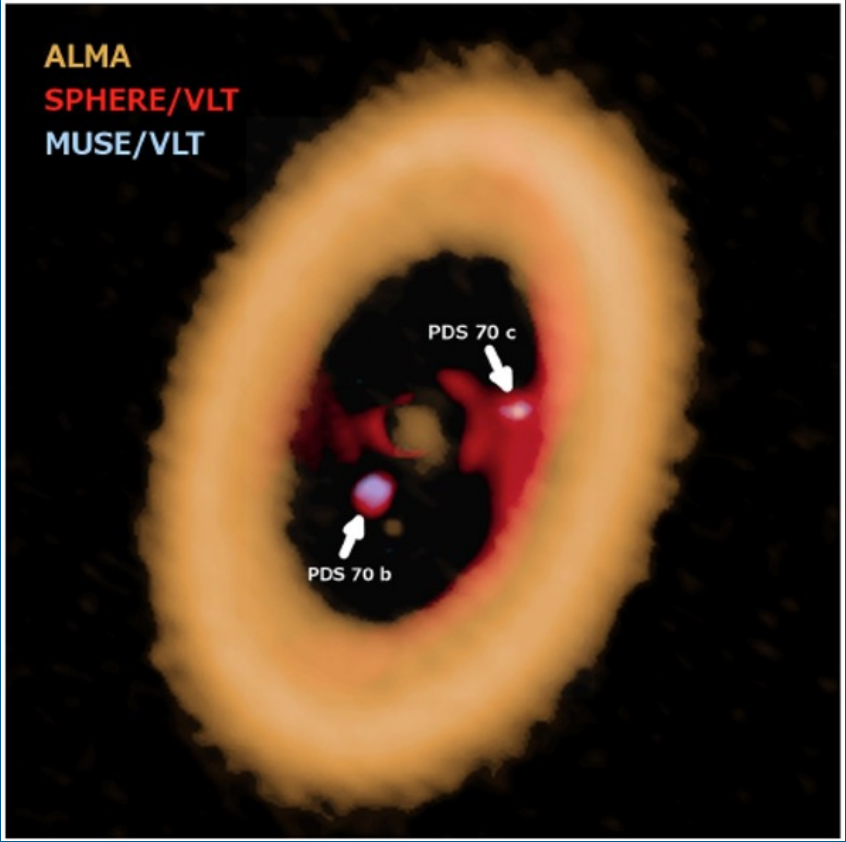

Planetary Properties and the Fingerprints of Formation

Ralph E. Pudritz

McMaster University

June 22-26, 2026

Perspectives of Planet and Star Formation:

in Honour of Thomas Henning

Thanks to….
Former Ph.D. students;
Matthew Alessi (Data Scientist, McMaster Health Sciences)
Alex Cridland (Staff Astronomer, LMU,)
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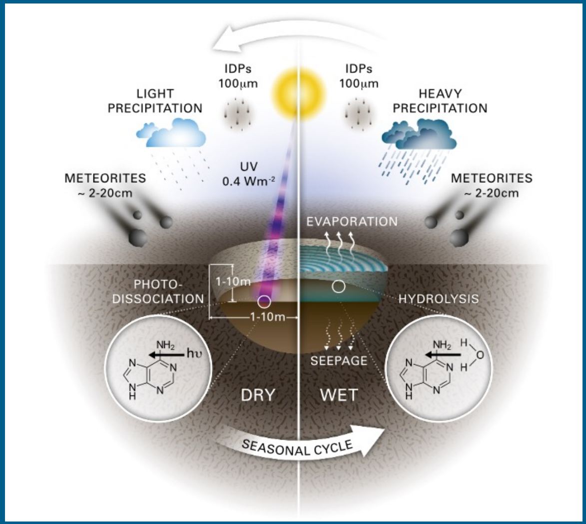
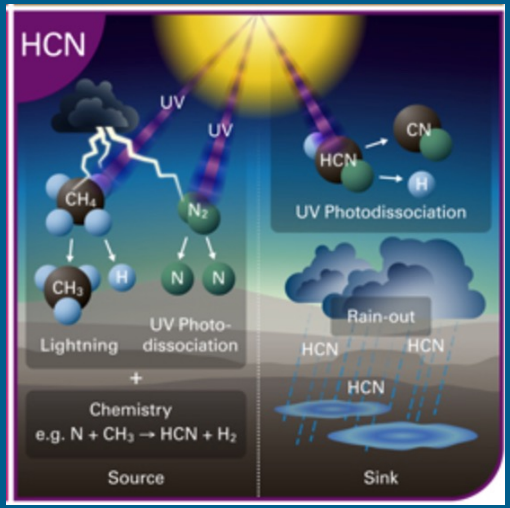
Image credit: ALMA(ESO/NOAJ/NRAO) A. Isella, ESO

Thomas and Origins of Life

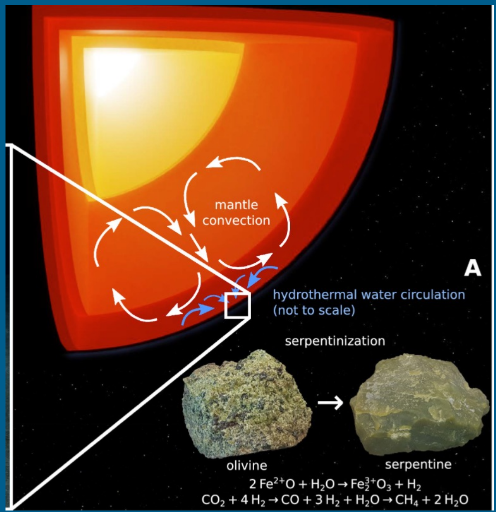
Starting from your support of my wonderful sabbatical leave at MPIA in 2015/16…. a garden grew….



Origin of the RNA world: The fate of nucleobases in warm little ponds;
Pearce, Pudritz, Semenov, and Henning; 2017. PNAS



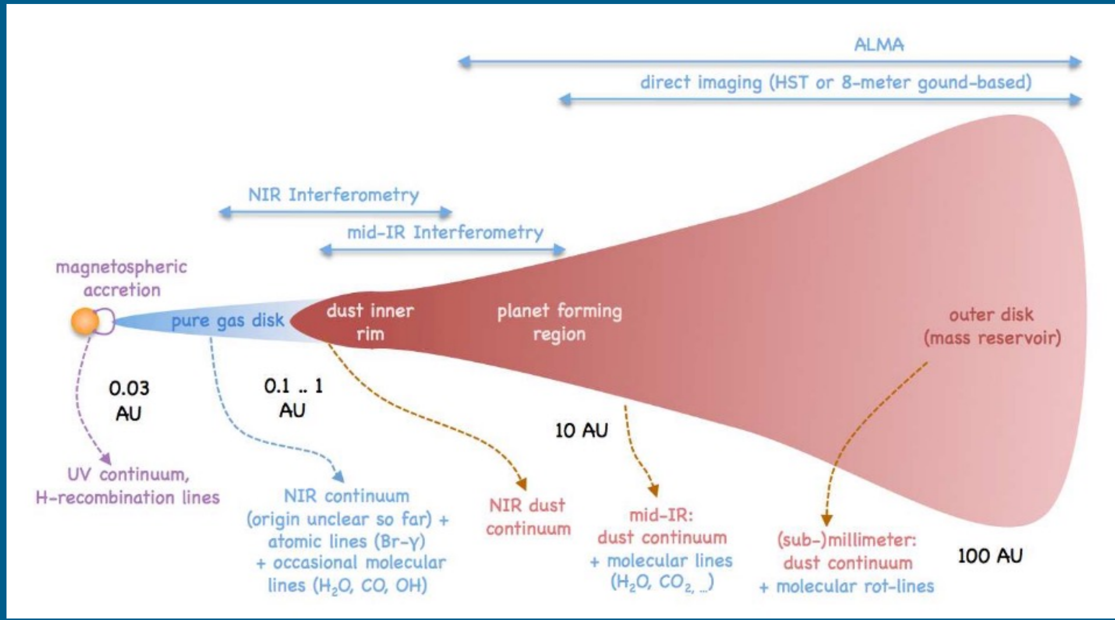
Towards RNA life on Early Earth: From atmospheric HCN to biomolecular production in warm little ponds; Pearce, Pudritz, Molaverdikhani, Henning, Cerrillo, 2022, ApJ



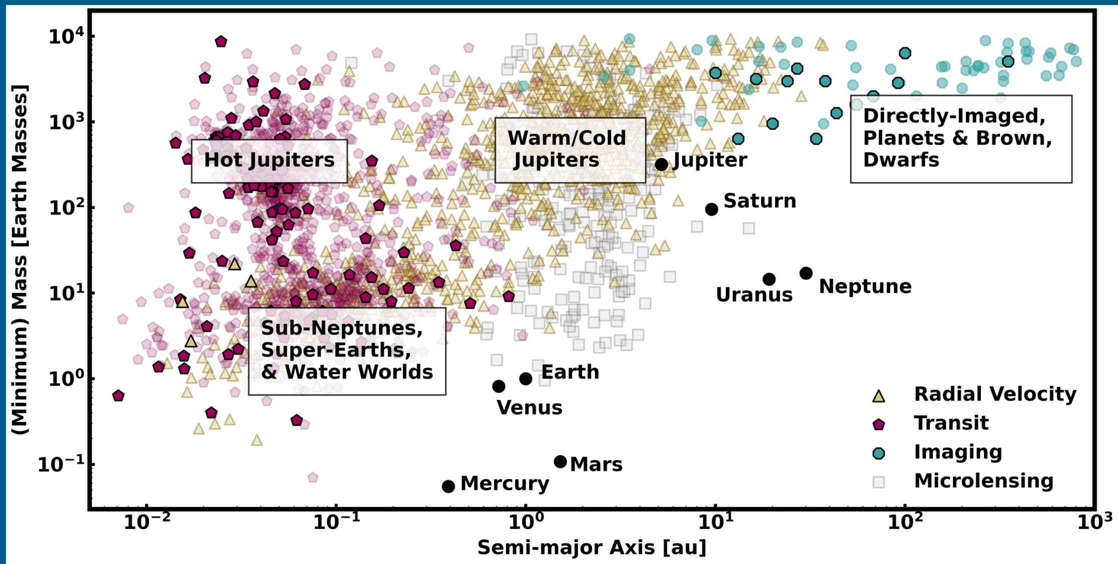
Deep Mantle–Atmosphere Coupling and Carbonaceous Bombardment: Options for Biomolecule Formation on an Oxidized Early Earth;
Paschek, Henning, Molaverdikhani, Miyazaki, Pearce, Pudritz, Semenov; 2024, ApJ

M-a diagram: Connecting PPDs with exoplanet populations

- PPD Inner Edges:
  - co-rotation (gas)
  - sublimation (dust)
  - Many planets inside sublimation region!
- Warm Jupiters at a few AU + low occurrence beyond 10 AU
  - water ice line effect?
- super-Earths; mini-Neptunes: 1-10 M_E the most common planets
  - disk lifetime effect?



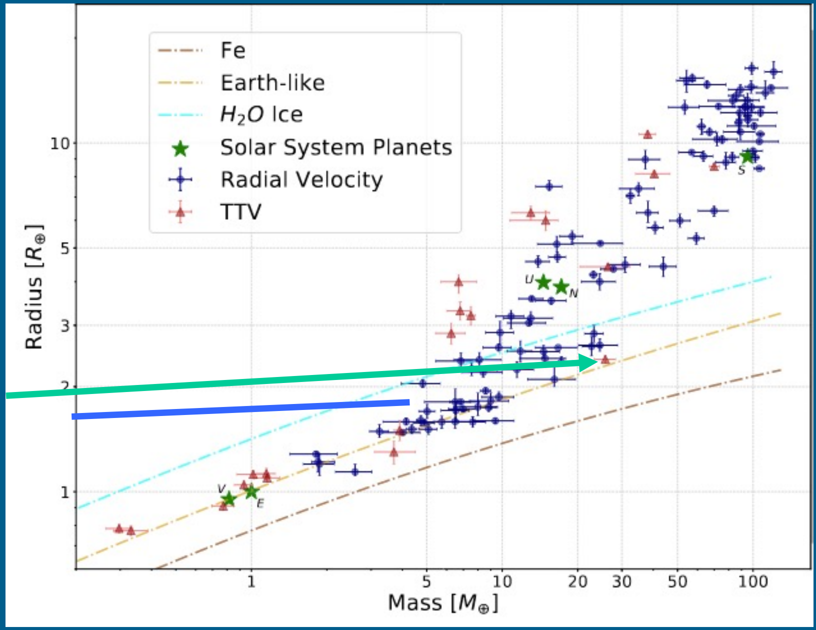
Dullemond & Monnier 2010



Adapted from Kempton & Knutson 2024

M-R diagram & Planetary Populations

- Rocky sequence ends ~ 25 M_E -> pebble isolation mass?
  (eg. Bitsch+2018)

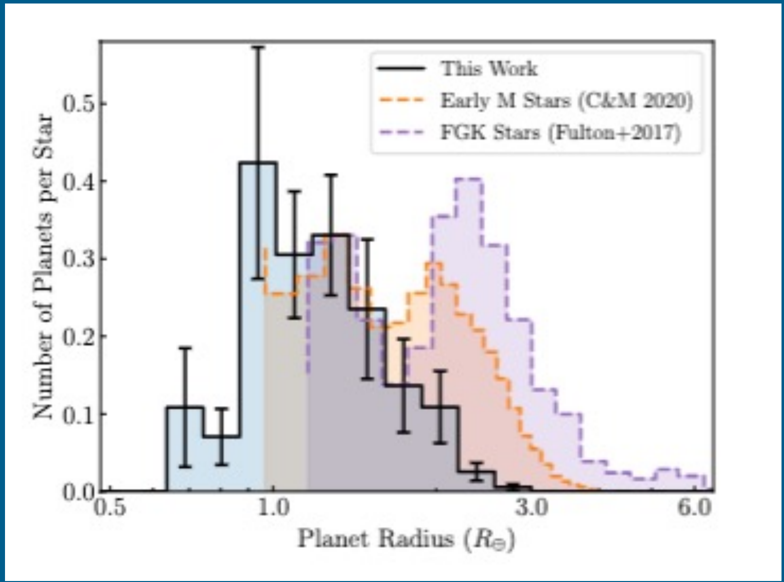


Otegi + 2019

- Radius valley @ ~ 1.7 R_E
- Photoevaporation - or - core powered loss of atmospheres of one population (Owen & Wu2013; Ginzburg+2018) ?

  or

- Two different populations: migration of ice rich mini-Neptunes and steam atmospheres (Burn+2024)?



Gillis, Cloutier, Pass 2026

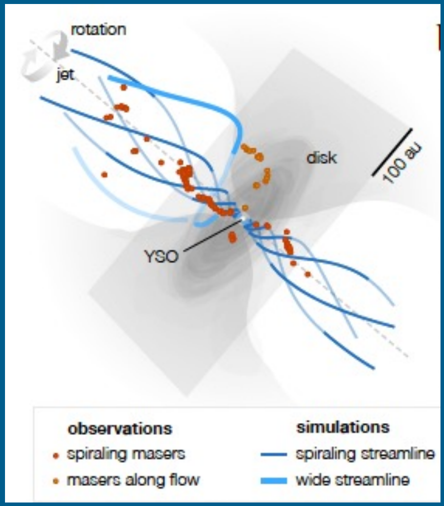
2. Physical Processes

2.1 PPDs - Angular Momentum Transport: Jets and Outflows - unified as MDWs

Outflows resolved – confirmation of MDW theory*

- ALMA: rotating molecular DW, launching radii to 25 AU
  (Lee+2017, Hirota+2017, Chen+2016, Bjerkeli 2016; Pascucci+2025;
  reviews: Pudritz & Ray 2019, Pascucci+2023)

- Masers and rotating outflow: resolved to 0.05 AU (Moscadelli… Henning..2021, 2026)

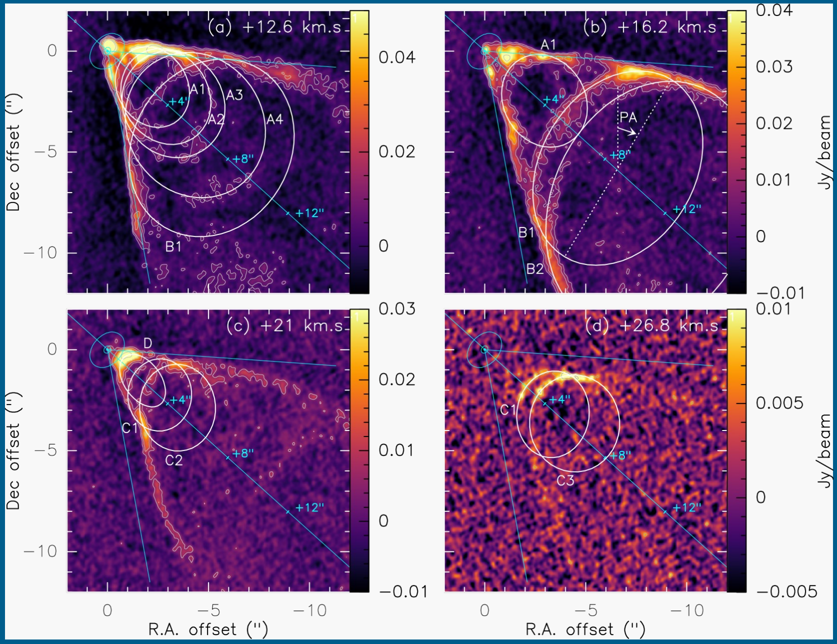


*__Theory of MHD disk winds__: AGNs - Blandford & Payne 1982, protostellar systems Pudritz & Norman 1983, 1986, Fereirra&Pelletier 1995, Turner+PPVI 2014, Lesur 2023..
Simulations: Ouyed + 1997, Non-ideal MHD: Bai and Stone 2013, Gressel + 2015…)

Layered MDWs: connection to disk structure

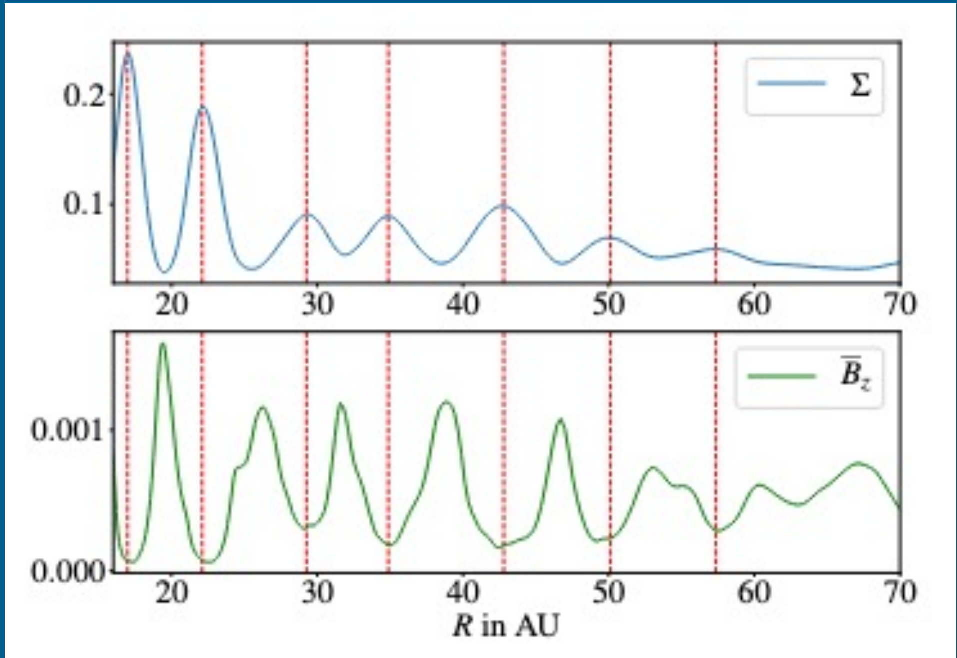
- ALMA CO – layered, rotating outflow shells from HL Tau: Shells B1a, B1b, B2 maps to disk @ 55, 67, 86 A (Bacciotti + 2025)

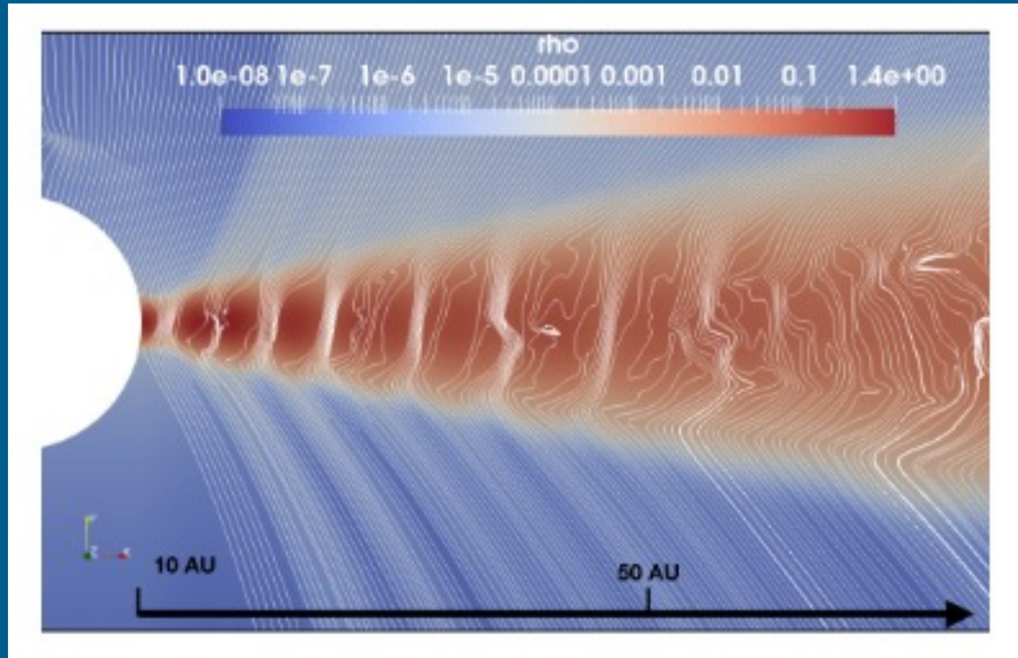
- JWST nested FeII, H_2 , CO (Pascucci+2025)



Structure induced by MHD disk winds?

(Riols+2019,2020,; Suriano+2019, 2020, Aoyama & Bai 2023)





Riols+2020

Enduring magnetic flux concentration in gaps:

- MDWs drive gap/ring formation, pressure bumps

Is this how planet formation starts?

•

2.2 Dust evolution in smooth disks with MDWs:

(Goksu, Pudritz, Delage 2026 in prep)

Model:

- Hybrid evolution: MDW and turbulence (Suzuki+2016, Hasegawa+2016)
- Disk heating by stellar irradiation (Chiang & Goldreich 1994)
- Dust evolution and coagulation - DustPy code

(Chambers 2019)

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(r^{1/2}\nu\Sigma\right)\right] + \frac{1}{r}\frac{\partial}{\partial r}\left(r v_w \Sigma\right) - \dot{\Sigma}_w,$$

Turbulent diffusion + Wind driven advective flow + mass loss

$$v_w = \frac{(B_\phi B_z)|^S}{\pi\Sigma\Omega}$$ (advective speed of accretion flow)

- Model MDW with 2 parameters :

- Fraction of accretion speed due to MDW (f_w)
- wind mass loss rate (K);

$$v_w = f_w v_0 \left(\frac{T}{T_0}\right)^{1/2},$$

$$\dot{\Sigma}_{g,\mathrm{wind}} = \frac{K f_w v_0 \Sigma}{r_0}\left(\frac{r}{r_0}\right)^{-3/2}$$

Dust size evolution in hybrid models

Initial condition: total accretion rate

$$\dot{M}_{tot} = \dot{M}_{turb} + \dot{M}_{wind}$$

K=0 : negligible mass loss rate

K=0.6: $\dot{M}_w$ / $\dot{M}_a$ ~ 1

Observational constraints on turbulence:

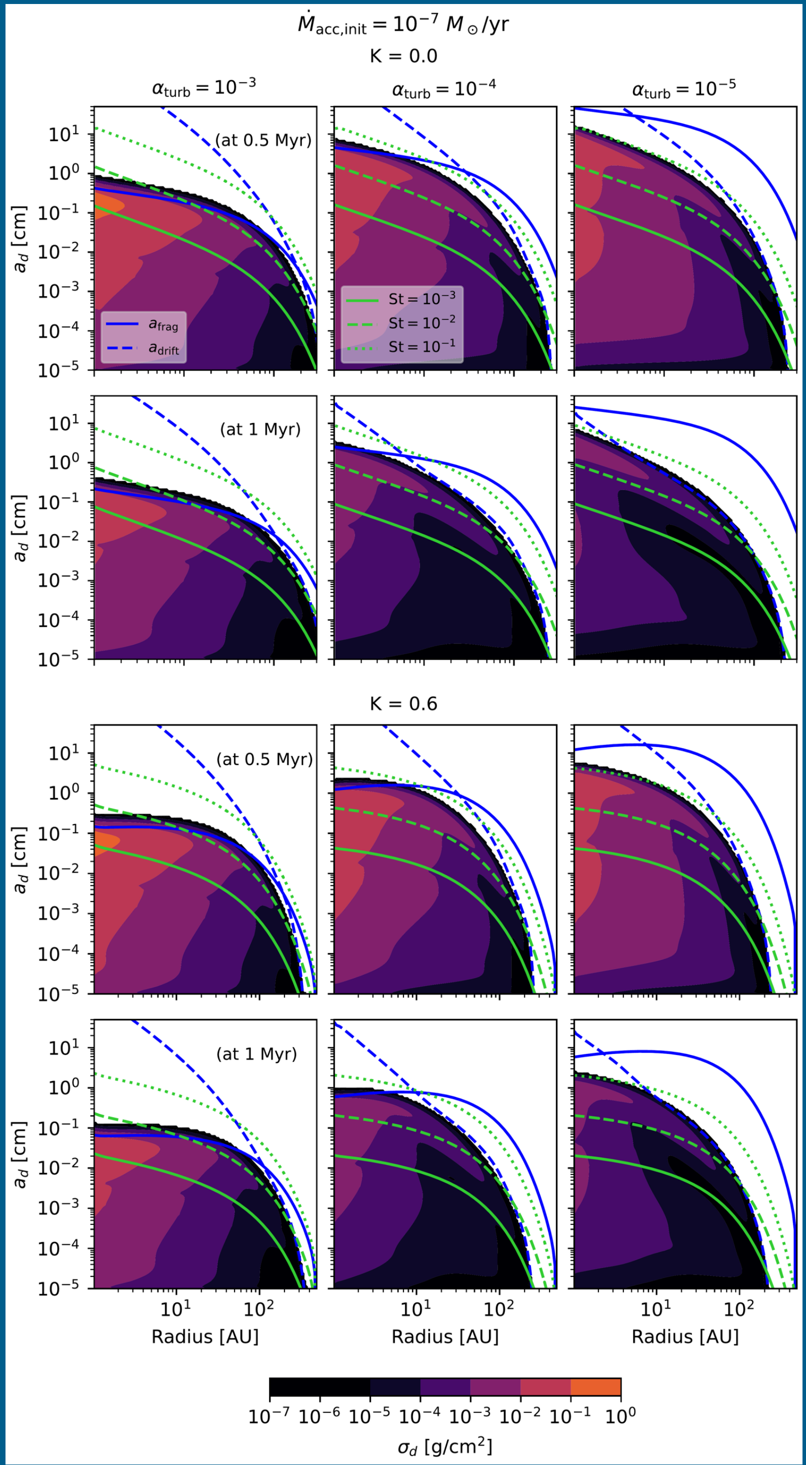
$$\alpha_{turb} \sim 10^{-3} - \ 10^{-4}$$

(Teague's talk)

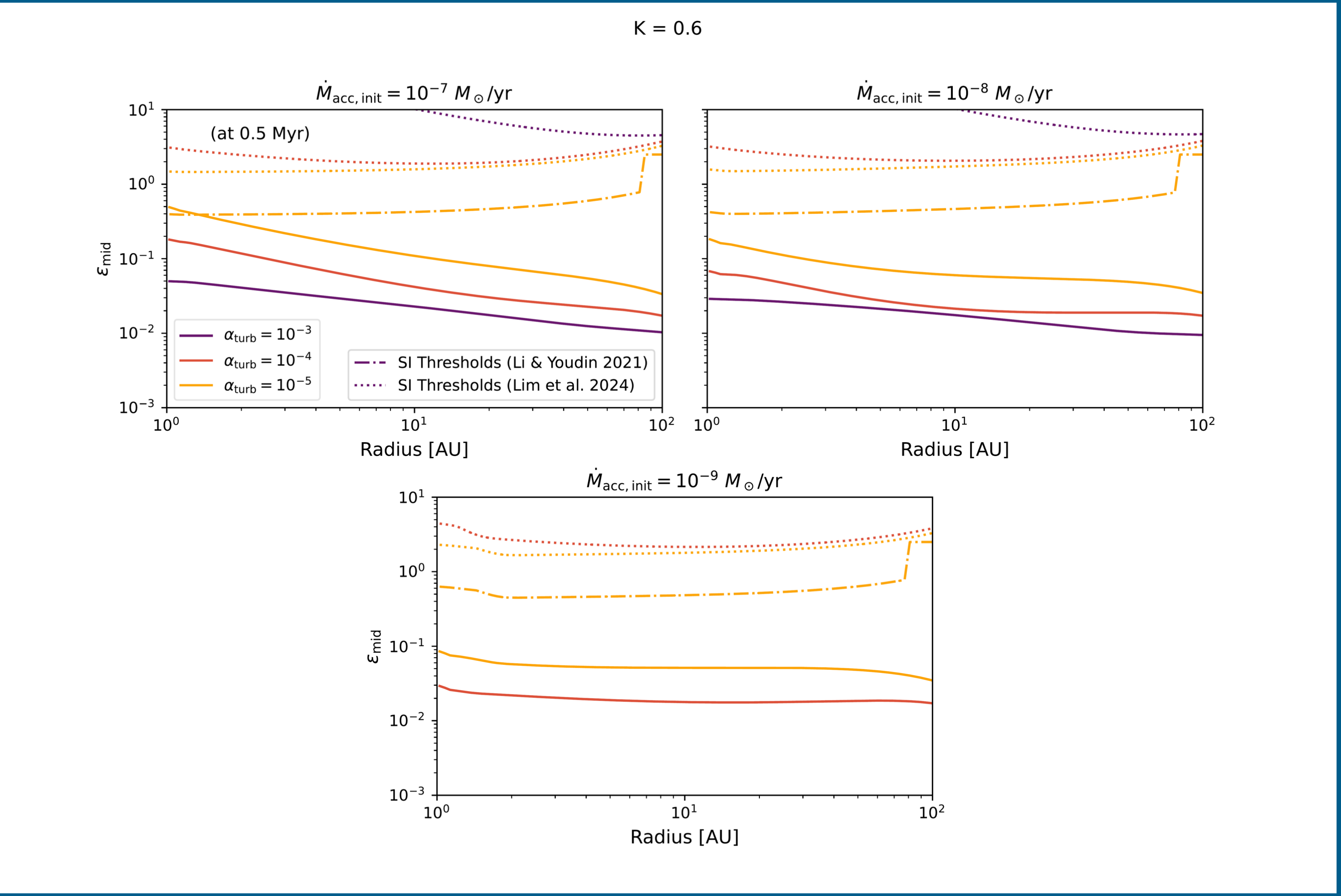
Results:

- low turbulence: dust size 2 decades larger;
- Radial drift limit dominates fragmentation below:

$$\alpha_{turb} \sim 10^{-4}$$



Critical threshold for planetesimal formation reached?



Main result:

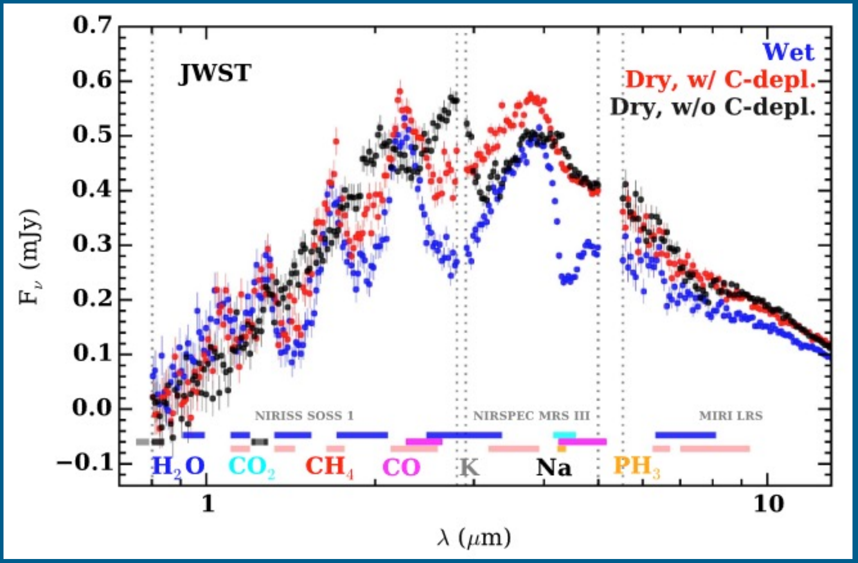
No planetesimal formation in uniform disk; not even in most extreme case:
very high accretion rates $\dot{M}_w \sim \dot{M}_a$ + very low turbulence ($\alpha \sim 10^{-5}$);on scales ~ 1AU

3. Population Synthesis:

A bold step! (Mordasini +2016)

Combine planet formation with disk chemistry – predict JWST osrvations!

Inspiration for our work
(Cridland+2016, 2019, Alessi& Pudritz 2022,….)



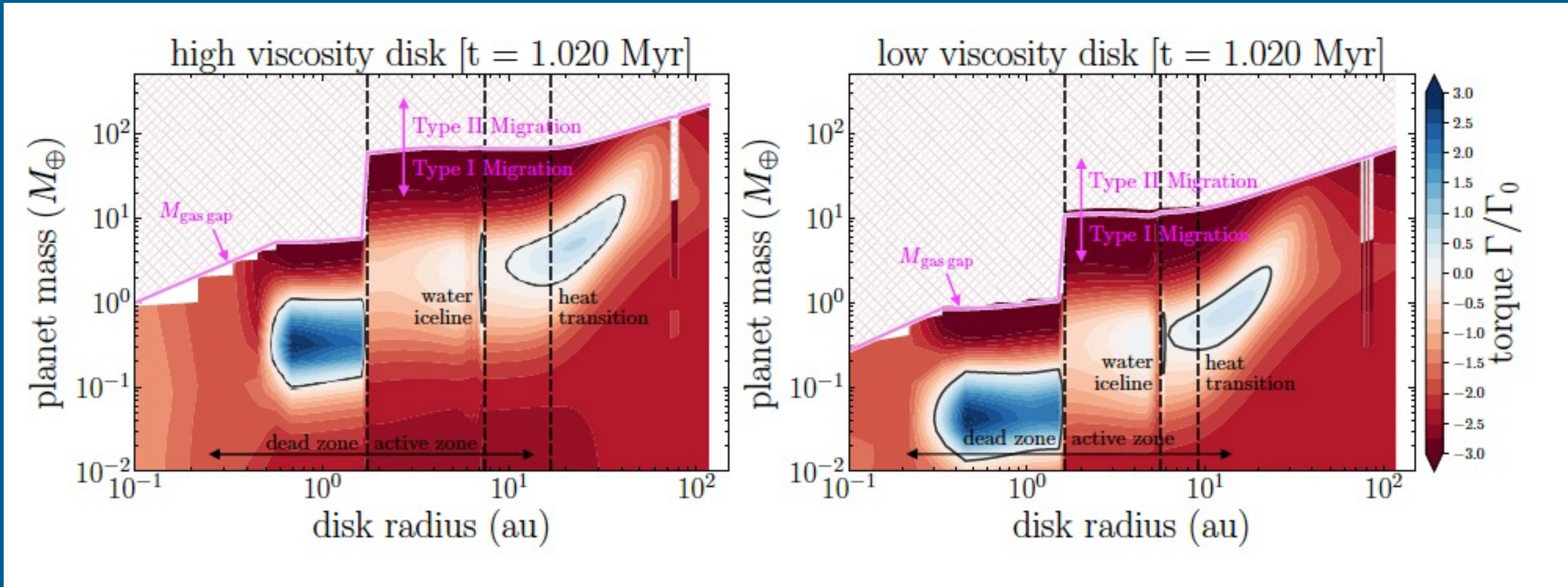
Mordasini…Henning…+2016,

3.1 Migration and planet traps

(Speedie, Pudritz, Cridland, Meru & Booth 2022)

$\Gamma = \Gamma_L + \Gamma_C$ Planet traps: Γ=0

Migration Theory: Tanaka Paadekooper+2011; Torque maps: Coleman & Nelson 2014)



$\alpha = 10^{-3}$ $\alpha = 10^{-4}$

• Planet traps: - zero net torque (Hasegawa & Pudritz 2011, 2012, Cridland + 2019)

-Dead zones : inner edge of DZ, (Masset et al 2006); outer edge of DZ (Matsumura & Pudritz 2007, 2009, Hasegawa & Pudritz 2010 Alessi+2016)

-ice lines : (Kretke & Lin 2012, Matsumura + 2007, Hasegawa & Pudritz 2010)

-Heat transition : viscous to stellar heating (Hasegawa & Pudritz 2010, Lyra + 2010)

3.2 Combined Effect of Disk Winds and Turbulence on Planetary Populations

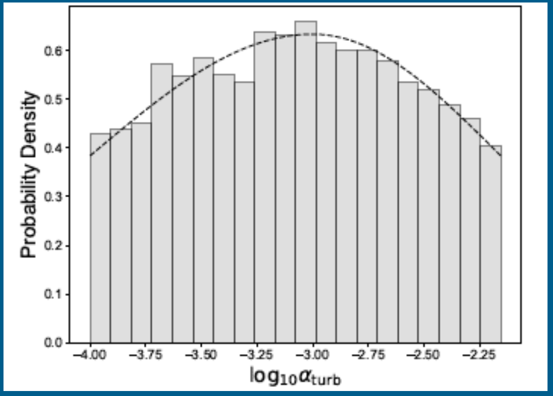
(Alessi & Pudritz 2022)

Model:

- Hybrid model: turbulent and MDW (Suzuki+2016, Hasegawa+2016)
- Disk heating: viscosity (inner) and stellar (Chiang & Goldreich 1994)
- Equilibrium disk chemistry (Alessi, Inglis, Pudritz 2020)
- Analytic self-similar solution for disk evolution (Chambers 2019)
- $\dot{M}_w$ / $\dot{M}_a$ ~ 0.1 (theory and observations)
- Migration: Type 1- in planet traps; Type II

Simulations:

-Over 3,000 models; each with disk chemistry/planetary composition computed



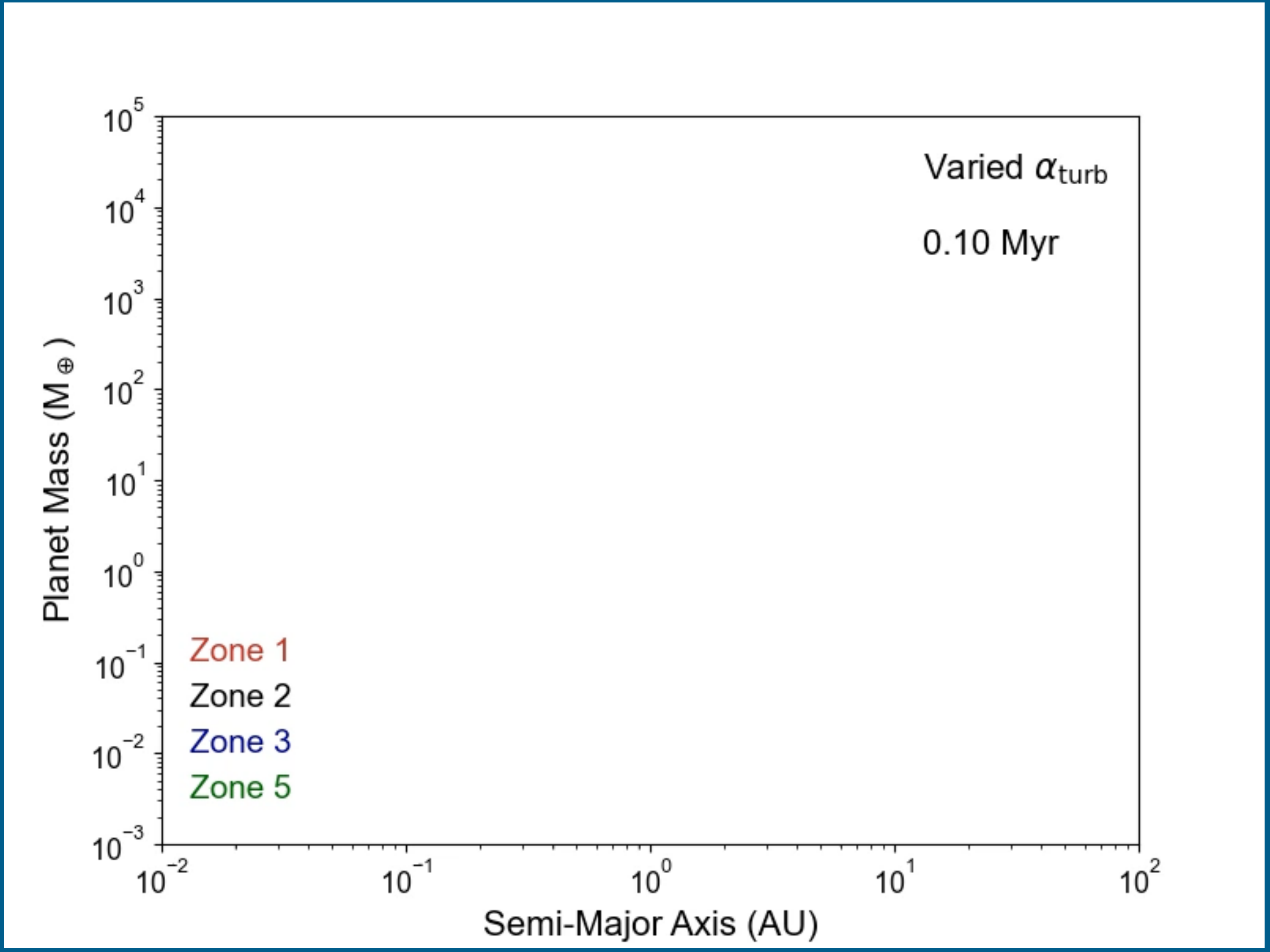
Stochastic variation of:

- disk column density, metallicity, life-times, turbulent α

- one model parameter f_m:

max planet mass = f_m $M_{gas\ gap}$

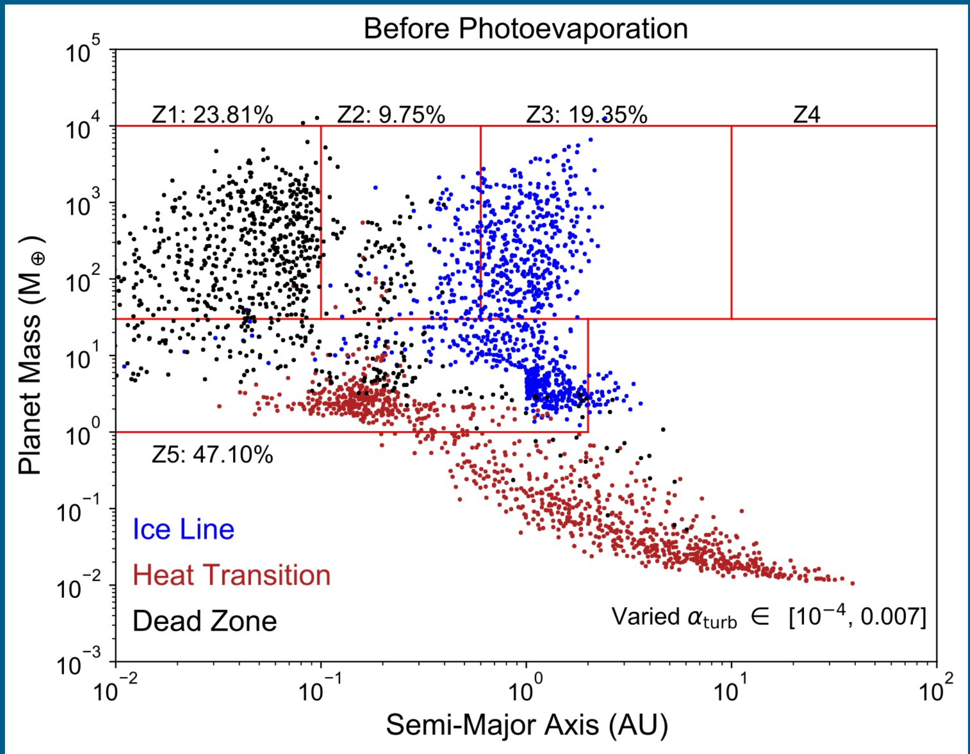
Pop Synthesis: Evolution in the M-a diagram – 50 AU disk – over distribution of turbulence levels

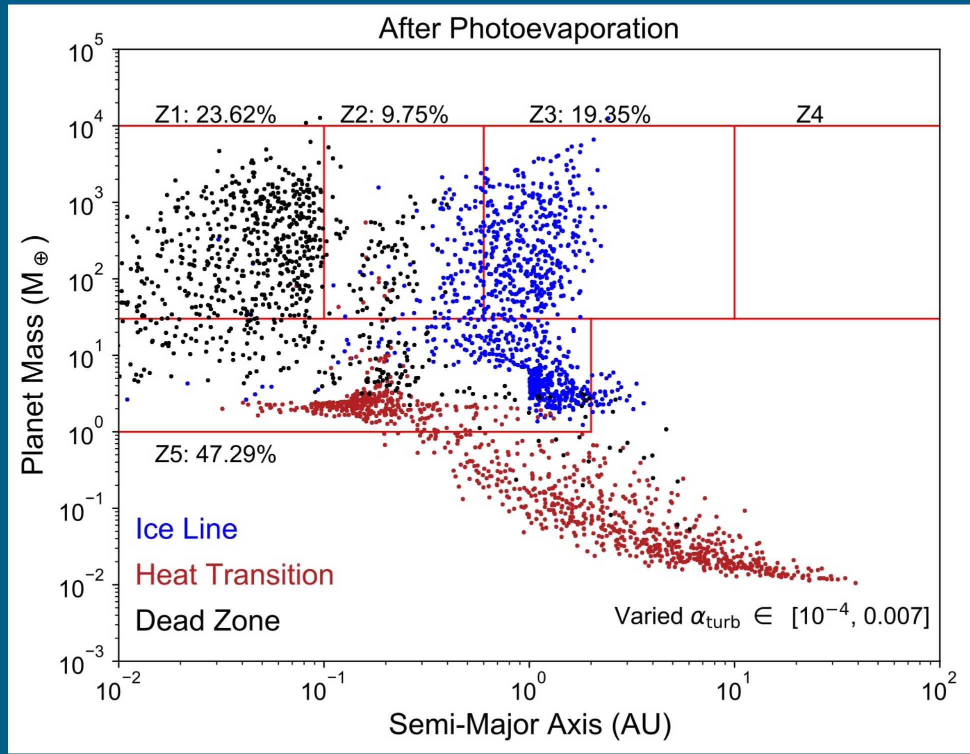


Tracks populating:
Hot Jupiters (Zone 1 - red);
Warm Jupiters (Zone 3 - blue);
SuperEarths (Zone 5- green)

Alessi and Pudritz, 2022;

Best fit to M-a diagram populations:
Intermediate disk initial radii – 50 AU + variable turbulence

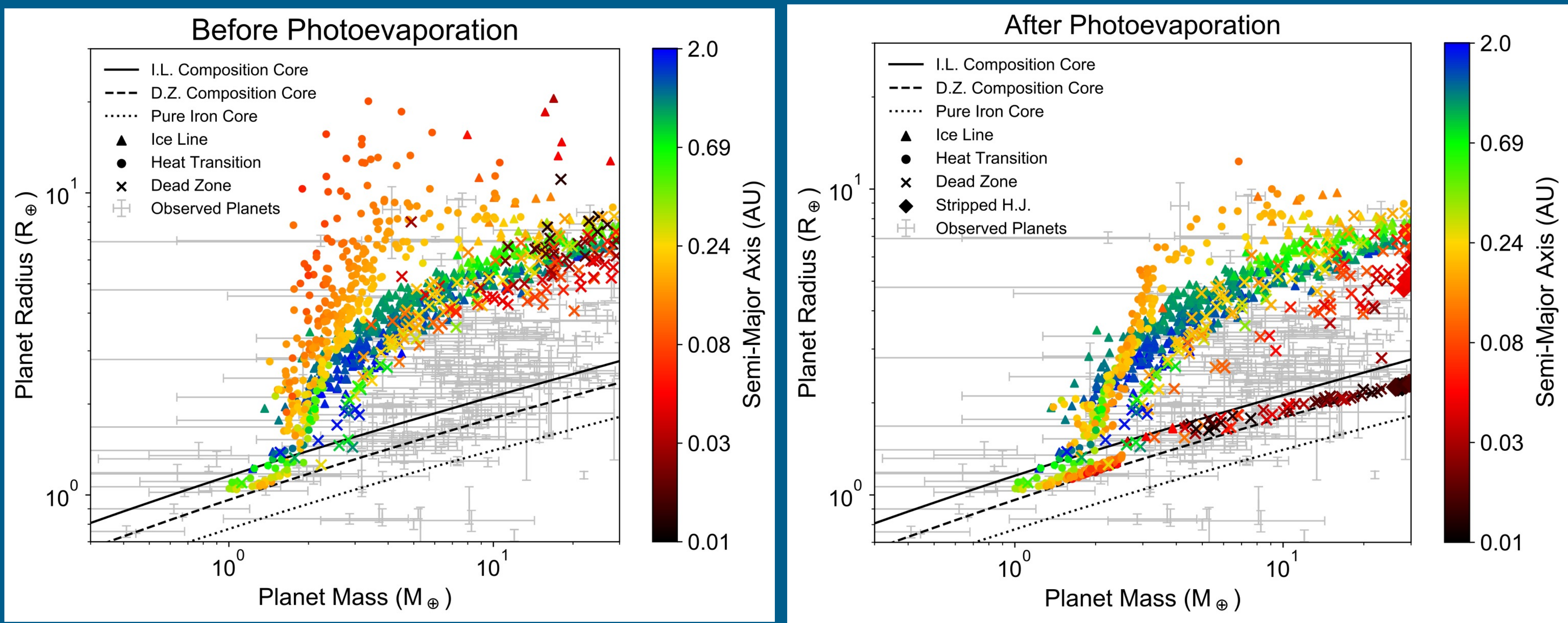




Larger populations at small orbital radii for MDWs than in viscous disks -

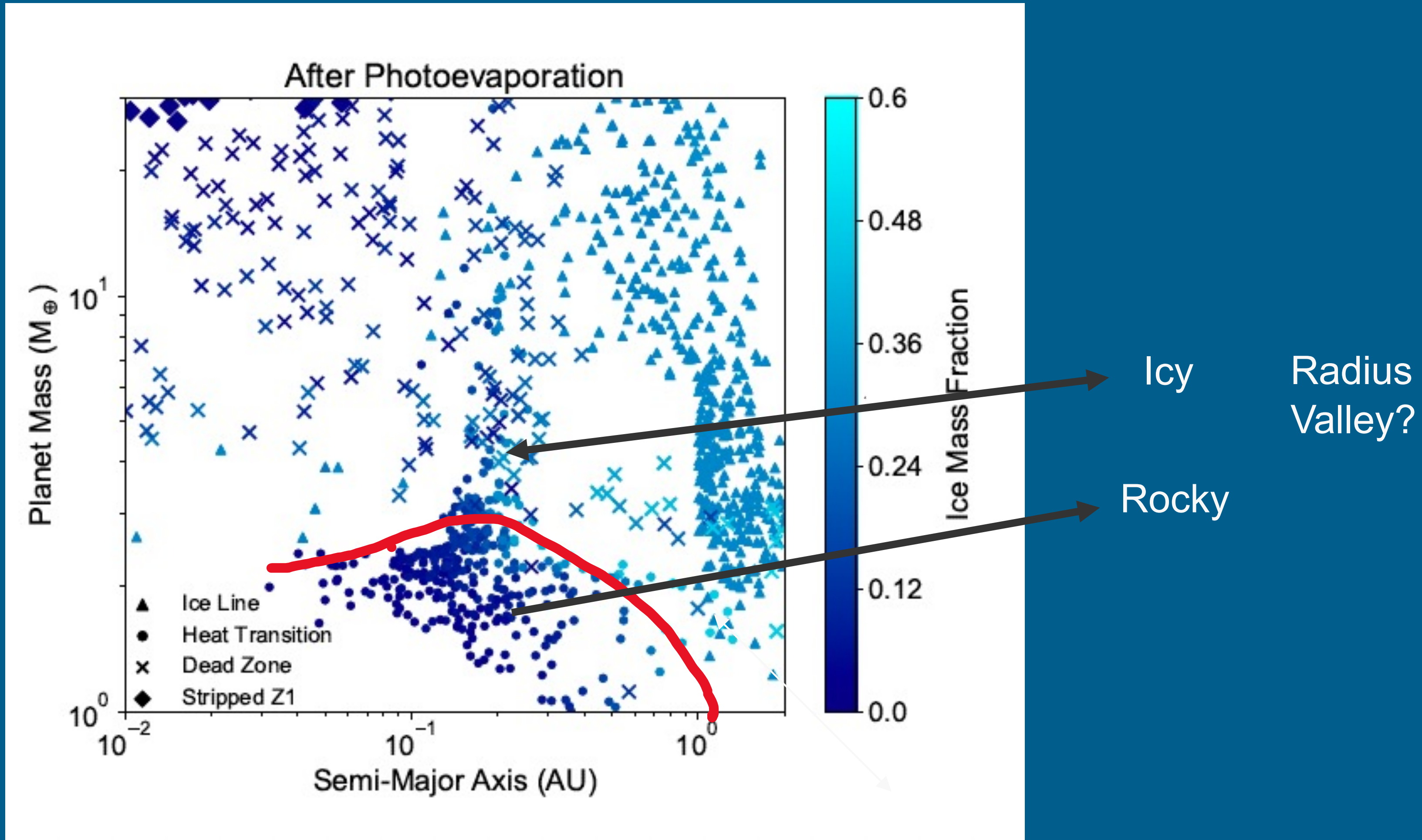
Planetary M-R and atmospheres for SuperEarths generated in different size disks

(Alessi and Pudritz, 2021, following Alessi, Inglis, & Pudritz 2020)



Photoevaporation of close-in hot Jupiters, creates a lot of stripped planets – and better fit to the observations.

Ice Mass Fractions



Dry and Ice rich SEs and Sub Neptunes migrate to deep inside iceline.

3.3 New, Verified Planetary Interior Models

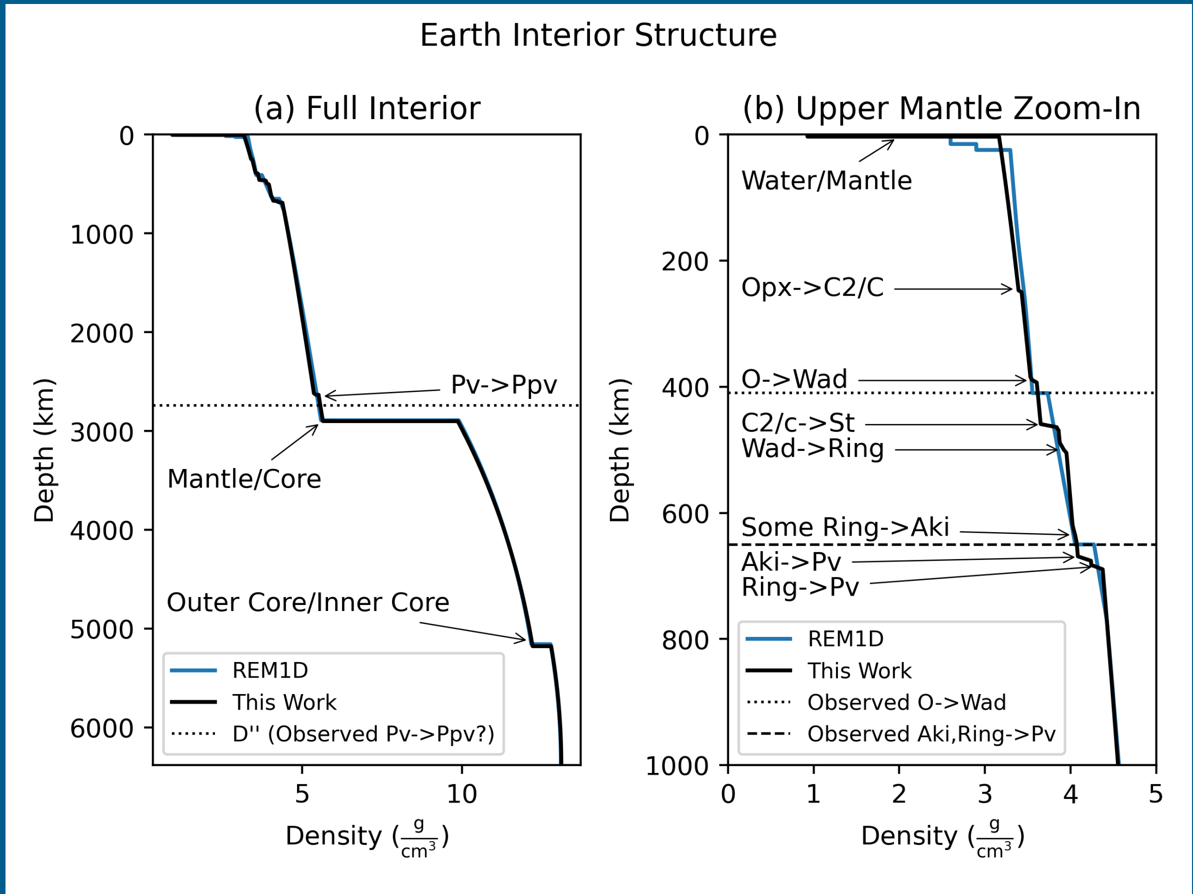
Bennett Skinner, Ralph Pudritz, Ryan Cloutier 2026, MNRAS

- Build best available models of planetary interiors low – intermediate masses to accuracy < 1%

- Compared to Zheng+2019 (standard EOS treatment – “old radii”), updated EOS for:
  - water: AQUA (Haldeman+2020)
  - H/He: Chabrier & Debras (2021)
  - Mantle: thermal contribution, varied minerology – not just silicates
  - Iron core: iron in a variety of phases, iron/sulfur mixtures, (Haldeman+2024)

- Verification: Fit to better than 0.5% of seismology informed, whole Earth interior structure model; “ REM1D”

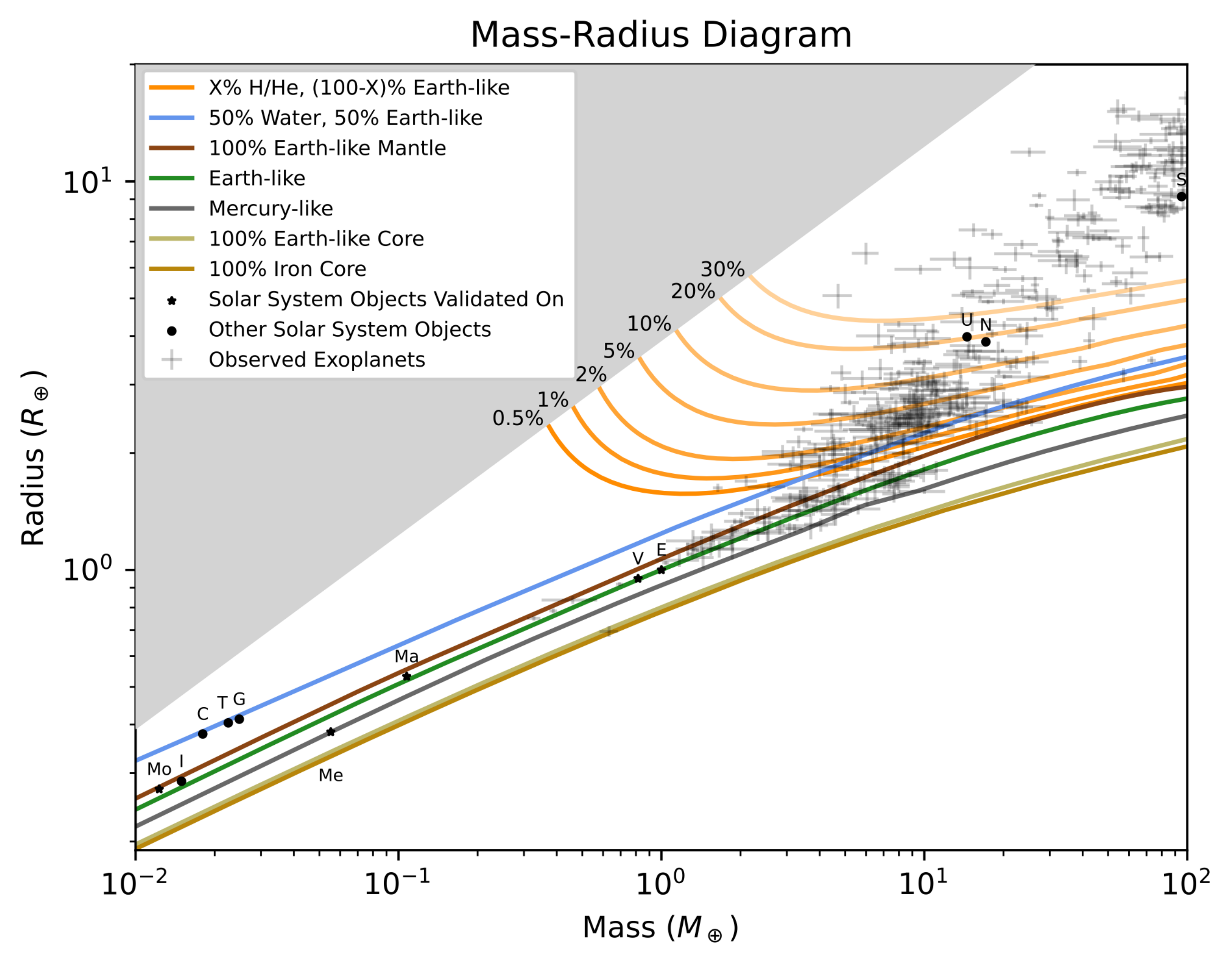
Verification against Earth reference model



Earth reference model REM1D derived from seismic data and other constraints – overlaid with Skinner, Pudritz, Cloutier 2026.

Horizontal lines - observed phase transitions in Earth's interior. Eg. minerals: Pv – Perovskite, O - Olivine

Computed M-R curves:
verified against Earth, Mars, Venus, Mercury, Moon, Enceladus

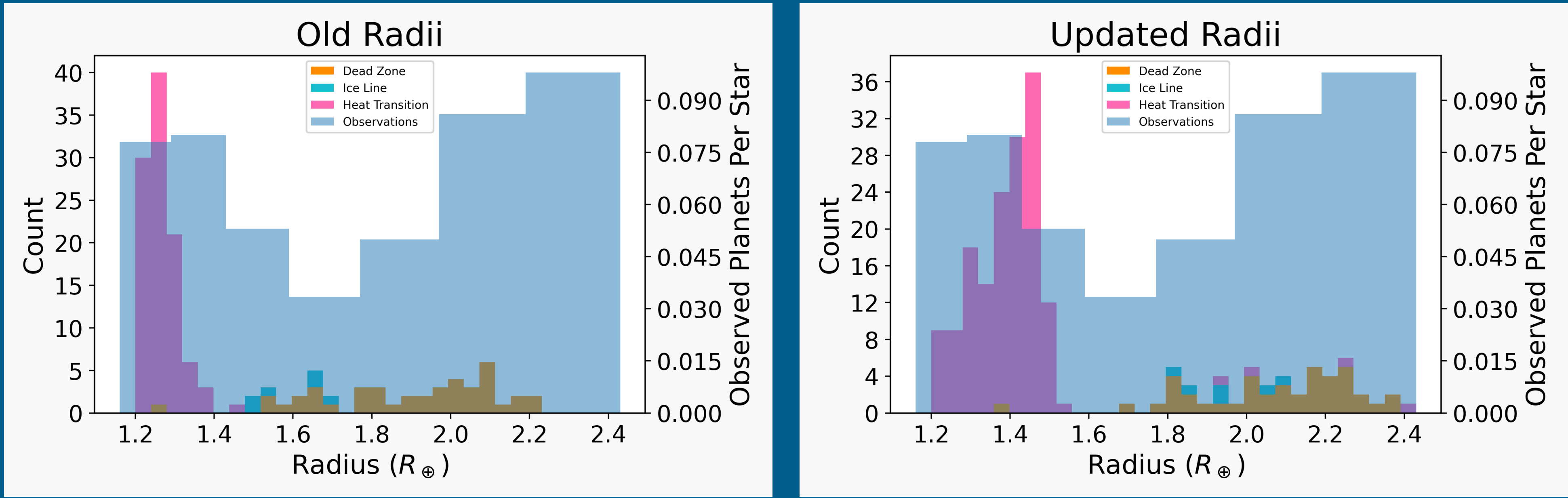


The M-R data available in GitHub repository at:

https://github.com/Bennett-Skinner/SkinnerPudritzCloutier2025-MR-curves/

2. One application: Radius valley in MDW populations?

(Skinner, Pudritz, Cloutier in progress)



Radius valley appears – steam atmosphere mini-Neptunes migrated into inner region – enhanced over pure viscous torques

Perspectives:

- MDWs fundamentally change the ball game of planet formation:
  - angular momentum loss
  - nearly laminar accretion flow -> rapid dust growth/evolution
  - PPD properties (disk radius, column density,..)
  - planet migration
  - planet composition / structure / populations

(Review, Pudritz, Cridland, Inglis, Alessi 2026, in Handbook of Exoplanets, 2nd Edition (Springer))

- The future:
  - How and where do pressure bumps form?
  - Necessary conditions for observed planet populations?
  - Are other non-planetary mechanisms “predictive”?
  - Can MDWs create pressure bumps sufficient to form first planets?
  - What properties /distributions would these have?

Much joy in your new evolutionary stage Thomas!

- Scientist (Emeritus: the best part?)
- Collaborator
- Traveler
- Thinker
- Writer
- ….. !

A leisurely outing to Kolmar and some Alsatian wine….

Heidelberg Schloss Beleuchtung, July 8, 2023.
Image credits - me