Demography of planetary systems

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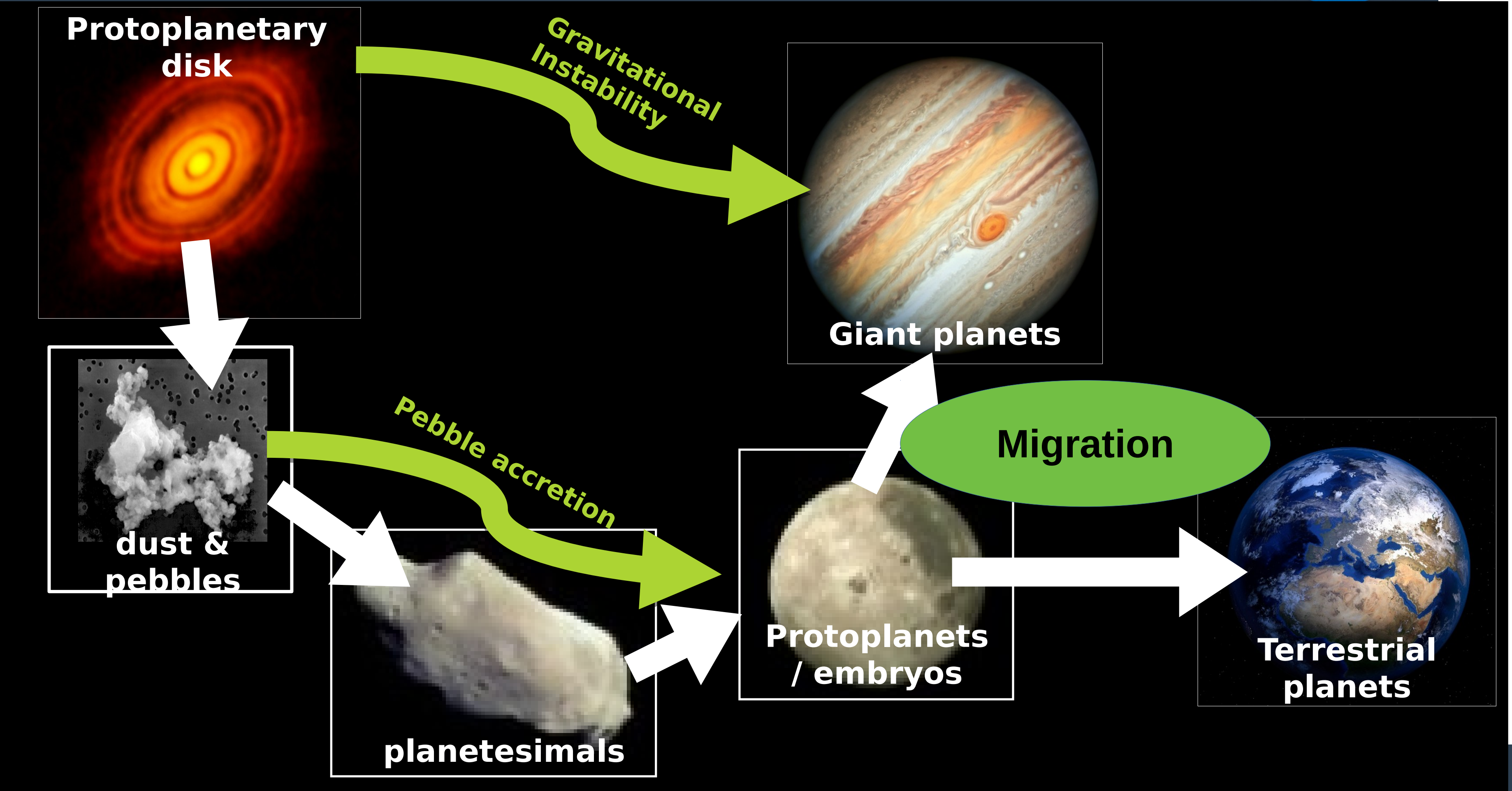
Content

- Planet Formation
- Exoplanet Demographics
- Planetary population synthesis
- Exoplanetary radius valley

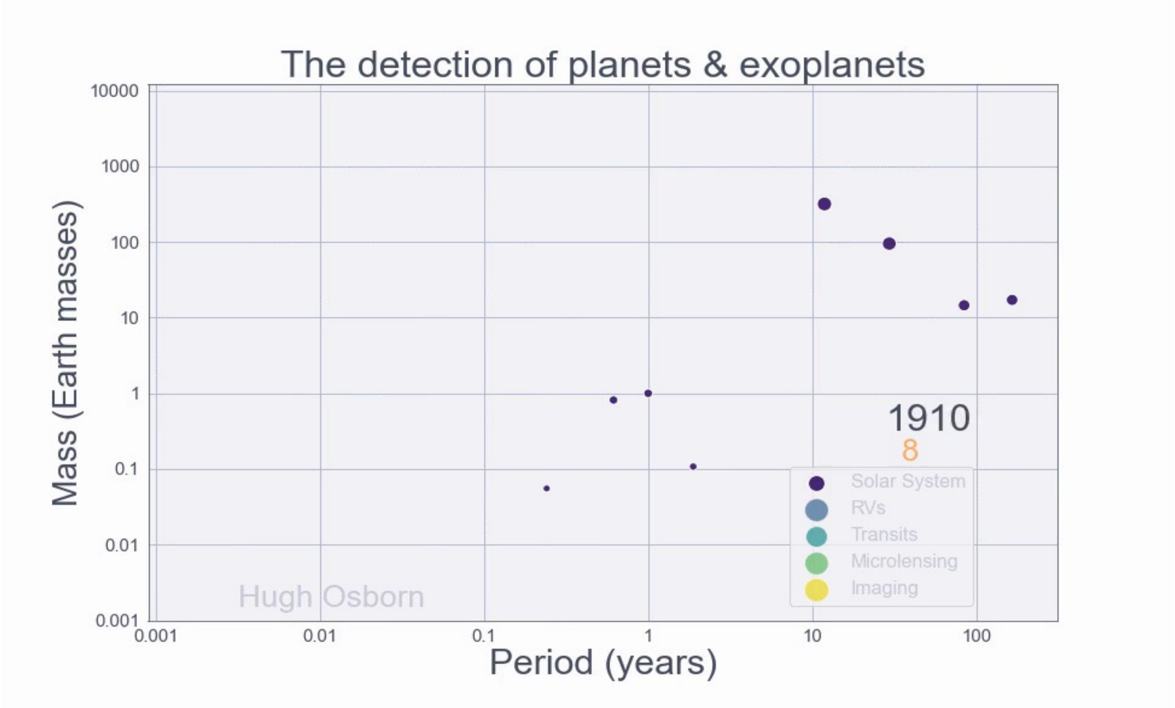
Credits: NASA, ESA, M. Hutchison

Planet Formation Overview



Exoplanet Demographics

- **Thousands of discoveries**
- **Enables Statistical studies**



Exoplanet Demographics

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    - Neptunian desert / hot-Neptune desert
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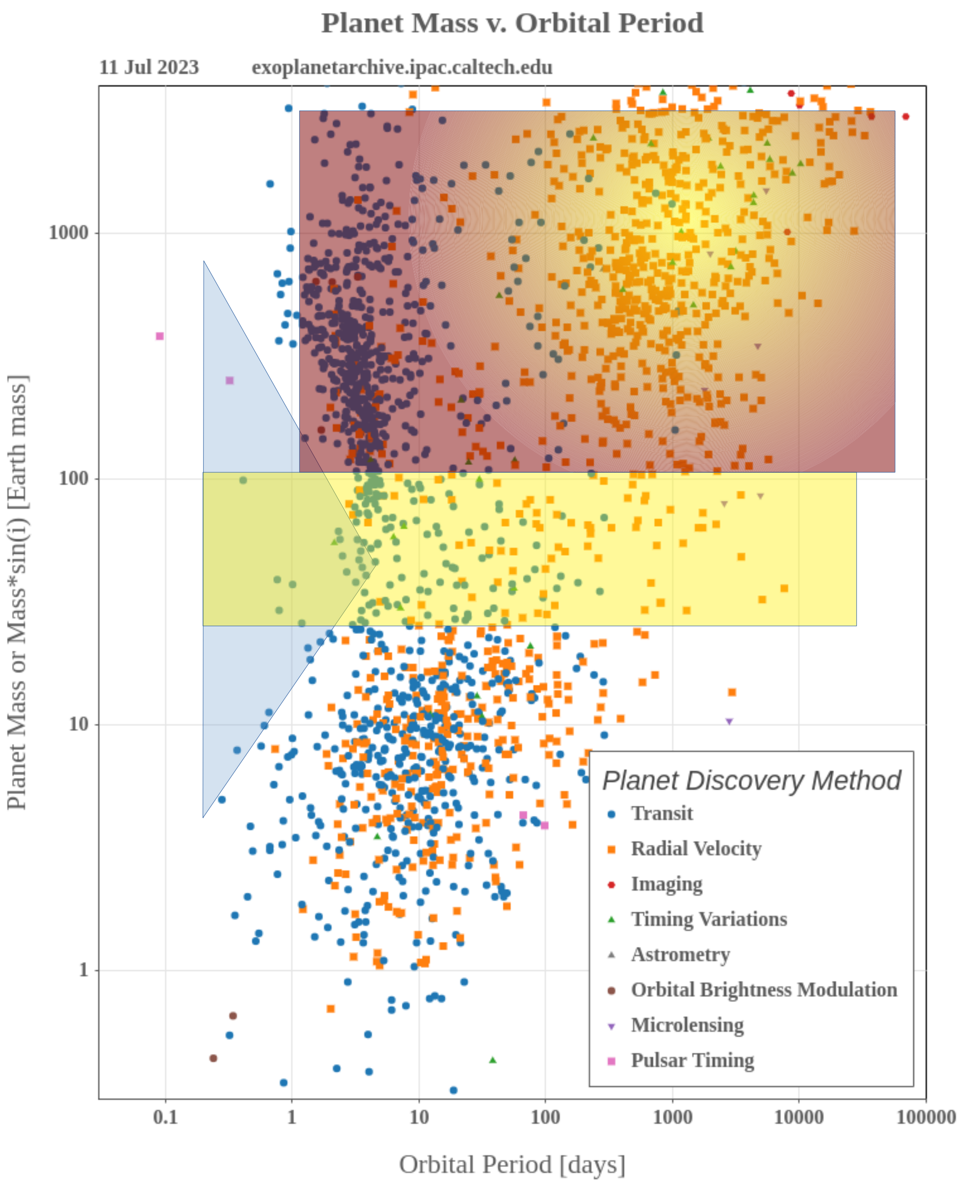
  - Hot Jupiter/Cold Jupiters (Mayor&Queloz 1995)
    - Turnover at iceline (Suzuki+ 2016,Pascucci+ 2018, Fernandes+ 2019)



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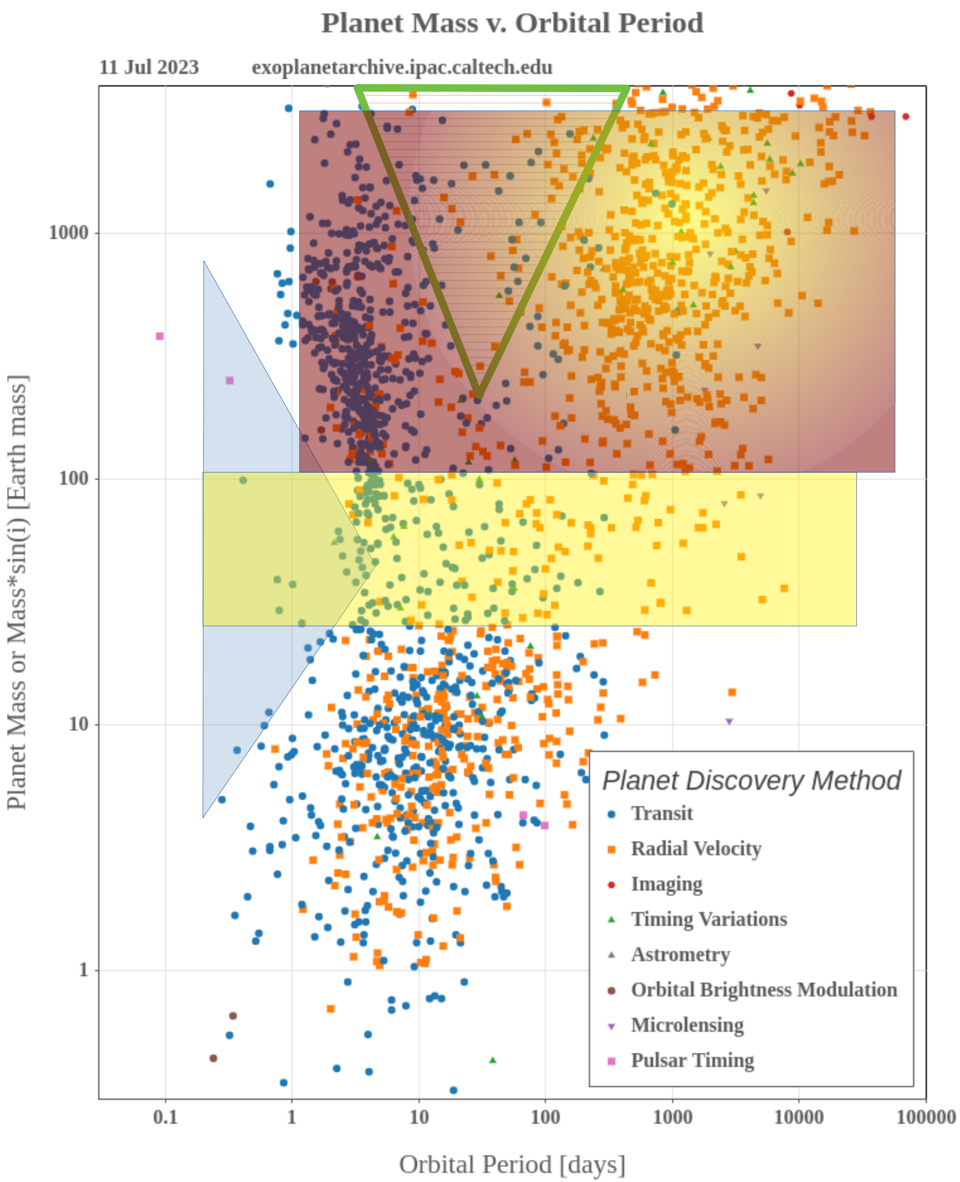

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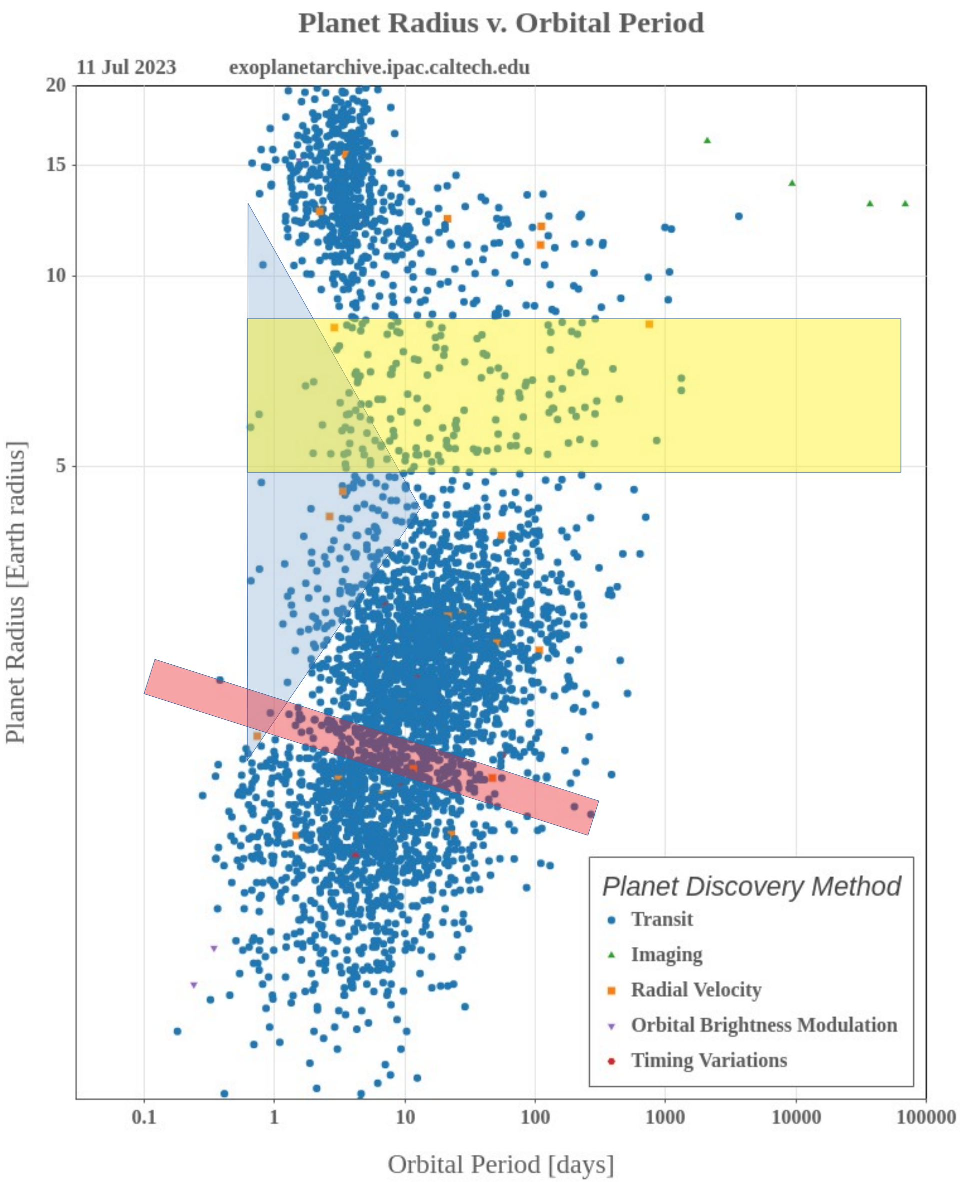
  - Radius Valley (Fulton+2017)
    - Slope with stellar mass & orbital period/irradiation?



Exoplanet Demographics

- **Trends**
  - with stellar [Fe/H]
    - Increasing with giant planet incidence (e.g. Santos+2001)
    - Relatively flat for Earth-type planets (Buchhave+2013)
    - Eccentricity of giant planets increases (Dawson+2013)

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    - Relatively flat for Earth-type planets (Buchhave+2013)
    - Eccentricity of giant planets increases (Dawson+2013)
  - with stellar mass
    - Increasing giant planet occurrence (Endl+ 2006, Butler+ 2006, Gaidos+ 2013, Ghezzi+ 2018, Jordán et al. 2022)
    - But exceptional giants around late M dwarfs exist (Sabotta+2021, Bryant+2023)

Exoplanet Demographics

- **Characterization stage: Compositional statistics**
  - Over-density of water-worlds (Luque&Palle 2022)

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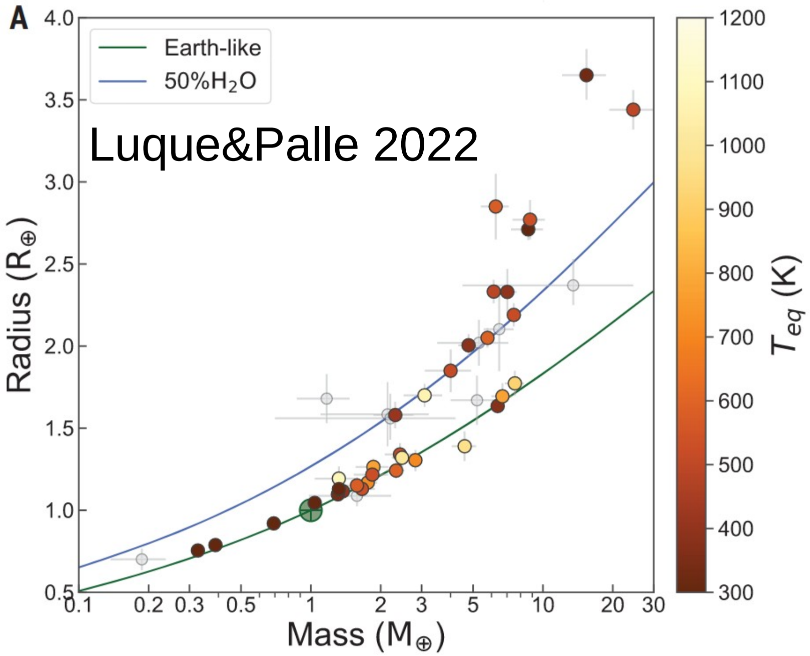

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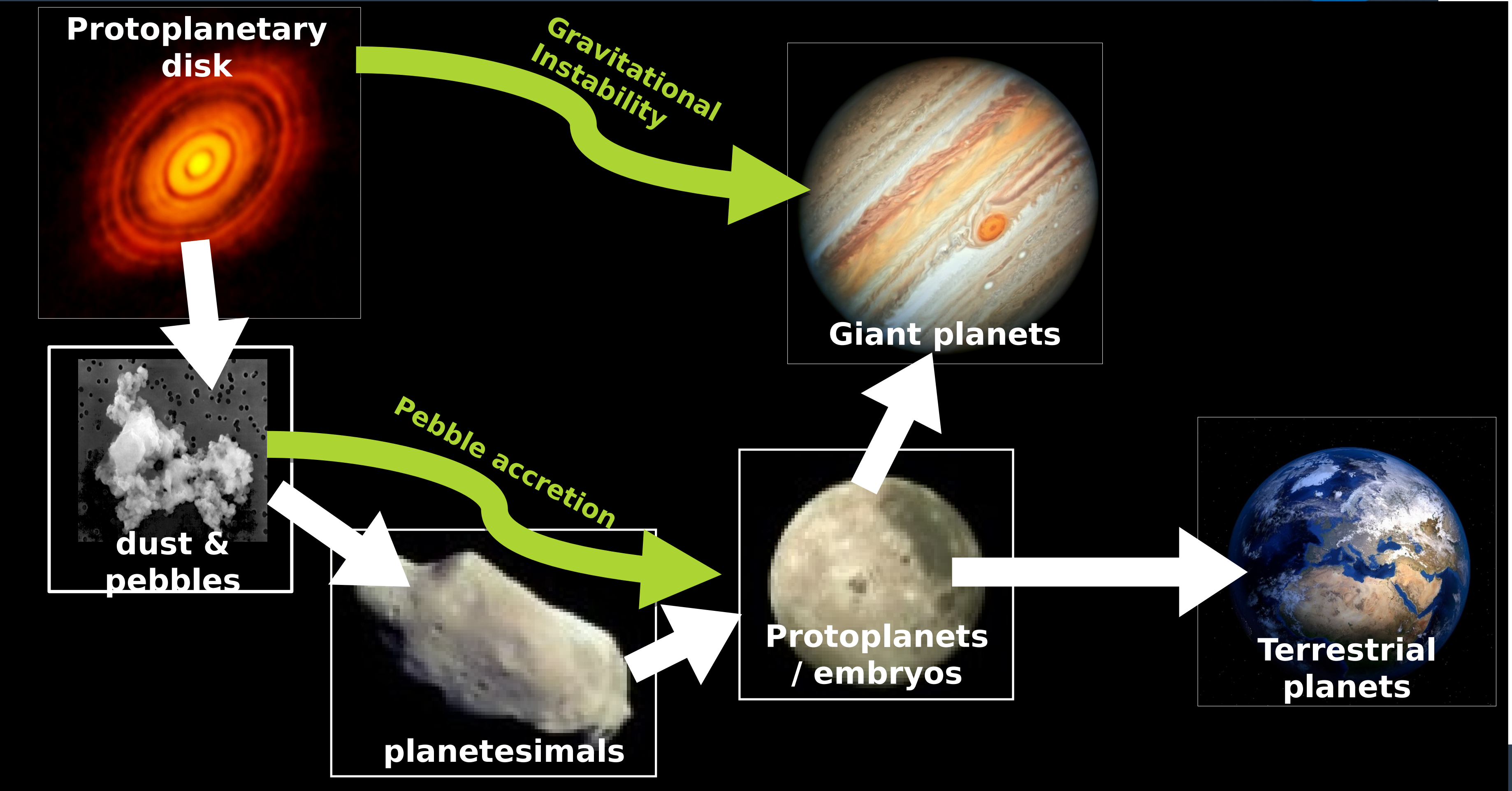

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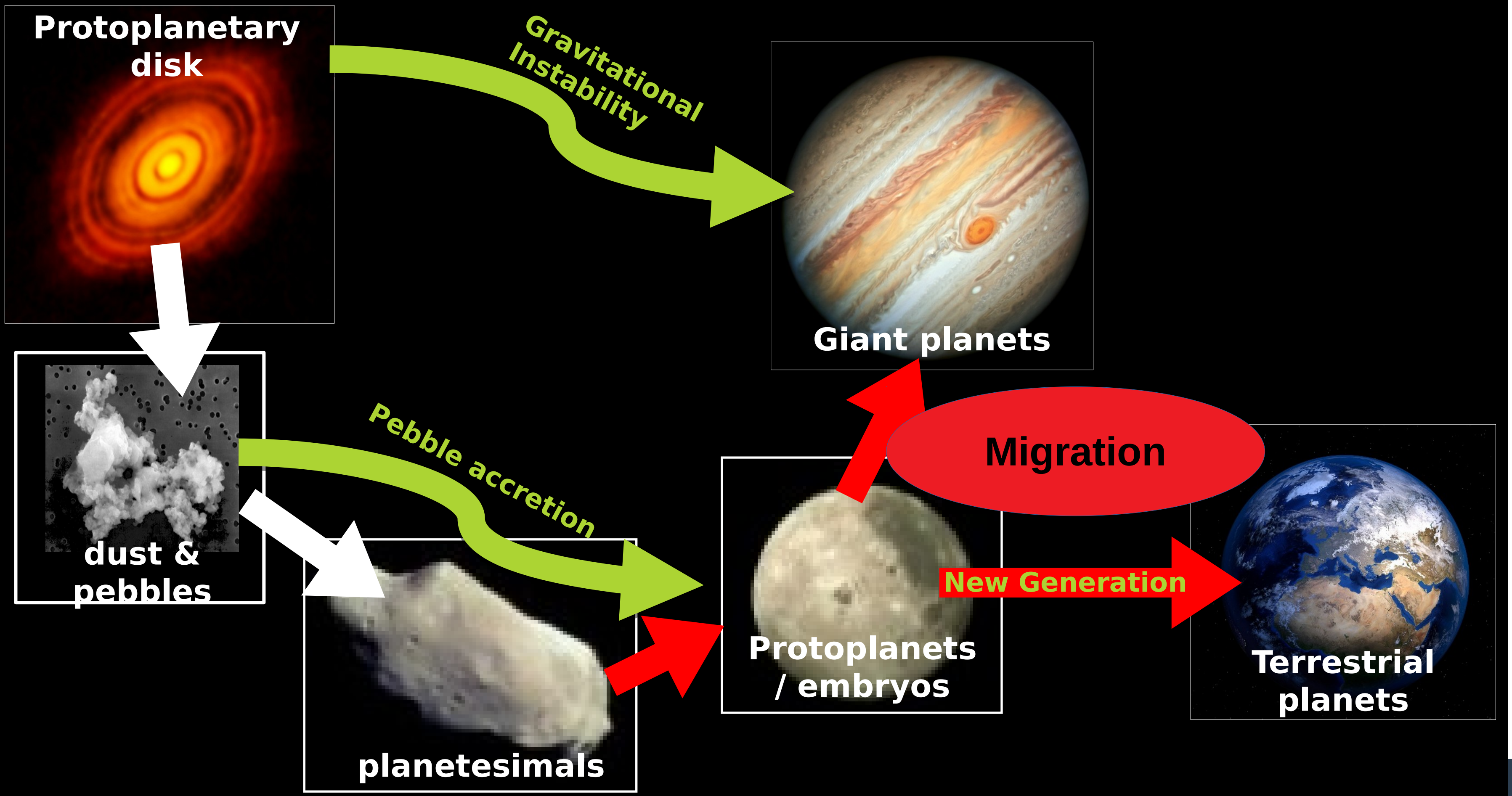

Planetary Population Synthesis

- **Connects observed disks with observed planets via formation models**
- **New generation of simulations**
  - Emsenhuber+ 2021 (a,b), Schlecker+ 2021 (a,b), Burn+ 2021
  - Start with already formed, small planetesimals and moon-sized embryos in smooth disks
  - Single stars
  - Global models including evolution of planets

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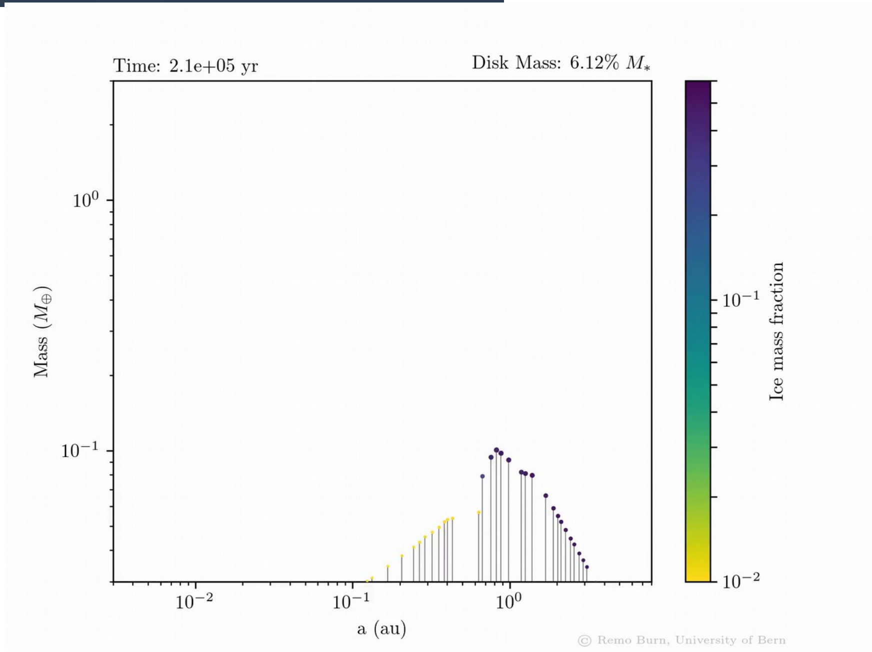
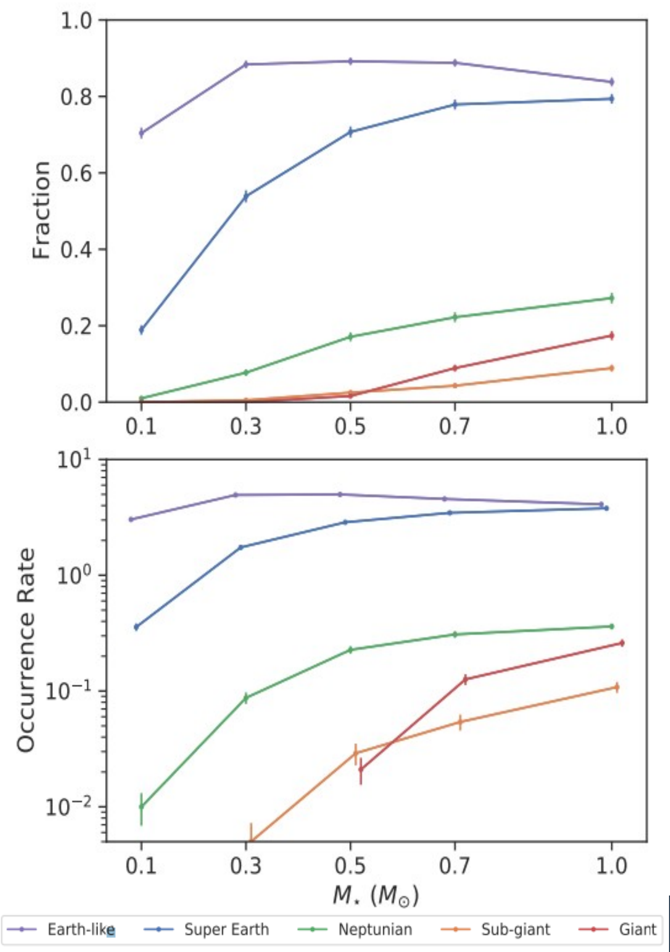


Planetary Population Synthesis

- **Trends with stellar mass**
  - Qualitative agreement with observations
  - Tens of percent chance for each star to host a planet in the habitable zone

Burn+ 2021



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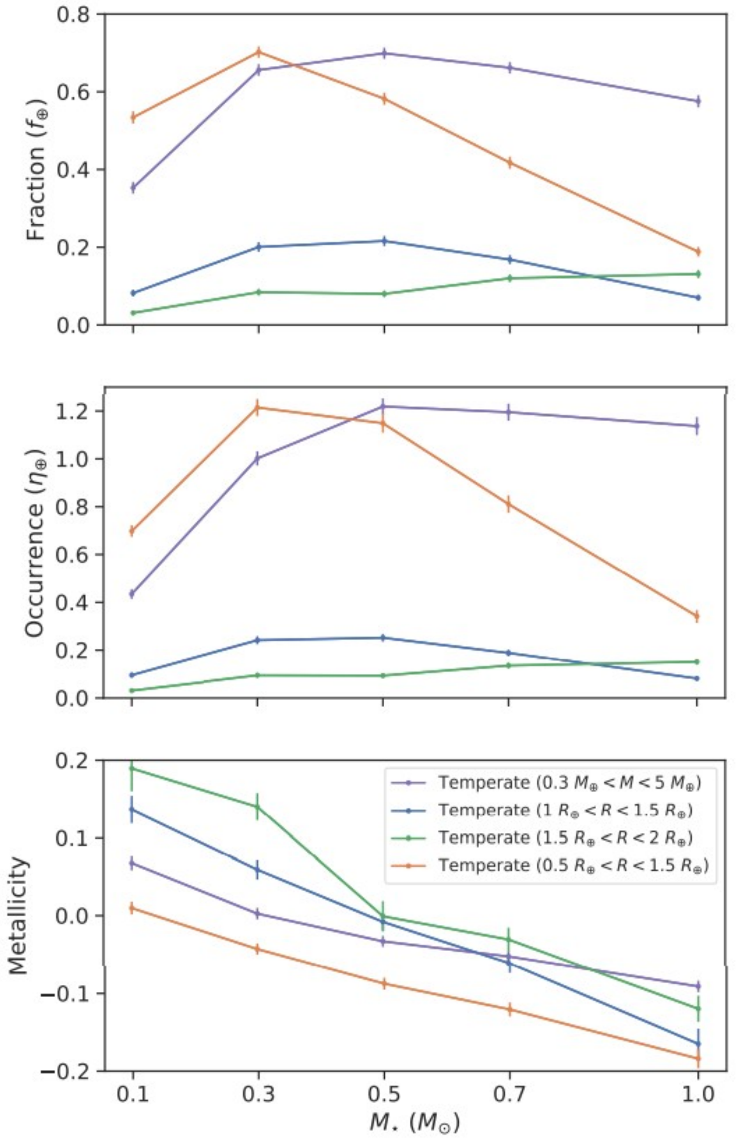
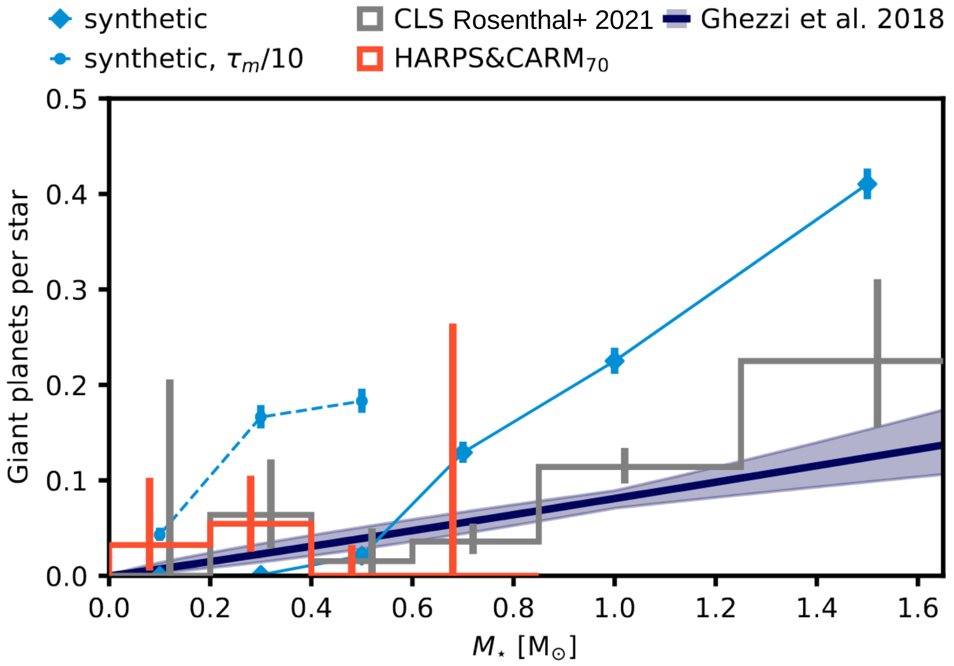


Planetary Population Synthesis

- **Giant Planets exist around low-mass stars**
  - Not predicted by standard models
    - zero giants for stellar Masses < 0.3 solar masses
  - Not necessarily a mass problem → Reduced/inhibited migration allows for some giant planet formation



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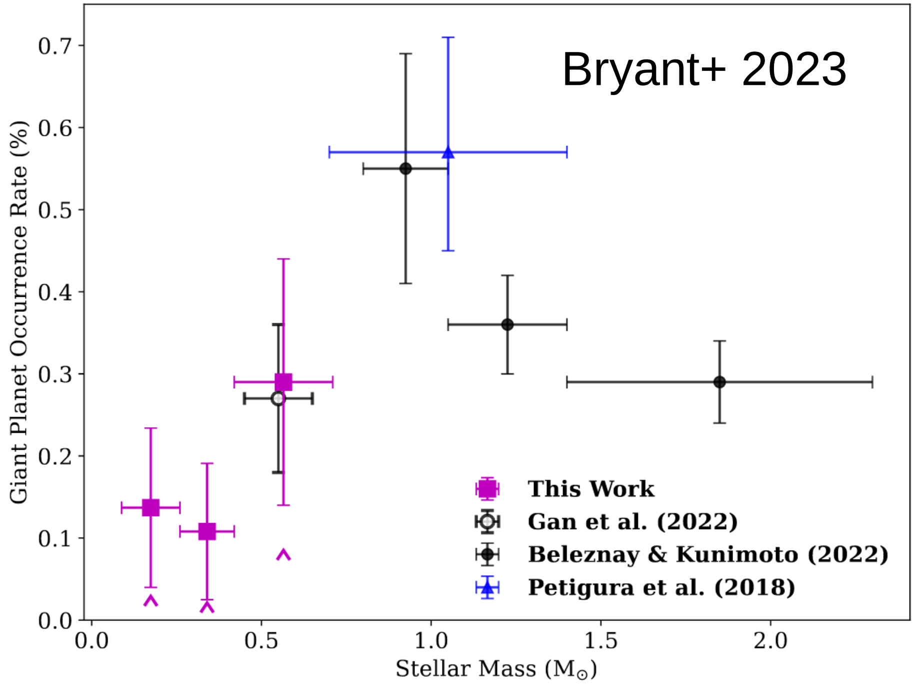
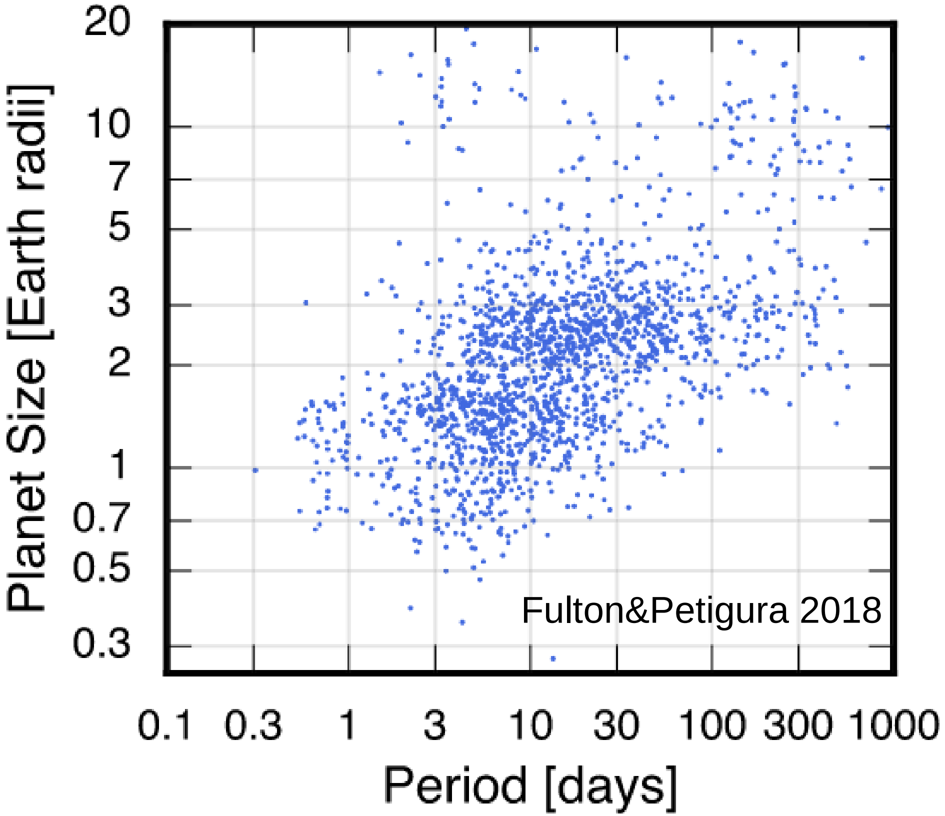


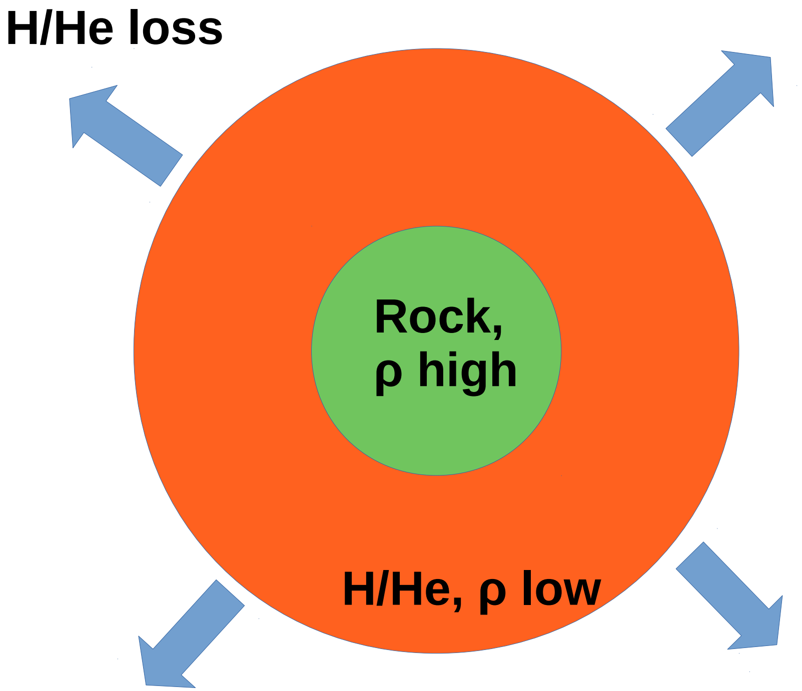
Radius Valley

- **Observed radius valley (Fulton+2017,2018)**
- **Observational constraints**
  - Inconclusive direct evidence He absorption (Kasper+2020, Zhang+2022), H_2O detection (Benneke+2019)
  - Indirect evidence for water worlds (Diamond-Lowe+2022, Luque&Palle 2022, for M stars)
- **Mass loss process can shape the valley (core- or XEUV-powered, e.g. Owen 2019 for a review)**



Radius Valley

Possible sub-Neptune

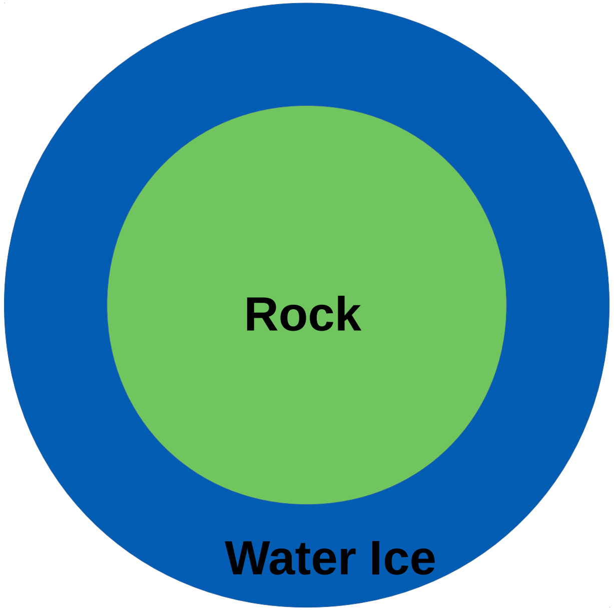


Orbital Migration

- **Indications for orbital migration of planets**
  - (near-)resonant systems
  - super-Earth formation
  - theoretical necessity
- **Leads to water world formation**

Radius Valley

Possible sub-Neptune?

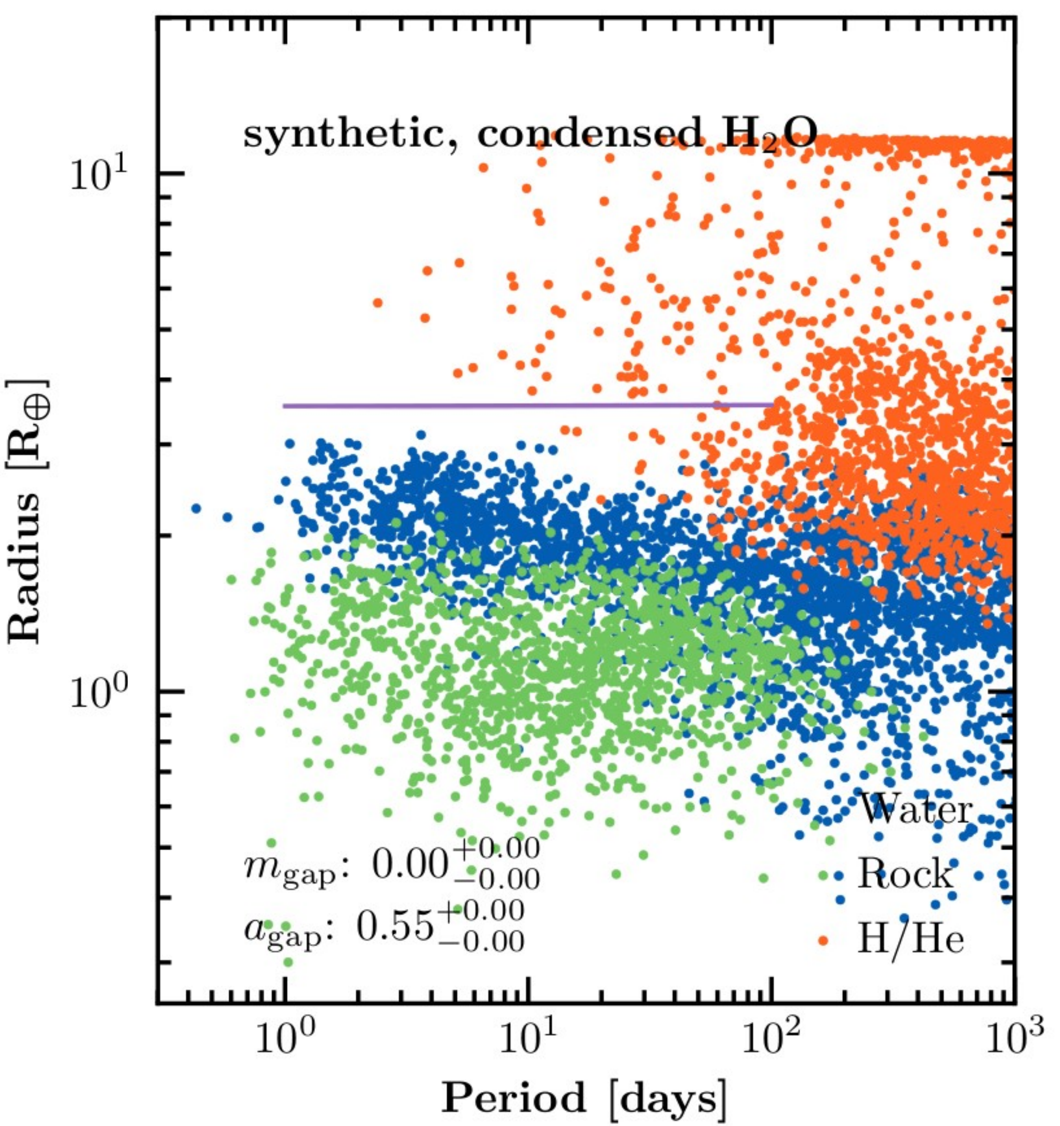


Methods

- **Solar-type star**
- **Formation (Emsenhuber+2021)**
  - planetesimal-based solid accretion
  - N-body interactions (N_{ini}=100, calculated for 100 Myr)
  - Giant impacts
    - Impact stripping
  - Orbital migration
  - Consistent gas accretion with 1D internal structure calculation
- **Evolution**
  - Cooling & contraction with initial stage given by formation
  - **Atmospheric escape of H/He mixture (Kubyshkina & Fossati 2021)**
  - Stellar evolution in X-ray and bolometric luminosity
  - **Interior structure with rock and condensed ice (Seager+2007)**
  - Tidal orbital decay
- **Apply observational Kepler bias**
  - KOBE, Mishra+2021

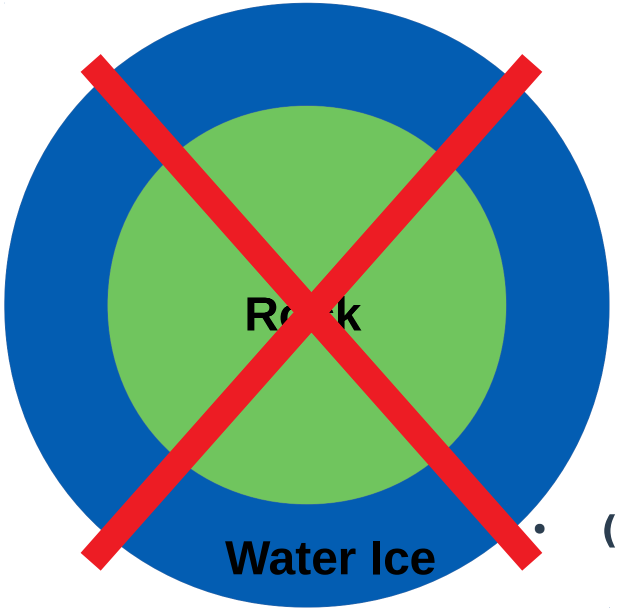
Results

- **Condensed H_2O**
- **Valley at wrong location (3-4 Re)**
- **Depends on mass distribution**



Radius Valley

Impossible sub-Neptune



- (see also Jin&Mordasini 2018)

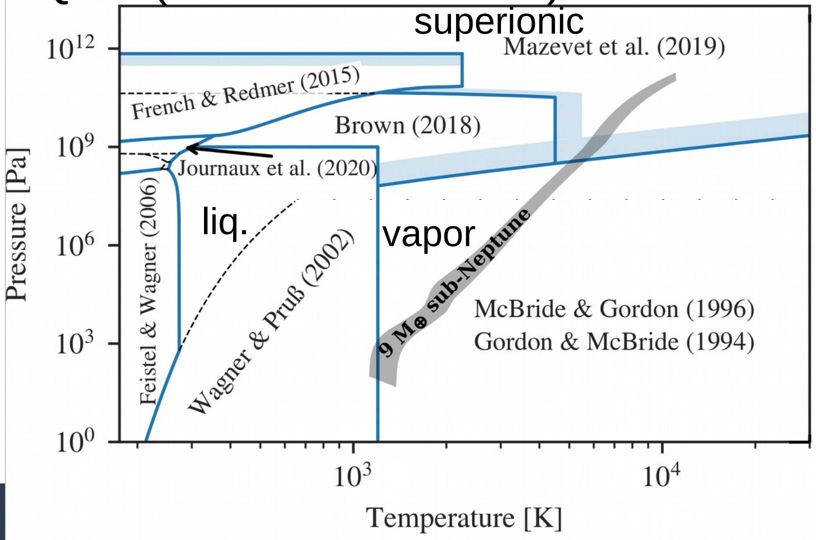
Phases of water

- **Expect vapor interior to runaway greenhouse limit (e.g. Boukrouche 2021)**
- **Water in close-in sub-Neptune is in supercritical vapor and superionic fluid state**

$$a_{\text{runaway}} = \sqrt{\frac{(1-\alpha_{\text{al}})L_\star}{16\pi I_{\text{OLR}}}}$$

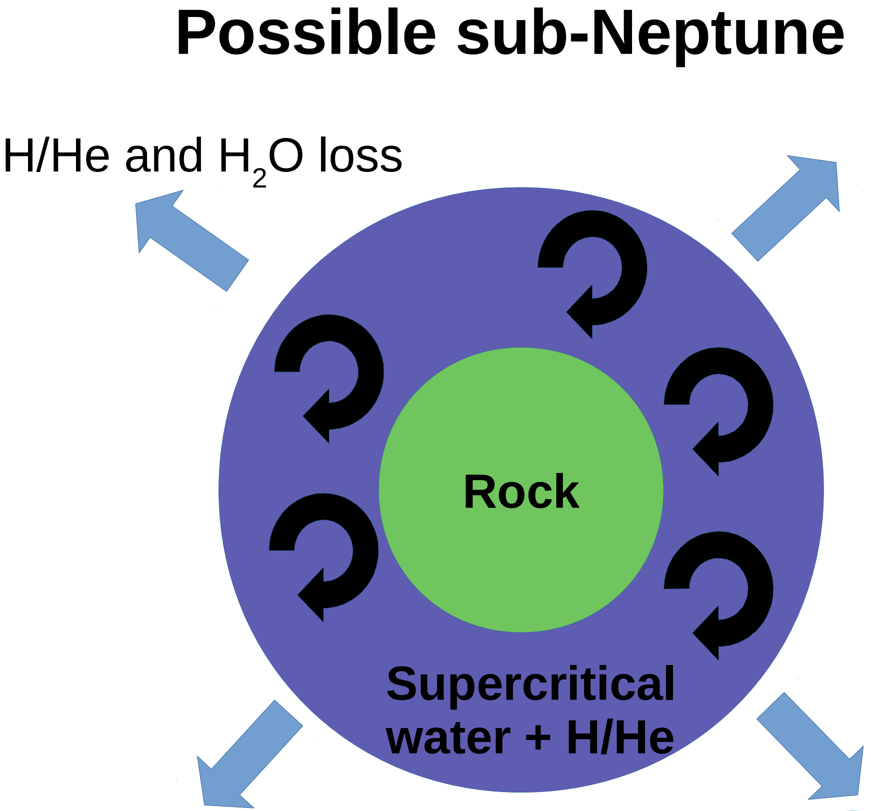
$$I_{\text{OLR}} = 281\,\text{W}\,\text{m}^{-2}$$

AQUA (Haldemann+2020)



Radius Valley

- **Water should be in steam atmospheres (Turbet+2019)**
  - Could also explain the valley (Zeng+2019,Mousis+2020, Venturini+2020)
  - (Partial) Mixing with H/He is expected (Pierrehumbert 2022)
- **Can a uni-modal planet mass distribution reproduce the observed valley if there are steam atmospheres?**



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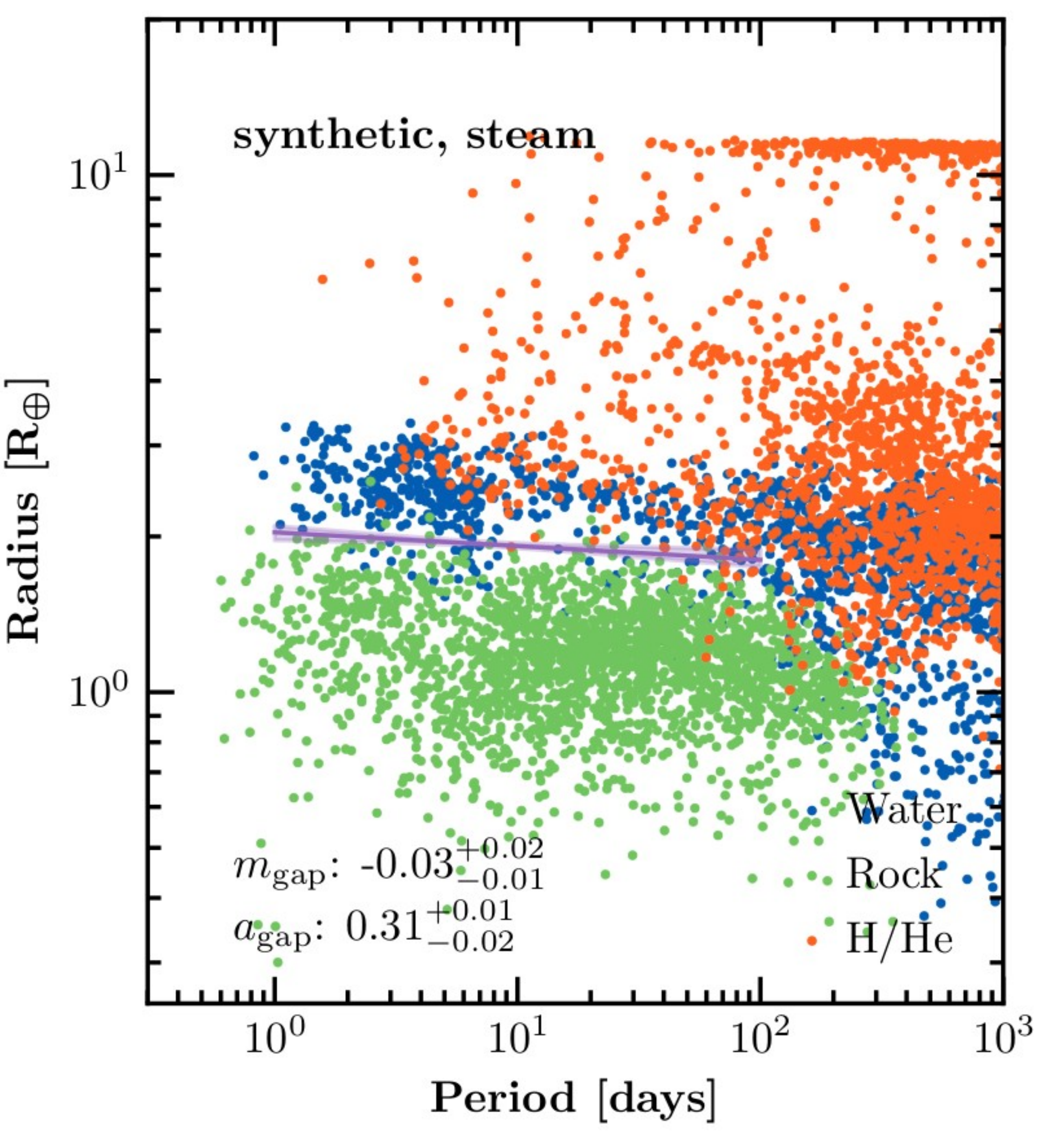
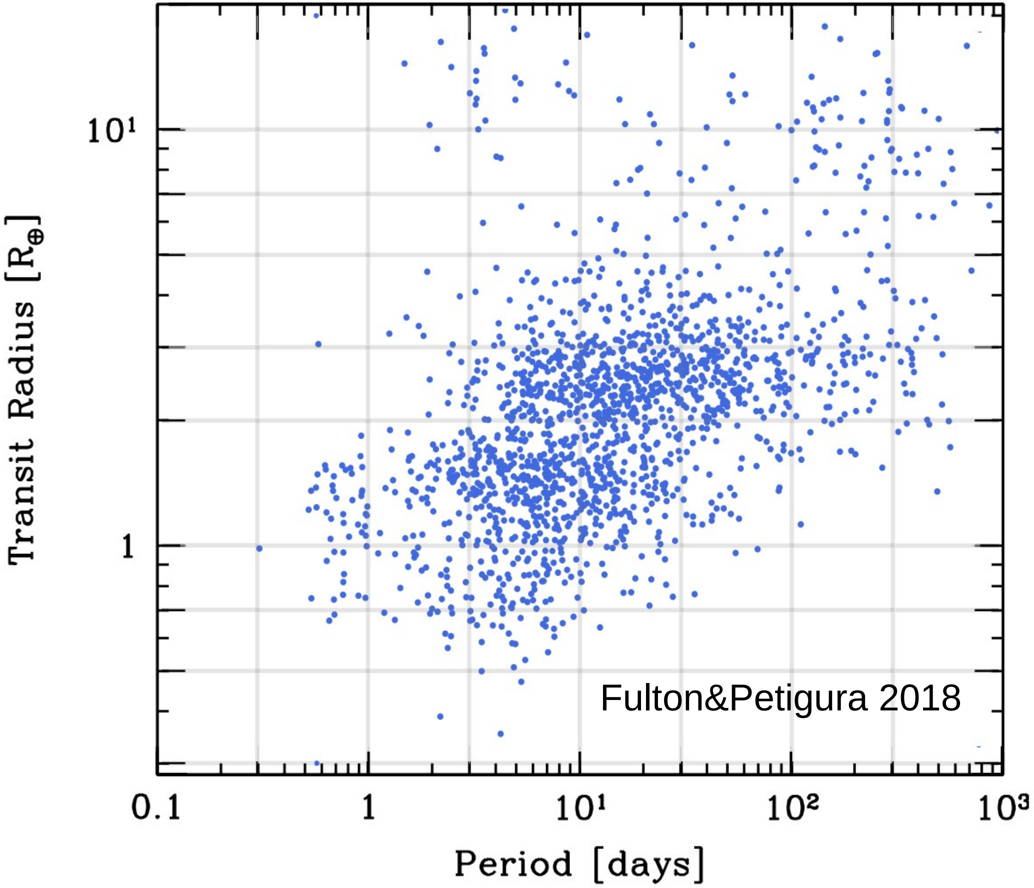
  - **Atmospheric escape of water+H/He mixture**
    - **H/He: Kubyshkina & Fossati 2021**
    - **Water: Johnstone 2020**
  - Stellar evolution in X-ray and bolometric luminosity
  - **Interior structure with new equation of state for water** (AQUA, Haldemann+2020)
  - Tidal orbital decay
- **Apply observational Kepler bias**
  - KOBE, Mishra+2021

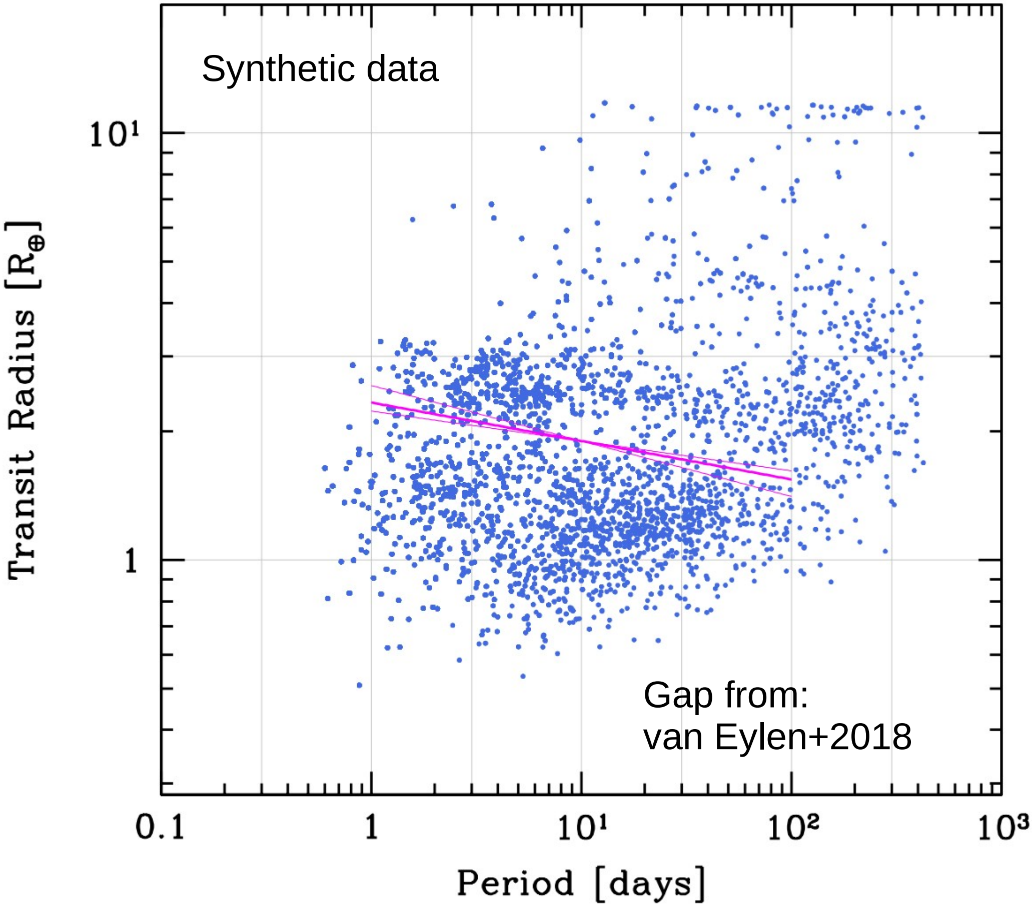
Results

- **Vapor H_2O mixed with H/He**
- **Valley at right location (3-4 R_E)**
- **Separates rocky from H_2O-rich**



Results with KOBE (Kepler Bias)





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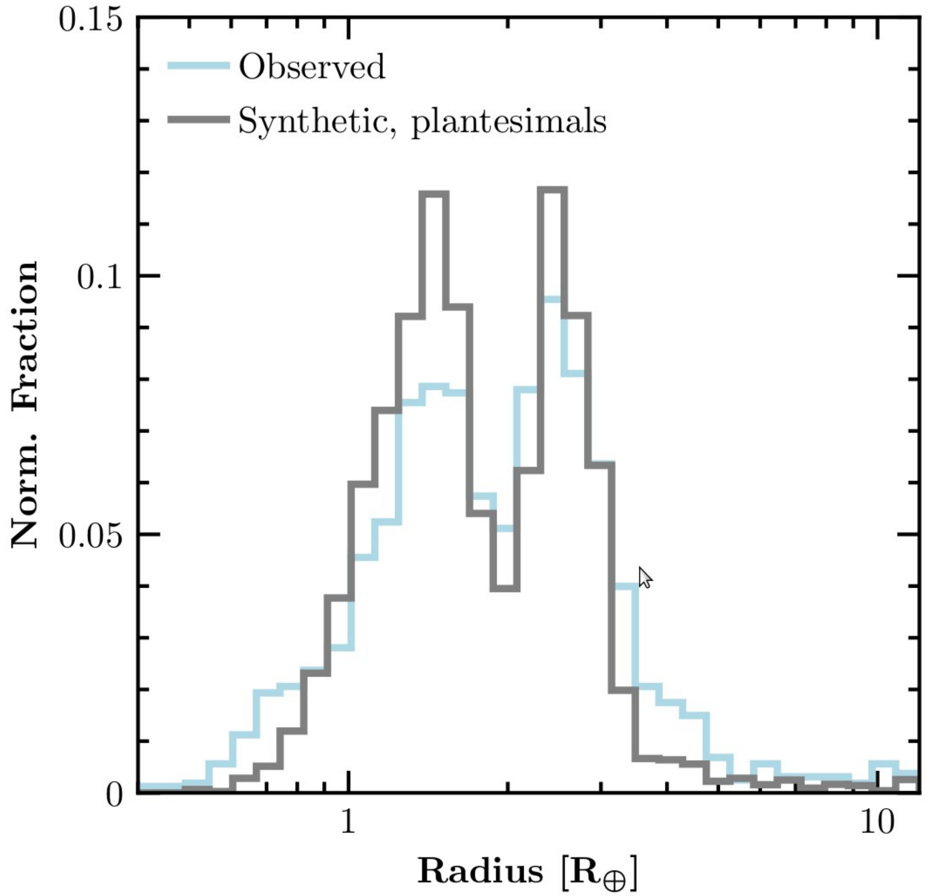
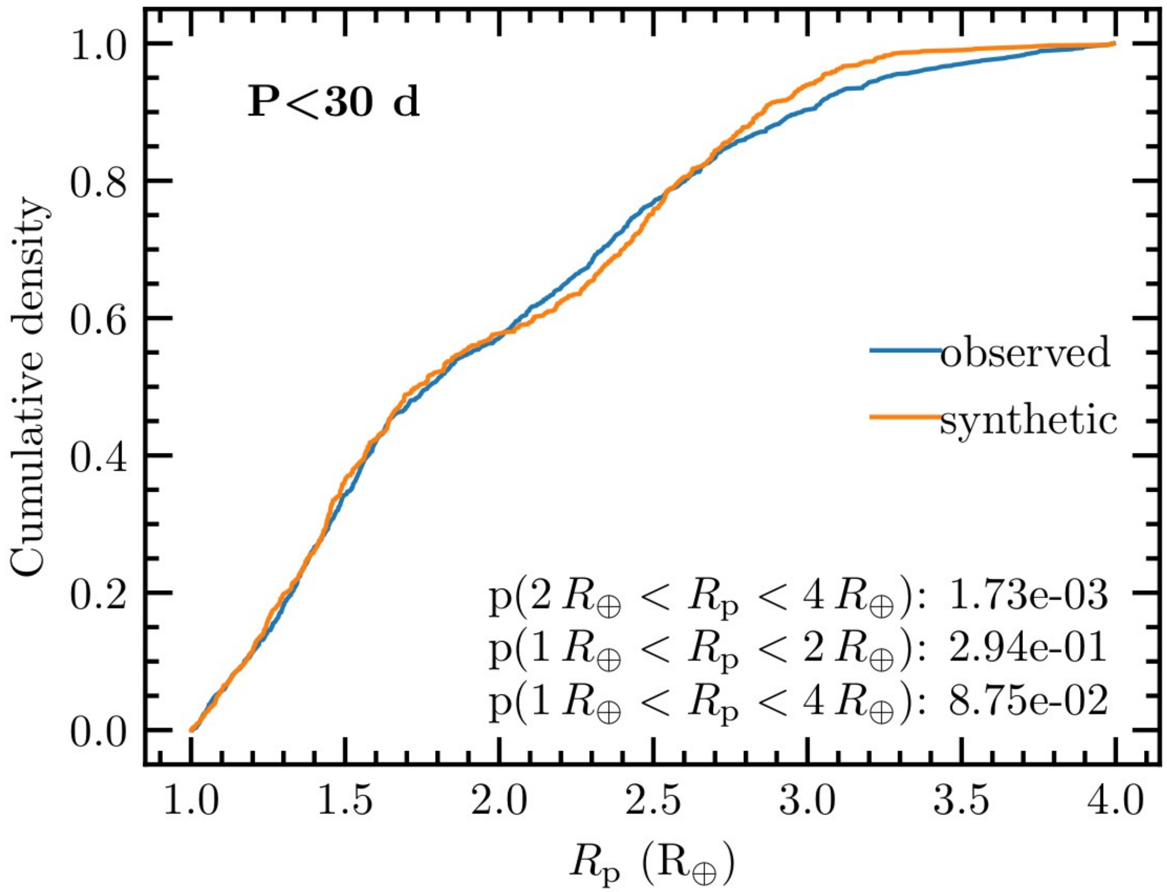
- **Radii agree qualitatively with observations**



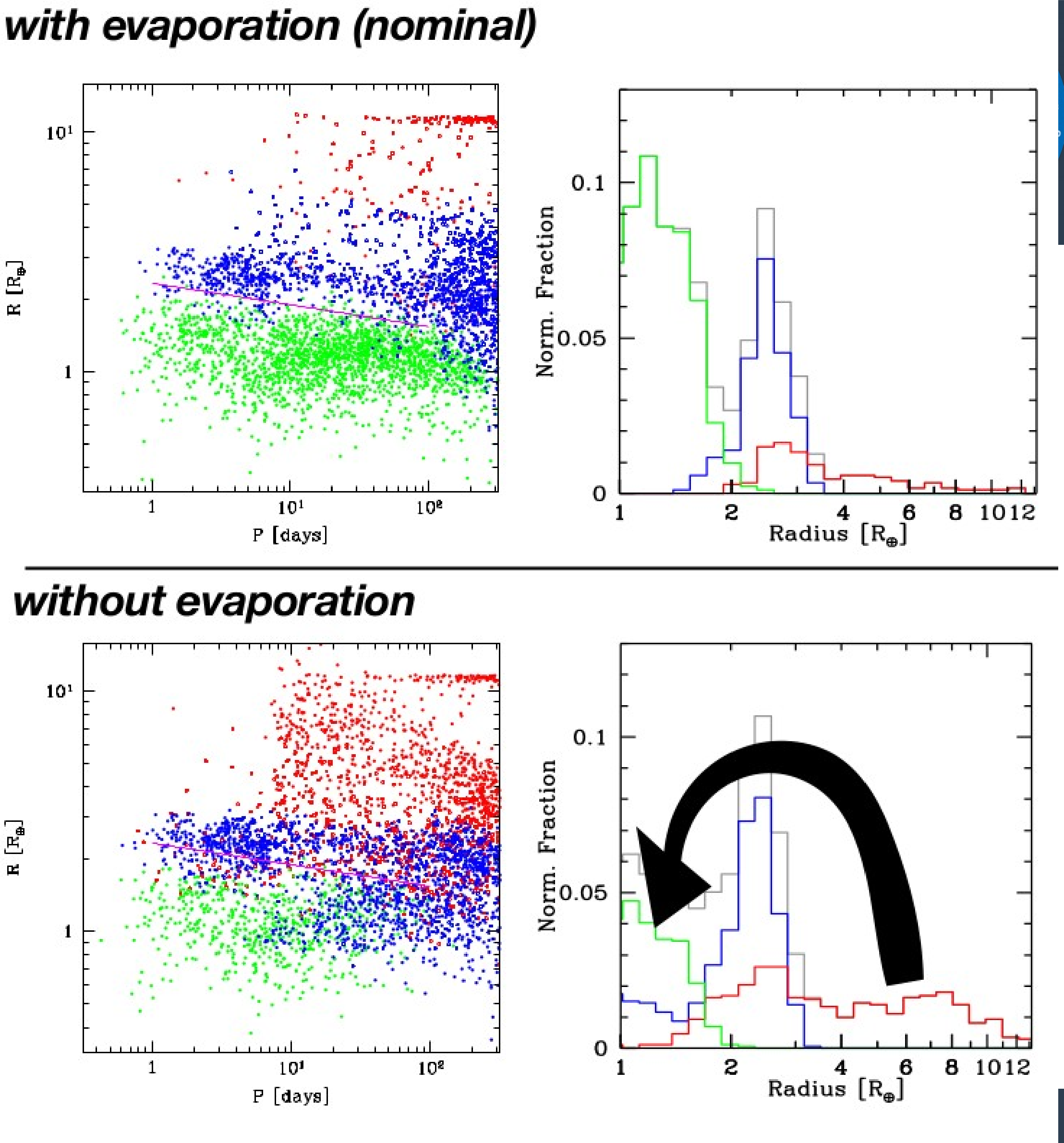
Results with KOBE (Kepler Bias)

- **Radii agree qualitatively with observations**
- **Within 30 d, even quantitatively**
  - Perfect match for rocky planets



Variations

- **Without evaporation, H/He rich planets populate all radii**
  - Makes evaporation a necessary but not dominant process



Conclusion

- **Updated planetary population synthesis models can be used for small planets**
  - Occurrence of habitable planets ranging from 0.1 to ~1 depending on size range
- **Reduction of giant planet formation increases habitable planet occurrence around intermediate mass stars**
- **Radius valley feature is not inconsistent with abundant water (steam) worlds**