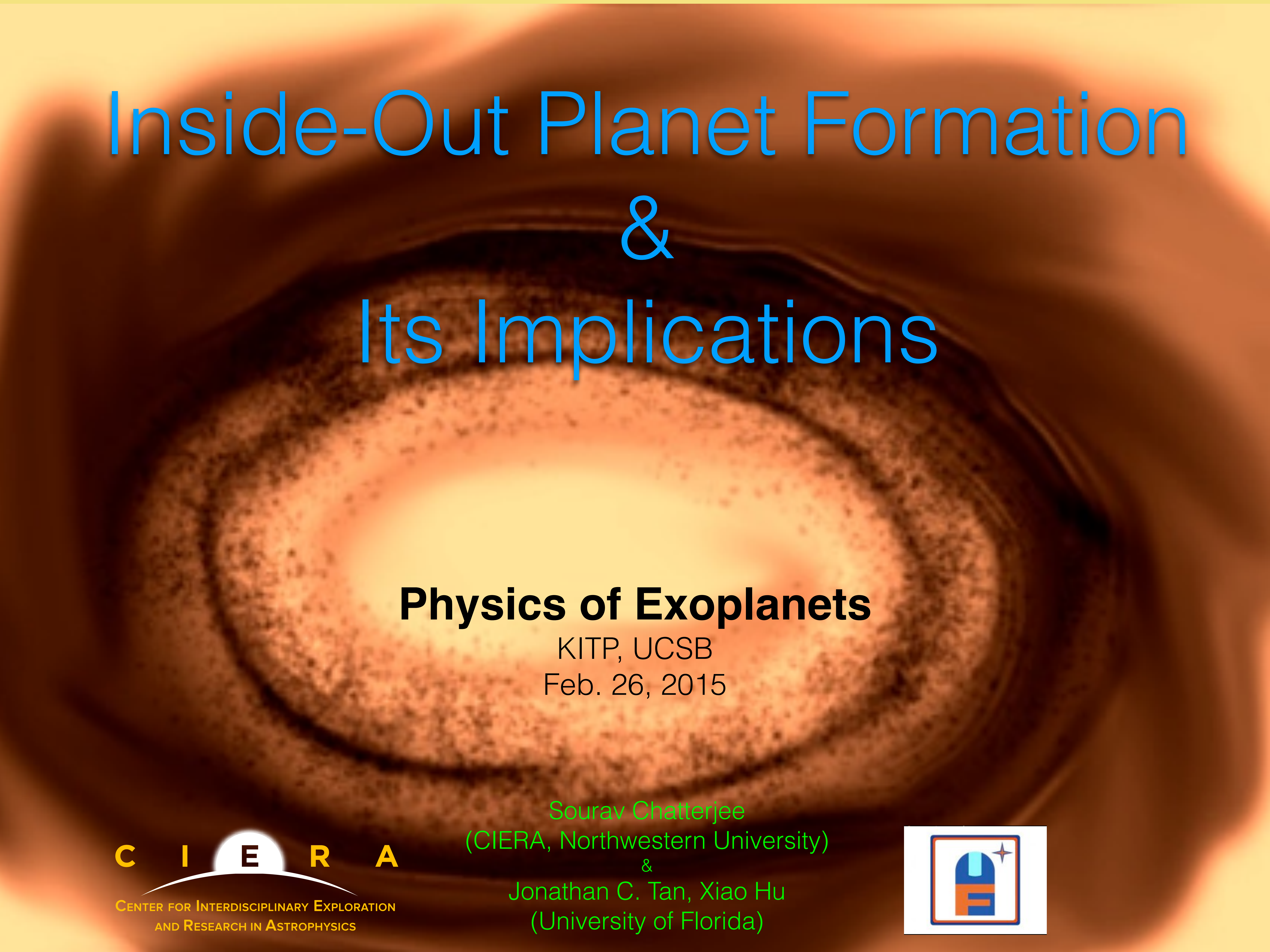


Inside-Out Planet Formation & Its Implications

Physics of Exoplanets

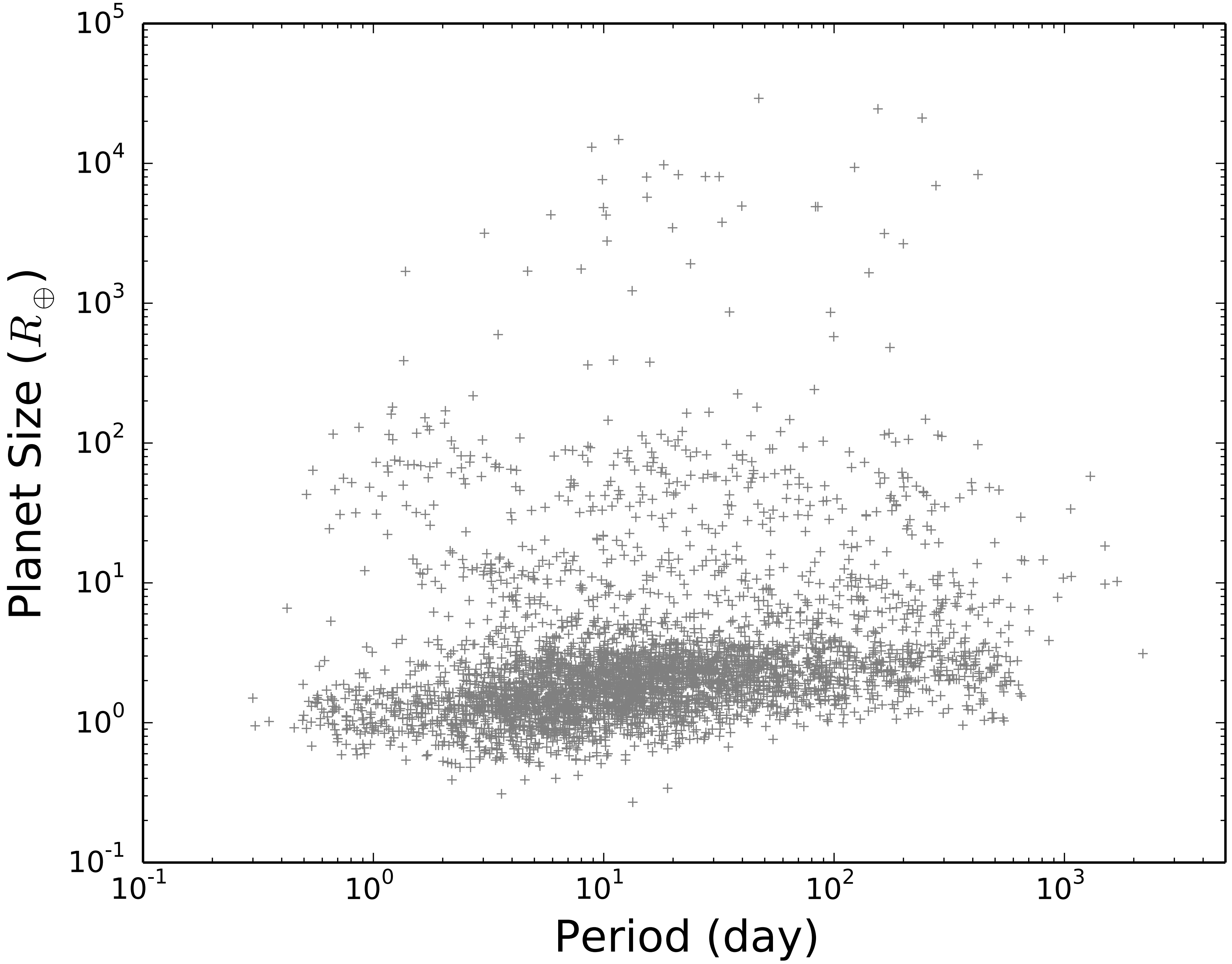
KITP, UCSB

Feb. 26, 2015

Sourav Chatterjee
(CIERA, Northwestern University)
&
Jonathan C. Tan, Xiao Hu
(University of Florida)

CIERA
Center for Interdisciplinary Exploration and Research in Astrophysics

Kepler Planet Candidates



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http://exoplanetarchive.ipac.caltech.edu

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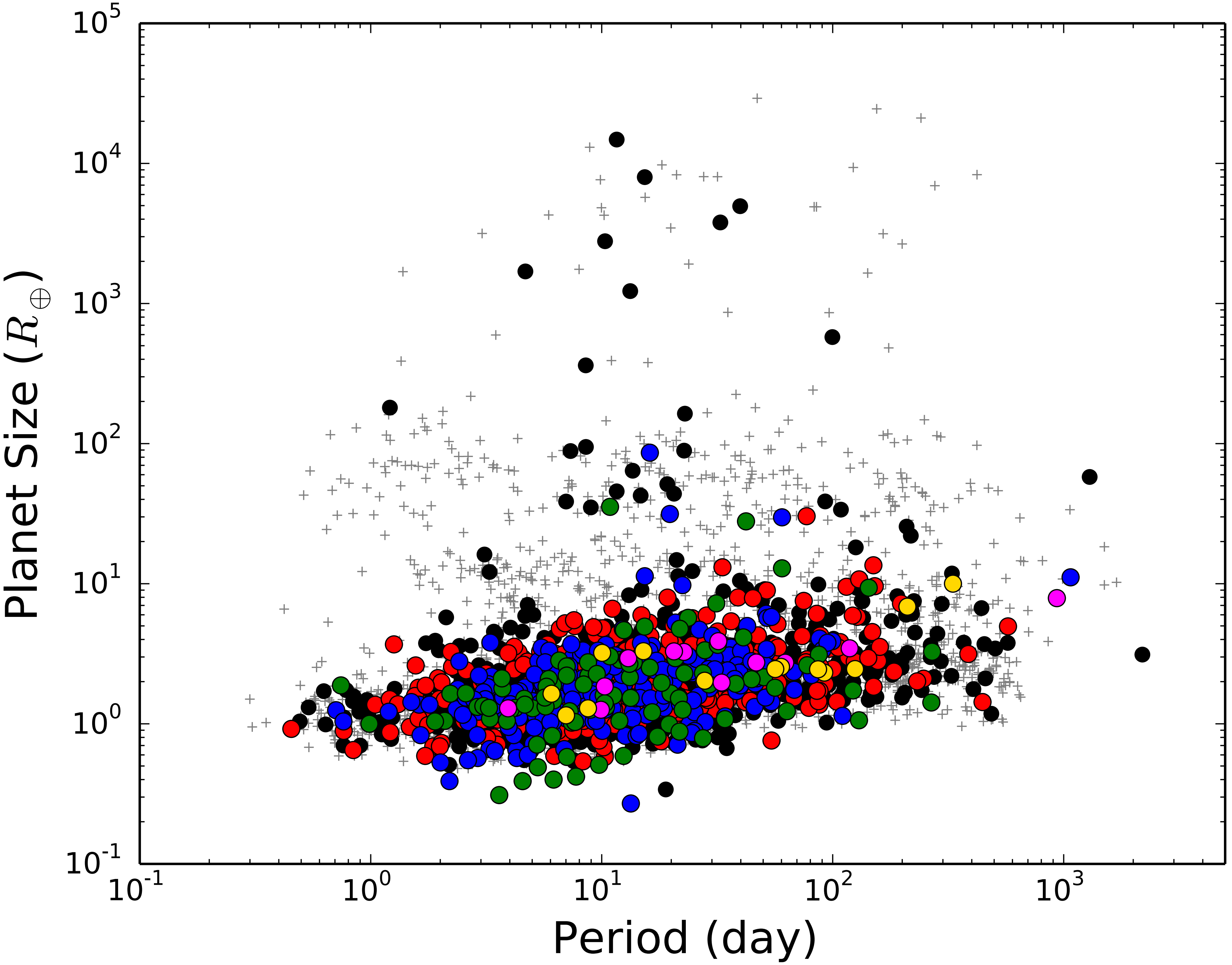

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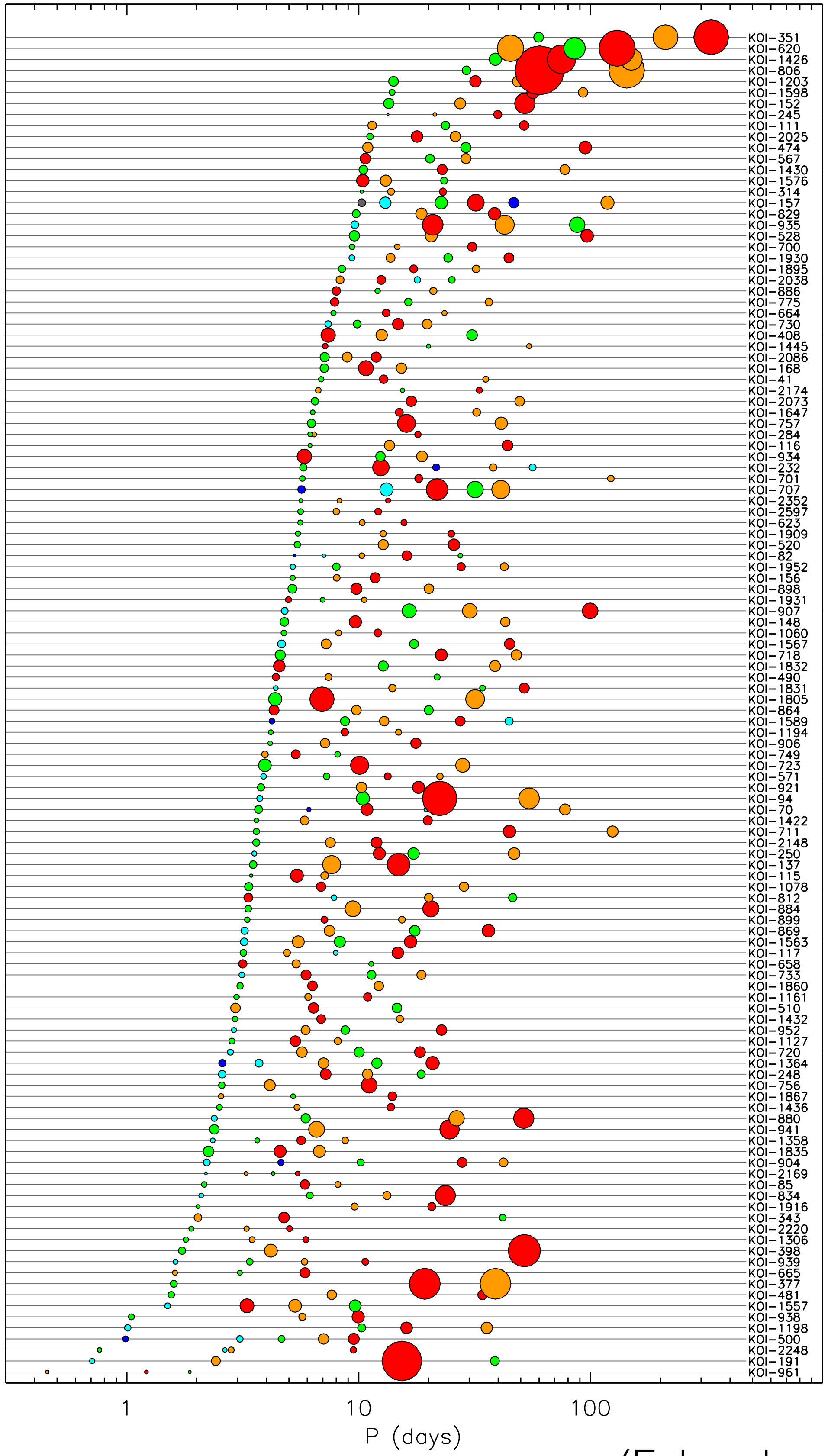
How do the Systems with Tightly-Packed Inner Planets (STIPs) Form?



(Fabrycky et al. 2014)

Formation then Inward Migration

(e.g., Kley & Nelson 2012; Cossou et al. 2013, 2014)

Formation in situ

(e.g., Chiang & Laughlin 2013; Hansen & Murray 2012, 2013)

How do the Multi-transiting Compact Systems Form?

Challenges

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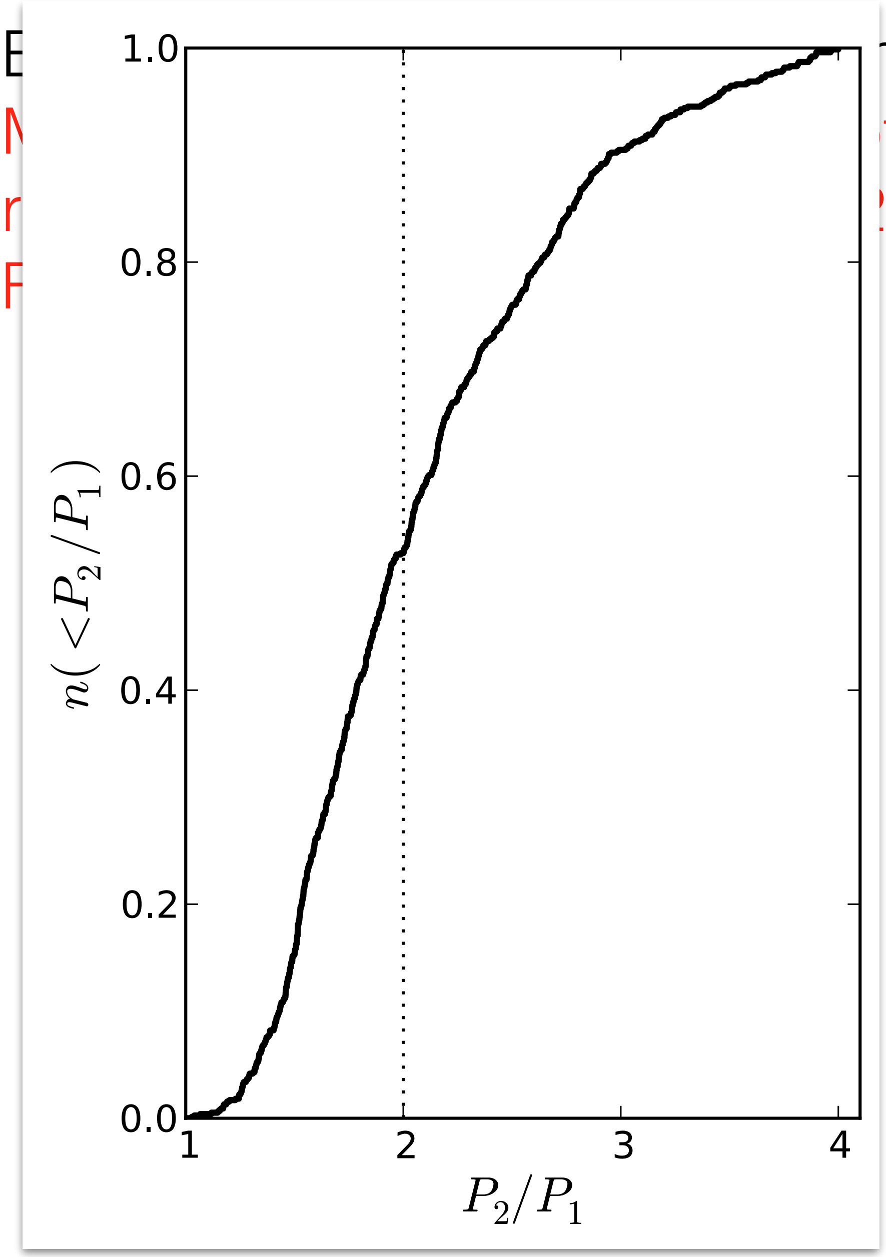

(Chatterjee & Ford 2015)

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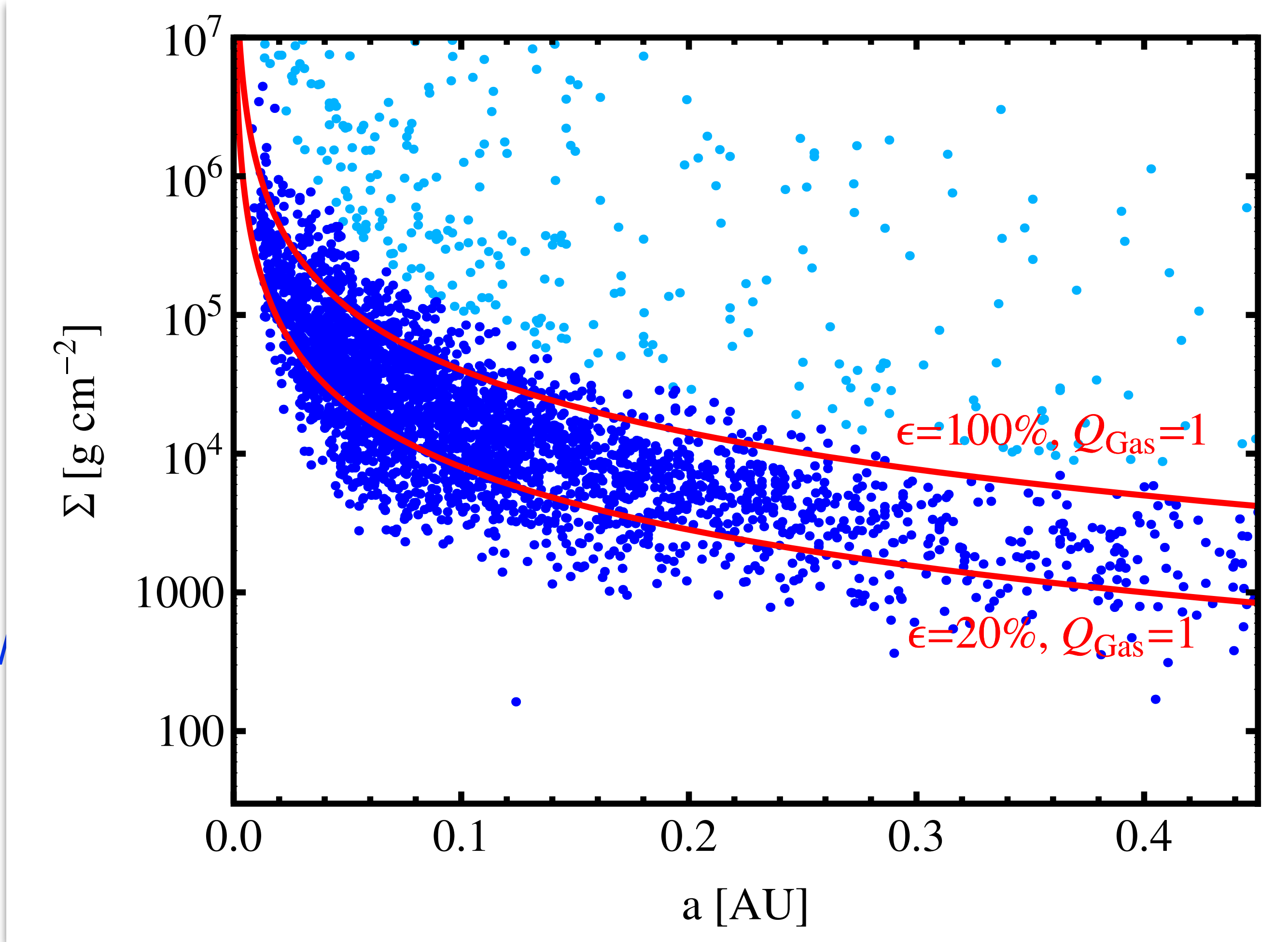

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- What if the inner disk is only enriched in solids (gas disk remains normal) and the enrichment is in a narrow ring?

The Inside-Out Planet Formation (IOPF) Model

Fast Inward Radial Drift of Pebbles

Pressure: $P \sim \alpha^{-9/10}\,(Gm_\star)^{17/20}\,(f_r\dot{m})^{4/5}\,r^{-51/20}$

Shakura & Sunyaev (1973)

Relative Speed: $v_{\rm gas} - v_{\rm pebble} \propto \left(\frac{r}{\rho}\frac{dP}{dr}\right)^{1/2}$

Drift Timescale: $t_{\rm drift} \sim 43.9 f_\tau^{-1}\alpha_{-3}^{1/5} m_{\star,1}^{1/5}\,(f_r\dot{m}_{-9})^{-2/5}\,r_{\rm AU}^{7/5}{\rm yr}$

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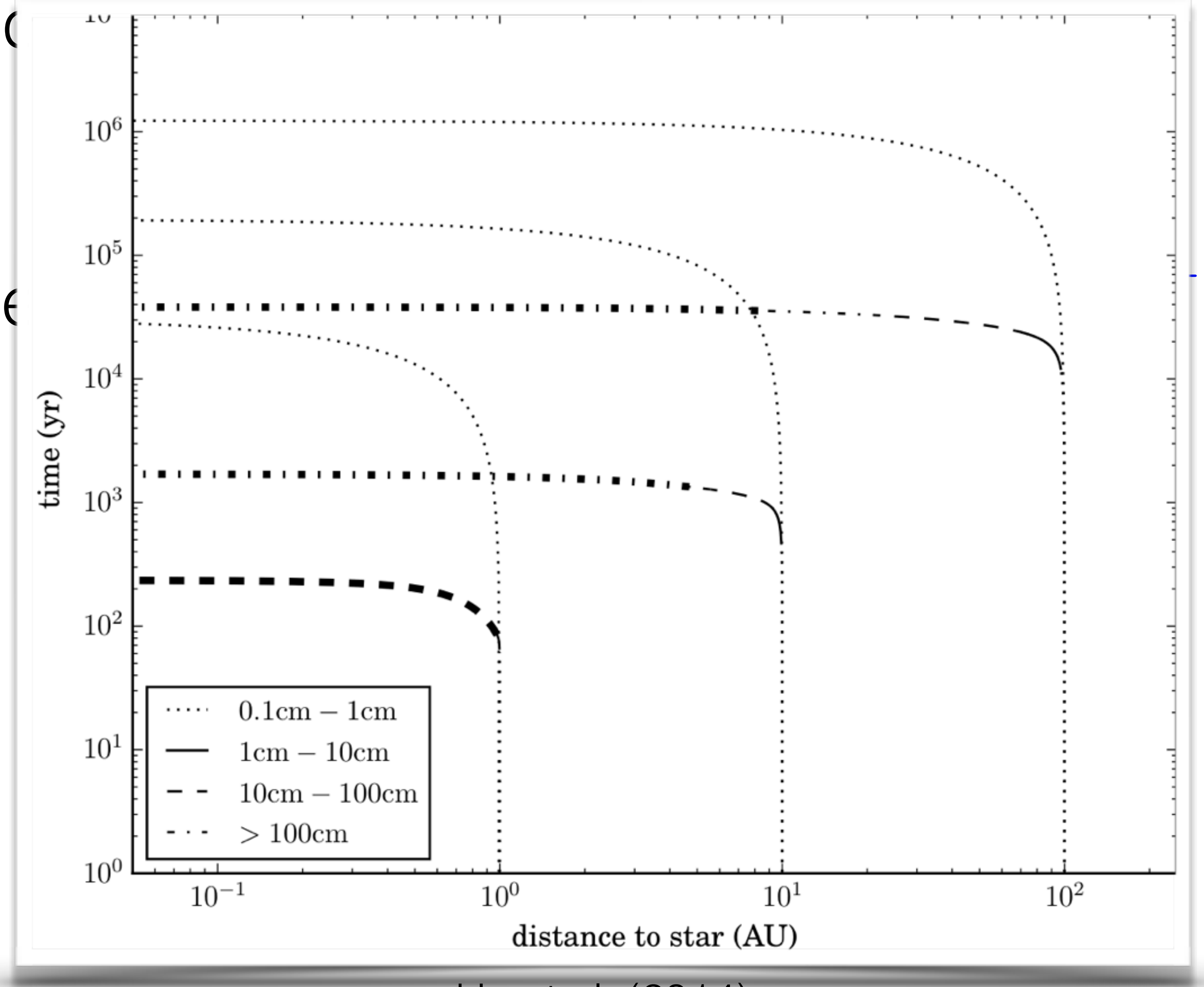

Hu et al. (2014)

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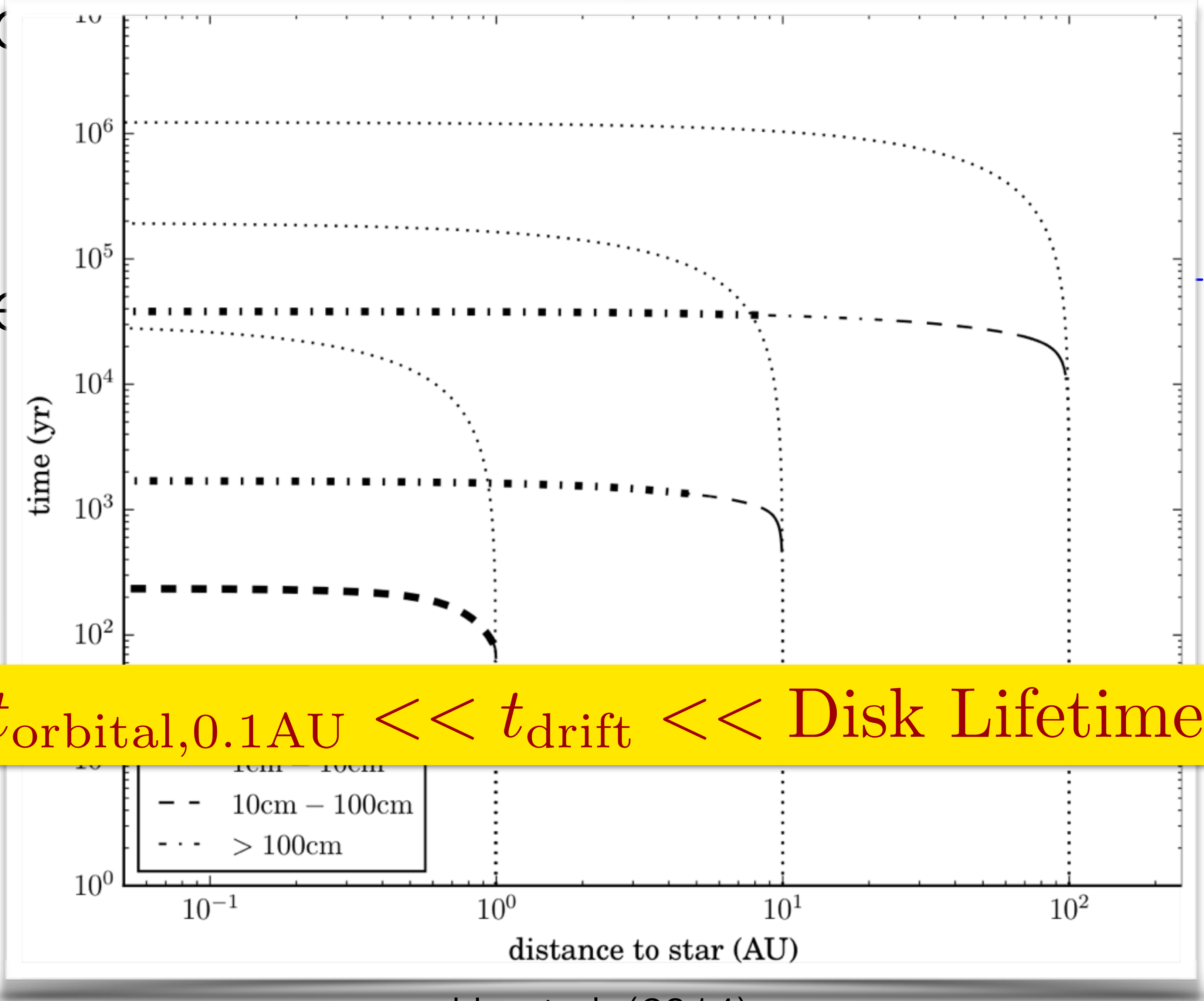

$t_{\rm orbital,0.1AU} << t_{\rm drift} <<$ Disk Lifetime

Hu et al. (2014)

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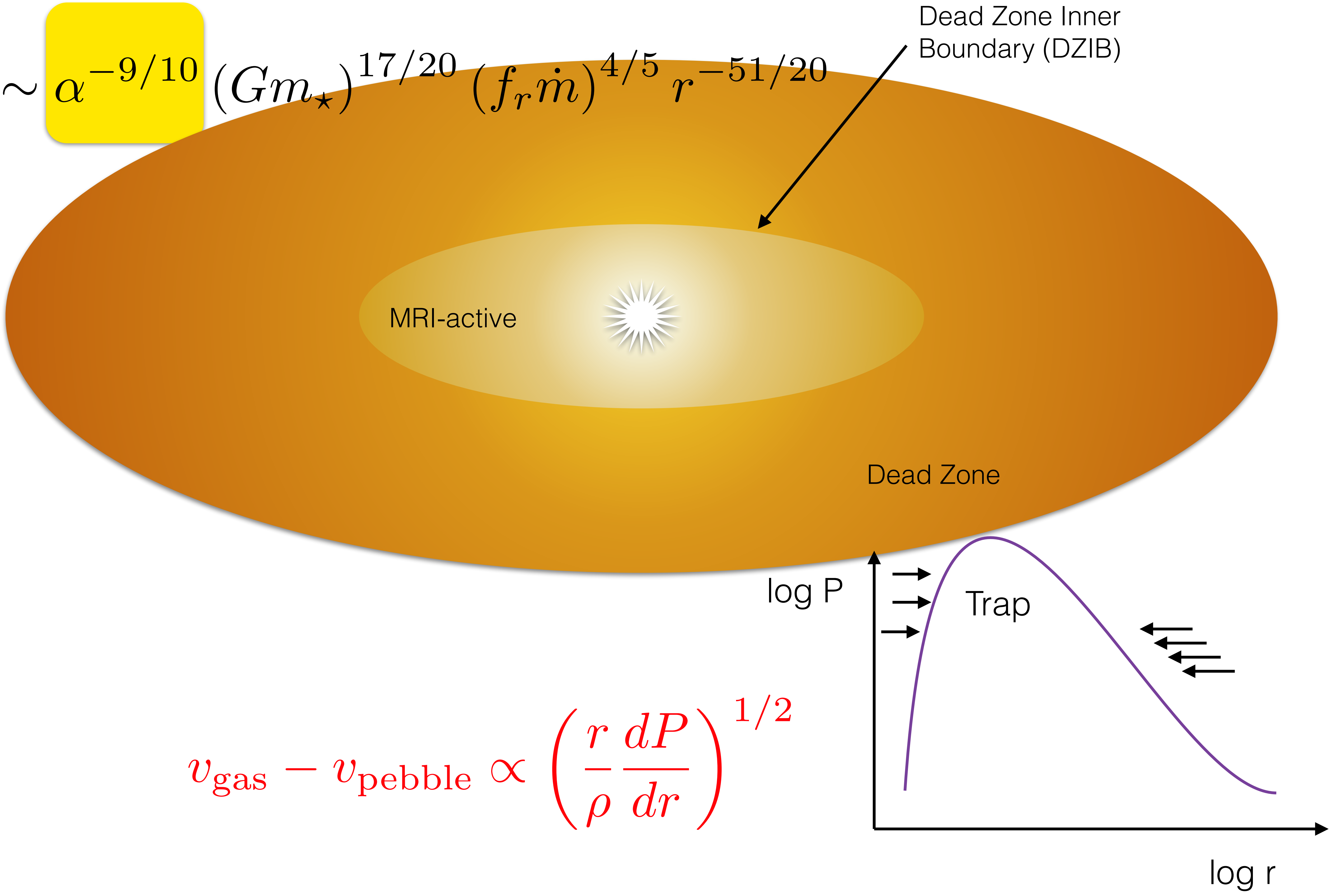

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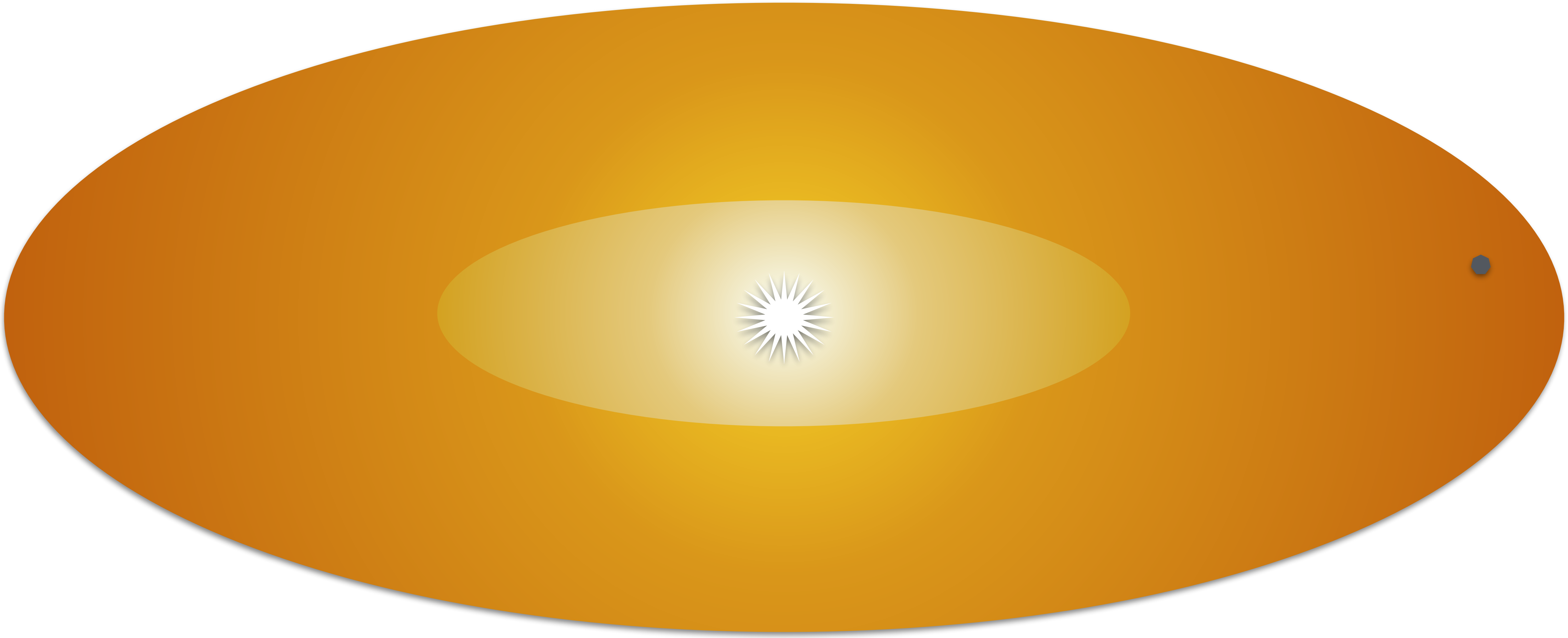

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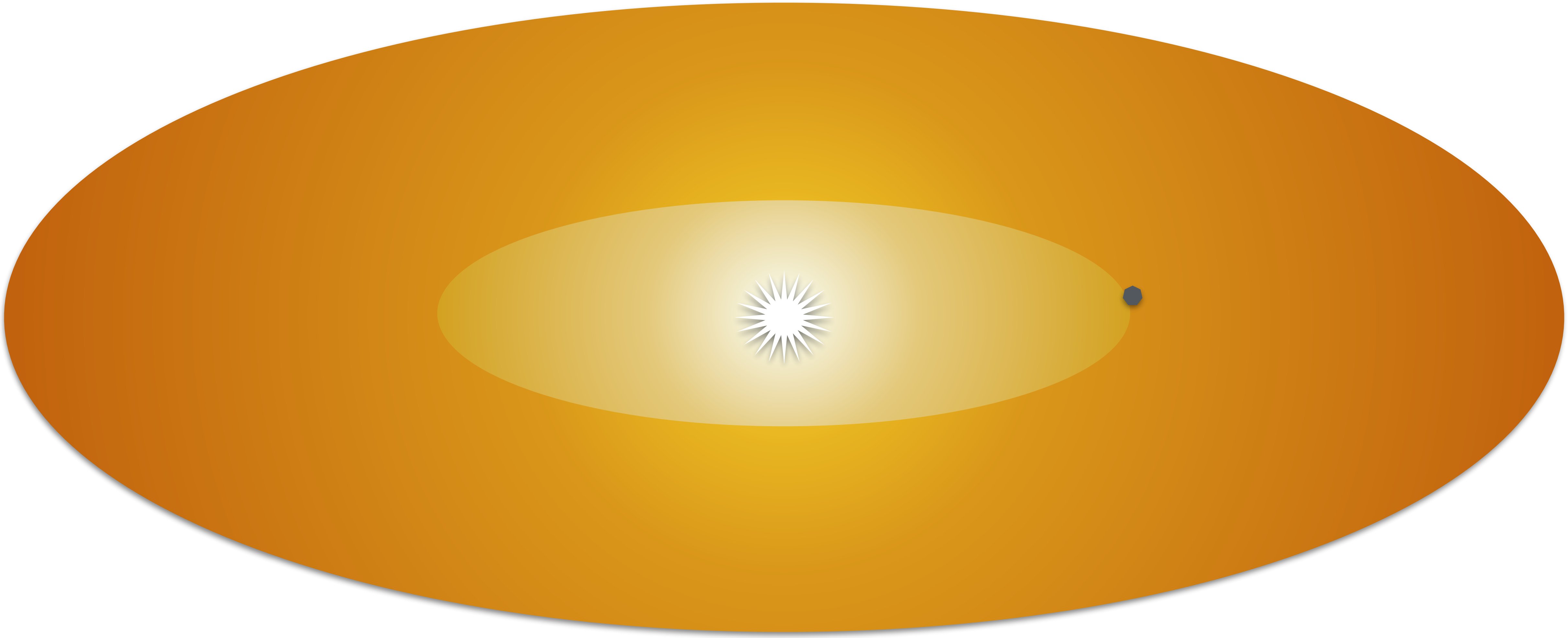

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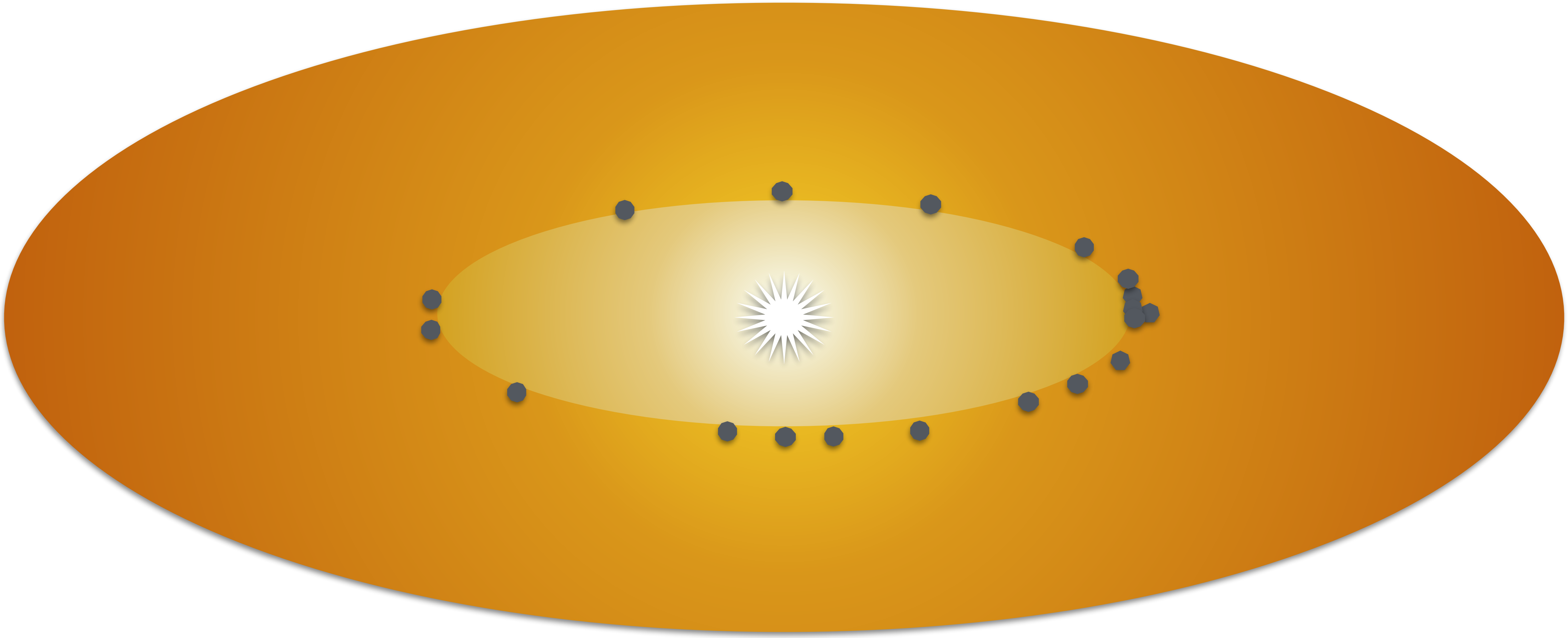

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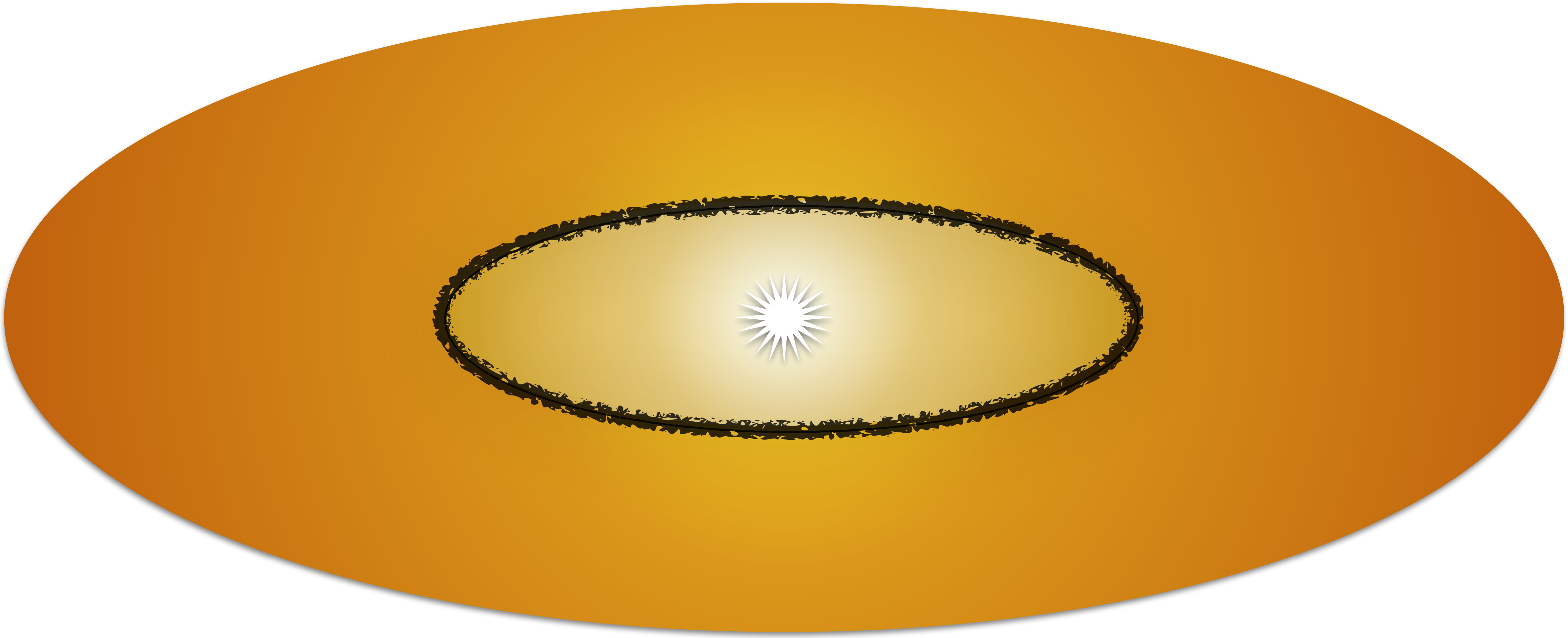

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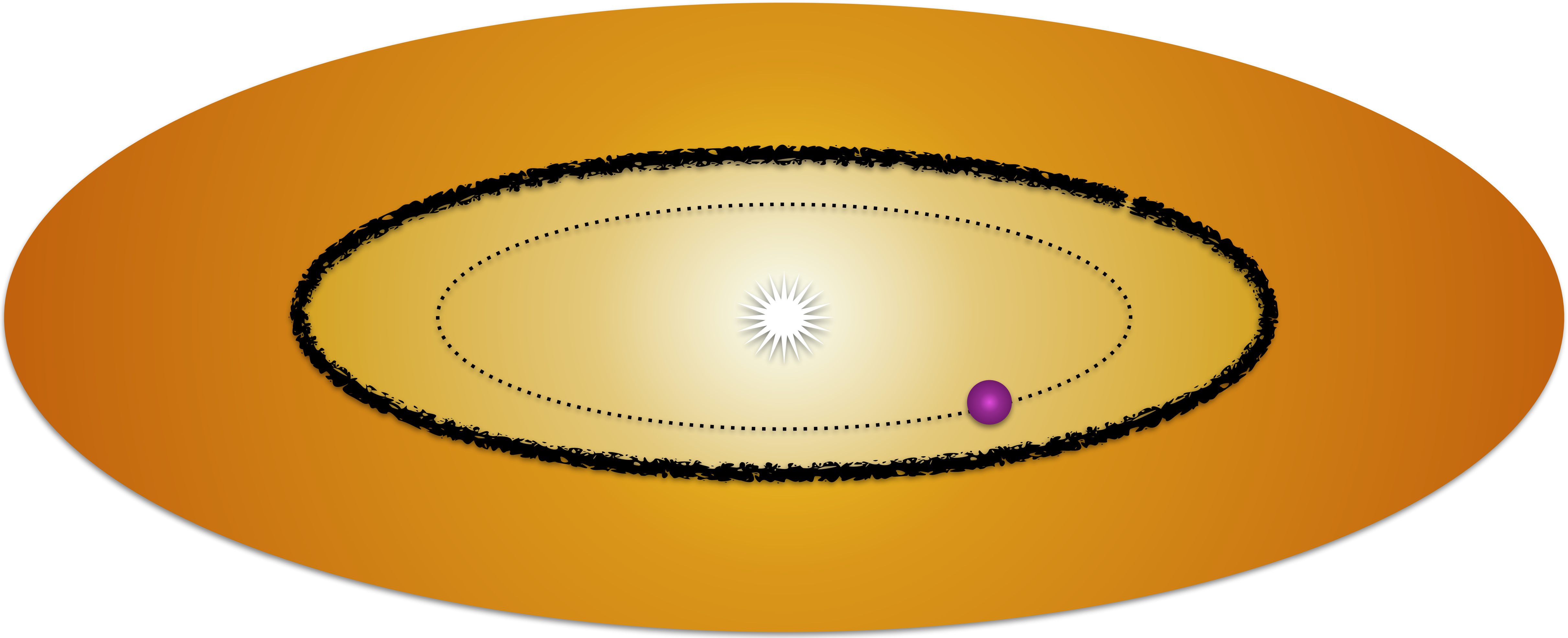


Location of the Dead-Zone Inner Boundary

Assumption 1: DZIB is first set by thermal ionization of alkali metals at T~1200 K

$$r_{1200\mathrm{K}} = 0.178\gamma_{1.4}^{-2/9}\kappa_{10}^{2/9}\alpha_{-3}^{-2/9}m_{*,1}^{1/3}(f_r\dot{m}_{-9})^{4/9}\ \mathrm{AU}$$

(Chatterjee & Tan 2014)

Uncertainties in $r_{1200\mathrm{K}}$: Energy extraction by a disk wind and opacity reduction due to dust destruction can reduce this value by a factor of a few (Zhang et al. 2013).

Assumption 2: Efficient pebble drift overwhelms any other stopping mechanism, e.g., shear instabilities (Weidenschilling 1980; Youdin & Shu 2002; Bai & Stone 2010), Rossby wave instabilities (Meheut et al. 2012; Lyra & Mac Low 2012).

Mass Scales for the Formed Planets

Toomre mass (M_T)

- velocity dispersion of pebbles ~ v_r (r_{DZIB})
- Toomre parameter Q ~ 1

Ring mass (M_R)

- all mass in the pebble enhanced ring creates a single planet

Gap opening mass (M_G)

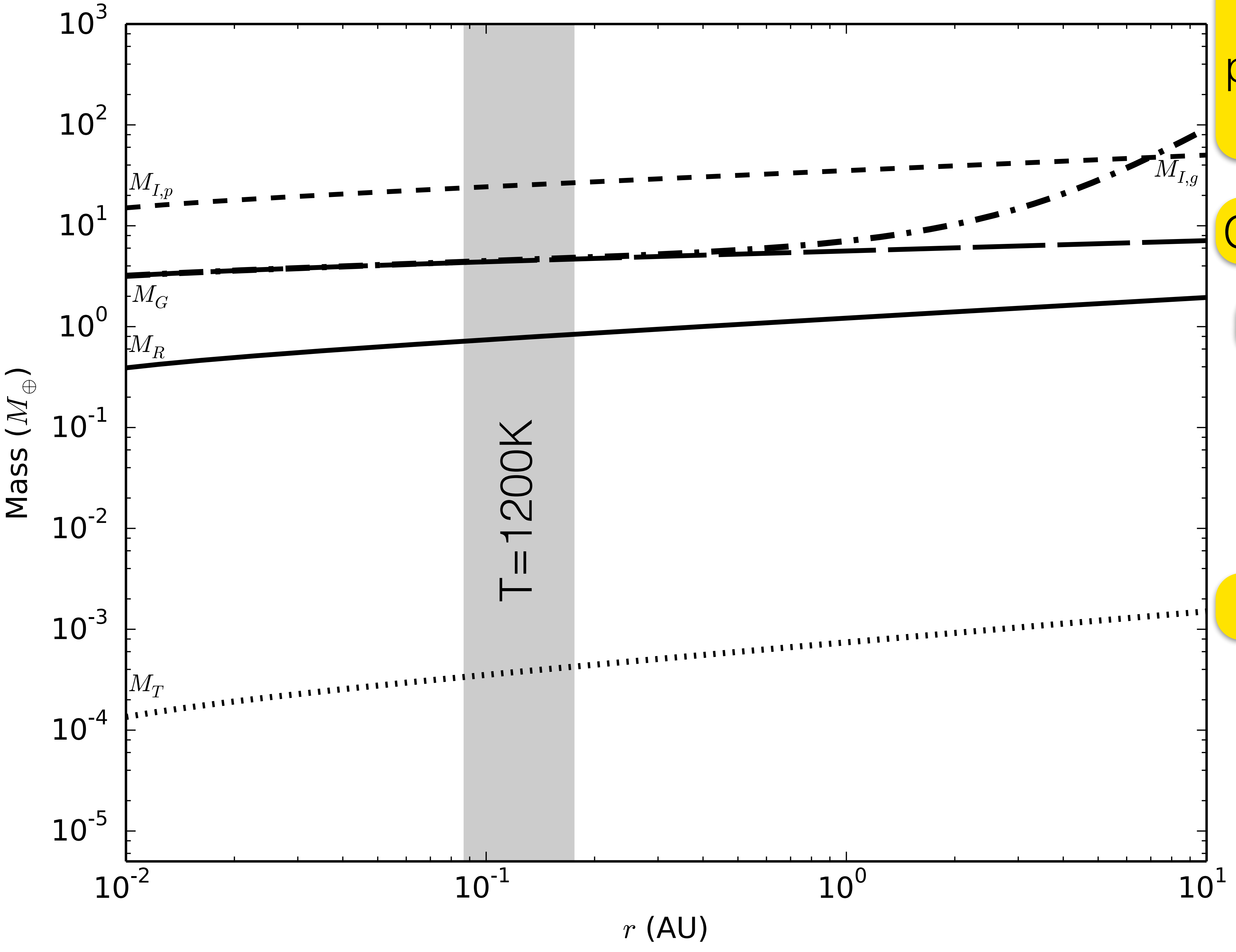
- fraction ϕ_G = 0.3 (Zhu et al. 2013) of viscous-thermal criterion (Lin & Papaloizou 1993)

Isolation masses
pebble dominated ($M_{I,p}$)
gas dominated ($M_{I,g}$)

- feeding zone ϕ_H ~ 3 (e.g., Lissauer 1987) of Hill radius R_H

Mass Scales for the Formed Planets

$$\alpha = 10^{-3}$$



$$\dot{m} = 10^{-9}\, M_\odot \text{ yr}^{-1}$$

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pebble dominated ($M_{I,p}$)
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Gap opening mass (M_G)

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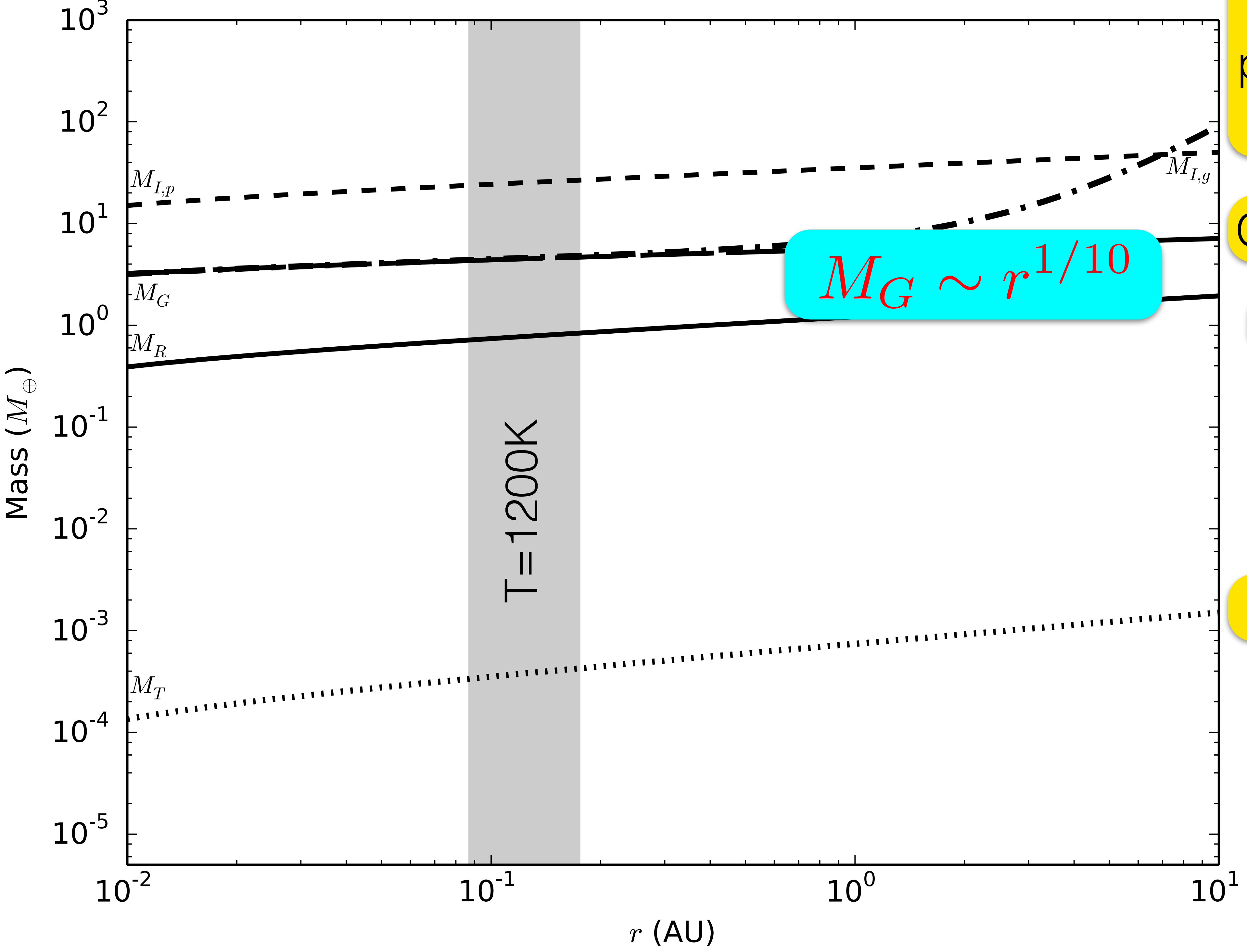

$M_G \sim r^{1/10}$

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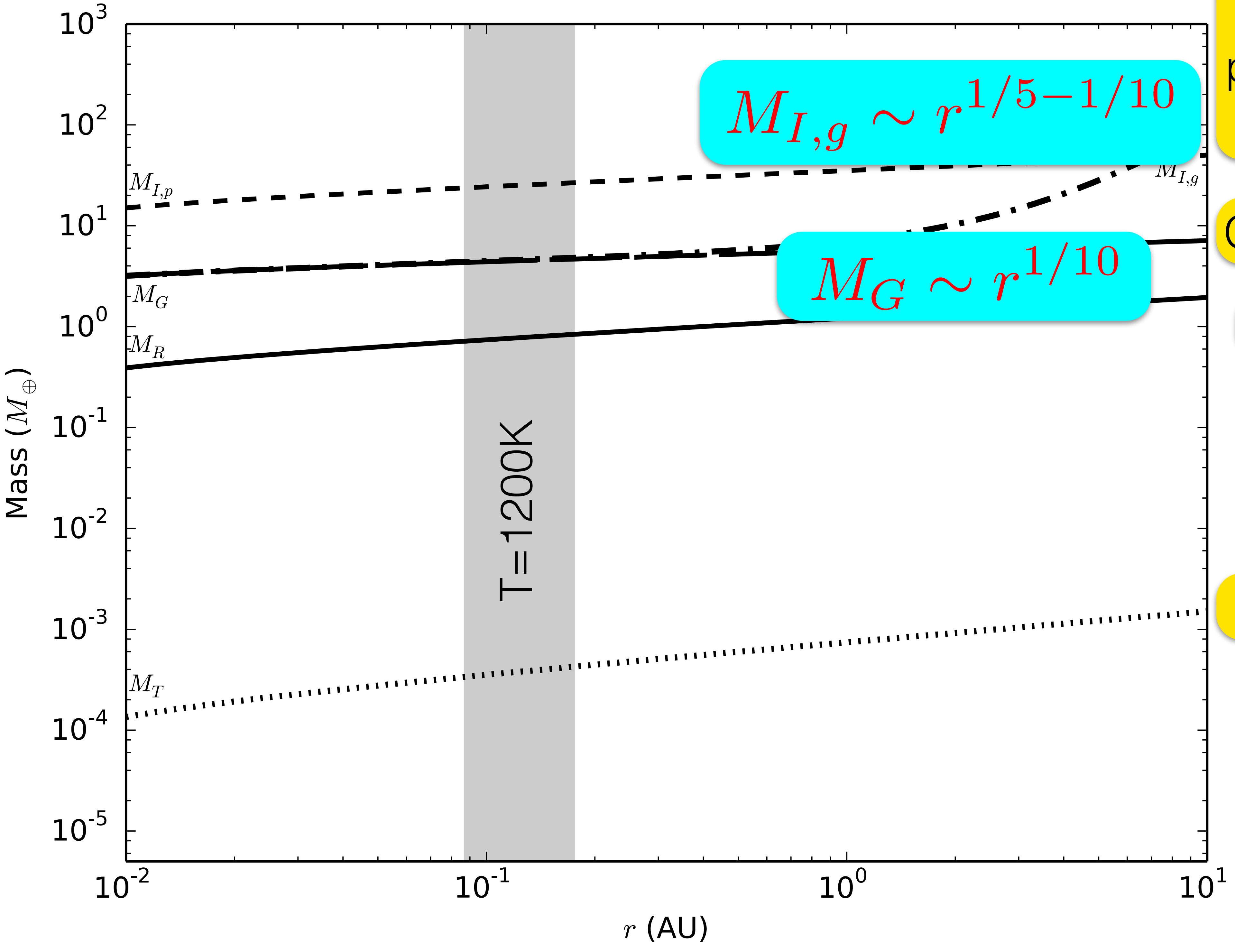

$M_{I,g} \sim r^{1/5-1/10}$

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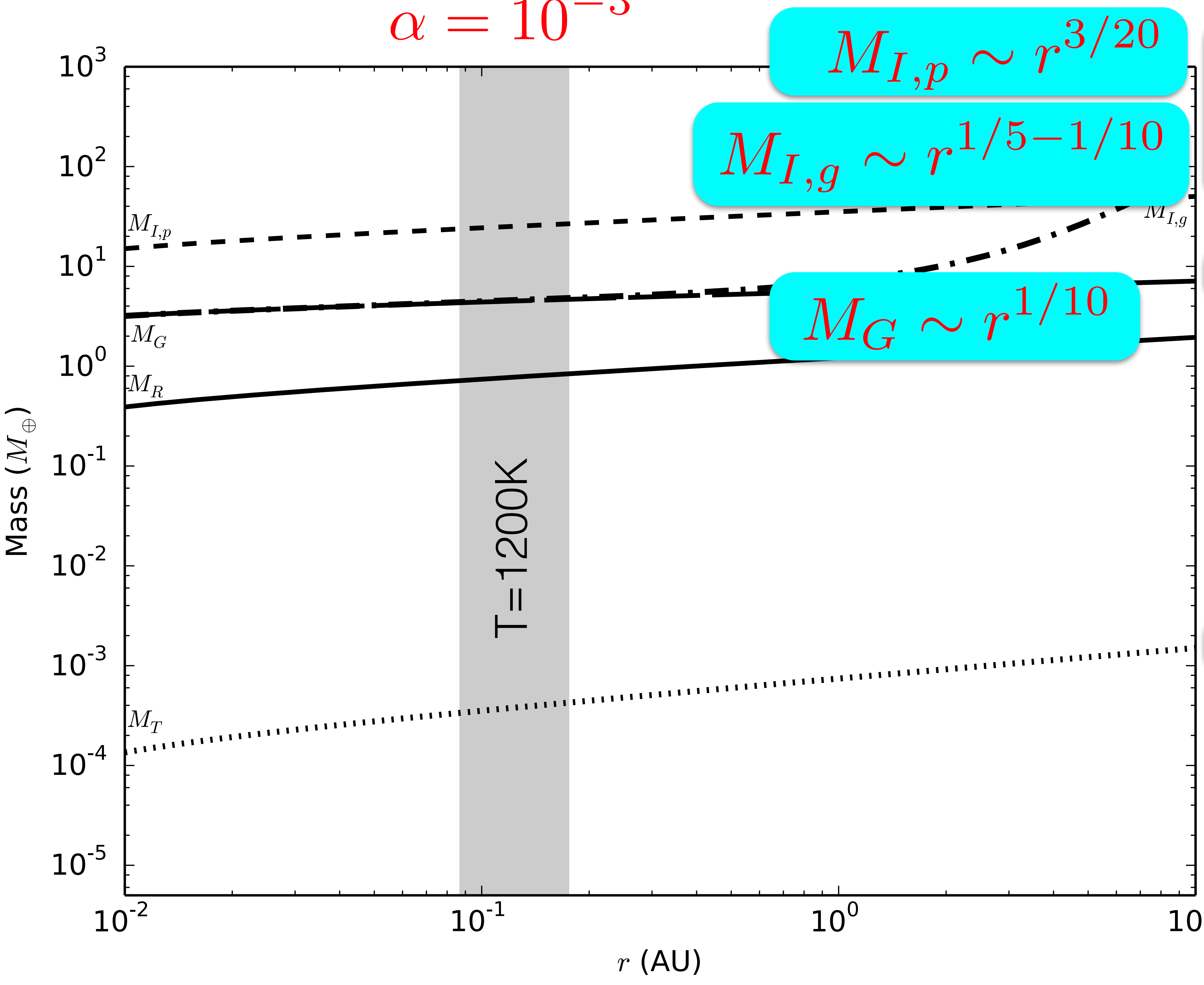

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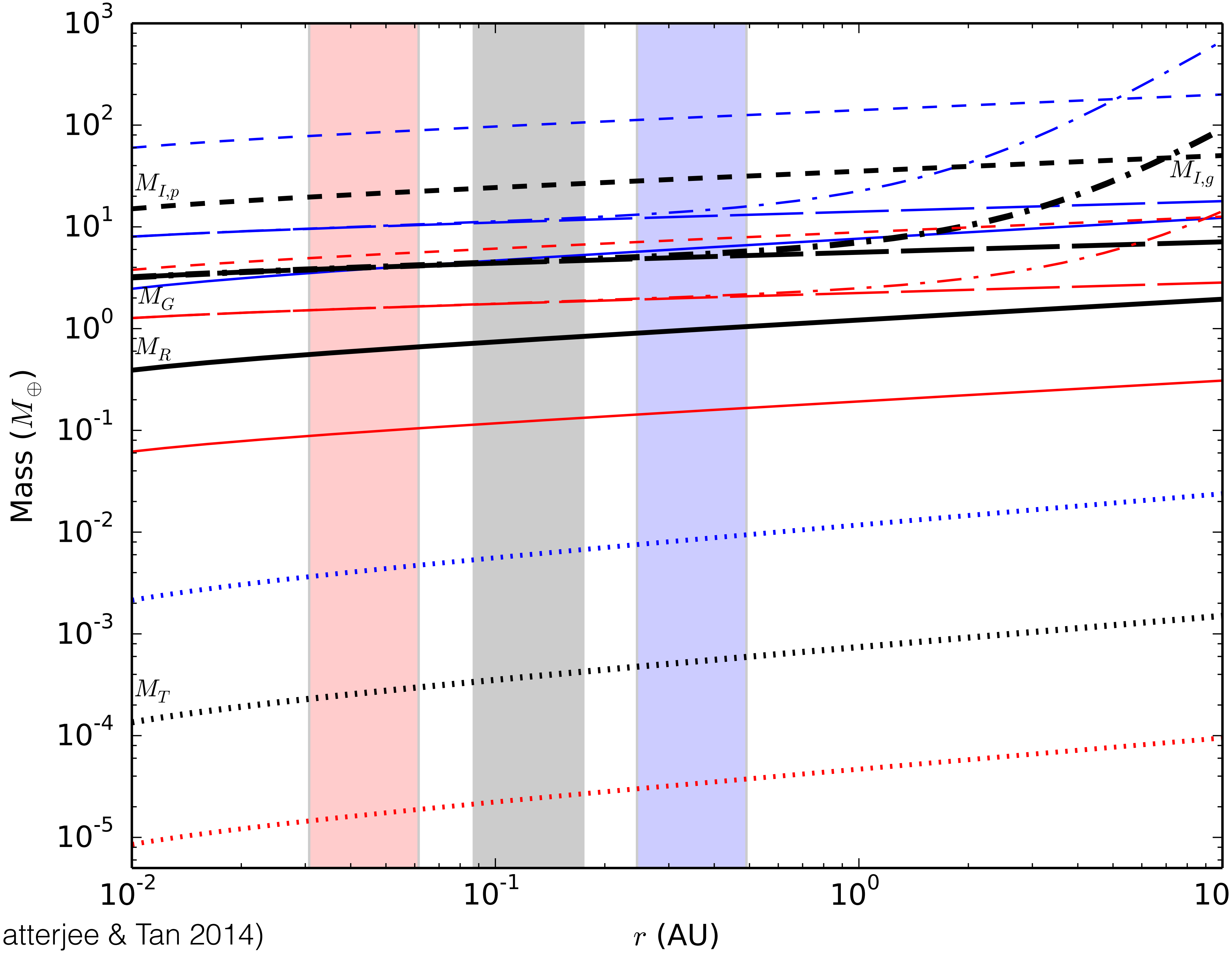
Mass Scales for the Formed Planets

Different accretion rates



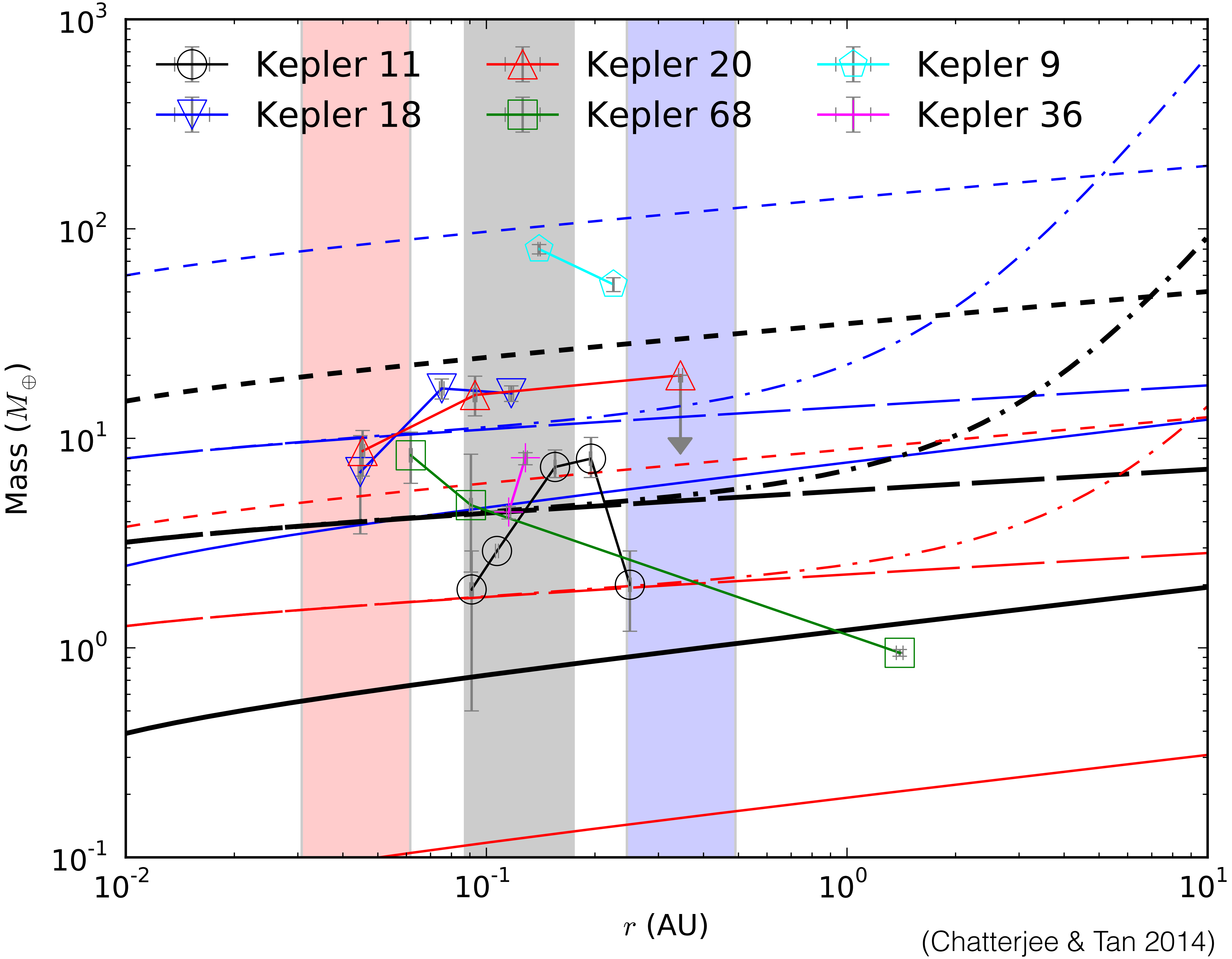
$\alpha = 10^{-3}$

(Chatterjee & Tan 2014)

$\dot{m} = 10^{-10}\,M_\odot\ \mathrm{yr}^{-1}$ $\dot{m} = 10^{-9}\,M_\odot\ \mathrm{yr}^{-1}$ $\dot{m} = 10^{-8}\,M_\odot\ \mathrm{yr}^{-1}$

Comparison with Kepler Data

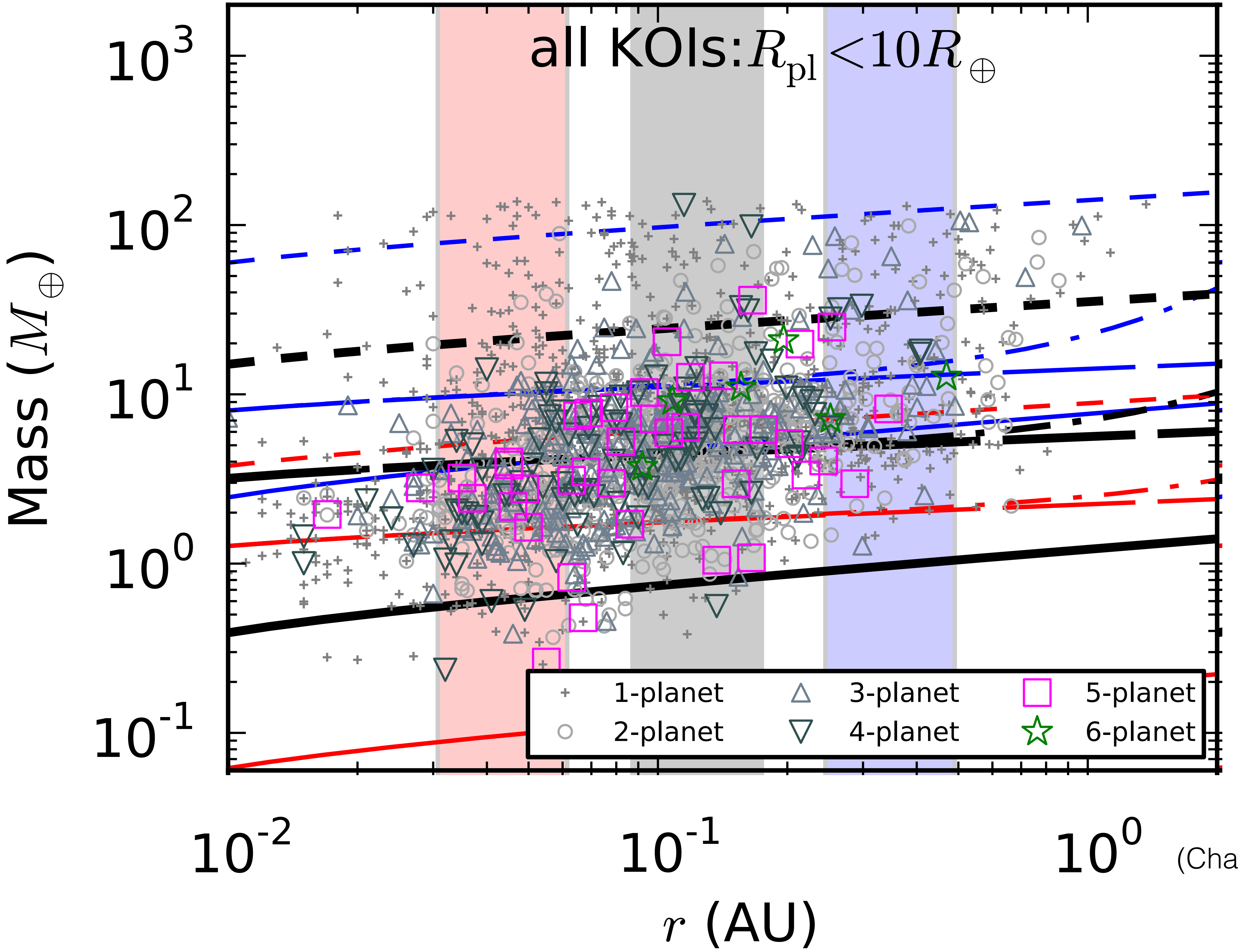
TTV Planets: Mass vs Orbital Radius



(Chatterjee & Tan 2014)

Comparison with Kepler Data

Kepler Planet Candidates: Mass vs Orbital Radius

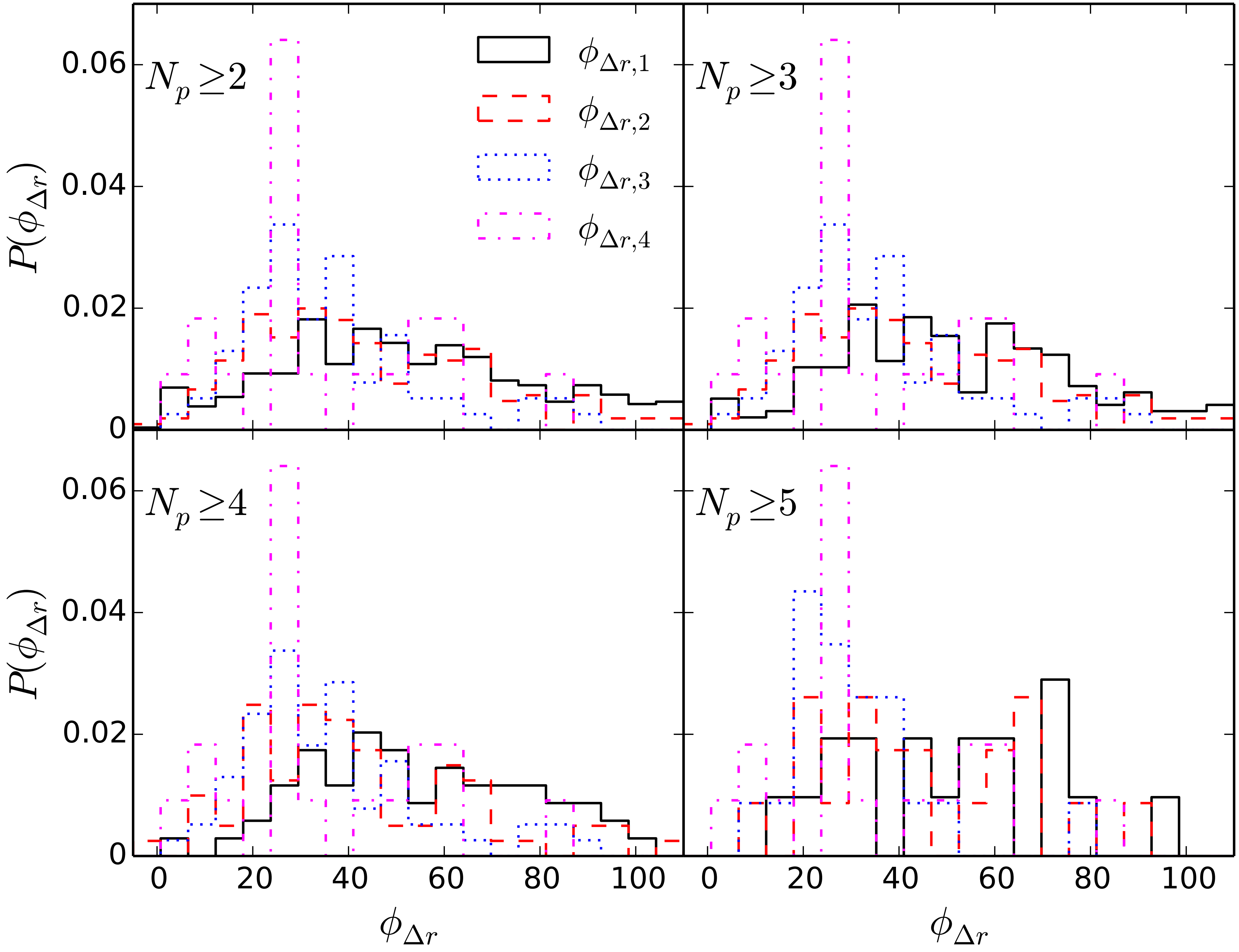


(Chatterjee & Tan 2014)

Assuming simple M-R relation from Lissauer et al. (2011)

Comparison with Kepler Data

KPCs: Planet-Planet Separations



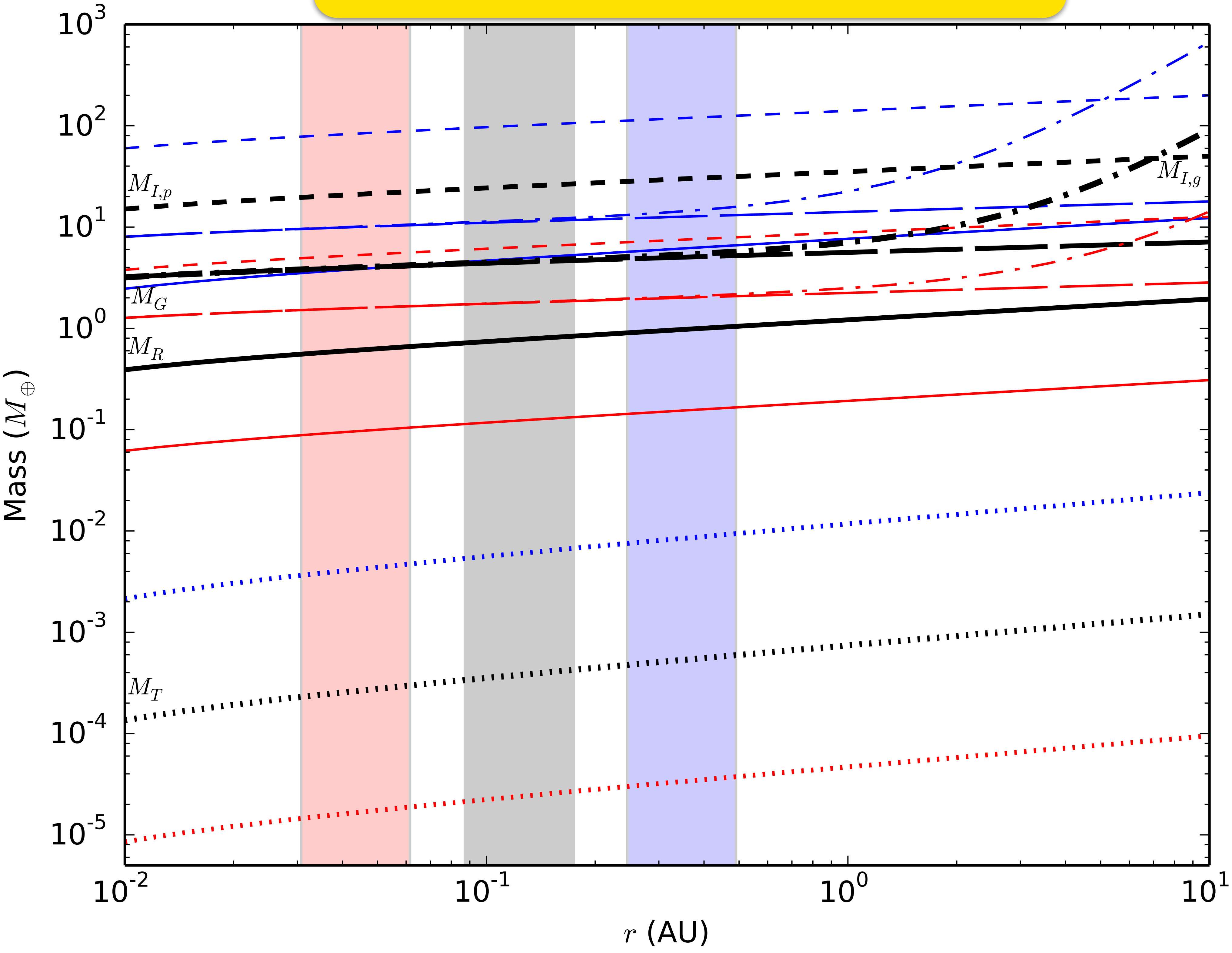
$$\phi_{\Delta r} \equiv \frac{r_{i+1} - r_i}{R_{H,i}}$$

(Chatterjee & Tan 2014)

Comparison with Kepler Data

Innermost Planet Mass vs Orbital Radii

$$M_G = 5\phi_{G,0.3}\alpha_{-3}r_{0.1\mathrm{AU}}\ M_\oplus$$



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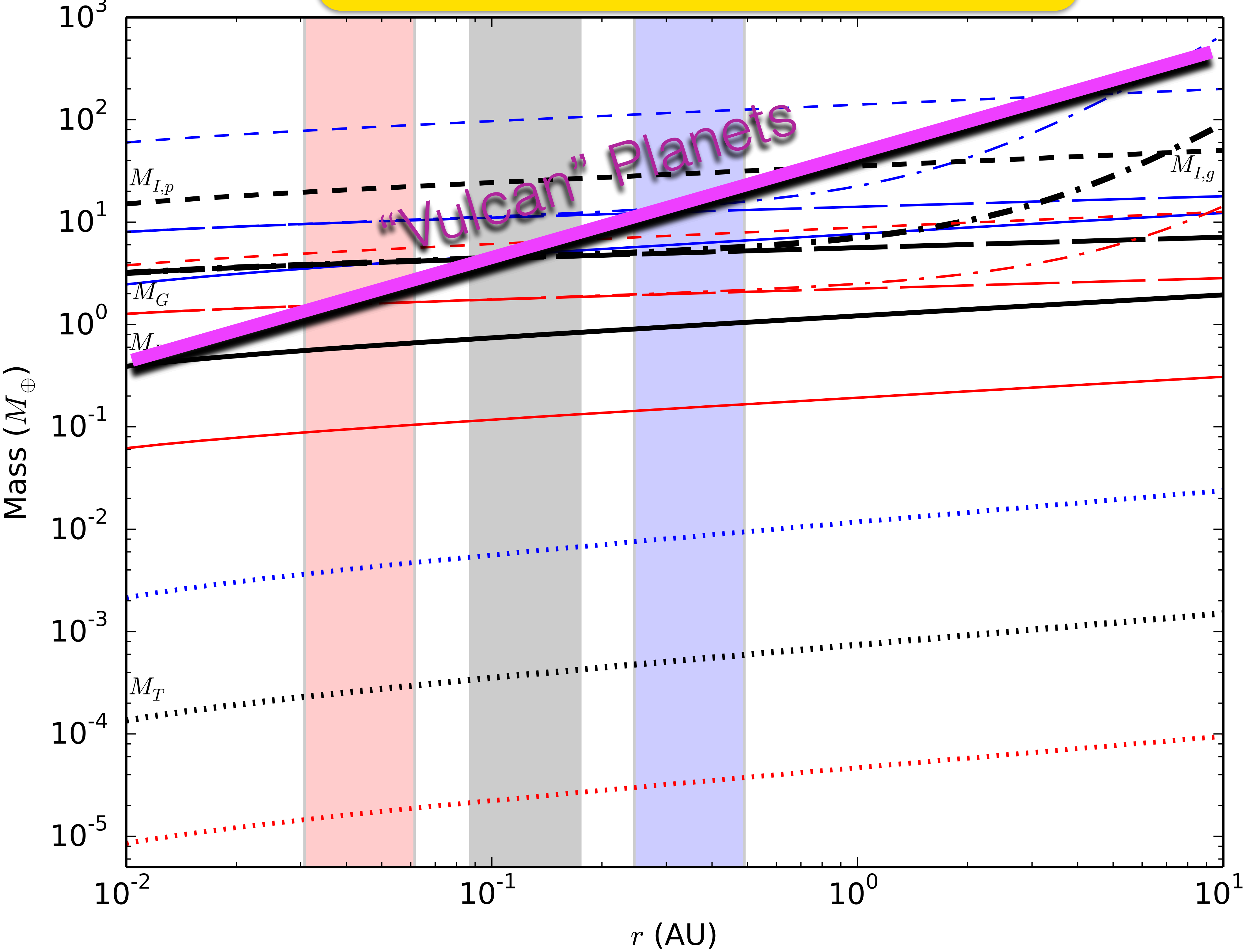
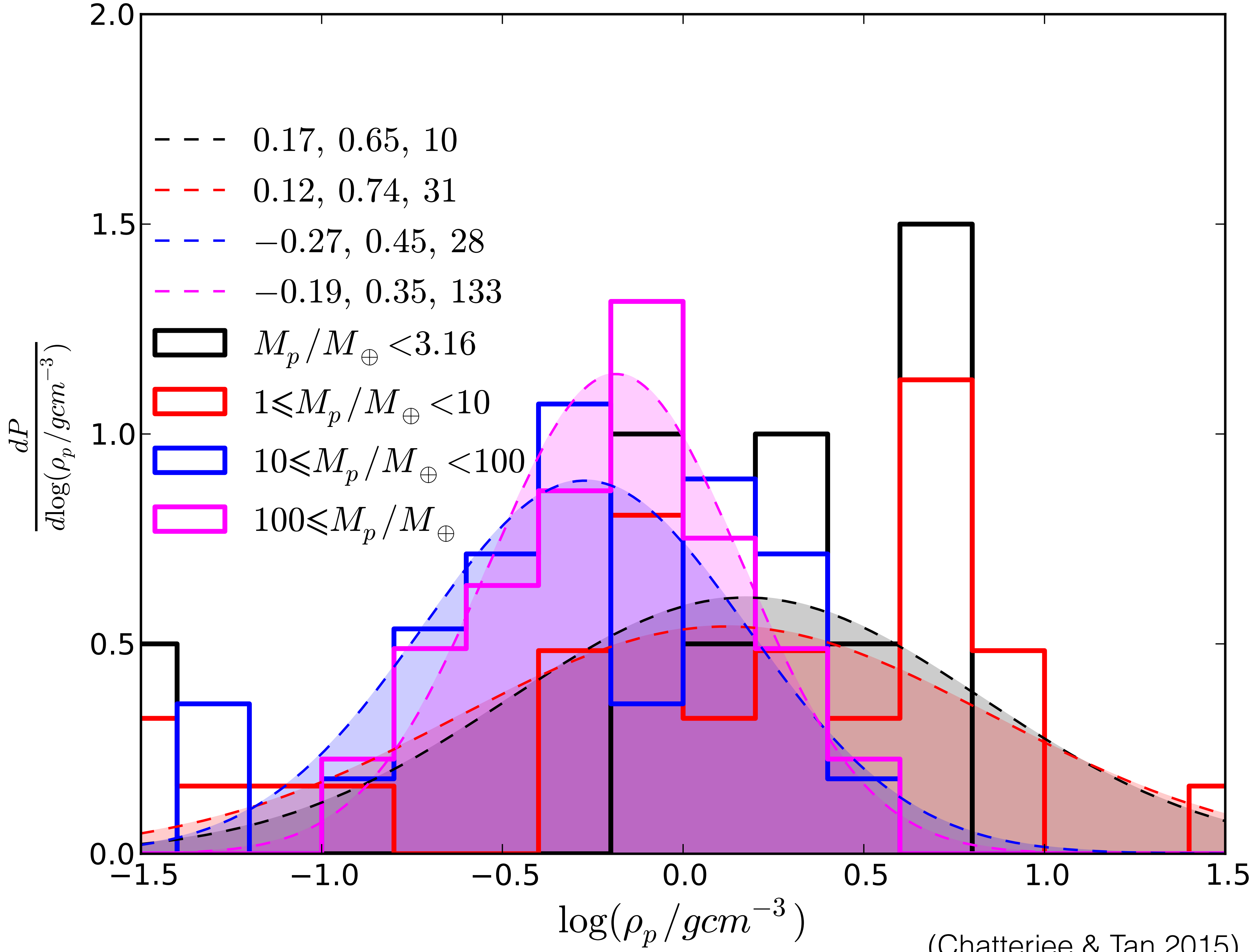


Comparison with Kepler Data

Converting Mass to Radius



(Chatterjee & Tan 2015)

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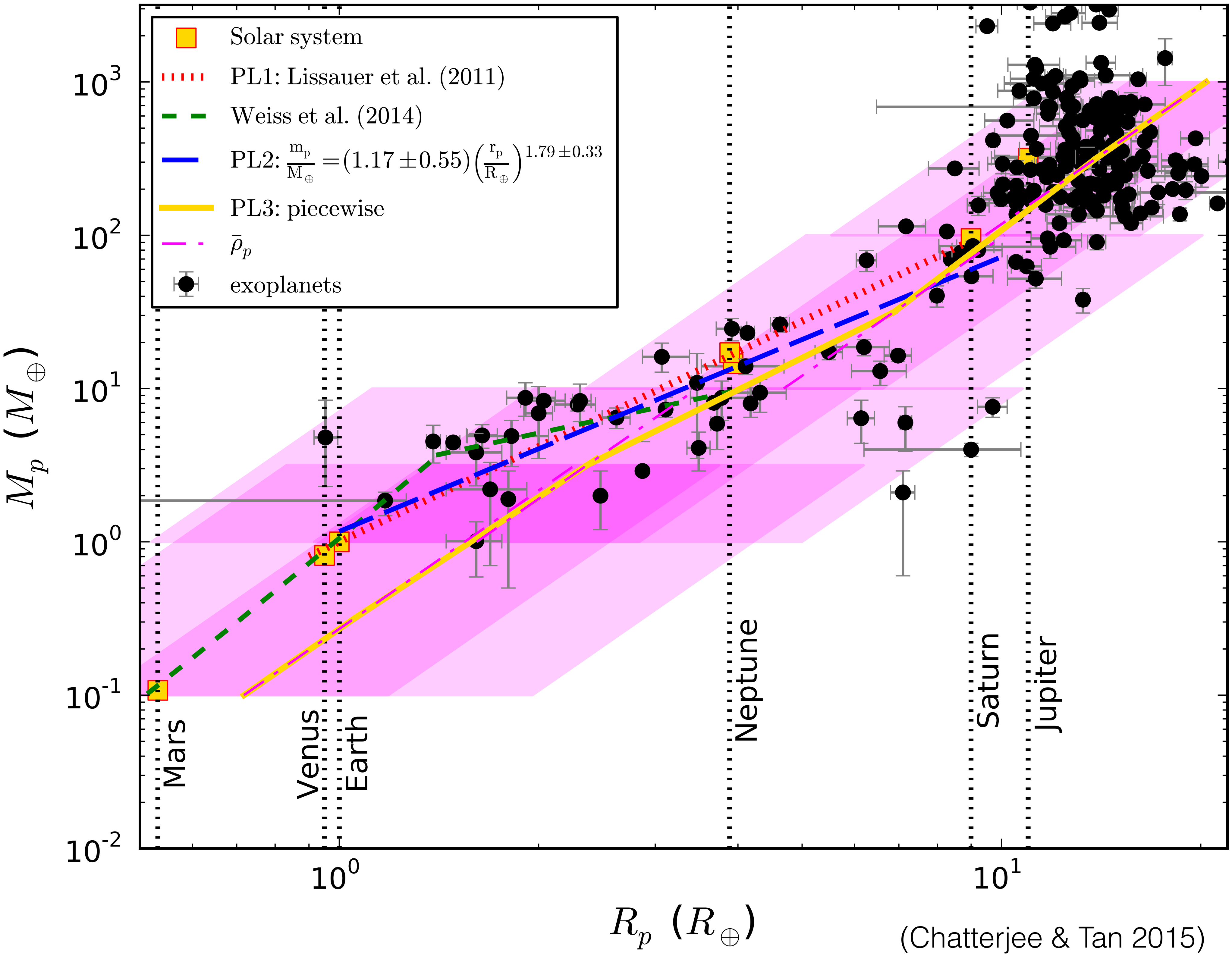

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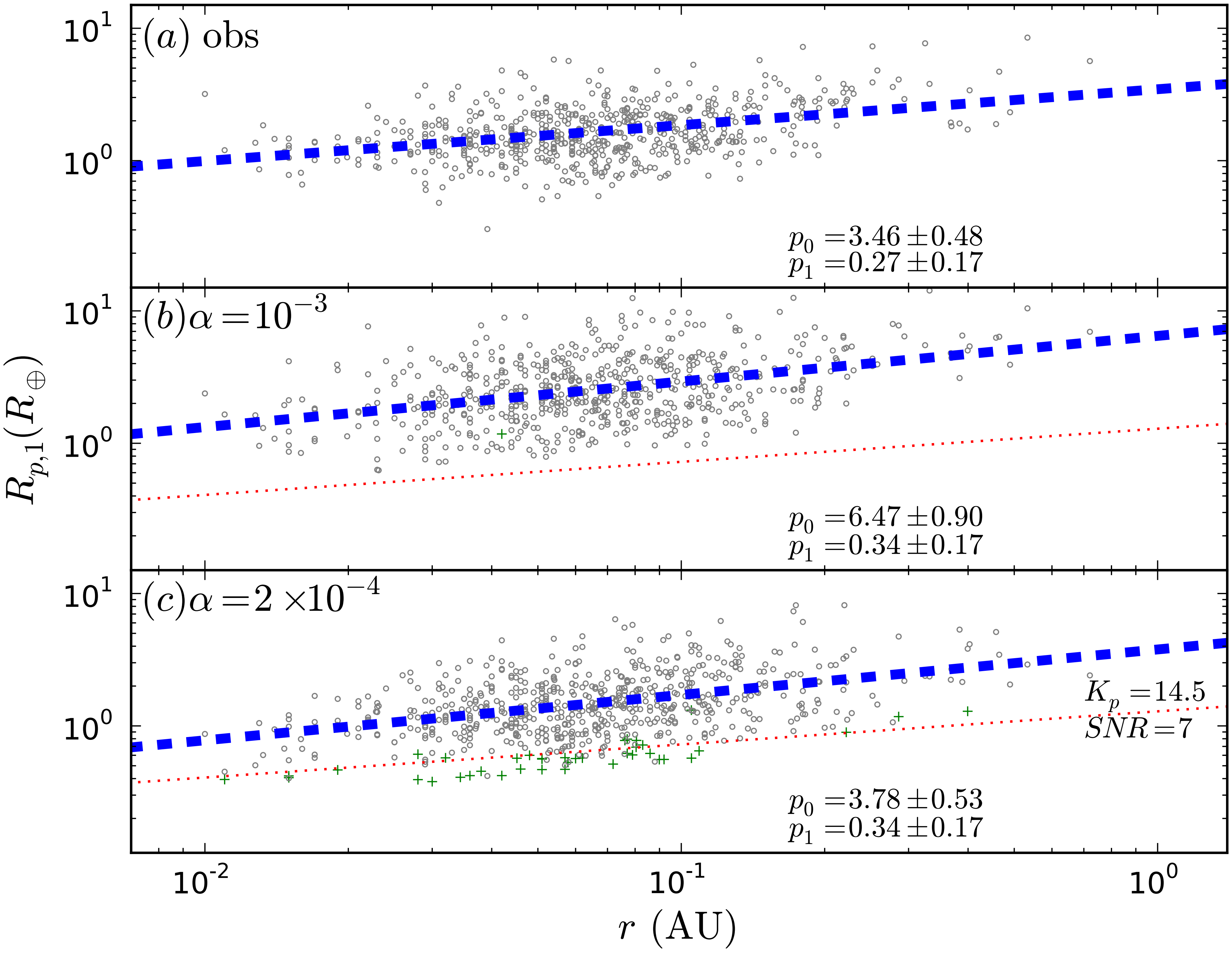
Comparison with Kepler Data

“Vulcans”: Planet Size & Orbital Radius



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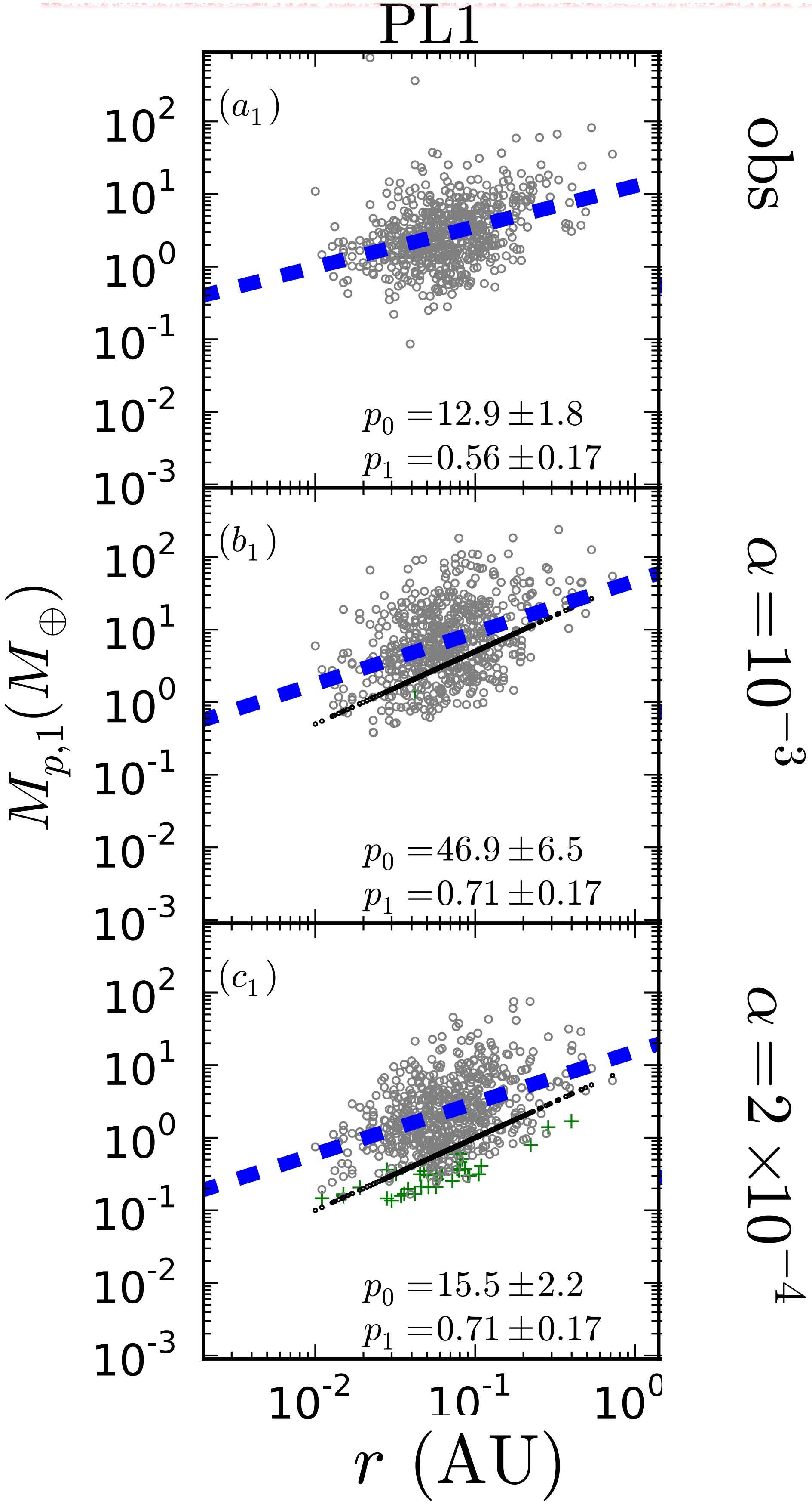

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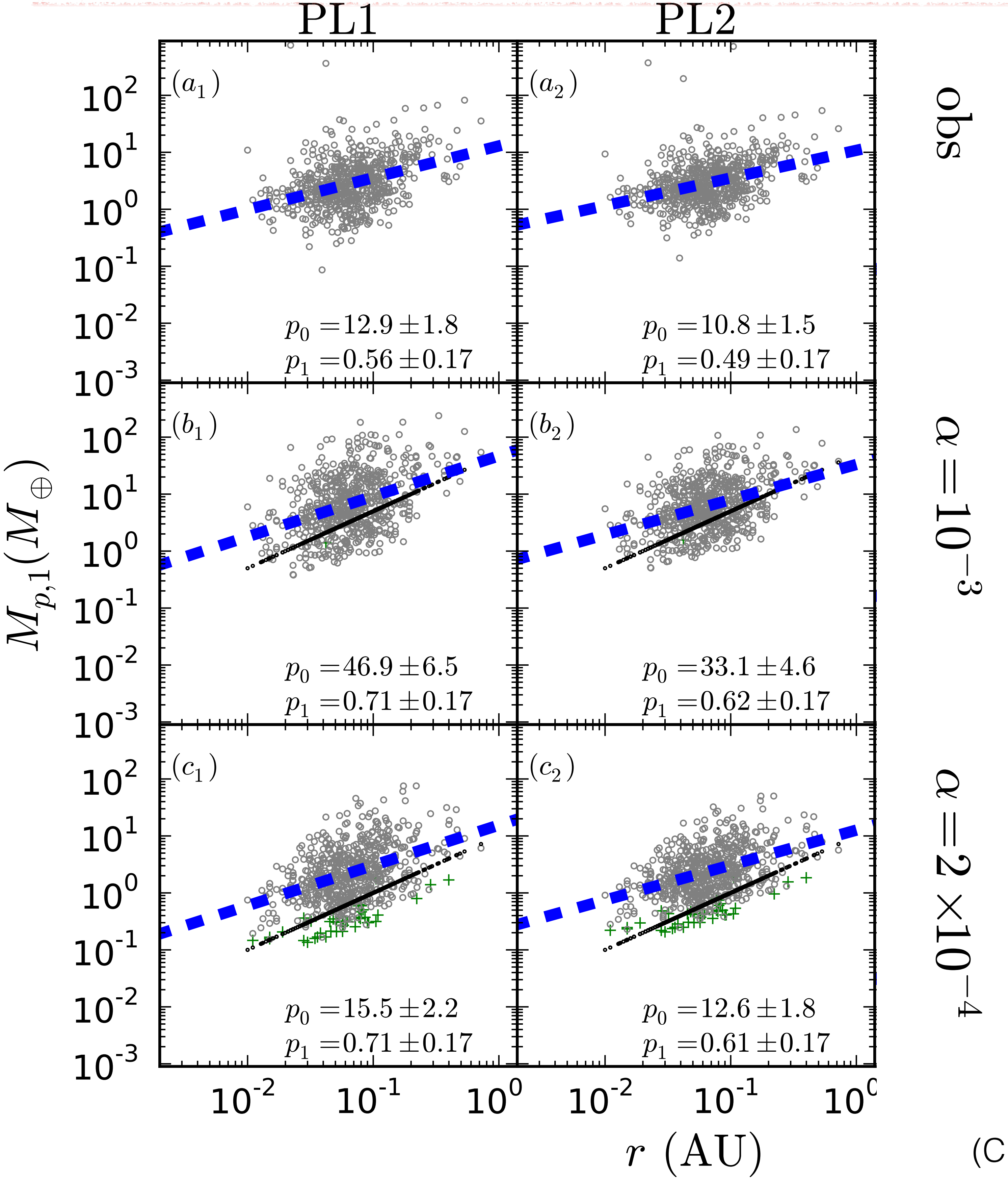

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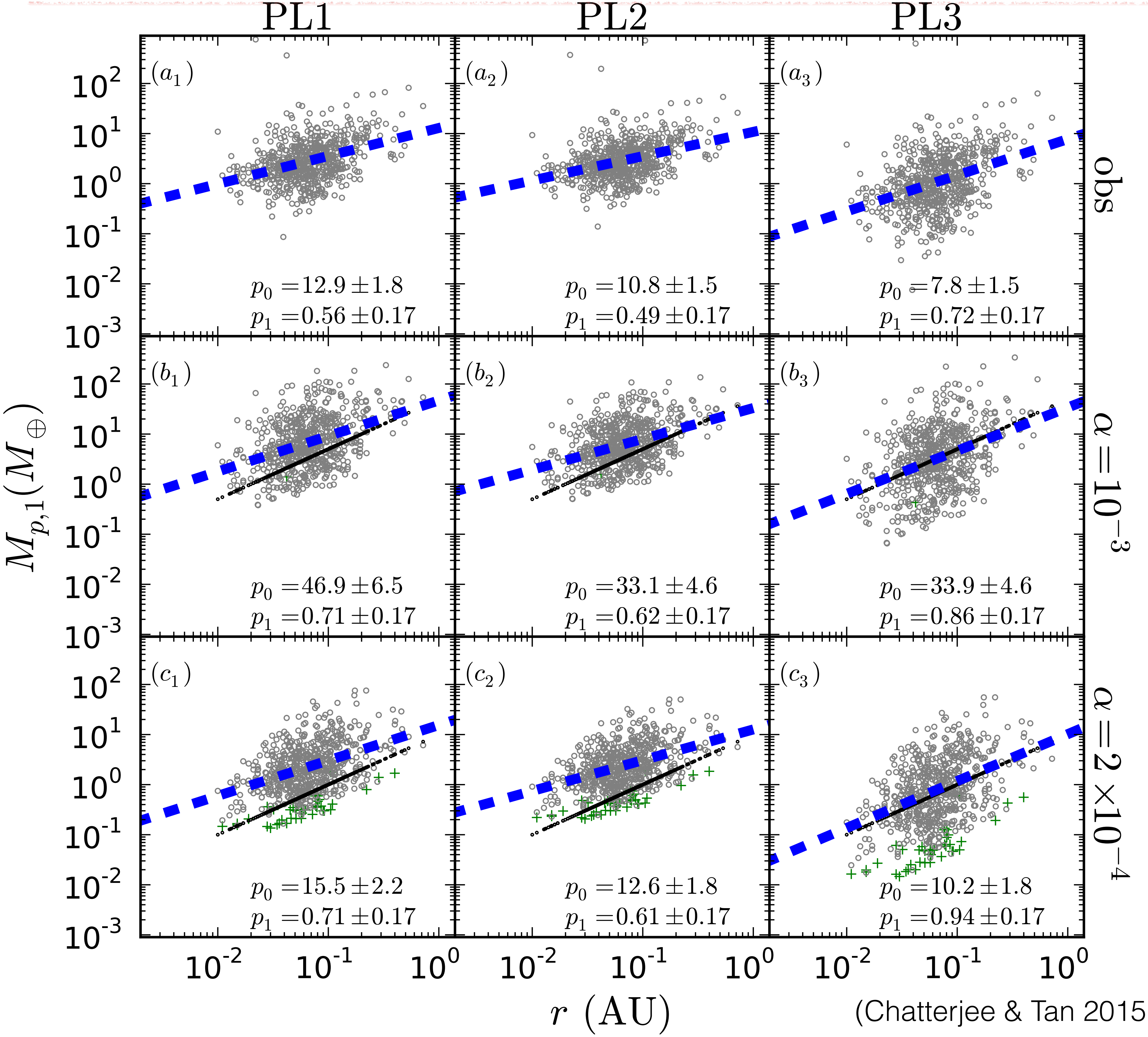

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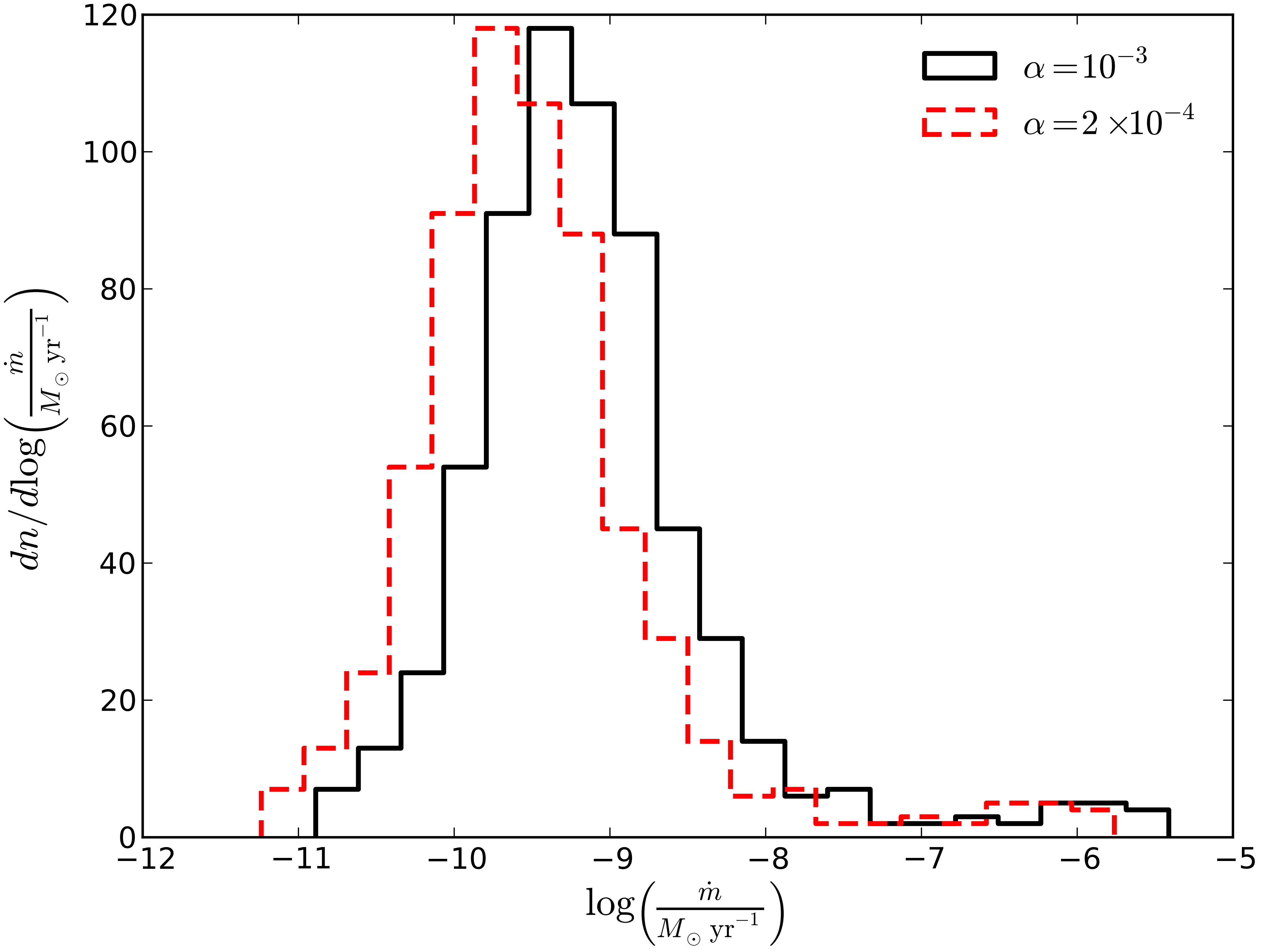
Comparison with Kepler Data

“Vulcans”: Required Accretion Rates



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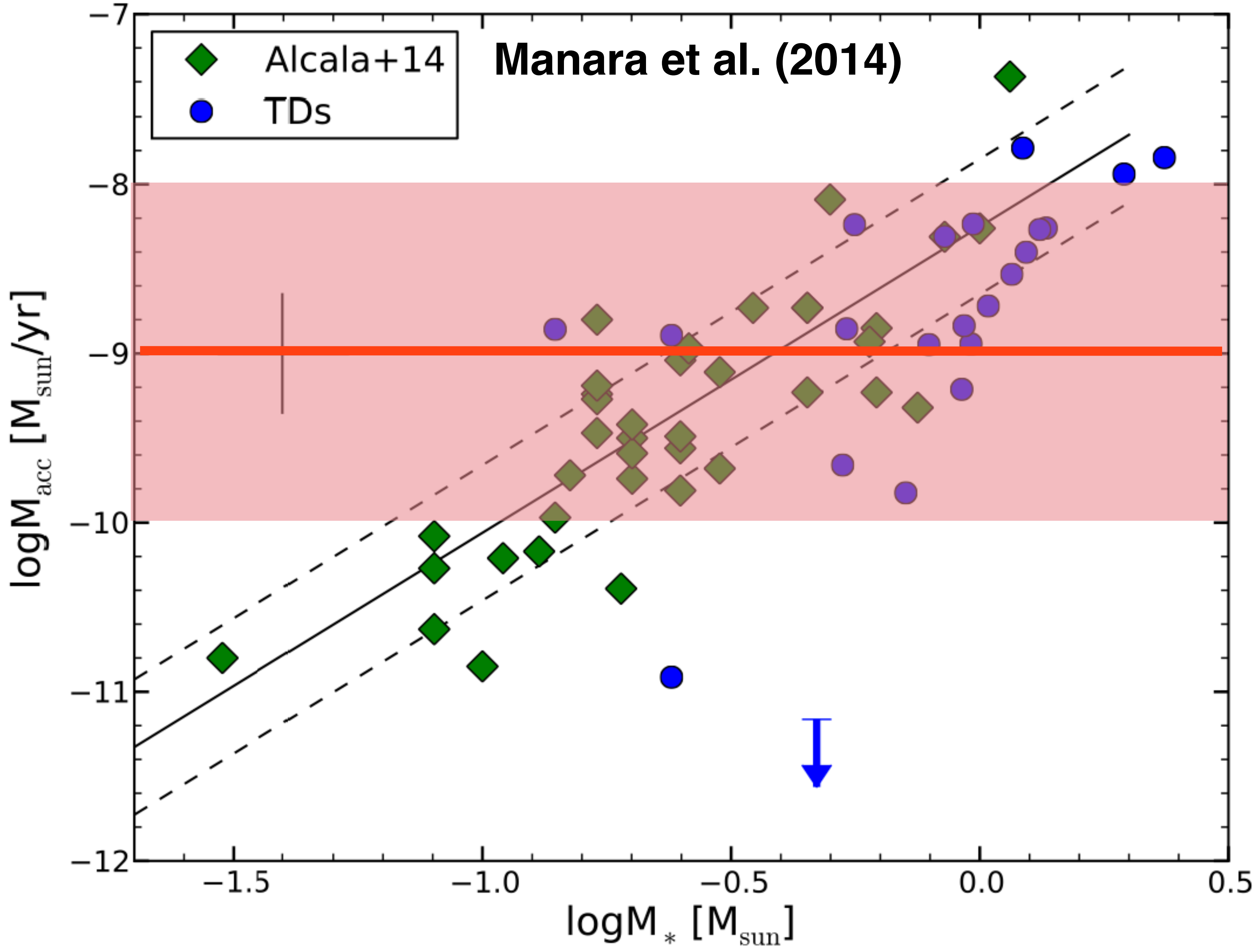

Accretion rates for 22 accretion disks tracing gas inside 0.2 AU.
Similar values for classical T-Tauri stars (Alcala et al. 2014).

Features of this Model

- Rapid radial drift of pebbles enrich the inner disk. No need to appeal for extraordinary disk density profiles.
  - No “m-size barrier”, actually “m-size **supply**”.
- These are the first planets created in the system.
  - Contrast to e.g., Grand-Tac model.
- Can create 1-10 $M_\oplus$ on tightly-packed short-period orbits starting from typical disks.
- Predicts flat scalings of planet mass with orbital radius. Likely consistent with data.
- Orbital spacing between adjacent planets is a large factor of R_H.
  - No reason to form or not form resonant chains.
- Predicts a linear scaling between “Vulcan” planet mass and orbital radius.
  - Consistent with current data (both scaling and normalization) with the caveat that mass is estimated from radius for Kepler systems.
  - Can be verified or falsified with RV-measured masses of “Vulcans”.
- Indicates a plausible source of divergence between Kepler multi and Solar system analogs:
  - Strong local pressure traps formed early or not.