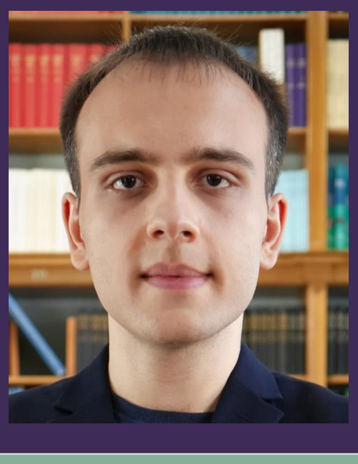

Most Rocky Sub-Neptunes are Molten: Mapping the Solidification Shoreline for Gas Dwarf Exoplanets

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Summary

- Sub-Neptunes are the most common type of discovered exoplanet, yet many aspects of their nature remain poorly understood, particularly their potential habitability.
- If sub-Neptunes with H_2-dominated (μ<3.8 g mol−1) atmospheres and Earth-like interiors, i.e., Gas Dwarfs, have magma oceans, they will not be habitable.
- We find that the vast majority of sub-Neptunes, if they are gas dwarfs, have permanent magma oceans. This implies that habitable sub-Neptunes could be rare.

Methods

- We use the PROTEUS modelling framework (Lichtenberg et al 2021; Nicholls et al 2024; Nicholls et al 2025) to model the coupled-interior atmospheric evolution of gas dwarfs from an initially molten state.
- PROTEUS solves for the thermal structure of the mantle, the thermal structure of the atmosphere, and the partitioning of volatiles between the mantle and the atmosphere.
- Planetary evolution continues until either the mantle solidifies, or the planet achieves energetic equilibrium. The later state corresponds to a permanent magma ocean.

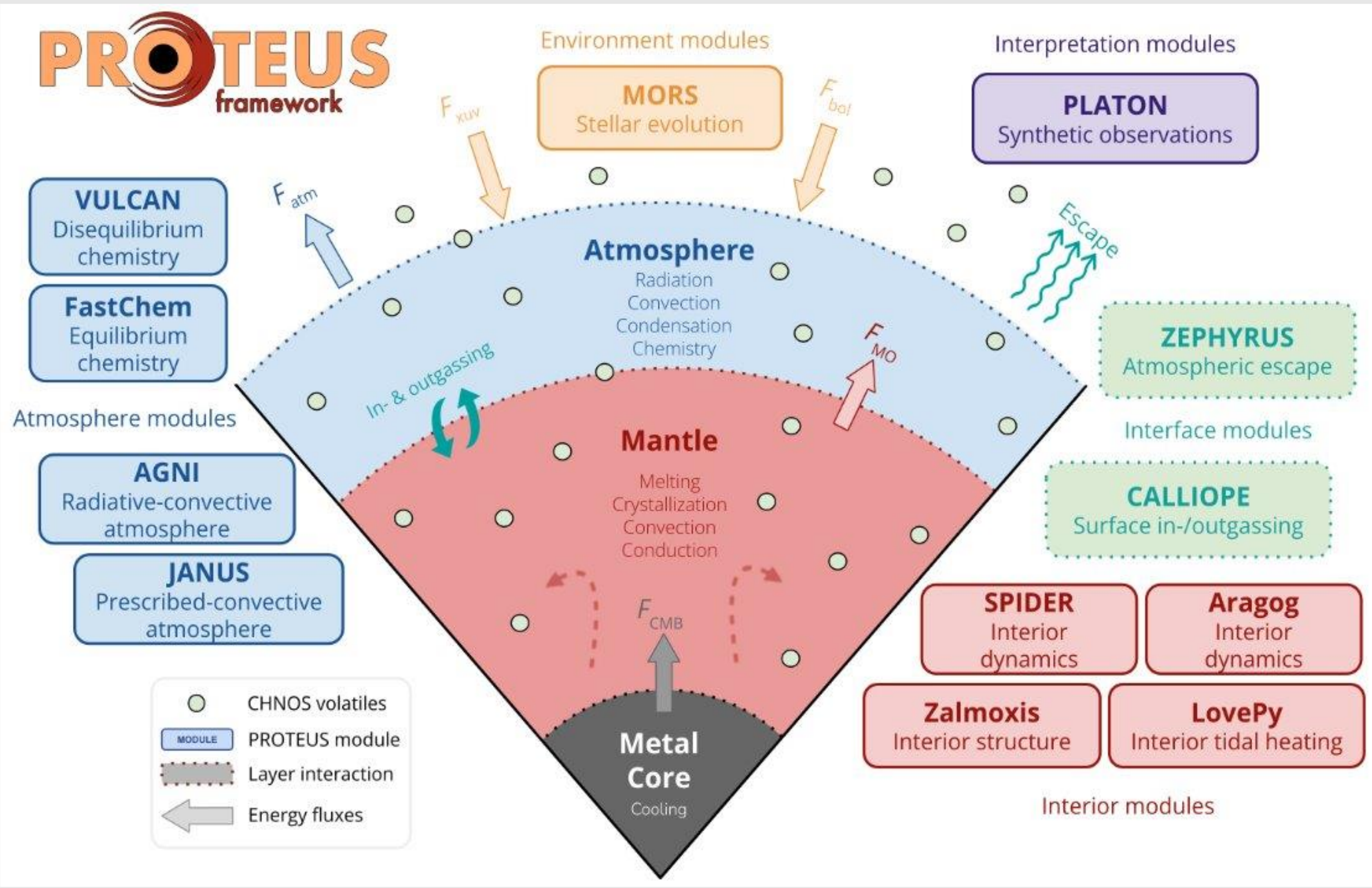

Fig 1: Summary of the PROTEUS modelling framework, including all the sub-modules (credit: PROTEUS Collaboration).

References

- Lopez, Eric D., and Jonathan J. Fortney. The Astrophysical Journal 792.1 (2014): 1.
- Lichtenberg, Tim, et al. Journal of Geophysical Research: Planets 126.2 (2021): e2020JE006711.
- Nicholls, Harrison, et al. Journal of Geophysical Research: Planets 129.12 (2024): e2024JE008576.
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The Solidification Shoreline

- We determine the instellation flux as a function of envelope mass fraction at which the thermal steady state transitions from a solidified mantle to a permanent magma ocean (i.e., the 'solidification shoreline').
- We find that 98% of detected sub-Neptunes lie in the region of this parameter space consistent with them having a permanent magma ocean (fig 2).

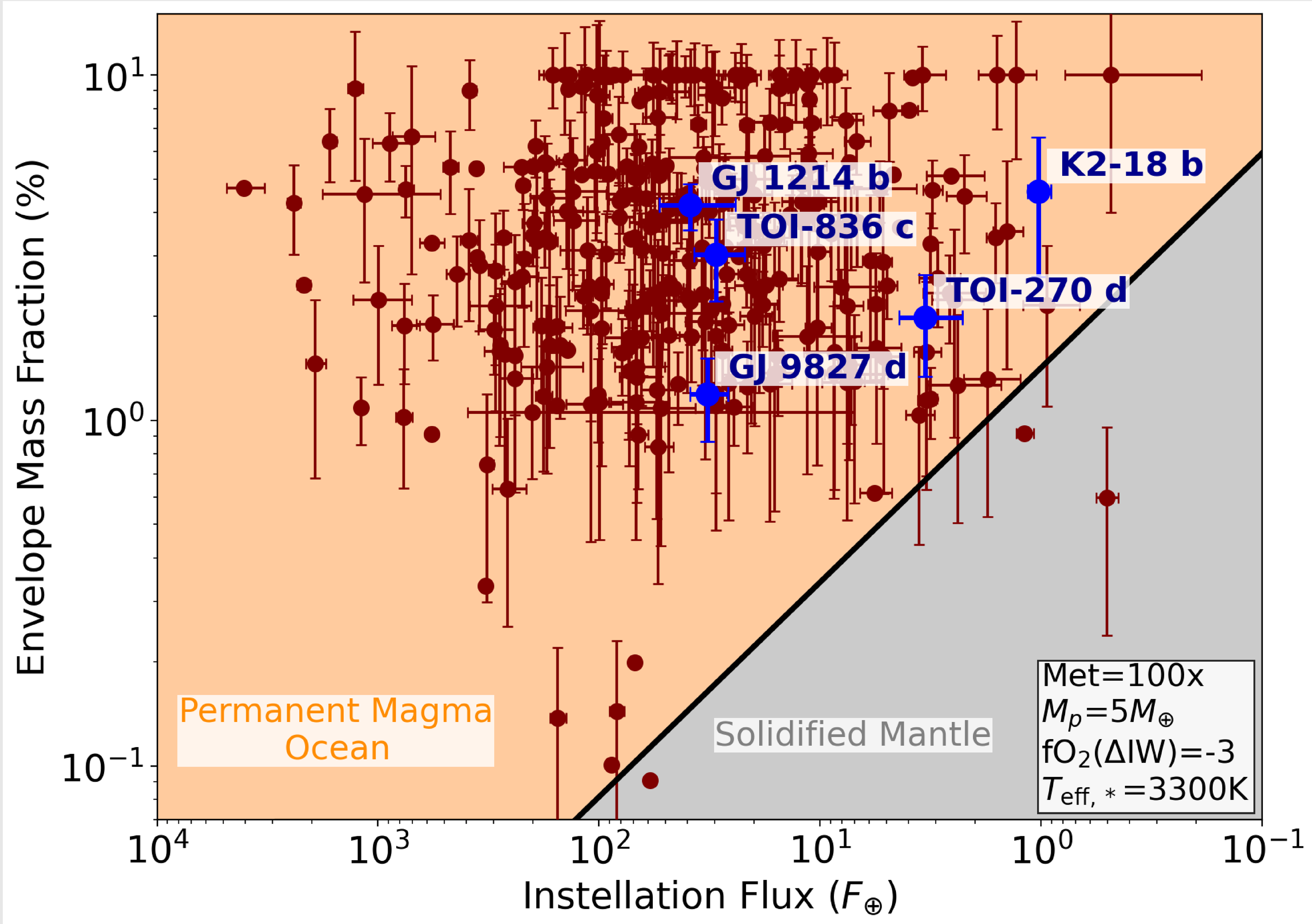

Fig 2. The instellation flux as a function of envelope mass fraction at which the thermal steady state of a gas dwarf transitions from a solidified mantle to a permanent magma ocean. Detected sub-Neptunes are plotted, with their EMF estimated using equation 2 in Lopez and Fortney (2014).

The Effects of Atmospheric Composition

- Given the effect of atmospheric opacity on surface heating, the location of the shoreline could change for different atmospheric compositions resulting from oxidising or carbon-rich mantles.
- However, atmospheric compositions that deviate from an H2-dominated case have mean molecular weights greater than 3.8 g mol[-1], placing them outside our gas dwarf classification (fig 3).
- Therefore, the solidification shoreline, applied specifically to gas dwarfs, is insensitive to atmospheric composition.

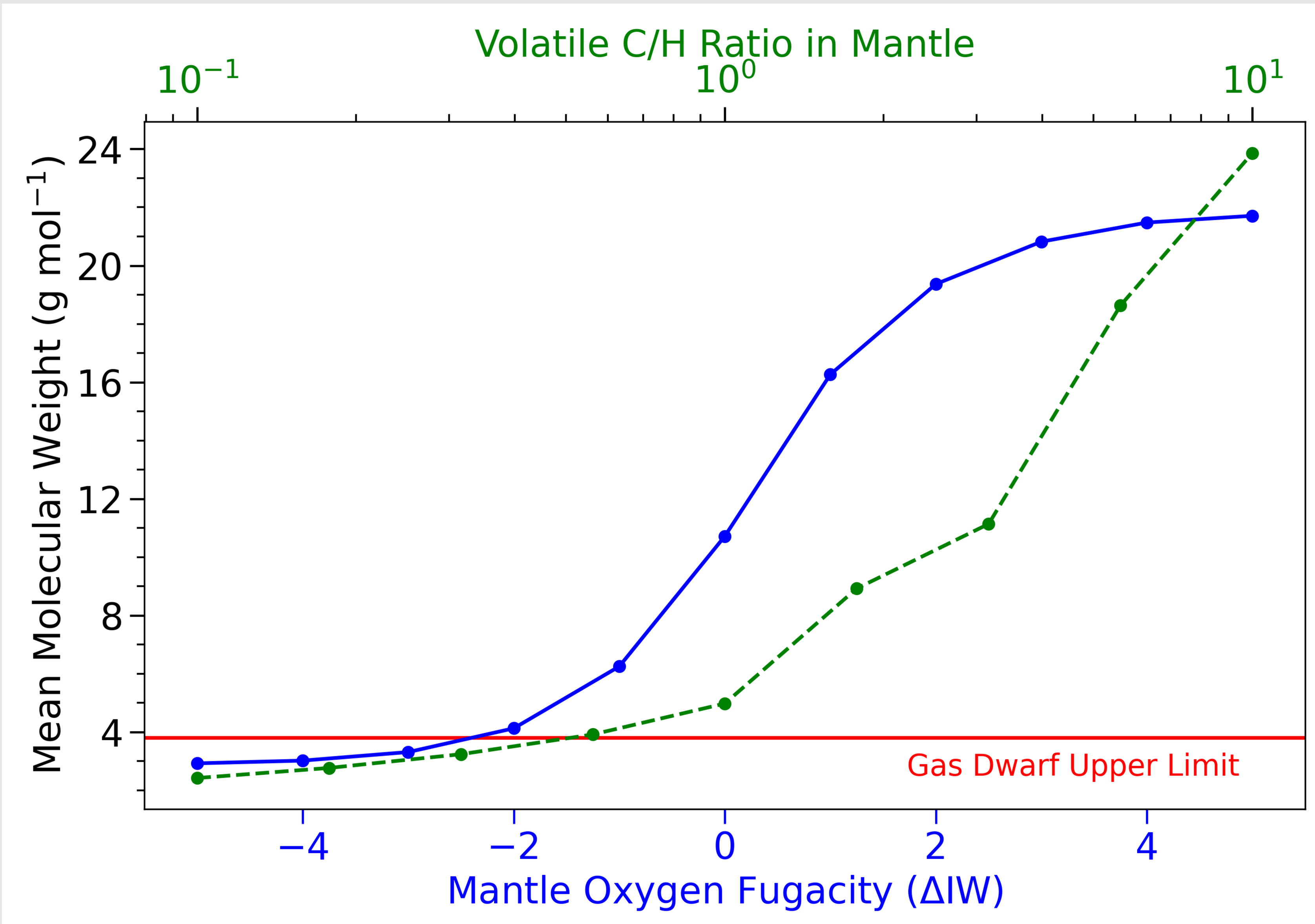

Fig 3. Atmospheric mean molecular weight as a function of mantle oxygen fugacity (solid) and volatile C/H ratio (dotted).

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