Evolution of Circumstellar Disks and Planet Formation

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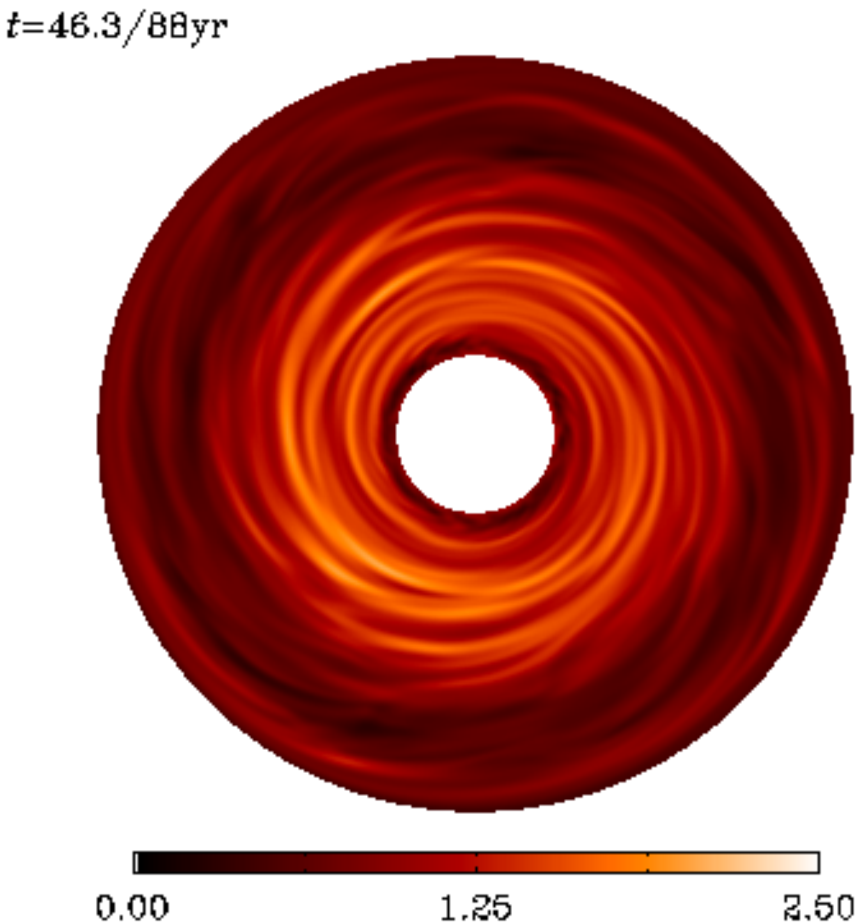
Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by
the Magneto-Rotational Instability

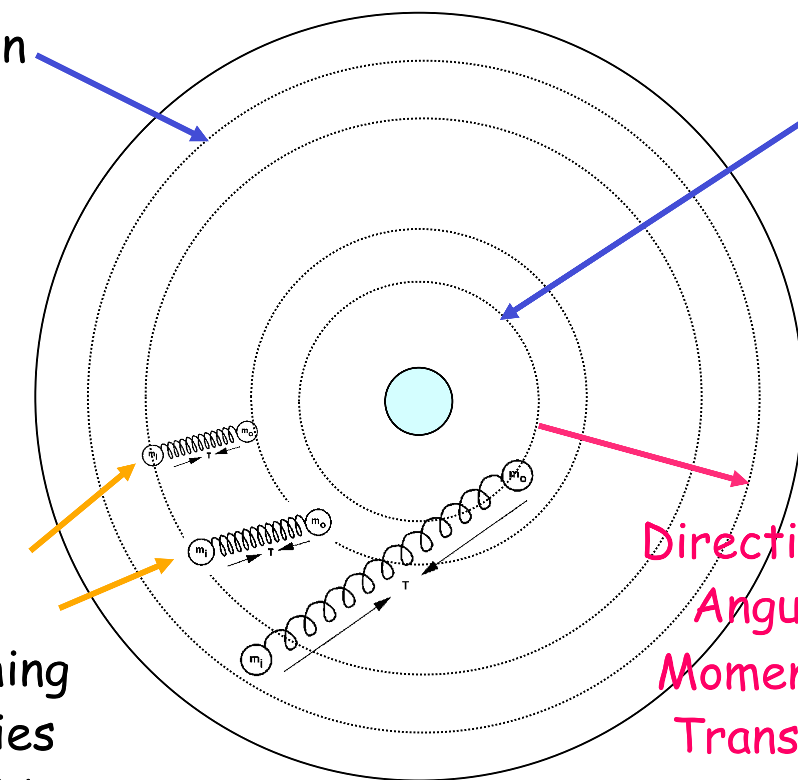


Magnetized disk
Lyra et al. (2008a)

MRI sketch

Slower Rotation

Faster Rotation

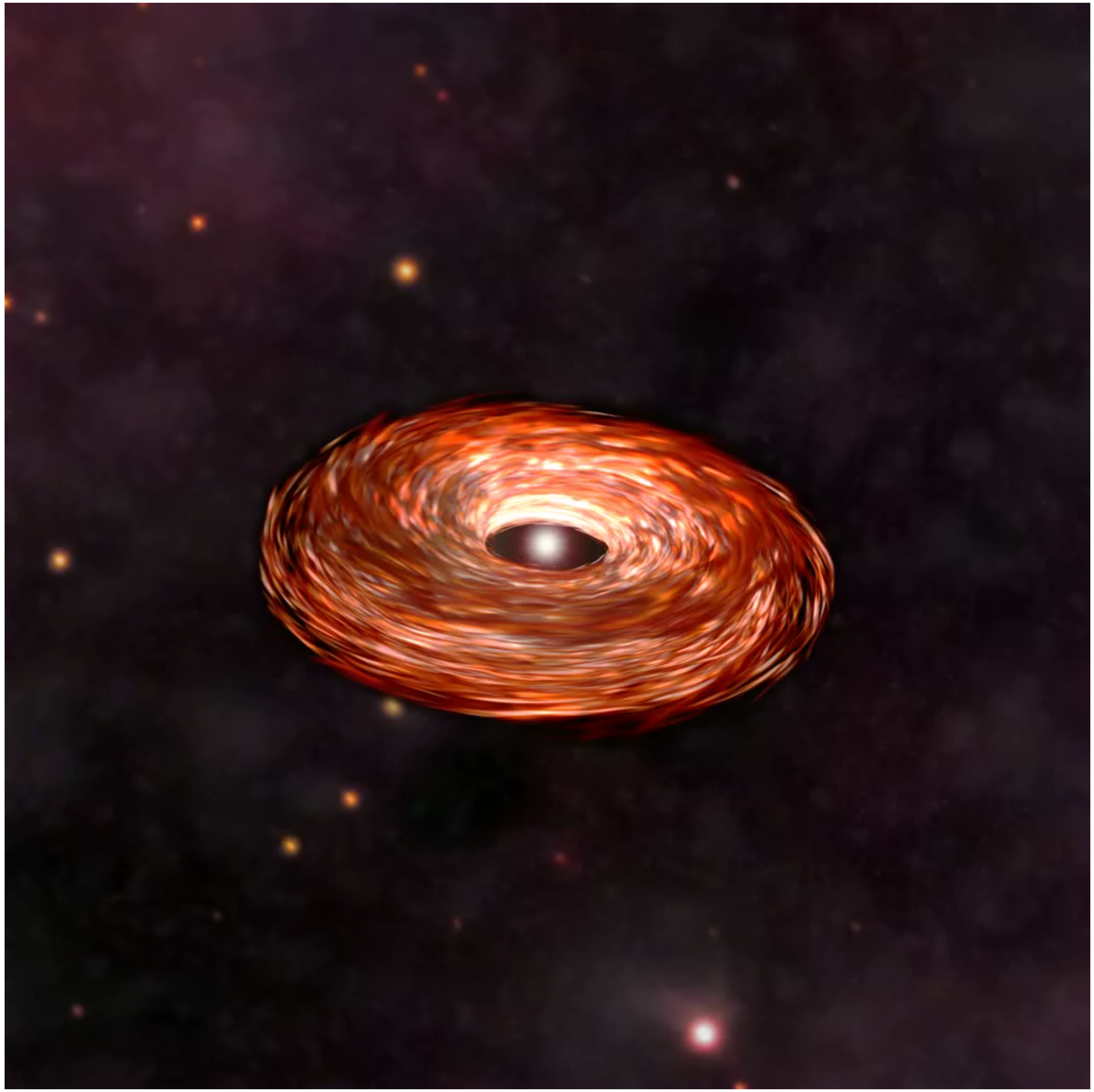


Stretching amplifies B-field

Direction of Angular Momentum Transport

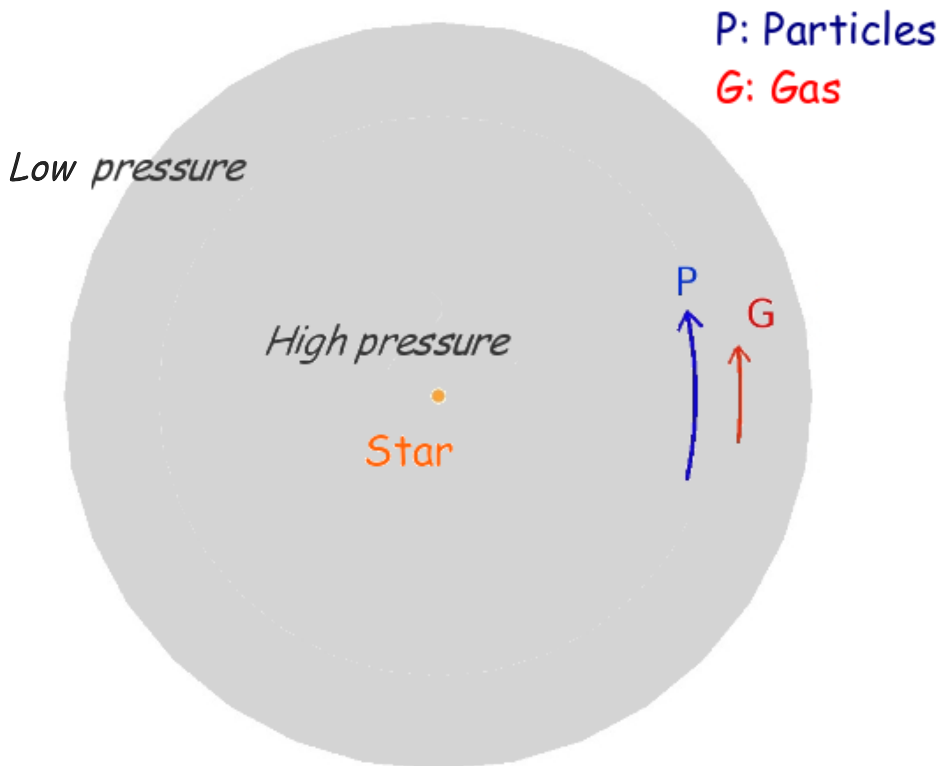
Unstable if angular velocity decreases outward

Magneto-Rotational Instability

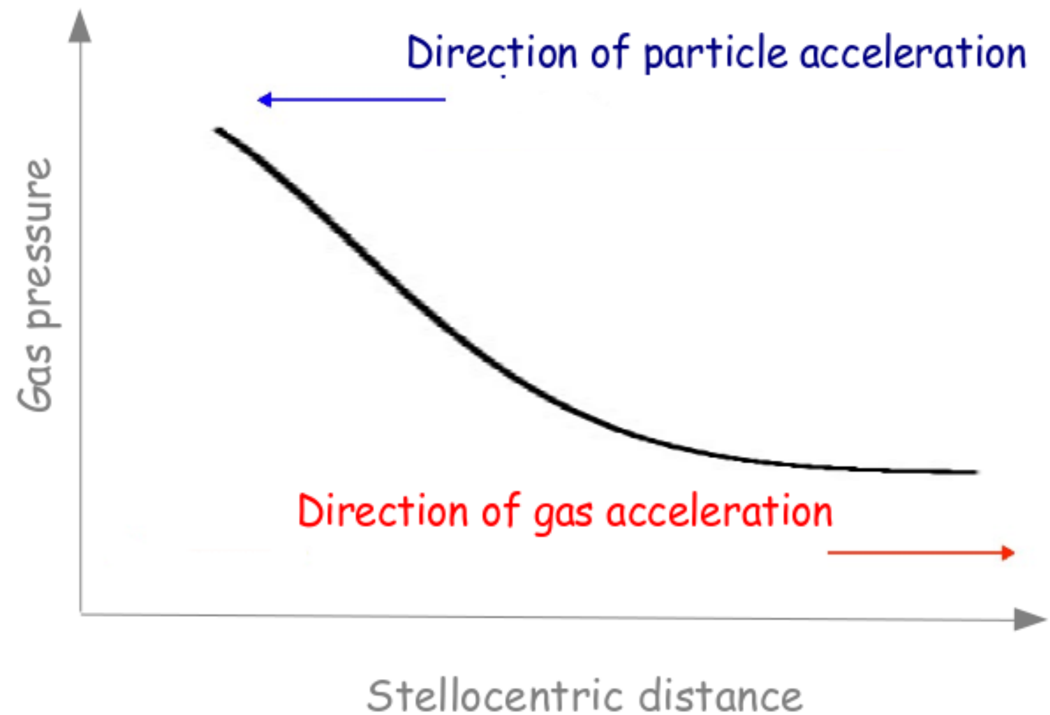


Video credit: Mario Flock (MPIA/CEA)

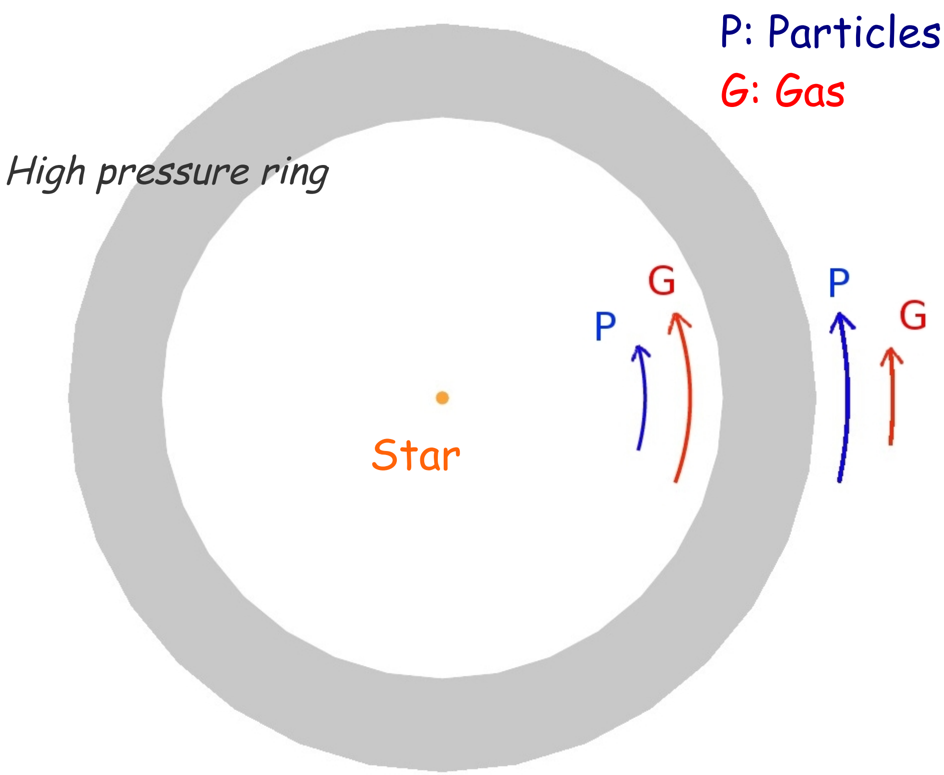
Particle drift



Adapted from Whipple (1972)



Pressure Trap



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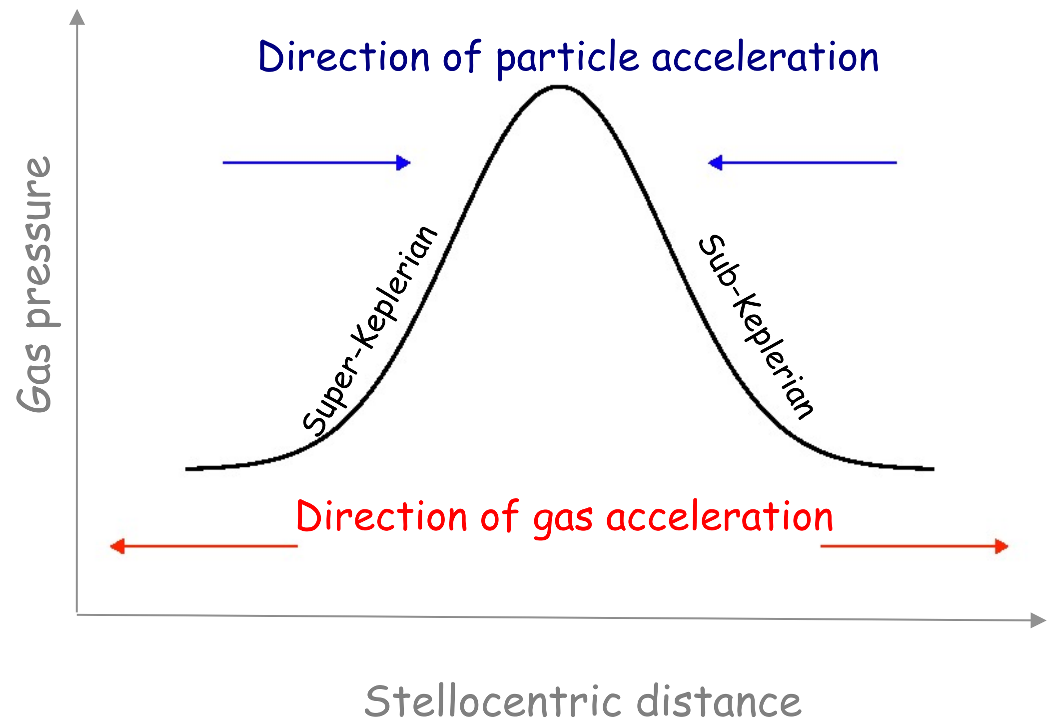
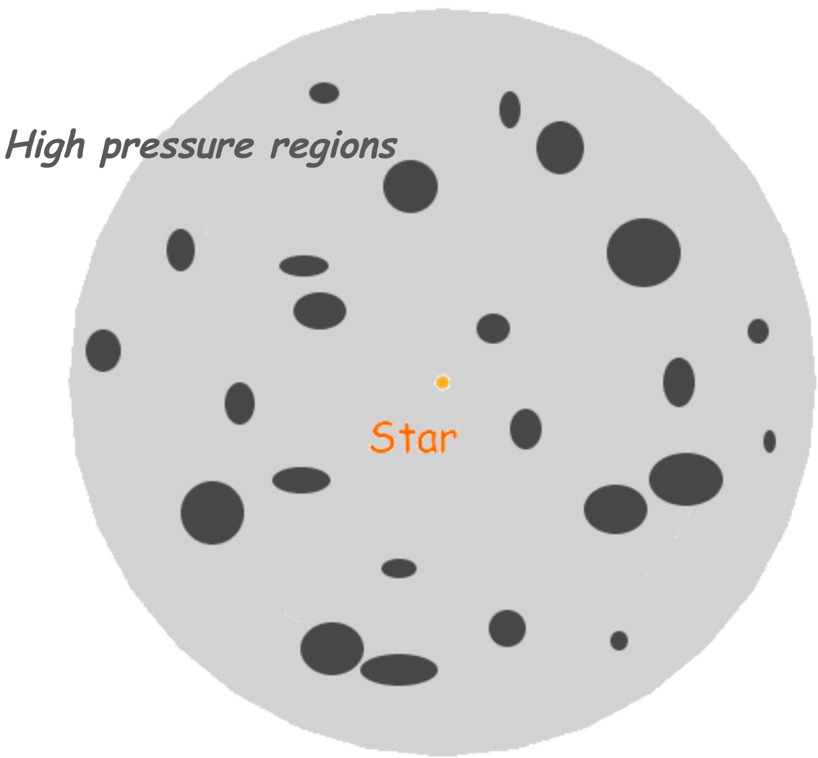
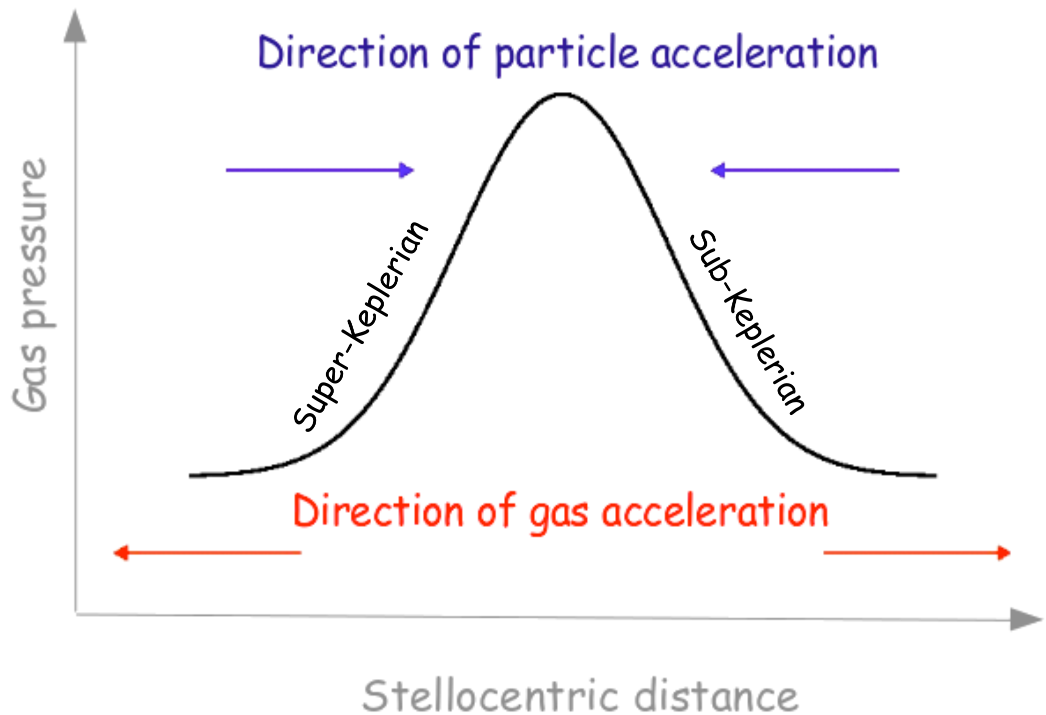
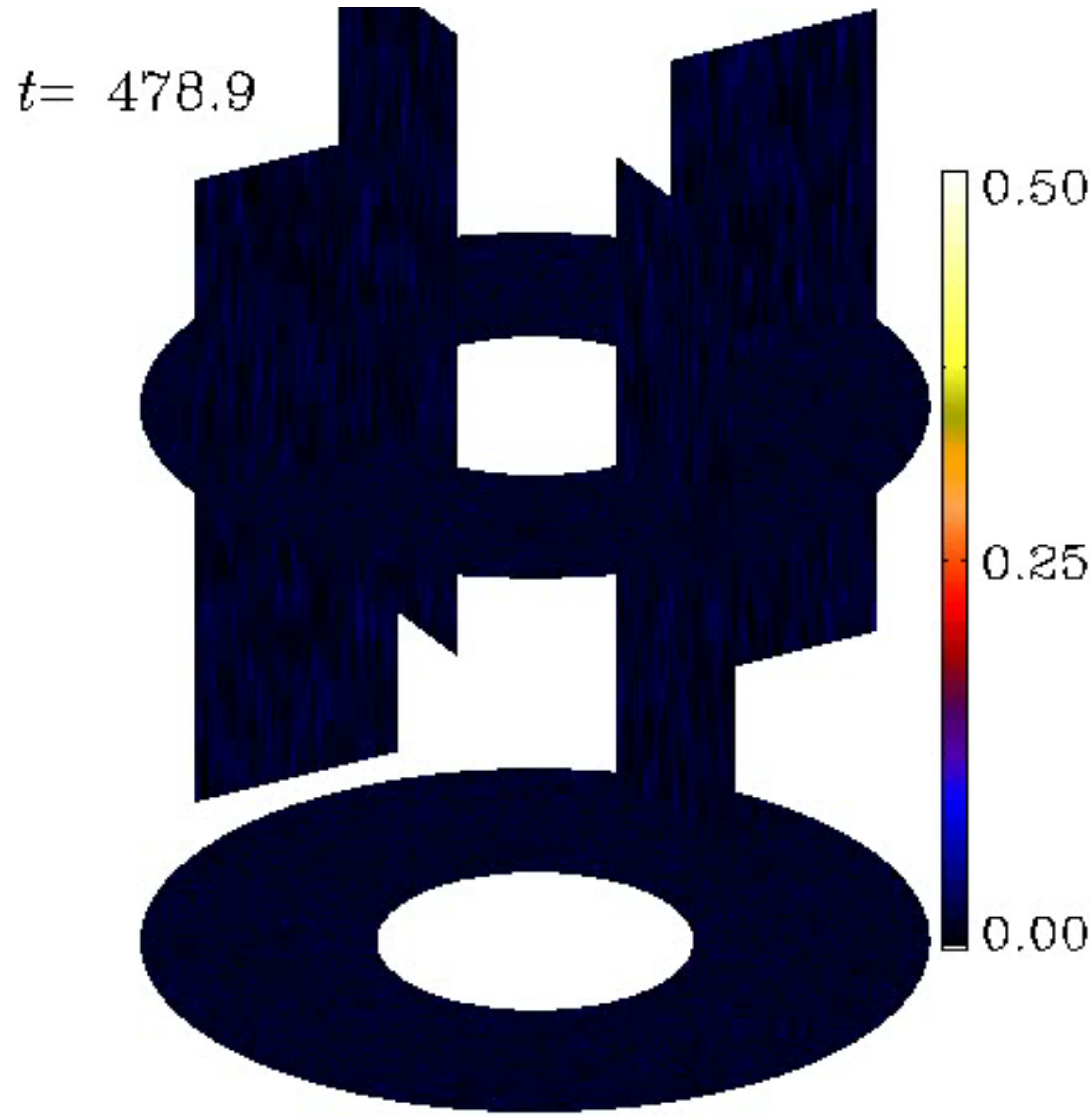


Pressure Trap



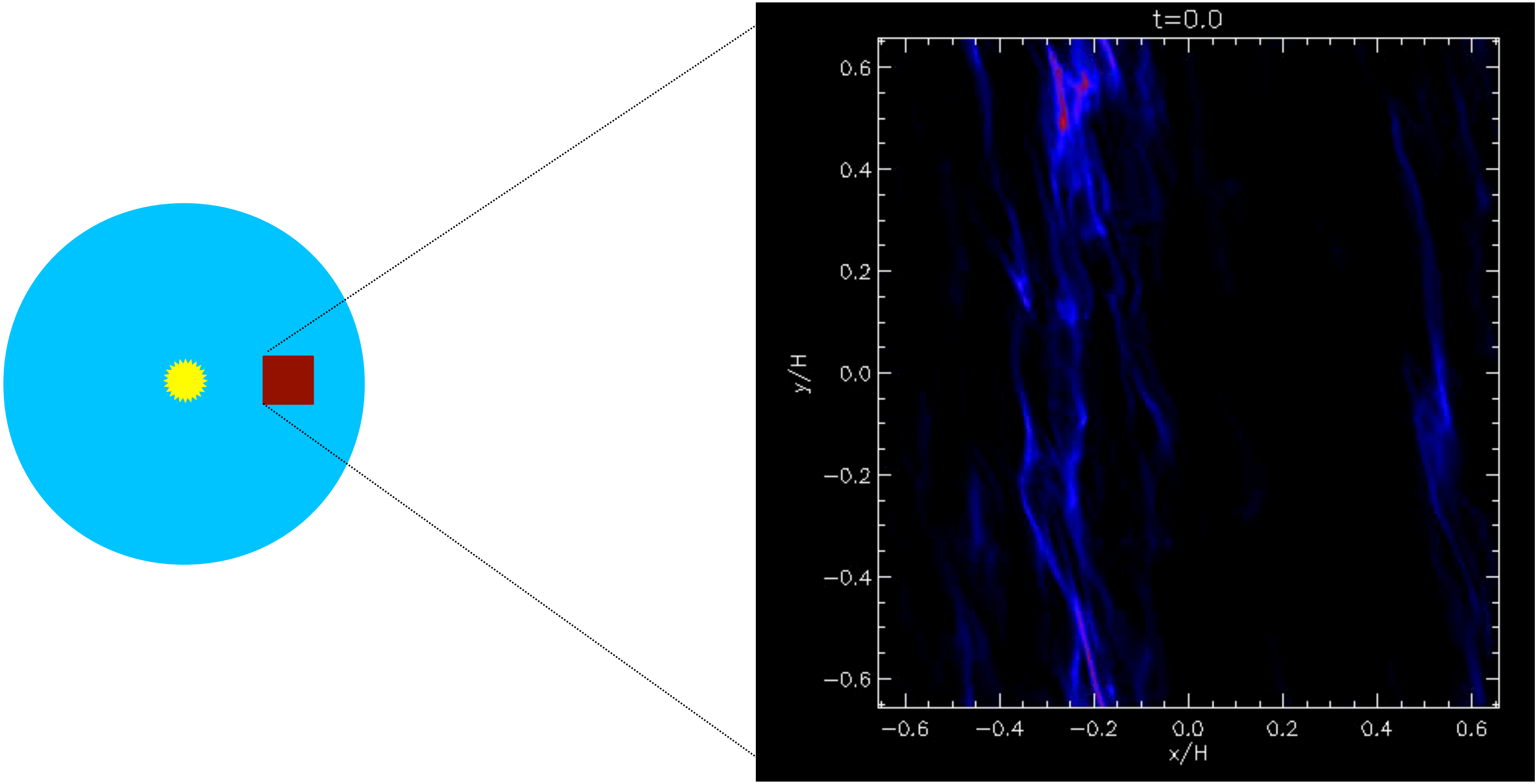


Turbulence concentrates solids mechanically in pressure maxima



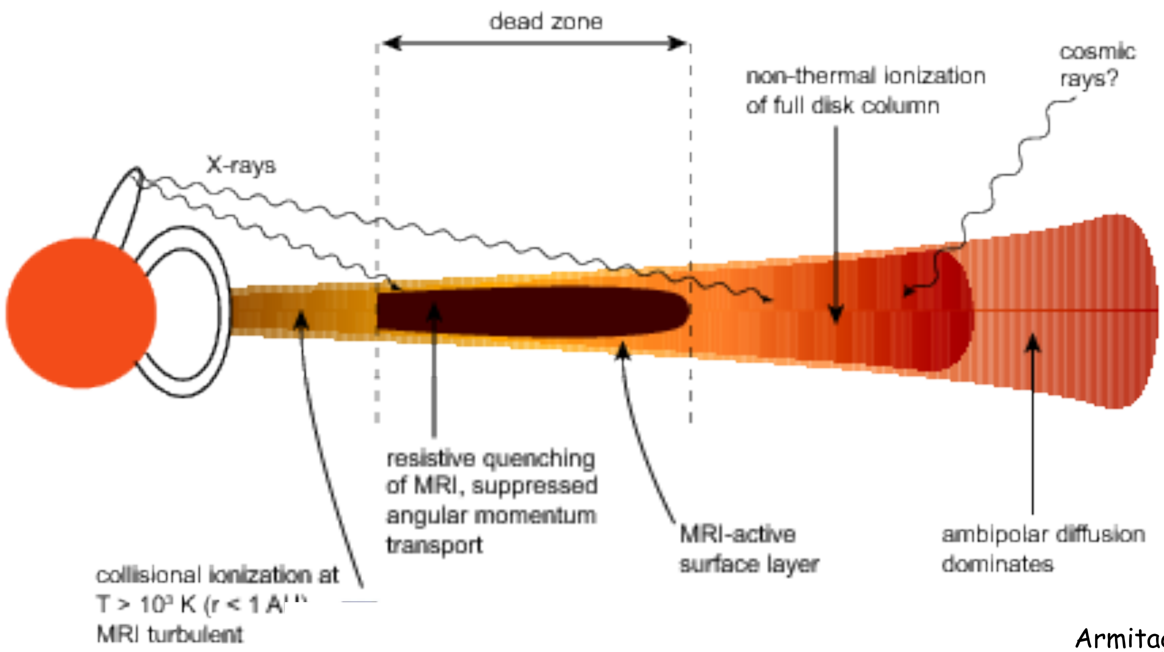
Lyra et al. (2008a)

Gravitational collapse into planetesimals



Johansen et al. (2007)

Dead zones are robust features of accretion disks



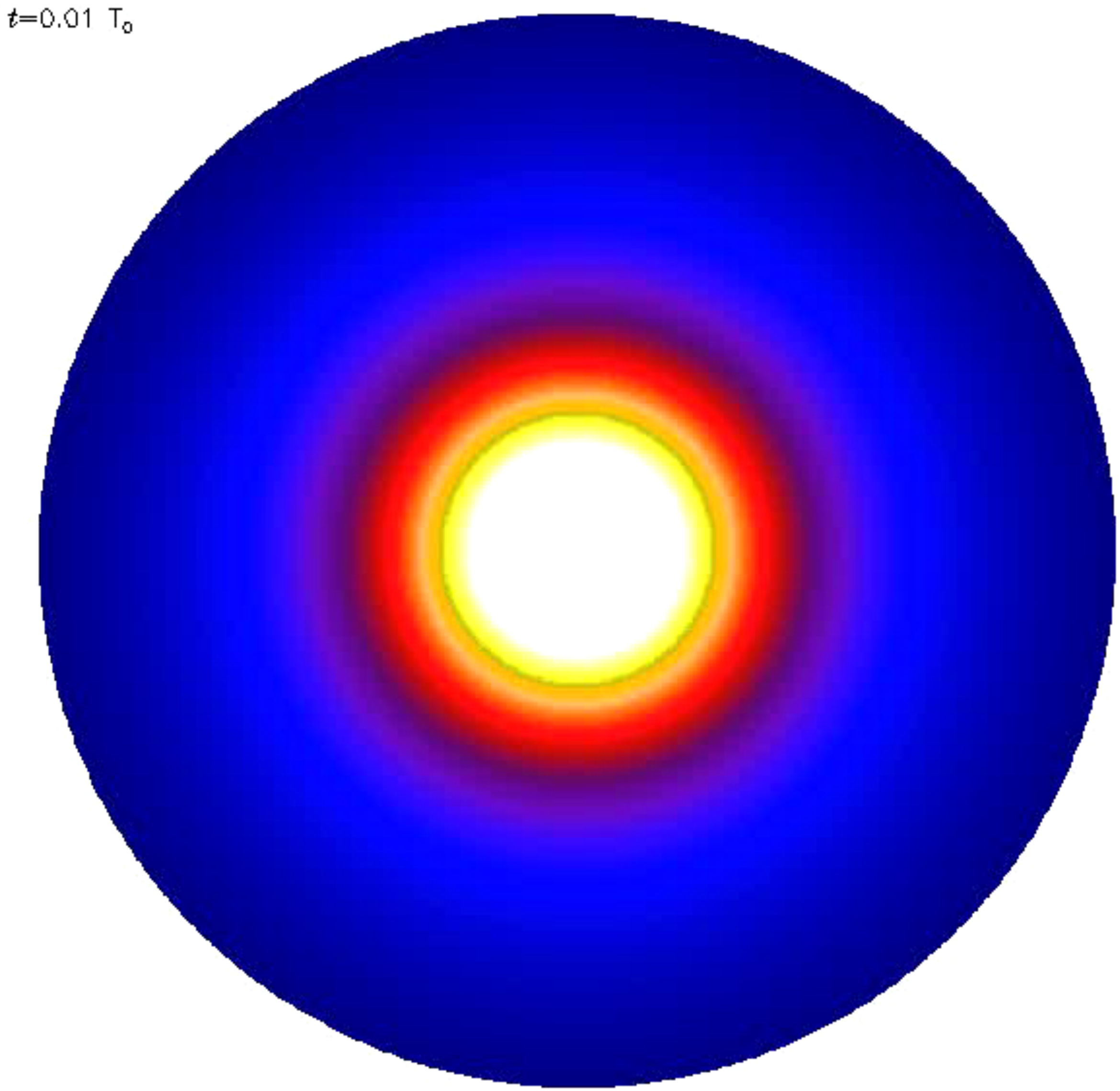
Armitage (2010,
after Gammie 1996)

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

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

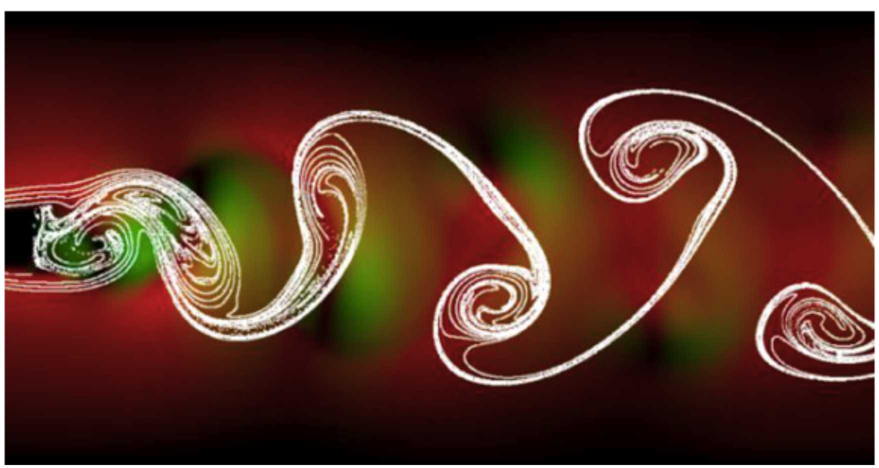
There should be a **magnetized, active zone**,
and a **non-magnetic, dead zone.**

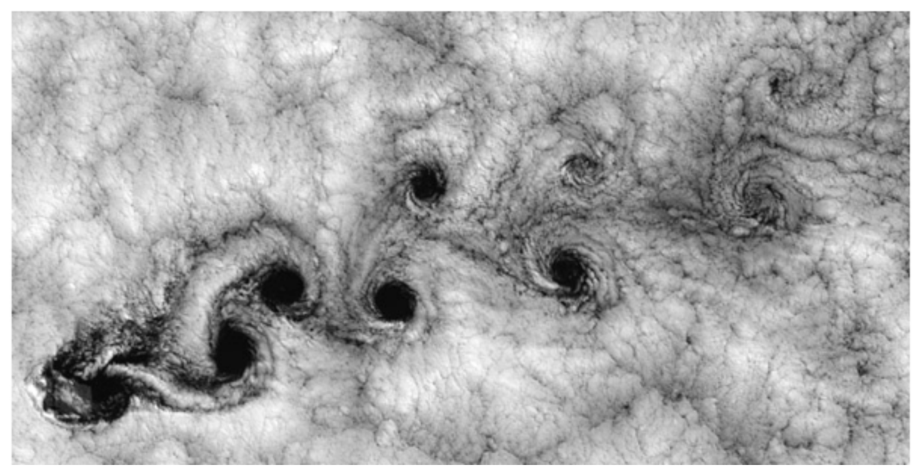
Active/Dead zone boundary



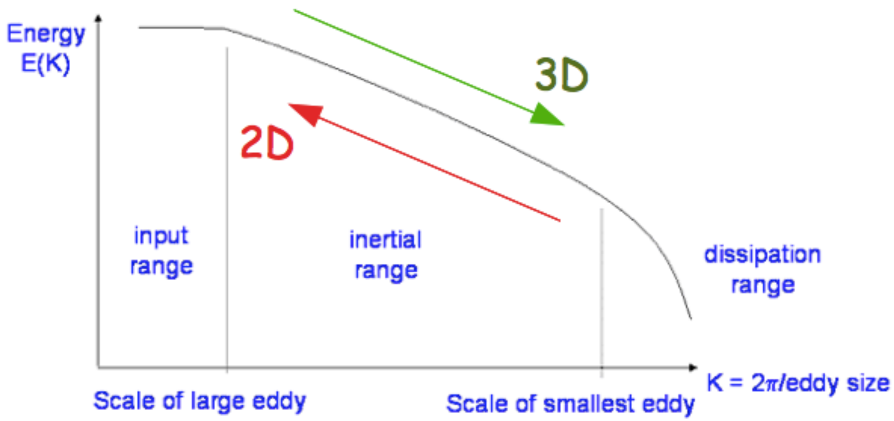
Lyra & Mac Low (2012)

Vortices – An ubiquitous fluid mechanics phenomenon

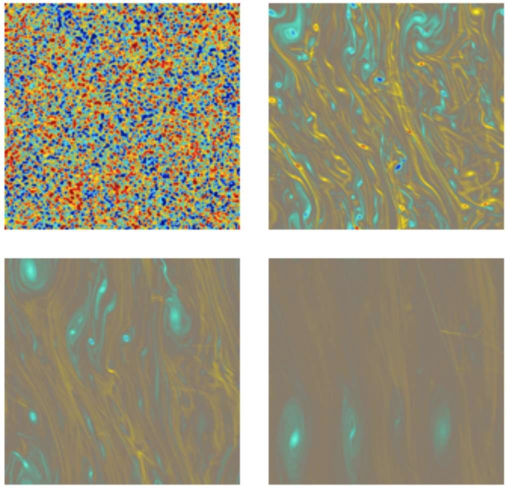




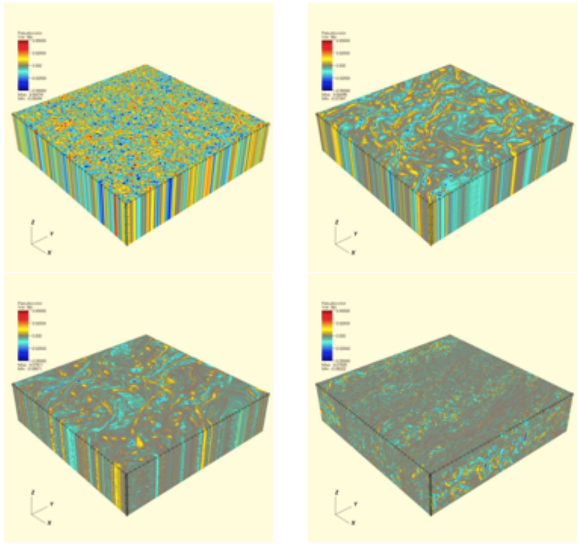
The energy cascade



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



2D



3D

Inverse Cascade

No 3D instability
Eddies merge

Direct Cascade

Destruction occurs
faster than merging

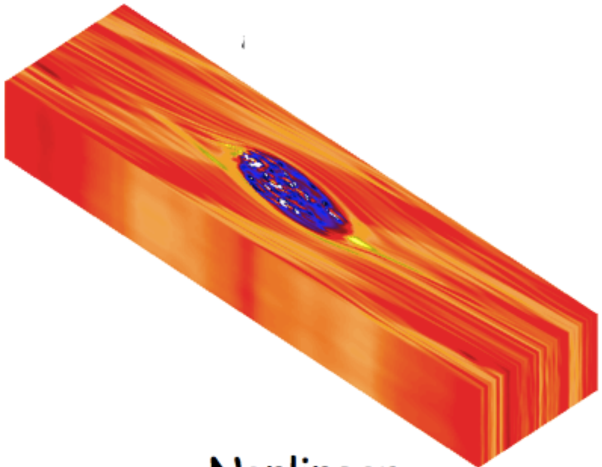
Sustaining vortices

Mechanisms to

inject vorticity

to replenish the vorticity lost in the direct cascade

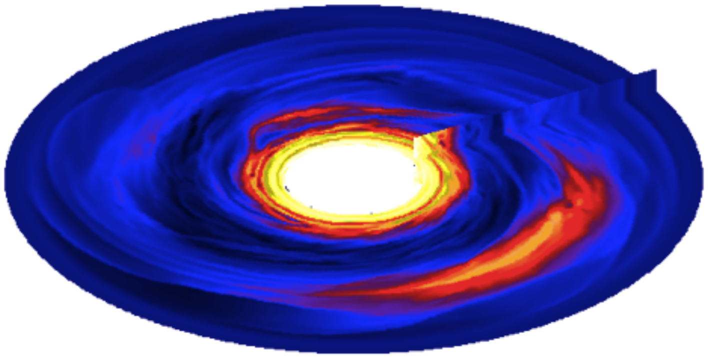
Baroclinic Instability



Nonlinear

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

Rossby Wave Instability

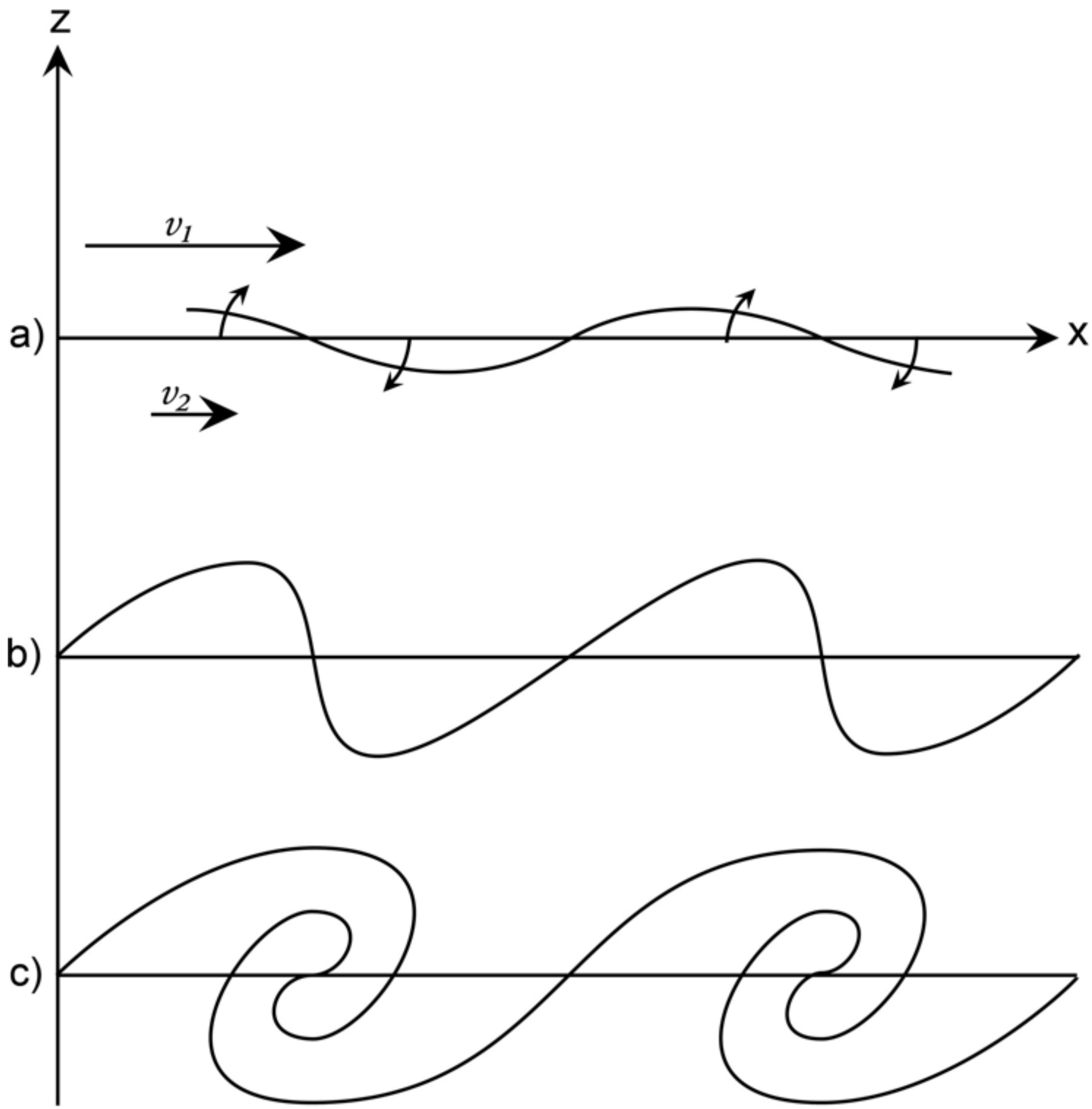


Linear

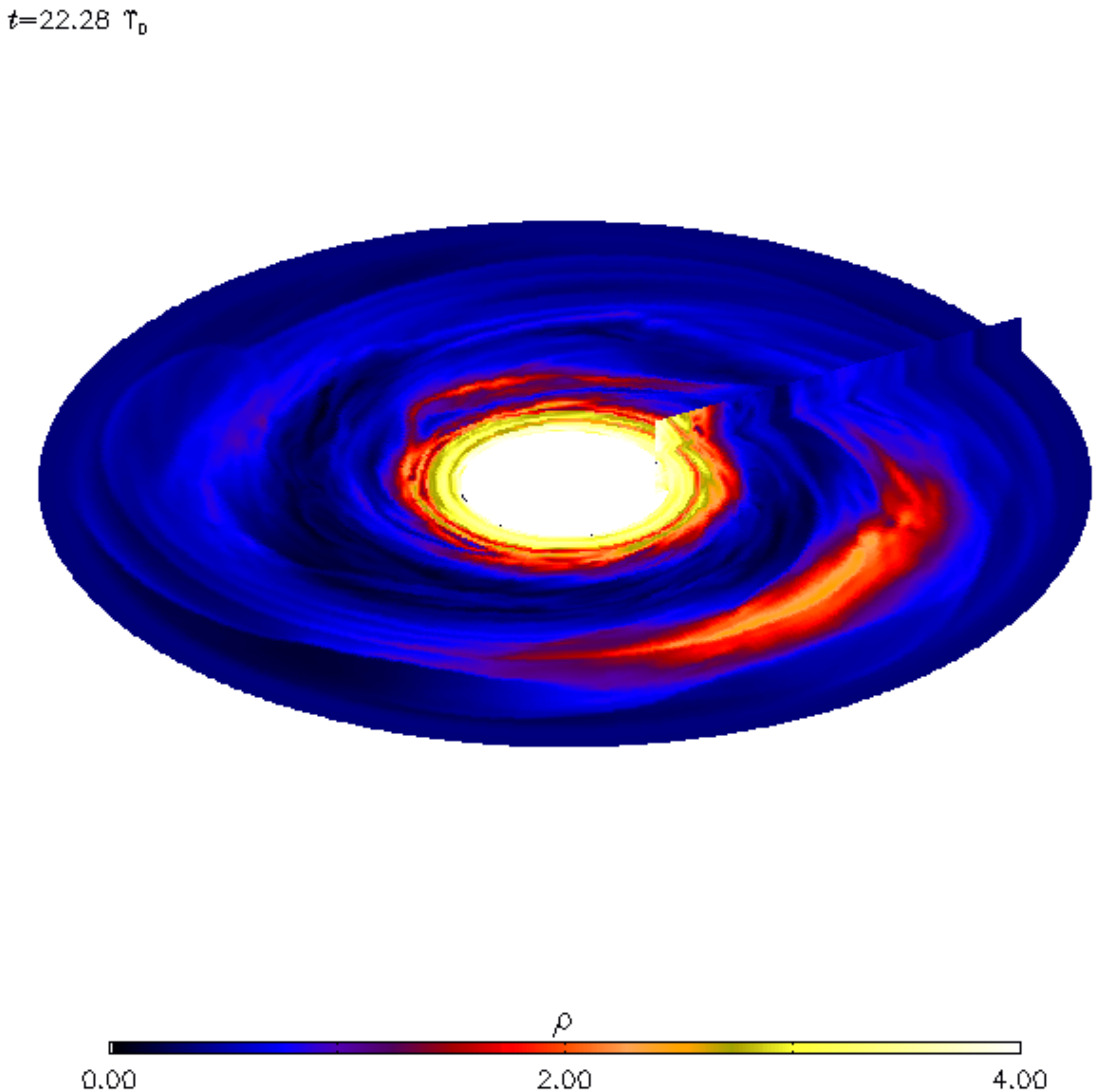
Powered by:
Modification of shear profile
(external vortensity reservoir)

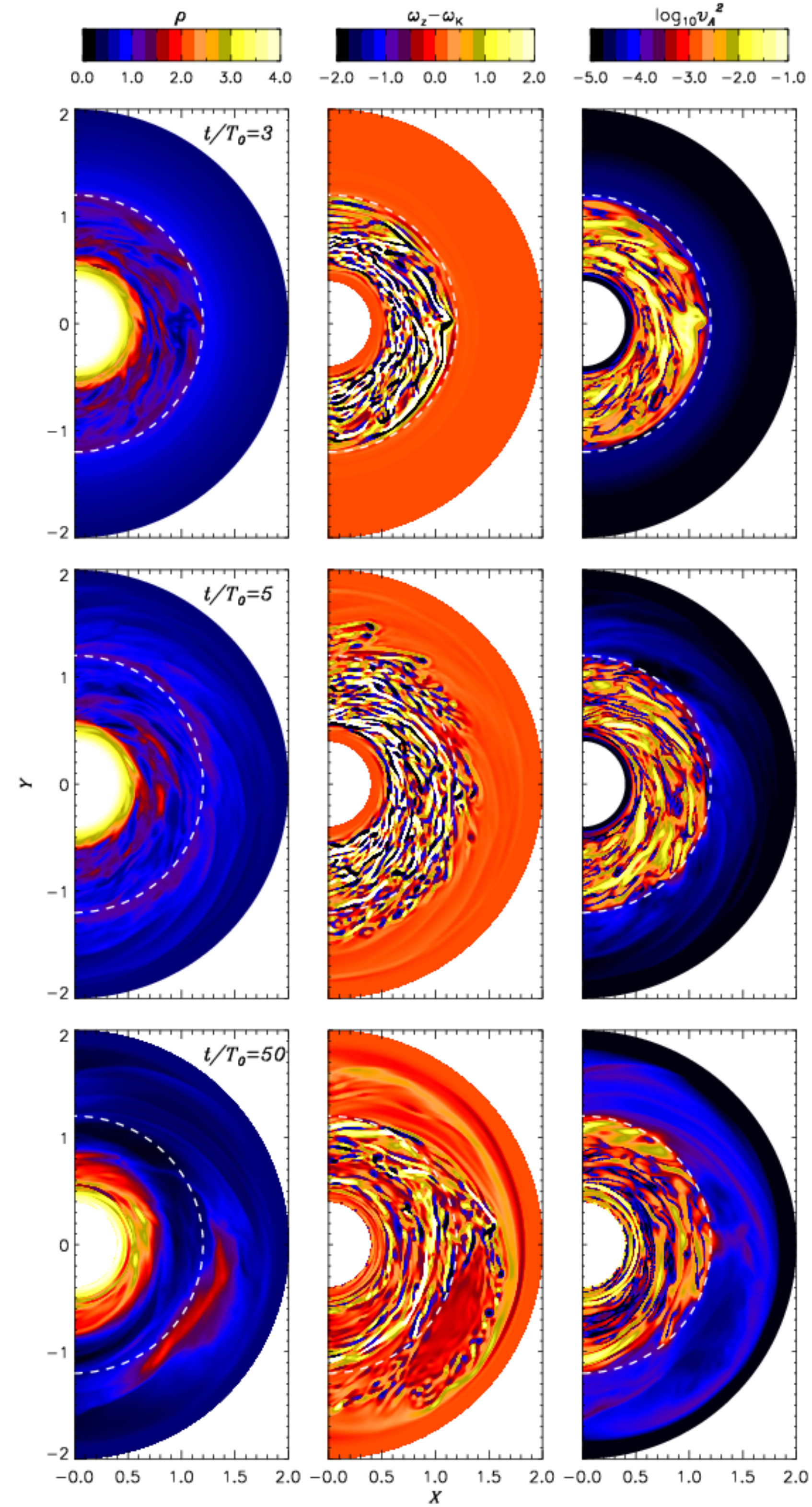
Rossby Wave Instability

(or.... Kelvin-Helmholtz in rotating disks)



Active/Dead zone boundary

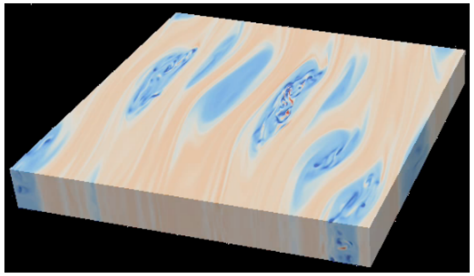




Magnetized inner disk + resistive outer disk

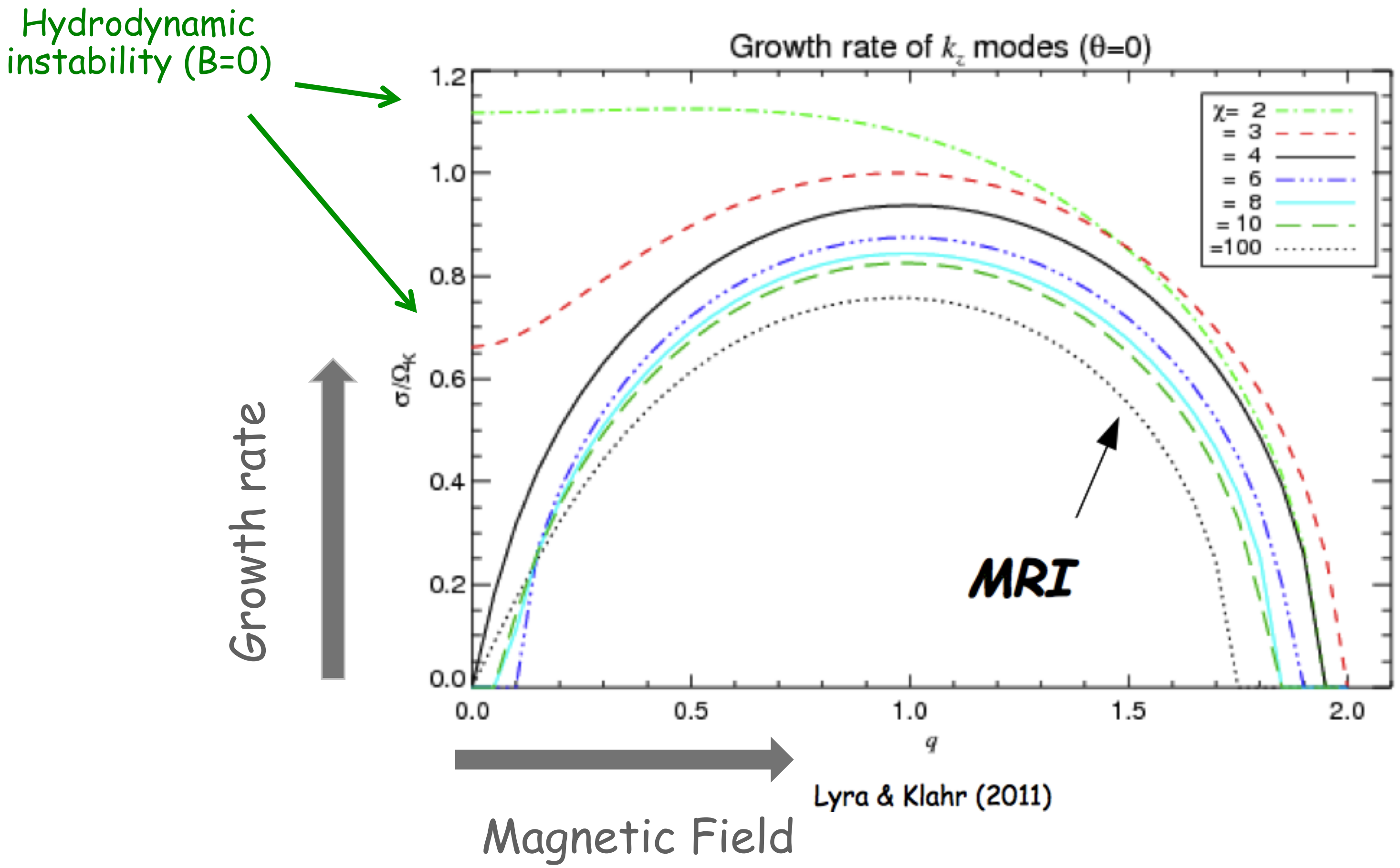
Lyra & Mac Low (2012)

Elliptic instability



Lesur & Papaloizou (2010)

See also
Pierrehumbert 1986
Bayly 1986
Kerswell 2002
Lesur & Papaloizoy 2009
Lesur & Papaloizou 2010
Lyra & Klahr 2011
Lyra 2013



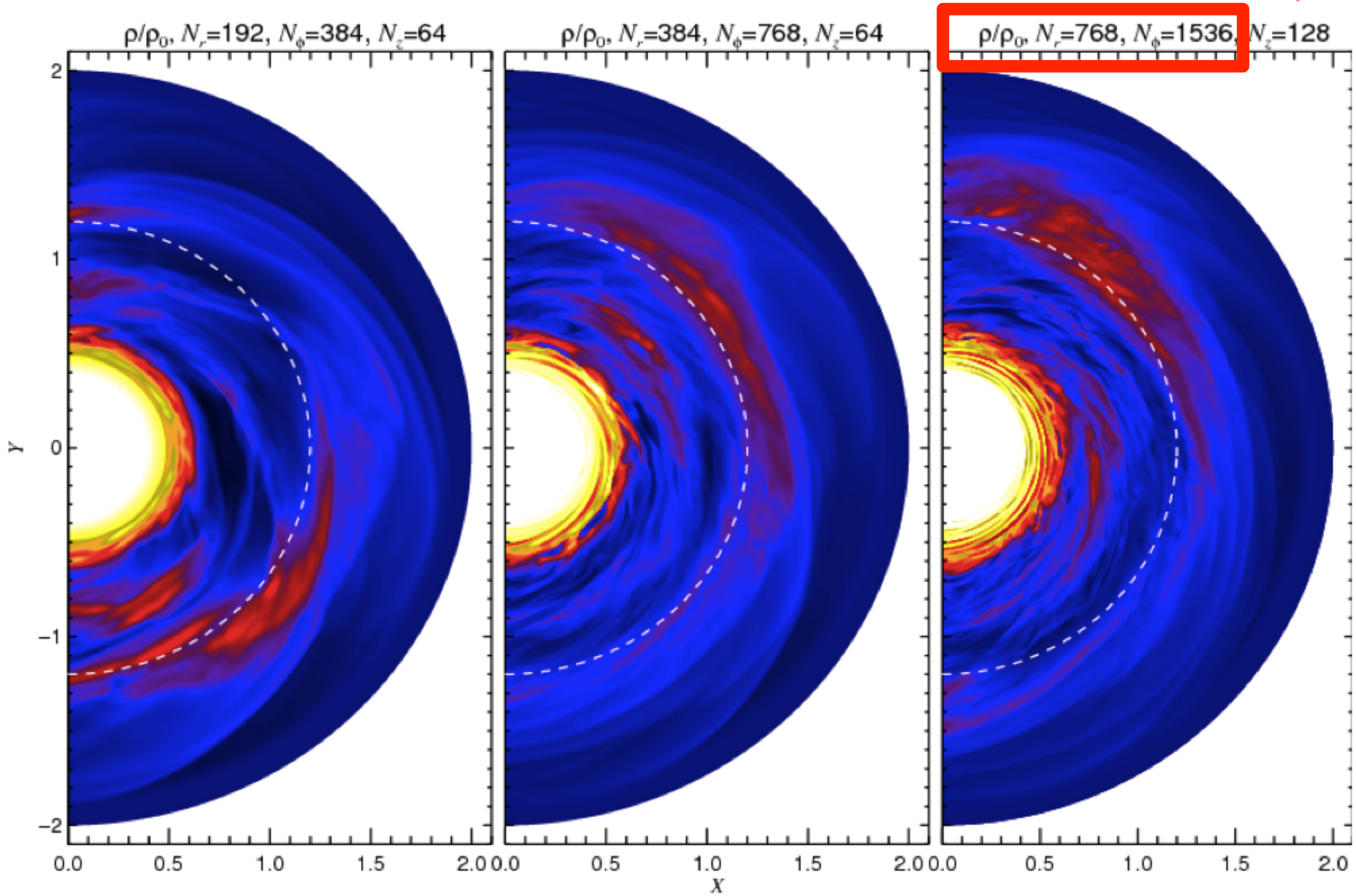
Lyra & Klahr (2011)

Infinitely elongated vortices are equivalent to **shear flows**.

They are subject to an **MRI-like instability** when magnetized.

Convergence

Resolution

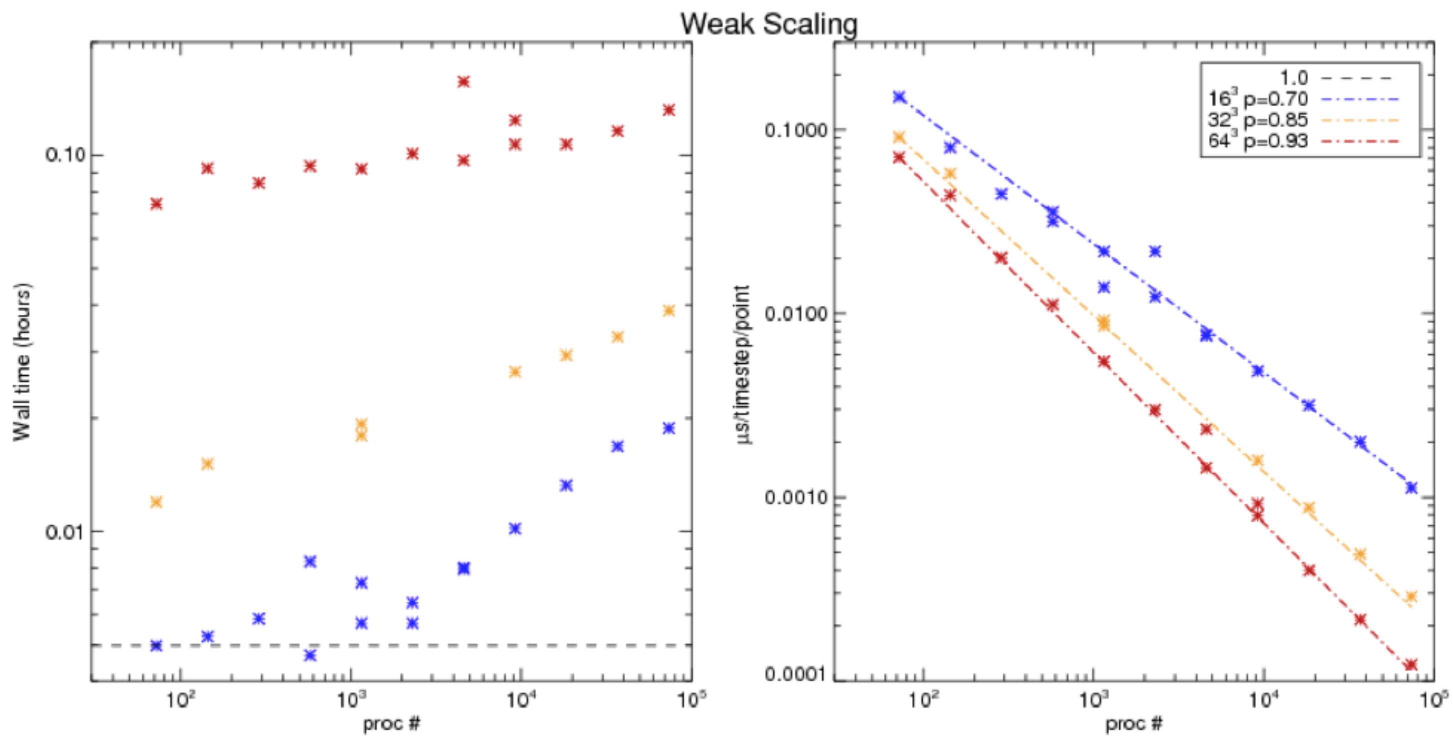


Lyra & Mac Low (2012)

High end computing

The Pencil Code

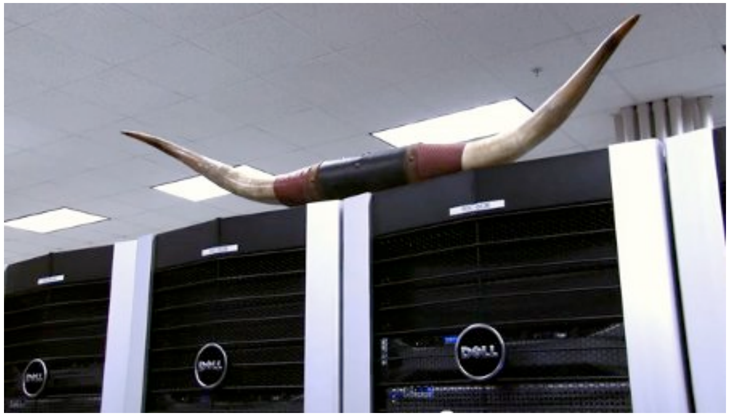
Brandenburg & Dobler (2002)



Good scaling up to > **70,000 processors !**

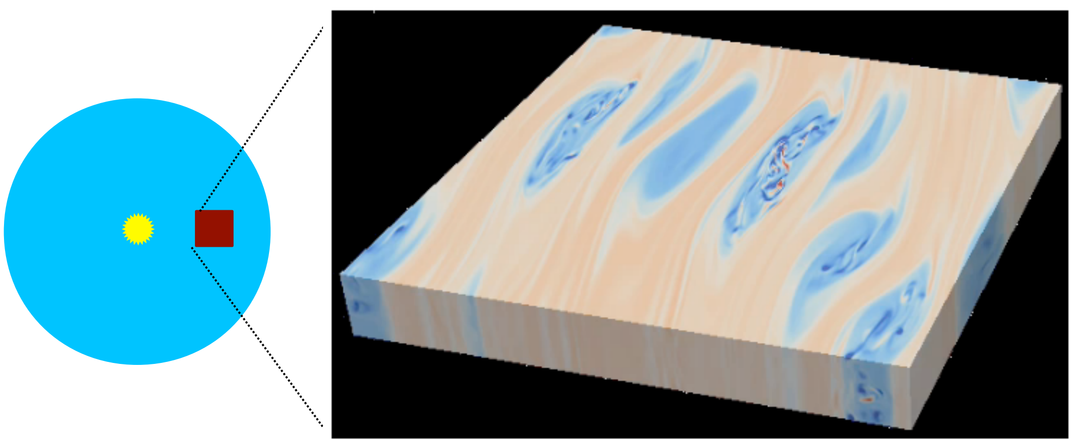
(At NICS - Kraken)

A new >100,000 proc supercluster - Stampede



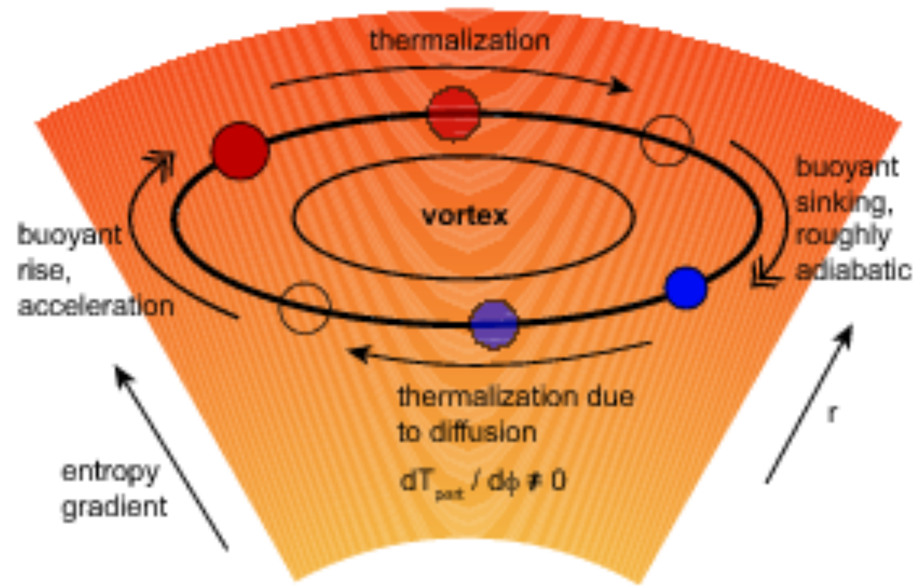
Baroclinic Instability - Excitation and self-sustenance of vortices

1. Radial entropy gradient
2. Thermal diffusion



Lesur & Papaloizou (2010)

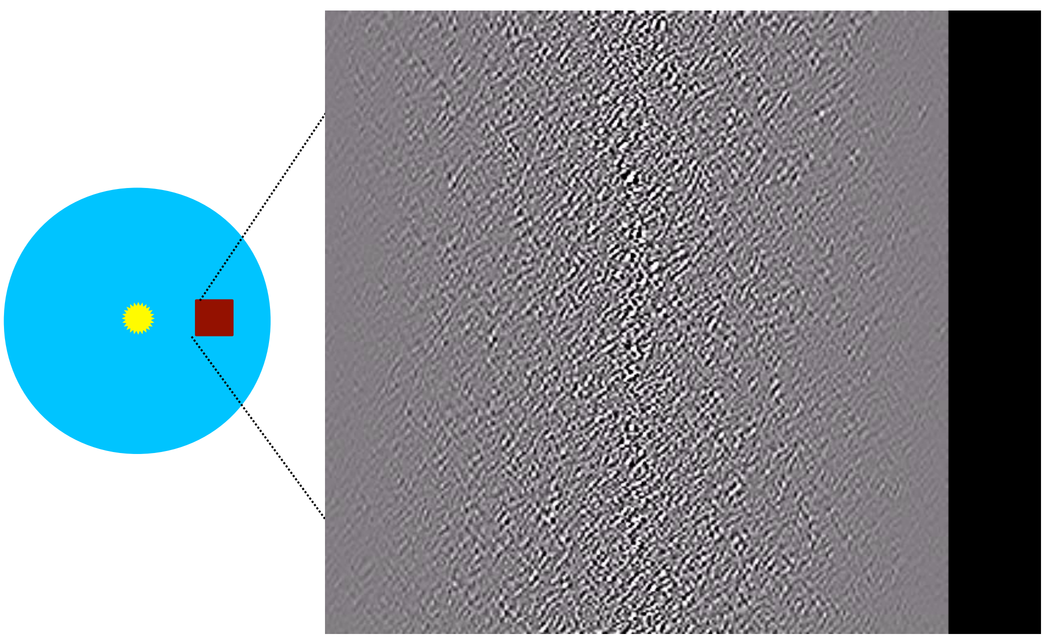
Sketch of the Baroclinic Instability



Armitage (2010)

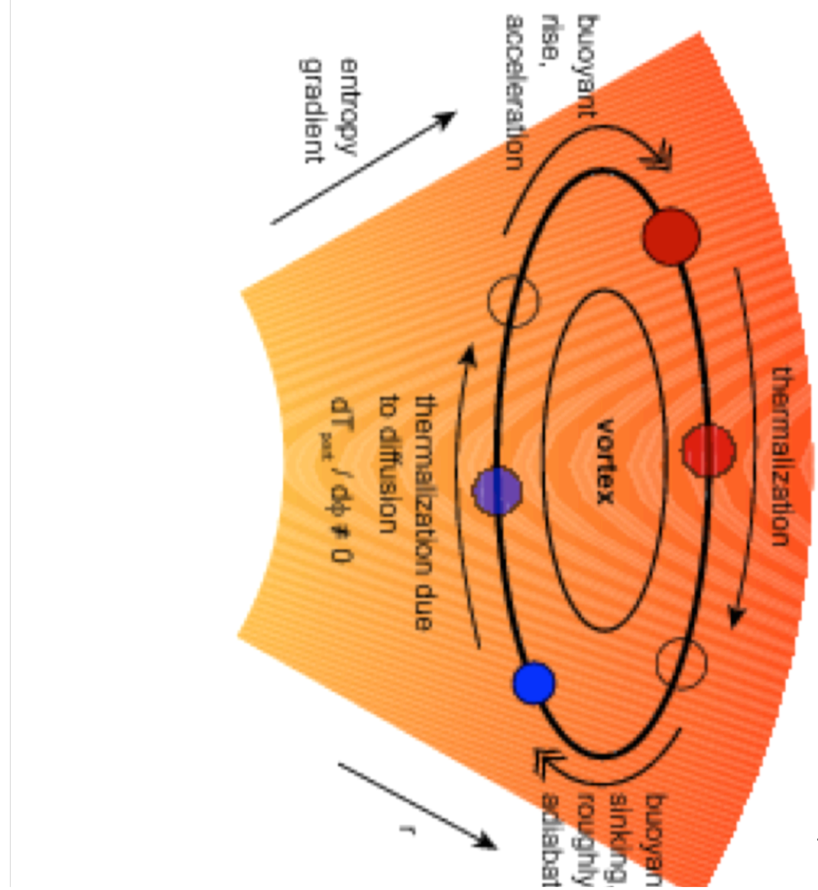
$$\frac{\partial \omega}{\partial t} = \underbrace{-(\boldsymbol{u}\cdot\nabla)\omega}_{\text{advection}} \underbrace{-\omega(\nabla\cdot\boldsymbol{u})}_{\text{compression}} + \underbrace{(\omega\cdot\nabla)\boldsymbol{u}}_{\text{stretching}} + \underbrace{\frac{1}{\rho^2}\nabla\rho\times\nabla p}_{\text{baroclinicity}} + \underbrace{\nu\nabla^2\omega}_{\text{dissipation}}$$

Baroclinic Instability - Excitation and self-sustenance of vortices



Lyra & Klahr (2011)

Sketch of the Baroclinic Instability



Armitage (2010

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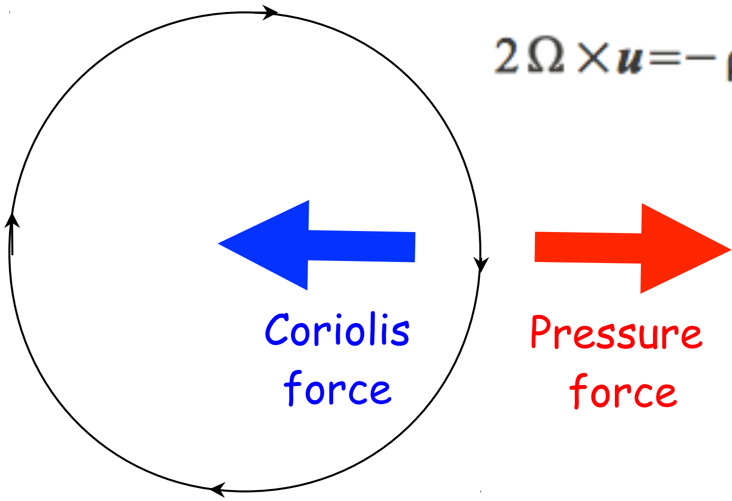
Turbulent eddies concentrate solids,
turning them into planetesimals...

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

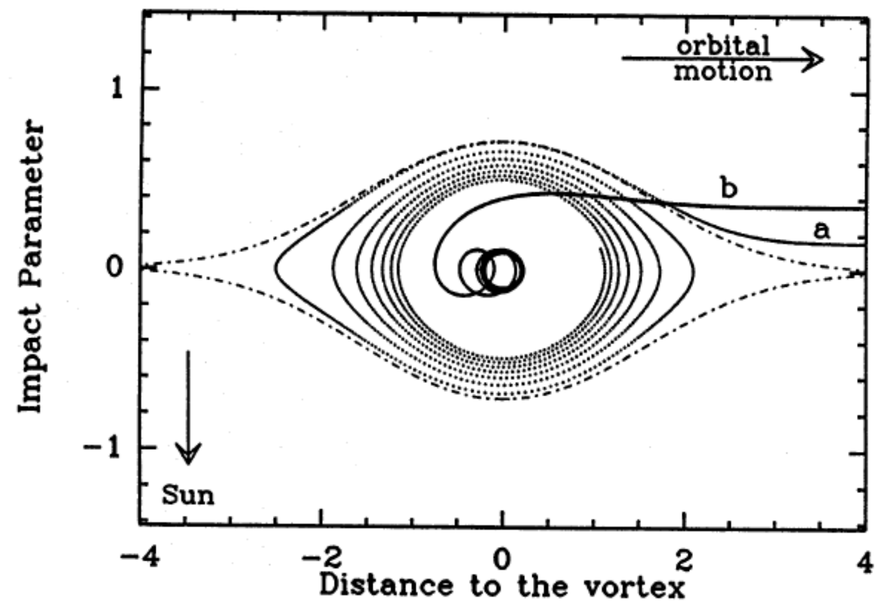
The Tea-Leaf effect

Geostrophic balance:

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



Vortex streamline



Barge & Sommeria (1995)

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

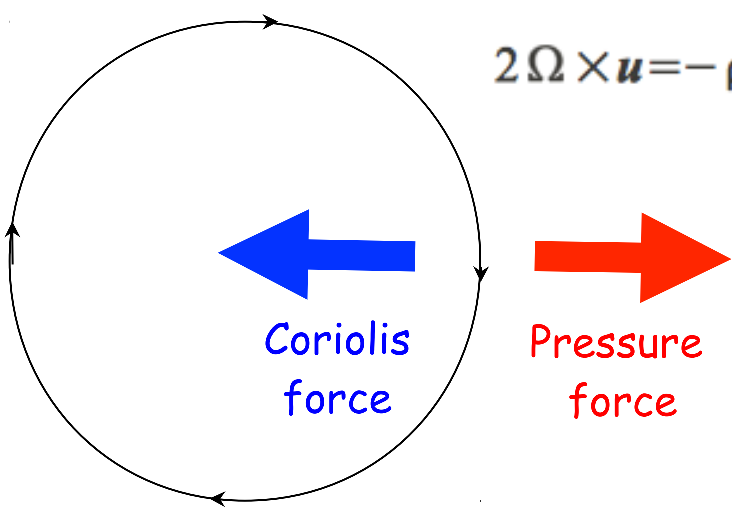
Aid to planet formation (Barge & Sommeria 1995)

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

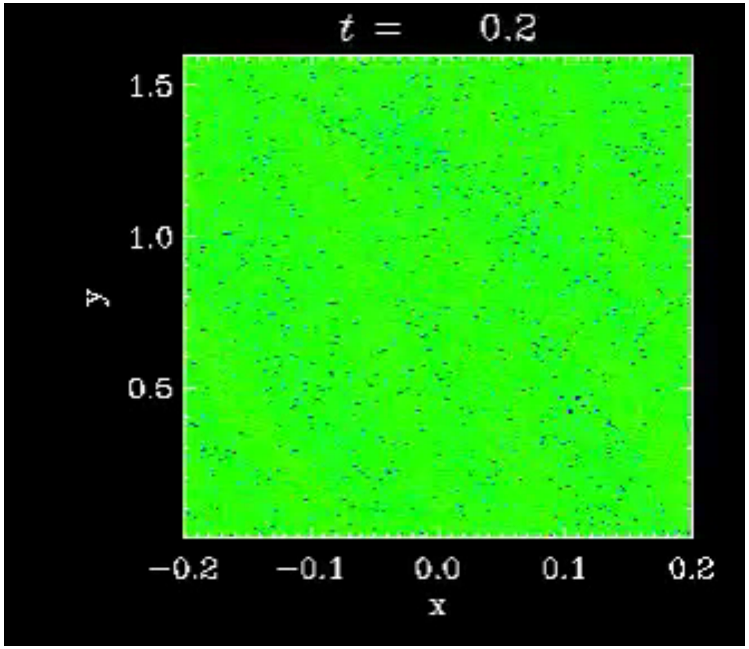
The Tea-Leaf effect

Geostrophic balance:

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



Vortex streamline



Raettig et al. (2012)

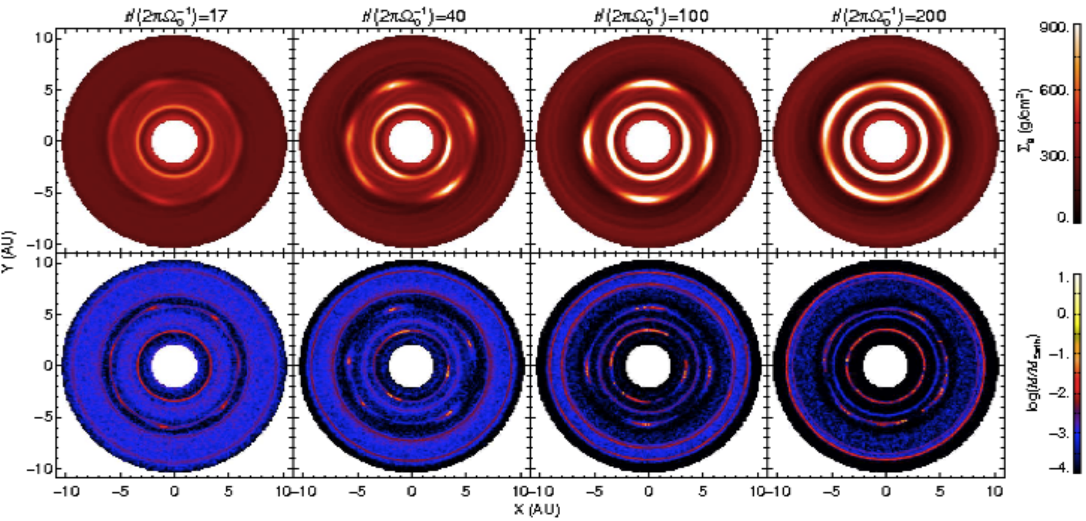
Particles do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation (Barge & Sommeria 1995)

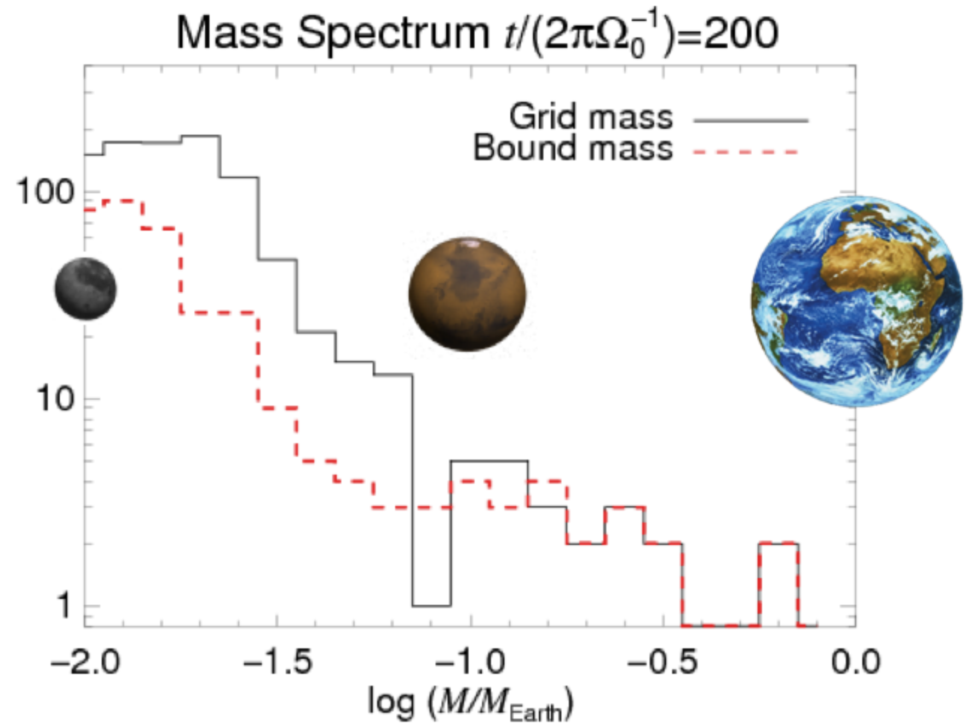
Speed up planet formation enormously
(Lyra et al. 2008b, 2009a, 2009b, Raettig, Lyra & Klahr 2012)

Vortices and Planet Formation

Gas



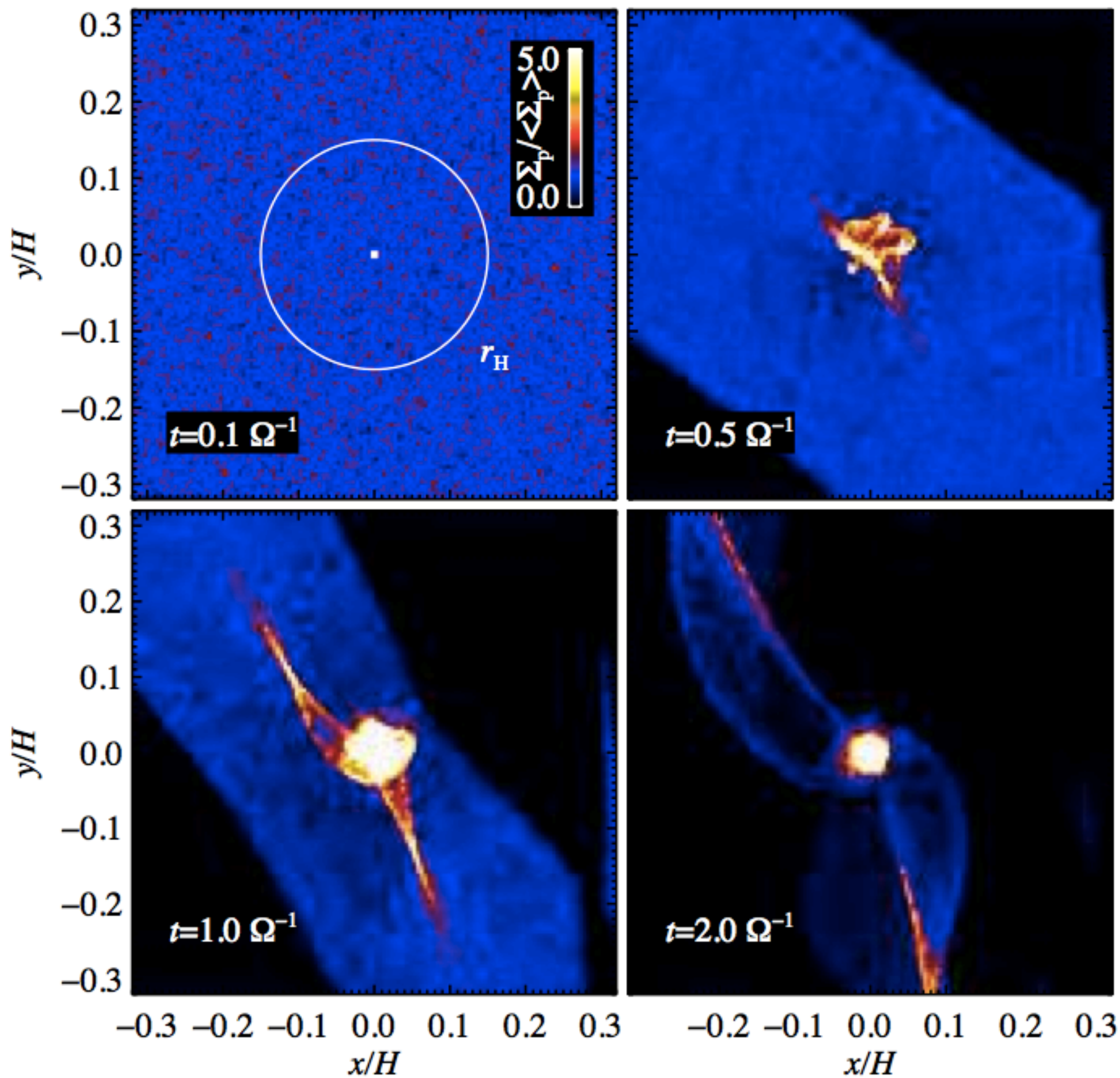
Particles



Collapse into Mars mass objects

(Lyra et al. 2008b, 2009a, 2009b,

Rapid formation of planetary cores

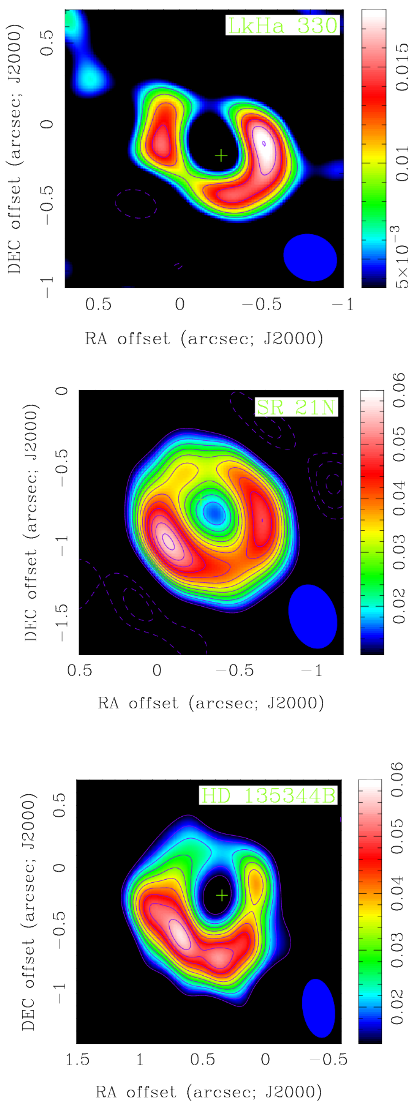


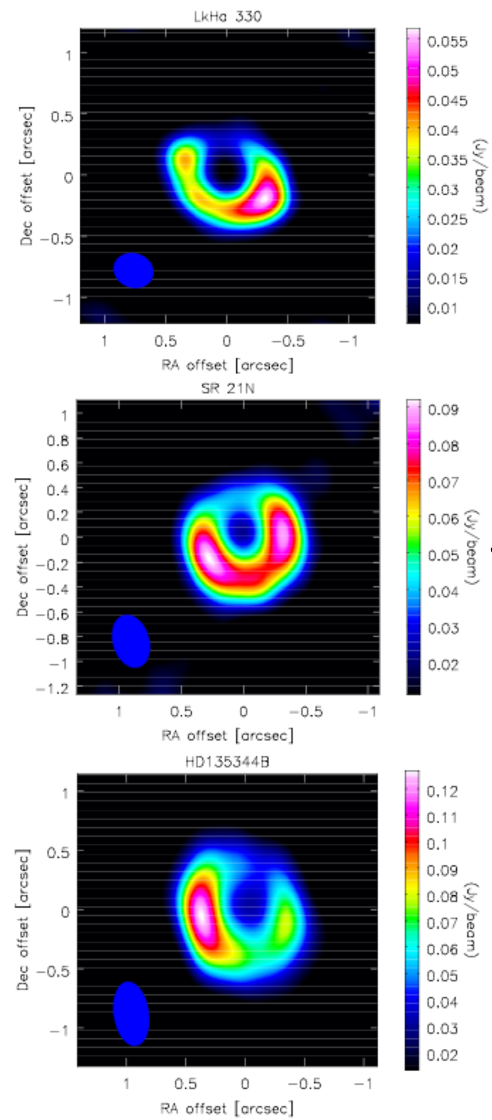
Lambrechts & Johansen (2012)

A possible detection of vortices in disks?

Observations

Brown et al. (2009)





Models

Simulated observations of Rossby vortices

Regaly et al. (2012)

And out of Science embargo on June 6th….

A Major Asymmetric Dust Trap in a Transition Disk

Nienke van der Marel,[1*] Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]

The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection of a dust trap in the disk around the star Oph IRS 48 using observations from the Atacama Large Millimeter/submillimeter Array (ALMA). The 0.44-millimeter–wavelength continuum map shows high-contrast crescent-shaped emission on one side of the star, originating from millimeter-sized grains, whereas both the mid-infrared image (micrometer-sized dust) and the gas traced by the carbon monoxide 6-5 rotational line suggest rings centered on the star. The difference in distribution of big grains versus small grains/gas can be modeled with a vortex-shaped dust trap triggered by a companion.

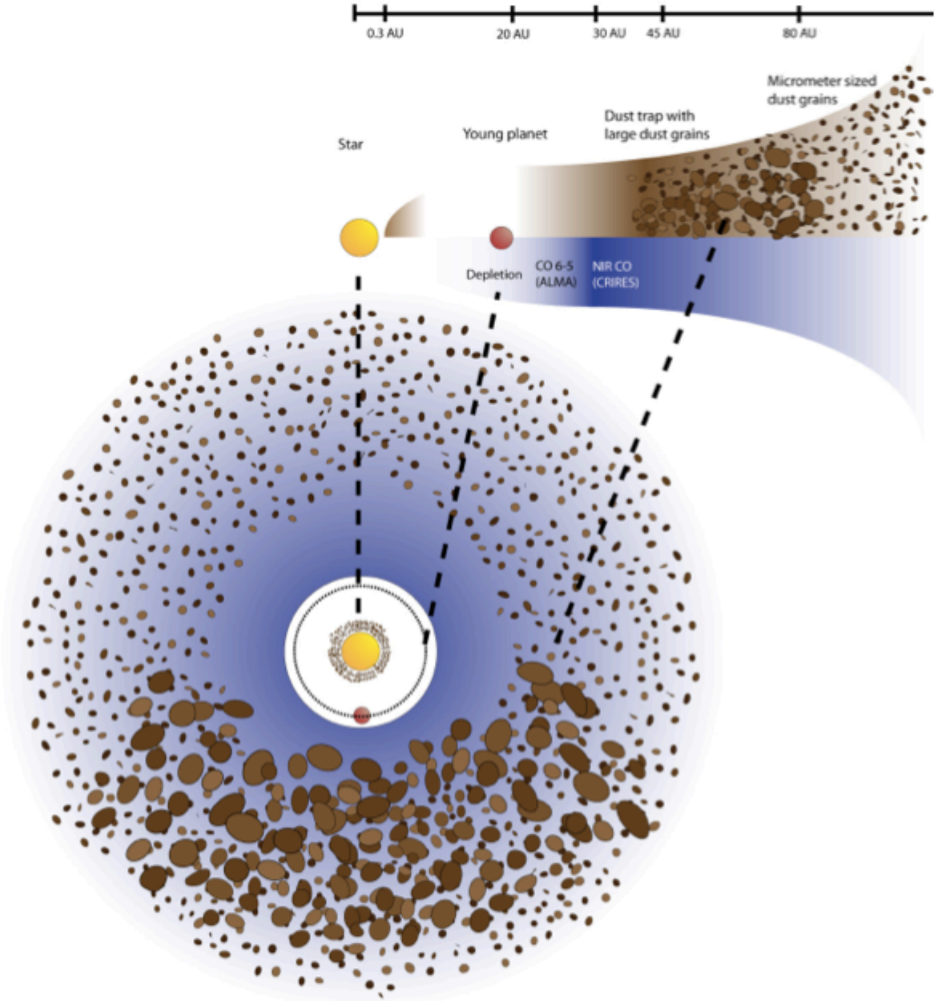
Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

iencemag.org SCIENCE VOL 340 7 JUNE 2013 1199

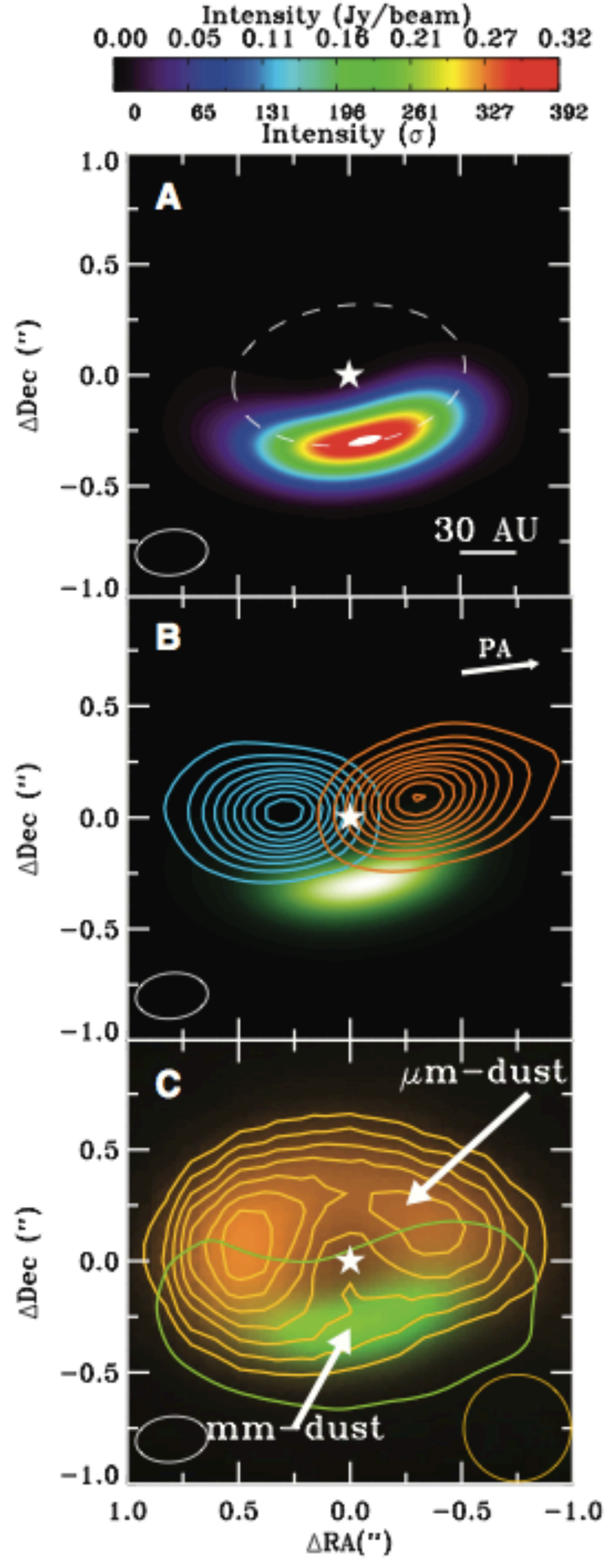
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The ALMA "dust trap"



van der Marel et al. (2013)



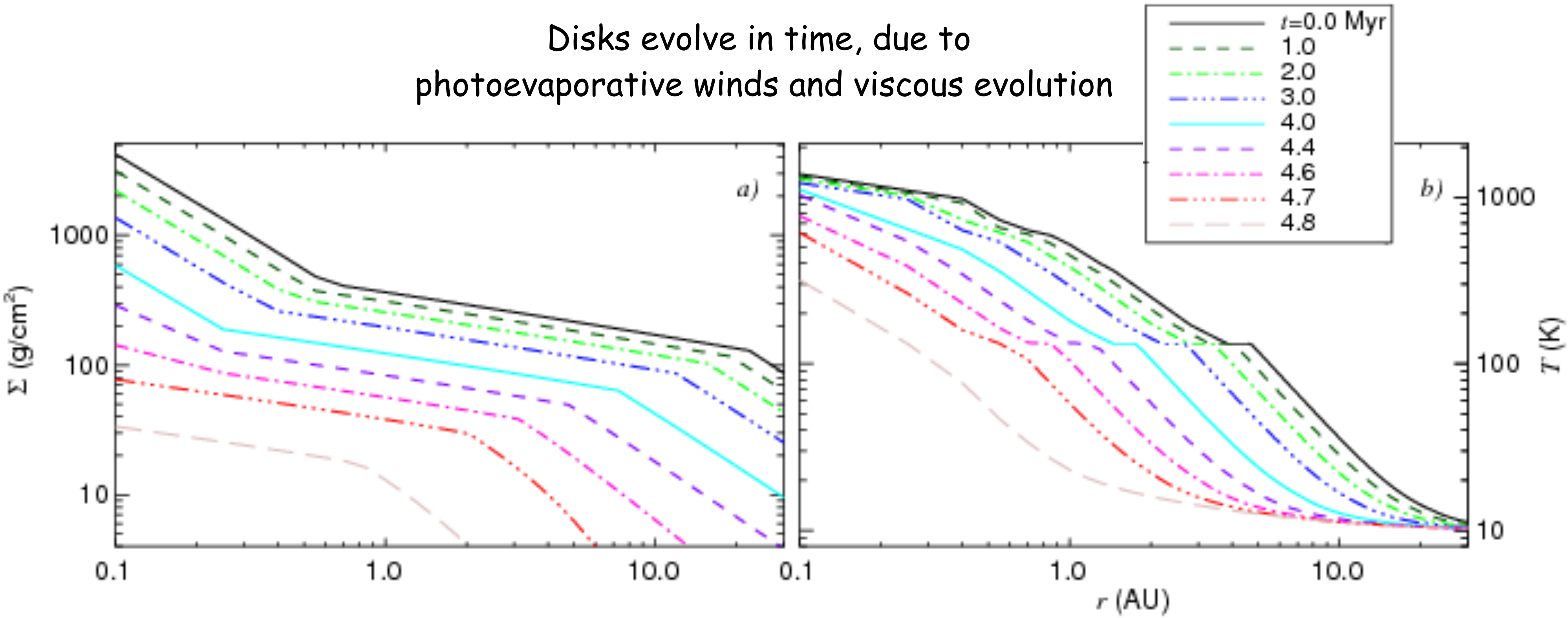
asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

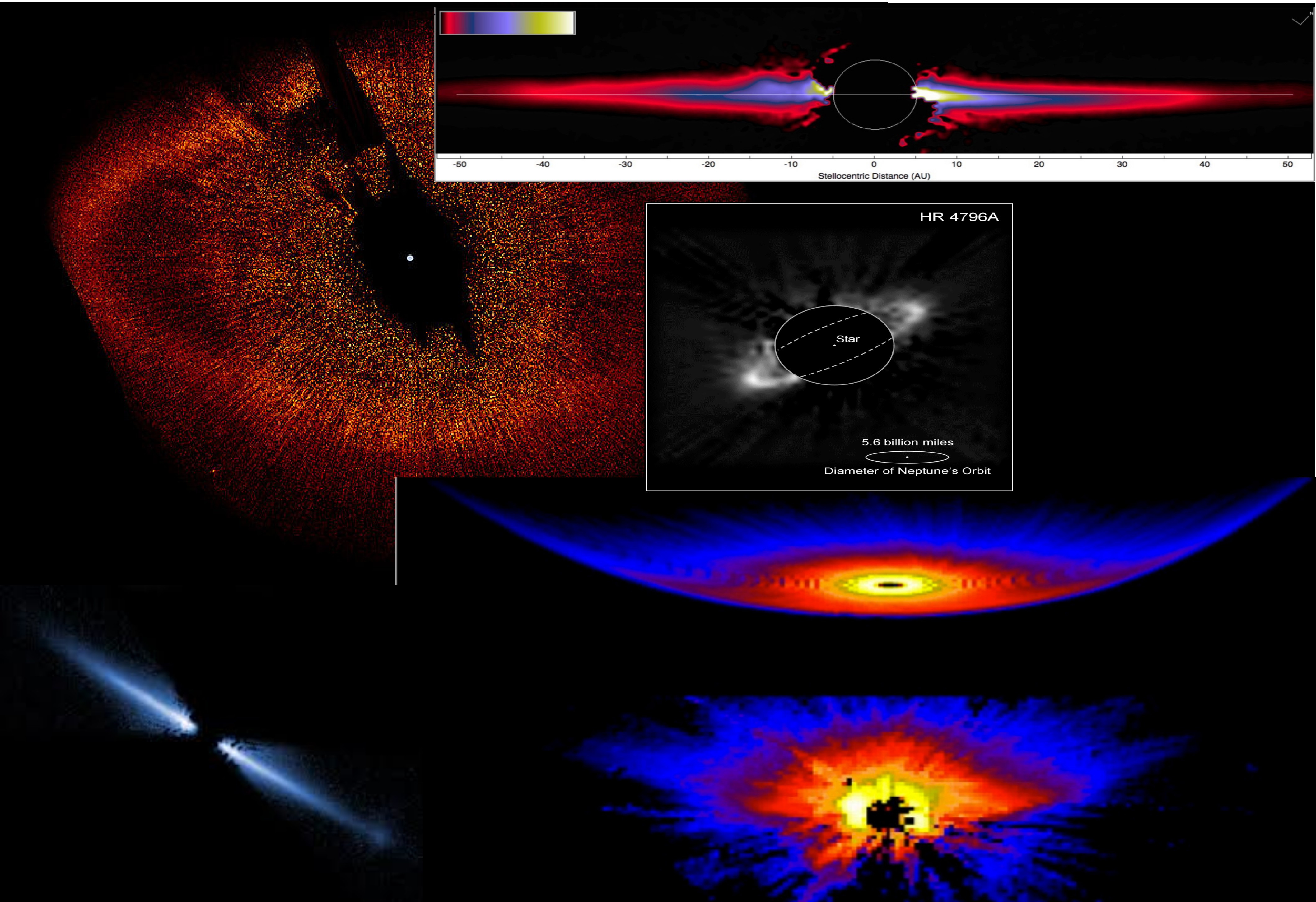
Micron-sized dust follows gas

Transitional disks – The thinning phase

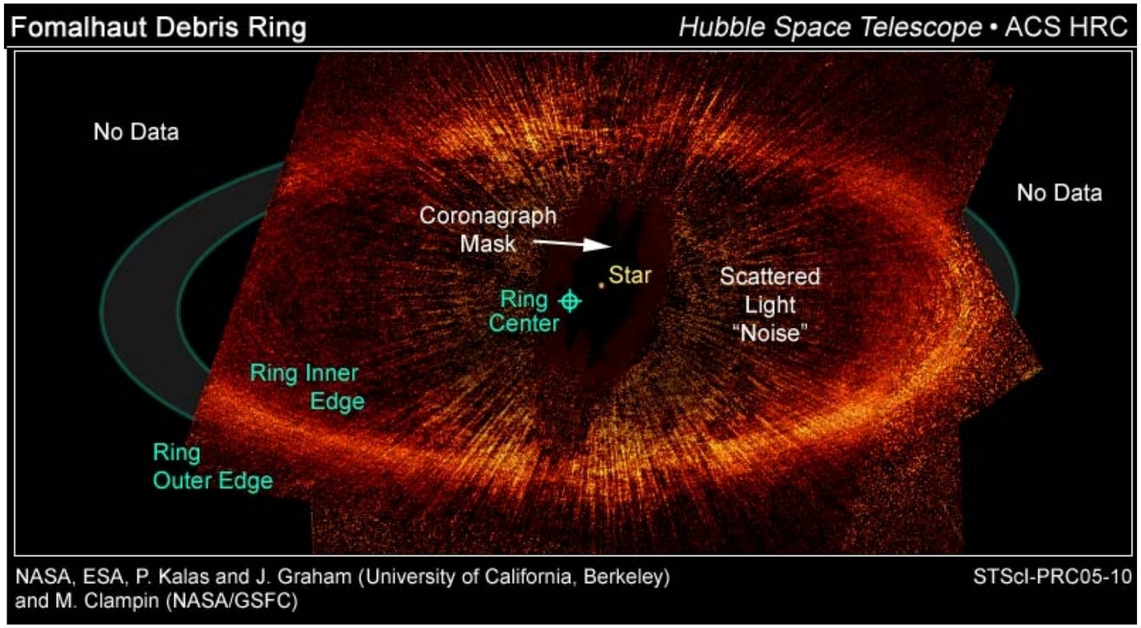
Disks evolve in time, due to
photoevaporative winds and viscous evolution



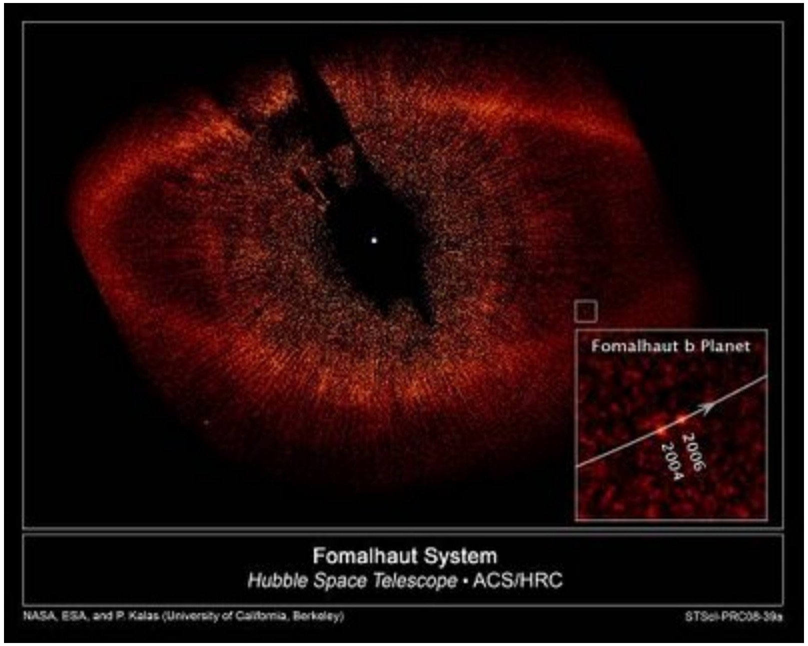
Debris disks – The gas-poor phase



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

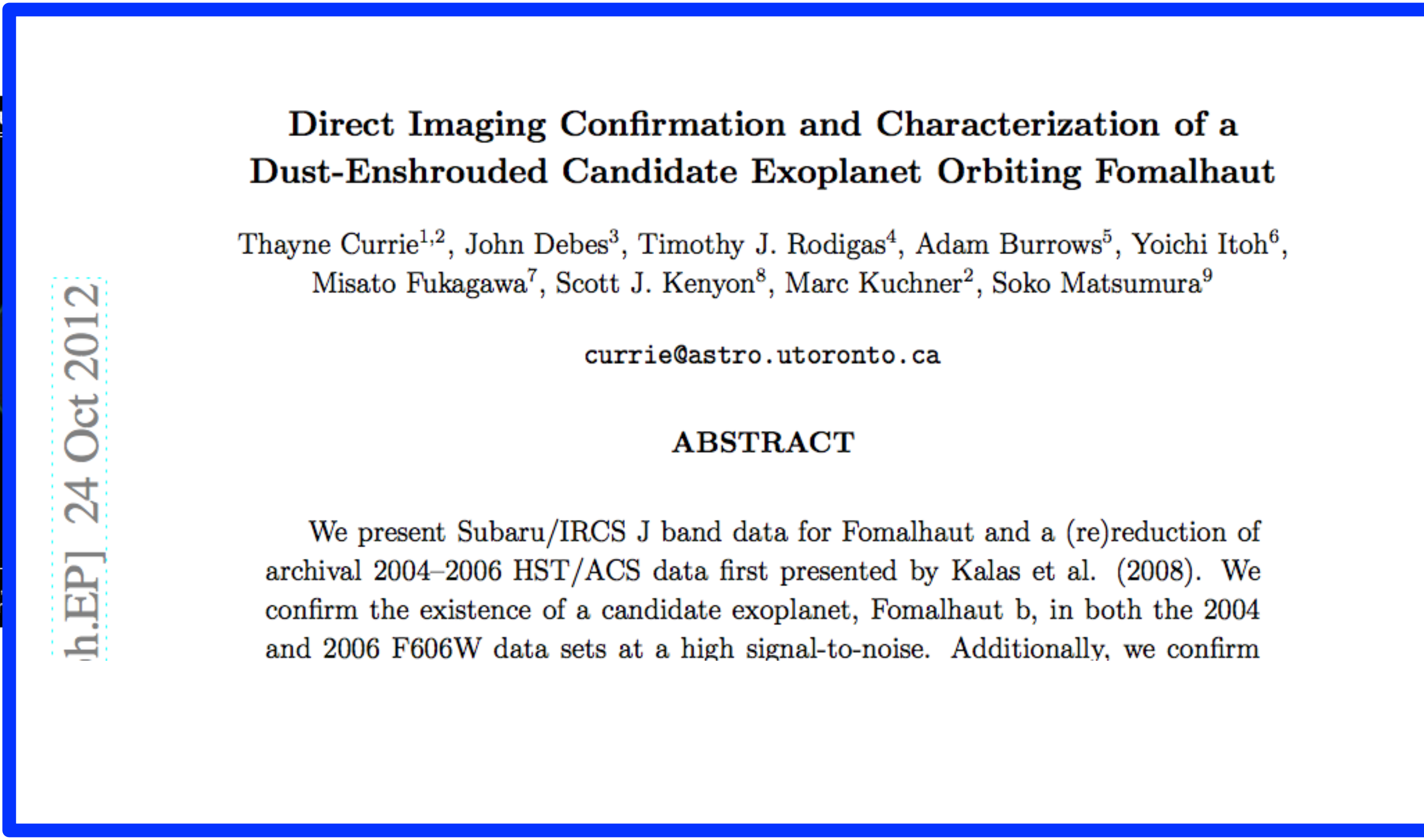
Key words: circumstellar matter – planetary systems – stars: early-type

Online-only material: color figures

Planet not detected in infrared

Sharp and eccentric rings in debris disks:
Signposts of planets

However (take two)…..



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

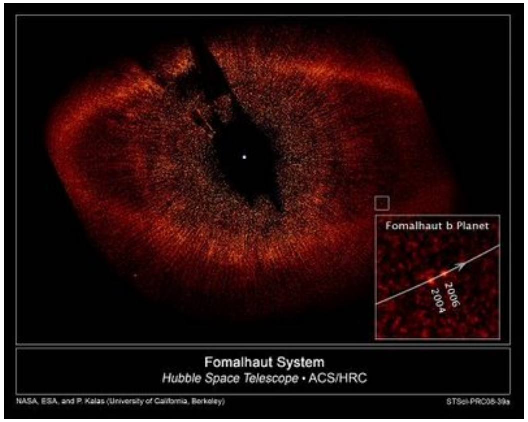
Currie et al. 2012

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.

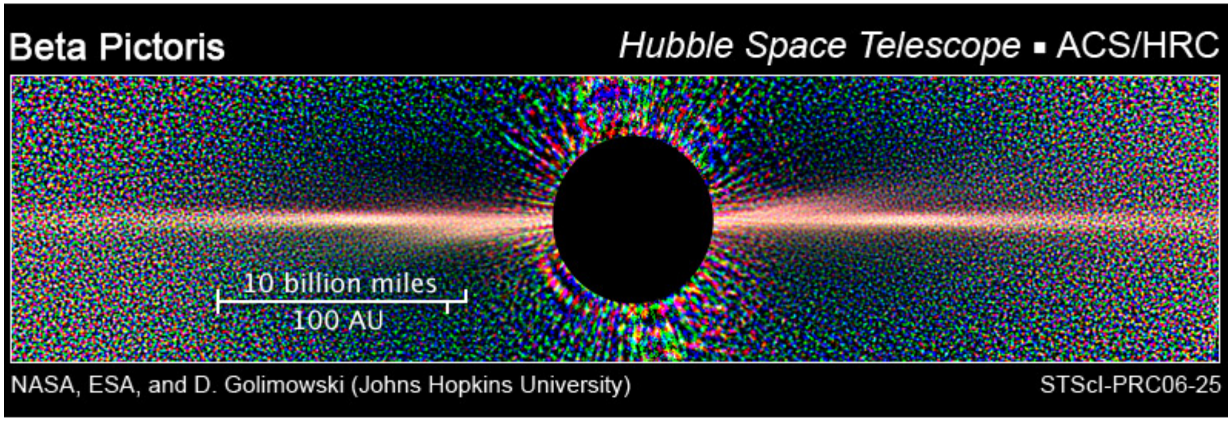
Observed optical emission requires reflection by ***something*** of several Jupiter radii



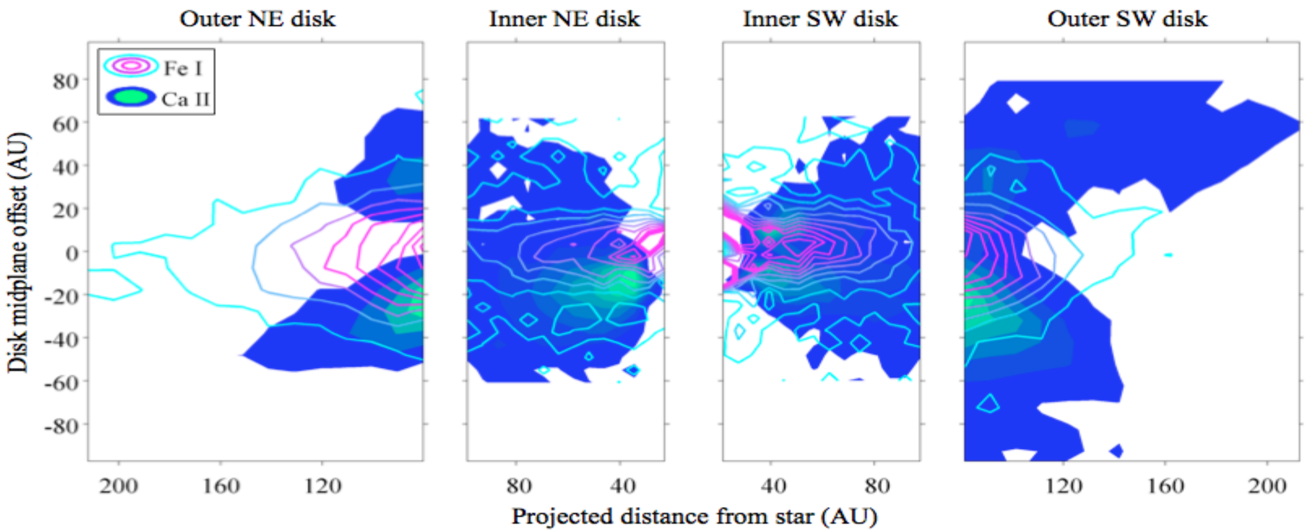
Are there alternative explanations?

Debris disks are not completely gas-free

Dust



Gas



VLT imaging by Nilsson et al. (2012)

Gas in debris disks

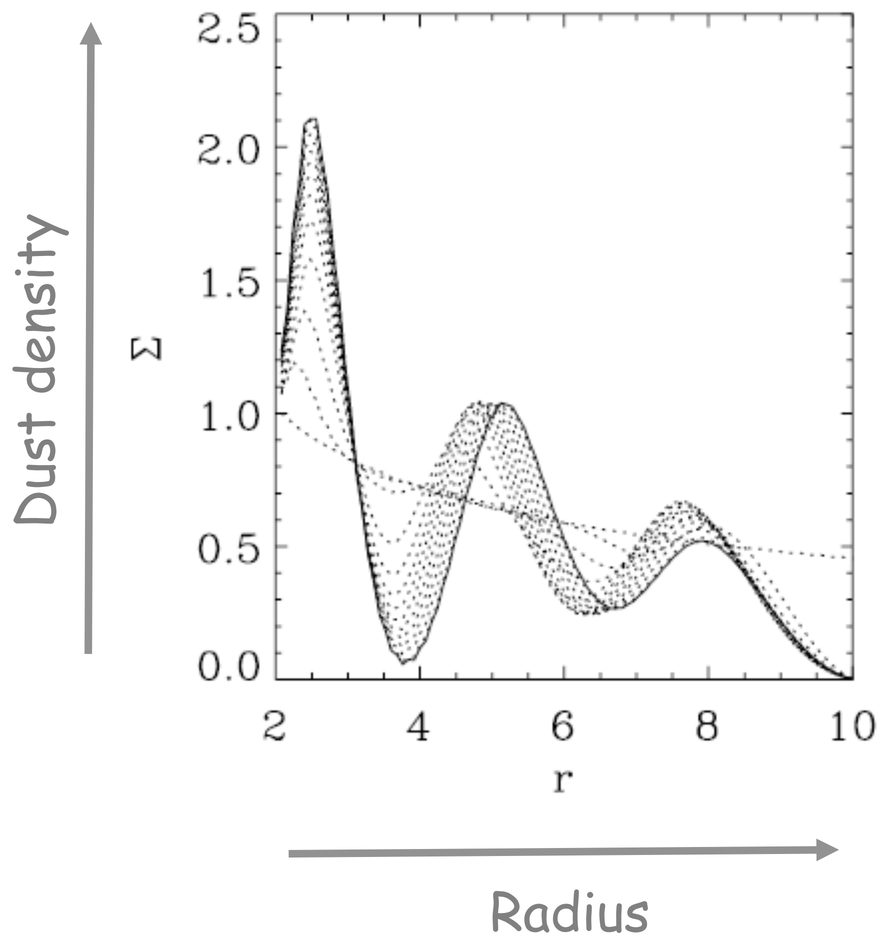
Detections

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?	

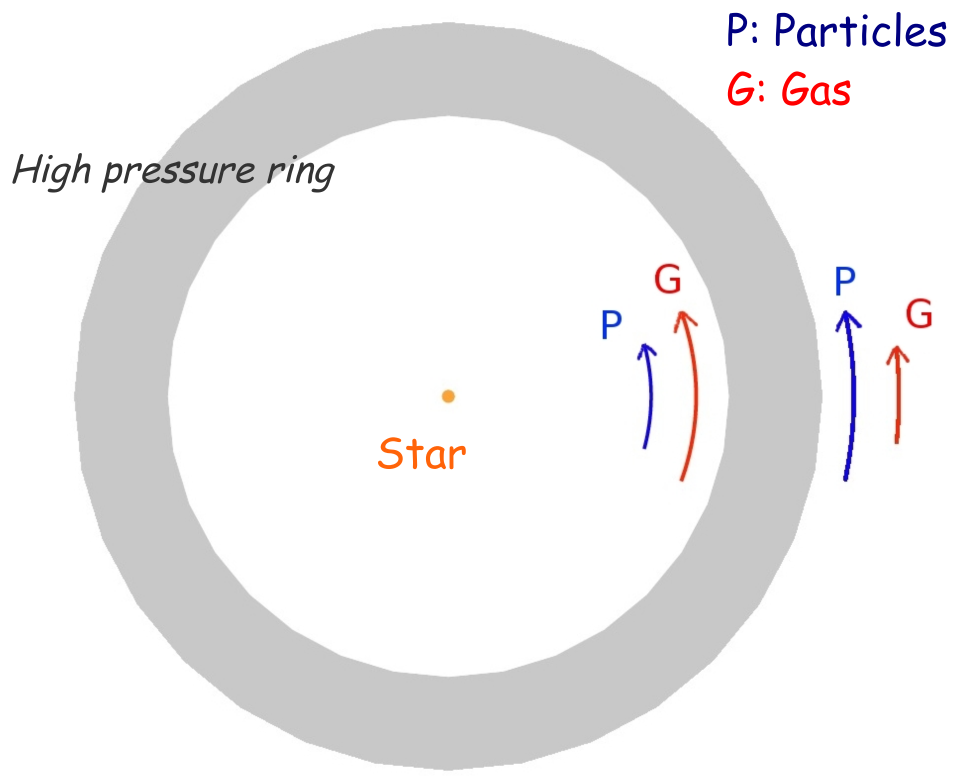
Dust and gas together leads to instability...



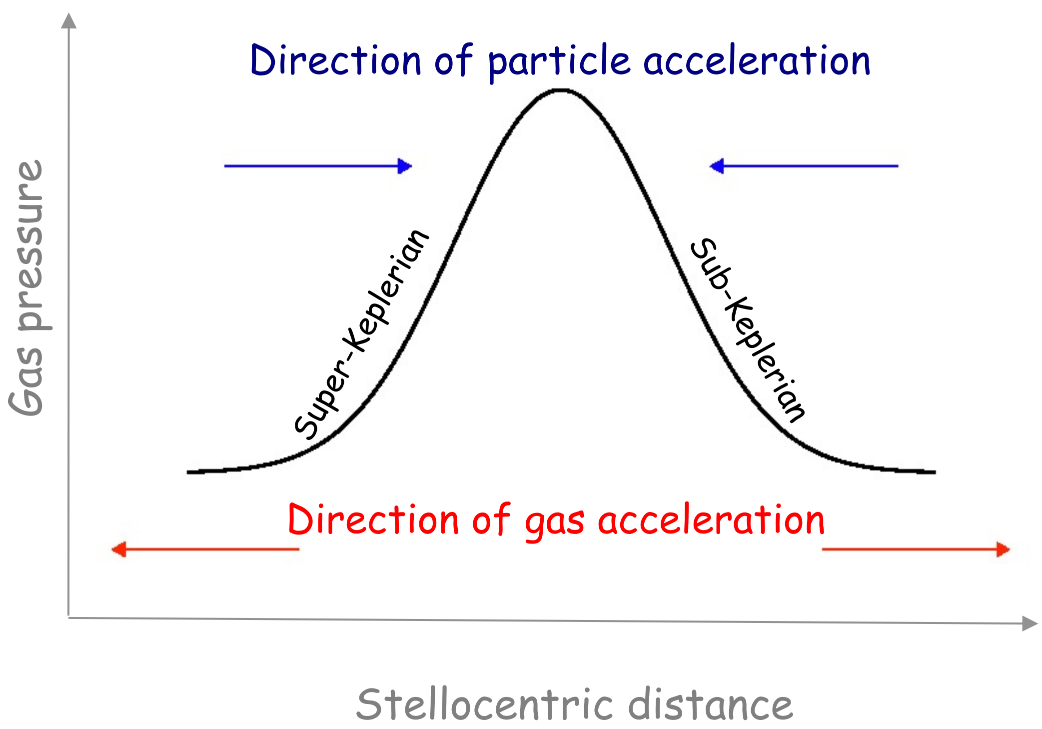
Klahr & Lin (2005)

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

Particles move toward pressure maxima

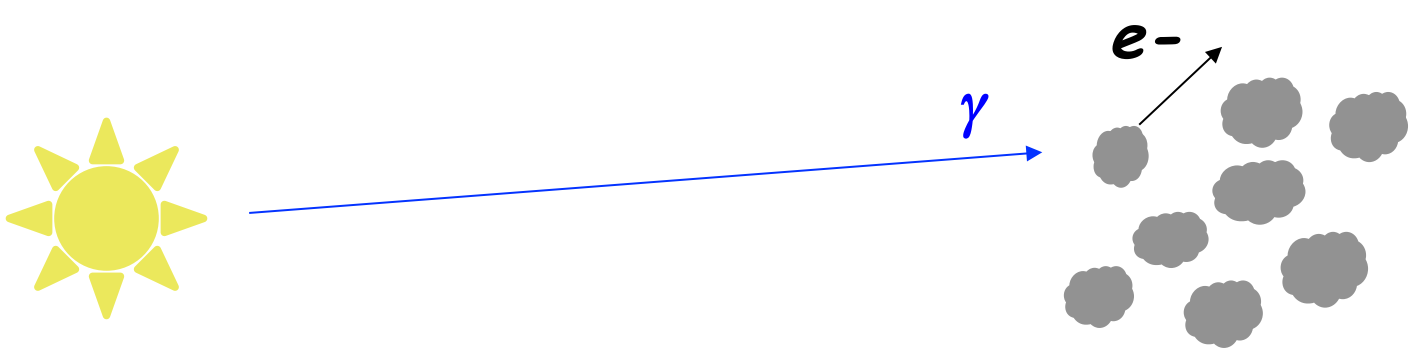


Adapted from Whipple (1972)



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

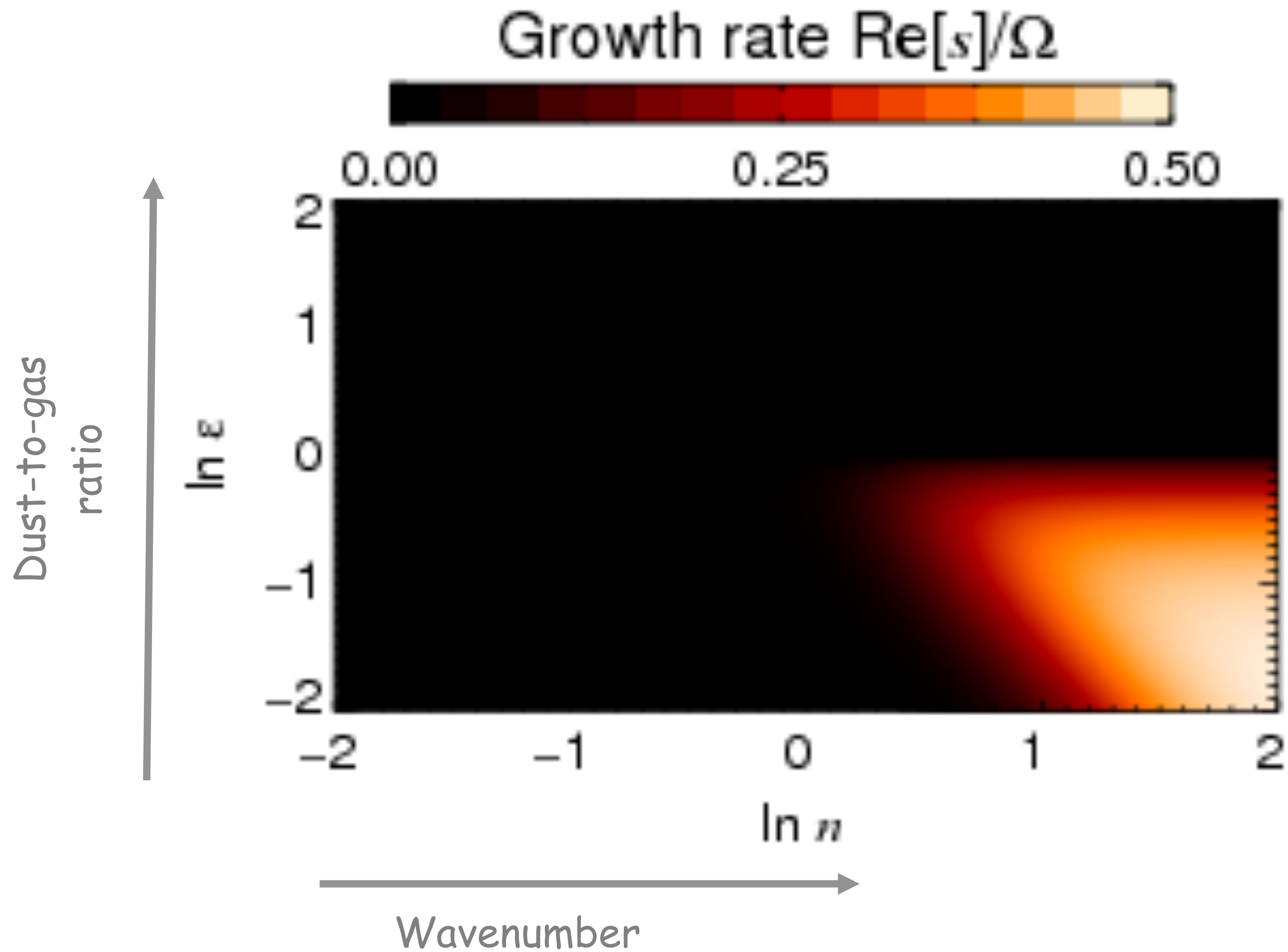
Runaway process: instability

Dust heats gas

Heated gas = high pressure region

High pressure concentrates dust

Linear Analysis



Photoelectric Instability

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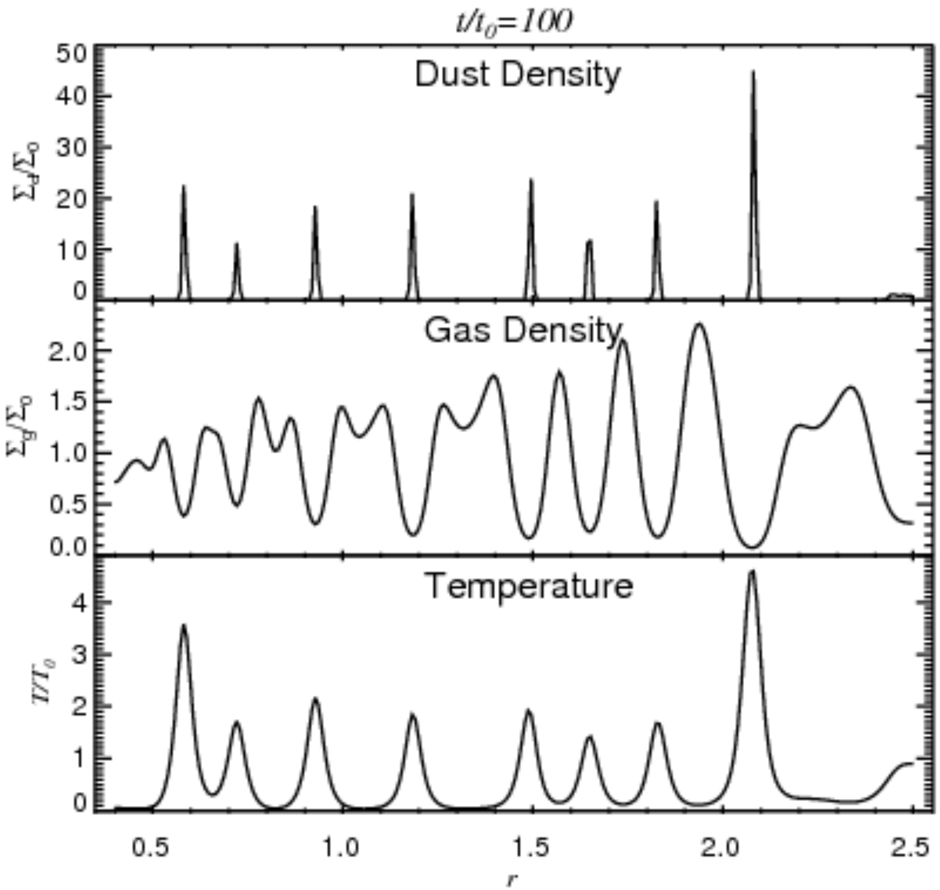
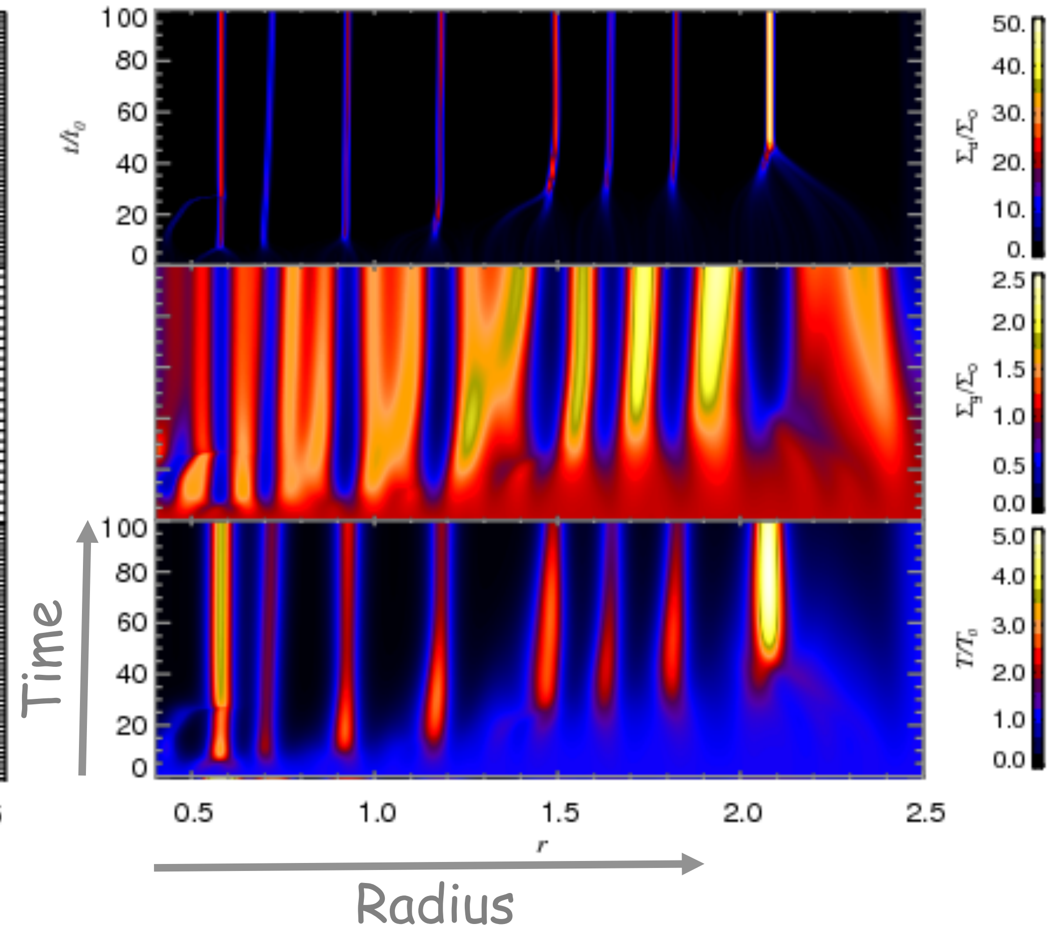




Narrow hot dust rings

Cold gas collects between rings

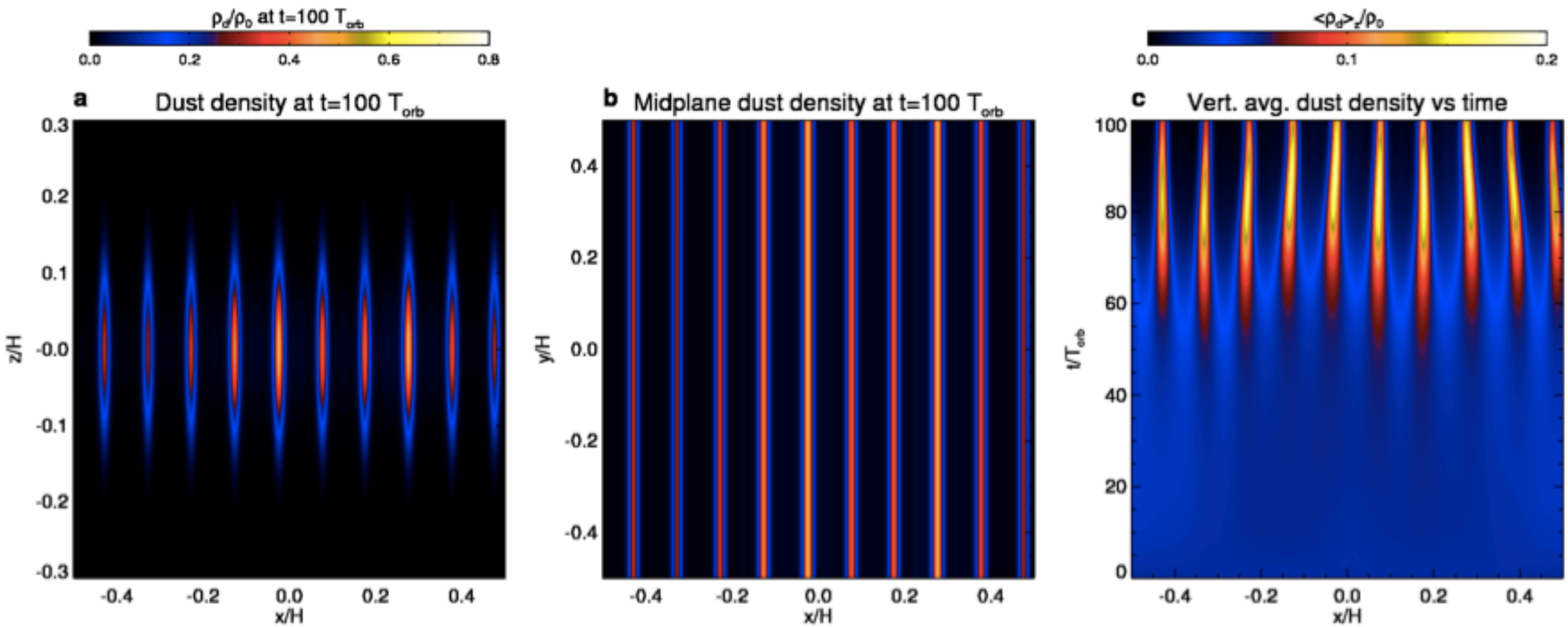
Photoelectric Instability

Dust heats gas

Heated gas = high pressure region

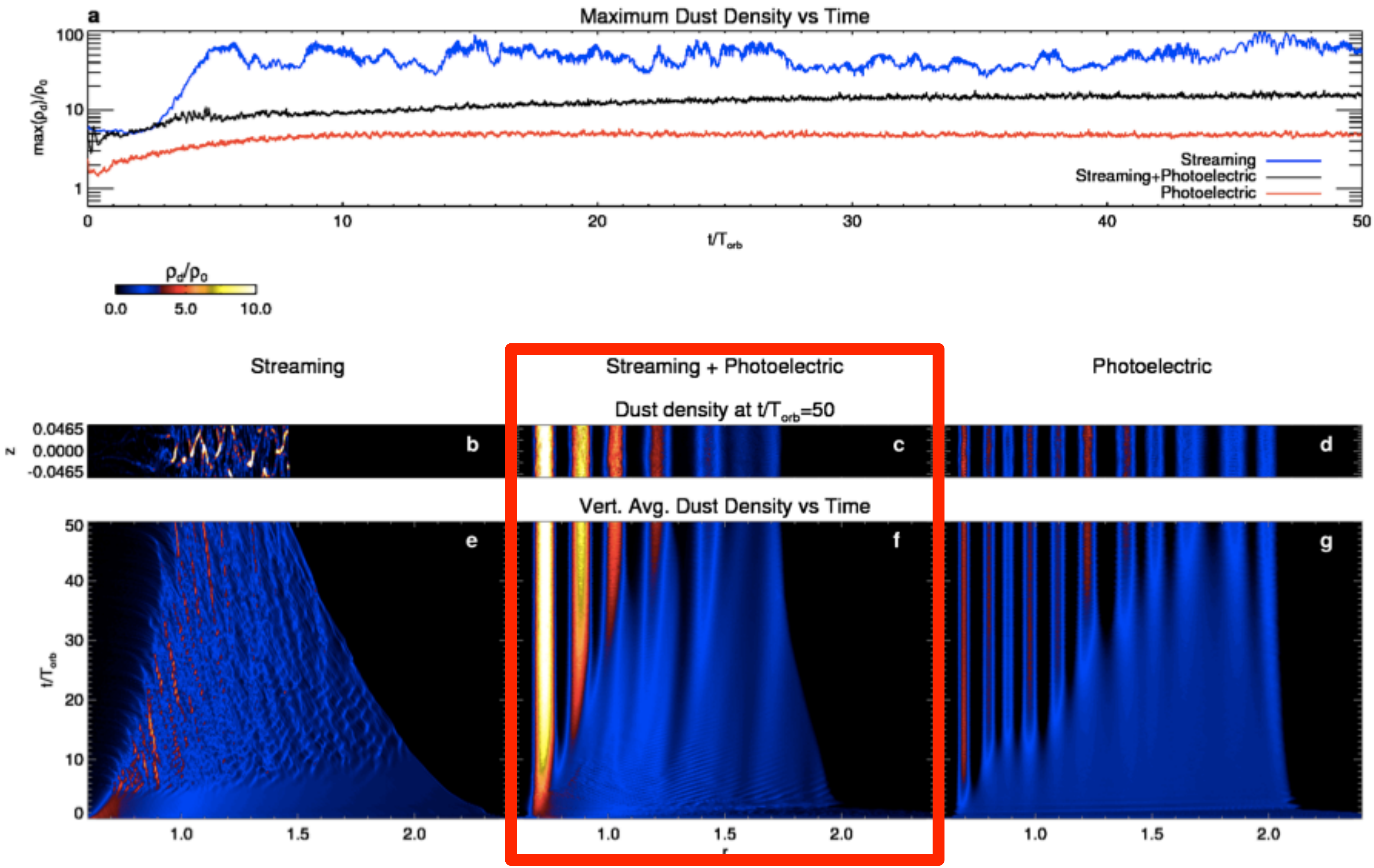
High pressure concentrates dust

3D Stratified



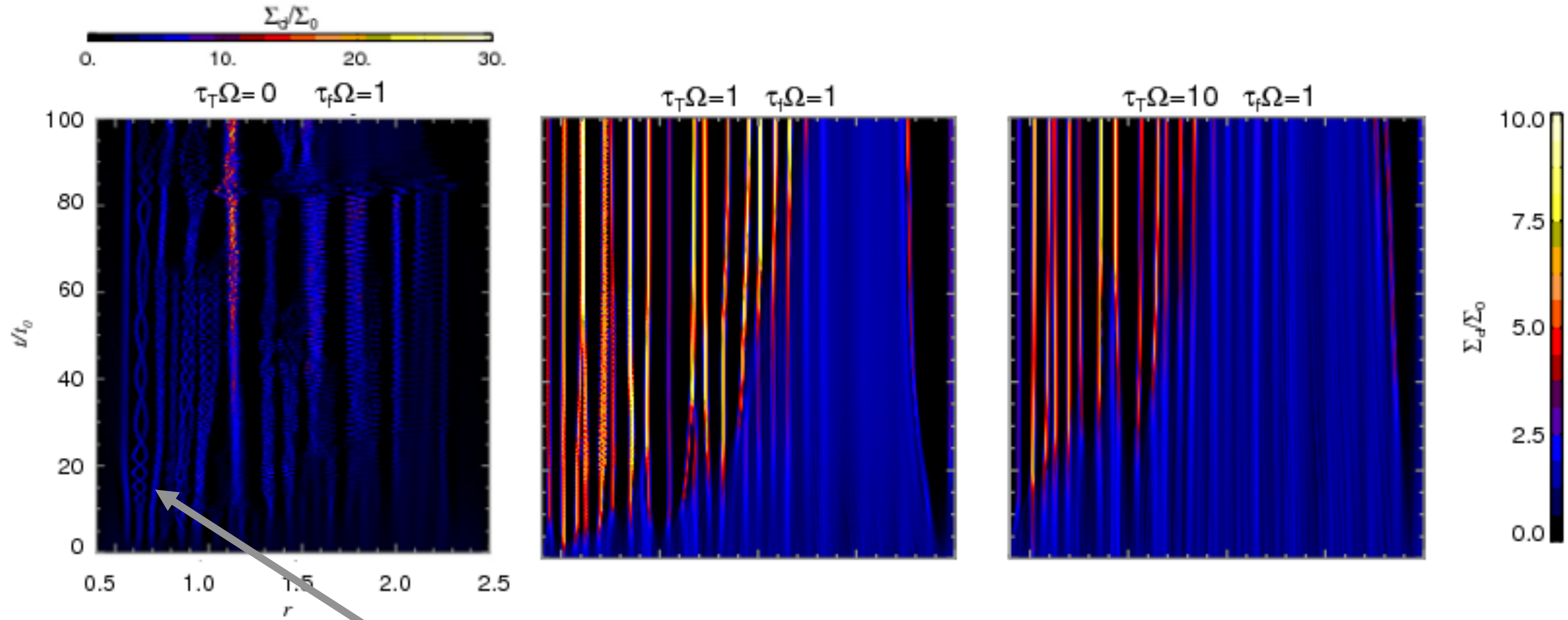
Photoelectric vs Streaming Instability

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



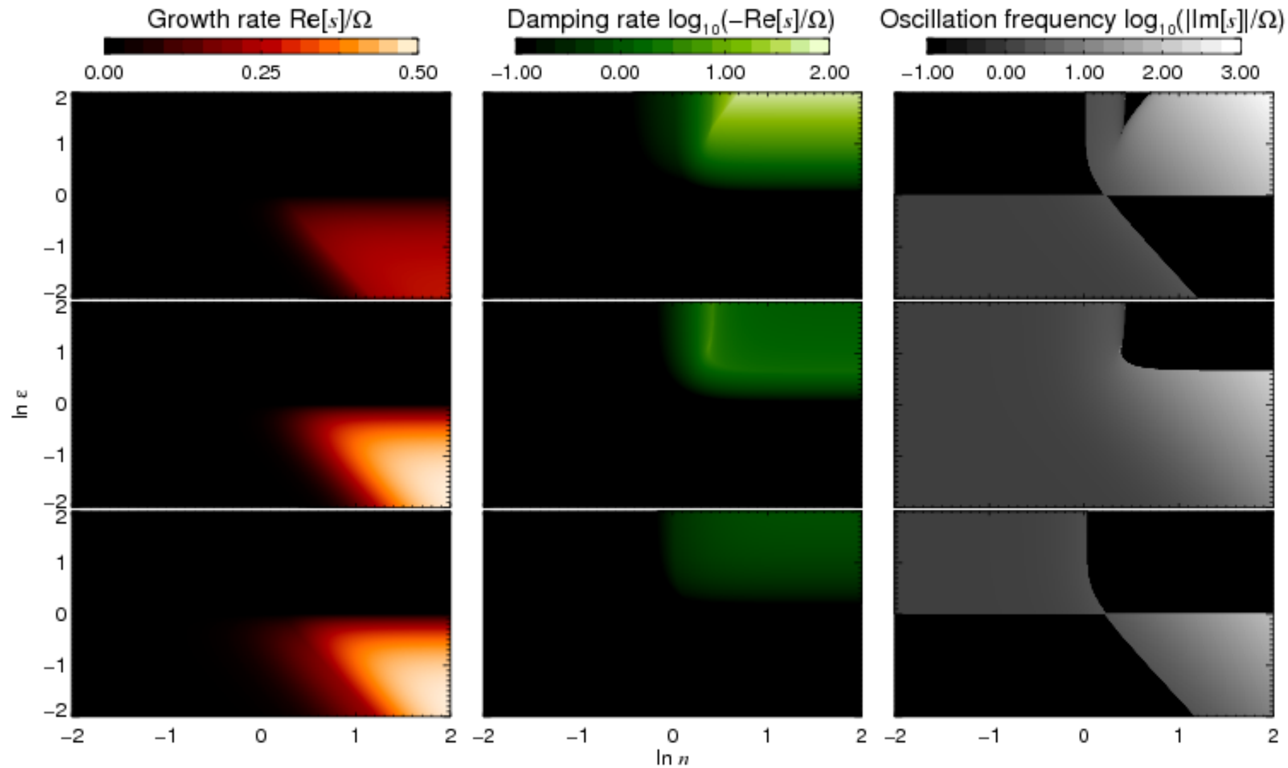
Oscillations

Thermal coupling time



Oscillations appear
with decreasing thermal time.

Solutions

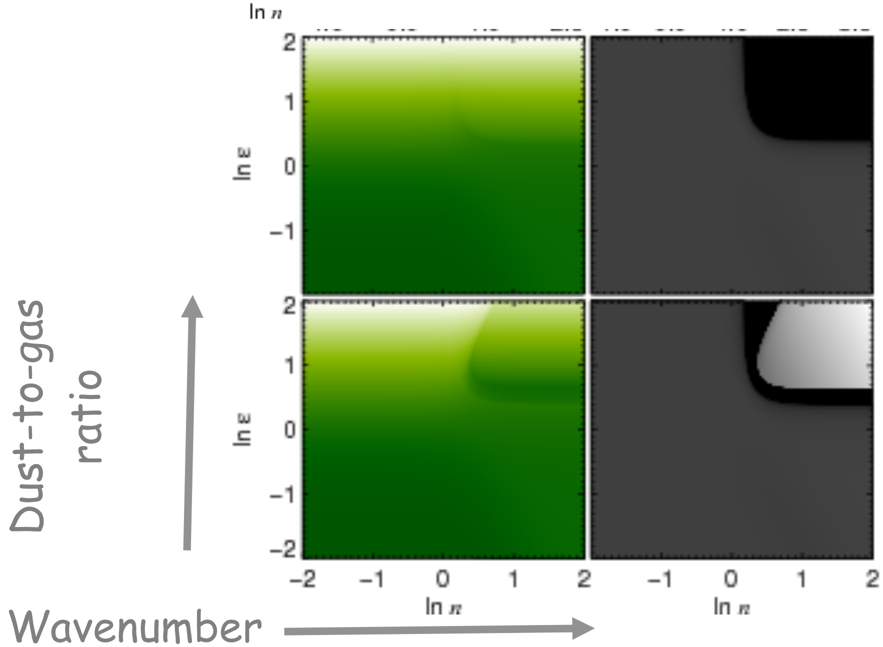


Dispersion relation

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

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

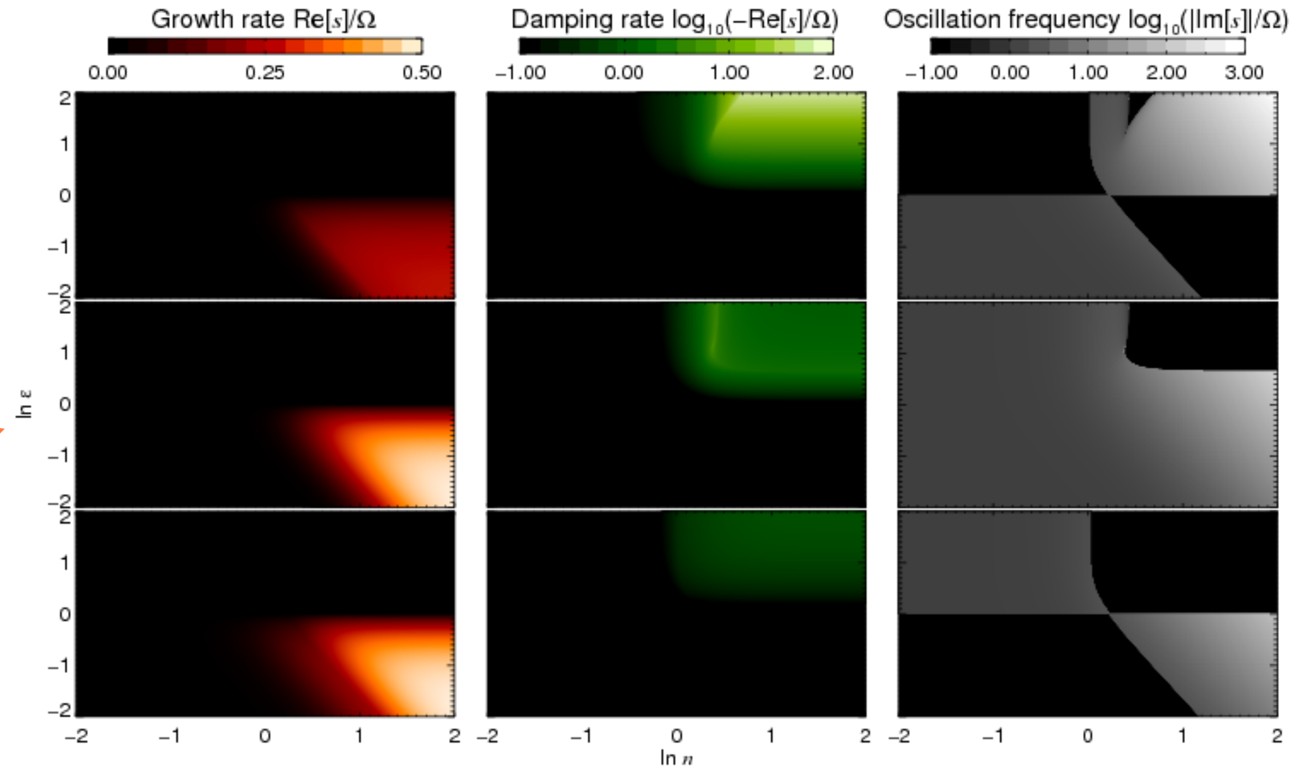
$\epsilon = \Sigma_d / \Sigma_g$ $\quad n = kH$ $\quad \omega = s/\Omega$



Solutions

Instability

Overstability



Damped and free Oscillations

Dispersion relation

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$$A = 1$$
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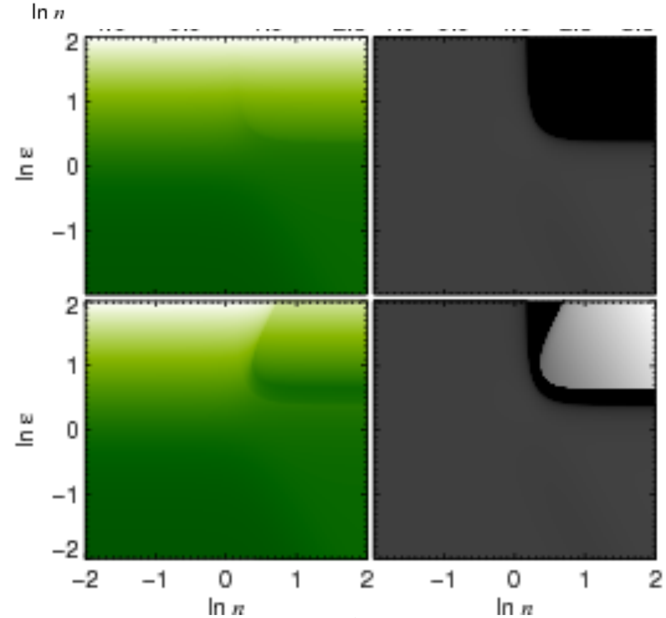


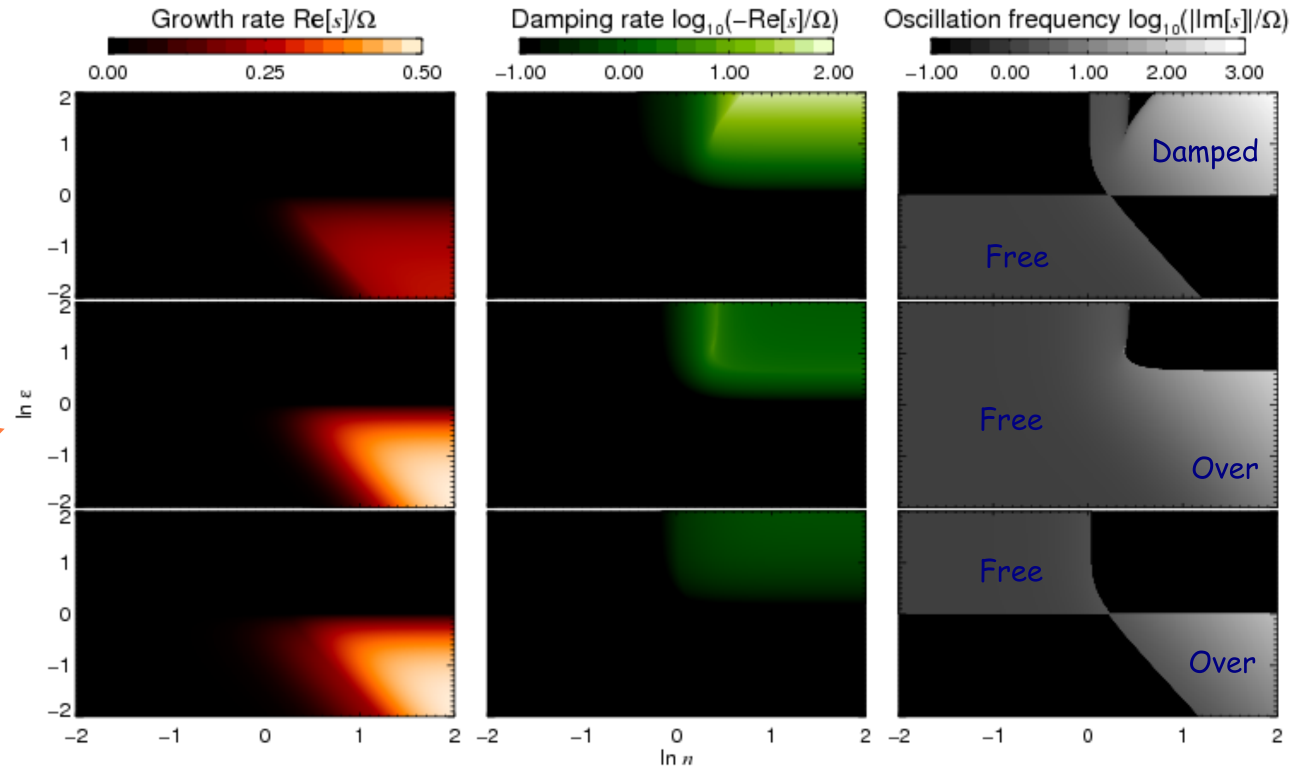
Dust-to-gas ratio

Wavenumber

Solutions

Instability

Overstability



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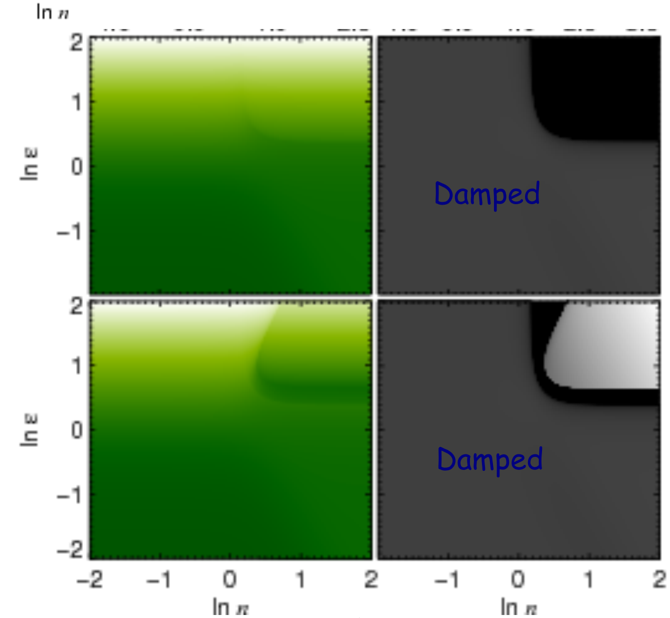
Dust-to-gas ratio



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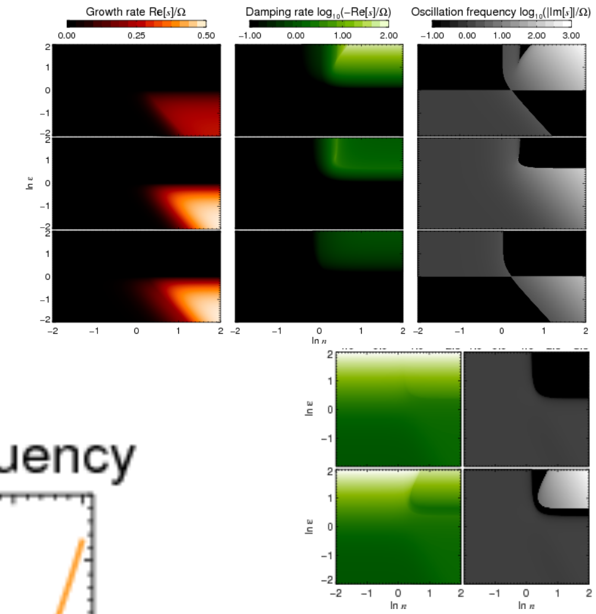
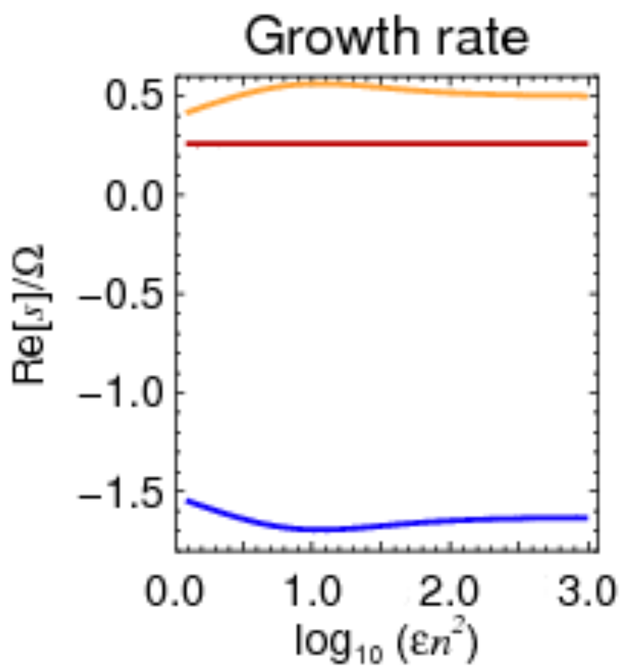
Solutions

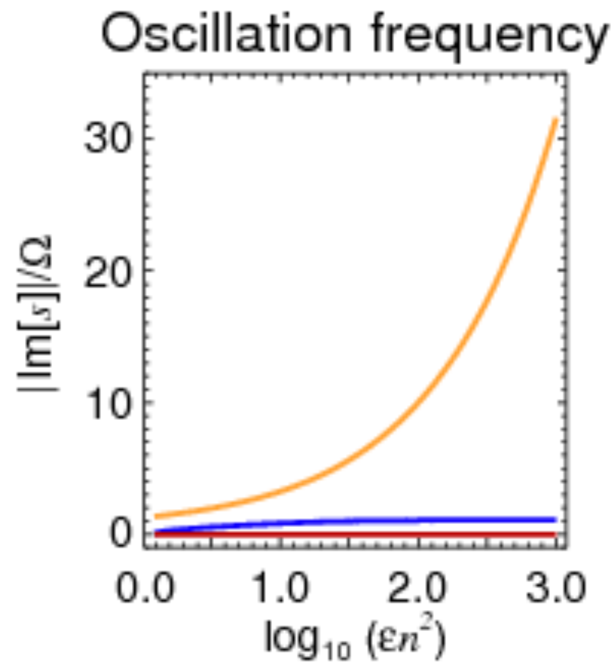


Overstability

Instability

Oscillations





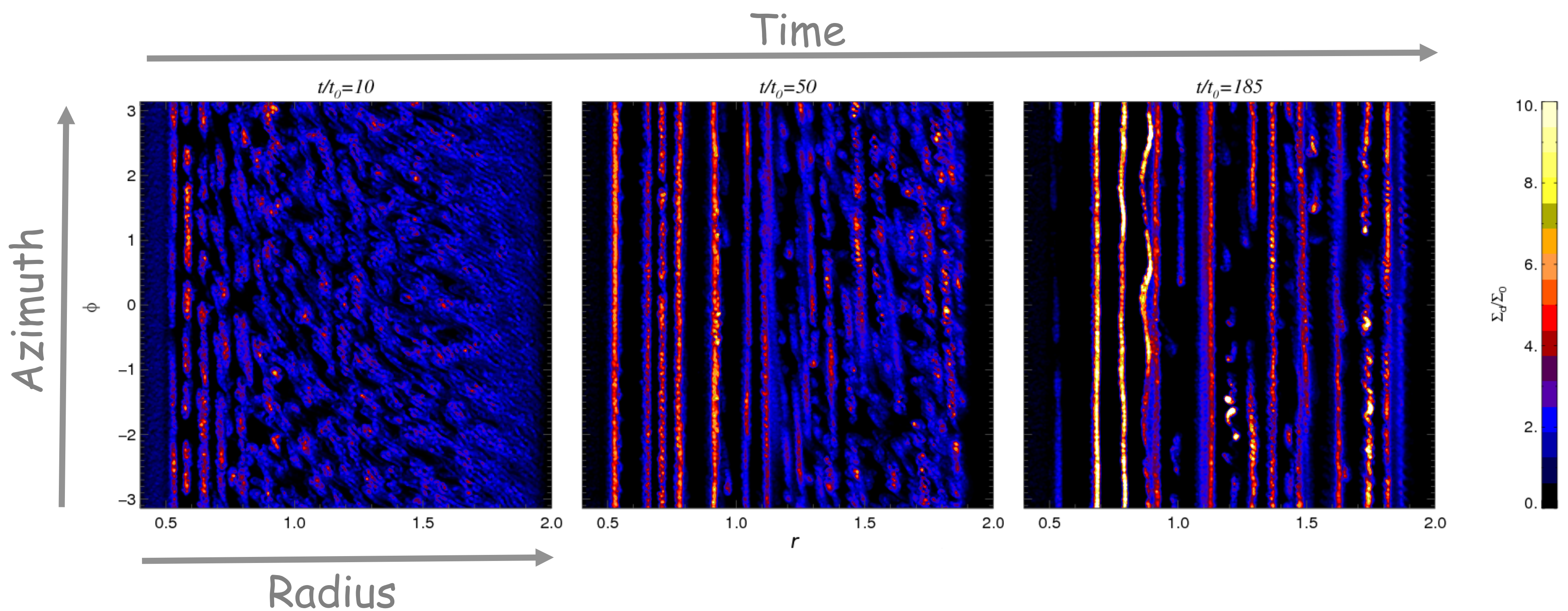
Max growth rate: Omega/2.

Million-fold amplification in five orbits!

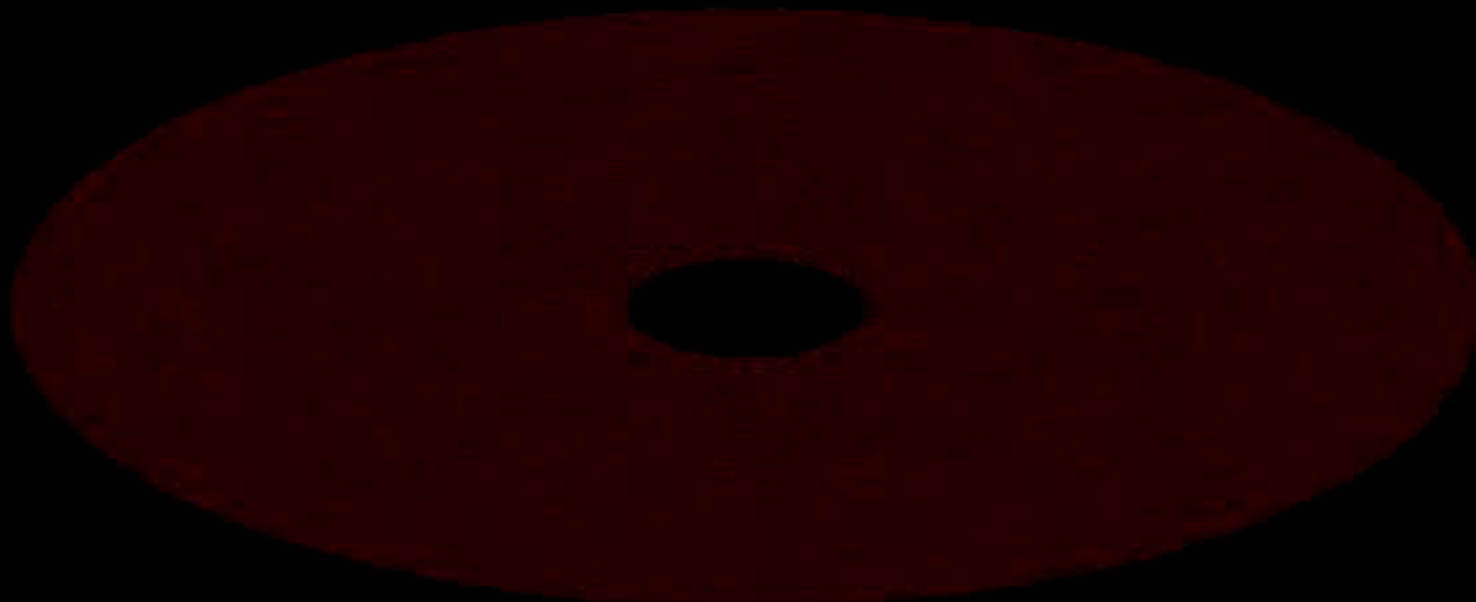
A very powerful instability.

The model in r-ϕ: Eccentric rings

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

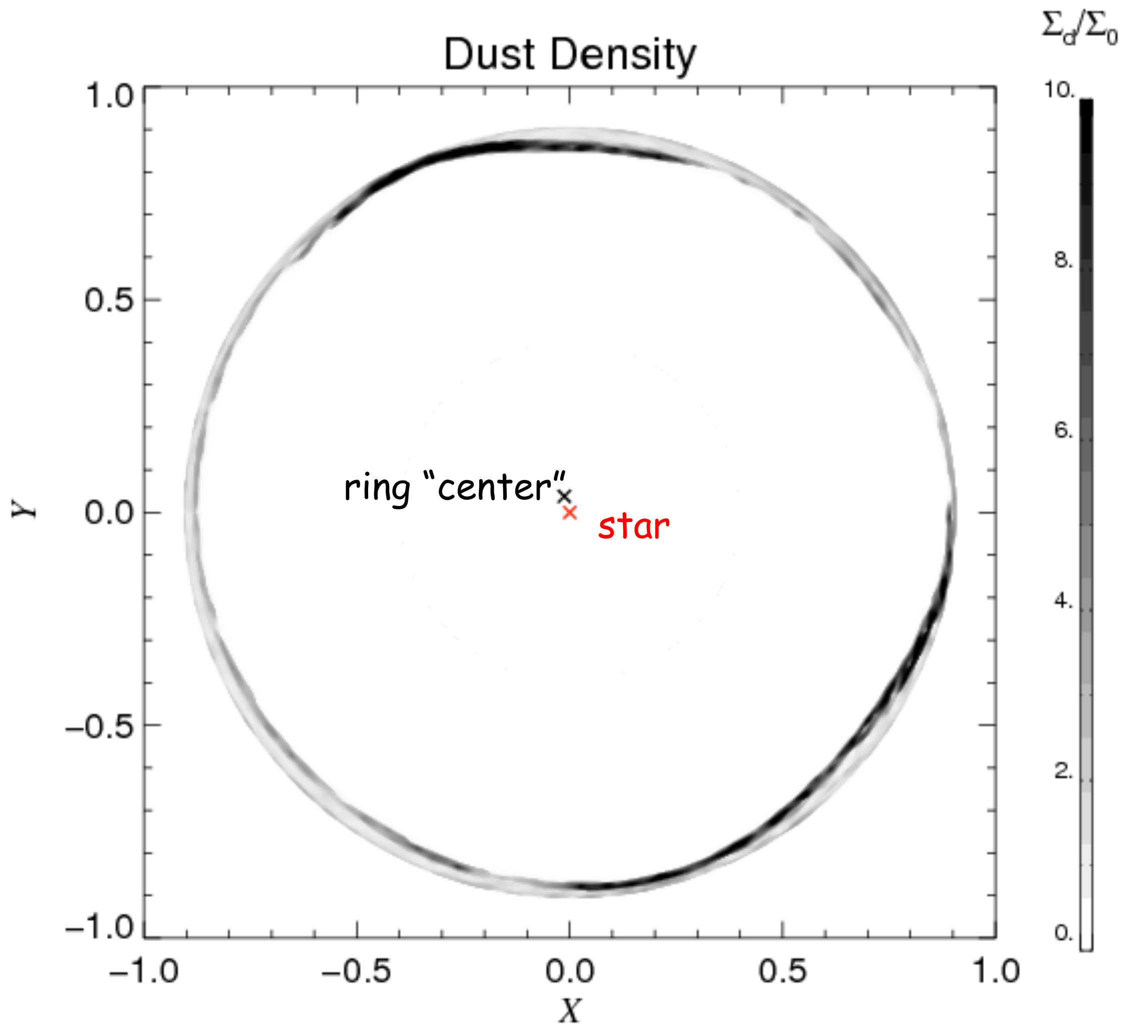


Epicyclic oscillations
make the ring appear ***eccentric !!!***



Lyra & Kuchner (2013, Nature, accepted)

Ring eccentricity



Eccentricity e=0.04

LETTER

doi:10.1038/nature12281

Formation of sharp eccentric rings in debris disks with gas but without planets

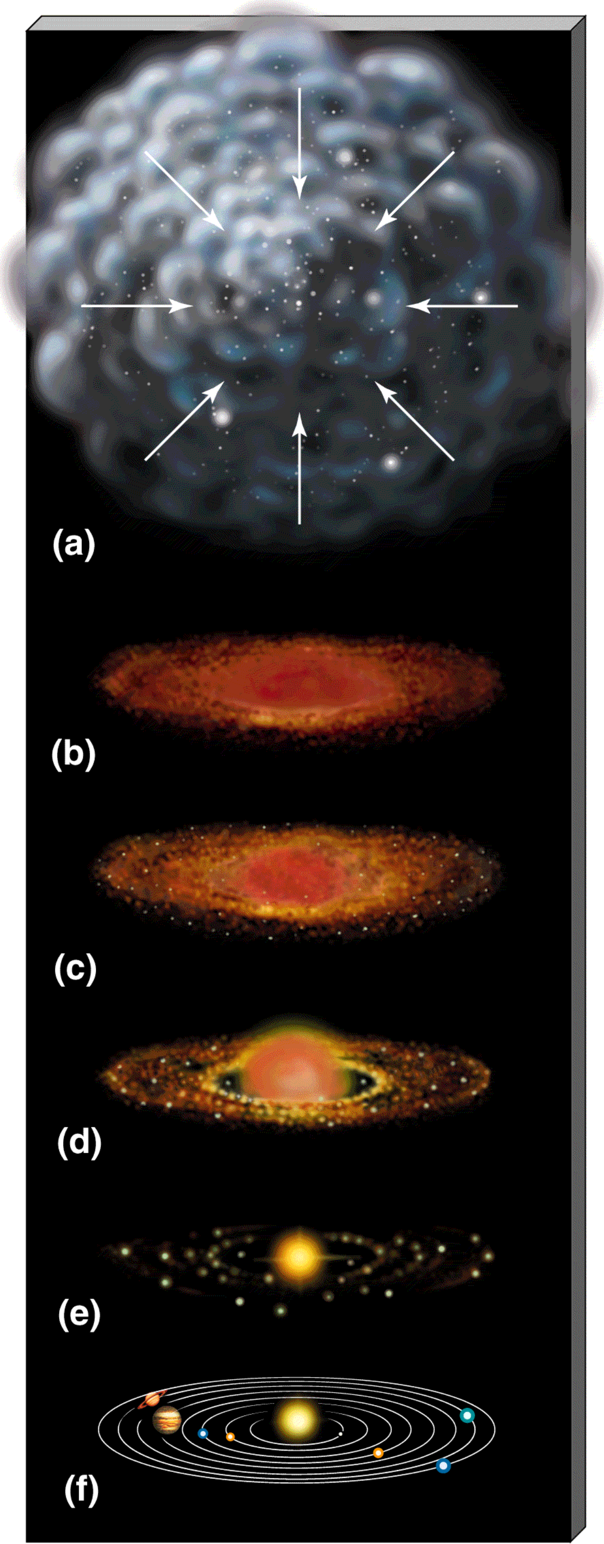
W. Lyra[1,2,3] & M. Kuchner[4]

'Debris disks' around young stars (analogues of the Kuiper Belt in our Solar System) show a variety of non-trivial structures attributed to planetary perturbations and used to constrain the properties of those planets[1–3]. However, these analyses have largely ignored the fact that some debris disks are found to contain small quantities of gas[4–9], a component that all such disks should contain at some level[10,11]. Several debris disks have been measured with a dust-to-gas ratio of about unity[4–9], at which the effect of hydrodynamics on the structure of the disk cannot be ignored[12,13]. Here we report linear and nonlinear modelling that shows that dust–gas interactions can produce some of the key patterns attributed to planets. We find a robust clumping instability that organizes the dust into narrow, eccentric rings, similar to the Fomalhaut debris disk[14]. The conclusion that such disks might contain planets is not necessarily required to explain these systems.

Disks around young stars seem to pass through an evolutionary phase when the disk is optically thin and the dust-to-gas ratio ε ranges from 0.1 to 10. The nearby stars β Pictoris[5,6,15–17], HD32297 (ref. 7), 49 Ceti (ref. 4) and HD 21997 (ref. 9) all host dust disks resembling ordinary debris disks and also have stable circumstellar gas detected in molecular CO, Na I or other metal lines; the inferred mass of gas ranges from lunar masses to a few Earth masses (Supplementary Information). The gas in

We present simulations of the fully compressible problem, solving for the continuity, Navier–Stokes and energy equations for the gas, and the momentum equation for the dust. Gas and dust interact dynamically through a drag force, and thermally through photoelectric heating. These are parametrized by a dynamical coupling time τ_f and a thermal coupling time τ_T (Supplementary Information). The simulations are performed with the Pencil Code[21–24], which solves the hydrodynamics on a grid. Two numerical models are presented: a three-dimensional box embedded in the disk that co-rotates with the flow at a fixed distance from the star; and a two-dimensional global model of the disk in the inertial frame. In the former the dust is treated as a fluid, with a separate continuity equation. In the latter the dust is represented by discrete particles with position and velocities that are independent of the grid.

We perform a stability analysis of the linearized system of equations that should help interpret the results of the simulations (Supplementary Information). We plot in Fig. 1a–c the three solutions that show linear growth, as functions of ε and $n = kH$, where k is the radial wavenumber and H is the gas scale height ($H = c_s/\sqrt{\gamma}\Omega_K$, where c_s is the sound speed, Ω_K the Keplerian rotation frequency and γ the adiabatic index). The friction time τ_f is assumed to be equal to $1/\Omega_K$. The left and middle panels show the growth and damping rates. The



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.

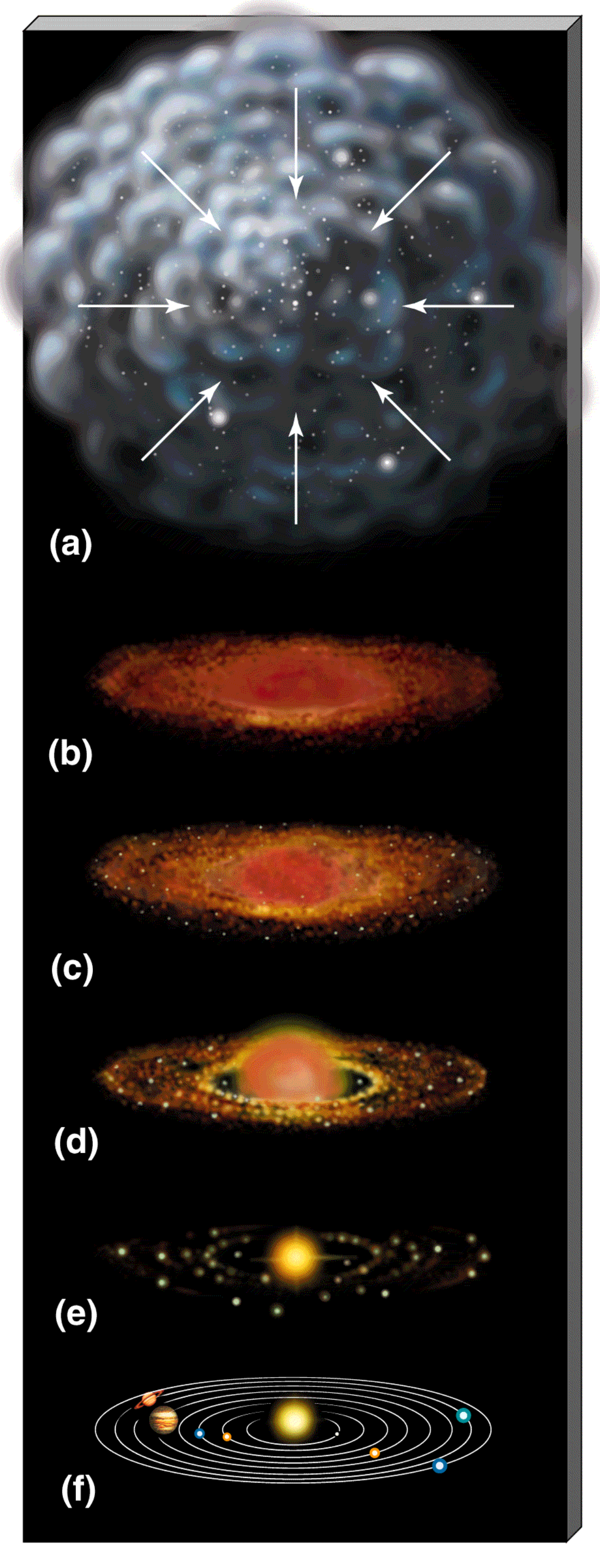
Convergent migration leads to resonances, these are disrupted by turbulent forcing. Collisions between embryos gives rise to oligarchs.

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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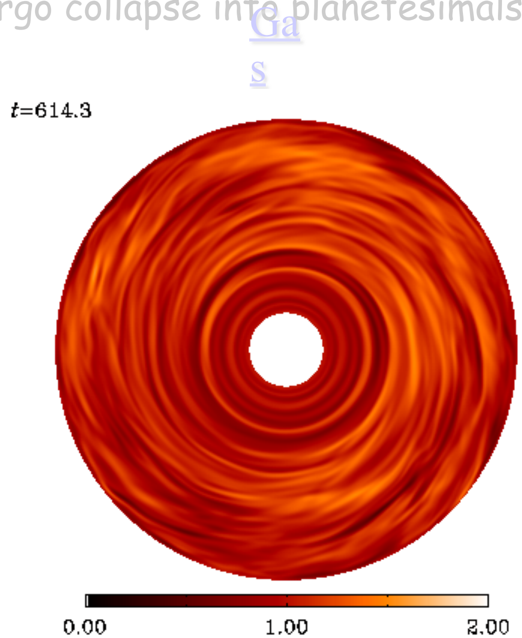

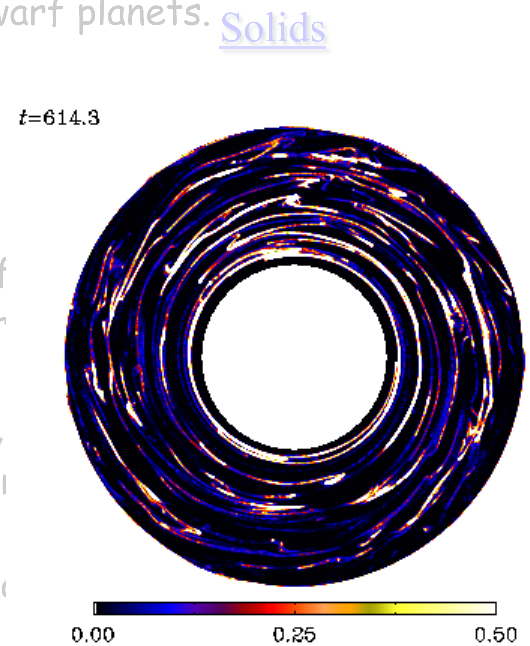

Vort… one. … Mars-mass

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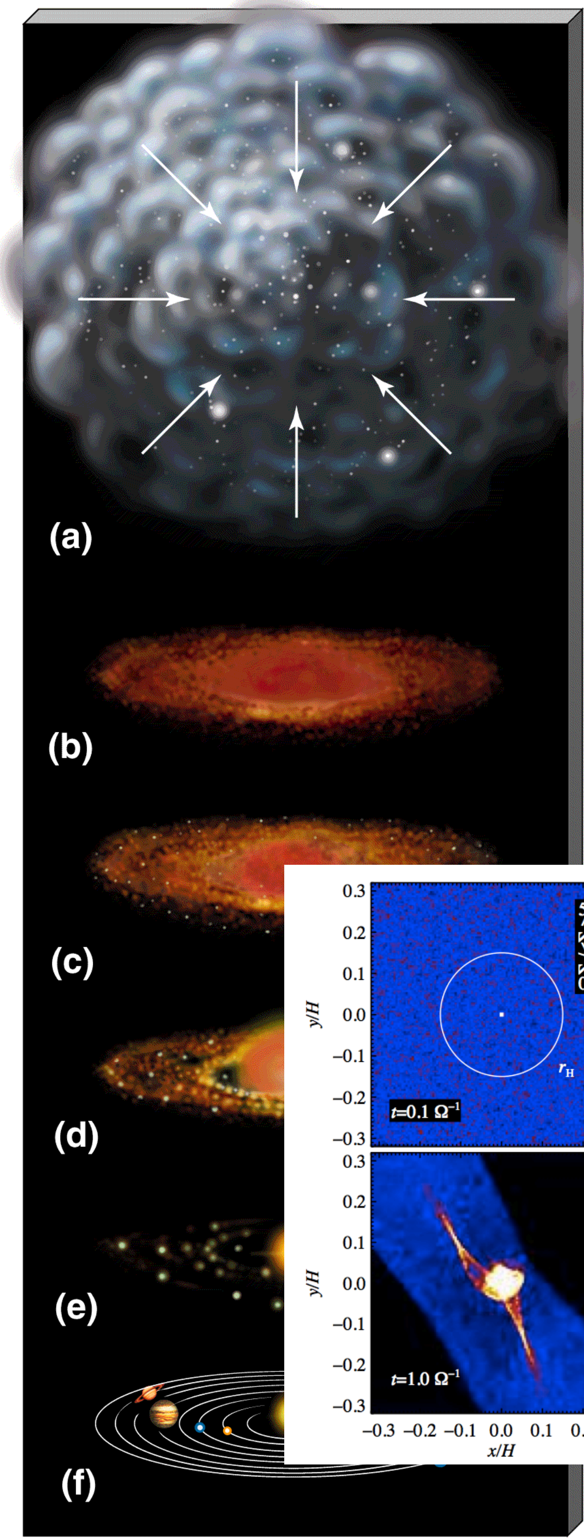

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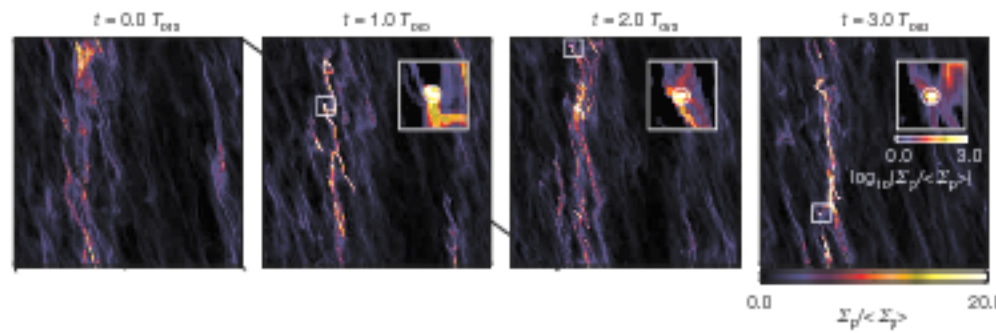

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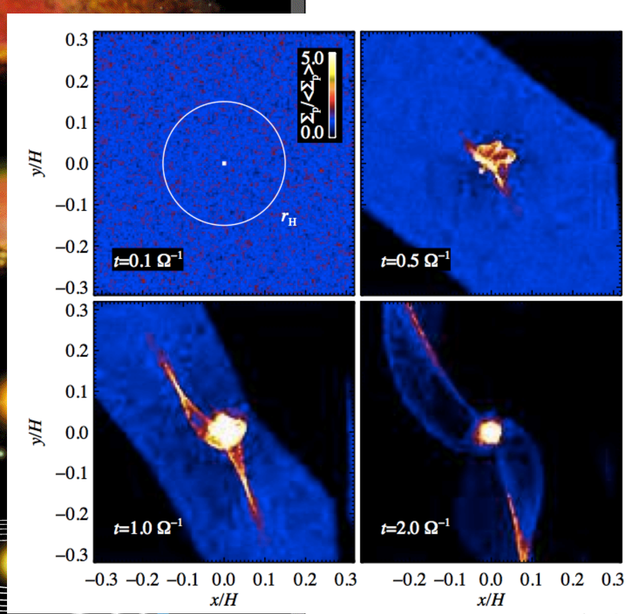

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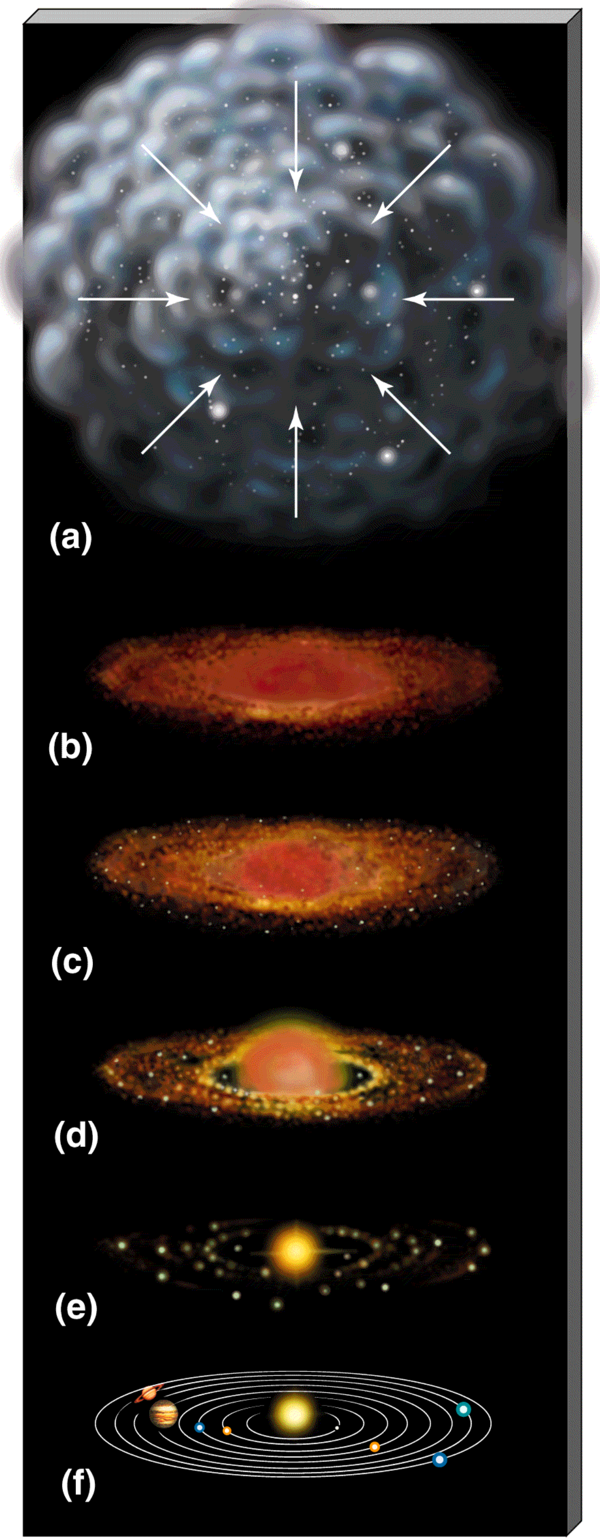

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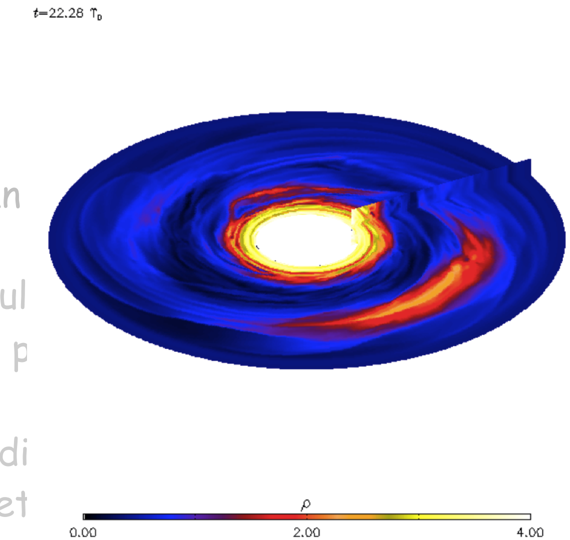

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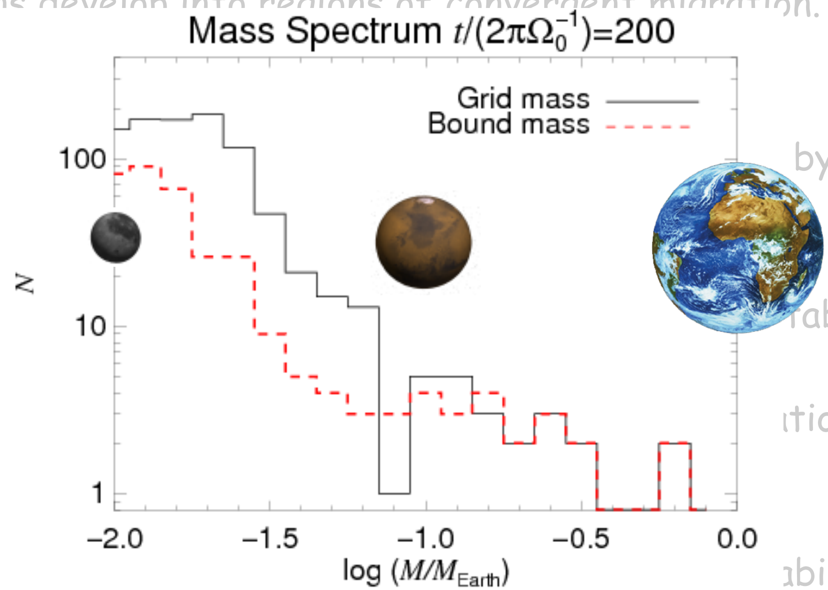

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N-body interac ation produce the
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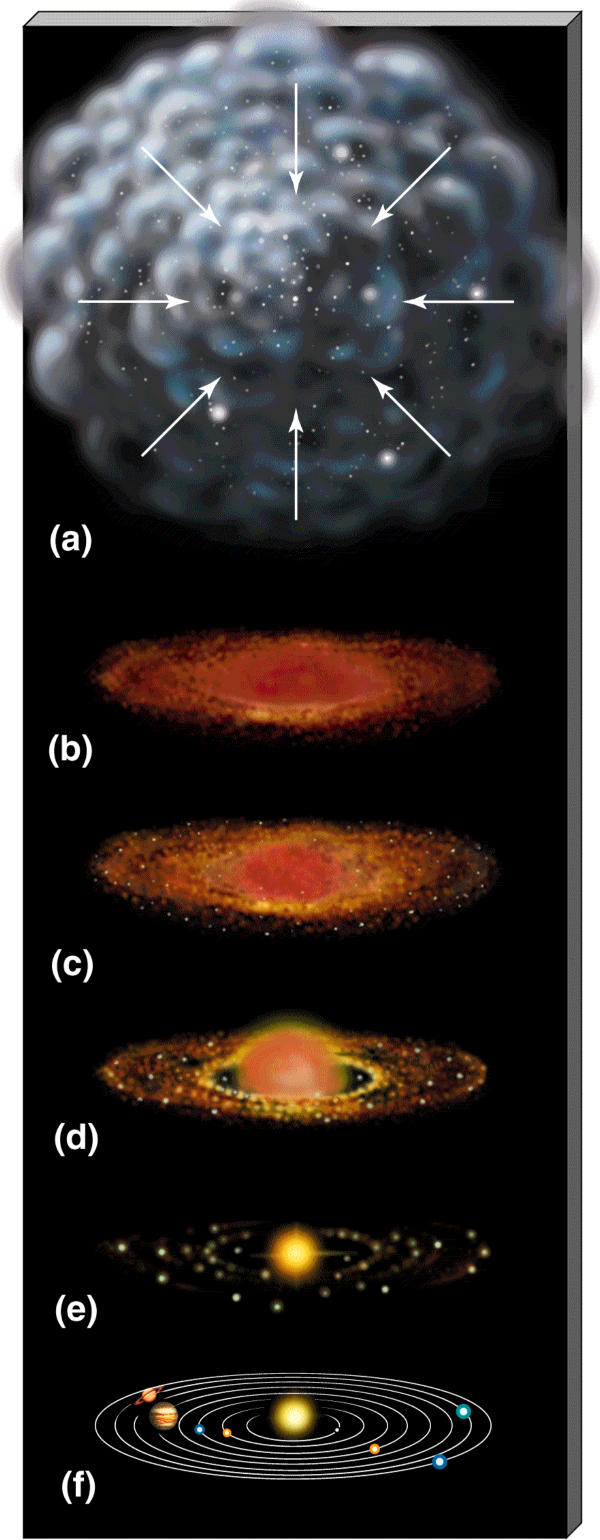

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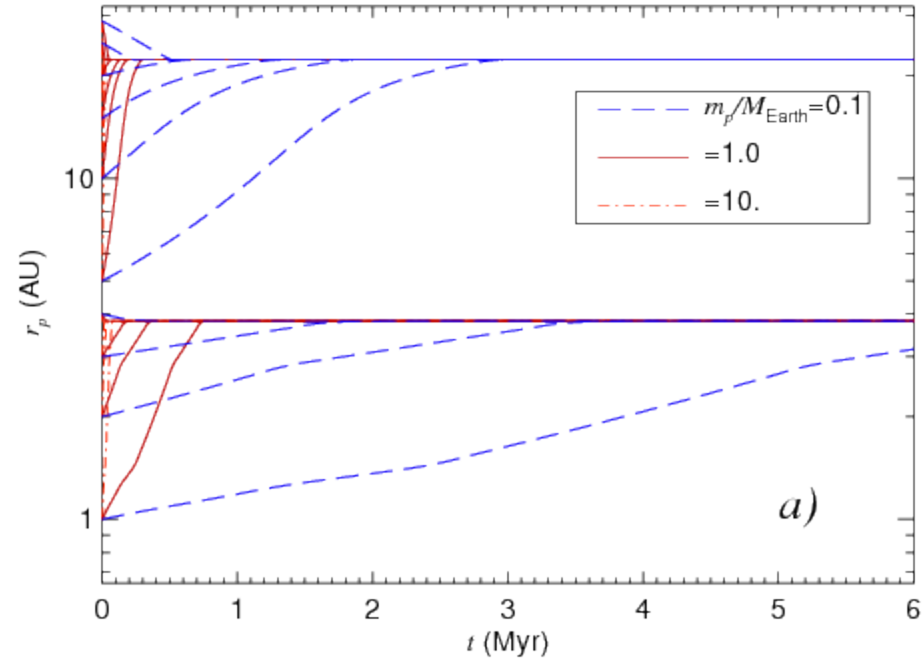

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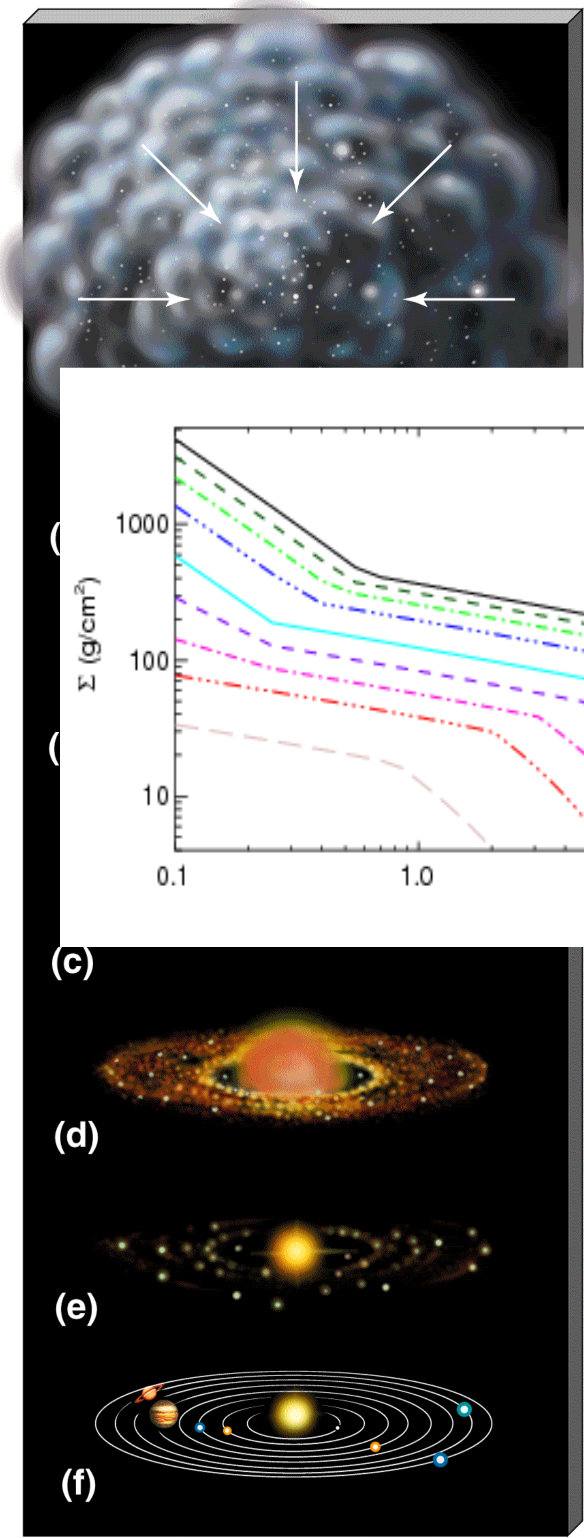

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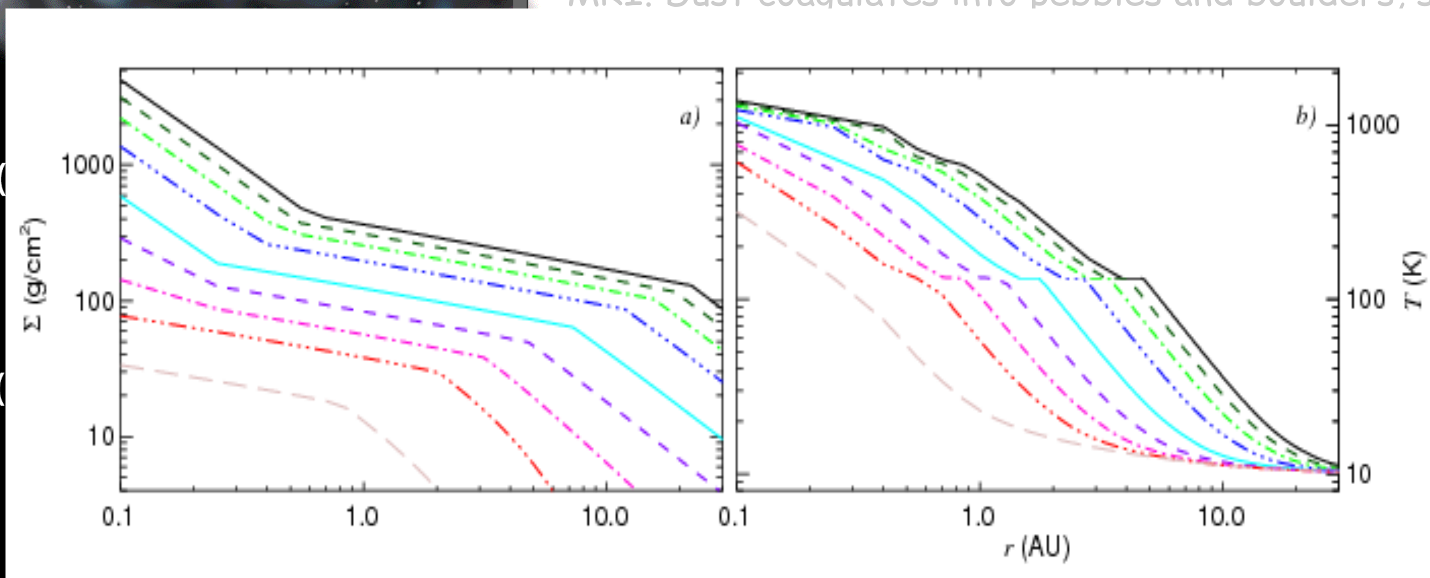

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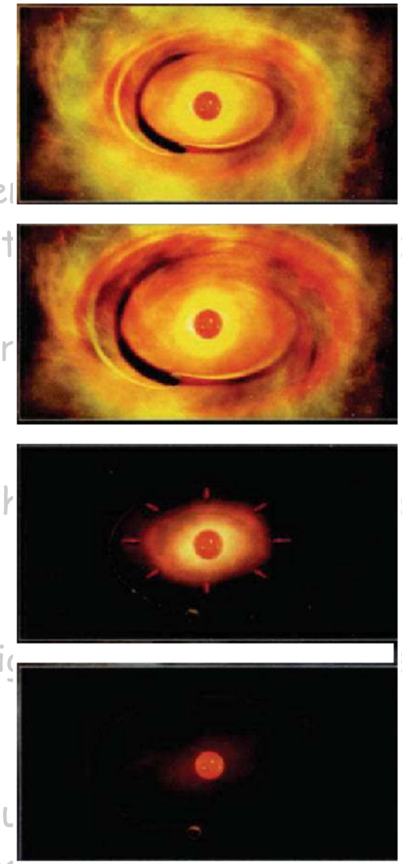

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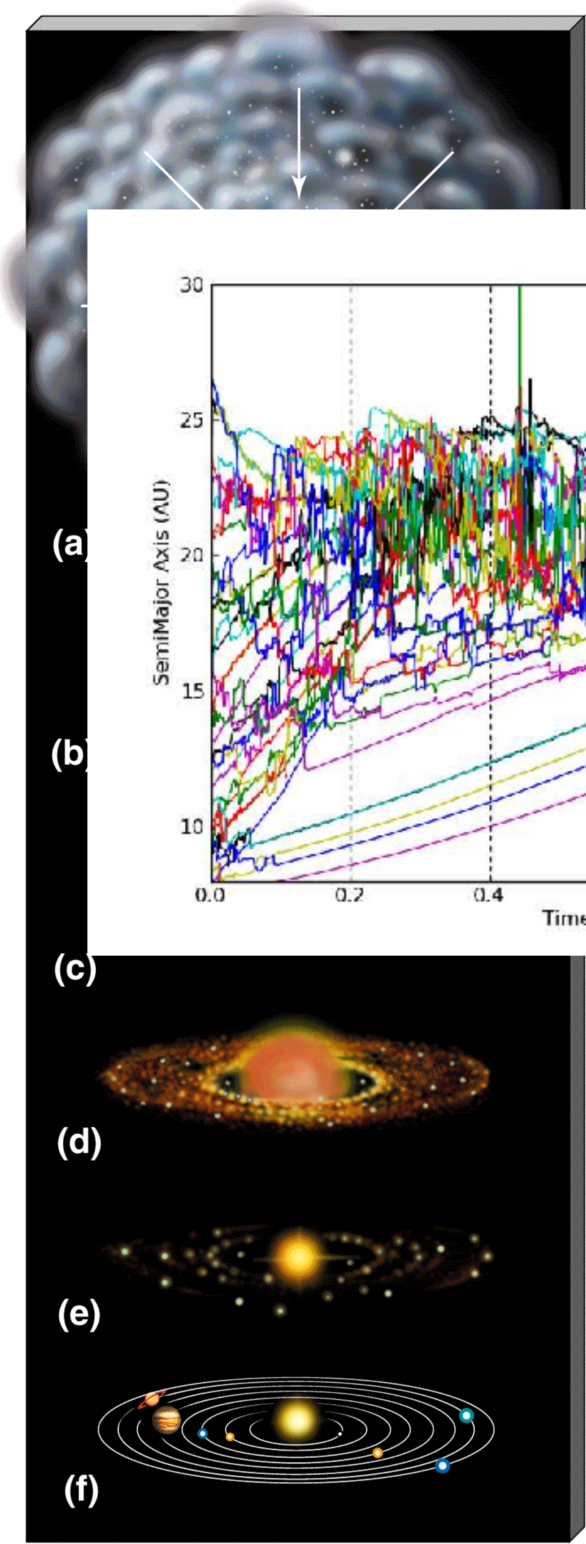

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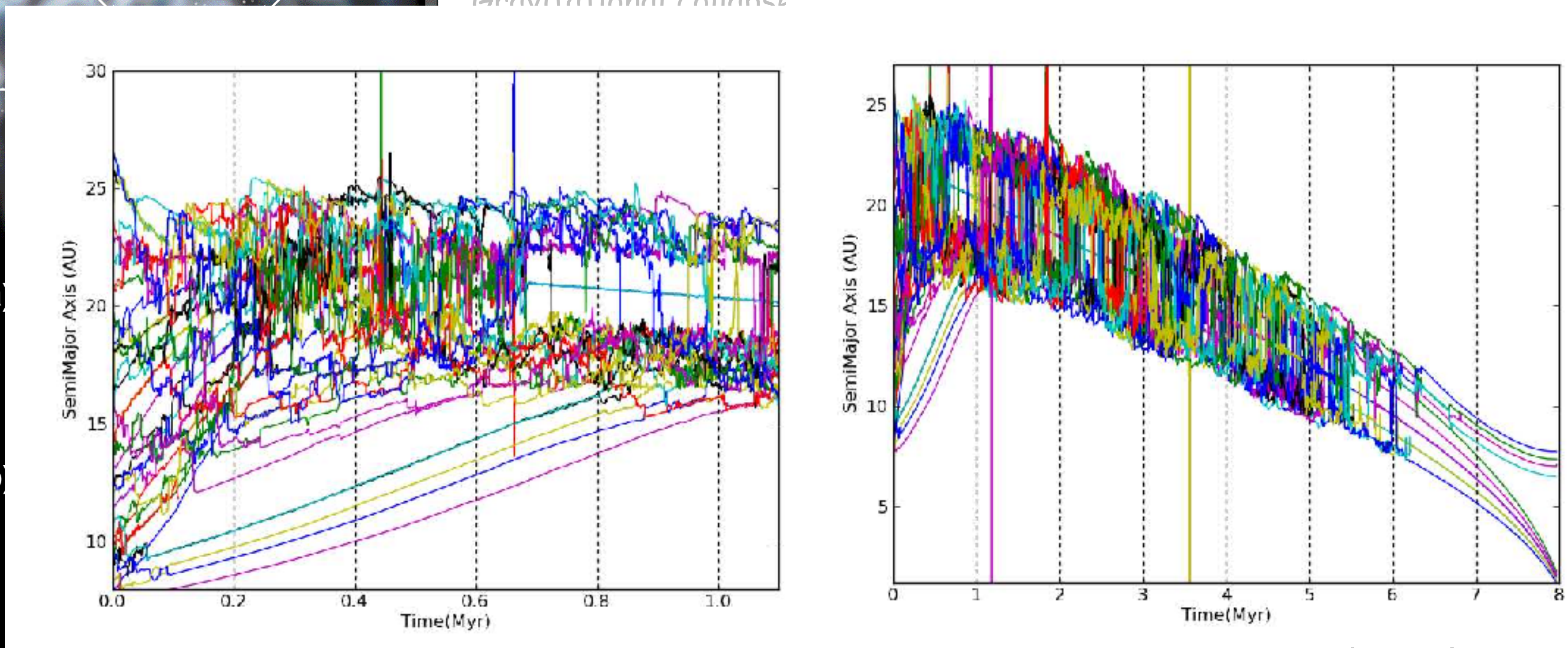

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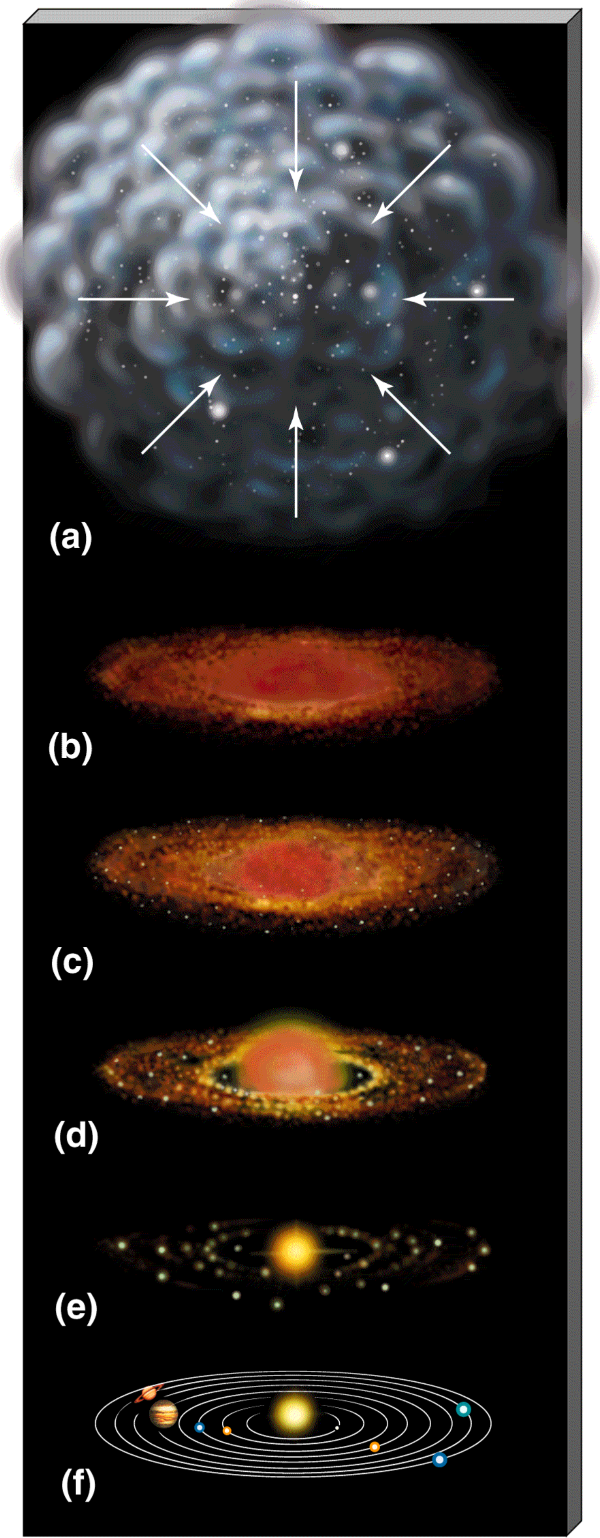

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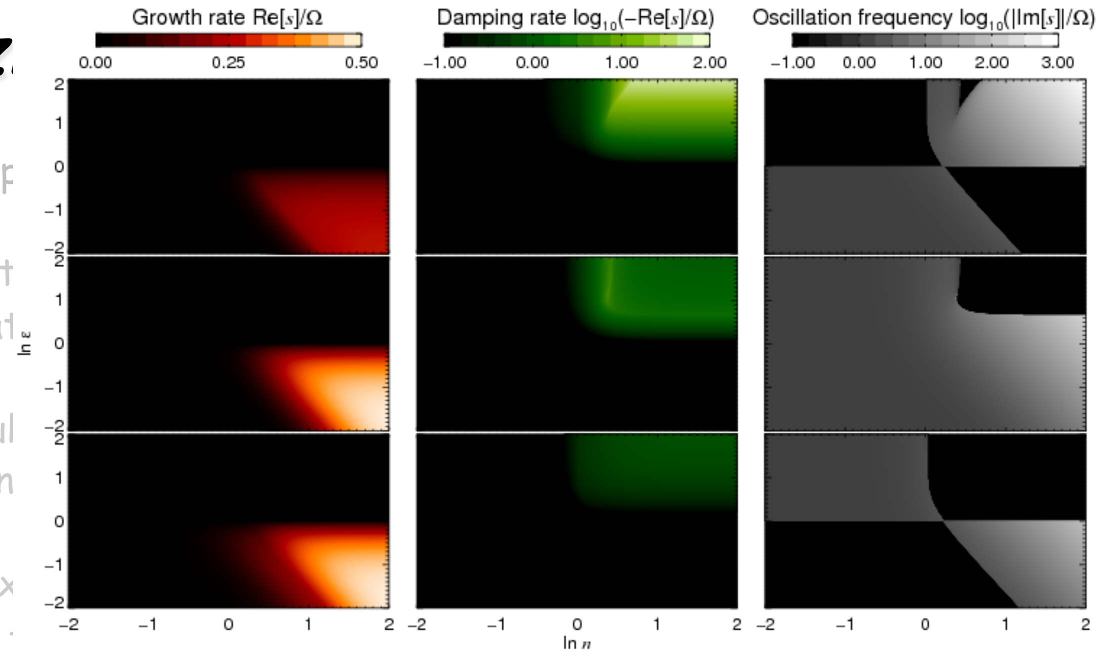

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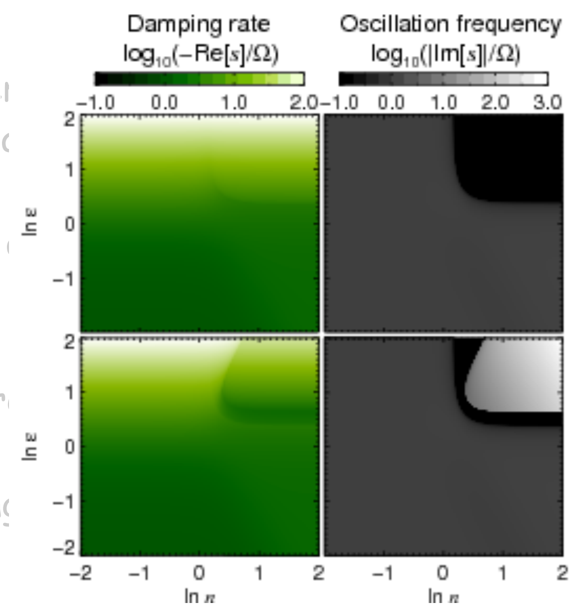
High pressure concentrates dust



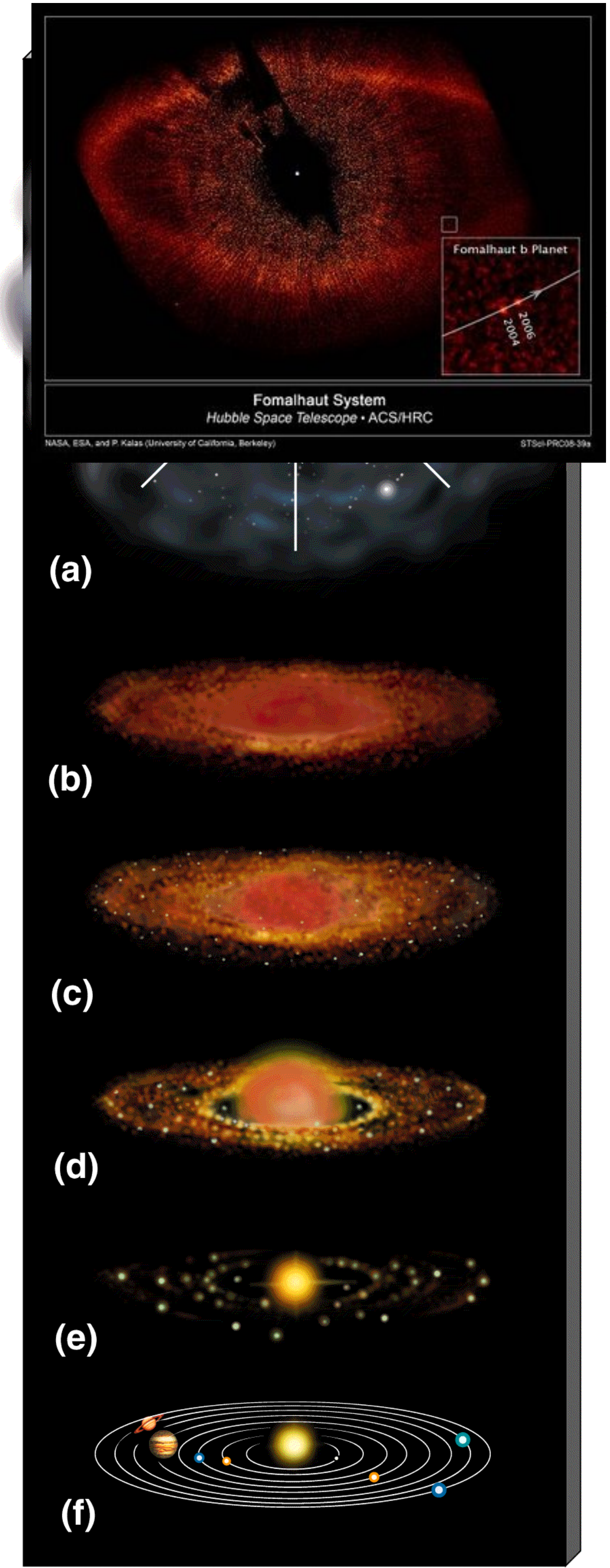
forcing. Collisions between embryos gives rise to

The disk thins due to photoevaporation. Planets r

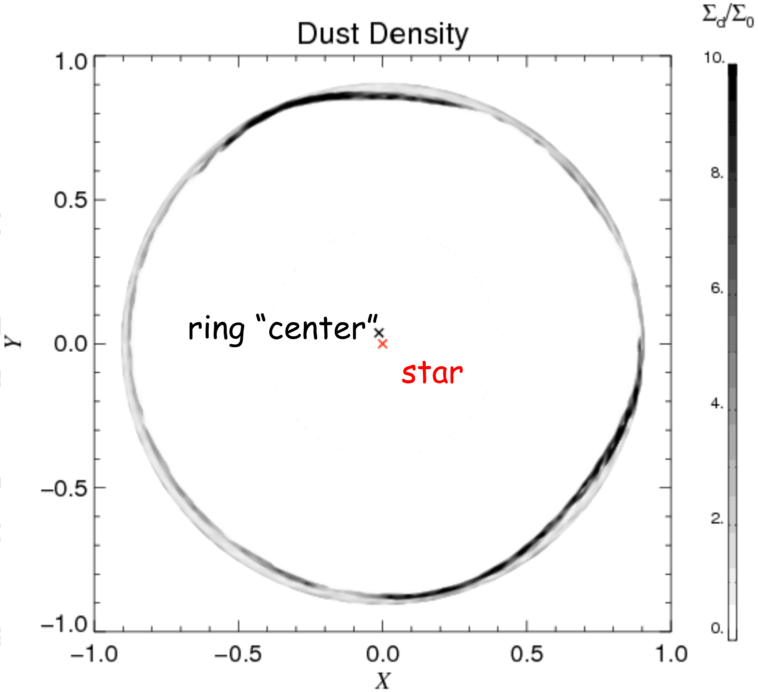
N-body interactions and stochastic forcing durin
system's final architecture.

Debris disks with gas are subject to a photoelectric instability

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



Summarizing



Gravitational collapse of an interstellar c

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

Rocks in the turbulent medium are trapp
undergo collapse into planetesimals and c

Vortices may be excited in the dead zone
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.

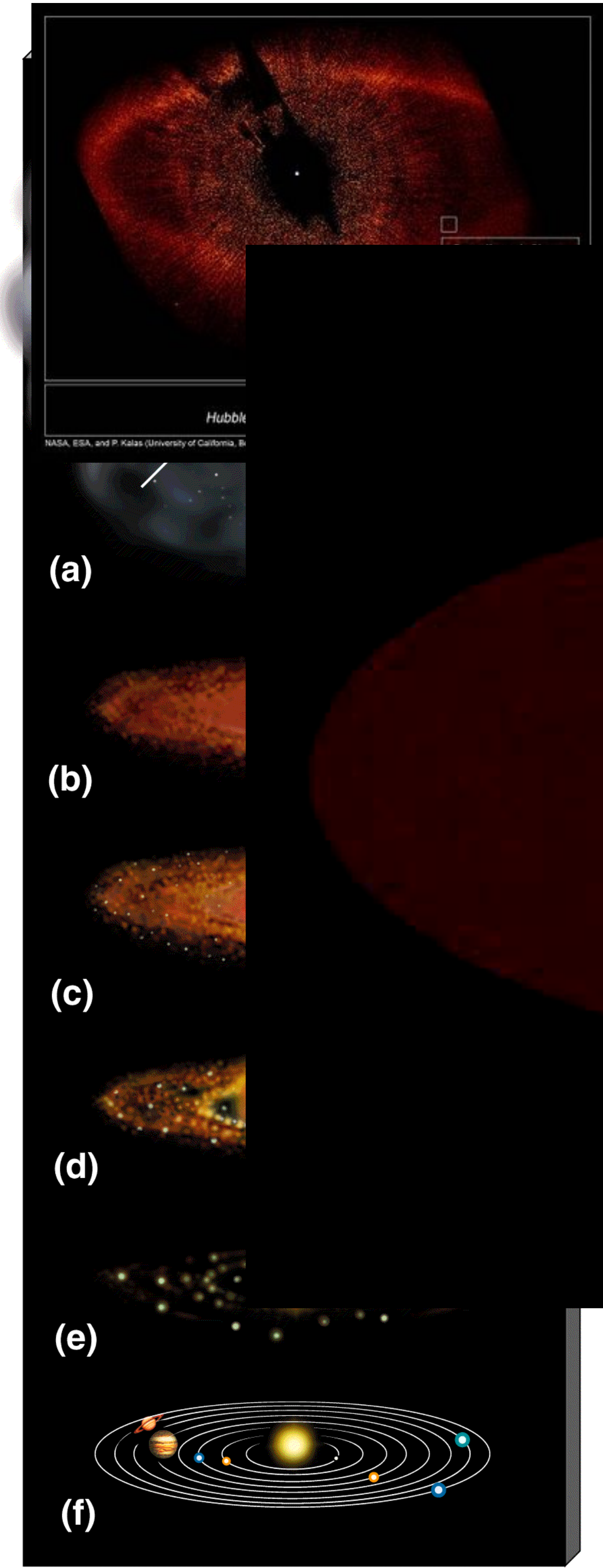
Convergent migration leads to resonances, these are disrupted by turbulent forcing. Collisions between embryos gives rise to oligarchs.

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

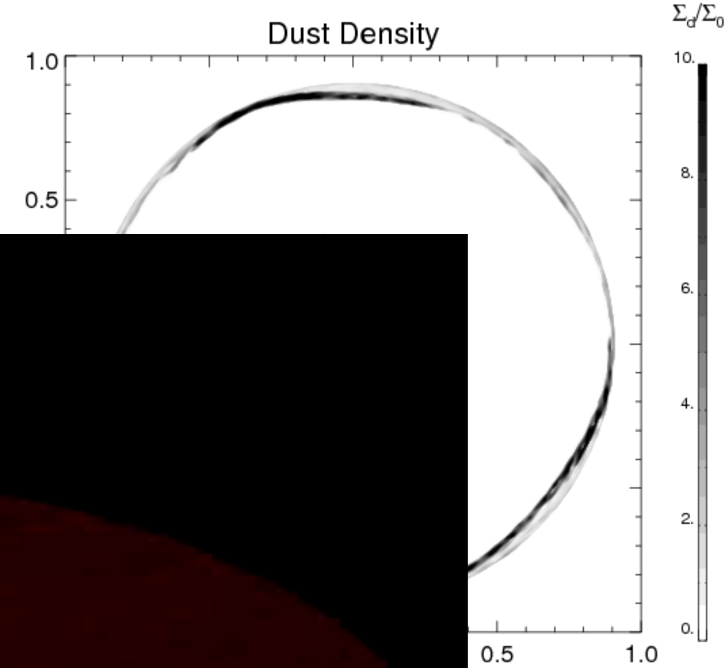
N-body interactions and stochastic forcing during disk evaporation produce the system's final architecture.

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

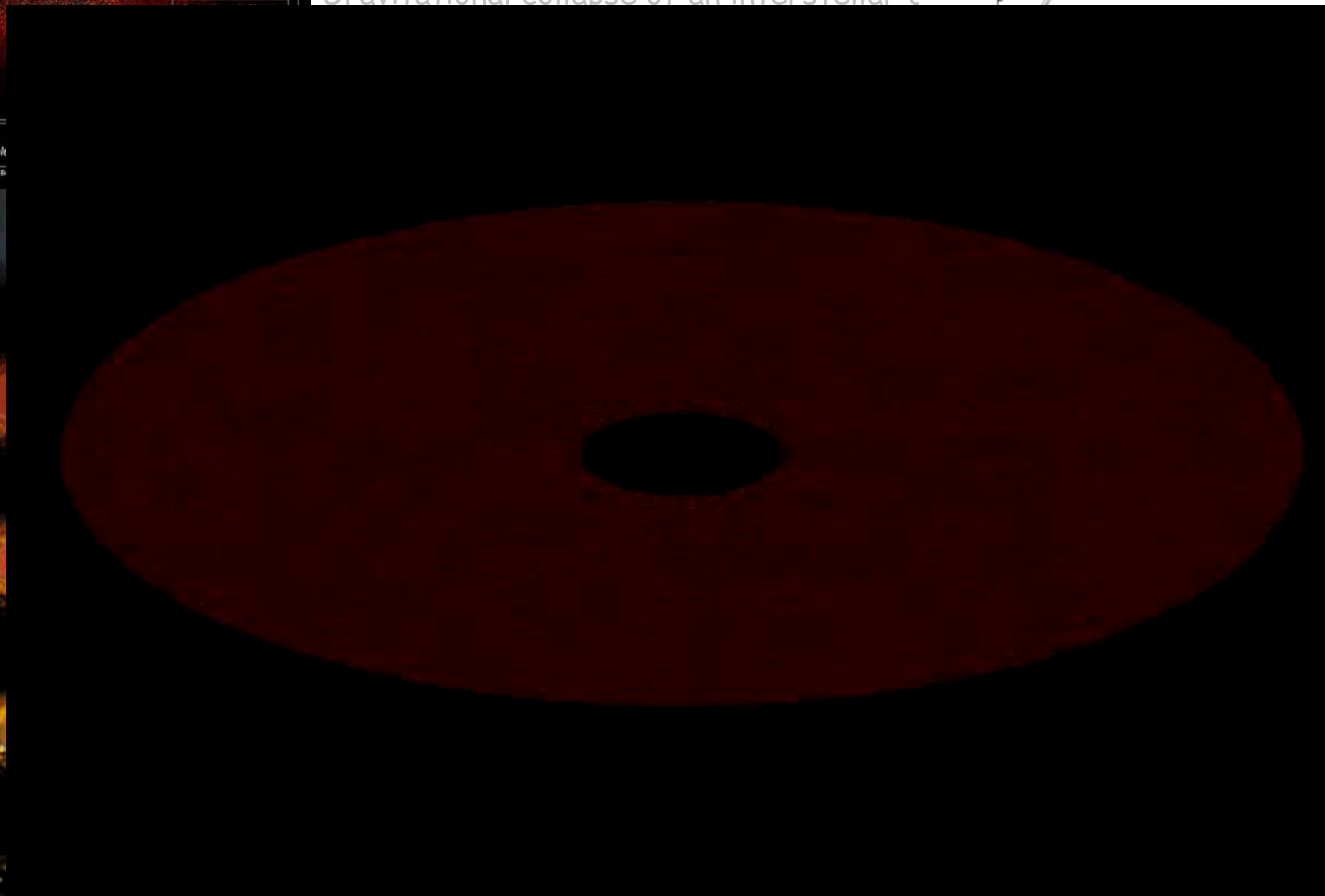
The instability generates sharp eccentric rings. **Caution before shouting “planet!”.**
Not all that glitters is gold.



Summarizing



Gravitational collapse of an interstellar c



mass planets

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rbits.

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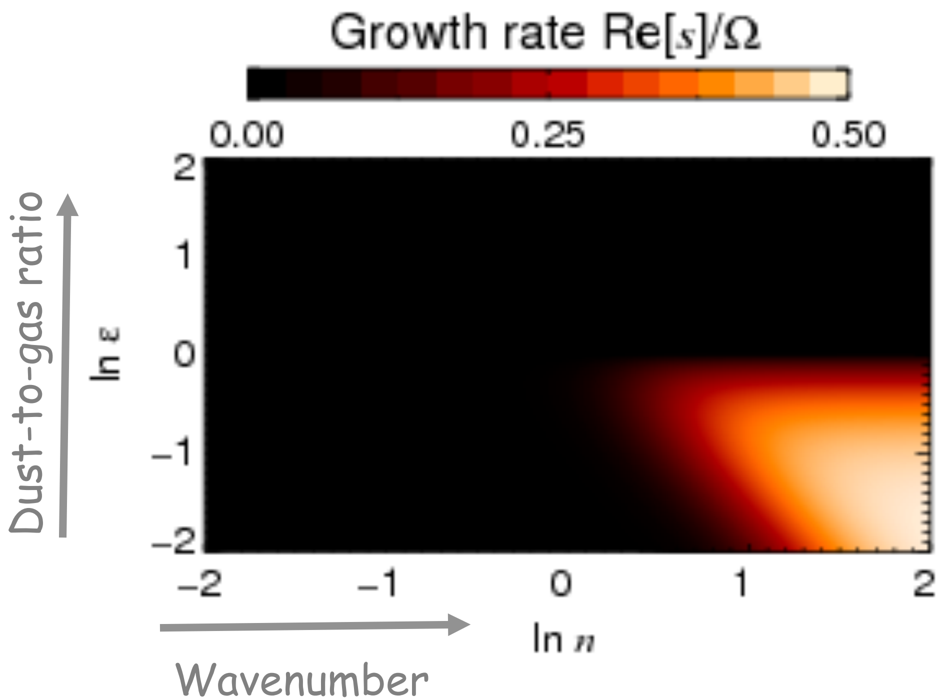
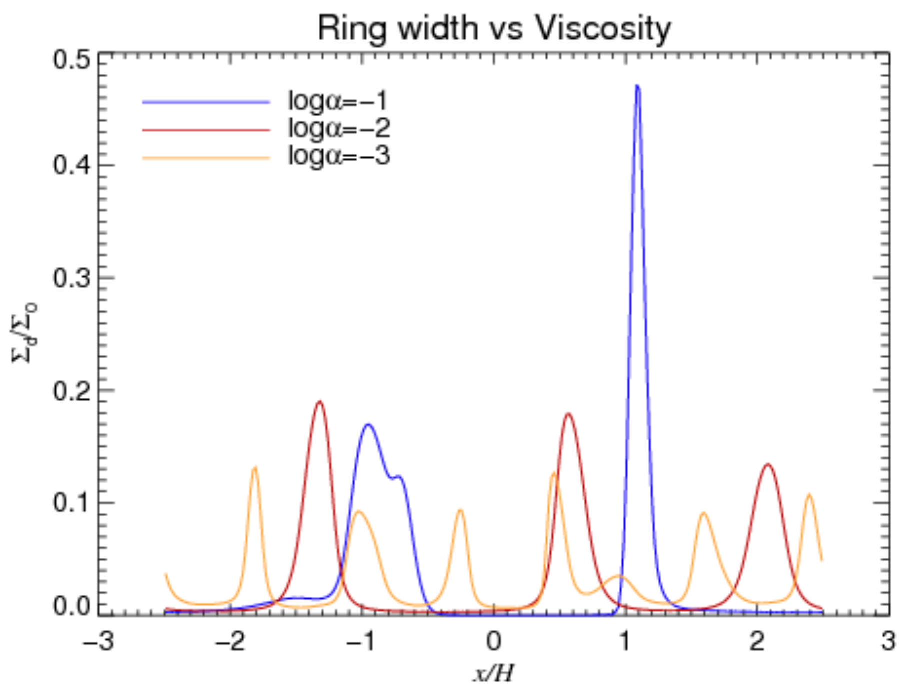
Debris disks with gas are subject to a thermo-centrifugal instability

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

Ring width

Ring spacing is determined
by the wavelength of maximum growth.

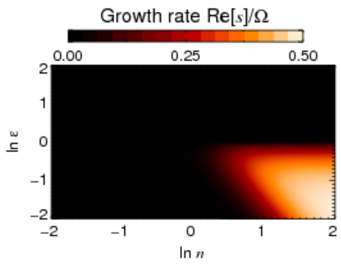


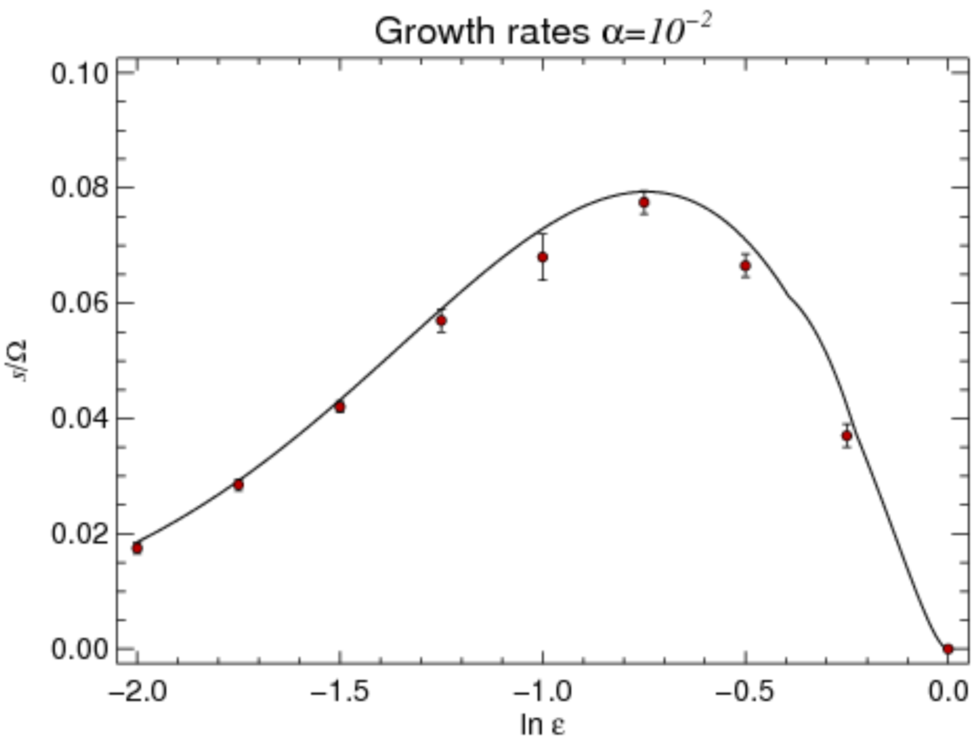


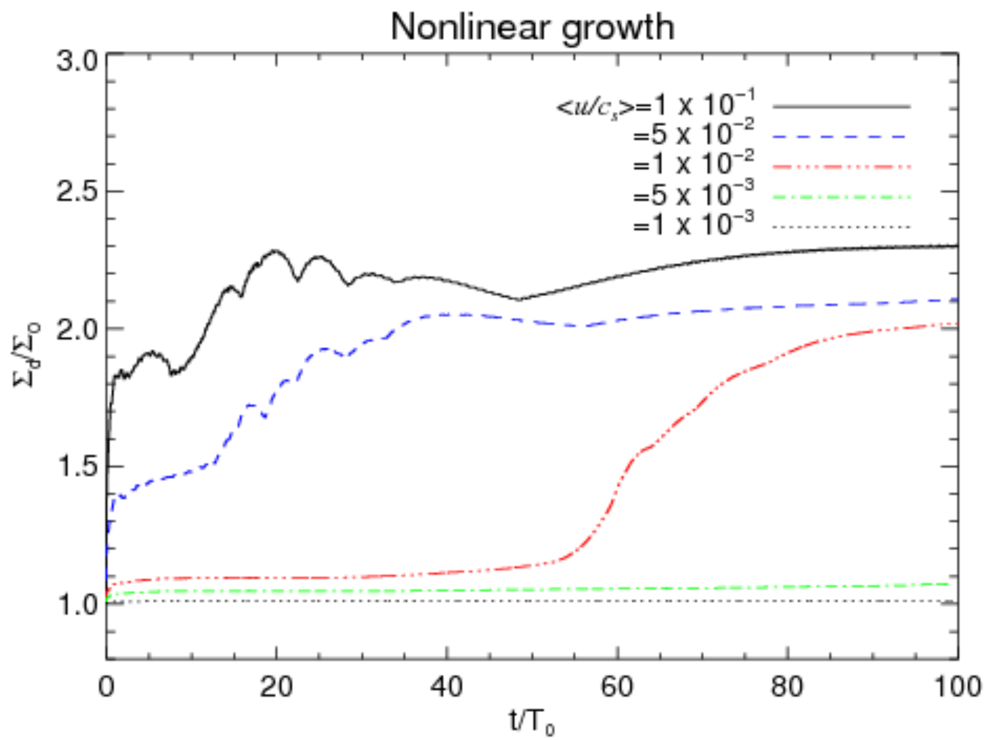
Which in turn is determined by viscosity

Ring spacing ~ 10 Kolmogorov lengths

Linear and nonlinear growth



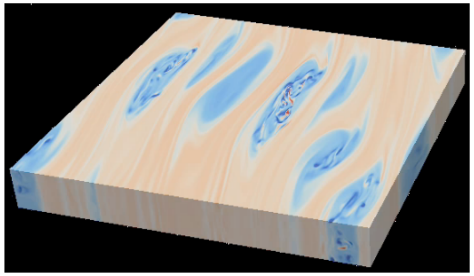




Linear growth only exists for $\varepsilon < 1$

But there is **nonlinear growth** beyond !

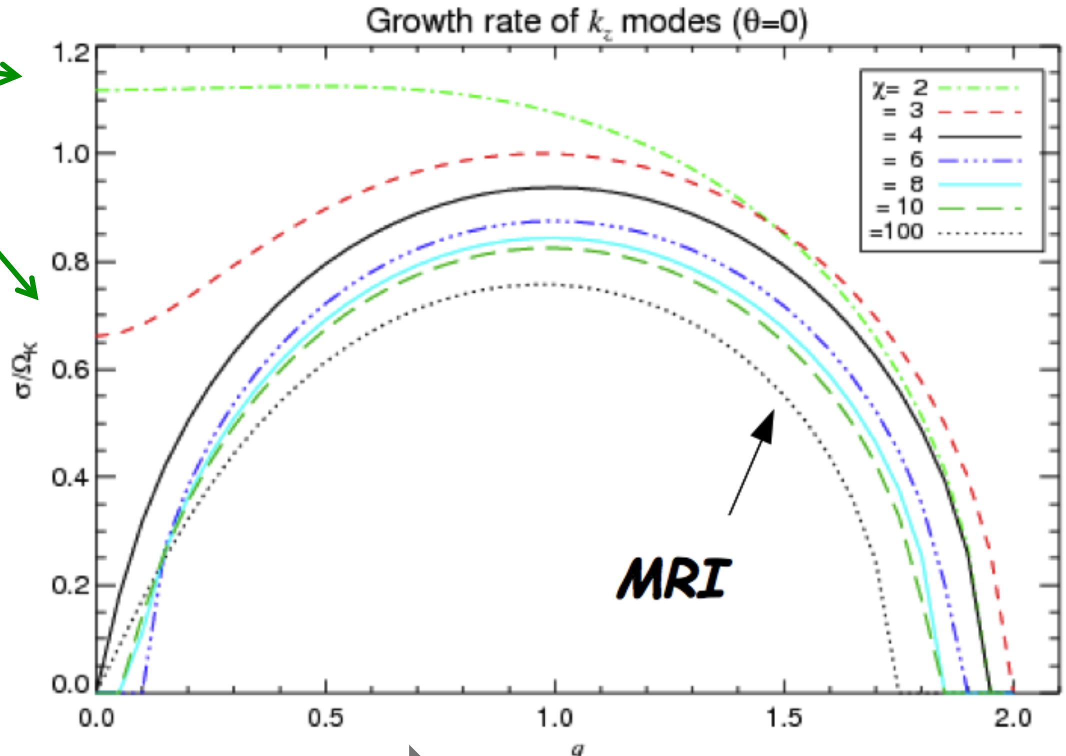
"Elliptic" Instability



Lesur & Papaloizou (2010)

See also
Pierrehumbert 1986
Bayly 1986
Kerswell 2002
Lesur & Papaloizoy 2009
Lesur & Papaloizou 2010
Lyra & Klahr 2011
Lyra 2013

Hydrodynamic instability (B=0)



Growth rate

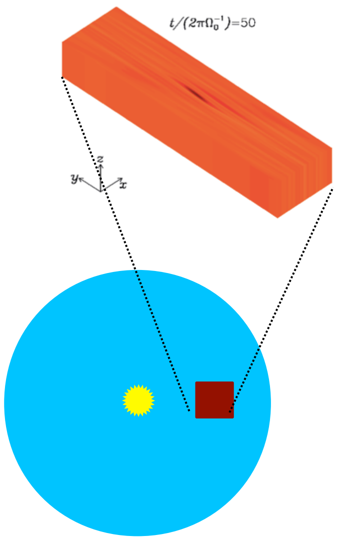
Magnetic Field

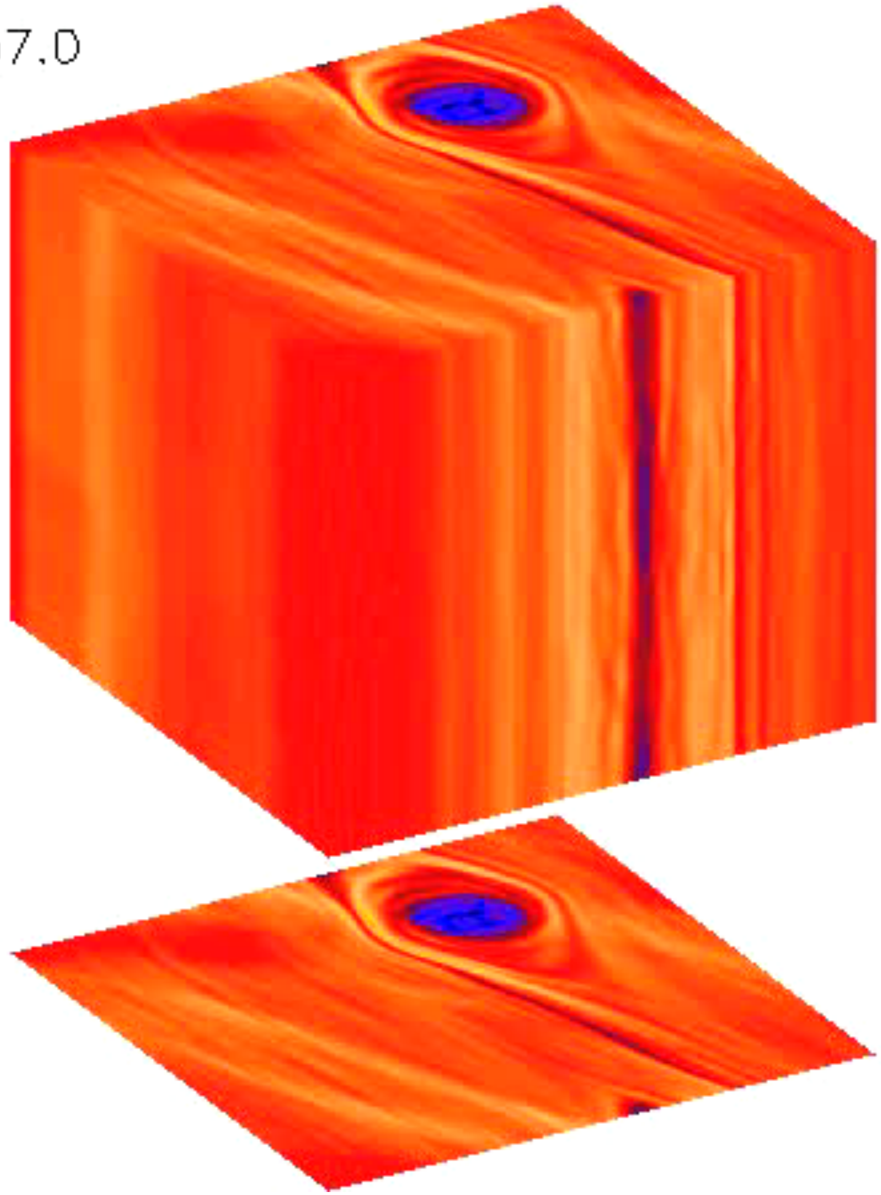
Lyra & Klahr (2011)

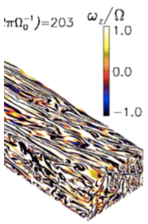
Infinitely elongated vortices are equivalent to **shear flows**.

They are subject to an MRI-like instability when magnetized.

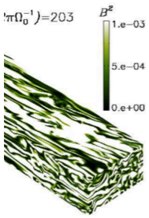
Baroclinic instability and layered accretion







Vorticity



Mag. Energy