Violence in Planet Formation

Edward W. Thommes
University of Guelph

Exoplanets Rising: Astronomy and Planetary Science at the Crossroads
Kavli Institute for Theoretical Physics, UC Santa Barbara, 2 April 2010

“The best way to deal with ~~bureaucrats~~ planets is with stealth and sudden violence.”

-Butros Butros-Ghali, Former UN Secretary General

Cast

Collaborators:

- Sourav Chatterjee (Northwestern)
- Martin Duncan (Queen's)
- Natasha Holmes (Guelph, now UBC, M.Sc.)
- Hal Levison (SwRI)
- Doug Lin (UCSC/KITP)
- Ryan Massey (Guelph, M.Sc.)
- Soko Matsumura (Maryland)
- Makiko Nagasawa (Tokyo Tech)
- Fred Rasio (Northwestern)
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Special appearances by:

- Mortensen, V.
- van Damme, J.-C.
- Connery, S.
- Asterix & Obelix
- Thurman, U.
- Willis, B.
- Stallone, S.
- McDowell, M.

A history of violence

- Exoplanets: orbits imply unruly history
- Solar System: Average planetary system or "gated community"?
- Repeated theme of orderly evolution transitioning to chaos

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Dynamical instability models

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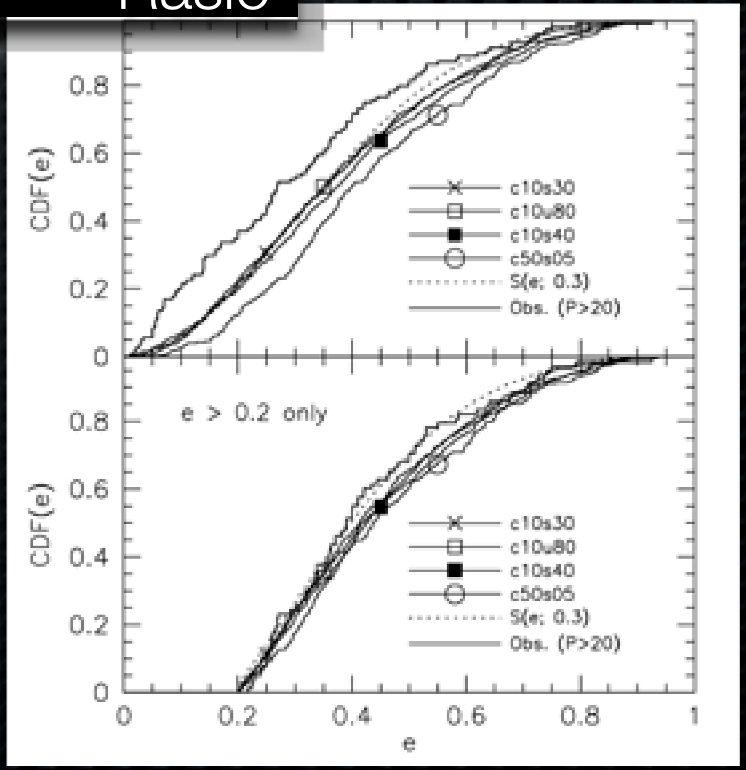
- Subsequent work:
  - Simple scattering reproduces exoplanet *e*-distribution quite well (Juric & Tremaine 2008, Chatterjee et al. 2008), systems need only be "dynamically active"
  - Nagasawa, Ida & Bessho (2008): scattering+Kozai+tidal circularization=hot Jupiters

Rasio



Juric & Tremaine (2008)

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Simulation Time: 00.0 years

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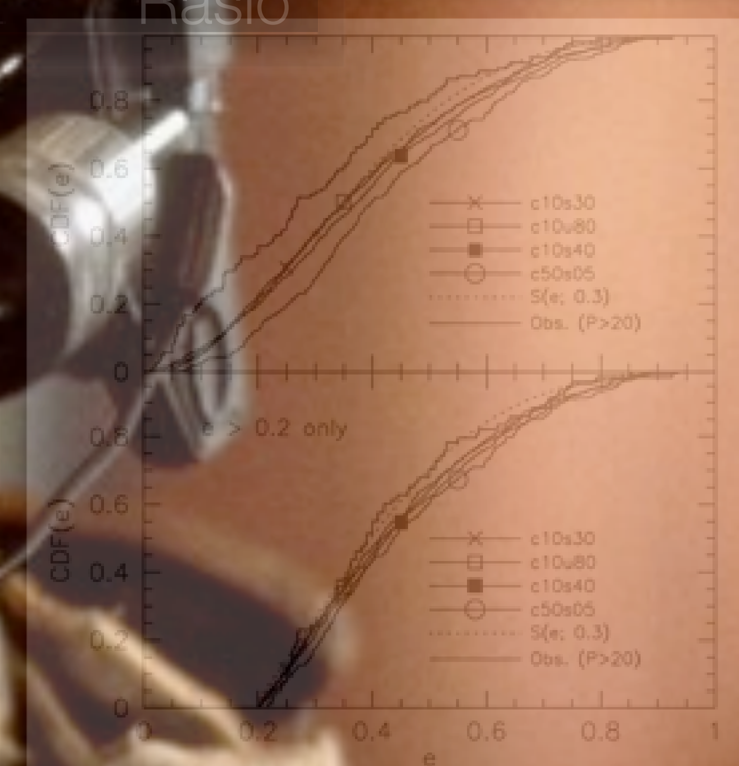

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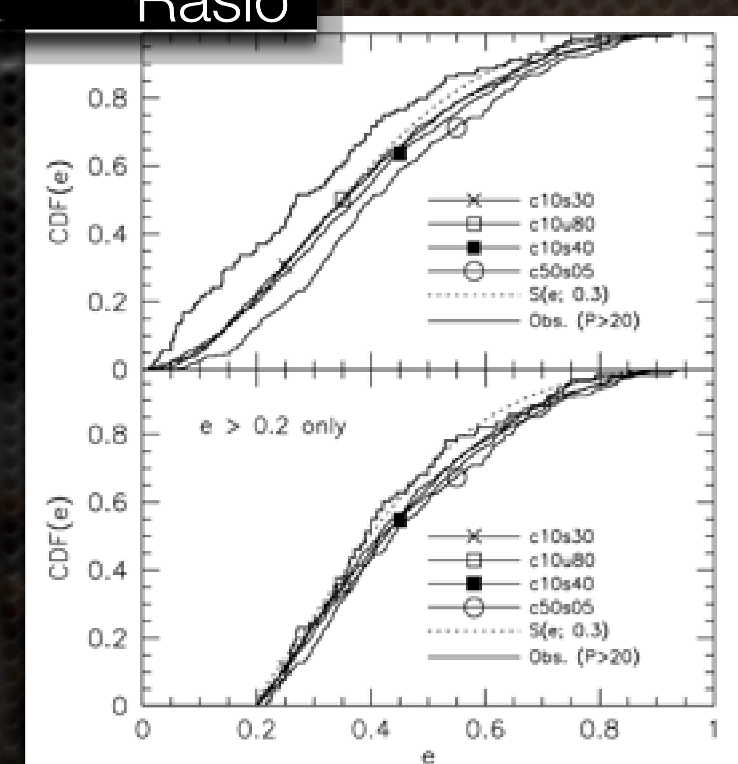

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Violence in the Solar System?

- Scattering origin for Uranus and Neptune (Thommes, Duncan & Levison, *Nature* 1999)
  - ice giants form in Jupiter-Saturn zone, simply **“failed cores”** scattered out when Jupiter/Saturn accrete gas
  - **dynamical friction** with planetesimal disk re-circularizes scattered cores
  - addresses problem of **prohibitive formation time** at 20+ AU

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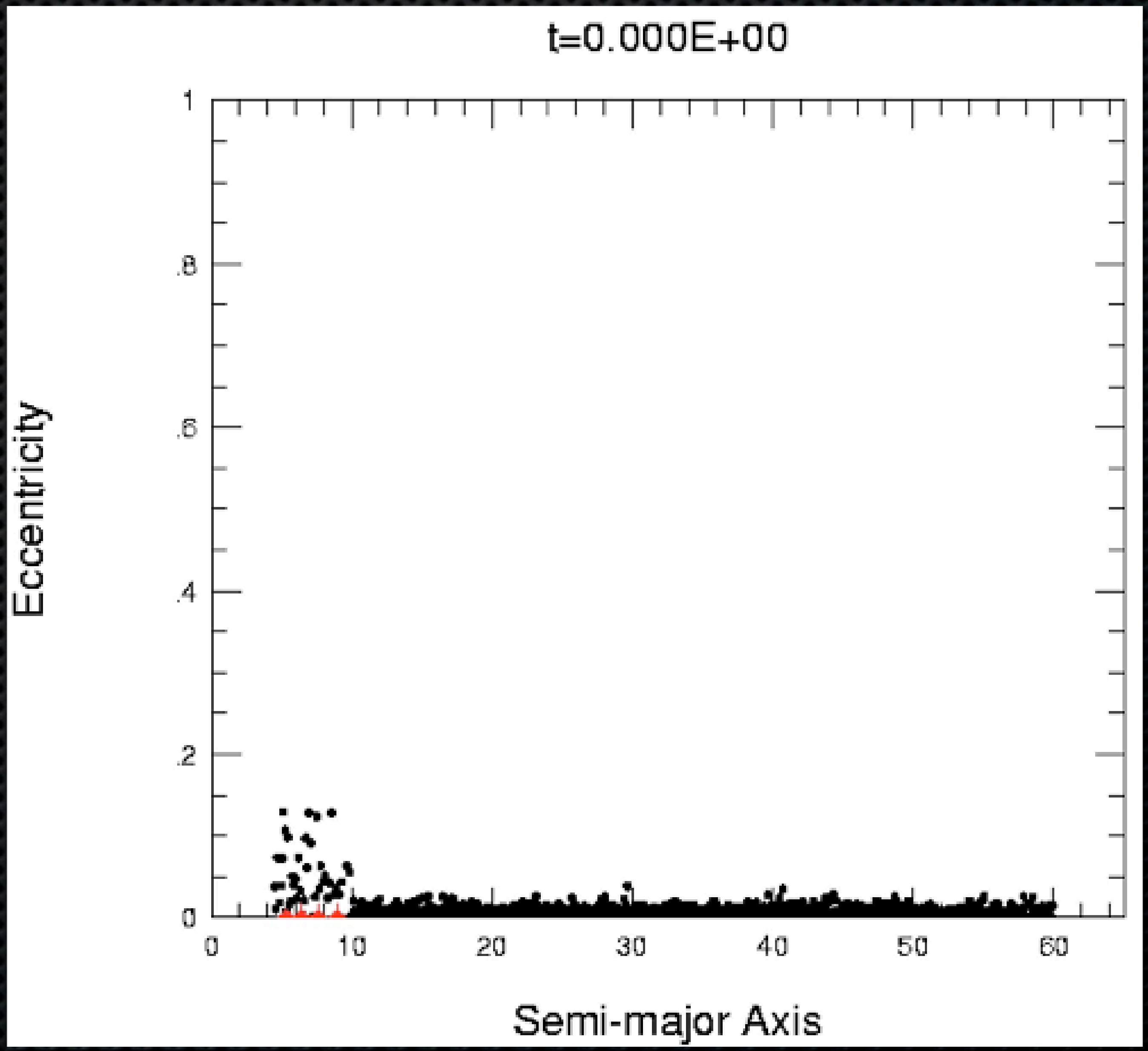

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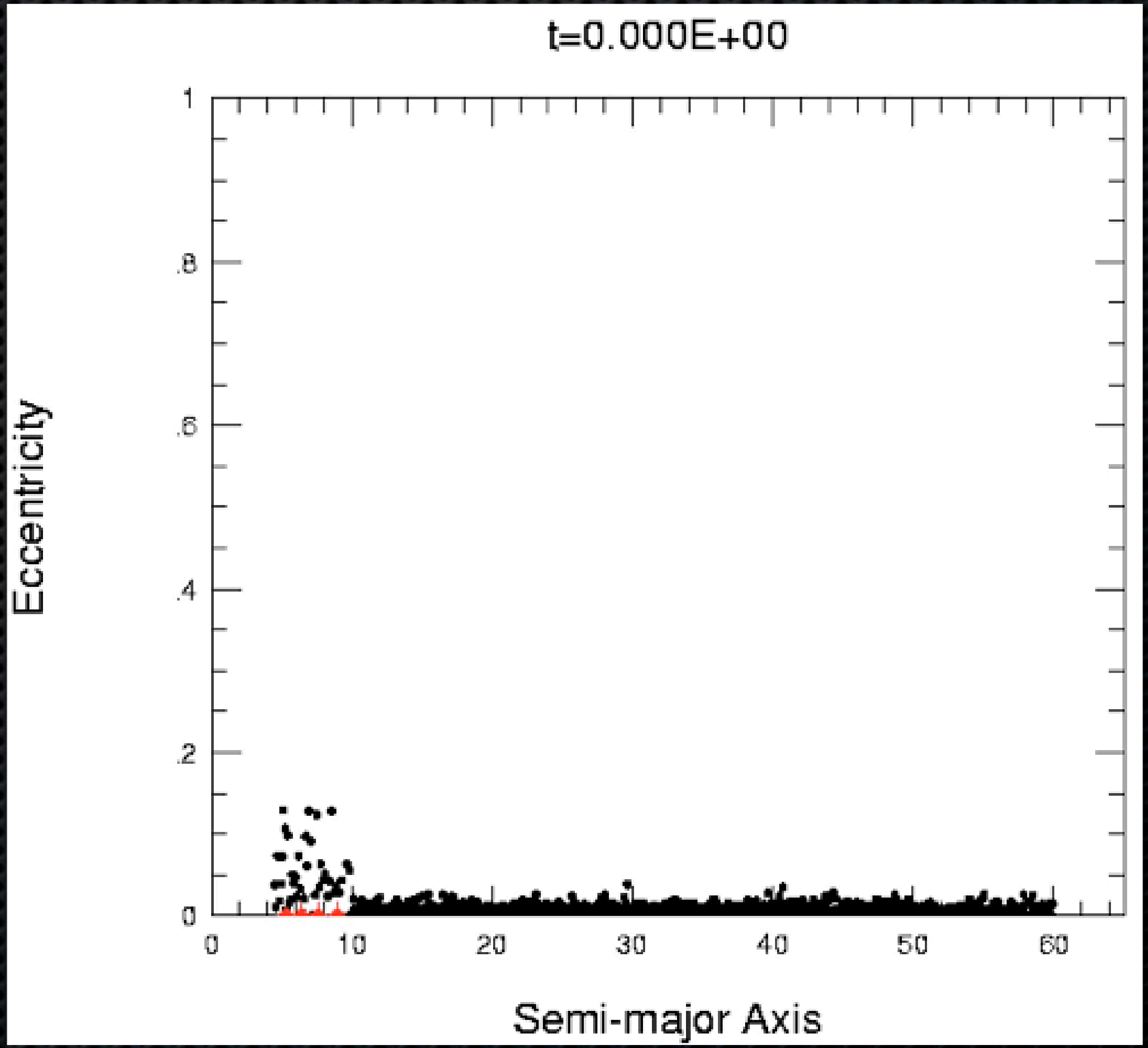

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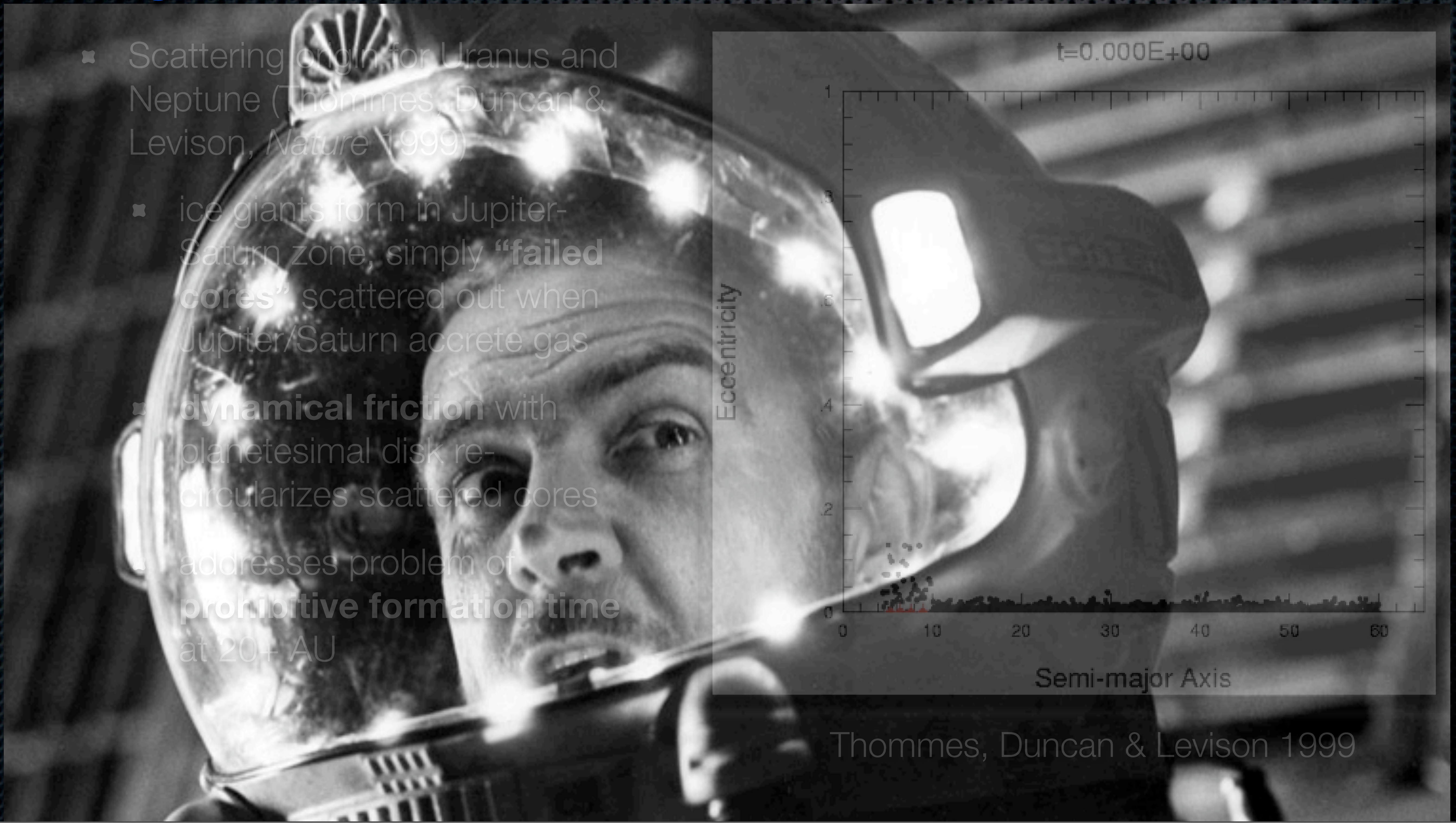

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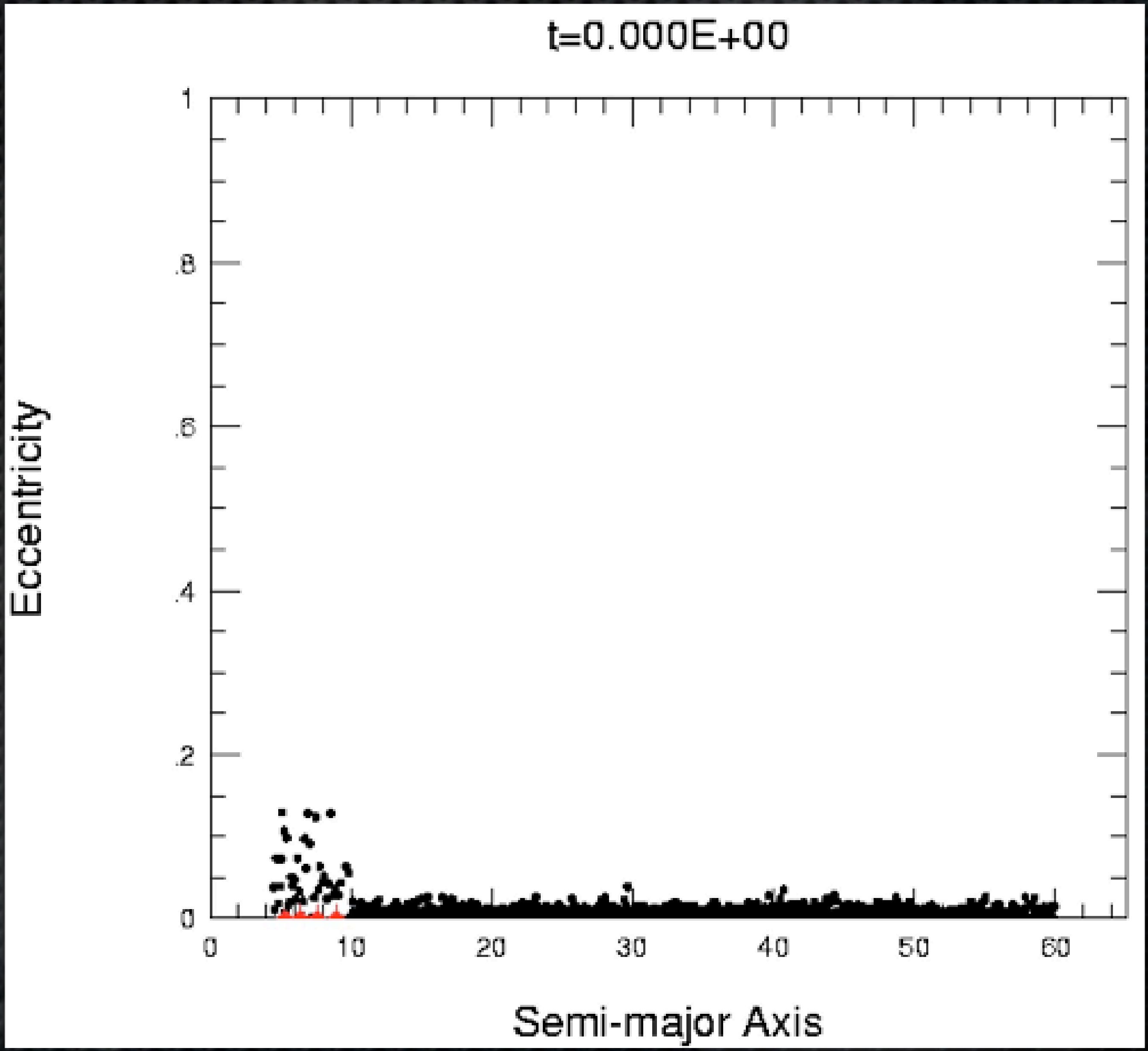
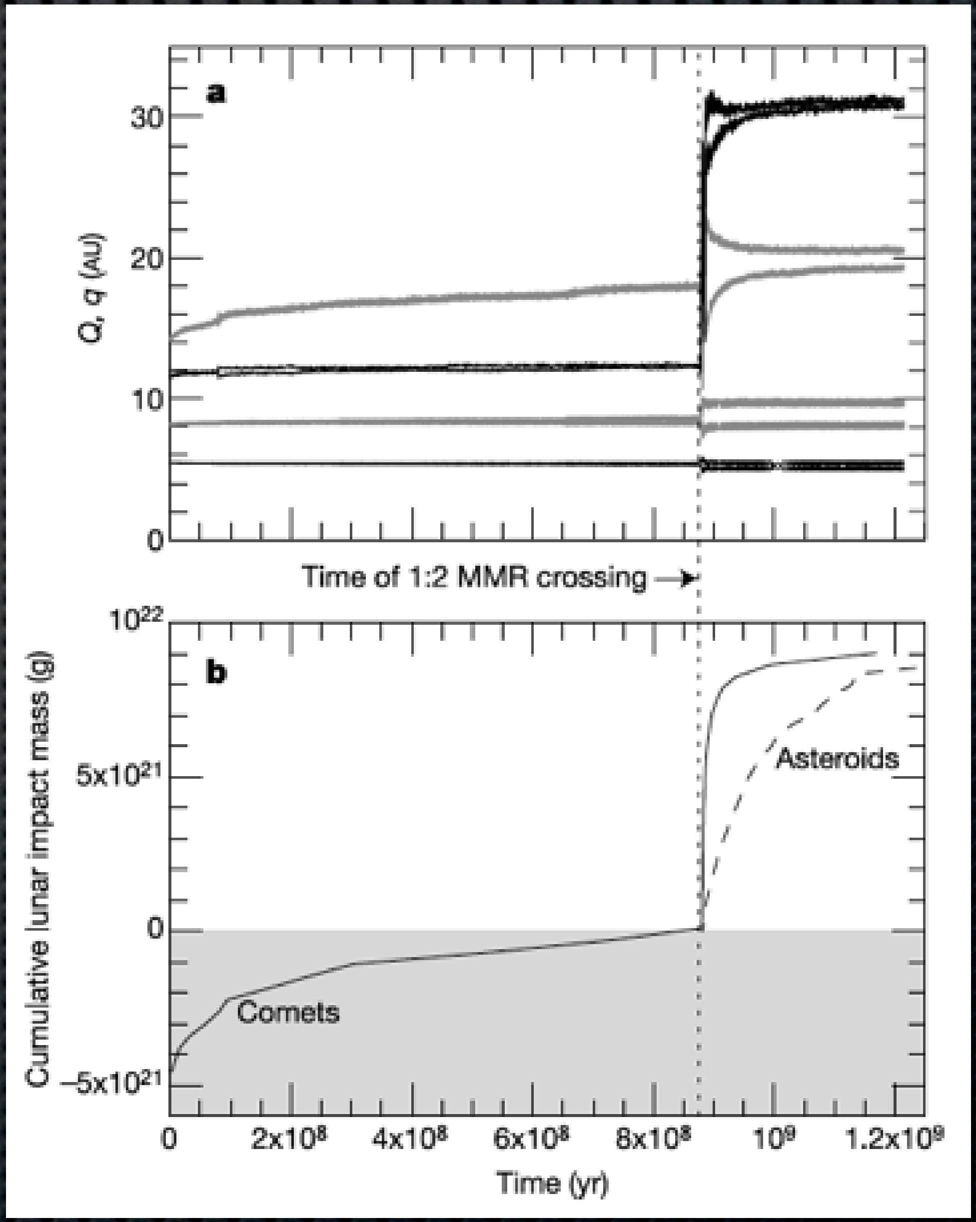


Thommes, Duncan & Levison 1999

Solar System violence II: The Late Heavy Bombardment

- “Nice” model: Gomes et al., *Nature* 2005)
  1. start with **initially-compact** Solar System of Thommes et al (1999)
  2. ...make it remain compact for **700 Myrs**...
  3. ...and have it blow apart when Jupiter and Saturn **divergently** cross their 2:1 resonance (Peale 1986, Chiang, Fischer & Thommes 2002)
- Problem: **2.** needs **significant fine-tuning**
- **Fix**: lock everything into stabilizing mean-motion resonances (Morbidelli et al. 2007, Thommes et al. 2008)
  - ...still difficult to assemble, but at least 700 Myr stability becomes plausible
  - generalized version of mechanism may break MMRs, produce high eccentricities at late times in exoplanetary systems (Thommes et al. 2008)



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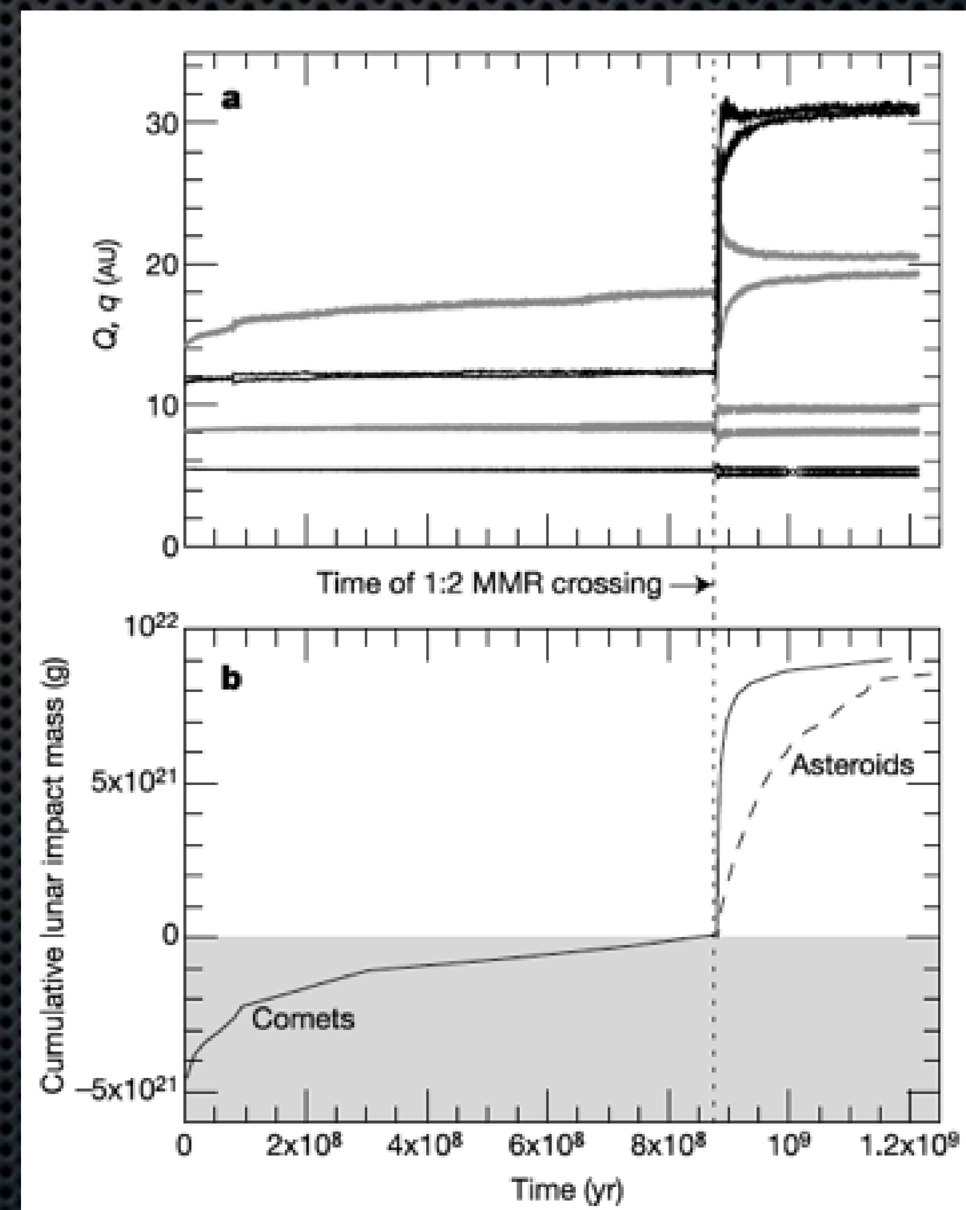

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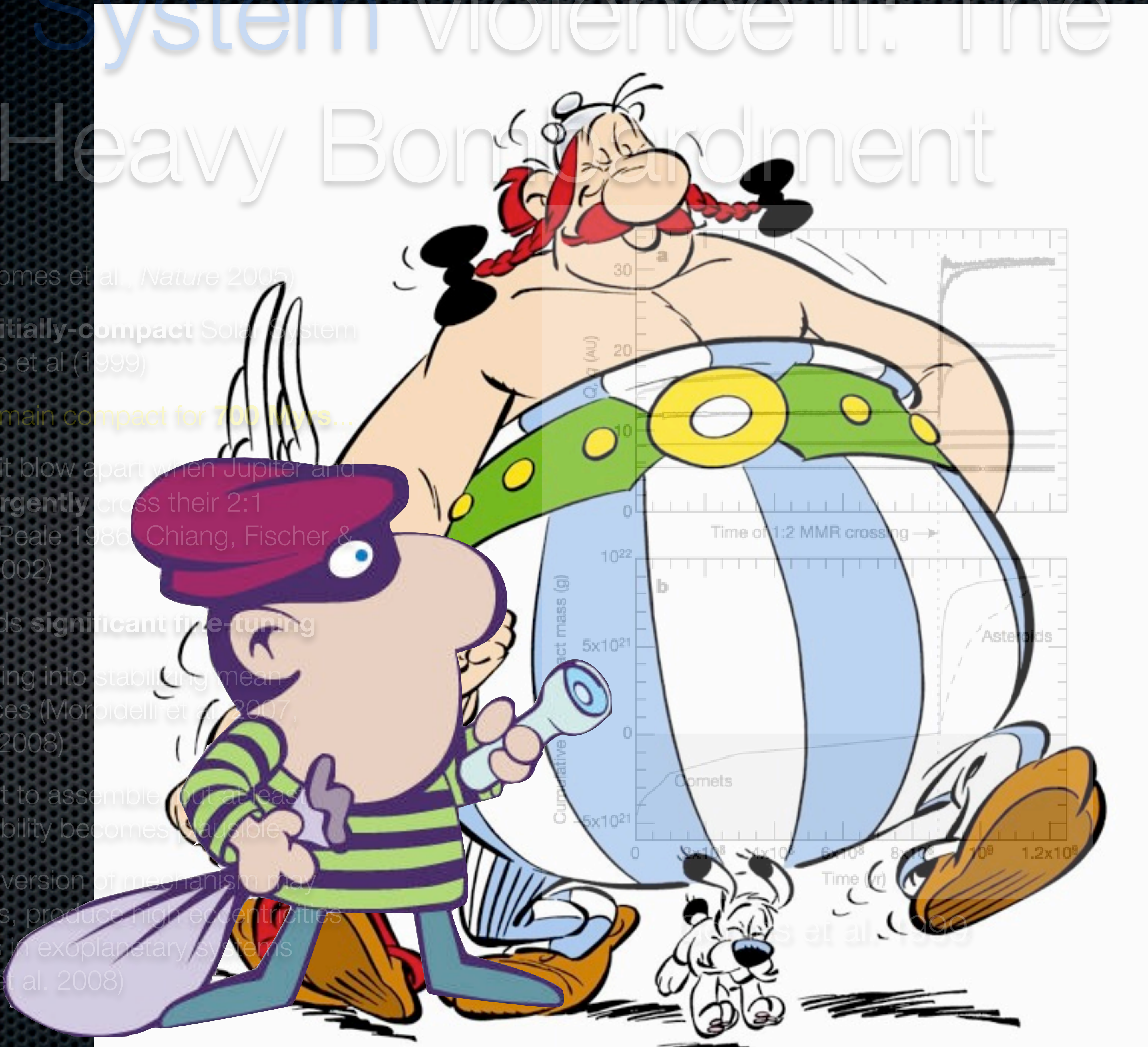

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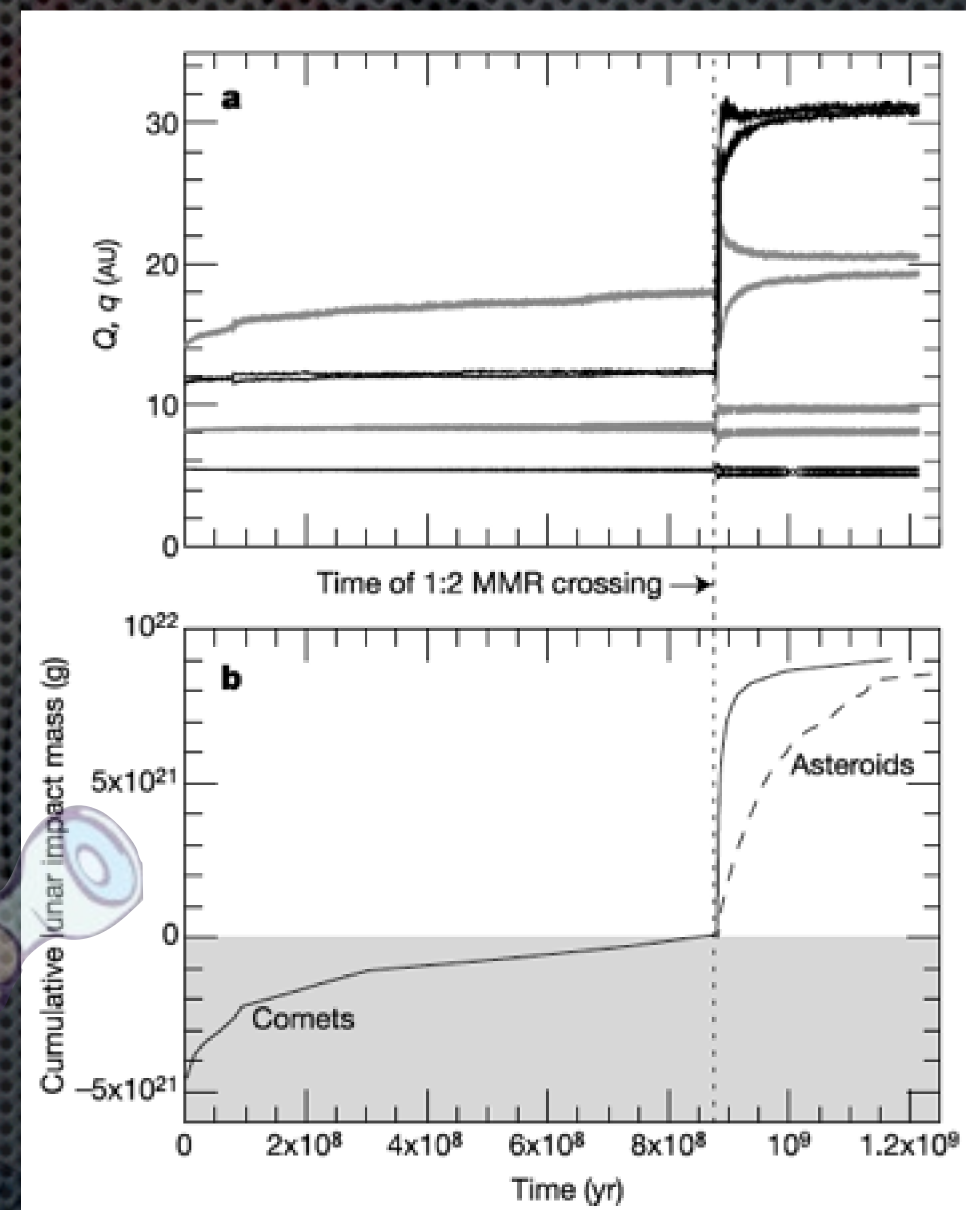

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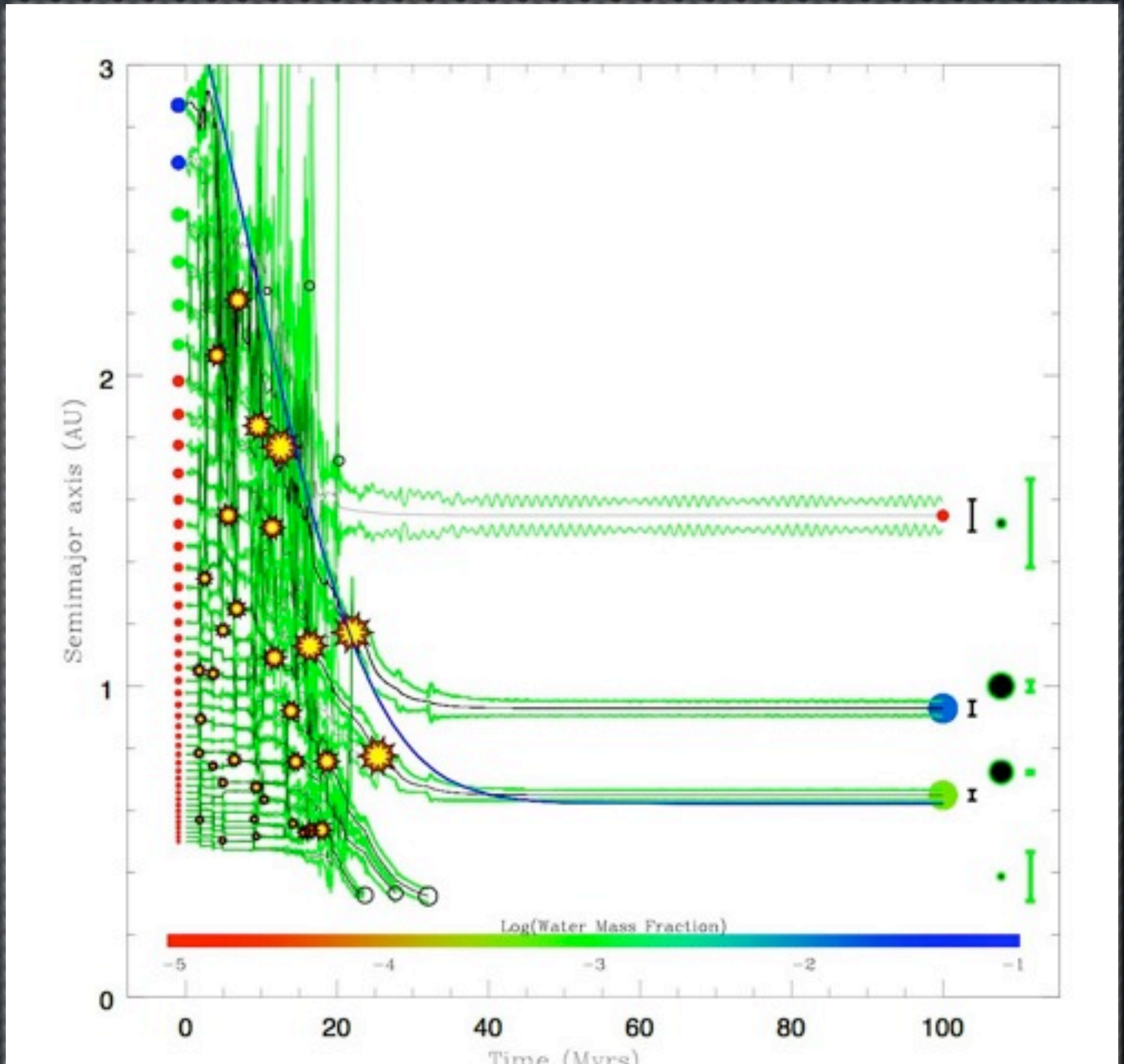
Solar System violence III: Terrestrial planets by "dynamical shakeup"

- Nagasawa, Lin & Thommes (2005), Thommes, Nagasawa & Lin (2008)
- ν_5 **secular resonance** of exterior gas giant sweeps inward as gas disk dissipates
- Eccentricities of terrestrial protoplanets excited
  - mergers happen **rapidly**
  - **inward migration** as eccentricities damped
- The "giant impact" stage of terrestrial planet formation can play out in just **a few 10s of Myrs** (vs. several 100 Myrs in standard model)
- Type I effects of remnant gas produce **low, Solar System-like eccentricities**



Thommes, Nagasawa & Lin

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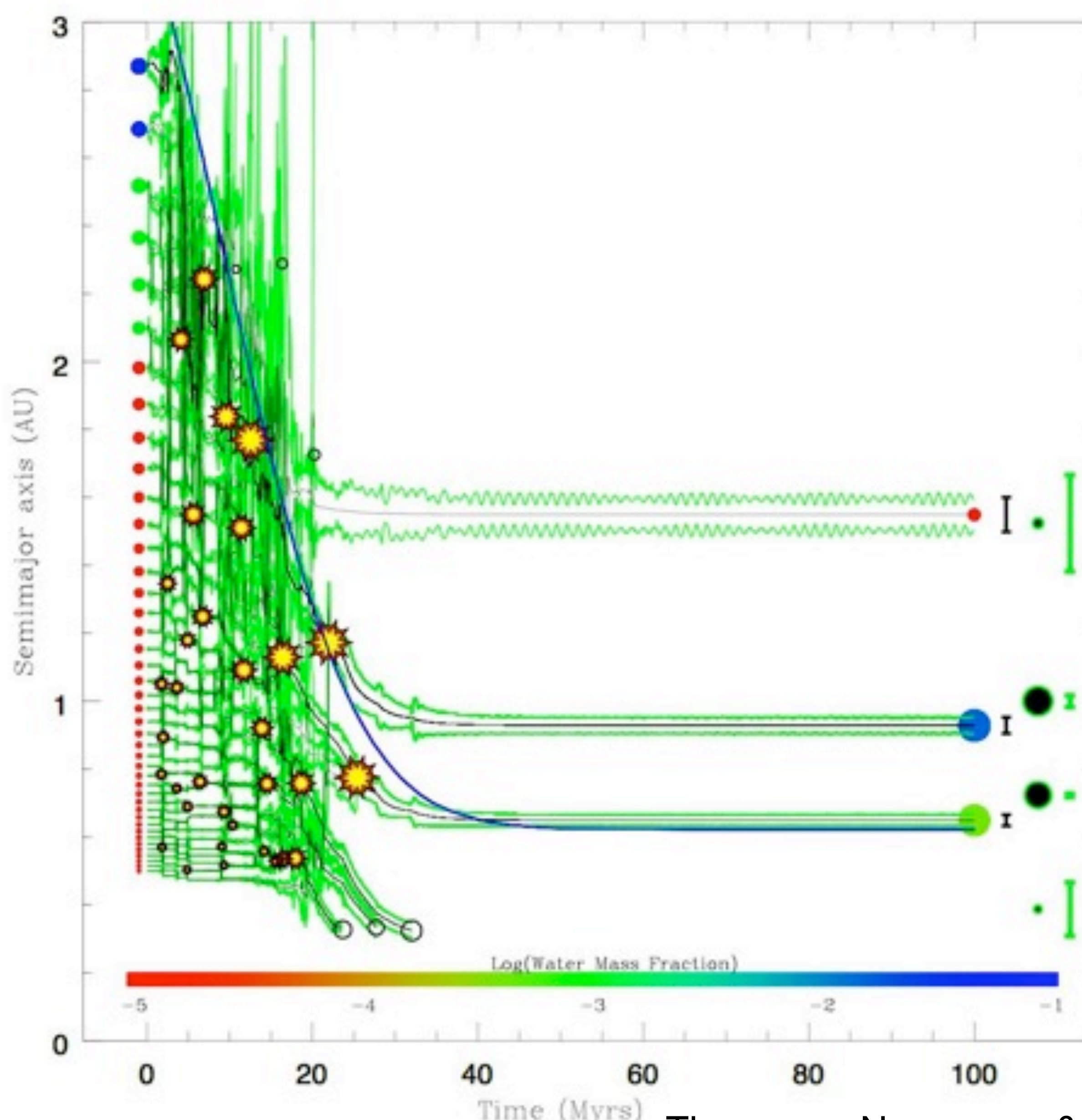

Thommes, Nagasawa & Lin

Giant planet violence: Runaway cores

- Latest semianalytic oligarchic growth model successfully produces cores (Chambers 2008)...
- But N-body study (Levison, Thommes & Duncan 2010) shows **new wrinkles:**
  - major planetesimal **redistribution** by embryos; smooth plsml disk assumption oversimplified
  - cores grow in **rapid “runaway migration” modes**
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  - fragmentation usually bad, unless fragment size ∈ [3m, 30m]

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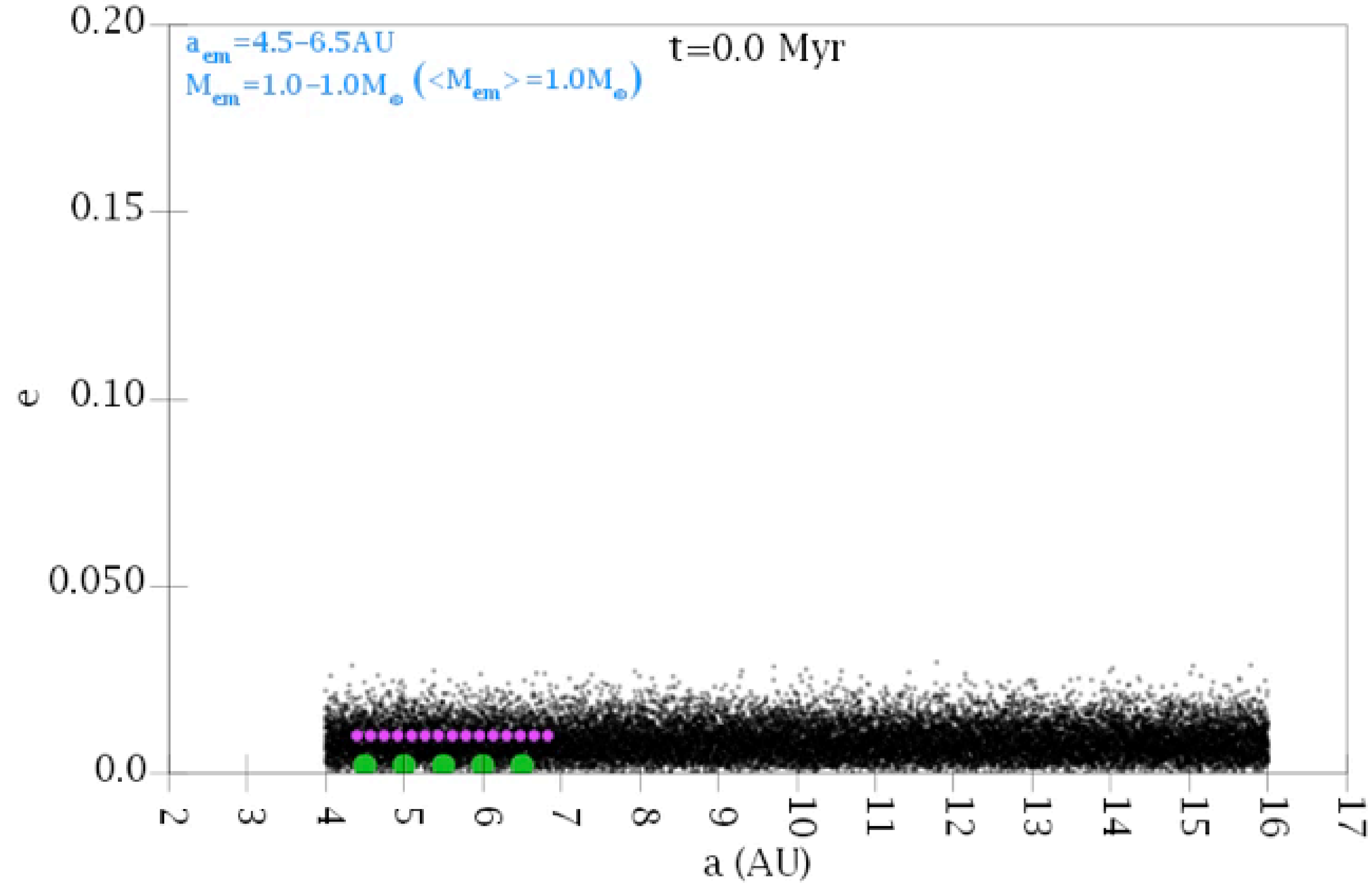

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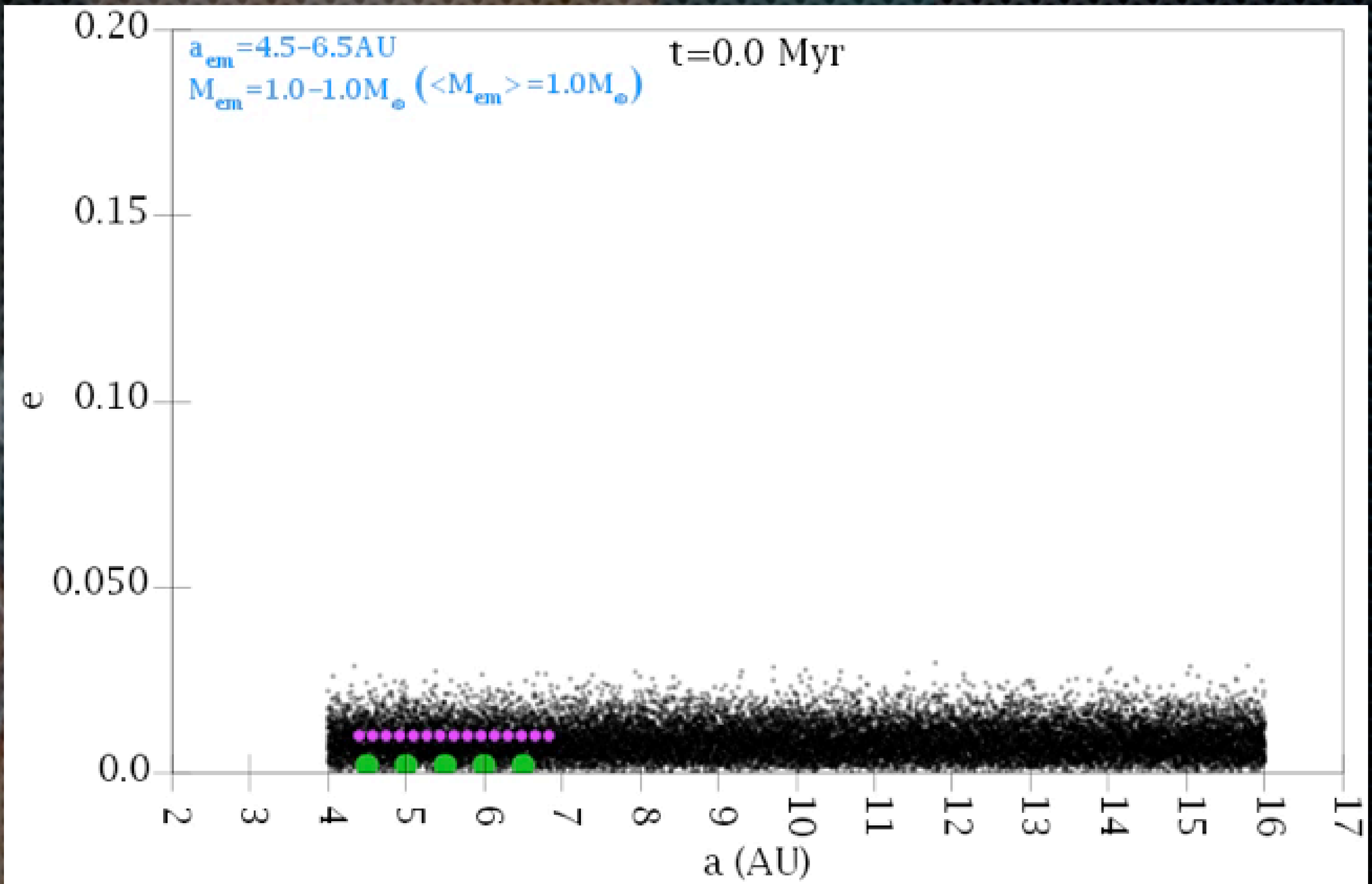
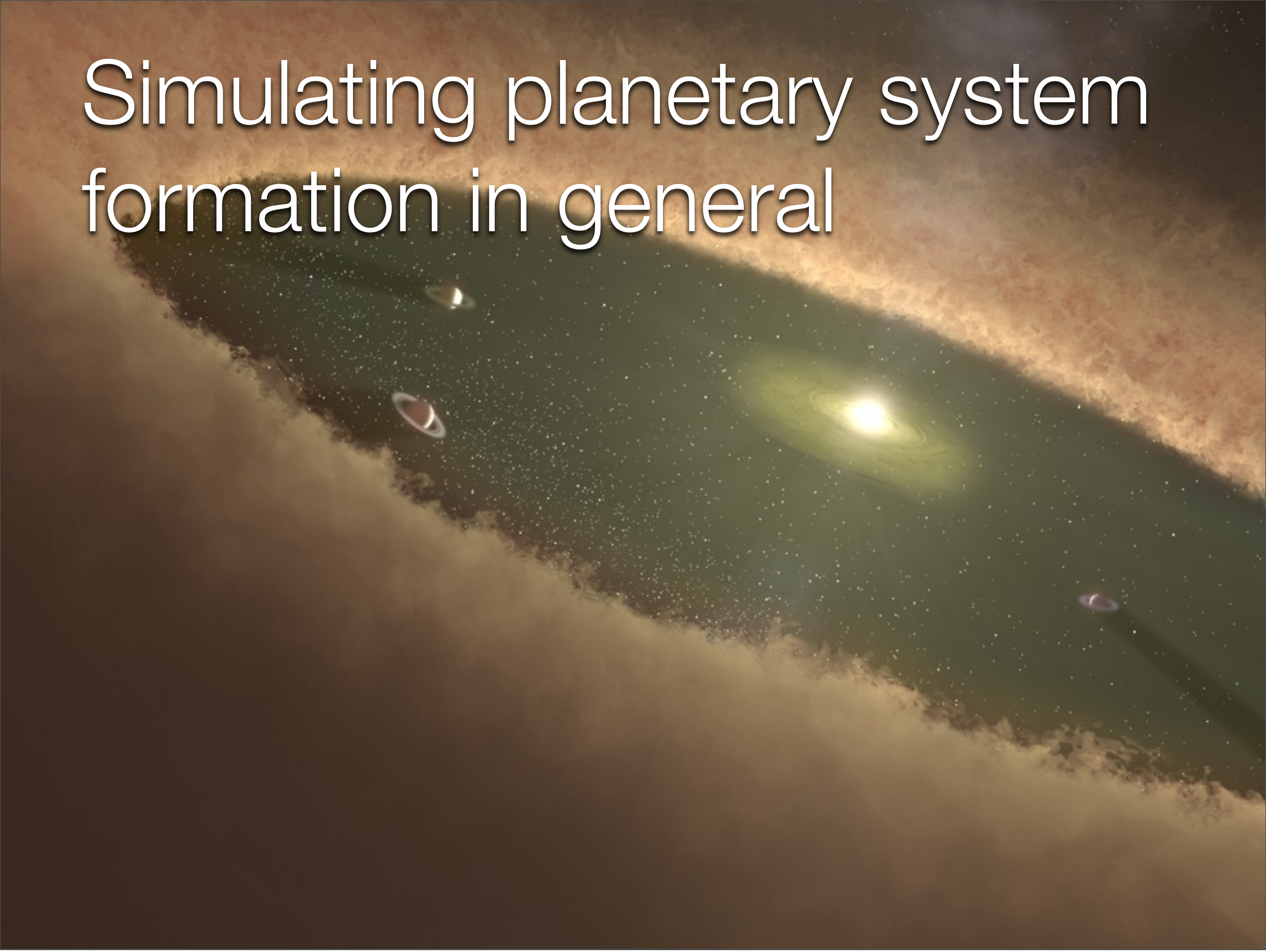


Levison, Thommes & Duncan 2010

Simulating planetary system formation in general



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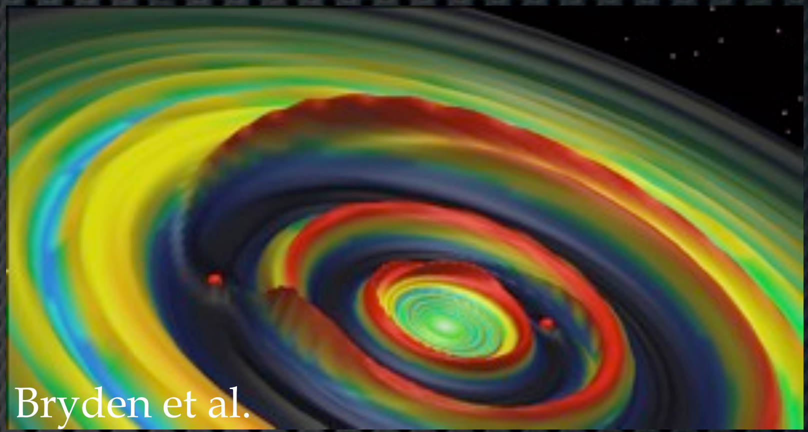
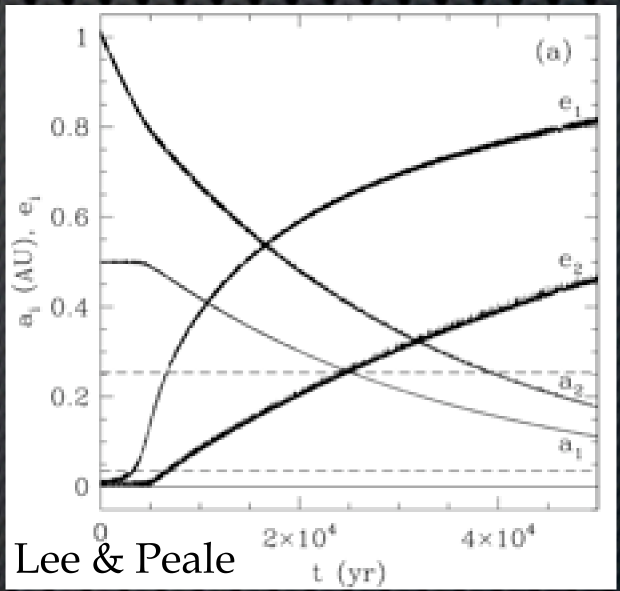
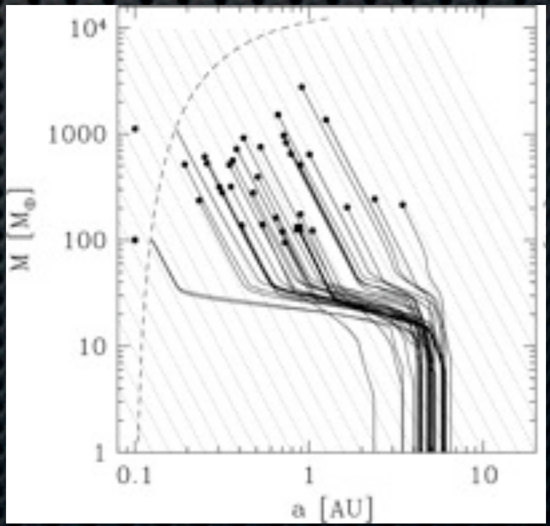


Bryden et al.

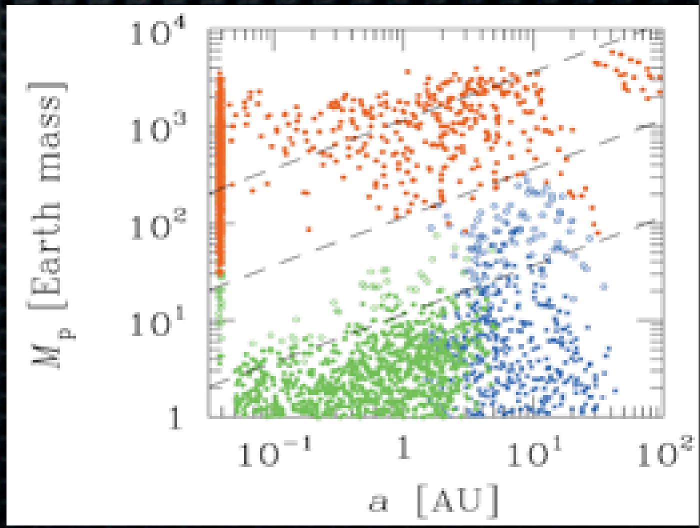
- **Full 2d/3d hydrodynamic simulations:** e.g. Artymowicz, Bryden, Edgar, Klahr, Kley, Lin, Lubow, Masset, Nelson, Papaloizou, Quillen, Rice, Tanigawa, Varnière, Watanabe...
  - all the physics, but high computational cost; only short “snapshots” possible
- **N-body with simple “disk forces”:**
  - Early stages: Kokubo & Ida 2002, Thommes, Duncan & Levison 2003 (gas drag only; 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
- **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), Mordasini et al. (2009)



Lee & Peale



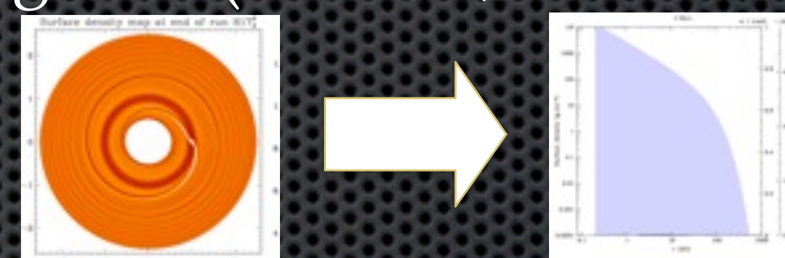
Mordasini, Alibert et al.



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)

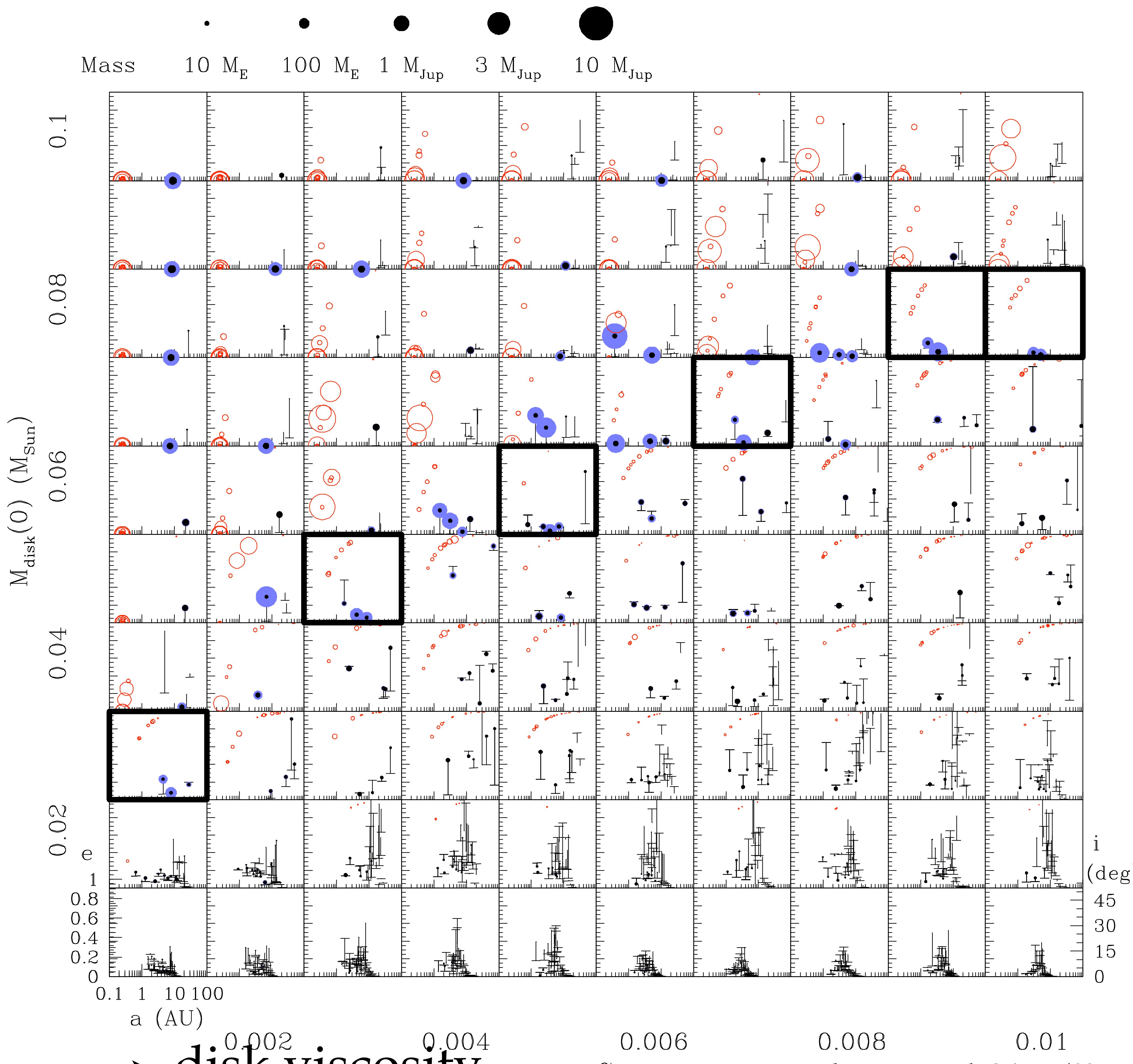
$$\frac{\partial \Sigma_{\rm gas}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[3r^{1/2}\frac{\partial}{\partial r}(\nu \Sigma_{\rm gas} r^{1/2}) - \frac{r^{1/2}}{\pi\sqrt{GM_*}}\frac{\partial T}{\partial r}\right]$$

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:

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

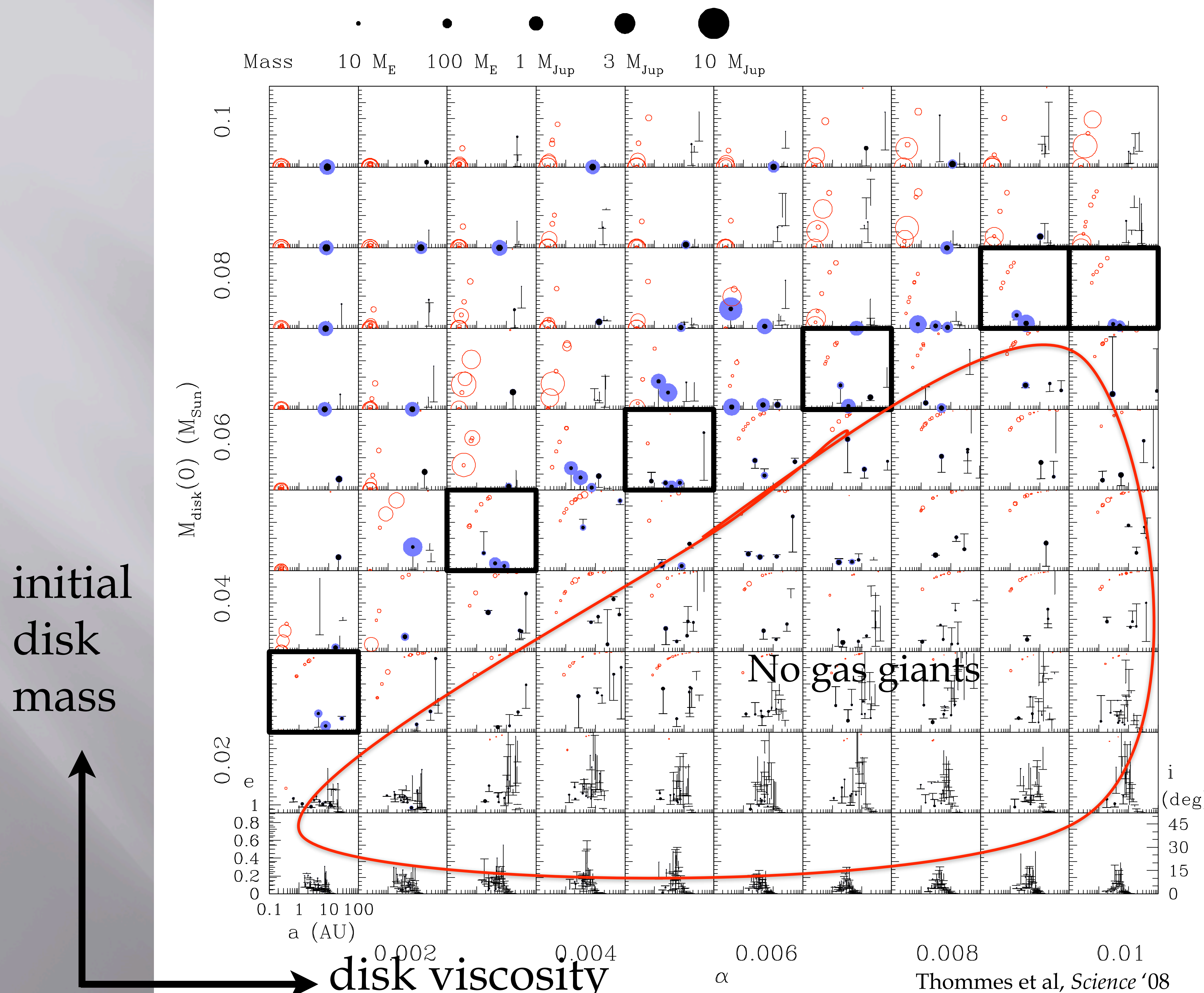
- Gas accretion:
  - assume core accretion
  - Early core accretion: fit to Pollack et al. (1996), like Bryden et al. (2000)
  - Later: fit to hydro simulations (Tanigawa & Watanabe 2002). **See Machida et al. (2010) for latest...**
- Solids accretion: Oligarchic growth (Kokubo & Ida 1998) with gas-envelope enhancement, scaled to Chambers (2006)
- **...Can model life of a typical protostellar disk in 1-2 weeks.**

initial
disk
mass

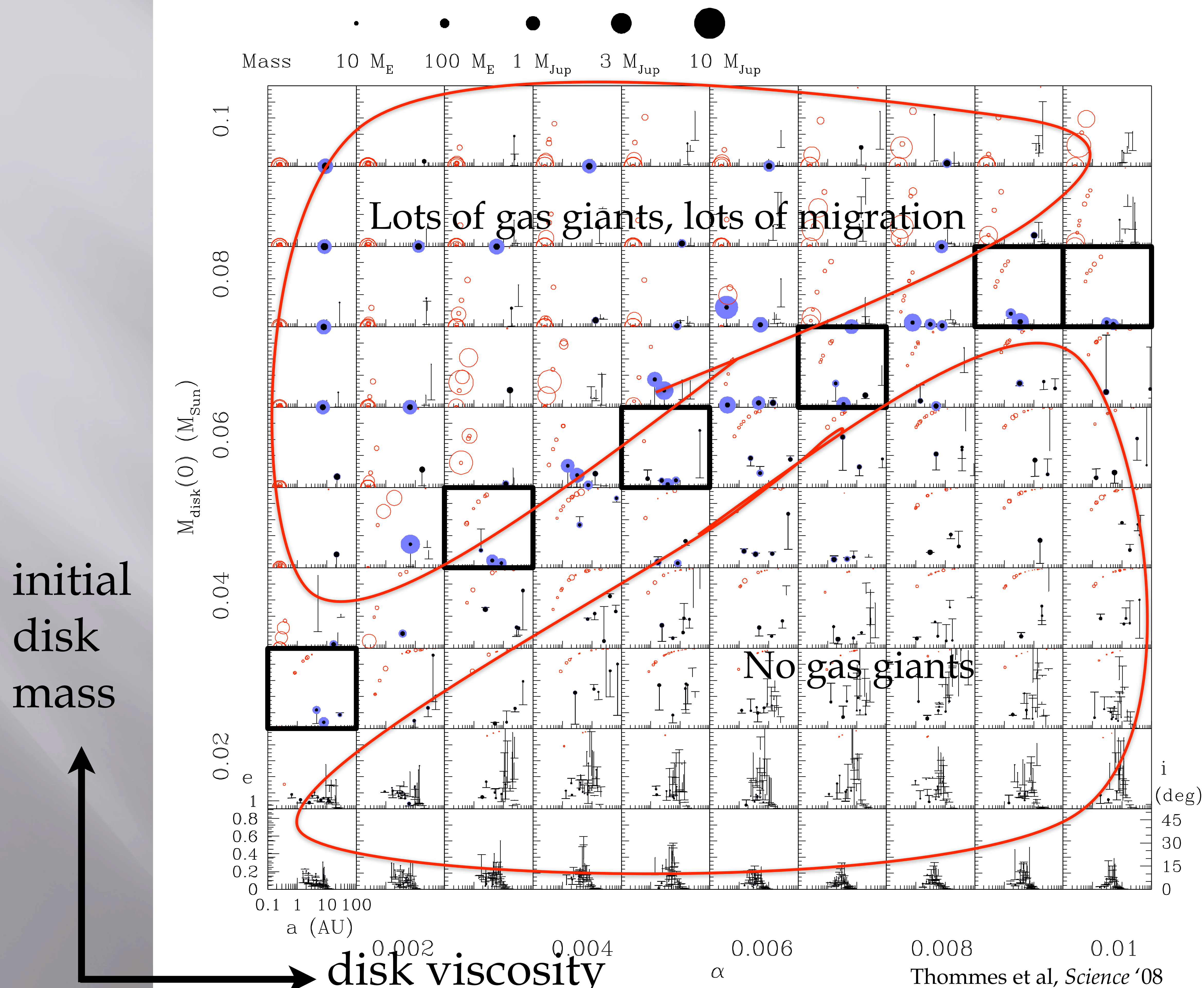


disk viscosity

Thommes et al, *Science* '08



Mass
10 M_E
100 M_E
1 M_{Jup}
3 M_{Jup}
10 M_{Jup}
$M_{disk}(0)$ (M_{Sun})
0.1
0.08
0.06
0.04
0.02
e
1
0.8
0.6
0.4
0.2
0
0.1 1 10 100
a (AU)
i
(deg)
45
30
15
0
No gas giants
0.002
0.004
0.006
0.008
0.01
α
initial disk mass
disk viscosity
Thommes et al, *Science* '08


Mass
10 M_E
100 M_E
1 M_{Jup}
3 M_{Jup}
10 M_{Jup}
Lots of gas giants, lots of migration
No gas giants
$M_{disk}(0)$ (M_{Sun})
0.1
0.08
0.06
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e
1
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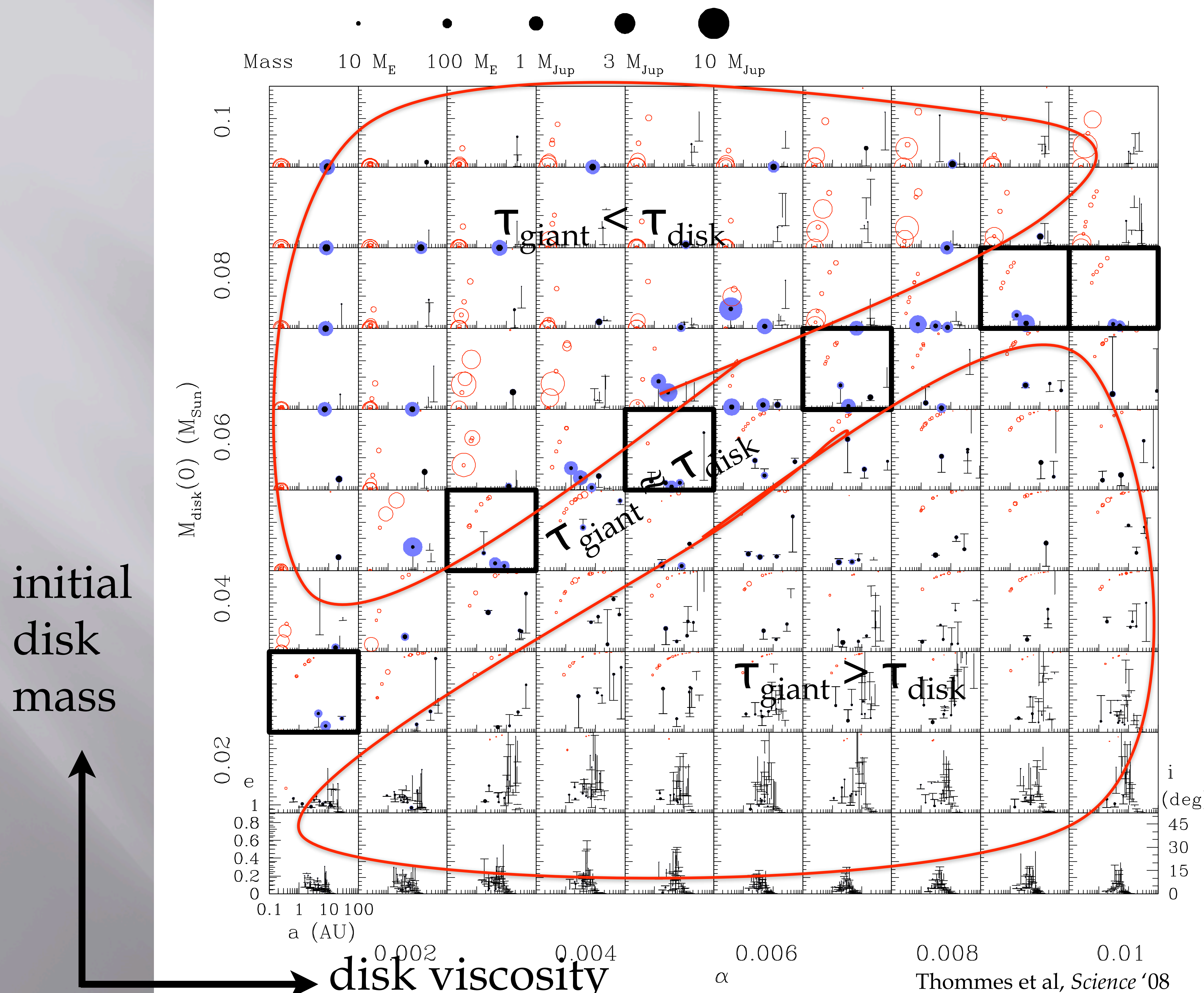

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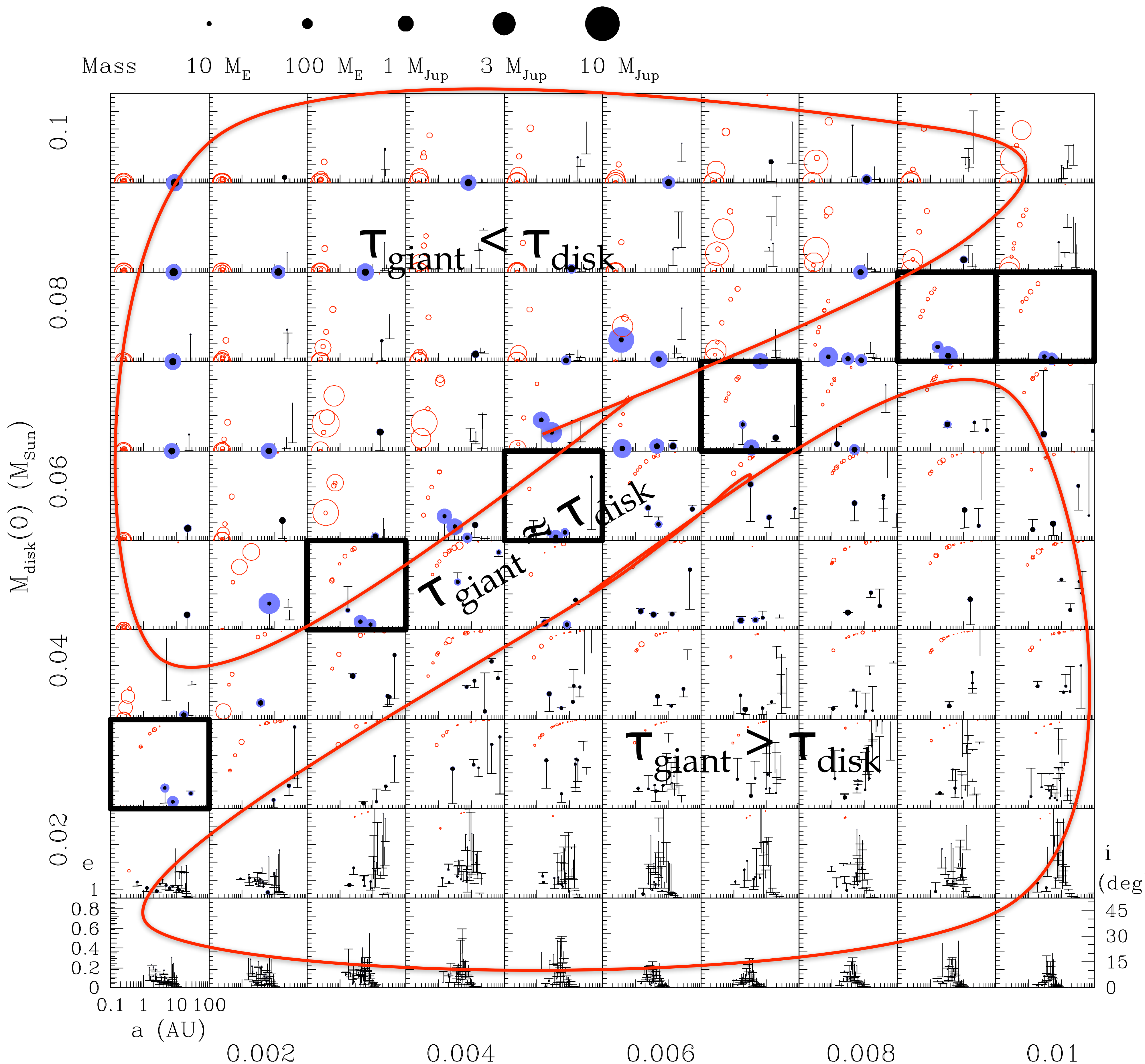

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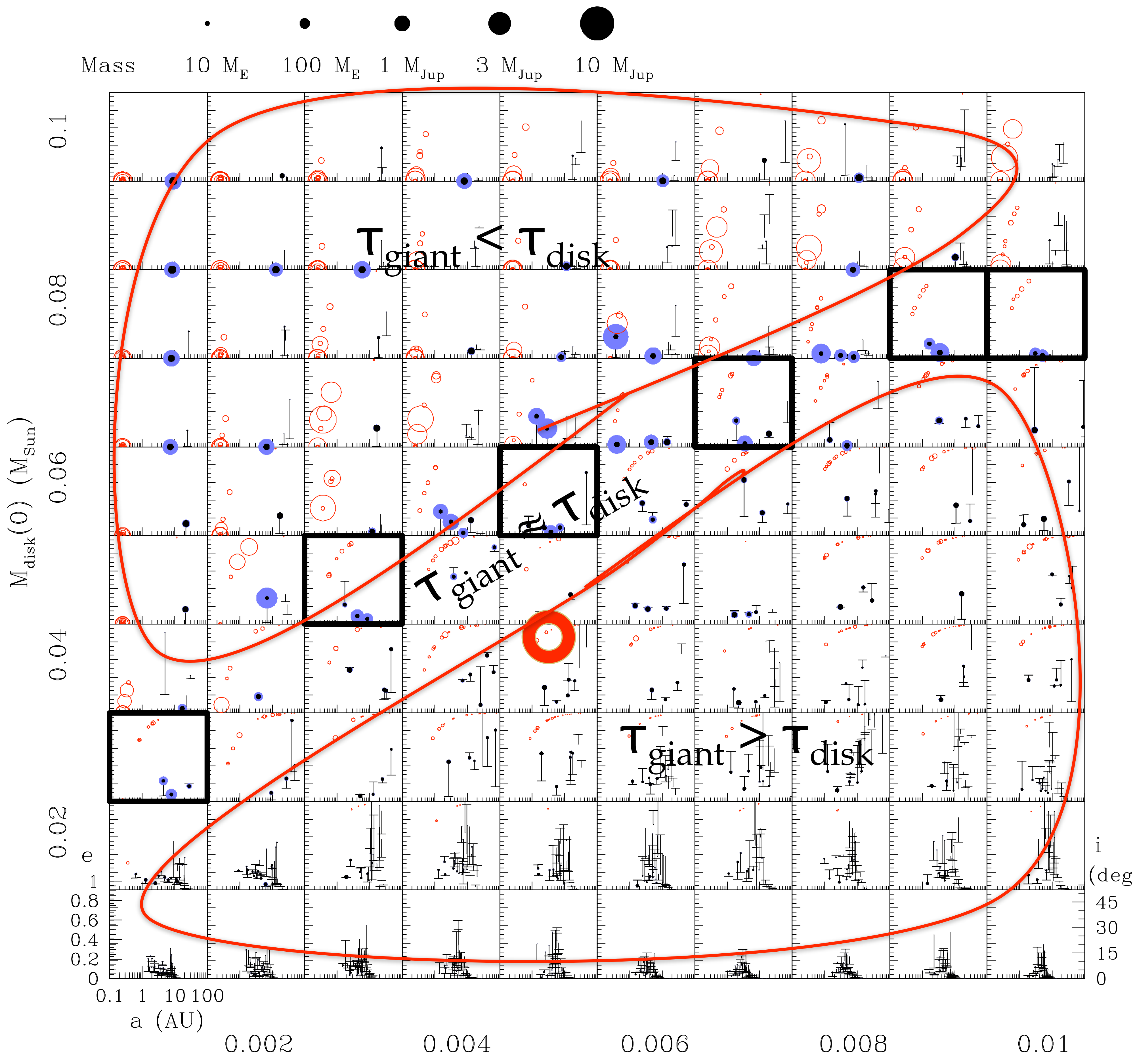

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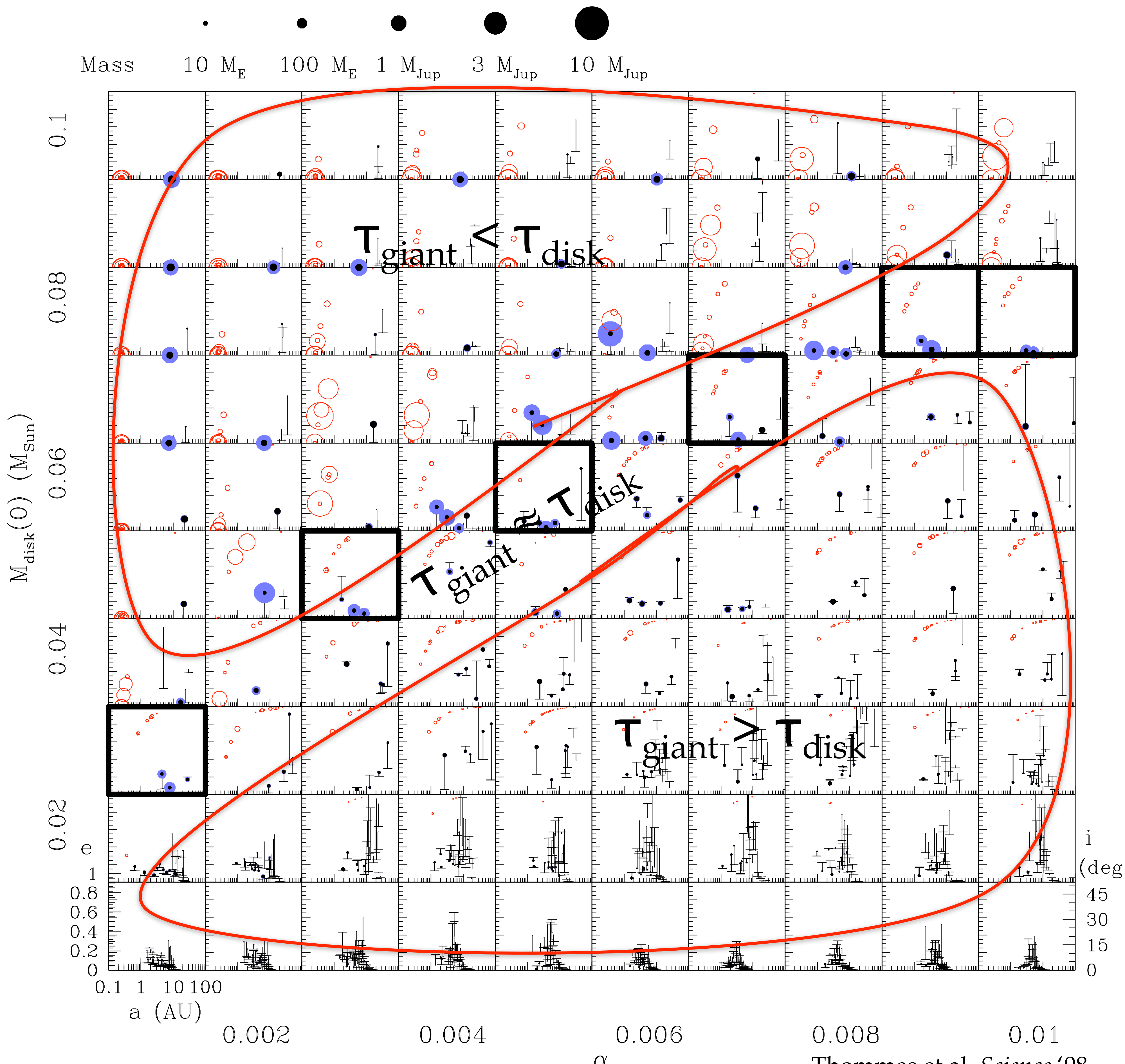

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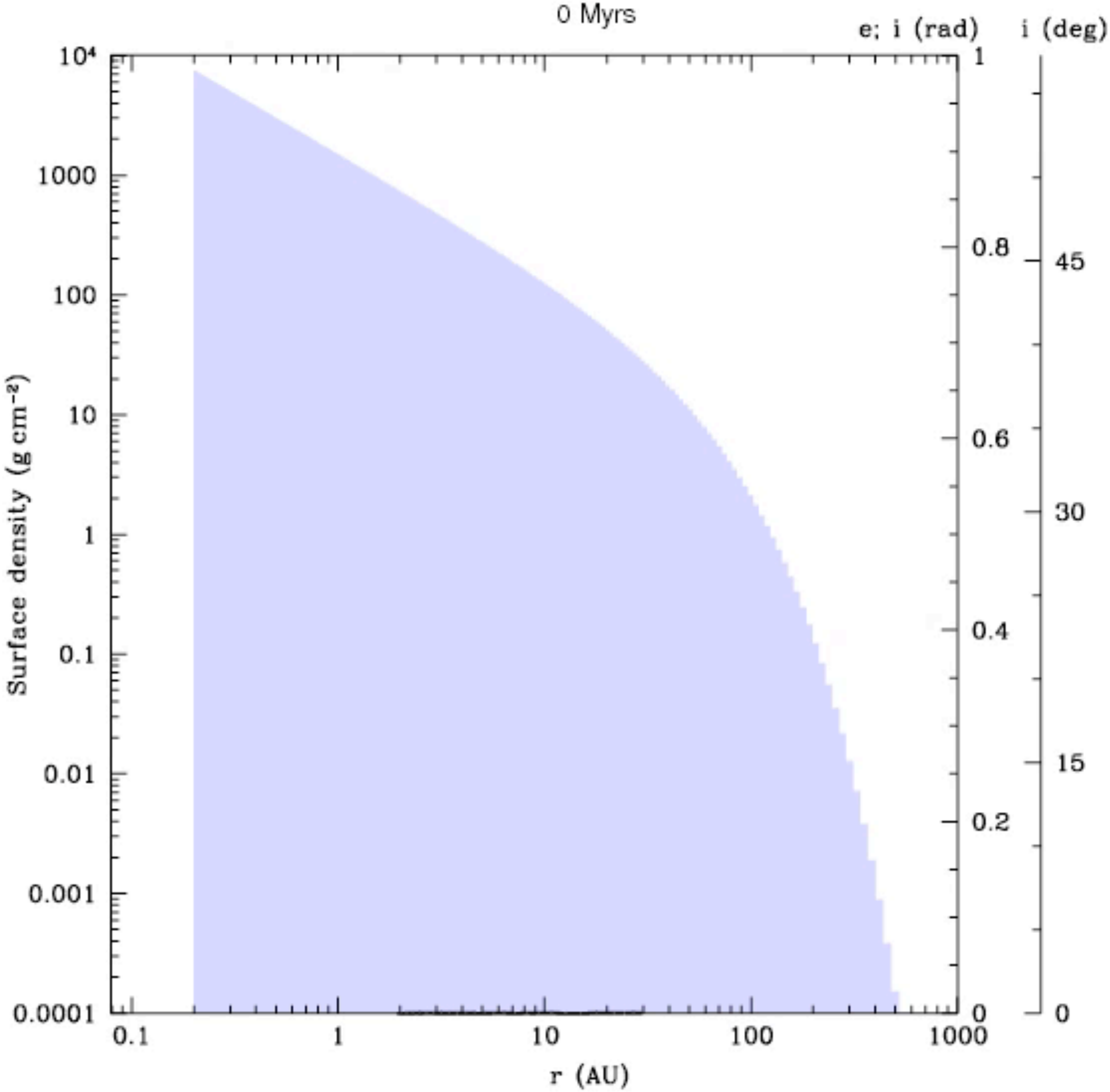

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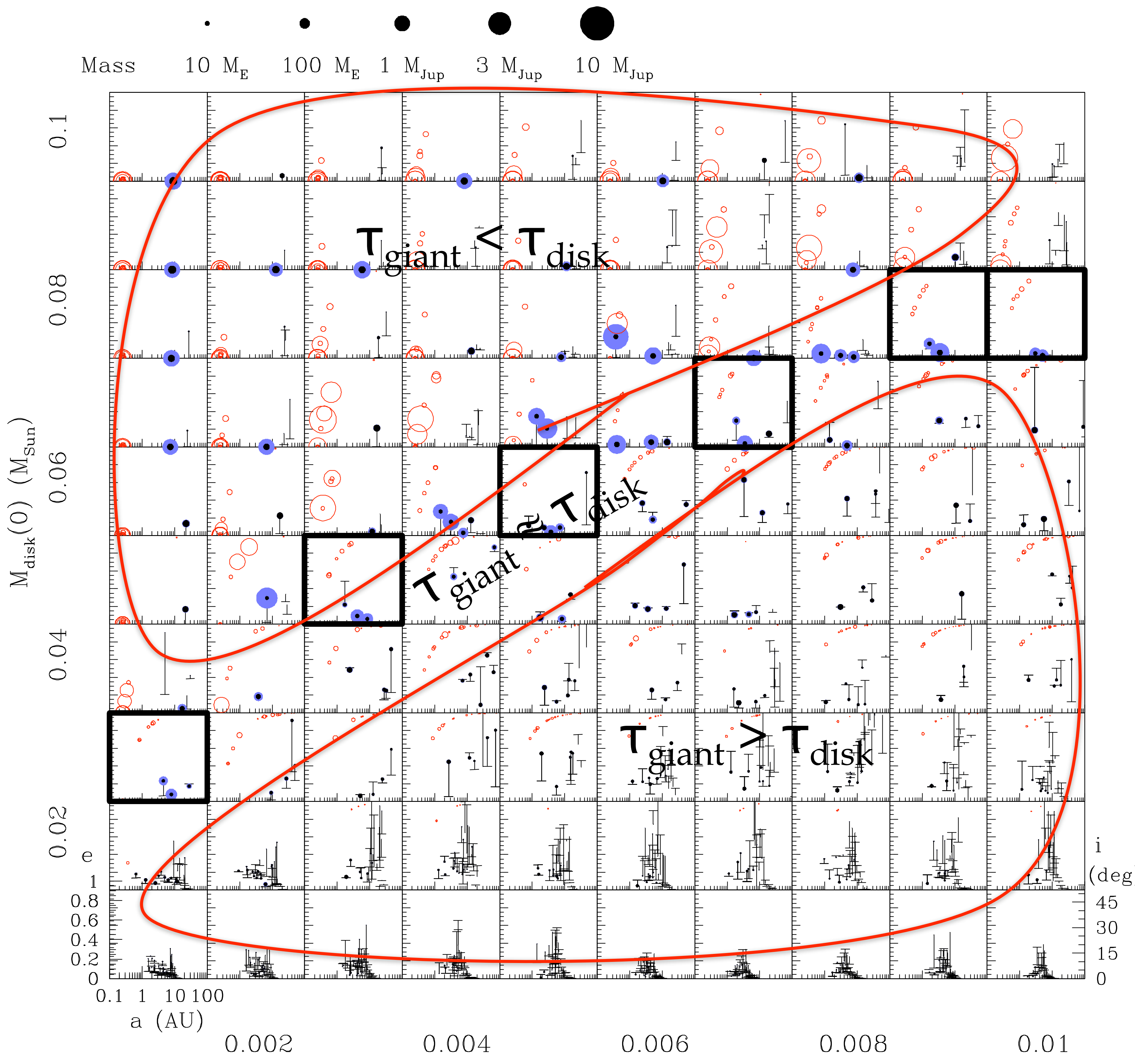

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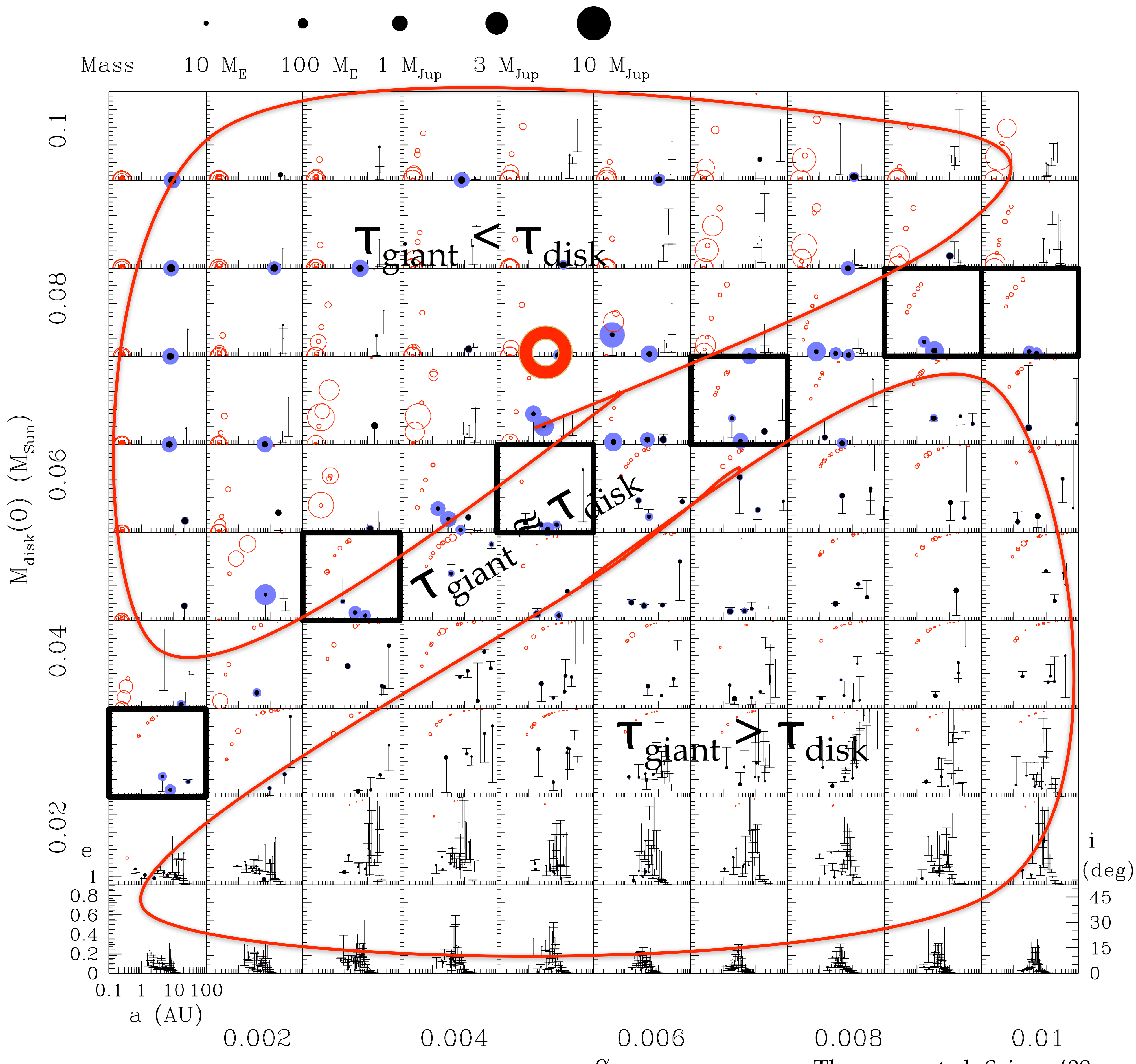

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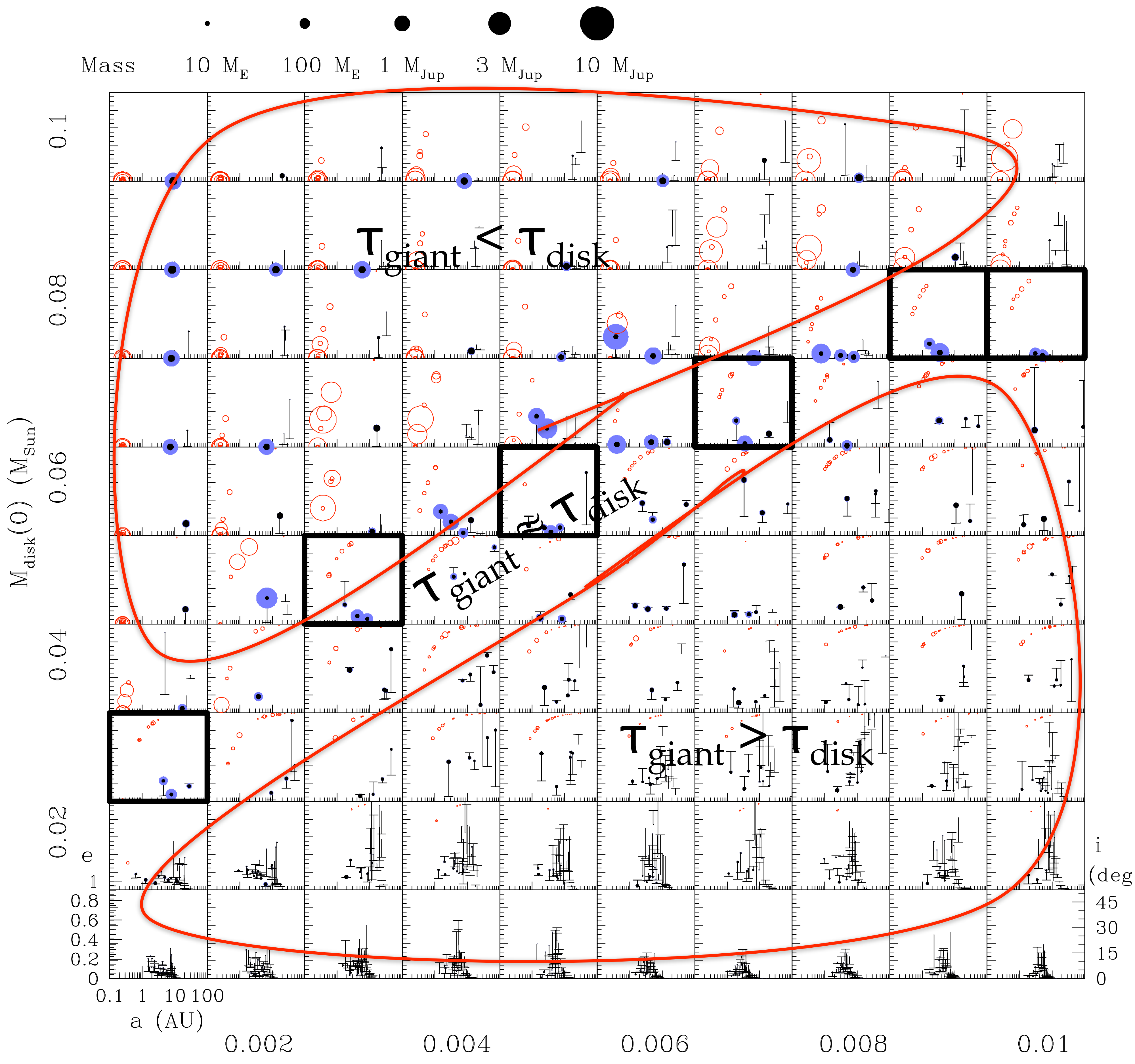

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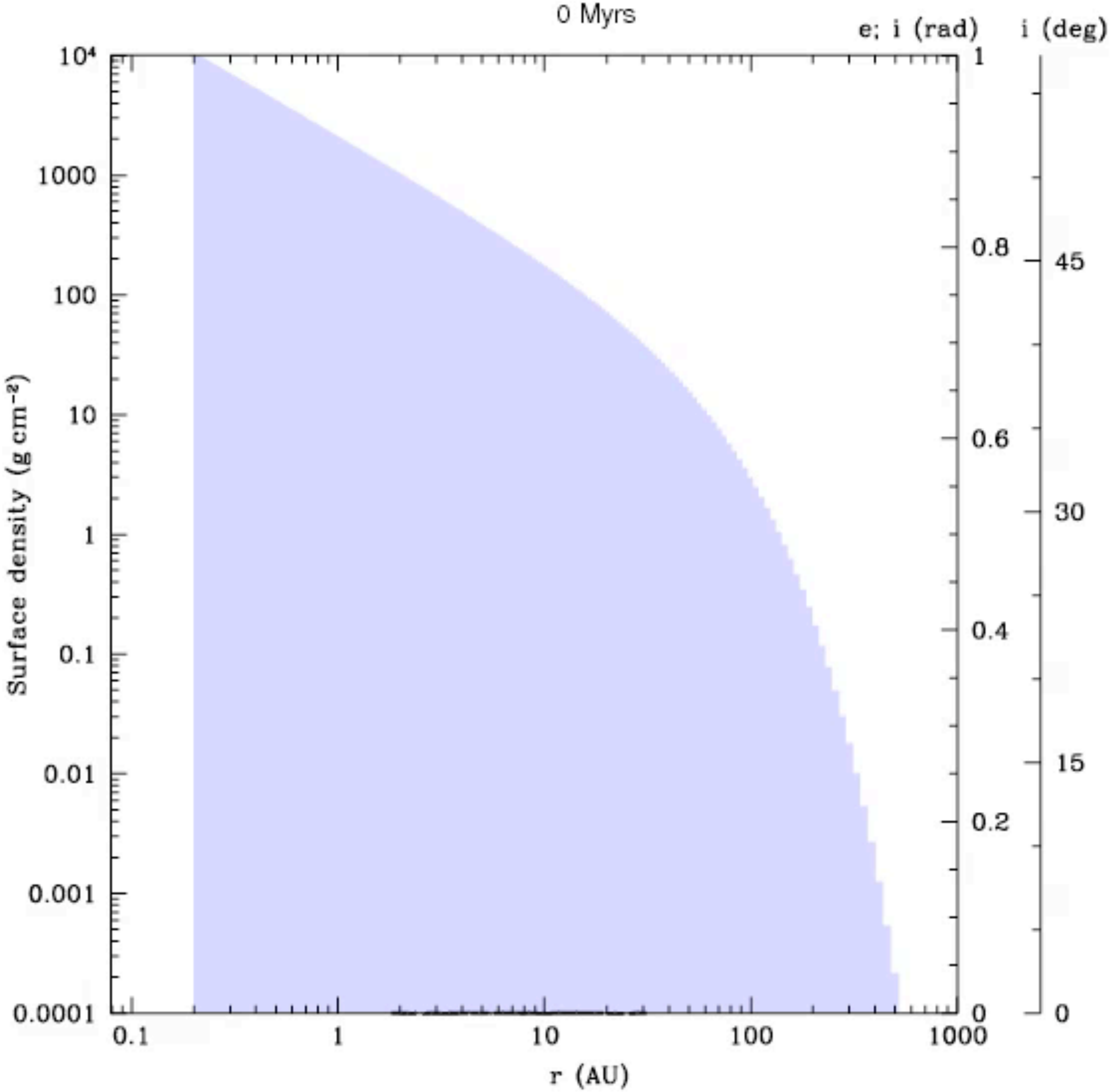

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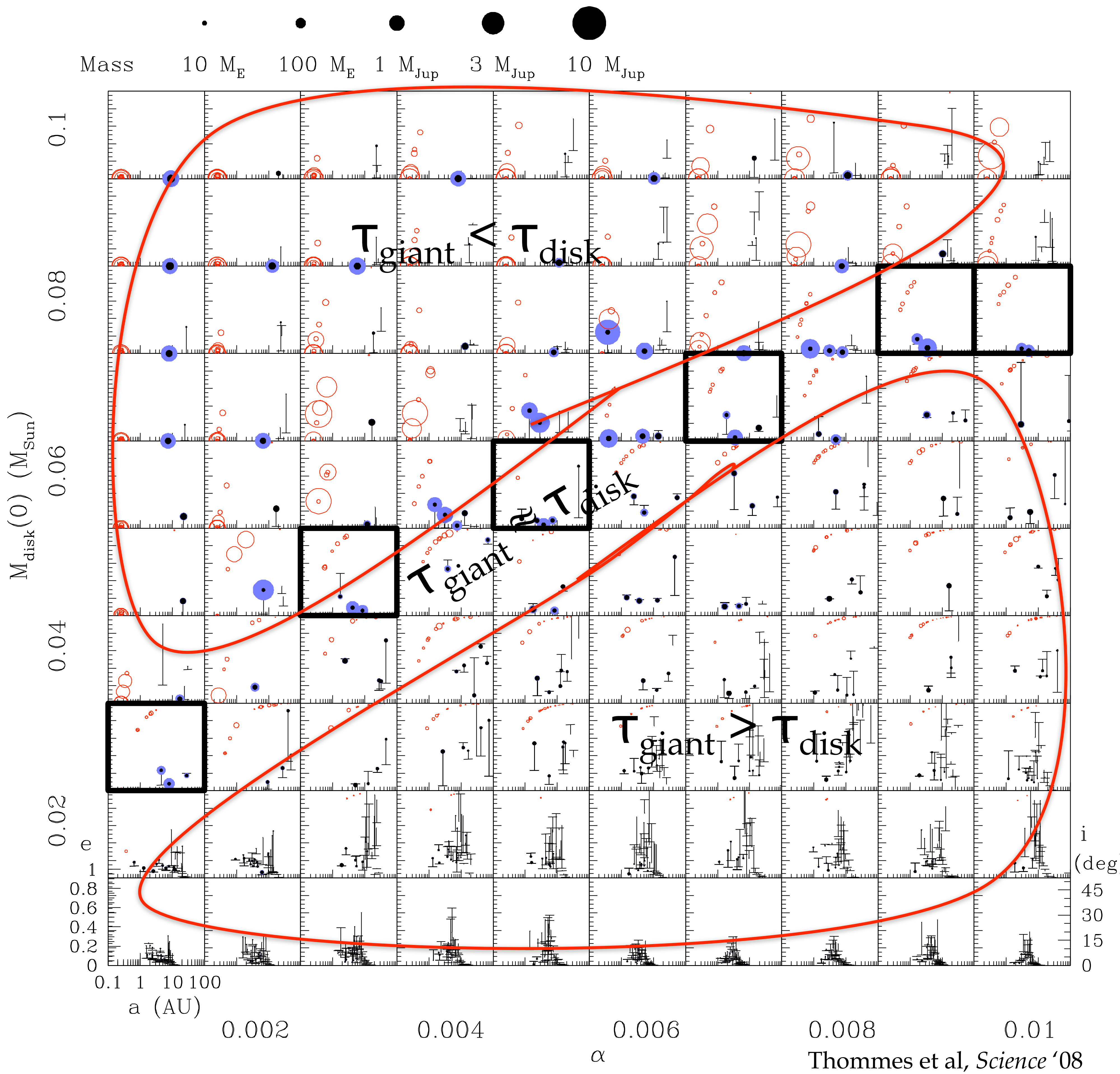

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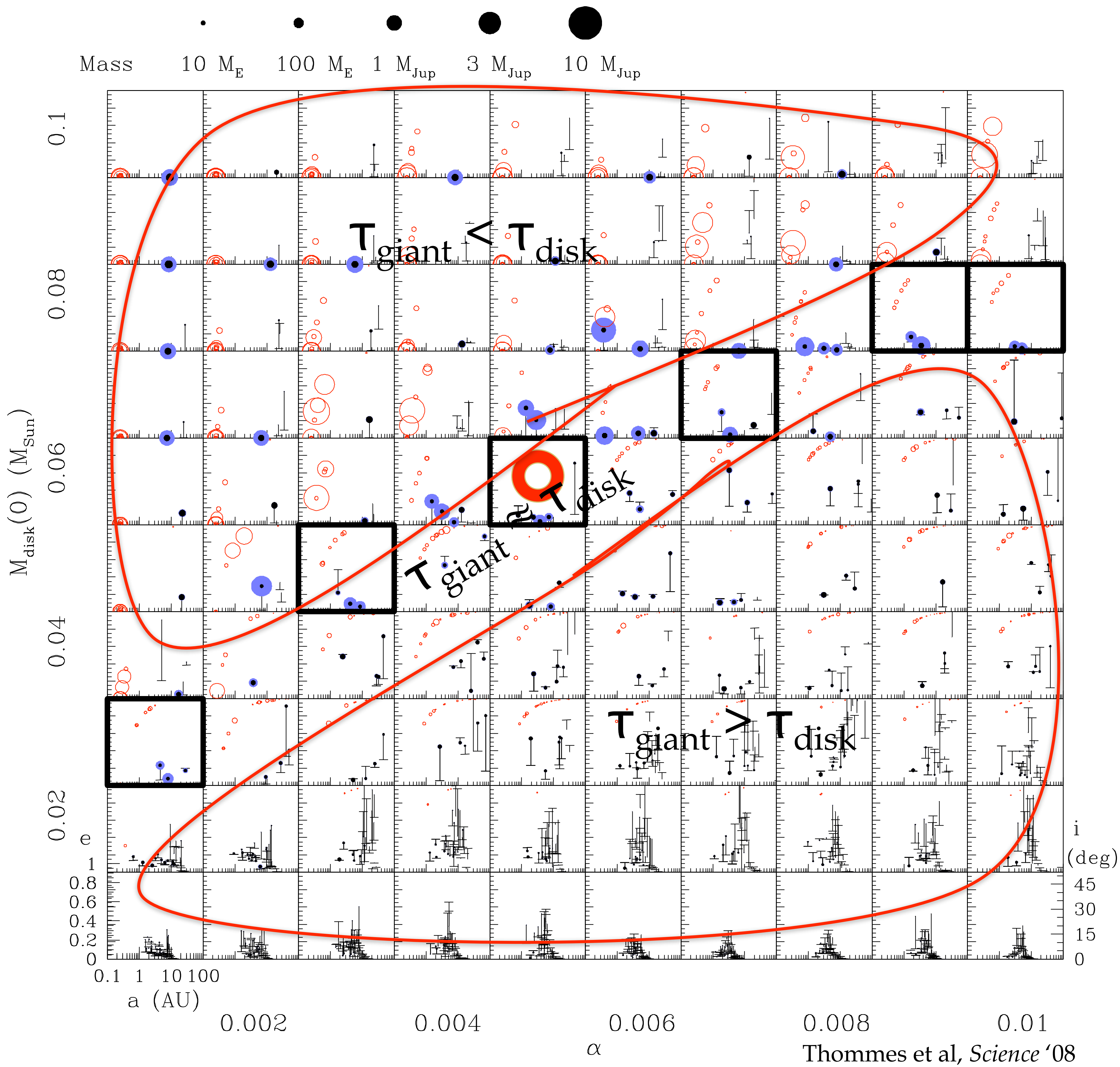
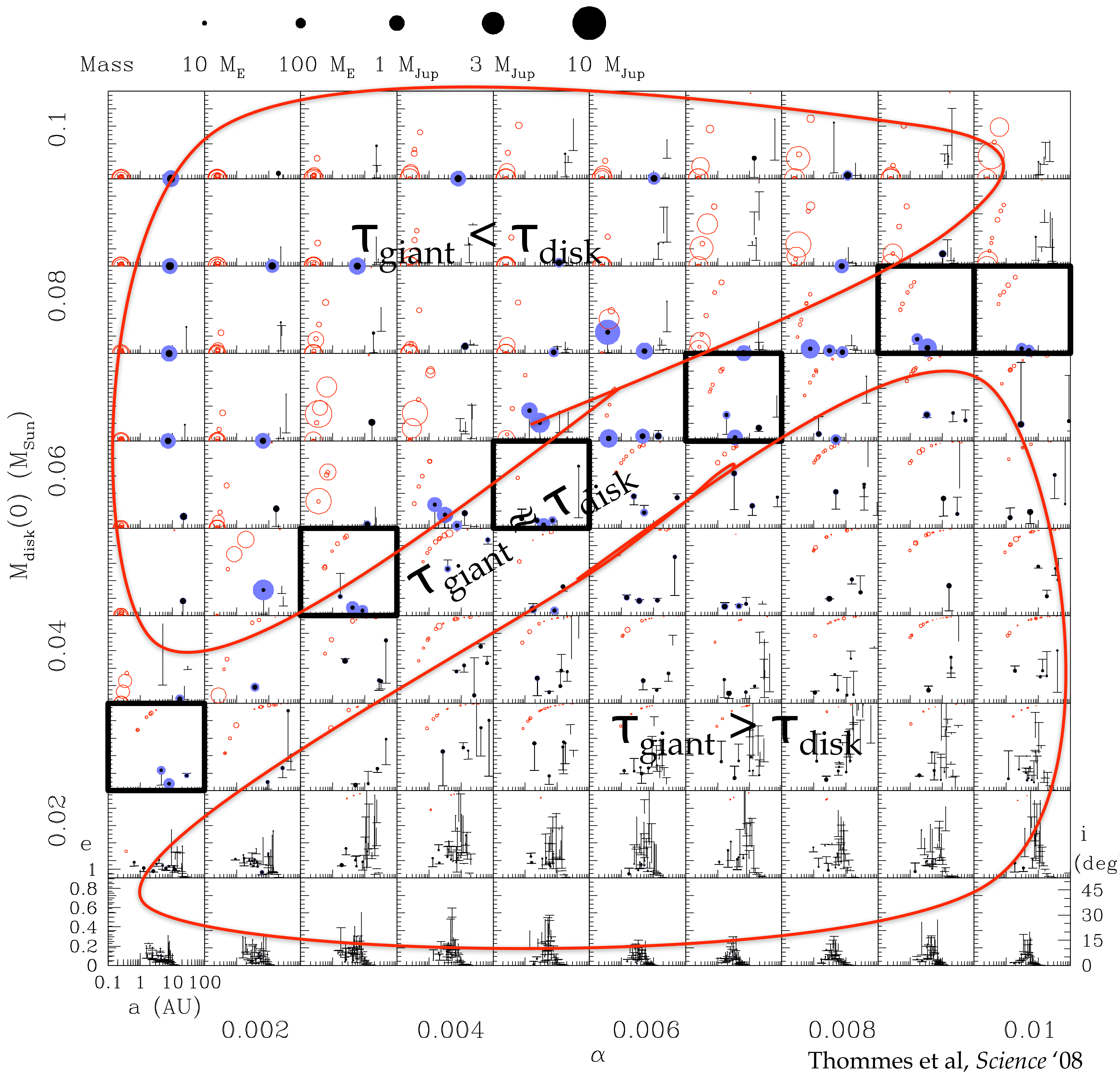


Mass
10 M_E
100 M_E
1 M_{Jup}
3 M_{Jup}
10 M_{Jup}
$\tau_{giant} < \tau_{disk}$
$\tau_{giant} \approx \tau_{disk}$
$\tau_{giant} > \tau_{disk}$
$M_{disk}(0)$ (M_{Sun})
0.1
0.08
0.06
0.04
0.02
e
1
0.8
0.6
0.4
0.2
0
0.1 1 10 100
a (AU)
0.002
0.004
0.006
0.008
0.01
α
i (deg)
45
30
15
0
Thommes et al, *Science* '08



Mass
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100 M_E
1 M_Jup
3 M_Jup
10 M_Jup
τ giant < τ disk
τ giant ≈ τ disk
τ giant > τ disk
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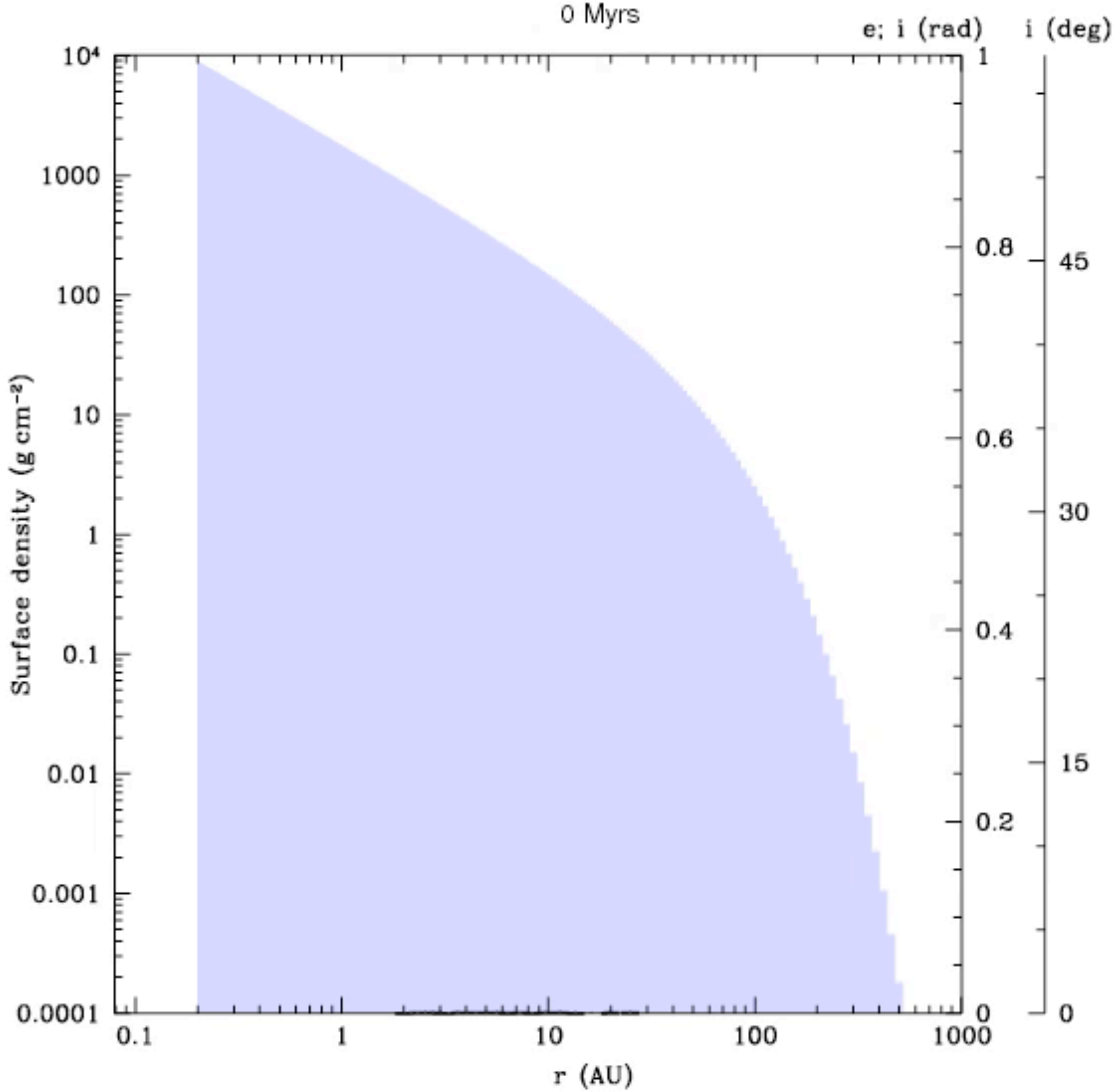

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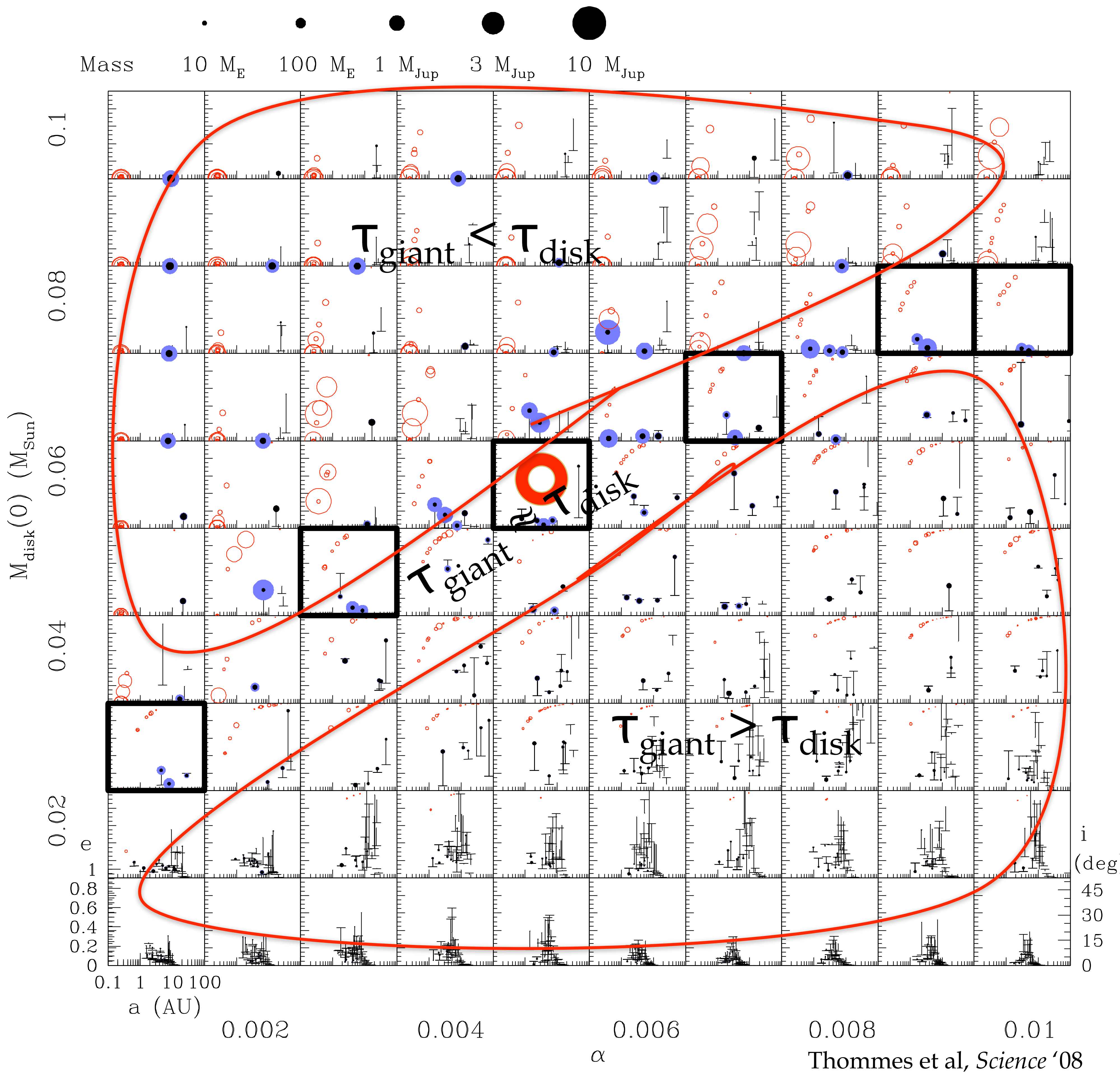
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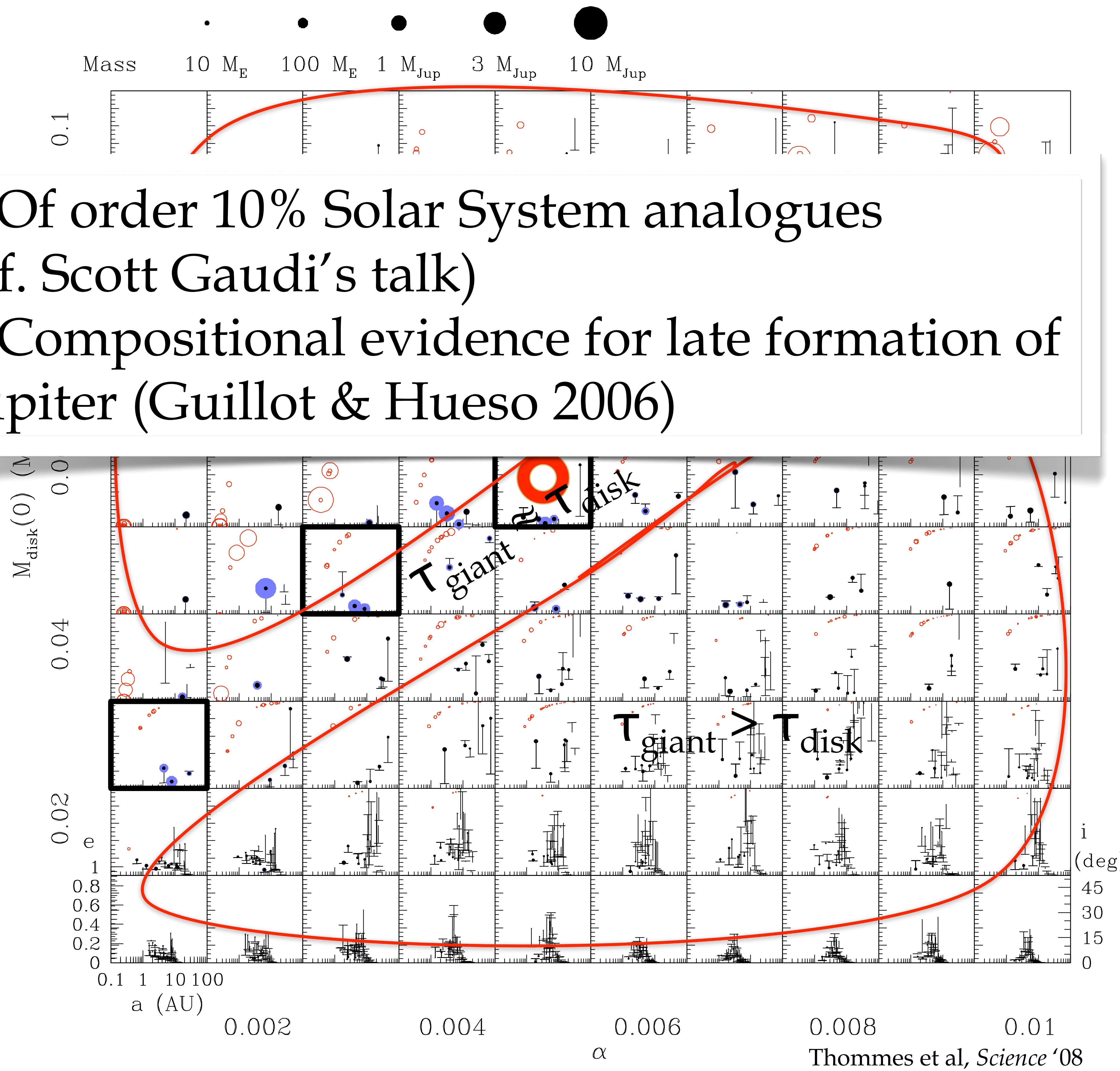
Thommes et al, *Science* '08

- Of order 10% Solar System analogues (cf. Scott Gaudi's talk)
- Compositional evidence for late formation of Jupiter (Guillot & Hueso 2006)



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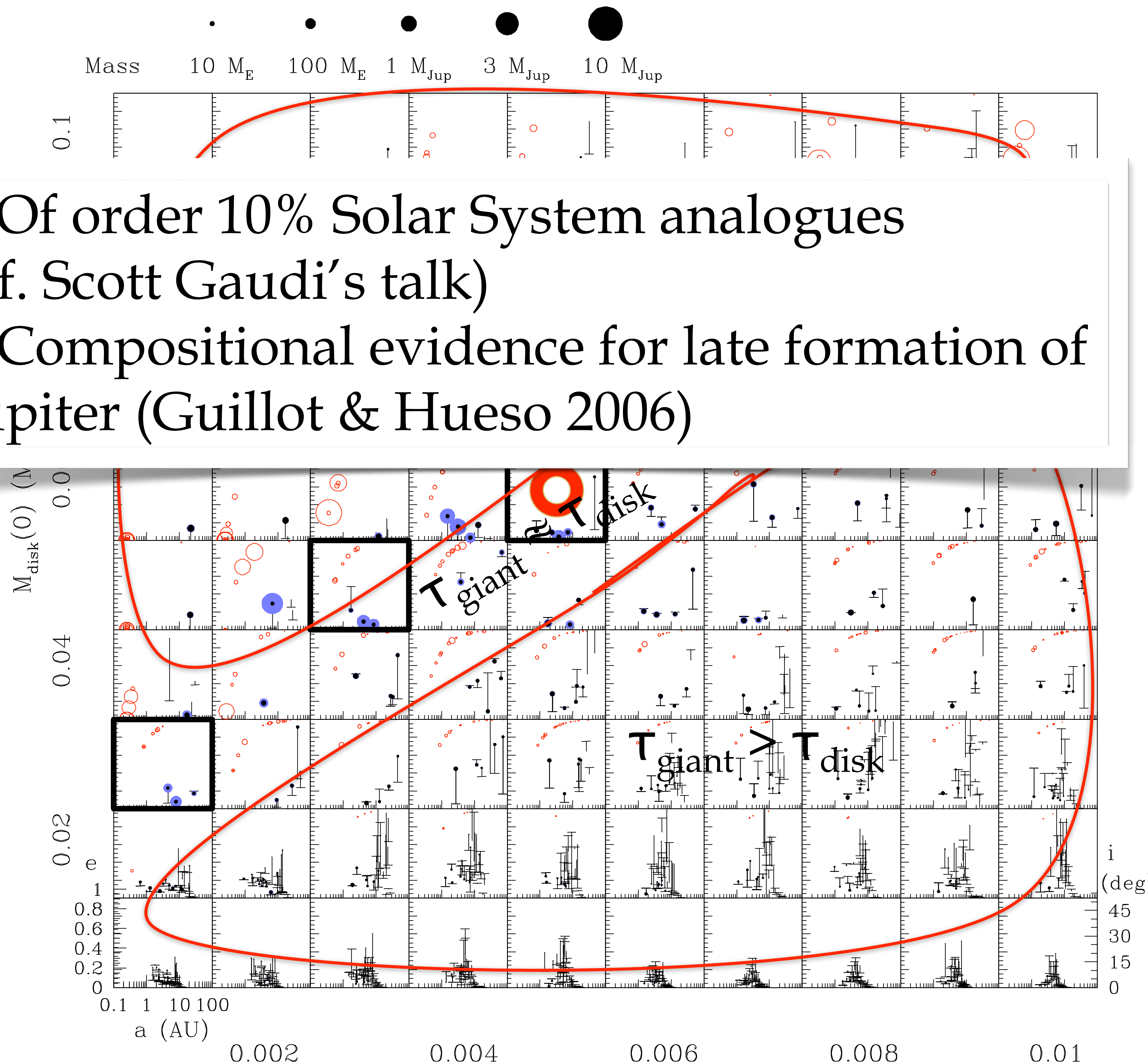
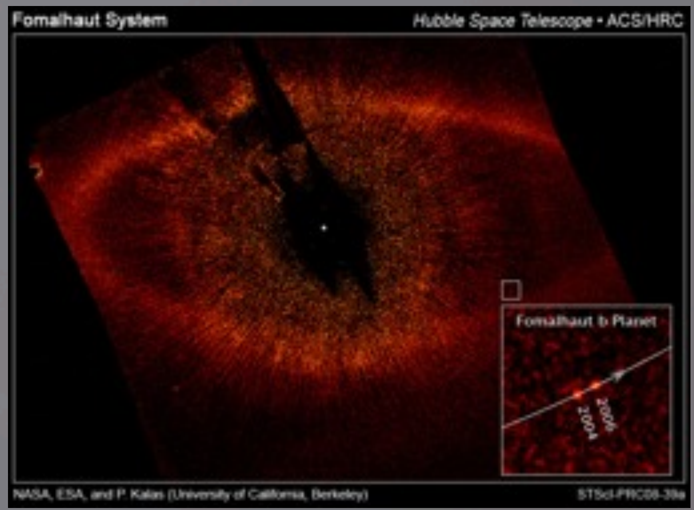
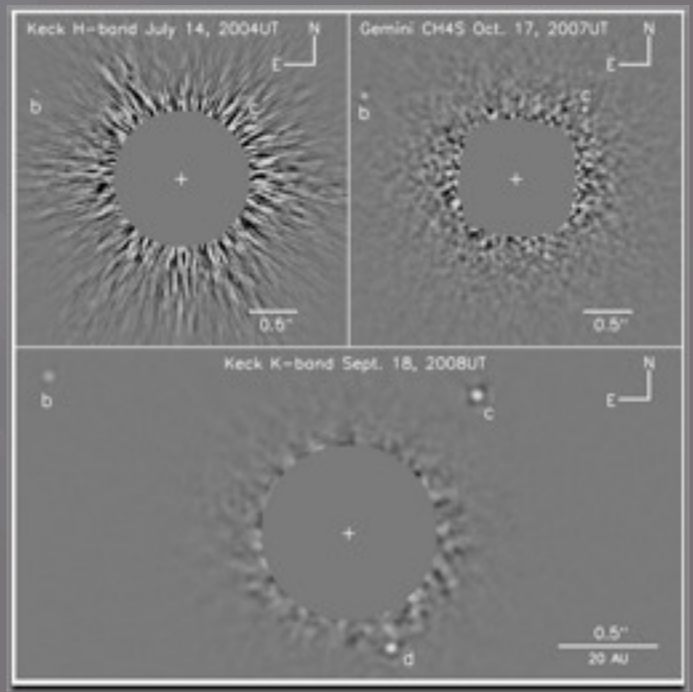


Thommes et al, *Science* '08

Distant giant planets

- Fomalhaut b:
  - Kalas et al. (2008): companion at ~115 AU
  - <3 M_{Jup} (Marengo et al. 2000, Chiang et al. 2009)
  - 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 instability? Easier at large r but still problematic (**cf. Lucio Mayer's talk**)

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

- "Underappreciated" Neptunes (**cf. David Stevenson's talk**) to the rescue!
- 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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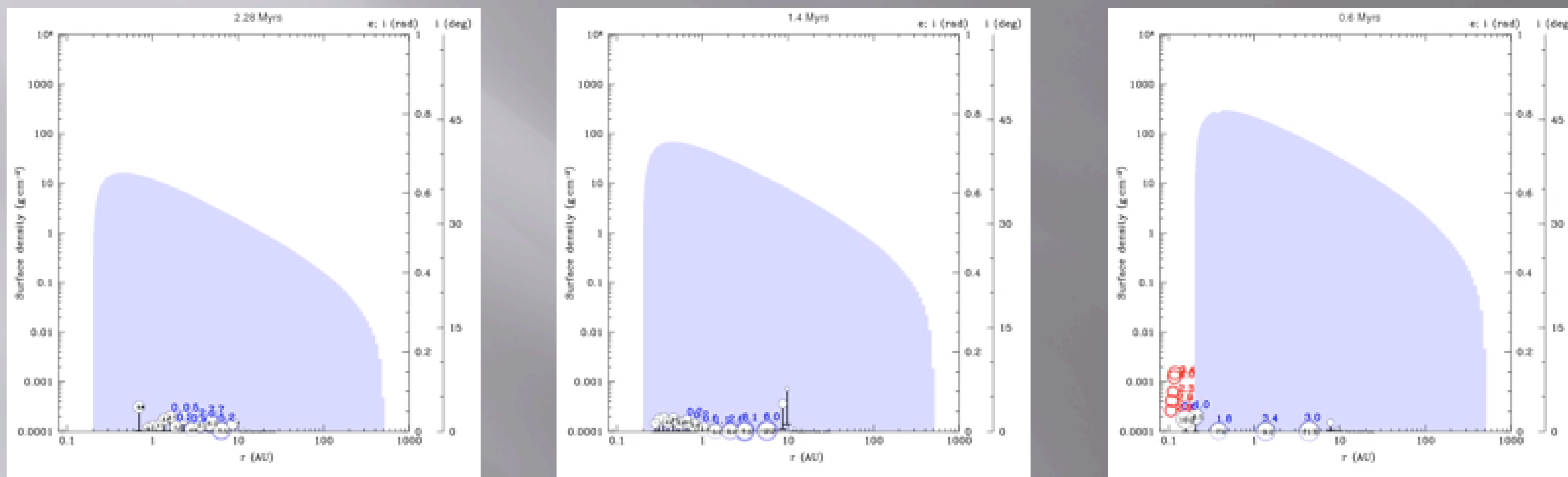

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An HR 8799 analogue

Thommes, Russell & Holmes

- FARGO 2-D planet-disk hydrocode (Masset 2000, http://fargo.in2p3.fr/)
  - Accretion scheme modified for core accretion (initially much slower!)
  - Initial conditions: 1.5 M_{Sun} star, cores of 10-20 M_{Earth}, one with head start, 300 AU radius disk, total mass ~0.03 M_{Sun}, α=0.01

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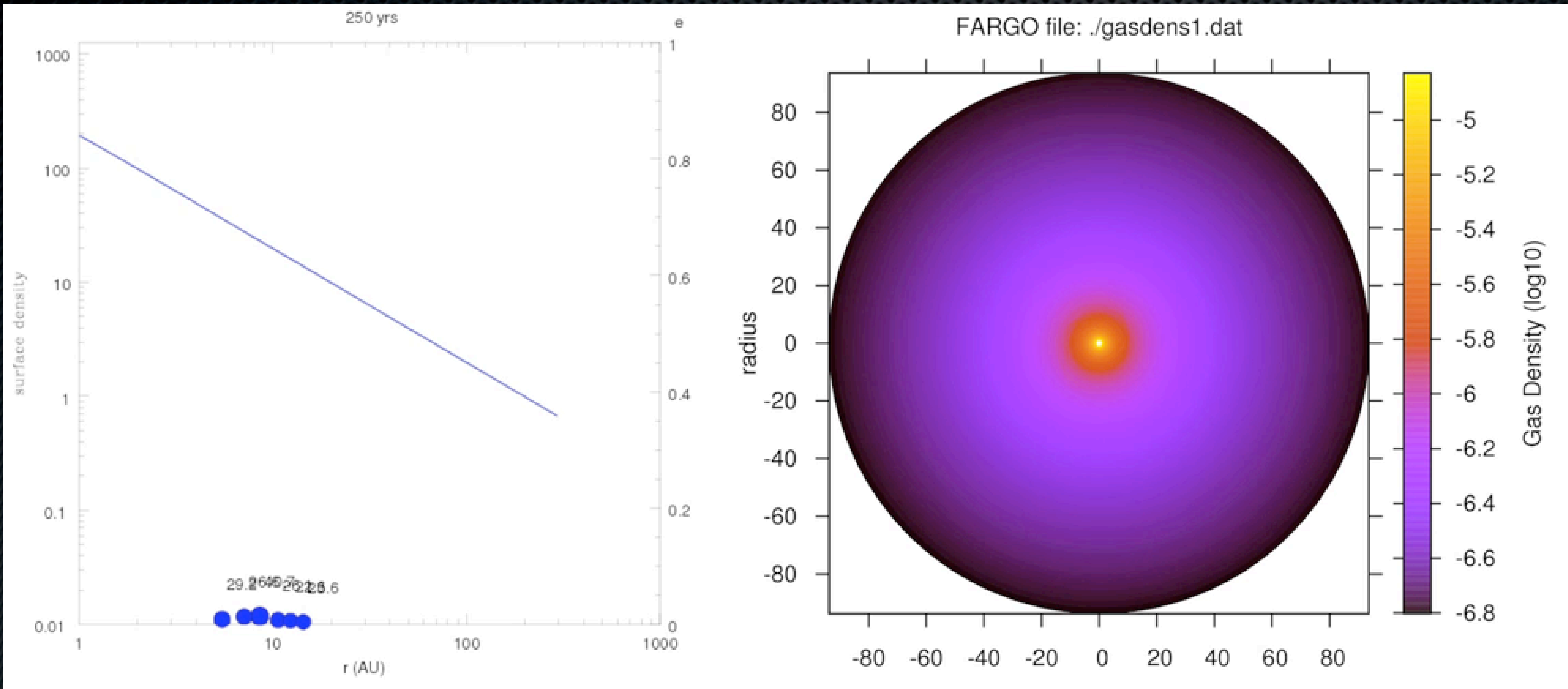

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...and Fomalhaut b

Thommes, Russell & Holmes

- Initial conditions: 2 M_{Sun} star, single 15 M_{Earth} core with peri=10 AU, apo=1000 AU (post-scattering), 300 AU radius disk, total mass ~0.01 M_{Sun}, α=0.01

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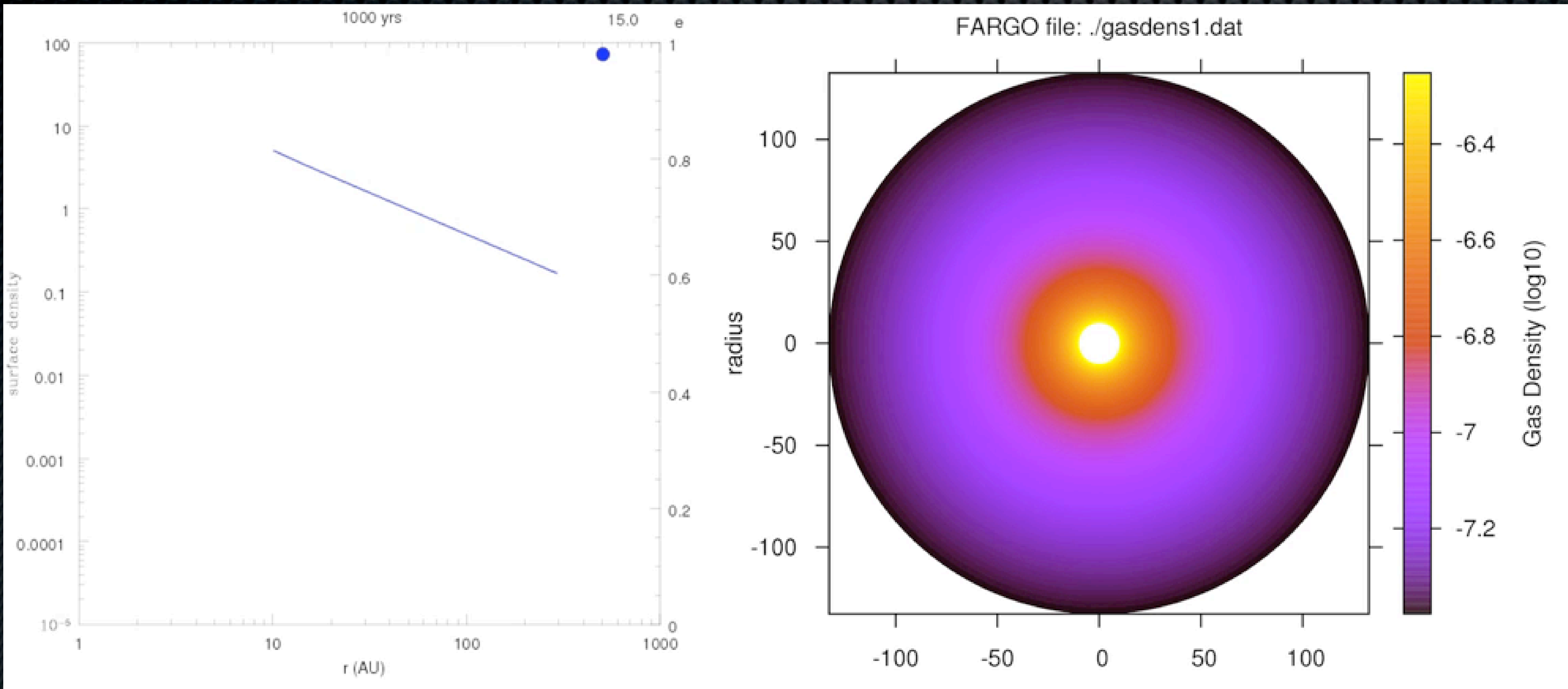

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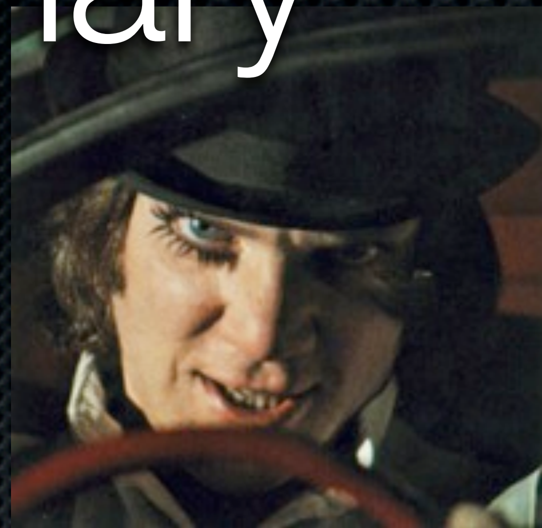
Summary



This work supported by NSERC, SHARCNET, Spitzer Theoretical Research Program, NSF

Summary

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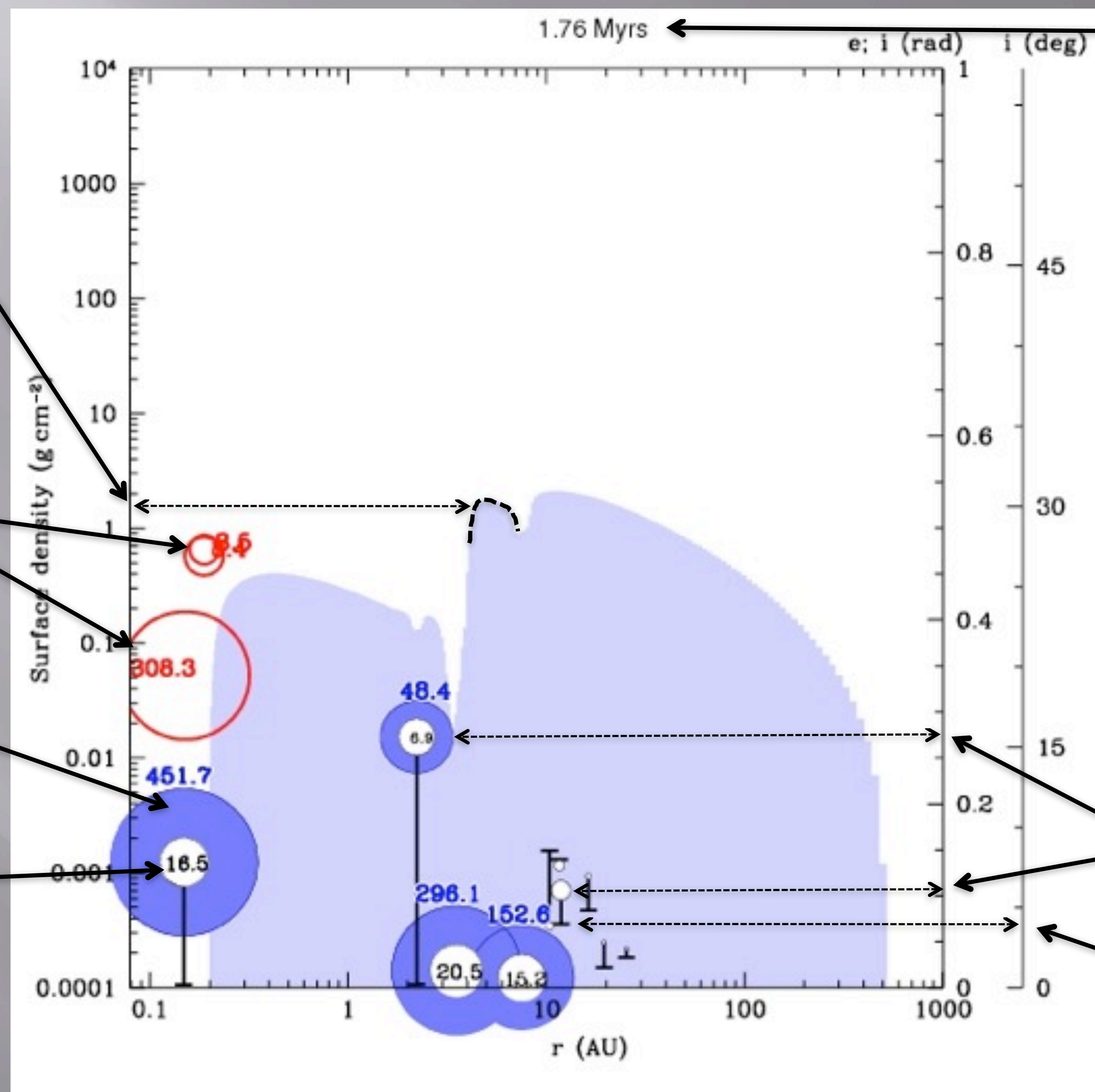
How we plot the output: Example "movie frame"

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