

McMaster  
University



Emerging Researchers in Exoplanet Science Symposium IX  
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# Water as a Potential Sculptor of the M Dwarf Radius Valley

<https://tinyurl.com/Bennett-Skinners-ERES-IX>



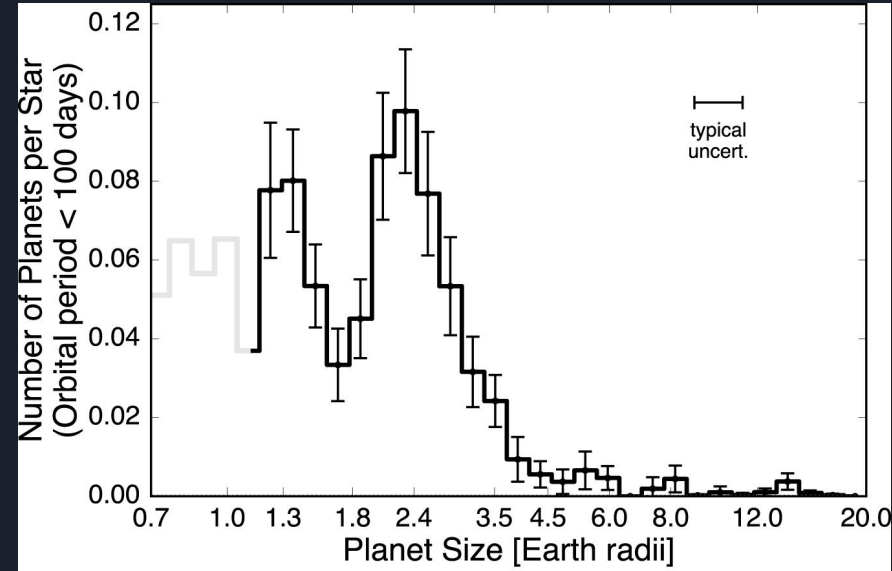
Talk by Bennett Skinner  
Work advised by Ryan Cloutier & Ralph Pudritz  
Some data provided by Komal Bali (ETH Zürich) and  
Matthew Alessi (Formerly McMaster)



**What is the radius valley?**

# The Radius Valley

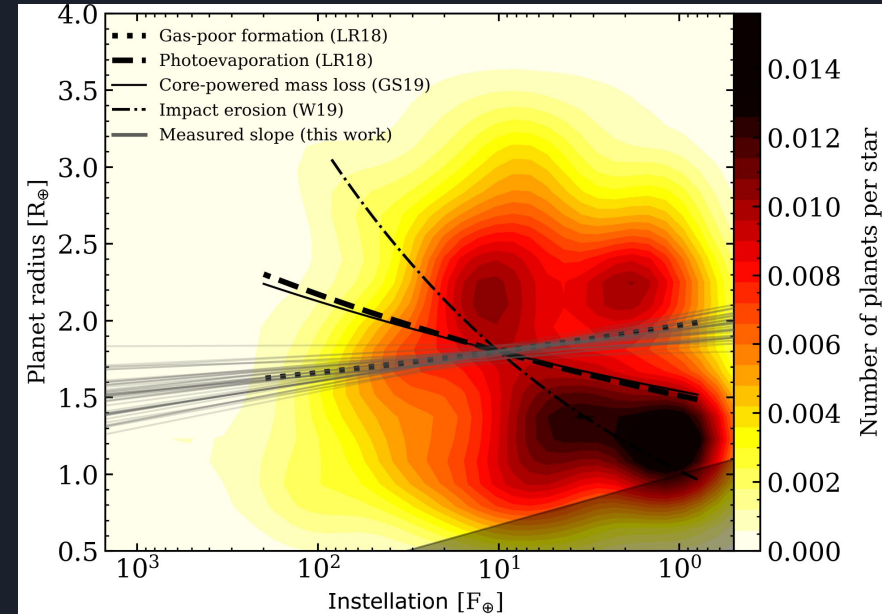
- Close-in Planet radii distribution bimodal (Fulton et al. 2017)
  - Super-Earths peaking at  $\sim 1.3 R_{\oplus}$
  - Sub-Neptunes peaking at  $\sim 2.4 R_{\oplus}$
  - Gap between them at  $\sim 1.8 R_{\oplus}$
- Implies some mechanism forming two separate populations or splitting one population
- Larger radii  $\rightarrow$  less dense material
- Smaller radii  $\rightarrow$  more dense material



Fulton et al. (2017) Figure 7 Top Panel

# The Radius Valley Slope

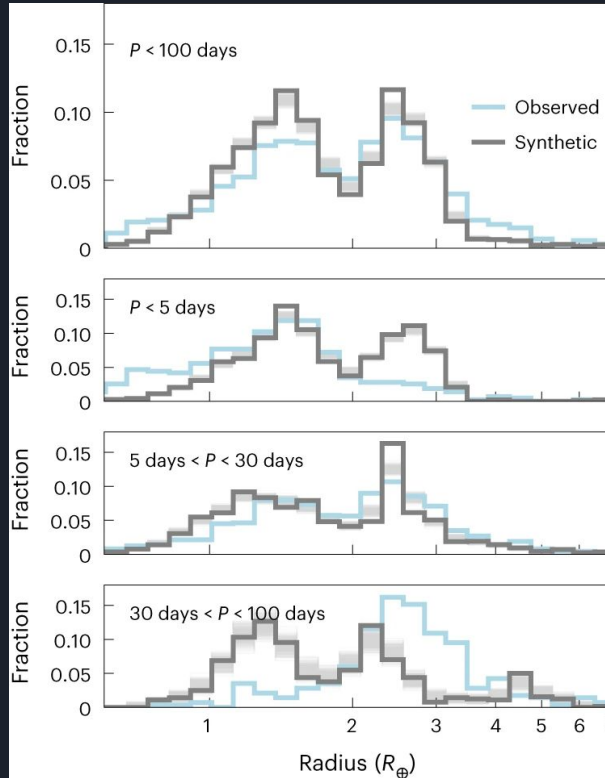
- The slope of radius valley location vs. instellation leaves a trace of how the valley was formed
- Sunlike stars: positive slope
  - Matches predictions for atmospheric loss caused by either:
    - Photoevaporation (Lopez & Rice 2018)
    - Core-powered mass loss (Gupta & Schlichting 2019)
  - Sub-Neptunes 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



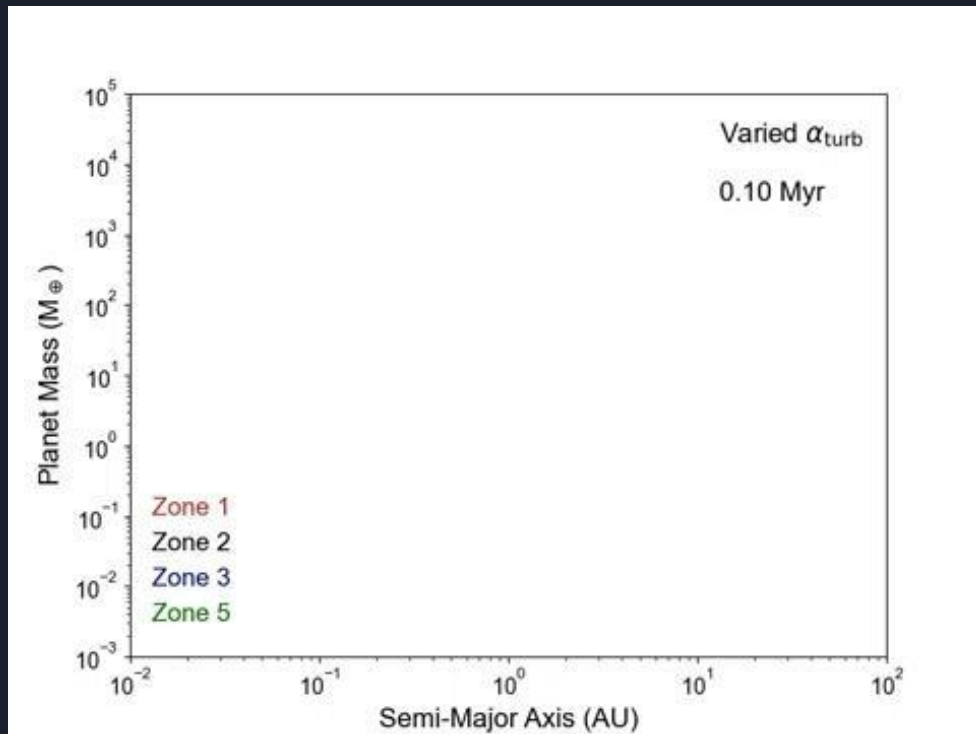
Burn et al. (2024) Figure 1



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

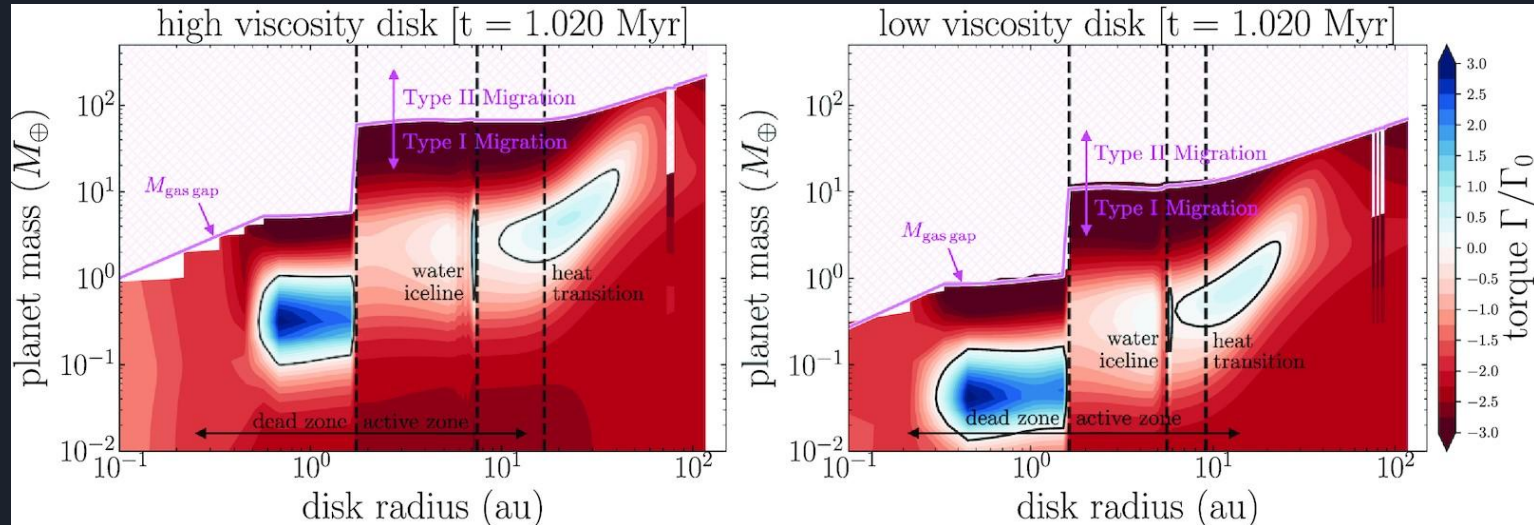
# McMaster Planet Population Synthesis Model

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



# 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

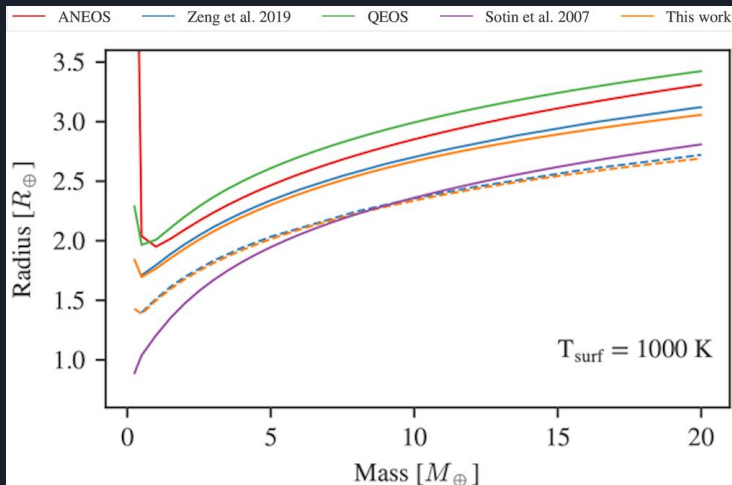
$$\frac{\partial \Sigma}{\partial t} = \underbrace{\frac{3}{r} \frac{\partial}{\partial r} \left[ r^{1/2} \frac{\partial}{\partial r} (r^{1/2} \nu \Sigma) \right]}_{\text{Turbulent disk viscous evolution}} + \underbrace{\frac{1}{r} \frac{\partial}{\partial r} (r v_w \Sigma)}_{\text{Wind-driven accretion}}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



**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

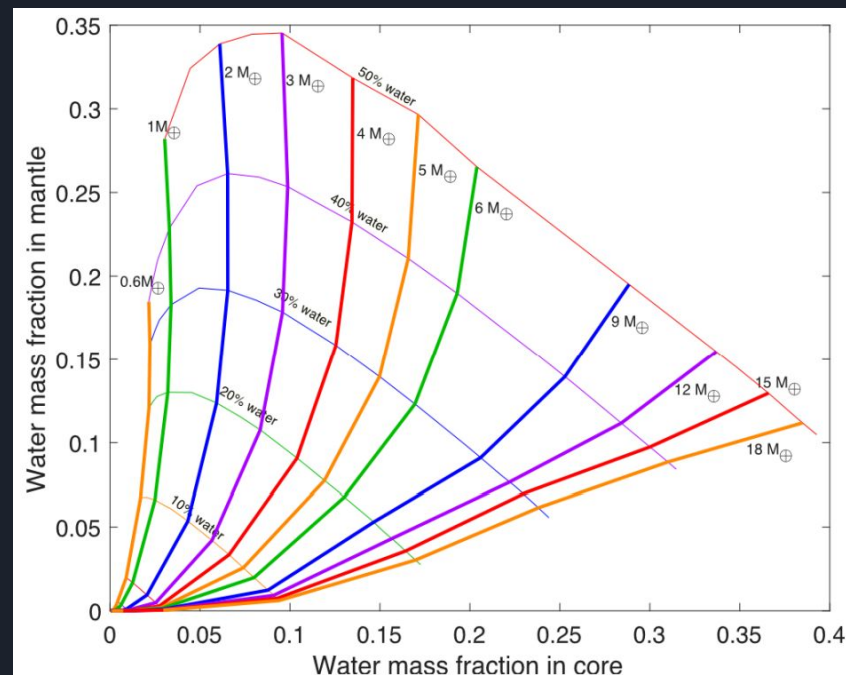
- Equations of State (EOS) used to calculate radii updated
  - Opacities: Freedman et al. (2008) → Freedman et al. (2014)
  - Hydrogen/Helium: Chabrier & Debras (2019) → Chabrier & Debras (2021)
  - Water: Various → AQUA (Haldemann et al. 2020)
  - Silicates: Caracas & Cohen (2008) → Sotin et al. (2007)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



Haldemann et al. (2020) Figure 11

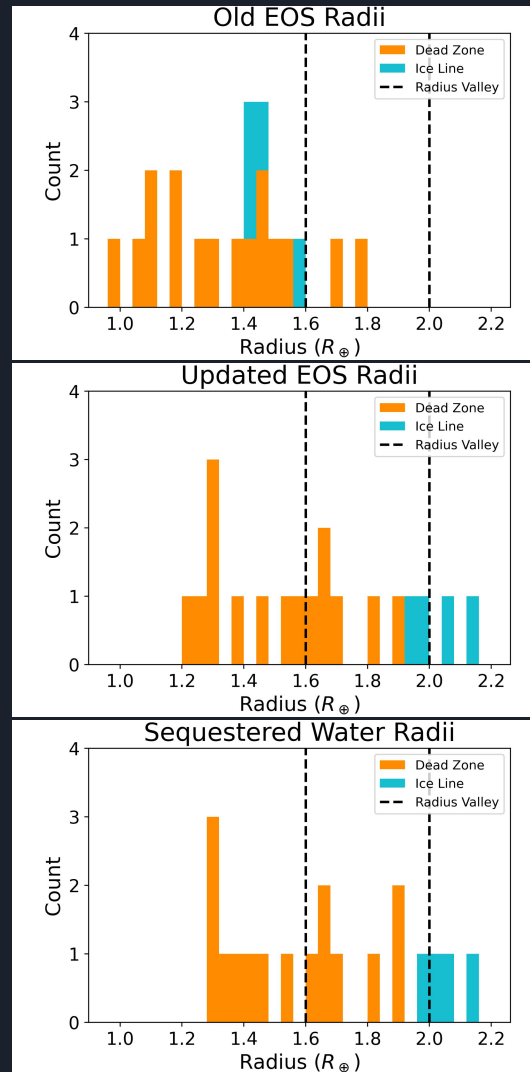
# Water sequestration

- 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



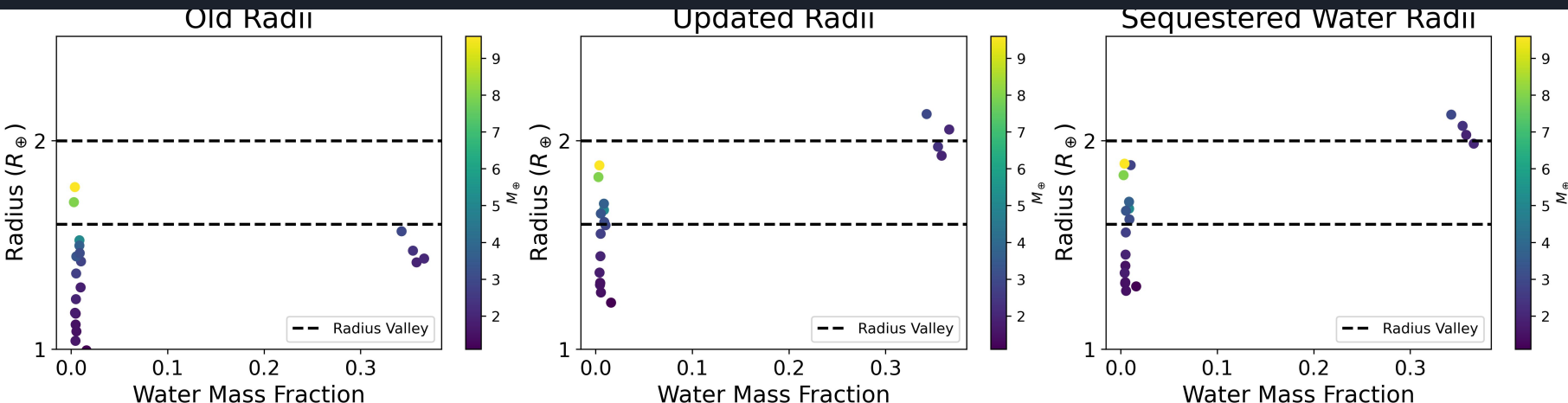
# Histograms: No disk winds

- 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



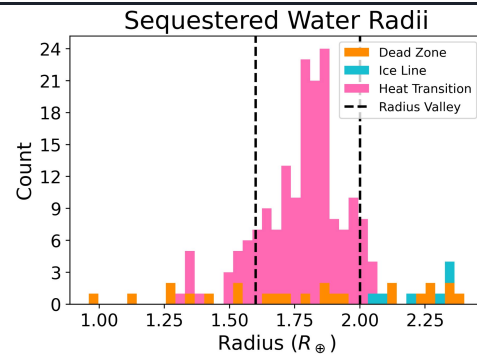
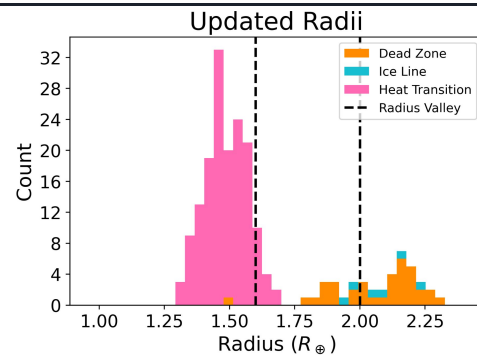
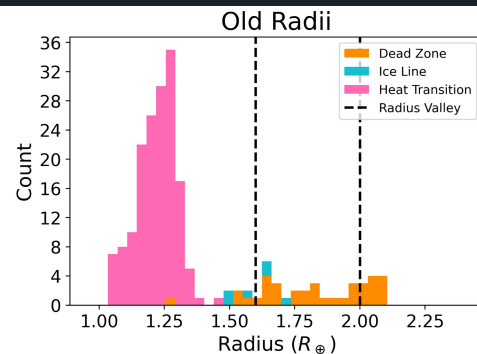
# Why the difference when recalculating radii?

- 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



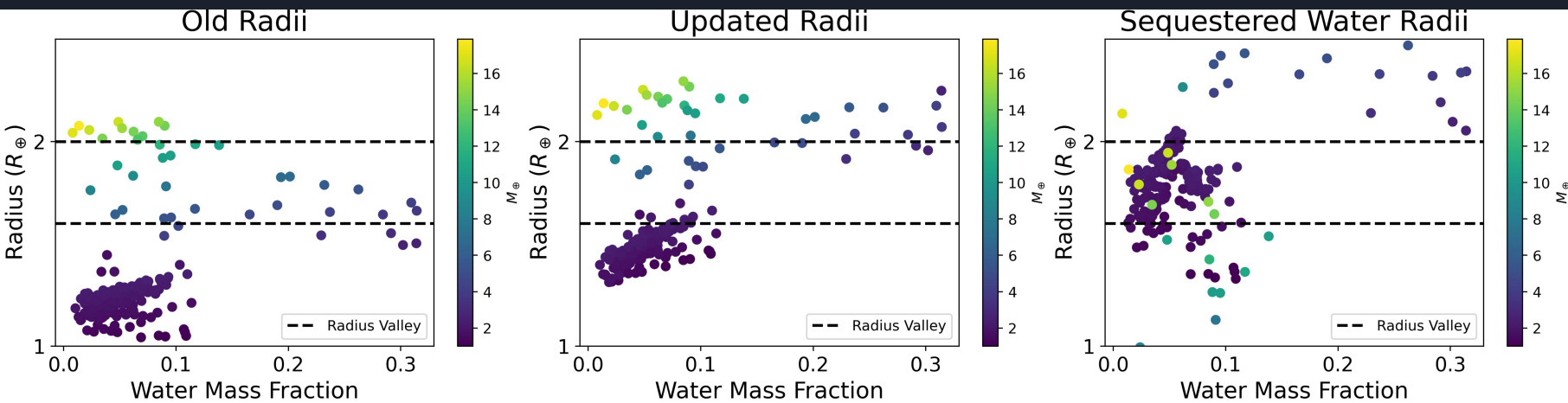
# Histograms: Disk Winds

- 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

# 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  $1\sigma$  above median
- $10^{-4}$  chosen as lower limit also due to observed values of  $\alpha$

