Planet-Disk Interaction

Wilhelm Kley
Institut für Astronomie & Astrophysik
& Kepler Center for Astro and Particle Physics Tübingen

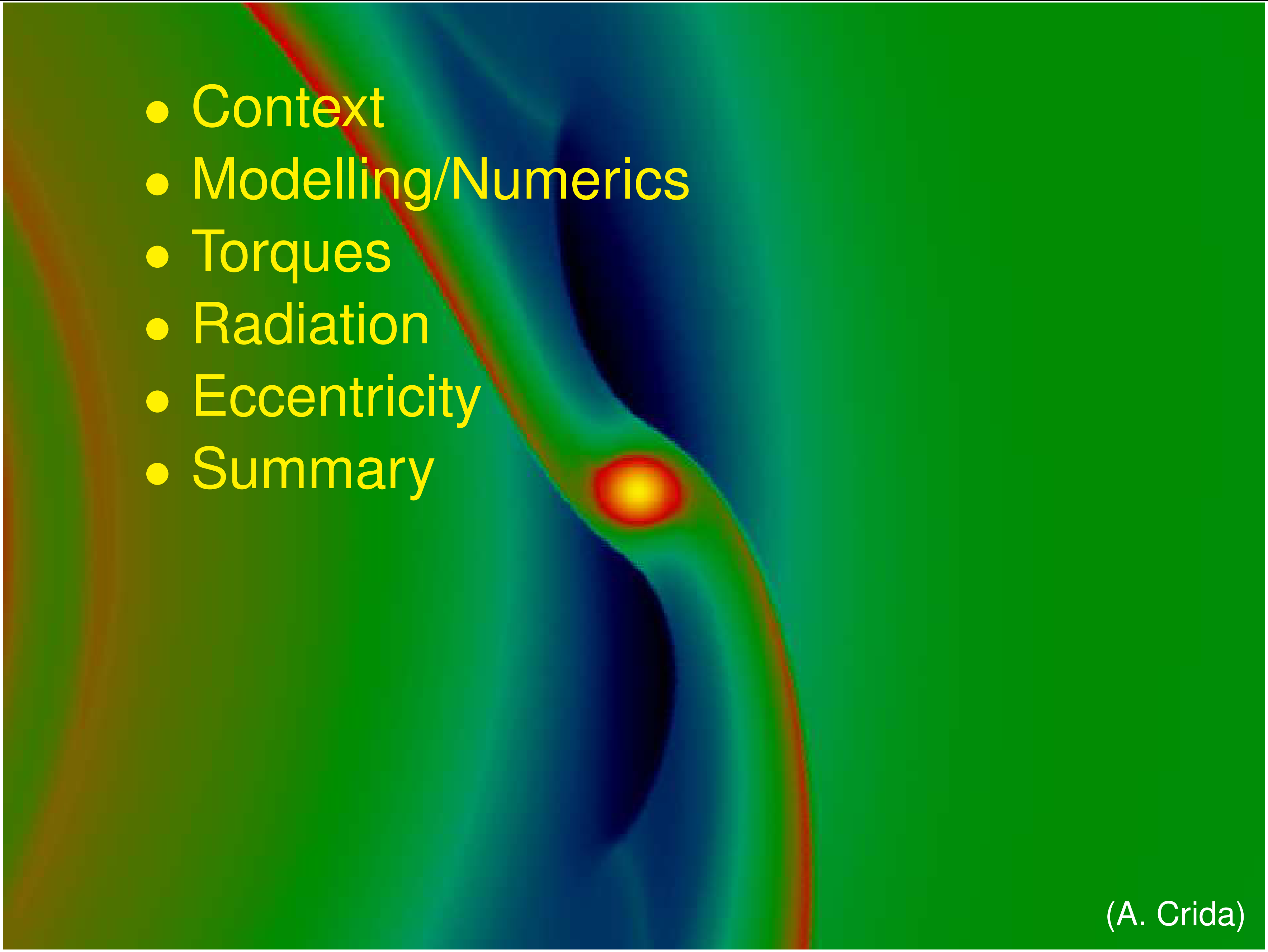
EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

DFG
Research Group
Planet Formation

22. August, 2013

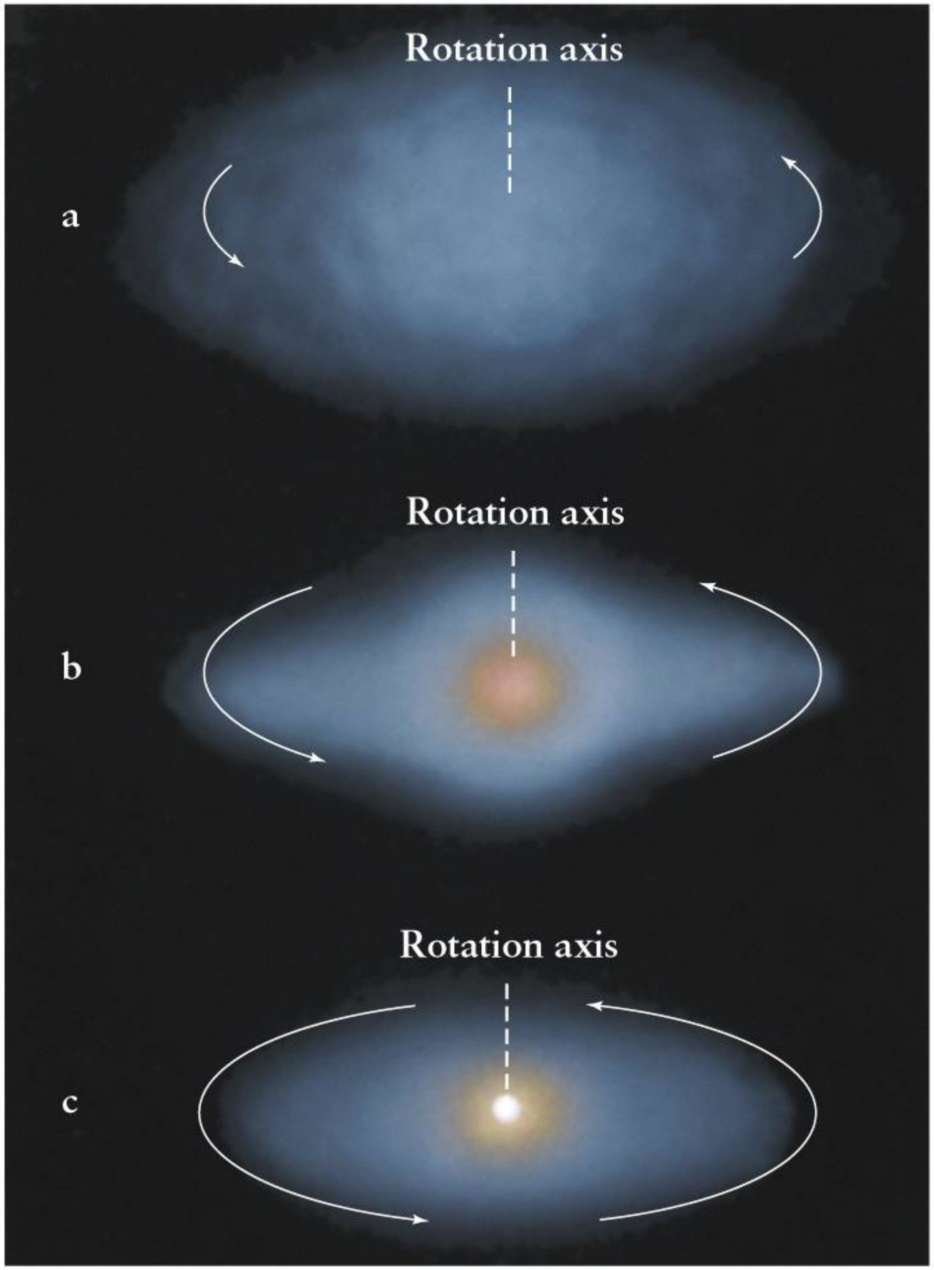
Organisation

- Context
- Modelling/Numerics
- Torques
- Radiation
- Eccentricity
- Summary



(A. Crida)

Planet 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 $\Rightarrow$ Flattening

Protosun in center / disk formation

(based on Kant & Laplace, 1750s)

Planets form in protoplanetary disks

$\equiv$ Accretion Disks (99% Gas, 1% Dust)

$\Longrightarrow$

Flat system, uniform rotation, circular orbits

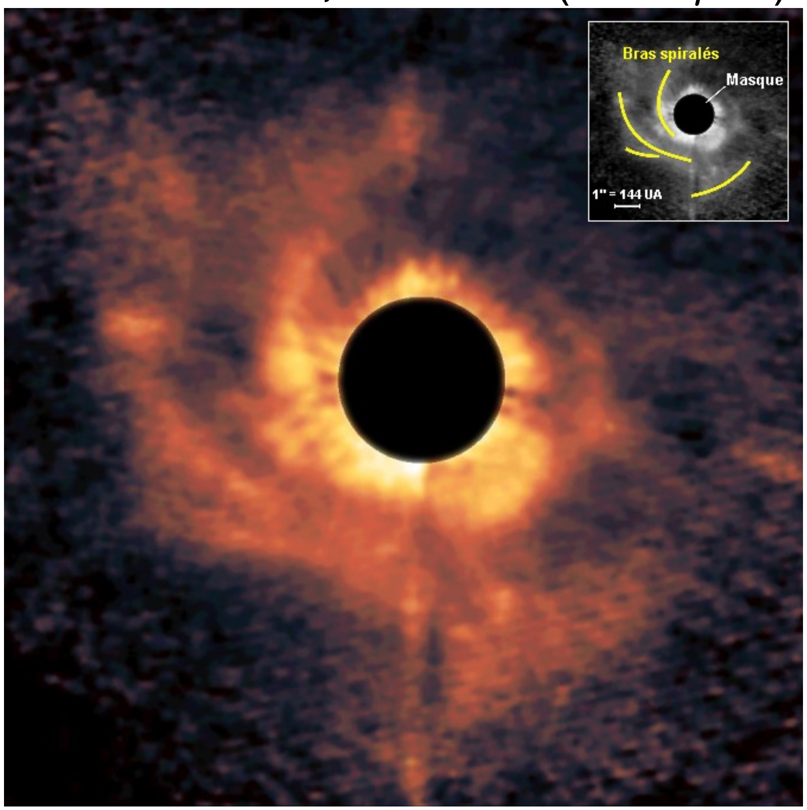
As in Solar System, Kepler Systems

Disks: Observational Evidence

Here: AB Aurigae (Herbig Ae star)

Direct Imaging :

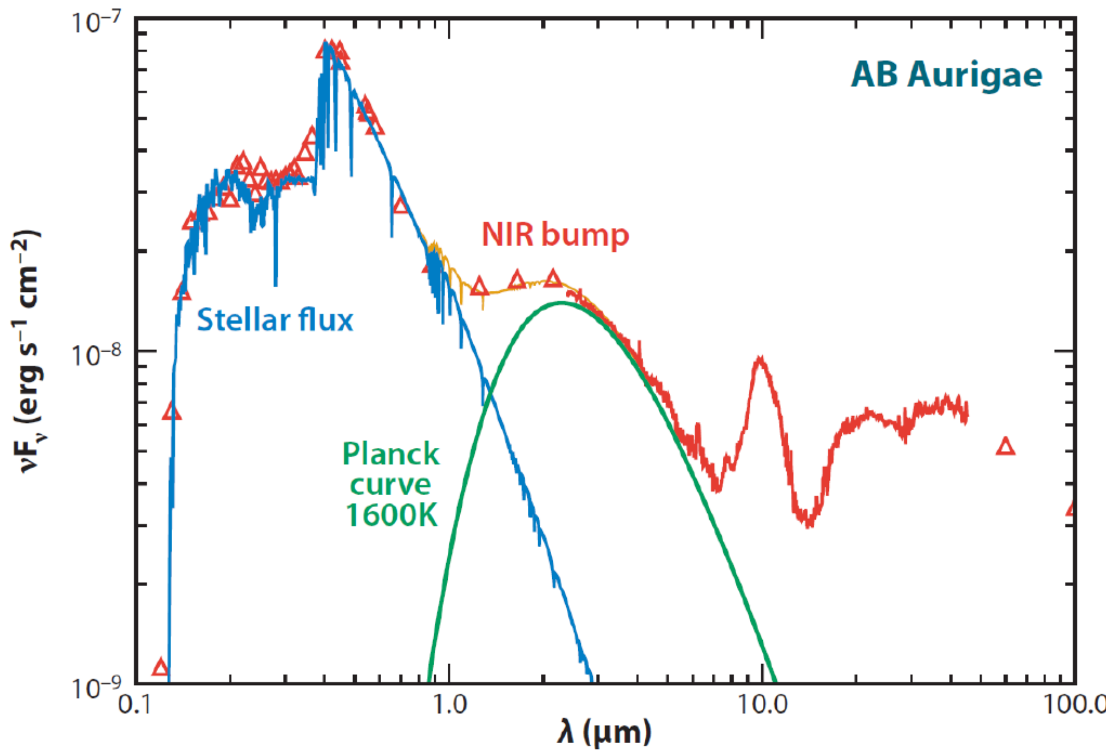
Subaru AO, H-Band (1.65 μm)



(Fukagawa ea, 2004)

Spectral Energy Distribution (SED)

IR-Excess (over stellar contribution)



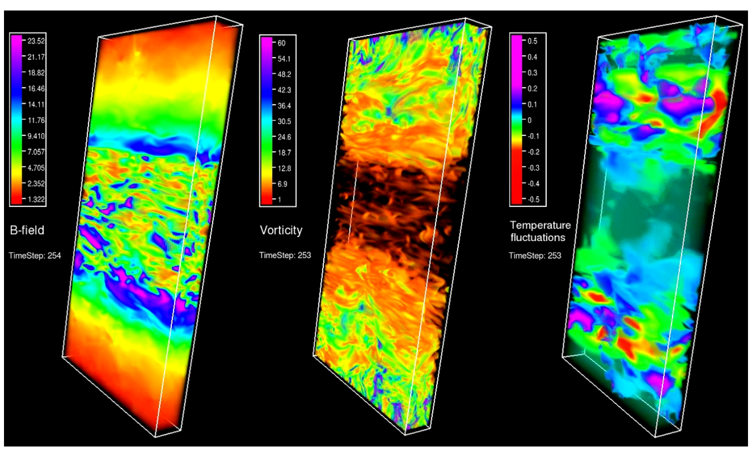
(Dullemond & Monnier, 2010)

Idea: obtain disk structure and dynamics

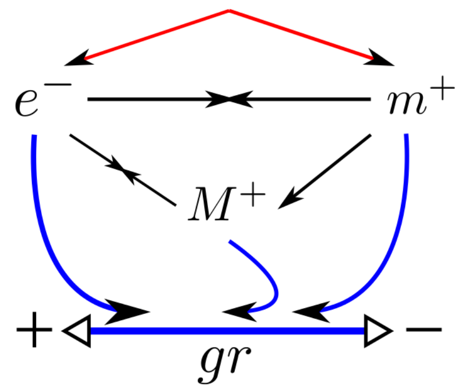
- precondition for planet formation
- indicators for the presence of planets

Turbulence in disks

3D MHD Simulations:
- Local stratified Box
- Non ideal MHD
- Radiation Transport
- Ionising sources
- Chemical network
- at different radii

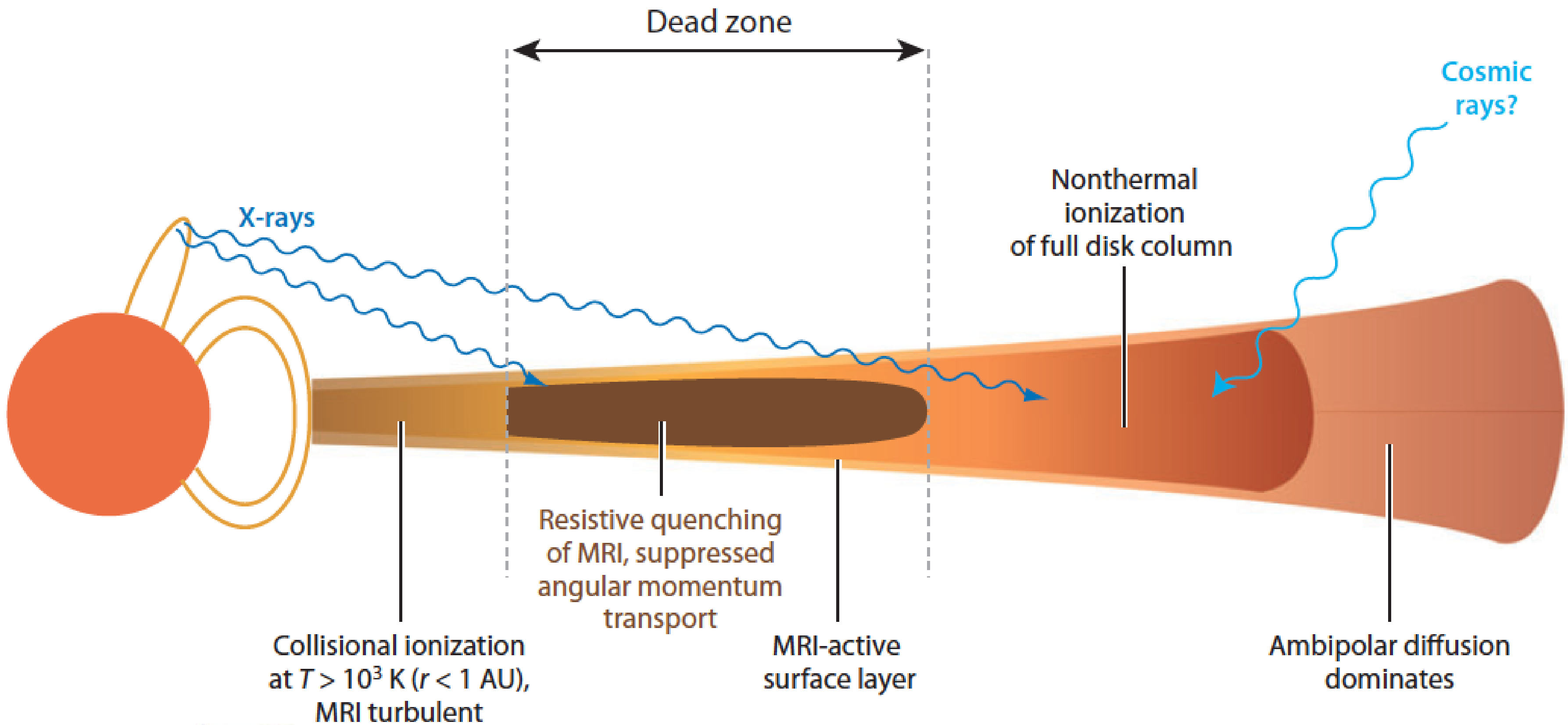


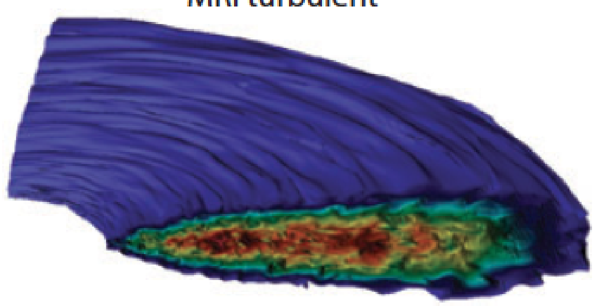
Chemical Network
(after Ilgner & Nelson, 2006)



Outcome:
(Flaig ea. 2012)
- Saturation level
- Vertical structure
- Surface temperature
- Transport efficiency (α)
- Deadzones
- Velocity field for dust

Disks: Global Structure

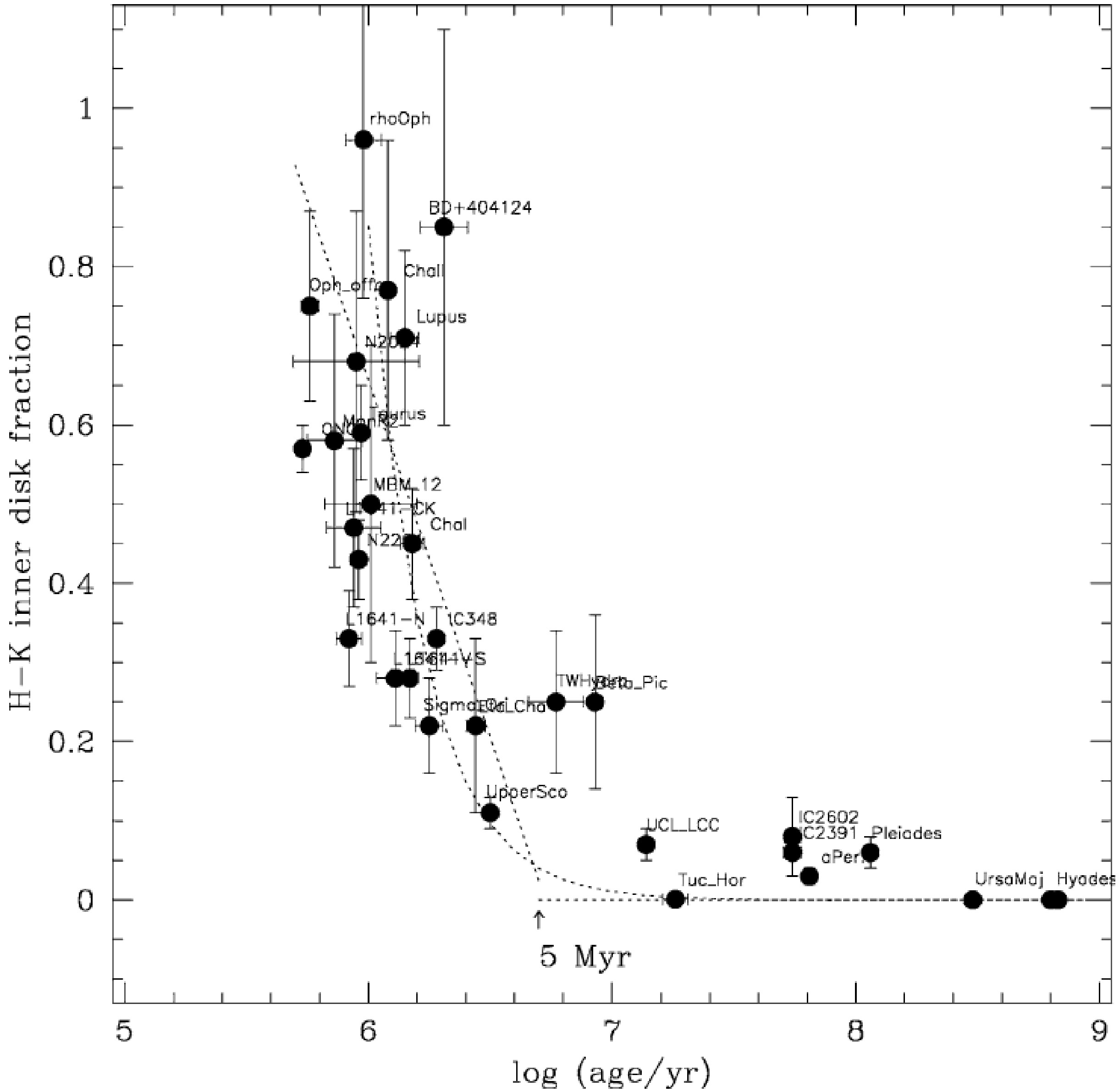




(P. Armitage, 2011)

The origin of the angular momentum transport in disks not clear
(HD or MHD turbulence)   Problem: low ionization and non-ideal MHD-effects

Disks: Lifetimes



From IR-Excess

IR-Excess vs. Stellar Age

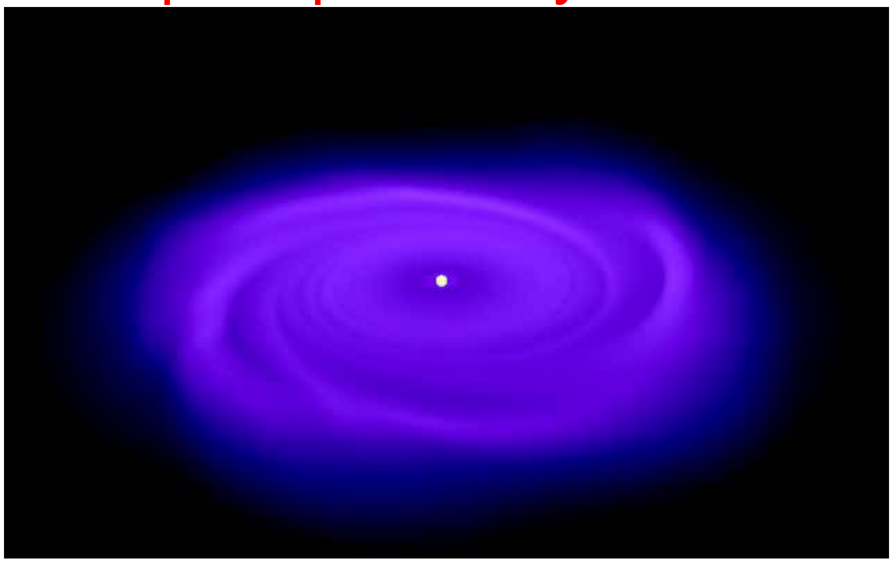
Lifetimes:
approx. 10^6-10^7 Years

(Montmerle et al. 2006)

- Need efficient ang.mom. transport
  - Anomalous Viscosity
  - Turbulence
- Planets form fast

Standard Planet Formation Scenarios

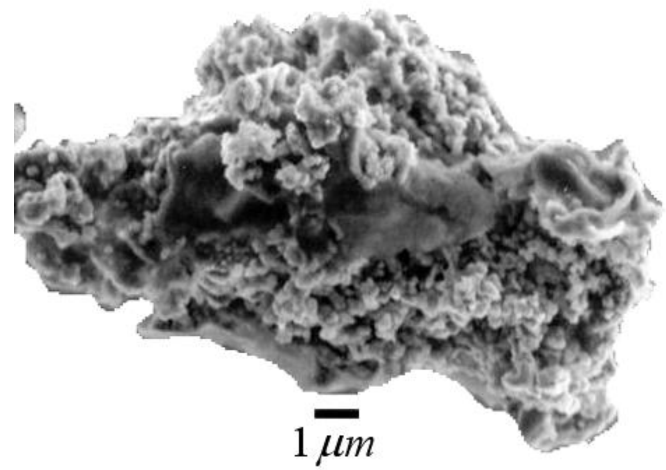
Gravitational Instability in protoplanetary Disk



Growth of unstable modes in spiral arms

Advantage: Very fast formation
Disadvantage: Condition, cores

Coagulation of Dust/Gas in Disk



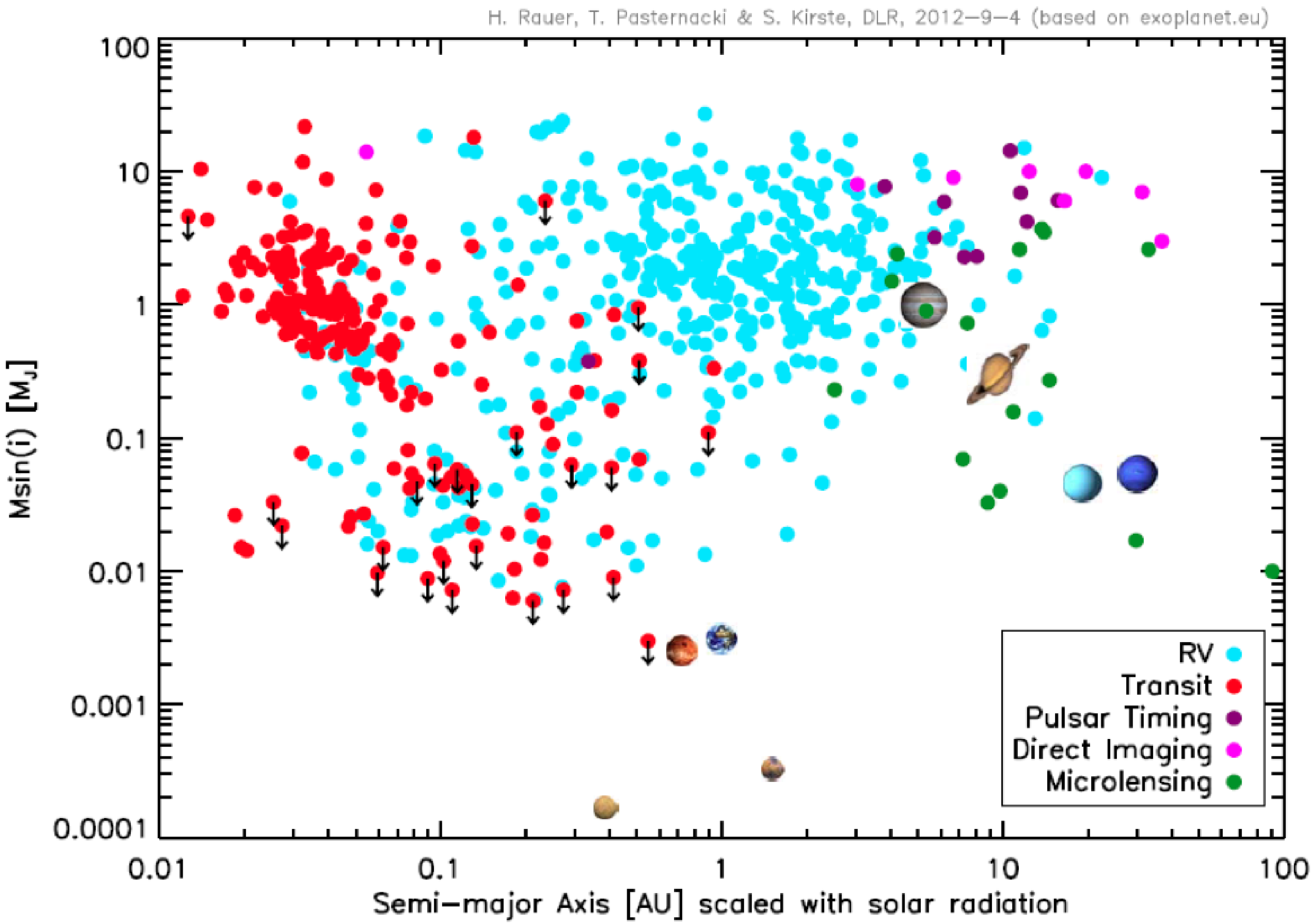
Growth through sequence of collisions & coagulations

Late Phase: Gas accretion onto Core

Advantage: Cores of Planets
Disadvantage: Long timescales

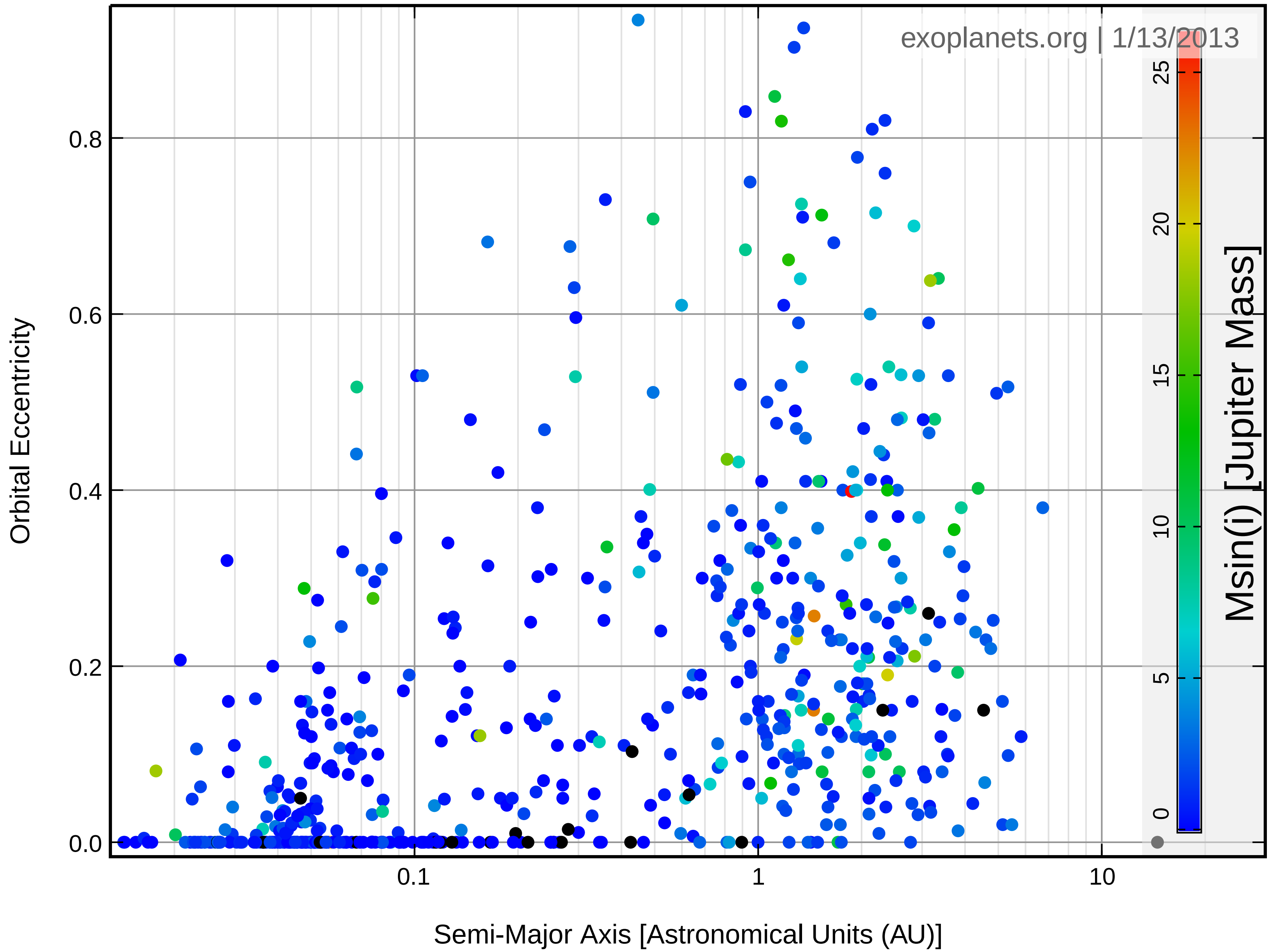
Planets are embedded in disk: interact gravitationally
Exert torques on each other: Orbital evolution (Migration)
Evidence: HOT Planets (near the star), resonant configurations

Exoplanets: Mass-Distance



High masses, very and close in, and very far away

Exoplanets: Eccentricity-Distance



High eccentricity and high inclinations (dynamically excited)

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 **and** evolve in disks:

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

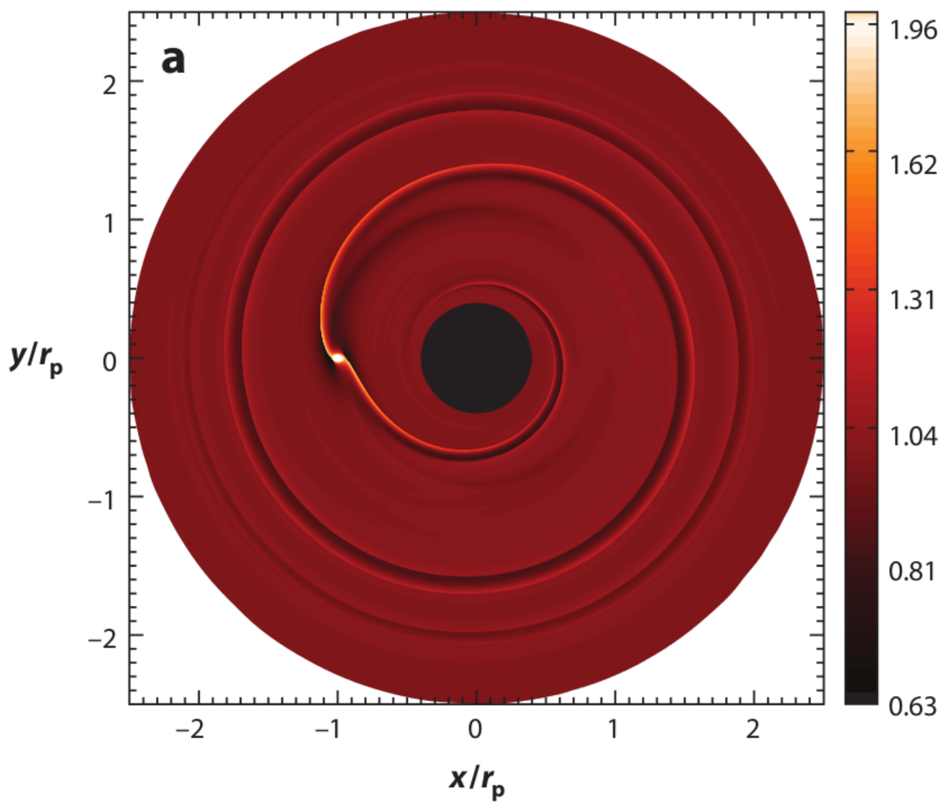
Have 2 contributions: Spiral arms & Corotation effects

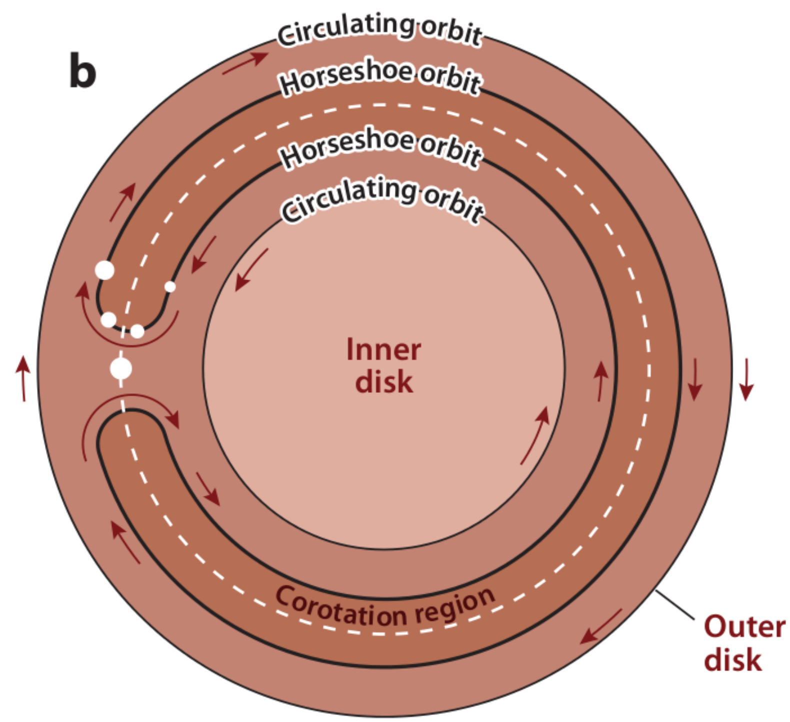
(more details: Annual Review article by Kley & Nelson, ARAA, 50, 2012)

Two main contributions

1) Spiral arms (Lindblad Torques) (Typically inward)

2) Horseshoe region (Corotation Torques) (Typically outward)





Properties of Migration: in radiative disks, in turbulent disks, in self-gravitating disks, tidally driven migration (Kozai), Stellar Irradiation, runaway (type-III) migration (SolSys)

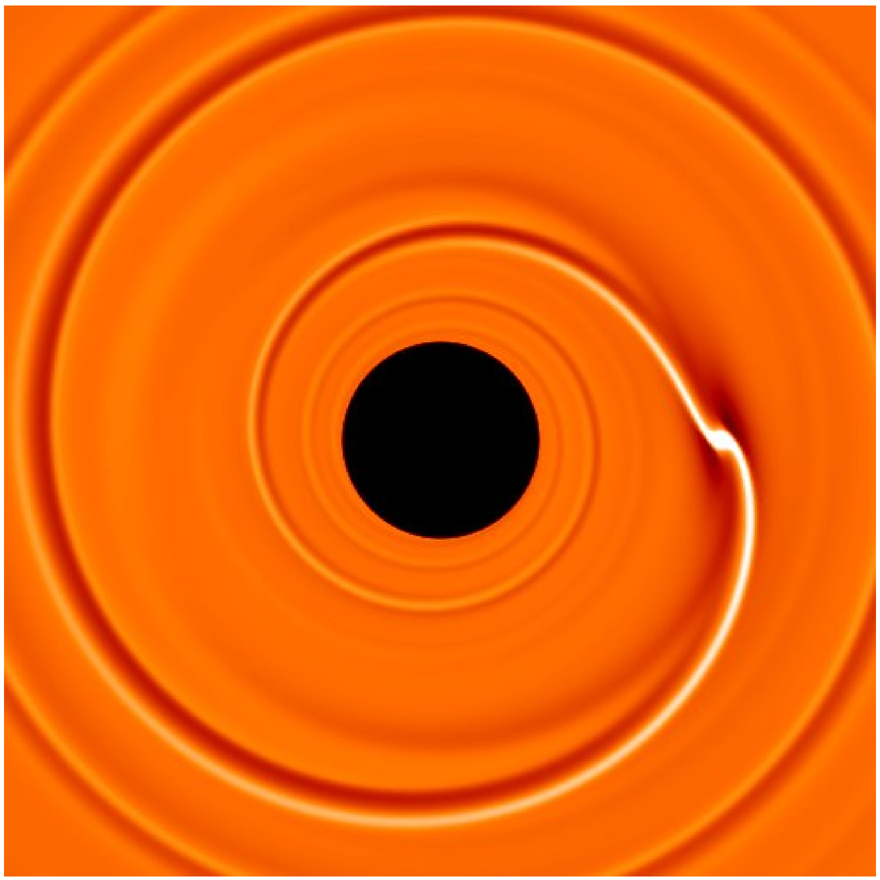
Eccentricity & Inclination: Check influence of the disk and Dynamical Processes

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

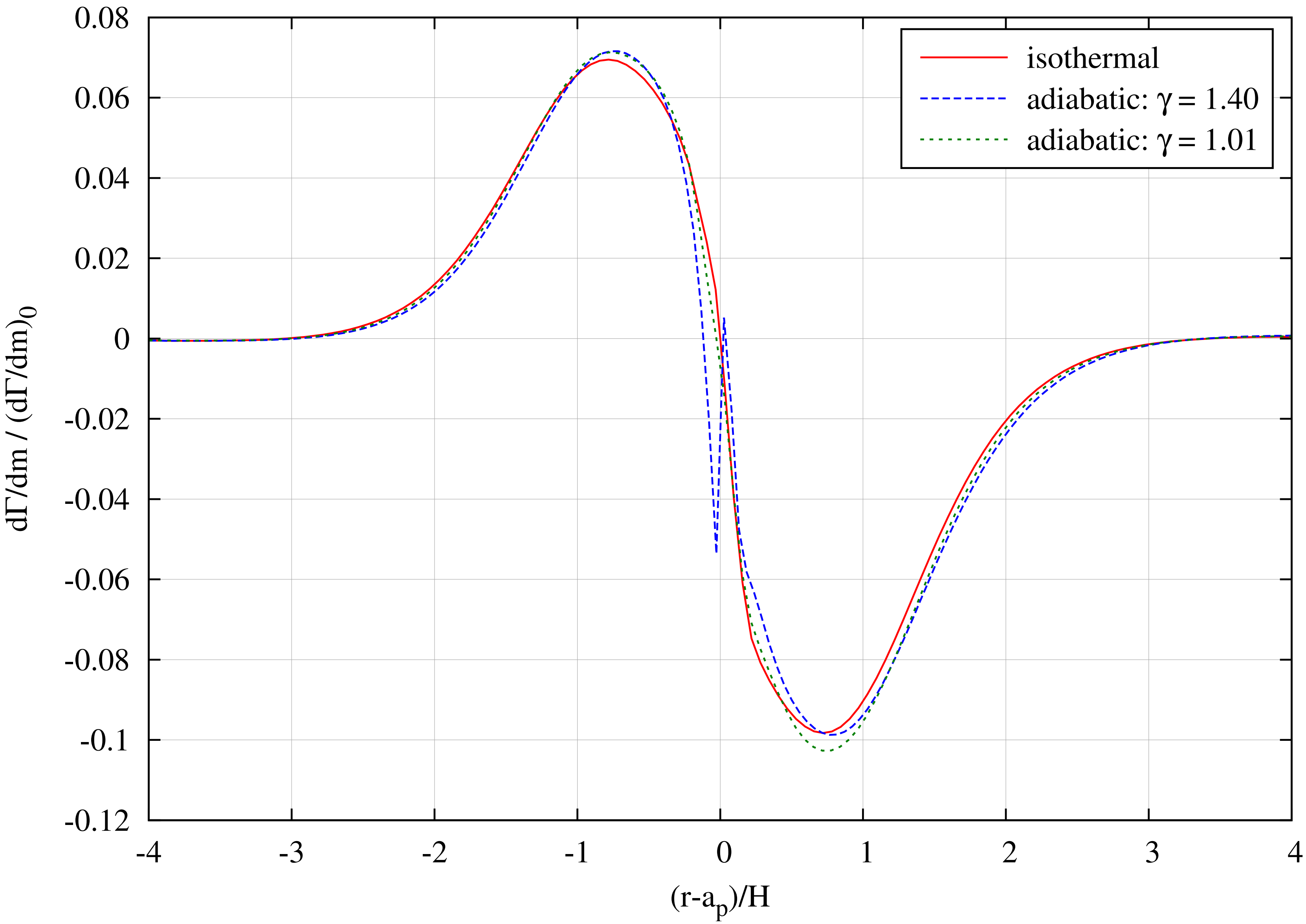
Most important:
Strength & Direction ?

Typically: Outer spiral wins
$\Longrightarrow$ Inward Migration

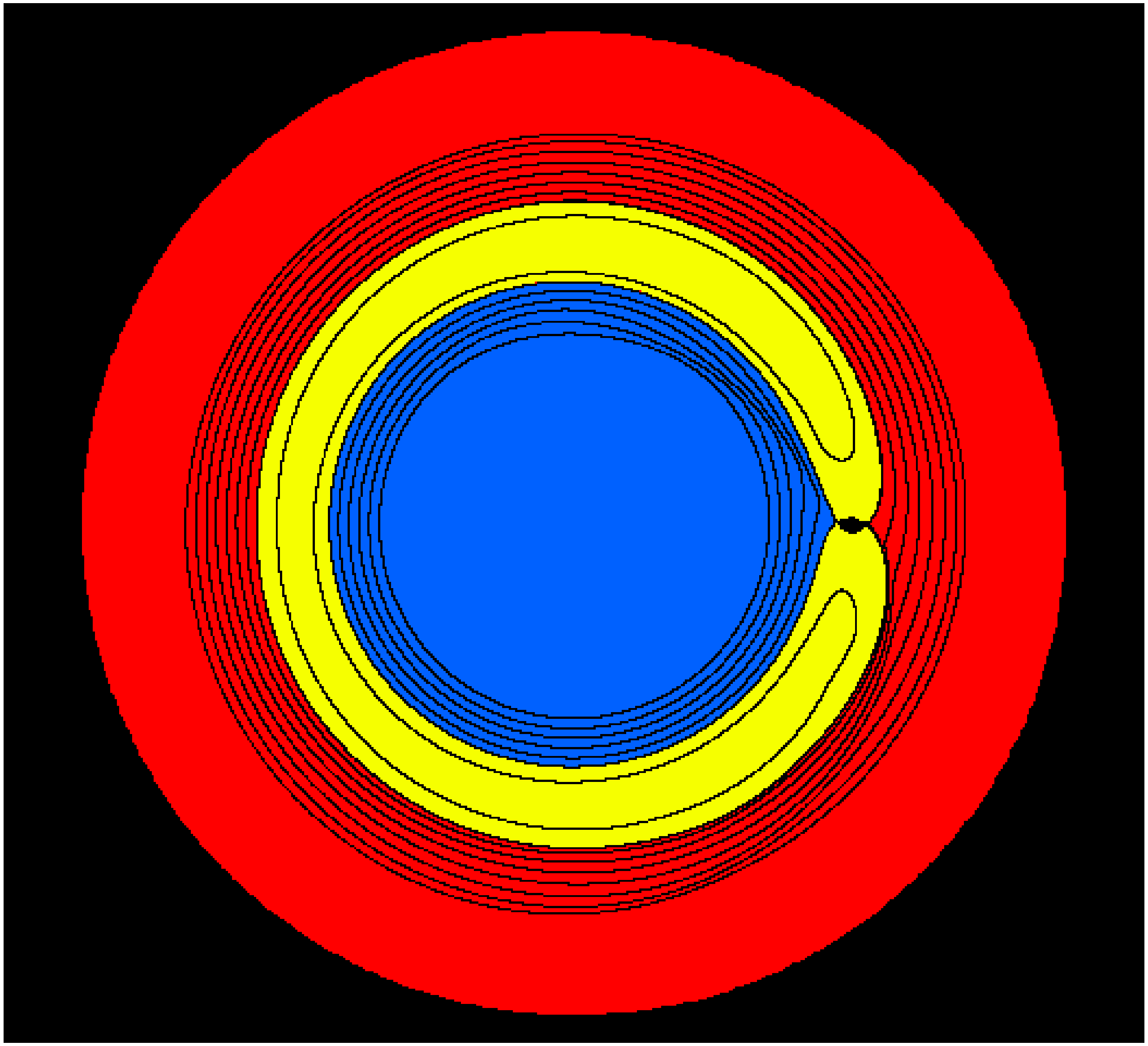
Torque scales with:
inv. Temp. $(H/r)^{-2}$, M_p^2, M_d

Lindblad torque: radial torqedensity

$$\Gamma_{\rm tot} = 2\pi \int \frac{d\Gamma}{dm}(r)\,\Sigma(r)\,r dr \quad \text{mit} \quad \left(\frac{d\Gamma}{dm}\right)_0 = \Omega_{\rm p}^2(a_{\rm p}) a_{\rm p}^2 q^2 \left(\frac{H}{a_{\rm p}}\right)^{-4}, \quad H_{\rm adi} = \sqrt{\gamma} H_{\rm iso}$$



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)

Goals

Evolution of planet in Disk

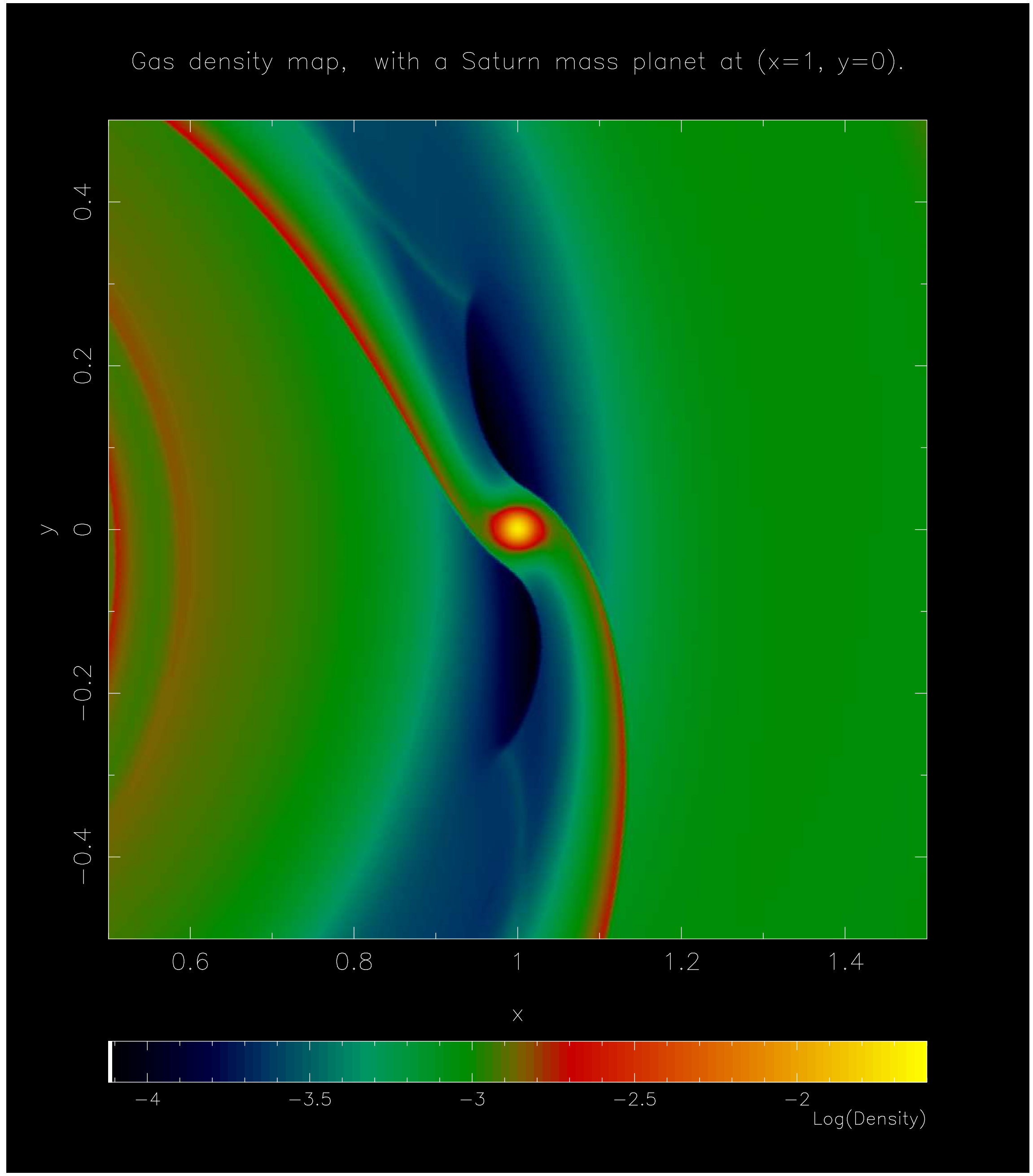
Require:

Torques
(disk pulls on planet)
⟹ Migration rate

Accretion
(planet attracts material)
⟹ Mass growth rate

On the right:
Saturn mass planet in disk
- Spiral arms
- Envelope around planet
- Gap formation

(A. Crida)



Modelling

The problem is full 3D: requires MHD, radiation transport, self-gravity

Often simplifications are used

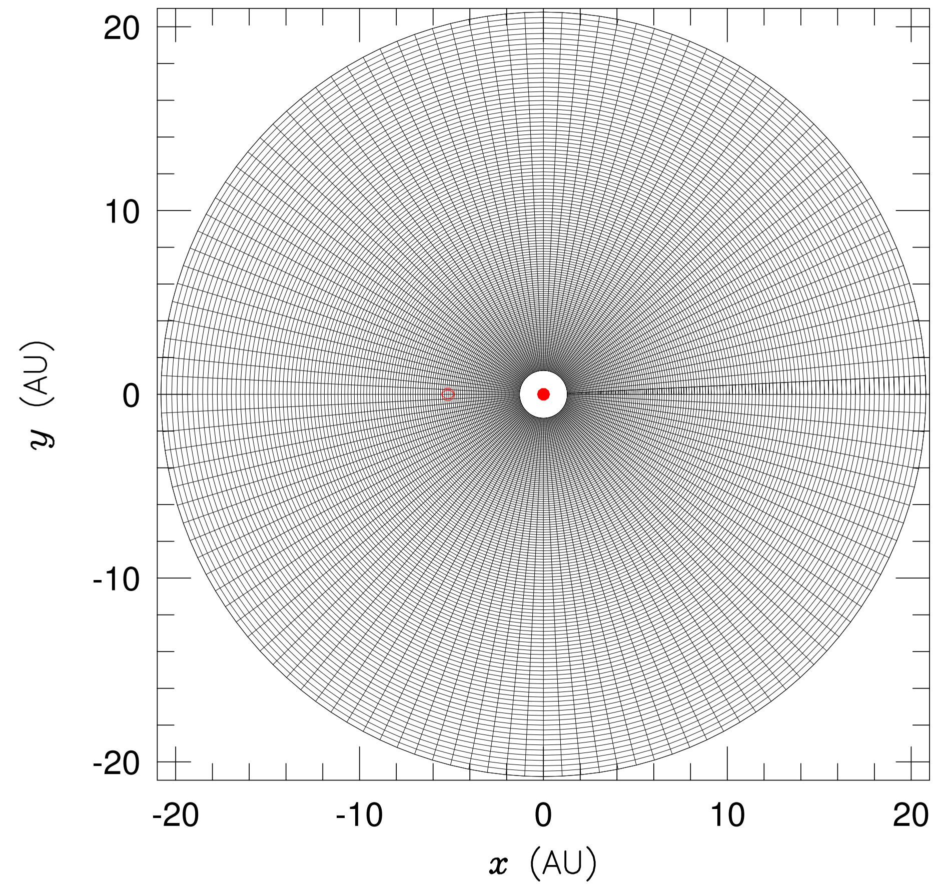
- Dimensions
  - assume that the disk is flat $\Rightarrow$ vertical averaging
  - perform simulations in 2D ($r - \varphi$ Coordinates)
  - recently simulations in 3D
- Physics
  - often isothermal, to avoid solving an energy equation
  - use pure hydrodynamics (no MHD)
  - model angular momentum transport through (eff.) viscosity
  - no self-gravity of disk
  - no radiative transport
- Numerics
  - in 2D: cylindrical coordinates
  - in 3D: sperical polar coordinates
  - velocities in ϕ are much larger $\rightarrow$ special treatment
  - Planet: pointmass potential, special treatment in 2D required

Actors

Star (1 $M_\odot$), Disk (0.01 $M_\odot$), Planet (M_p = $M_{\rm Jup}$)

Disk: Hydrodynamical Evolution (Grid-Sample: 128x128)

- In potential of Star & Planet
- 2D (r, φ or $x - y$)
- $r_{\rm min}$ = 2.08, $r_{\rm max}$ = 10.4 AU
- locally isothermal: $T \propto r^{-1}$
- const. viscosity: $\nu = const.$



Planet: At 5.2 AU

- here on fixed orbit
- point mass (smoothed potential)

Compare 17 Codes in De Val-Borro & 22 Co-authors, MN (2006)

EU comparison project: `http://www.astro.princeton.edu/~mdevalbo/comparison/`

Equations-2D: Conservative

Mass Conservation

$$\frac{\partial \Sigma}{\partial t} + \nabla \cdot (\Sigma \mathbf{u}) = 0 \qquad \mathbf{u} = (u_r, u_\varphi) = (v, r\omega)$$

Radial Momentum

$$\frac{\partial (\Sigma v)}{\partial t} + \nabla \cdot (\Sigma v \mathbf{u}) = \Sigma\, r(\omega + \Omega)^2 - \frac{\partial p}{\partial r} - \Sigma \frac{\partial \Phi}{\partial r} + f_{\mathrm{r}}$$

Angular Momentum

$$\frac{\partial [\Sigma r^2 (\omega + \Omega)]}{\partial t} + \nabla \cdot [\Sigma r^2 (\omega + \Omega) \mathbf{u}] = -\frac{\partial p}{\partial \varphi} - \Sigma \frac{\partial \Phi}{\partial \varphi} + f_\varphi$$

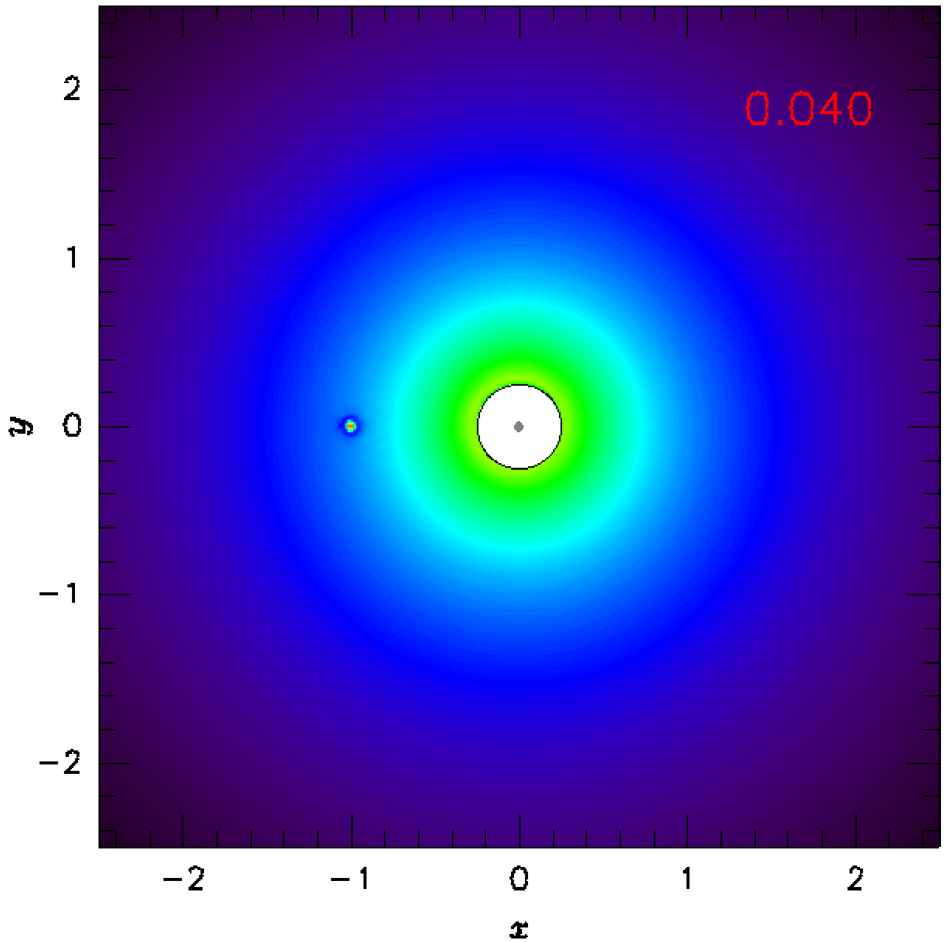
Energy

$$H/r = const. \Longrightarrow T \propto 1/r \qquad p = \Sigma\, T/\mu$$

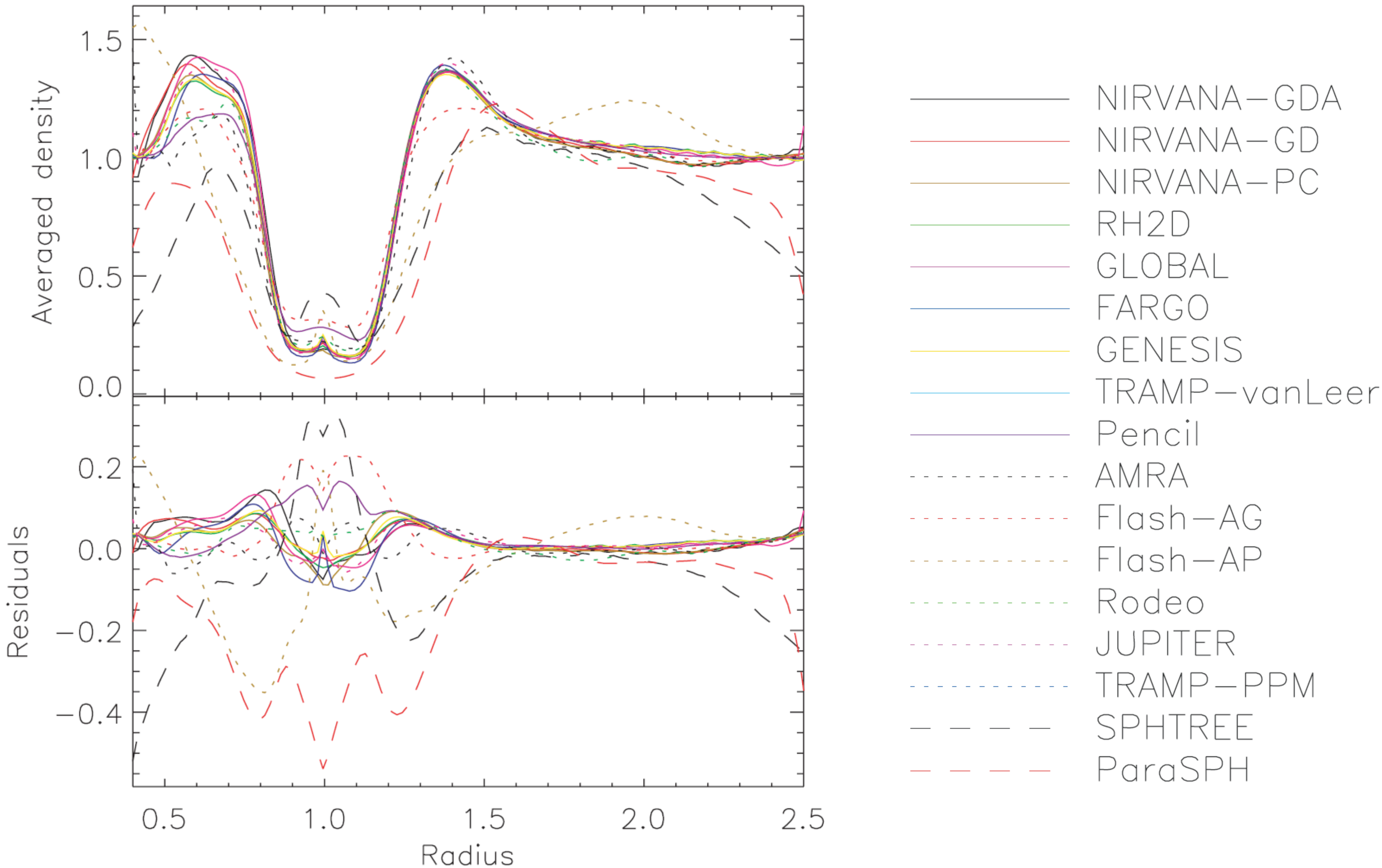
Ω: rotation of coord. system $= \Omega_p$ Φ: planet potential, f_r, f_φ: viscosity

Typical Result

Viscous disc: M_p = 1 M_{Jup}, a_p = 5.2 AU ()



EU comparison: Results on Gap profile



Types: solid - Upwind, HighOrder, short-dashed - Riemann, long-dashed SPH; (Cyl. vs. Cartesian)

Coriolis Terms I

Angular Momentum Equation $\omega =$ angular velocity in rotating frame

Conserved (as before)

$$\frac{\partial[\Sigma r^2(\omega + \Omega)]}{\partial t} + \nabla \cdot [\Sigma r^2(\omega + \Omega)\mathbf{u}] =$$

$$-\frac{\partial p}{\partial \varphi} - \Sigma \frac{\partial \Phi}{\partial \varphi} + f_\varphi$$

Not-Conserved (Explicit)

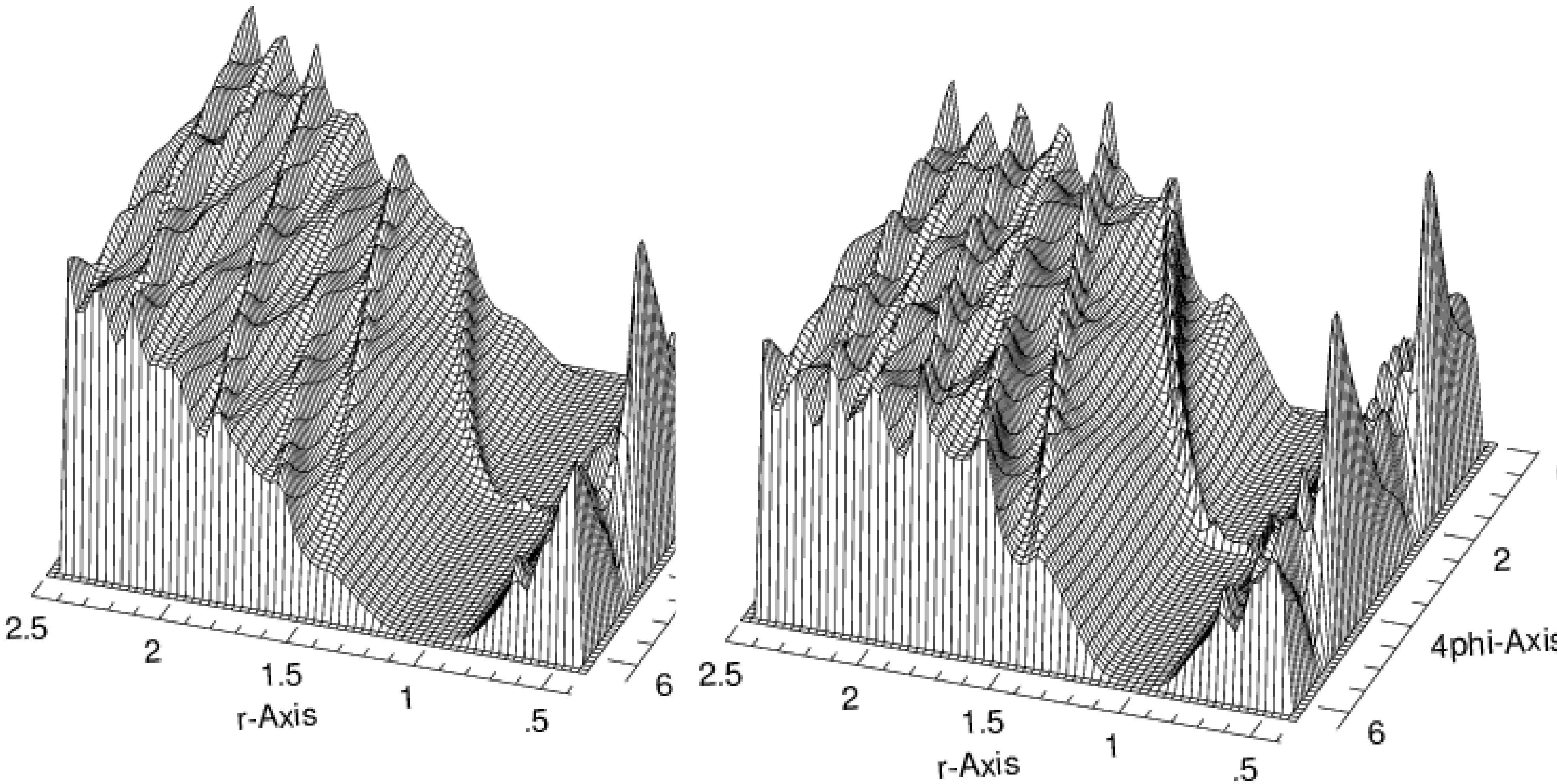
$$\frac{\partial[\Sigma r^2 \omega]}{\partial t} + \nabla \cdot [\Sigma r^2 \omega \mathbf{u}] = -2\,\Sigma\, v \Omega\, r$$

$$-\frac{\partial p}{\partial \varphi} - \Sigma \frac{\partial \Phi}{\partial \varphi} + f_\varphi$$

Coriolis Terms II

Non-Conservative

Conservative



Conservative results: identical to inertial frame

$\Longrightarrow$ If rotating frame: Use conservative formulation

FARGO - Basics

A Fast eulerian transport Algorithm for differentially rotating disks

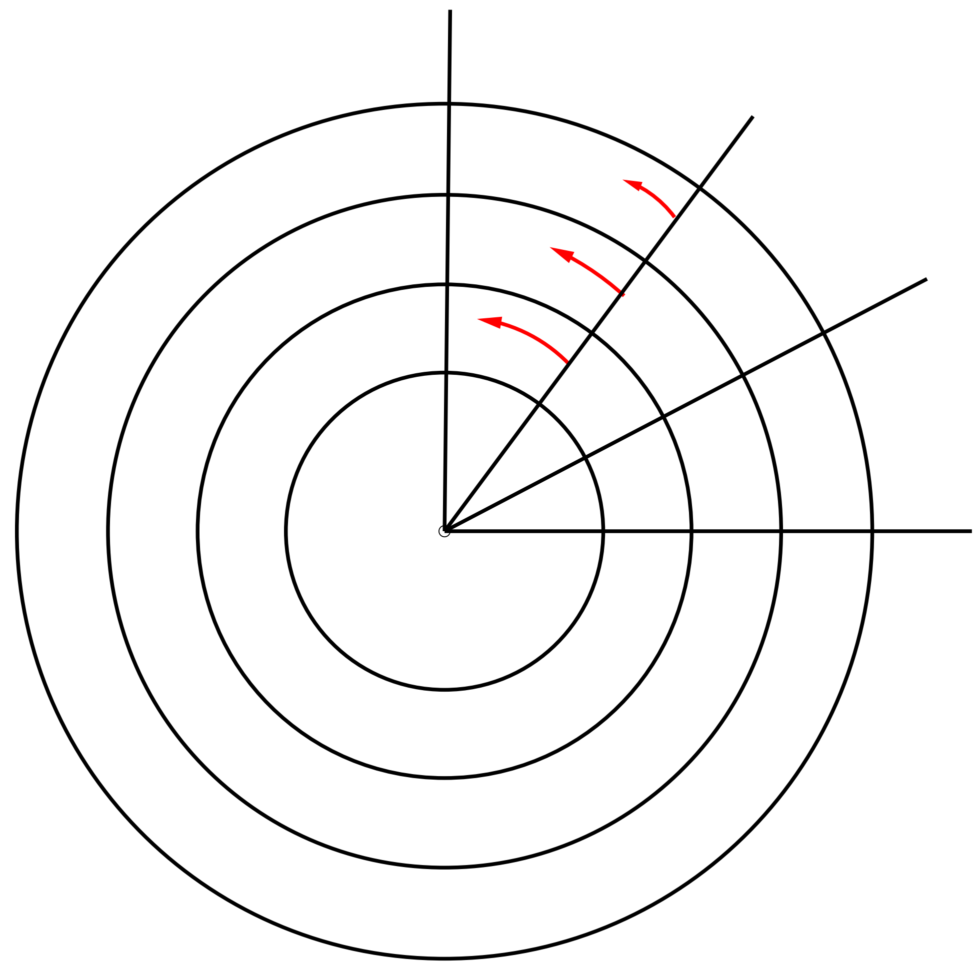
Description of the Fargo-Code: (Masset, A&A 2000) (`http://fargo.in2p3.fr/`)

The problem:
- Cylindrical coord. system
- explicit code

$\rightarrow$ Courant condition:

$$\Delta t < \frac{\Delta\varphi}{\omega}$$

with $\omega \propto r^{-3/2} \rightarrow \Delta t \propto r^{3/2}$



The solution:
Calculate average velocity $\bar{\omega}_i$
of ring i, and perform Shift over
$n_i = \mathtt{Nint}(\bar{\omega}_i \Delta t / \Delta\varphi)$ gridcells

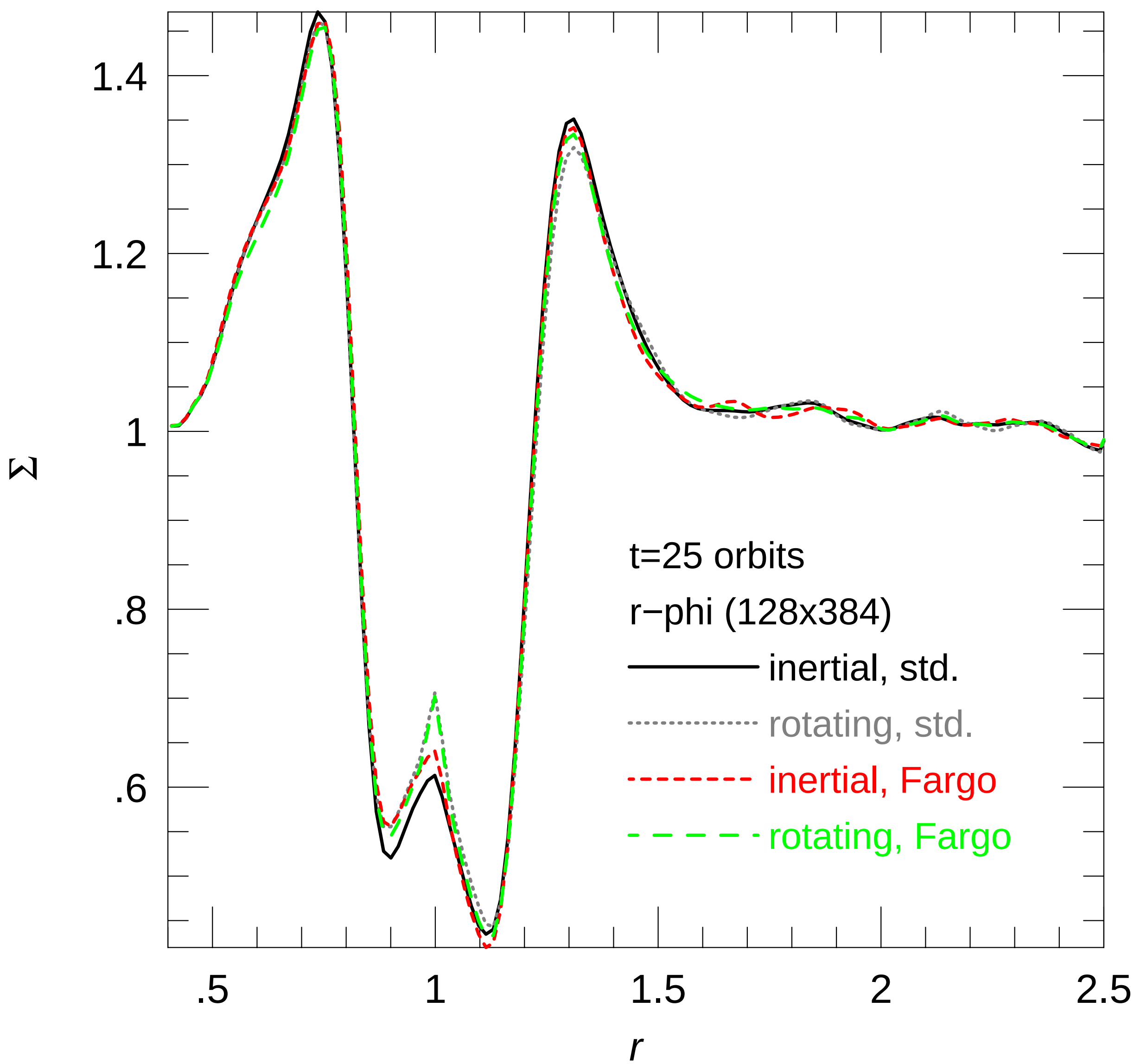
Transport on with remaining velocity
$\Longrightarrow$ much larger Δt

Take care: no ring separation

FARGO-method implemented in many codes: e.g. `PLUTO`

FARGO - Results

Azimuthally averaged surface density



Fargo vs. Standard inertial vs. rotating

Jupiter mass planet after 25 Orbits

Used Timesteps
– 51000
– 39000
– 5800
– 5800

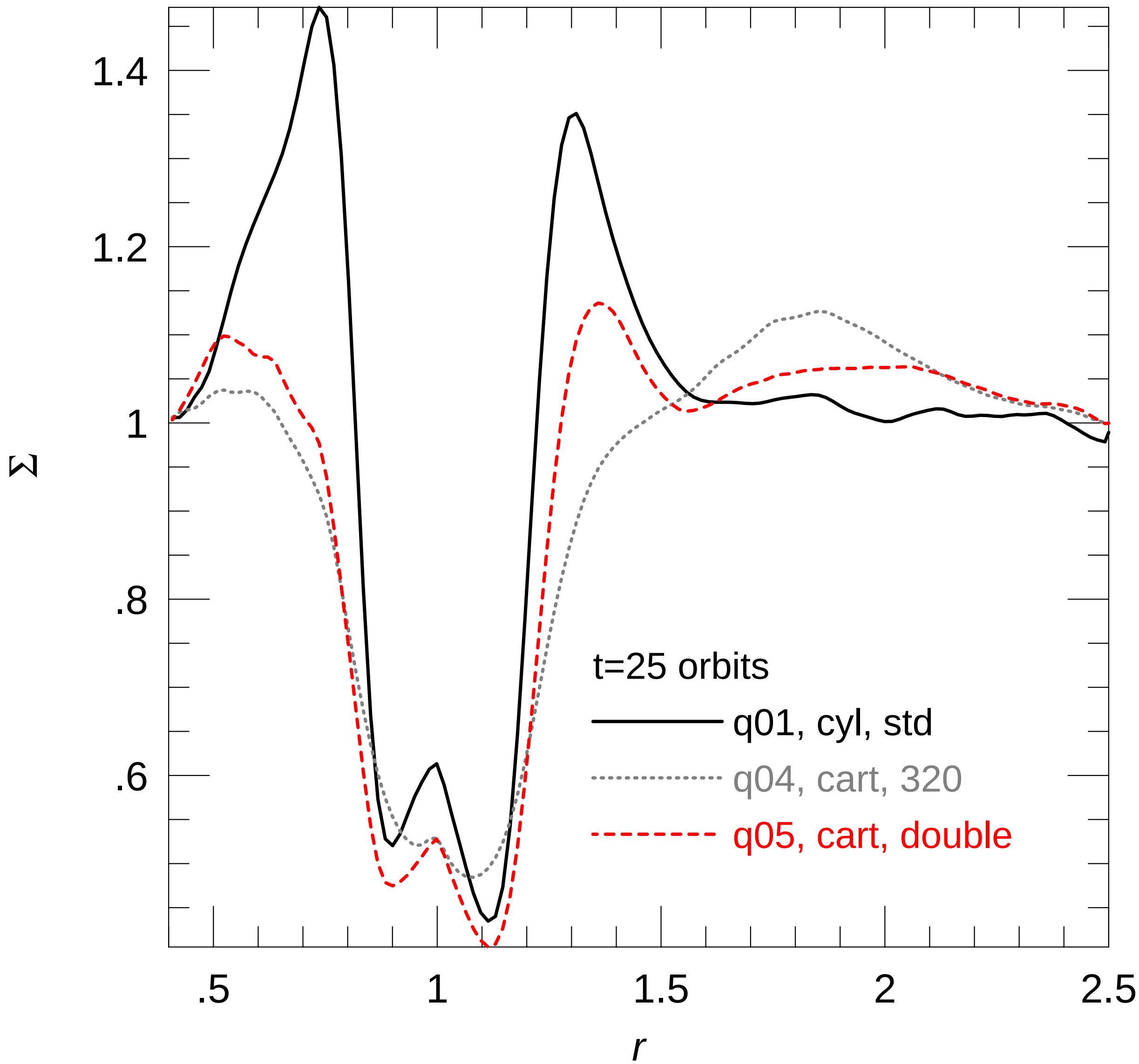
⟹ Identical results !
⟹ Huge Savings !

larger savings for log-grid

Implemented also in 3D

The Grid

Azimuthally averaged surface density



Cartesian vs. Cylindrical

(inertial frame)

Jupiter mass planet
after 25 Orbits

Models

– Cyl.: 128×384
– Cart.: 320×320
– Cart.: 640×640

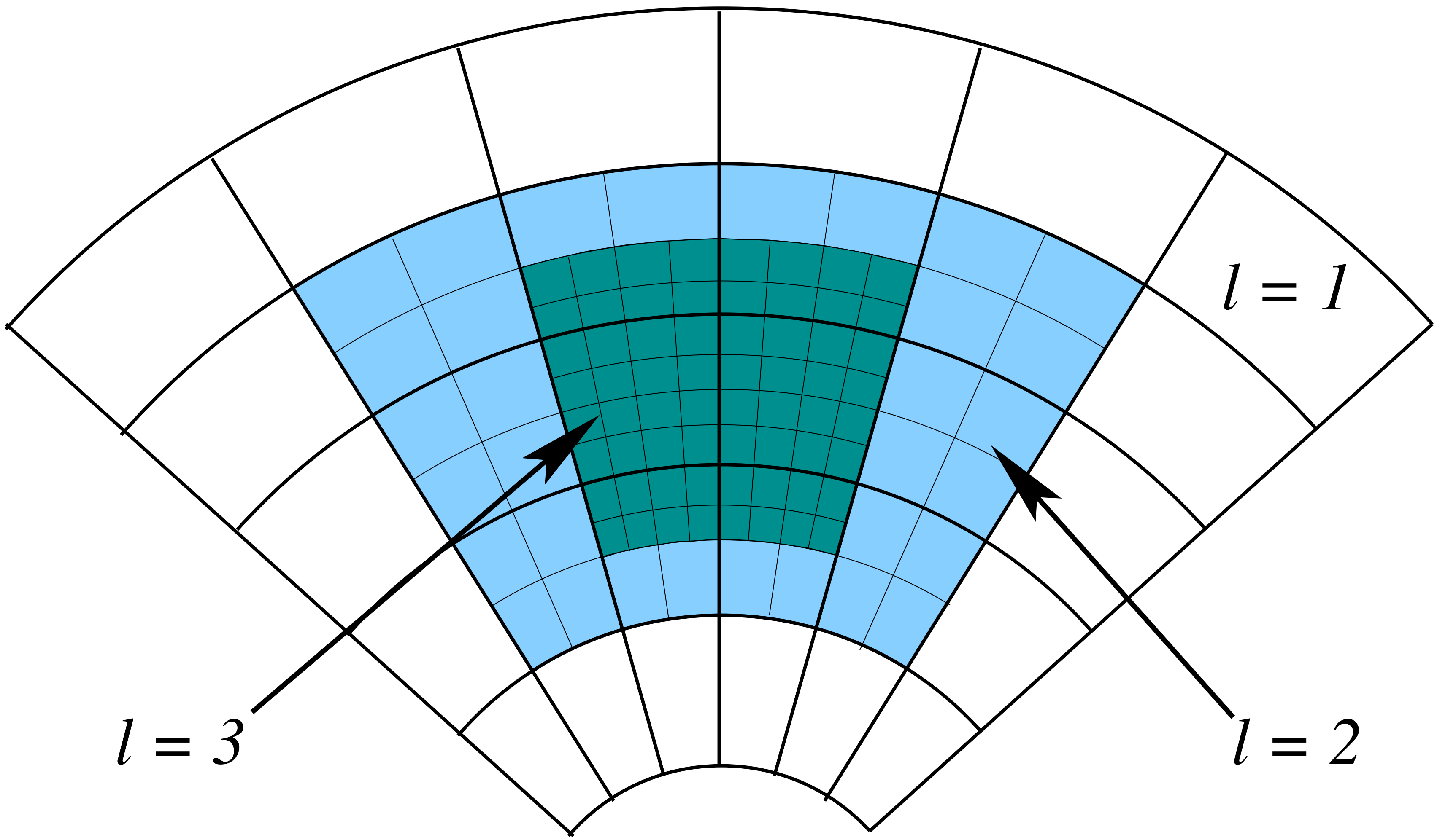
$\Longrightarrow$ Cartesian problematic !

– no operator-splitting
– 2nd order RK-integrator

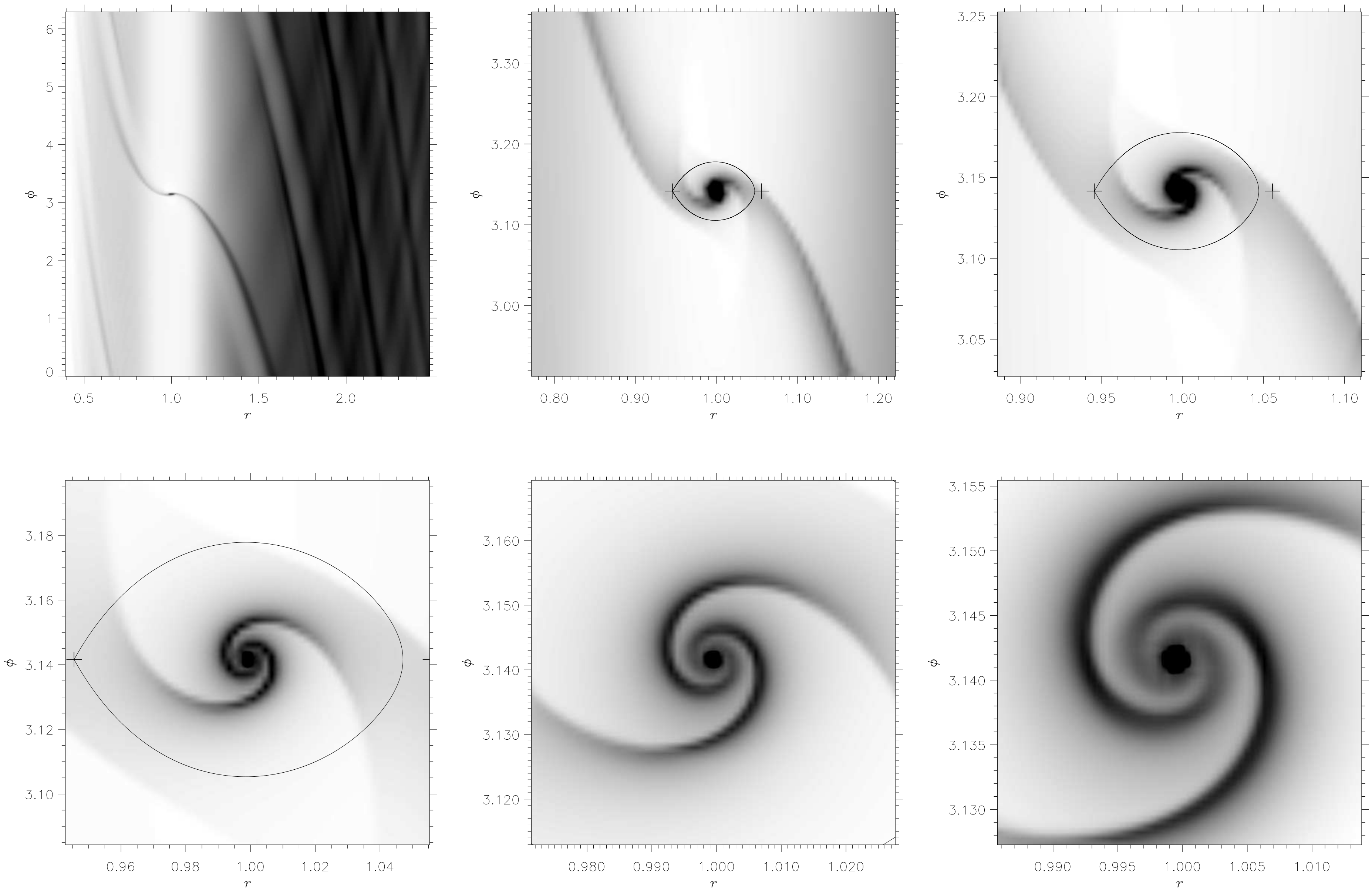
[only PENCIL code reasonable
(HiOrder)]

Nested Grid I

Nested-Grid System: Centered on Planet - corotating frame
Advantage: High resolution near planet, grid fixed in advance (no AMR)
(D'Angelo et al. 2002/03)



Nested Grid II 1 M_J (here 2D, $\varphi - r$ plots)

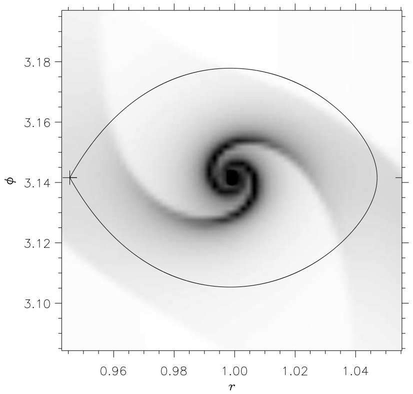


(D'Angelo et al., 2002,   PhD Thesis Tübingen, 2004)

Torque calculation

Sum over all grid-cells, $\Gamma_{tot} = \sum_{cells} (x_p F_y - y_p F_x)$

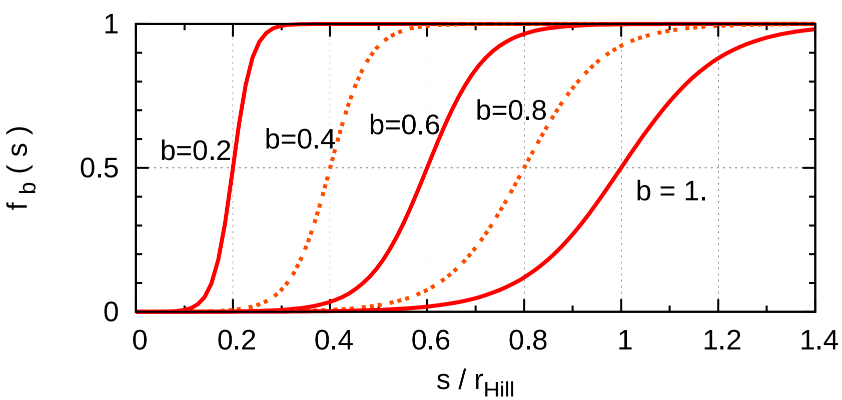
Which parts belong to planet ?



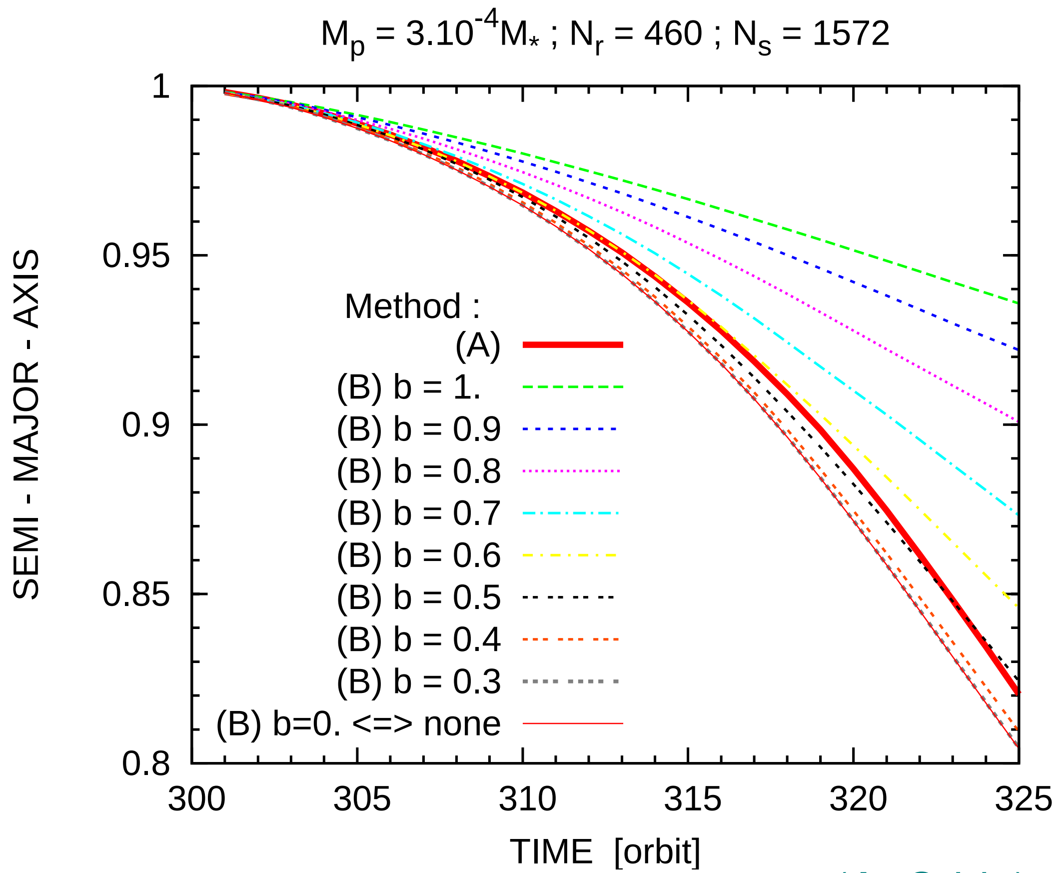
Use Truncation Radius

$R_{trunc} \approx \; 0.5 - 1.0 \, R_{roche}$

Smooth tapering-function f_b



Migration of Saturn mass planet



(A. Crida)

– (A) fully self-gravitating

$\Longrightarrow$ need $b \approx 0.5 - 0.6$

The linear isothermal Torque

Torque **on** the planet:

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

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

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

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

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

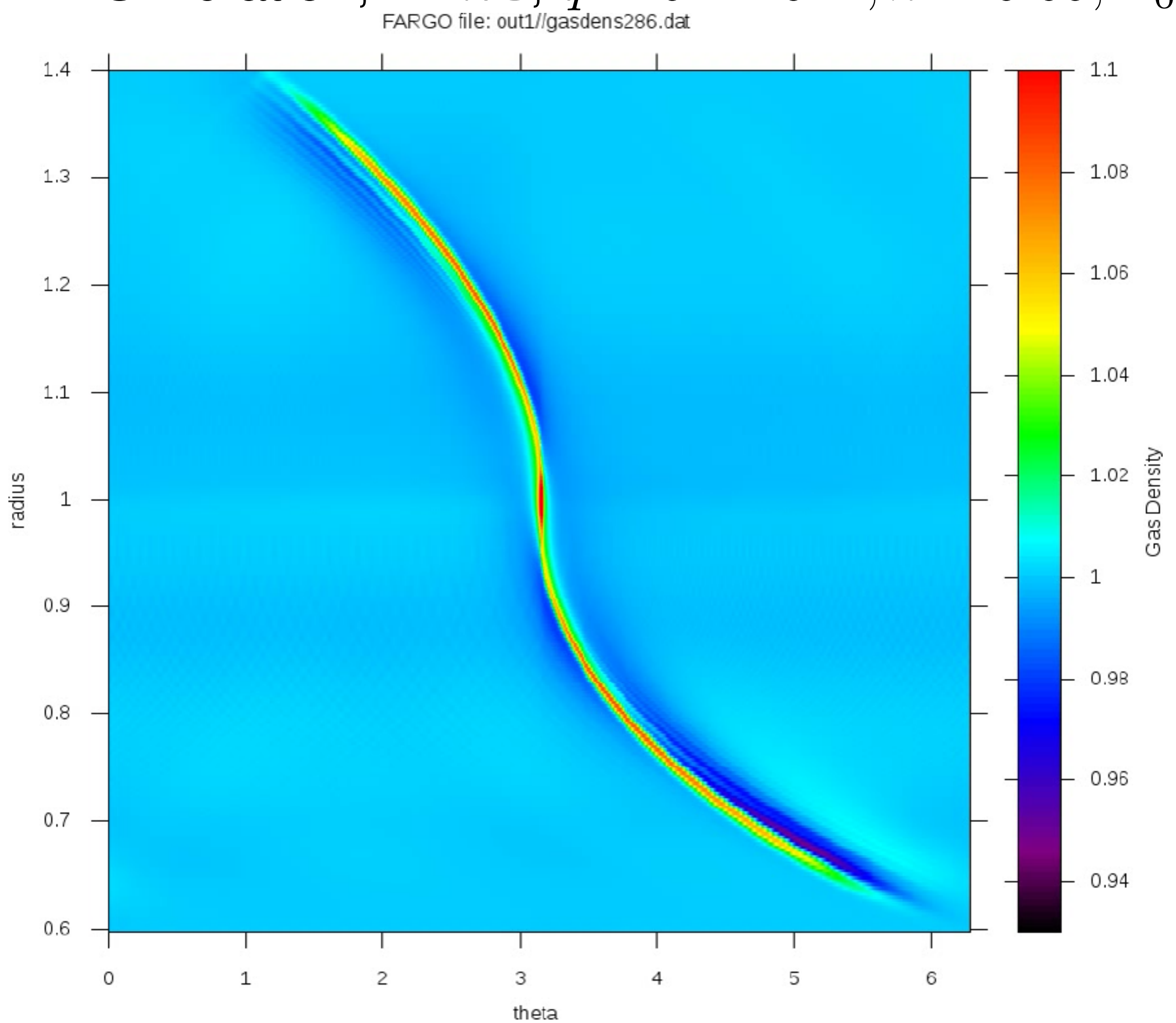
Standard model

Parameter	Symbol	Value
mass ratio	$q = M_\mathrm{p}/M_*$	6×10^{-6}
aspect ratio	$h = H/r$	0.05
nonlinearity parameter	$\mathcal{M} = q^{1/3}/h$	0.36
kinematic viscosity	ν	inviscid
potential smoothing	ϵ_p	$0.1H$
radial range	$r_\mathrm{min} - r_\mathrm{max}$	$0.6 - 1.4$
angular range	$\phi_\mathrm{min} - \phi_\mathrm{max}$	$0 - 2\pi$
number of grid-cells	$N_r \times N_\phi$	256×2004
spatial resolution	Δr	$H/16$
damping range at r_min		$0.6 - 0.7$
damping range at r_max		$1.3 - 1.4$

2D, isothermal, inviscid, high resolution, low mass planets. Parameter for a study to test the accuracy and stability of the FARGO-algorithm.
Analyze, torque distribution, wake profile, gravitational smoothing
(Kley ea. 2012)

Density: Standard Modell

2D Simulation, `FARGO`, $q = 6 \times 10^{-6}, h = 0.05, \Sigma_0 = const.$



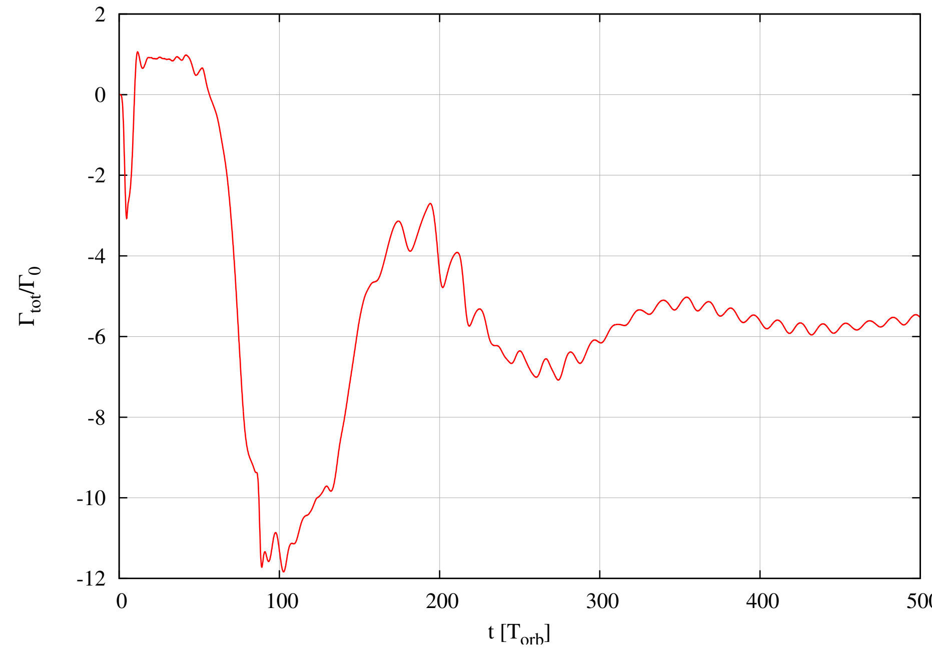
(Tobias Müller, Tübingen)

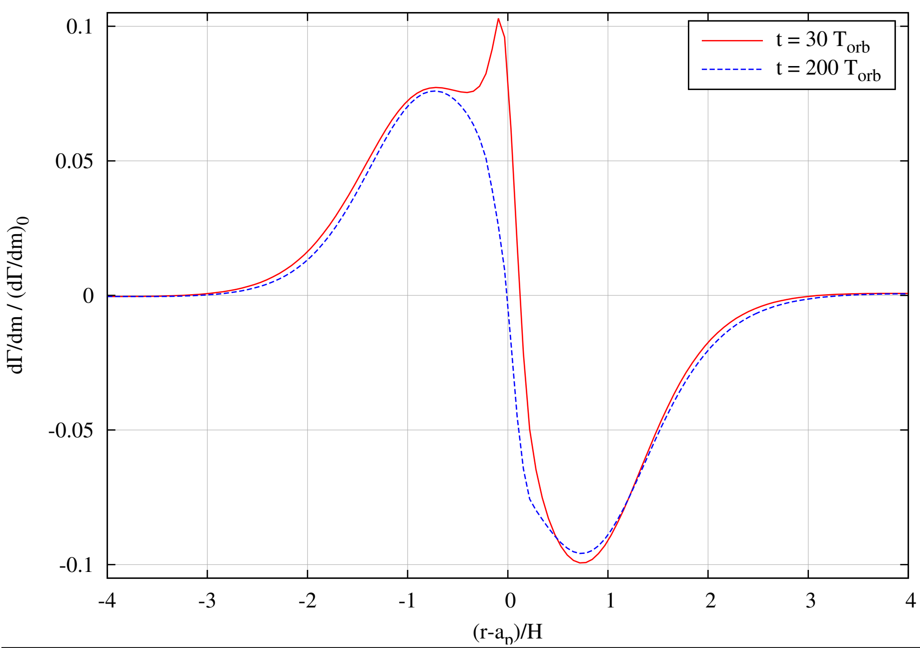
Results: $\Gamma_{\rm tot}(t)$, $d\Gamma/dm(r)$, Wake

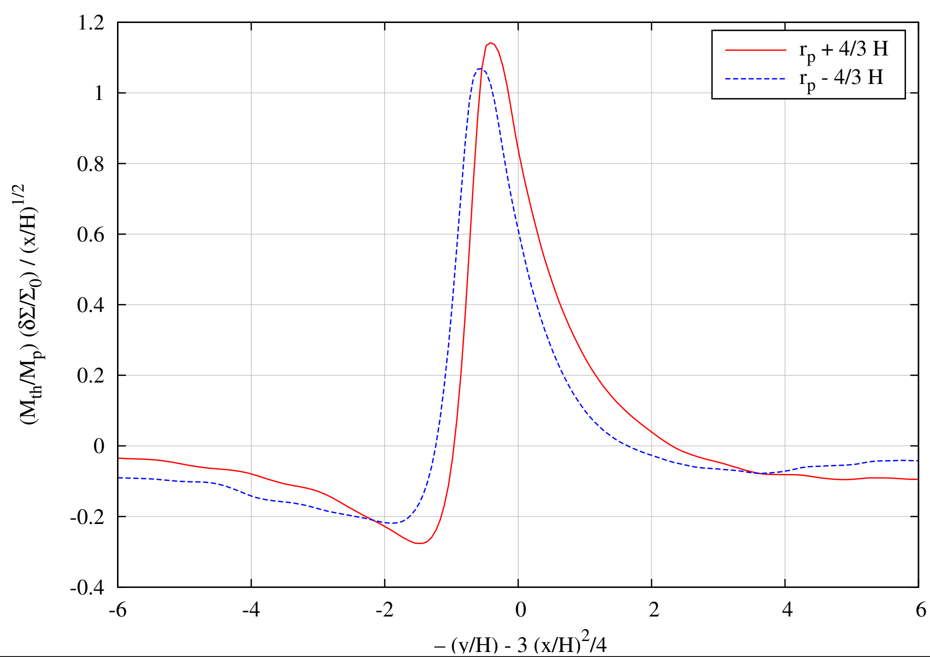
$$\Gamma_{\rm tot} = 2\pi \int \frac{d\Gamma}{dm}(r)\,\Sigma(r)\,r dr$$

$$\left(\frac{d\Gamma}{dm}\right)_0 = \Omega_{\rm p}^2(a_{\rm p}) a_{\rm p}^2 q^2 \left(\frac{H}{a_{\rm p}}\right)^{-4}$$

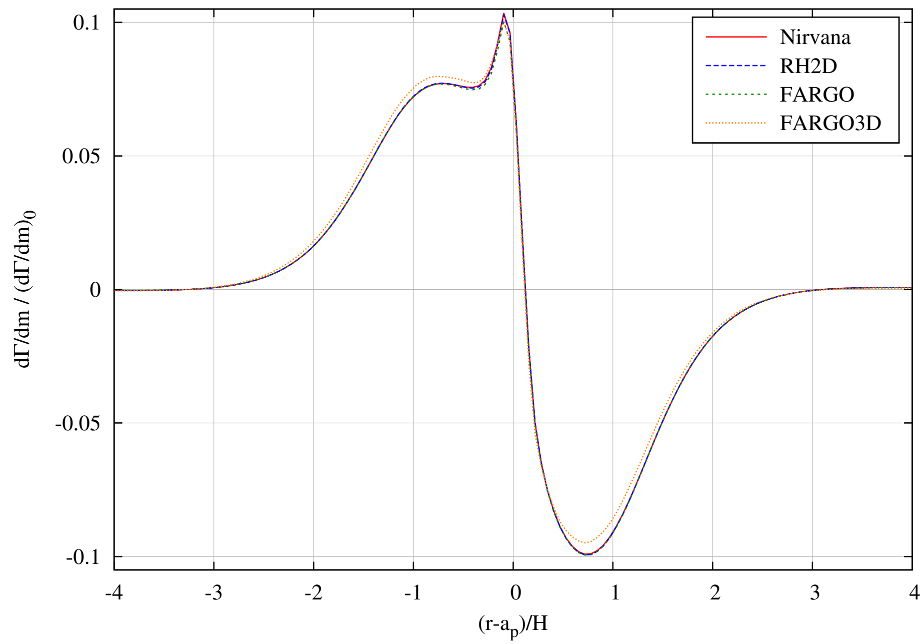
$$\Gamma_0 = \Sigma_0\, \Omega_{\rm p}^2(a_{\rm p}) a_{\rm p}^4 q^2 \left(\frac{H}{a_{\rm p}}\right)^{-2}$$

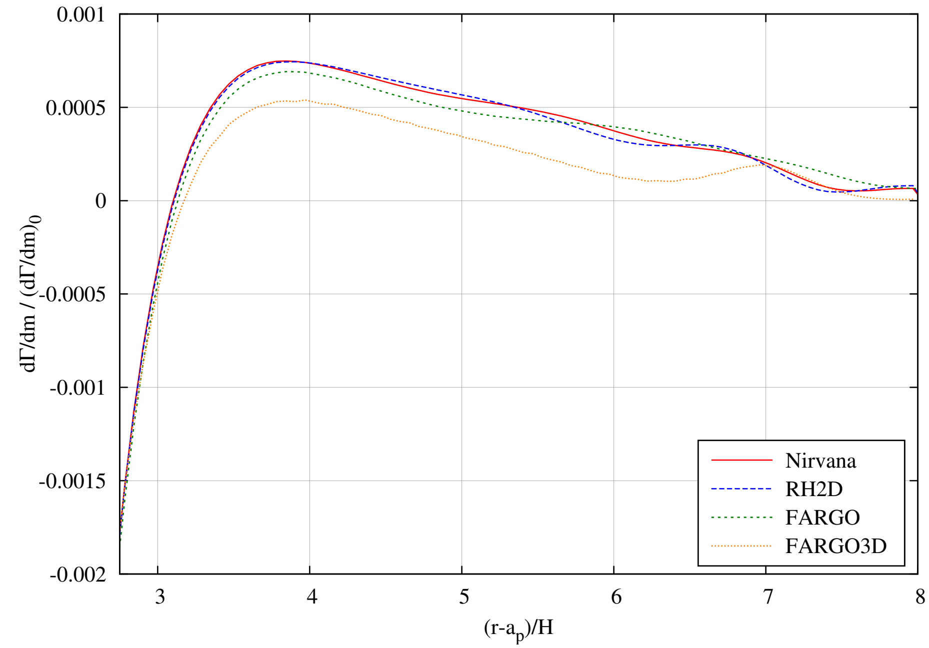


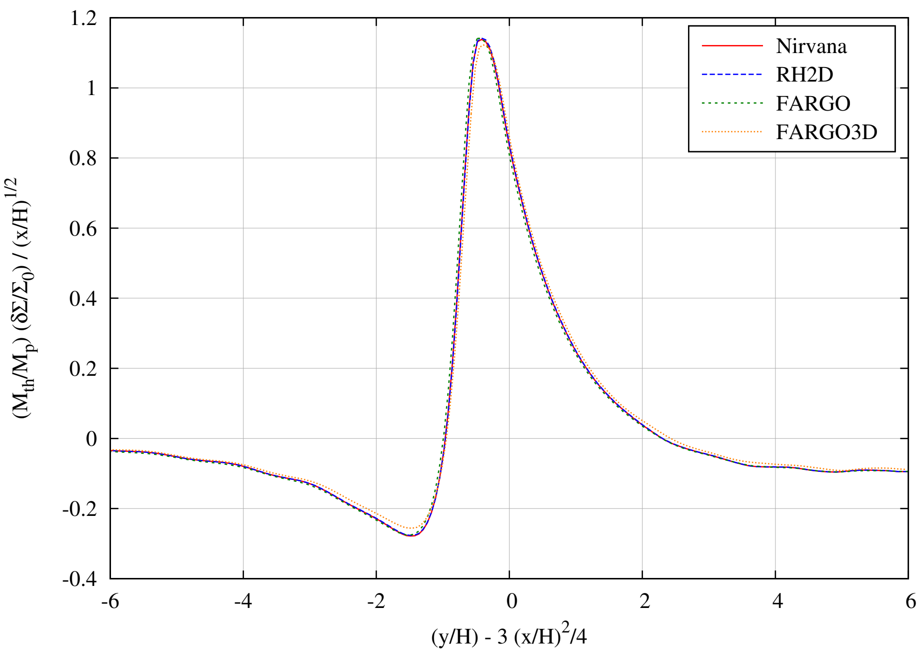




Codes Comparision







- all codes agree very well
  - on torque density and wake form
- all see the torque reversal at $r - r_p \approx 3.2H$

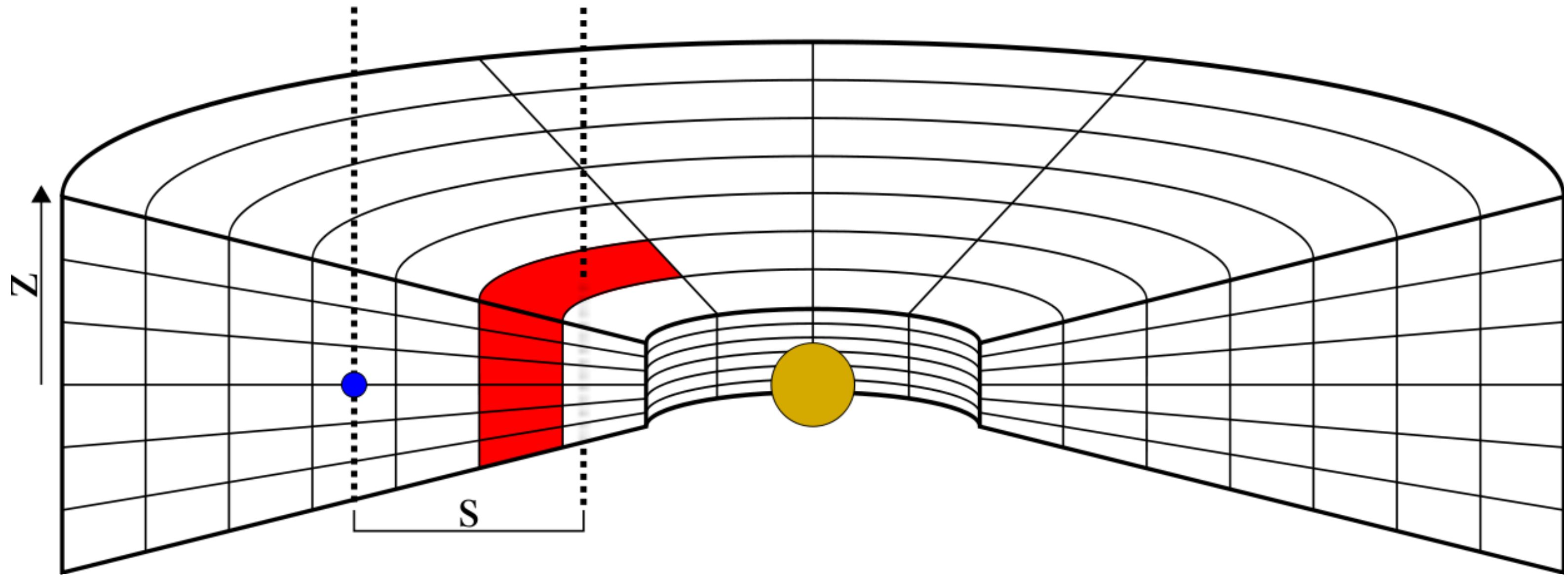
Vertical Averaging

In 2D simulations: Epsilon-potential (s is distance from planet to gridpoint)

$$\Phi_p^{2D} = -GM_p \frac{1}{(s^2 + \epsilon^2)^{1/2}}$$

But: 2D eqns. are obtained from 3D by vertical averaging: $\Rightarrow$ force density (force/area)

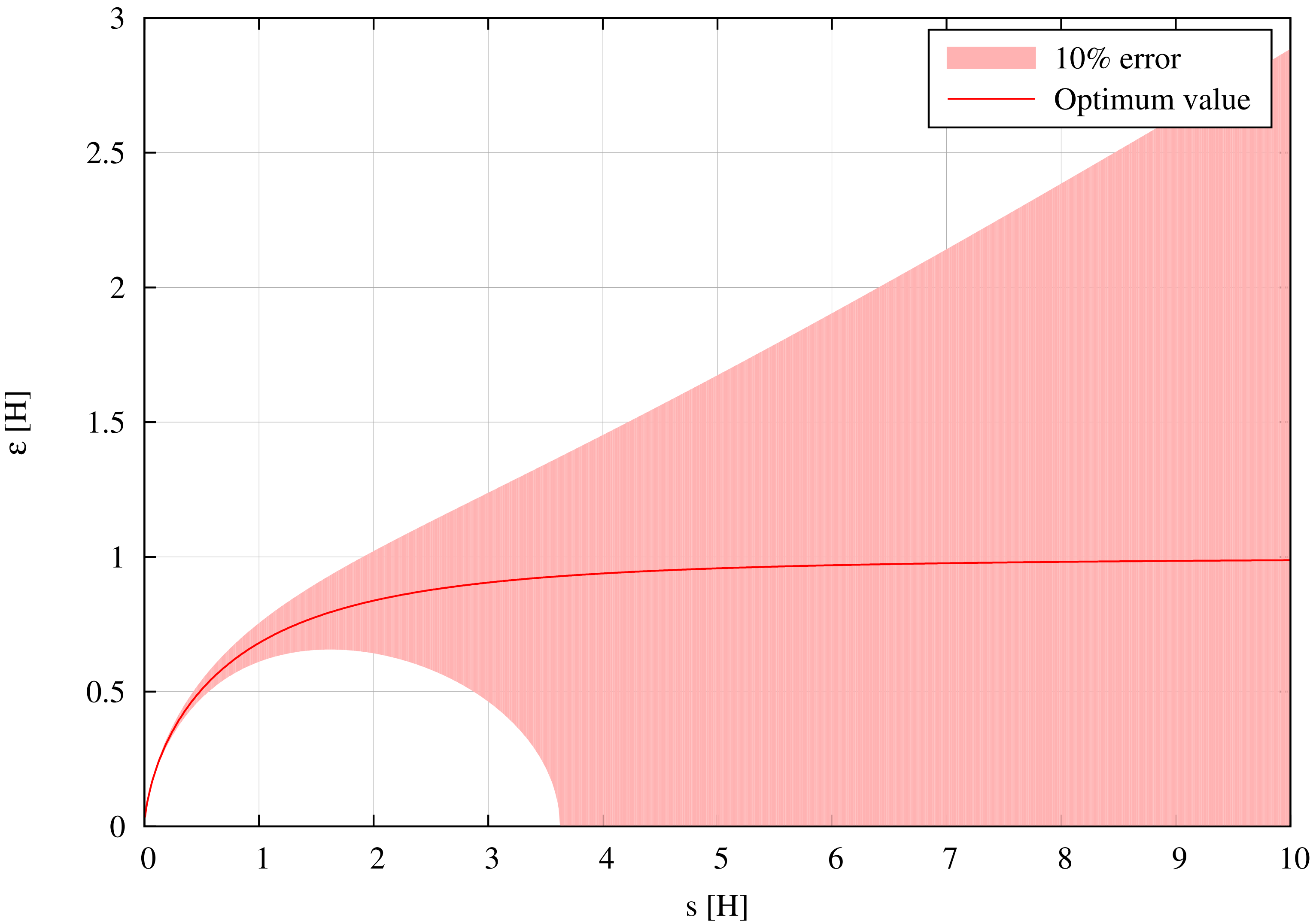
$$F_{\rm p}(s) = -\int \rho \frac{\partial \Phi_{\rm p}}{\partial s}\, dz = -GM_{\rm p} s \int \frac{\rho}{(s^2 + z^2)^{\frac{3}{2}}}\, dz$$



NOTE: In general $\nabla \Phi_{\rm p}^{\rm 2D} \neq \frac{\int \rho \nabla \Phi \, dz}{\Sigma}$ (specific force)

Calculate optimum ϵ

What ϵ makes $\nabla \Phi_{\rm p}^{\rm 2D} = \frac{\int \rho \nabla \Phi \, dz}{\Sigma}$

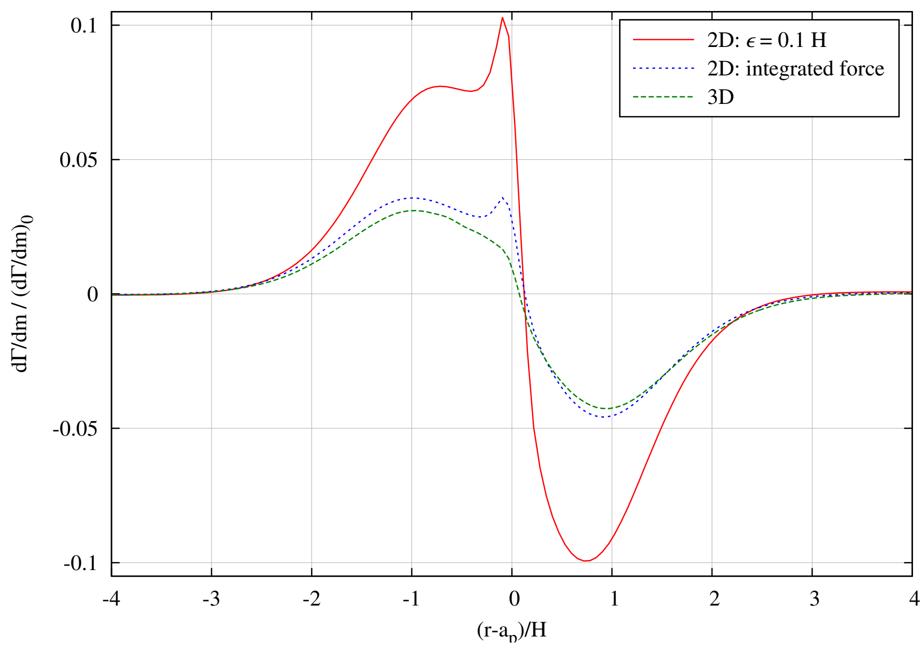


Müller ea 2012

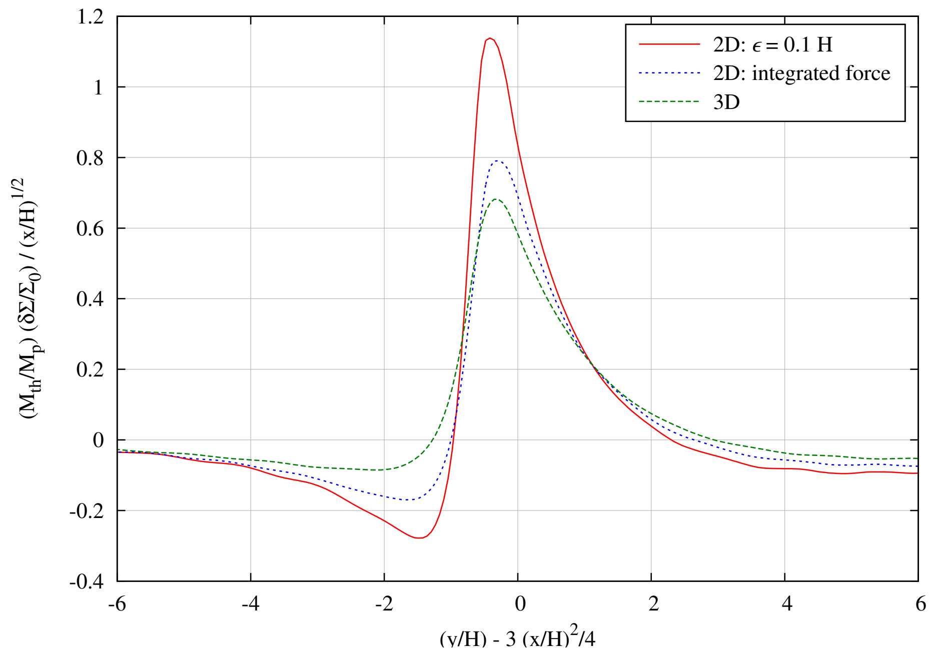
- optimum ϵ distance dependend,
- $\epsilon \Rightarrow 1$ for $s \Rightarrow \infty$

Torque and Wake profile

Torque-density

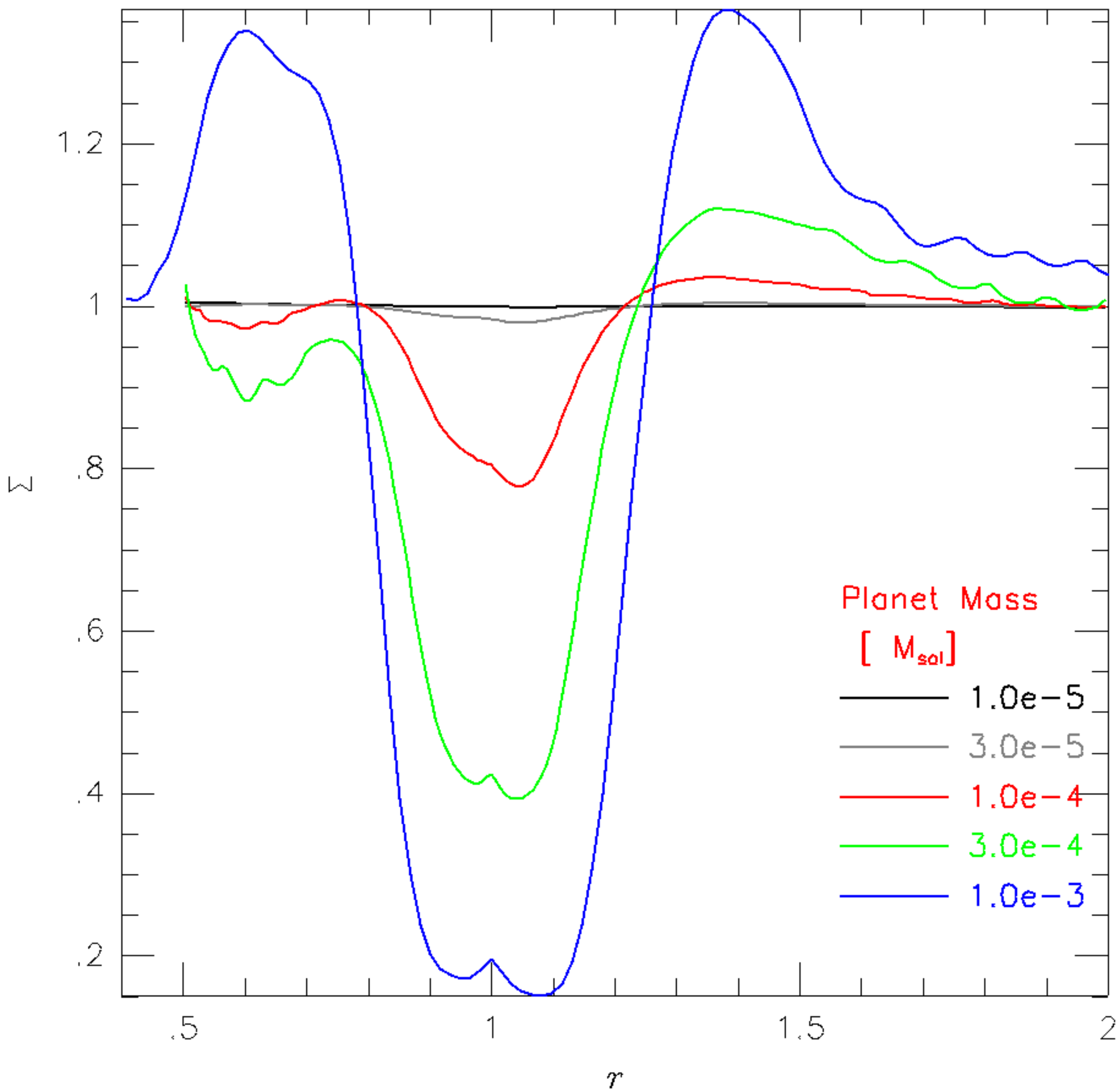


Linear wake-profile



- $\epsilon = 0.1$ leads to large overestimate of torques
- $\epsilon = 0.6 - 0.7$ agrees with 3D results
- good agreement vertical integrated force with 3D results

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

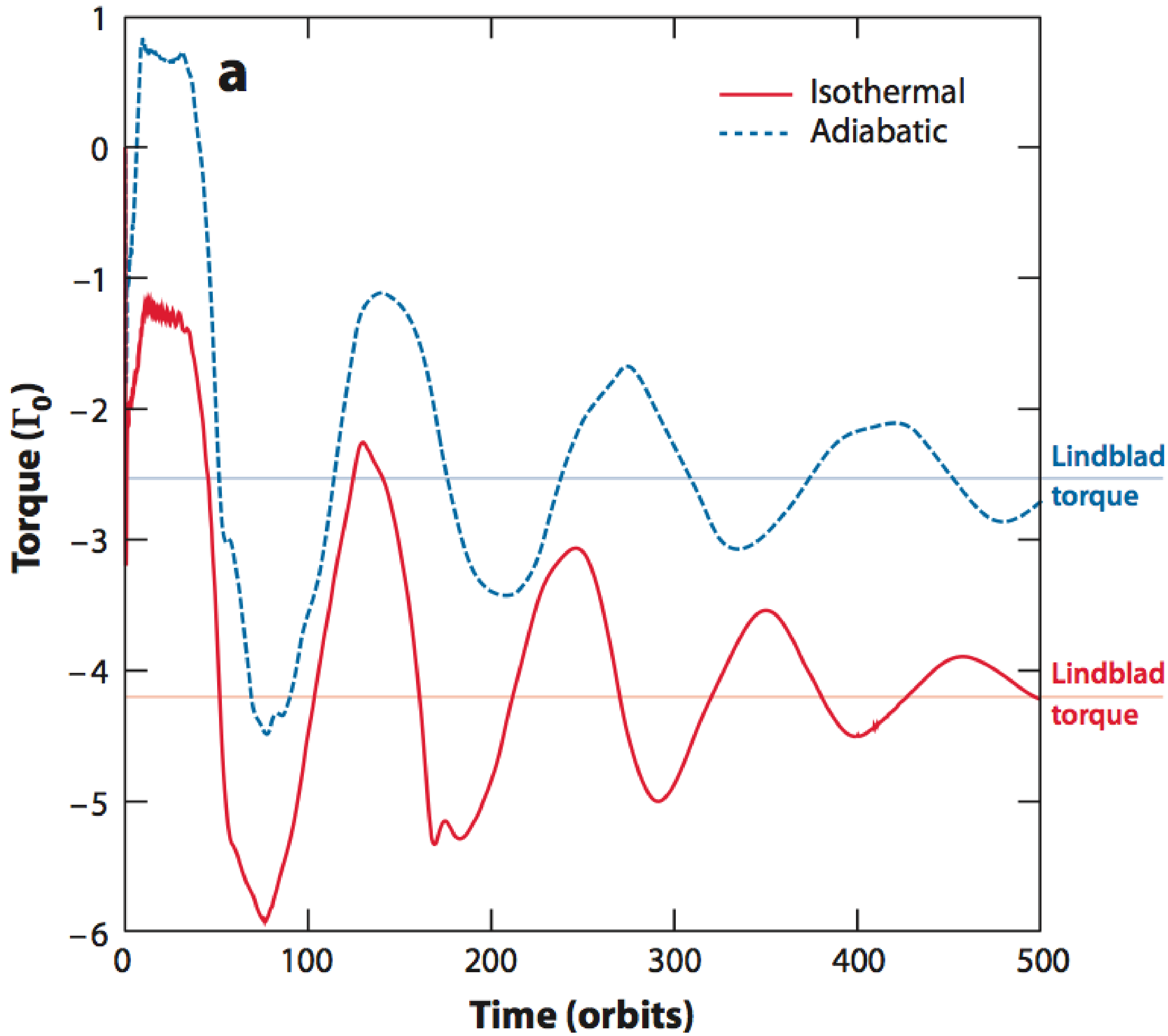
Note:
for barotropic and inviscid flows:

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

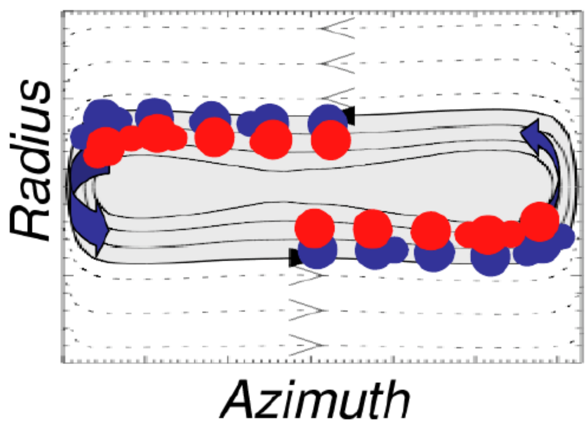
Torque depends on:
Gradients of ω_z/Σ, S
ω_z Vorticity
S Entropy

Gradients are wiped out in the corotation region

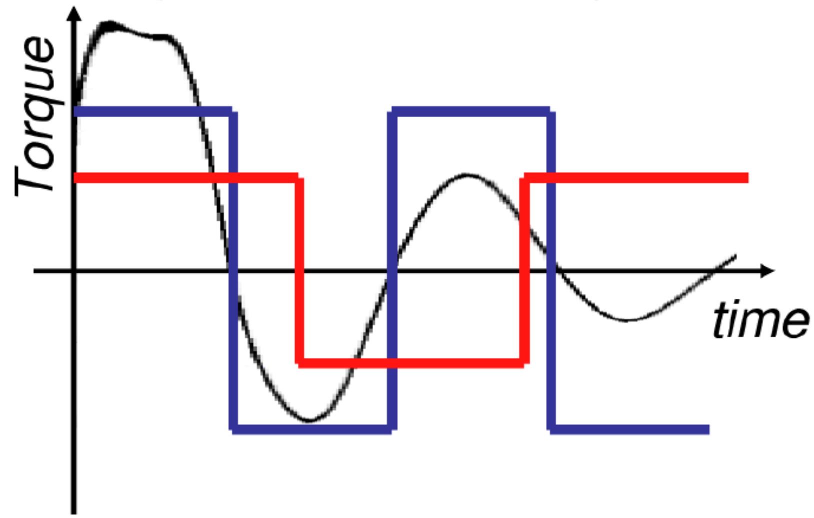
Total torque vs. time - isothermal - adiabatic



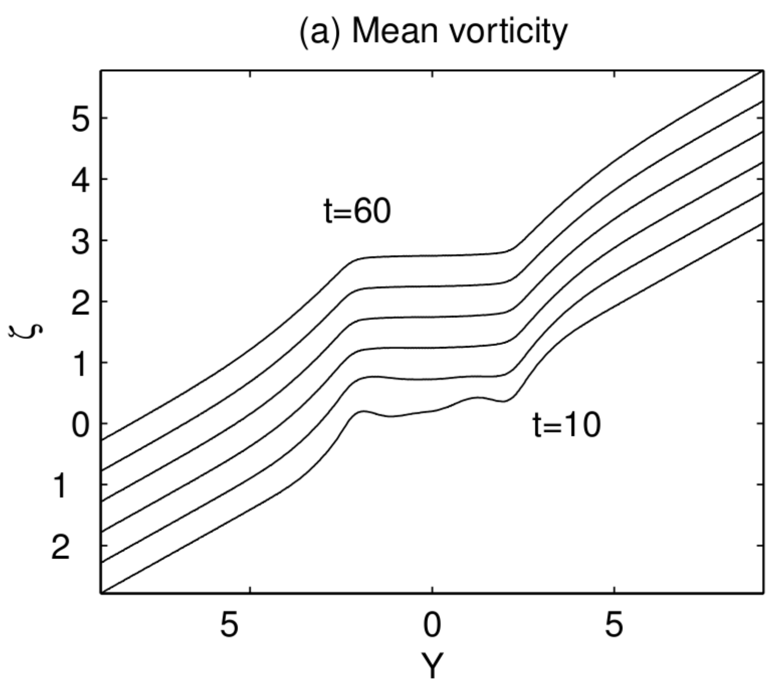
Saturation - Origin



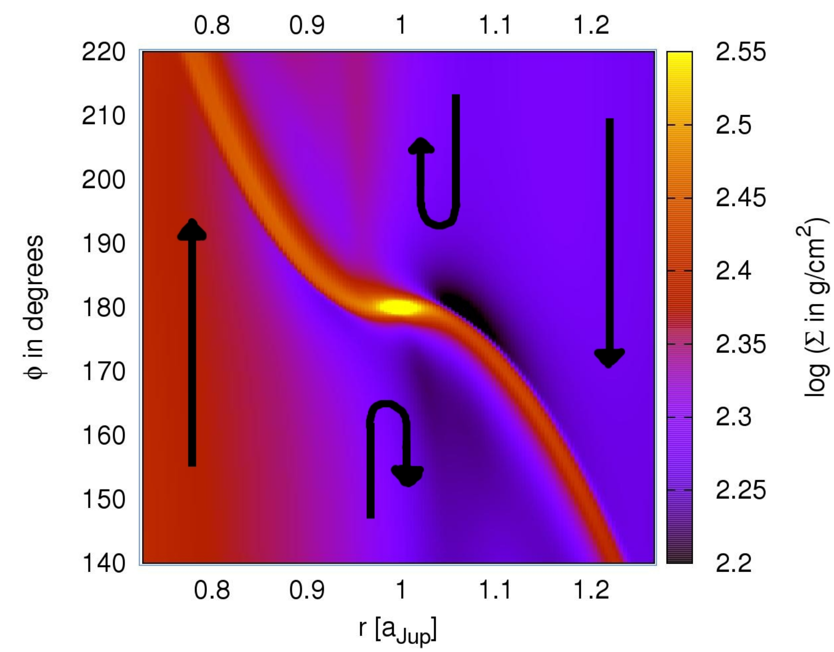
(F. Masset)



Red and Blue Orbits have different periods
⇒ Phase mixing



(Balmforth & Korycanski)



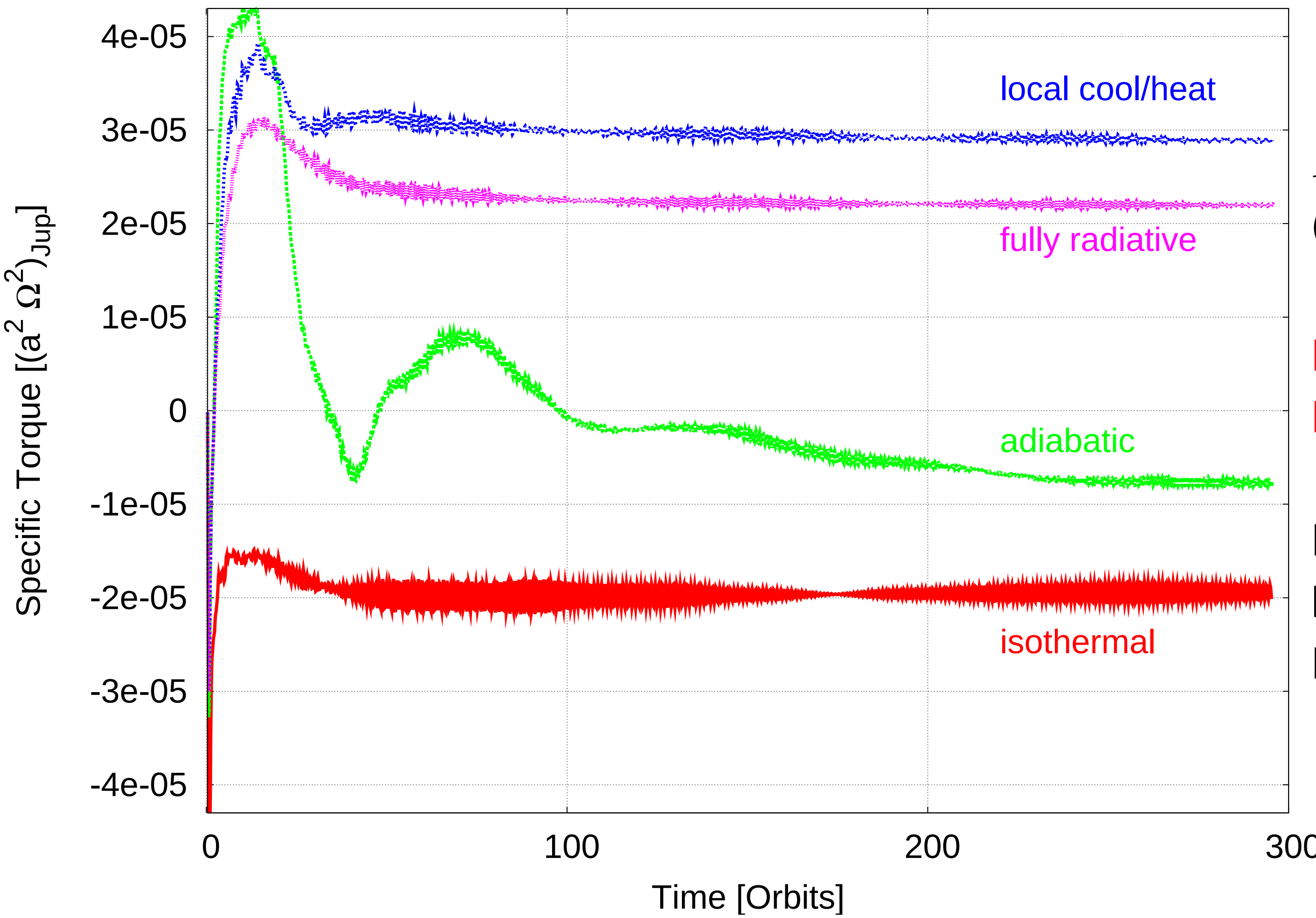
3D radiative disk (B. Bitsch)

Disk physics

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

Adiabatic: Pressure Work, Viscous heating (D), radiative cooling (Q) ($\propto T_{eff}^4$)

radiative Diffusion: in disk plane (realistic opacities)



$M_p = 20 M_{earth}$

(Kley&Crida '08)

Disk Physics determines

Direction of motion

see also:

Paardekooper & Mellema '06

Baruteau & Masset '08

Paardekooper & Papaloizou '08

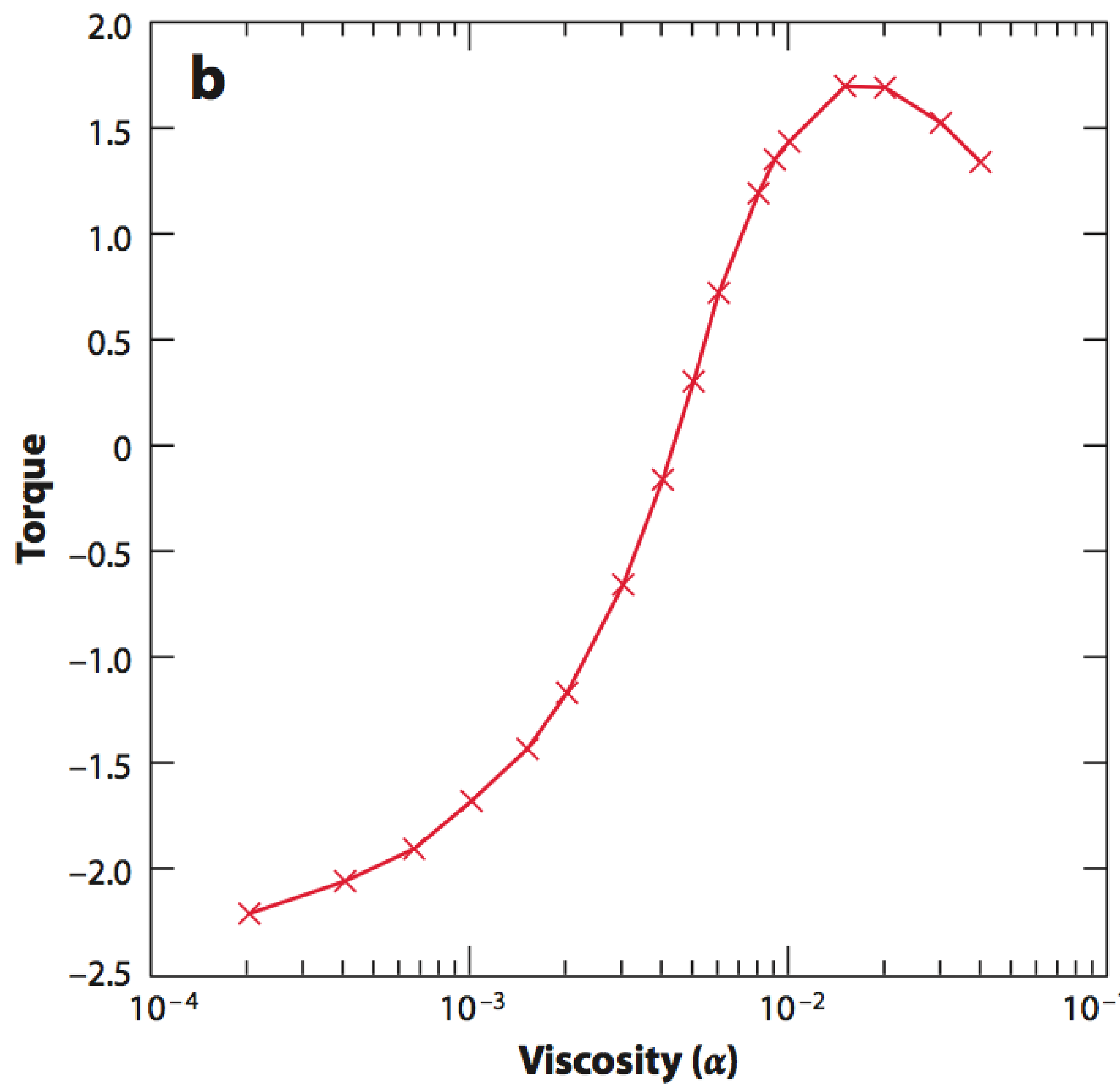
Role of viscosity

Total torque
vs. viscosity:

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

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

$\frac{\text{Local disk properties}}{\text{matter}}$

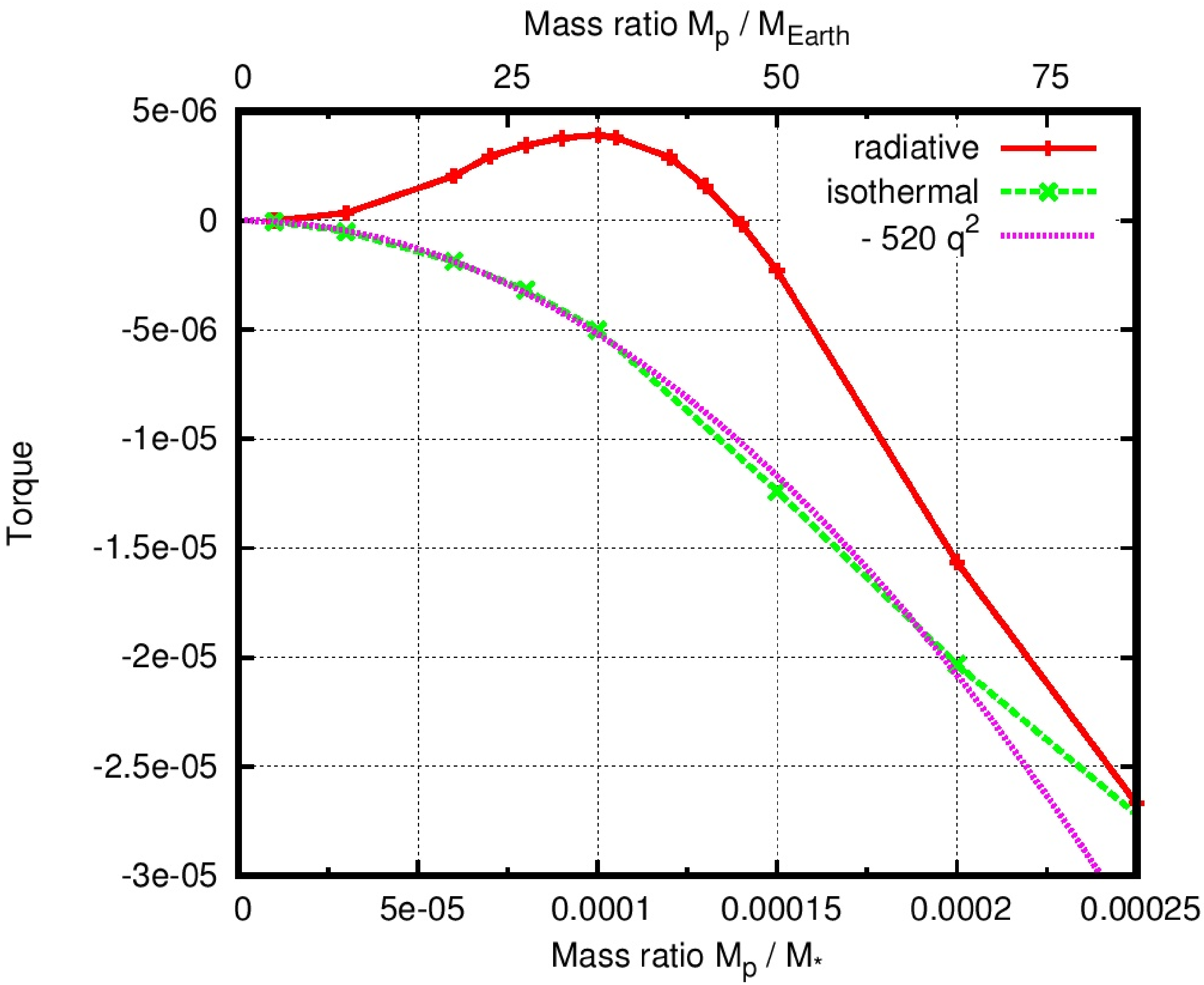


(Kley & Nelson 2012)

$\Rightarrow$ 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)

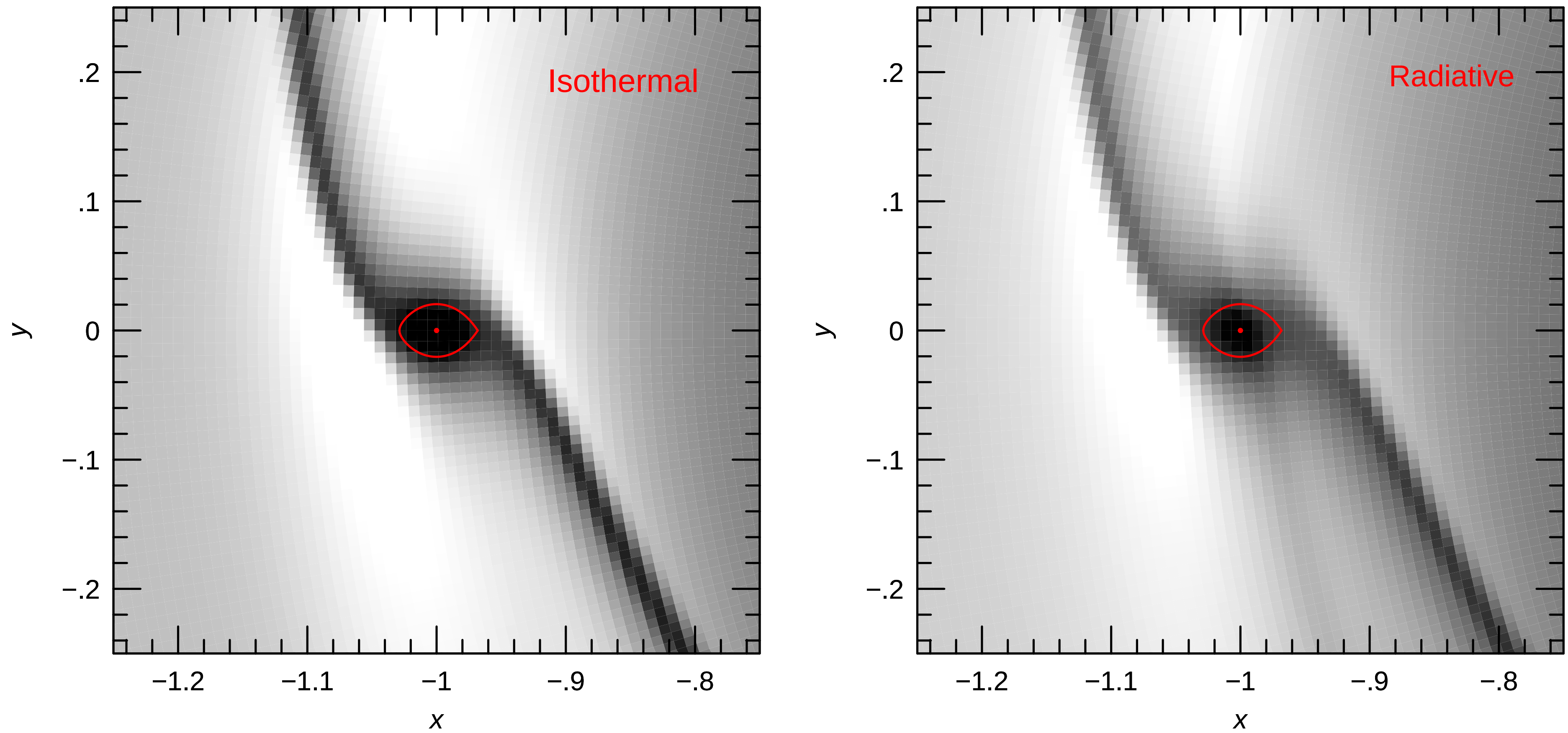
In full 3D

(Kley ea 2009)

With irradition:

Bitsch ea. (2012)

Compare density



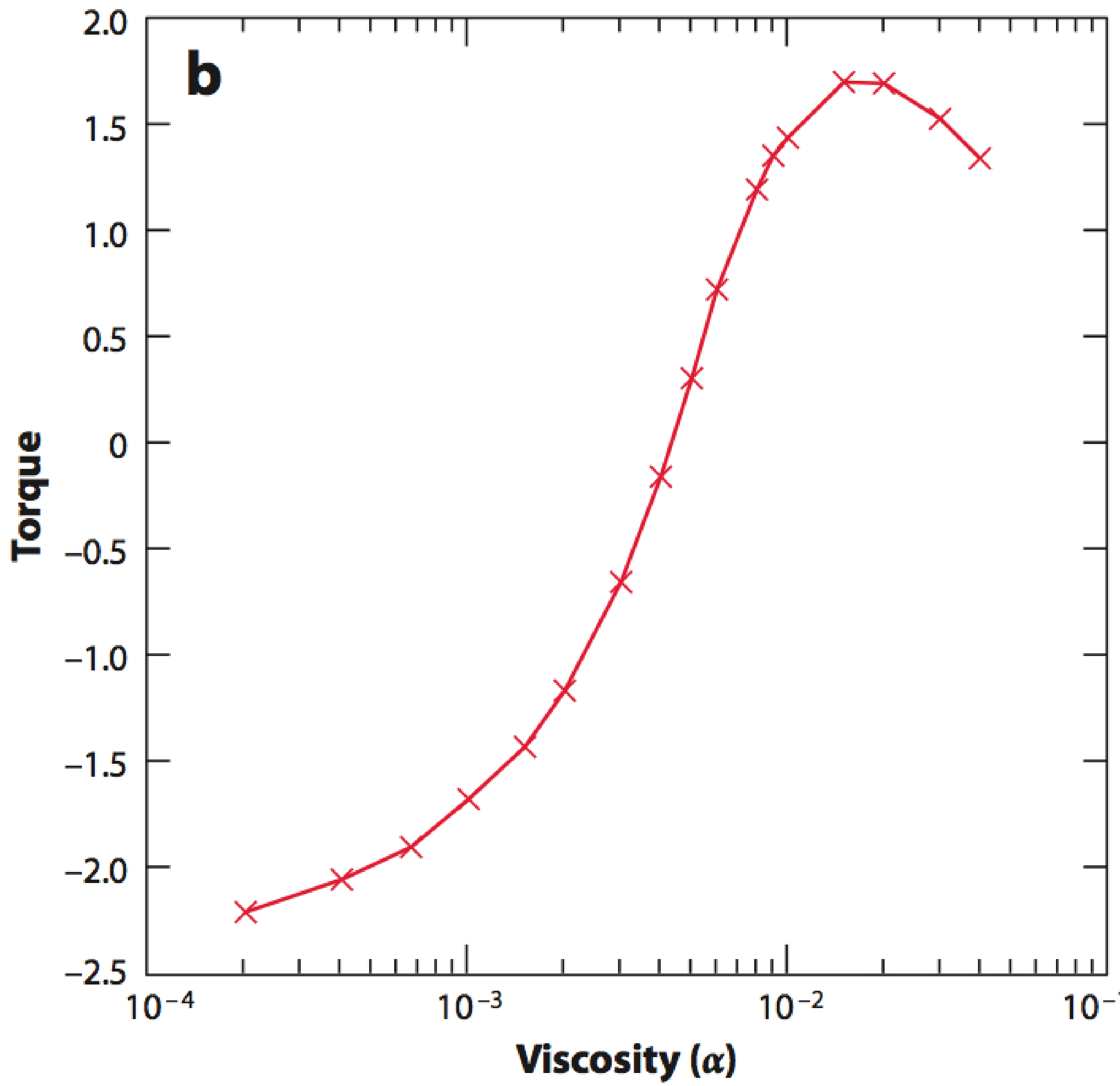
- wider spirals in radiative case (reduce torque)
- density maximum 'ahead' of planet (pulls planet forward)

$\Longrightarrow$ possibly positive torques

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

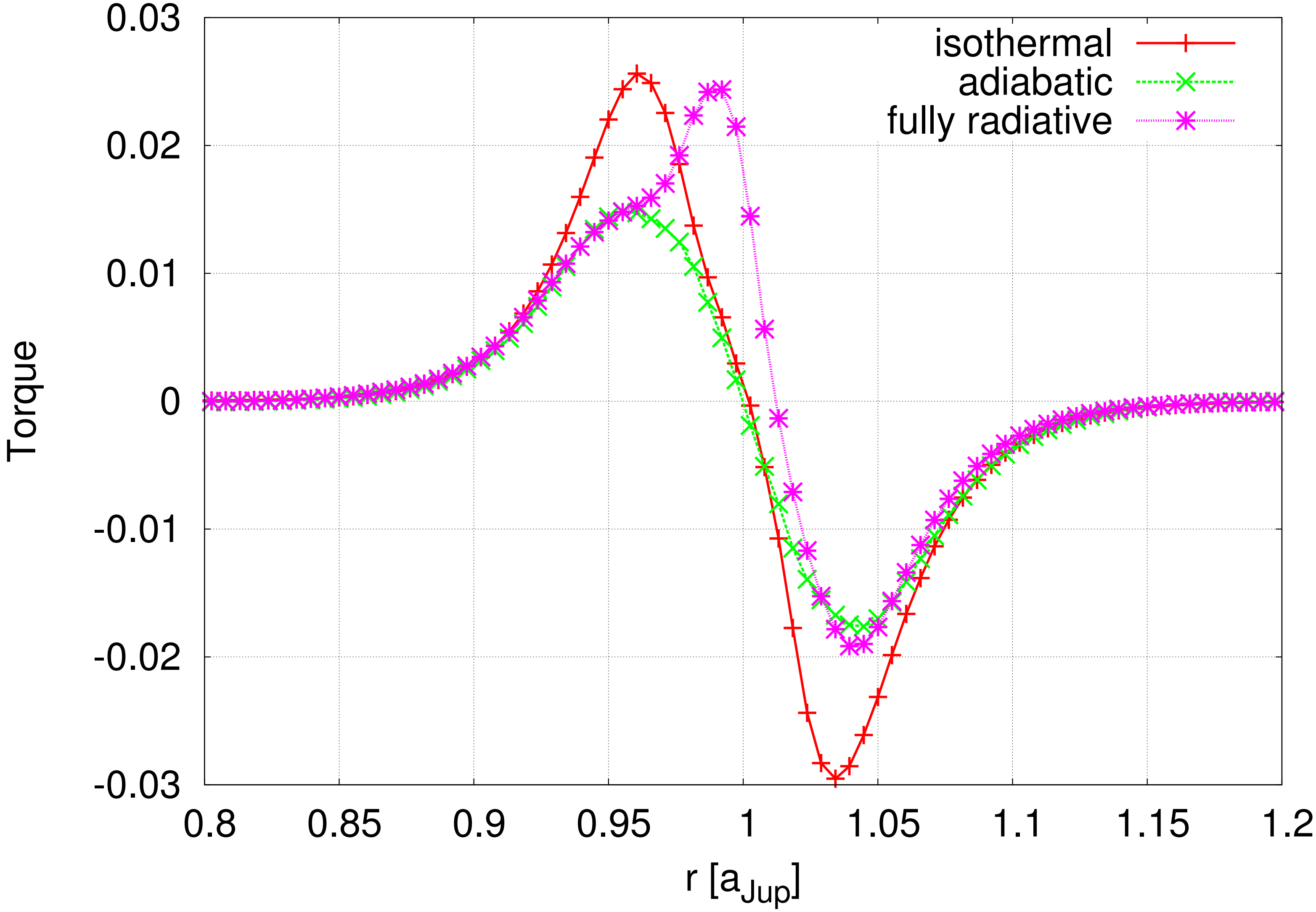
(Kley & Nelson 2012)

$\Rightarrow$ Need viscosity to prevent saturation !

Radial Torque density

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

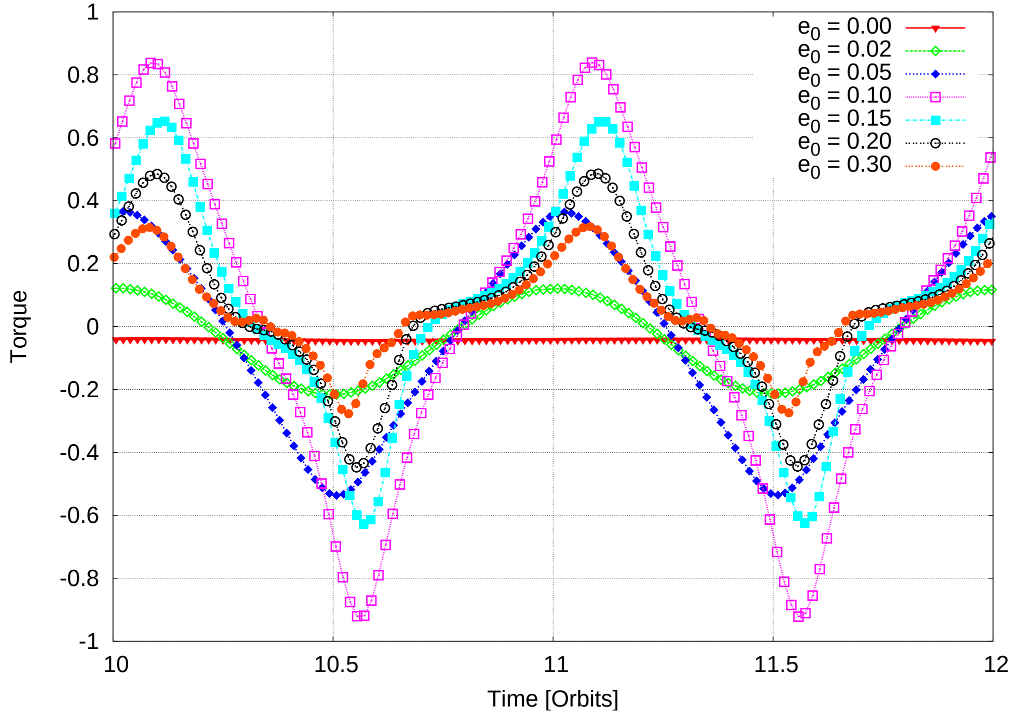
$d\Gamma/dm$, with $\Gamma_{\rm tot} = 2\pi \int (d\Gamma/dm) \Sigma dr$ Radiative: $\Rightarrow$ additional positive contrib.



Planets on eccentric Orbits

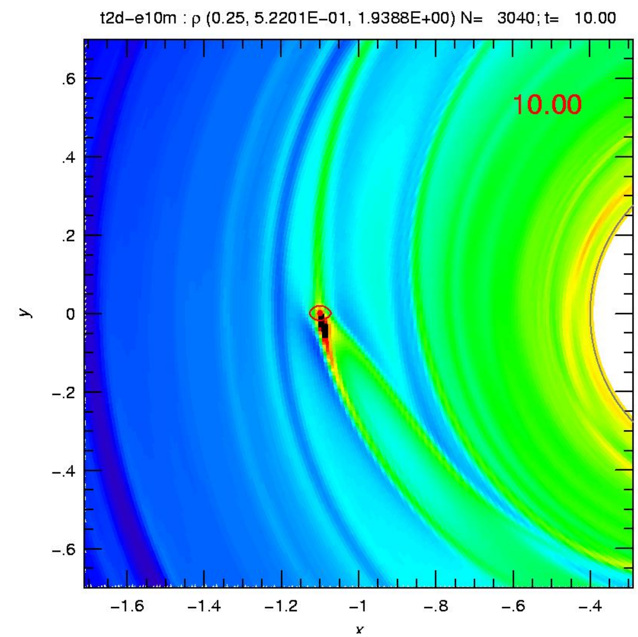
Torque on planet due to disk

$$T_{\rm disk} = - \int_{\rm disk} (\vec{r} \times \vec{F})\Big|_z \, df$$



Power: Energy loss of planet

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



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

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

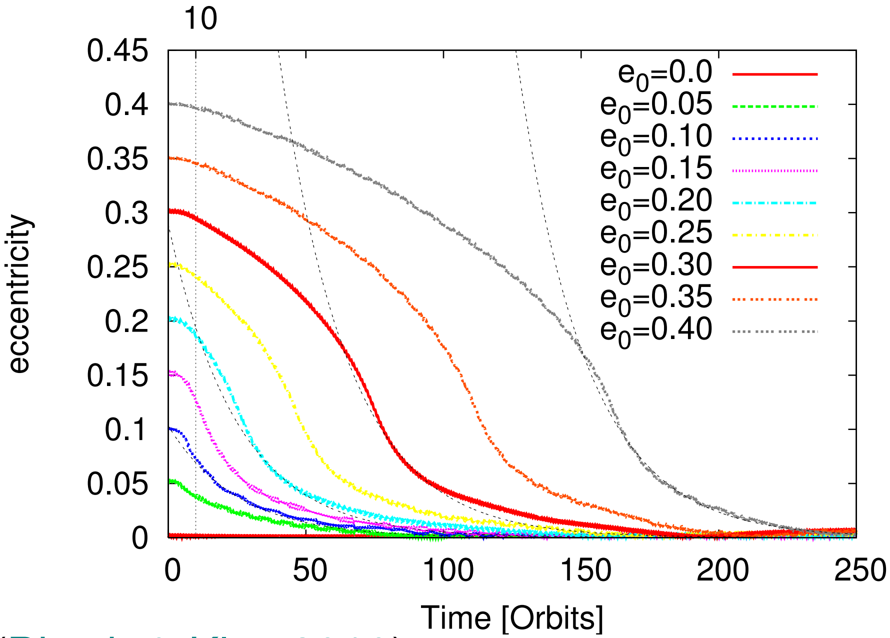
$$E_{\rm p} = -\frac{1}{2}\frac{G M_* m_{\rm p}}{a}$$

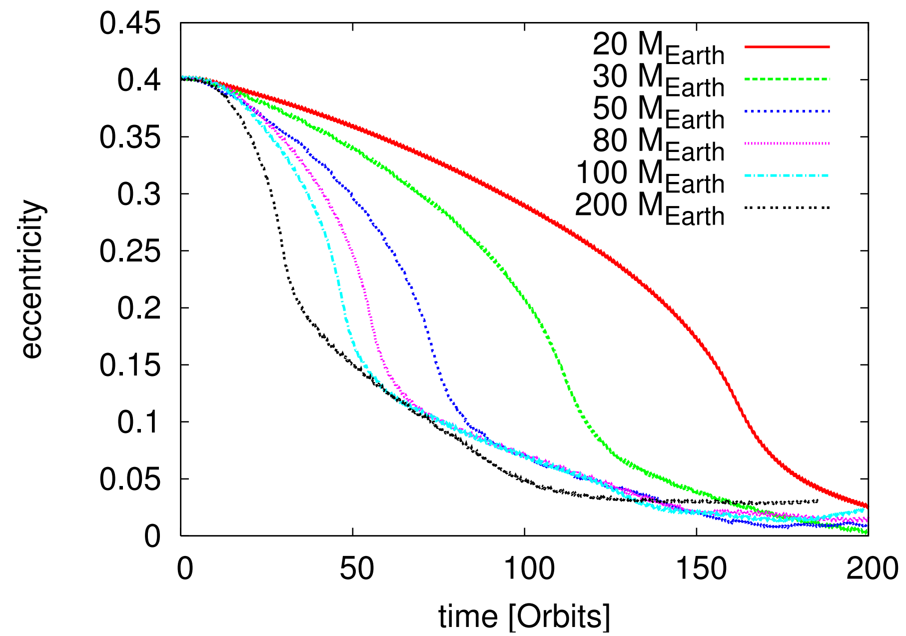
$$\frac{\dot{E}_{\rm p}}{E_{\rm p}} = \frac{\dot{a}}{a} = \frac{P_{\rm disk}}{E_{\rm p}}$$

In 3D radiative disks

Planet mass $M_p = 20 M_{\rm Earth}$
- Vary Eccentricity

Vary Planet Mass $10 - 200 M_{\rm Earth}$
- Fixed $e_0 = 0.40$





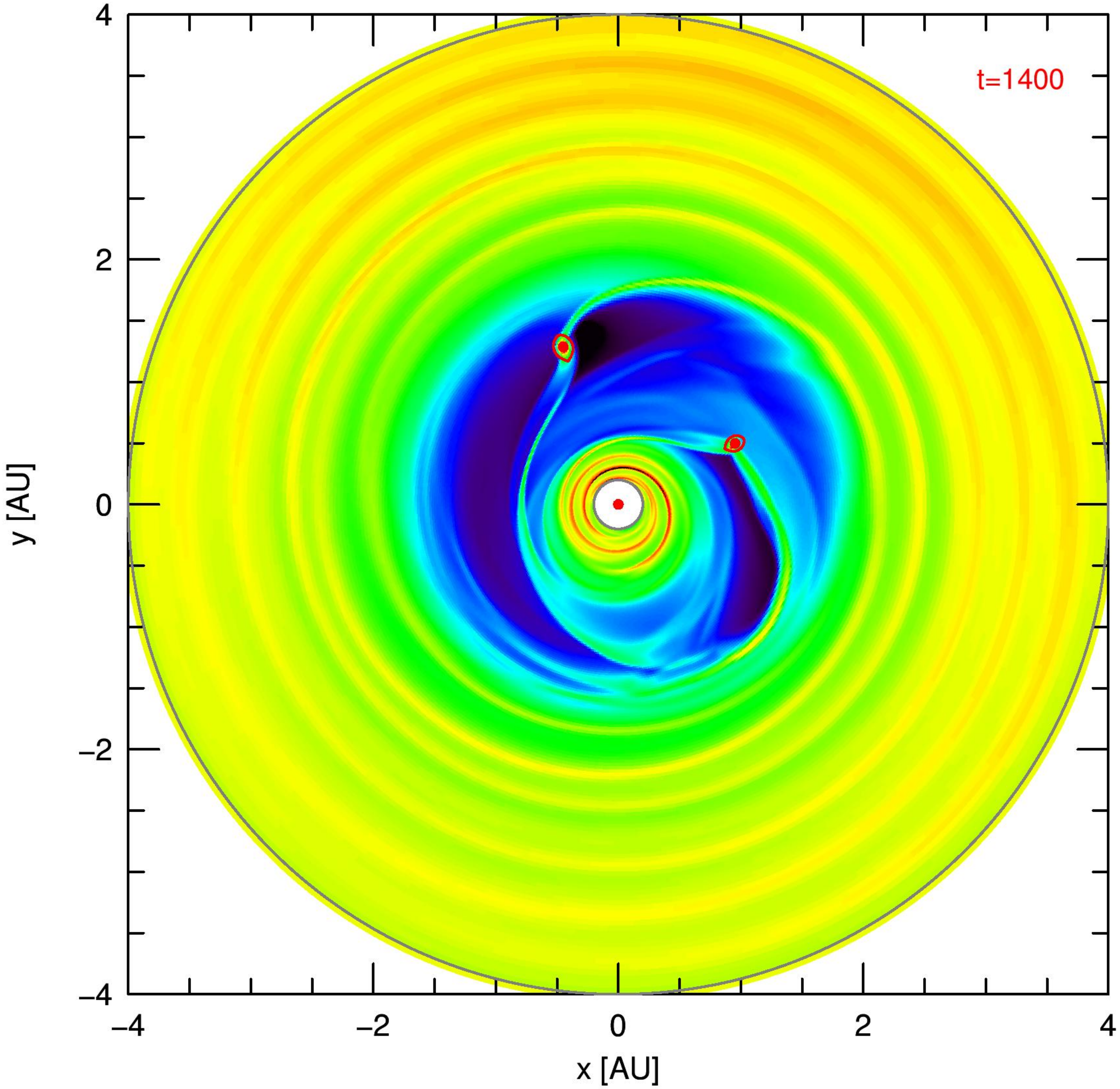
(Bitsch & Kley 2010)

- e-damping for all planet masses.
  Small e: exponential damping, large e: $\dot{e} \propto e^{-2}$
- Need $e < 0.01 - 0.02$ for outward migration to work (radiative disks)

$\Longrightarrow$ Need multiple objects ! (Scattering)

Resonant capture & Gap

2 massive planets in disk (HD 73526 $\approx 2.5 M_{\rm Jup}$ each)



Two planets:
joint, large gap

Outer planet :
Pushed inward
by outer disk

Inner planet :
Pushed outward
by inner disk

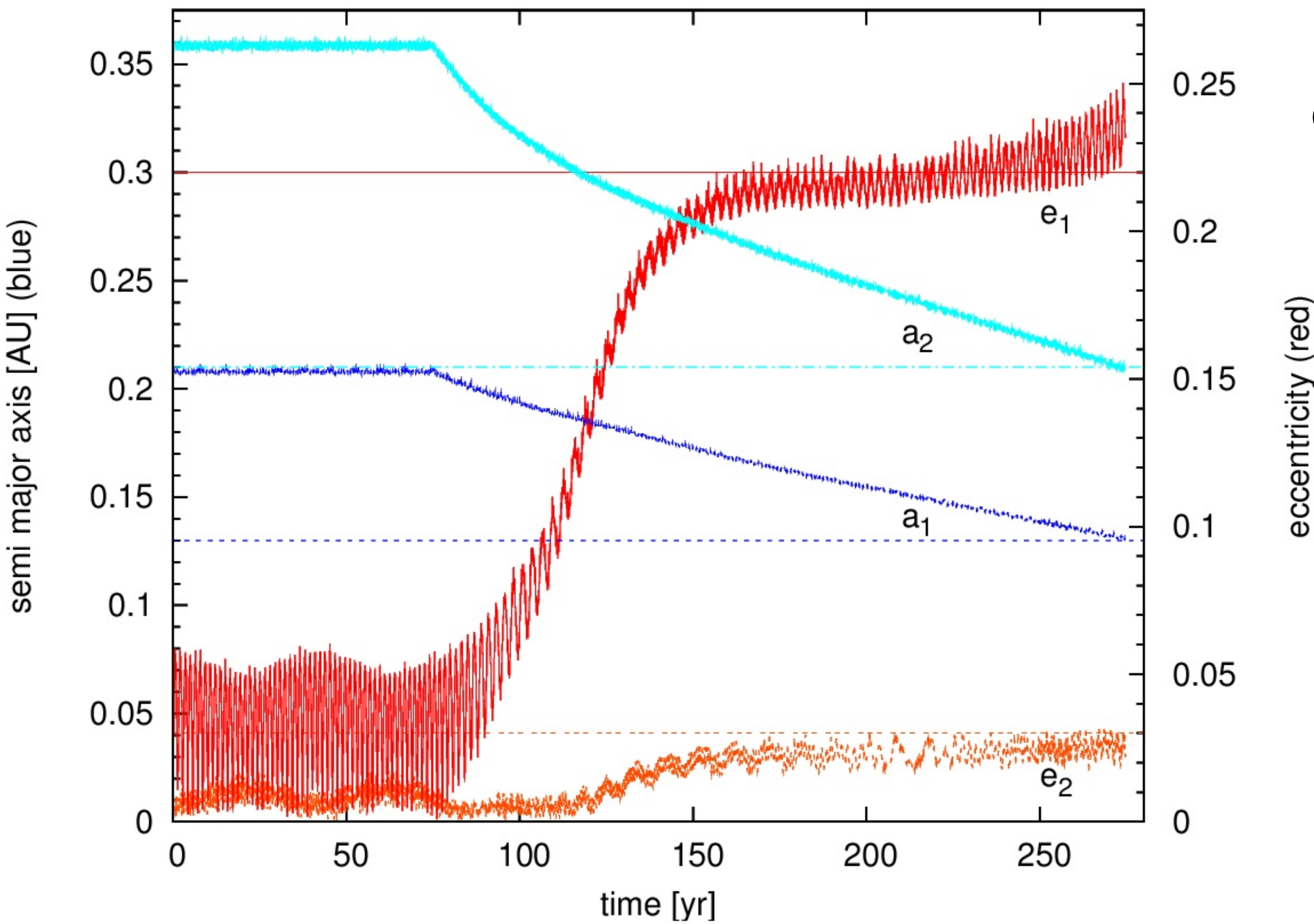
Separation reduction:
Resonant capture

(Sandor, Kley & Klagyivik 2007)

compare: HD142527

Eccentricity Pumping

Here: System-parameter of GJ 876 (damping of inner & outer disk)



Compactification

Excitation

(Crida ea 2008)

System ends in: apsidal corotation, with correct eccentricities

Less disk damping: $\Rightarrow$ much higher e $\Rightarrow$ possible Instability

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

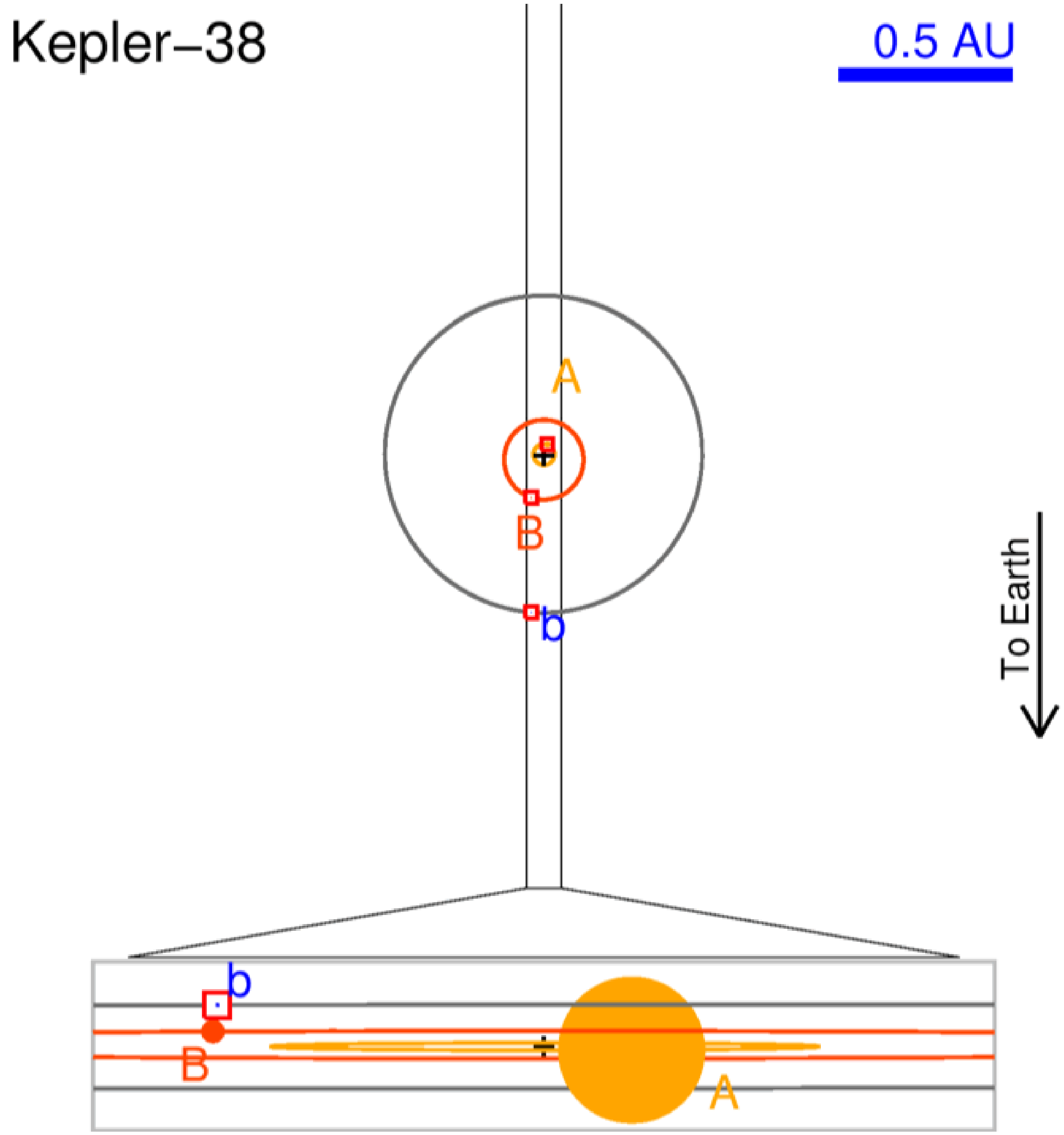
- Existence of resonant systems

  - Clear evidence for planetary migration

- Hot Jupiters (Neptunes) & Kepler systems

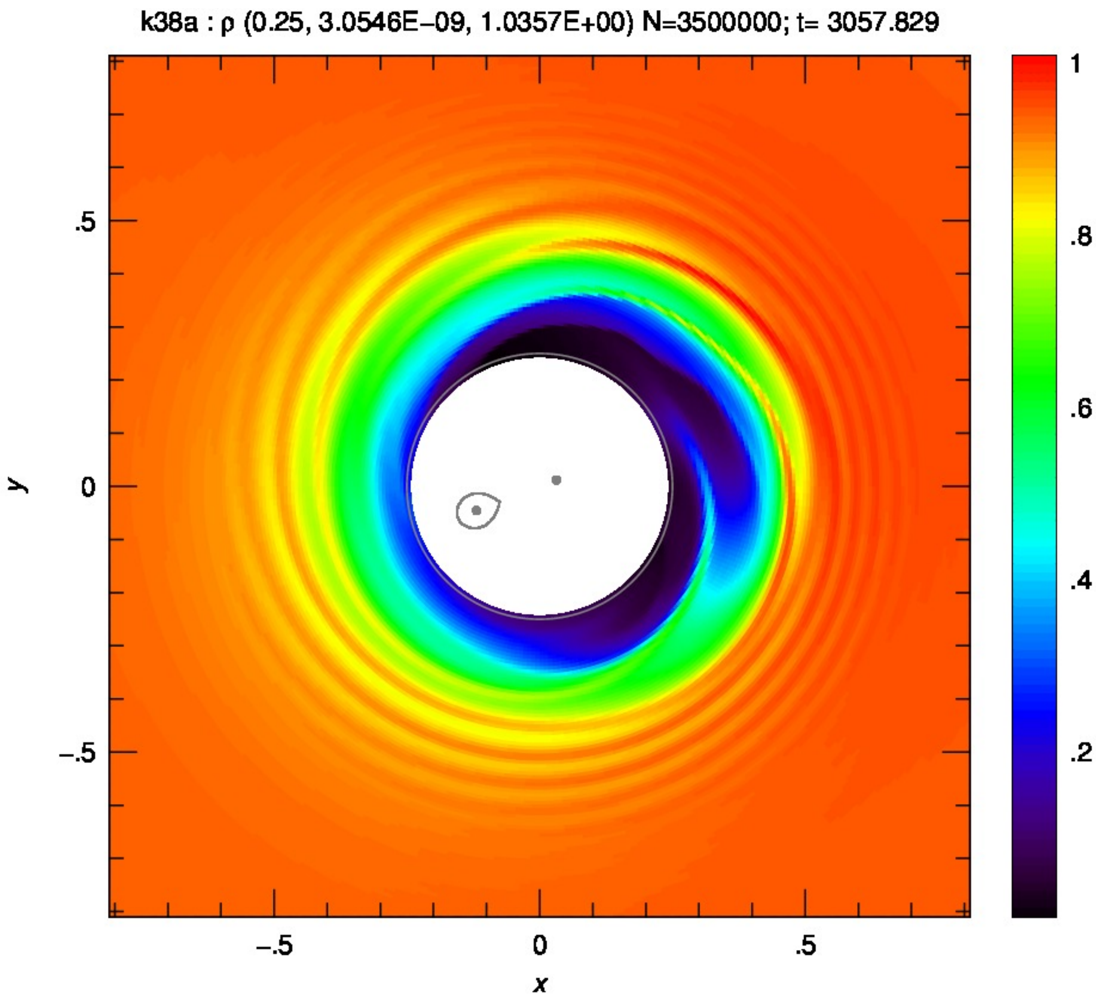
  - Clear evidence for planetary migration

System Architecture



Kepler 38

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

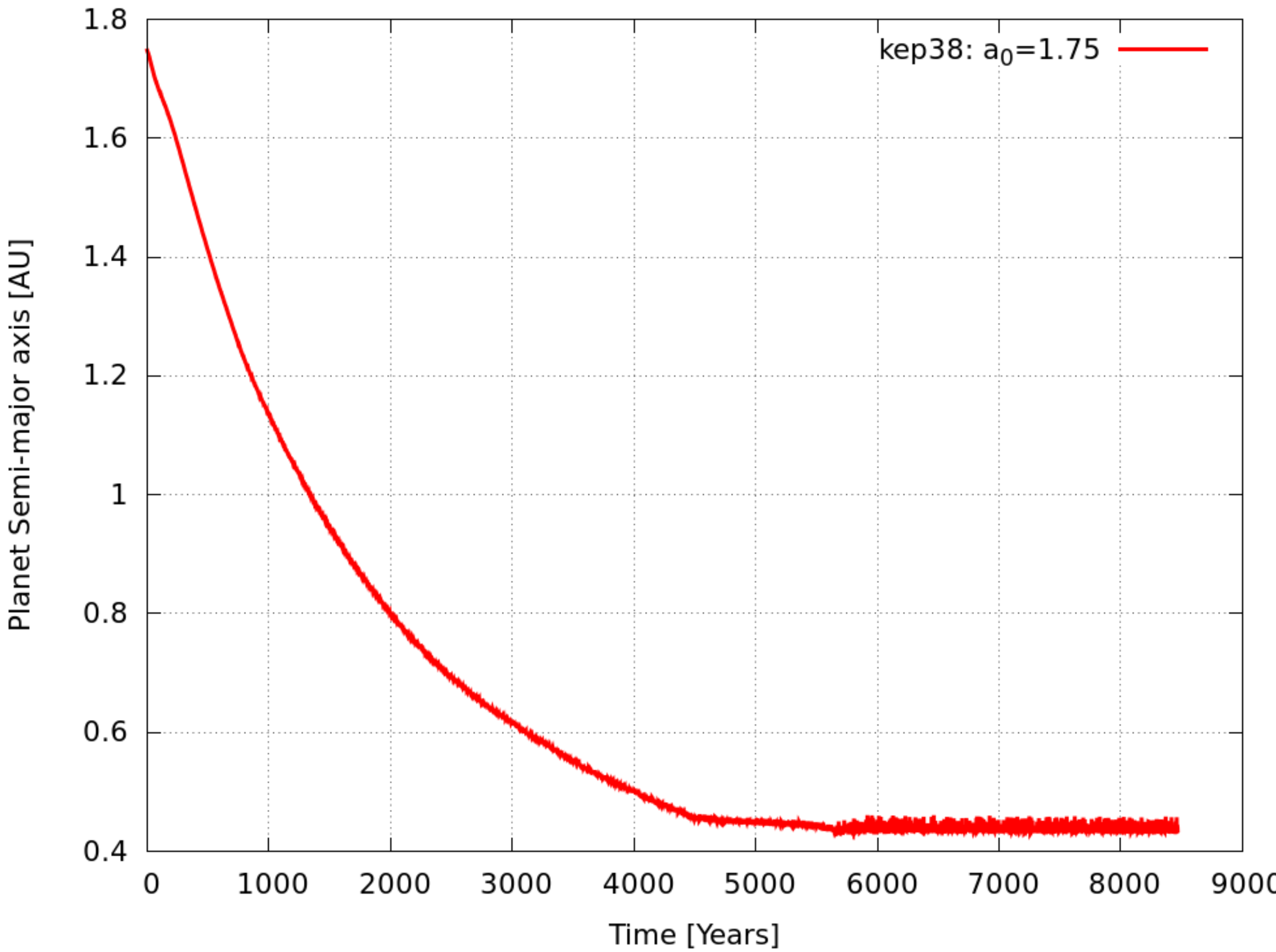


Binary Parameter:
$M_1 = 0.95 M_\odot$,
$M_2 = 0.25 M_\odot$
$a_B = 0.15$ AU
$e_B = 0.10$

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/Outlook

New properties of extrasolar Planets

- High Masses
- Large eccentricities
- Close distances

Planet-disk simulations

- Coord. System
- Angular momentum conservation
- FARGO-Accelaration
- Grid-Refinement
- Thermodynamics

Accurate accretion & migration history of planets requires

- Full 3D simulations
- High resolution (locally)
- Radiation transport
- Self-Gravity
- Magnetic Fields

The End