The Formation and orbital Evolution of Planets

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DFG
Research Group
Planet Formation

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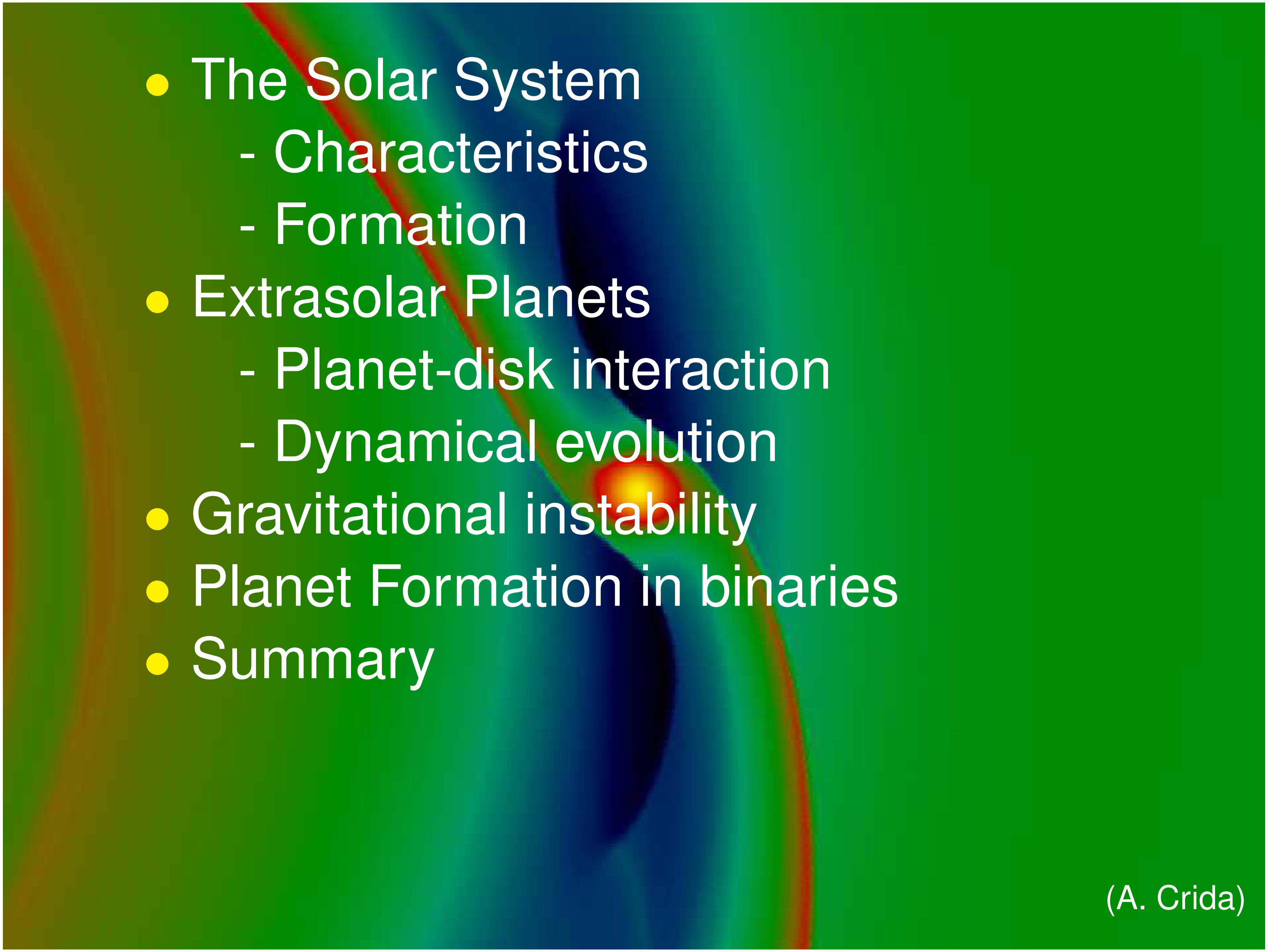
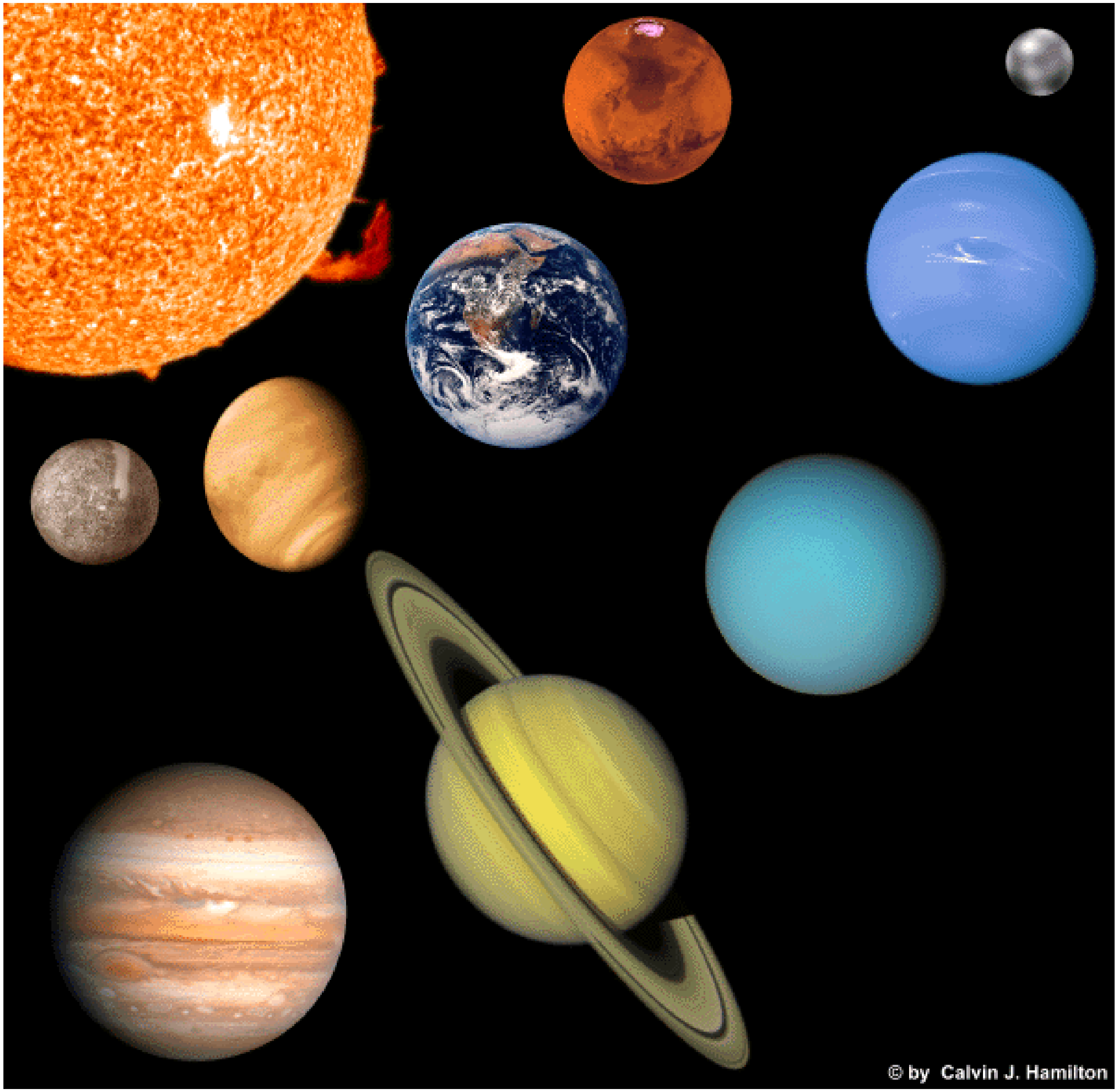
Organisation



- The Solar System
  - Characteristics
  - Formation
- Extrasolar Planets
  - Planet-disk interaction
  - Dynamical evolution
- Gravitational instability
- Planet Formation in binaries
- Summary

(A. Crida)

The Planets



© by Calvin J. Hamilton

Sun

Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptun

(Pluto)

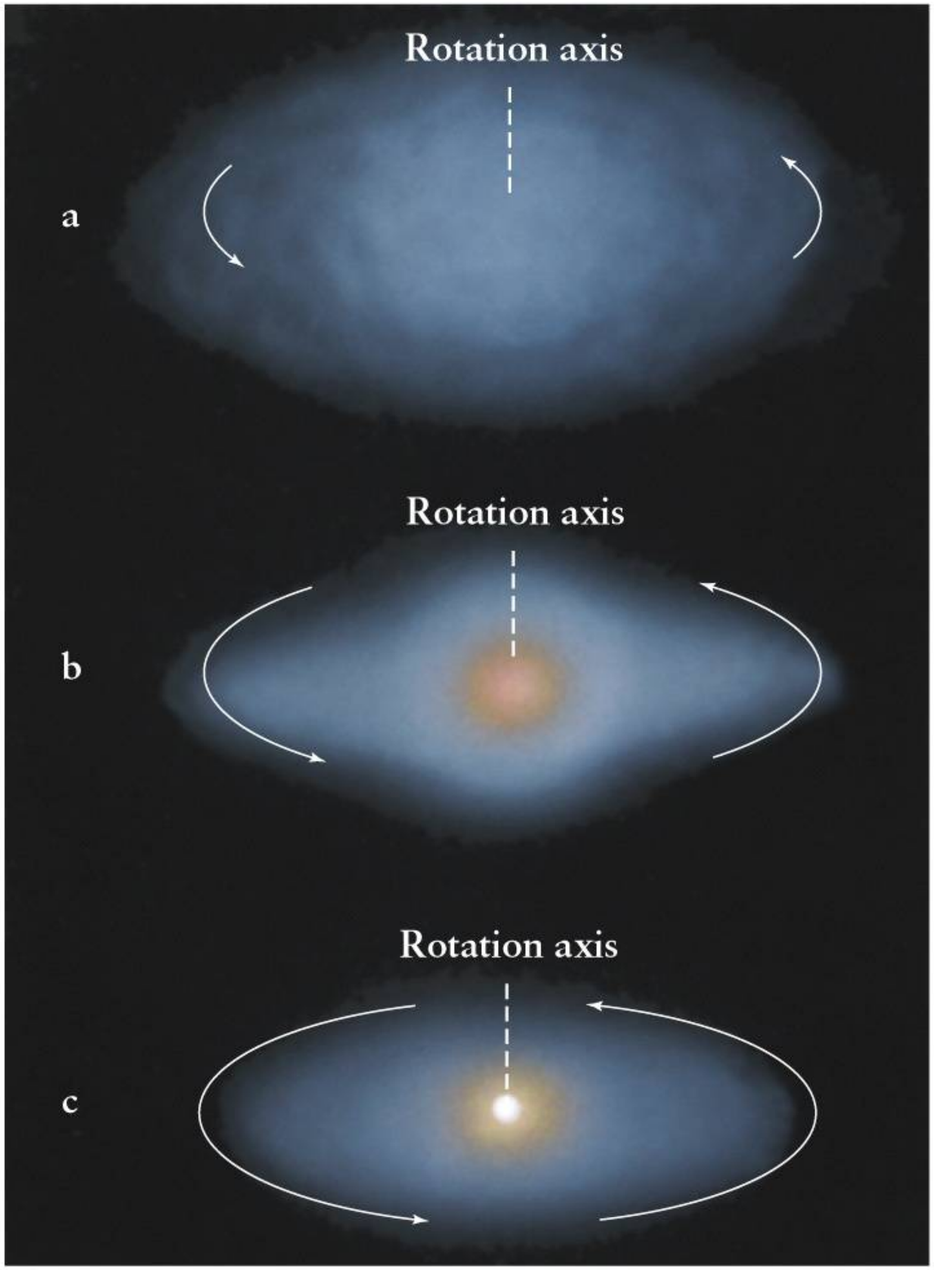
Main properties

8 Planets:	Mercury to Neptune
5 Dwarf Planets:	Ceres, Pluto, Eris, Makemake, Haumea
Minor bodies:	TNO, asteroids, comets
Tiny bodies:	meteorites, dust

- coplanar, circular, uniform orbits (cf. Kepler candidates)

- Solid and gaseous planets (with Cores)
- prograde rotation (with exceptions)
- 99% of mass in Sun
- 99% of angular momentum in planets
- Age: about 4.5 billion years

Formation: Overview



Historic View:
(Leukippos, 480-420 BC)
“The worlds form in such a way, that the bodies sink into the empty space and connect to each other.”

Modern View:
Collaps of an interstellar
Molecular Cloud
Slight rotation ⇒ Flattening
Protosun in center / disk formation
(based on Kant & Laplace, 1750s)

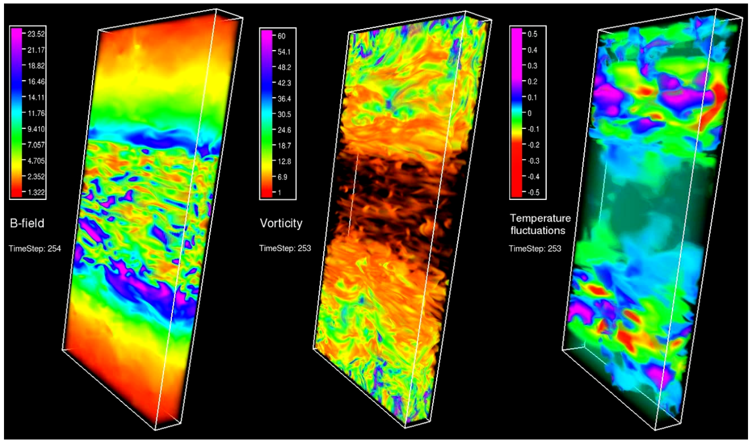
Planets form in protoplanetary disks
≡ Accretion Disks (99% Gas, 1% Dust)

⟹

Flat system, uniform rotation, circular orbits

Disk-Structure

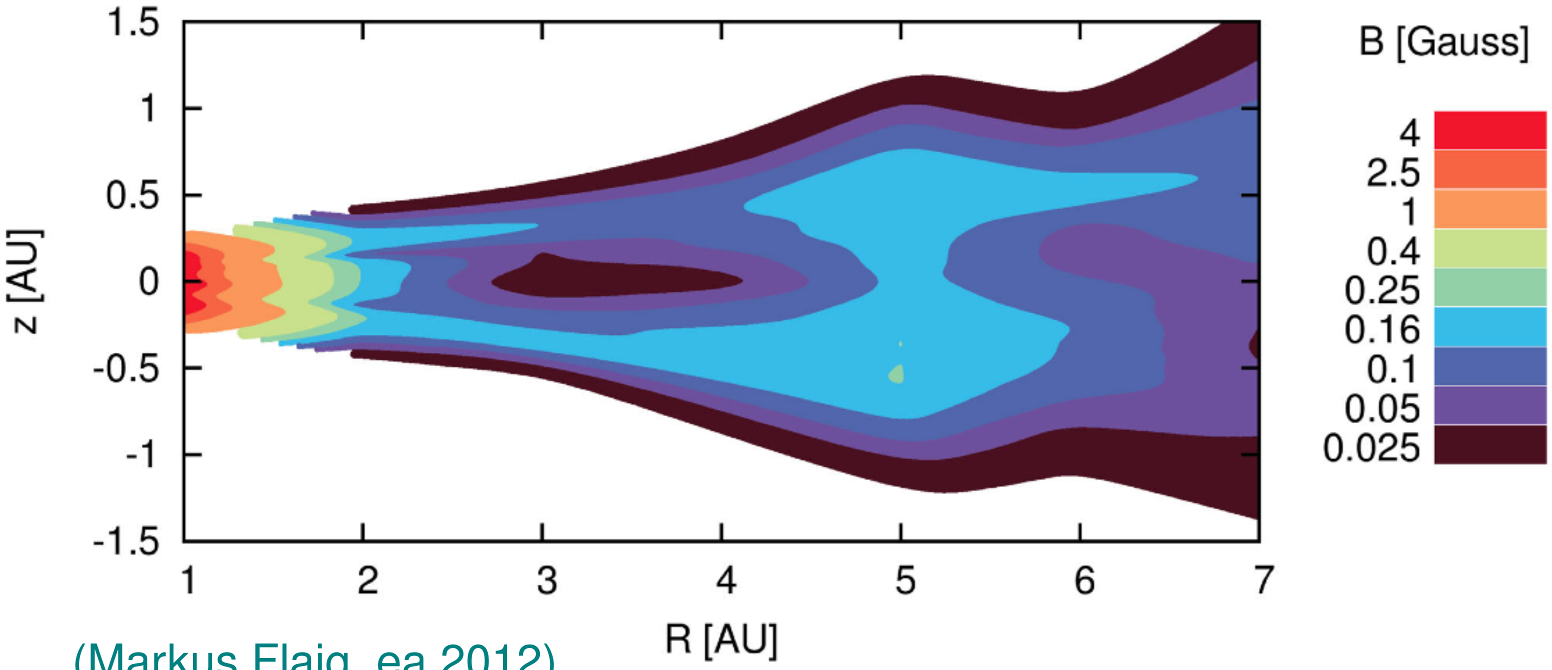
3D MHD Turbulence with Radiation Transport and chemical network in Accretion disks: Stratified *Local Shearing Box*, (Movie: 6 Orbits)



Outcome: (Talk: J.Simon, N. Turner

Poster: M. Flock, M. Hanasz)

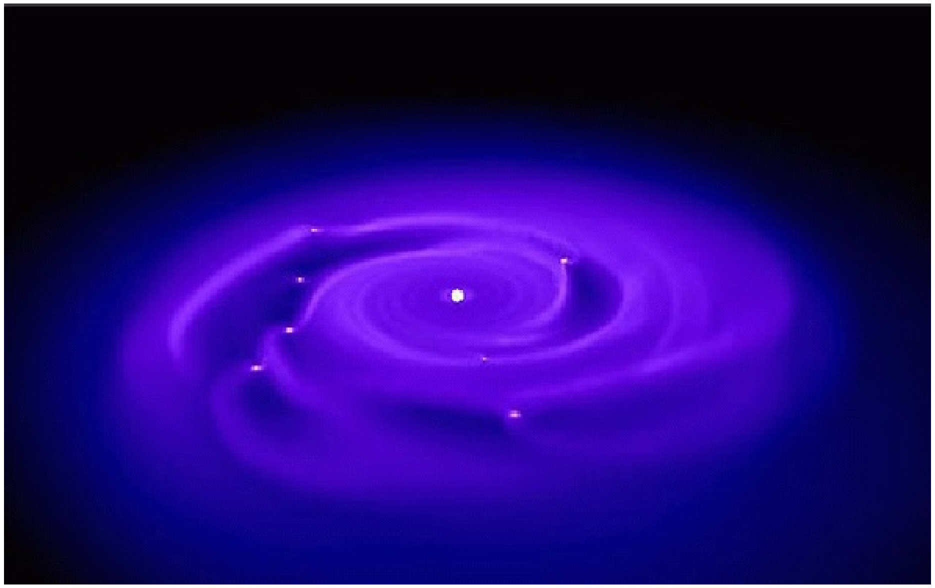
- Saturation level
- Vertical structure
- Surface temperature
- Transport efficiency (α)
- Deadzones



(Markus Flaig, ea 2012)

Two main scenarios

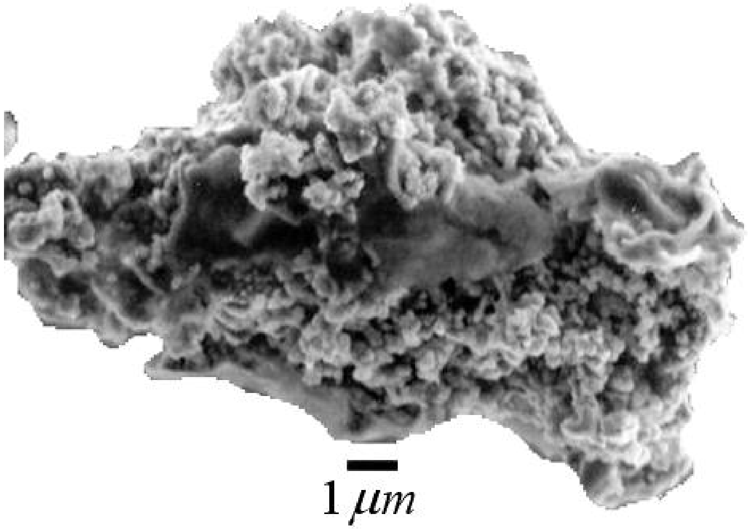
Gravitational-Instability (top-down)



(L. Mayer)

Self-gravitating disk
Density-Fluctuations grow
Spiral arms ⇒ planets
Fast formation (10^3 years)
No cores
(Good for distant planets)

Sequential Accretion (bottom-up)



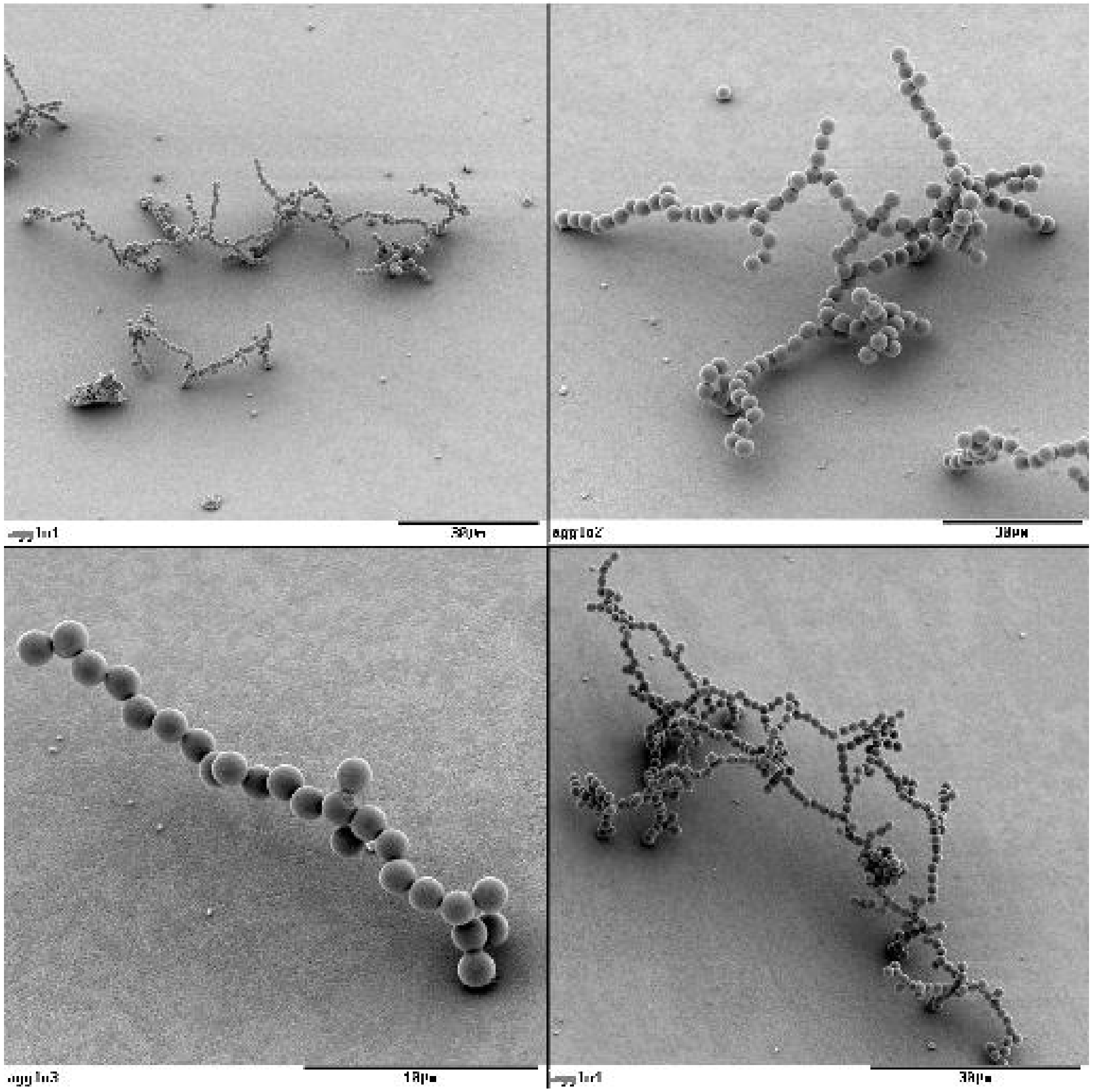
(NASA, U2)

From small to large particles
Slow formation (10^6 Years)
Need: High sticking probability

(Comets, asteroids, solid planets, cores of planets)
(Preferred for Solar System)

Dust Growth

Laboratory-Experiments μm-sized particles



(J. Blum)

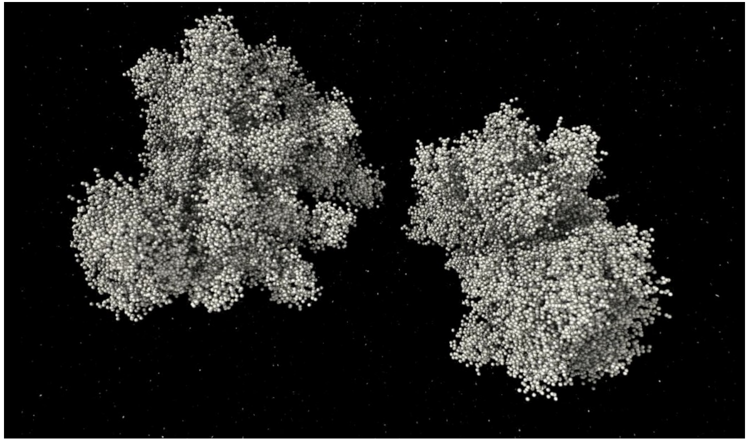
Sticking through:
Van der Waals forces

Fractal Growth

works up to cm-sizes

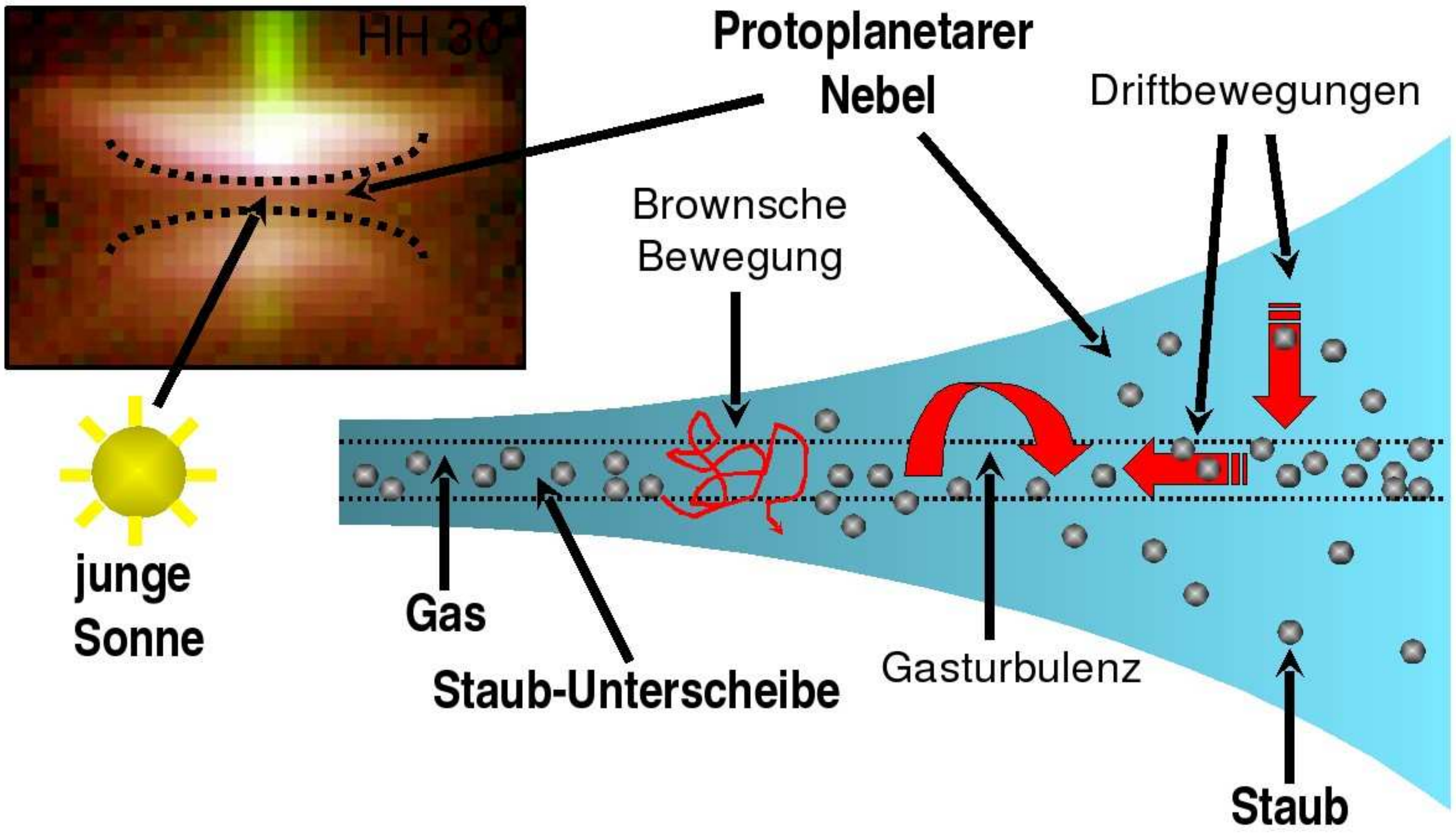
Numerical Simulations

Here: Molecular dynamics



(Alexander Seizinger, Tübingen)

Particle dynamics in disk



(Jürgen Blum)

Particles have relative velocity with respect to the gas ⇒ frictional forces

Problem I: Fast radial drift towards star (for 1m Size: 1 AU / 100 Years)
Problem II: Destructive Collisions
Note: Disk is hotter near central star, best condensation beyond iceline

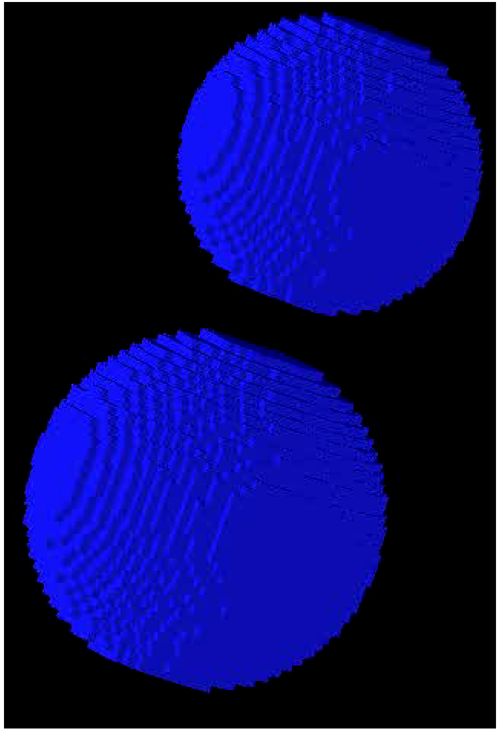
Collisions

Check growth of planetesimals by collisions/accretion

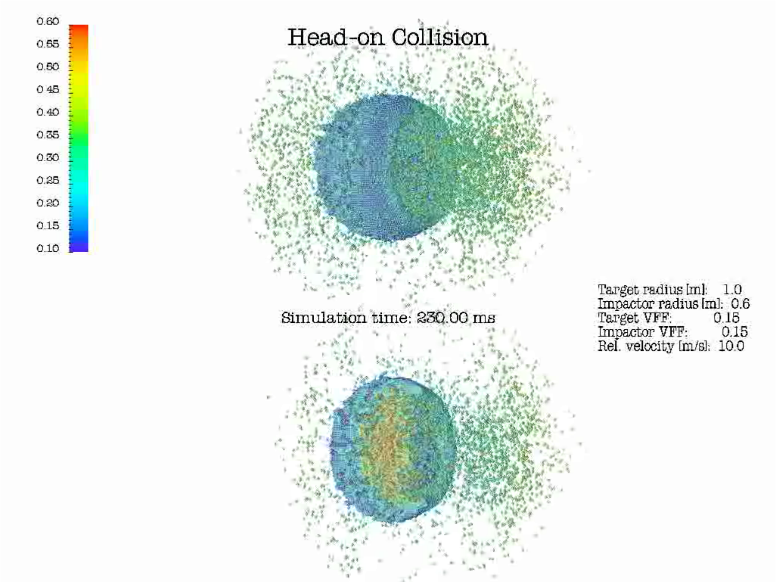
SPH (Smoothed-Particle-Hydrodynamics) using 250,000-500,000 particles

Here: Elastic-plastic strength model, formation and evolution of cracks

2 Basalt Spheres:



Porous Objects:



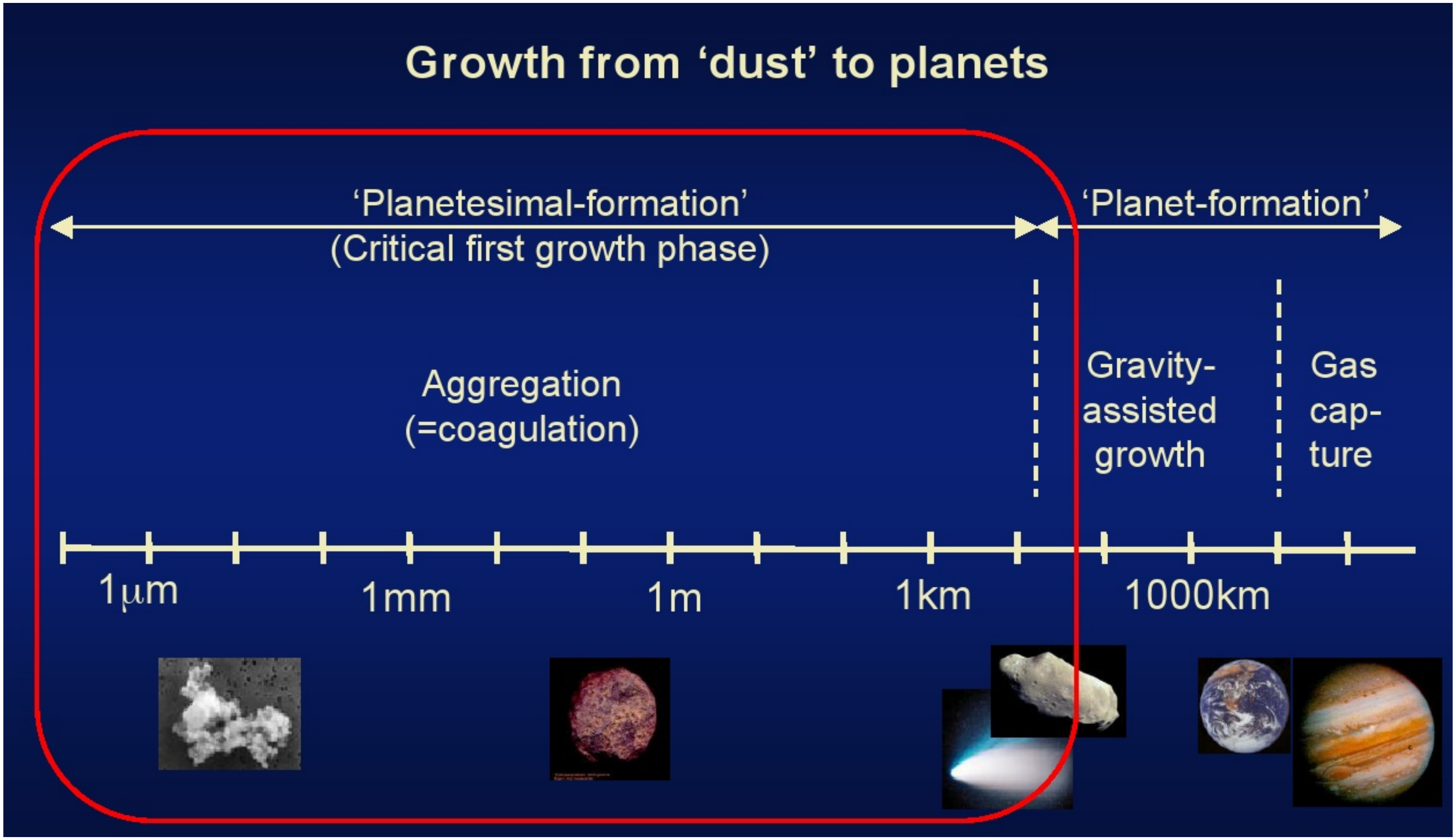
(cp. small objects in Solar System)

(Schäfer, Geretshauser, Speith, Meru; Tübingen) (Geretshauser ea., 2010, 2011a,b)

See talk by Roland Speith

to overcome growth barriers: Talks: J. Blum, F. Windmark

How to form massive planets



Growth from ‘dust’ to planets

‘Planetesimal-formation’
(Critical first growth phase)

‘Planet-formation’

Aggregation
(=coagulation)

Gravity-
assisted
growth

Gas
cap-
ture

(C. Dullemond)

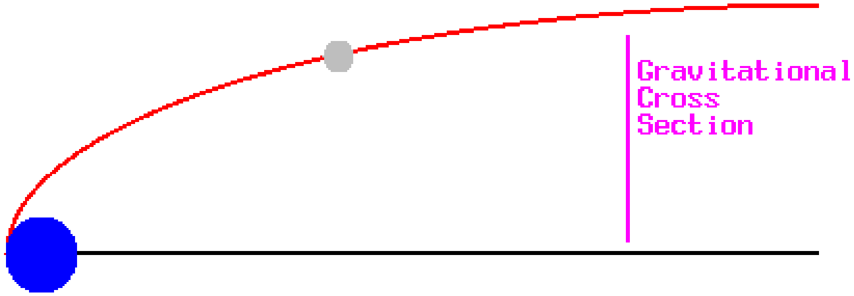
Dust ⇒ Planetesimals (μm ⇒ 1-10km, through Collisions)
Mass rich planets: Gravitation & Gas Accretion

Growth processes

Important: *Gravitational Focussing*

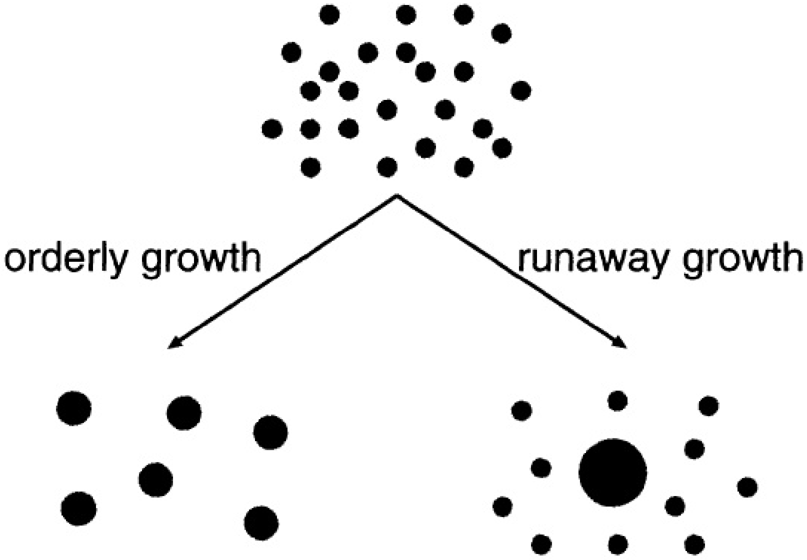
Two bodies grow through physical collisions

Mutual gravitational attraction increases the effective cross section



$$\sigma_{\mathrm{grav}} = \sigma_{\mathrm{geo}} \left[1 + \left(\frac{v_{\mathrm{esc}}}{v_{\mathrm{rel}}} \right)^2 \right]$$

$\Longrightarrow$ Strongly enhanced collision probability



Two modes: (Kokubo, 2001)

a) Ordered

mass ratio of two particles approaches unity

b) Runaway

Large particles grow faster $\propto M^{4/3}$

c) Pebble accretion ?: $\propto M^2$

(Lambrechts & Johansen, 2012; Morbidelli & Nesvorny, 2012)

Gas Giants

Core-instability model

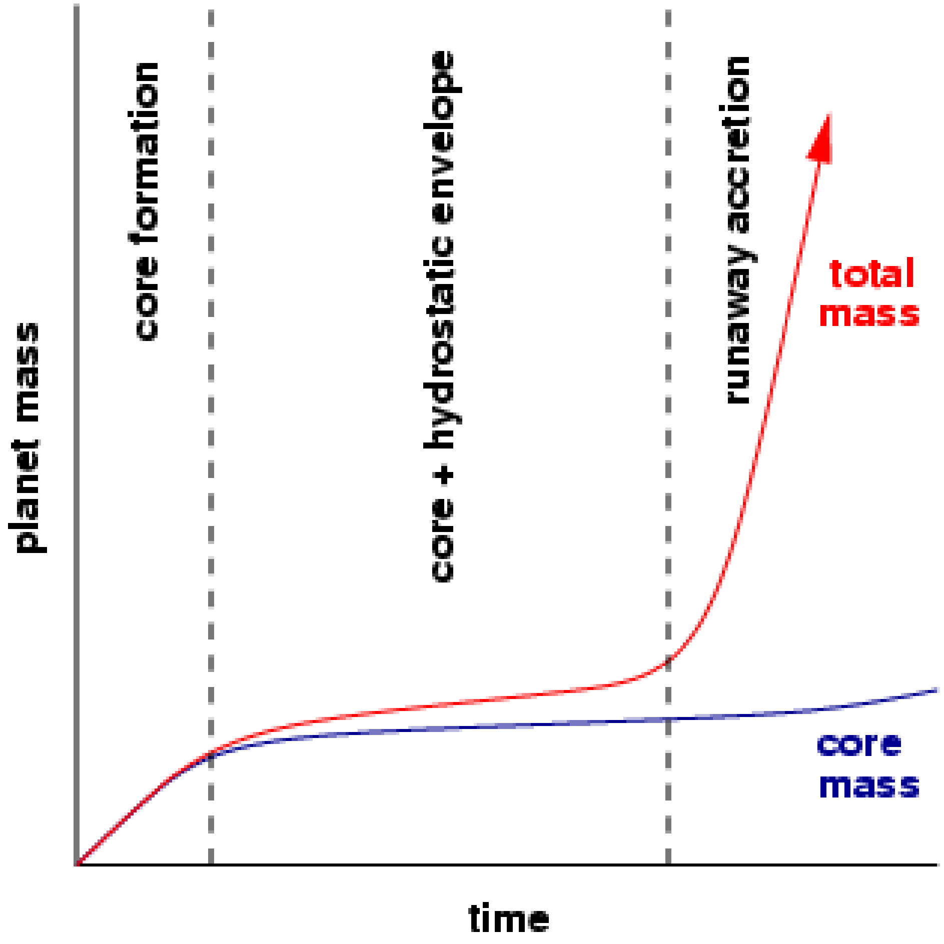
First solid core (as terrestrial)
Then: Accretion of Gas Envelope
(runaway)

Core formation time $< 10^6$ years
Hydrostat. phase: $\approx 10^6$ years

Many details not known:
Opacity: κ_R
Chemical composition: μ
Accretion rate: $\dot{M}_{env}$
3D effects: CP-disk

Migration through disk

Schematic growth



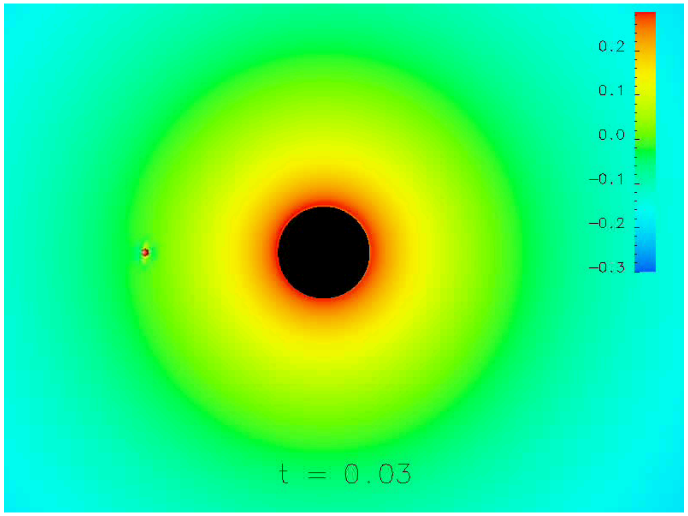
(Scholarpedia)

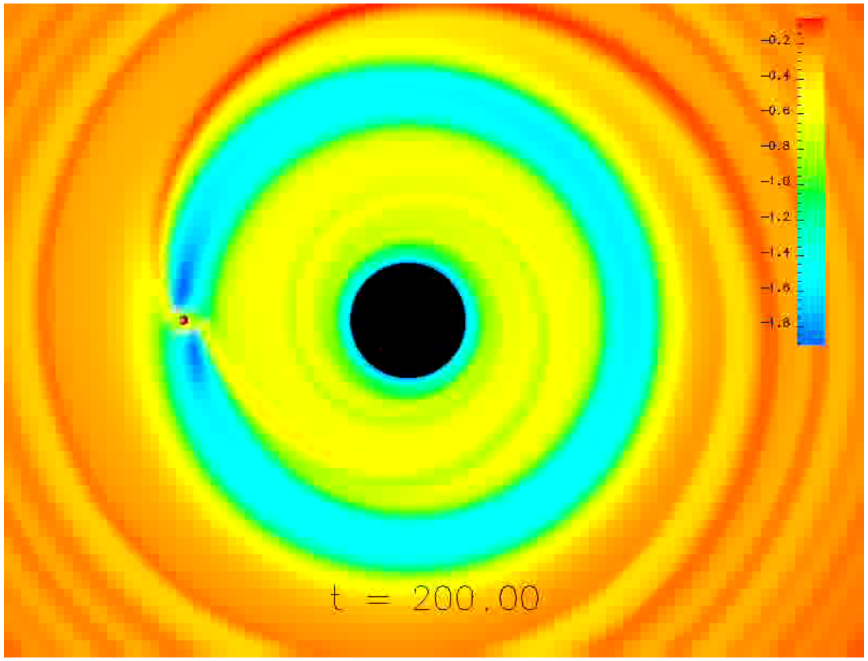
Gap Opening Process

M_p = 1 M_{Jup}, a_p = 5.2 AU, into disk around 1 M_{sol} star

Viscous hydrodynamical evolution

2D-Finite Volume Method





Spiral waves turn into shockwaves:

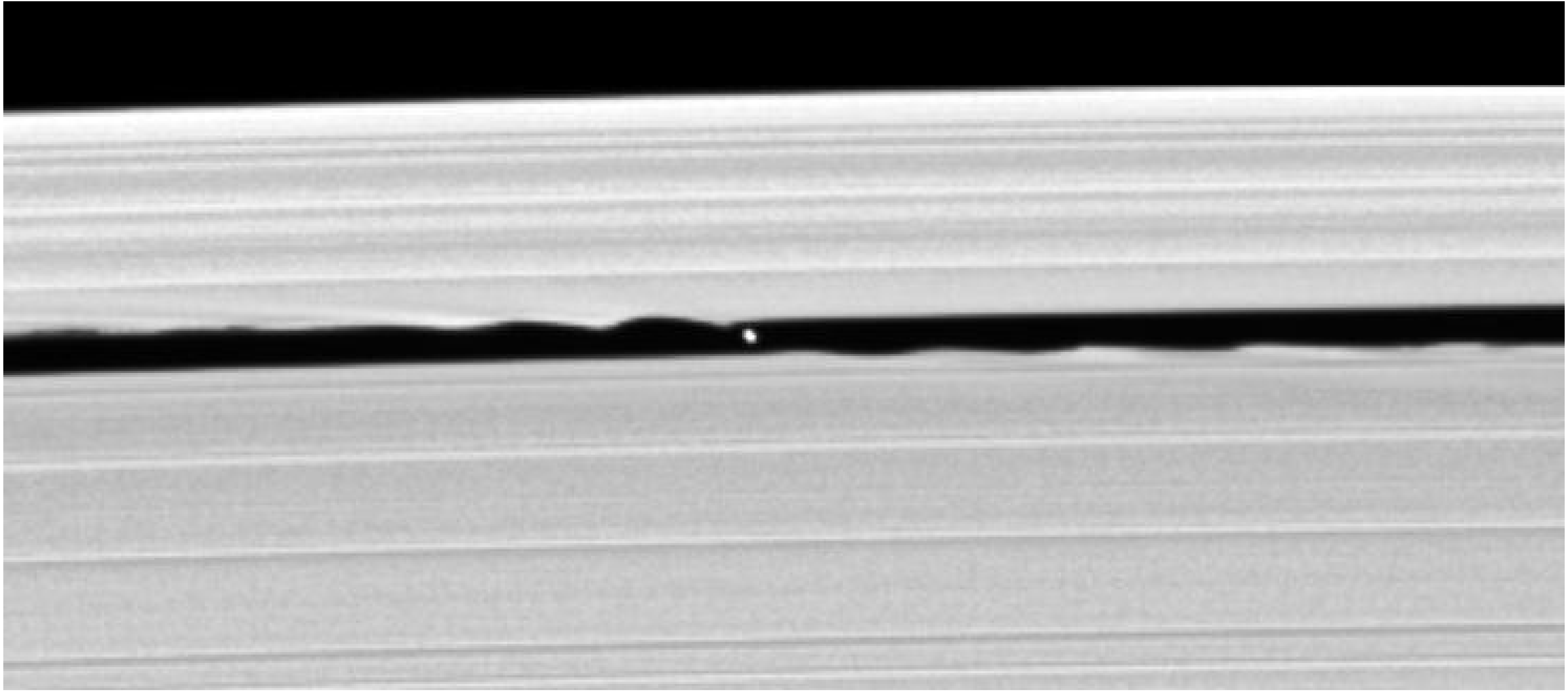
$\Rightarrow$ dissipation & ang.mom. deposition $\Rightarrow$ Gap

Gap formation limits growth to about 1 M_{Jup}

Details (gap width & depth) depend on: Viscosity, pressure, planet mass

Evidence of Gap Opening

Moon (S/2005 S1) in Keeler Gap, Cassini (May 1, 2005)
(Gap-Width ≈ 40 km, Planet-Diameter $\approx$ 7 km)



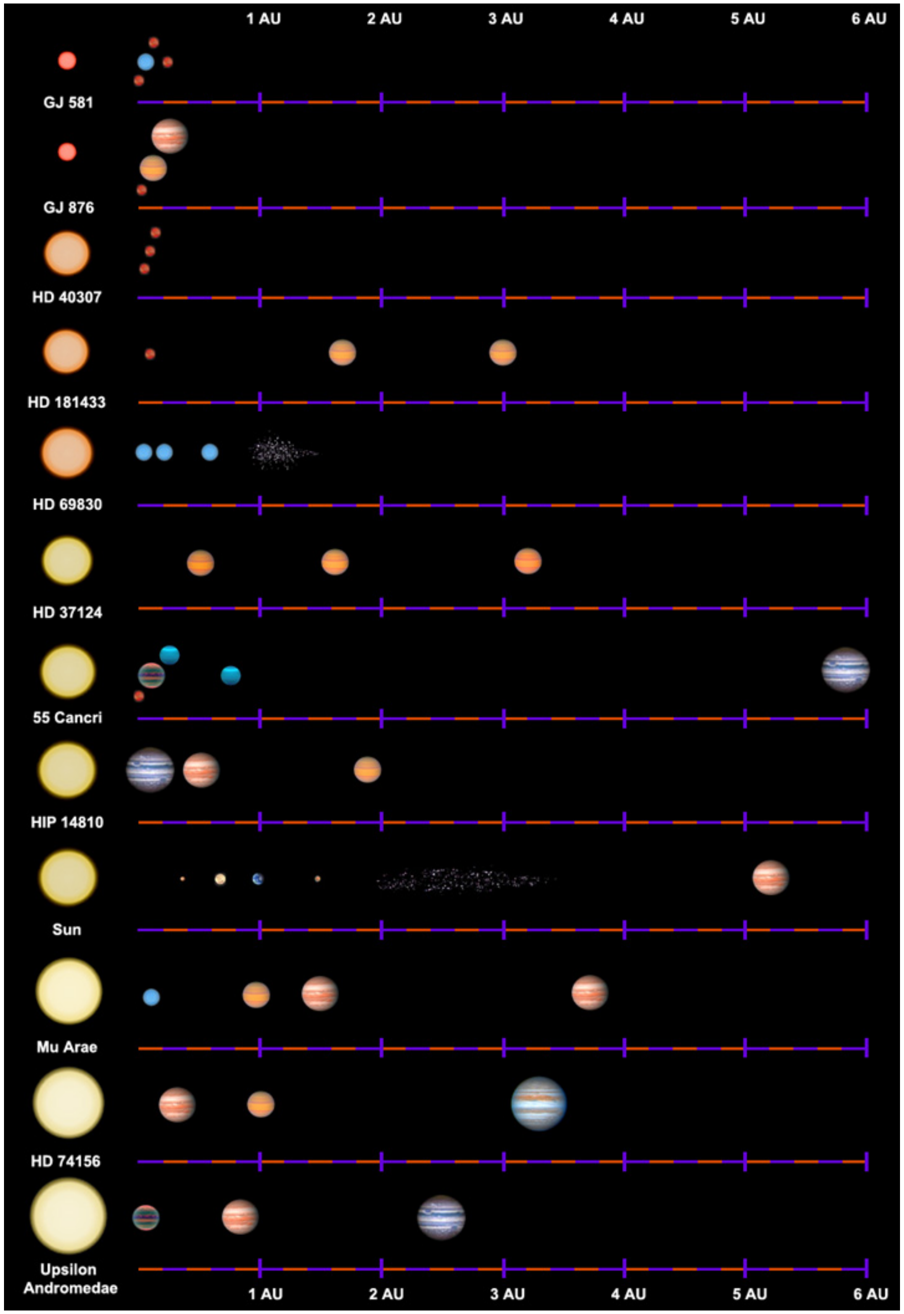
Here: Zero pressure, low viscosity $\Longrightarrow$ Very clean gap

Summary Formation

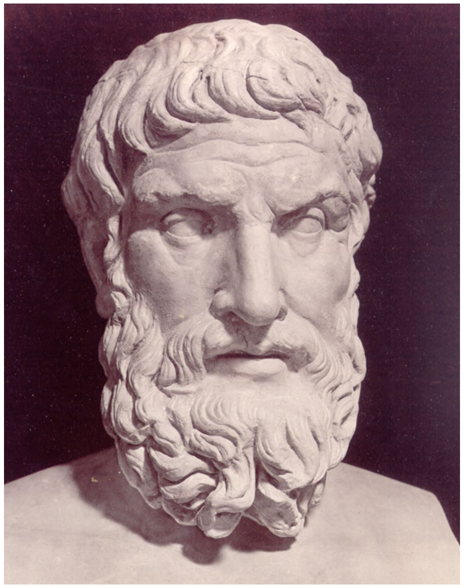
- Planets form in protoplanetary disk
  (in one plane, circular orbits)
- Sequence of sticking collisions
- Inner planets: solid
- Outer planets: gaseous with cores
- Maximum Mass $\approx$ 1 $\mathrm{M}_{\mathrm{Jup}}$ (gap formation)

What about the extrasolar planets ?

Planetary Systems

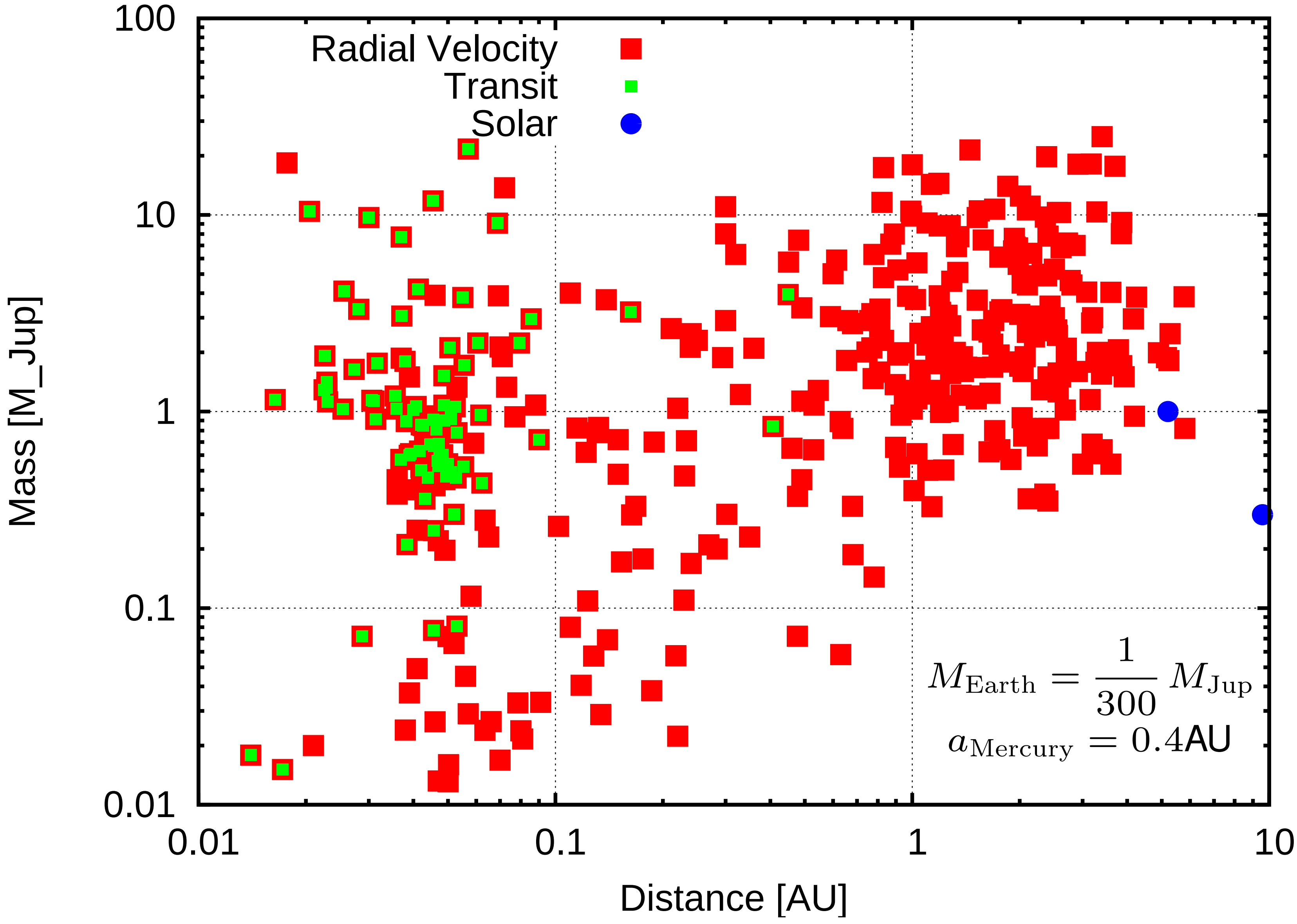


Epicurus (ca. 341-270 BC)
“There is an infinite number of worlds, some similar to ours some very different.”



Mass and Distance

Small distances (hot Jupiters) & large masses (Data: exoplanet.eu)



$$M_{\text{Earth}} = \frac{1}{300} M_{\text{Jup}}$$

$$a_{\text{Mercury}} = 0.4\text{AU}$$

$\Longrightarrow$ Need migration and mass growth!

First Formation Problems

- Not possible to form hot Jupiters in situ
  - disk too hot for material to condense
  - not enough material
- Difficult to form massive planets
  - gap formation

But planets grow in disks:

⇒ Have a closer look at planet-disk interaction

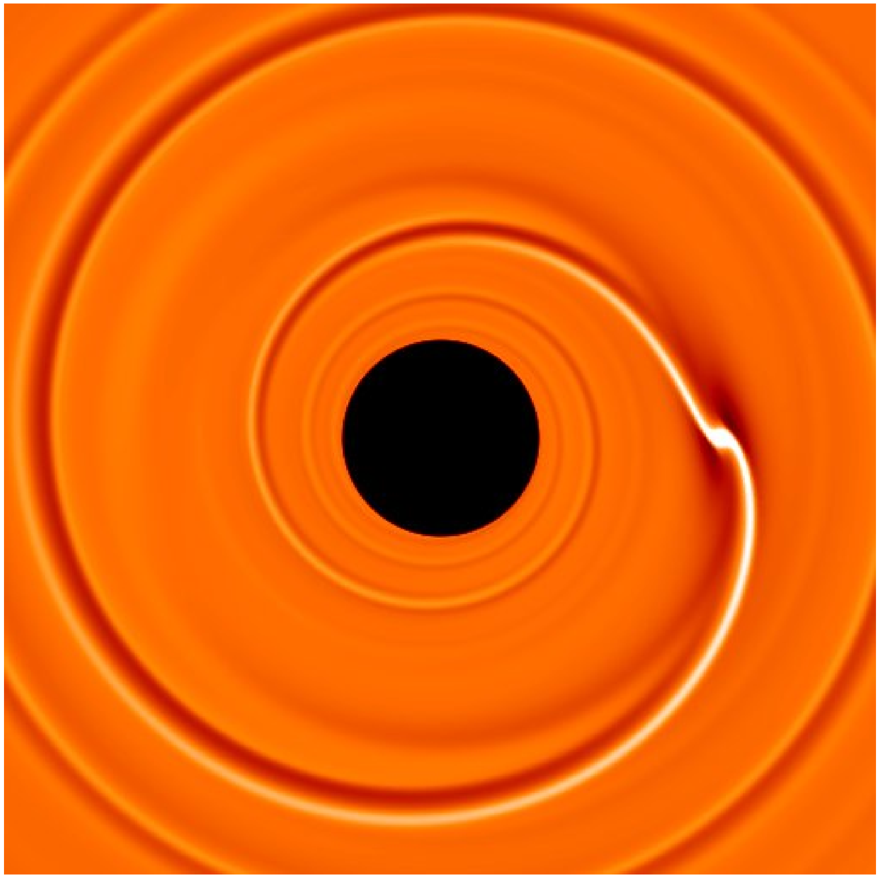
see Annual Review article: Kley & Nelson, ARAA, 50 (2012)

Lindblad Torques (Spiral arms)

Young planets are embedded in gaseous disk

Creation of spiral arms:
- stationary in planet frame

- Linear analysis,
  - 2D hydro-simulations



(Masset, 2001)

Inner Spiral
- pulls planet forward:
- positive torque

Outer Spiral
- pulls planet backward:
- negative torque

$\longrightarrow$ Net Torque

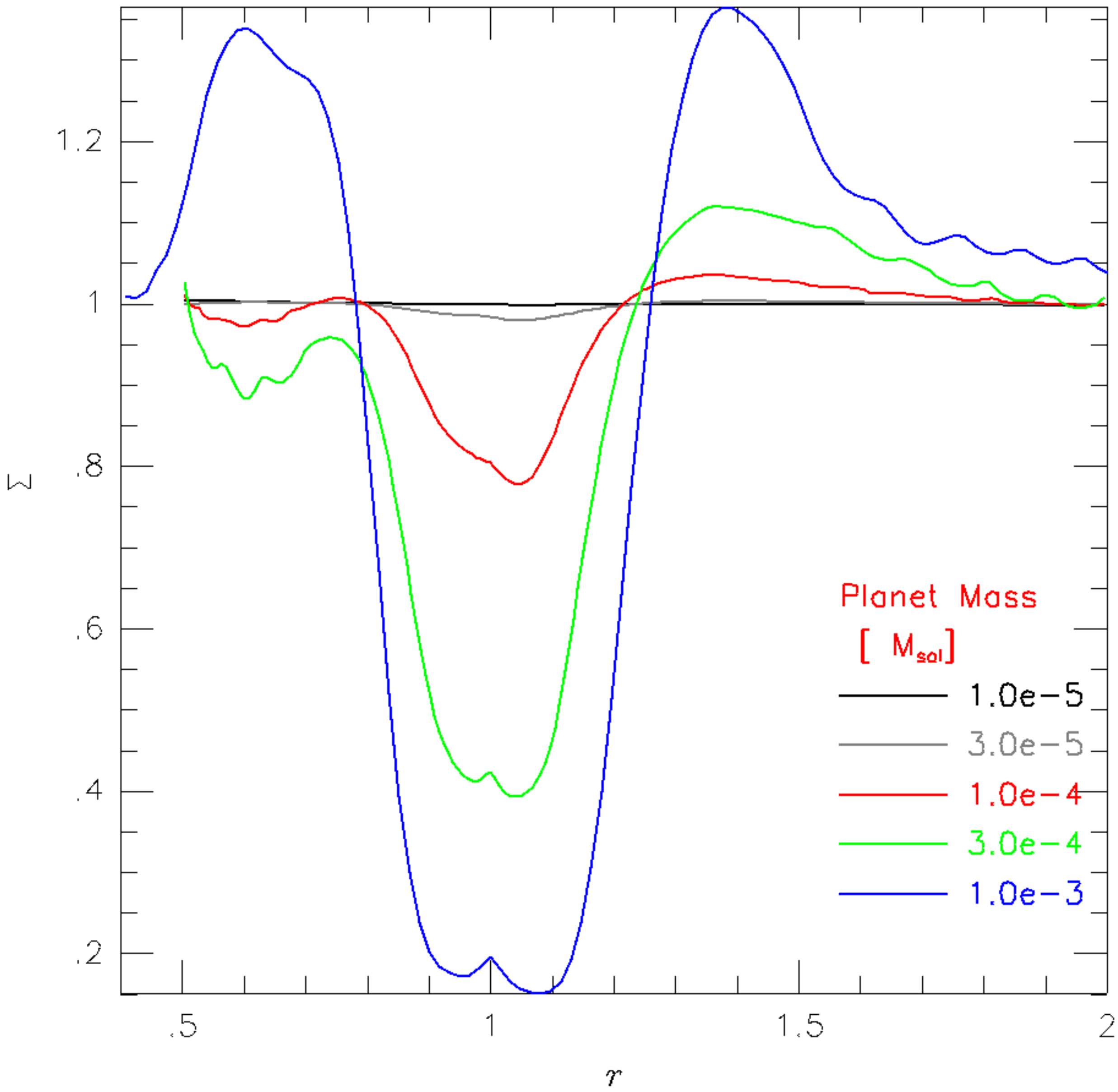
$\Longrightarrow$ Migration

Most important:
Strength & Direction ?

Typically: Outer spiral wins
$\Longrightarrow$ Inward Migration

Torque scales with:
inv. Temp. $(H/r)^{-2}$, M_p^2, M_d

Gap width: Type I ⇒ Type II



$M_p = 0.01\ M_{Jup}$

$M_p = 0.03\ M_{Jup}$

$M_p = 0.1\ M_{Jup}$

$M_p = 0.3\ M_{Jup}$

$M_p = 1.0\ M_{Jup}$

Depth depends on:
- M_p
- Viscosity
- Temperature

Torques reduced:

Migration slows

Type I ⇒ Type II

linear ⇒ non-linear

Migration: Evidence I

- RV-Obs.: $\approx$ 50 multi-planet extrasolar planetary systems

  $\approx 1/4$ contain planets in a low-order mean-motion resonance (MMR)

  mostly in a 2:1 configuration (eg. GJ 876, HD 128311, HD 82943, ...)

  recently 3:2 (HD 45364) and 3:1 (HD 60532)

  In Solar System: 3:2 between Neptune and Pluto (plutinos)

- Resonant capture through convergent migration process

  dissipative forces due to disk-planet interaction

- Existence of resonant systems

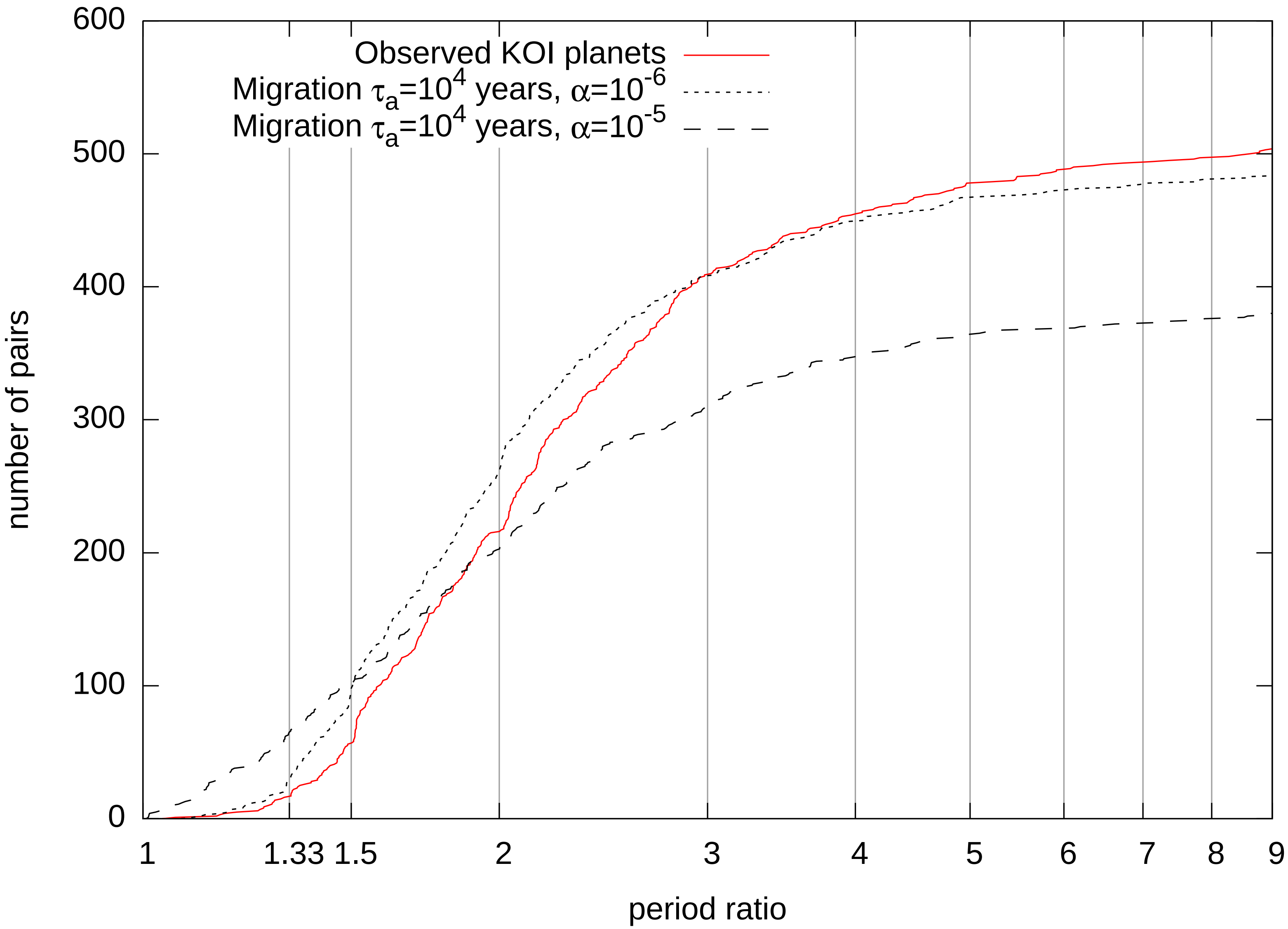
  $\Longrightarrow$ Clear evidence for planetary migration

- Hot Jupiters (Neptunes) & Kepler systems

  $\Longrightarrow$ Clear evidence for planetary migration

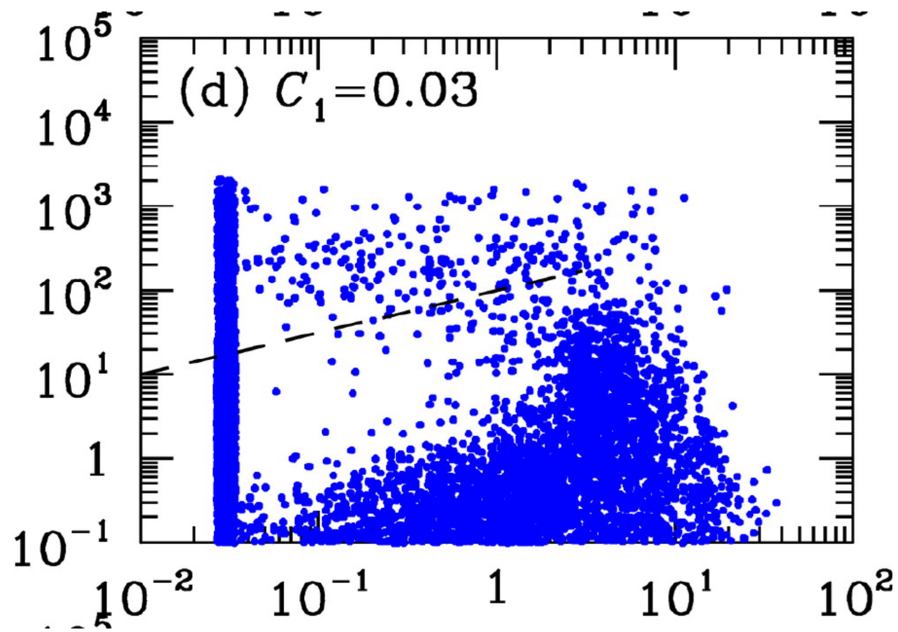
Migration: Evidence II

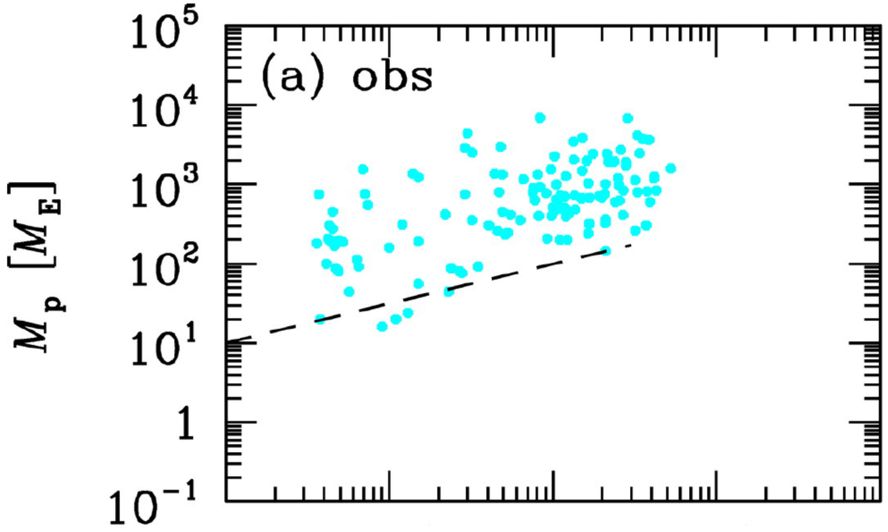
Migration (τ = 10^4yrs) with stochastic forcing (H. Rein, 2012)



– observed, - - - stronger stochastic forcing, · · · weak forcing

Check with Population synthesis





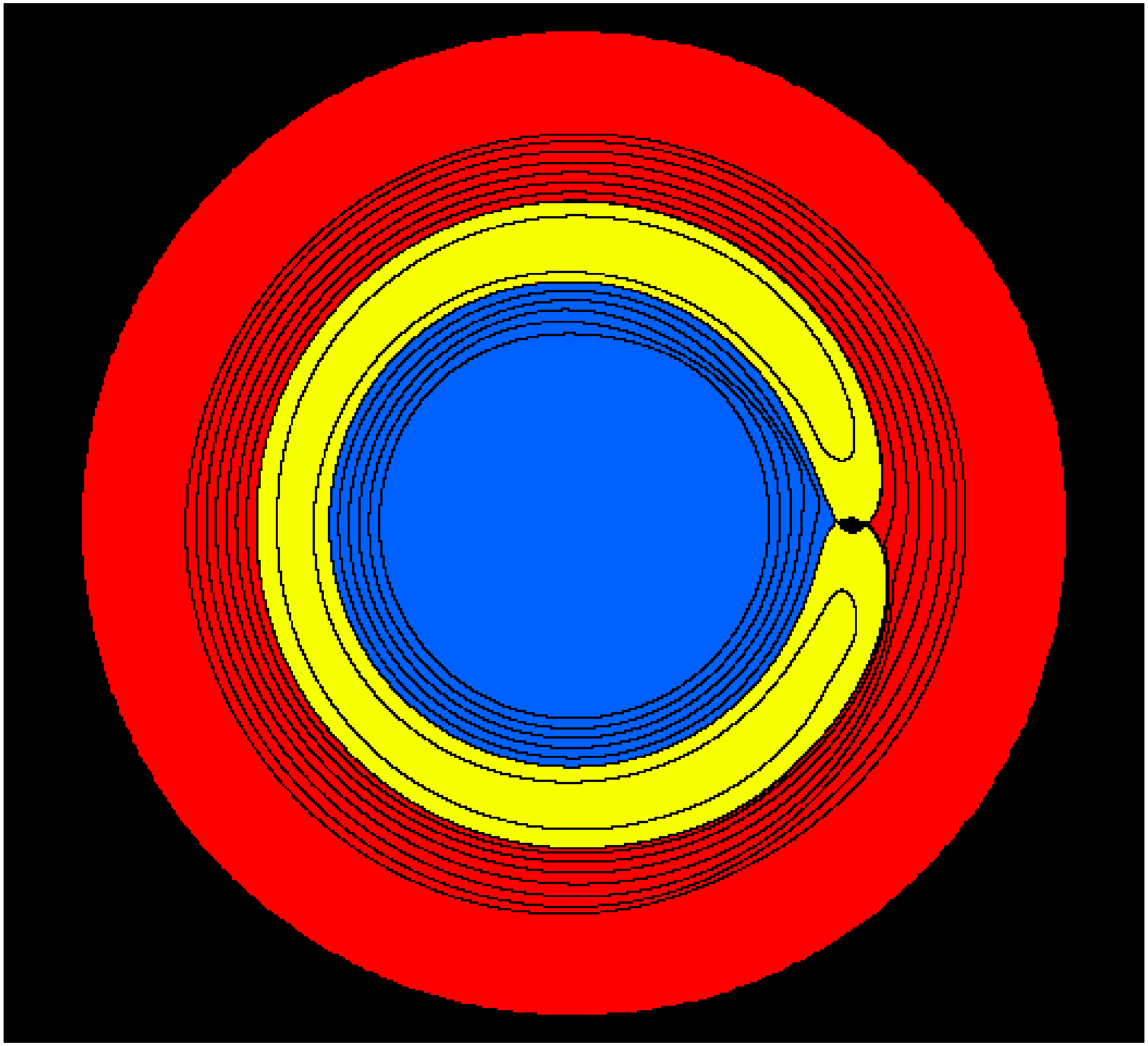
Migration too efficient!

Only strong reduction of Type I gives reasonable results

(Ida & Lin; Mordasini, Alibert & Benz)

⇒ Need improvements:
- stochastic migration
- inviscid, self-grav. disks
- radiative disks (corotation effects)

Corotation effects: Principle



(F. Masset)

3 Regions

Outer disk (spiral)

Inner disk (spiral)

$\Longrightarrow$ Lindblad torques

Horseshoe (coorbital)

$\Longrightarrow$ Corotation Torques

(Horseshoe drag)

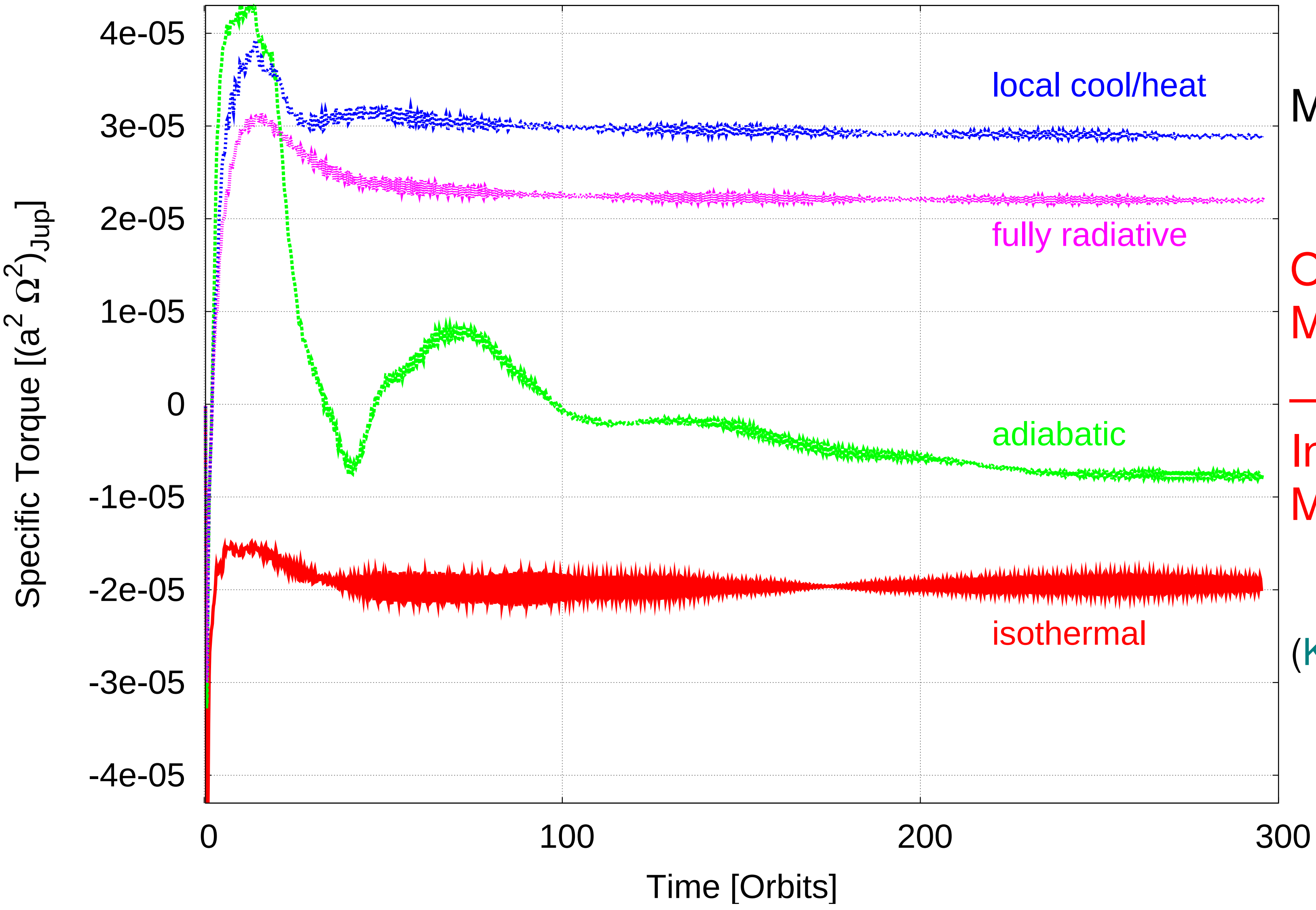
Scaling with:

- Vortensity gradient
- Entropy gradient

(Talk by: C. Baruteau)

Physics matters

$$\frac{\partial \Sigma c_{\rm v} T}{\partial t} + \nabla \cdot (\Sigma c_{\rm v} T \mathbf{u}) = -p\nabla \cdot \mathbf{u} + D - Q - 2H\nabla \cdot \vec{F}$$



M_p = 20 $M_{\rm Earth}$

Outward Migration

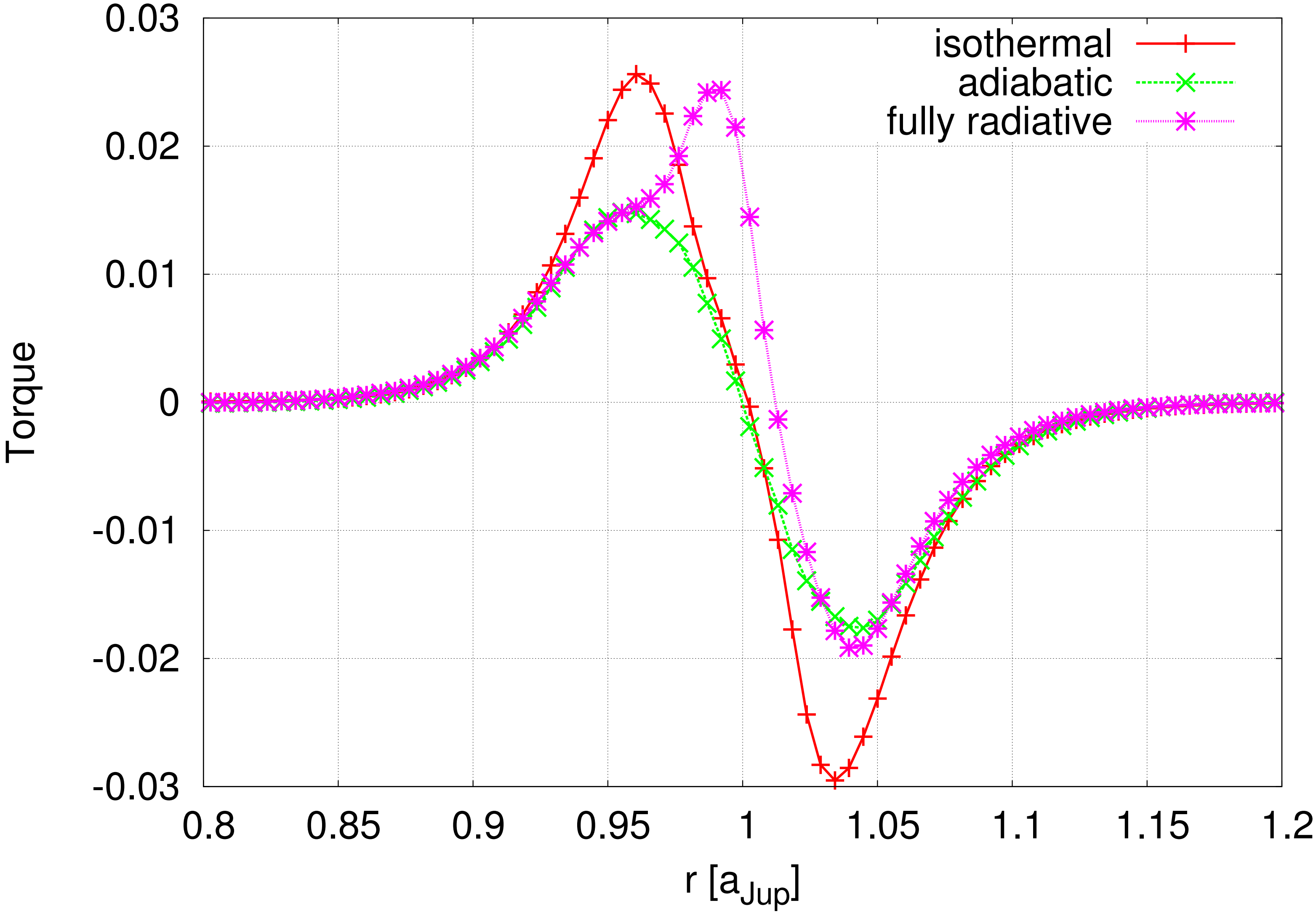
Inward Migration

(Kley&Crida '08)

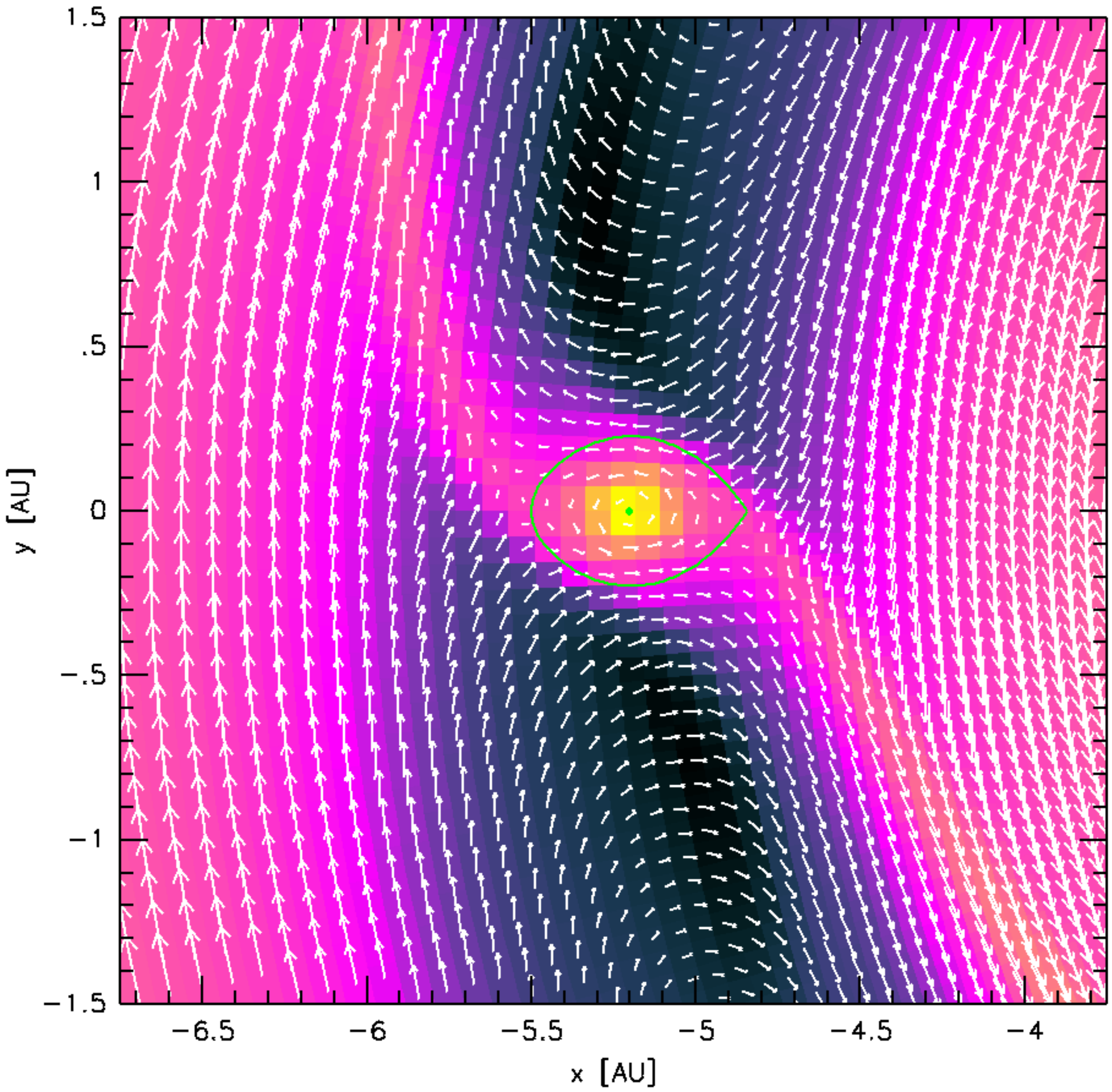
Radial Torque density

3D-simulations, radiative diffusion, 20 $M_{\rm Earth}$ planet (Kley, Bitsch & Klahr 2009)

$d\Gamma/dm$, with $\Gamma_{\rm tot} = 2\pi \int (d\Gamma/dm)\Sigma dr$ Radiative: ⇒ additional positive contrib.



Flow field & Mass grow



Surface Density
at 200 Orbits

Green Dot: Planet
Green Line:
Roche-Lobe

m_p = 1 M_{Jup}
a_p = 5.2 AE

Flow-Field
$\longrightarrow$ Mass growth
up to a few M_{Jup}
$\longrightarrow$ prograde rotation

(WK, 2000)

Summary Migration (Type I,II)

Planet-disk interaction: Torques on Planet

Isothermal Migration is inward & rapid (lose planets)

But: $\Gamma_{\rm tot} = \Gamma_{\rm L} + \Gamma_{\rm HS,ent} + \Gamma_{\rm HS,vort}$

Outward in radiative disks

Mass limit due to gap opening

Driven by:

Vortensity gradient

maintained by: viscosity

Entropy gradient

maintained by: rad. diffusion (or cooling)

- cooling time $\approx$ libration time

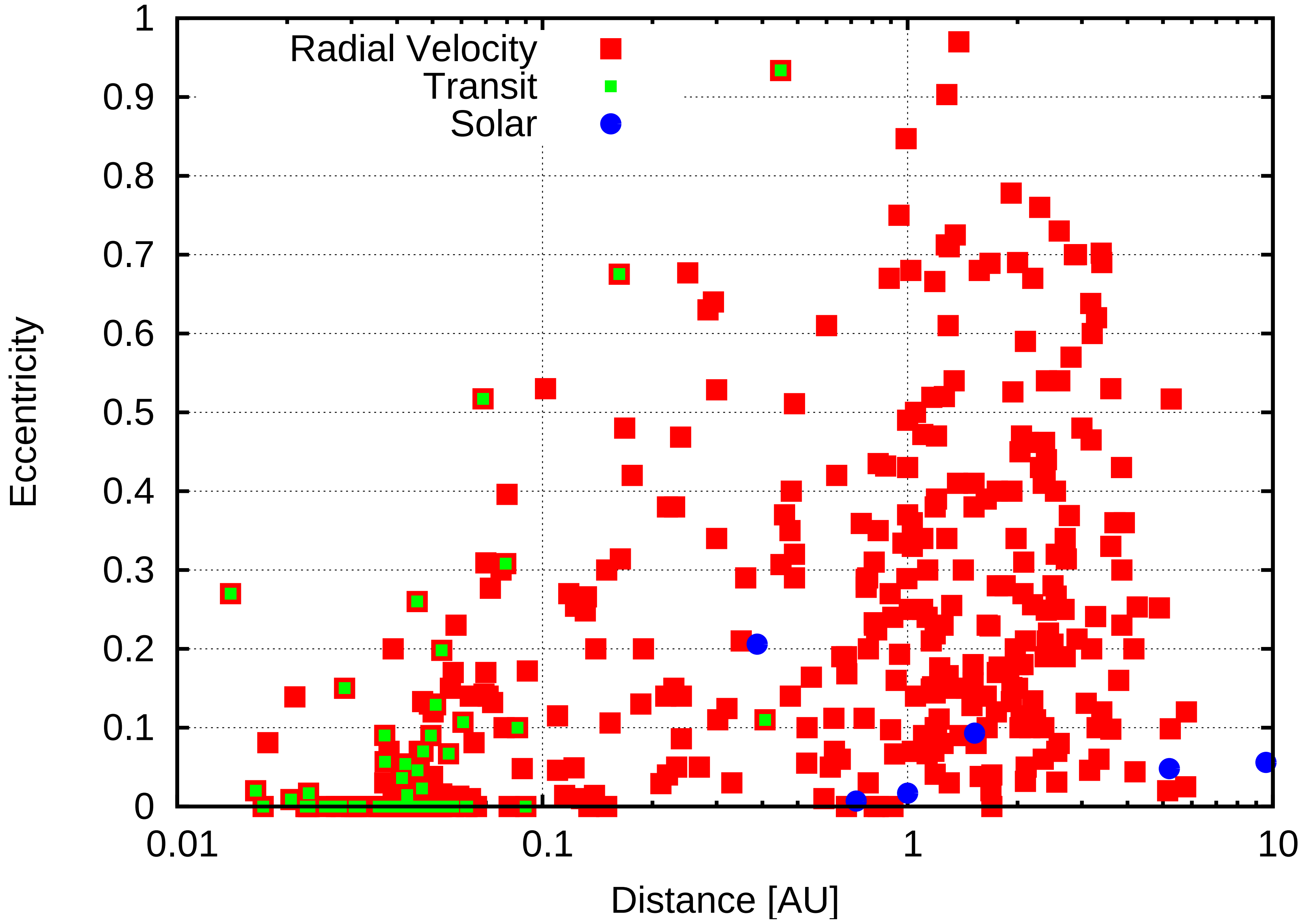
Need viscosity

approximate torque formulae: Paardekooper ea; Masset&Casoli

More details: Talks by C. Baruteau and B. Bitsch

Eccentricity Distribution

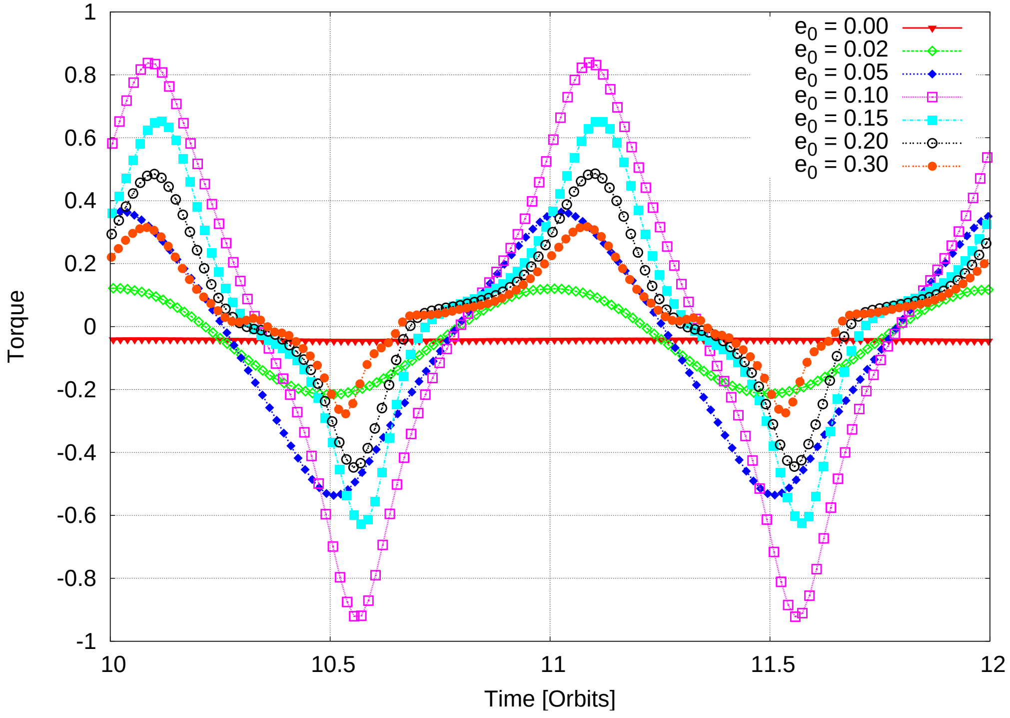
Large eccentricities (similar to binary stars) (Data: exoplanet.eu)



Low mass Planets on eccentric Orbits

Torque on planet due to disk

$$\Gamma_{\rm disk} = \int_{\rm disk} \left. (\vec{r}_{\rm P} \times \vec{F}) \right|_z \, df$$

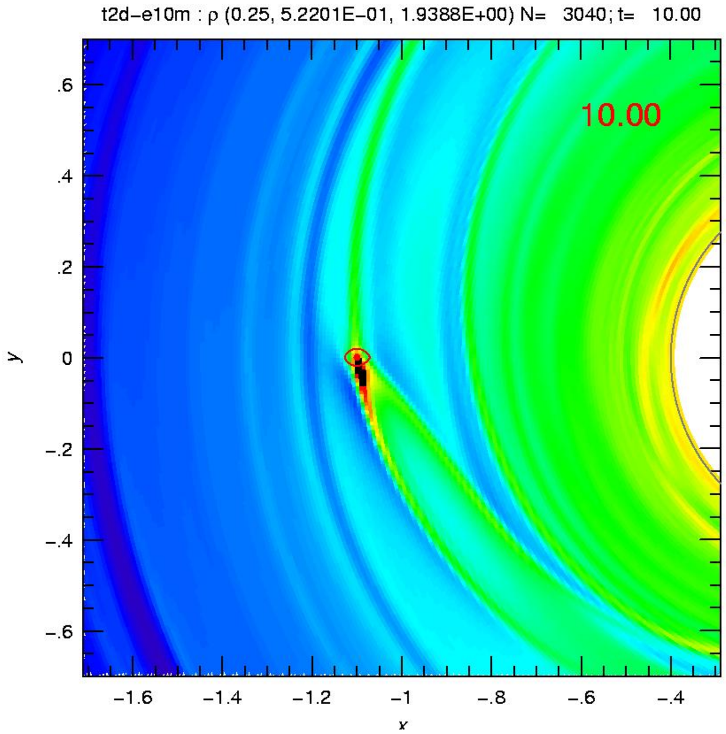


$$L_{\rm p} = m_{\rm p} \sqrt{G M_* a} \sqrt{1 - e^2}$$

$$\frac{\dot{L}_{\rm p}}{L_{\rm p}} = \frac{1}{2}\frac{\dot{a}}{a} - \frac{e^2}{1-e^2}\frac{\dot{e}}{e} = \frac{\Gamma_{\rm disk}}{L_{\rm p}}$$

Power: Energy loss of planet

$$P_{\rm disk} = \int_{\rm disk} \dot{\vec{r}}_{\rm p} \cdot \vec{F} \, df$$



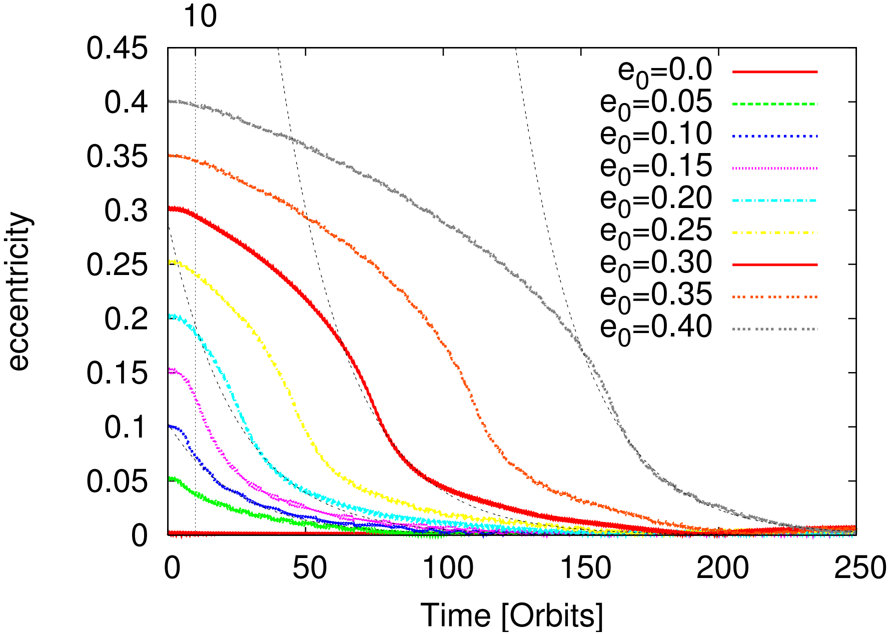
$$E_{\rm p} = -\frac{1}{2}\frac{G M_* m_{\rm p}}{a}$$

$$\frac{\dot{E}_{\rm p}}{E_{\rm p}} = \frac{\dot{a}}{a} = \frac{P_{\rm disk}}{E_{\rm p}}$$

In 3D radiative disks

Fix planet mass $M_\mathrm{p} = 20 M_\mathrm{Earth}$

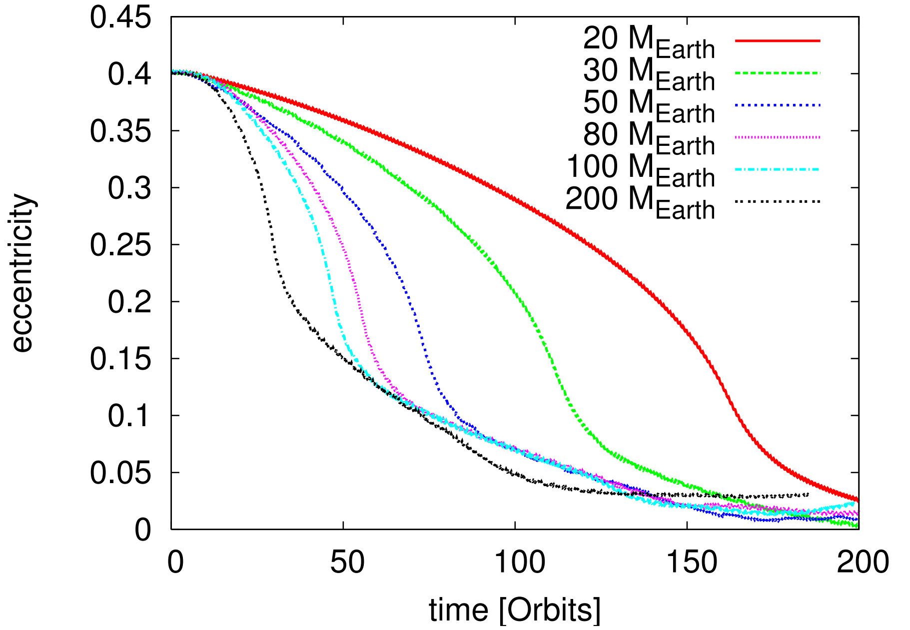
- Vary initial Eccentricity



(Bitsch&Kley '10)

Vary Planet Mass $10 - 200 M_\mathrm{Earth}$

- Same $e_0 = 0.40$



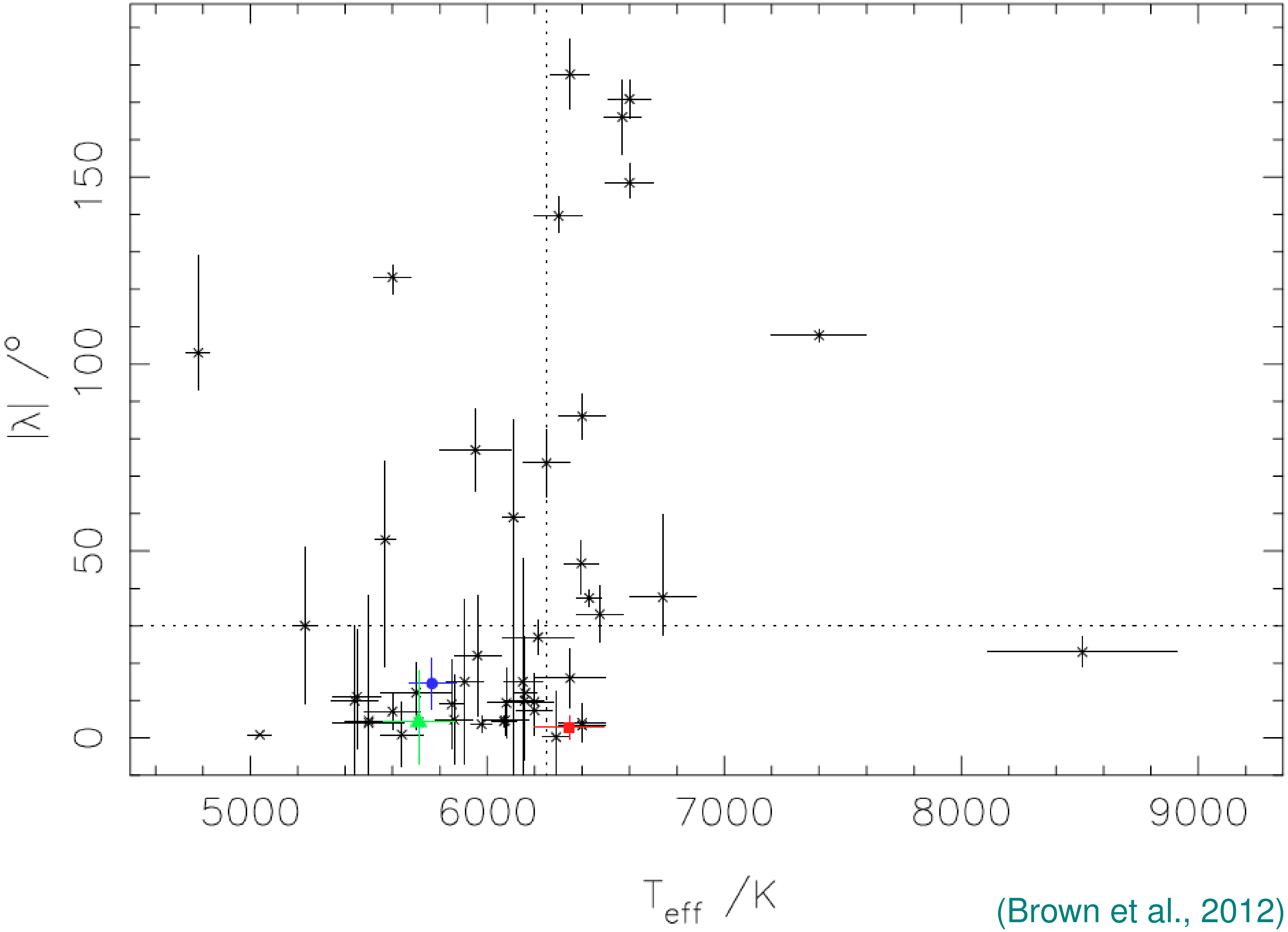
- e-damping for all planet masses.

  Small e: exponential damping, large e: $\dot{e} \propto e^{-2}$

- Migration outward upto $e \approx 0.02 - 0.03$

$\Longrightarrow$ Need multiple objects ! (and Scattering)

Observed Obliquity

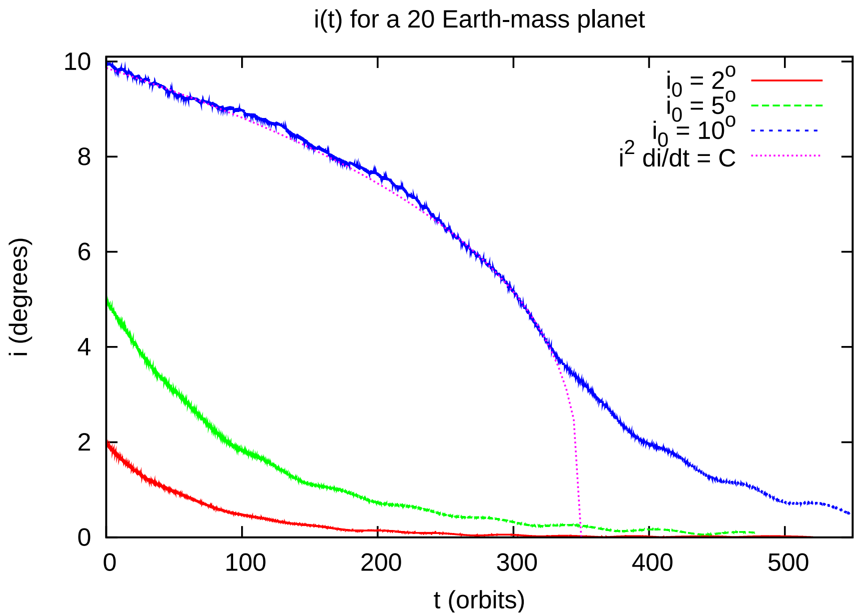


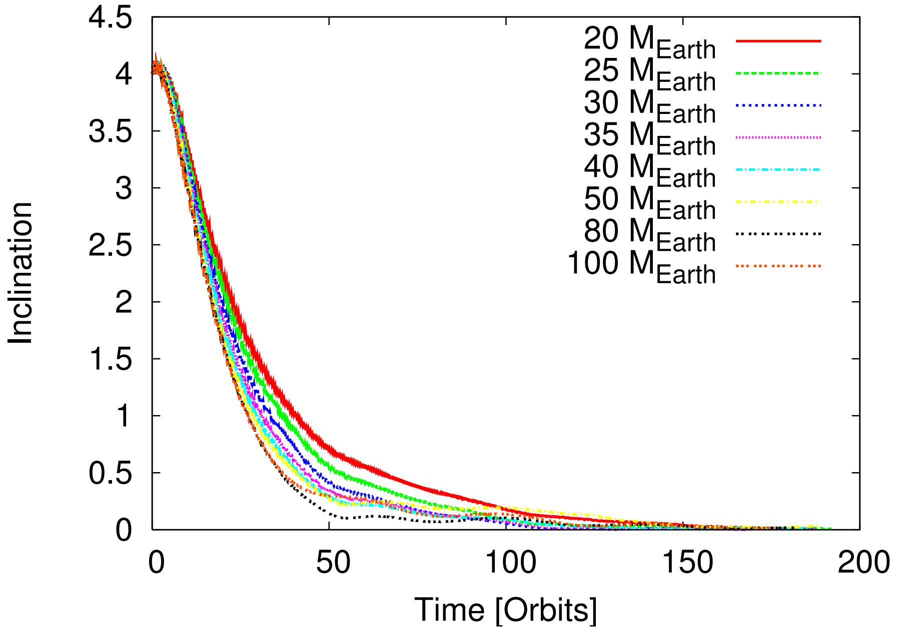
(Brown et al., 2012)

Planets in 3D radiative disks

Fix planet mass $M_\mathrm{p} = 20 M_\mathrm{Earth}$
- Vary inital Inclination

Vary Planet Mass $20 - 100 M_\mathrm{Earth}$
- Same $i_0 = 4$deg





(Cresswell ea 2007; Bitsch&Kley 2011)

- i-damping for all planet masses.

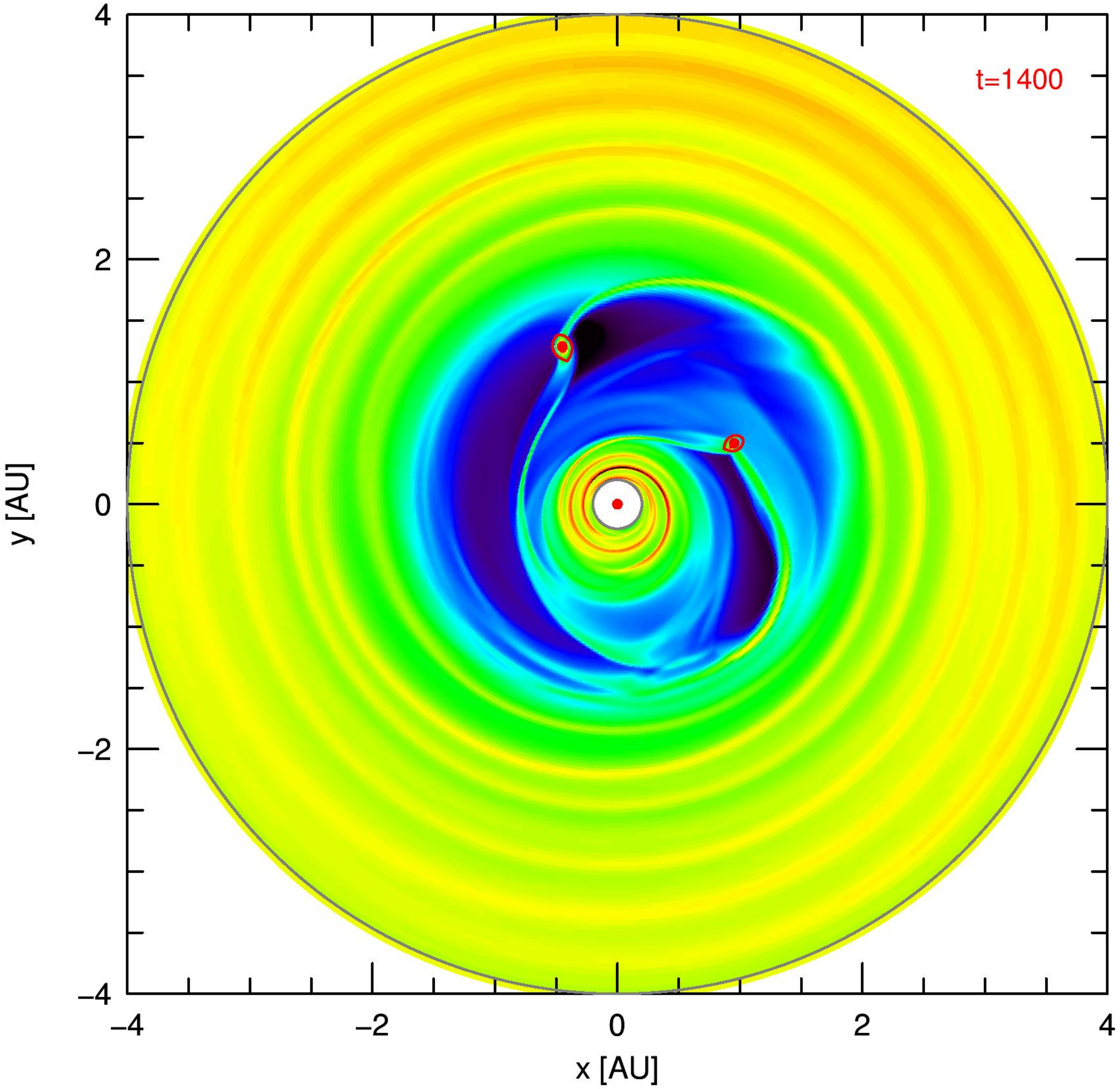
  Small i: exponential damping, large i: $\dot{i} \propto i^{-2}$

- Migration still outward upto $i \approx 4^o$

$\Longrightarrow$ Need multiple objects ! (Scattering)

Resonant capture

2 massive Planets in disk



Two planets:
joint, large gap

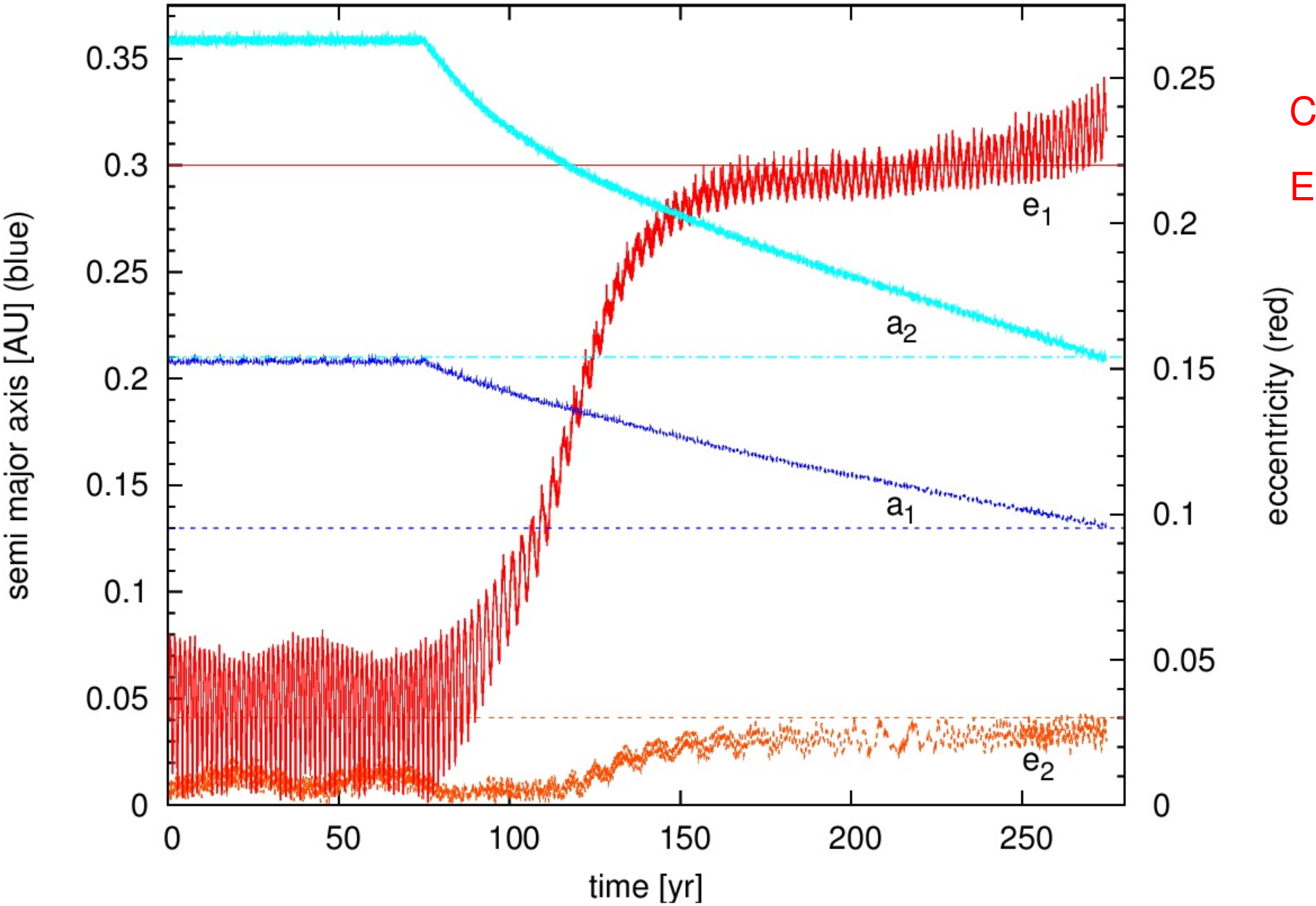
Outer planet :
Pushed inward

Inner planet :
Pushed outward

Seperation reduction:
Resonant capture

Pumping through Resonances

Here: System-parameter of GJ 876 (2 planets in 2:1 resonance, 60:30 days)



Compactification

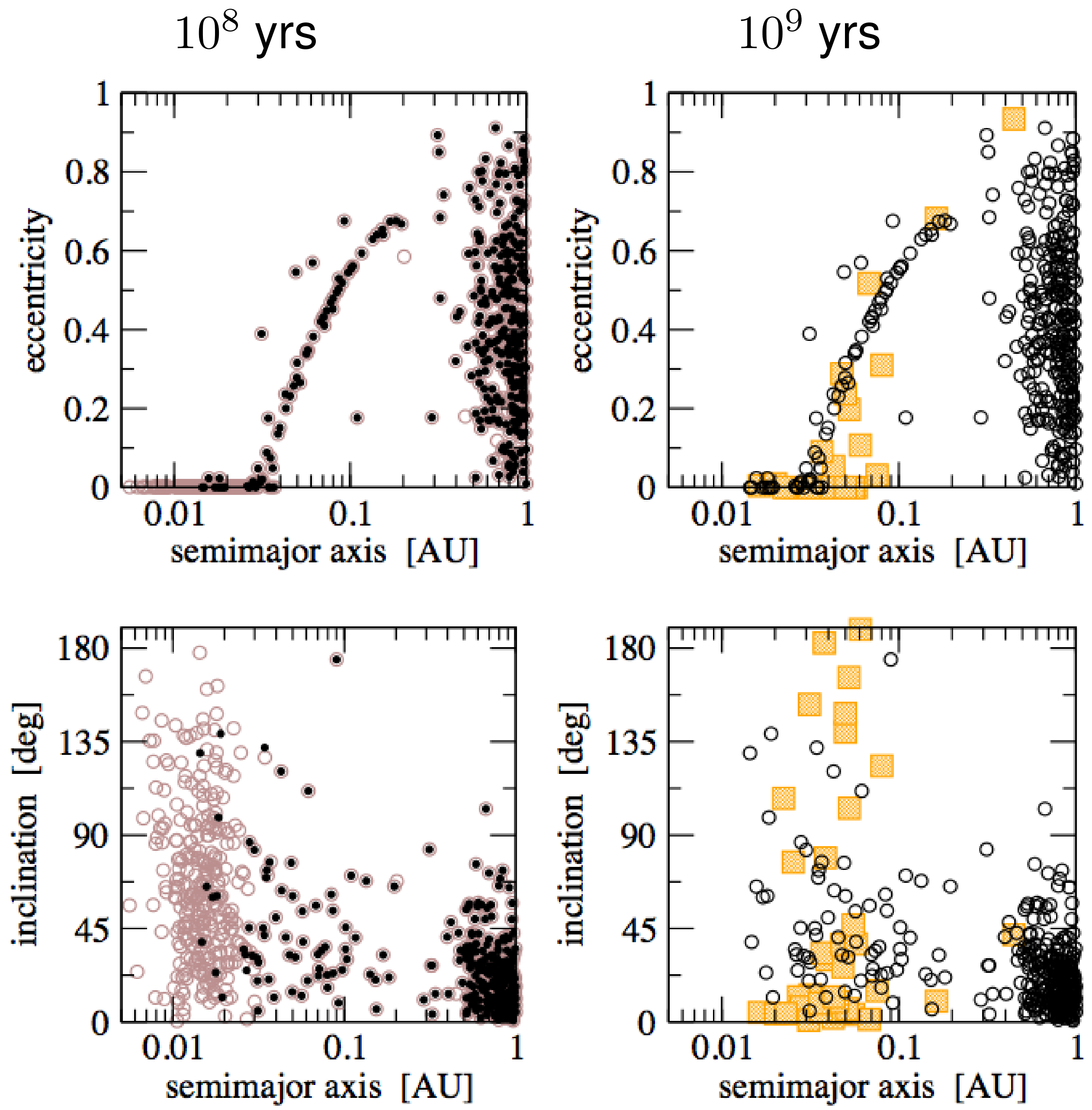
Excitation

(Crida ea., 2007)

System ends in: apsidal corotation, with correct eccentricities

Less disk damping: ⇒ much higher e ⇒ Instability

Producing Eccentricities & Inclinations



3 or 4 body simulations:

Start with:

- system close to resonance

Include:

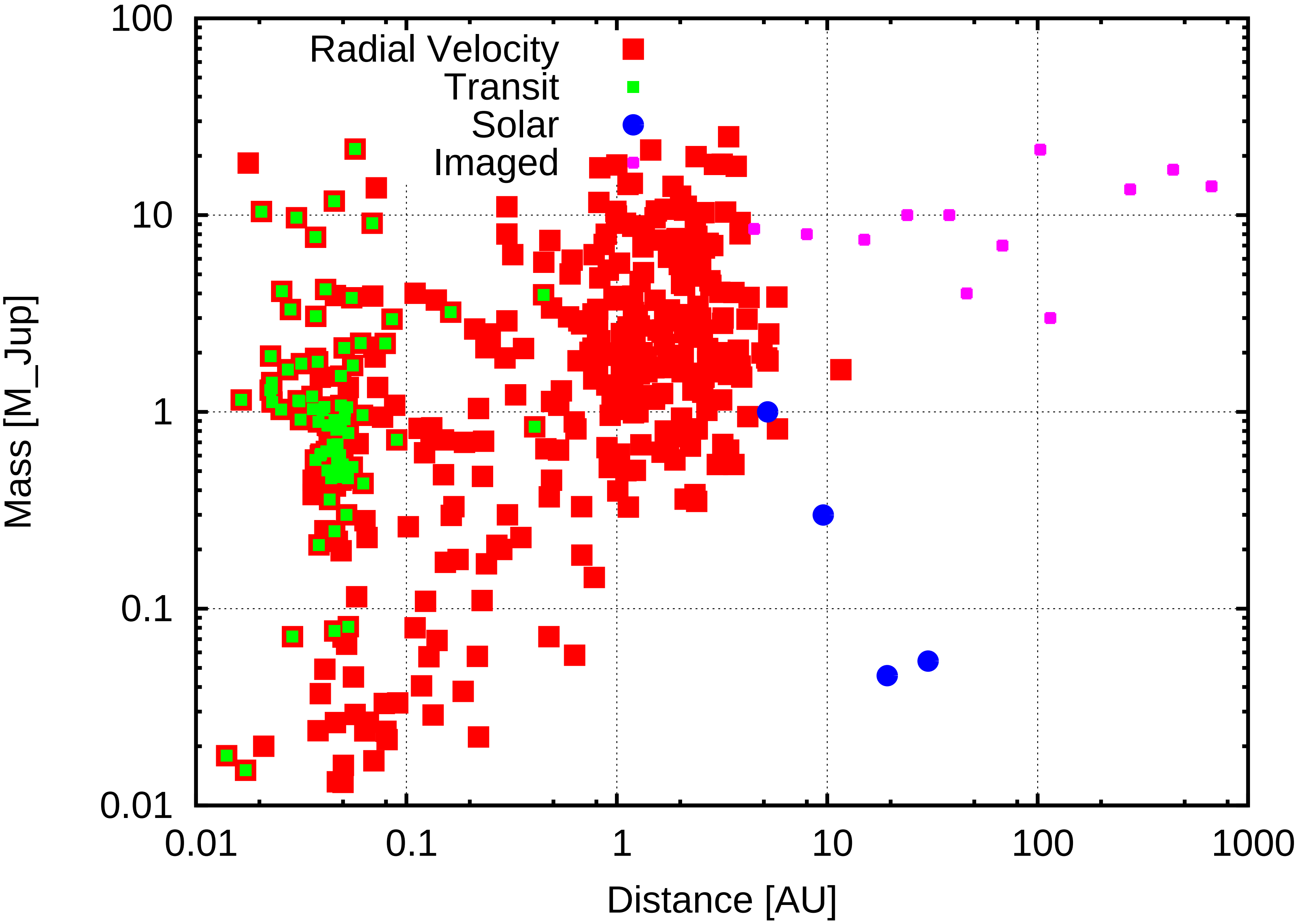
- star-planet interaction

(Beauge & Nesvorny 2012)

Directly imaged planets

Large distances (several hundred AU)

(Data: exoplanet.eu)



Principle

Consider local density perturbation in disk

Analytical

Stability-Criterion (Toomre)

$$Q \equiv \frac{c_s \kappa_0}{\pi G \Sigma_0} > 1$$

with

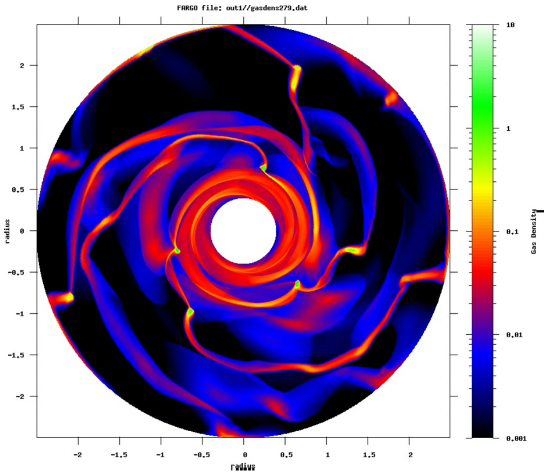
$c_s =$ sound velocity
$\kappa_0 =$ Epicyclic-Frequency (Ω_K)
$\Sigma_0 =$ surface density

- Pressure & Rotation stabilize
- Density destabilizes

Numerical

Evolution of an isothermal Disk

- Finite-Difference Hydrodynamics
- Viscous Disk



(Tobias Müller, Tübingen)

Disk heats up upon compression, need fast cooling

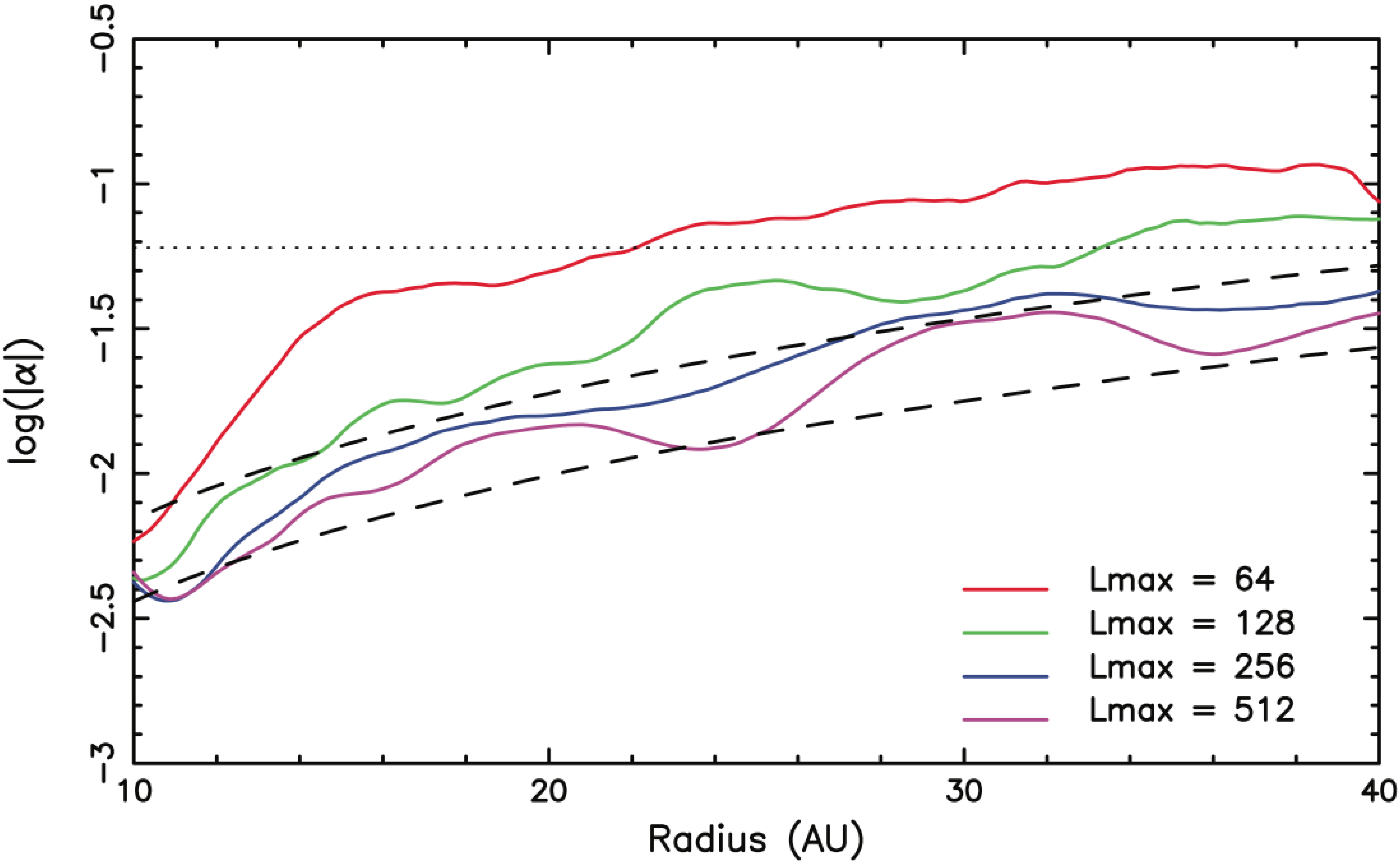
Require: coolingtime $\approx$ orbital period $\Rightarrow$ fast formation

Only in large distances from star (larger 40-50 AU, no cores)

Numerical Resolution I

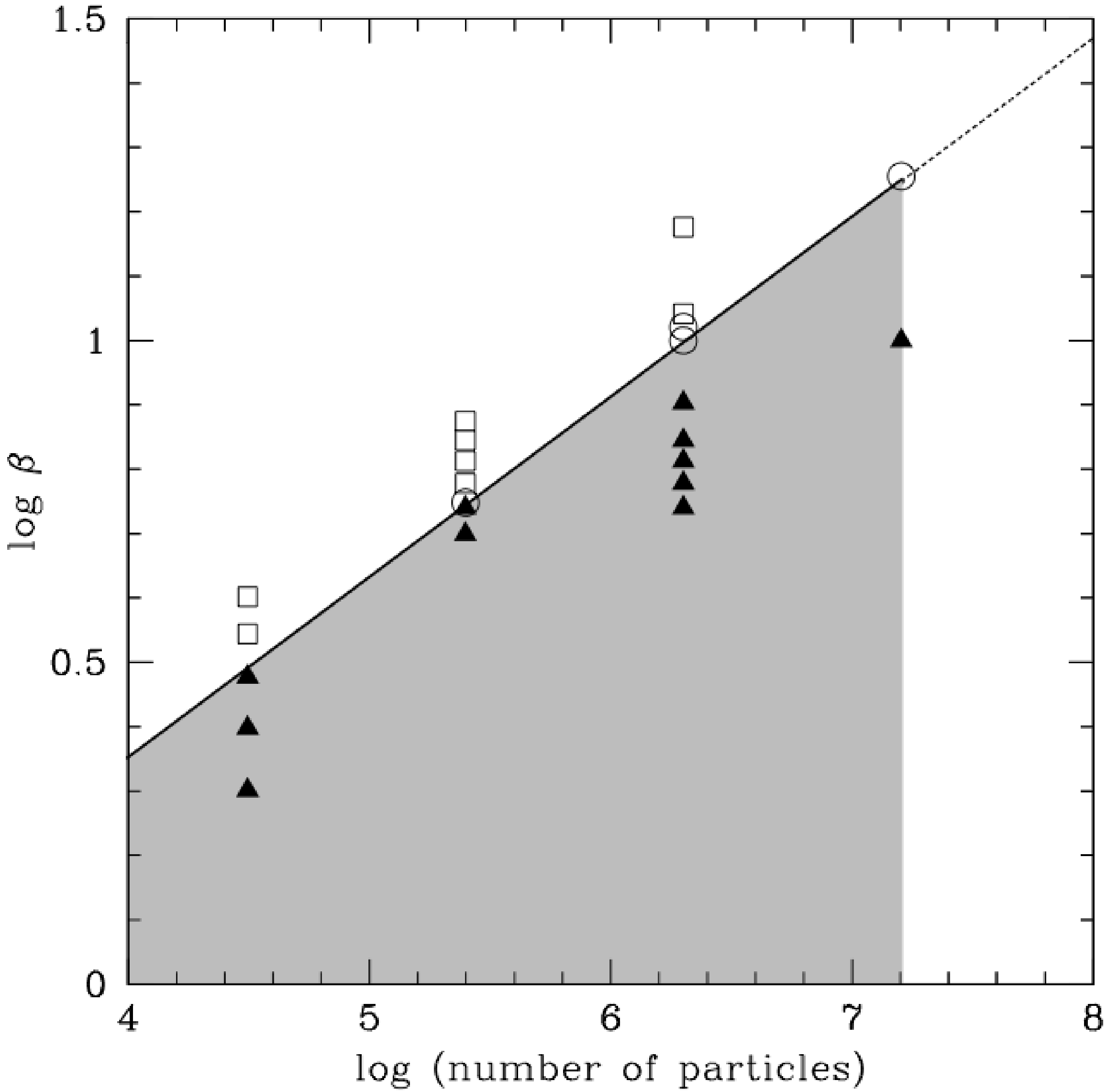
3D grid simulations - Gravitational stresses: $T_{r\varphi} \propto \int_{disk} g_r g_\varphi df$

- lower stresses for higher resolution



(Scott ea. 2012)

Numerical Resolution II



(Meru & Bate 2010)

3D SPH simulations

$$\tau_{cool} = e_{th} / \left(de_{th}/dt \right)$$

$$\tau_{cool} = \beta \, \Omega^{-1}$$

Test Instability:
☐ stable
▲ fragmenting

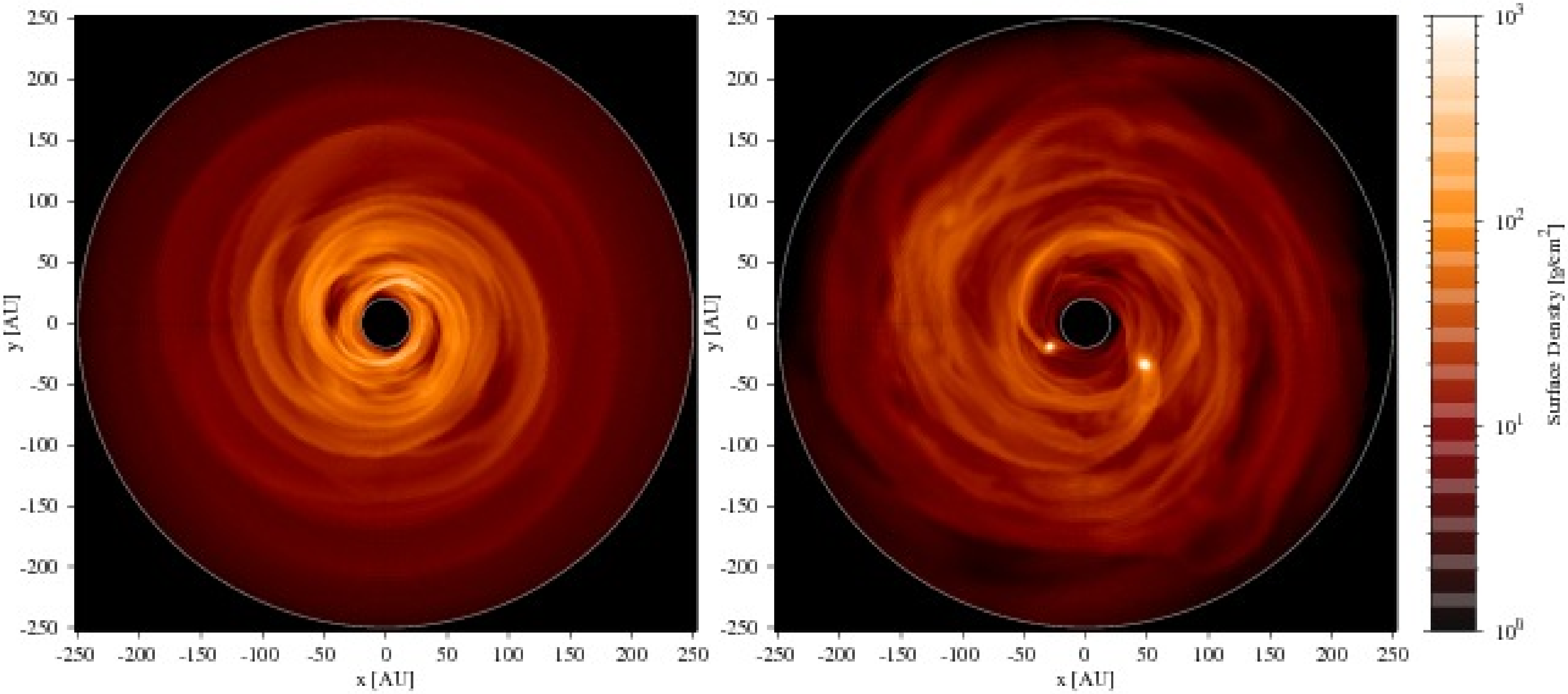
More fragmentation
in HighRes disks

Potential smoothing

2D Grid simulations (`FARGO`) (smoothing takes vertical height into account)

$$\Psi =\propto \frac{1}{(s^2+\epsilon^2)}$$

$\epsilon = 0.6H$ $\epsilon = 0.006H$ (Müller, Kley & Meru 2012)



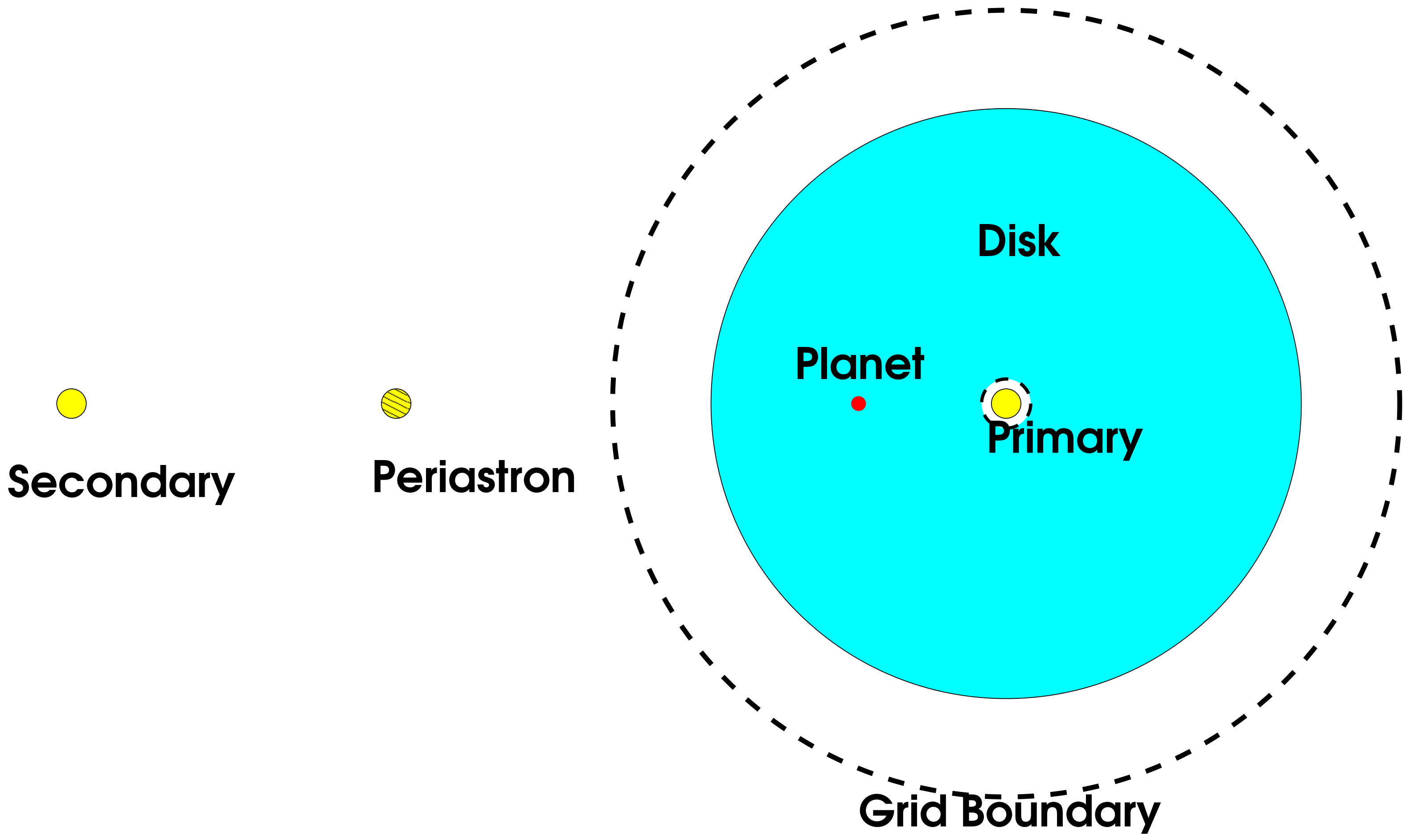
Realistic smoothing: $\epsilon \approx H$ $\Rightarrow$ Less fragmentation

Open issues

- Numerics
- Cooling efficiency
- Irradiation from star
- Fate of fragments
  - tidal disruption
  - core formation
  - relation to FU Ori

Talk by: S. Nayakshin

Numerical Setup



Binary (γ Cephei)

M$_1$=1.4 M$_\odot$, M$_2$=0.4M$_\odot$, a_b=20 AU, e_b=0.4

Grid: [0.5, 8.0] AU

Disk-Dynamics

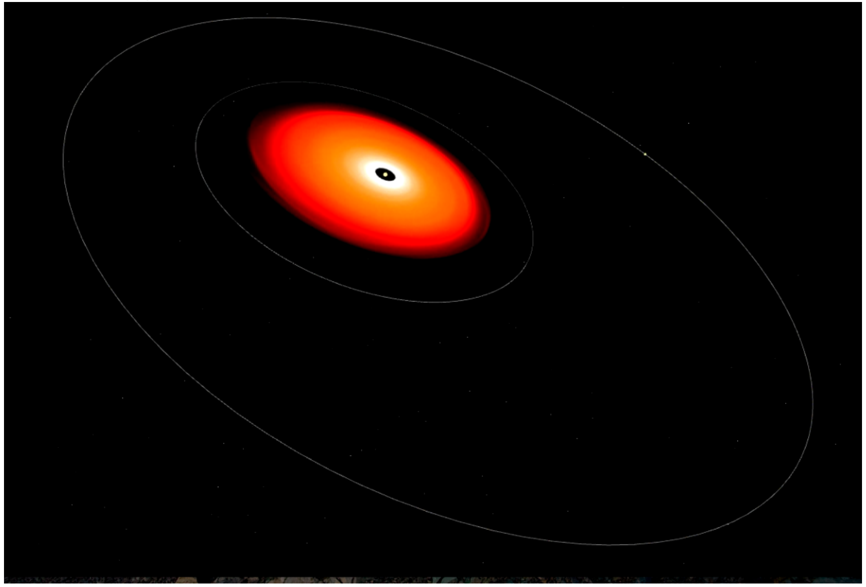
2D viscous accretion disk

locally isothermal

$r_{\min} = 0.5, r_{\max} = 8.0$ AU

Grid: 256 × 576

Density structure:



(Tobias Müller)

Strong dynamical interaction

$\Rightarrow$ Planet Formation more difficult

(A. Nelson, 2001)

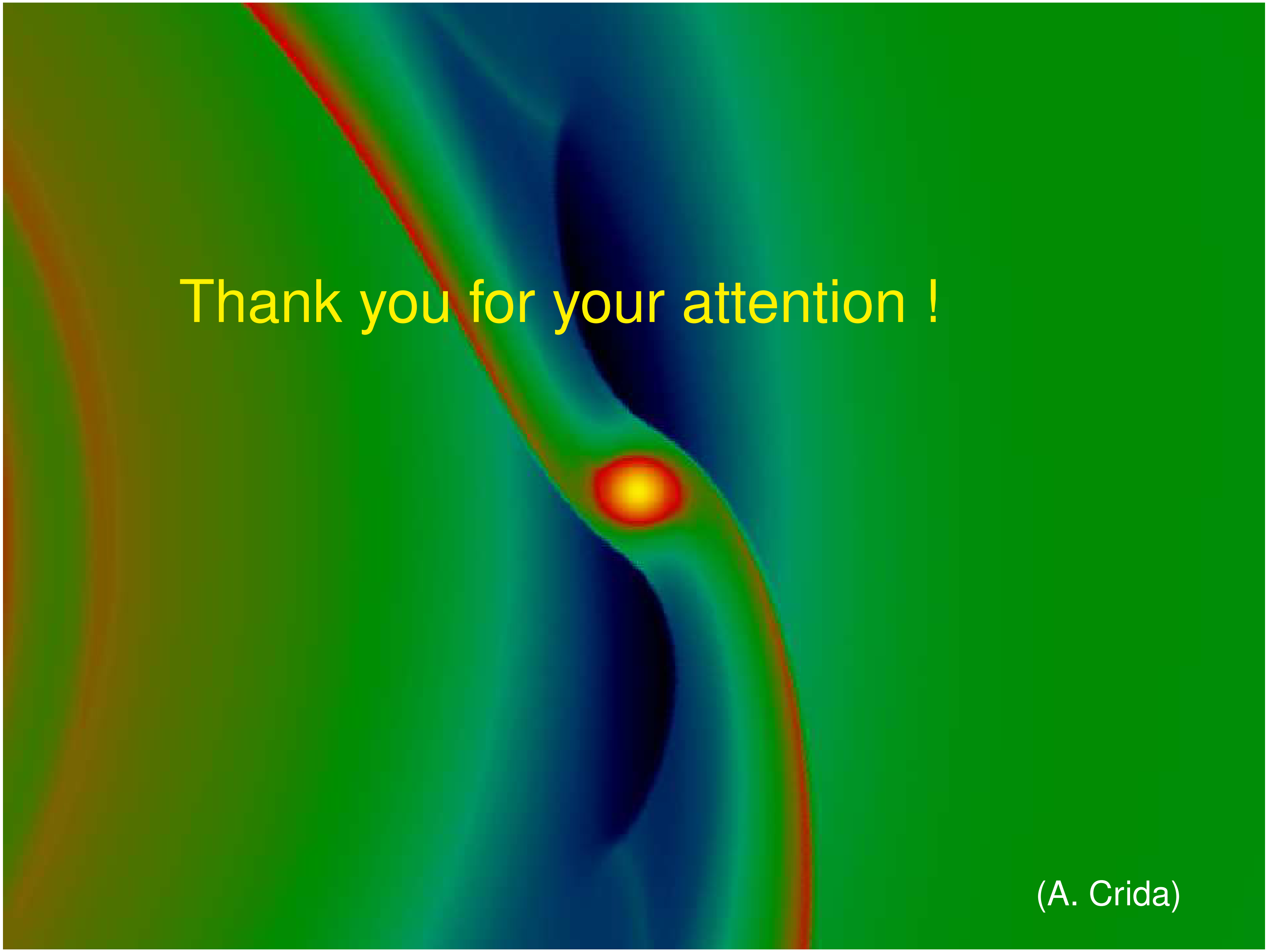
both: sequ. acc. & GI

- Disk heating
- Enhanced collision velocities

Summary

- Planets form in disks
  - flat systems
- Planet-disk interaction moves planets
  - Inward for isothermal disks
  - possibly outward/slowed in radiative disks
- Eccentricity & Inclination damped by disk
- Eccentric & inclined planets through scattering
- Distant planets through gravitational instability
- Planet formation in binaries more difficult

The End



Thank you for your attention !

(A. Crida)