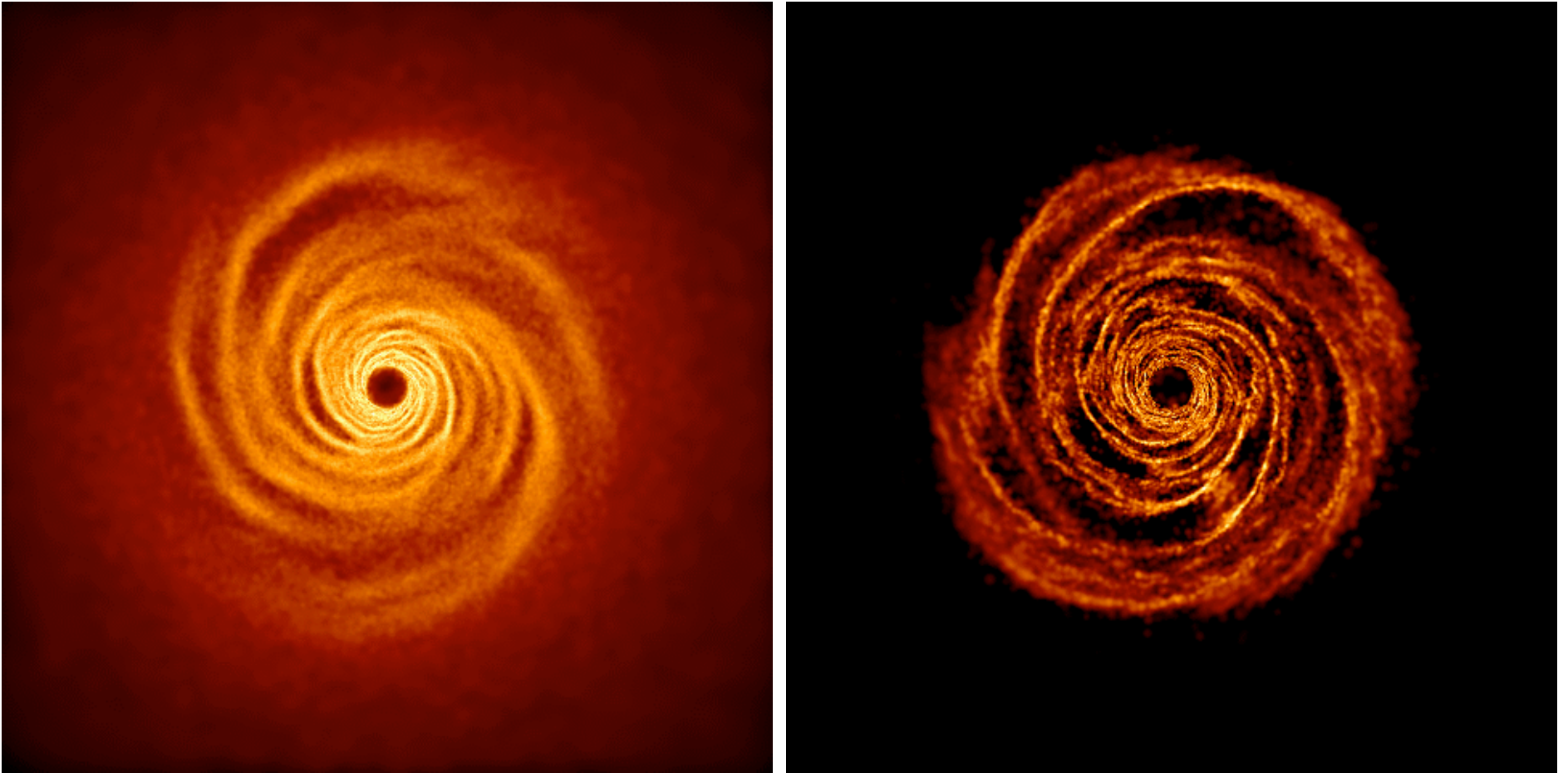


Formation and Migration of Extrasolar Planets



Phil Armitage (University of Colorado, Boulder)

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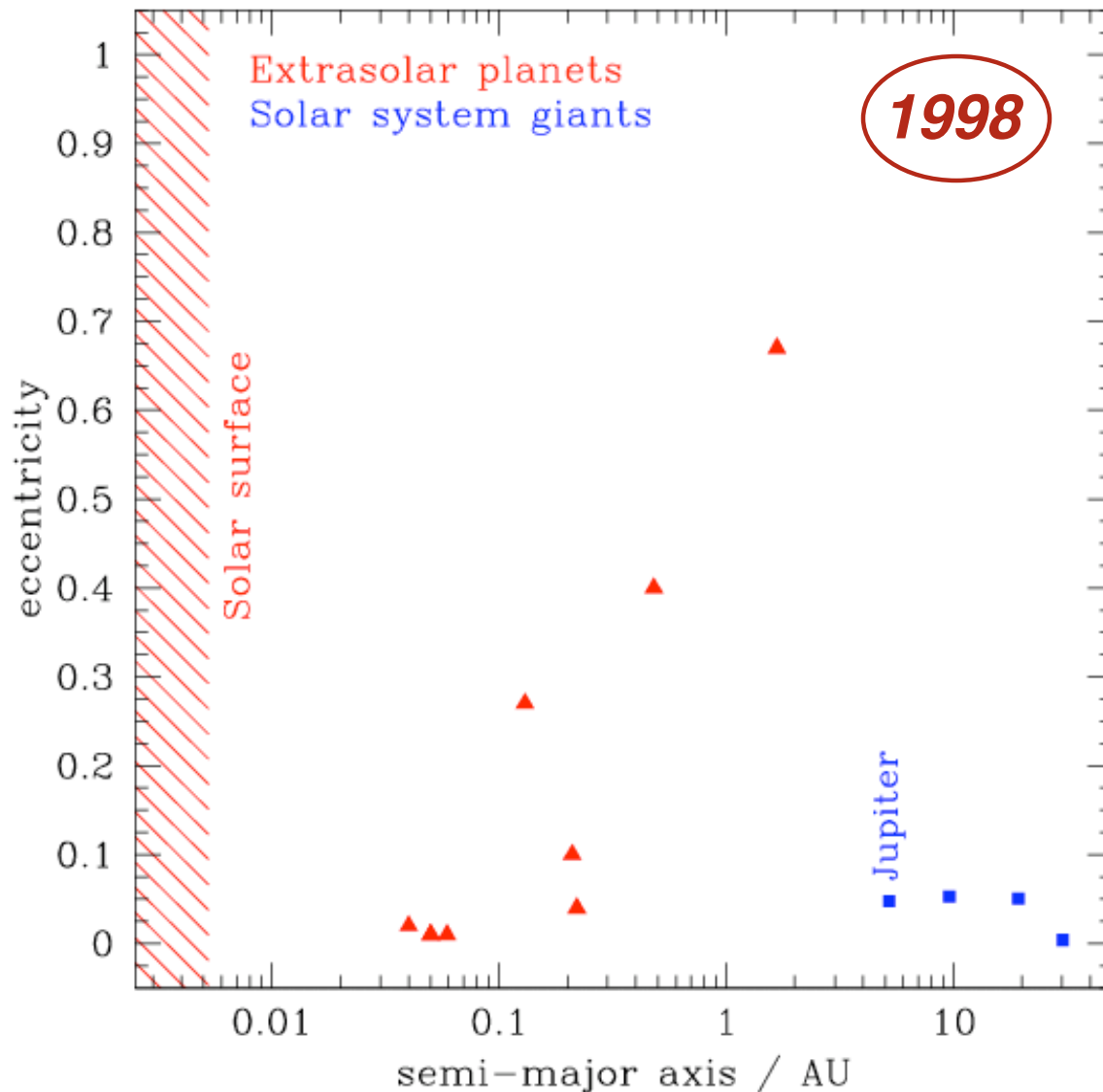
Outline

- **Observed properties of extrasolar planets**
- **Theoretical implications**
- **Implications for the frequency of Solar System-like planetary systems**

*Collaborators: Dimitri Veras (Colorado), Ken Rice (St Andrews)
+ Matthew Bate, Ian Bonnell, Cathie Clarke, Sandra Jeffers,
Mario Livio, Steve Lubow, Francesco Palla, Jim Pringle,
Steve Vine, Kenny Wood*

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Radial velocity surveys



Data from exoplanets.org compilation

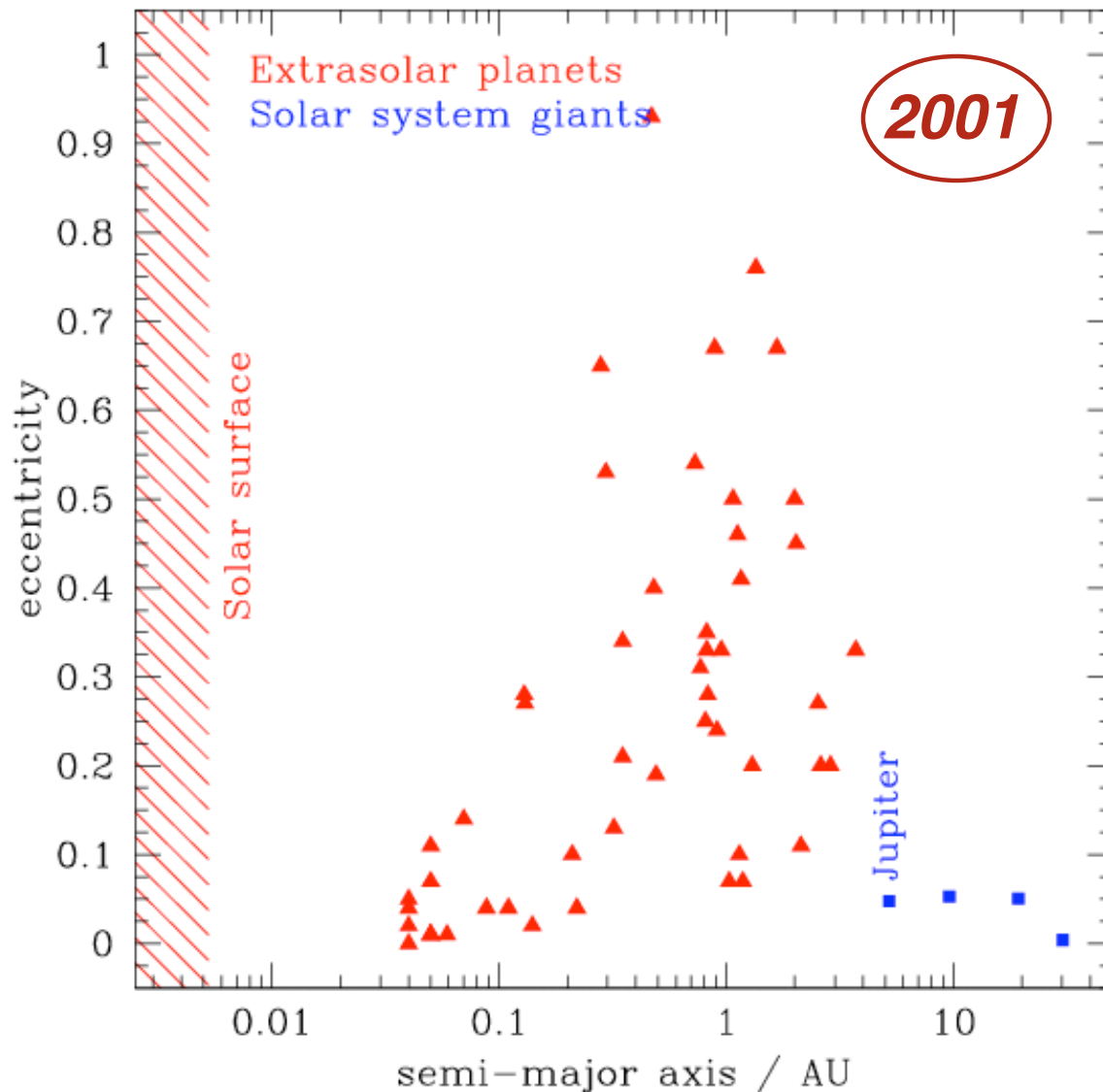
Giant planets are:

- **Common (FGKM star $f > 5\%$)**
- **Populate broader range of parameter space (a , e , M_p) than in the Solar System**

c.f. Marcy et al. (2004), in 'Extrasolar Planets: Today and Tomorrow'

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Radial velocity surveys



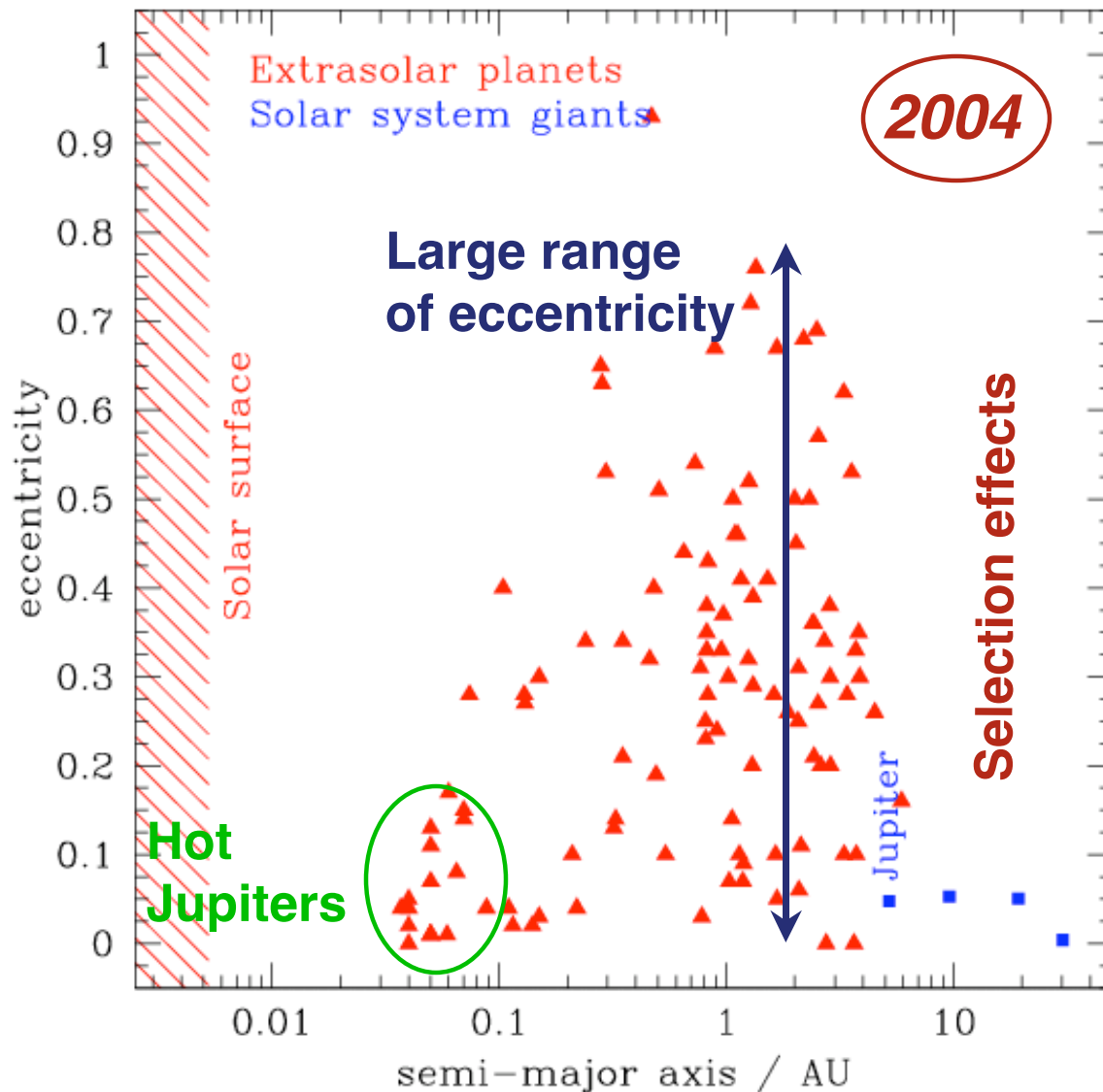
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- Common (FGKM star $f > 5\%$)
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Data from exoplanets.org compilation

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Radial velocity surveys



Hot Jupiters
($a < 0.1$ au) in $\sim 1\%$
of FGKM stars

Eccentricity is
distributed uniformly
in $0 < e < 0.7$ for
planets further out

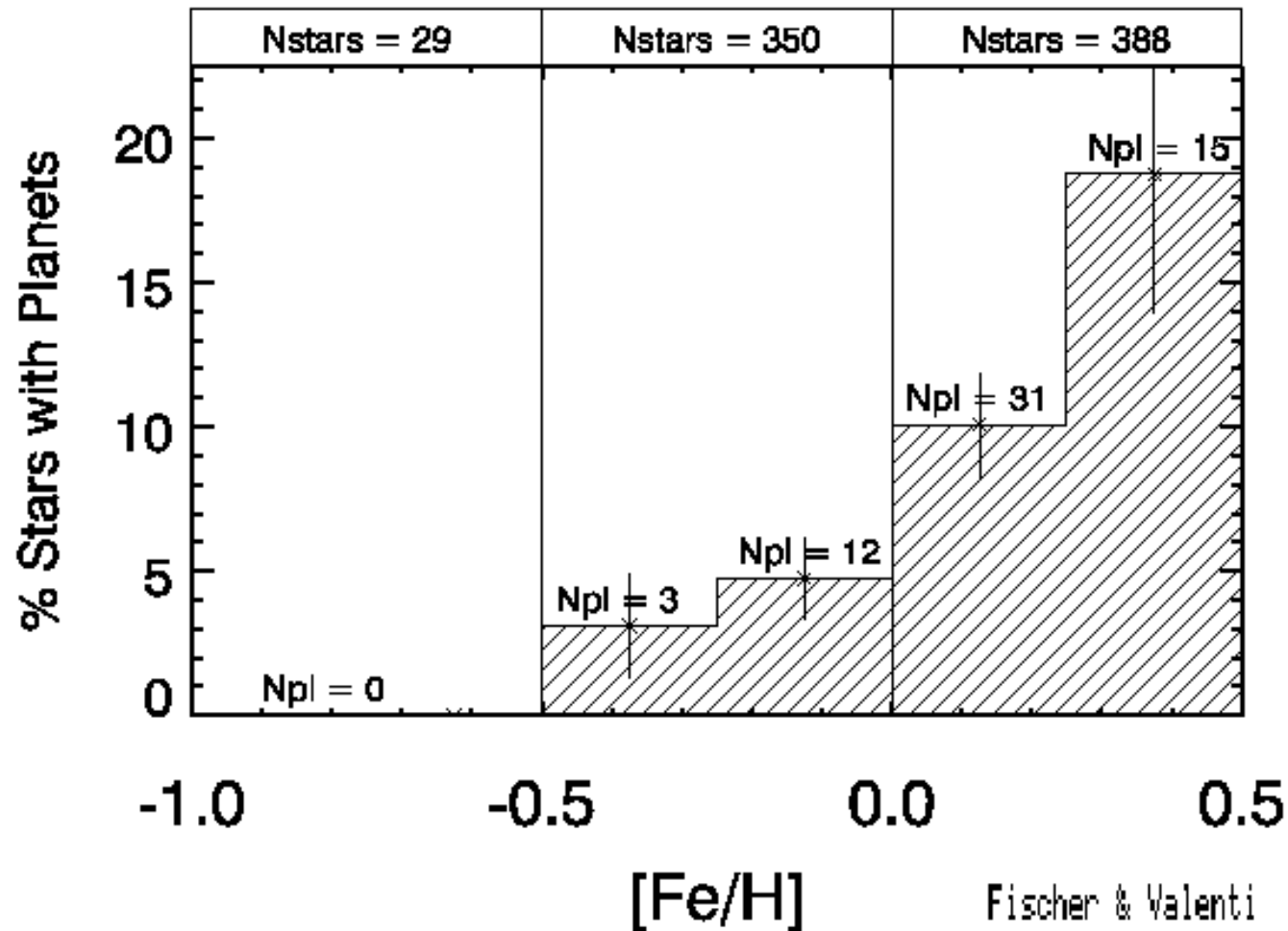
Incompleteness
rising for $a > 3$ au

Mass function rises
to low masses down
to detection limit at
 $M_p \sim M_{\text{Saturn}}$

Data from exoplanets.org compilation

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Detectable planets are more frequent around metal-rich stars



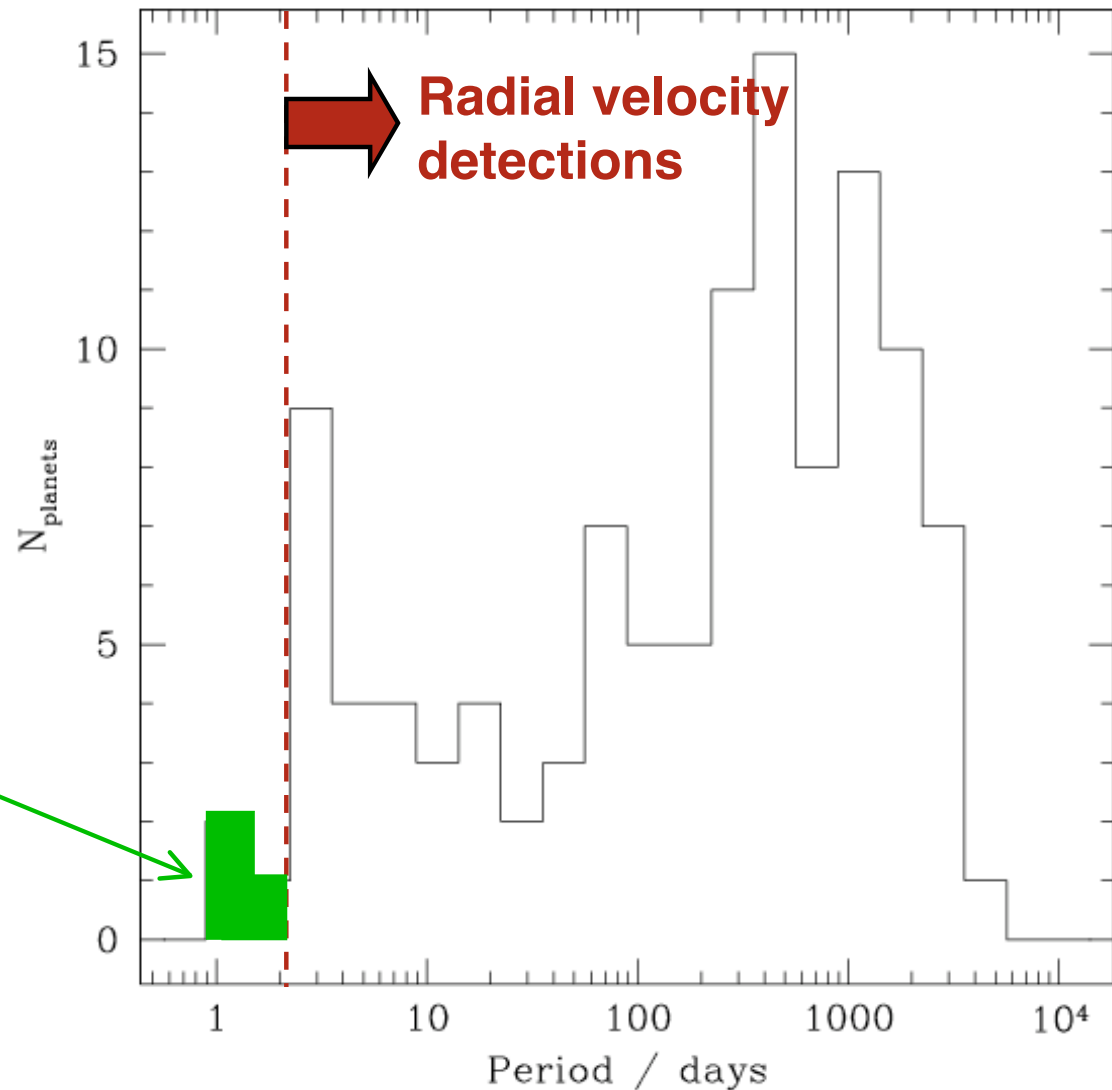
Fischer, Valenti & Marcy (2004)

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Characteristics of initial transit detections

Small but non-zero frequency of planets with super-short ($P = 1\text{-}2$ days) orbital periods

Transit detections; Konacki et al. (2003, 2004), Bouchy et al. (2004)



Theoretical implications

How do massive planets form?

- **via core accretion**
- **or gravitational disk instability...**

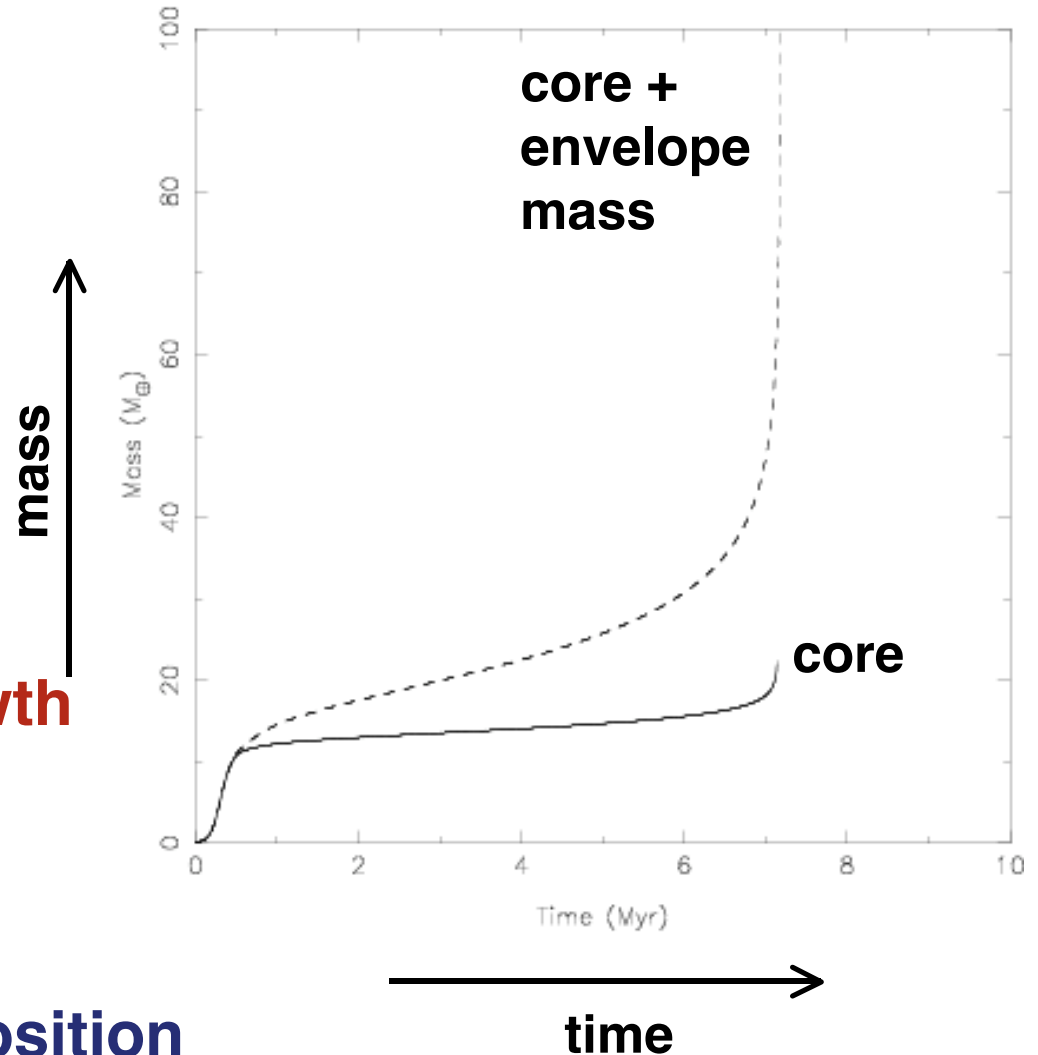
Can we understand the orbital distribution of planets?

- **existence of hot Jupiters**
- **number of planets as a function of orbital radius**
- **mass function**
- **eccentricity distribution**

Giant planet formation mechanisms

Core accretion model:

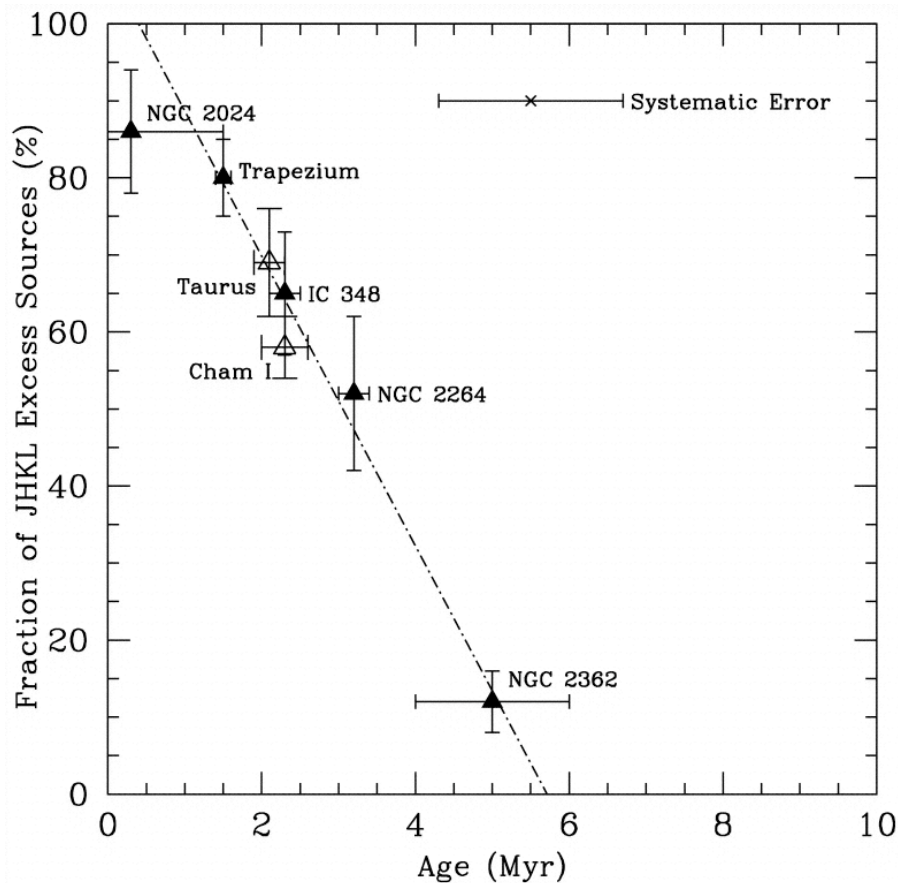
- 1) Formation of a rock / ice core from collision of planetesimals
- 2) Coupled growth of the core and hydrostatic envelope
- 3) Runaway envelope growth once core exceeds a critical mass



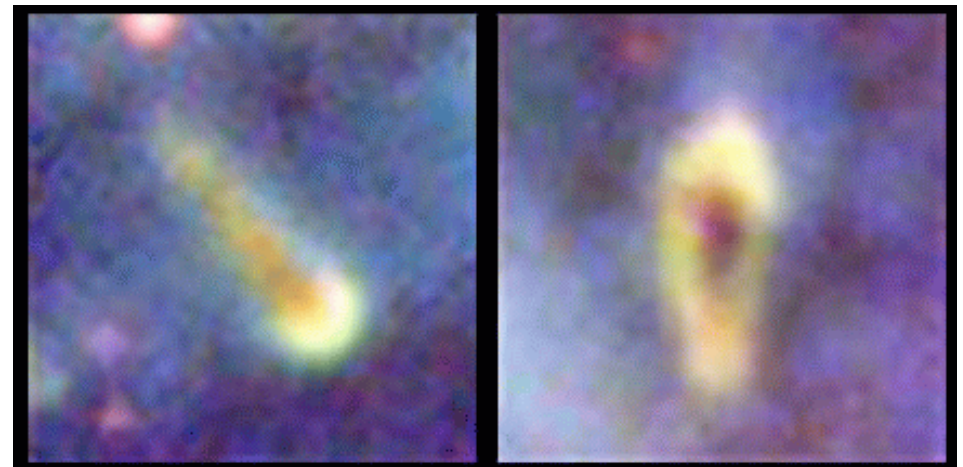
Consistent with the composition of Saturn, Uranus & Neptune; and with the metallicity bias of extrasolar planet hosts

Formation time scale is set by the disk mass and surface density profile, but can be long:

} ~10 Myr for Jupiter, longer for
outer giant planets (*Pollack et al. 1996*)



Haisch, Lada & Lada (2001)

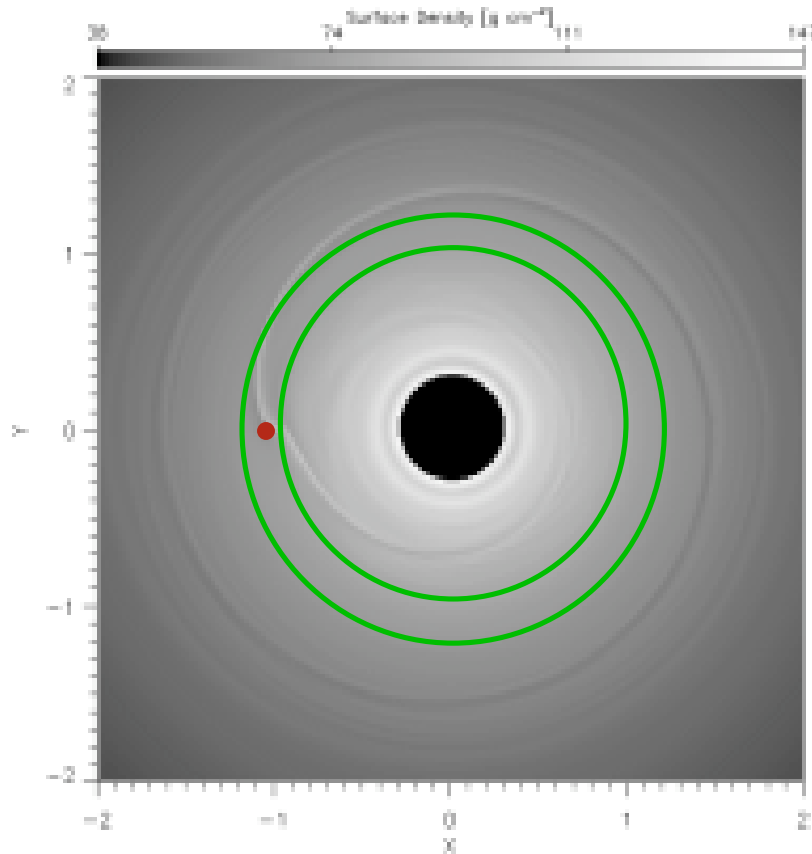


Smith, Bally & Morse (2003)

**Can core accretion form
giant planets in the typical
star formation environment?**

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Growth is slow because a static core feeds from a narrow annulus in the disk:



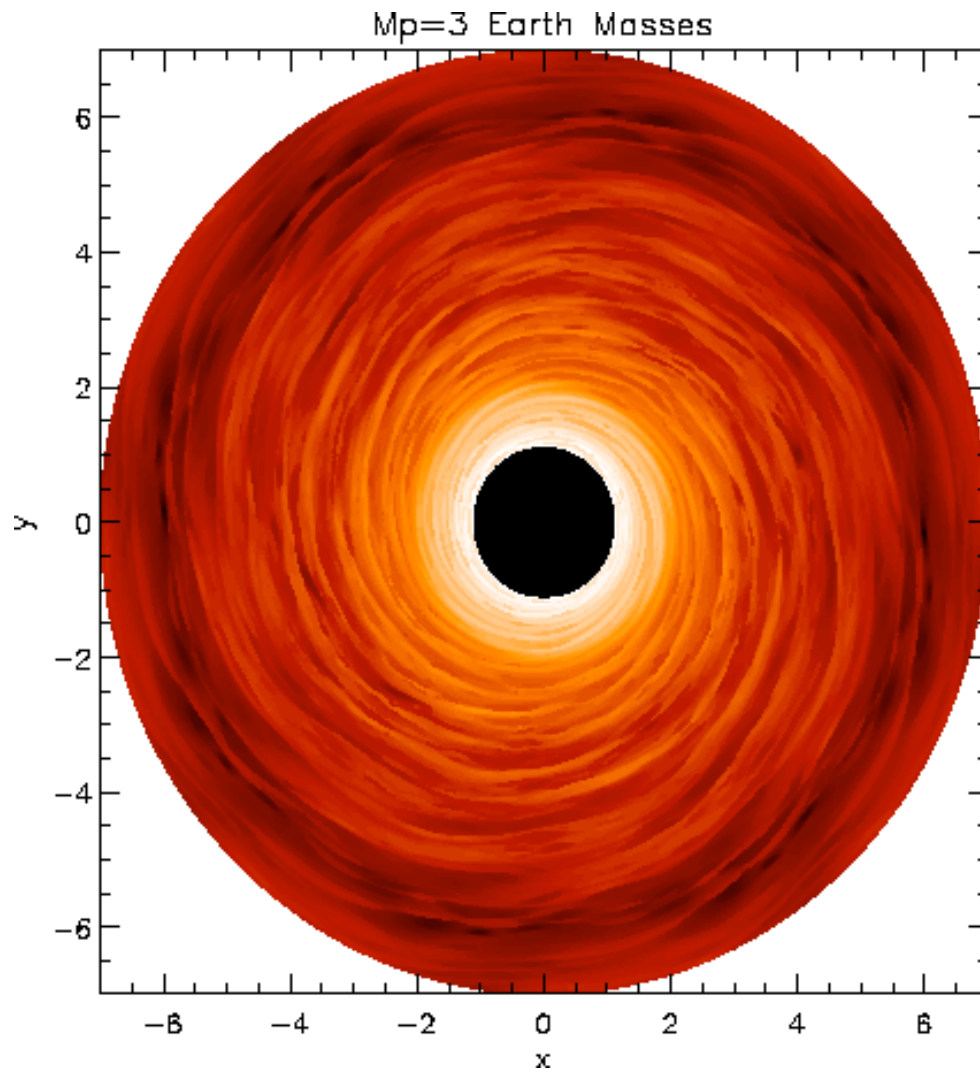
Bate et al. (2003)

$$\frac{\dot{M}}{a} = \sqrt{12 + e_H^2} \frac{M_p}{3M_*}^{1/3}$$

...a few % for an Earth mass core embedded in the disk

Faster growth is possible if there is relative motion between the core and the planetesimals in the disk (e.g. Ward 1989)

Disk turbulence mobility of the core



For low masses, turbulent density fluctuations \gg spiral waves excited in the gas disk by the core

Stochastic exchange of angular momentum between gas and core

Core random walks in r

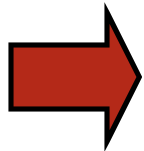
Demonstrated for MHD disk turbulence, but likely to be generic if turbulence drives accretion

*Simulations by Nelson & Papaloizou (2004),
also Laughlin, Steinacker & Adams (2004)*

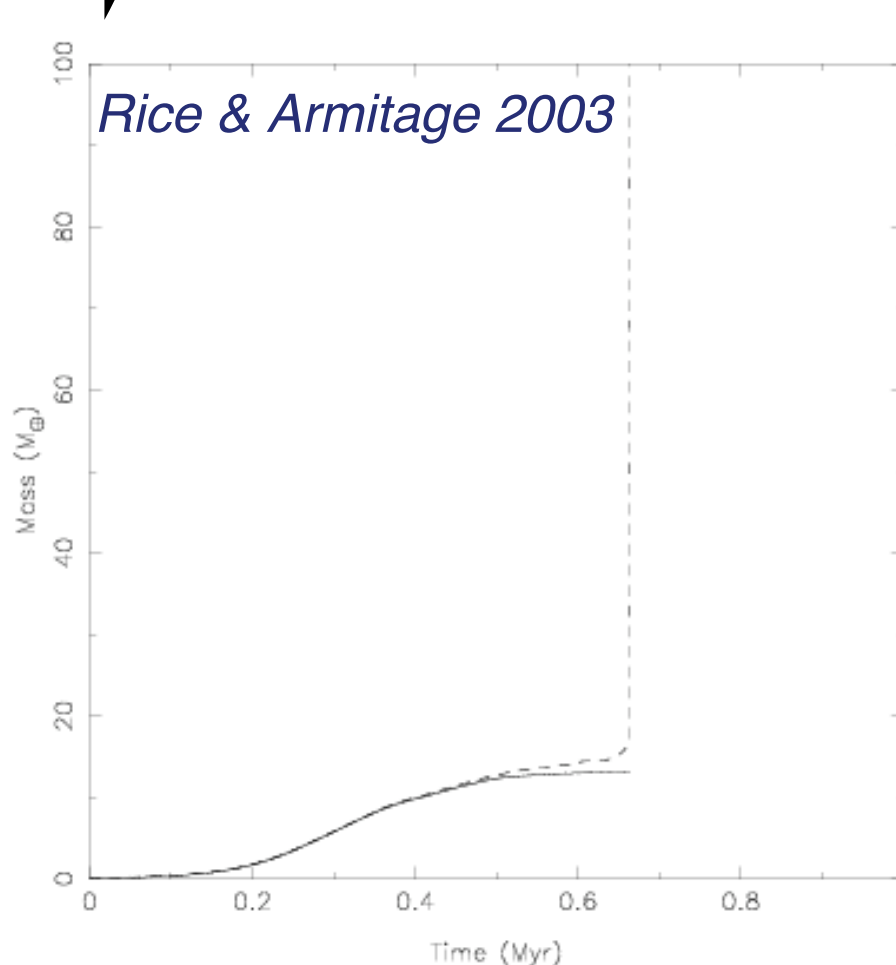
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Two-fold impact on core accretion:

- core samples a higher average density of planetesimals
- core accretion rate is highly time-variable - on average core exceeds critical mass sooner



Slow phase of core + static envelope is shortened



Highly simplified models of core accretion with random walking cores accelerate time to runaway accretion by ~order of magnitude

Only most extreme star formation environments hostile to planet formation

t = 1 Myr

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Giant planet formation mechanisms

Gravitational disk instability model - fragmentation of the protoplanetary disk into bound substellar objects

Requires:

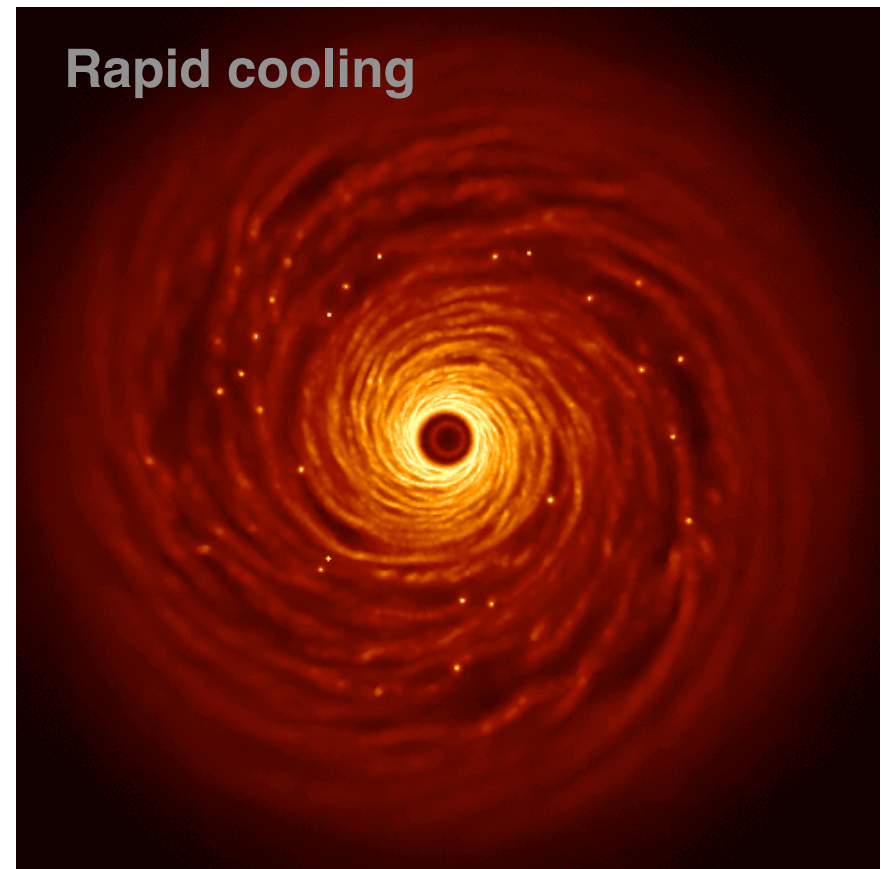
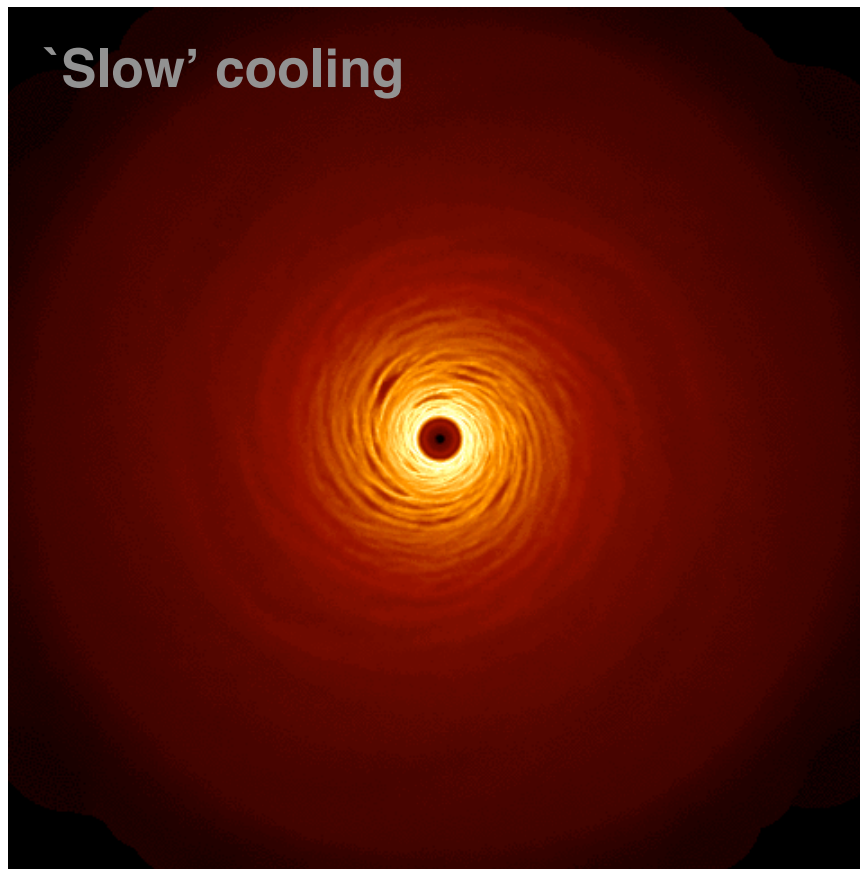
1) Massive disk $Q = \frac{c_s^2}{\Sigma G} \gg 1$ (Toomre 1964)

Definitely occurs in AGN disks; no direct evidence in protoplanetary disks

Plausibly satisfied at early epochs

2) Cooling time comparable to the dynamical time

$$t_{cool} \approx 3 \times 10^1 \quad (\text{Gammie 2000})$$



Rice et al. 2003

Might be satisfied at large disk radii (~10 au)

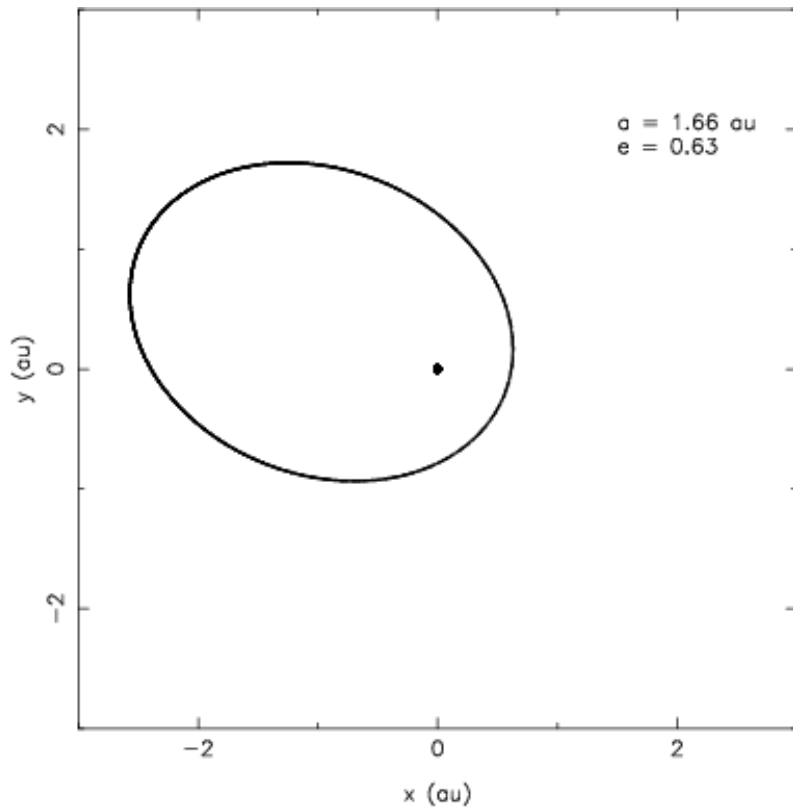
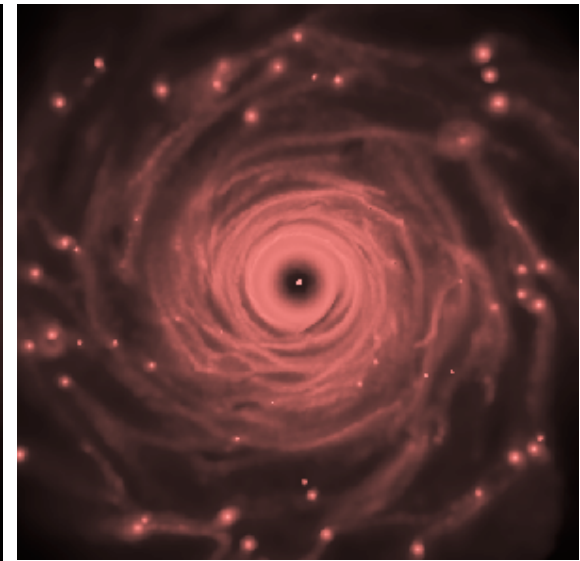
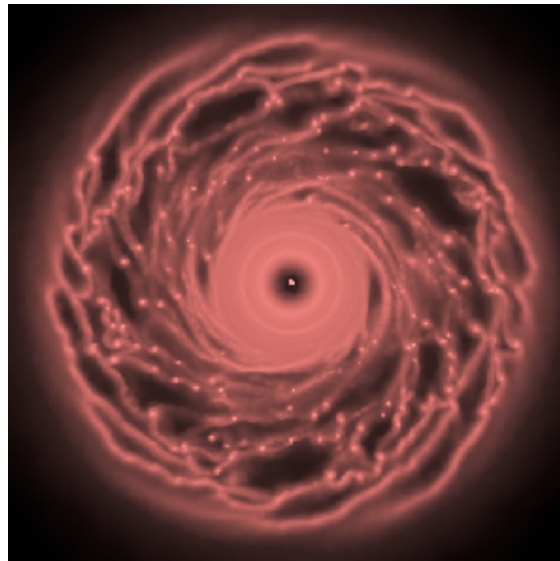
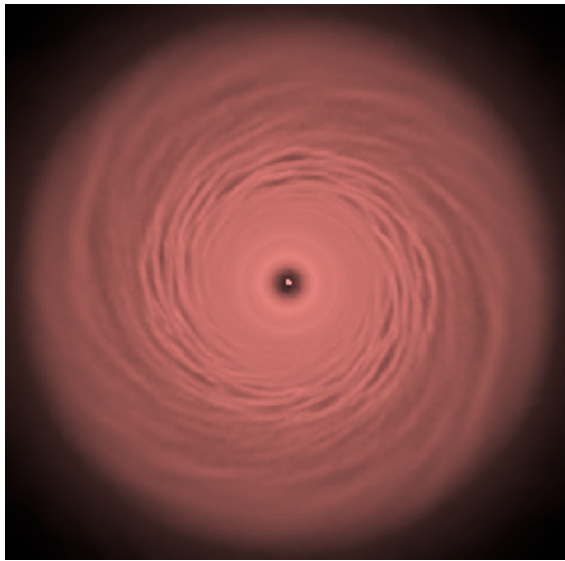
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Hydrodynamic simulations by: *Boss (2003); Pickett et al. (2003); Mayer et al. (2002); Johnson & Gammie (2003)*

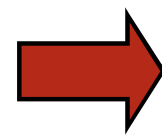
Assume that fragmentation occurs - what is the outcome?

- formation of multiple substellar objects
- ongoing accretion and gravitational interactions
- ejection of most of the bodies once the gas is gone, leaving (typically) the most massive on an eccentric orbit

Can simulate this process in reasonable detail, though not from self-consistent initial conditions *(Rice et al. 2003)*



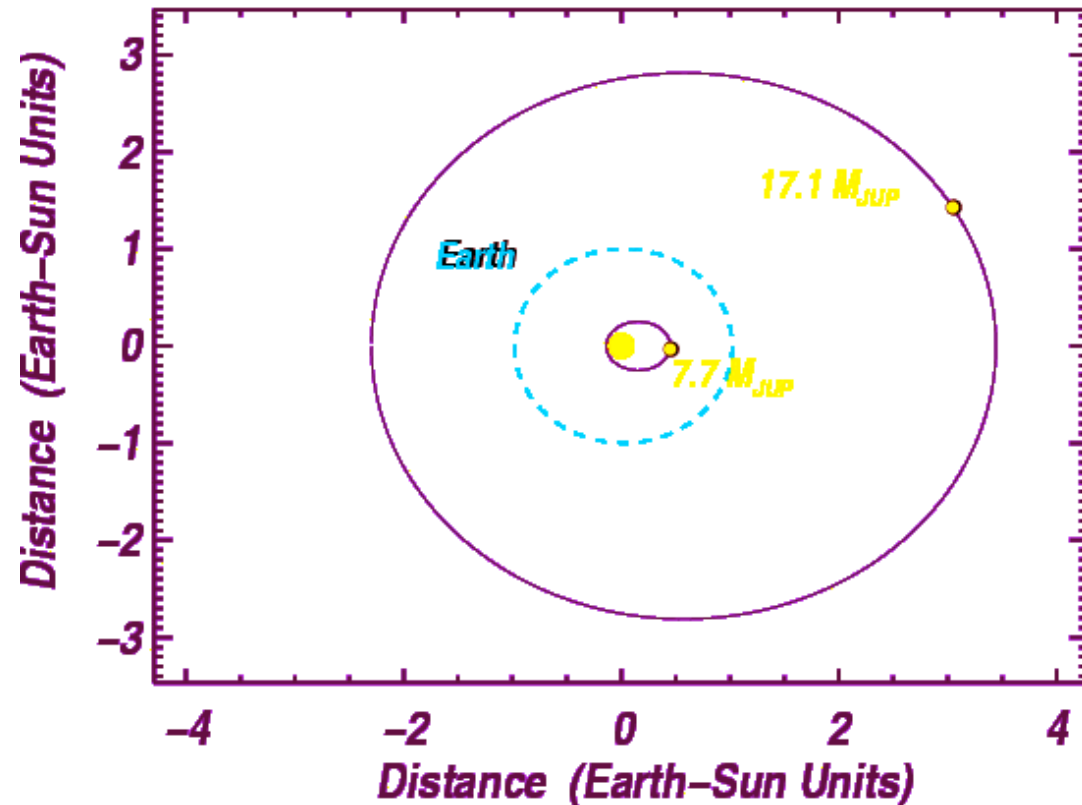
**Hydrodynamic simulations +
N-body evolution once most
of the gas is accreted**



**One or two very massive
planets / brown dwarfs
in eccentric orbits at
radii of $\sim 1 \text{ au}$**

Are the most massive planets formed from disk instability?

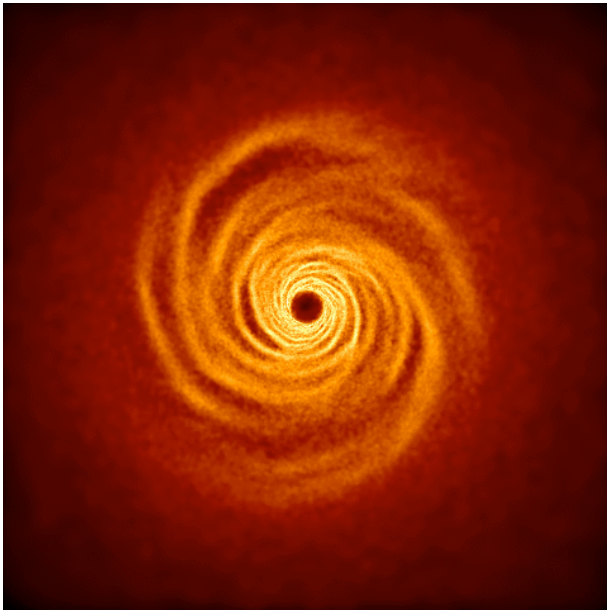
Two Companions Orbiting HD168443



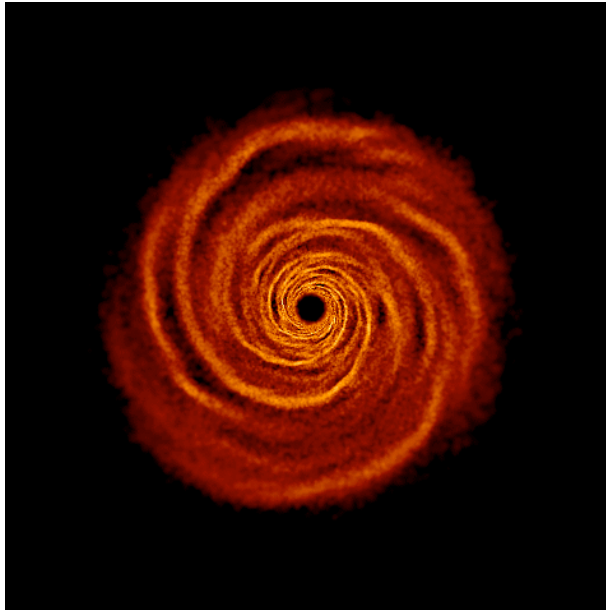
Systems known with the right architecture... M_p near the D burning boundary with eccentric orbits at small radii

Expect a different host metallicity distribution if the most massive planets form from disk instability... current evidence is inconclusive

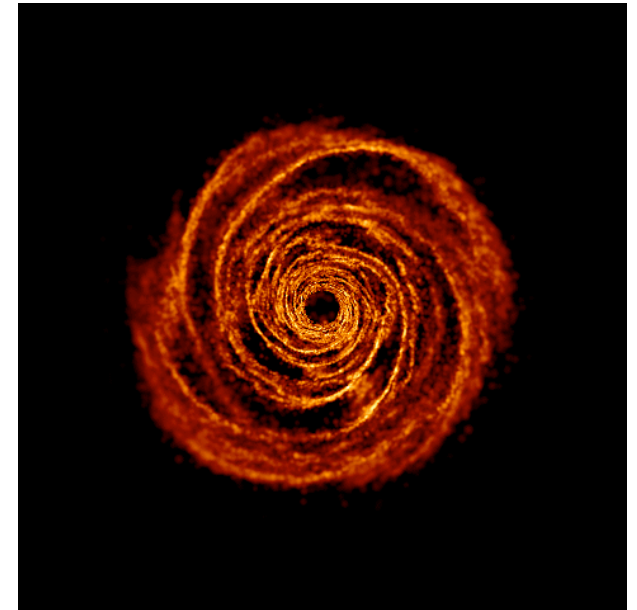
Currently investigating whether gravitational instability *without* fragmentation accelerates earlier stages of planet formation (Rice, Pringle, Armitage, in preparation)



Gas surface density



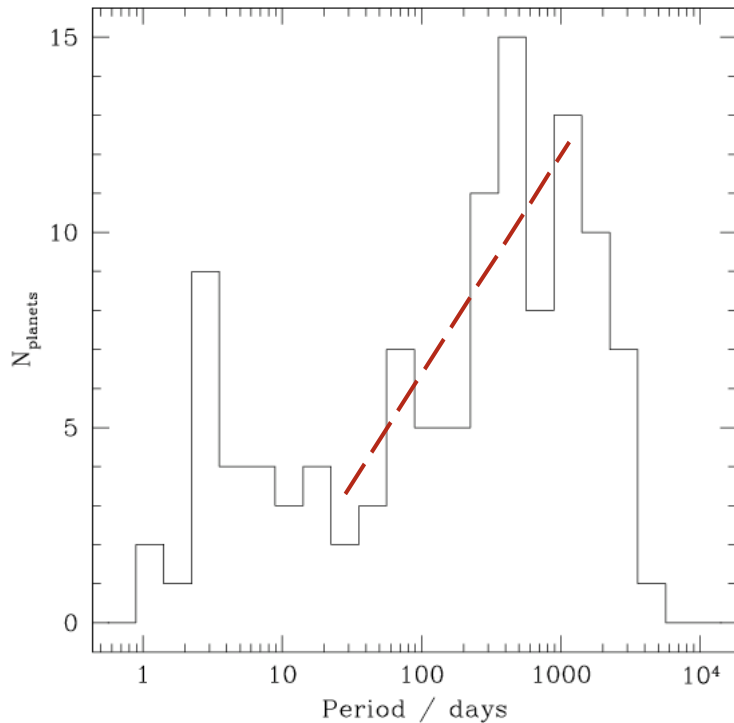
Solid, $r = 10\text{m}$



Solid, $r = 0.5\text{m}$

Smaller bodies that feel significant aerodynamic drag as well as gravitational forces are concentrated in spiral arms - higher collision rate

Statistics of extrasolar planets



Raw count of extrasolar planets shows that typical planet is at relatively large radius

$$\frac{dN}{d \log a}, \frac{dN}{d \log P} \quad \dots \text{increasing functions}$$

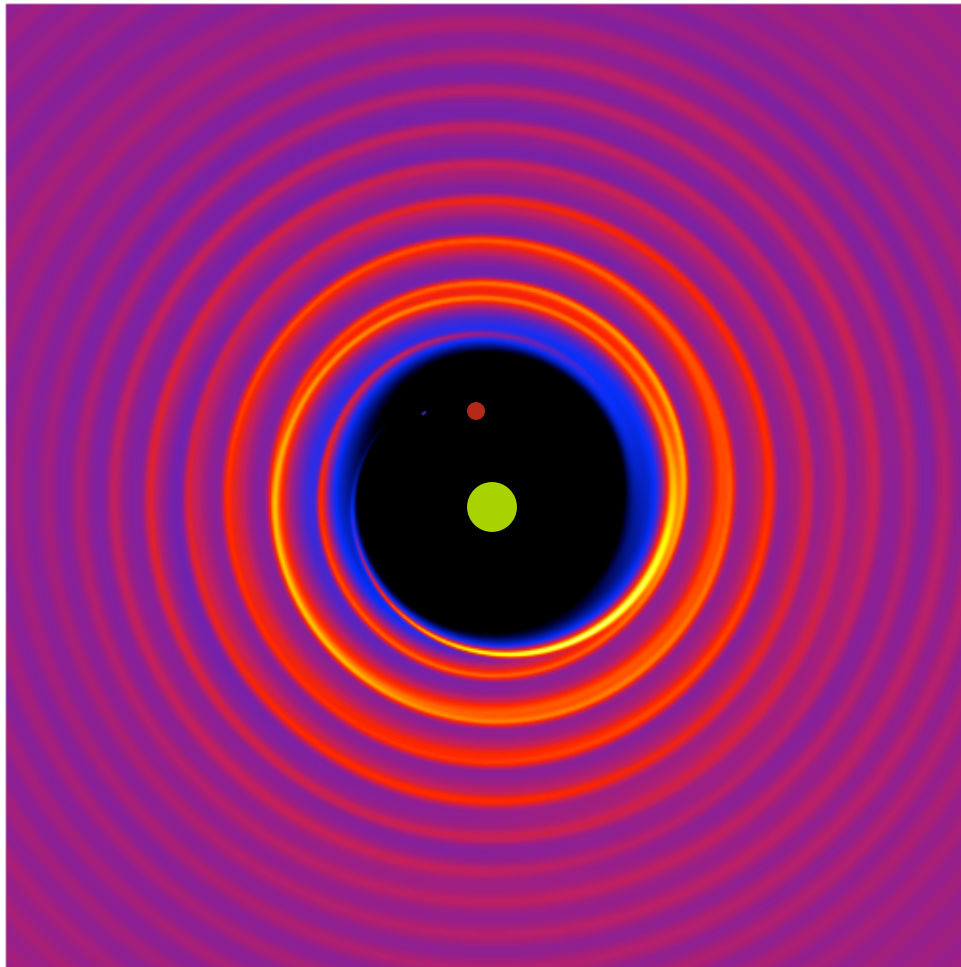
Low mass planets are harder to detect at large radius, so stronger effect in an unbiased sample

Reflects a combination of:

- radii at which massive planets form
- post-formation *migration*

Migration is *required* for the closest hot Jupiters

Unknown whether core accretion can efficiently form planets at sub-au orbital radii



*2D laminar disk simulation,
Armitage & Natarajan (2002)*

**Probable mechanism:
planet - disk interaction**

- planet excites waves at location of resonances
- angular momentum exchange leads to orbital migration
- for \sim Saturn mass planets and above, interaction is strong enough to form an annular *gap* in the disk

Construct model for planet distribution based on disk driven migration:

- planets form at radii of several au and greater (5 au)
- planets form at random epochs
- once formed, migrate inward or outward depending upon the radial velocity in the protoplanetary disk

Fate of a planet depends on when it forms...

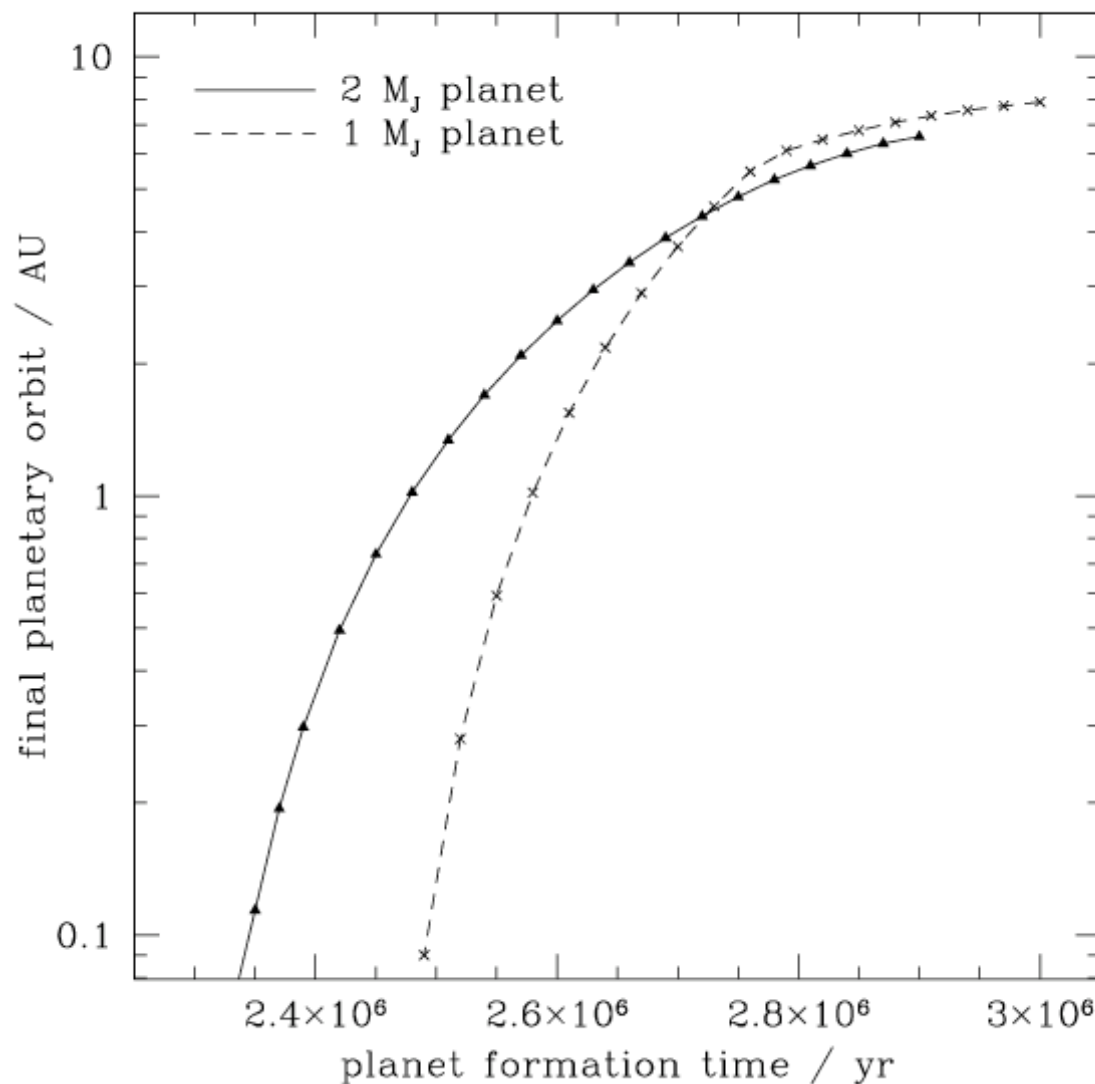
Too early - consumed by star

Too late - no migration

Just right - migrates and is stranded at observable radii as the disk is dissipated

e.g. Lin, Bodenheimer & Richardson 1996; Trilling et al. 1998, 2002

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Requires more fine tuning to strand a planet at 0.1 au vs 3 au - typical planet is found far out

Significant chance of outward migration if there is mass loss from the outer disk e.g. photoevaporation

Armitage et al. 2002; Veras & Armitage 2004

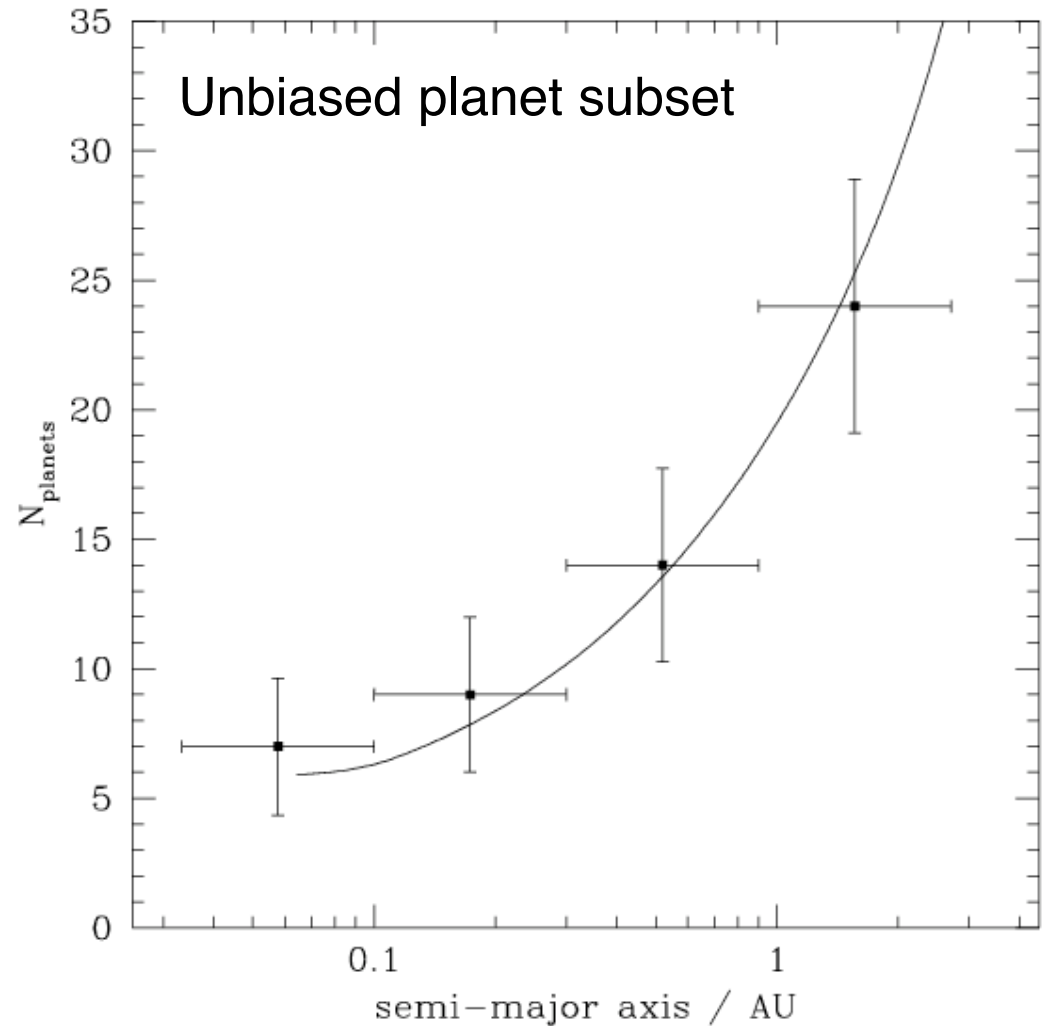
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Derived distribution with radius is consistent with observations, but large errors...

Where extrasolar planets are being found is consistent with a major role for migration

Relative paucity of high mass planets could be due to slower accretion across gaps as the mass becomes larger?

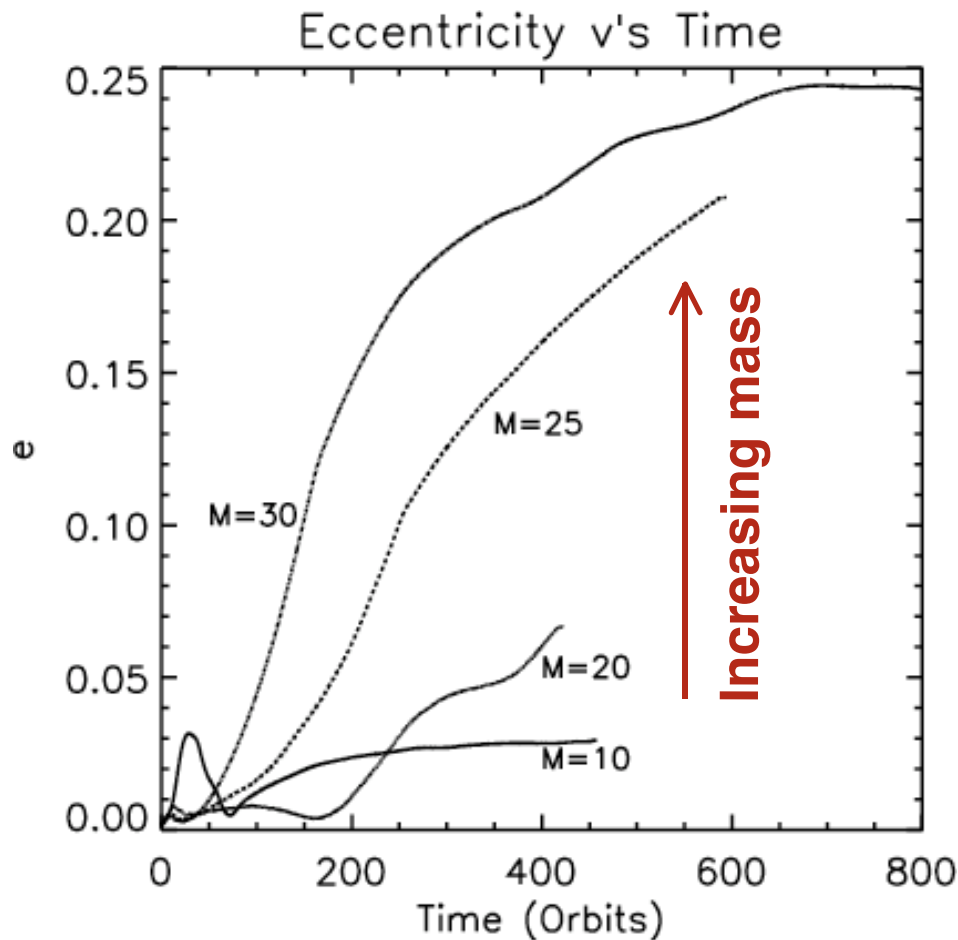
Expect to find giant planets at large radii around more massive stars, or stars formed in clustered environments



Eccentricity

Possible models:

- **Excitation of eccentricity from planet - disk interactions**
(*Ogilvie & Lubow 2003; Goldreich & Sari 2003*)
- **Gravitational interaction between multiple planets**



Planet - disk interaction

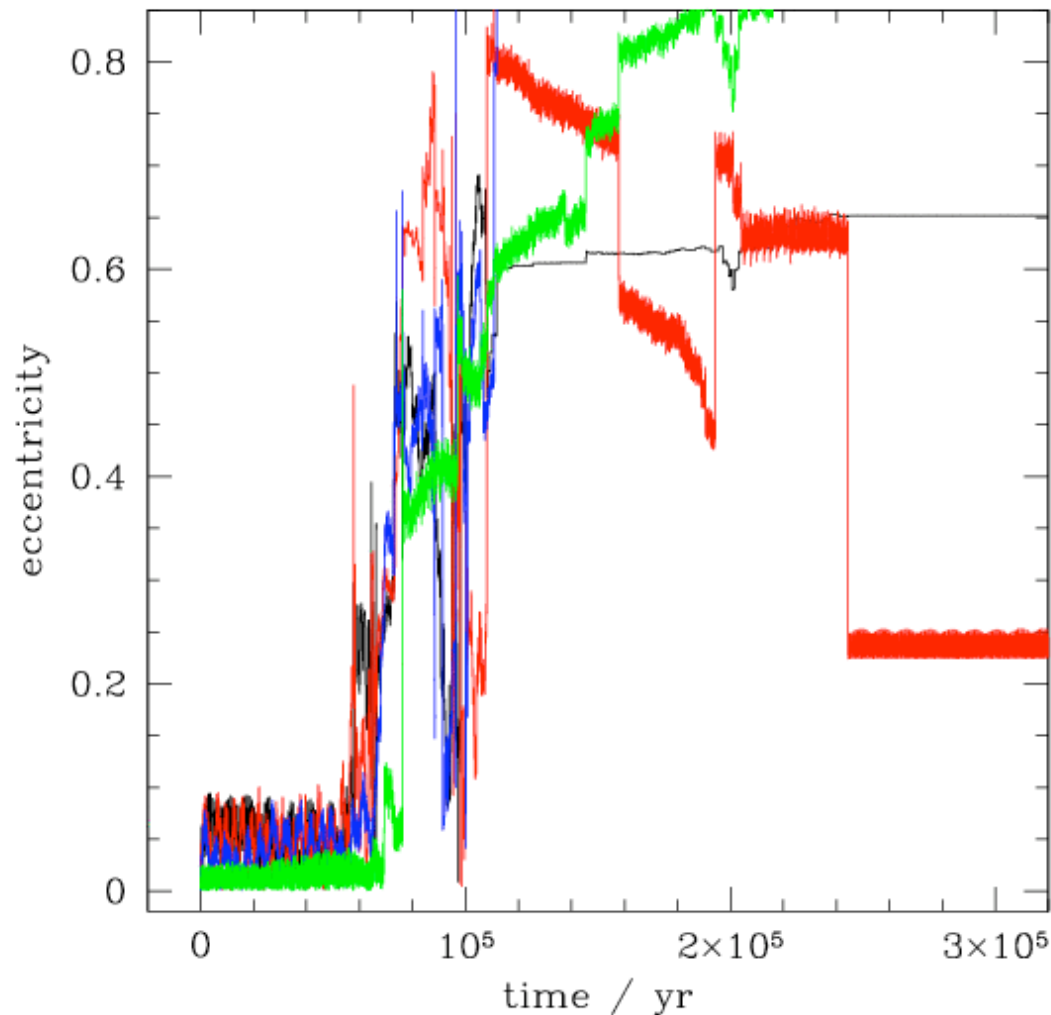
Interaction between a brown dwarf and a gas disk clears a wide gap; leads to growth in eccentricity

Could work at lower M_p - depends upon details of turbulence in the disk

Papaloizou, Nelson & Masset, 2001

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Planet - planet scattering



Very readily yields plausible eccentricity if:

- initial system is crowded enough
- migration across resonances

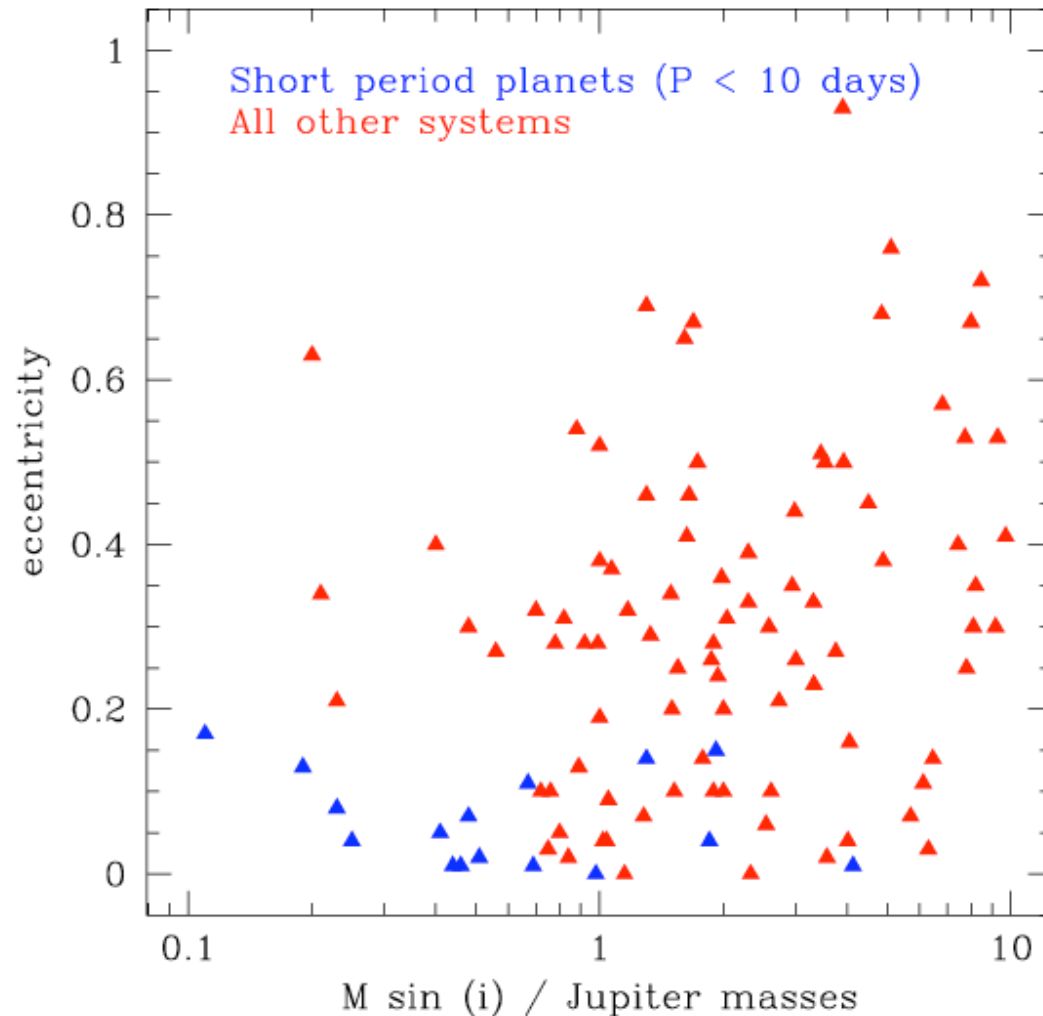
Is multiple massive planet formation common enough?

← Example: 4 planets with $M_p = 2 M_{\text{jupiter}}$, $a = 5, 7.5, 12, 20$ au

(e.g. Ford, Havlickova & Rasio 2001; Marzari & Weidenschilling 2002)

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Empirical evidence: mass / eccentricity plot shows no non-trivial correlation for extrasolar planets

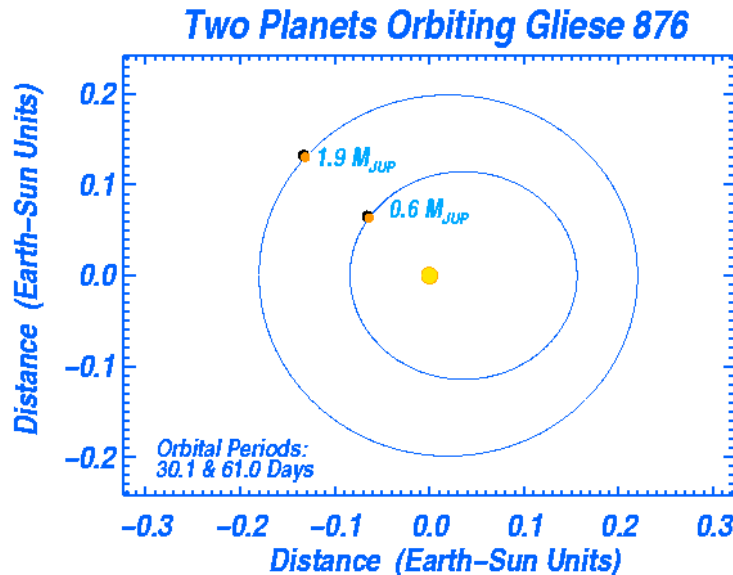


Expect eccentricity excitation from planet - disk interactions to be easier for more massive planets

But... multiple planet systems are more stable for low M_p , and collision cross-section is also greater...

Of 8 known multiple planet systems, resonances may be important in half

e.g. Gliese 876: two massive planets in a stable 2:1 resonance



Scenario:

- Massive planet formation is common
- Migration drives planets to interact: resonant capture or instability

How common is our Solar System?

- No evidence that most extrasolar giant planets formed via different mechanisms than in the Solar System (though can't rule that out...)
- Masses of our gas giants are comparable to extrasolar planet masses
- Migration is likely important in forming most *observed* extrasolar planetary systems, but typical planet probably lies at larger radii similar to that of Jupiter
- Best guess is that low eccentricity is uncommon, but not exceptional, at least for a single giant planet