GOLDSCHMIDT
BARCELONA 2019
18–23 AUGUST

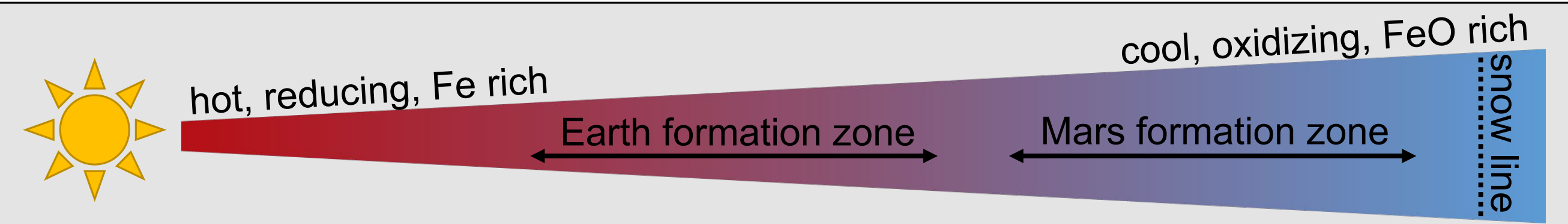
Martian core formation:

Implications from the Hf–W system

Matthew C. Brennan[1]*, Rebecca A. Fischer[1], Francis Nimmo[2], David P. O'Brien[3]
[1]Department of Earth and Planetary Sciences, Harvard University; [2]Department of Earth and Planetary Sciences, UC Santa Cruz; [3]Planetary Science Institute
*mcbrennan@g.harvard.edu

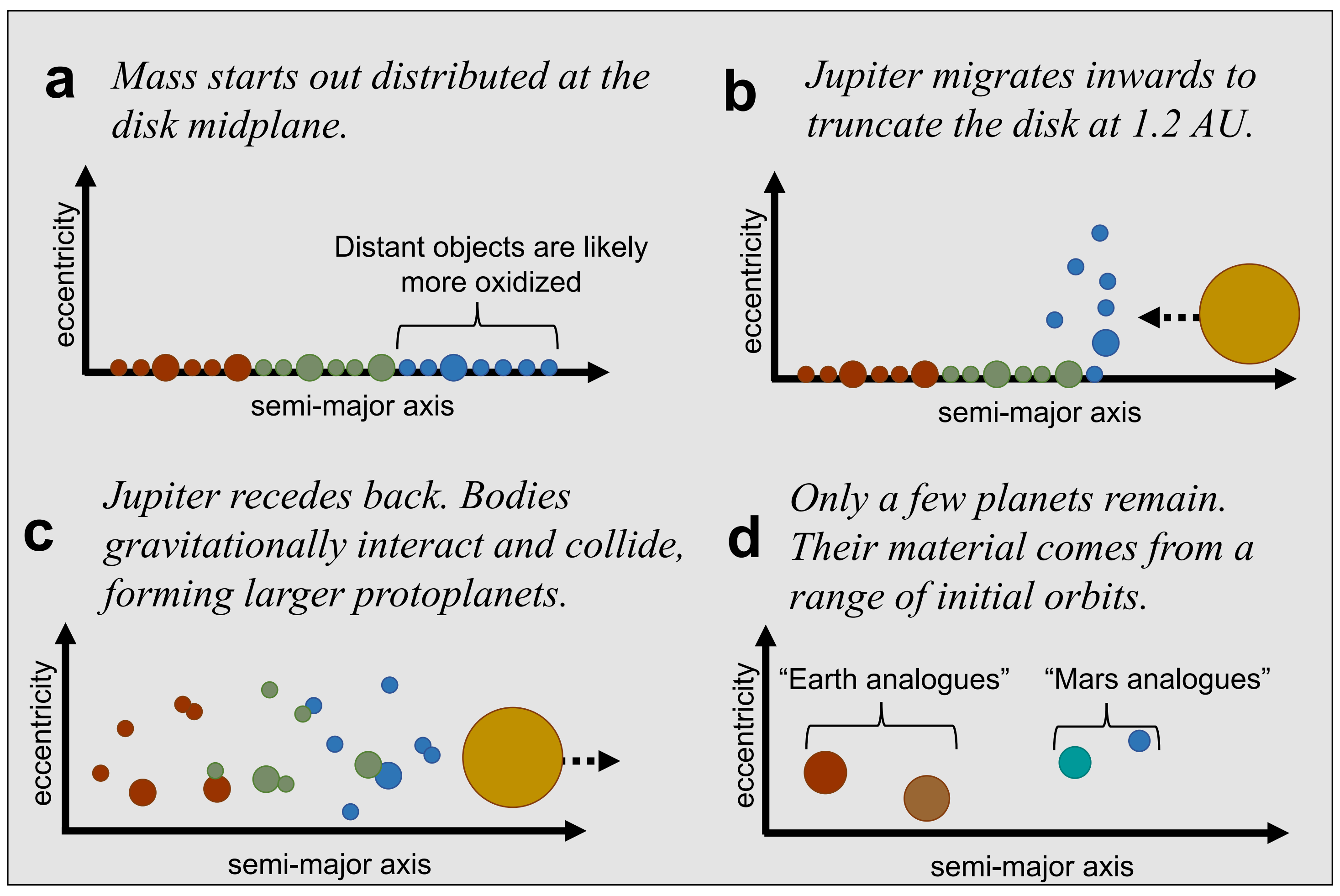
Background/Motivation

- The Martian mantle is enriched in iron and moderately-volatile elements, but depleted in chalcophile elements relative to Earth's mantle [1].
- These properties could be explained if Mars formed from volatile-rich, oxidized materials. Materials like these are likely to have condensed further out in the protoplanetary disk [2].
- Uncovering the narrative of Martian formation requires combining geochemical evidence with models of planetary accretion and core formation.
- Our previous modeling of major, minor, and trace elements during Martian core formation [3] suggests a high degree of metal–silicate equilibration, which can be further tested with the Hf–W system.



Temperature decreases with distance from the sun, allowing more volatiles (including O-bearing species) to condense.

Planetary accretion: *N*-body models



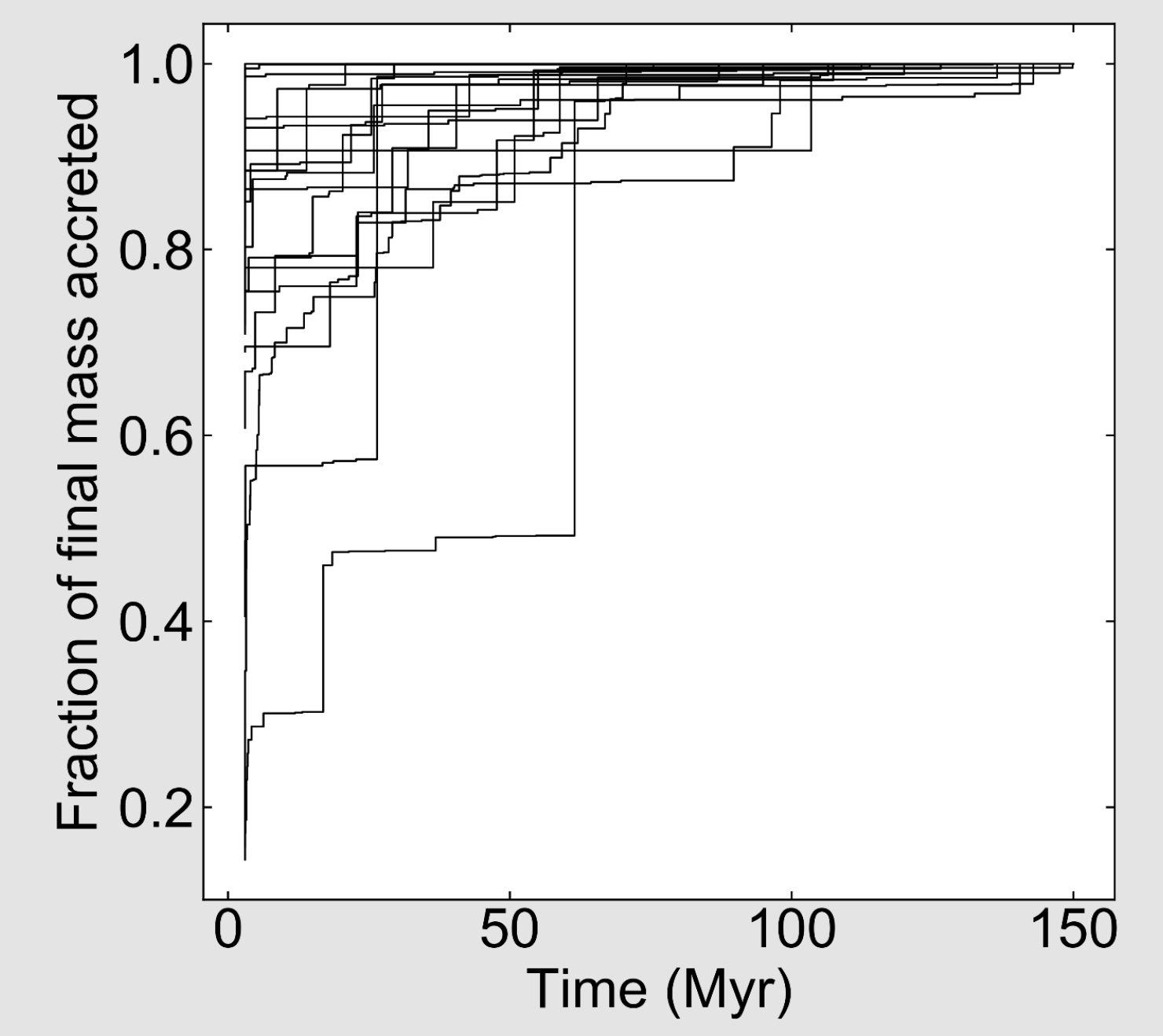
a *Mass starts out distributed at the disk midplane.*

b *Jupiter migrates inwards to truncate the disk at 1.2 AU.*

c *Jupiter recedes back. Bodies gravitationally interact and collide, forming larger protoplanets.*

d *Only a few planets remain. Their material comes from a range of initial orbits.*

- *N*-body models simulate the mutual gravitation of a large number of protoplanetary bodies. Examining the resulting solar system configurations can reveal possible planetary dynamical histories.
- The behavior of the gas giants influences terrestrial planet accretion. Here, we examine the Grand Tack [7], in which Jupiter truncates the early disk.



N-body growth histories of our Mars analogues [8]. Times are post-CAI.

Geochemical evidence: Hf–W

- The hafnium–tungsten (Hf–W) decay system is often used to date core formation due to the short half-life of ^{182}Hf and the differing metal–silicate affinity of its daughter product (^{182}W).

Hf	refractory lithophile	^{180}Hf	Stable
		^{182}Hf	Unstable ($t_{1/2}$ = 9 Myr)
W	refractory siderophile	^{183}W	Stable
		^{182}W	Stable (daughter of ^{182}Hf)

- $f^{Hf/W}$ is the ratio of stable ^{180}Hf to stable ^{183}W, and describes how strongly siderophile W is during core formation.

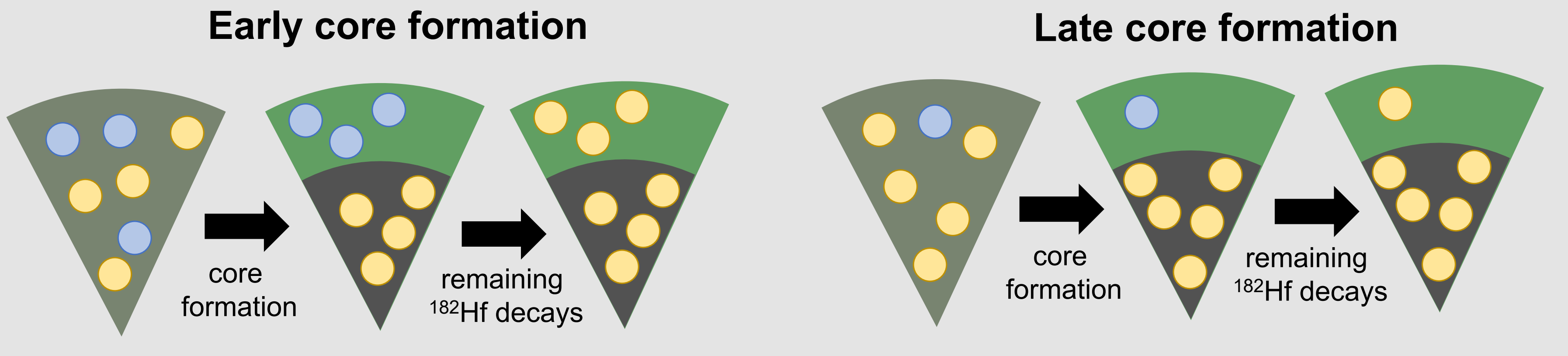
$$f^{Hf/W} = \frac{\left({}^{180}Hf/{}^{183}W\right)_{mantle}}{\left({}^{180}Hf/{}^{183}W\right)_{CHUR}} - 1$$

  - Earth's $f^{Hf/W}$ (12 ± 2) [4] is larger than the value for Mars (2.0 ± 0.8) [4] because W is less siderophile at higher pressures [e.g., 5].

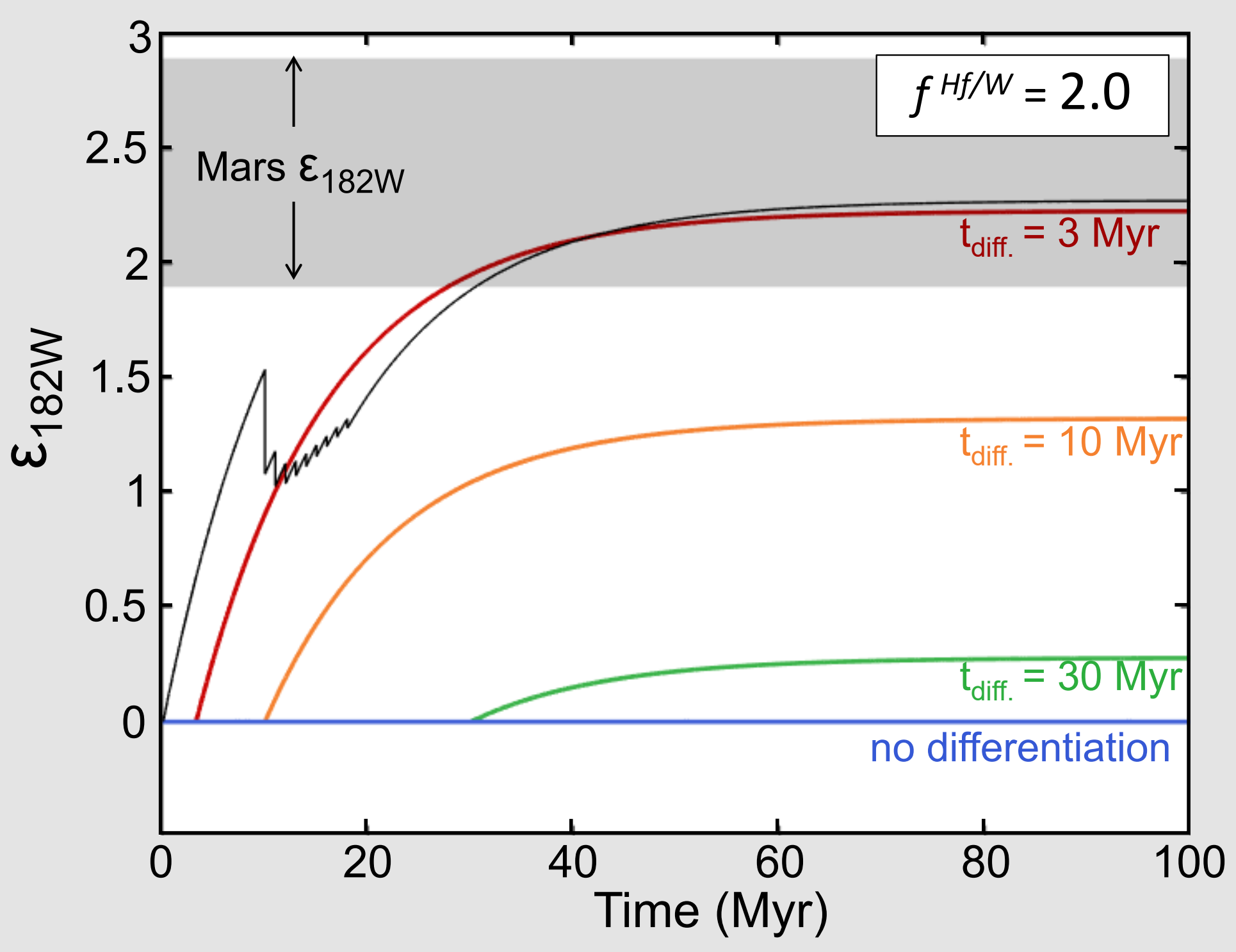
- ε_{182W} is the ratio of radiogenic ^{182}W to non-radiogenic ^{183}W, and describes how early core formation was completed.

$$\varepsilon_{182W} = \left[\frac{\left({}^{182}W/{}^{183}W\right)_{mantle}}{\left({}^{182}W/{}^{183}W\right)_{CHUR}} - 1\right] \times 10^4$$

  - ε_{182W} of Earth (1.9 ± 0.2) [4] and Mars (2.4 ± 0.5) [4] are similar. The smaller $f^{Hf/W}$ value in Mars means that its core formation must have ended earlier [e.g., 6] to build up a similar ε_{182W}.



Decay of ^{182}Hf (blue) to ^{182}W (yellow) during and after core formation. Bodies that differentiate early end up with more ^{182}W in their mantles.



To calculate the evolution of ε_{182W}, previous studies [e.g., 4,6] usually assumed that core formation occurred at a discrete time (colored lines).

However, realistic planetary growth is episodic, with portions of core material being added with each accreted body. The black line shows one example of a more complex history that also can match the Martian ε_{182W}.

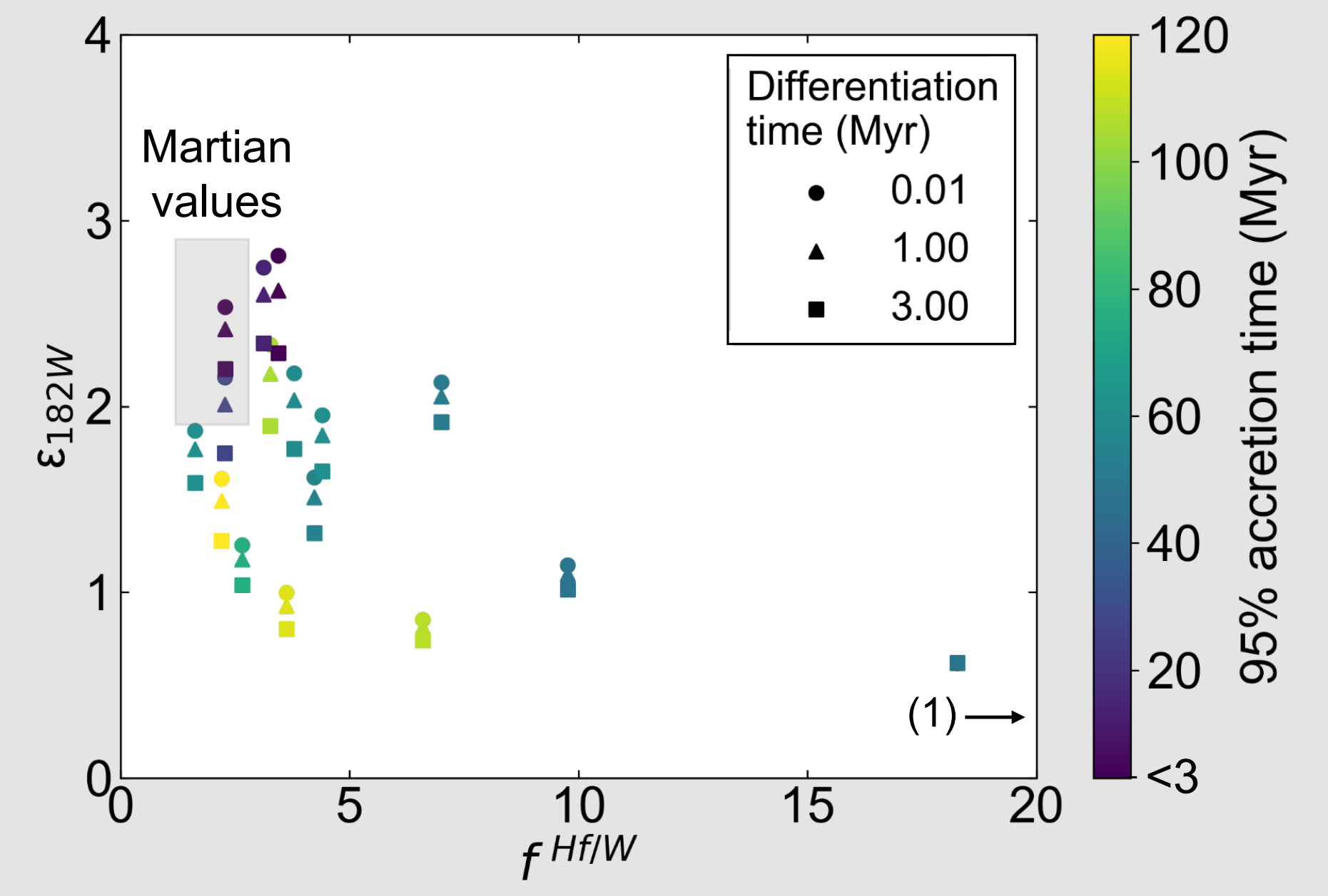
Core formation: preliminary results

Using a set of Grand Tack *N*-body outputs [8], we have modeled the metal–silicate partitioning of W [5] during accretion of 18 Mars analogues and tracked the decay of ^{182}Hf. The analogues' final ε_{182W} and $f^{Hf/W}$ signatures are highly sensitive to the style and timing of core formation.

Except where indicated, core formation calculations were performed with the following model parameters:

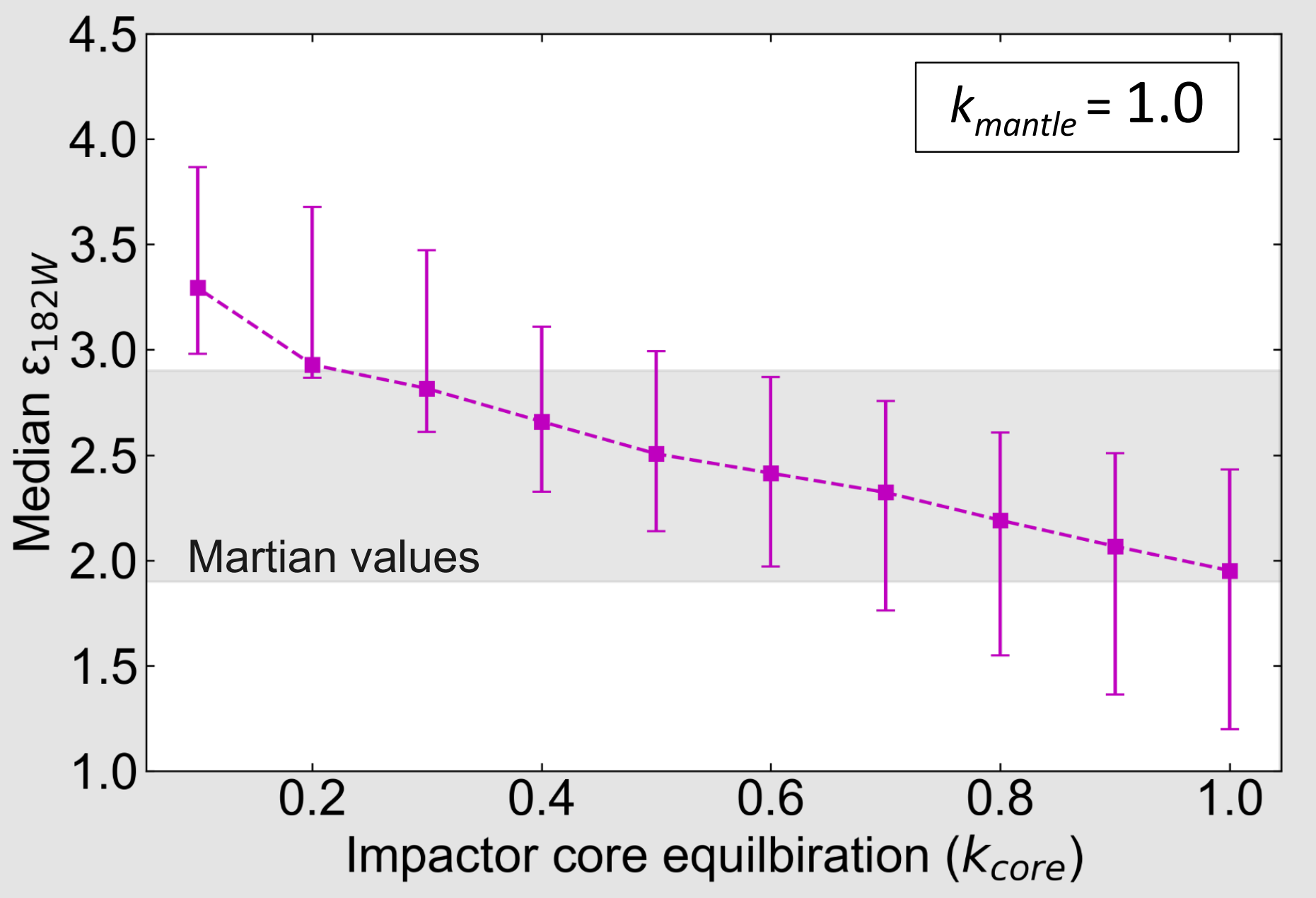
Time of differentiation	0.01 Myr
Time of simulation start	3 Myr
k_{core}	1.0
k_{mantle}	1.0
Inner disk fO_2	IW–4.0
Outer disk fO_2	IW–1.5
Location of fO_2 step	1.4 AU

Timing of formation



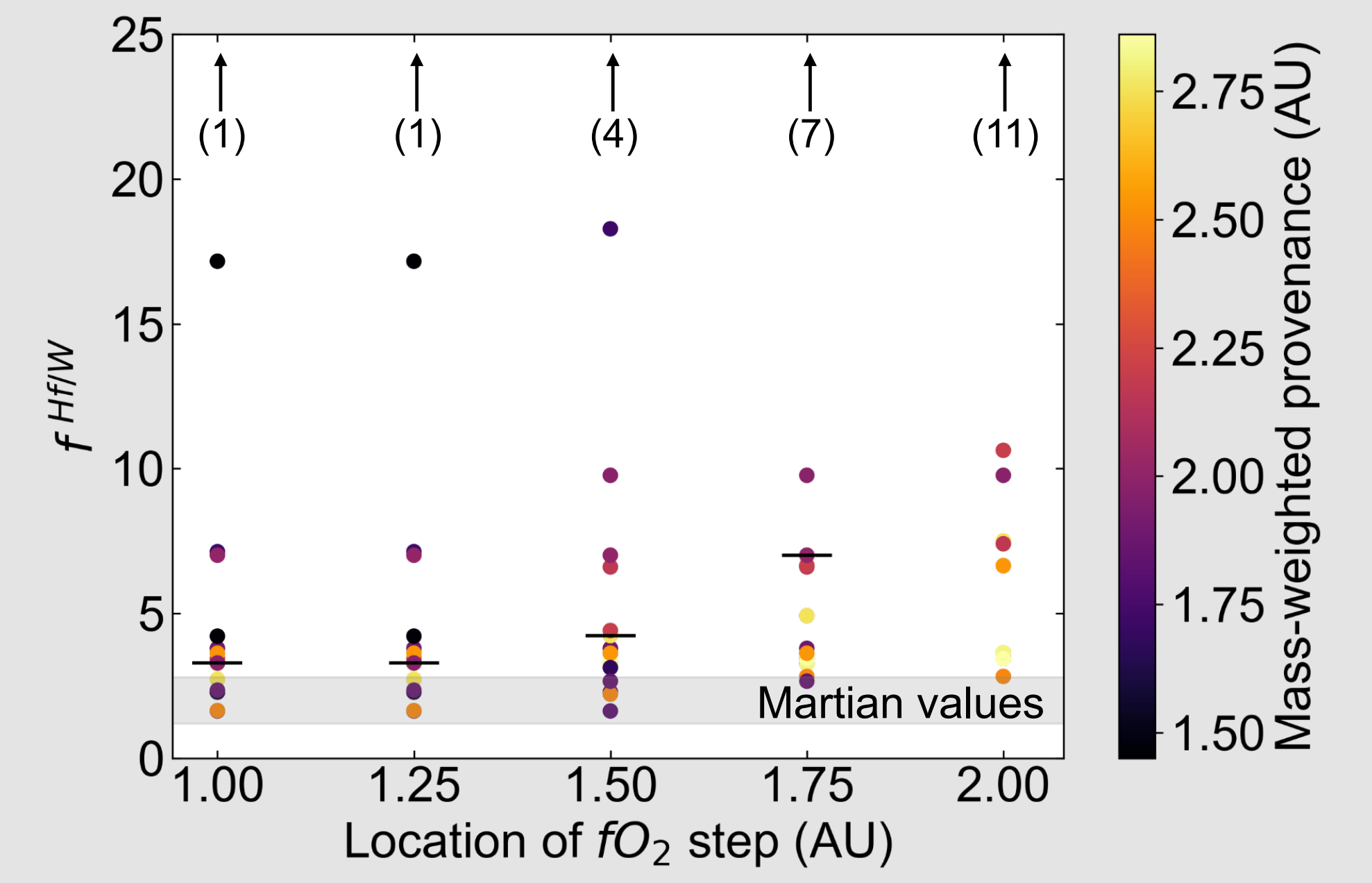
The ε_{182W} values of the Mars analogues versus their $f^{Hf/W}$. Times are relative to CAI condensation. Most analogues reach 50% mass before the start of the simulation at 3 Myr [6].

Partial equilibration



Median ε_{182W} of Mars analogues for different degrees of metal–silicate equilibration. More equilibration lowers ε_{182W}. Error bars represent lower and upper quartiles.

Oxidation state of protoplanetary disk



Analogue $f^{Hf/W}$ versus the location of the reduced-to-oxidized transition. A larger reduced region leads to higher median $f^{Hf/W}$ (black bars) and more analogues with high $f^{Hf/W}$ (top numbers).

Future work

- Many of the Mars analogues experience most of their growth during the pre-simulation "oligarchic regime" [e.g., 6]. This period may have significantly influenced their initial Hf–W signatures.
- *N*-body simulations may be run in different dynamical regimes, such as EJS/CJS [9], which imply different amounts of mixing between the inner and outer disks [e.g., 10].
- Complete core formation simulations include partitioning of other elements and self-consistent fO_2 evolution [e.g., 11].

References

1. H. Wänke & G. Dreibus (1988) *Phil. Trans. A*. 325, 545–557.
2. D. Rubie et al. (2015) *Icarus* 248, 89–108.
3. M. Brennan et al. (in review), https://eartharxiv.org/j654b/
4. S. Jacobsen (2005) *Ann. Rev. Earth Plan. Sci.* 33, 531–570.
5. E. Cottrell et al. (2009) *EPSL* 281, 275–287.
6. N. Dauphas & A. Pourmand (2011) *Nature* 437, 489–492.
7. K. Walsh et al. (2011) *Nature* 475, 206–209.
8. D. O'Brien et al. (2014) *Icarus* 239, 74–84.
9. R. Fischer & F. Ciesla (2014) *EPSL* 392, 28–38.
10. R. Fischer et al. (2018) *EPSL* 482, 105–114.
11. R. Fischer & F. Nimmo (2018) *EPSL* 499, 257–265.

See also our paper on Martian core formation and geophysical properties (in review) [3]: https://eartharxiv.org/j654b/

This work was funded by a NASA Emerging Worlds grant (NNX17AE27G) to R.A.F. and F.N. and an NSF Graduate Research Fellowship to M.C.B.