MODELING PLANET POPULATIONS II:
Interactions and Distant Giant Planets

Edward Thommes
University of Guelph & KITP

Kavli Institute for Theoretical Physics
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Image: NASA

Collaborators

Soko Matsumura (Northwestern , now Maryland)

Fred Rasio (Northwestern)

Sourav Chatterjee (Northwestern)

John Russell (Guelph, M.Sc.)

Natasha Holmes (Guelph, now UBC)

Ryan Massey (Guelph, now M.Sc.)

Marc Van Acker (Guelph)

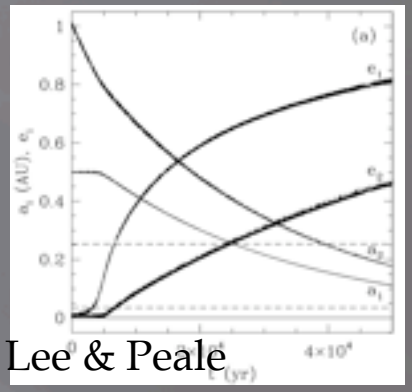
University of Guelph

Simulating young planetary systems: Different approaches

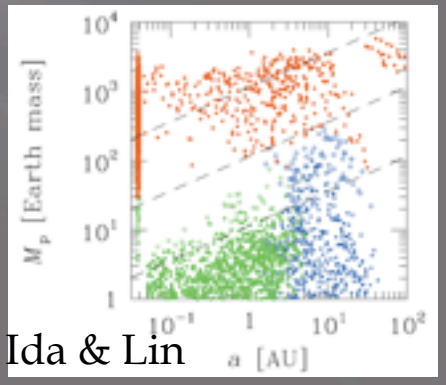
- **Full 2d/3d hydrodynamic simulations:** e.g. Artymowicz, Bryden, Edgar, Klahr, Kley, Lin, Lubow, Masset, Nelson, Papaloizou, Quillen, Rice, Tanigawa, Varnière, Watanabe...
  - all the physics, but high computational cost
    only short 10^3 - 10^4 orbit "snapshots"


Bryden et al.

- **N-body with simple "disk forces":**
  - Early stages: Kokubo & Ida 2002, Thommes, Duncan & Levison 2003 (gas drag; type I,II not incl.)
  - type II regime: e.g. Lee & Peale 2002, Adams & Laughlin 2003, Thommes & Lissauer 2003, Moorhead & Adams 2005 Lee, Thommes & Rasio 2008, MH Lee & Thommes 2009


Lee & Peale

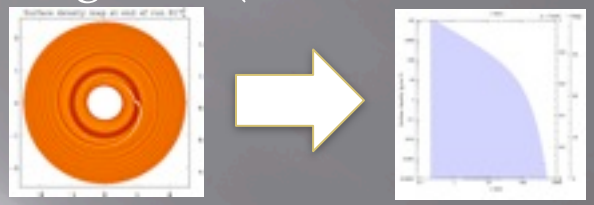
- **Monte Carlo calculations of a planet in a disk:**
  - Early stages (cores, type I migration): Alibert et al. (2005), Thommes & Murray (2006), Thommes, Nilsson & Murray (2007)
  - From beginning to end: Ida & Lin (2004a, b, 2005, 2008)



Ida & Lin

Thommes, Matsumura & Rasio (*Science* 2008): A hybrid N-body + gas disk code:

- Further development of Thommes (2005) code
- N-body part: SyMBA symplectic integrator (Duncan, Levison & Lee 1998)
- Gas disk: 1-d, alpha viscosity
- Planet-disk torques
  - Linear regime (type I): migration rate from Tanaka, Takeuchi & Ward (2002)
  - Nonlinear regime (type II): planet-disk torque density (Goldreich & Tremaine 1980, Ward 1997)



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

where $\partial T/\partial r$ is the torque density experienced by the disk due to a planet of mass $M = \mu M_*$ and orbital radius r_p:

$$\frac{\partial T}{\partial r} = \mathrm{sgn}(r - r_p)\frac{2\mu^2 \Sigma_{\rm gas} r_p^4 \Omega_p^4}{r(1+4\xi^2)\kappa^2} m^4 \psi^2$$

- Gas accretion:
  - assume core accretion
  - Early core accretion: fit to Pollack et al. (1996), like Bryden et al. (2000)
  - Later: fit to hydro simulations (Tanigawa & Watanabe 2002). **But see Machida et al. (2010) for latest...**
- Solids accretion: Oligarchic growth (Kokubo & Ida 1998) with gas-envelope enhancement, scaled to Chambers (2006)
- **...Can model life of a typical protostellar disk in a few weeks.**

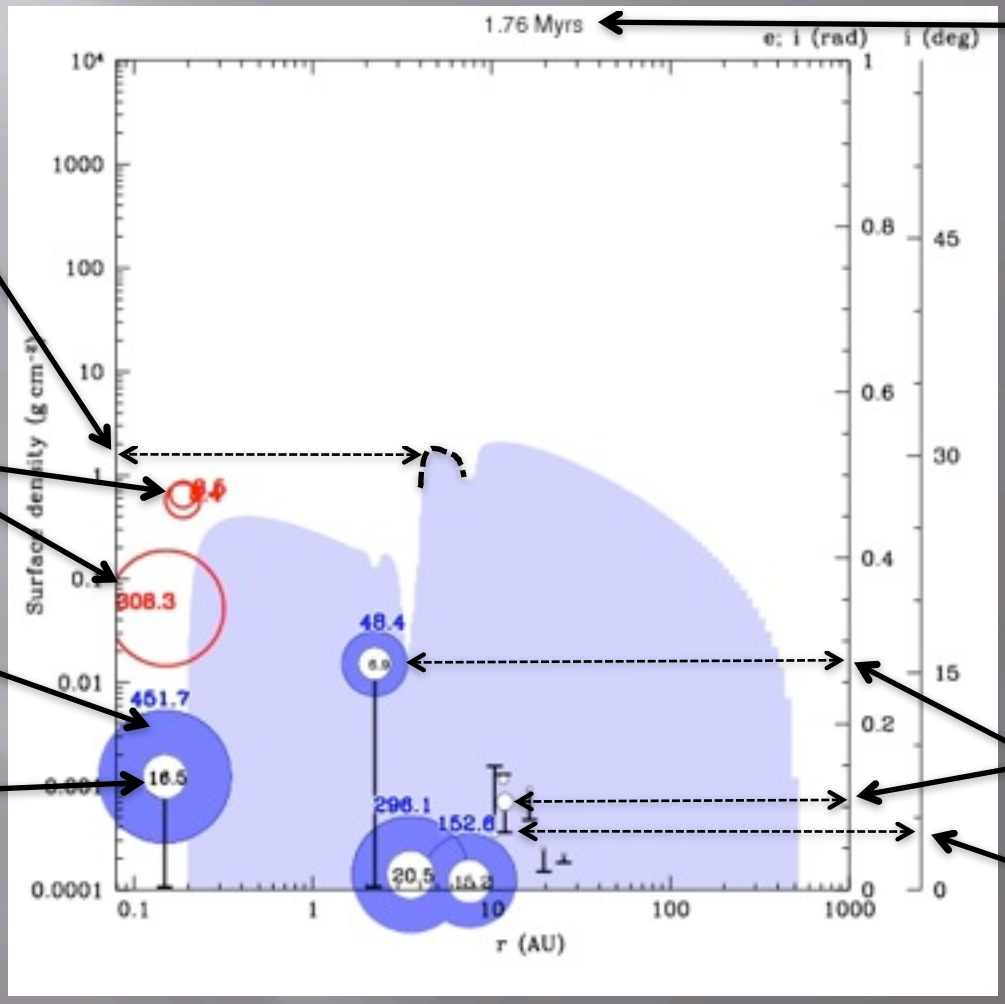
How we plot the output: Example "movie frame"

Gas disk surface density

"Afterimage" of planets removed at inner edge (label: Earth masses, total)

Planetary gas envelope (label: Earth masses)

Planetary solid core (label: Earth masses)

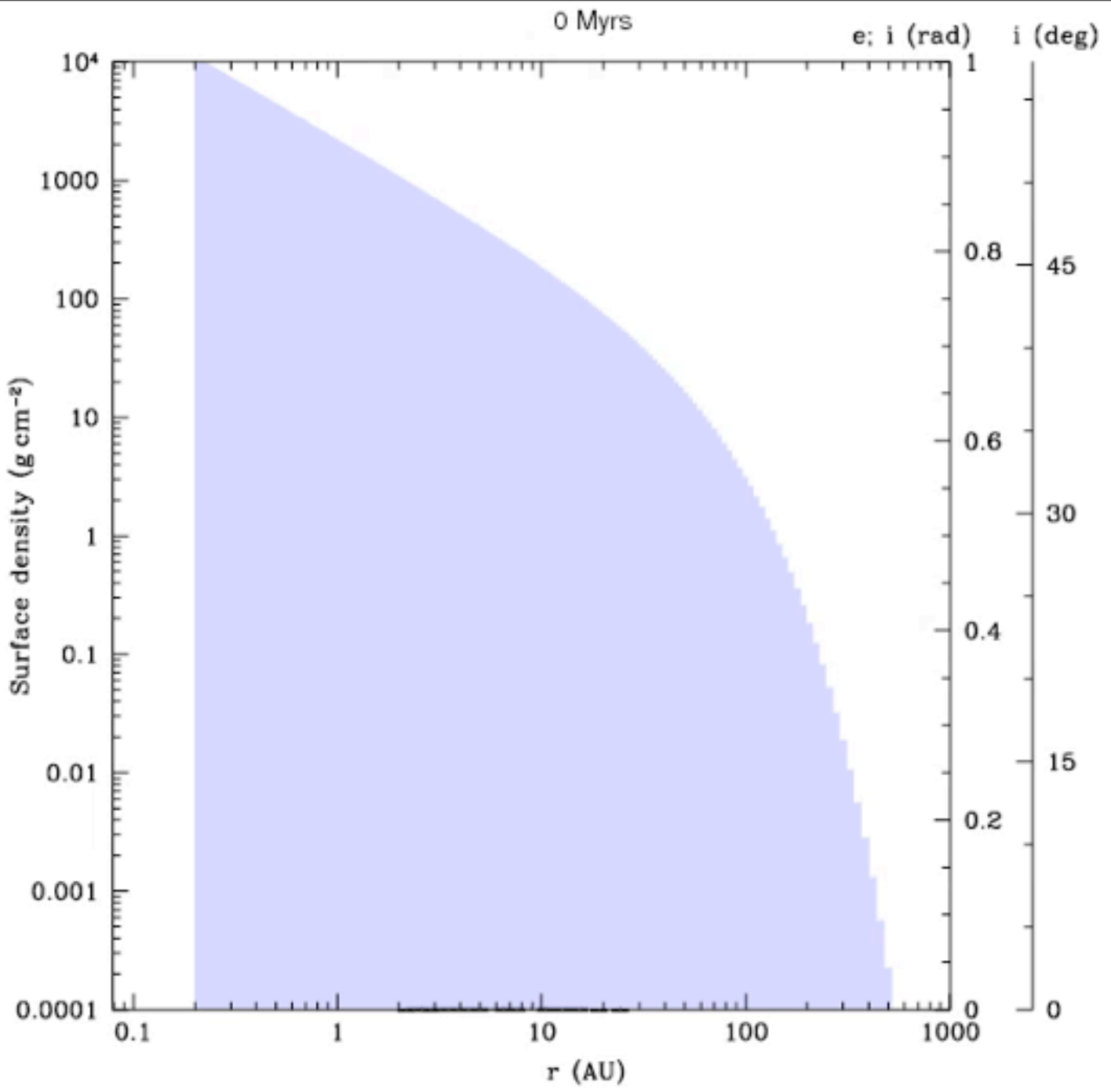


Simulation time

Planet eccentricity

Planet inclination

Thommes, Matsumura & Rasio, *Science* 2008



Thommes, Matsumura & Rasio, *Science* 2008

Thommes, Matsumura & Rasio, *Science* 2008

An initial burst of gas giant formation

Core accretion:

time to grow a gas giant = [time to finish core] + [time until runaway gas envelope accretion]

$=\tau_{core} + \tau_{KH}$

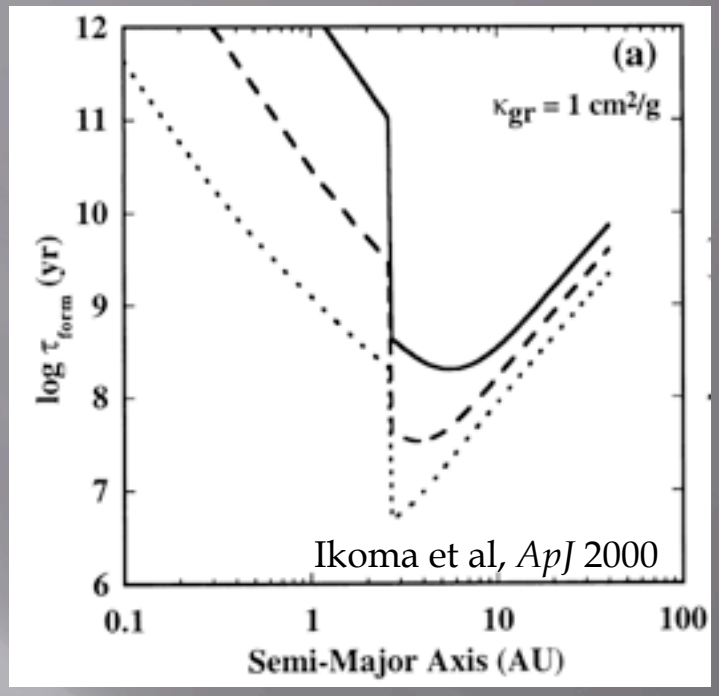
τ_{core} **increases** with r,

final mass M_{iso} **increases** with r,

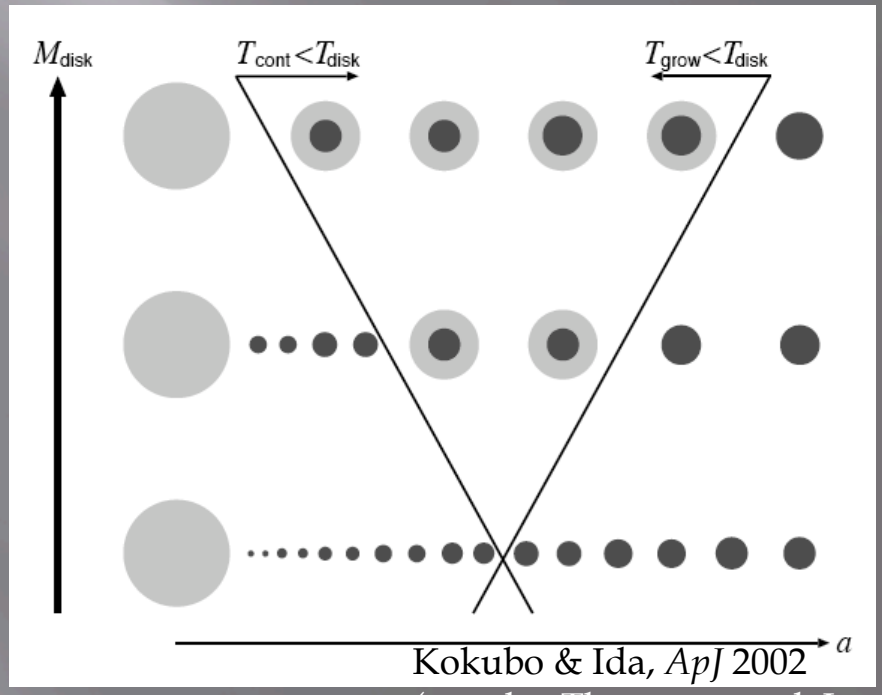
τ_{KH} **decreases** with M_{iso}

minimum gas giant formation time, $=\tau_{giant}$, occurs at some radius. For typical parameters, this is in the Jupiter-Saturn region (Ikoma, Nakazawa & Emori 2000)

initial **burst** of gas giant formation at time τ_{giant} starts at one radius, spreads and slows down



Ikoma et al, *ApJ* 2000



Kokubo & Ida, *ApJ* 2002

(see also Thommes et al, Icarus 2003)

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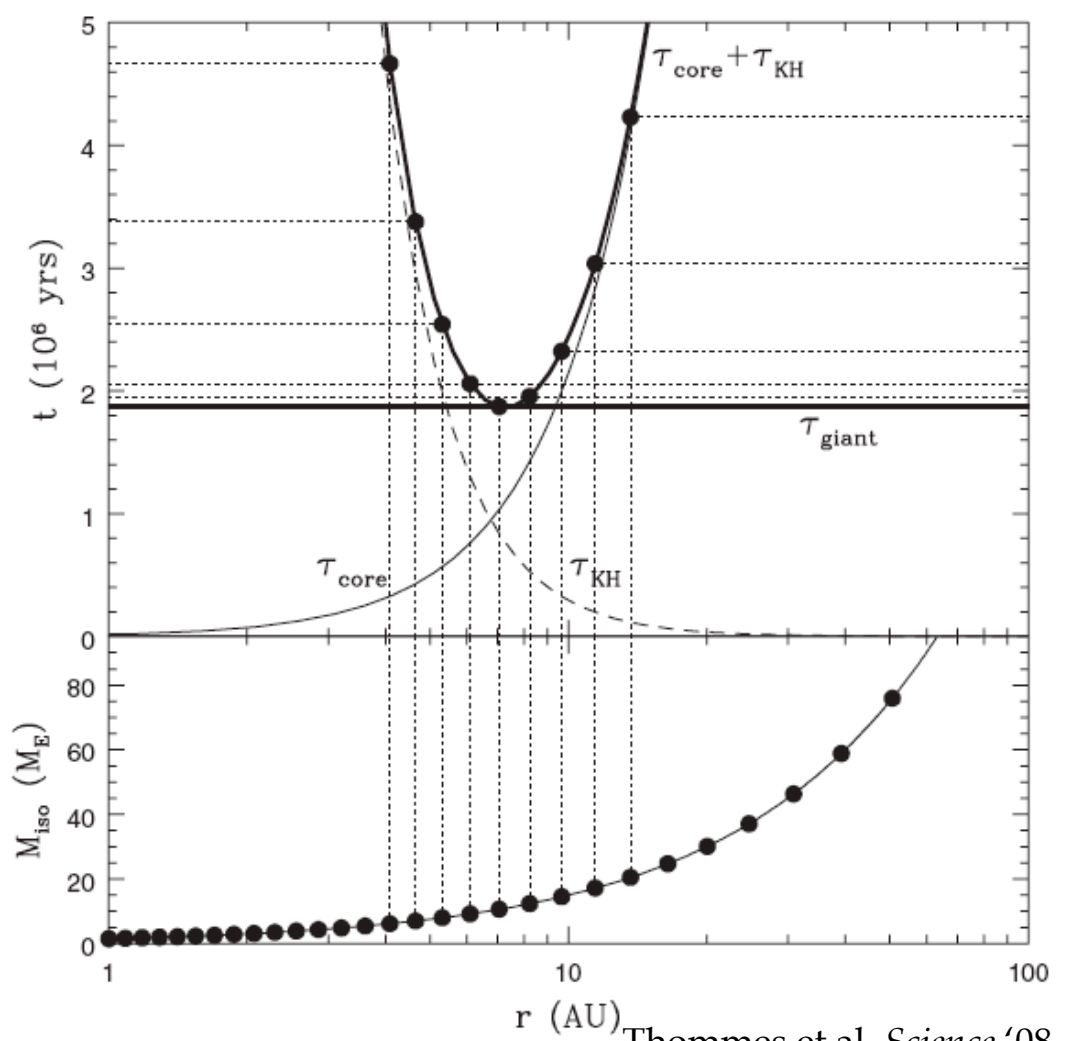
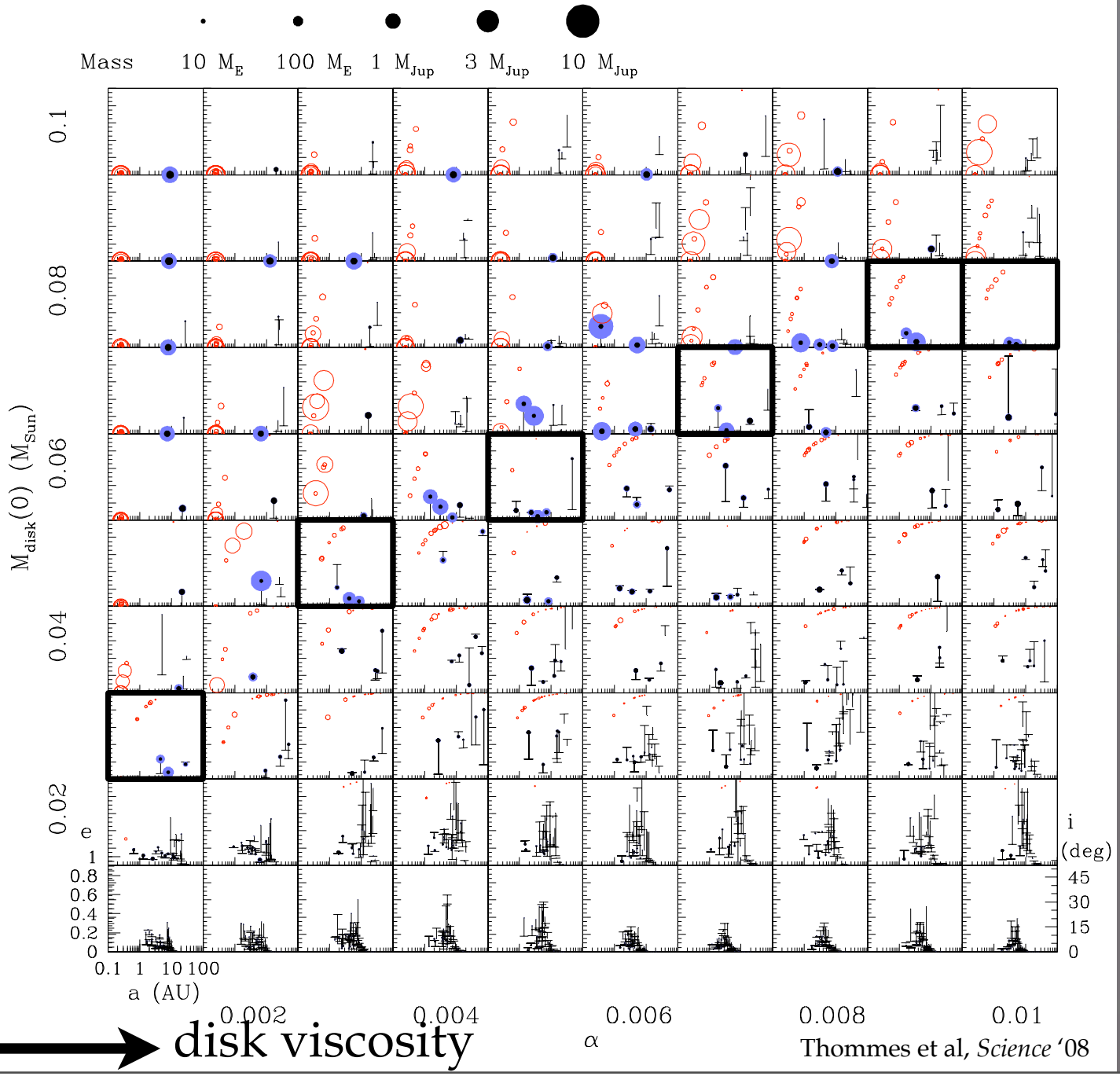


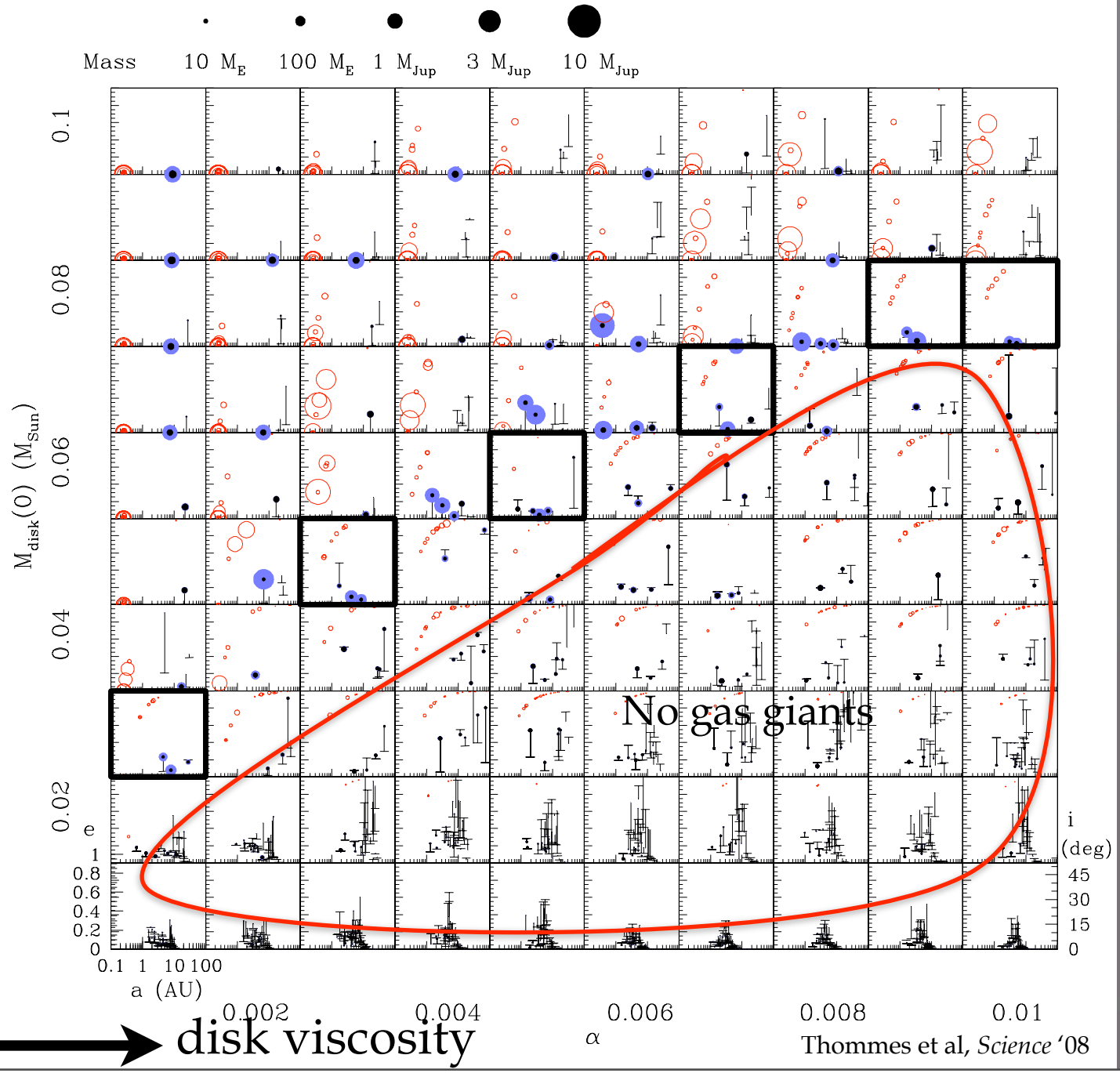
Thommes et al, *Science* '08



initial disk mass

disk viscosity

Thommes et al, *Science* '08



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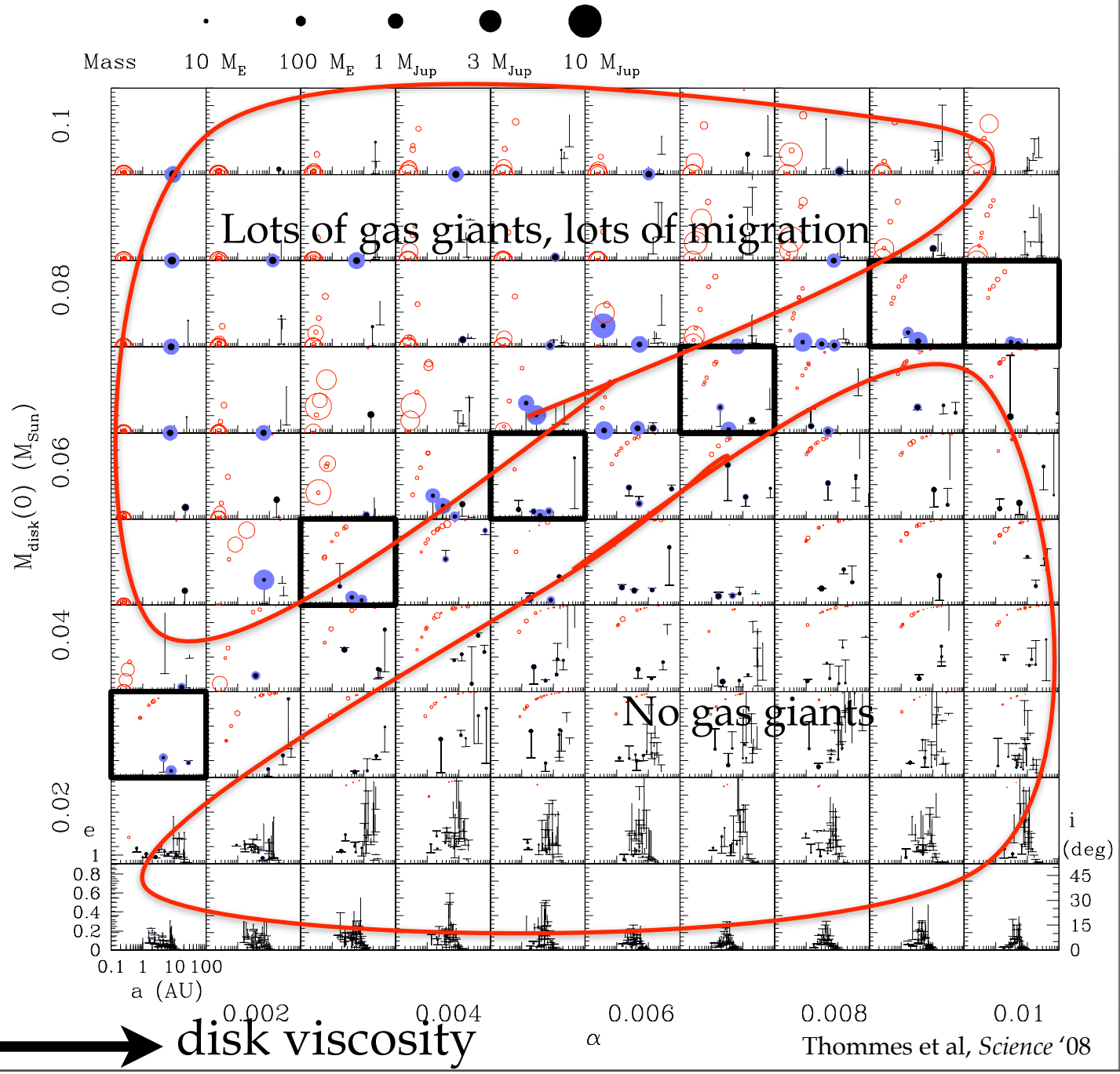

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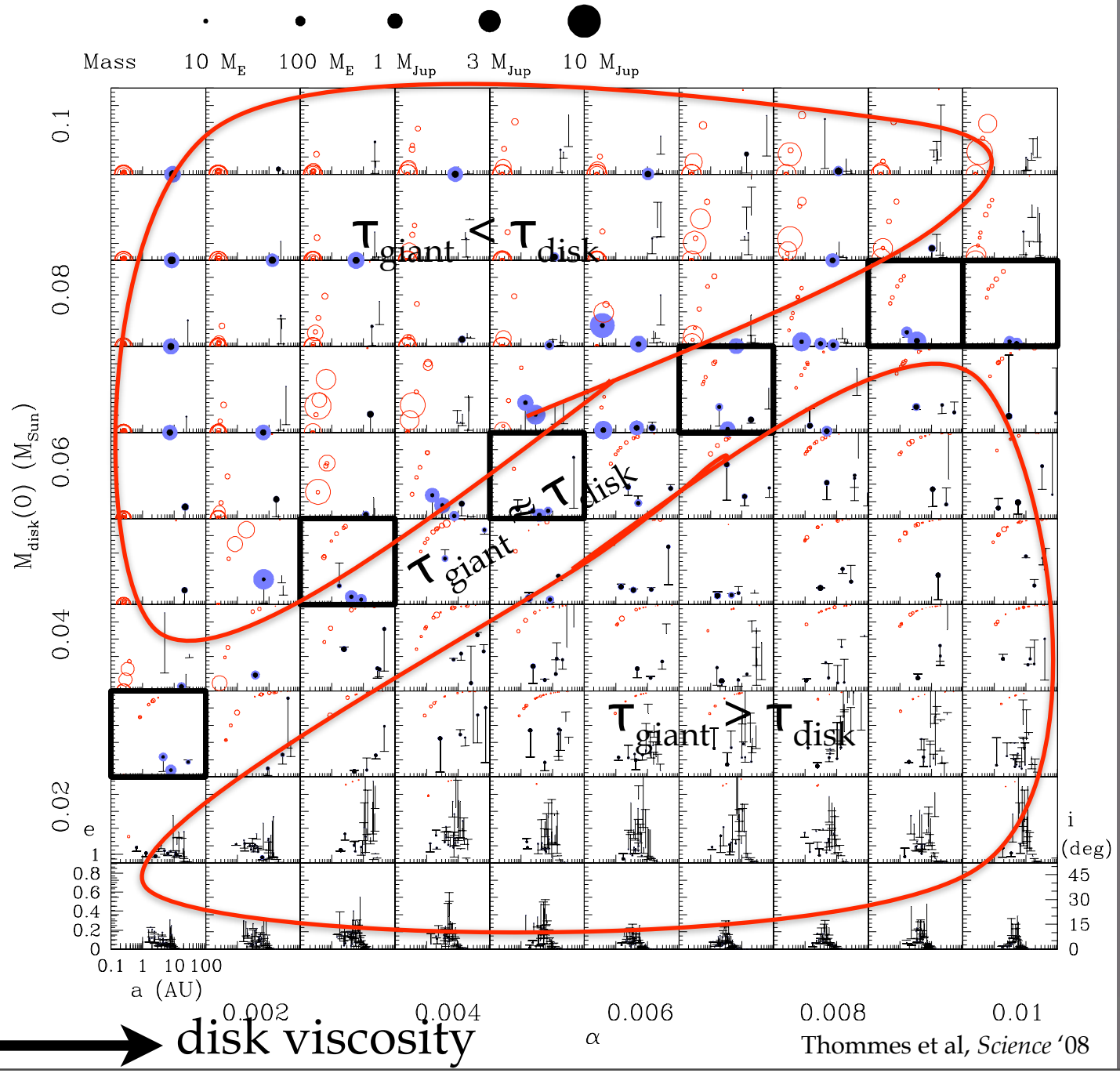

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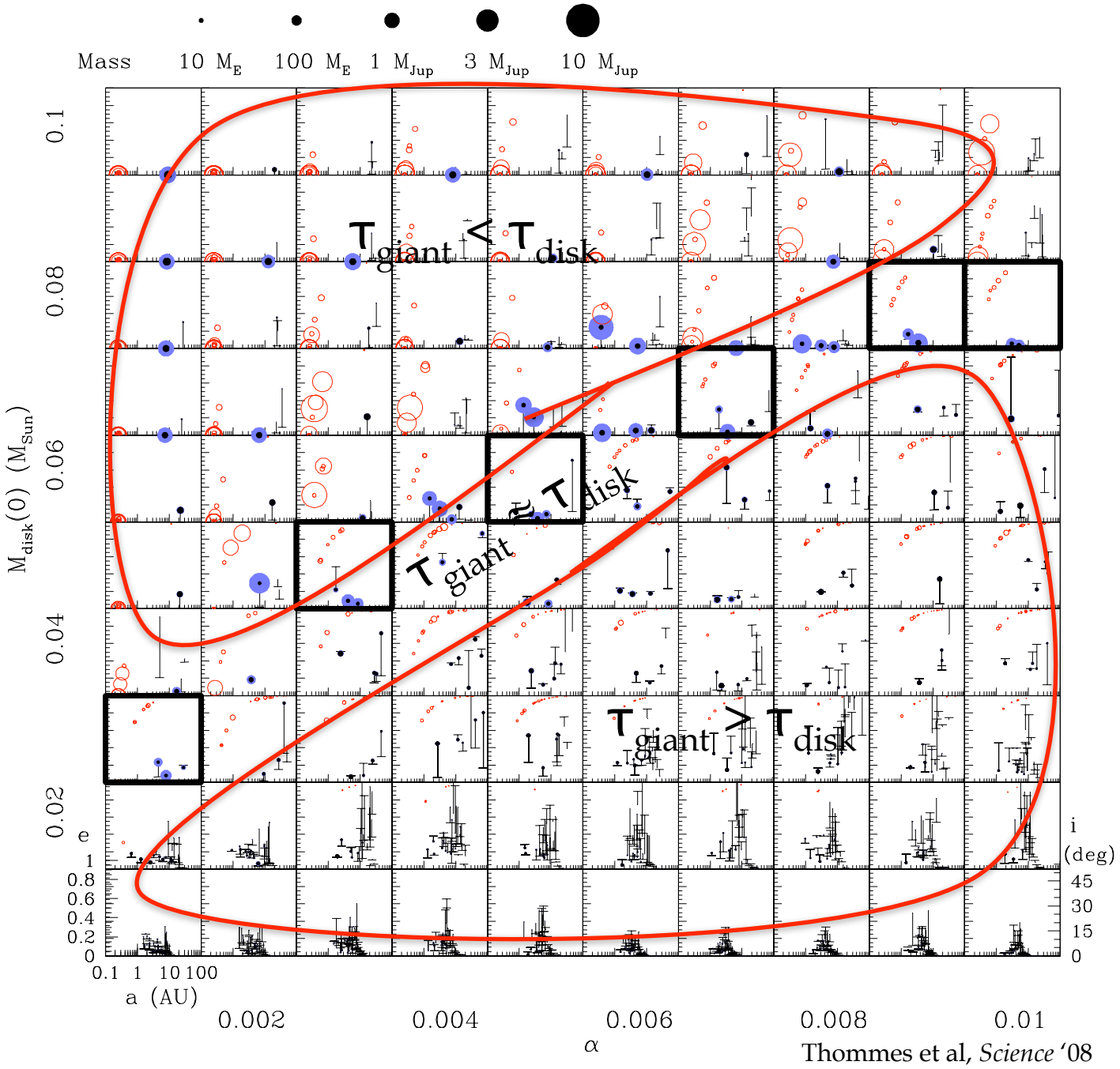

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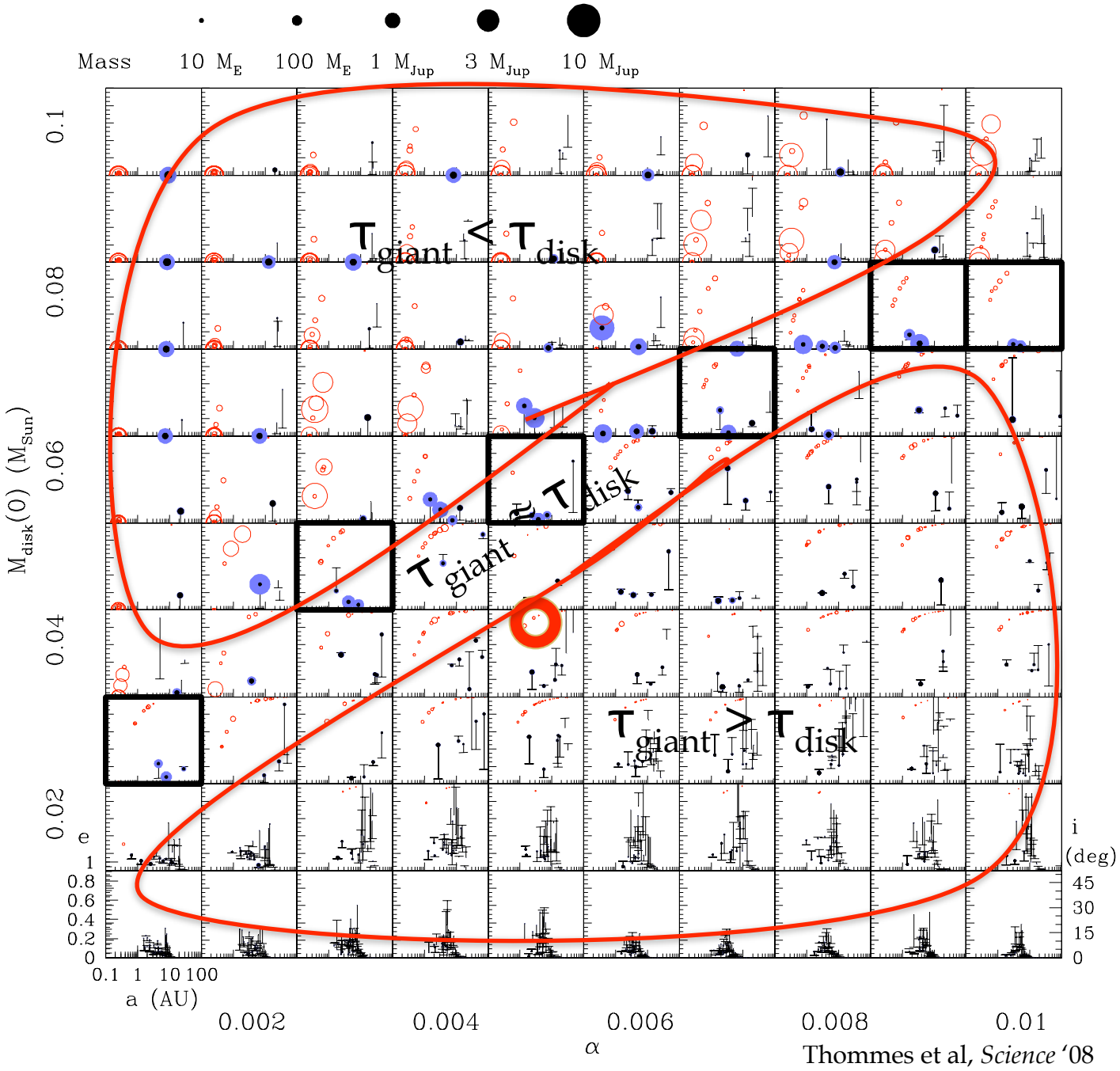

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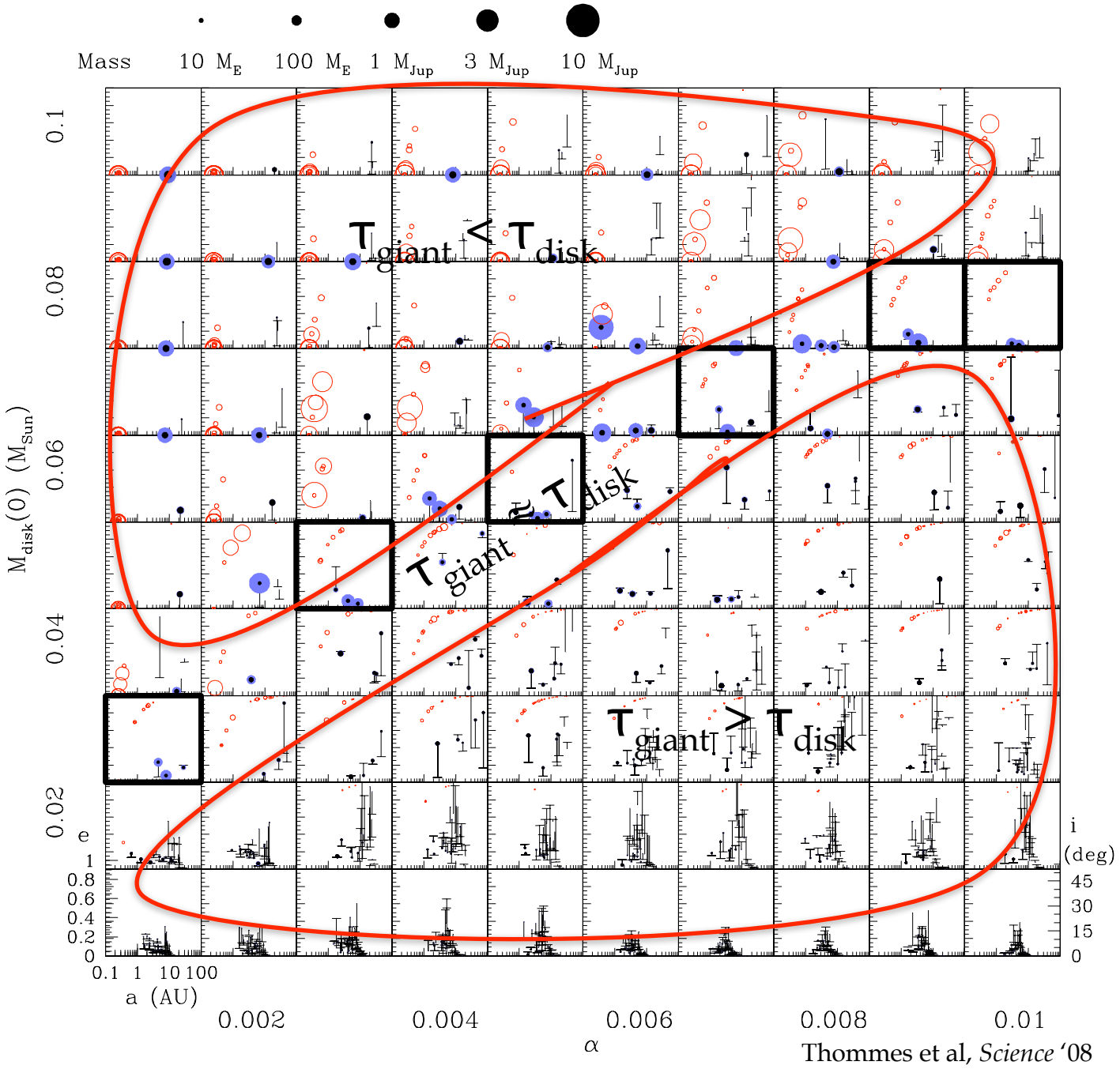

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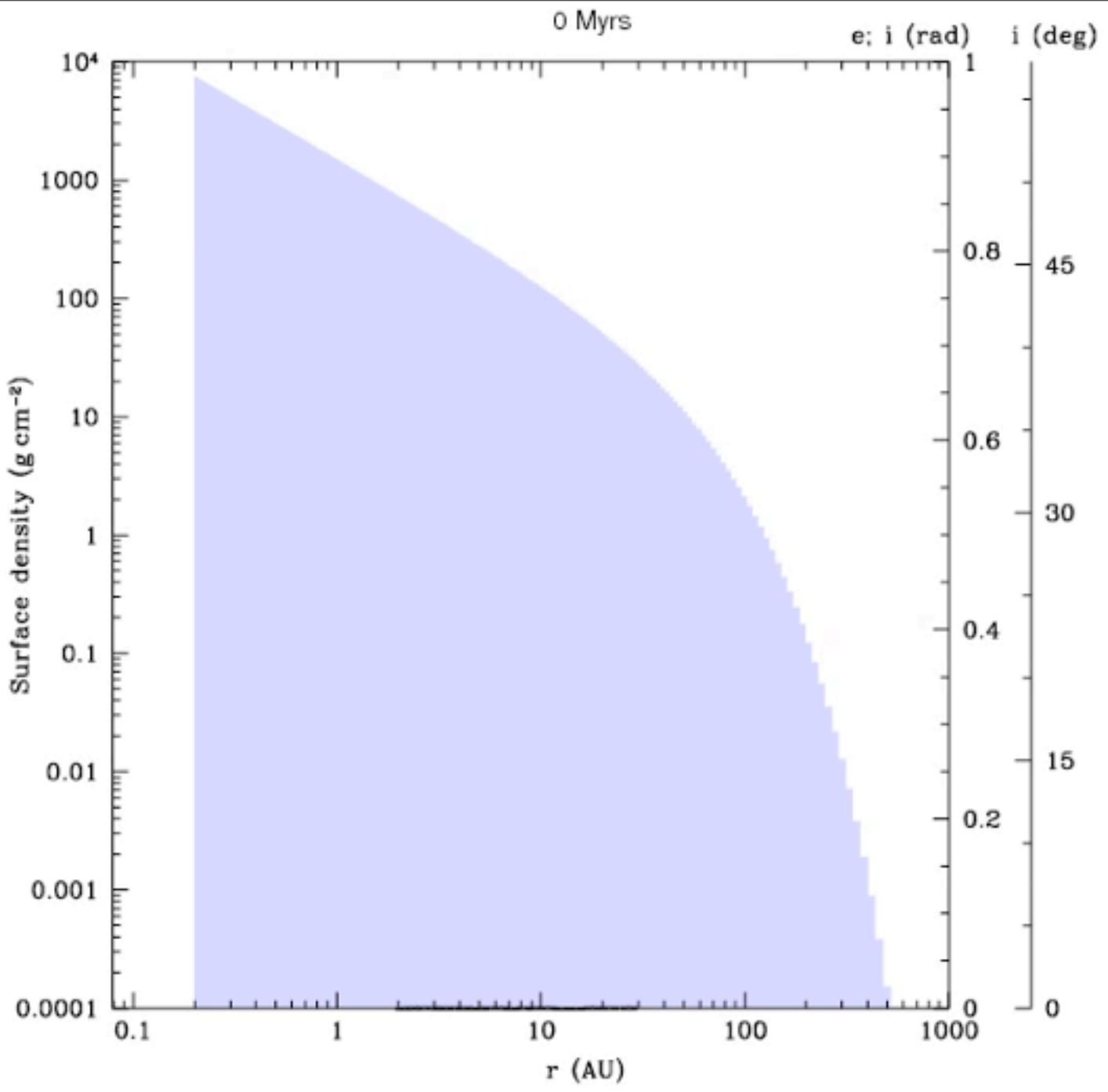

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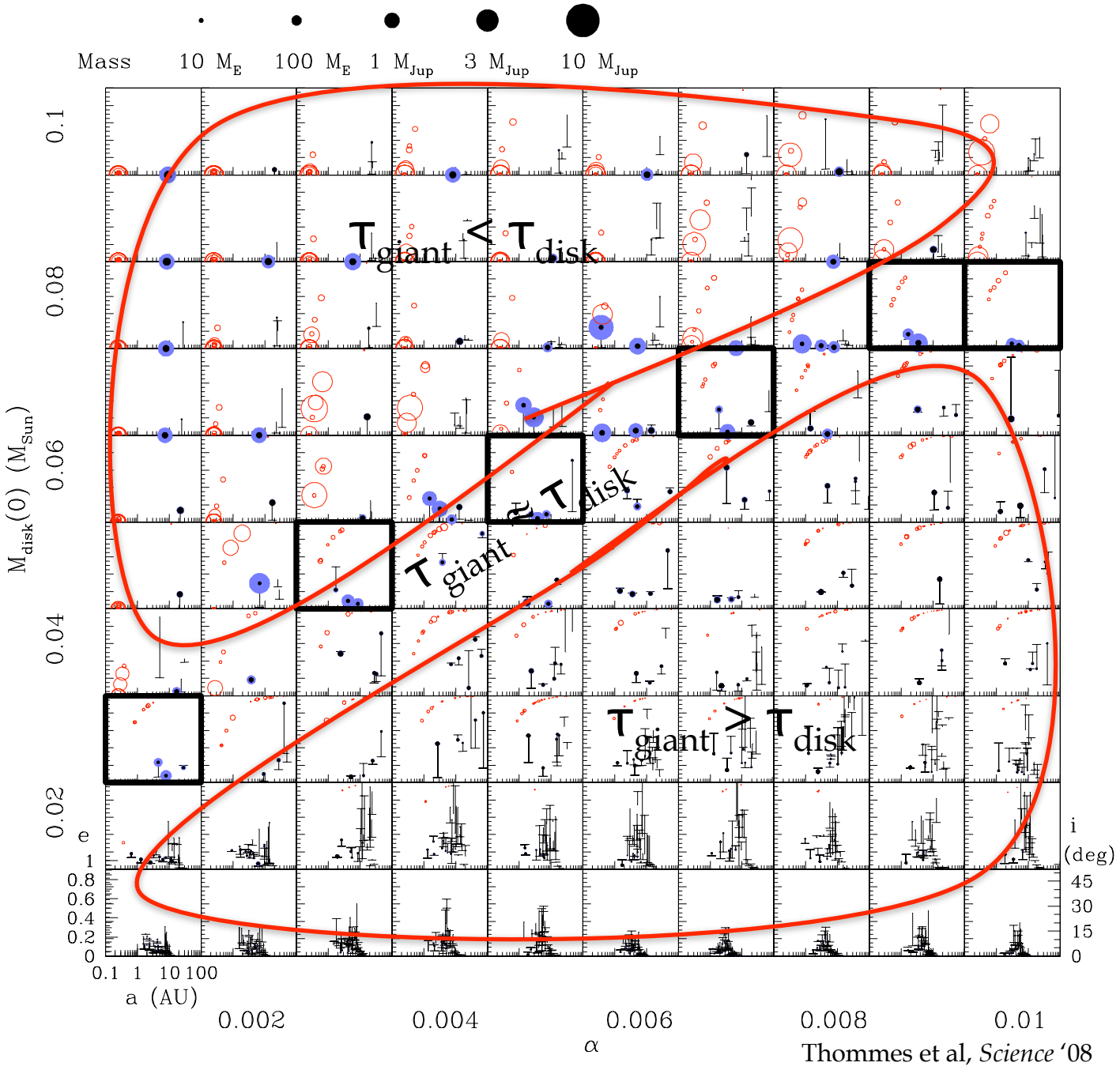

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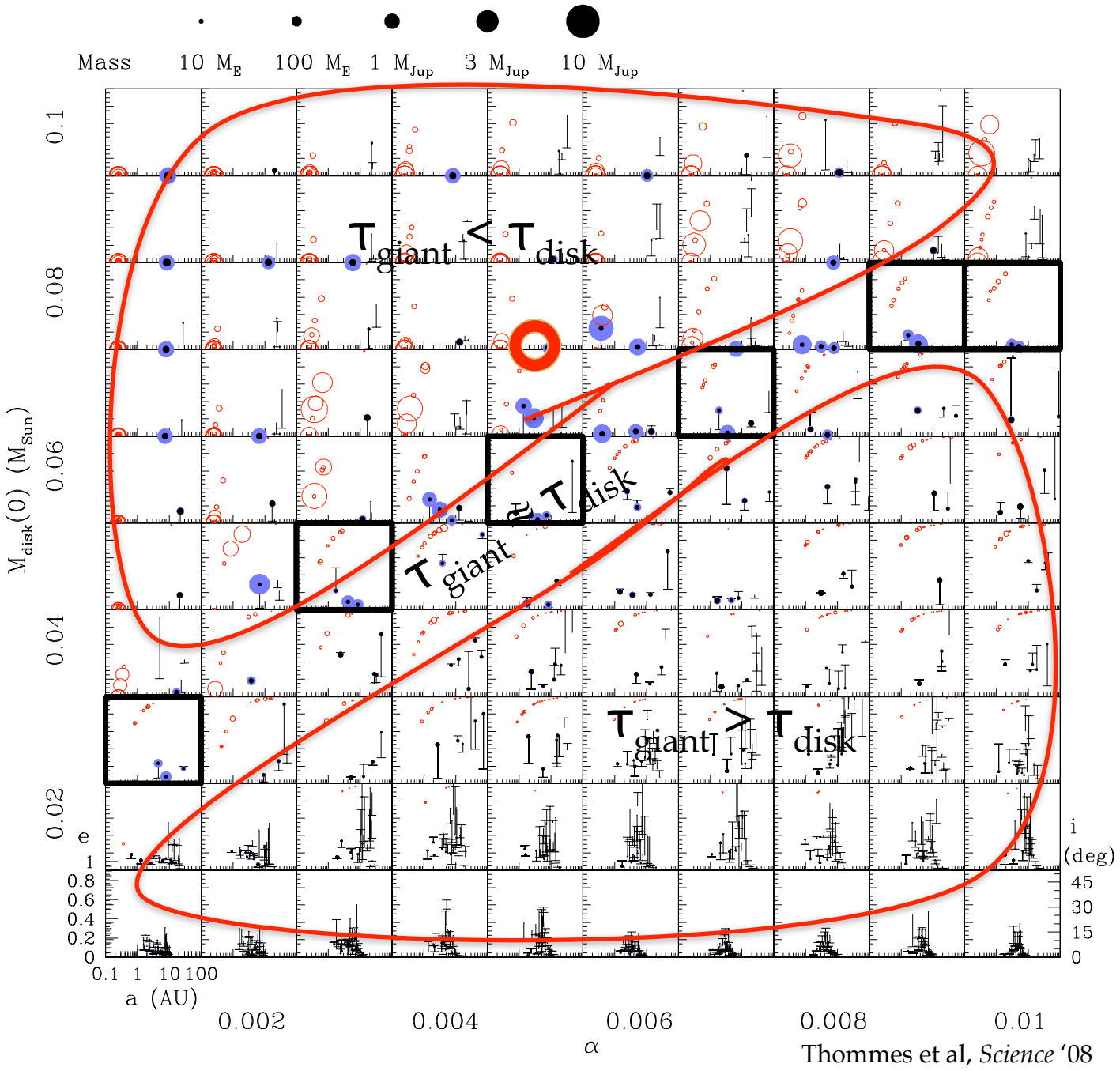

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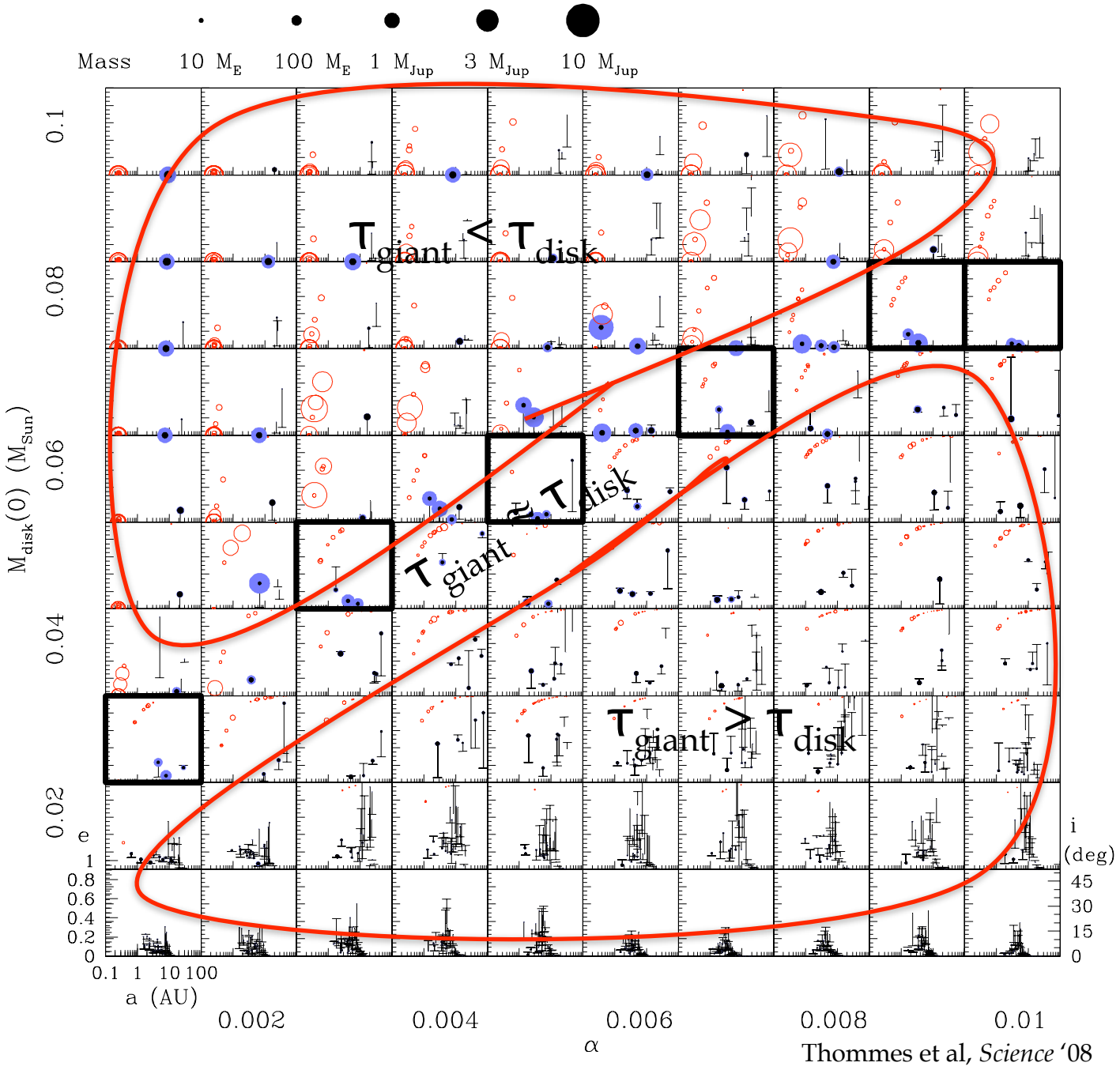

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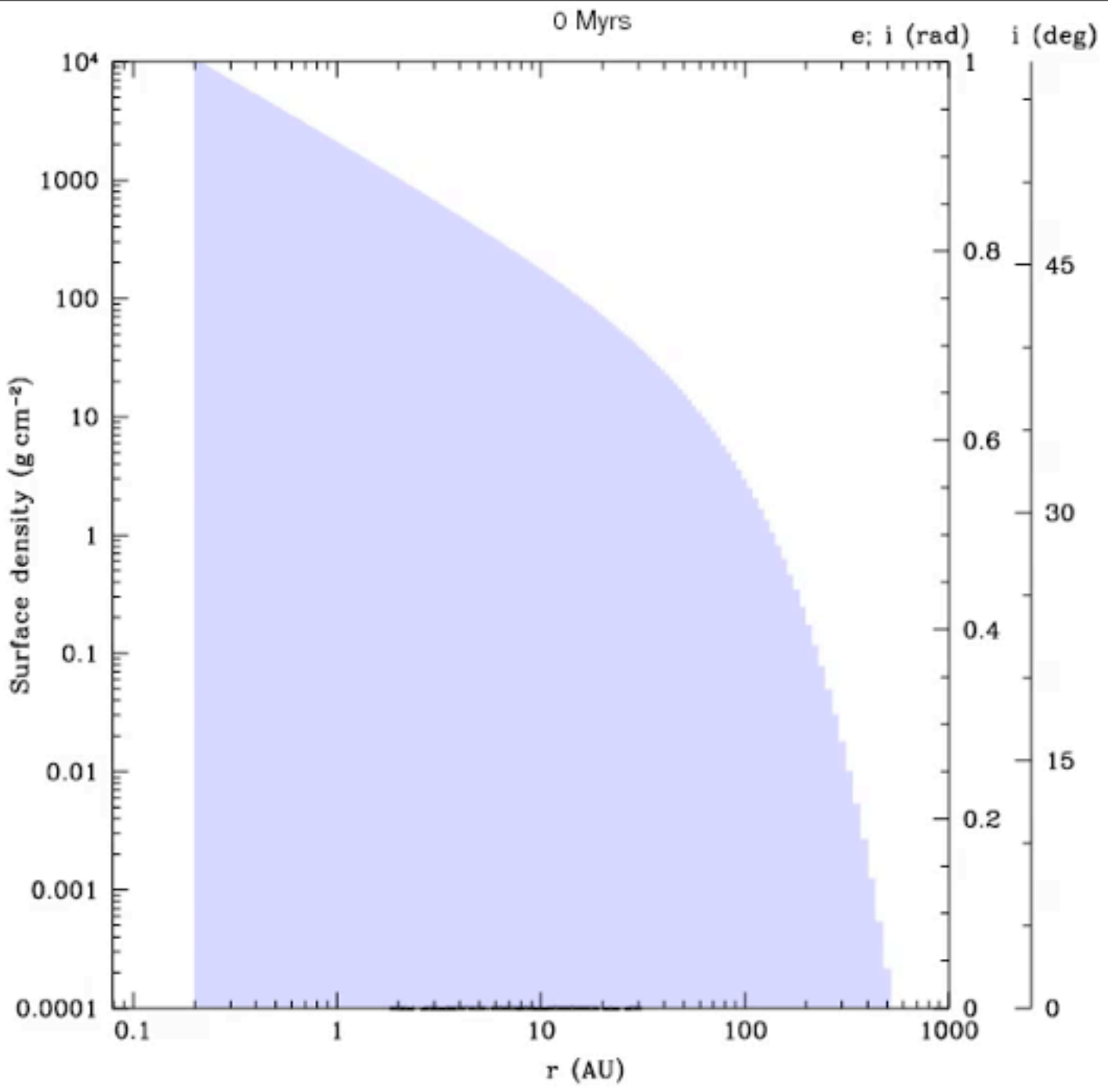

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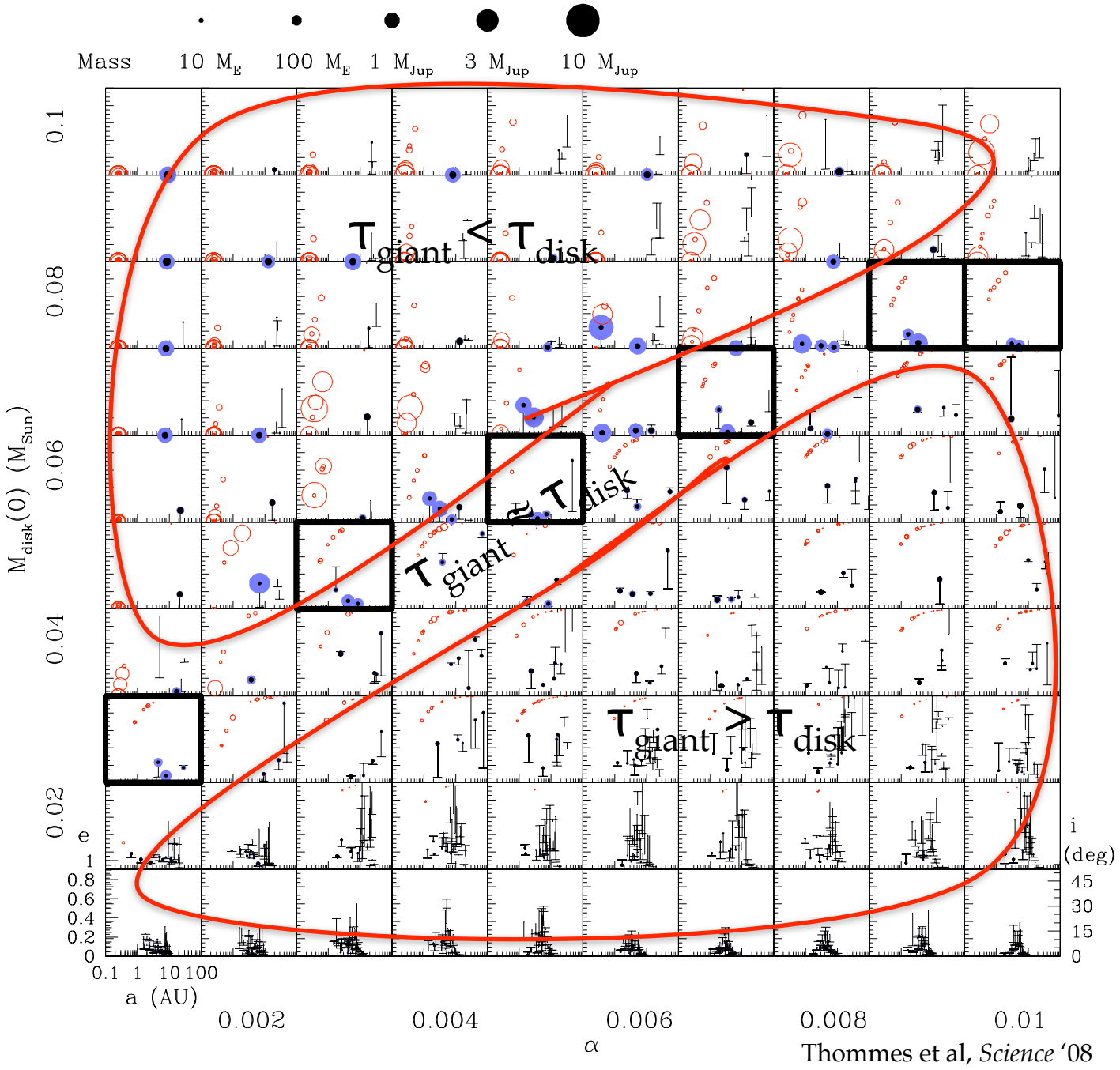

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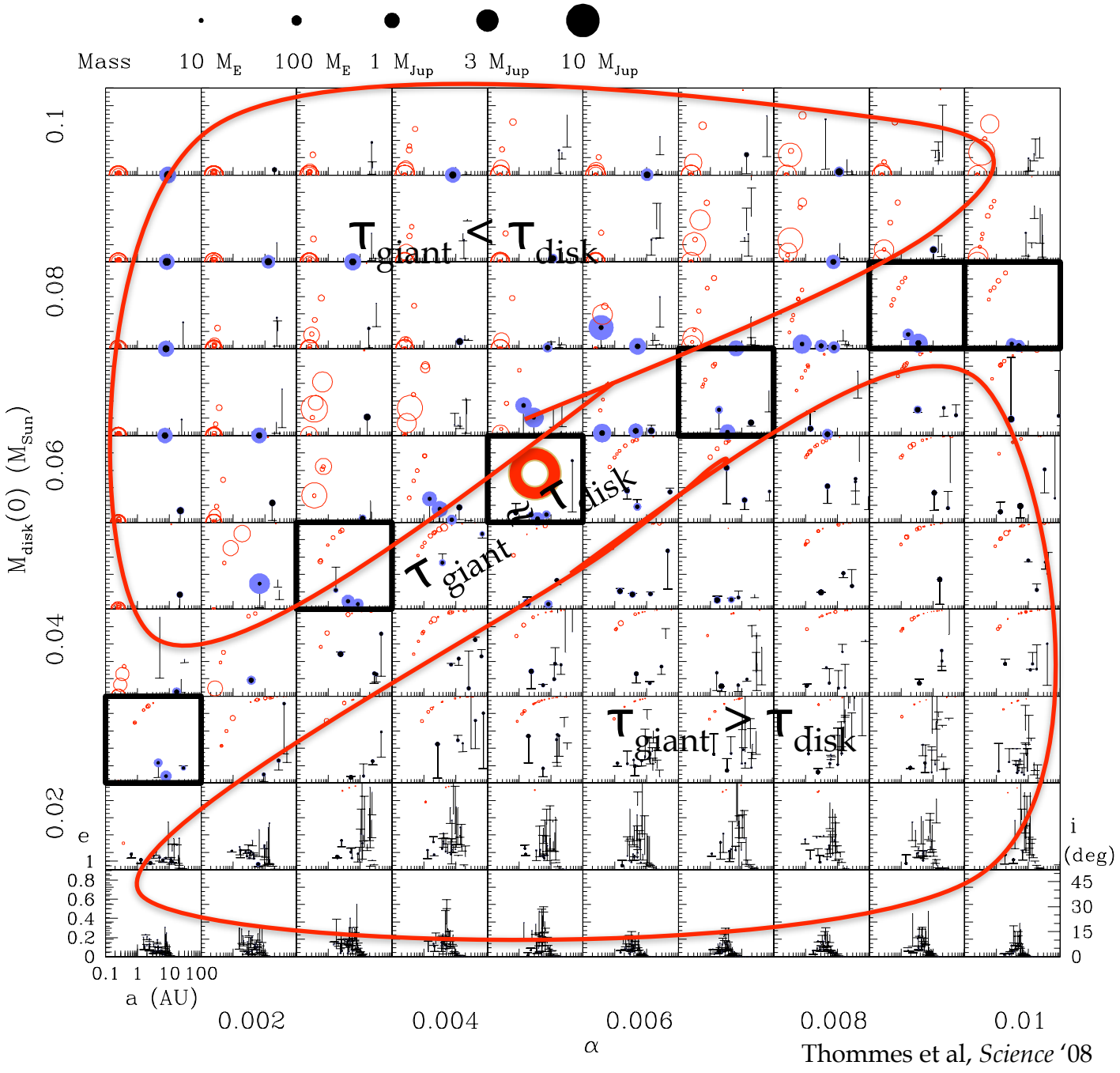

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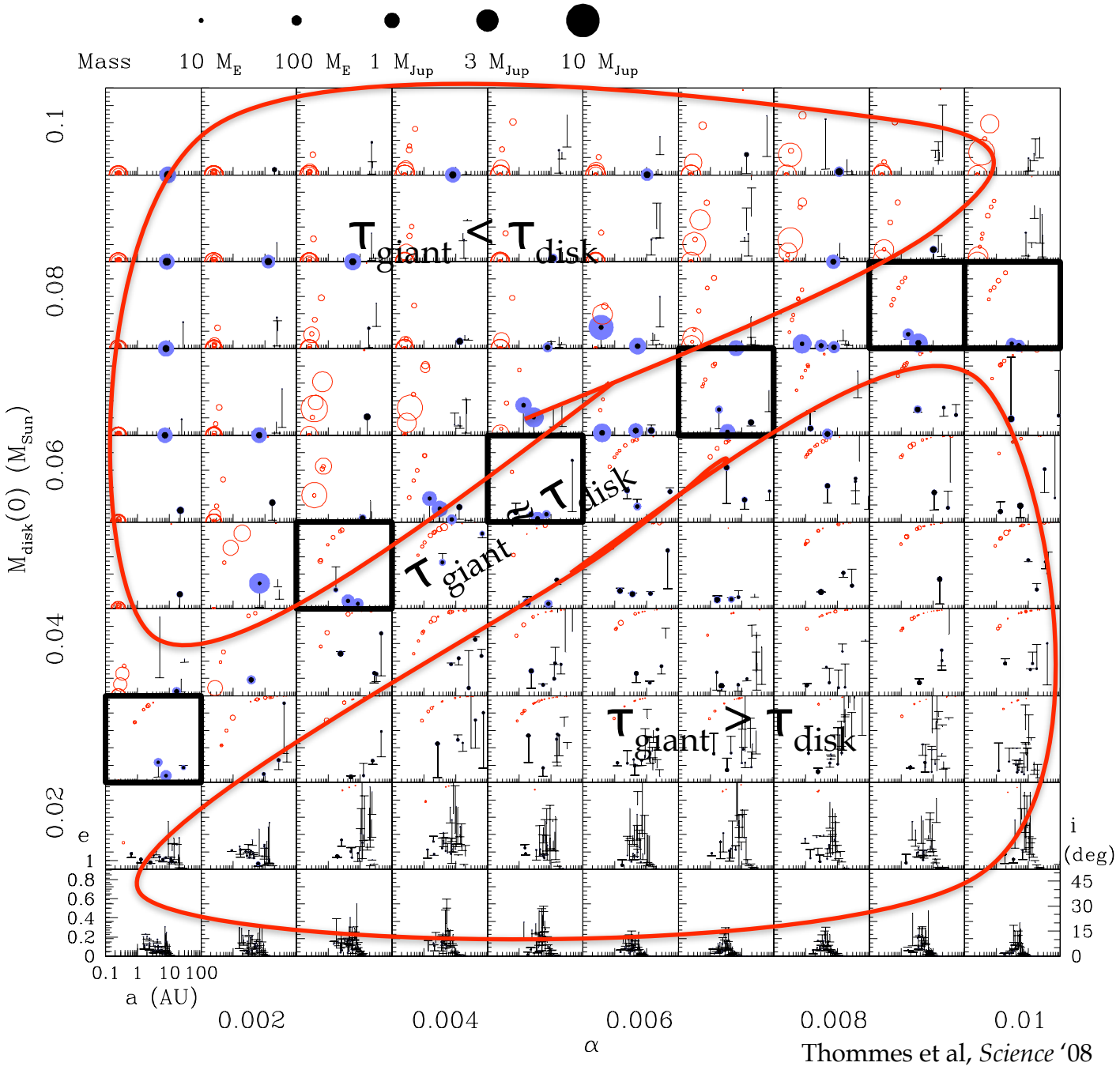

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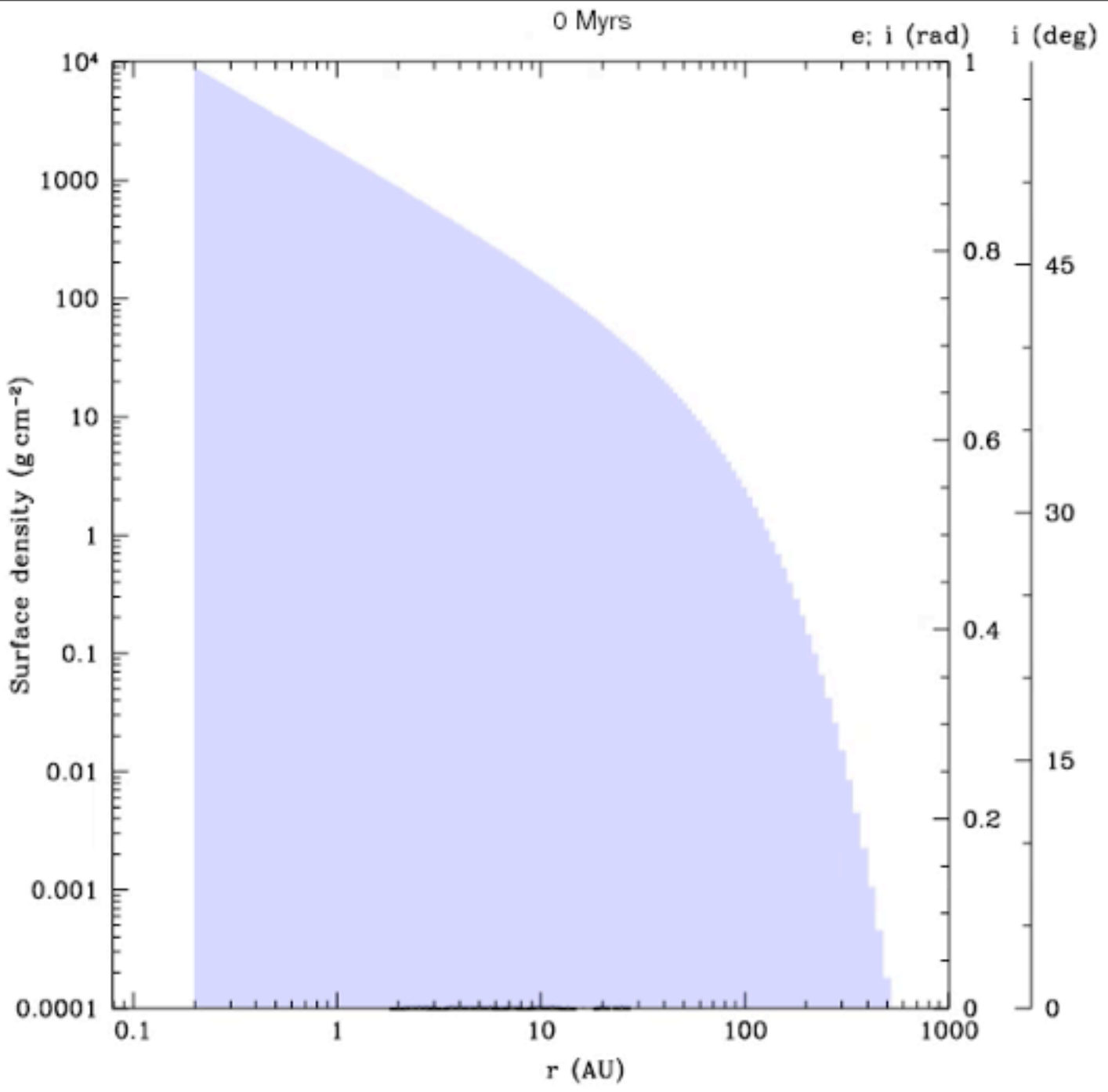

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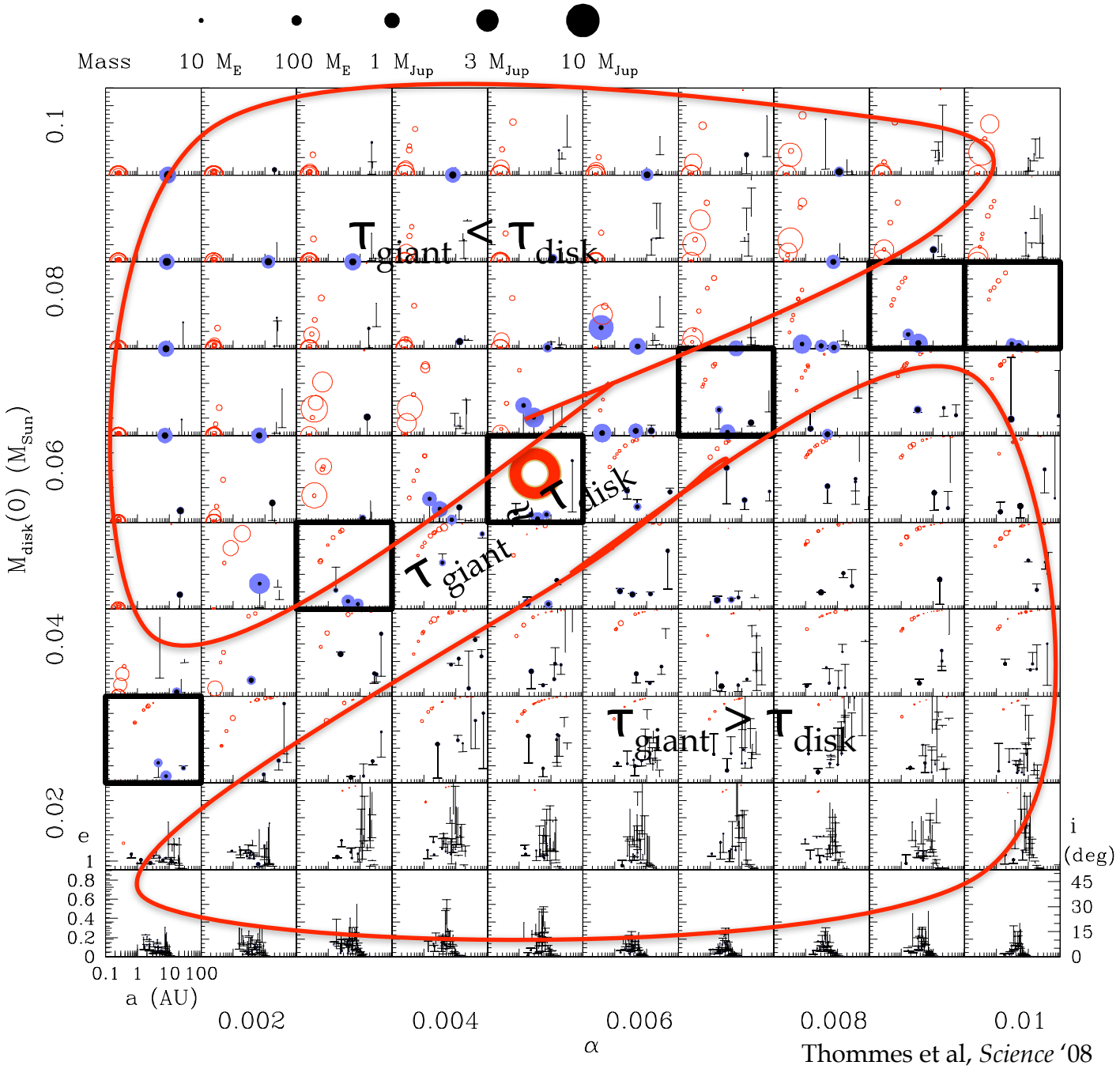

Thommes et al, *Science* '08

Throwing out the leftovers

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- Onset of gas giant formation usually sends out "spray" of scattered cores
- Solves the problem of Uranus and Neptune: originate in the Jupiter/Saturn region, then scattered out (Thommes, Duncan & Levison, *Nature* 1999)
  - ...thus Uranus/Neptune analogues common!
- But that's not all...

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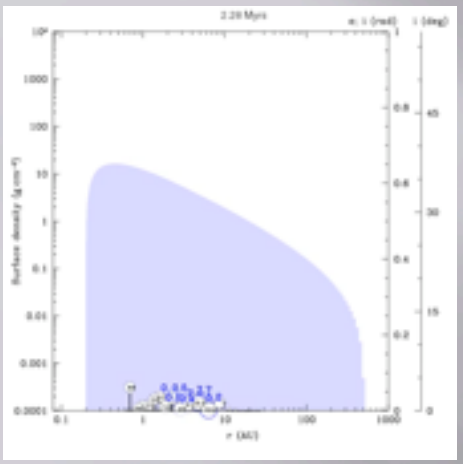

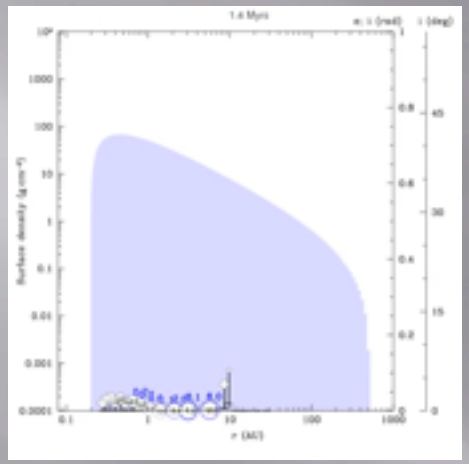

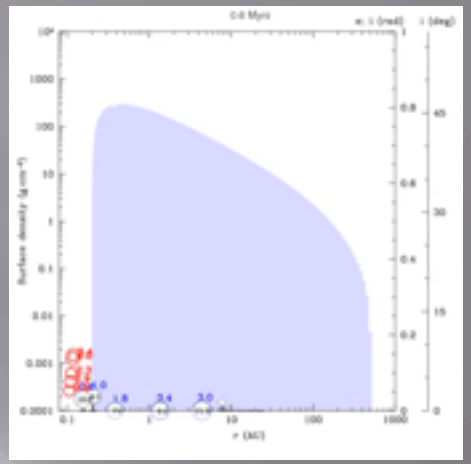

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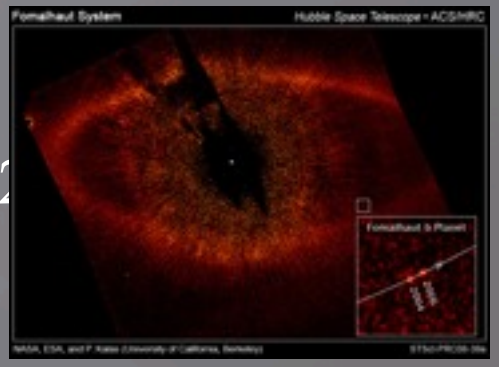
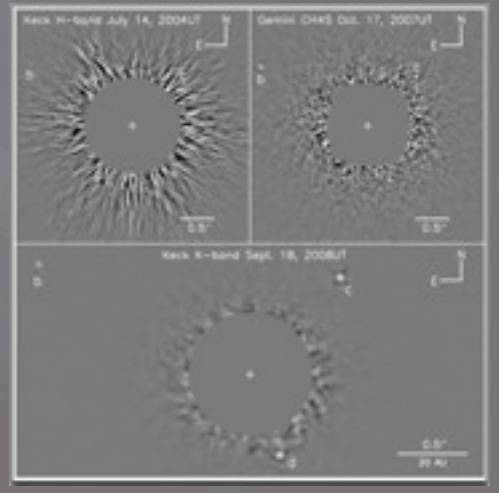
- But that's not all...

Distant giant planets

- Fomalhaut b:
  - Kalas et al. (2008): companion at ~115 AU
  - <3 M_{Jup} (Marengo et al. 2000, Chiang et al. 2
  - low eccentricity, e~0.1



- HR 8799: Marois et al. (2008)
  - d: 24 AU, 10 M_{jup}
  - c: 38 AU, 10 M_{jup}
  - b: 68 AU, 7 M_{jup}
  - ...and all e < 0.4



- 1RXS J160929.1-210524
  - Lafreniere et al. (2008): 330 AU, ~8 M_{jup}

How the $#@& do you grow something like this?!?

- in-situ core accretion? ☹ Not beyond 35 AU (Dodson-Robinson et al. 2009)
- post-formation outward migration...?
  - ...by planetesimal scattering (Hahn & Malhotra 1999 Gomes et al. 2005)? ☹ Not enough plsml mass
  - ...by type III? ☹ Too short-range (Peplinski et al. 2008), anyway not applicable for $M > M_{jup}$
  - ...of 2 planets sharing a gap (Masset & Snellgrove 2001, Crida et al. 2009)? ☹ Requires non-accreting planets
- post-formation scattering? ☹ Stable orbits unlikely (Dodson-Robinson et al. 2009)
- direct gravitational instabily? ☹ Always problematic

Alternative: (i) scatter cores
(ii) cores accrete gas

- Advantages:
  - Cores easily scattered
  - At large radius, core's planetesimal accretion choked off ➡ facilitates runaway gas accretion (Pollack et al. 1996, Ikoma et al. 2000)

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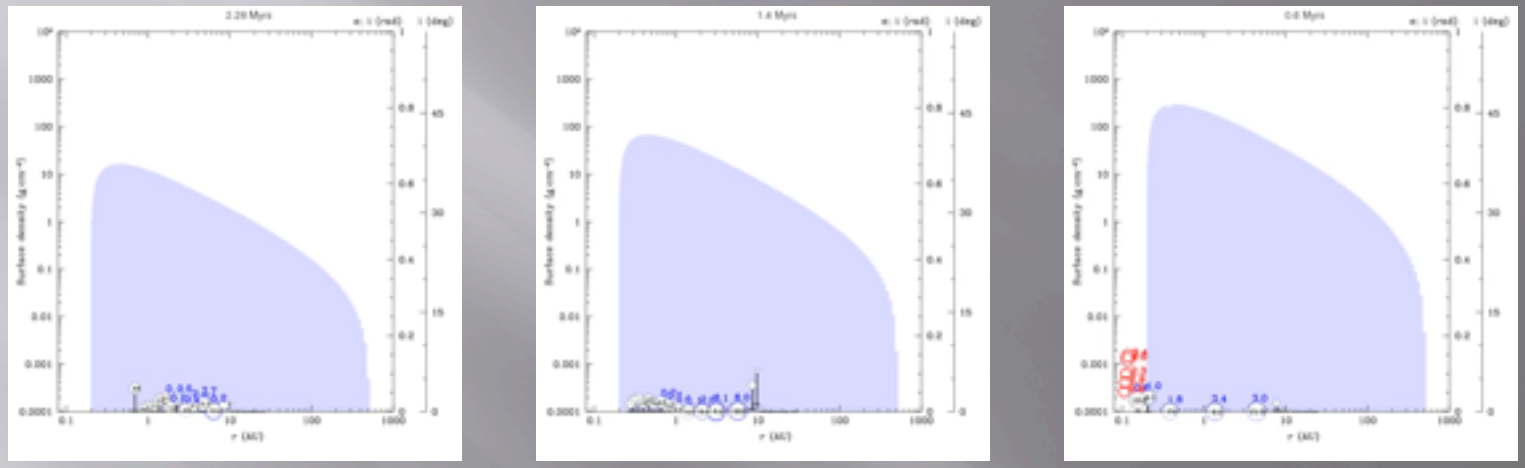

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2D hydro simul

log spacing in radius, 100 and 200 rings/ decade (i.e. 200X314, 400X628)
-> scale height =2.5 and 5 cells at 1 AU, 8 and 16 cells at 100 AU (disk is flared)

- FARGO (Masset 2000, http://fargo.in2p3.fr/)
  - Accretion scheme modified for core accretion (much slower!)
  - Initial condition: M=15 M_Earth, q=10 AU, Q=500 AU, depleted gas disk (1/20 Σ_{MMSN})

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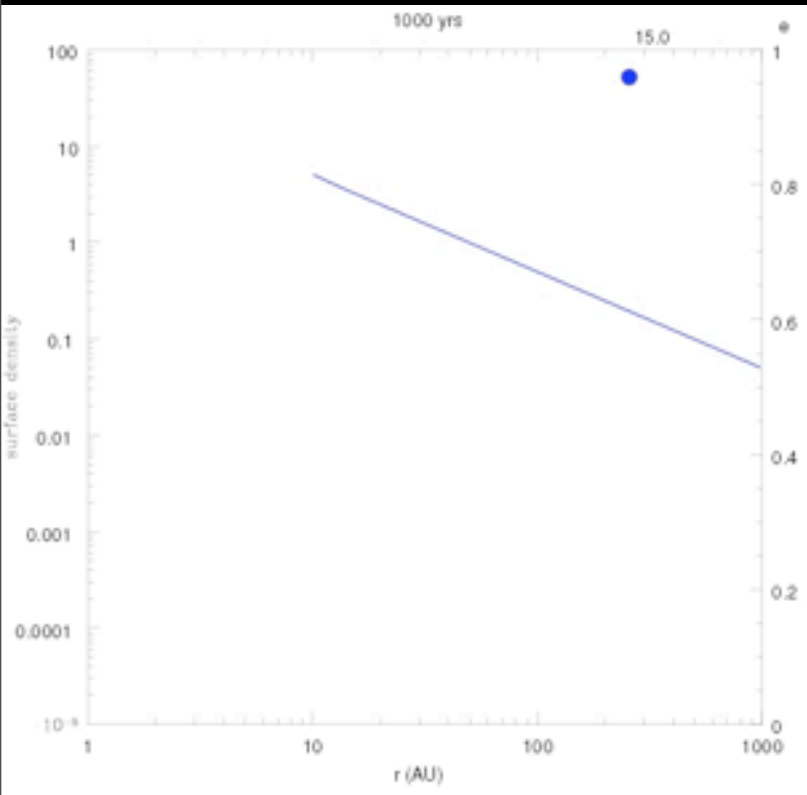

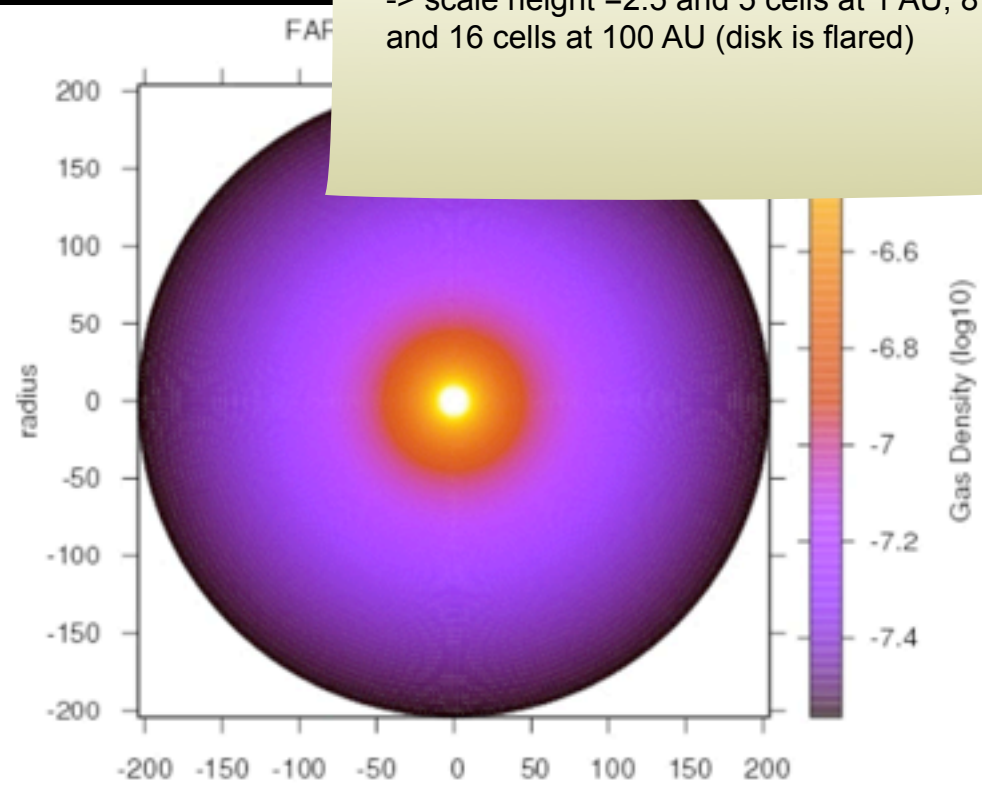

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Summary

- Planetary systems born in complex, stochastic interplay of **planet-disk interaction**, **planet-planet interaction**, and **competitive accretion**
- ... **hot Jupiters, resonances, crowded systems, high eccentricities**
- Solar System analogues when $\tau_{giant} \approx \tau_{disk}$ **probably less common**
- Scattered cores **ARE** common. End up as
  - failed cores, i.e. **Uranus/Neptune analogues**
  - **distant giant planets**
  - possible variant: **outward core migration** by planetsimal scattering (Levison, Thommes & Duncan 2010, **arXiv:0912.3144**

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