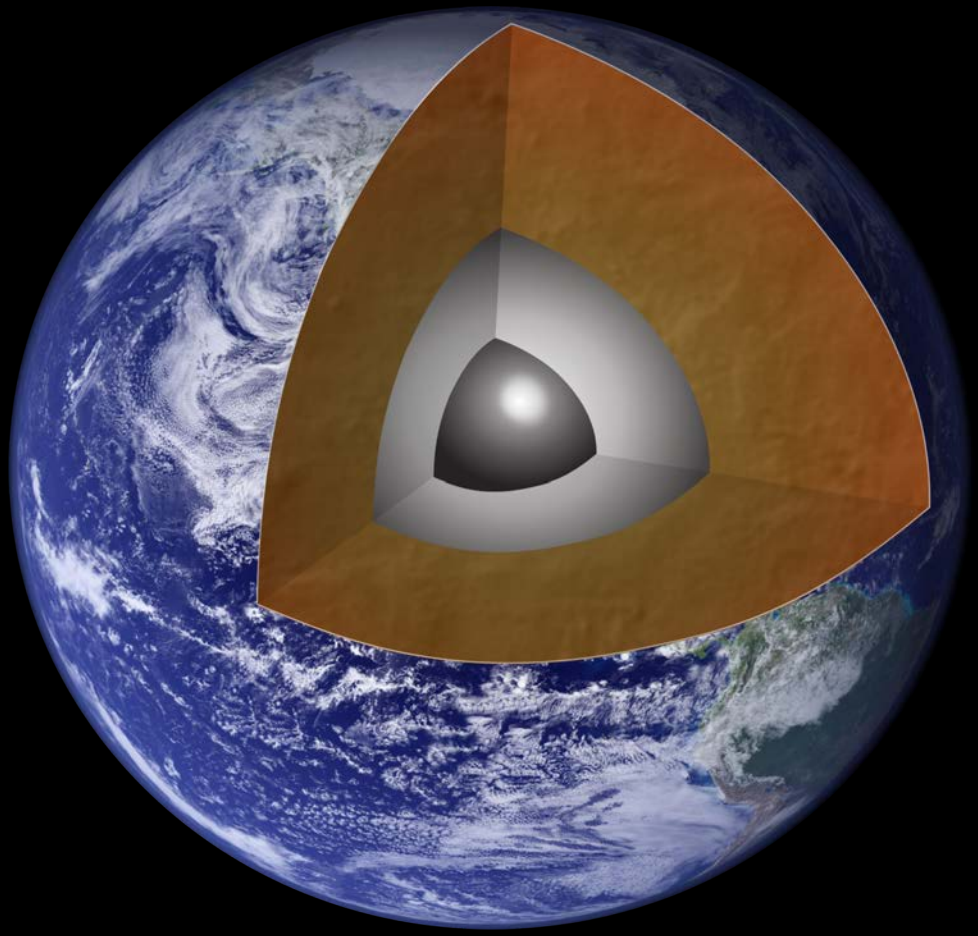
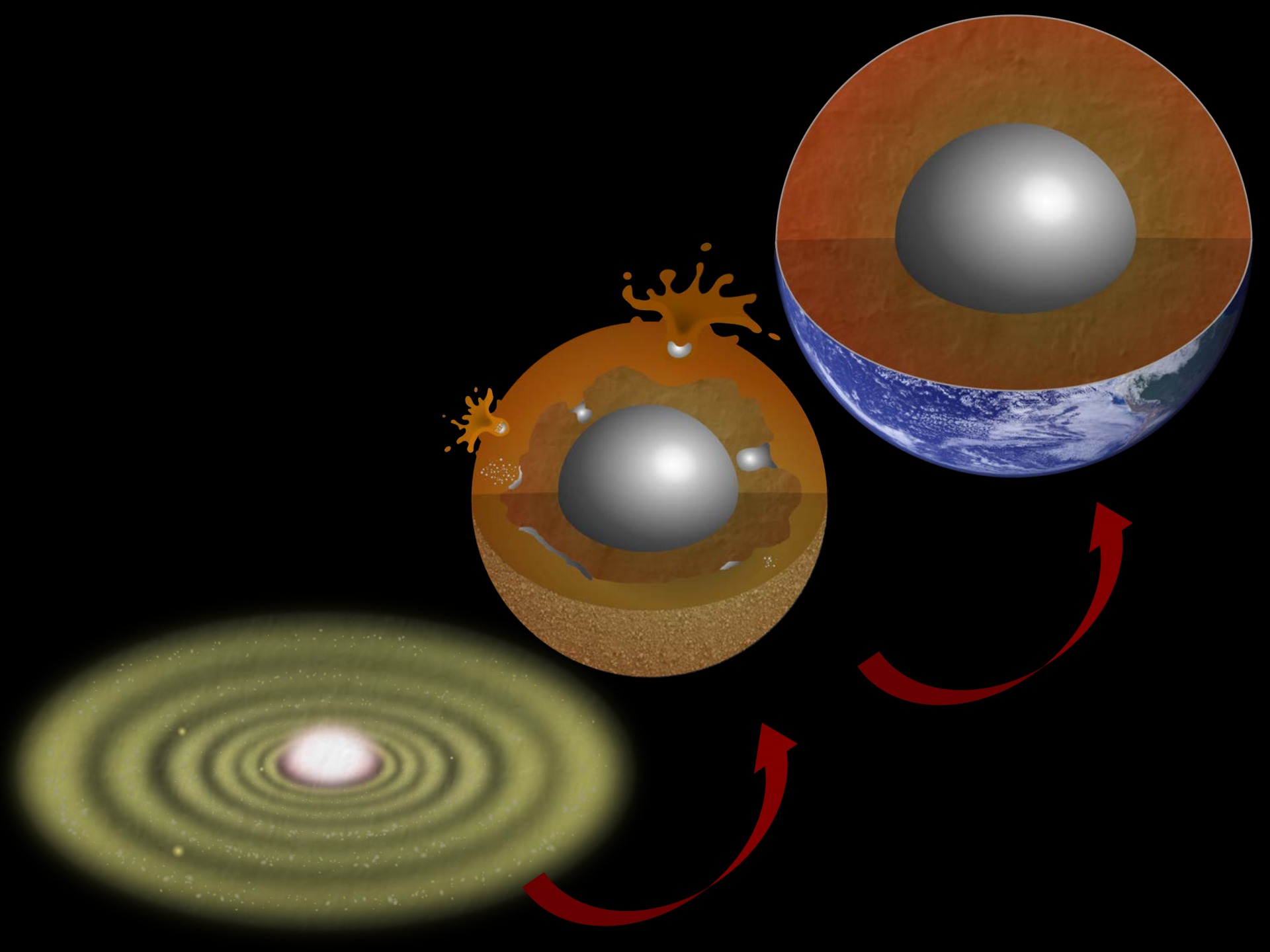
Core formation on Earth and Mars



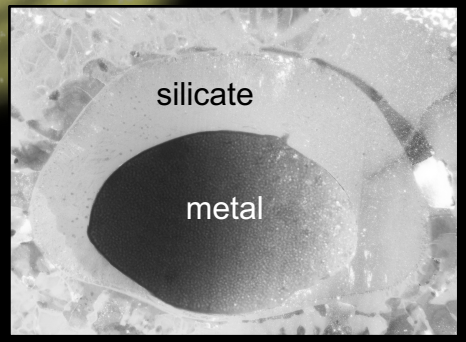
Rebecca A. Fischer

Harvard University

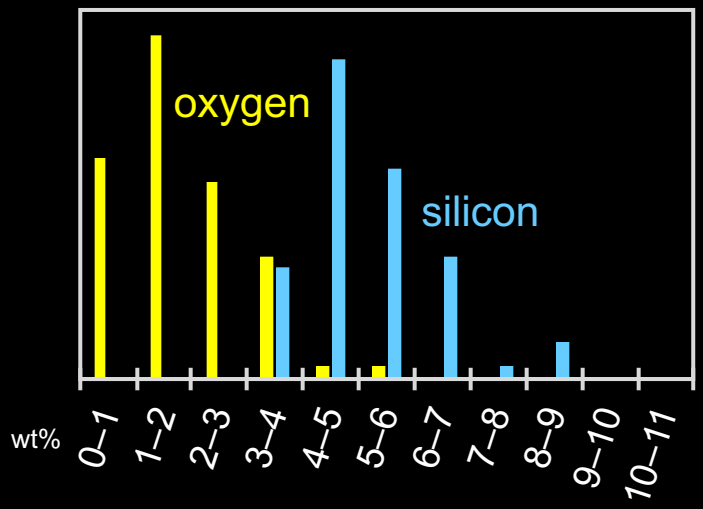
COMPRES



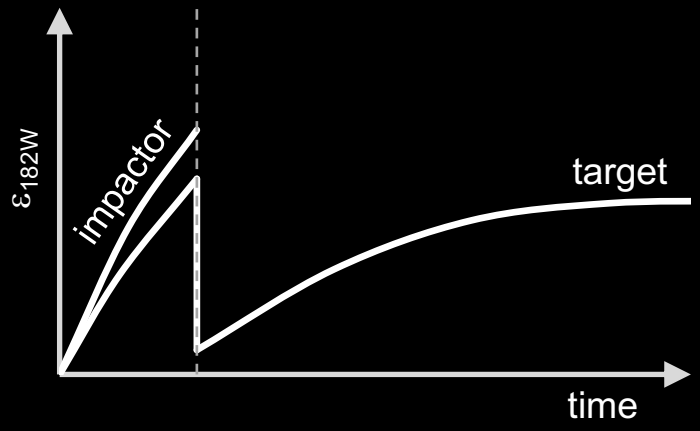
Part I: Introduction and background



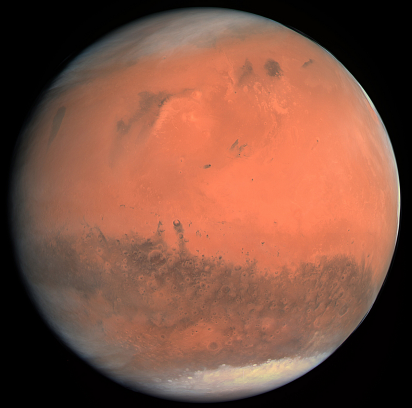
Part 2: Earth's trace elements and light elements



Part 3: Earth's Hf–W isotopes



Part 4: Core formation on Mars



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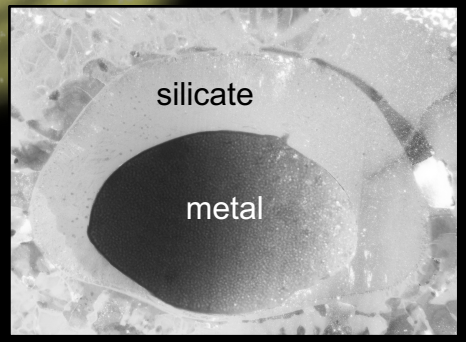

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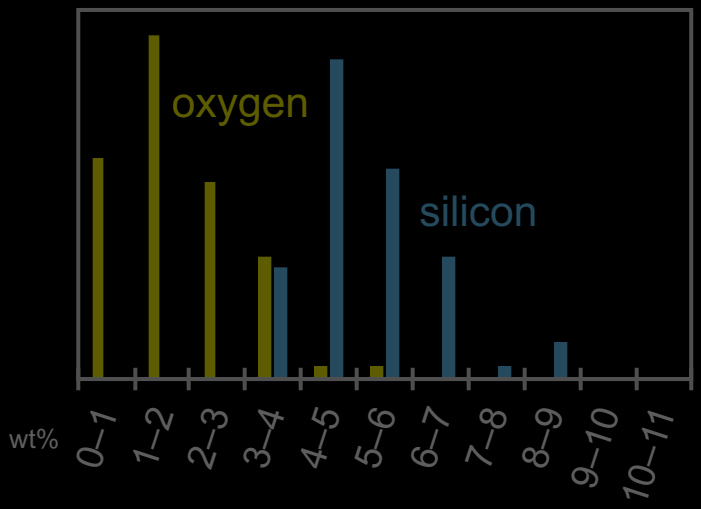

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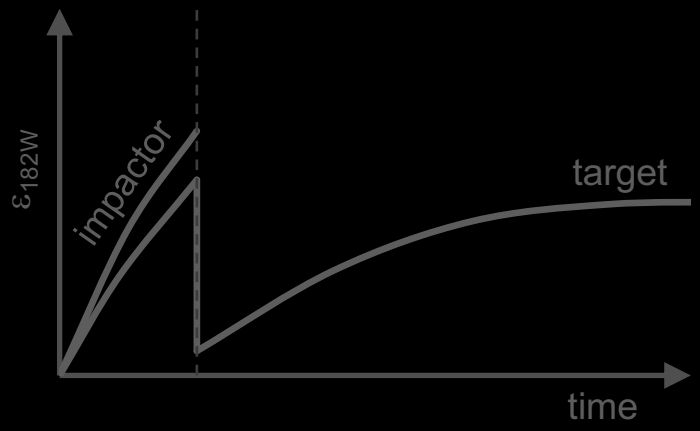

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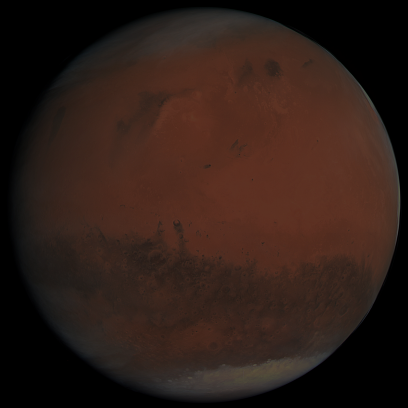
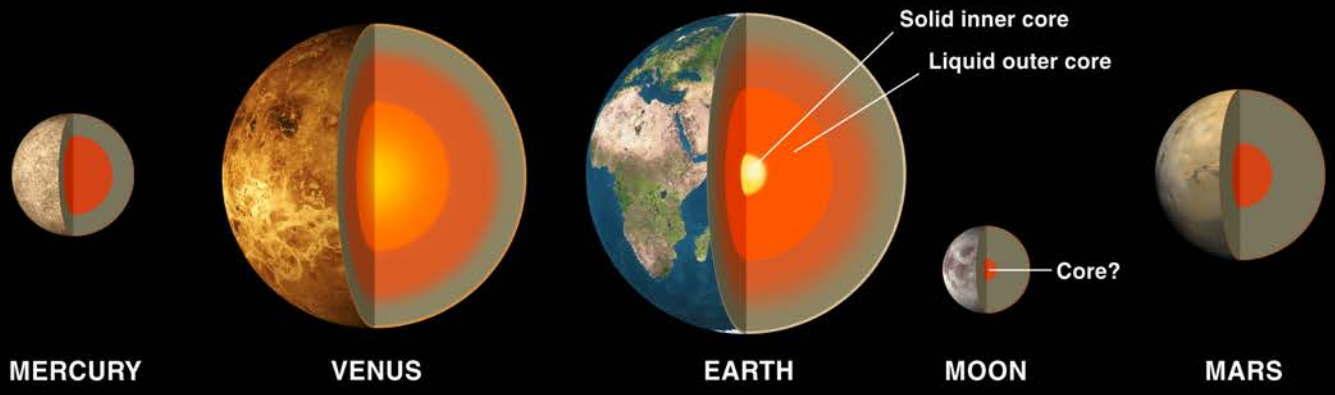
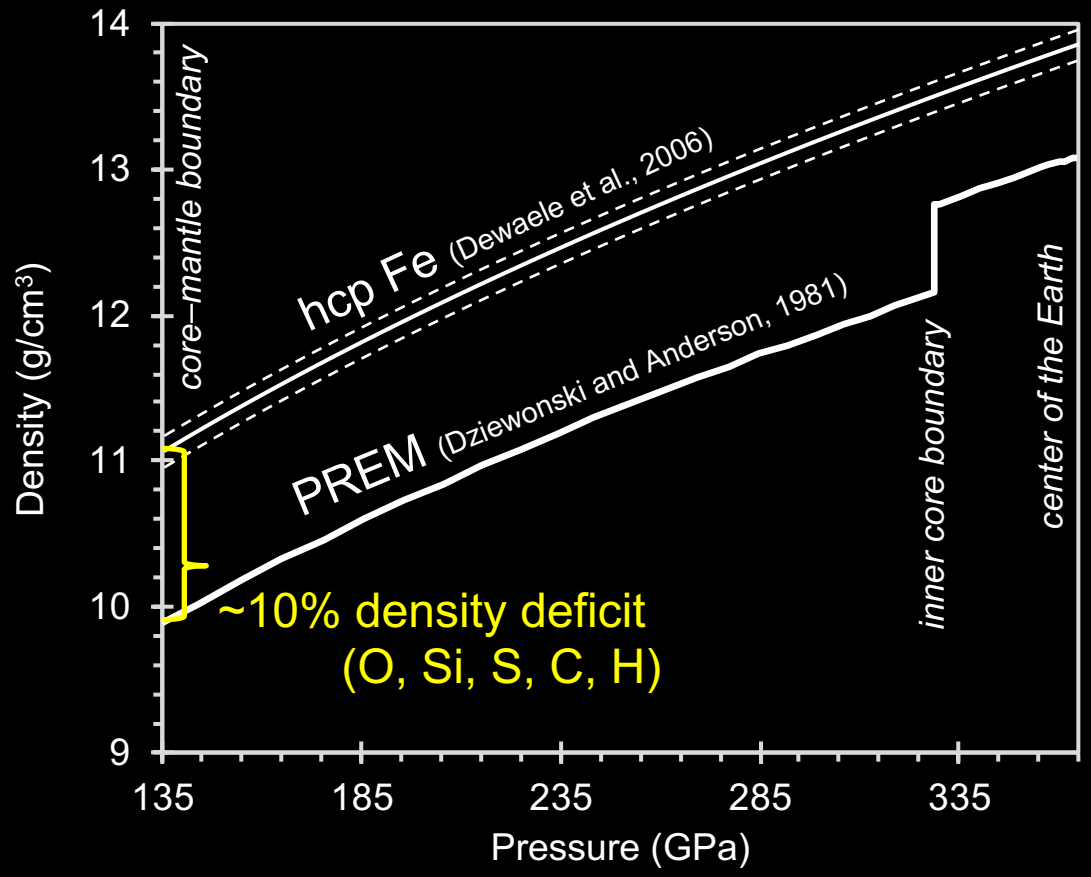


Why study core formation?

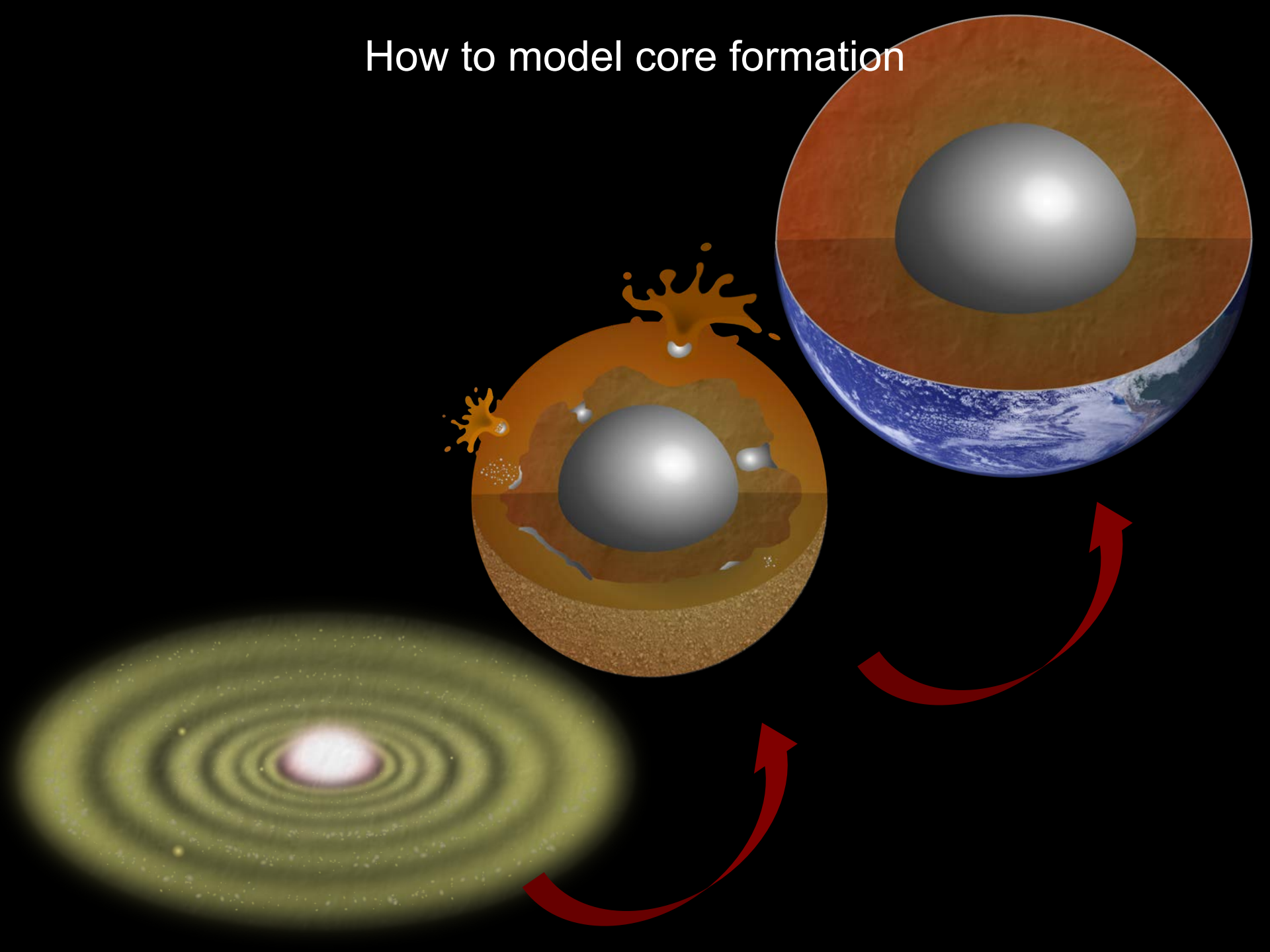


- Ubiquitous process
- Fundamental mechanisms: Earth (and Mars) as case study
  - Timing
  - Depth of equilibration
  - Degree of equilibration
- Composition



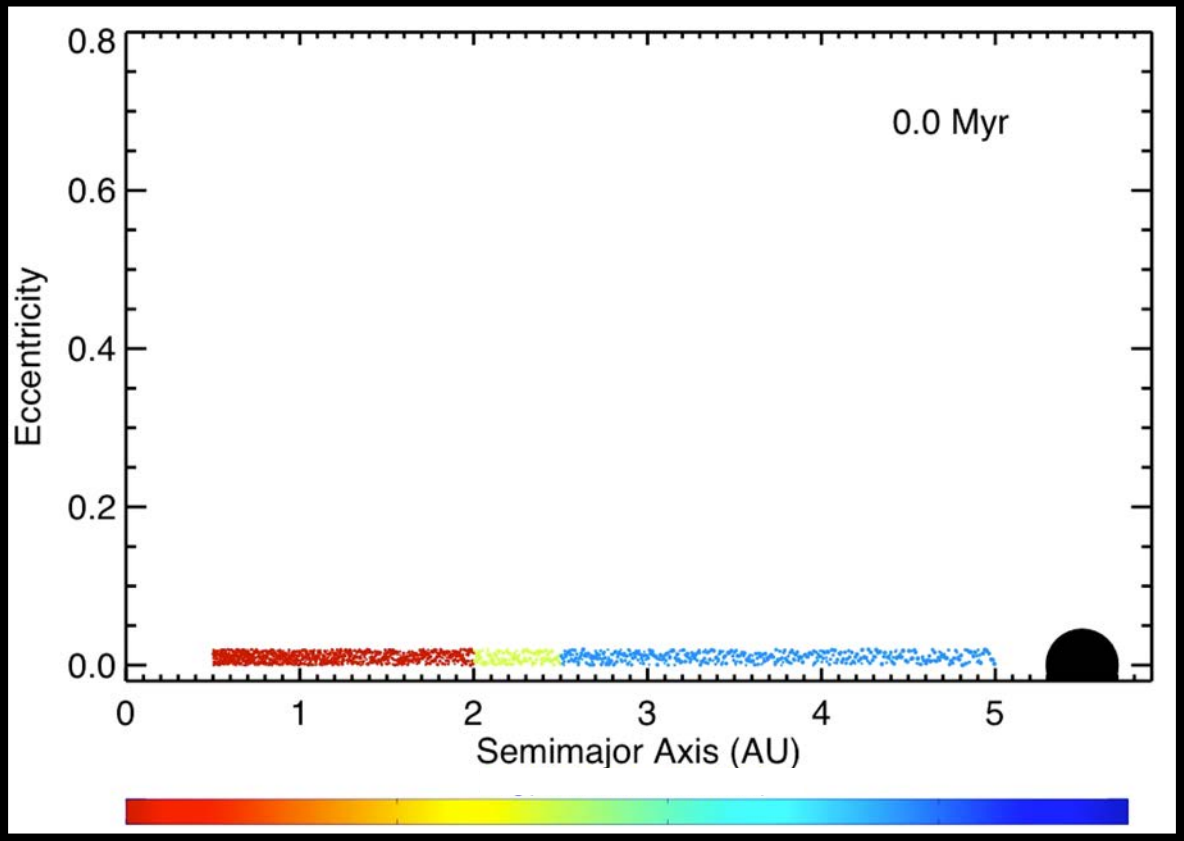
- Ubiquitous process
- Fundamental mechanisms
  - Timing
  - Depth of equilibration
  - Degree of equilibration
- Composition
  - Core light elements: dynamo, thermal structure
  - Mantle: mineralogy/structure, physical properties

How to model core formation



Accretion simulations

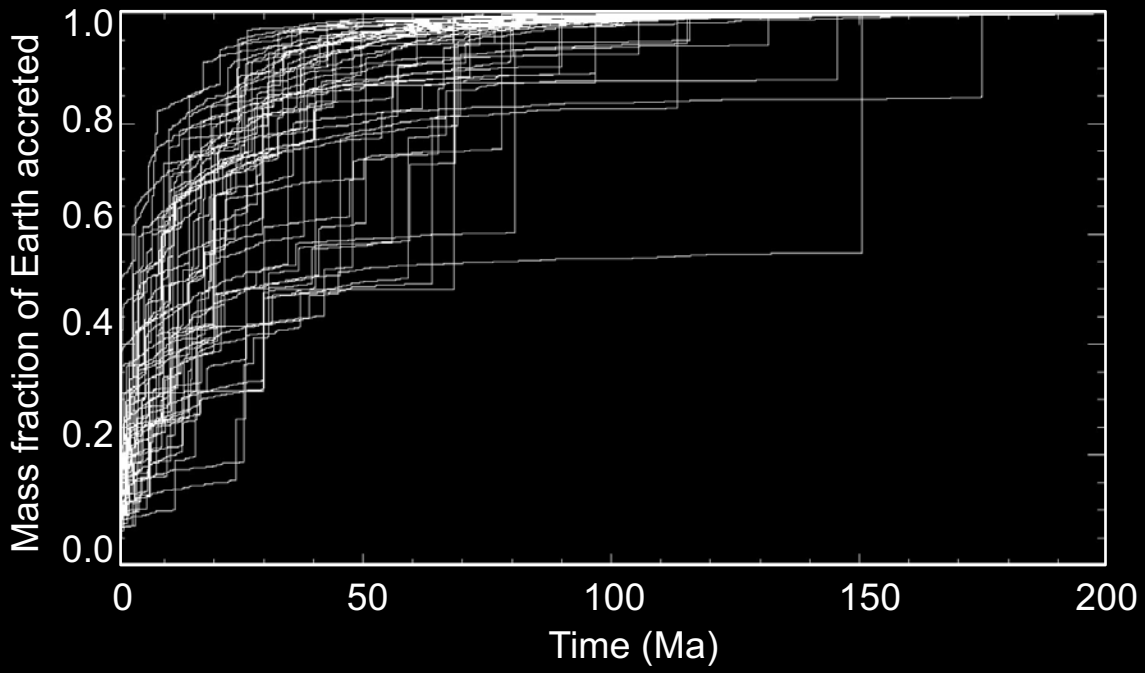
- *N* bodies in orbit around the Sun, interact gravitationally, accrete
- Example from Raymond et al. (2006):



- Fischer and Ciesla (2014): suite of 100 simulations forming 73 “Earths”

Accretion simulations

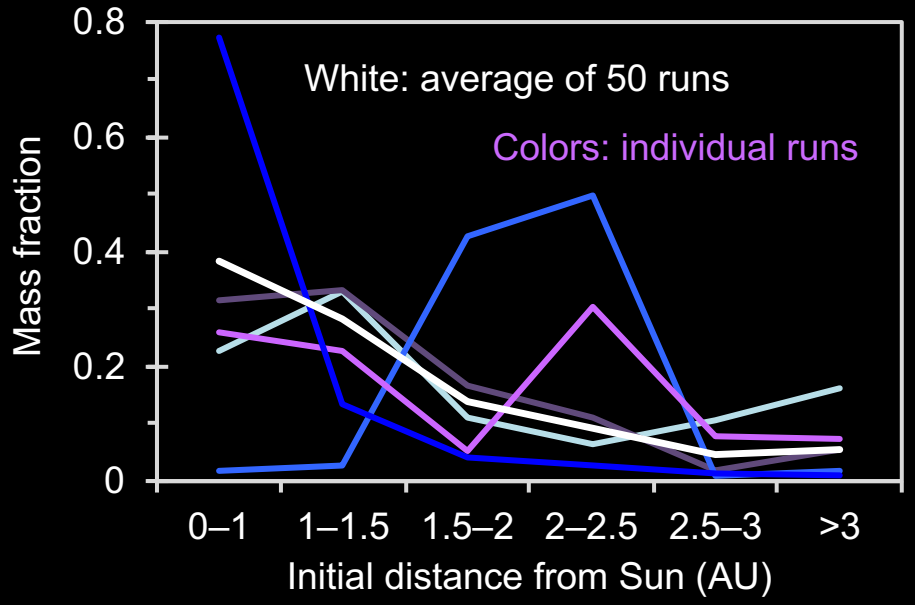
- Mass evolution of the Earth



Fischer and Ciesla (2014), EPSL

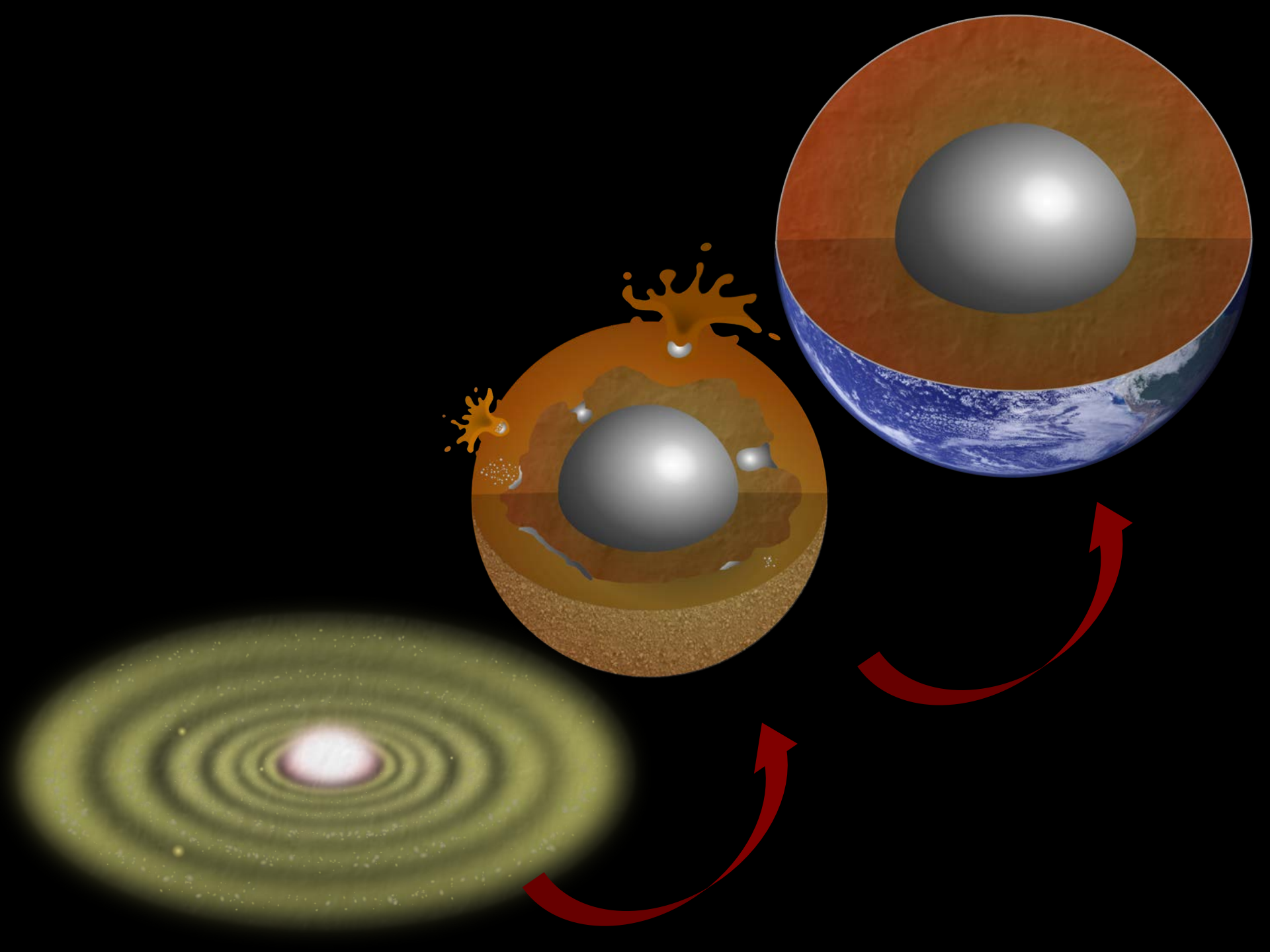
Accretion simulations

- Mass evolution of the Earth
- Provenance of Earth's building blocks



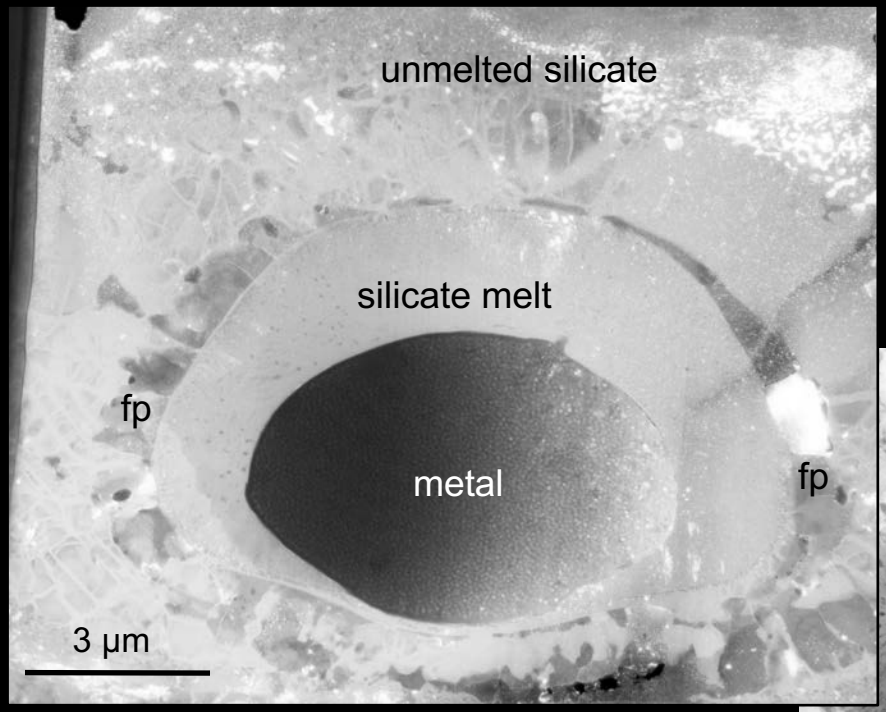
Feeding zone expands with time.
Earth accretes more material from farther from the Sun at later times.

Fischer and Ciesla (2014), EPSL



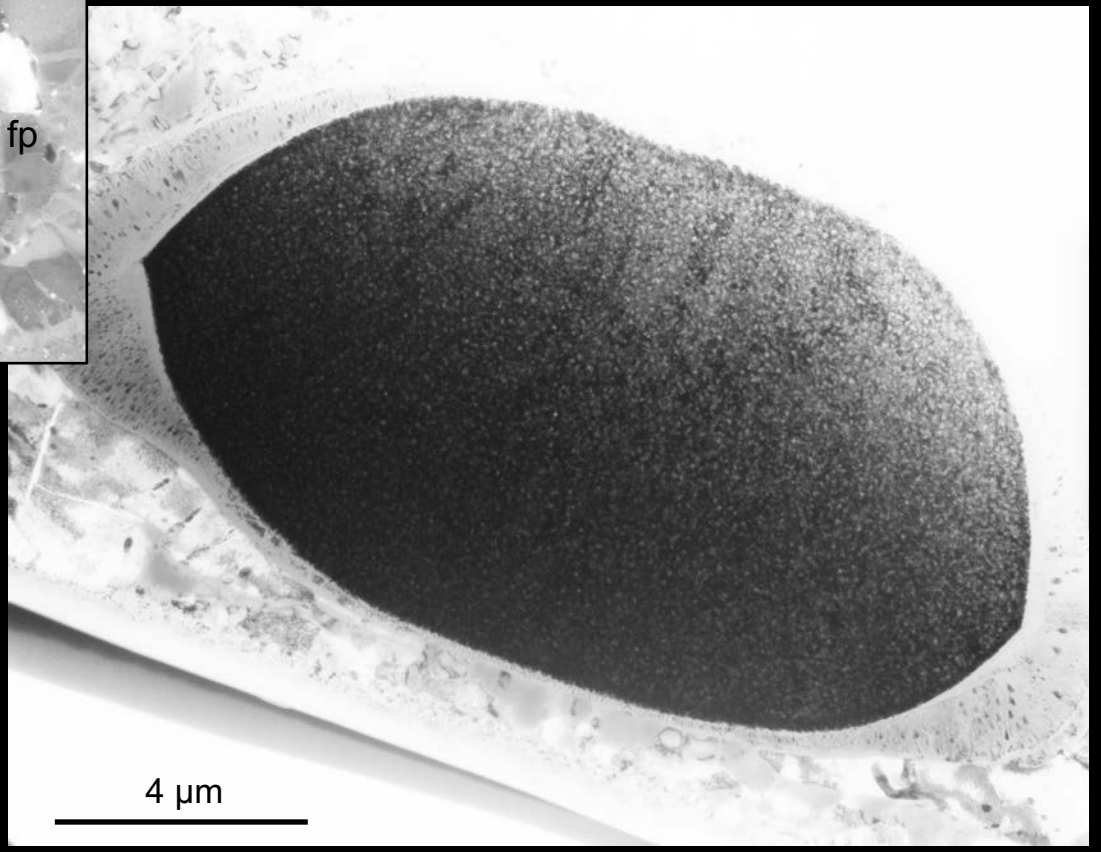
Laser-heated
diamond anvil cell
31–100 GPa,
up to 5700 K

Metal–silicate
partitioning of Ni,
Co, V, Cr, Si, O



57 GPa, 4400 K
1 wt% Si, 10 wt% O

100 GPa, 5700 K
9 wt% Si, 11 wt% O



Metal–silicate partitioning of Ni, Co, V, Cr, Si, O

Focused Ion Beam (FIB)

Transmission Electron Microscopy (TEM)

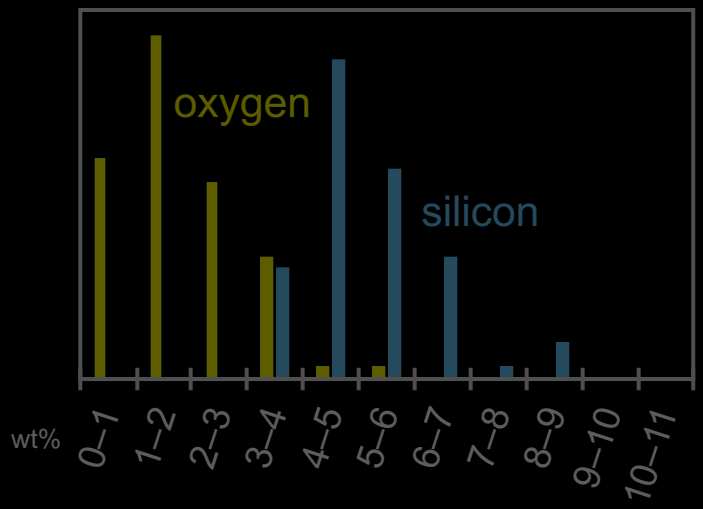
Combine with data from LVP community

Fischer et al. (2015), GCA

Part I: Introduction and background

- Accretion simulations: mass evolution, provenance
- High *P*–*T* experiments on metal–silicate partitioning

Part 2: Earth's trace elements and light elements



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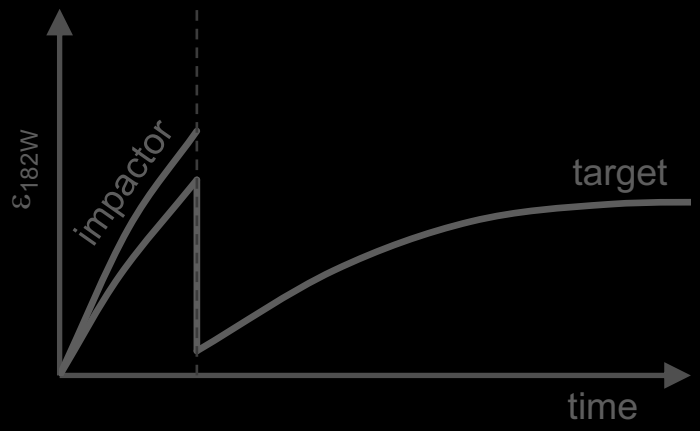
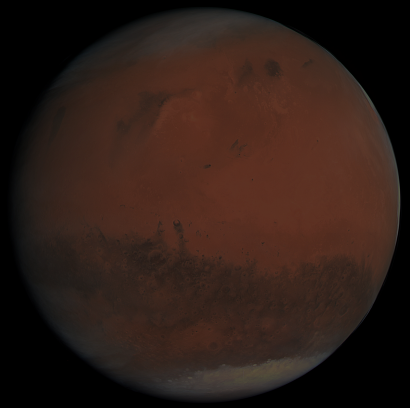


Part 4: Core formation on Mars



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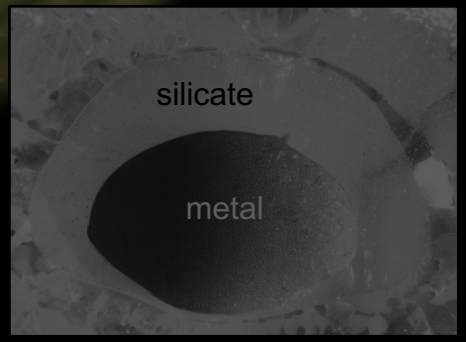

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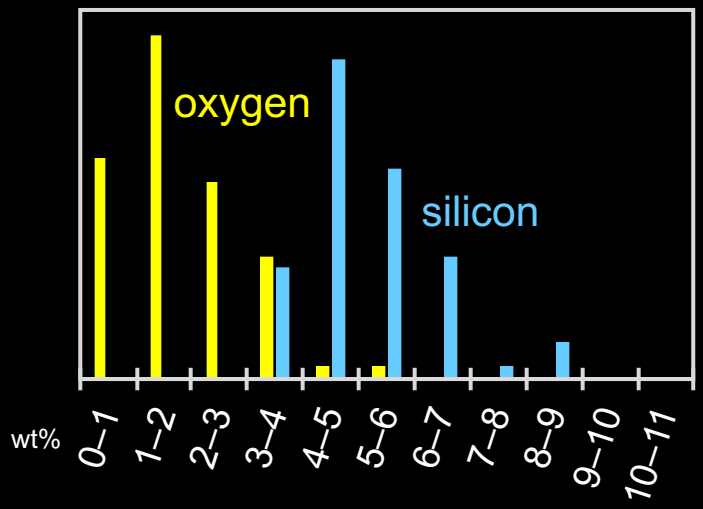

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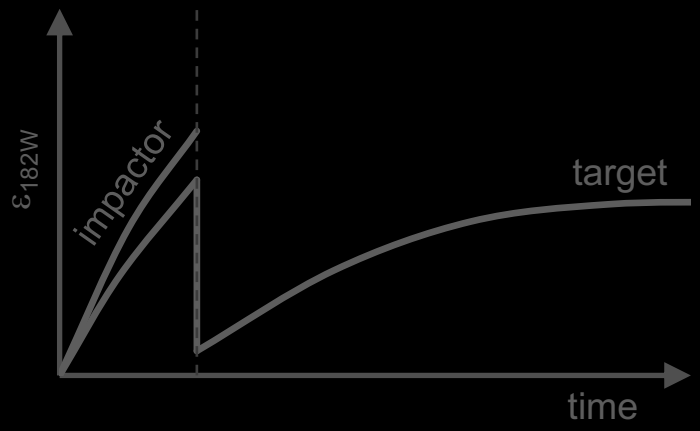

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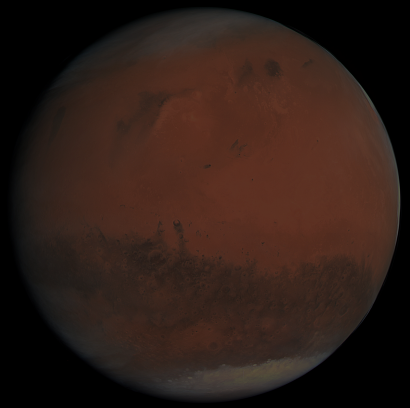
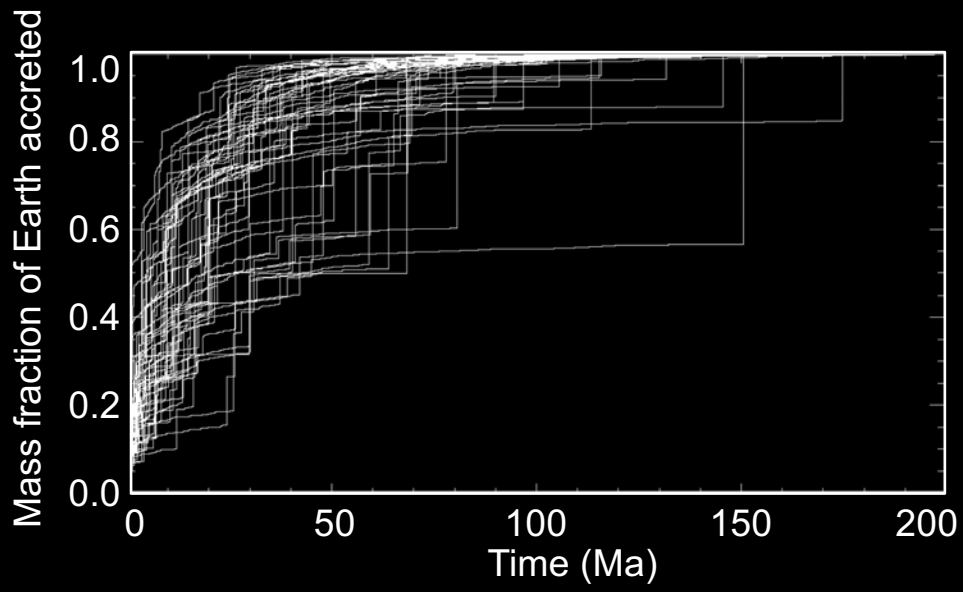
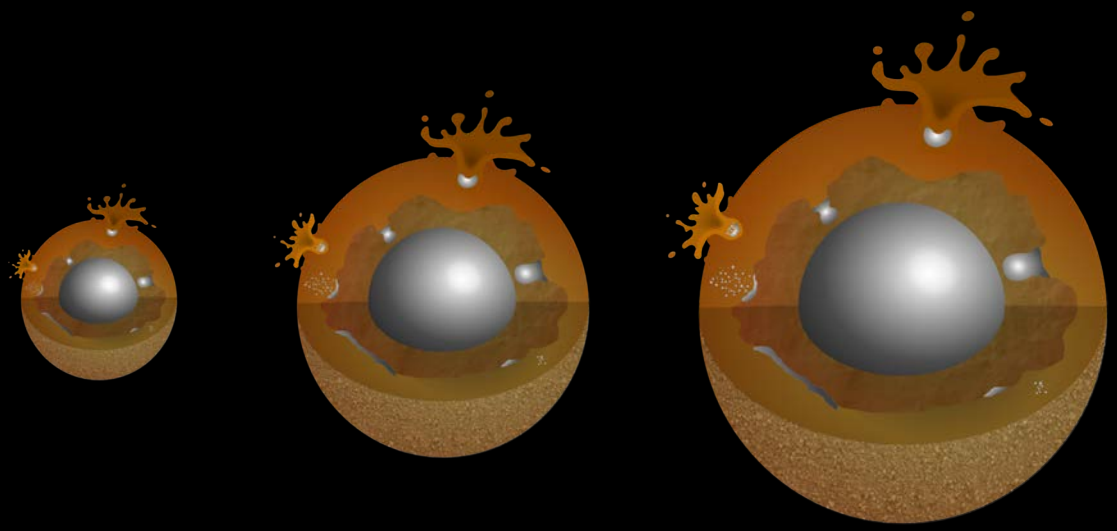


Chemistry of accretion model

- ~CI composition with step in fO_2
- High *P*–*T* metal–silicate partitioning
  - Full equilibration
  - 55% of the CMB *P*, liquidus *T* (Andrault et al., 2011; Rubie et al., 2011)
  - Self-consistent fO_2 evolution (Rubie et al., 2011, 2015)
  - Mass balance equations and partitioning coefficients (Fischer et al., 2015; Mann et al., 2009; Shofner et al., 2014)
  - Integration over range of *P*–*T* conditions





Fischer et al. (2017), EPSL

Chemistry of accretion model

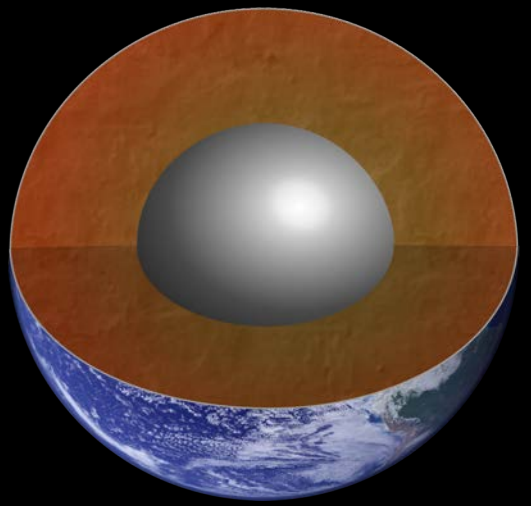
Elements in the model:

Si, O, Mg, Fe, Al, Ca, Ni, Co,
Nb, Ta, V, Cr, Hf, W

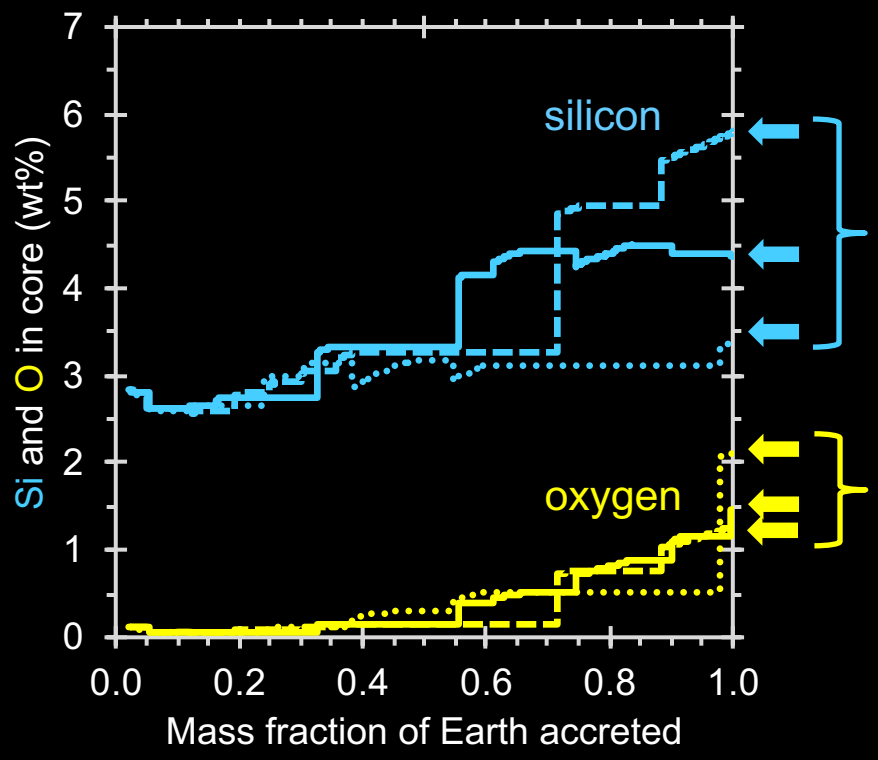
Si, O: core composition

Ni, Co: core formation conditions

Hf, W: core formation conditions
and timing



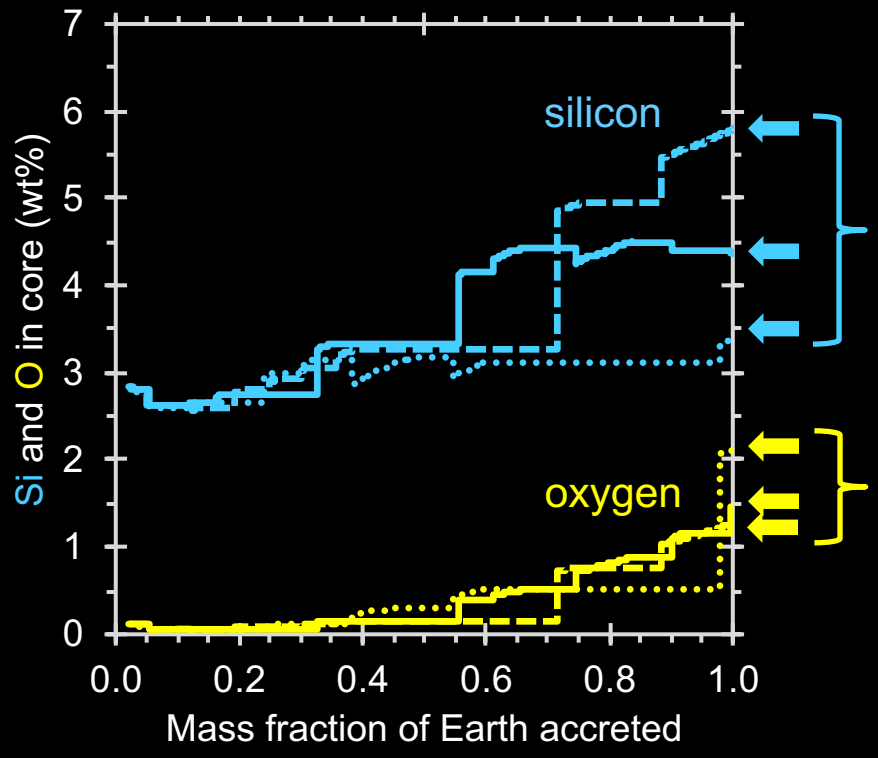
Si and O in the core

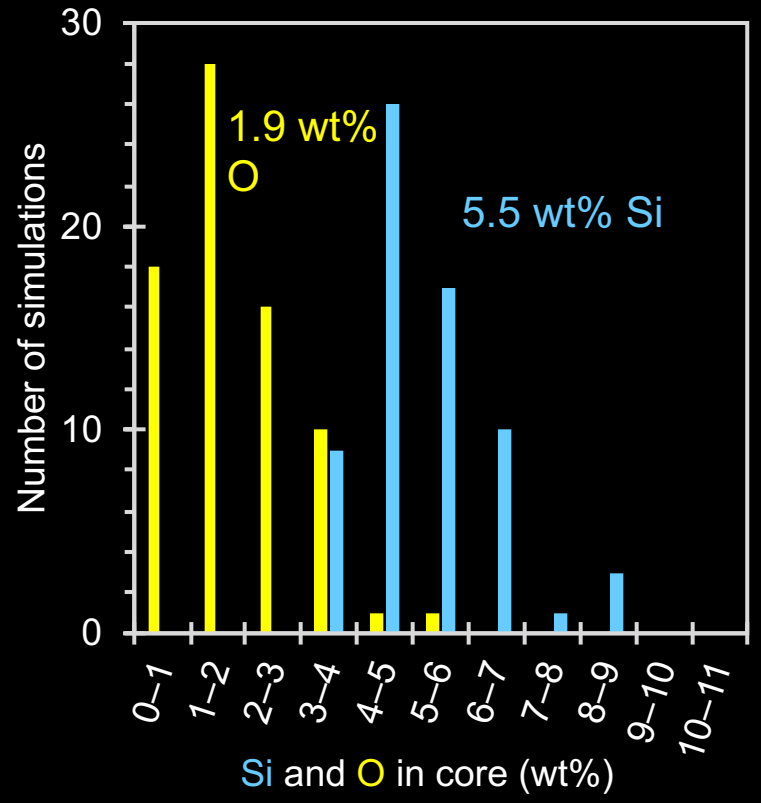


Three simulations, each Earth analogue is ~1 Earth mass
Variability due to accretion history

Fischer et al. (2017), EPSL

Si and O in the core



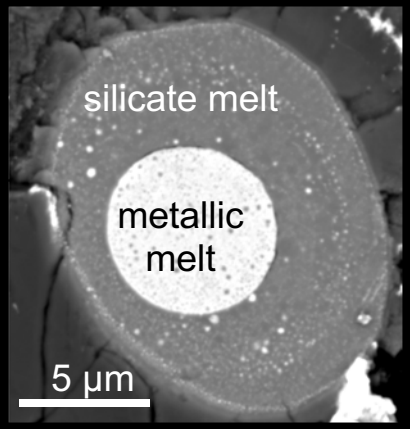


Three simulations, each Earth analogue is ~1 Earth mass
Variability due to accretion history

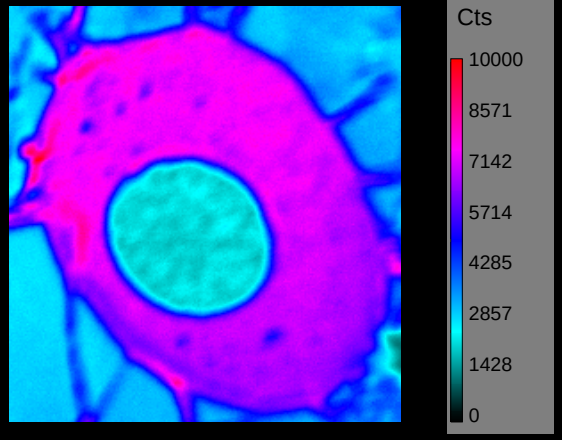
Both O and Si in core (likely Si>O)
Compare to core density: low C, S, H?

Fischer et al. (2017), EPSL

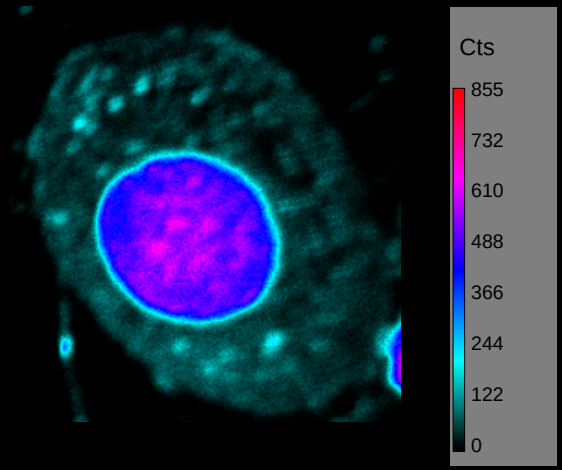
What about C, S, H in the core?



Backscattered electron image (50 GPa, 5200 K)



NanoSIMS ^{16}O map



NanoSIMS ^{12}C map

C becomes less siderophile at higher *P–T*

Core formation model: max. 0.09–0.20 wt% C in core

Consistent with volatile depletions (e.g., McDonough, 2003)

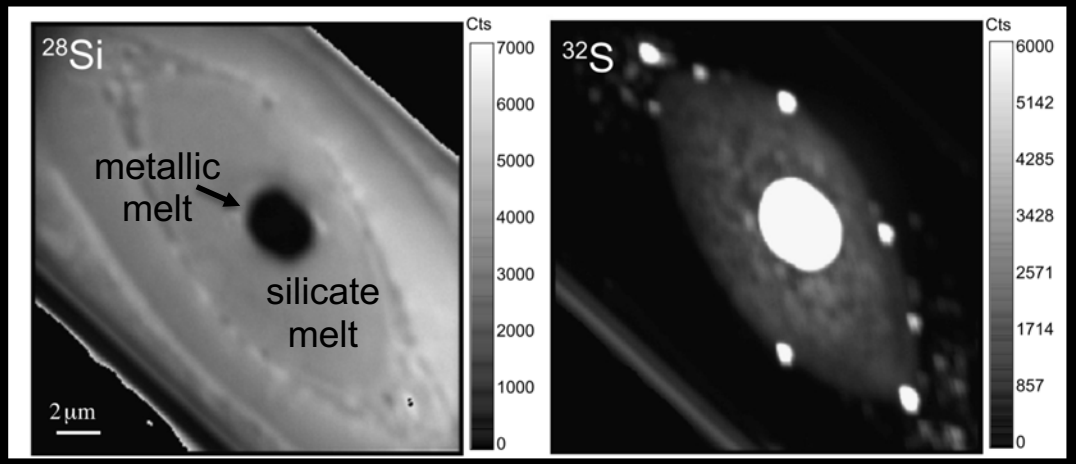
Low compared to Si and O

Accounts for ~80–90% of Earth's C budget

Fischer et al. (2020), PNAS

What about C, S, H in the core?

NanoSIMS maps (65 GPa, 3500 K)



Suer et al. (2017), EPSL

S becomes less siderophile at higher *P–T*

Core formation model: ~1–2 wt% S in core

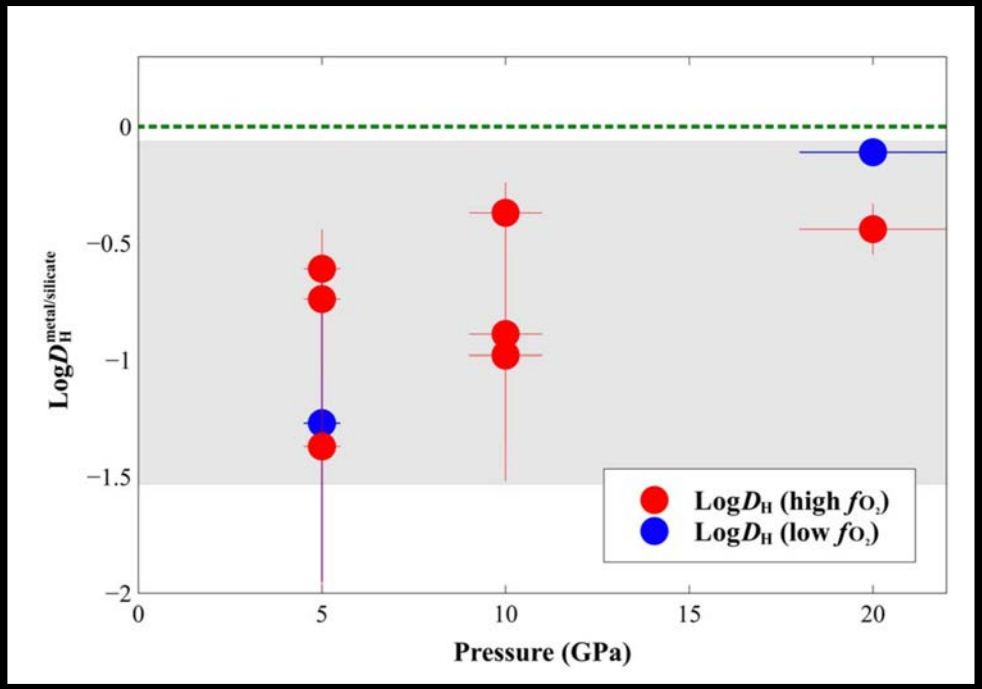
Consistent with volatile depletions (e.g., McDonough, 2003)

Comparable level to Si and O

Accounts for vast majority of Earth's S budget

What about C, S, H in the core?

siderophile



lithophile

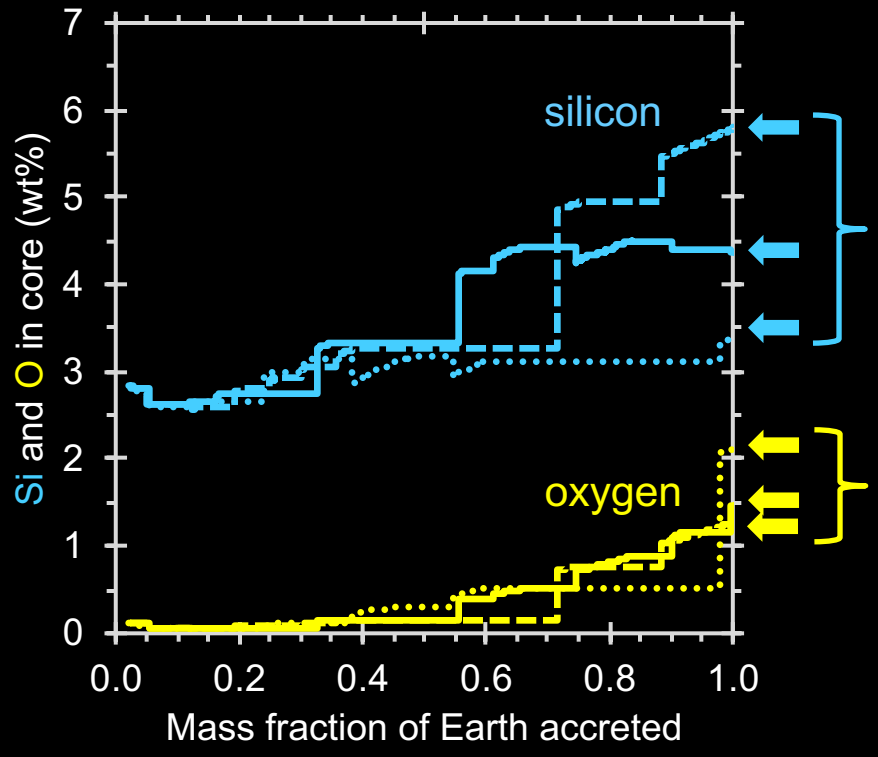
Clesi et al. (2018), Sci. Adv.

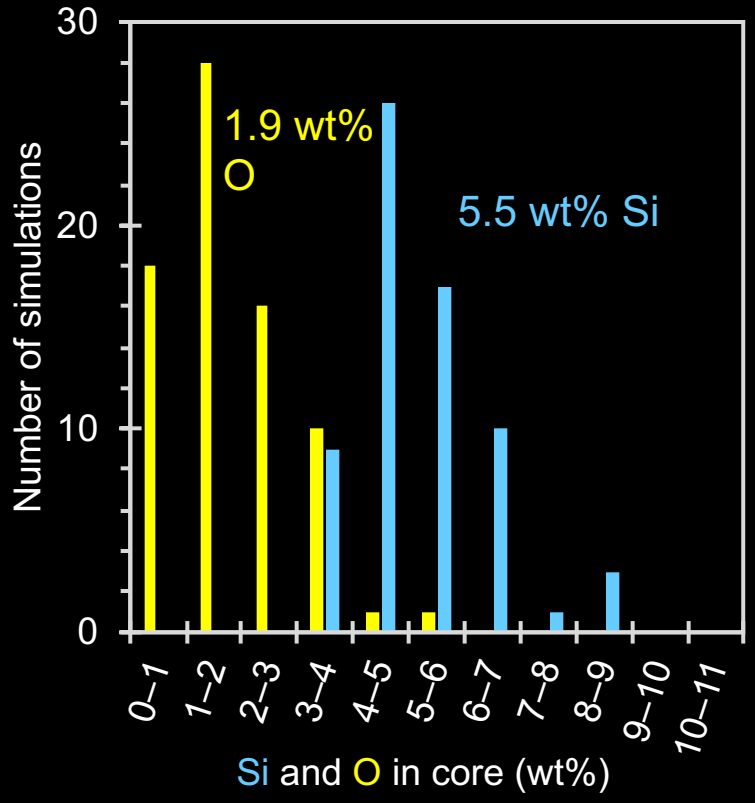
H much more controversial, no data from highest *P–T*

Core formation model: ~60 ppm H in core (Clesi et al., 2018)

Other studies argue for much more H (e.g., Fukai and Suzuki, 1986; Okuchi, 1997; Iizuka-Oku et al., 2017)

Si and O in the core



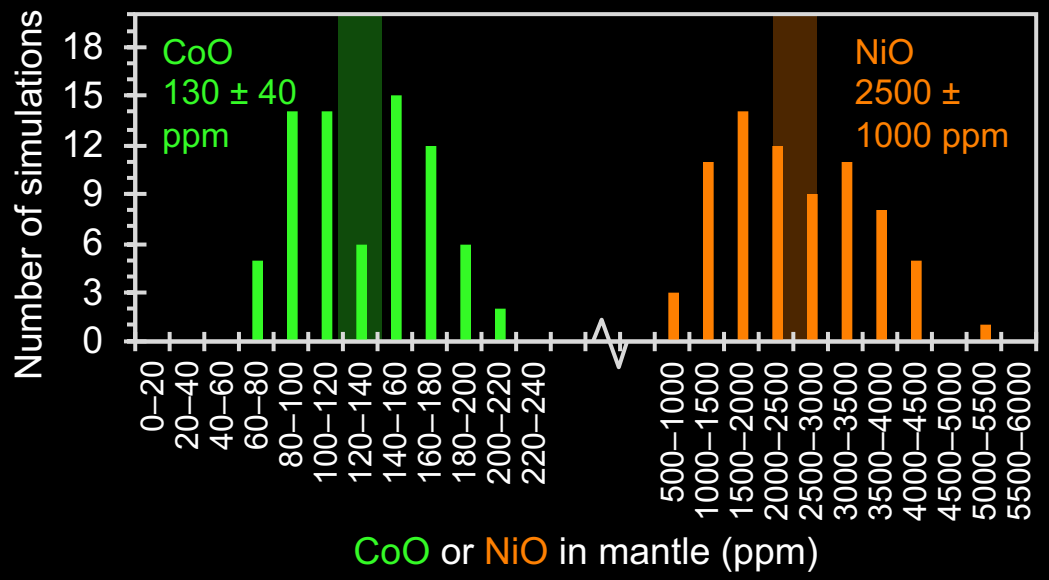


1.9 wt% O, 5.5 wt% Si, 1–2 wt% S, <0.2 wt% C, trace H?
Approximately the right density

Fischer et al. (2017), EPSL

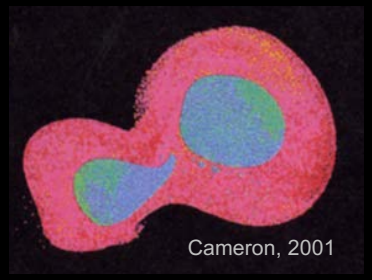
Trace elements in the mantle

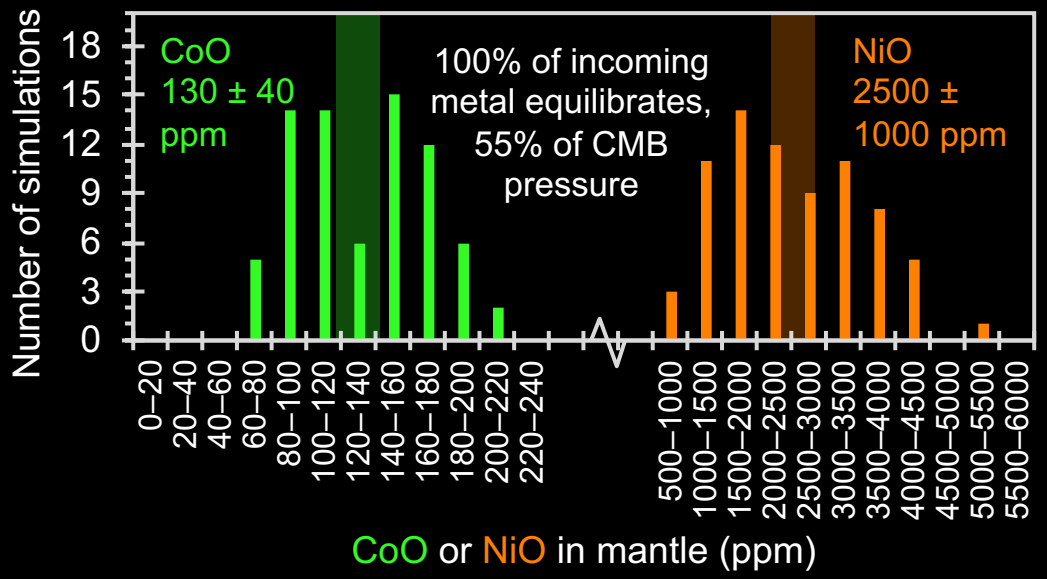
Conditions that give plausible core compositions also match Earth's mantle trace element abundances



Fischer et al. (2017), EPSL

Partial equilibration of the core





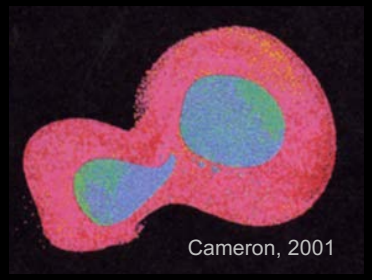
Core:
5.5 wt% Si,
1.9 wt% O

Geochemical estimates:
k = 30–80%
(Nimmo et al., 2010; Rudge et al., 2010)

Likely varied with impactor size
(e.g., Deguen et al., 2011)

Fischer et al. (2017), EPSL

Partial equilibration of the core



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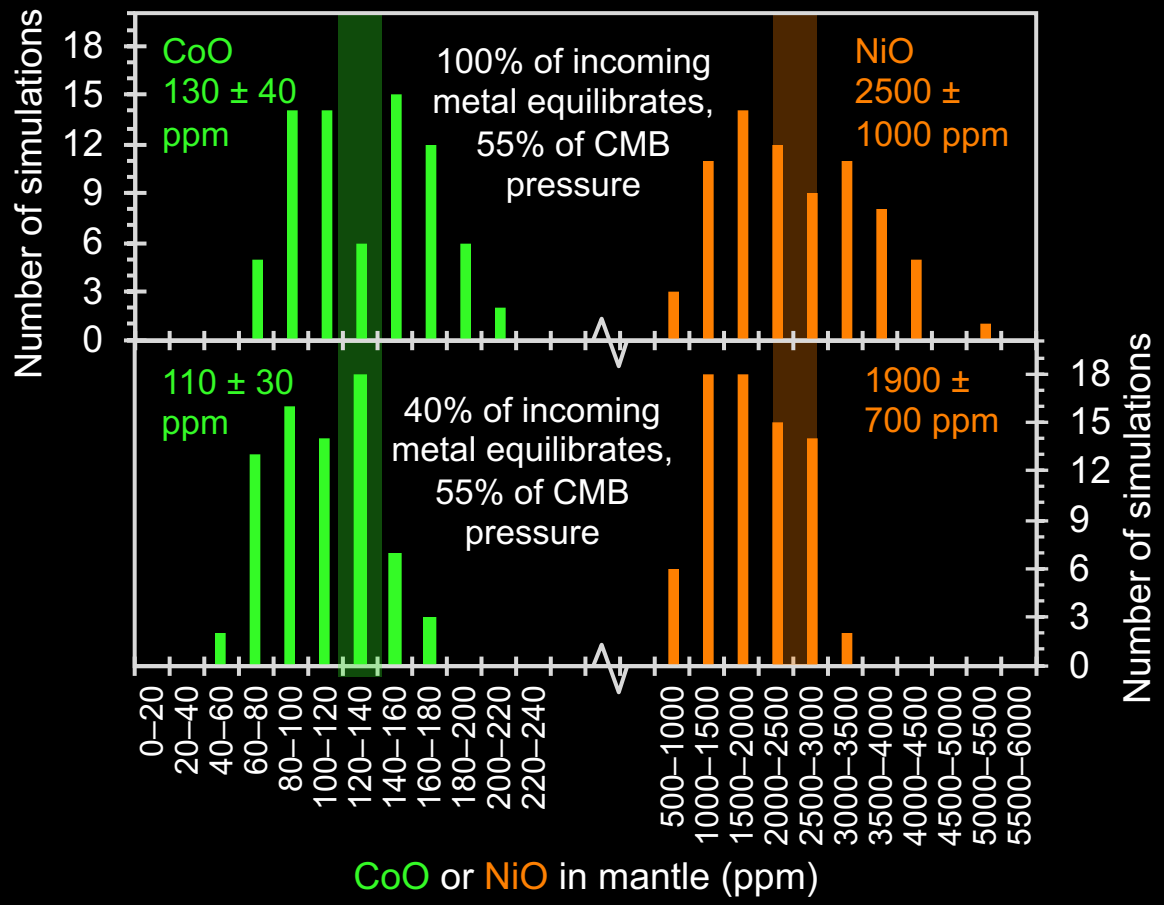
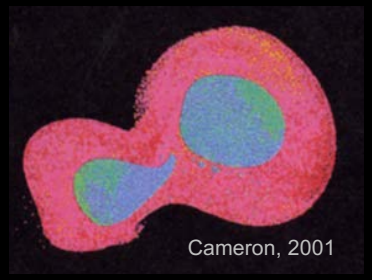


Core:
5.5 wt% Si,
1.9 wt% O

4.2 wt% Si,
0.8 wt% O

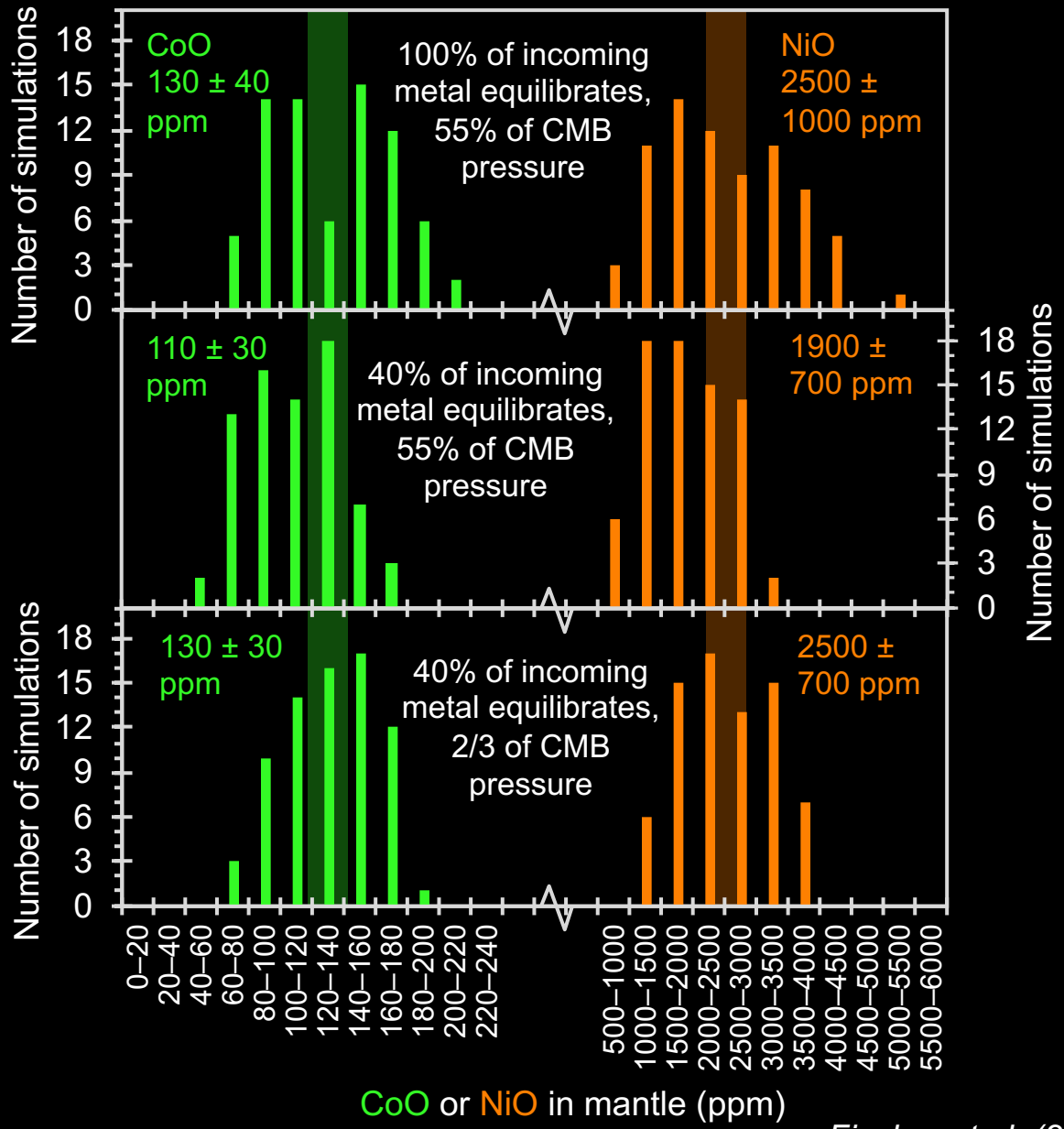
Fischer et al. (2017), EPSL

Partial equilibration of the core



Strong tradeoffs between depth and amounts of silicate and metal equilibrating

Targets for future work to understand core formation



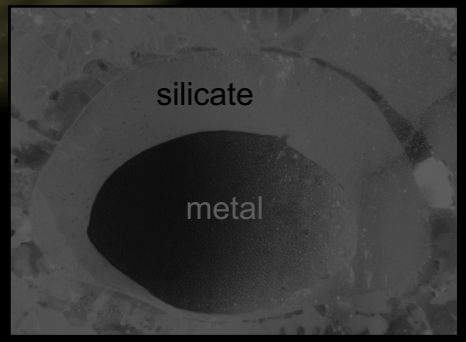
Core:
5.5 wt% Si,
1.9 wt% O

4.2 wt% Si,
0.8 wt% O

5.0 wt% Si,
1.4 wt% O

Fischer et al. (2017), EPSL

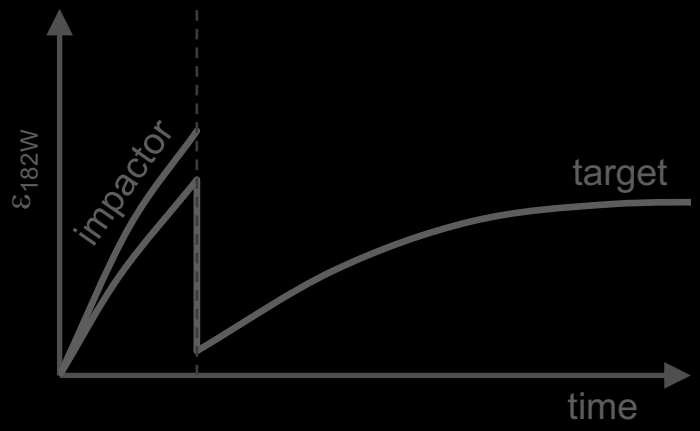
Part I: Introduction and background



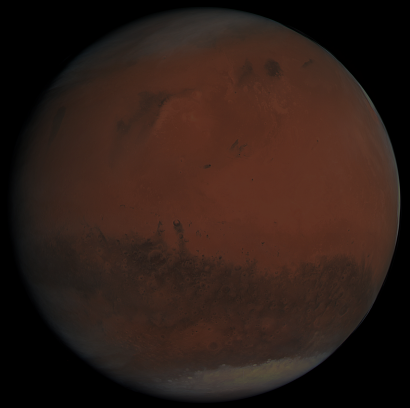
Part 2: Earth's trace elements and light elements

- Mantle composition implies ~5.5 wt% Si, ~2 wt% O in the core (low S, C, H?)
- Tradeoffs in depth/degree of equilibration, most sensitive to these and accretion history
- Best targets for future studies

Part 3: Earth's Hf–W isotopes



Part 4: Core formation on Mars



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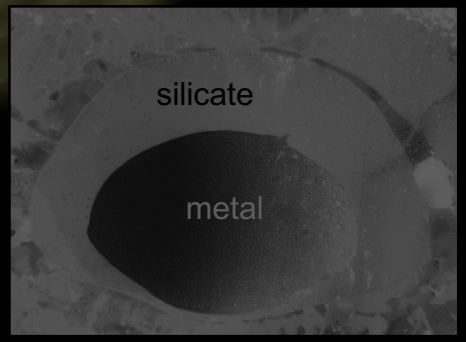

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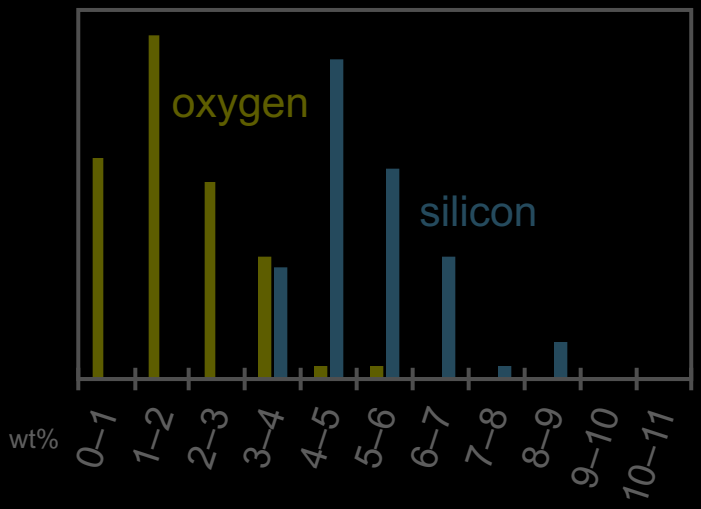

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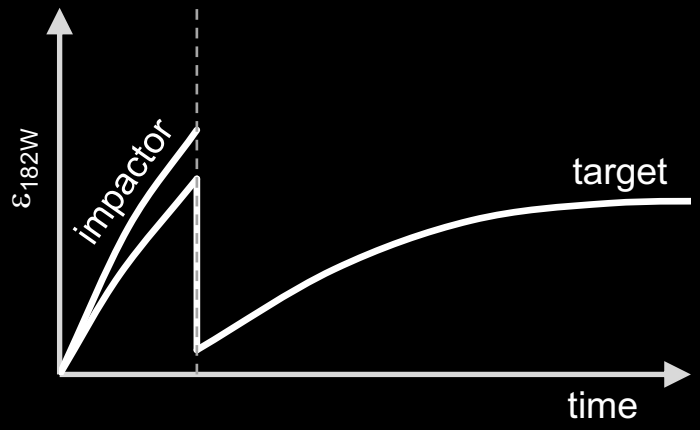

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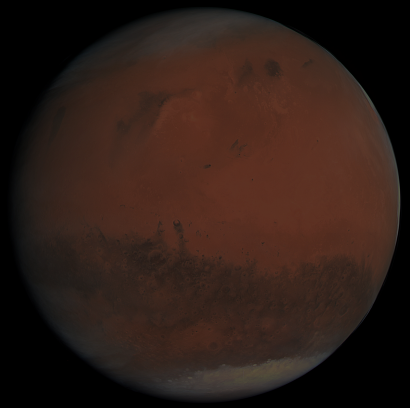


The Hf–W isotopic system

- ^{182}Hf decays to ^{182}W, half-life 9 Ma
- Hf is lithophile, W is moderately siderophile
- Decay of mantle ^{182}Hf creates excess ^{182}W relative to other W isotopes
- Observations:

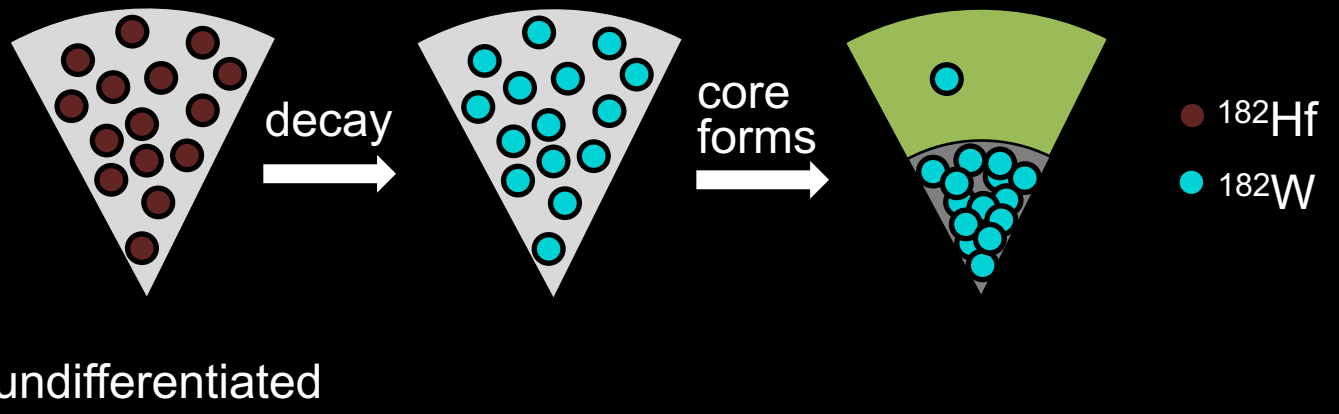
$$\varepsilon_{182\mathrm{W}} = \left[\frac{\left(X^{182\mathrm{W}}/X^{183\mathrm{W}}\right)}{\left(X^{182\mathrm{W}}/X^{183\mathrm{W}}\right)_{\mathrm{CHUR}}} - 1\right] \times 10^4 = 1.9 \pm 0.1$$

(e.g., Kleine et al., 2002; Schoenberg et al., 2002; Yin et al., 2002)

- *Sensitive to both timing and conditions of core formation*

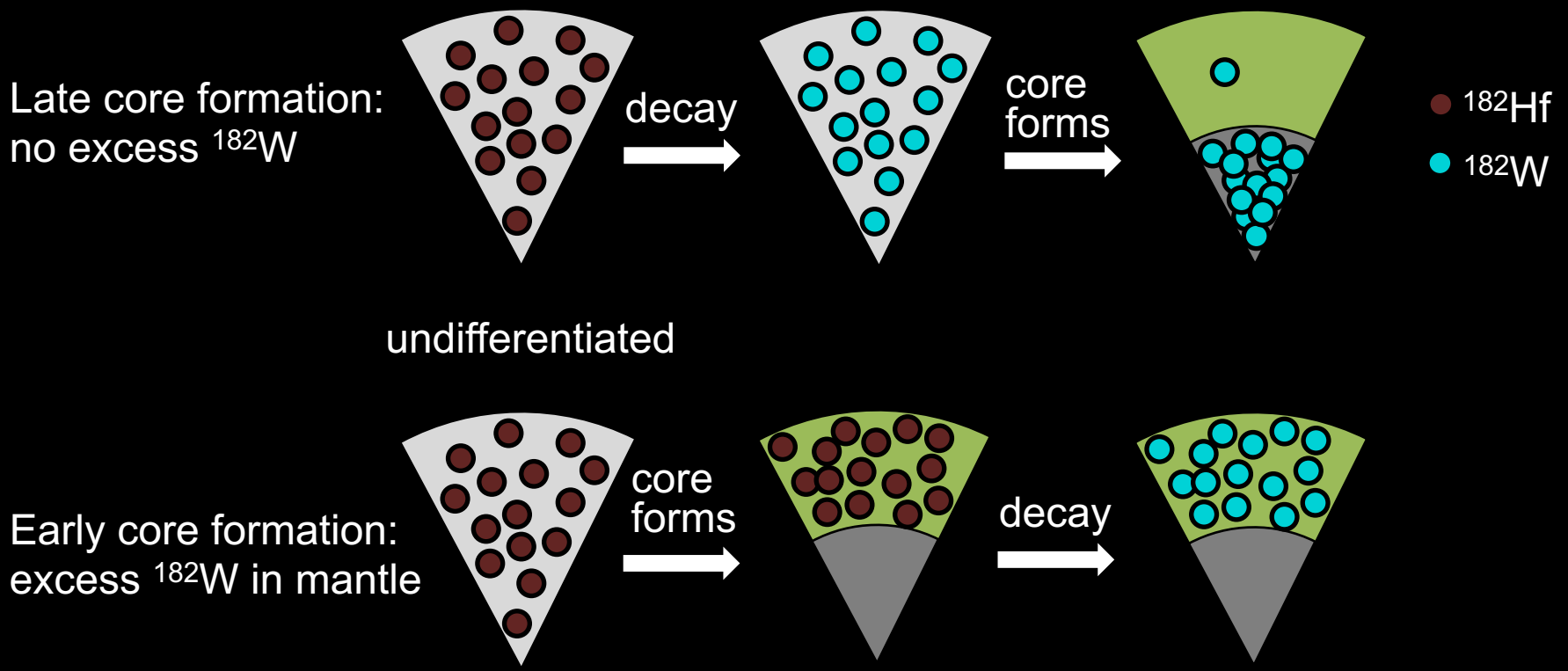
Timing of core formation from the Hf–W system

Late core formation:
no excess ^{182}W



undifferentiated

Timing of core formation from the Hf–W system

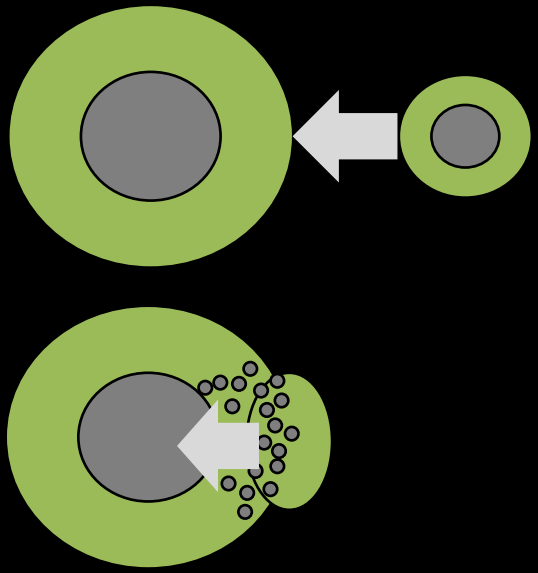


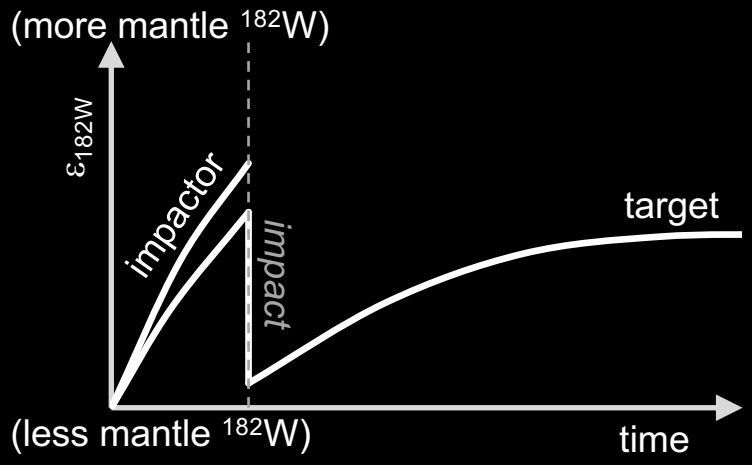
Conditions of core formation from the Hf–W system

Two endmembers:

Re-equilibration (k ~ 1)

Core merging (k ~ 0)





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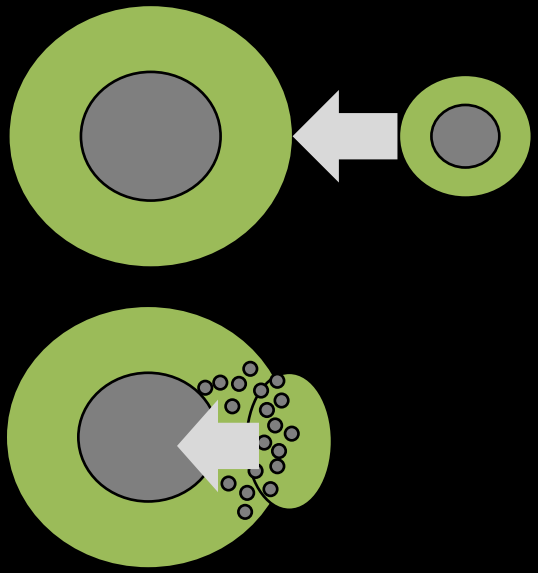

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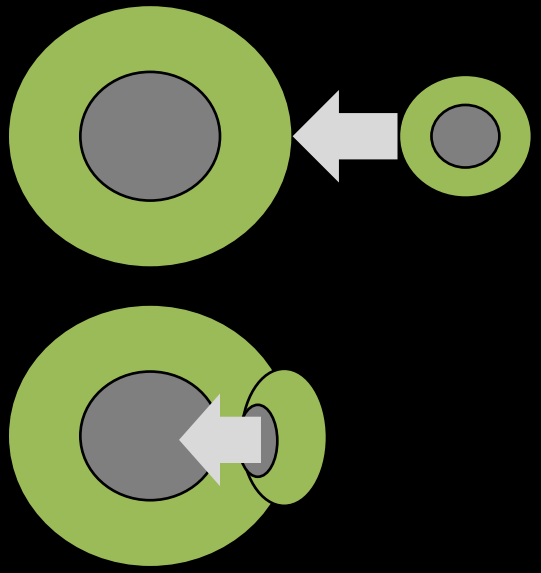
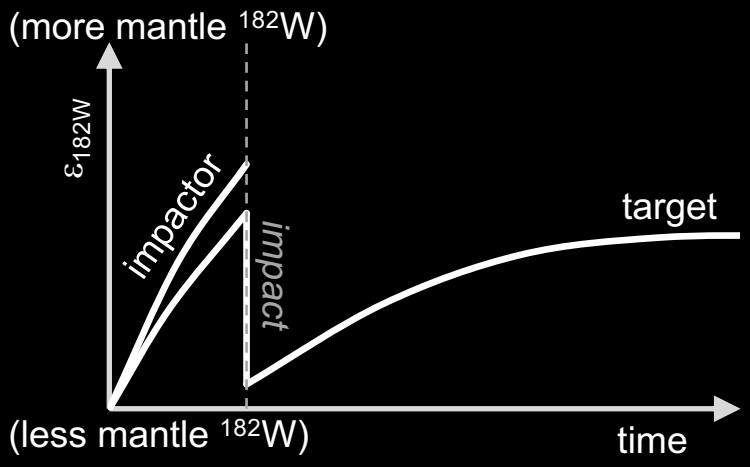
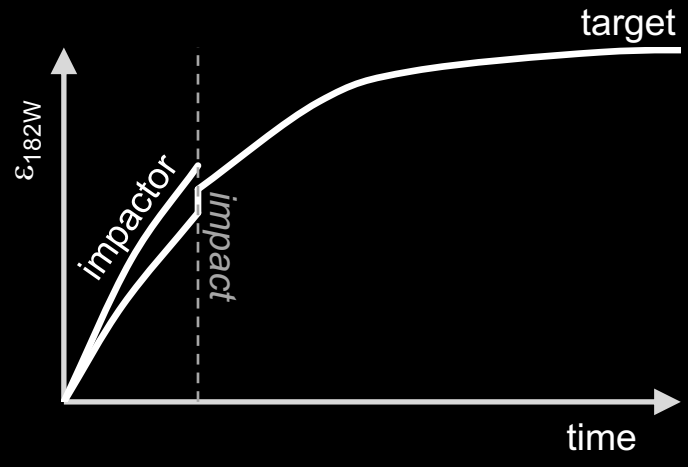
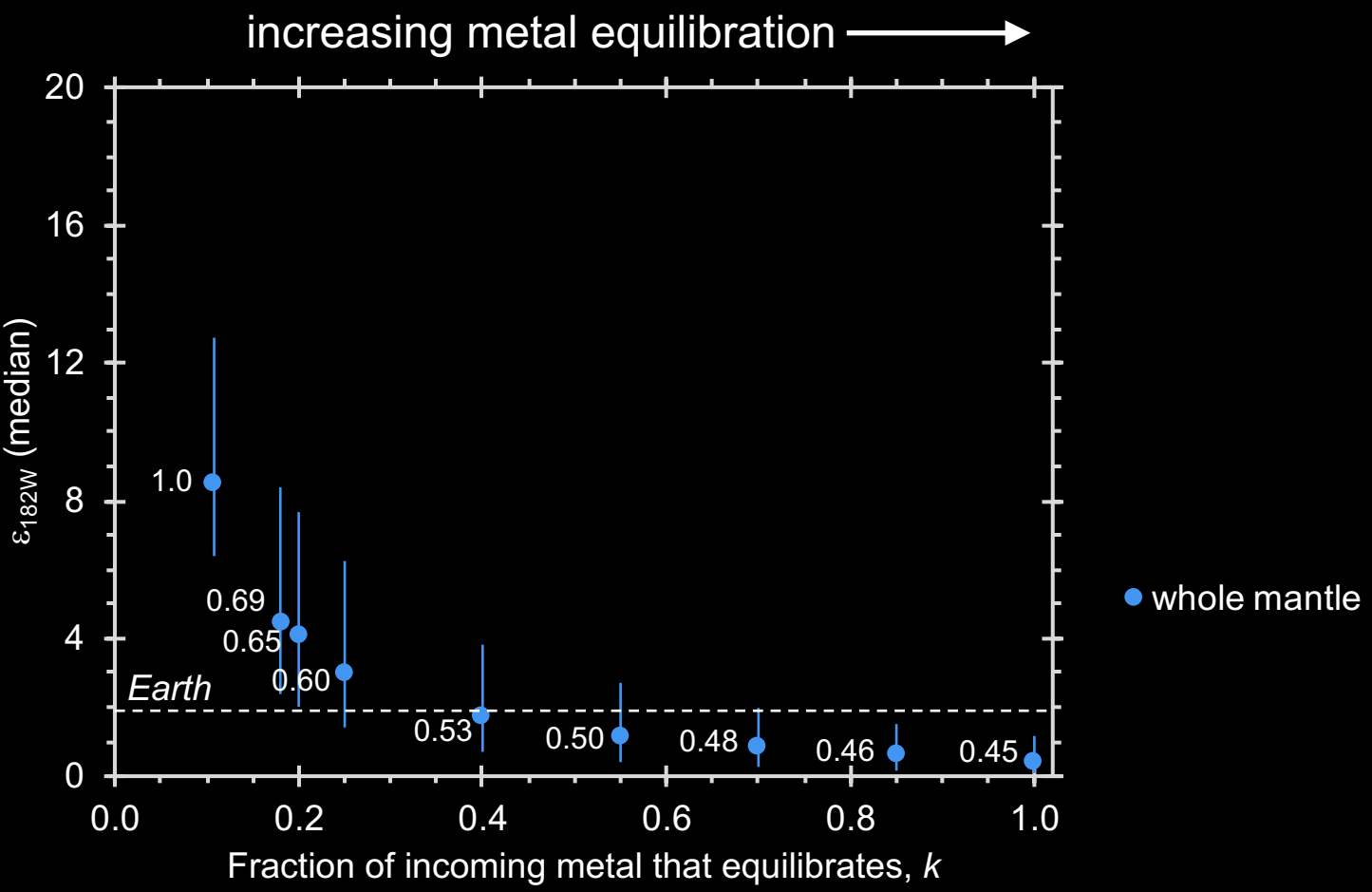






Equilibration reduces the W anomaly

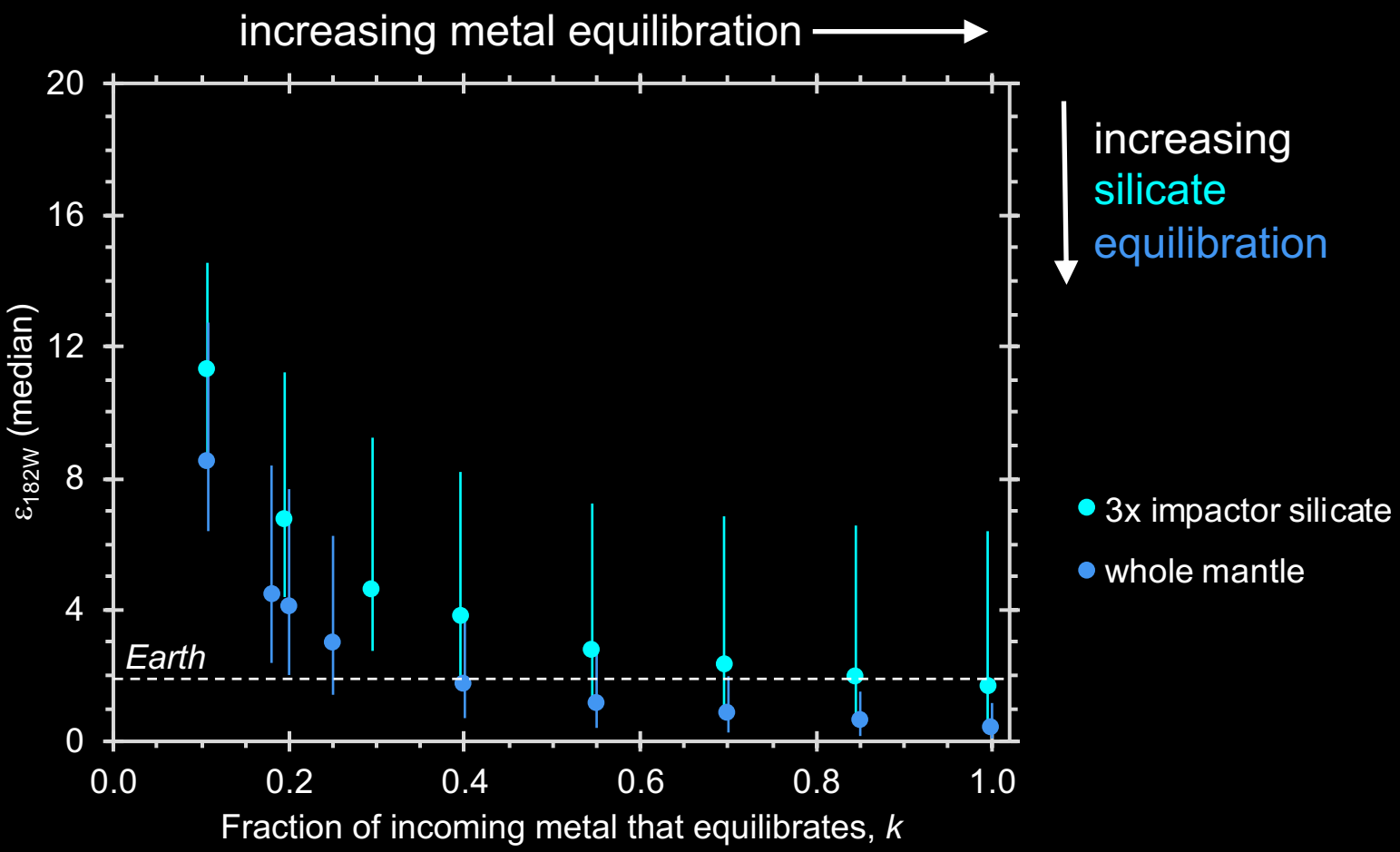
Effect of metal equilibration



- Change depth and *k* simultaneously to match mantle composition
- Best match: *k* = 0.4 (Nimmo et al., 2010) and depth ≈ 55% of CMB
- Range allowed, depend on accretion history

Fischer and Nimmo (2018), EPSL

Effect of silicate equilibration



- Best match: k = 0.9

Fischer and Nimmo (2018), EPSL

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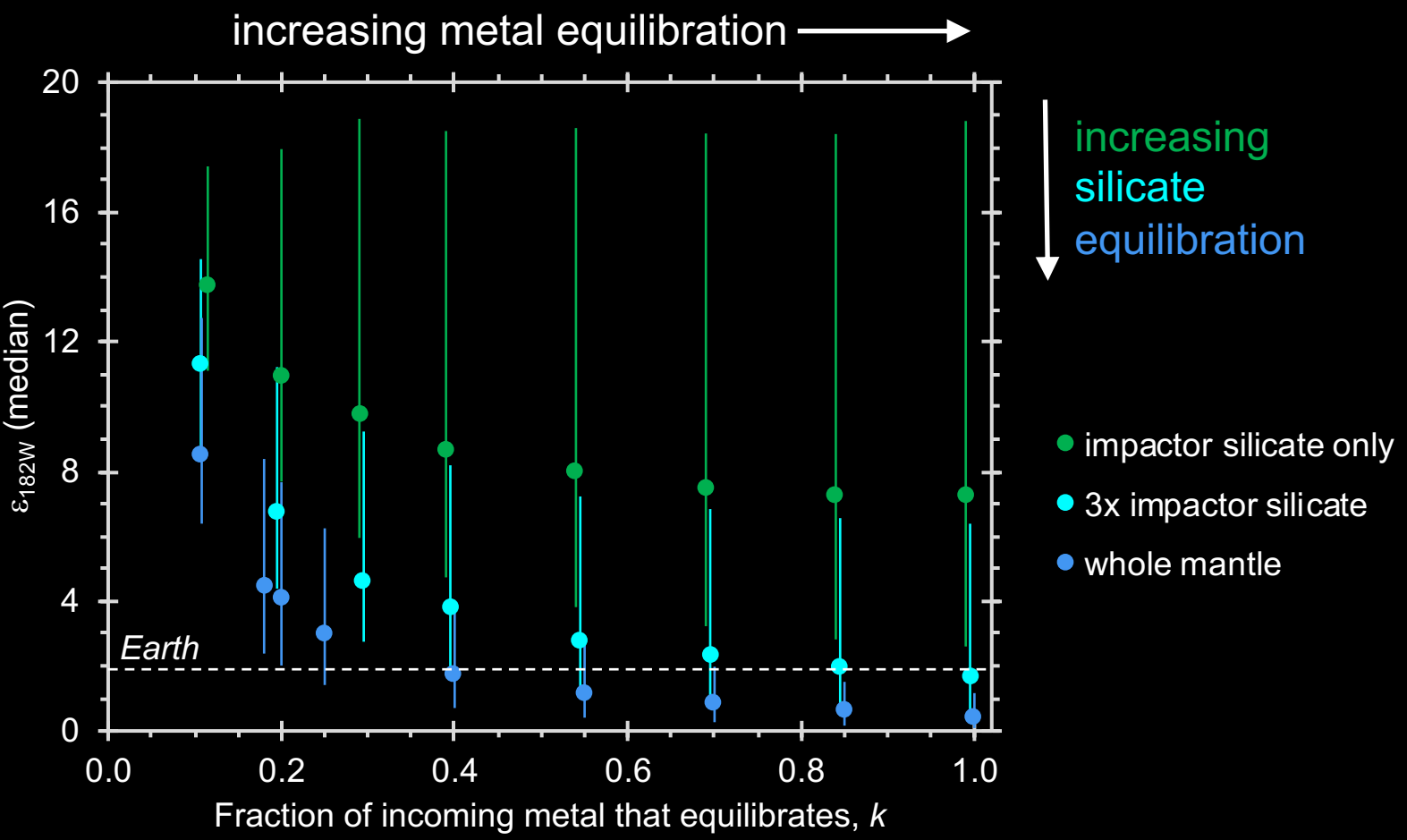
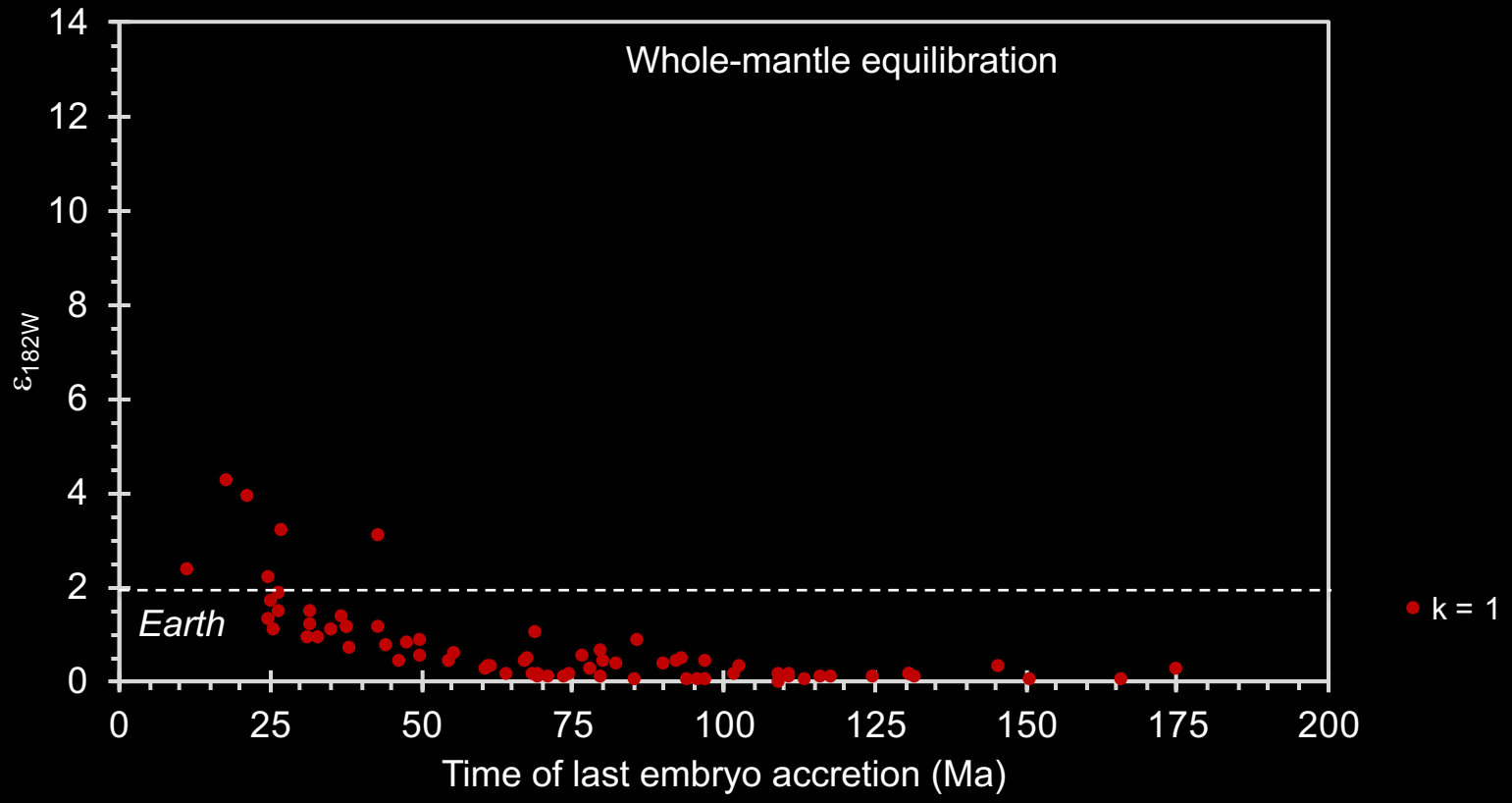


- Equilibration reduces the W anomaly
- Must equilibrate with ≥ 3x impactor silicate mass
- k > 0.2 (depth < 0.65x CMB pressure)

Fischer and Nimmo (2018), EPSL

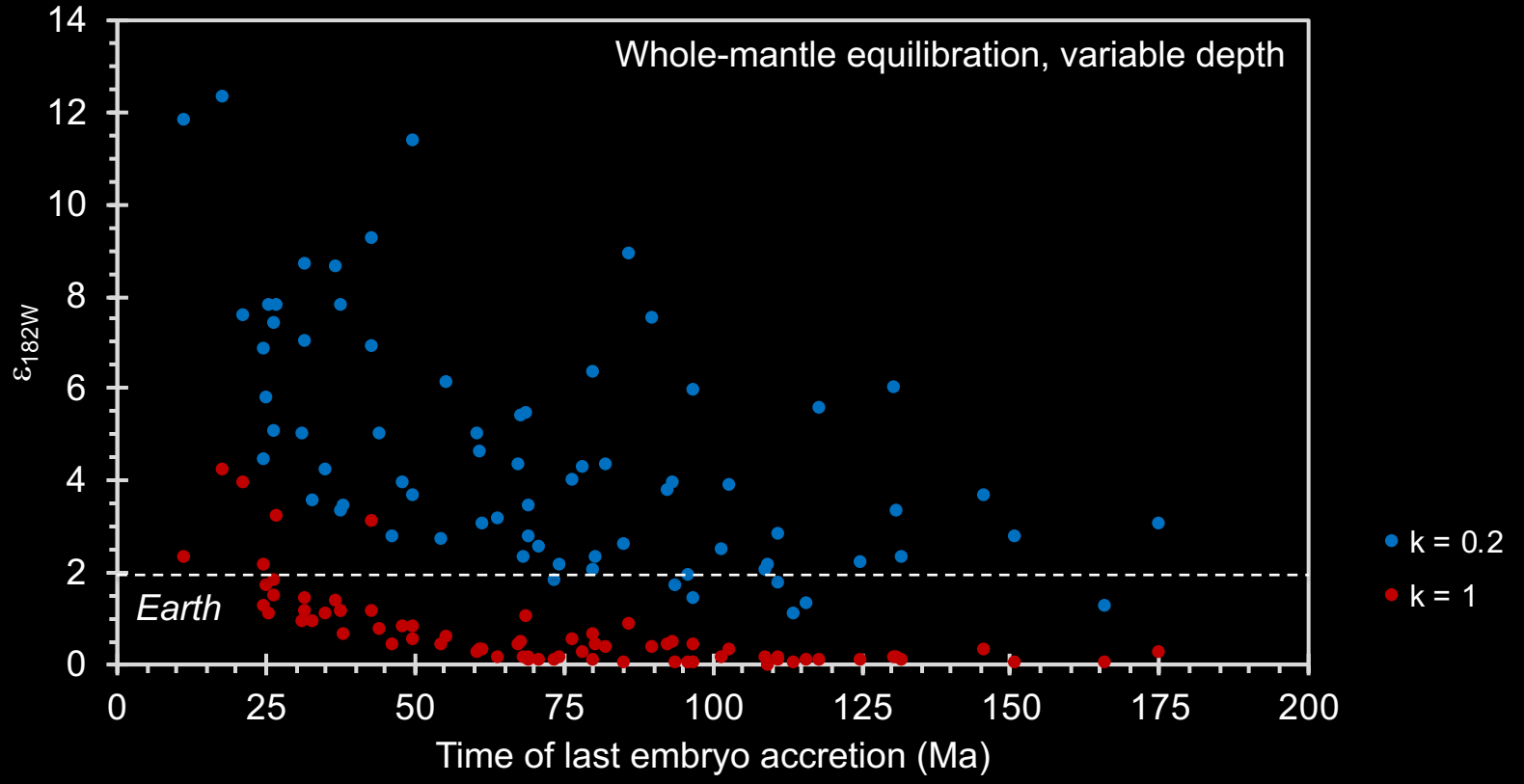
Timing of core formation



- Whole-mantle equilibration, *k* = 1.0: last embryo accretion at ~20–40 Ma

Fischer and Nimmo (2018), EPSL

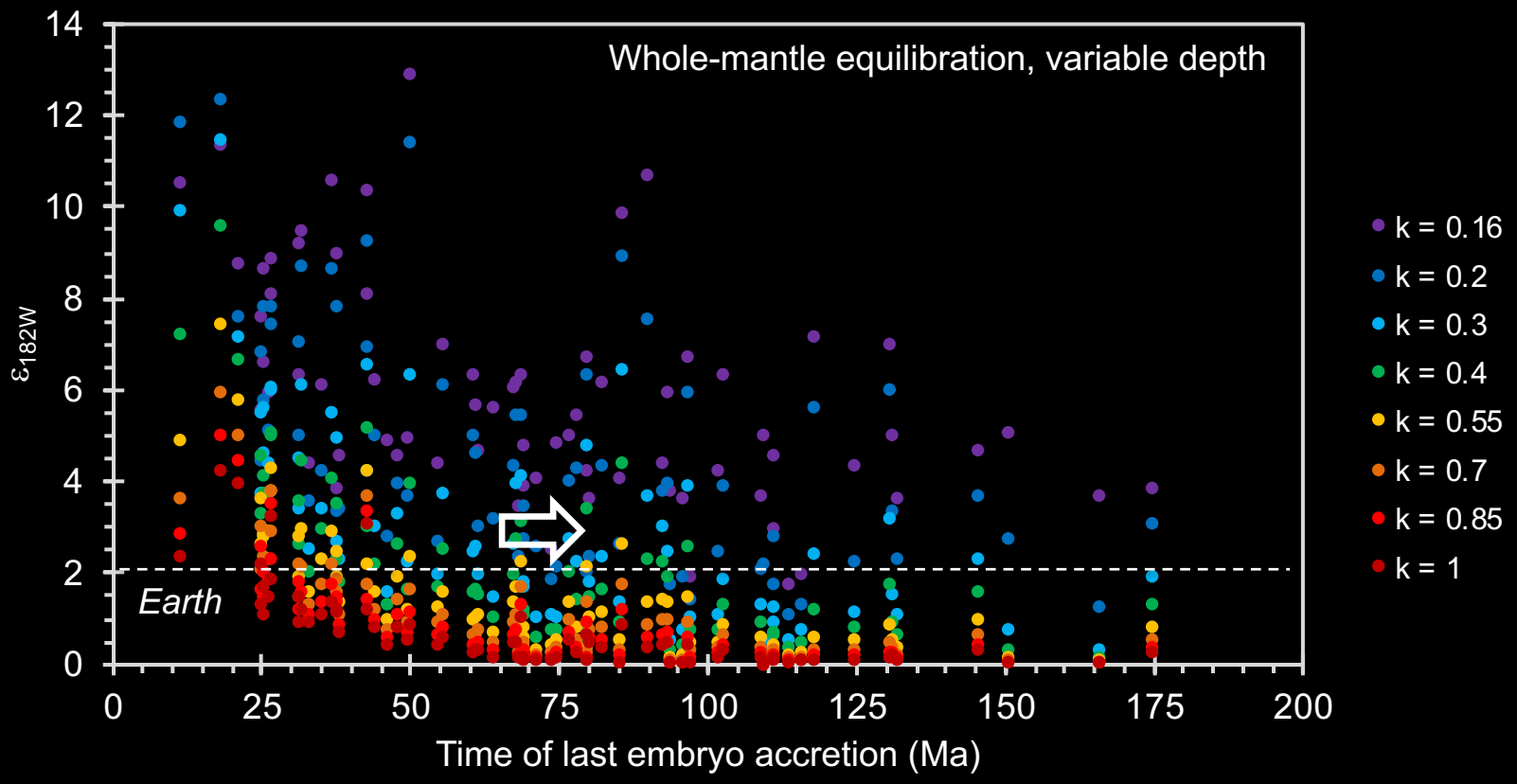
Timing of core formation



- Whole-mantle equilibration, *k* = 1.0: last embryo accretion at ~20–40 Ma
- Whole-mantle equilibration, *k* = 0.2: last embryo accretion at ~75–175+ Ma

Fischer and Nimmo (2018), EPSL

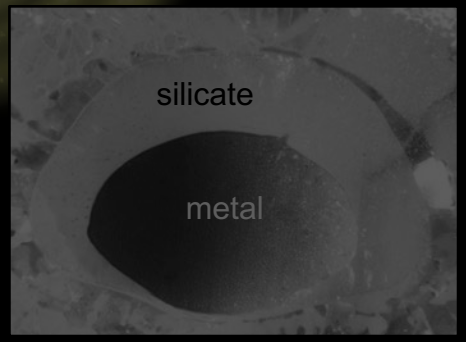
Timing of core formation



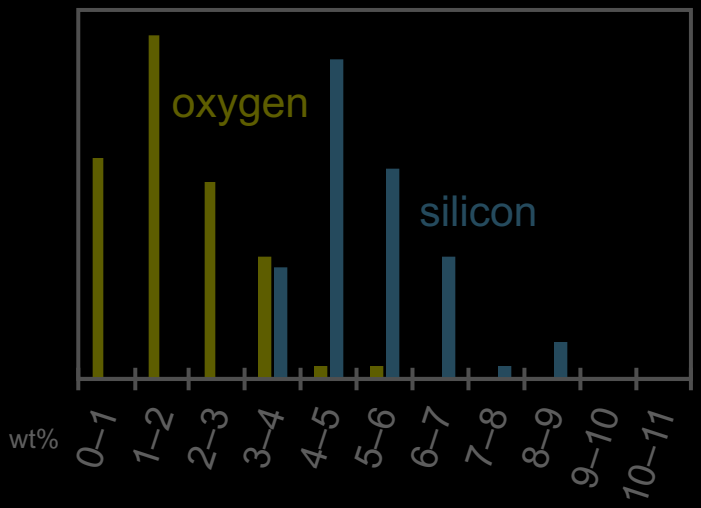
- Range of *k* and formation timescales allowed – interpret with caution
- Late veneer mass (t > 65 Ma; Jacobson et al., 2014) gives k < 0.55
- Tradeoff between *k*, silicate mass, depth, and formation timescale
- Later formation time requires less equilibration

Fischer and Nimmo (2018), EPSL

Part I: Introduction and background



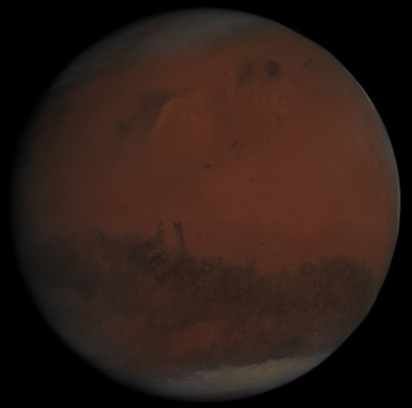
Part 2: Earth's trace elements and light elements



Part 3: Earth's Hf–W isotopes

- Tradeoff between depth/degree of equilibration, timing
- $0.2 < k < 0.55$, corresponds to depth of ~0.5–0.7x CMB pressure
- >3x impactor silicate mass
- Tighter constraints on core formation process than trace elements

Part 4: Core formation on Mars



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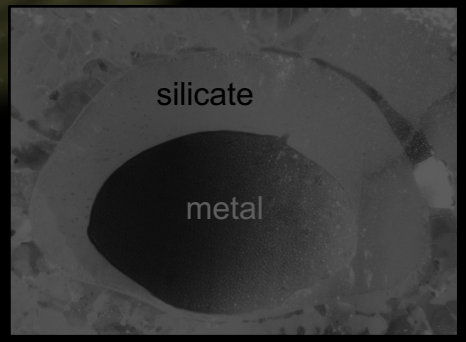

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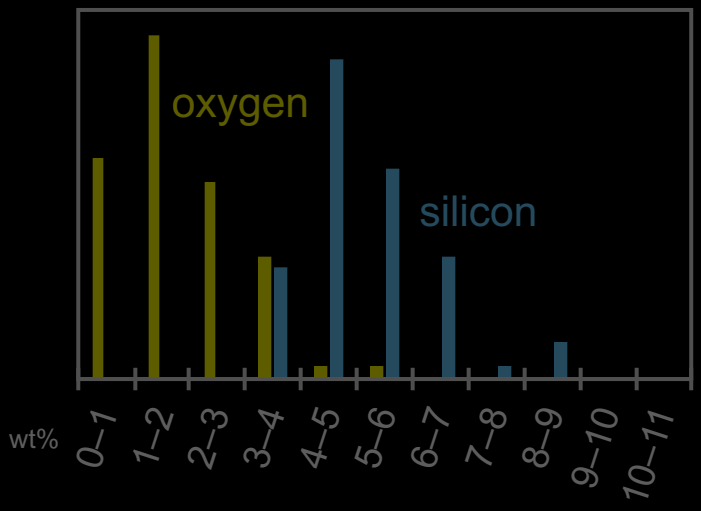

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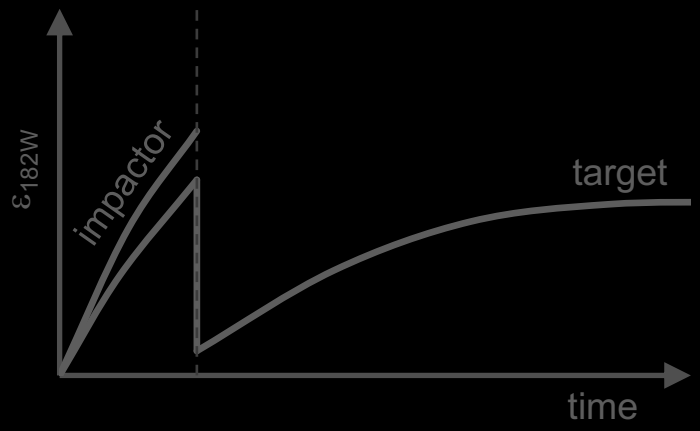

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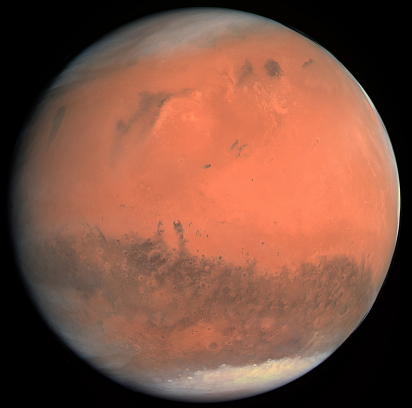

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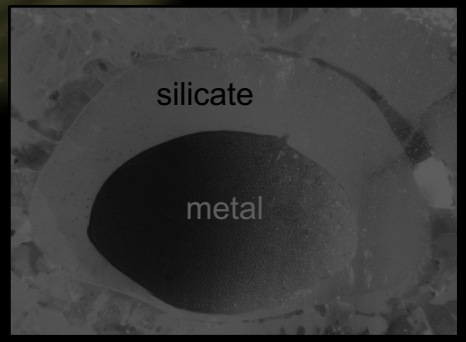

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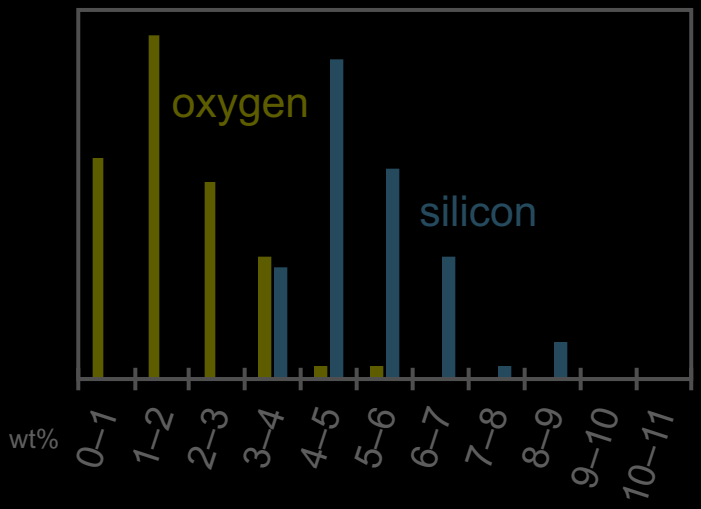

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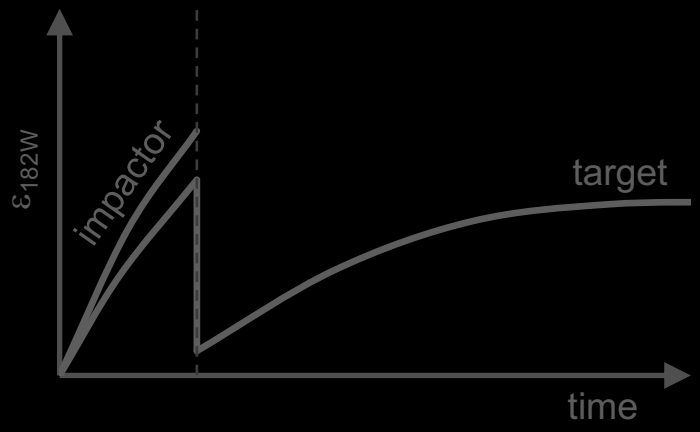
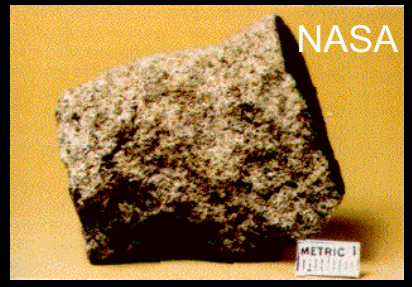
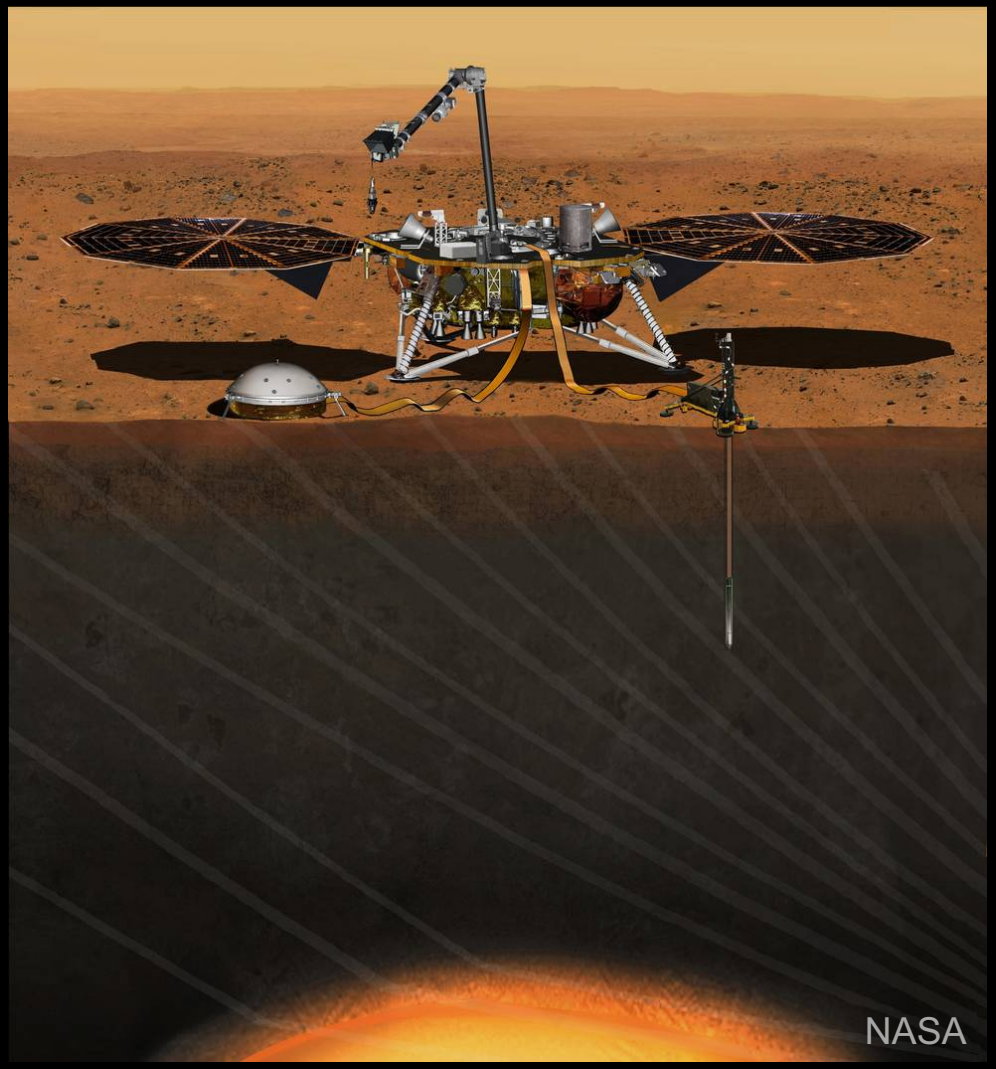


Part 4: Core formation on Mars

Why study Martian core formation?

- Are core formation mechanisms the same across terrestrial planets?
- SNC meteorites
- InSight mission





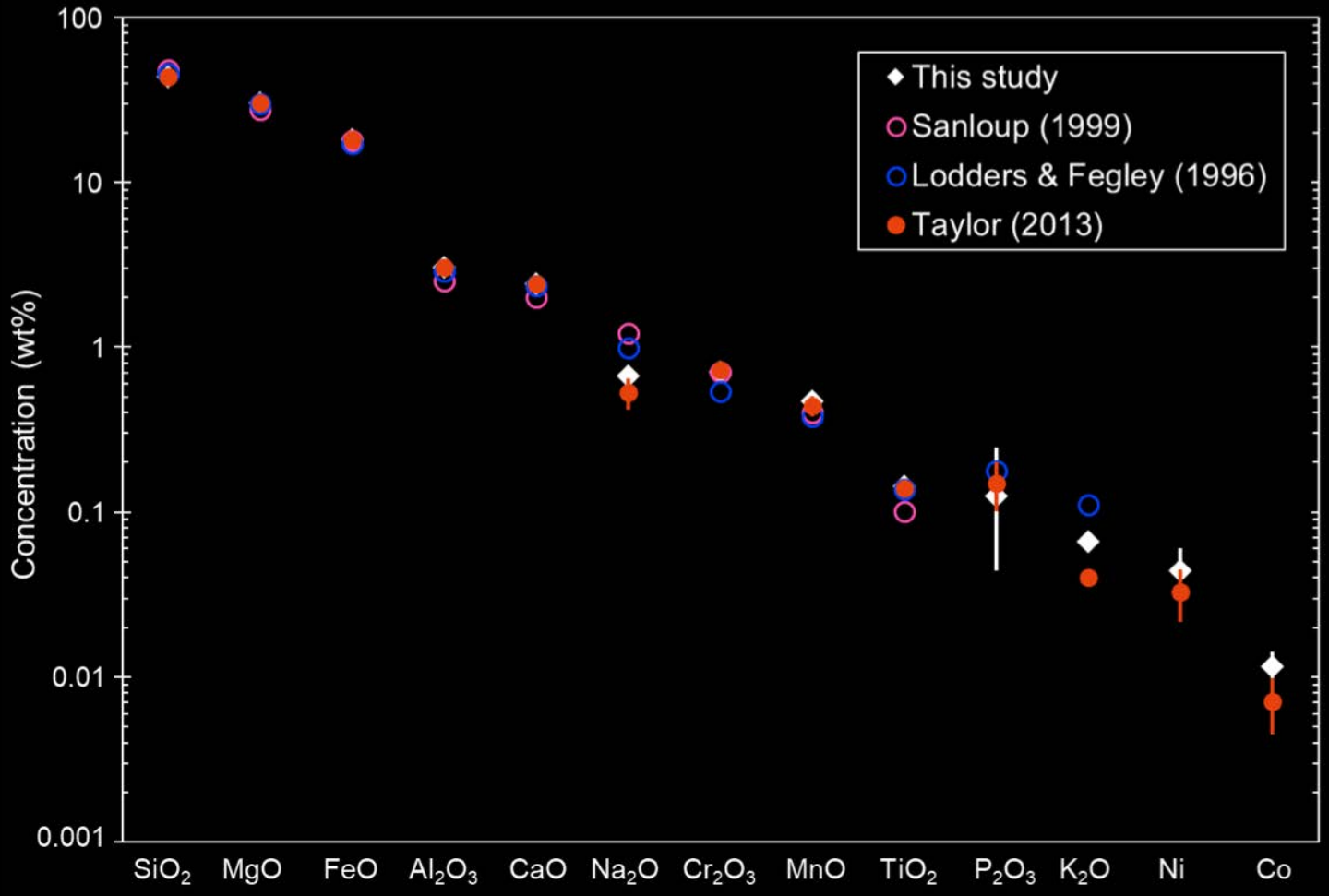
Mars core formation model

- Similar to Earth models
- Prescribed mass evolution (working on including *N*-body simulations, Hf–W isotopes)
- Very sensitive to volatile content: CI chondrite, enriched in refractory elements by 1.9x, based on lithophile volatiles (Taylor, 2013)

Brennan et al. (2020), EPSL

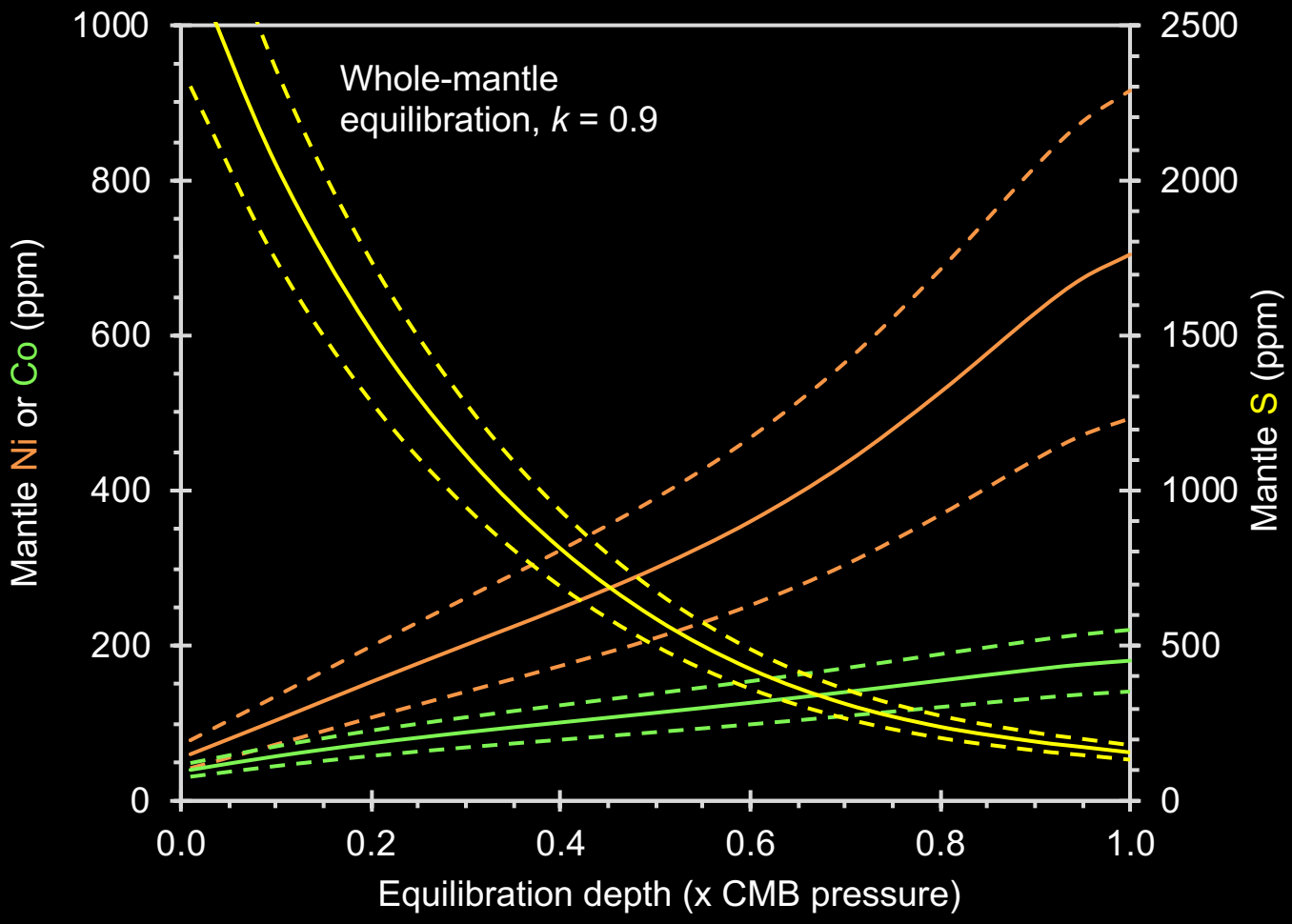
Martian mantle composition

- Compare to Martian mantle calculated from SNCs
- Good match to major, minor, and trace elements
- Higher fO_2 than Earth



Brennan et al. (2020), EPSL

Depth of equilibration



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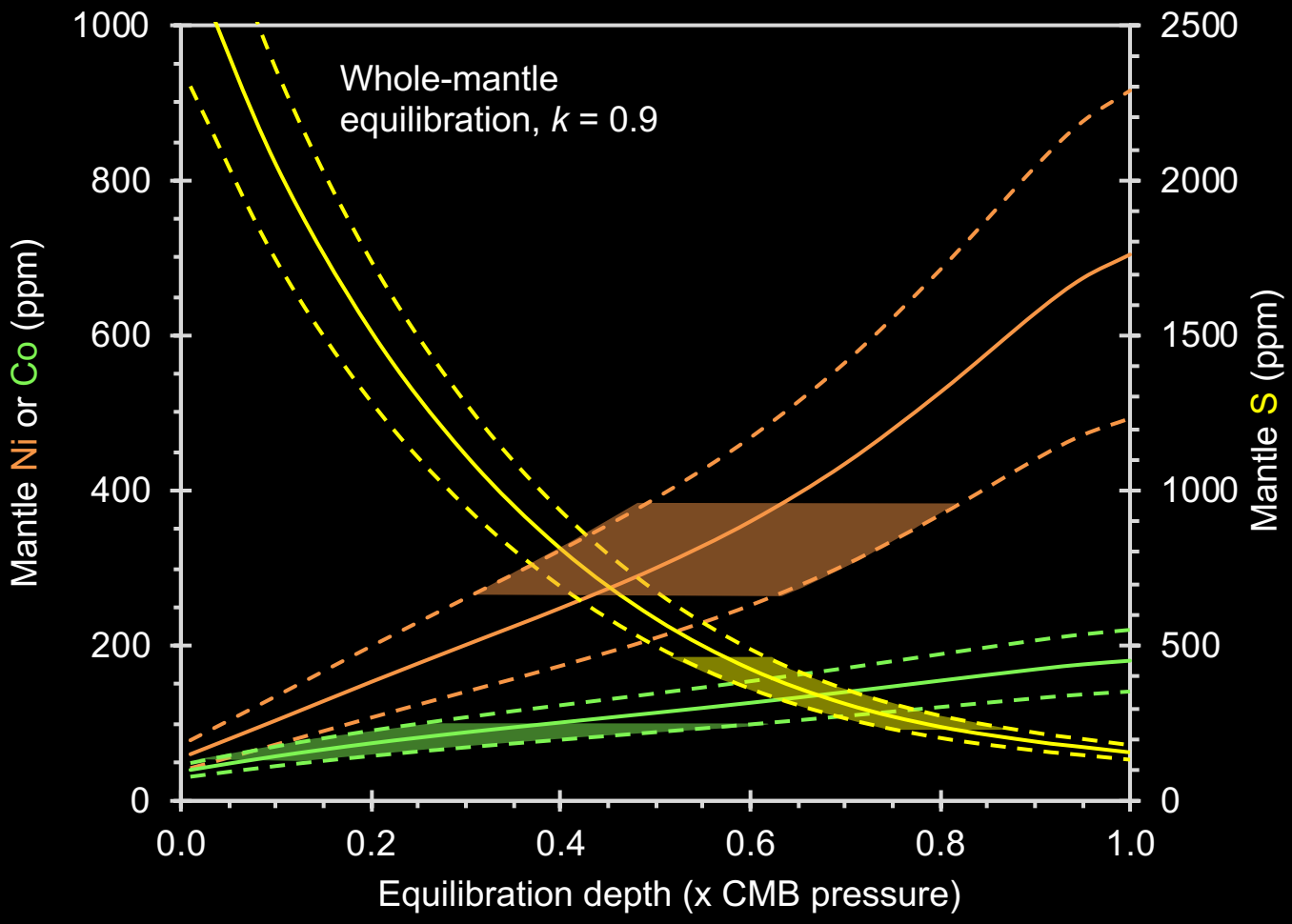

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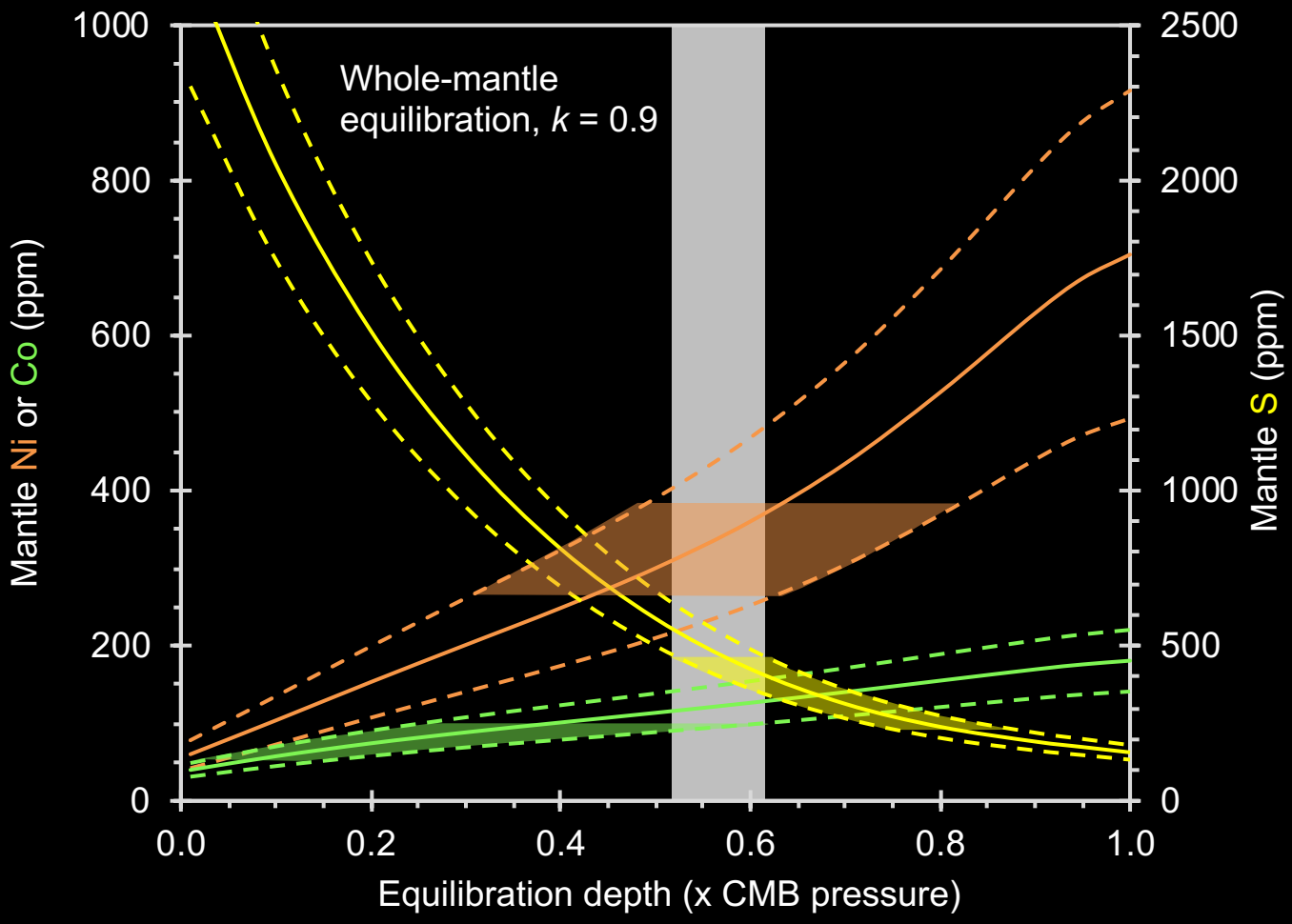
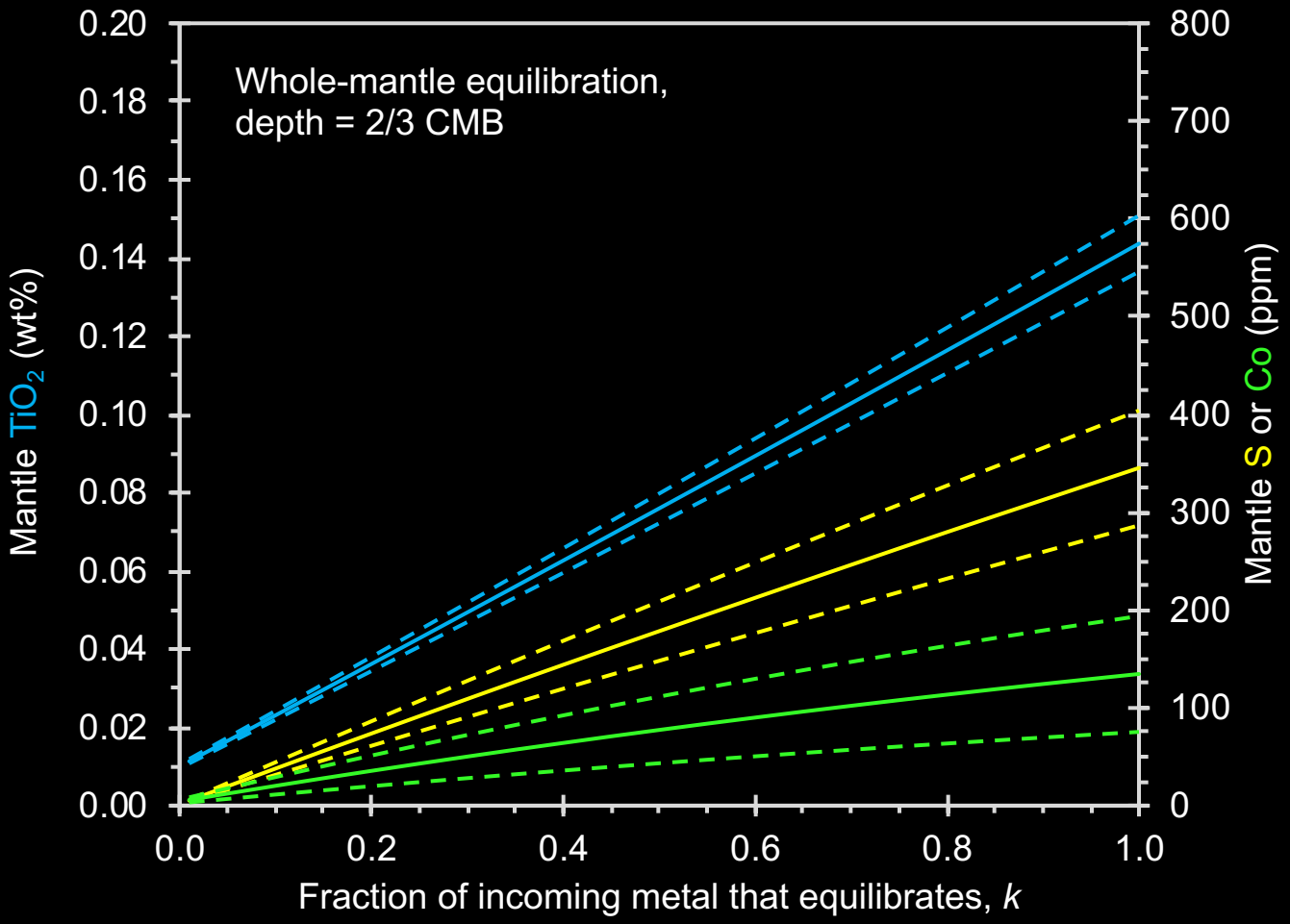


Depth ~0.5–0.6x CMB (comparable to Earth)

Depends on volatile content

Brennan et al. (2020), EPSL

Degree of equilibration



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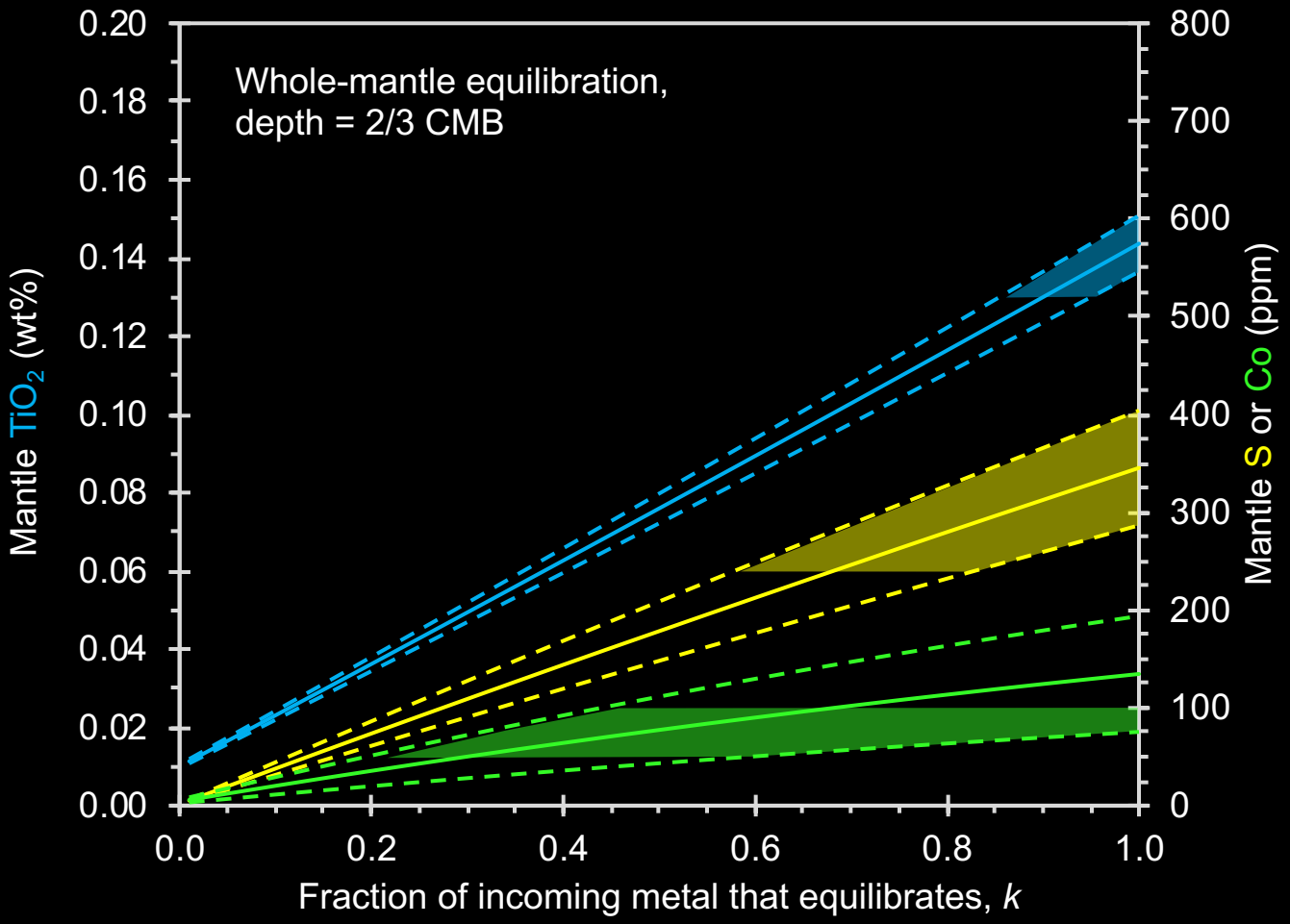

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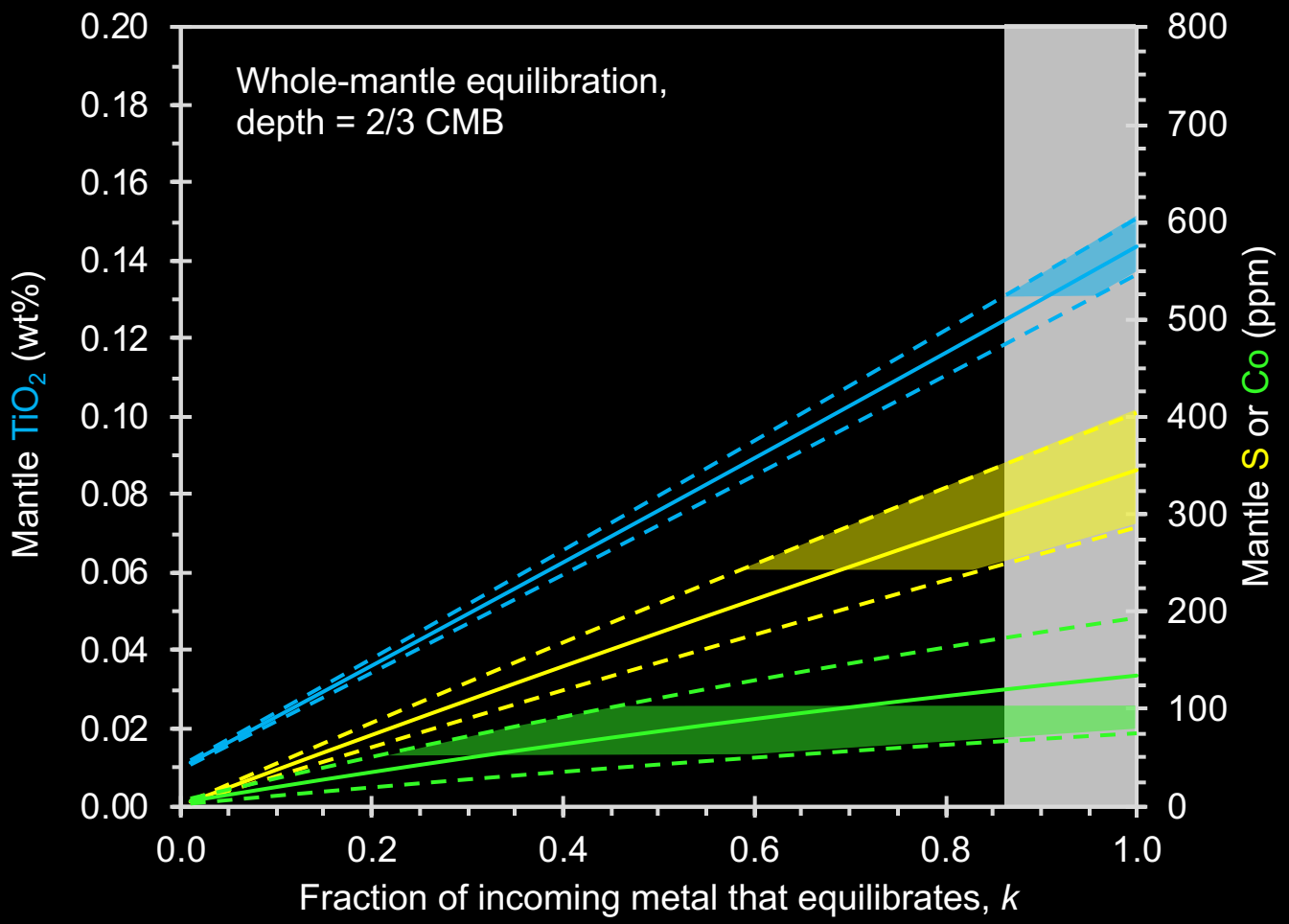
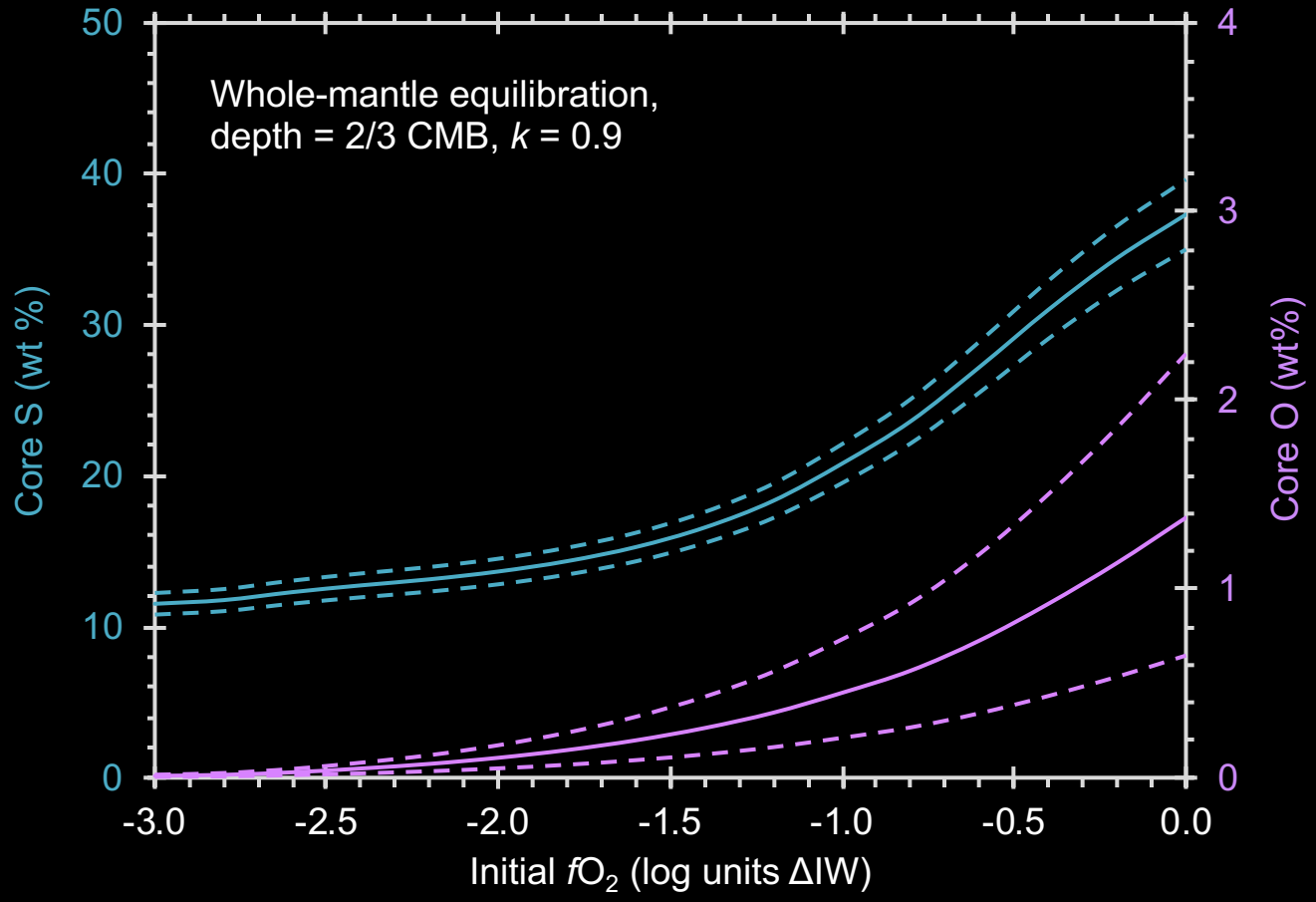


High degree of metal equilibration: k = 0.85–1.0 (Earth: k = 0.2–0.55)

Degree of silicate equilibration: >20% of target silicate (comparable to Earth)

Brennan et al. (2020), EPSL

Core composition



Brennan et al. (2020), EPSL

Core composition

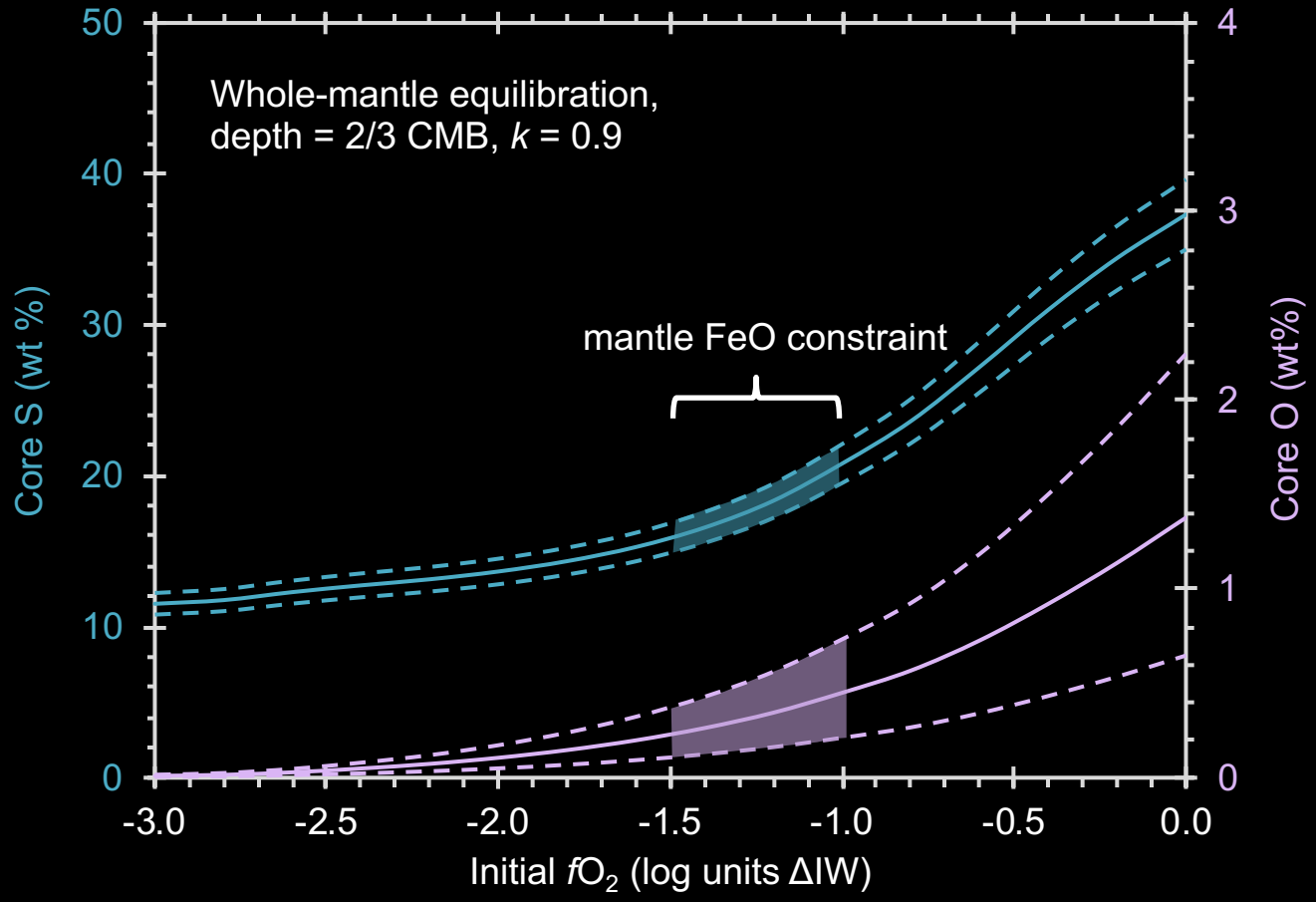
Iron plus:

- 7.0 ± 0.8 wt% Ni
- 18 ± 2 wt% S
- 0.3 ± 0.3 wt% O
- Negligible Si

Core mass fraction = 0.17–0.26

Core radius, density/velocity profiles

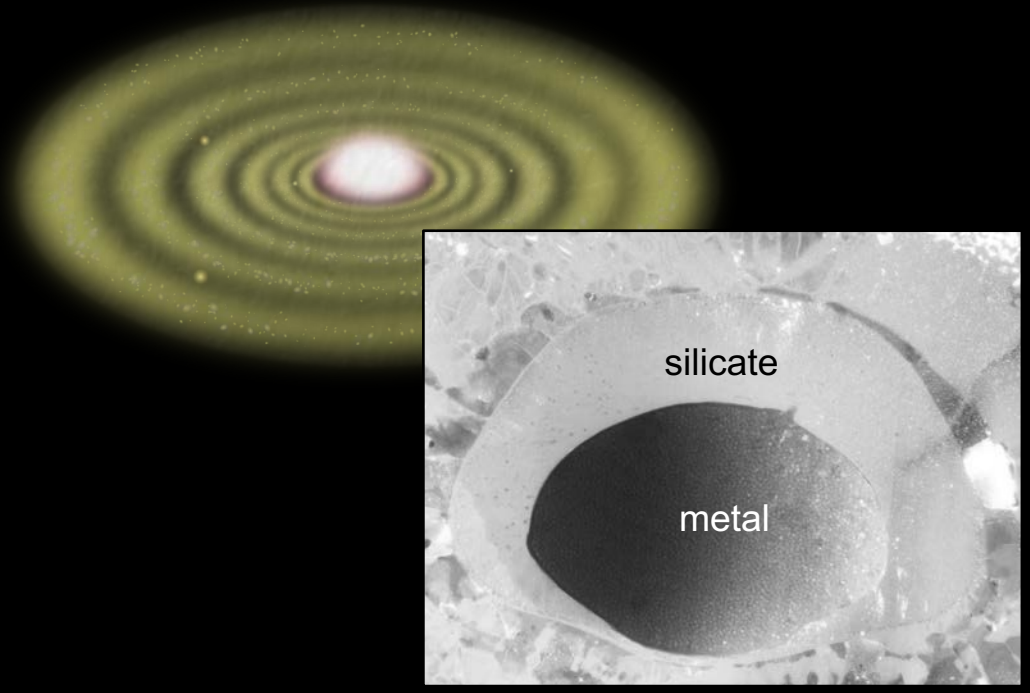
Seismic observables



Brennan et al. (2020), EPSL

Conclusions

- Accretion simulations and metal–silicate partitioning experiments as prerequisites



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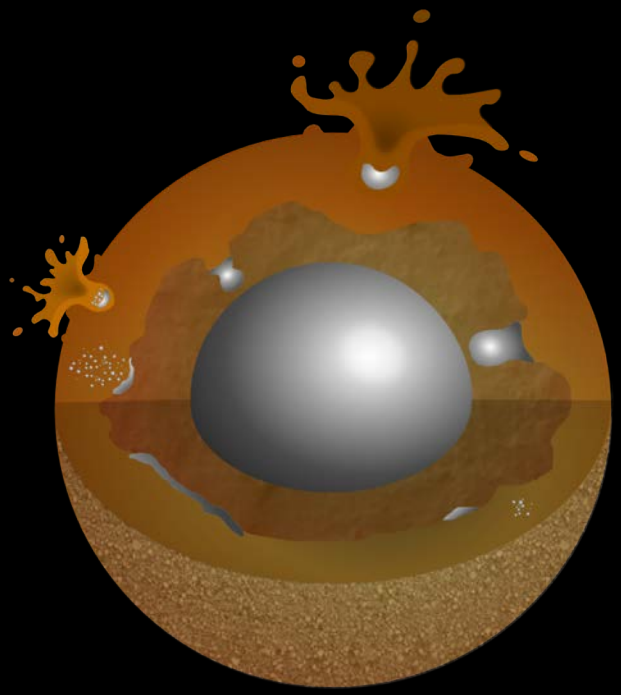
- Tradeoffs between depth, timing, and degree of equilibration
- Composition most sensitive to depth/degree of equilibration and accretion history



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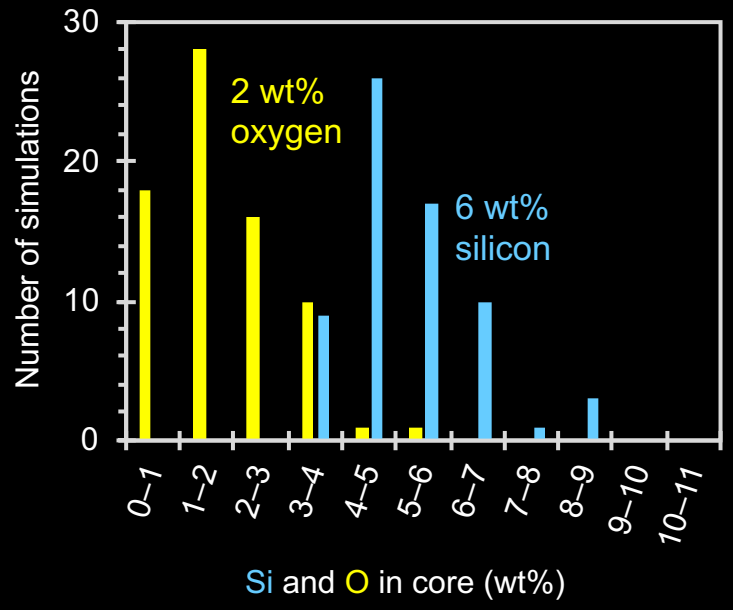
- Earth's core: 6 wt% Si, 2 wt% O (small amounts of S, C, H)
- Mars's core: 18 wt% S, <1 wt% O, negligible Si



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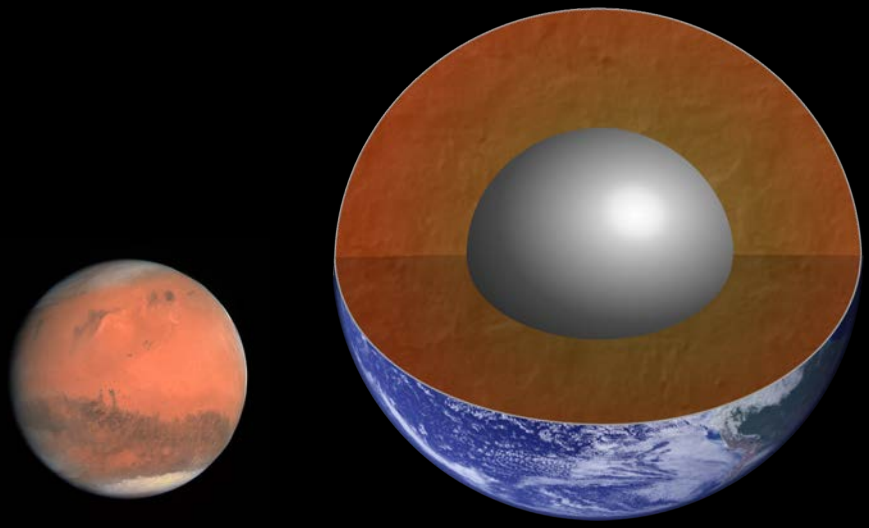
- Mars's core: 18 wt% S, <1 wt% O, negligible Si
- Degree of metal equilibration: 0.2–0.55 for Earth, >0.85 Mars
- Rule out very small amount of silicate equilibration for Earth/Mars
- Depth of equilibration 0.5–0.7x CMB for Earth/Mars



Conclusions

- Accretion simulations and metal–silicate partitioning experiments as prerequisites
- Tradeoffs between depth, timing, and degree of equilibration
- Composition most sensitive to depth/degree of equilibration and accretion history
- Earth's core: 6 wt% Si, 2 wt% O (small amounts of S, C, H)
- Mars's core: 18 wt% S, <1 wt% O, negligible Si
- Degree of metal equilibration: 0.2–0.55 for Earth, >0.85 Mars
- Rule out very small amount of silicate equilibration for Earth/Mars
- Depth of equilibration 0.5–0.7x CMB for Earth/Mars

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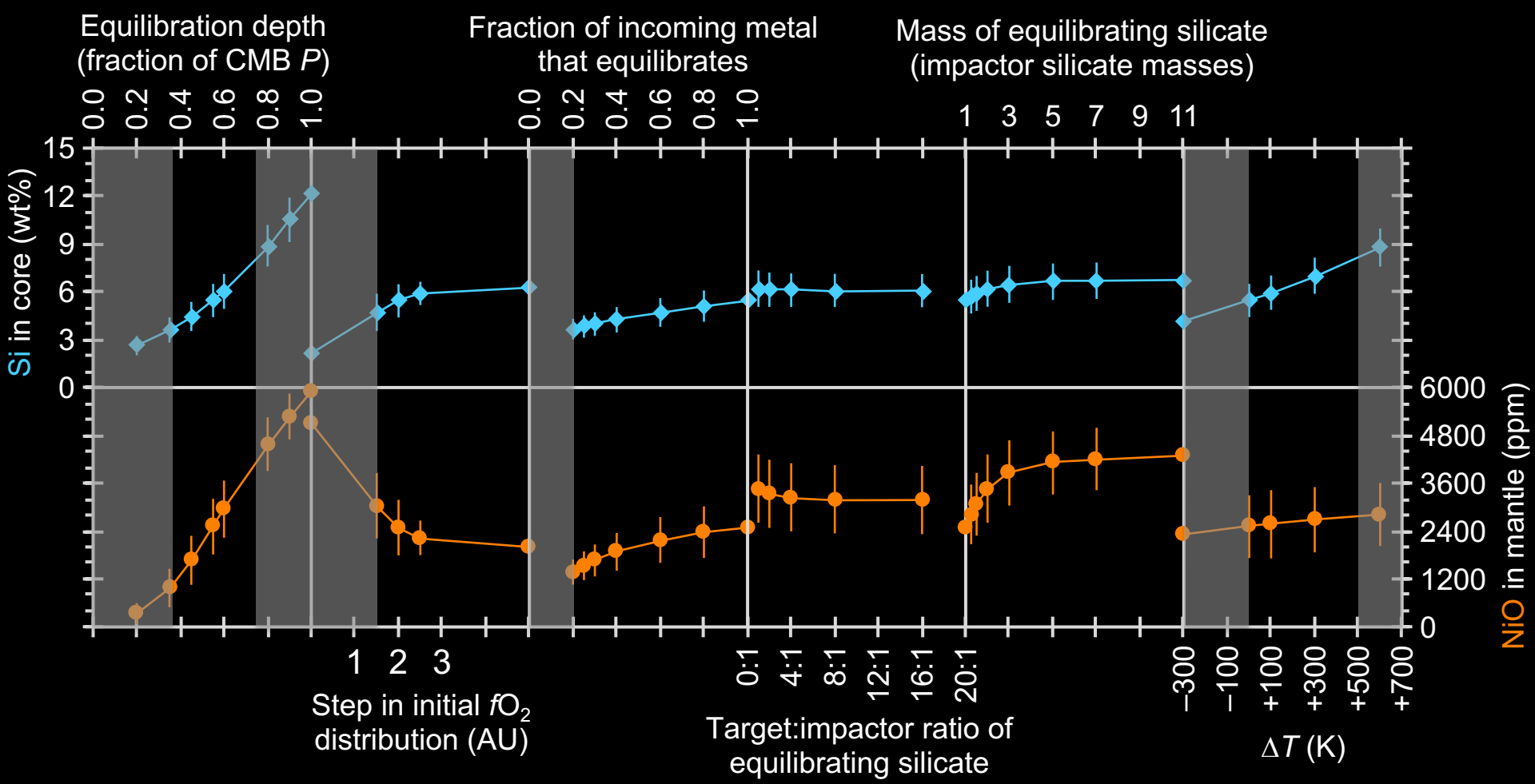
Sensitivities of core and mantle compositions

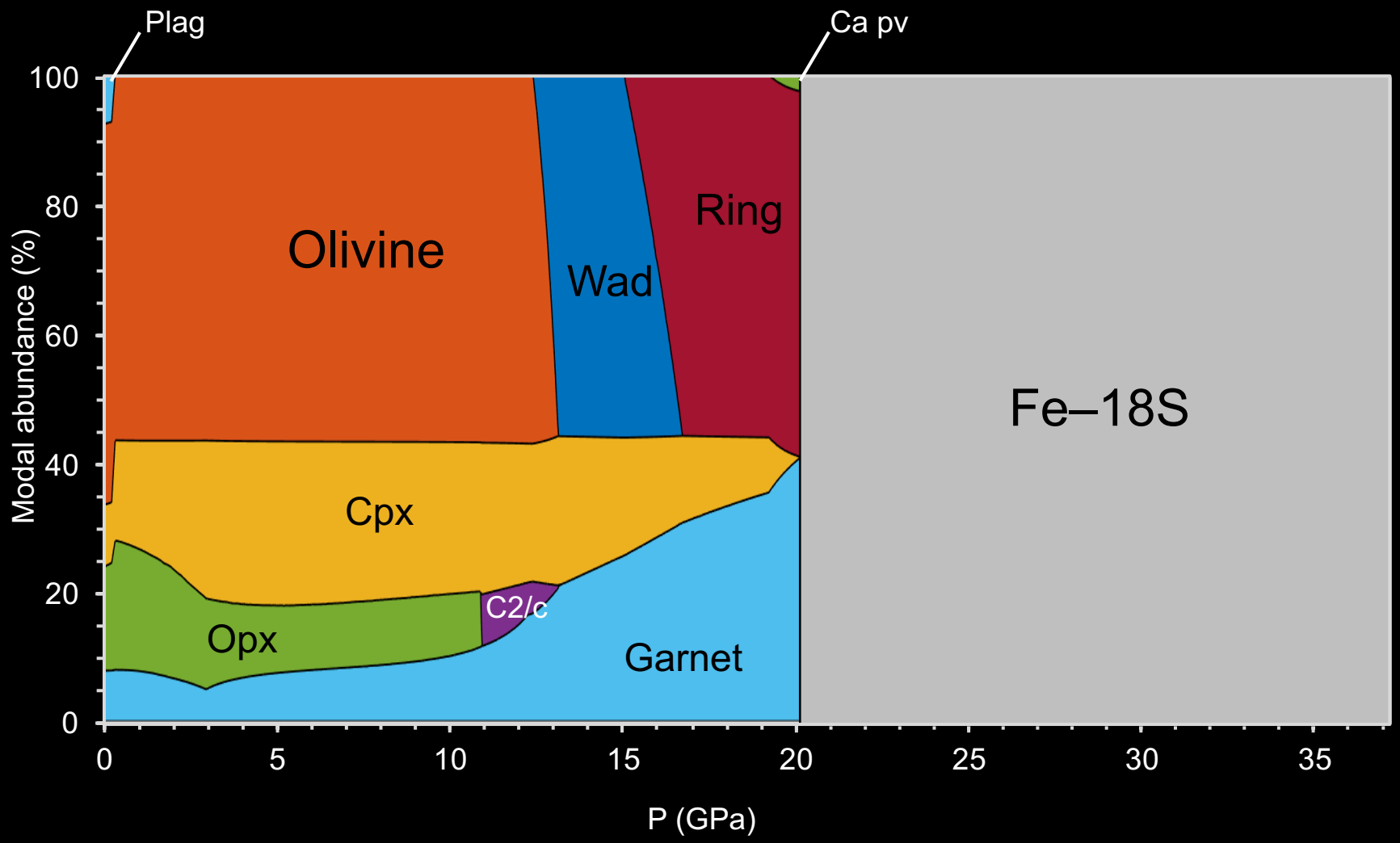


Variable sensitivity

Which factors are best targets for future studies to understand composition

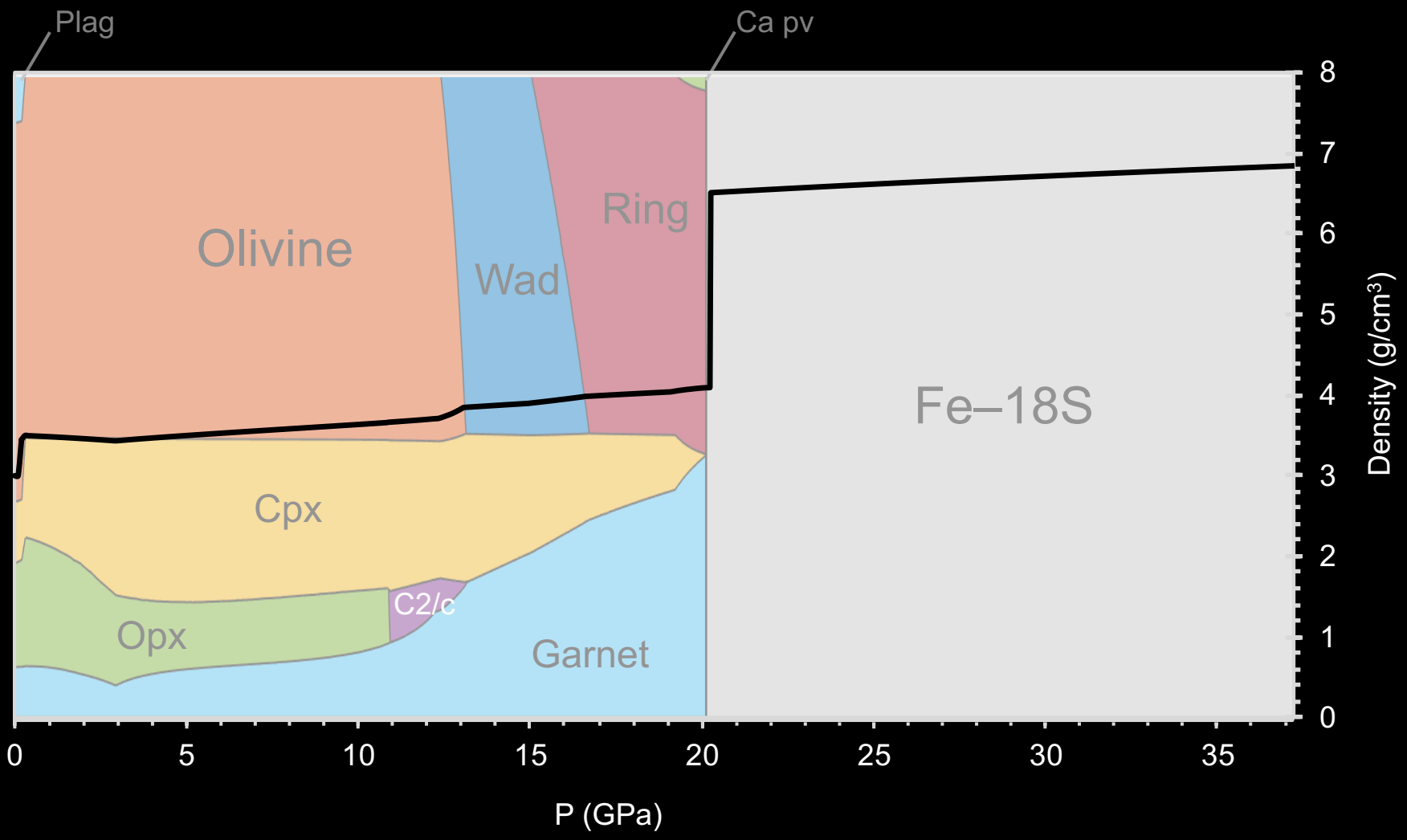
Fischer et al. (2017), EPSL

Geophysical model



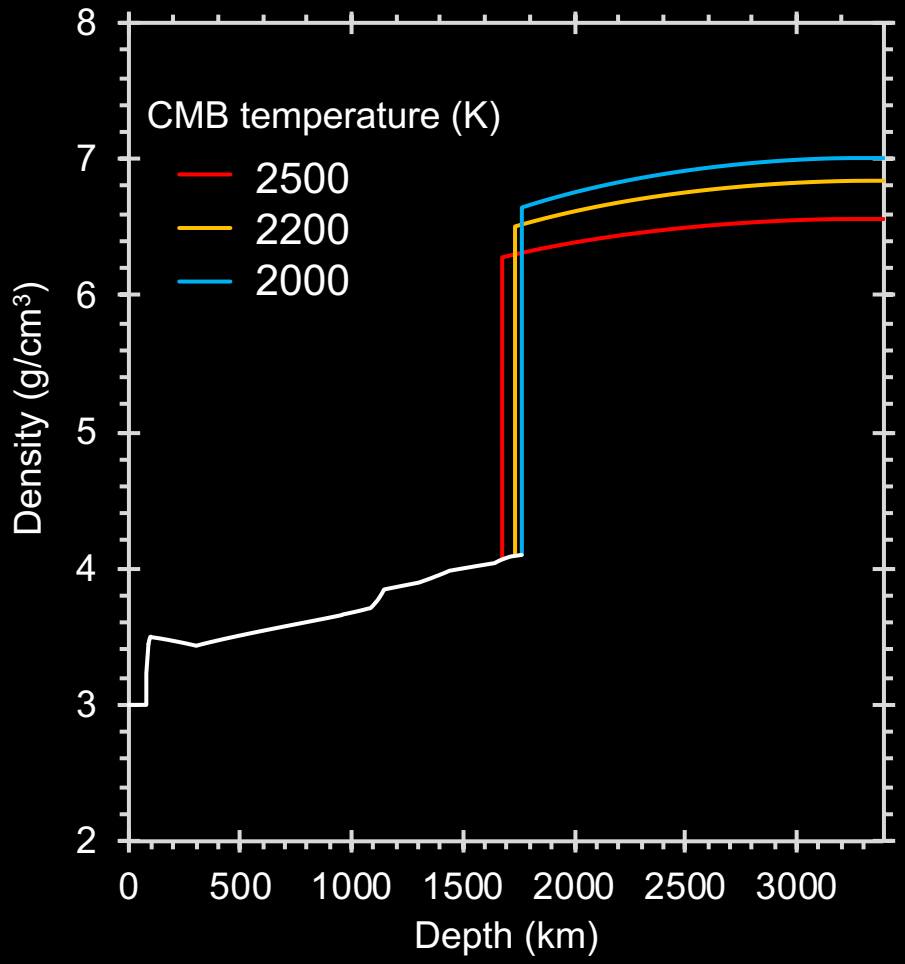
Brennan et al. (2020), EPSL

Geophysical model



Brennan et al. (2020), EPSL

Geophysical model

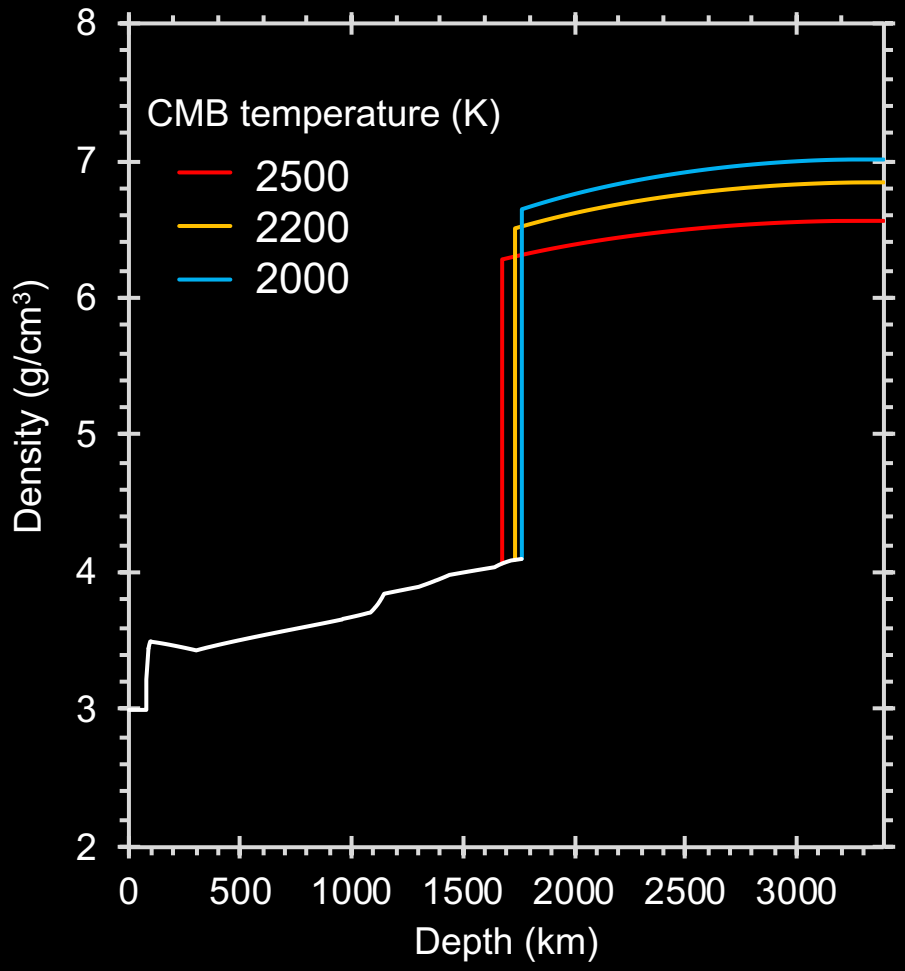


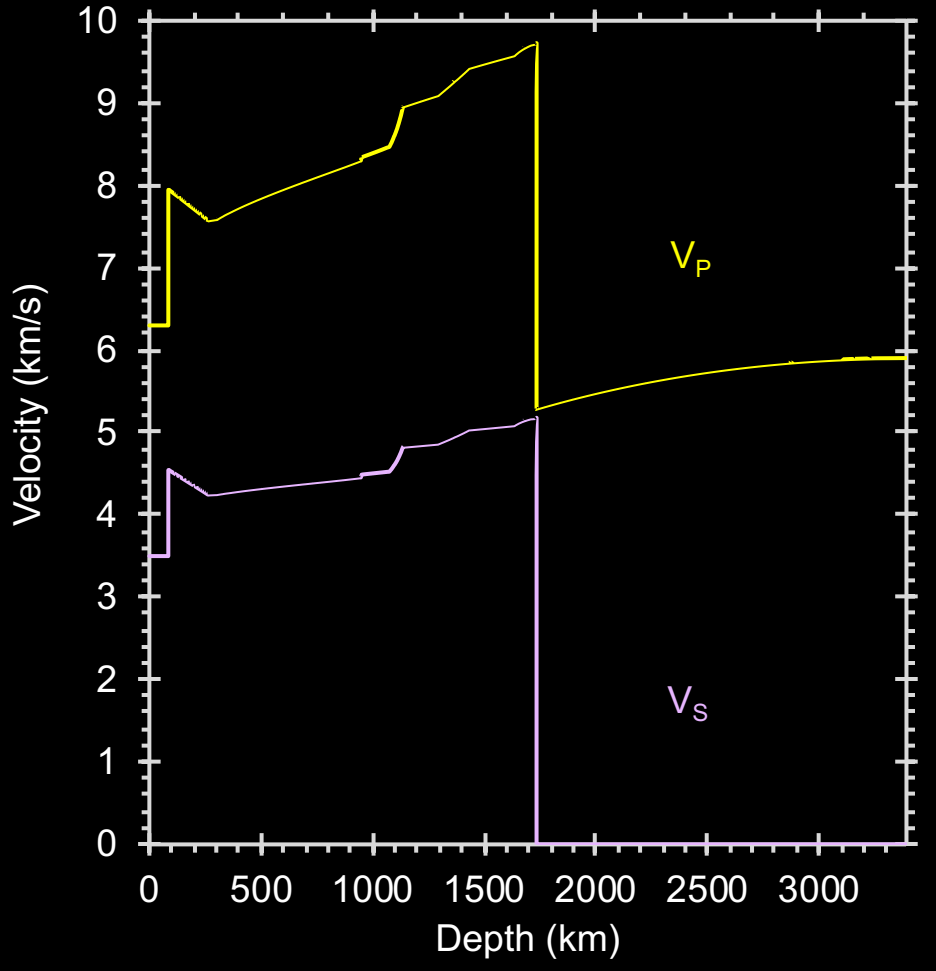
Effects of:

- Core *T*
- Mantle *T*
- S content
- Crust thickness
- Δ*V* of melting of Fe–S alloys

Brennan et al. (2020), EPSL

Geophysical model

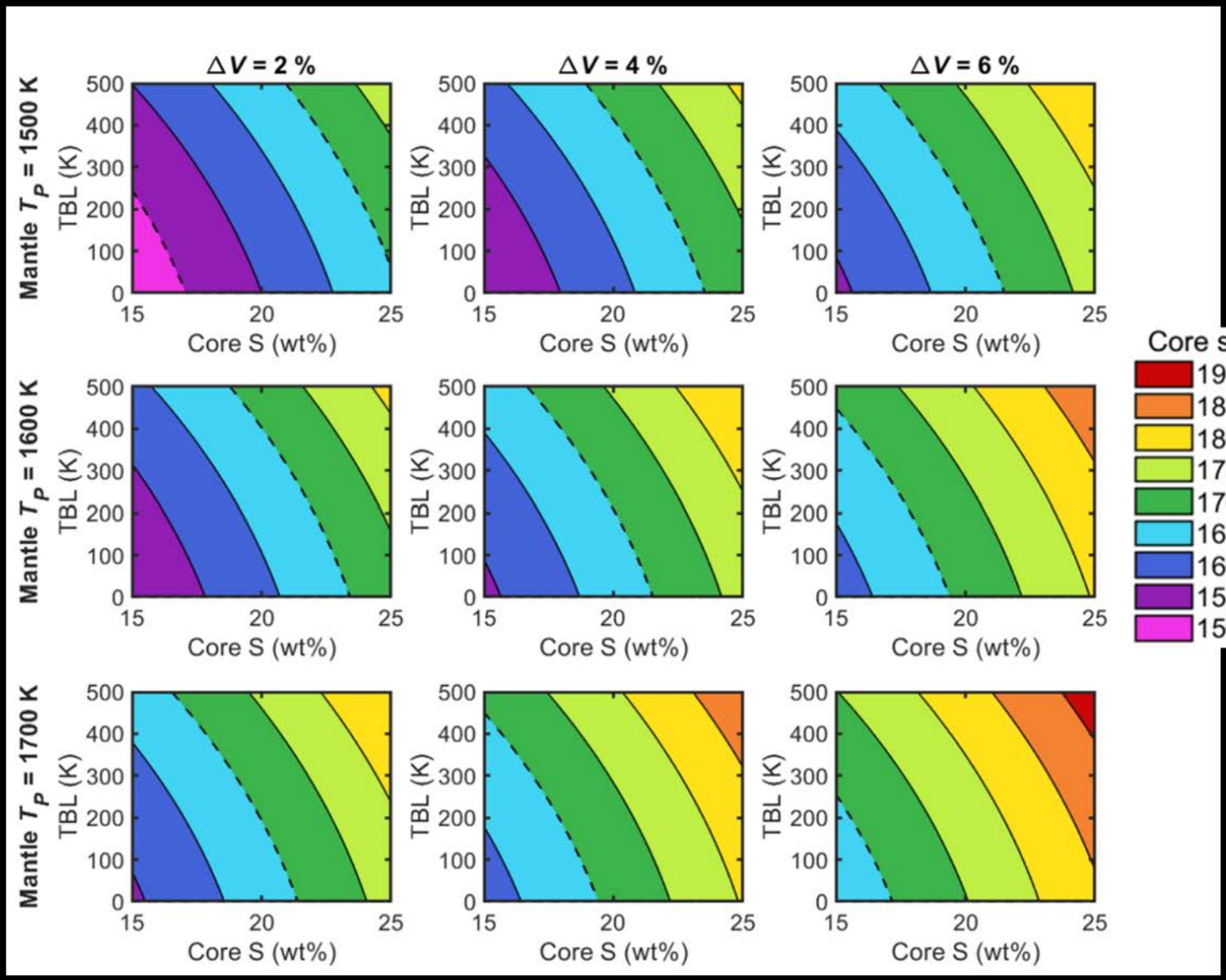




- Core radius
- Seismic travel times
- Normal modes

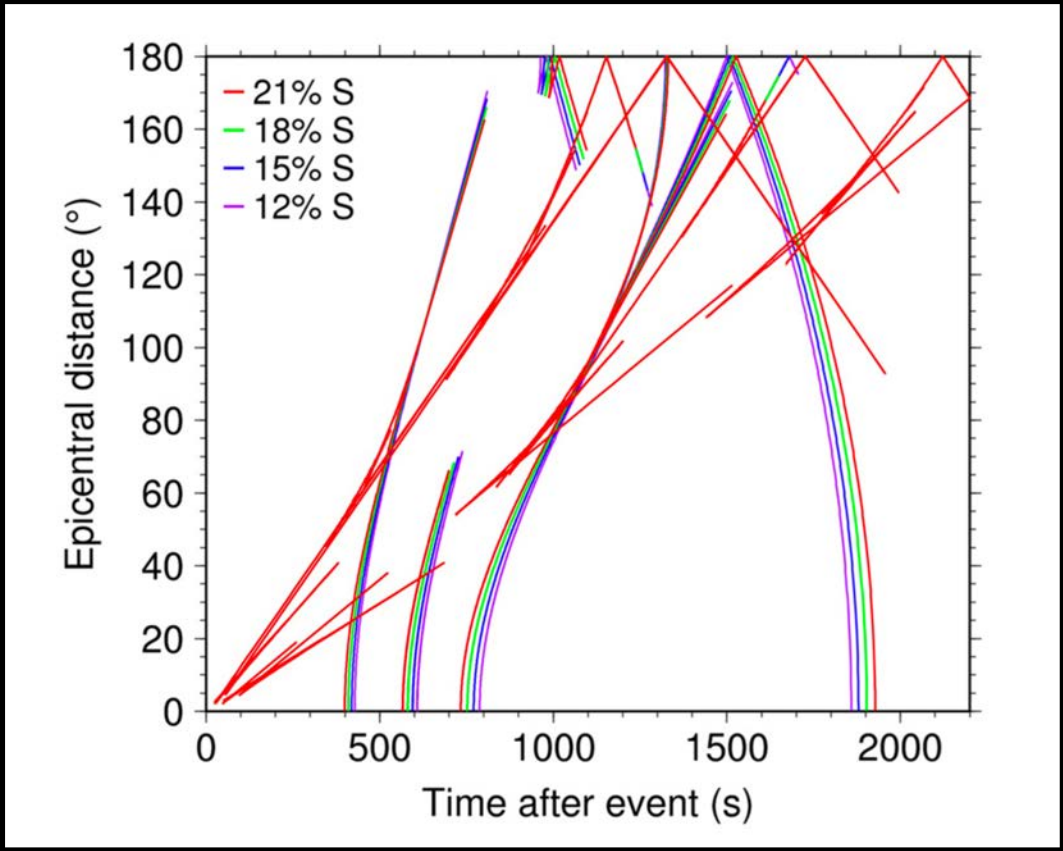
Brennan et al. (2020), EPSL

Martian core radius



Brennan et al. (2020), EPSL

Martian body wave travel times



Brennan et al. (2020), EPSL