# Planet-planet Scattering

*Phil Armitage (Colorado)*

- **successes**
- **non-successes**
- **tests**
- **relation to (outer) Solar System**

*with:* Sean Raymond, Re'em Sari & Noel Gorelick
*thanks:* computing resources courtesy of Google

# Early planetary system evolution *expected* to be a mess, best left to observers

**Some processes are “well”-understood:**

- Kozai resonance
- planet-planet scattering
- planetesimal scattering (c.f. Nice model)
- effect of stellar fly-bys

**…but don’t know if they occur rarely / often / always**

**Other processes definitely happen:**

- Type II migration
- damping or excitation of e / i by gas disk
- accretion across gaps

**…but are poorly understood**

# Surprise: planet-planet scattering *alone* appears to explain the observed f(e)

Assume: all or most (giant) planets at small a form (or migrate into) in multiple systems (N=2, 3…) that are unstable over long time periods

Systems relax by combination of ejections, planet-star collisions, planet-planet collisions, leaving eccentric survivors *(Rasio & Ford '96; Weidenschilling & Marzari '96)* whose eccentricity distribution matches that seen *(Chatterjee et al. '08; Juric & Tremaine '08, many others…)*

# A numerical experiment

Start with 3 massive planets, masses 0.3 $M_J$ < M < 5 $M_J$, dN / dM ~ $M^{-1.1}$, radius 1.3 $R_J$

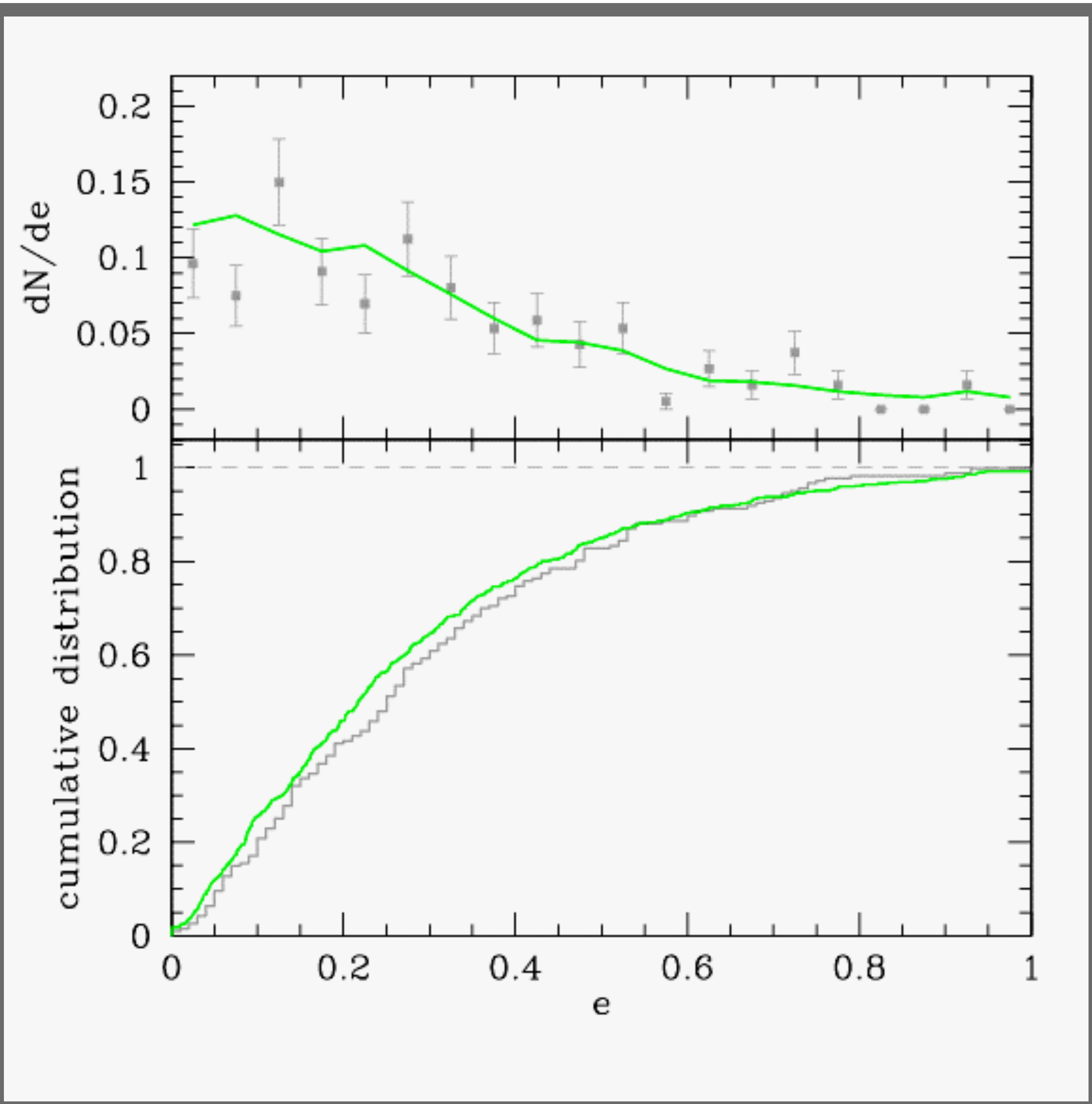
e = 0, i ~ 0

Inner planet at 4.5 AU, fixed spacing K=4 mutual Hill radii:

$$r_{h,m} = \left( \frac{M_i + M_{i+1}}{3M_*} \right)^{1/3} \frac{a_i + a_{i+1}}{2}$$

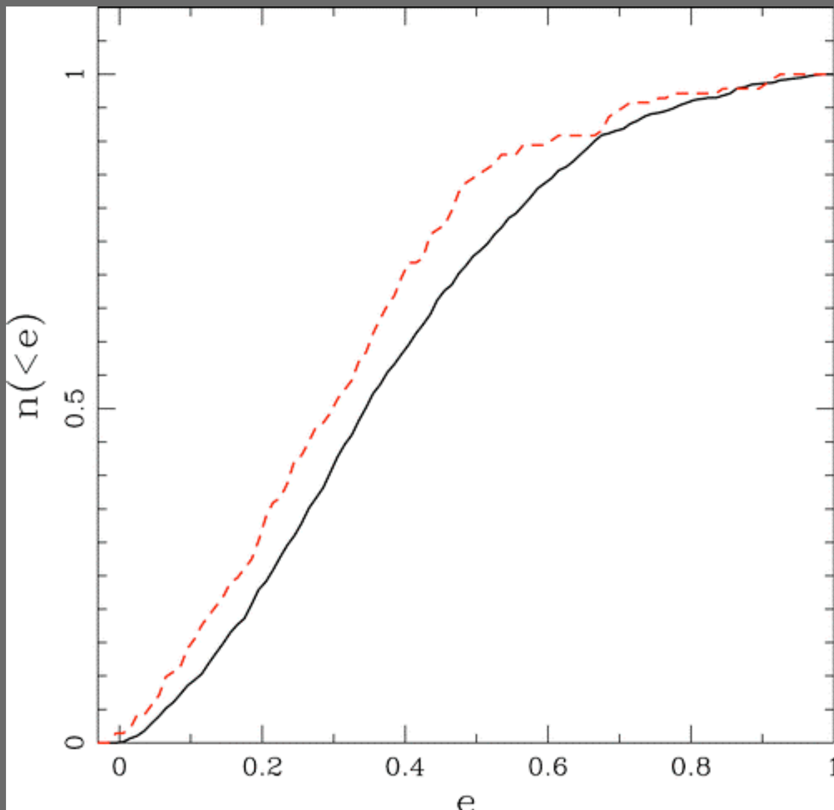
*(yields systems that are typically unstable on an moderately long time scale c.f. Chambers et al. '96; Chatterjee et al. '08)*

Evolve for ~30 Myr, consider the statistics of the unstable systems (the vast majority)



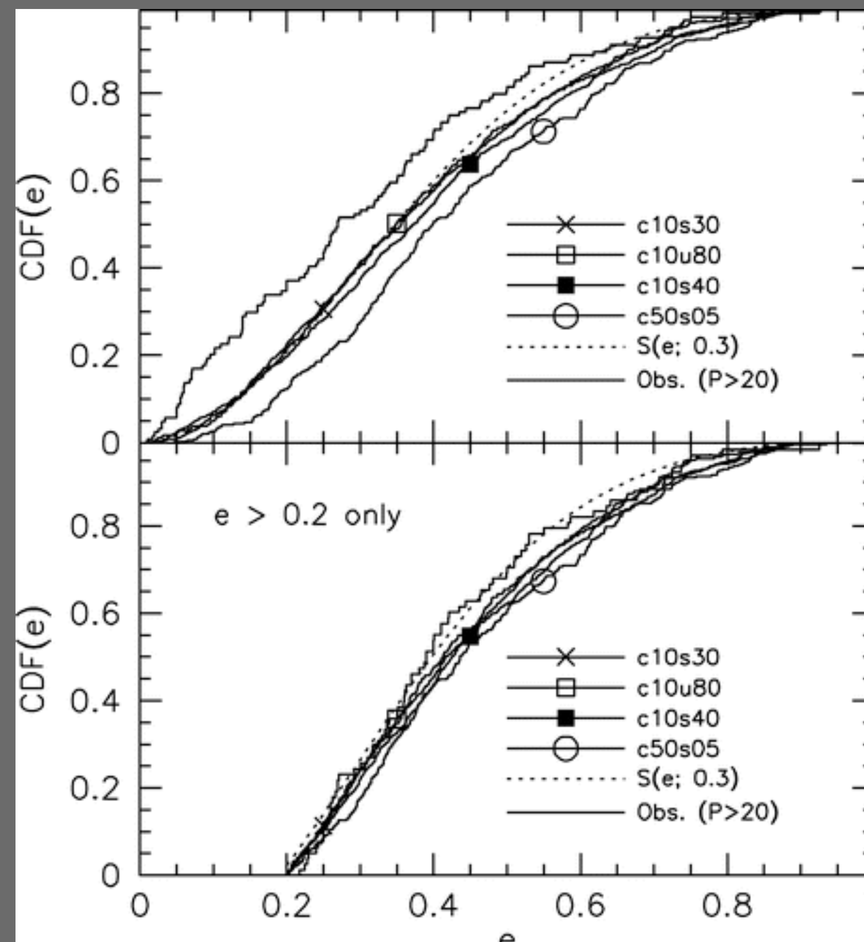

Predicted distribution is statistically indistinguishable from the observed one

Jason Wright's compilation: a > 0.25 AU, M.sin(i) < 10 $M_J$, planets with fitted eccentricity



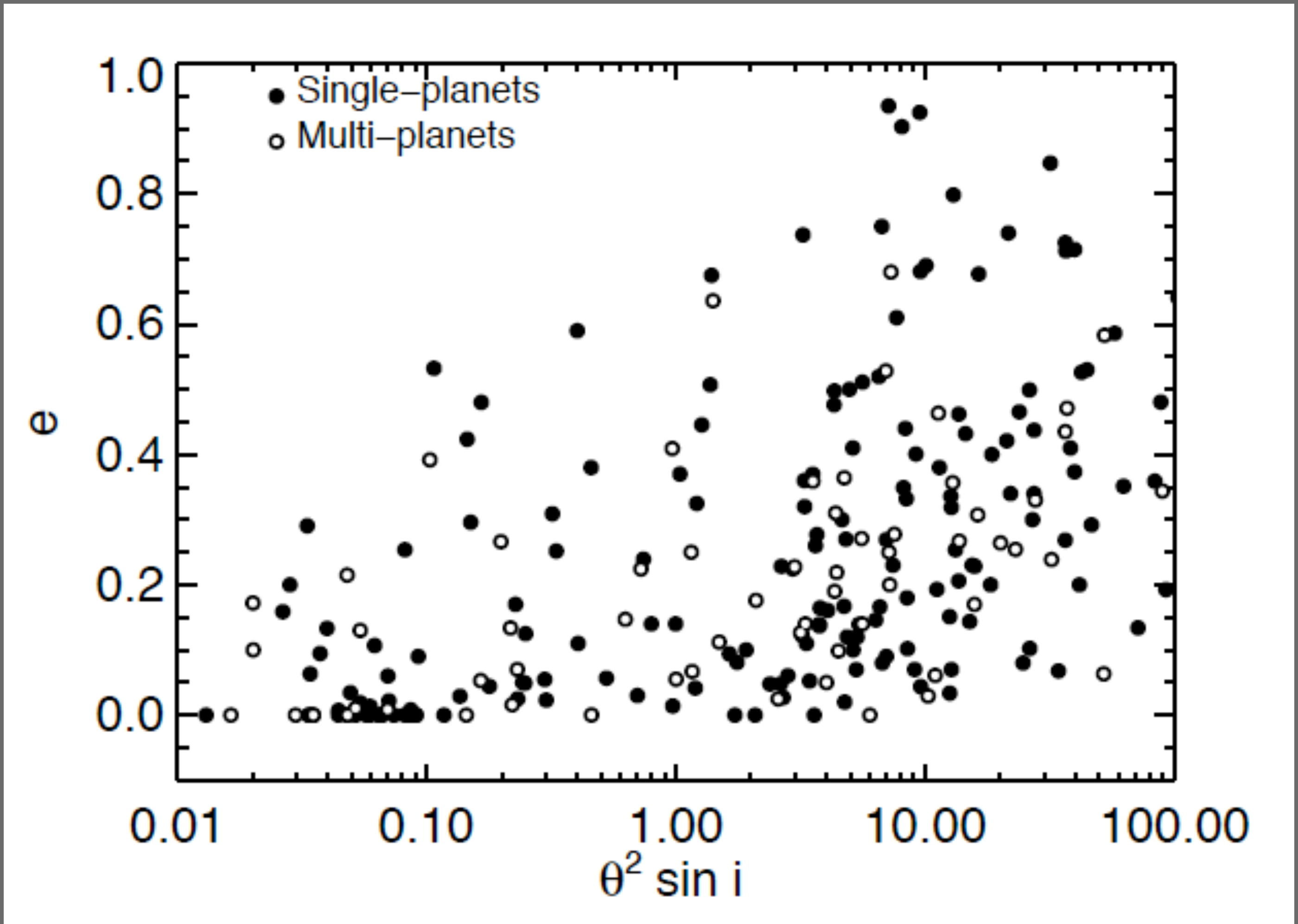

*Chatterjee et al. ‘08*

*Juric & Tremaine ‘08*



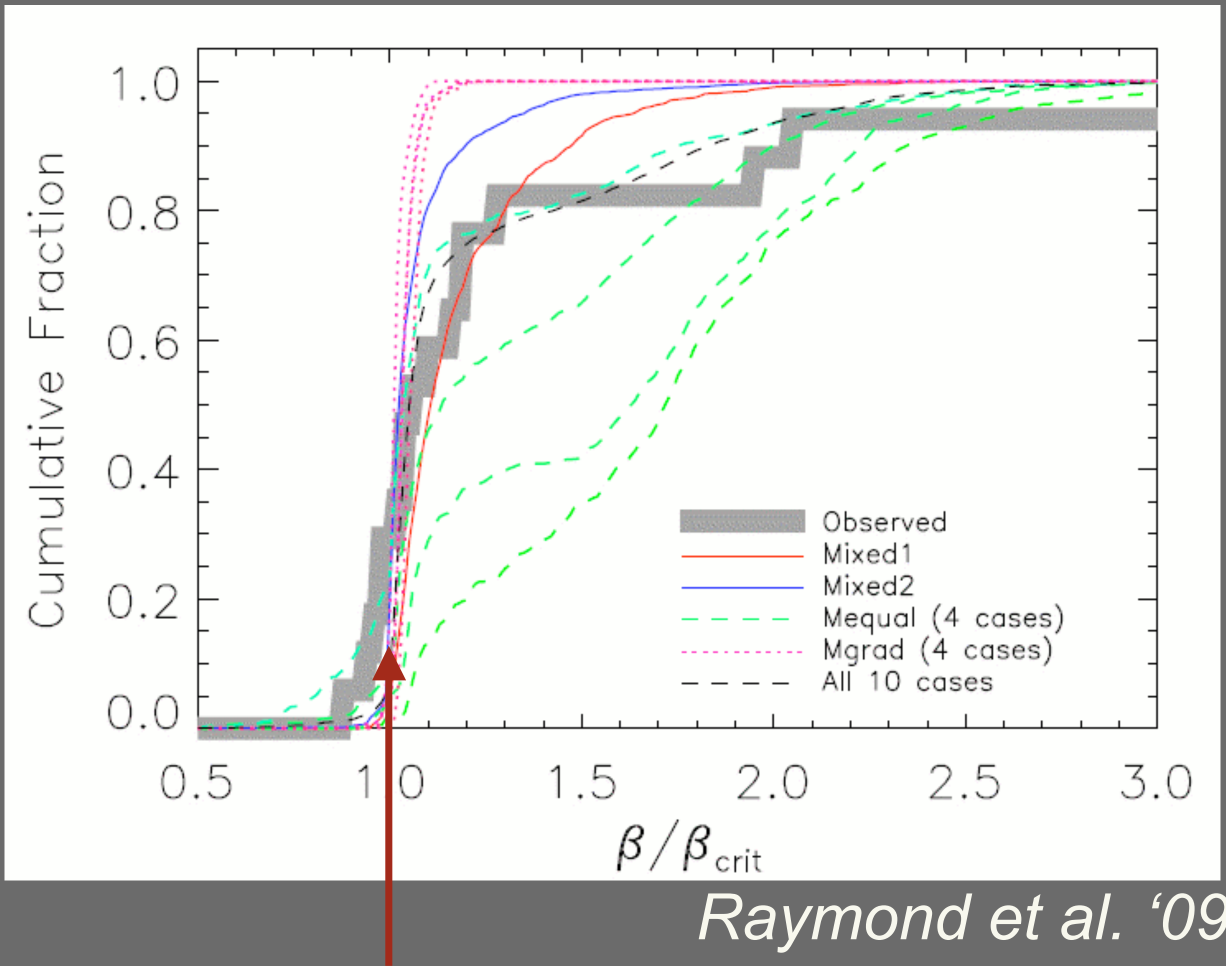

Not universal, but reasonable diversity of unstable initial conditions evolve similarly *(Chatterjee et al. ‘08; Juric & Tremaine ‘08; Ford & Rasio ‘08; Raymond et al. ‘08)*

# Statistical evidence for scattering




Correlation of eccentricity with $\theta = v_{esc} / v_K$ is consistent with scattering *(Ford & Rasio '08; Wright et al. '09)*

# Statistical evidence for scattering




Distribution of separations of multiple-planet systems *in units of minimum needed for Hill stability*

c.f. Gladman '93; after Marchal & Bozis '82

*Raymond et al. '09*

Observed and simulated systems cluster near minimum separation needed for stability

# But: completely different scenarios possible

- most eccentricities (up to e ~ 0.3-0.4) generated by **gas disk** excitation (plausible: see D'Angelo et al. '06; Moorhead & Adams '08 for recent perspectives on uncertainties)
- high e tail generated by (e.g.) Kozai which also yields highly inclined hot Jupiters

Are there weaknesses to the planet-planet scattering story?

# Physical collisions: where are you?

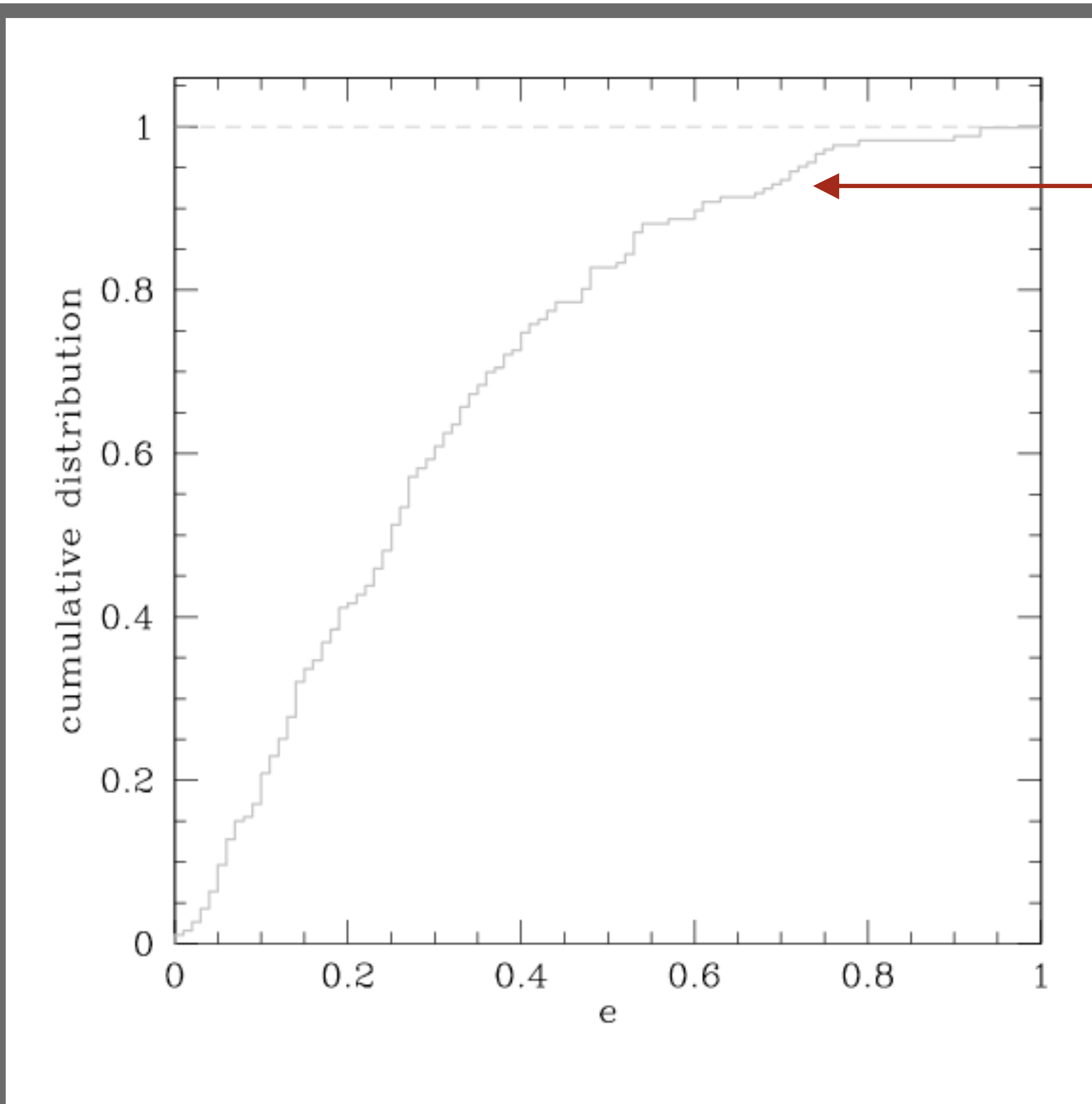
Expect radial variation in the eccentricity distribution:

- fraction of instabilities that lead to physical collisions goes up as orbital radius decreases (high $v_K$ / $v_{esc}$)
- 2 planets collide from low e orbits: merger also has low e

*c.f. Ford, Havlickova & Rasio (2001):*

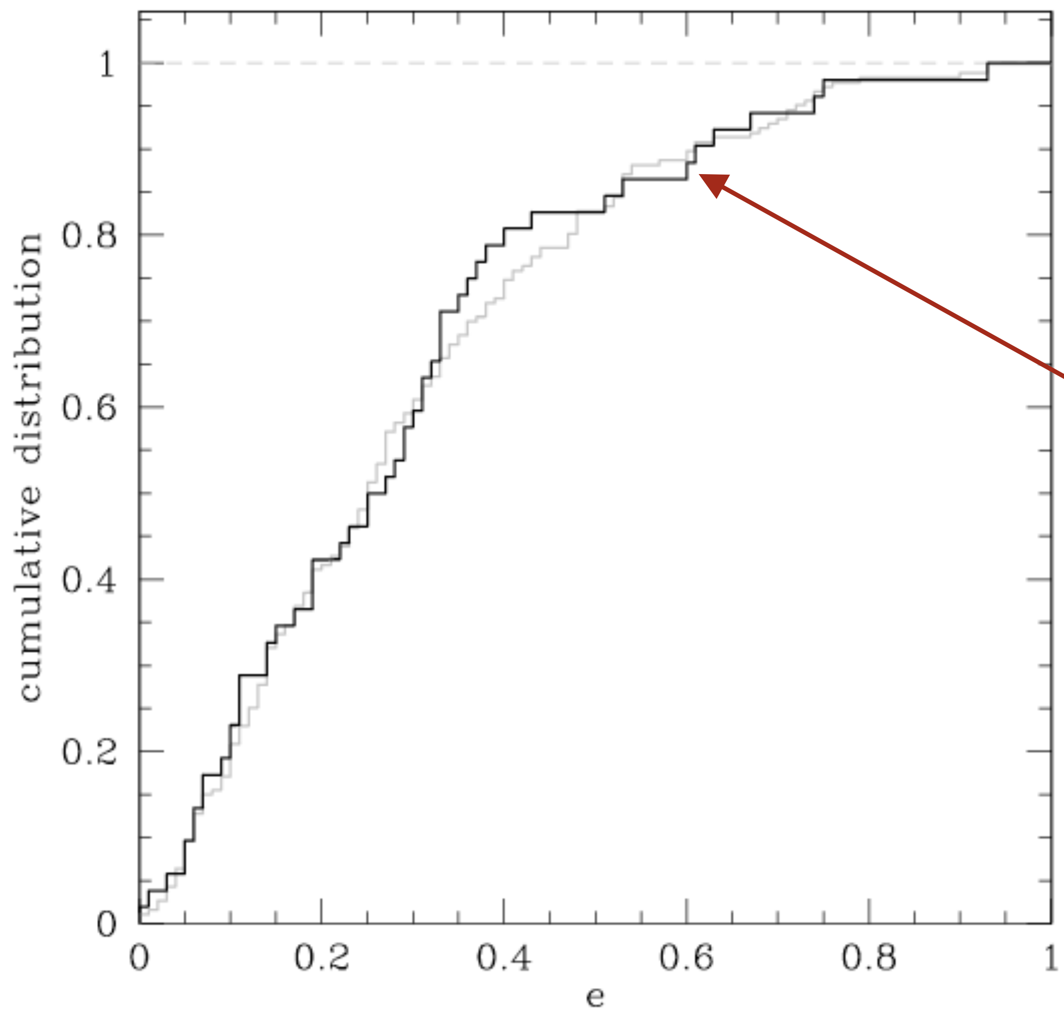
> "While highly eccentric orbits can be produced naturally by these interactions, collisions between the two planets, which occur frequently in the range of observed semimajor axes, would result in many more nearly circular orbits than in the observed sample."

Original concern applied to equal mass planet systems, but expect (weaker) effect generally unless significant initial eccentricity…




Observed distribution (excluding close-in hot Jupiters) of all planets

*No observed dependence* of eccentricity on orbital radius (e.g. Ford & Rasio 2008)




Observed distribution (excluding close-in hot Jupiters) of all planets

Planets with:
0.25 AU < a < 1 AU

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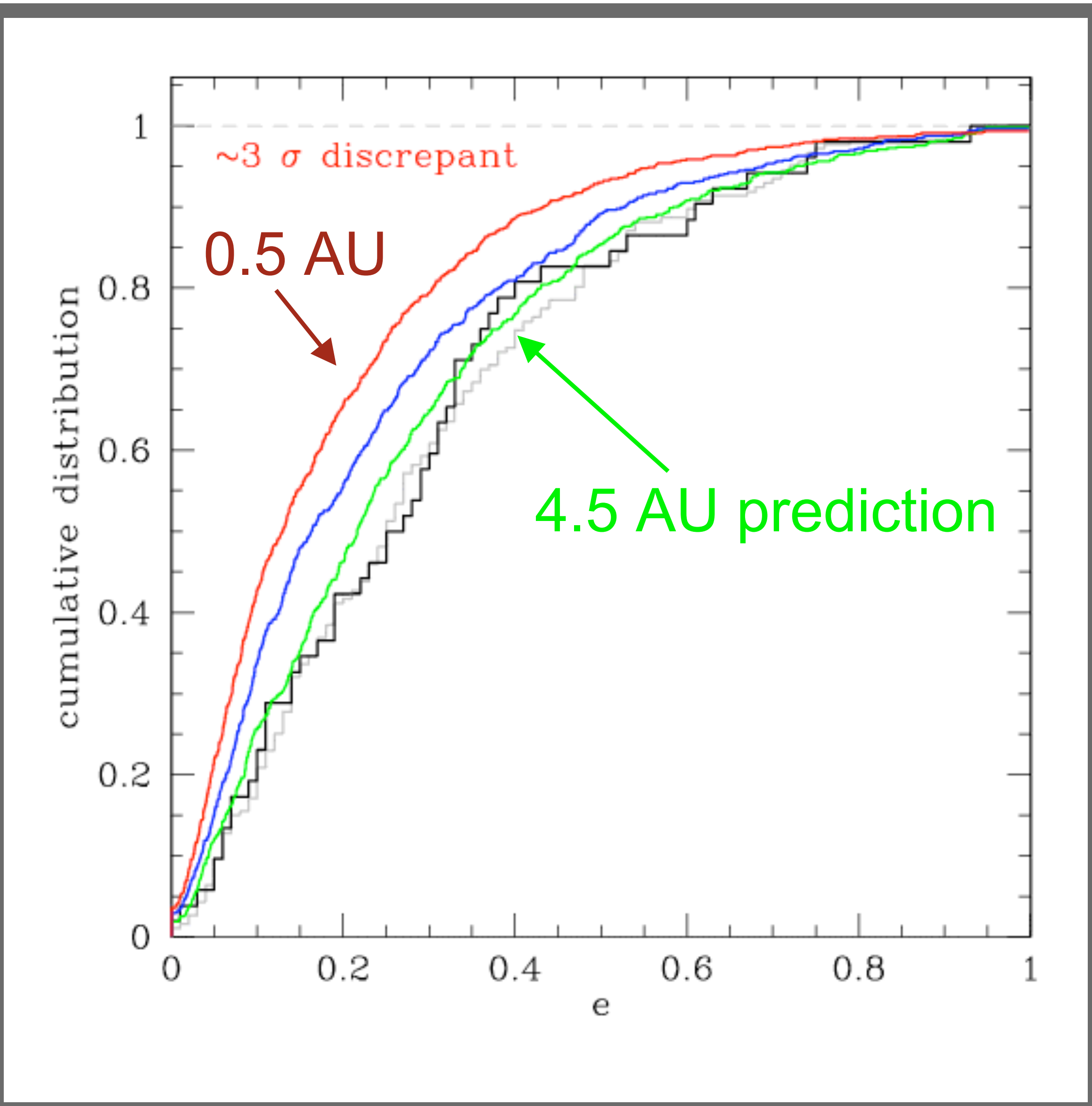


Observed distribution (excluding close-in hot Jupiters) of all planets

Planets with:
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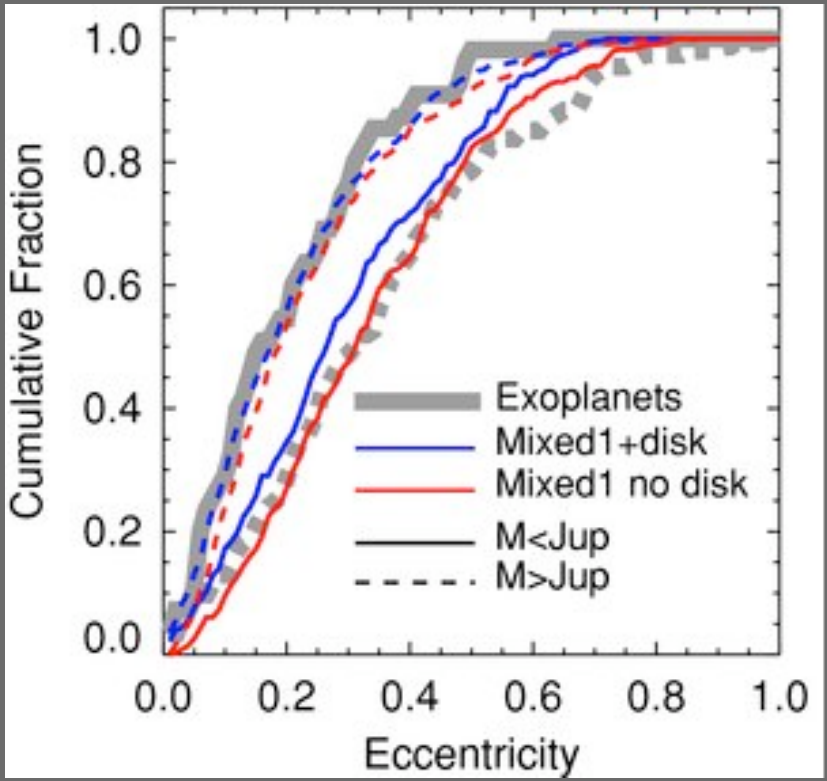
Various 3-planet scattering models are disfavored at modest significance (2.5 - 3$\sigma$) from comparison to small radius sample, *assuming* the observed eccentricities are unbiased

# Mass-eccentricity correlation

More massive planets have higher eccentricity than less massive planets at moderate significance *(Wright et al. 09)*




Good news: scattering predicts the right magnitude of the effect

Bad news: sign is wrong… (easier to excite the eccentricity of a lower mass body)

*Raymond, Armitage & Gorelick (2010)*

Can reverse “natural” prediction: require that masses of planets in individual systems are strongly correlated (plausible?)

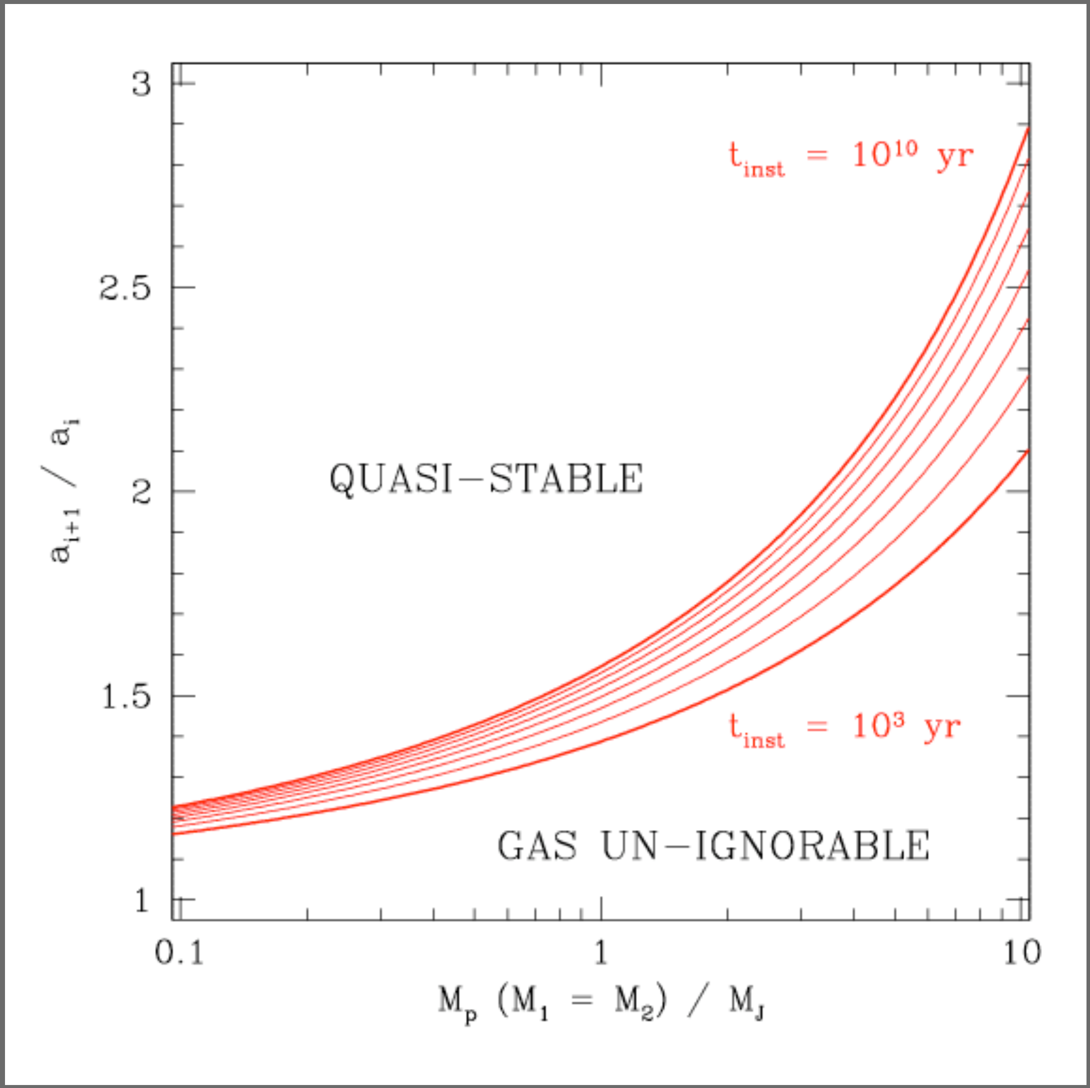
# But what does it mean?

Not a complete theory: “not obvious” that early phase of gas dominated dynamics separable from subsequent purely N-body phase (Ed Thommes’ talk; Moorhead & Adams 2006; Moeckel et al. ‘08…)

Qualitative constraints:

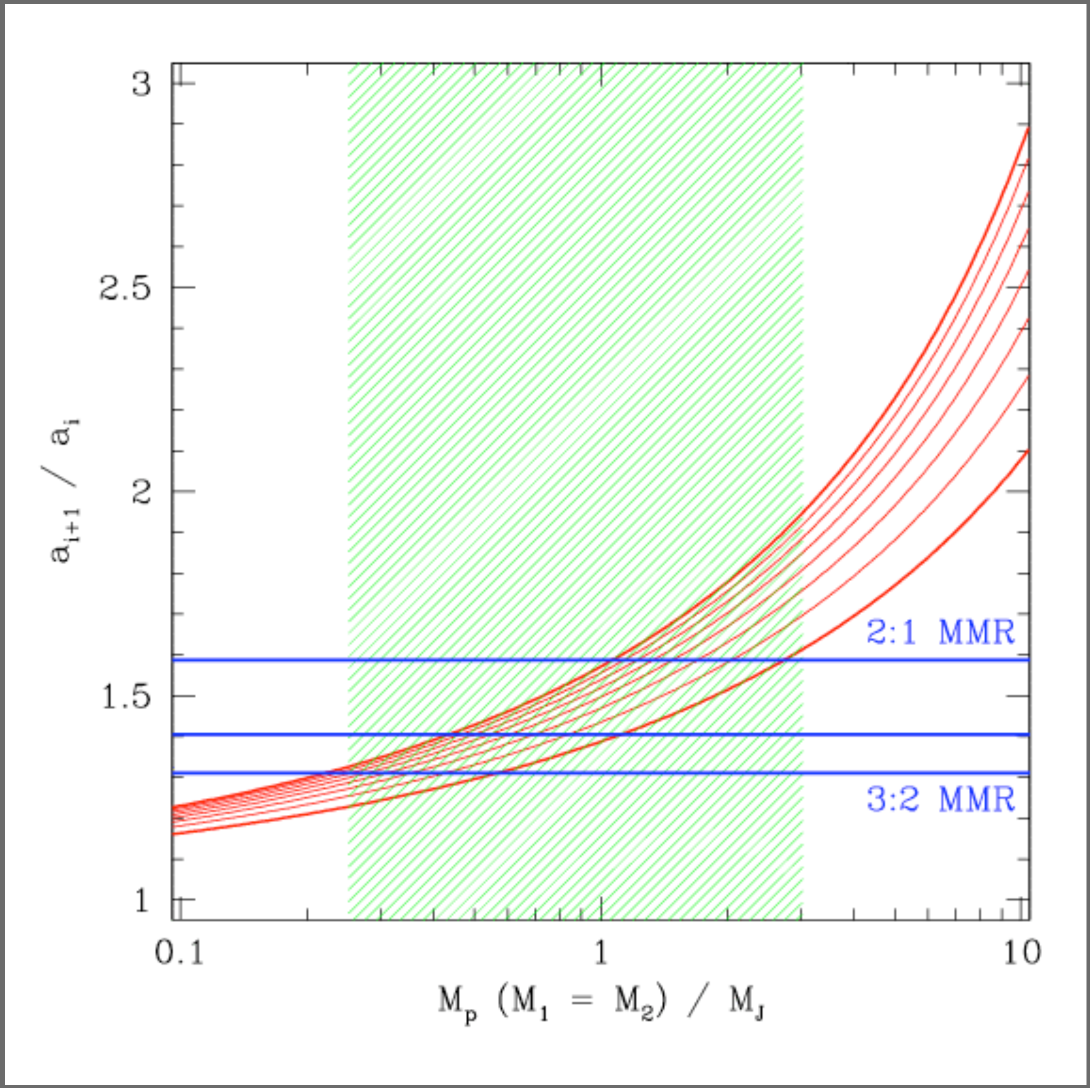
- require that multiple cores form, typically grow into a system of at least two (3+ better) massive planets (very plausible)
- separation is such that instability occurs on time scale neither too short (gas *would* matter) nor >> Gyr (???)

# At given mass, Goldilocks instability time scale requires a fairly narrow separation range (but not very narrow as for N=2)



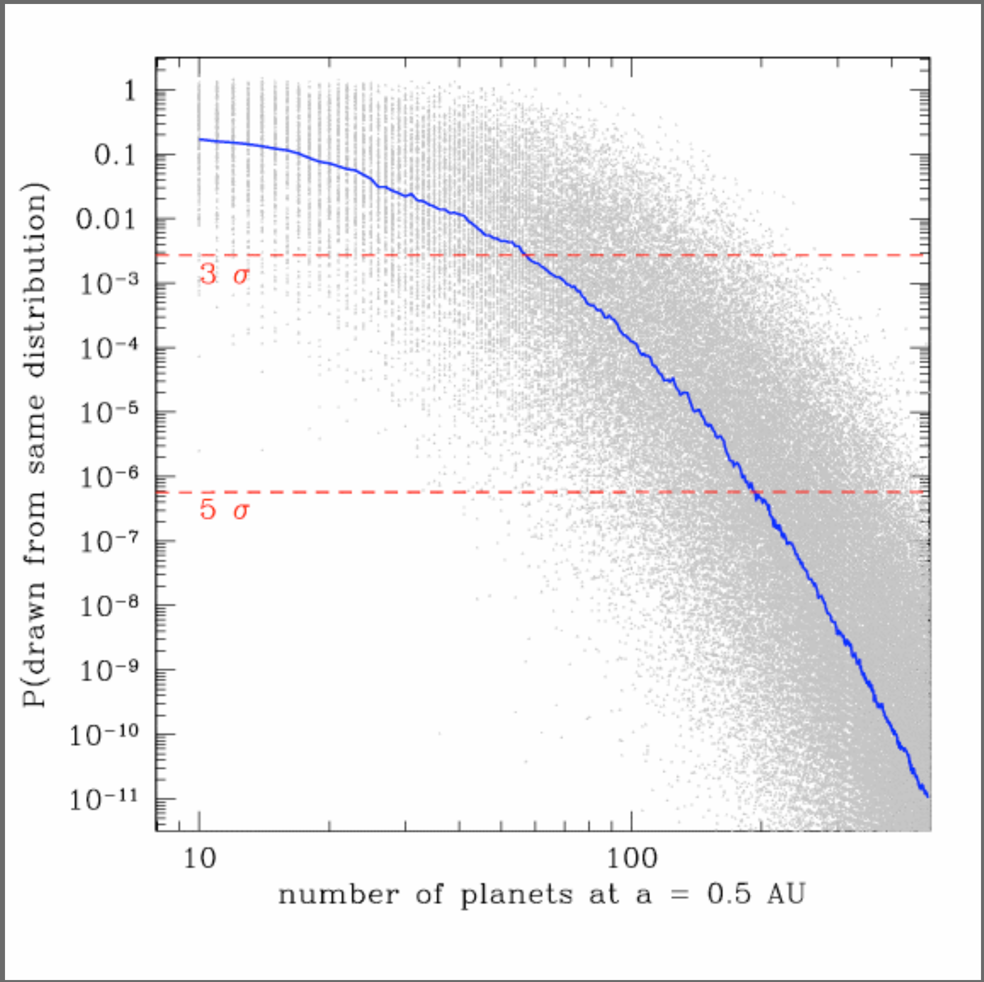

*using median instability time-scale estimates away from mean motion resonance from Chatterjee et al. '08*

Required initial conditions are close to major mean-motion resonances for a broad range of interesting masses…




Exoplanet scattering ***could*** be similar to Solar System models where giant planets form in resonances (e.g. current Nice model)

# Tests: same statistics, but better…

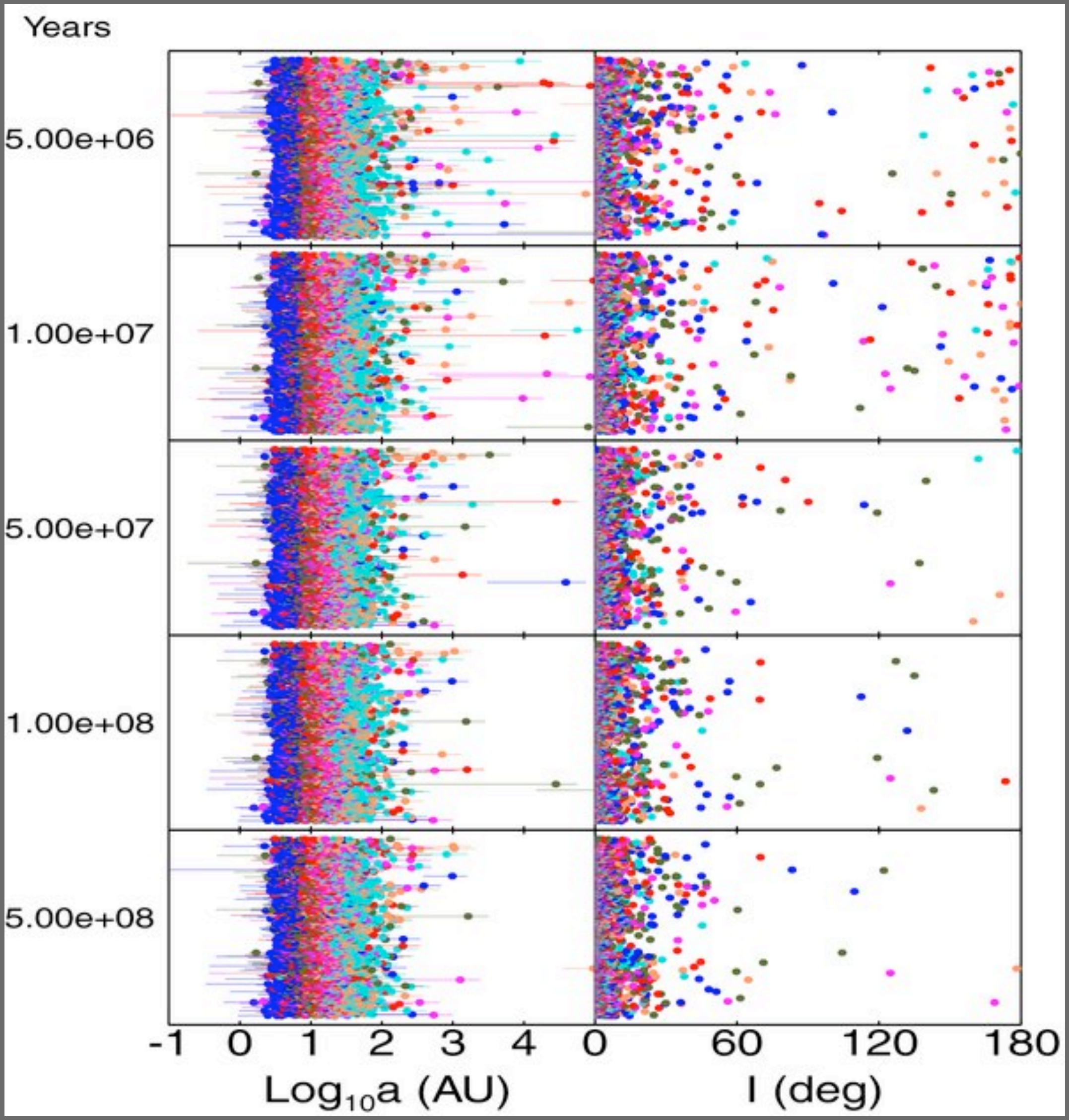



No smoking gun (proof or disproof) of scattering with current sample

Need larger samples, BUT NOT MUCH LARGER, plus **work to determine the selection functions of the surveys** *(e.g. Cumming et al. '08)*

*Predicted* (median) significance for detecting radial dependence of f(e) due to collisions

# Tests: *very* long period planets

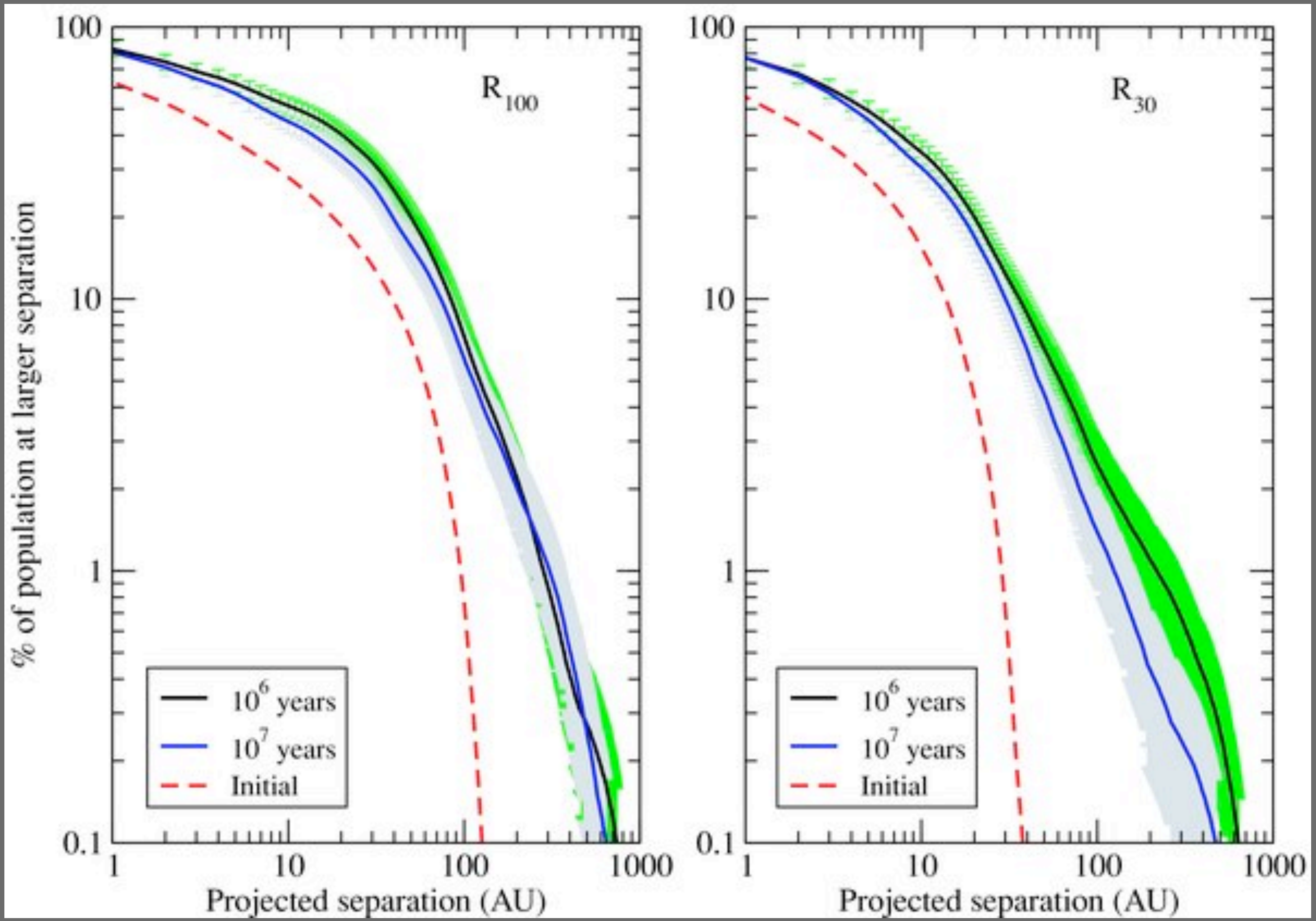



*Veras et al. '09*

Veras, Crepp & Ford (2009); Scharf & Menou (2009)

Scattering predicts some extremely long period (a = $10^3$ - $10^4$ AU) planets in young systems

Highly eccentric (*not* like HR8799) planets waiting to be finally ejected




*Scharf & Menou '09*

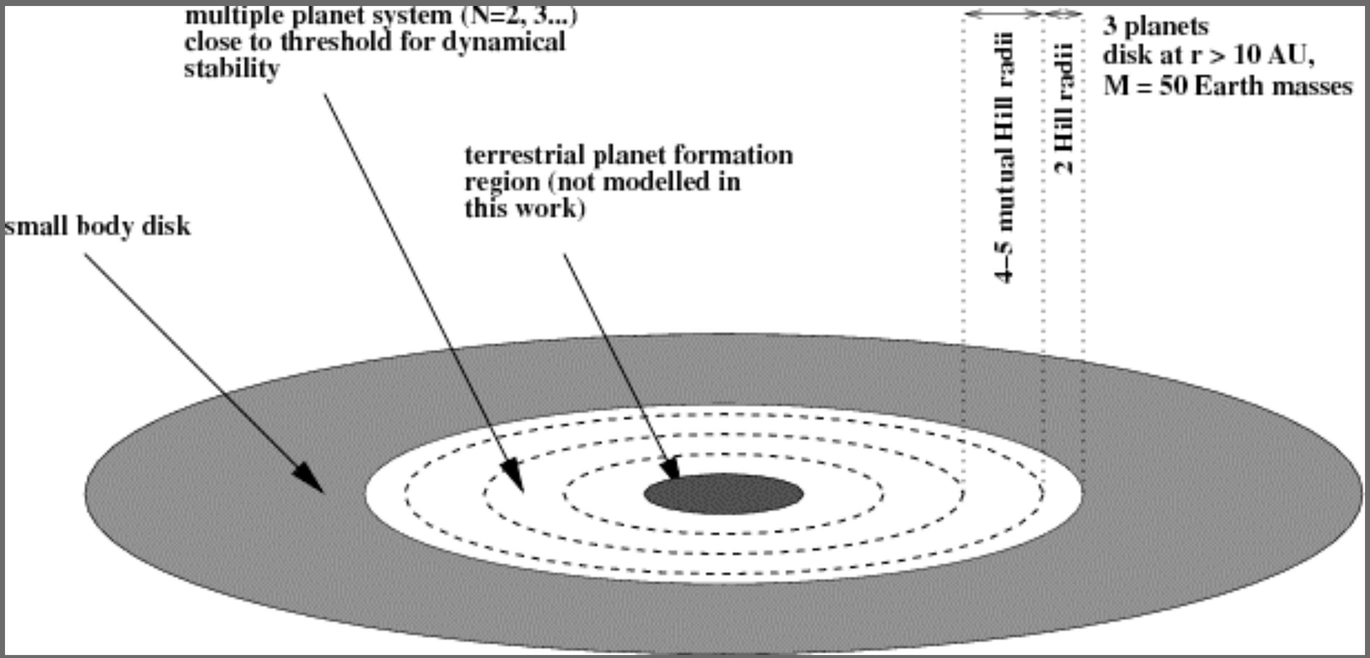
Rare systems: ~1% or less of the population expected at very large radius for ~$10^7$ yr

Single detection of a low mass ($M_J$ not 10 $M_J$), eccentric planet at > $10^2$ AU strong argument for scattering…

# Link to (outer) Solar System dynamics

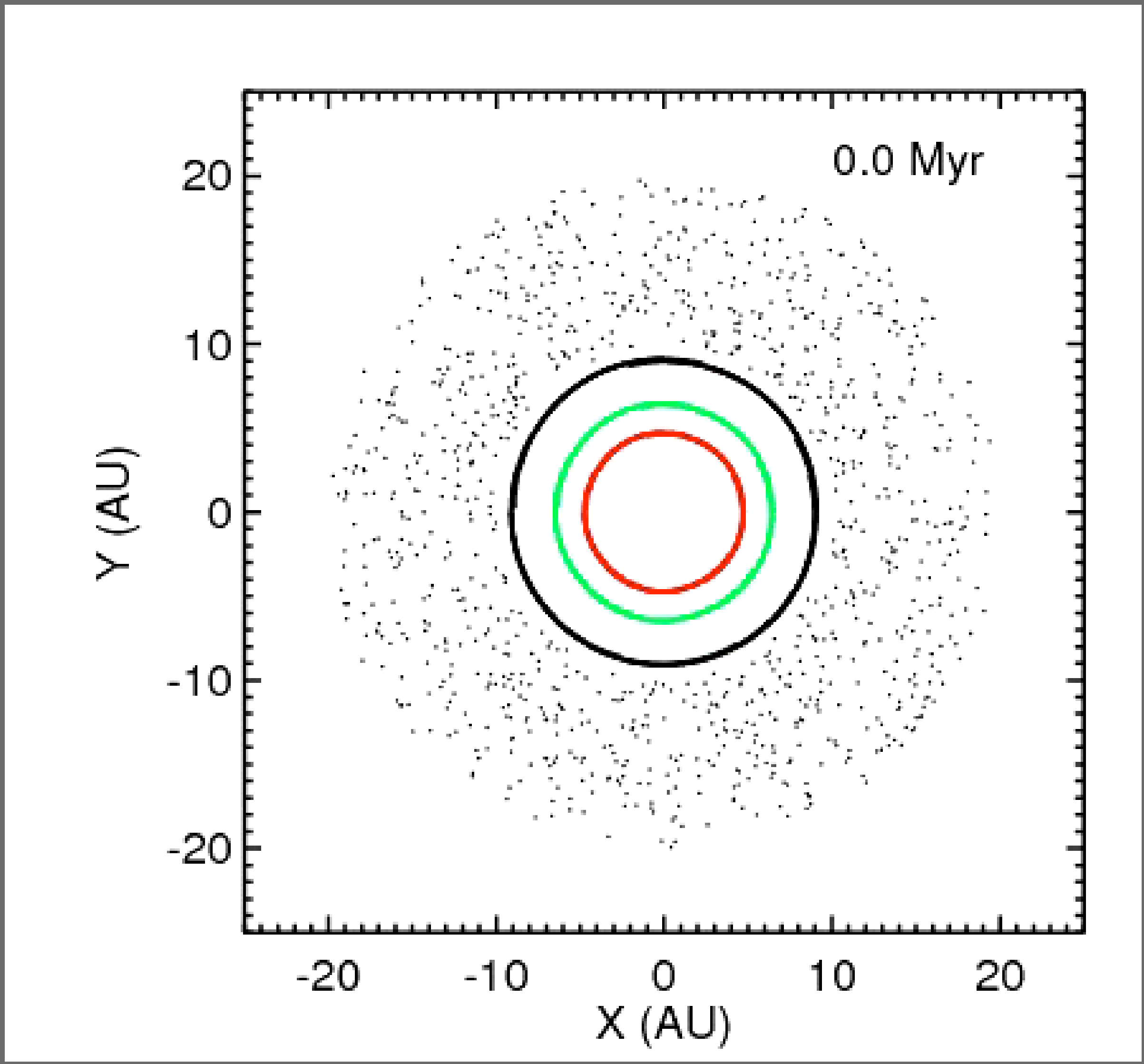
Dynamical influence of *small bodies* thought to be critical to outer Solar System evolution (Malhotra ‘95)

Expect outer disks of debris to be ubiquitous




Planetesimal scattering negligible at small radii (mass of debris within few $r_H << M_P$), but should become important for exoplanet surveys at larger radii than currently probed

# Link to (outer) Solar System dynamics




*Raymond, Armitage & Gorelick (2010)*

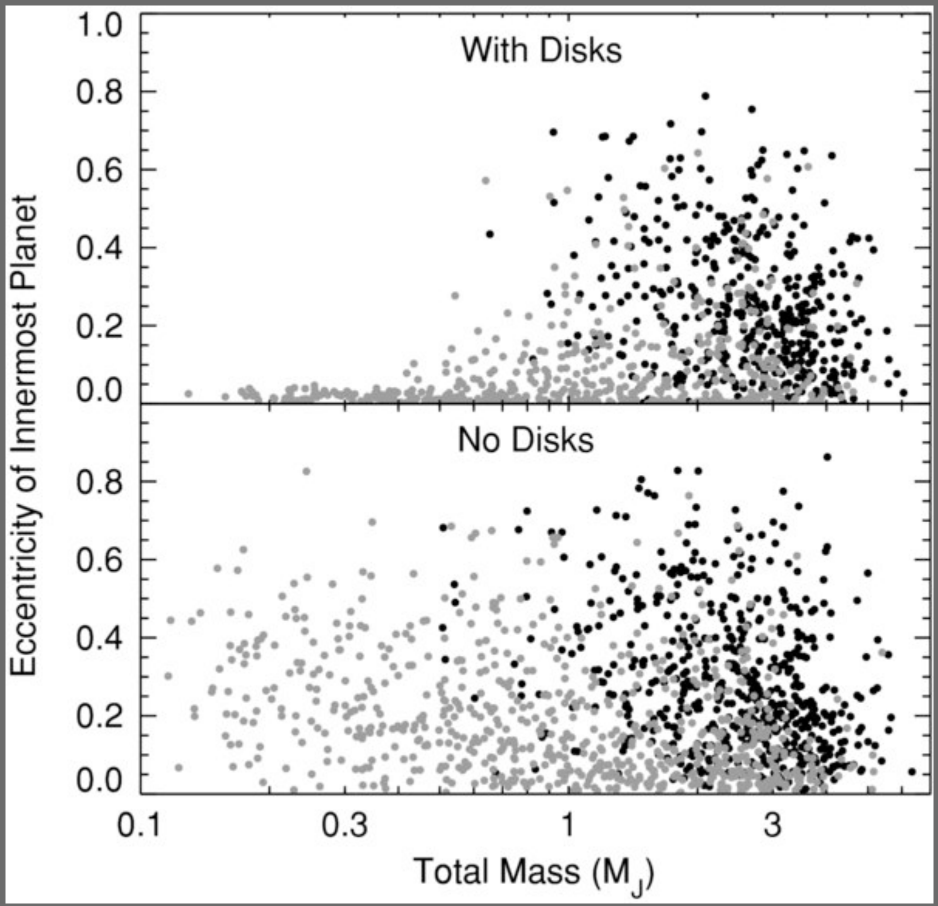
New physics:

- slow converging or diverging migration
- resonance capture
- damping of scattered planets

Ensemble of 5000 integrations of 3 planets + planetesimal disks

# Scattering by planets *plus* planetesimals

Intermediate radii (~10 AU), expect to see systems in which **both** planet-planet and planetesimal scattering are dynamically important




*Raymond et al. (2010)*

Predict:

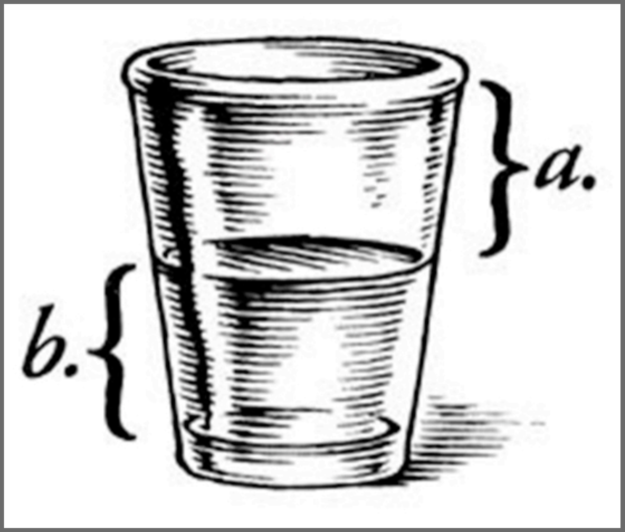
- transition to low e orbits for lower mass planets ($M \sim M_{Sat}$)
- very high resonant fraction for high mass planets (maybe many Laplace-type resonant chains)

Missing link between current exoplanets and outer Solar System

# Summary

Planet-planet scattering involves bold hypothesis (all systems are unstable); makes predictions with ~zero free parameters

No unambiguous evidence for "next order" predicted statistical properties




Think about *disk* excitation + small fraction scattering or Kozai?

Amazing agreement with observed f(e)

Near-term tests require better statistics (x 2), observing very long period planets

Combination with planetesimal scattering: bridge to outer Solar System dynamics