The turbulent birth of planets

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Ottawa, October 2012

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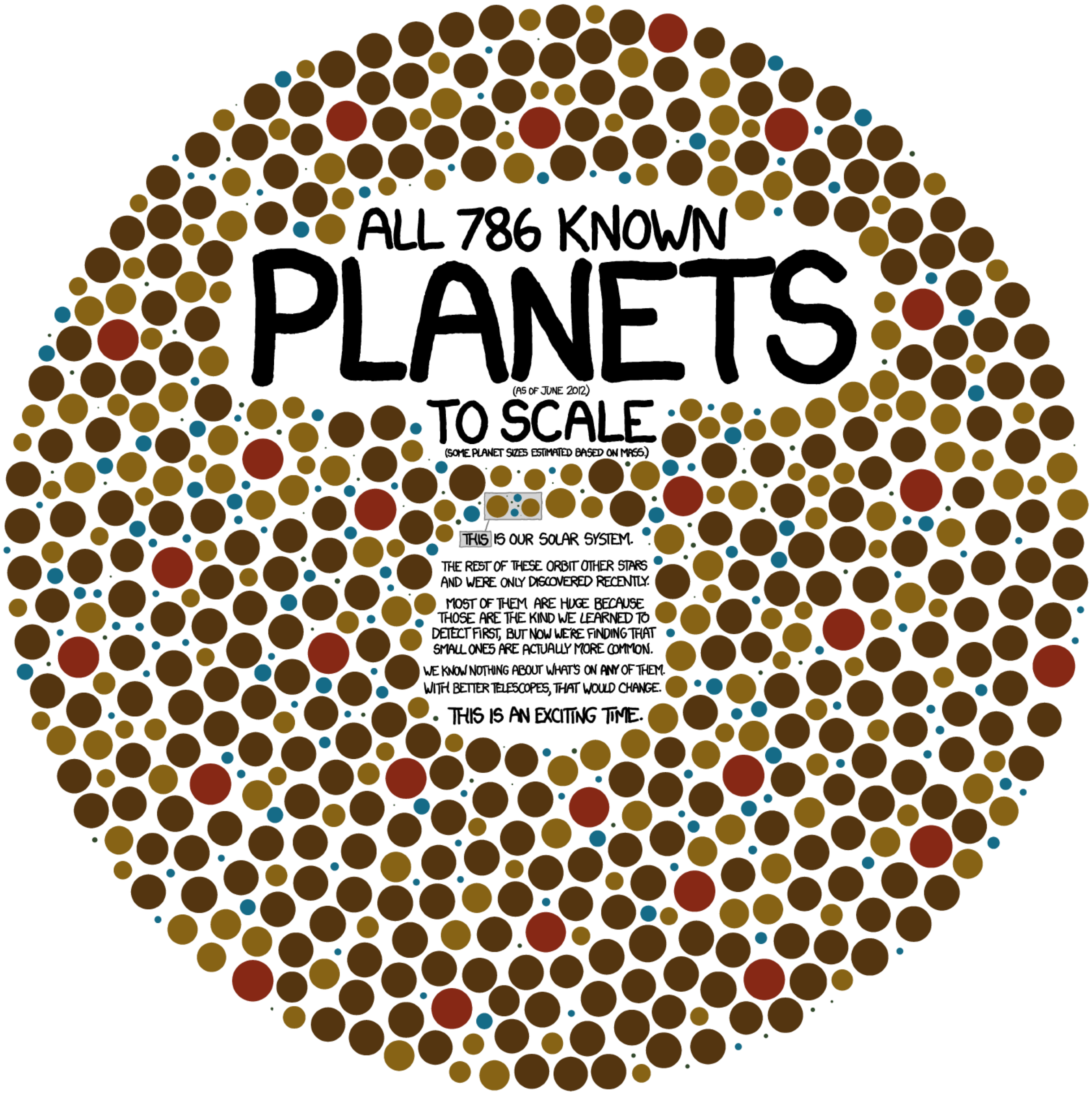
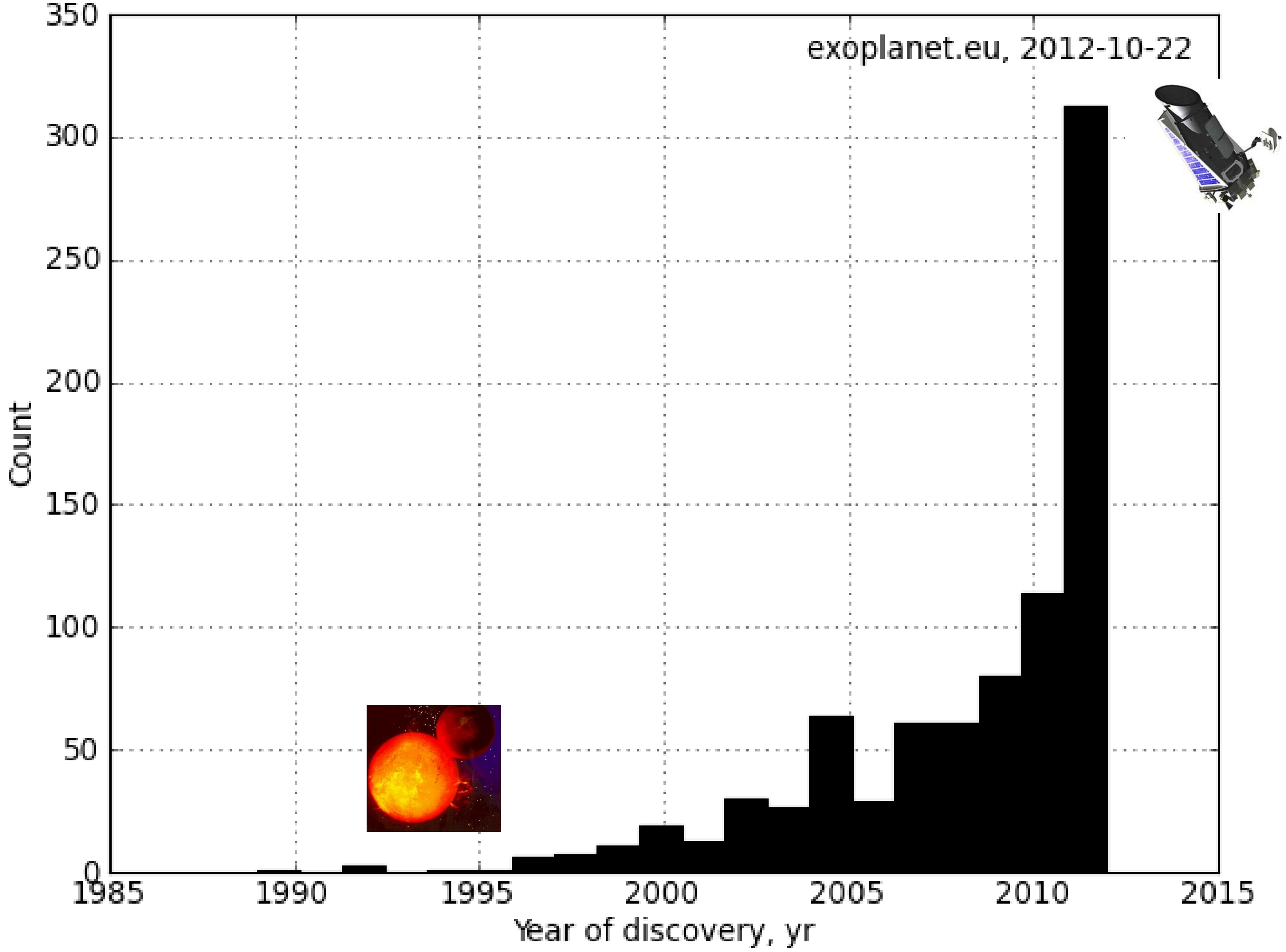
Exoplanets



ALL 786 KNOWN
PLANETS
(AS OF JUNE 2012)
TO SCALE
(SOME PLANET SIZES ESTIMATED BASED ON MASS.)
THIS IS OUR SOLAR SYSTEM.
THE REST OF THESE ORBIT OTHER STARS AND WERE ONLY DISCOVERED RECENTLY.
MOST OF THEM ARE HUGE BECAUSE THOSE ARE THE KIND WE LEARNED TO DETECT FIRST, BUT NOW WE'RE FINDING THAT SMALL ONES ARE ACTUALLY MORE COMMON.
WE KNOW NOTHING ABOUT WHAT'S ON ANY OF THEM.
WITH BETTER TELESCOPES, THAT WOULD CHANGE.
THIS IS AN EXCITING TIME.

Exoplanets

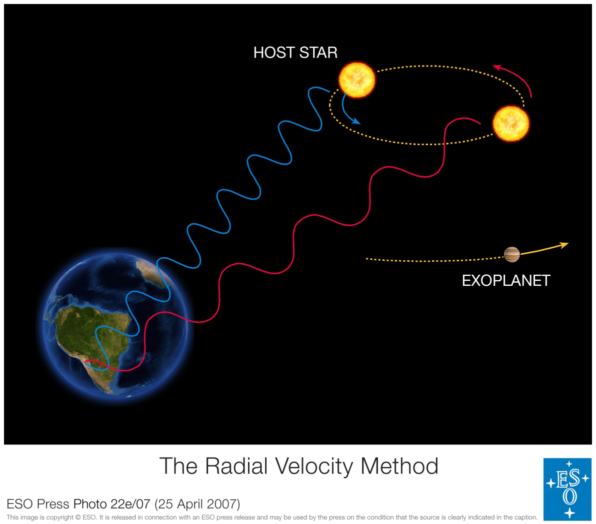


843 confirmed planets, and counting!

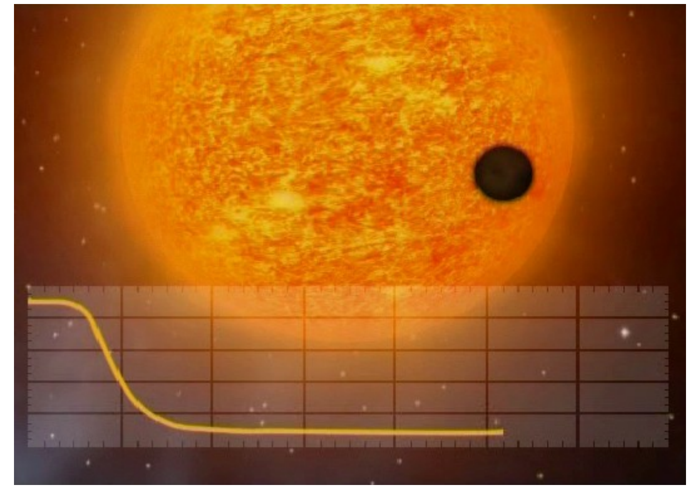
(Maybe already 844 until the end of this talk....)

Exoplanets

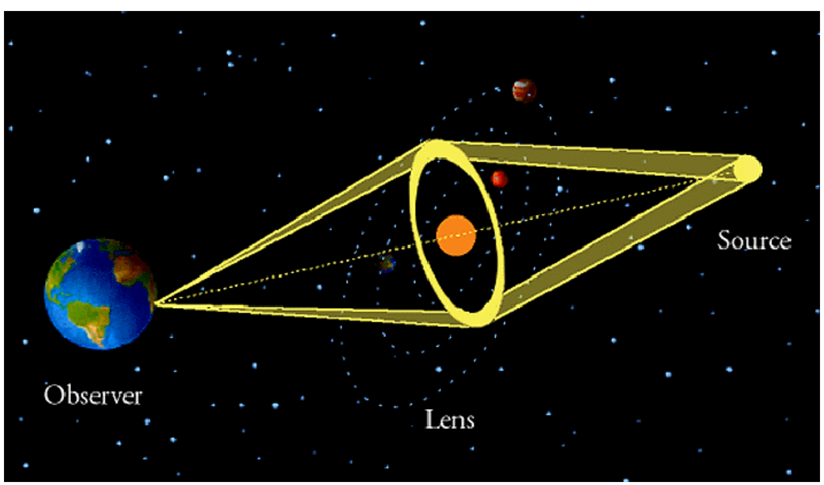
Detection methods



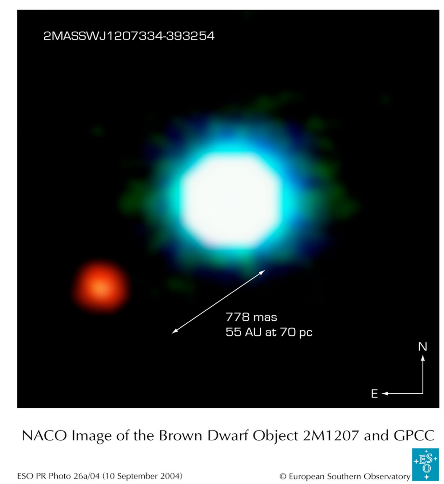
Radial Velocity



Transit

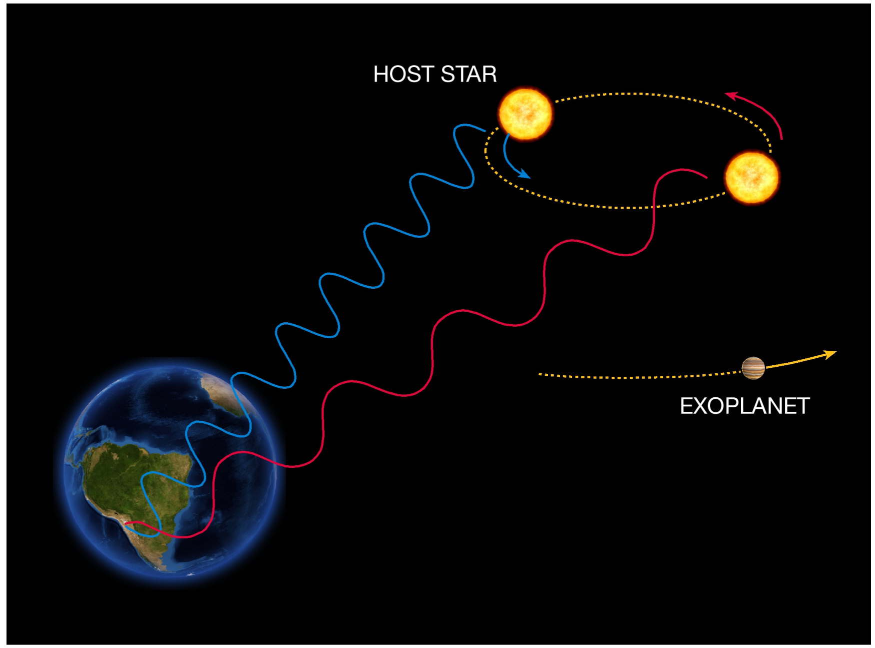


Microlensing



Direct Imaging

Exoplanets - Radial Velocity

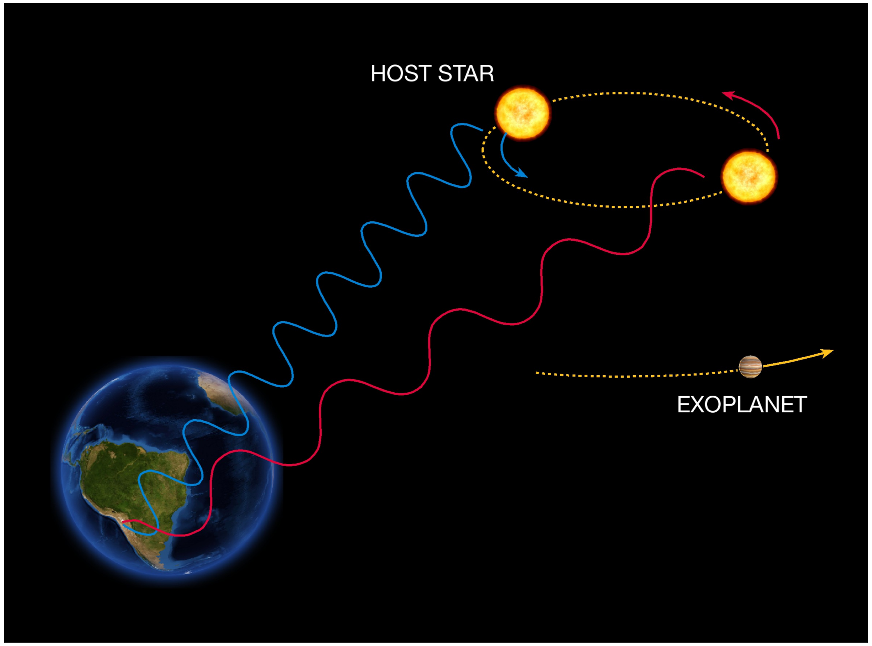


The Radial Velocity Method

ESO Press Photo 22e/07 (25 April 2007)

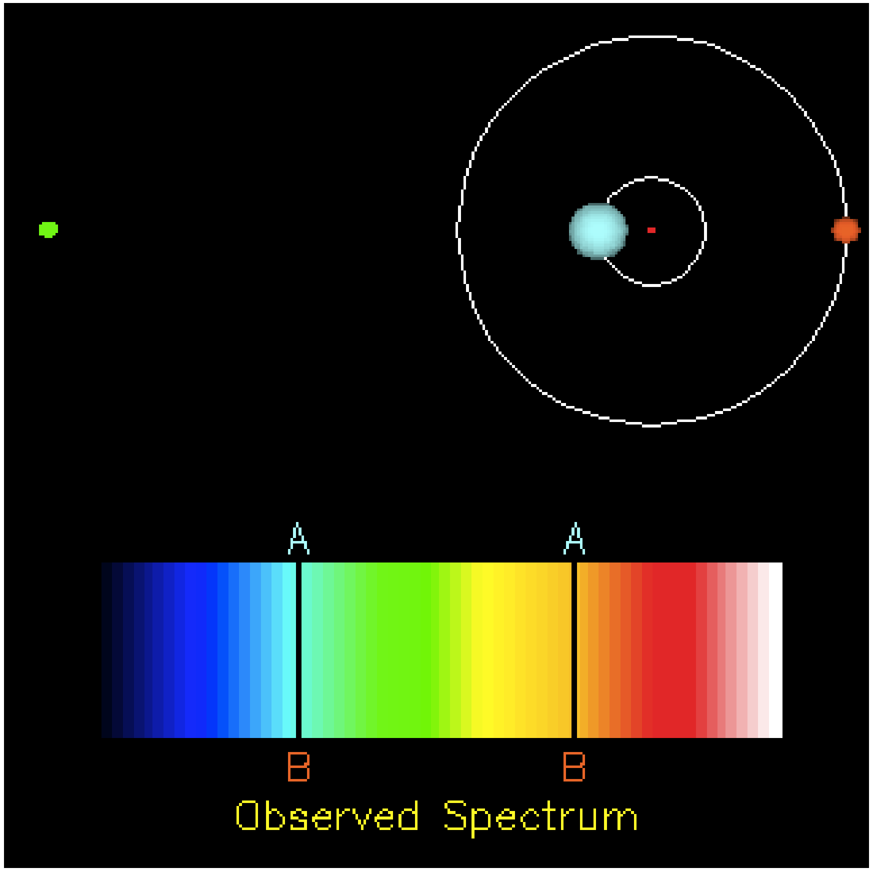
Star and planet orbit a common center of mass

Exoplanets - Radial Velocity



The Radial Velocity Method

ESO Press Photo 22e/07 (25 April 2007)

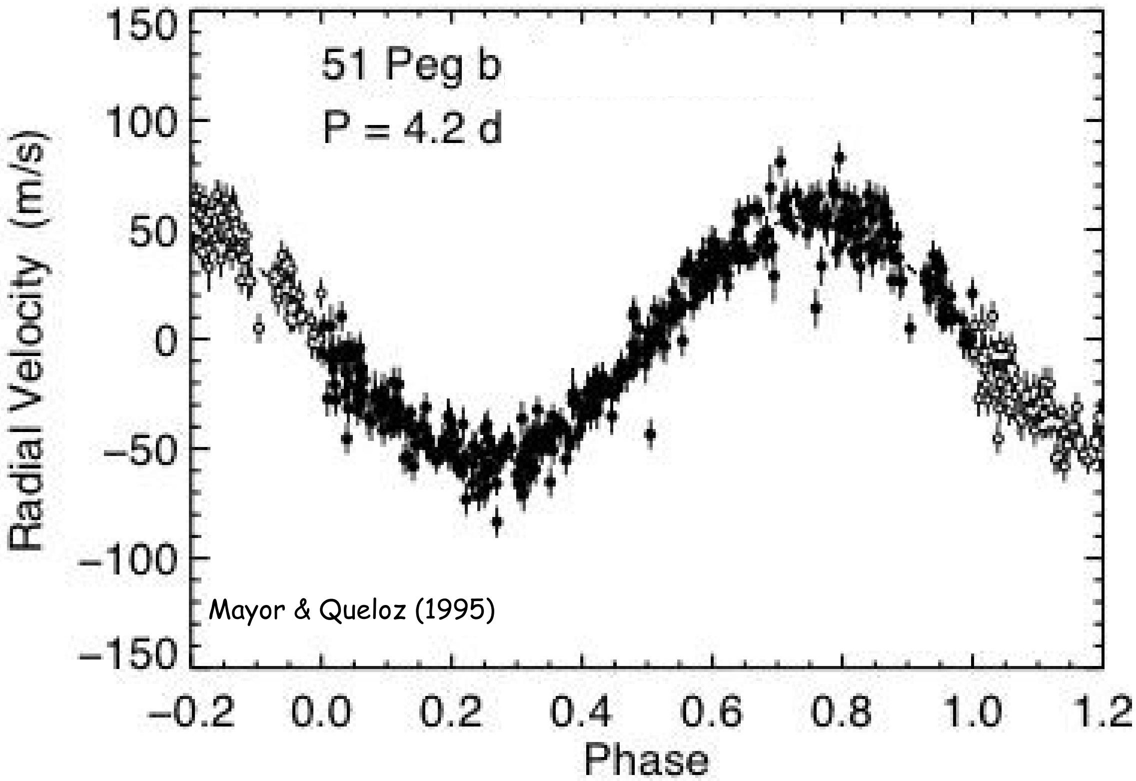


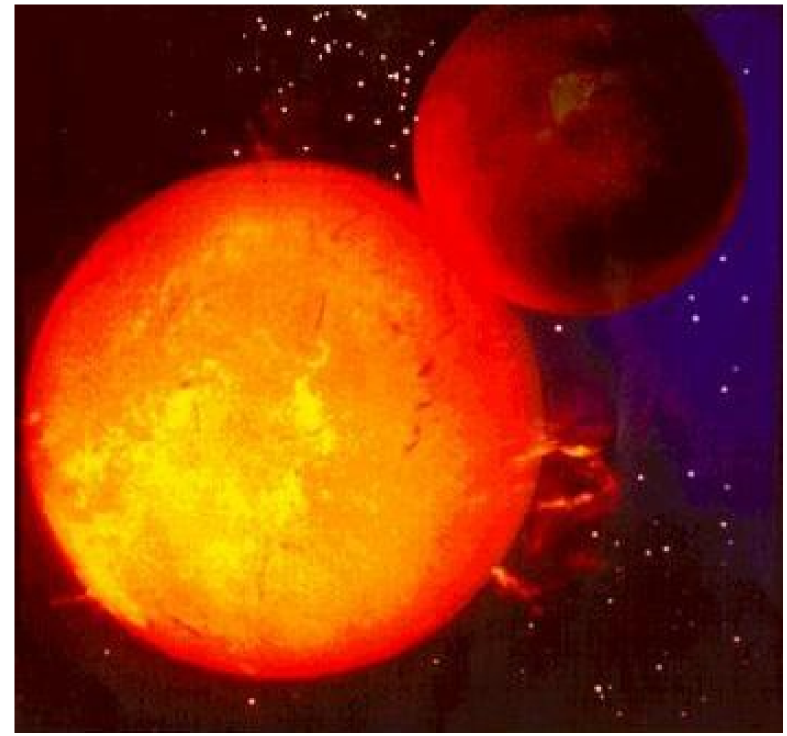
Star and planet orbit a common center of mass

Even if we cannot see the planet, we can measure the motion of the star

51 Pegasi b

The first exoplanet around a solar-type star





$M \sin i$ = 0.472 +/- 0.039 M_J

T_{eq} = 1284 +/- 19 K

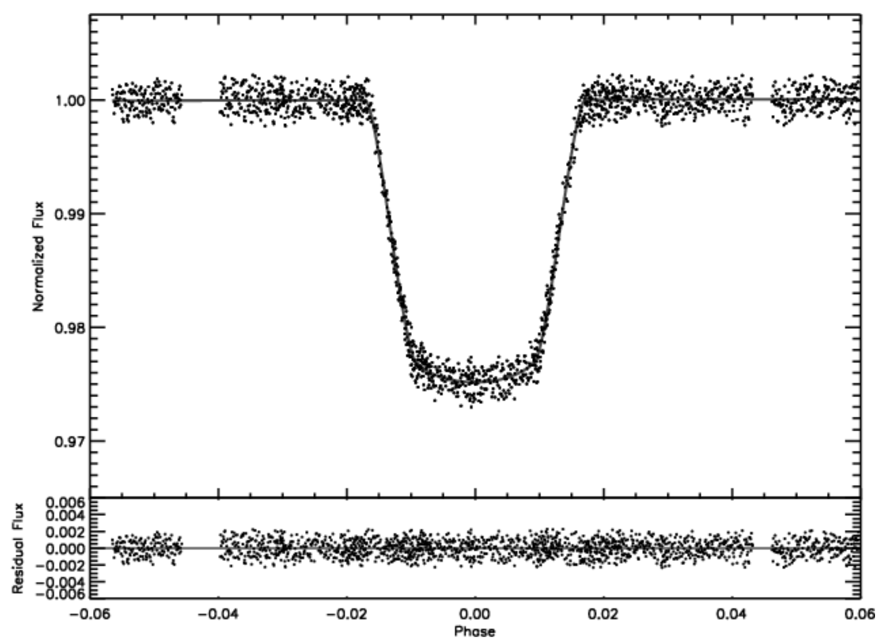
A Hot Jupiter !!

Exoplanets - Transit

The planet transits the star if the orientation of the orbit is favorable

A Jupiter-size planet produces a flux dip at the 0.01 level.

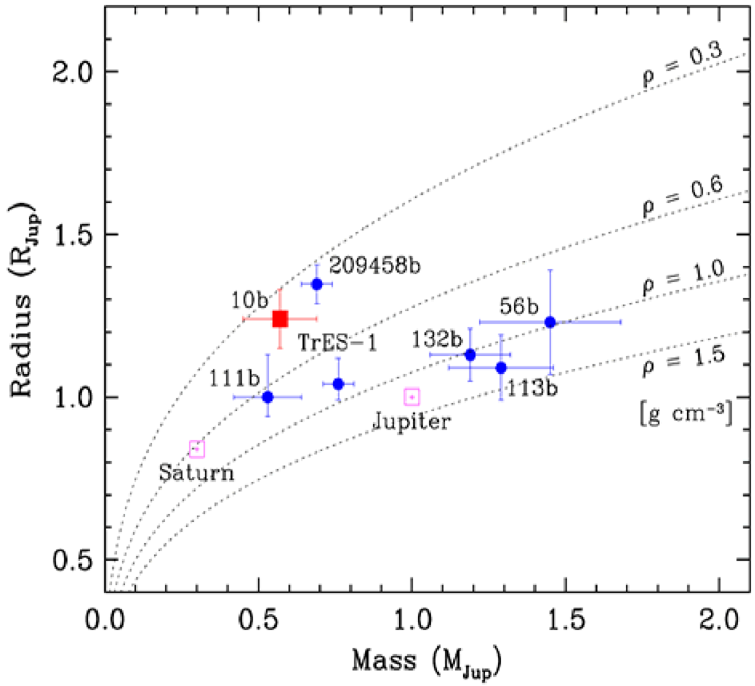
Detectable!!

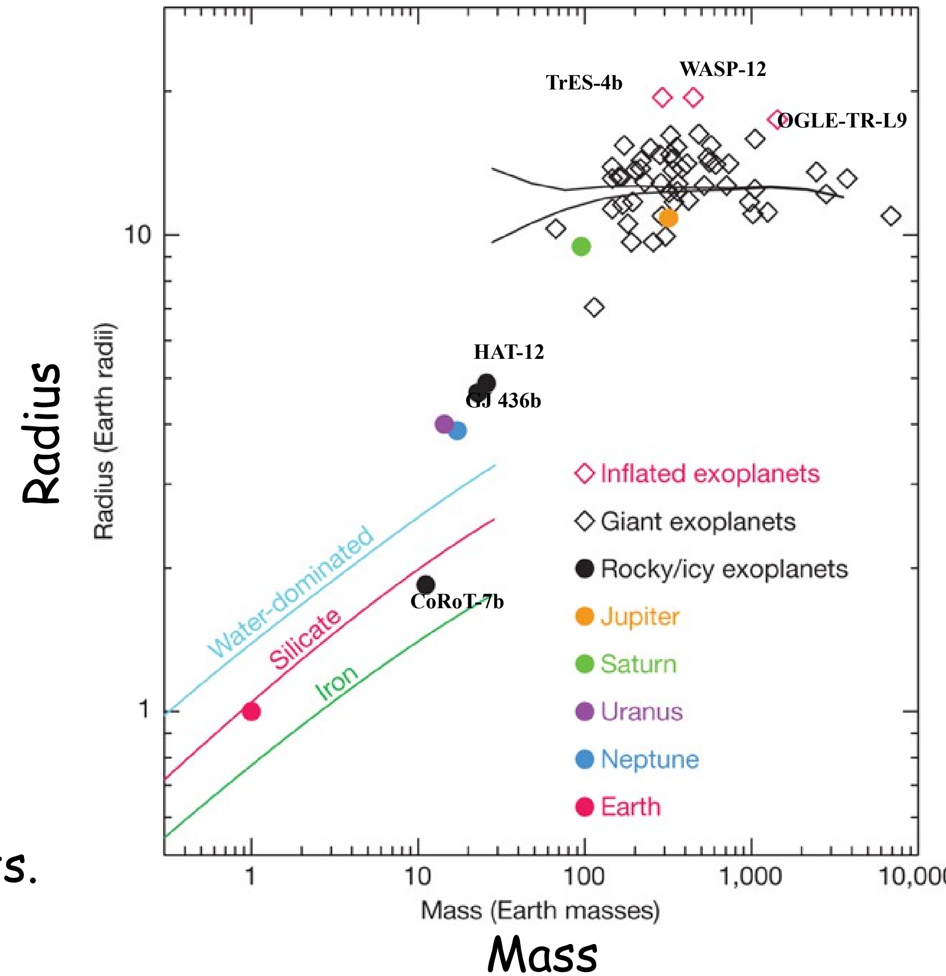


Exoplanets - Transit

Transits allow for determination of both mass and radius!

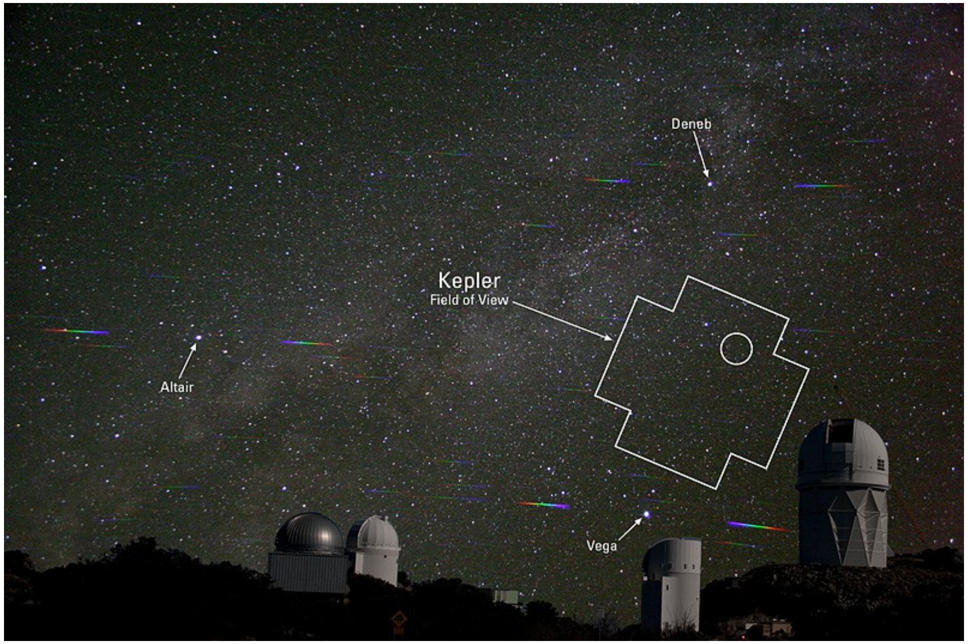
We can measure **densities**...

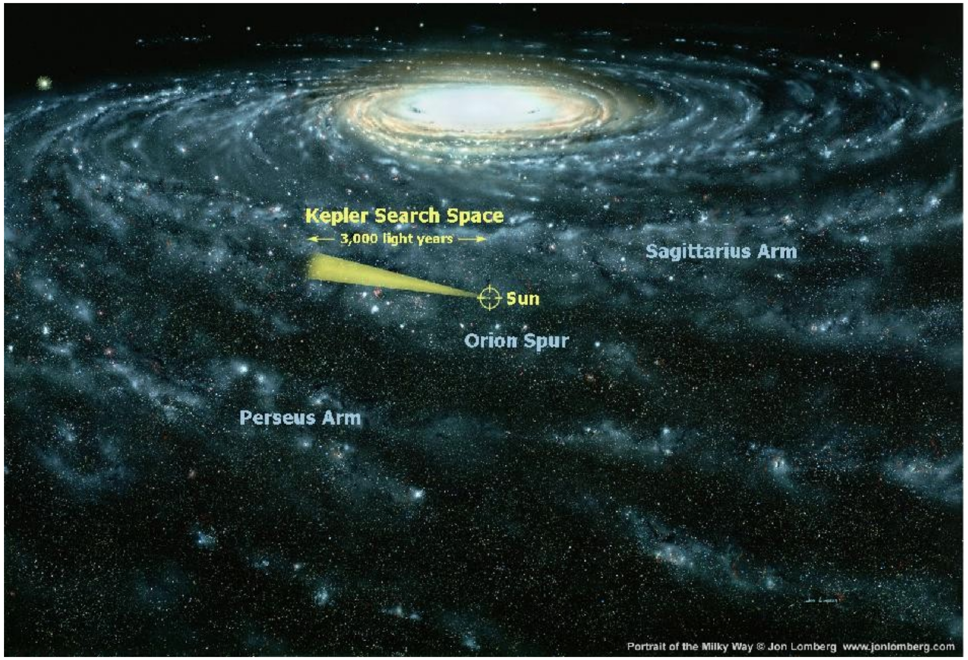




... and make educated guesses about **composition and structure** of the planets.

Kepler mission

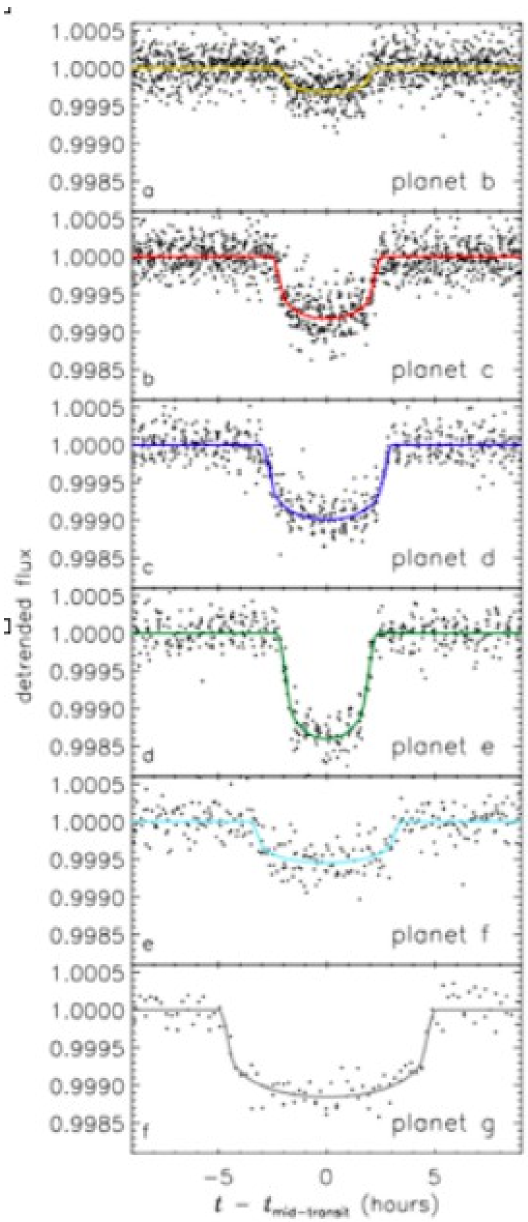




Continuously observe a single area of the sky,

monitoring 150,000 stars for transits

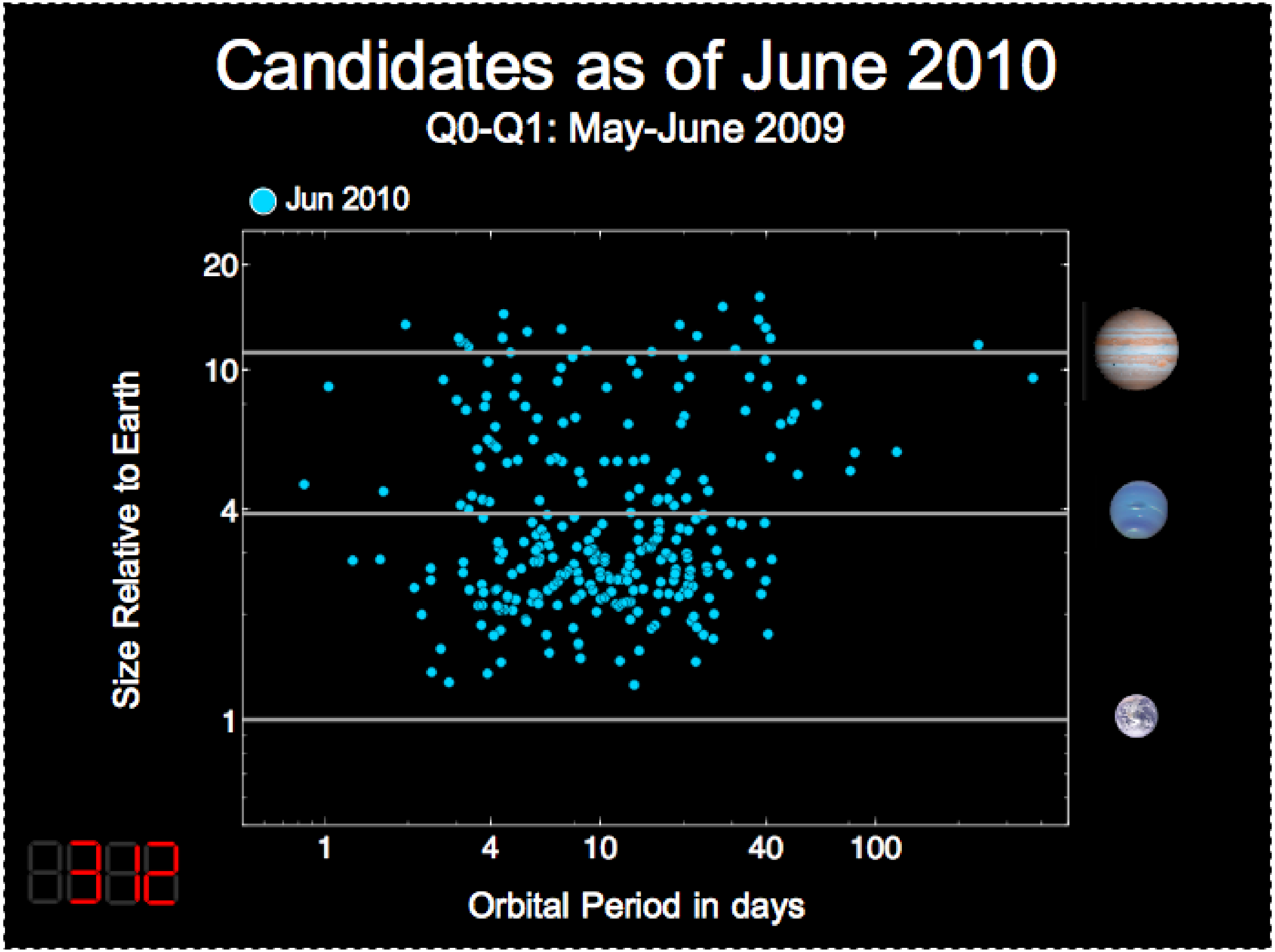
Kepler mission



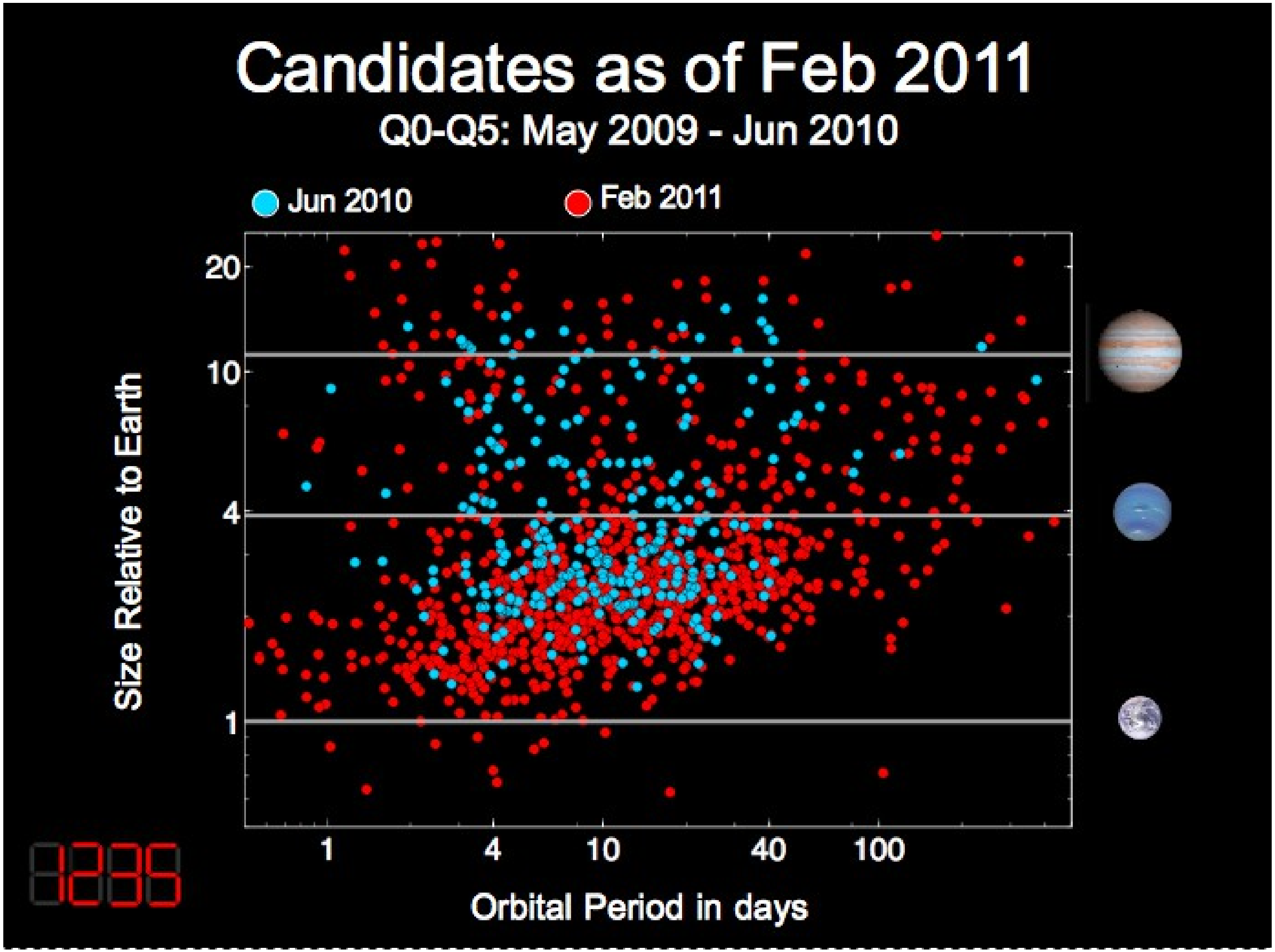
Lissauer et al. (2012)

Photometry at 10^{-4} precision

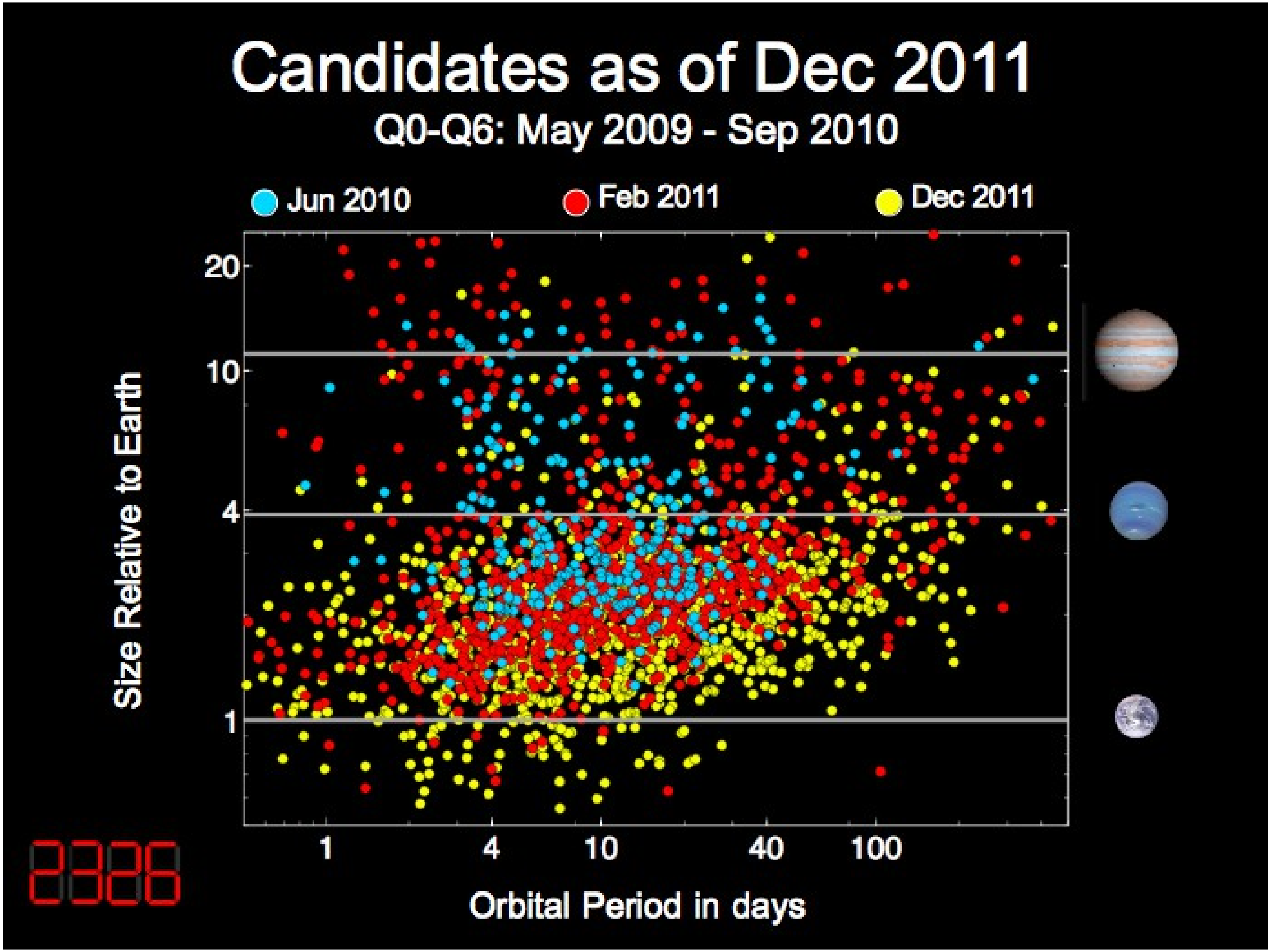
Kepler mission



Kepler mission

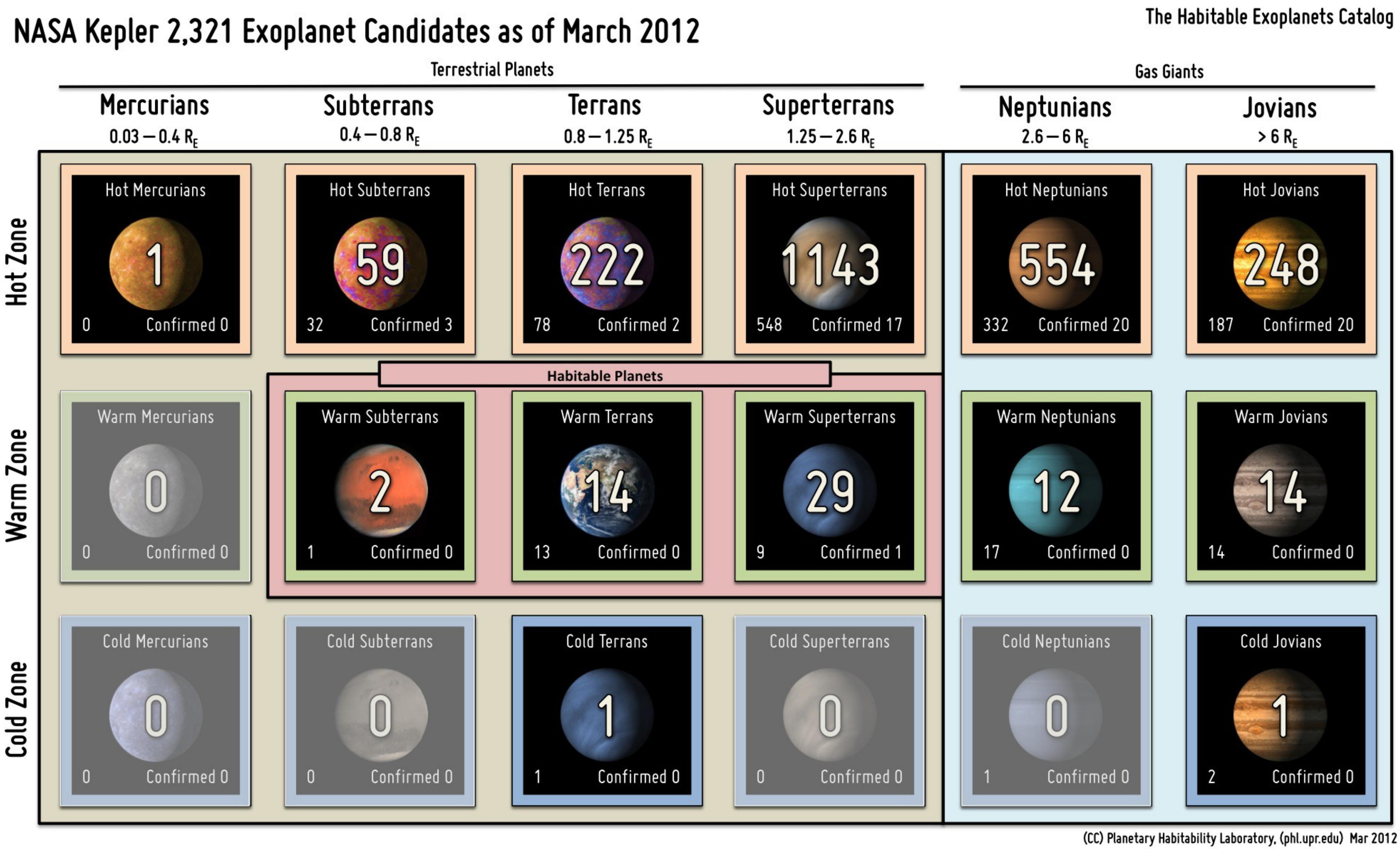


Kepler mission

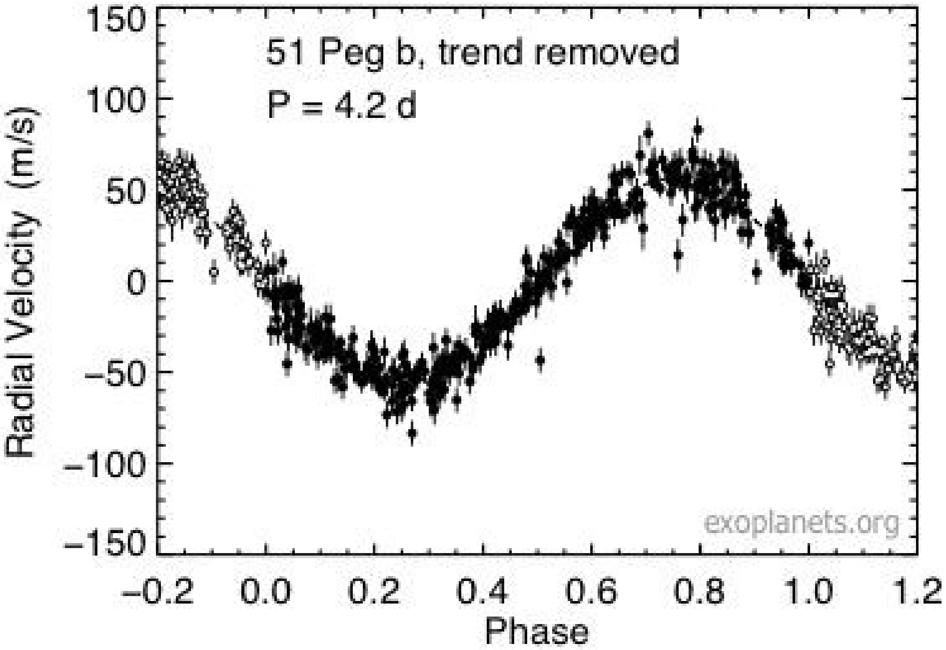


Kepler mission

Kepler's "periodic table" of planets



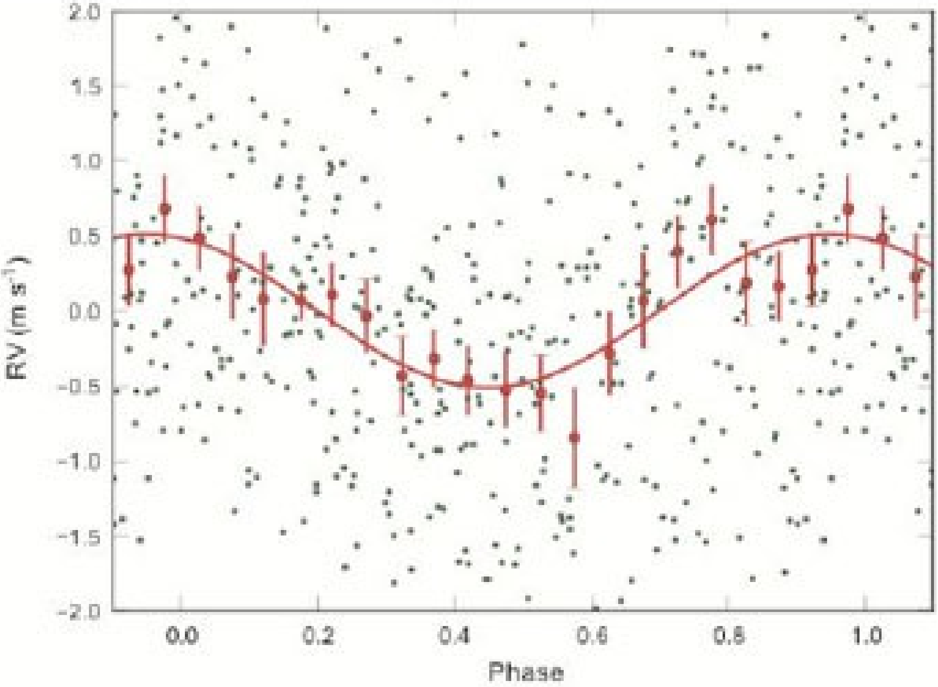
Radial Velocity can still impress



The first RV exoplanet
20 m/s precision

Mayor & Queloz (1995)

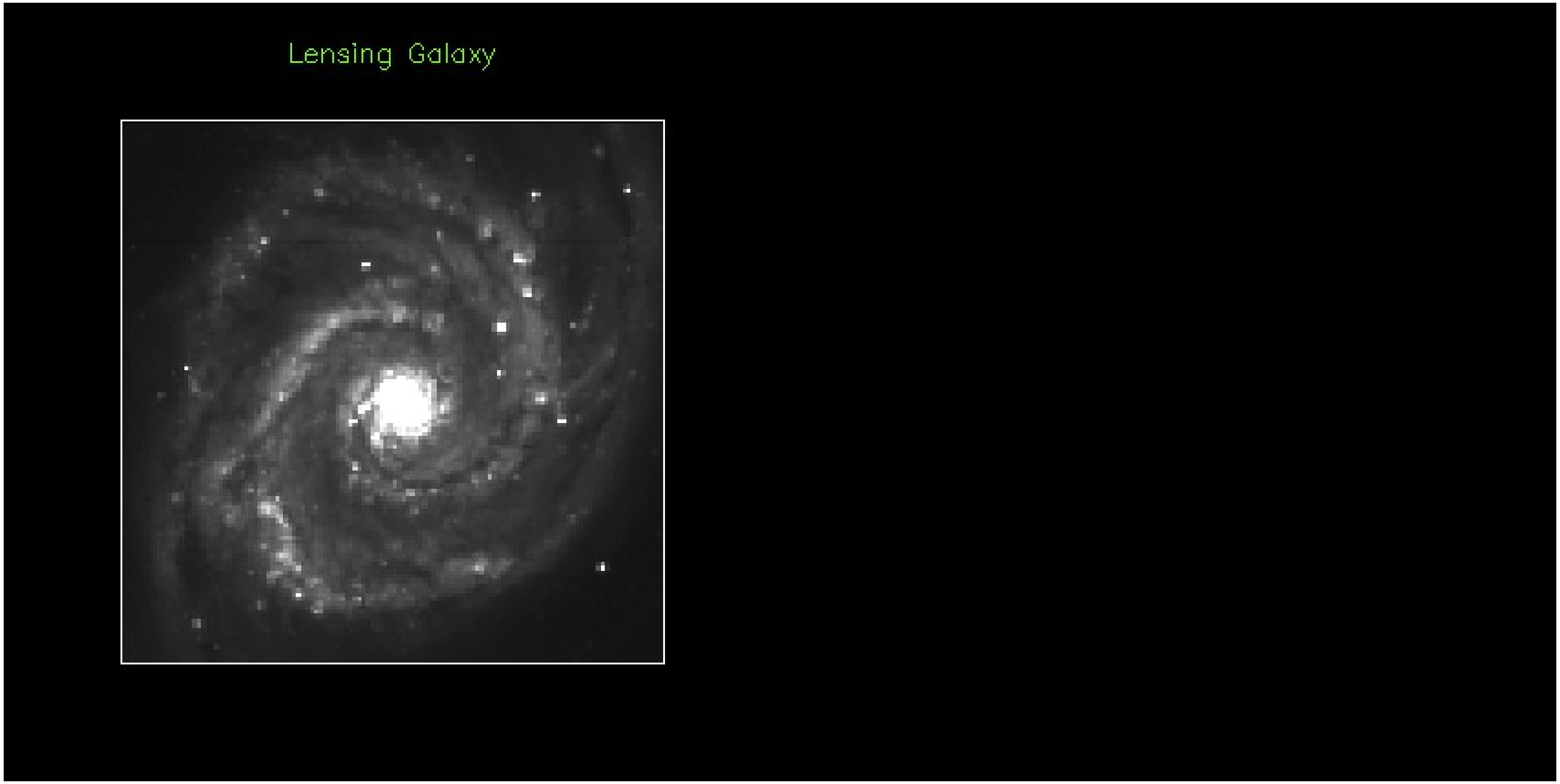
Alpha Centauri Bb



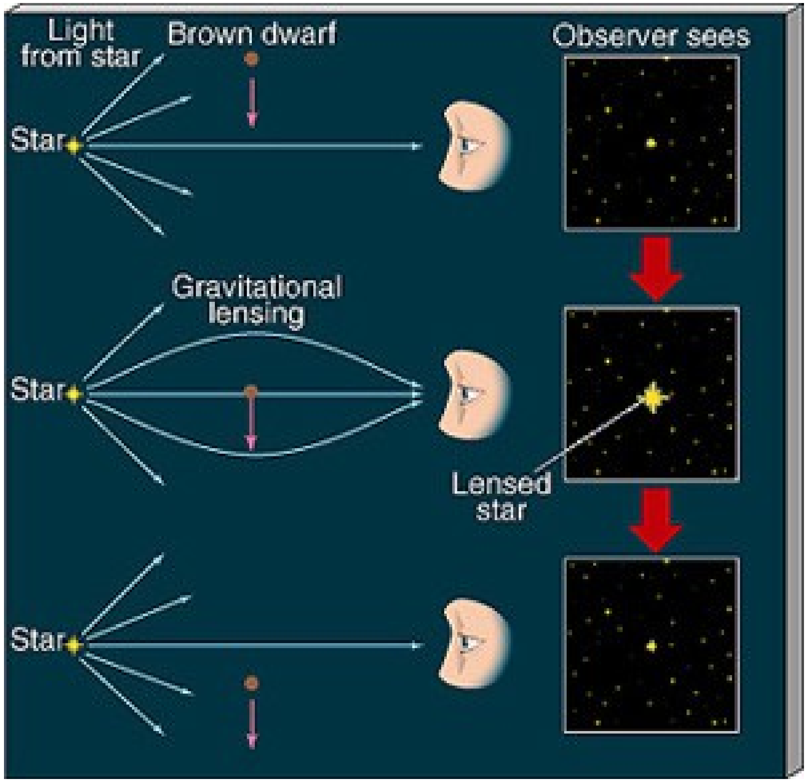
The latest RV exoplanet
< 1 m/s precision

Pepe et al. (2012)

Gravitational Lensing



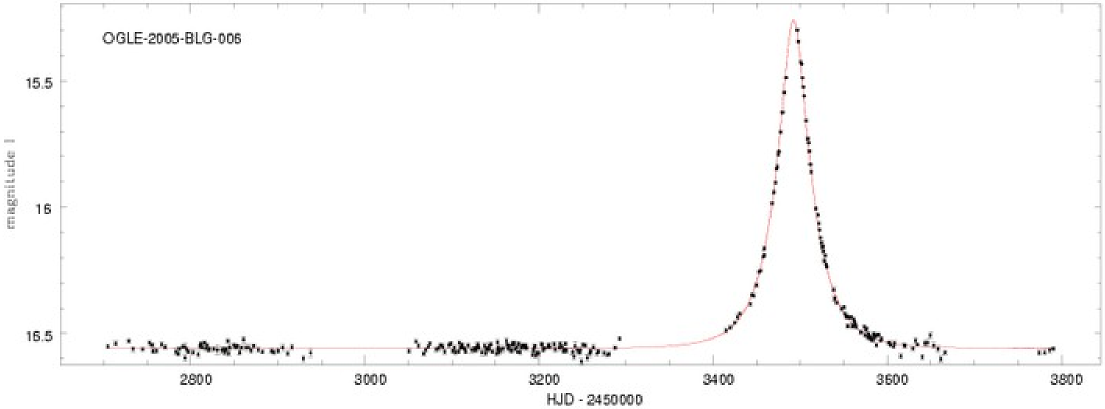
Exoplanets - Microlensing



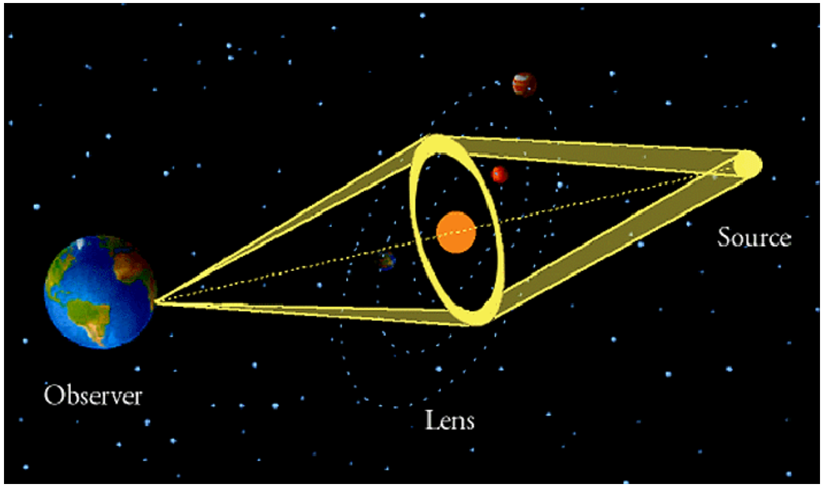
Microlensing
is a gravitational lensing event produced not by a galaxy but by a **star or substellar object**

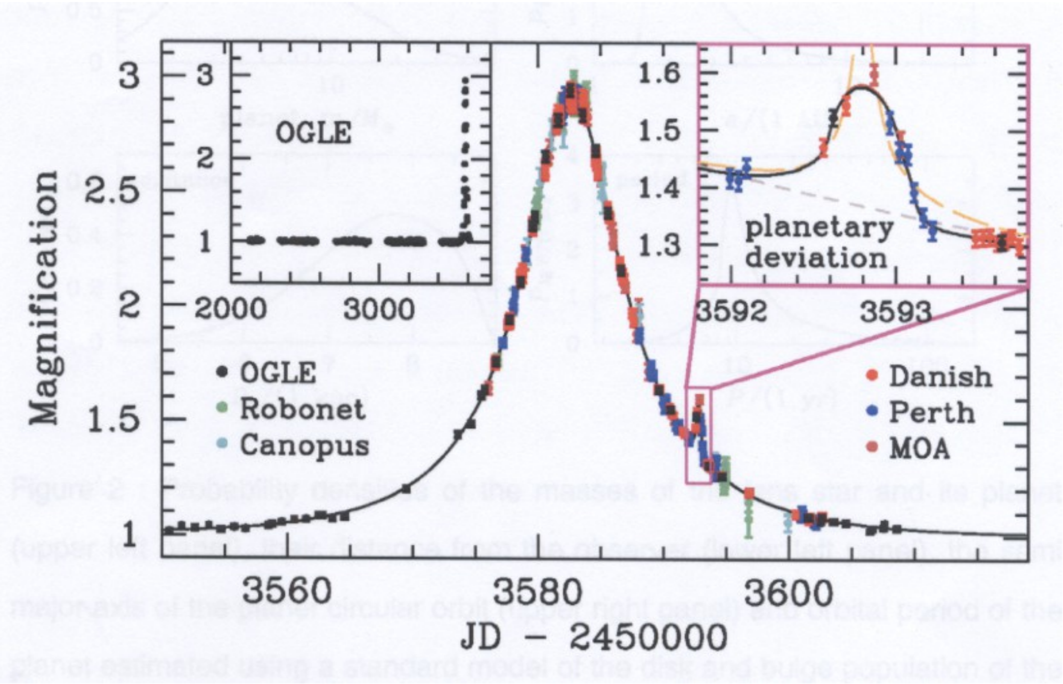
We do not resolve the multiple images: They all appear blurred

The lensing event is seen as a magnification of the lensed star.



Exoplanets - Microlensing





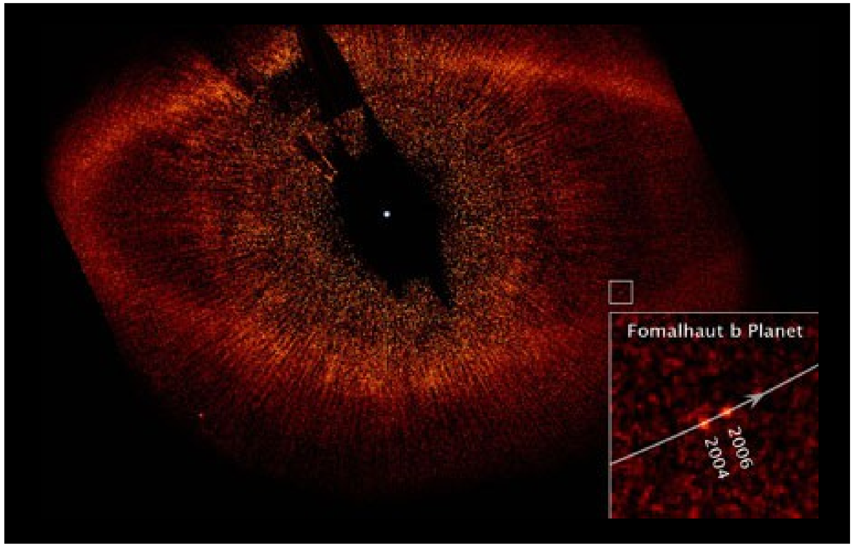
A planet around a lens star may
produce a ***secondary*** lensing event

Exoplanets – Direct Imaging

A firefly next to a lighthouse

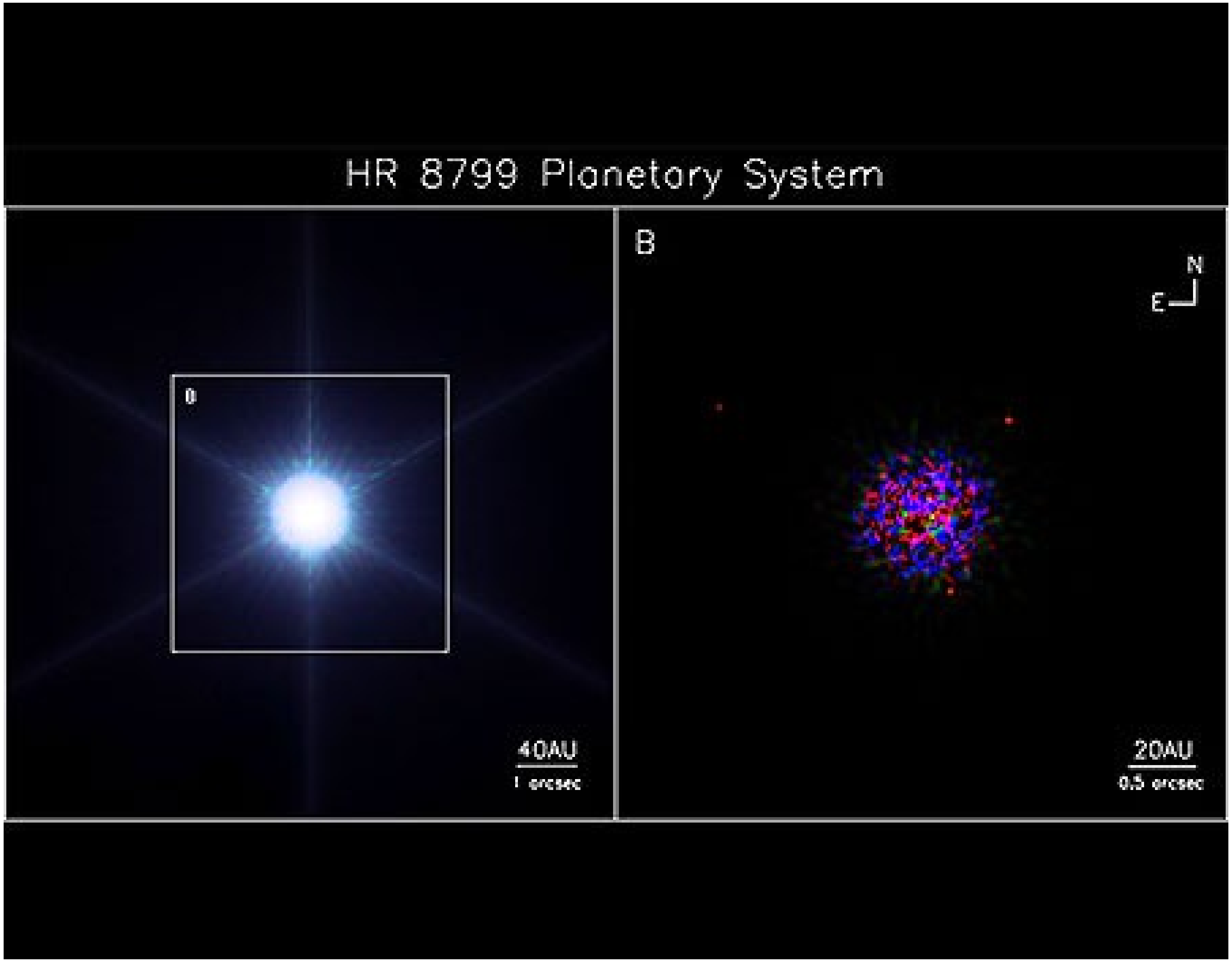
Block the starlight
and check the surroundings

The bright star **Fomalhaut**
8 parsecs away



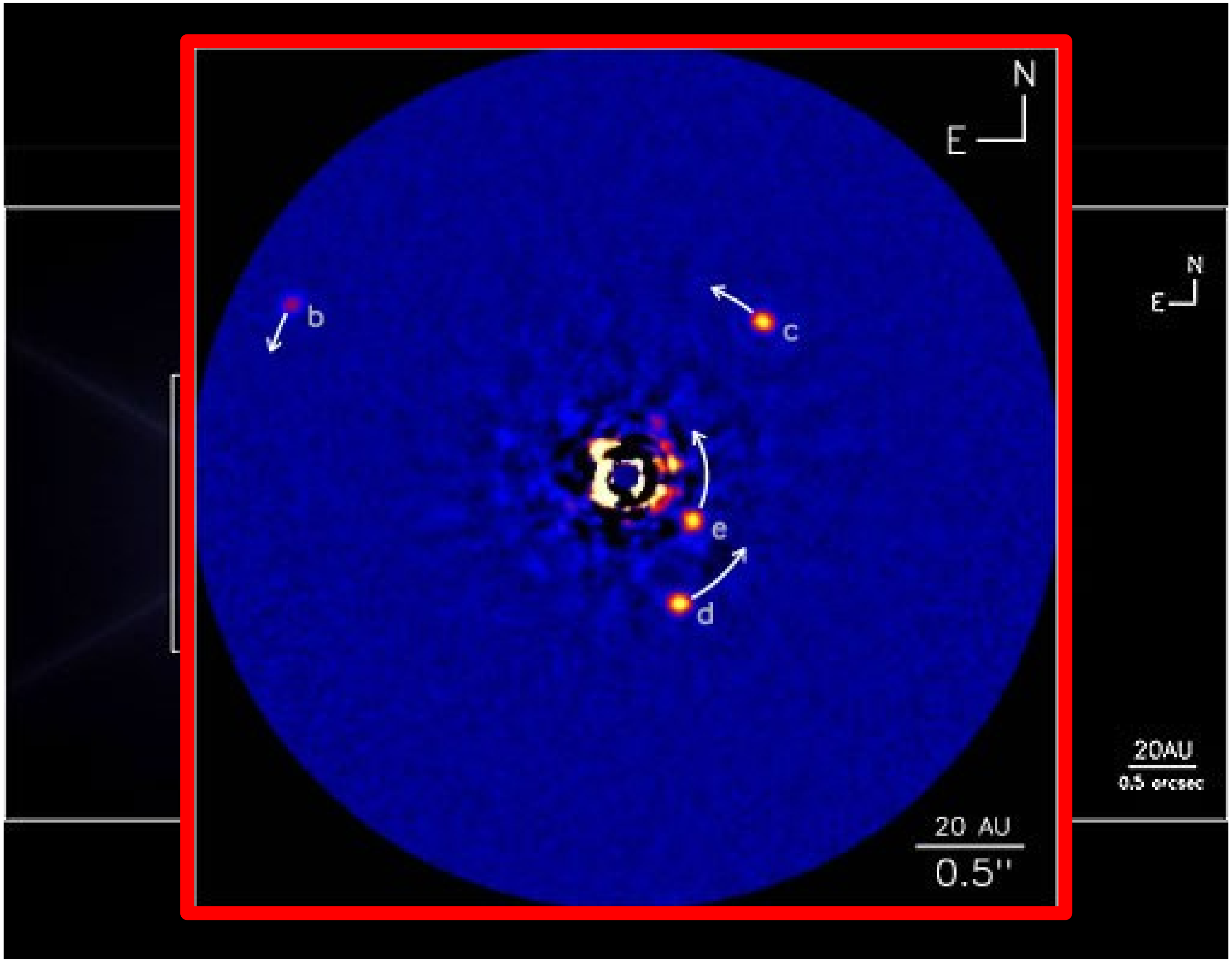
A (controversial) planet,
Fomalhaut b, detected in 2006,
at ~100 AU from the star.

Exoplanets - Direct Imaging



Four planets around HR 8799 !!

Exoplanets - Direct Imaging

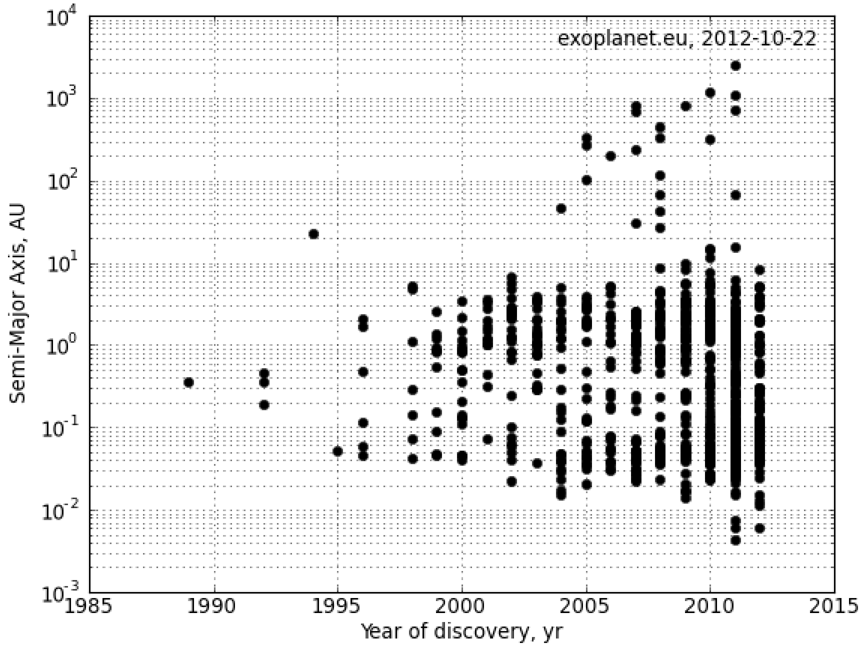


Four planets around HR 8799 !!

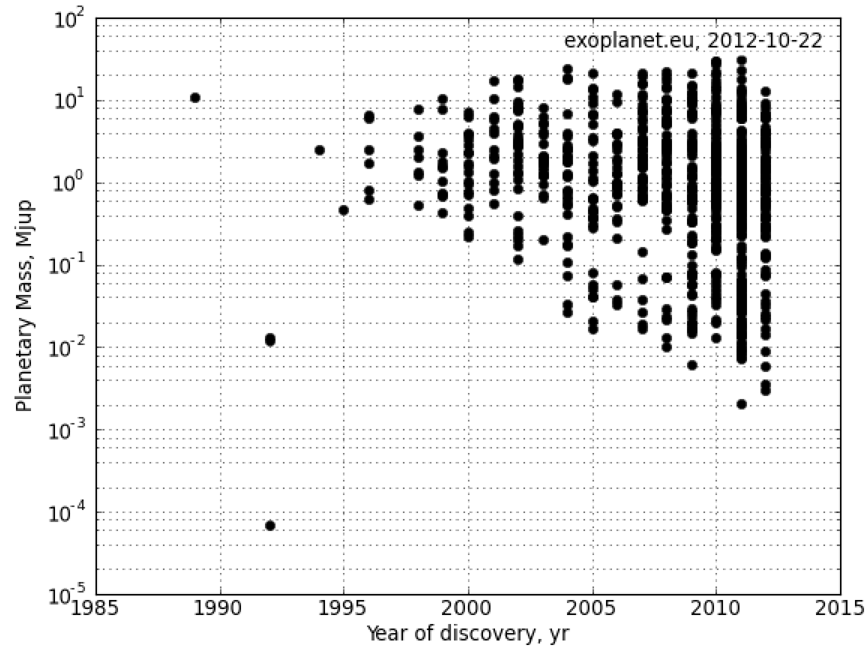
Timeline of exoplanet discoveries

In time...

Semi-major axis vs time



Mass vs time

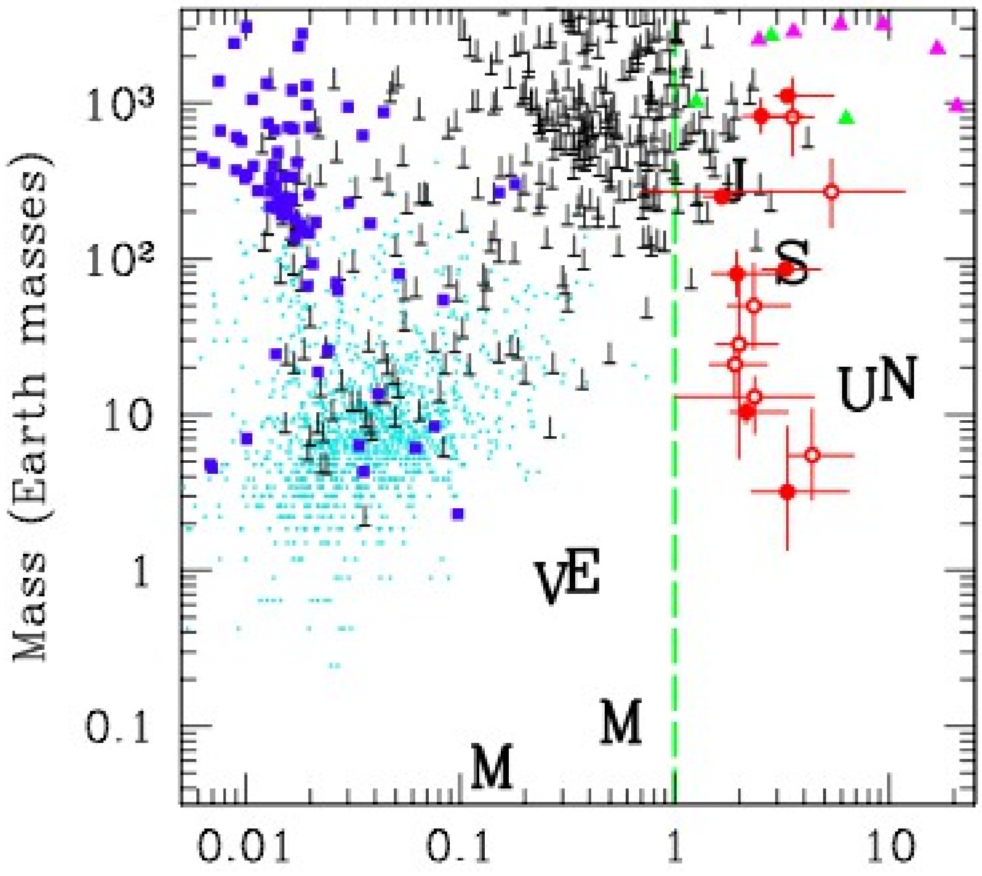


.... we have access to **longer monitoring periods**, enabling detection of planets in **wider orbits**.

.... and the **increasing sensitivity** of the instruments, allows for the detection of **lower mass** planets.

The situation

Exoplanet discoveries

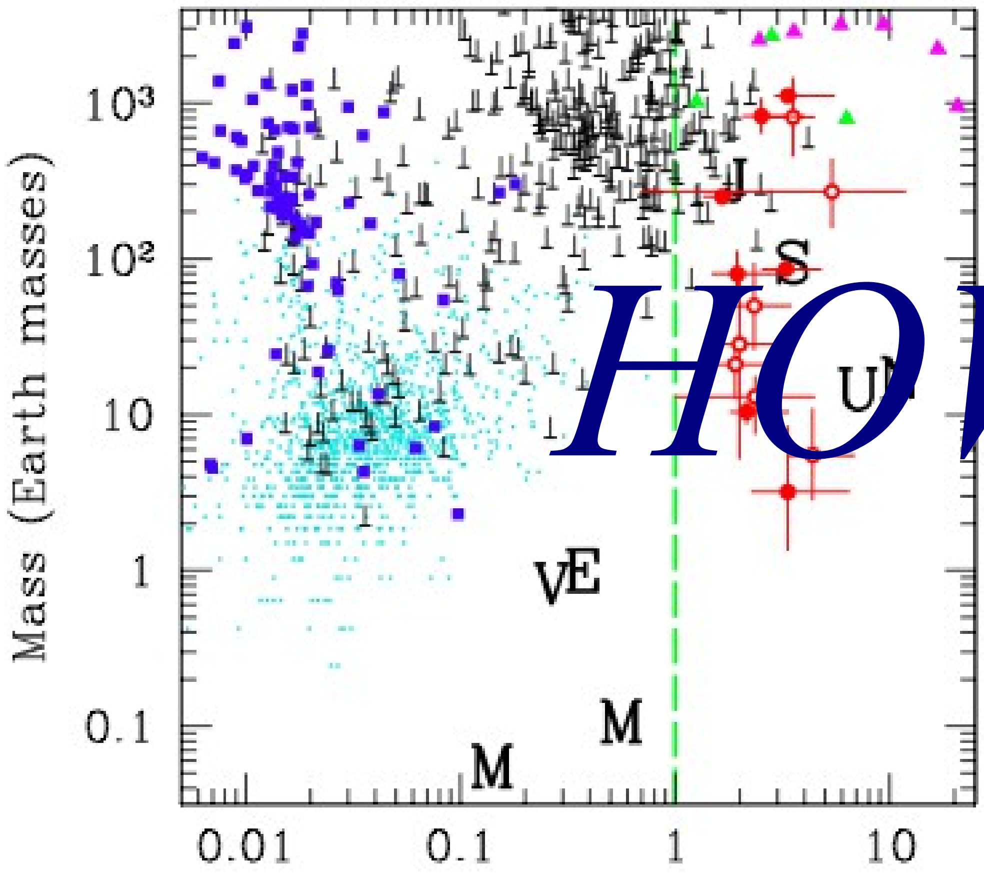


SMA / 2.7 AU ($M_*/M_\odot$)

Transit
Kepler Transit
Radial Velocity
Microlensing
Direct Imaging

The situation

Exoplanet discoveries



SMA / 2.7 AU ($M_*/M_\odot$)

HOW?

Transit

Kepler Transit

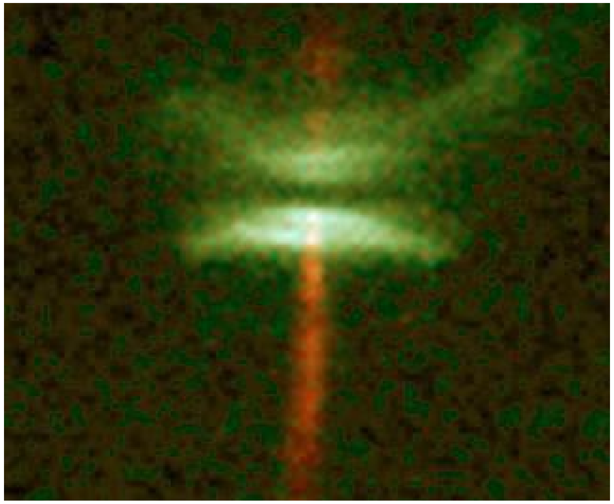
Radial Velocity

Microlensing

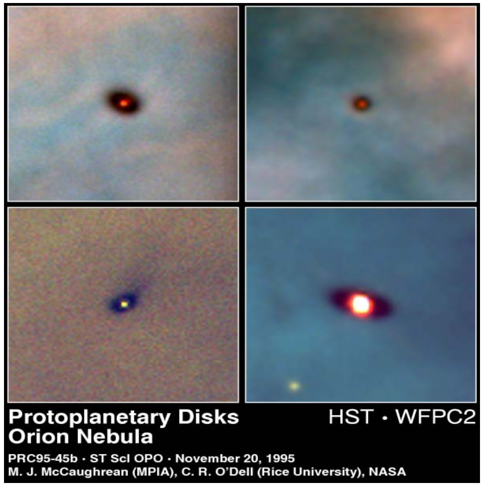
Direct Imaging

Star Formation

Protoplanetary Disks

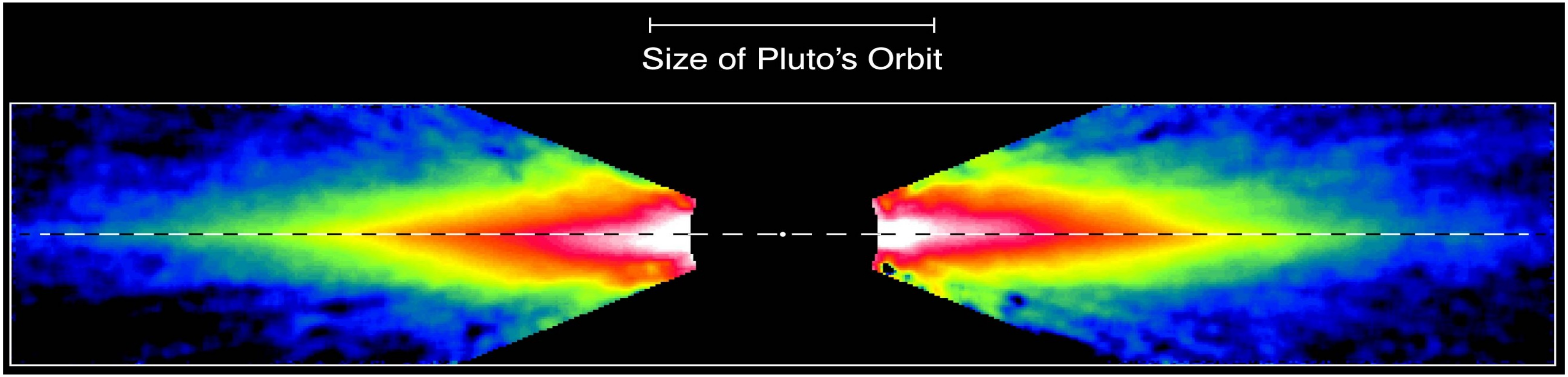


Dust lane
blocks view



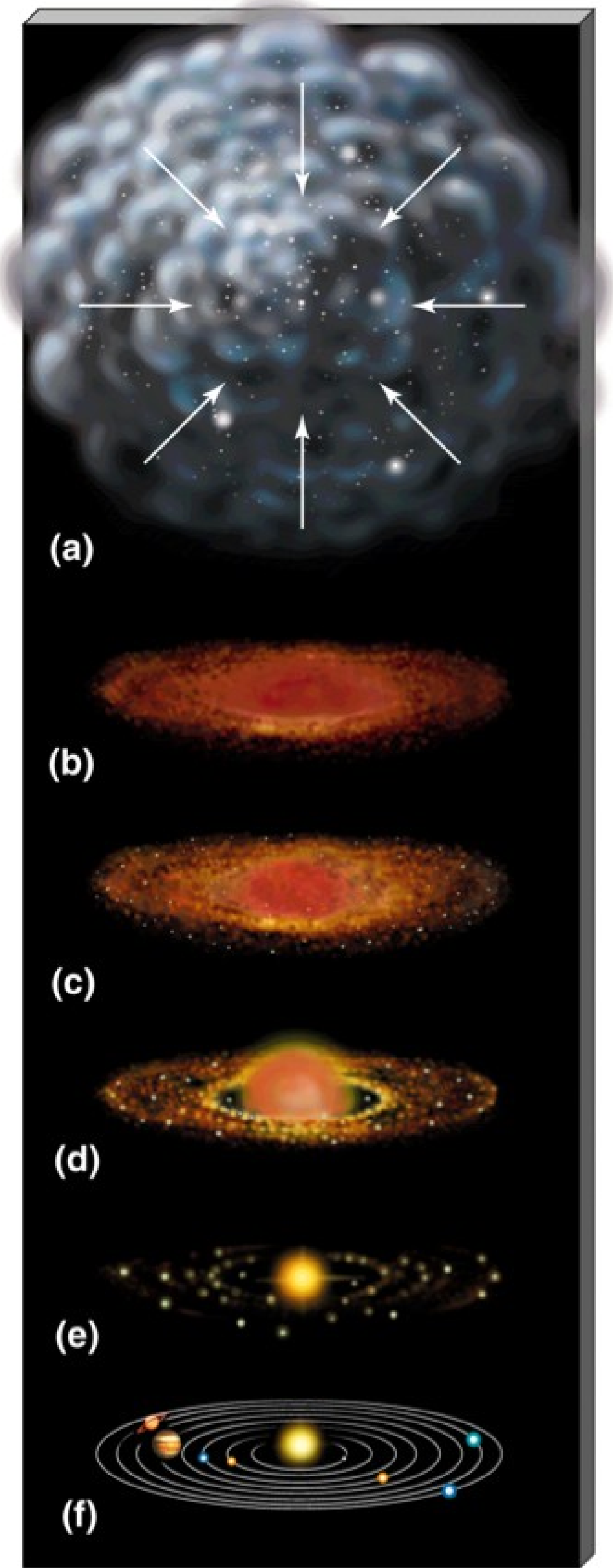
A light background
reveals the disks

Face-on disk
in reflected light



The disk of Beta Pictoris

Protoplanetary Disks



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

Protoplanetary Disks

PP disk fact sheet

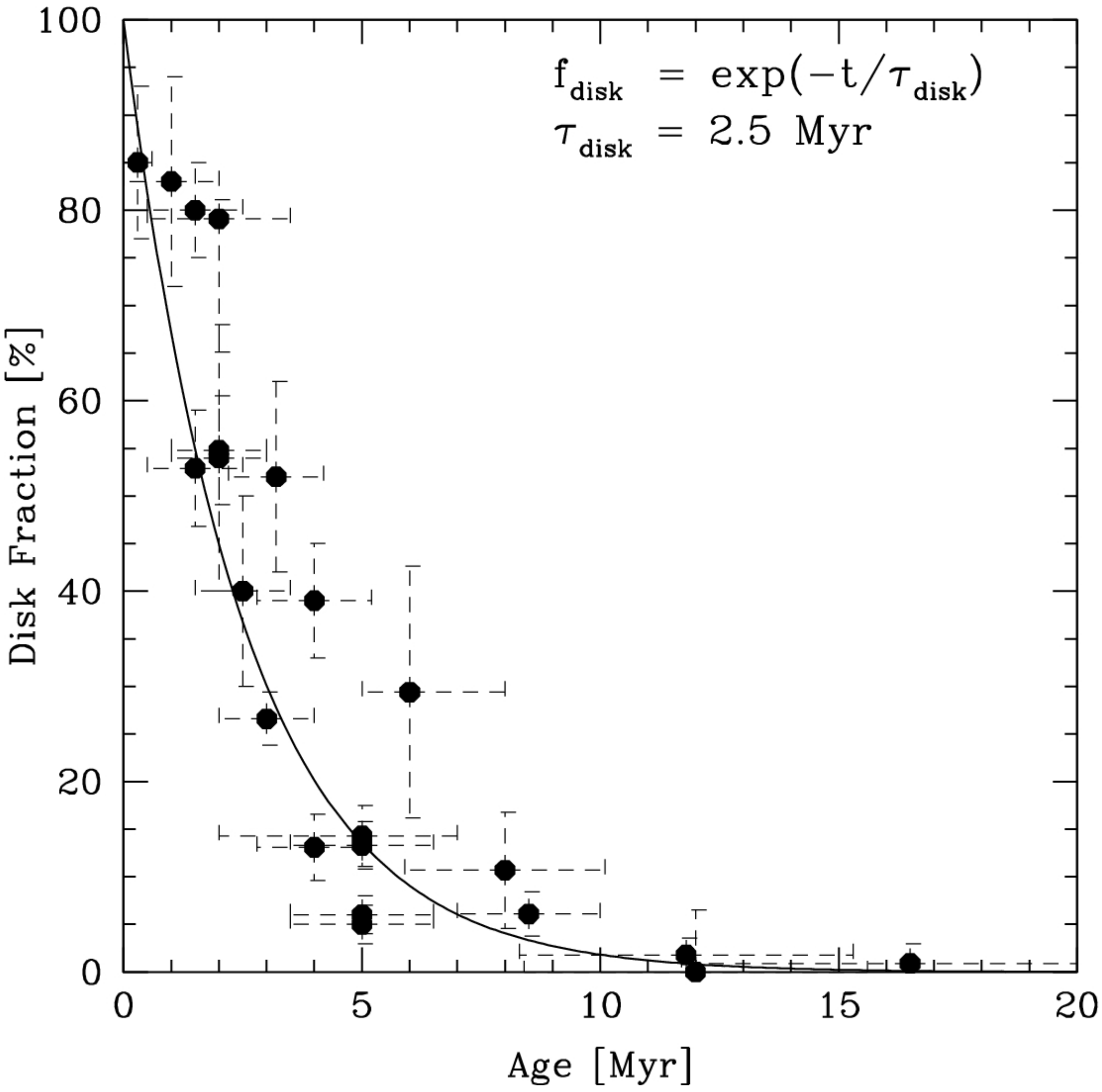
Density: 10^{13} – 10^{15} cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

Scale: 0.1-100 AU
(1 AU = 1.49×10^{13} cm)

Mass: 10^{-3} – 10^{-1} $M_\odot$
(1 $M_\odot$ = 2×10^{33} g)

Disk Lifetime



Mamajek et al. (2009)

Disks evaporate with an *e*-folding time of *2.5 Myr*.

Protoplanetary Disks

PP disk fact sheet

Density: 10^{13} – 10^{15} cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

Scale: 0.1-100 AU
(1 AU = 1.49×10^{13} cm)

Mass: 10^{-3} – 10^{-1} Msun
(Msun = 2×10^{33} g)

Lifetime: ~10 Myr

Accretion

"The central problem
of nearly 30 years of accretion disk theory
is to understand how they accrete"

Balbus & Hawley 1998

Accretion time for molecular viscosity

$$\nu : cm^2\, s^{-1} \qquad \nu = l^2 / t_{coll} = l\, V_t \qquad t_{acc} = r^2 / \nu$$

For a newly formed disk

$$r = 10^{14}\, cm\, ;\, n = 10^{15}\, cm^{-3}\, ;\, \sigma = 10^{-16}\, cm^{-2}$$

$$l = 1/(n\, \sigma) = 10\, cm\, ;\, V_t = 10^5\, cm\, s^{-1}$$

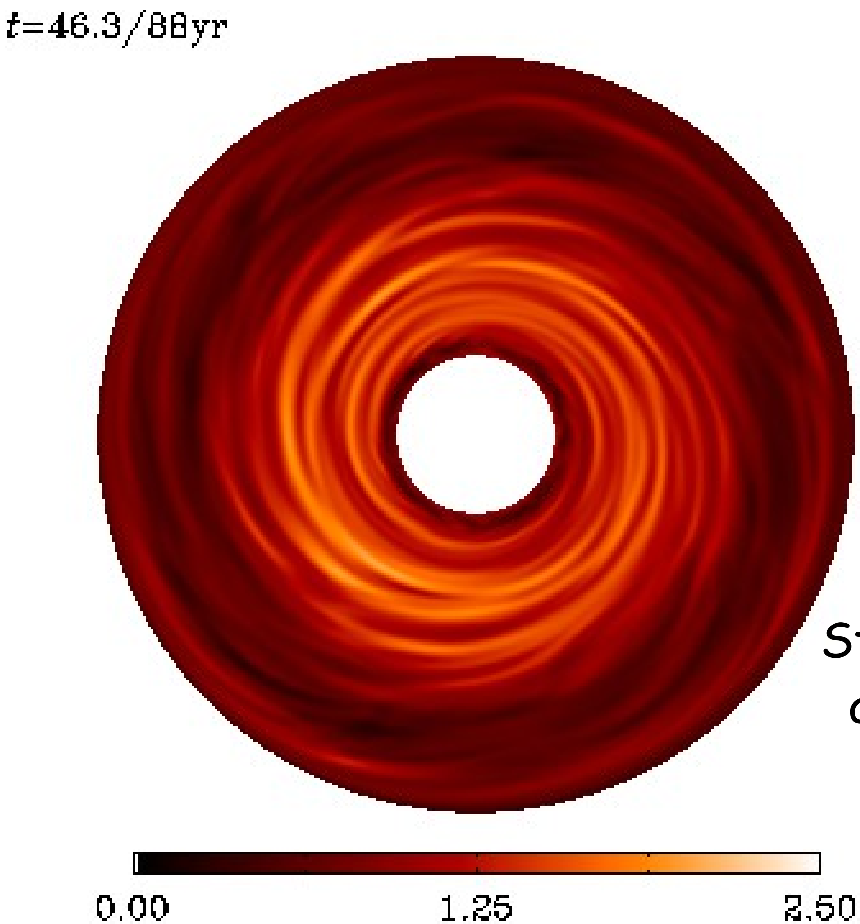
$$t_{acc} = 10^{13}\, yr$$

Observations reveal that disks only live up to 10^7 – 10^8 yr

Much more powerful viscosity needed!

Accretion in disks occurs via turbulent viscosity

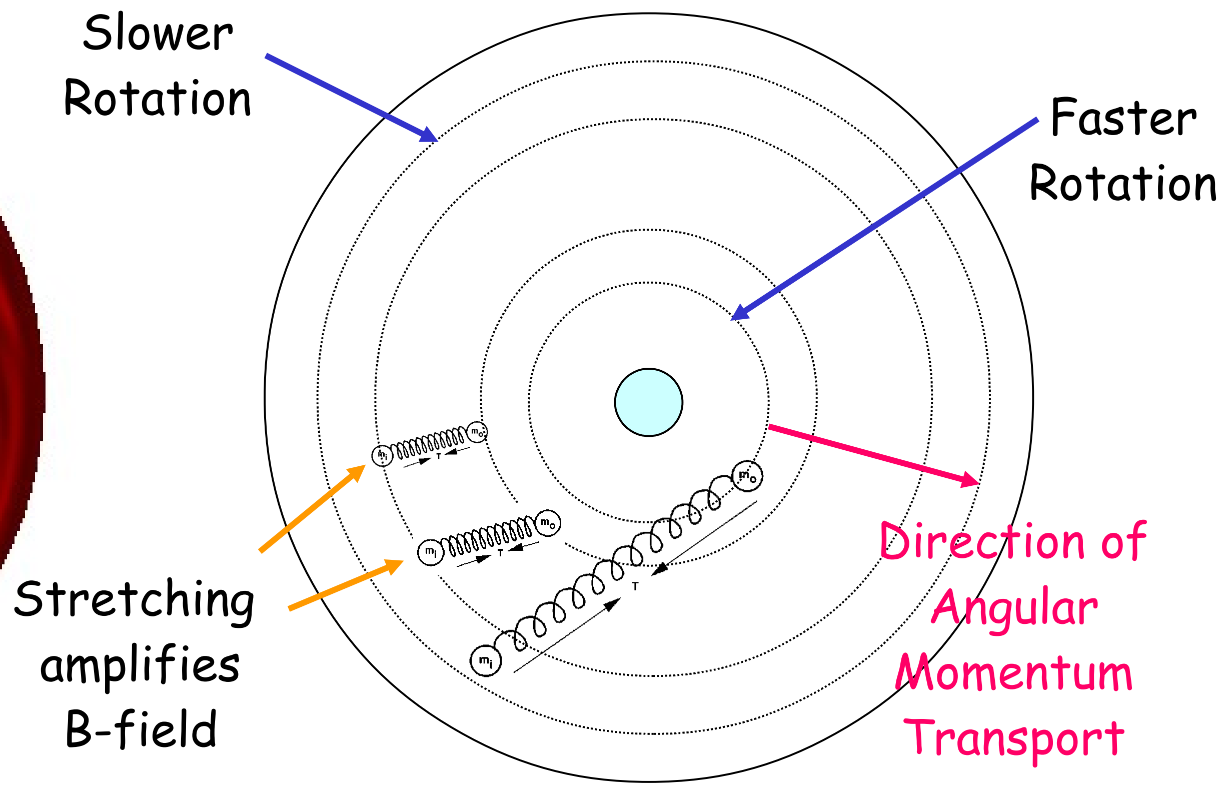
Turbulence in disks is enabled by
the Magneto-Rotational Instability



Magnetized disk

Lyra et al. (2008a)

MRI sketch



Unstable if angular velocity decreases outward

Accretion in disks occurs via turbulent viscosity

Turbulence in disks is enabled by the Magneto-Rotational Instability

Magnetized disk

Lyra et al. (2008a)

MRI sketch

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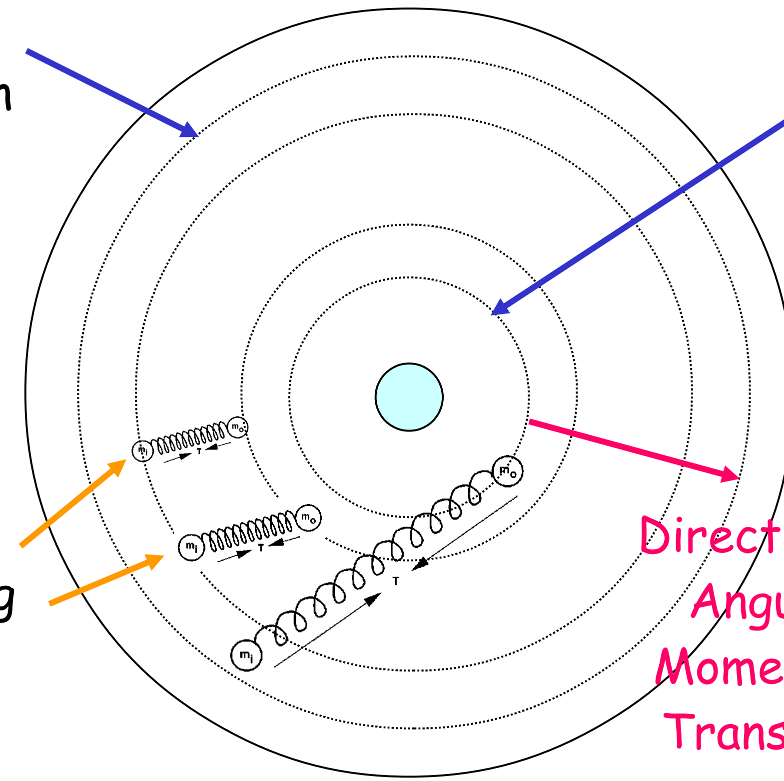
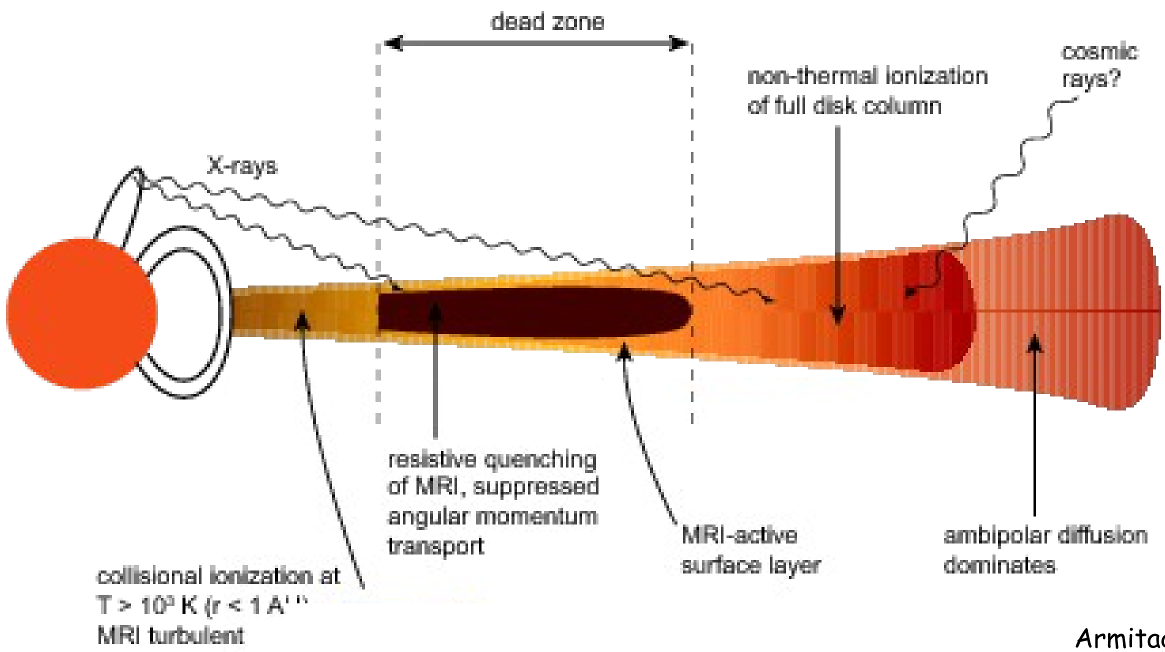


Unstable if angular velocity decreases outward

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



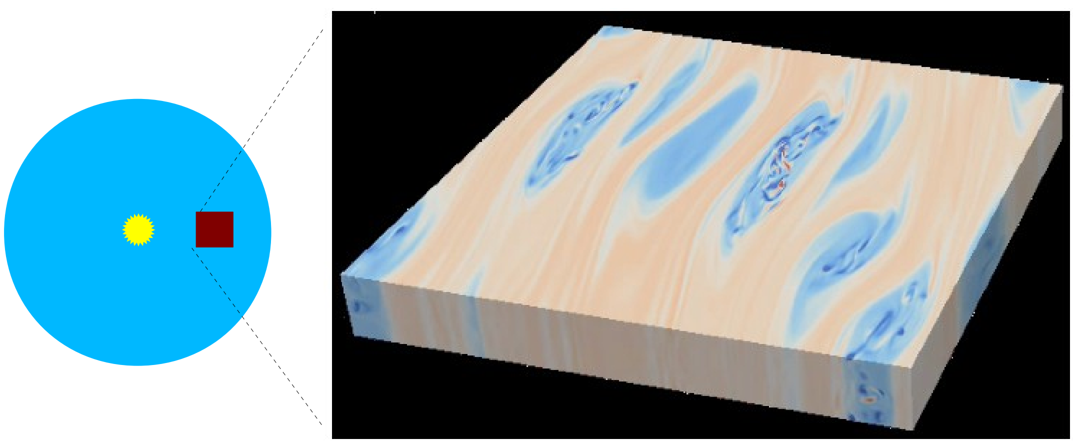
Armitage (2010)

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

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

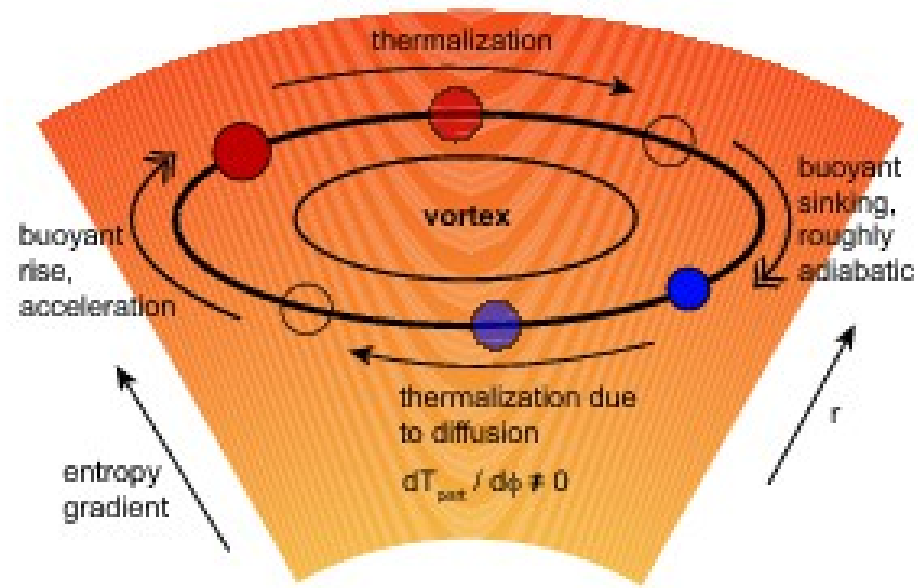
There should be a non-magnetic,
hydrodynamical, source of turbulence in the **dead zone.**

Baroclinic Instability - Excitation and self-sustenance of vortices



Lesur & Papaloizou (2010)

Sketch of the
Baroclinic Instability

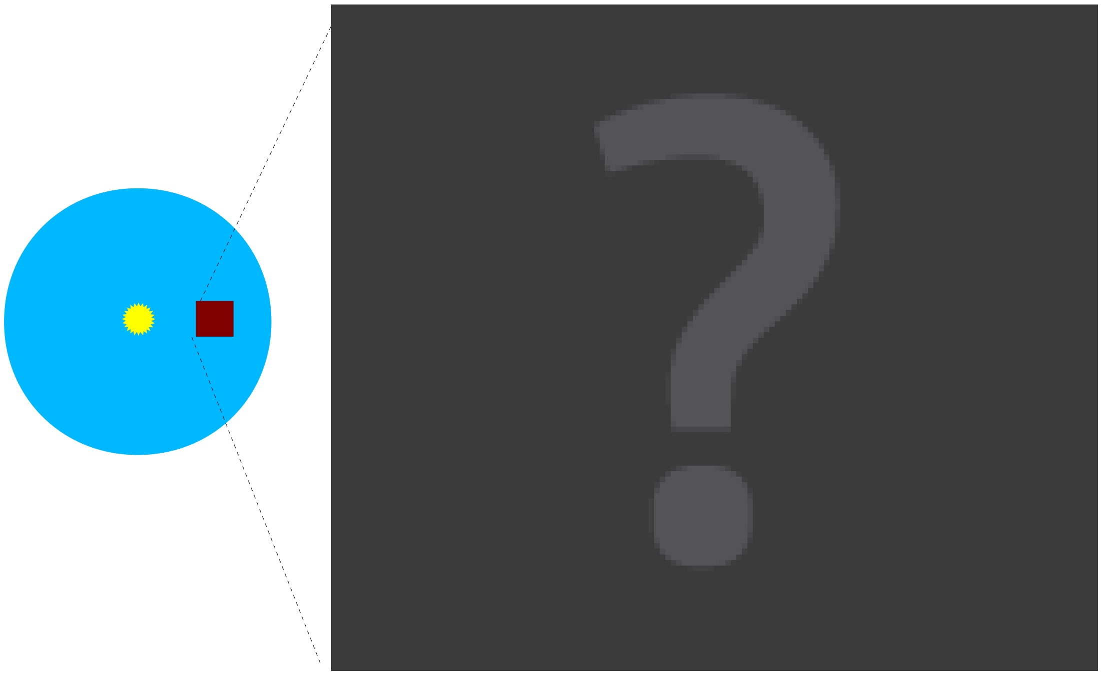


Armitage (2010)

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

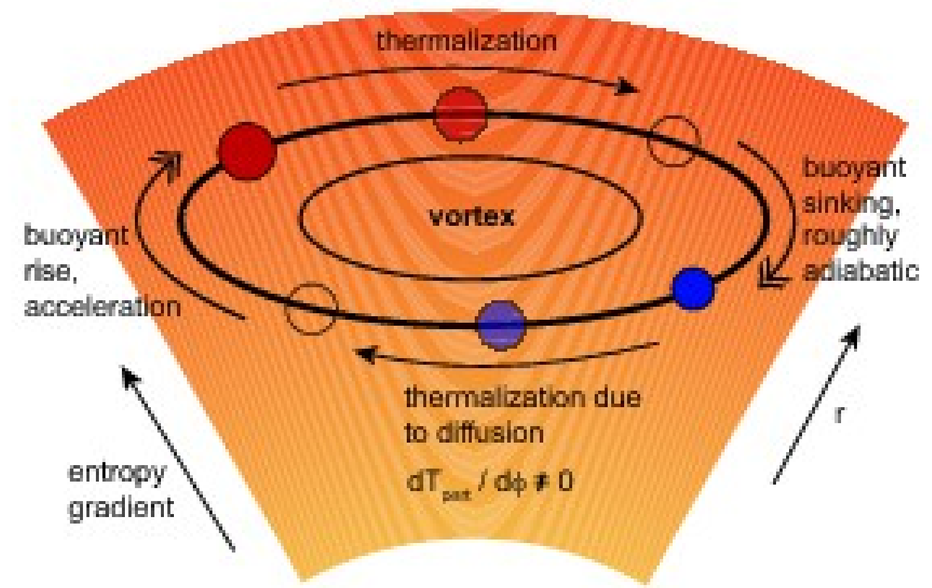
advection — compression — stretching — baroclinicity — dissipation

Baroclinic Instability - Excitation and self-sustenance of vortices



Lyra & Klahr (2011)

Sketch of the
Baroclinic Instability

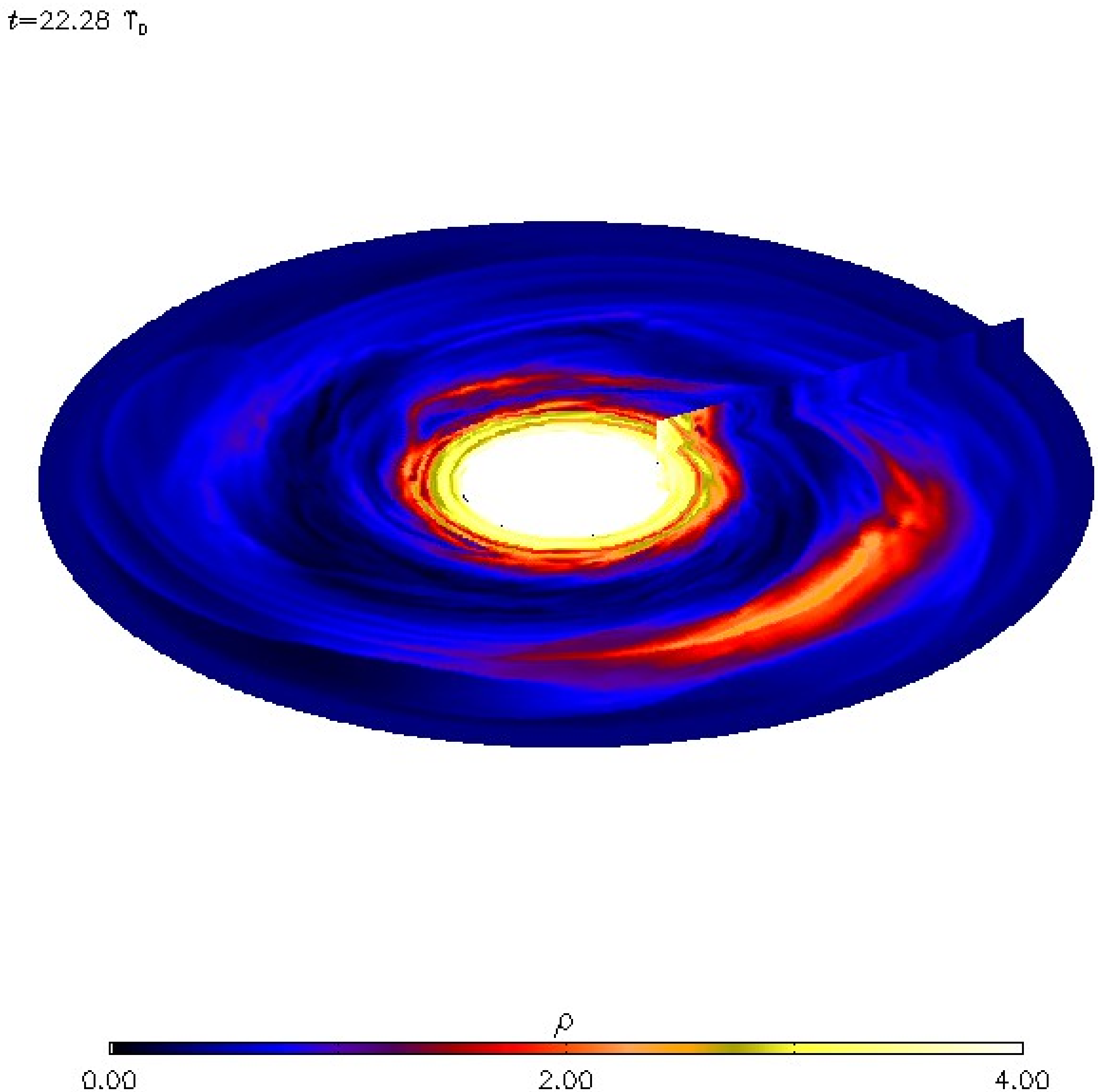


Armitage (2010)

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

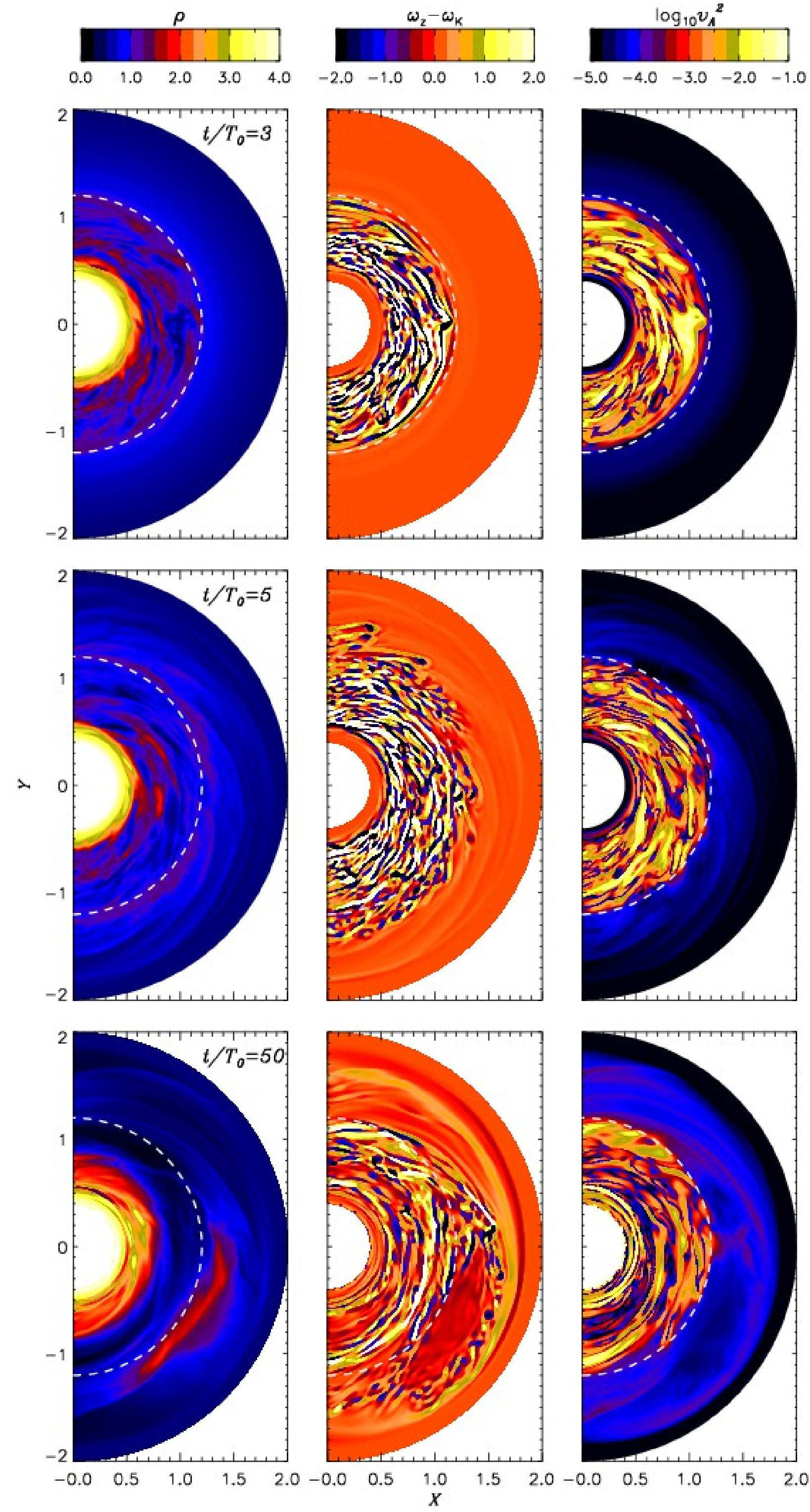
advection, compression, stretching, baroclinicity, dissipation

Active/dead zone boundary

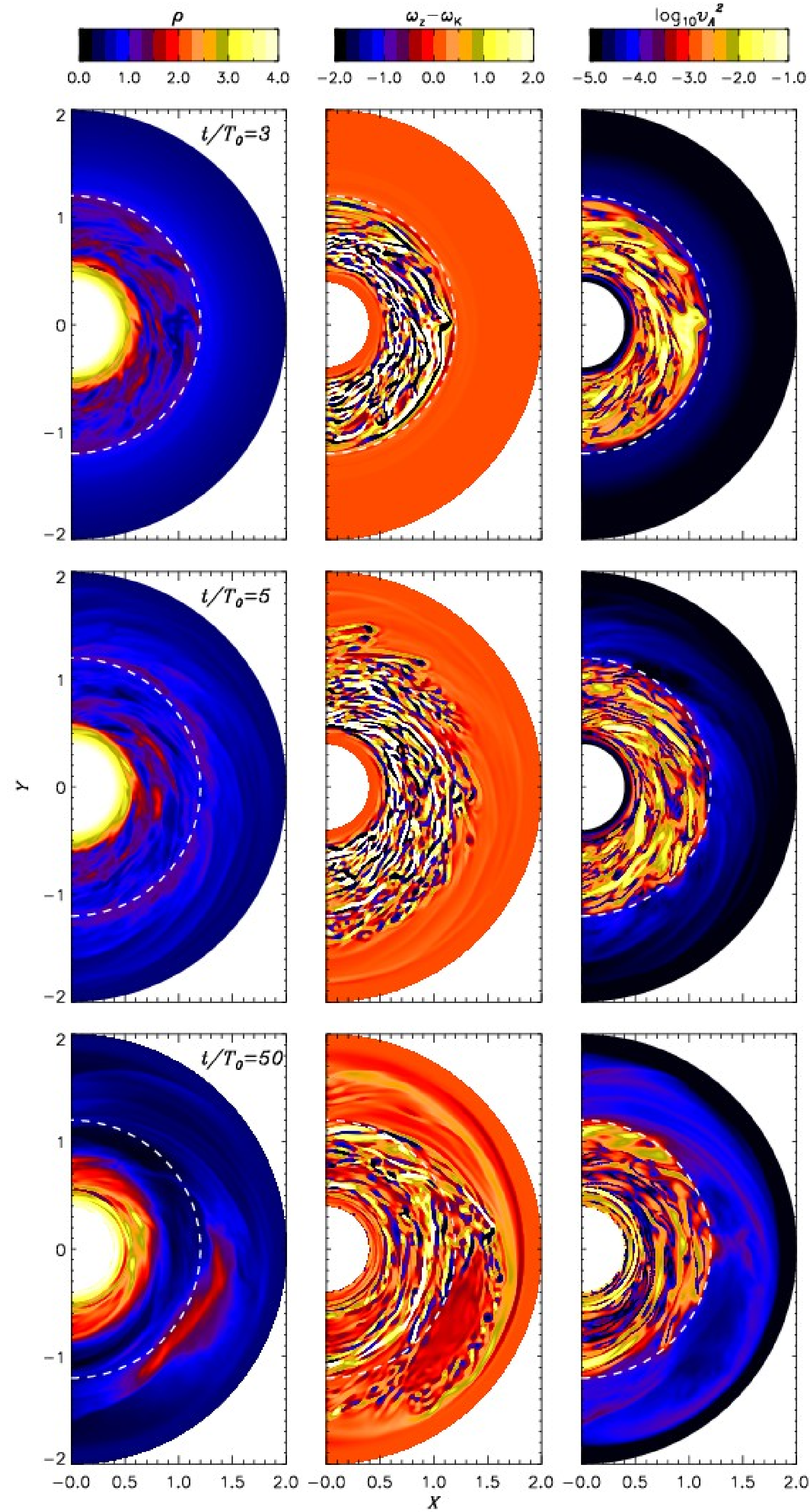


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)



Active/dead zone boundary

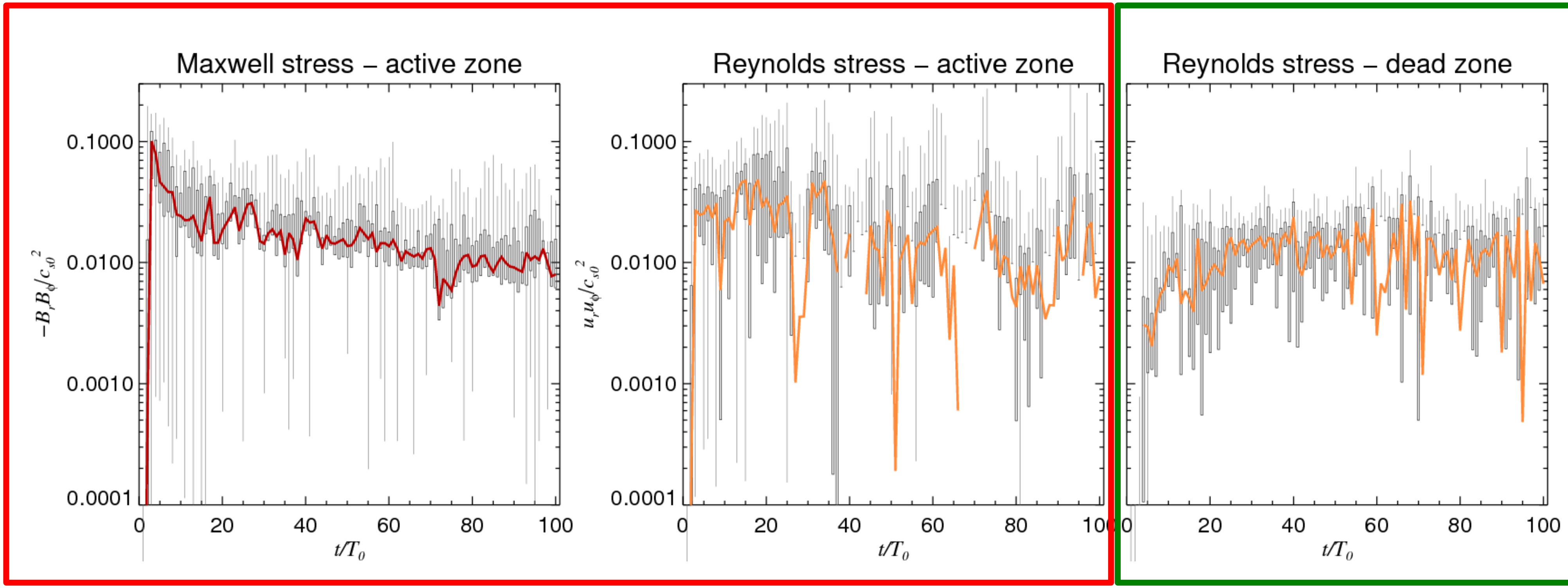


Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Significant angular momentum transport

Active zone   Dead zone



Large mass accretion rates in the dead zone,

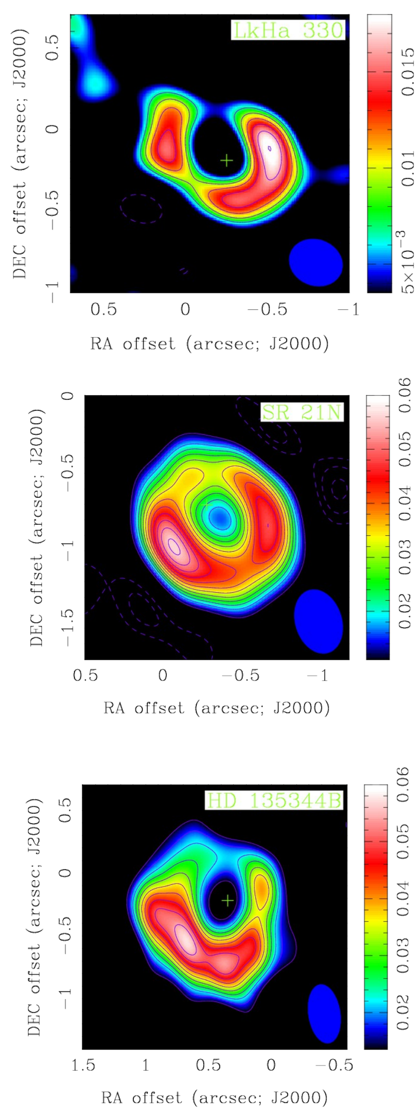
comparable to the MRI in the active zone!

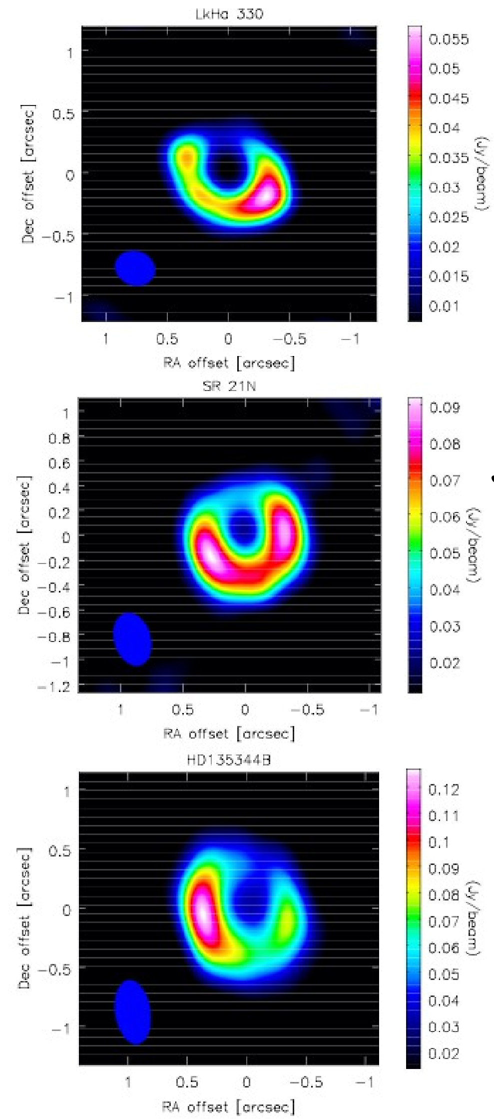
Lyra & Mac Low (2012)

A possible detection of vortices in disks

Observations

Brown et al. (2009)

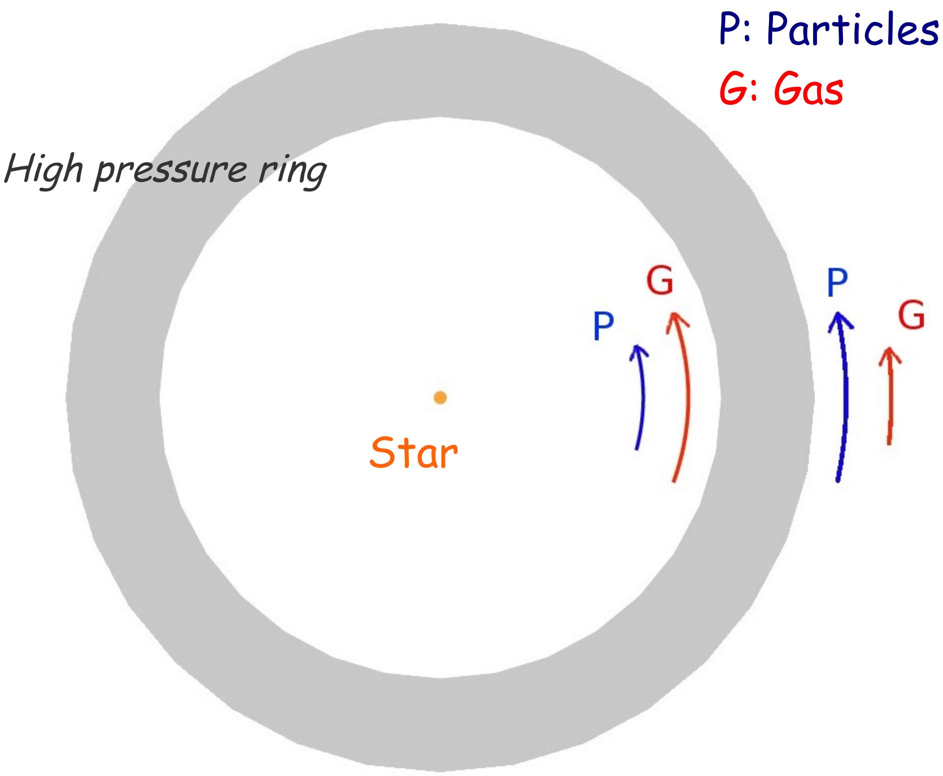


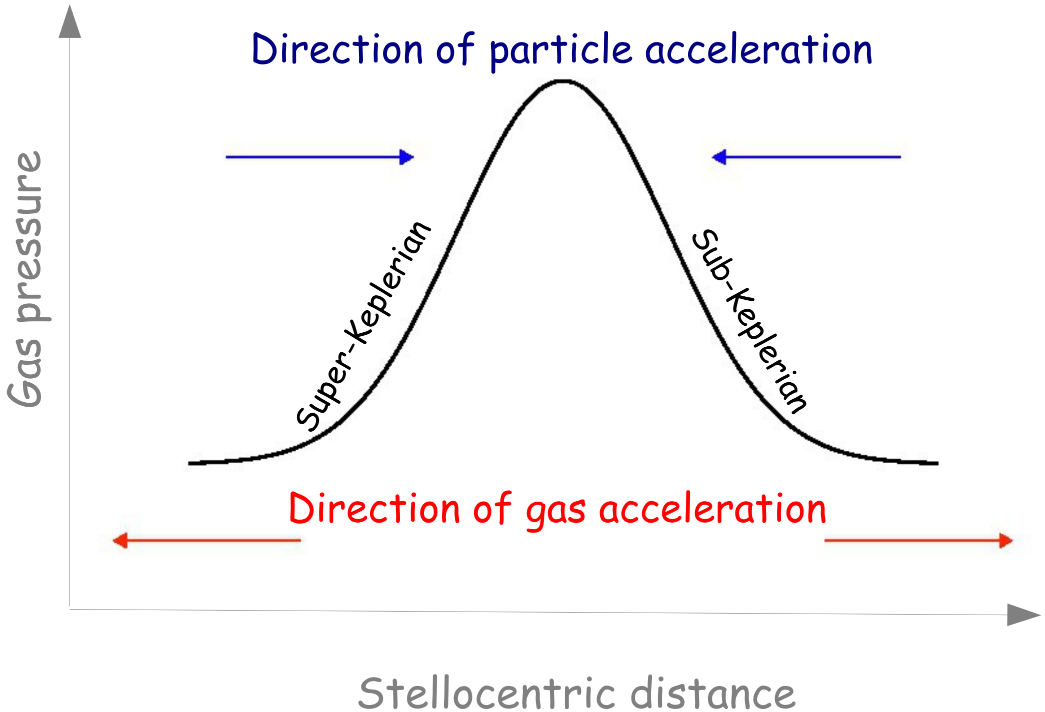


Simulated observations of Rossby vortices

Regaly et al. (2012)

Forming planets in turbulent disks





Adapted from Whipple (1972)

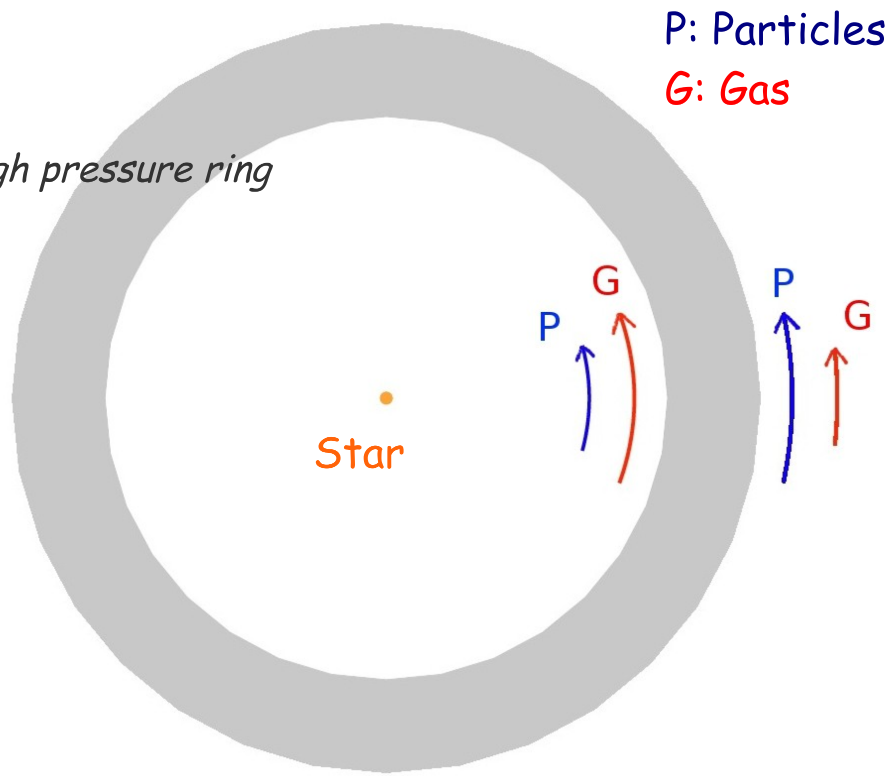
Forming planets in turbulent disks

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

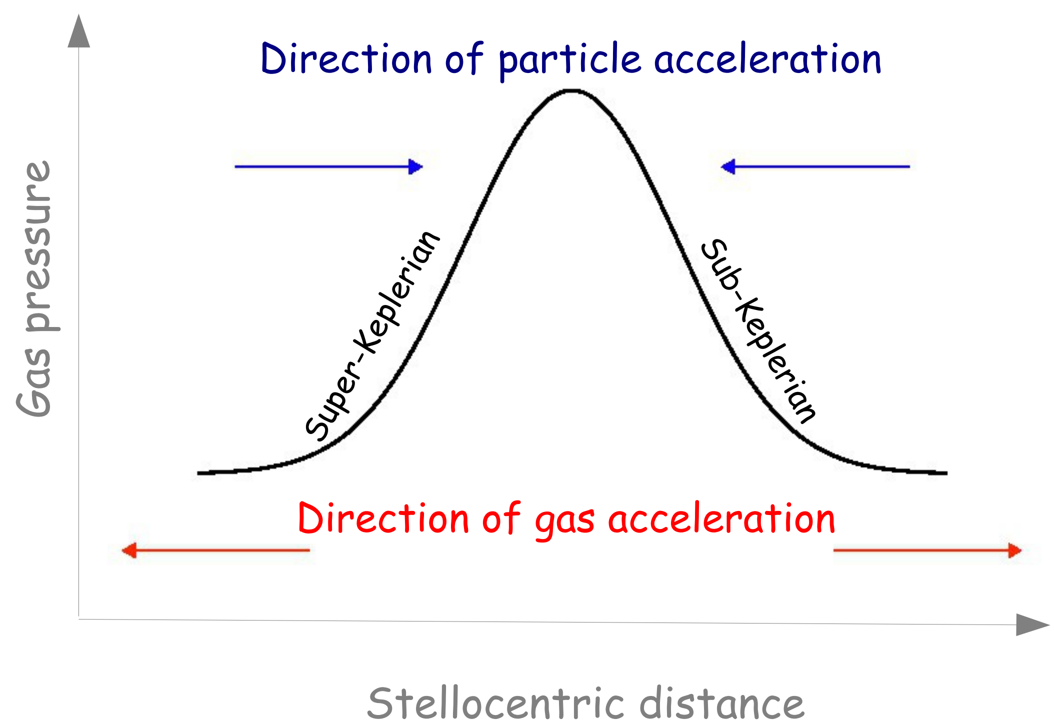
Particles $$\frac{d\boldsymbol{w}}{dt} = -\nabla\Phi - \frac{(\boldsymbol{w}-\boldsymbol{u})}{\tau}$$

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

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



Adapted from Whipple (1972)



Solid particles

move **toward**

pressure maxima

Turbulence concentrates solids mechanically in pressure maxima

Lyra et al. (2008)

Gravitational collapse into planetesimals

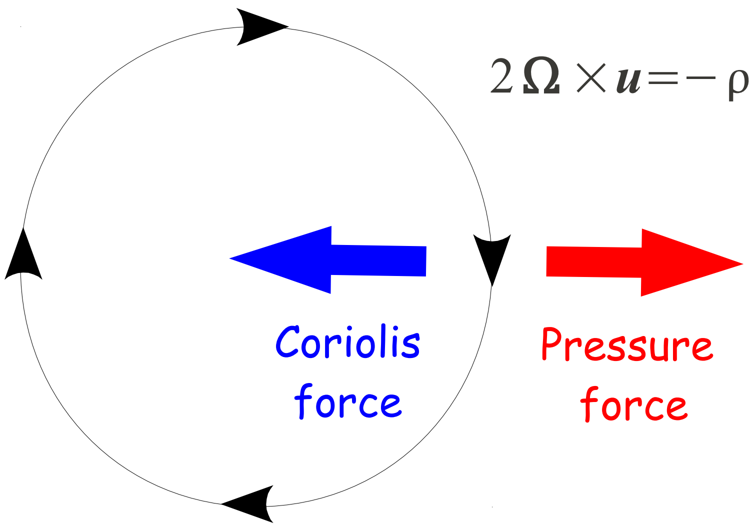
Johansen et al. (2007)

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

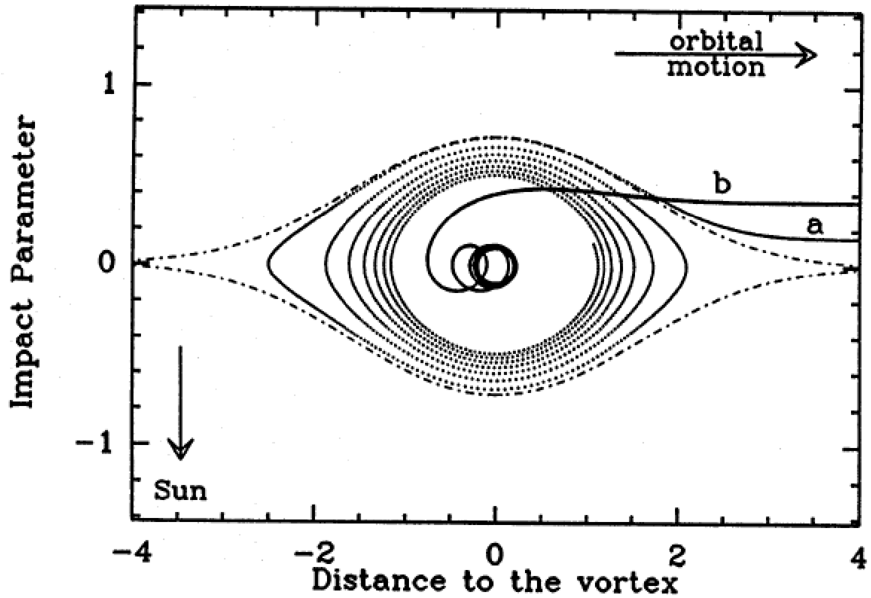
...and vortices are **huge** eddies!

Planet Formation via *Vortex Thruway*

Geostrophic balance:



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



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)

Planet Formation via *Vortex Thruway*

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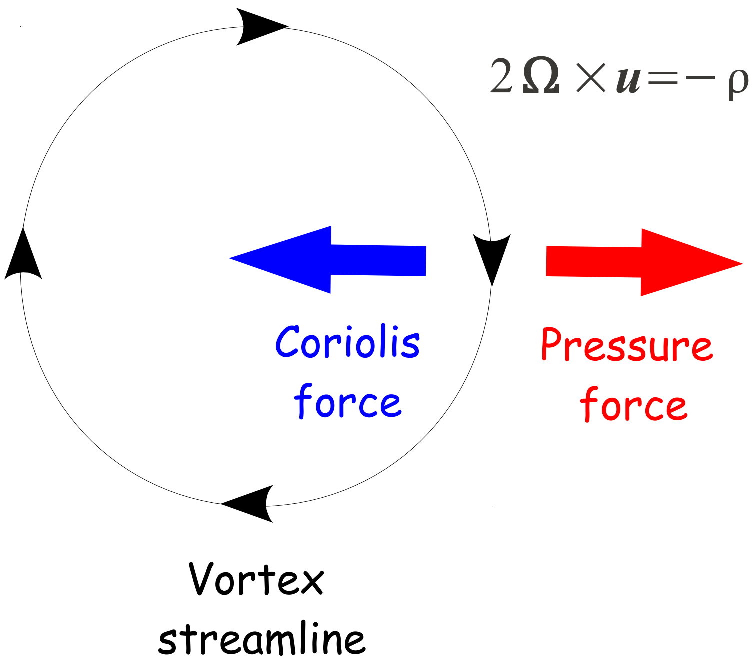

$$2\boldsymbol{\Omega}\times\boldsymbol{u}=-\rho^{-1}\nabla p$$

Raettig et al. (2012)

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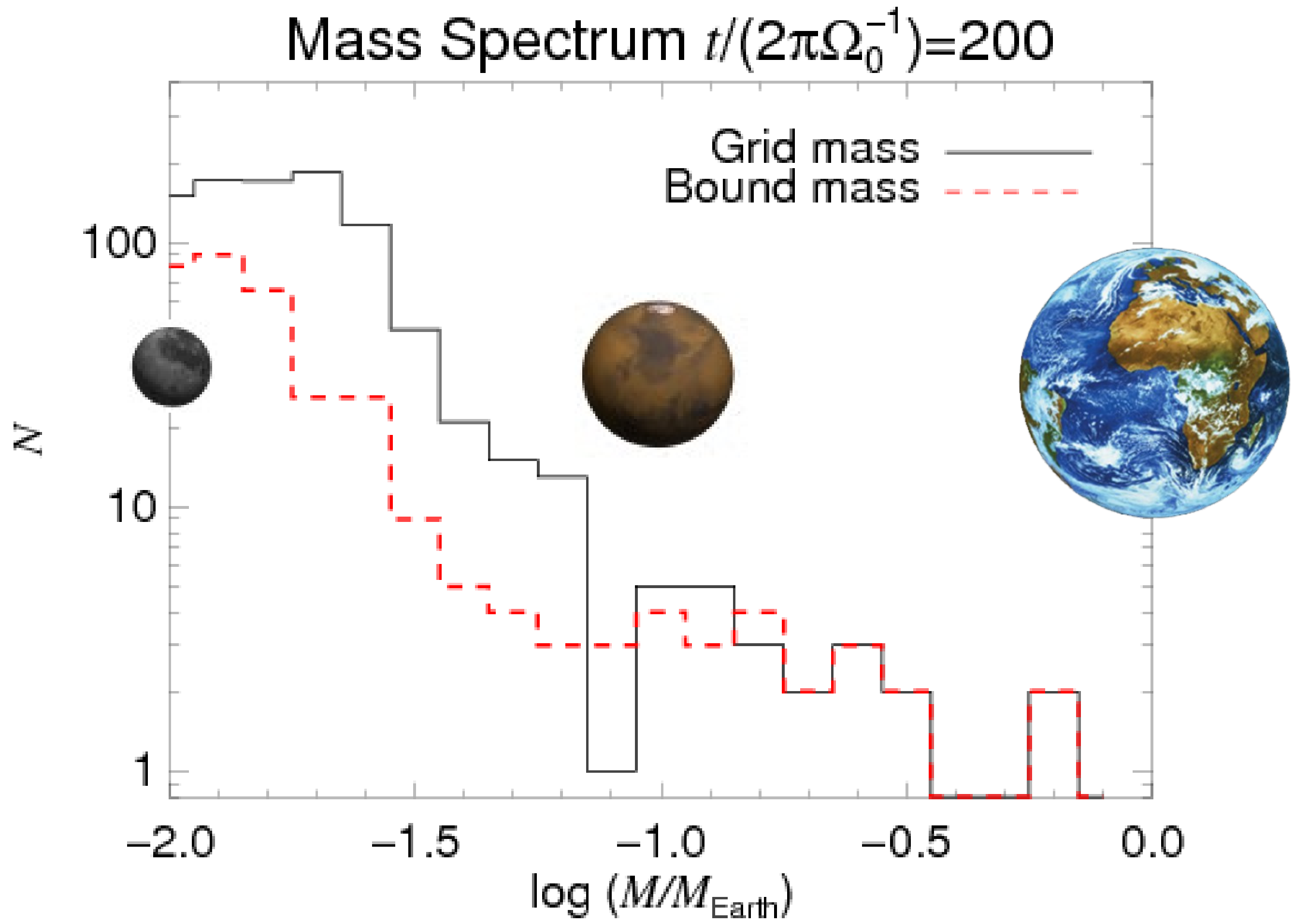
The Initial Mass Function of planets

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

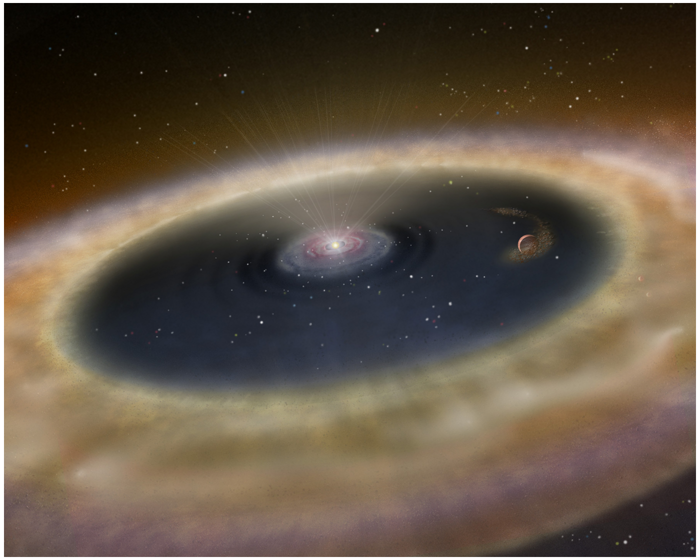
The Initial Mass Function of planets

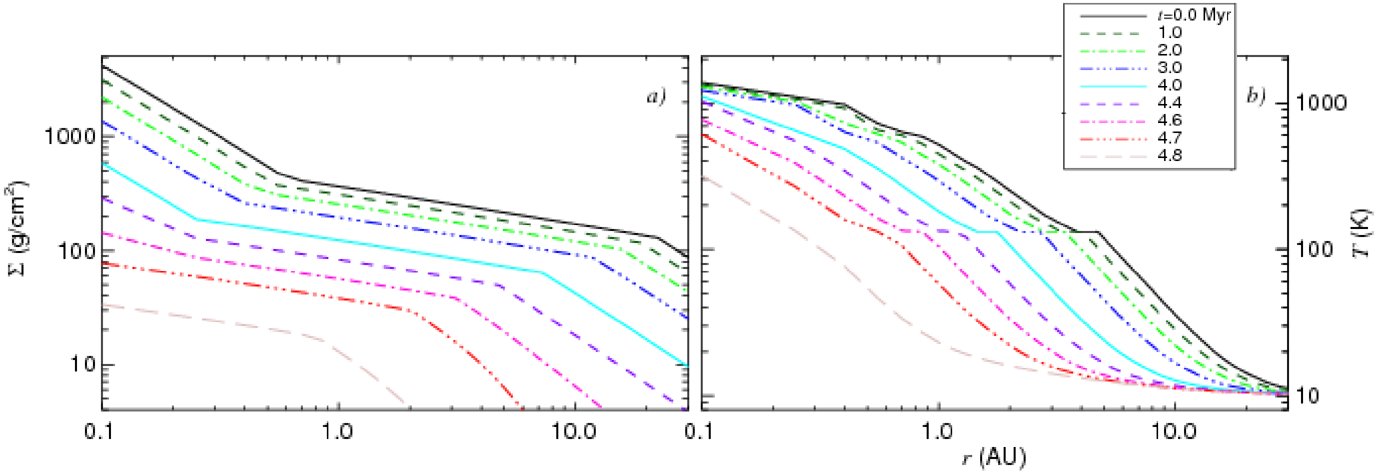


•Mass spectrum by the end of the simulation
•300 bound clumps were formed
•Power law d(log N)/d(log M)=-2.3 +/- 0.2
•20 of these are more massive than Mars

Transitional disks – The thinning phase

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





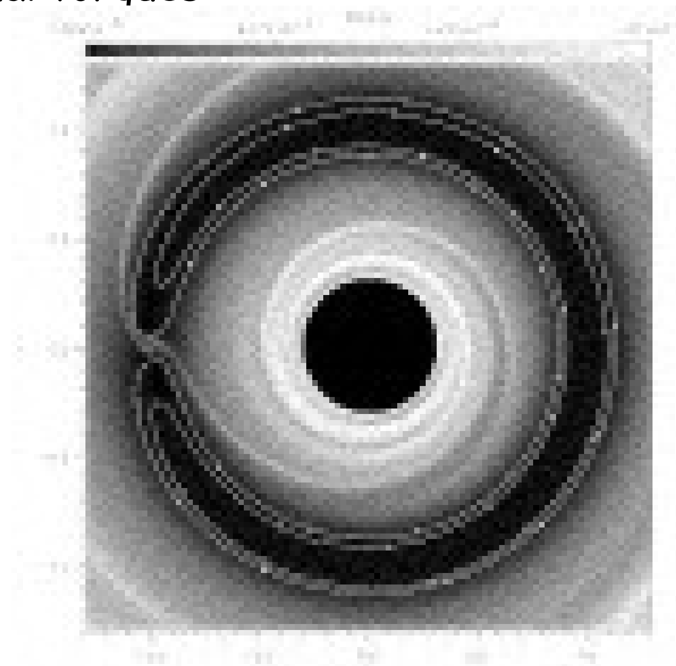
Lyra, Paardekooper, & Mac Low (2010)

Planets form and start to migrate

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

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

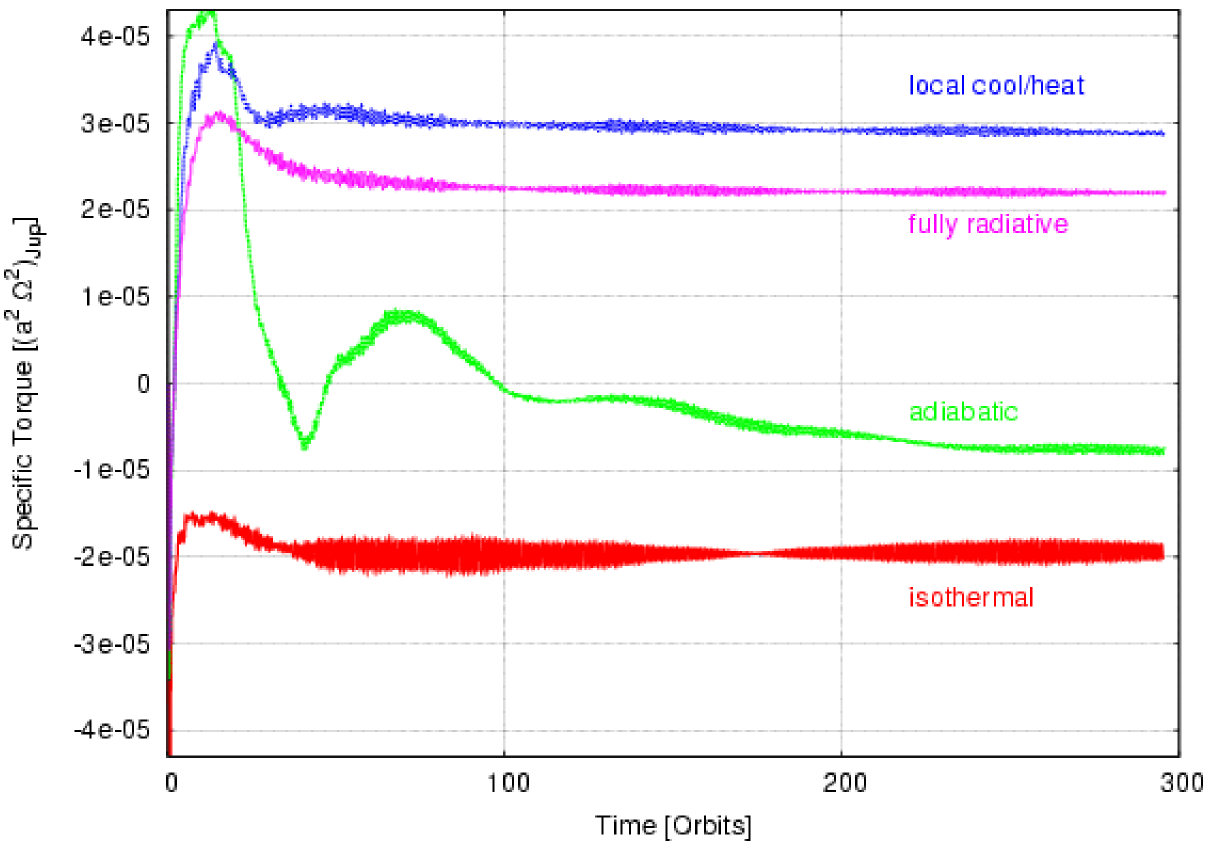
Nelson & Kley (2012, Annual Review)



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.

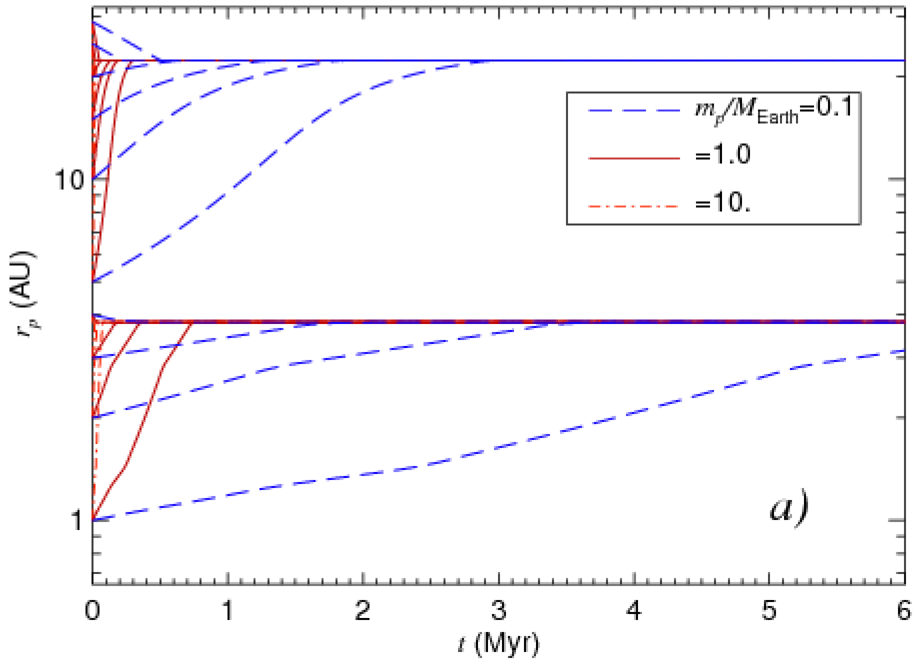
Paardekooper & Mellema (2006)

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
Bitsch & 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

Planets form and start to migrate

Planet-disk interaction leads to angular momentum exchange

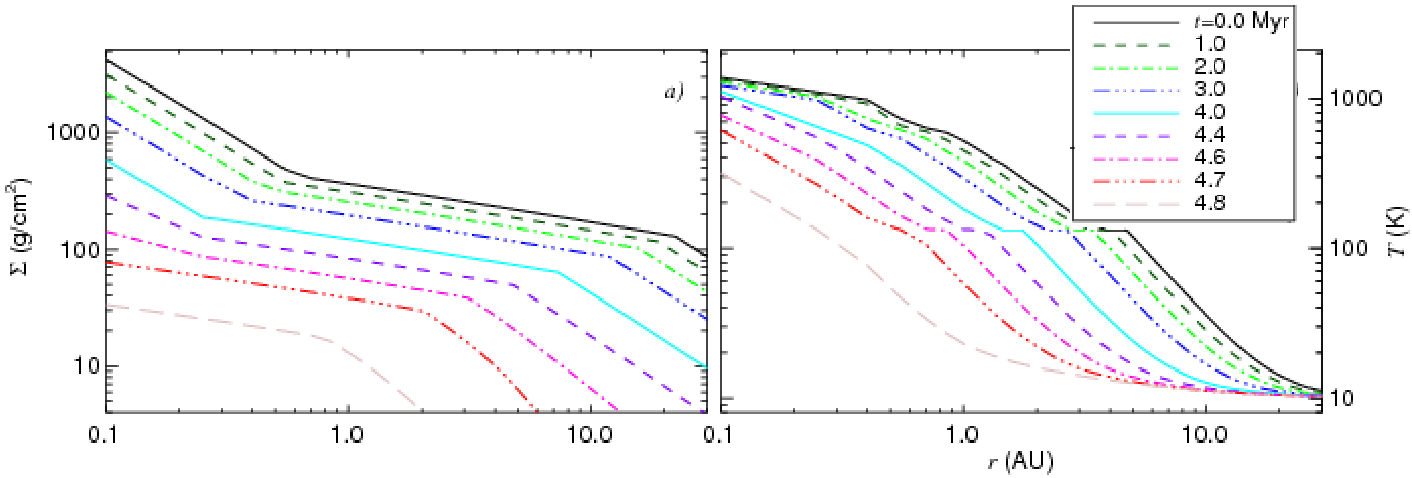


Lyra, Paardekooper, & Mac Low (2010)

Planet traps where migration is convergent (τ=0, $d\tau/dr$ < 0).

Migration in Evolutionary Models

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



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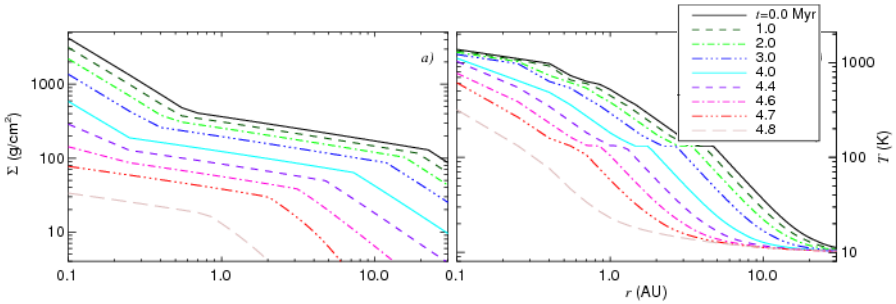

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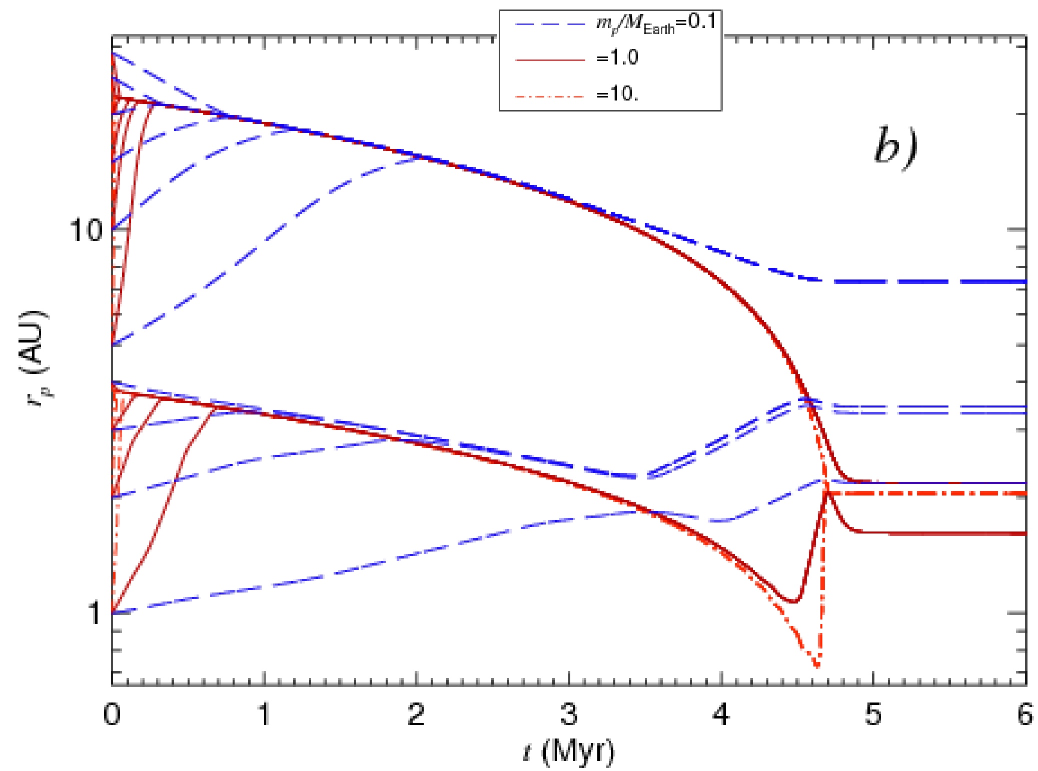
isothermal regions.

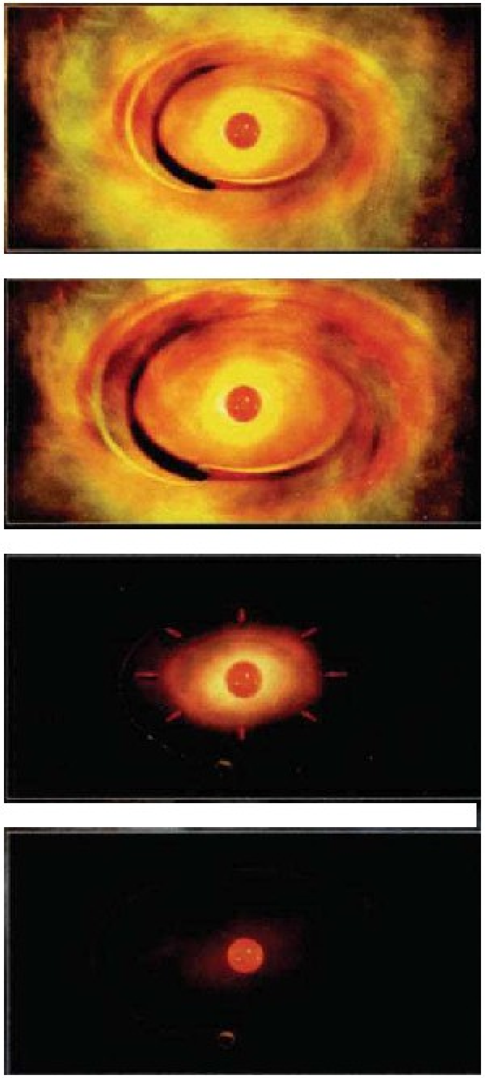
Single planets in a planetary trap evolve in **lockstep with the gas** at the accretion timescale.

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



Lyra, Paardekooper, & Mac Low (2010)

Migration in Evolutionary Models



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

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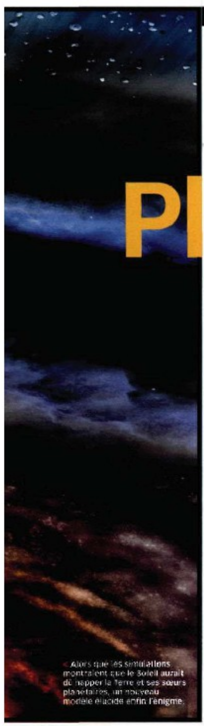
"La Terre sauvée"



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

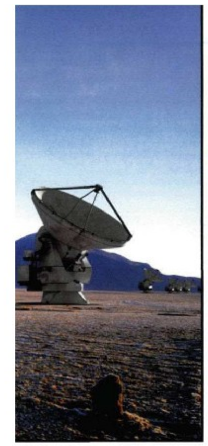
On sait pourquoi elles survivent à leur étoile

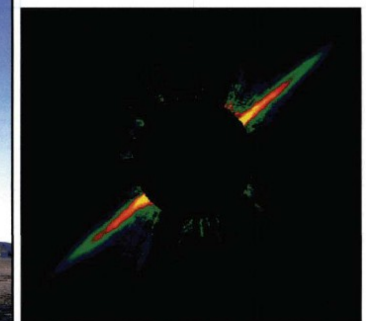
Par Román Ikonicoff

"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.

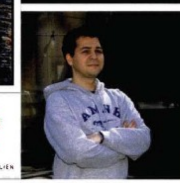
LA TERRE NE DEVRAIT PAS EXISTER

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…

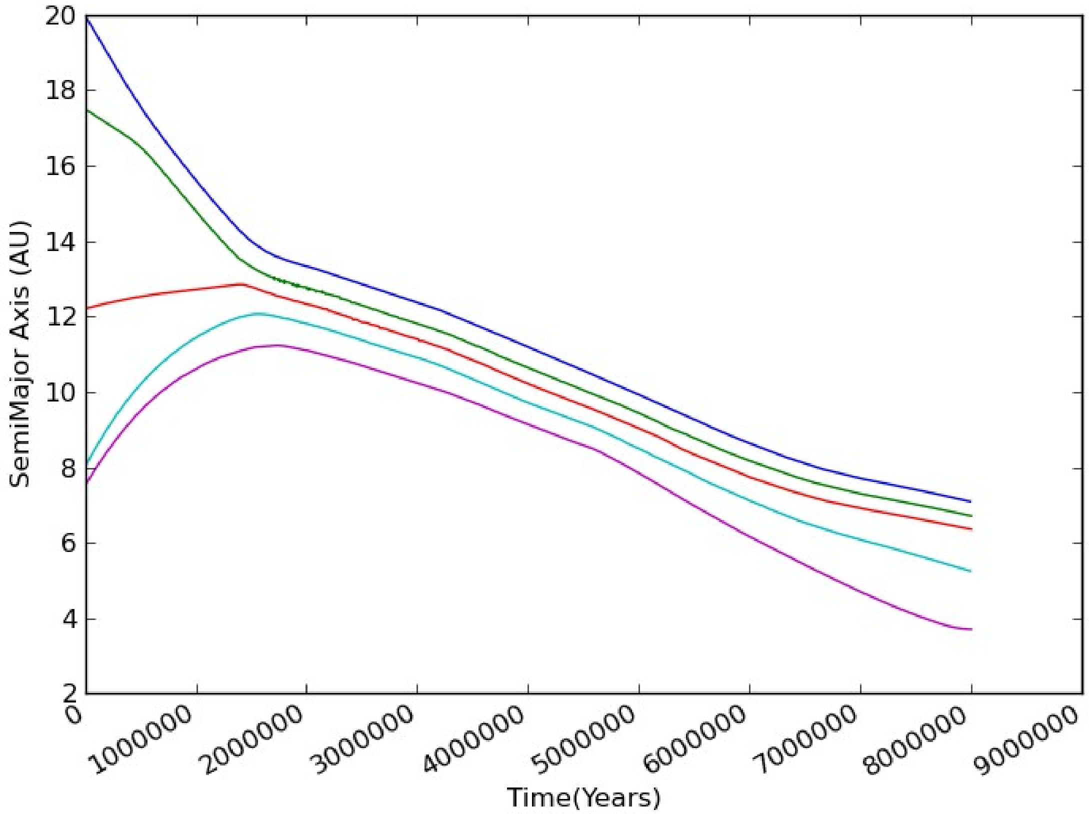
DONNÉES CONCRÈTES DÈS 2011

"*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)

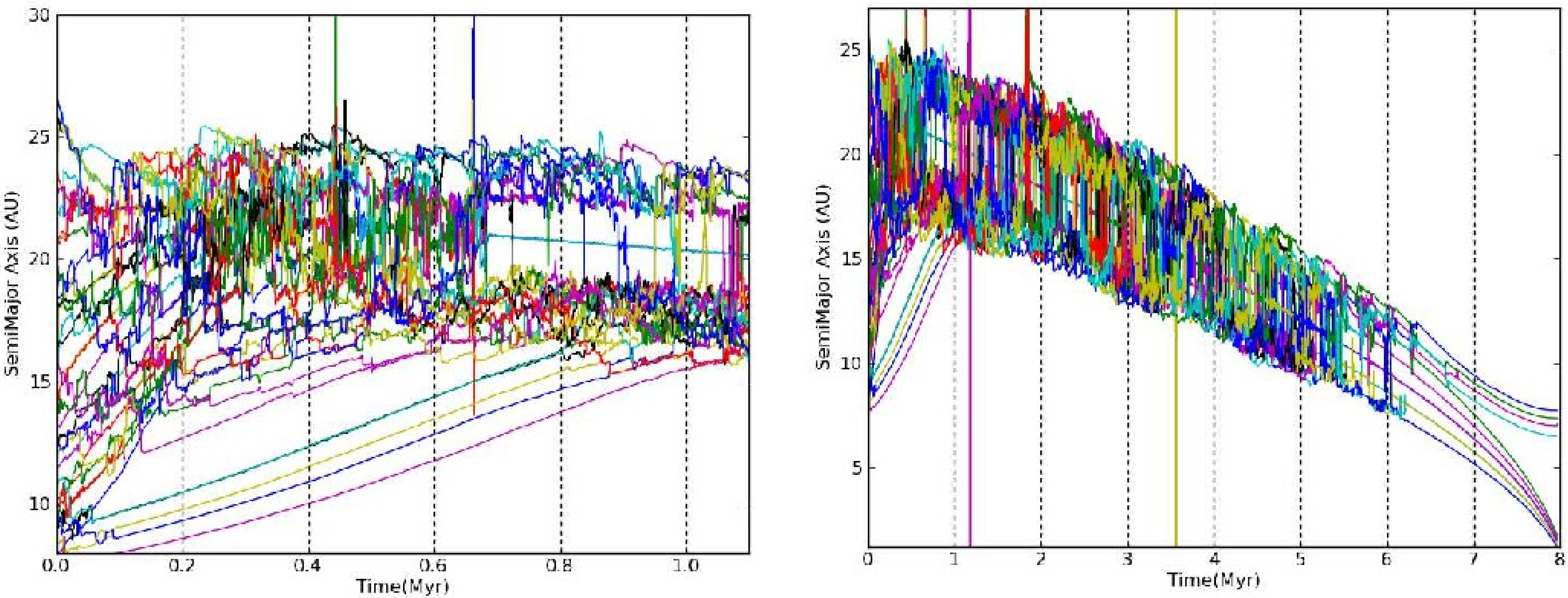
Orbital migration of interacting planets in a radiative evolutionary model

Combines

migration + N-body + photoevaporation + turbulence

modelled as stochastic forcing

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

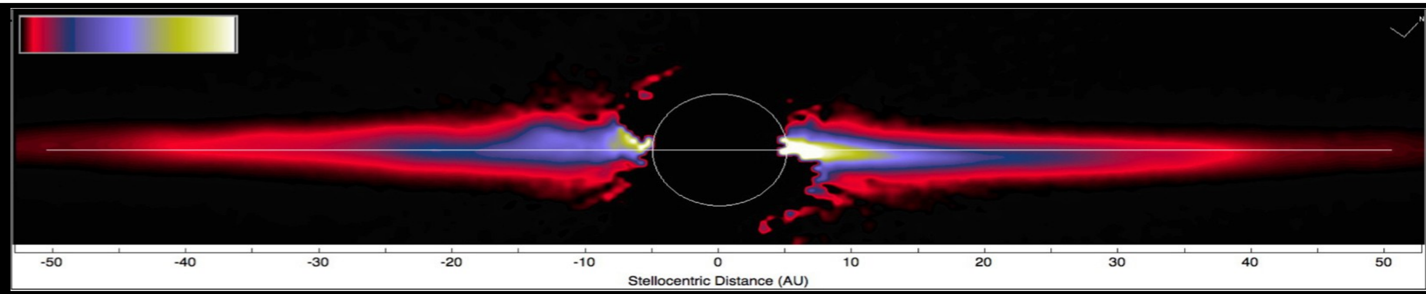


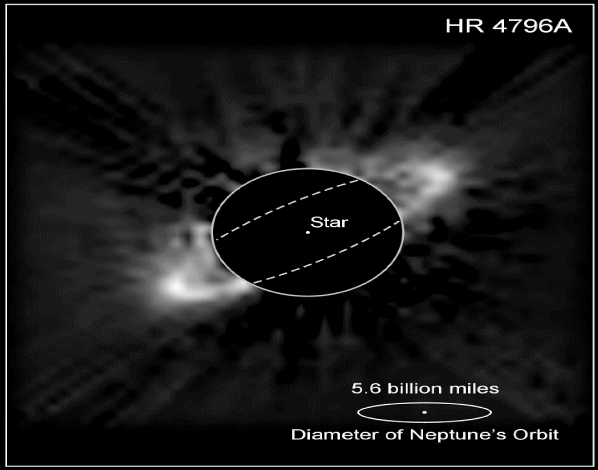
Horn et al. (2012)

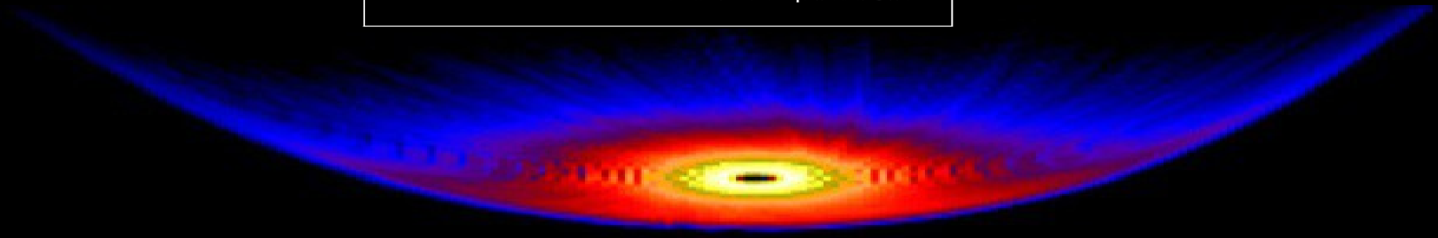
Orbital migration of interacting planets in a radiative evolutionary model

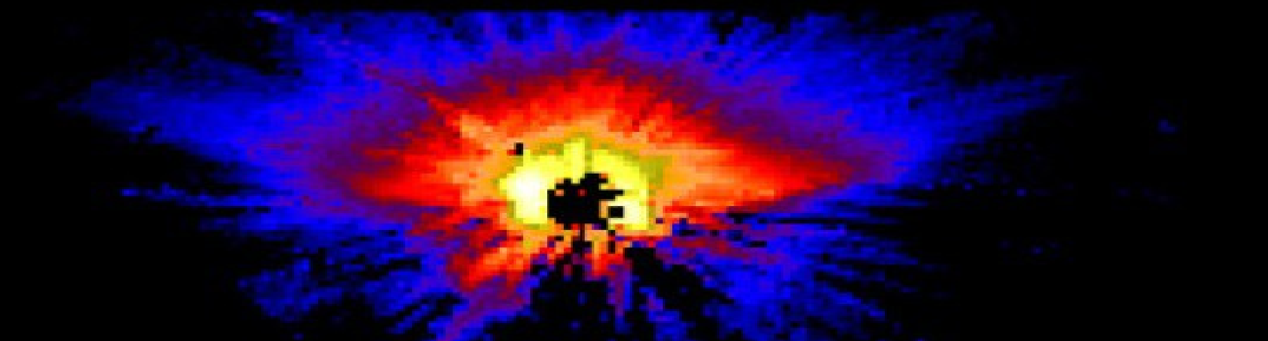
Horn et al. (2012)

Debris disks – The gas-poor phase

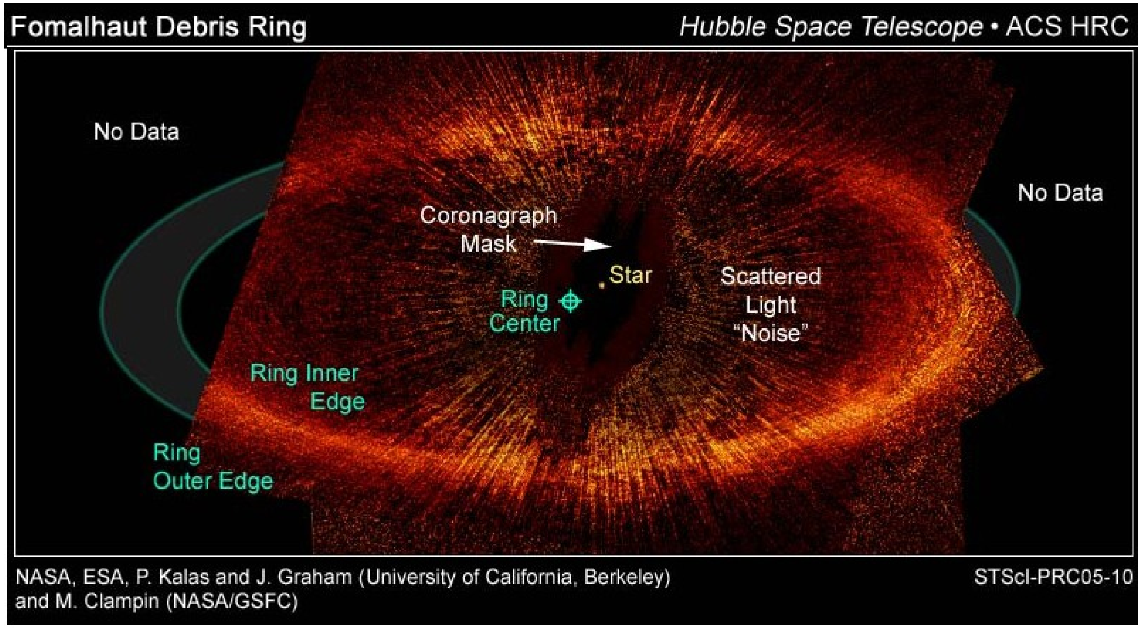


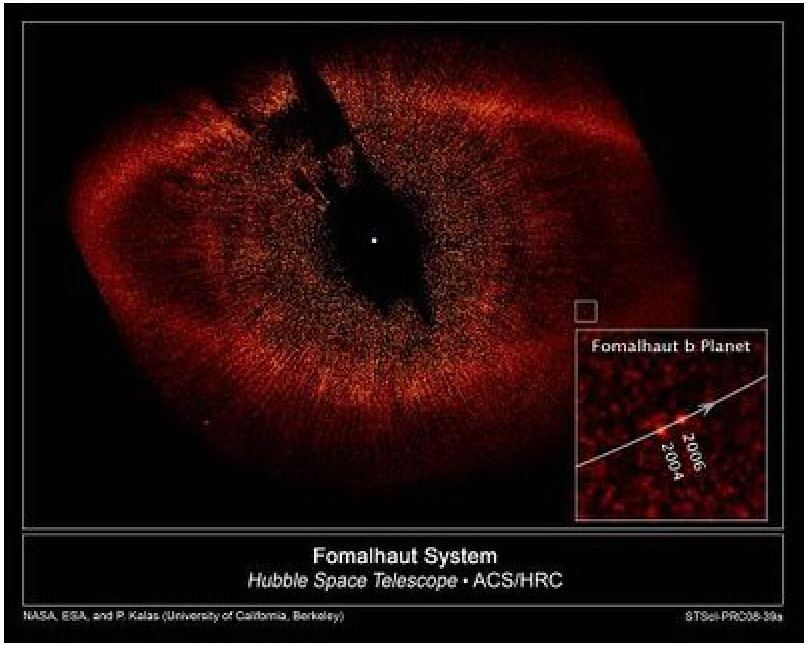






Sharp and eccentric rings in debris disks: Signposts of planets





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

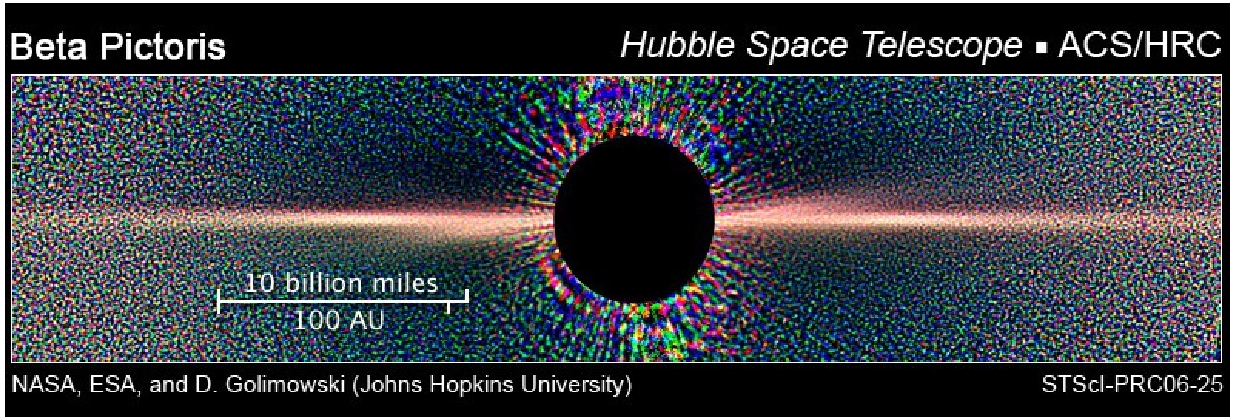
Online-only material: color figures

Planet not detected in infrared

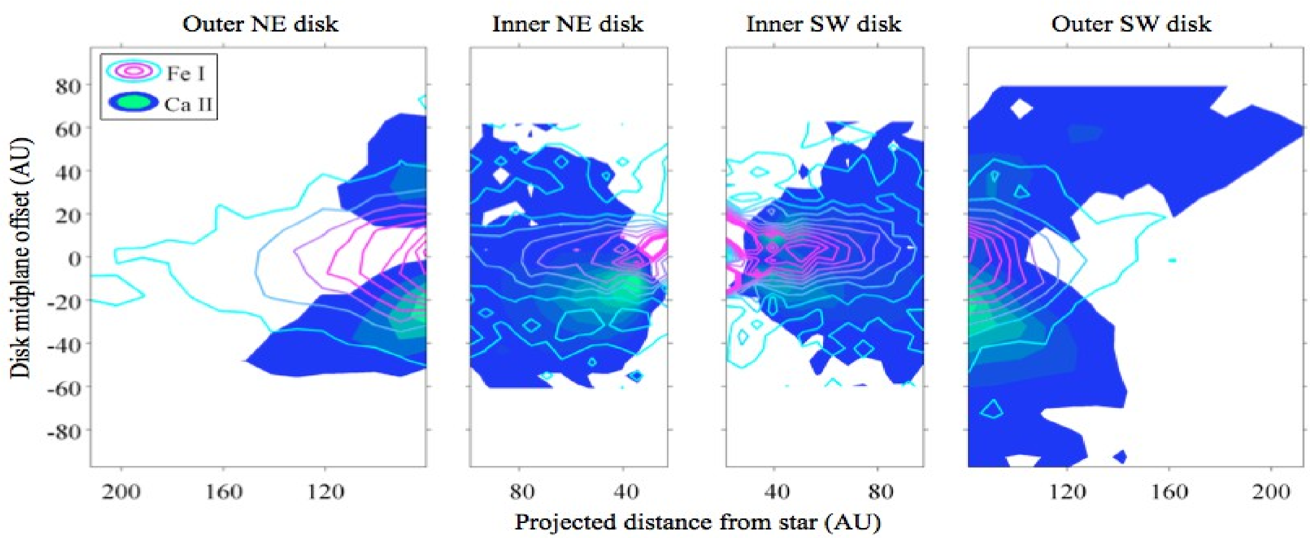
Are there alternative explanations?

Debris disks are not completely gas-free

Dust



Gas



VLT imaging by Nilsson et al. (2012)

Gas in debris disks

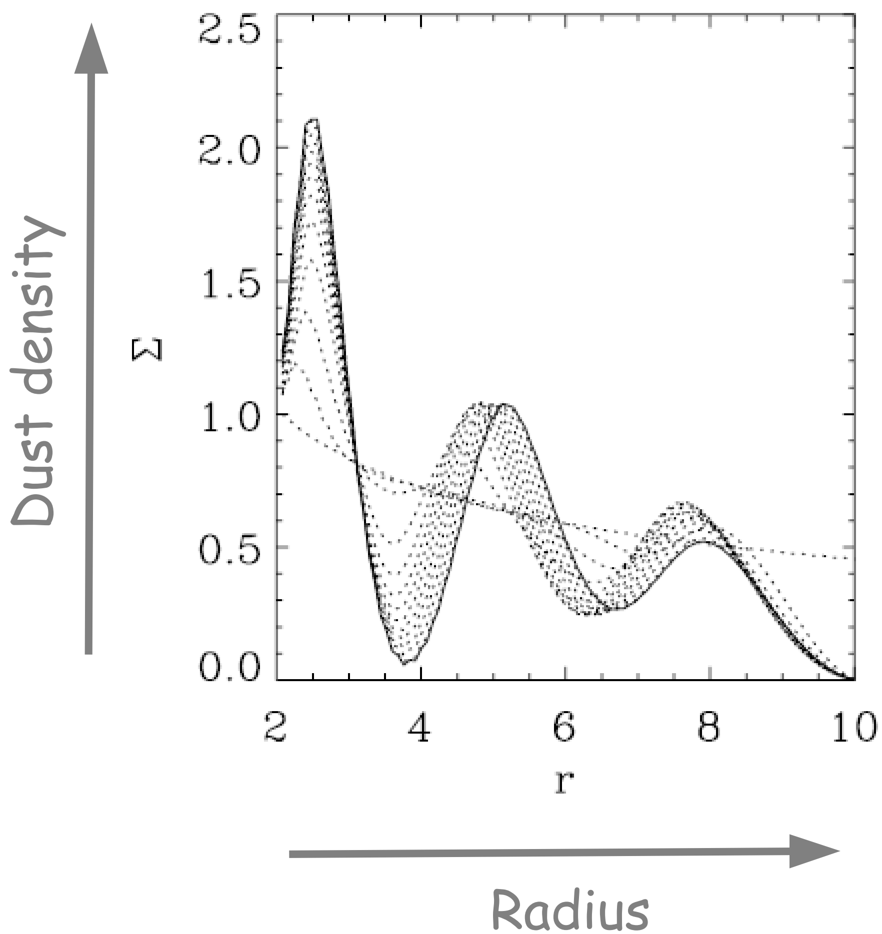
Detections

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

Source of gas: Outgassing processes

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

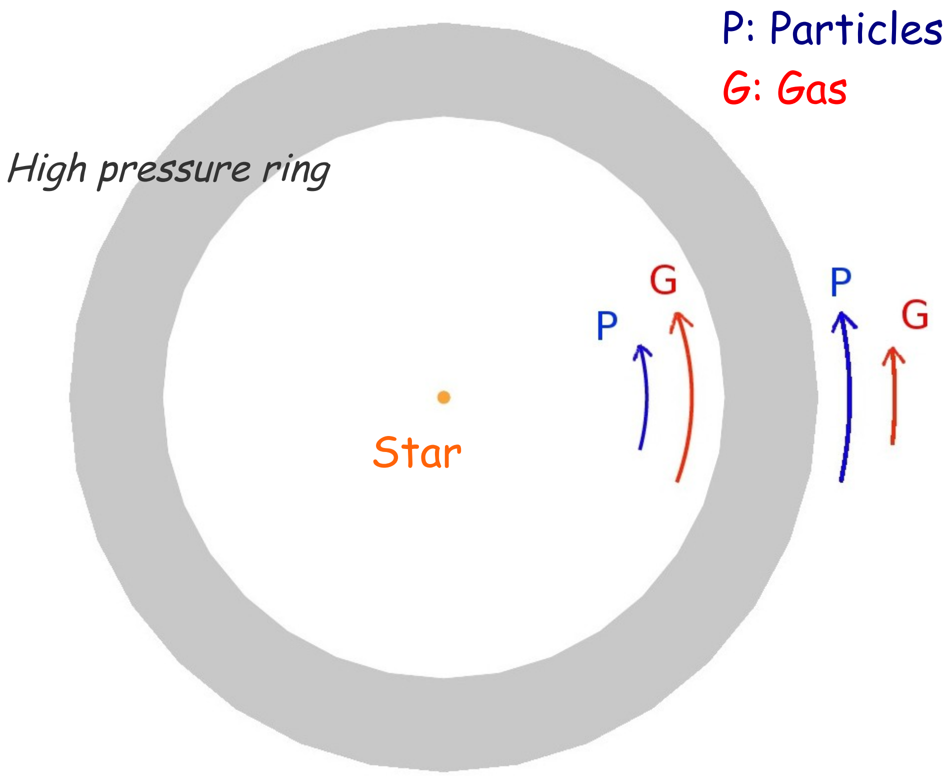
Dust and gas together leads to instability...



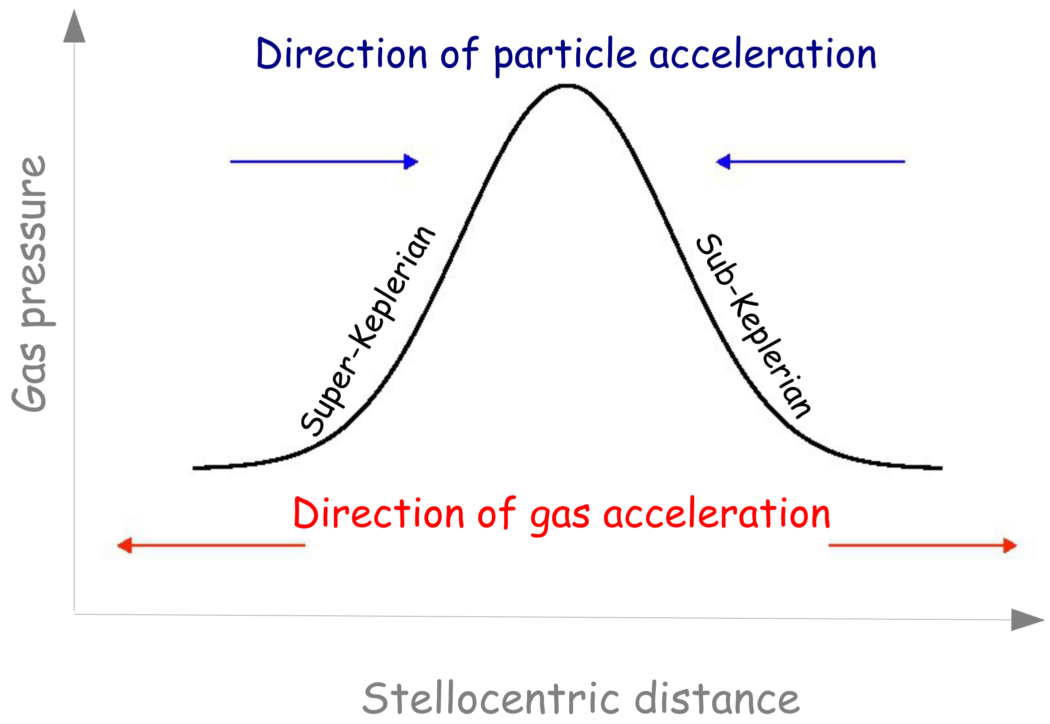
Klahr & Lin (2005)

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

Particles move toward pressure maxima

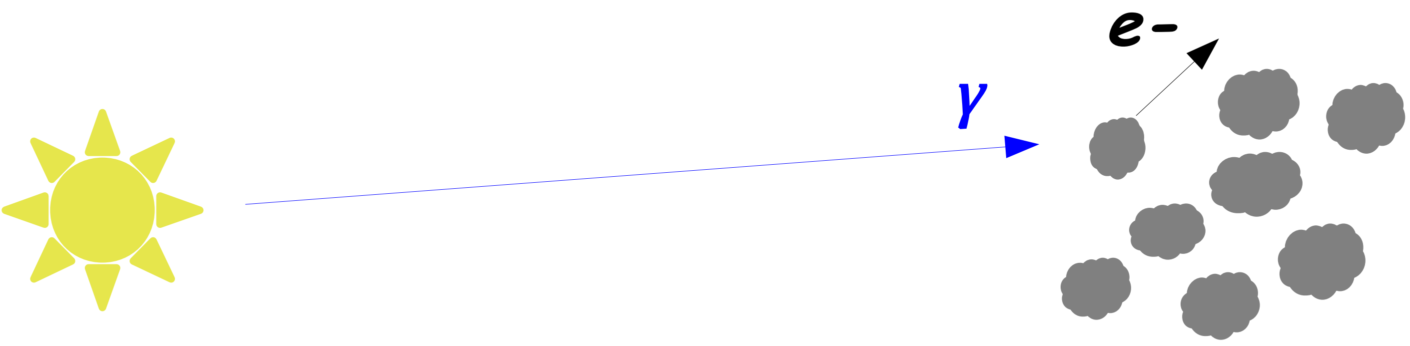


Adapted from Whipple (1972)



Photoelectric heating

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



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

Gas is photoelectrically heated by the dust itself

Runaway process: instability

Dust heats gas

Heated gas = high pressure region

High pressure concentrates dust

Runaway process: instability

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

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

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

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

Lyra & Kuchner (2012)
2D

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

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

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

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

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

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

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

Inertia for both gas and dust

Energy equation

Drag force and
drag force backreaction

Linear Analysis

Dust

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

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

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

Gas

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

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

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

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

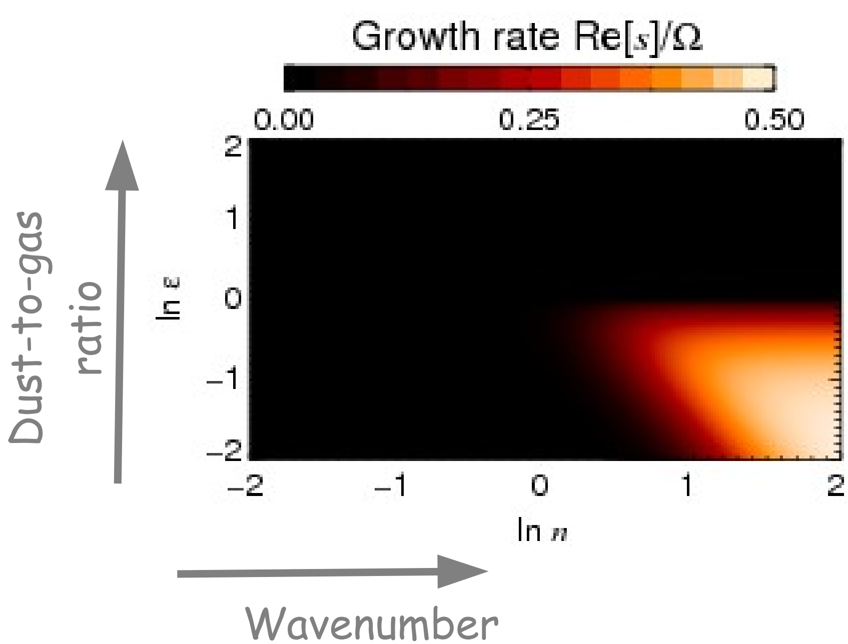
$$\psi' = \hat{\psi}\exp(ikx + st)$$

Dispersion relation

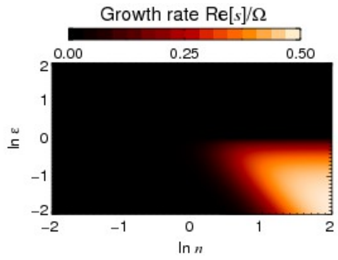
$$A\omega^5 + B\omega^4 + C\omega^3 + D\omega^2 + E\omega + F = 0$$

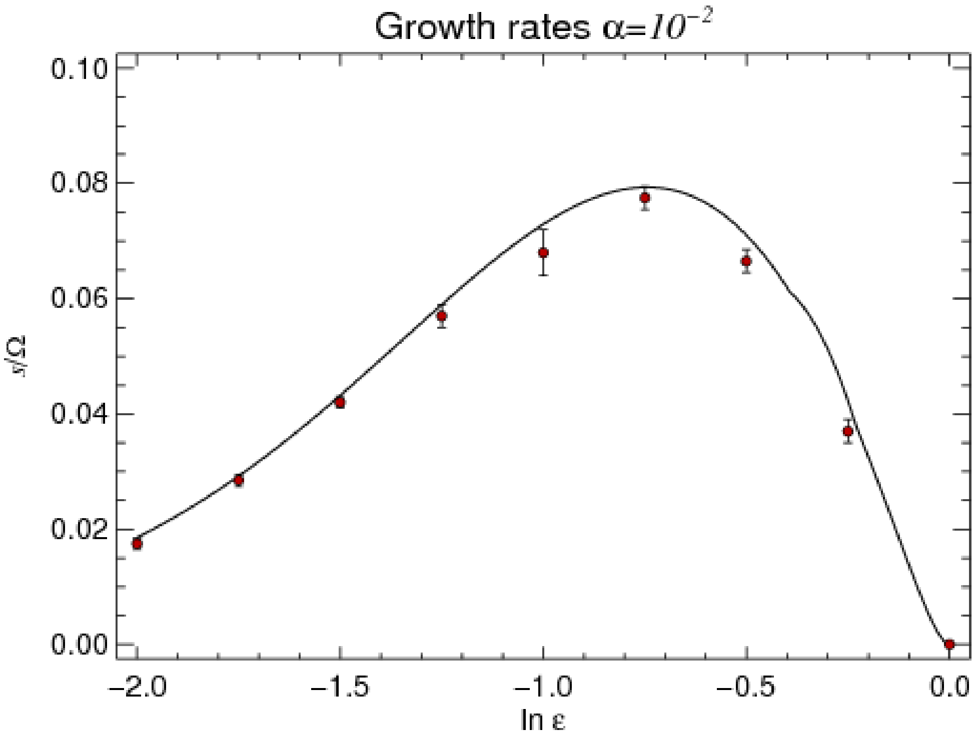
$$A = 1$$
$$B = 2\epsilon + 2$$
$$C = \epsilon^2 + \epsilon(n^2+2) + 3$$
$$D = \epsilon^2 n^2 + \epsilon(3n^2+2) + 2$$
$$E = \epsilon^2(2n^2+1) + \epsilon(3n^2+2) + 2$$
$$F = \epsilon^2 n^2 - \epsilon n^2$$

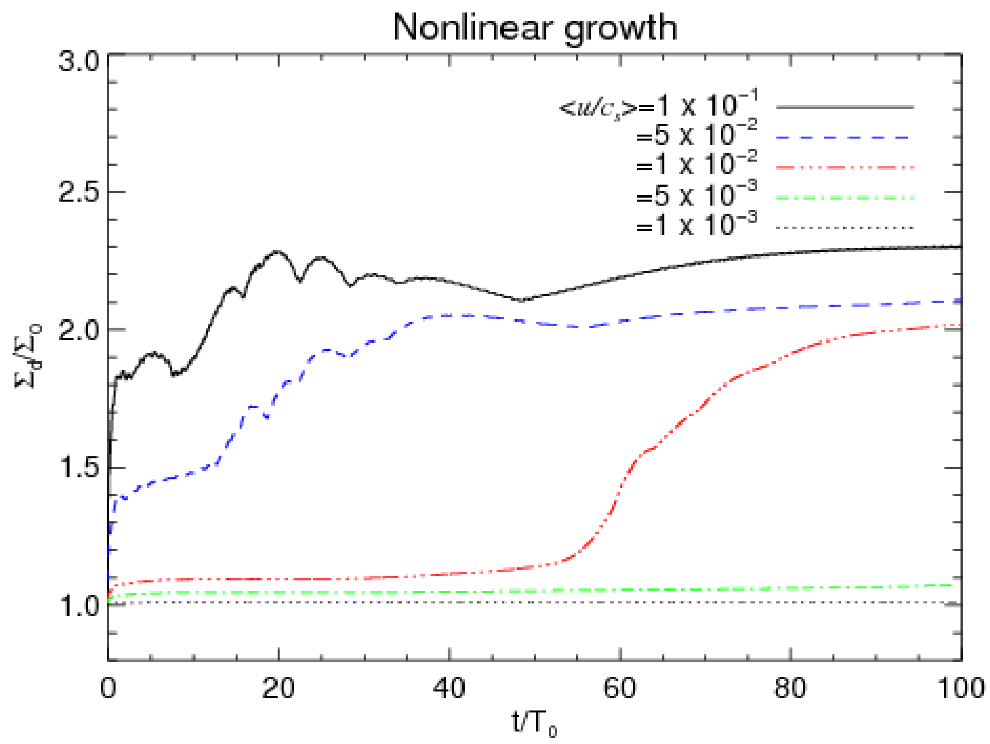
$\epsilon = \Sigma_d / \Sigma_g$ $\quad n = kH$ $\quad \omega = s/\Omega$



Linear and nonlinear growth







Linear growth only exists for $\varepsilon < 1$

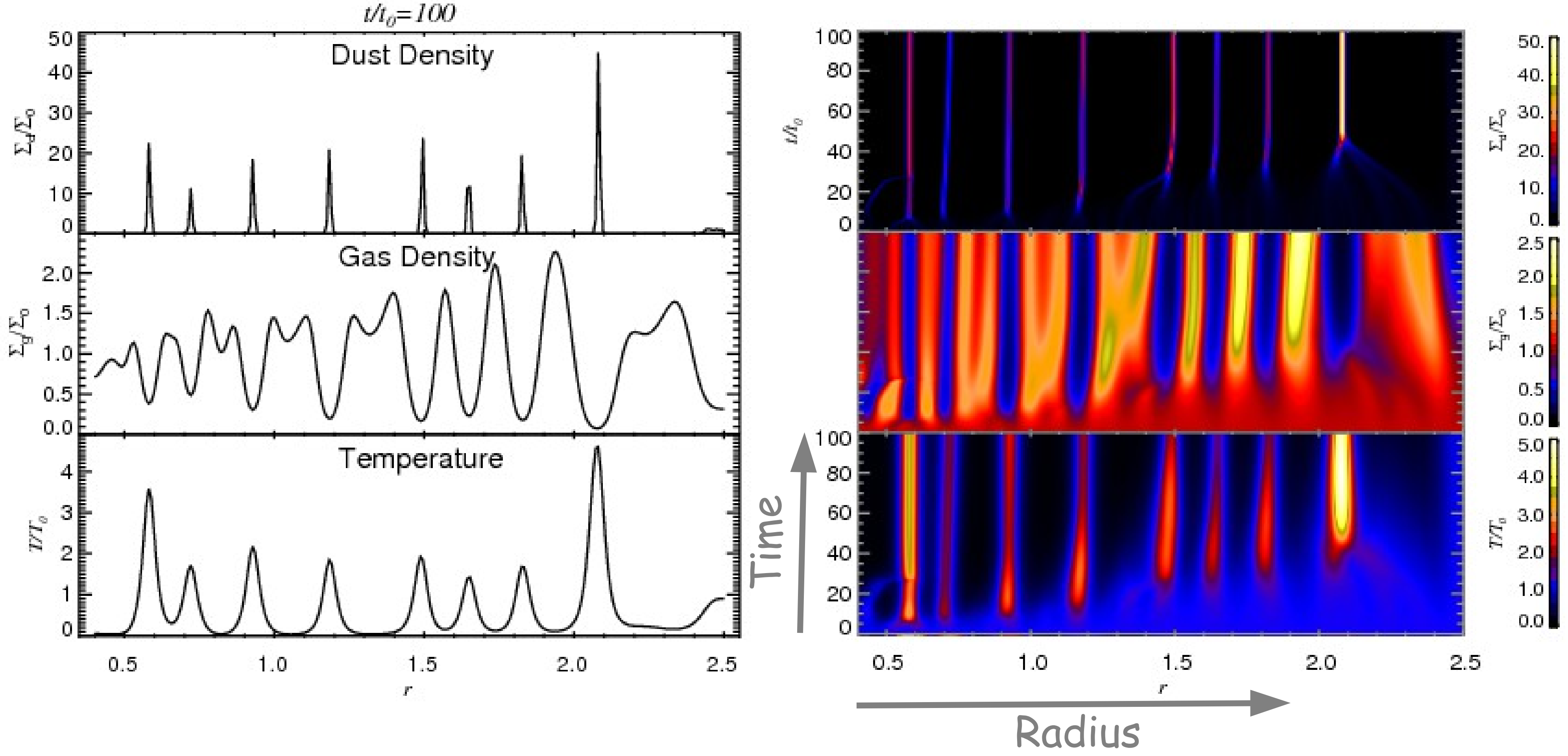
But there is **nonlinear growth** beyond !

Instability

Dust heats gas

Heated gas = high pressure region

High pressure concentrates dust

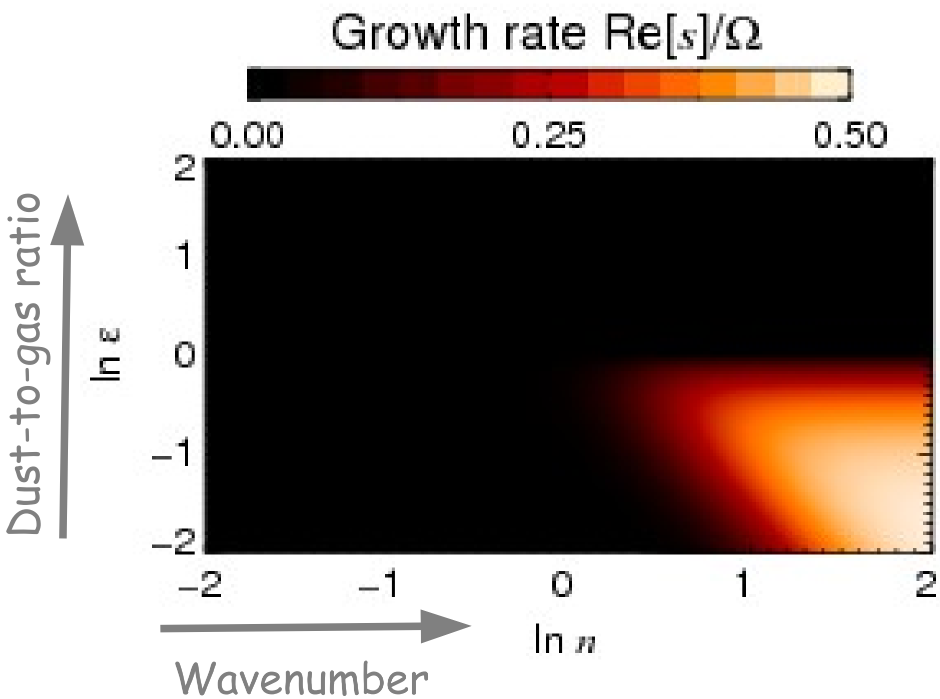


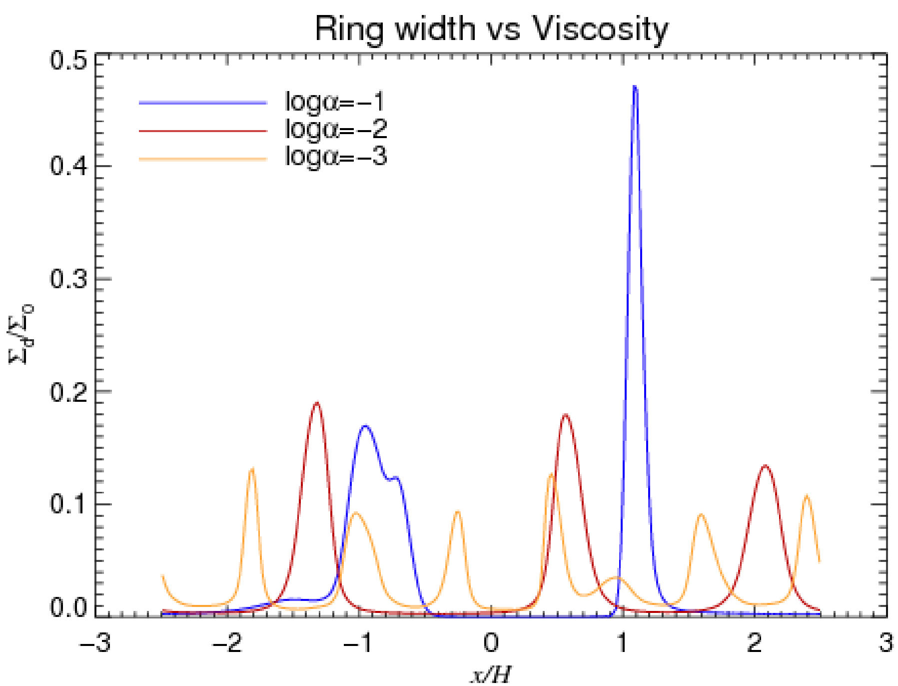
Narrow hot dust rings

Cold gas collects between rings

Ring width

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



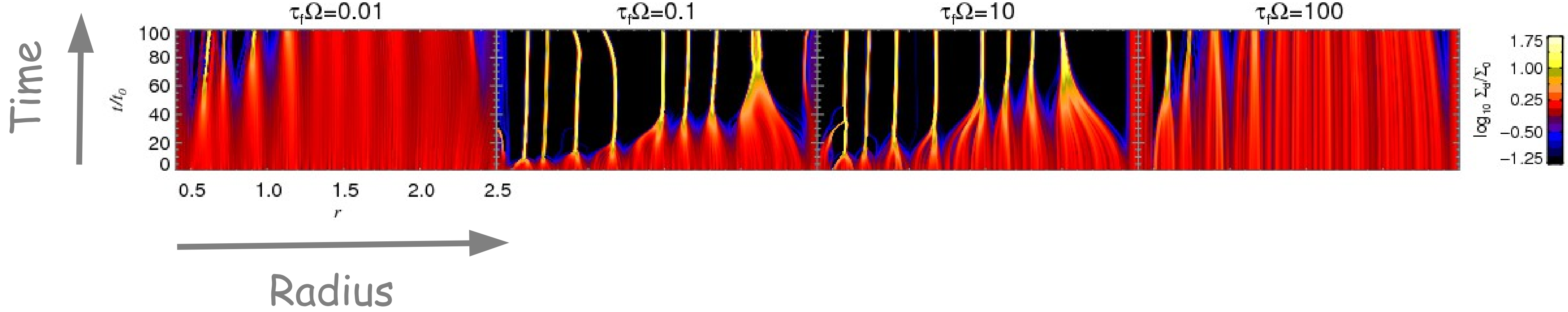


Which in turn is determined by viscosity

Ring width ~ 10 Kolmogorov lengths

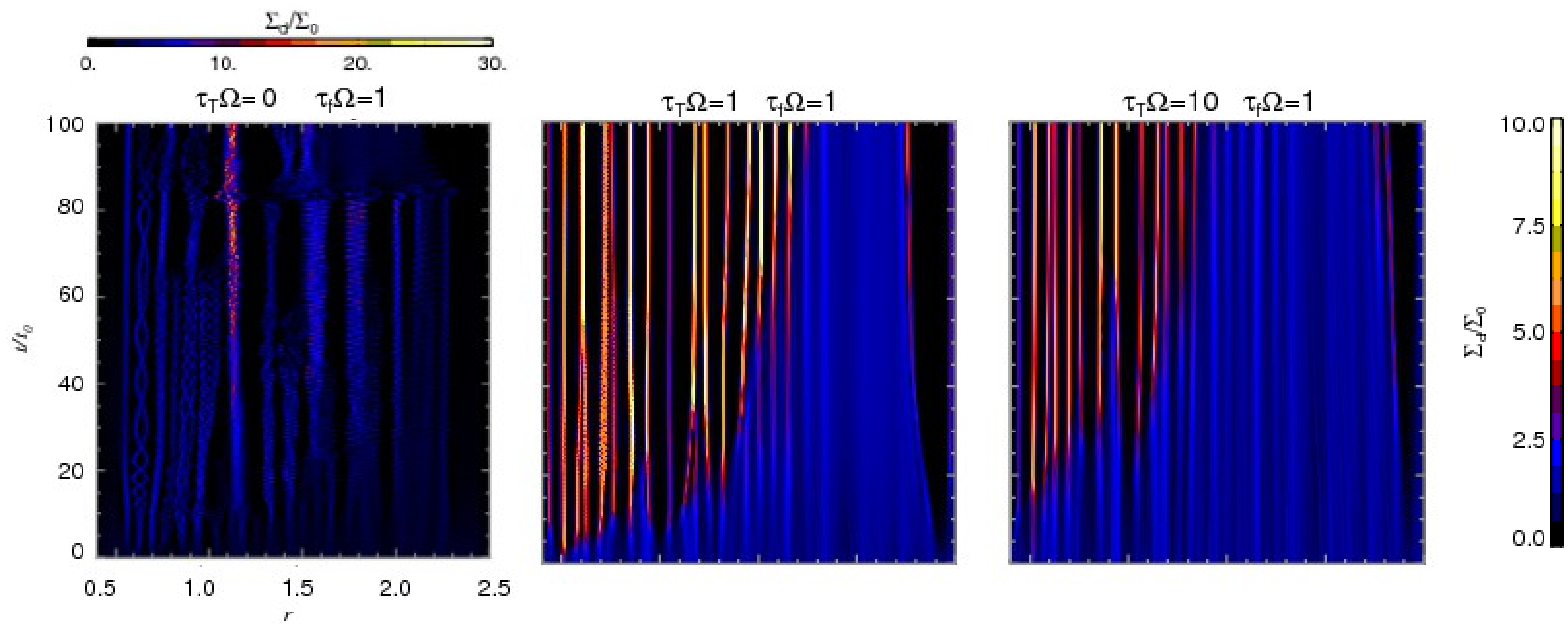
Robustness

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



Oscillations

Thermal coupling time



Oscillations

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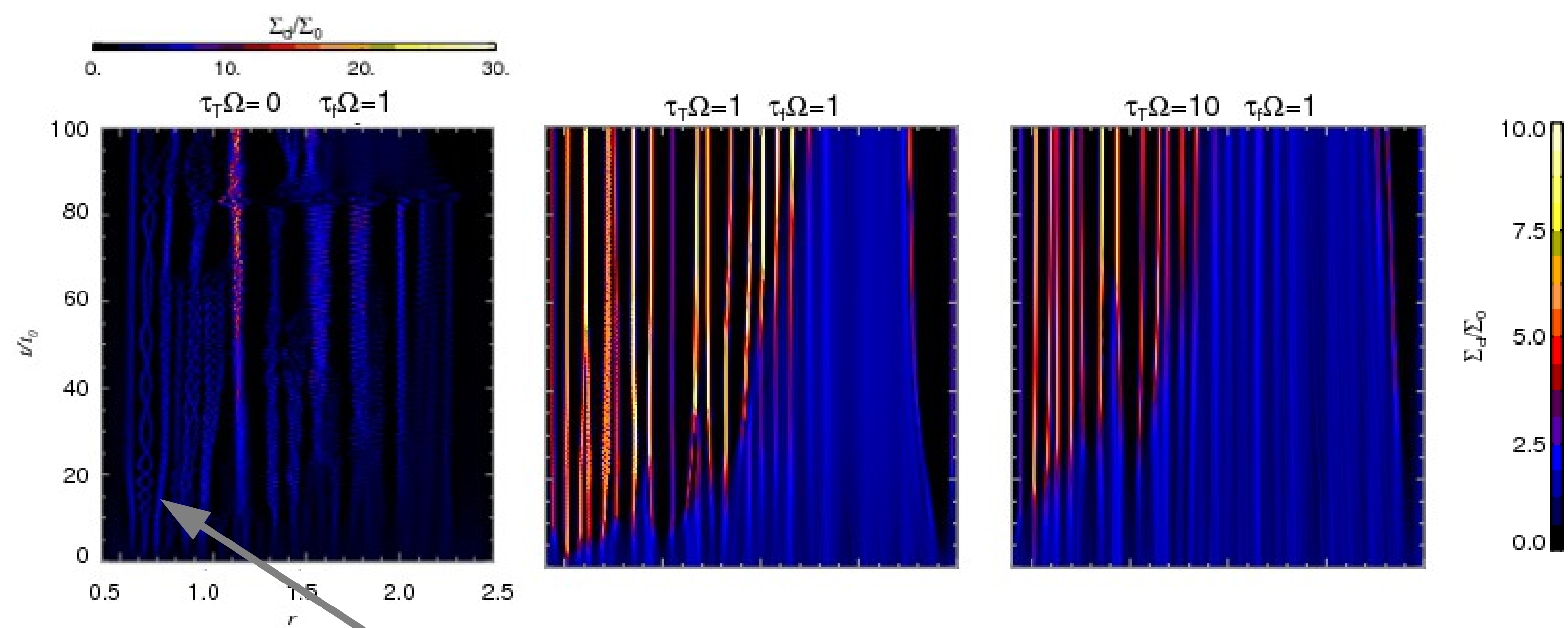
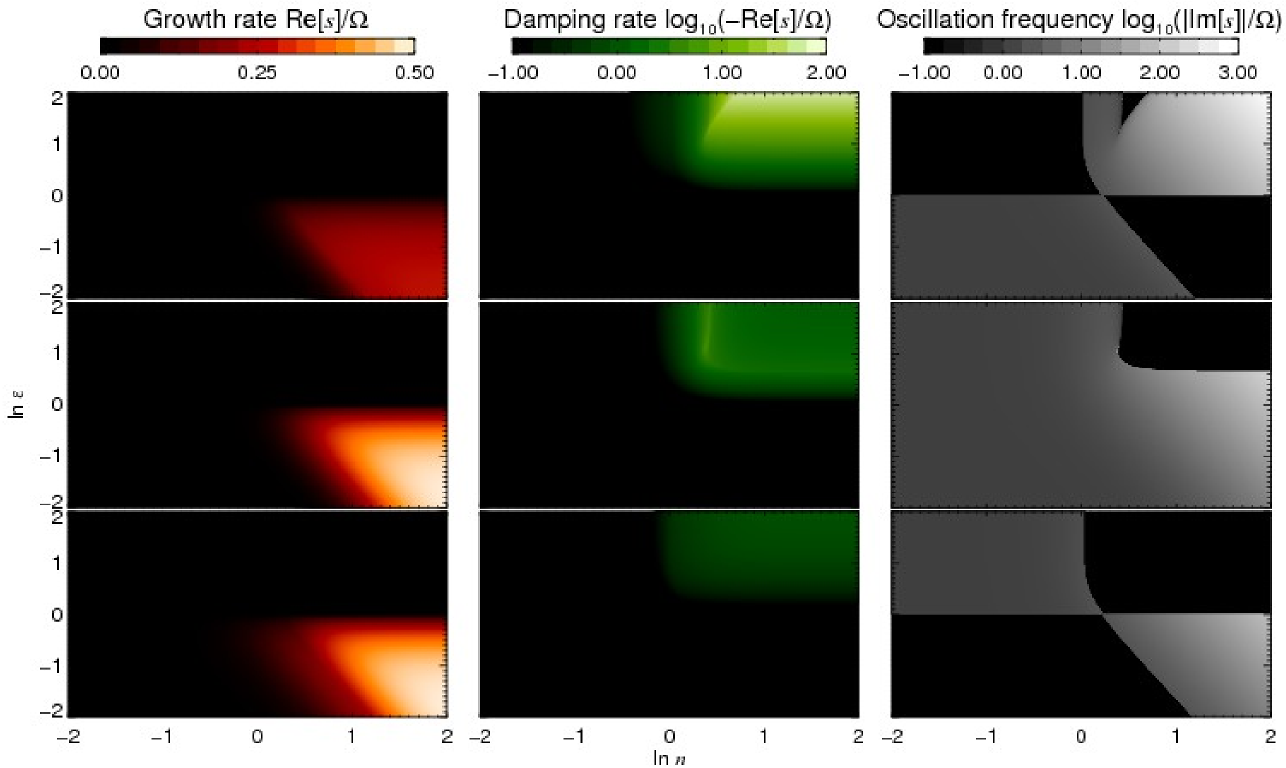


Oscillations appear
with decreasing thermal time.

Solutions



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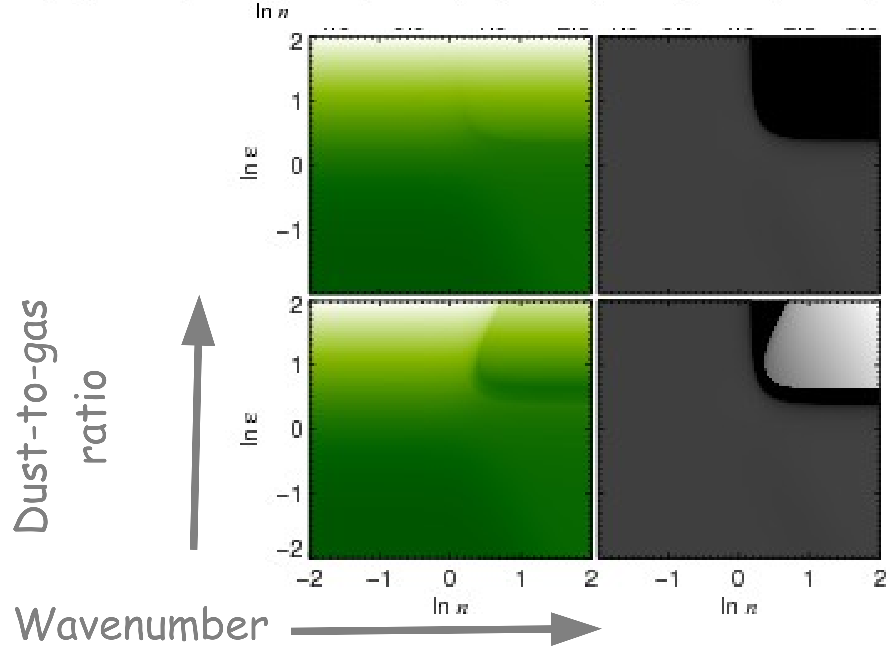
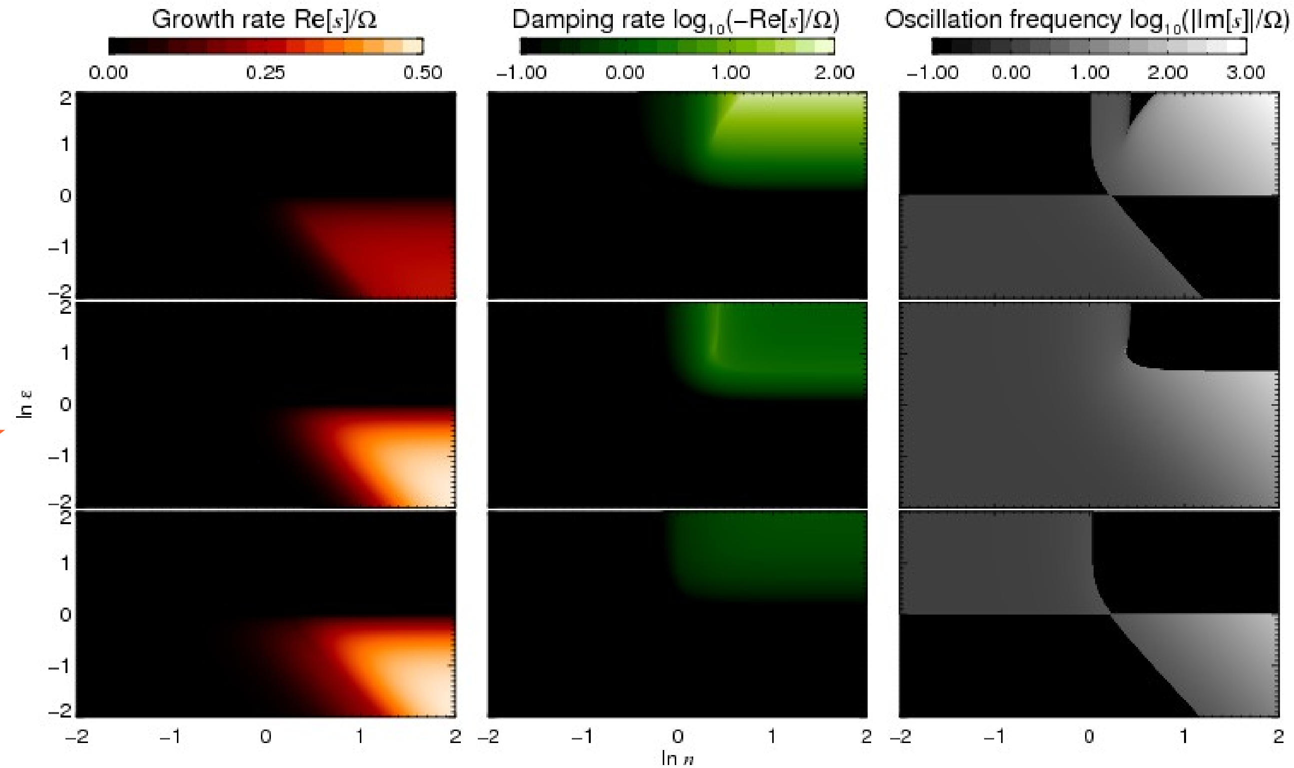


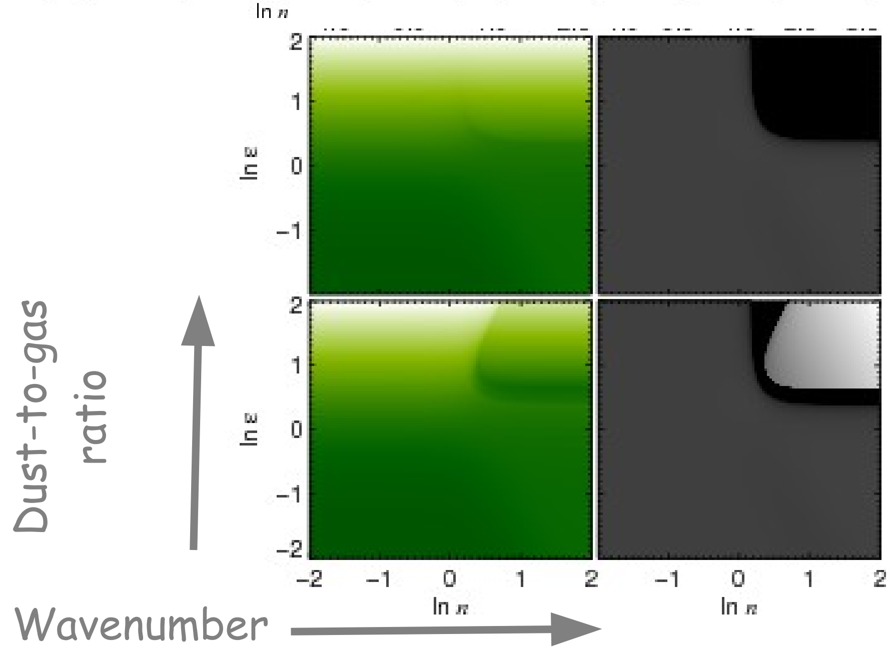
Solutions

Instability

Overstability



Damped and free Oscillations



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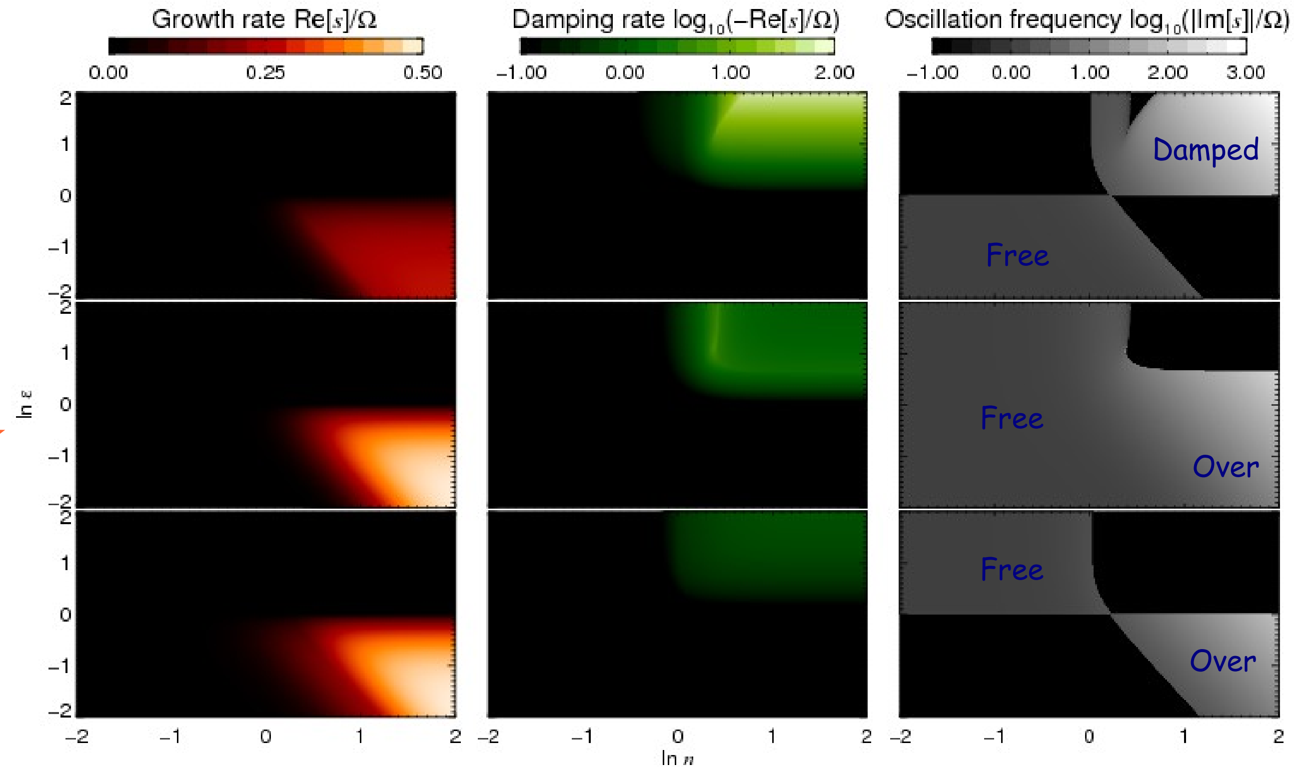

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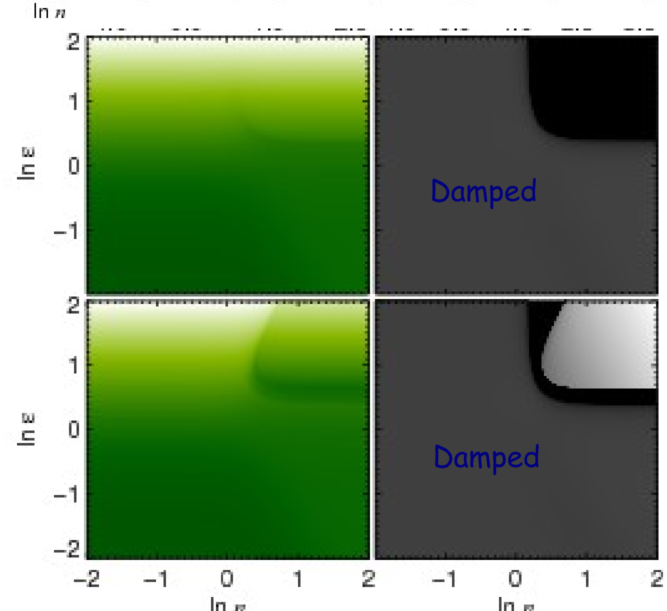
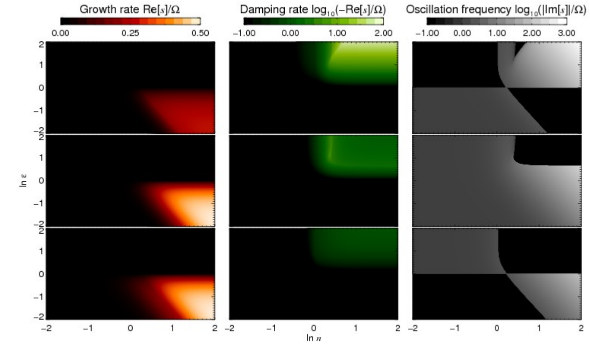
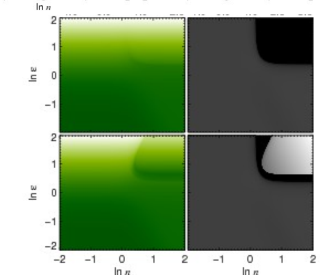
Dust-to-gas ratio



Wavenumber

Solutions

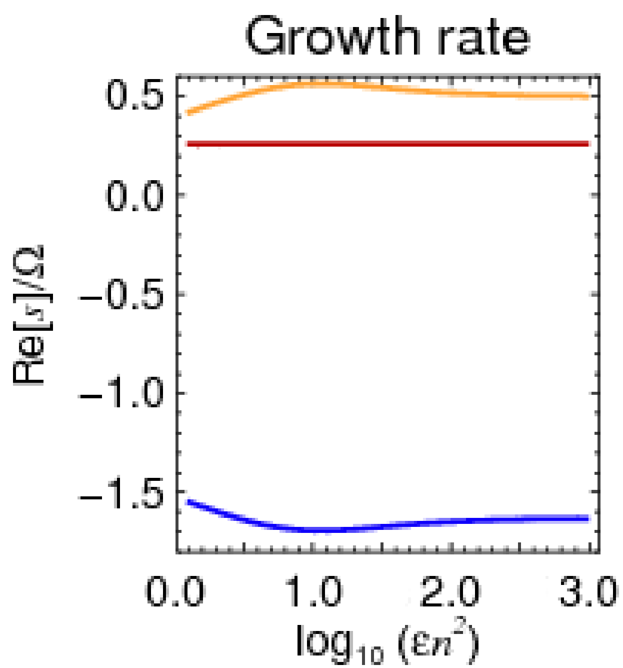


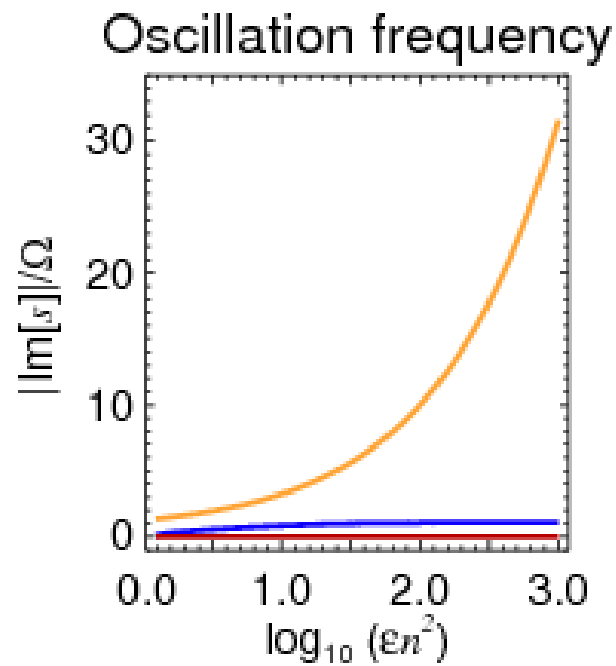


Overstability

Instability

Oscillations





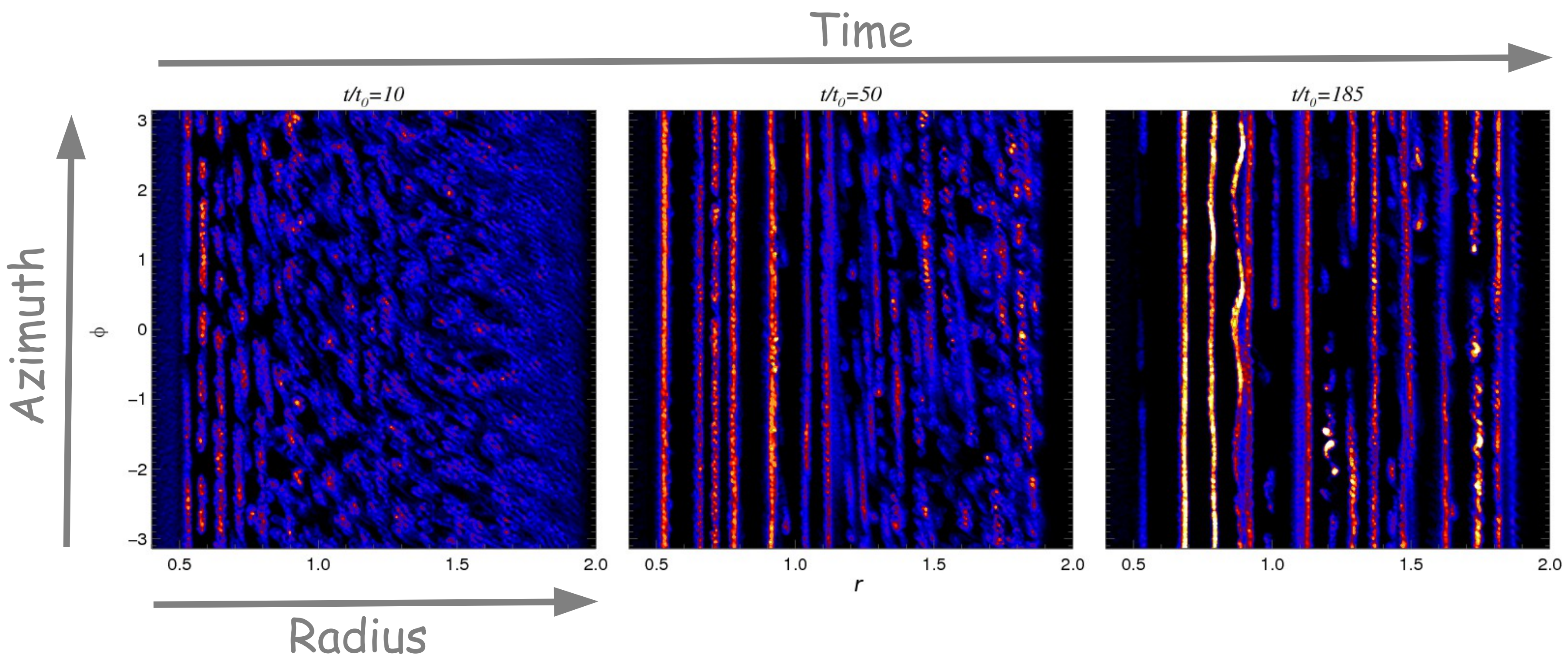
Max growth rate: $\Omega/2$.

Million-fold amplification in five orbits!

A very powerful instability.

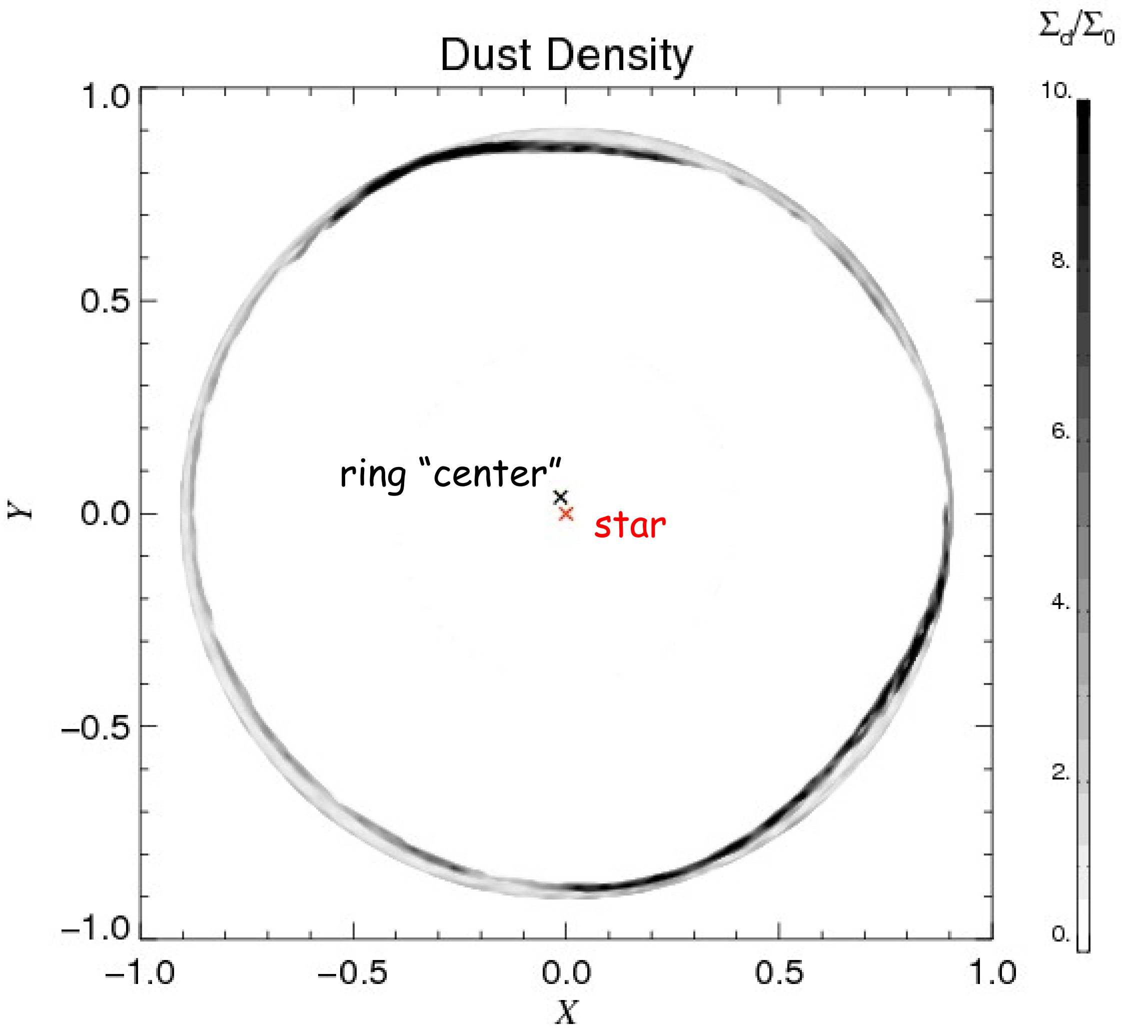
The model in 2D: Eccentric rings

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

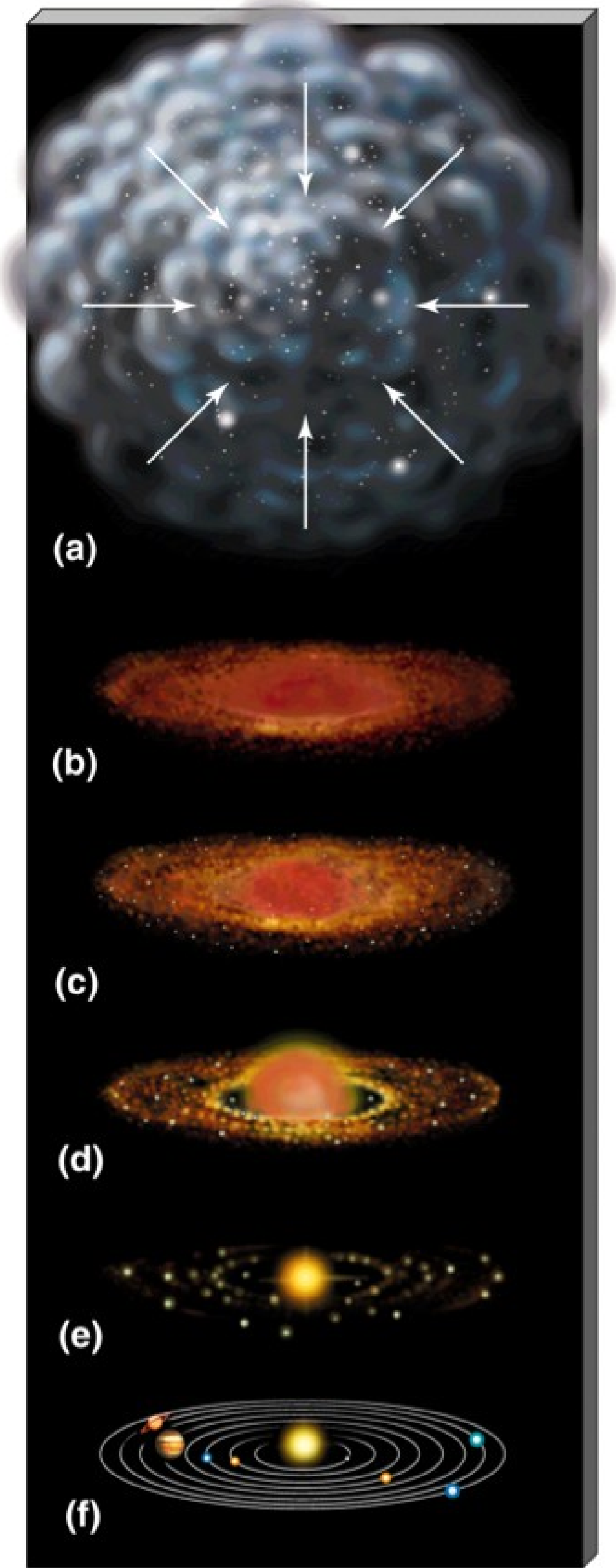


Epicyclic oscillations
make the ring appear ***eccentric !!!***

Ring eccentricity



Eccentricity e=0.04



Summarizing

Gravitational collapse of an interstellar cloud

Outward transport of angular momentum through turbulence generated by the MRI. Dust coagulates into pebbles and boulders, sedimenting towards the midplane.

Rocks in the turbulent medium are trapped in transient pressure maxima and undergo collapse into planetesimals and dwarf planets.

Vortices may be excited in the dead zone. Inside them, the first dozens of Mars-mass embryos are formed. IMF ~ -2

Opacity transitions develop into regions of convergent migration. Low mass planets converge to these zones by inward/outward migration.

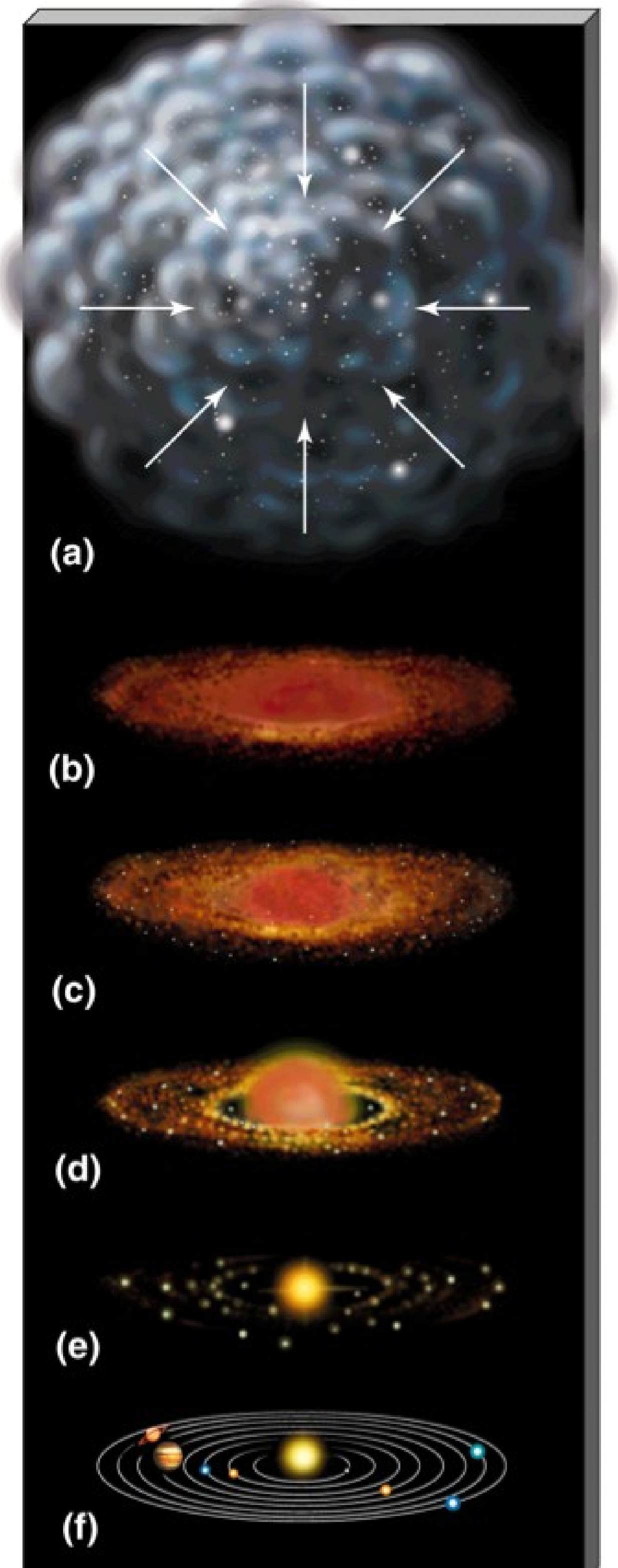
Convergent migration leads to resonances, these are disrupted by turbulent forcing. Collisions between embryos gives rise to oligarchs.

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

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

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

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



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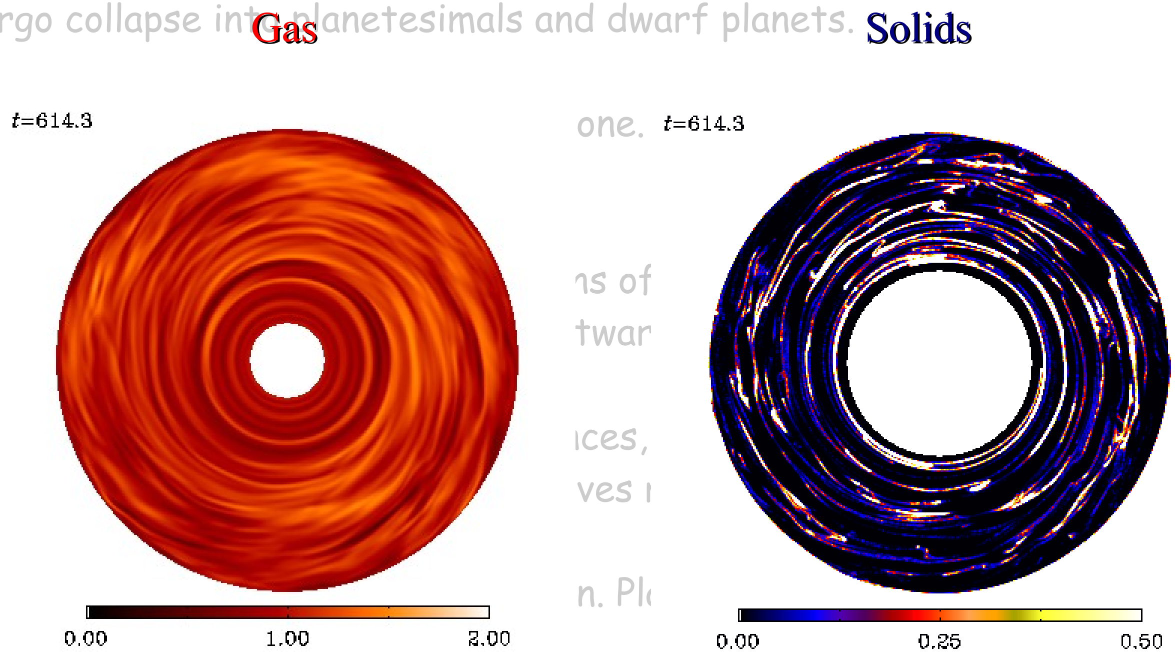

Vort[…] one. […] Mars-mass[…]

Opac[…]ns of […] planets conve[…]twar[…]

Conv[…]ces, forci[…]ves […]

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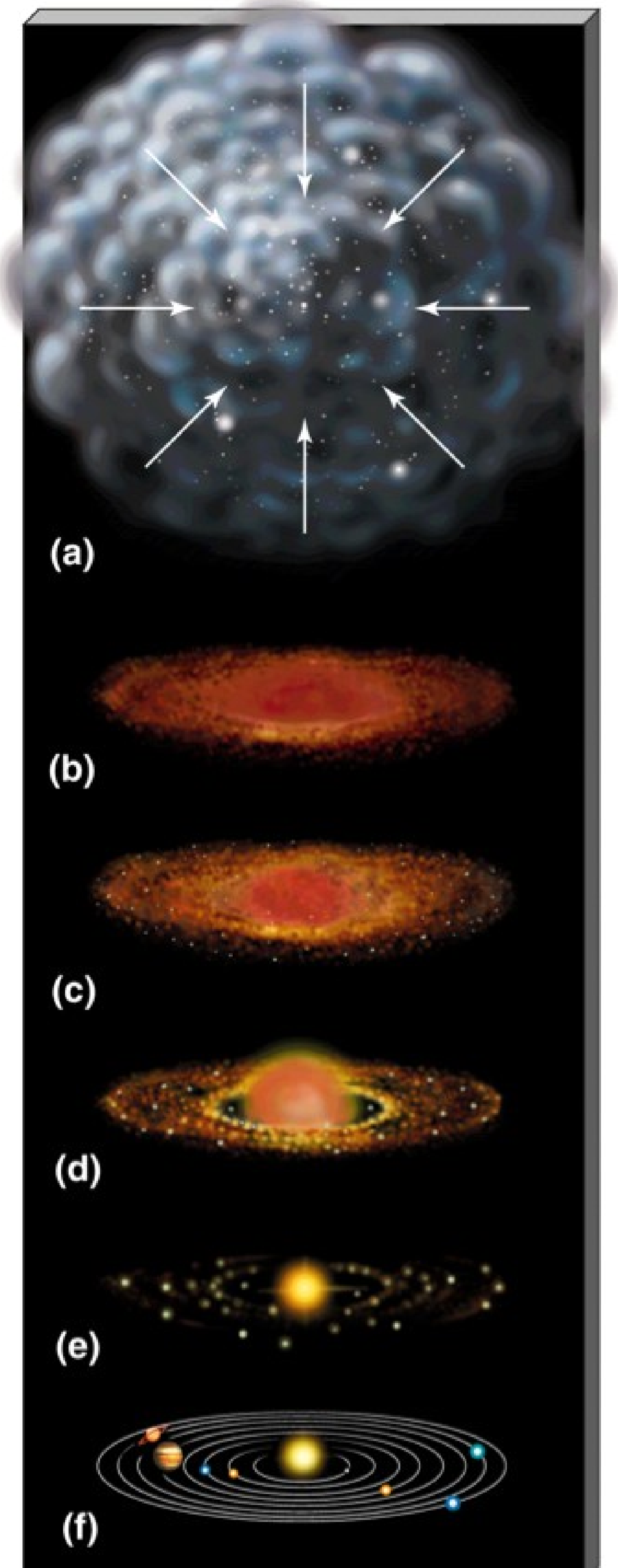

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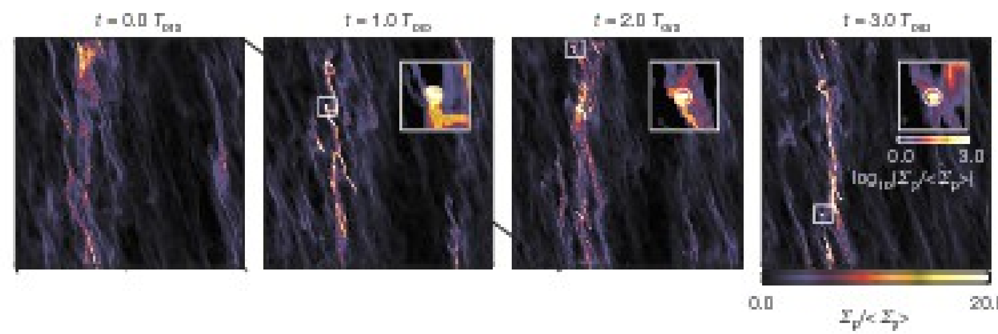

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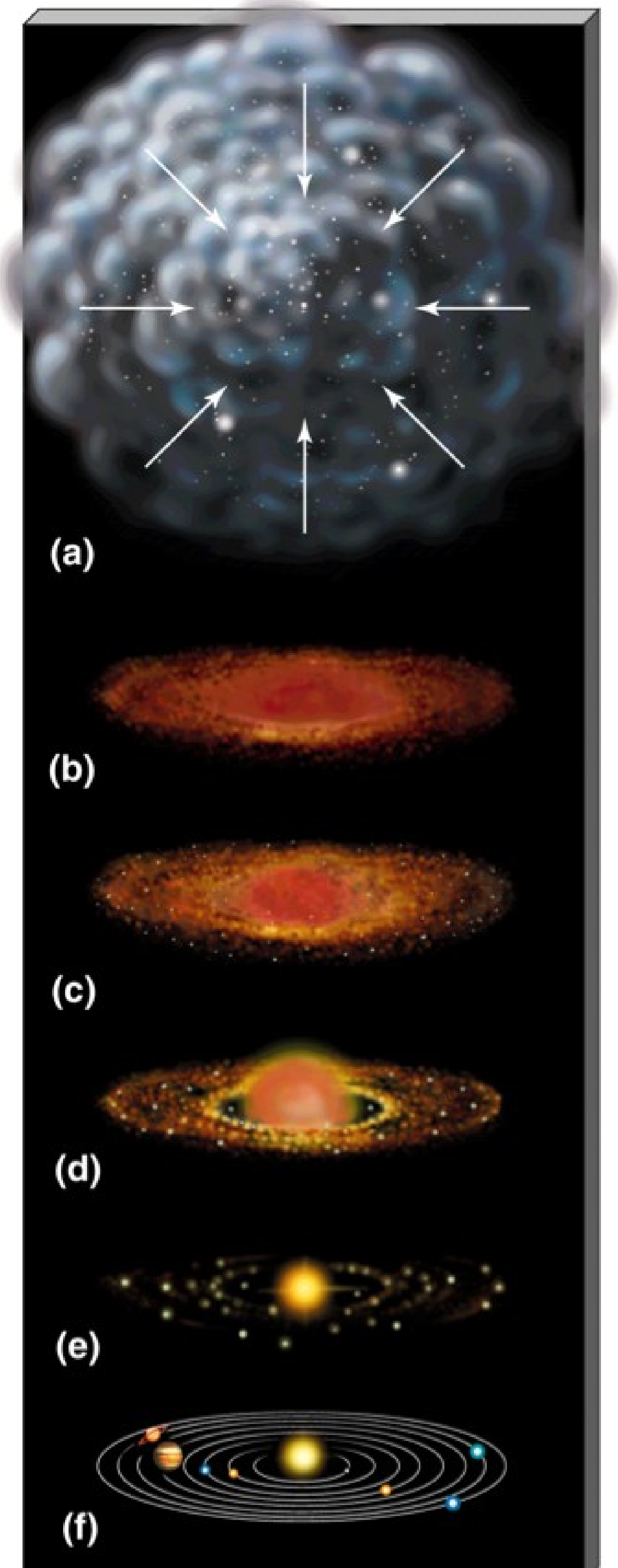

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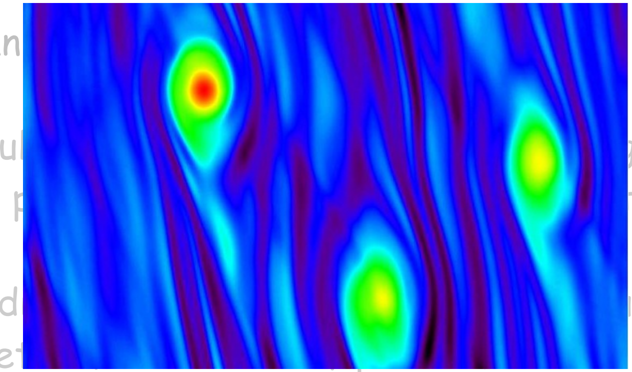

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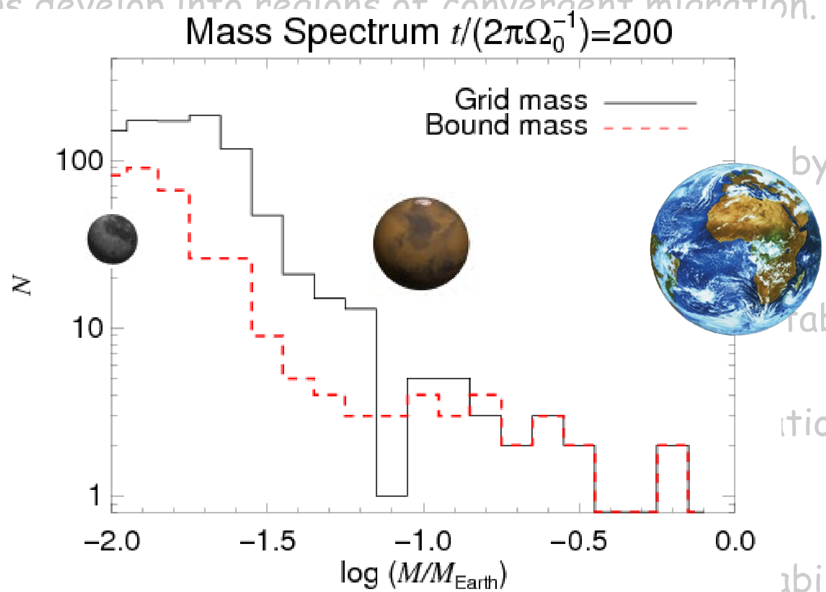

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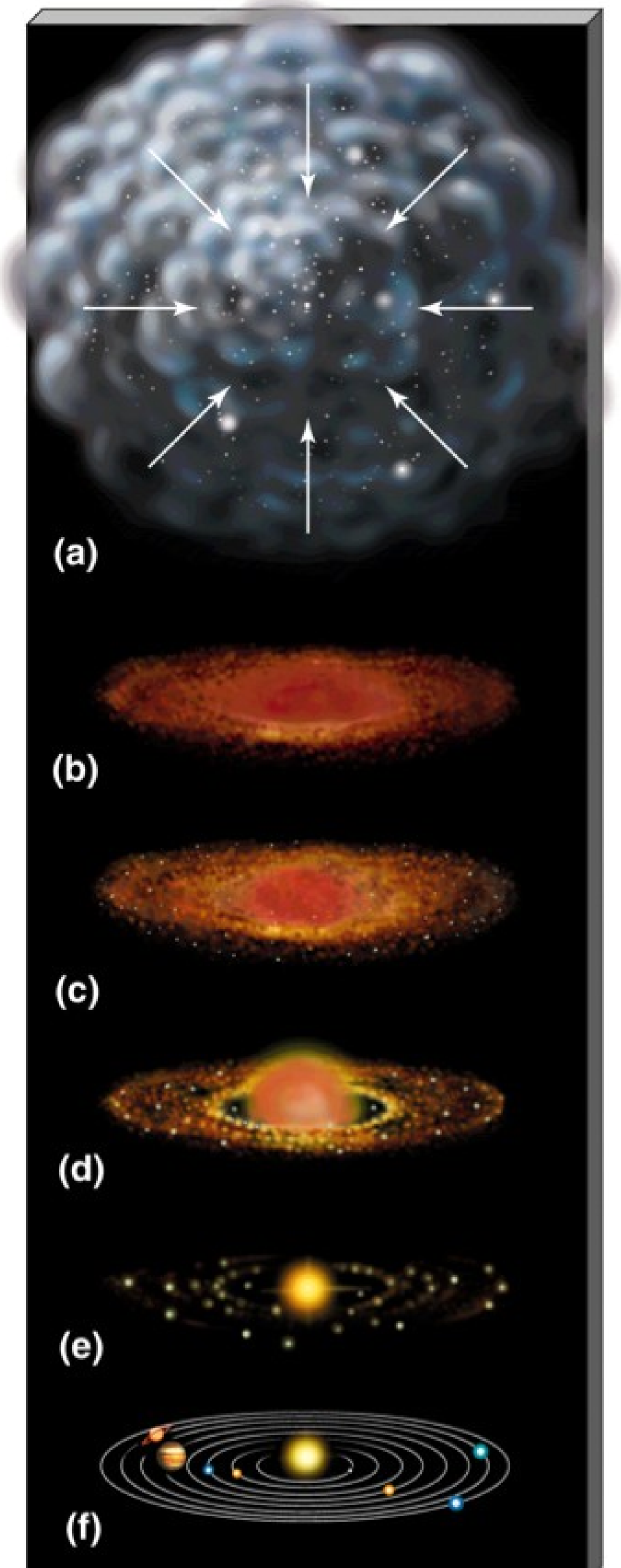

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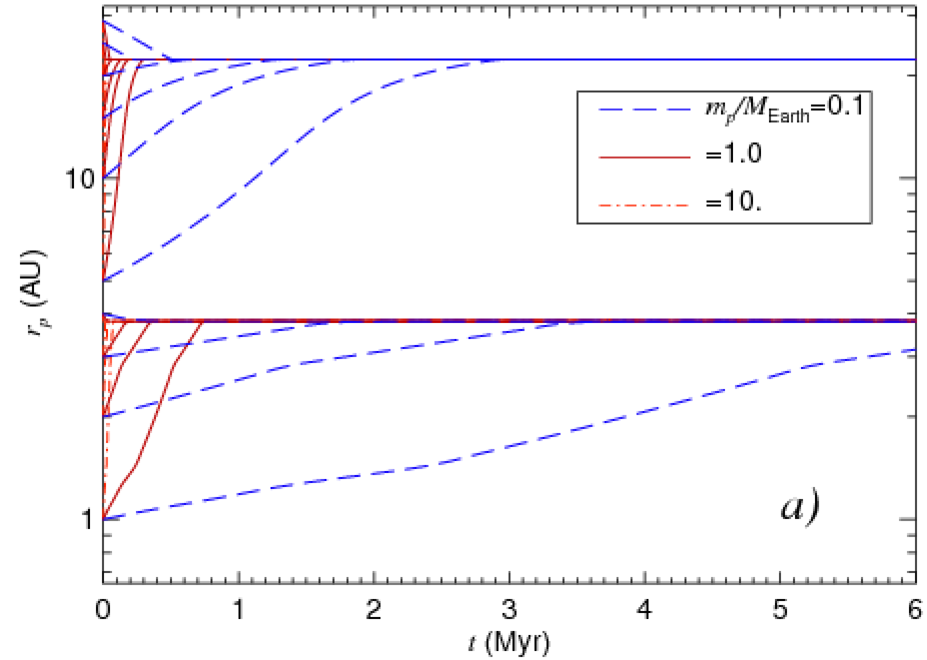

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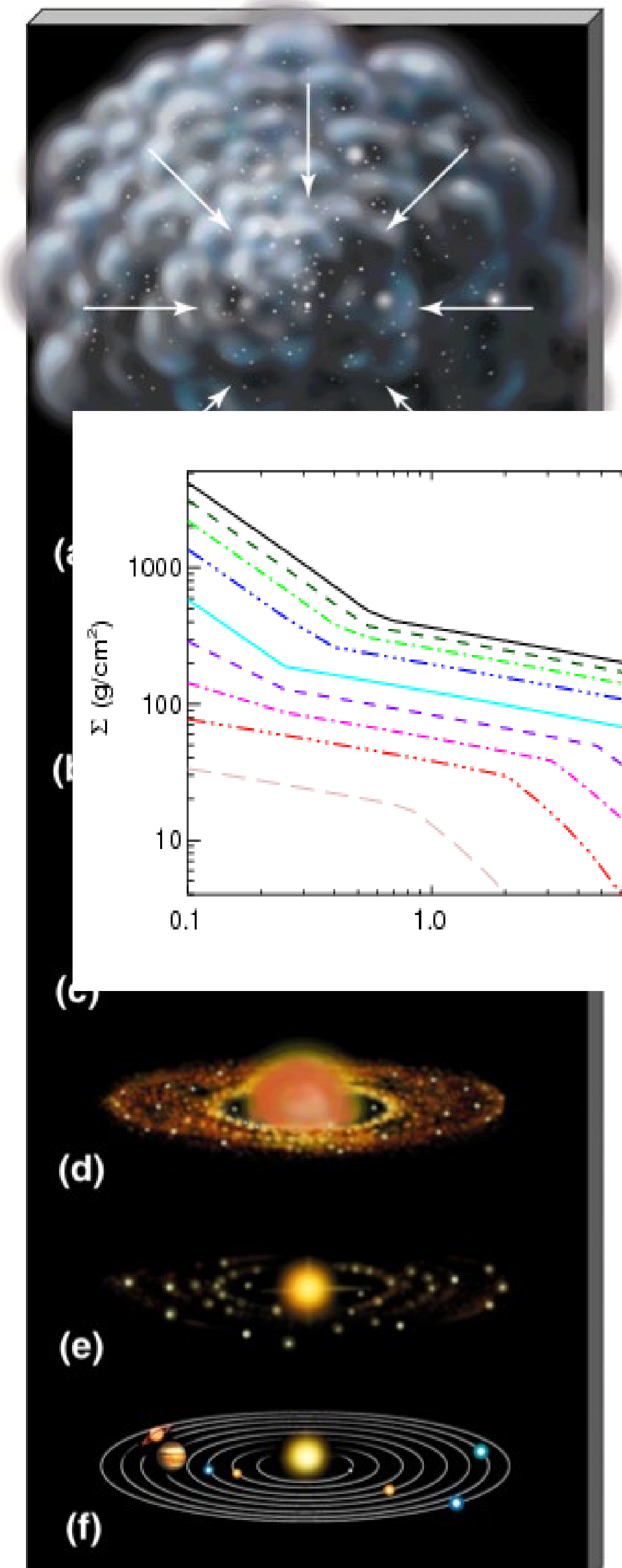

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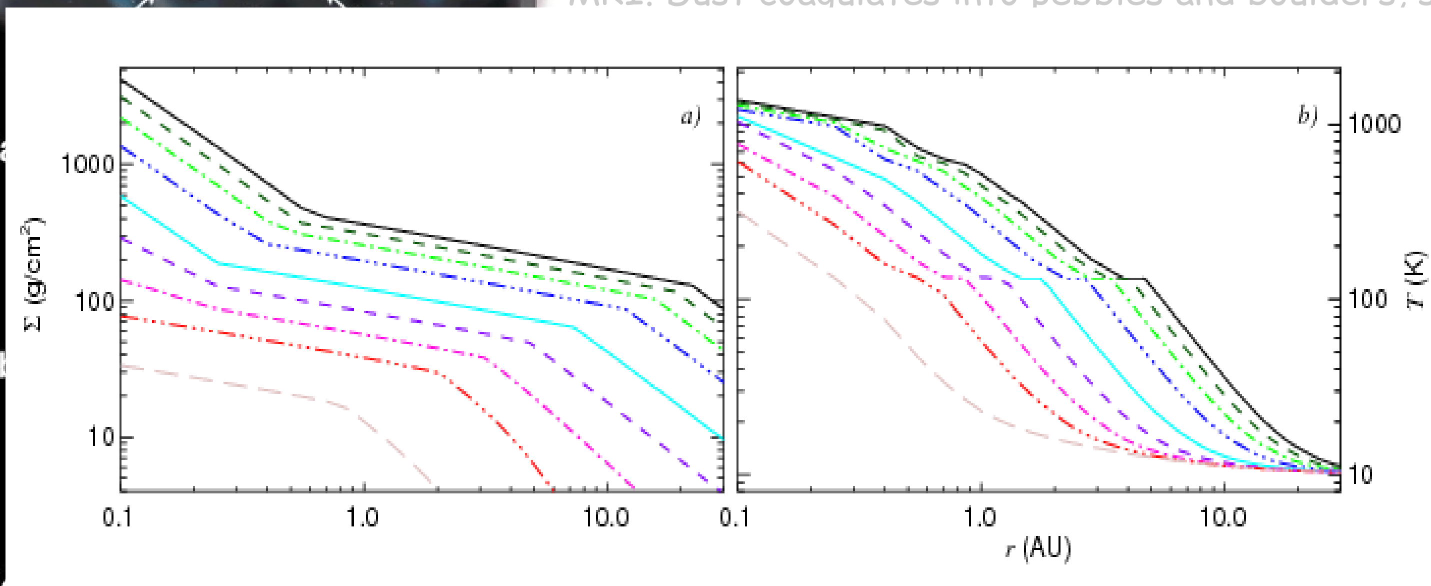

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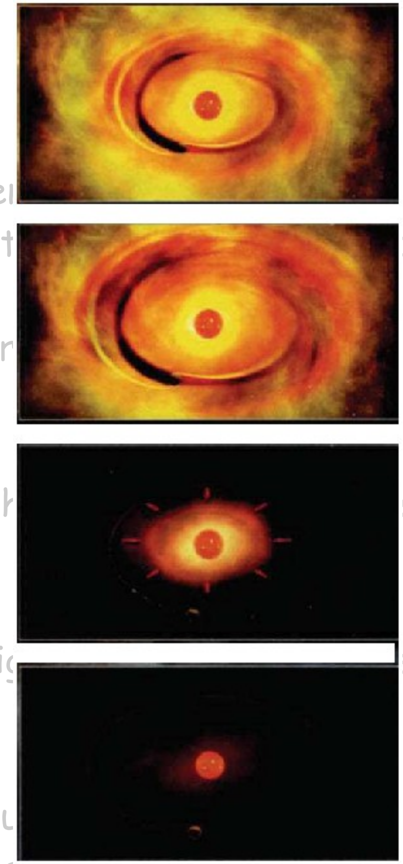

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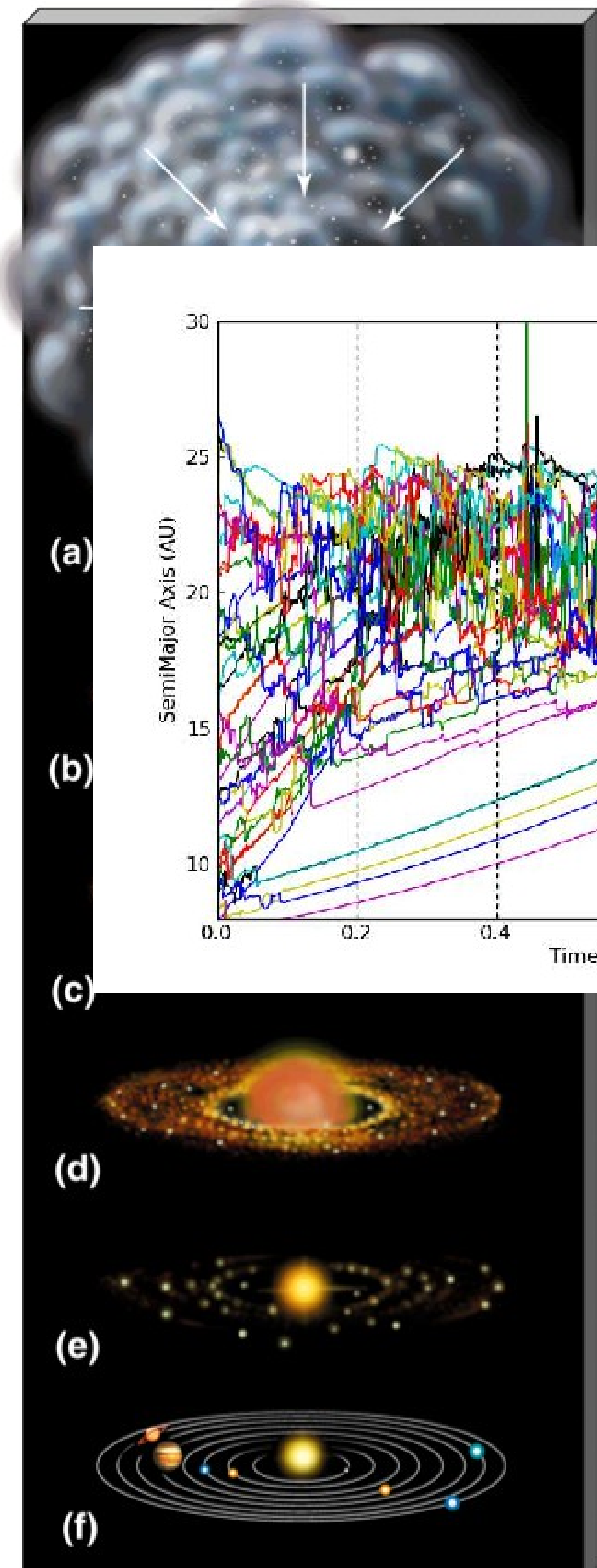

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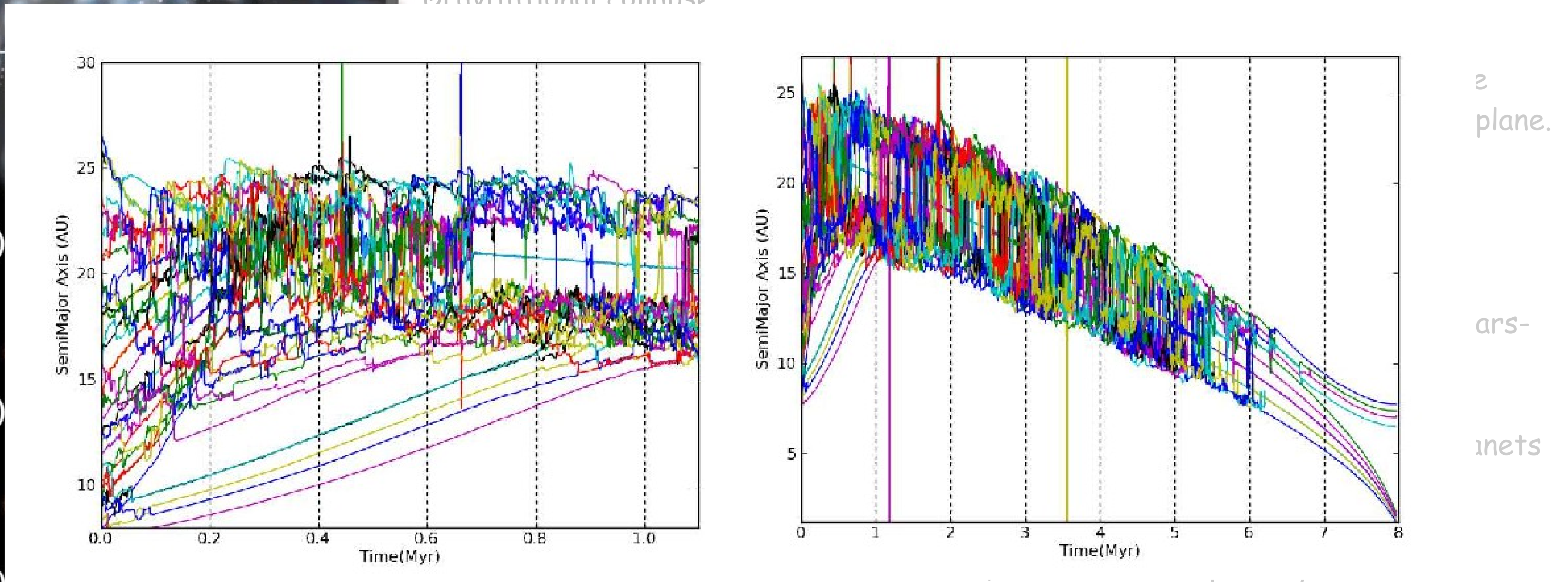

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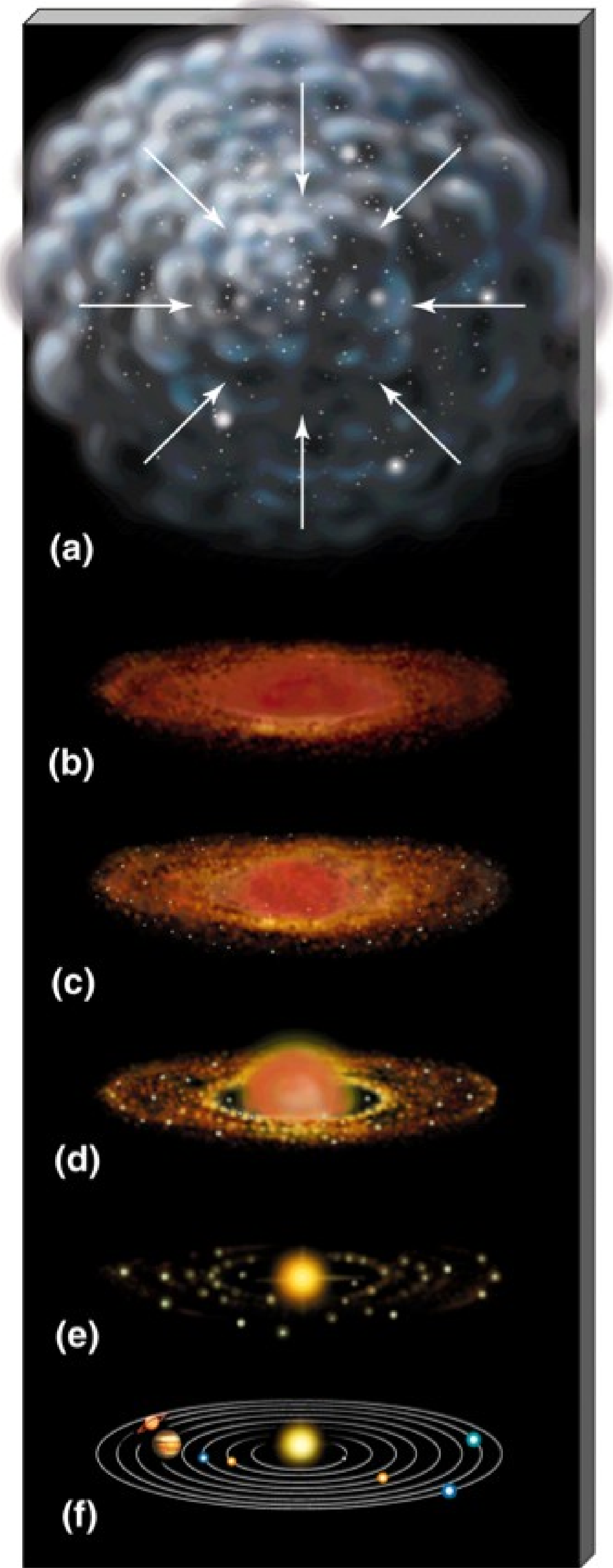

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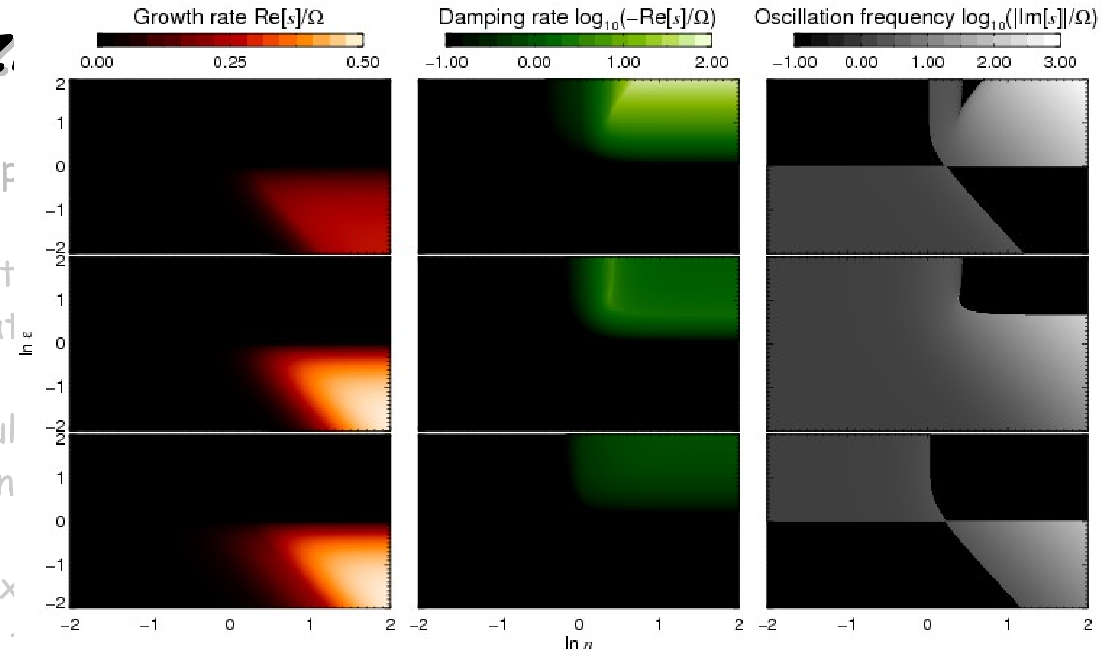

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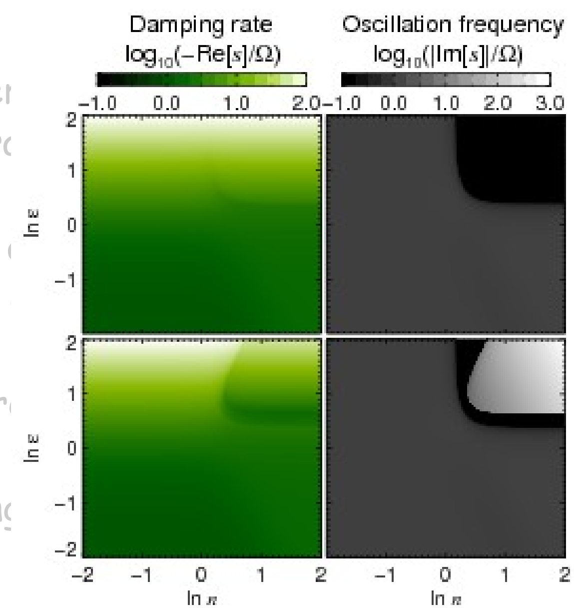

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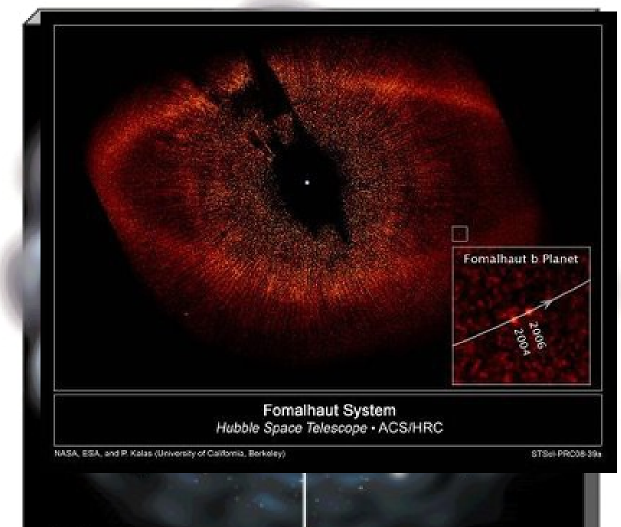

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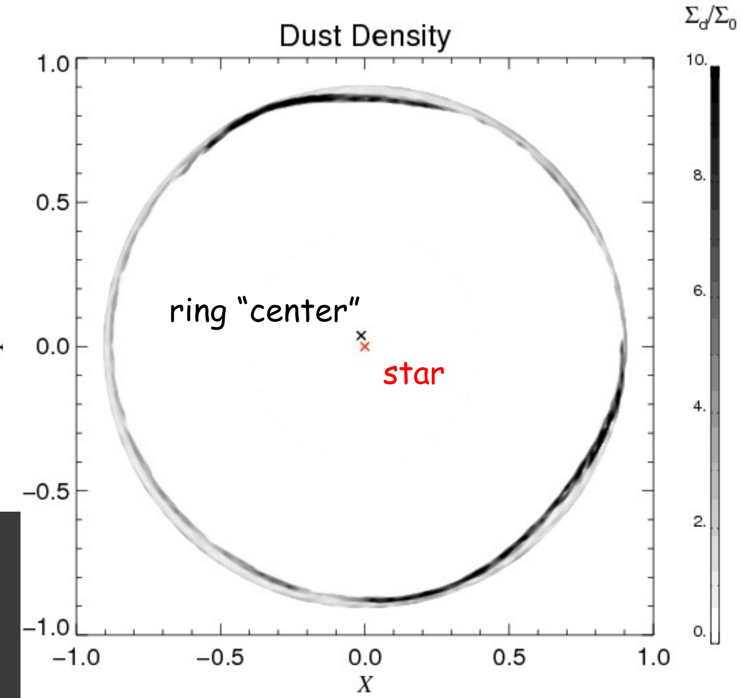

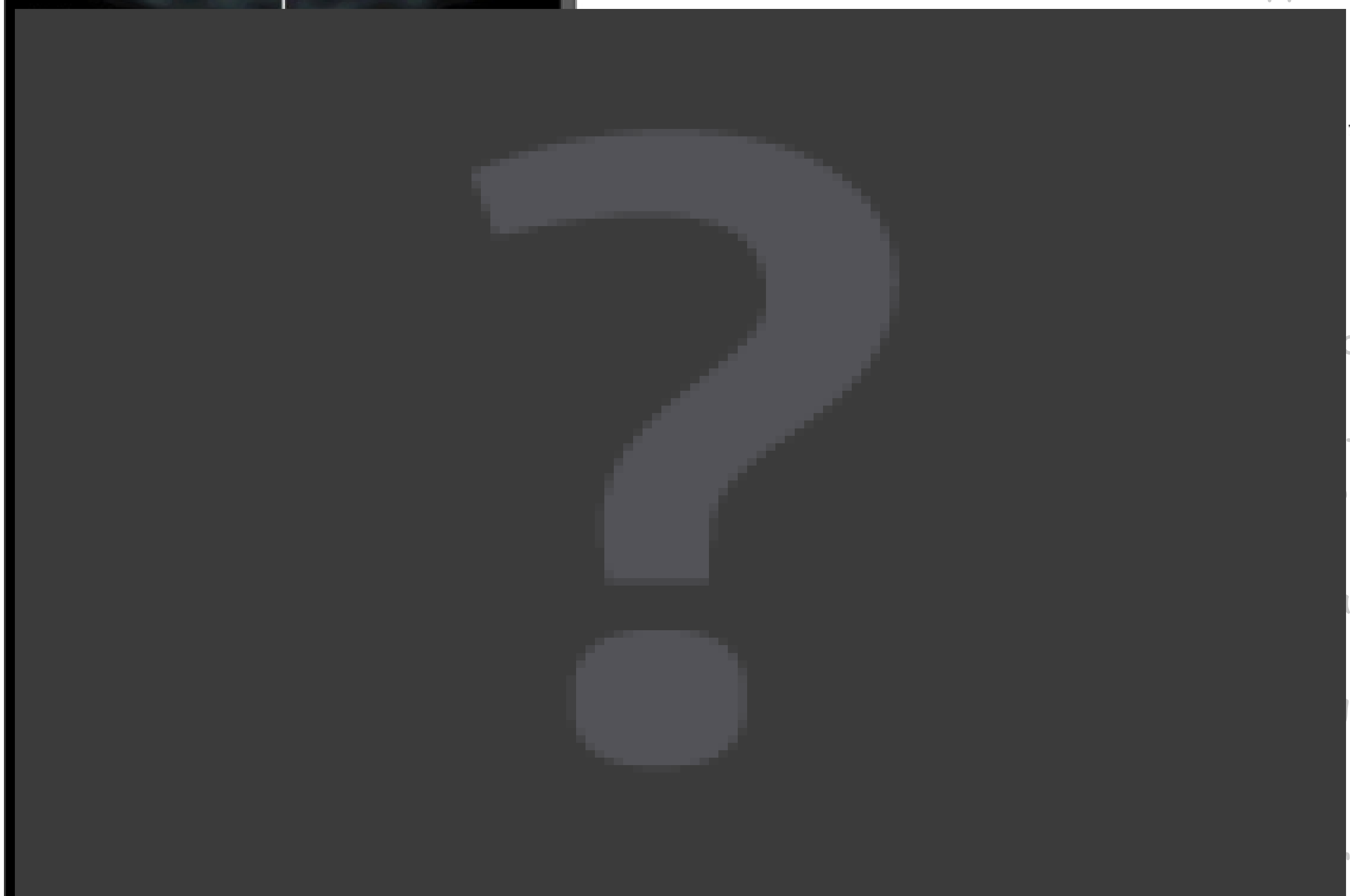

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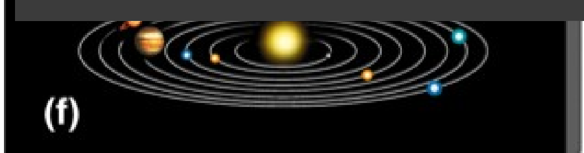

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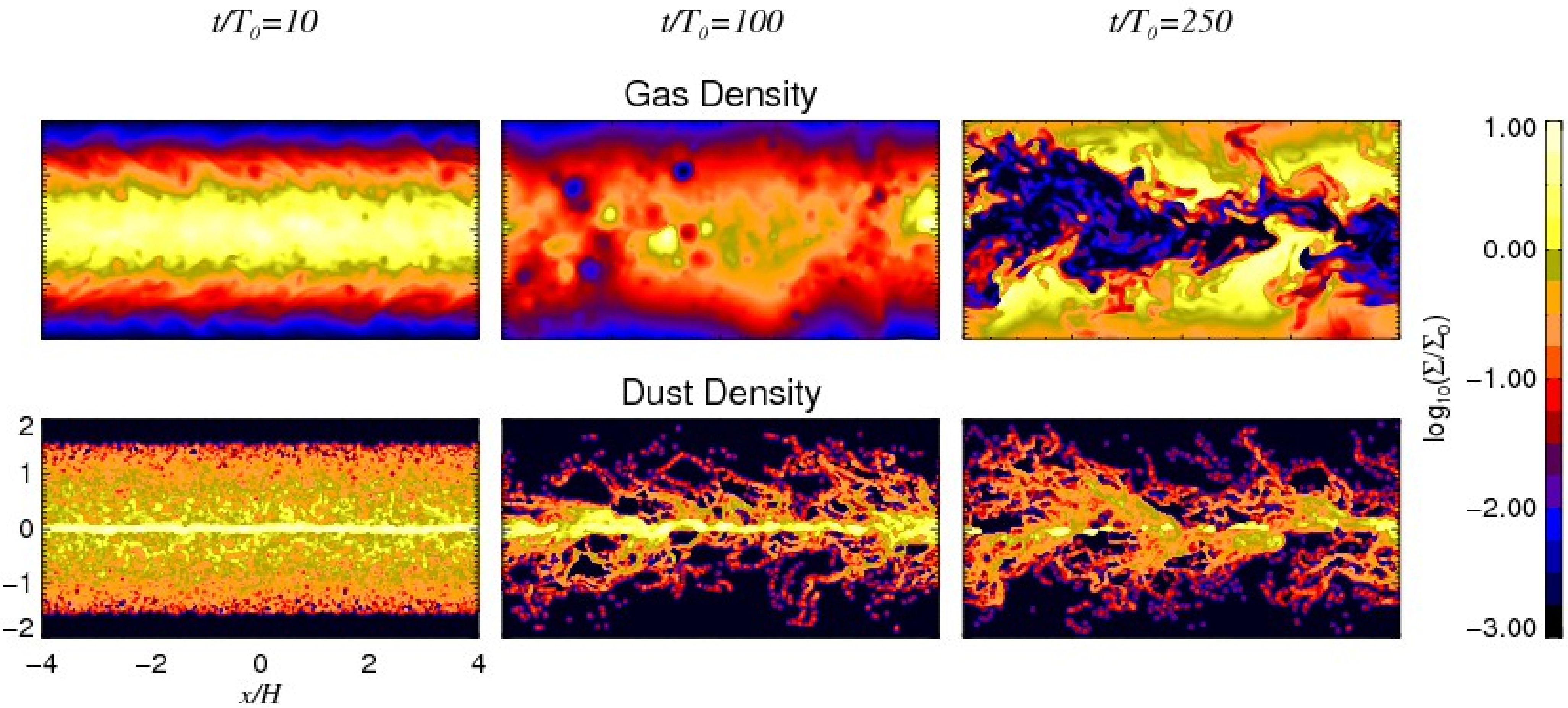

t/T0=10
t/T0=100
t/T0=250
Gas Density
Dust Density
2
1
0
−1
−2
z/H
−4
−2
0
2
4
x/H
1.00
0.00
−1.00
−2.00
−3.00
log10(Σ/Σ0)