Water as a Potential Sculptor of the M Dwarf Radius Valley

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https://tinyurl.com/Bennett-Skinner-ERES-IX

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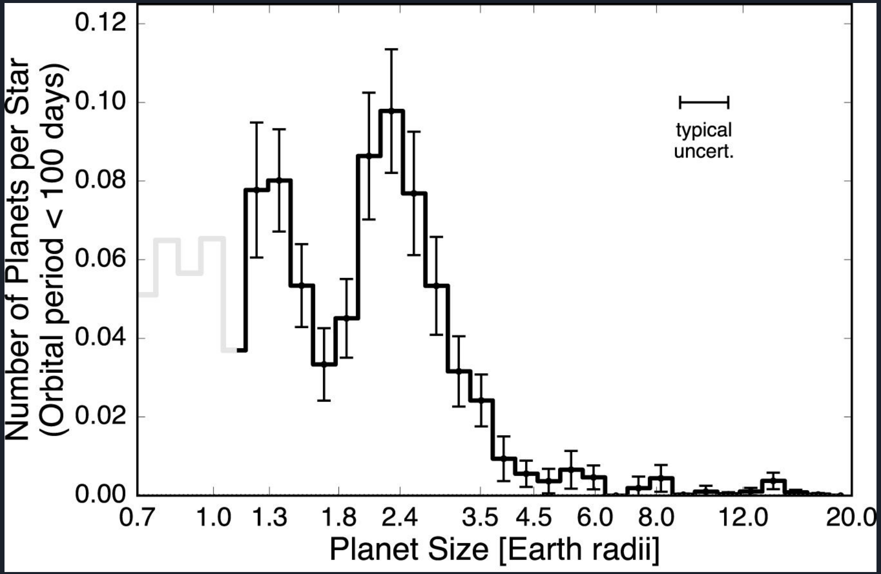
What is the radius valley?

The Radius Valley

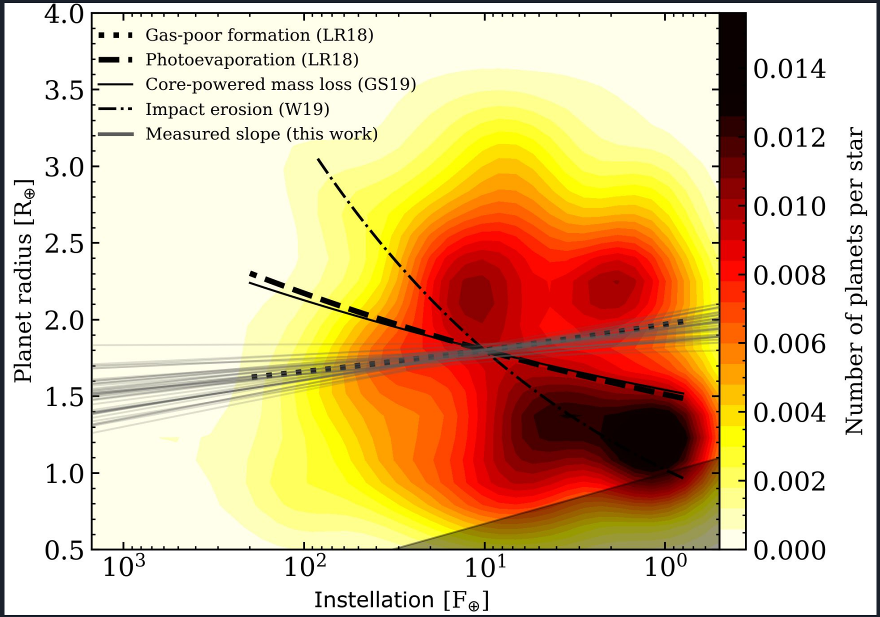
- Close-in Planet radii distribution bimodal (Fulton et al. 2017)
  - Super-Earths peaking at ~1.3 R⊕
  - Sub-Neptunes peaking at ~2.4 R⊕
  - Gap between them at ~1.8 R⊕
- Implies some mechanism forming two separate populations or splitting one population
- Larger radii → less dense material
- Smaller radii → more dense material



Fulton et al. (2017) Figure 7 Top Panel

The Radius Valley Slope

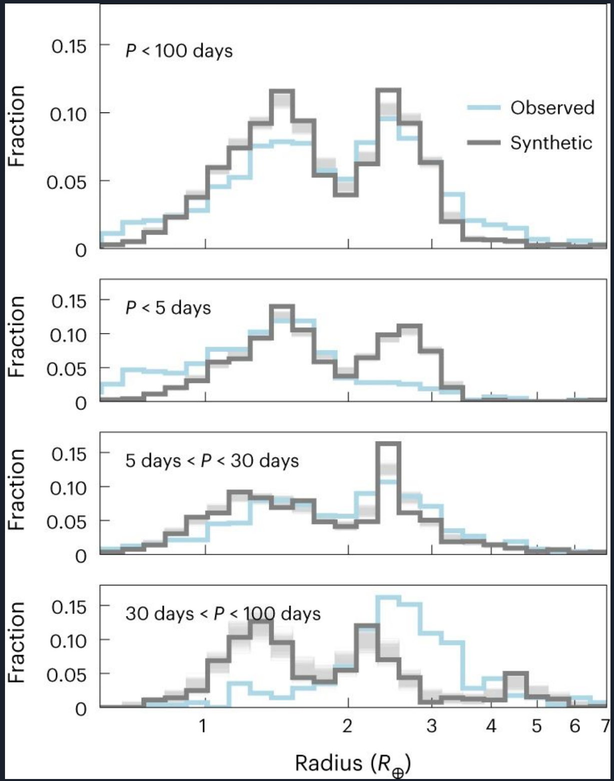
- The slope of radius valley location vs. instellation leaves a trace of how the valley was formed
- Sunlike stars: positive slope
  - Matches predictions for atmospheric loss caused by either:
    - Photoevaporation (Lopez & Rice 2018)
    - Core-powered mass loss (Gupta & Schlichting 2019)
  - Sub-Neptunes are super-Earths with a H/He envelope
- M stars: negative slope
  - Different formation mechanism?



Cloutier & Menou (2020) Figure 11

Sub-Neptunes as Water Worlds?

- Water, like H/He, has a low density, so sub-Neptunes could be water-rich
- Planet Population Synthesis models reproduce sunlike radius valley w/ water-rich formation, migration, and photoevaporation (Burn et al. 2024)
    - Super-Earths rocky worlds formed in-Situ
    - Sub-Neptunes water-rich worlds that formed outside iceline and migrated

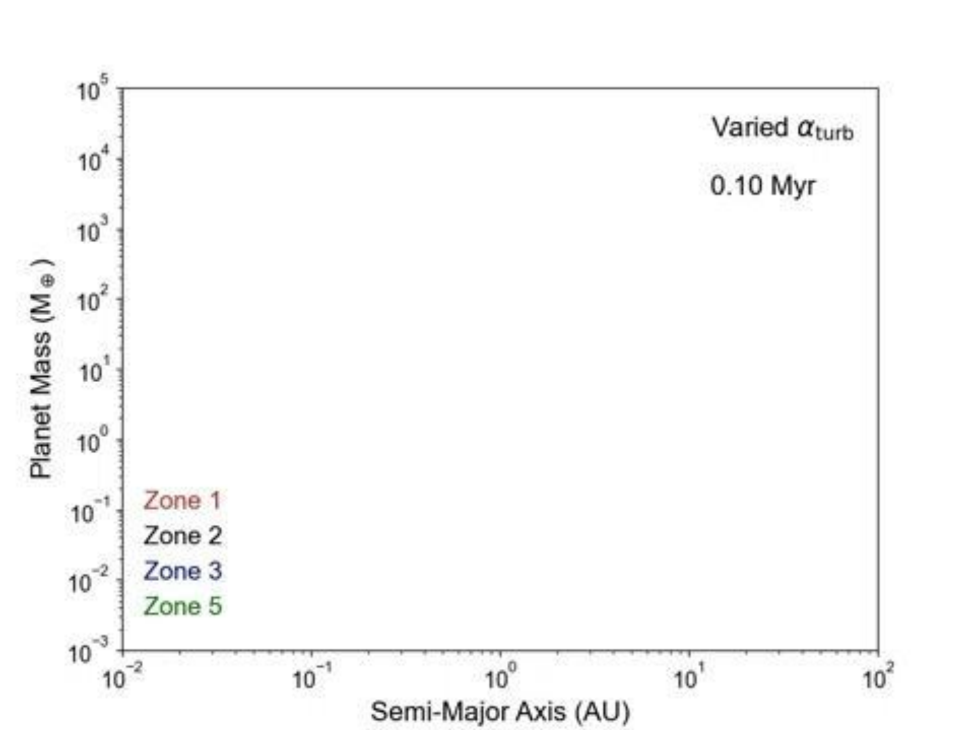


Burn et al. (2024) Figure 1

If atmospheric mass loss does not explain the radius valley slope around M Dwarfs, then maybe inwards-migrating water-rich worlds do.

McMaster Planet Population Synthesis Model

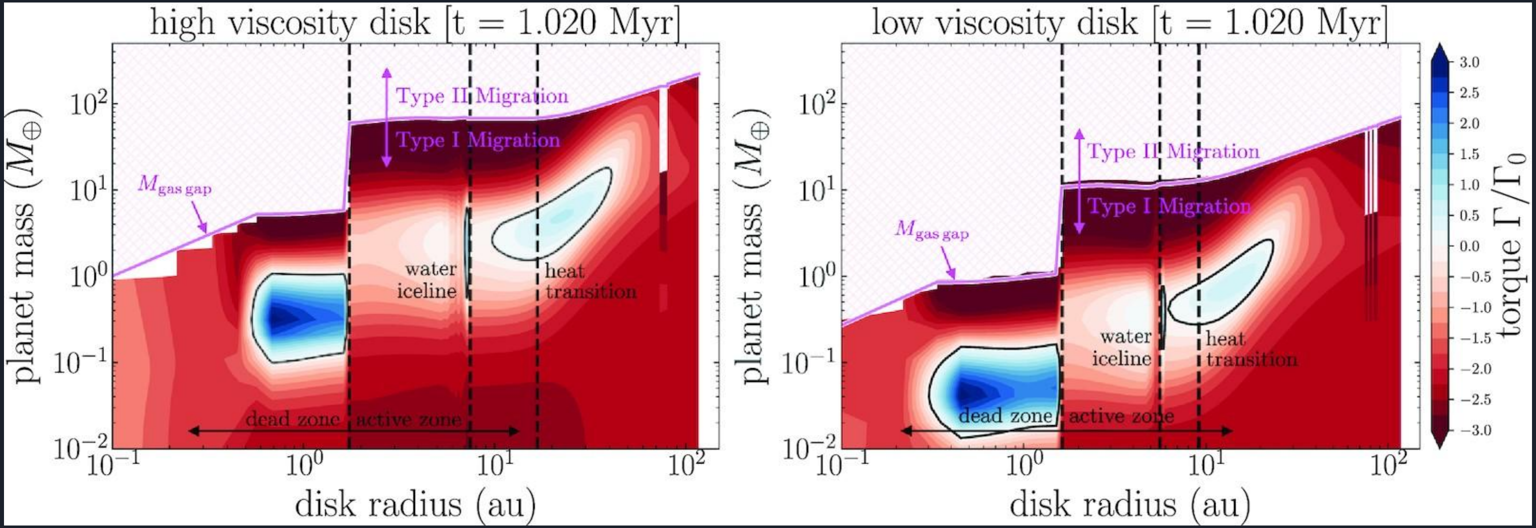
- Simulates planet formation in 1D
  - One lunar-mass embryo/disk
  - Embryo grows via planetesimal accretion
  - Sunlike star
  - Disk evolved self-consistently via turbulent viscosity



Alessi & Pudritz (2022) Supporting Information

Planet Migration & Traps

- Planet migration can be inwards or outwards directed, depending on local disk properties
    - General inwards migration, but outwards-directed corotation torque can overwhelm inwards-directed Lindblad torque when disk properties vary from one side of planet to other
    - This creates “traps” that planets form and grow in at the dead zone, iceline, and heat transition
    - Traps closer in lower viscosity disk



Speedie et al. (2022) Figure 2

Disk Winds

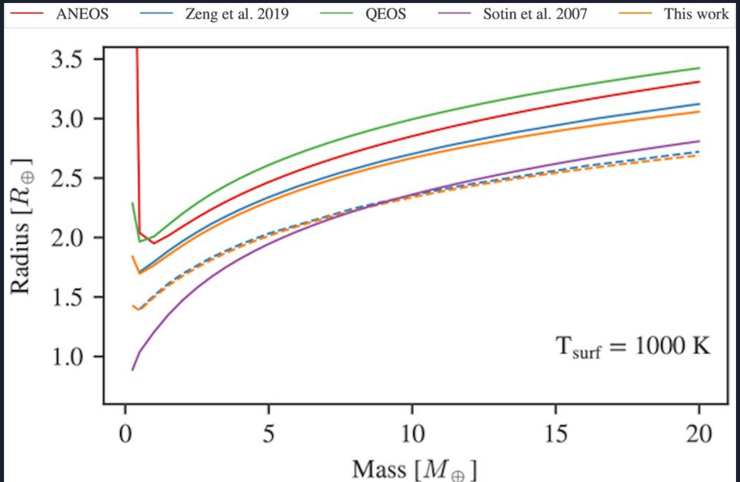
- Observed disk turbulent viscosities lower than needed for planet formation models (Pinte et al. 2022, Flaherty et al. 2018)
- Disk winds can generate an effective viscosity to make up the difference (Alessi & Pudritz 2022)
- Disk winds have been extensively observed to occur (Pascucci et al. 2023, Pascucci et al. 2024 submitted)
- Modeling disk winds allows viscosities to be lowered to realistic values

$$\frac{\partial \Sigma}{\partial t} = \underbrace{\frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(r^{1/2}\nu\Sigma\right)\right]}_{\text{Turbulent disk viscous evolution}} + \underbrace{\frac{1}{r}\frac{\partial}{\partial r}\left(r v_w \Sigma\right)}_{\text{Wind-driven accretion}} - \underbrace{\dot{\Sigma}_w}_{\text{Mass loss from wind}}$$

Does the McMaster Planet Population Synthesis Model reproduce the position of the radius valley for planets with no H/He envelope around sunlike stars when the equations of state used are updated?

New Equations of State

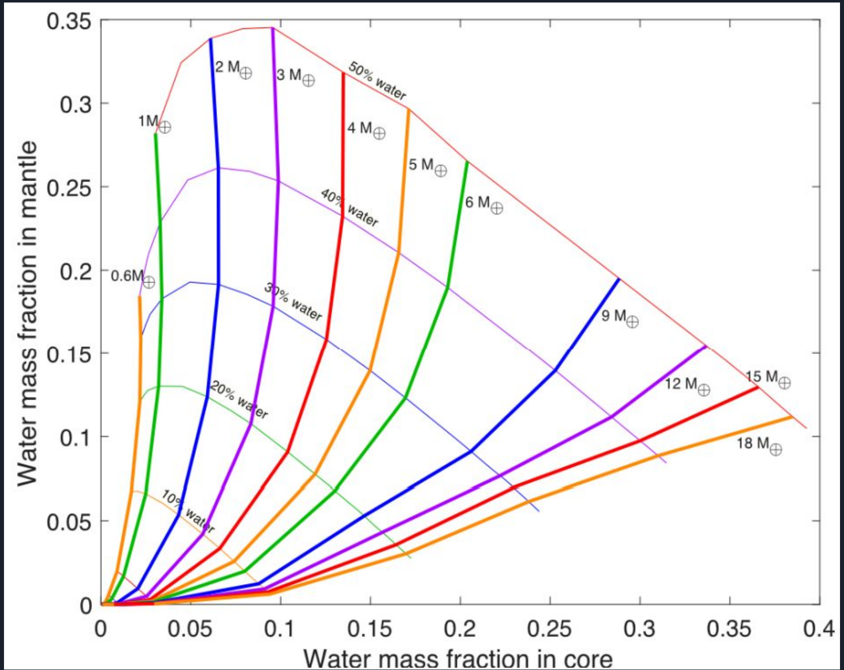
- Equations of State (EOS) used to calculate radii updated
  - Opacities: Freedman et al. (2008) → Freedman et al. (2014)
  - Hydrogen/Helium: Chabrier & Debras (2019) → Chabrier & Debras (2021)
  - Water: Various → AQUA (Haldemann et al. 2020)
  - Silicates: Caracas & Cohen (2008) → Sotin et al. (2007)
  - Iron: Seager et al. (2007) → SEOS (Hakim et al. 2018)



Haldemann et al. (2020) Figure 11

Water sequestration

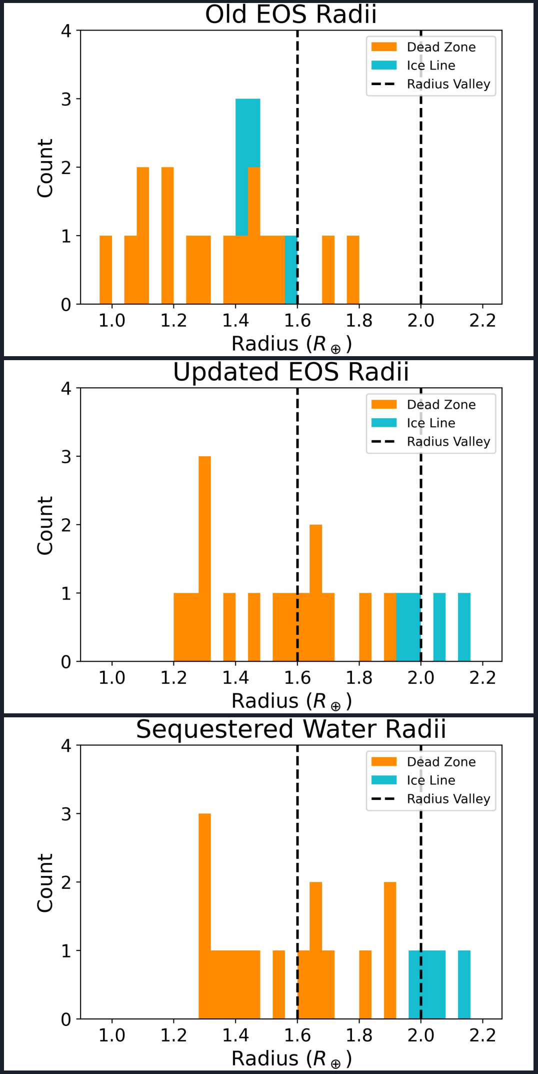
- Water preferentially incorporates into silicates and iron at high pressures (Luo, Dorn, and Deng (2024) submitted)
    - The majority of water in water worlds may be inside their mantle and core



Luo, Dorn, and Deng (2024) preprint Figure 4

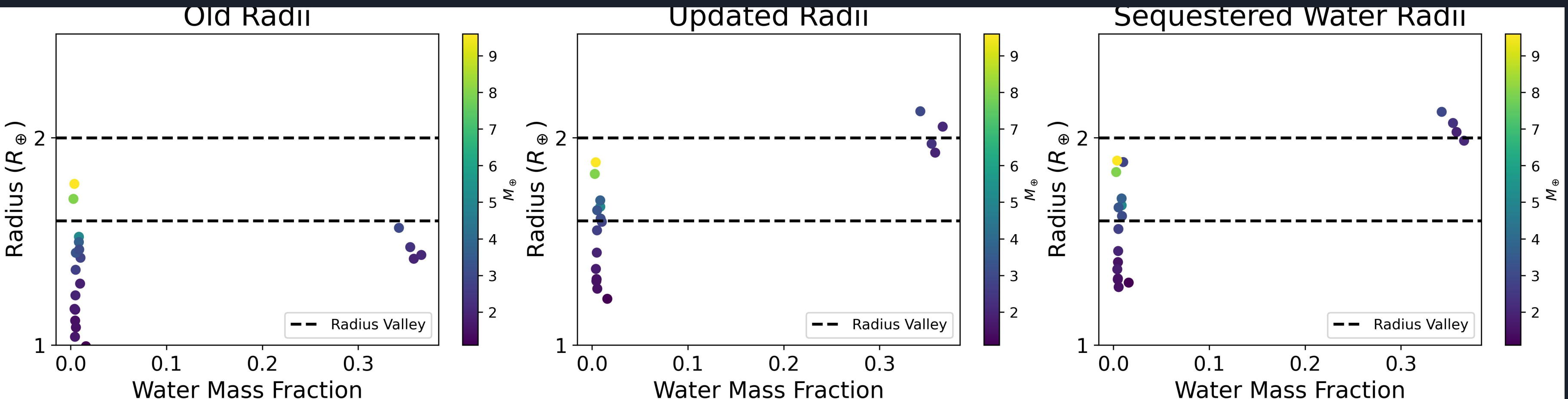
Histograms: No disk winds

- Very few close-in low-atmosphere planets formed
- Updating EOS OR sequestering water causes:
    - Dry dead zone planets to slightly increase in radius
    - Ice-rich ice line planets to move from below to in/above the radius valley



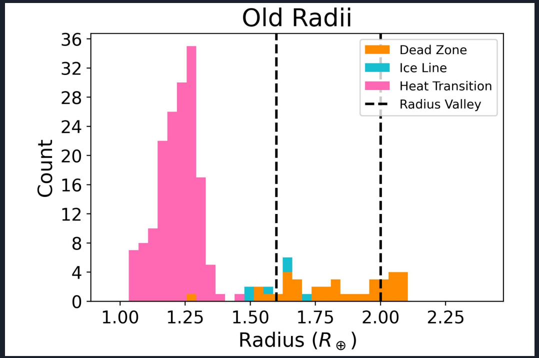
Why the difference when recalculating radii?

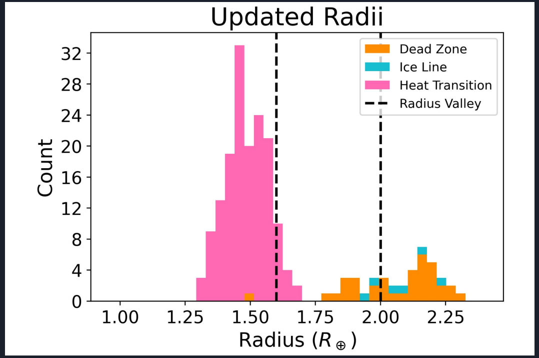
- Dead zone planets low water content, ice line planets high water content
- Updating EOS causes all planetary radii to increase, but water worlds most effected
  - Temperature structure in water convective rather than following liquid-solid boundary
  - Iron generally denser than found by previous equation of state
  - Redefining radius to be defined by the transit radius rather than theoretical radius

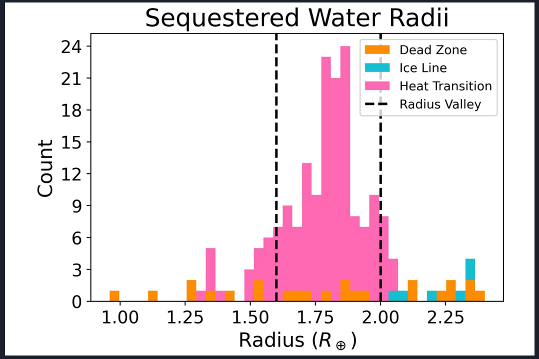


Histograms: Disk Winds

- Many close-in no atmosphere planets formed
- Updating EOS causes:
  - Mostly but not entirely dry heat transition planets to slightly increase in radius towards the lower peak of the radius valley
  - Mostly but not entirely wet dead zone and iceline planets to move from inside the radius valley towards its upper end
- Sequestering water causes:
  - Mostly but not entirely dry heat transition planets to significantly increase in radius towards the center of the radius valley
  - Mostly but not entirely wet dead zone and iceline planets to scatter over entire parameter space

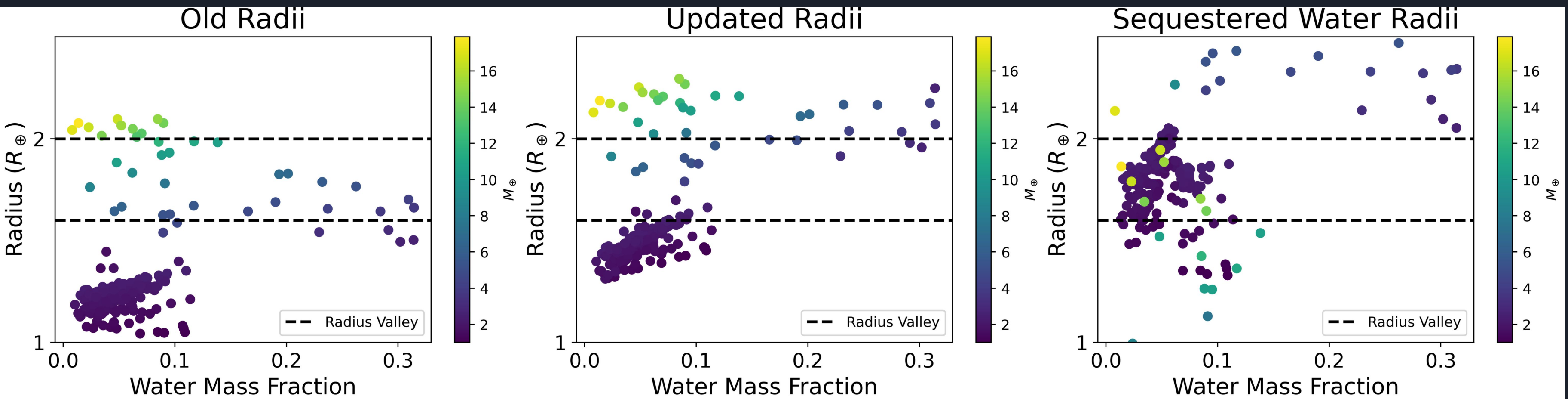






Why the difference when adding winds?

- Heat transition and thus planets formed in it closer to star in lower-viscosity disk
- Nearby traps in lower-viscosity disk can cross the iceline
    - Planets accrete both inside and outside the iceline →
    - Water content more broadly distributed →
    - More scatter in planetary radii



Summary & Future Work

- The radius valley is a bimodal radius distribution caused by a difference in composition
  - Smaller peak → rocky, higher peak → H/He-enveloped and/OR water-rich
  - Radius valley around M dwarfs different from around sunlike stars → water worlds?
- The McMaster Planet Population Synthesis Model simulates sunlike star planet formation
  - The dead zone barrier, water iceline, and heat transition trap planets
    - Barriers closer at lower viscosities, increasing spread of planetary radii
  - Inclusion of disk winds allows turbulent viscosity to be dropped to observed levels
- ***Updating Equations Of State moves water worlds to the upper edge of the radius valley***
- ***Water worlds contribute to–but don't fill–the sunlike sub-Neptune population***
- Next: tune model for M dwarfs
  - See if expectation of the water world sub-Neptune contribution being larger is borne out

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Viscosity Parameters

- Log-normal assumed due to variety of disk morphologies
- Median of 10^{-3} assumed due to agreement of planet population synthesis models using this value with observations
- 0.007, observed upper limit for TW Hya (Flaherty et al. 2018), chosen as 1σ above median
- 10^{-4} chosen as lower limit also due to observed values of α