Sharp eccentric rings in debris disks
Who needs a planet?

Wladimir (Wlad) Lyra
Carl Sagan Fellow

NASA-JPL/Caltech
American Museum of Natural History
Max-Planck Institute for Astronomy
University of Uppsala

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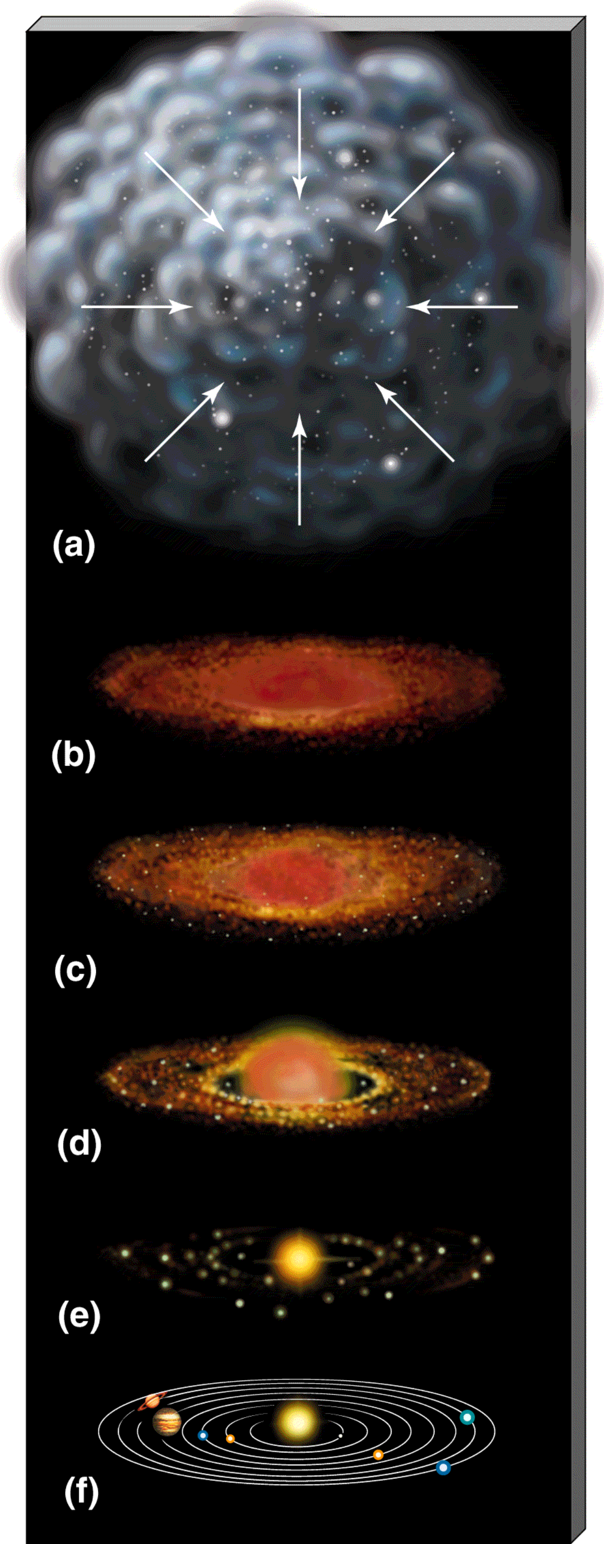
Collaborators:
Axel Brandenburg (Stockholm), Kees Dullemond (Heidelberg), Anders Johansen (Lund), Brandon Horn (Columbia), Hubert Klahr (Heidelberg), Marc Kuchner (Goddard), Mordecai-Mark Mac Low (AMNH), Sijme-Jan Paardekooper (Cambridge), Nikolai Piskunov (Uppsala), Natalie Raettig (Heidelberg), Zsolt Sandor (Innsbruck), Neal Turner (JPL), Andras Zsom (MIT).



A disk life story

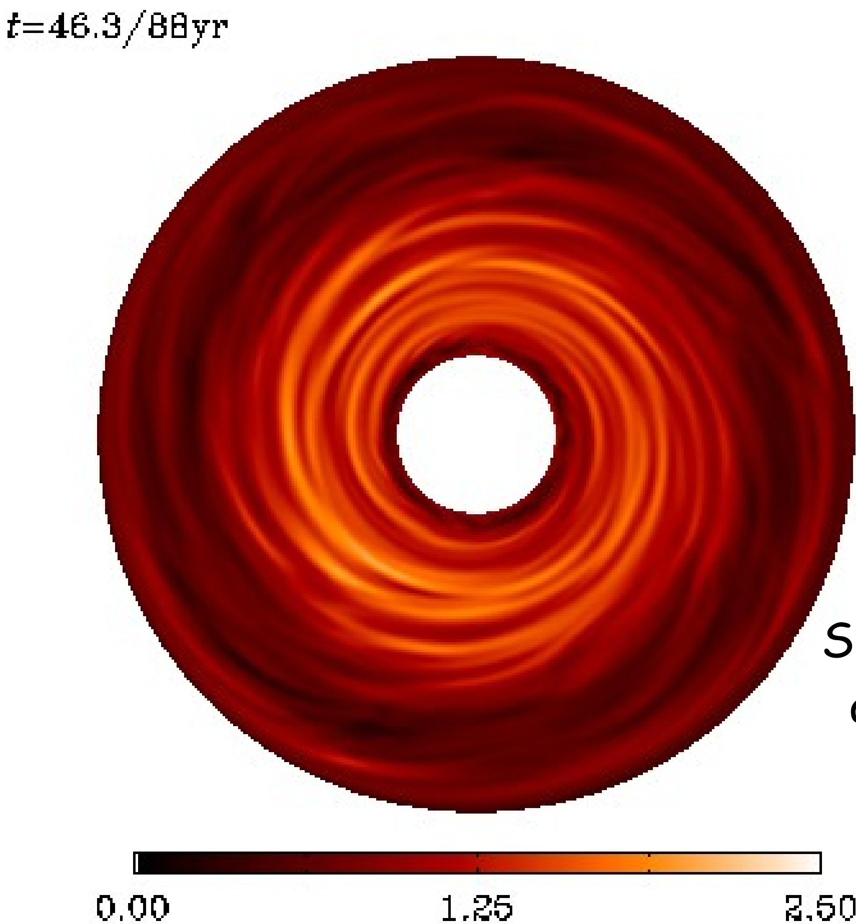
Gas-rich phase (< 10 Myr)
T-Tauri Disks
Accretion and Planet Formation

Thinning phase (~10 Myr)
Transitional Disks
Planet retention

Gas-poor phase (>10 Myr)
Debris Disks
Stabilization of architecture and Planet Detection

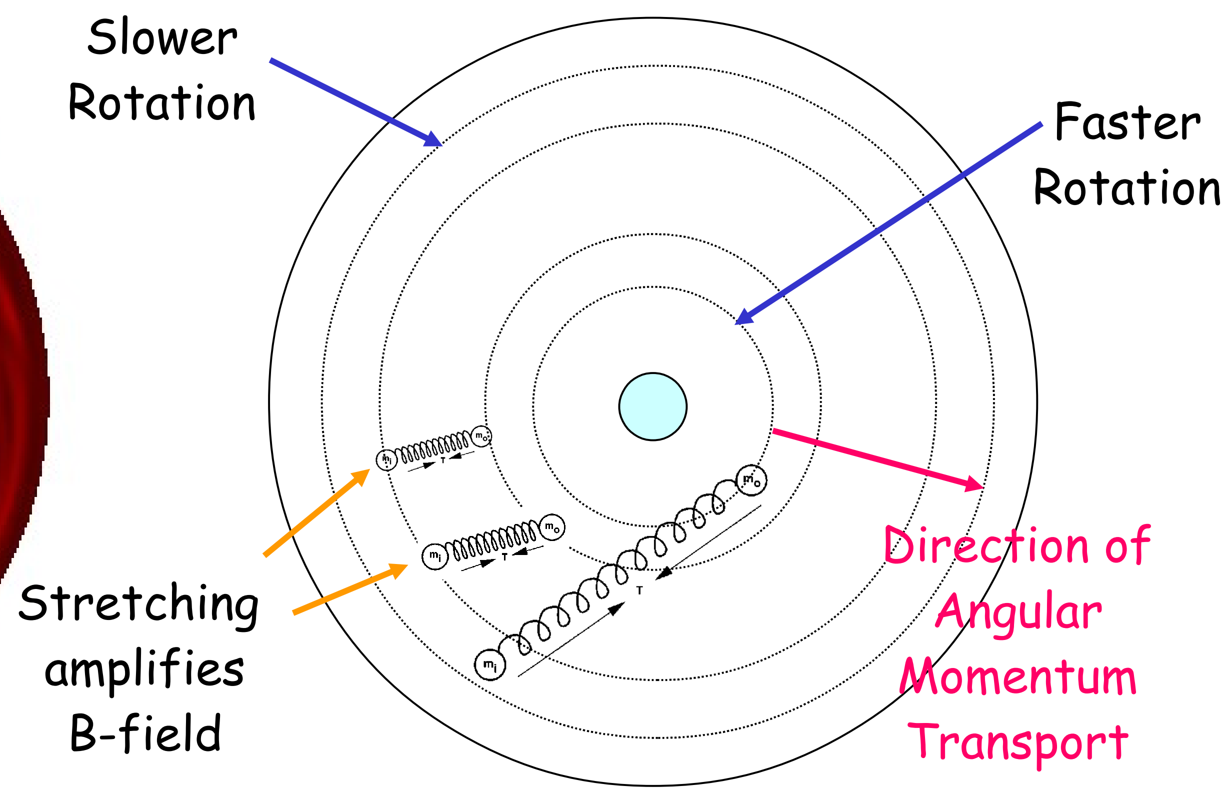
Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability



Magnetized disk
Lyra et al. (2008a)

MRI sketch



Unstable if angular velocity decreases outward

Accretion in disks occurs via turbulent viscosity

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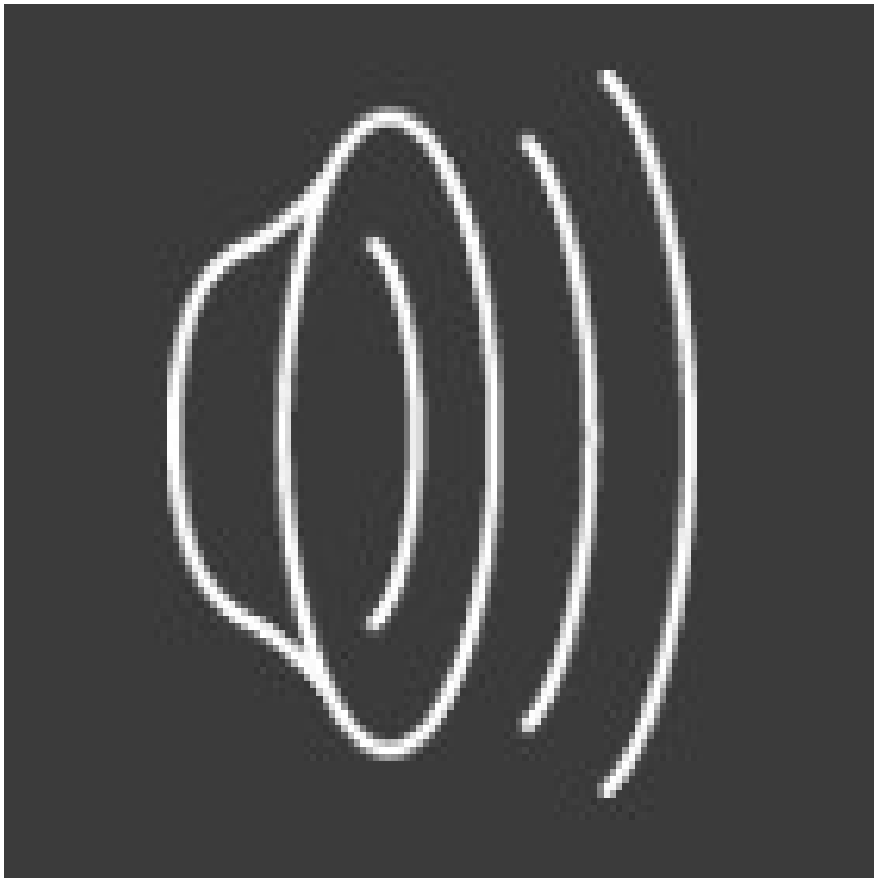
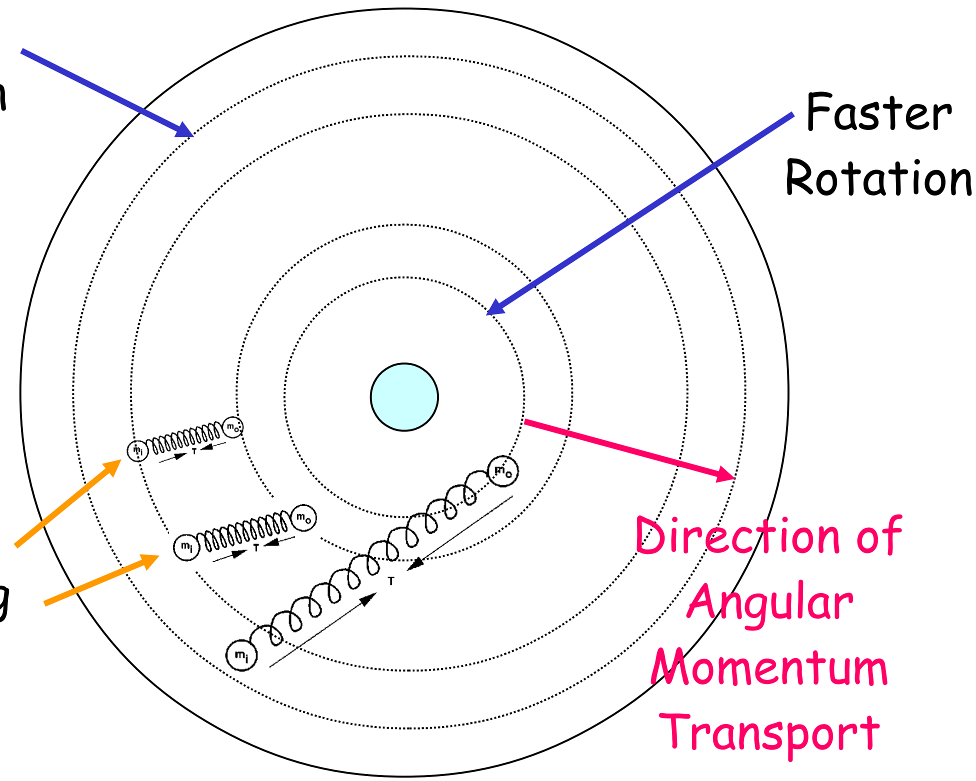
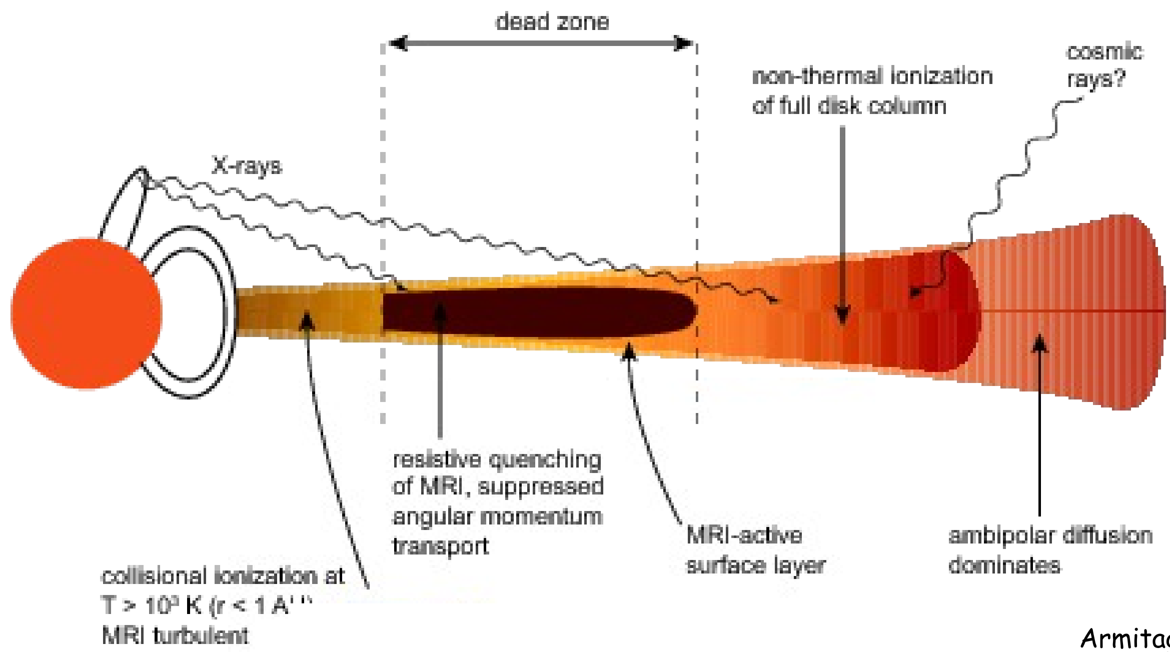


Magnetized disk
Lyra et al. (2008a)



Unstable if angular
velocity decreases
outward

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



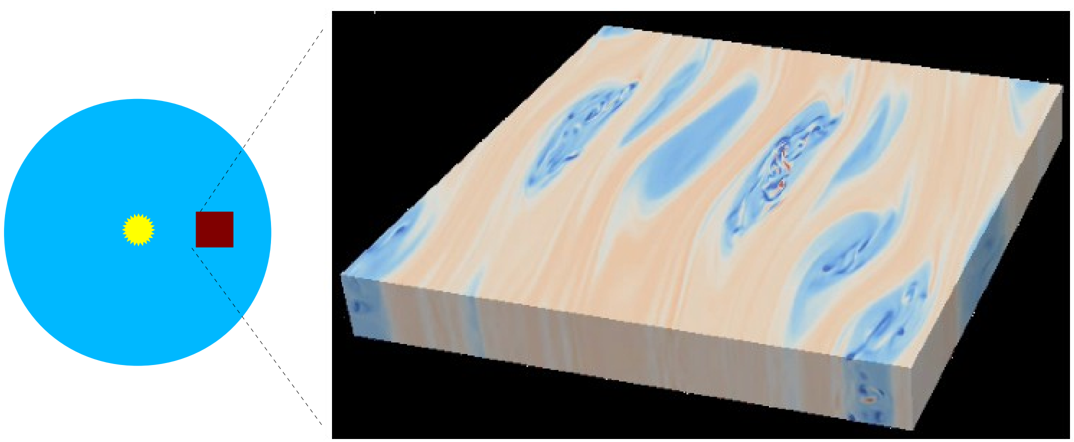
Armitage (2010)

Disks are cold and thus poorly ionized
(Blaes & Balbus 1994)

Therefore, accretion is **layered** (Gammie 1996)

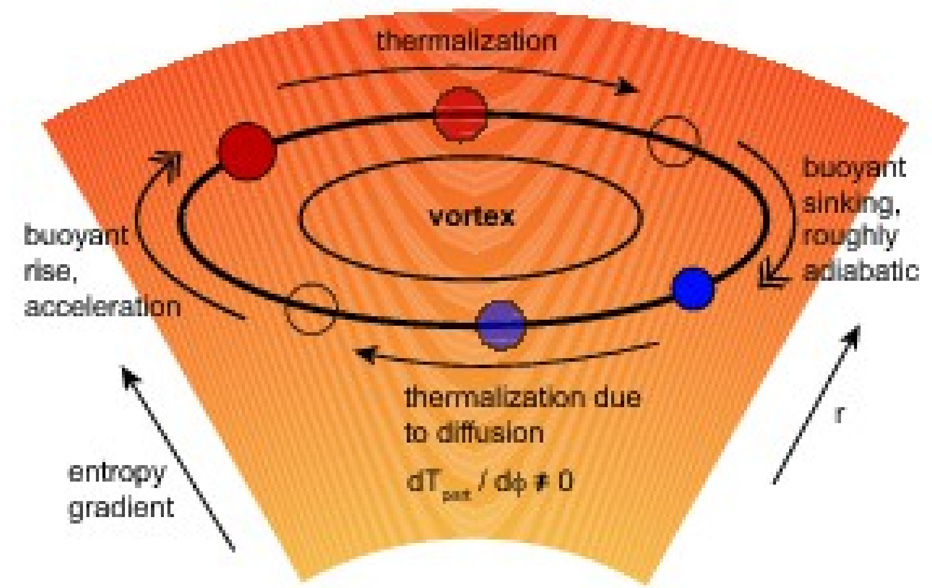
There should be a non-magnetic,
hydrodynamical, source of turbulence in the **dead zone.**

Baroclinic Instability – Excitation and self-sustenance of vortices



Lesur & Papaloizou (2010)

Sketch of the
Baroclinic Instability

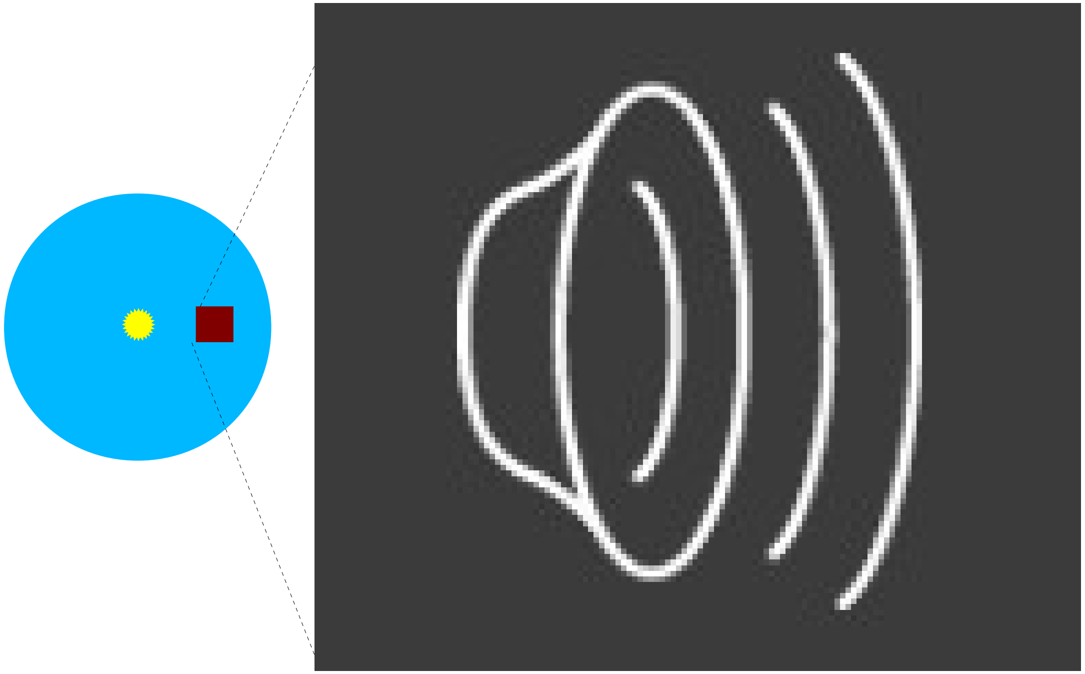


Armitage (2010)

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

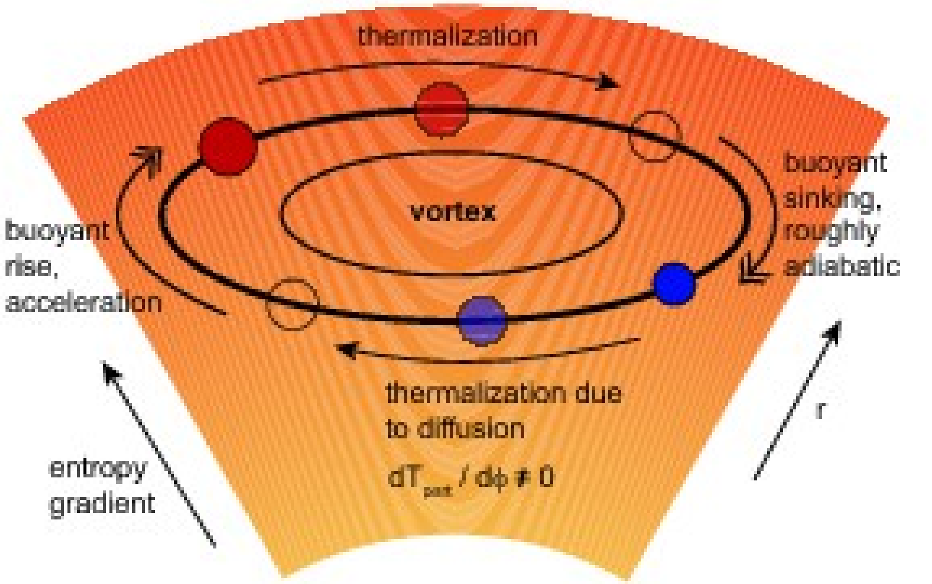
advection — compression — stretching — baroclinicity — dissipation

Baroclinic Instability – Excitation and self-sustenance of vortices



Lyra & Klahr (2011)

Sketch of the Baroclinic Instability



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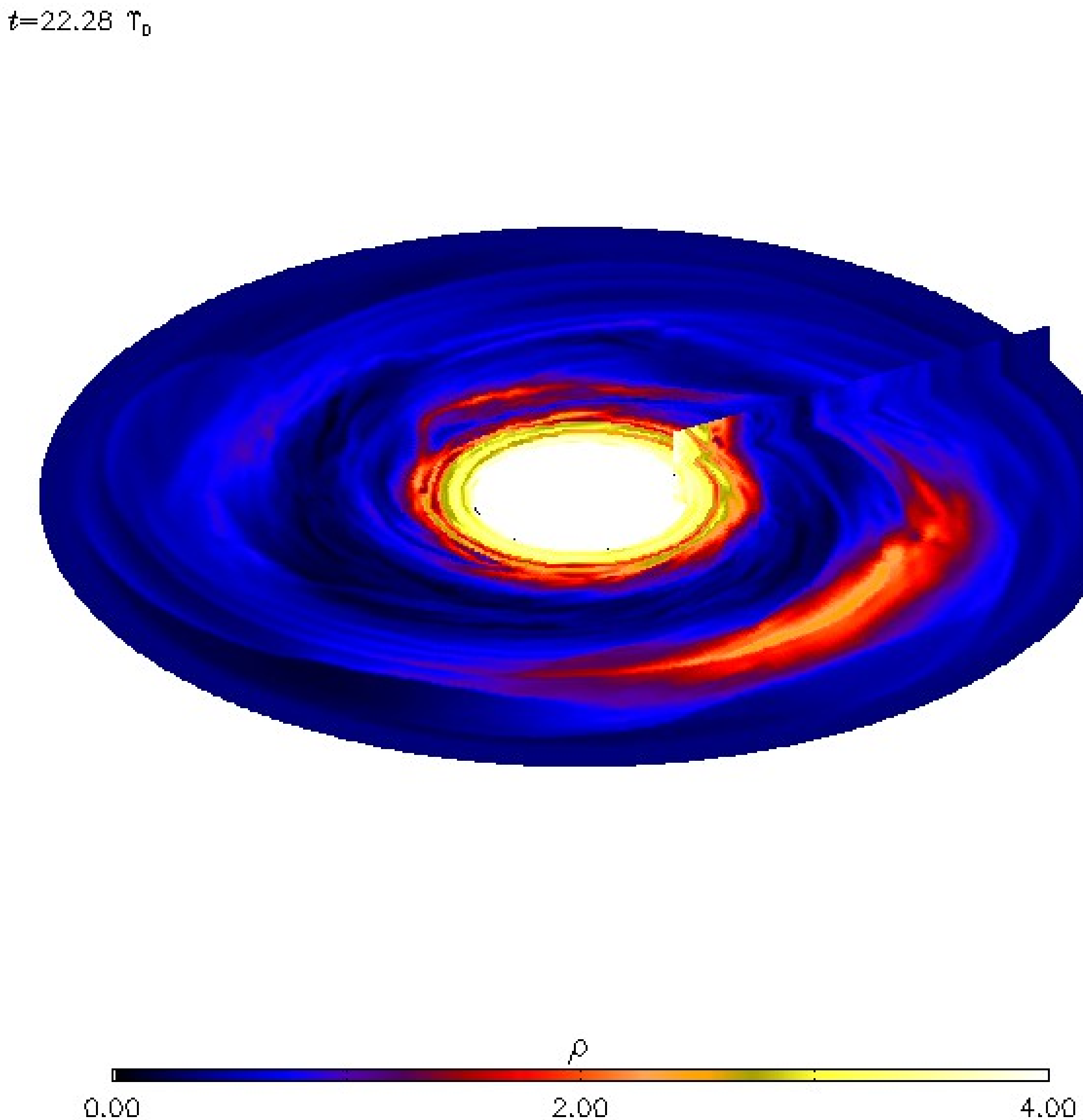
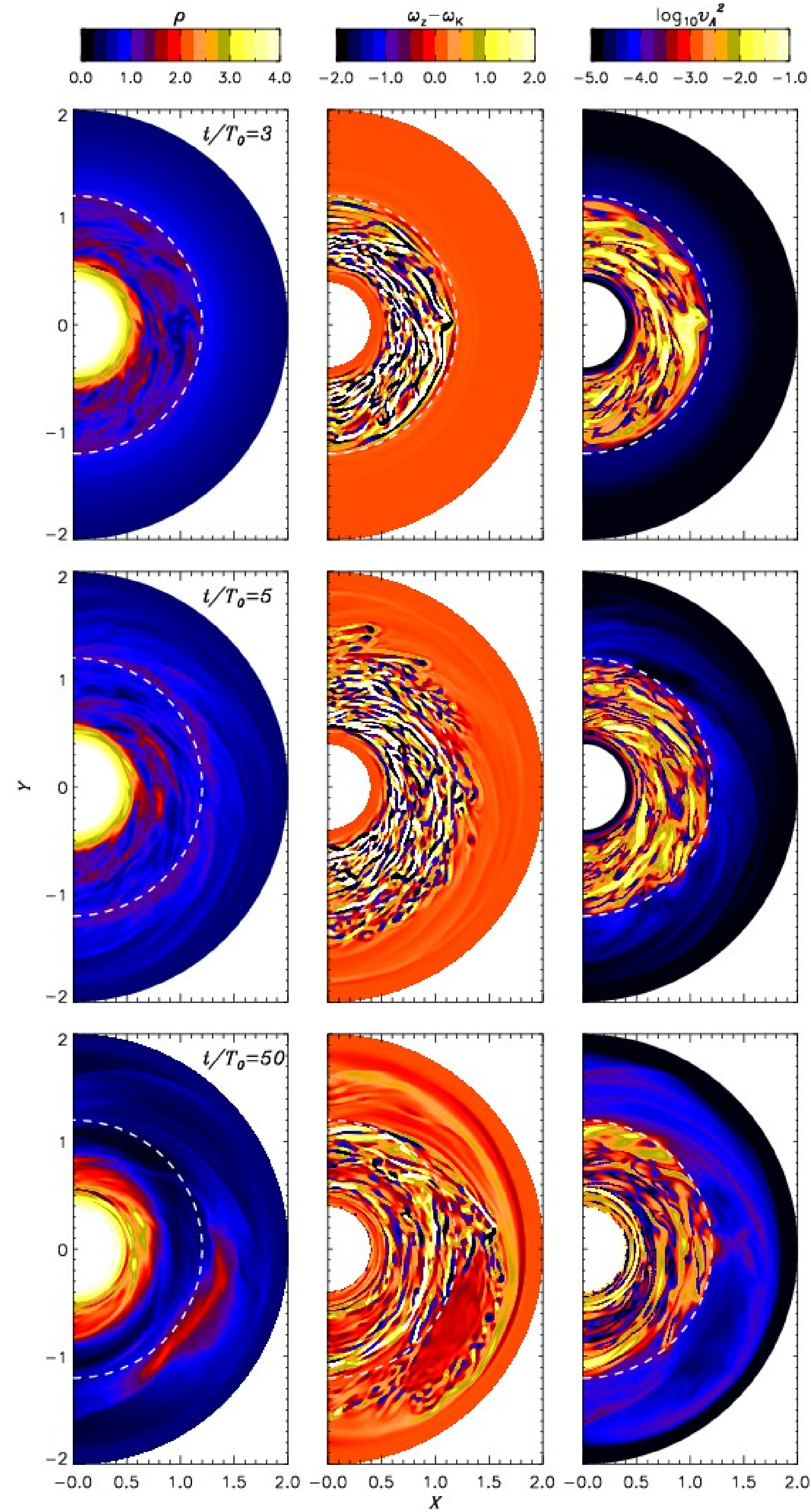
advection — compression — stretching — baroclinicity — dissipation

Active/dead zone boundary

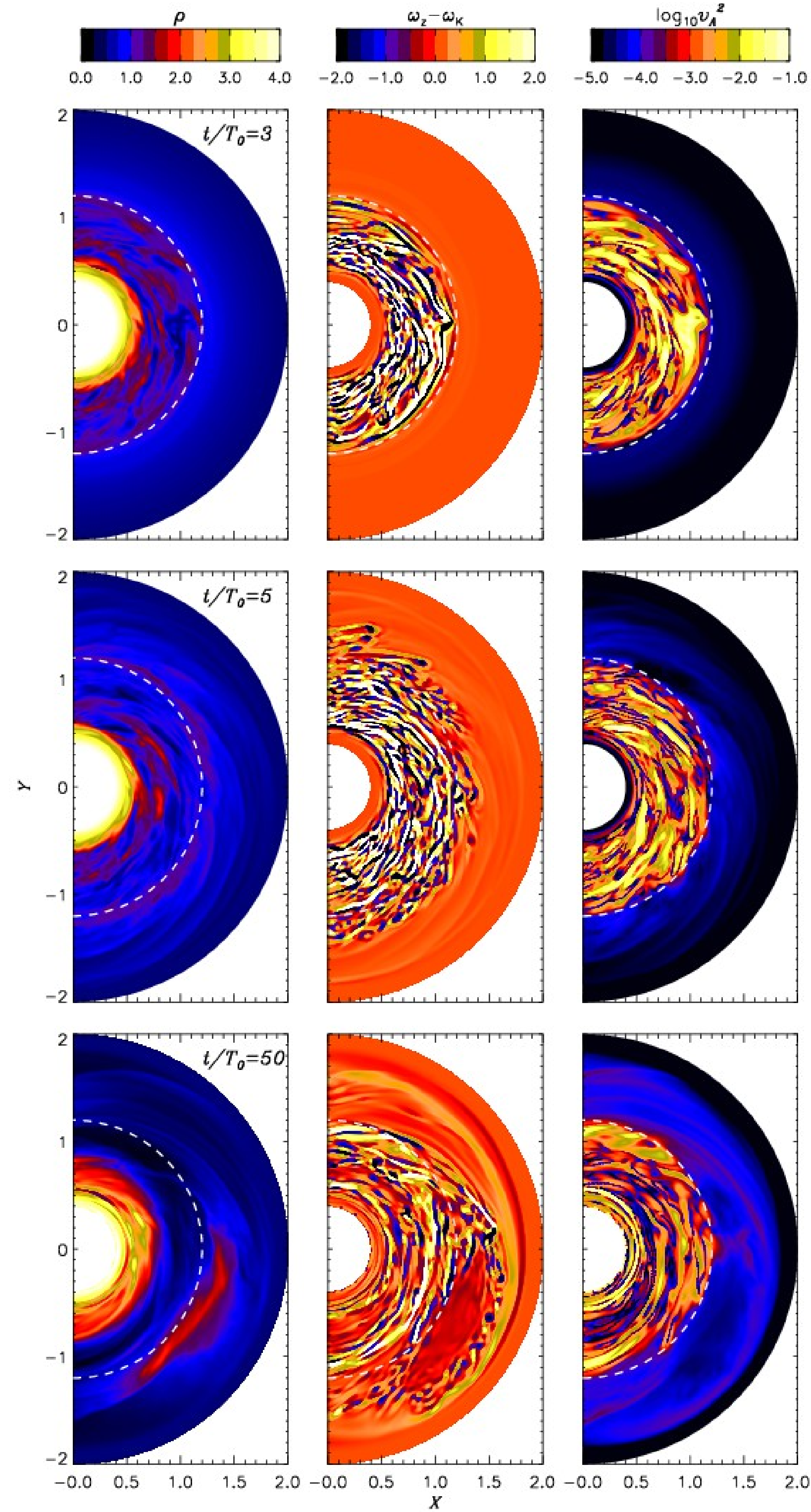




Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

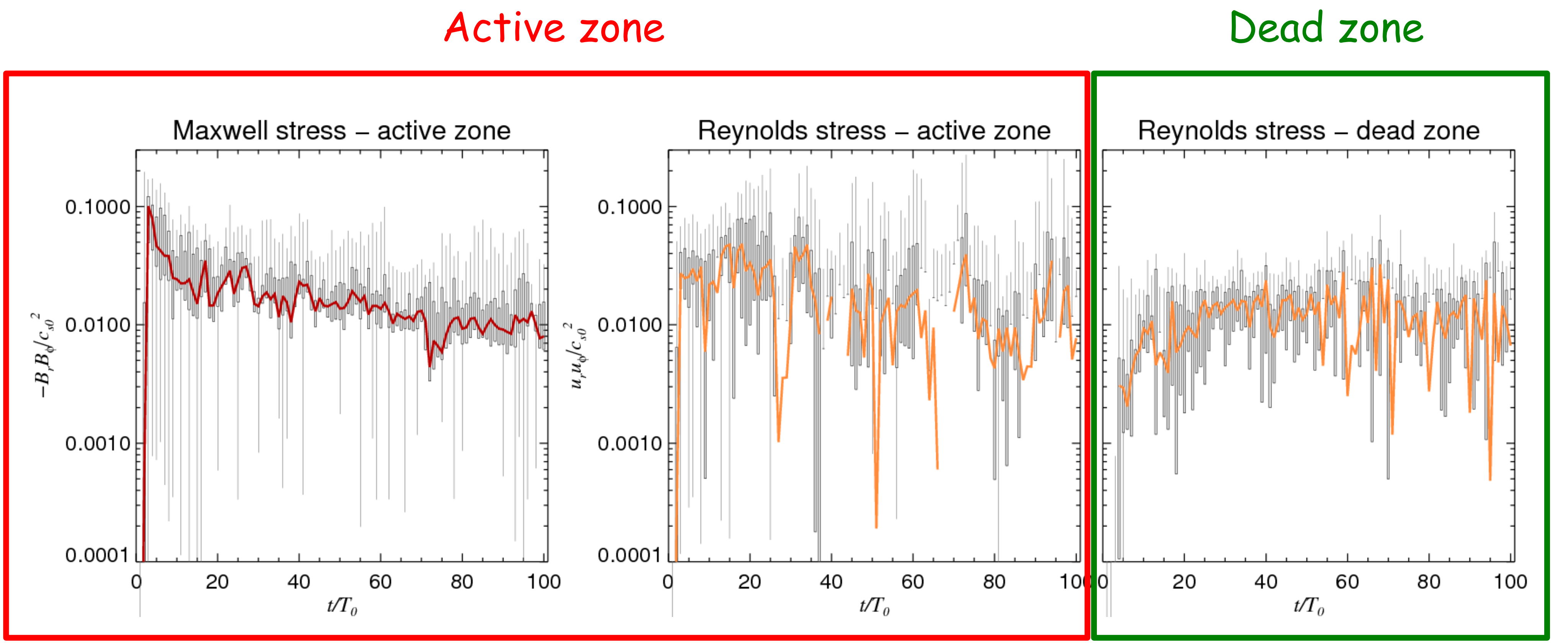
Active/dead zone boundary



Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Significant angular momentum transport



Large mass accretion rates in the dead zone,

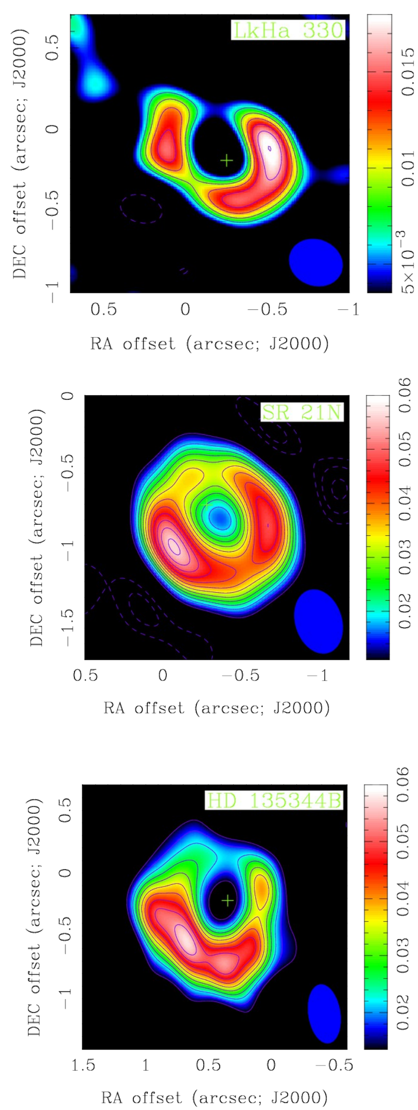
comparable to the MRI in the active zone!

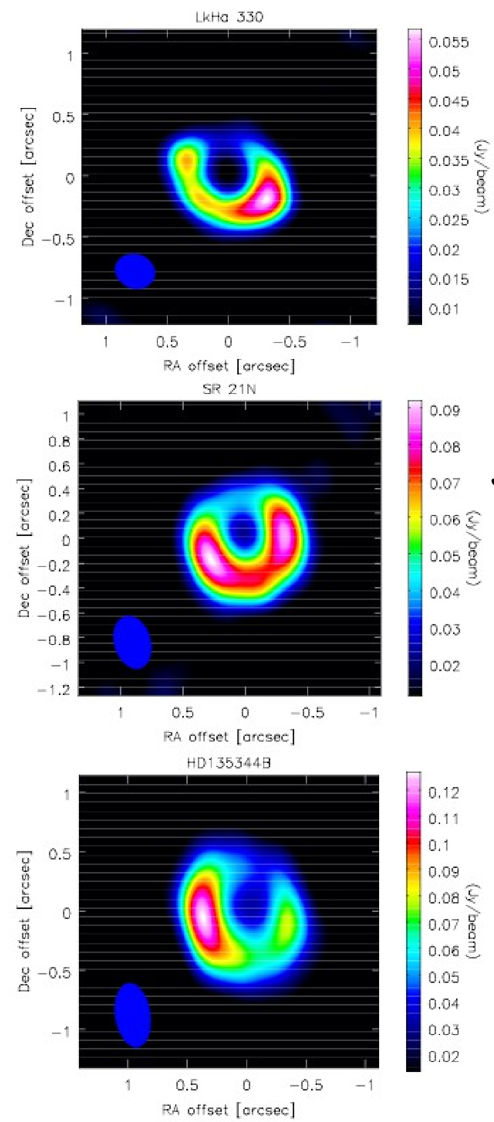
Lyra & Mac Low (2012)

A possible detection of vortices in disks

Observations

Brown et al. (2009)

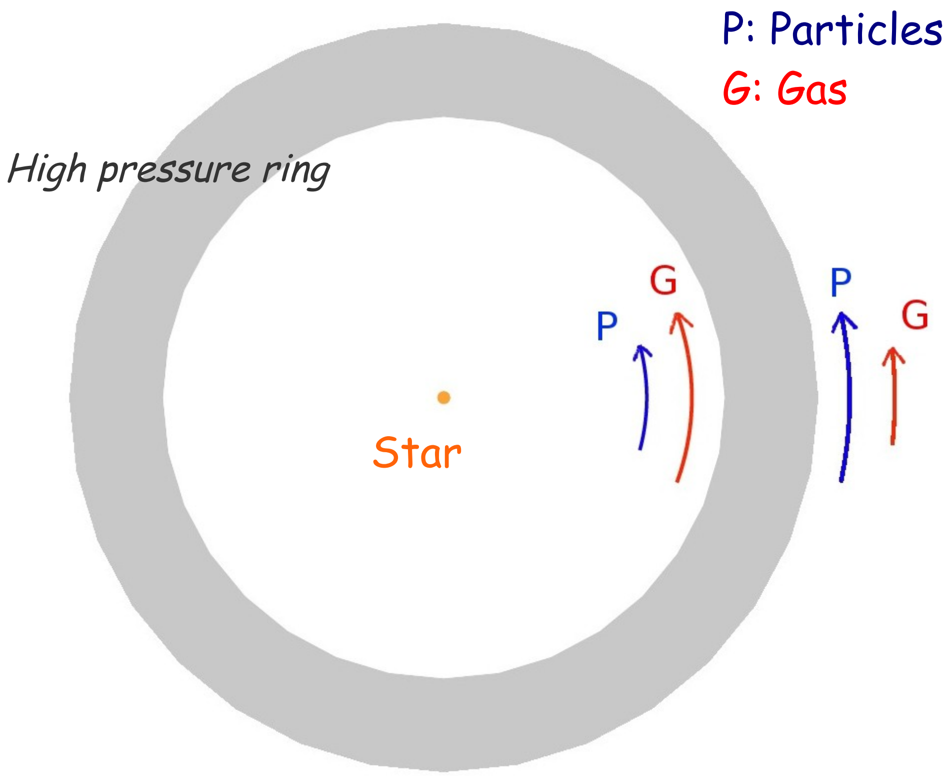


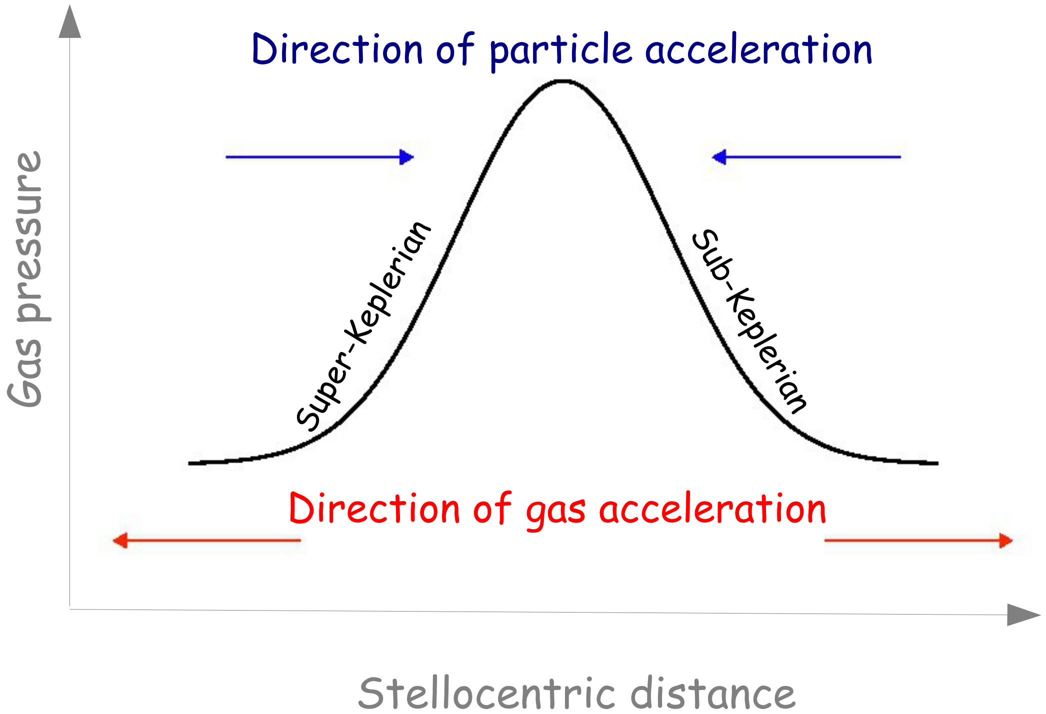


Simulated observations of Rossby vortices

Regaly et al. (2012)

Forming planets in turbulent disks





Adapted from Whipple (1972)

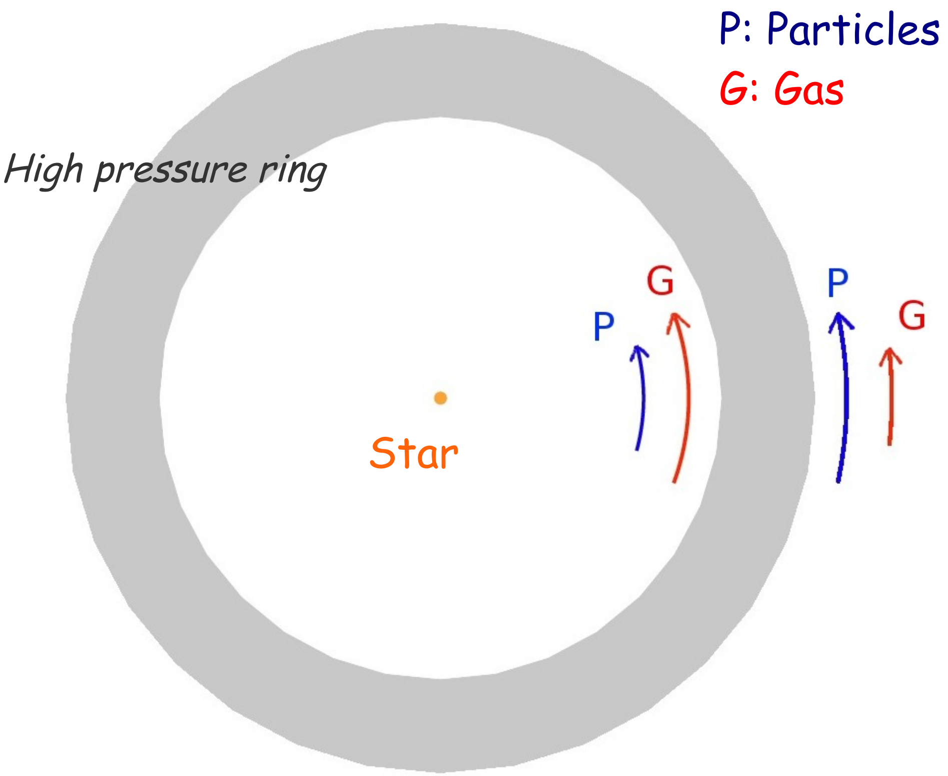
Forming planets in turbulent disks

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

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

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

The drag force pushes the particles *toward* the pressure gradient



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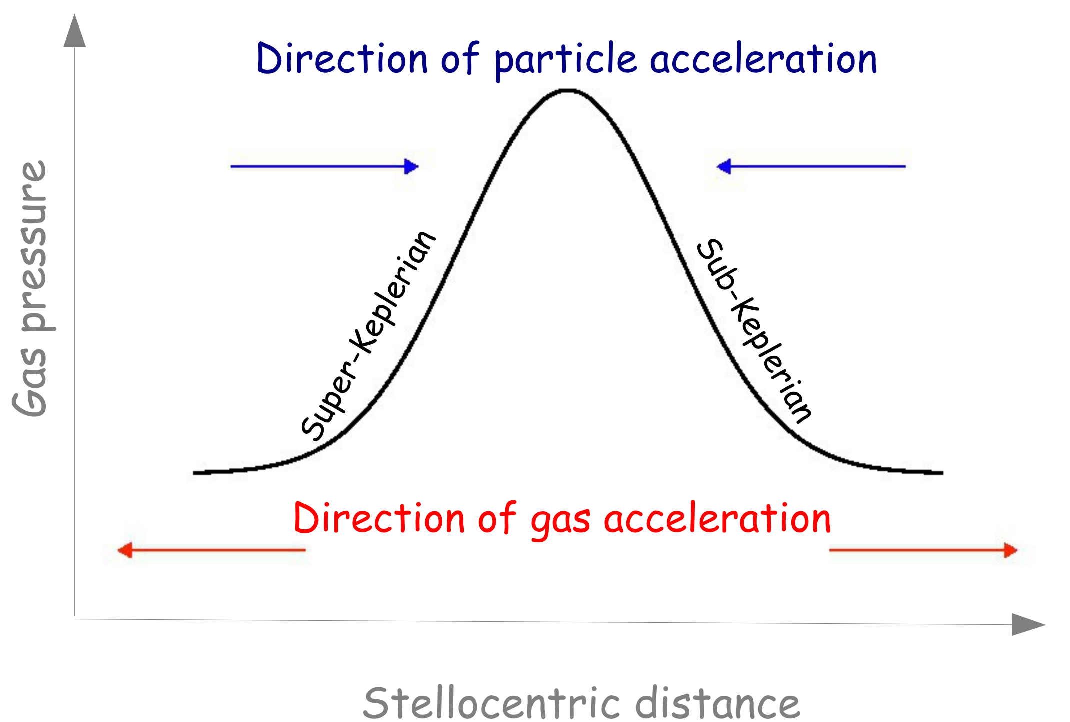
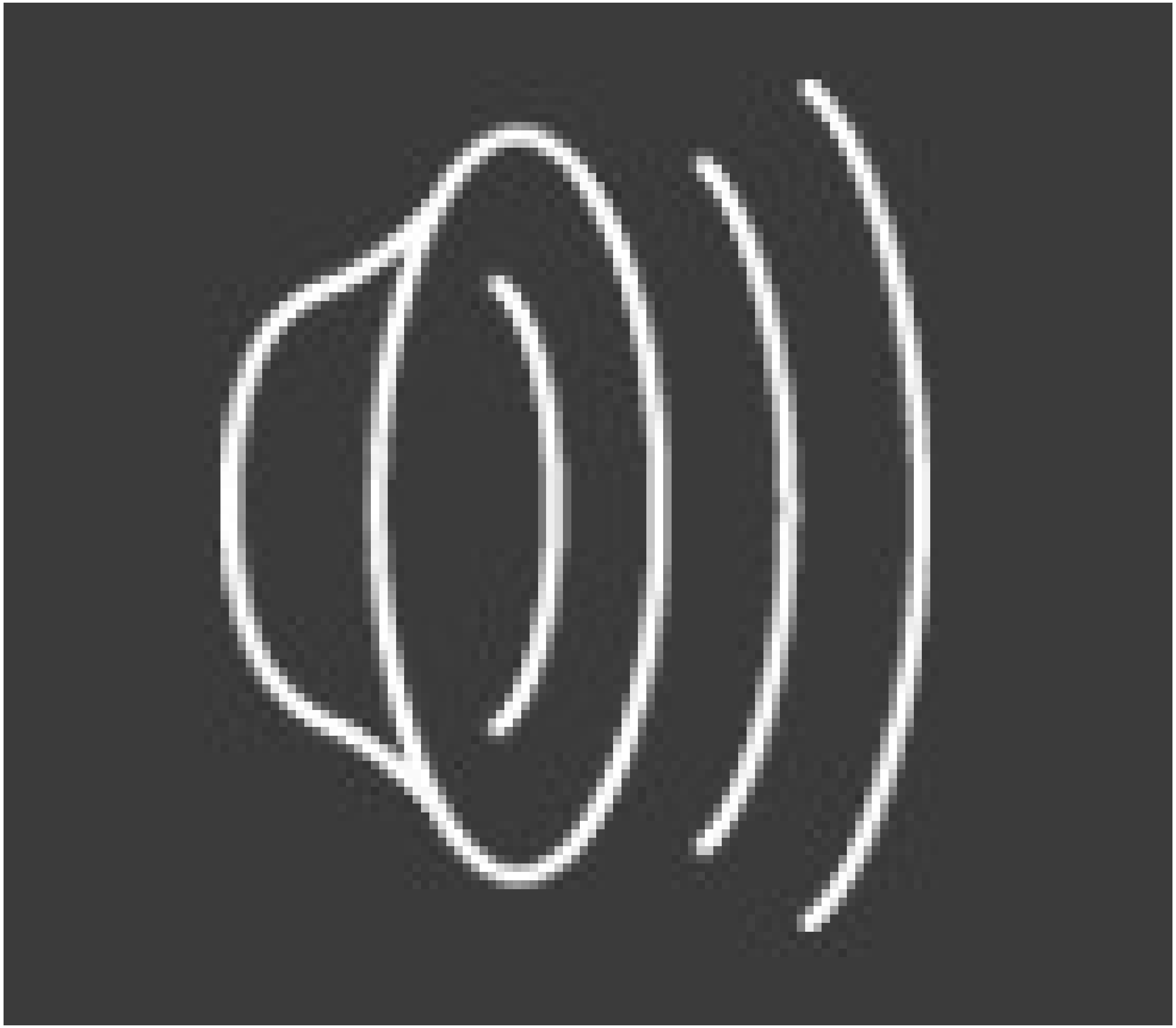


Solid particles

move **toward**

pressure maxima

Turbulence concentrates solids mechanically in pressure maxima



Lyra et al. (2008)

Gravitational collapse into planetesimals

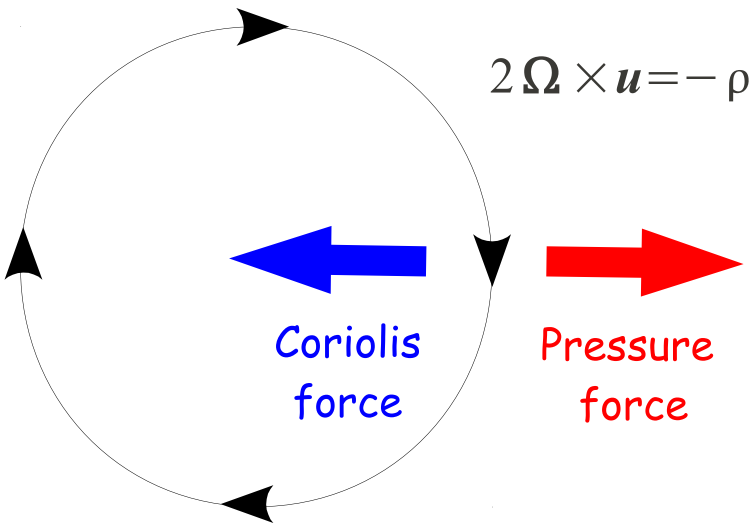
Johansen et al. (2007)

Turbulent eddies concentrate solids, turning them into planetesimals...

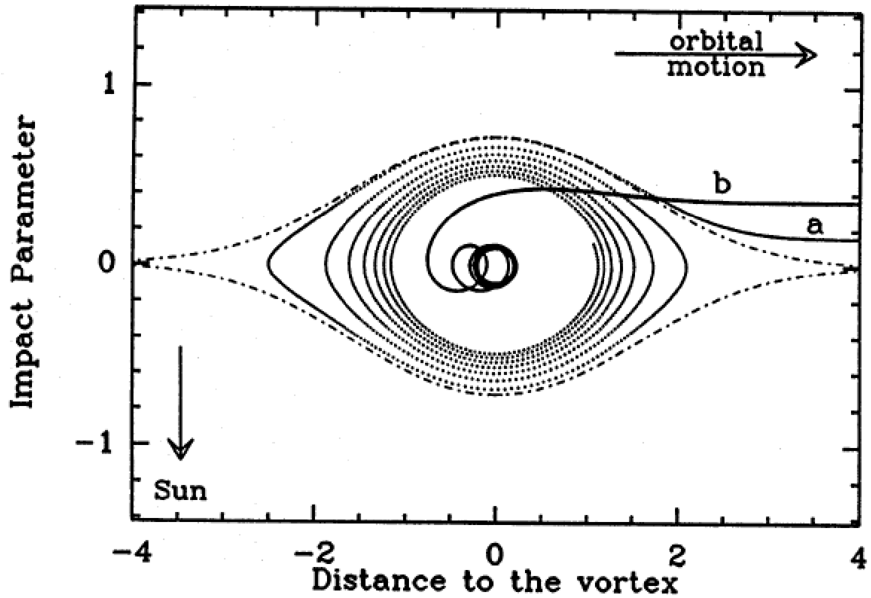
...and vortices are **huge** eddies!

Planet Formation via *Vortex Thruway*

Geostrophic balance:



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



Barge & Sommeria (1995)

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

Aid to planet formation (Barge & Sommeria 1995)

Speed up planet formation enormously
(Lyra et al. 2008b, 2009a, 2009b, Raettig, Lyra & Klahr 2012)

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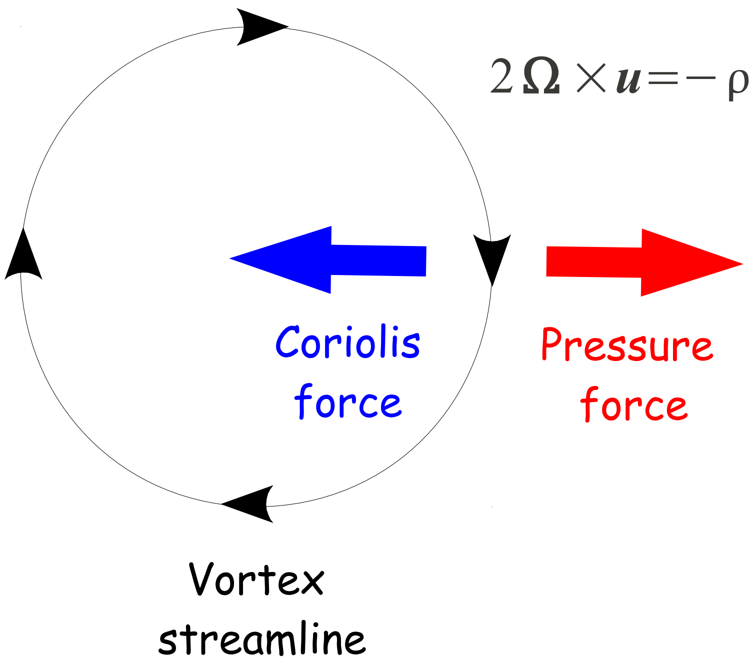

Raettig et al. (2012)

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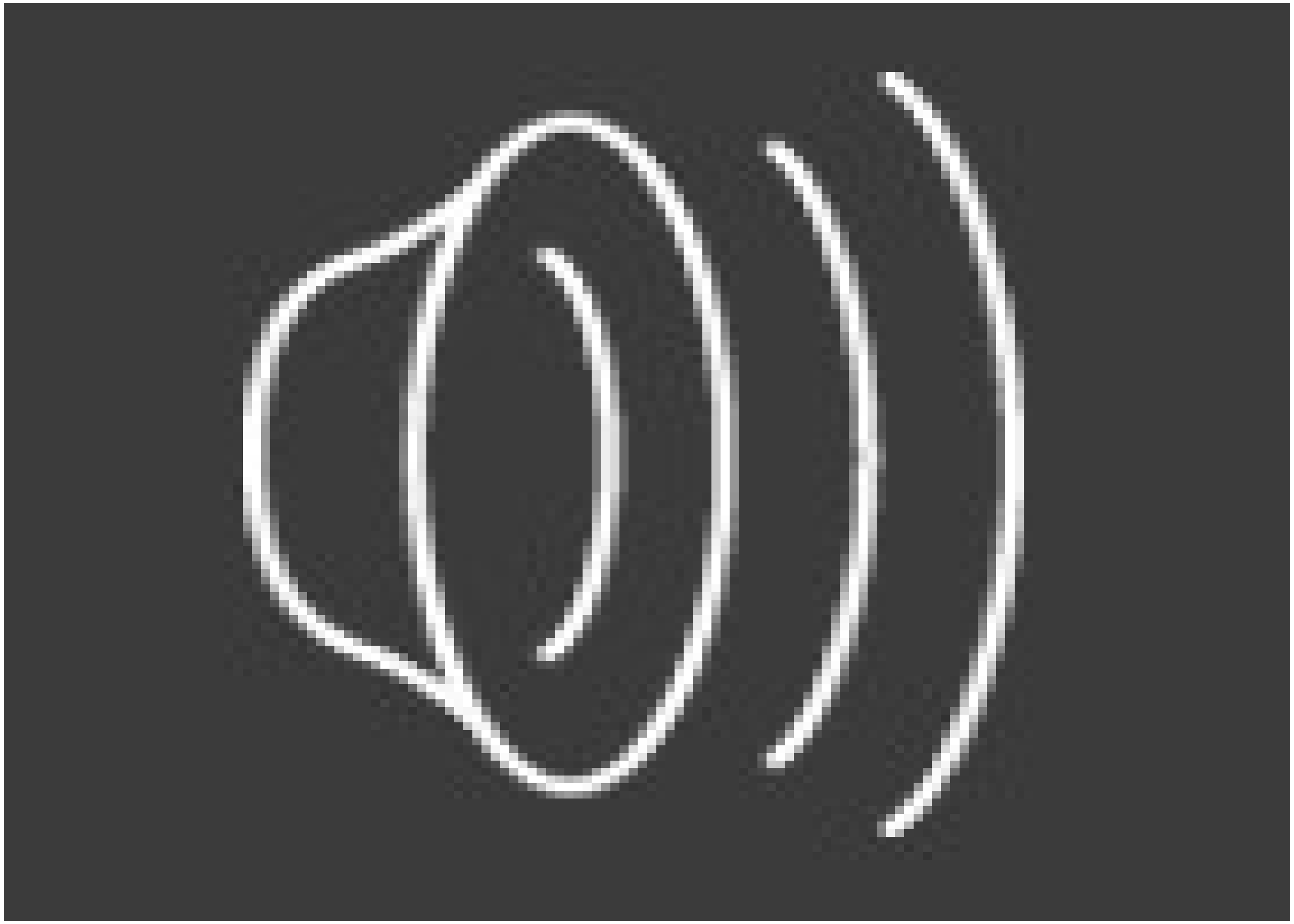
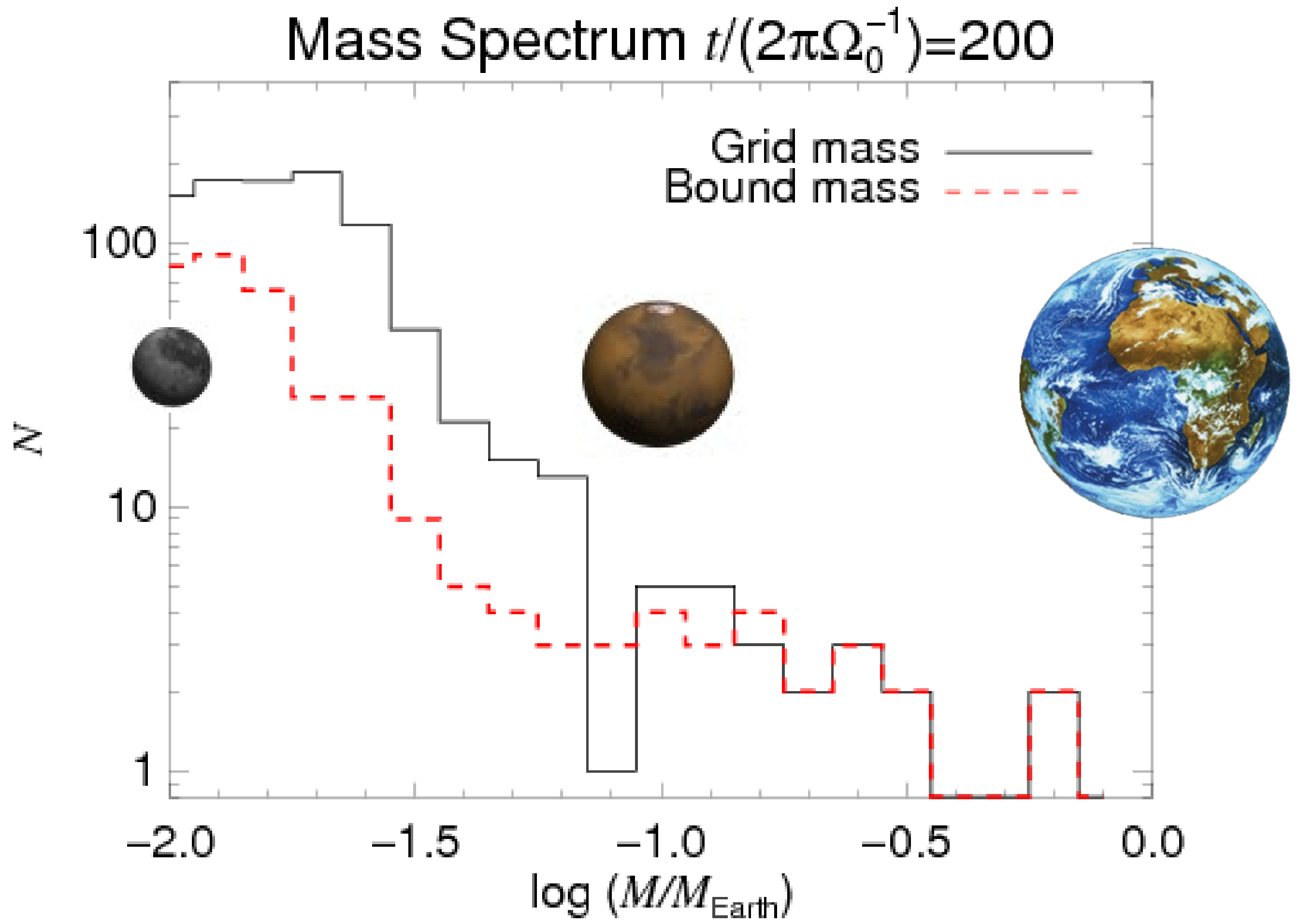
The Initial Mass Function of planets



•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



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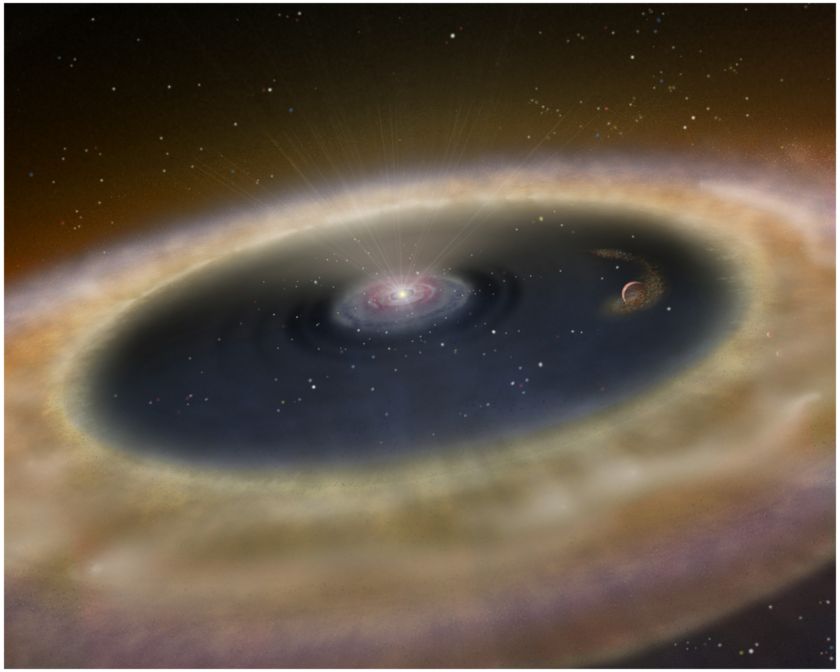
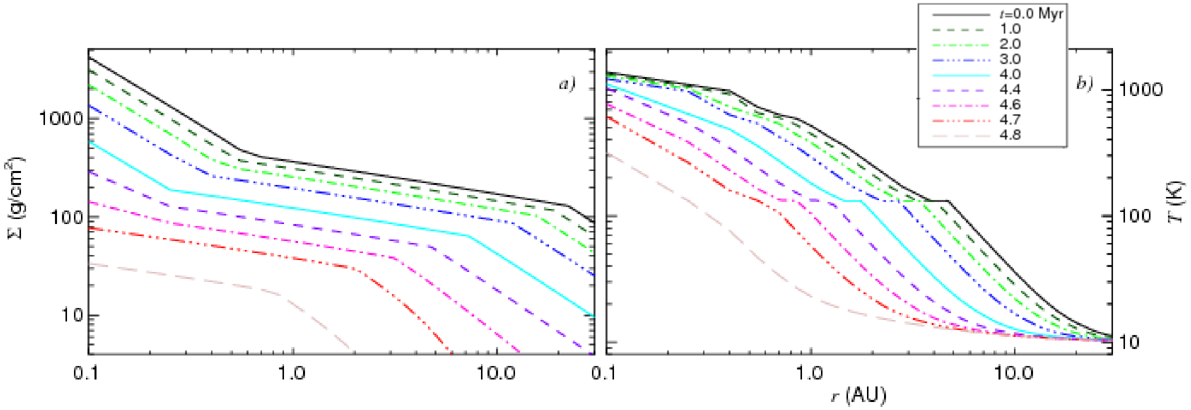
Transitional disks – The thinning phase



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

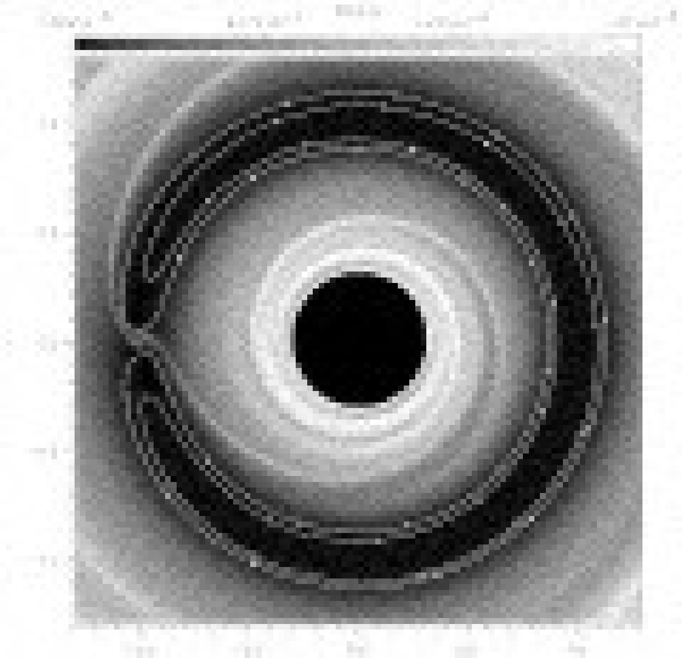


Lyra, Paardekooper, & Mac Low (2010)

Planets form and start to migrate

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

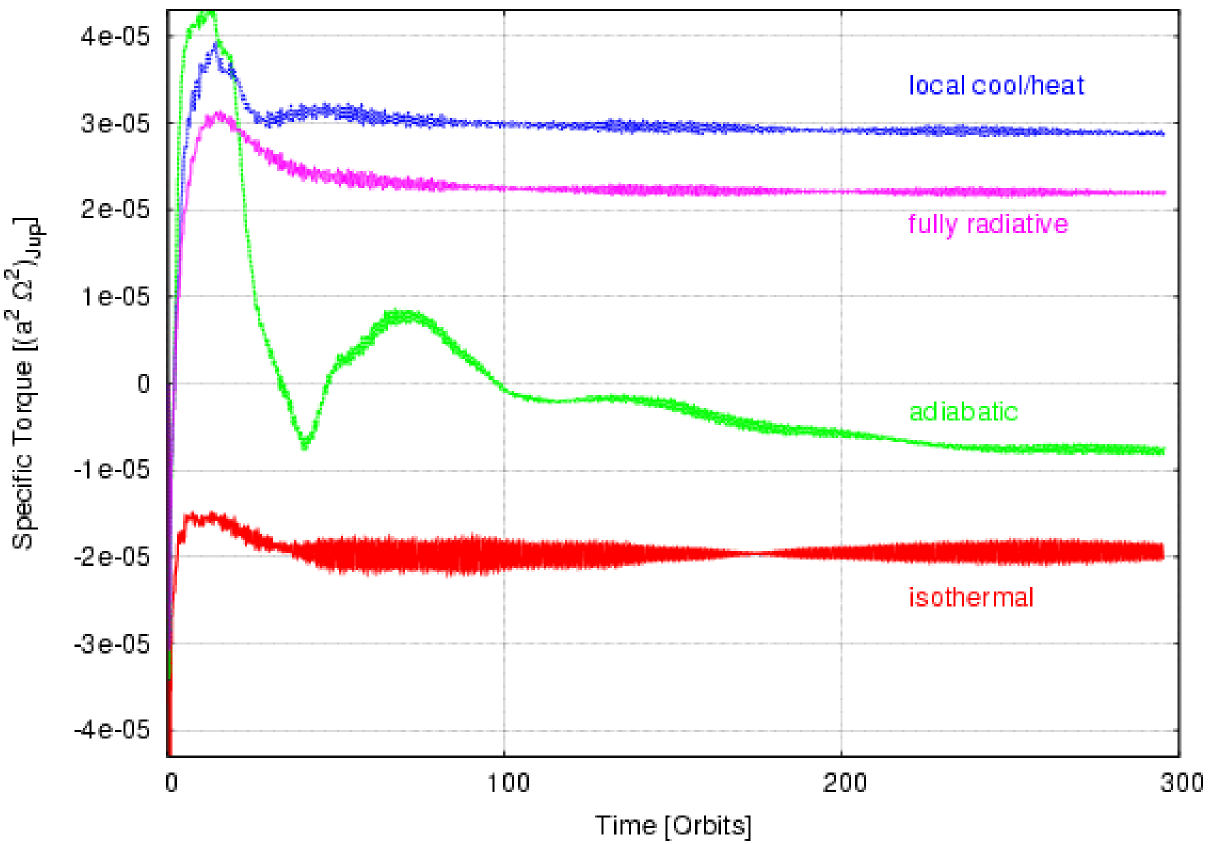
One armed spiral: Lindblad resonance
Horseshoe libration: Co-rotational torques



Lubow et al. (1999)

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

Planets form and start to migrate



Kley & Crida (2008)

Paardekooper & Mellema (2006)

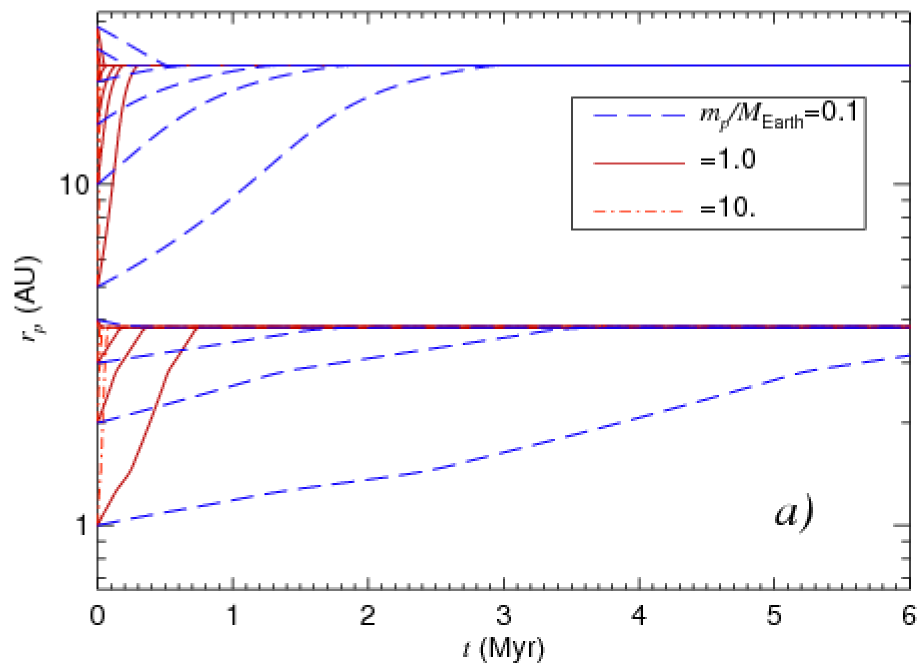
Non-isothermal
co-rotational torque may lead to outward migration

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

Rule of thumb: ***Migration is outwards** in **steep temperature gradients**, **inwards** in **isothermal regions**.*

Planets form and start to migrate

Planet-disk interaction leads to angular momentum exchange

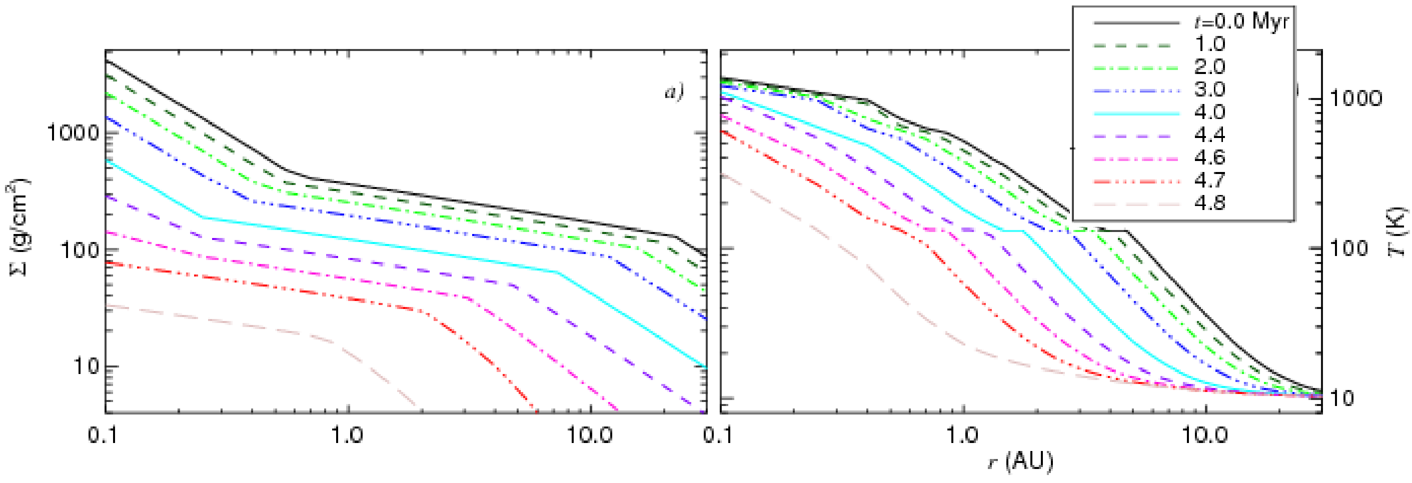


Lyra, Paardekooper, & Mac Low (2010)

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



Lyra, Paardekooper, & Mac Low (2010)

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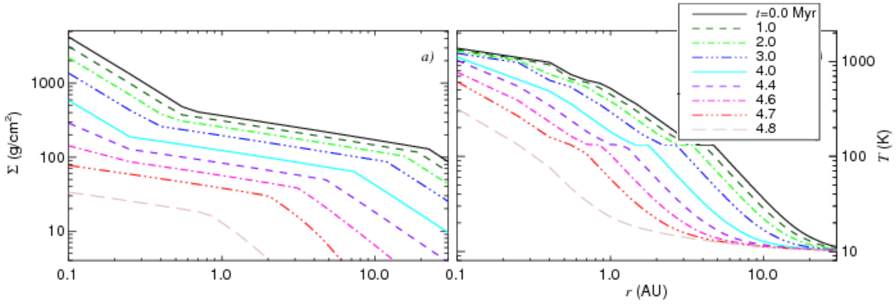

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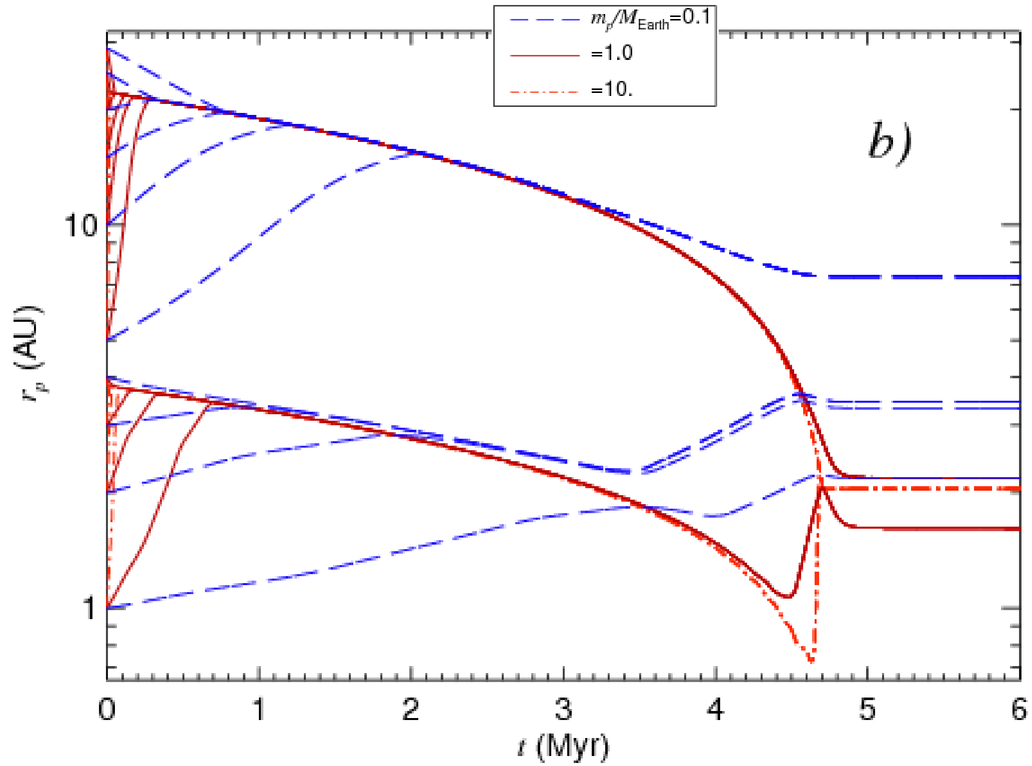
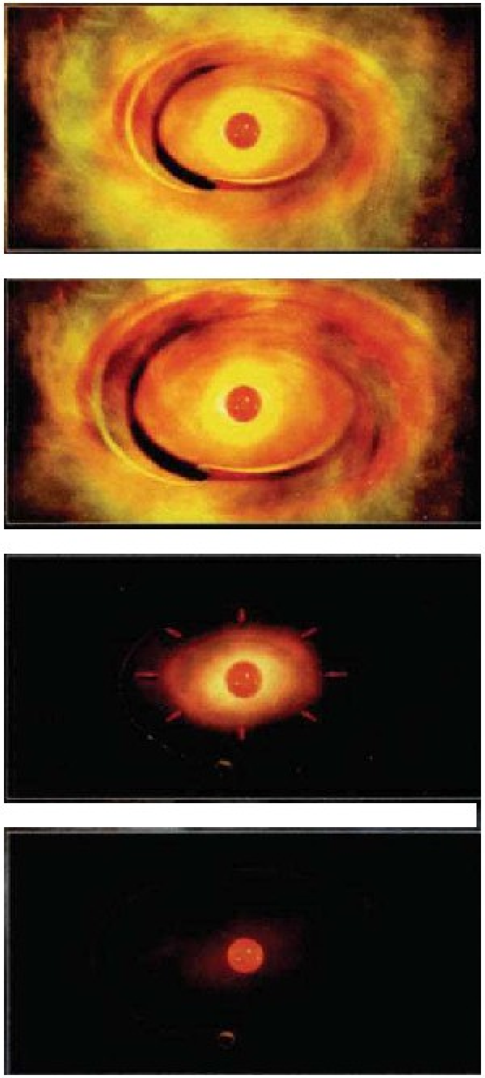
Single planets in a planetary trap evolve in **lockstep with the gas** at the accretion timescale.

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



Lyra, Paardekooper, & Mac Low (2010)

Migration in Evolutionary Models



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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

"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 →

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

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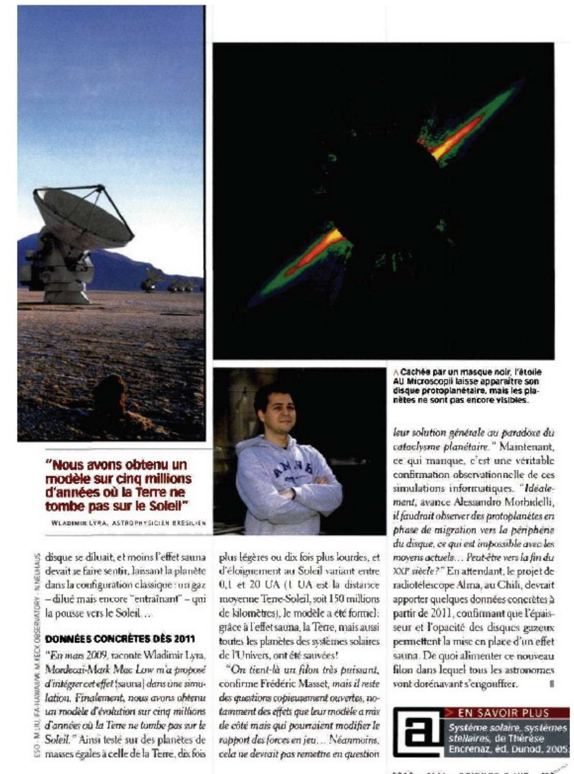


"Nous avons obtenu un modèle sur cinq millions d'années où la Terre ne tombe pas sur le Soleil"

WLADIMIR LYRA, ASTROPHYSICIEN BRÉSILIEN

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

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

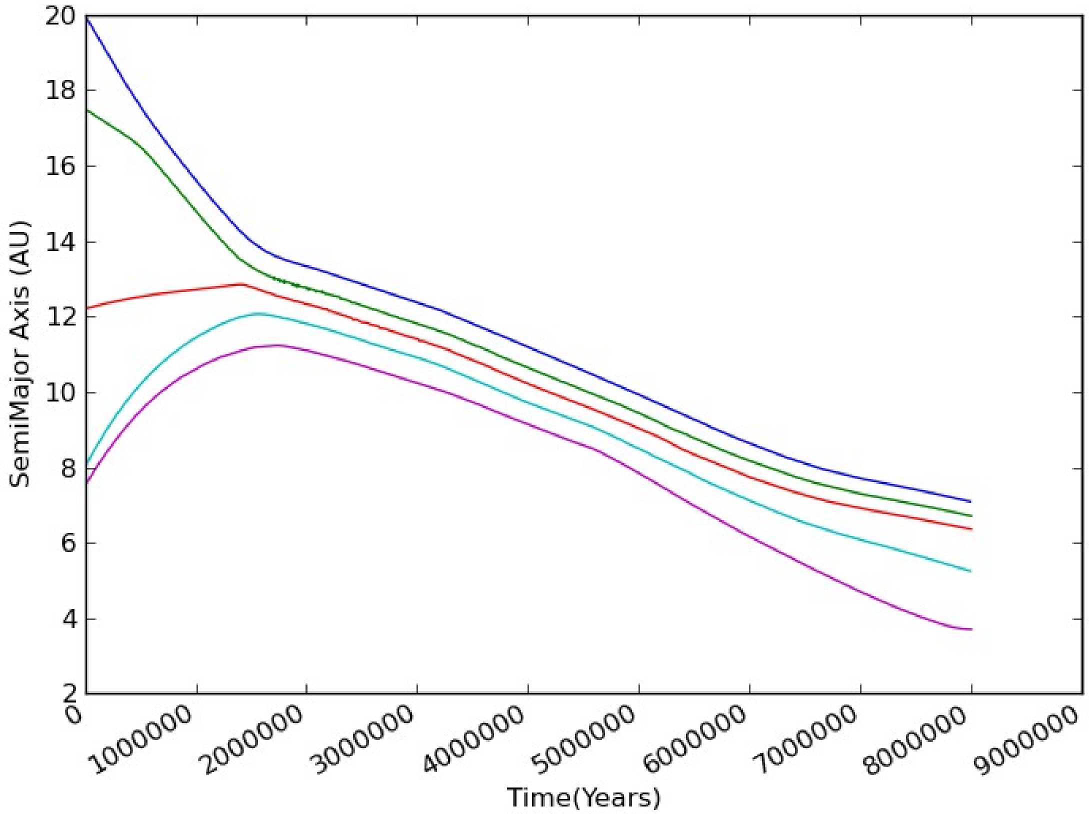
"*En mars 2009*, raconte Wladimir Lyra, *Mordecai-Mark Mac Low m'a proposé d'intégrer cet effet* [sauna] *dans une simulation. Finalement, nous avons obtenu un modèle d'évolution sur cinq millions d'années où la Terre ne tombe pas sur le Soleil.*" Ainsi testé sur des planètes de masses égales à celle 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.

2010 > MAI > SCIENCE & VIE 101

Migration + N-Body in Evolutionary Models



Migration in resonance!

see also

Sandor, Lyra & Dullemond (2011)

Hellary & Nelson (2012)

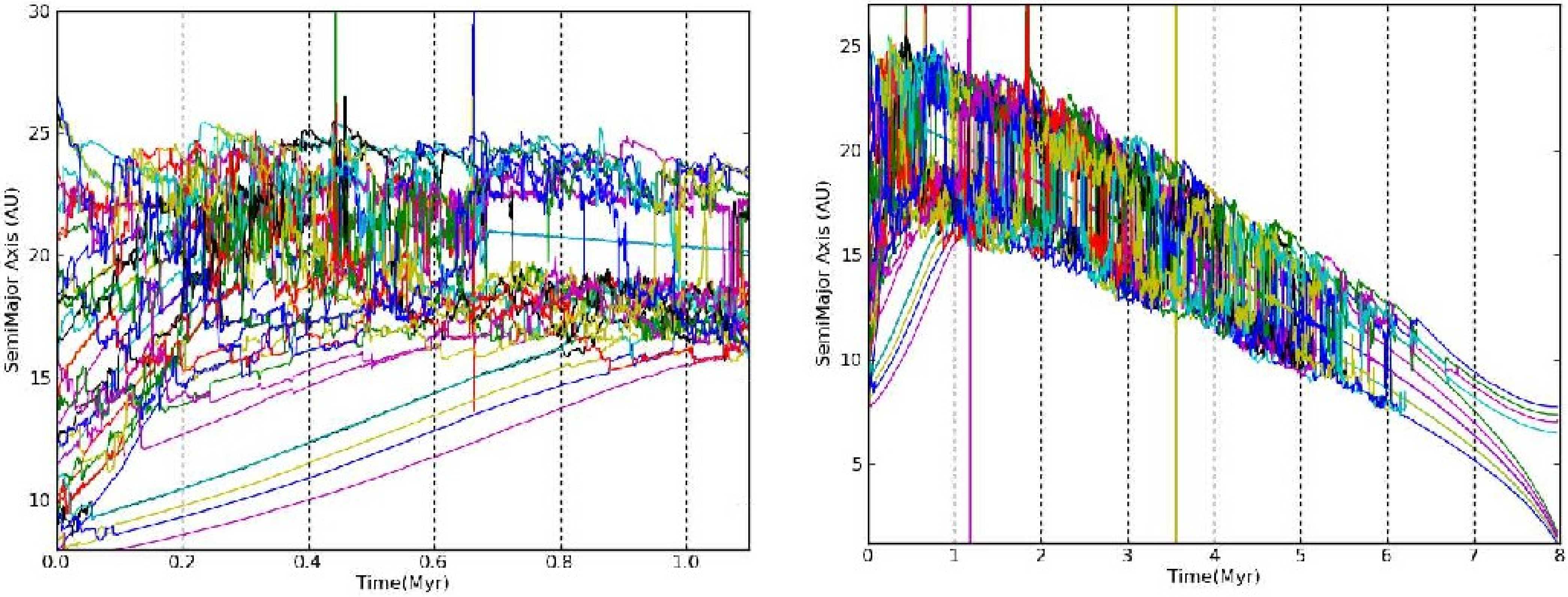
Orbital migration of interacting planets in a radiative evolutionary model

Combines

migration + N-body + photoevaporation + turbulence

modelled as stochastic forcing

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

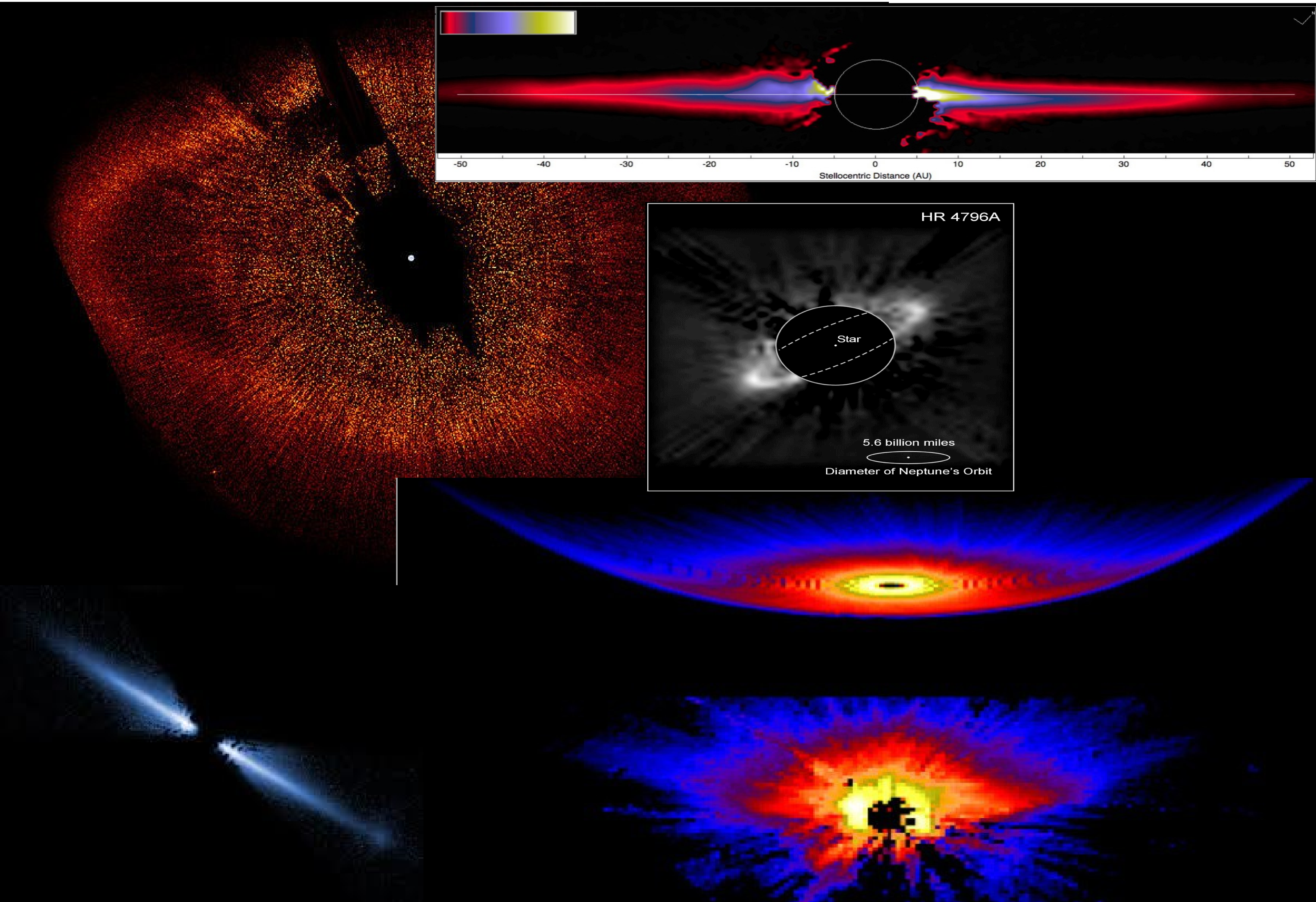


Horn et al. (2012)

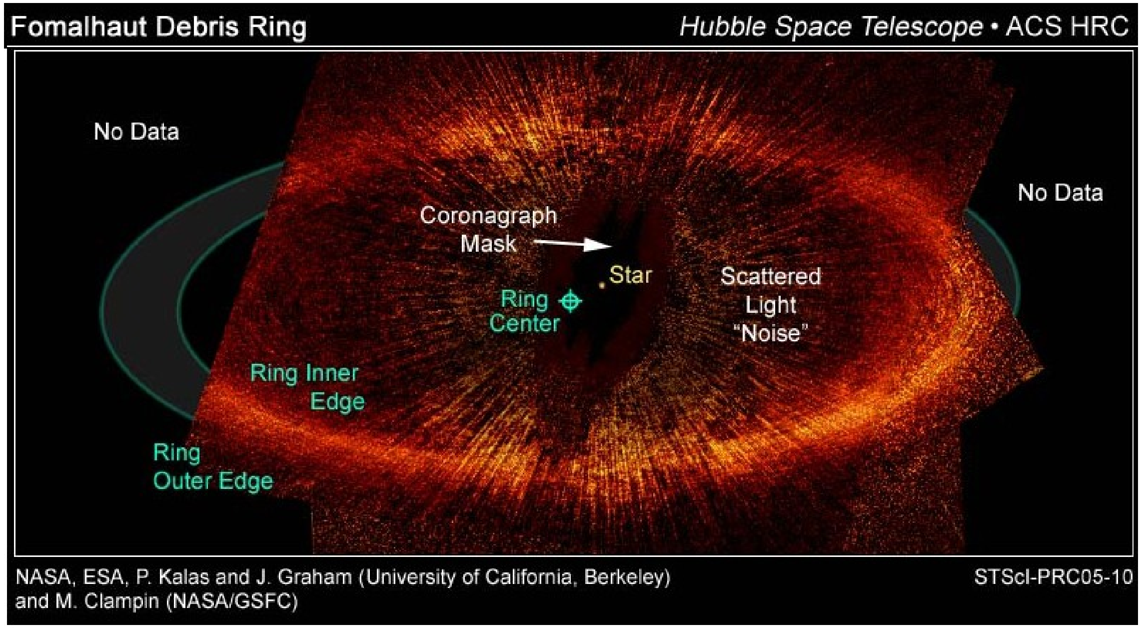
Orbital migration of interacting planets in a radiative evolutionary model

Horn et al. (2012)

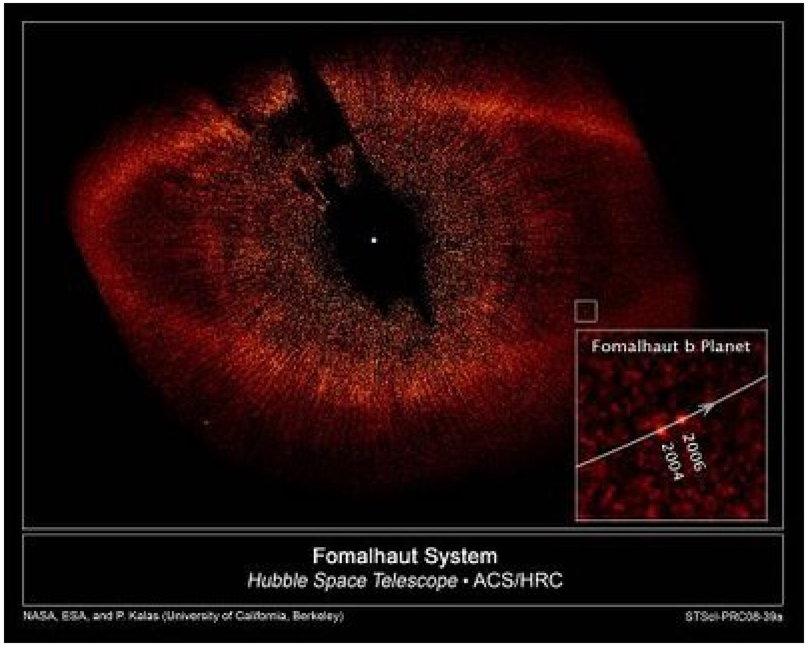
Debris disks – The gas-poor phase



Sharp and eccentric rings in debris disks: Signposts of planets



Narrow sharp eccentric ring



Detection of a source quickly heralded as a planet Fomalhaut b

Sharp and eccentric rings in debris disks: Signposts of planets ?

However.....

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INFRARED NON-DETECTION OF FOMALHAUT b: IMPLICATIONS FOR THE PLANET INTERPRETATION

MARKUS JANSON[1,5], JOSEPH C. CARSON[2], DAVID LAFRENIÈRE[3], DAVID S. SPIEGEL[4], JOHN R. BENT[2], AND PALMER WONG[2]

[1] Department of Astrophysical Sciences, Princeton University, Princeton, NJ, USA; janson@astro.princeton.edu

[2] College of Charleston, Charleston, WV, USA

[3] Department of Physics, University of Montreal, Montreal, Canada

[4] Institute for Advanced Studies, Princeton, NJ, USA

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ABSTRACT

The nearby A4-type star Fomalhaut hosts a debris belt in the form of an eccentric ring, which is thought to be caused by dynamical influence from a giant planet companion. In 2008, a detection of a point source inside the inner edge of the ring was reported and was interpreted as a direct image of the planet, named Fomalhaut b. The detection was made at ~600–800 nm, but no corresponding signatures were found in the near-infrared range, where the bulk emission of such a planet should be expected. Here, we present deep observations of Fomalhaut with *Spitzer*/IRAC at 4.5 μm, using a novel point-spread function subtraction technique based on angular differential imaging and Locally Optimized Combination of Images, in order to substantially improve the *Spitzer* contrast at small separations. The results provide more than an order of magnitude improvement in the upper flux limit of Fomalhaut b and exclude the possibility that any flux from a giant planet surface contributes to the observed flux at visible wavelengths. This renders any direct connection between the observed light source and the dynamically inferred giant planet highly unlikely. We discuss several possible interpretations of the total body of observations of the Fomalhaut system and find that the interpretation that best matches the available data for the observed source is scattered light from a transient or semi-transient dust cloud.

Key words: circumstellar matter – planetary systems – stars: early-type

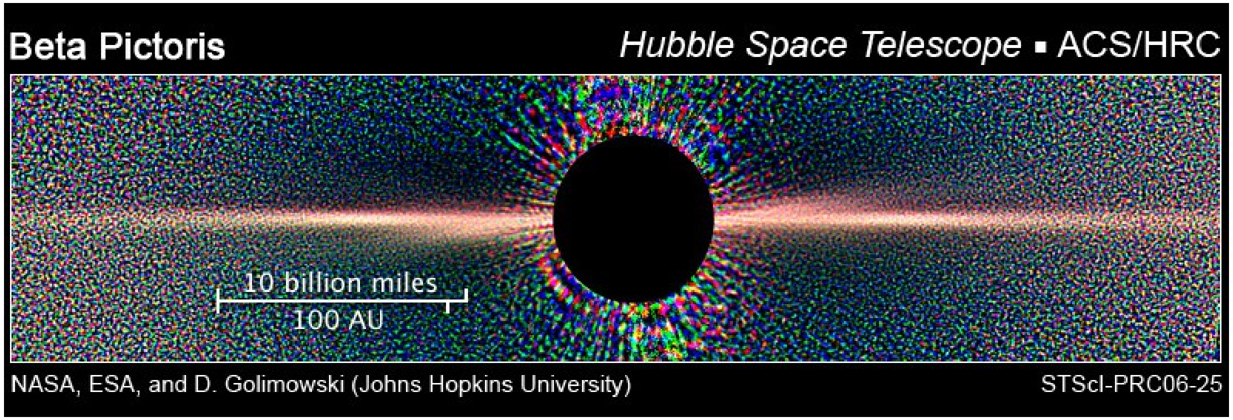
Online-only material: color figures

Planet not detected in infrared

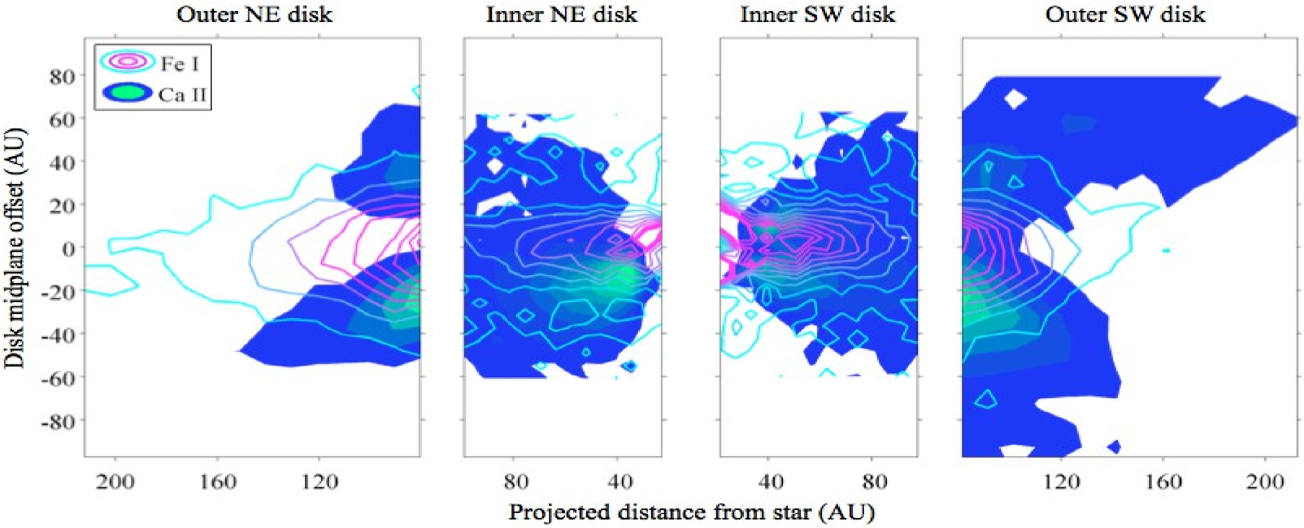
Are there alternative explanations?

Debris disks are not completely gas-free

Dust



Gas



VLT imaging by Nilsson et al. (2012)

Gas in debris disks

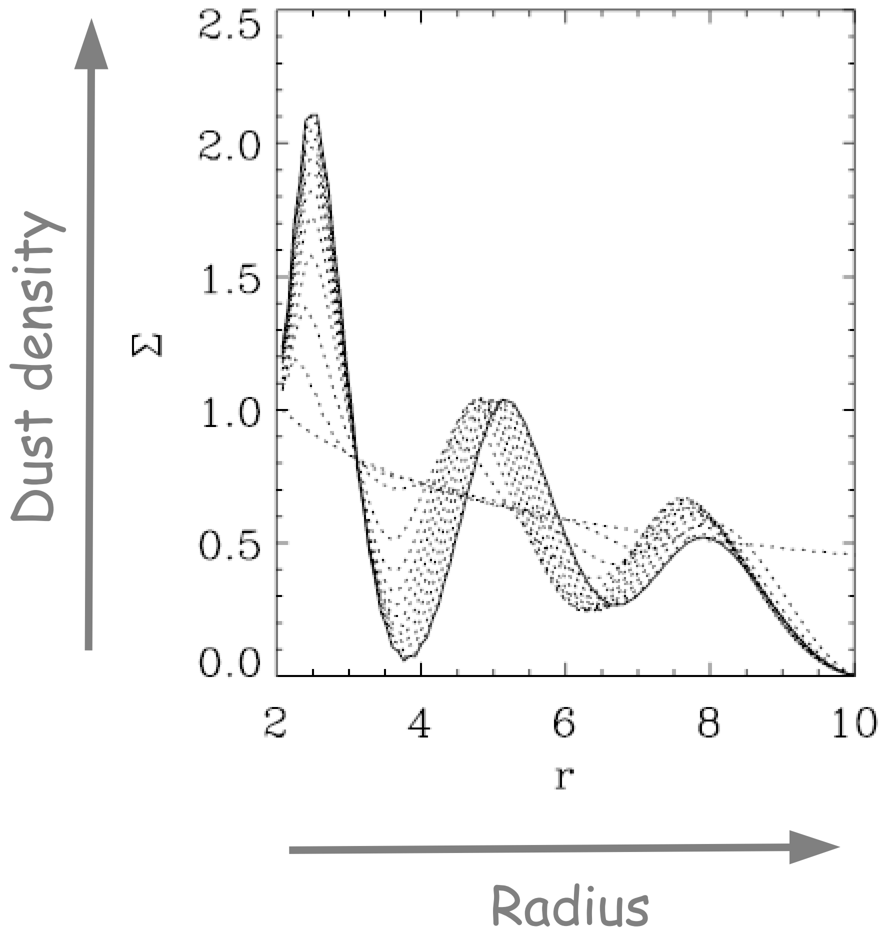
Detections

β Pictoris	many species	Lagrange et al. (1998), ...
51 Ophiuchi	many species	Roberge et al. (2002)
σ Herculis	C II, N II	Chen & Jura (2003)
HD 32297	Na I, CII	Redfield (2007), Donaldson et al. (2012)
HD 135344	H2, CO	Thi et al. (2001), Pontoppidan et al. (2008)
49 Ceti	H2, CO	Dent et al. (2005), Roberge et al. (2012)
AU Mic	H2	France et al. (2007)
HD172555	SiO	Lisse et al. (2009)

Source of gas: Outgassing processes

·Infalling comets	Beust & Valiron (2007)
Grain sublimation	e.g. Rafikov (2012)
Grain-Grain collisions	Czechowski & Mann (2007)
Photo-stimulated desorption	Chen et al. (2007)
Planet-Planet collisions	Van den Ancker (2001), Lisse (2008)
Primordial?	

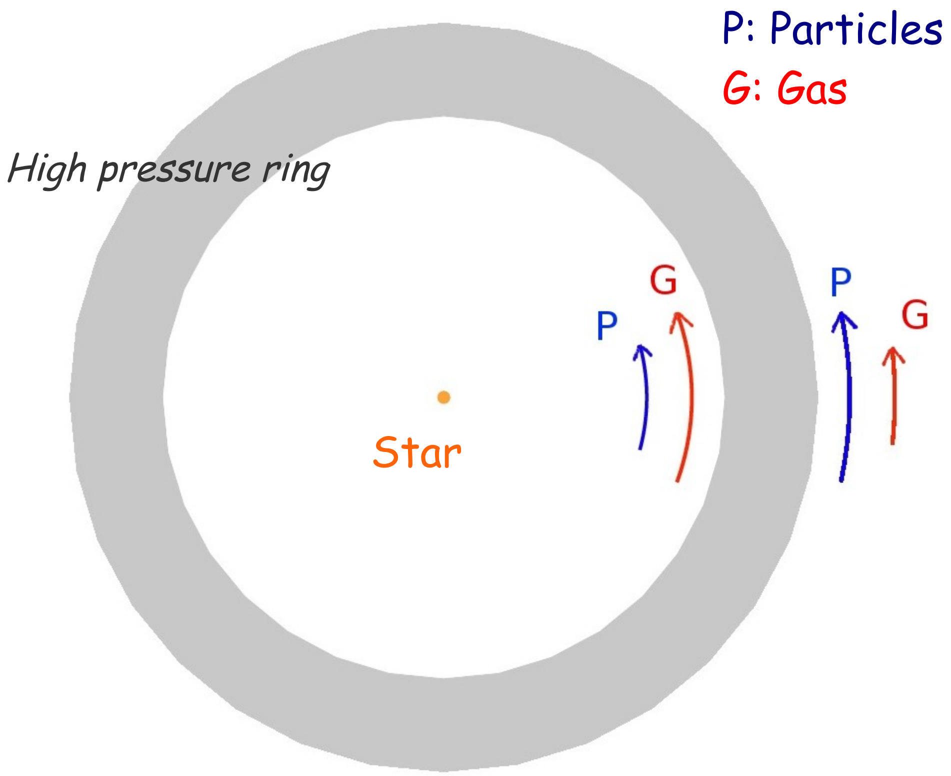
Dust and gas together leads to instability...



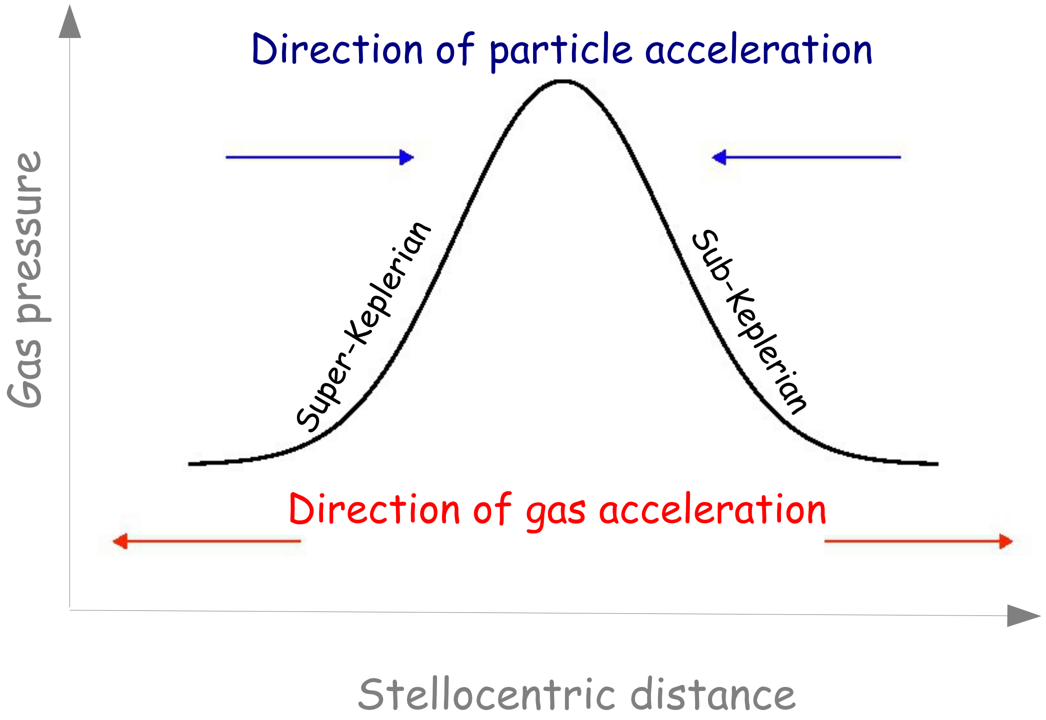
Klahr & Lin (2005)

Suggested that an instability might cause dust in debris disks to clump together.

Particles move toward pressure maxima

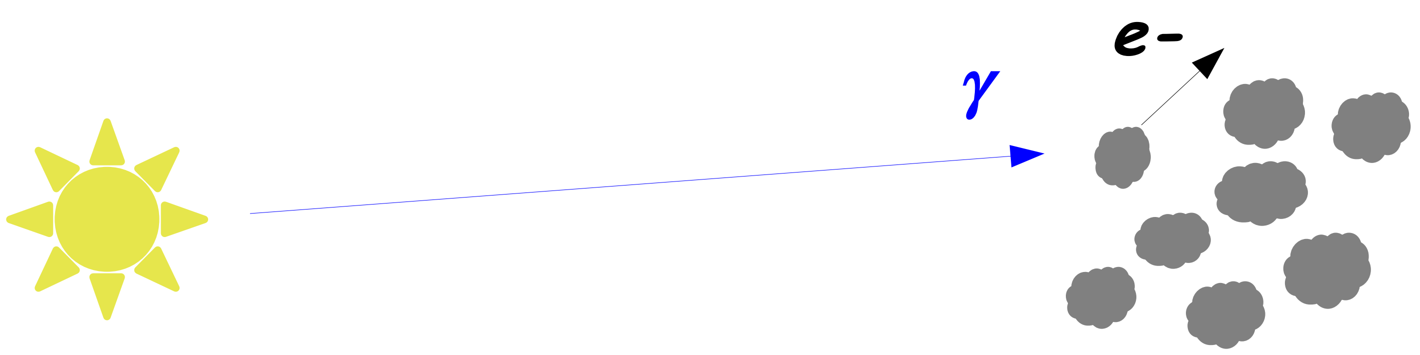


Adapted from Whipple (1972)



Photoelectric heating

In optically thin debris disks,
the **dust** is the **main heating agent** for the gas.



Dust intercepts starlight directly,
emits electron, that heats the gas.

Gas is photoelectrically heated by the dust itself

Runaway process: instability

Dust heats gas
Heated gas = high pressure region
High pressure concentrates dust

Runaway process: instability

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Model equations

Klahr & Lin (2005) used a simplified, 1-D model.

$$\frac{\partial}{\partial t}\Sigma_d + \frac{1}{r}\frac{\partial}{\partial r} r\Sigma_d v_r = 0.$$

Continuity equation

$$V_\phi = \Omega r + \frac{1}{2\Omega\Sigma_g}\frac{\partial}{\partial r}P$$

Terminal velocity

$$T_g = T_0 \left(\frac{\Sigma_d}{\Sigma_0}\right)^\beta,$$

Equation of state

Model equations

Our simulation adds much more physics, and works in 2D.

Klahr & Lin (2005)
1D

$$\frac{\partial}{\partial t}\Sigma_d + \frac{1}{r}\frac{\partial}{\partial r} r\Sigma_d v_r = 0.$$

$$V_\phi = \Omega r + \frac{1}{2\Omega\Sigma_g}\frac{\partial}{\partial r}P$$

$$T_g = T_0\left(\frac{\Sigma_d}{\Sigma_0}\right)^\beta,$$

Inertia for both gas and dust

Energy equation

Drag force and
drag force backreaction

Lyra & Kuchner (2012)
2D

$$\frac{\partial \Sigma_g}{\partial t} = -(\boldsymbol{u}\cdot\boldsymbol{\nabla})\Sigma_g - \Sigma_g \boldsymbol{\nabla}\cdot\boldsymbol{u}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} = -(\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} - \frac{1}{\Sigma_g}\boldsymbol{\nabla}P - \boldsymbol{\nabla}\Phi - \frac{\Sigma_d}{\Sigma_g}\boldsymbol{f}_d$$

$$\frac{\partial S}{\partial t} = -(\boldsymbol{u}\cdot\boldsymbol{\nabla})S - \frac{c_v}{T}\frac{(T-T_p)}{\tau_T}.$$

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

$$\frac{d\boldsymbol{v}}{dt} = -\boldsymbol{\nabla}\Phi + \boldsymbol{f}_d$$

$$f_d = -\frac{(v-u)}{\tau_f}$$

$$T_p = T_0\frac{\Sigma_d}{\Sigma_0}.$$

Linear Analysis

Dust

$$D_w \Sigma_d = -\Sigma_d \nabla \cdot \boldsymbol{w}$$

$$D_w w_x = 2\Omega w_y - \frac{1}{\tau_f}(w_x - u_x)$$

$$D_w w_y = -\frac{1}{2}\Omega w_x - \frac{1}{\tau_f}(v_y - u_y)$$

Gas

$$D_u \Sigma_g = -\Sigma_g \nabla \cdot \boldsymbol{u}$$

$$D_u u_x = 2\Omega u_y - \frac{1}{\Sigma_g}\frac{\partial P}{\partial x} - \frac{\epsilon}{\tau_f}(u_x - w_x)$$

$$D_u u_y = -\frac{1}{2}\Omega u_x - \frac{1}{\Sigma_g}\frac{\partial P}{\partial y} - \frac{\epsilon}{\tau_f}(u_y - w_y)$$

$$\psi = \psi_0 + \psi'$$

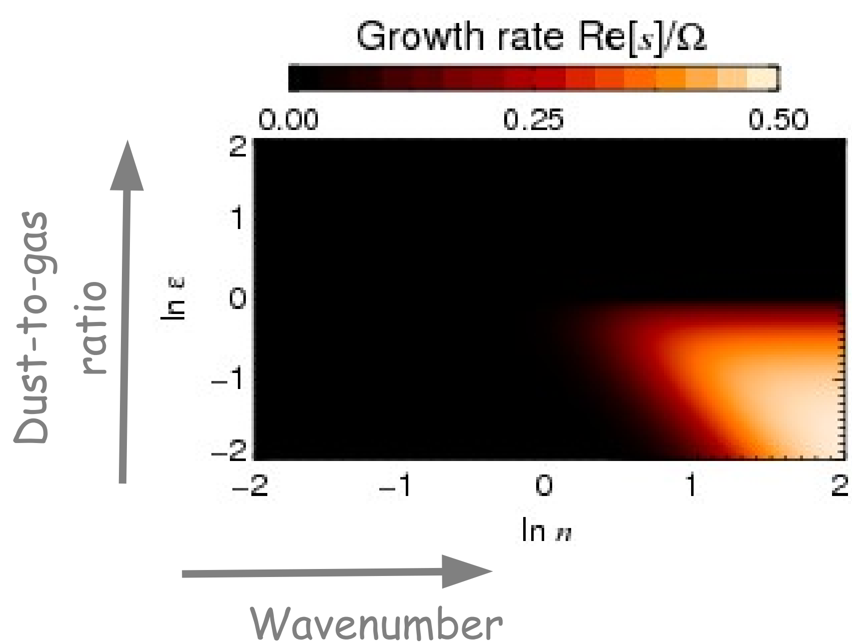
$$\psi' = \hat{\psi}\exp(ikx + st)$$

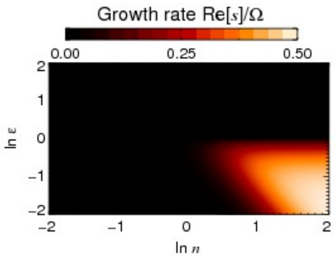
Dispersion relation

$$A\omega^5 + B\omega^4 + C\omega^3 + D\omega^2 + E\omega + F = 0$$

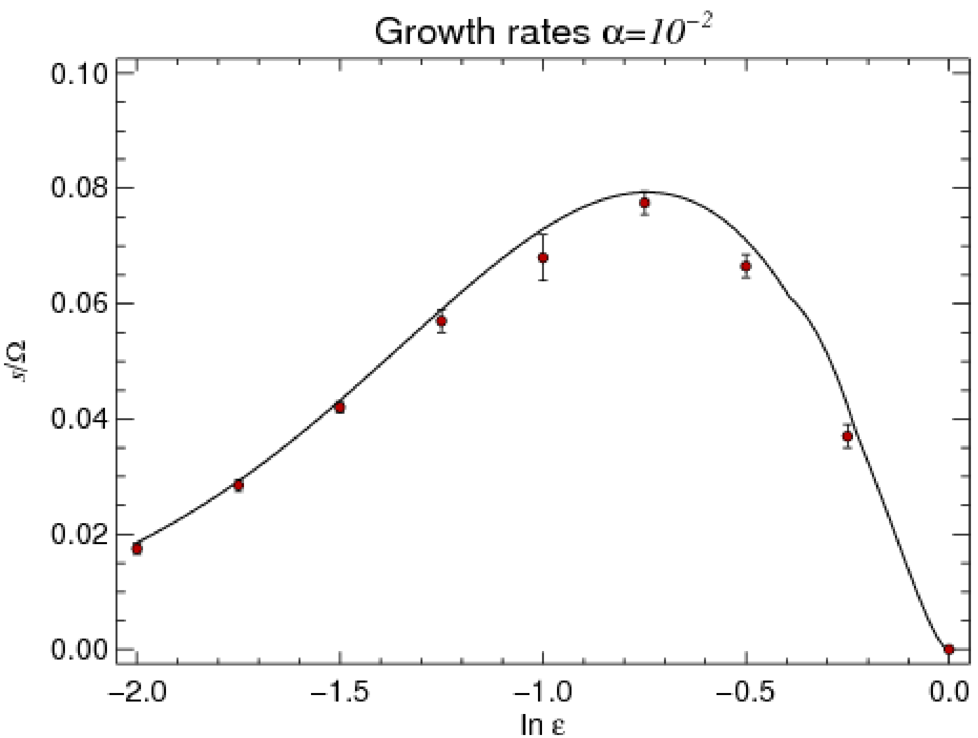
$$A = 1$$
$$B = 2\epsilon + 2$$
$$C = \epsilon^2 + \epsilon(n^2+2) + 3$$
$$D = \epsilon^2 n^2 + \epsilon(3n^2+2) + 2$$
$$E = \epsilon^2(2n^2+1) + \epsilon(3n^2+2) + 2$$
$$F = \epsilon^2 n^2 - \epsilon n^2$$

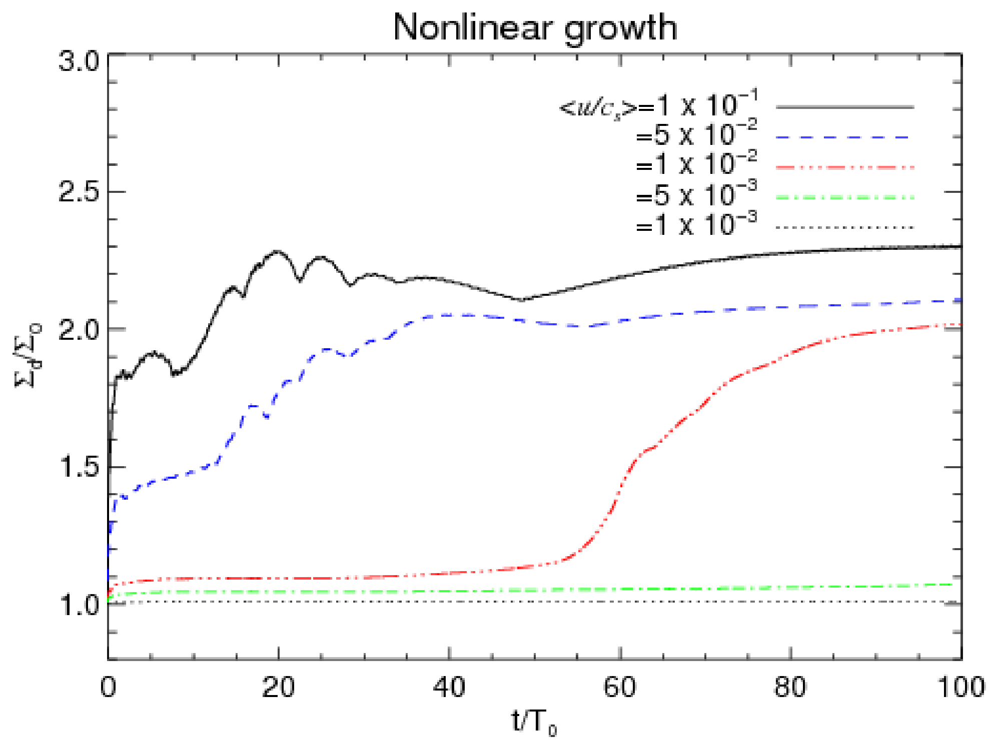
$\epsilon = \Sigma_d / \Sigma_g$ $\quad n = kH$ $\quad \omega = s/\Omega$





Linear and nonlinear growth



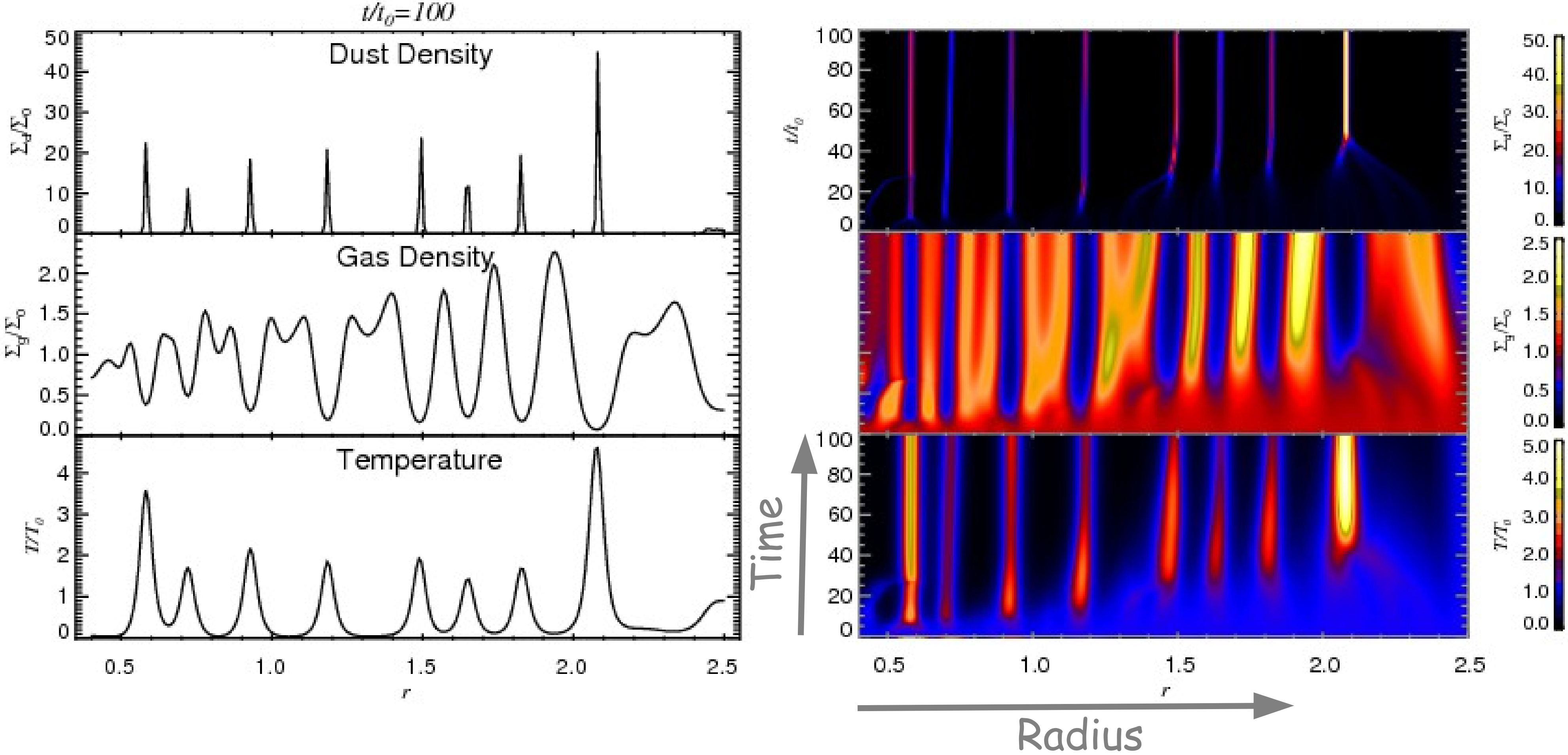


Linear growth only exists for $\varepsilon < 1$

But there is
nonlinear growth
beyond !

Instability

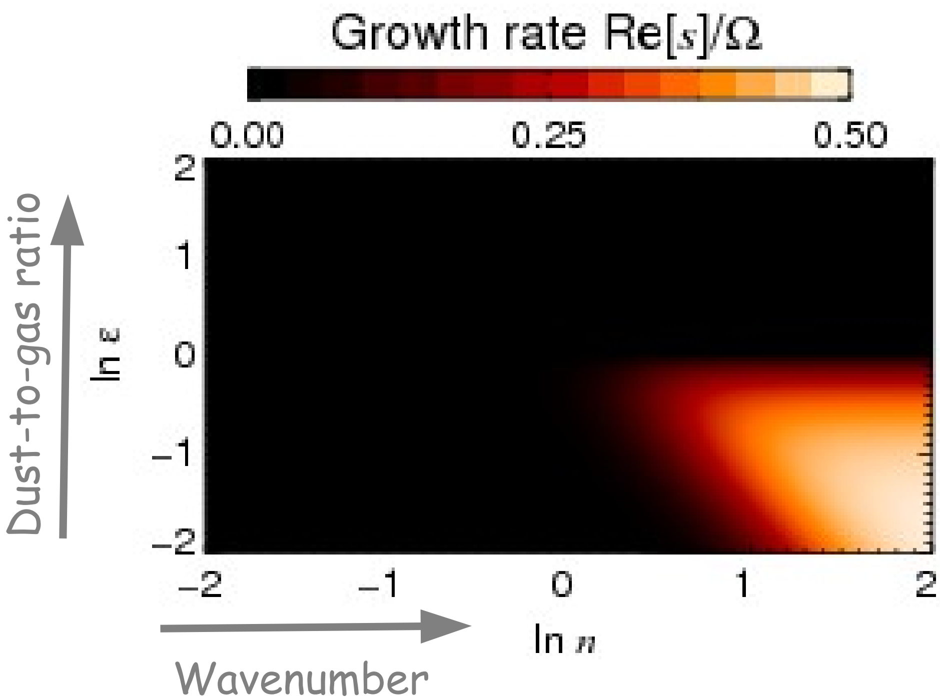
Dust heats gas
Heated gas = high pressure region
High pressure concentrates dust

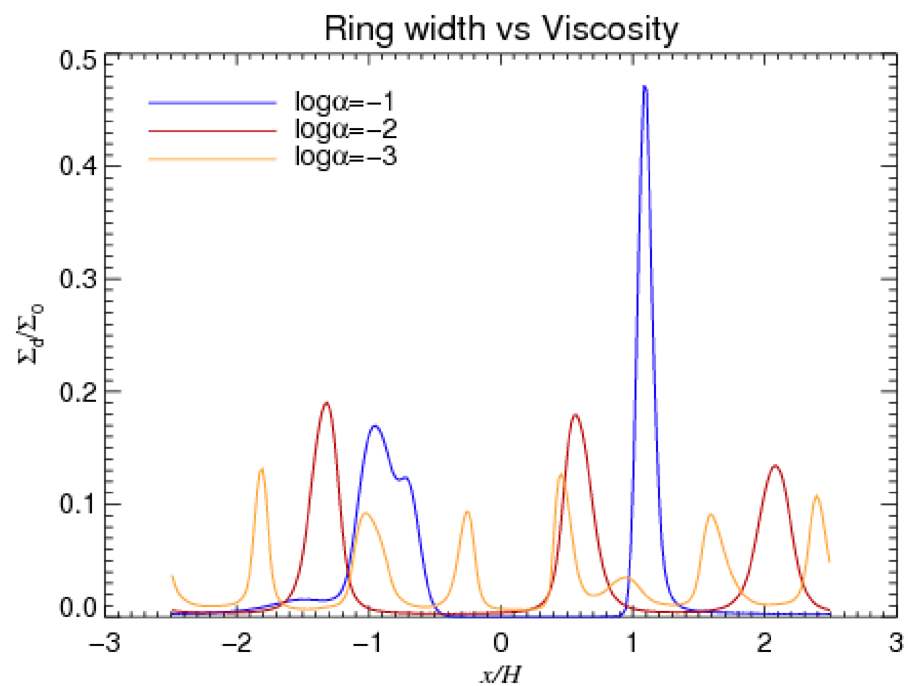


Narrow hot dust rings
Cold gas collects between rings

Ring width

Ring spacing and width is determined by the wavelength of maximum growth.



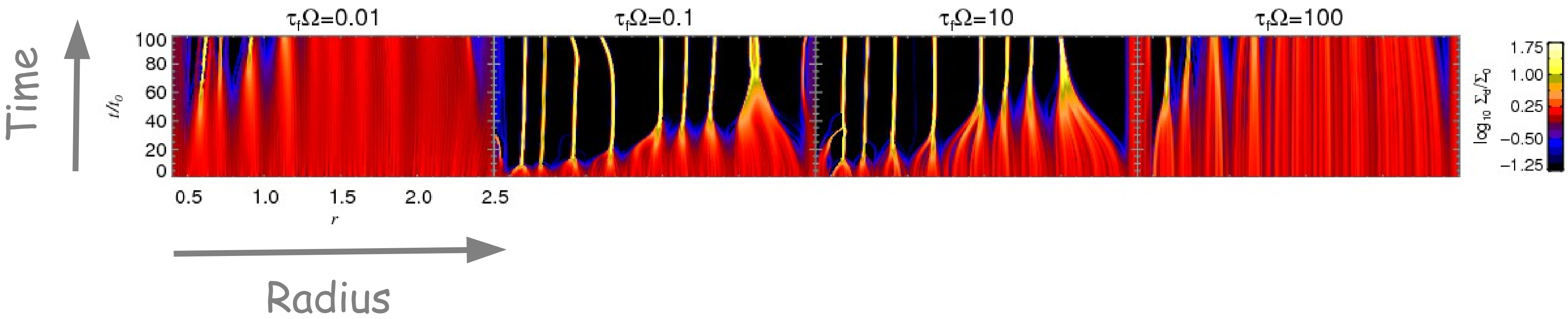


Which in turn is determined by viscosity

Ring width ~ 10 Kolmogorov lengths

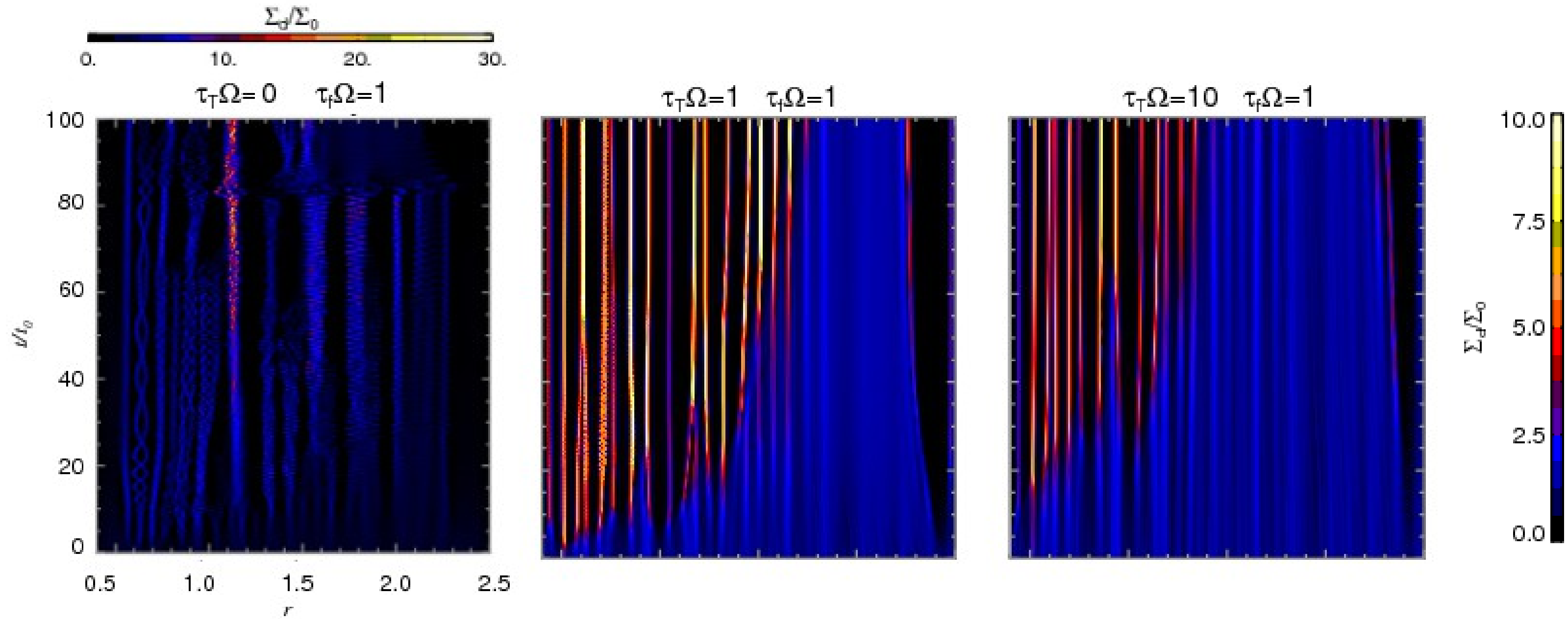
Robustness

Growth over 4 orders of magnitude in dust-gas coupling time (friction time)



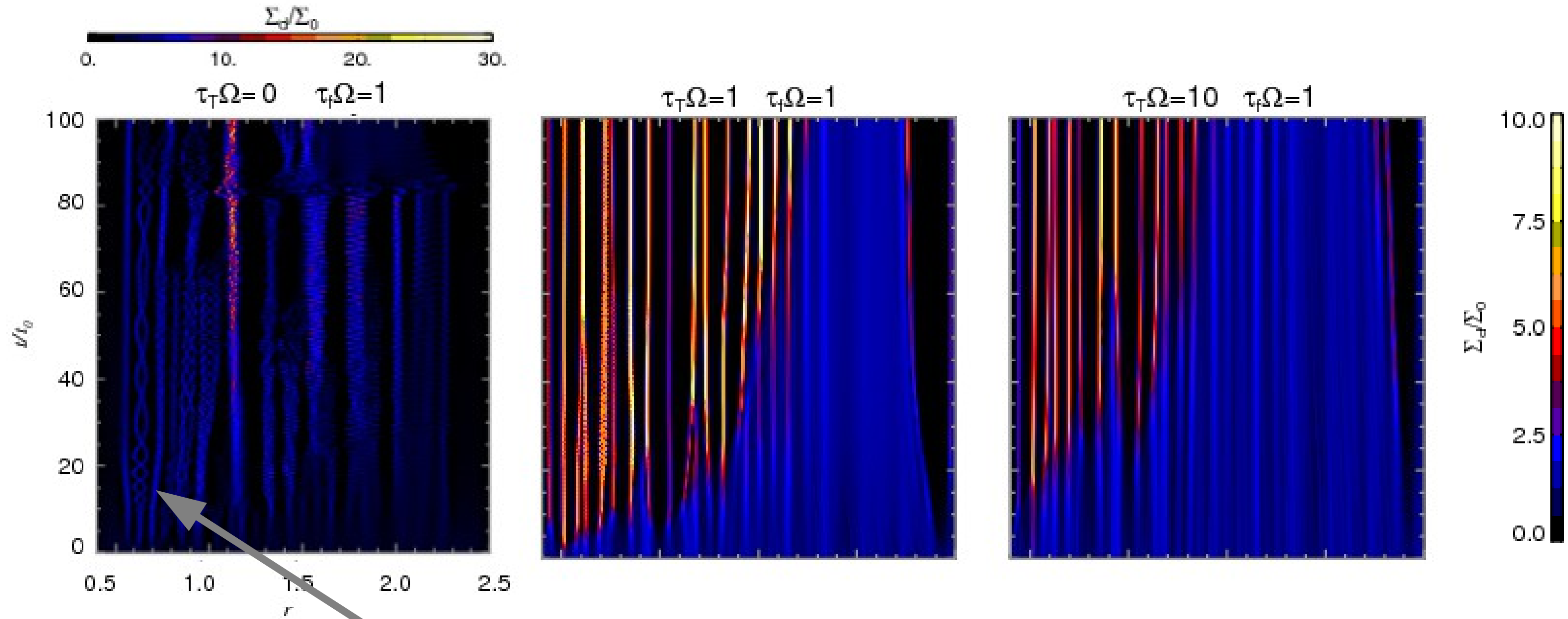
Oscillations

Thermal coupling time



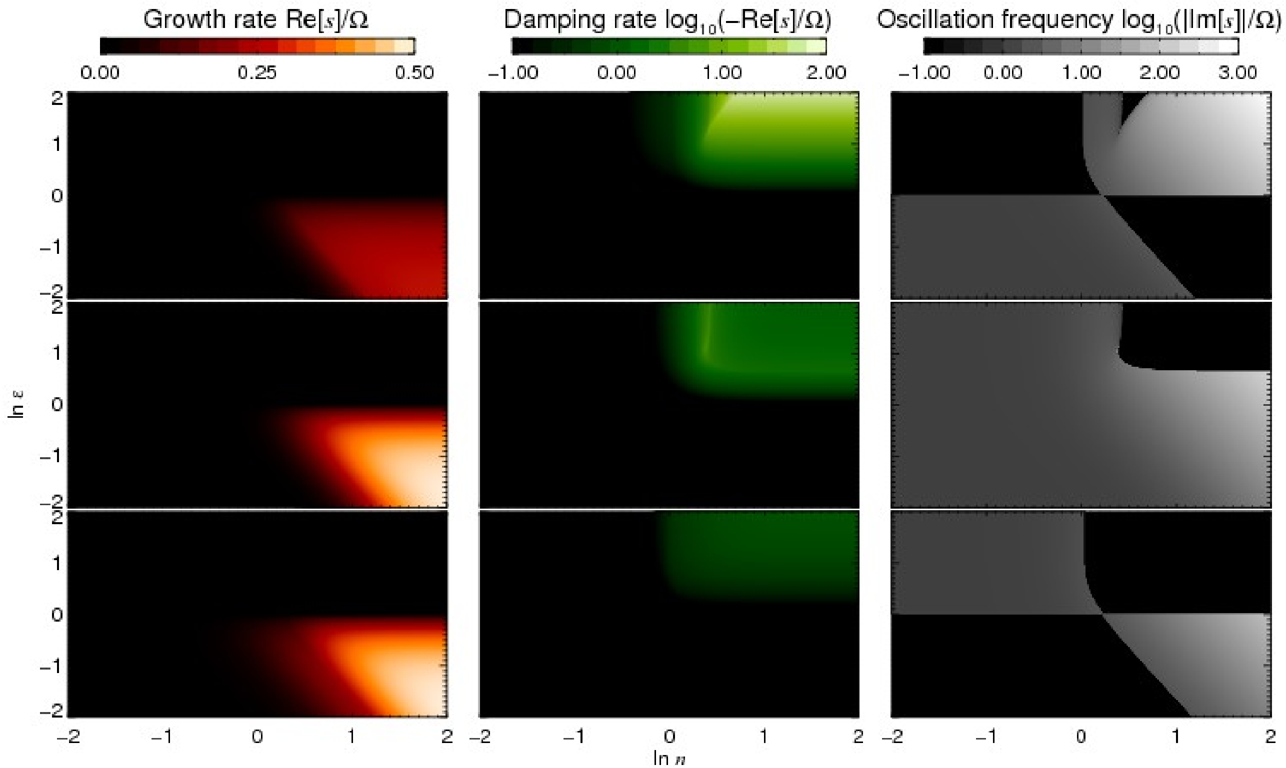
Oscillations

Thermal coupling time →



Oscillations appear
with decreasing thermal time.

Solutions



Dispersion relation

$$A\omega^5 + B\omega^4 + C\omega^3 + D\omega^2 + E\omega + F = 0$$

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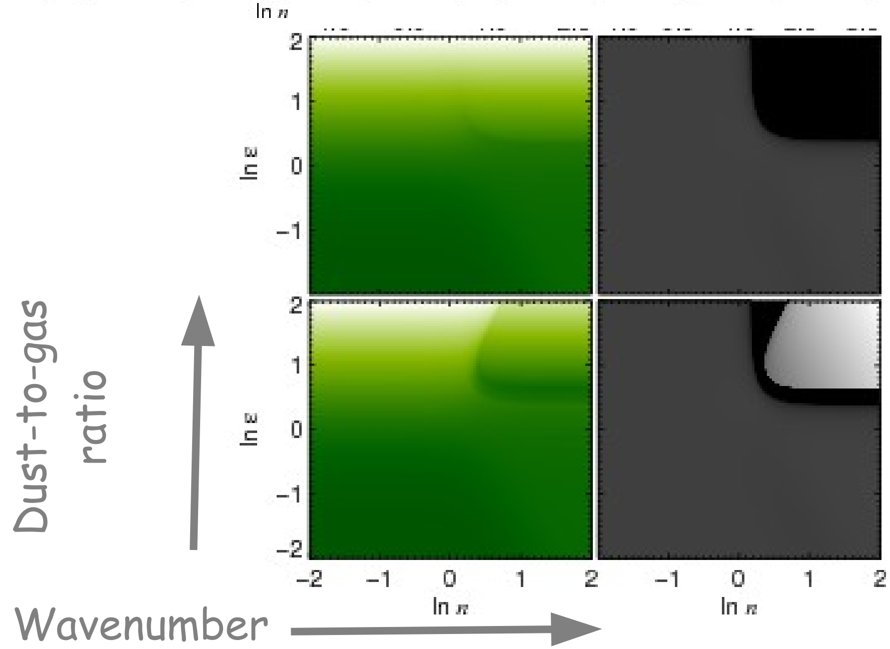
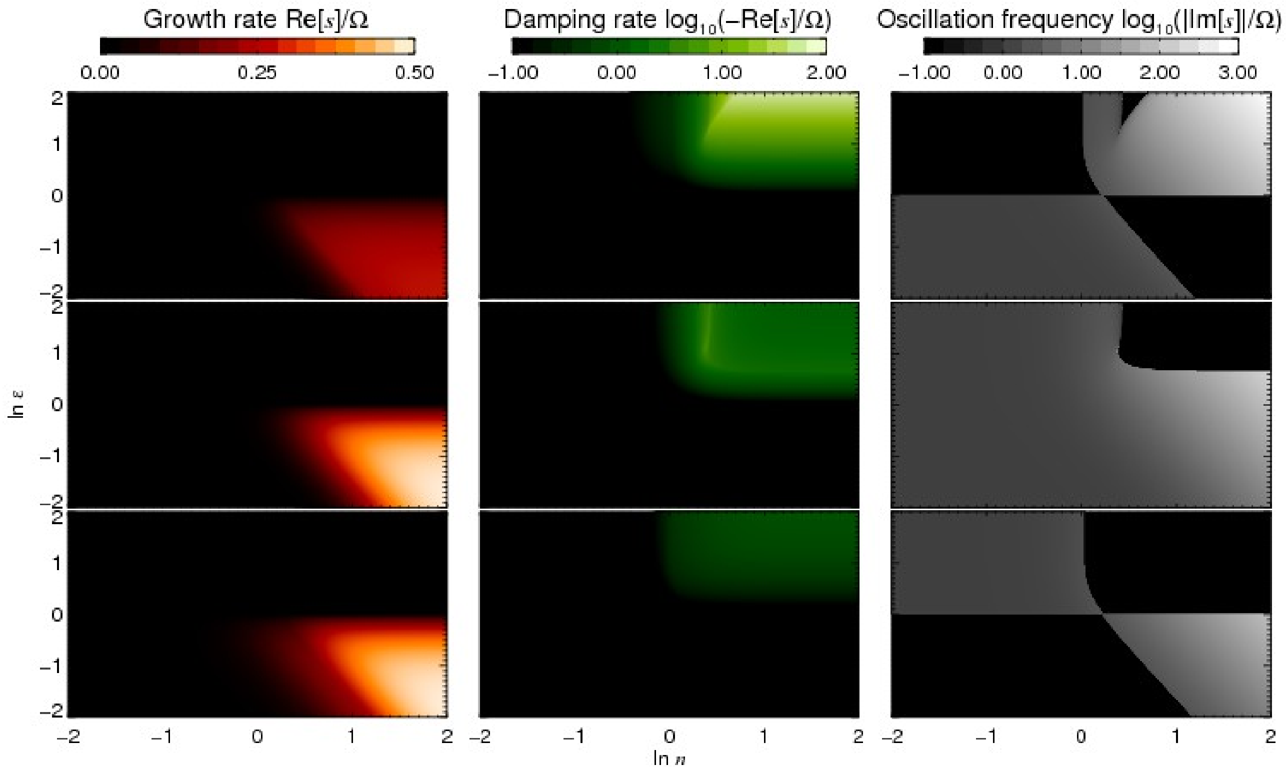


Solutions

Instability

Overstability



Damped and free Oscillations

Dispersion relation

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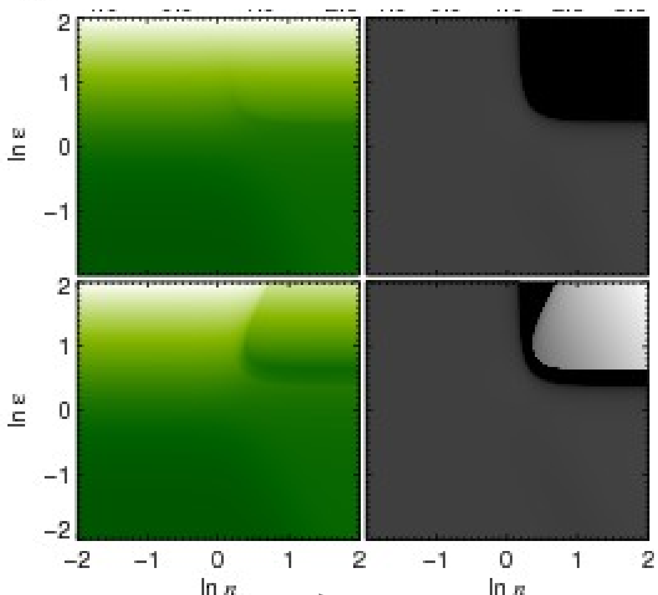
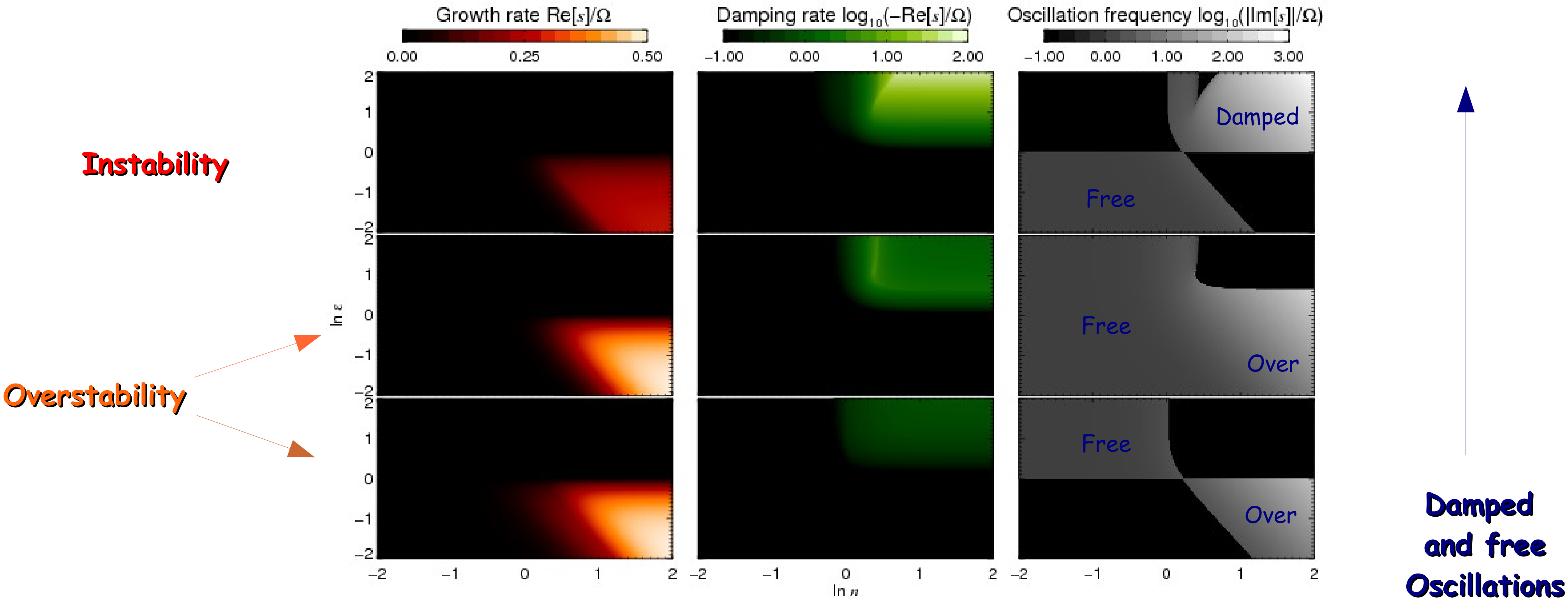
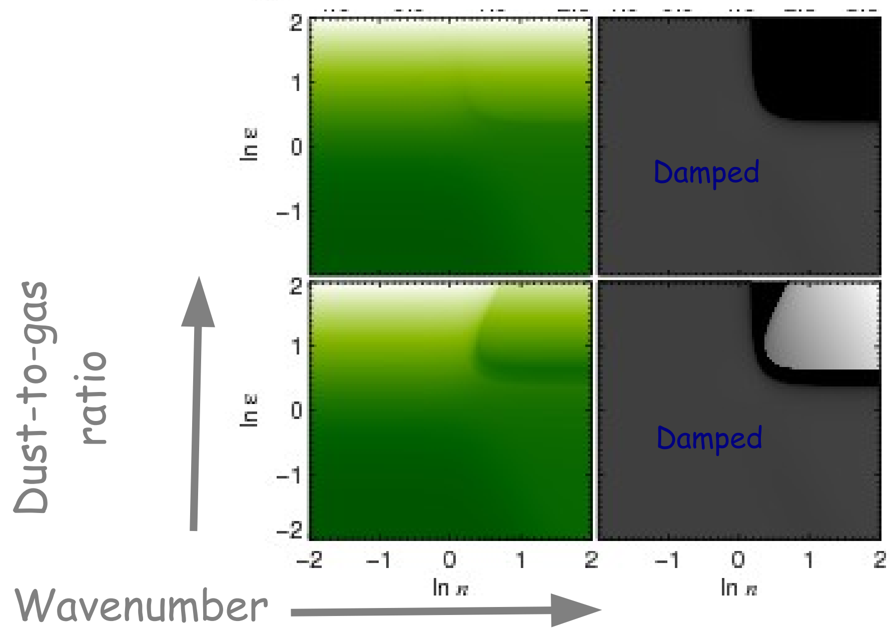
Dust-to-gas ratio



Wavenumber

Solutions





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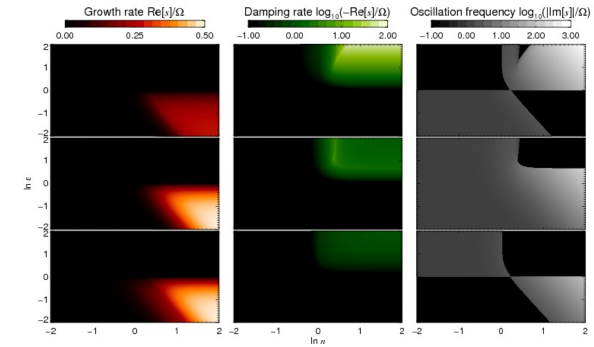
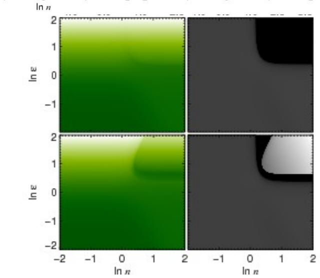
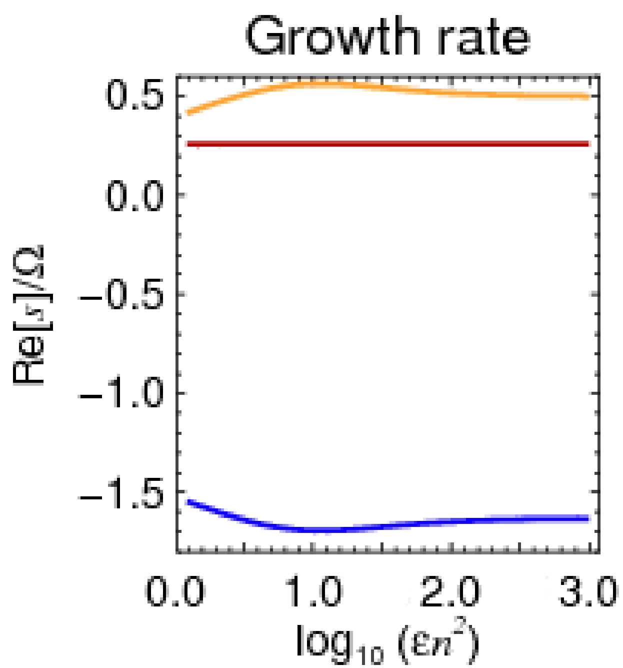


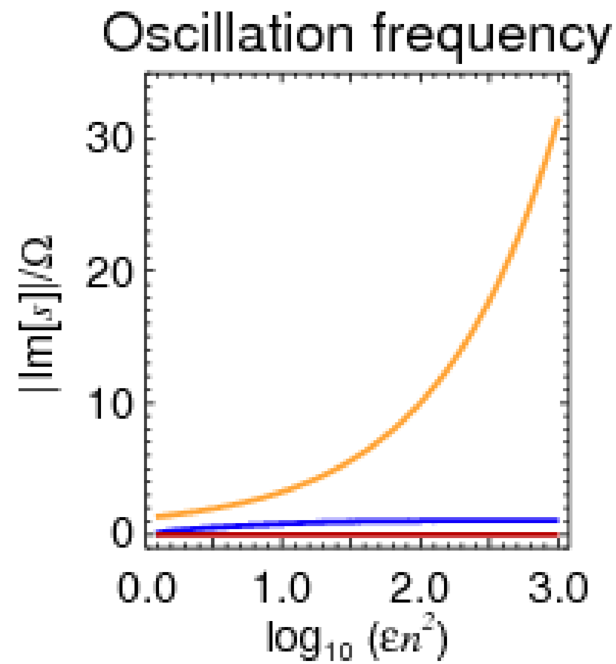


Overstability

Instability

Oscillations





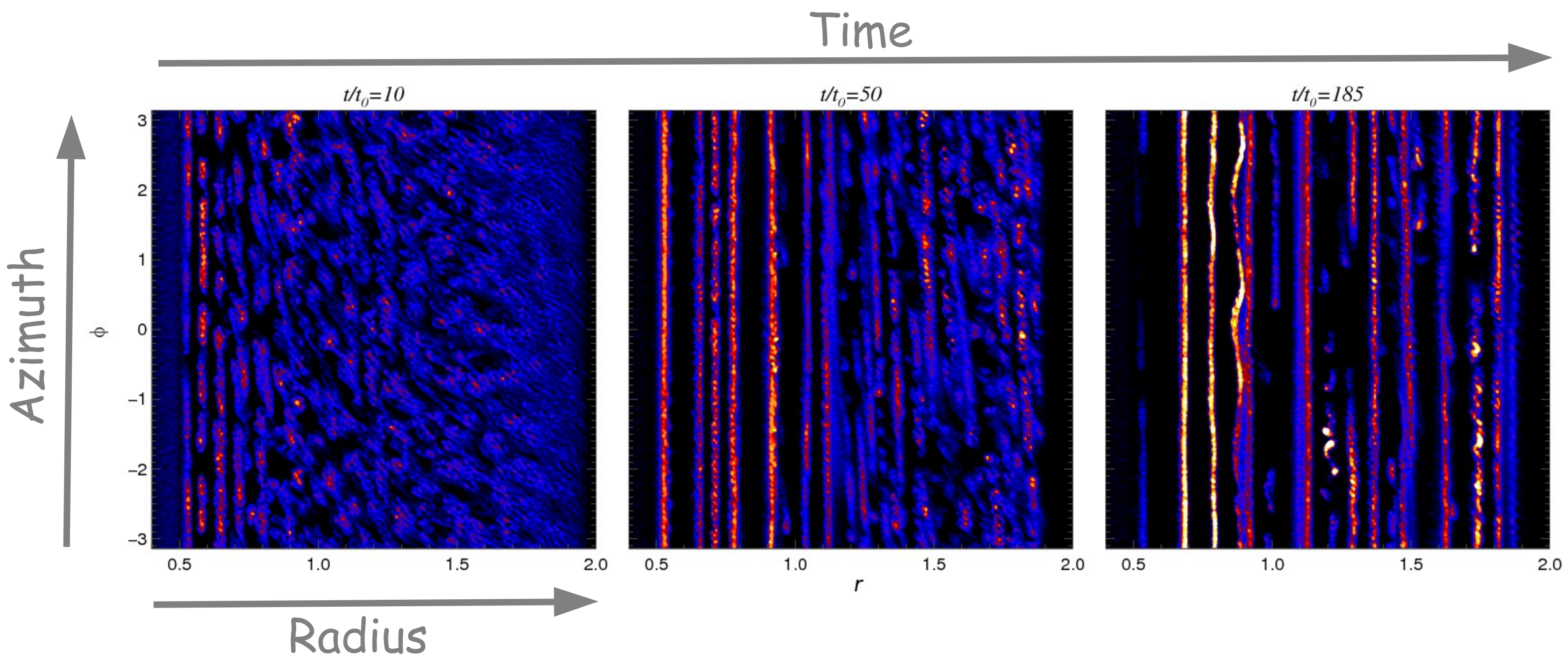
Max growth rate: $\Omega/2$.

Million-fold amplification in five orbits!

A very powerful instability.

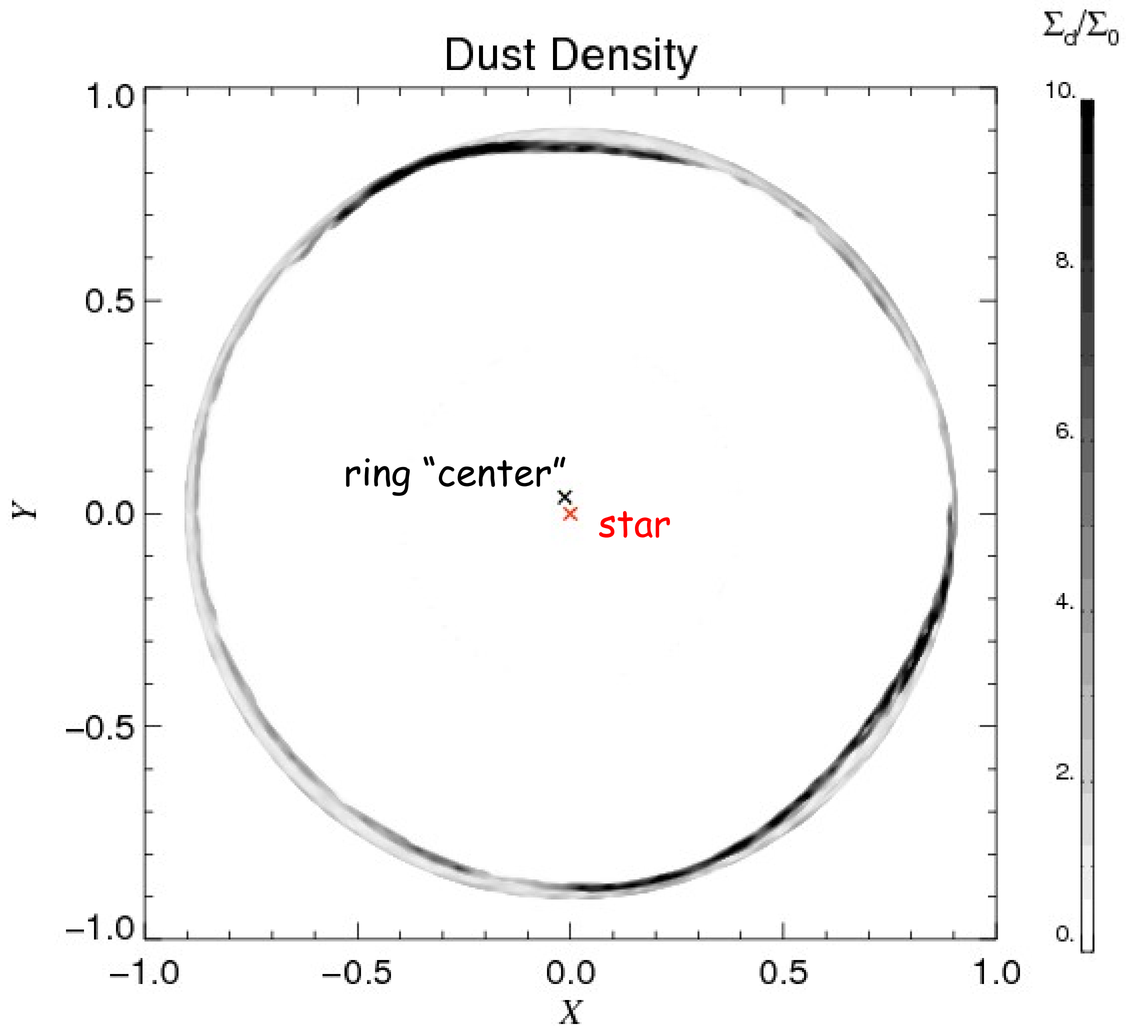
The model in 2D: Eccentric rings

Growth of axisymmetric modes
+
Damping of nonaxissymetric modes.
= *Rings !!!*

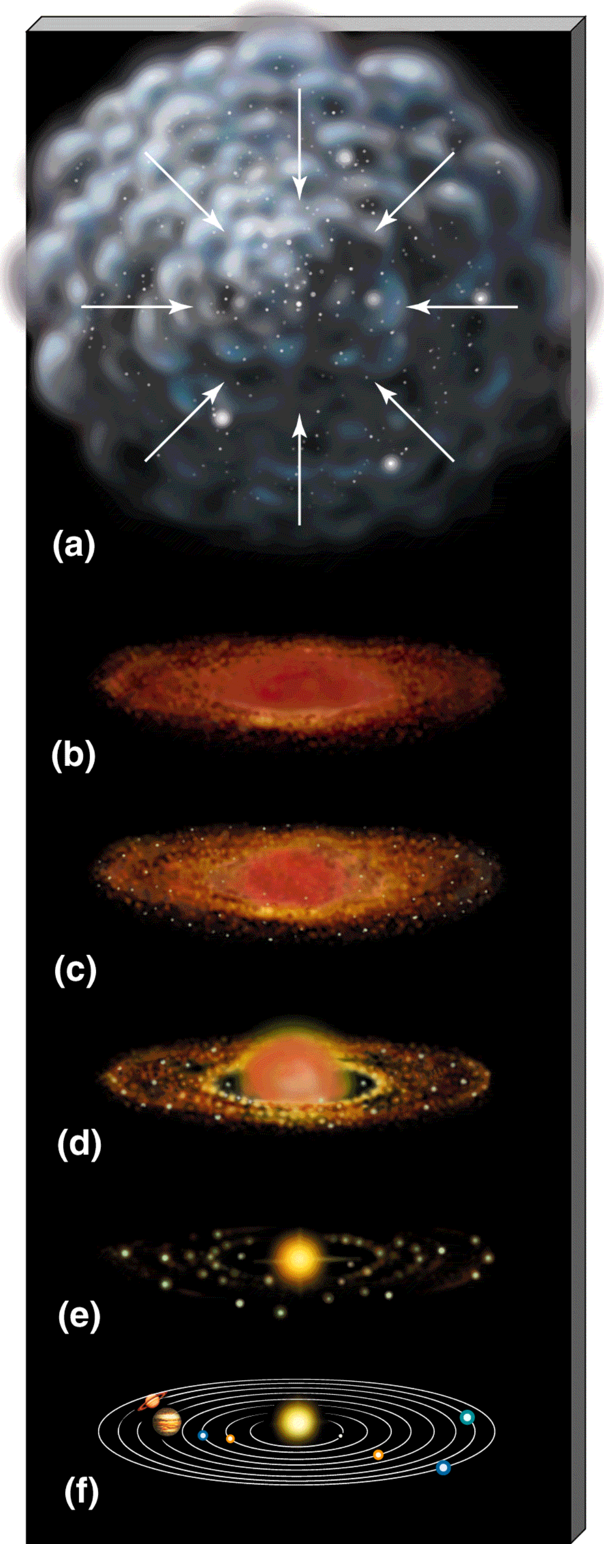


Epicyclic oscillations
make the ring appear ***eccentric !!!***

Ring eccentricity



Eccentricity e=0.04



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.

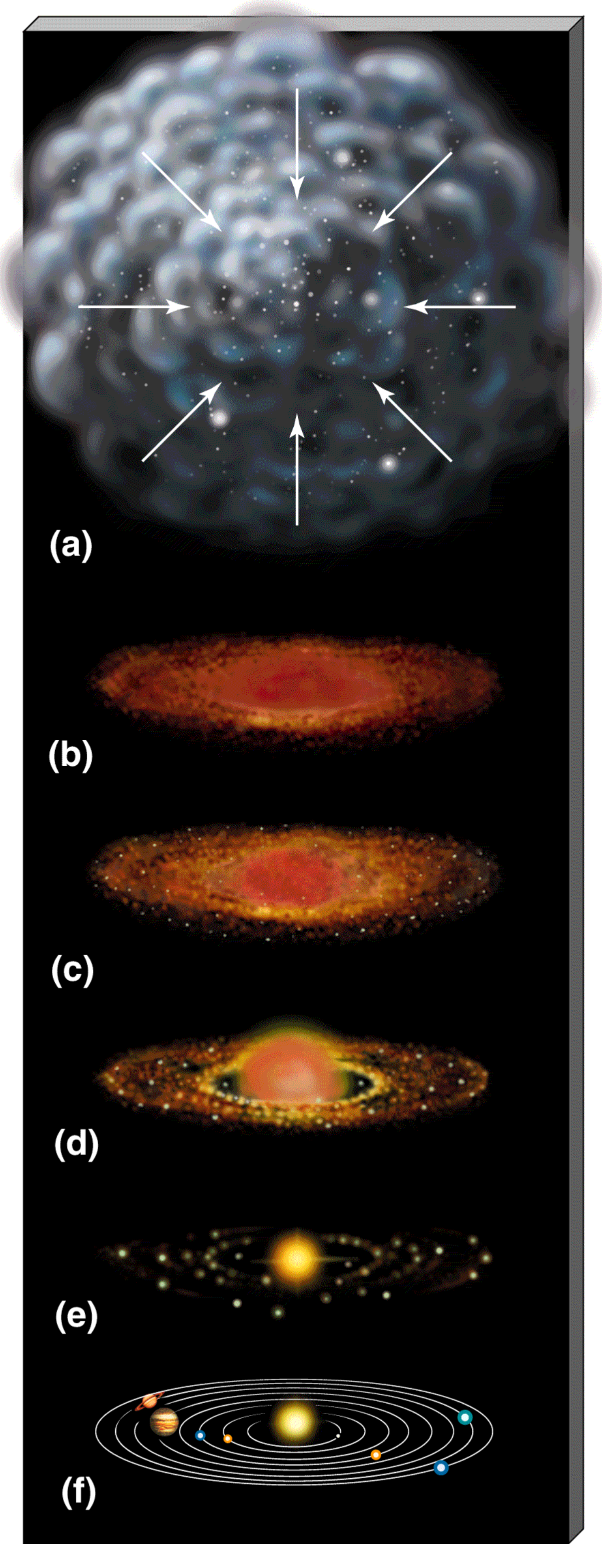
Convergent migration leads to resonances, these are disrupted by turbulent forcing. Collisions between embryos gives rise to oligarchs.

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.

Debris disks with gas are subject to a thermo-centrifugal instability

The instability generates sharp eccentric rings. Caution before shouting "planet!". Not all that glitters is gold.



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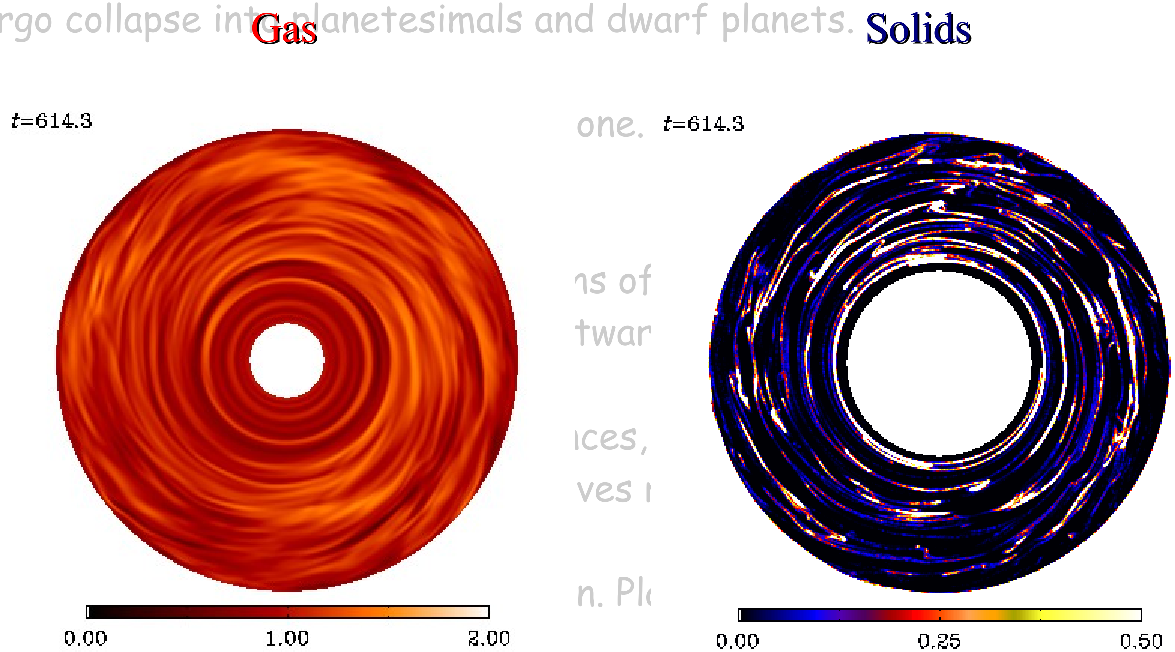

Vorti... one. ... Mars-mass

Opac... ns of ... planets conve... twar...

Conv... ices, forci... ves ...

The ... n. Pl...

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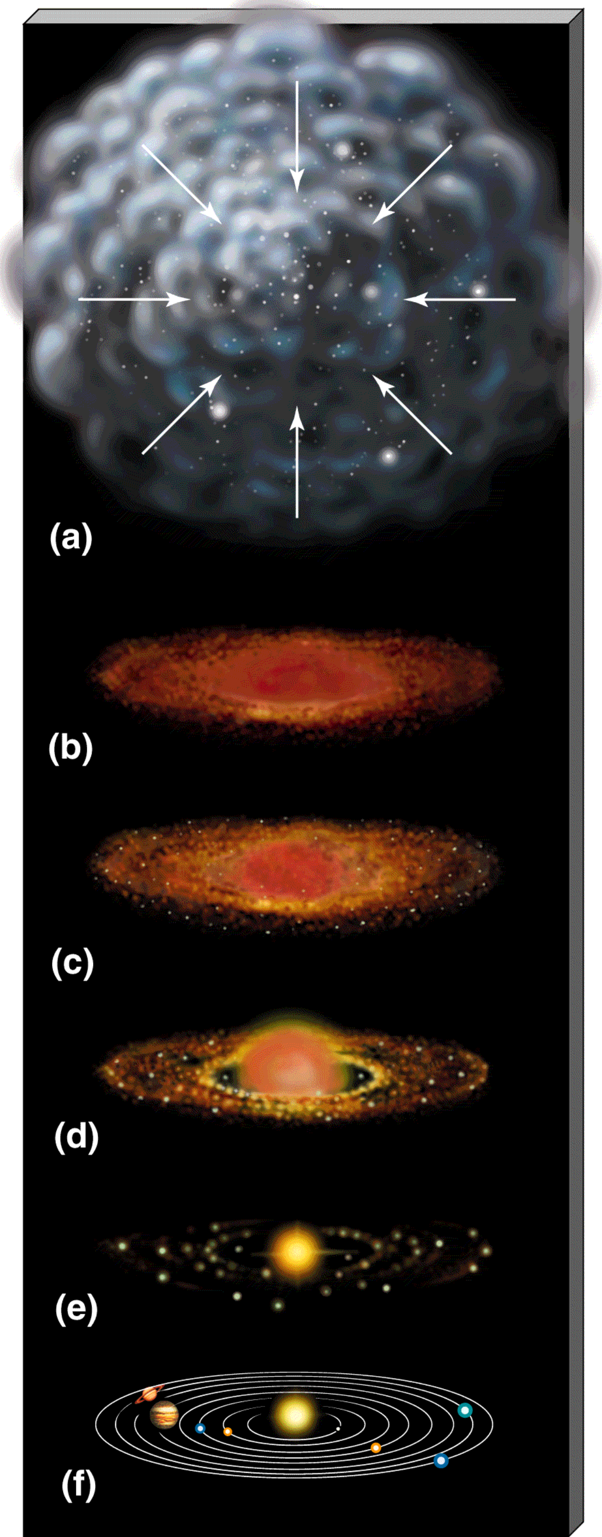

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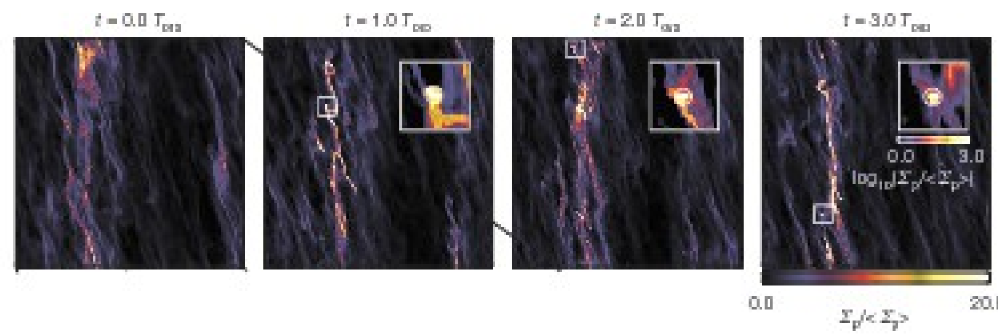
converge to thes



Convergent migr
forcing. Collision

The disk thins du

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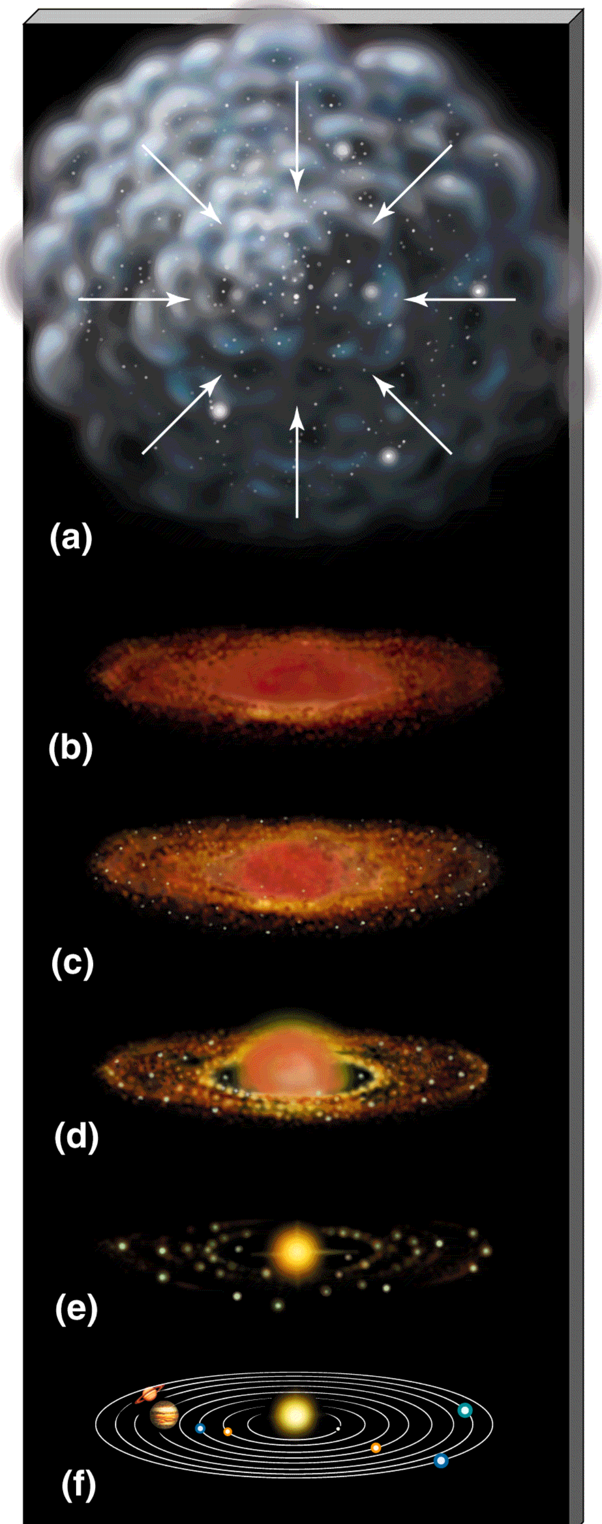

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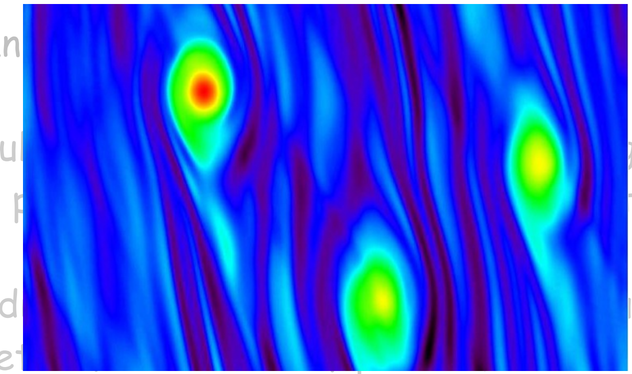

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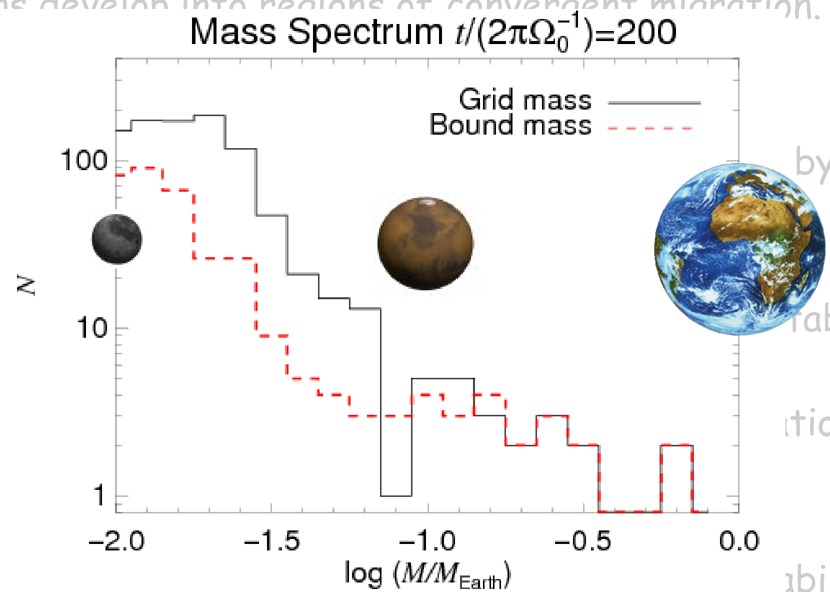

Convergent mig by turbulent forcing. Collisio

The disk thins table orbits.

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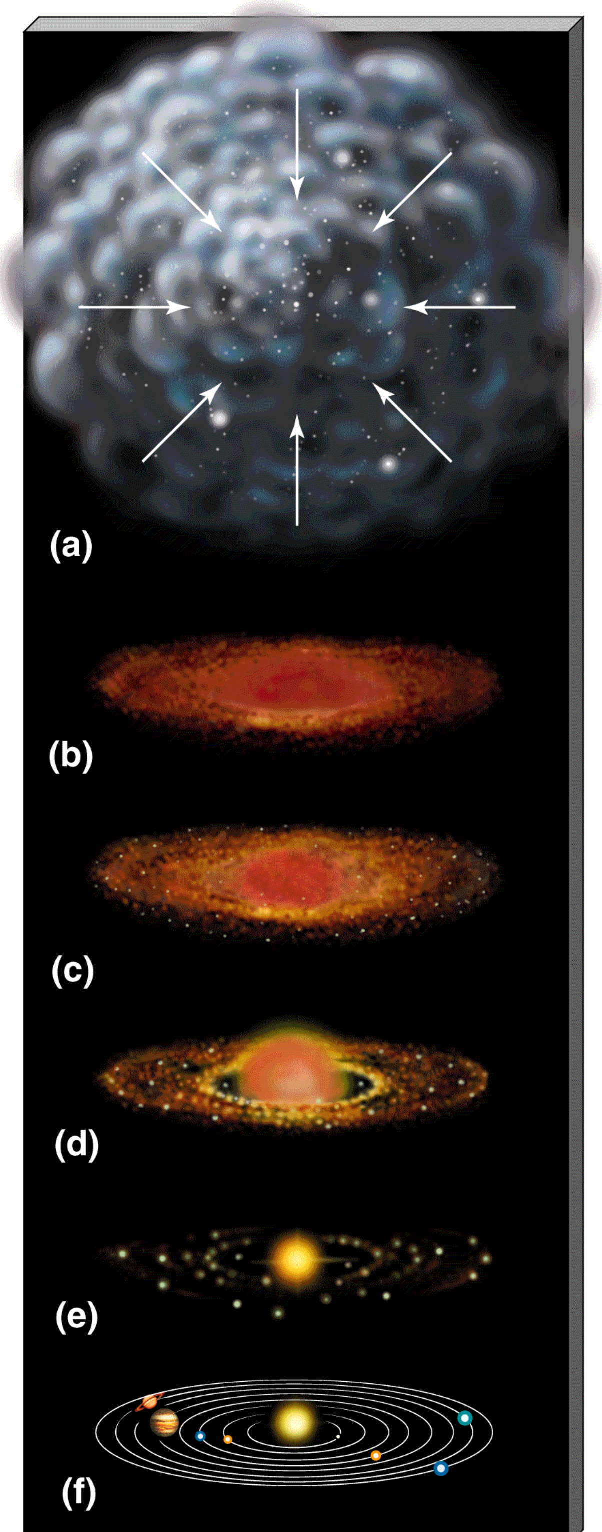

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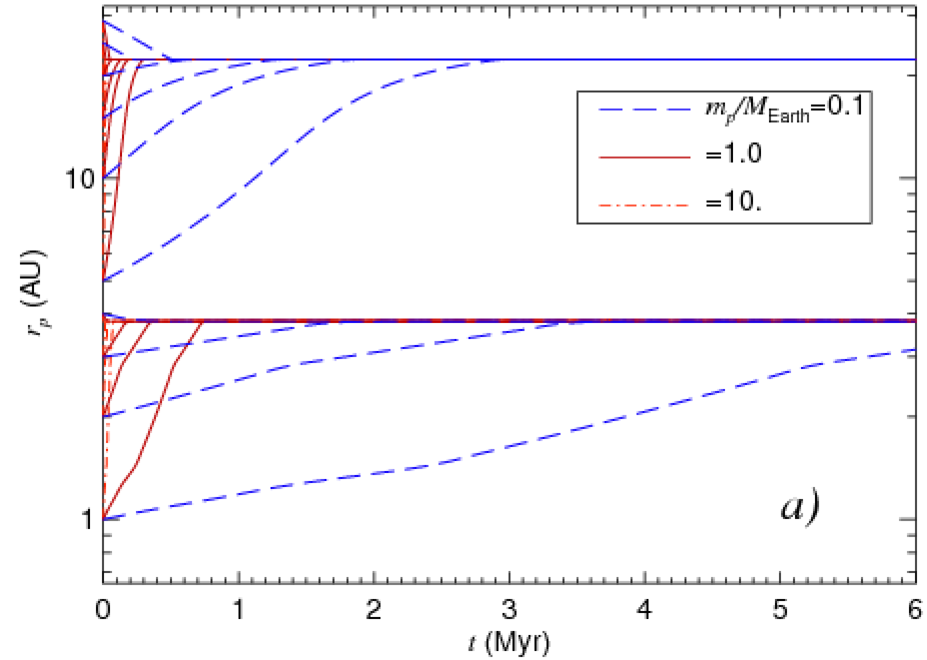

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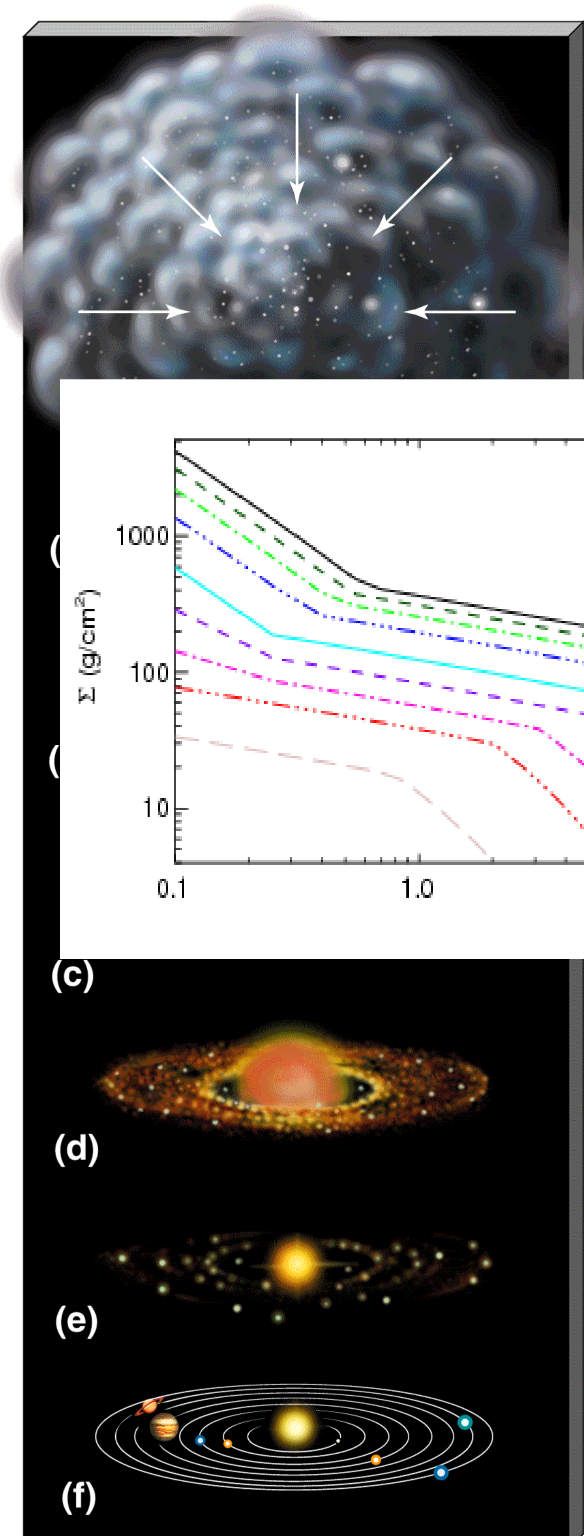

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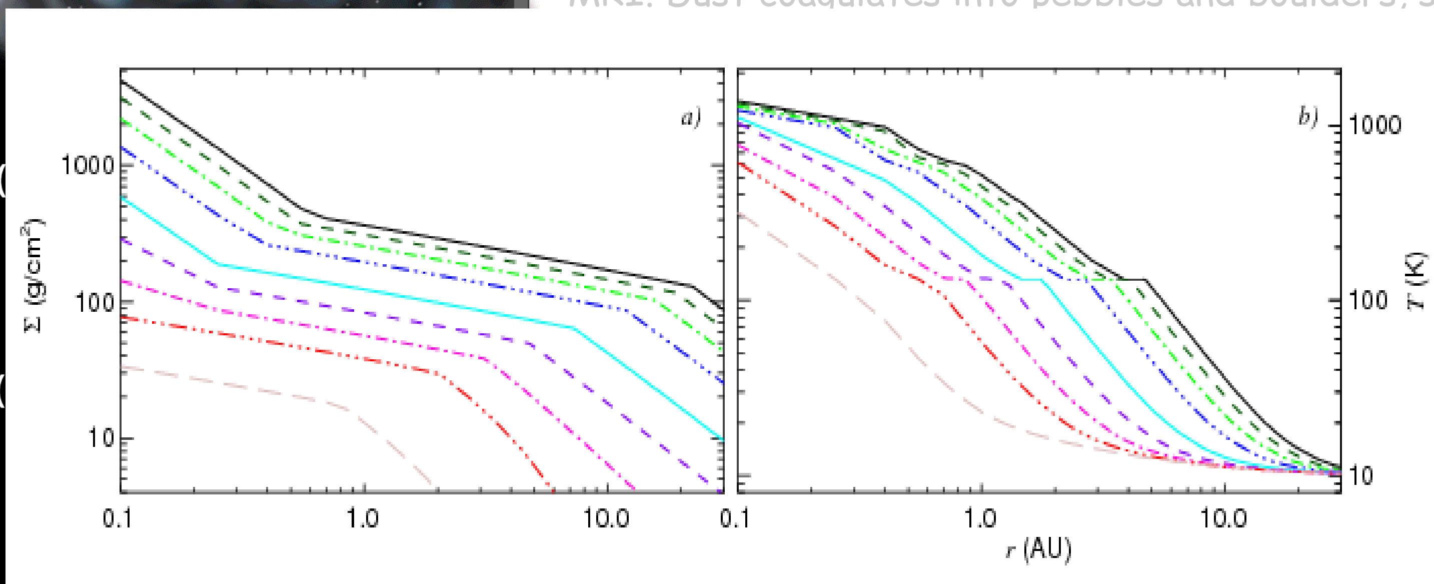
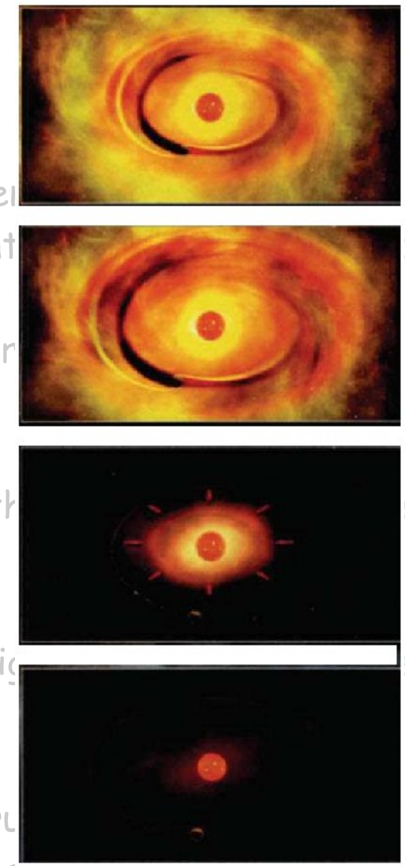
Outward transport of angular momentum through turbule
MRI. Dust coagulates into pebbles and boulders, sediment ... ane.





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forcing. Collisions between embryos gives rise to oligarchs

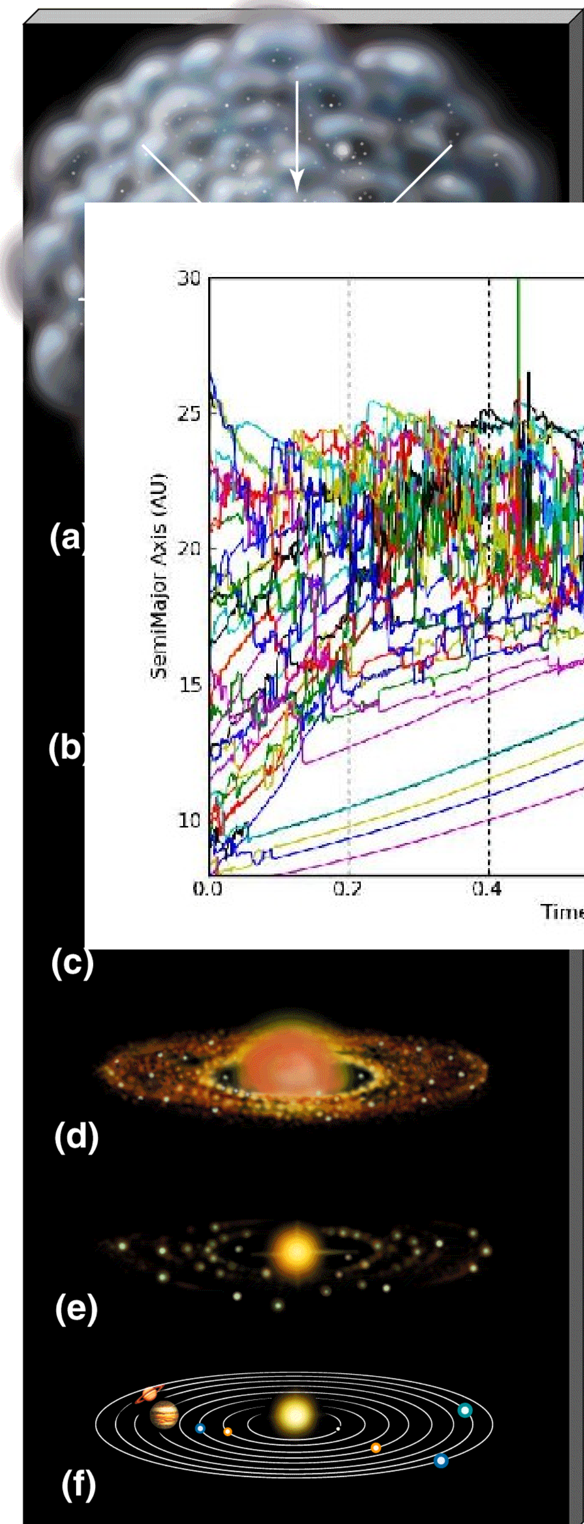
The disk thins due to photoevaporation. Planets released into stable orbits.

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

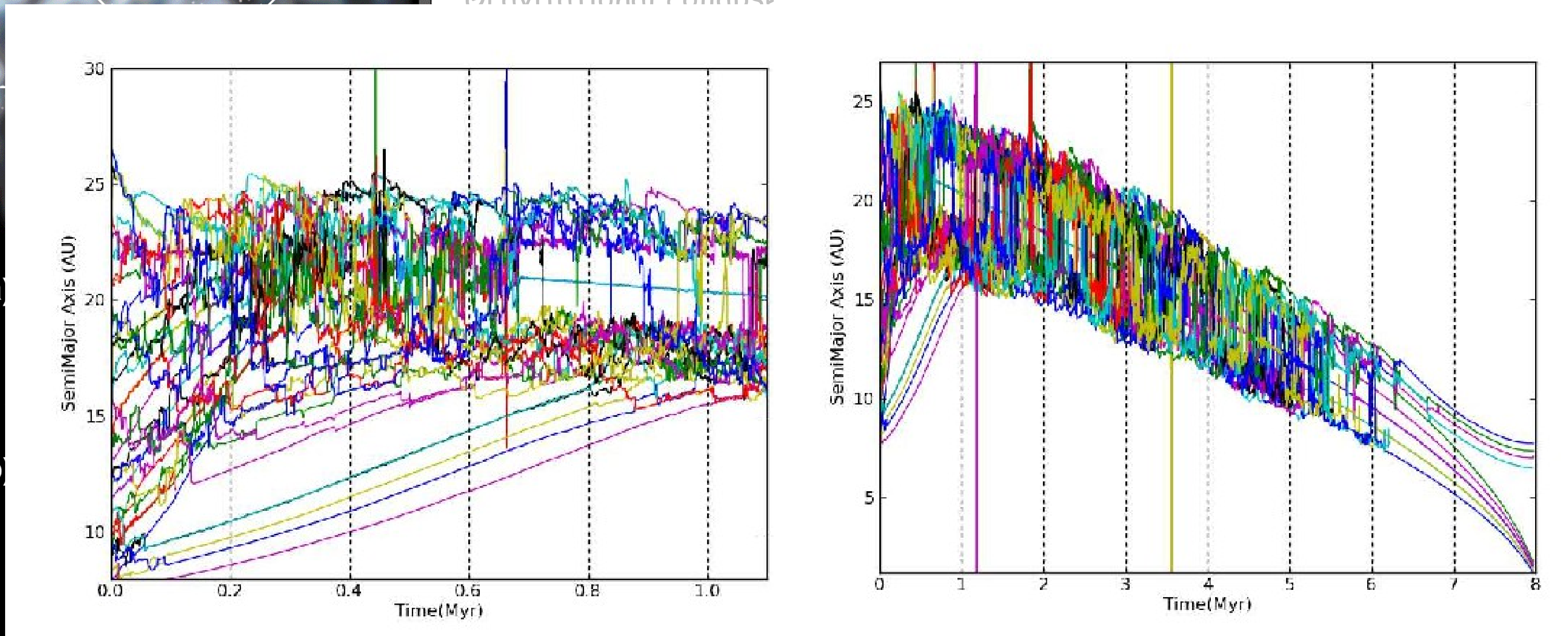
Debris disks with gas are subject to a thermo-centrifugal instability

The instability generates sharp eccentric rings. Caution before shouting “planet!”. Not all that glitters is gold.

Summarizing



Gravitational collapse of an interstellar cloud



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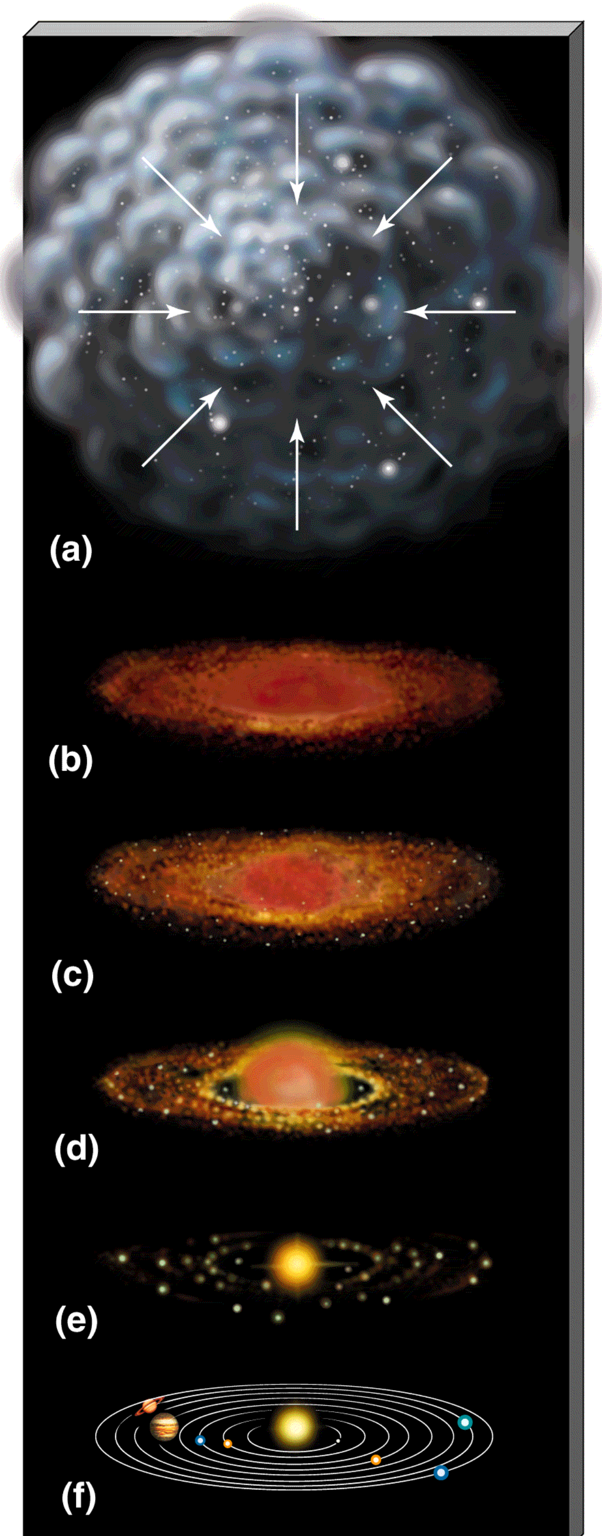
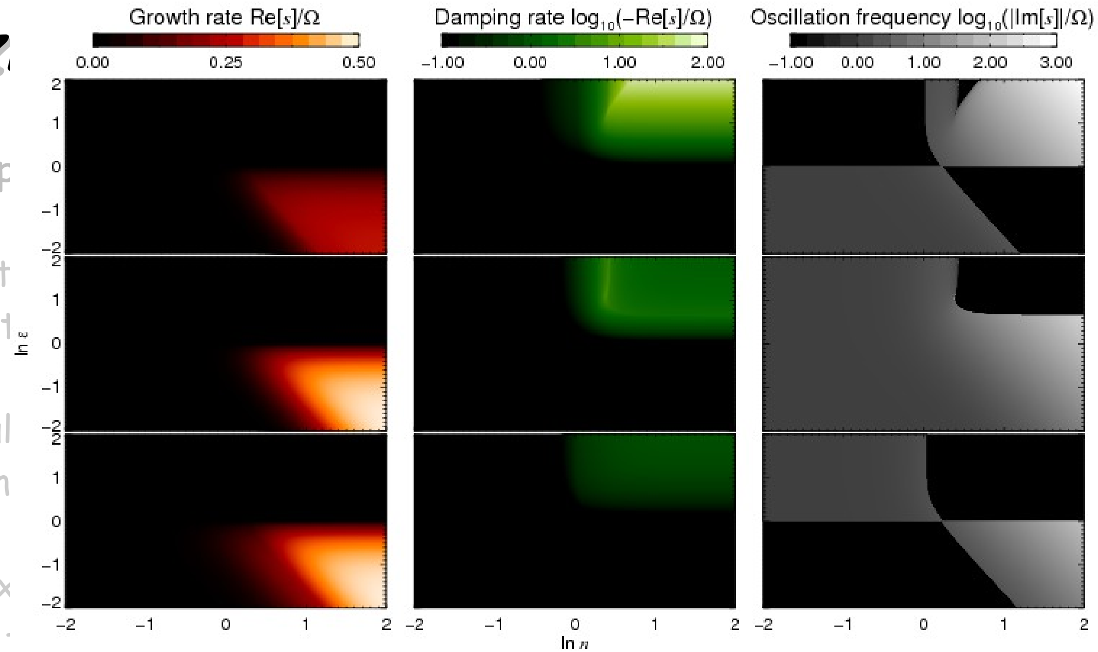


Summariz



Gravitational collap

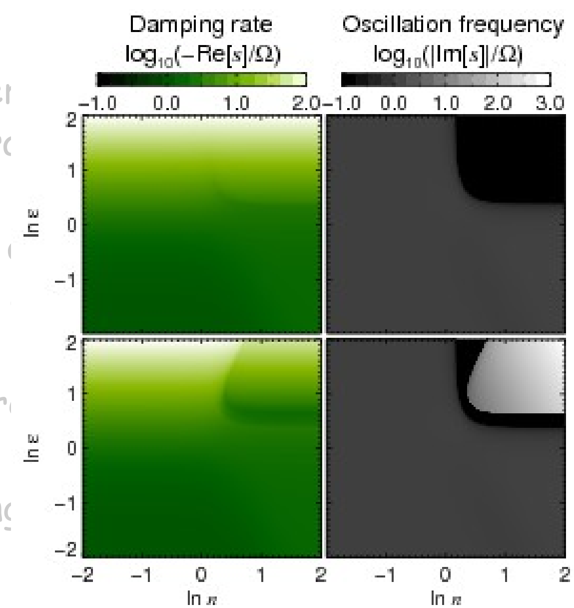
Outward transport
MRI. Dust coagulat

Rocks in the turbul
undergo collapse in

Vortices may be ex
mass embryos are

Opacity transitions develop into regions of conve
ge to these zones by inward/outwa

Dust heats gas
Heated gas = high pressure region
High pressure concentrates dust



Convergent migration leads to resonances, these
forcing. Collisions between embryos gives rise to

The disk thins due to photoevaporation. Planets r

N-body interactions and stochastic forcing durin
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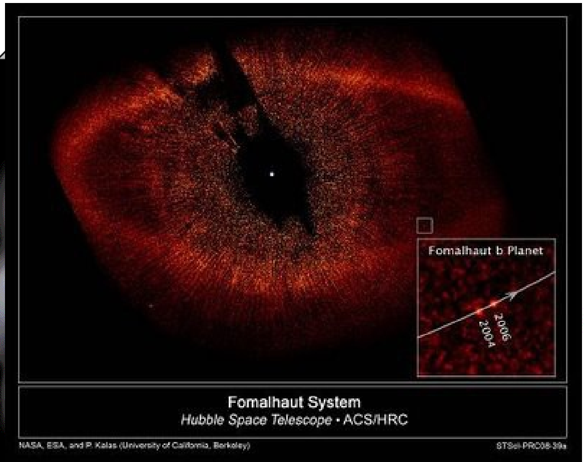
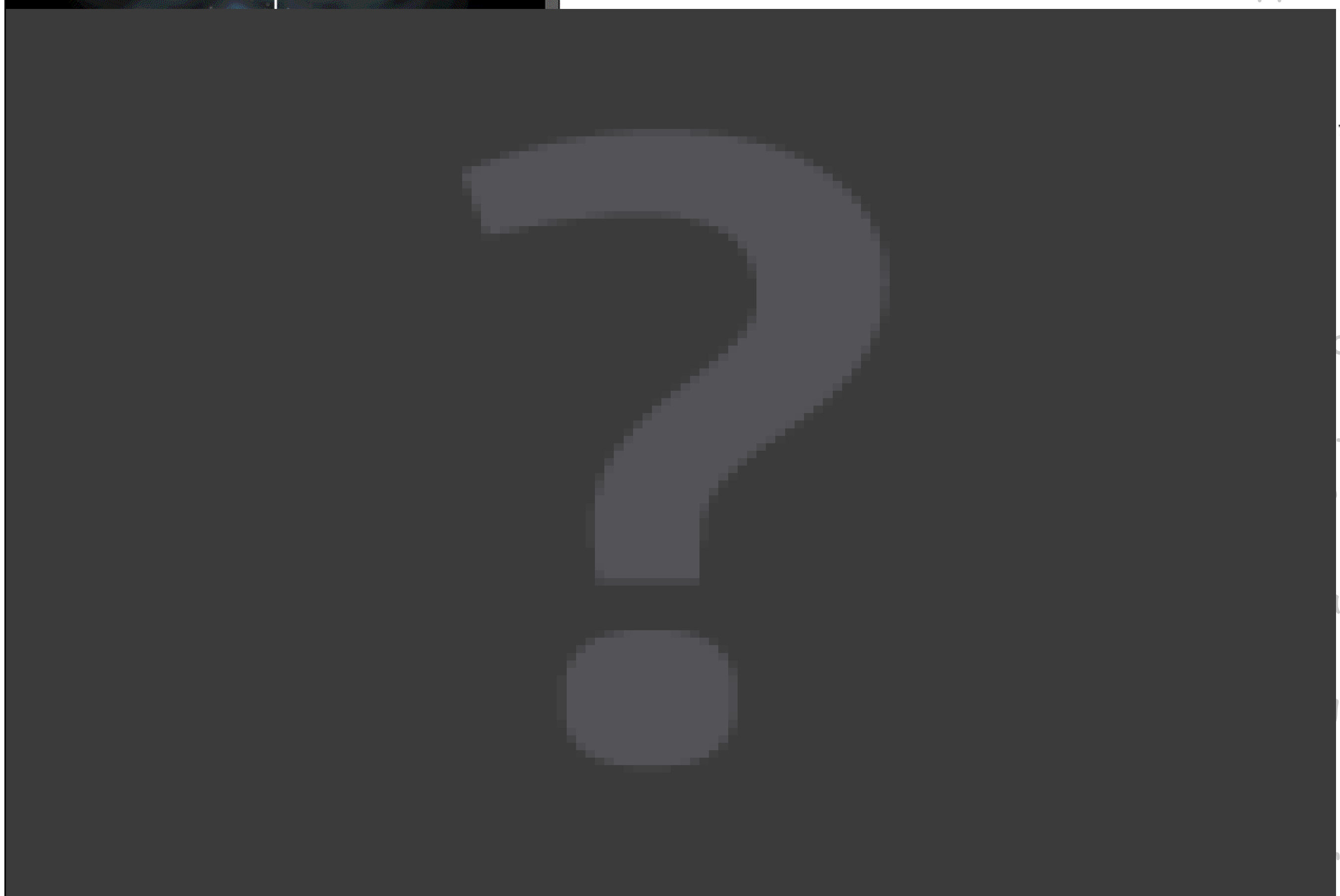


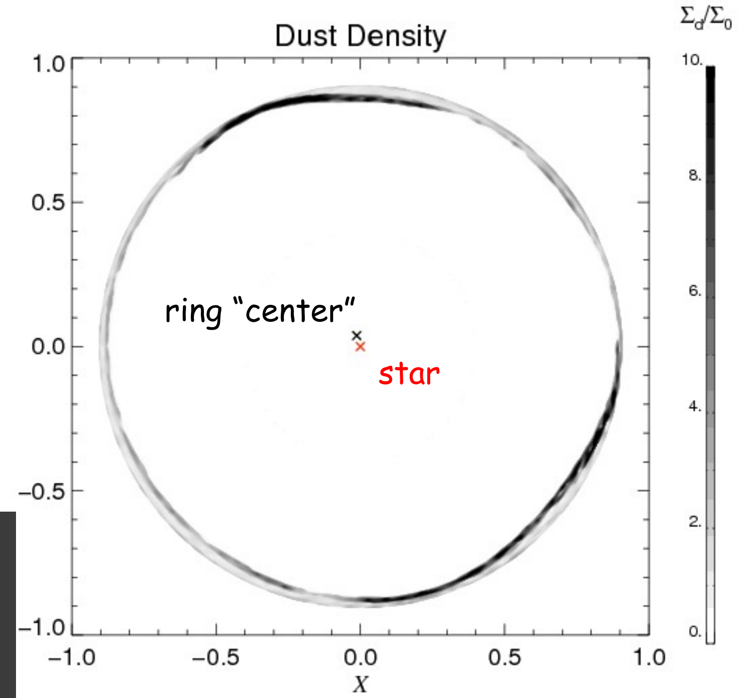
Summarizing

Gravitational collapse of an interstellar c

Outward transport of angular momentum
MRI. Dust coagulates into pebbles and b

Rocks in the turbulent medium are trapp





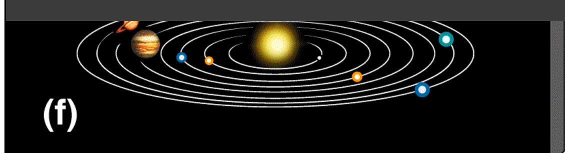
convergent migration. Low mass planets
d migration.

these are disrupted by turbulent
ise to oligarchs.

nets released into stable orbits.

during disk evaporation produce the

mo-centrifugal instability



The instability generates sharp eccentric rings. **Caution before shouting "planet!".**
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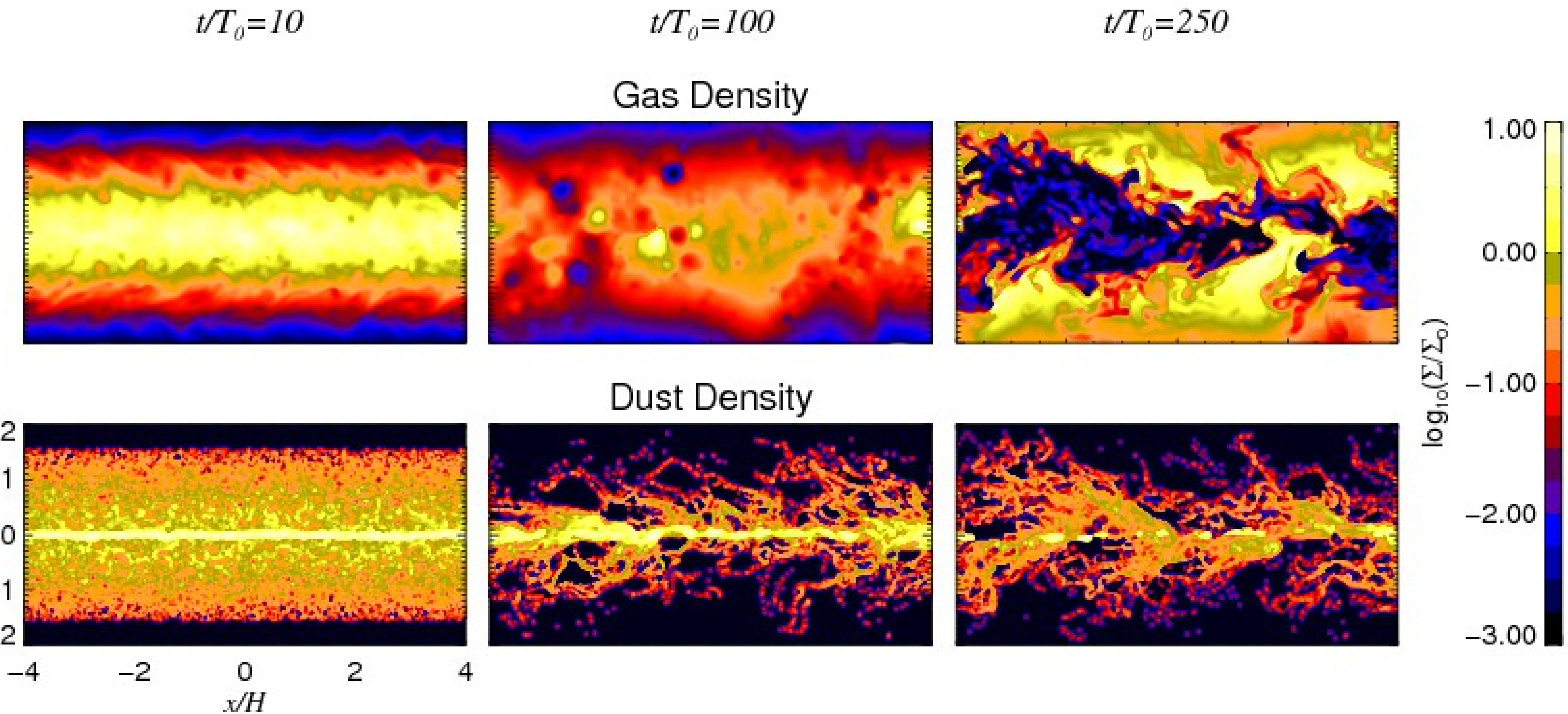
t/T0=10
t/T0=100
t/T0=250
Gas Density
Dust Density
z/H
x/H
−4
−2
0
2
4
2
1
0
−1
−2
1.00
0.00
−1.00
−2.00
−3.00
log10(Σ/Σ0)