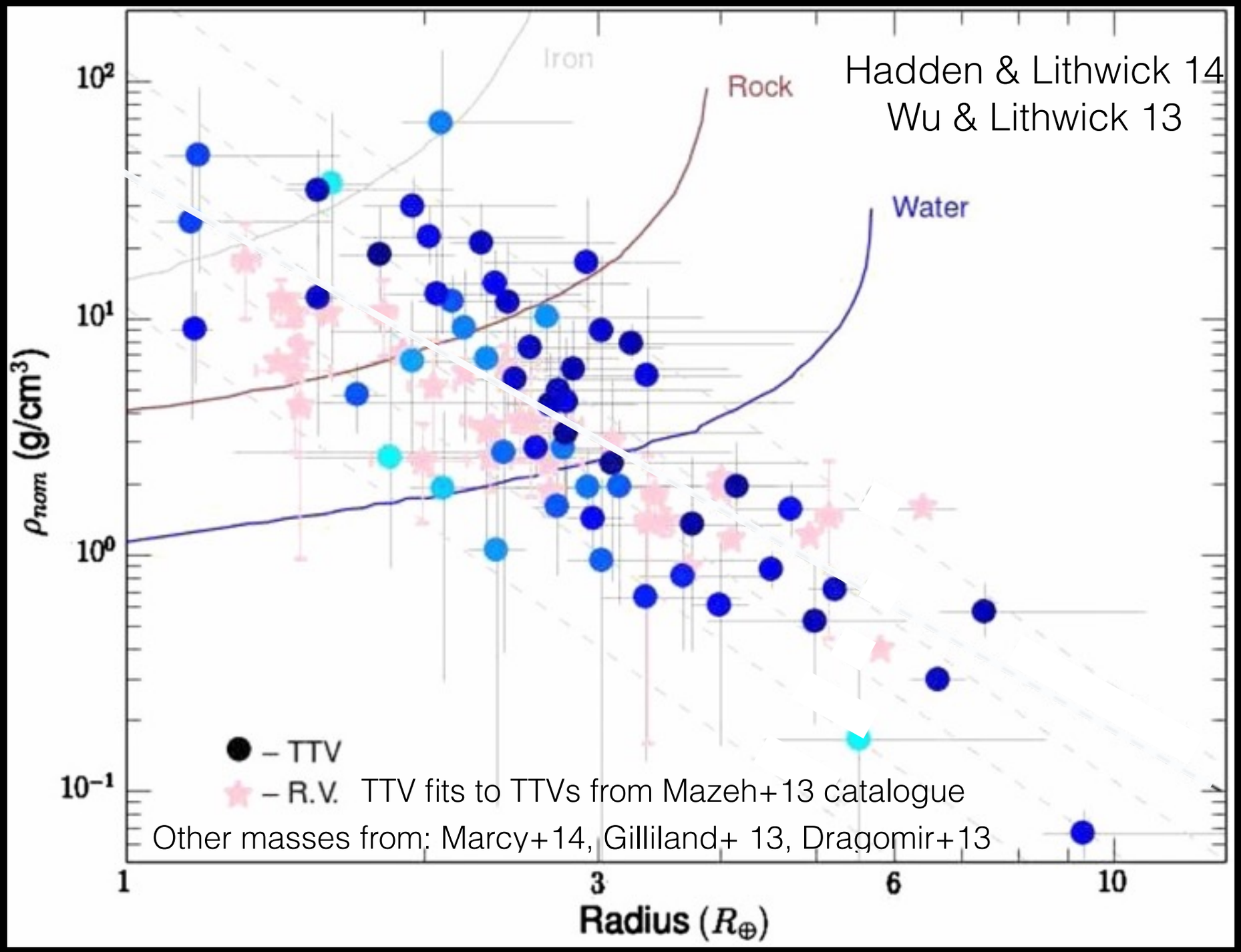
TTV Planets: Farm to Table

Rebekah (Bekki) Dawson (UCB Miller Fellow / —> PSU)

In collaboration with: Eugene Chiang (UCB), Eve Lee (UCB);
SAMSI Noise and Detrending Support Group (incl. R. Angus, G. J. Babu, T. Barclay, E. Ford, D. Foreman-Mackey, J. Fraine, B. Montet, B. Nelson, B. Quarles, R. Wolpert)

A variety of small planets with TTV mass measurements



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Interpretation

Dynamics

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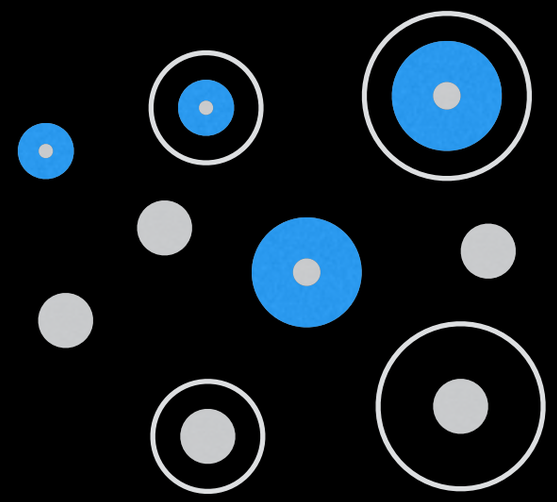

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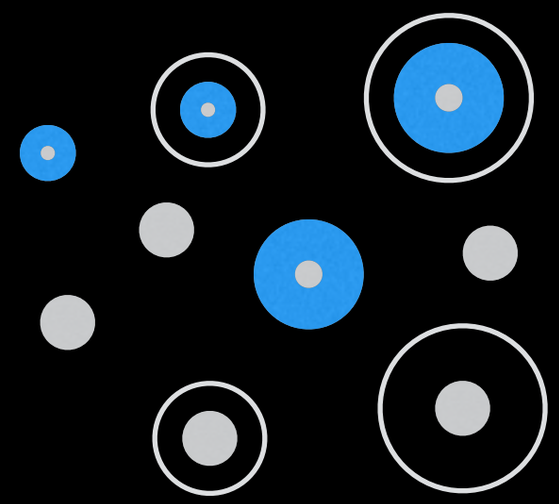

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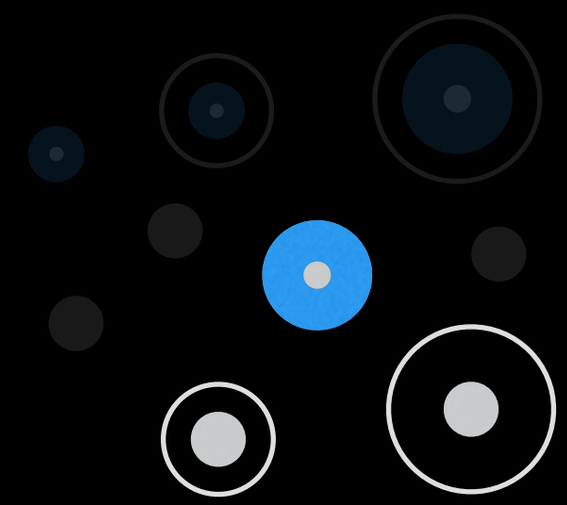

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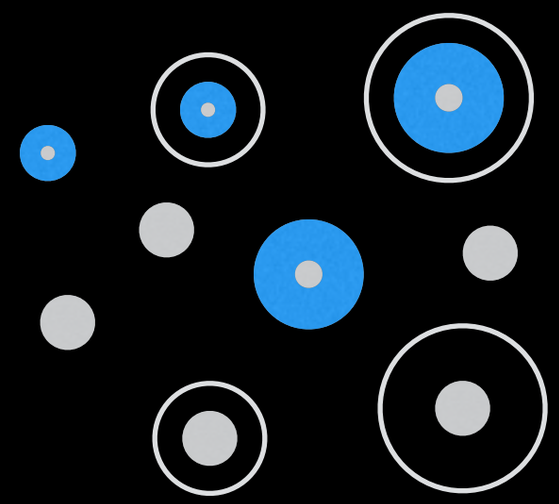

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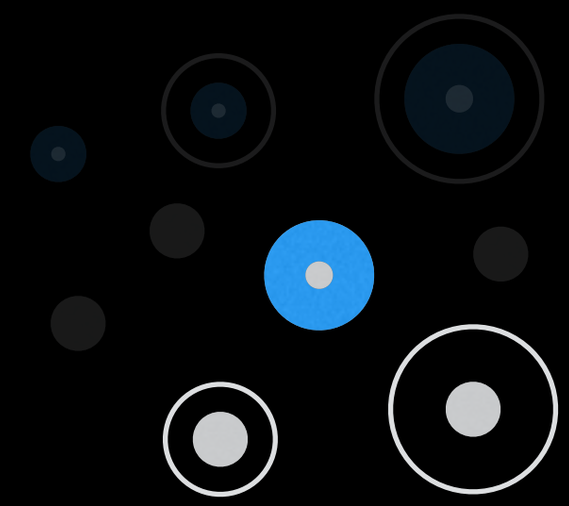

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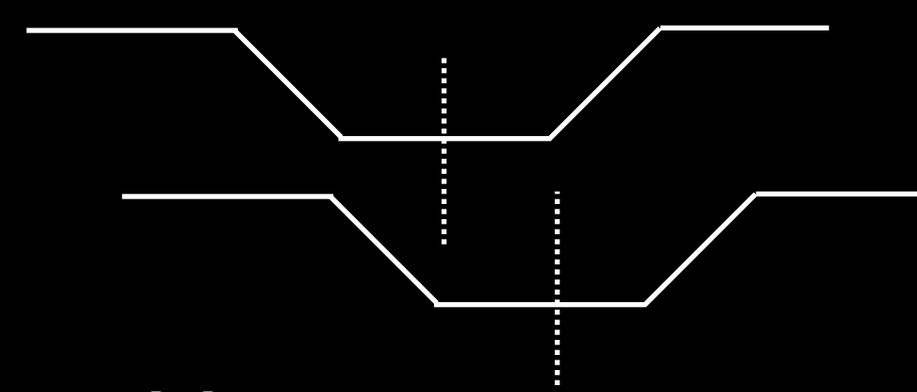

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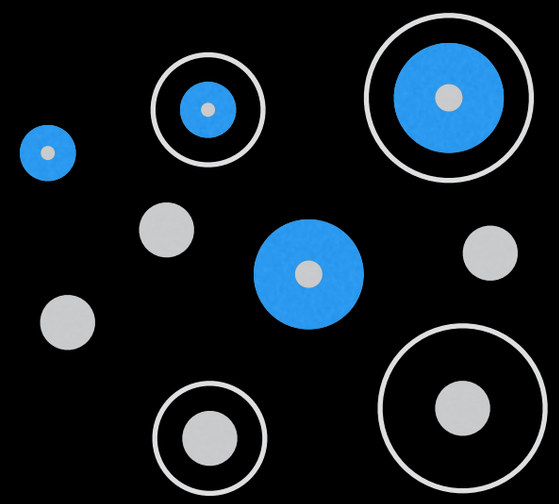

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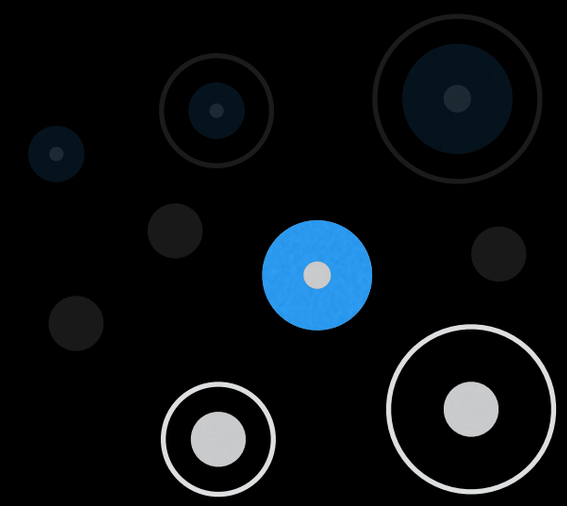

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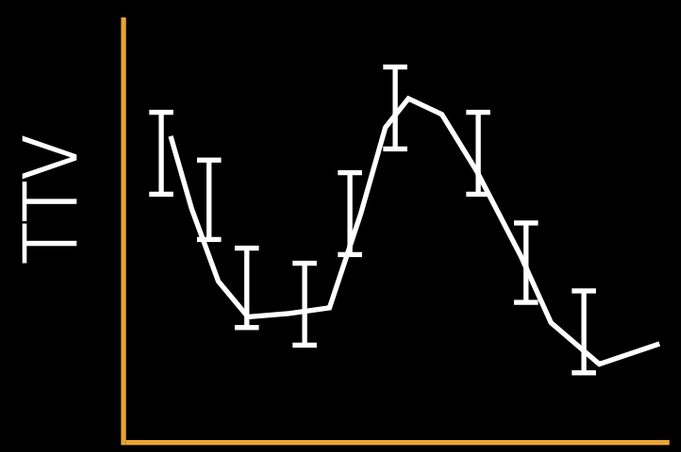

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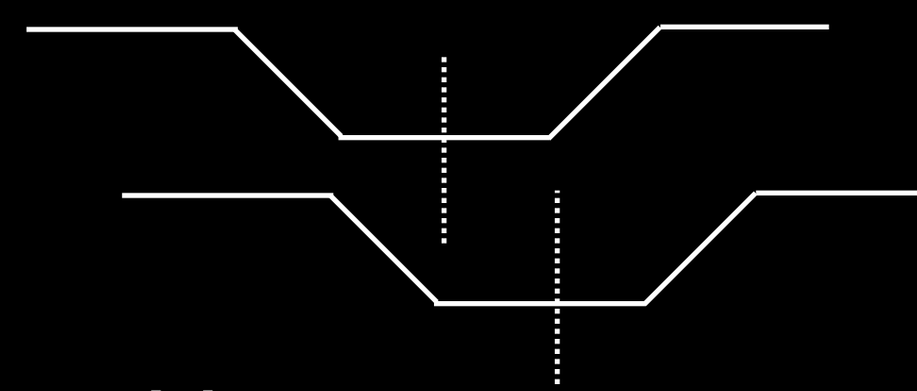

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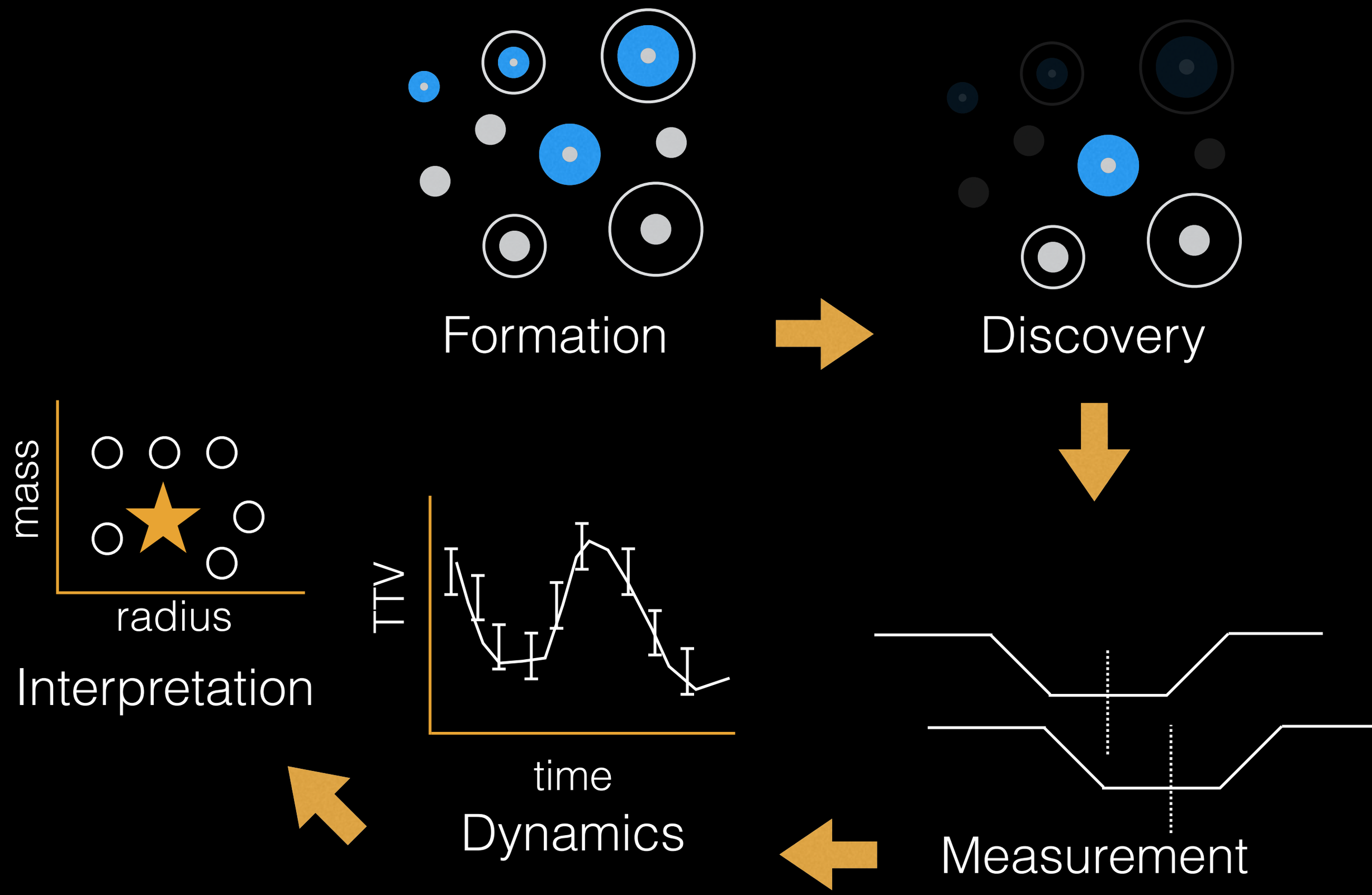

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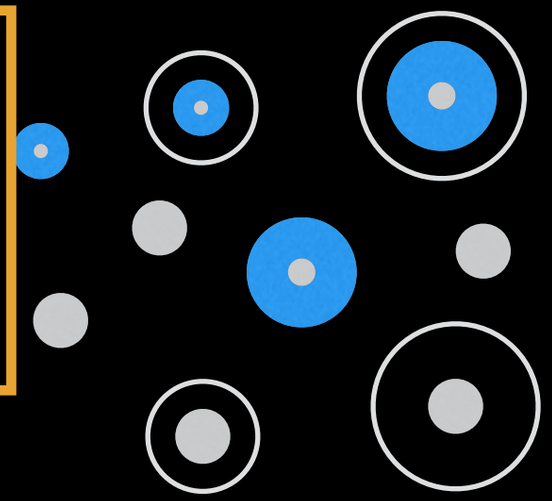
TTV Planets: Farm to Table

1. What physical processes are responsible for the diversity of small exoplanet compositions?



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1. What physical processes are responsible for the diversity of small exoplanet compositions?

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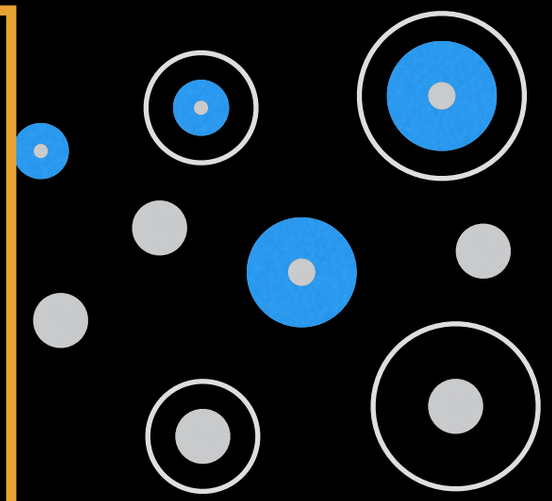

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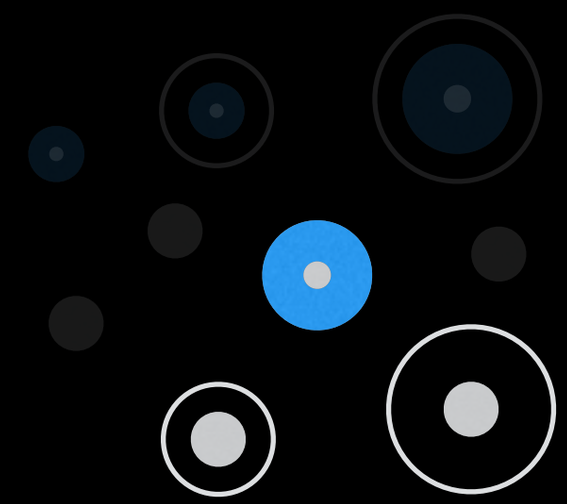

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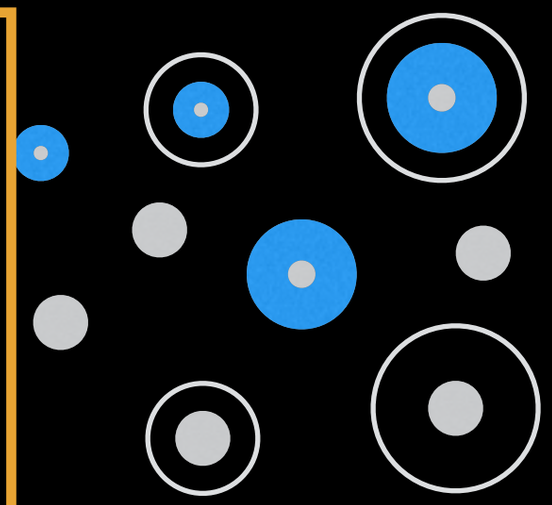
TTV Planets: Farm to Table

1. What physical processes are responsible for the diversity of small exoplanet compositions?

2. Are TTV planets a special population?

3. How do we robustly infer transit times from noisy data?



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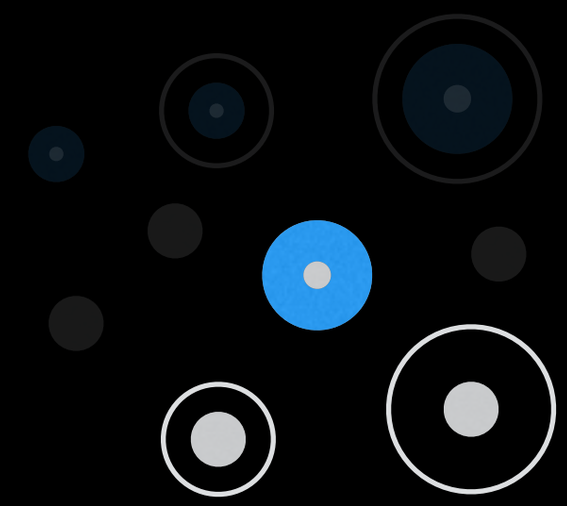

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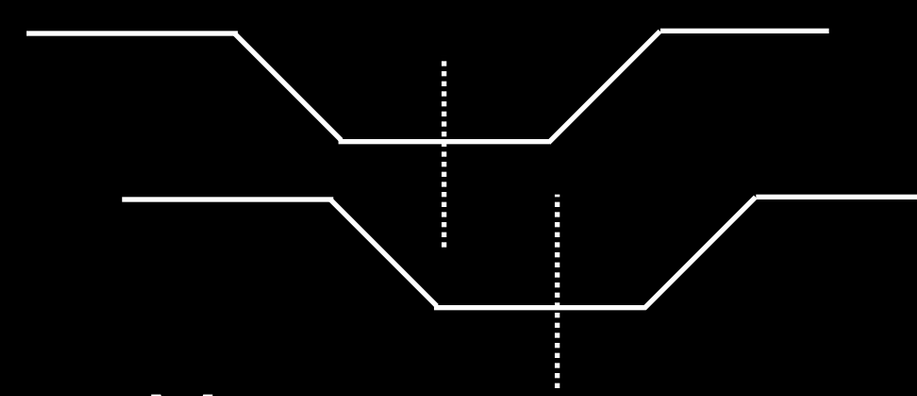
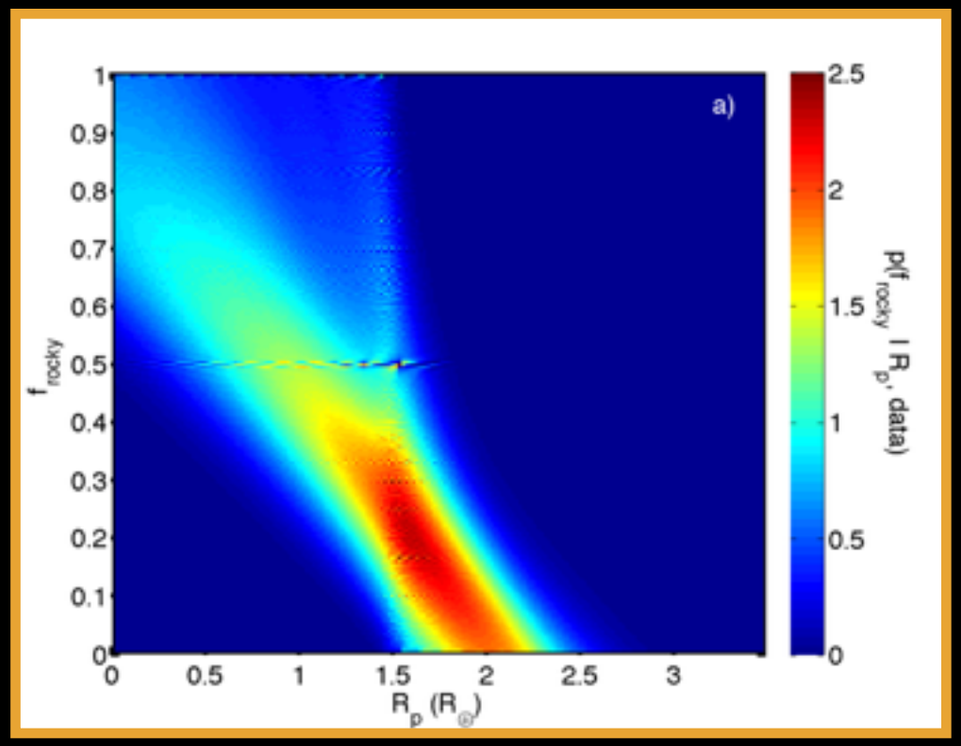
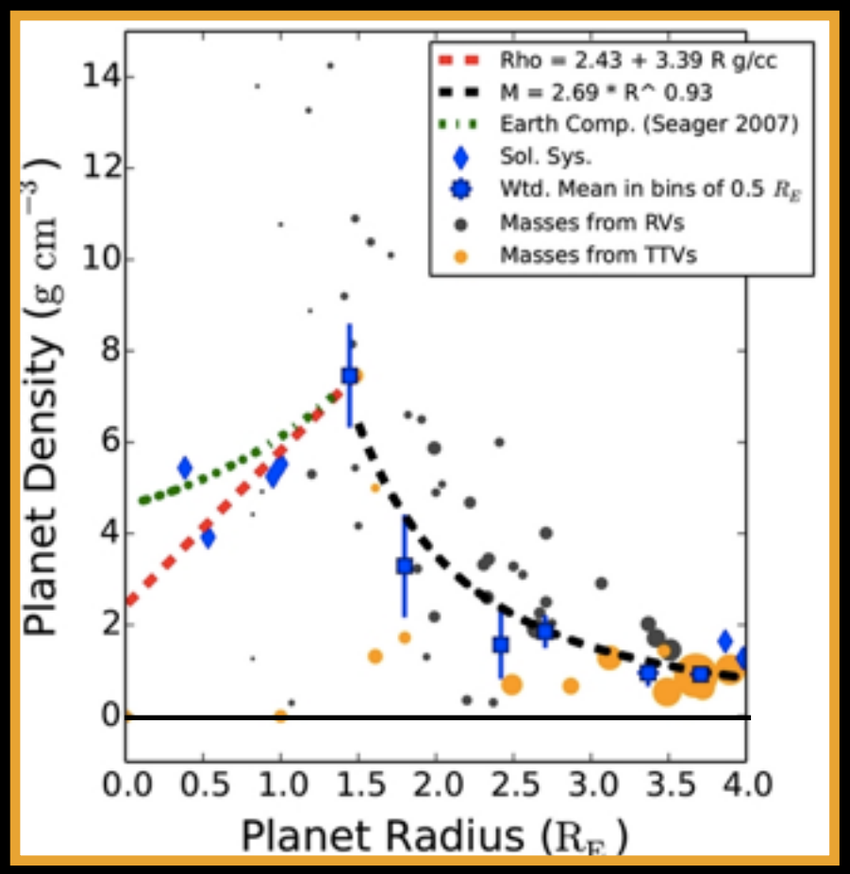


Measurement

Two(+) populations of small exoplanet compositions

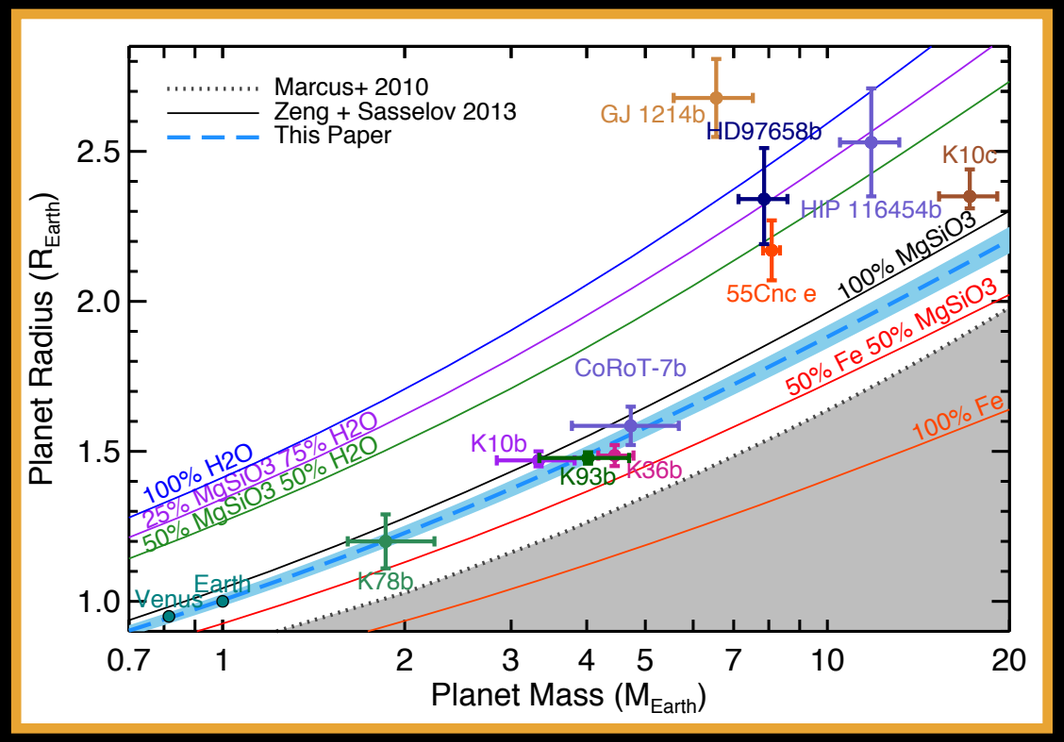
Rogers 14





Weiss & Marcy 14
(featured by Howard)

Dressing & Charbonneau 15



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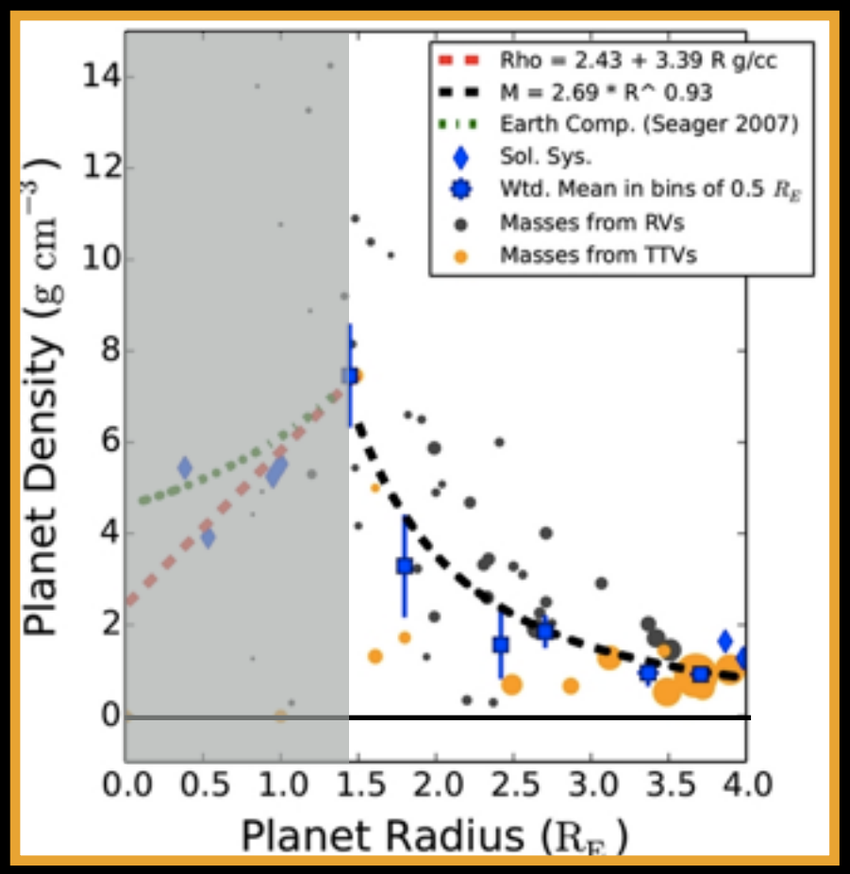

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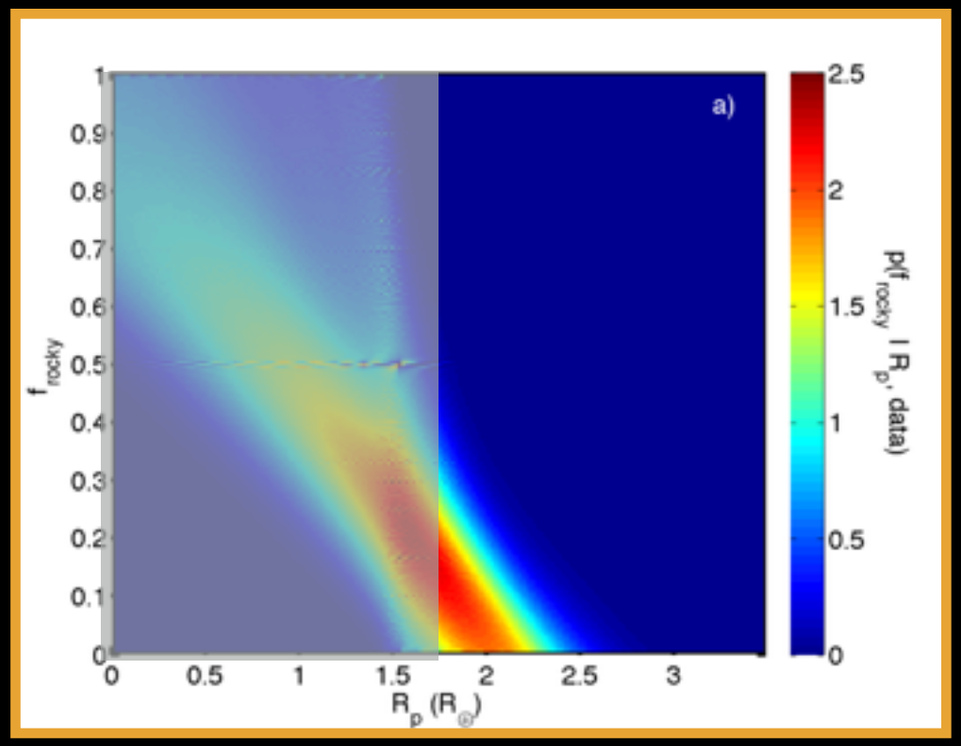

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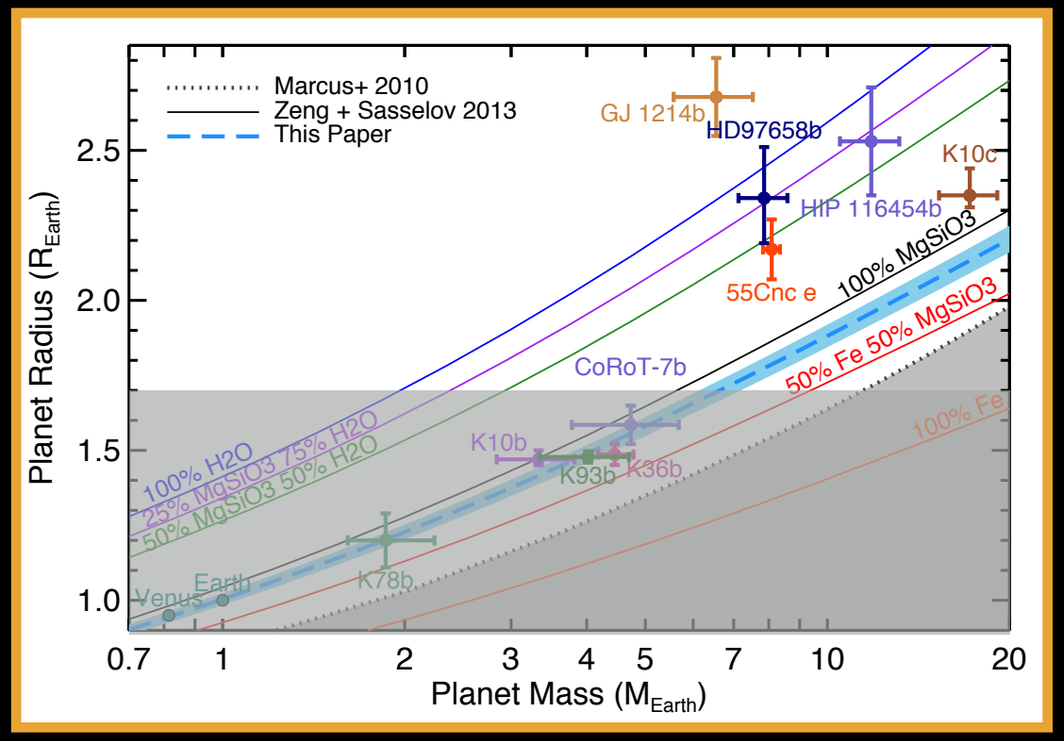

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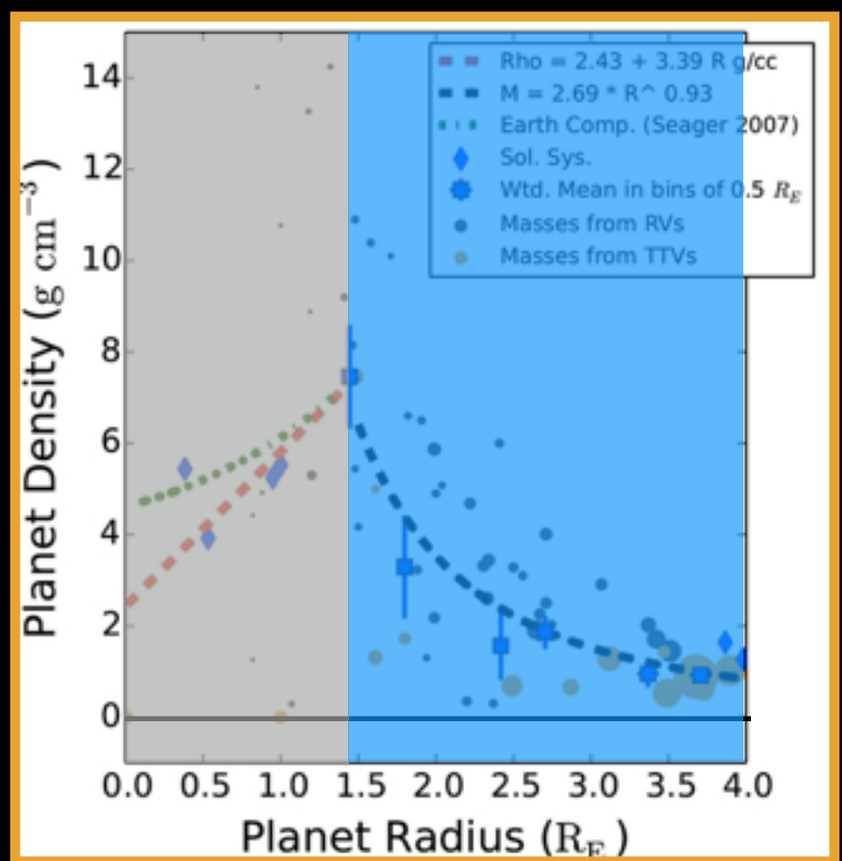

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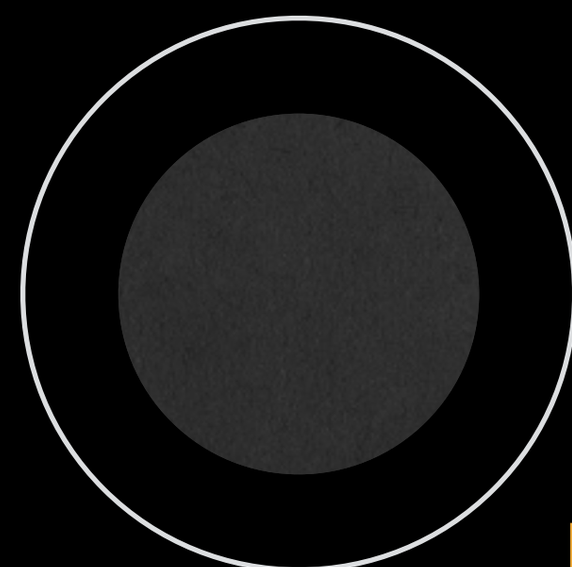

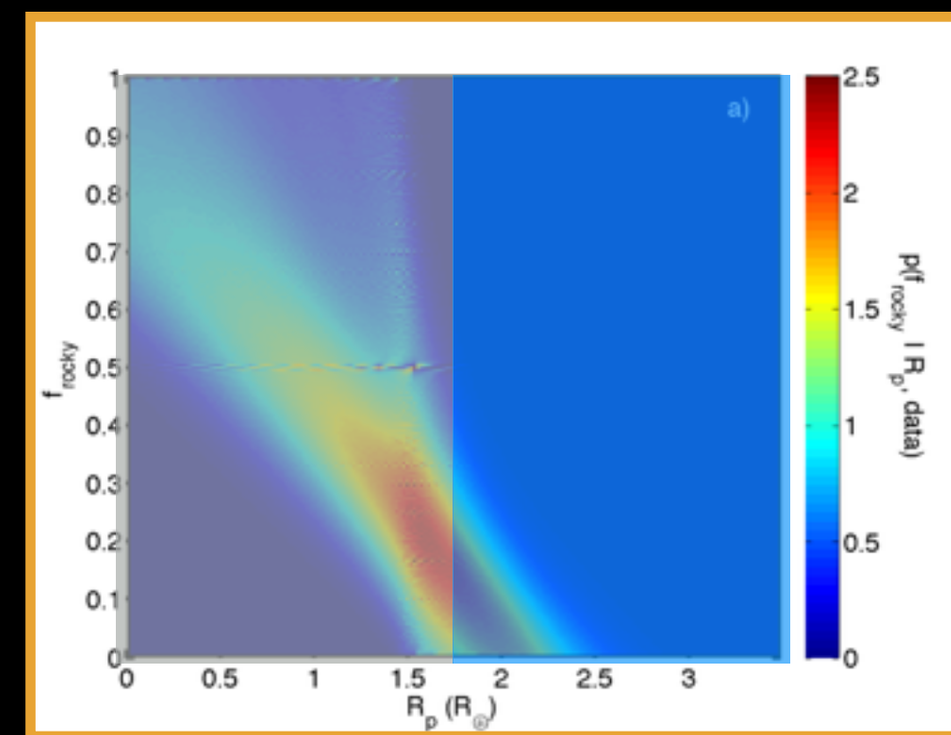

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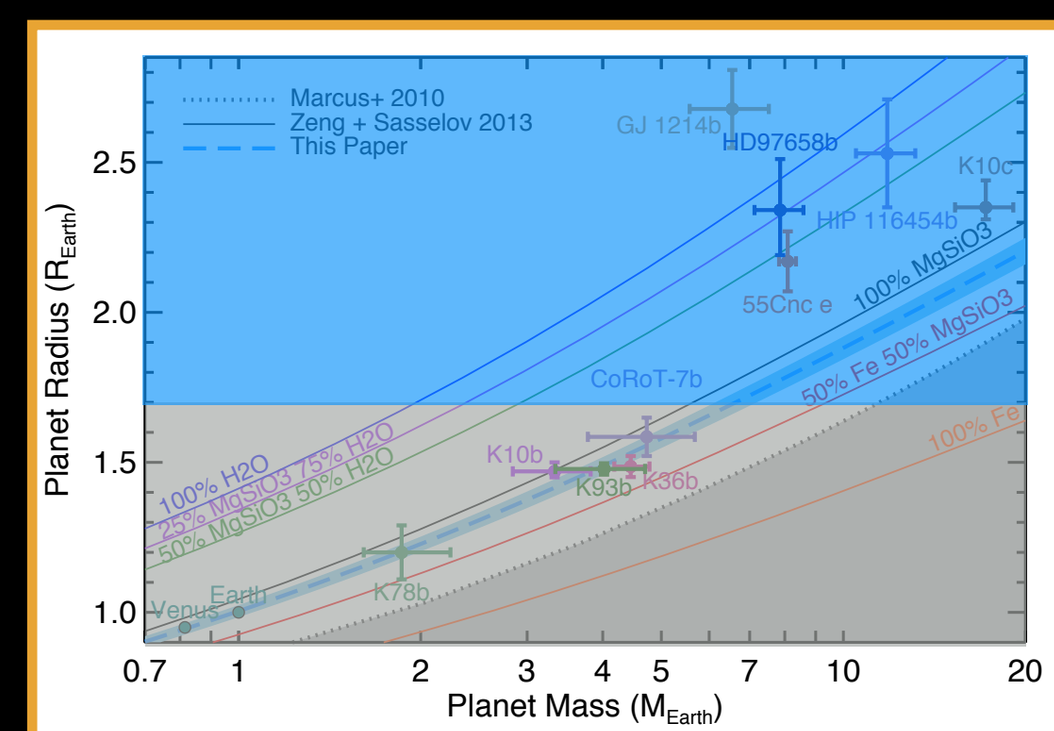

Multiple possible physical processes can make rocky vs. gas-enveloped planets

Formation

- Formation from icy vs. dry planetesimals
- Accretion of nebular gas

Evolution

- Collisions
- Photoevaporation
- Outgassing

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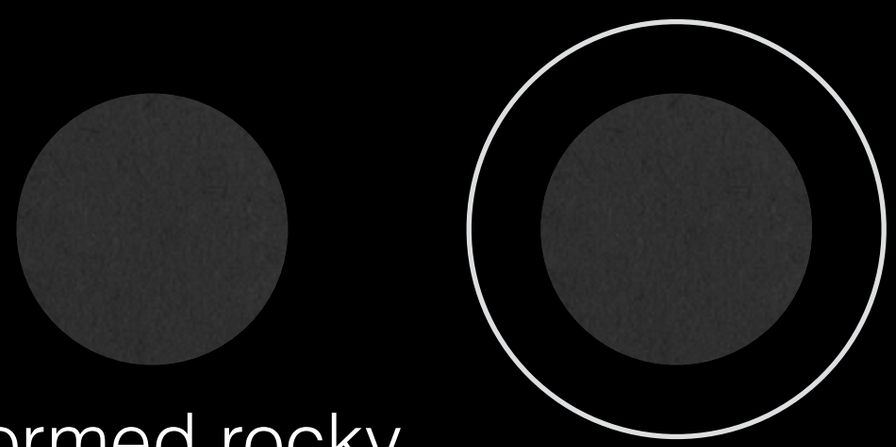


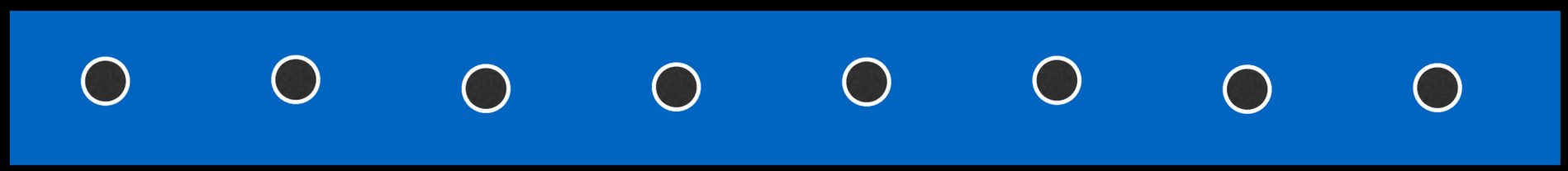
formed rocky

formed with gas envelope

Planet formation at close separations occurs in stages

e.g. Schlichting 14, Inamdar & Schlichting 15

1) Isolation mass embryos grow in gas disk



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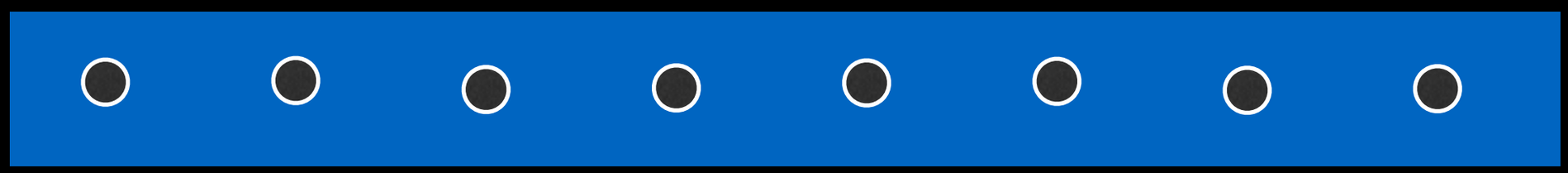

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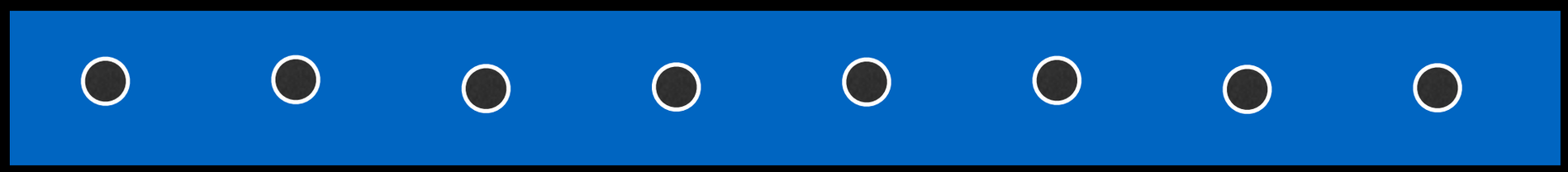


2) Gas damping prevents orbit crossings; embryos chill

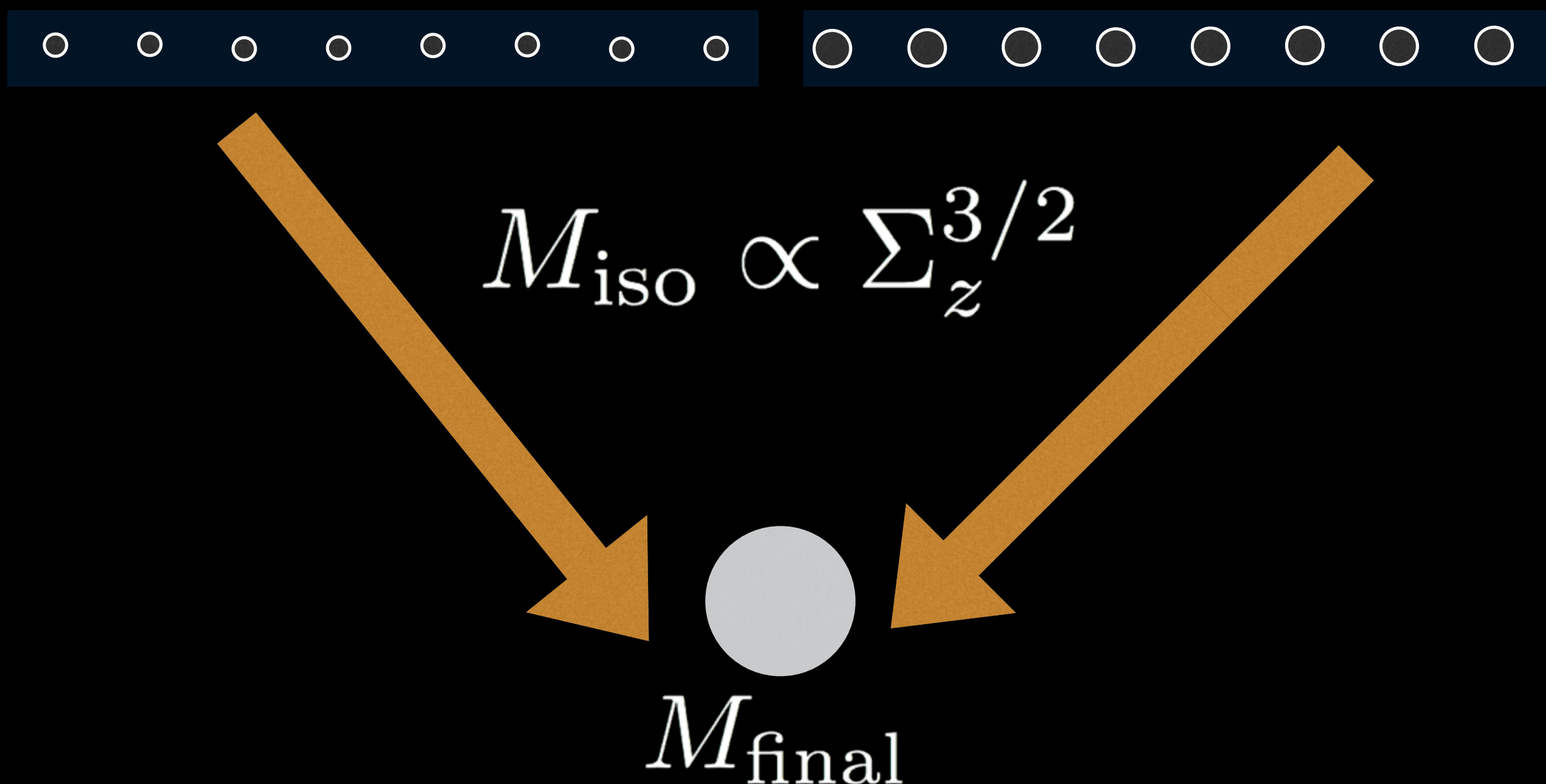
3) Gas density reaches solid density; damping shuts off

4) “Core” grows collisionally, accretes any remaining gas

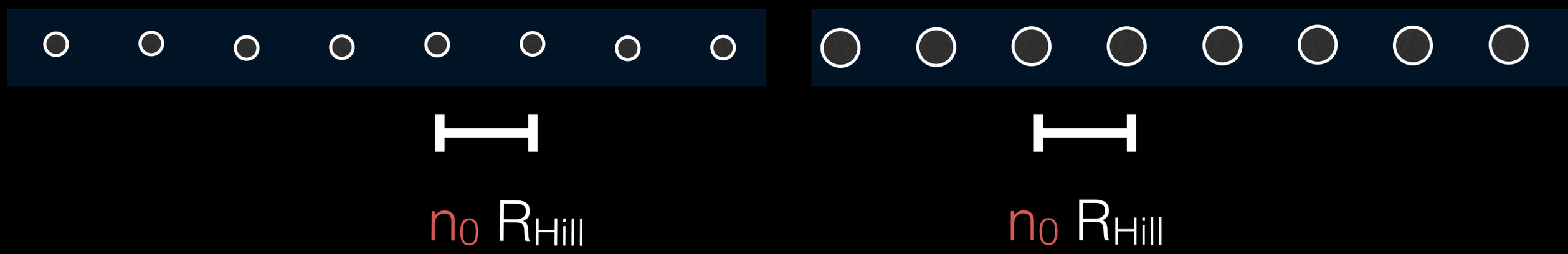
Surface solid density Σ_z affects "core" growth

low Σ_z high Σ_z

More mergers necessary to grow in low Σ_z disk



Surface solid density (Σ_z) affects growth timescale



merger timescale:

$$\log t = C1\ n_0 + C2$$

e.g. Chambers 96, Yoshinaga+ 99, Smith & Lissauer 09

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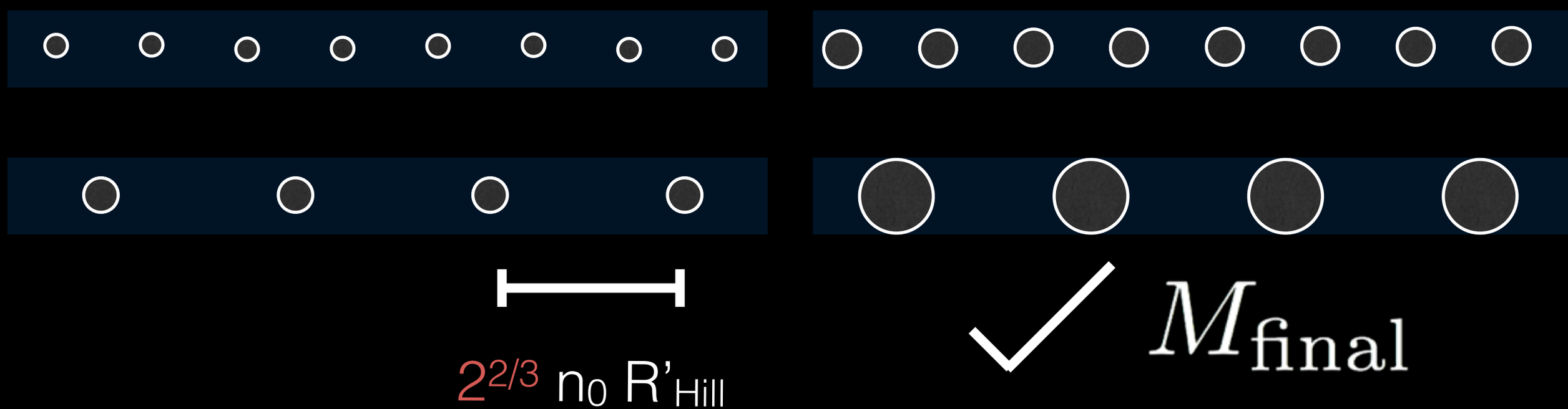

$$\log t = C1\ 2^{2/3}\ n_0 + C2$$

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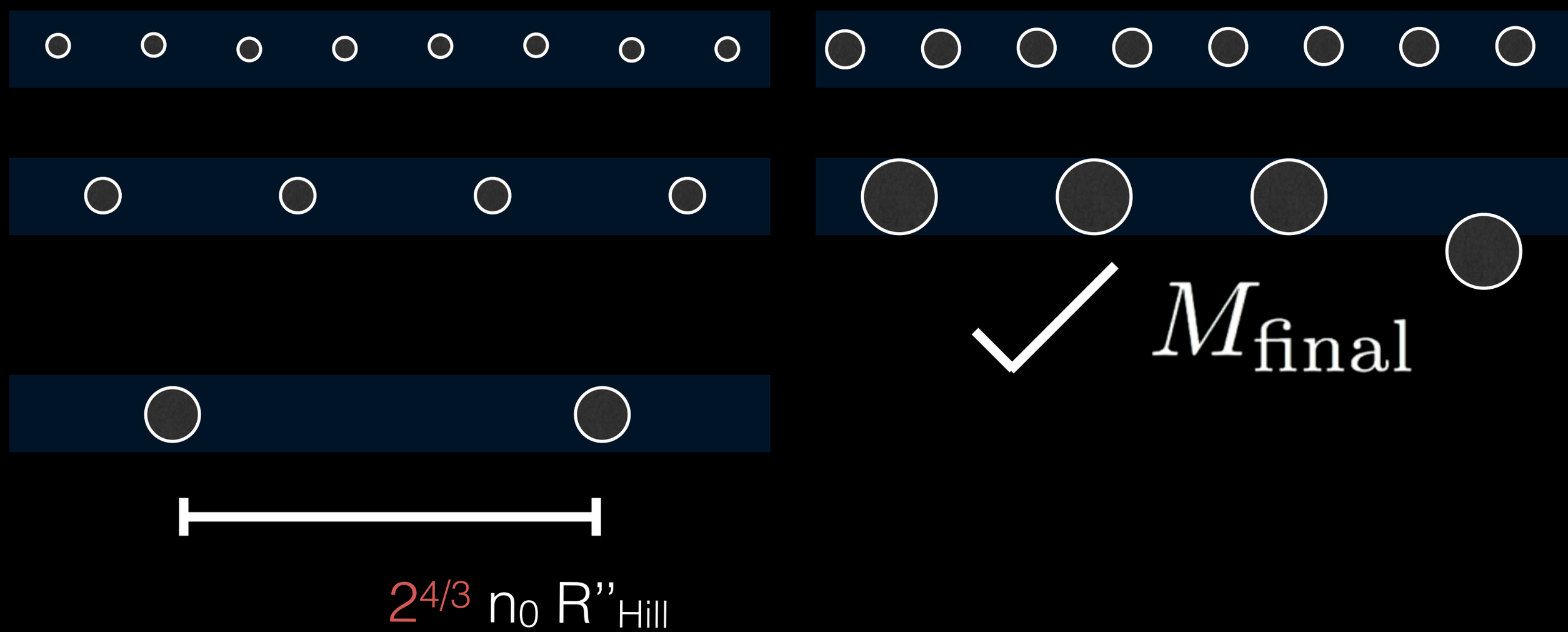
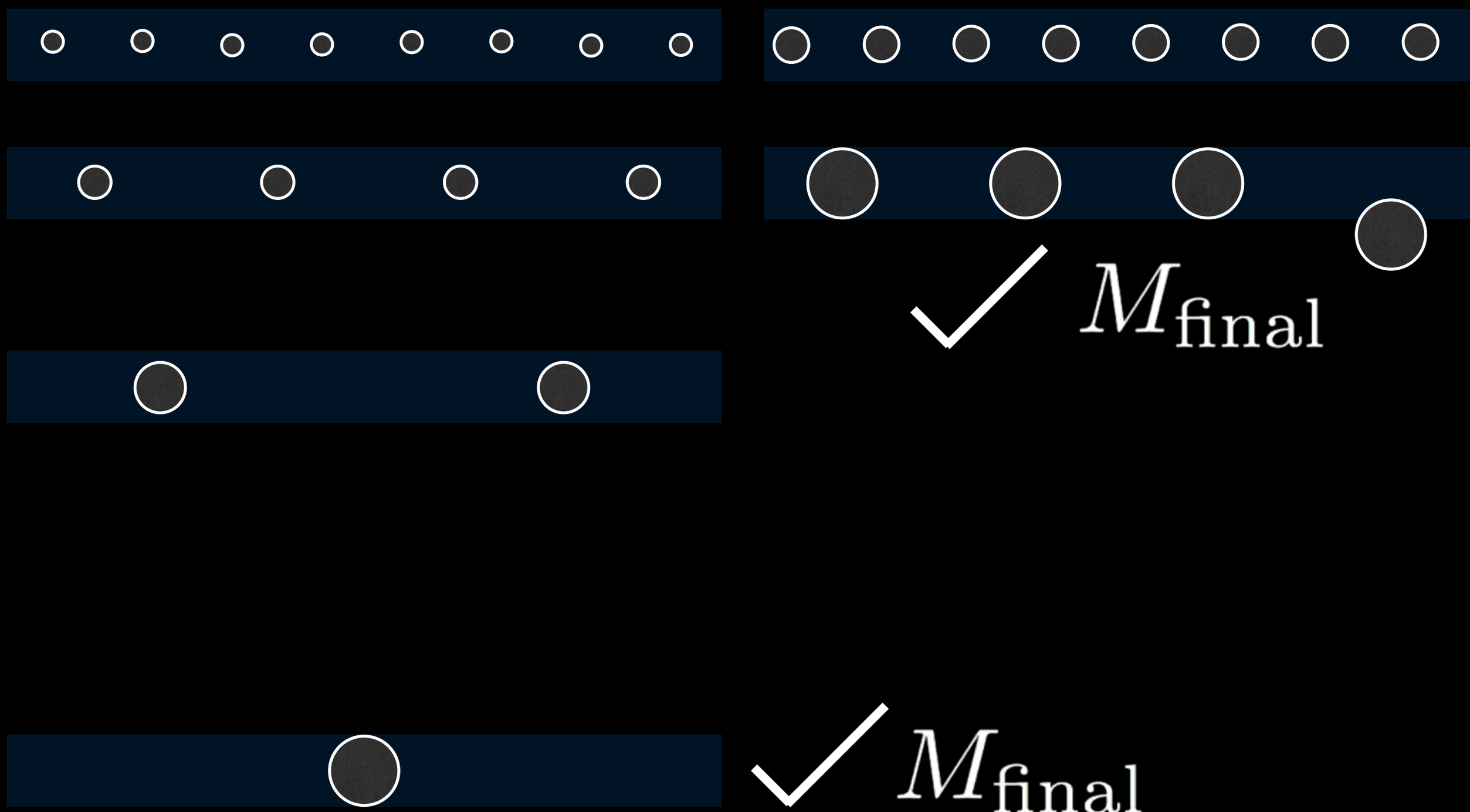
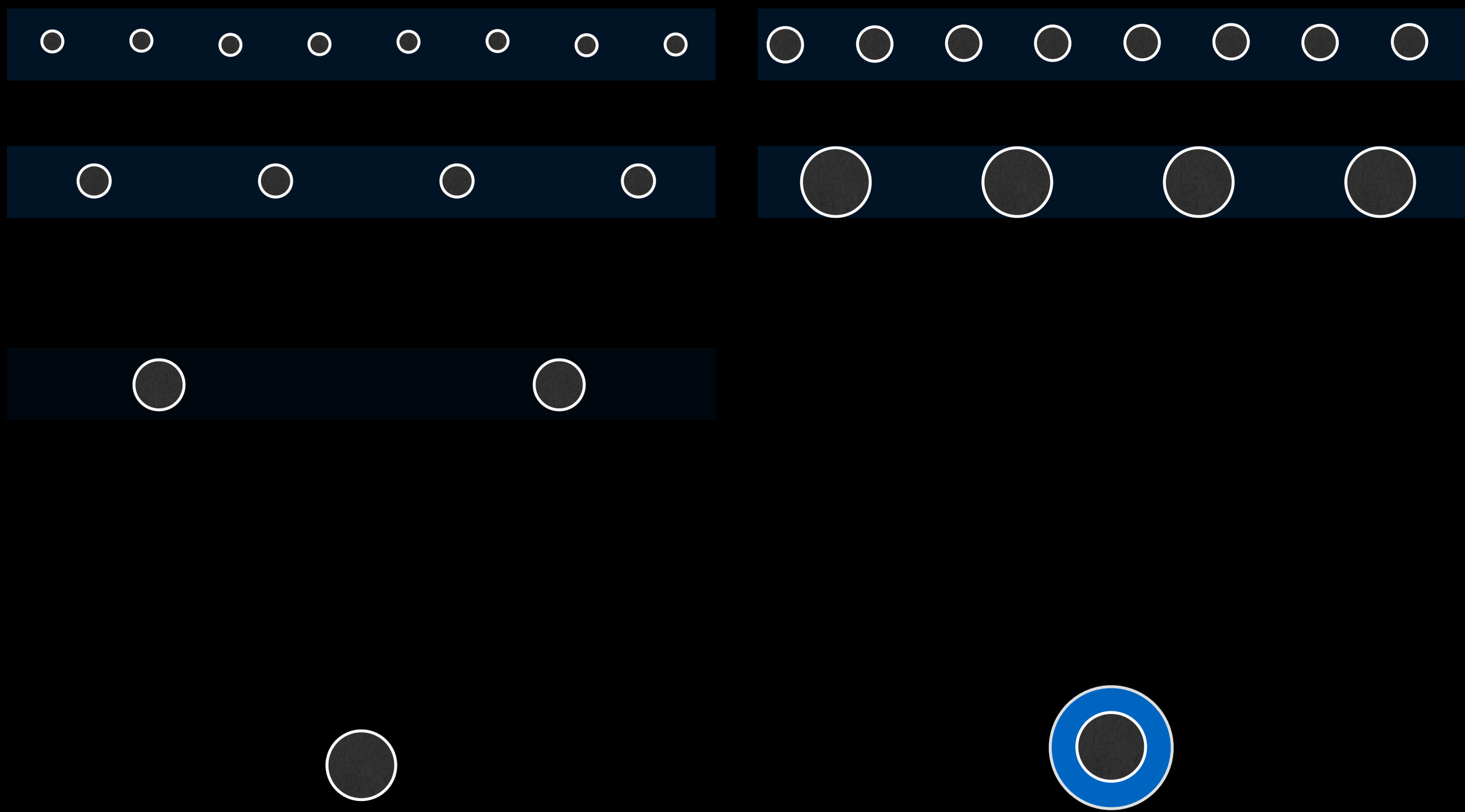


$$\log t = C1\ 2^{4/3}\ n_0 + C2$$

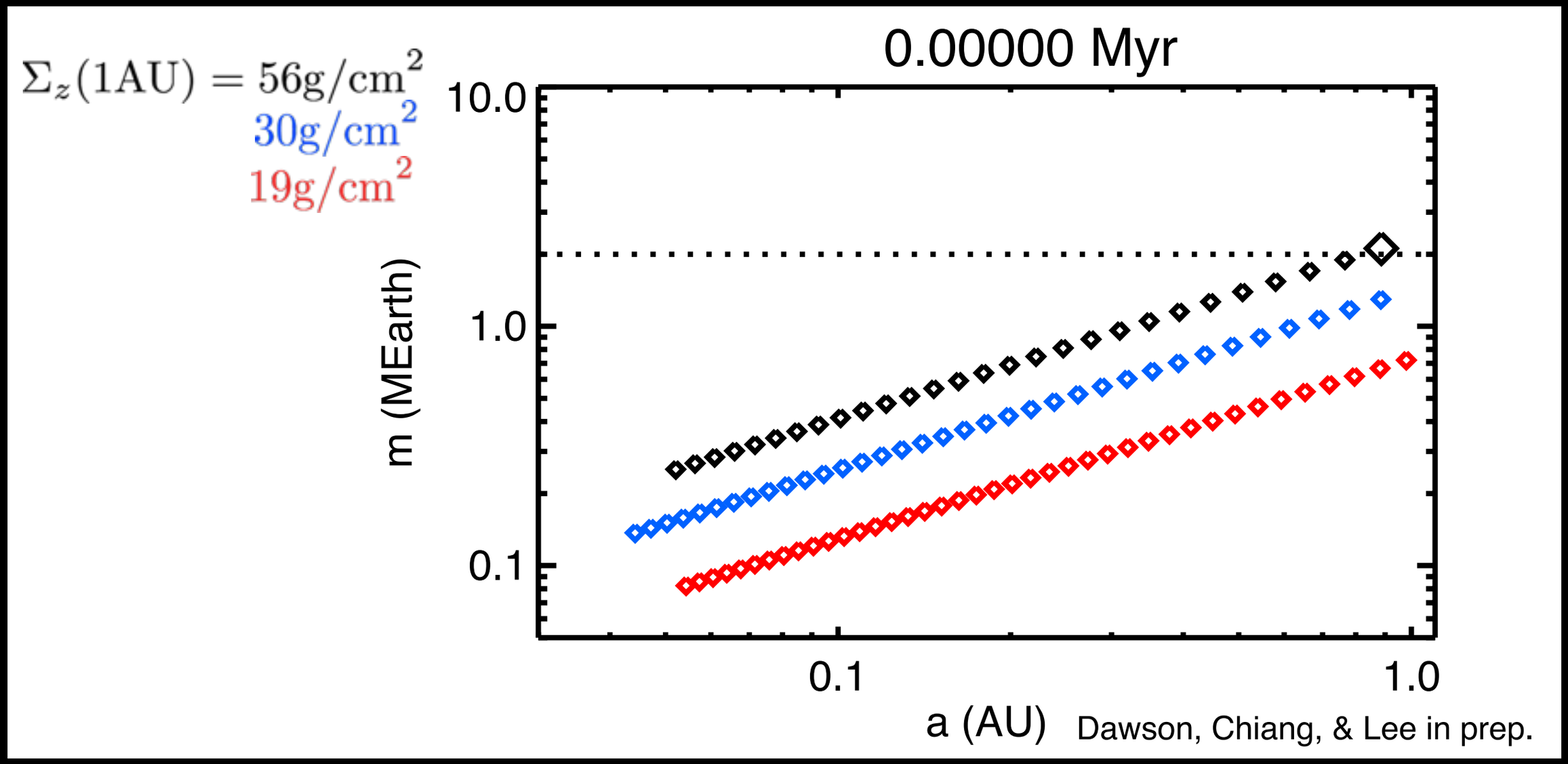
Surface solid density (Σ_z) affects growth timescale



Long growth timescale = rocky planet



Longer growth timescales in low surface solid density disks



N-body simulations, e.g. Chambers 96, Hansen & Murray 12

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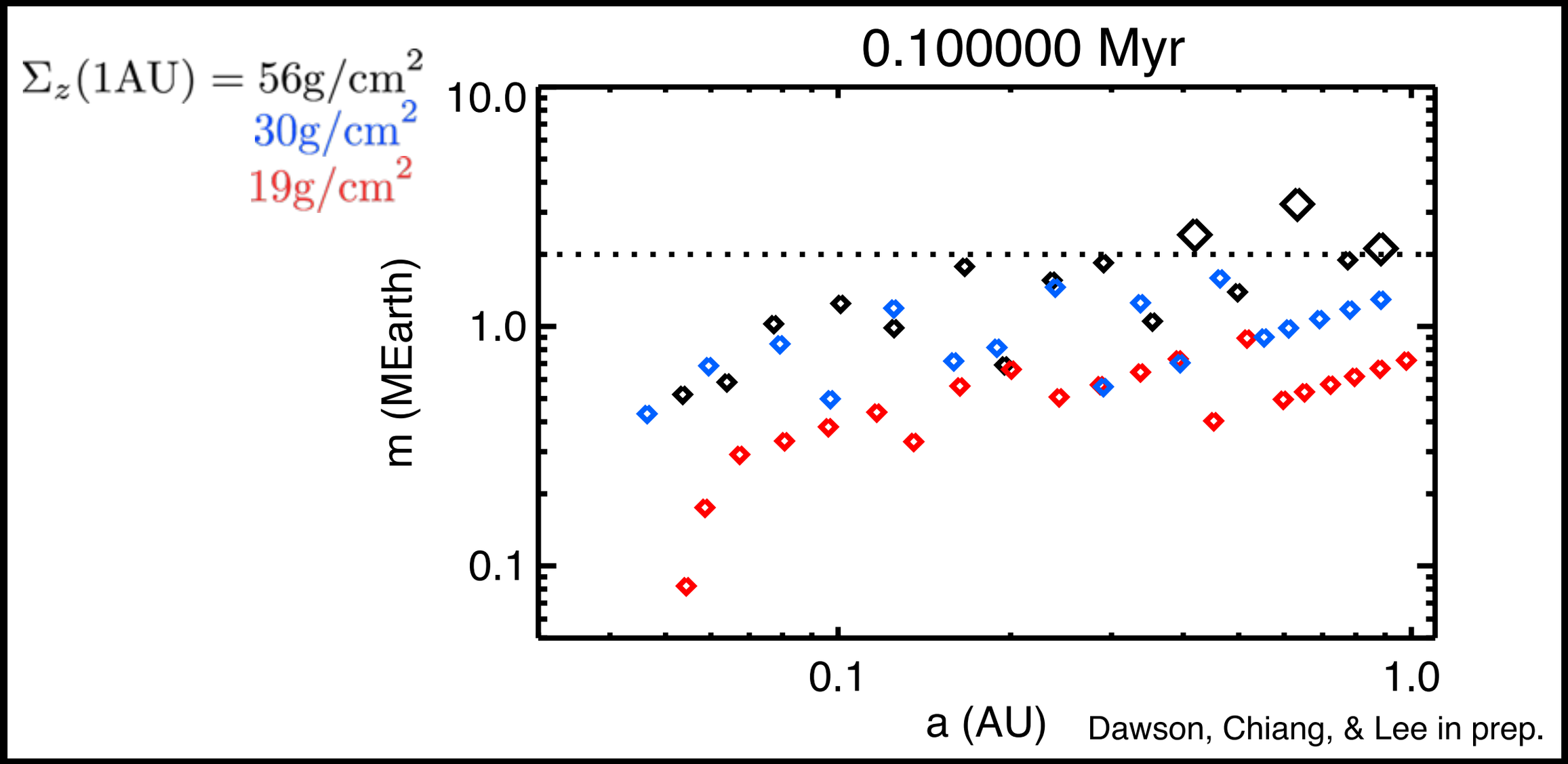

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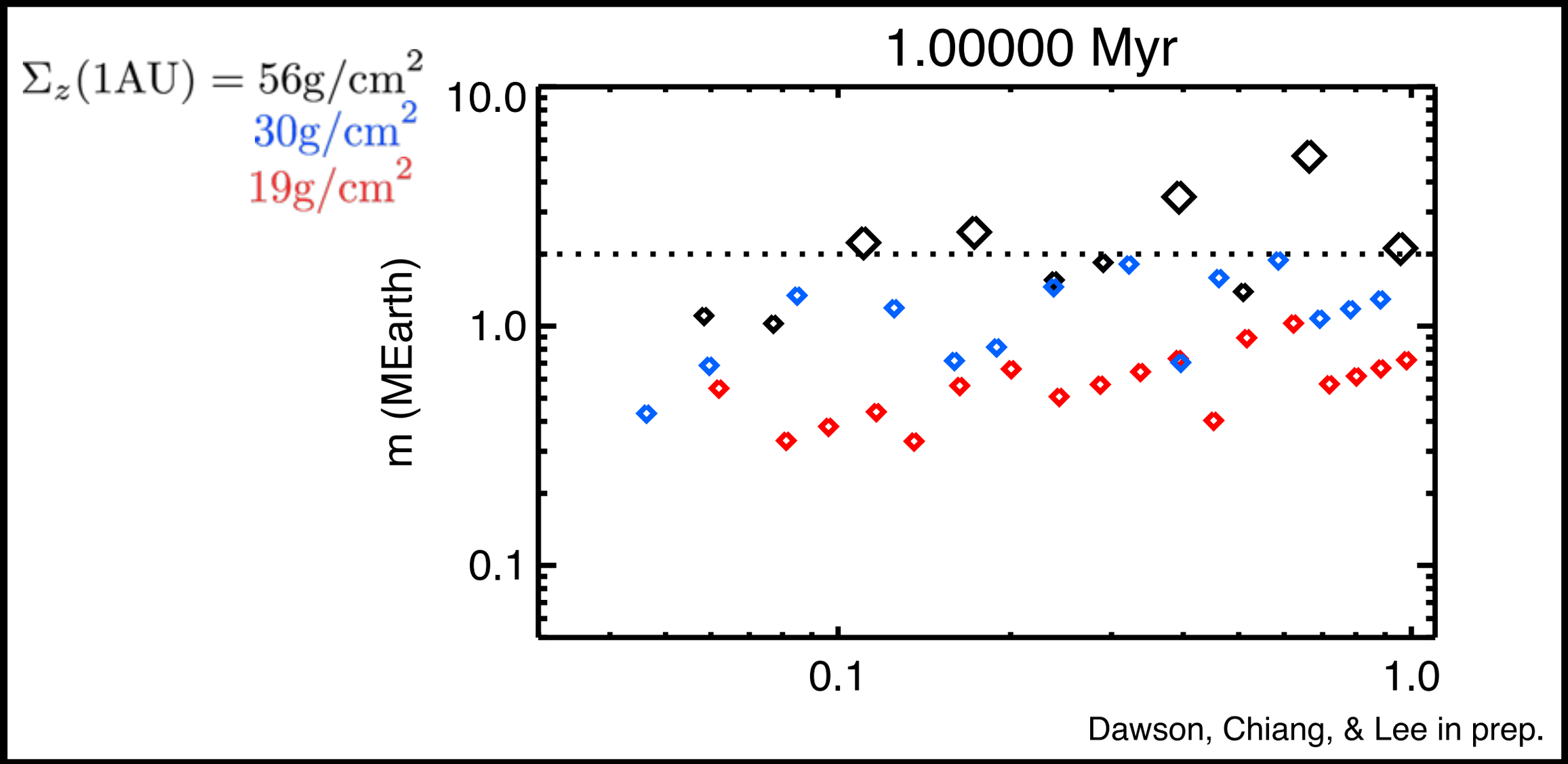

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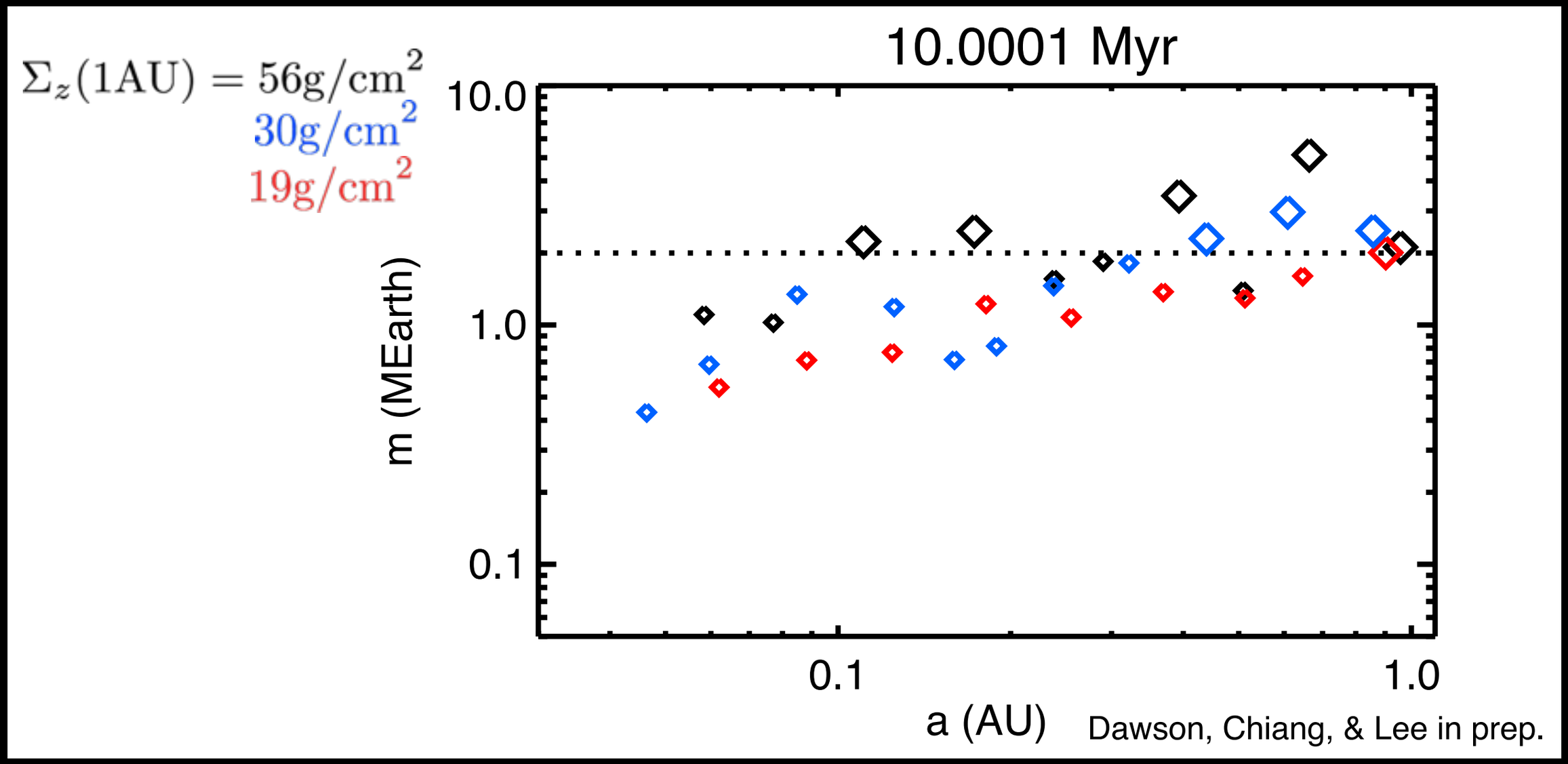
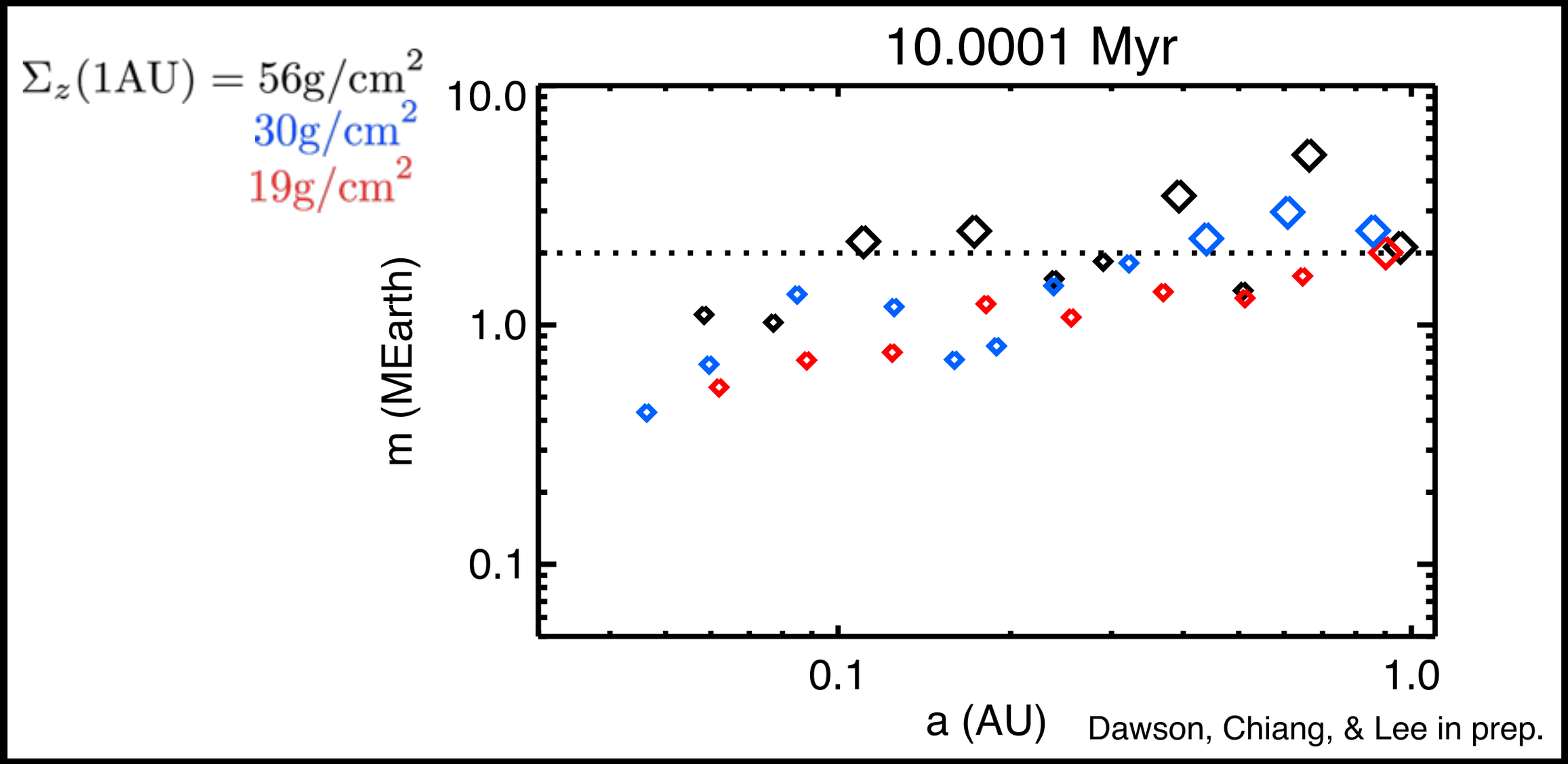


N-body simulations, e.g. Hansen & Murray 2012

Low surface density: by time the planet grows, the gas is gone



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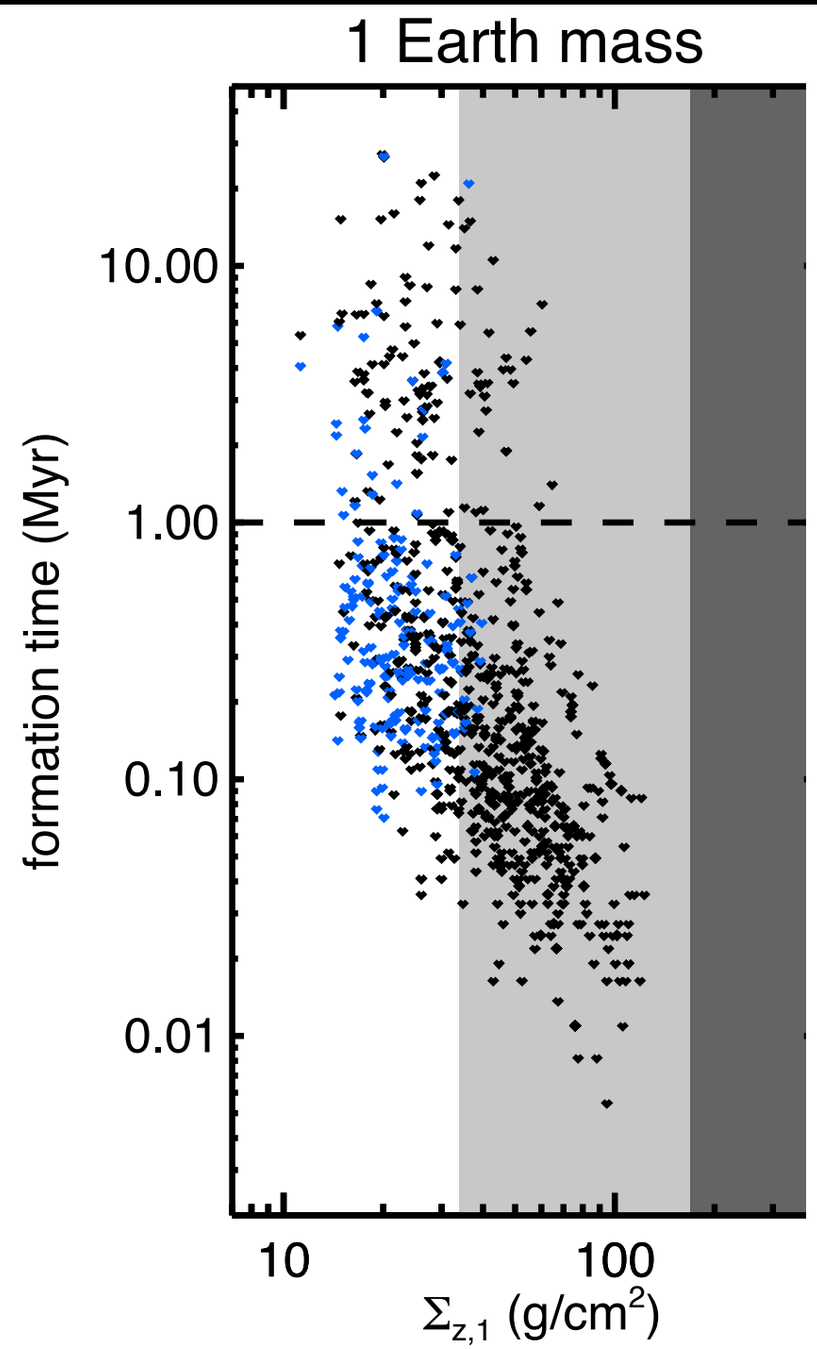
Longer growth timescales possible in low surface solid density disks

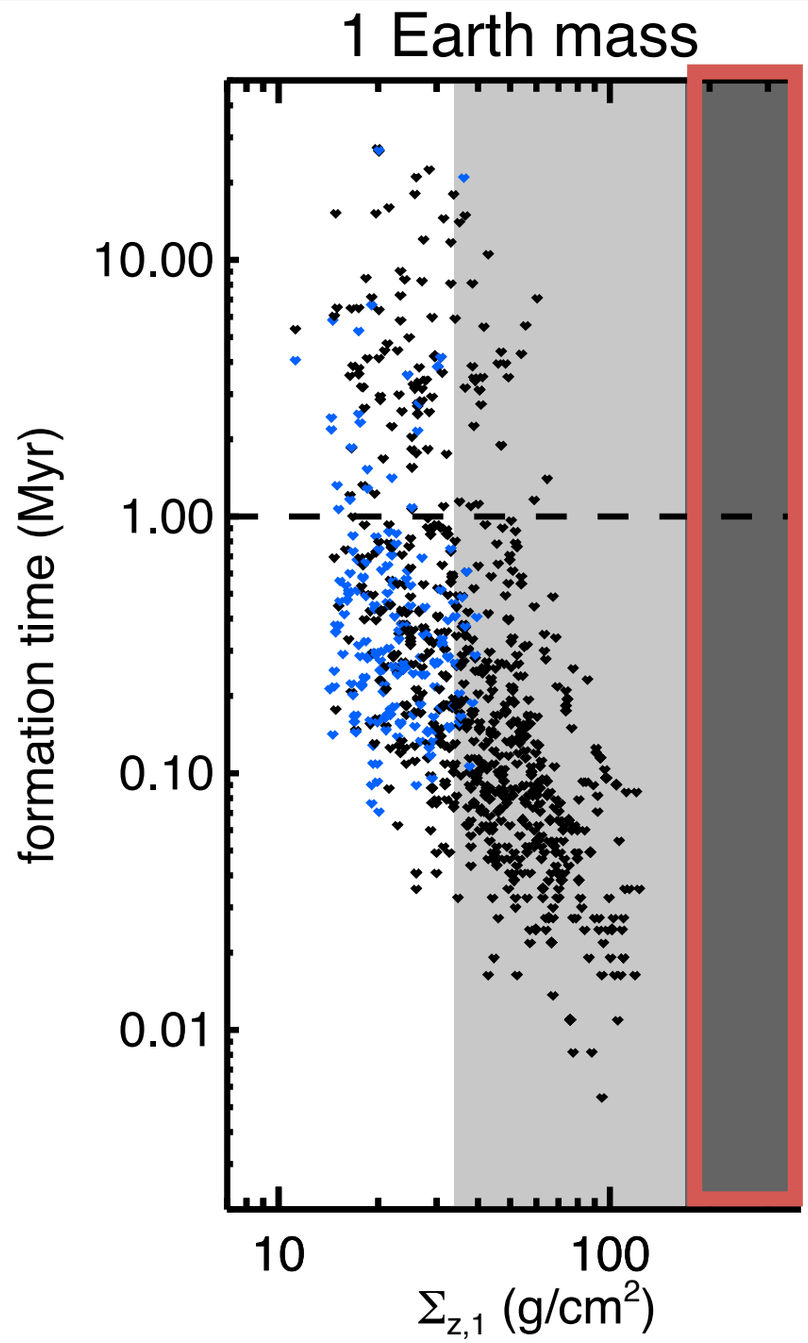


Results from 500 simulations

$0.04 < a < 1$ AU

Dawson, Chiang, & Lee in prep.

Longer growth timescales possible in low surface solid density disks



isolation mass big enough

e.g. Schlichting 14

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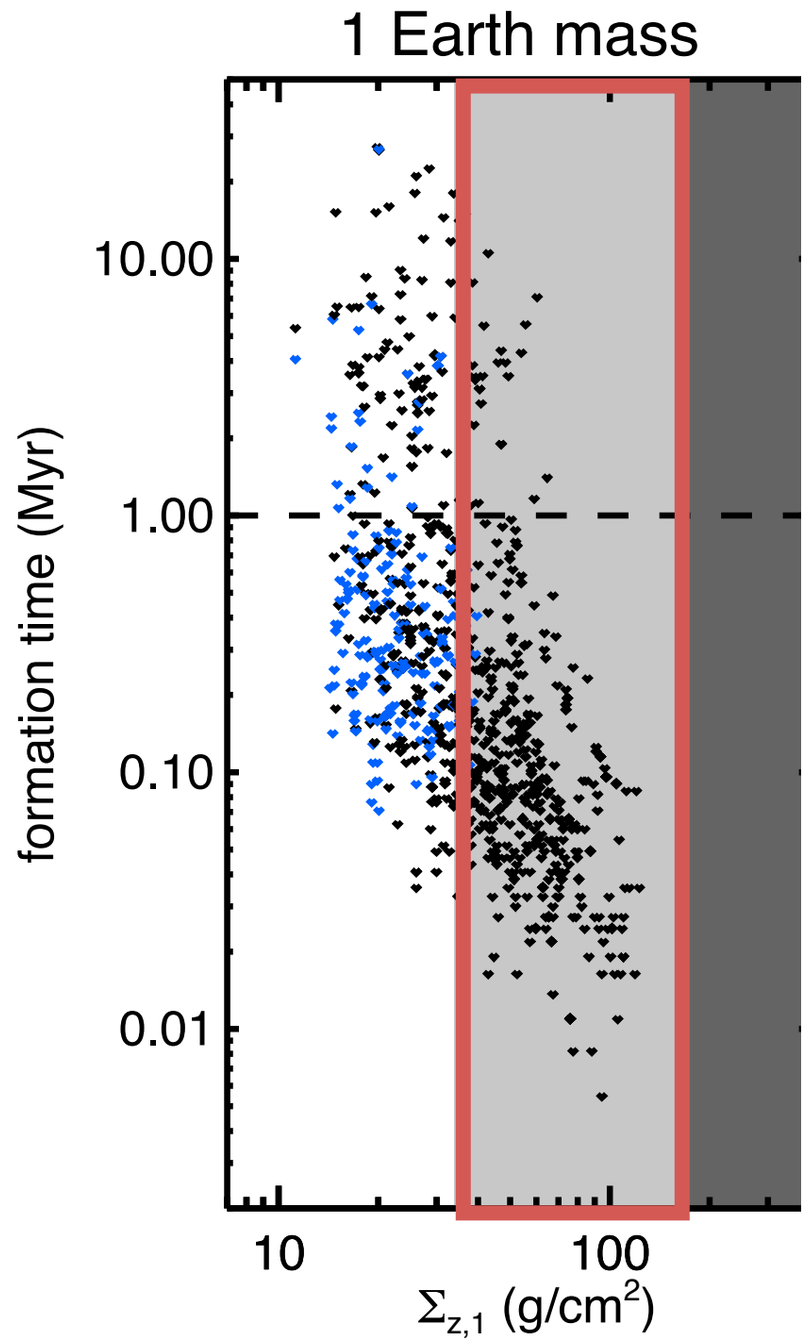

isolation mass big enough somewhere

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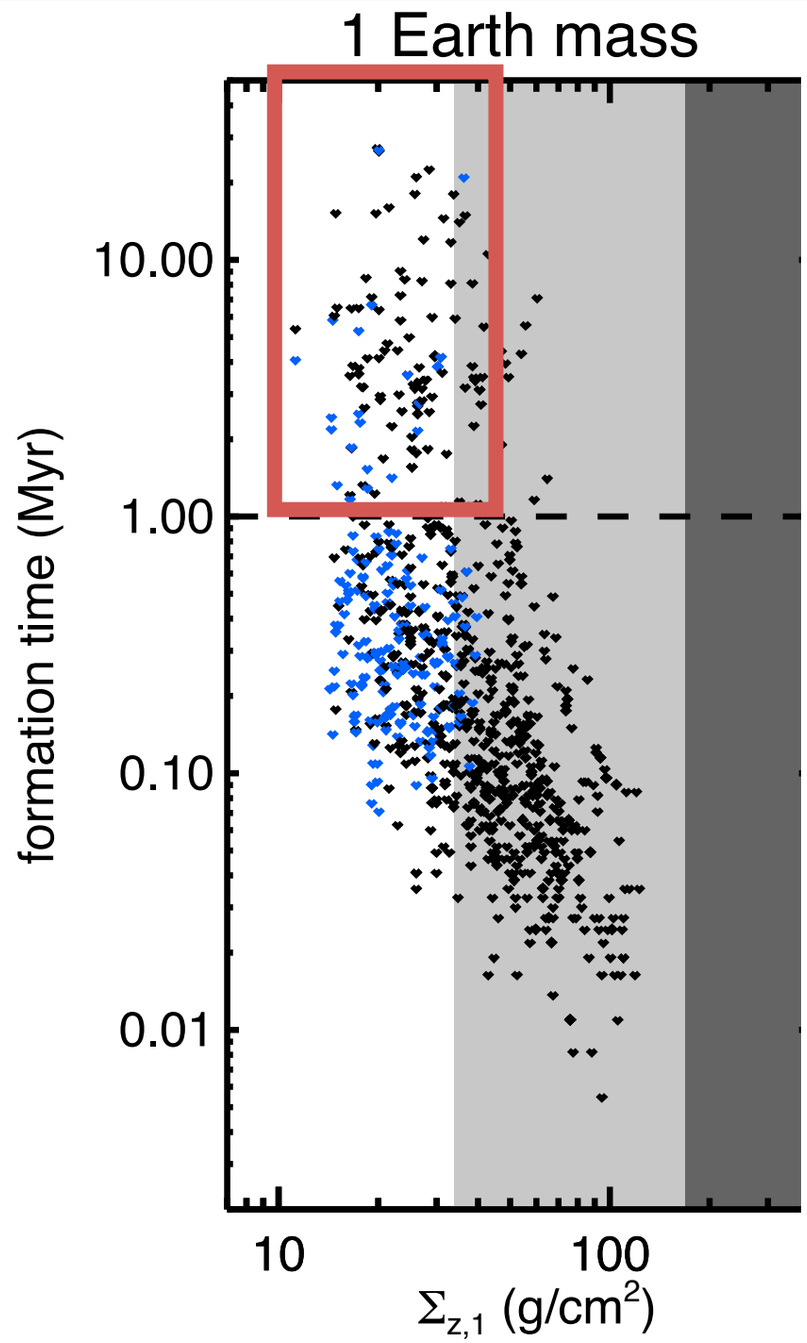

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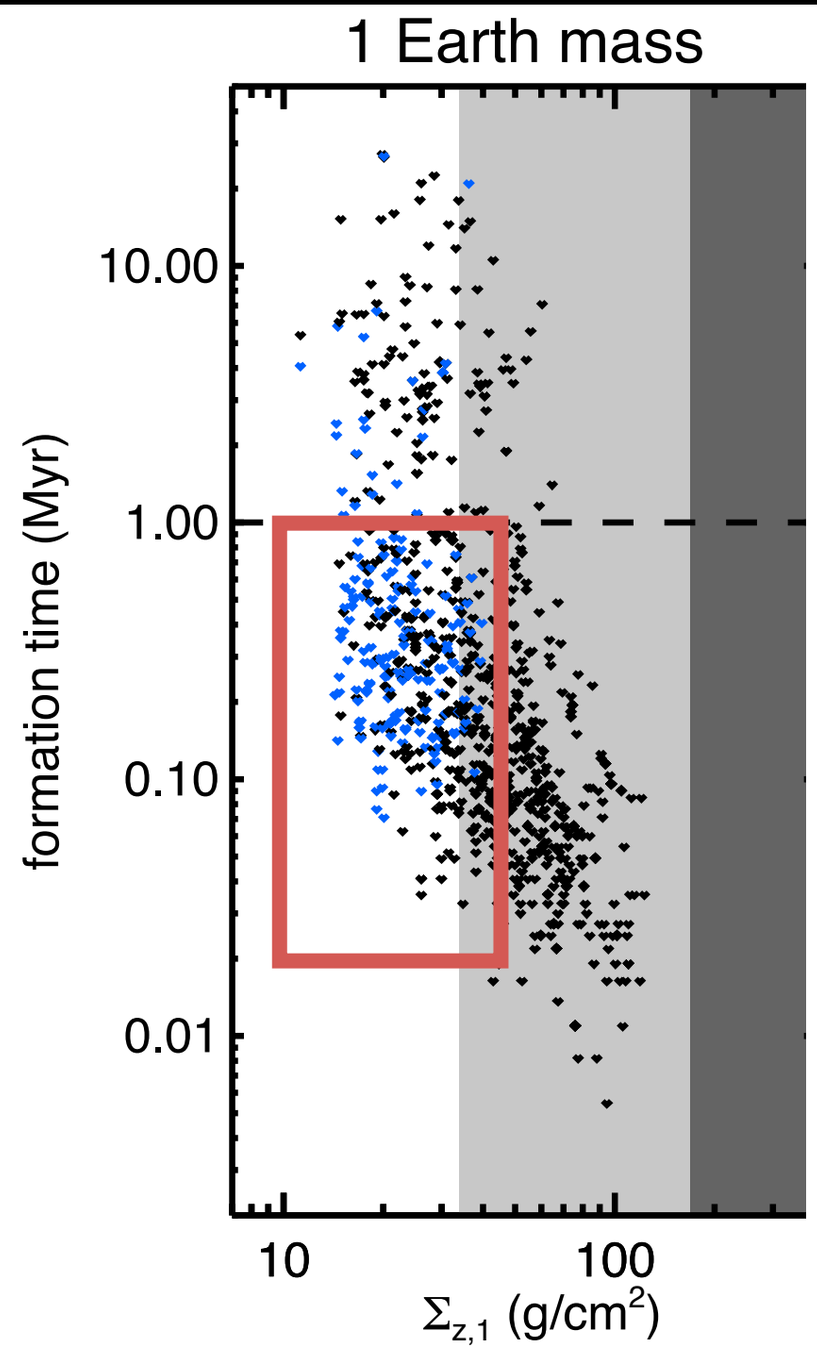

Grew quickly despite low surface solid density

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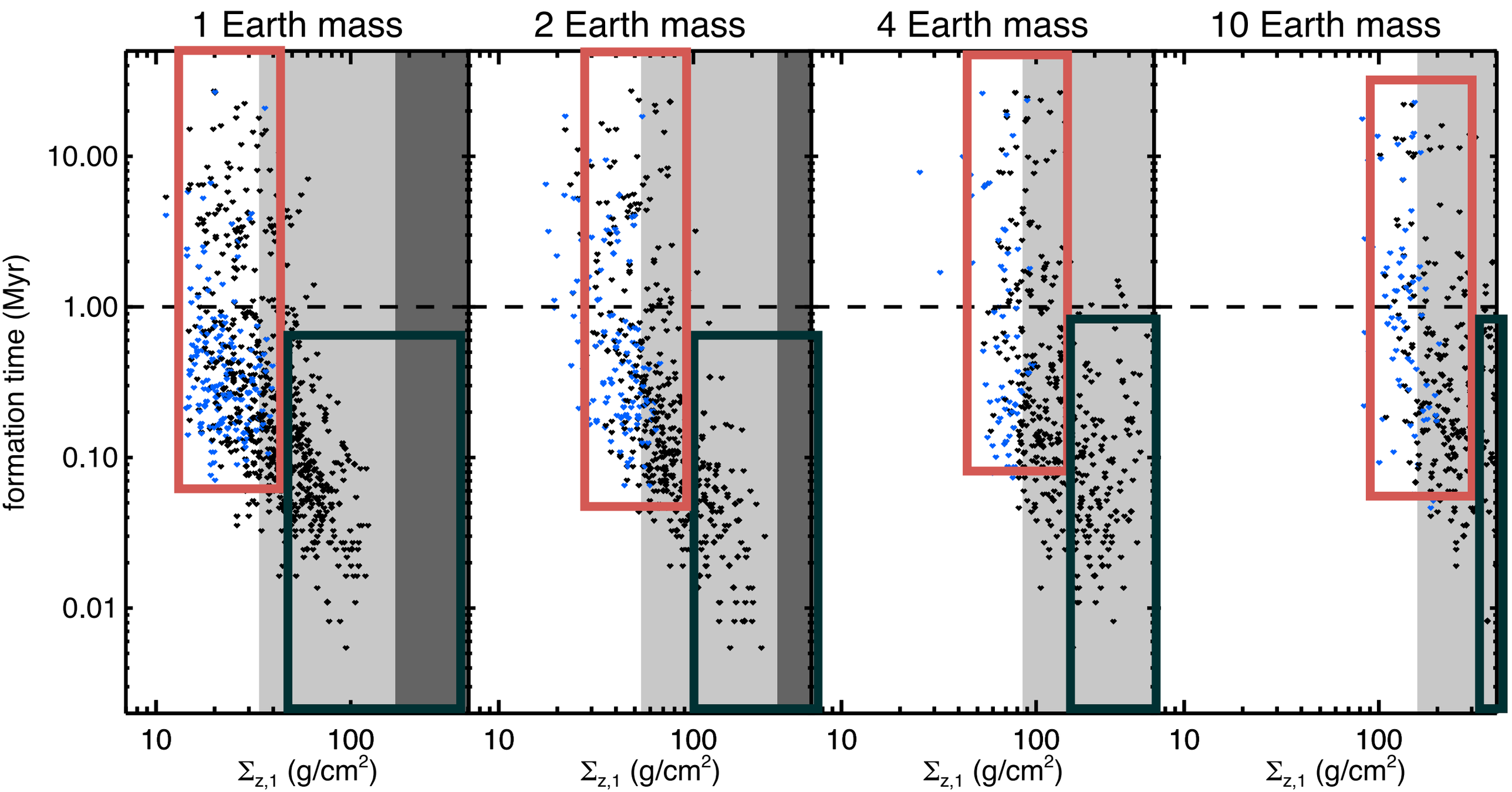

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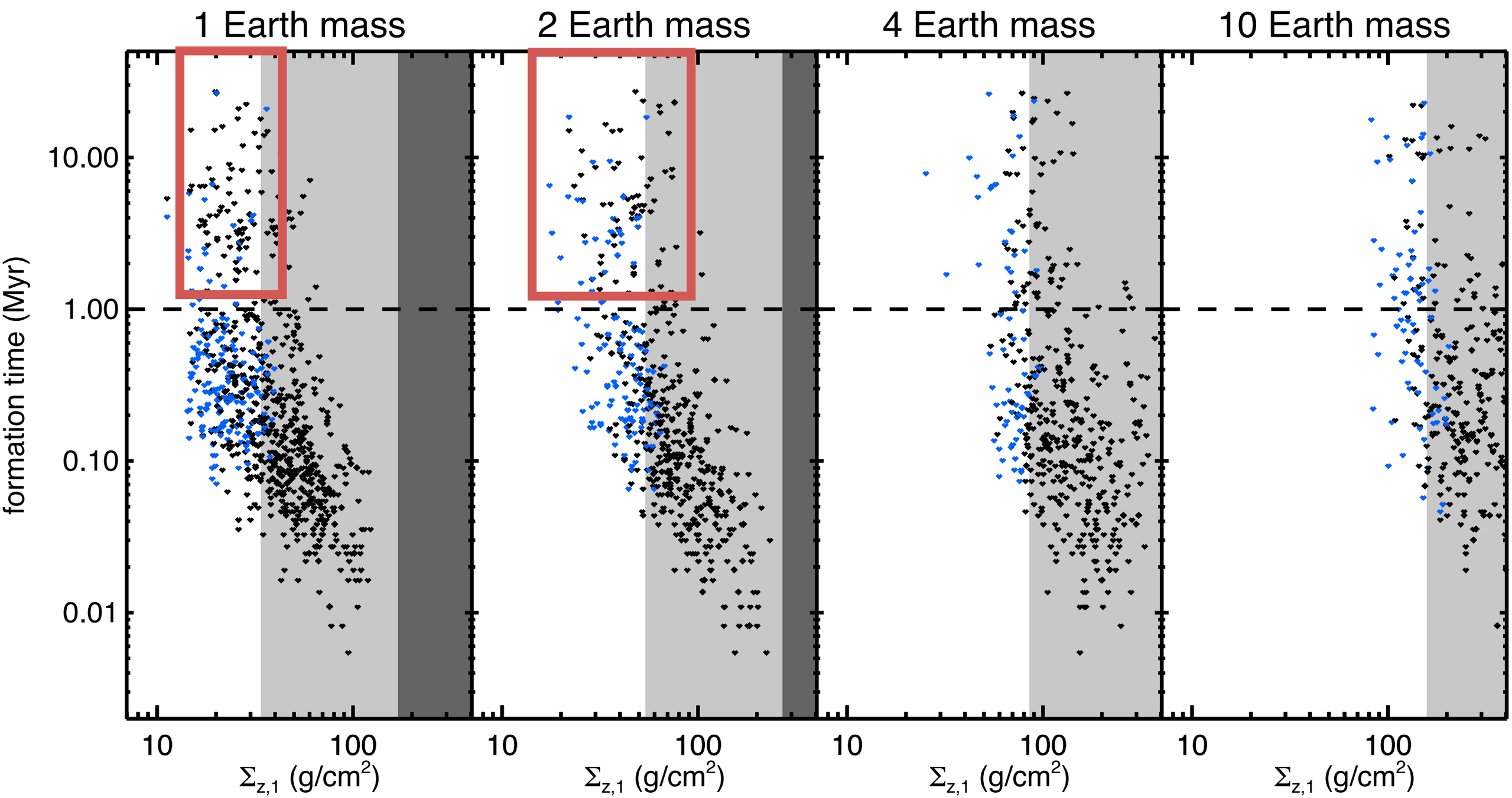

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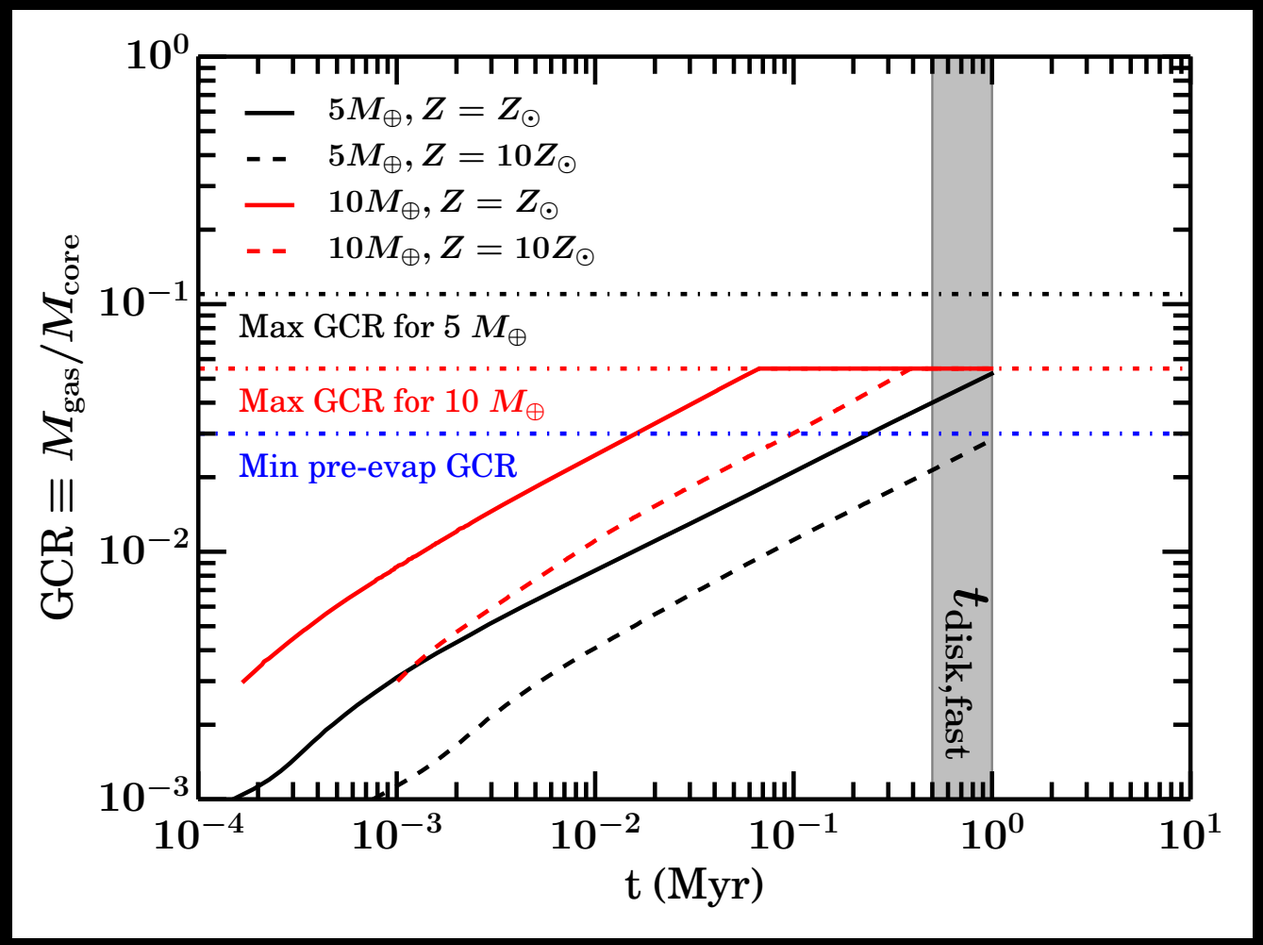
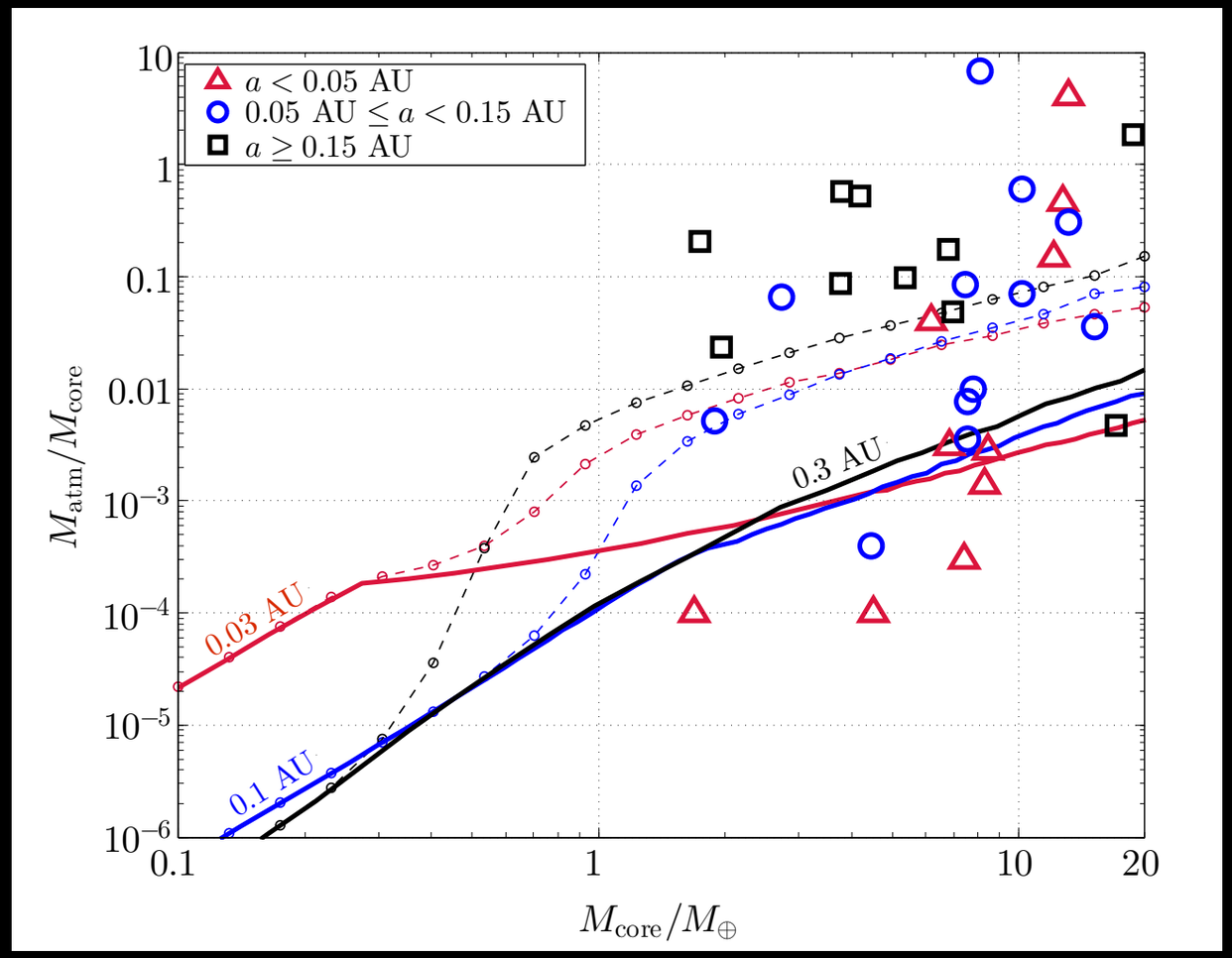
Forming mini Neptunes through in situ gas accretion

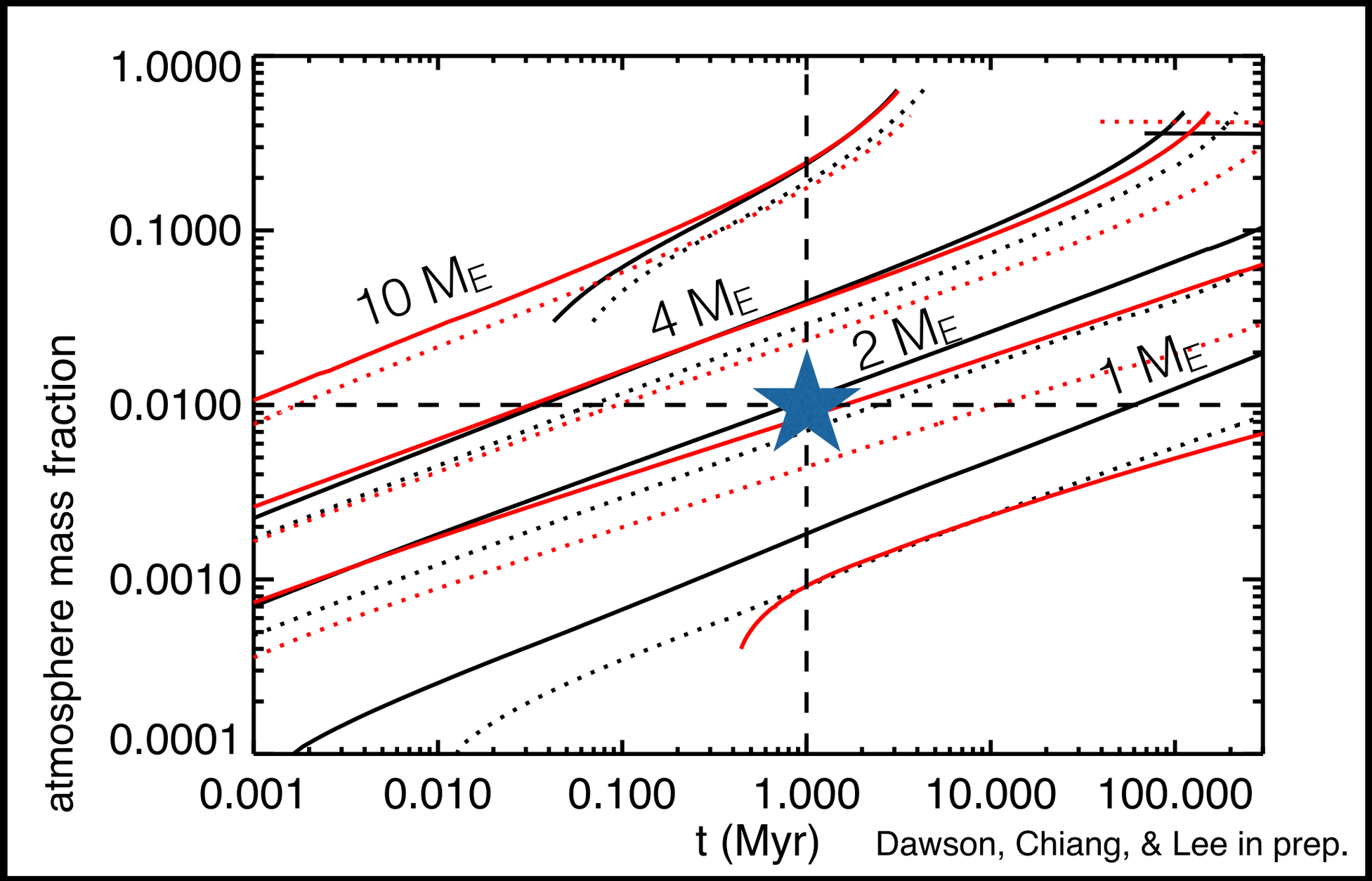
Lee, Chiang, & Ormel 14



Inamdar & Schlichting 15

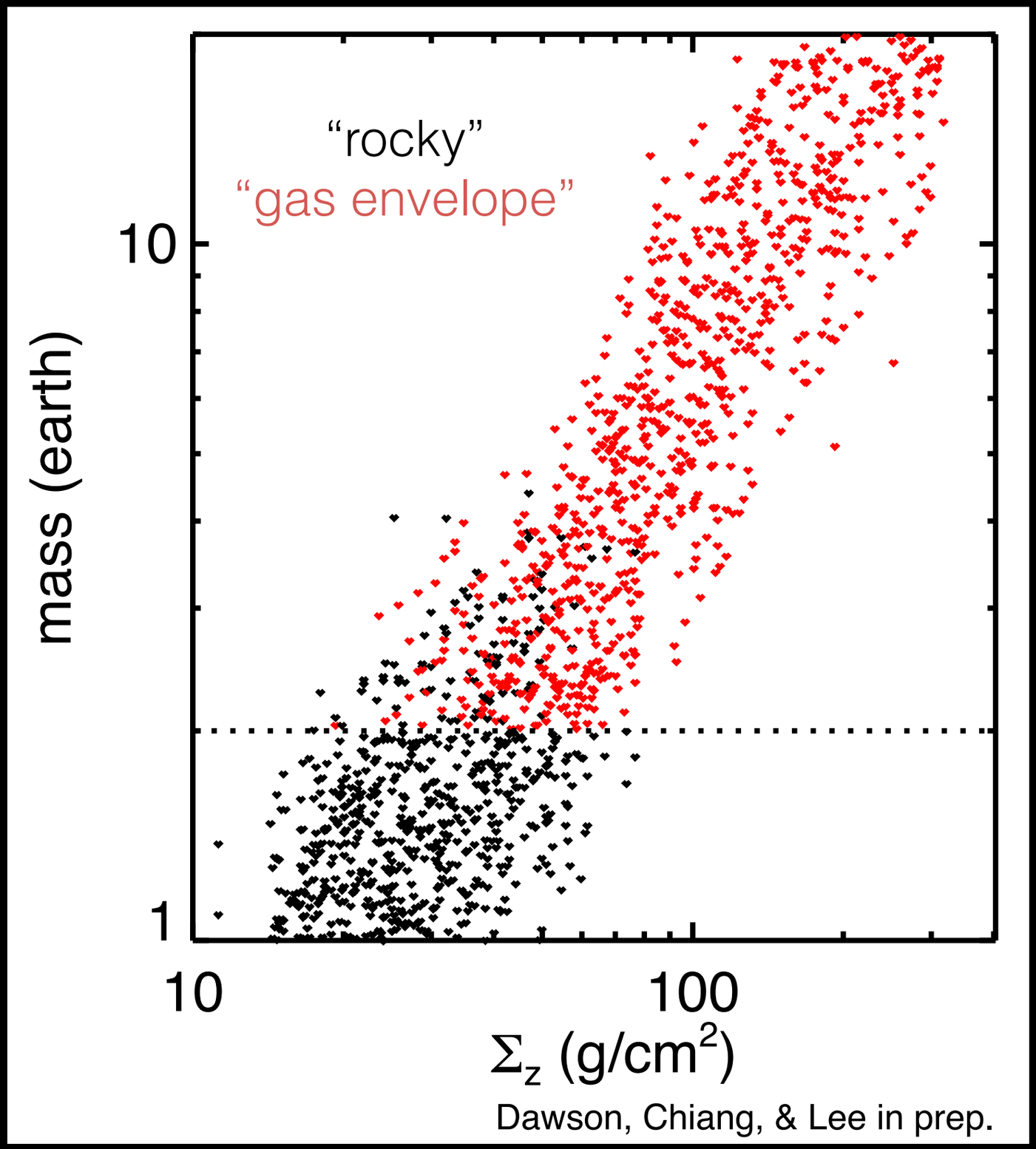


Time to accrete after core forms



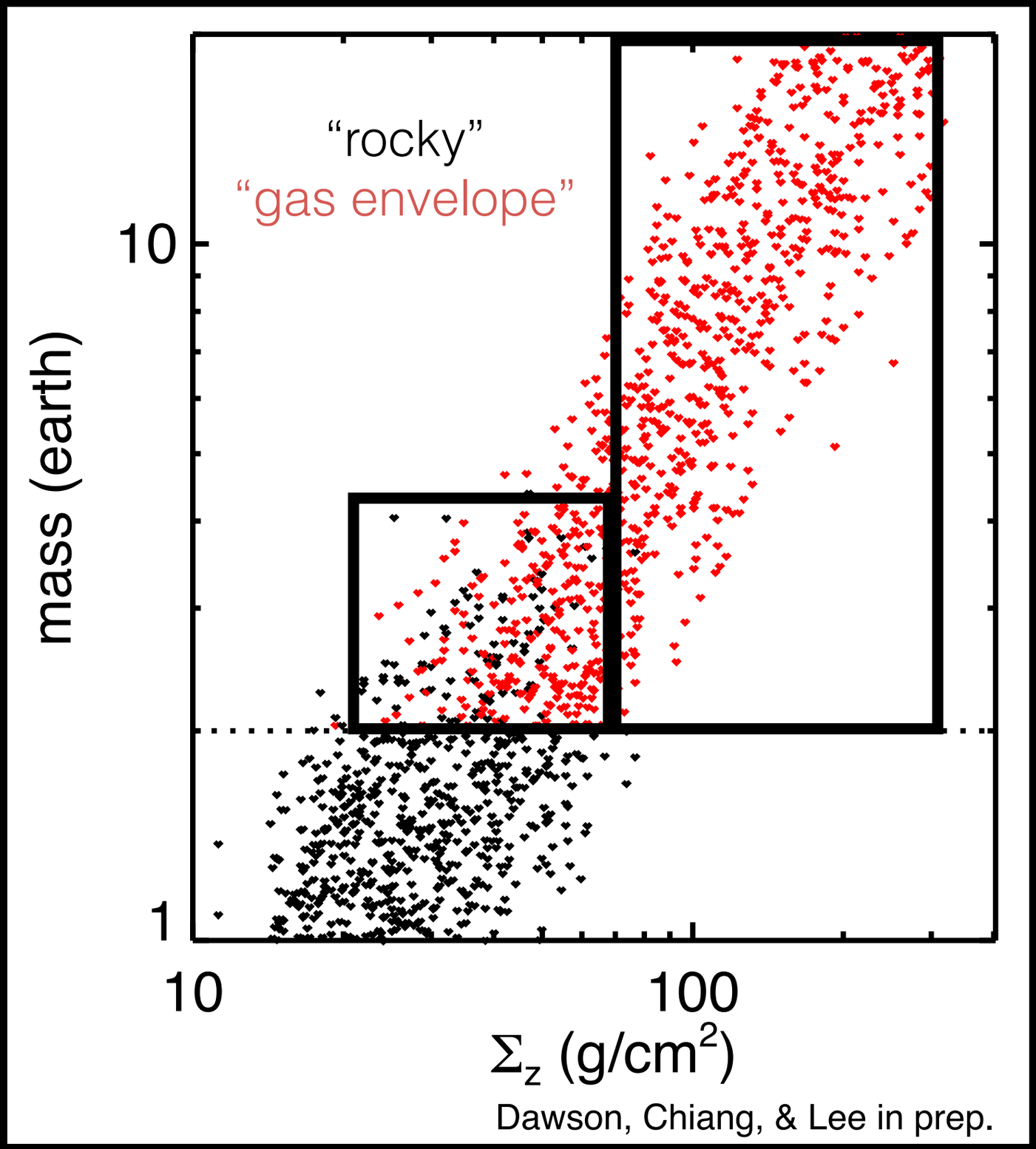
Eve Lee's accretion models

Compositional outcomes



Cut off =
grew to 2 Earth mass
in < 1 Myr

Compositional outcomes



Cut off =
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Compositional outcomes

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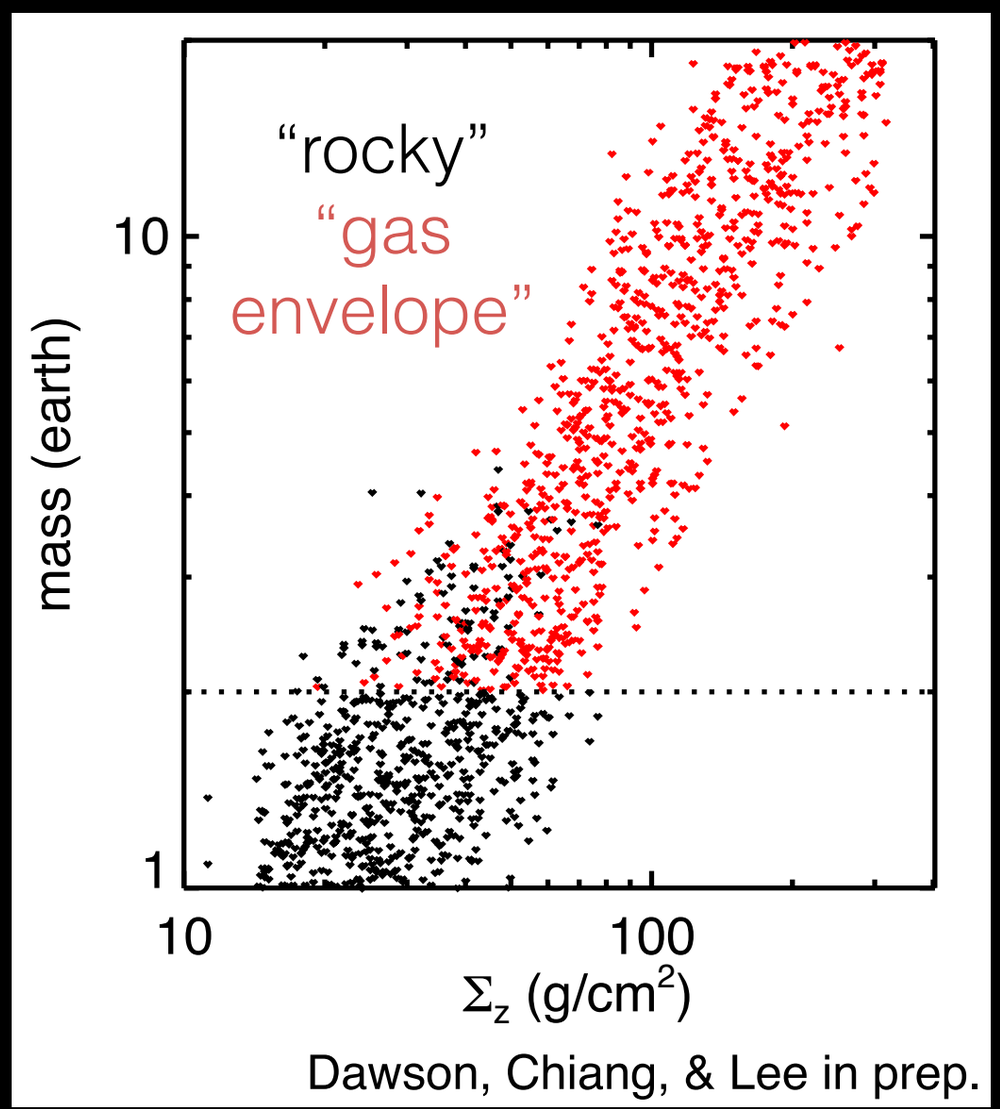
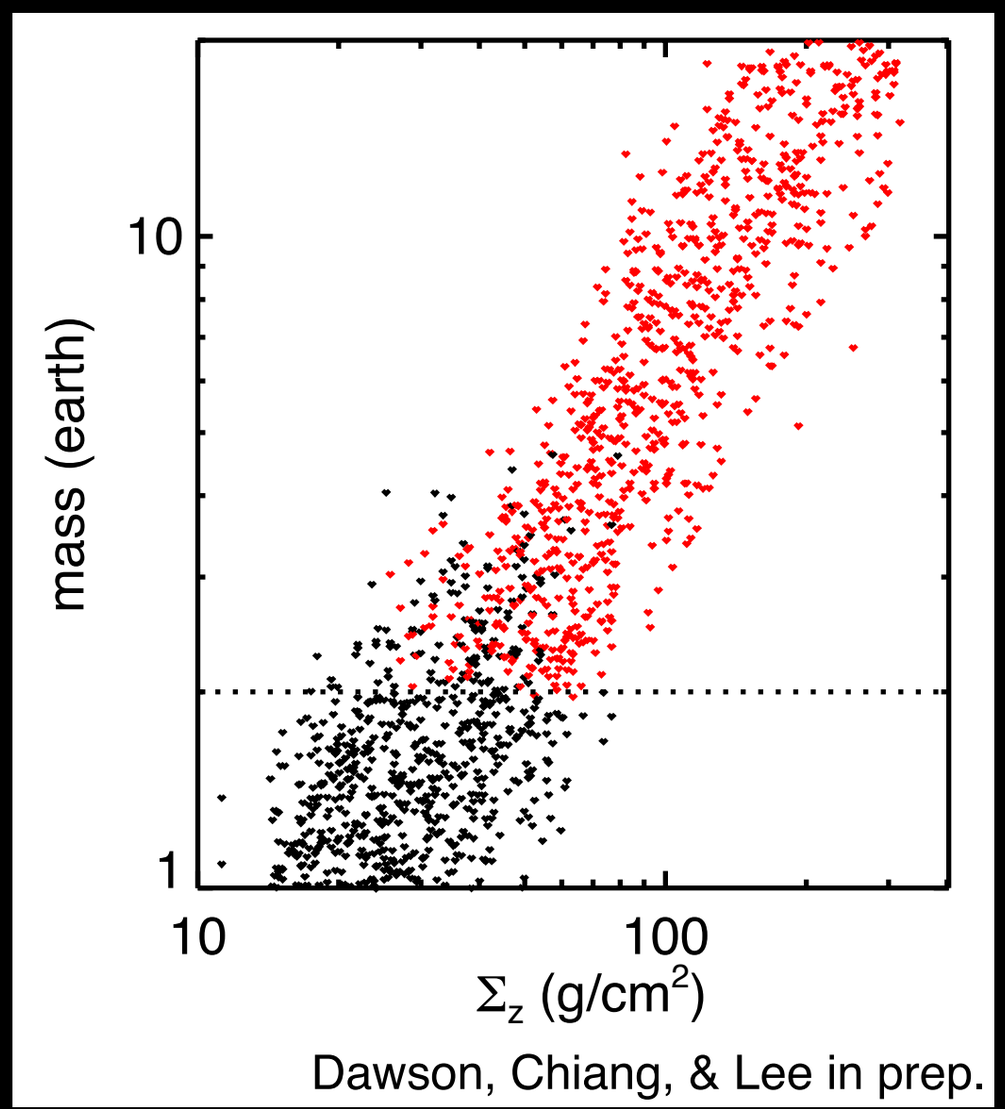


Mergers + gas accretion

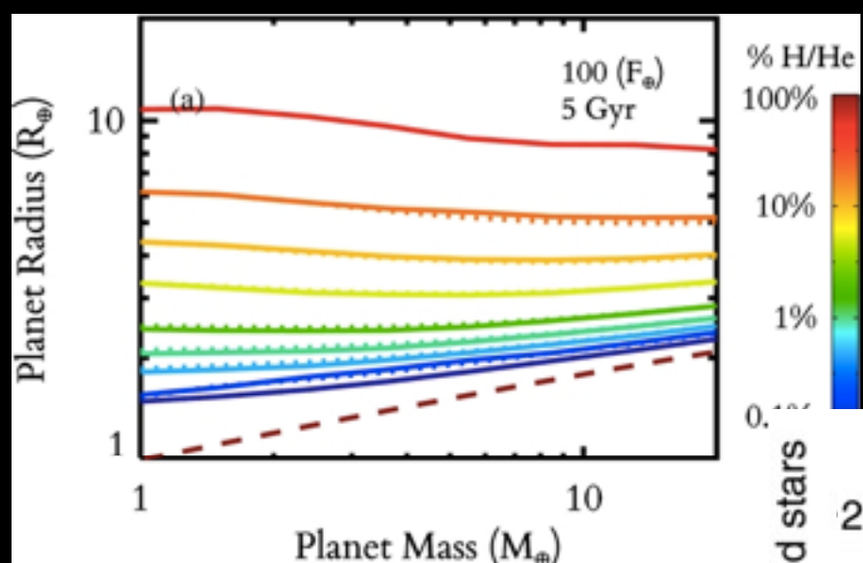
cut off = 1% H/He



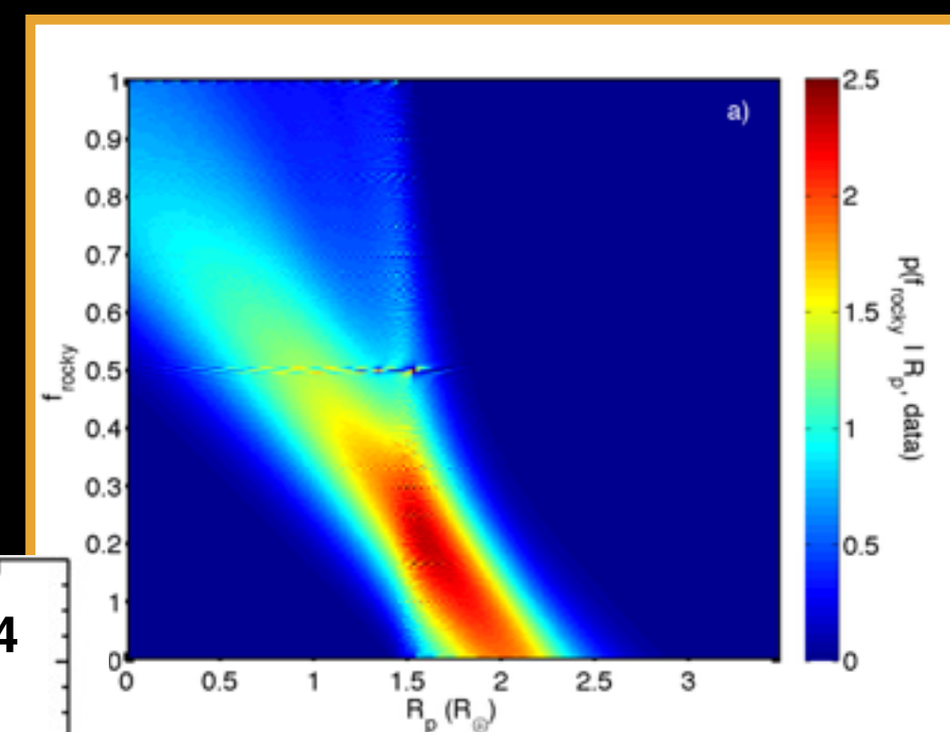
High surface solid densities may also have longer to grow

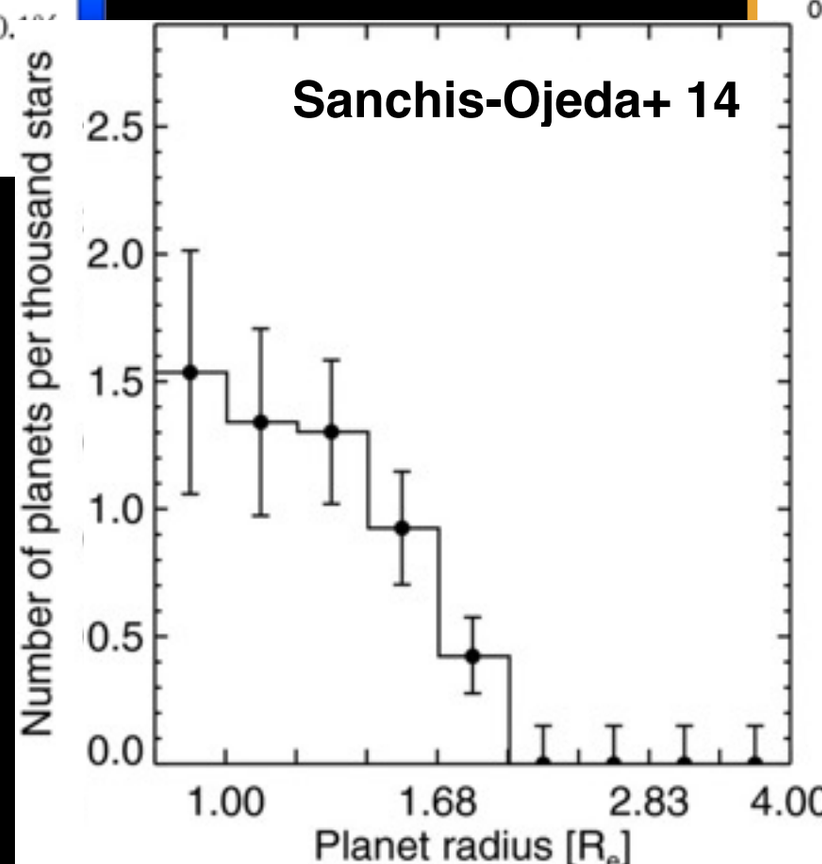
Comparison to observations: radius as a proxy for composition

Lopez & Fortney 14

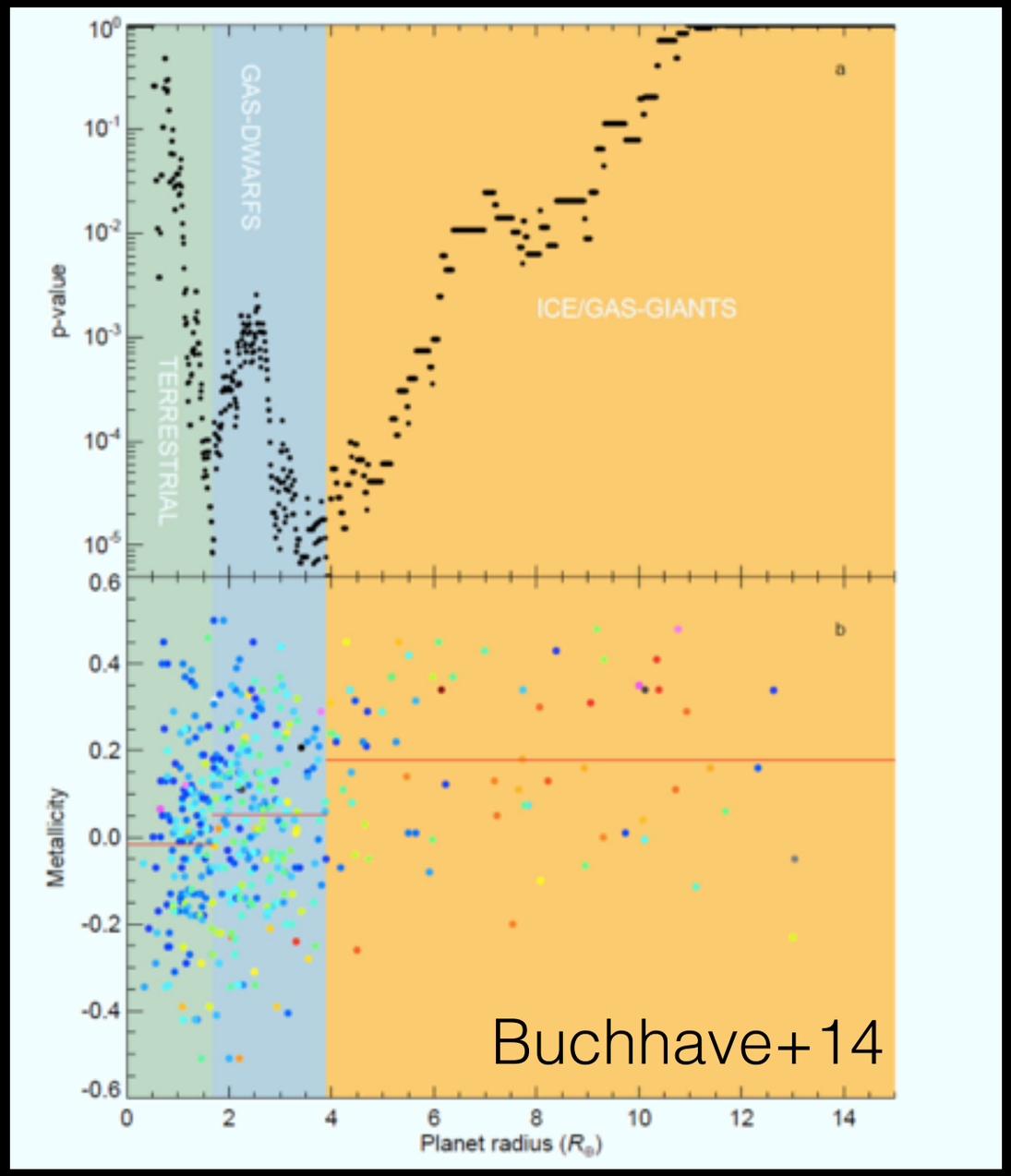


Rogers 14



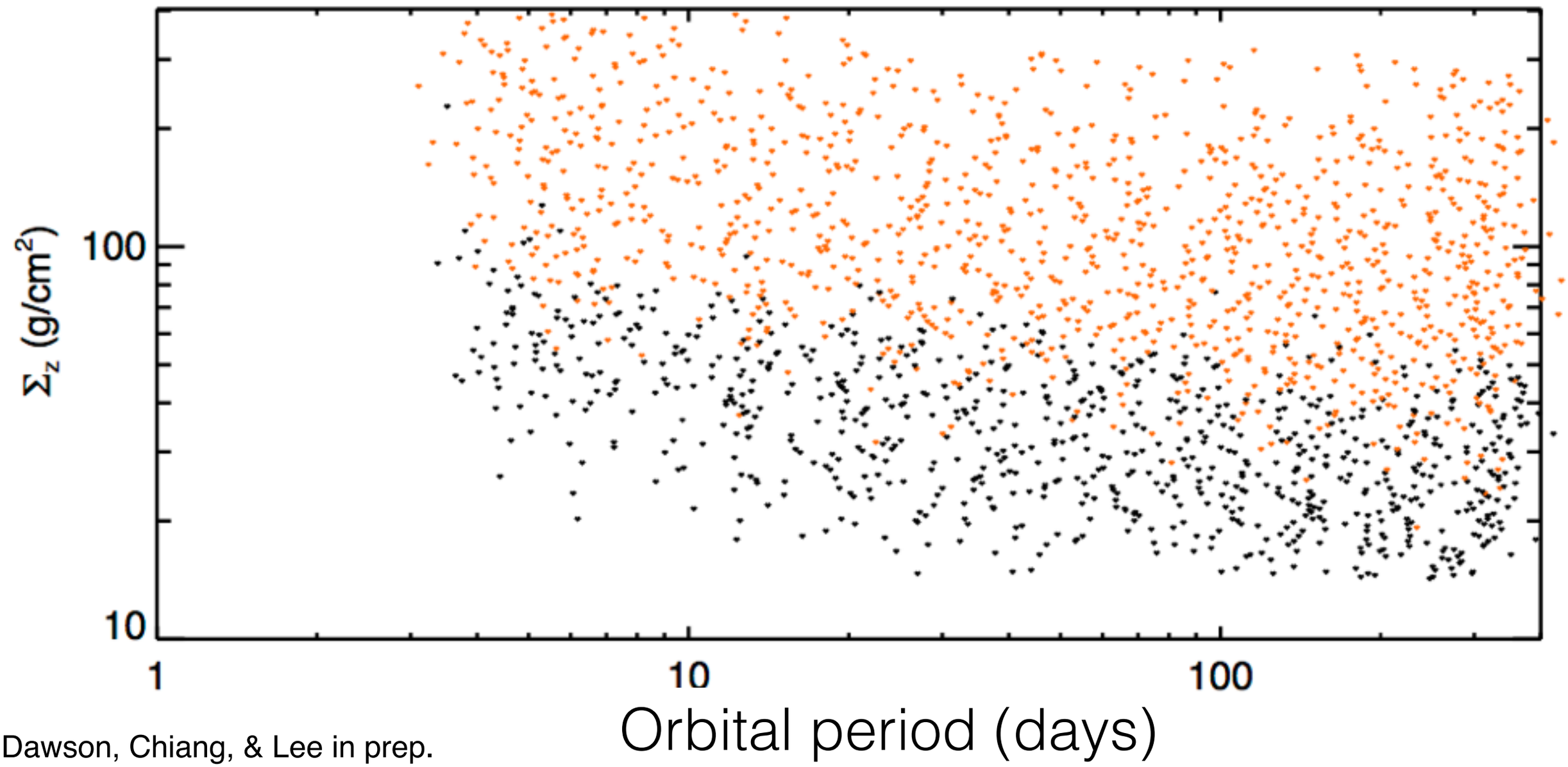


Comparison to observations: host star metallicity as a proxy for surface solid density



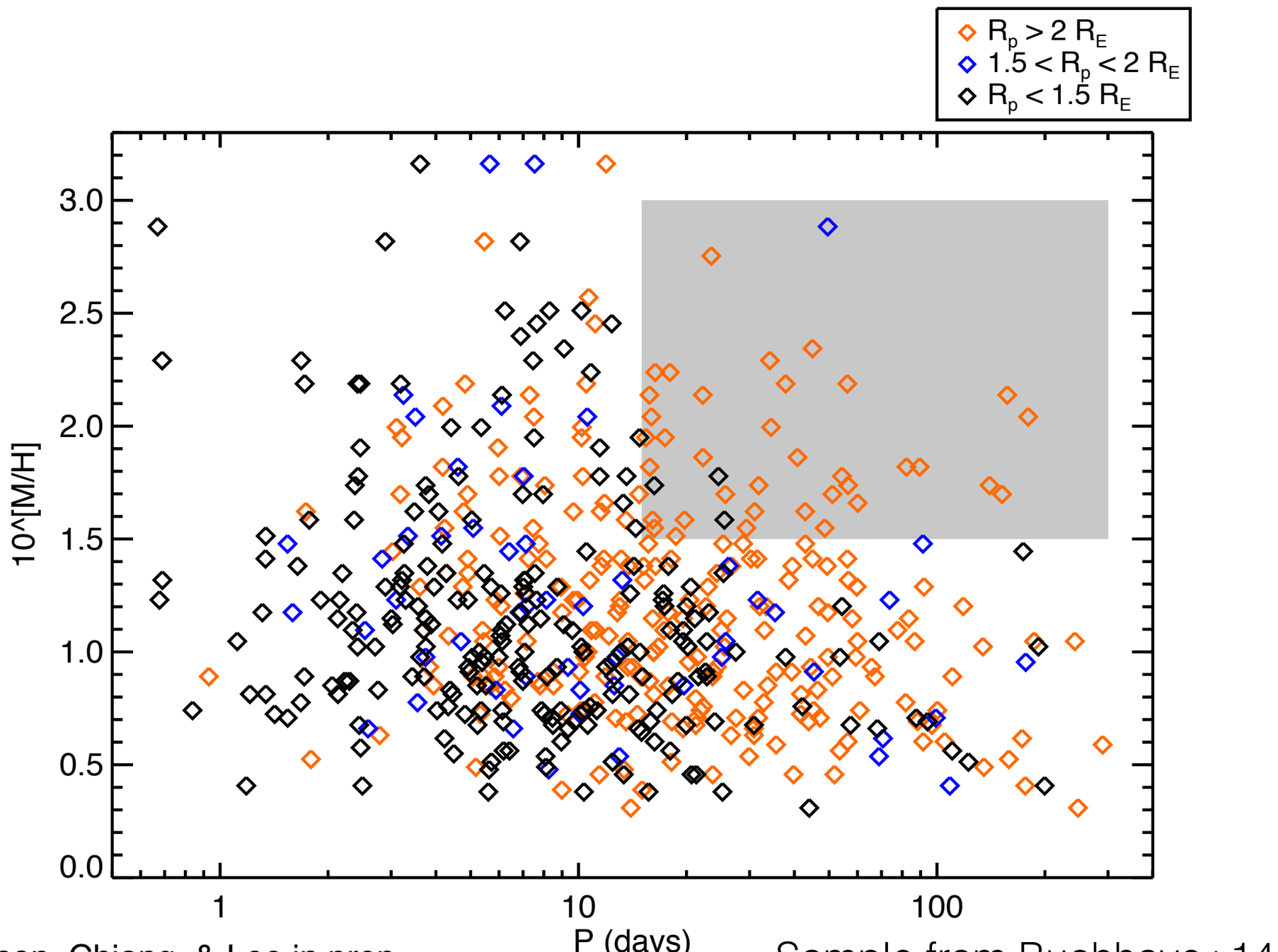
Planets above 2 Earth radii may orbit higher metallicity stars:
Buchhave+ 14, Wang & Fischer 2014
but also Schlaufman 2015

We expect: metal-rich stars lack rocky planets beyond reach of photo evaporation



Dawson, Chiang, & Lee in prep.

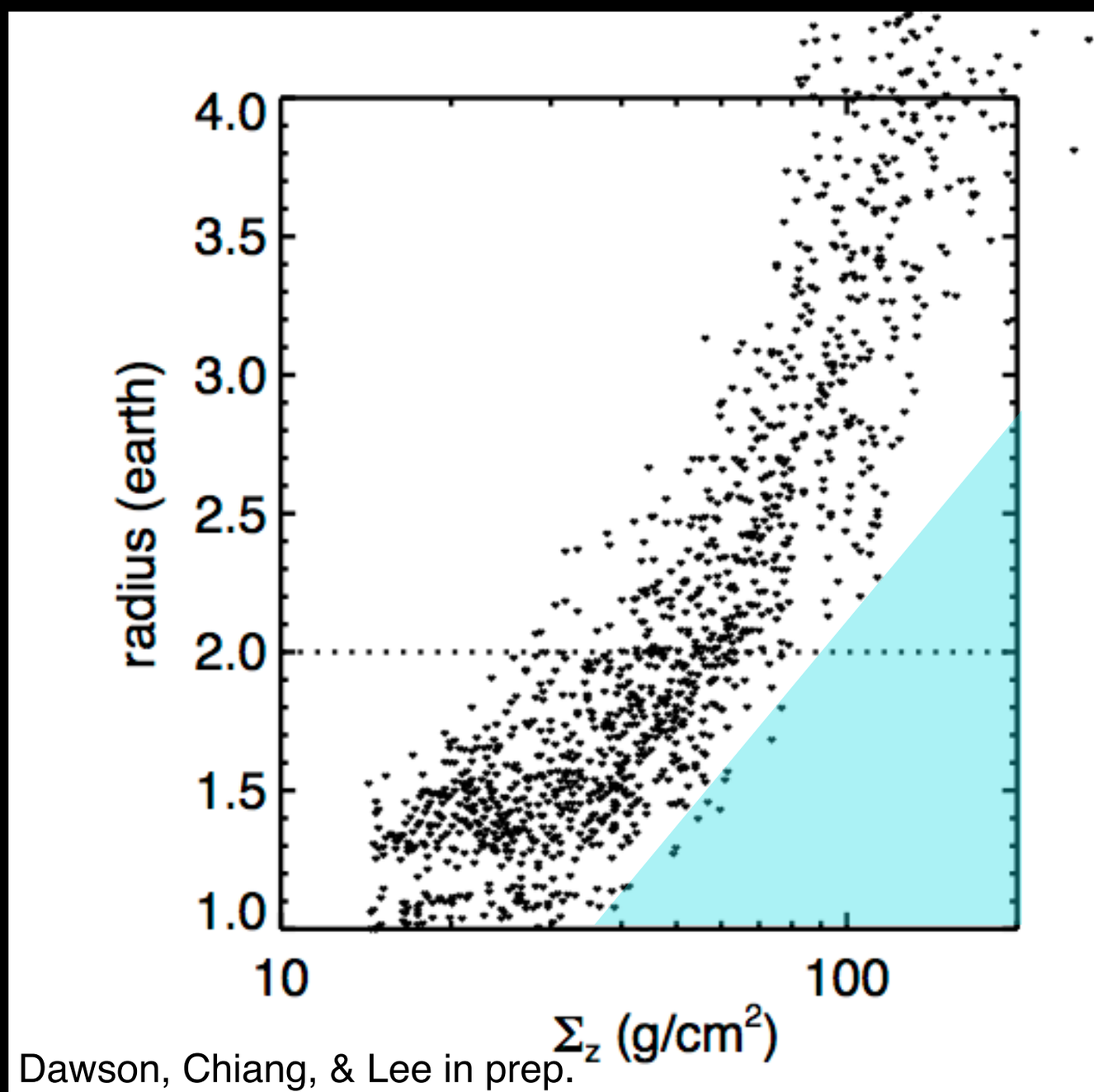
Metal-rich stars lack rocky planets beyond reach of photo evaporation



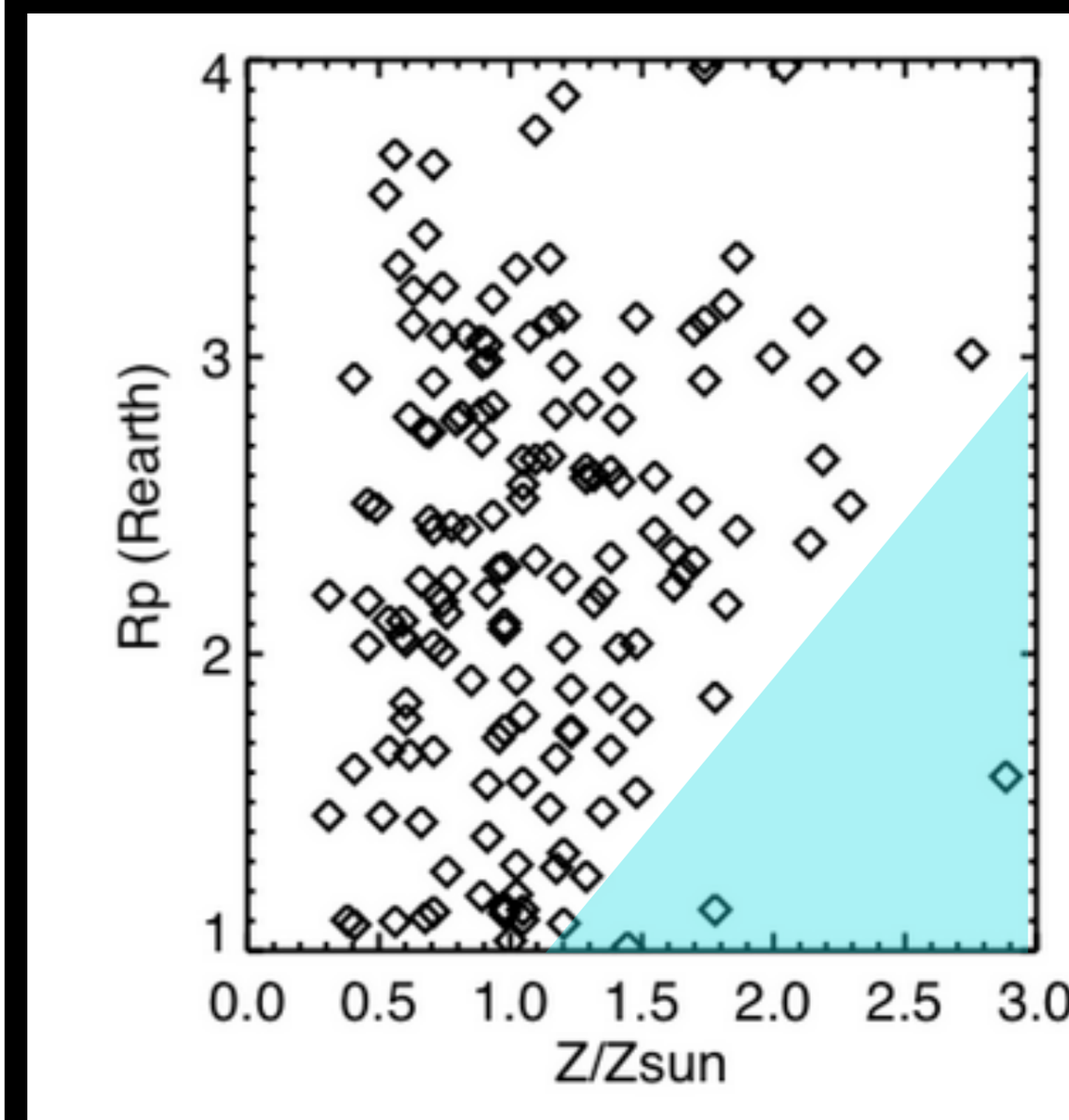
Dawson, Chiang, & Lee in prep.

Sample from Buchhave+14

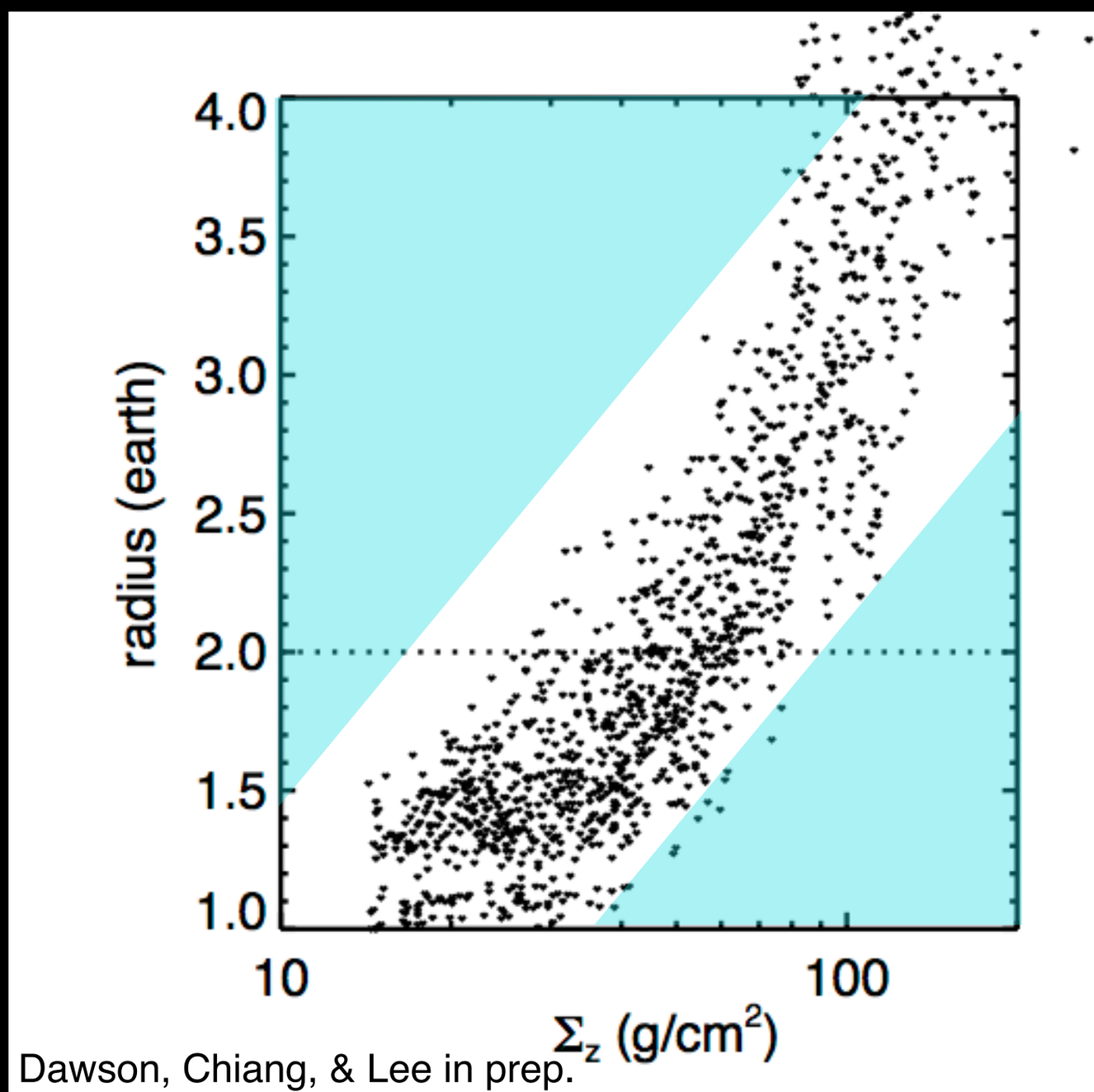
Planet radius increases with host star metallicity



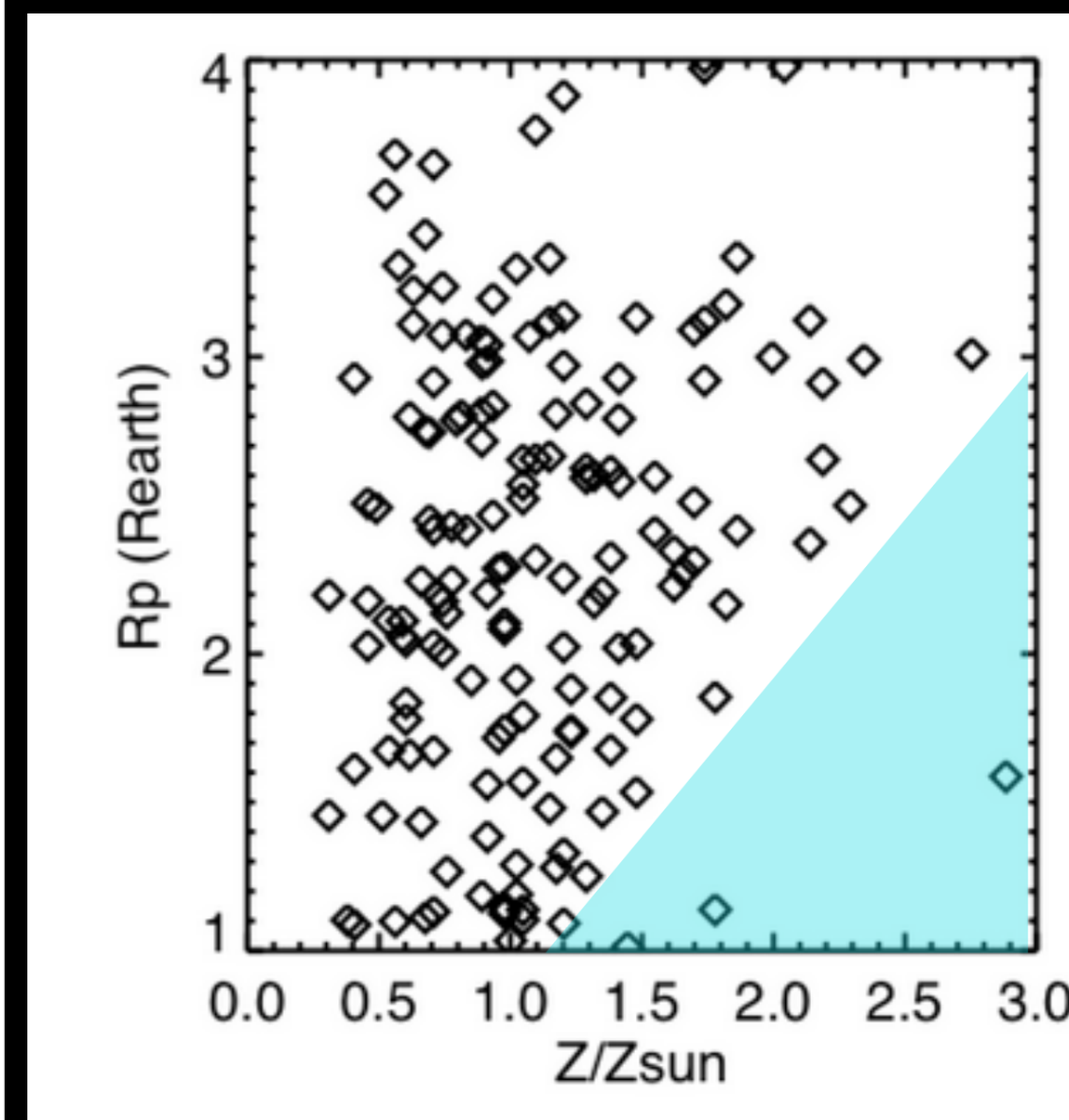
Dawson, Chiang, & Lee in prep.



Planet radius increases with host star metallicity



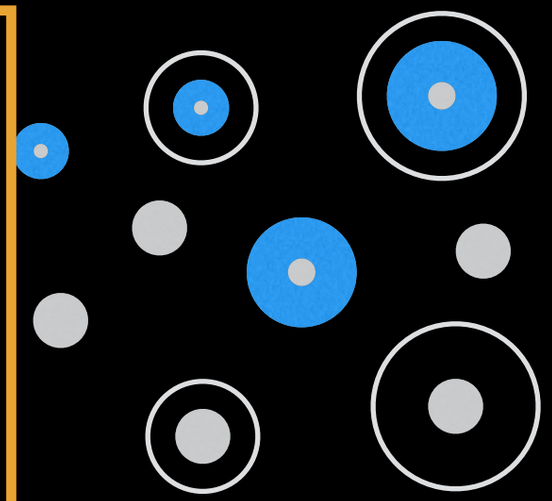
Dawson, Chiang, & Lee in prep.



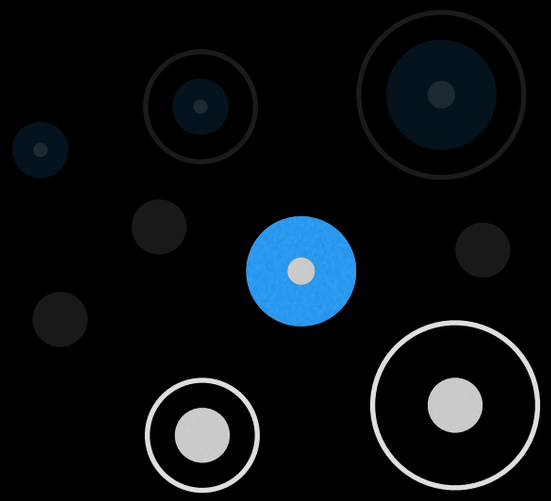
TTV Planets: Farm to Table

1. What physical processes are responsible for the diversity of small exoplanet compositions?

2. Are TTV planets a special population?



Formation



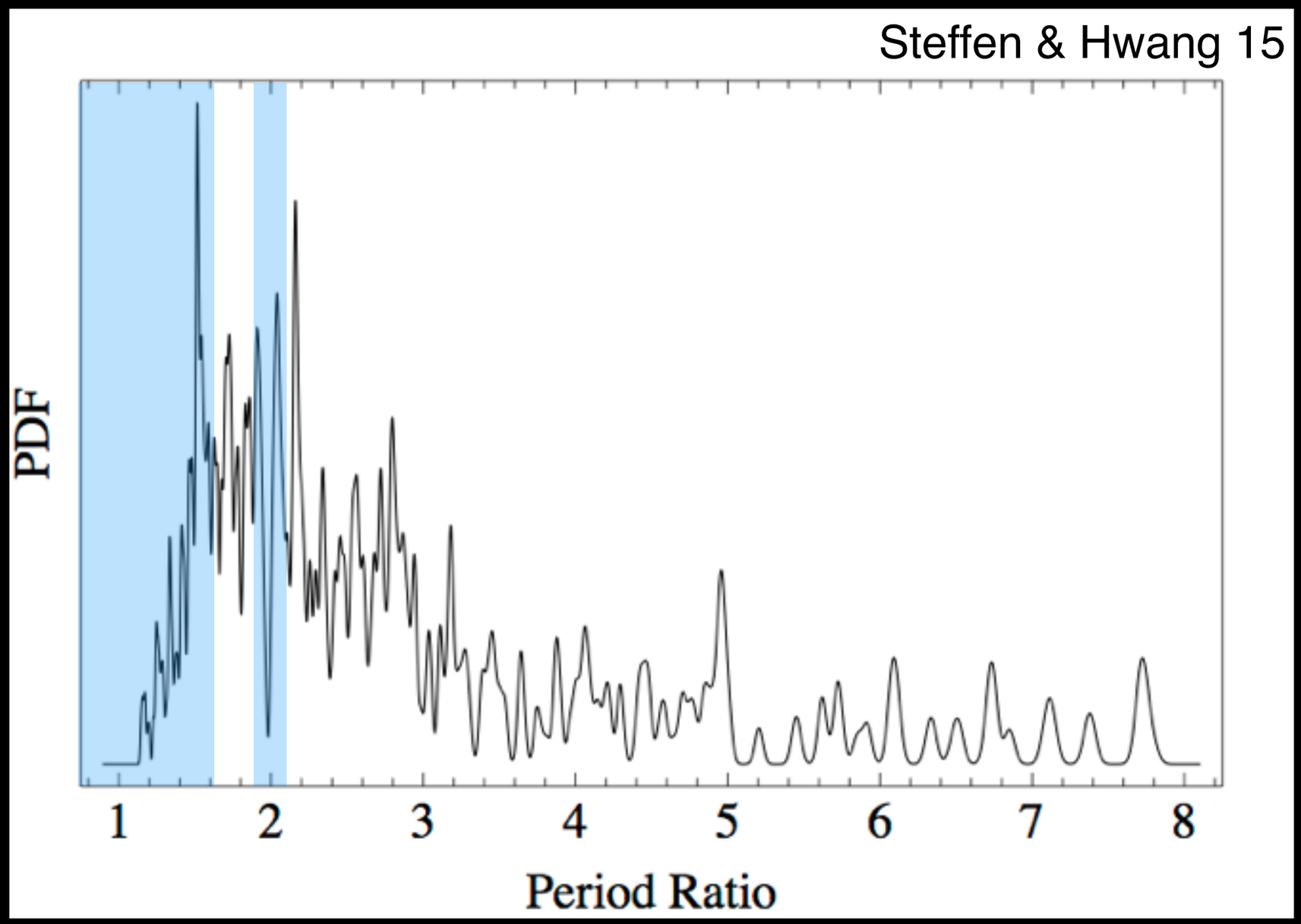
Discovery

Interpretation

Dynamics

Measurement

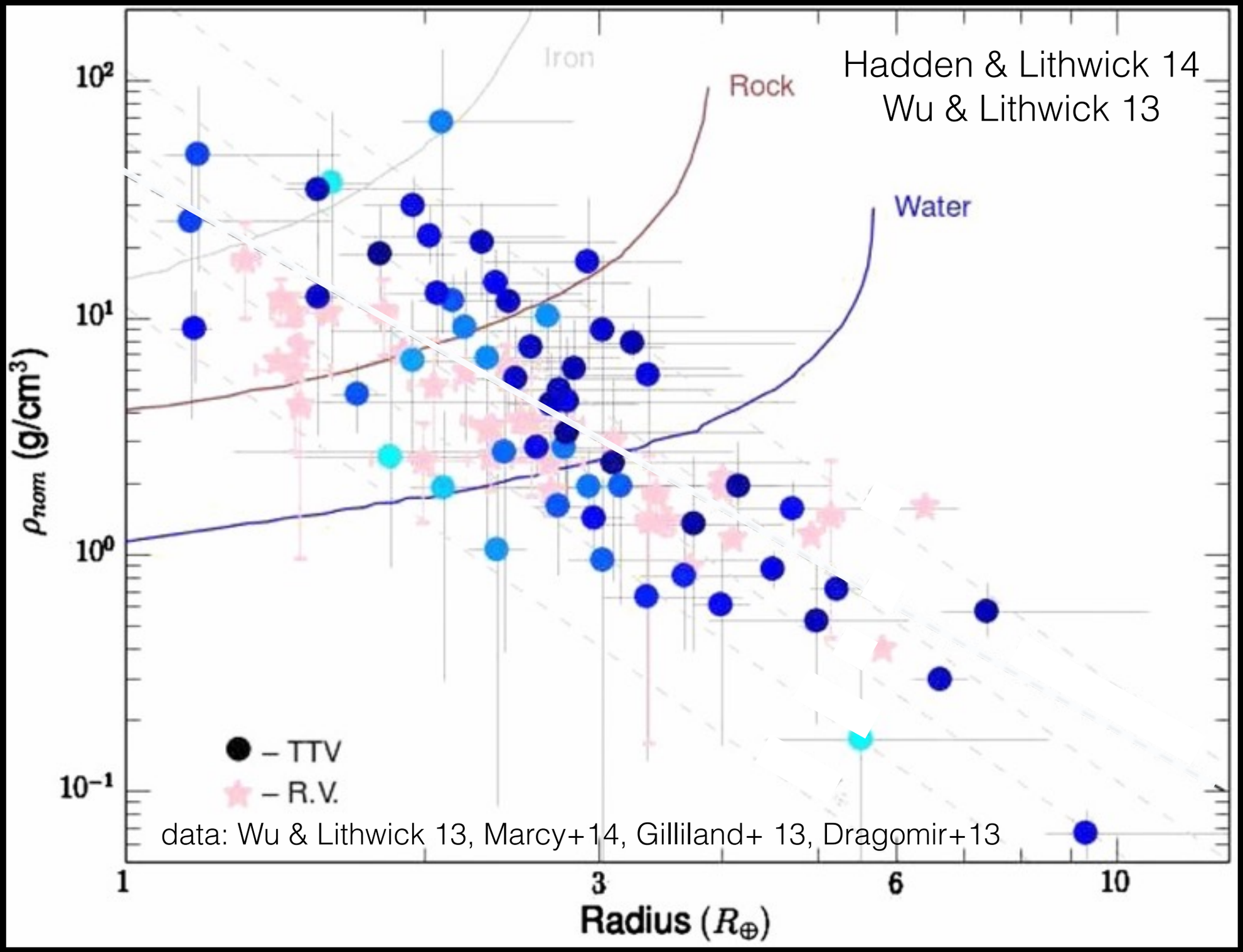
TTV planets are near orbital resonance but not unusual in the spacing distribution



See also Fabrycky+14

Goldreich & Schlichting 14: small, migrating planets rarely get permanently caught in resonance

bulk density



See also Wolfgang+ in prep

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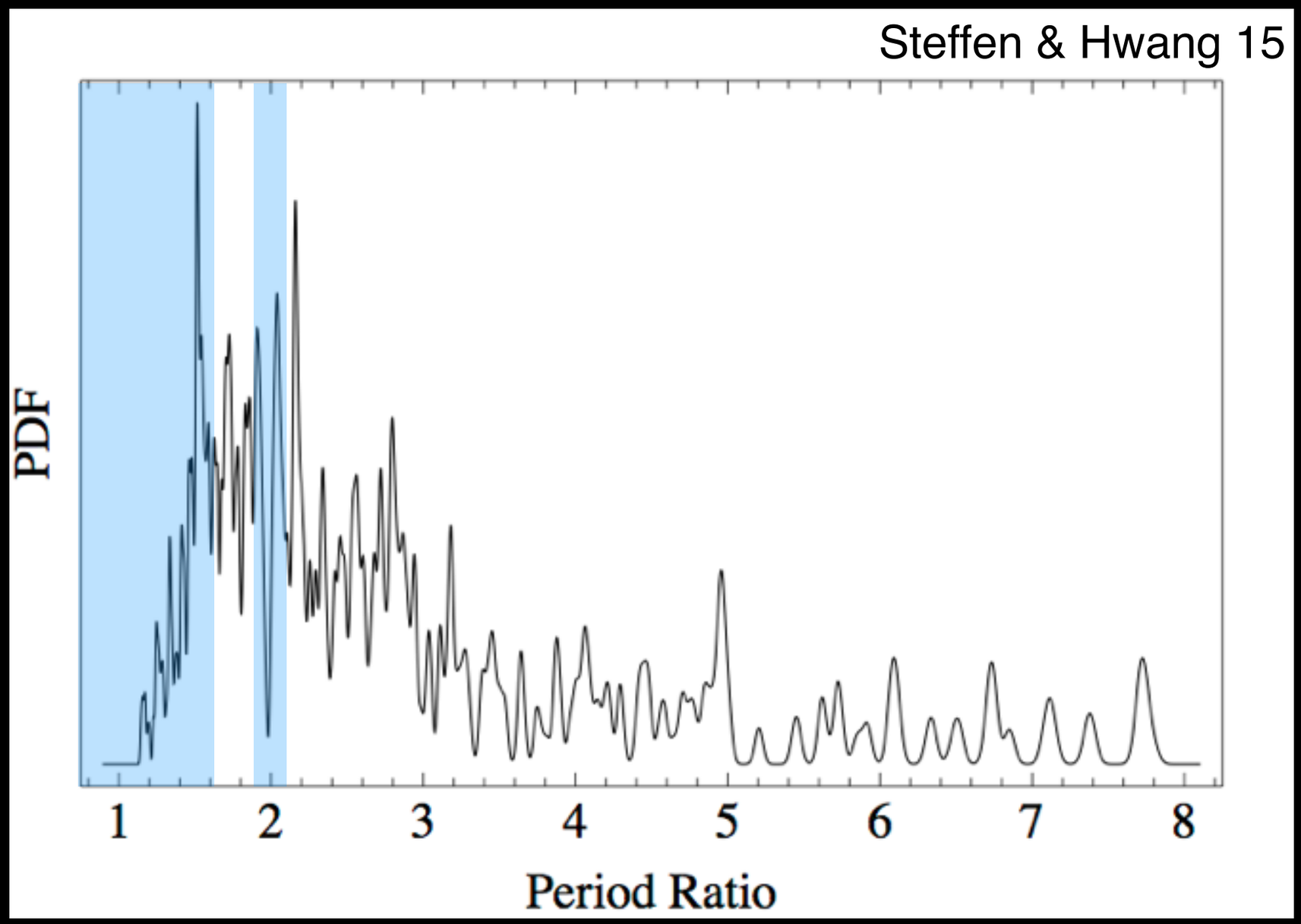

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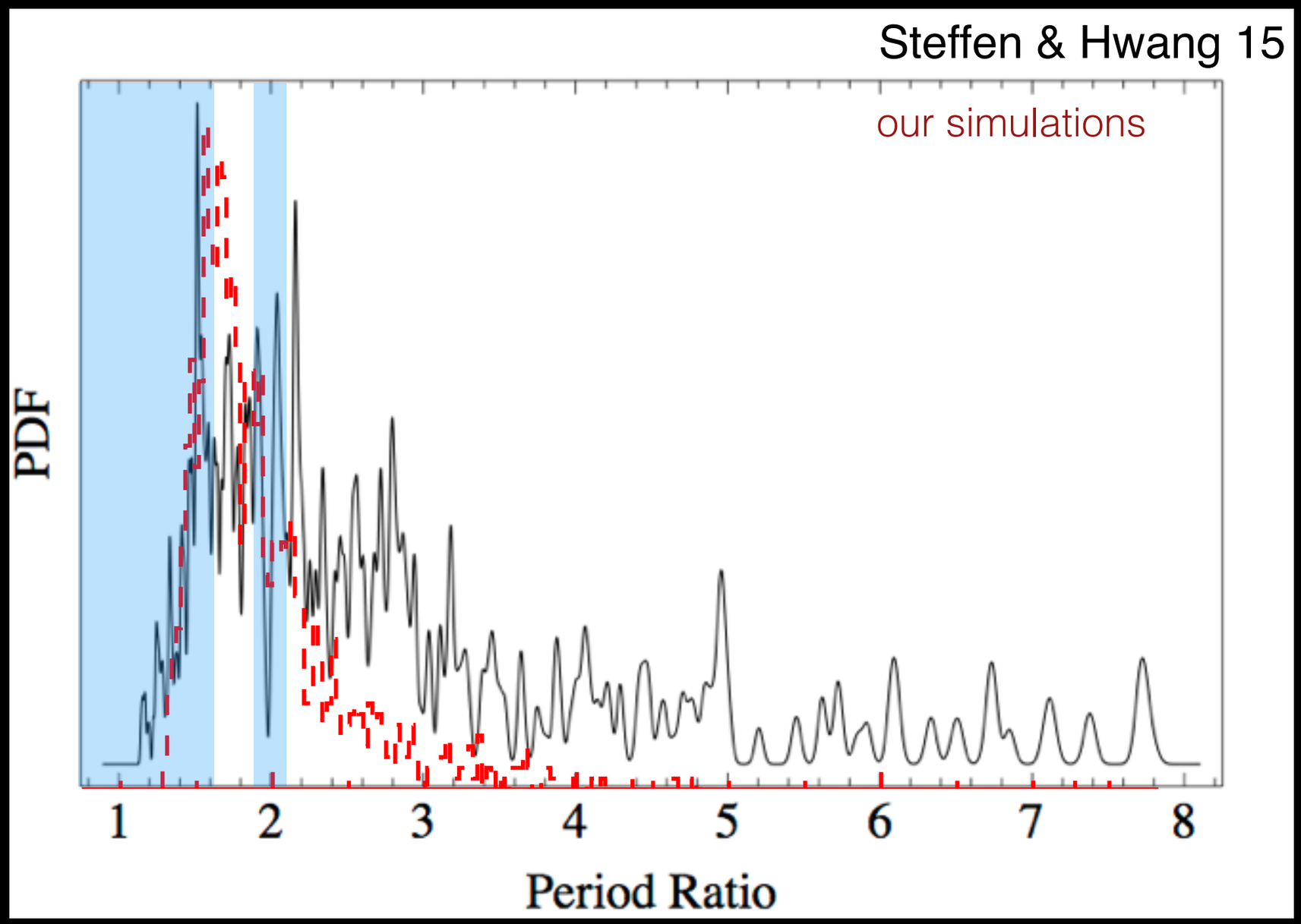
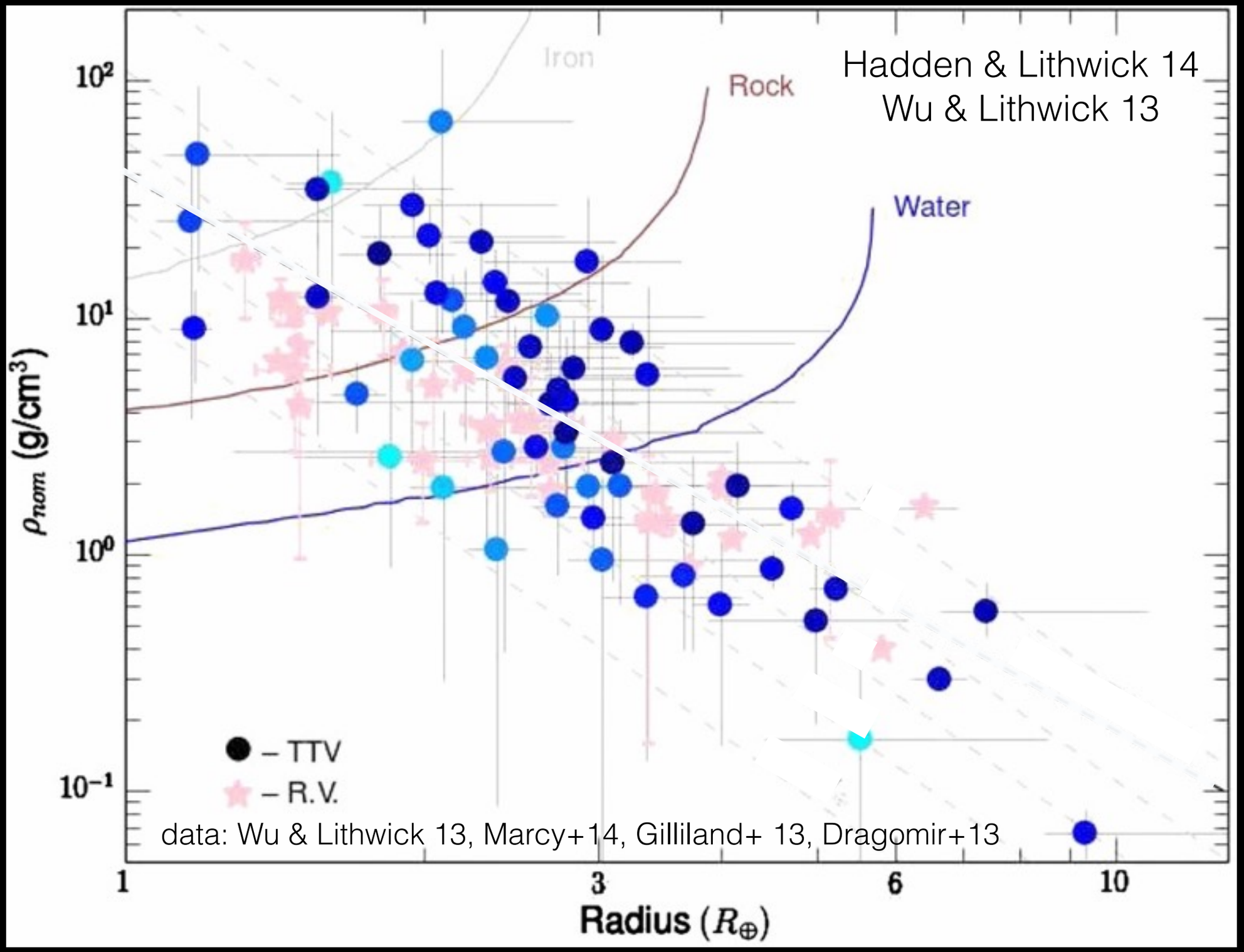


See also Fabrycky+14

Goldreich & Schlichting 14: small, migrating planets rarely get permanently caught in resonance

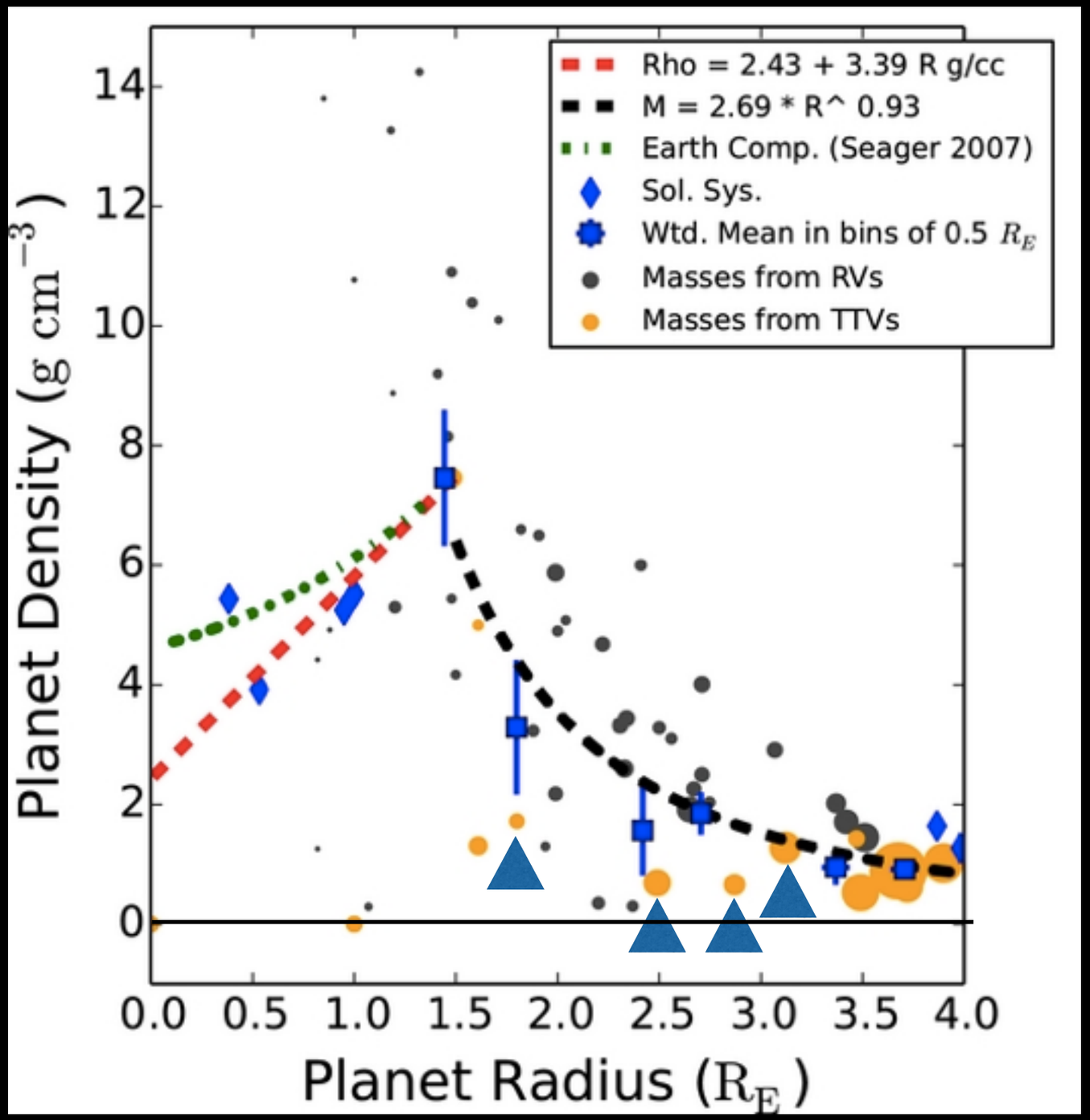
The TTV and RV population are not strikingly different in density vs. radius



bulk density

See also Wolfgang+ in prep

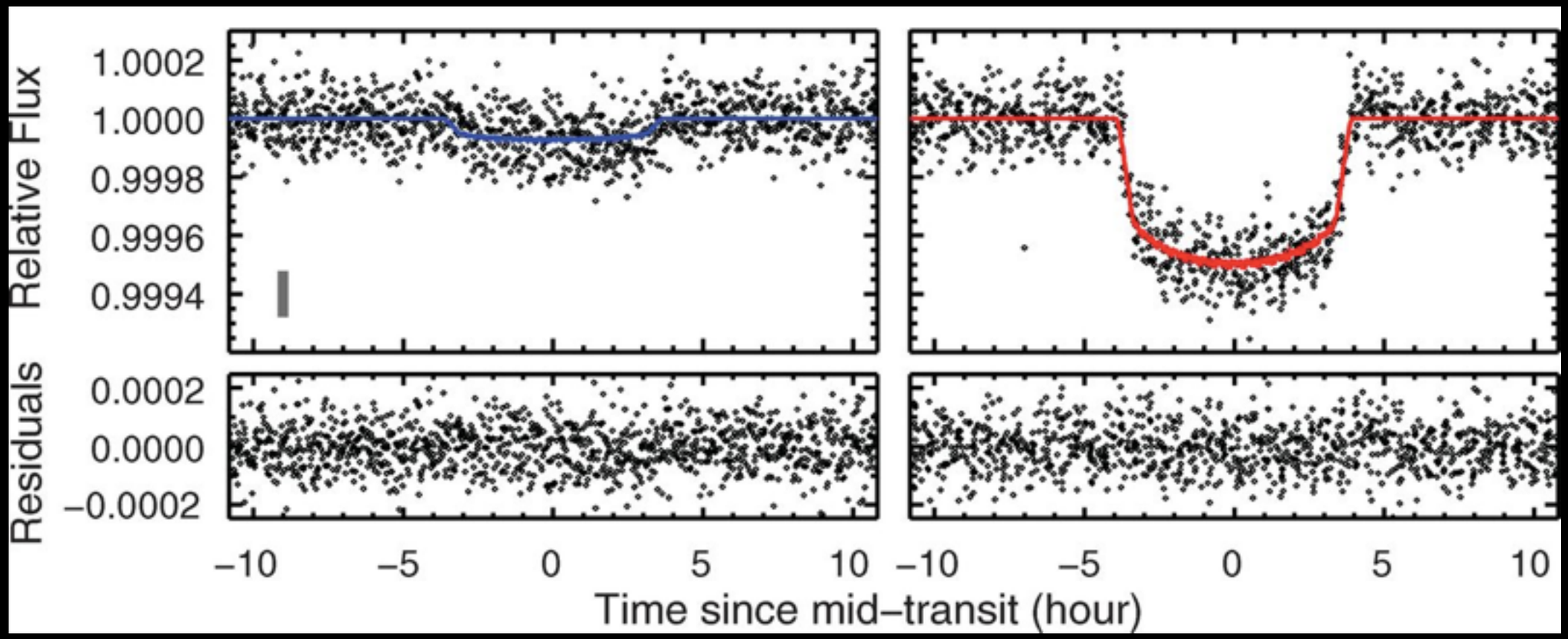
Kepler-11 planets have low densities



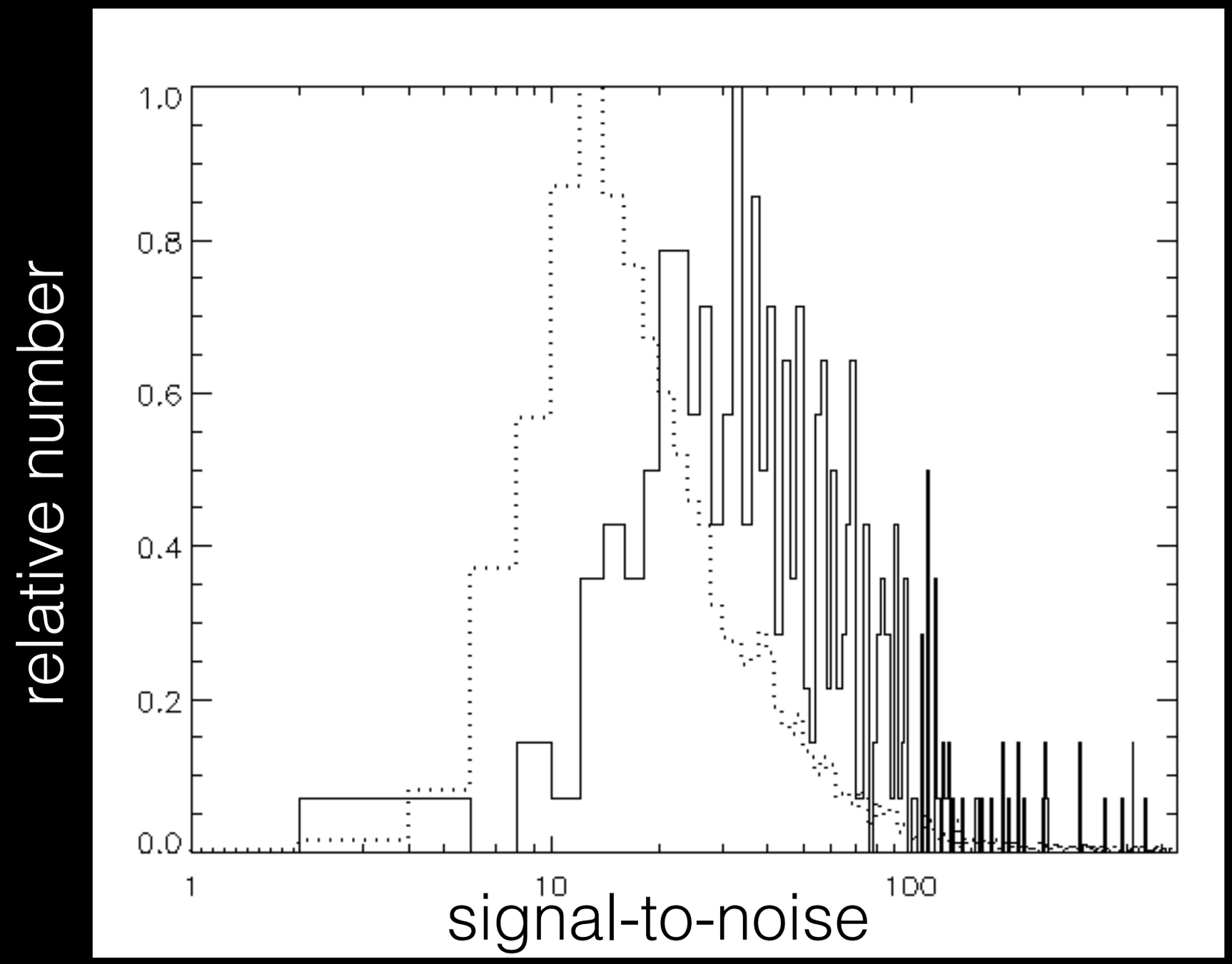
Weiss & Marcy 14

Large radii amplify TTV signals

Kepler 36, Carter, Agol+ 12

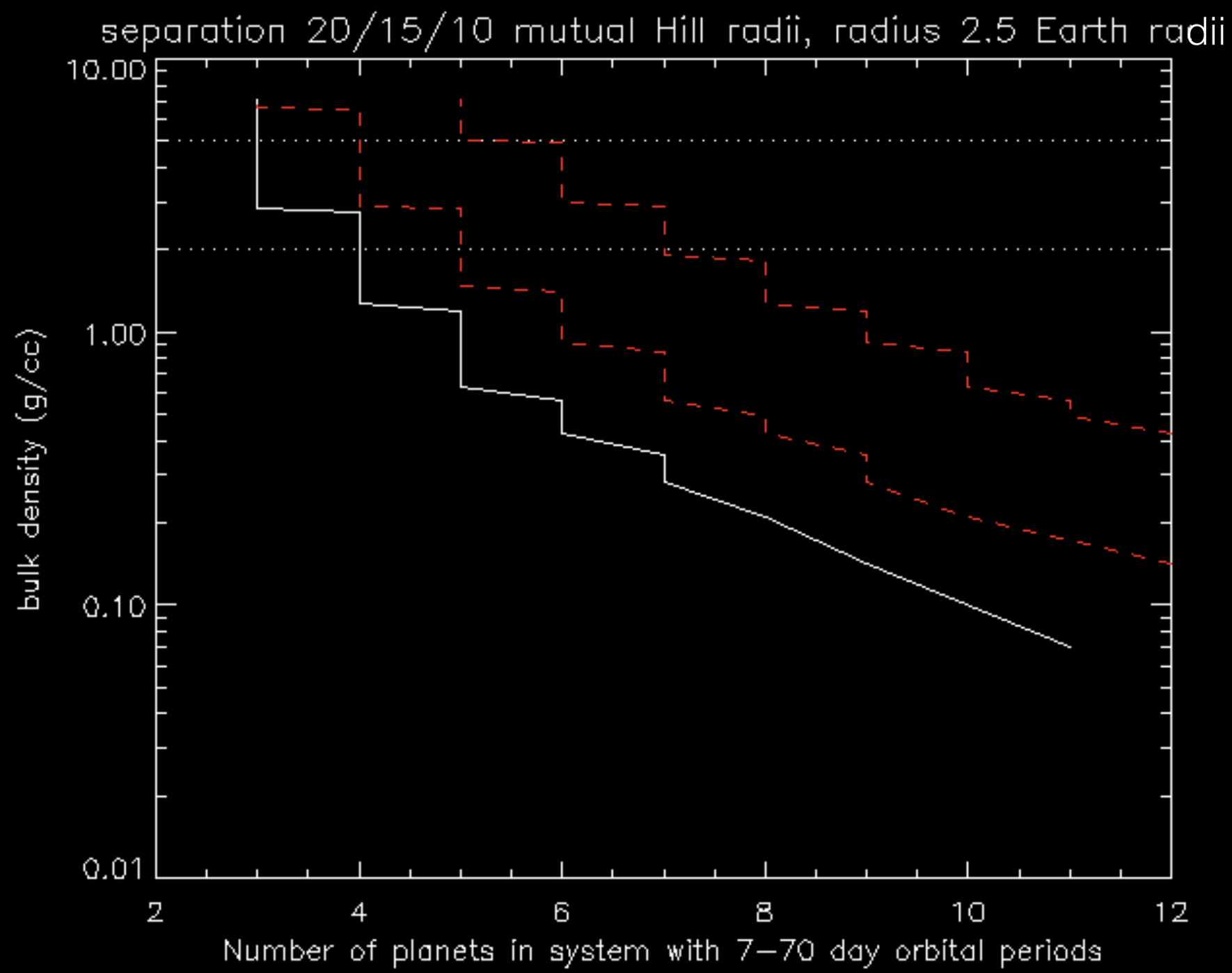


Large radii amplify TTV signals



Also:Planets in a given system are similar sizes, Ciardi, Fabrycky+ 1

Selection effects give low density for high multiplicity systems

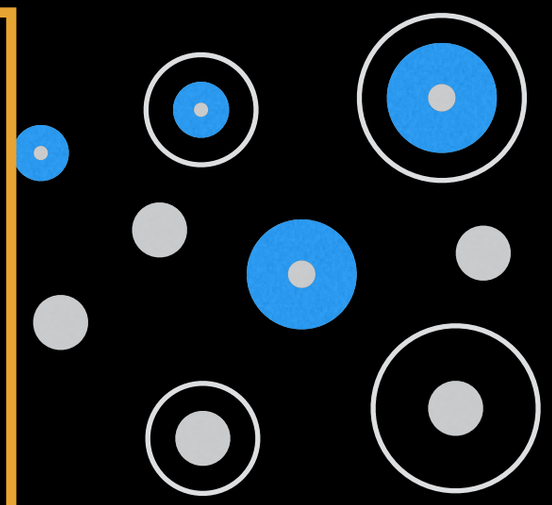


TTV Planets: Farm to Table

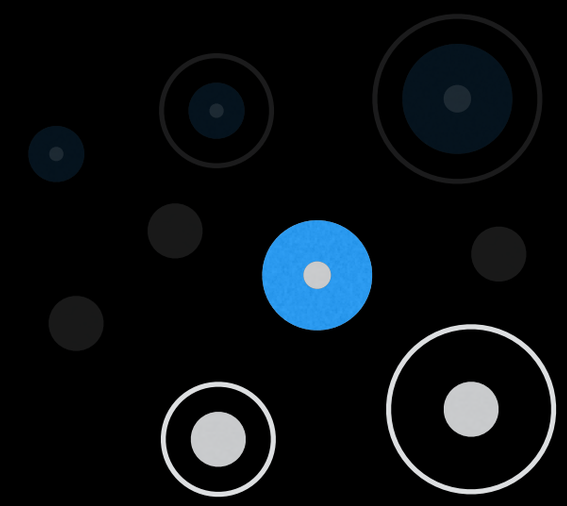
1. What physical processes are responsible for the diversity of small exoplanet compositions?

2. Are TTV planets a special population?

3. How do we robustly infer transit times from noisy data?



Formation



Discovery

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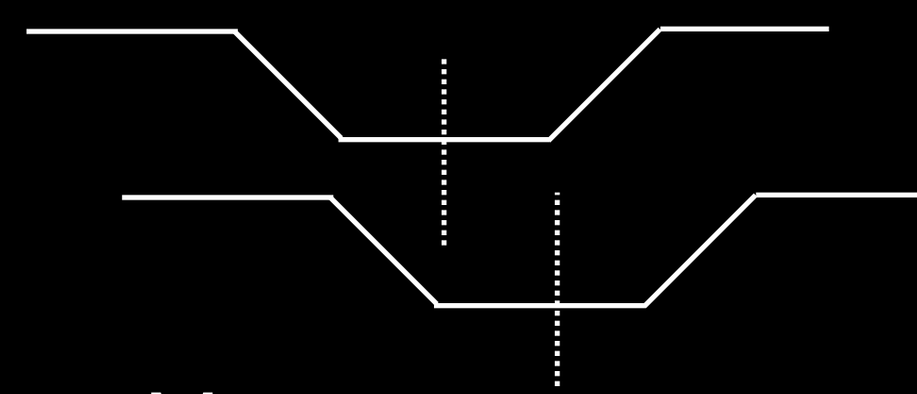
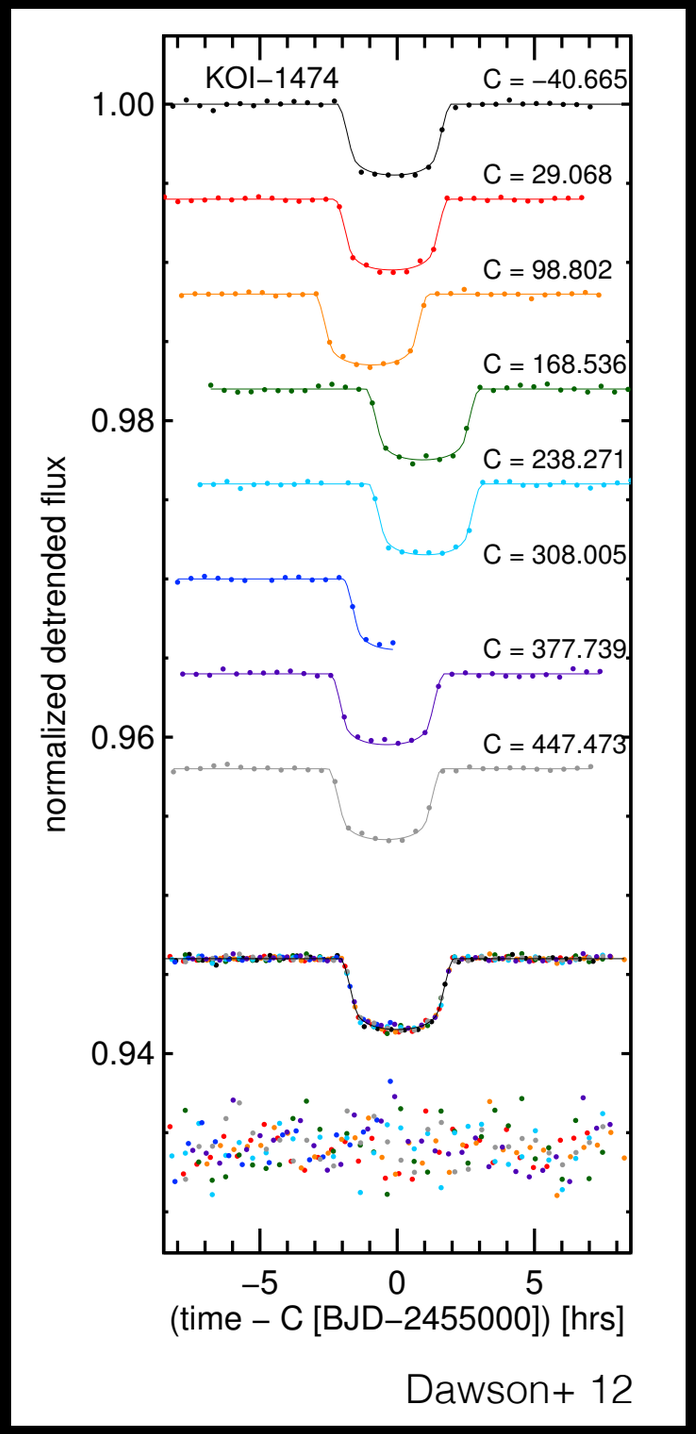
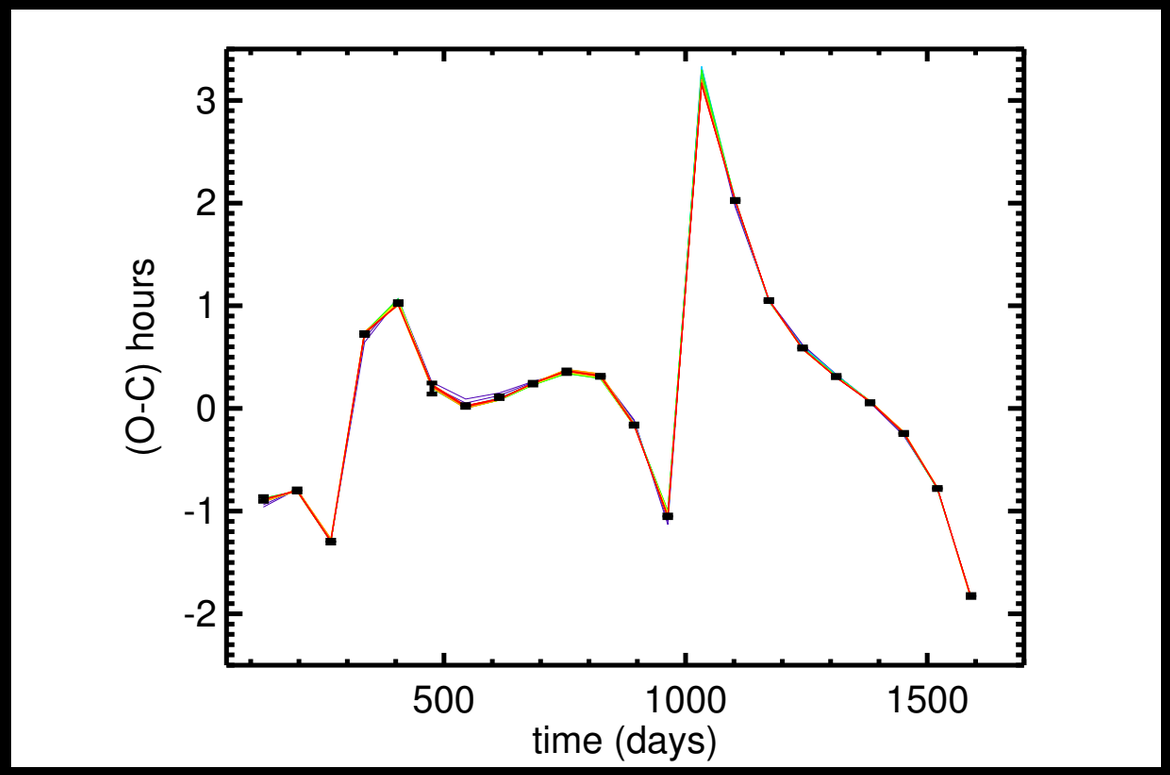


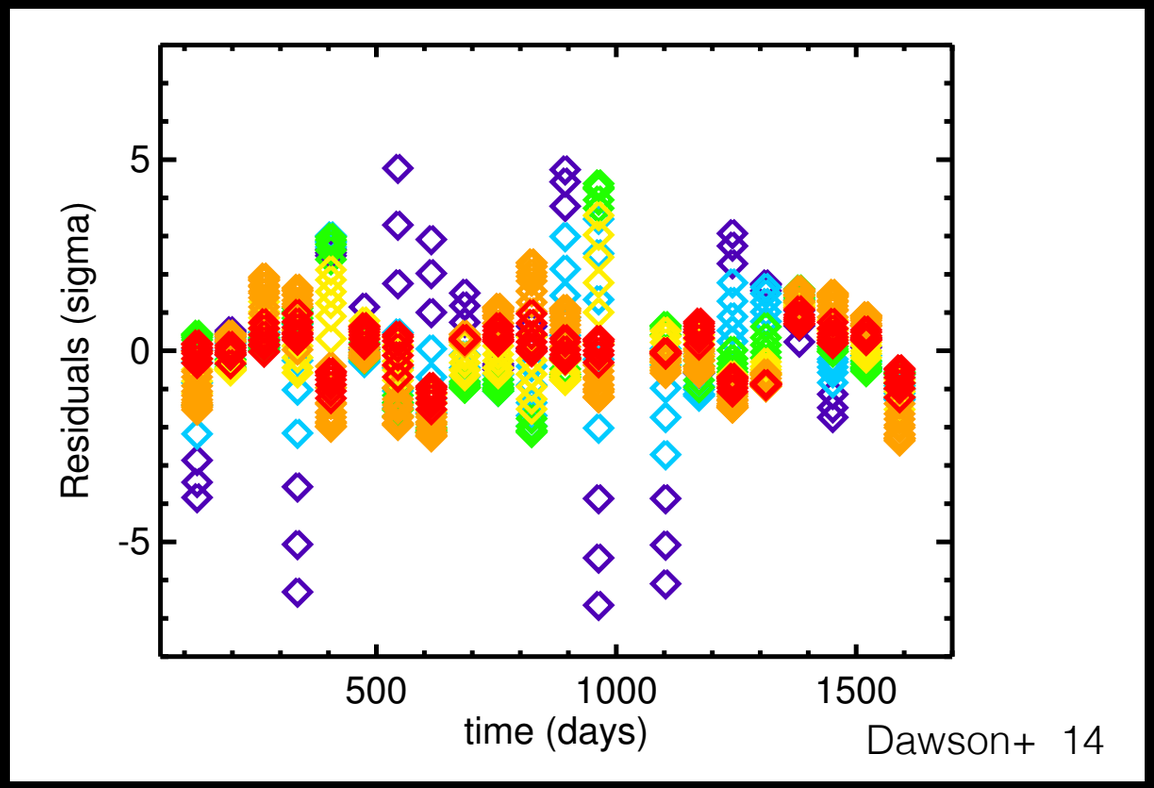
Measurement

Illustrative case: the 3D architecture of a giant planet system, Kepler-419

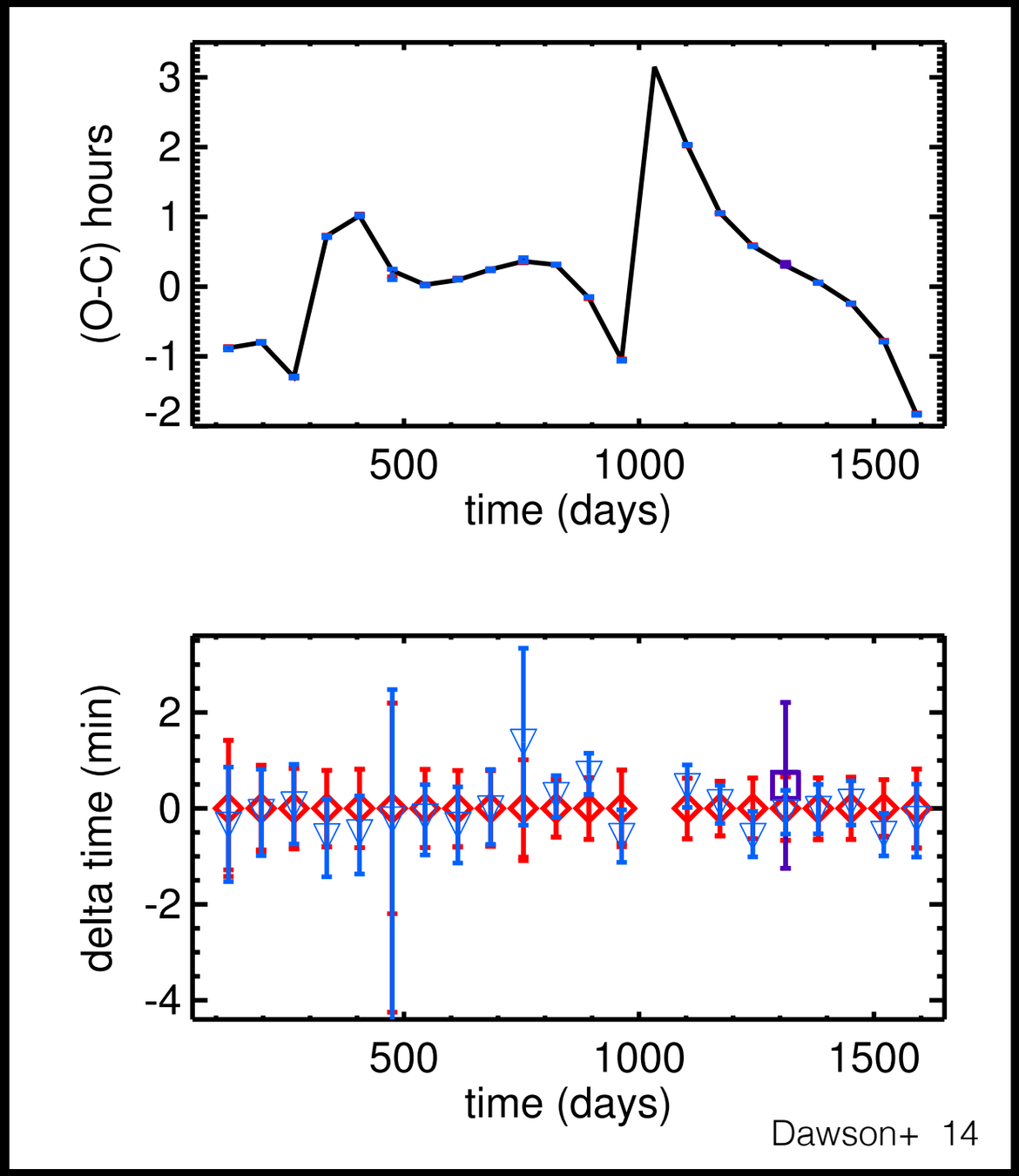


An orbital angle had a very subtle effect on the signal but was essential to constraining the system's dynamical origin





Two approaches to account for noise were consistent

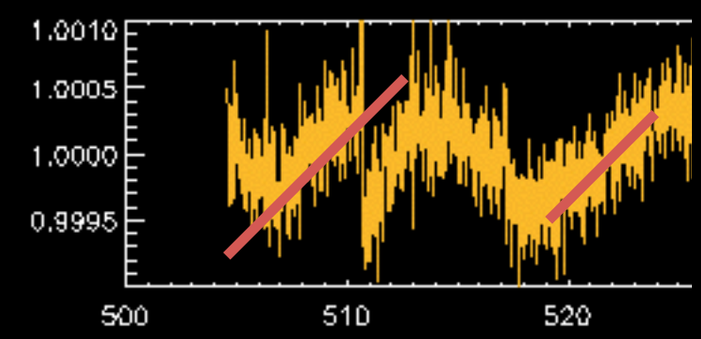


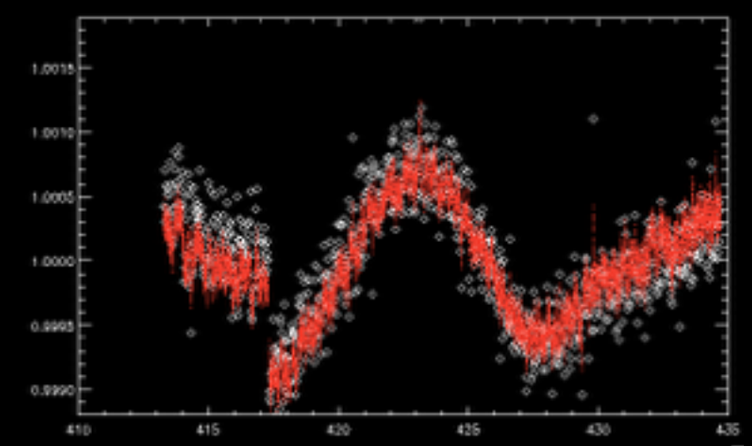
Approach 1 (R. Dawson)
Approach 2 (D. Foreman-Mackey)

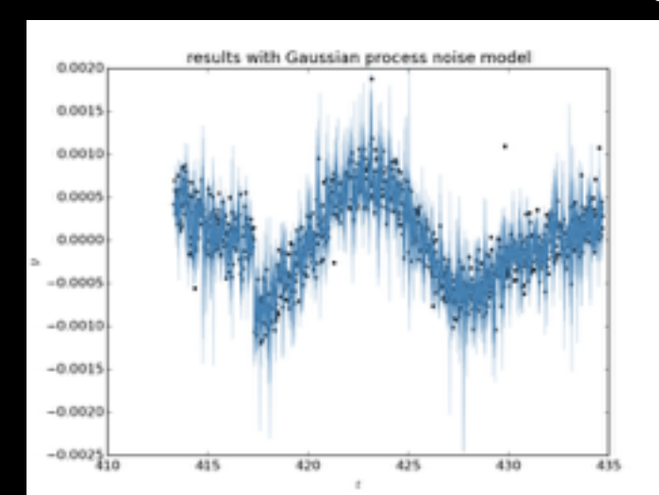
Based on residuals, estimated uncertainties are too *large*

The Detrending Menu

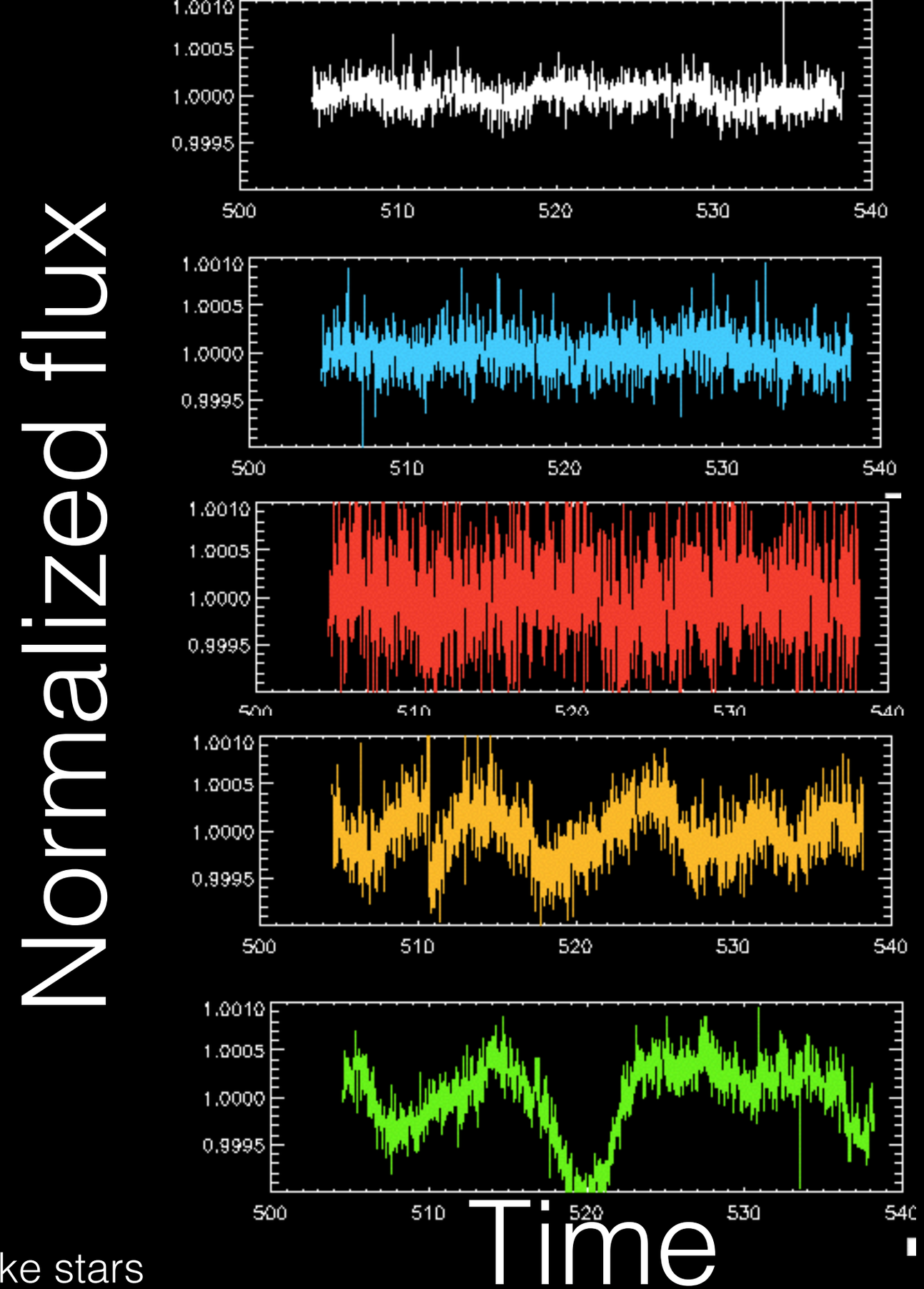
- White noise
- Polynomial trend (order)
- Wavelets (e.g. Carter & Winn 09) (spectral index, family)
- Gaussian processes (kernel), e.g. Ambikasaran+ 14
- Detrending vs. model noise + signal together
- Fit noise from out-of-transit data: discard, prior, simultaneous







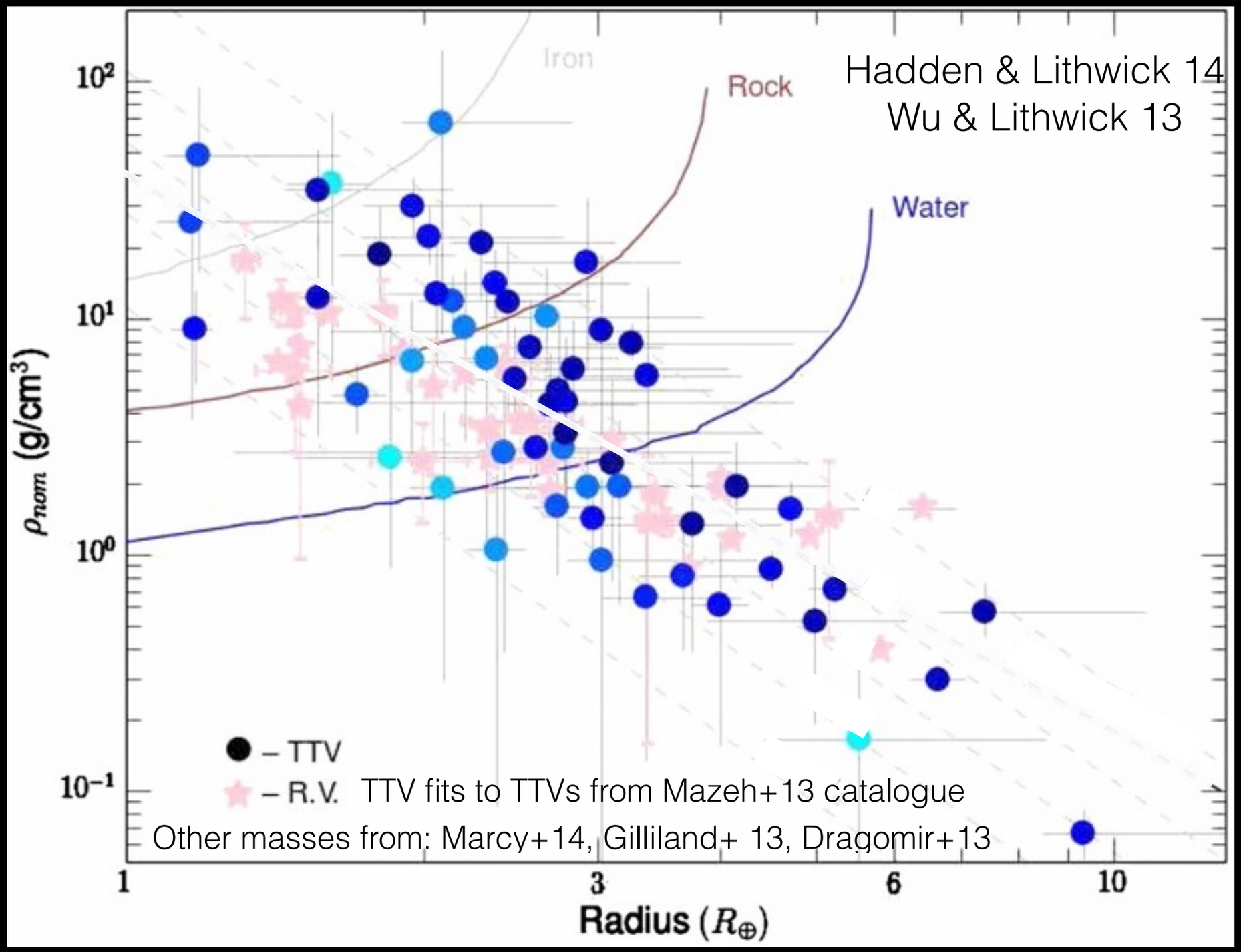
Noise in *Kepler* light curves: a laboratory



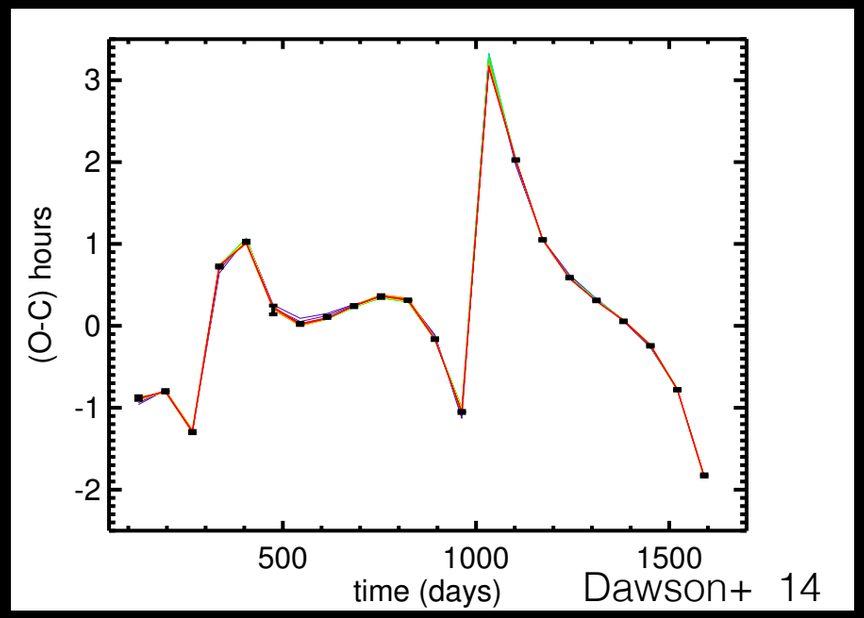
Sun-like stars

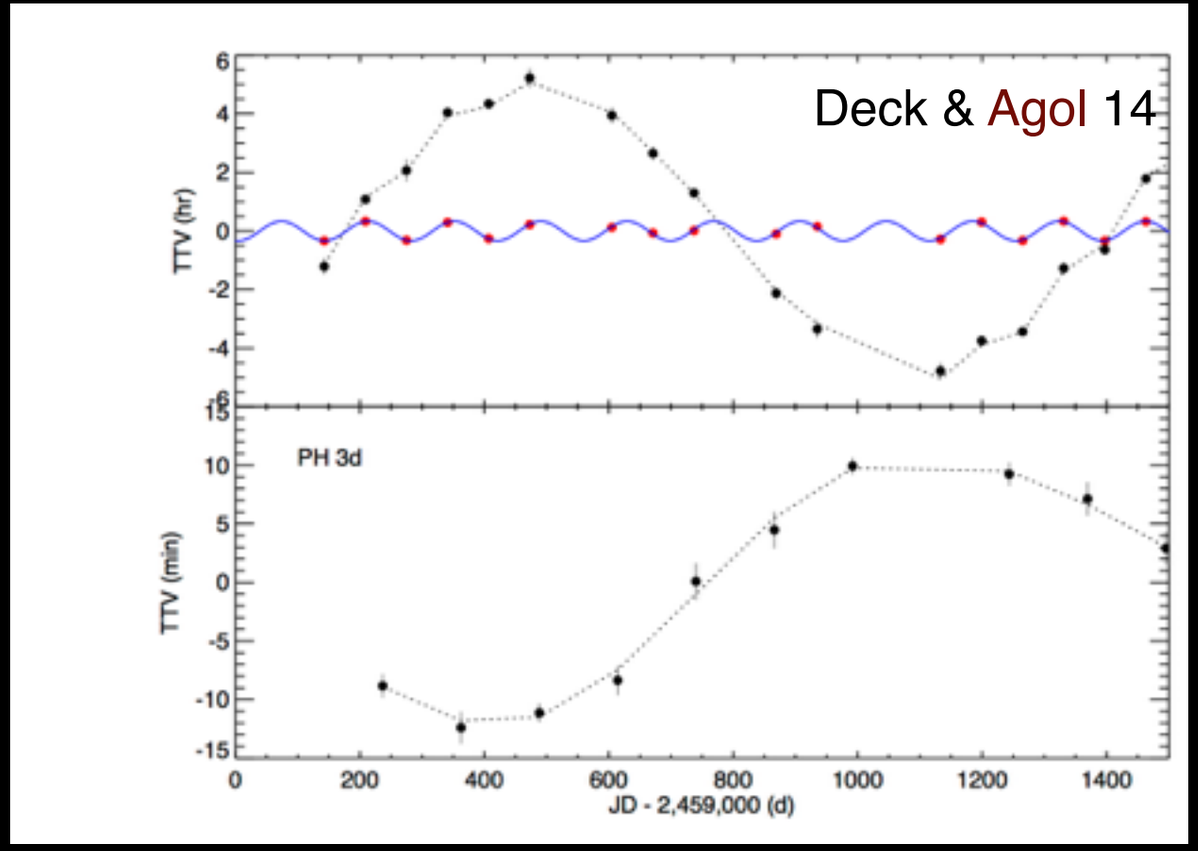
Already corrected by *Kepler* for instrumental systematics using principal component analysis

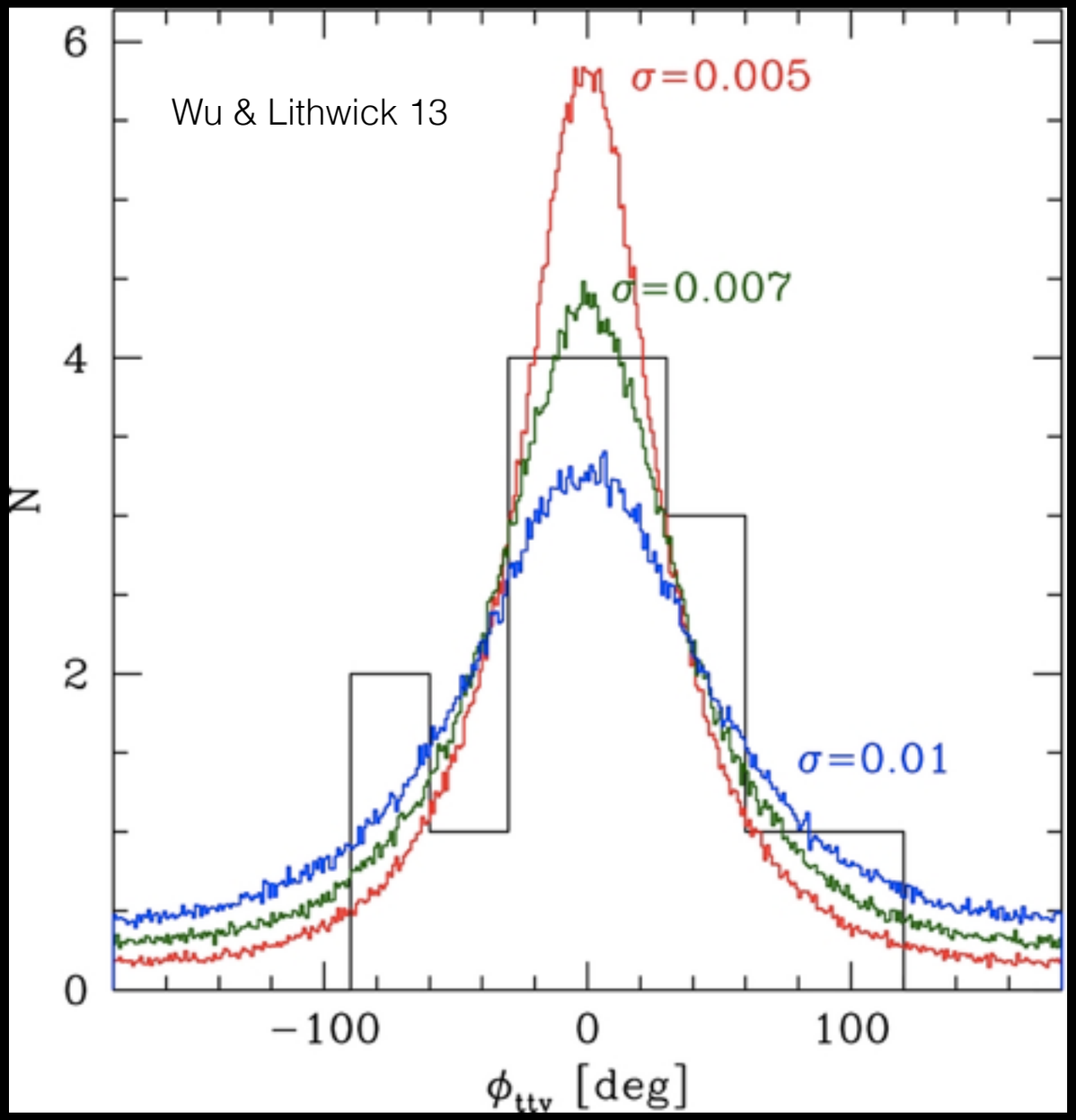
Error bars on this plot *aren't* all dominated by uncertainties in the transit times



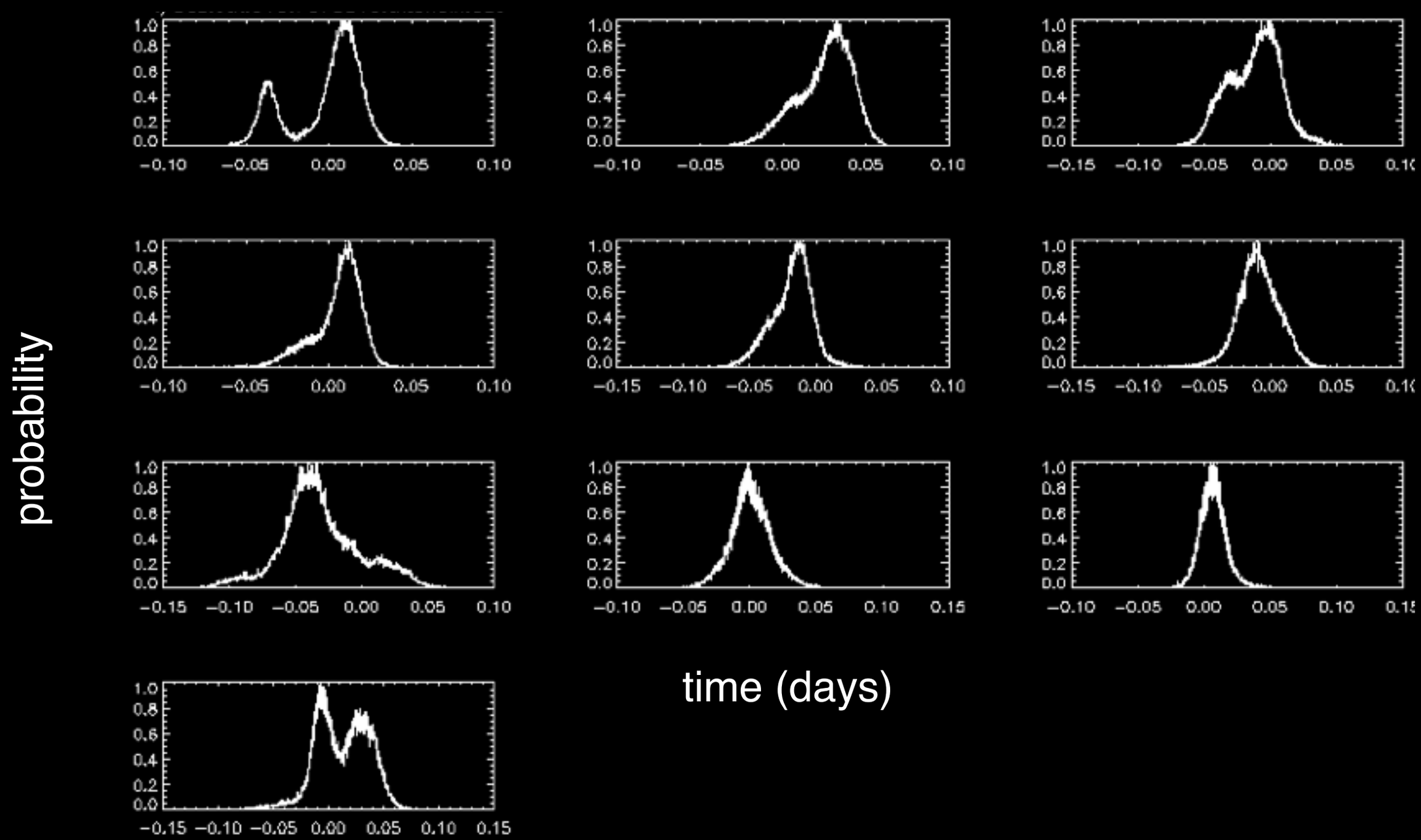
Realistic posteriors necessary for higher order effects and population-wide inferences





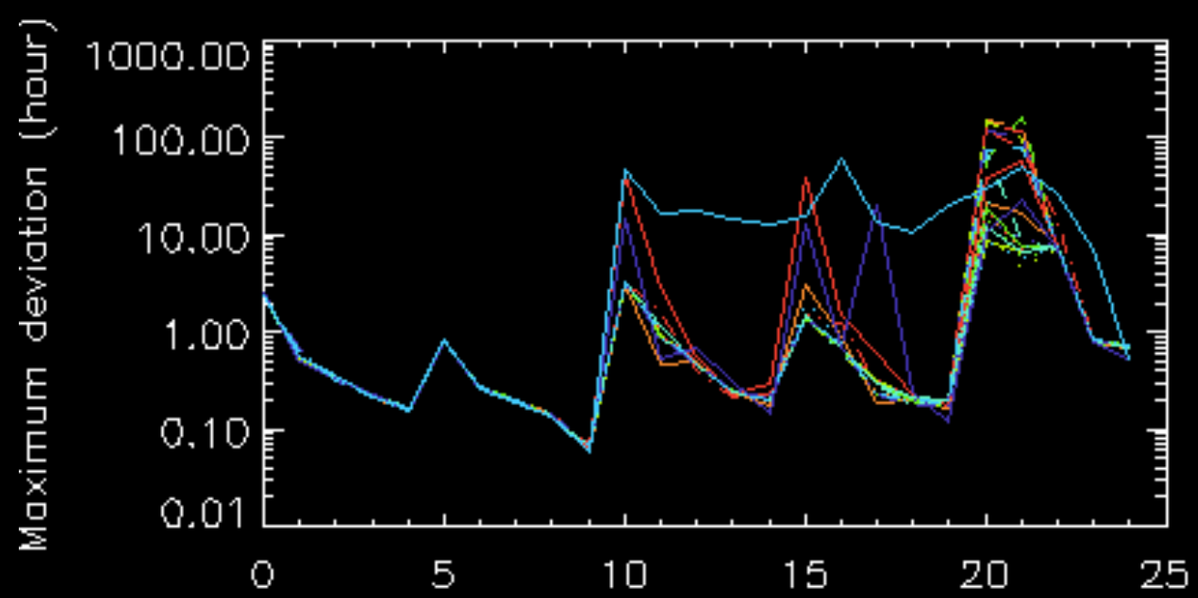


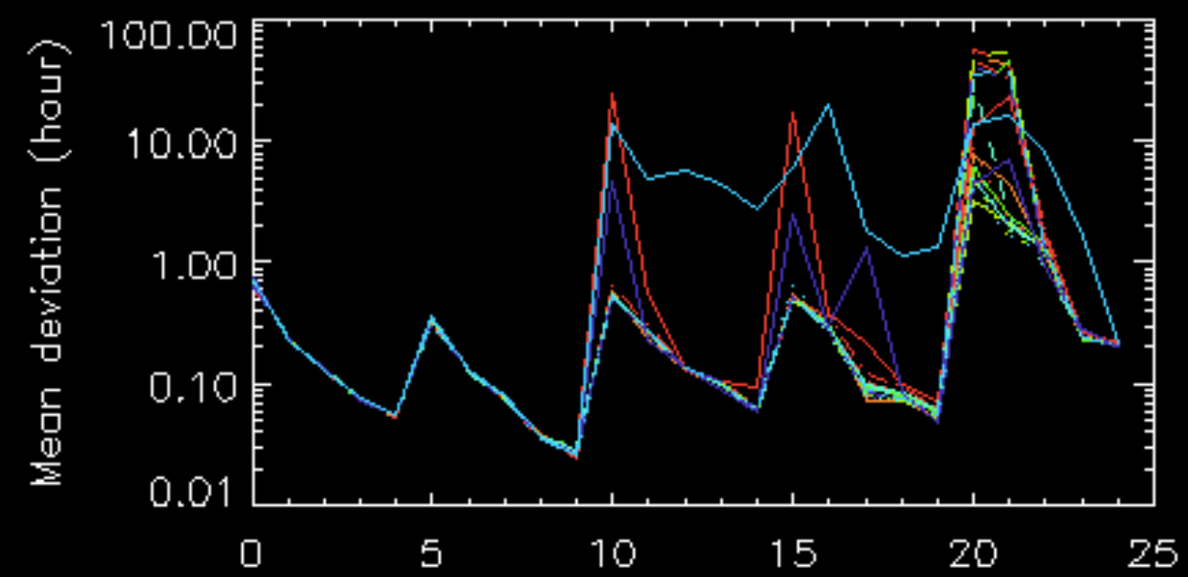
Transit time posteriors can be multi-modal



See also, Catalogue of TTV posteriors: Montet+ in prep.

Precision: how close is the time to what we injected?



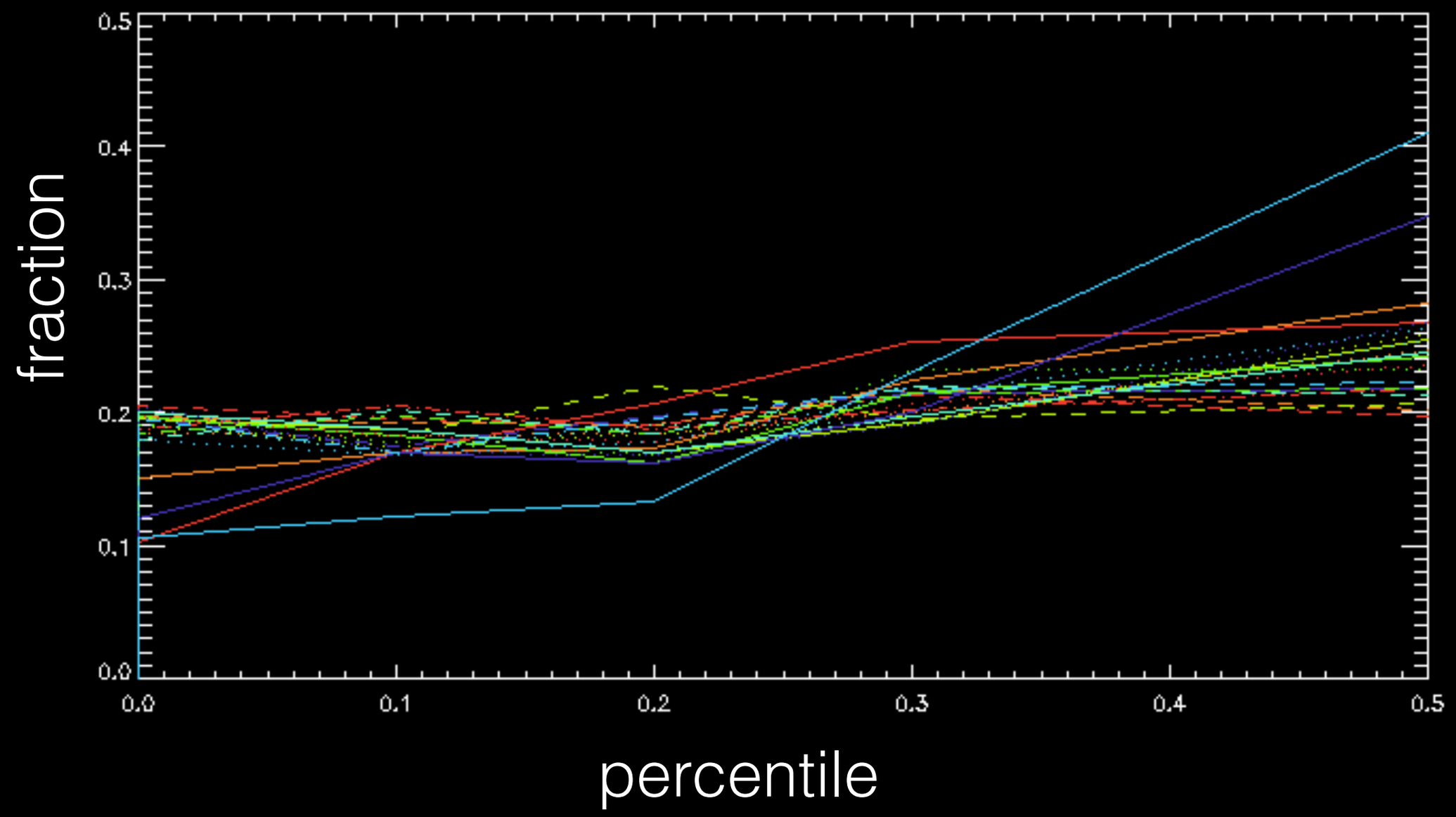


Signal Type

Poor recovery: White noise only, wavelets only, wavelets only

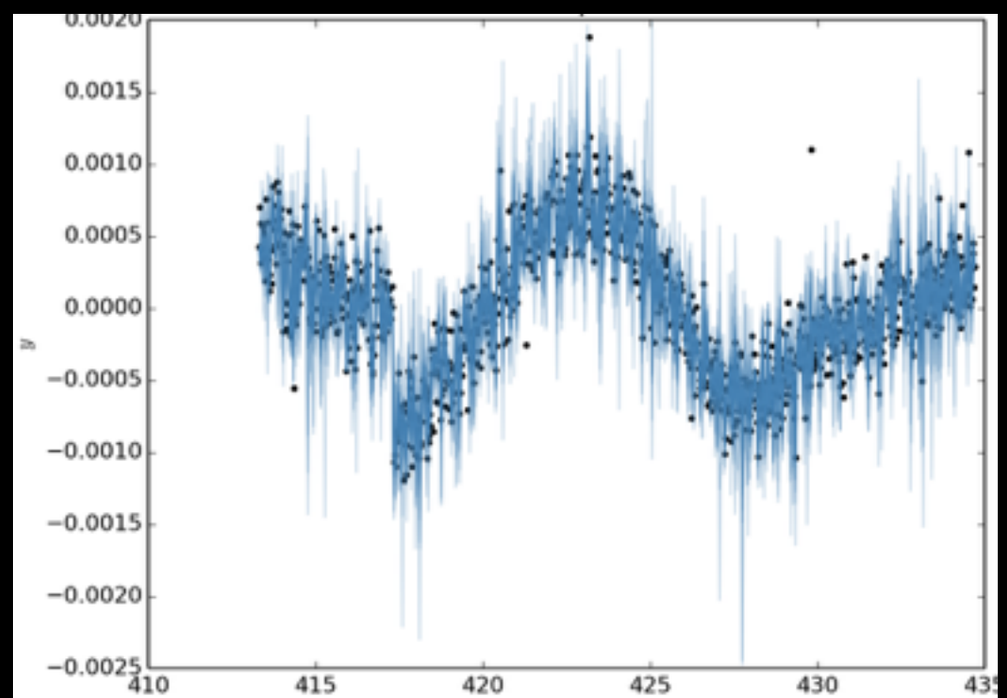
Accuracy: are the probabilities of the true times consistent?

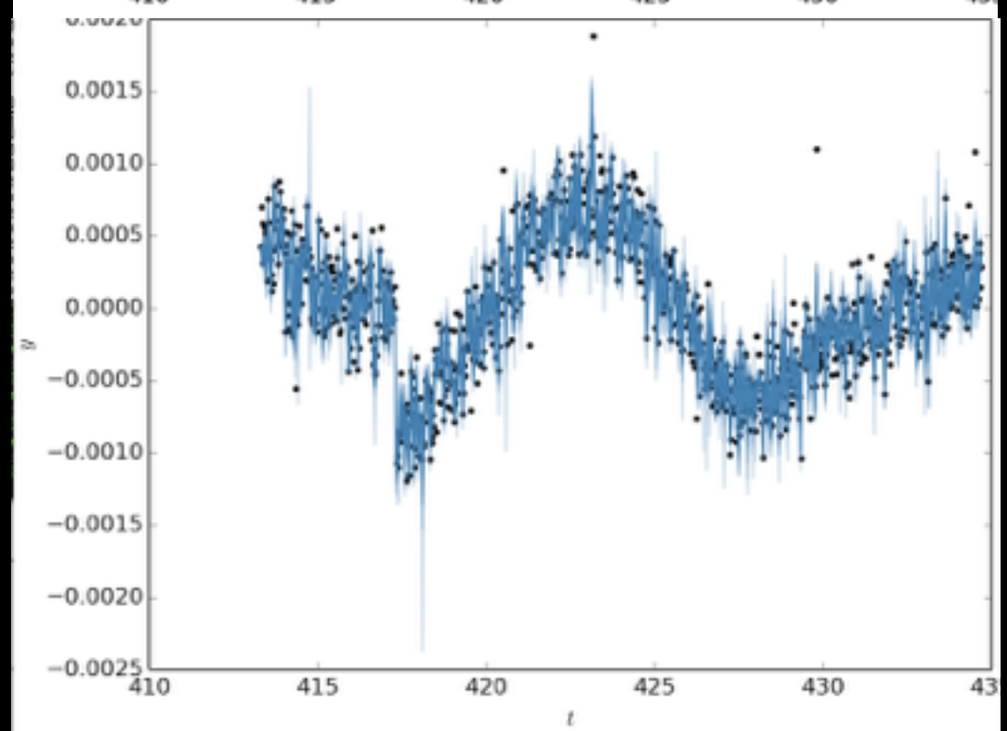
Only for linear trends fit simultaneously with other noise (dotted)
Otherwise, uncertainties are overestimated

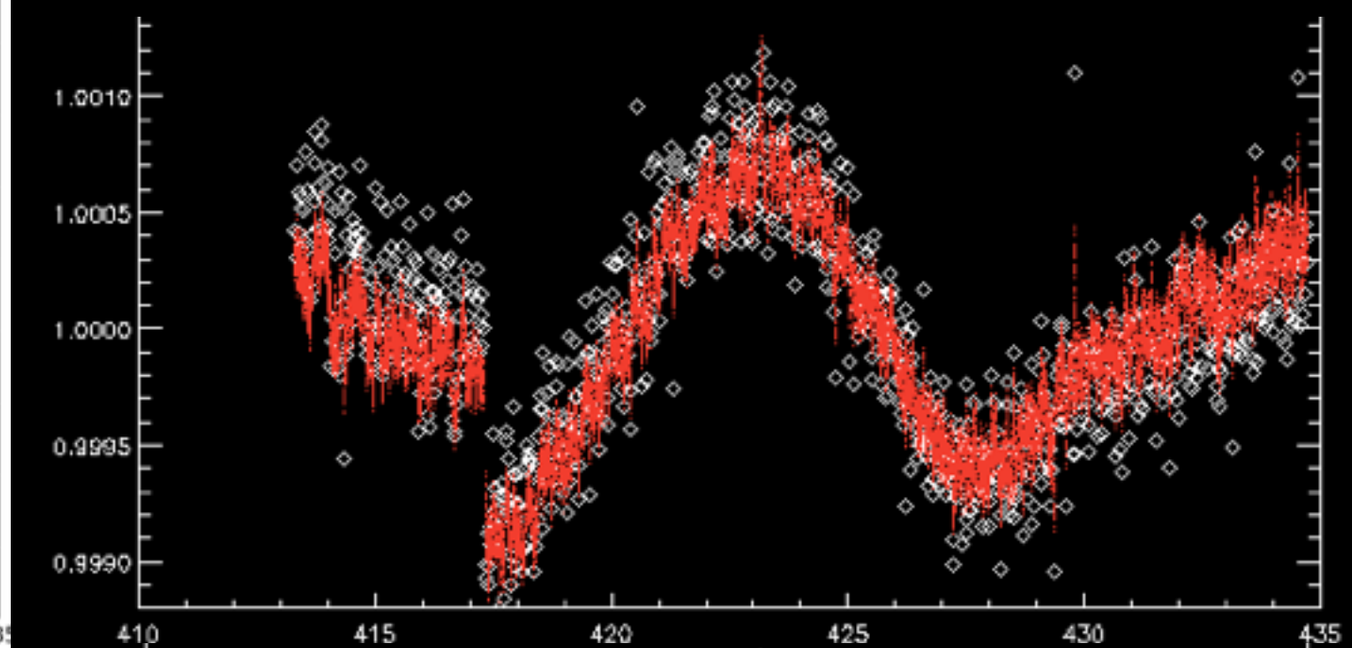


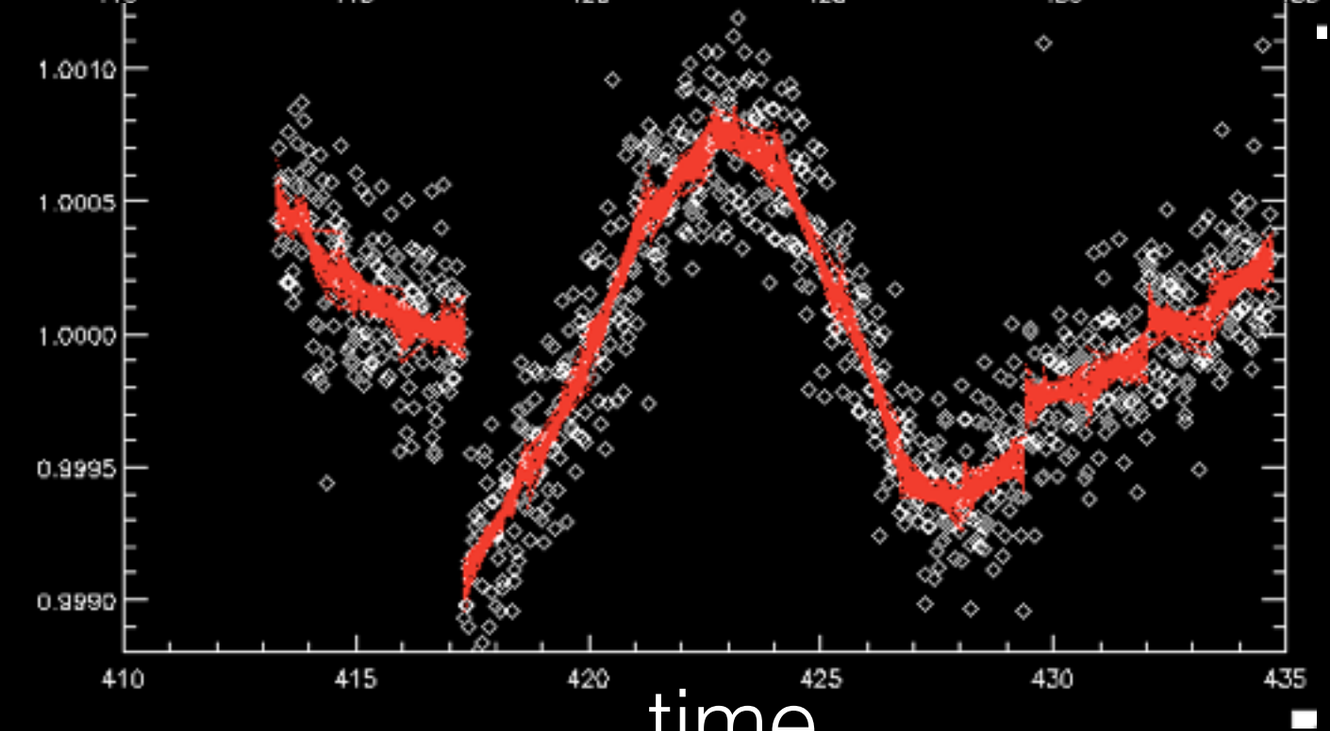
Polynomial component needed to avoid overestimate noise

inferred correlated noise









time

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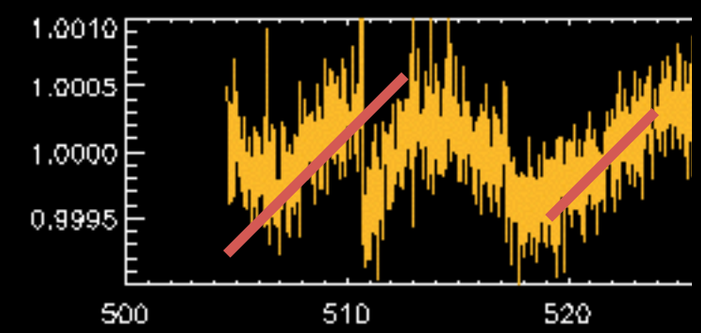
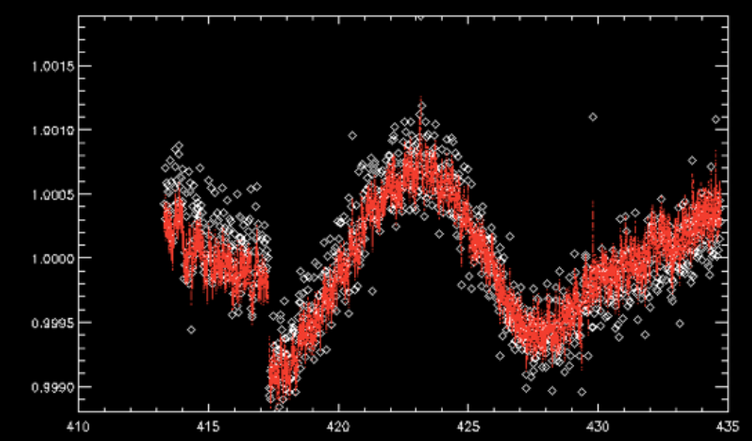
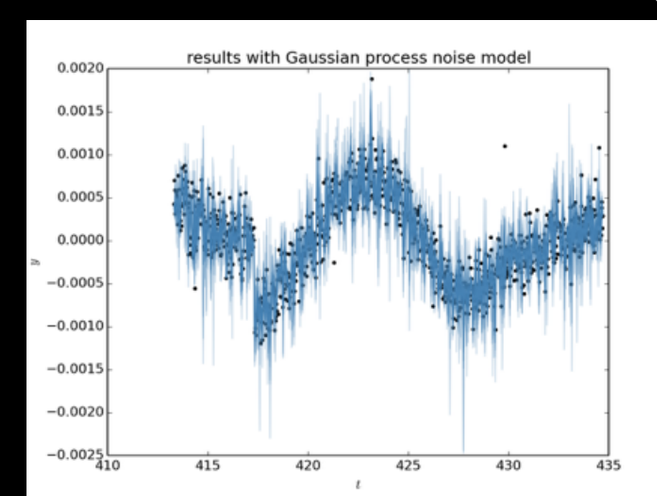
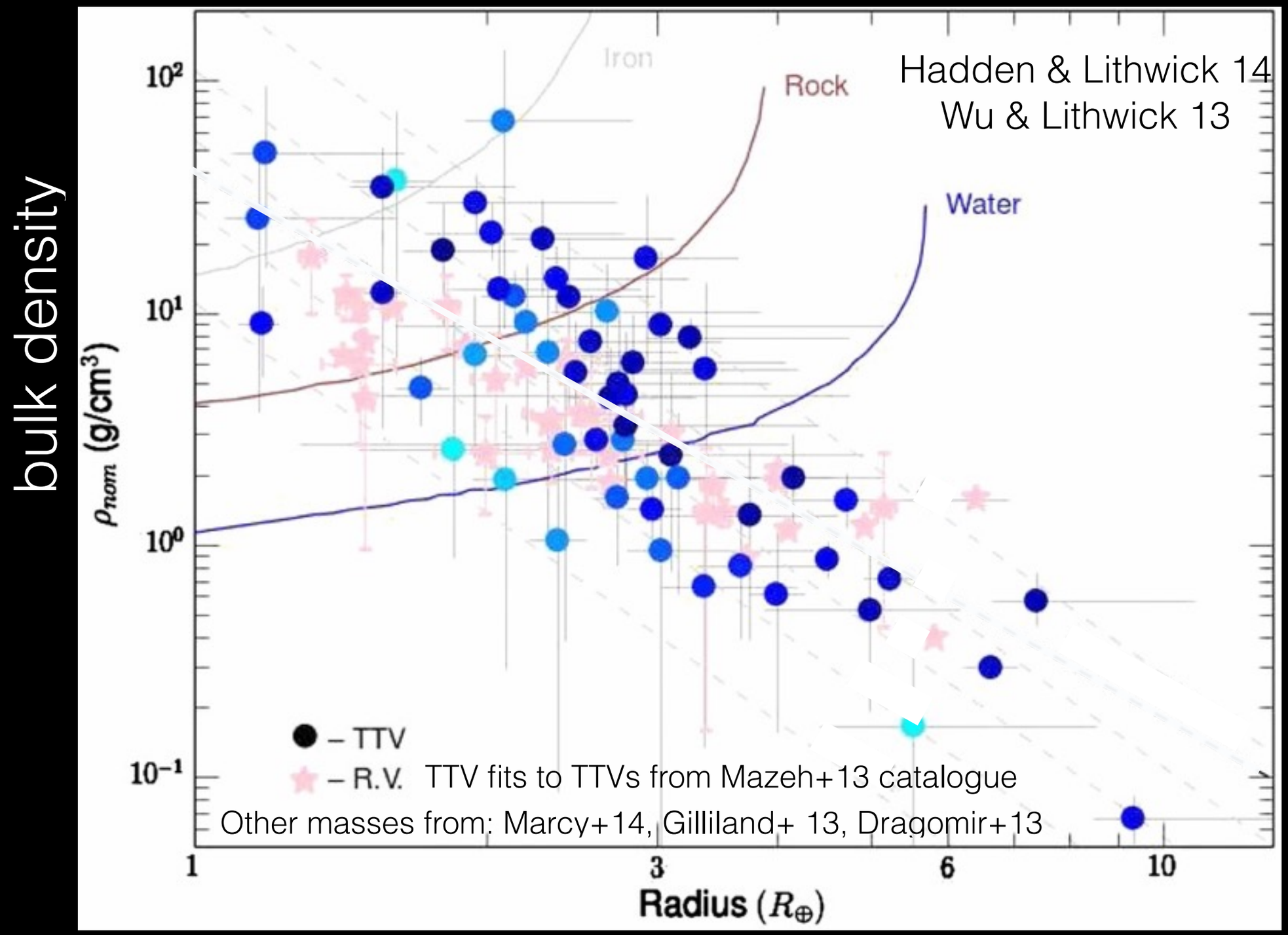






Next step: TTV twins



TTV Planets: Farm to Table

Formation

Discovery

Interpretation

Dynamics

Measurement

Conclusions

- The disk's surface solid density — for which host star metallicity is a proxy — plays an important role in forming super Earths vs. mini Neptunes

- TTV planets do not show evidence of being a special population

- To measure accurate and precise TTV posteriors, white+correlated noise must be modeled simultaneously with planet signal