The gas-rich phase: Dynamics of the Turbulent Solar Nebula

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Dynamics and Formation of the Oort Cloud, Lille, October 2011

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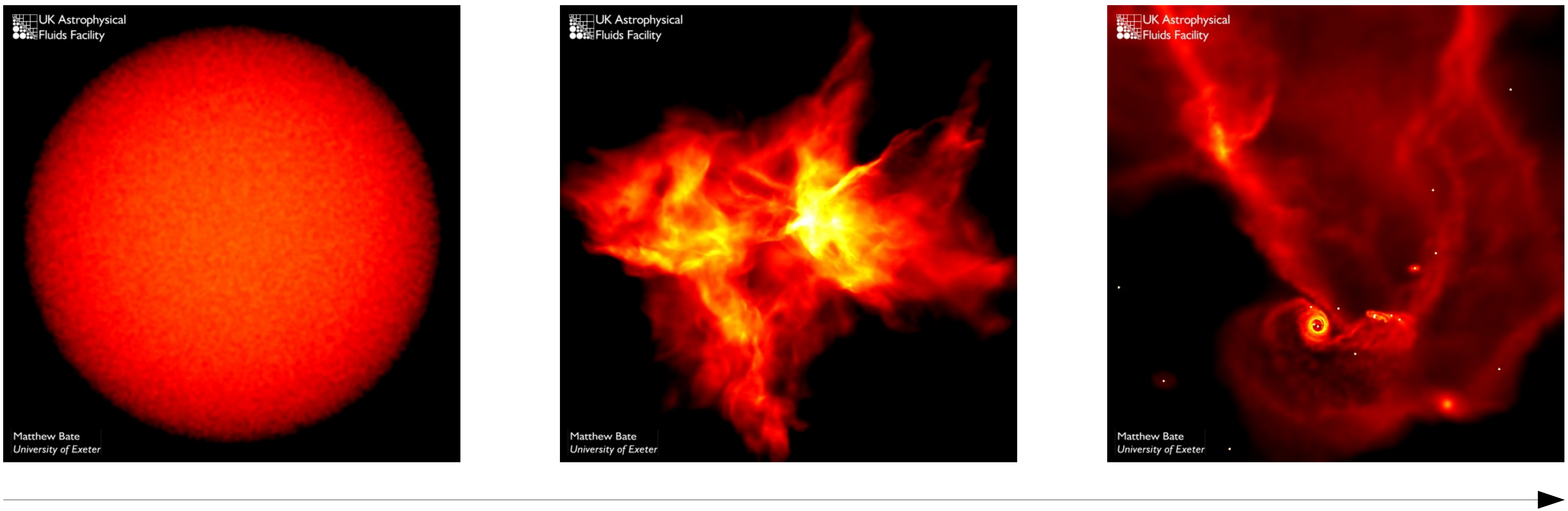
Sijme-Jan Paardekooper (Cambridge), Nikolai Piskunov (Uppsala),
Natalie Raettig (Heidelberg), Zsolt Sandor (Heidelberg), Andras Zsom (Heidelberg).

Star Formation – Bate, Bonnell & Bromm (2003)



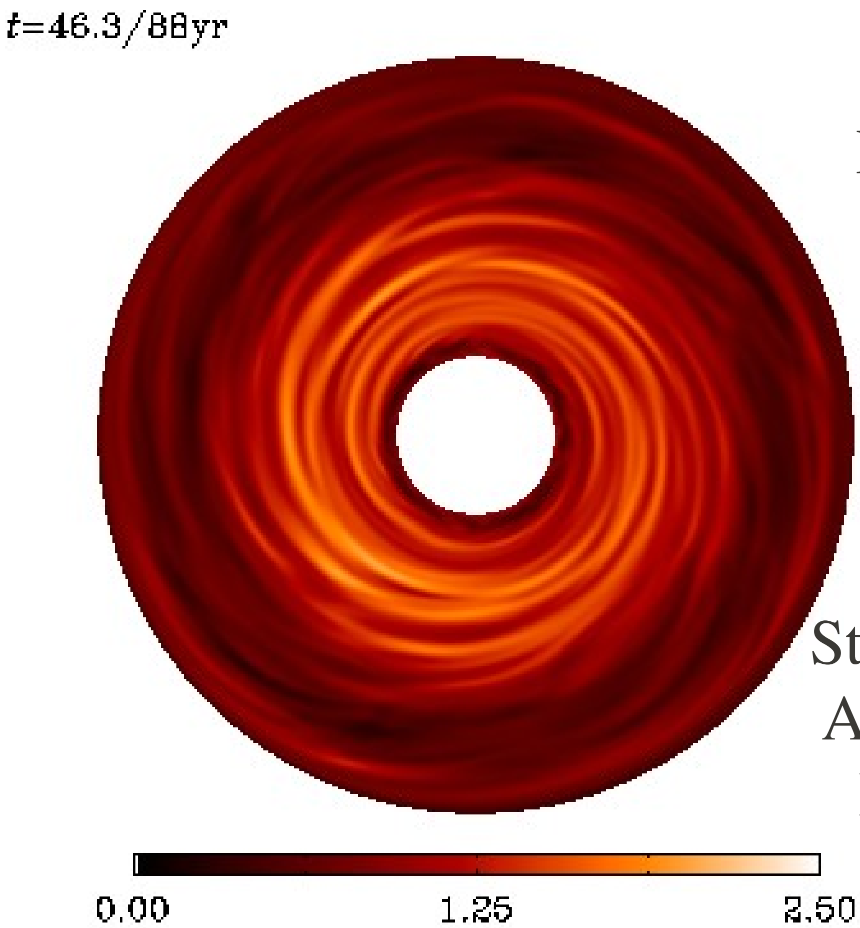
Some stars are seen to be born with lots of **surrounding gas.**

This gas is bound to the star and referred to as

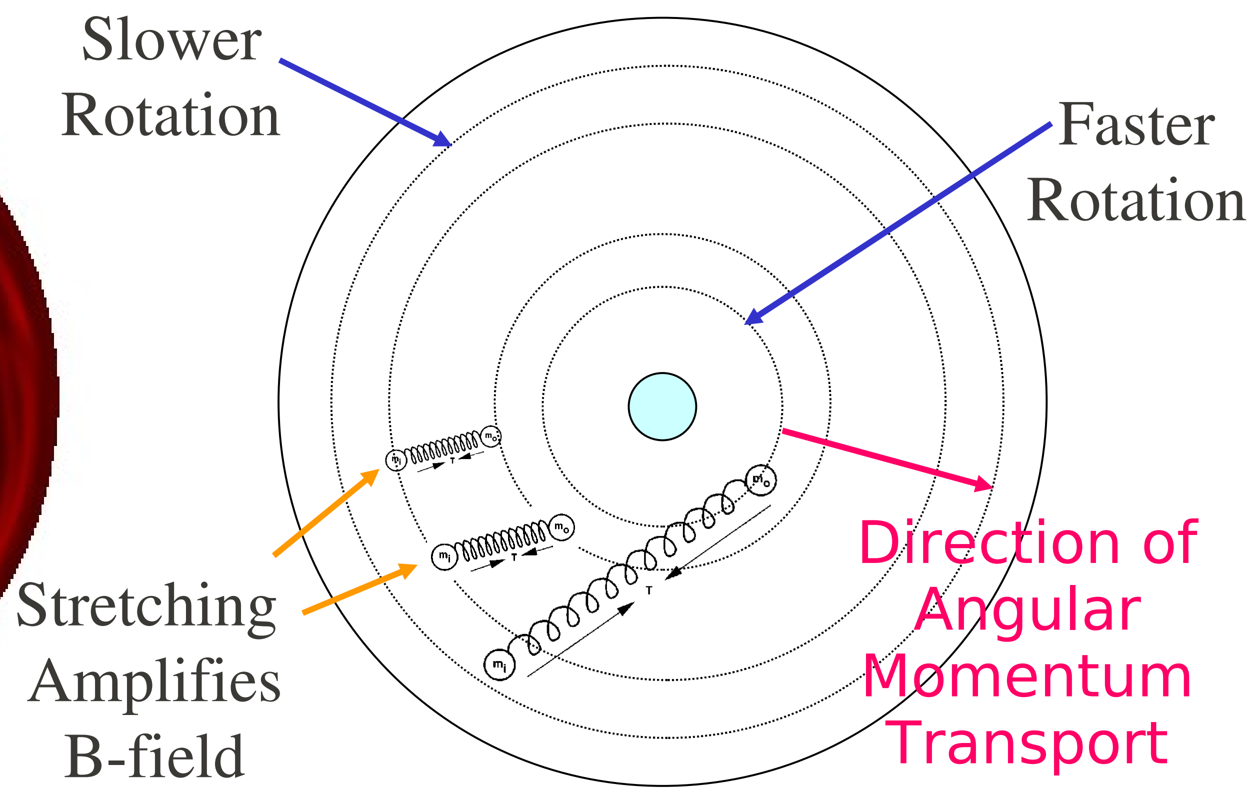
circumstellar disk or *protoplanetary disk.*

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

Turbulence concentrates solids mechanically in pressure maxima

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

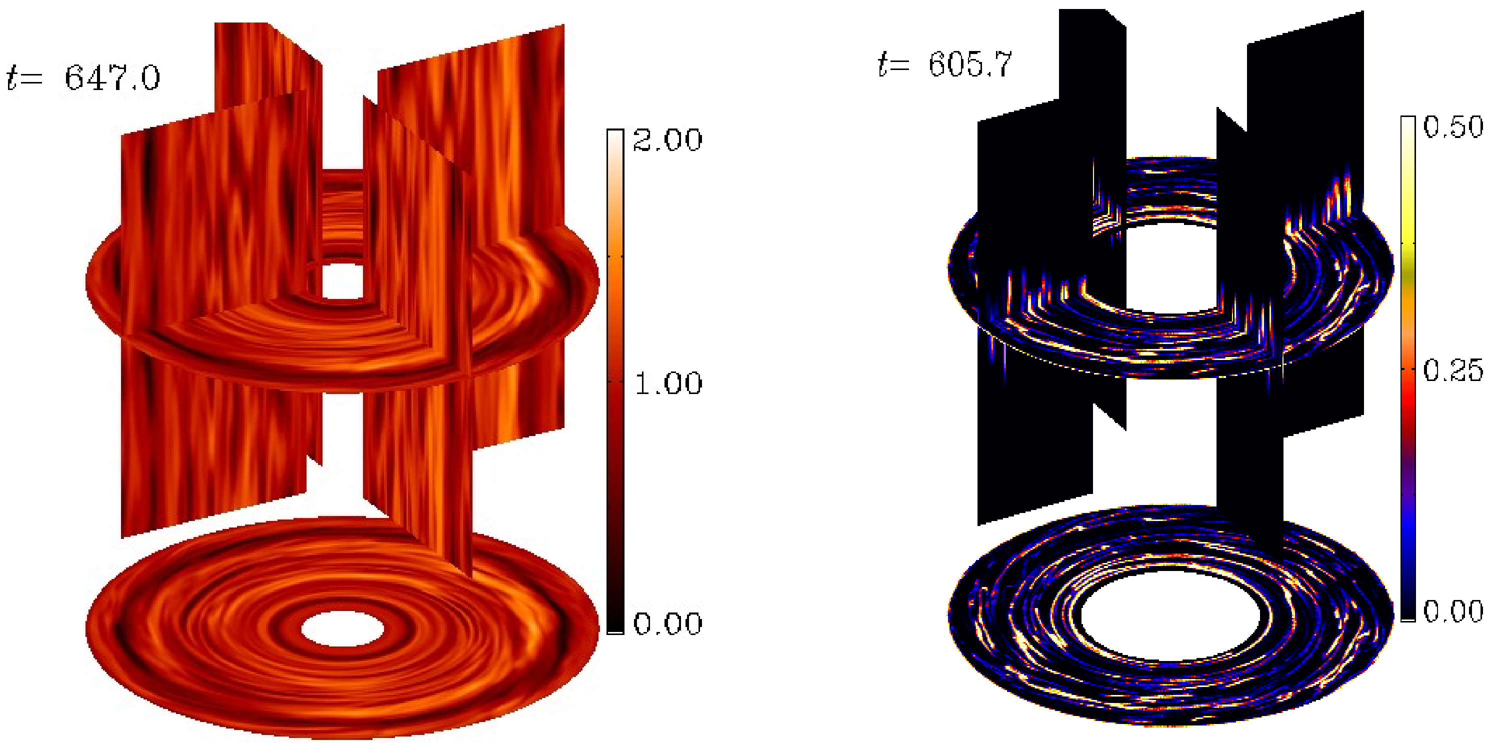
Solids $$\frac{d\boldsymbol{w}}{dt} = -\nabla\Phi - \frac{(\boldsymbol{w}-\boldsymbol{u})}{\tau}$$

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

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

Gas

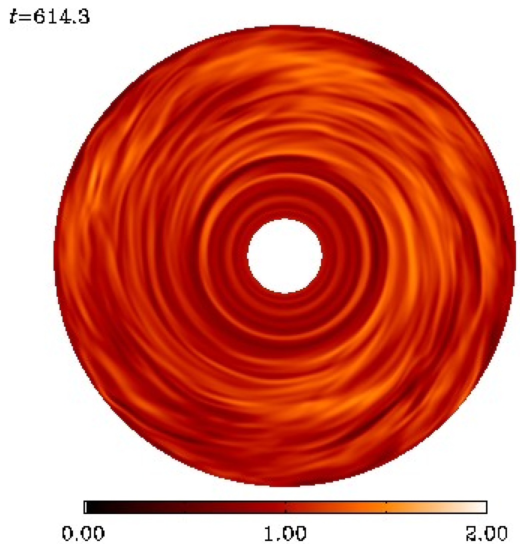
Solids

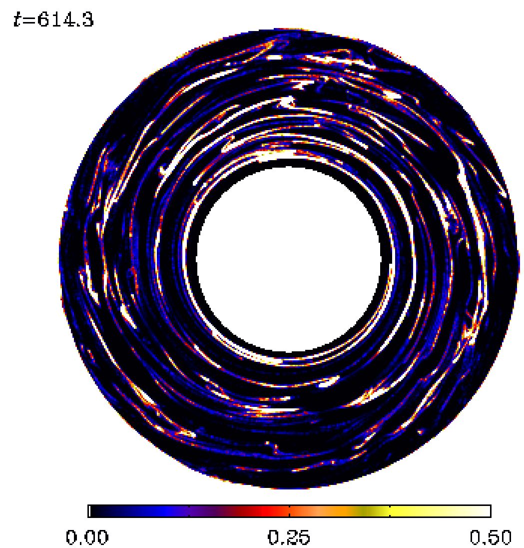


Intense Clumping!!

Source: Lyra et al. (2008a)

Solids in a turbulent disk





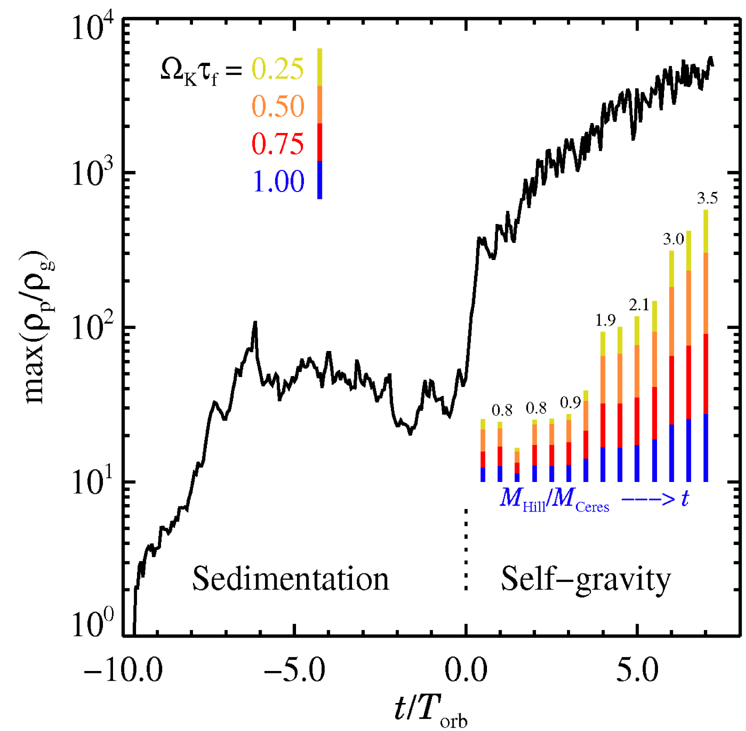
Source: Lyra et al. (2008a)

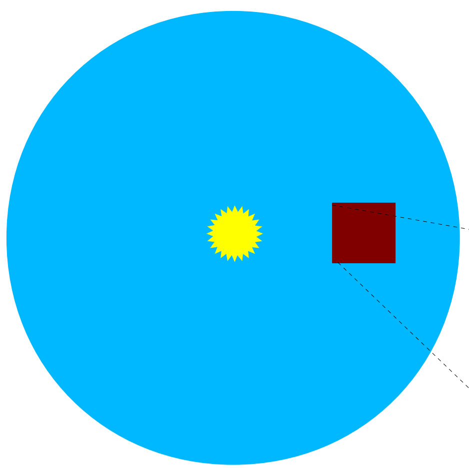
-Turbulent eddies are very efficient particle traps

-Correlation between gas and solids density maxima

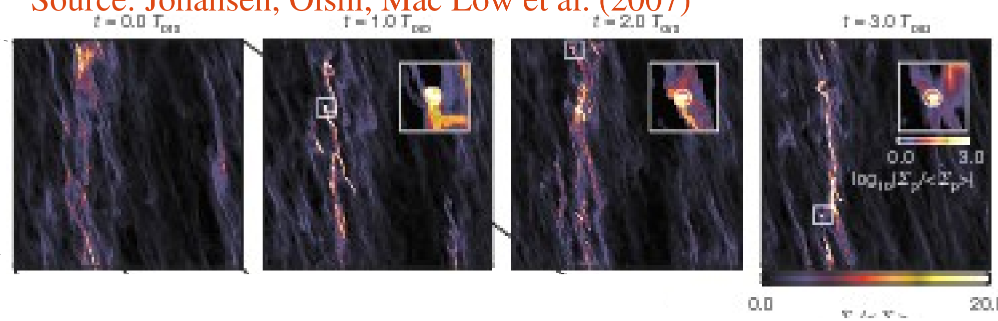
- Critical density for gravitational collapse of clumps

Breaching the meter size barrier by a giant leap

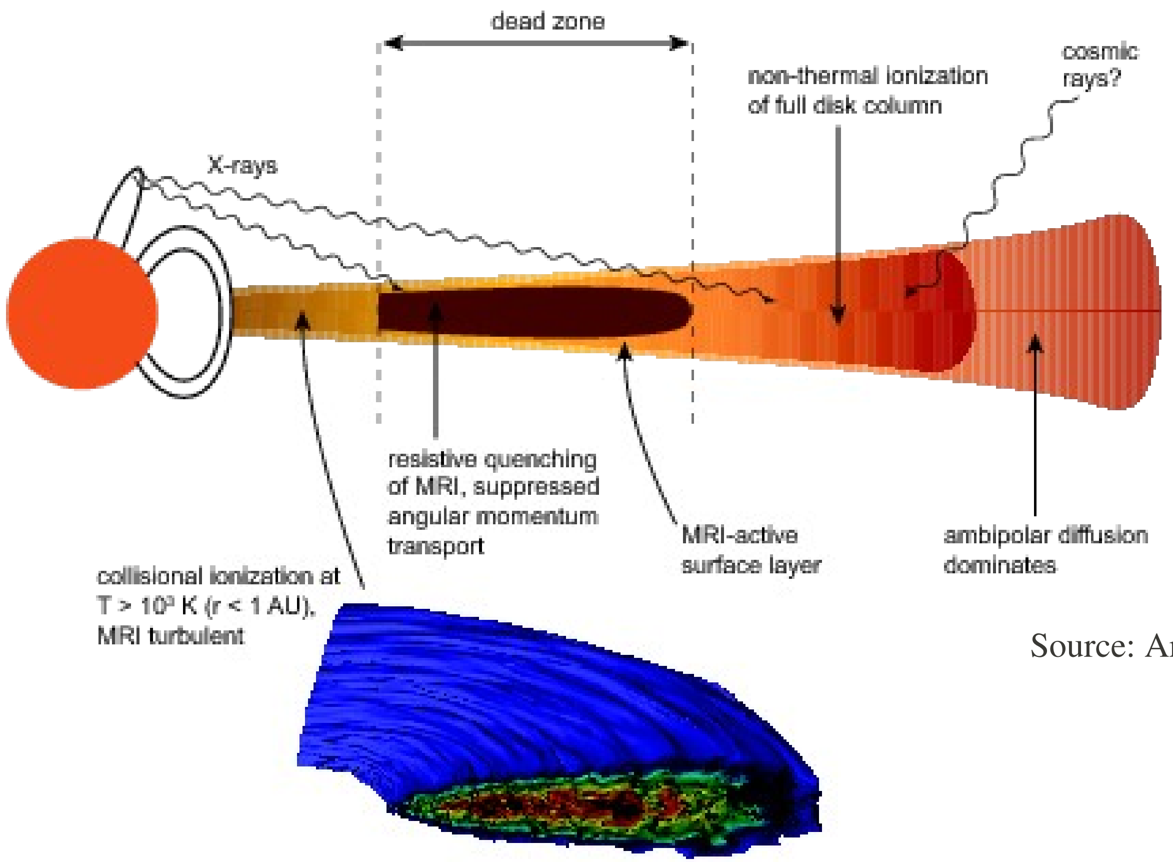




Source: Johansen, Oishi, Mac Low et al. (2007)



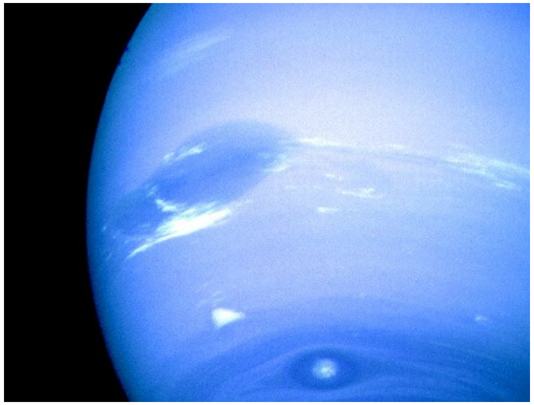
Alas... Dead zones are robust features of accretion disks



Source: Armitage (2010)

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

A possibility: Baroclinic Instability

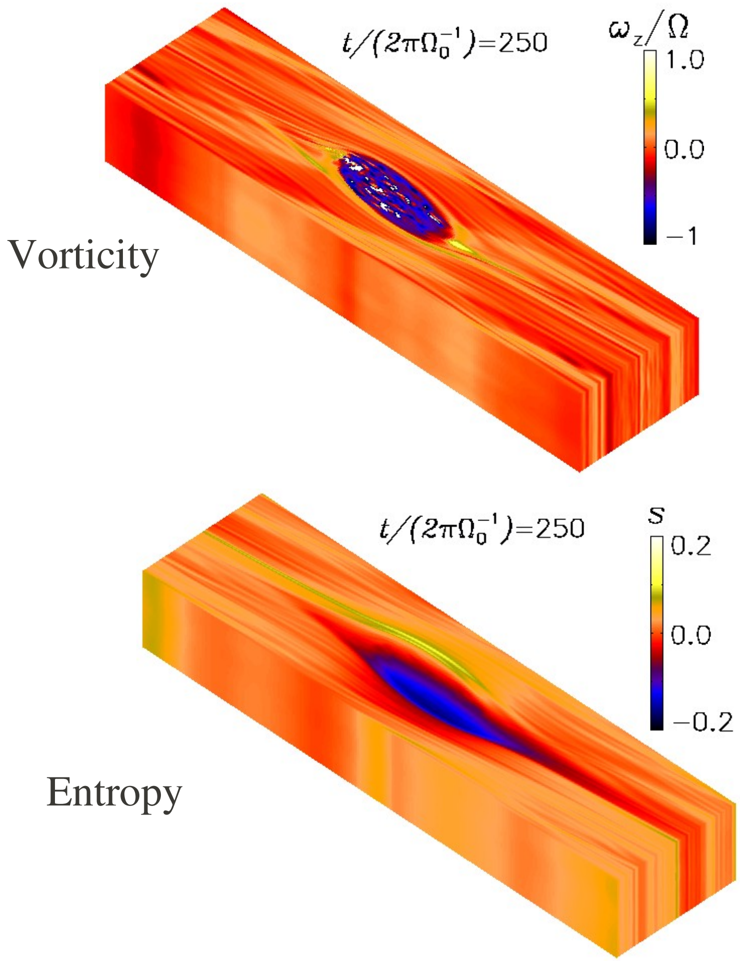


- Well known in planetary atmospheres

And vortices are:

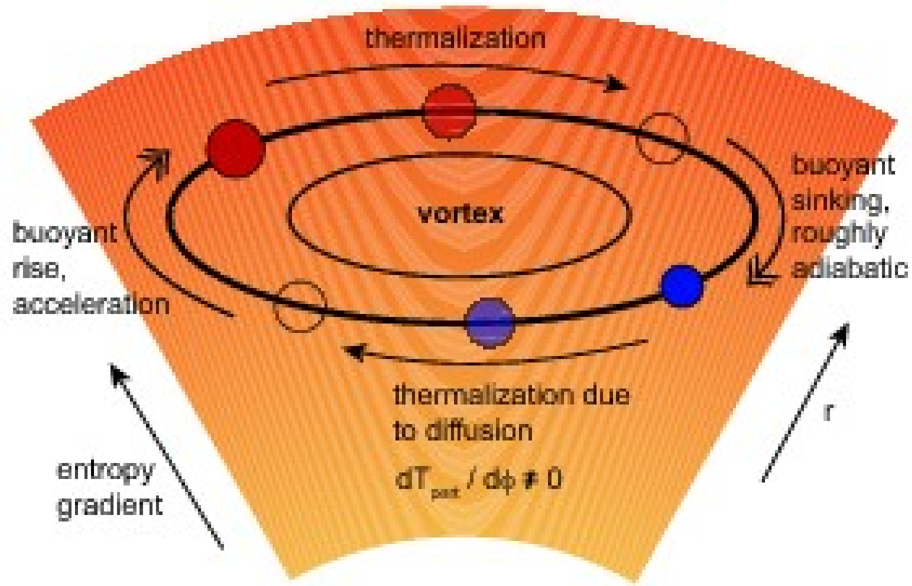
- A solution of the NS equations: persistent structures
- Very interesting for planet formation:

Baroclinic Instability – Excitation and self-sustenance of vortices



Source: Lyra & Klahr (2010)

Sketch of the Baroclinic Instability

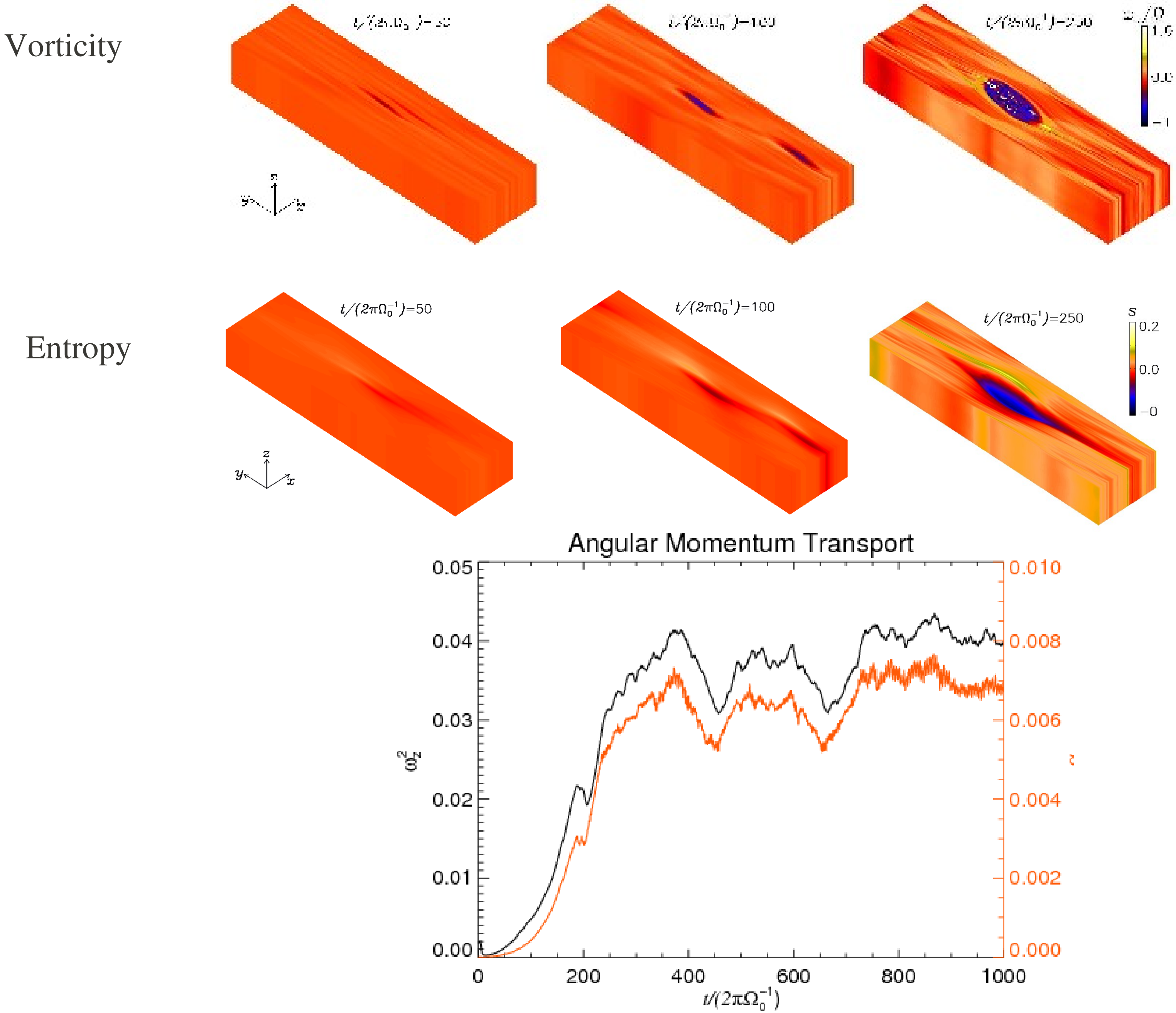


Source: Armitage (2010)

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

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

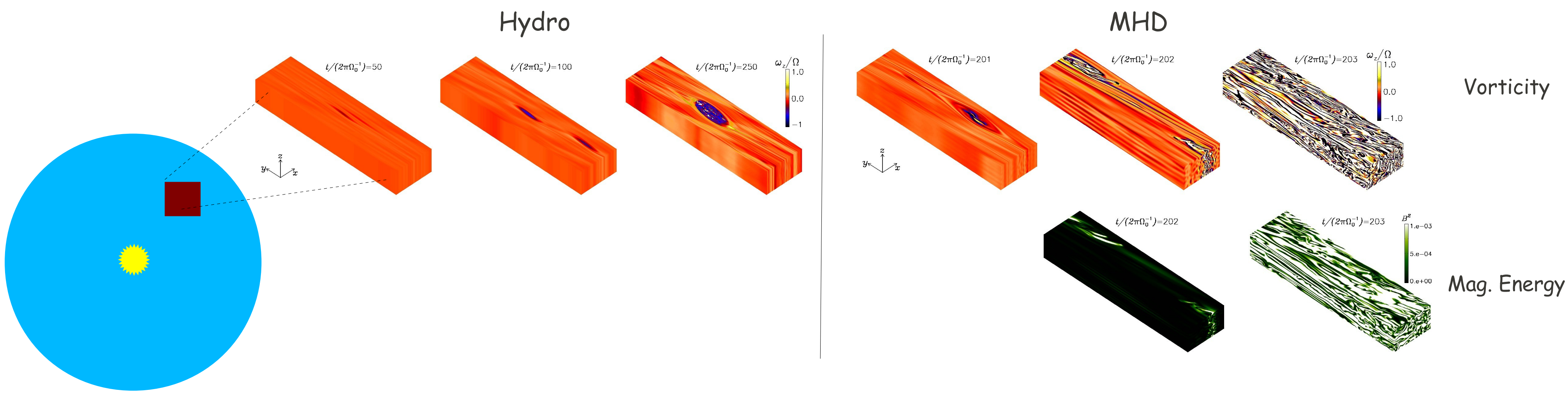
Baroclinic Instability – Excitation and self-sustenance of vortices



Lyra & Klahr (2011)

Interaction of Baroclinic and Magneto-Rotational Instabilities

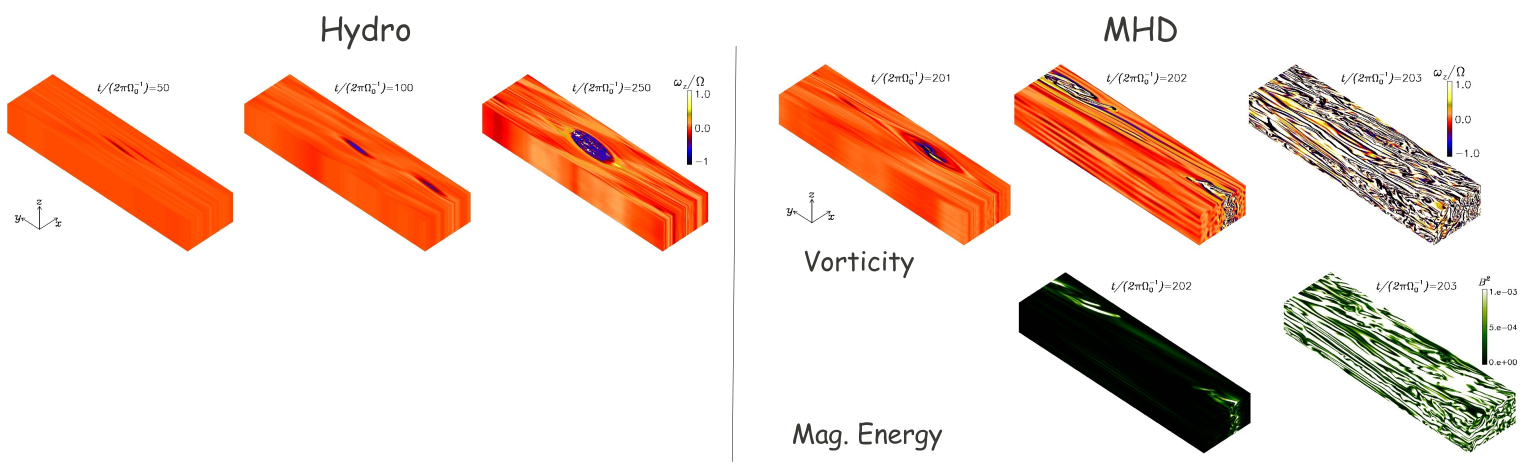
What happens when the vortex is magnetized?

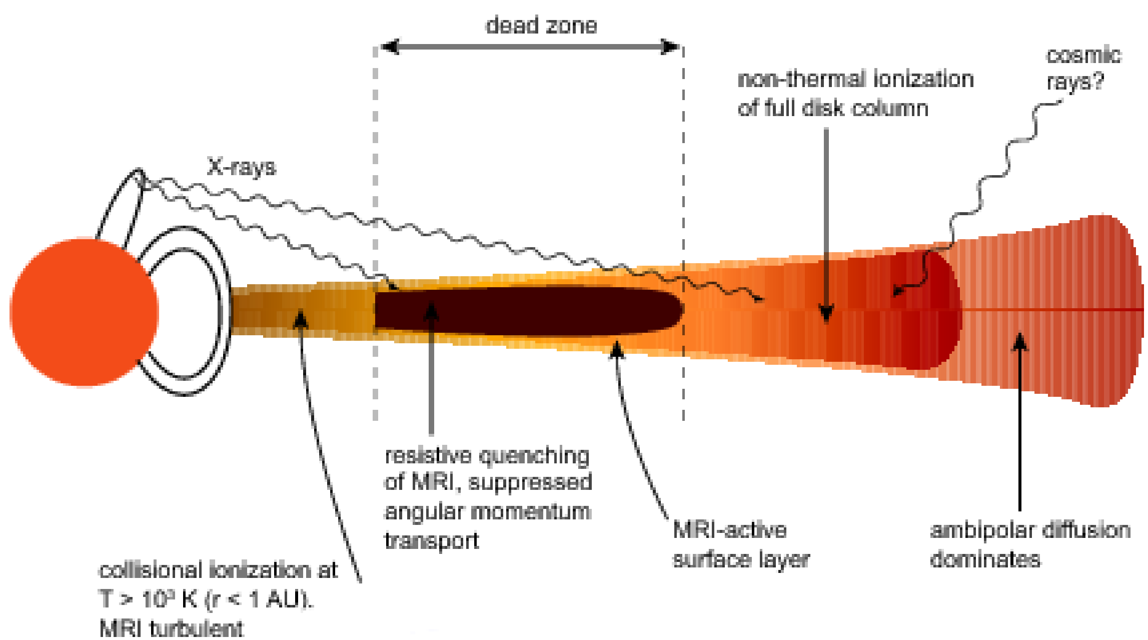


Vortex gone!

Lyra & Klahr (2011)

Suggested large-scale phenomenology





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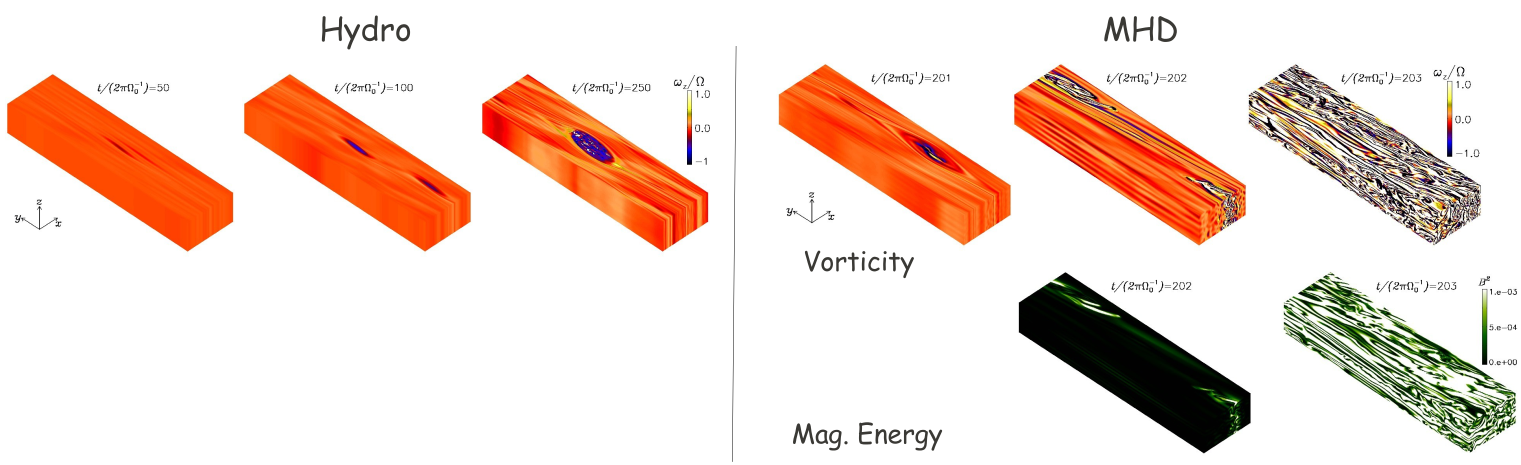
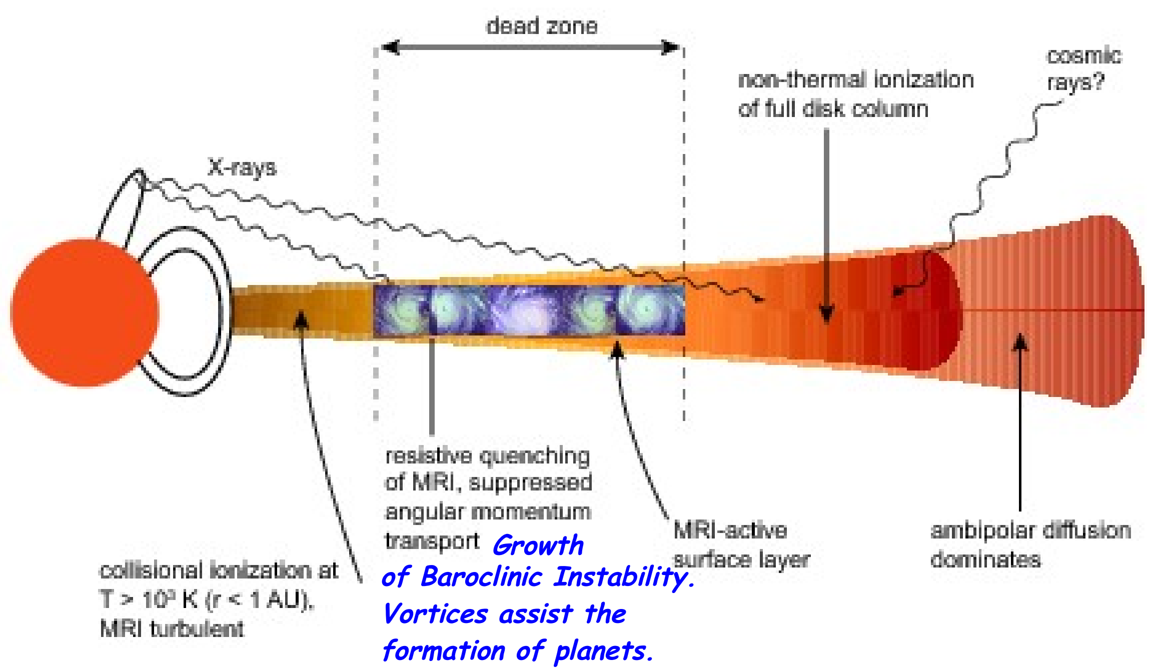
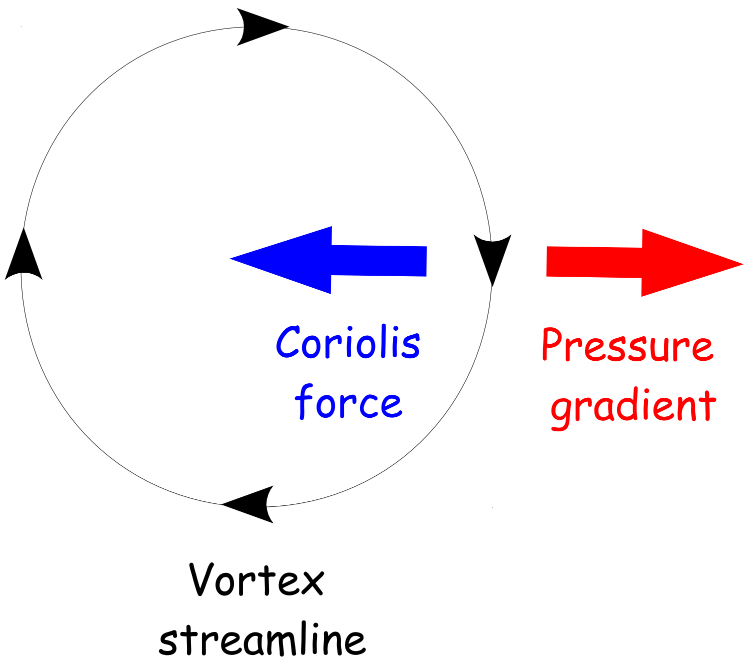




Vortex Equilibrium

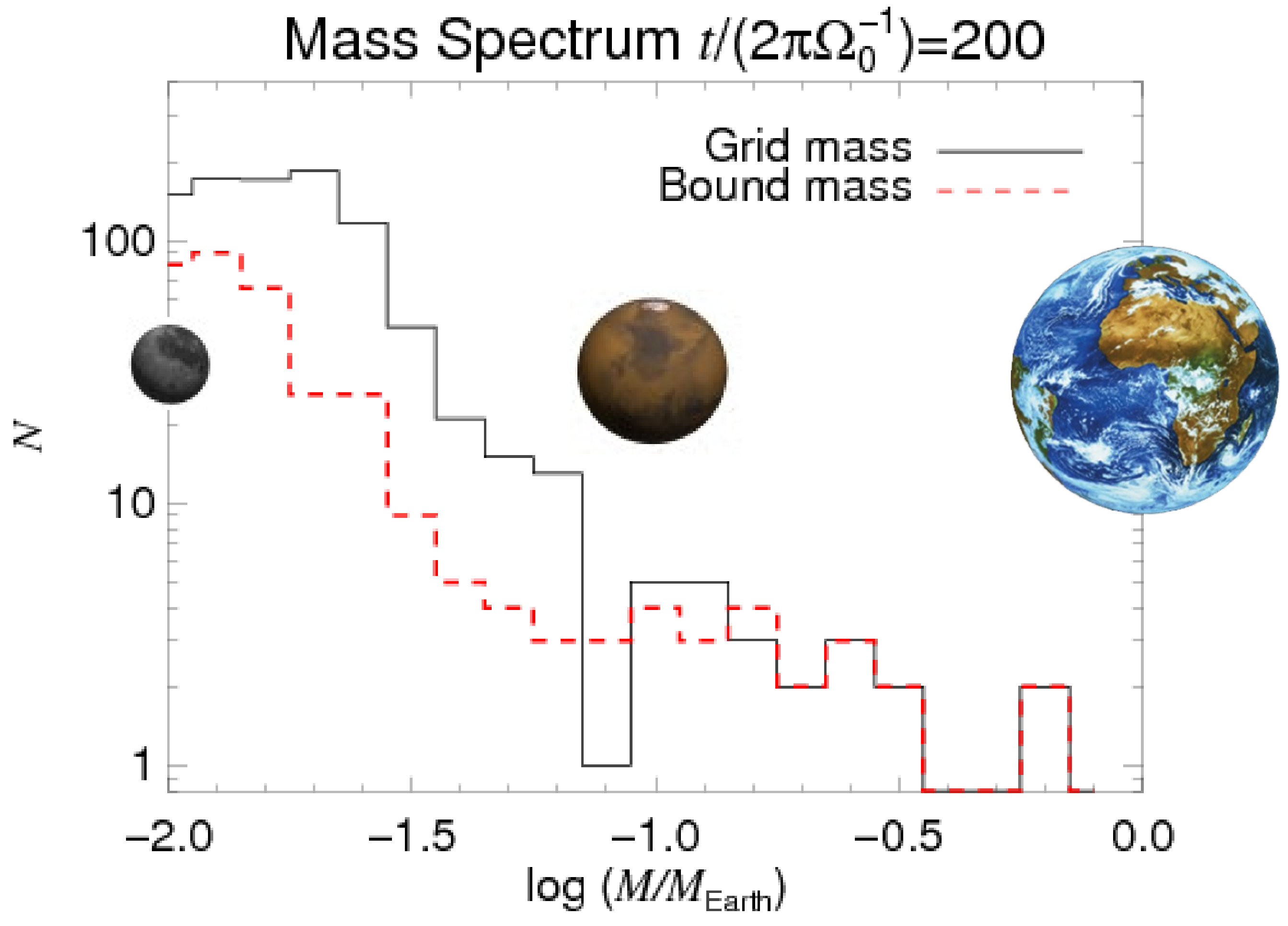


Geostrophic balance:

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

- Particles do not feel the pressure gradient.
- They just sink towards the center, where they accumulate.
- Aid to planet formation (von Weizsäcker, 1946)
- Revisited by Barge & Sommeria (1995)
- Raettig, Lyra, Klahr & Mac Low (in prep)

The Initial Mass Function of planets

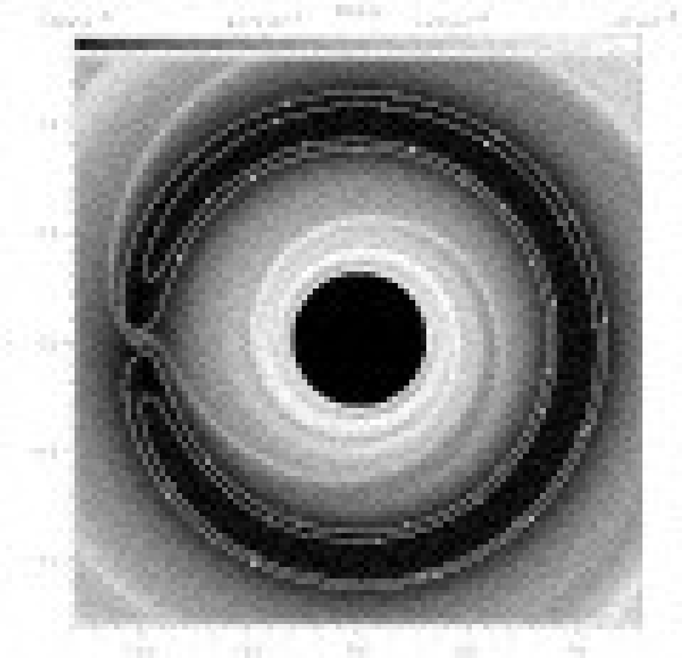


•Mass spectrum by the end of the simulation
•300 bound clumps were formed
•Power law d(log N)/d(log M)=-2.3 +/- 0.2
•20 of these are more massive than Mars

Planets form and start to migrate

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

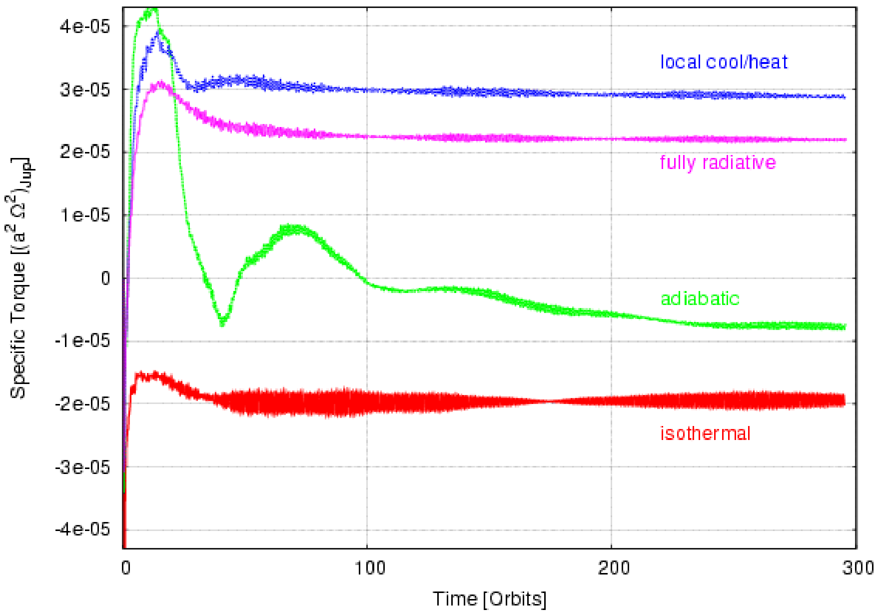
One armed spiral: Lindblad resonance
Horseshoe libration: Co-rotational torques



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

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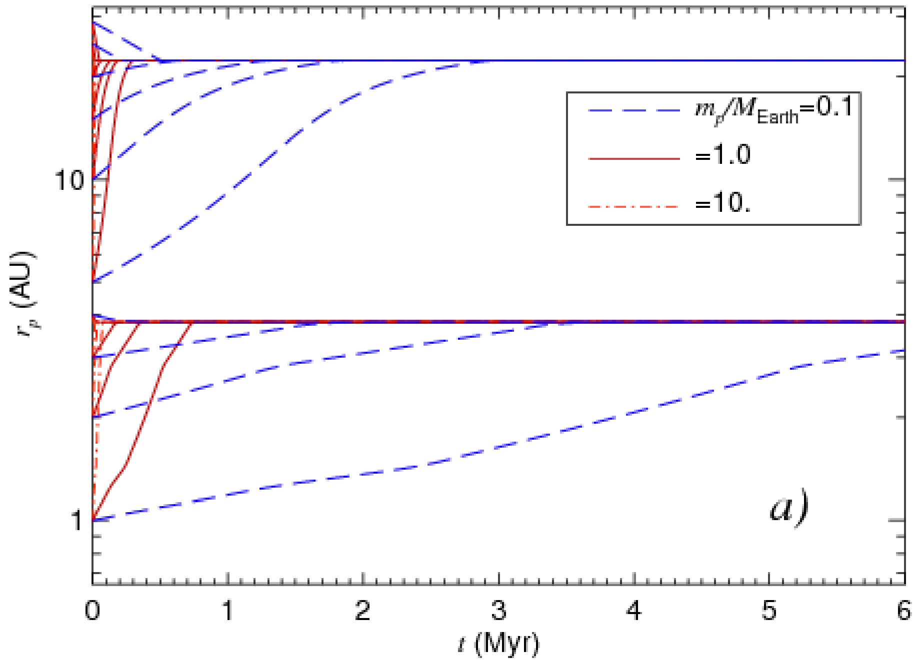
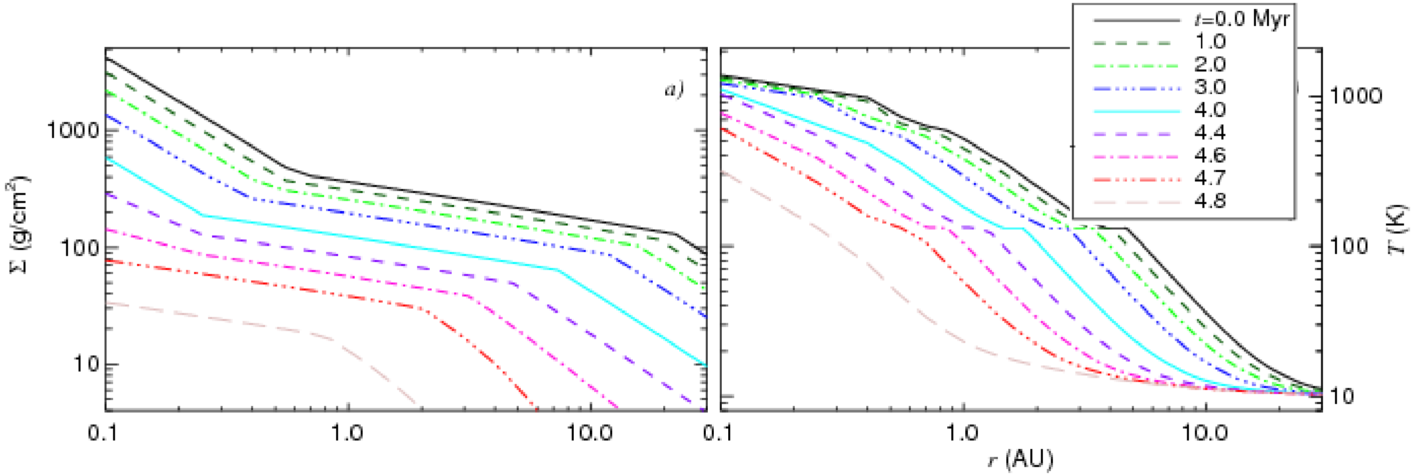


Source: Lyra, Paardekooper, & Mac Low (2010)

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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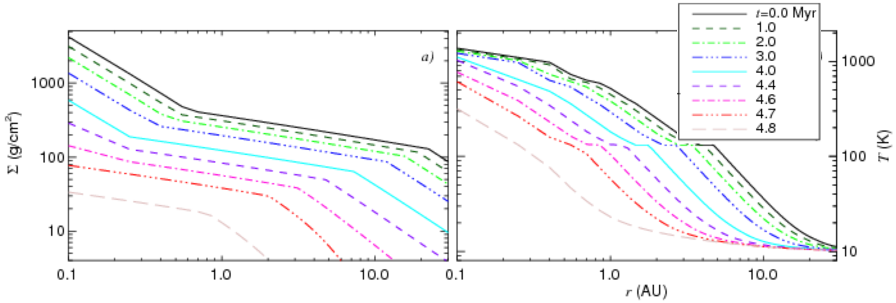
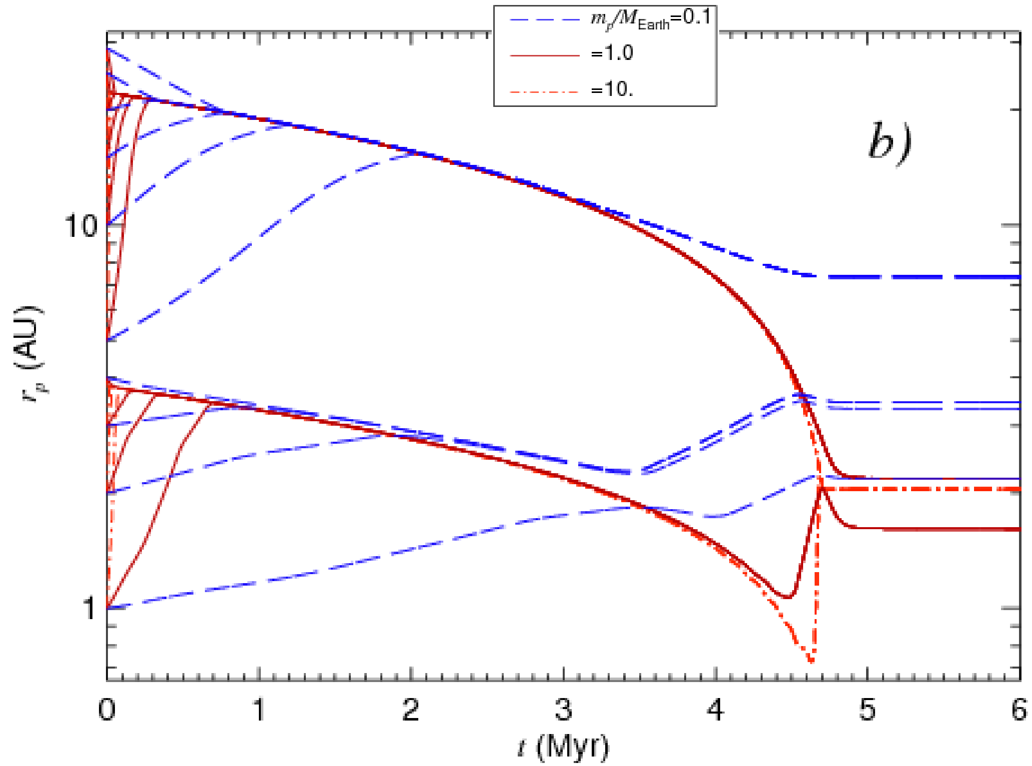


Rule of thumb: ***Migration is***

outwards in
steep temperature gradients,

inwards in
isothermal regions.



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

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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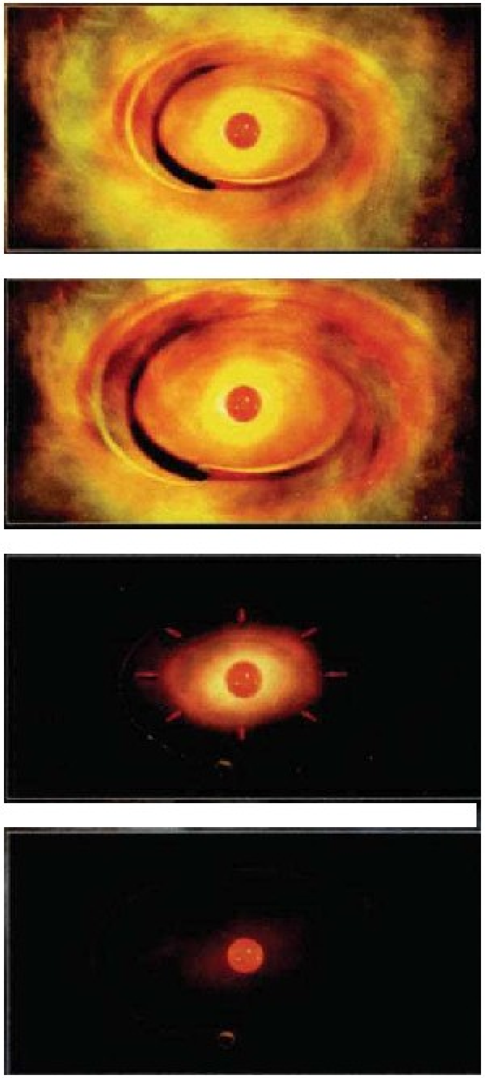

"La Terre sauvée"

REPÈRES Jusqu'à récemment, la naissance du système solaire – et de tous les systèmes planétaires – posait un problème insurmontable : en effet, d'après les modélisations informatiques, les planètes auraient dû être précipitées vers le Soleil avant même d'avoir atteint leur taille définitive, il y a 4,6 milliards d'années. Mais un nouveau modèle semble résoudre définitivement ce paradoxe.

Planètes
On sait pourquoi elles survivent à leur étoile

Par Román Ikonicoff

Alors que les simulations montraient que le Soleil aurait dû happer la Terre et ses sœurs planétaires, un nouveau modèle élucide enfin l'énigme.

"La Terre sauvée". Le titre de la conférence donnée en janvier 2010 par le Brésilien Wladimir Lyra, le Néerlandais Sijme-Jan Paardekooper et l'Américain Mordecai-Mark Mac Low, lors du 215e meeting de la Société astronomique américaine (AAS), était un brin malicieux.

LA TERRE NE DEVRAIT PAS EXISTER

Les trois chercheurs annonçaient ni plus ni moins avoir sauvé la Terre – et toutes les autres planètes du système solaire – d'une chute inéluctable sur le Soleil. Date prévue de ce cataclysme ? 4,6 milliards d'années... en arrière ! Autrement dit, notre planète bleue aurait échappé à une catastrophe qui n'a tout bonnement pas eu lieu – et nous sommes là pour en attester ! Au vrai, ce n'est donc pas la Terre que les trois scientifiques ont sauvée de la chute fatale... mais la communauté astrophysique. Car il faut savoir que depuis une vingtaine d'années, tous les modèles informatiques simulant la naissance du système solaire aboutissaient au même scénario catastrophe : toutes les planètes étaient précipitées dans la fournaise solaire bien avant d'atteindre l'âge de raison. Conclusion : Mars, Vénus, Saturne ou la Terre ne devraient pas exister. Pas plus que les "exoplanètes", ces centaines de planètes lointaines que les télescopes et satellites ont découvertes autour d'autres étoiles →

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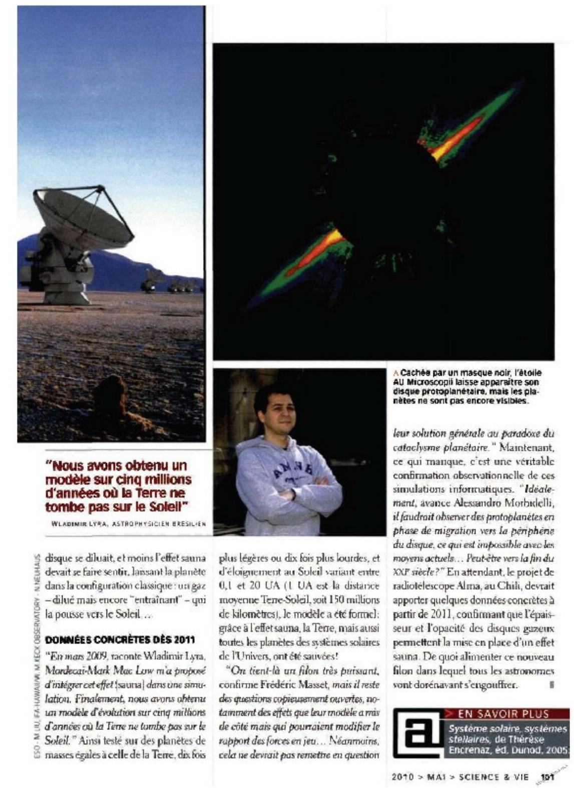

Cachée par un masque noir, l'étoile AU Microscopii laisse apparaître son disque protoplanétaire, mais les planètes ne sont pas encore visibles.

"Nous avons obtenu un modèle sur cinq millions d'années où la Terre ne tombe pas sur le Soleil"

WLADIMIR LYRA, ASTROPHYSICIEN BRÉSILIEN

ESO - M. LIU, IFA-HAWAII/W. M. KECK OBSERVATORY - N. NEUHAUS

disque se diluait, et moins l'effet sauna devait se faire sentir, laissant la planète dans la configuration classique : un gaz – dilué mais encore "entraînant" – qui la pousse vers le Soleil...

DONNÉES CONCRÈTES DÈS 2011

"*En mars 2009,* raconte Wladimir Lyra, *Mordecai-Mark Mac Low m'a proposé d'intégrer cet effet* [sauna] *dans une simulation. Finalement, nous avons obtenu un modèle d'évolution sur cinq millions d'années où la Terre ne tombe pas sur le Soleil.*" Ainsi testé sur des planètes de masses égales à celle de la Terre, dix fois plus légères ou dix fois plus lourdes, et d'éloignement au Soleil variant entre 0,1 et 20 UA (1 UA est la distance moyenne Terre-Soleil, soit 150 millions de kilomètres), le modèle a été formel : grâce à l'effet sauna, la Terre, mais aussi toutes les planètes des systèmes solaires de l'Univers, ont été sauvées !

"*On tient-là un filon très puissant,* confirme Frédéric Masset, *mais il reste des questions copieusement ouvertes, notamment des effets que leur modèle a mis de côté mais qui pourraient modifier le rapport des forces en jeu... Néanmoins, cela ne devrait pas remettre en question leur solution générale au paradoxe du cataclysme planétaire.*" Maintenant, ce qui manque, c'est une véritable confirmation observationnelle de ces simulations informatiques. "*Idéalement,* avance Alessandro Morbidelli, *il faudrait observer des protoplanètes en phase de migration vers la périphérie du disque, ce qui est impossible avec les moyens actuels... Peut-être vers la fin du XXIe siècle ?*" En attendant, le projet de radiotélescope Alma, au Chili, devrait apporter quelques données concrètes à partir de 2011, confirmant que l'épaisseur et l'opacité des disques gazeux permettent la mise en place d'un effet sauna. De quoi alimenter ce nouveau filon dans lequel tous les astronomes vont dorénavant s'engouffrer.

> EN SAVOIR PLUS
Système solaire, systèmes stellaires, de Thérèse Encrenaz, éd. Dunod, 2005

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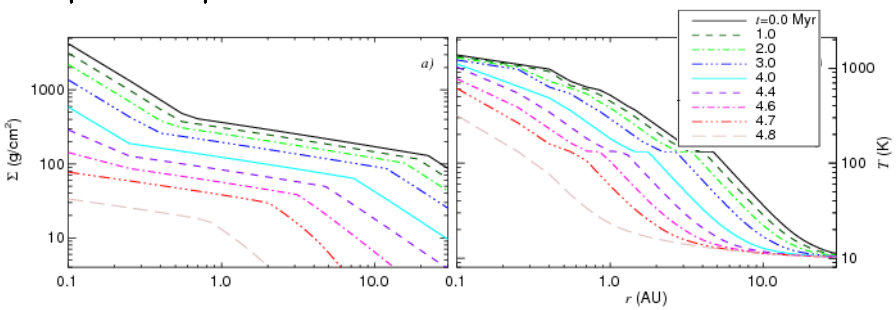
Disks evolve in time, due to
photoevaporative winds and viscous evolution



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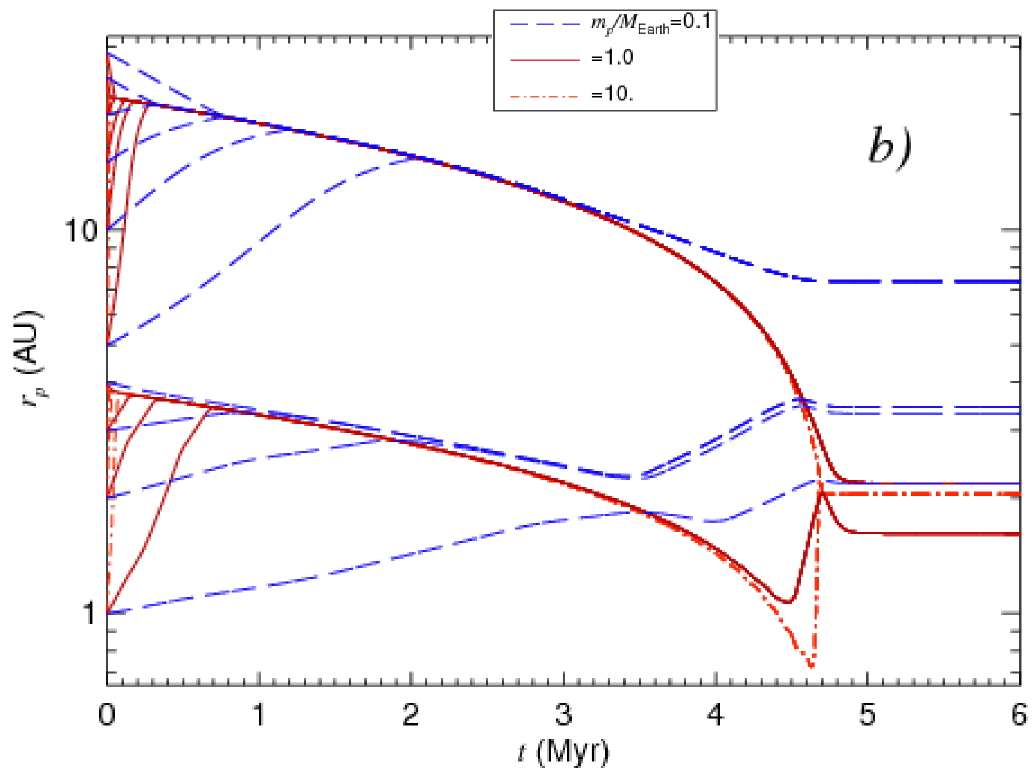
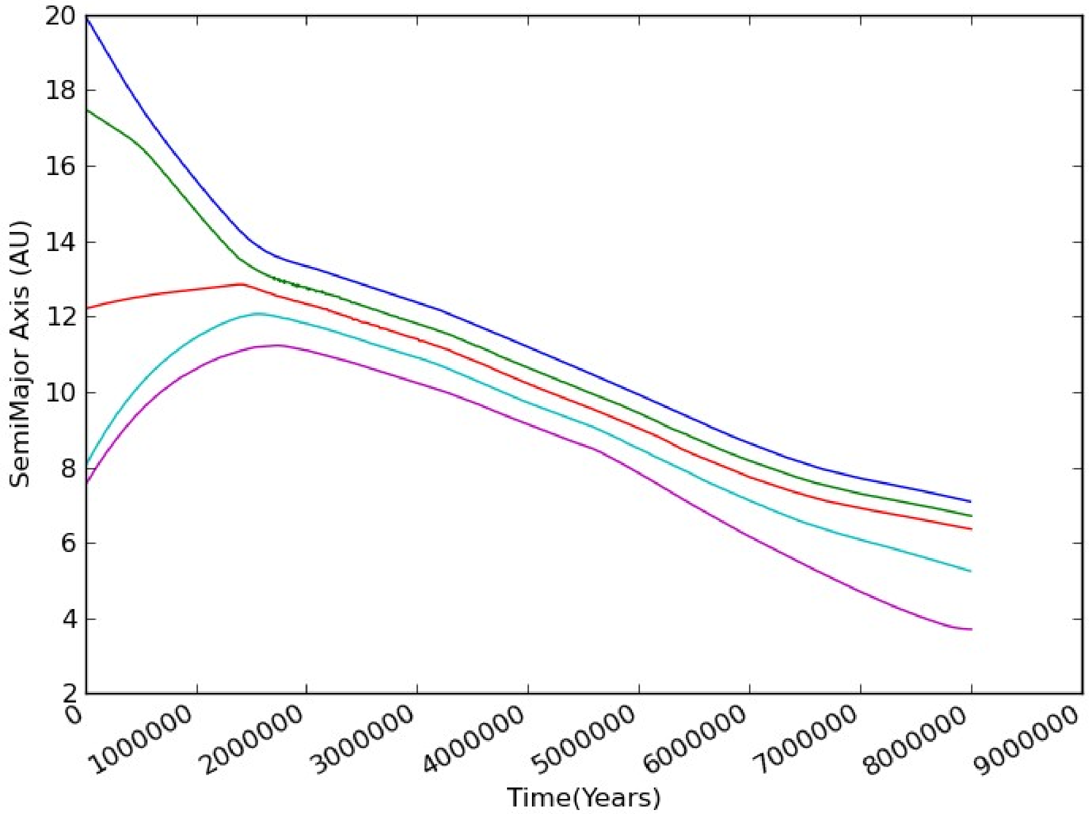


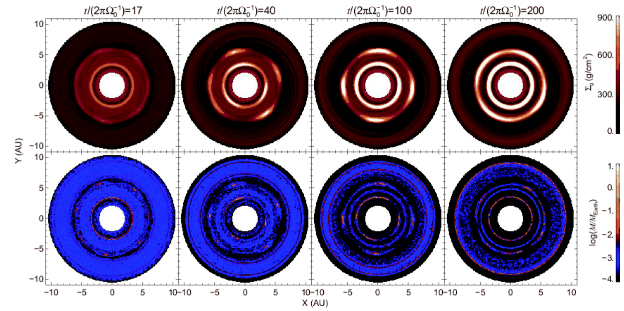
Source: Lyra, Paardekooper, & Mac Low (2010)

Migration + N-Body in Evolutionary Models



Migration in resonance!

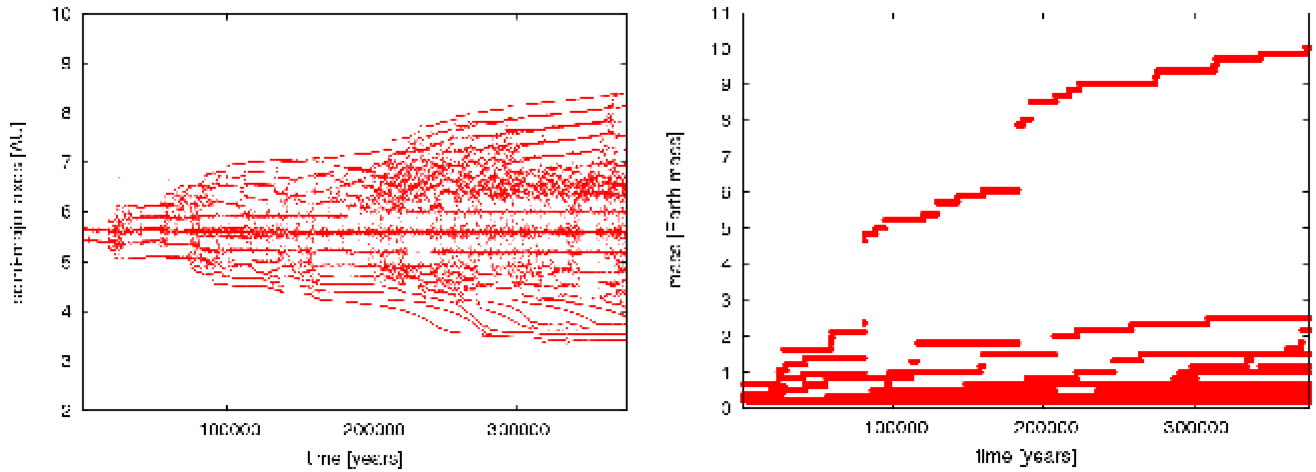
Forming giant planet cores at migration traps



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.

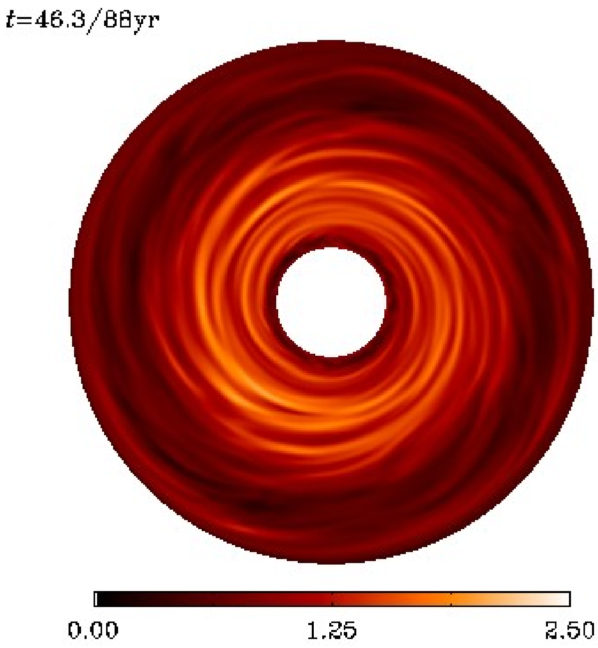
Parametrized turbulence

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

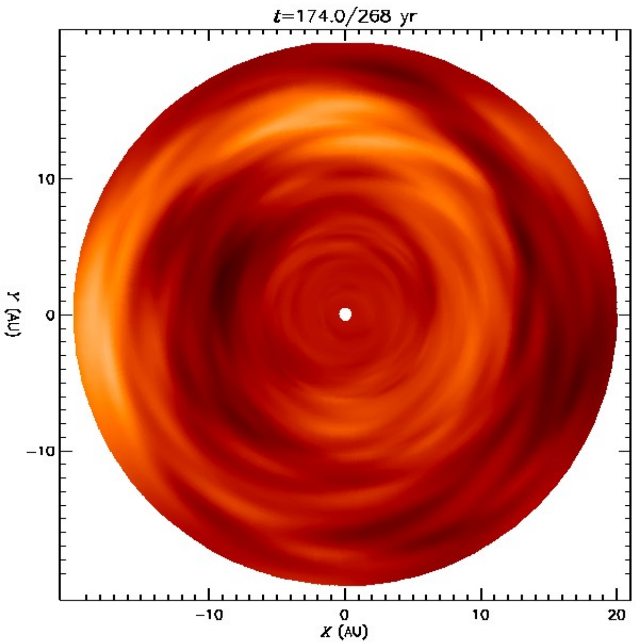
$$\Phi = A r^2 \Omega^2 \sum_{i=1}^{n} \Lambda_{c,m}$$

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

MHD modeling

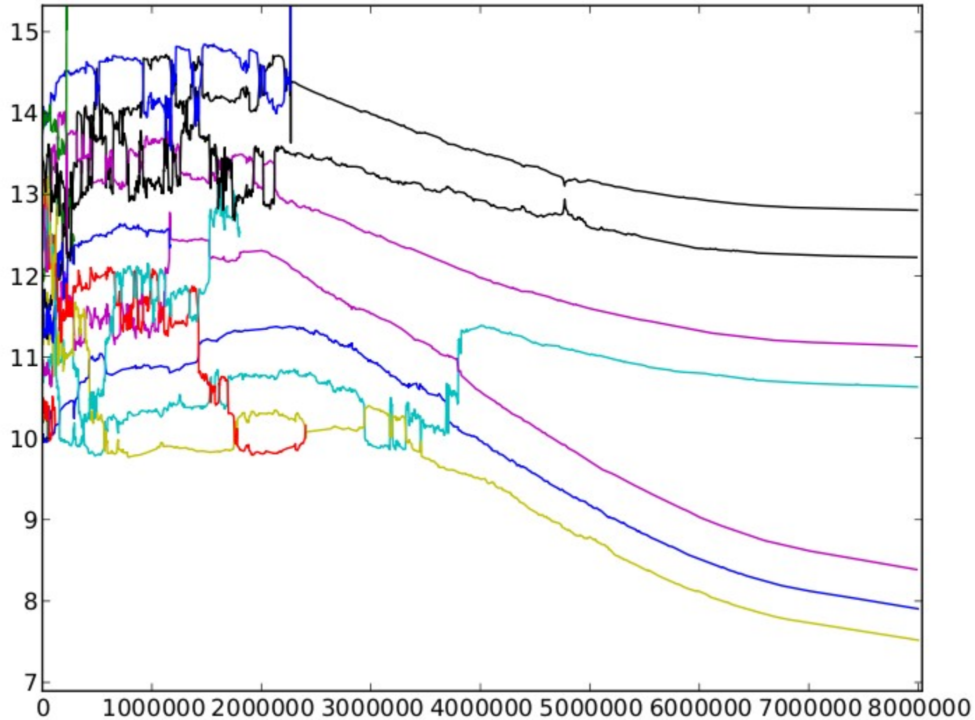


Linear superposition of modes



Orbital migration of interacting planets in a radiative evolutionary model

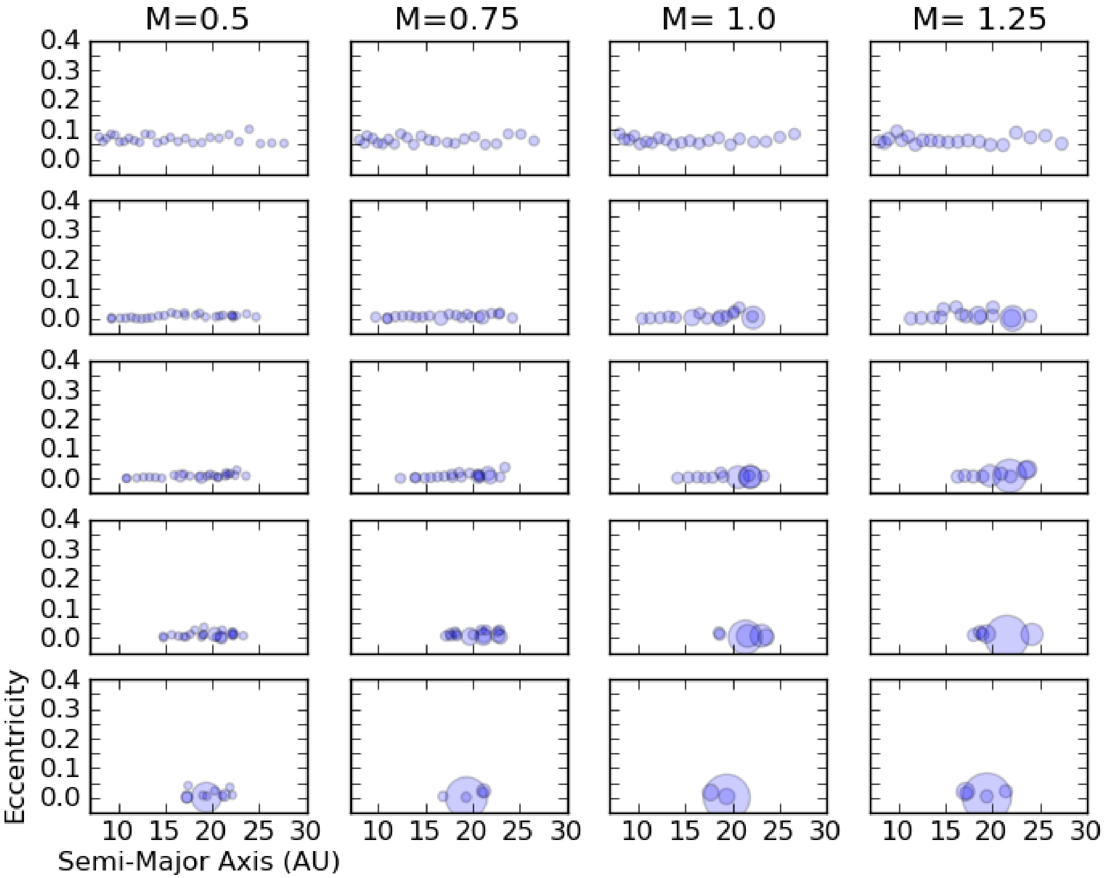
Combines
migration + N-body + photoevaporation + turbulence
modelled as stochastic forcing
(Laughlin et al. 2004, Ogihara et al. 2007)



Horn, Lyra, & Mac Low (in prep)

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

Orbital migration of interacting planets in a radiative evolutionary model



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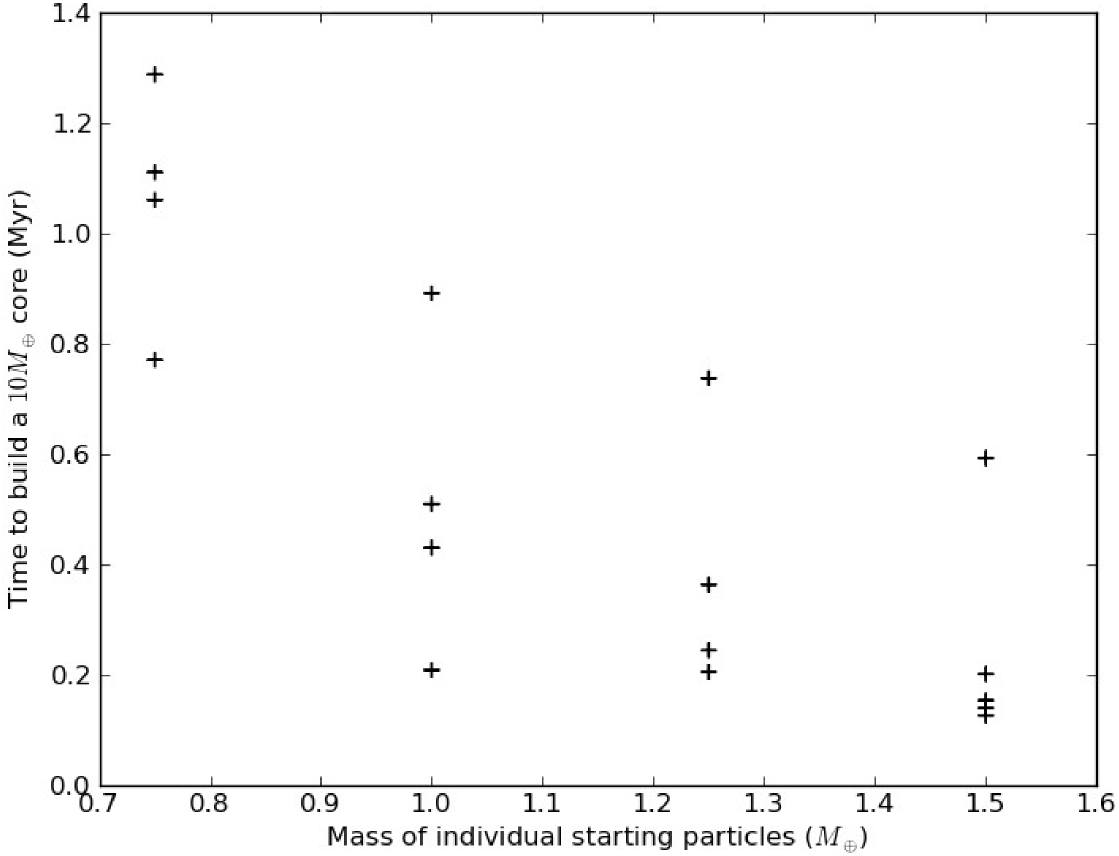

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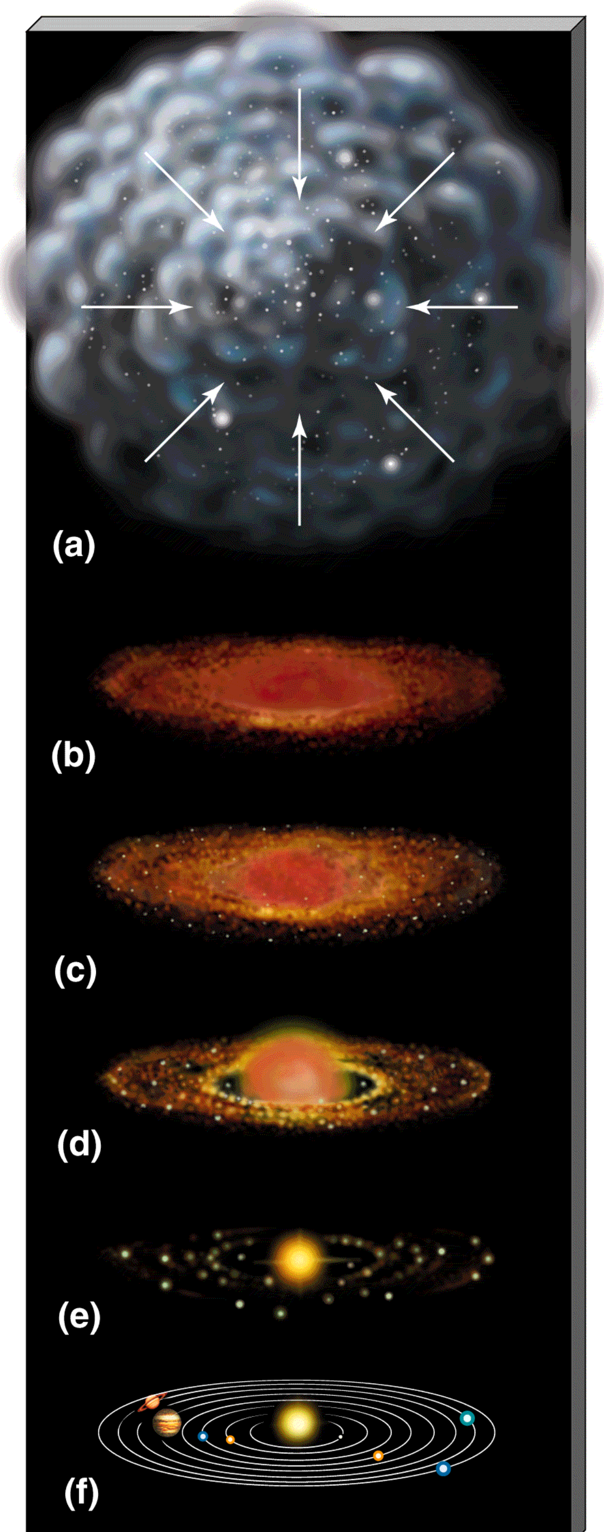
Summarizing



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.

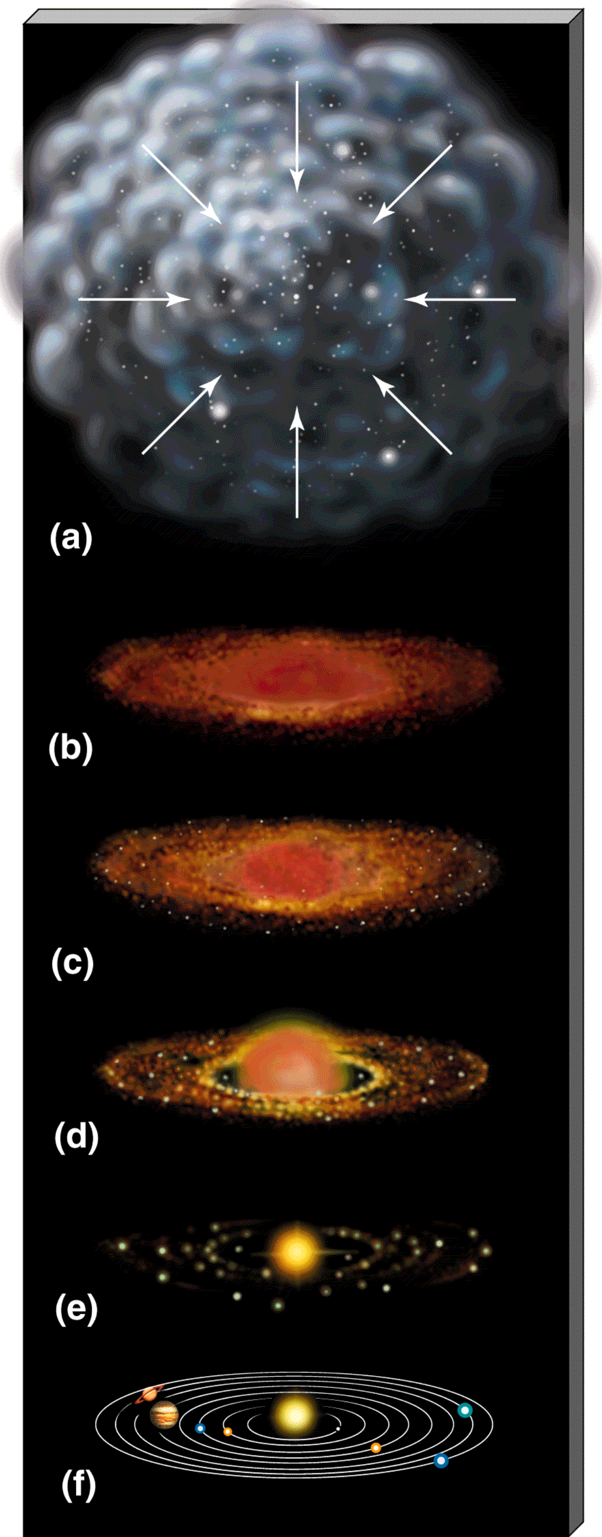
Vortices may be excited in the dead zone. Inside them, the first dozens of Mars-mass embryos are formed. IMF ~ -2

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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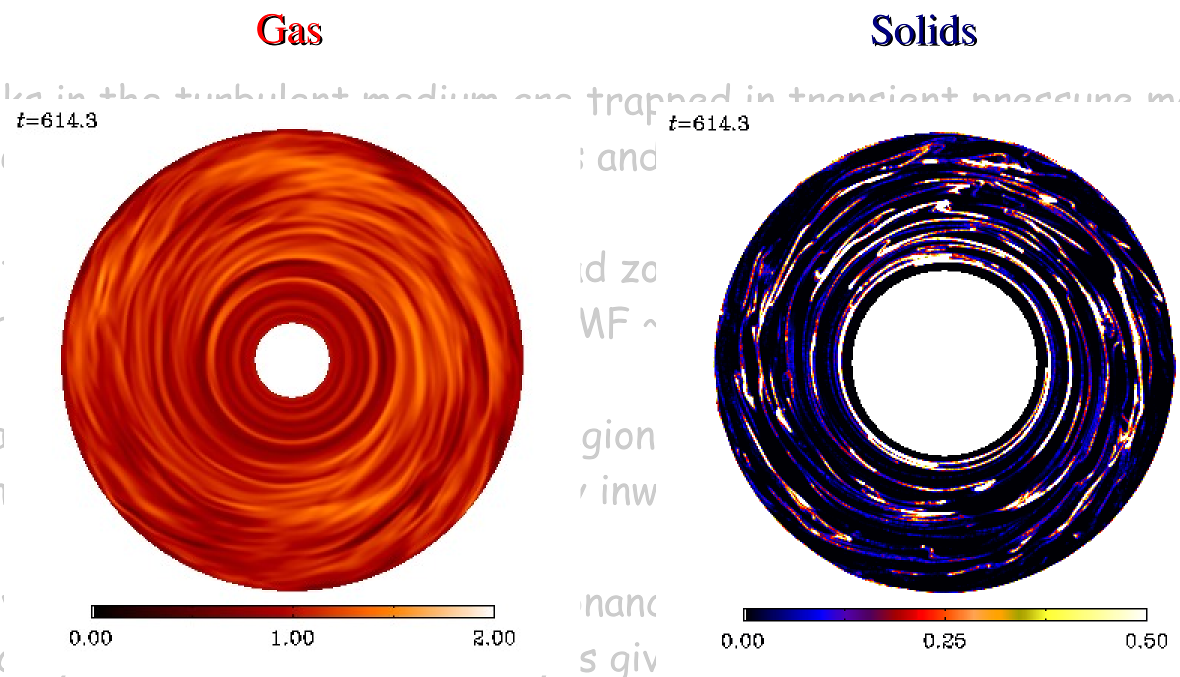
Rocks in the turbulent medium are trapped in transient pressure maxima and
und... and



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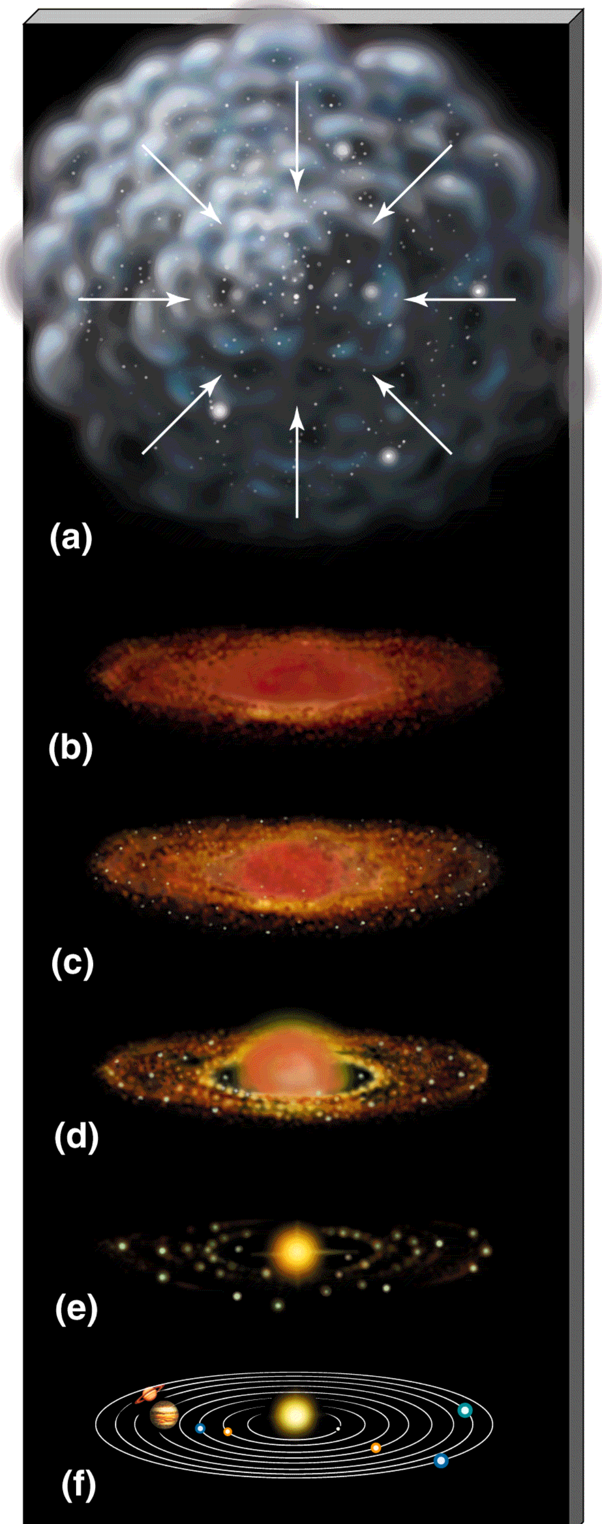
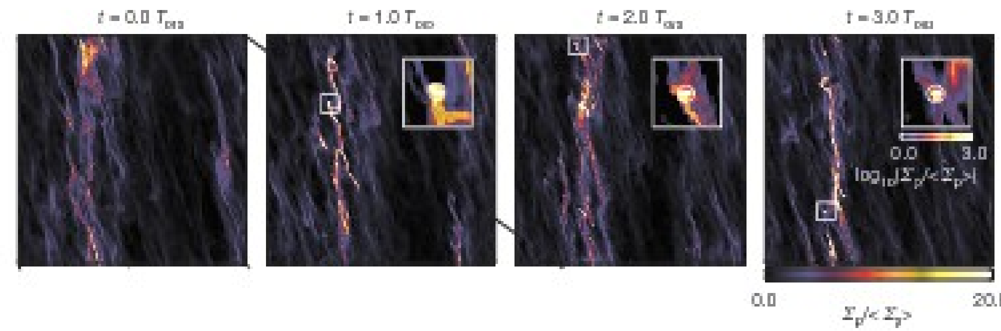
The disk thins due to photoevaporation. Planets released into stable orbits.

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



Summarizing

Gravitational collapse



Outward transport o
the MRI. Dust coagul
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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 d
Mars-mass embryos are formed.

Opacity transitions develop into
planets converge to these zones

Convergent migration leads to re
forcing. Collisions between embr

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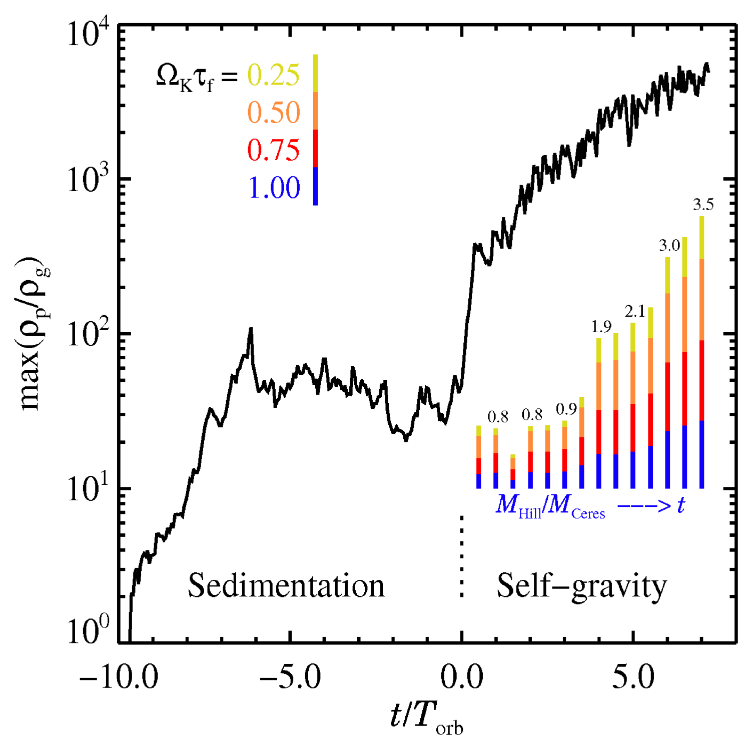

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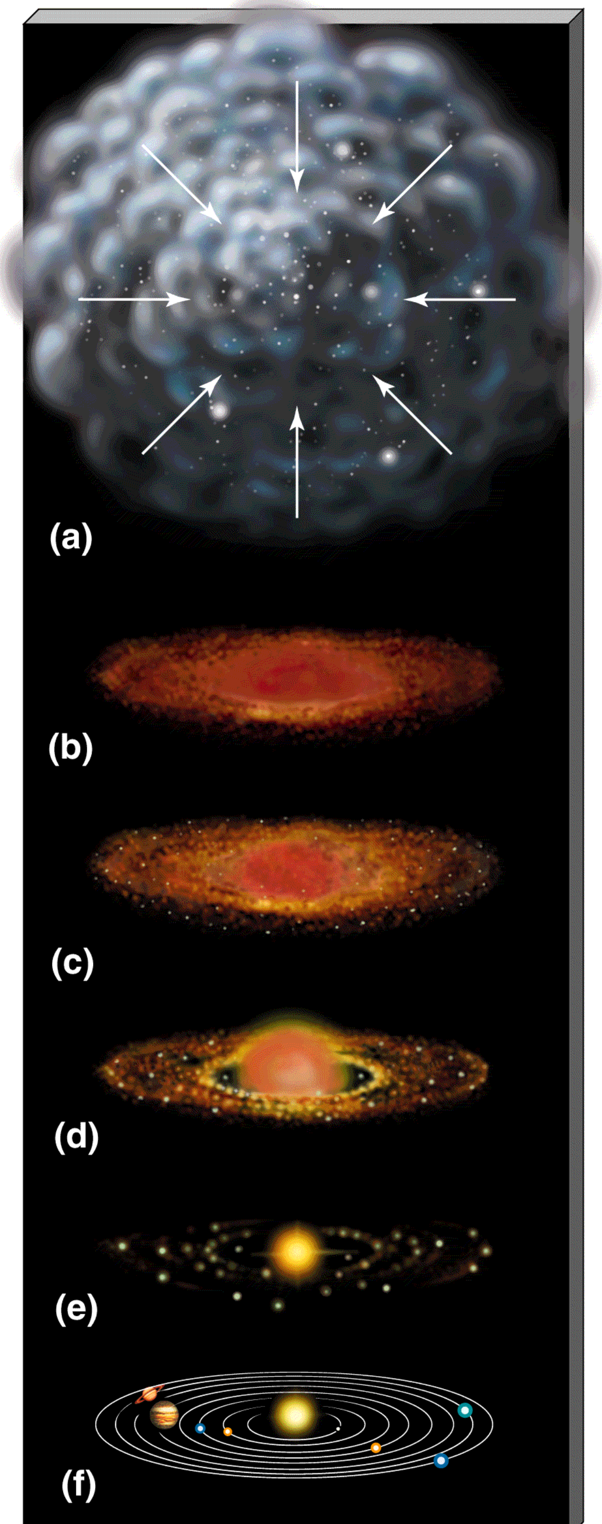
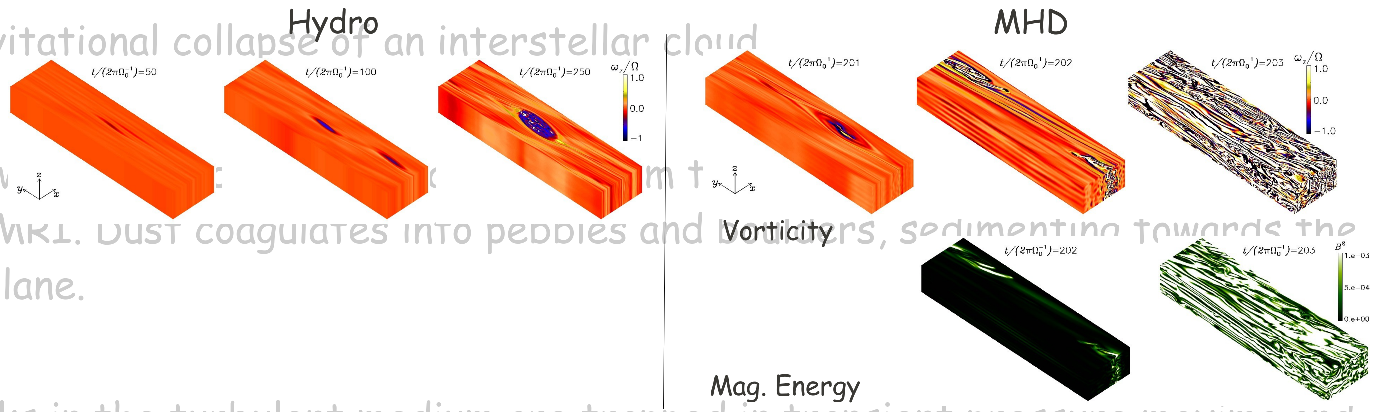
Summarizing



Gravitational collapse of an interstellar cloud



Outw… 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 within the dead zone (BI). Inside them, the first dozens of Mars-mass embryos are formed. IMF ~ -2

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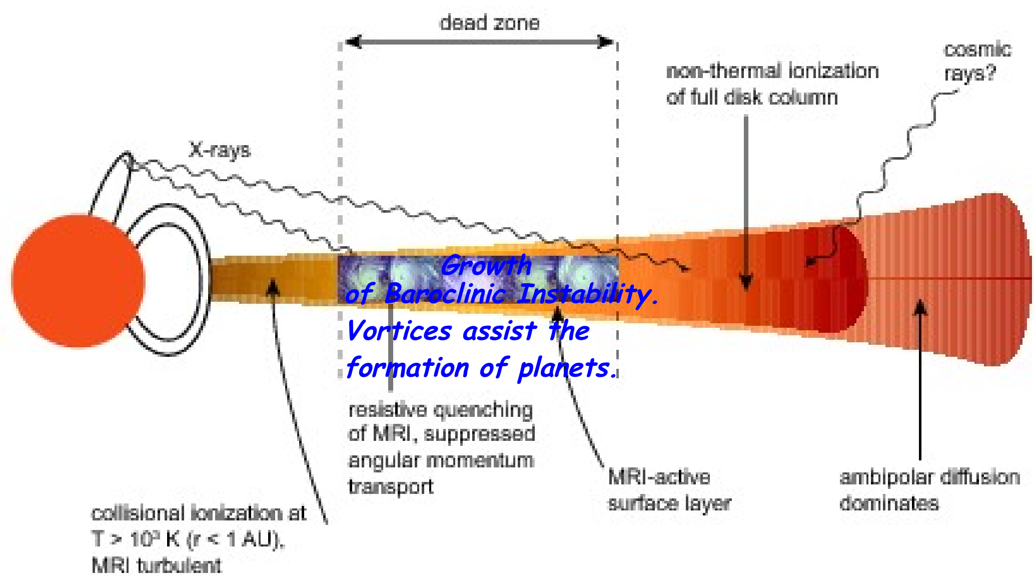

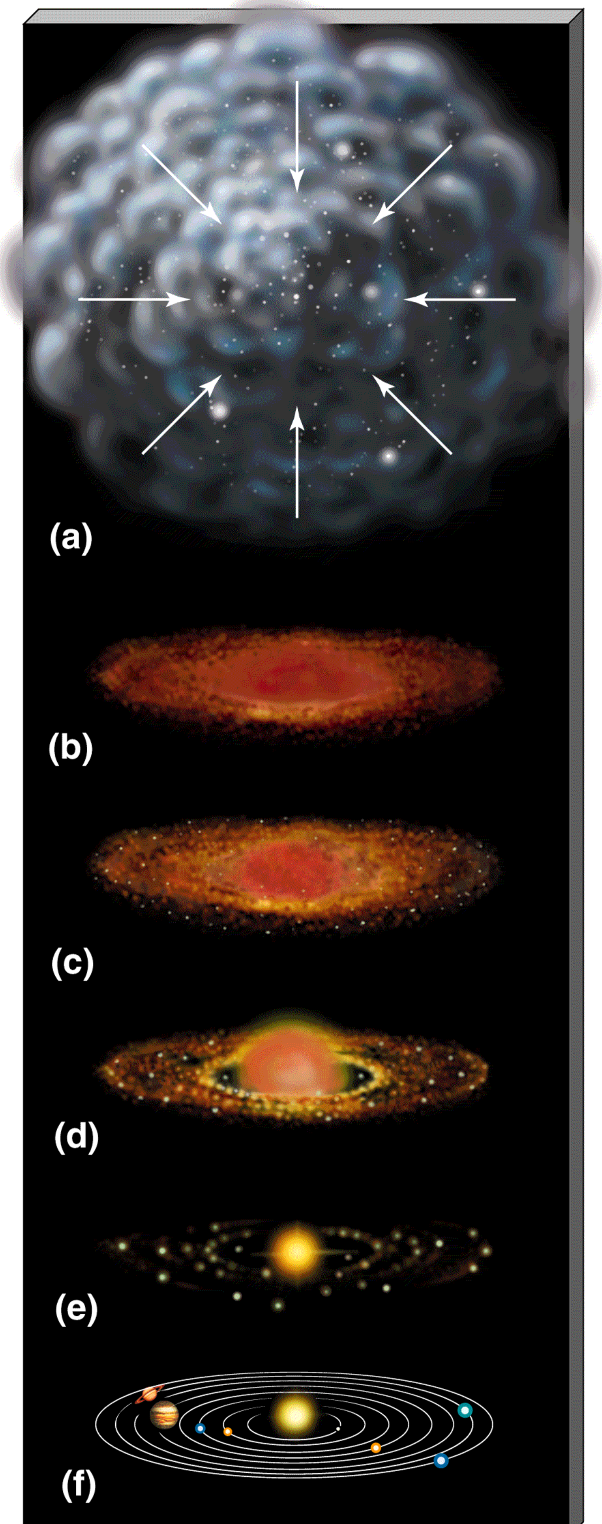

Summarizing

Gravitational collapse of an interstellar cloud

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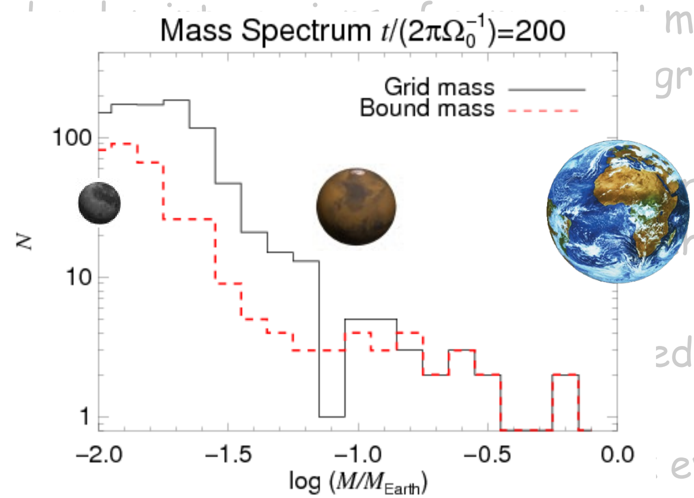
Opacity transitior ... migration. Low mass planets converge ... gration.

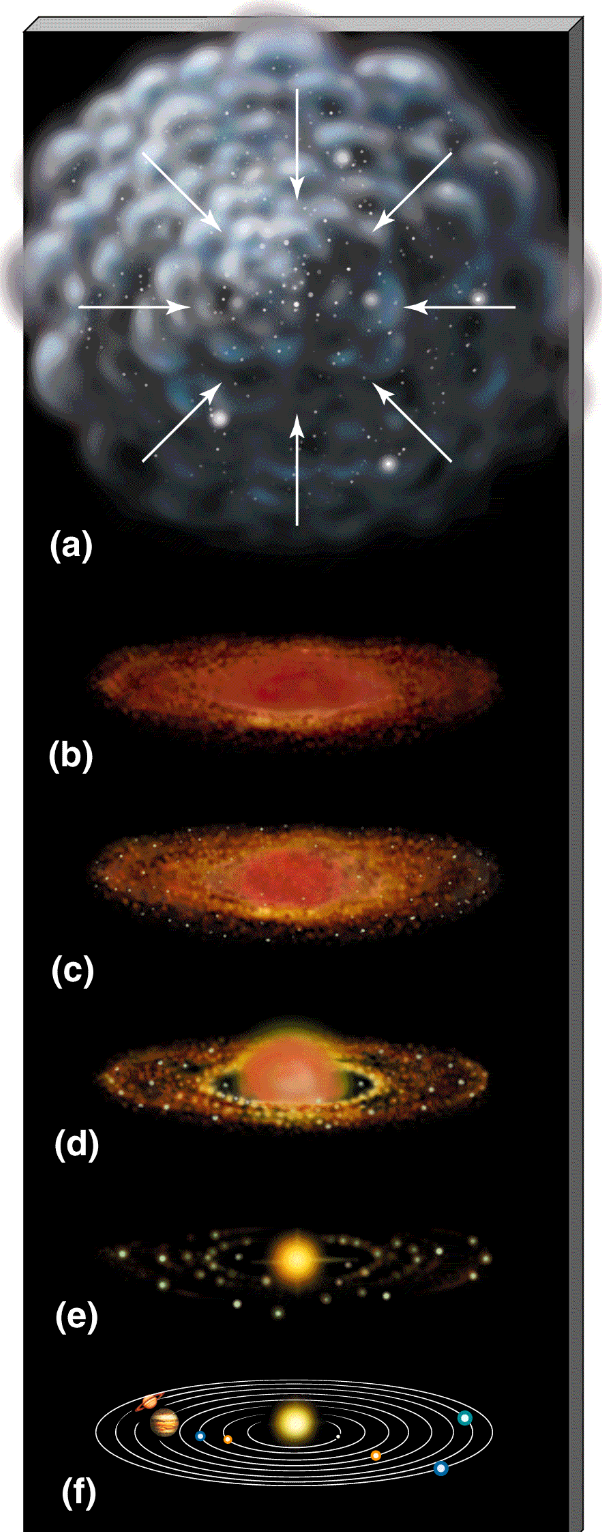


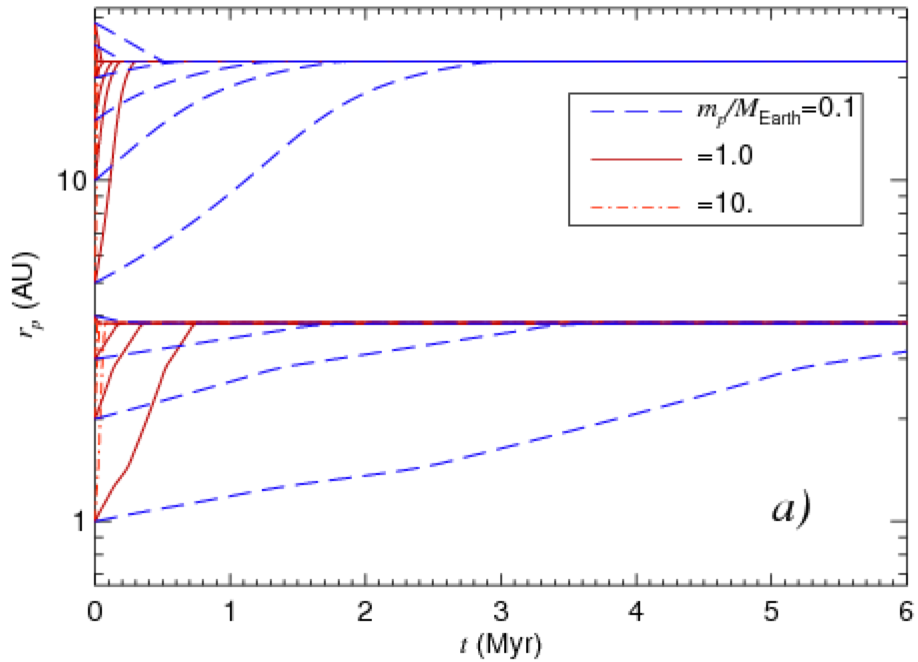
Convergent migra ... rupted by turbulent forcing. Collisions ... ns.

The disk thins du ... ed into stable orbits.

N-body interactio ... evaporation produce the system's final architecture.

Summarizing





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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.

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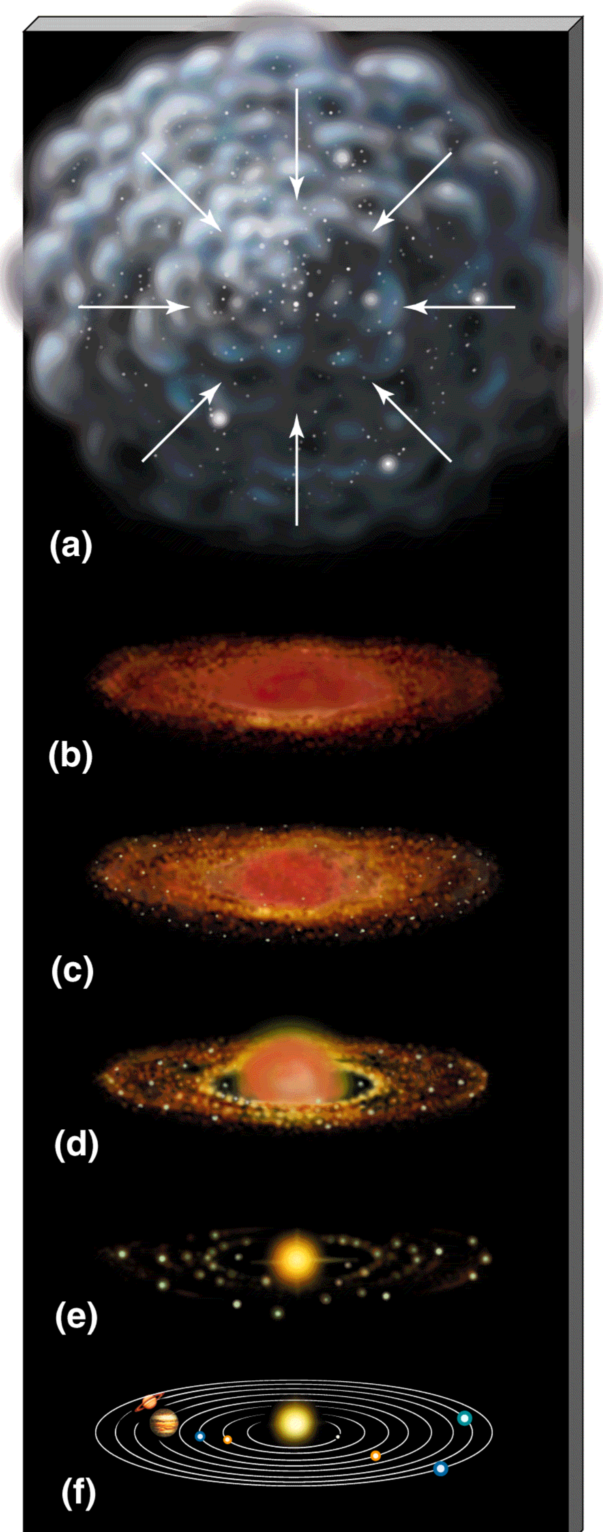

Summarizing

Gravitational collapse of an interstellar cloud

Outward transport of angular momentum through turbulence generated by

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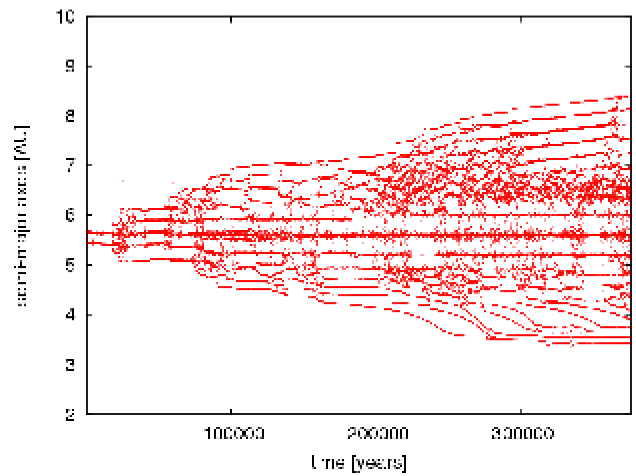

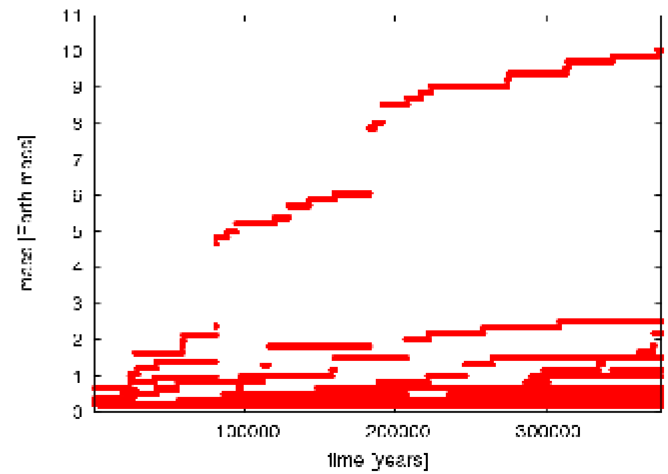

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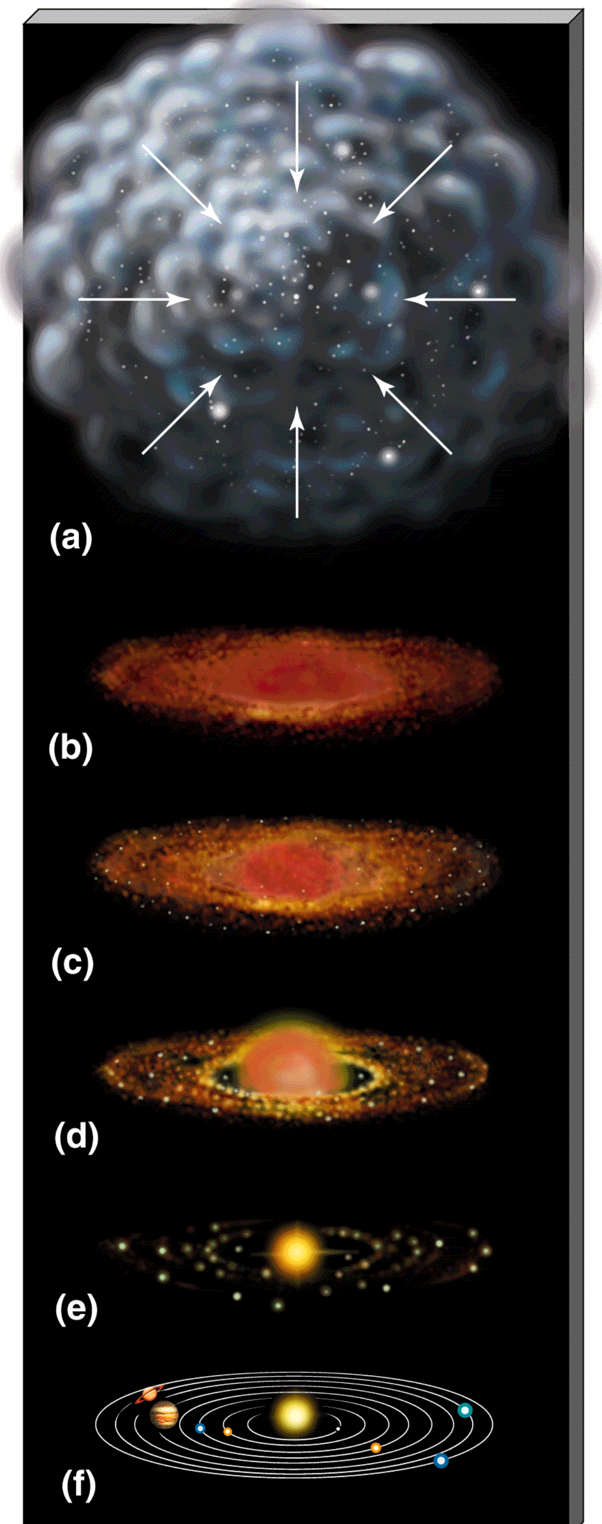
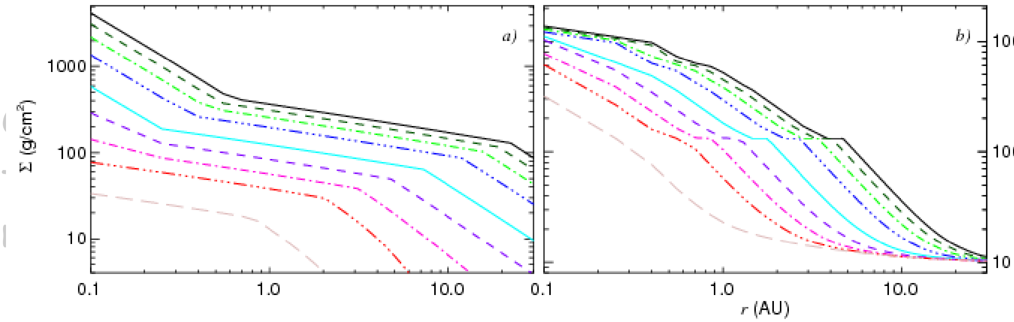
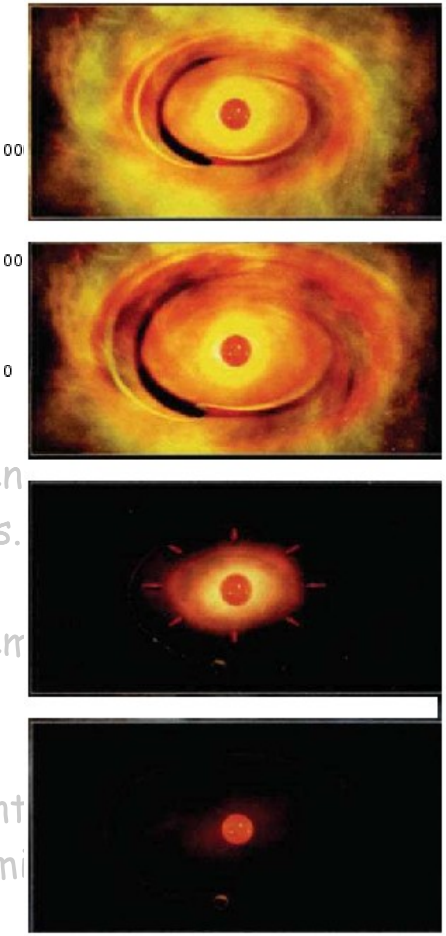
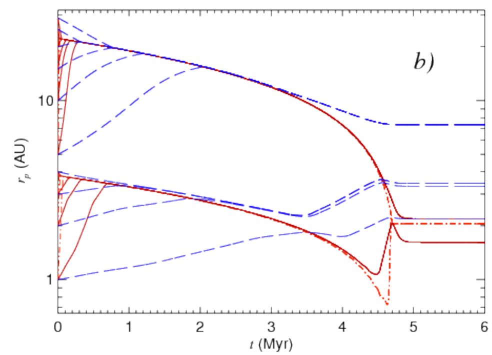


Summarizing





Rocks in the turbulent medium are trapped in transien
undergo col … dwarf planets.



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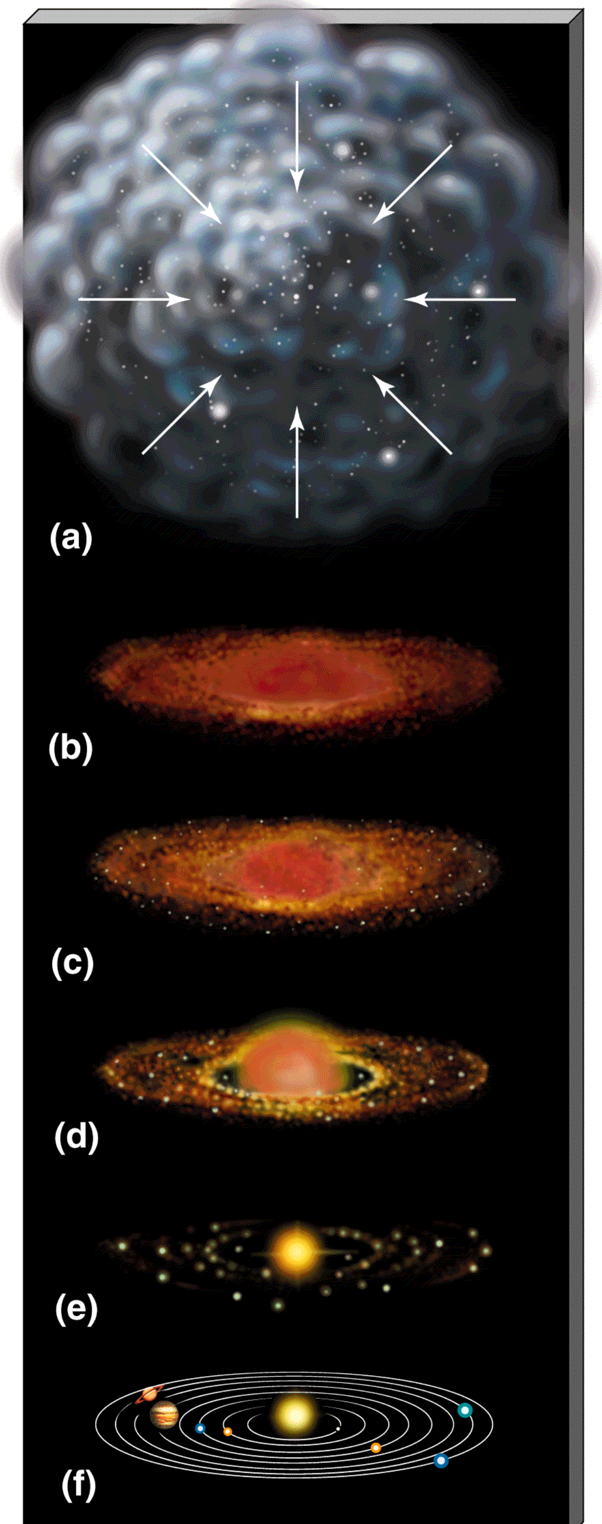

Summarizing

Gravitational collapse of an interstellar cloud

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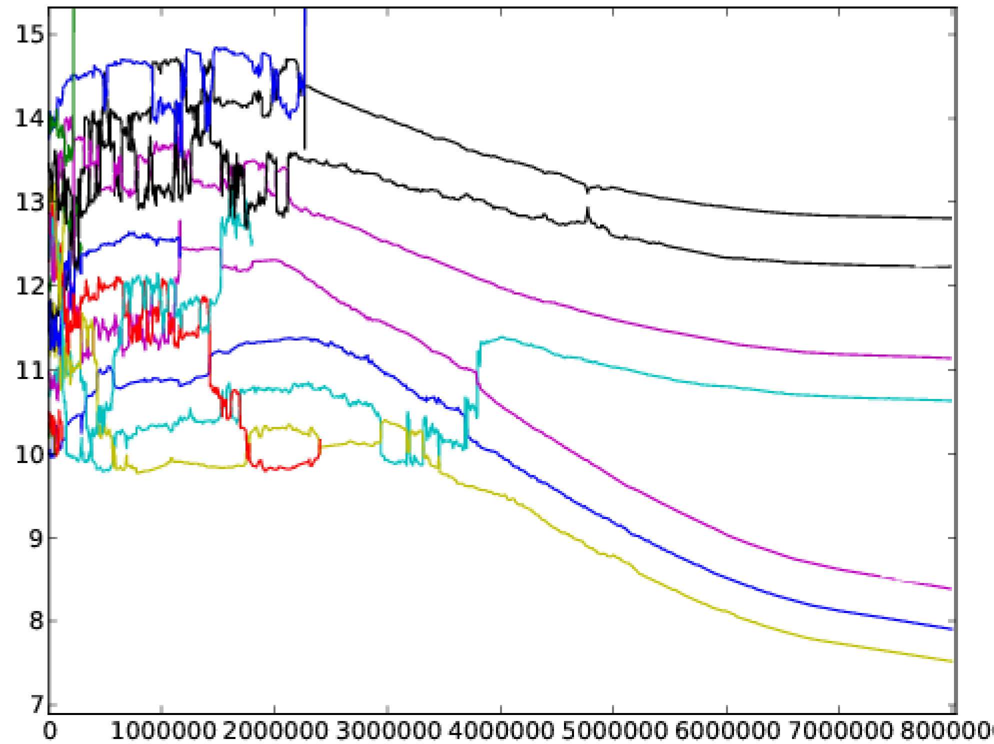

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