Disks and Massive Planet Formation

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Outline:

- Planet formation in the Solar System
- Observations = problems with simplest theory
- Migration: how important is disk turbulence?

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Traditional stages of planet formation

1) Dust (μm) to pebbles (cm)

Small dust particles are well-coupled to the gas, settling velocity is small *even without turbulence*:

$$v_z = -\frac{\Omega^2 z a_{dust}}{c_s}\left(\frac{\rho_{dust}}{\rho_{gas}}\right)$$

t_{settle} ~ 1Myr for a ~ 1μm at 1AU

Growth occurs via collisions + settling as size increases

Theoretically (eg Dullemond & Dominik 05) and observationally (eg Shuping et al. 03) this is not believed to be a rate limiting step

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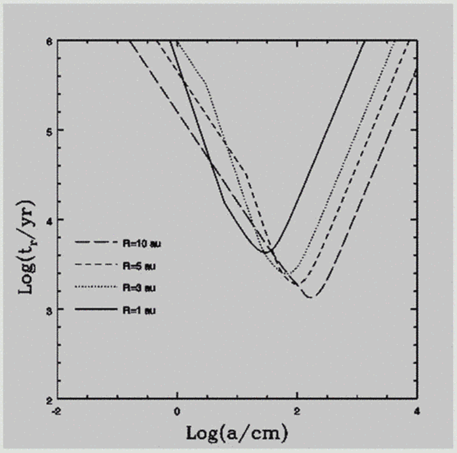
2) Pebbles (cm) to planetesimals (>km)

Must occur rapidly - otherwise solids lost into the star due to aerodynamic drag against the gas

$$\frac{v_\phi^2}{r} = \frac{GM_*}{r^2} + \frac{1}{\rho}\frac{dP}{dr}$$

`headwind' is $O(h/r)^2$



t_{drift} ~ 10^4 yr or less, AND collisions of m-scale objects may not be very sticky

gravitational instability of a dust layer???

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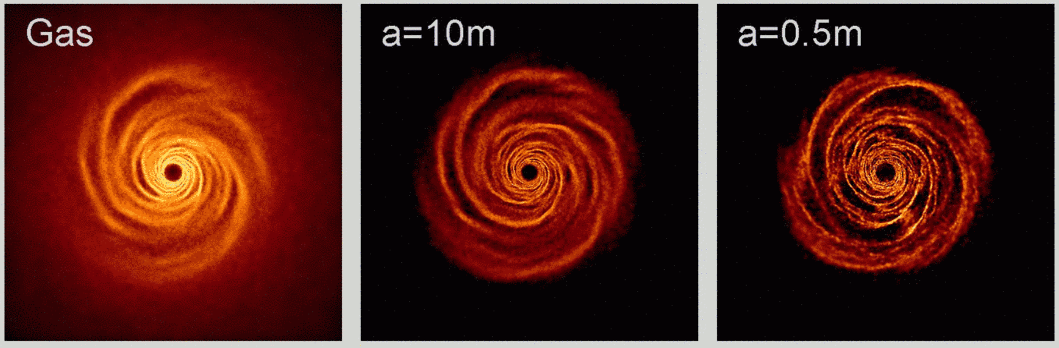

$$\frac{v_\phi^2}{r} = \frac{GM_*}{r^2} + \frac{1}{\rho}\frac{dP}{dr}$$

If the disk is *very* turbulent, can enhance solids at pressure maxima

e.g. self-gravity in the gas (Rice et al. 04) could locally enhance gas / dust ratio at a=50cm by ~10^2

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3) Planetesimals to terrestrial planets and giant planet cores

N-body (N ~ 10^{11}) evolution under gravity.

Growing planet accretes from an annulus of width:

$$\Delta r \approx \text{few } r_H \qquad r_H = \left(\frac{M_p}{3M_*}\right)^{1/3} a$$

Allows rapid growth up to an isolation mass (at which point annulus is depleted of planetesimals):

$$M_{iso} \propto a^3 \sigma_p^{3/2}$$

- typically ~0.1 Earth masses at 1AU, ~Earth mass at 5AU

Growth beyond isolation is slower, but can plausibly form Earth in ~100 Myr. Control variable for structure of the terrestrial planets is σ_p (eg Raymond et al. 04)

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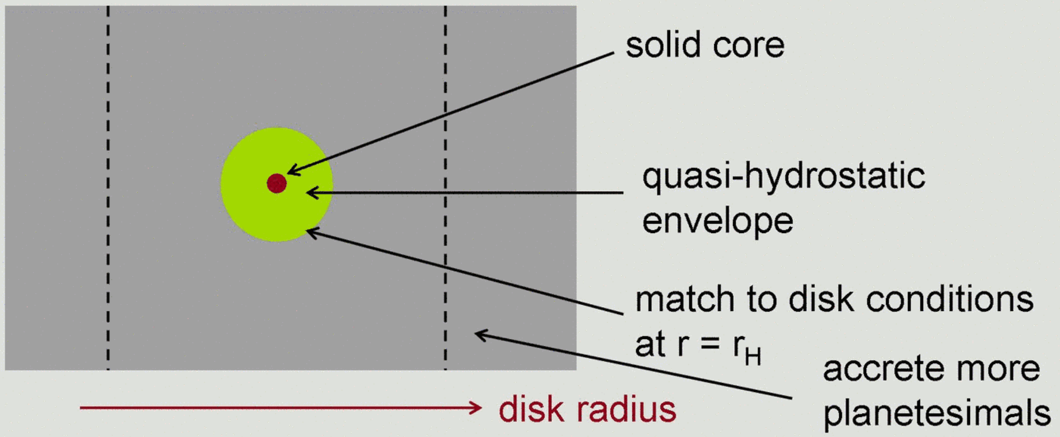
4) Giant planet envelopes



Luminosity: from accretion of planetesimals (E deposited near core) + contraction of gas

Growth model: series of quasi-static states at fixed orbital radius. Stellar structure problem with unknown M but known R(M).

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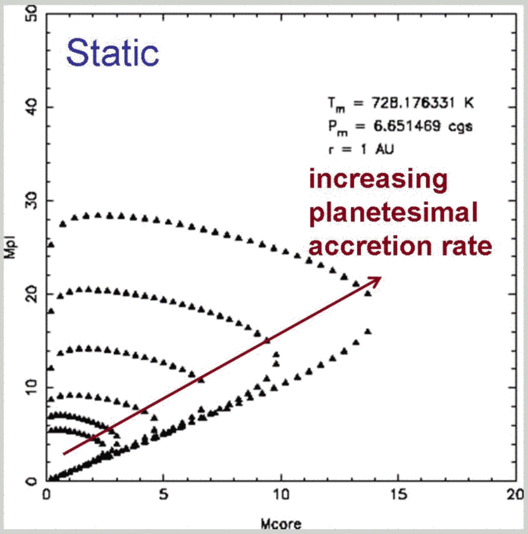

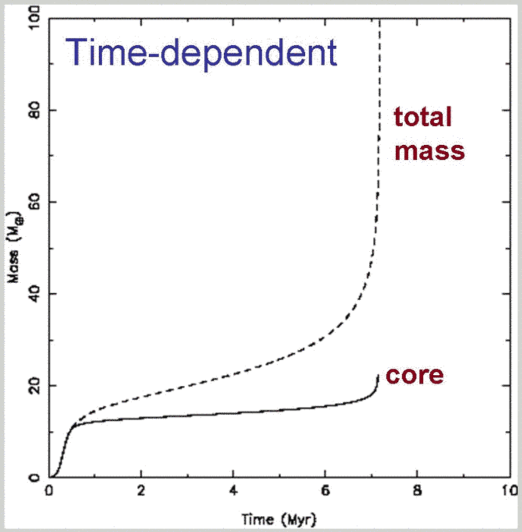

Solutions: critical core mass for any planetesimal accretion rate - once exceeded rapid gas accretion (cf critical mass plots in Papaloizou & Terquem 99)

Baseline models for Jupiter (Pollack et al. 1996) have t_{crit} ~ 10Myr and M_{core} ~ $20M_{Earth}$

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Observations

Solar system problems:

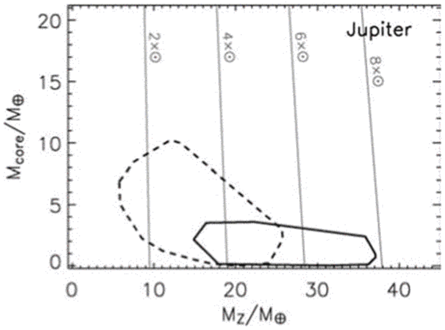

Figure 7 Constraints on Jupiter's interior structure based on Saumon & Guillot (2004). The value of the core mass ($M_{\rm core}$) is shown in function of the mass of heavy elements in the envelope (M_Z) for models matching all available observational constraints. The dashed region corresponds to models matching the laser compression experiments. The plain box corresponds to models matching the pulsed power and convergent shock compression experiments (see text). Grey lines indicate the values of M_Z that imply uniform enrichments of the envelope in heavy elements by factors of two to eight times the solar value ($Z_\odot = 0.0149$), respectively.

Jupiter's core mass is thought to be less than 10 M_{earth} (review Guillot 2005)

Reducing the planetesimal accretion rate `solves' this, but increases the formation time

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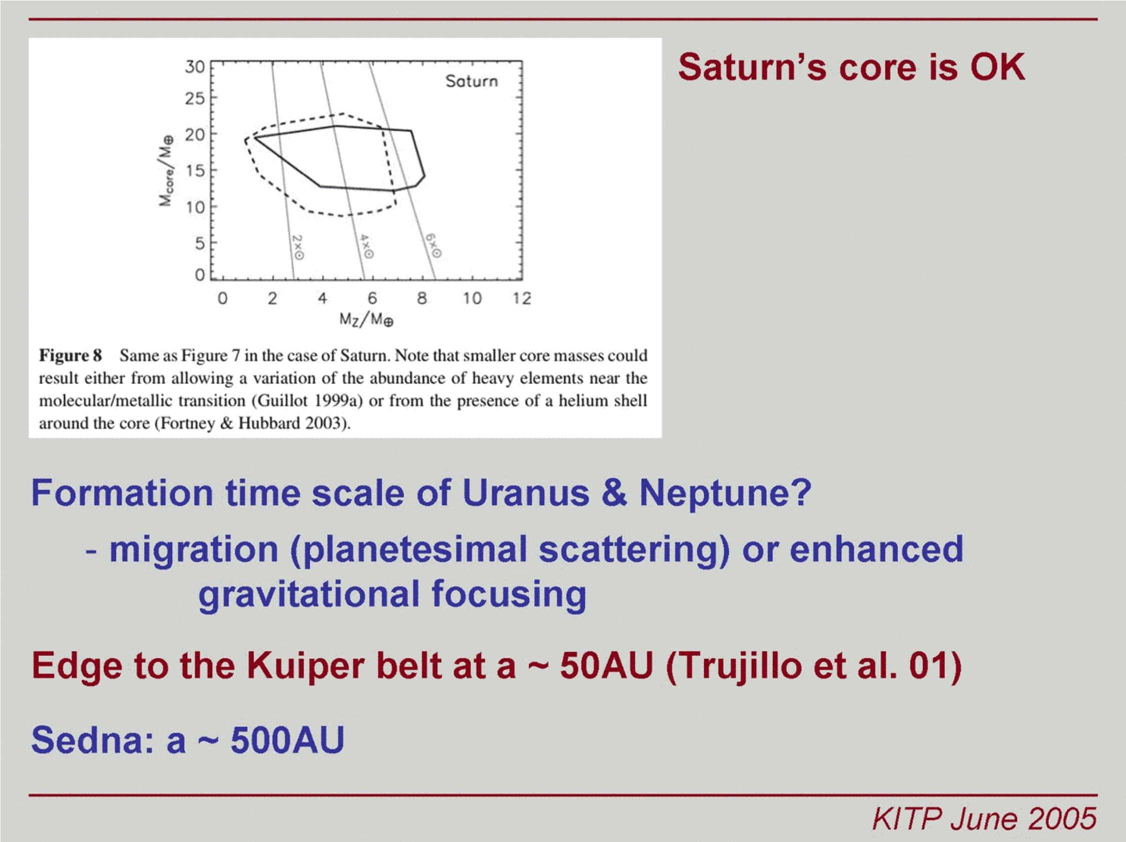

Saturn's core is OK

Figure 8 Same as Figure 7 in the case of Saturn. Note that smaller core masses could result either from allowing a variation of the abundance of heavy elements near the molecular/metallic transition (Guillot 1999a) or from the presence of a helium shell around the core (Fortney & Hubbard 2003).

Formation time scale of Uranus & Neptune?

- migration (planetesimal scattering) or enhanced gravitational focusing

Edge to the Kuiper belt at a ~ 50AU (Trujillo et al. 01)

Sedna: a ~ 500AU

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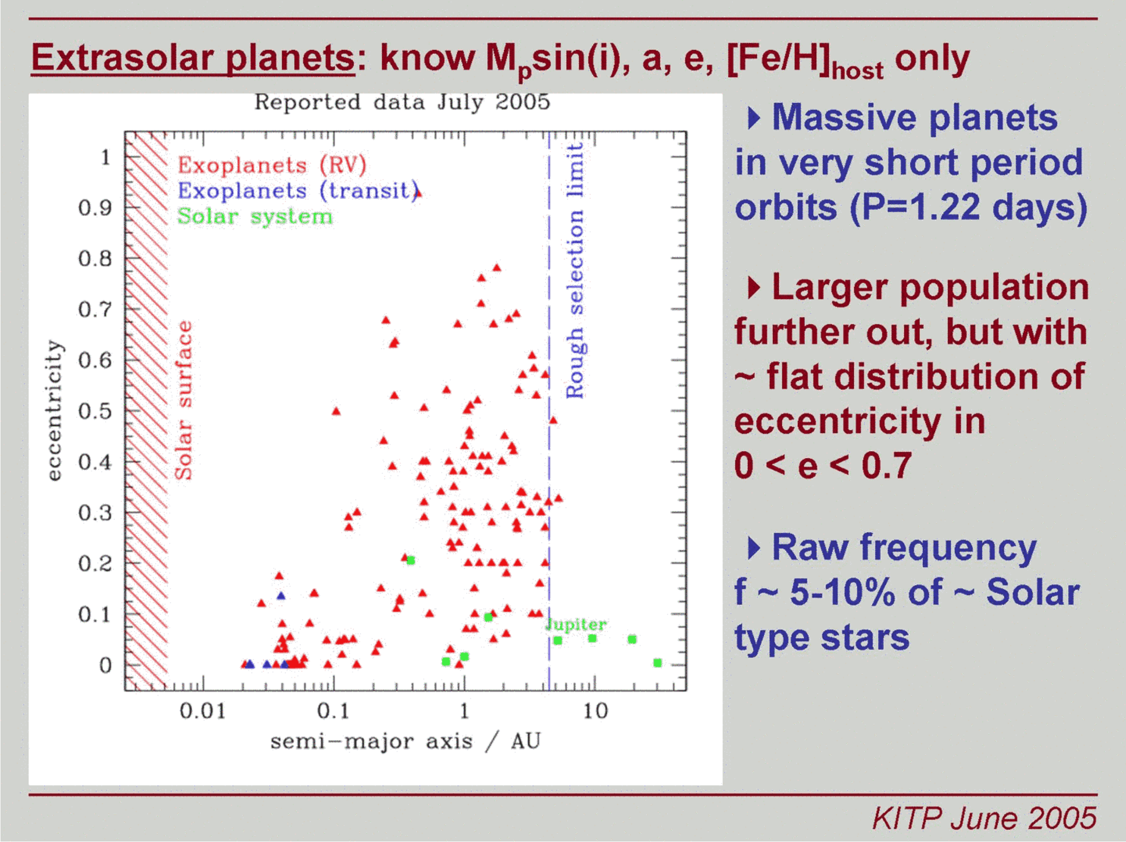

Extrasolar planets: know $M_p\sin(i)$, a, e, $[Fe/H]_{host}$ only

- Massive planets in very short period orbits (P=1.22 days)
- Larger population further out, but with ~ flat distribution of eccentricity in 0 < e < 0.7
- Raw frequency f ~ 5-10% of ~ Solar type stars

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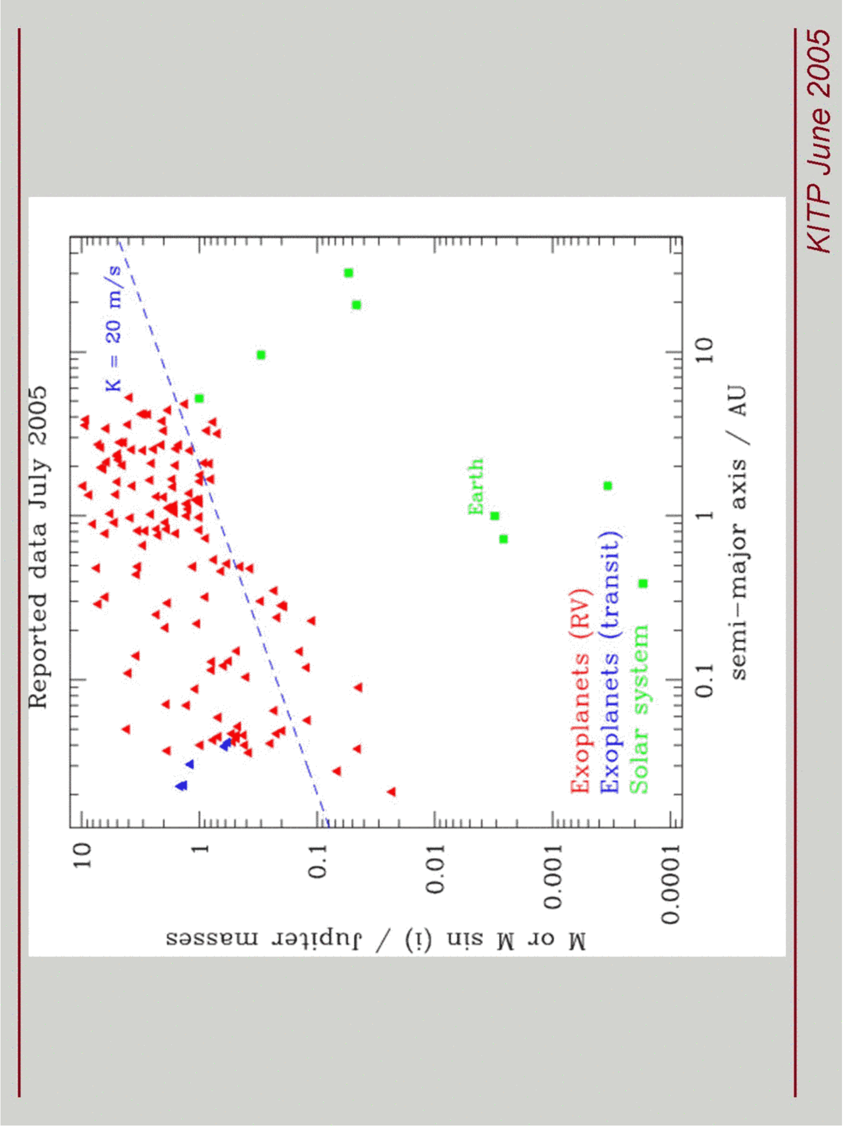
Reported data July 2005
K = 20 m/s
Earth
Exoplanets (RV)
Exoplanets (transit)
Solar system
M or M sin (i) / Jupiter masses
10
1
0.1
0.01
0.001
0.0001
semi-major axis / AU
0.1
1
10
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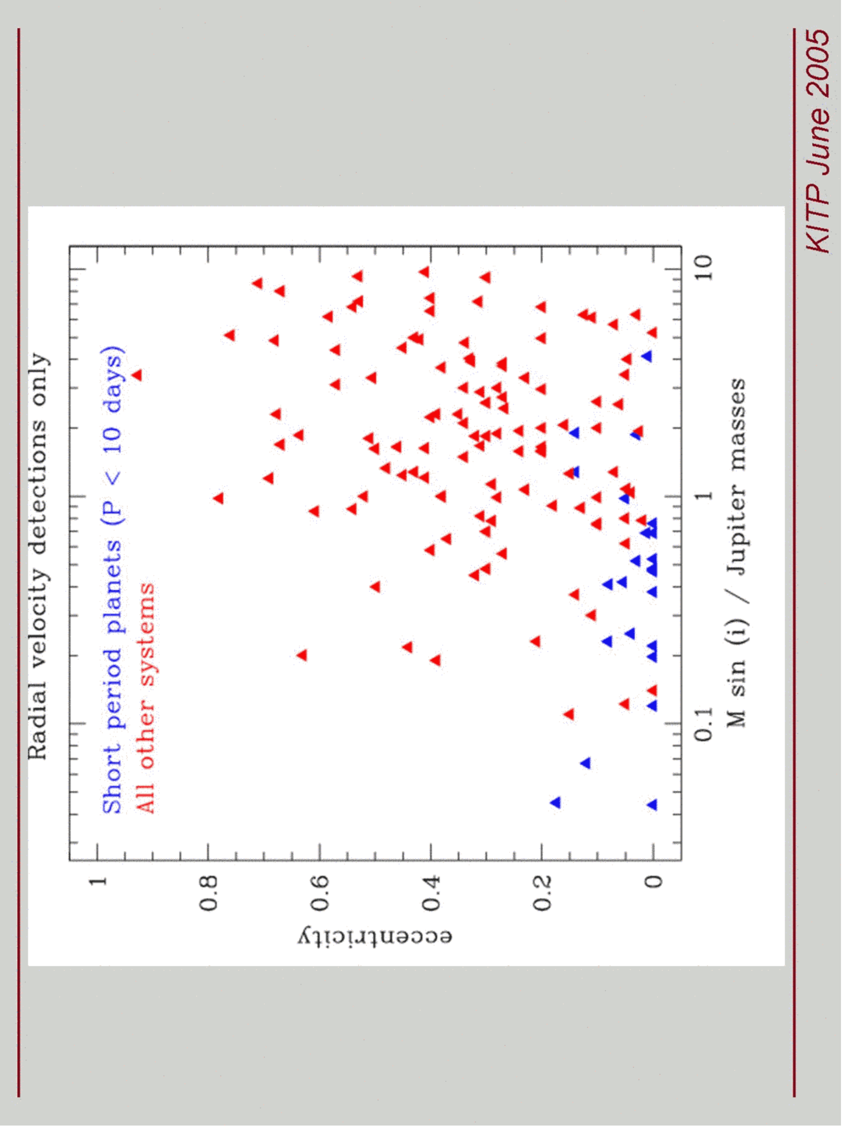
Radial velocity detections only
Short period planets (P < 10 days)
All other systems
eccentricity
1
0.8
0.6
0.4
0.2
0
M sin (i) / Jupiter masses
0.1
1
10
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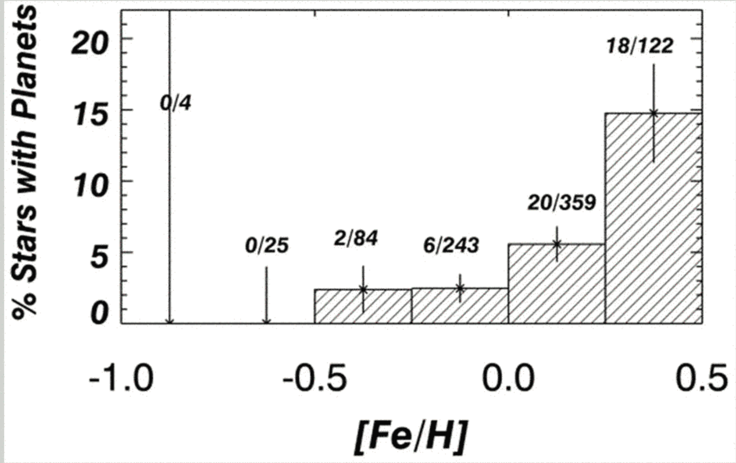

Fischer & Valenti, ApJ, 622, 1102 (2005)

BUT… f_{planet}([Fe/H]) is very consistent with expectations of core accretion - most observed extrasolar planets did not form from disk instability or fragmentation

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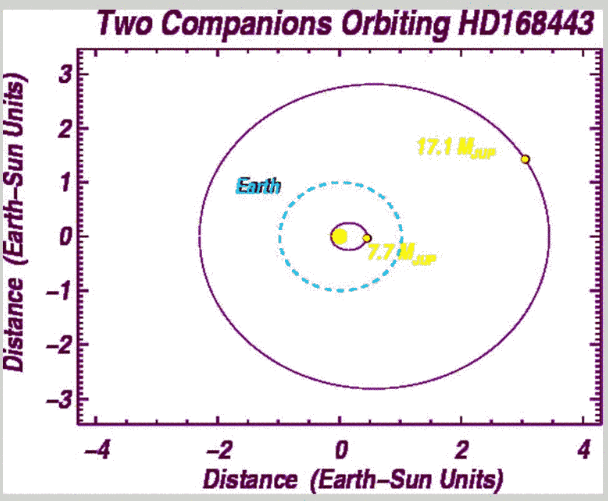

+ odd individual systems

Metallicity distribution for hosts of the most massive \`planets' is not yet well measured

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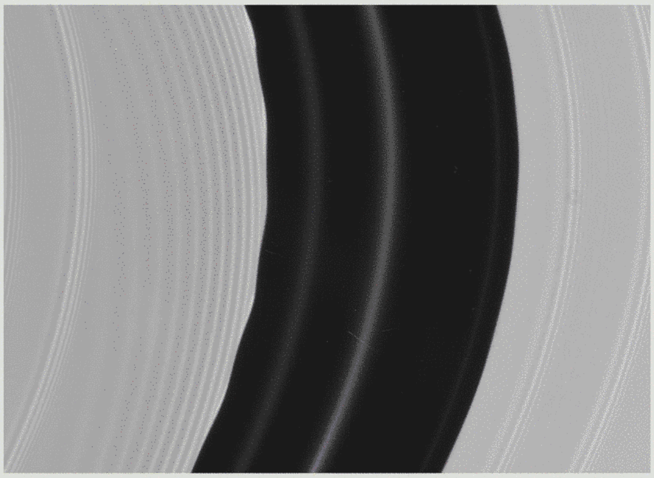
Migration

Gravitational interaction between planet and disk:

- Angular momentum exchange
- Planet migration
- Perturbation to Σ



Effect on the (particle) disk can be seen in Saturn's rings

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2D, *laminar* disk simulation for illustration only!

Planet mass grows slowly from 3 M_{Earth} to 10 $M_{Jupiter}$

Shown in an almost corotating frame

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Type I: planet remains embedded in gas ($M \sim M_{Earth}$)

Type II: planet clears a gap ($M \sim M_{Jupiter}$)

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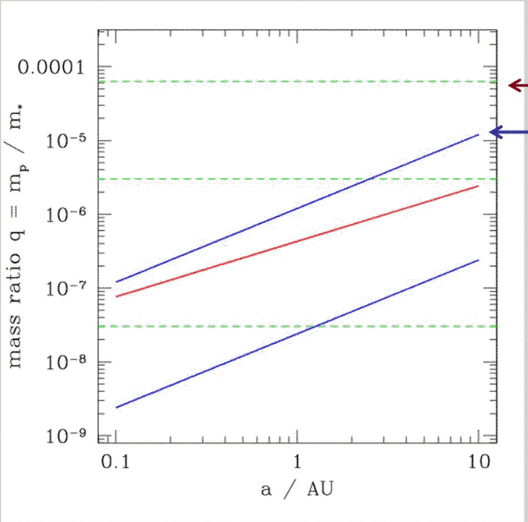
Type I migration and core accretion

$$\frac{v_{migrate}}{v_{Kepler}} \approx -3q\frac{r_p^2\Sigma}{M_*}\left(\frac{h}{r_p}\right)^{-2}$$

Type I estimate (Tanaka, Takeuchi & Ward) is about 1 cm/s per Earth mass (minimum mass Solar nebula)



critical core mass

migration time scale of 1 Myr

1) Cores do not form in situ
2) Hard to reach a critical core mass before core is lost to the star

Depends on background model (Menou & Goodman 04)

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Low mass migration in turbulent disks:

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

Potential fluctuations at ~10^{-4} level yield a random torque on low mass planets

$$T_{turbulent} \propto M_p$$

$$T_{\text{Type I}} \propto M_p^2$$

Additive?

Simulations:

Laughlin, Steinacker & Adams (2004)

Nelson & Papaloizou (2004)

Σ slice of disk + boundary layer: 3D, ideal MHD, unstratified, isothermal, h/r ~ 0.1

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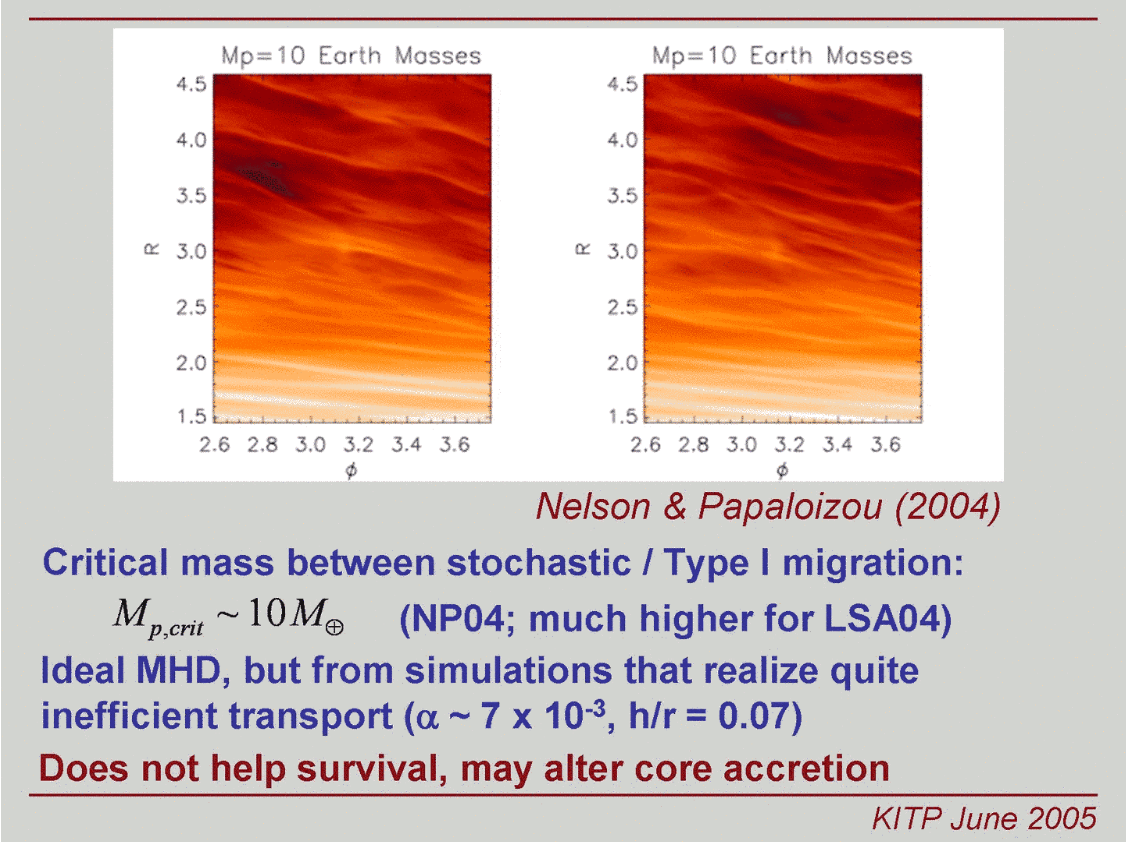

Nelson & Papaloizou (2004)

Critical mass between stochastic / Type I migration:

$M_{p,crit} \sim 10 M_\oplus$ **(NP04; much higher for LSA04)**

Ideal MHD, but from simulations that realize quite inefficient transport ($\alpha \sim 7 \times 10^{-3}$, h/r = 0.07)

Does not help survival, may alter core accretion

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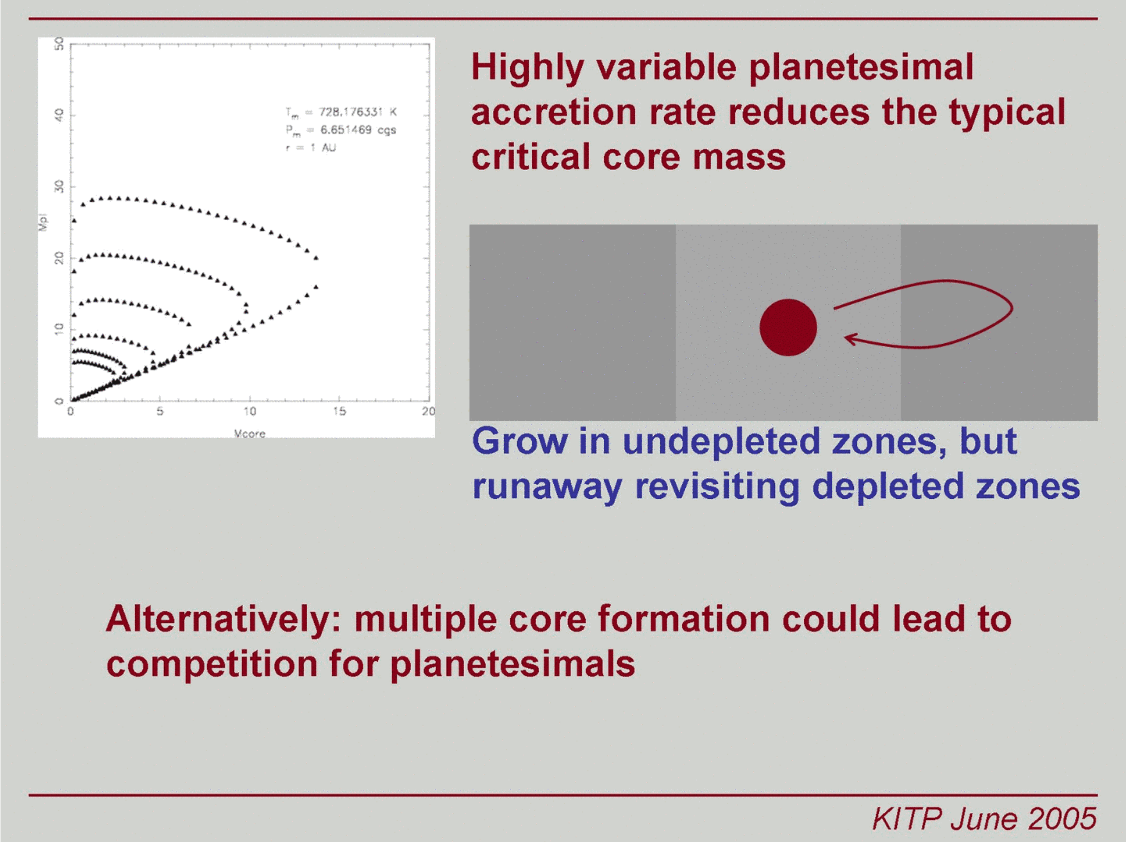

Highly variable planetesimal accretion rate reduces the typical critical core mass

Grow in undepleted zones, but runaway revisiting depleted zones

Alternatively: multiple core formation could lead to competition for planetesimals

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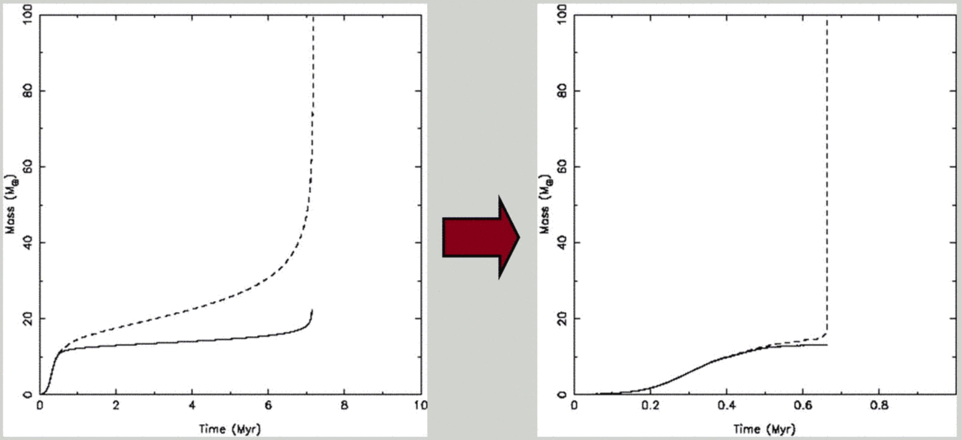


Rice & Armitage 2003

Dominant random walk component:

- **Large reduction in time to runaway**
- **Can trade some of that off for smaller core mass**

Type II migration uncertainties:

- **Disk model**
- **Numerical convergence at gap opening**
- **Turbulence**

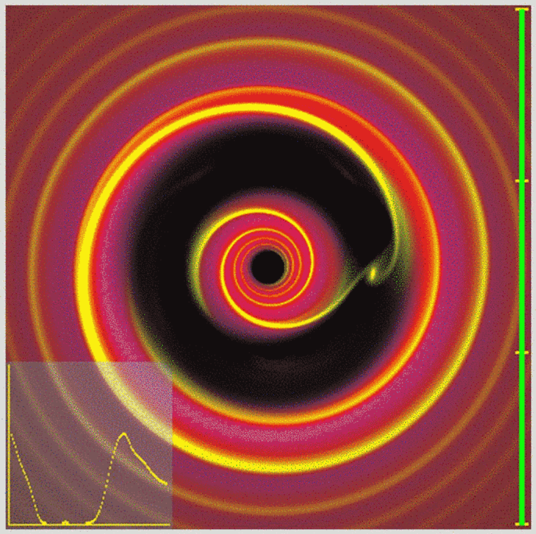
Does the interaction lead to eccentricity growth?

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Winters, Balbus & Hawley ‘03

Type II migration is basis for a model for Hot Jupiters:

- Planets form at `large' radii (a > 4 AU)
- Migrate inward within gaps
- Lost to the star or stall as gas is lost



Potentially quite wasteful (depending on the disk evolution model)

QuickTime™ and a
GIF decompressor
are needed to see this picture.

Armitage et al. 02, Trilling et al. 02

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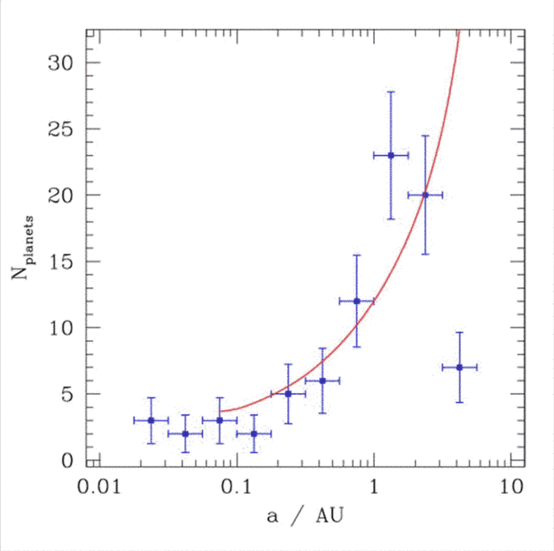
Predicted distribution of stalled planets from 1D disk + planet model

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[3r^{1/2}\frac{\partial}{\partial r}\left(\upsilon\Sigma r^{1/2}\right) - \frac{r^{1/2}}{\pi\sqrt{GM_*}}\frac{\partial T}{\partial r}\right]$$



Consistent with observed distribution of extrasolar planets (selection effects corrected)

Predicts abundance of planets embedded in gas disks (evidence for GM Aur, CoKu Tau/4)

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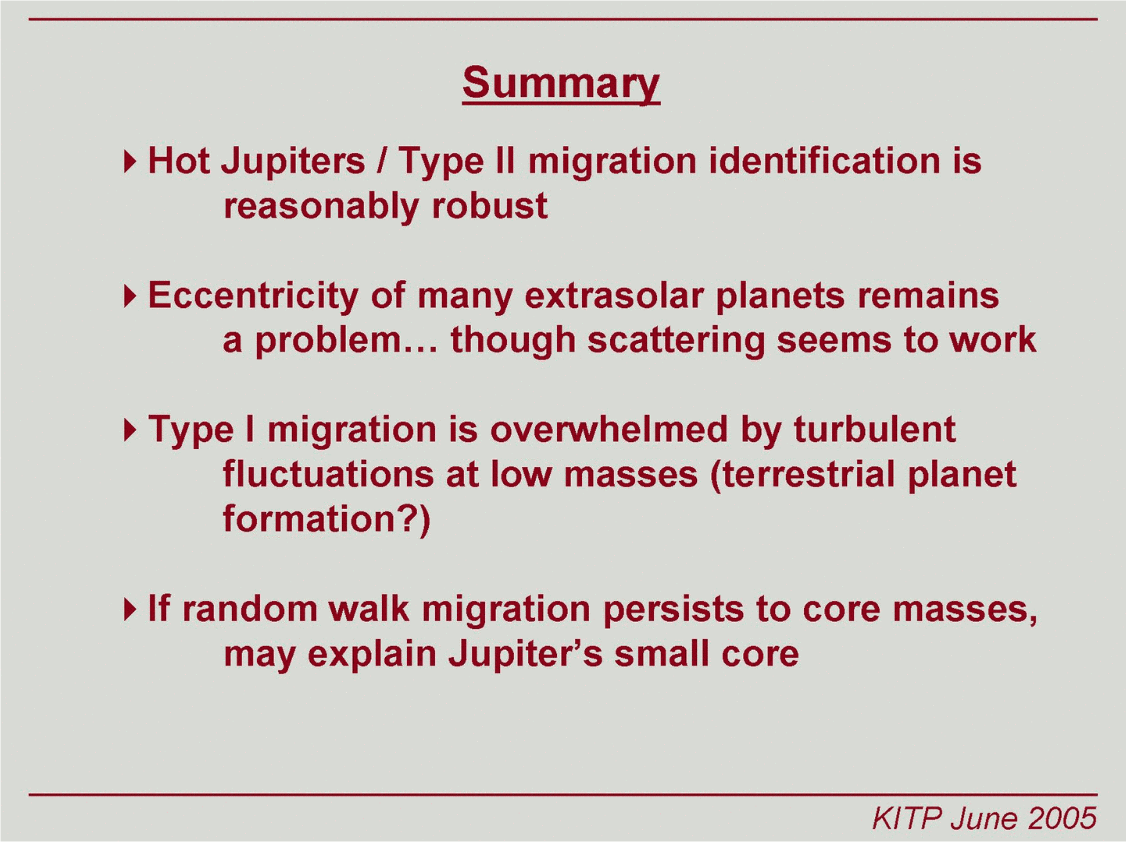

Summary

- Hot Jupiters / Type II migration identification is reasonably robust
- Eccentricity of many extrasolar planets remains a problem… though scattering seems to work
- Type I migration is overwhelmed by turbulent fluctuations at low masses (terrestrial planet formation?)
- If random walk migration persists to core masses, may explain Jupiter's small core

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