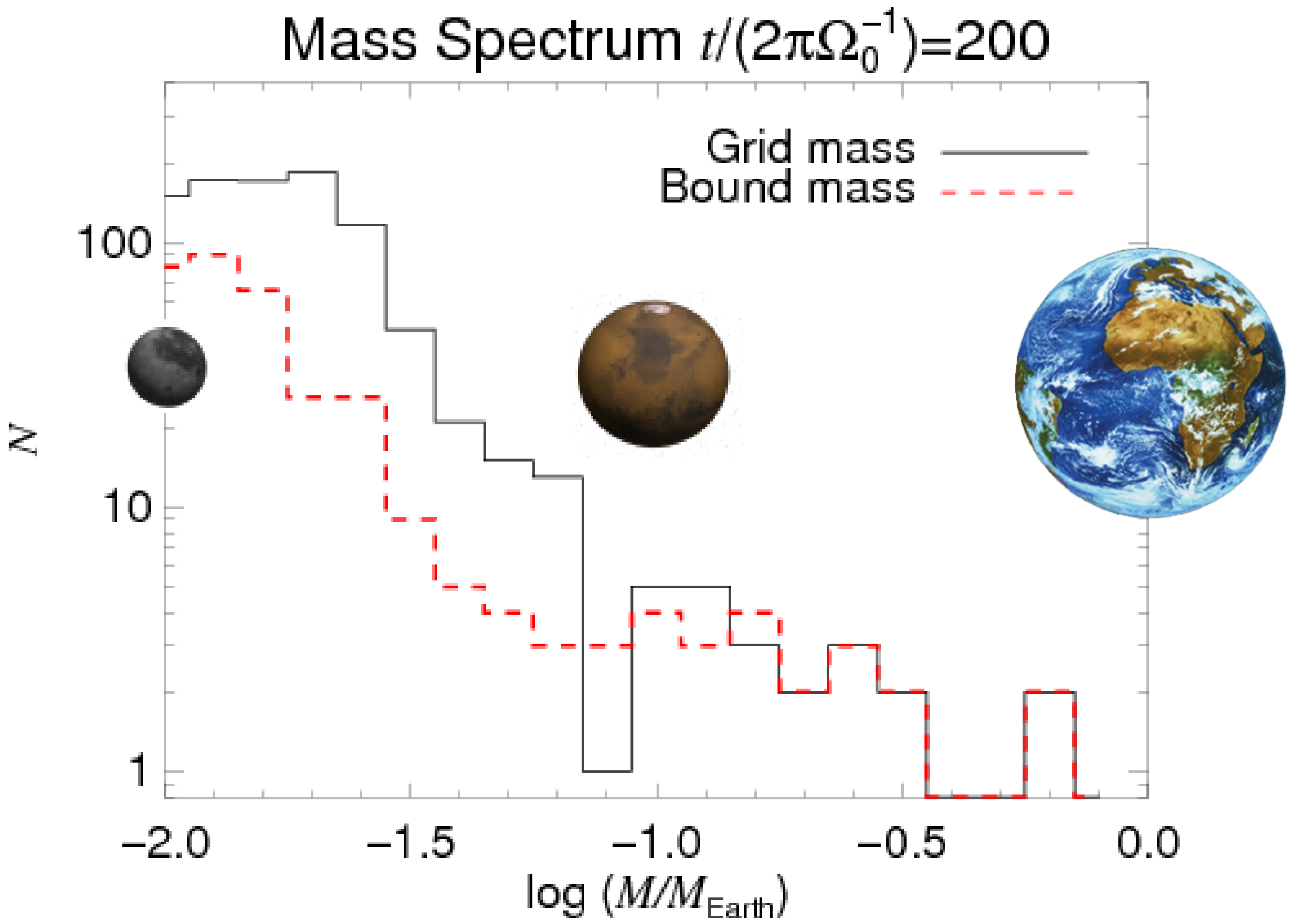


Source: Lyra et al. (2008b)

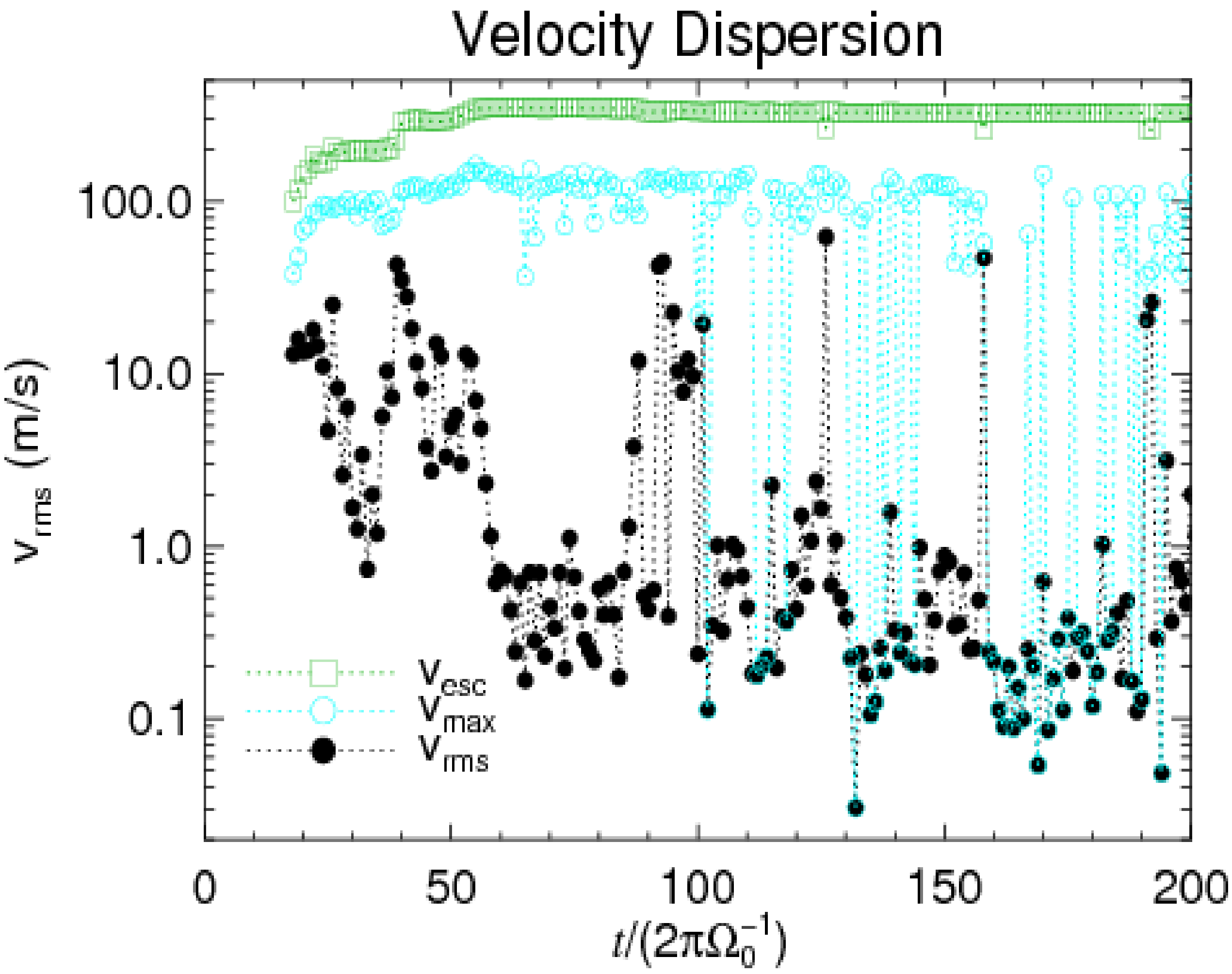
Result: A planet formation burst!



- Maximum mass: 0.6 Earth Masses
- Time between apperance of the vortices and collapse into a Mars sized embryo: 5 orbits

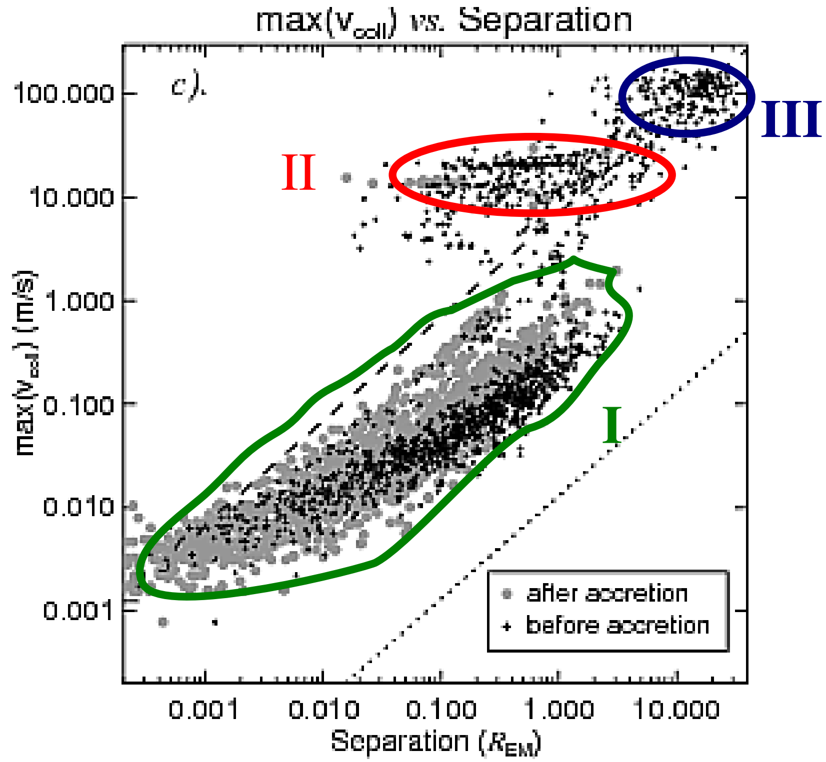


- Mass spectrum by the end of the simulation
- 300 bound clumps were formed
- Power law d(log N)/d(log M)=-2.3 +/- 0.2
- 20 of these are more massive than Mars



- Internal velocity dispersion is far below escape velocity
- Even the *maximum* velocity is below escape velocity
- rms internal velocities of the order of **1-10 m/s**.

Collisional velocity history of the most massive embryo



Fragmentation threshold velocity: 10-20 m/s

The majority of the particles never experience a collision faster than 1m/s

3 groups in the Separation vs. Collisional speed plot

I – Low speeds at short separations

II – High speeds at short separations **Only group II undergoes fragmentation**

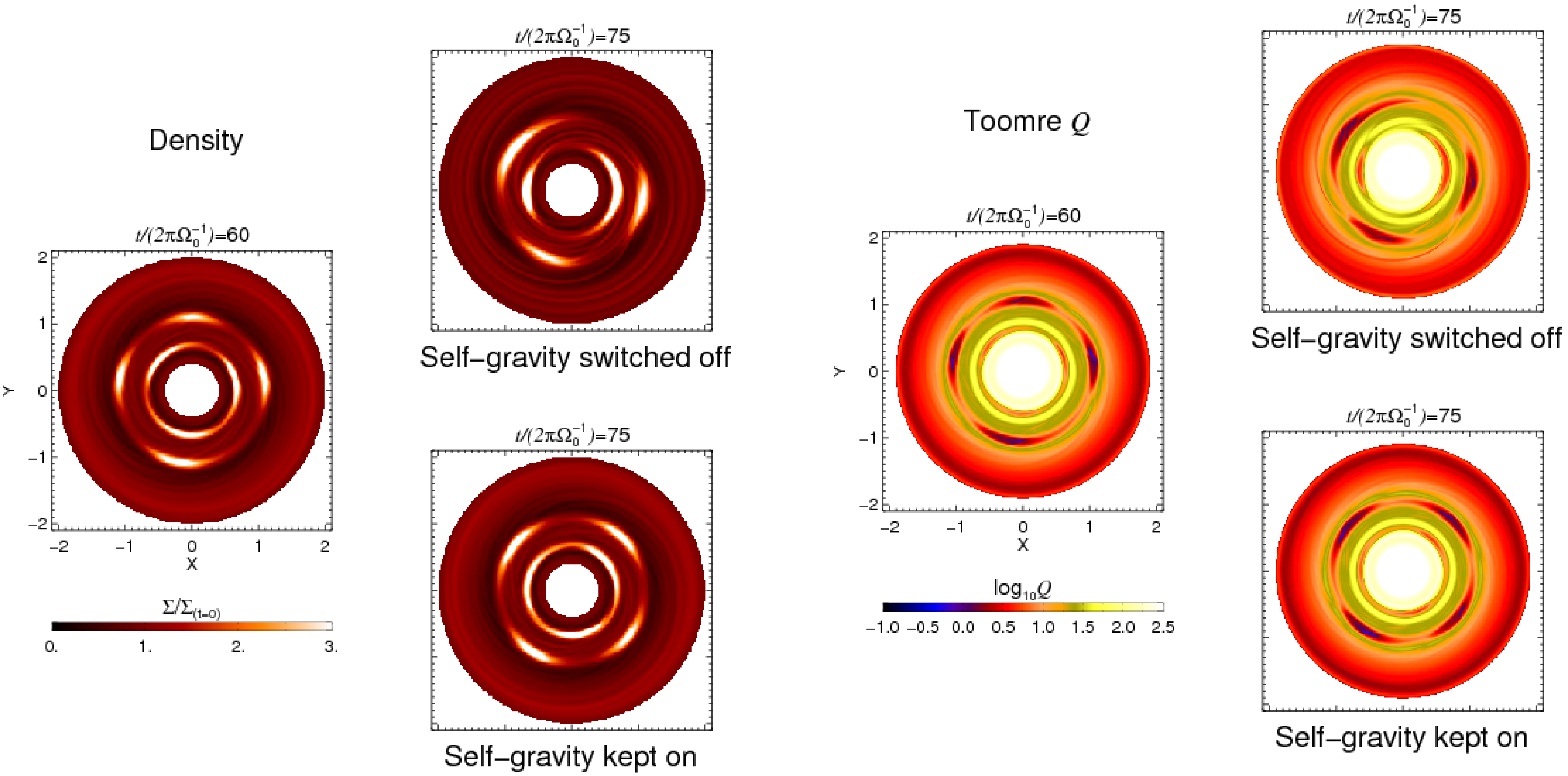
III – High speeds at large separations

Before accretion: 18% in group II, 70% in group I

After accretion: >99% in group I

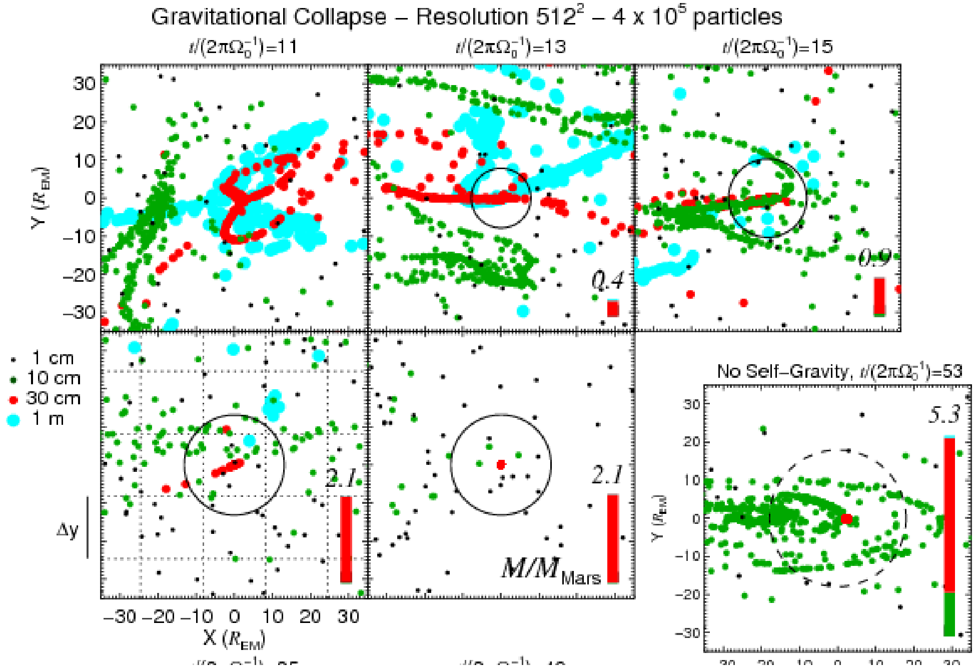
Self-gravity halts the inverse cascade!

The vortices reach the Jeans length



See also Mamatsashvili & Rice (2009)

Tidal disruption



Mass is far greater without selfgravity

WHY??

TIDAL INTERACTION WITH
THE FIELD OF MASSIVE VORTICES
AFFECTS THE EMBRYOS!

A (very) simple tidal model

Tidal force

$$F_T \propto R \nabla a$$

$$\nabla a = -\nabla^2 \Phi$$

$$F_T \propto R \rho_g$$

Gravitational force

$$F_g = -\frac{GM}{R^2}$$

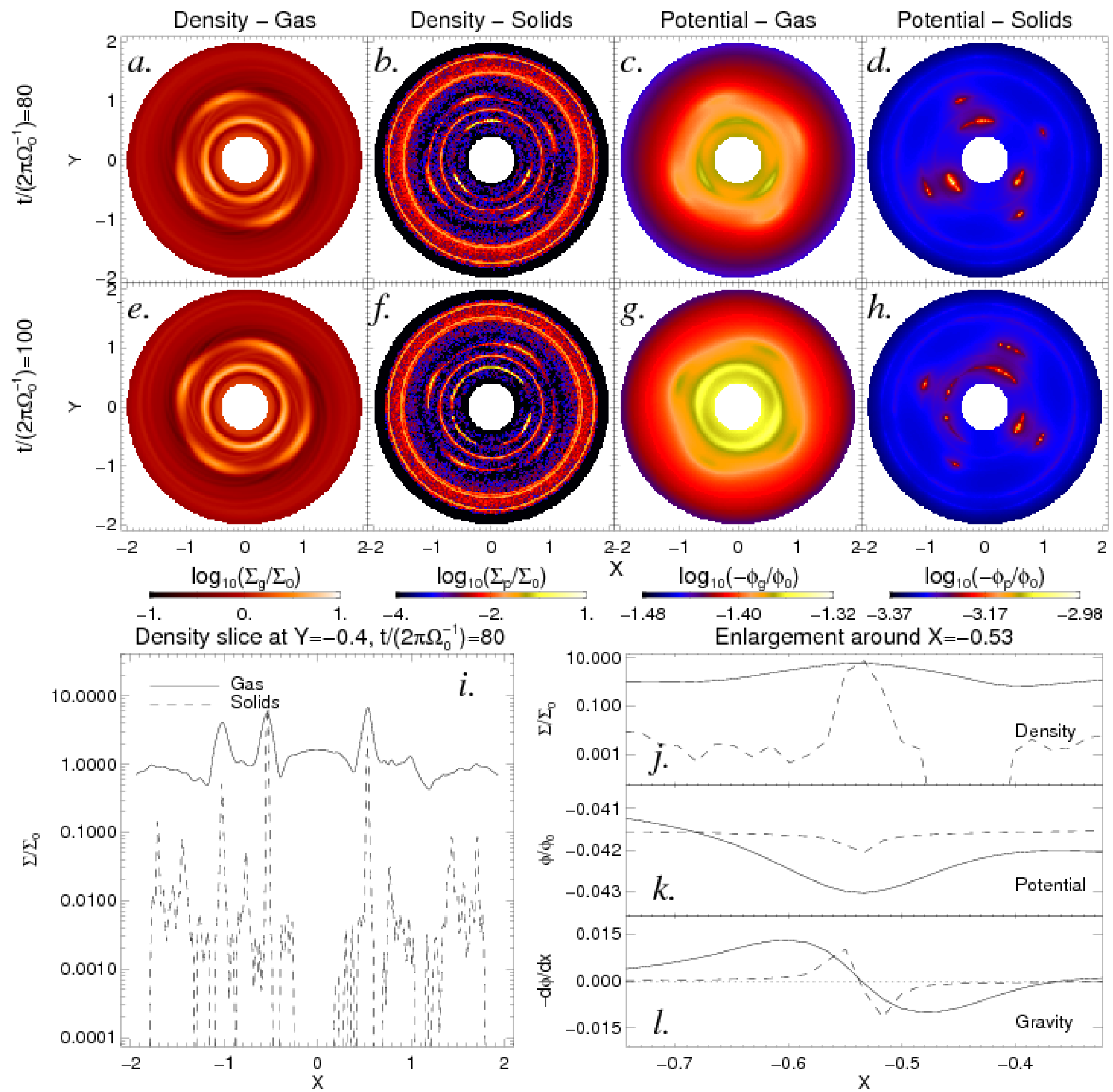
$$M = 4/3 \pi R^3 \rho_p$$

$$F_g \propto R \rho_p$$

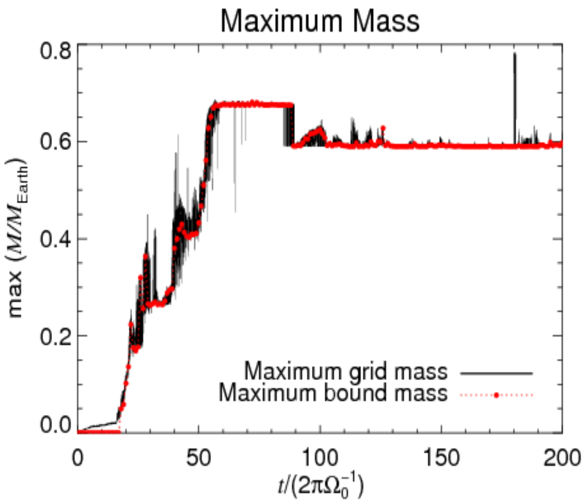
The relative strength of the tides is

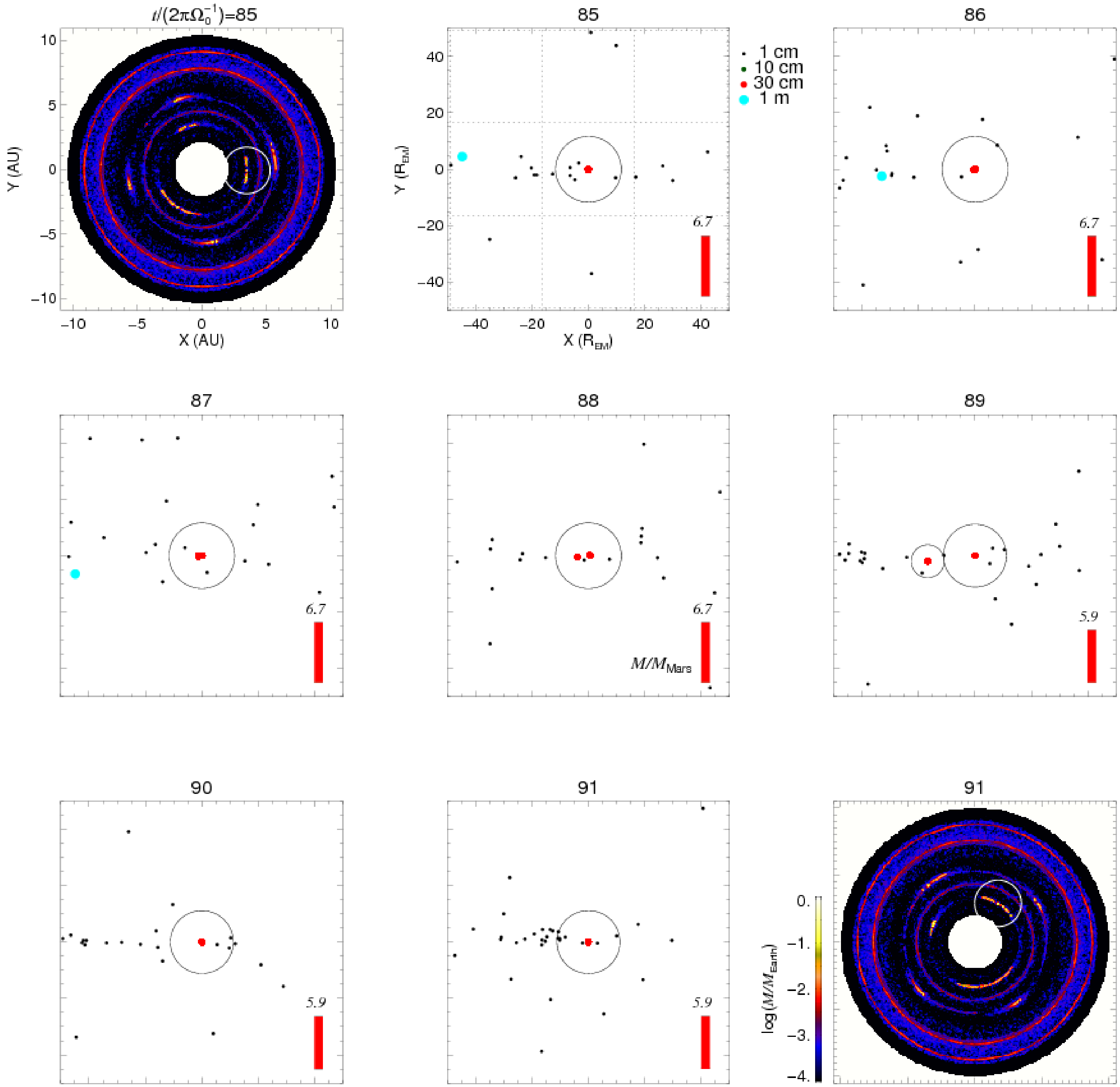
$$\zeta = \frac{F_T}{F_g} \propto \frac{\rho_g}{\rho_p}$$

... proportional to the gas-to-solids ratio

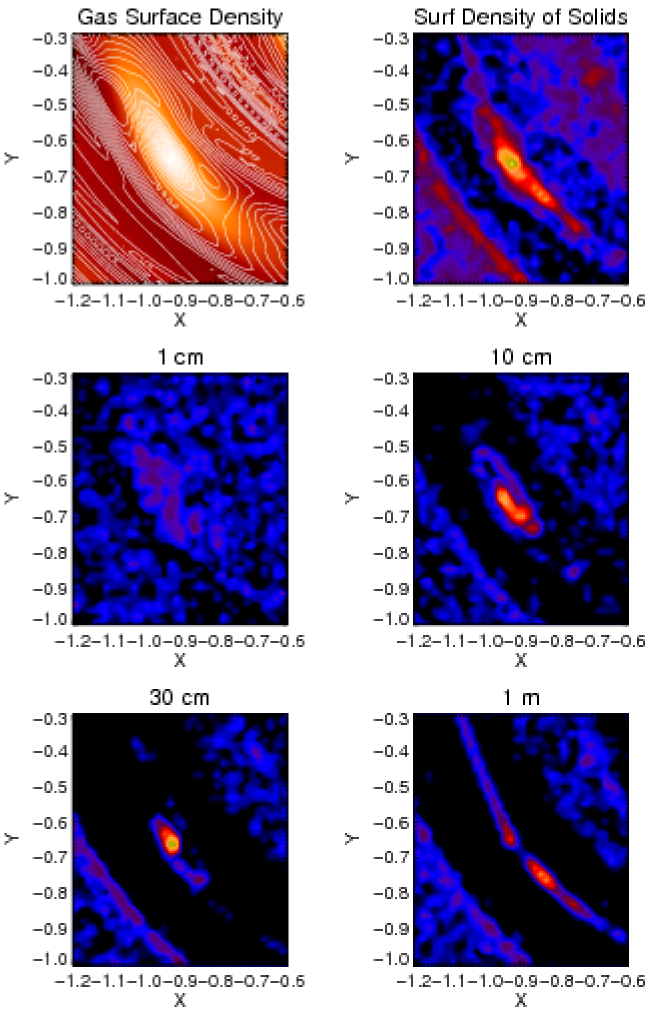


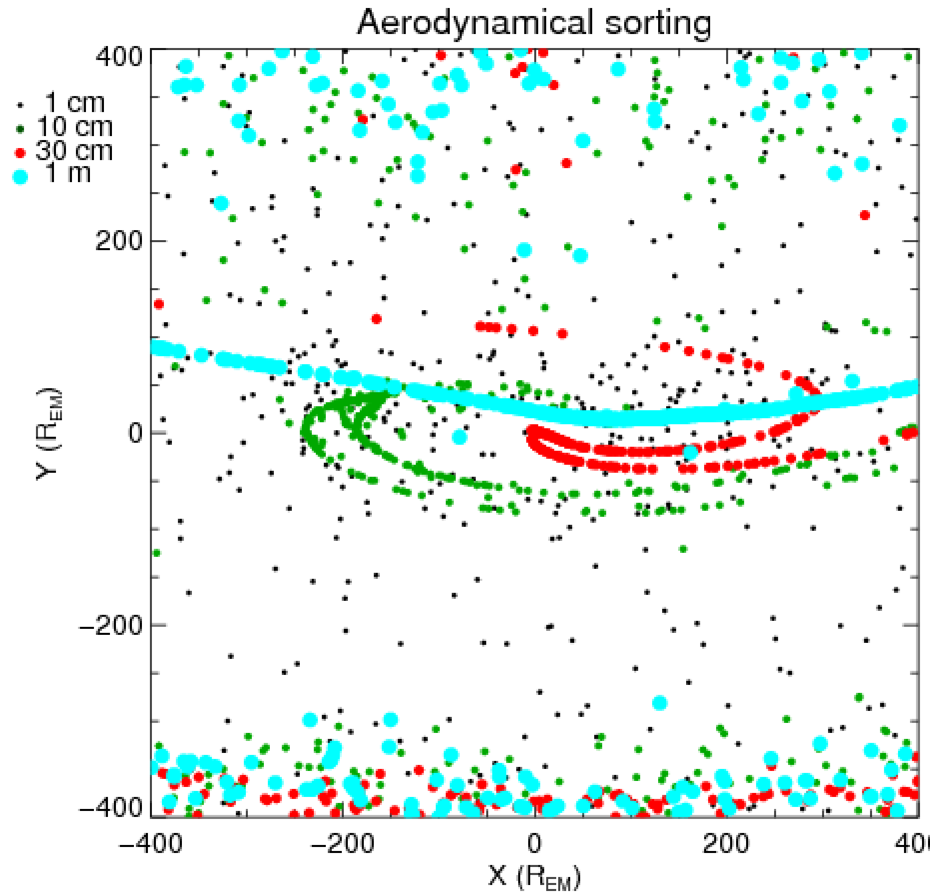
Tidal disruption





Size sorting





Preferential trapping for particles of 10 and 30 cm radii

Differential drag – aerodynamical sorting

First bound structures are formed of same-sized particles

Erosion

The liquid drop analogy of Cuzzi et al. (2008)

Stability:

ram pressure vs *surface tension*

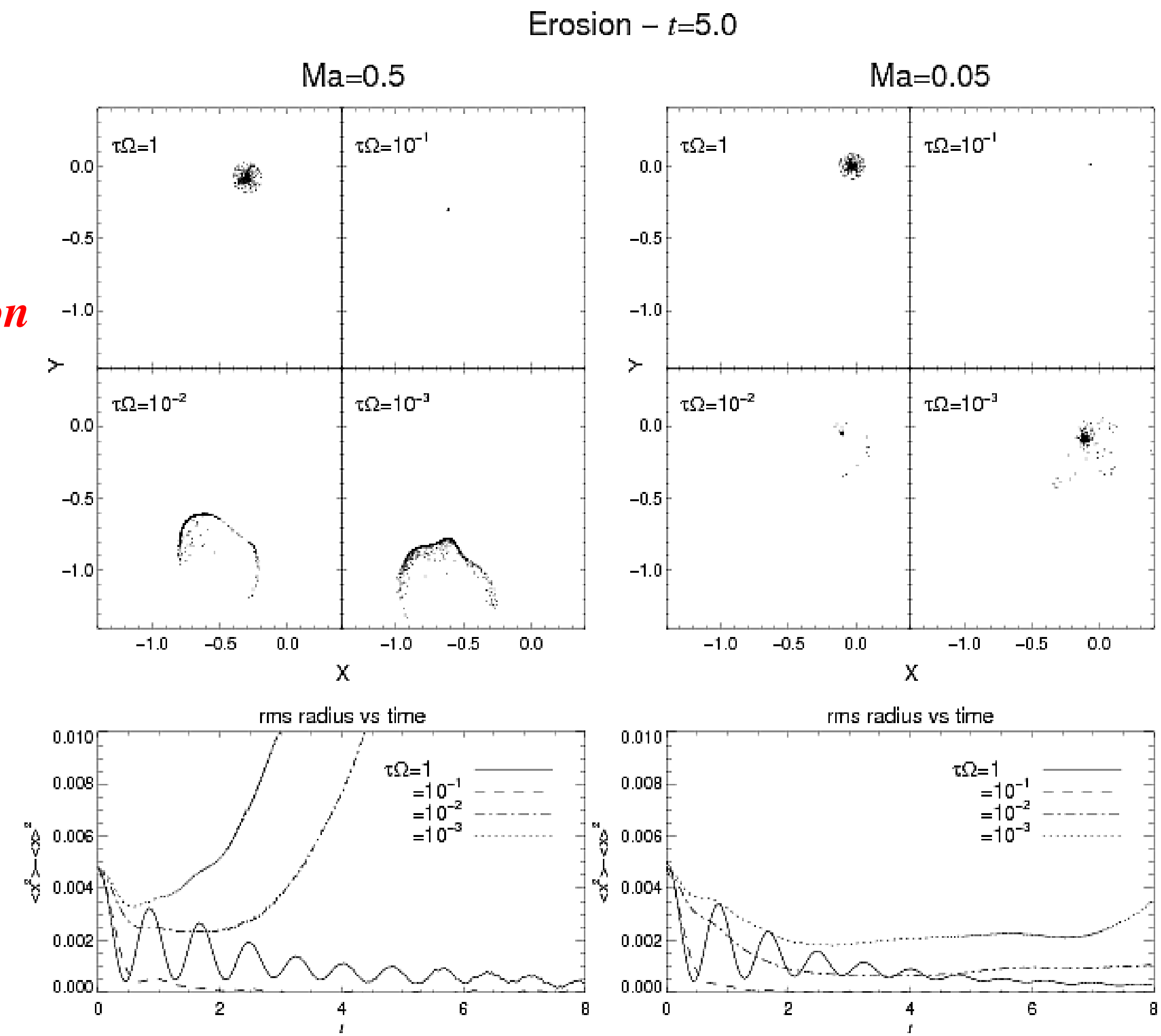
Weber number

We = drag / tension

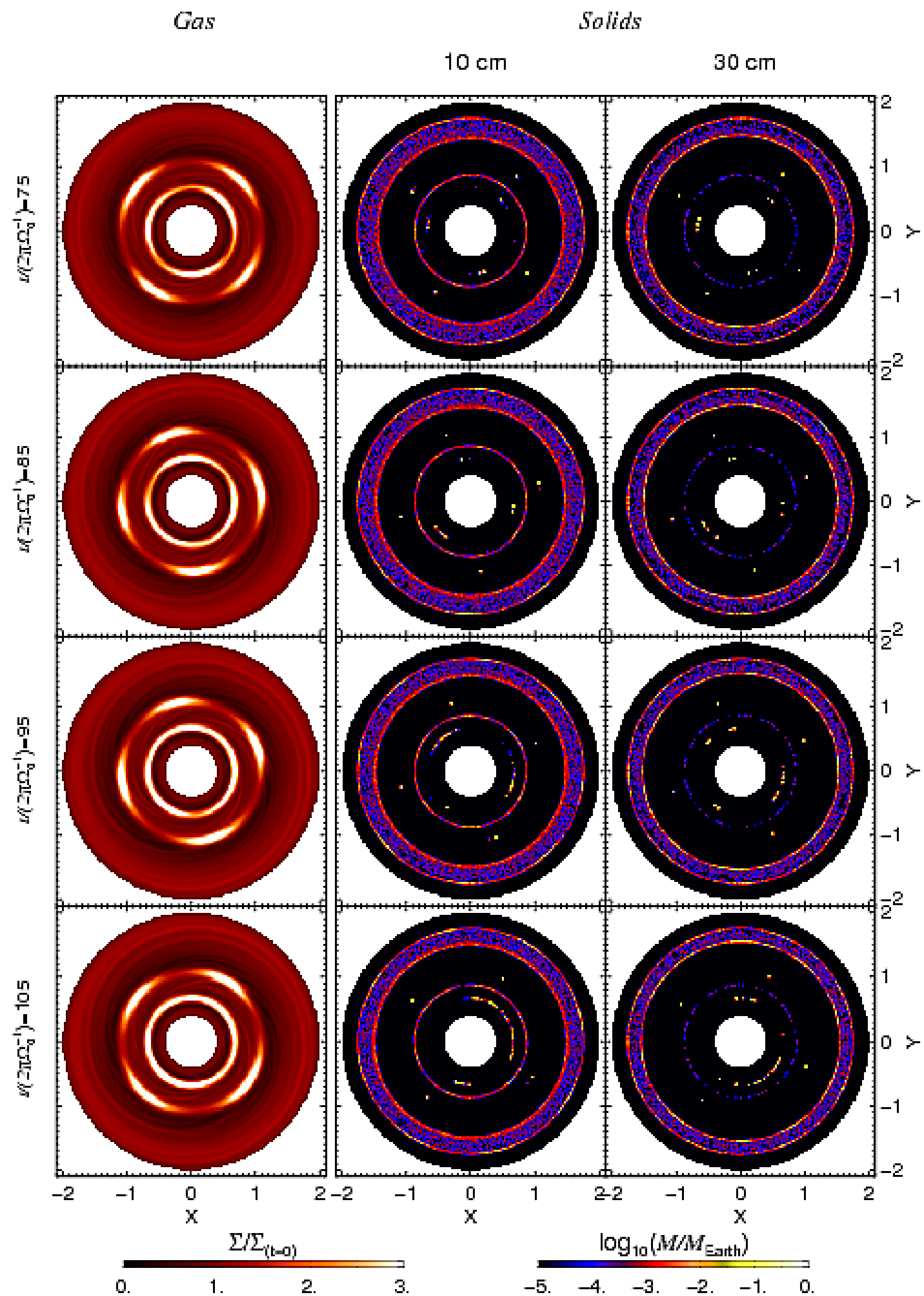
For a forming planet, selfgravity provides the tension

$$We_G = \frac{|f_D|}{|\nabla \Phi|}$$

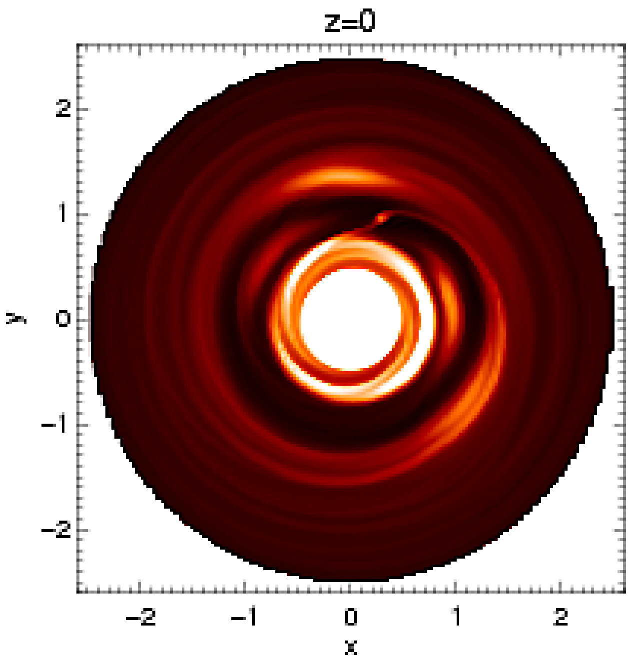
$$= \frac{Ma\, c_s}{\tau \pi G \Sigma_p}$$



<u>*Tidal Disruption + Size sorting + Erosion = Hell in the inner disk*</u>



Another way of exciting the RWI:

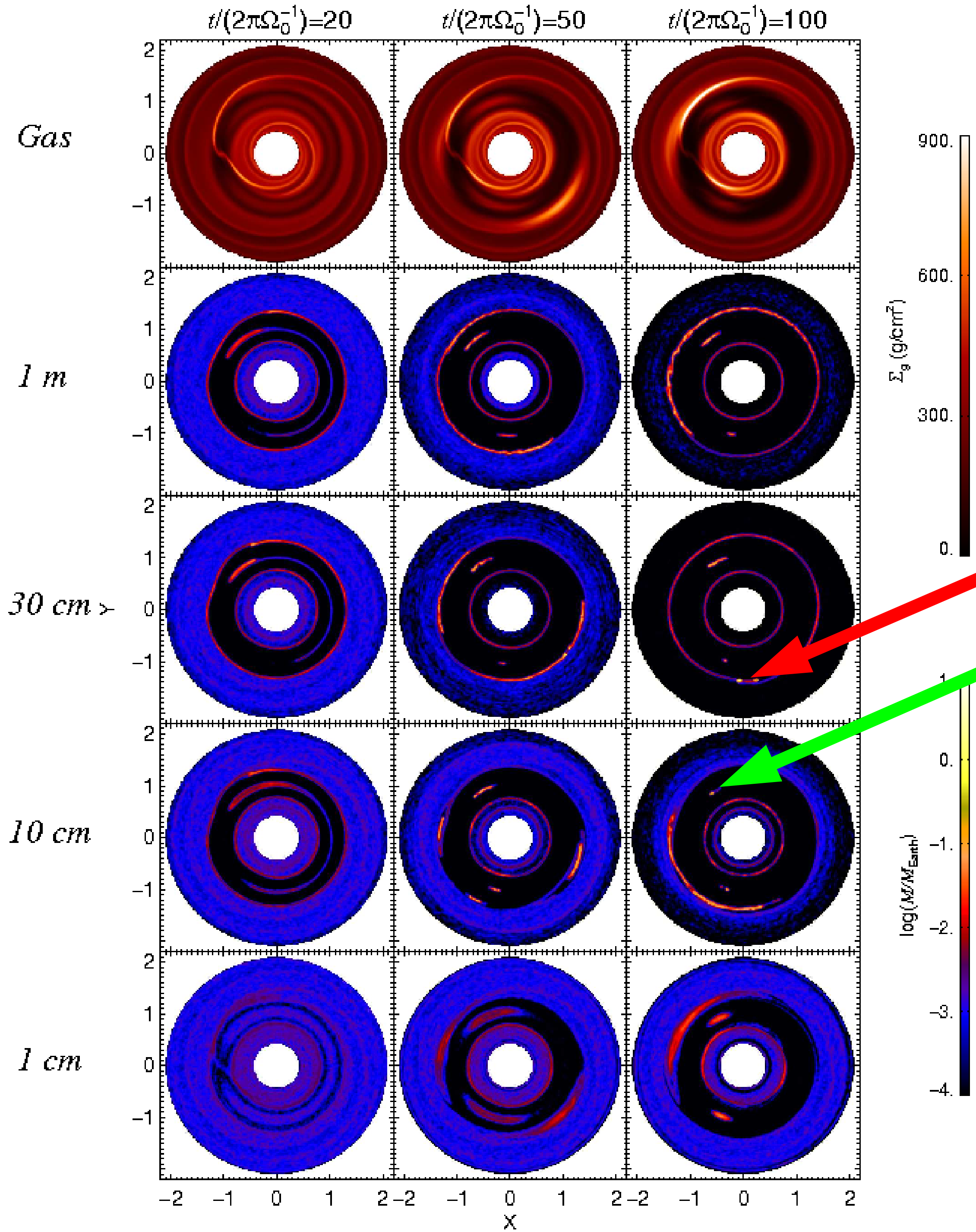


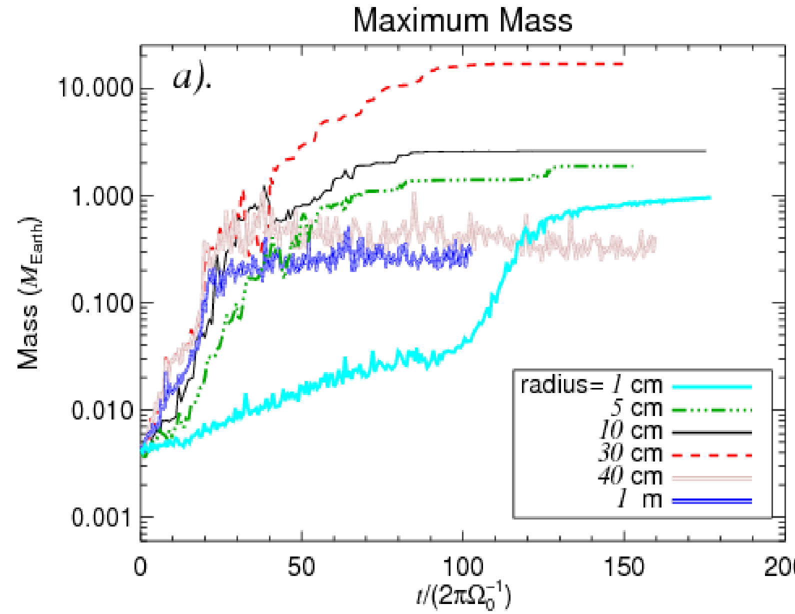
MIND THE GAP

Gap edges also produce vortices

Care for some particles?

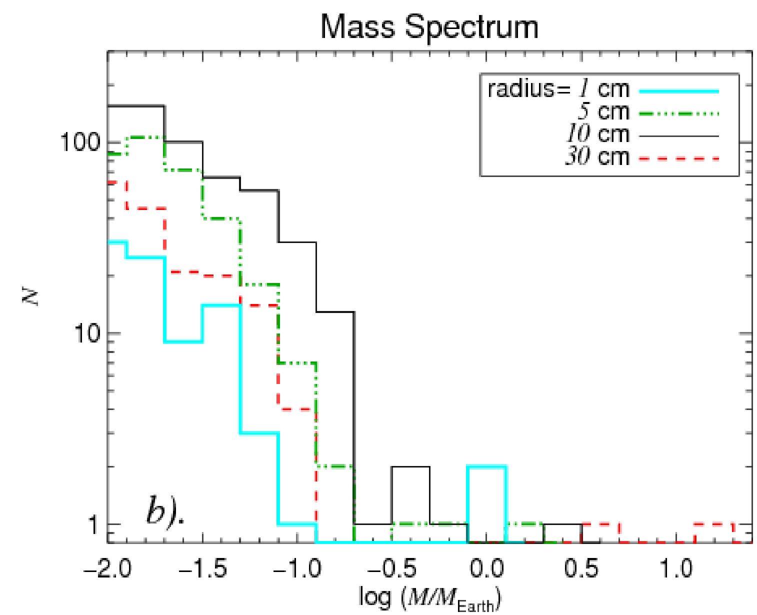
Source: Lyra et al. (2008c)



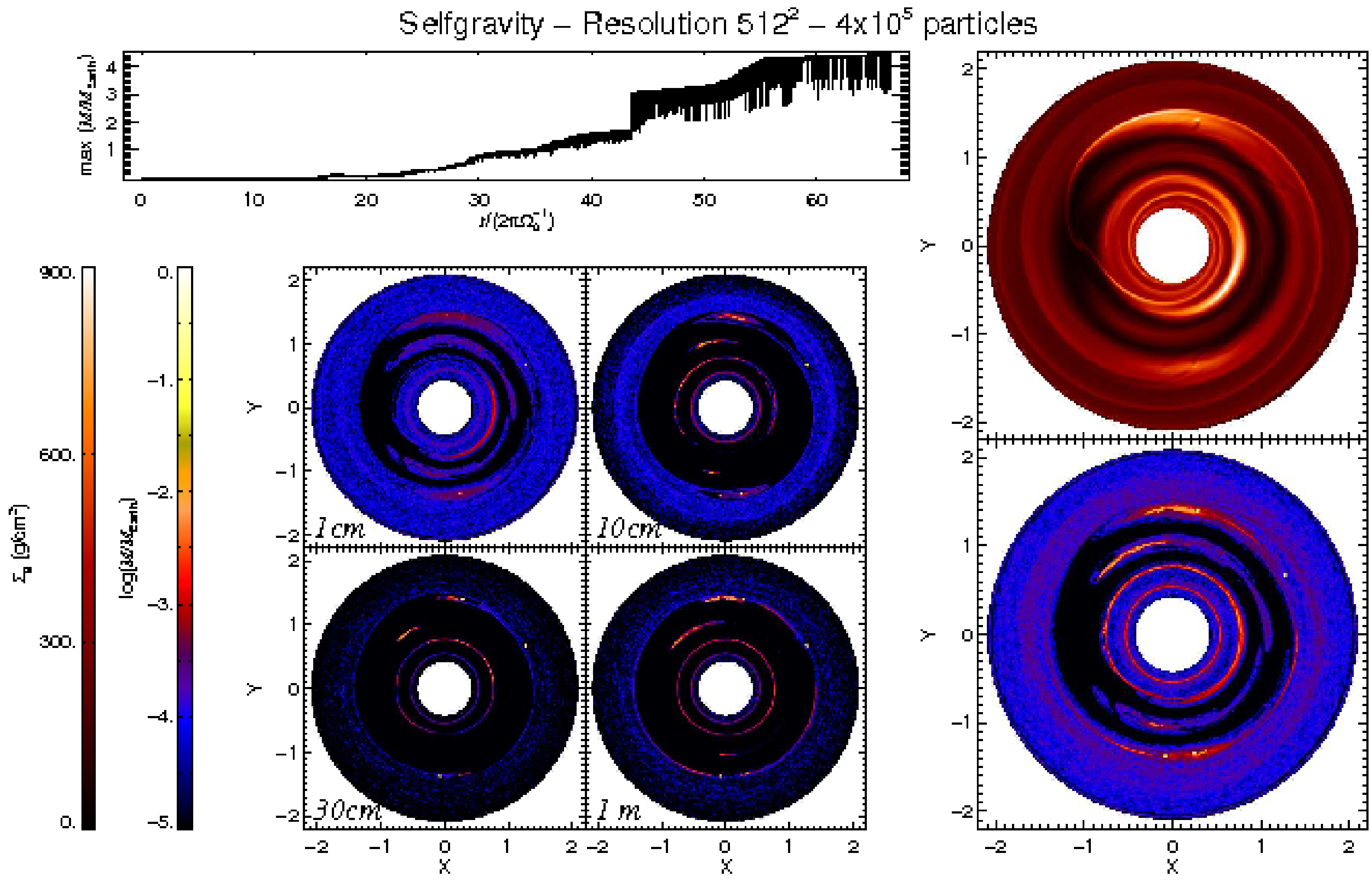


17 Earth masses!

A Trojan planet of 2.6 Earth masses

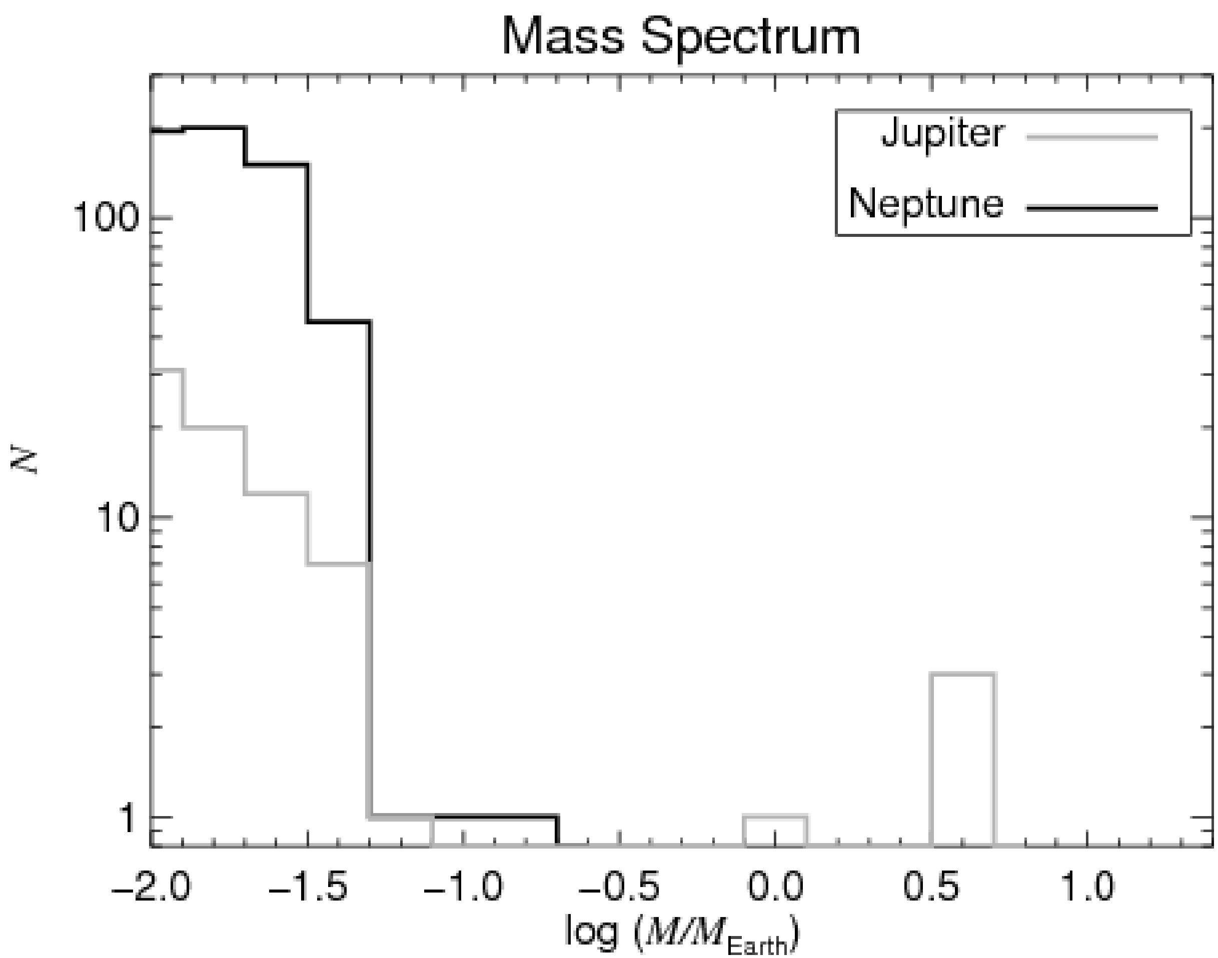


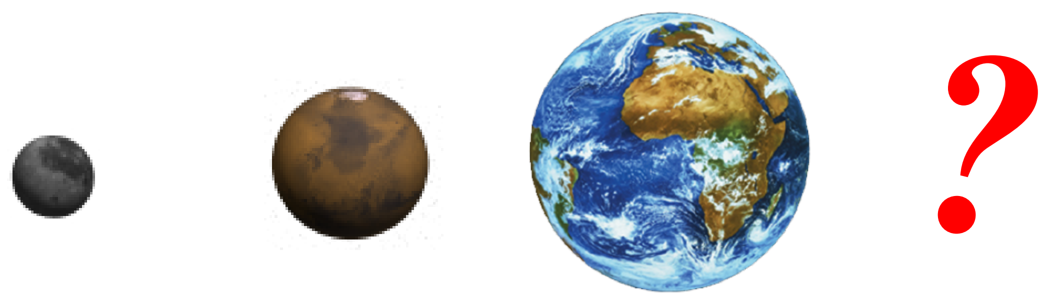
A spectrum of particle sizes



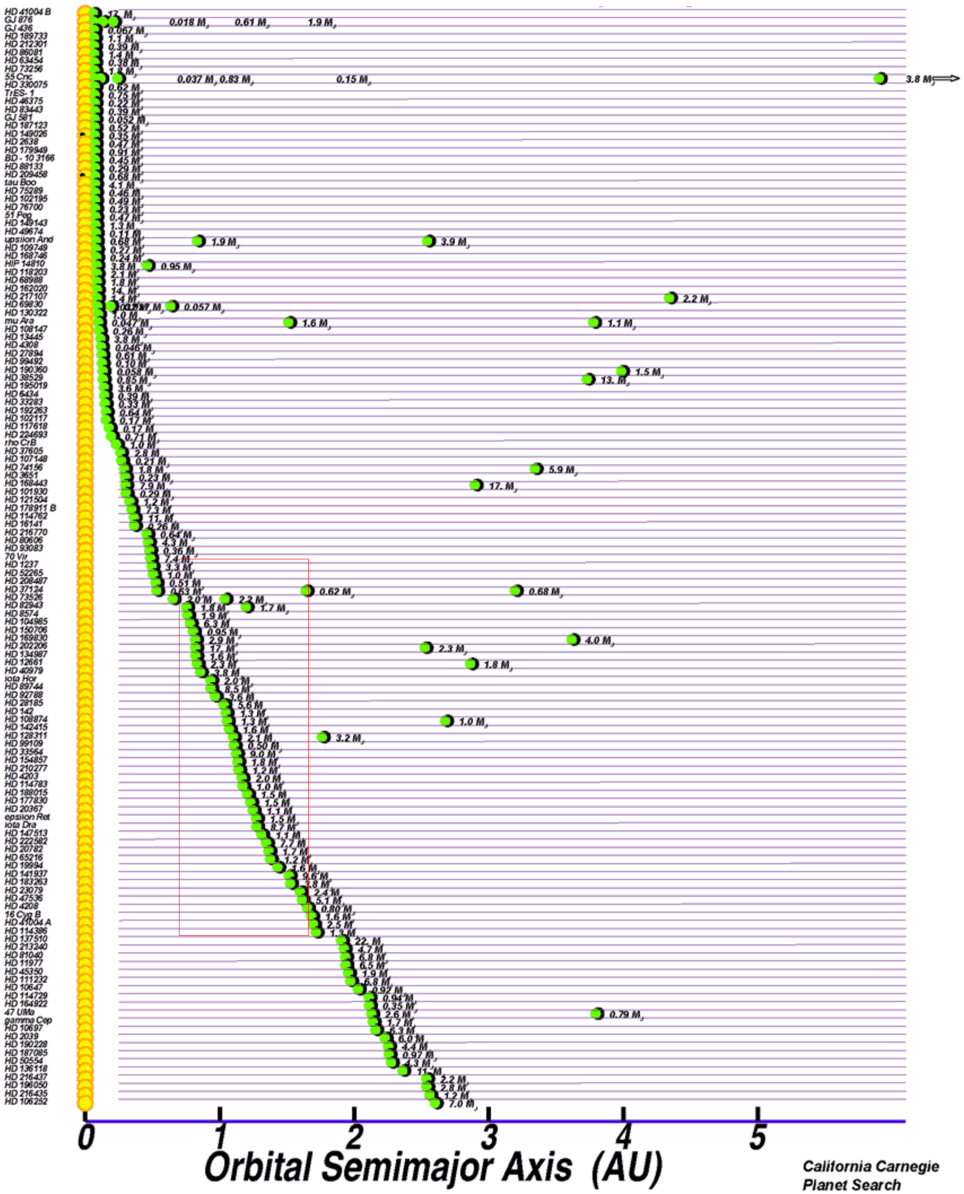
3 super-Earths formed + Mars mass Trojans

Mass spectrum for Jupiter-mass and Neptune-mass perturbers





“This allows for the addition of solar-type stars
with gas giant planets in Earth-like orbits...



... in the list of potentially
habitable stellar systems”

(Lyra et al. 2008c, arXiv 0810.3192)

Wait a sec, did you say "HABITABLE"??

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Habitable worlds may hide in Jupiter-like planets wake

November 3rd, 2008 - 12:36 pm ICT by ANI -

London, Nov 3 (ANI): Computer generated simulations by a scientist have indicated that habitable planets may be hidden in the wake of Jupiter-like planets as they orbit distant stars.

According to a report in New Scientist, Wladimir Lyra of the Uppsala Astronomical Observatory in Sweden has developed the simulations.

When a gas giant coalesces from the swirling nebula of gas and dust surrounding a young star, the planets gravity forms a wake ahead and behind it, concentrating enough matter there for it to clump together and form smaller, rocky planets like Earth.

Objects born in Jupiters wake may have merged to form the planet Saturn, which was then nudged into its current position by the gravity of other planets, according to the team.

Outside our solar system, some gas giant planets have been detected in the habitable zone of their stars. Their wakes may harbour rocky, Earth-size worlds.

Its an exciting possibility, said Sara Seager of MIT (Massachusetts Institute of Technology).

According to Seager, such planets could be found by the small gravitational tugs they exert on their larger, known siblings, an idea supported by recent calculations by Nikku Madhusudhan and Joshua Winn, also of MIT. (ANI)

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Habitable worlds may hide in gas giants' wake

01 November 2008

From New Scientist Print Edition. Subscribe and get 4 free issues.

HABITABLE planets may be lurking in the wake of Jupiter-like planets as they orbit distant stars.

When a gas giant coalesces from the swirling nebula of gas and dust surrounding a young star, the planet's gravity forms a wake ahead and behind it, concentrating enough matter there for it to clump together and form smaller, rocky planets like Earth. That's according to simulations led by Wladimir Lyra of the Uppsala Astronomical Observatory in Sweden. Objects born in Jupiter's wake may have merged to form the planet Saturn, which was then nudged into its current position by the gravity of other planets, the team says (www.arxiv.org/abs/0810.3192).

Outside our solar system, some gas giant planets have been detected in the habitable zone of their stars. Their wakes may harbour rocky, Earth-size worlds. "It's an exciting possibility," says Sara Seager of MIT. She notes that such planets could be found by the small gravitational tugs they exert on their larger, known siblings, an idea supported by recent calculations by Nikku Madhusudhan and Joshua Winn, also of MIT.

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Planeternas turbulenta födelse

2009-02-17

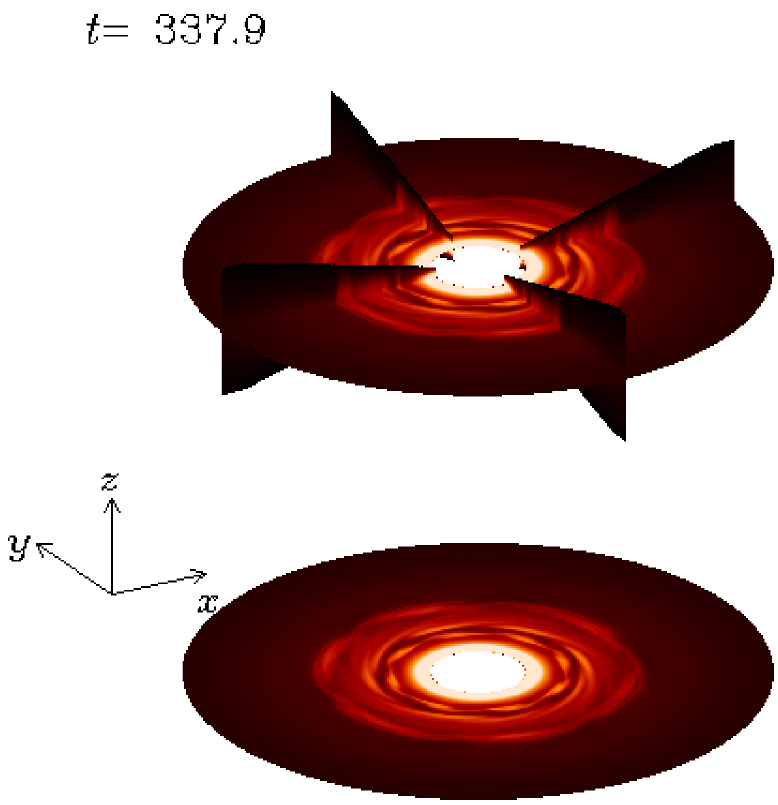
Pressmeddelande från Uppsala universitet

Nya rön vad gäller planetbildning, extrasolära plan stjärnbildning presenteras i den avhandling i astror fram vid Uppsala universitet den 26 februari. Med h hydrodynamiska simuleringar har de tittat närmare kraften vid planetbildning.

Planetbildning sker i skivor av gas och stoft kring en nyfödd stjärna. [koagulation, då kolliderande mikrometersmå stoftpartiklar bygger up gruskorn och meterstora bumlingar med hjälp av elektromagnetiska kan inte riktigt förklara hur större kroppar bildas utan att de alltför sr dras in mot stjärnan eller förstörs i kollisioner.

Conclusions

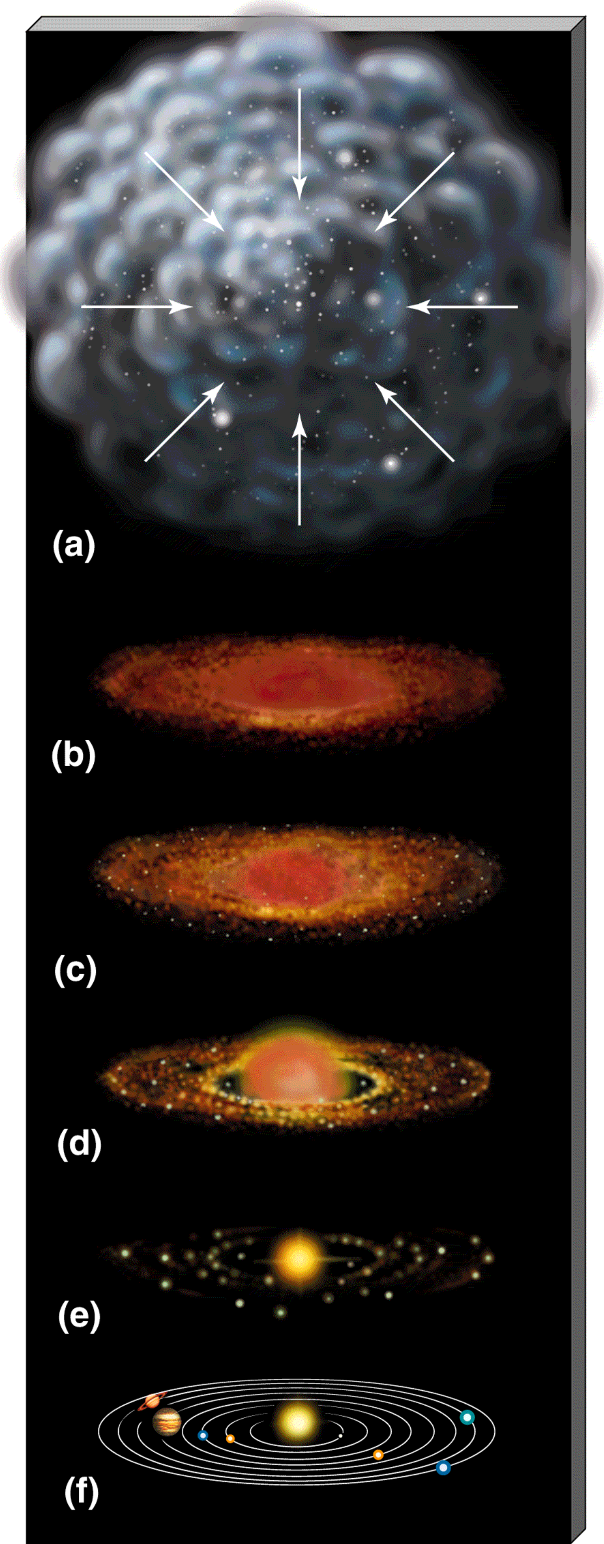
- Gravitational collapse of the layer of solids into Mars sized embryos naturally occurs in the presence of the RWI
- A giant planet can help form a second massive core
- Trojan Earths may be common in the exo-planetary zoo
- The borders of the dead zone are very promising places for forming planets



Immediate Future

- Extend the simplistic model to a ***3D*** configuration, modeling the dead zone with the MRI and ambipolar diffusion, to study how the RWI reacts to these more realistic conditions.

- Understand the collisional speeds: is it real that they are so low?



Summarizing...

Gravitational collapse of an interstellar cloud

Outward transport of angular momentum through turbulence generated by the MRI. Dust coagulates into pebbles and boulders, sedimenting towards the midplane.

Rocks in the turbulent medium are trapped in transient pressure maxima and undergo collapse into planetesimals and dwarf planets.

The presence of a dead zone excites the RWI. Inside vortices, the first dozens of Mars-mass embryos are formed.

Embryos collide and give rise to the oligarchs (?)

When Jupiter is formed, a second round of planet formation is triggered (Trojan planets, Saturn?)

Nice model: Jupiter and Saturn cross 2:1 MMR and define the architecture of the Solar System

Theoretical Modelling

$$\frac{\partial \rho_g}{\partial t} = -\left(\boldsymbol{u}\cdot\nabla\right)\rho_g - \rho_g \nabla\cdot\boldsymbol{u}$$

$$\frac{\partial s}{\partial t} = -\left(\boldsymbol{u}\cdot\nabla\right)s + \frac{1}{\rho T}\left(\nabla\cdot\left(K\nabla T\right) + \eta\mu_0 \boldsymbol{J}^2 + 2\rho\nu\boldsymbol{S}^2\right)$$

$$p = \rho_g c_s^2/\gamma$$

$$\frac{\partial \boldsymbol{A}}{\partial t} = \boldsymbol{u}\times\boldsymbol{B} - \eta\mu_0\boldsymbol{J}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} = -\left(\boldsymbol{u}\cdot\nabla\right)\boldsymbol{u} - \nabla\Phi - \rho_g^{-1}\left(\nabla p + \boldsymbol{J}\times\boldsymbol{B} + \rho_p f_d\right) + 2\rho_g^{-1}\nabla\cdot\left(\nu\rho_g\boldsymbol{S}\right)$$

$$\boldsymbol{\Phi} = \boldsymbol{\Phi}_{sg} - \sum_i^N \frac{GM_i}{\left|\boldsymbol{r}-\boldsymbol{x}_i\right|}$$

$$\nabla^2\Phi_{sg} = 4\pi G\left(\rho_g + \rho_p\right)$$

$$f_d = -\left(\frac{3\rho_g C_D\left|\boldsymbol{w}-\boldsymbol{u}\right|}{8\,a_{\bullet}\,\rho_{\bullet}}\right)\left(\boldsymbol{w}-\boldsymbol{u}\right)$$

$$\frac{d\boldsymbol{w}}{dt} = -\nabla\Phi - f_d$$

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{w}$$

__What triggers the vortices?__

Rossby Wave Instability

(Lovelace et al 1999, Li et al 2000, Li et al 2001)

-Non-Axisymetric

-Triggered by an extremum of $L = \frac{\Sigma\,\Omega}{\kappa^2}(P\,\Sigma^{-\gamma})^{2/\gamma}$ (=pressure bumps)

HYDRO INSTABILITY IN DISKS:

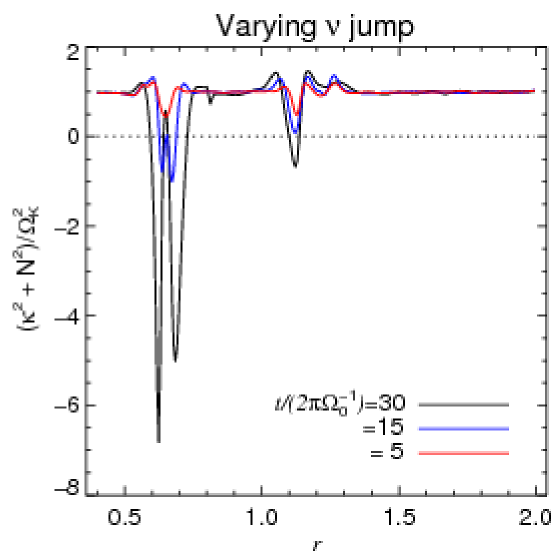
radial perturbations

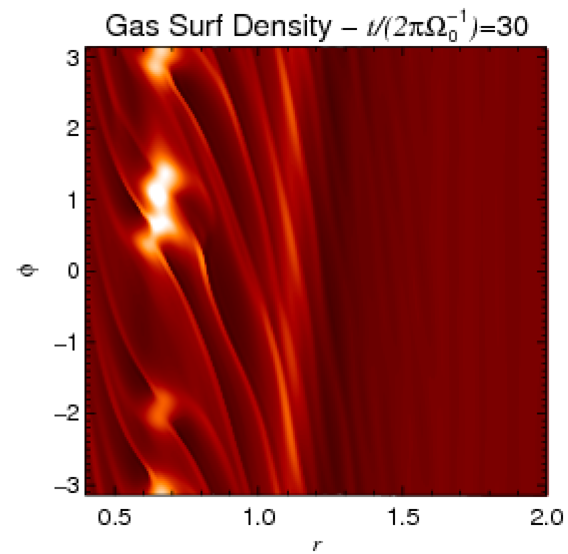
$$\kappa^2 + N^2 < 0$$

epicyclic frequency   Brunt-Väisälä frequency

azimuthal perturbations

$$\frac{dL}{dr} = 0 \qquad \left|\frac{d^2 L}{dr^2}\right| > A_{trsh}$$





-Perturbed enthalpy obeys $\eta'' + C(r)\,\eta = 0$ (i.e., **Trapped!** Modes experience growth)

- Dispersion relation similar to that of Rossby waves in planetary atmospheres
- <u>Saturated state</u>: Vortices when RWs break and coalesce

Sharpness of the viscosity jump

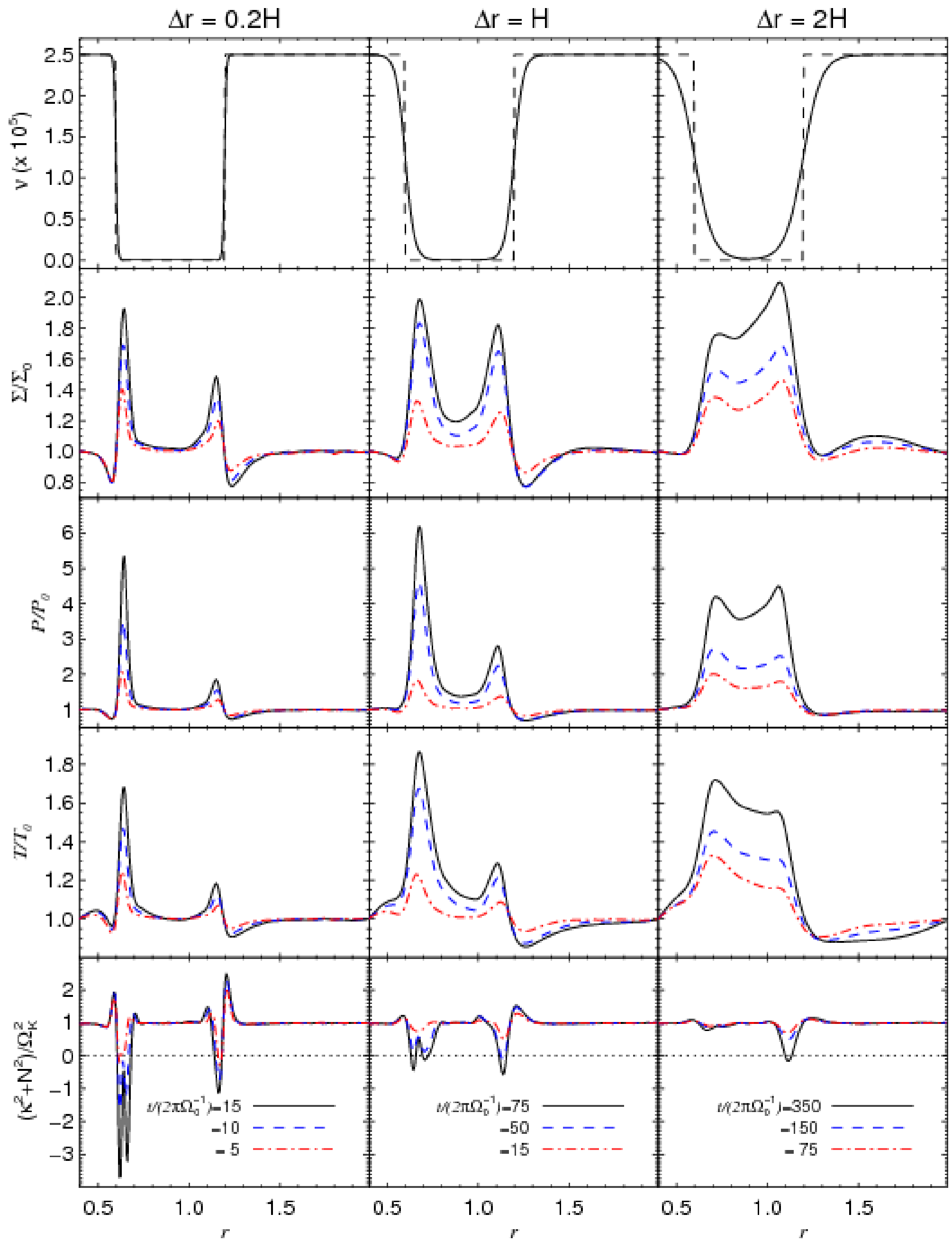
viscosity

density

pressure

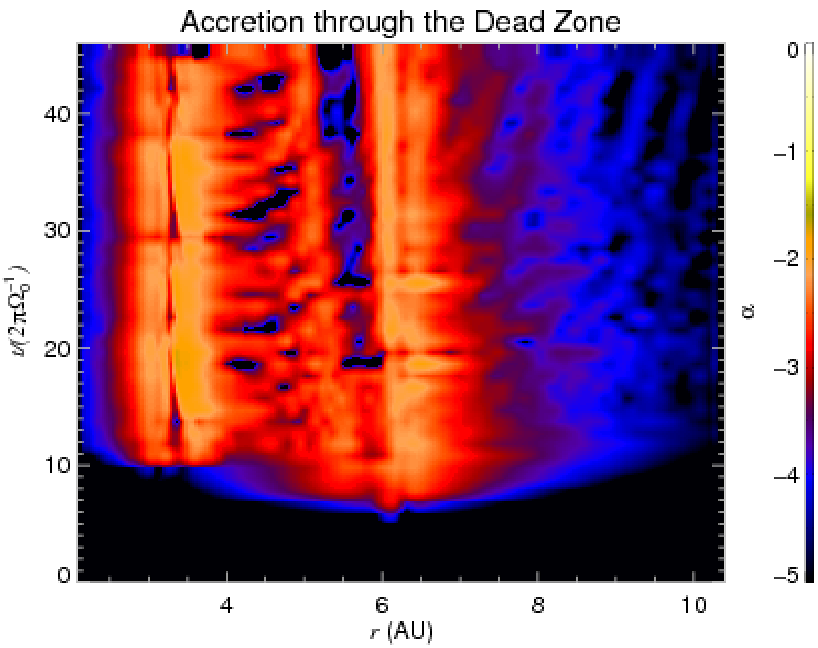
temperature

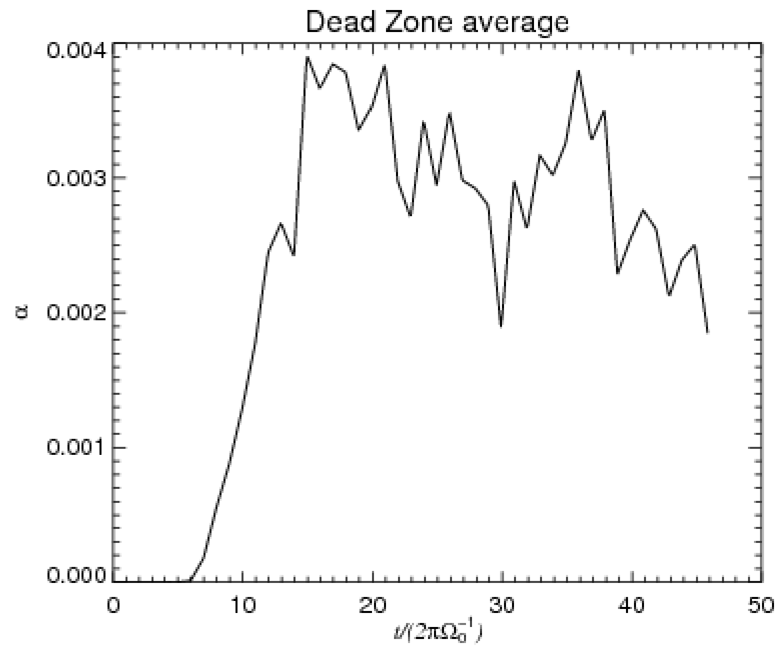
Solberg-Hoiland criterion



Accretion through the dead zone

The Rossby waves carry angular momentum...





... and accrete through the Dead Zone with alpha ~ 3e-3

Similar to the MRI itself!! (1e-2)

Does the RWI revive the Dead Zone?

Shall we speak of an "***Undead Zone***" instead?

Turbulence stresses transport angular momentum

Closure model of Shakura & Sunyaev (1973)

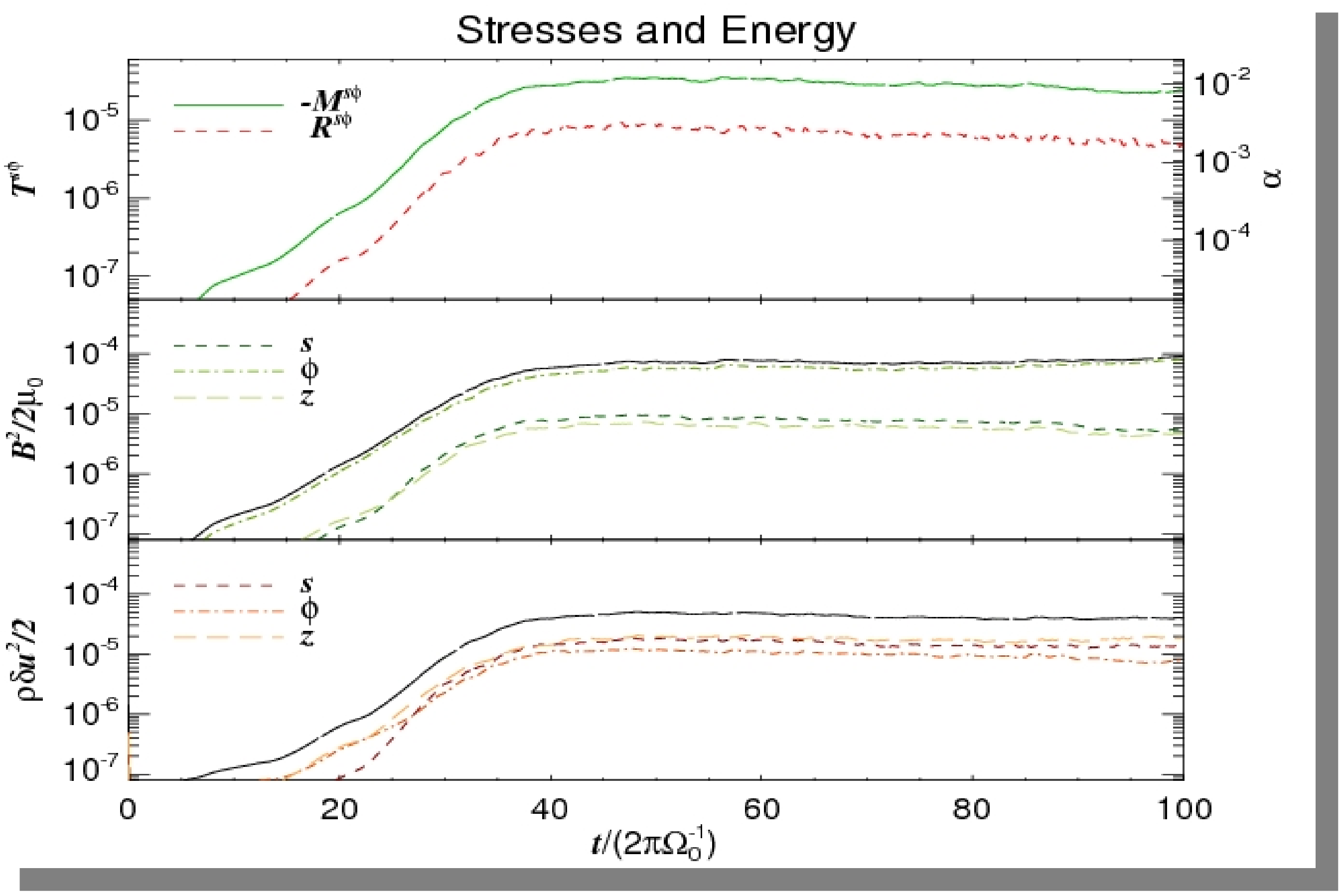
$$\partial_t \overline{L_\phi} + \nabla\cdot(\overline{L_\phi}\,\bar{\boldsymbol{u}}) = -\nabla\cdot(r\,T^{r\phi})$$ Reynolds Equation

$$\partial_t L_\phi + \nabla\cdot(L_\phi\,\boldsymbol{u}) = -\nabla\cdot(r^{-1} q\,\nu\,L_\phi)$$ Navier-Stokes Equation

$$L_\phi = \rho\,\Omega\,r^2$$

$$q = -\frac{d\ln\Omega}{d\ln r}$$

$$T^{r\phi} = q\,\alpha\,P \longrightarrow \nu = \alpha\,c_s^2\,\Omega^{-1}$$



α viscosity = 10^{-2}

Large scale B_ϕ field

Isotropic E_{kin}