Highly Inclined Planets from Planet-Planet Scattering plus Tidal Damping

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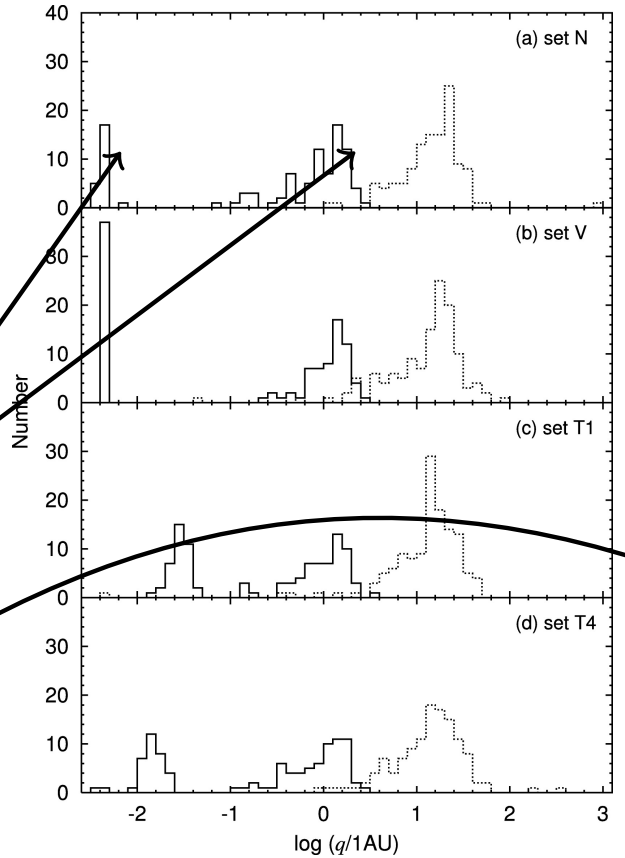
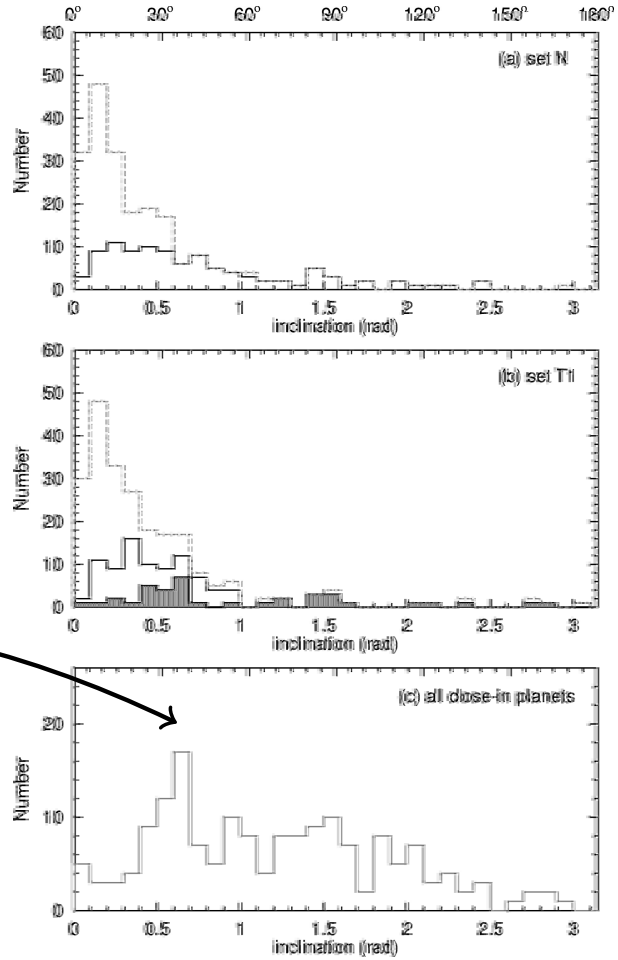
Previous Scattering Results Differ

Nagasawa et al. 2008, 2011

- $a_{1,i} \sim 5.0 au$
- Inner Planet: Solid Line (Double-peaked)
- Fraction $q < 0.1$ au $15\% - 35\%$
- $\sim 70\%$ "close-in" planets $i > 40^\circ$
- Similar results in 2011





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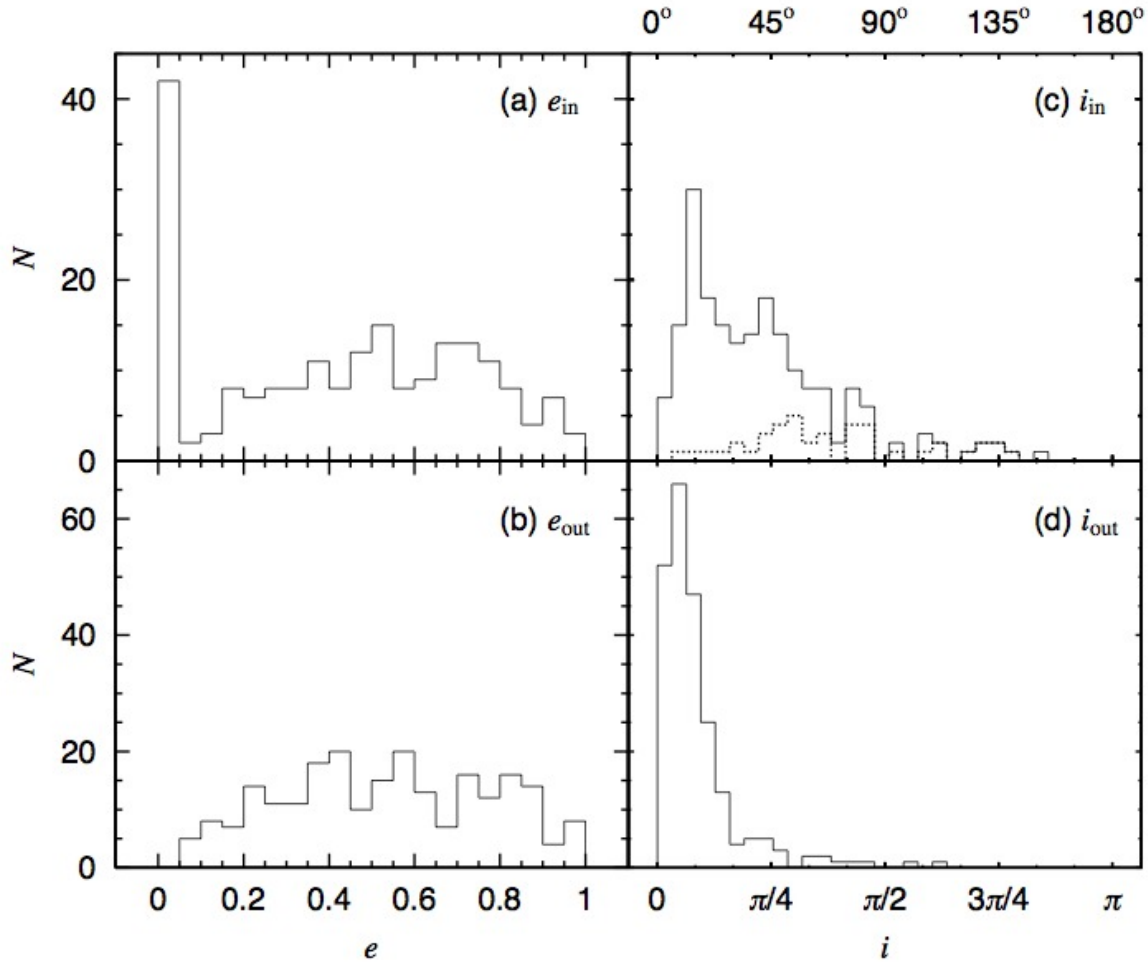
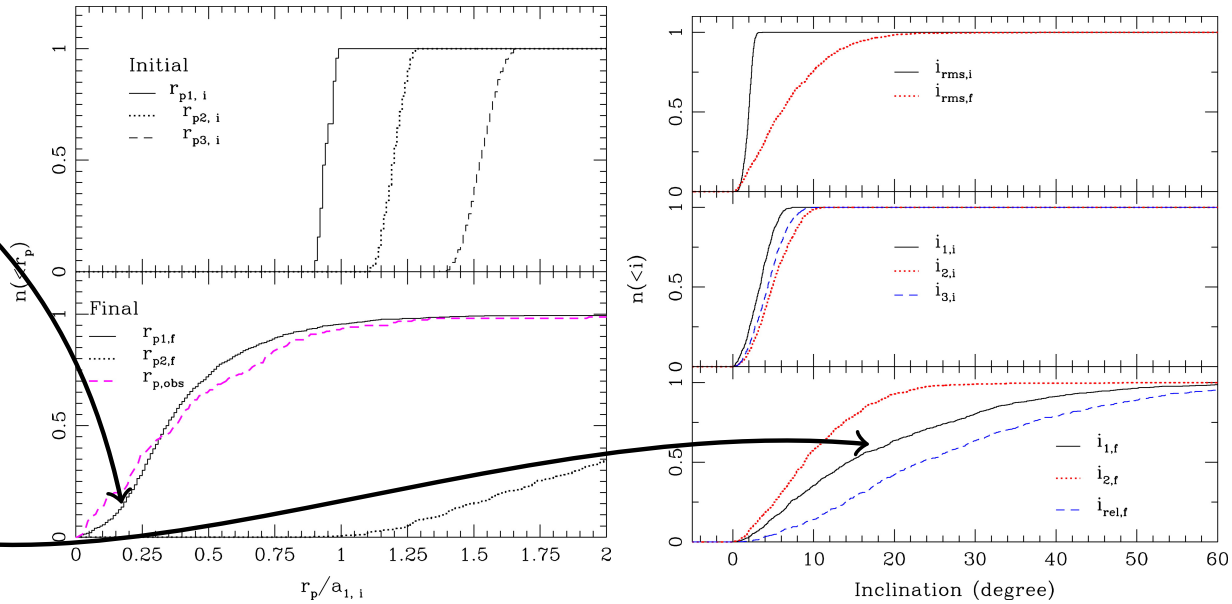


Previous Scattering Results Differ

Chatterjee et al. 2008

- $a_{1,i} \sim 3.0 au$
- $< 5\%$ have $q < 0.1$ au
- $< 10\%$ of inner planets have $i > 40^\circ$
- Similar results from Juric & Tremaine 2008, Raymond et al. 2010, 20011
- At odds with Nagasawa et al.



Basic **Undamped** Simulations: Similar Results From Nagasawa & Chatterjee ICs

Inner Planet: Inclination vs. Pericenter at 10^8 yrs

- $10^3 \times$ Nagasawa ICs ($a_{1,i} \sim 5.0\,au$)
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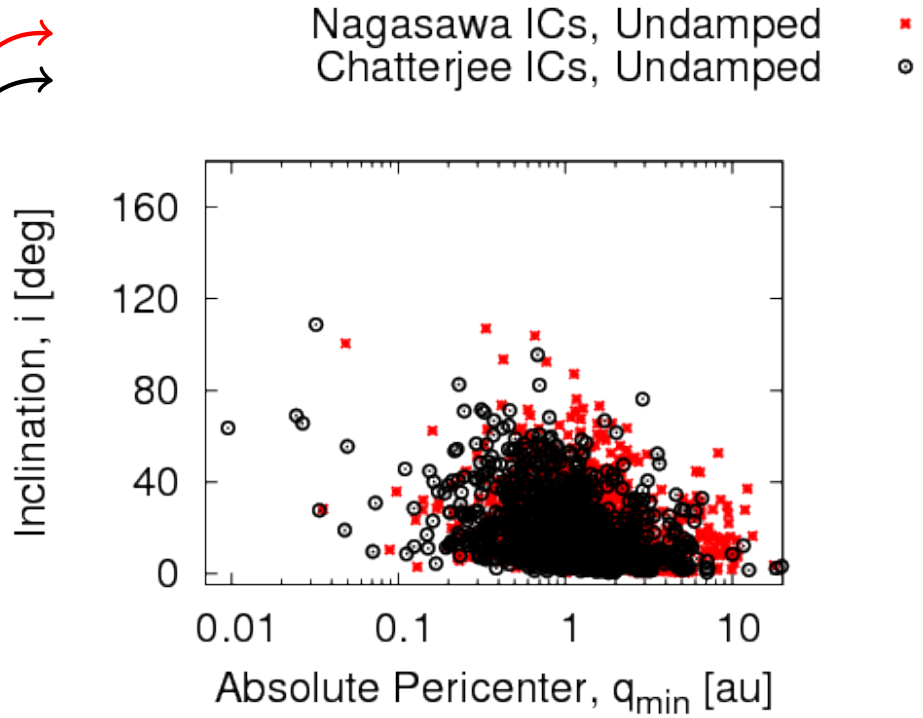

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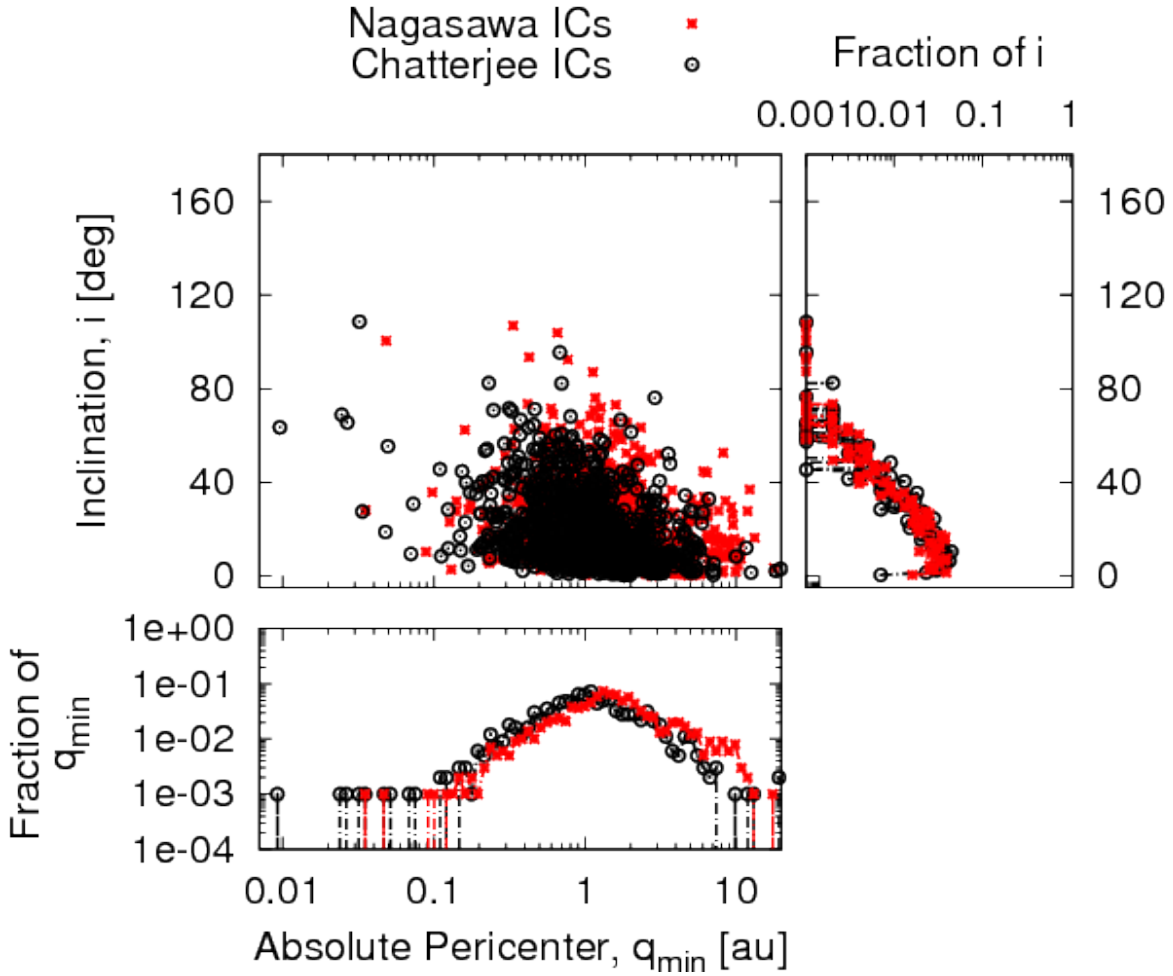

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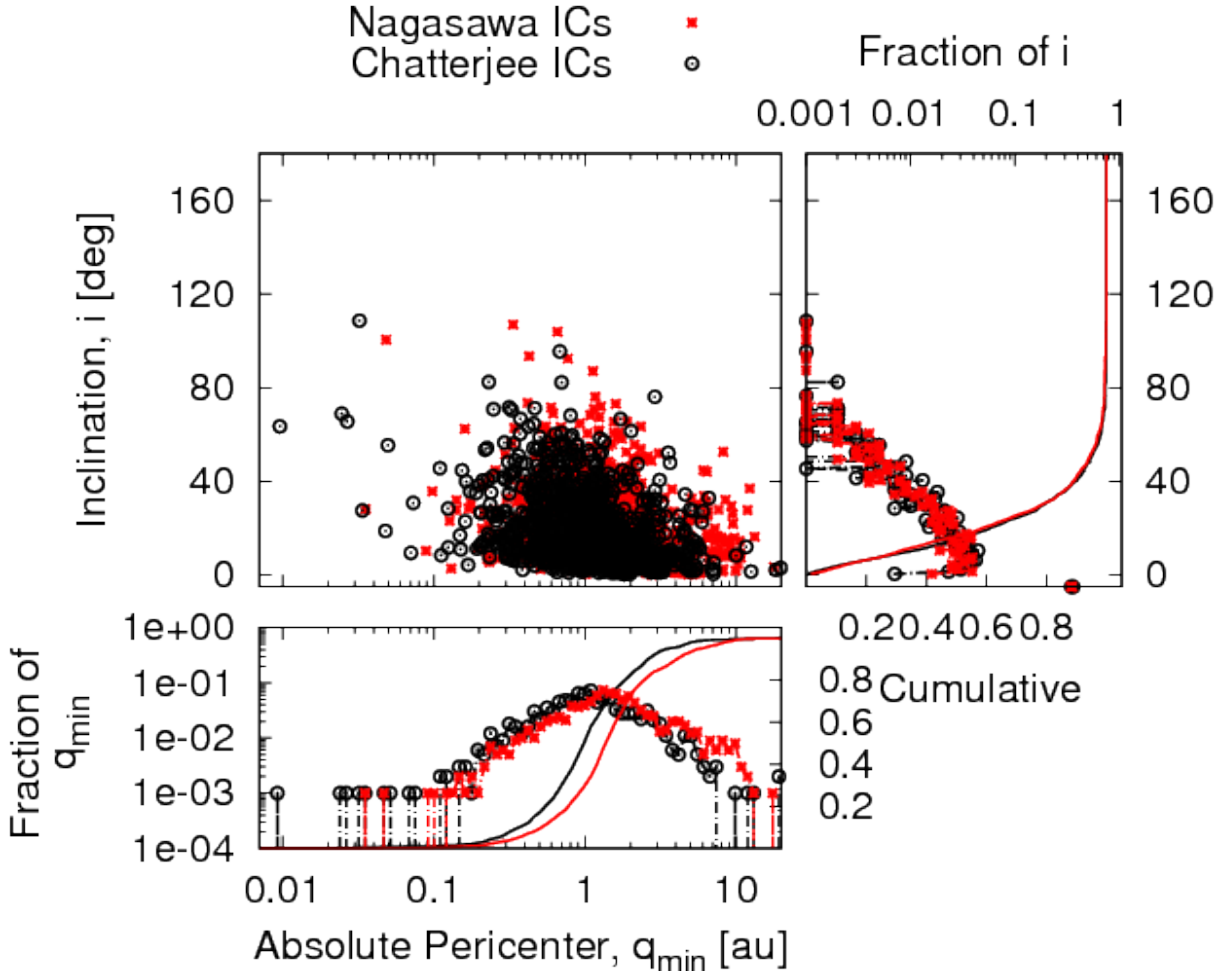

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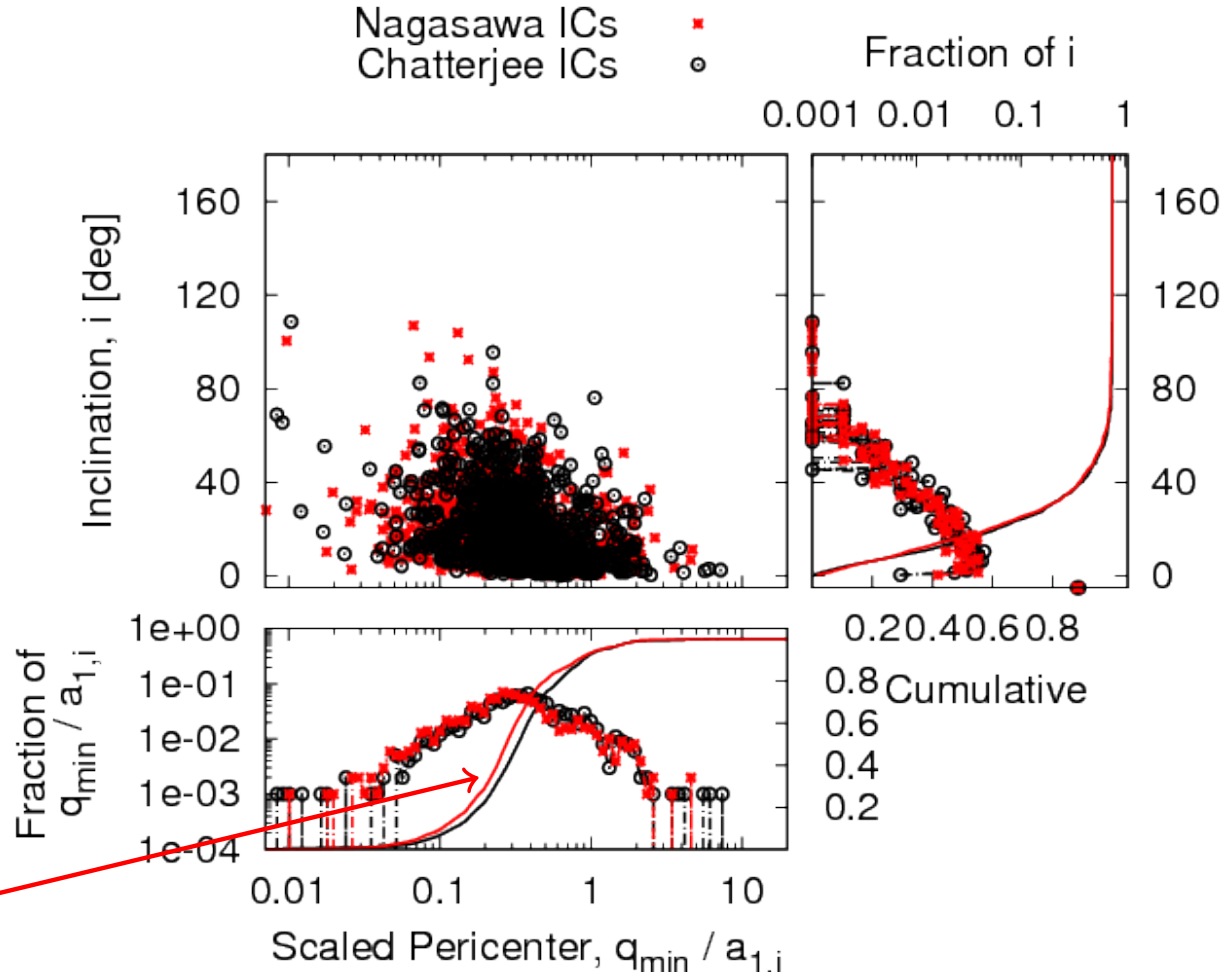
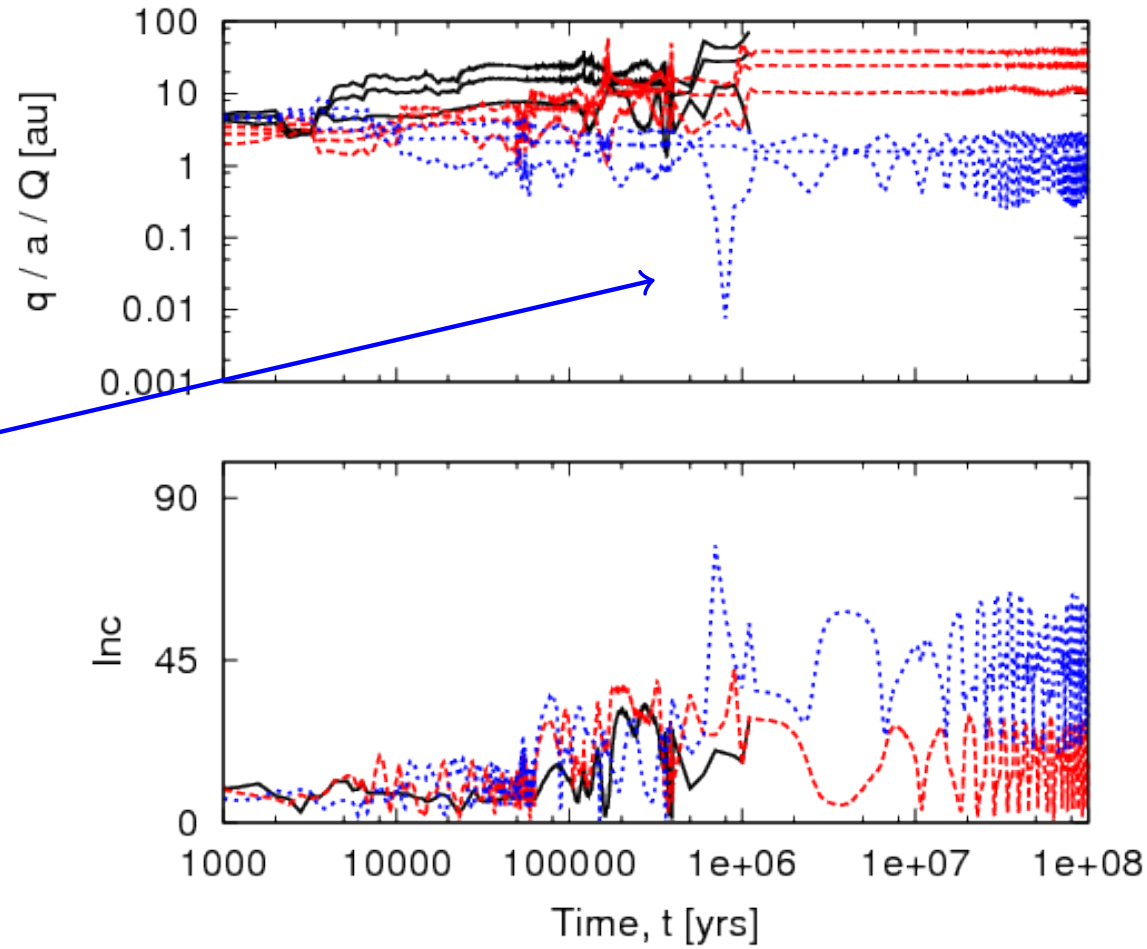


Understanding Scattering Results: Chatterjee ICs

Chatterjee ICs

- Measurements taken at the *end* (10^8 yrs)
- Simulations have a middle
  - Interesting Events
- Time of Minimum Pericenter
  - Distributions differ
- Add Tides
  - Distributions differ



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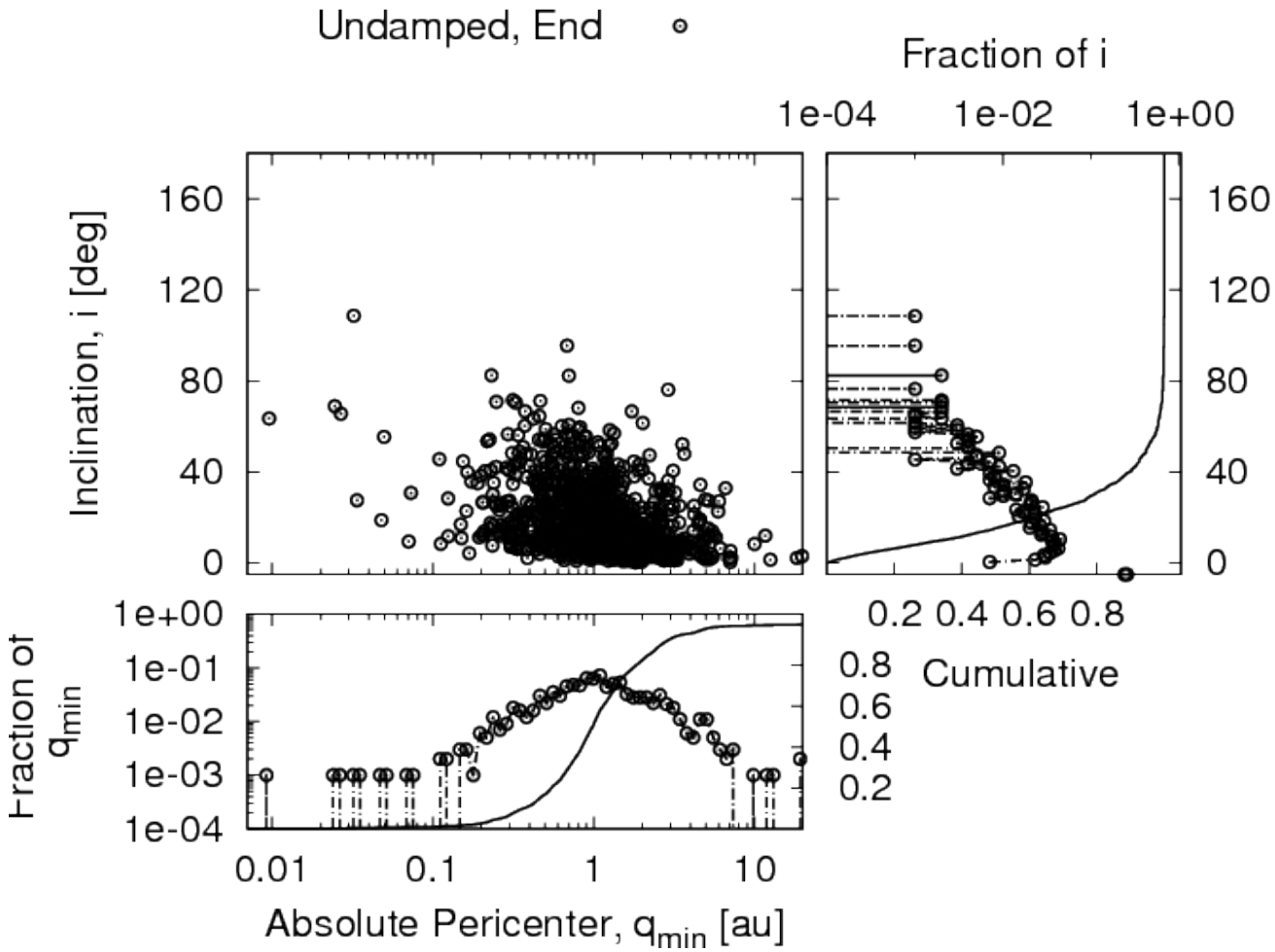

Tidal model essentially as per Nagasawa et al. 2008

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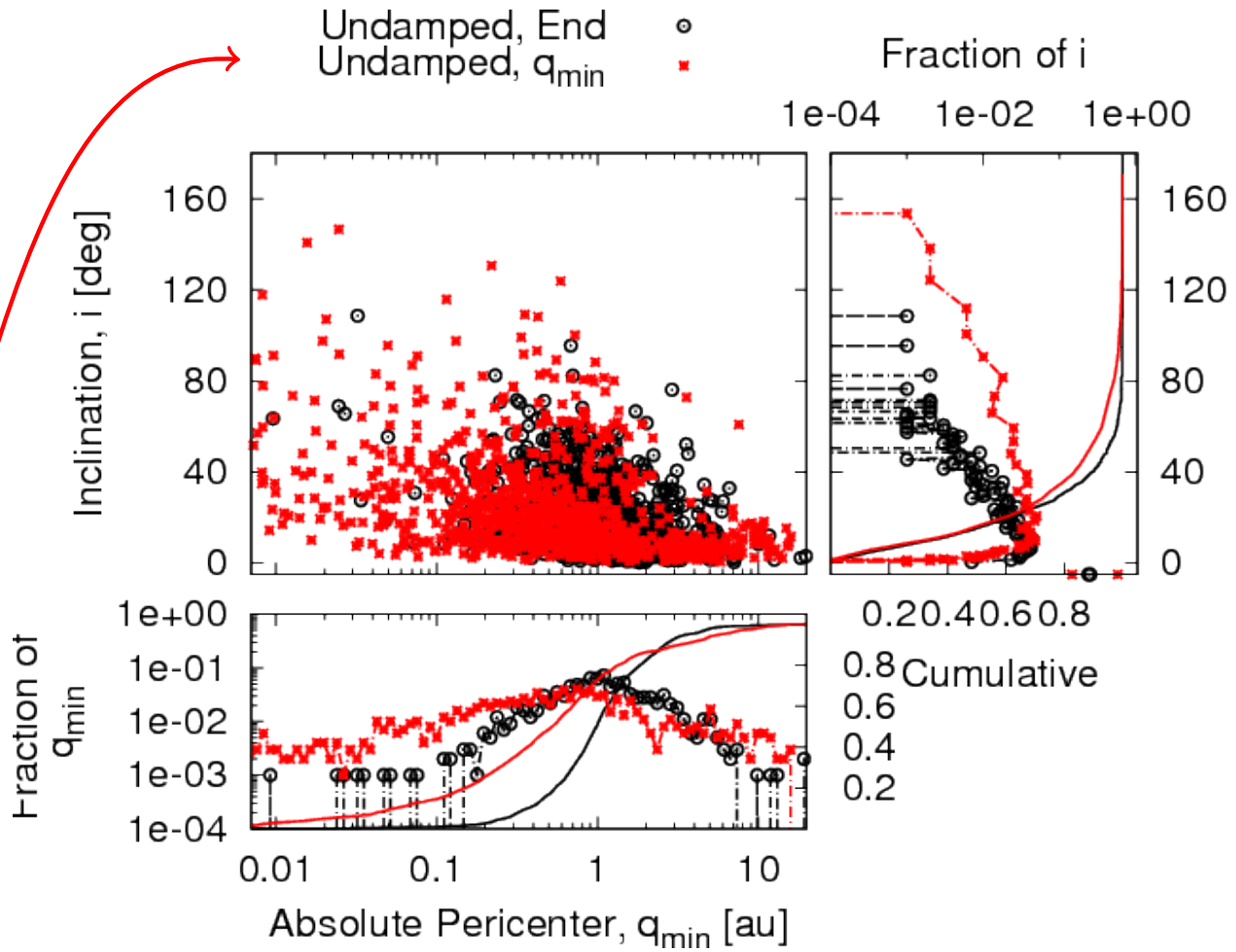

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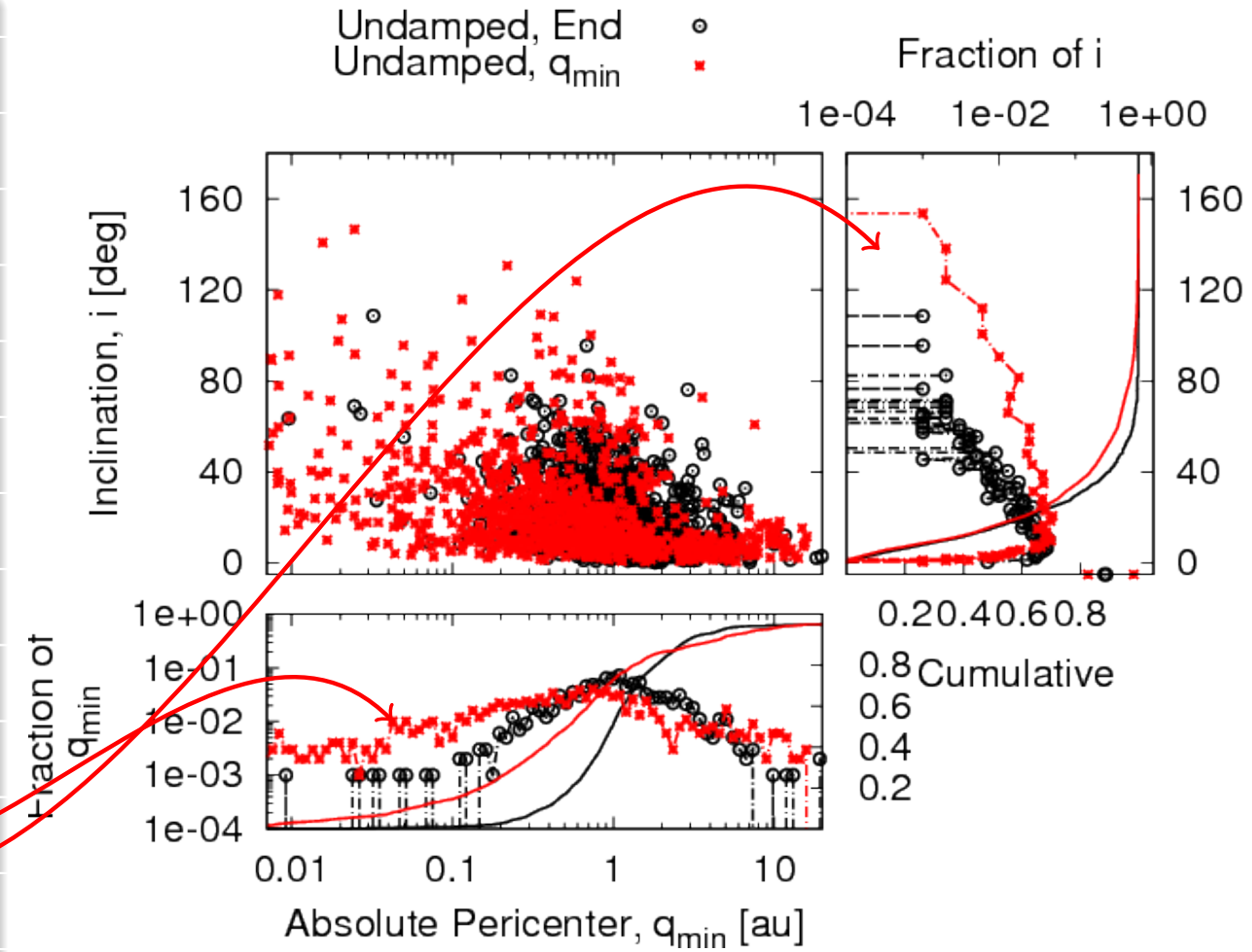

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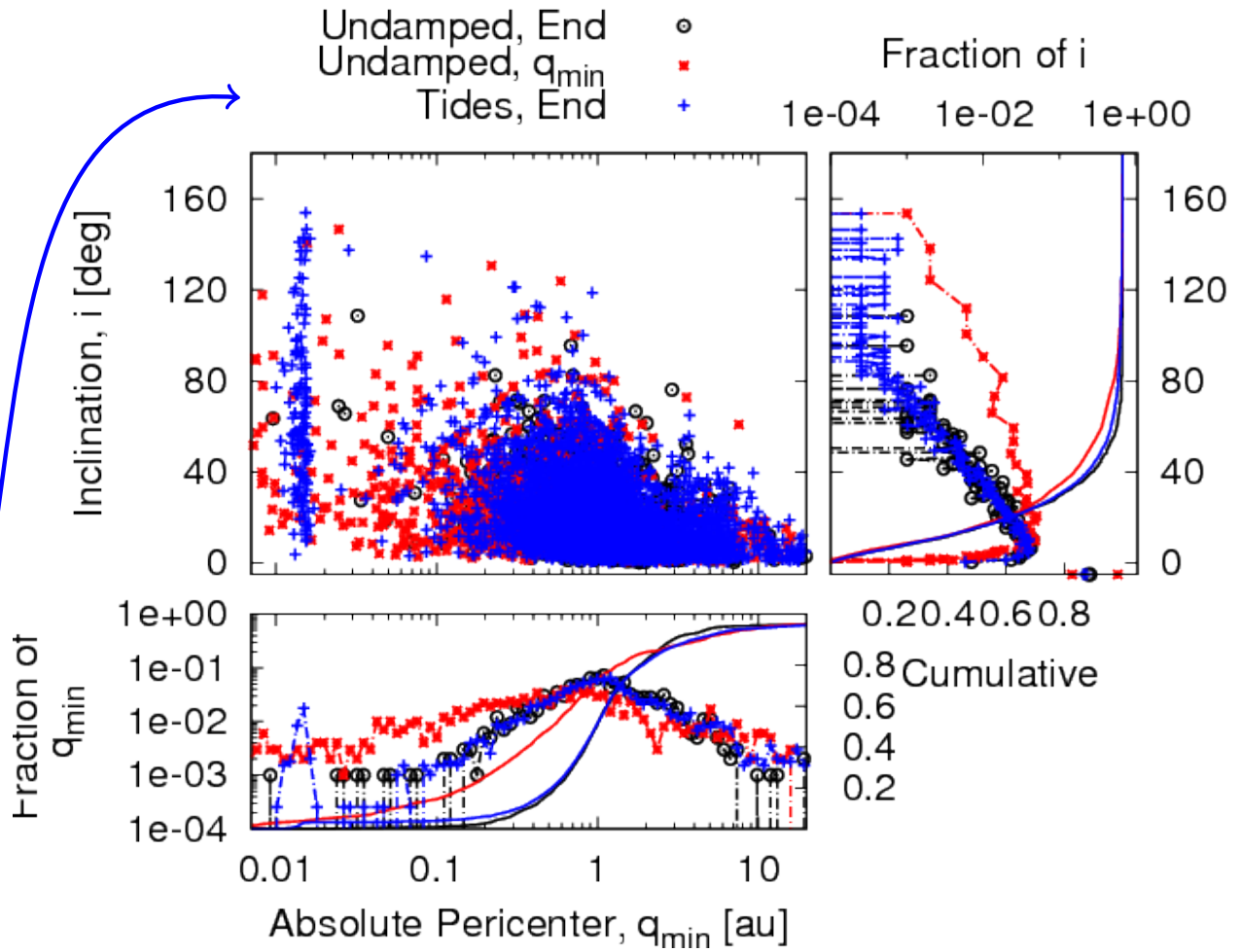

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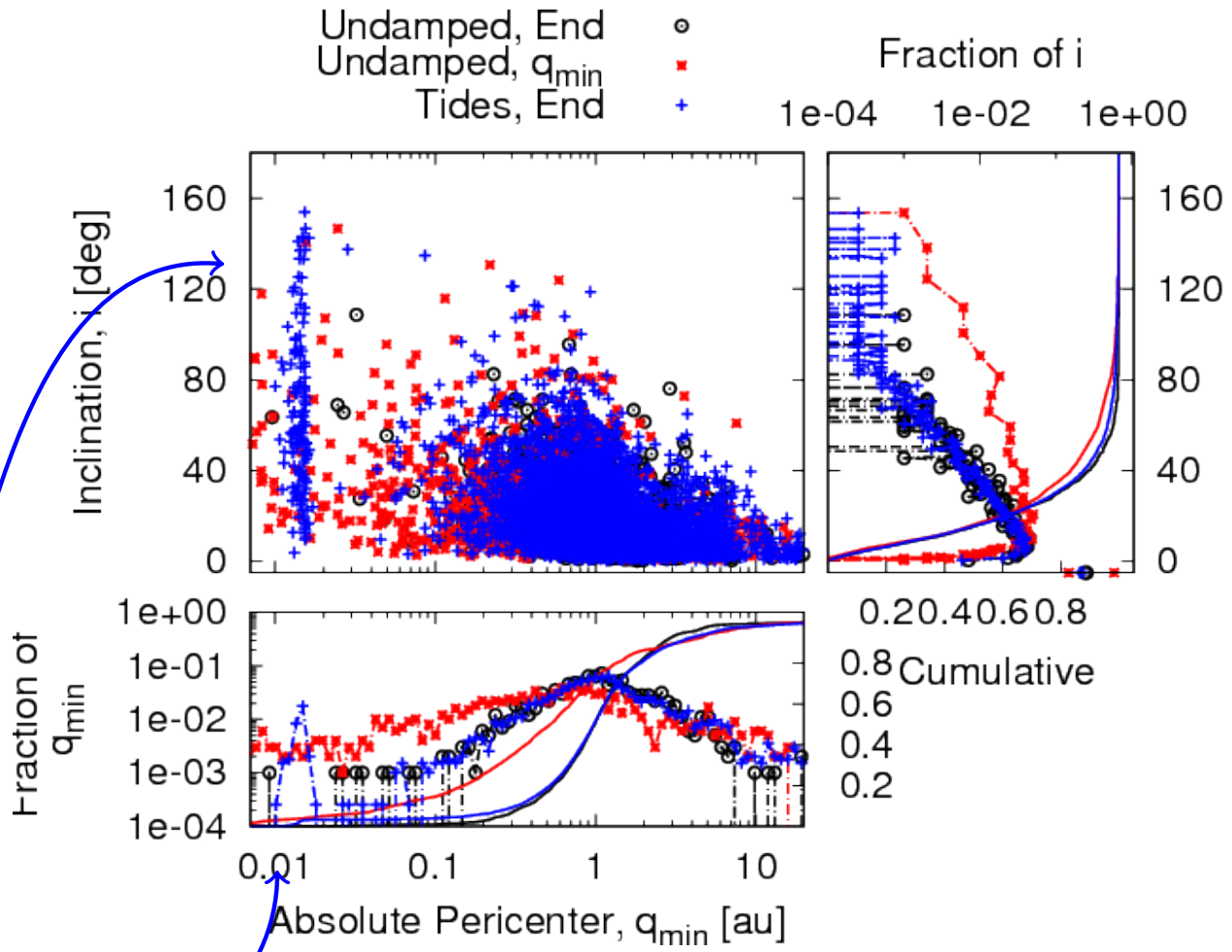

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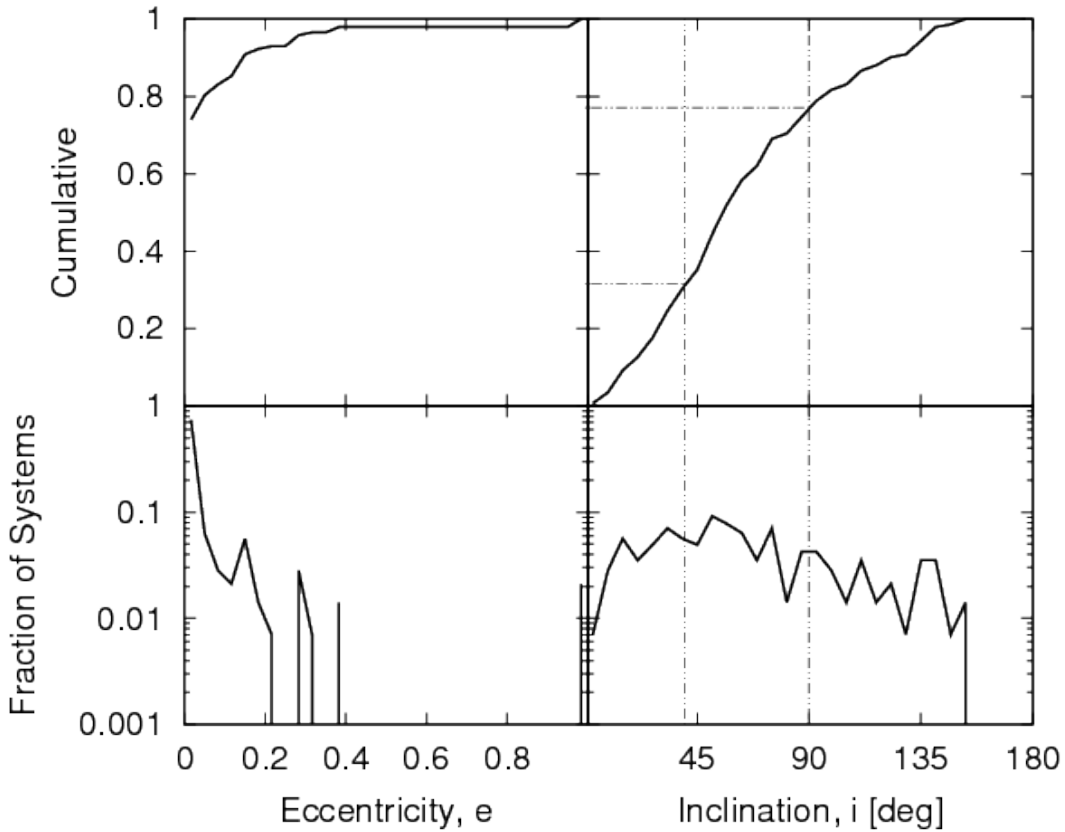
Hot Jupiters: Broad Inclination Distribution

e & i from Planet-planet scattering

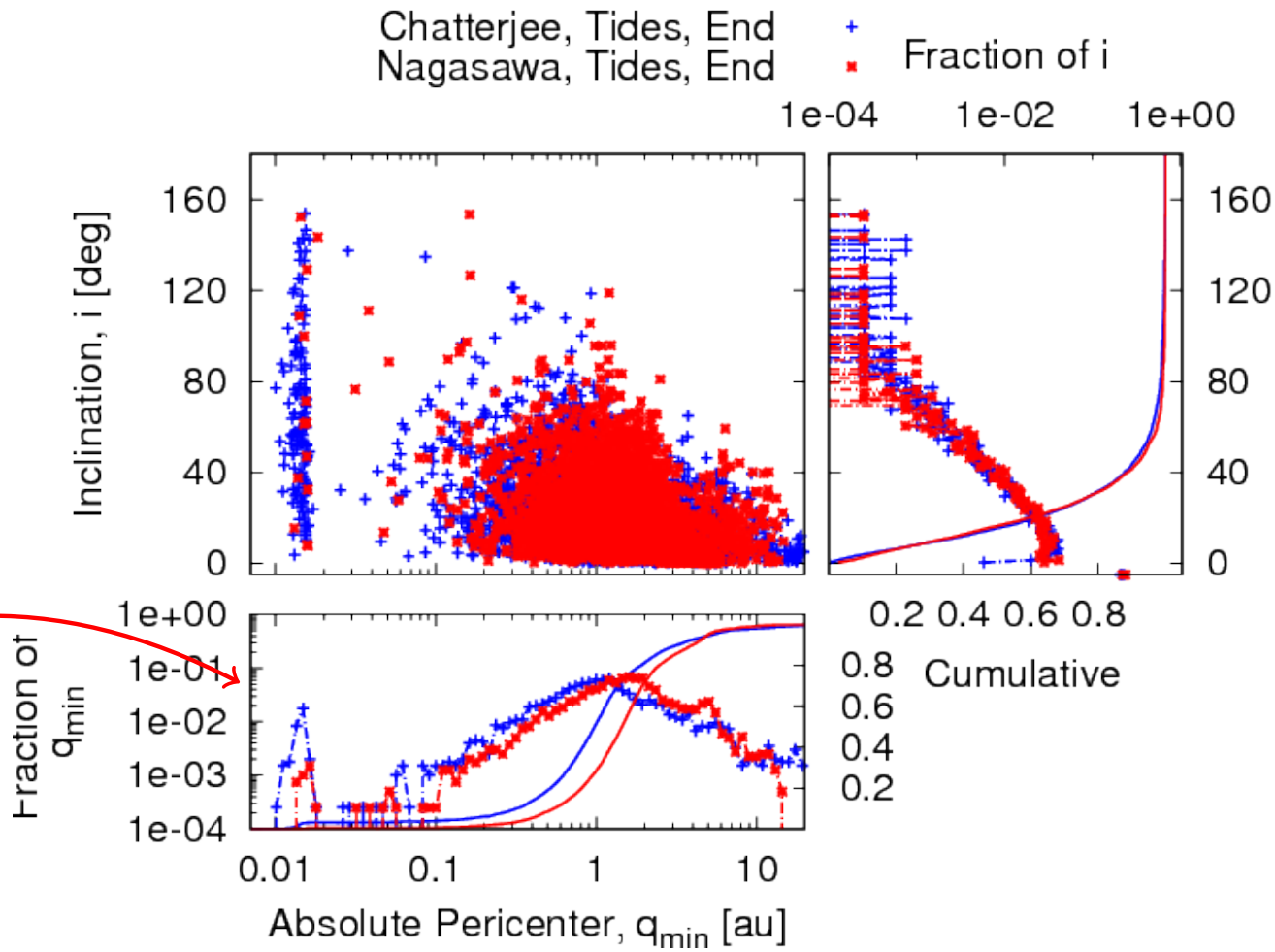
- Circularized planets can be highly inclined
  - $\sim 70\%$ $i > 40°$
  - $\sim 25\%$ $i > 90°$
- Inclination Distribution Similar to Nagasawa



Hot Jupiters Rarer than seen in Nagasawa et al 2008

Planet-Planet Scattering Rarely Produces Hot Jupiters

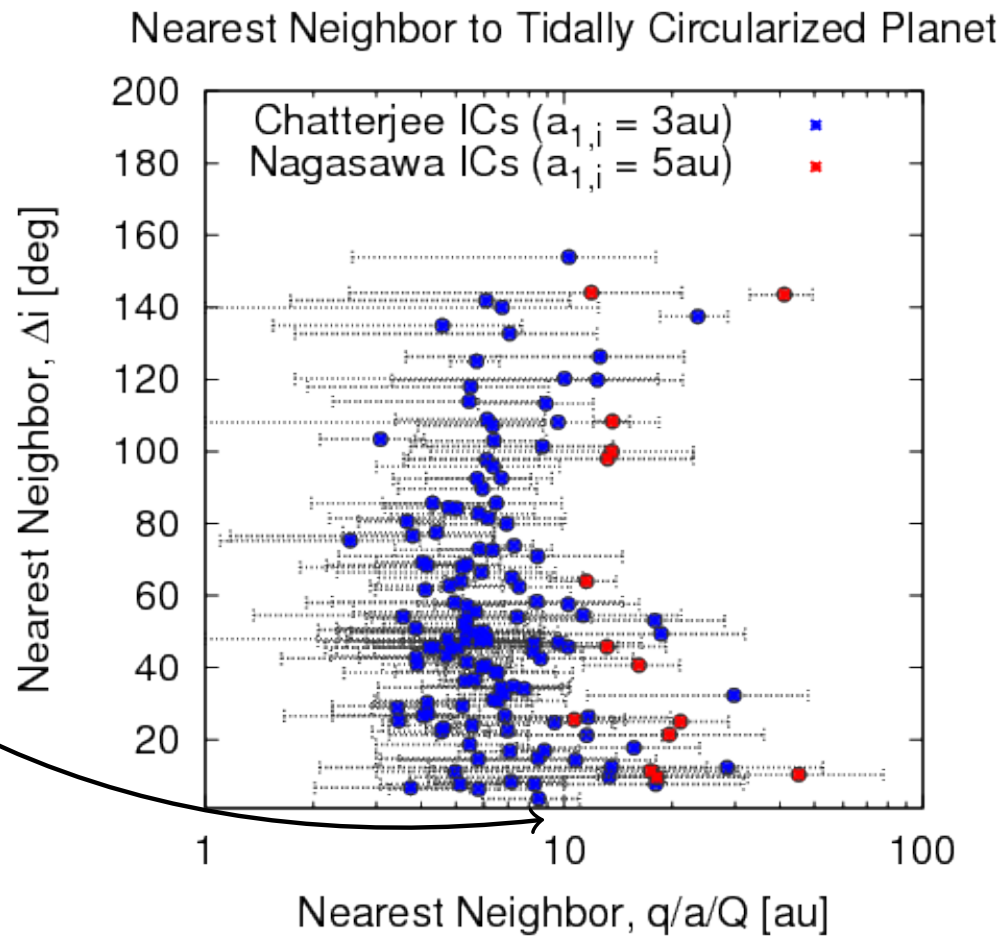
- Nagasawa ICs ($a_{1,i} = 5.0\,au$) more distant than Chatterjee ICs ($a_{1,i} = 3.0\,au$)
- Few Hot Jupiters Created
- Chatterjee ICs , $f_{q<0.1\,au} \sim 5\%$
- Nagasawa ICs , $f_{q<0.1\,au} < 1\%$



Hot Jupiters are Lonely

If planet-planet scattering is important, nearest neighbor to hot Jupiter...

- ... is far away
- ... contains information on ICs
- ... *may* be driven by (planet-planet) Kozai



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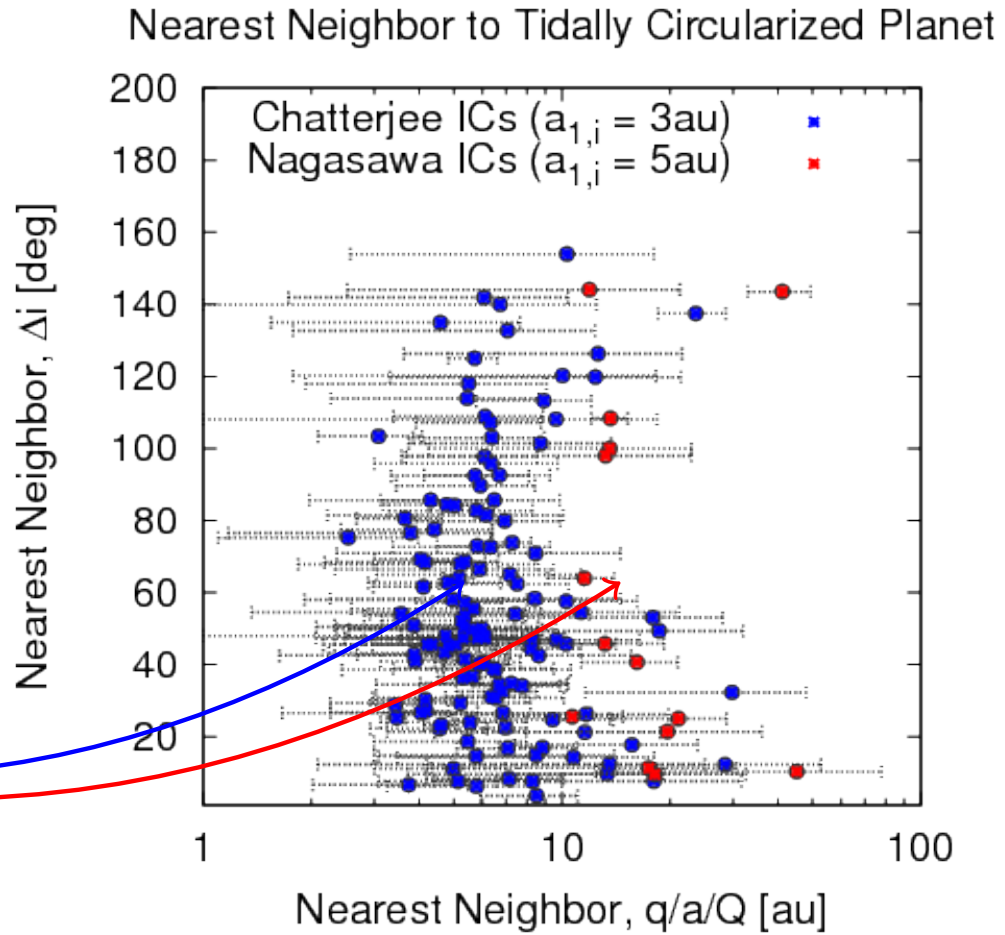

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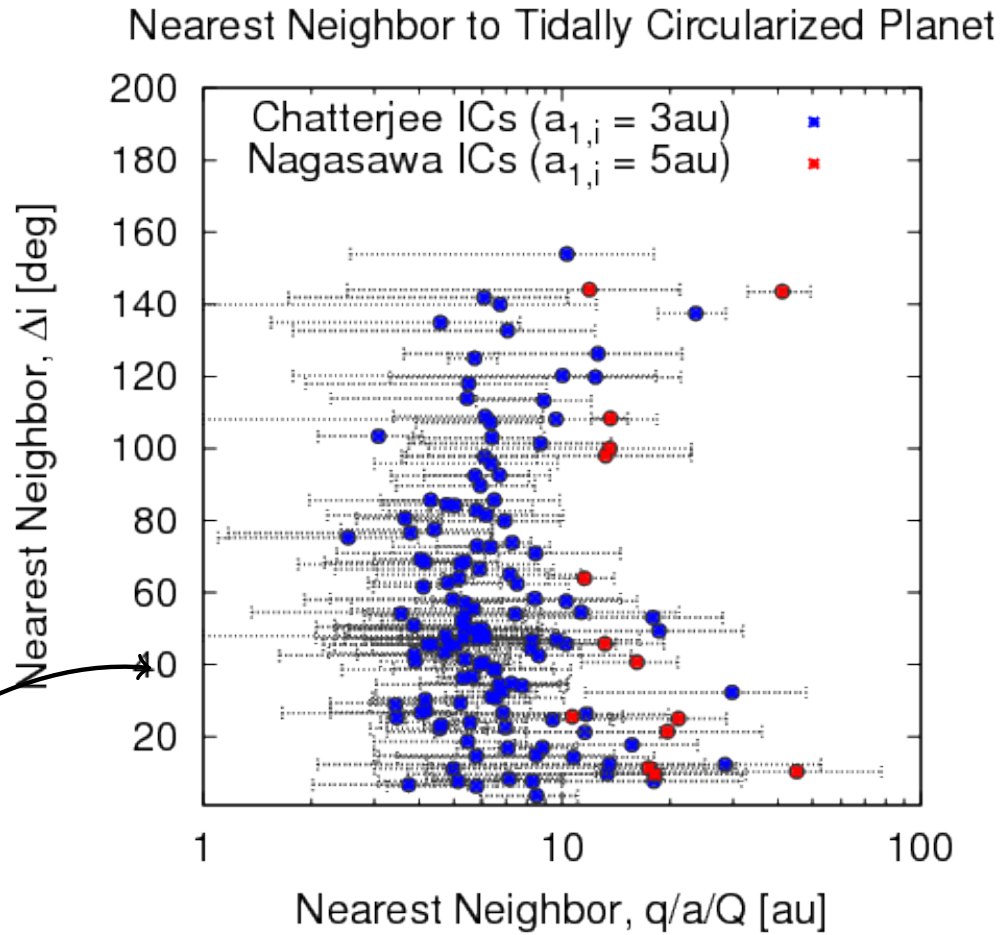
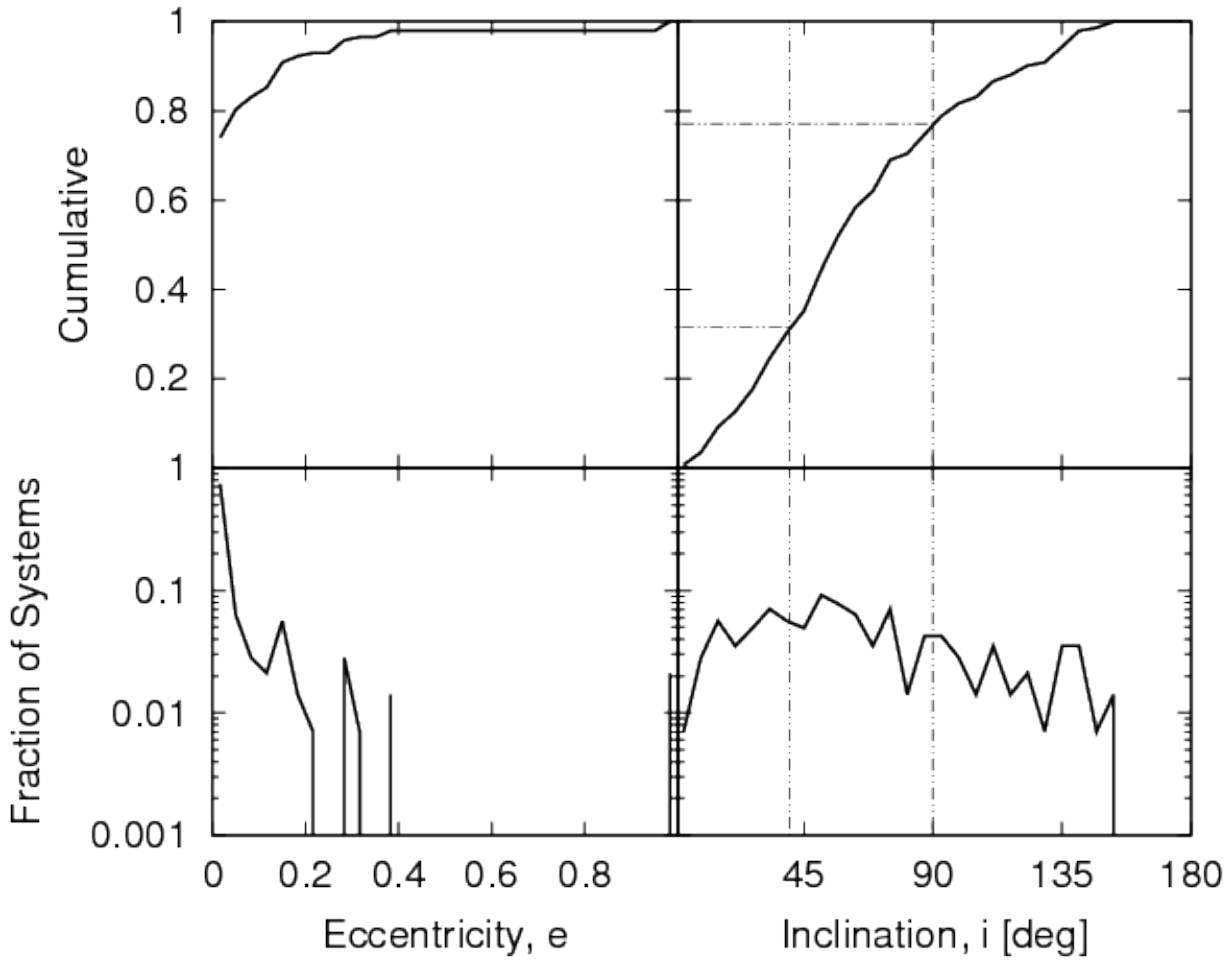


Overall Eccentricity & Inclination Distributions

e & i from Planet-planet scattering

- Circularized planets can be highly inclined
- Distributions shift with pericenter
- Current Eccentricity Observations (above e = 0.1) Favor Scattering from Small Semi-Major Axes



RV Planets, $e > 0.1$, $M_P > 0.1 M_J$

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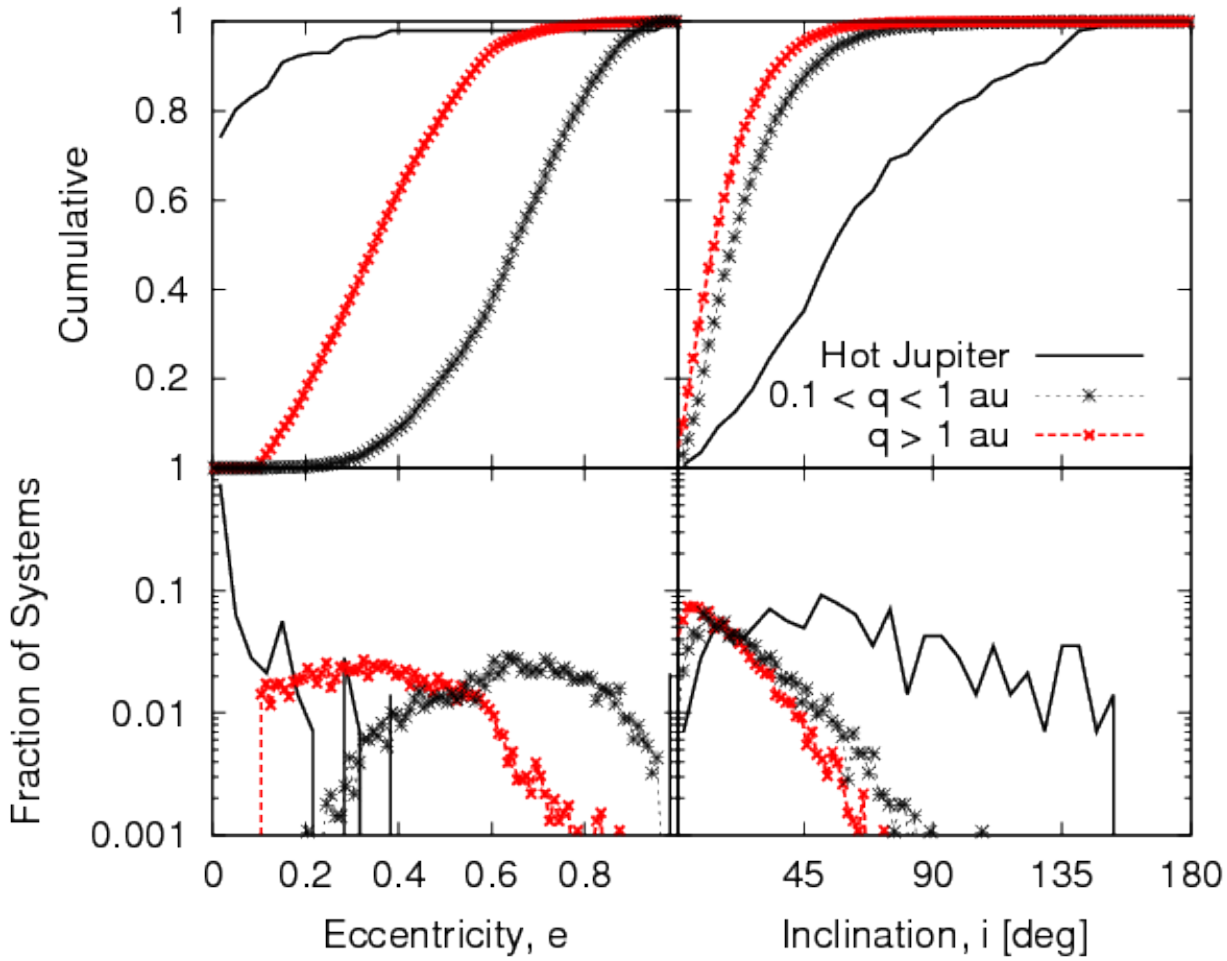

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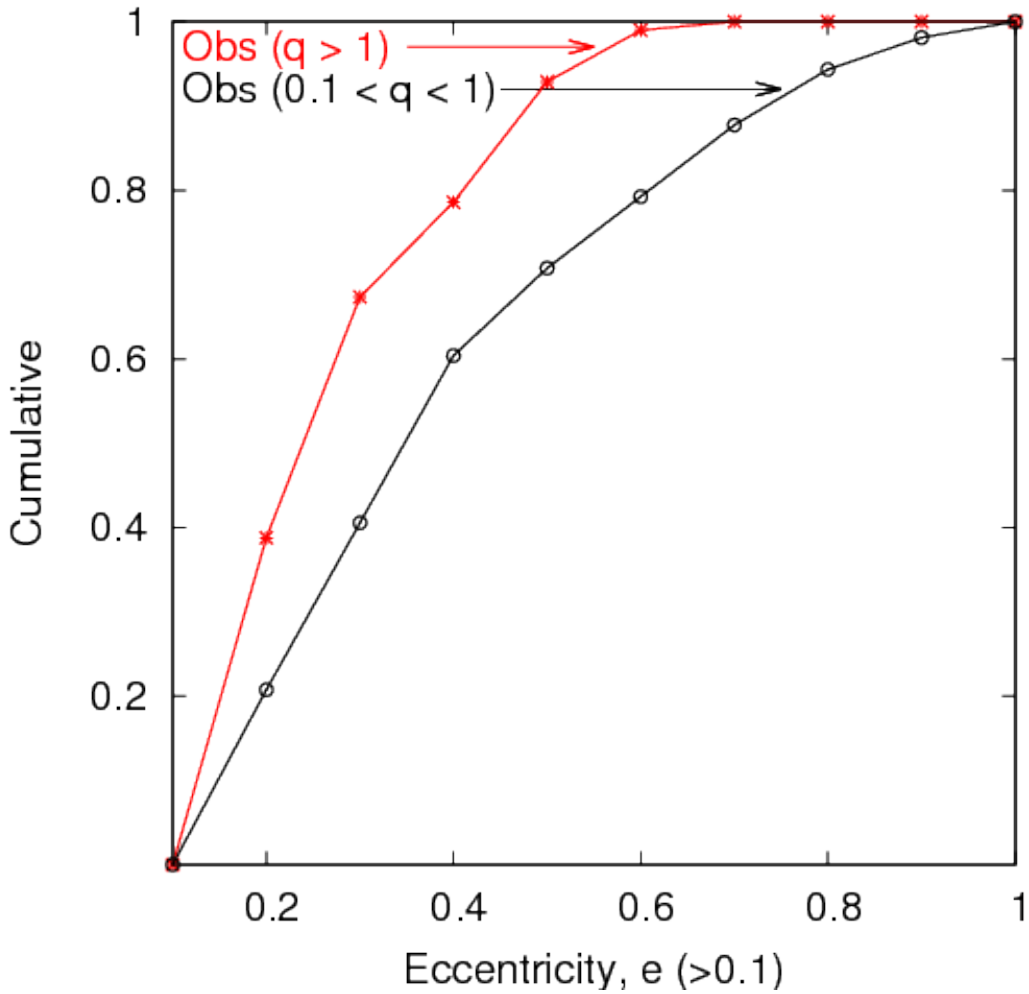

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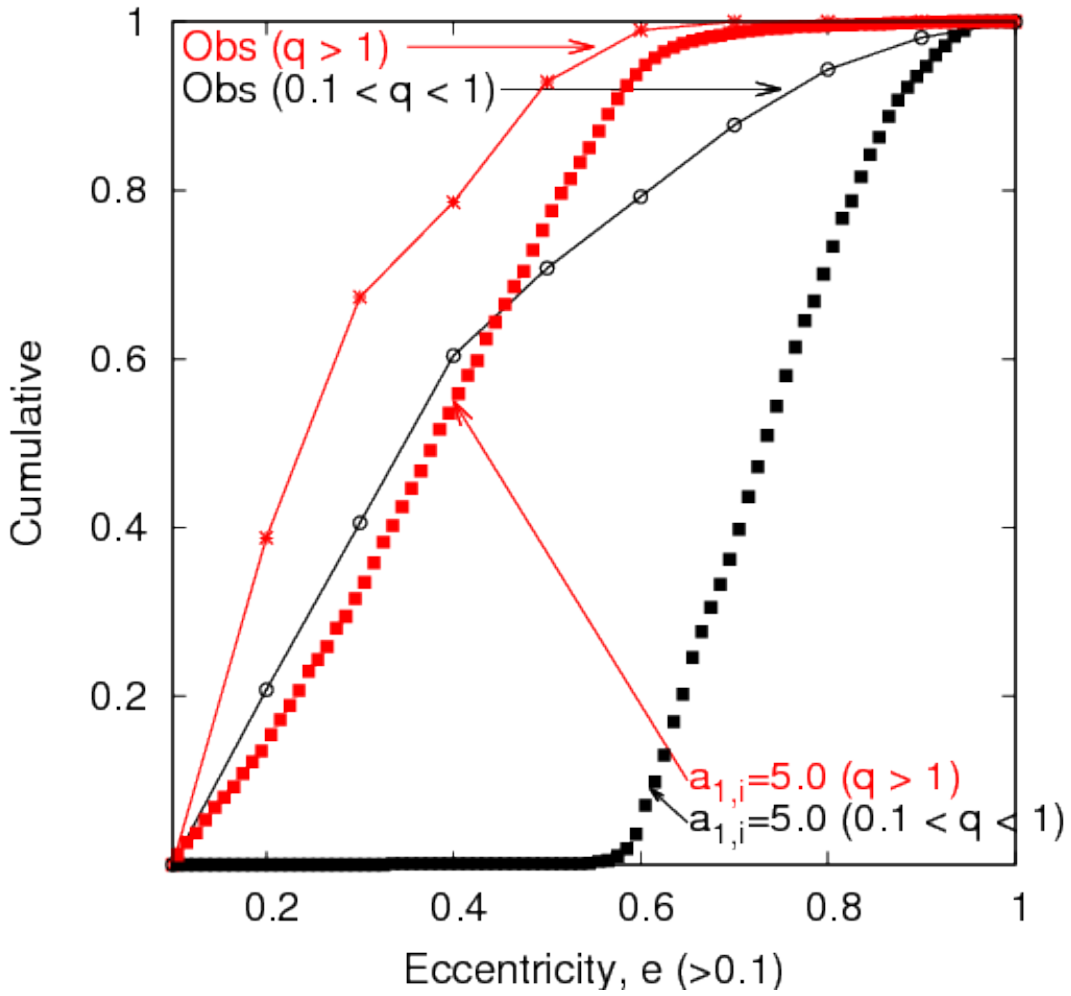

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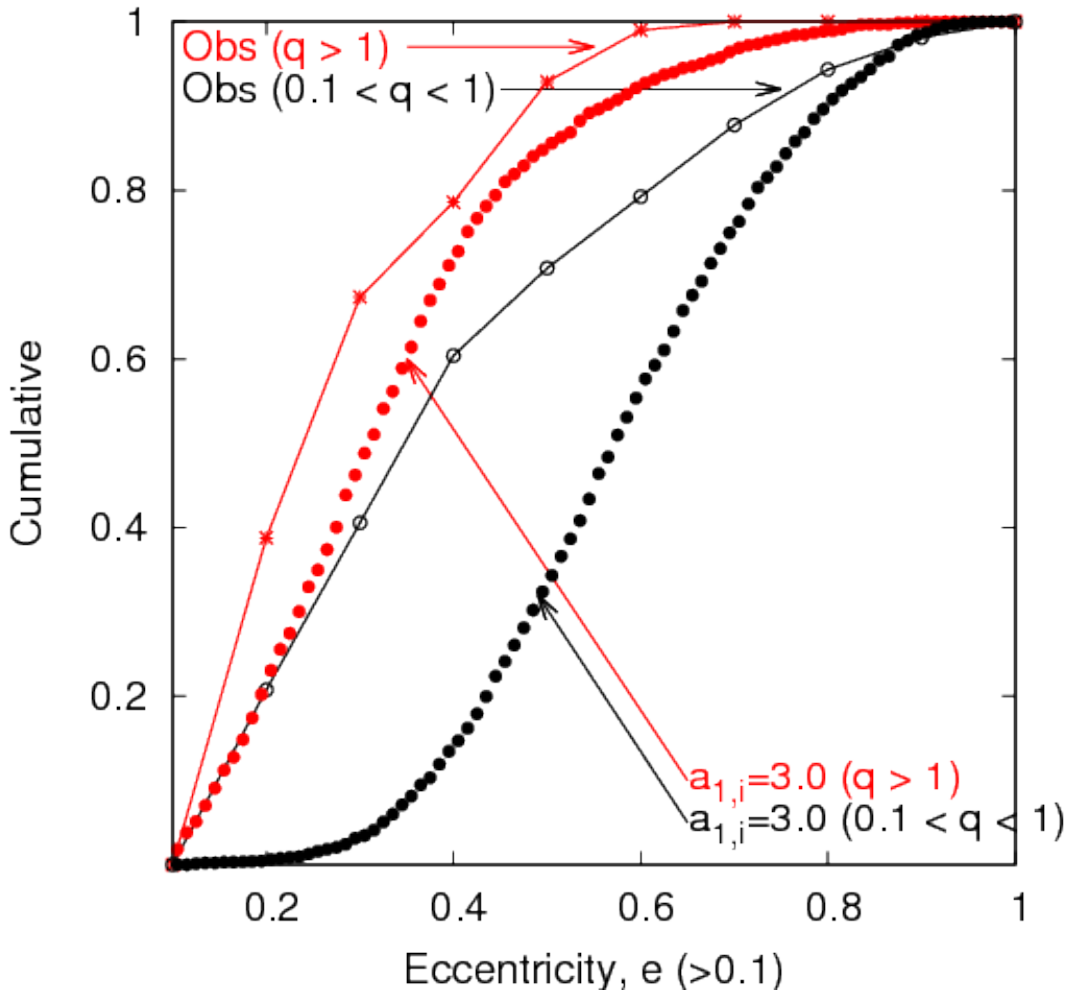

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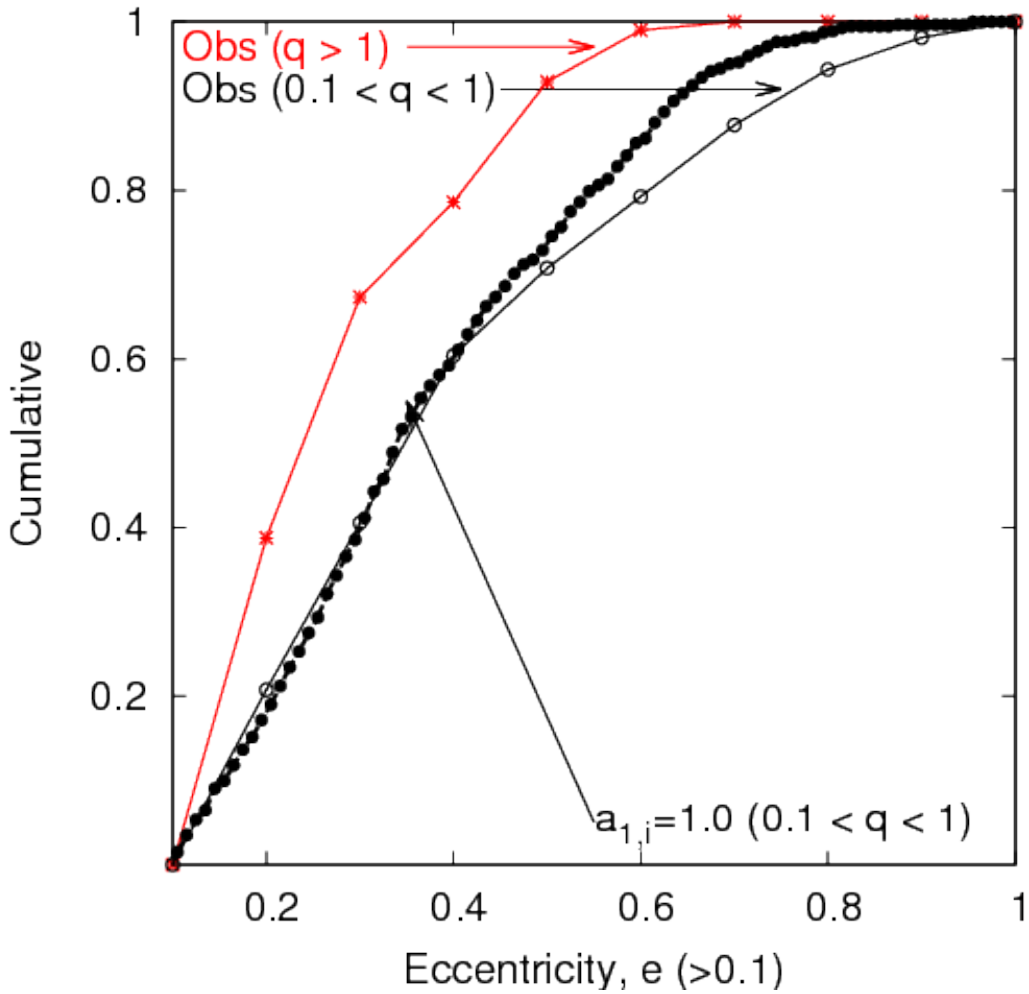

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Summary

- Agreement...
  - As in Nagasawa et al. 2008 (& 2011), $\sim 70\%$ of Hot Jupiters from scattering have $i > 40^{\circ}$
- Disagreement...
  - Fraction scattered to q < 0.1 and circularized is much smaller than Nagasawa et al 2008: $\sim 1 - 5\%$
  - Each Hot Jupiter Implies Numerous Scattered Systems which have Not Circularized
- Hot Jupiters...
  - Many High Inclinations
  - Nearest neighbors are distant, but give information on ICs
- Eccentricity & Inclination Distributions
  - Fixed ICs (semi-major axis) $\Rightarrow$ Lower $< e >$ & $< i >$ at larger pericenters
  - Current RV Observations Support Trend & Favor Scattering from ICs with $a_{1,i} = 1 - 3\, au$

Fin

Additional / Back-up