Planet formation and (orbital) Evolution

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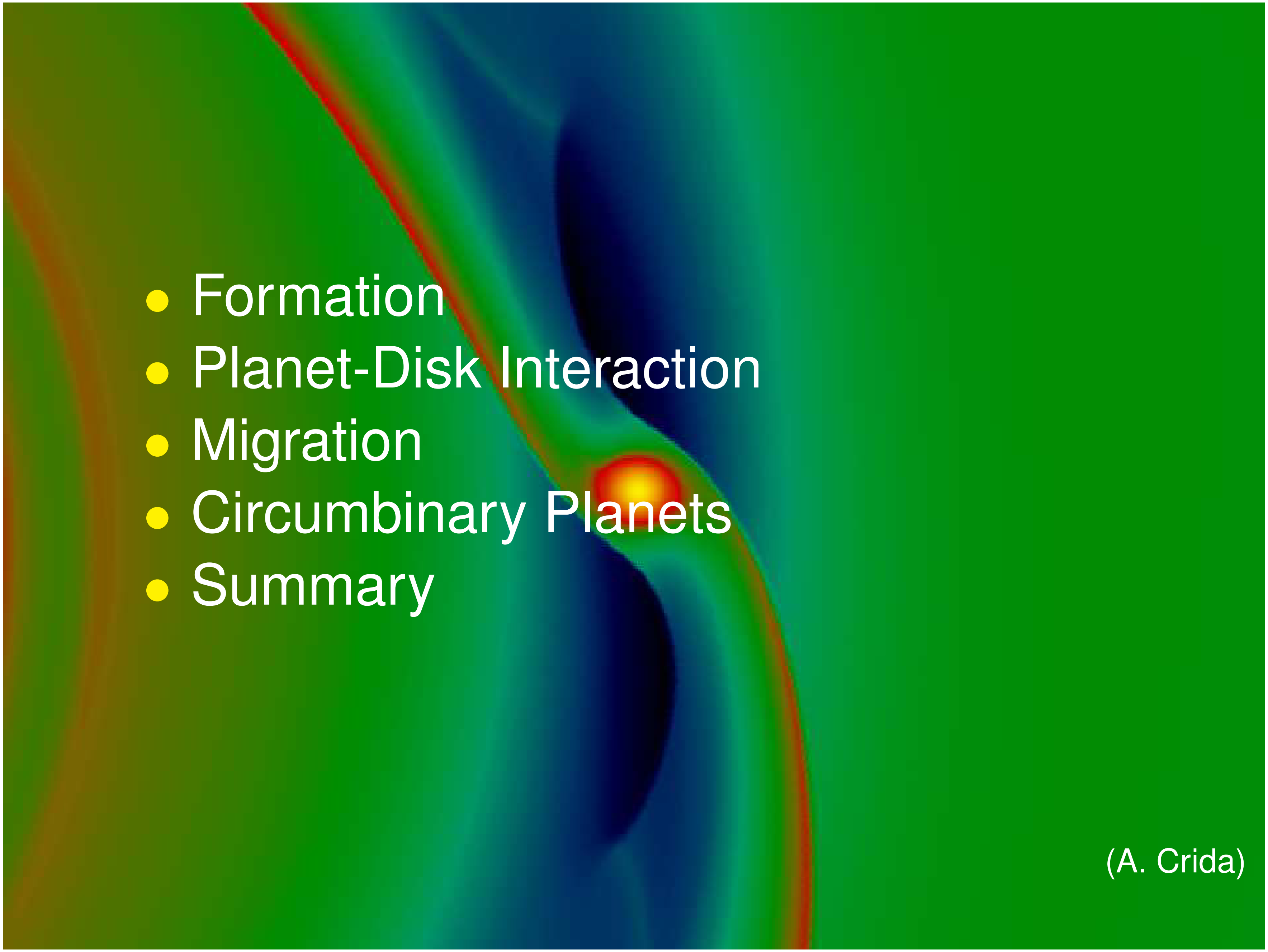
31. July, 2013

Organisation

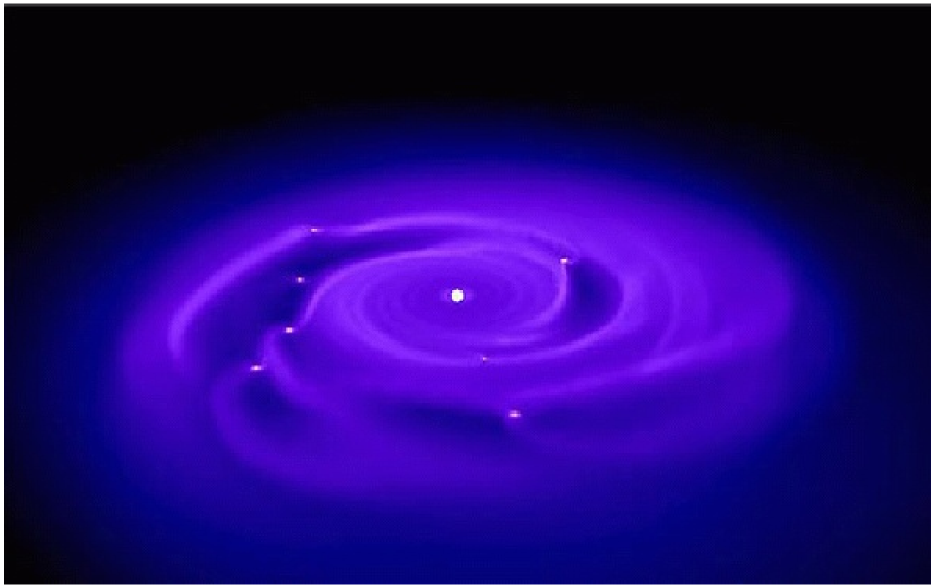


- Formation
- Planet-Disk Interaction
- Migration
- Circumbinary Planets
- Summary

(A. Crida)

Two main scenarios

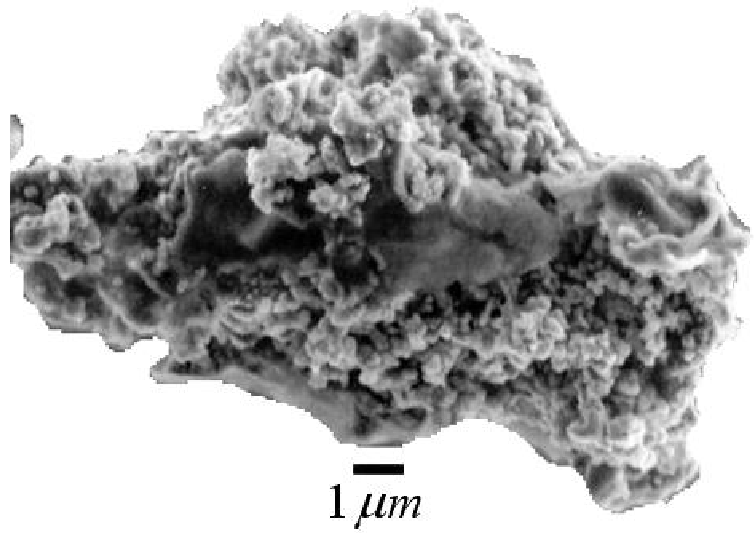
Gravitational-Instability (top-down)



(L. Mayer)

Self-gravitating disk
Density-Fluctuations grow
Spiral arms ⇒ planets
Fast formation (10^3 years)
Core Formation ?
(possibly for distant planets)

Sequential Accretion (bottom-up)



(NASA, U2)

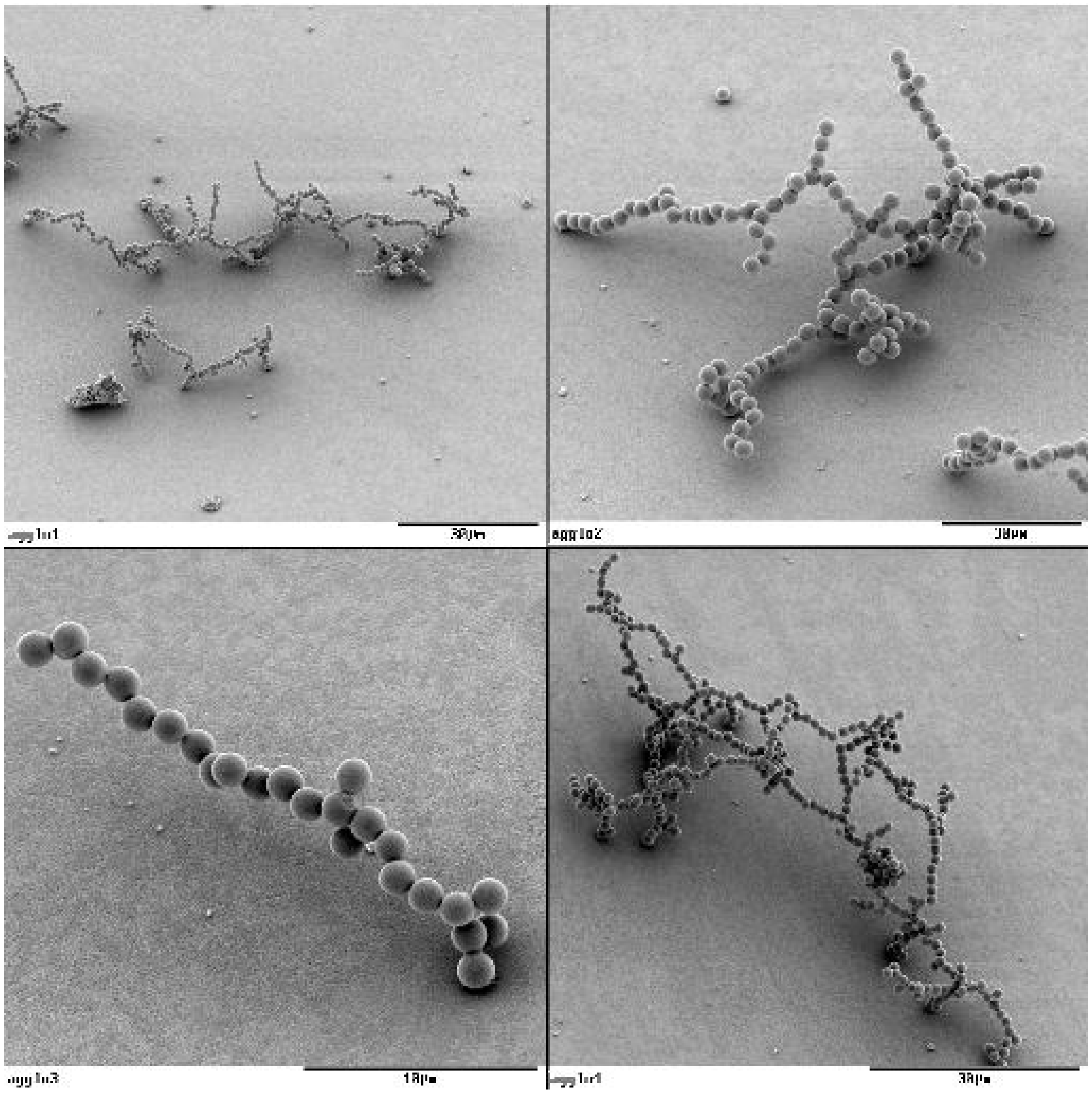
From small to large particles
Slow formation (10^6 Years)
Need: High sticking probability

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

Formation

Dust Growth

Laboratory-Experiments μm-sized particles



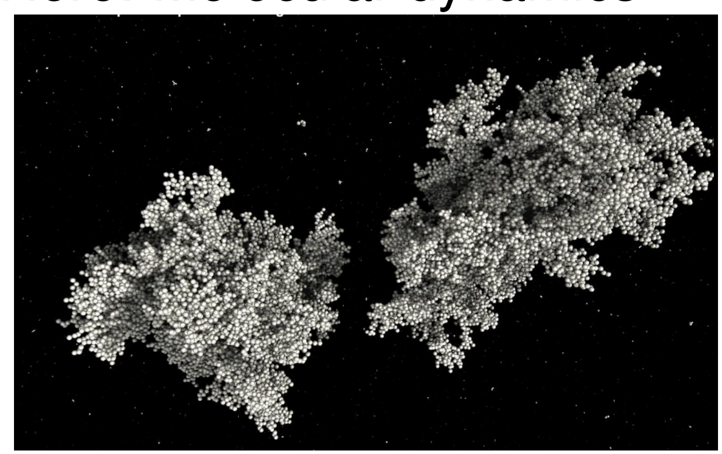
(J. Blum, Braunschweig)

Sticking through:
Van der Waals forces

Fractal Growth:
works up to cm-sizes
for ices much larger

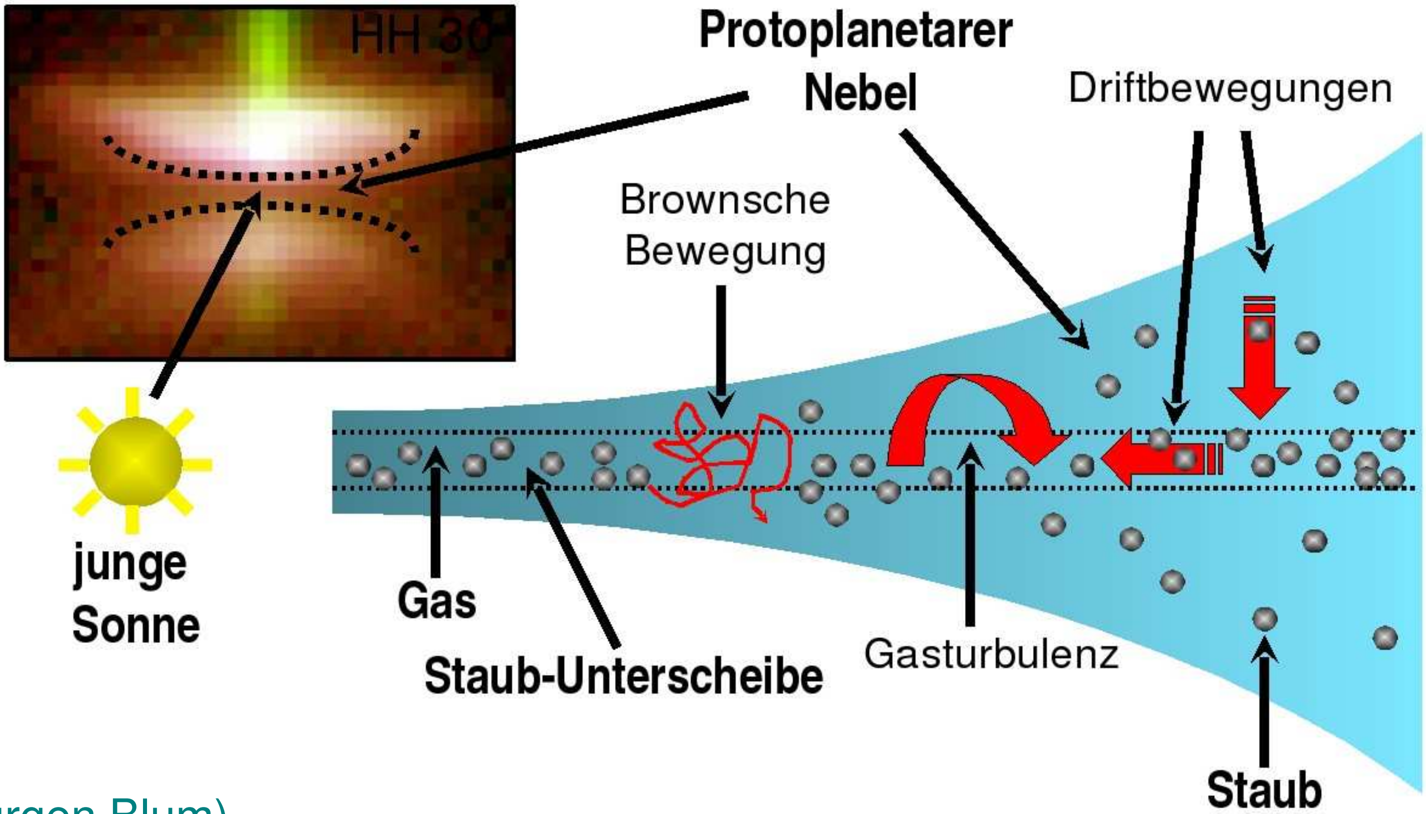
followed by compaction

Numerical Simulations
Here: Molecular dynamics



(Alexander Seizinger, Tübingen)

Particle dynamics in disk



(Jürgen Blum)

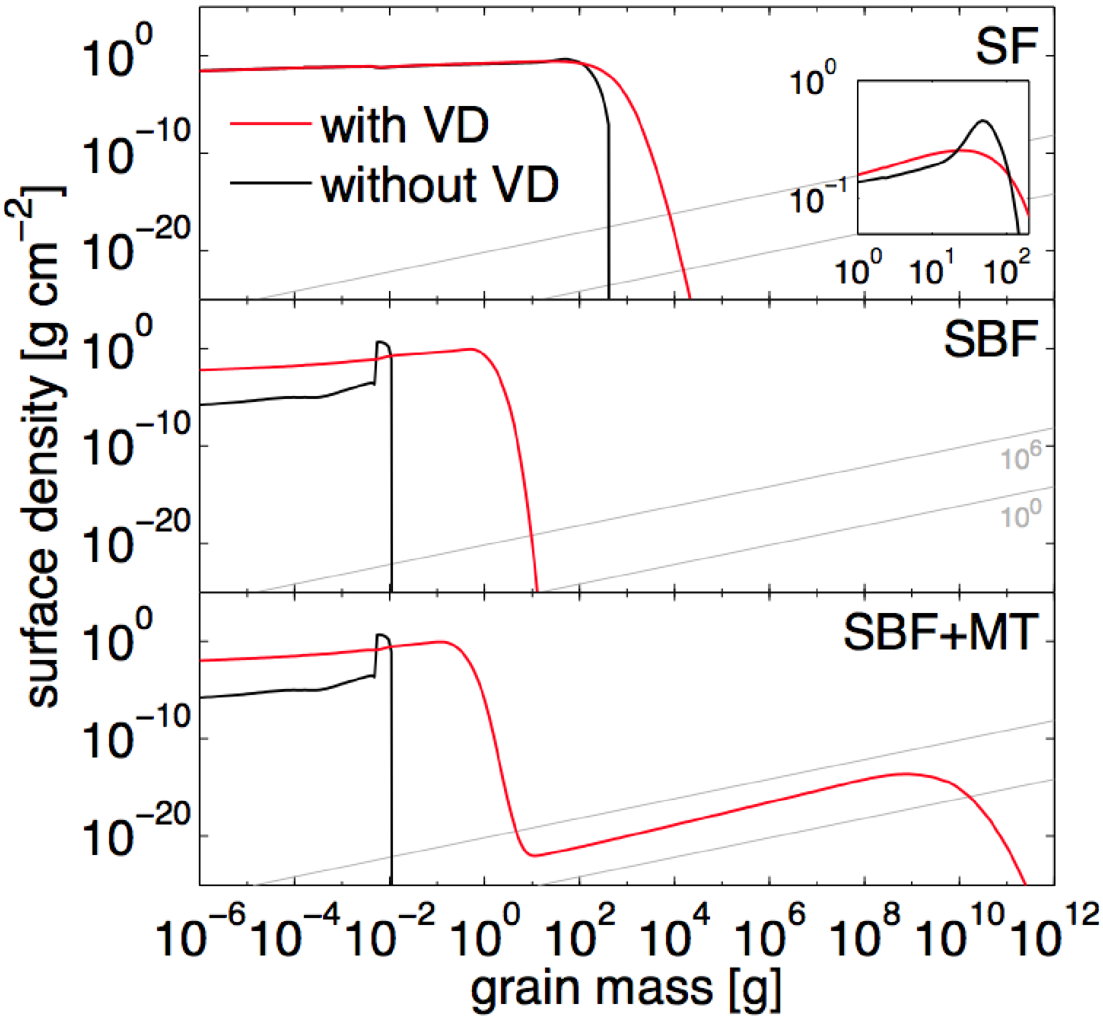
Particles have relative velocity with respect to the gas ⇒ frictional forces

Problem I: Fast radial drift towards star (for 1m Size: 1 AU / 100 Years)
Problem II: Destructive Collisions (Bouncing)

Note: Disk is hotter near central star, better condensation beyond iceline

Mediating Growth

Enhanced Growth via a velocity distribution



SF:
Sticking + Fragmentation

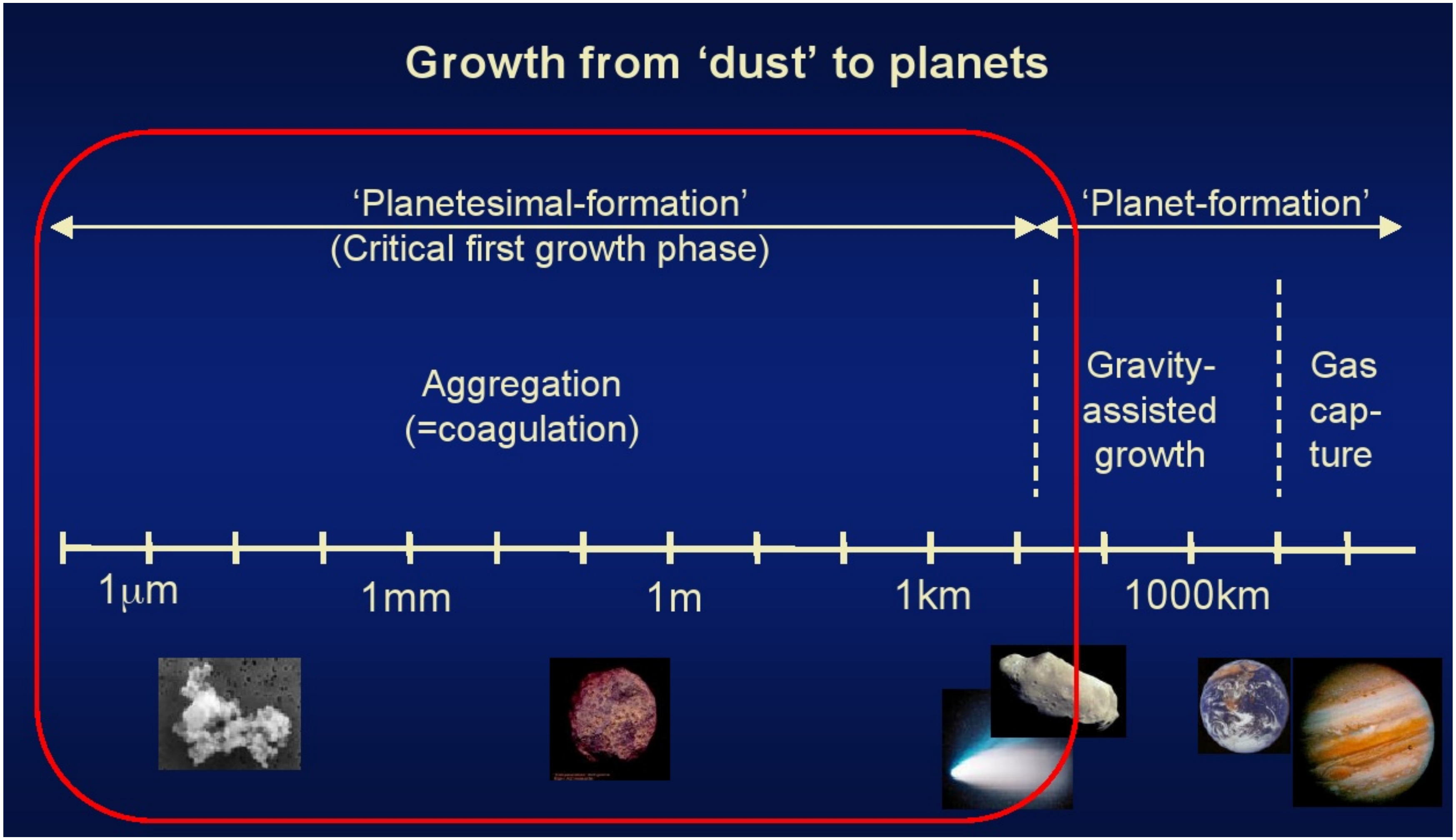
SBF:
Sticking, Bouncing & Fragmentation

SBF+MT:
mass transfer added

(Fredrick Windmark)

Other options: Dust in inhomogeneities (turbulence, vortices, pressure jumps)

How to form massive planets



(C. Dullemond)

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

Planet 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
- Eccentric and inclined orbits
  - planets form in flat disks (on circular orbits)

But planets grow in disks:

$\Rightarrow$ Have a closer look at planet-disk interaction

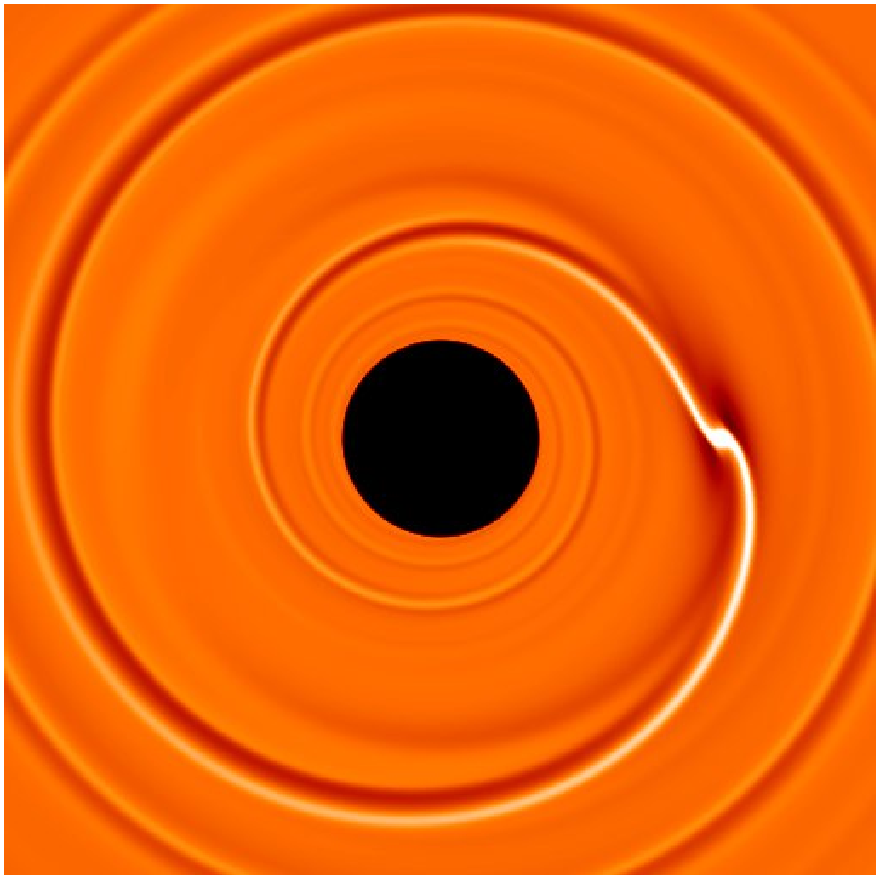
Have two contributions: Spiral arms & Corotation effects

(more details: Annual Review article by 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,
- Hydro simulations



(Masset, 2001)

Inner Spiral
- pulls planet forward:
- positive torque

Outer Spiral
- pulls planet backward:
- negative torque

$\longrightarrow$ Net Torque

$\Longrightarrow$ Migration

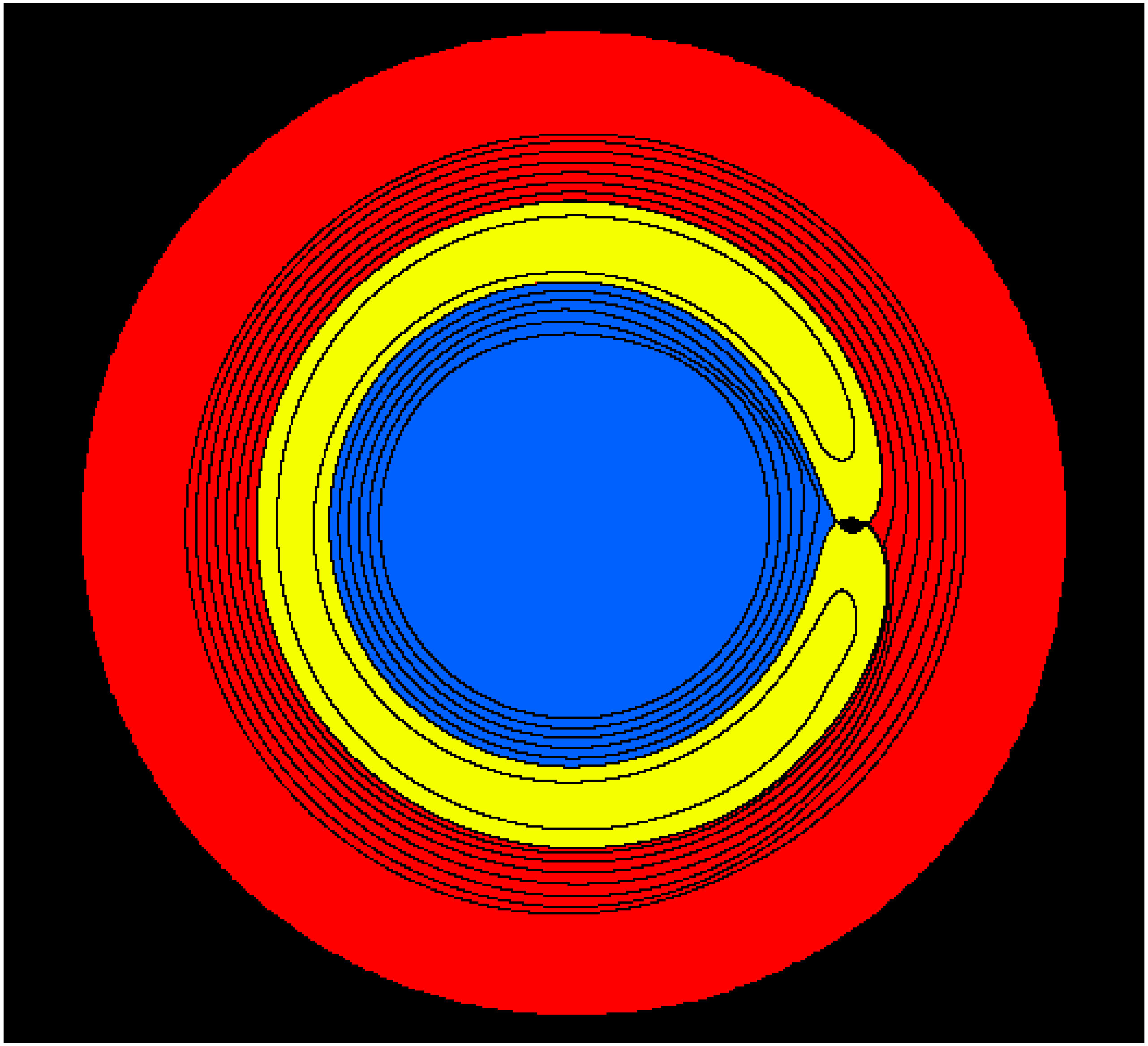
Most important:
Strength & Direction ?

Typically: Outer spiral wins
$\Longrightarrow$ Inward Migration

Explains Hot Jupiters

But: Too rapid !

Corotation Torque (Horseshoe region)



(F. Masset)

3 Regions

Outer disk (spiral)
Inner disk (spiral)
$\Longrightarrow$ Lindblad torques

Horseshoe (coorbital)
$\Longrightarrow$ Corotation Torques
(Horseshoe drag)

Scaling with:
- Vortensity gradient
(Vorticity/density)

Positive or negative

Counterbalances
Lindblad Torques

The linear isothermal Torque

Torque **on** the planet:

$$\Gamma_{\rm tot} = - \int\limits_{\rm disk} \Sigma(\vec{r}_{\rm p} \times \vec{F})\, df \;=\; \int\limits_{\rm disk} \Sigma(\vec{r}_{\rm p} \times \nabla\psi_{\rm p})\, df \;=\; \int\limits_{\rm disk} \Sigma \frac{\partial \psi_{\rm p}}{\partial \varphi} df \qquad (1)$$

3D analytical (Tanaka et al. 2002) and numerical (D'Angelo & Lubow, 2010)

$$\Gamma_{\rm tot} = -(1.36 + 0.62\beta_\Sigma + 0.43\beta_T)\,\Gamma_0. \qquad (2)$$

where

$$\Sigma(r) = \Sigma_0\, r^{-\beta_\Sigma} \qquad \text{and} \qquad T(r) = T_0\, r^{-\beta_T} \qquad (3)$$

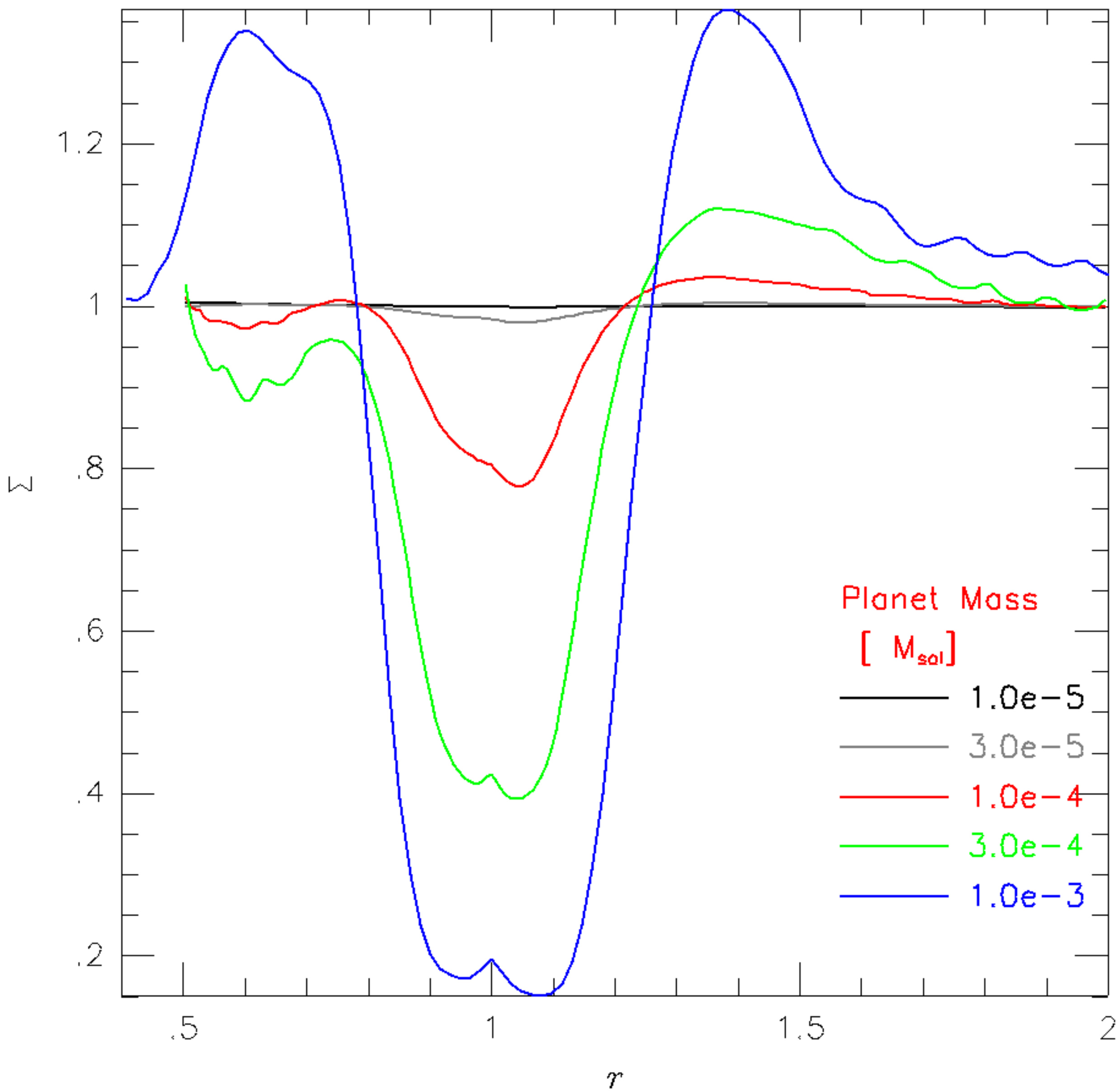
and normalisation

$$\Gamma_0 = \left(\frac{m_{\rm p}}{M_*}\right)^2 \left(\frac{H}{r_{\rm p}}\right)^{-2} \left(\Sigma_{\rm p} r_{\rm p}^2\right)\, r_{\rm p}^2 \Omega_{\rm p}^2, \qquad (4)$$

$$\Rightarrow \text{ Migration } \quad \dot{J}_{\rm p} = \Gamma_{\rm tot} \quad \Rightarrow \quad \frac{\dot{a}_{\rm p}}{a_{\rm p}} = 2\,\frac{\Gamma_{\rm tot}}{J_{\rm p}} \qquad (5)$$

Low Planet Mass (Type I): Typically Negative & fast

Gap formation: 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

Planet moves with
(viscous) disk

Saturation - Effect

2D hydro-simulations:
- small mass
- inviscid

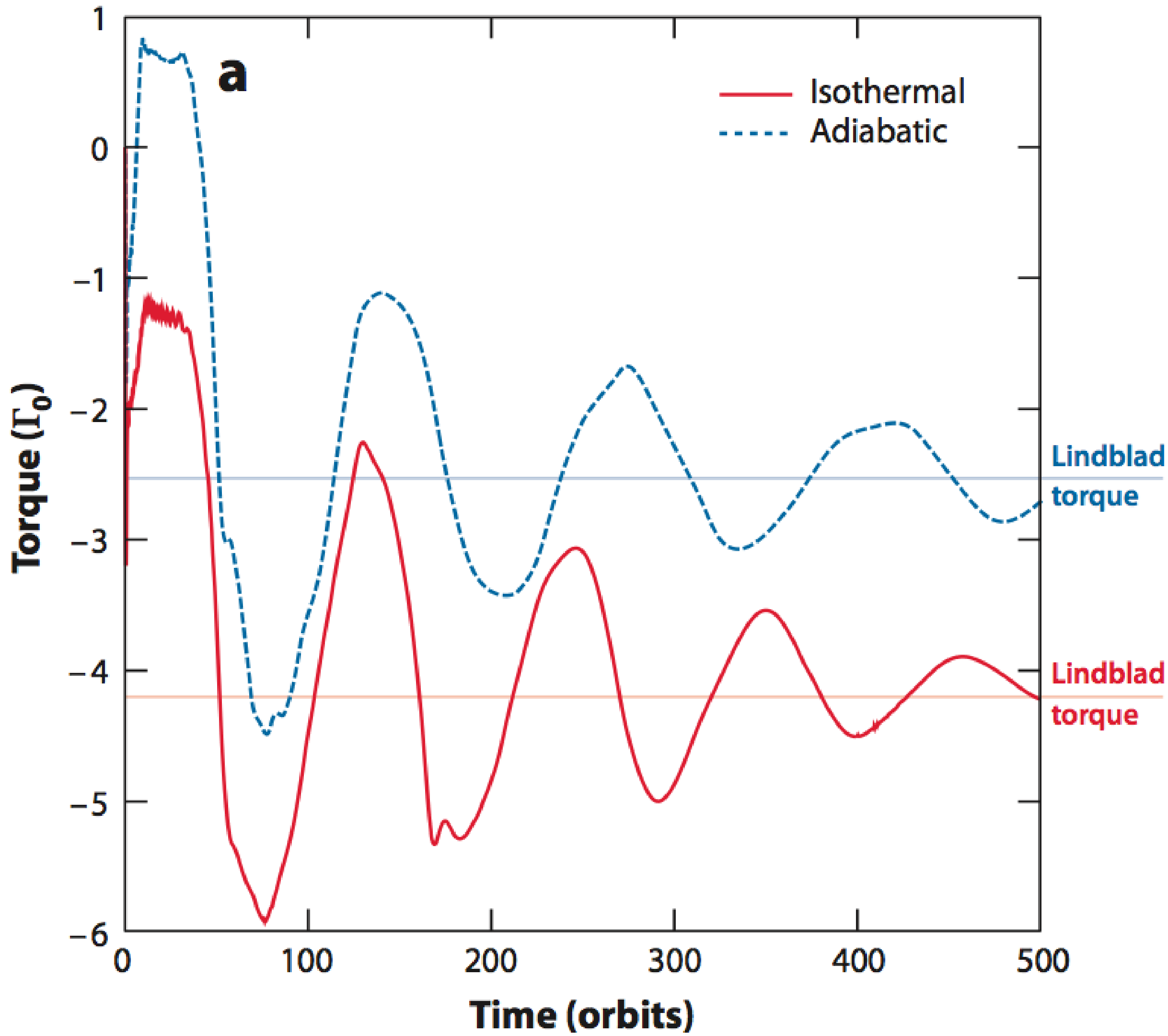
Note:
for barotropic and inviscid flows:

$$\frac{d}{dt}\left(\frac{\omega_z}{\Sigma}\right) = 0$$
$$\frac{dS}{dt} = 0$$

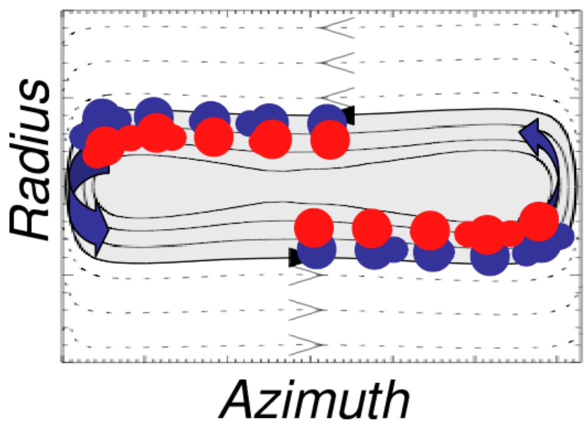
Torque depends on:
Gradients of ω_z/Σ, S
ω_z Vorticity
S Entropy

Gradients are wiped out in the corotation region

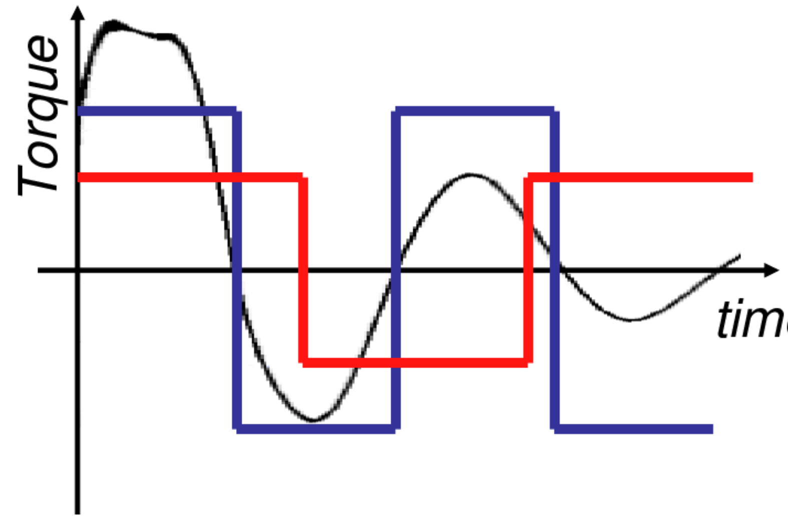
Total torque vs. time - isothermal - adiabatic



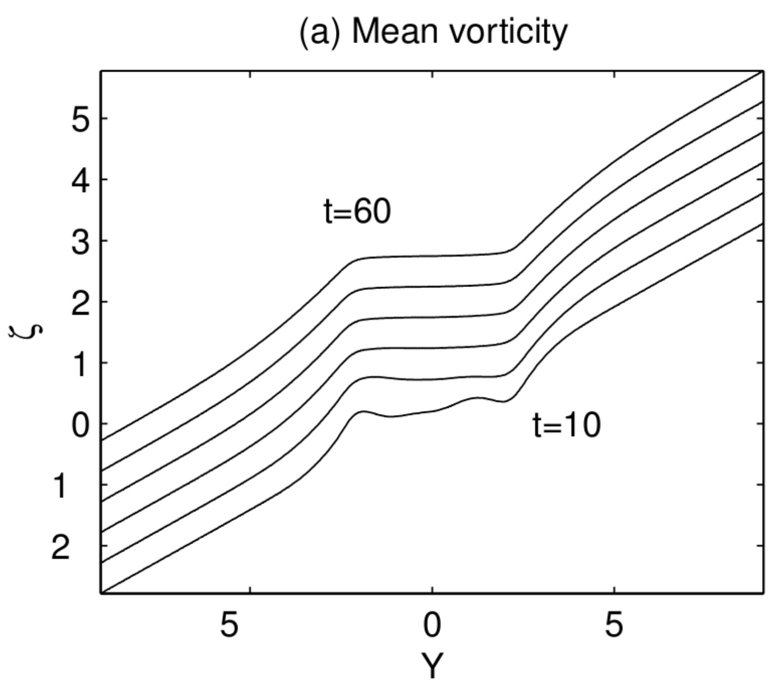
Saturation - Origin



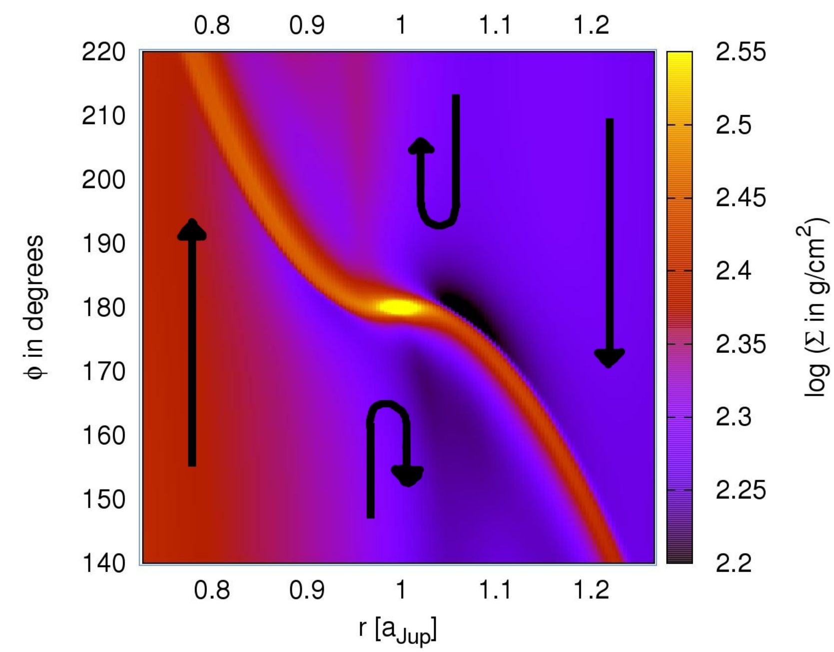
(F. Masset)



Red and Blue Orbits have different periods
⇒ Phase mixing



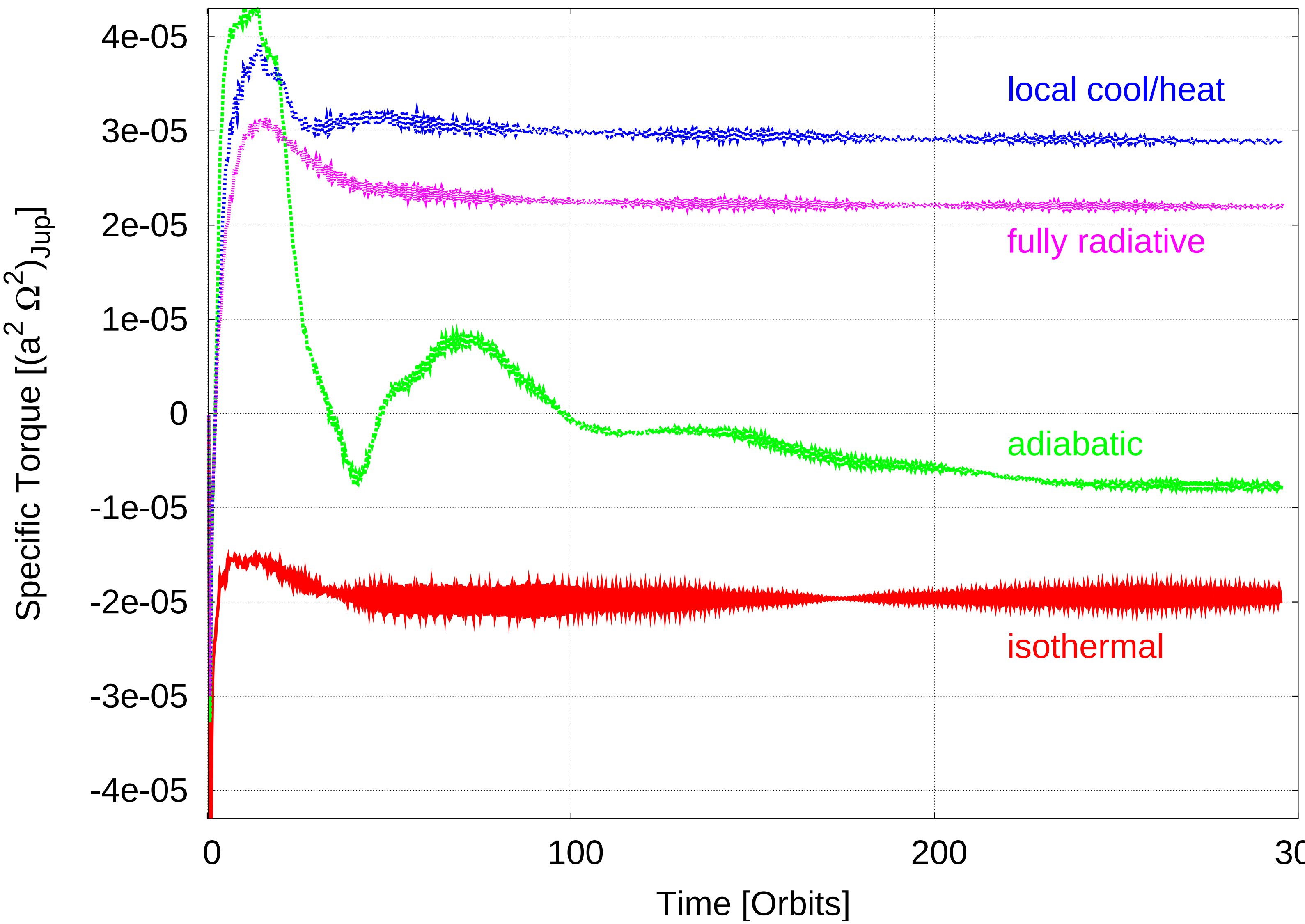
(Balmforth & Korycanski)



3D radiative disk (B. Bitsch)

Torques maintained in radiative disks

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



$M_p = 20\ M_{\rm Earth}$

Outward Migration

Inward Migration

(Kley&Crida '08)

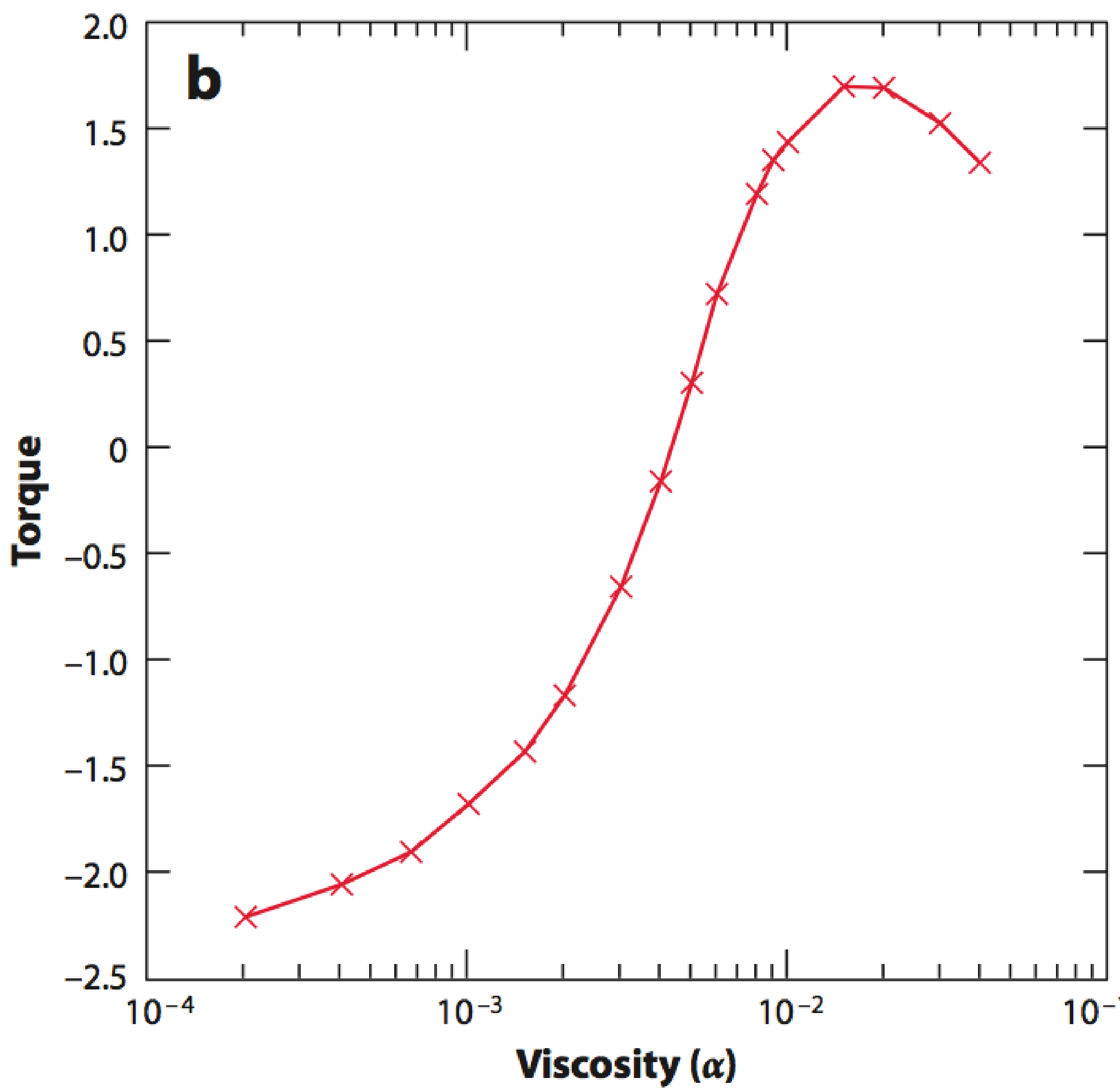
Role of viscosity

Total torque
vs. viscosity:

in viscous α-disk
2D radiative model
- in equilibrium

Efficiency depends
of ratio of timescales
$\tau_{\rm visc}/\tau_{\rm librat}$
$\tau_{\rm rad}/\tau_{\rm librat}$

Local disk properties
matter

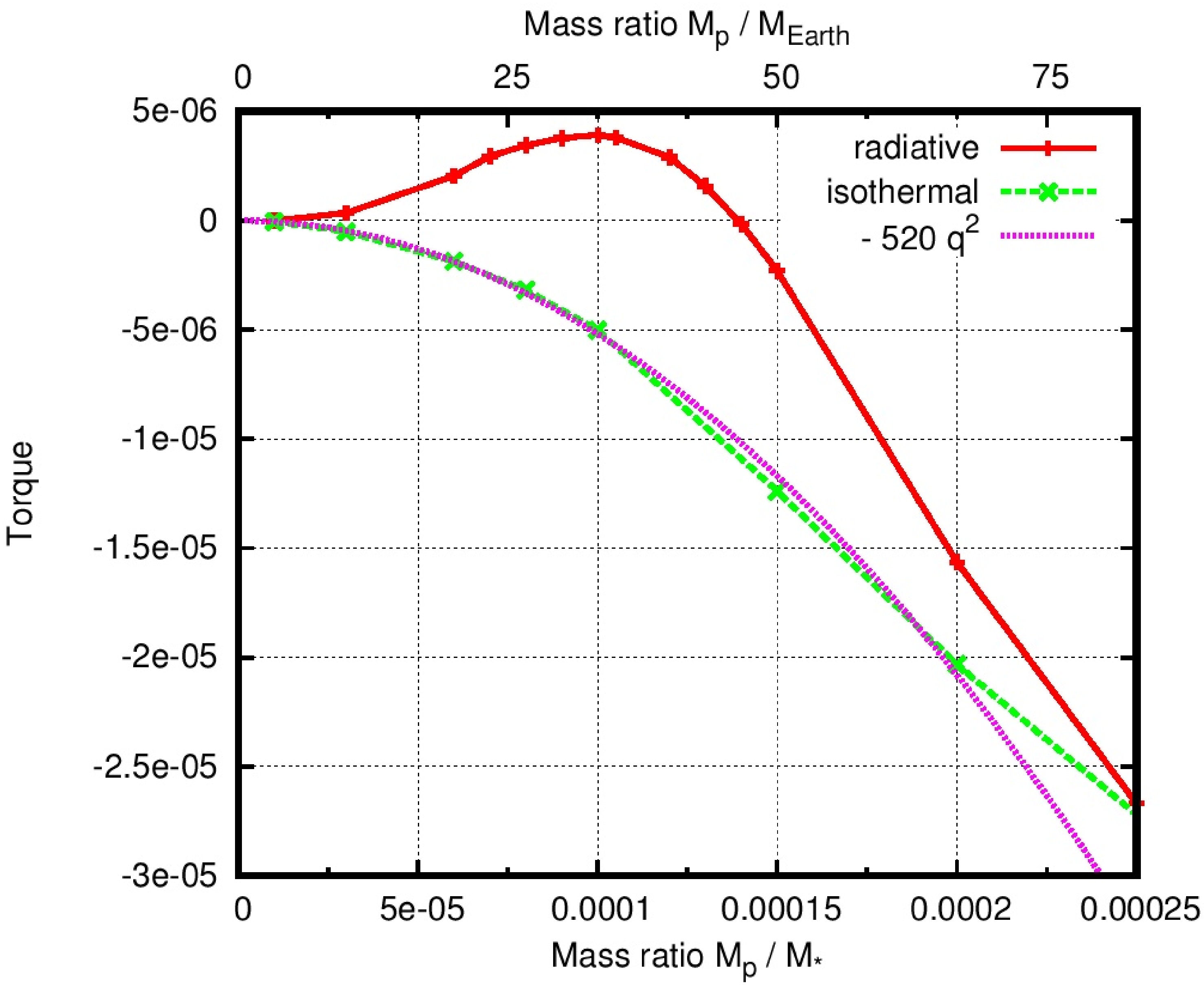


(Kley & Nelson 2012)

⇒ Need viscosity to prevent saturation !

Mass dependence

Isothermal and radiative models. Outward migration for $M_p \leq 40\ M_{Earth}$



Vary M_p

(Kley & Crida 2008)

In full 3D

(Kley ea 2009)

With irradition:

Bitsch ea. (2012)

Evidence

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

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

  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

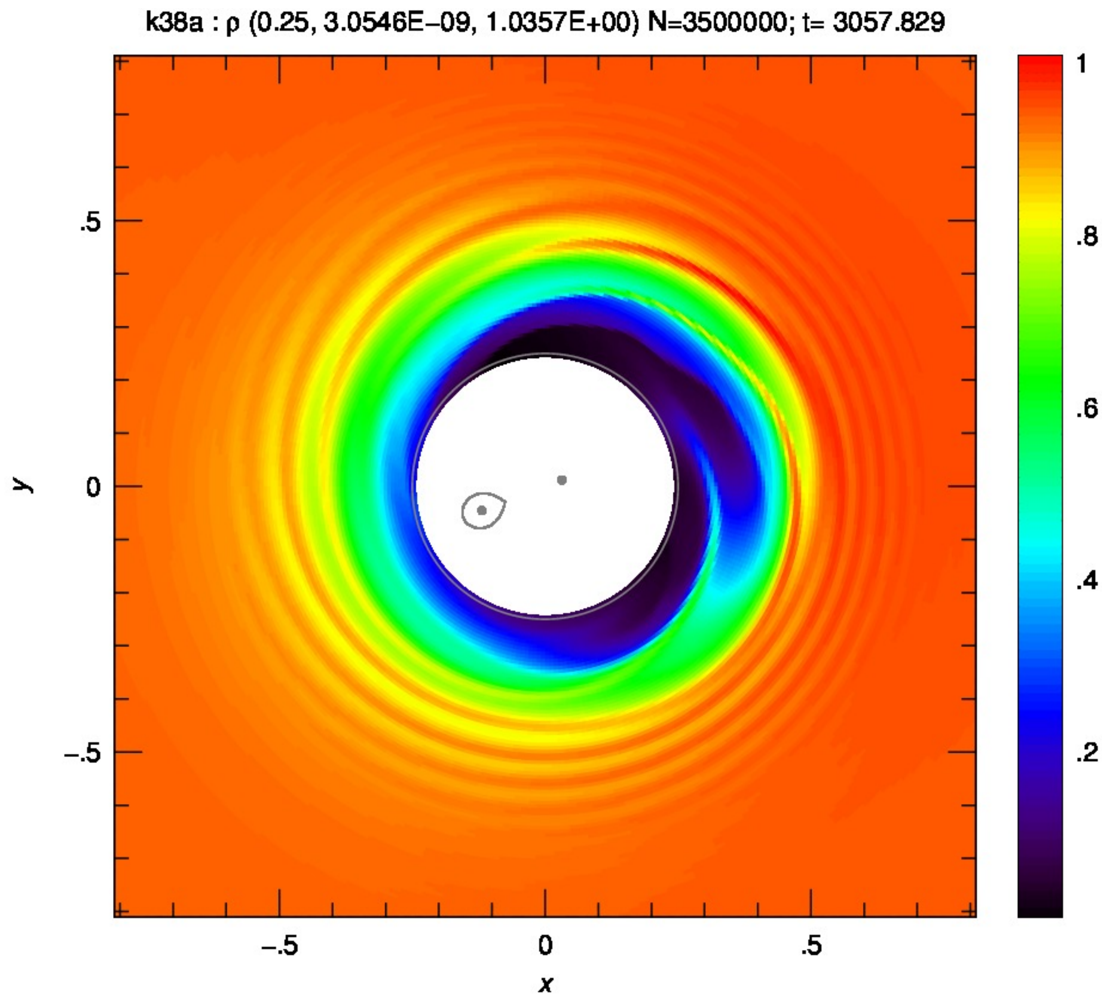
 - Clear evidence for planetary migration (next Talk: R.Nelson)

- Hot Jupiters (Neptunes) & Kepler systems

 - Clear evidence for planetary migration

Kepler 38

Animation of disk around Binary Star
(shown is the surface density)



Binary Parameter:

$M_1 = 0.95 M_\odot$,

$M_2 = 0.25 M_\odot$

$a_B = 0.15$ AU

$e_B = 0.10$

Planet Parameter:

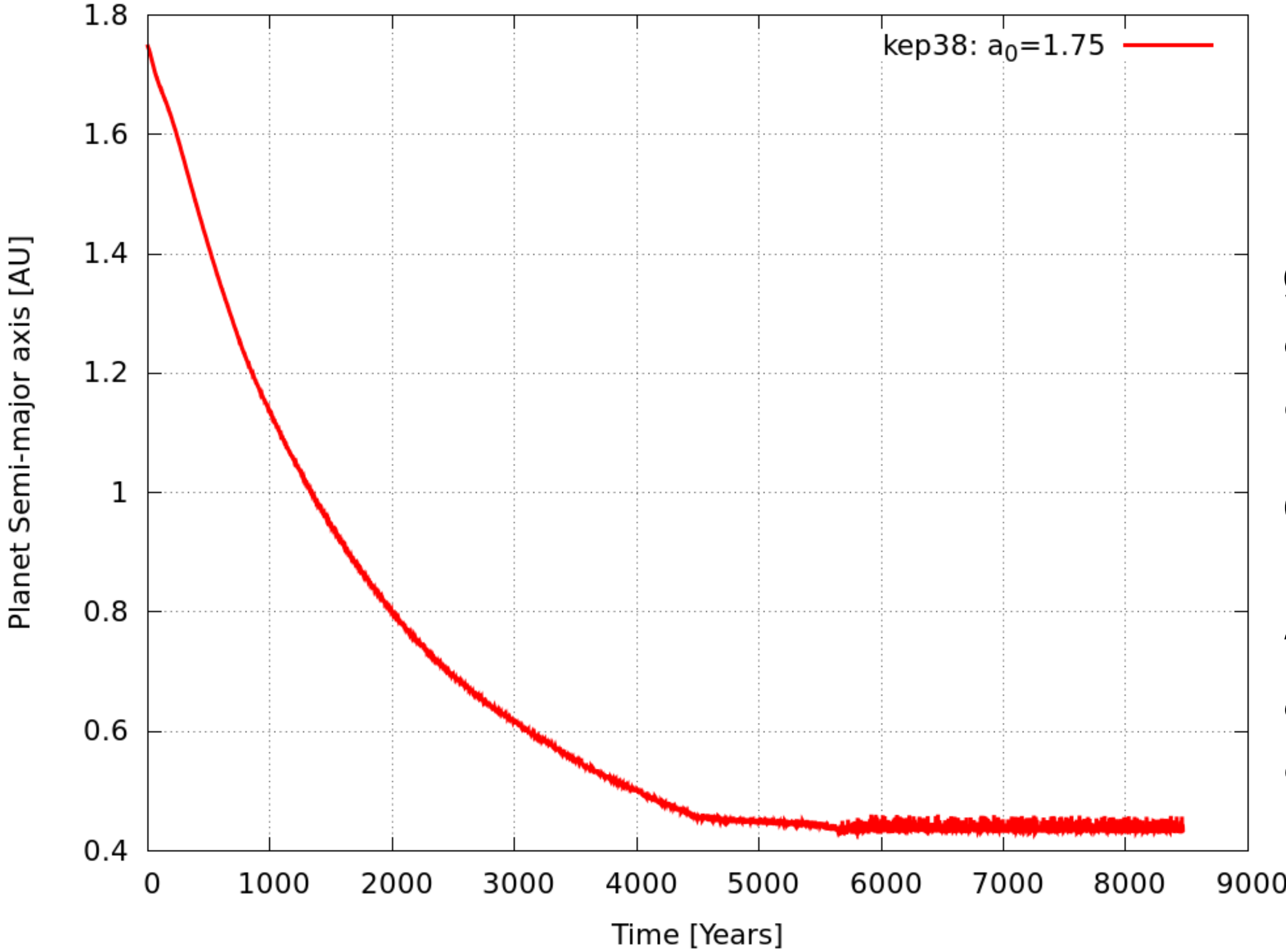
$m_p = 0.36 M_{Jup}$

$a_p = 0.46$ AU

$e_p = 0.03$

Kepler 38

Migration of planet in disk



Planet stops at gap edge with:

$a_p = 0.43$ AU

$e_p = 0.15$ AU

Observed Planet Parameter:

$m_p = 0.36 M_{Jup}$

$a_p = 0.46$ AU

$e_p = 0.03$

(Kley & Haghighipour, in prep.)

(see also: Pierens & Nelson, 2013)

Summary

Planets form through bottom-up process

- Dust agglomeration, core formation, rapid gas accretion

Planets migrate in disks

- Lindblad and Corotation Torques
- Inward or outward, depending on local disk physics

Example: Circumbinary Planet

The Plato Connection:

Interpret Orbital and Physical Parameter through simultaneous modeling of Formation and Evolution
(very useful: multiple systems)

$\Rightarrow$ see the following talks !

The End