Gas in debris disks
A new way to produce patterns?

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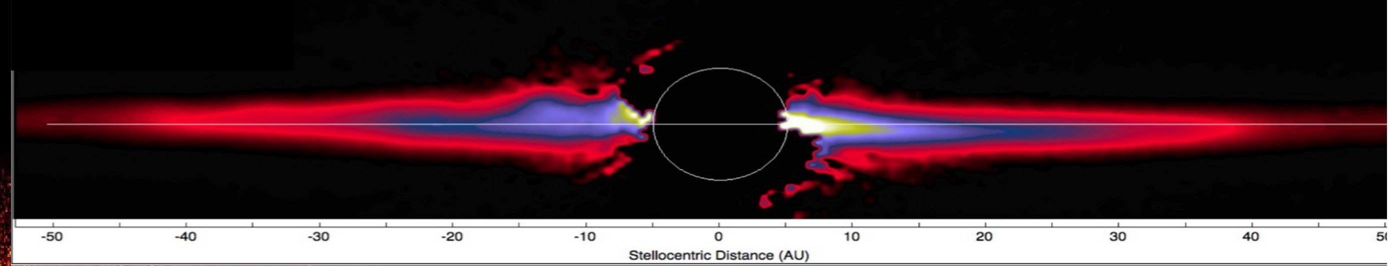
IAU Beijing - 2012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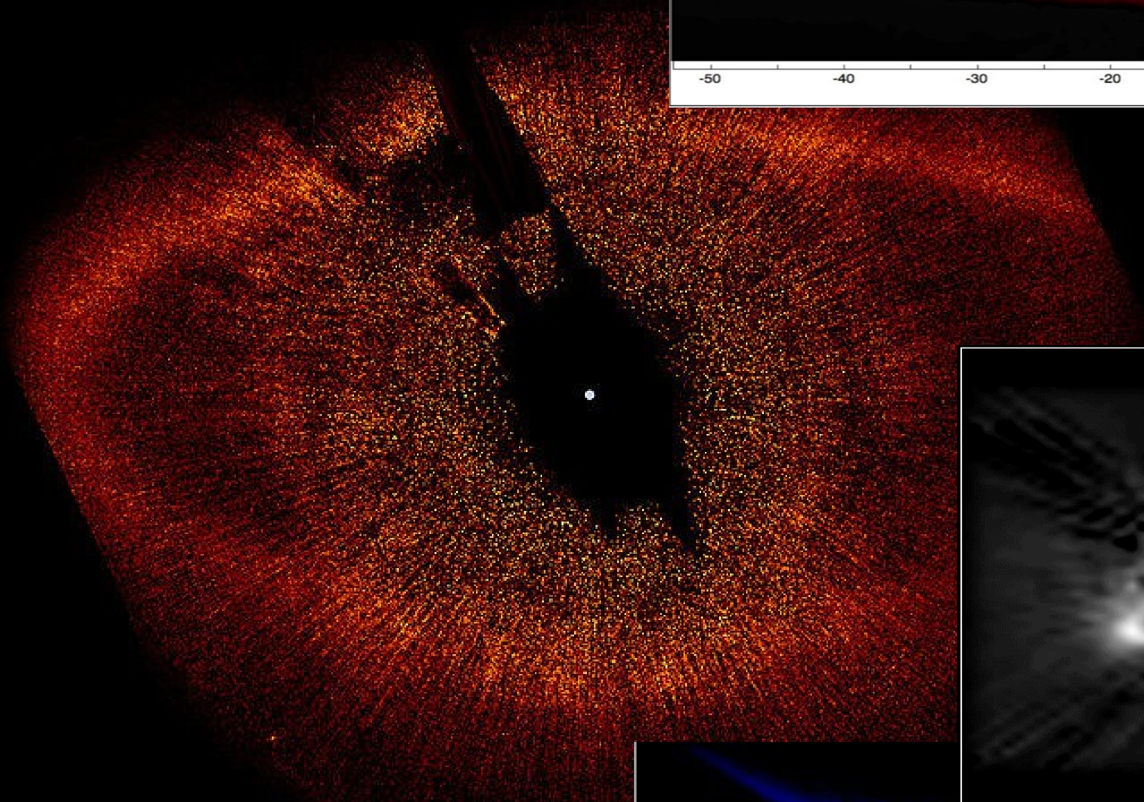
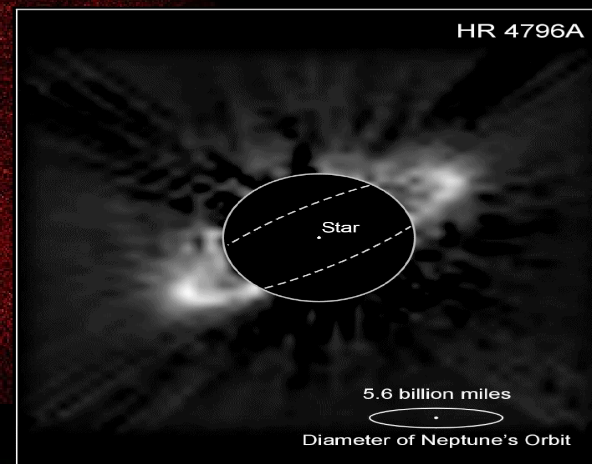
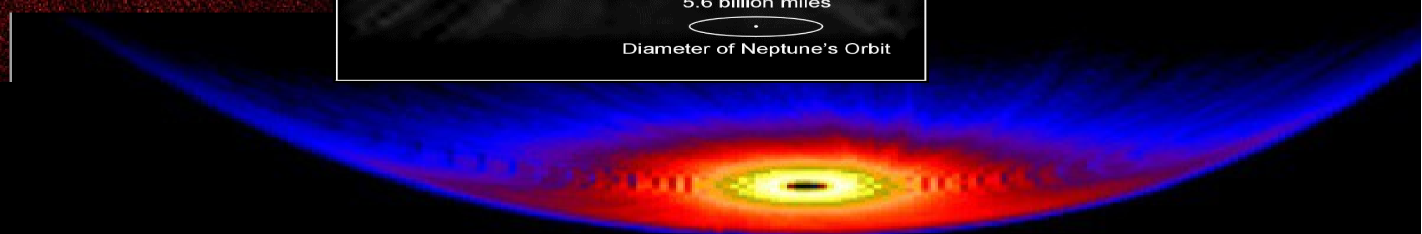
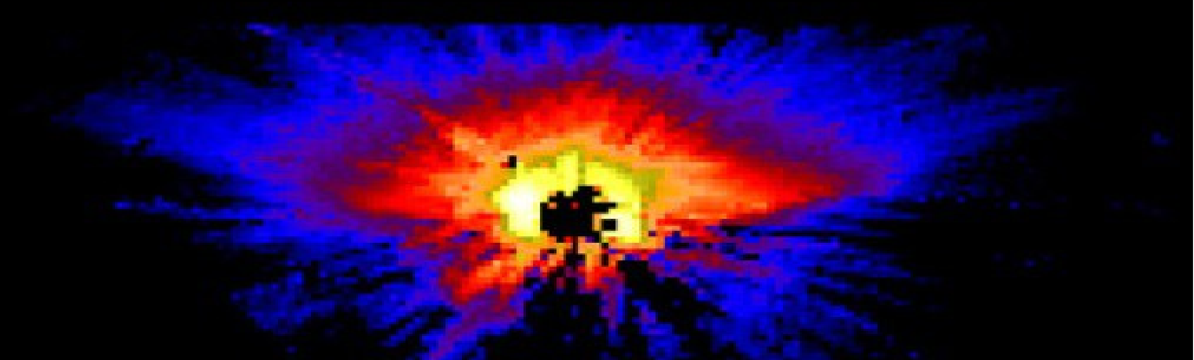
Stellocentric Distance (AU)

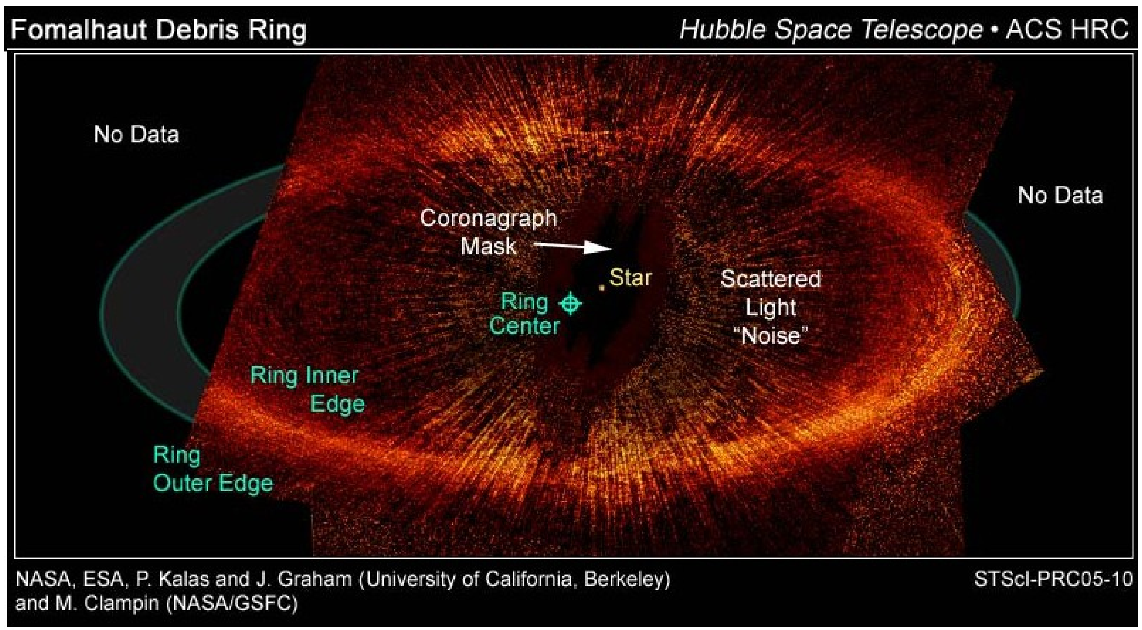


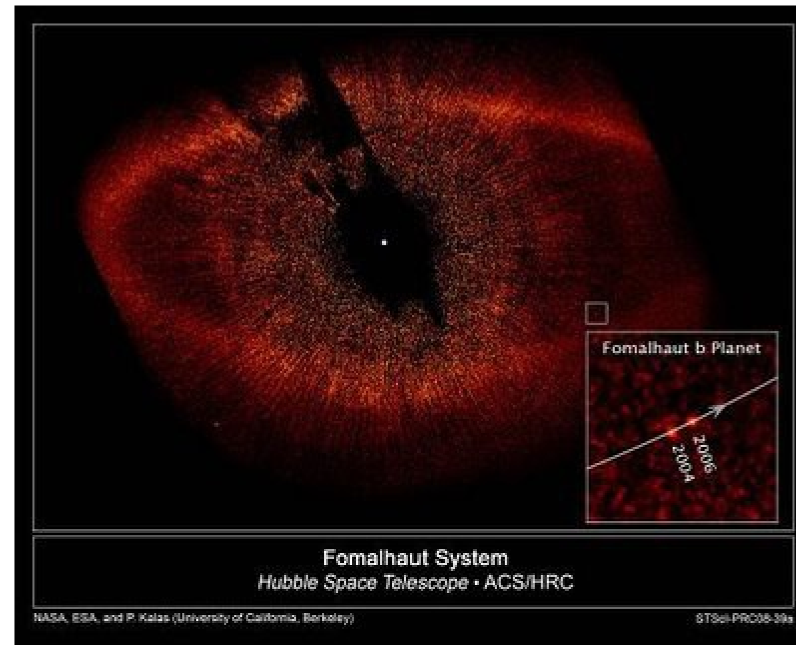

HR 4796A
Star
5.6 billion miles
Diameter of Neptune's Orbit





Sharp and eccentric rings in debris disks: Signposts of planets



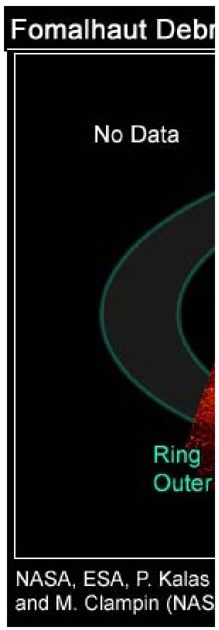


Narrow sharp eccentric ring

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

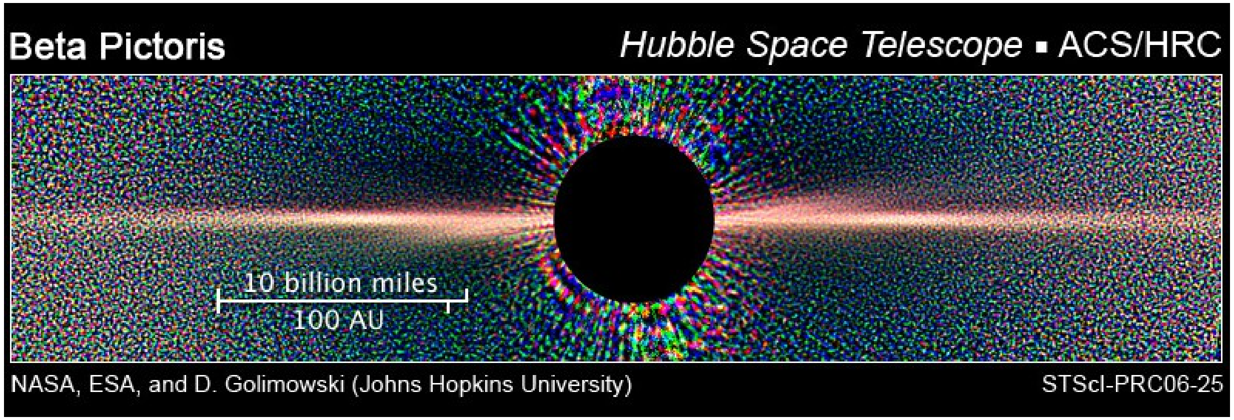
Online-only material: color figures

Planet not detected in infrared

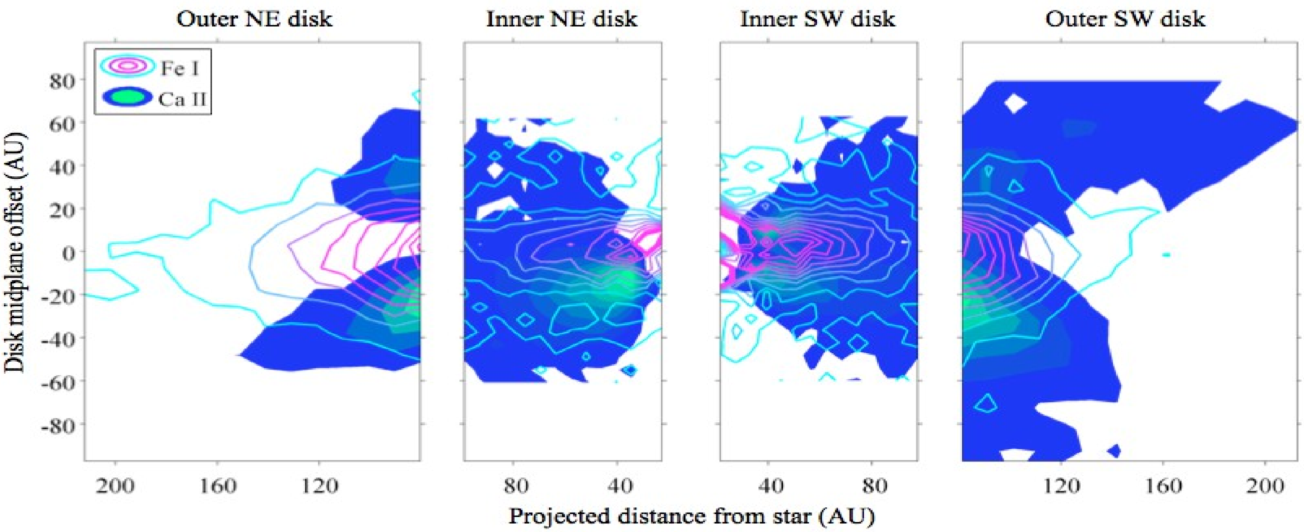
Are there alternative explanations?

Gas in debris disks

Dust



Gas



VLT imaging by
Nilsson et al. (2012)

Some debris disks have gas!

Gas in debris disks

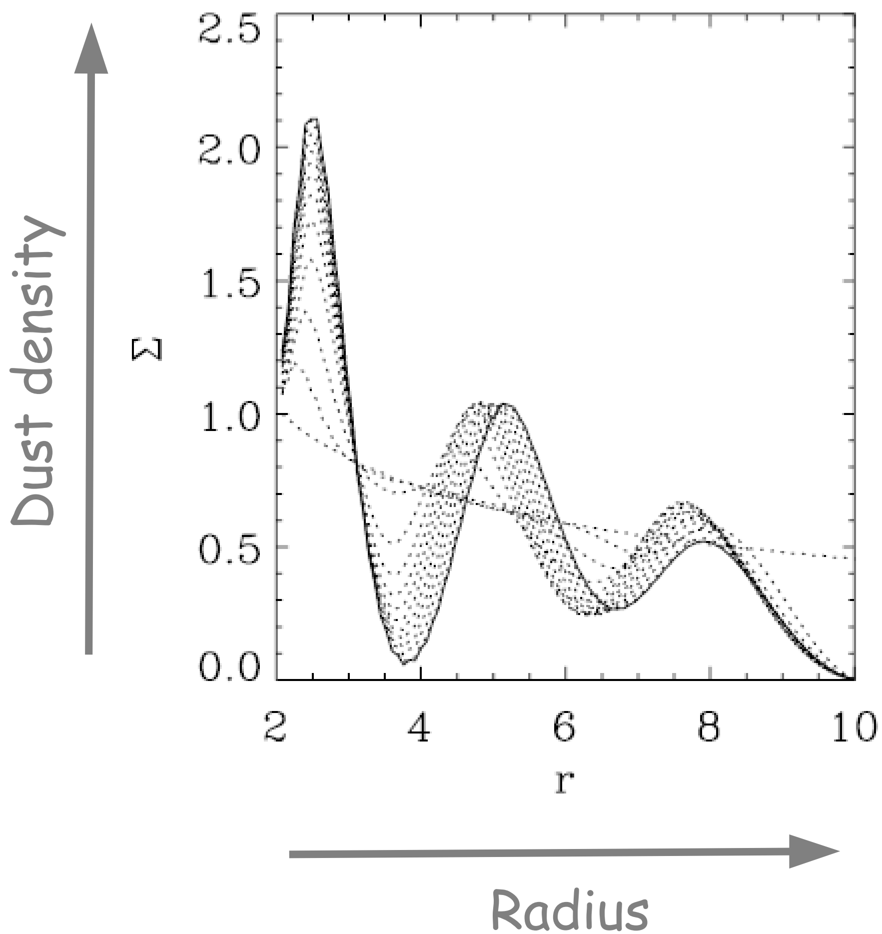
Detections

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

Primordial	
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)
Radiogenic heating of planetesimals	

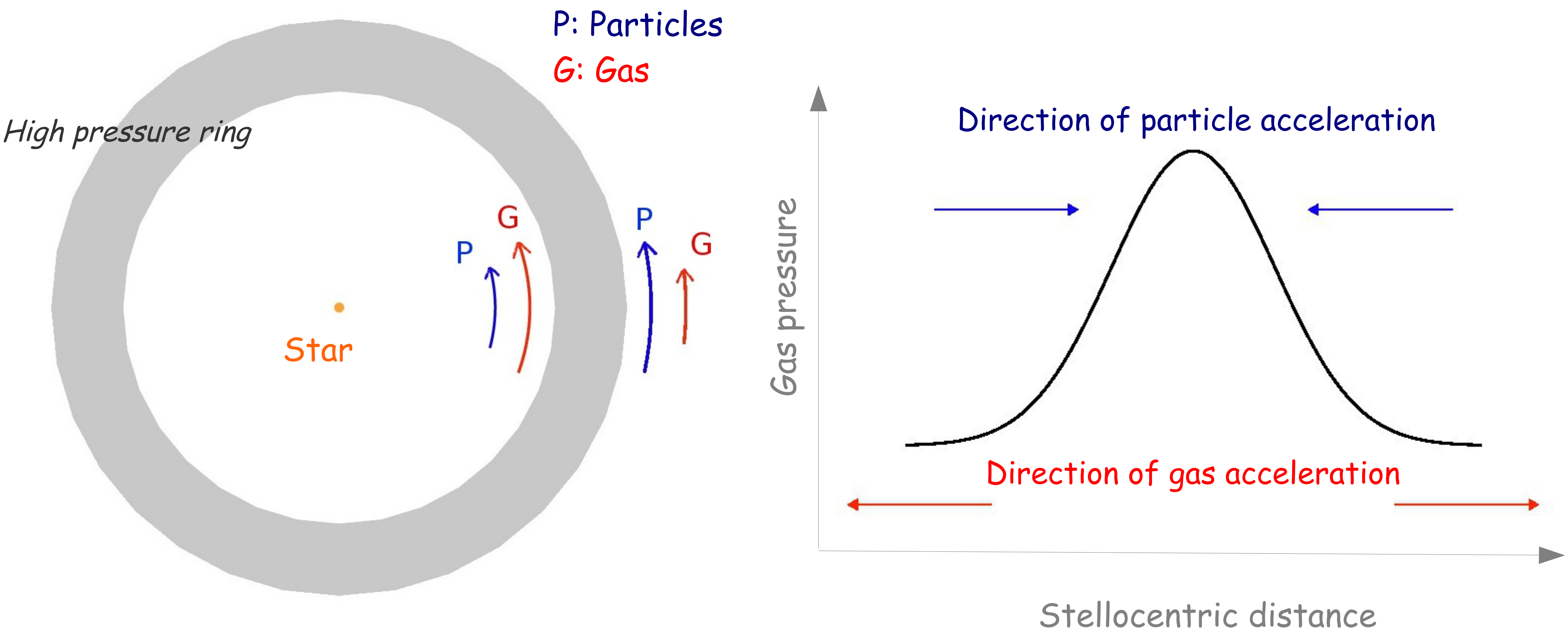
Dust and gas together leads to instability...



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)

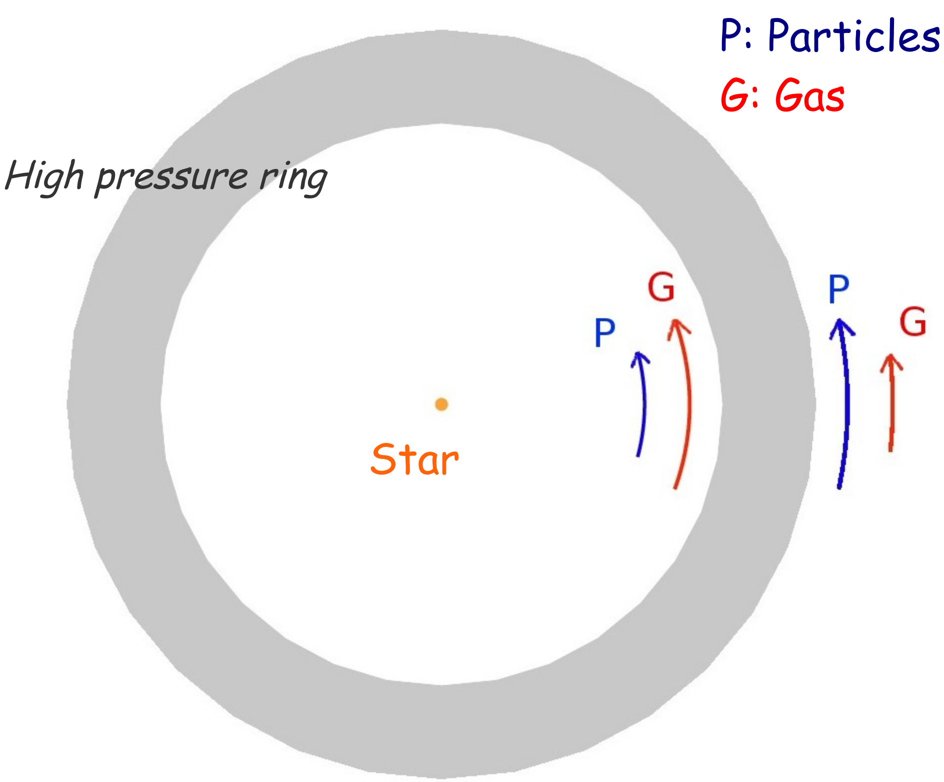
Particles move toward pressure maxima

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

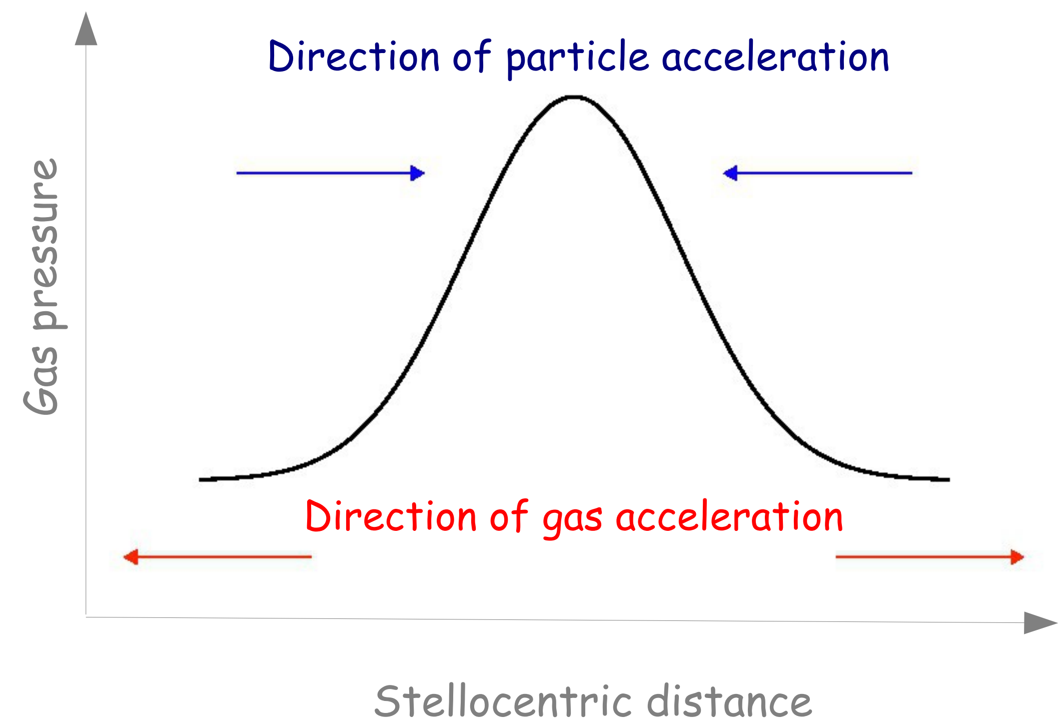
Particles $$\frac{d\boldsymbol{w}}{dt} = -\nabla\Phi - \frac{(\boldsymbol{w}-\boldsymbol{u})}{\tau}$$

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

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

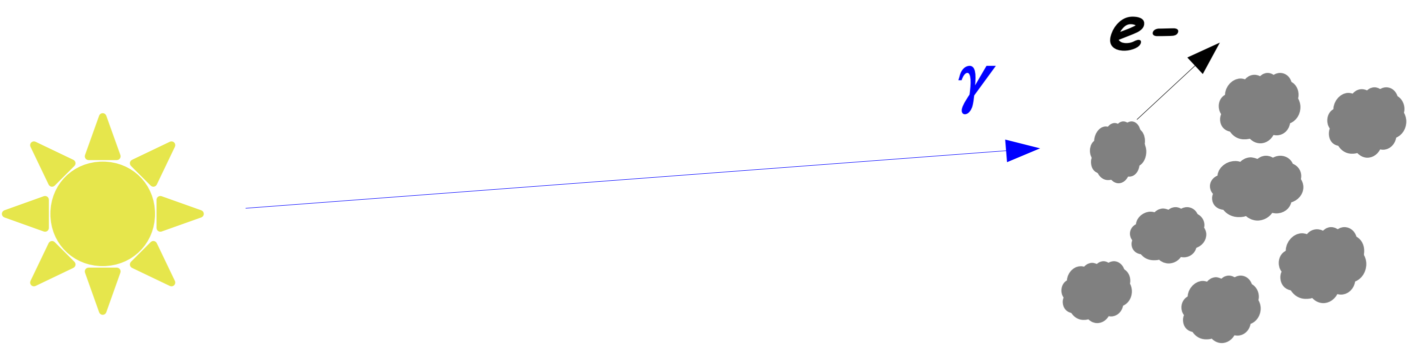


Adapted from Whipple (1972)



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 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

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

Dust velocity caused by tailwind/headwind

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

Equation of state

Model equations

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

Klahr & Lin (2005)

1D

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

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

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

Lyra & Kuchner (2012)

2D

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

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

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

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

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

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

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

Inertia for both gas and dust

Energy equation

Drag force and
drag force backreaction

Instability

Dust heats gas

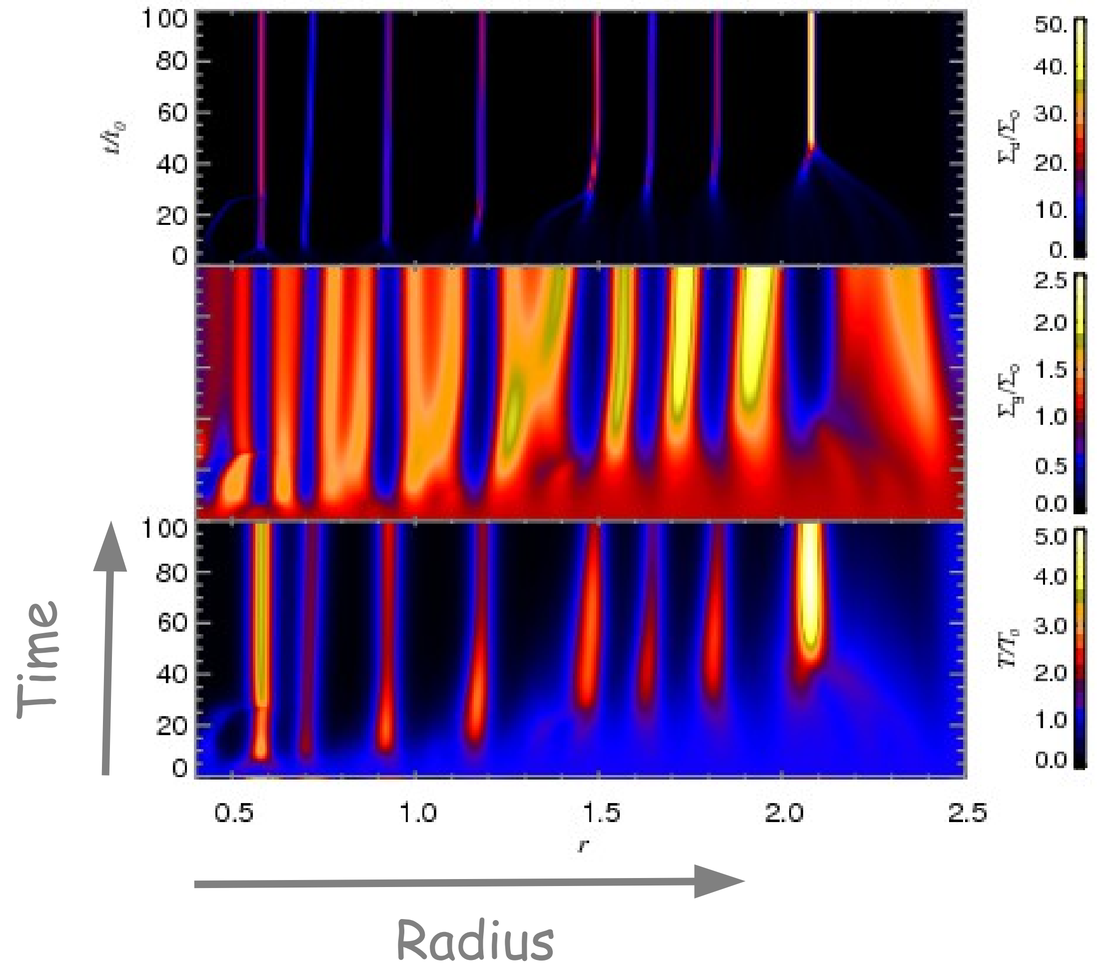
Heated gas = high pressure region

High pressure concentrates dust

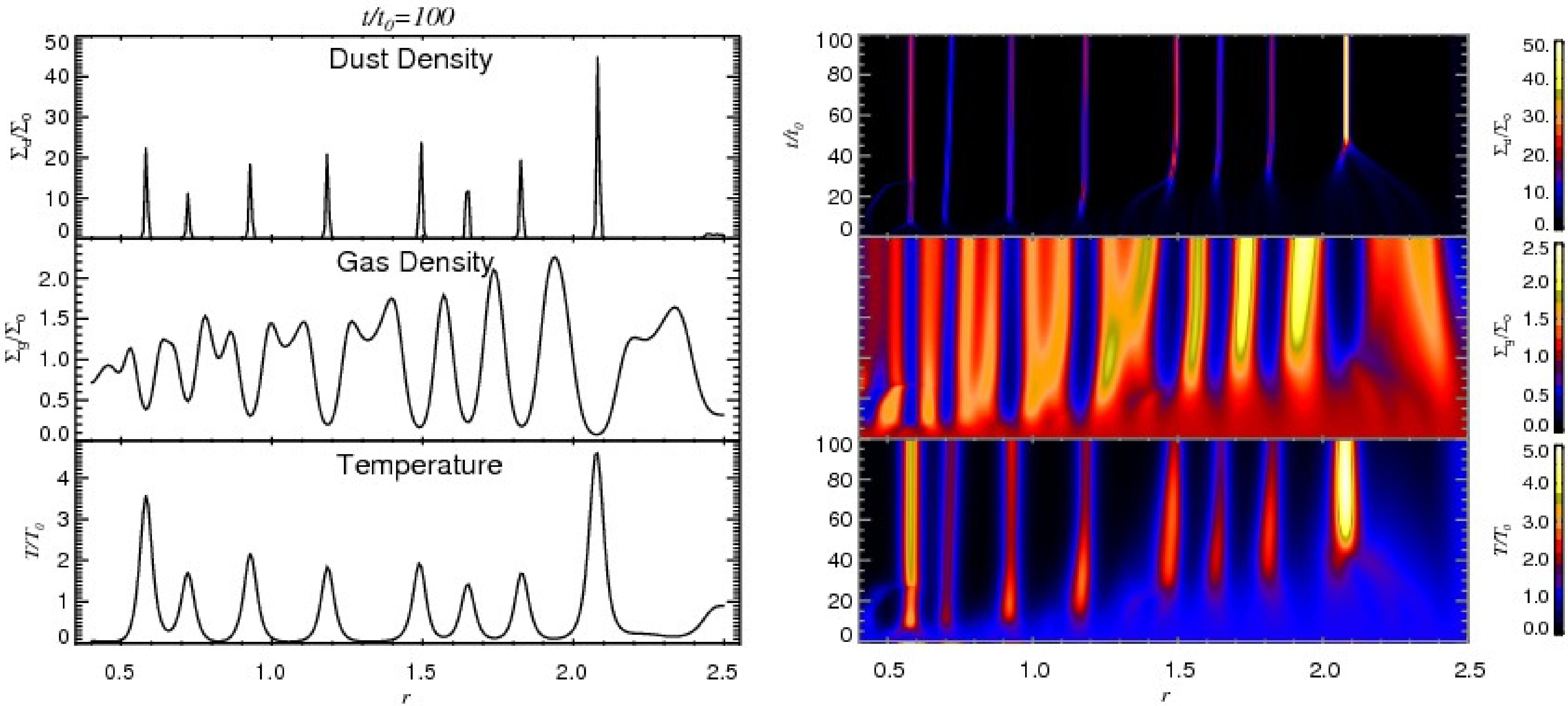
Dust density

Gas density

Temperature



Instability



Narrow hot dust rings
Cold gas collects between rings

Linear Analysis

Dust

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

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

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

Gas

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

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

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

$$\epsilon = \Sigma_d / \Sigma_g \qquad D_v = \partial_t + \boldsymbol{v}\cdot\nabla - q\Omega x \partial_y$$

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

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

$$(\boldsymbol{M} - \boldsymbol{I}\omega)\cdot\boldsymbol{\sigma} = 0$$

$$\boldsymbol{M} = \begin{bmatrix} -1 & 2 & 1 & 0 \\ -1/2 & -1 & 0 & 1 \\ \epsilon(1 - n^2/\omega) & 0 & -\epsilon(1 + n^2/\omega) & 2 \\ 0 & \epsilon & -1/2 & -\epsilon \end{bmatrix}$$

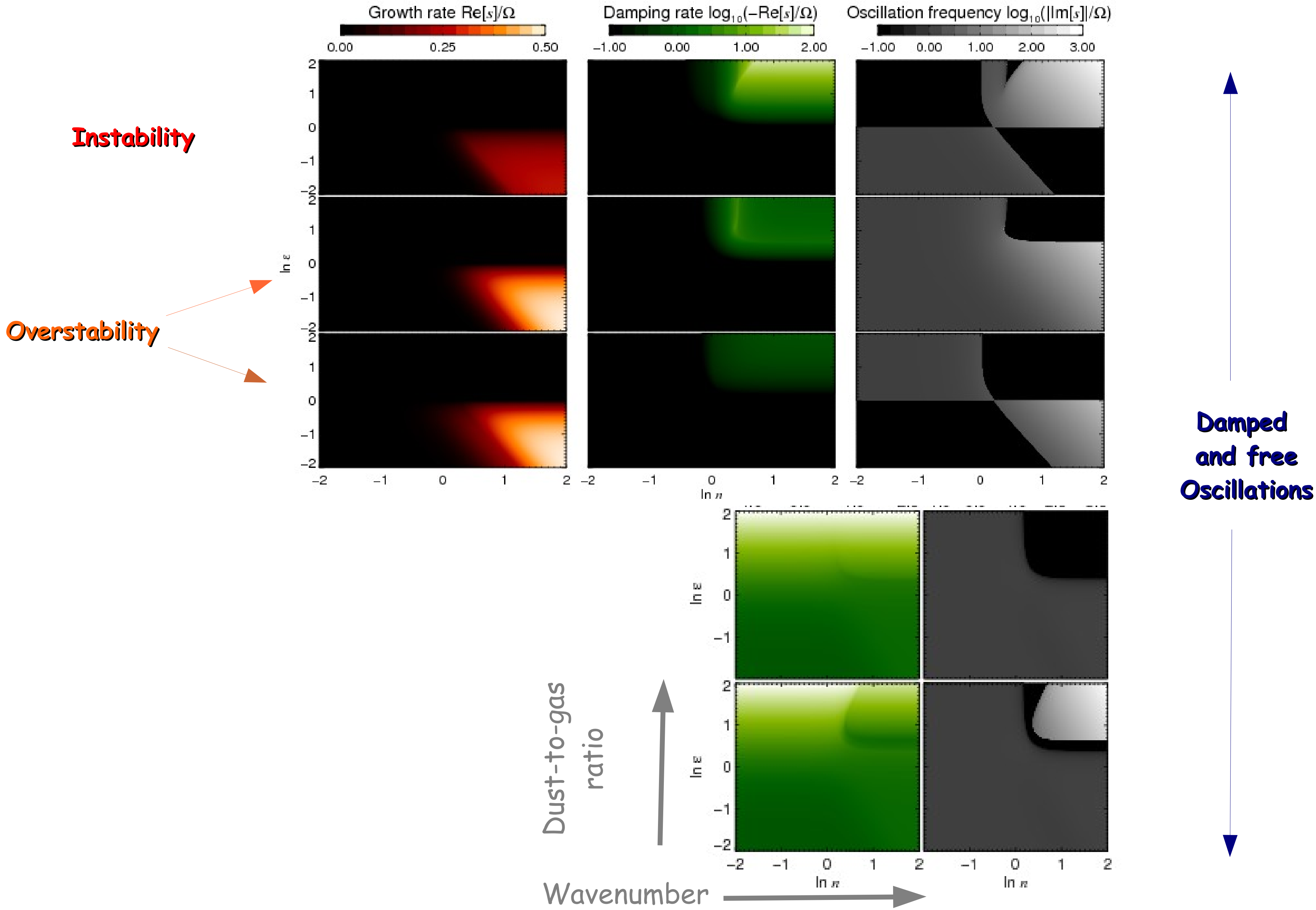
$$\boldsymbol{\sigma} = (\hat{w}_x, \hat{w}_y, \hat{u}_x, \hat{u}_y)^T \qquad \omega = s/\Omega \qquad n = kH$$

Dispersion relation

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

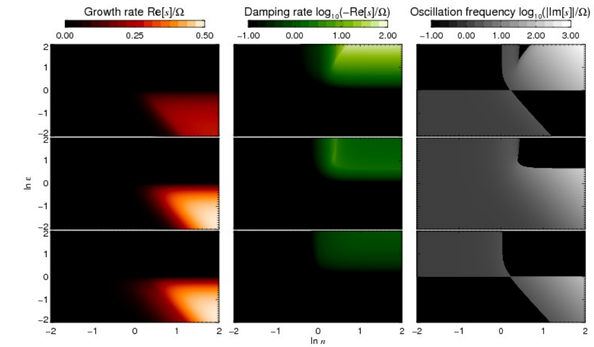
$$A = 1$$
$$B = 2\epsilon + 2$$
$$C = \epsilon^2 + \epsilon(n^2 + 2) + 3$$
$$D = \epsilon^2 n^2 + \epsilon(3n^2 + 2) + 2$$
$$E = \epsilon^2(2n^2 + 1) + \epsilon(3n^2 + 2) + 2$$
$$F = \epsilon^2 n^2 - \epsilon n^2$$

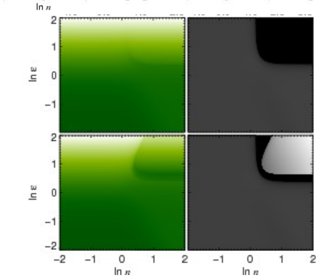
Solutions



Growth rate Re[s]/Ω
0.00
0.25
0.50
Damping rate log$_{10}$(−Re[s]/Ω)
−1.00
0.00
1.00
2.00
Oscillation frequency log$_{10}$(|Im[s]|/Ω)
−1.00
0.00
1.00
2.00
3.00
ln ε
ln κ
Instability
Overstability
Damped and free Oscillations
Dust-to-gas ratio
Wavenumber

Solutions

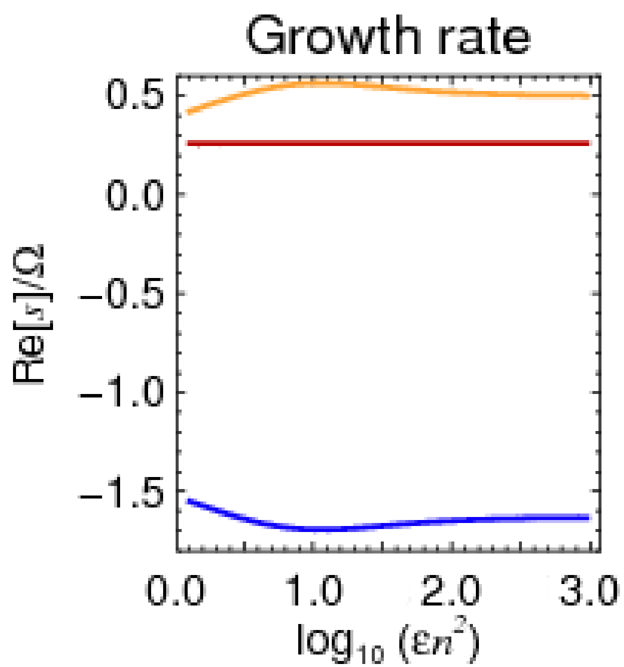


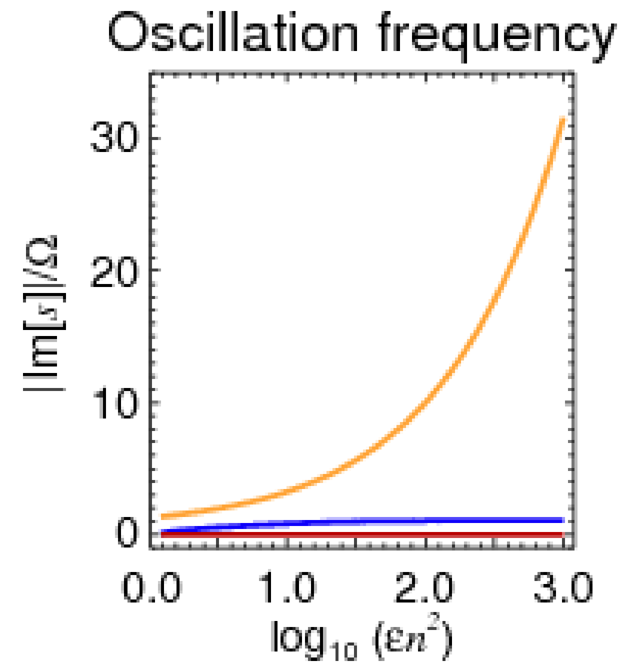


Overstability

Instability

Oscillations





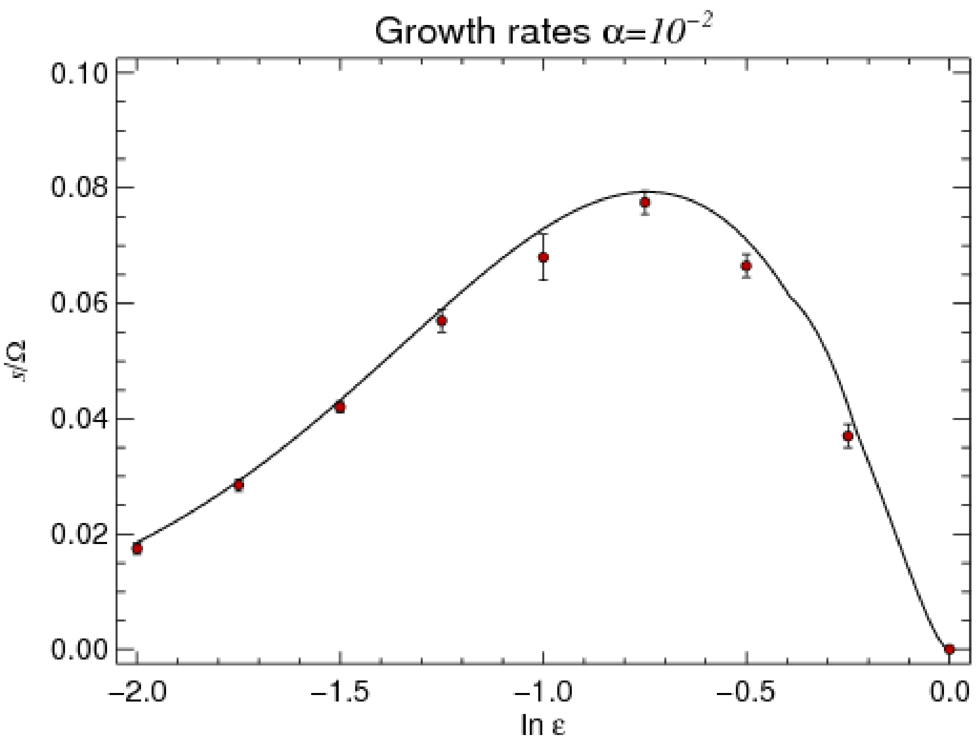
Max growth rate: Omega/2.

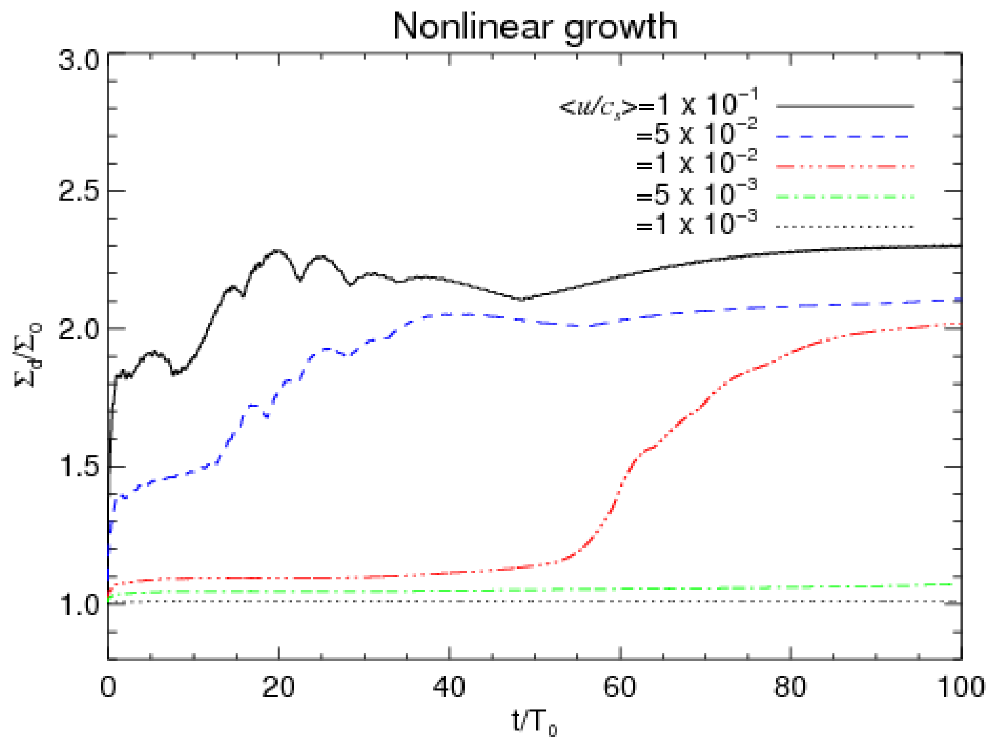
Million-fold amplification in five orbits!

A very powerful instability.

Linear and nonlinear growth

Linear growth only exists for $\varepsilon < 1$





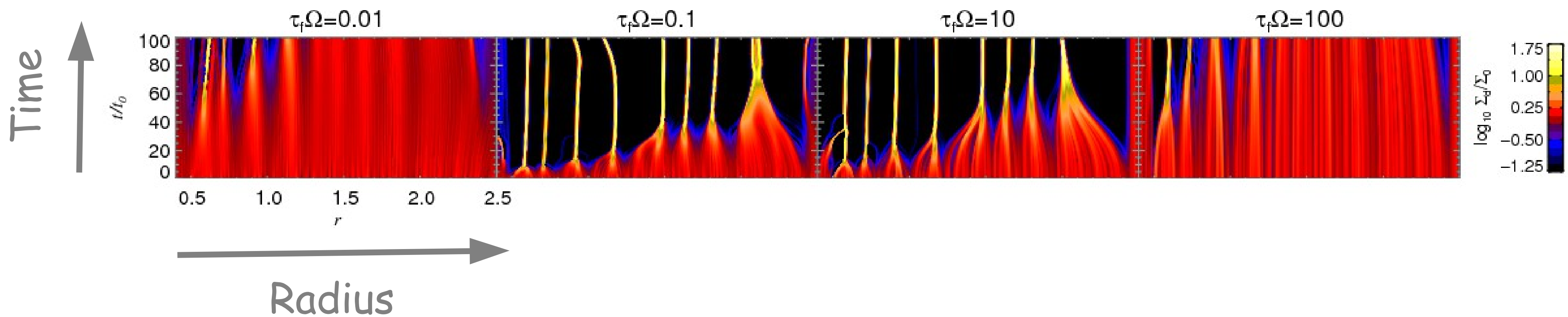
But there is

nonlinear growth

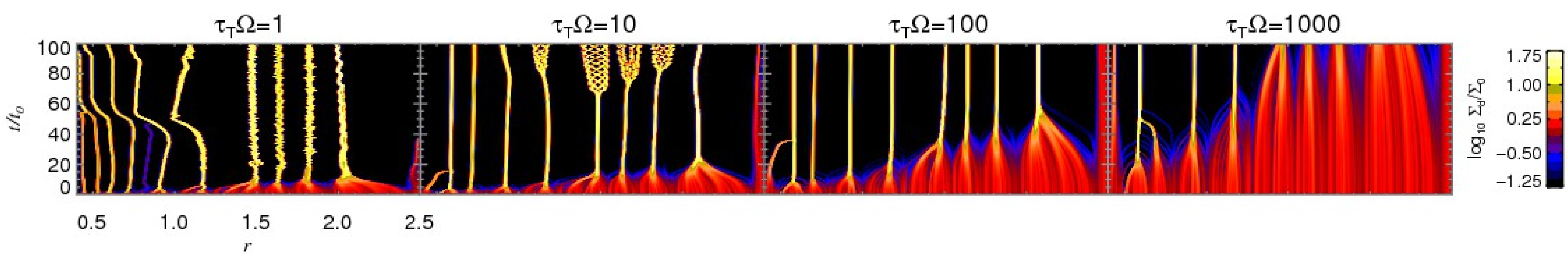
beyond !

Robustness

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



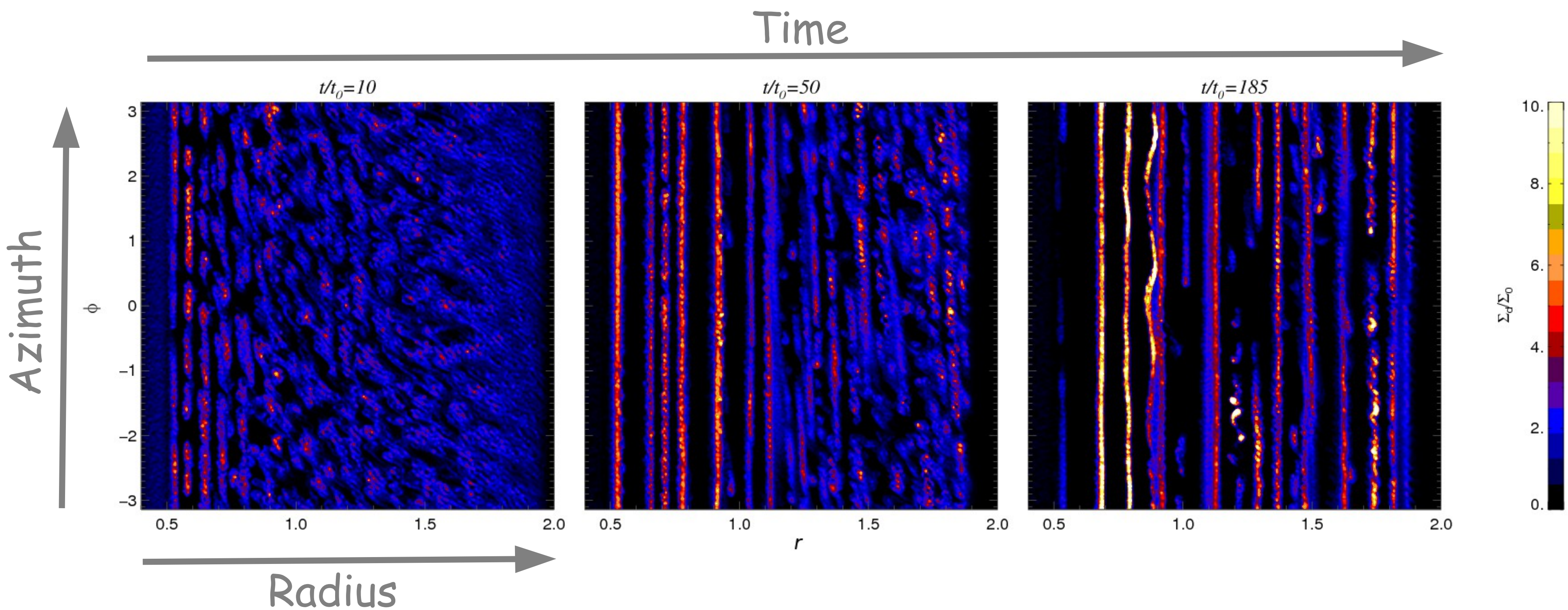
Growth over 4 orders of magnitude in thermal time



The model in 2D: Eccentric rings

Growth of **axisymmetric** modes
+
Damping of **nonaxissymetric** modes.

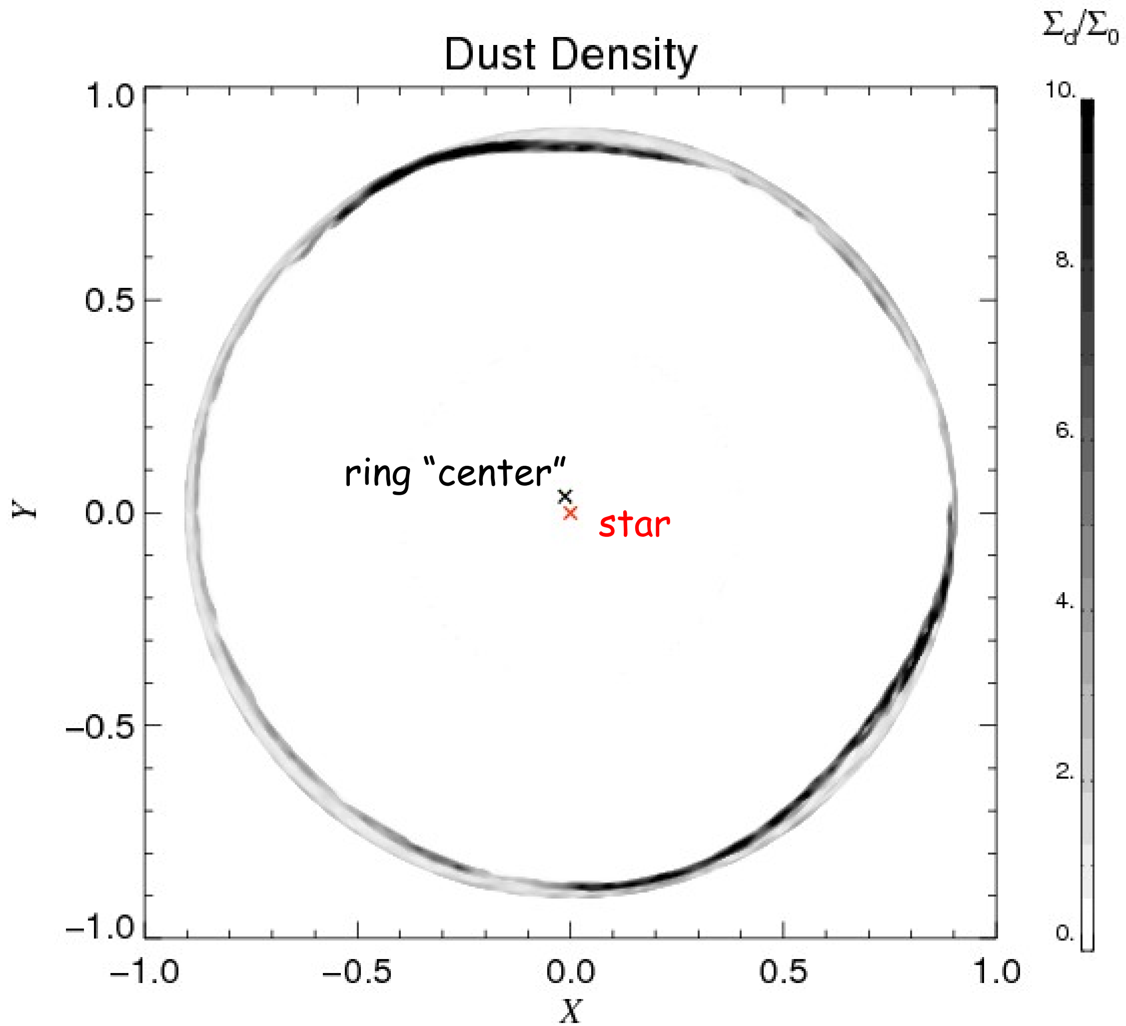
= ***Rings !!!***



Epicyclic oscillations

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

Ring eccentricity



Eccentricity e=0.04

Summary

Hydrodynamical instability in Debris Disks with Gas

- Different instability than Klahr & Lin (2005):
  - short time scale:
    dynamical time, not radial drift time
- Robust to inertia, drag backreaction, 2-D effects
- Yields narrow rings with eccentricities up to ~0.04 so far

Future Work:

- 3-D
- Magnetic fields
- Collisions

arXiv:1204.6322

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SHARP ECCENTRIC RINGS IN PLANETLESS HYDRODYNAMICAL MODELS OF DEBRIS DISKS.

WLADIMIR LYRA[1,2,3] AND MARC J. KUCHNER[4]

Draft version

ABSTRACT

Debris disks should not be completely gas-free, since there is second generation gas from outgassing of planetesimals and dust grains via sublimation, photodesorption, or collisions, generating a system of dust-to-gas ratio close to unity, where hydrodynamics cannot be ignored. A clumping instability exists in this configuration, that has been hitherto explored only in one-dimensional, incompressible models. We performed 2D numerical compressible models of a disk with comparable amounts of gas and dust to study the growth and development of this instability. Our model solves the momentum equation for the gas and dust, together with energy and continuity equations. We uncover that the backreaction of the drag force from the gas onto the dust shepherds rings, similar to those observed in debris disks and usually attributed to the presence of hypothetical undetected planets. We also uncover that the eccentricity of these rings, usually presented as convincing evidence for the presence of a planet, can actually be simply explained by a standing wave propagating along the ring. The rings support a spectrum of oscillations, with one particular mode representing epicyclic motion. The apparent eccentricity matches the eccentricity in observed systems. This suggests that the planet possibility, though thrilling, is not necessarily required to explain these systems.

1. INTRODUCTION

Disks around young stars appear to pass through an evolutionary phase when the disk is optically-thin and the dust to gas ratio is of order unity give or take an order of magnitude. It can be hard to precisely measure the total masses of the dust and gas in such disks, but the nearby stars β Pictoris (Lagrange et al. 1998; Olofsson et al. 2001; Brandeker et al. 2004; Roberge et al. 2006; Troutman et al. 2011), HD32297 (Redfield 2007), 49 Ceti (Zuckerman et al. 1995) and HD 21997 (Moor et al. 2011) all host disks of dust resembling ordinary debris disks and also have stable circumstellar gas detected in molecular CO, Na I or other metal lines; the inferred mass of

The result of this instability could be that the dust and gas clump into rings or spiral patterns or other structures that could be detected via coronographic imaging or other methods. Indeed, images of debris disks and transitional disks show a range of asymmetries and other structures that beg for explanation. Klahr & Lin (2005) raised the possibility that the instability they hypothesized could explain some of the observed structures. Alternative explanations for these structures sometimes rely on planetary perturbers–a tantalizing possibility. But we are interested in investigating any possible explanation for these disk structures that does not require a hidden planetary companion.

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Thanks for your attention !

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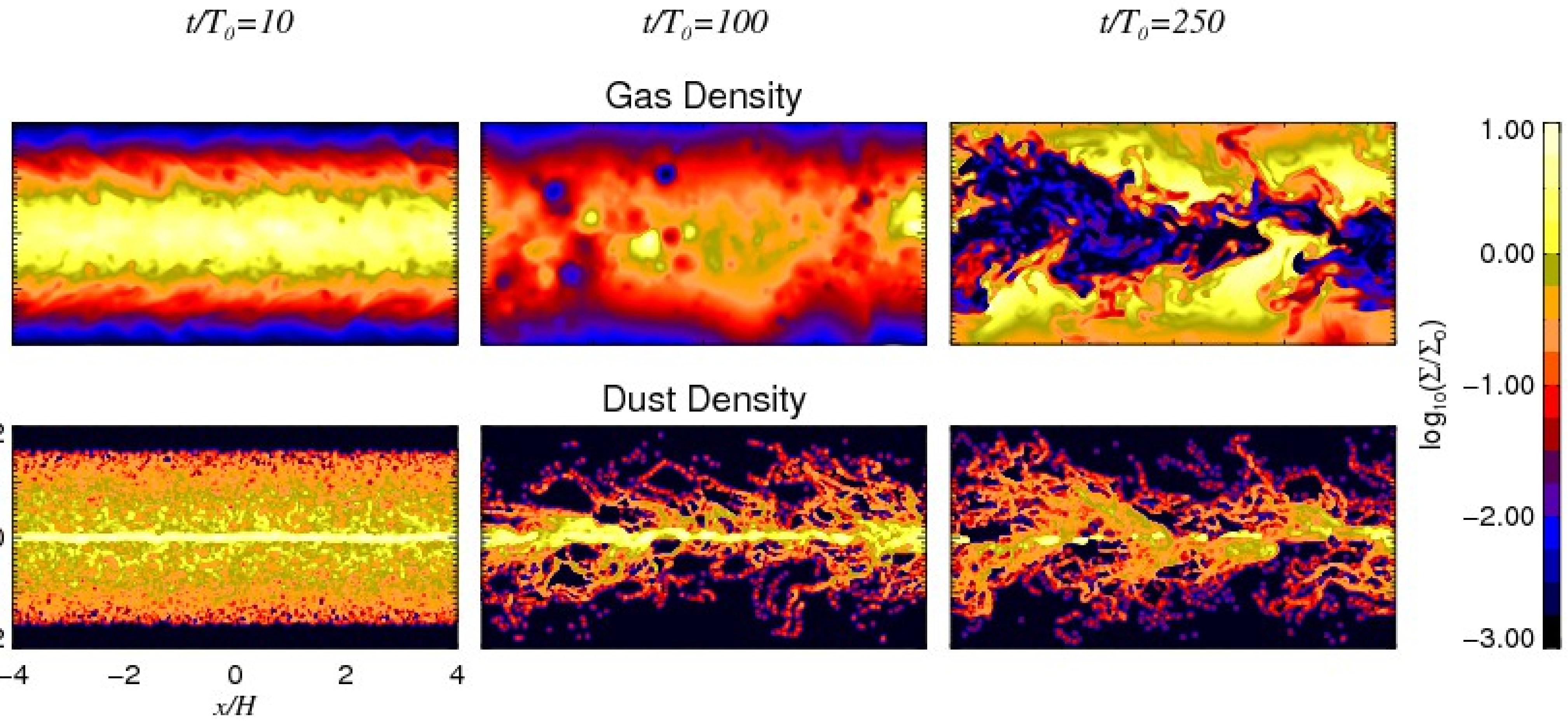

t/T0=10
t/T0=100
t/T0=250
Gas Density
Dust Density
z/H
x/H
log10(Σ/Σ0)
1.00
0.00
−1.00
−2.00
−3.00
2
1
0
−1
−2
−4
−2
0
2
4