Formation and Retention of Planets in Disks

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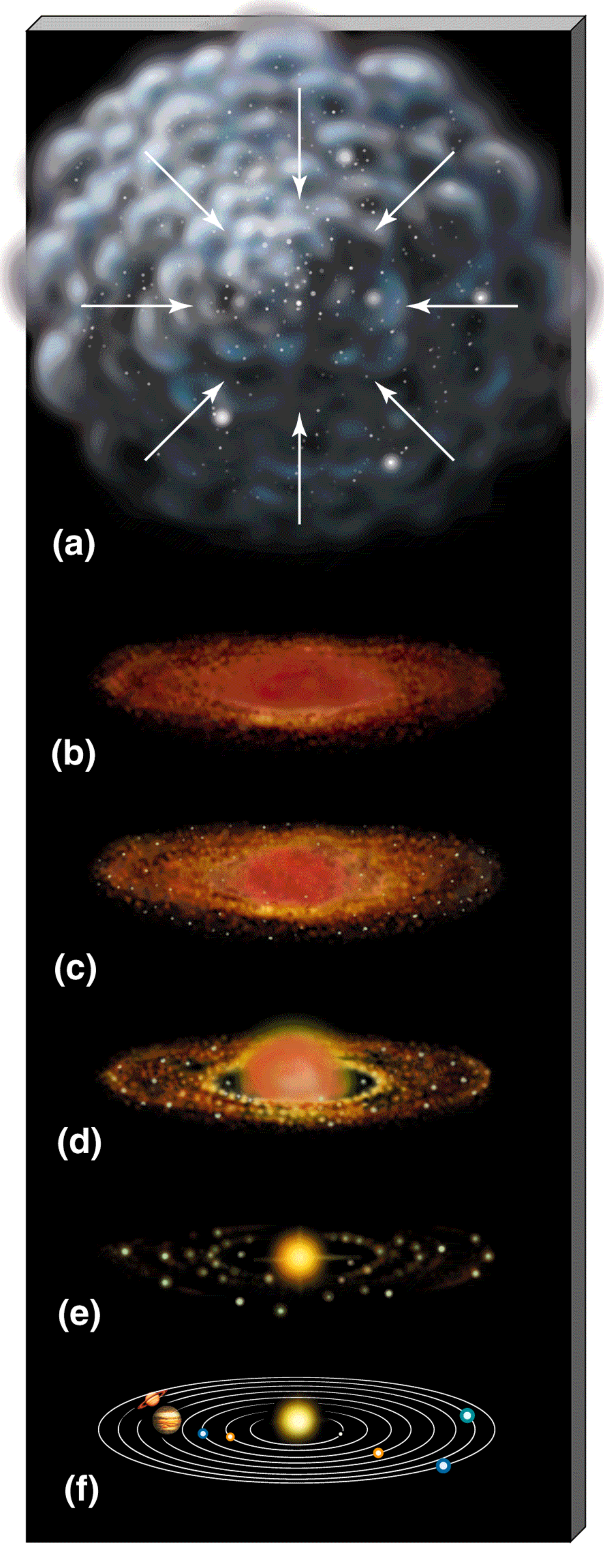


A disk life story

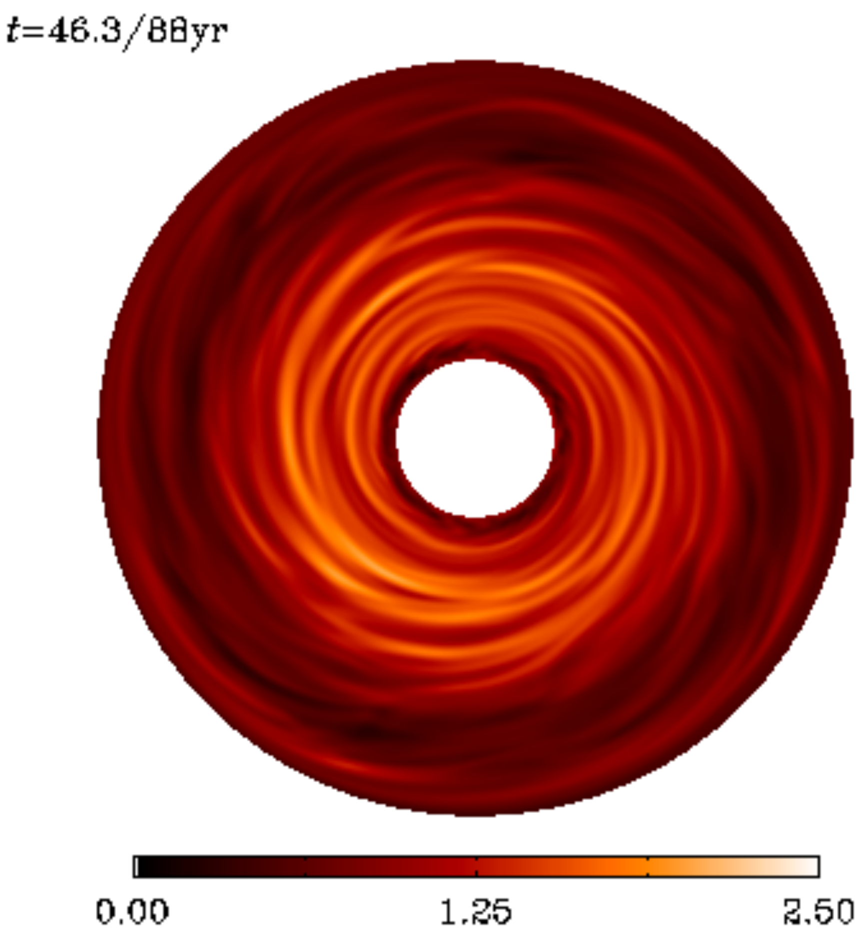
Gas-rich phase (< 10 Myr)
T-Tauri Disks
Accretion and Planet Formation

Thinning phase (~10 Myr)
Transitional Disks
Planet retention

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

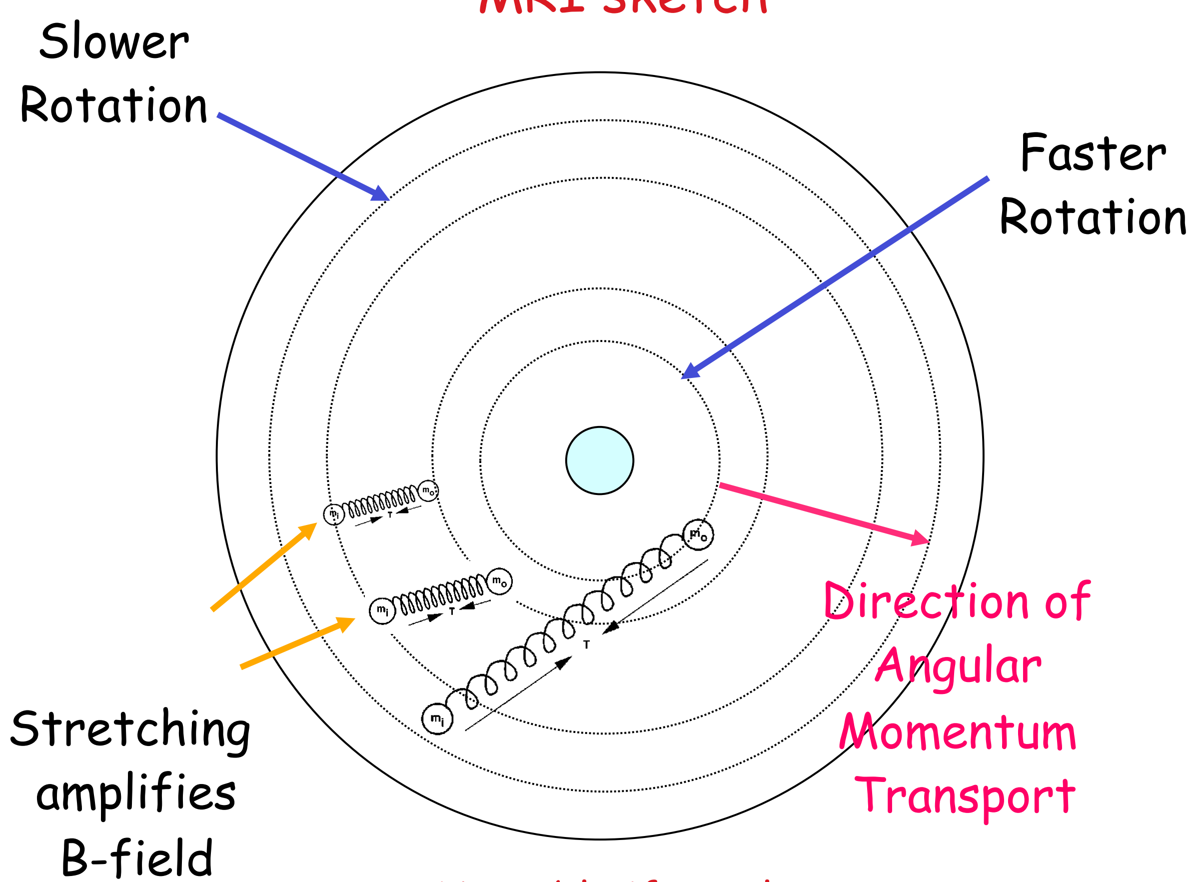
Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability



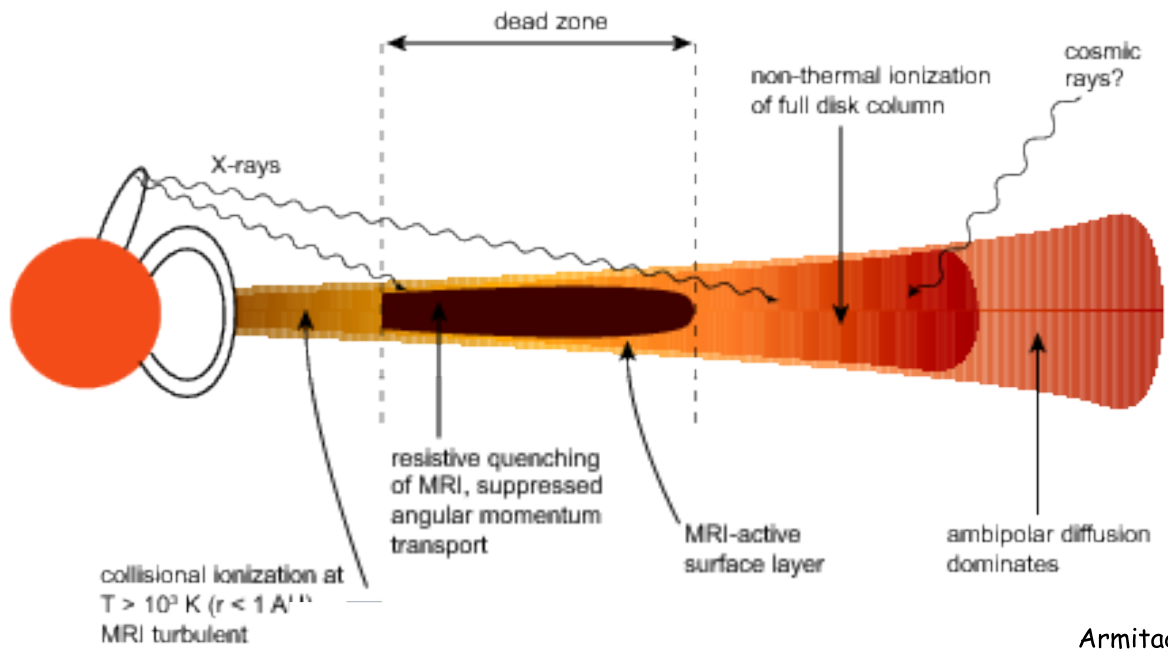
Magnetized disk
Lyra et al. (2008a)

MRI sketch



Unstable if angular velocity decreases outward

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



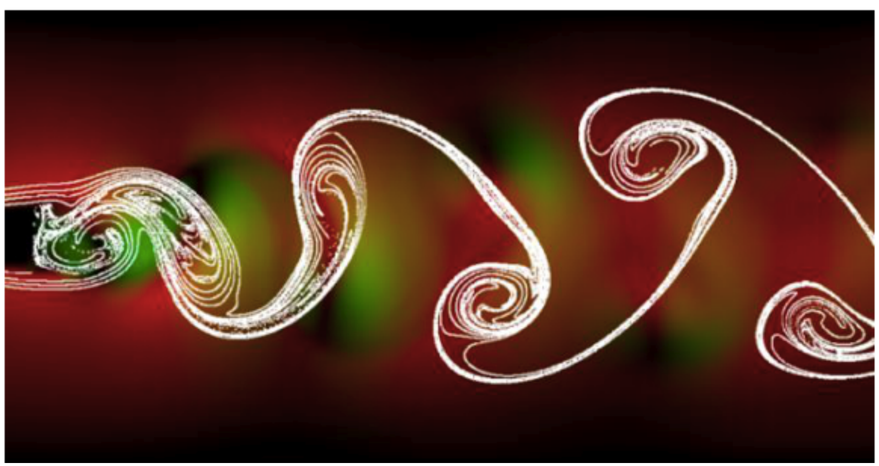
Armitage (2010)

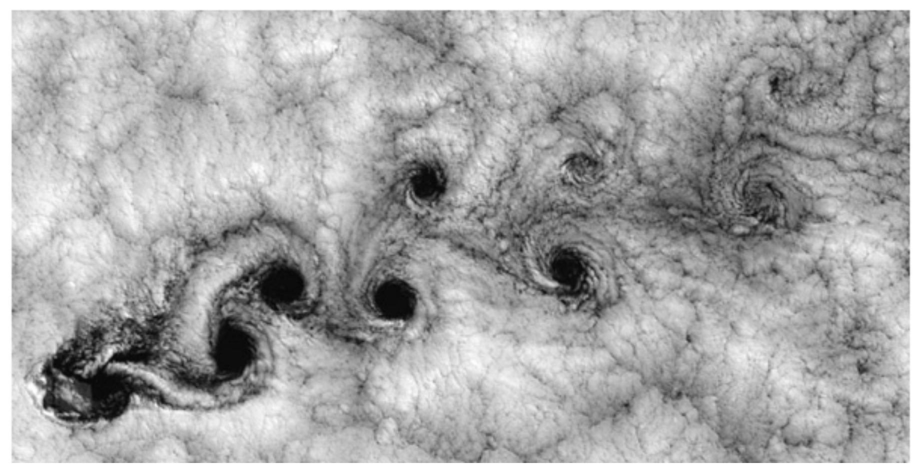
Disks are cold and thus poorly ionized
(Blaes & Balbus 1994)

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

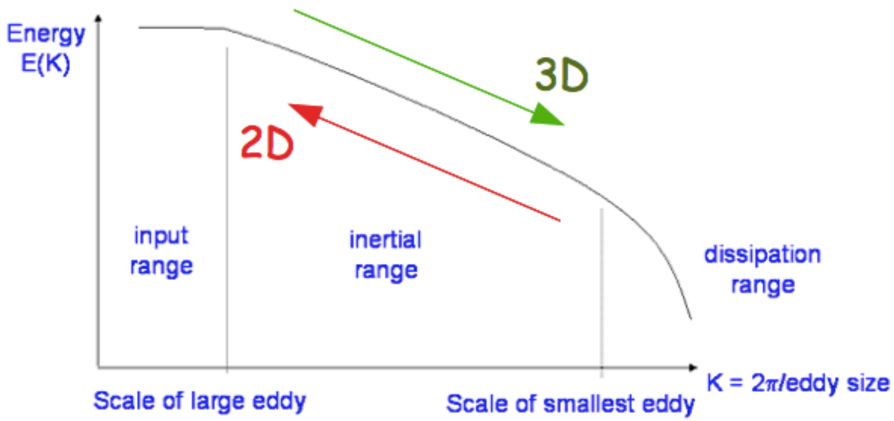
There should be a non-magnetic,
hydrodynamical, source of turbulence in the **dead zone.**

Vortices – An ubiquitous fluid mechanics phenomenon

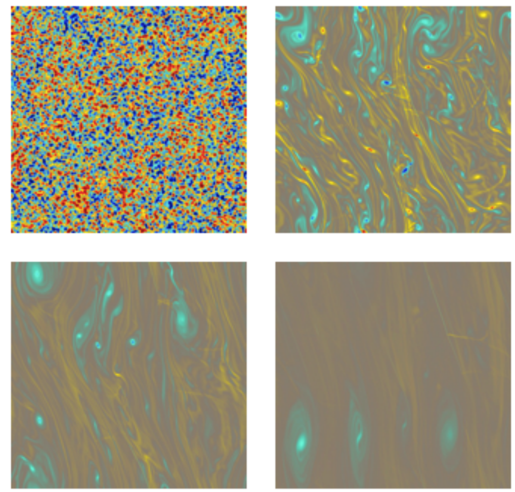




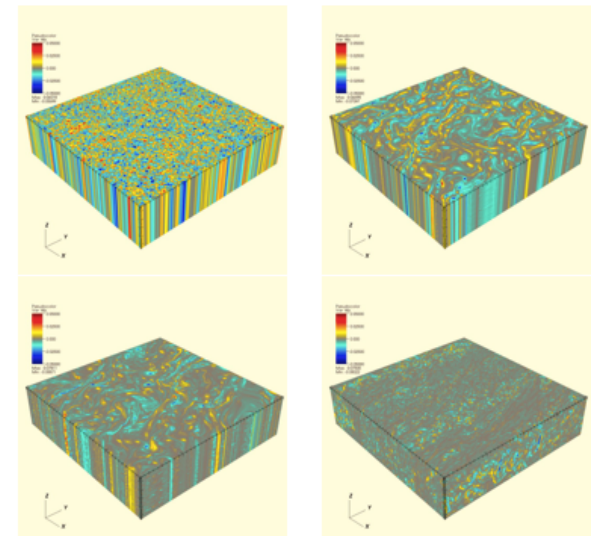
The energy cascade



Shen et al. (2006).
See also Batchelor (1967)



2D



3D

Inverse Cascade

No 3D instability
Eddies merge

Direct Cascade

Destruction occurs
faster than merging

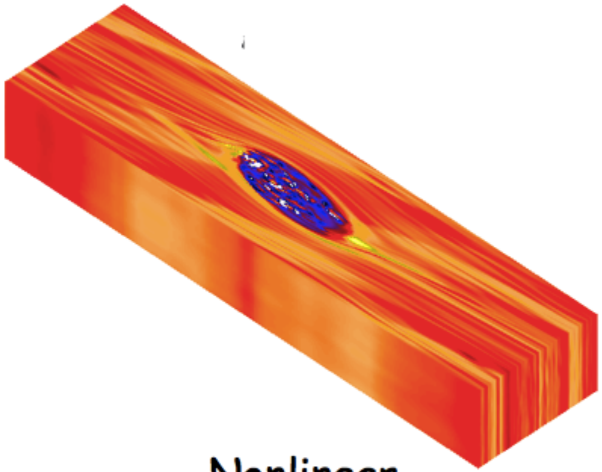
Sustaning vortices

Mechanisms to

inject vorticity

to counteract the vorticity lost in the direct cascade

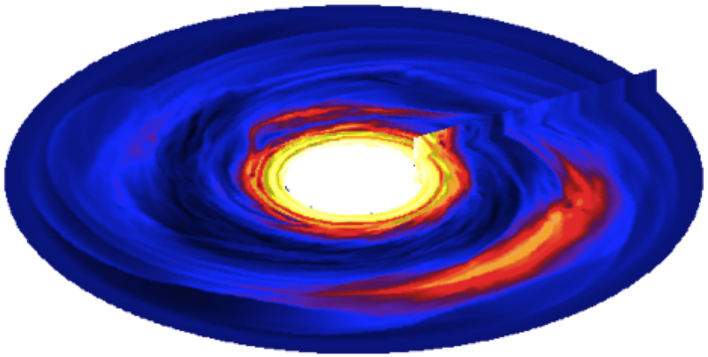
Baroclinic Instability



Nonlinear

Powered by:
buoyancy, thermal diffusion
(baroclinic source term)

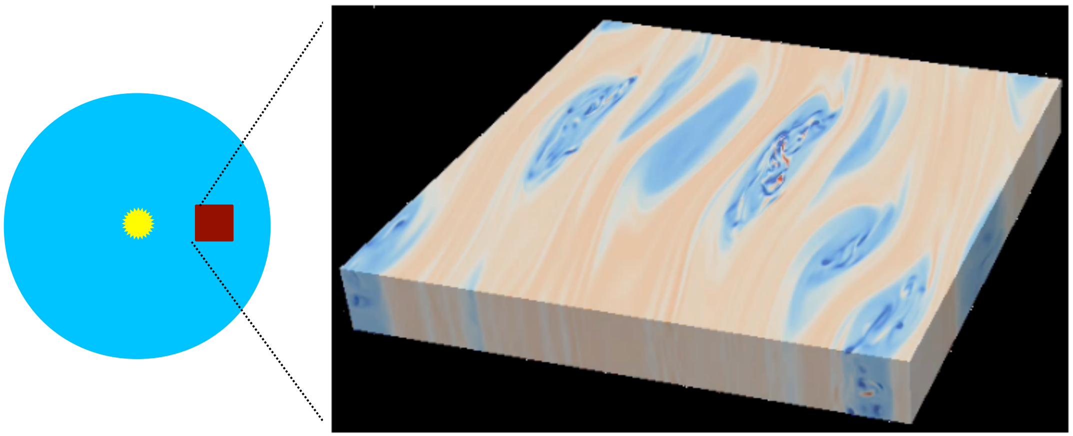
Rossby Wave Instability



Linear

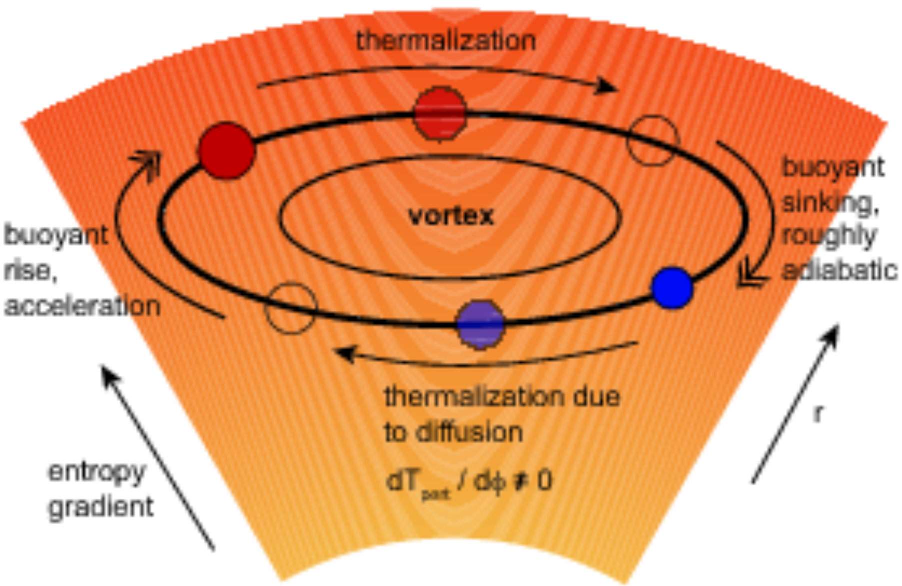
Powered by:
Modification of shear profile
(external vortensity reservoir)

Baroclinic Instability - Excitation and self-sustenance of vortices



Lesur & Papaloizou (2010)

Sketch of the Baroclinic Instability



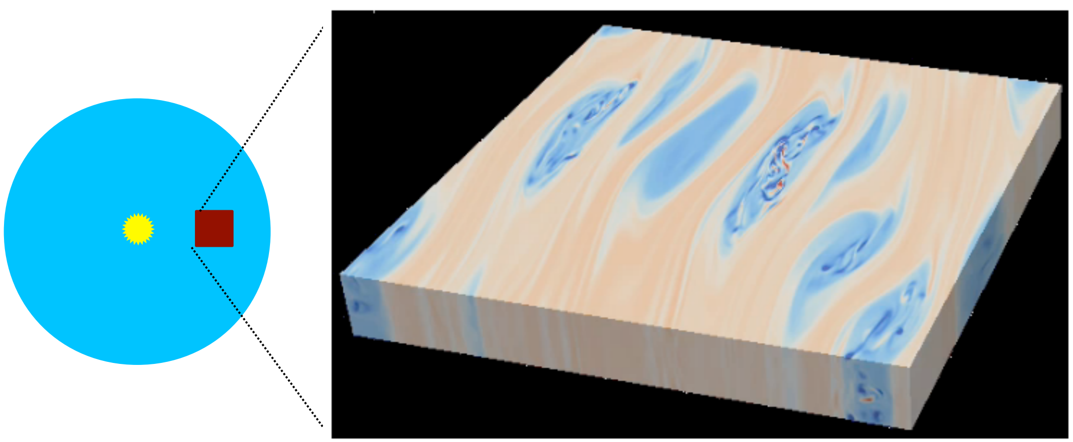
Armitage (2010)

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

advection — compression — stretching — baroclinicity — dissipation

Baroclinic Instability - Excitation and self-sustenance of vortices

1. *Radial entropy gradient*
2. *Thermal diffusion*



Lesur & Papaloizou (2010)

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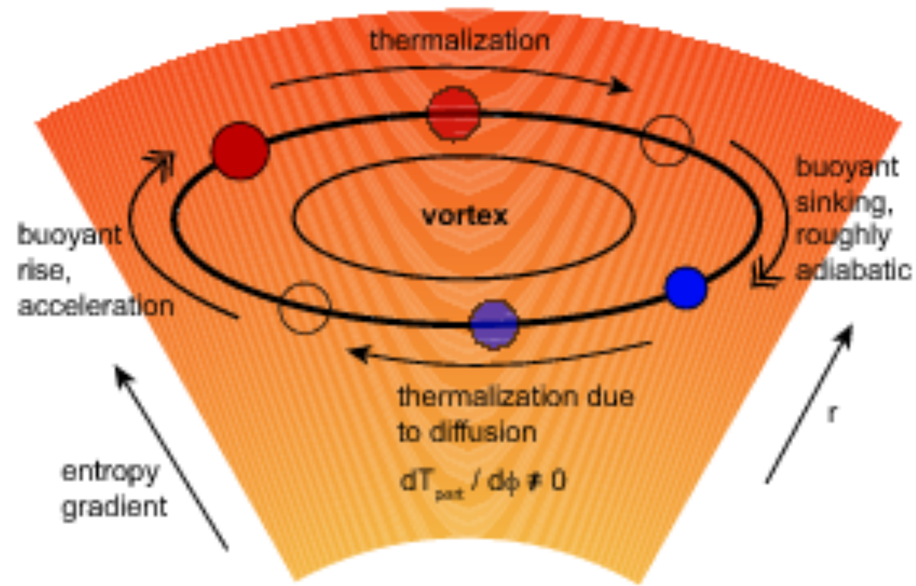

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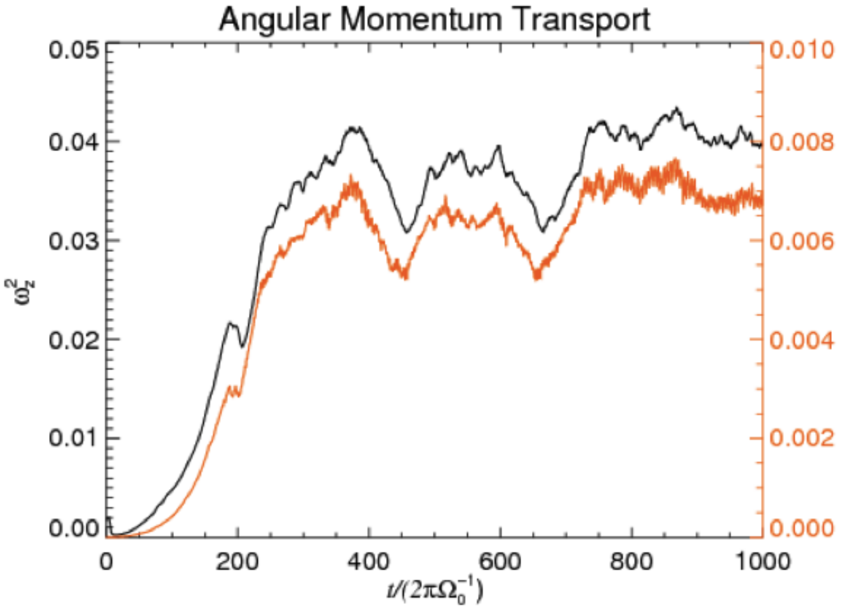
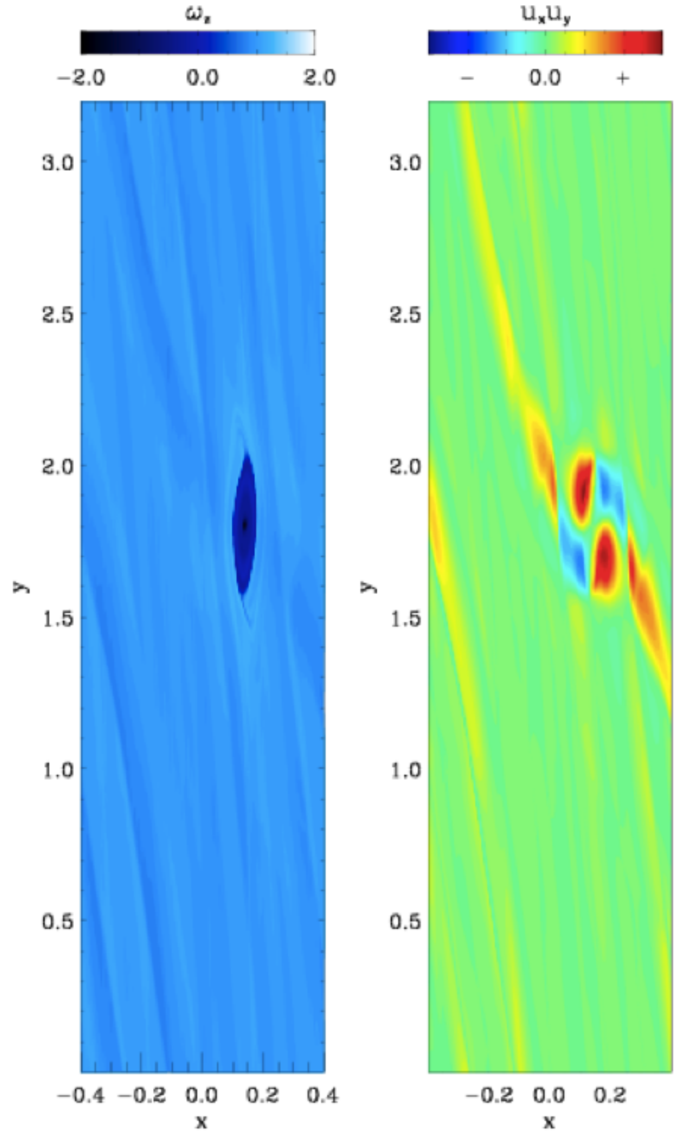
advection, compression, stretching, baroclinicity, dissipation

Baroclinic Instability and Accretion

Large mass accretion rates, comparable to the MRI!



Raettig, Lyra, & Klahr (2012)



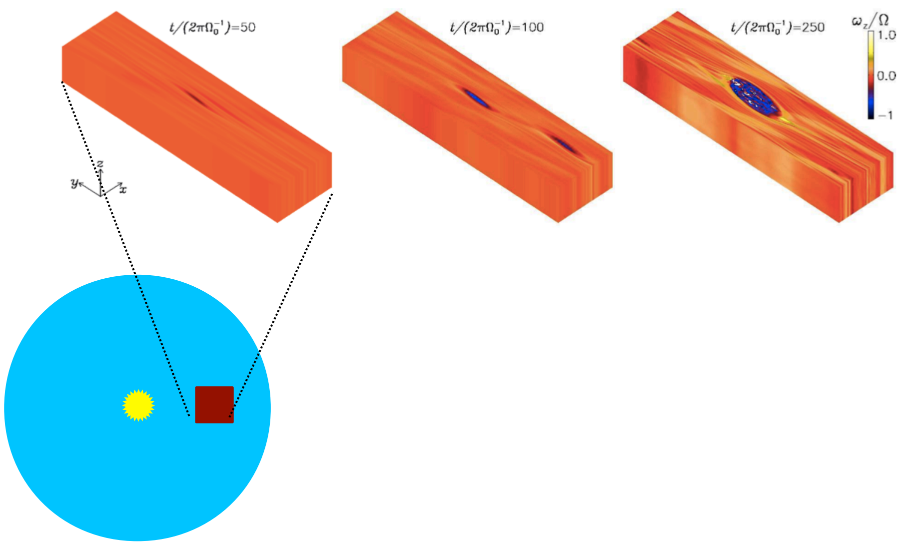
The angular momentum is carried by *waves* excited by the vortex

(see also Heinemann & Papaloizou 2008,2009)

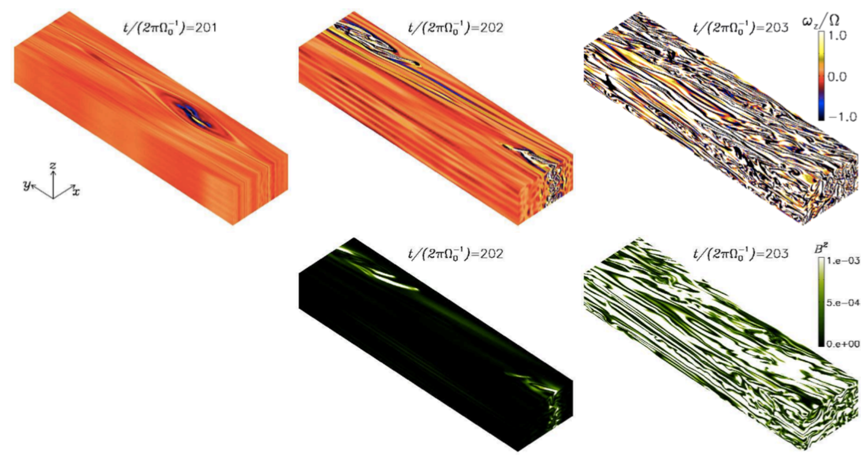
Baroclinic instability and layered accretion

What happens when the vortex is magnetized?

Hydro



MHD

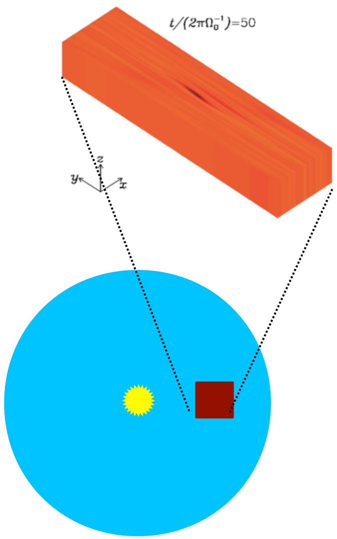


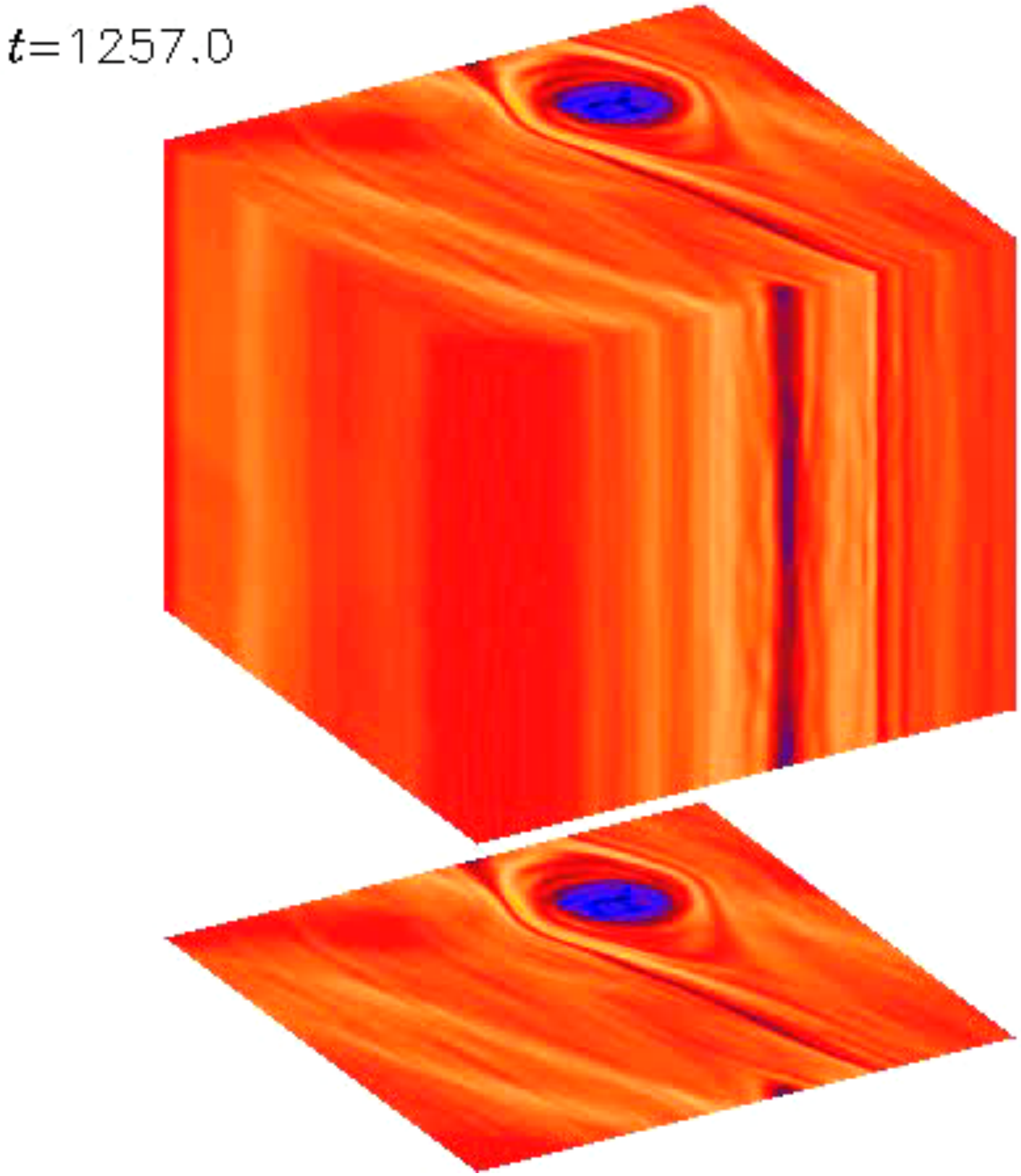
Vorticity

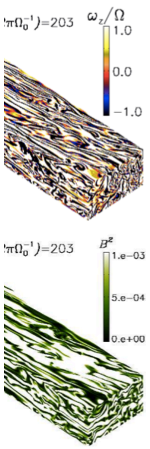
Mag. Energy

Lyra & Klahr (2011)

Baroclinic instability and layered accretion







Vorticity

Mag. Energy

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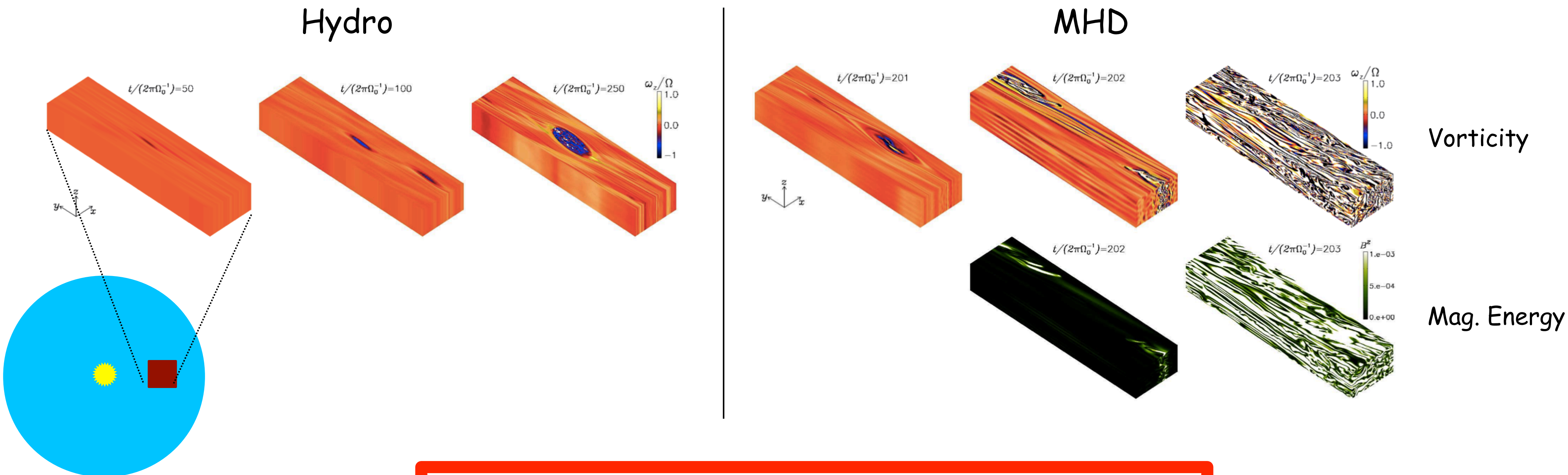
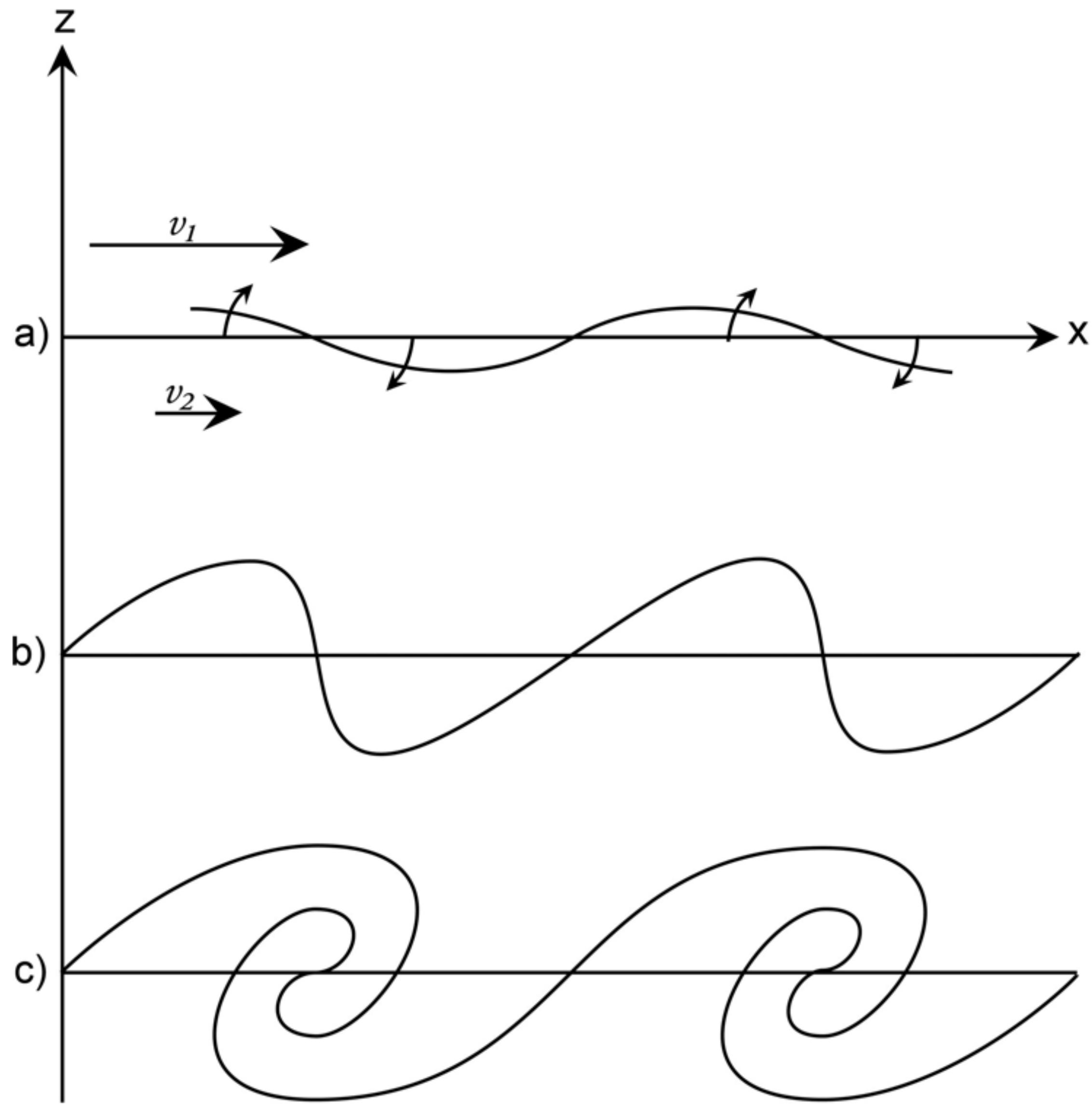


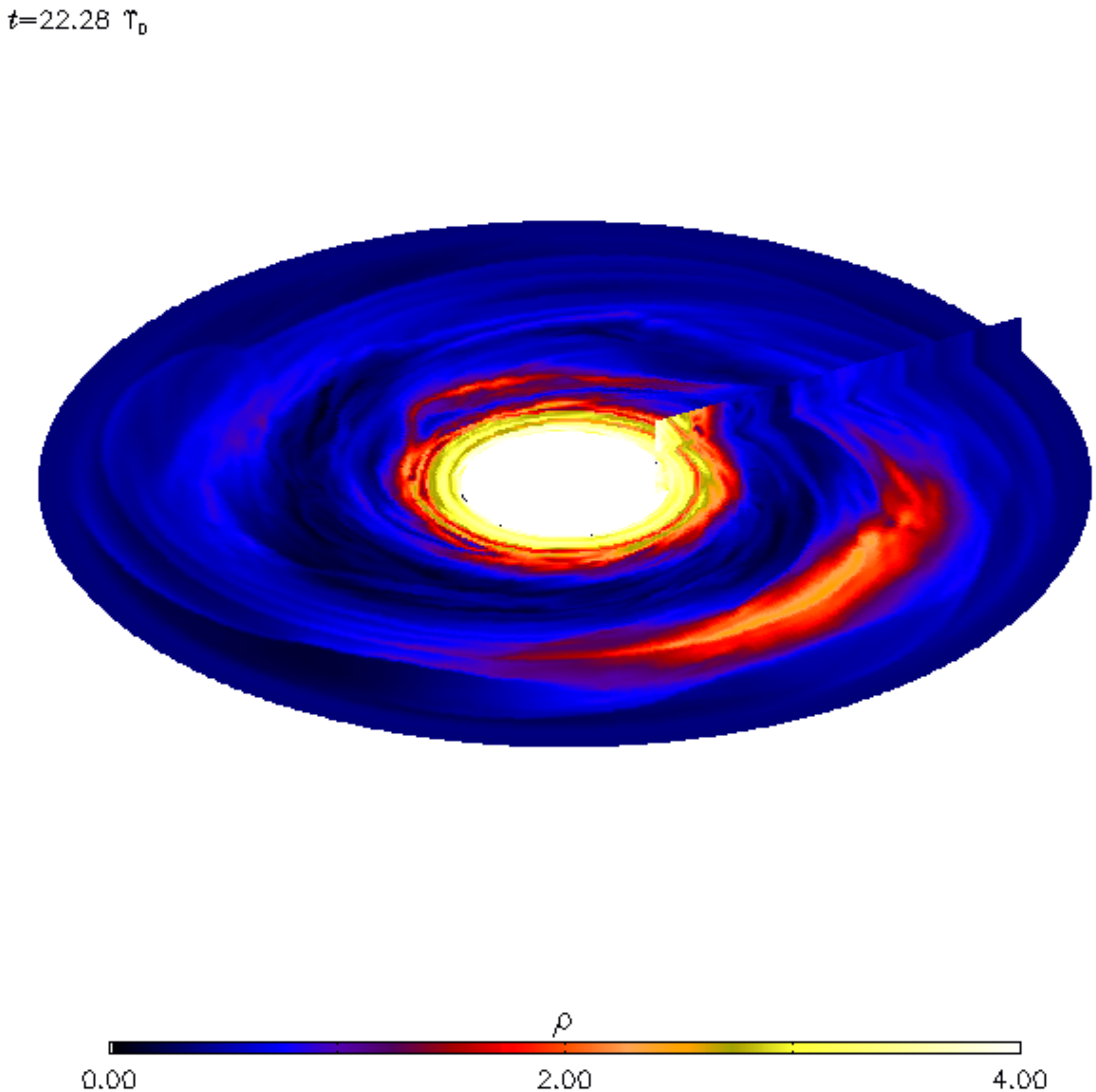
Baroclinic vortices
do ***not*** survive magnetization

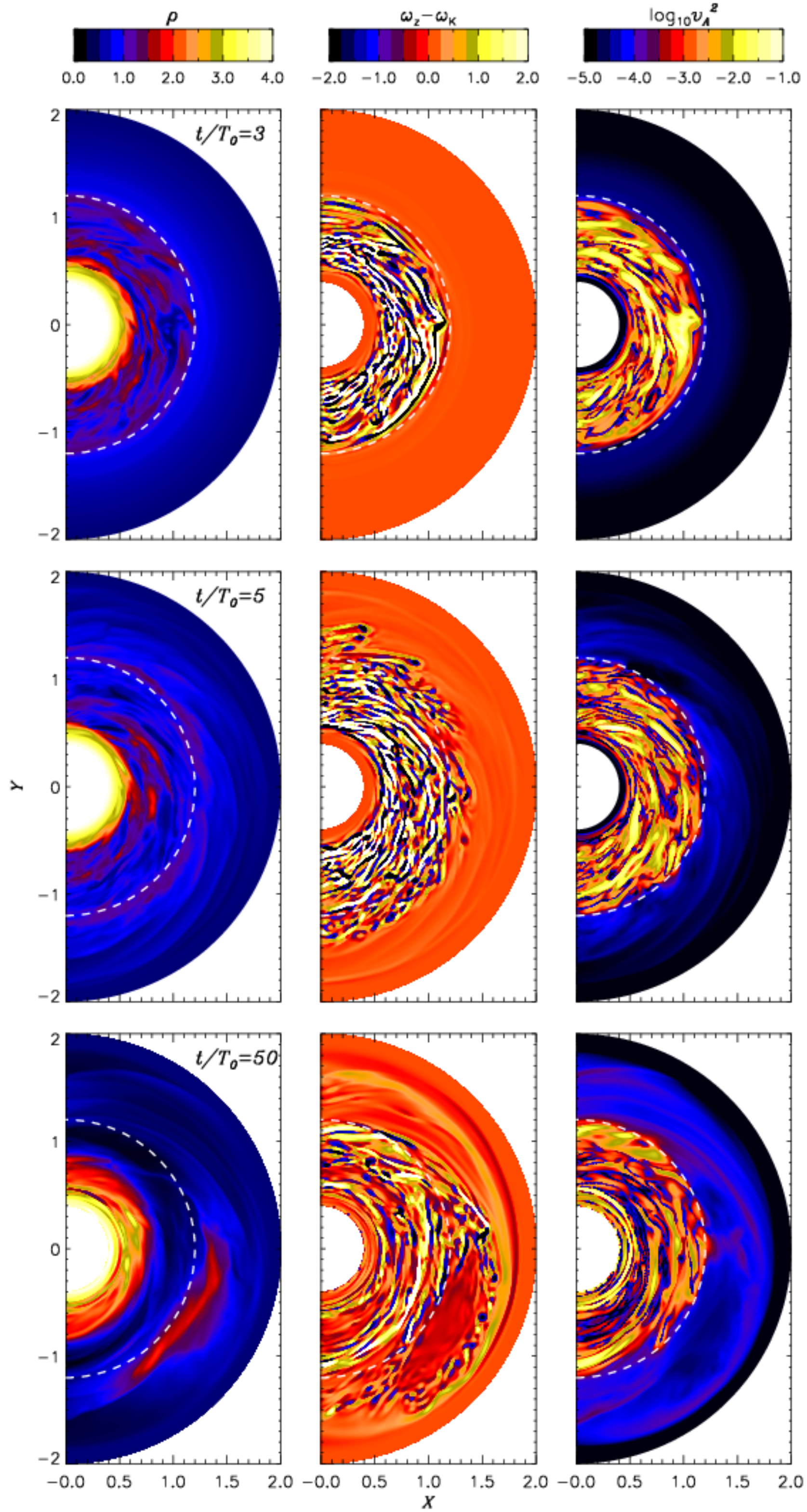
Lyra & Klahr (2011)

Rossby Wave Instability
(or.... Kelvin-Helmholtz in rotating disks)



Active/dead zone boundary

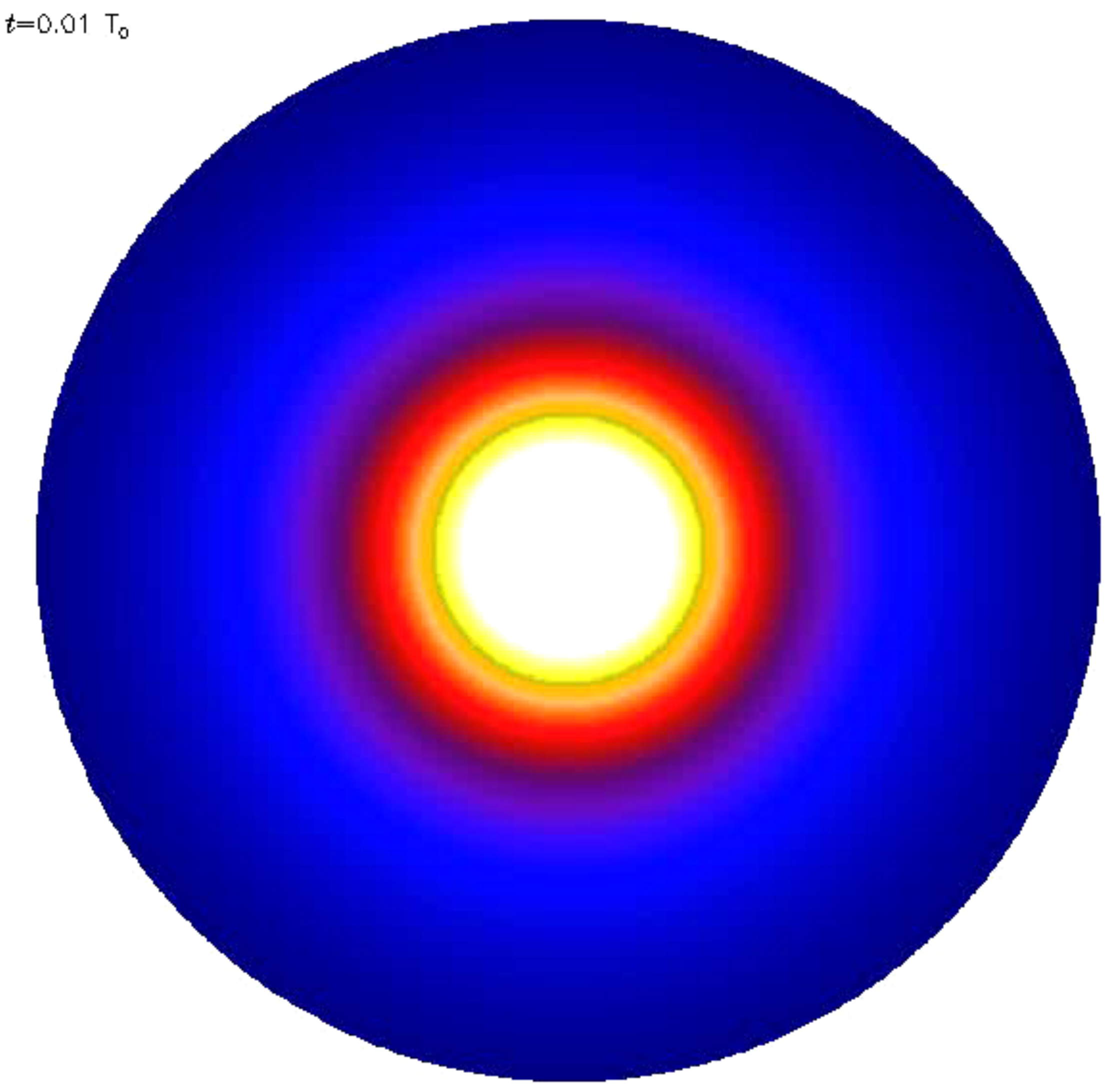


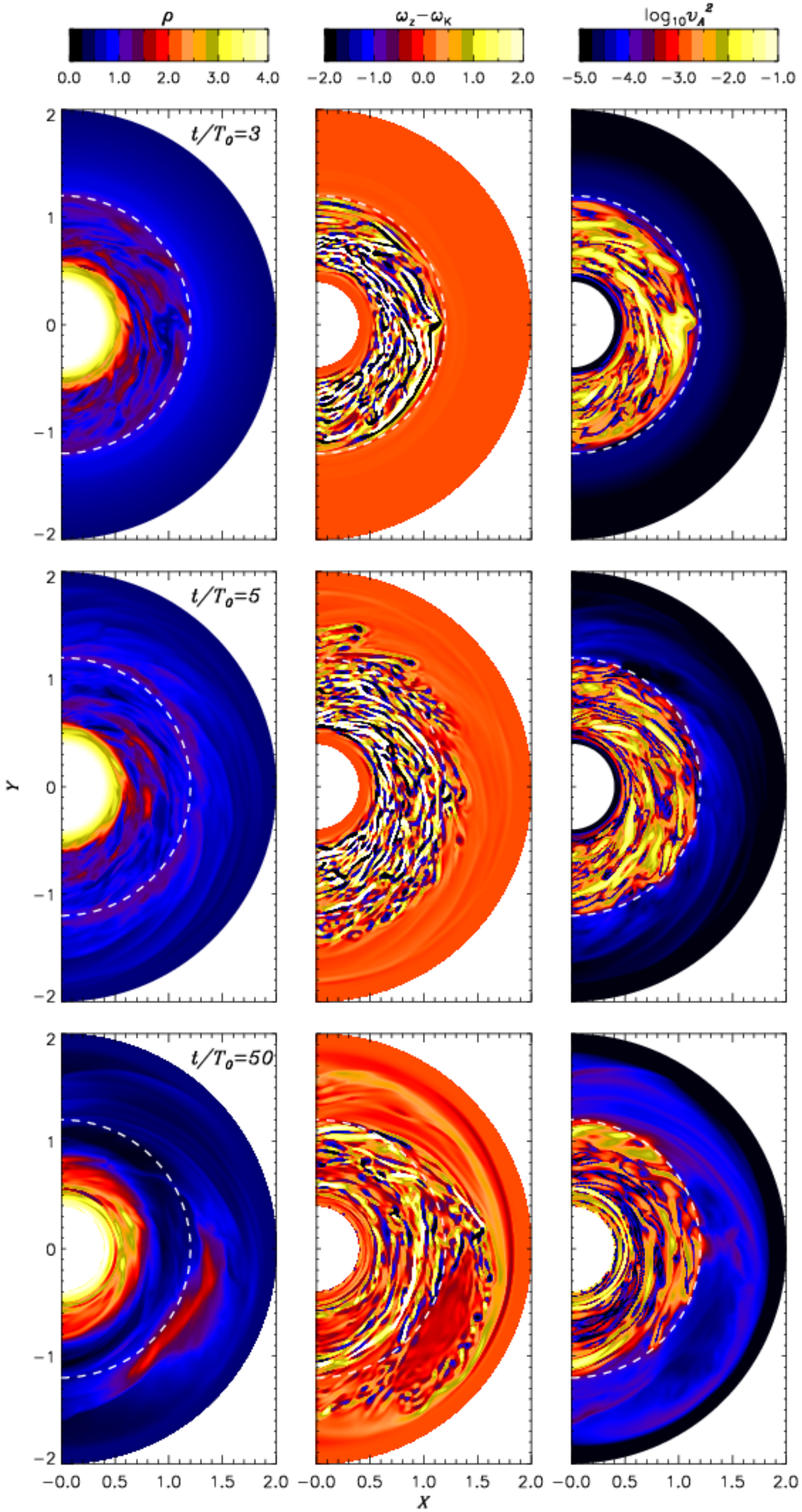


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Active/dead zone boundary

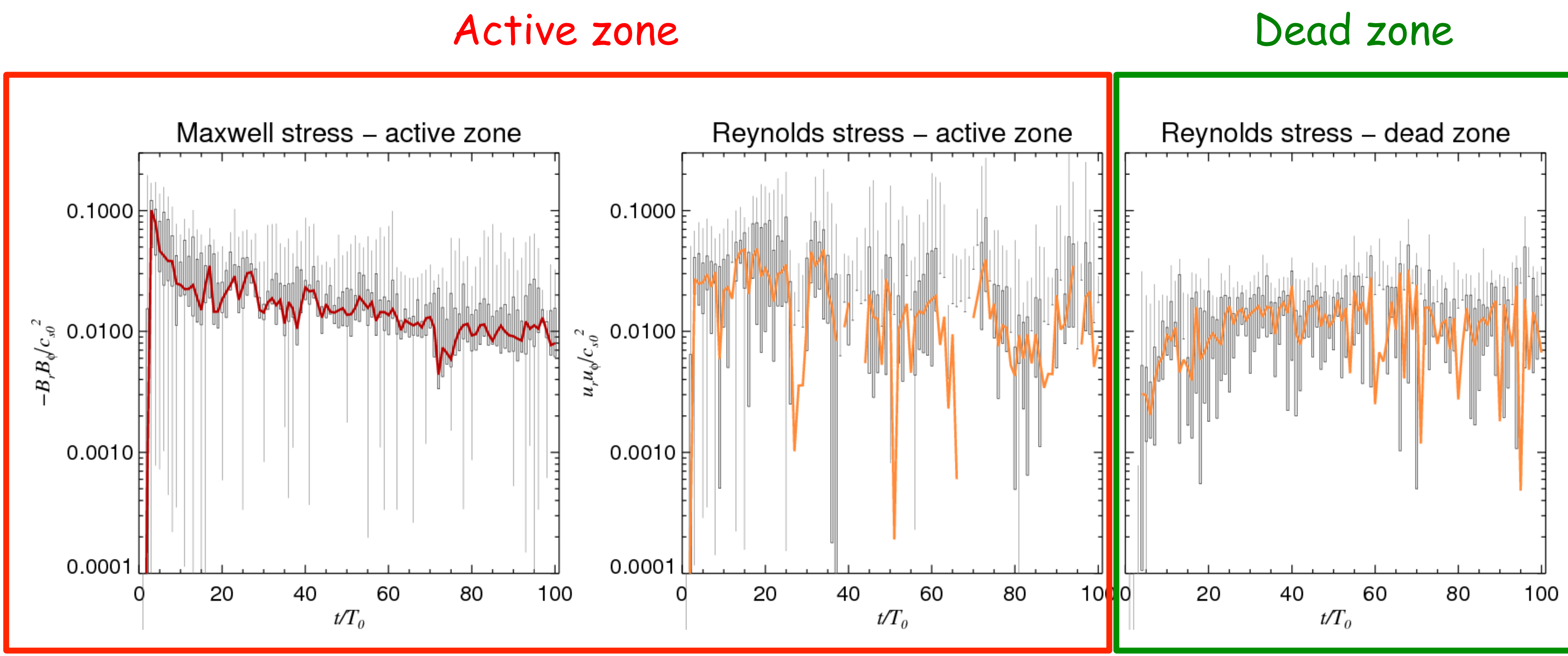




Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Significant angular momentum transport



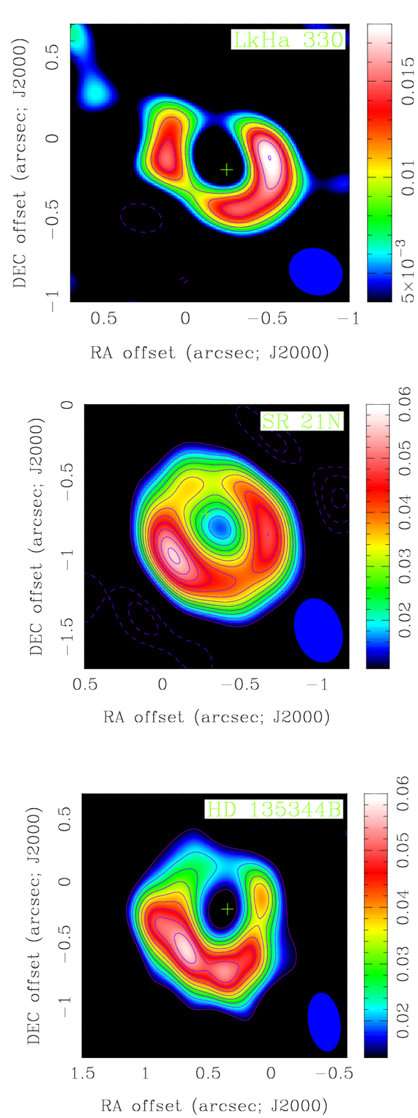
Large mass accretion rates in the dead zone,
comparable to the MRI in the active zone!

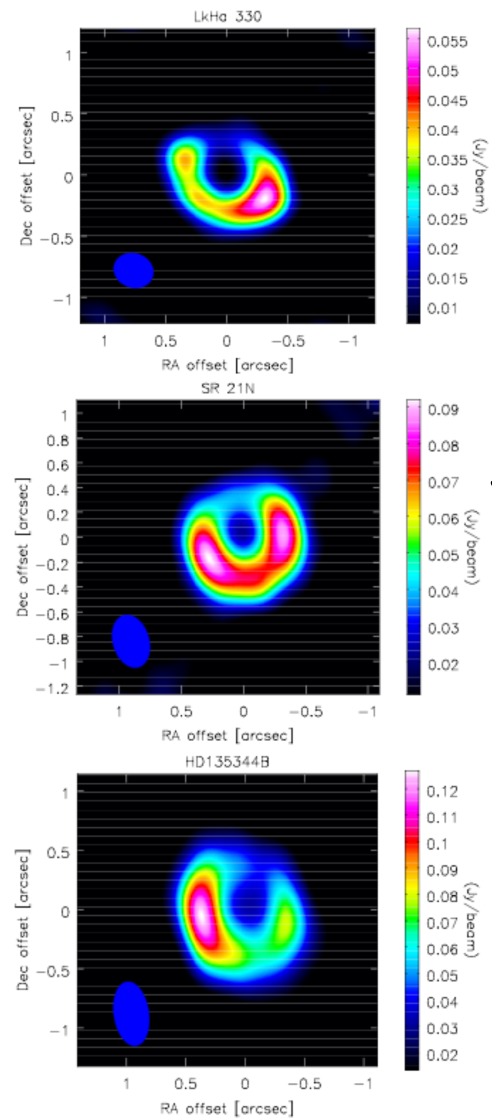
Lyra & Mac Low (2012)

A possible detection of vortices in disks

Observations

Brown et al. (2009)

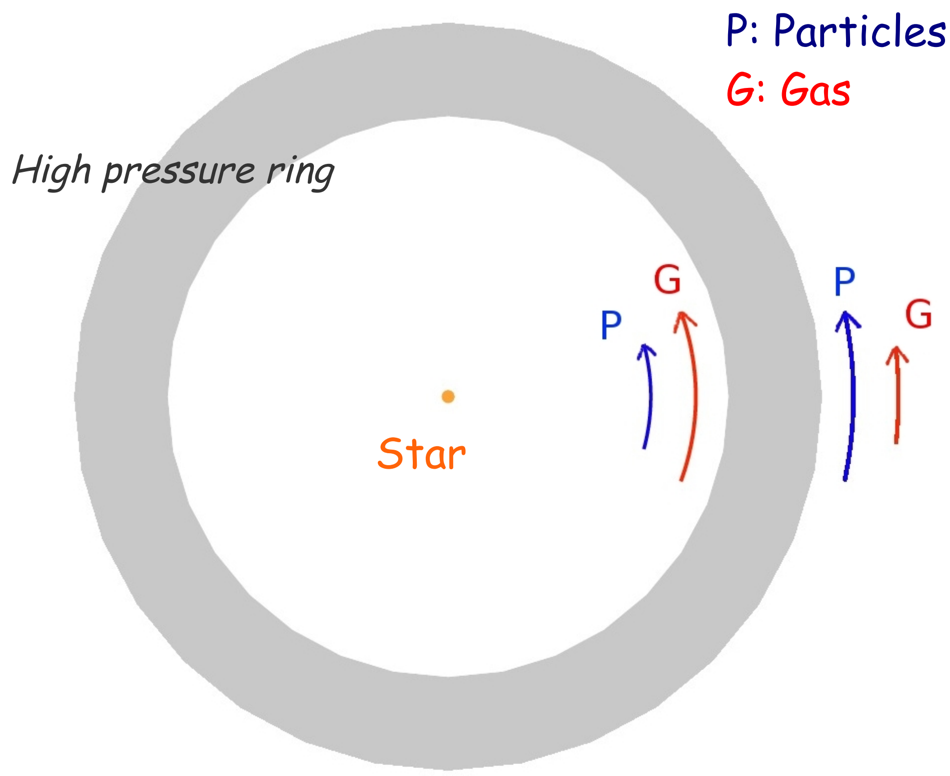




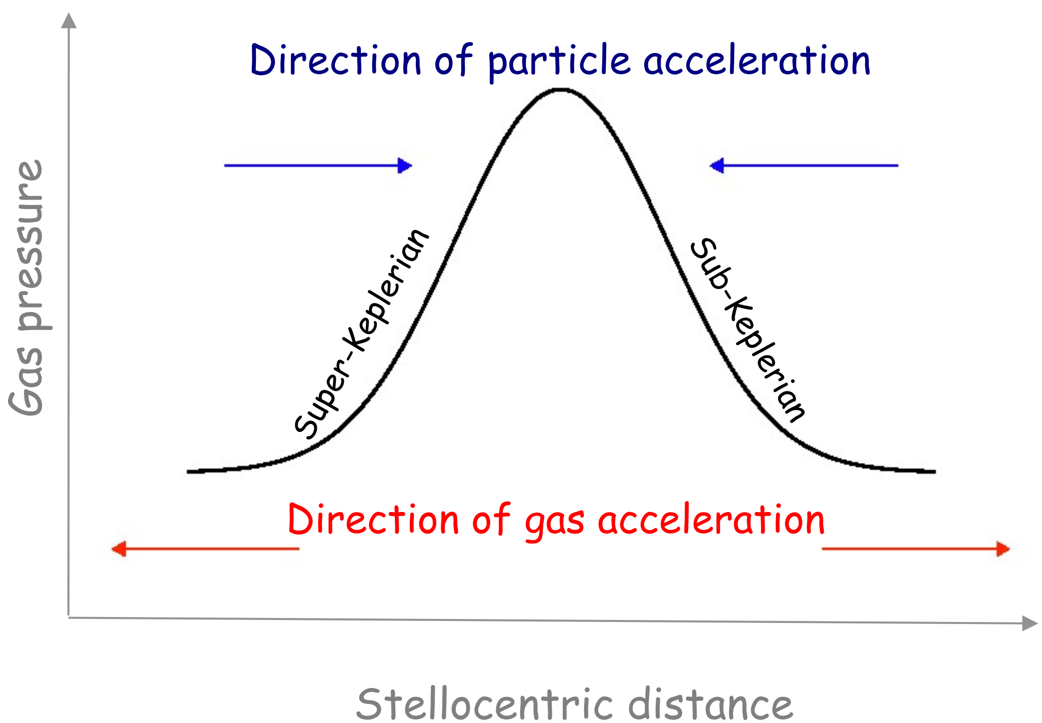
Simulated observations of Rossby vortices

Regaly et al. (2012)

Forming planets in turbulent disks



Adapted from Whipple (1972)



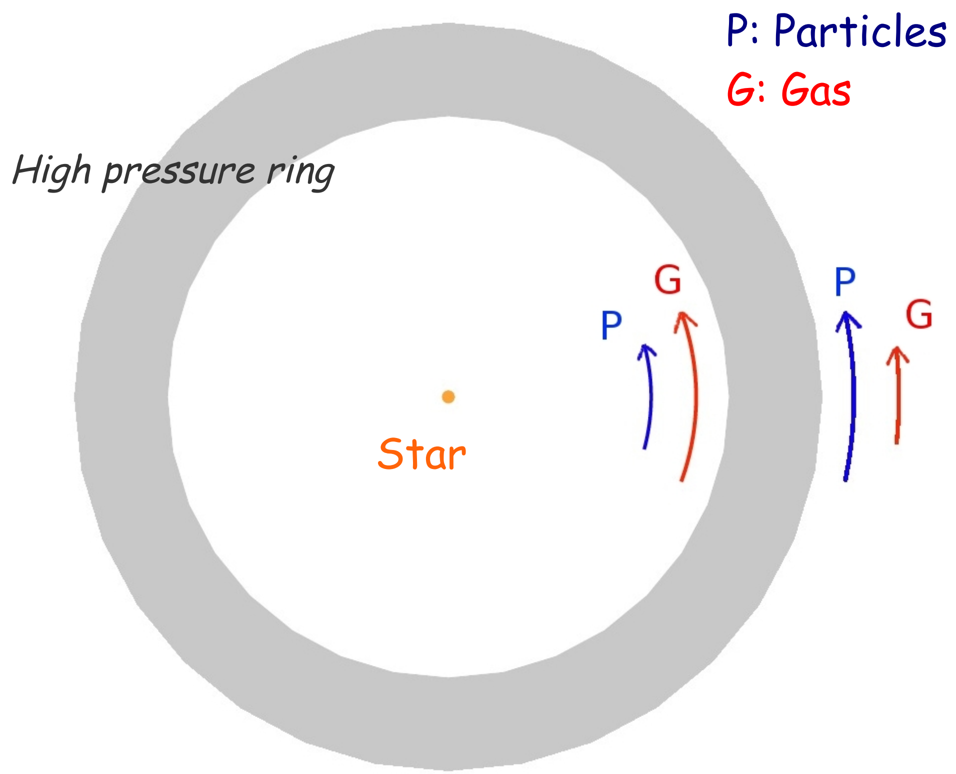
Forming planets in turbulent disks

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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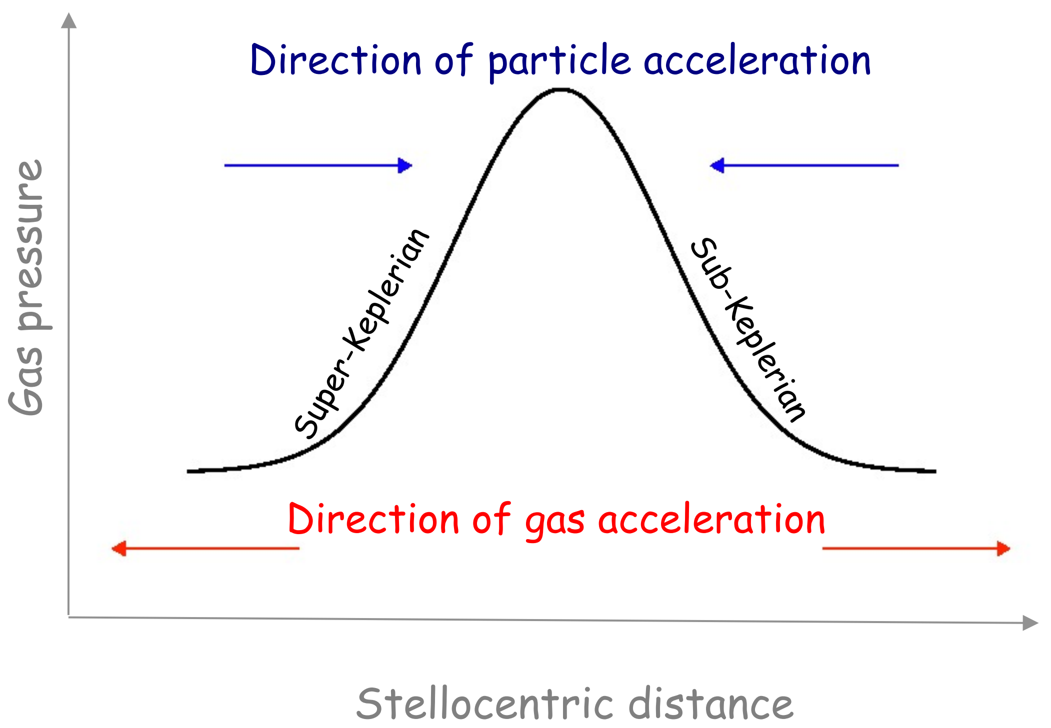
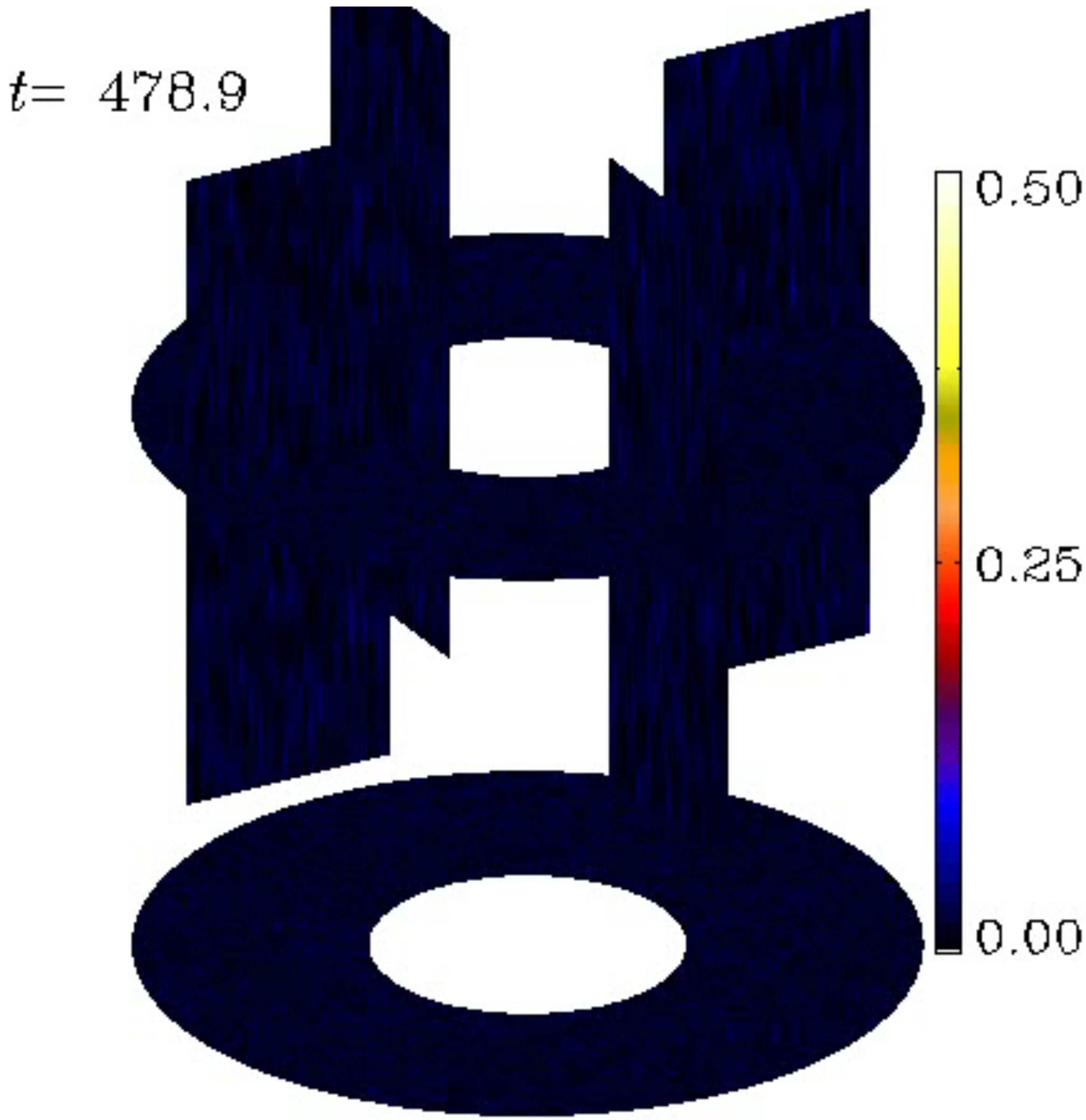


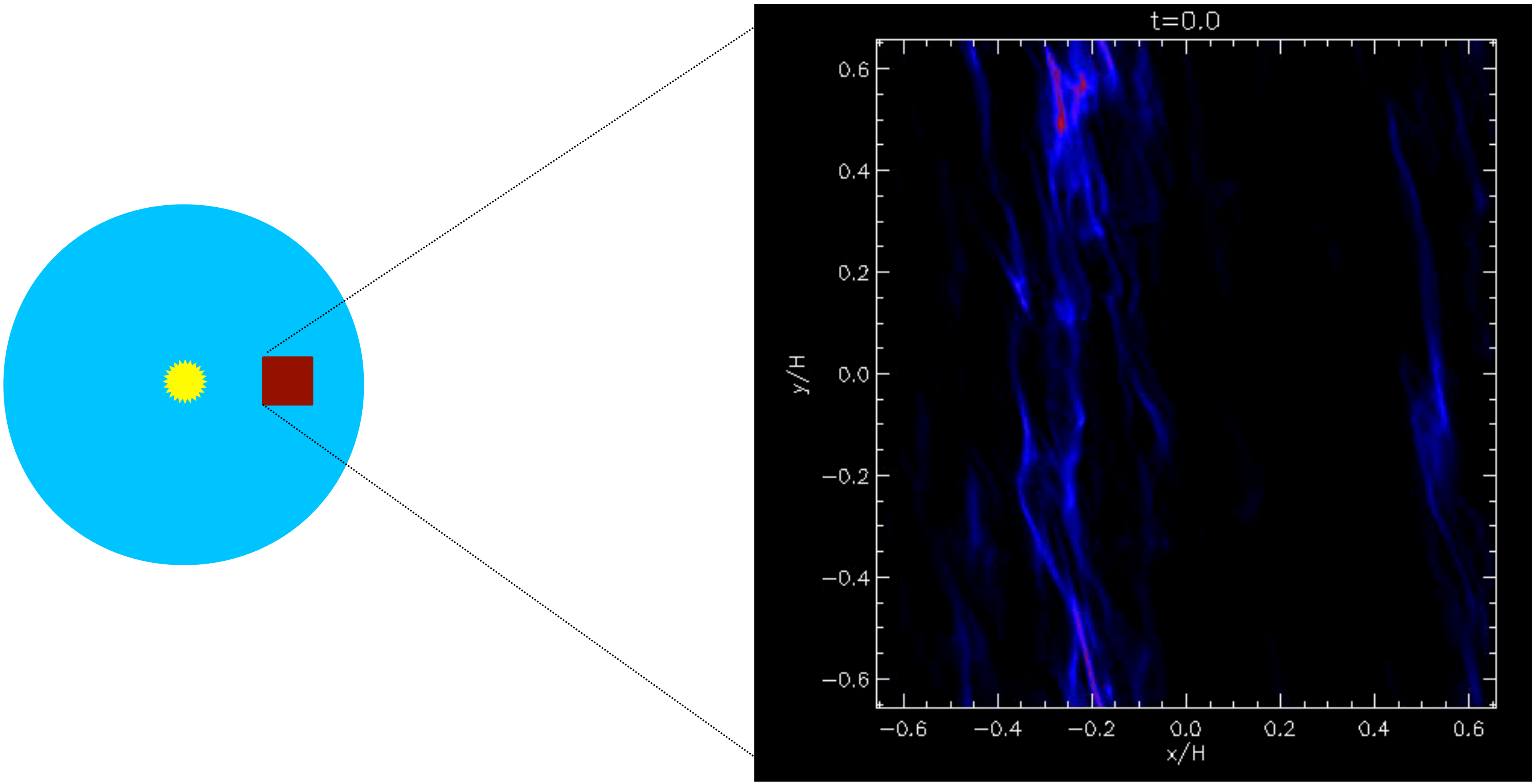
Solid particles move **toward** **pressure maxima**

Turbulence concentrates solids mechanically in pressure maxima



Lyra et al. (2008a)

Gravitational collapse into planetesimals



Johansen et al. (2007)

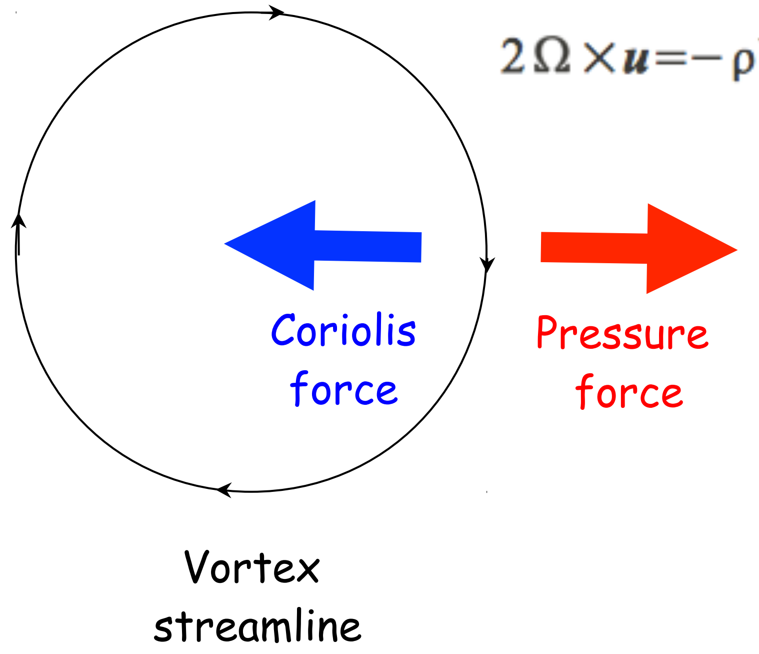
Turbulent eddies concentrate solids, turning them into planetesimals...

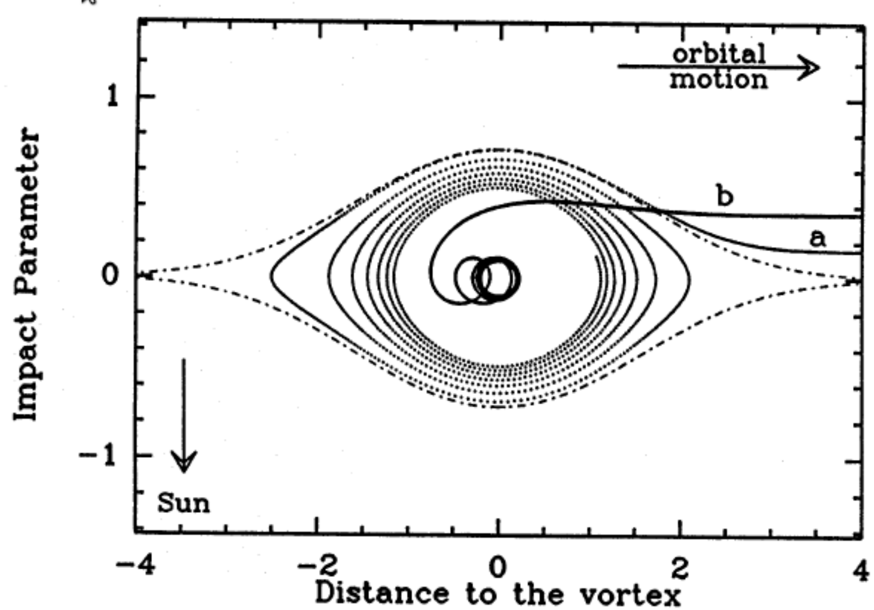
...and vortices are **huge** eddies!

The Tea-Leaf effect

Geostrophic balance:

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





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)

The Tea-Leaf effect

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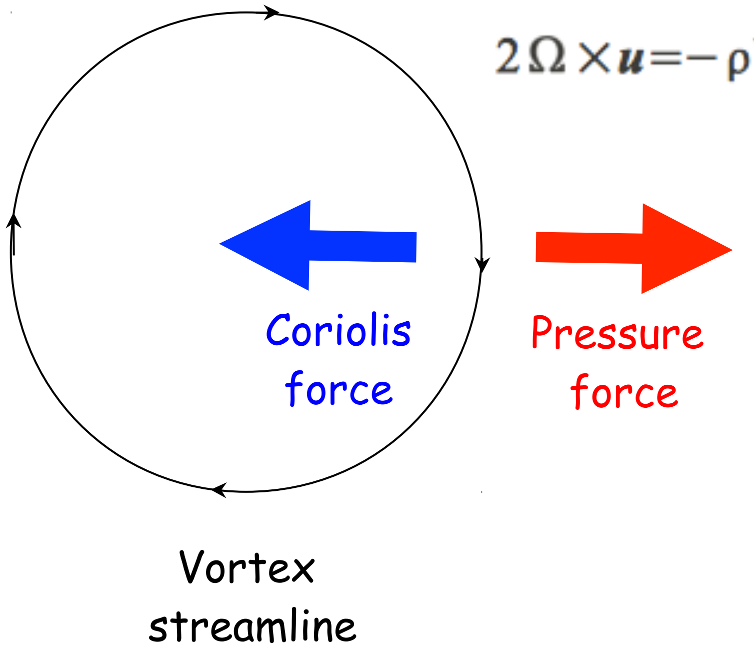

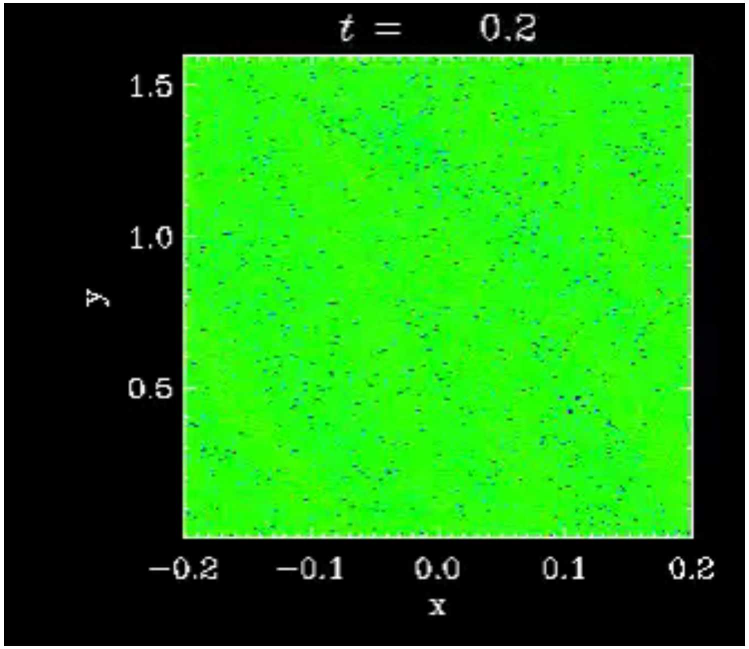

Raettig et al. (2012)

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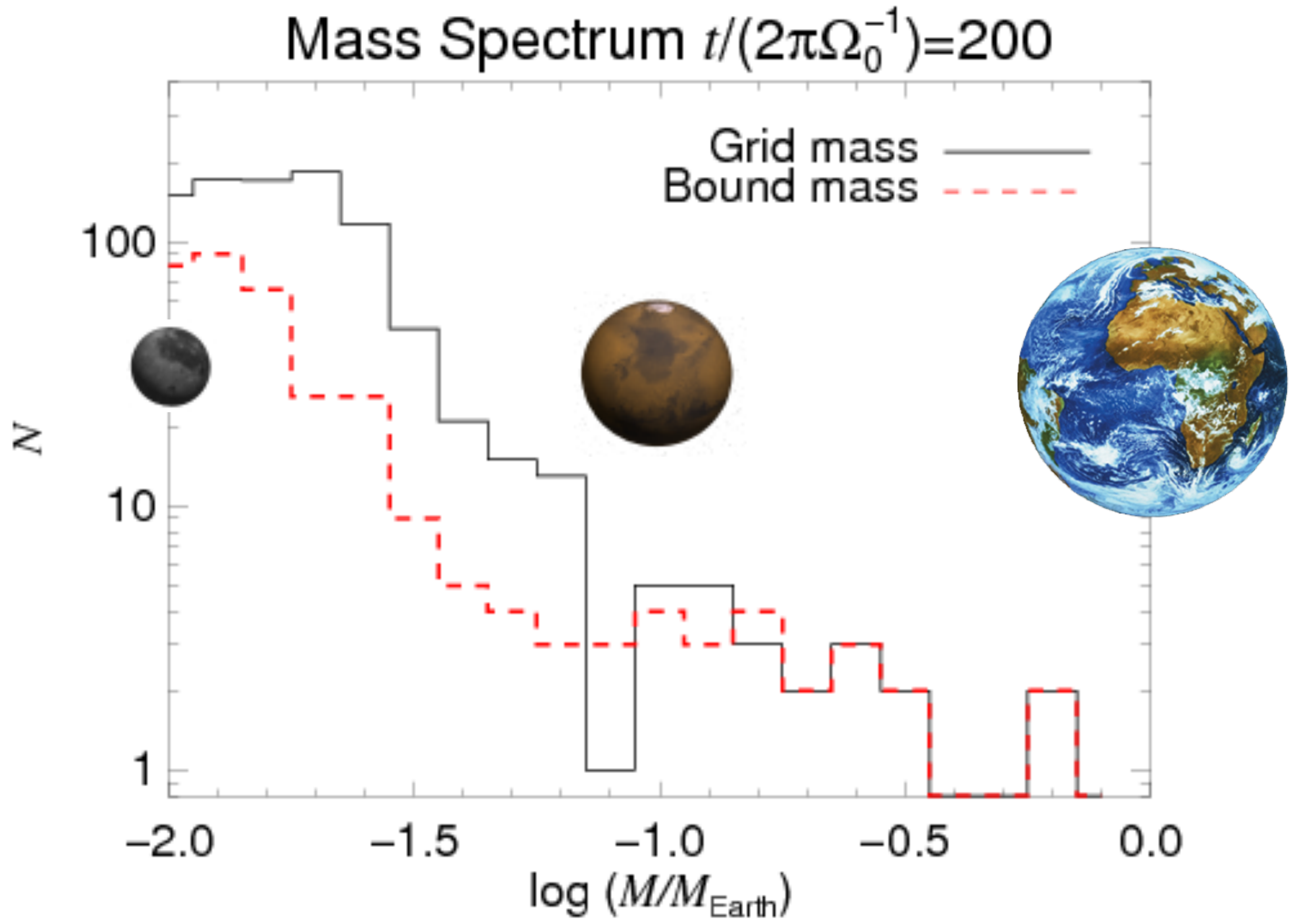
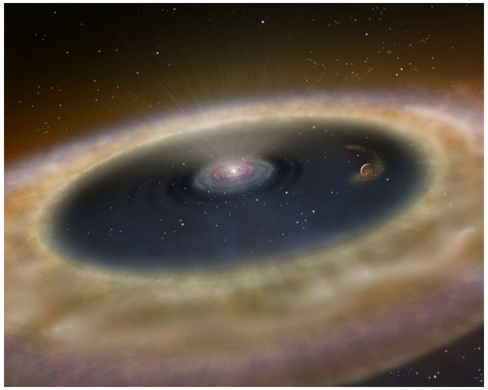
The Initial Mass Function of planets



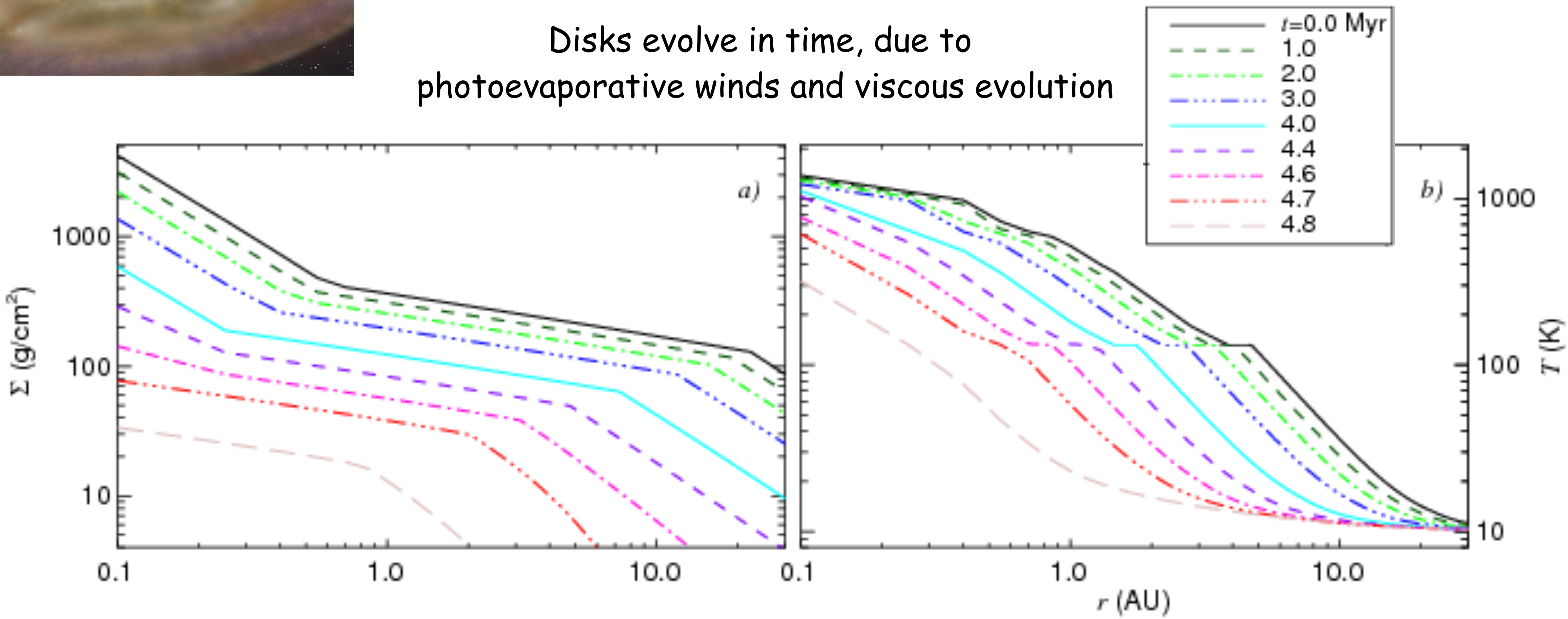
- Mass spectrum by the end of the simulation
- 300 bound clumps were formed
- Power law d(log N)/d(log M)=-2.3 +/- 0.2
- 20 of these are more massive than Mars

Lyra et al. (2009)

Transitional disks – The thinning phase



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

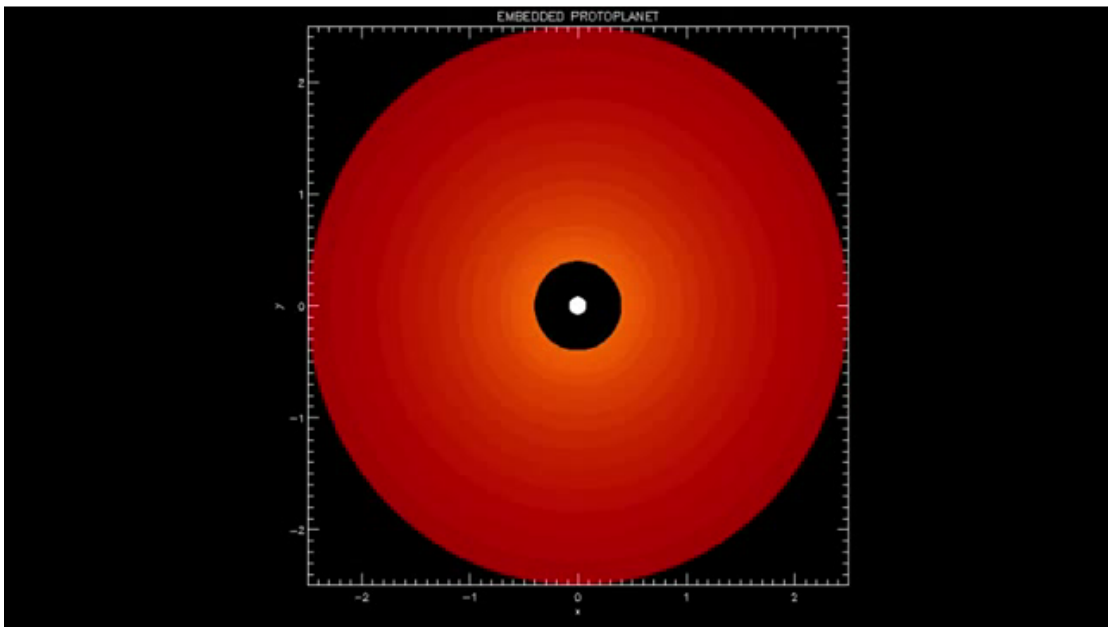


Lyra, Paardekooper, & Mac Low (2010)

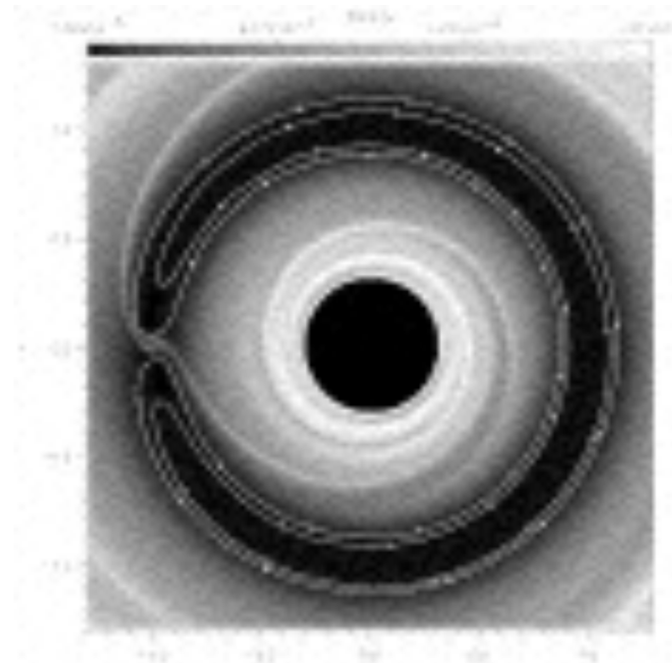
Planets form and start to migrate

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

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



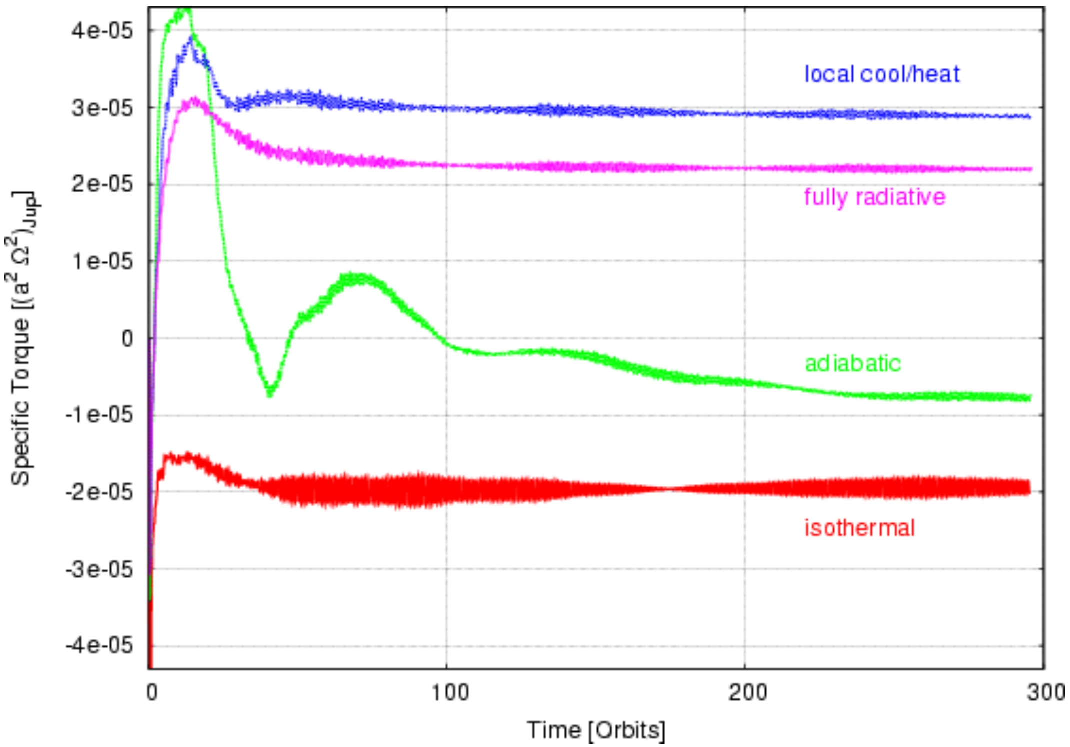
Kley & Nelson (2012, A&A Annual Review)



Lubow et al. (1999)

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

Planets form and start to migrate



Kley & Crida (2008)

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

outwards ***in***
steep temperature gradients,

inwards ***in***
isothermal regions.

Paardekooper & Mellema (2006)

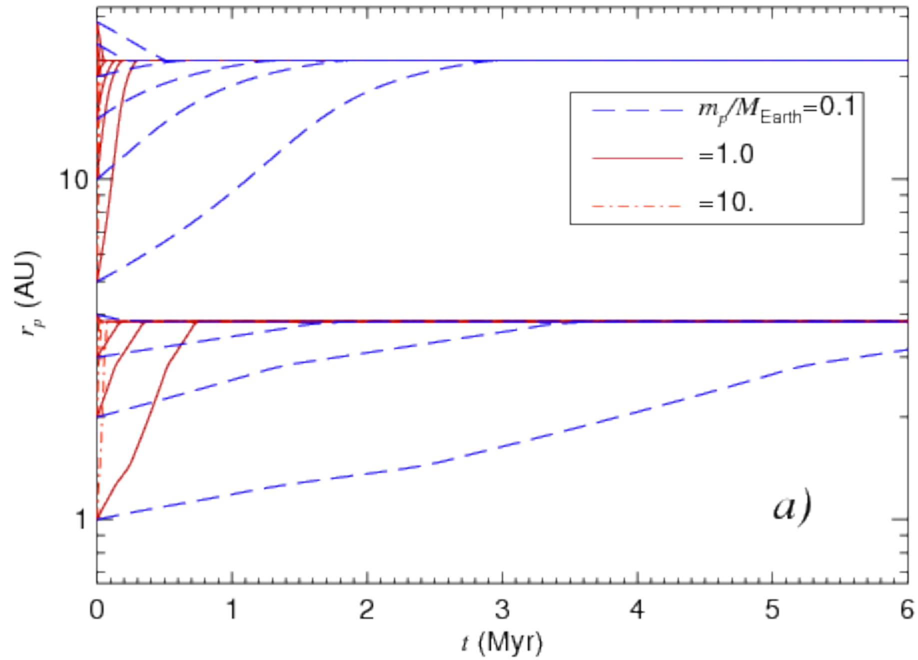
Non-isothermal co-rotational torque may lead to outward migration

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
Bitsch et al. 2012
Nelson & Kley 2012
Pierens et al. 2012
Bitsch et al. 2013
Zhu et al. 2013

Planets form and start to migrate

Planet-disk interaction leads to angular momentum exchange

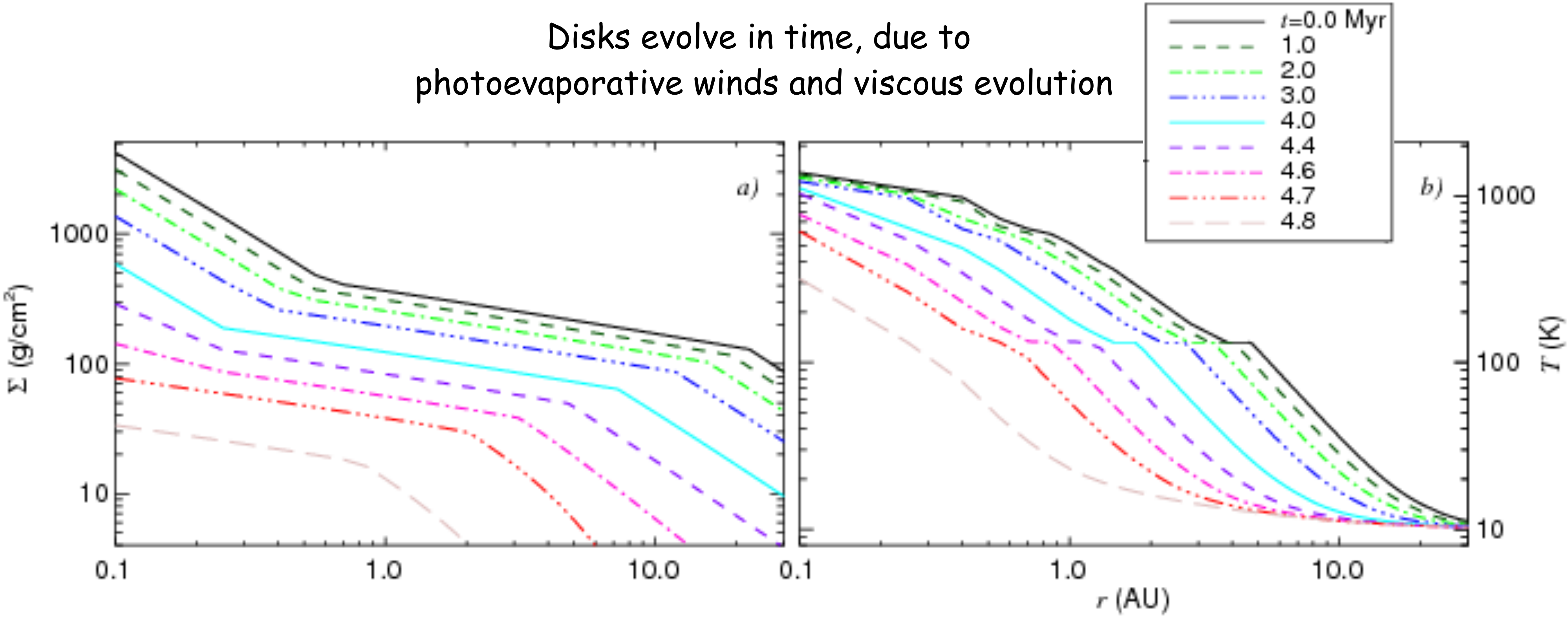


Lyra, Paardekooper, & Mac Low (2010)

Planet traps where migration is convergent (τ=0, dτ/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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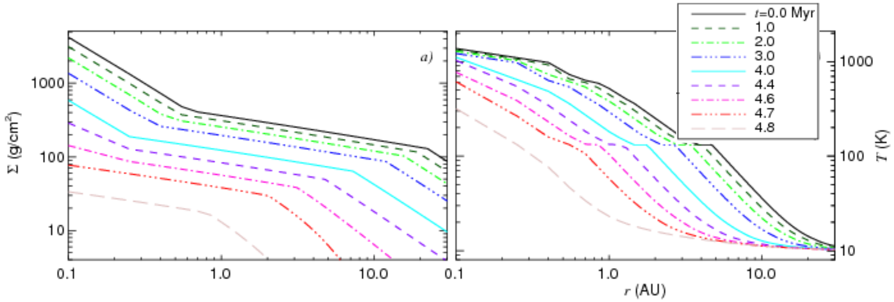


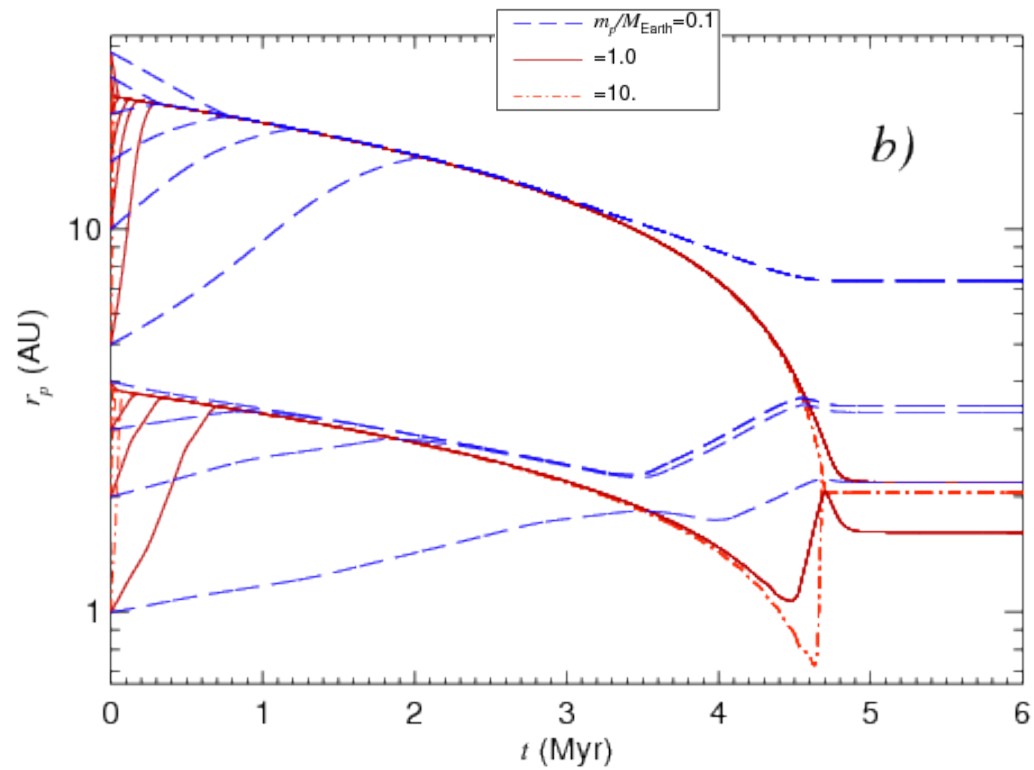
Rule of thumb: **Migration is**

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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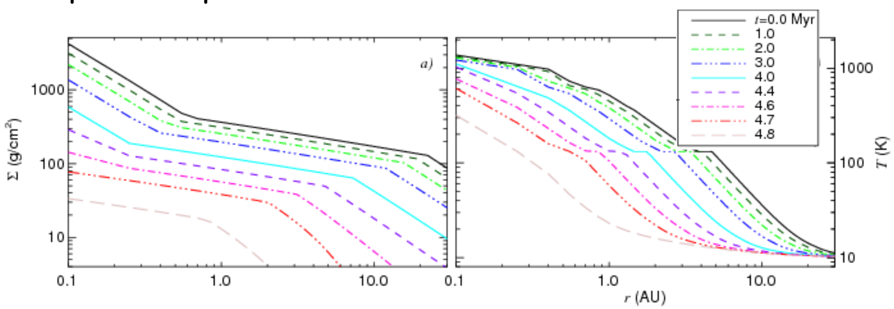

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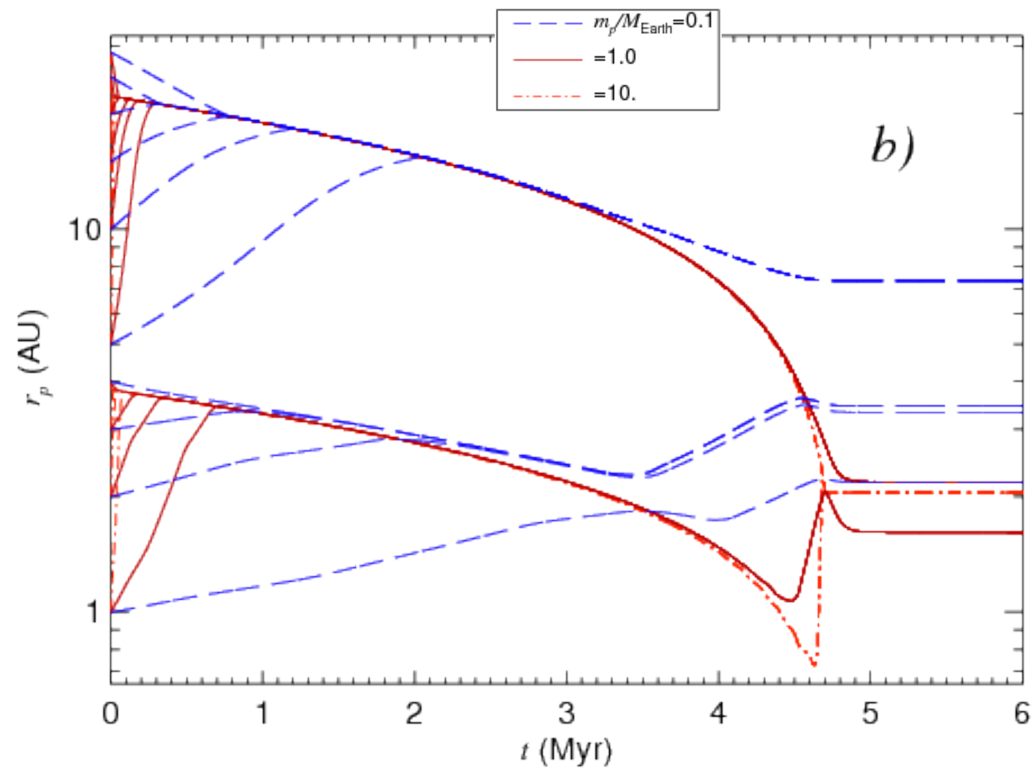

Lyra, Paardekooper, & Mac Low (2010)

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Migration in Evolutionary Models

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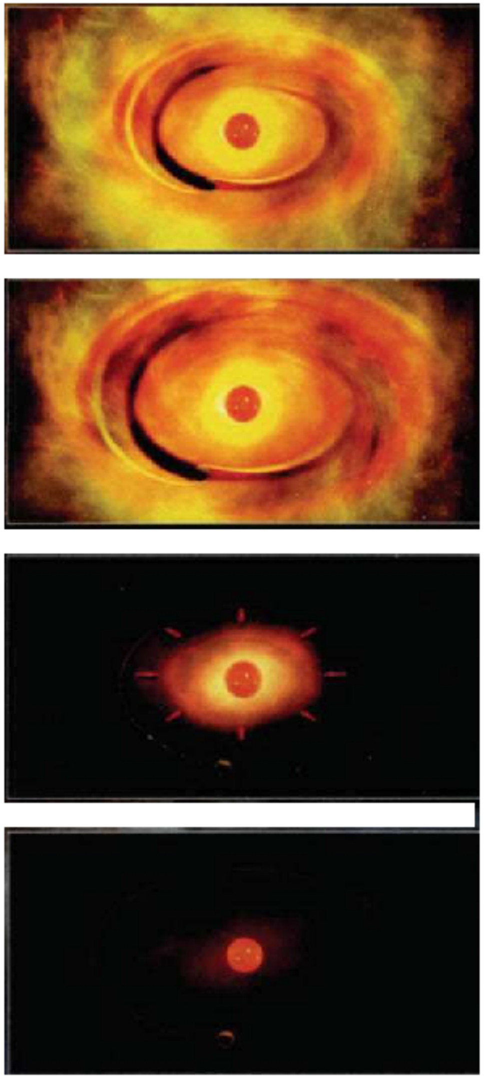
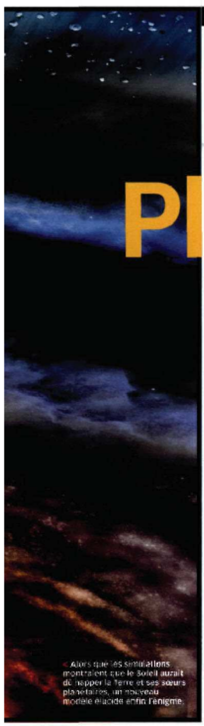


"La Terre sauvée"


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

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.*

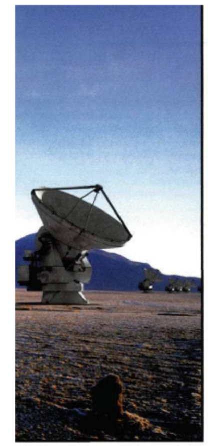
Planètes
On sait pourquoi elles survivent à leur étoile

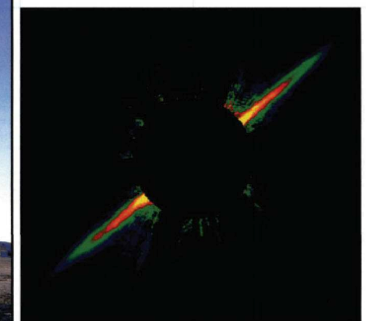
Par Román Ikonicoff

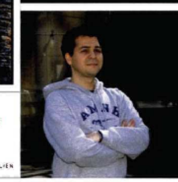
"La Terre sauvée". Le titre de la conférence donnée en janvier 2010 par le Brésilien Wladimir Lyra, le Néerlandais Sijme-Jan Paardekooper et l'Américain Mordecai-Mark Mac Low, lors du 215e meeting de la Société astronomique américaine (AAS), était un brin malicieux.

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 →







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...

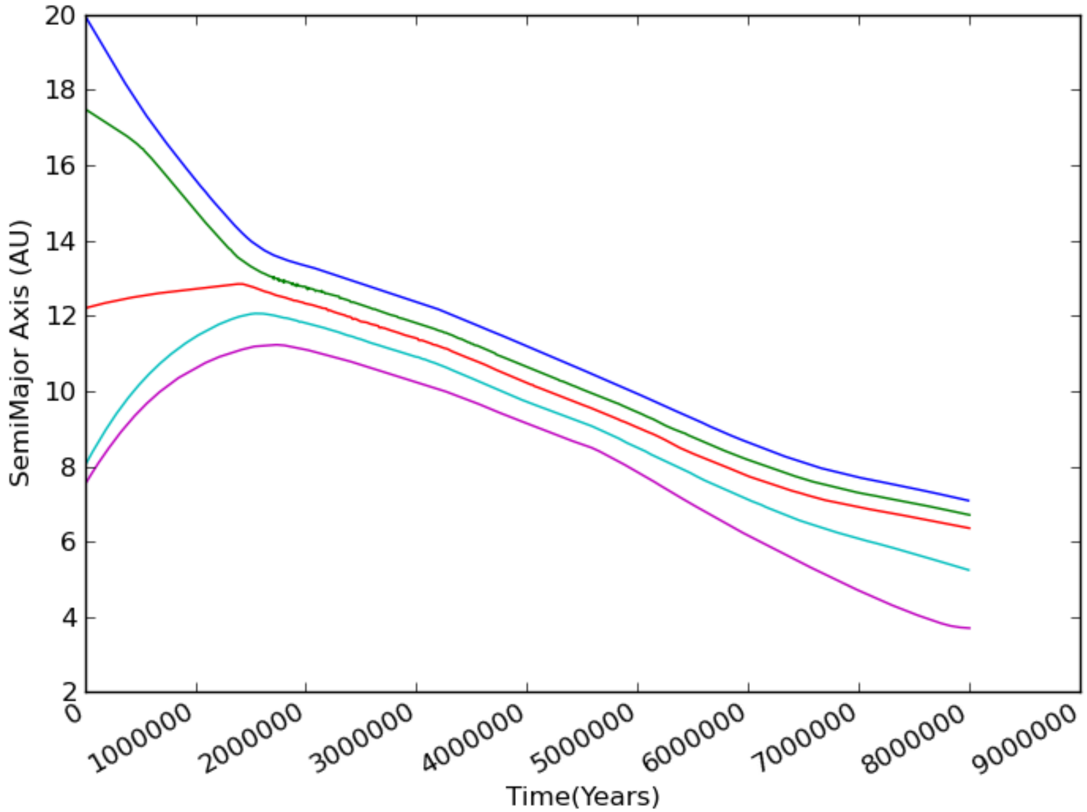
DONNÉES CONCRÈTES DÈS 2011

"*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.

Migration + N-Body in Evolutionary Models

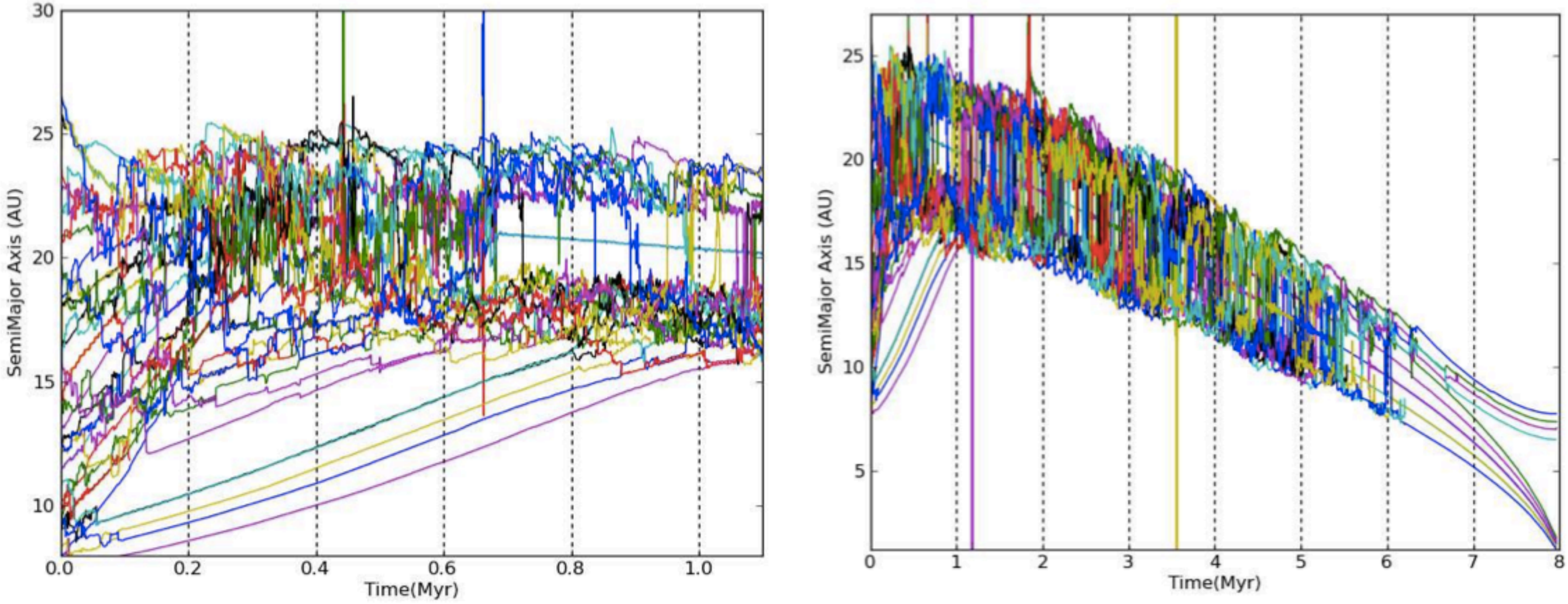


Migration in resonance !

See also
Sandor, Lyra & Dullemond (2011)
Hellary & Nelson (2012)

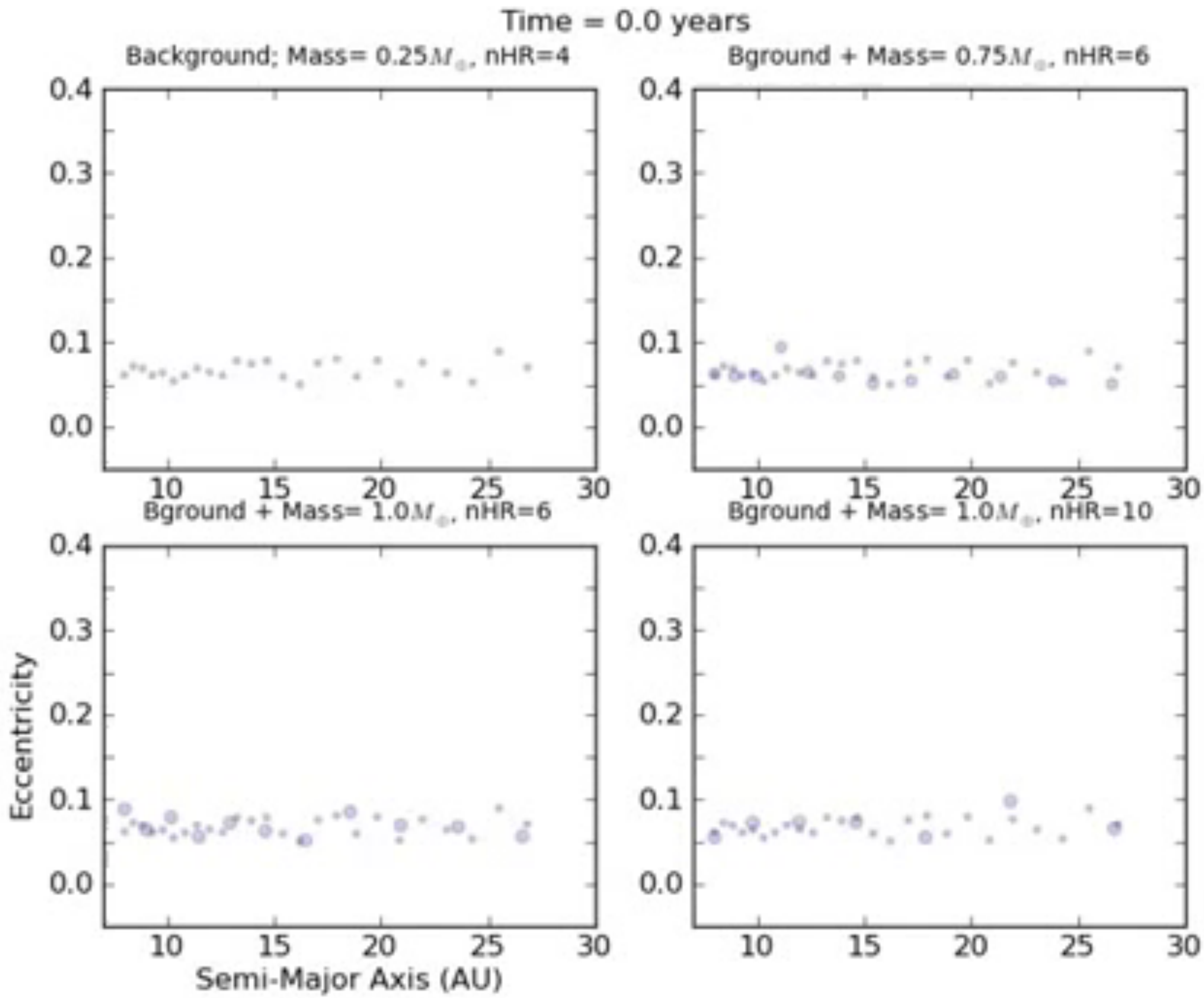
Orbital migration of interacting planets in a radiative evolutionary model

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



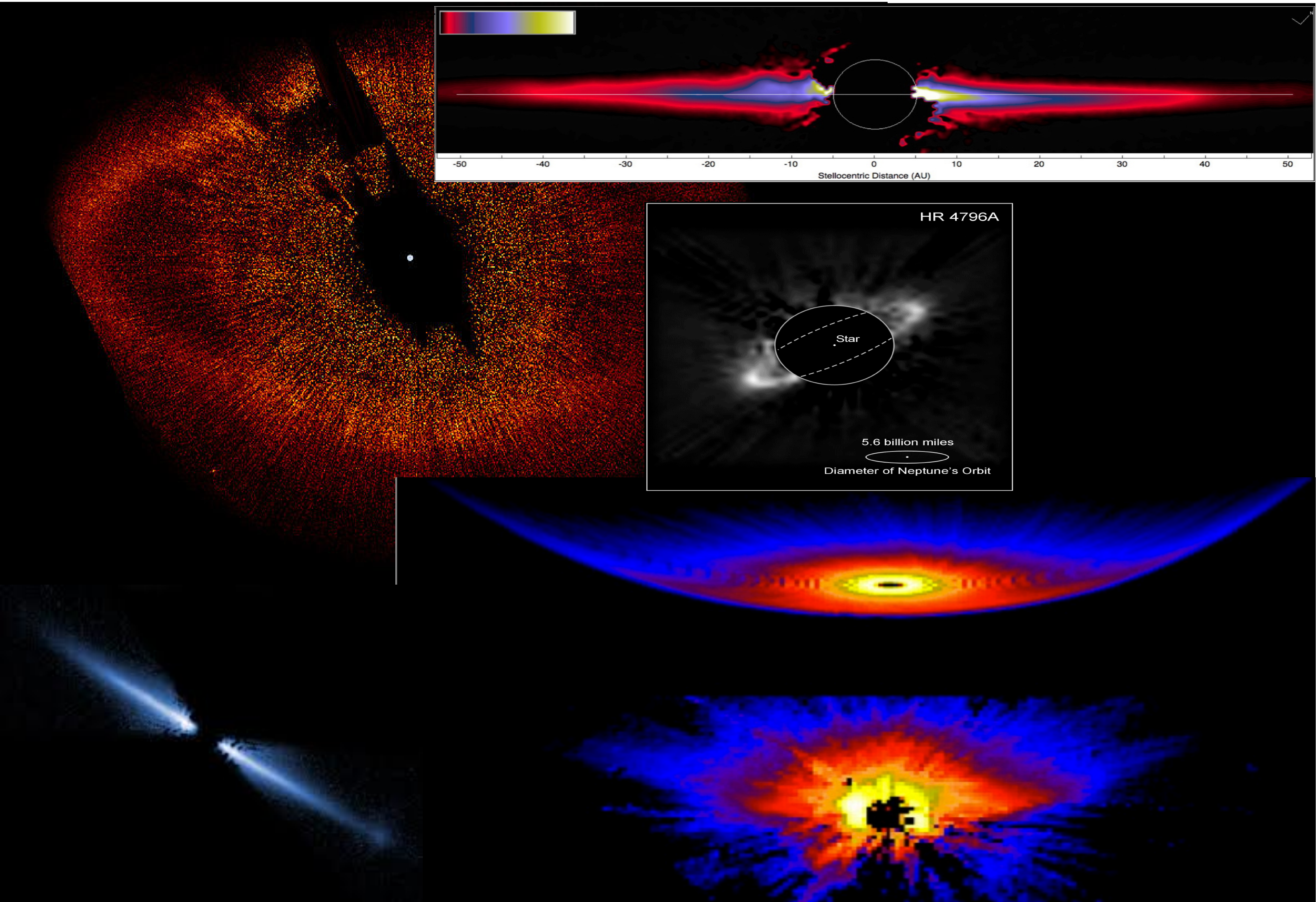
Horn et al. (2012)

Orbital migration of interacting planets in a radiative evolutionary model

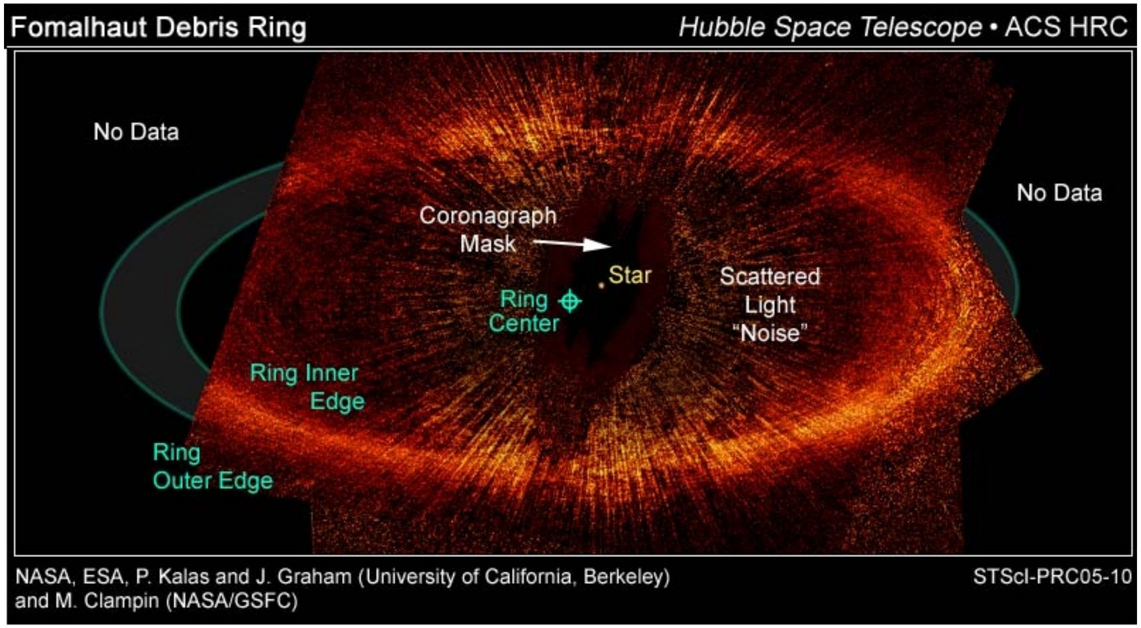


Horn et al. (2012)

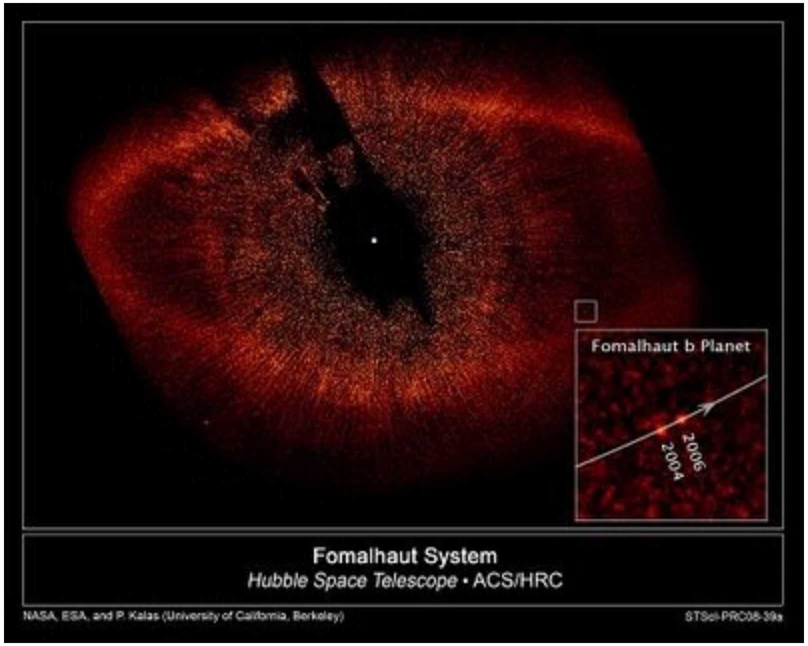
Debris disks – The gas-poor phase



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.....

THE ASTROPHYSICAL JOURNAL, 747:116 (7pp), 2012 March 10
doi:10.1088/0004-637X/747/2/116

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

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Received 2011 December 16; accepted 2012 January 12; published 2012 February 23

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

Sharp and eccentric rings in debris disks: Signposts of planets

However (take two)…..

h.EP] 24 Oct 2012

Direct Imaging Confirmation and Characterization of a Dust-Enshrouded Candidate Exoplanet Orbiting Fomalhaut

Thayne Currie[1,2], John Debes[3], Timothy J. Rodigas[4], Adam Burrows[5], Yoichi Itoh[6], Misato Fukagawa[7], Scott J. Kenyon[8], Marc Kuchner[2], Soko Matsumura[9]

currie@astro.utoronto.ca

ABSTRACT

We present Subaru/IRCS J band data for Fomalhaut and a (re)reduction of archival 2004–2006 HST/ACS data first presented by Kalas et al. (2008). We confirm the existence of a candidate exoplanet, Fomalhaut b, in both the 2004 and 2006 F606W data sets at a high signal-to-noise. Additionally, we confirm

It should not have been detected anyway…

Some of the Fom b controversy

Janson et al. 2012

Variability by 0.7-0.8 mag in F606W band

Astrometric orbit not apsidally aligned with the ring

No infrared emission

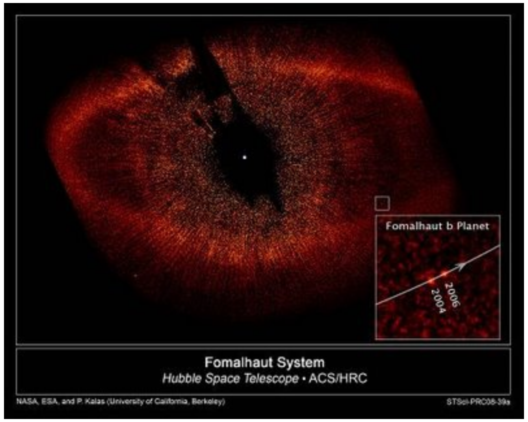
Currie et al. 2012

No variability found within 0.15 mag in the same band

Consistent with apsidal alignment

Thermal emission from 0.5 MJ would not be detectable.

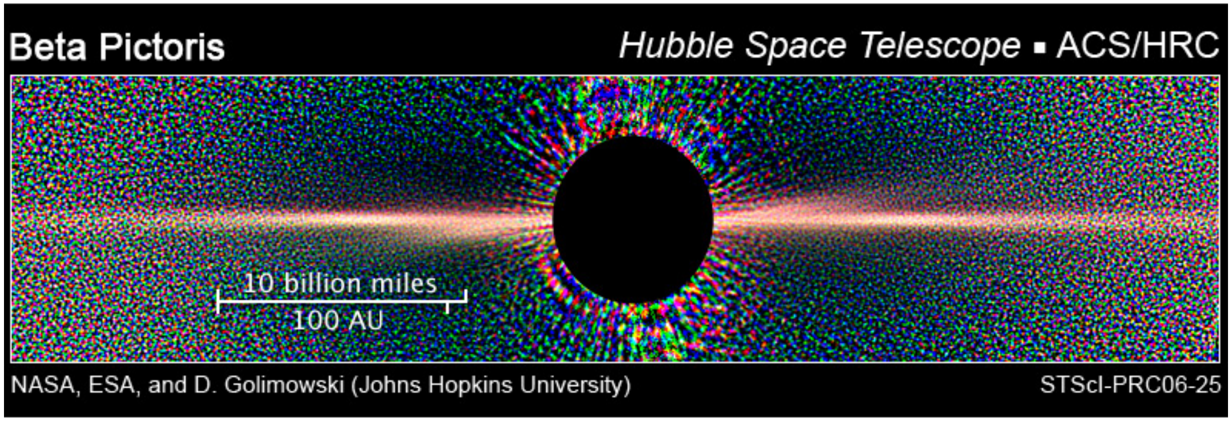
Observed optical emission requires reflection by ***something*** of several Jupiter radii



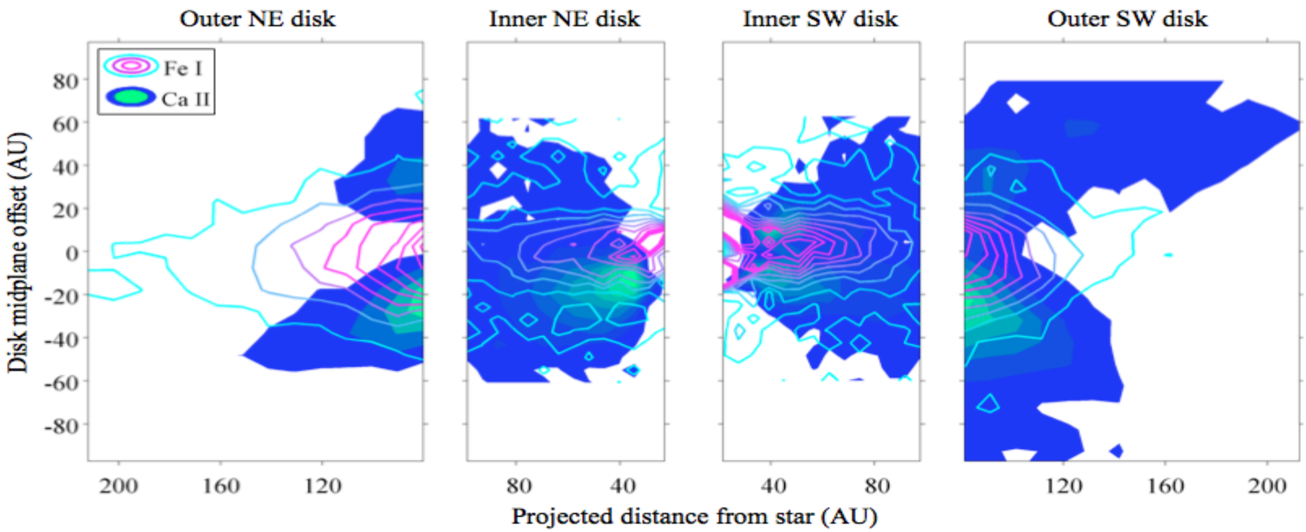
Are there alternative explanations?

Debris disks are not completely gas-free

Dust



Gas



VLT imaging by Nilsson et al. (2012)

Gas in debris disks

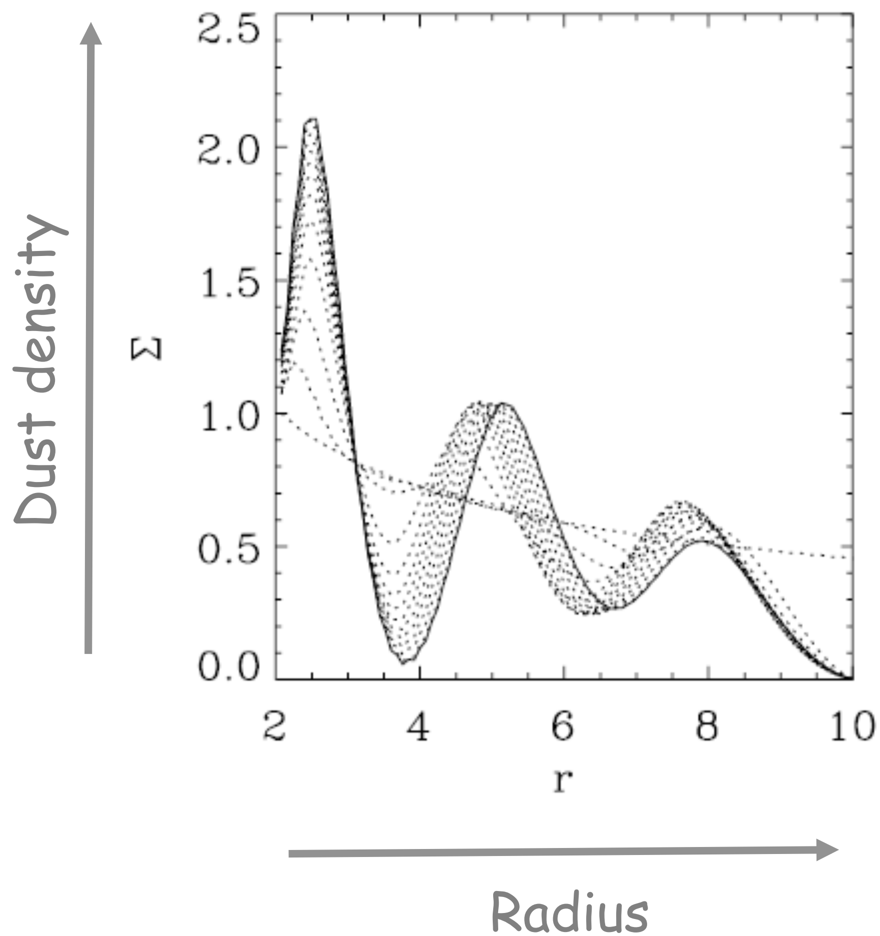
Detections

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?	

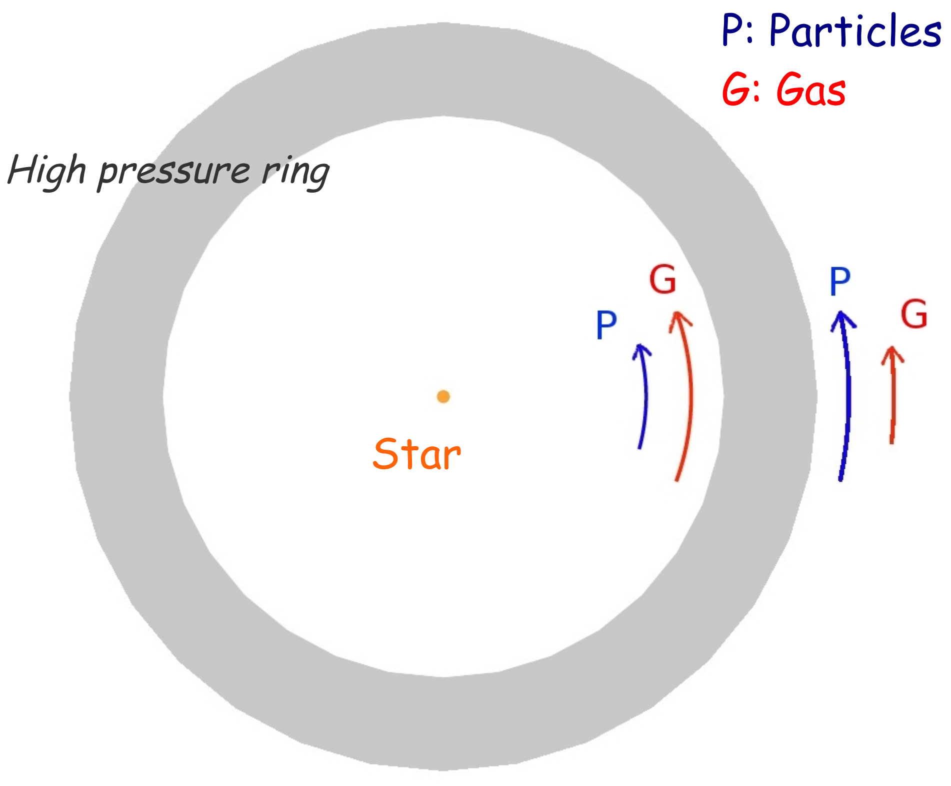
Dust and gas together leads to instability...



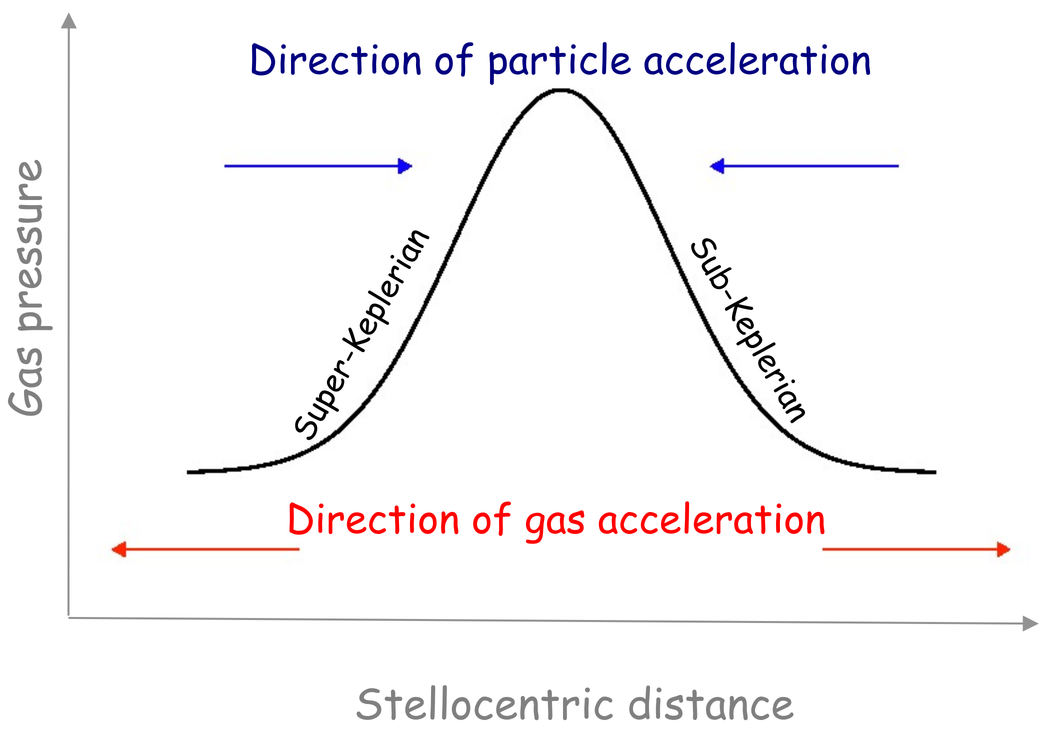
Klahr & Lin (2005)

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

Particles move toward pressure maxima

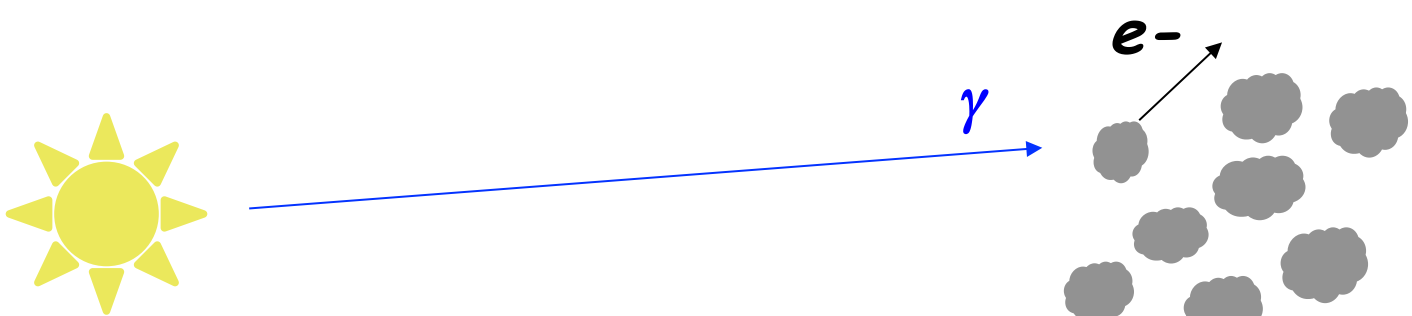


Adapted from Whipple (1972)



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

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

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

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

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

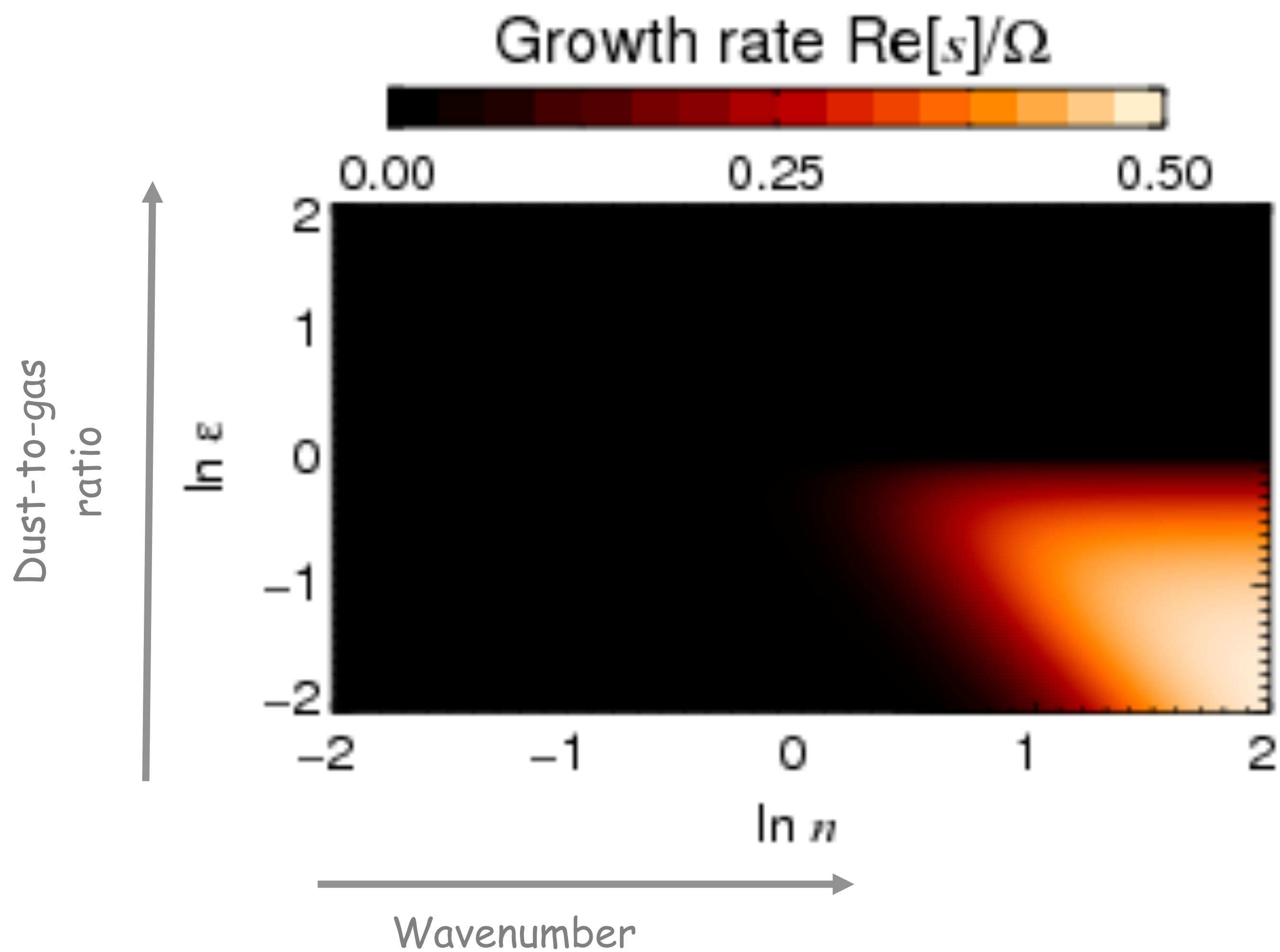
$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{v}$$

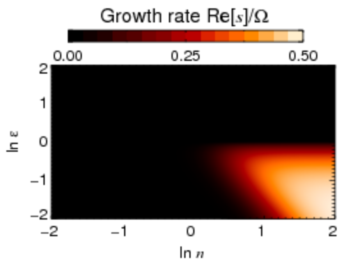
$$\frac{d\boldsymbol{v}}{dt} = -\boldsymbol{\nabla}\Phi + \boldsymbol{f}_d$$

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

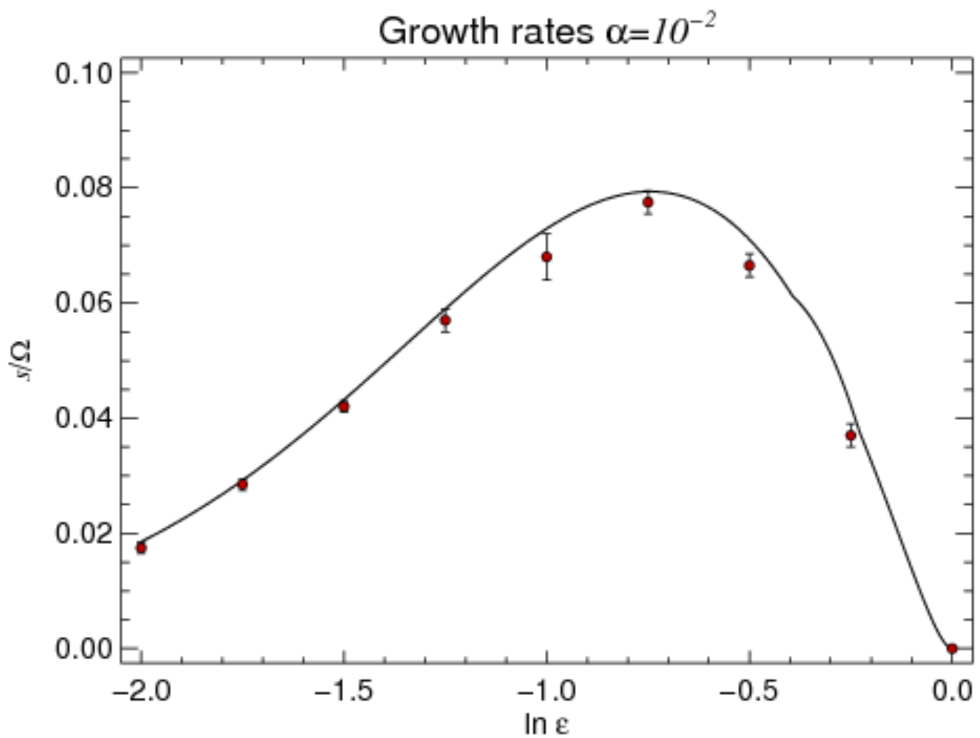
$$T_p = T_0\frac{\Sigma_d}{\Sigma_0}.$$

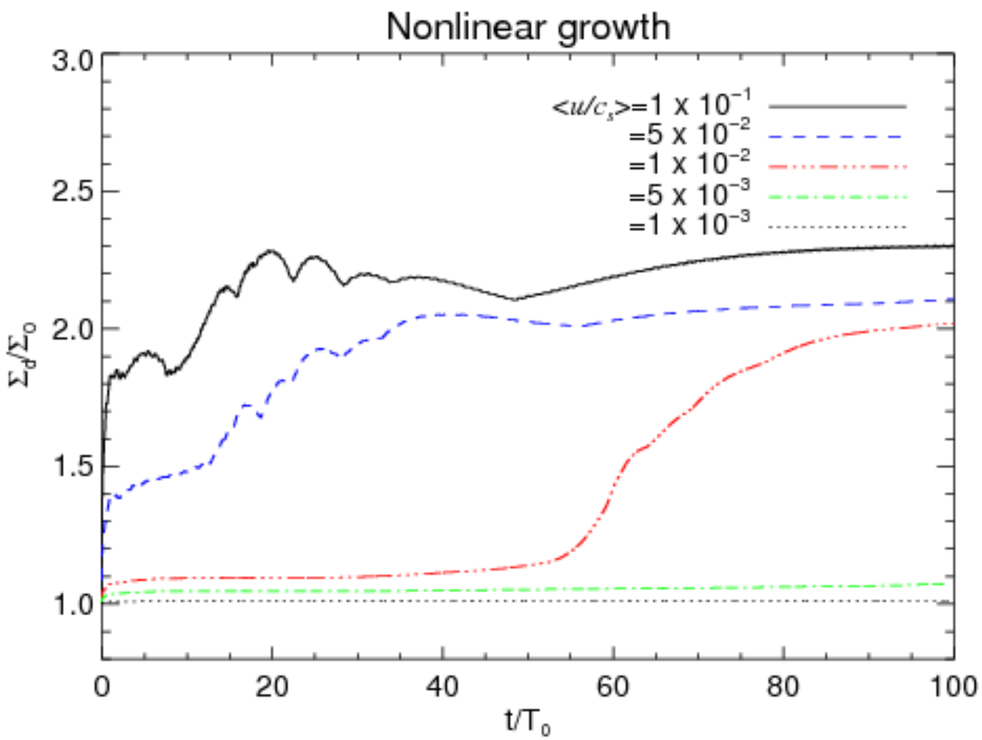
Linear Analysis





Linear and nonlinear growth



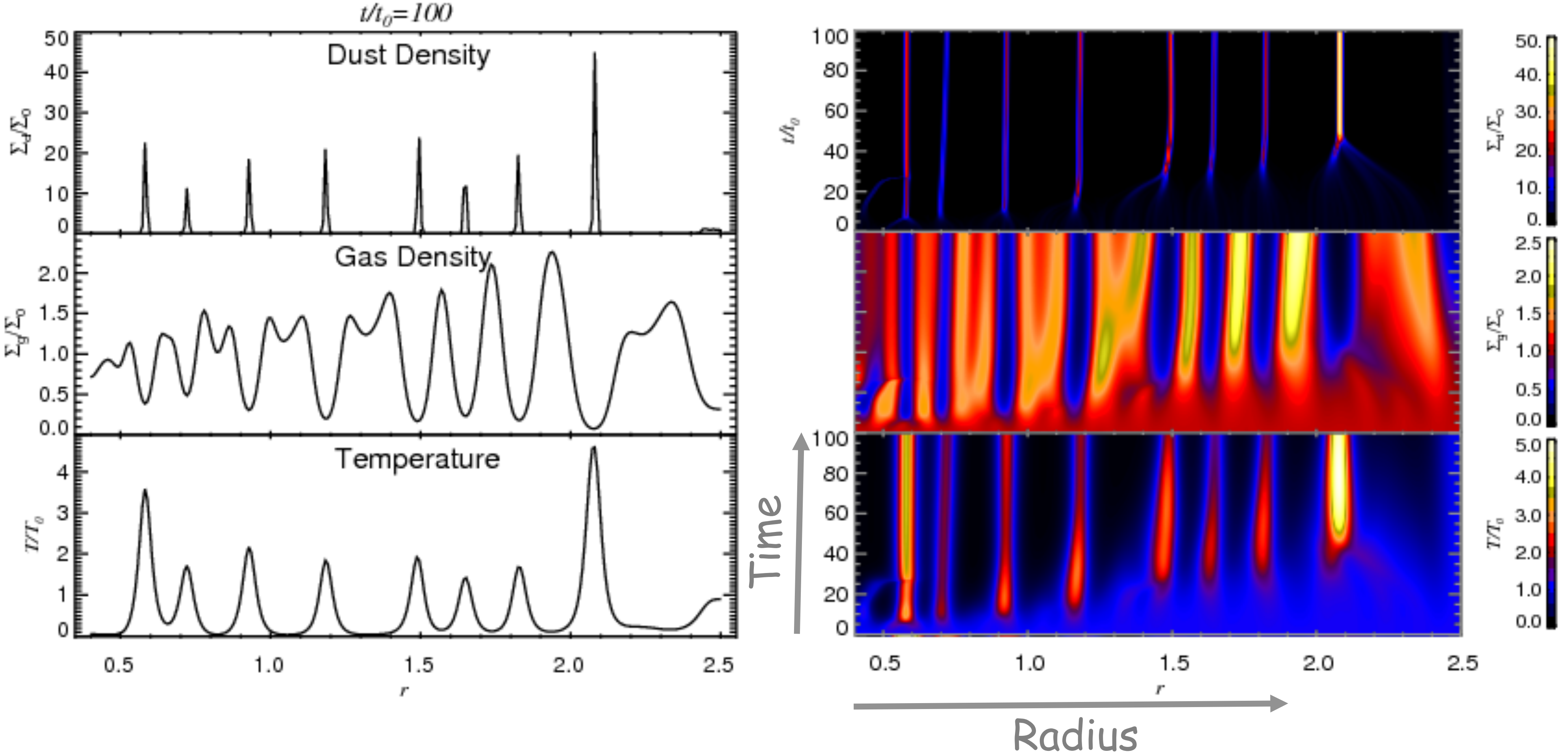


Linear growth only exists for ε < 1

But there is
nonlinear growth
beyond !

Instability

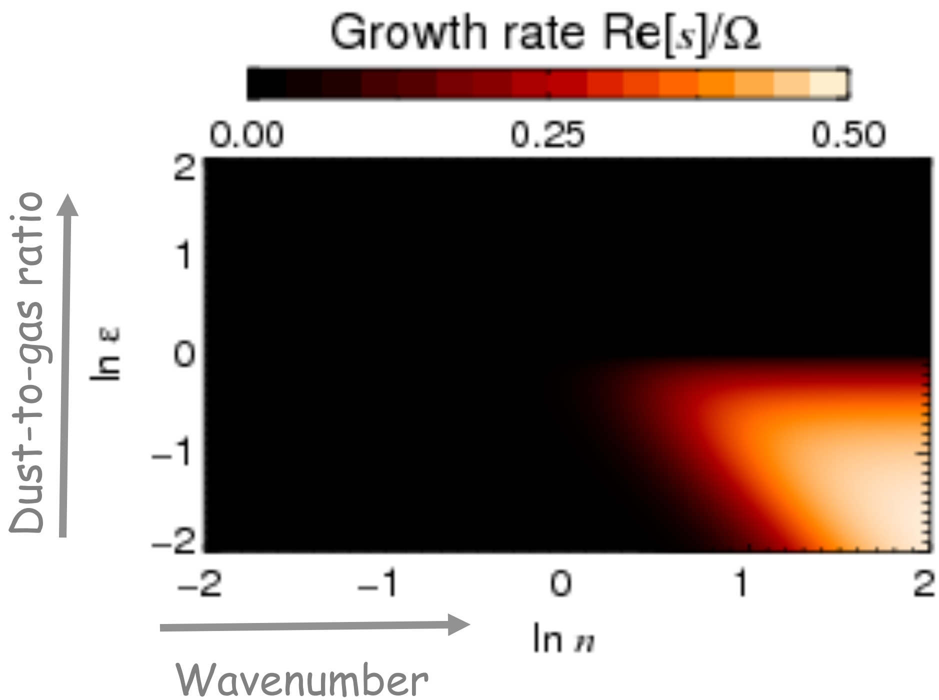
Dust heats gas
Heated gas = high pressure region
High pressure concentrates dust

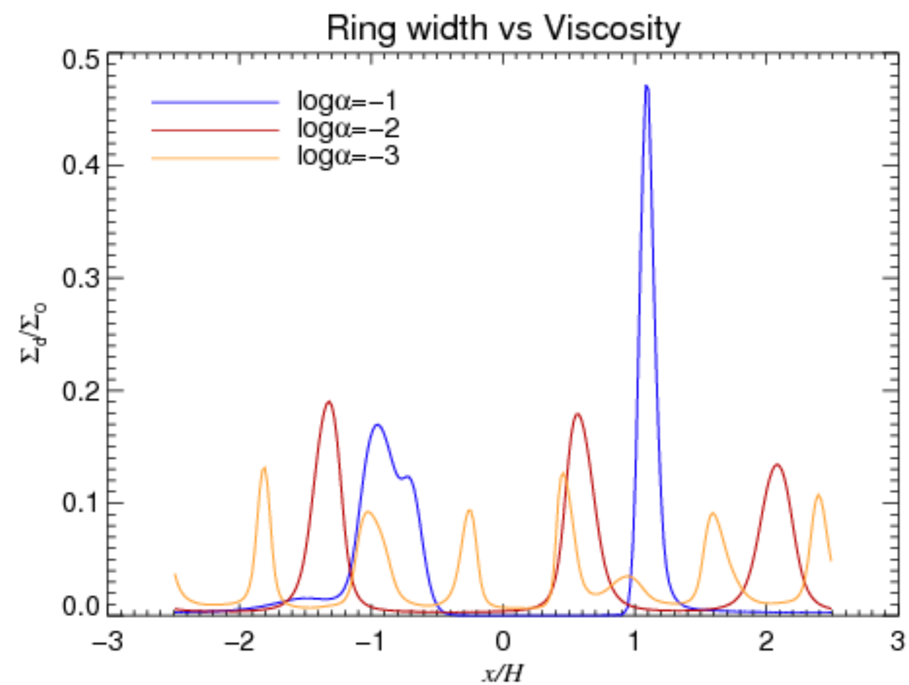


Narrow hot dust rings
Cold gas collects between rings

Ring width

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



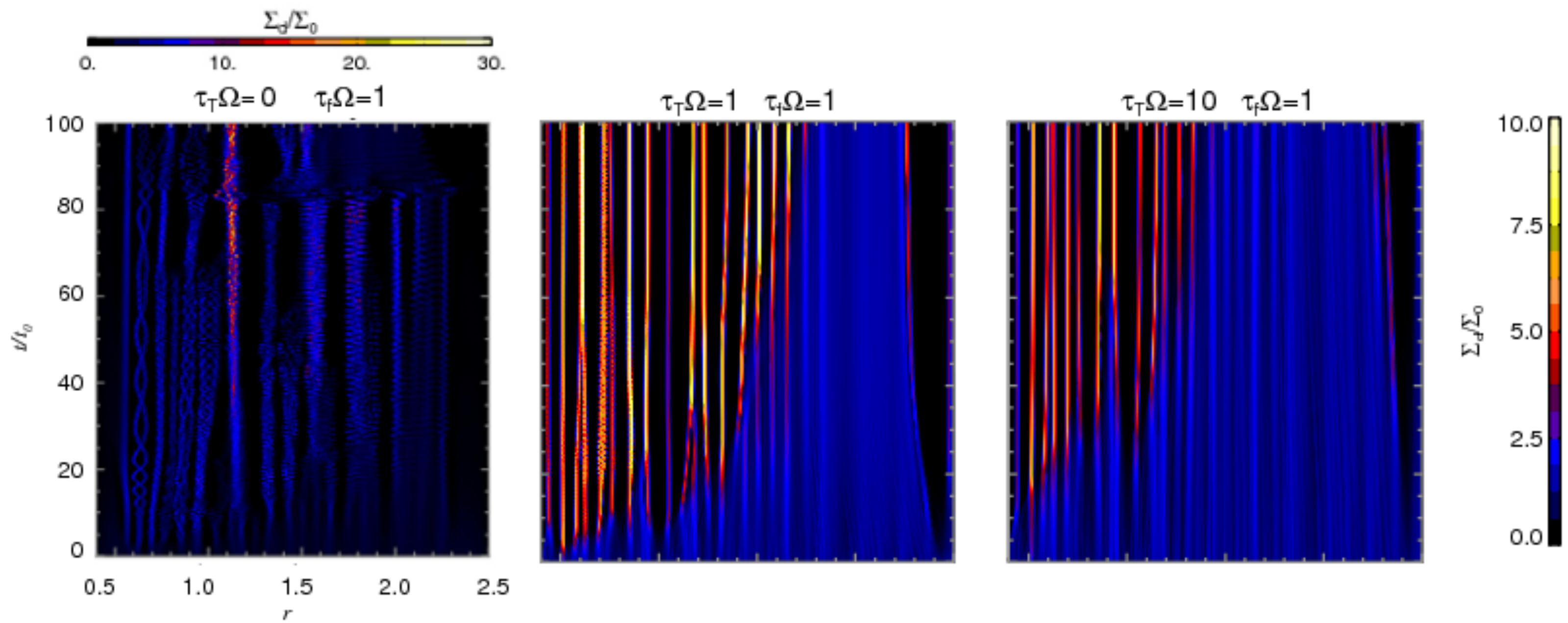


Which in turn is determined by viscosity

Ring width ~ 10 Kolmogorov lengths

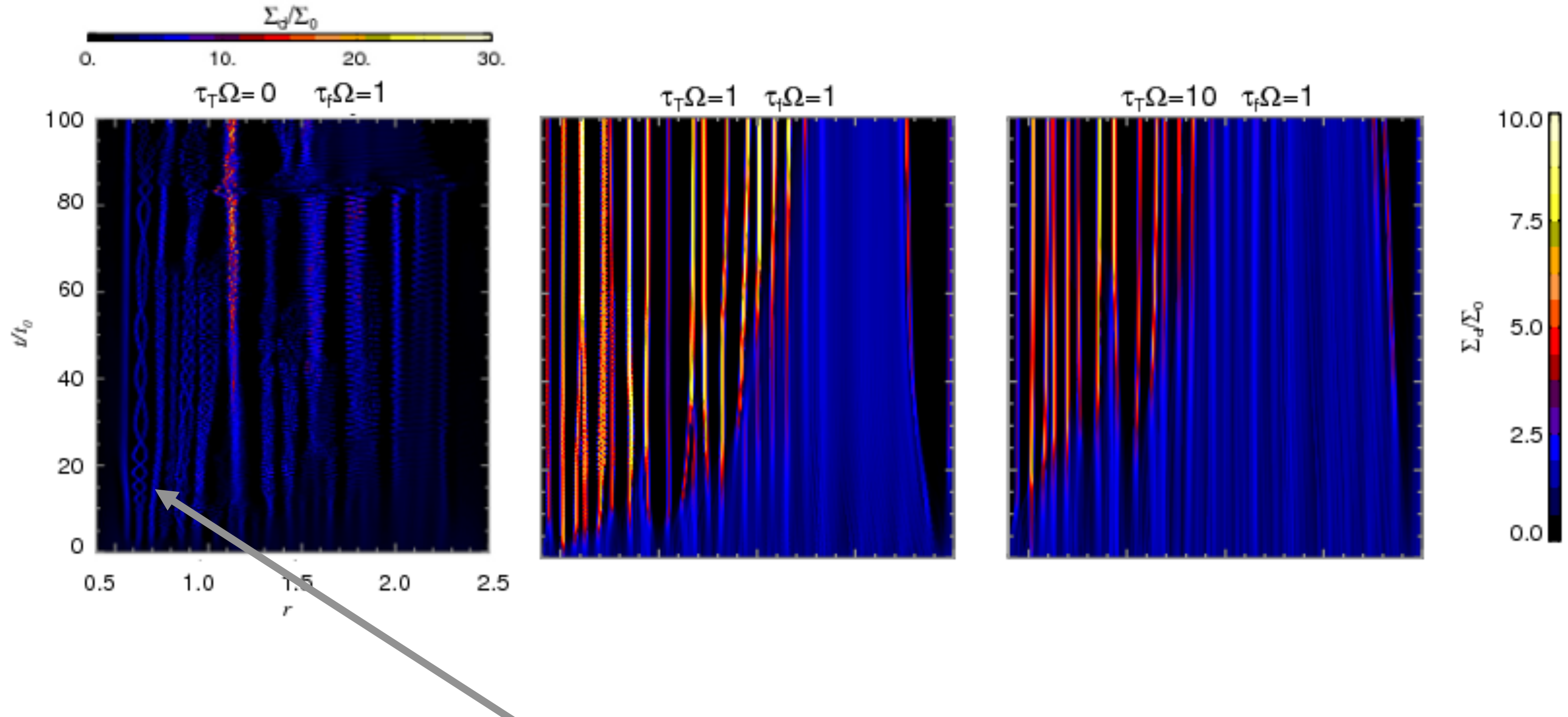
Oscillations

Thermal coupling time



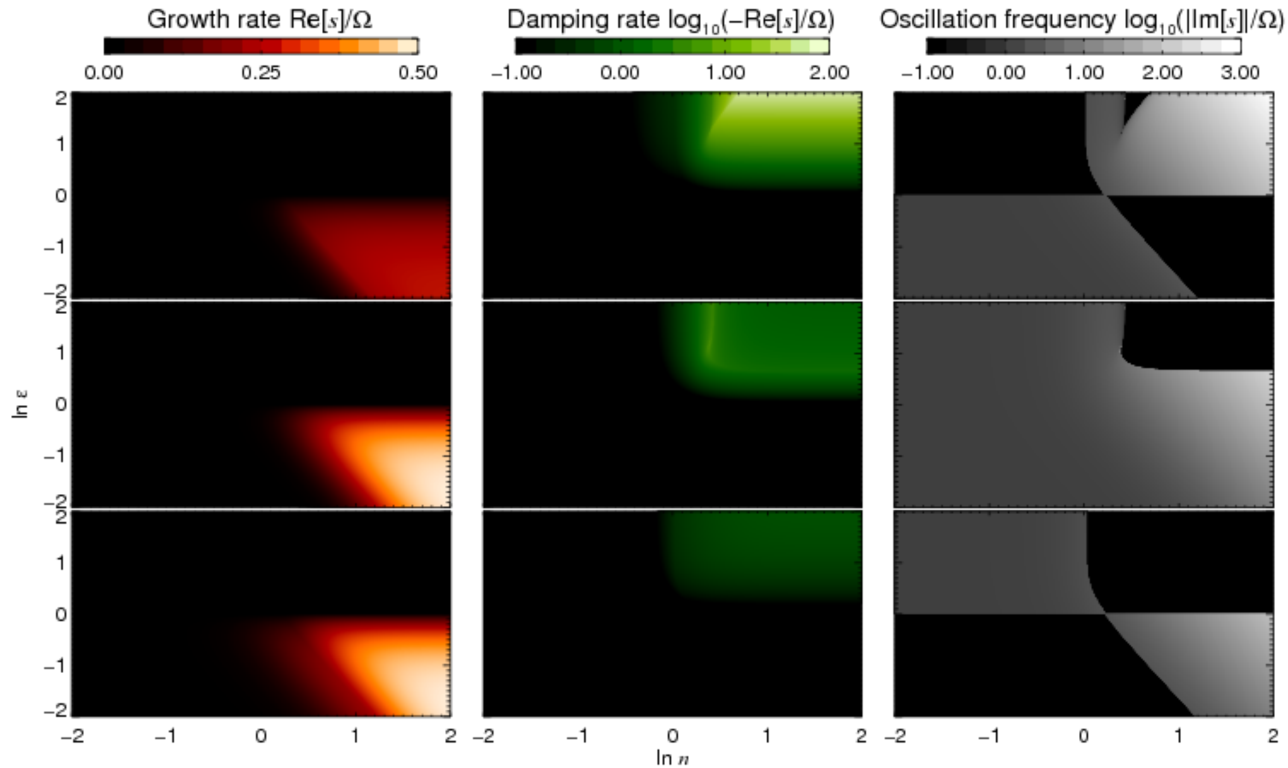
Oscillations

Thermal coupling time



Oscillations appear
with decreasing thermal time.

Solutions

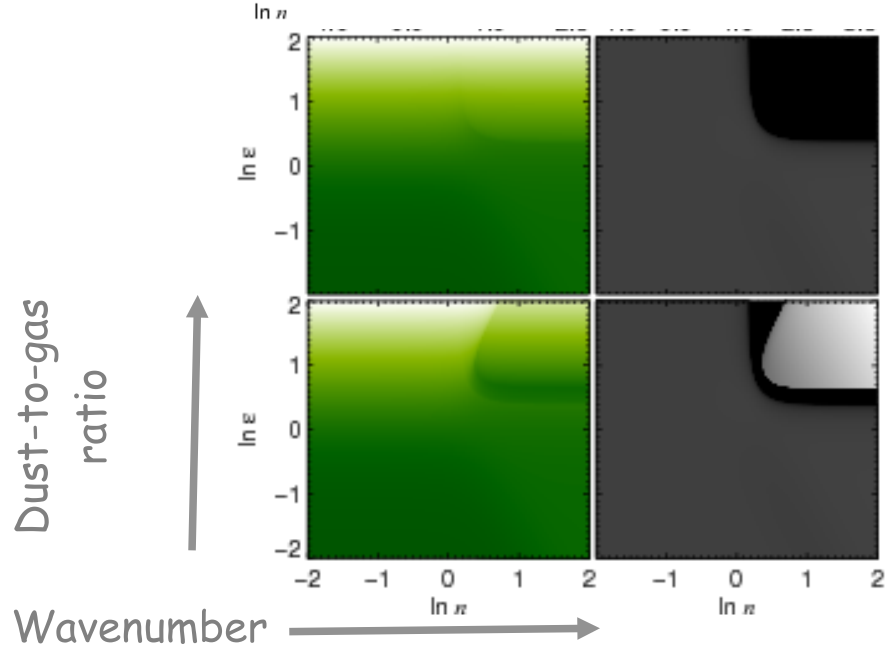


Dispersion relation

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

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

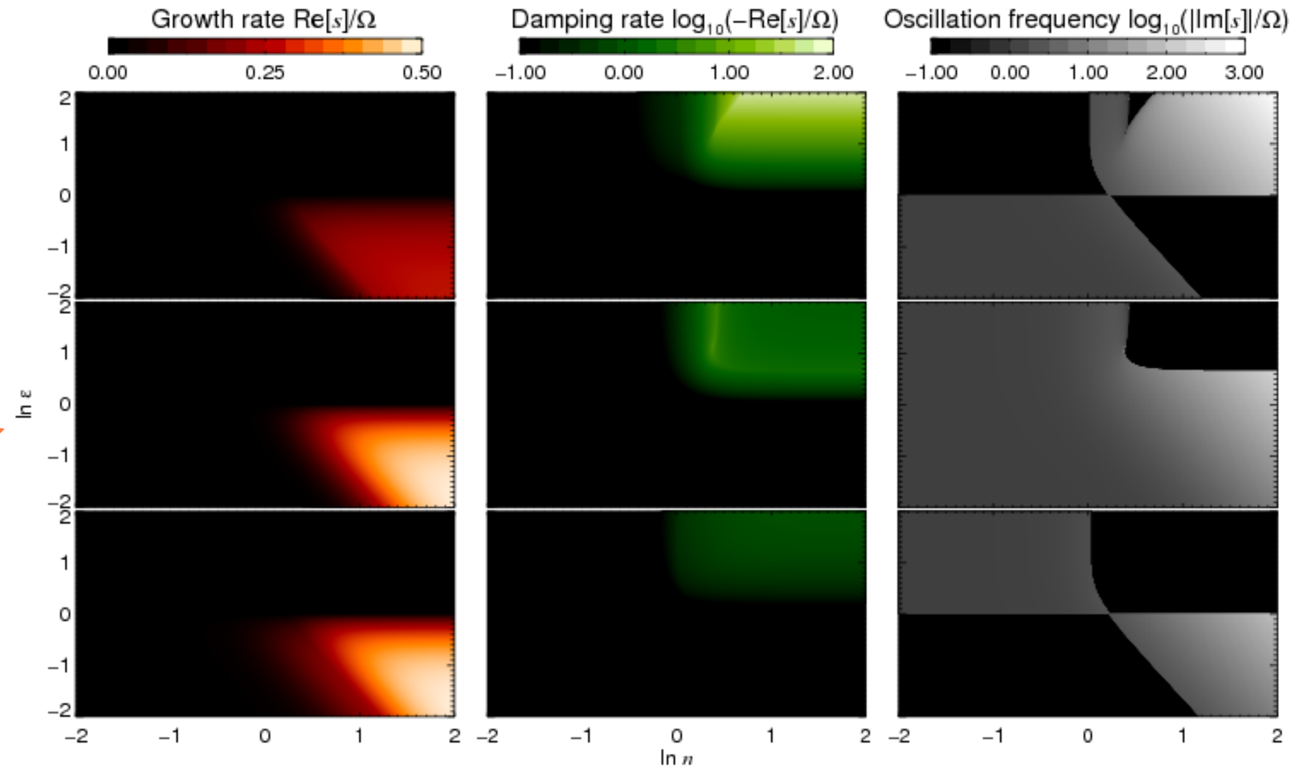
$\epsilon = \Sigma_d / \Sigma_g$ $\quad n = kH$ $\quad \omega = s/\Omega$



Solutions

Instability

Overstability



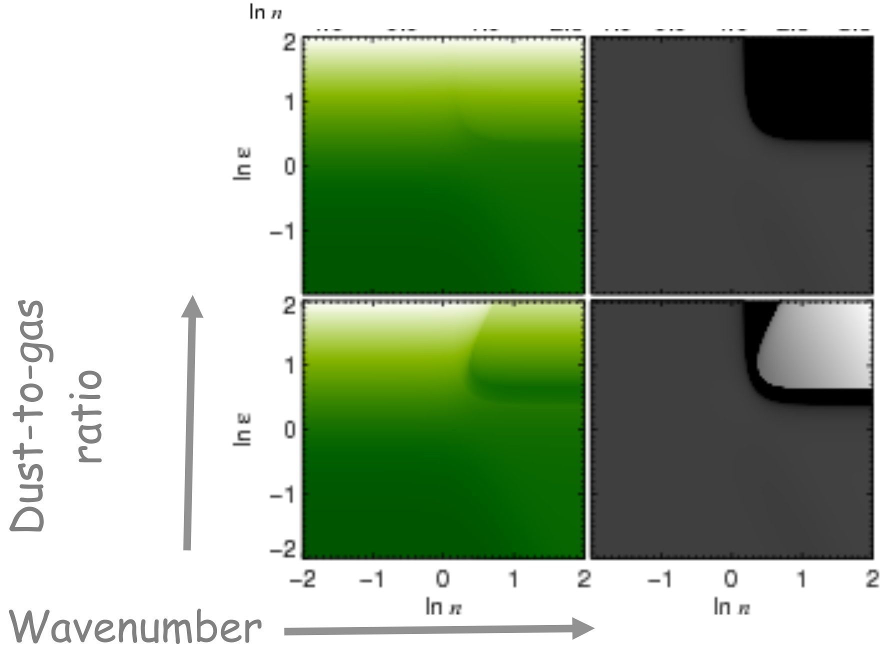
Damped and free Oscillations

Dispersion relation

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

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

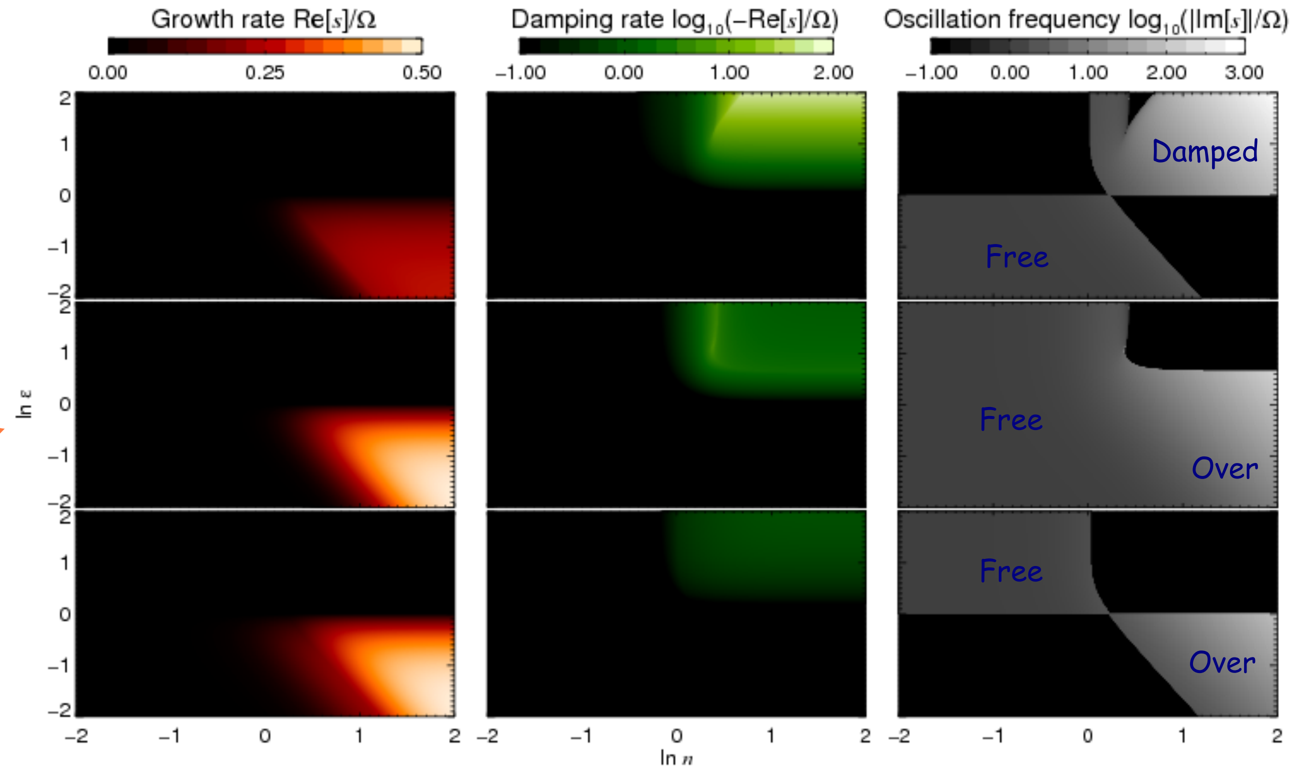
$\epsilon=\Sigma_d/\Sigma_g$ $\quad n=kH$ $\quad \omega=s/\Omega$



Solutions

Instability

Overstability



Damped and free Oscillations

Dispersion relation

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

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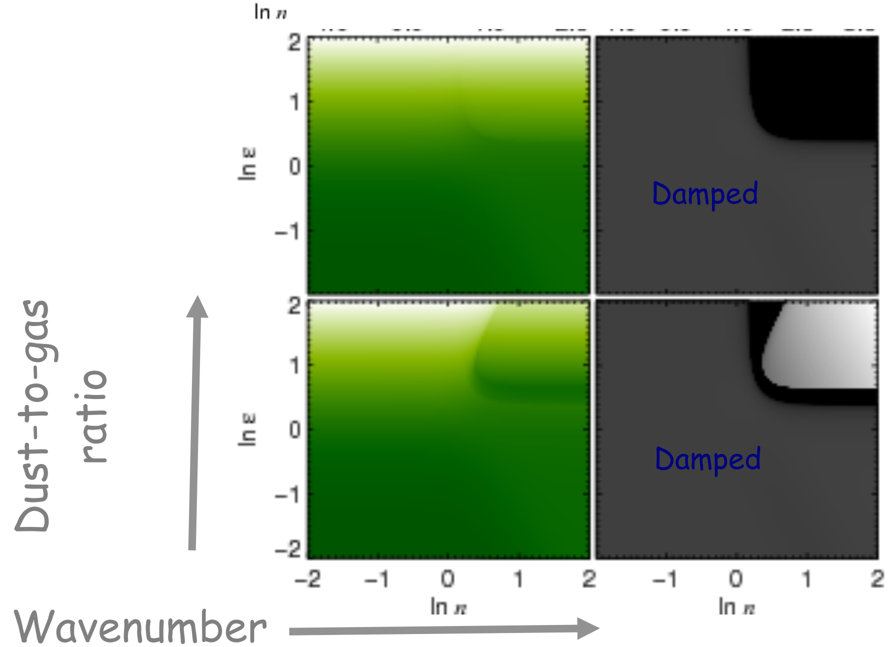
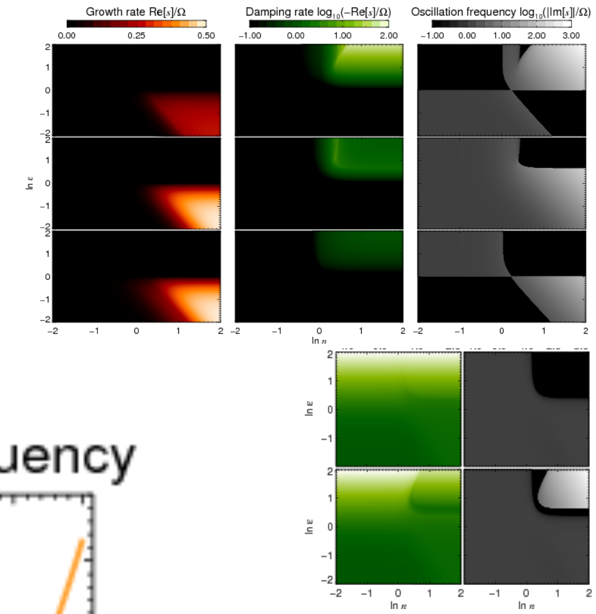
$$E = \epsilon^2(2n^2+1) + \epsilon(3n^2+2) + 2$$
$$F = \epsilon^2 n^2 - \epsilon n^2$$

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



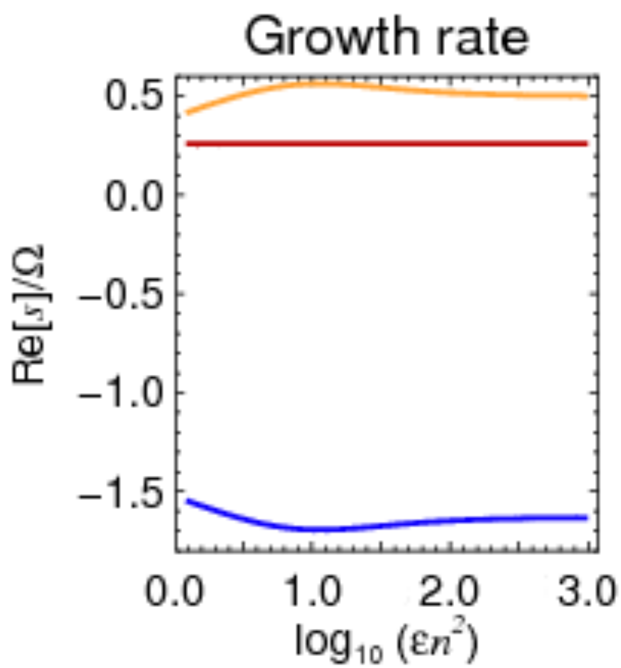
Solutions

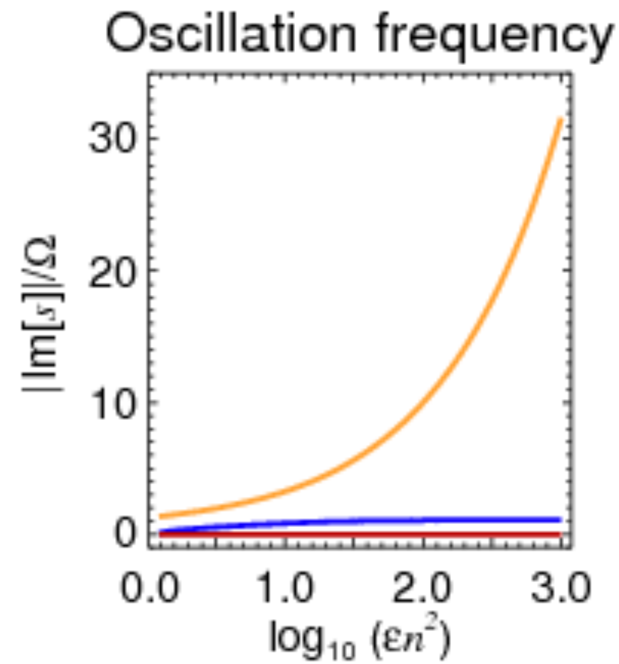


Overstability

Instability

Oscillations





Max growth rate: Omega/2.

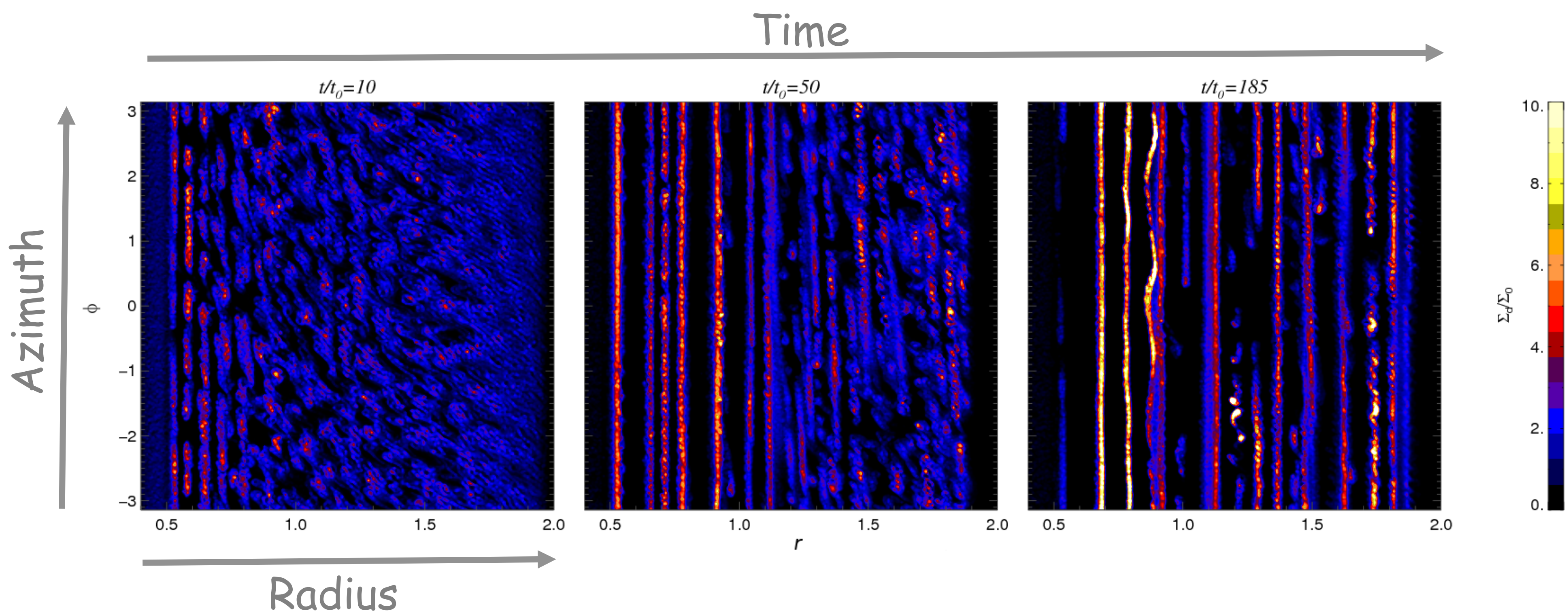
Million-fold amplification in five orbits!

A very powerful instability.

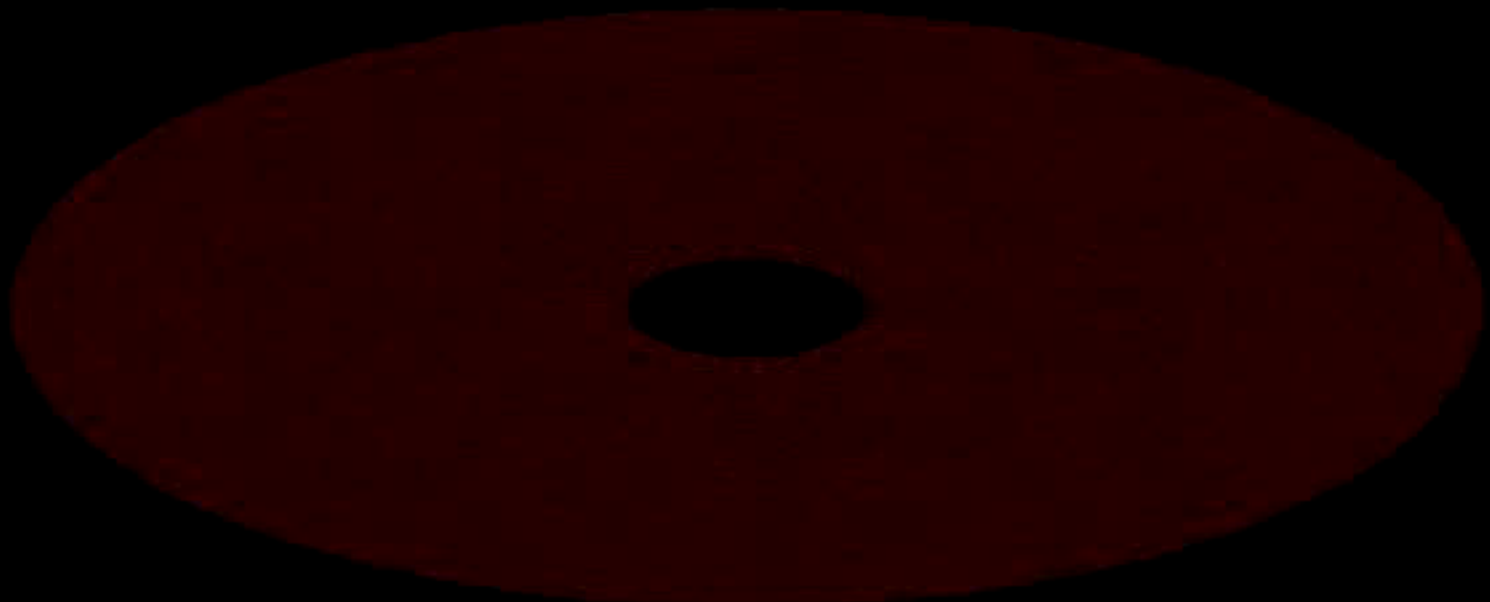
The model in 2D: Eccentric rings

Growth of axisymmetric modes
+
Damping of nonaxissymetric modes.

= ***Rings !!!***

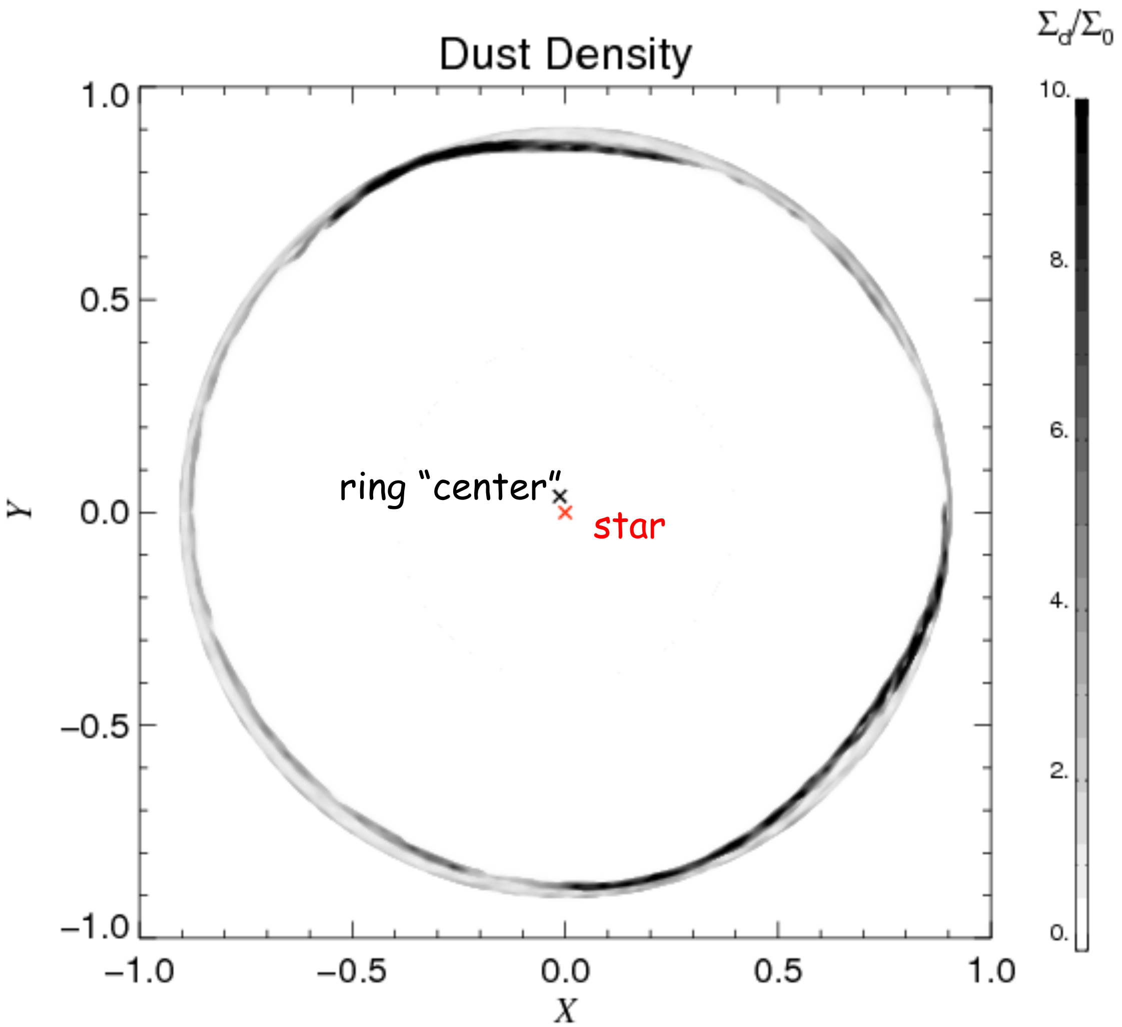


Epicyclic oscillations
make the ring appear ***eccentric !!!***



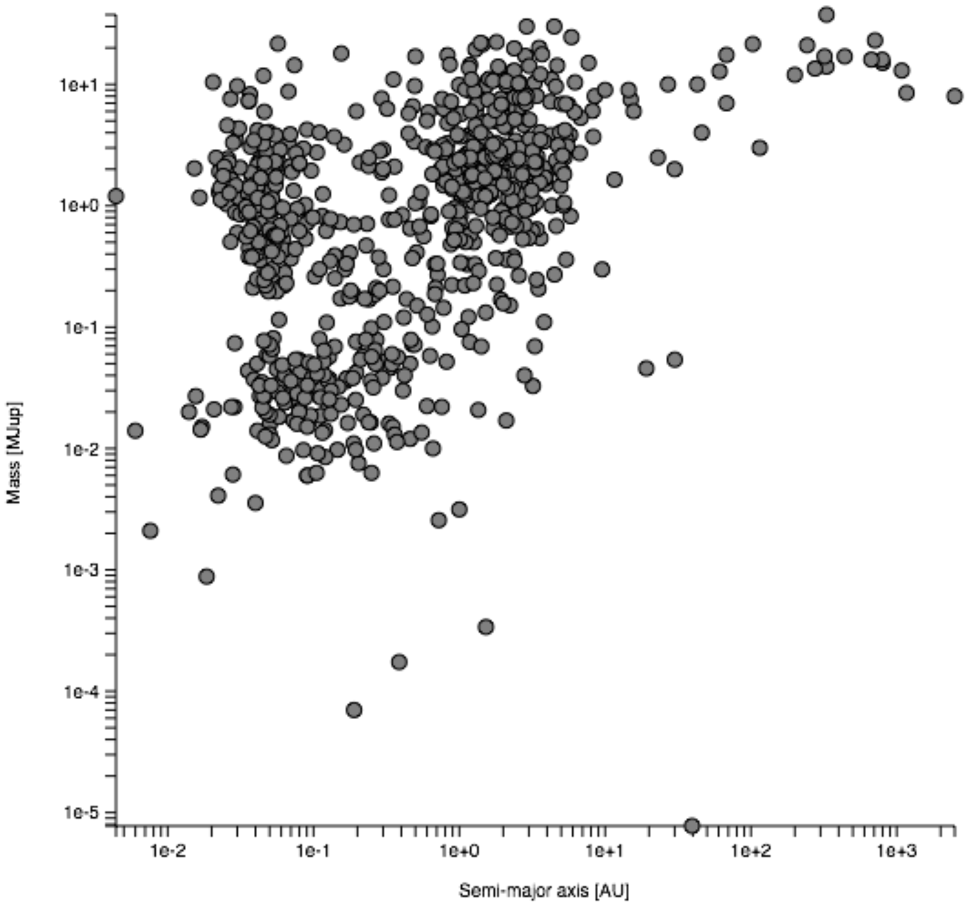
Lyra & Kuchner (2013, Nature, in review)

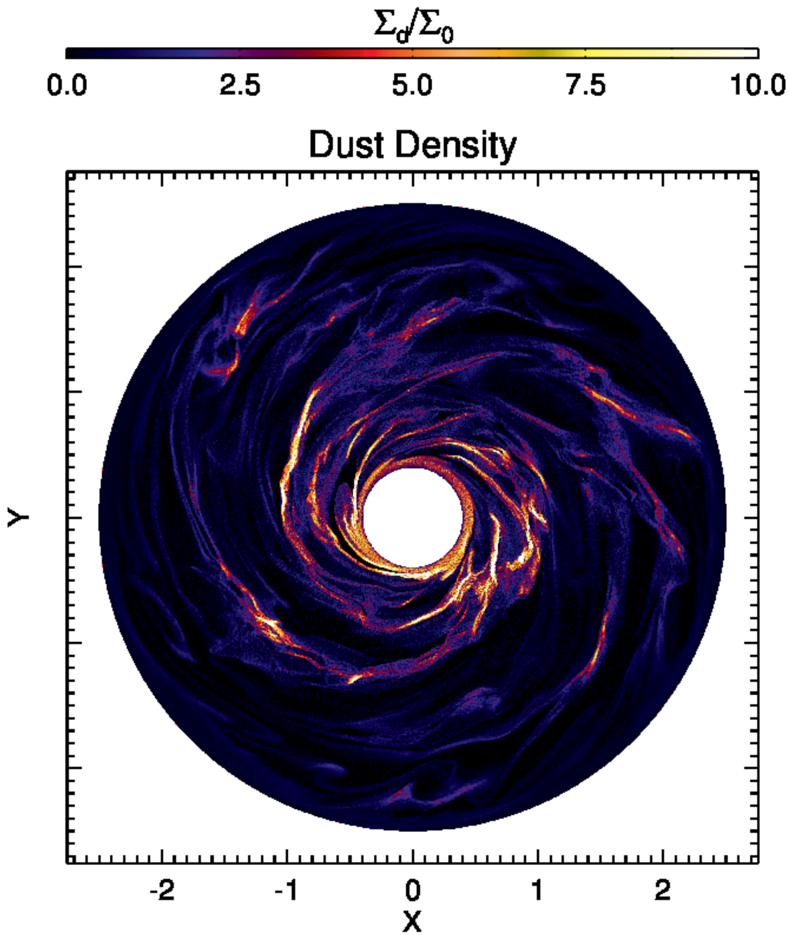
Ring eccentricity



Eccentricity e=0.04

Streaming instability in global models



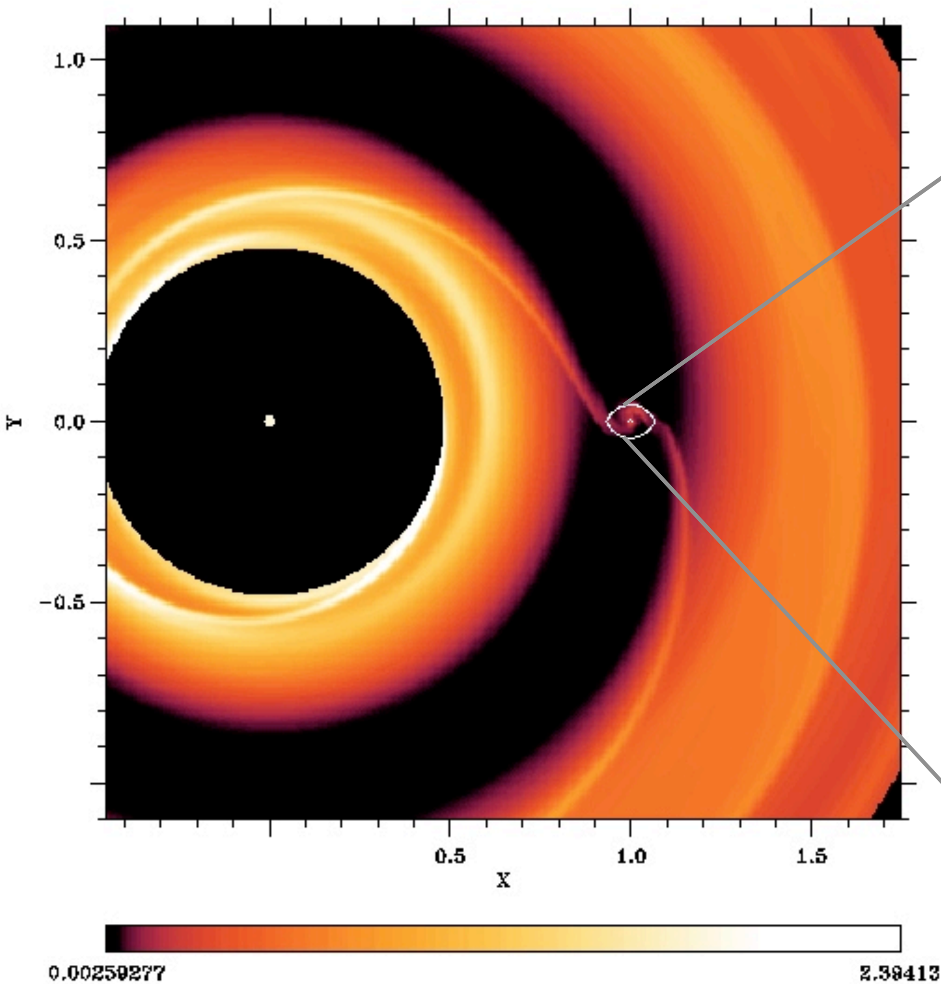


Lyra & Turner (2013, in prep)

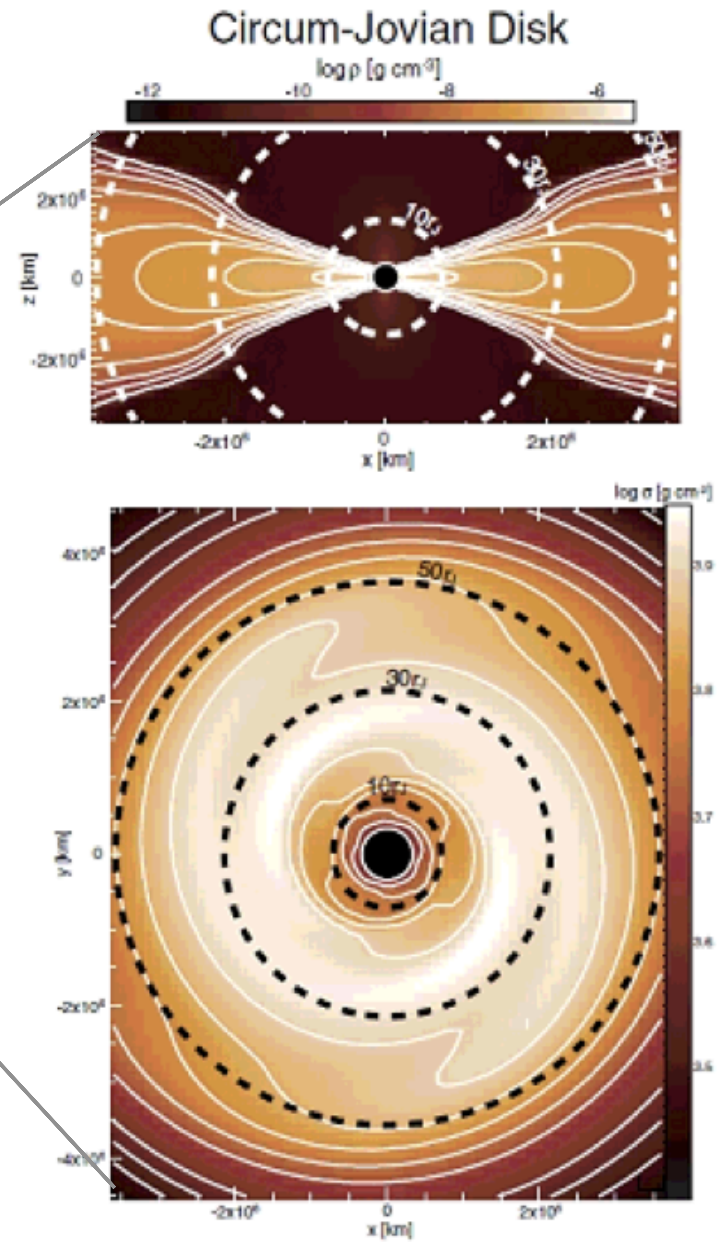
What is the mass spectrum?

Is there a strong mass-distance relationship?

Formation of Satellites



Credit: Pawel Artymowicz



Machida (2008)

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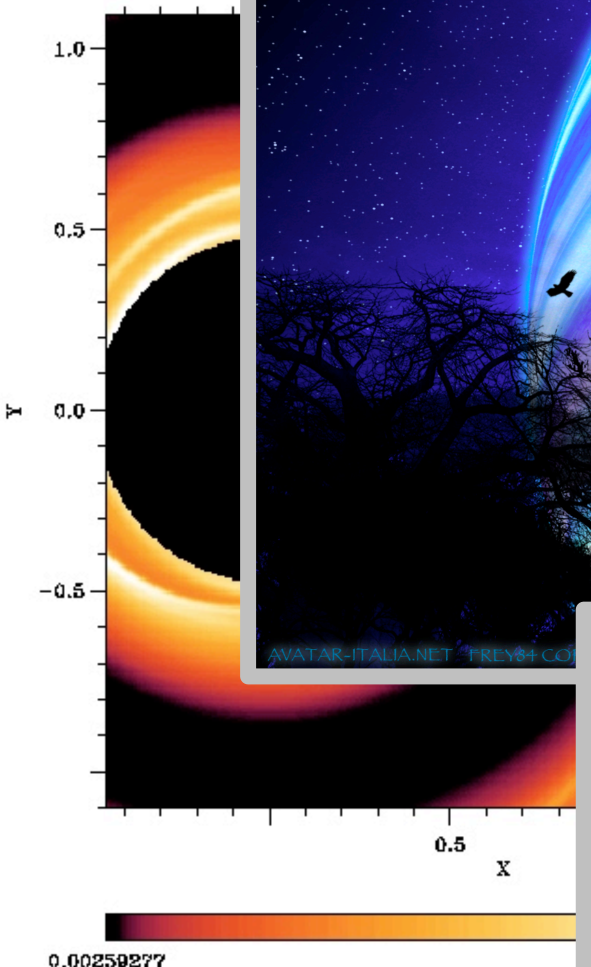
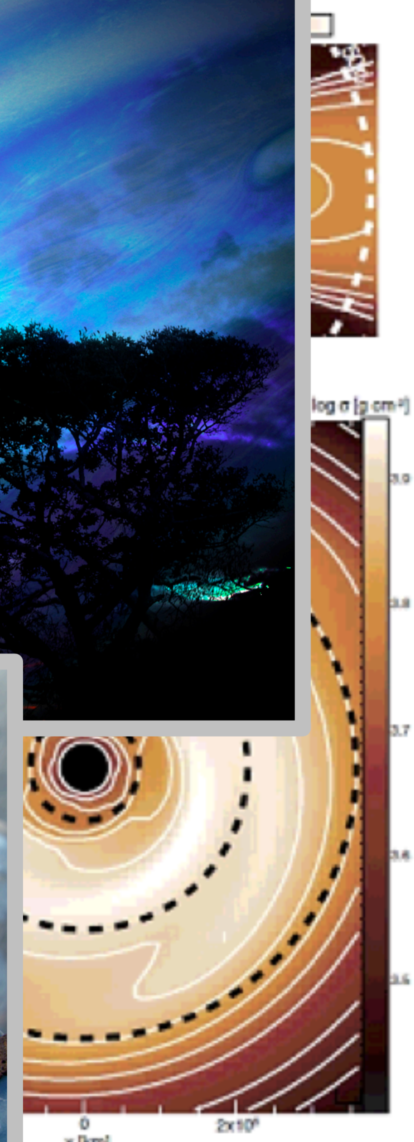
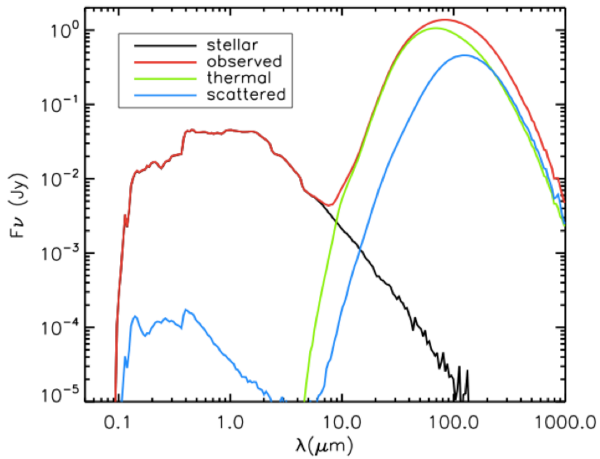


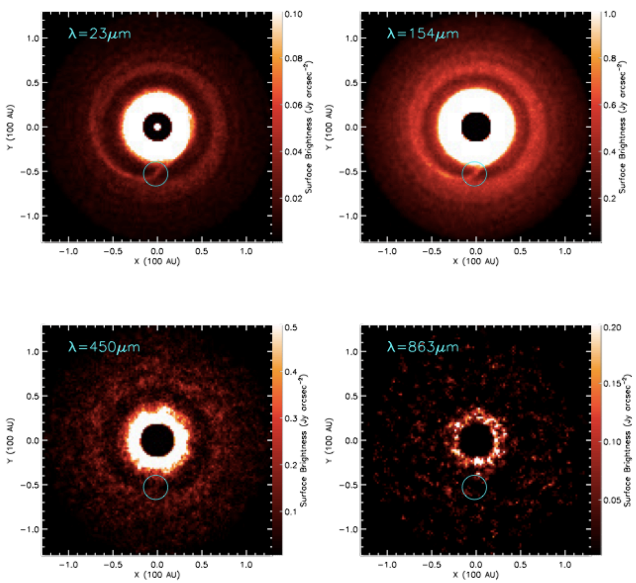


Credit: Pawel Ar

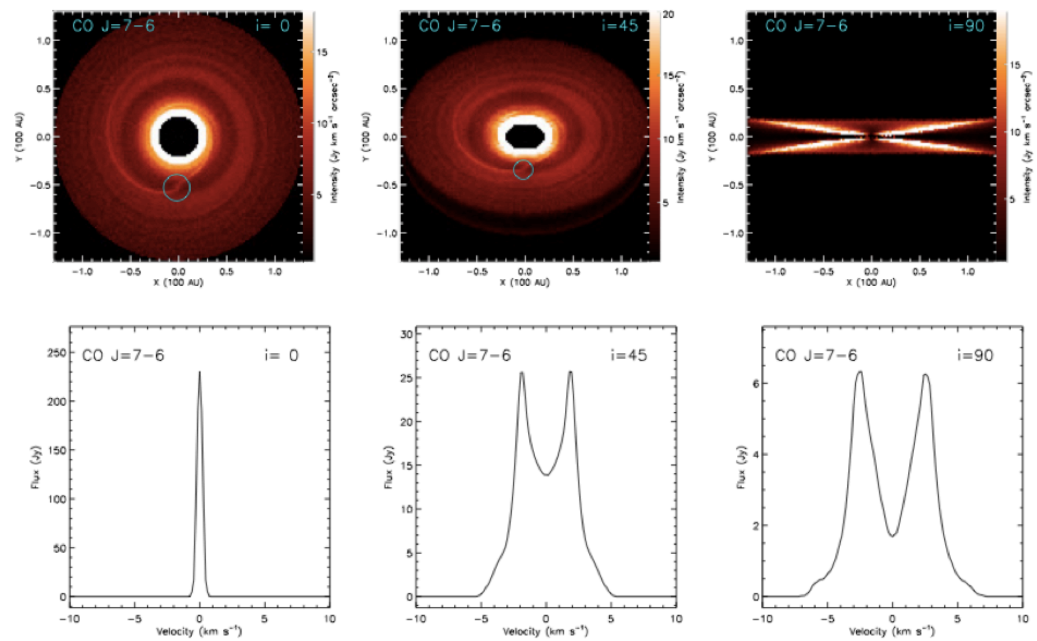
Machida (2008)

Combine full disk hydro models with Radiative Transfer for comparison with observations





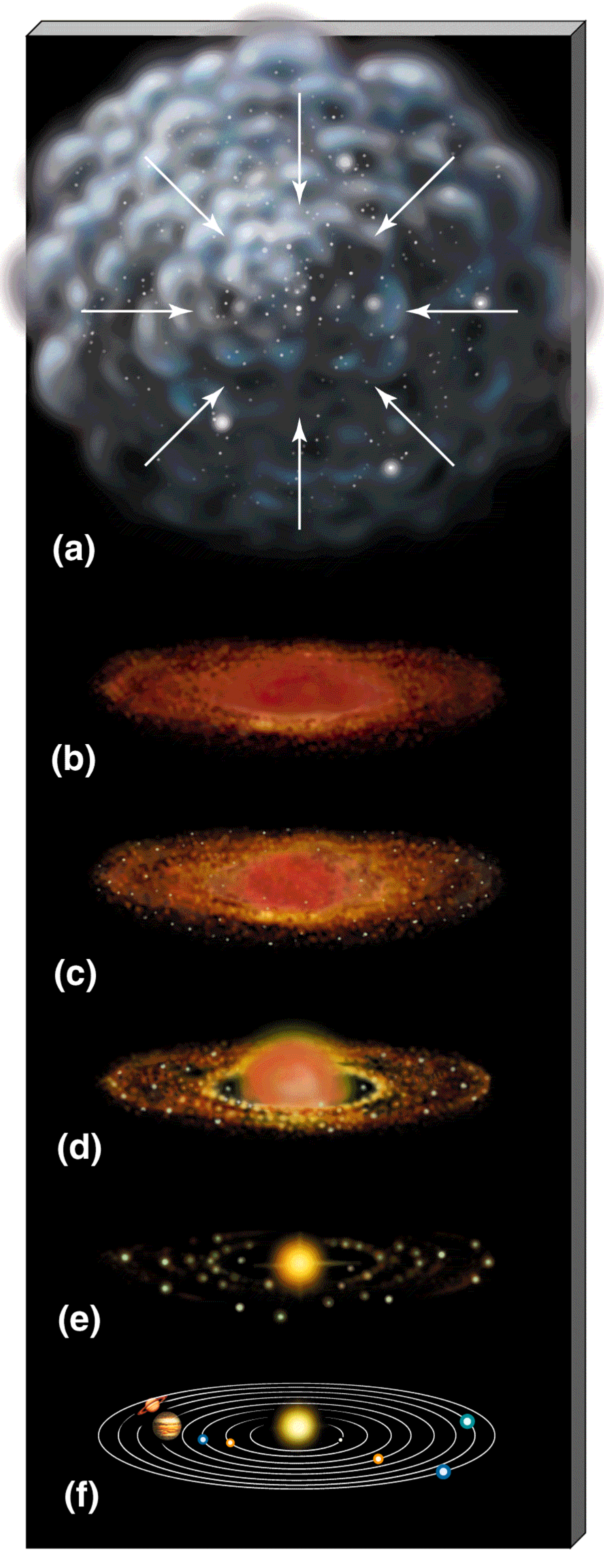
Simulated observations in far-IR and mm



Rovibrational lines of CO

(very) Preliminary results

Alex Richert (grad student, Penn State),
Yuexing Li (Penn State)



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.

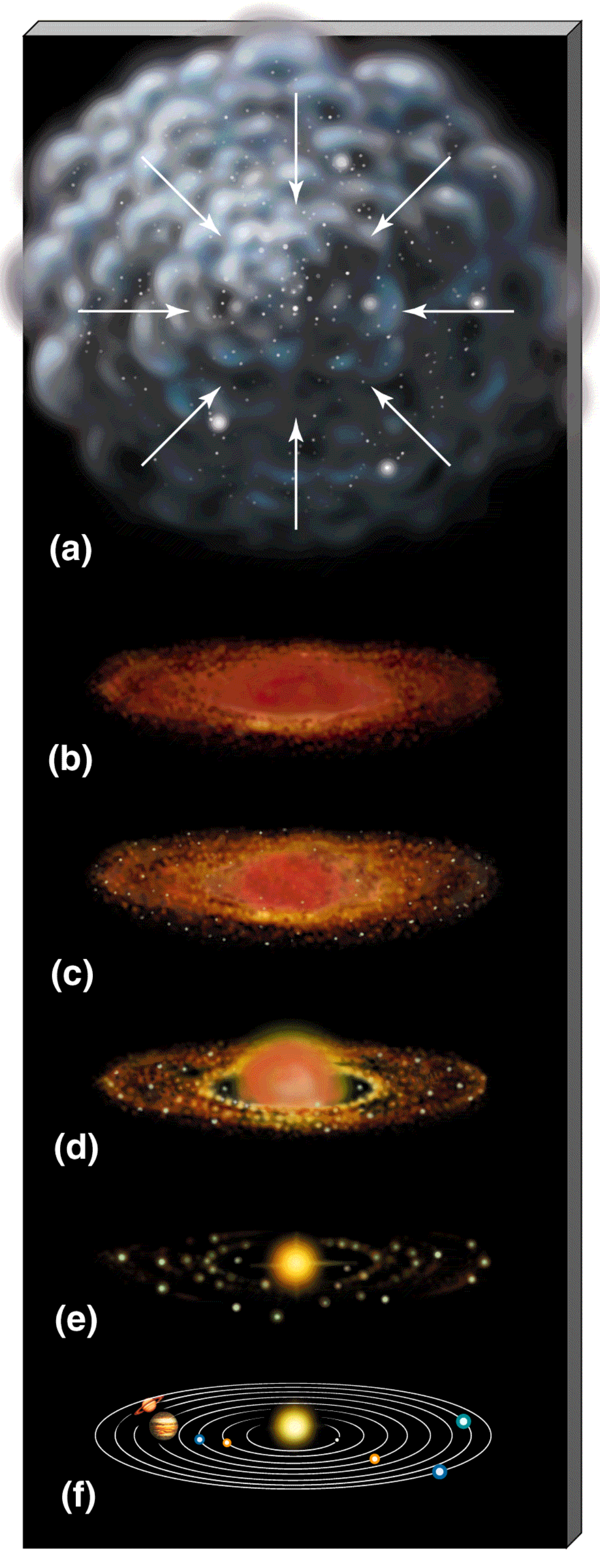
Convergent migration leads to resonances, these are disrupted by turbulent forcing. Collisions between embryos gives rise to oligarchs.

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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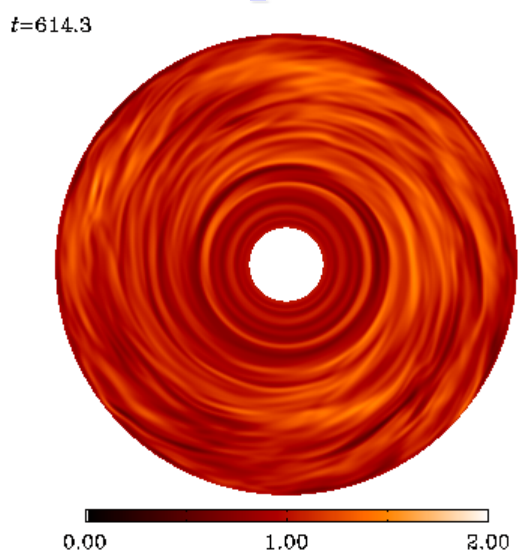
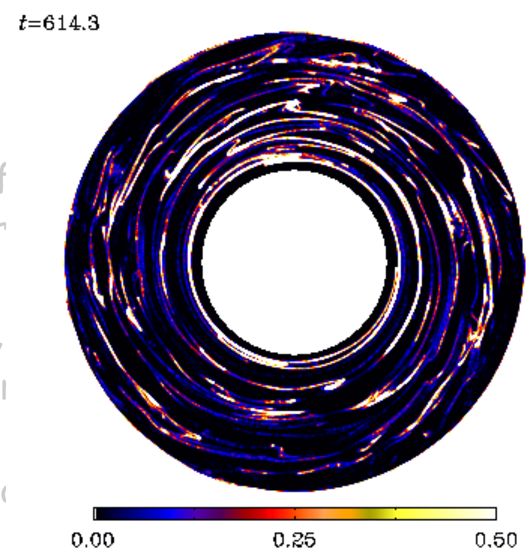


Solids



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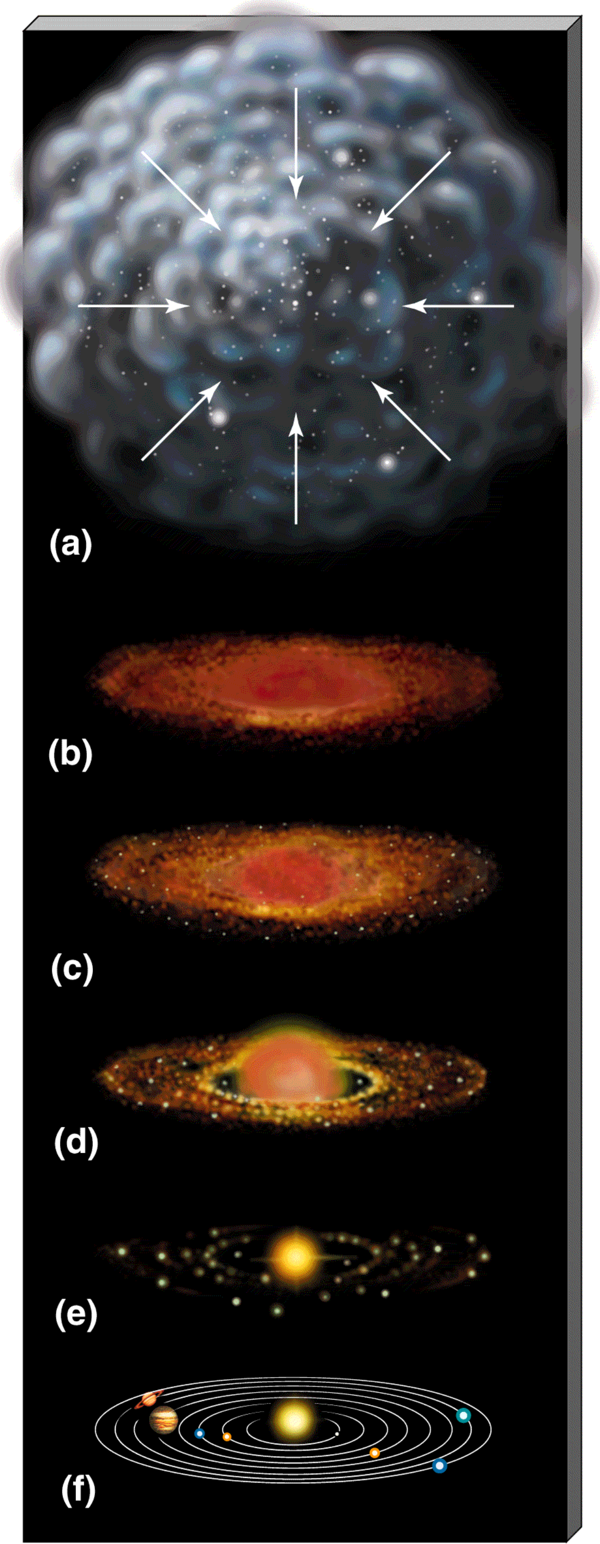

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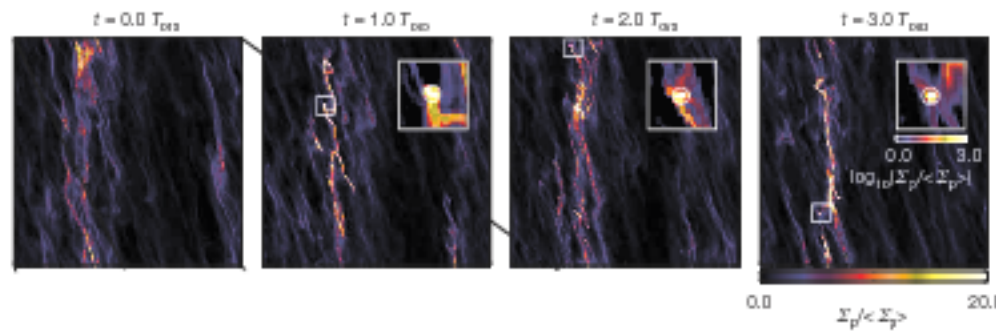

Convergent migr
forcing. Collision

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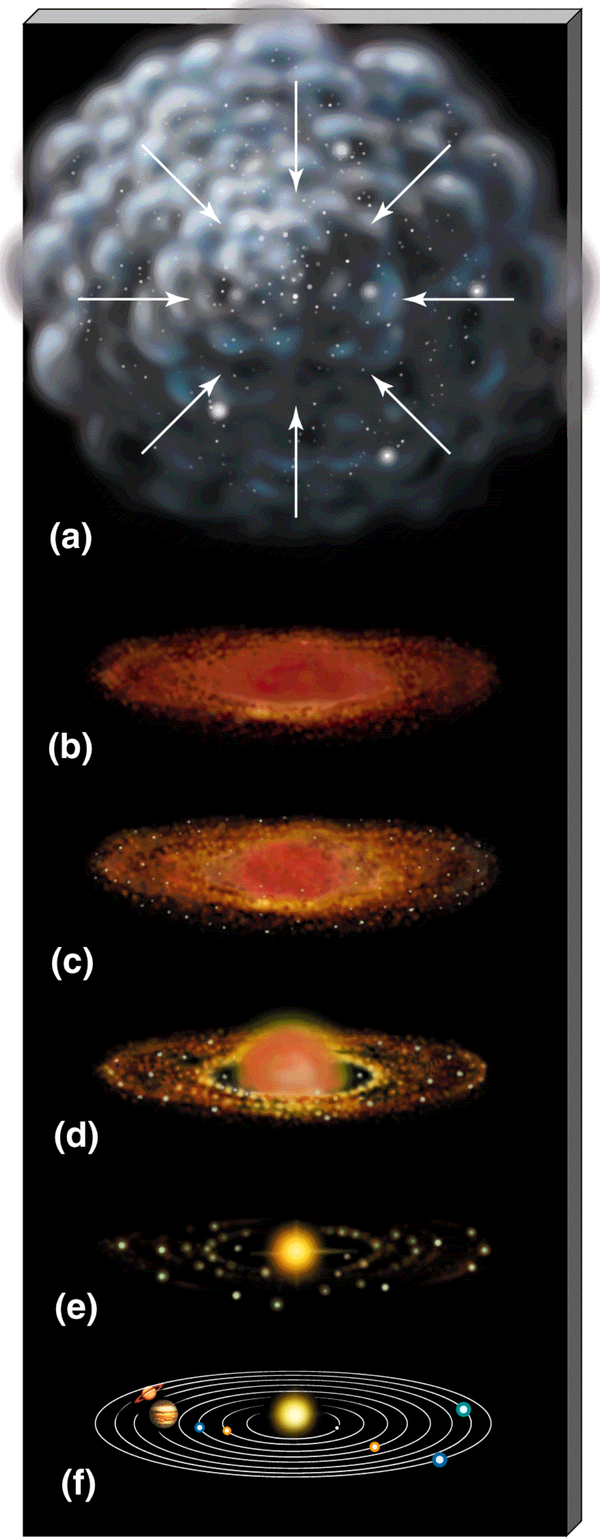

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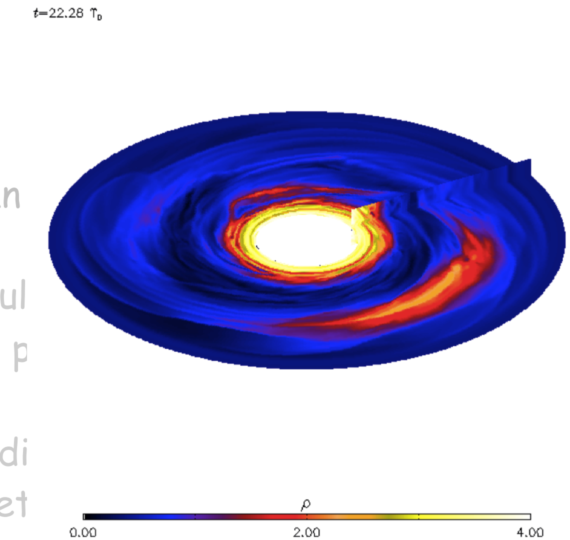

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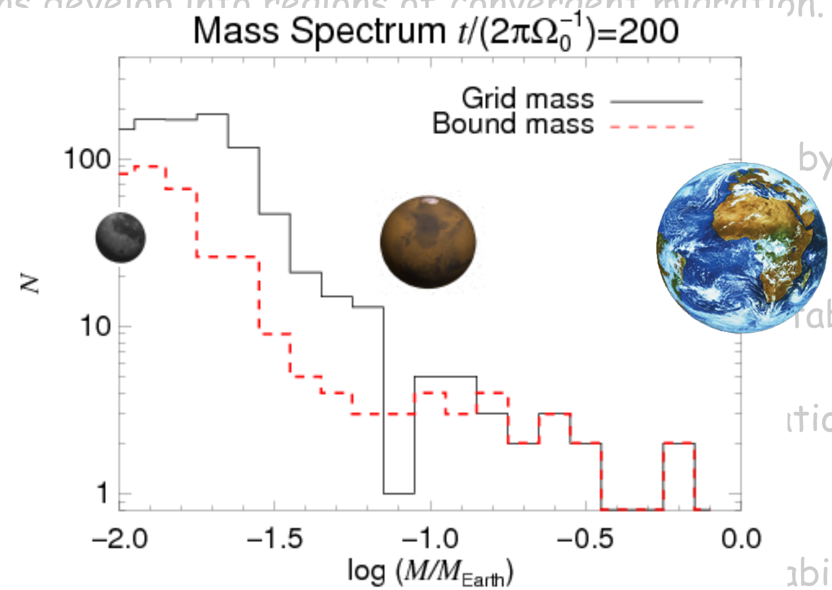

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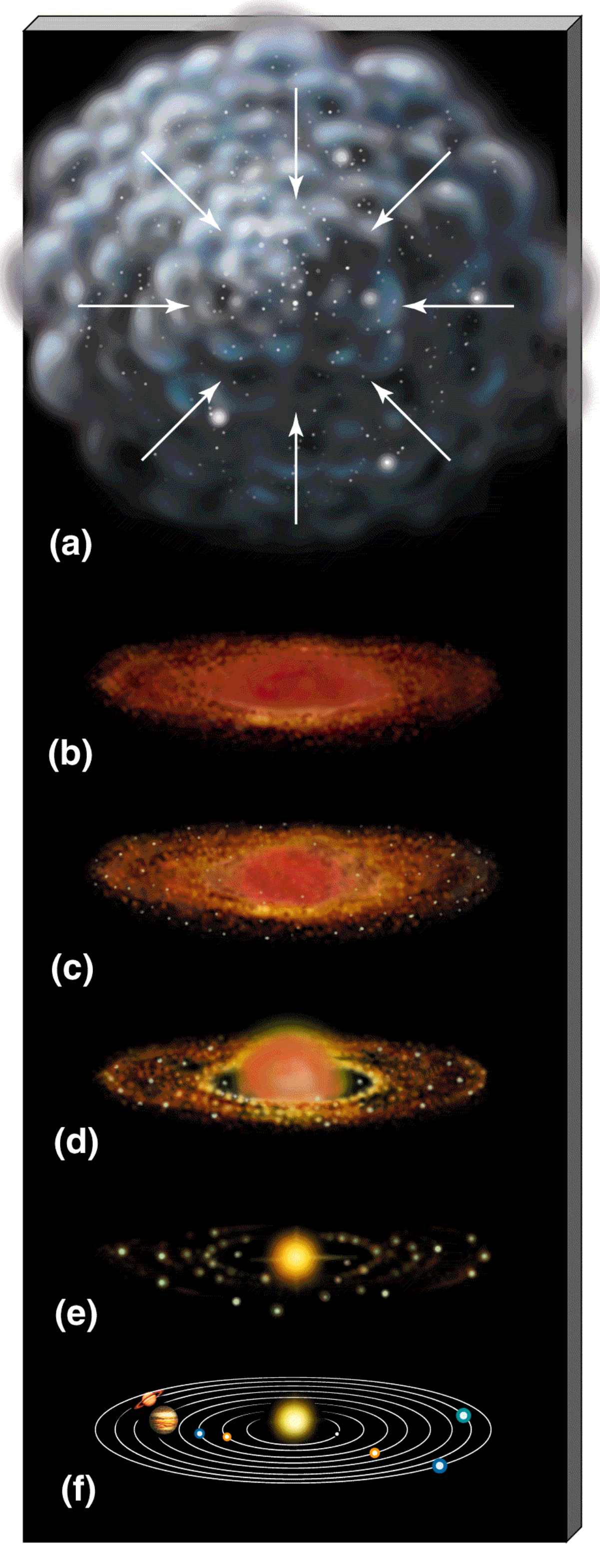

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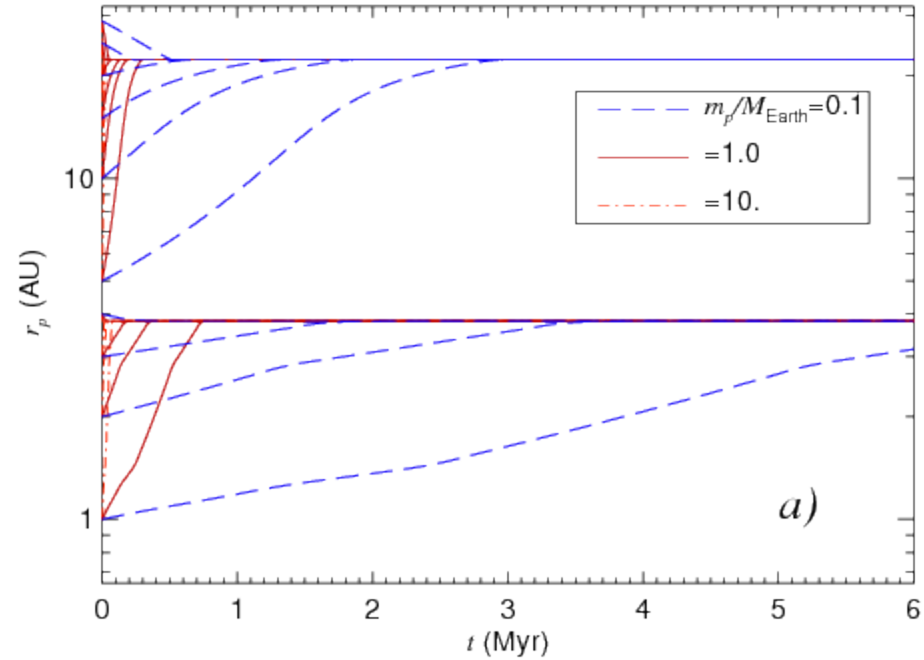

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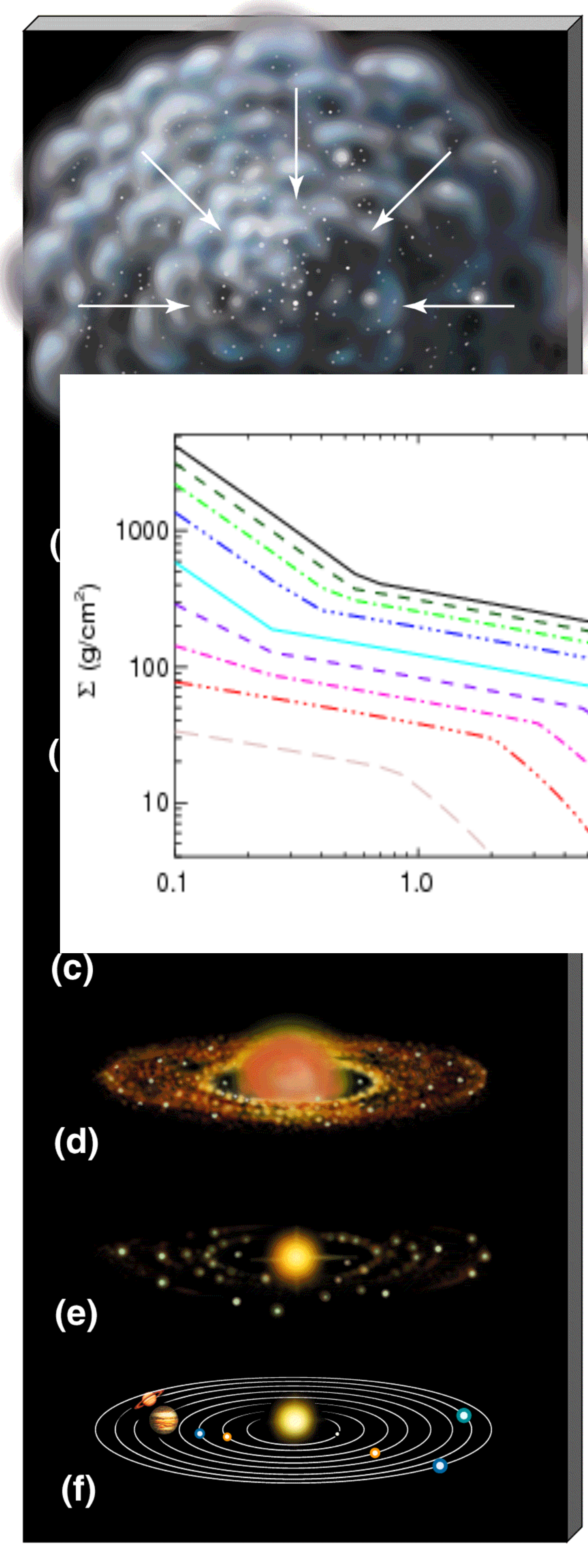

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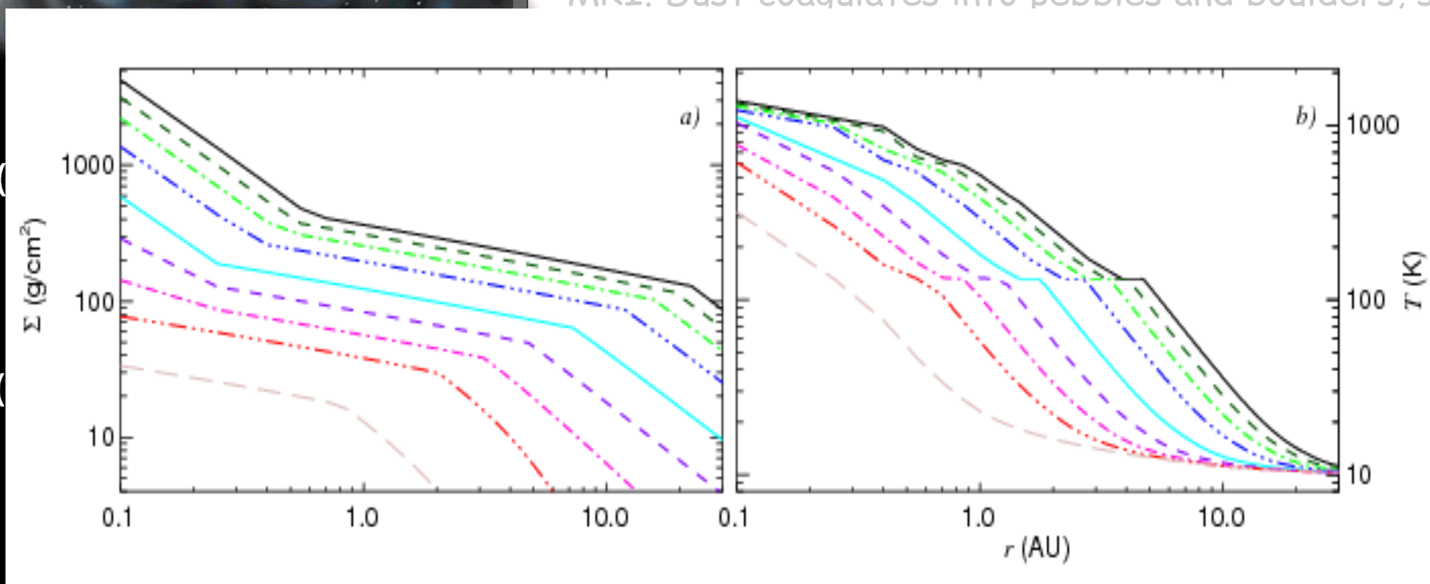

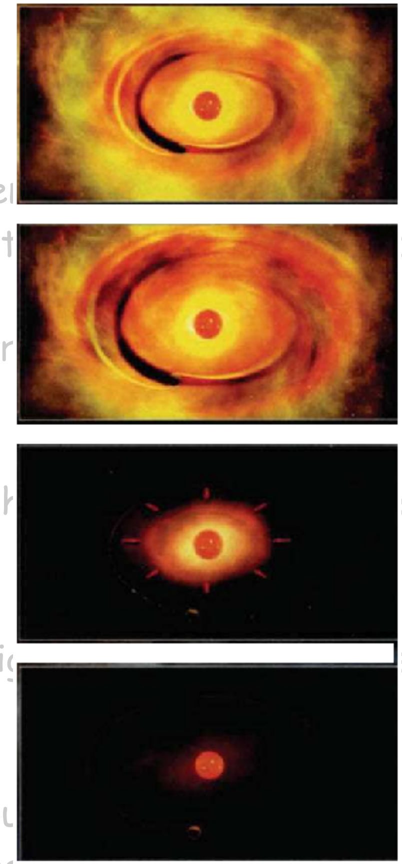

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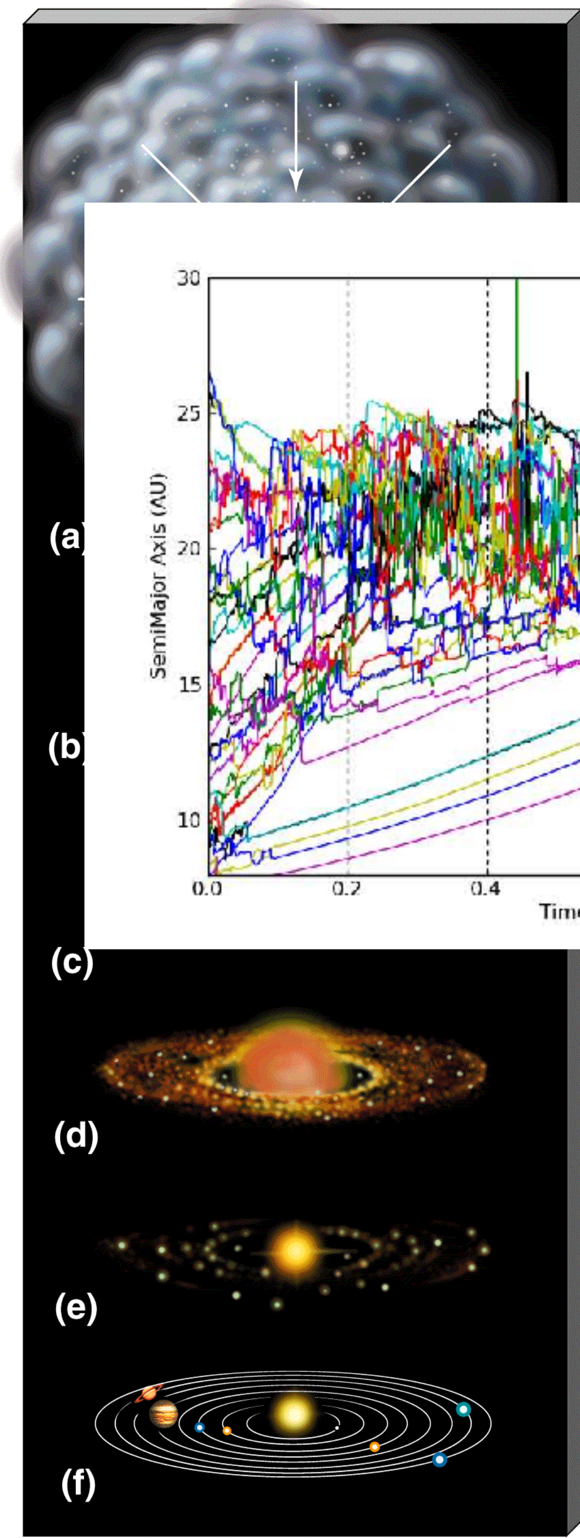

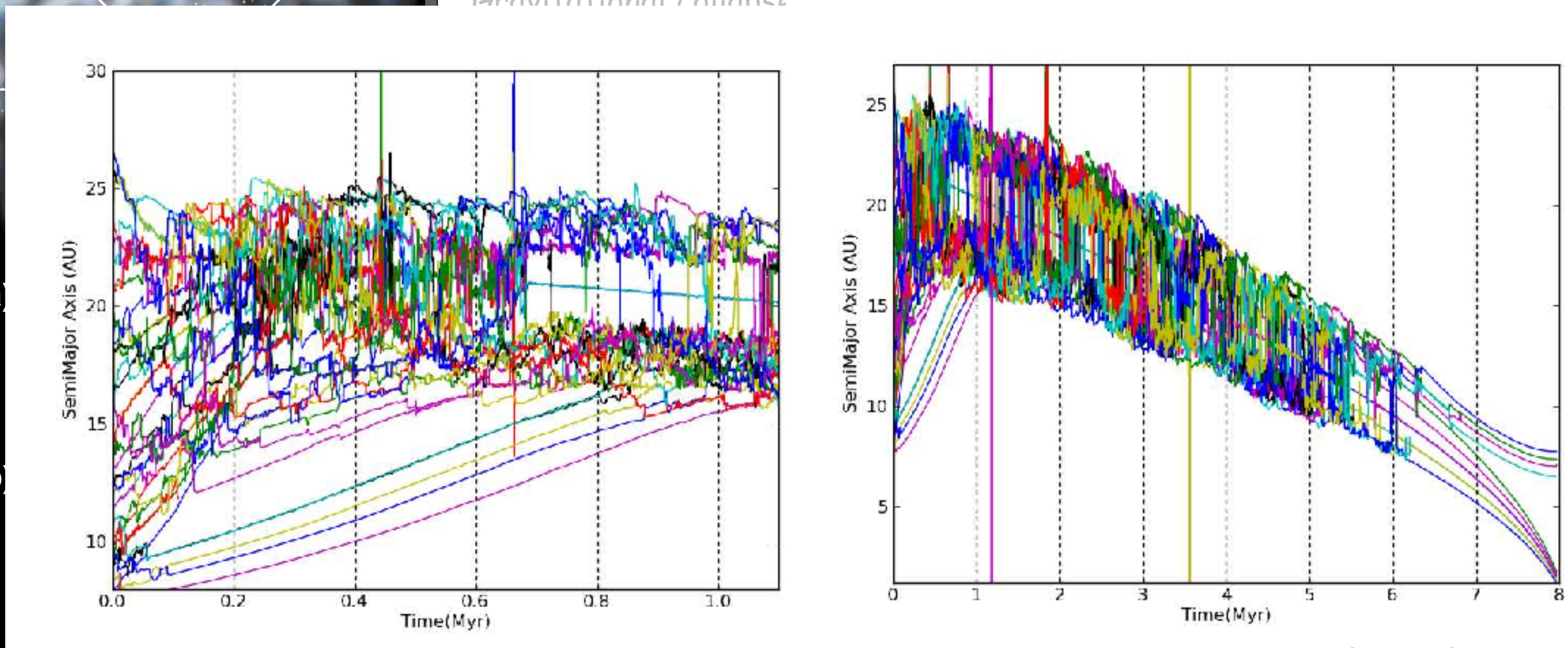

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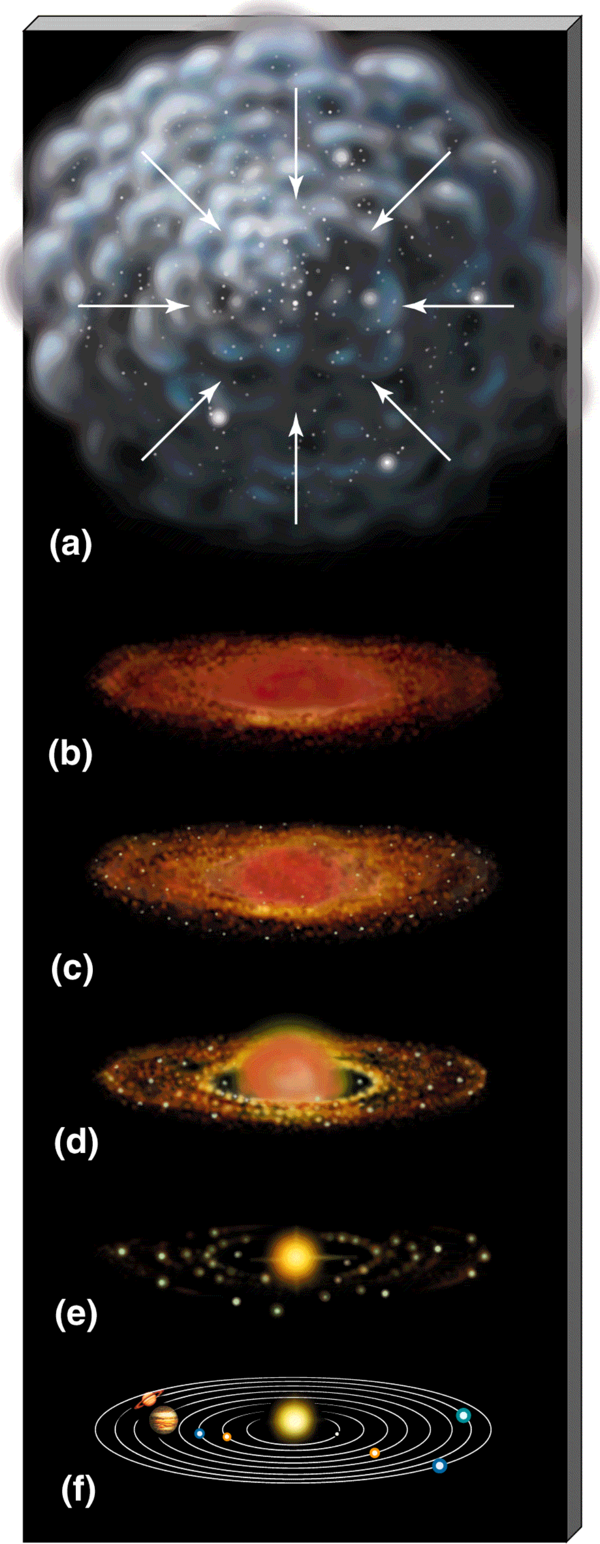

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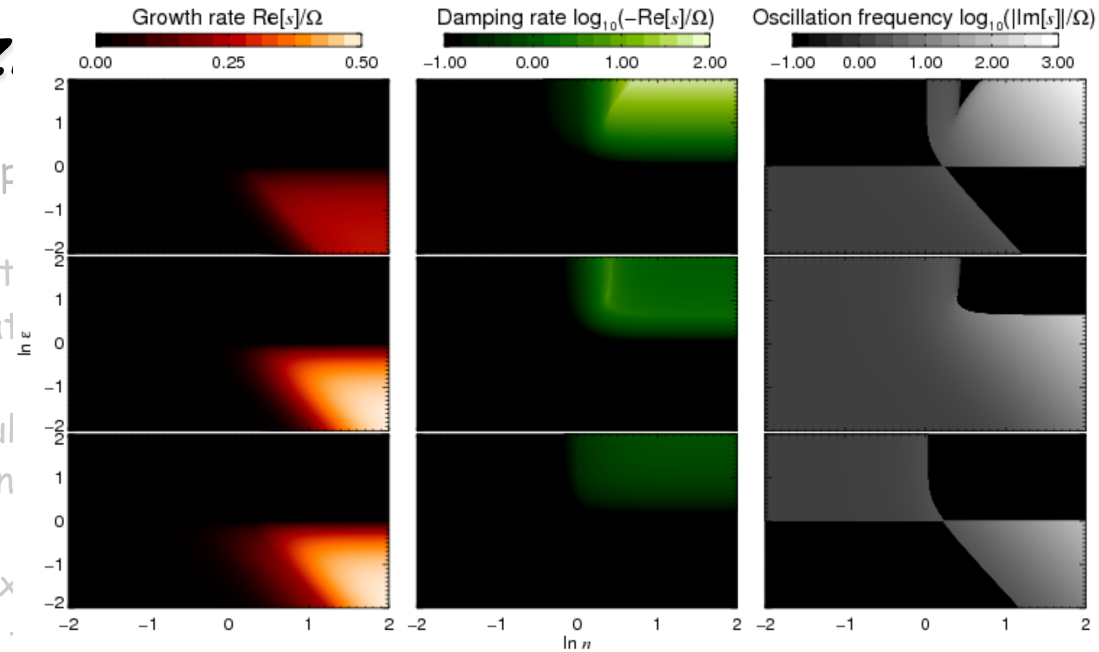


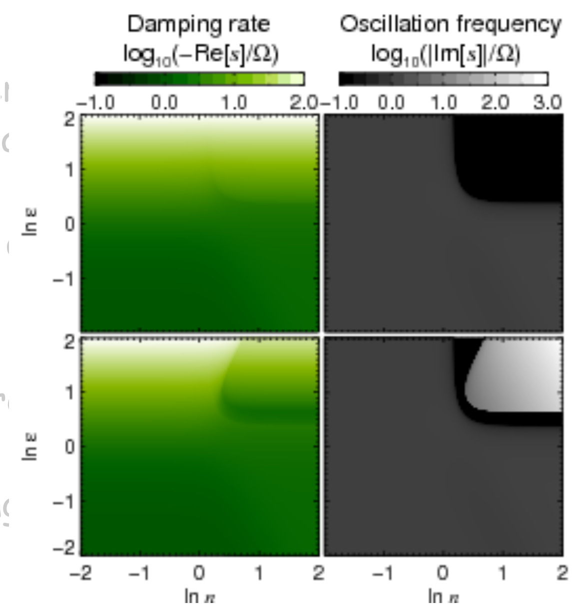
Gravitational collap

Outward transport
MRI. Dust coagulat

Rocks in the turbul
undergo collapse in

Vortices may be ex
mass embryos are

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



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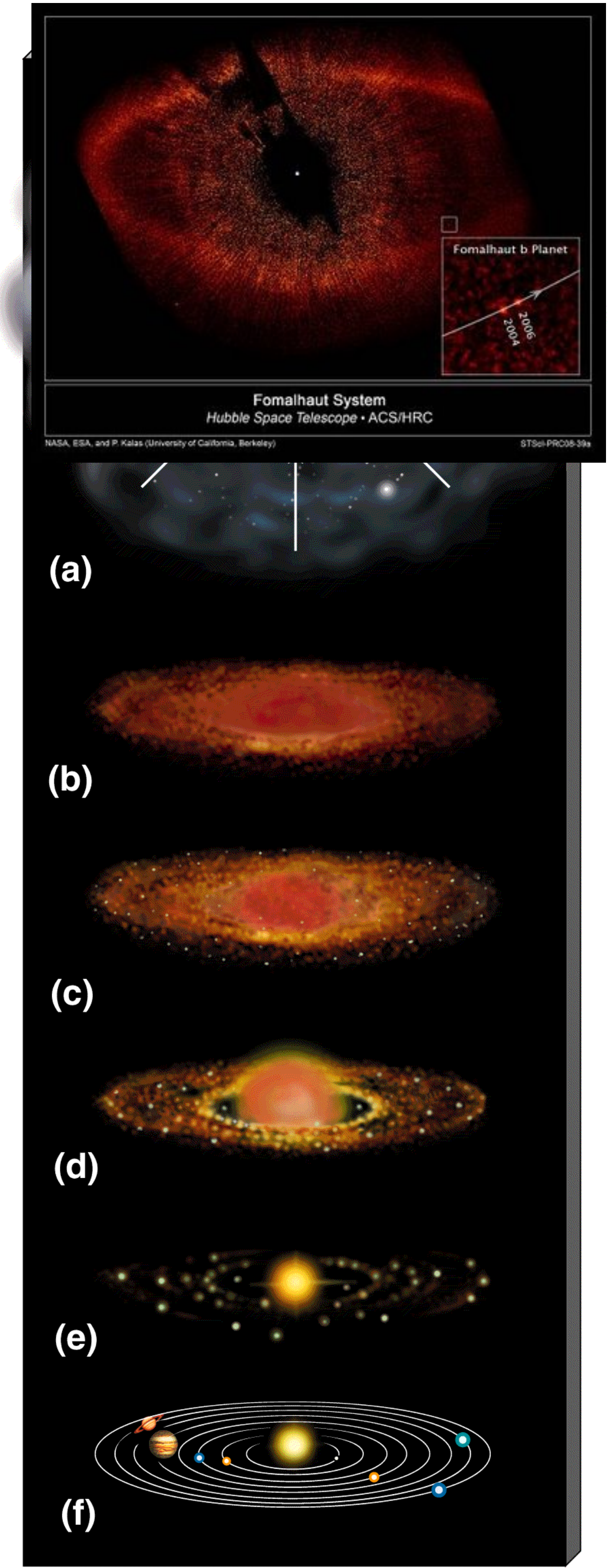

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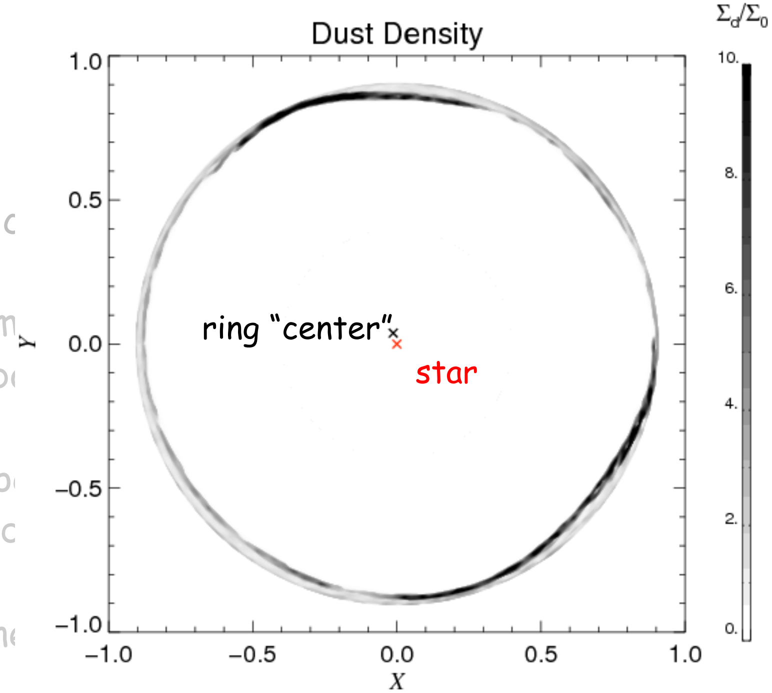

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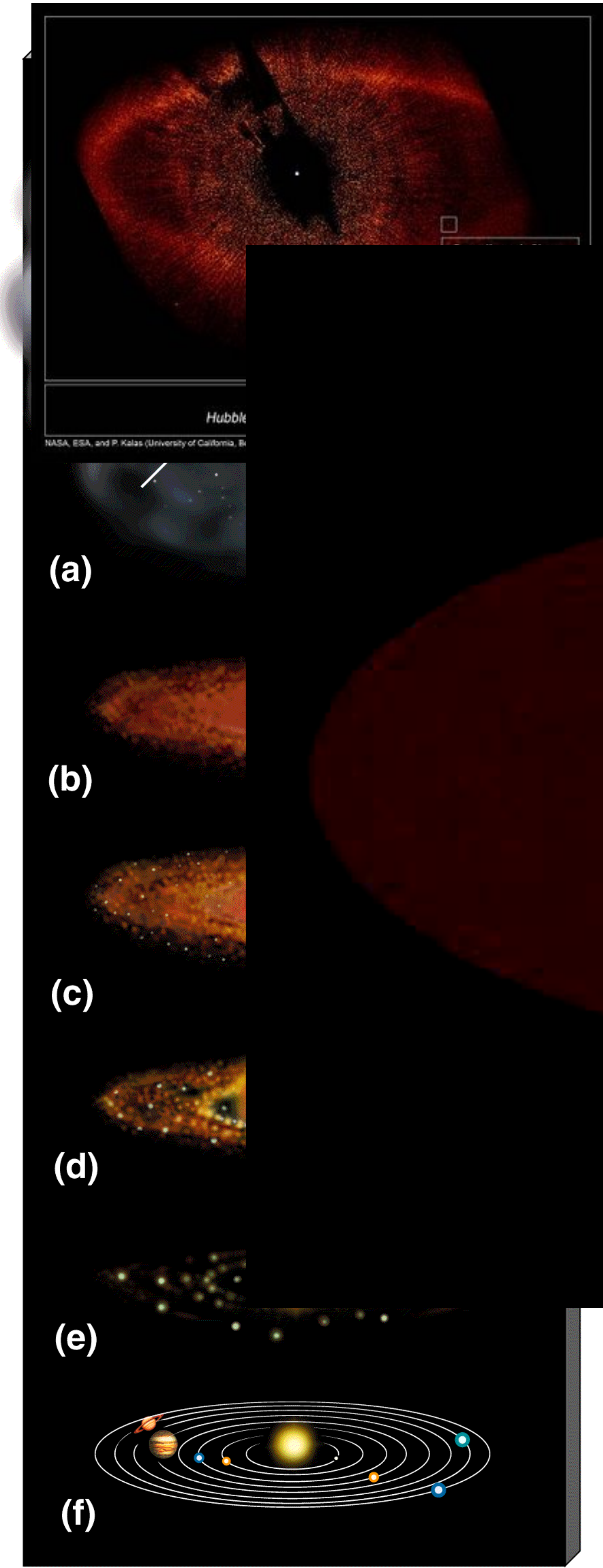

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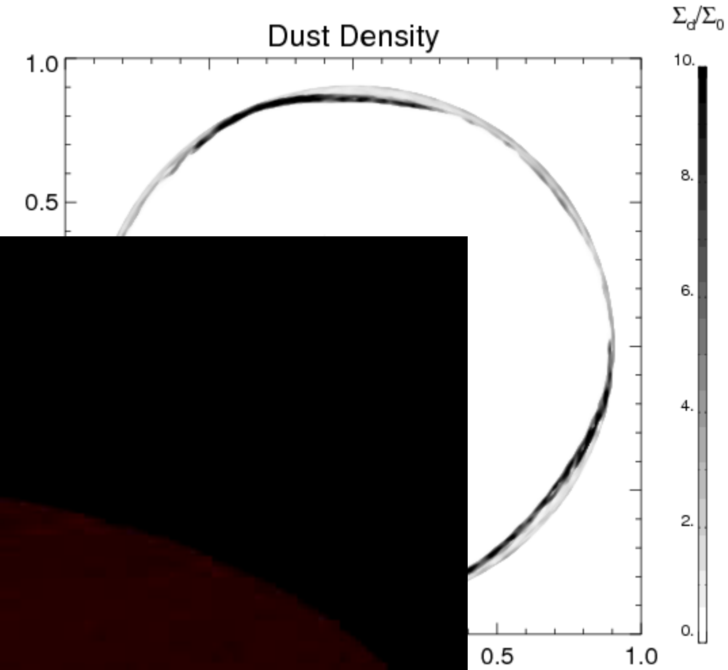

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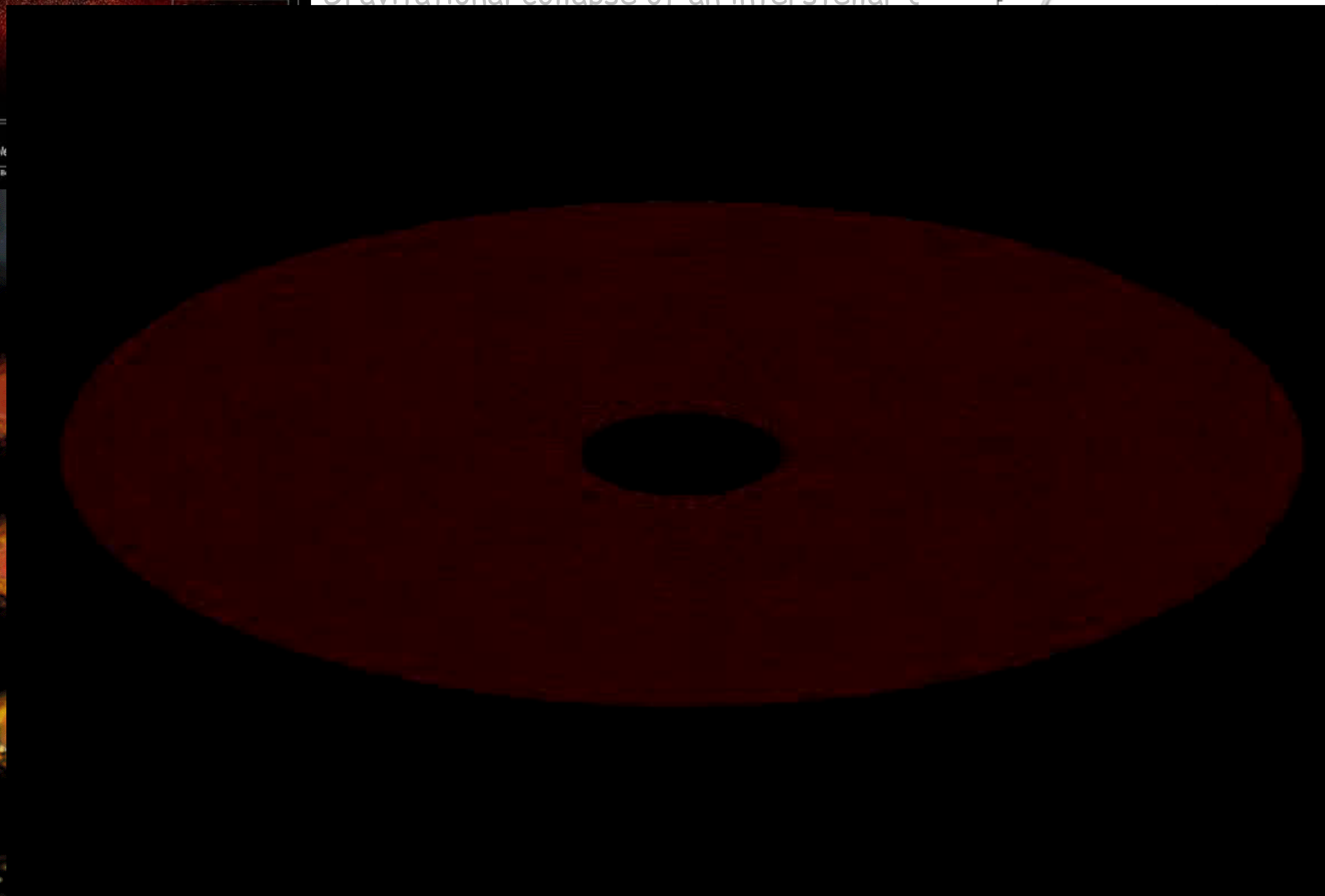

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