Planet-Disk Interaction & Migration

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Organization

- Problem Formulation
- Disk-Planet Modeling
  - Here: Viscous Disks
  - Types of Migration
- More Recent Results
  - Runaway Migration
  - Eccentricity

Observational Status

- Total: 135 (January, 2005)
- 2 Transiting Planets (HD 209458, TrES-1)
- OGLE-Transits: 4 (TR-56, -113, -132, -10)
- Systems with 2 or more planets: 14
- Planetary Systems in Binaries: 15 (or more)
- Planetary Systems in Mean Motion Resonance: 4
- Fraction of stars with planets: $\approx 5 - 7\%$
- Neutron Star planets
- $\longrightarrow$ Talk by Debra Fischer

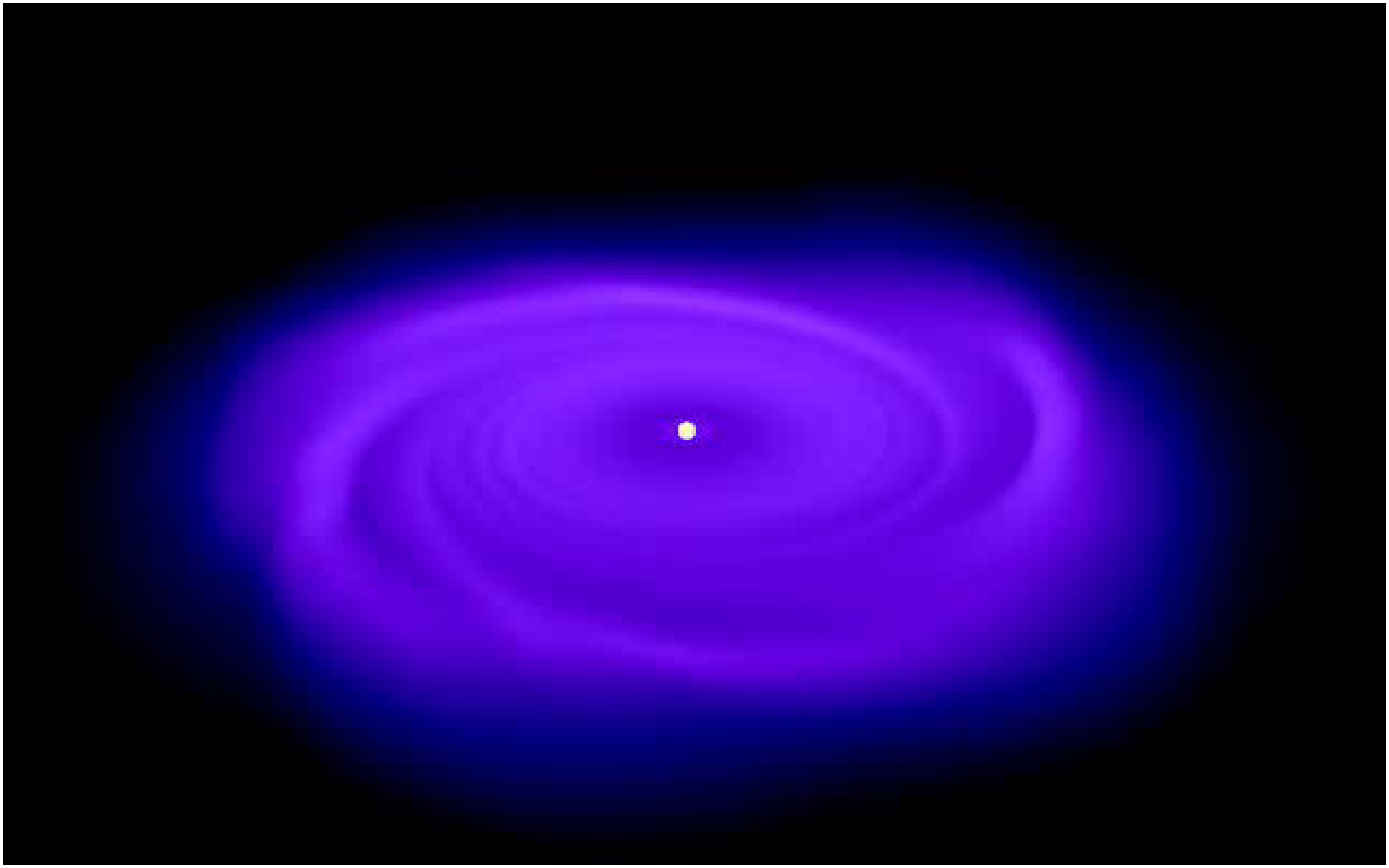
Theoretical Problems

- Large Masses (0.2-17 M_{Jup})
  Gap Formation (cf. Saturn's Rings)
- Small Distance (hot Jupiters) (0.04 - 4.8 AU)
  Snow Line (ca. 3 AU)
- Large Eccentricities (0.0 - 0.91)
  Formation on Circular Orbits
- Resonant Orbits (2:1, 3:1)
  Arbitrary Orbits
- Free Floaters (Jupiter-mass range)
  Too small for direct Collapse
- OGLE-Transits ($P_{orb} \approx 1.2$d)
  Very, very close to the star!

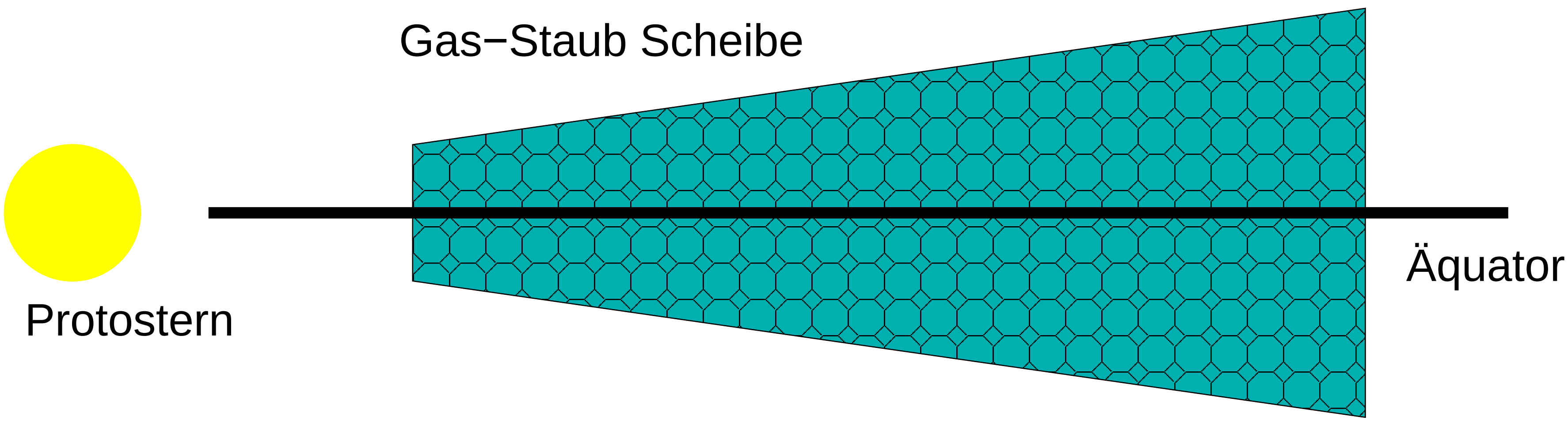
Planet-Formation: Scenario I

Gravitational Instability in protoplanetary Disk

Hydrodynamics: $M_{\rm Star} = 1\ M_\odot$, $M_{\rm Disk} = 0.1\ M_\odot$ (L. Mayer, 2002)



Coagulation of Dust/Gas in Disk



Growth: Dust $\Rightarrow$ Planets, (μm $\Rightarrow$ 1000km)
(Mass-growth of 35 Orders of Magnitude)

Through sequence of collisions & coagulations (Talks: J. Blum, S. Ida)

Planet-Disk Interaction

- Assume: Protoplanets have formed alread
- Study further Evolution in Disk consider gravitational interaction

Two ways:

- Linearization (Goldreich, Tremaine, Ward, Tanaka, ...)
- Hydrodynamical Calculations

Here: Hydrodynamical Calculations
(MHD $\longrightarrow$ R. Nelson's Talk)

Ingredients

Star (1 $M_\odot$), Disk (0.01 $M_\odot$), Planets ($\approx M_{\rm Jup}$)

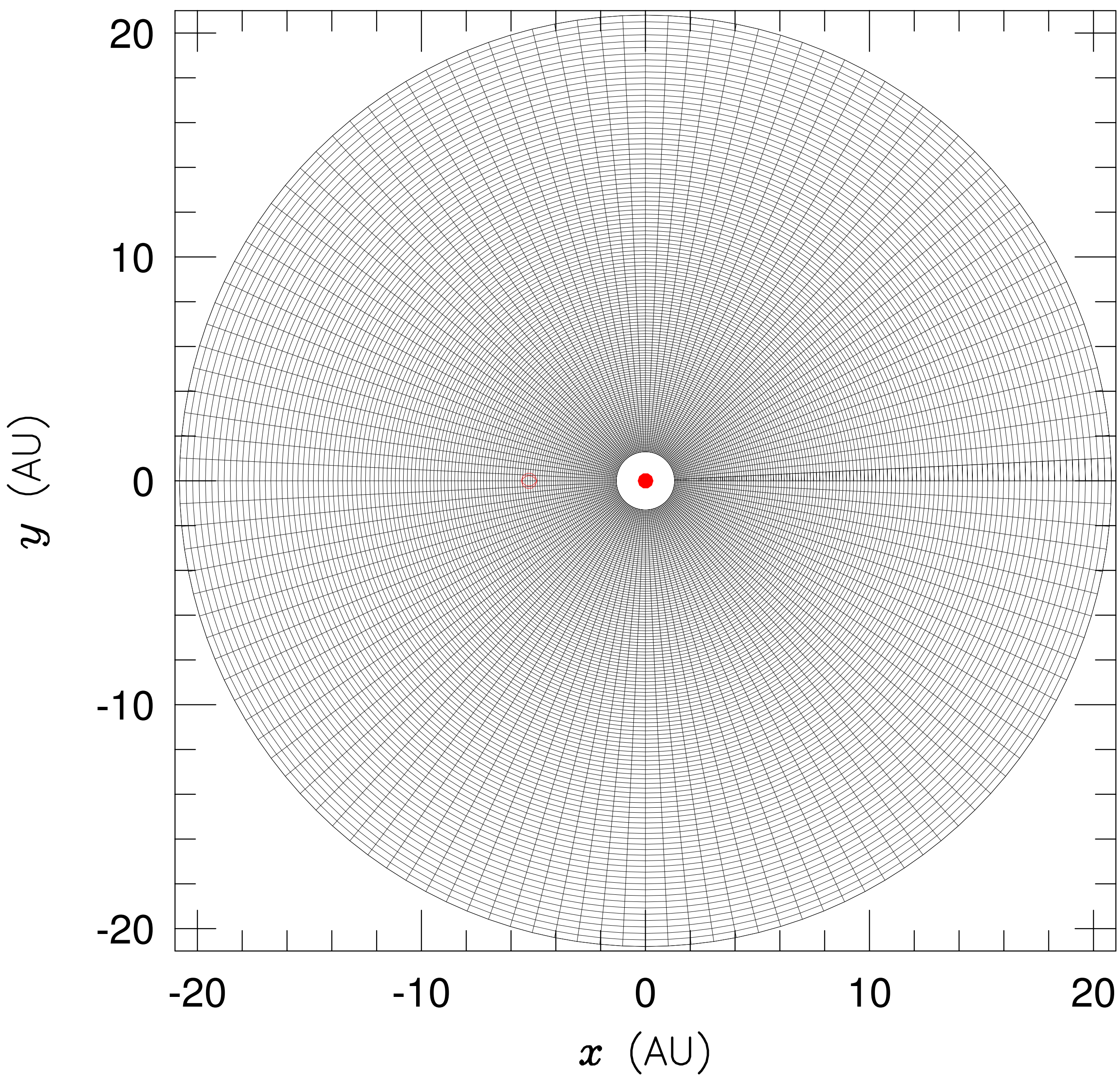
Disk: Hydrodynamical Evolution

- In Potential of Star & Planets
- Thin disk approximation: 1-30 AU
- 2D (r, φ), 3D (r, φ, ϑ)
- Physics: Temperature - T(r), Viscosity - α-model

Planets: N-Body

- Point Masses (smoothed potential)
- Back-reaction of Disk $\longrightarrow$ Orbital Evolution

Numerical Grid I



Grid:

128 x 128

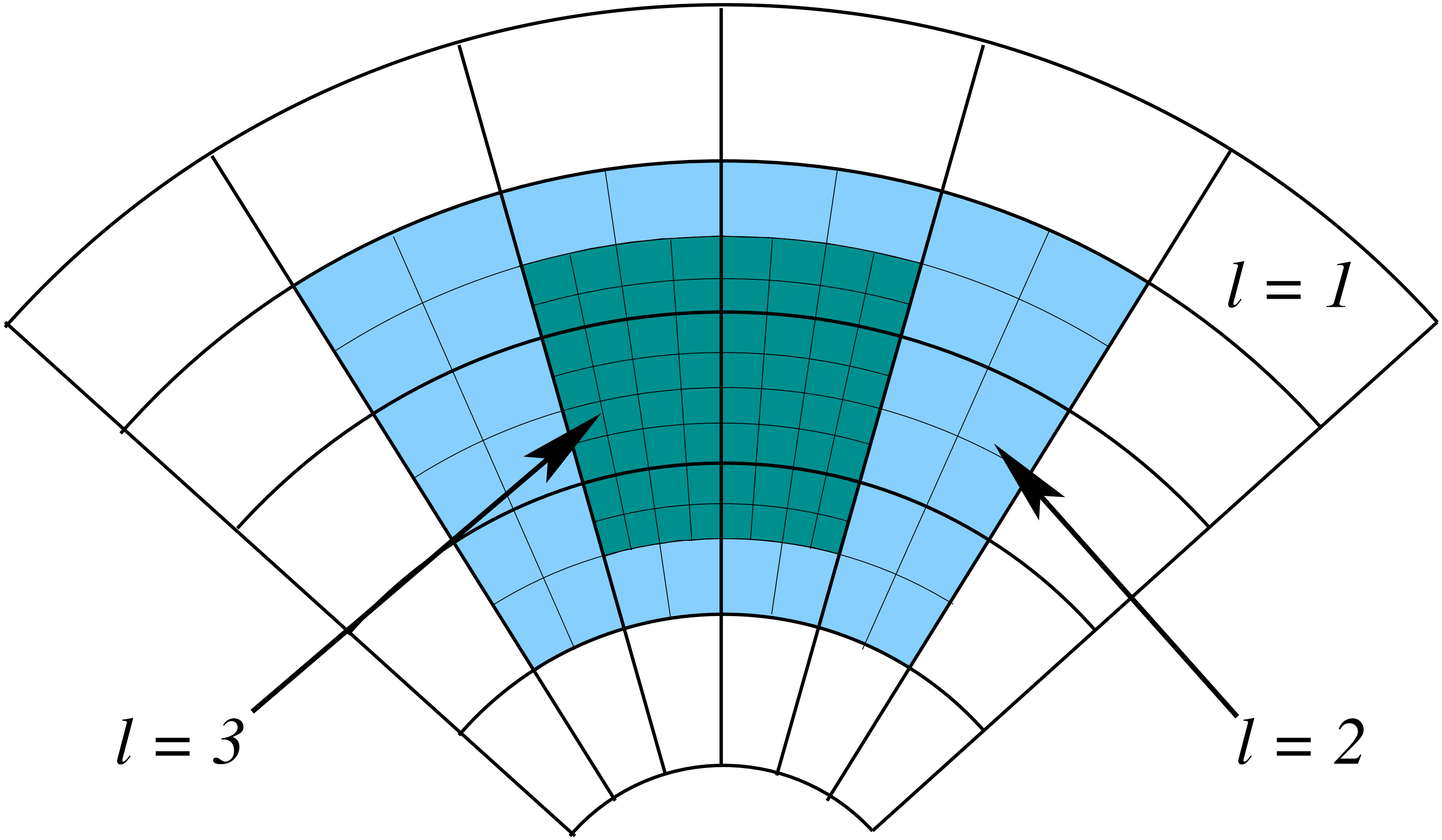
● Central Star

○ Roche Lobe

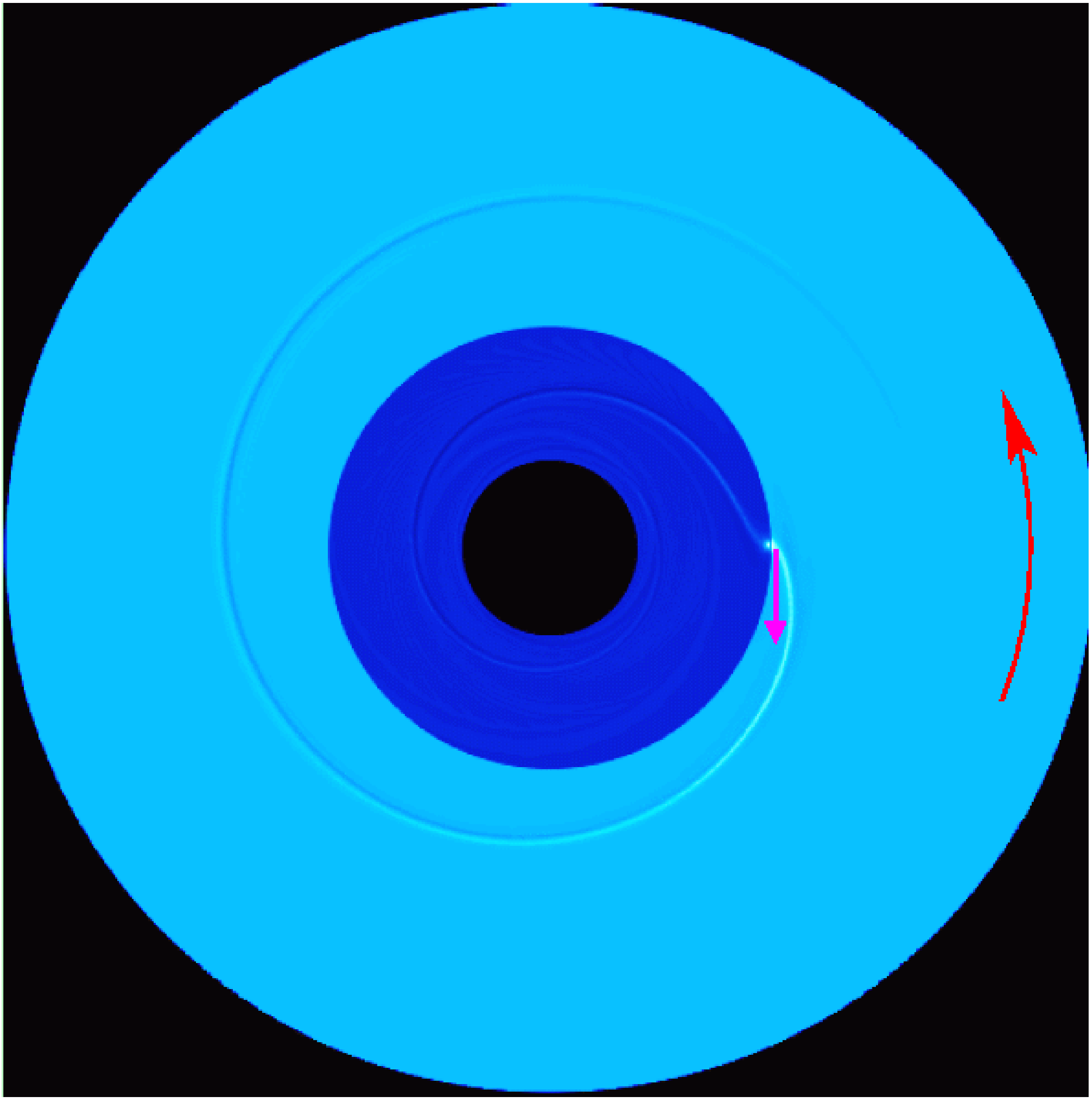
(W. Kley, 1999)

Numerical Grid II

Nested-Grid System: Centered on Planet (D'Angelo et al. 2002/03)



Small Mass Planets



$\longrightarrow$ Direction of Rotation

Wake:
Spiralwave

Inner Spiral:
positive Torque

Outer Spiral:
negative Torque

$\longrightarrow$ Net Force

(Masset, 2001)

Small Masses: Torque-Balance

- Total Torque negative: Planet looses Angular momentum
- Inward Migration: Towards star
- Rate: Dependent on differential net-torque

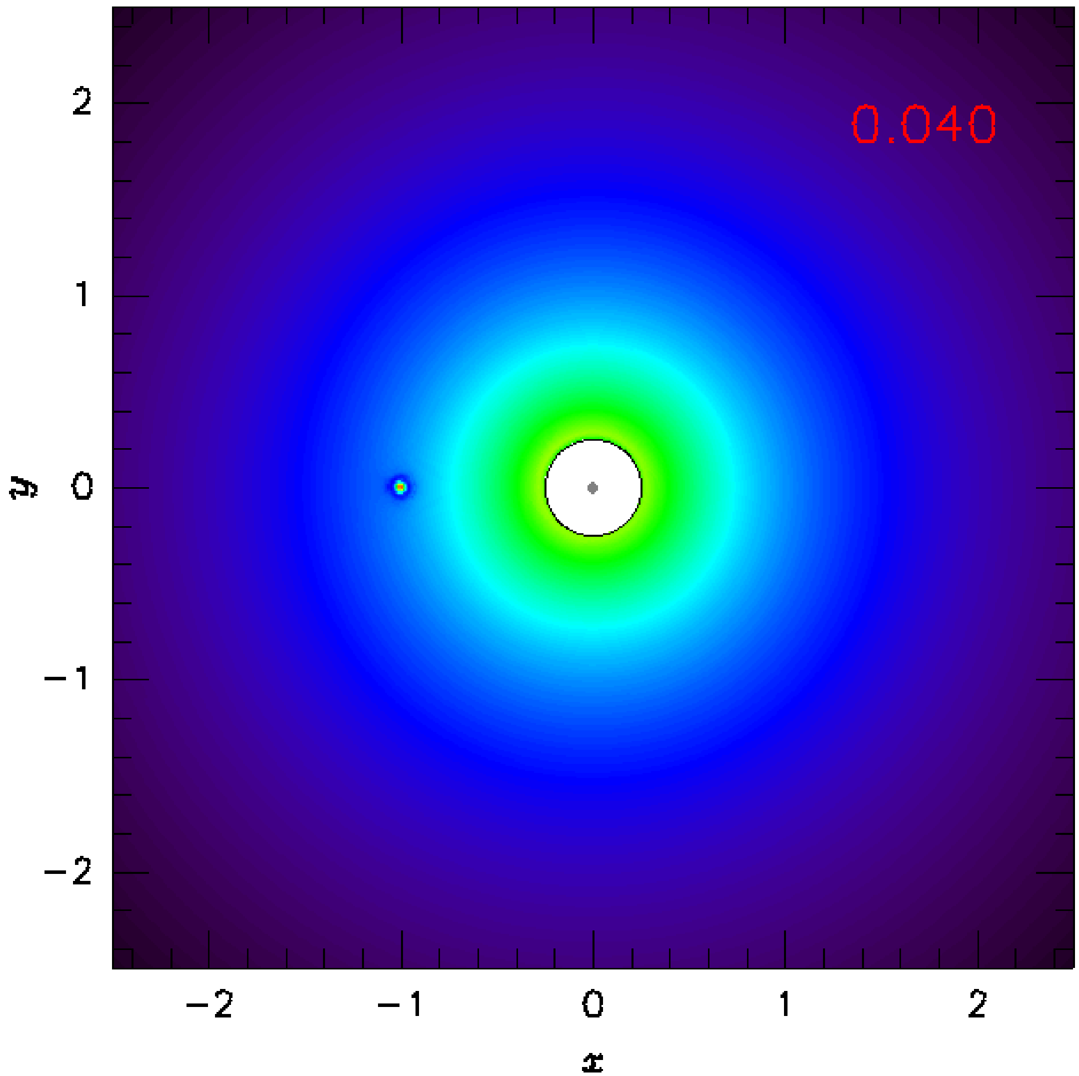
Linear Regime: Mass $< 0.3\ M_{\mathrm{Jup}}$, Typ I - Migration

- $\propto \Sigma$: Surface density
- $\propto M_{\mathrm{Planet}}$: Planet mass
- $\propto T^{-1}$: Inverse Temperatur (faster in thinner disks)

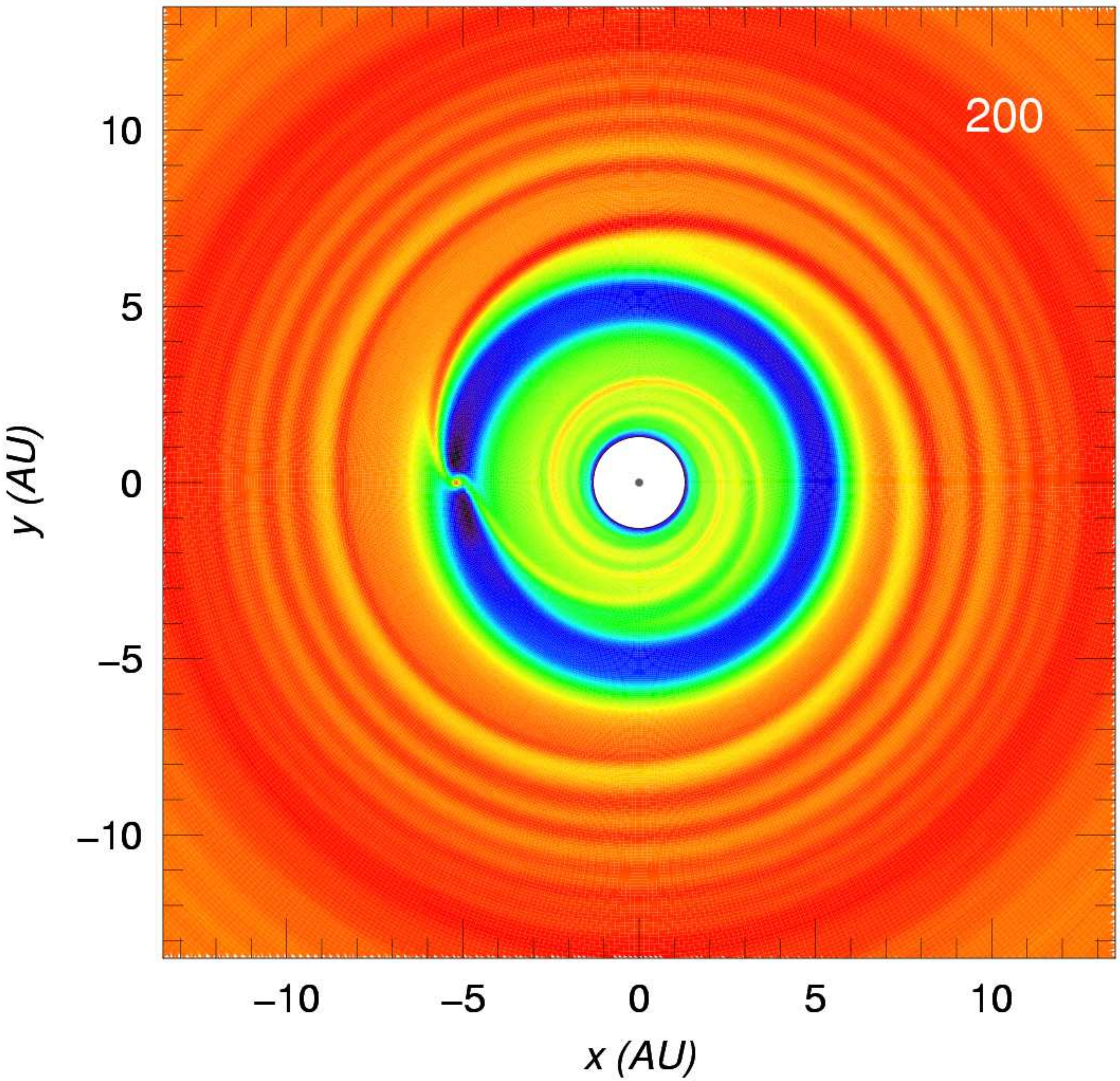
Time scale: 1 M_{Earth} at 1 AU: 10^5 Years (smaller than growth time)

Large Masses: Gap Opening

Viscous Disk: M_p = 1 M_{Jup}, a_p = 5.2 AU



Large Masses: Overview



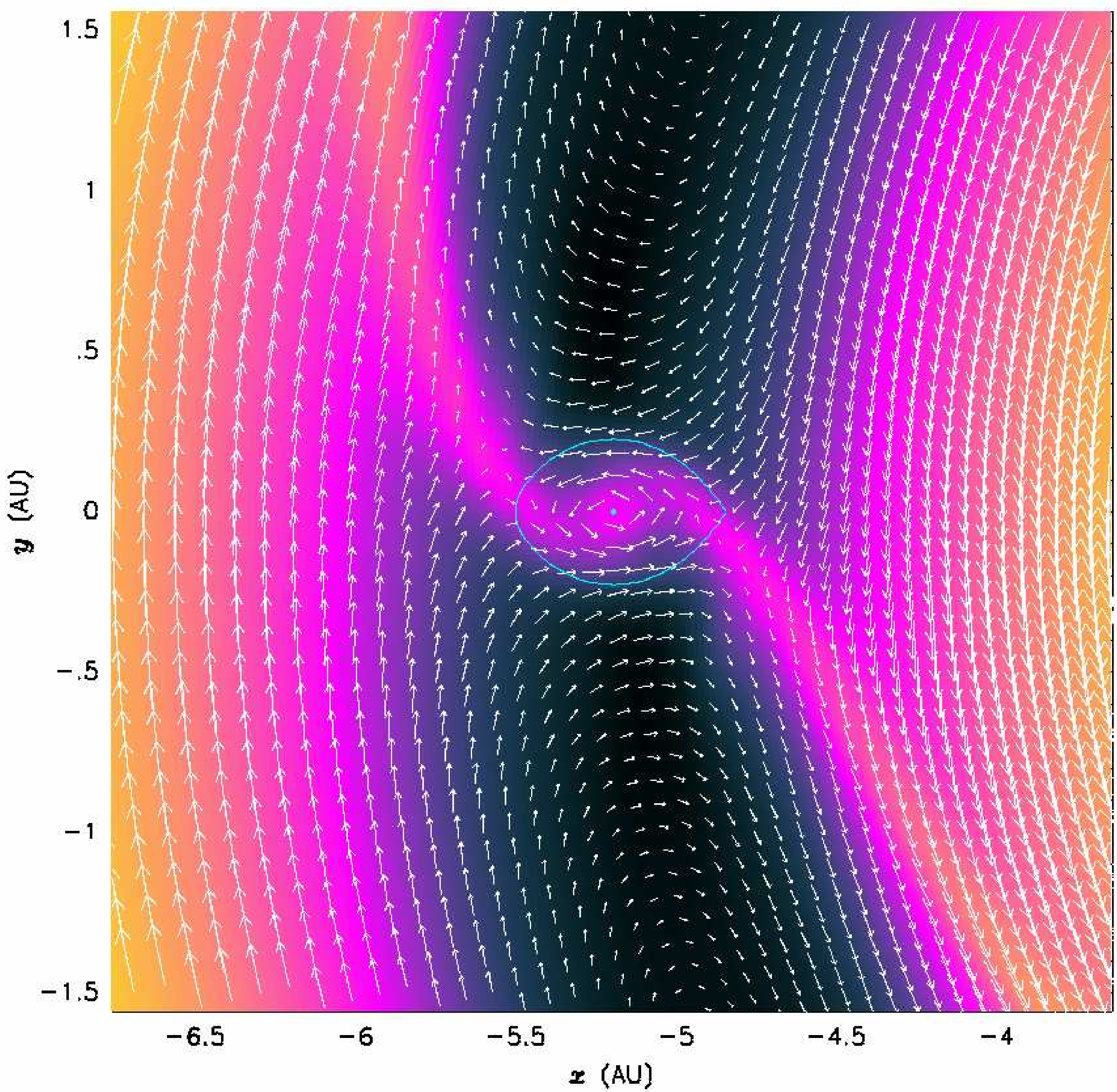
Hydrodynamical
Disk-Model
128×295
H/R = 0.05
$\nu = 10^{-5}$
$m_p = 1\ M_{Jup}$
$a_p = 5.2$ AU

Surface density
after 200 Orbits
$\approx$ stationary state

Spirals $\longrightarrow$ Shocks
Gap formation
Density contrast:
> 100

(Kley, 2001)

Large Masses: Flow-Field



Surface Density
at 200 Orbits

Blue Dot: Planet
Blue Line:
Roche-Lobe

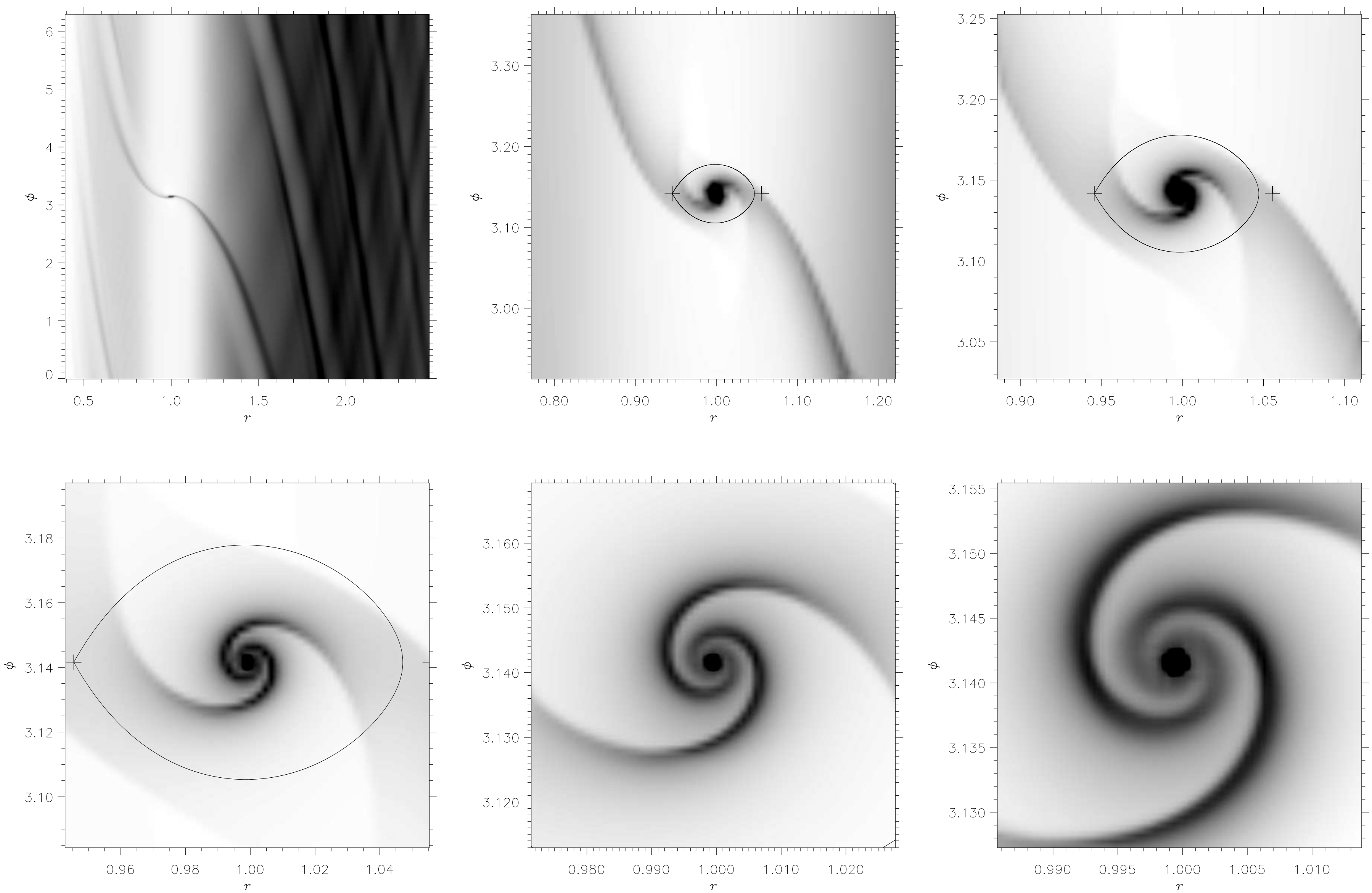
128×440

m_p = 1 M_{Jup}
a_p = 5.2 AE

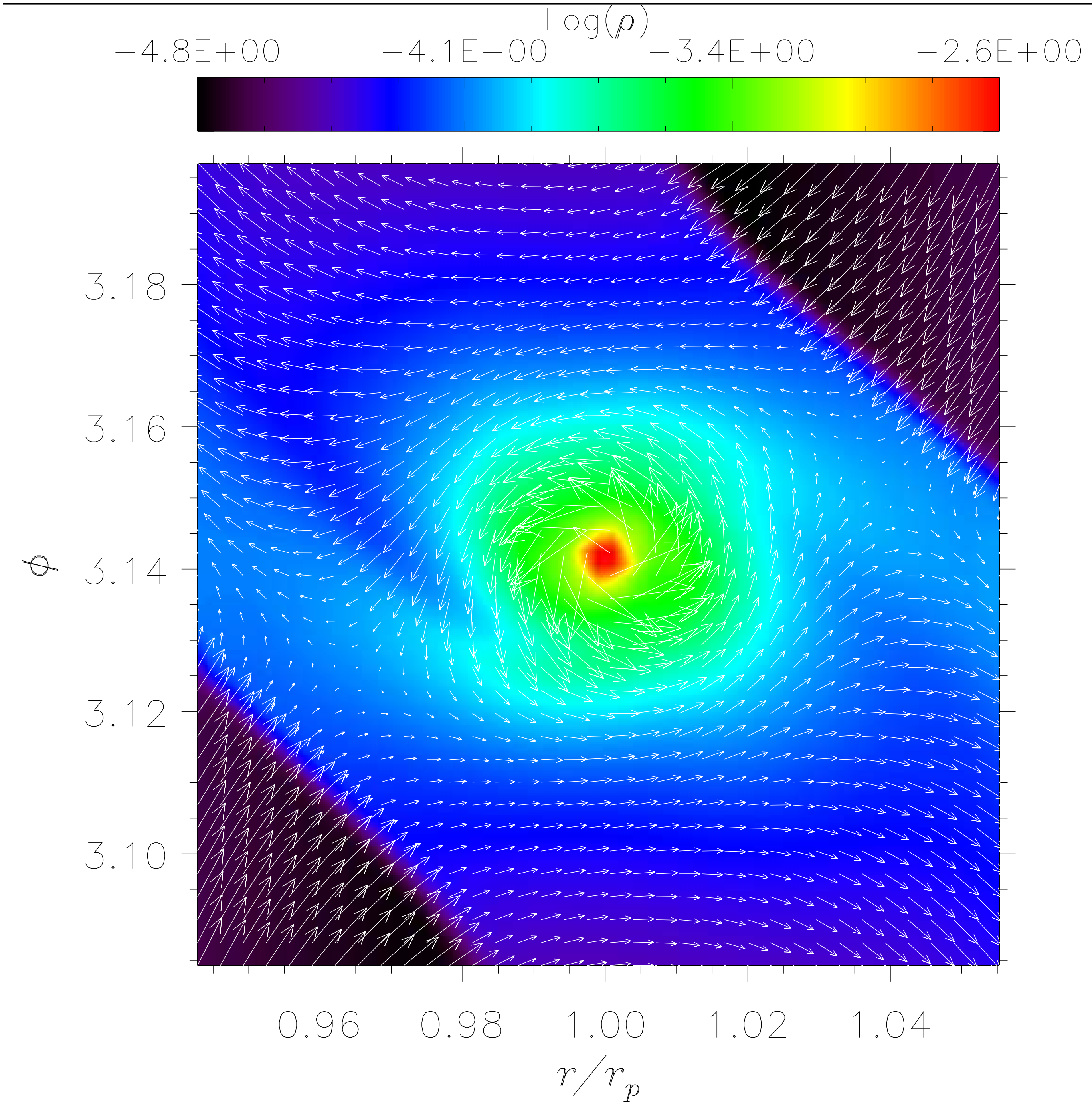
Flow-Field
$\longrightarrow$ Growth

(W. Kley, 2000)

2D Hydro, Nested Grid: 1 M_J



3D-Nested Grid: Results I

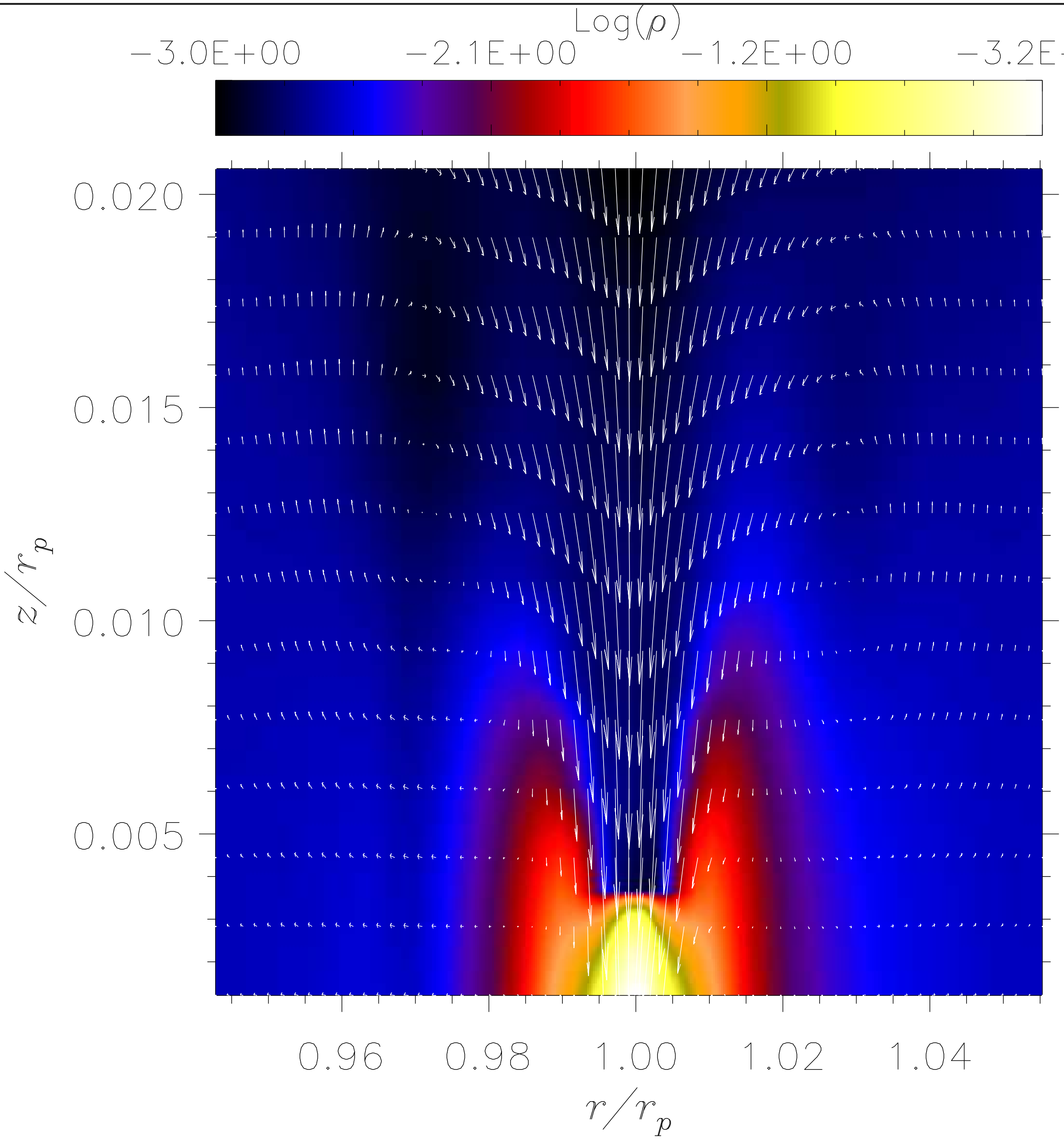


Saturn Mass

($r - \varphi$ plane)

(D'Angelo et al., 2002)

3D-Nested Grid: Results II

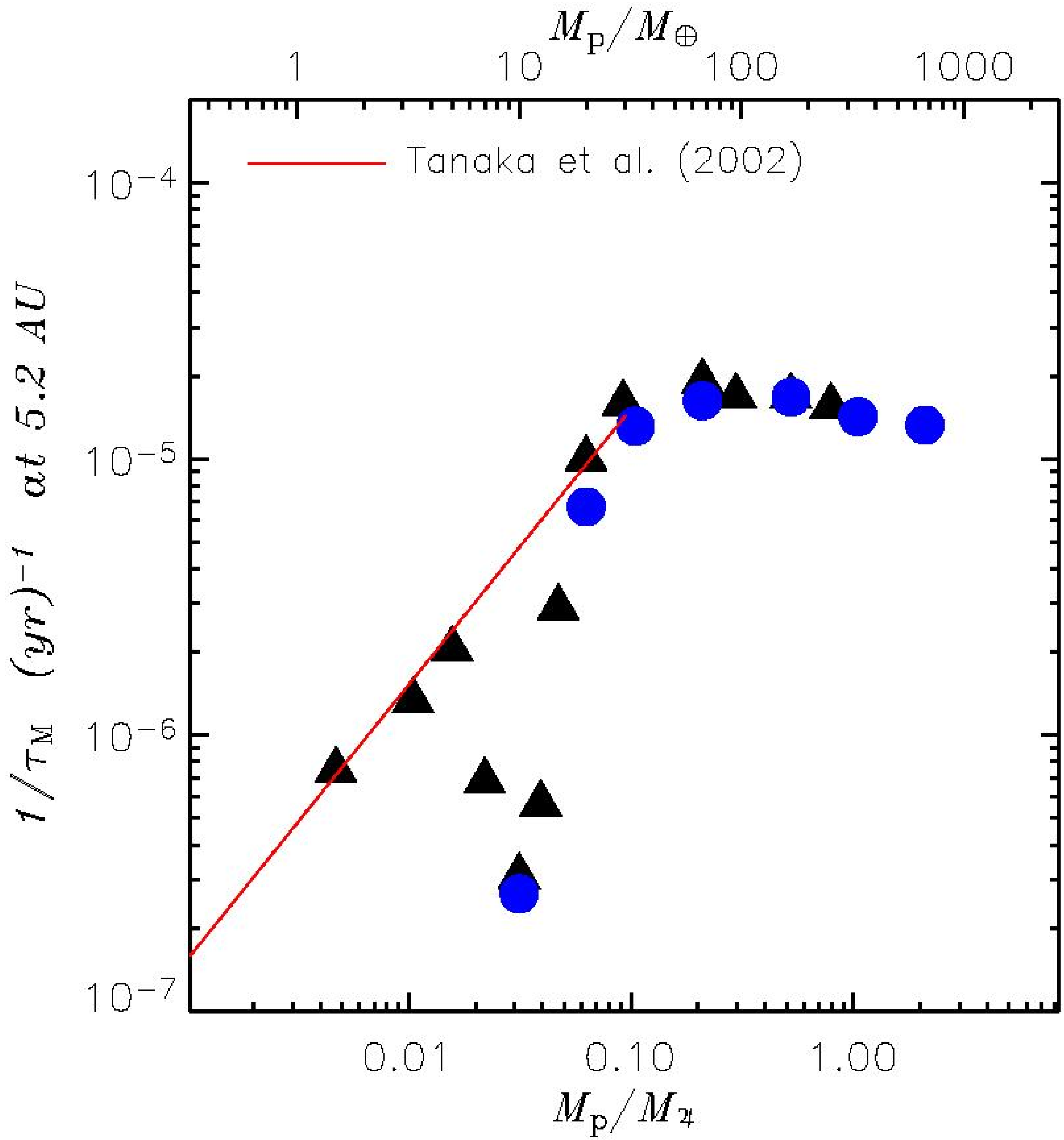


Saturn Mass

($r - z$ plane)

(D'Angelo et al., 2002)

Migration Rate

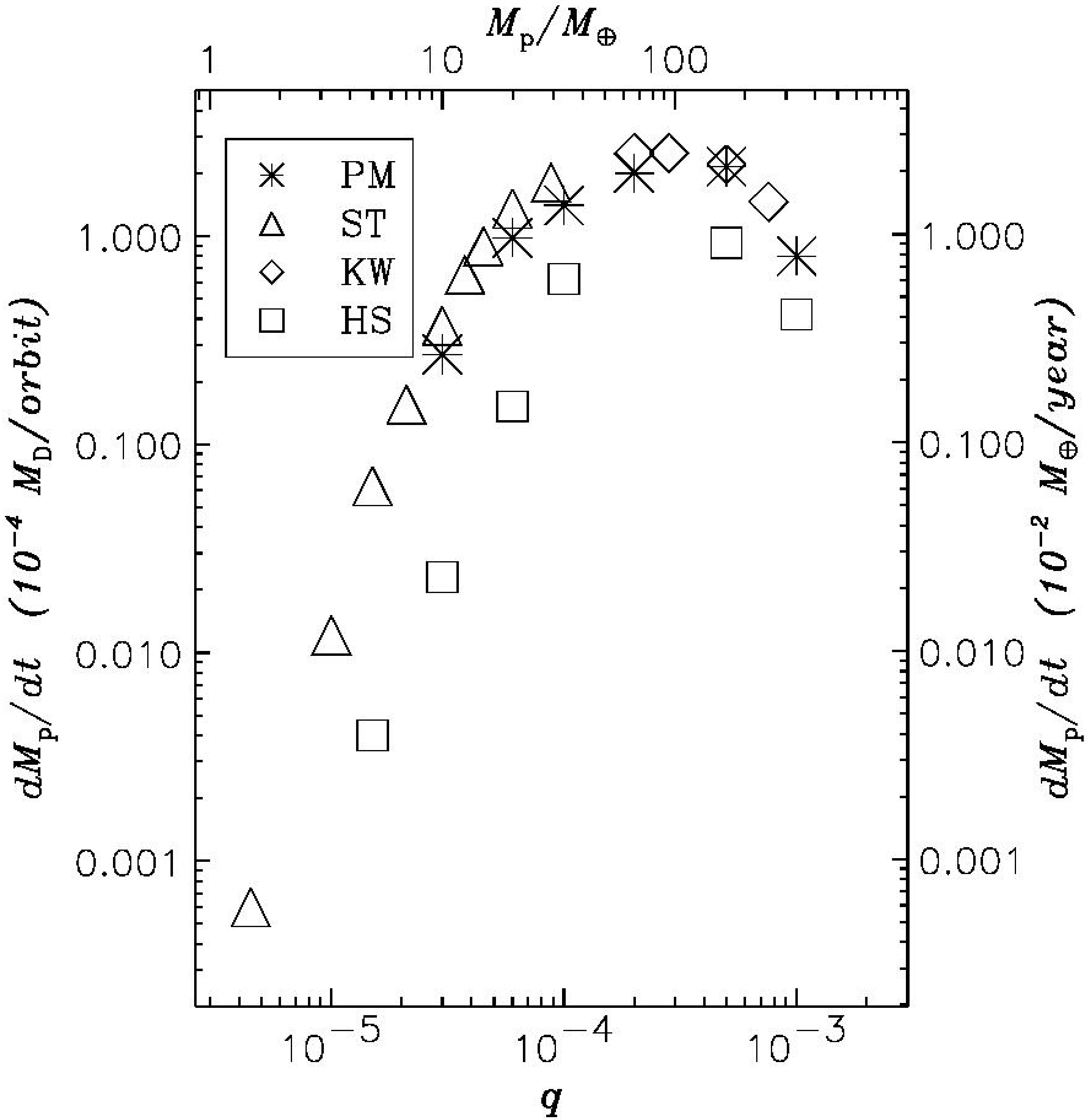


Symbols:
Full Hydro
3D-Nested Grid
Σ(r) $\propto$r$^{-1/2}$
D'Angelo et al. (2003)

Red Line:
Linear Theory
Tanaka et al. (2002)

Dip:
Corotation Effects
Depend on Σ(r)
Poster # 37:
(Masset et al.)

Accretion Rate



Symbols:
3D-Nested Grid
D'Angelo et al. (2003)

Results: Viscous laminar Disk

Excitation of Spiral Waves

Gap Formation	For Planets: $M_p > 0.5\ M_{Jup}$ Width: Equilibrium of gravitational-viscous Torques
Inward Migration	$\tau_{mig} \approx 10^5$ yr Typ I: M_p a few M_{Earth} Dip : $M_p \approx 10\ M_{Earth}$ Typ II: $M_p > 100\ M_{Earth}$
Mass Growth	upto $M_p \approx 5\ M_{Jup}$ then Gravity $>>$ Viscosity
Prograde Rotation	

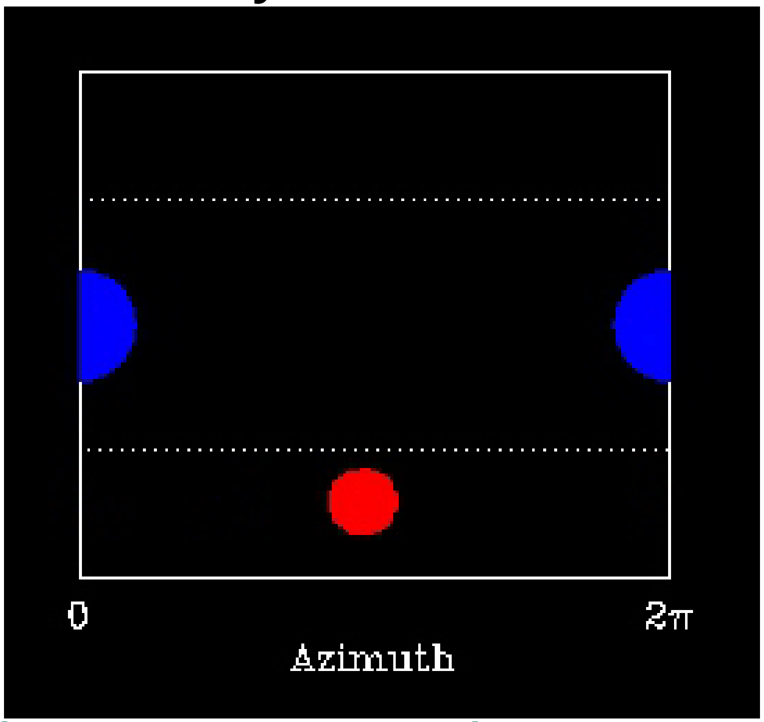
More recent Additions

- Type III Migration (Runaway migration)
- Inviscid Disks
- Eccentricity
- Resonances
- Magnetic Disks $\longrightarrow$ Talks: C. Terquem, R. Nelson

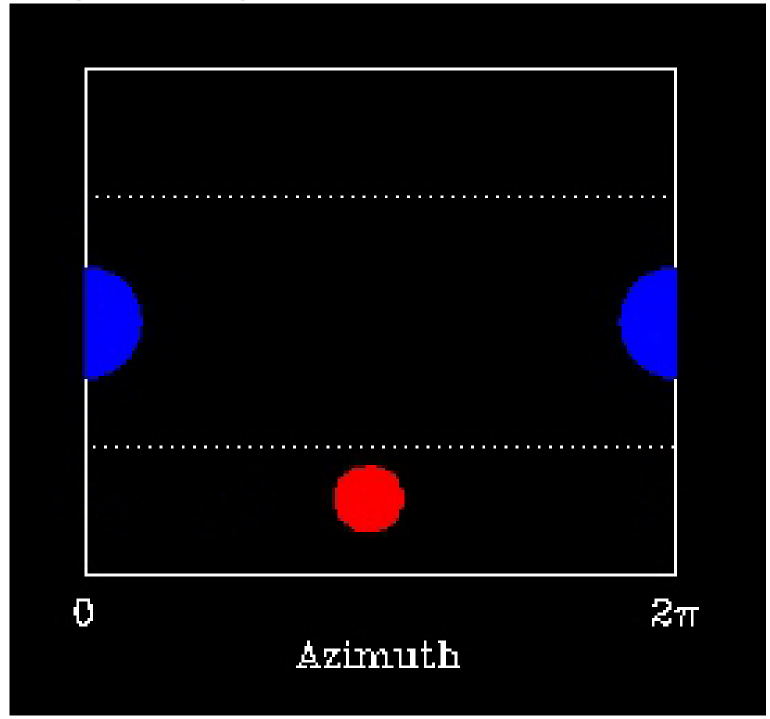
Type III Migration - Principle

Study influence of migration on torque balance

Stationary Planet



Migrating Planet



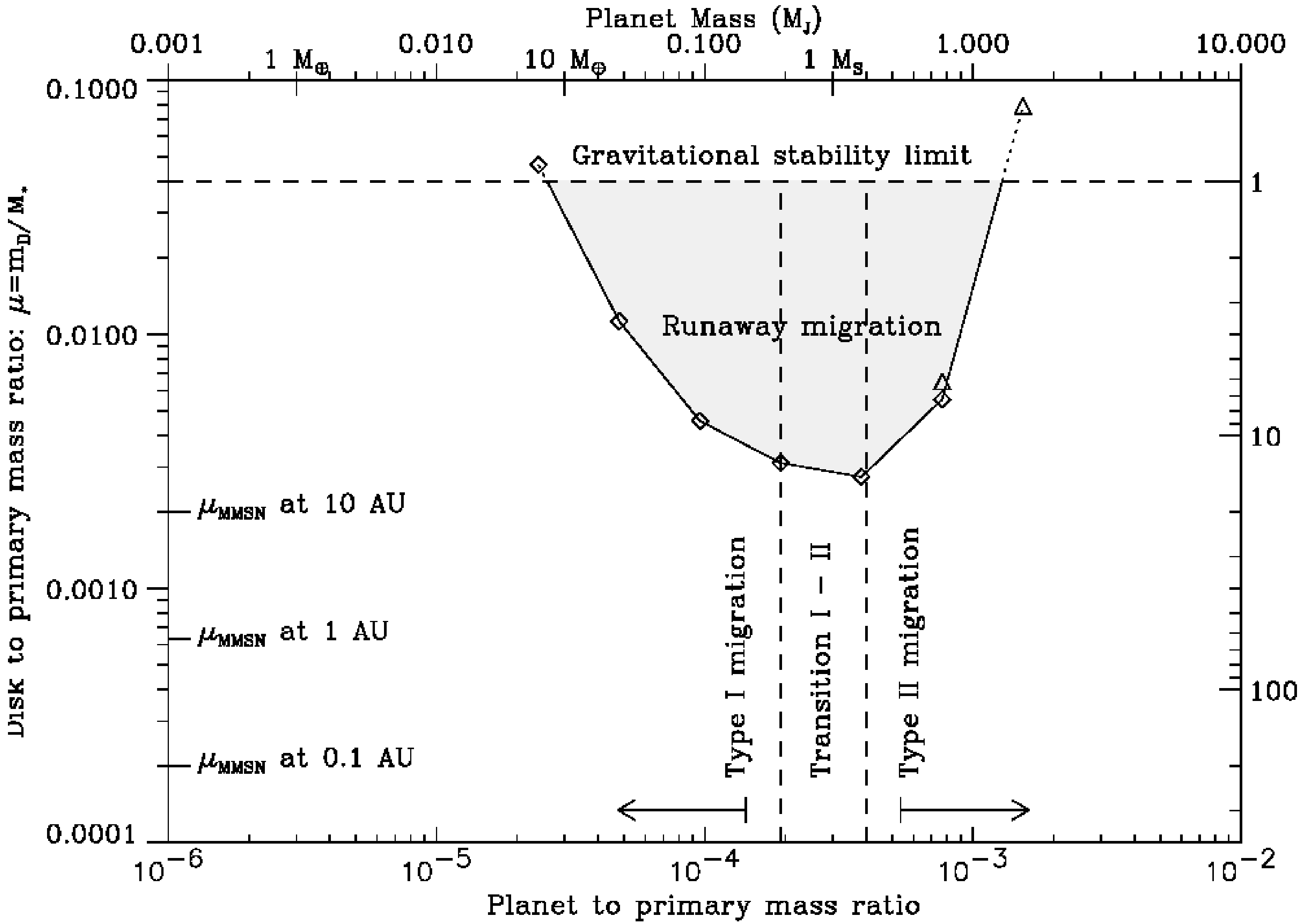
(F. Masset, 2002)

Uwind material crosses horseshoe region

Gains angular momentum, planet looses ⟶ Runaway

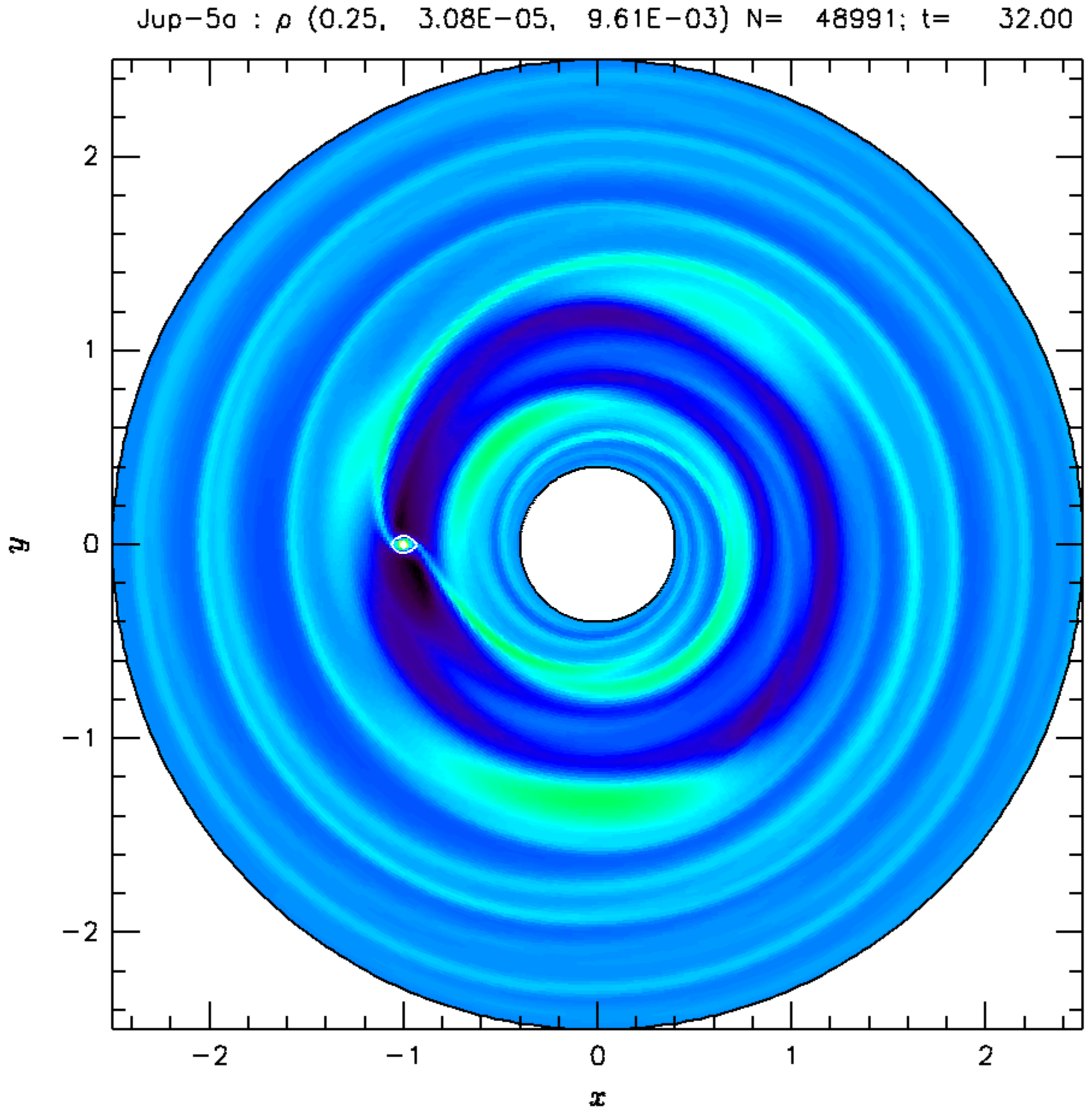
(see also Masset & Papaloizou, 2003;   Artymowicz)

Type III Migration - Regime



(Masset & Papaloizou, 2003; but see D'Angelo et al. '04)

Inviscid Disk



Switch on Planet
(in 5 Orbits)

Irregular Flow

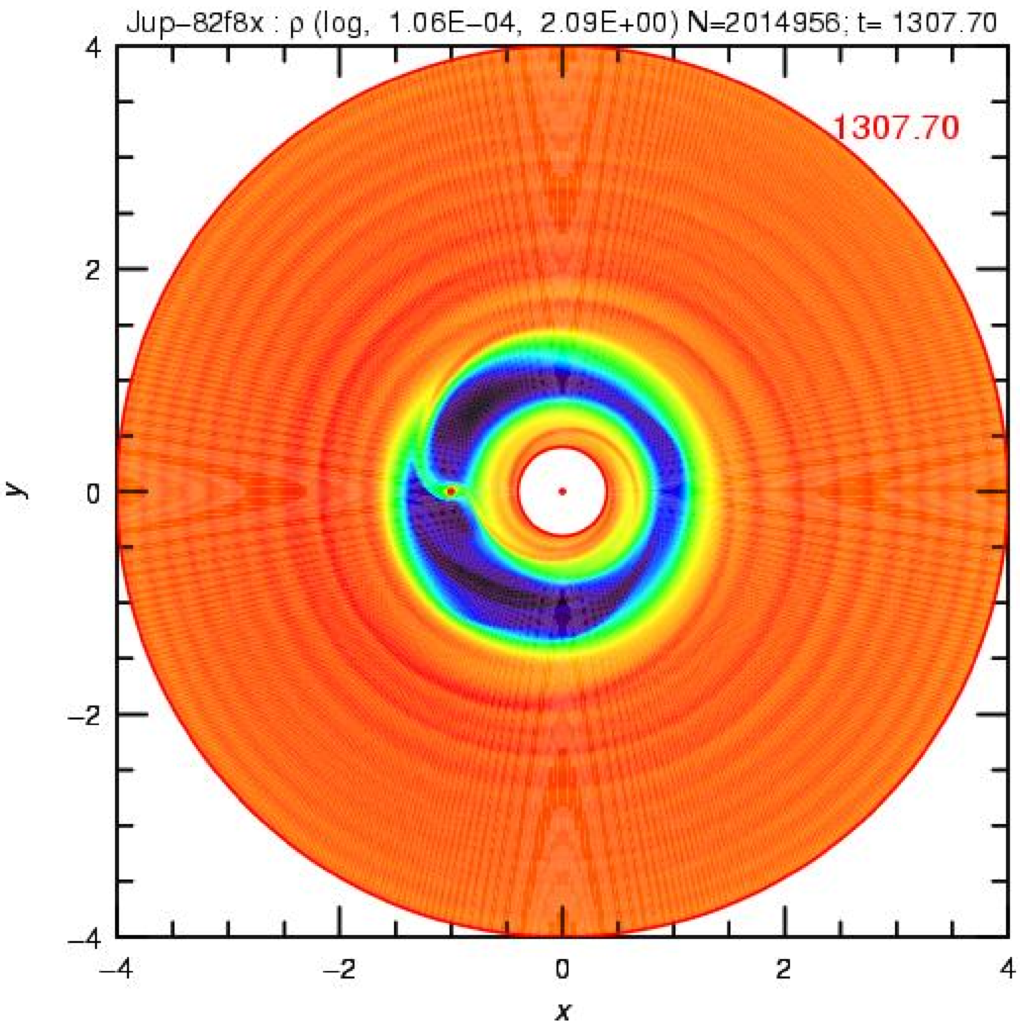
Vortex Formation

Vortices merge

(Li, Lin, 2003)
(Masset & Kley, 2003)

Eccentric Disk

Viscous Disk: $M_p = 4\ M_{Jup}$, $a_p = 5.2$ AU, Circular orbit



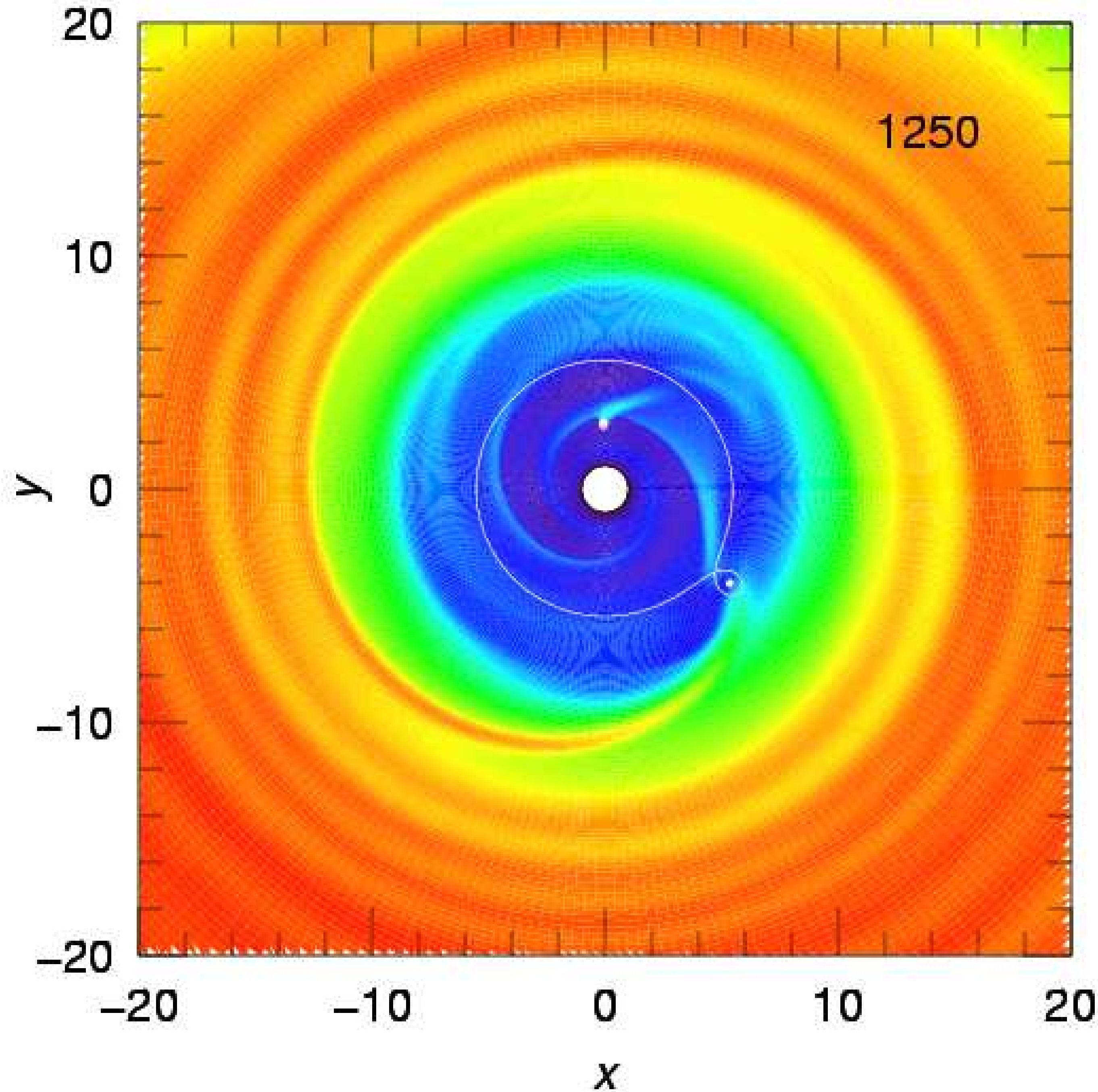
⇓

Talk: Gerben Dirksen

See also:

(Papaloizou, Nelson & Masset, 2001

Resonances



Inner Cavity:
$M_{out} > M_{in}$

Outer Planet:
Inward Migration

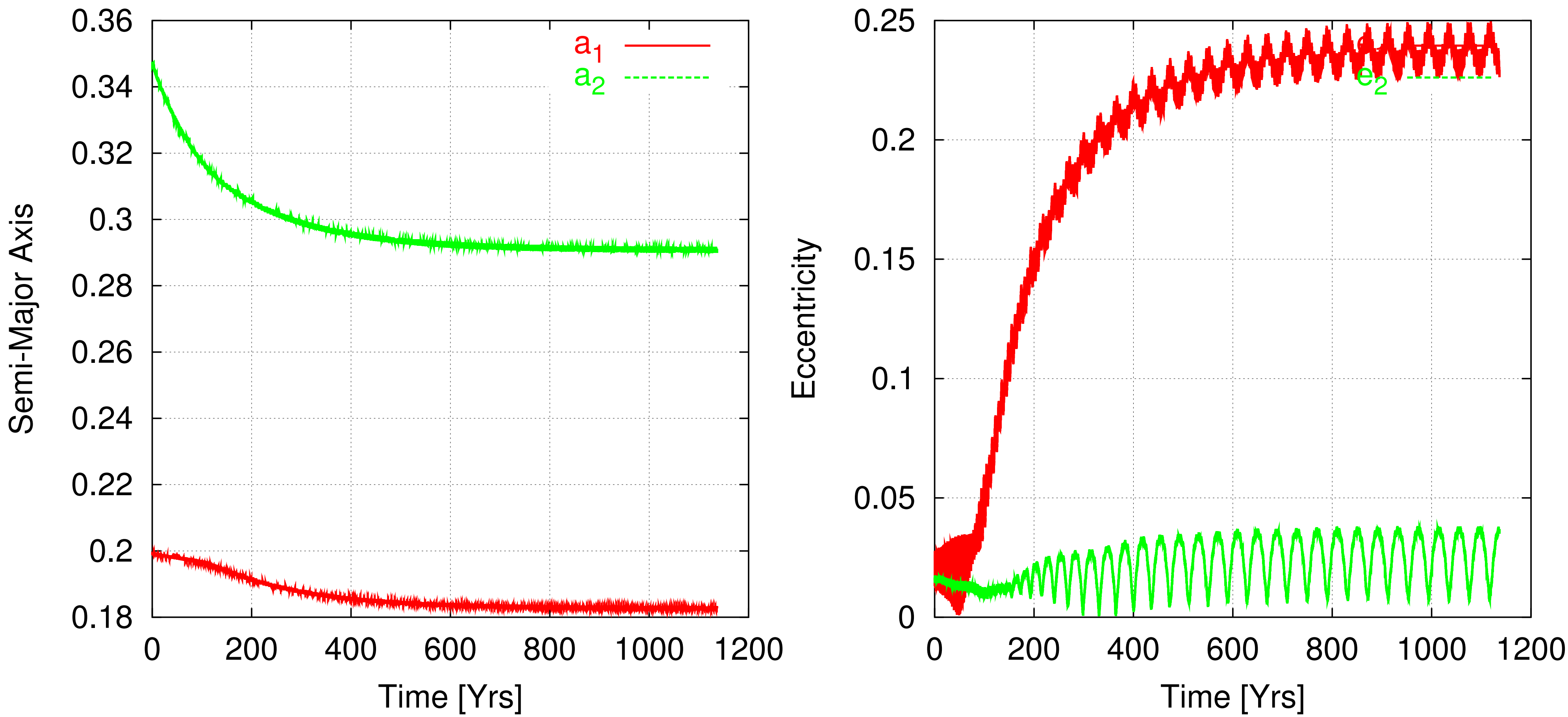
Inner Planet:
Stalled

$\Downarrow$

Resonant capture

Matching GJ 876

Disk dissipates during evolution



Note: Correct e values

Some Remaining Issues

Stopping Mechanism $\longrightarrow$ Vulcans, Jupiter

Inclined Orbits $\longrightarrow$ Disc Warping (β-Pic)

Radiative Transport $\longrightarrow$ Observational Appearance (ALMA)

Planets in Binaries $\longrightarrow$ Constraints on Formation

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End

The End