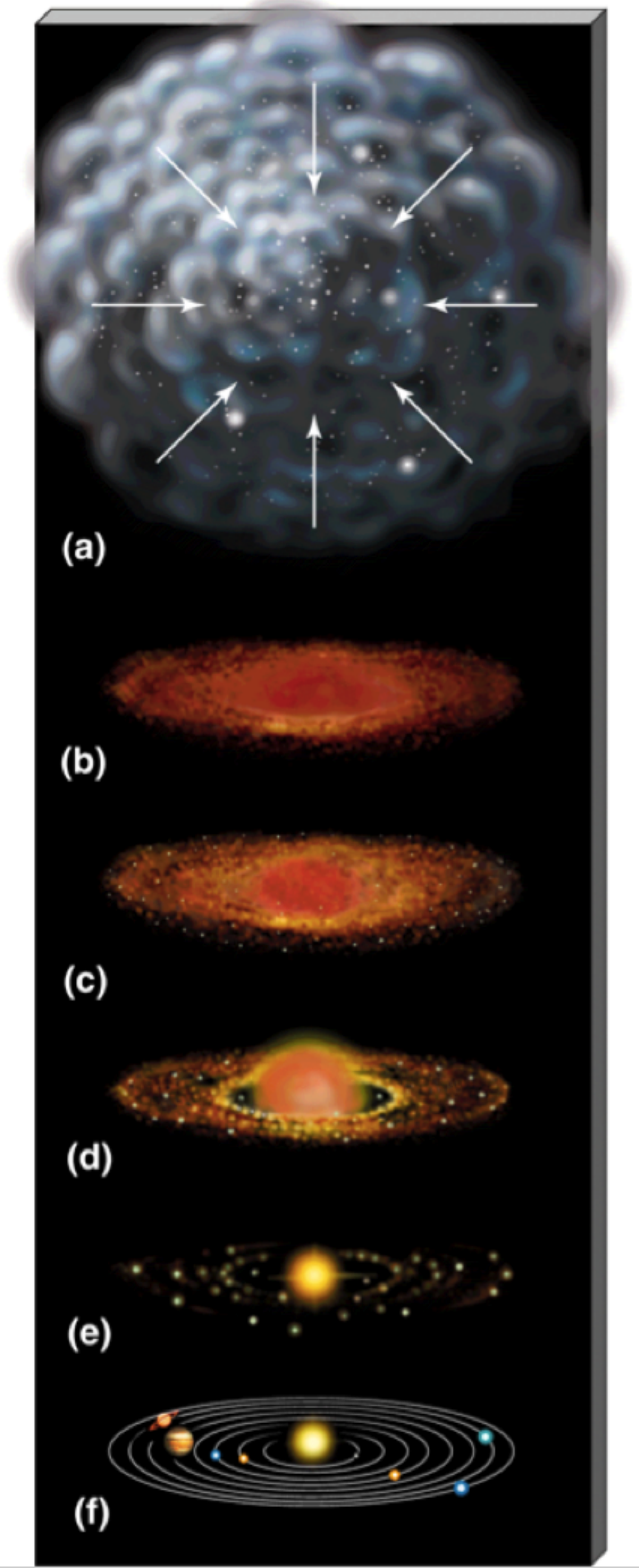
Gas in debris disks:
A new way to produce patterns?

Wlad Lyra
Sagan Fellow
Caltech-JPL

Marc Kuchner
NASA Goddard Space Flight Center

UC Berkeley – April 2014



Collapse of gas cloud

A disk life story

Formation of proto-star

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

Dust settling

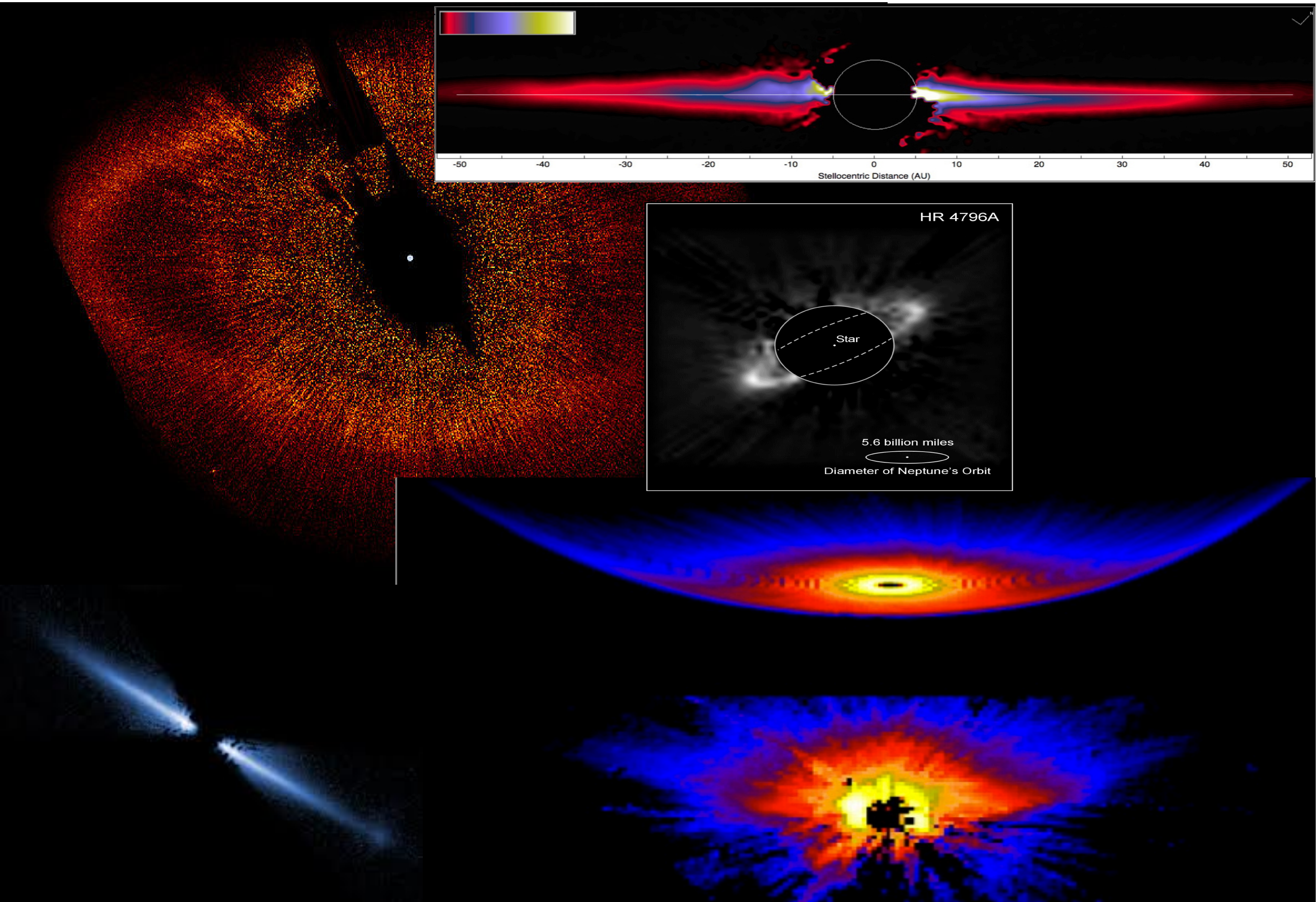
Thinning phase (~10 Myr)
Transitional Disks
Planet retention

Planetesimal formation

Gas dispersal

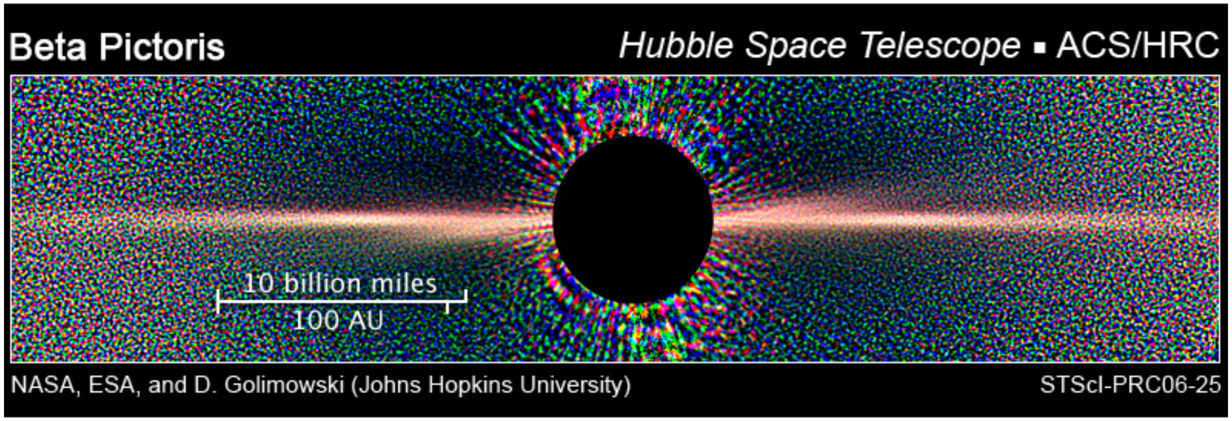
Gas-poor phase (>10 Myr)
Debris Disks
Stabilization of architecture and Planet Detection

Debris disks – The gas-poor phase

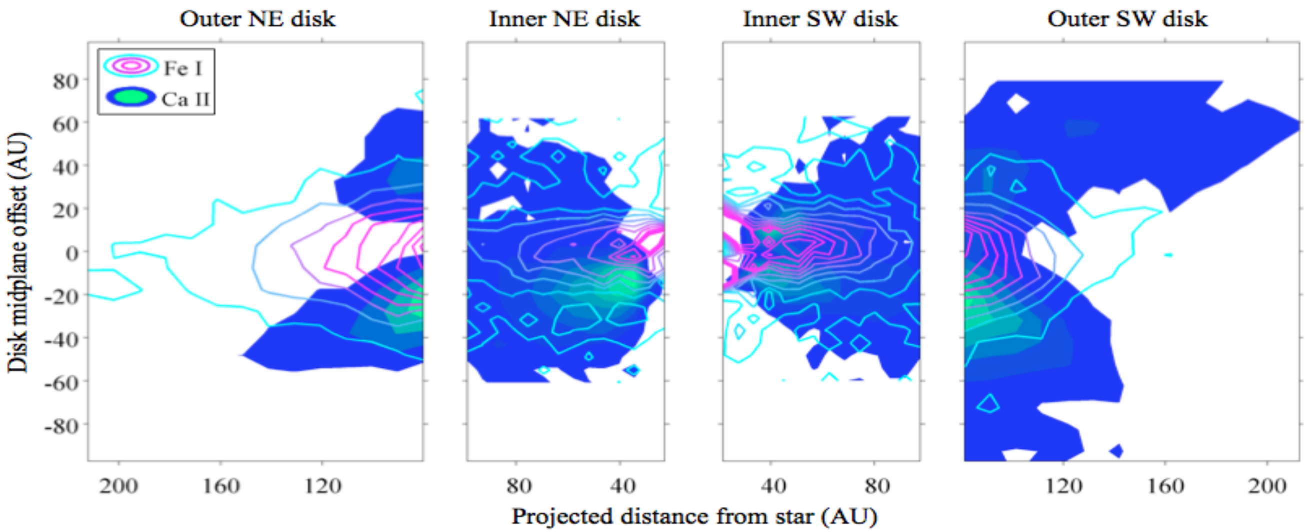


Debris disks are not completely gas-free

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?	

What is the dynamical effect of this gas?

LETTER

doi:10.1038/nature12281

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

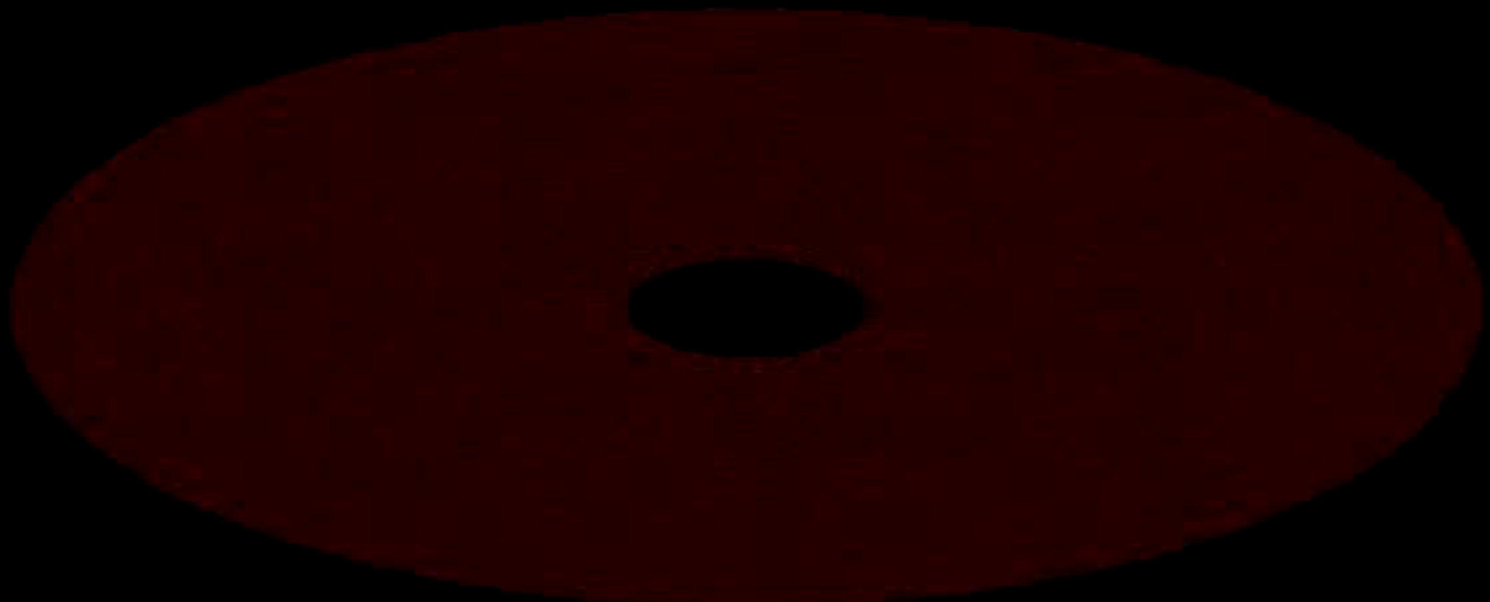
W. Lyra[1,2,3] & M. Kuchner[4]

'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 these disks is thought to be produced by planetesimals or dust grains

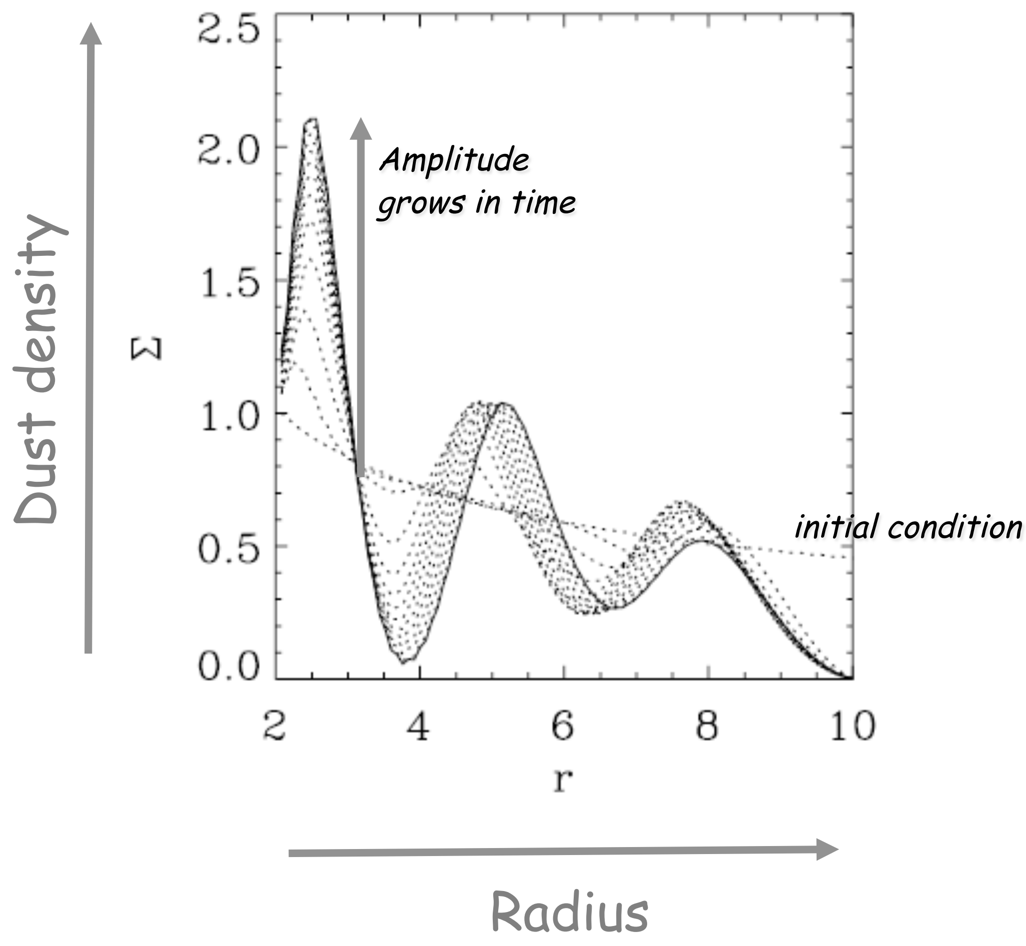
We present simulations of the fully compressible problem, solving for the continuity, Navier–Stokes and energy equations for the gas, and the momentum equation for the dust. Gas and dust interact dynamically through a drag force, and thermally through photoelectric heating. These are parametrized by 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 right panels show the oscillation frequencies. There is no linear insta-



Lyra & Kuchner (2013, Nature, 499, 184)

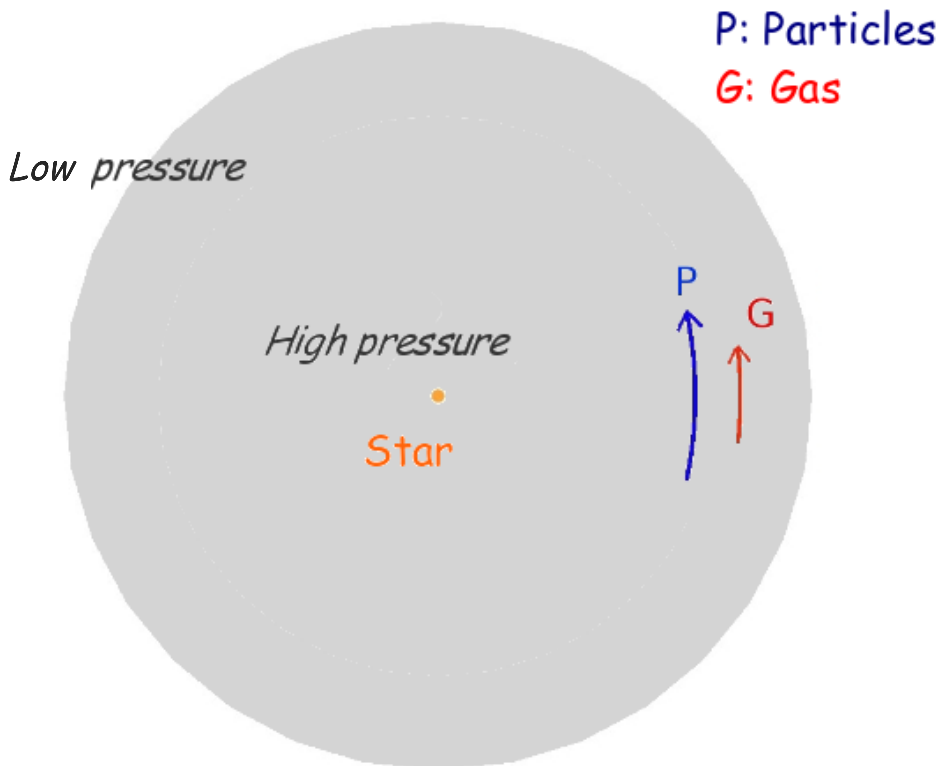
Dust and gas together leads to instability...



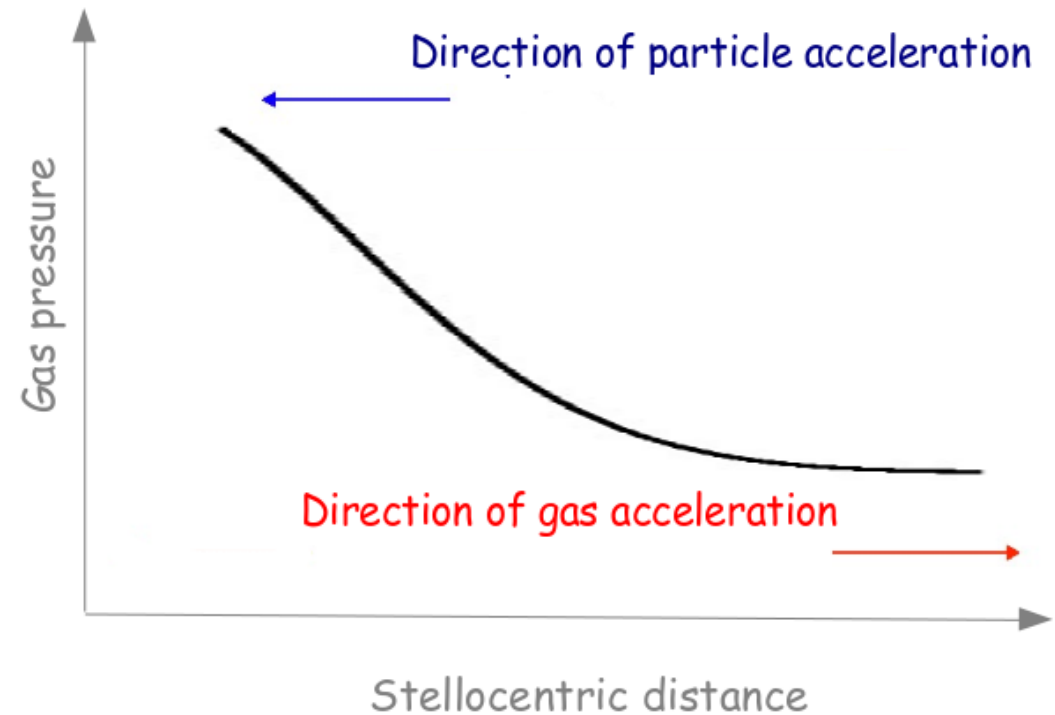
Klahr & Lin (2005)

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

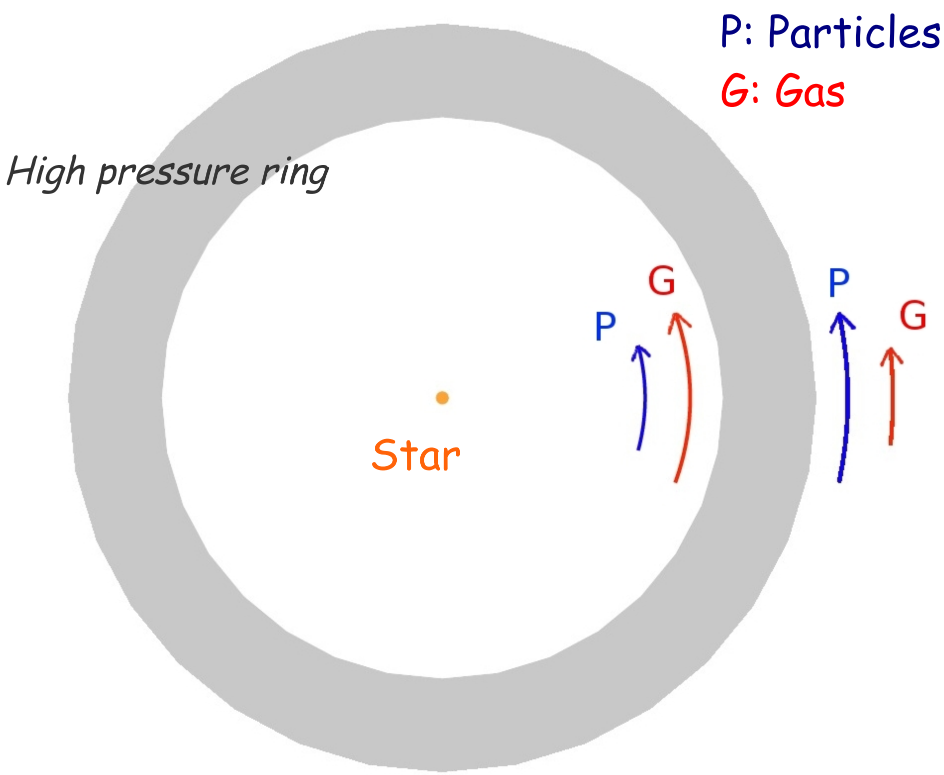
Particle drift



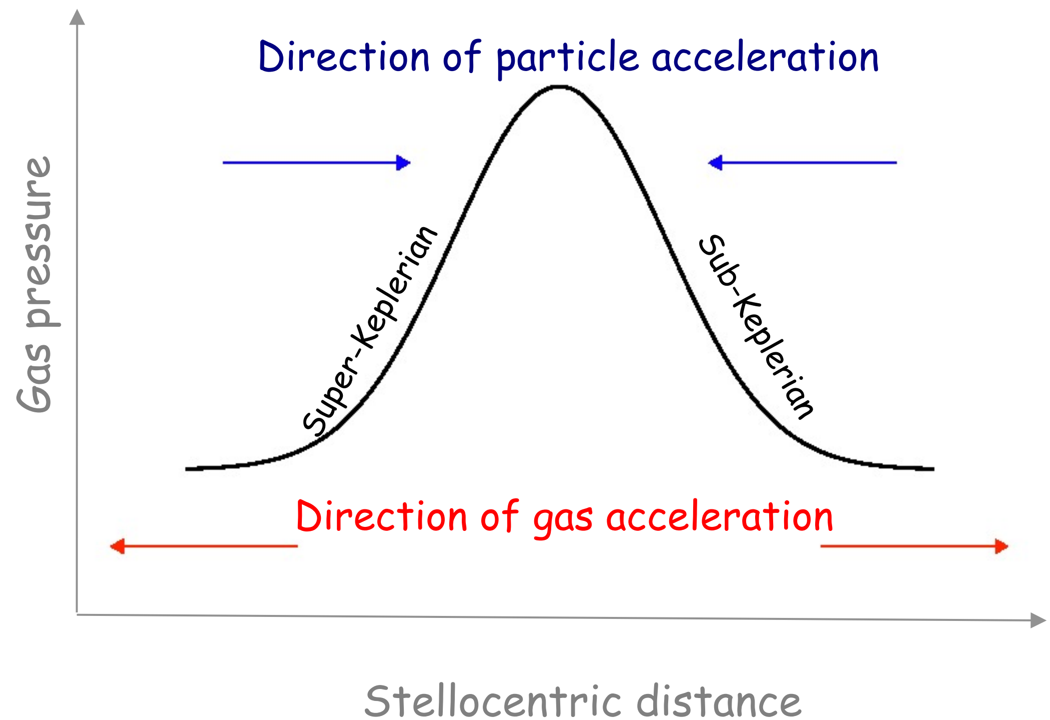
Adapted from Whipple (1972)



Pressure Trap



Adapted from Whipple (1972)



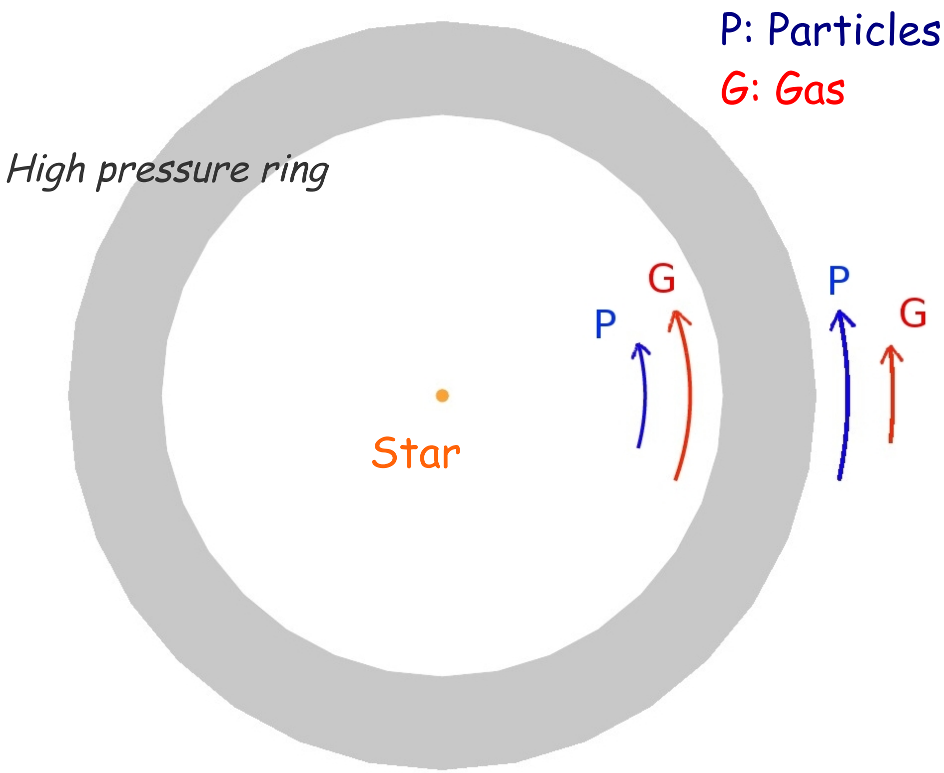
Pressure Trap

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

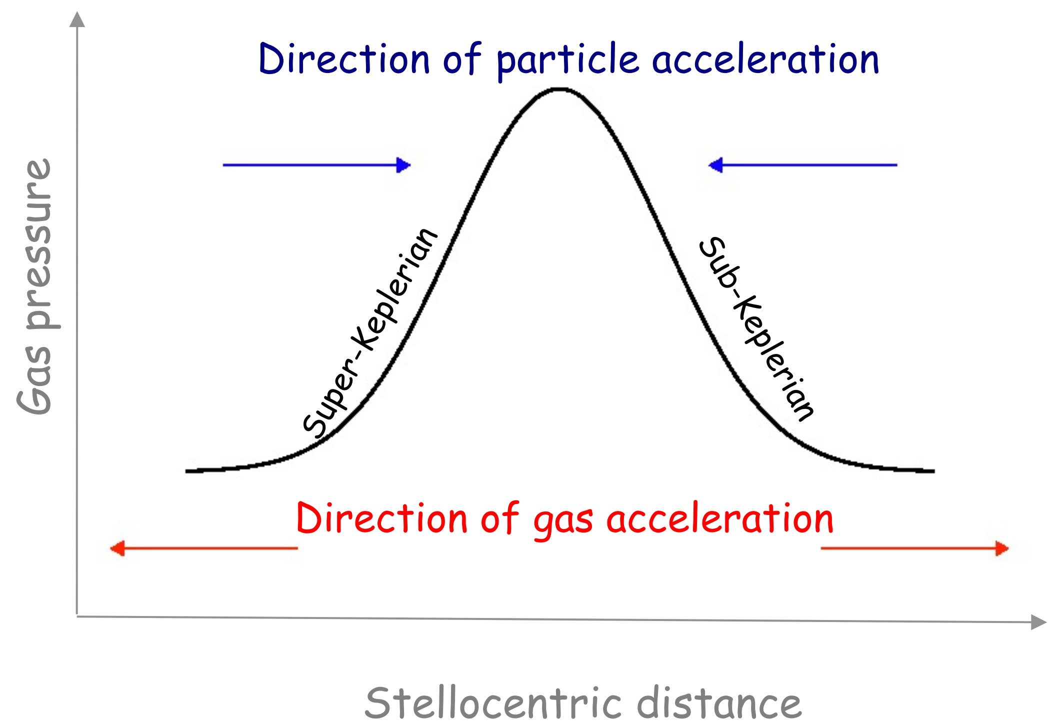
Particles $$\frac{d\boldsymbol{w}}{dt} = -\nabla\Phi - \frac{(\boldsymbol{w}-\boldsymbol{u})}{\tau}$$

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

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

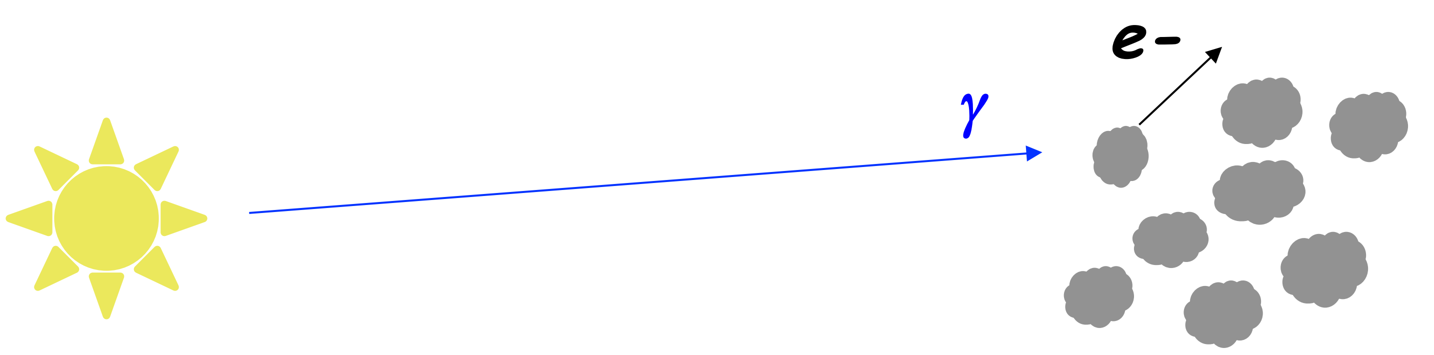


Adapted from Whipple (1972)



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

Runaway process: instability

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

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

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

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

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

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

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

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

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

Missing physics

Radiation Forces

Radiation pressure

Poynting-Robertson drag

Photophoresis

Collisions

Detailed treatment of heating and cooling

Multiple particle species

Linear Analysis

Dust

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

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

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

Gas

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

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

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

$$\lim_{\tau_T \to 0} P = c_v(\gamma - 1) T_0 \Sigma_g \Sigma_d / \Sigma_0$$

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

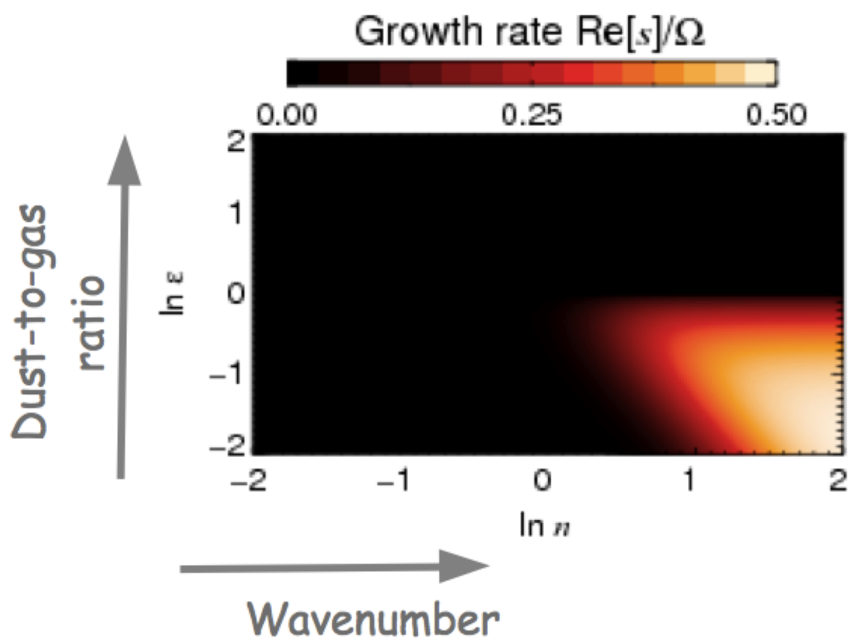
$$\psi' = \hat{\psi} \exp(ikx + st)$$

Dispersion relation

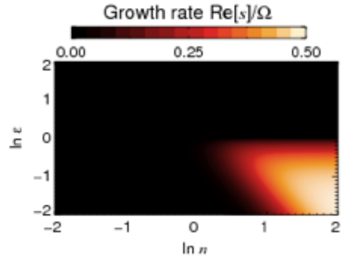
$$A\omega^5 + B\omega^4 + C\omega^3 + D\omega^2 + E\omega + F = 0$$

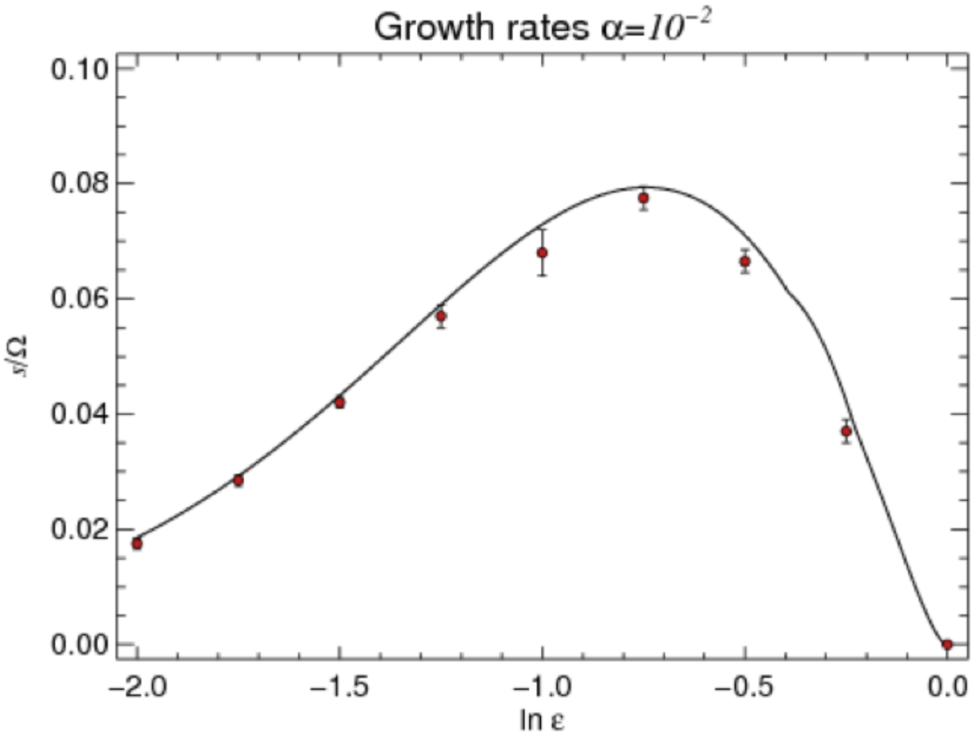
$$A = 1$$
$$B = 2\epsilon + 2$$
$$C = \epsilon^2 + \epsilon(n^2 + 2) + 3$$
$$D = \epsilon^2 n^2 + \epsilon(3n^2 + 2) + 2$$
$$E = \epsilon^2(2n^2 + 1) + \epsilon(3n^2 + 2) + 2$$
$$F = \epsilon^2 n^2 - \epsilon n^2$$

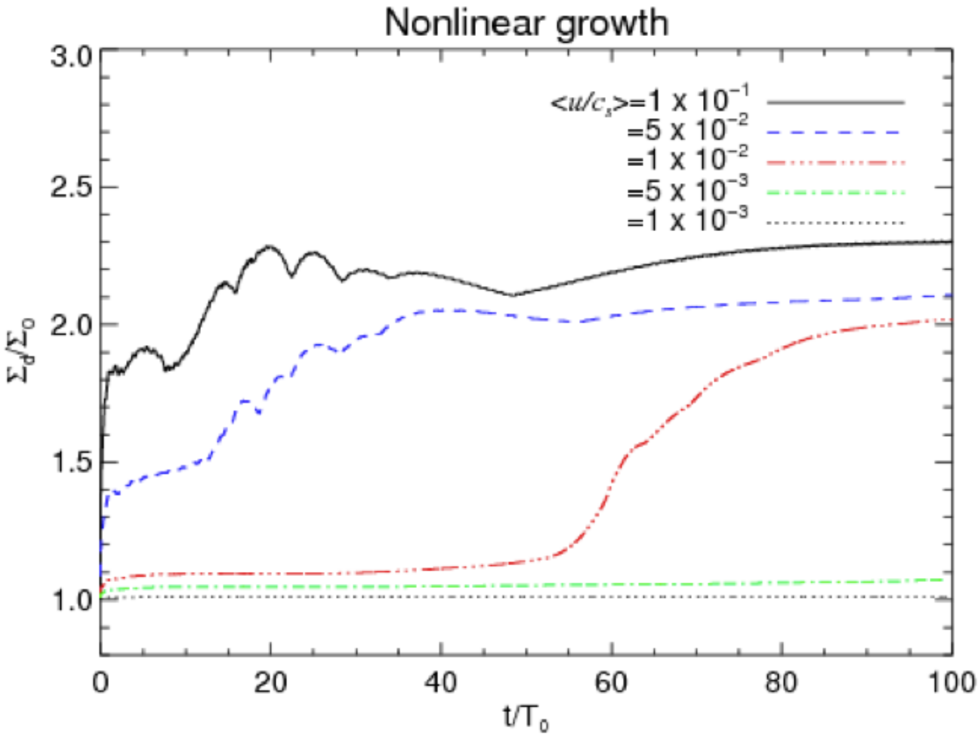
$\epsilon = \Sigma_d / \Sigma_g$ $\qquad n = kH$ $\qquad \omega = s/\Omega$



Linear and nonlinear growth







Linear growth only exists for e < 1

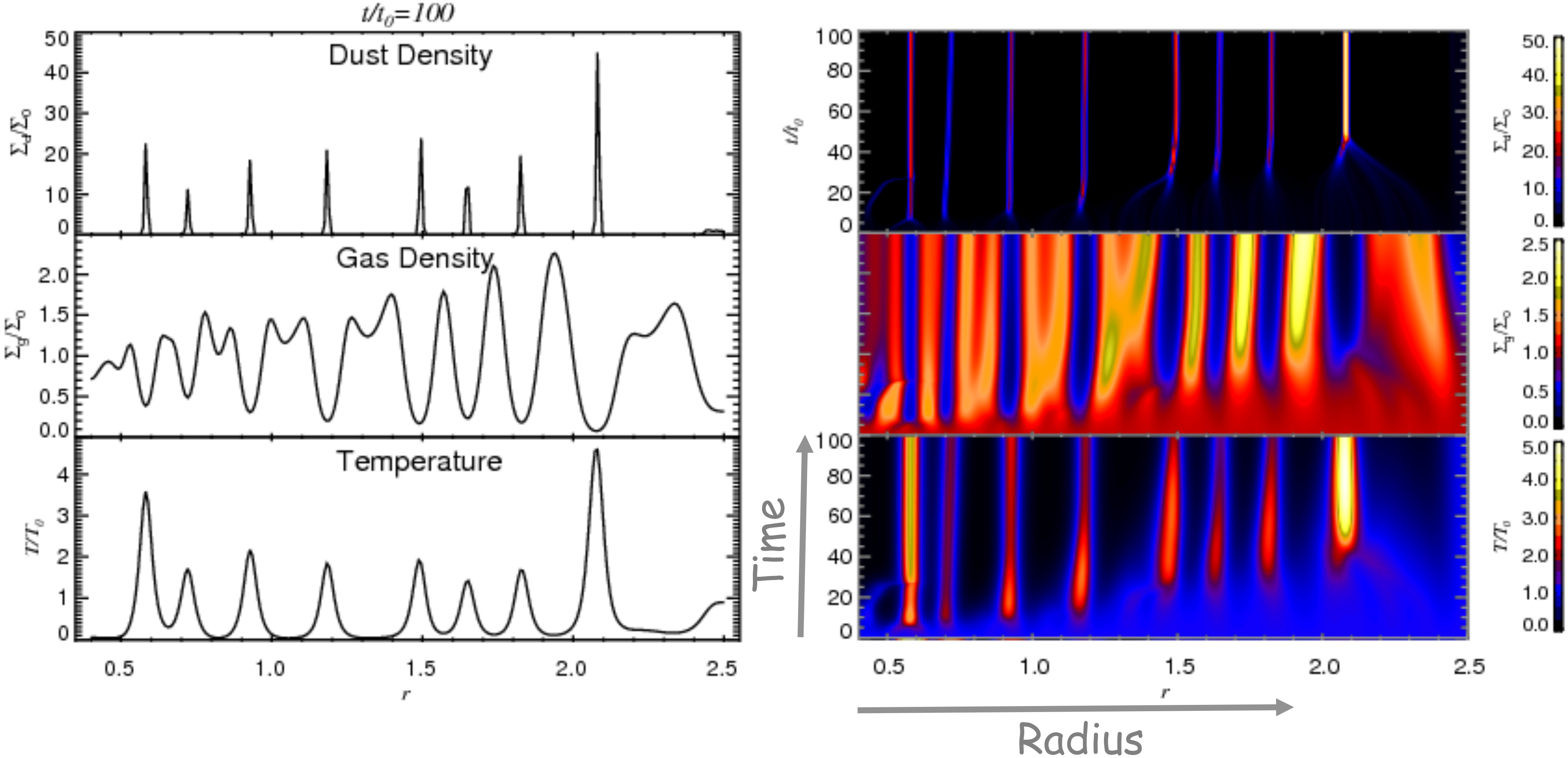
But there is
nonlinear growth
beyond !

Photoelectric Instability – Nonlinear evolution in 1D

Dust heats gas

Heated gas = high pressure region

High pressure concentrates dust

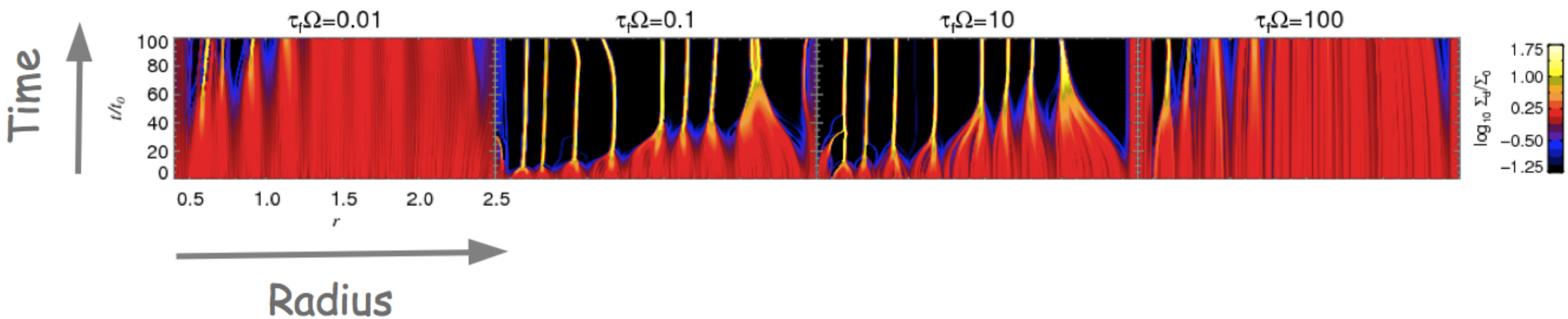


Narrow hot dust rings

Cold gas collects between rings

Robustness

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



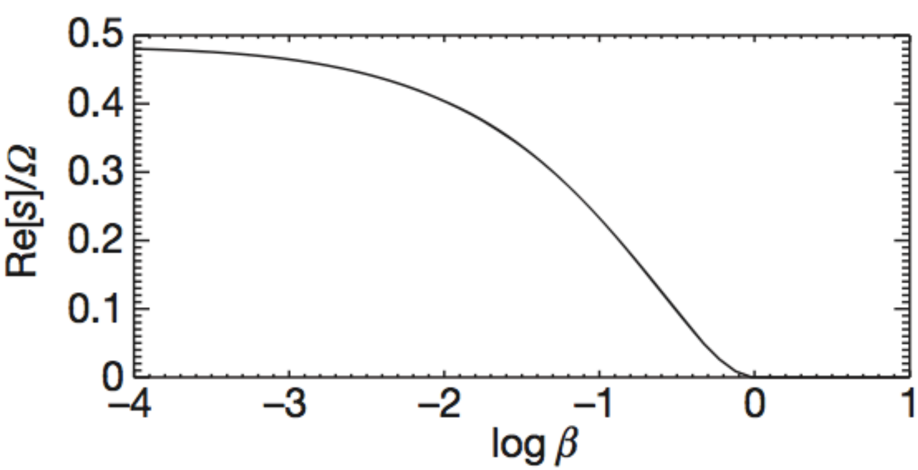
Photoelectric Instability

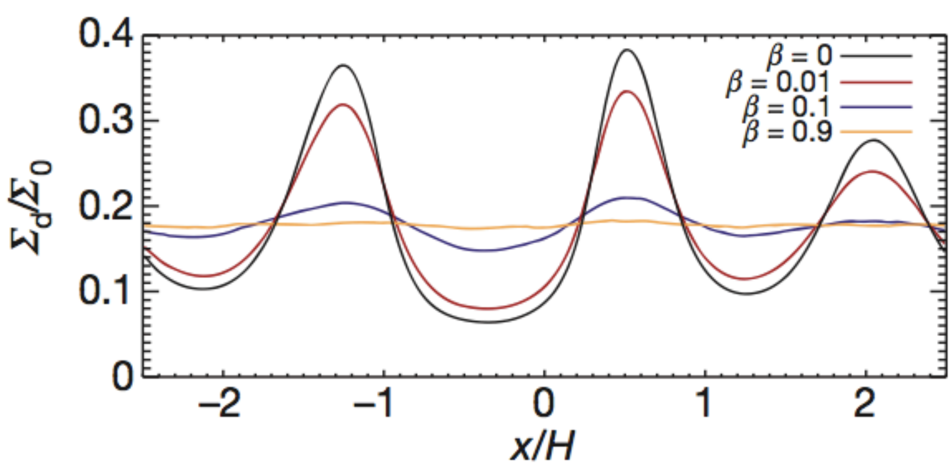
Other heating sources

$$p = \rho_g c_b^2 + p(\rho_d)$$

All other sources Photoelectric

$$\beta = \gamma \left(\frac{c_b}{c_s} \right)^2$$





Instability exists *only* when photoelectric heating dominates.

Photoelectric instability - 3D stratified local box

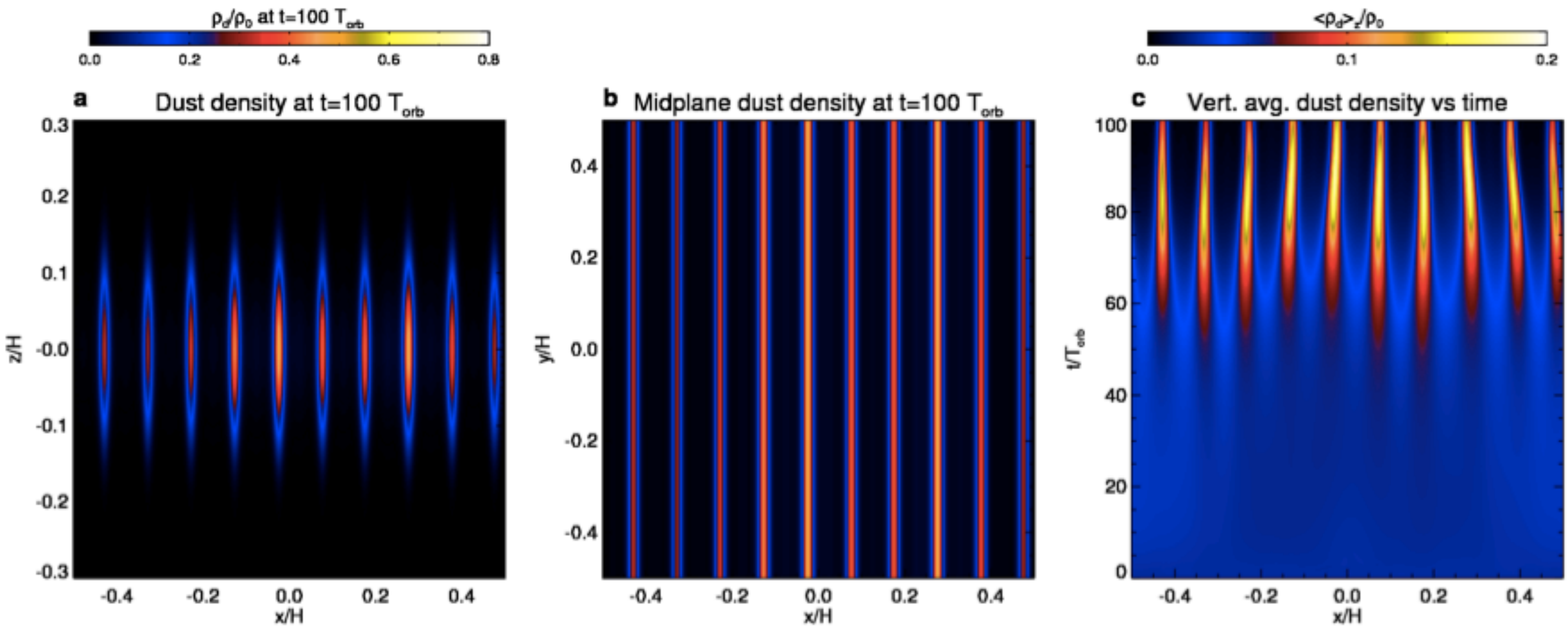
Photoelectric Instability

Dust heats gas

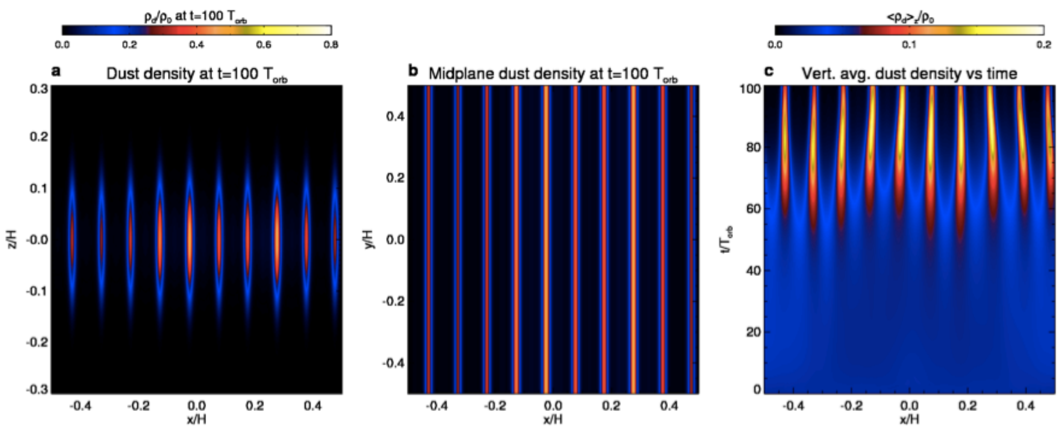
Heated gas = high pressure region

High pressure concentrates dust

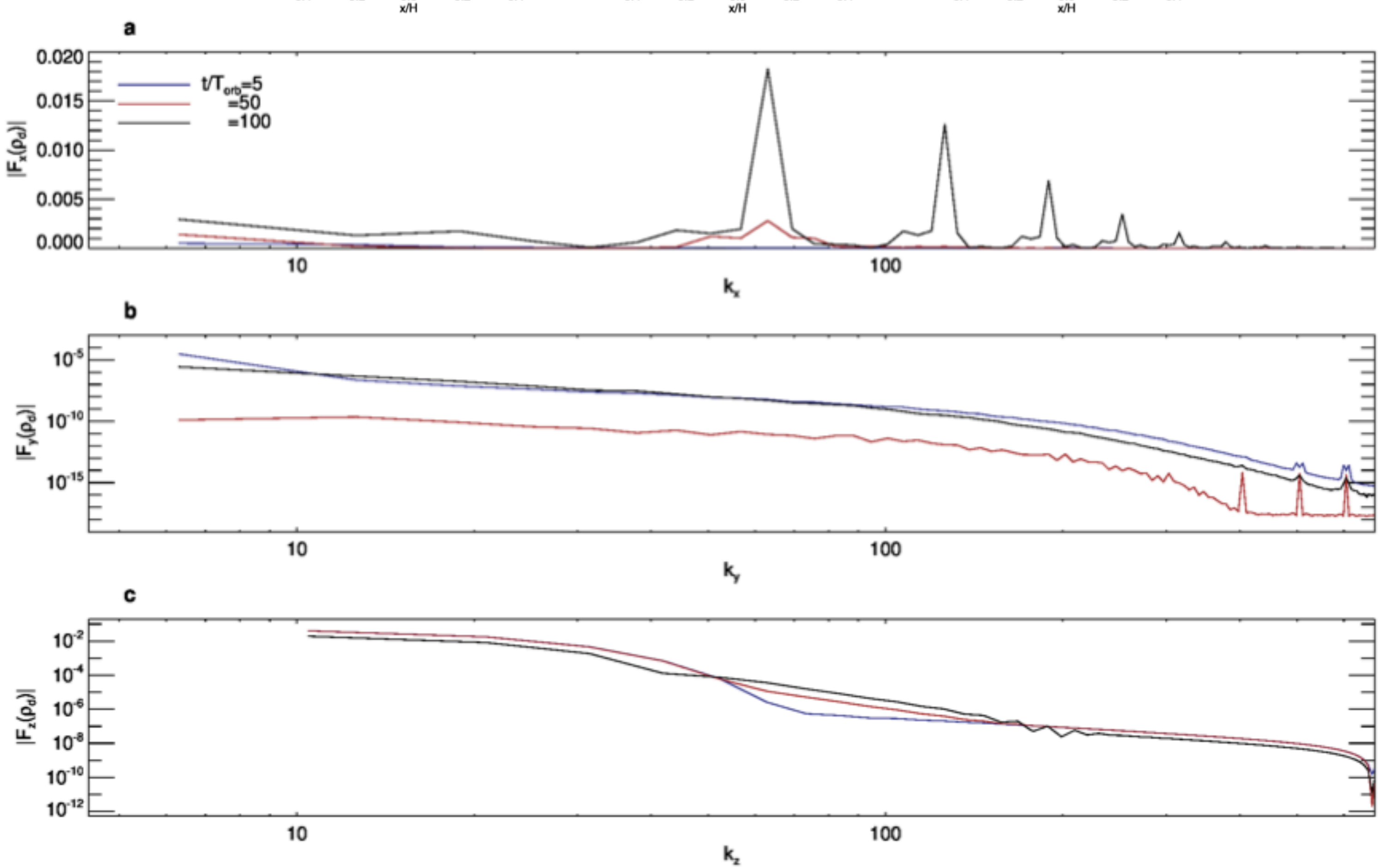
3D Stratified



Spectral power evolution – 3D stratified local box



No excitation of azimuthal or vertical modes.



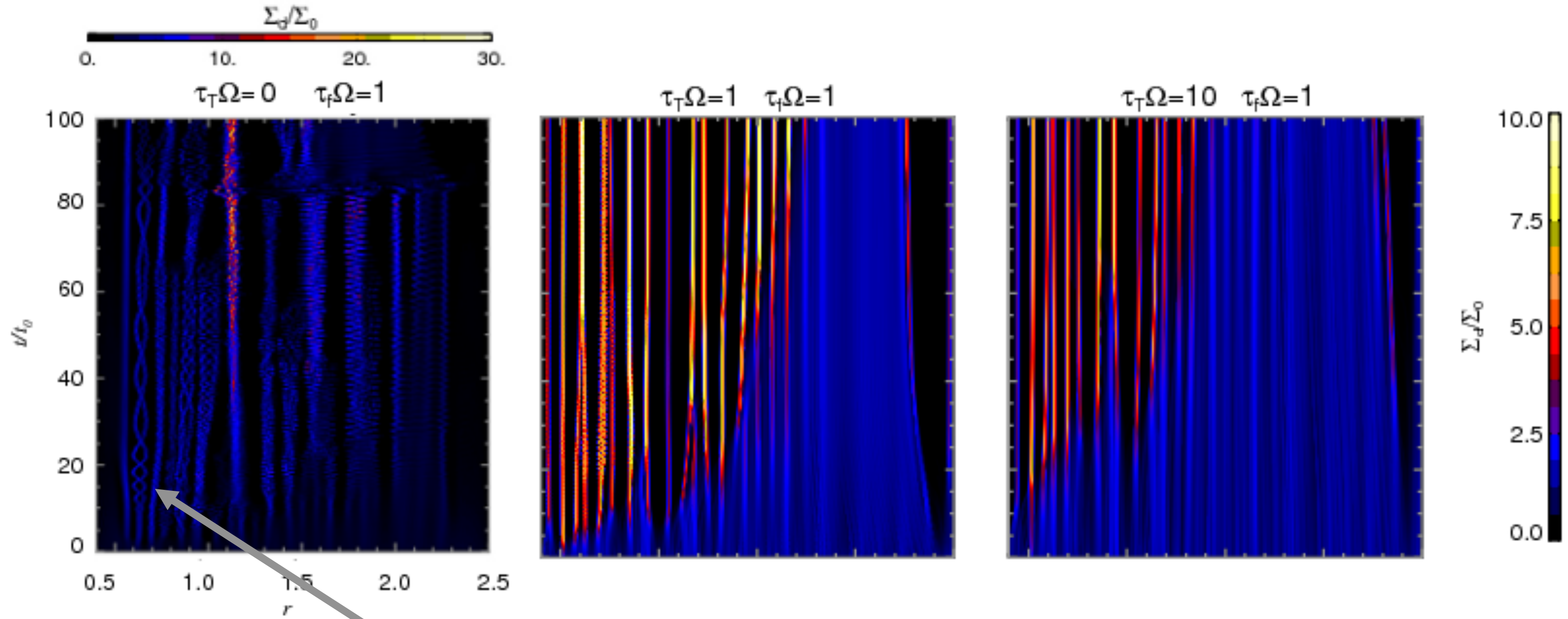
Radial

Azimuthal

Vertical

Oscillations

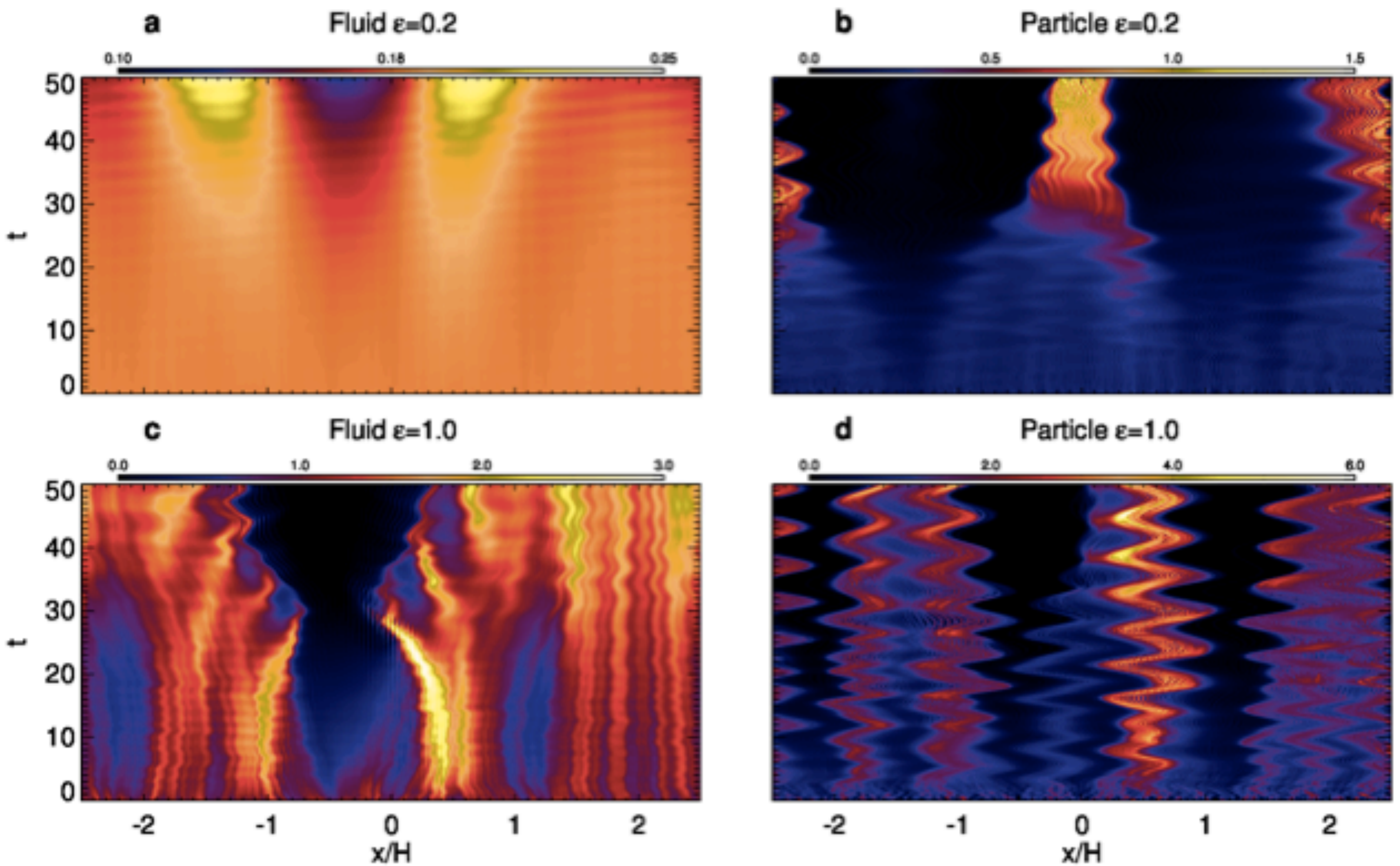
Thermal coupling time



Oscillations appear
with decreasing thermal time.

Oscillations

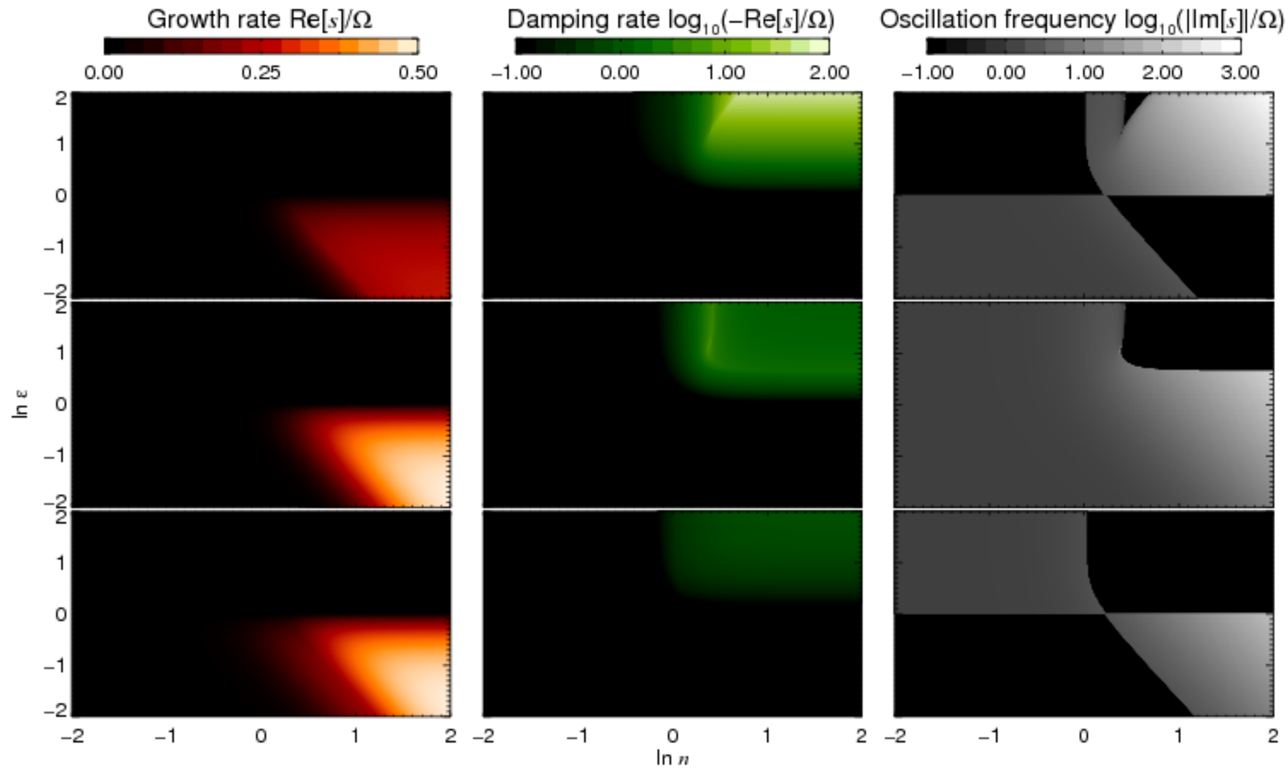
Low Reynolds number | *High Reynolds number*



Epicyclic oscillations

clear at high Reynolds numbers!

Solutions



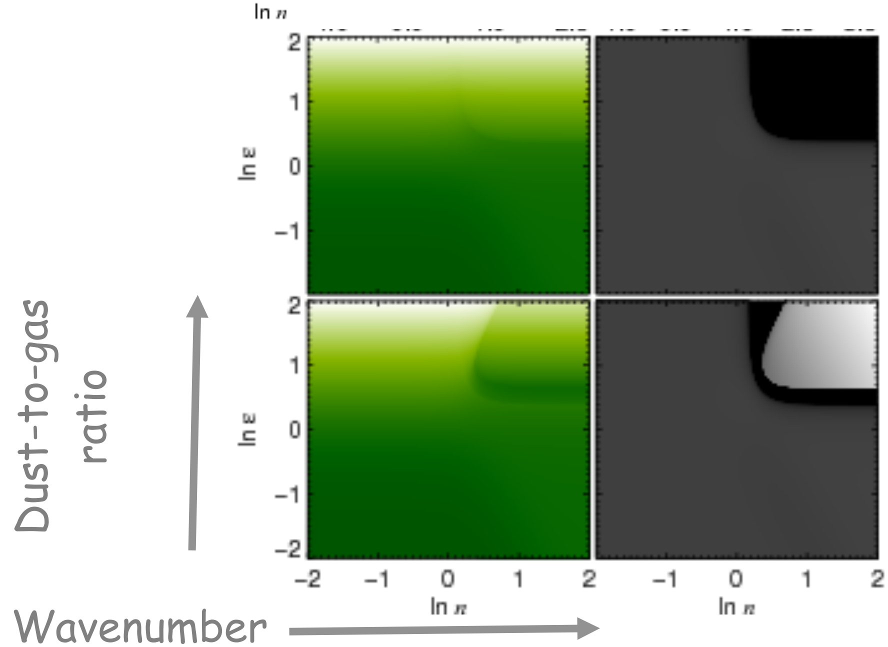
The dispersion relation is a 5[th] order polynomium, so there are five roots!

Dispersion relation

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

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

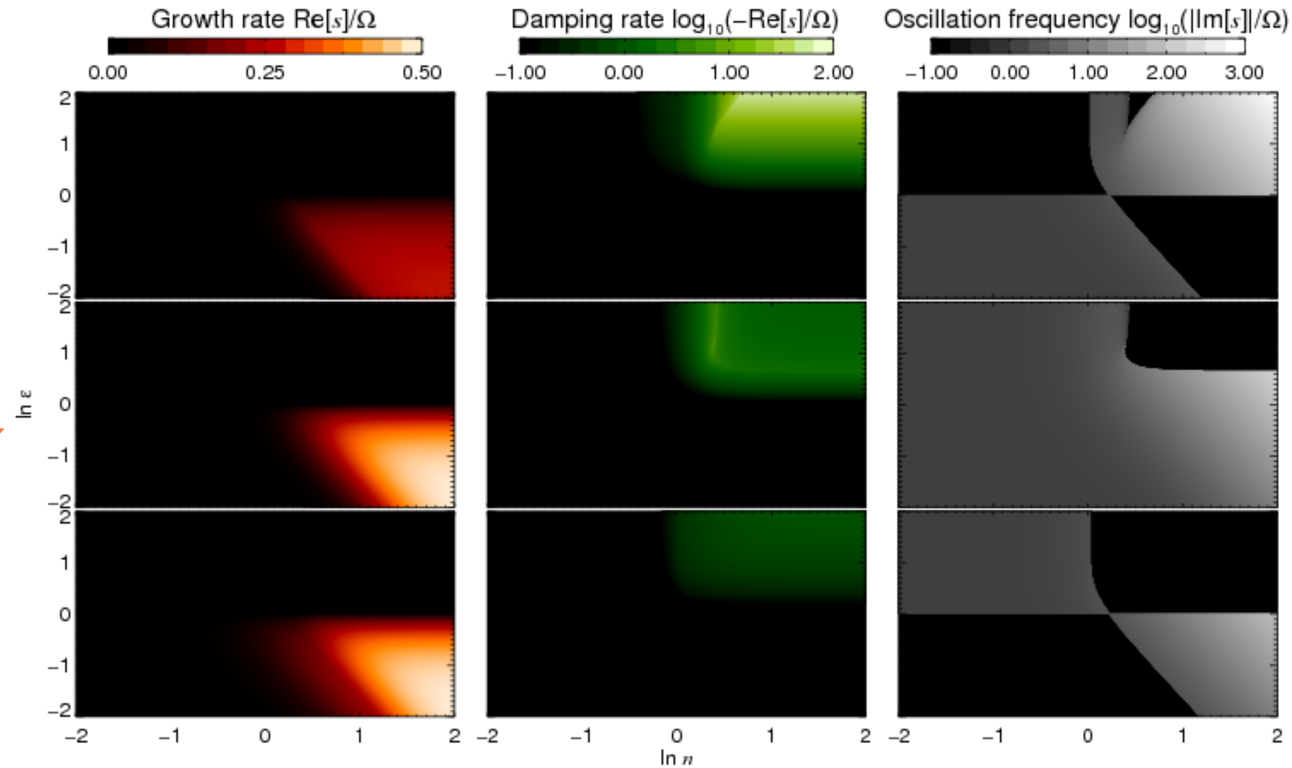
$\epsilon = \Sigma_d / \Sigma_g \qquad n = kH \qquad \omega = s/\Omega$



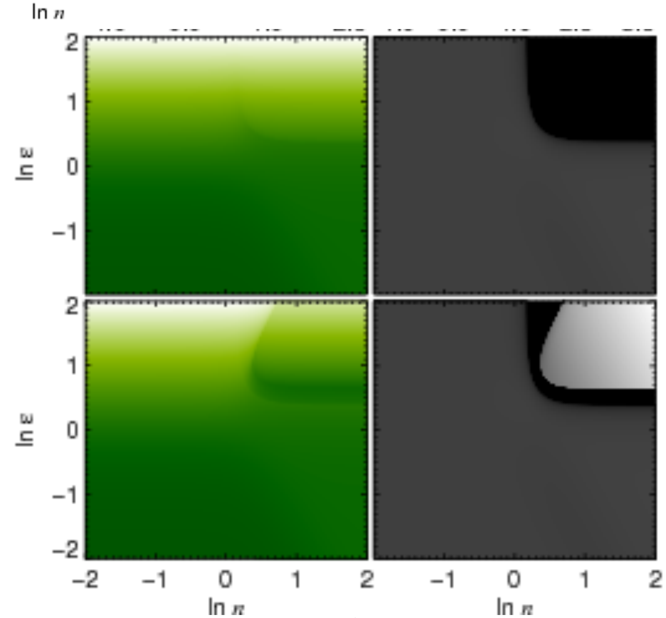
Solutions

Instability

Overstability



Damped and free Oscillations



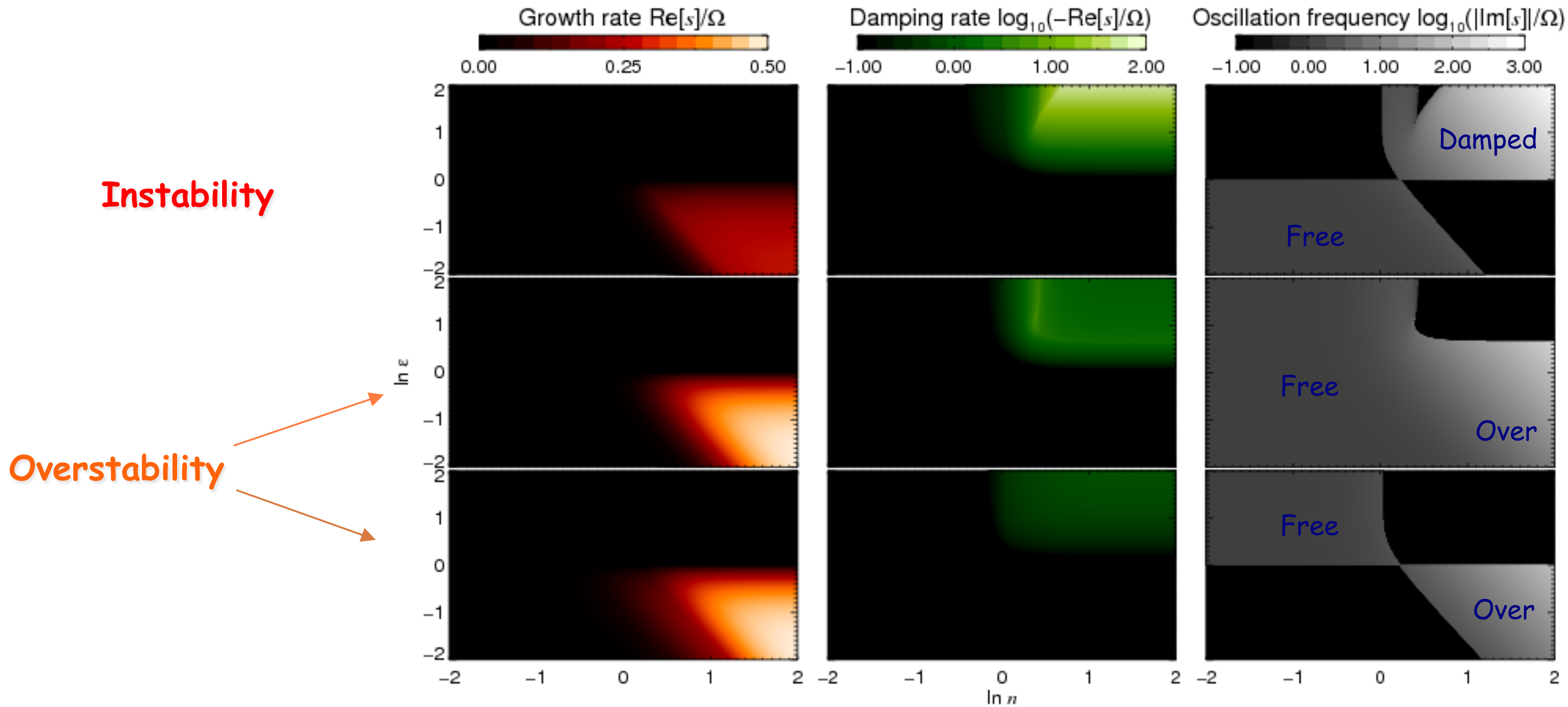
Dispersion relation

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

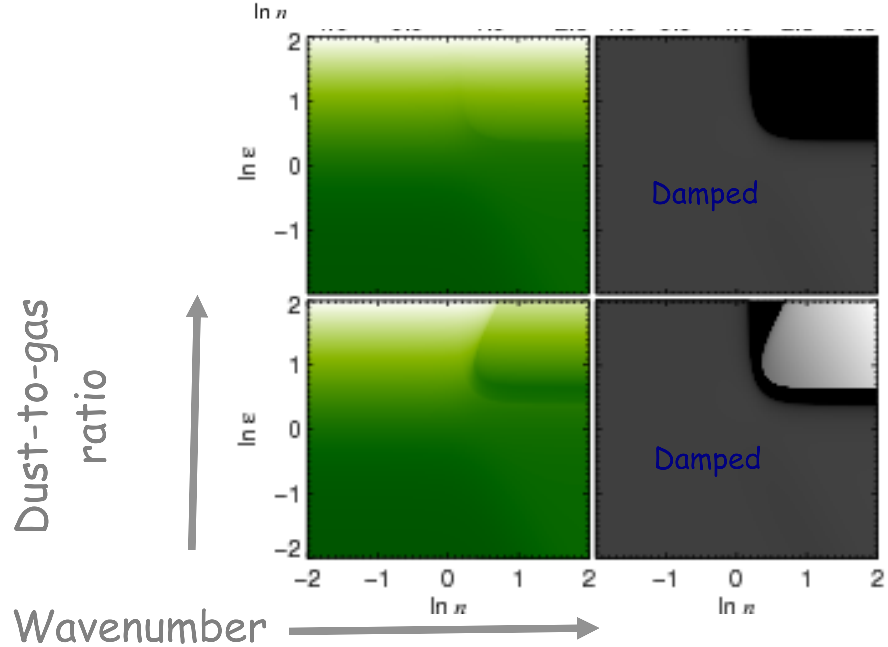
$$A=1$$
$$B=2\epsilon+2$$
$$C=\epsilon^2+\epsilon(n^2+2)+3$$
$$D=\epsilon^2 n^2+\epsilon(3n^2+2)+2$$
$$E=\epsilon^2(2n^2+1)+\epsilon(3n^2+2)+2$$
$$F=\epsilon^2 n^2-\epsilon n^2$$

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

Solutions



Damped and free Oscillations



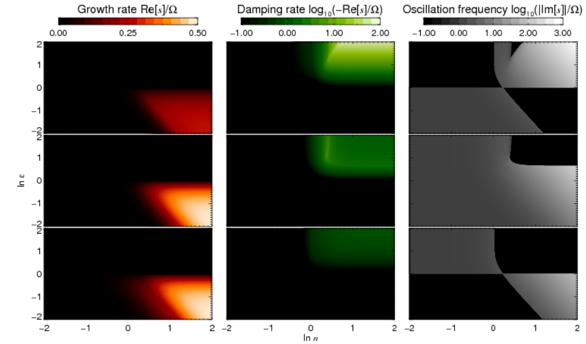
Dispersion relation

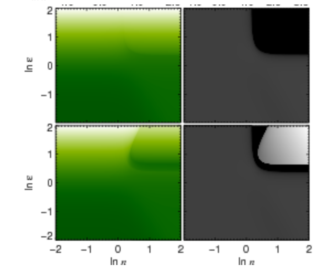
$$A\omega^5+B\omega^4+C\omega^3+D\omega^2+E\omega+F=0$$

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

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

Solutions

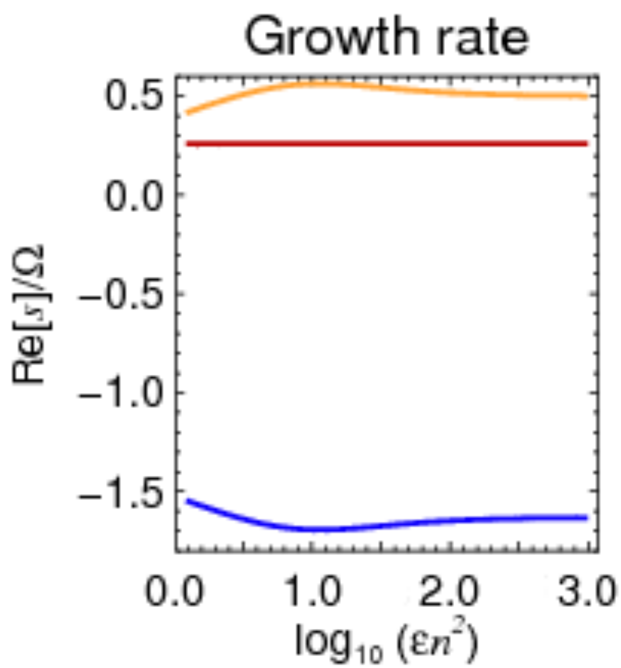


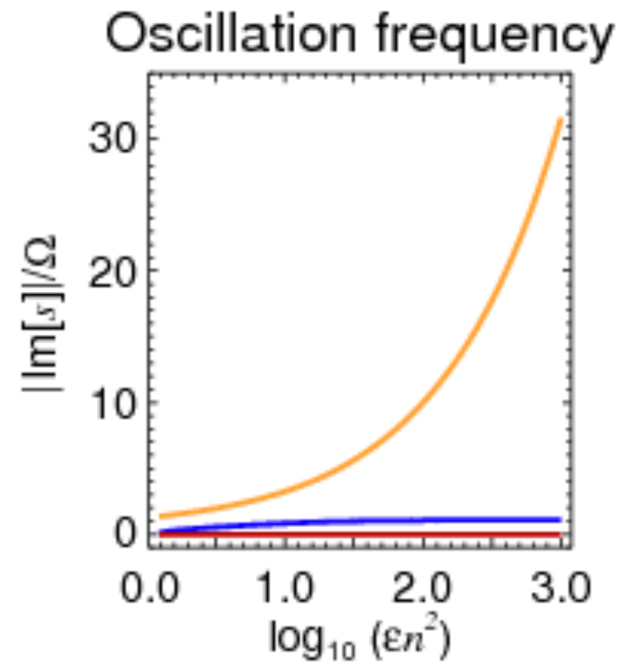


Overstability

Instability

Oscillations





Max growth rate: Omega/2.

Million-fold amplification in five orbits!

A very powerful instability.

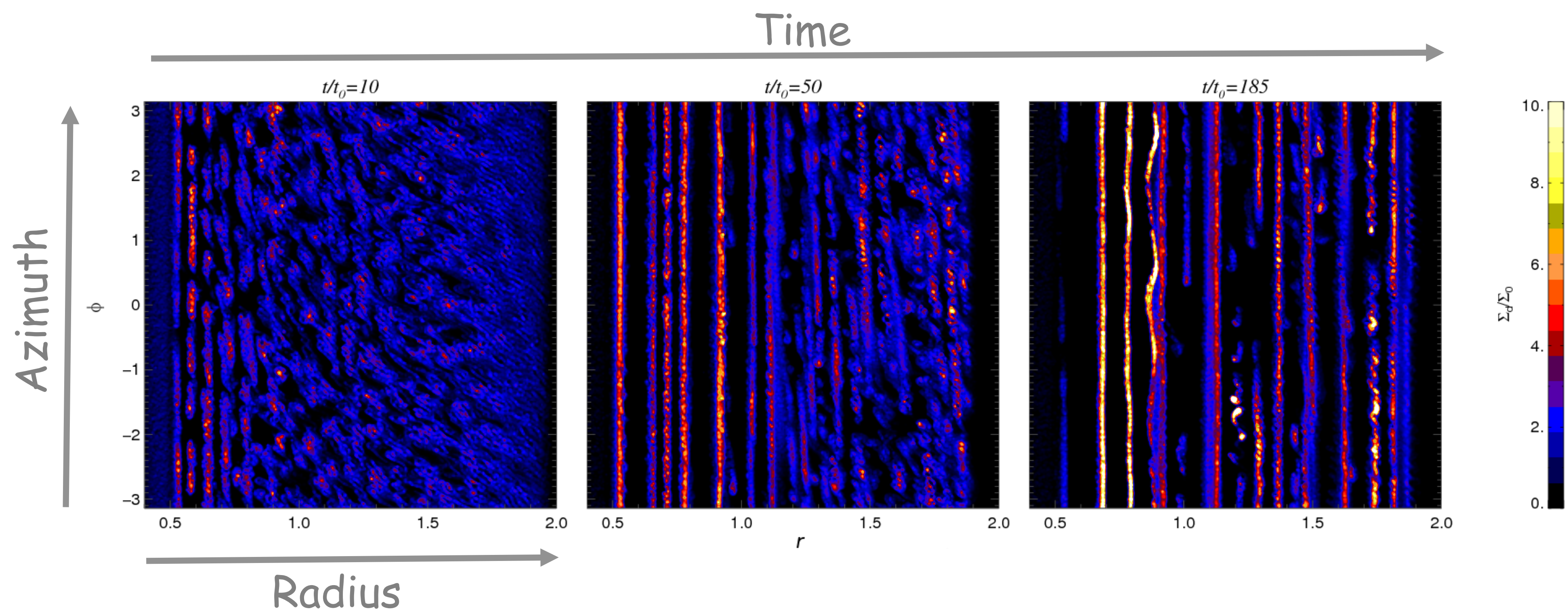
The model in r-ϕ: Eccentric rings

Growth of **axisymmetric** modes

+

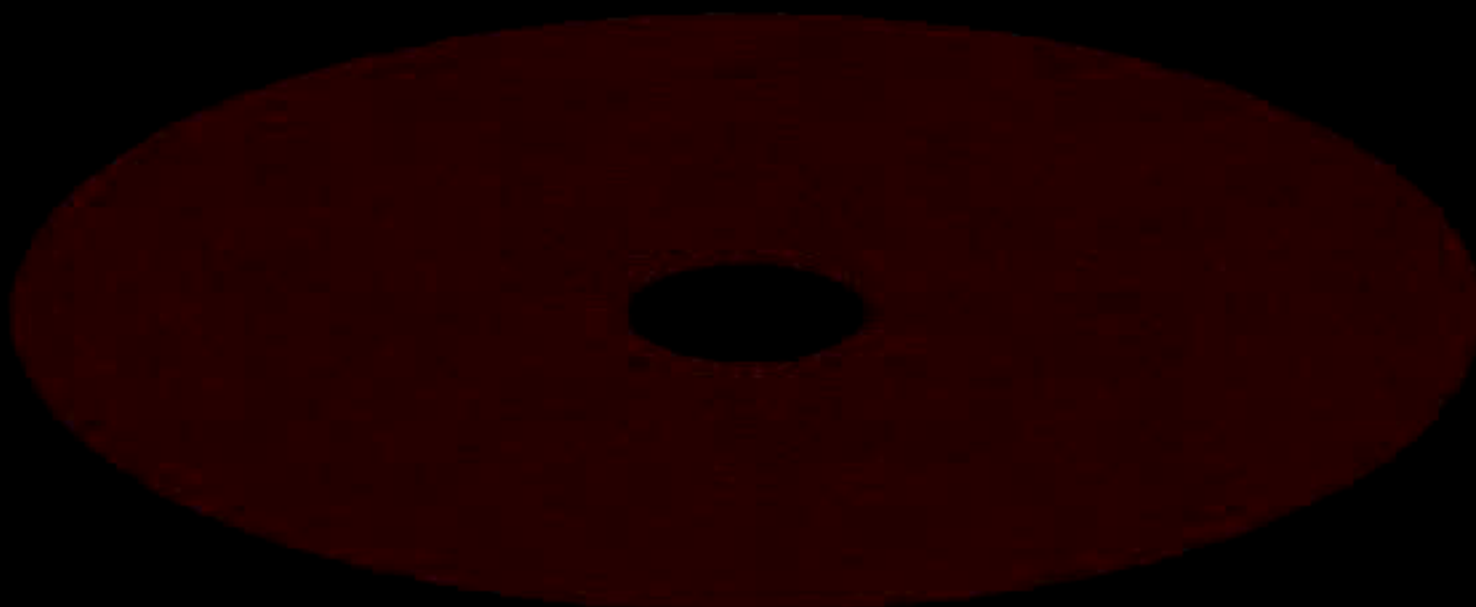
Damping of **nonaxissymetric** modes.

= ***Rings !!!***



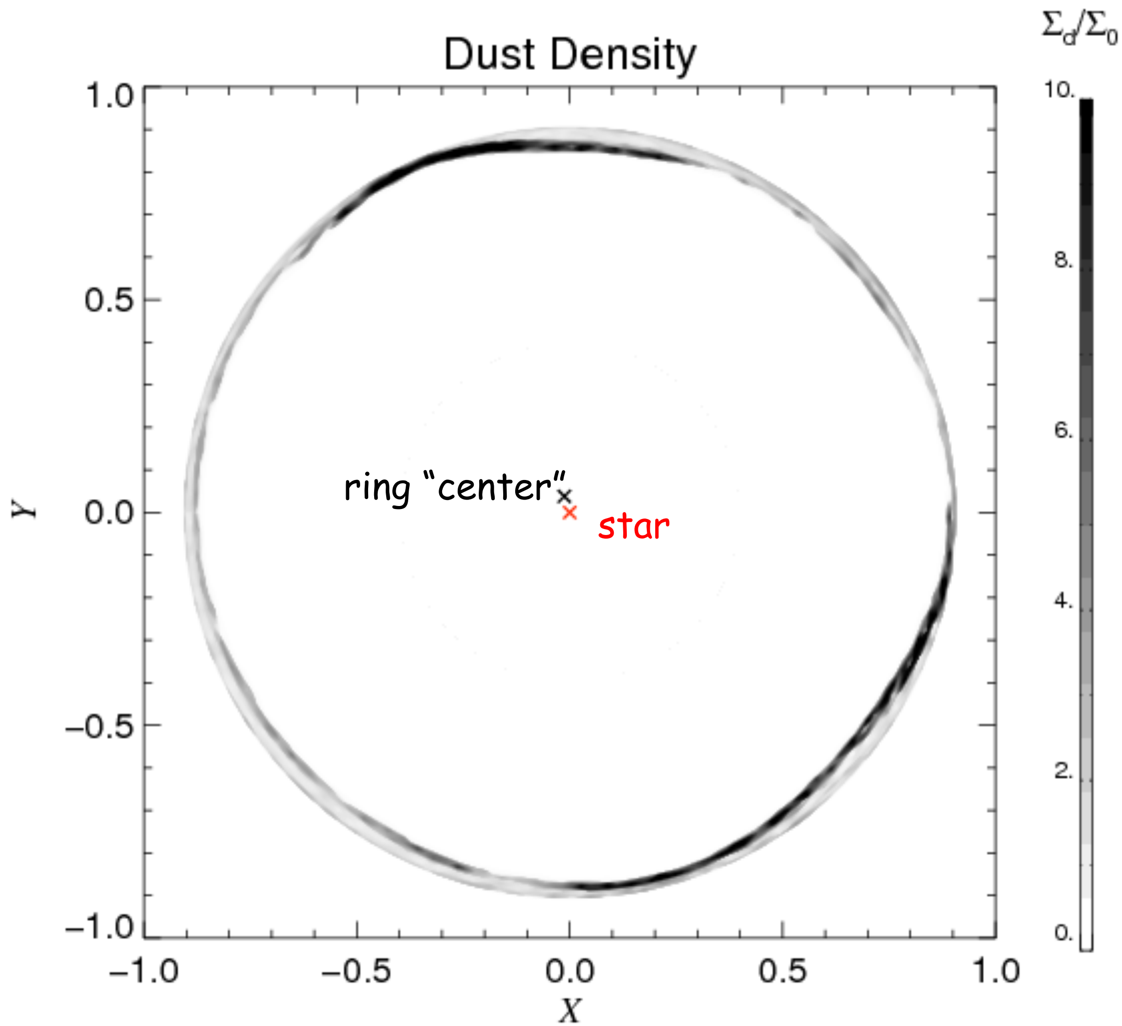
Epicyclic oscillations

make the ring appear ***eccentric !!!***



Lyra & Kuchner (2013, Nature, 499, 148)

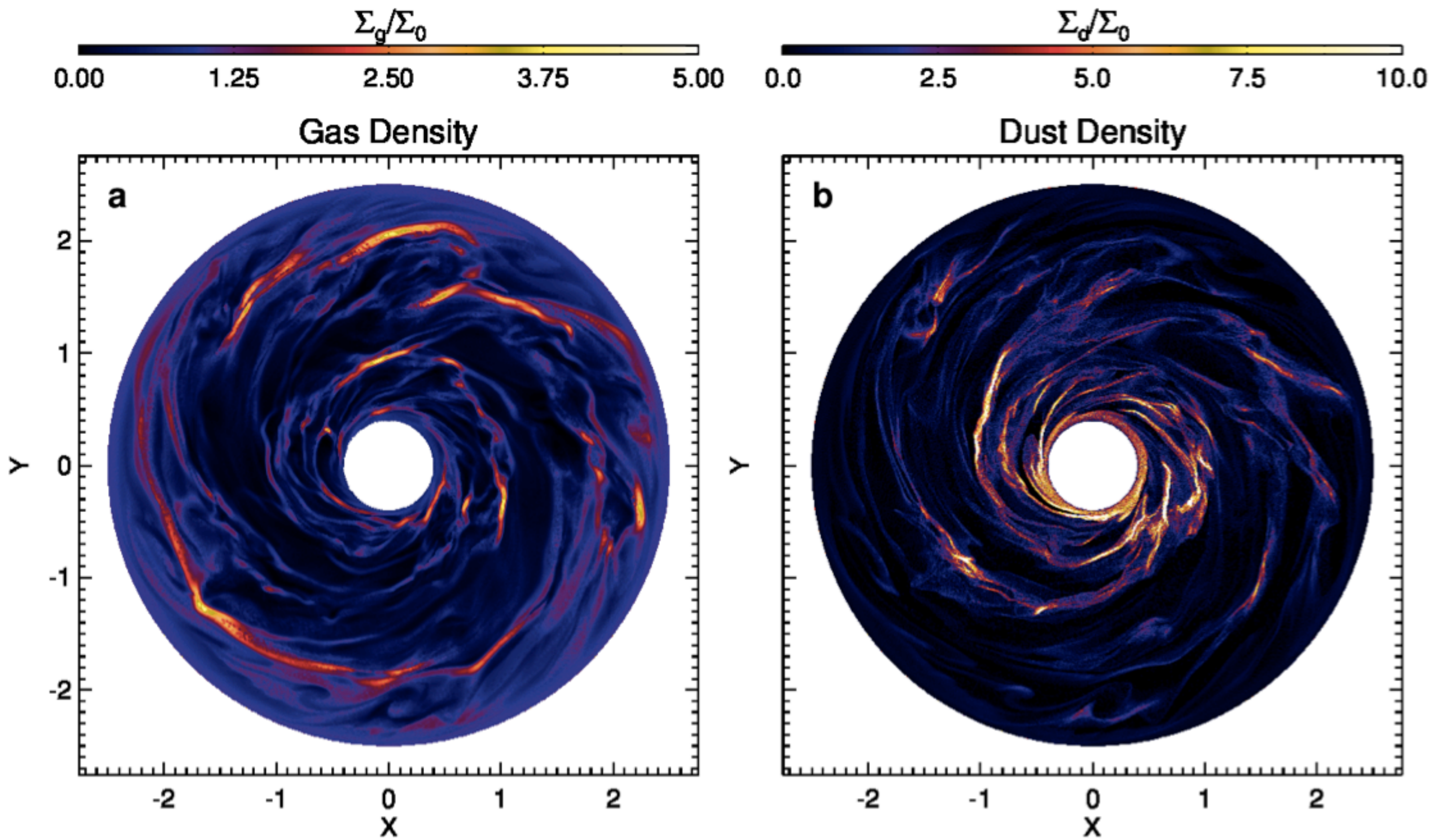
Ring Offset



Eccentricity e=0.04

Original Klahr and Lin 2005 does not work in 2D to make rings

Excluding the drag force backreaction



Break of axisymmetry
Power collects at high azimuthal wavenumbers.

Conclusions

There is a robust ring-forming

photoelectric instability

in optically thin gas-dust disks

Reproduces gross properties of observed systems

(rings, sharp edges, eccentricity)

Maximum for gas-to-dust ratio ~ 5

(probably more applicable to transitional disks)

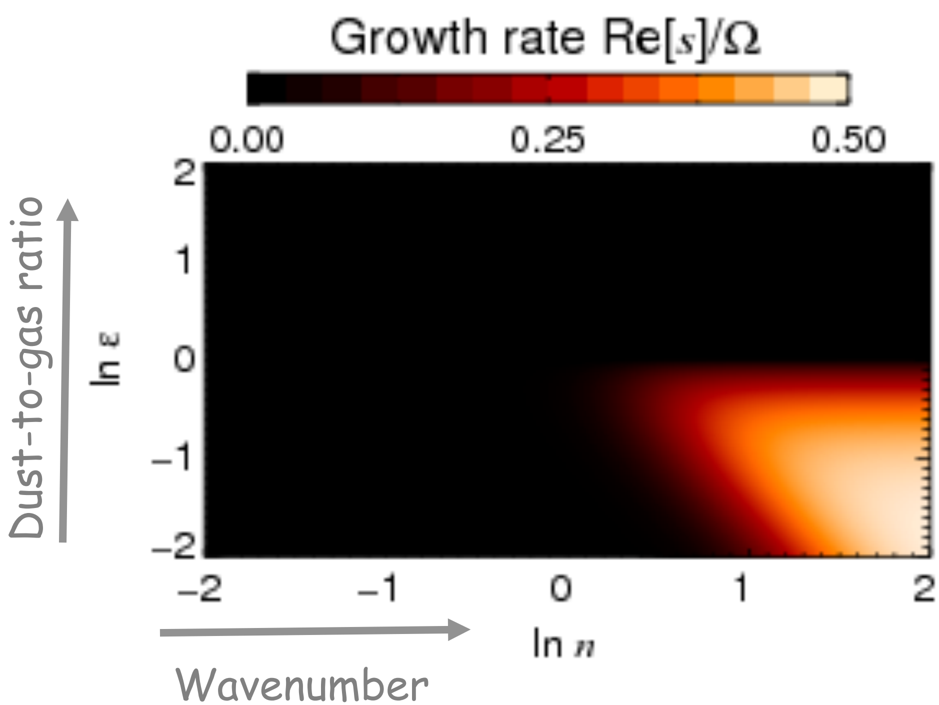
Future work:

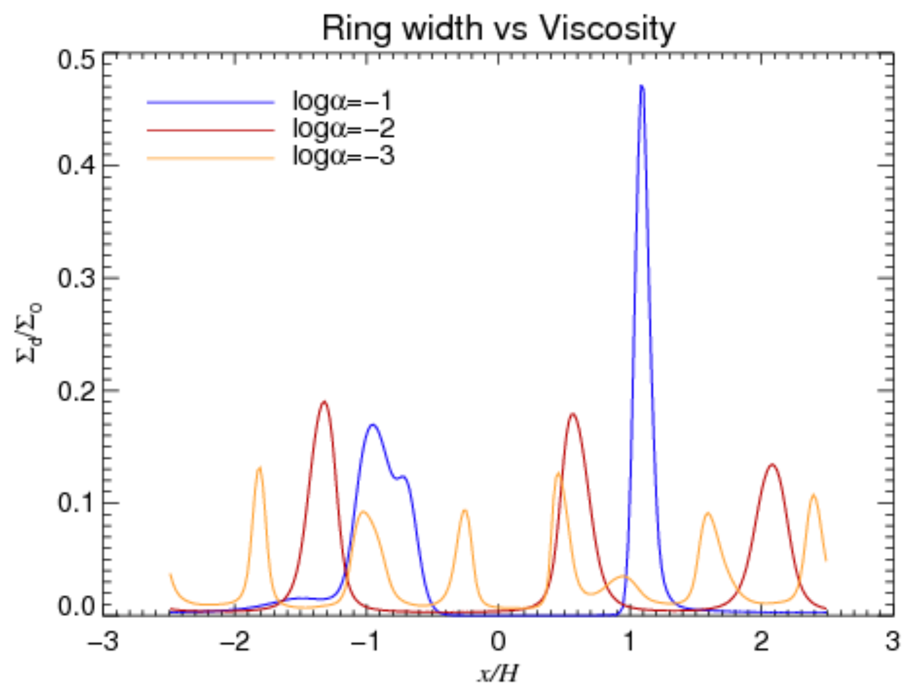
3D turbulence, Radiation forces, Collisions….

…. *(suggestions?)*

Ring Spacing

Ring spacing is determined
by the wavelength of maximum growth.





Which in turn is determined by viscosity

Ring spacing ~ 10 Kolmogorov lengths

Photoelectric vs Streaming Instability

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