Formation and Retention of Planets in Disks

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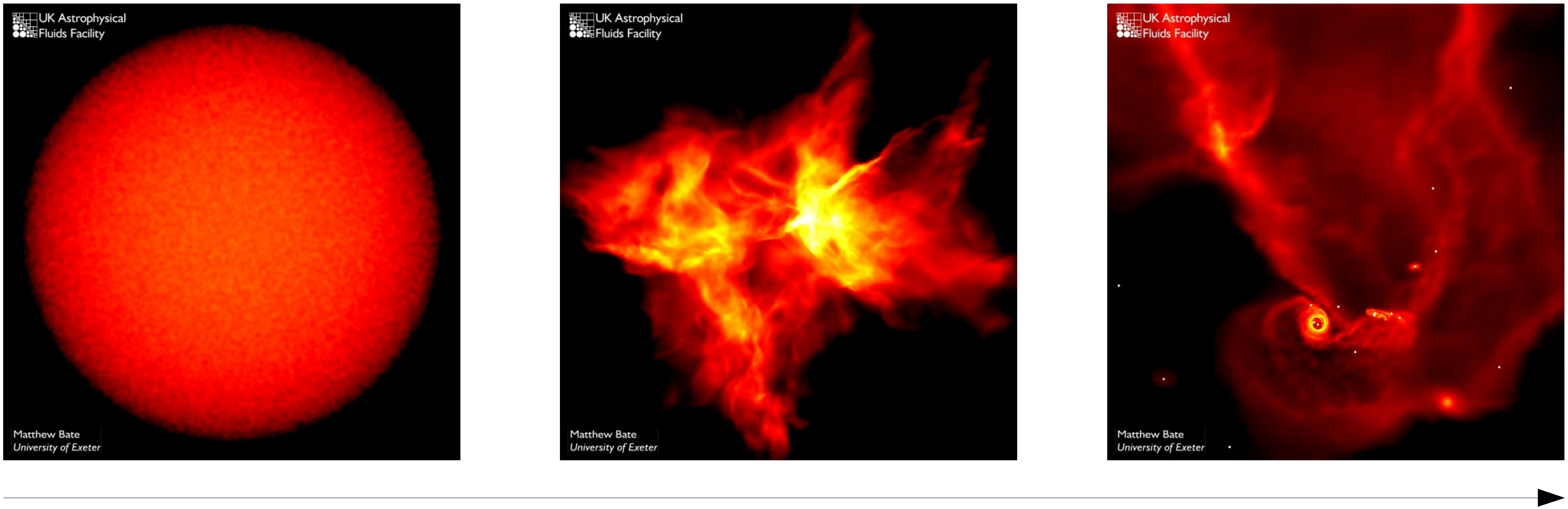
Star Formation – Bate, Bonnell & Bromm (2003)

Star Formation – Bate, Bonnell & Bromm (2003)



time

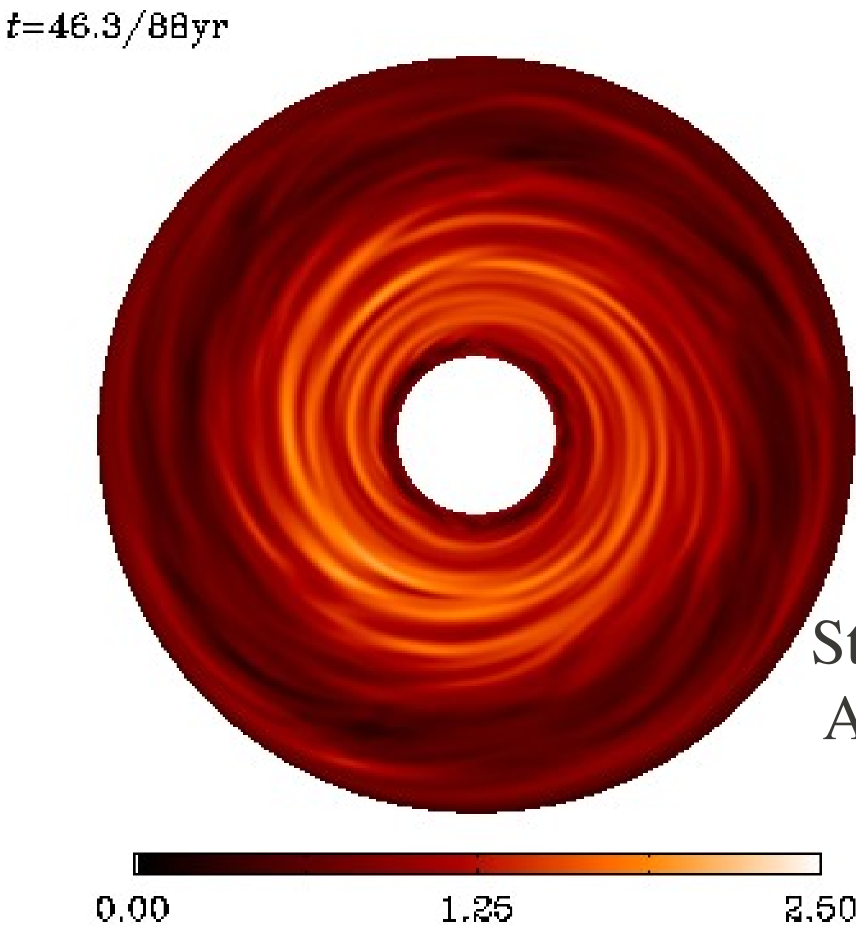
Some stars are seen to be born with lots of **surrounding gas.**

This gas is bound to the star and referred to as

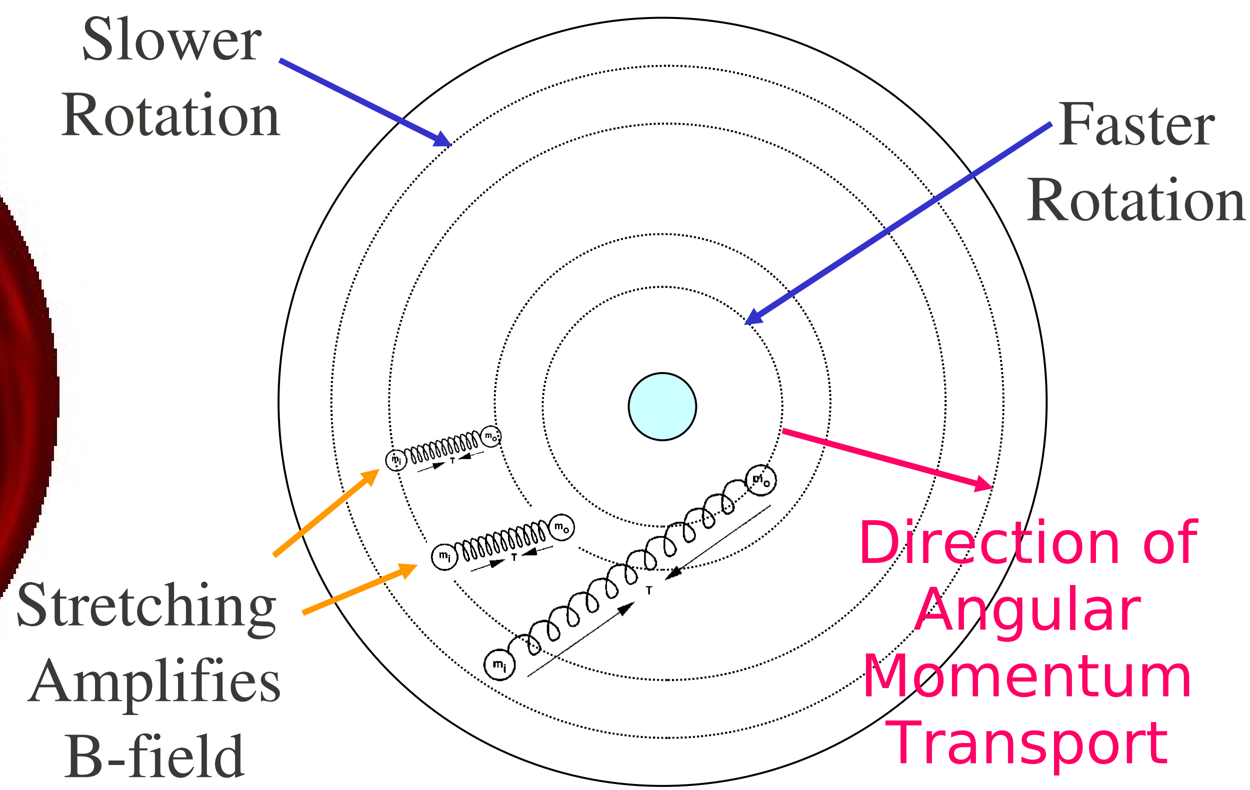
circumstellar disk or *protoplanetary disk.*

Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability



MRI sketch



Unstable if angular velocity decreases outward

Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
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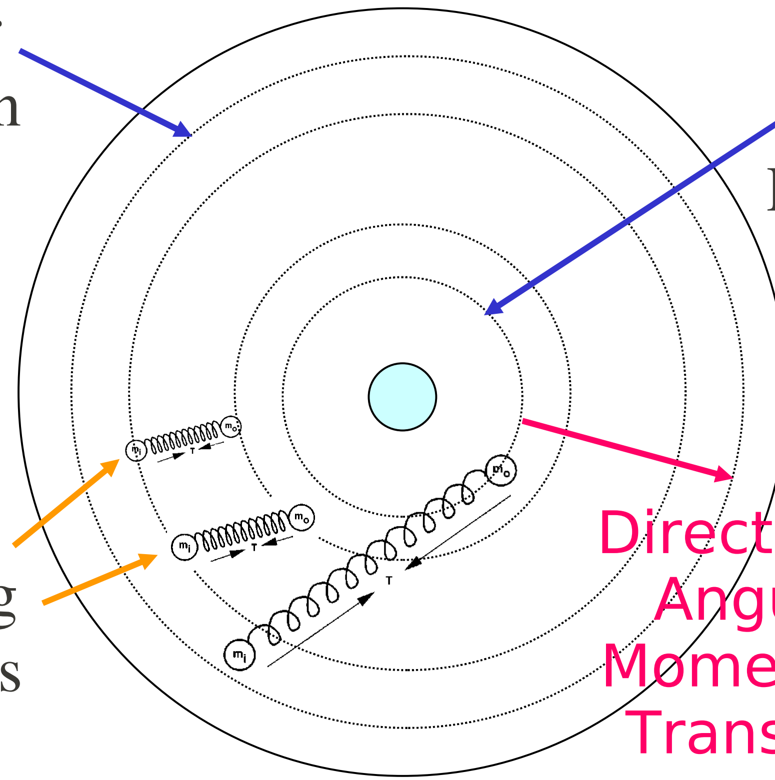
MRI sketch



Unstable if angular
velocity decreases
outward

Turbulence concentrates solids mechanically in pressure maxima

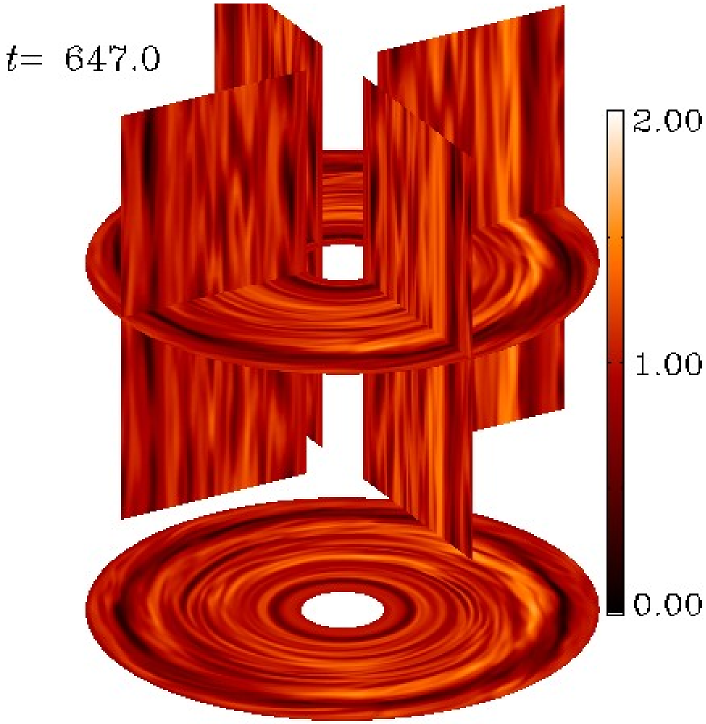
Gas $$\frac{D\boldsymbol{u}}{Dt} = -\nabla\Phi - \rho^{-1}\nabla p$$

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

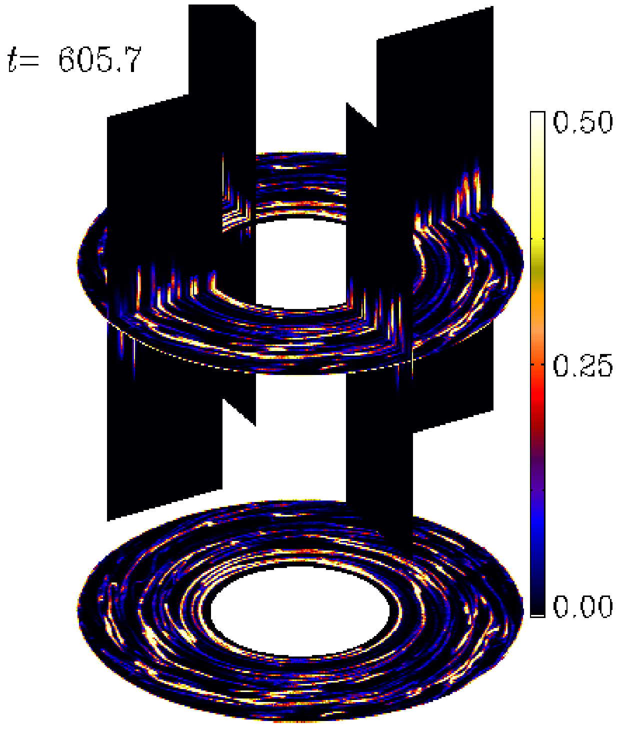
$$\boldsymbol{w} = \boldsymbol{u} + \tau\rho^{-1}\nabla p$$

The drag force pushes the solids *towards* the pressure gradient

Gas



Solids



Intense Clumping!!

Source: Lyra et al. (2008a)

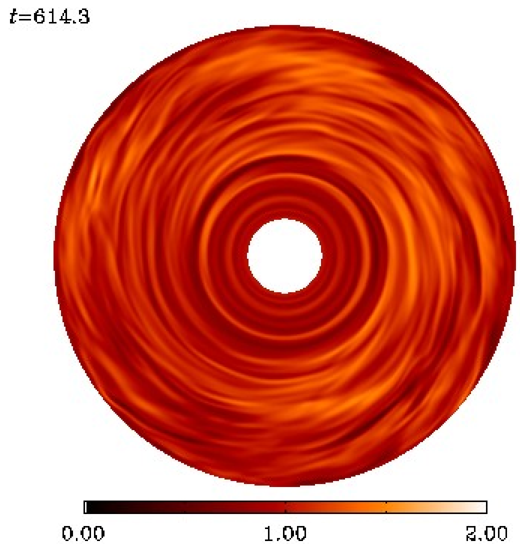
Solids particles

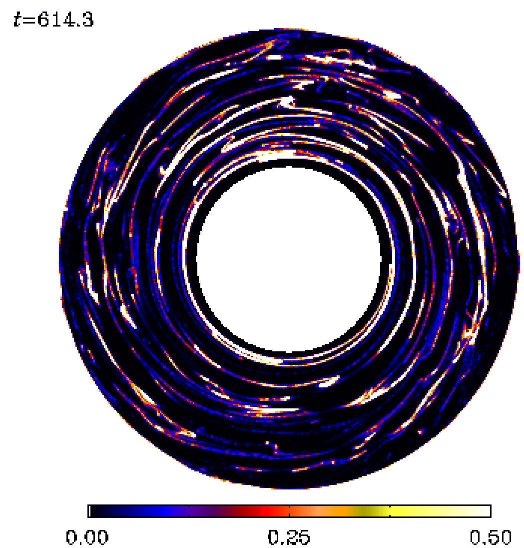
move <u>**toward**</u>

pressure maxima

Turbulence concentrates solids mechanically in pressure maxima

Solids in a turbulent disk





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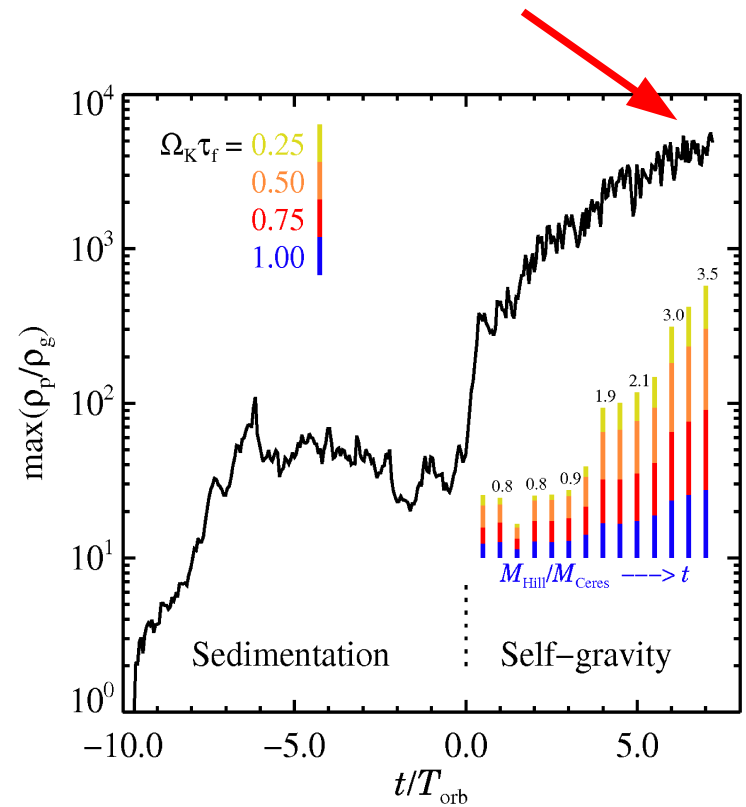
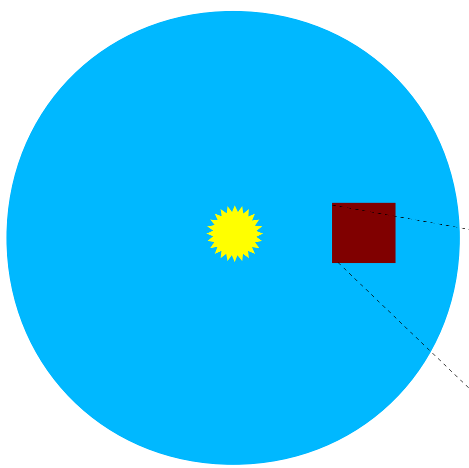
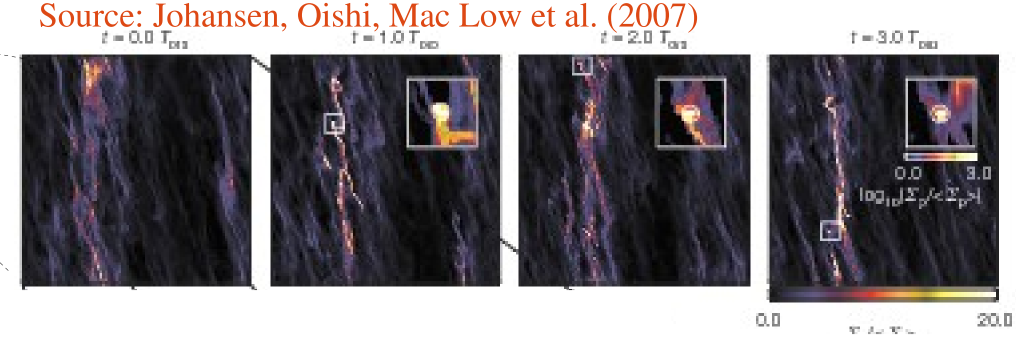
3x Ceres mass!



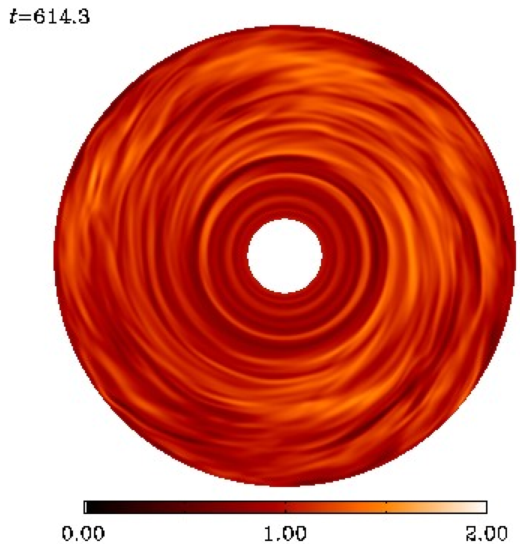
- -Turbulent eddies are very efficient particle traps
- -Correlation between gas and solids density maxima
- - Critical density for gravitational collapse of clumps



Source: Johansen, Oishi, Mac Low et al. (2007)



Solids in a turbulent disk



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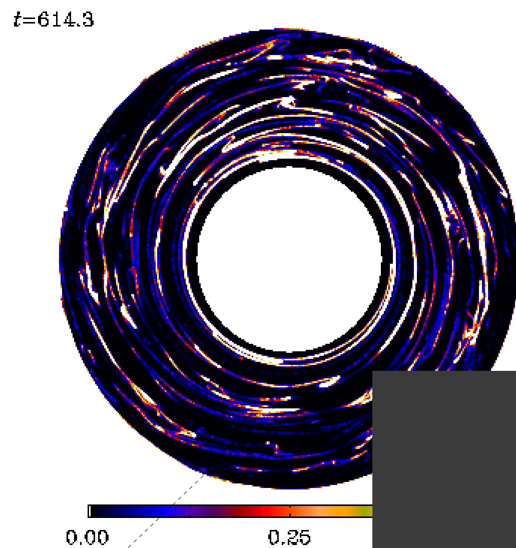

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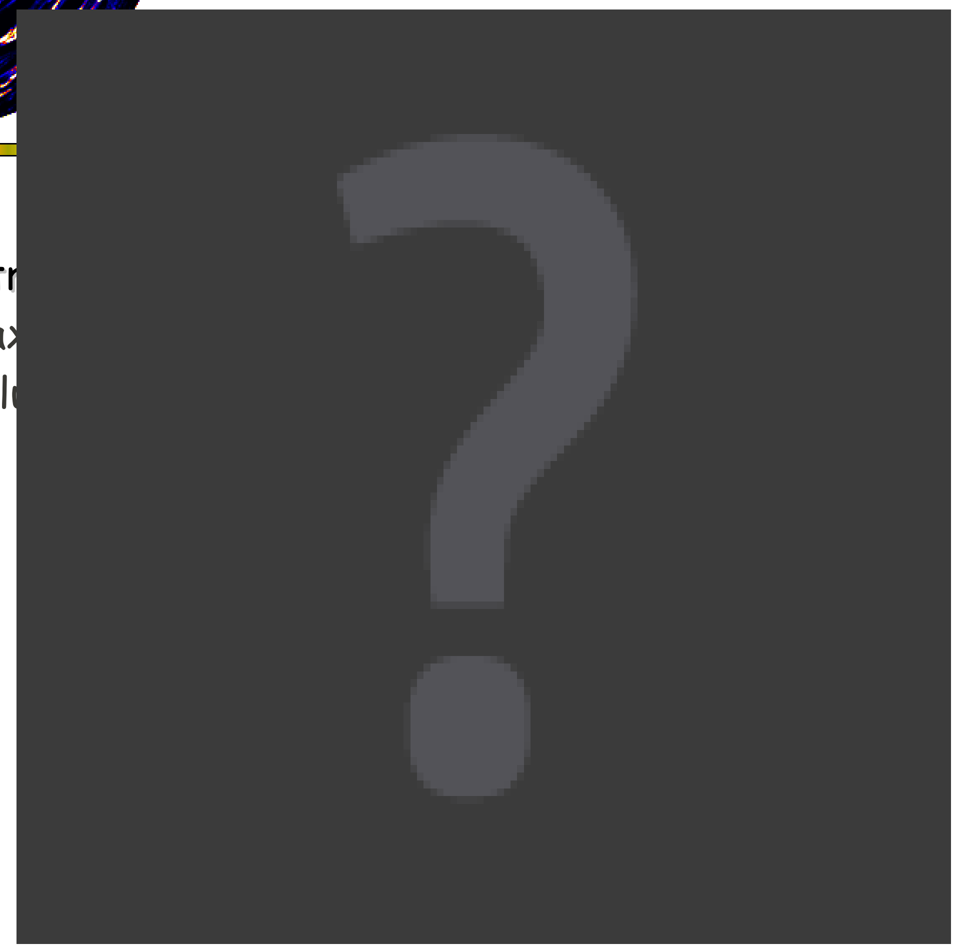

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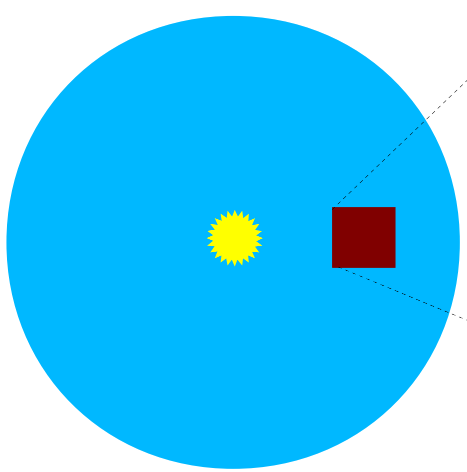
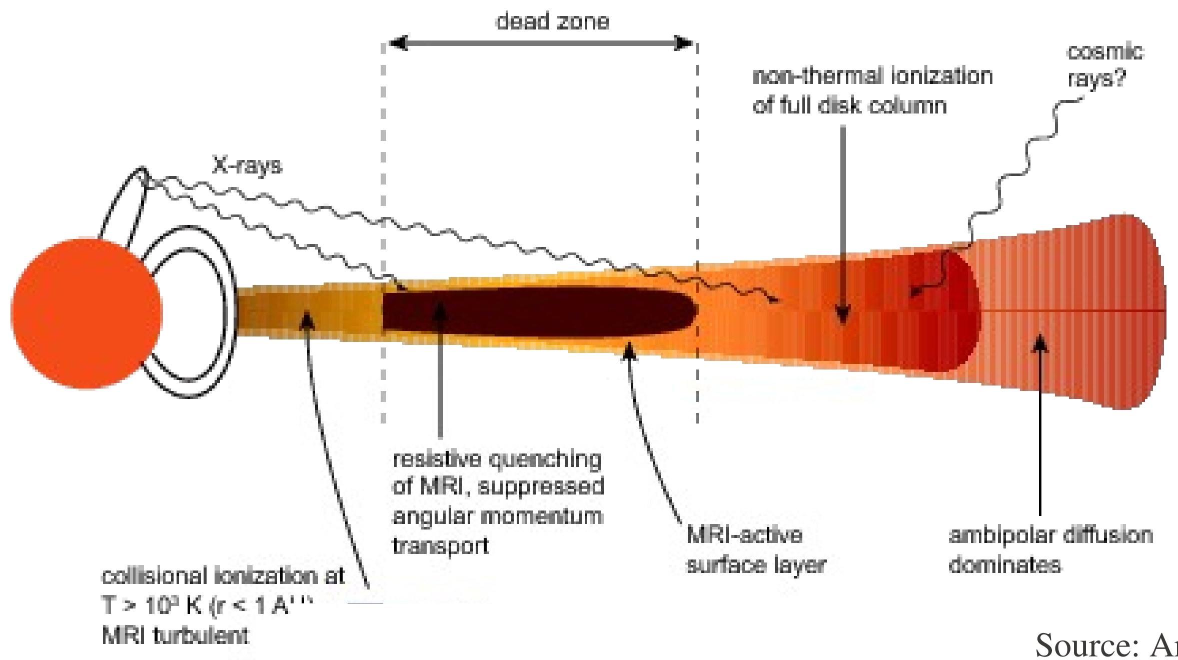


Alas... Dead zones are robust features of accretion disks

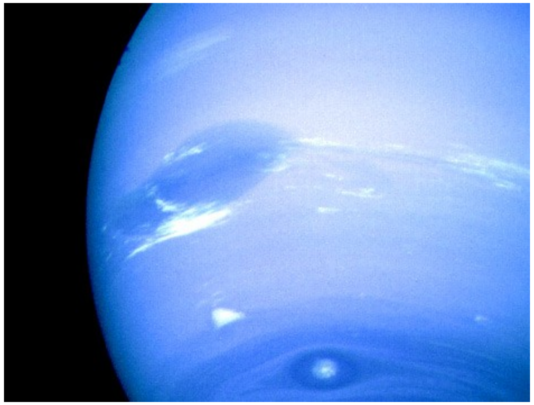


Source: Armitage (2010)

Therefore....

The search for **hydrodynamical routes**
for turbulence **continues**.

A possibility: Baroclinic Instability



- Well known in planetary atmospheres

And vortices are:

- A solution of the NS equations: persistent structures
- Very interesting for planet formation:

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TURBULENCE IN ACCRETION DISKS: VORTICITY GENERATION AND ANGULAR MOMENTUM TRANSPORT VIA THE GLOBAL BAROCLINIC INSTABILITY

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UCO/Lick Observatory, University of California, S
Received 2000 June 7; accepted 2002 Sep

Klahr & Bodenheimer (2003)

Klahr (2004)

THE ASTROPHYSICAL JOURNAL, 606:1070–1082, 2004 May 10
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THE GLOBAL BAROCLINIC INSTABILITY IN ACCRETION DISKS. II. LOCAL LINEAR ANALYSIS

Petersen et al. (2007a)

THE ASTROPHYSICAL JOURNAL, 658:1236–1251, 2007 April 1
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BAROCLINIC VORTICITY PRODUCTION IN PROTOPLANETARY DISKS. I. VORTEX FORMATION

Petersen et al. (2007b)

THE ASTROPHYSICAL JOURNAL, 658:1252–1263, 2007 April 1
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BAROCLINIC VORTICITY PRODUCTION IN PROTOPLANETARY DISKS. II. VORTEX GROWTH AND LONGEVITY

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The subcritical baroclinic instability in local accretion disc models

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Received date / Accepted 13 January 2010

Lesur & Papaloizou (2010)

Lyra & Klahr (2011)

A&A 527, A138 (2011)
DOI: 10.1051/0004-6361/201015568
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Astronomy & Astrophysics

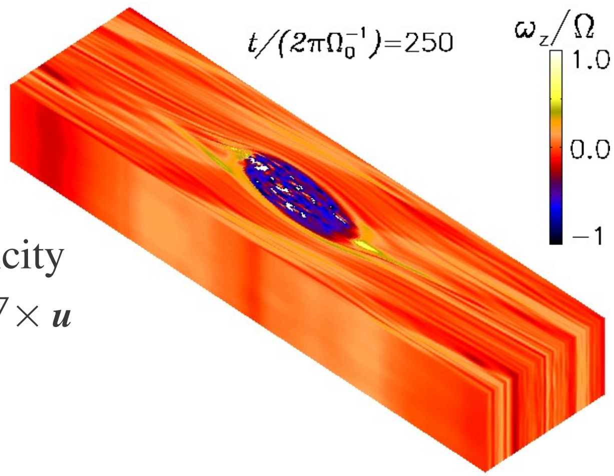
The baroclinic instability in the context of layered accretion

Self-sustained vortices and their magnetic stability in local compressible unstratified models of protoplanetary disks

W. Lyra[1,2] and H. Klahr[1]

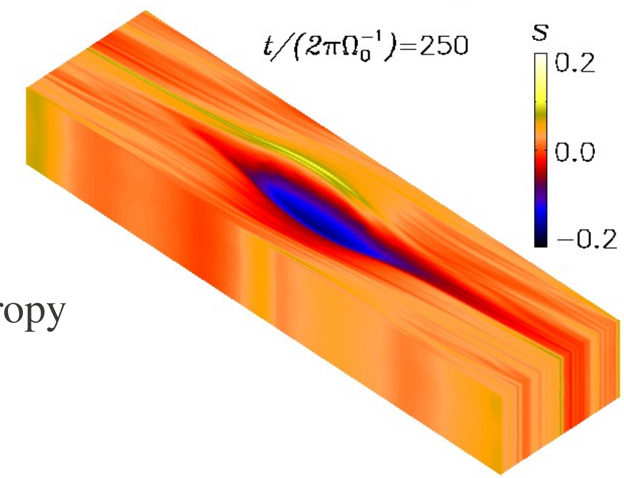
Baroclinic Instability – Excitation and self-sustenance of vortices

Baroclinic Instability – Excitation and self-sustenance of vortices



Vorticity

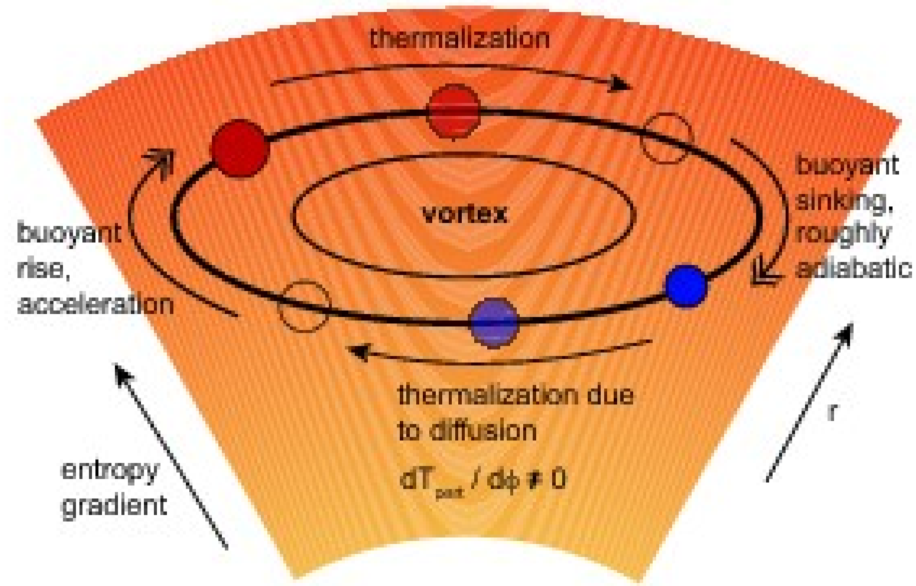
$\boldsymbol{\omega} = \nabla \times \boldsymbol{u}$



Entropy

Source: Lyra & Klahr (2010)

Sketch of the Baroclinic Instability



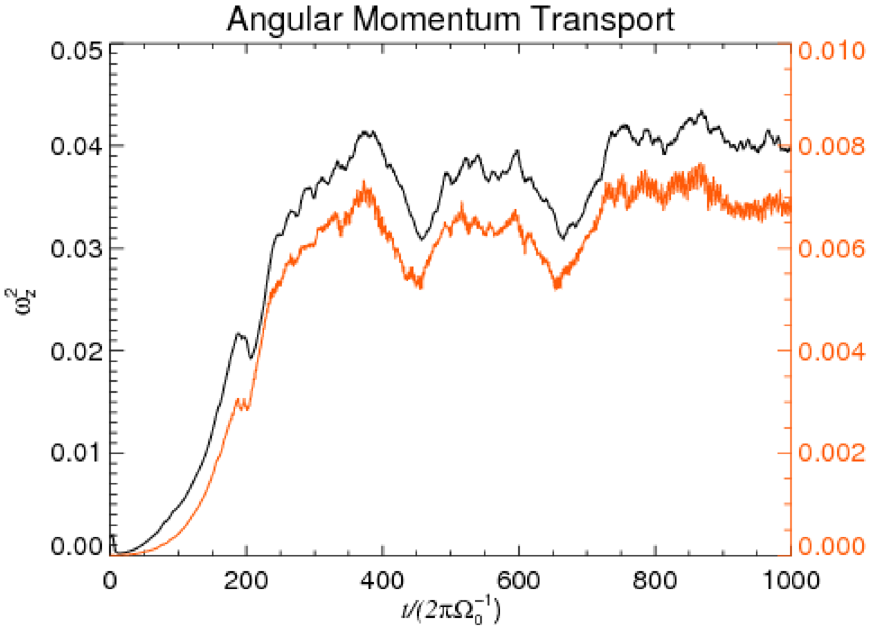
Source: Armitage (2010)

$$\frac{\partial \boldsymbol{\omega}}{\partial t} = -(\boldsymbol{u}\cdot\nabla)\boldsymbol{\omega} - \boldsymbol{\omega}(\nabla\cdot\boldsymbol{u}) + (\boldsymbol{\omega}\cdot\nabla)\boldsymbol{u} + \frac{1}{\rho^2}\nabla\rho\times\nabla p + \nu\nabla^2\boldsymbol{\omega}$$

advection — **compression** — **stretching** — **baroclinicity** — **dissipation**

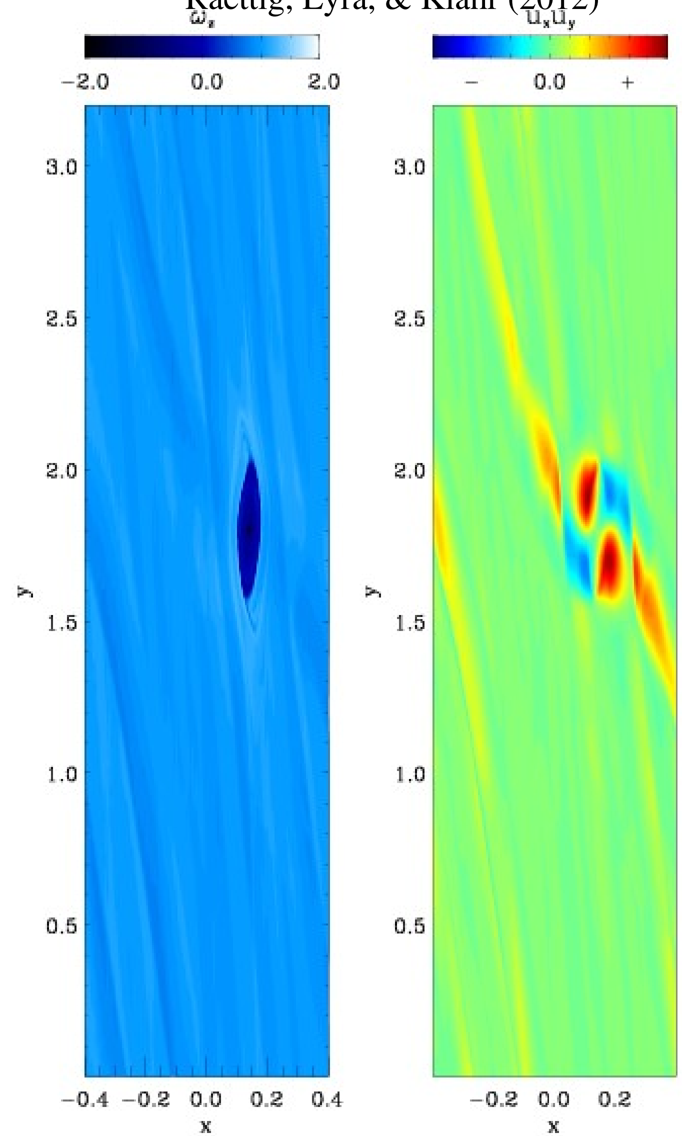
Baroclinic Instability and Accretion

Large mass accretion rates, comparable to the MRI!



Lyra & Klahr (2011)

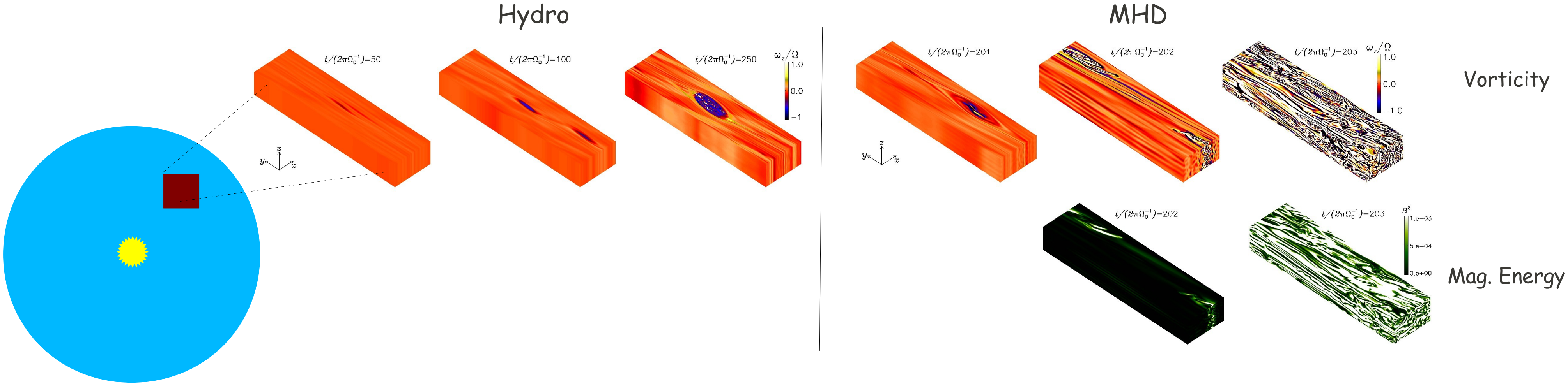
Raettig, Lyra, & Klahr (2012)



The angular momentum is carried by ***waves*** excited by the vortex

Interaction of Baroclinic and Magneto-Rotational Instabilities

What happens when the vortex is magnetized?



Vortex gone!

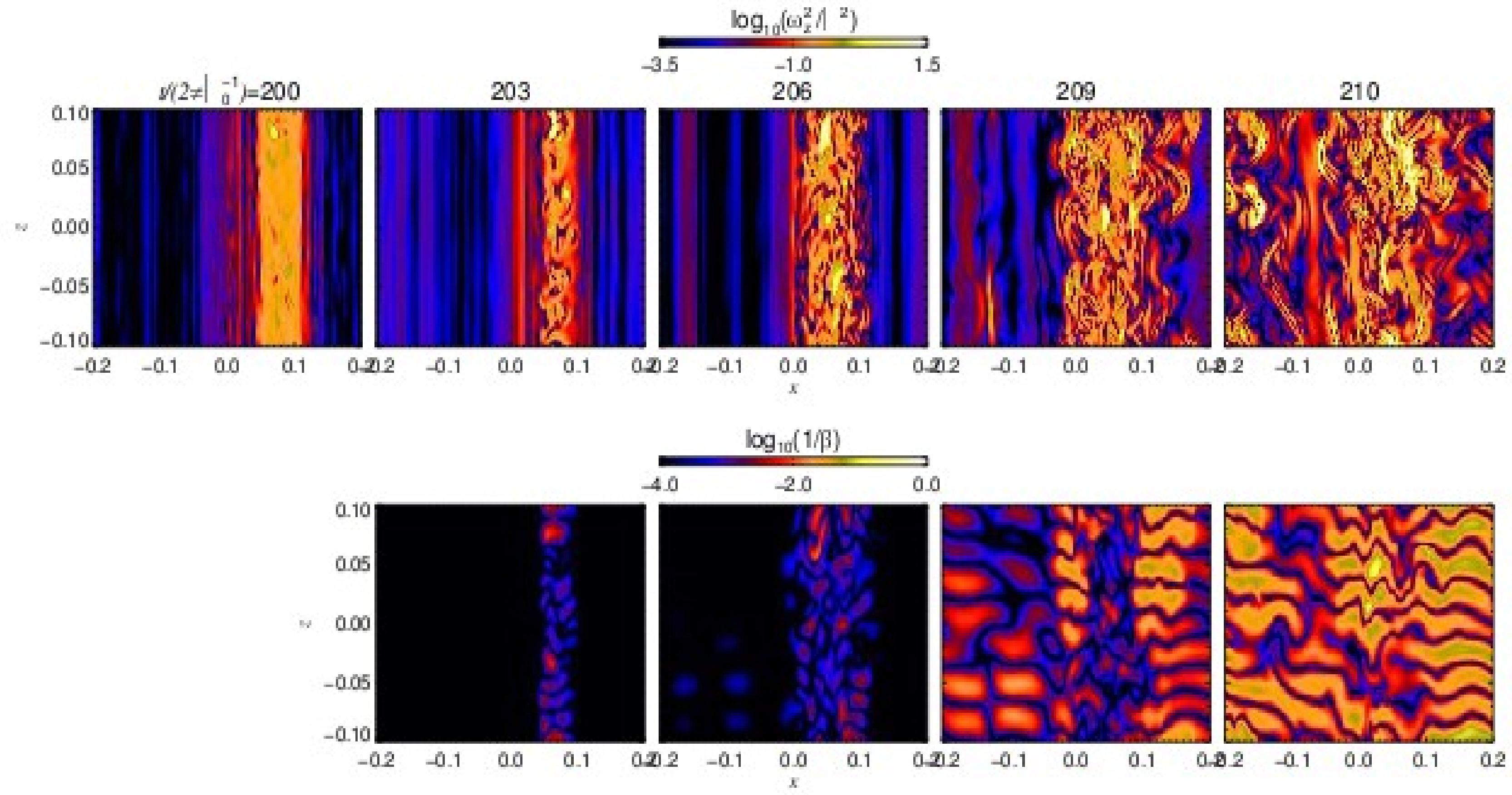
Lyra & Klahr (2011)

Interaction of Baroclinic and Magneto-Rotational Instabilities

What happens when the vortex is magnetized?

Lyra & Klahr (2011)

Interaction of Baroclinic and Magneto-Rotational Instabilities

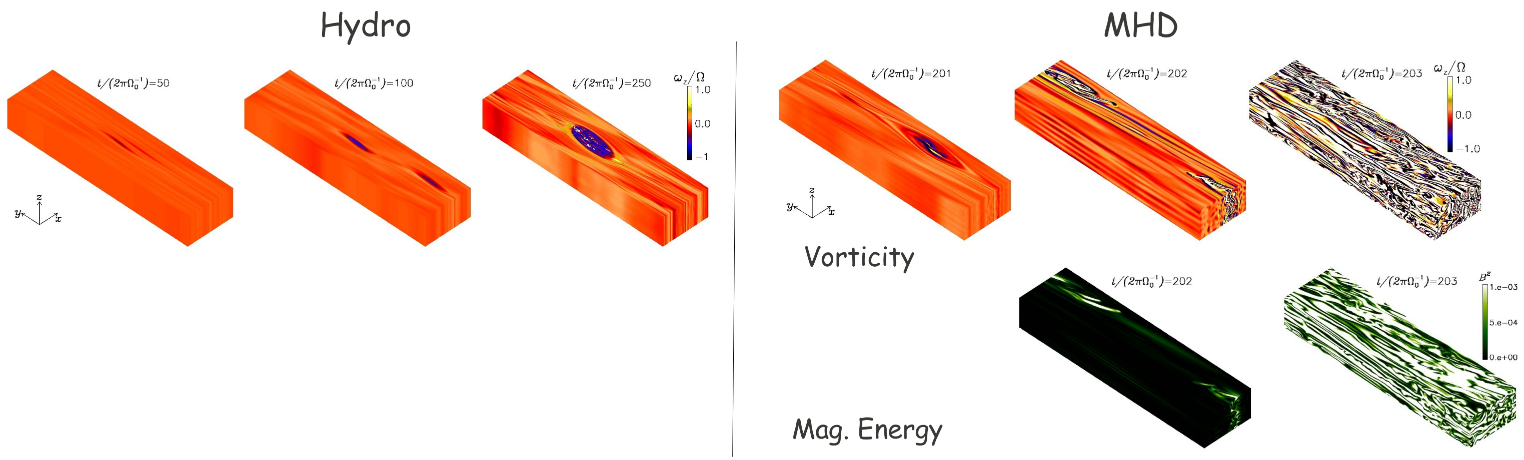


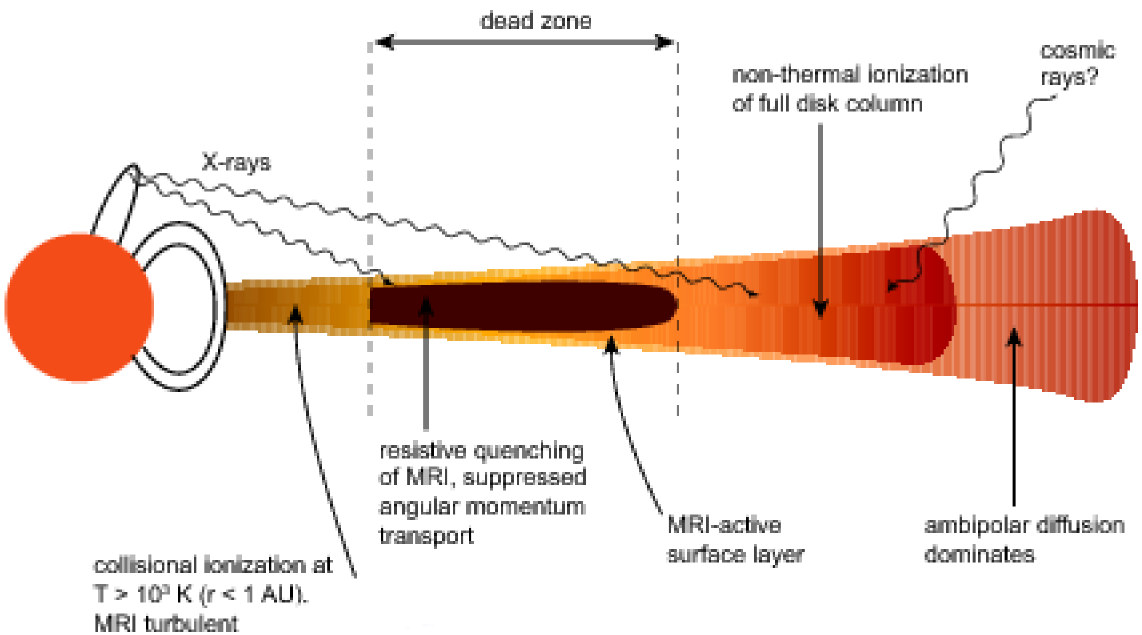
Enstrophy (Vorticity squared)

Mag. Energy

Vortices do not survive magnetization.
Restricted to dead zones.

Suggested large-scale phenomenology





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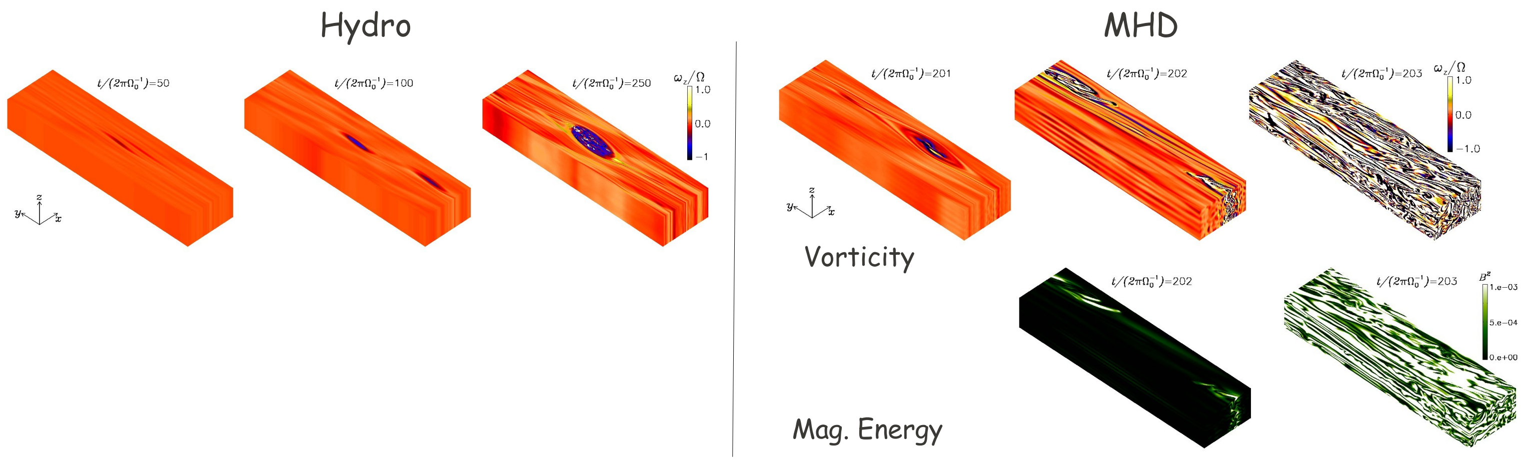
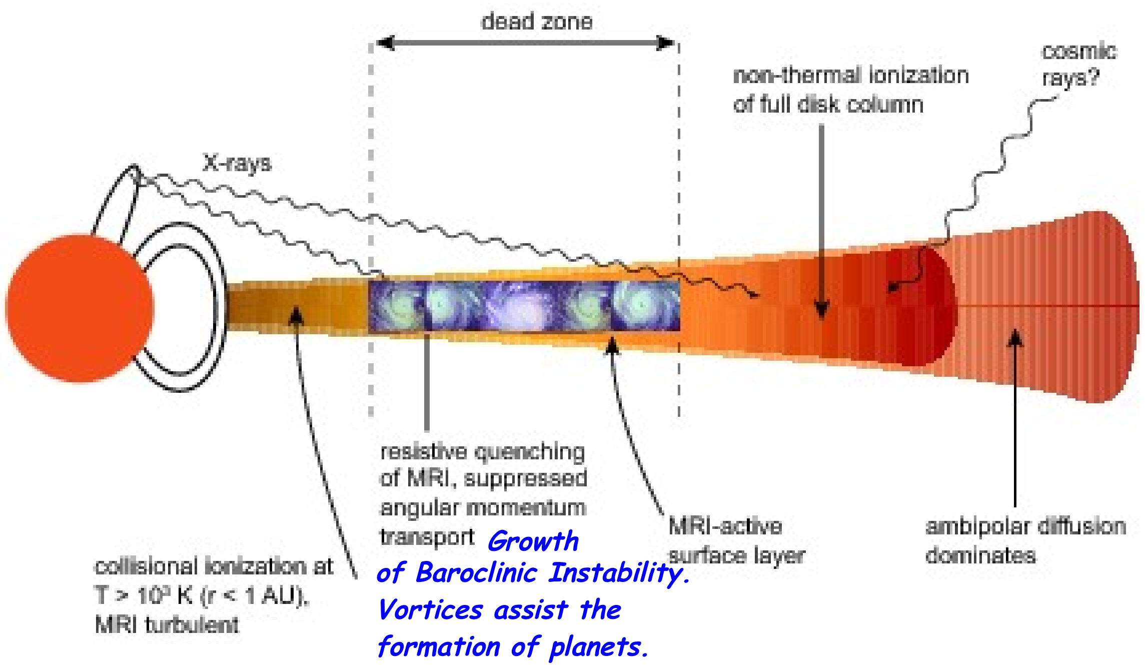
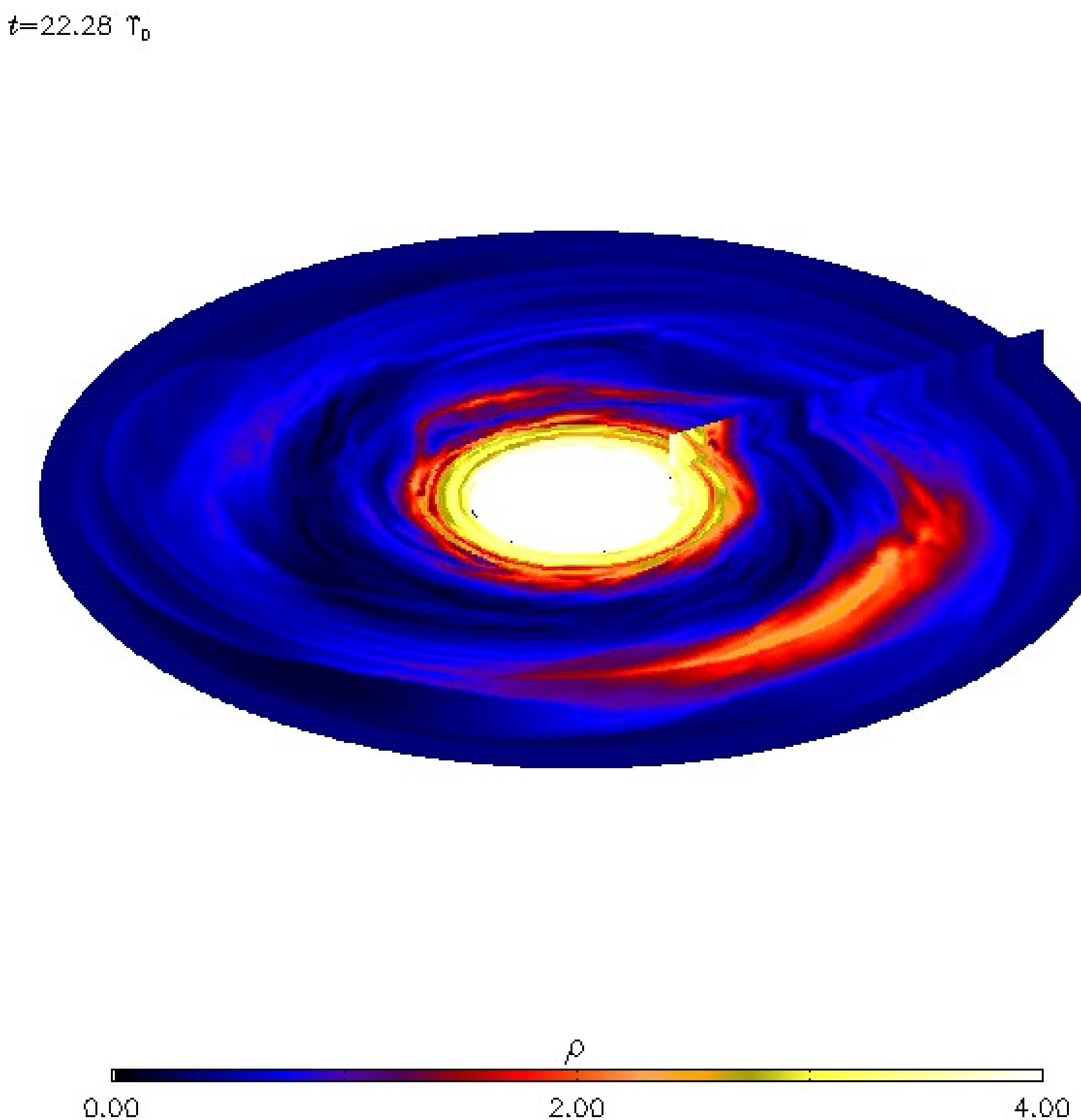
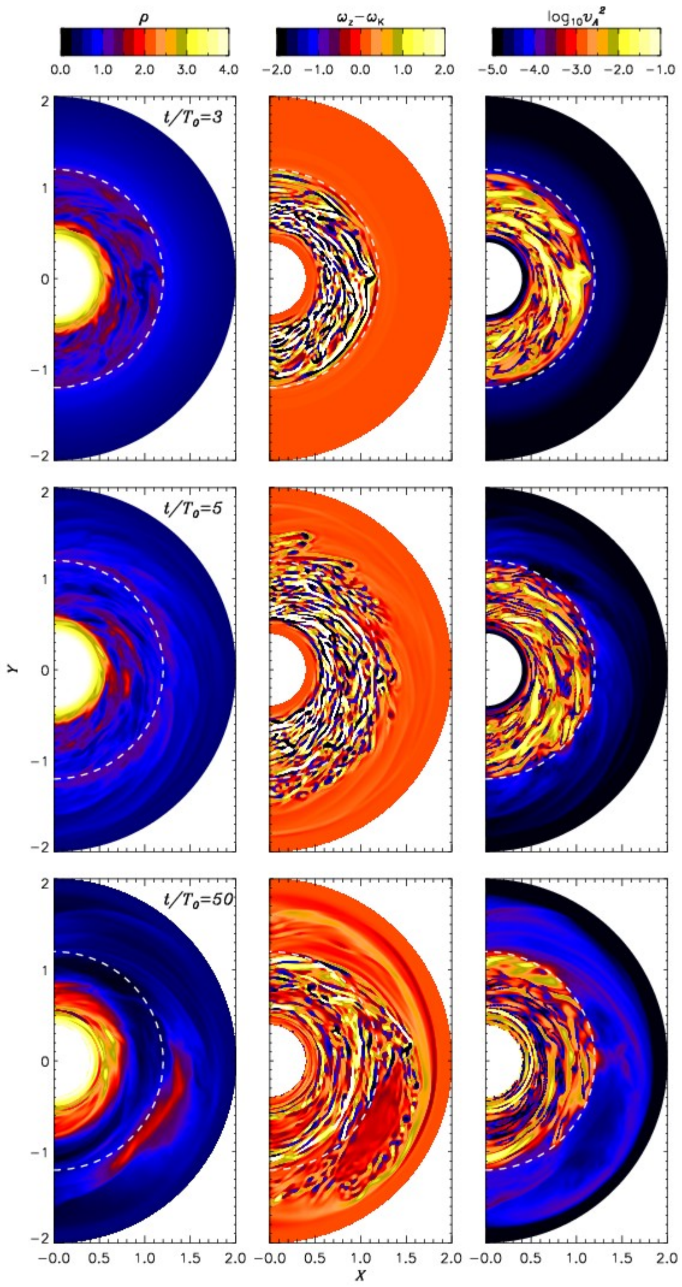




Active/dead zone boundary

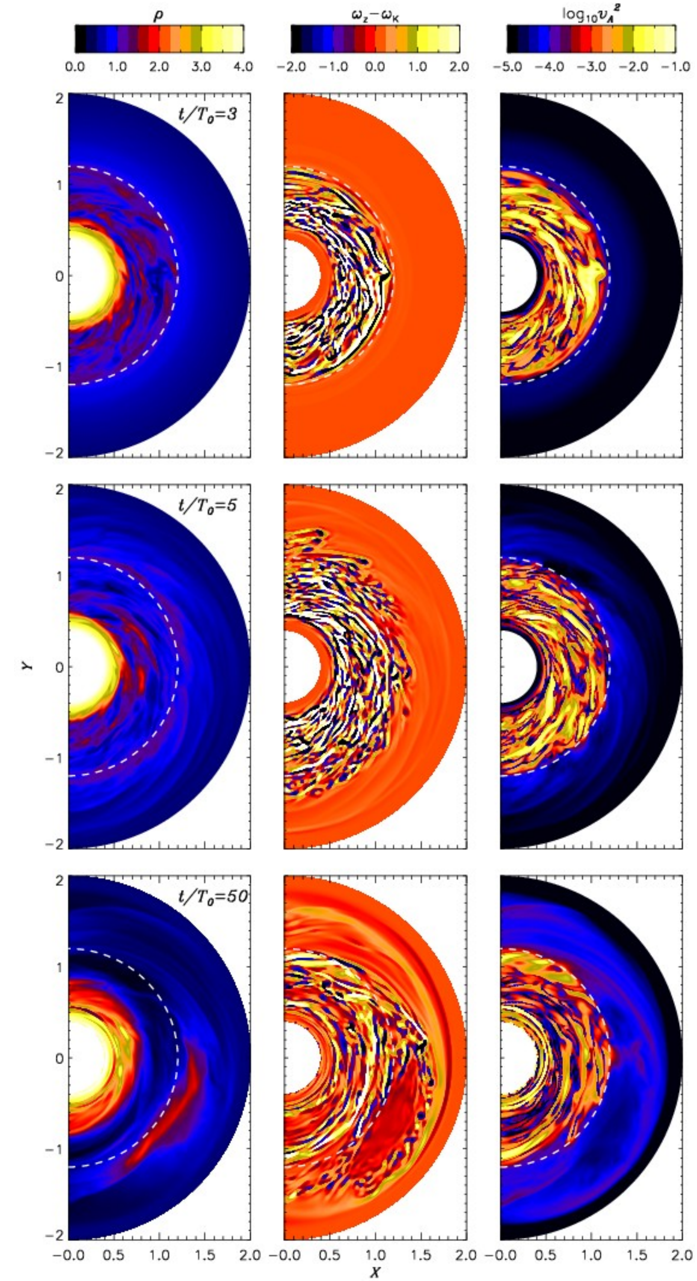




Magnetized inner disk + resistive outer disk

Lyra & Mac Low (submitted)

Active/dead zone boundary



Magnetized inner disk + resistive outer disk

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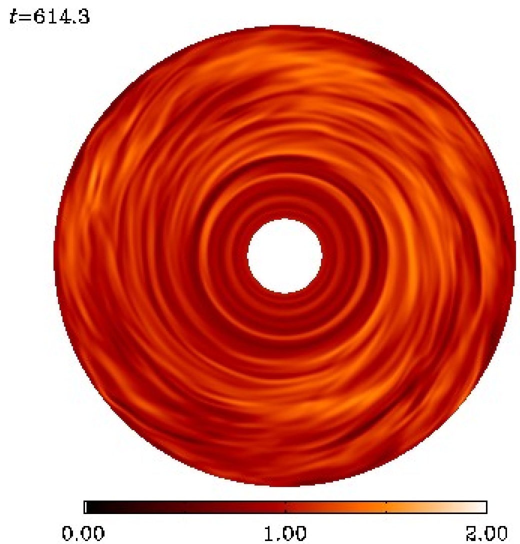
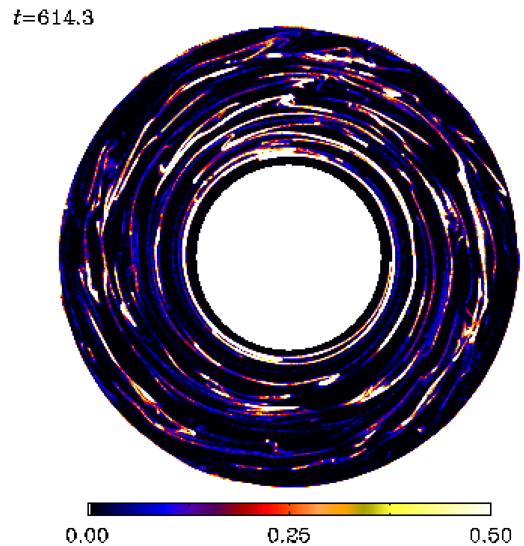
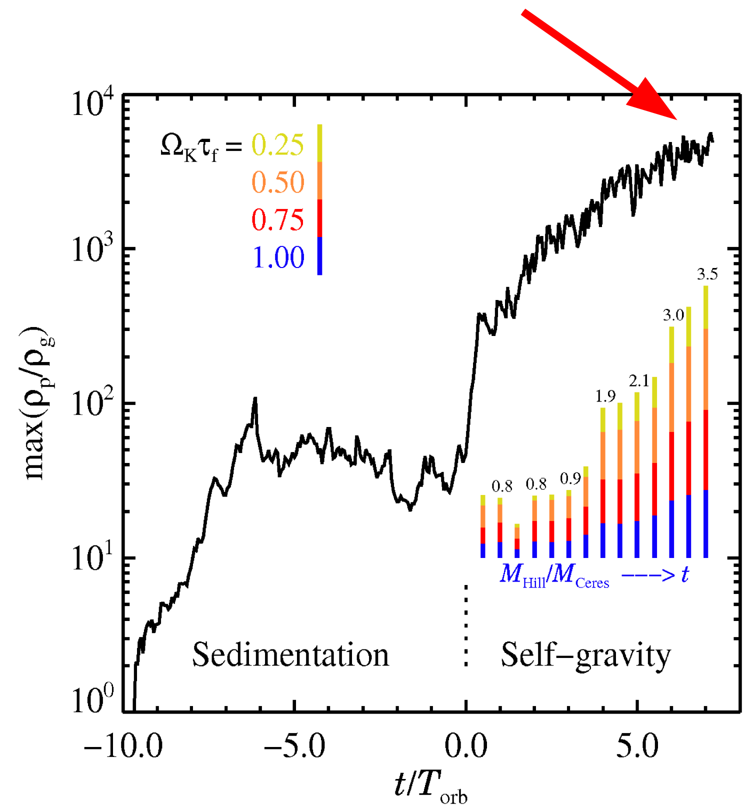
Forming planetesimals





Source: Lyra et al. (2008a)

3x Ceres mass!



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- Correlation between gas and solids density maxima
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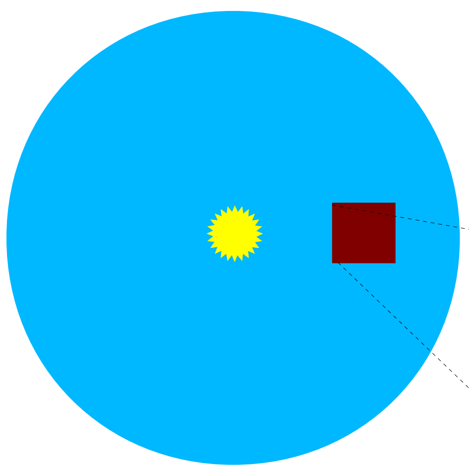

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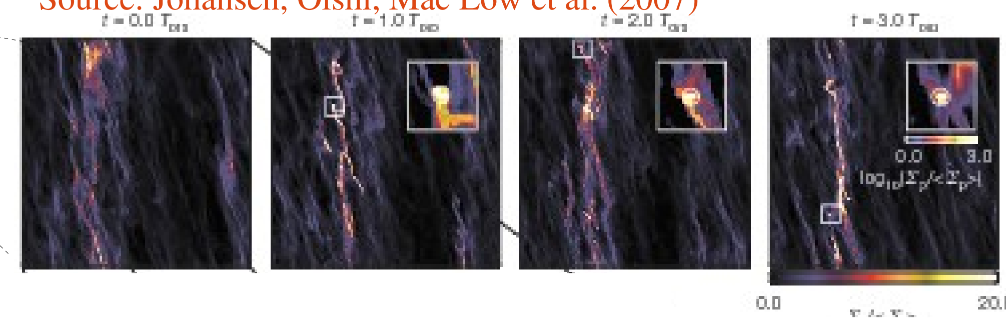
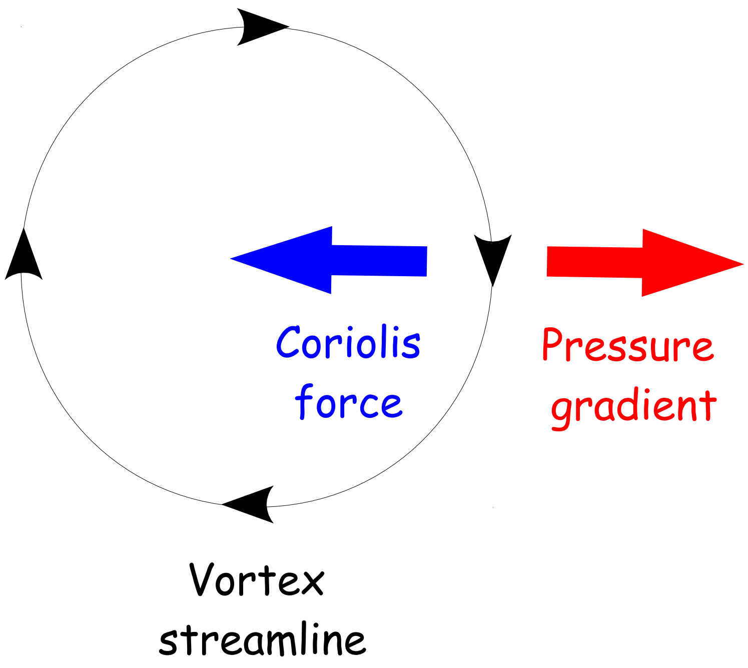


Eddies concentrate solids,
turning them into planetesimals...

...and vortices are **huge** eddies!

Vortex Equilibrium



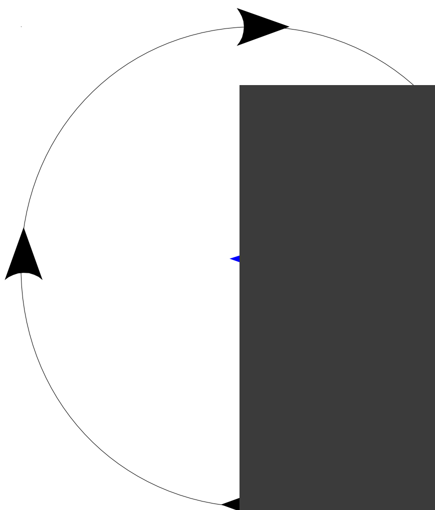
Geostrophic balance:

$$2\boldsymbol{\Omega}\times\boldsymbol{u}=-\rho^{-1}\nabla p$$

Particles do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation (von Weizsäcker, 1946)
Revisited by Barge & Sommeria (1995)
Raettig, Lyra, & Klahr (submitted)

Vortex Equilibrium



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$$- \rho^{-1} \nabla p$$

Vo

stre

ient.

Th ccumulate.

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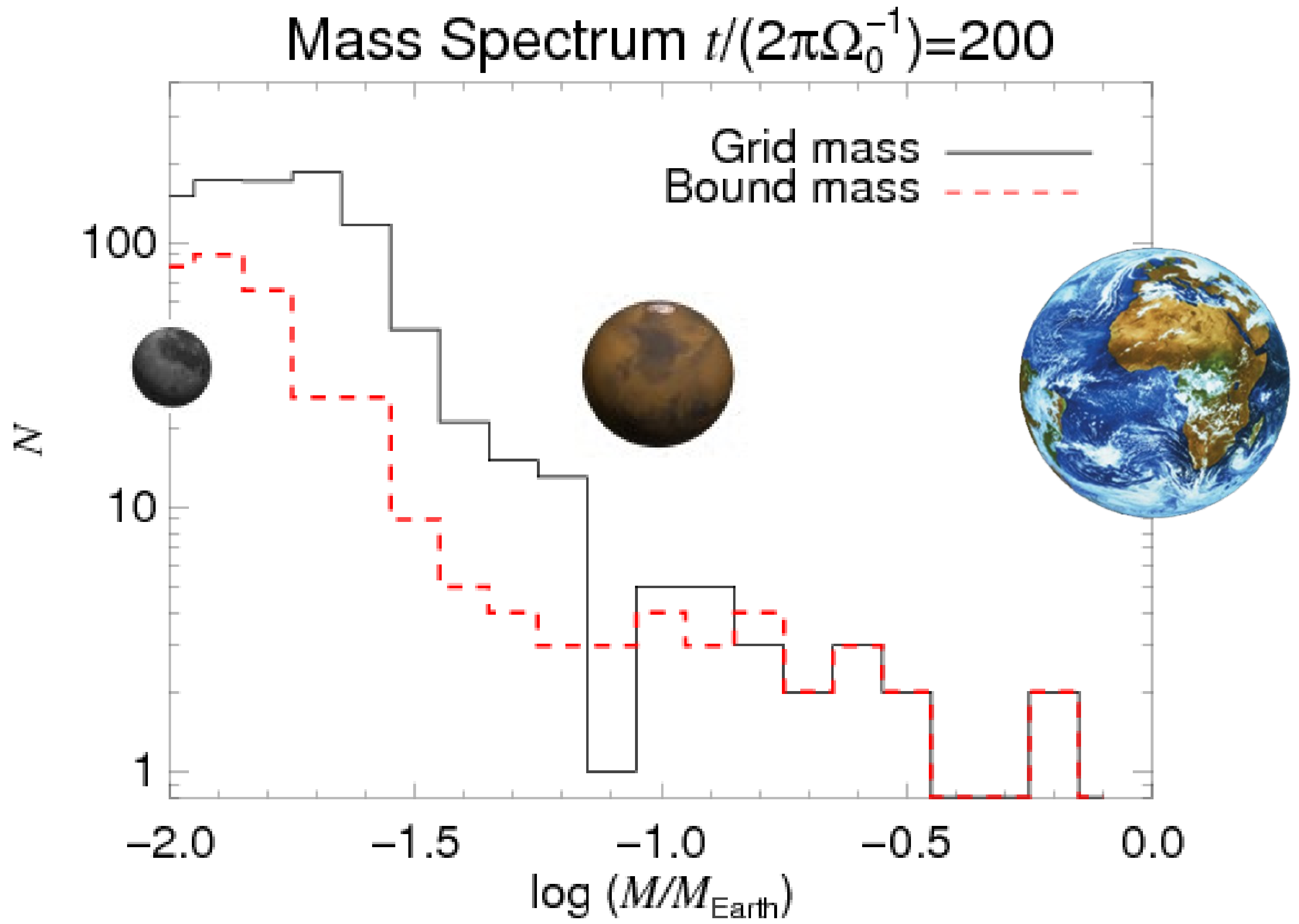
The Initial Mass Function of planets



•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

The Initial Mass Function of planets

•Mass spectrum by the end of the simulation

•300 bound clumps were formed

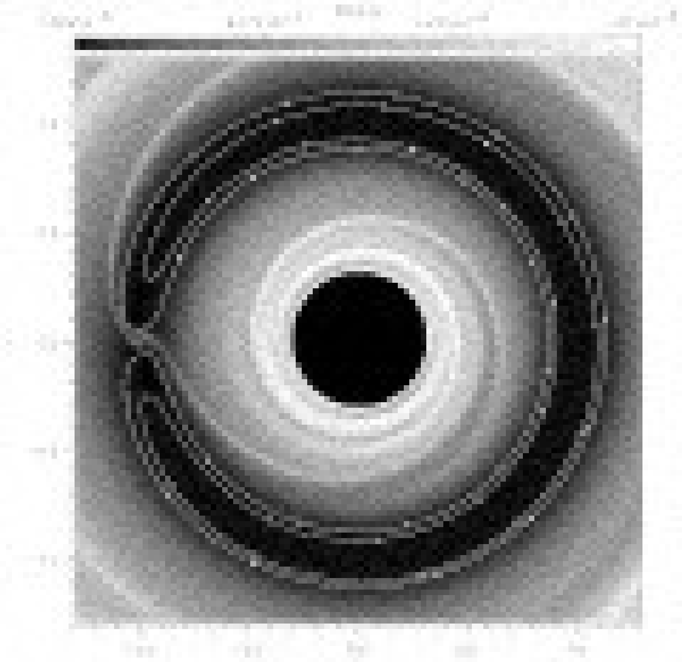
•Power law $d(\log N)/d(\log M)=-2.3 \pm 0.2$

•20 of these are more massive than Mars

Planets form and start to migrate

Planet-disk interaction leads to angular momentum exchange

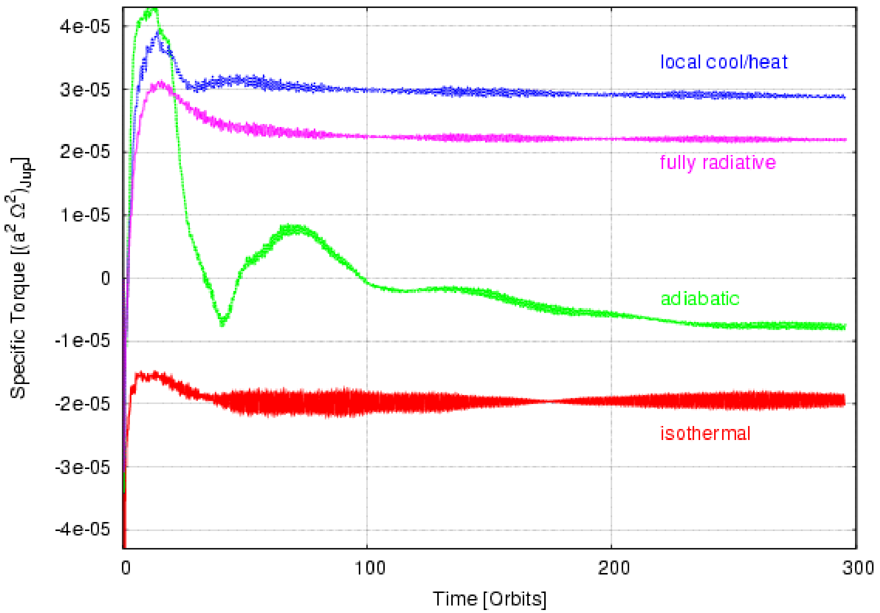
One armed spiral: Lindblad resonance
Horseshoe libration: Co-rotational torques



Source: Lubow et al. (1999)
Animations by Frederic Masset.

In isothermal disks,
the result is *inward migration*.

Planets form and start to migrate



Source: Kley & Crida (2008)

Paardekooper & Mellema (2006)

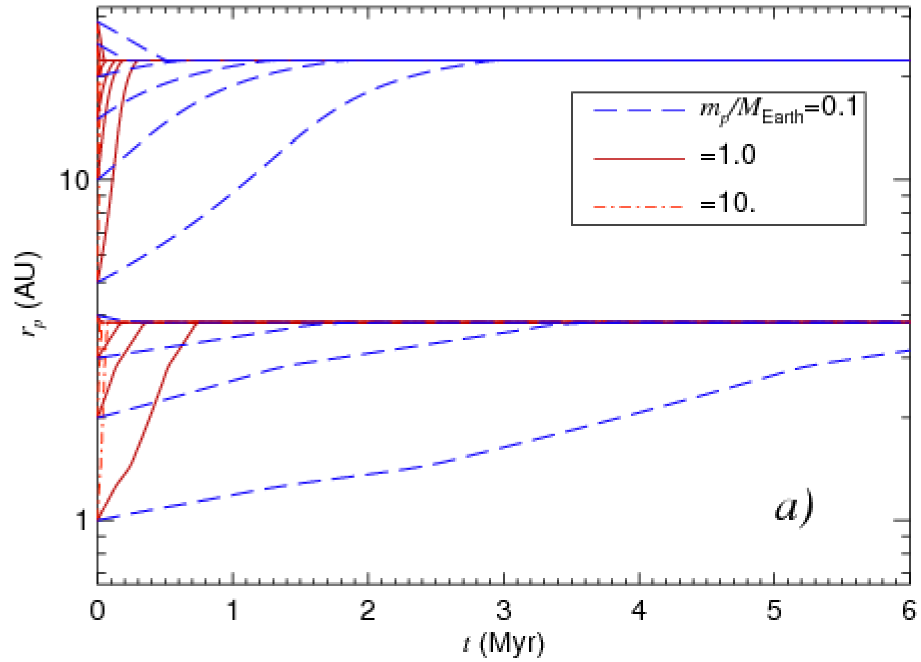
Non-isothermal
co-rotational torque may lead to outward migration

Hot topic!

Paardekooper & Mellema 2008
Baruteau & Masset 2008
Paardekooper & Papaloizou 2008
Kley & Crida 2009
Kley et al 2009
Paardekooper et al. 2010
Bitsh & Kley 2010
Lyra et al. 2010
Paardekooper et al. 2011
Ayliffe & Bate 2011
Yamada & Inaba 2011
Kley 2011

Planets form and start to migrate

Planet-disk interaction leads to **angular momentum exchange**

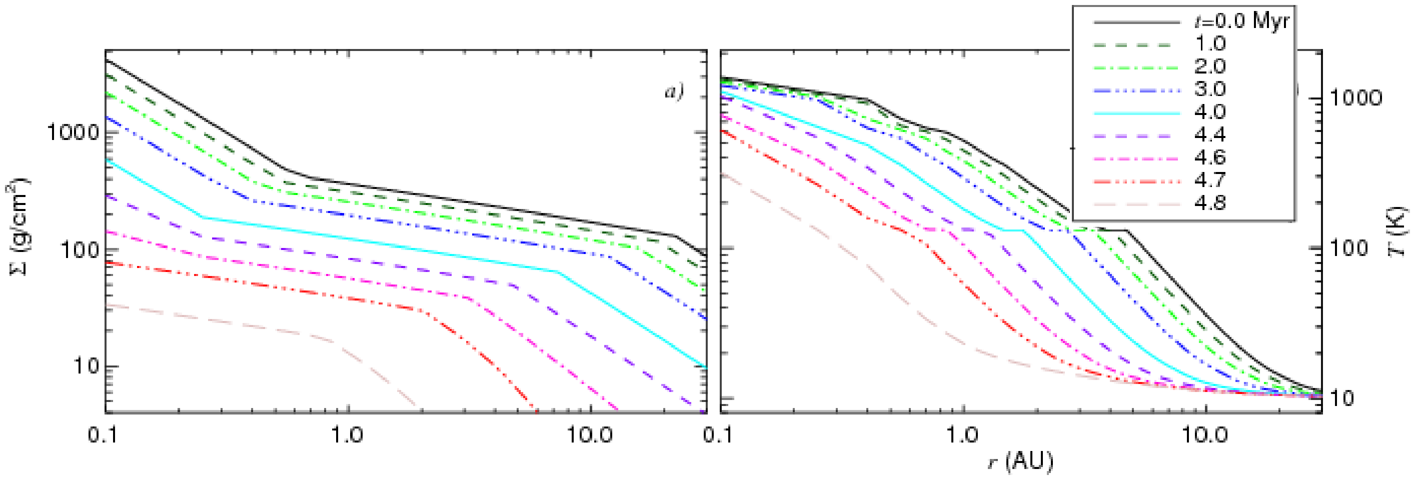


Source: Lyra, Paardekooper, & Mac Low (2010)

Planet traps where migration is convergent (τ=0, $d\tau/dr$ < 0).

Migration in Evolutionary Models

Disks evolve in time, due to
photoevaporative winds and viscous evolution



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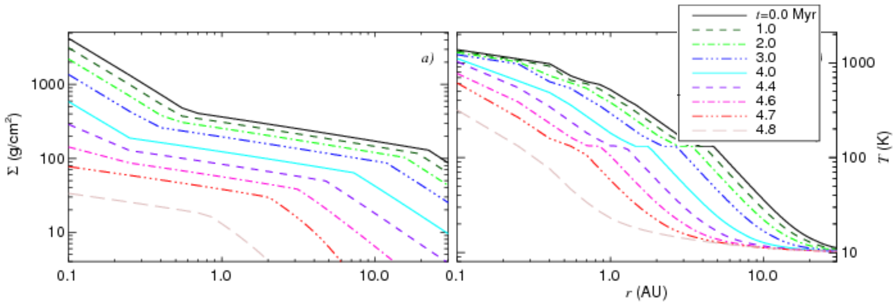


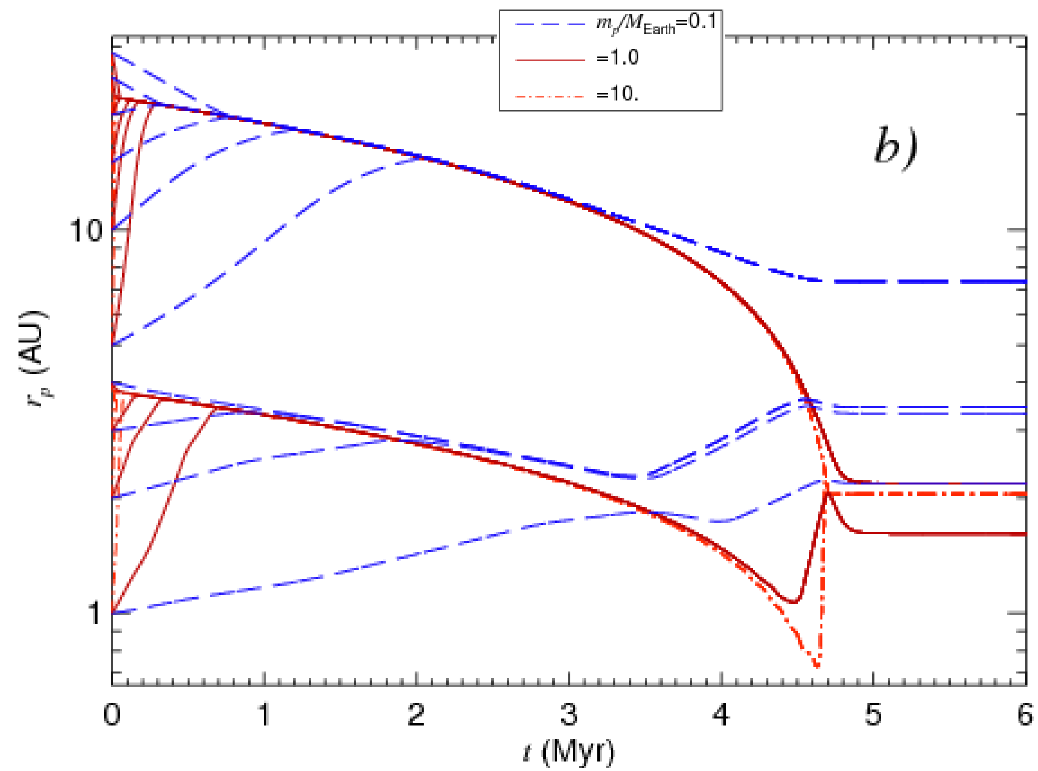
Rule of thumb: ***Migration is***

outwards in steep temperature gradients,

inwards in isothermal regions.

Single planets in a planetary trap evolve in lockstep with the gas at the accretion timescale.

At some point, the disk becomes **too thin** to drive accretion. The planet **decouples** and is **released** in a safe orbit.



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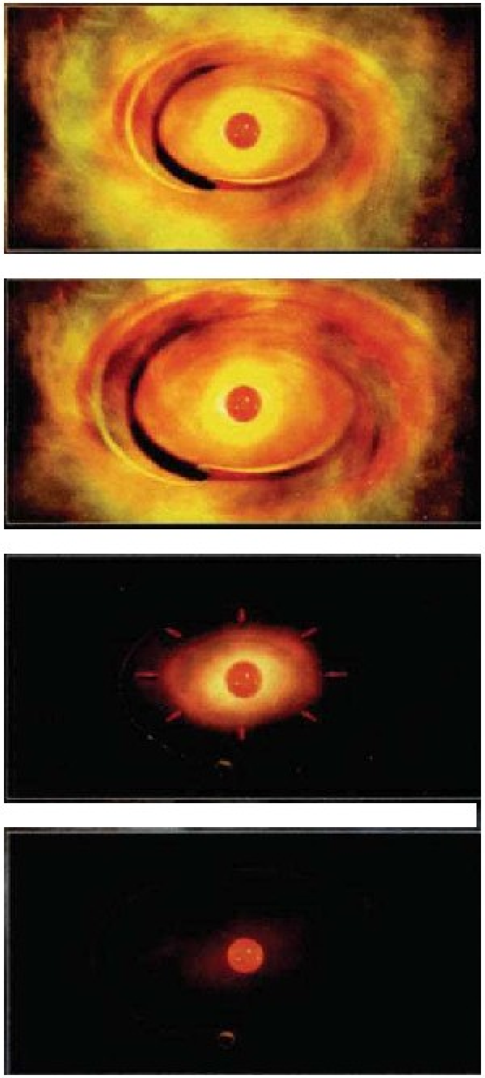

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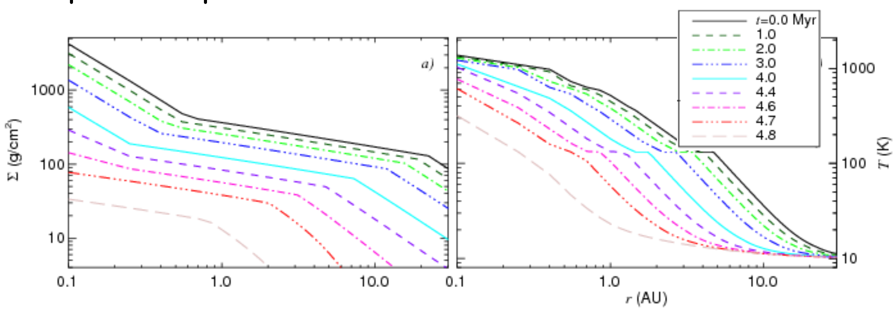

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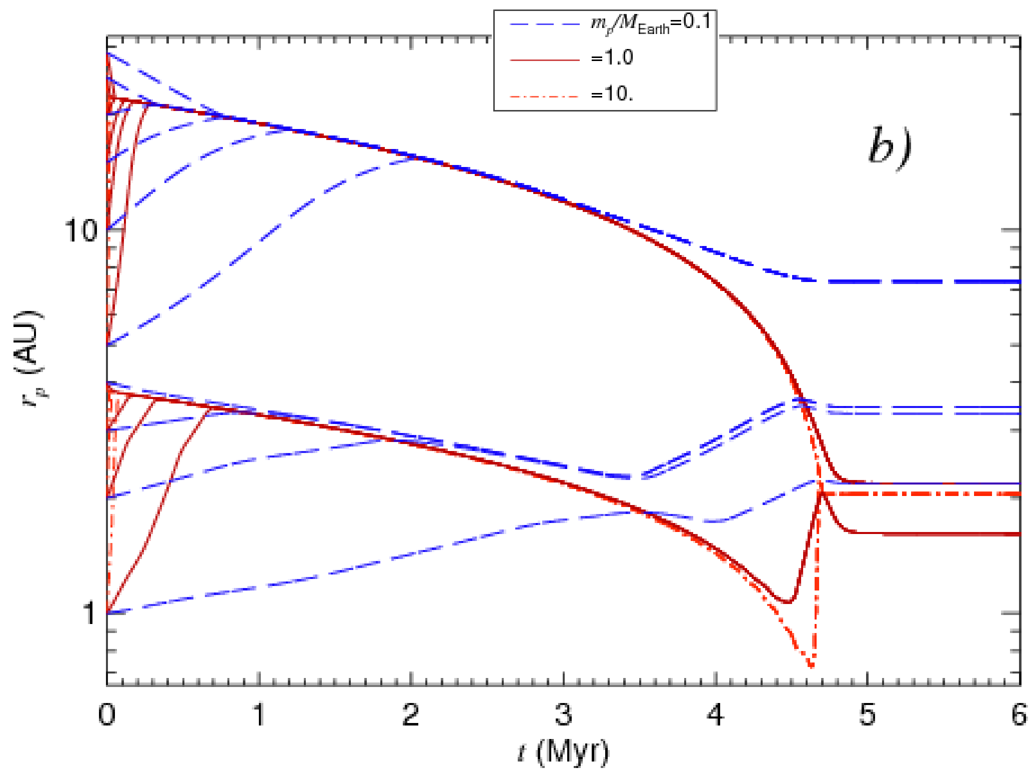

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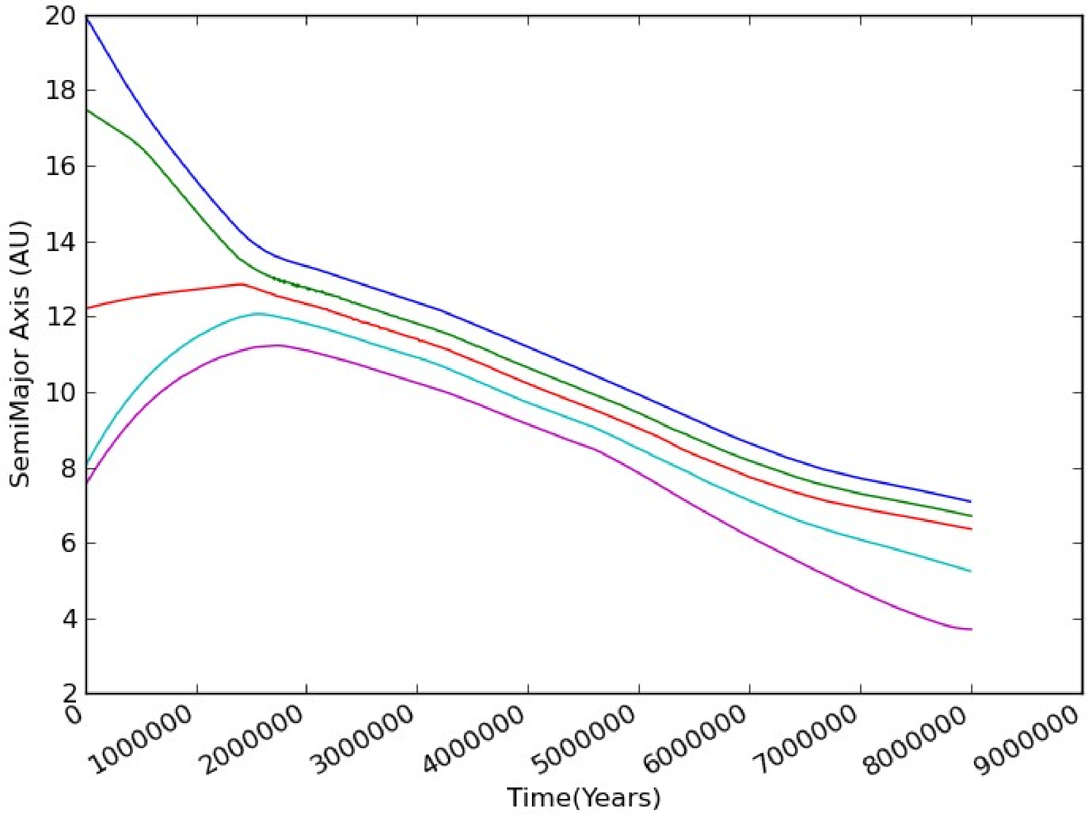
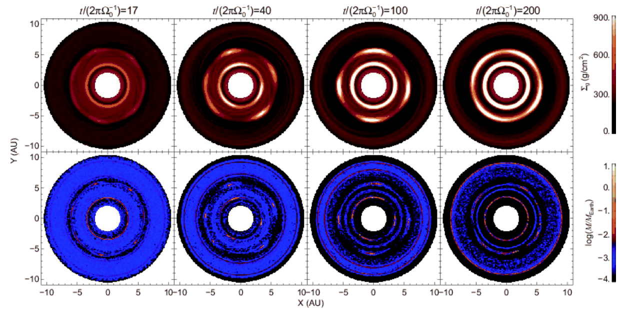
At some point, the disk becomes **too thin** to drive accretion. The planet **decouples** and is **released** in a safe orbit.

Migration + N-Body in Evolutionary Models



Migration in resonance!

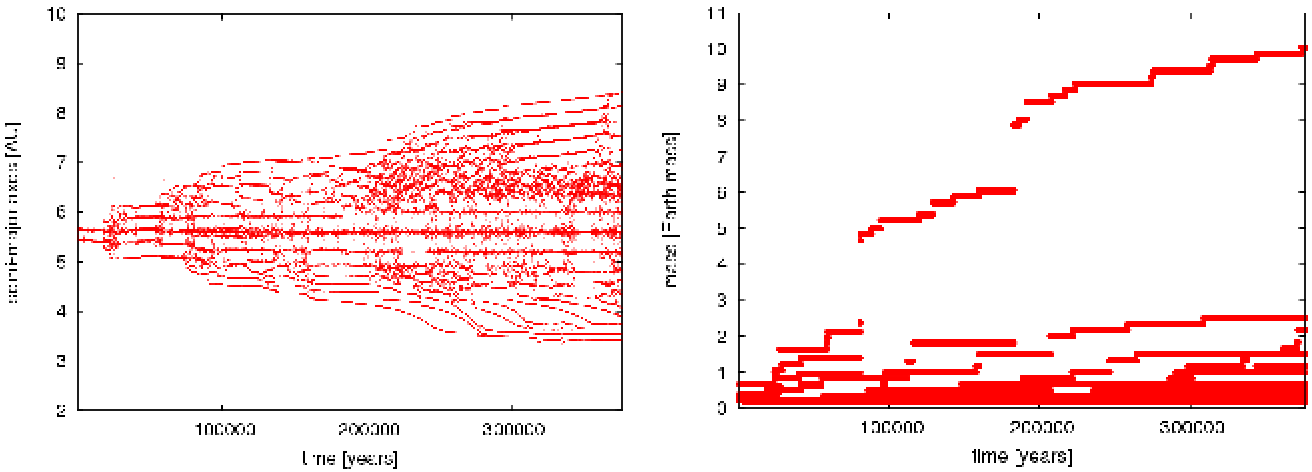
Forming giant planet cores at migration traps



Source: Lyra et al. (2008b)

Continuous planet formation:

a Mars-mass planet appears
at the migration trap, following a Poisson rate.



Source: Sándor, Lyra, & Dullemond (2011)

Planets escape trap via N-body interactions

Find inner/outer equilibrium position by
resonance trapping!

Resonance broken by further
planet formation, that disturbs the structure.

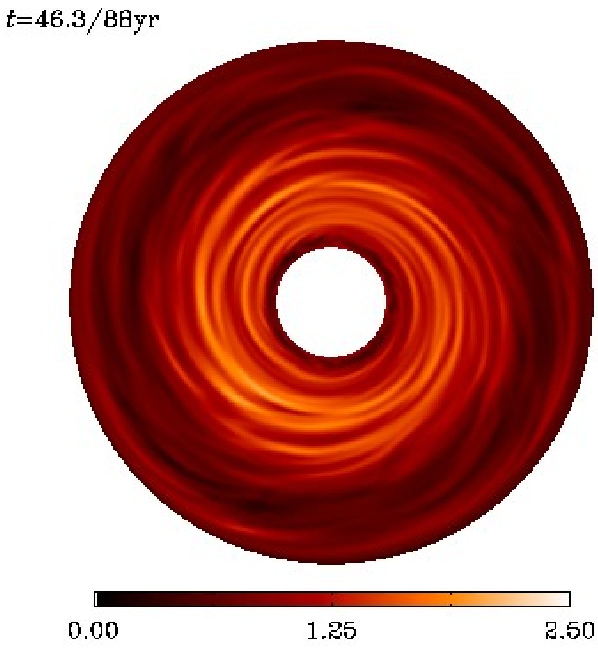
Parametrized turbulence

Stochastic forcing (Laughlin et al. 2004, Ogihara et al. 2007)

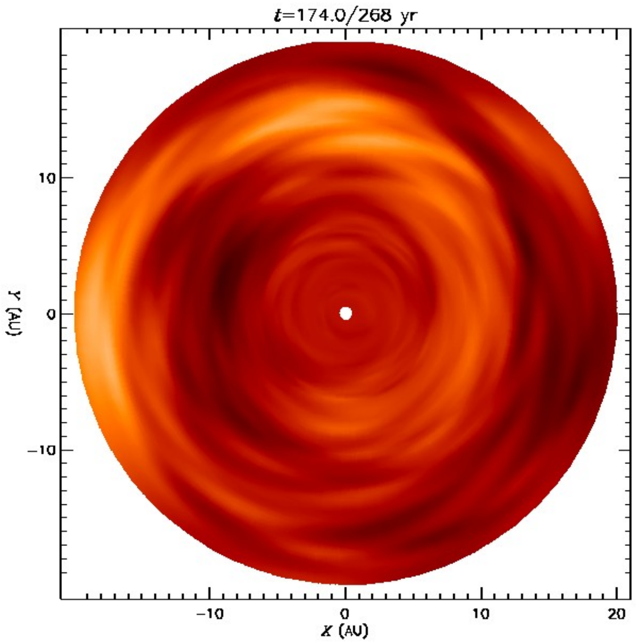
$$\Phi = A r^2 \Omega^2 \sum_{i=1}^{n} \Lambda_{c,m}$$

$$\Lambda_{c,m} = e^{-(r-r_c)^2/\sigma^2} cos(m\theta - \phi_c - \Omega_c \tilde{t}) \sin(\pi \tilde{t}/\Delta t)$$

MHD modeling



Linear superposition of modes



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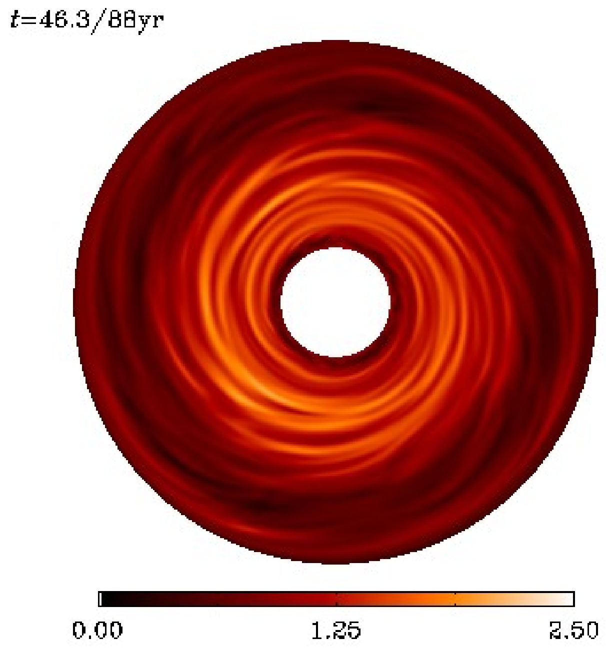

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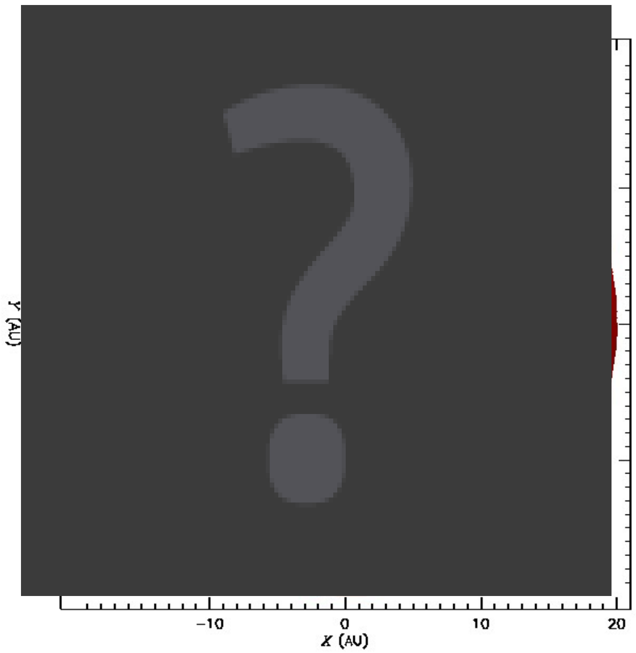


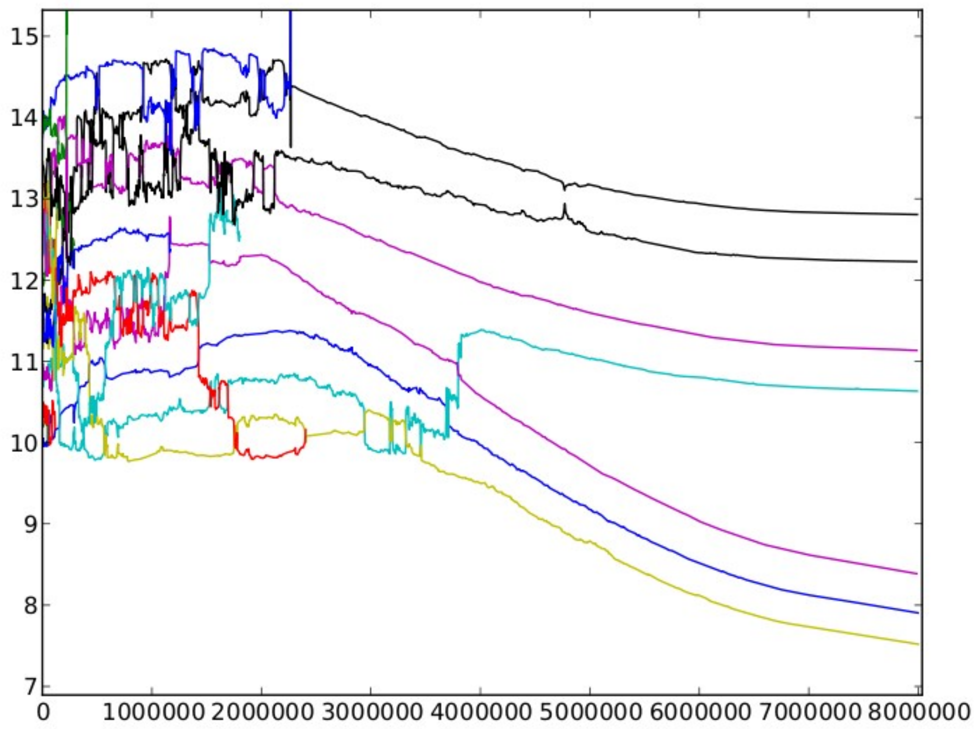
Orbital migration of interacting planets in a radiative evolutionary model

Combines

migration + N-body + photoevaporation + turbulence

modelled as stochastic forcing

(Laughlin et al. 2004, Ogihara et al. 2007)



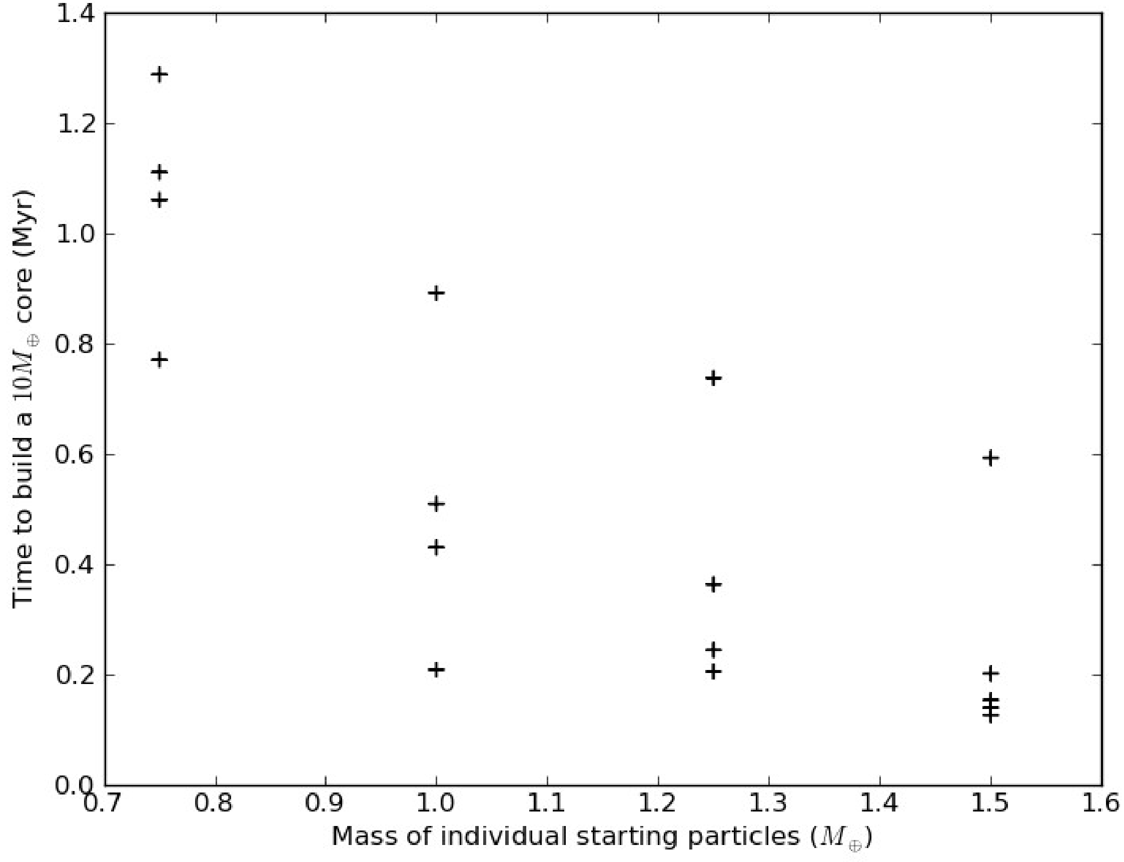
Horn, Lyra, Mac Low & Sandor (2012)

- 16 Earth mass bodies
- Resonances broken by turbulence
- System relaxes to oligarchs

Orbital migration of interacting planets in a radiative evolutionary model

Horn, Lyra, Mac Low & Sandor (2012)

Orbital migration of interacting planets in a radiative evolutionary model

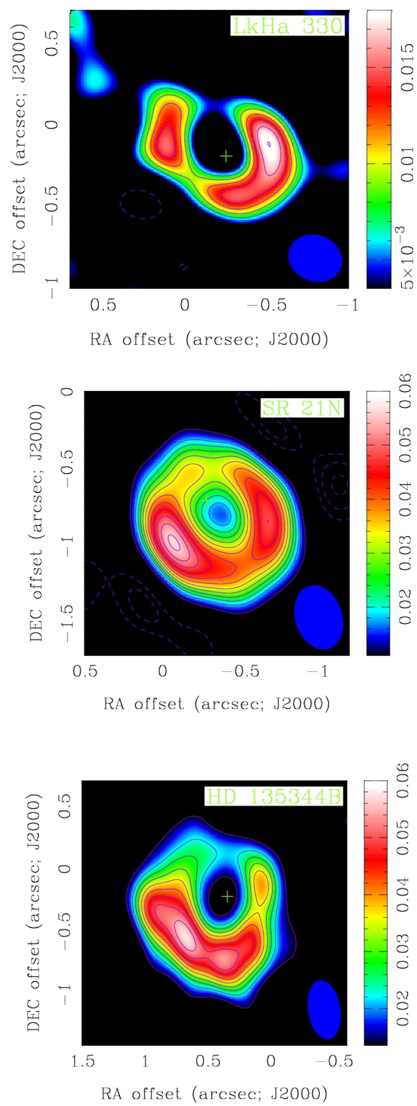


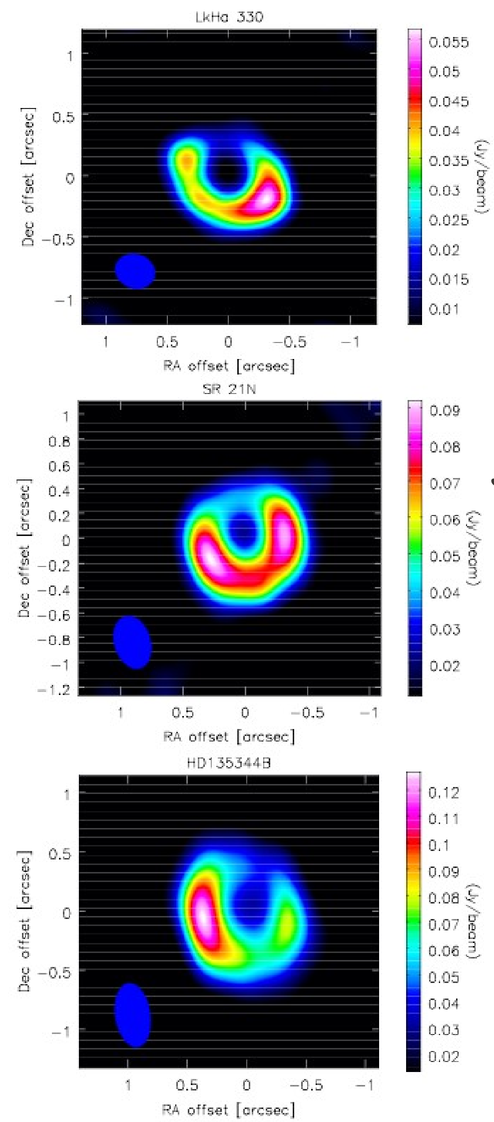
Horn, Lyra, Mac Low & Sandor (2012)

A possible detection of vortices in disks

Observations

Brown et al. 2009

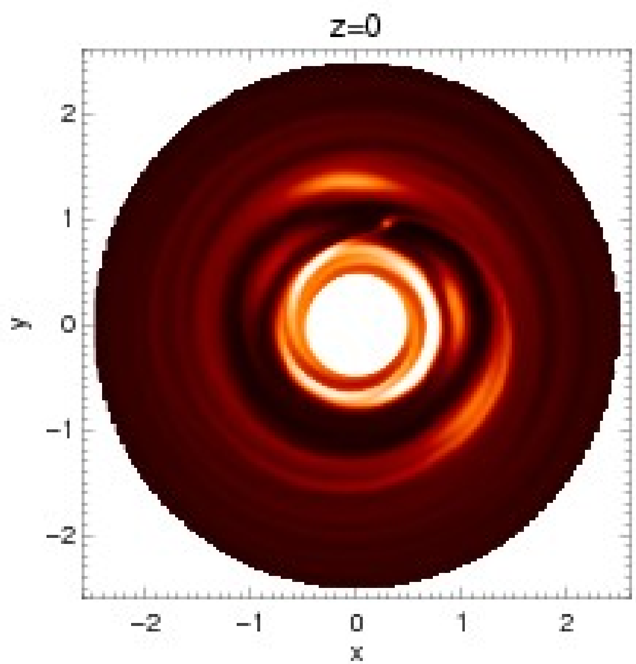




Simulated observations of Rossby vortices

Regaly et al. (2012)

Another way of exciting vortices:



MIND THE GAP

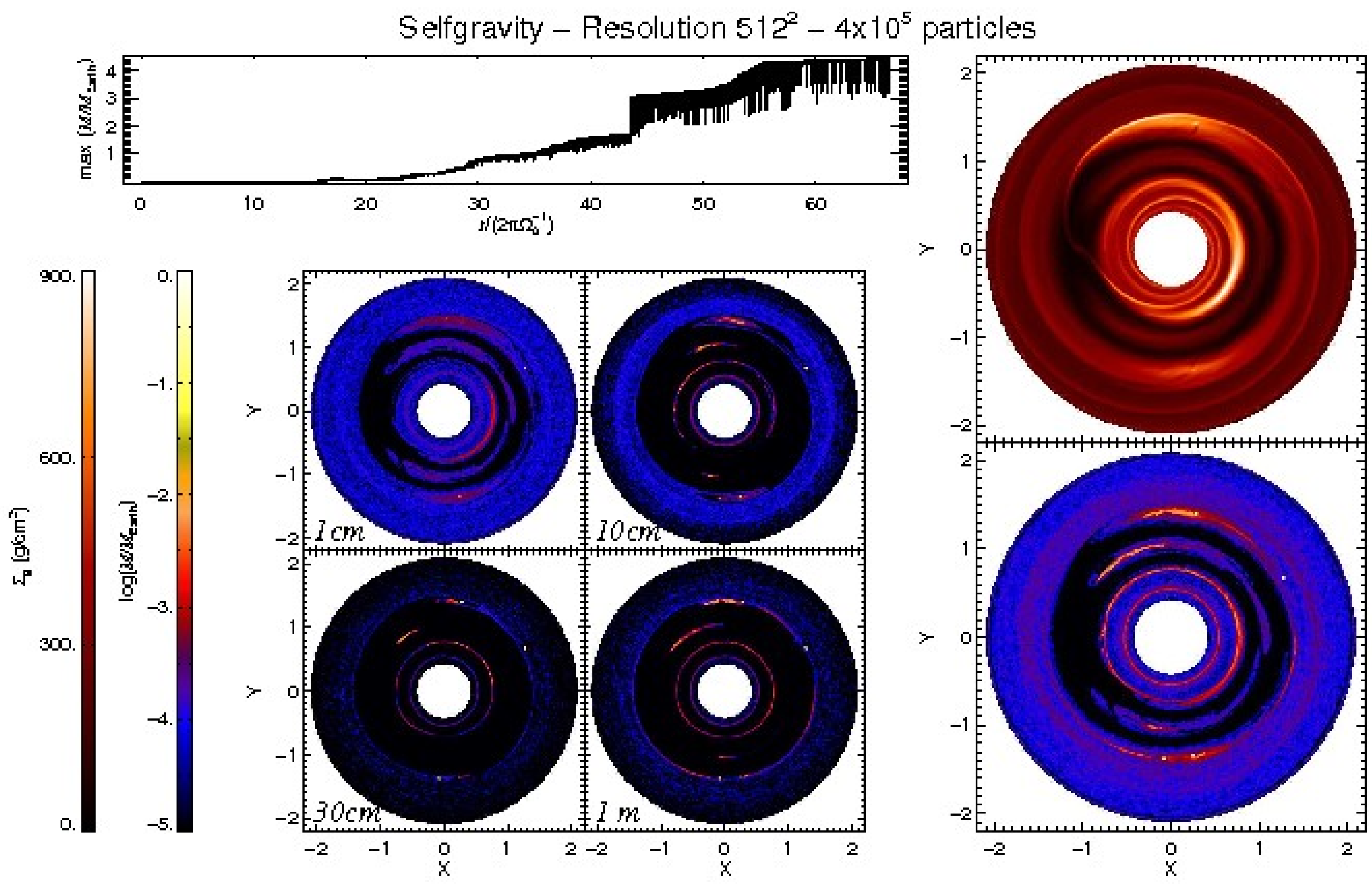
The edges of a planet-carved gap are also prone to vortex excitation.

What happens when particles are introduced?

Another way of exciting vortices:

What happens when particles are introduced?

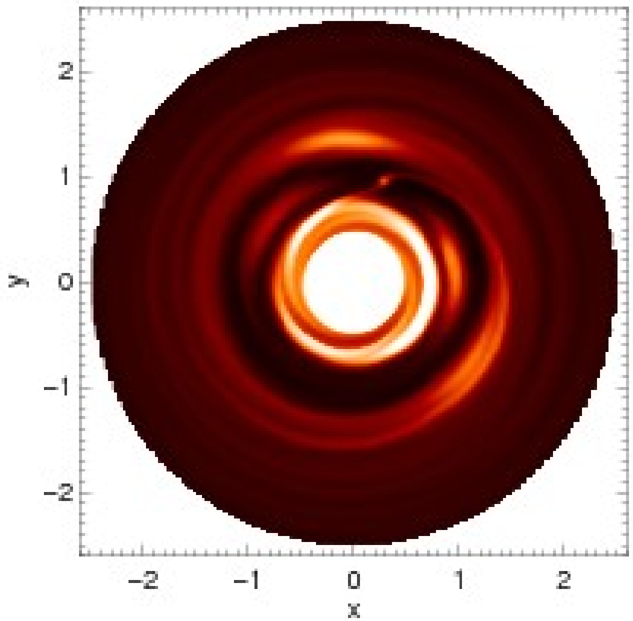
Trojan Planets!!



3 Super-Earths formed + Mars mass Trojans

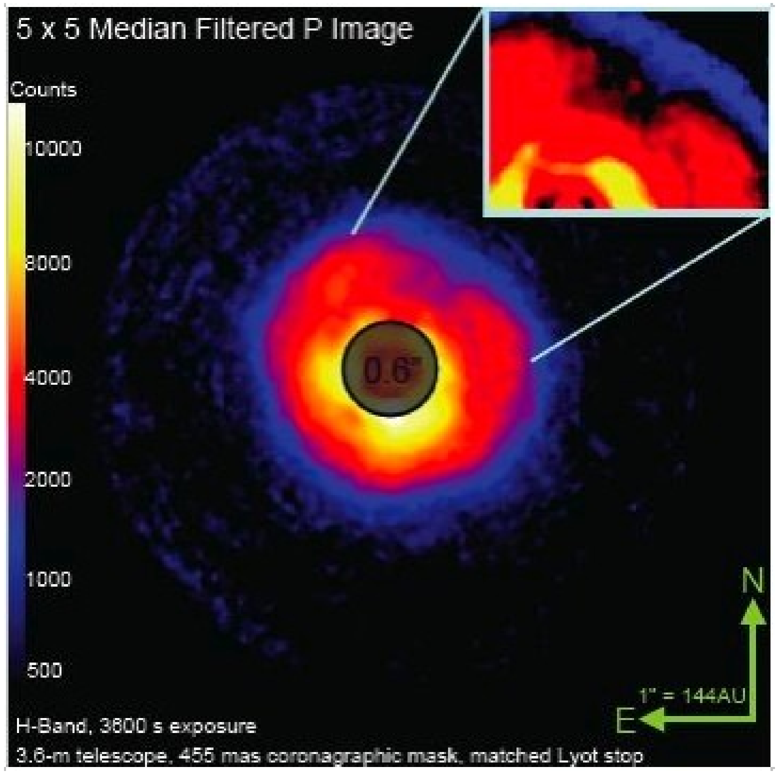
The wake of a planet in the AB Aurigae disk

Theoretical prediction



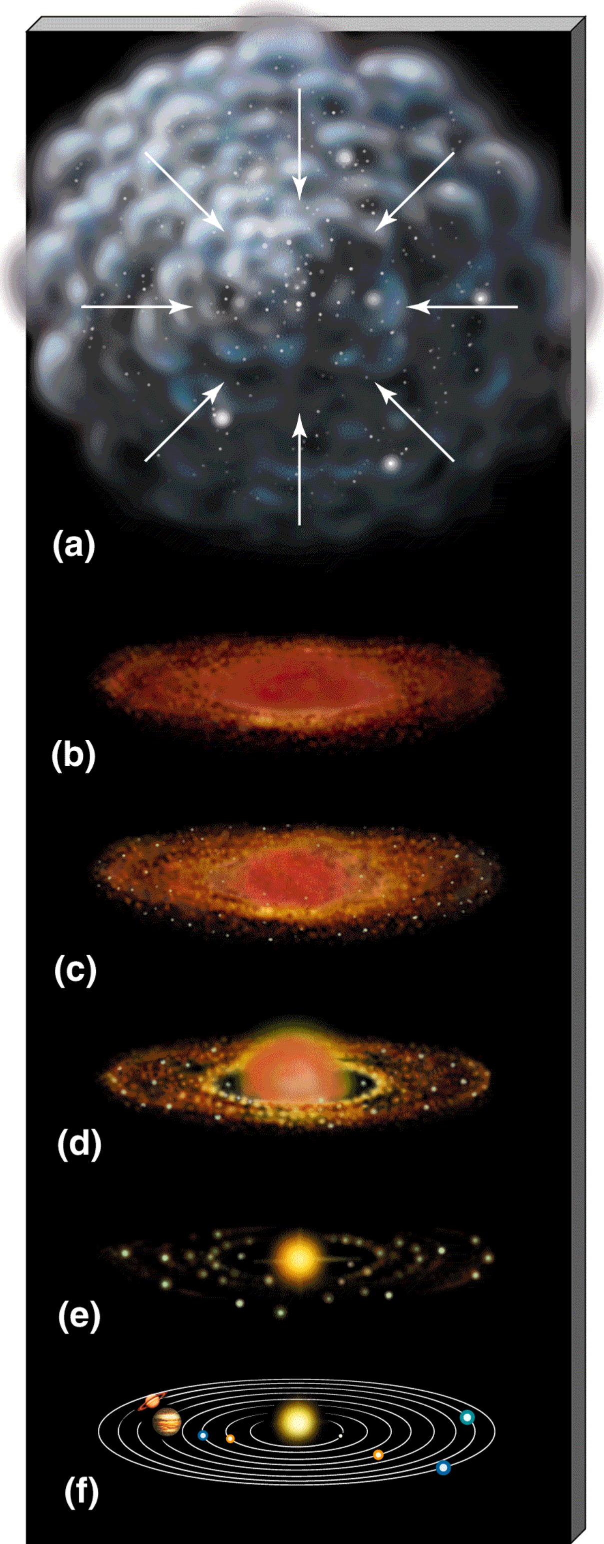
Lyra et al. (2009)

Observation



Oppenheimer et al. (2009)

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.

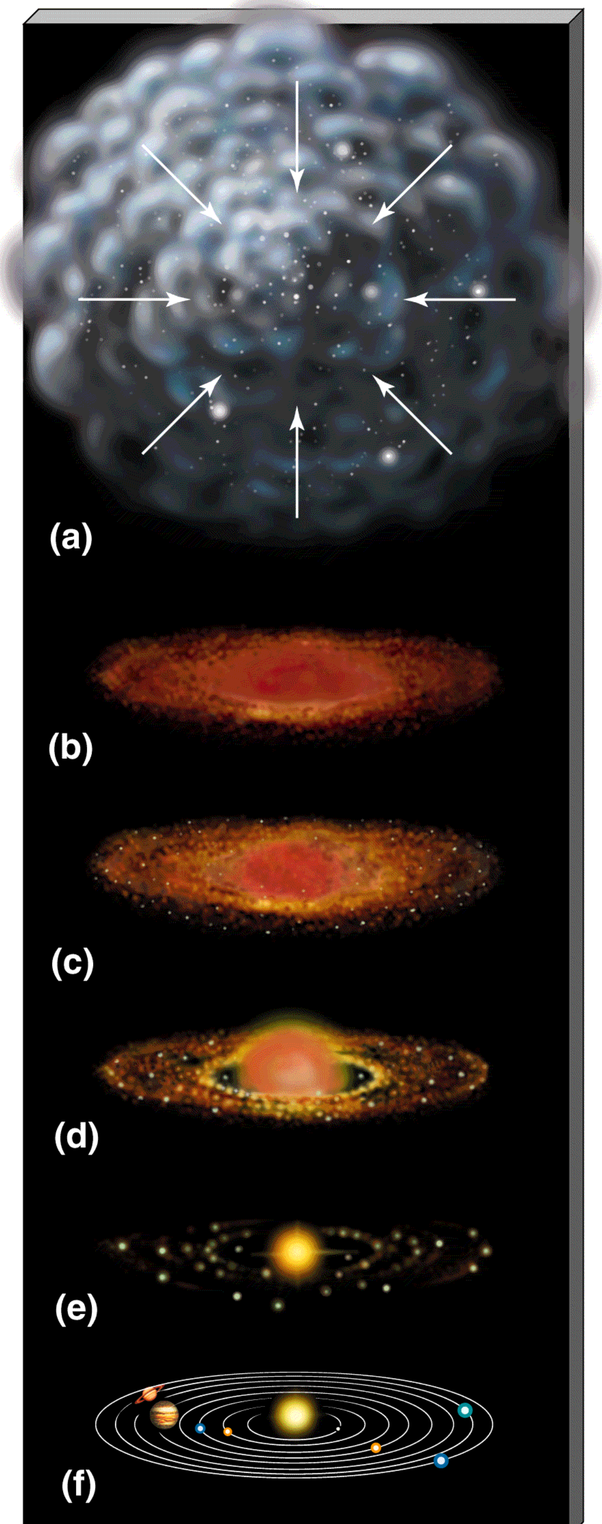
Vortices may be excited in the dead zone. Inside them, the first dozens of Mars-mass embryos are formed. IMF ~ -2

Opacity transitions develop into regions of convergent migration. Low mass planets converge to these zones by inward/outward migration.

Convergent migration leads to resonances, these are disrupted by turbulent forcing. Collisions between embryos gives rise to oligarchs.

The disk thins due to photoevaporation. Planets released into stable orbits.

N-body interactions and stochastic forcing during disk evaporation produce the system's final architecture.



Summarizing

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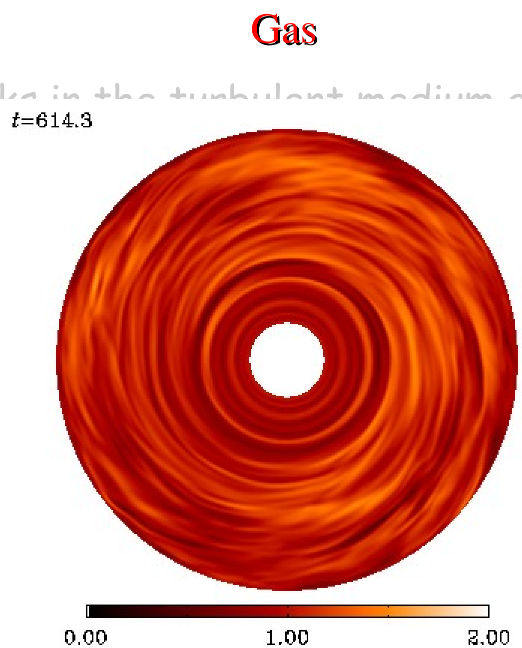

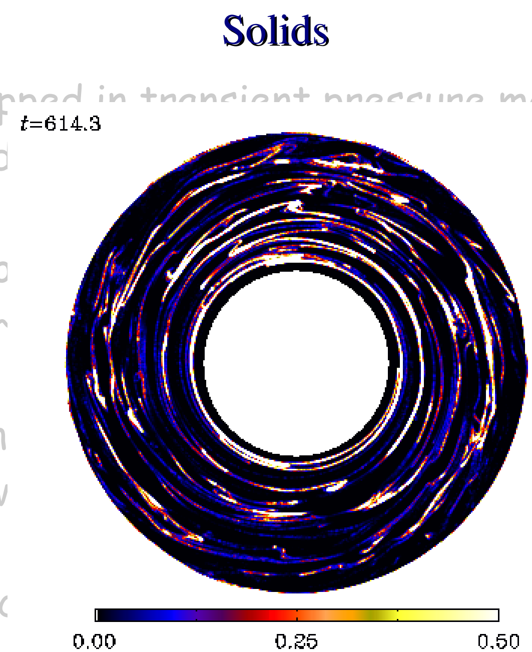

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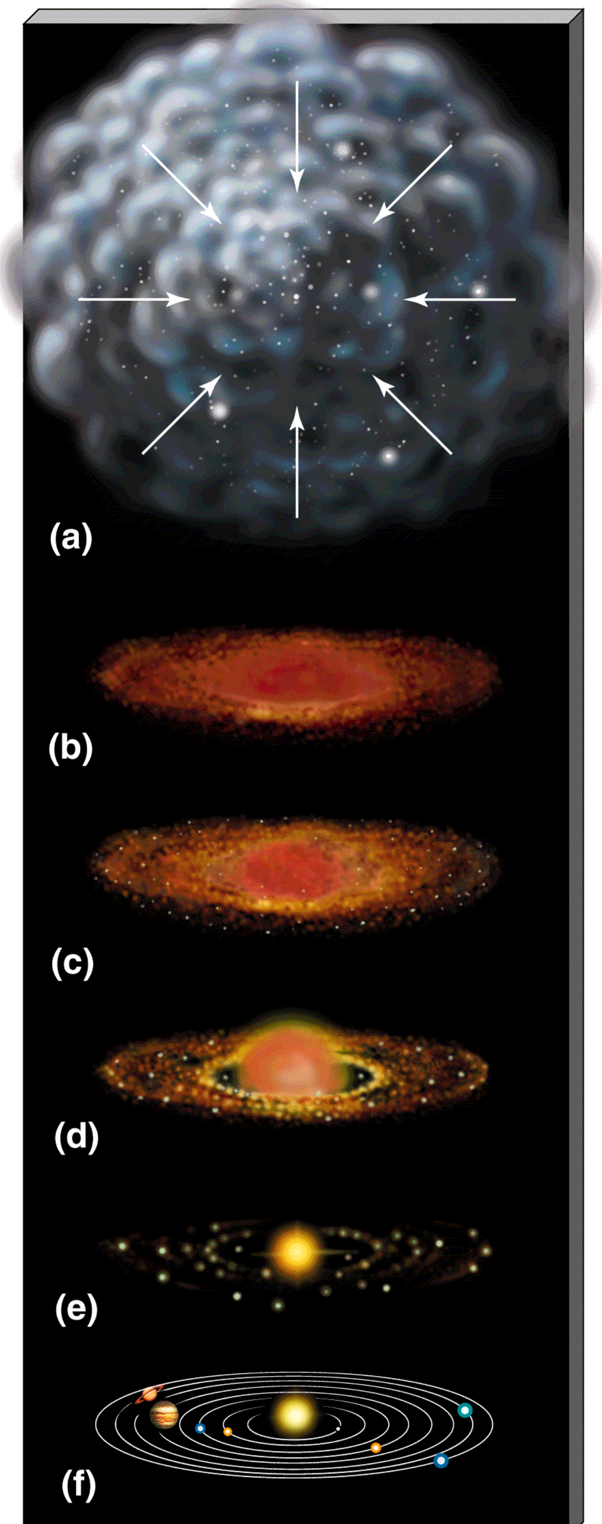

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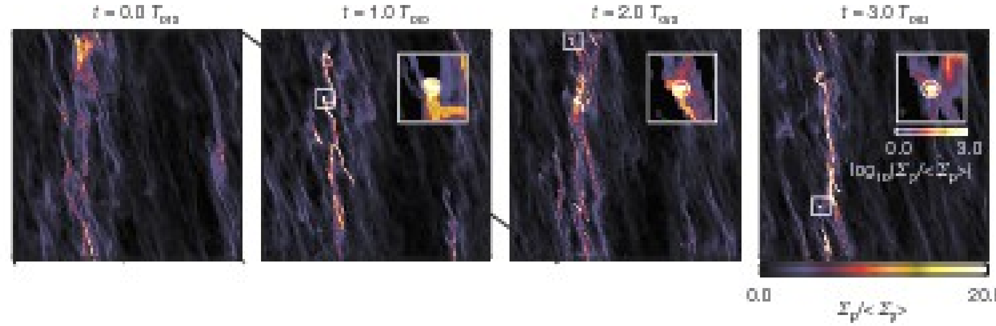

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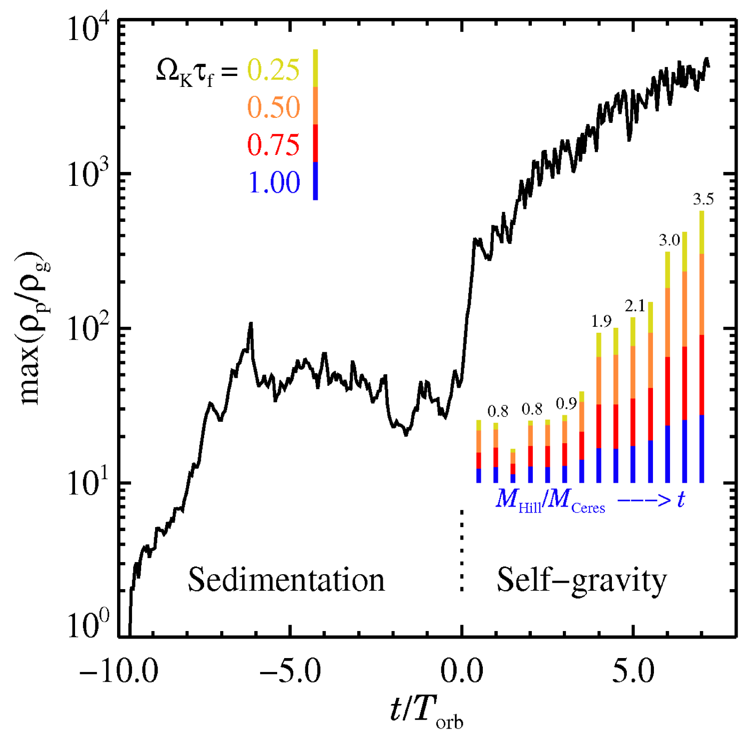

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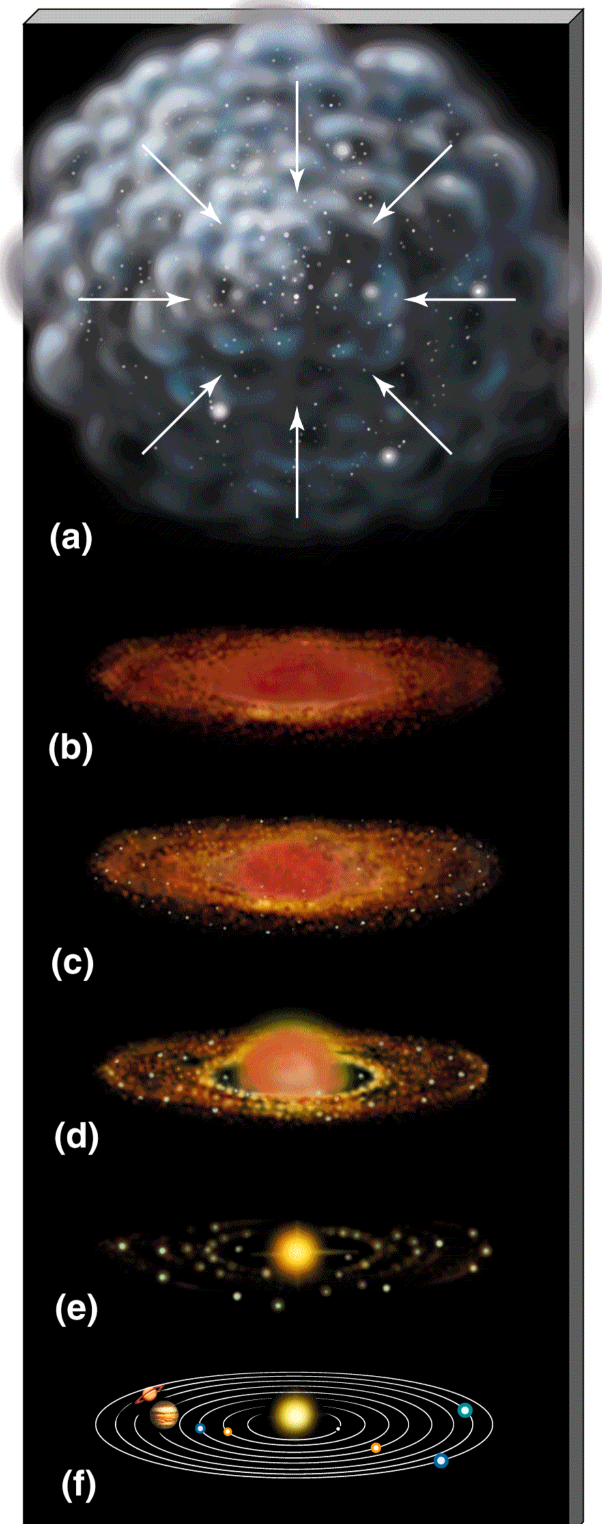
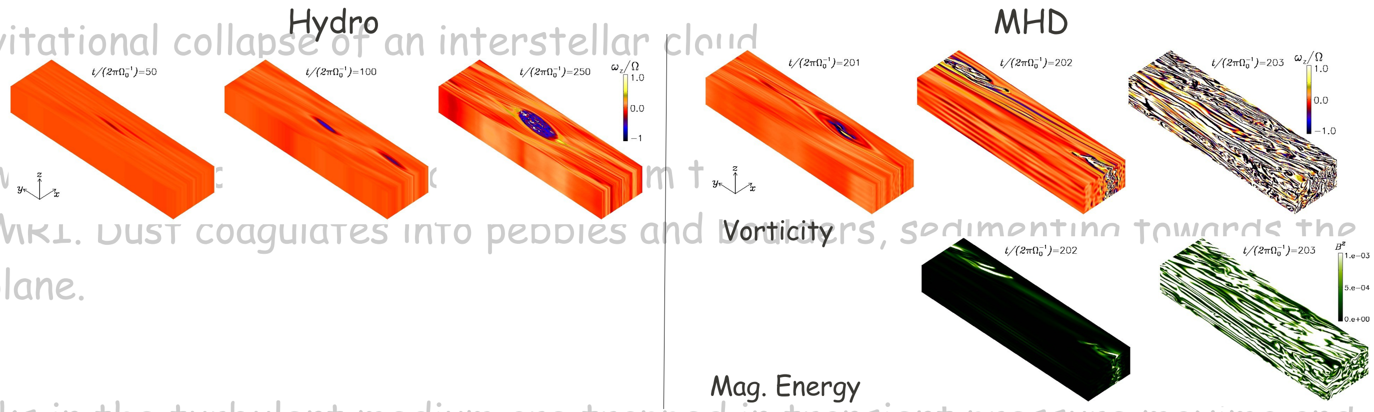


Gravitational collapse of an interstellar cloud



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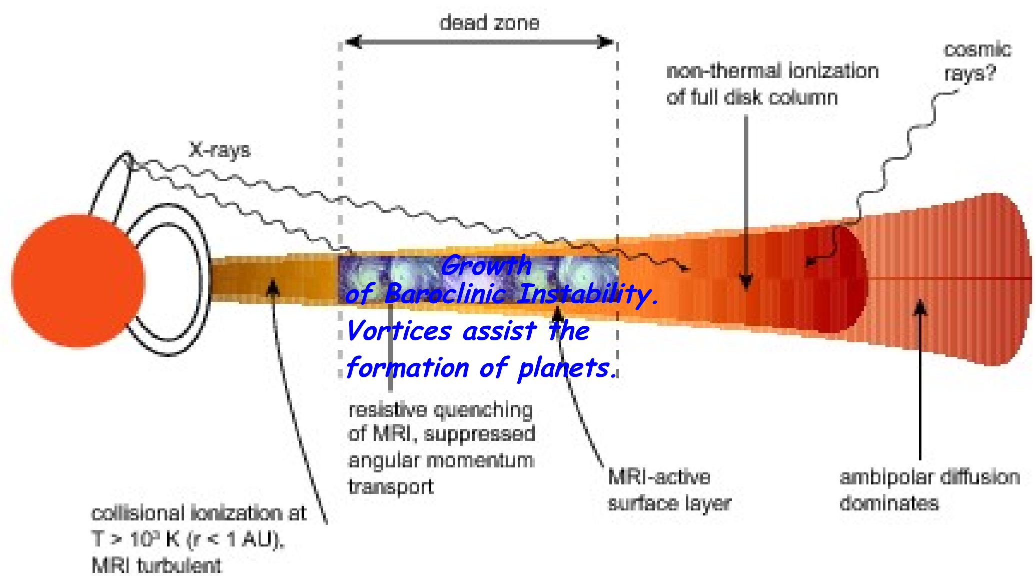

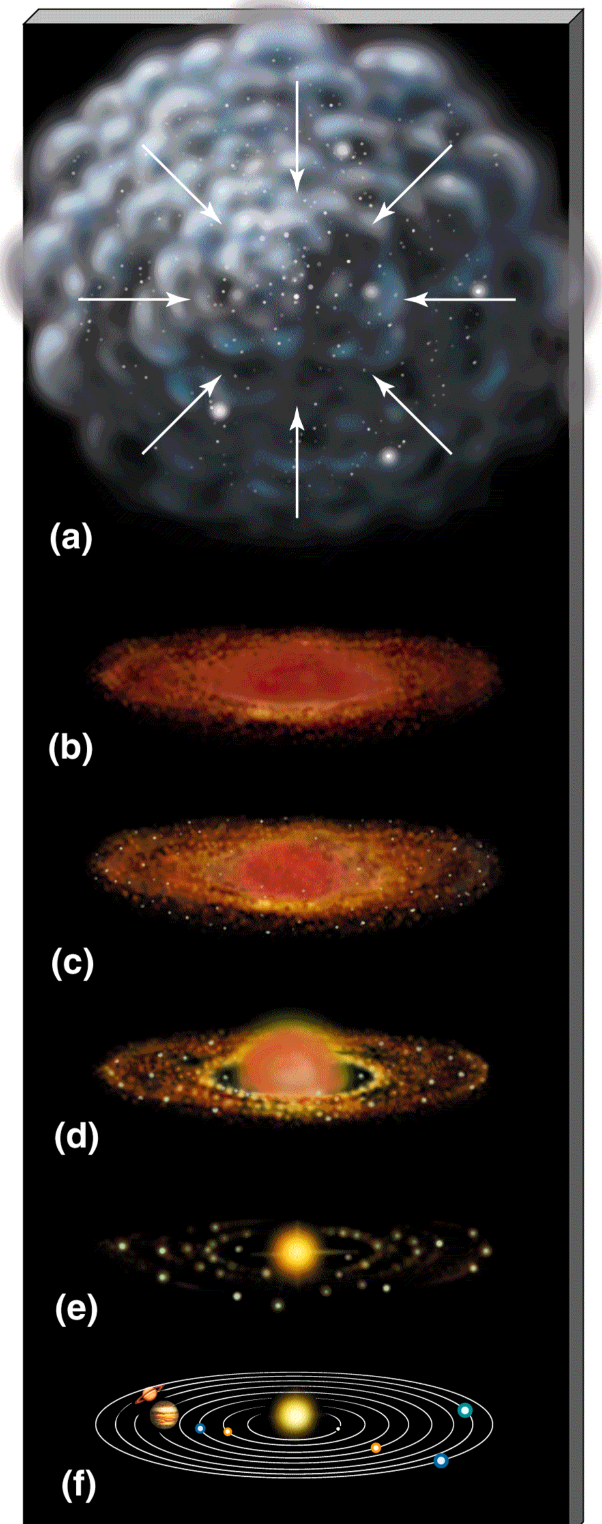

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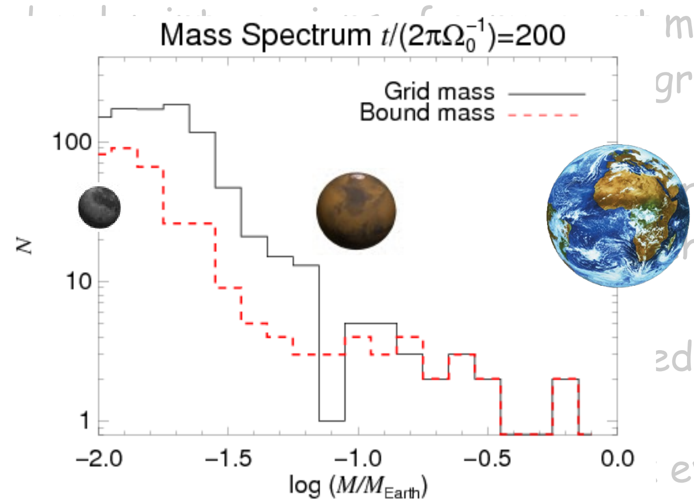

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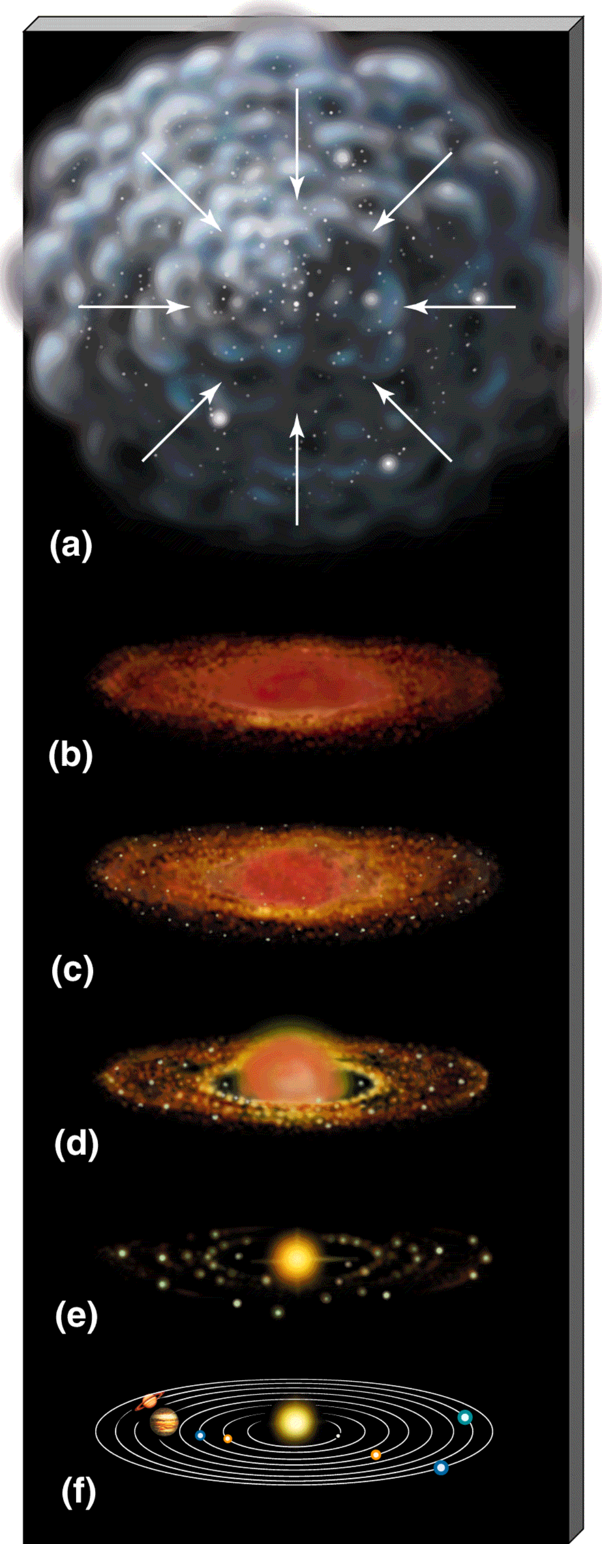
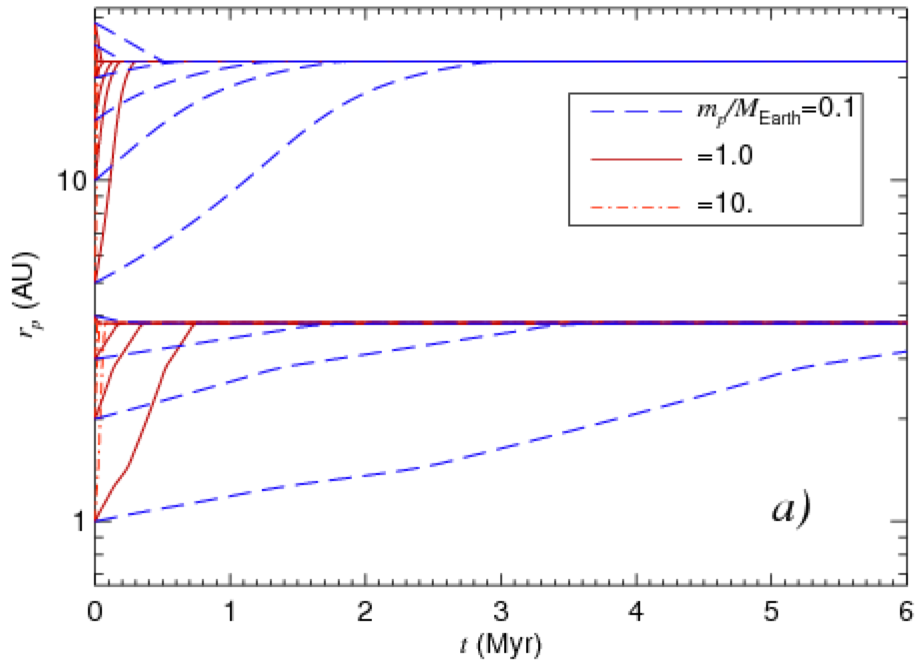
Summarizing





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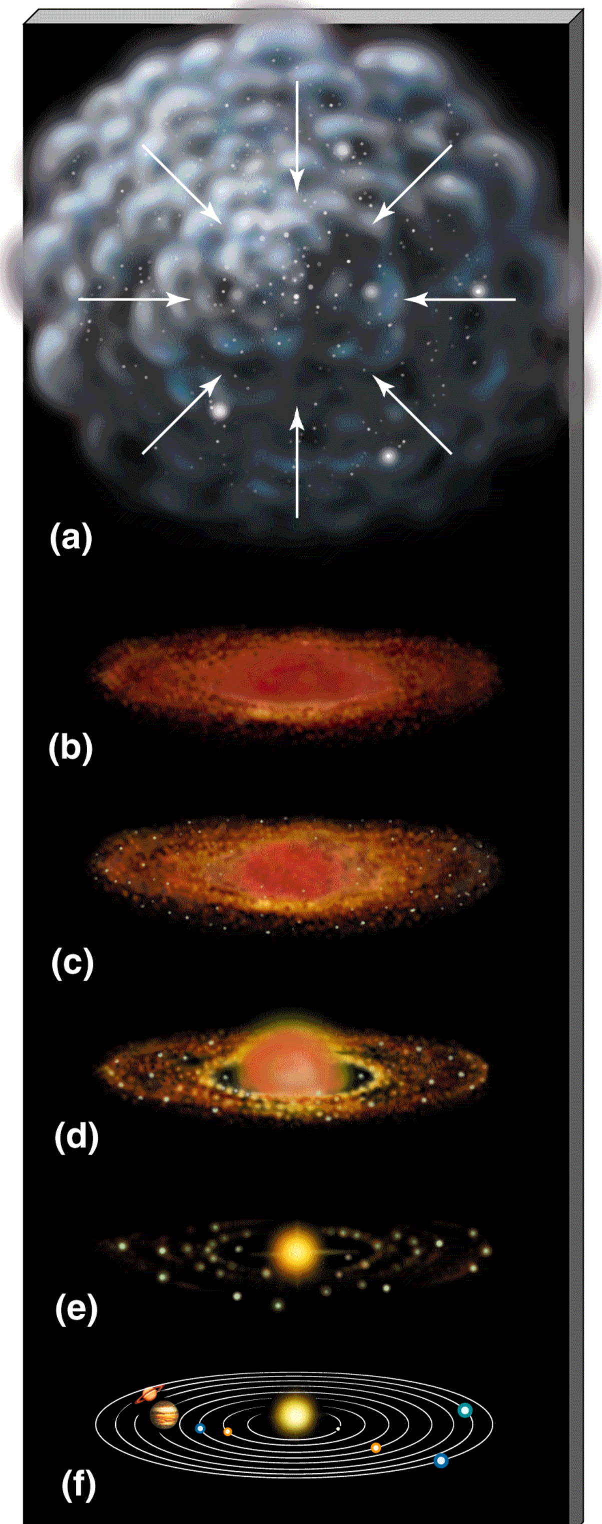

Summarizing

Gravitational collapse of an interstellar cloud

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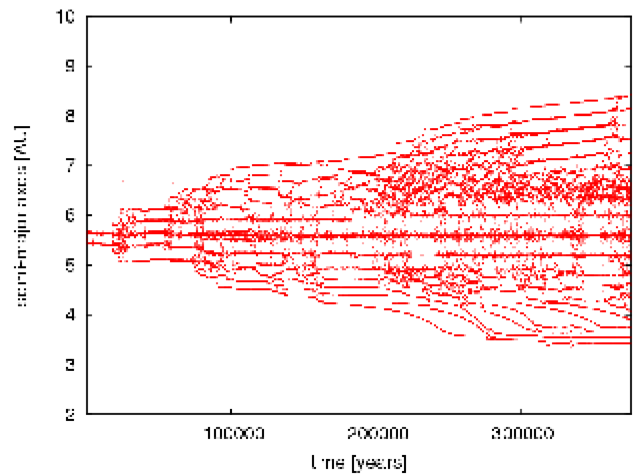

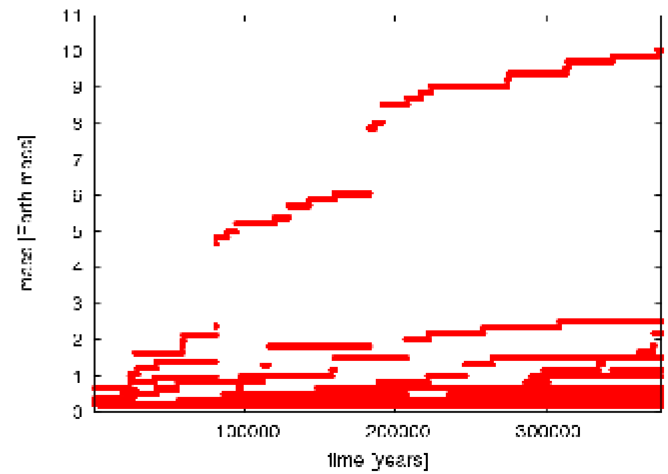

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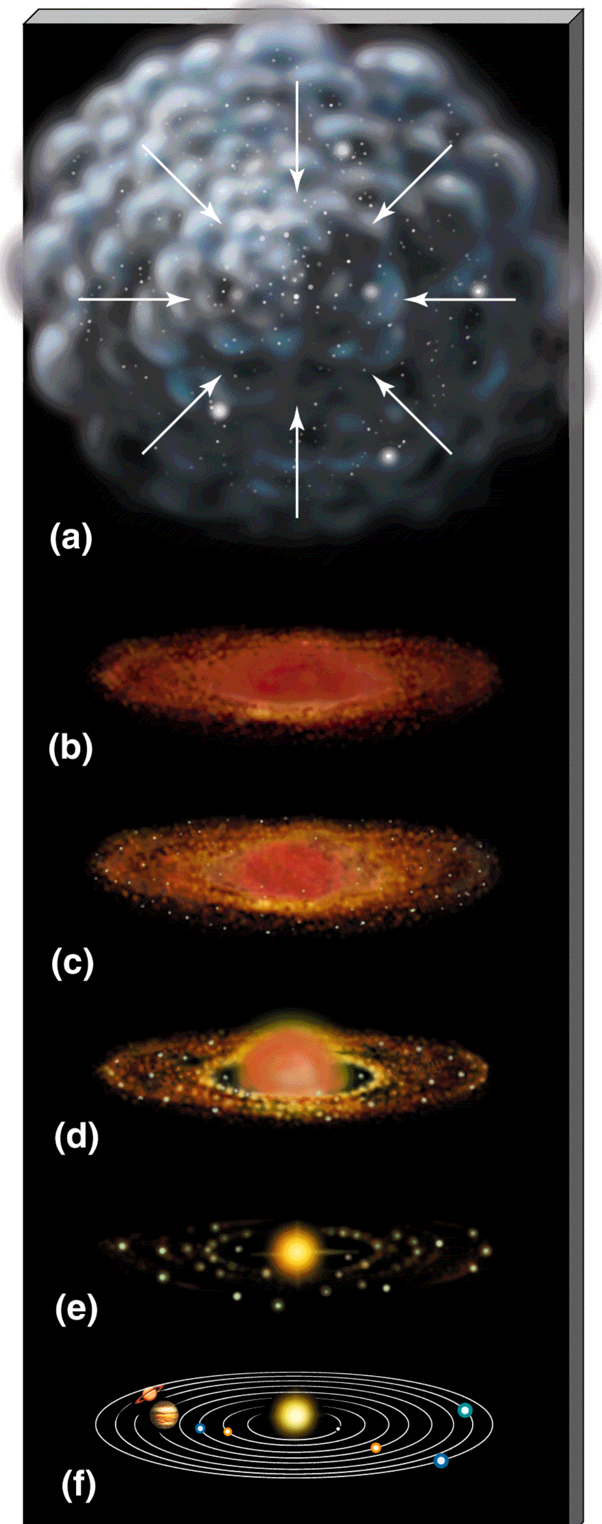
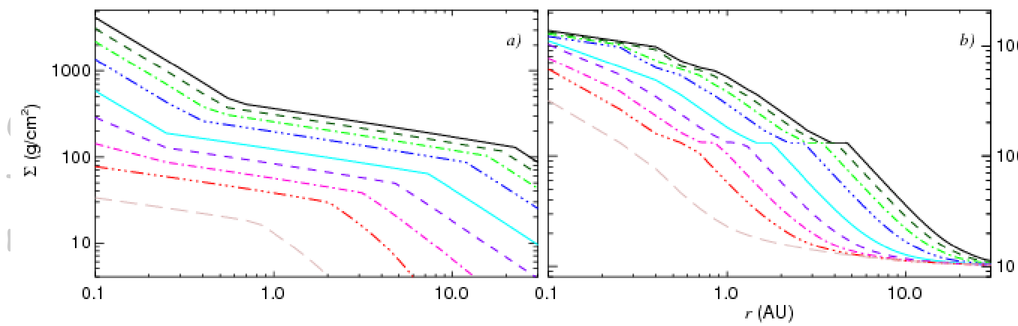
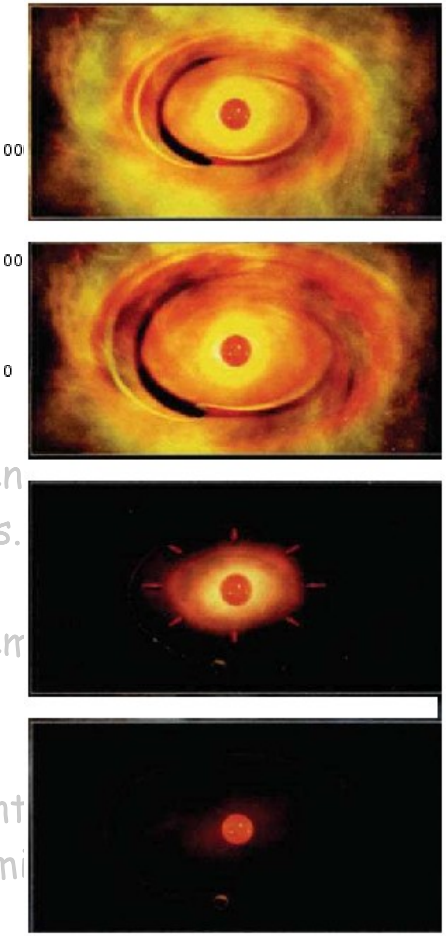


Summarizing





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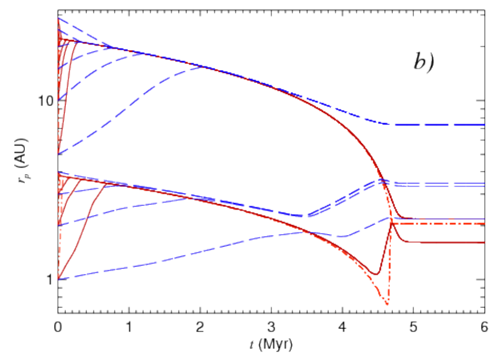

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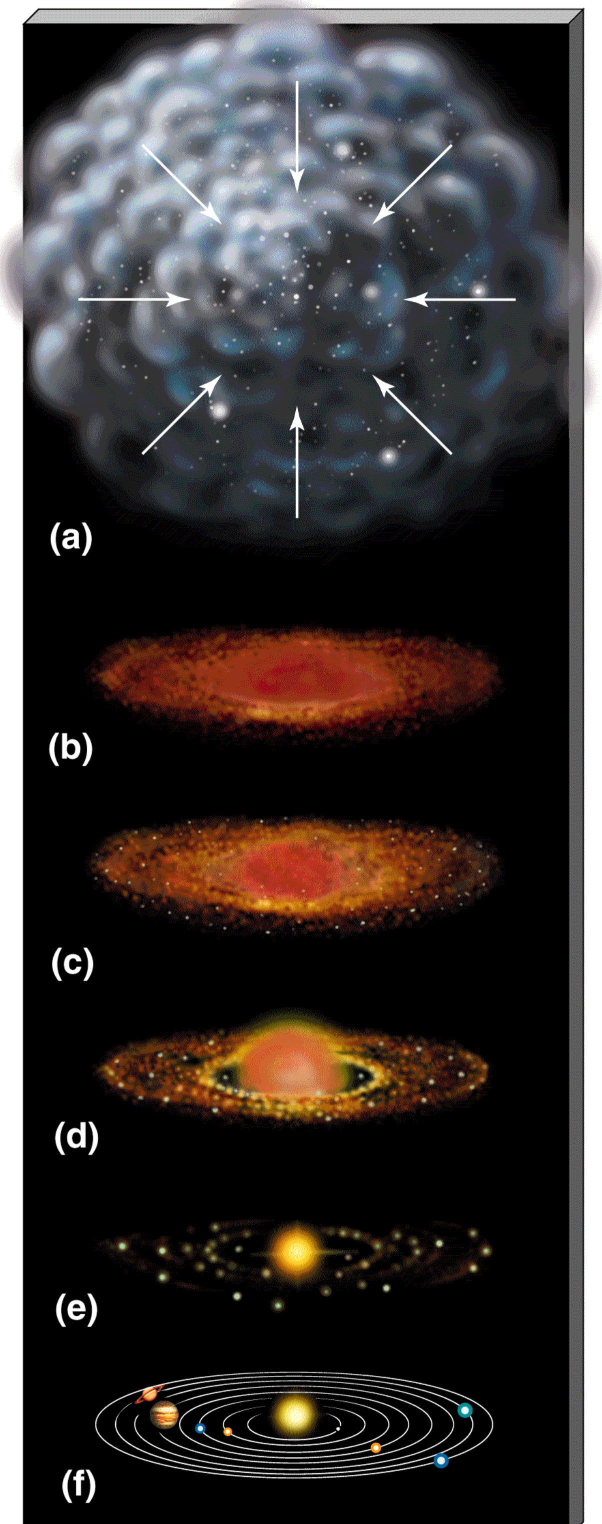

Summarizing

Gravitational collapse of an interstellar cloud

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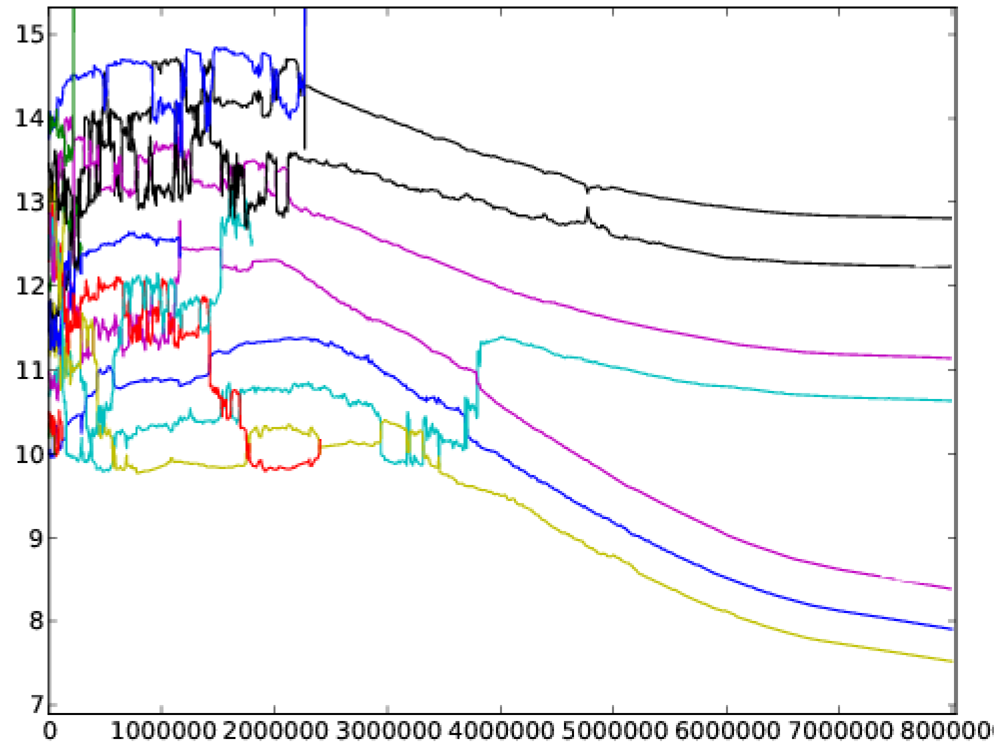

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