Building a Wet Planet from Dry Materials

S.-H. Dan Shim (심상헌)

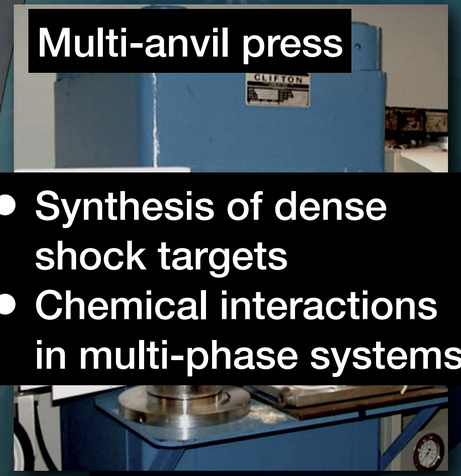
School of Earth and Space Exploration
Arizona State University

https://pbs.twimg.com/media/EQyZ7lKXYAE8R3Y?format=jpg&name=medium

Shim Lab

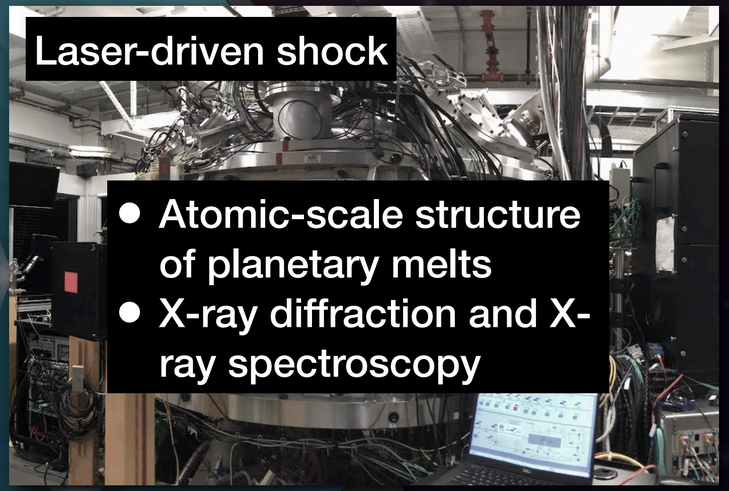
Laser-heated diamond-anvil cell

- H/H_2O-Silicate/Metal reaction
- Pulsed laser heating with gated synchrotron XRD



Multi-anvil press

- Synthesis of dense shock targets
- Chemical interactions in multi-phase systems



Laser-driven shock

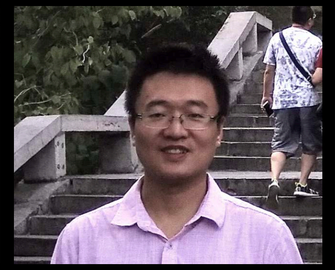
- Atomic-scale structure of planetary melts
- X-ray diffraction and X-ray spectroscopy

Synchrotron

X-ray free electron laser




Shim Lab @ASU







K. Leinenweber, A. Chizmeshya, S. Speziale, S. Chariton, V. Prakapenka, A. Vazan, A. Anbar, S. Desch, M. Li, E. Garnero, P. Buseck

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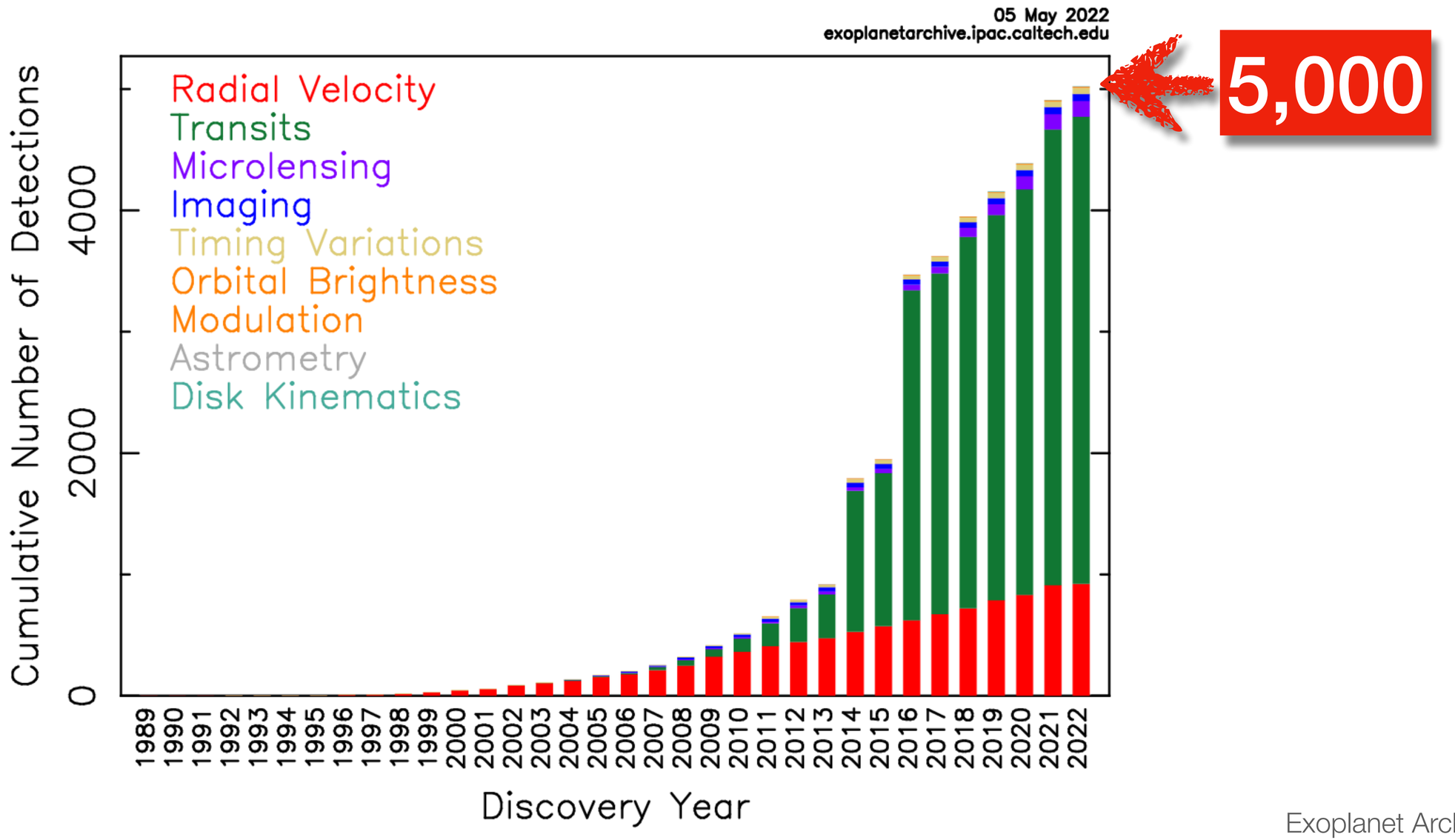
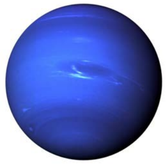
Materials of the Universe @ASU

Exoplanet Discoveries



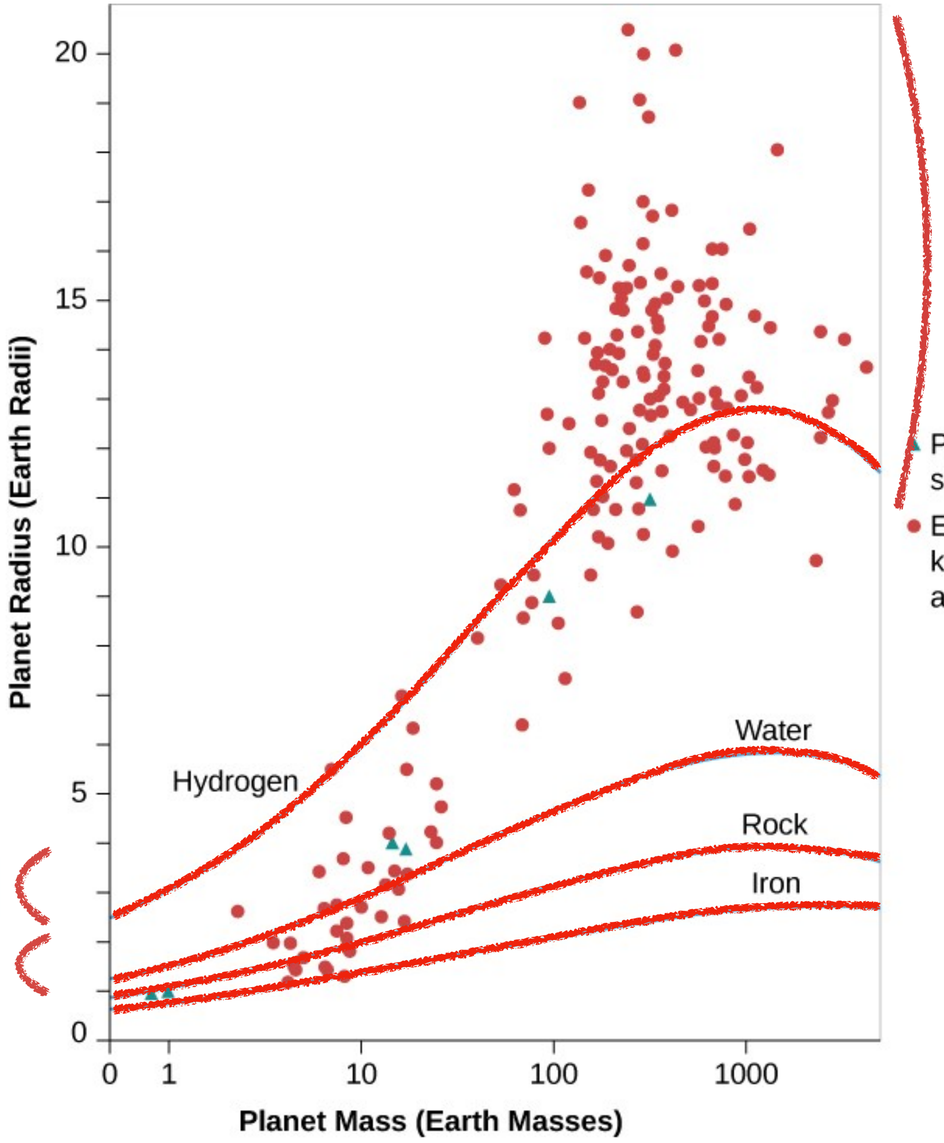
Exoplanet Archive

Mass-Radius



Sub-Neptunes

Super-Earths



Gas Giants

https://opentextbc.ca/astronomyopenstax/chapter/exoplanets-everywhere-what-we-are-learning/

LETTER

https://doi.org/10.1038/s41586-019-1114-6

Nanosecond X-ray diffraction of shock-compressed superionic water ice

Marius Millot[1,3]*, Federica Coppari[1,3]*, J. Ryan Rygg[1,2], Antonio Correa Barrios[1], Sebastien Hamel[1], Damian C. Swift[1] & Jon H. Eggert[1]

High-pressure physics plays a vital role for understanding exoplanets

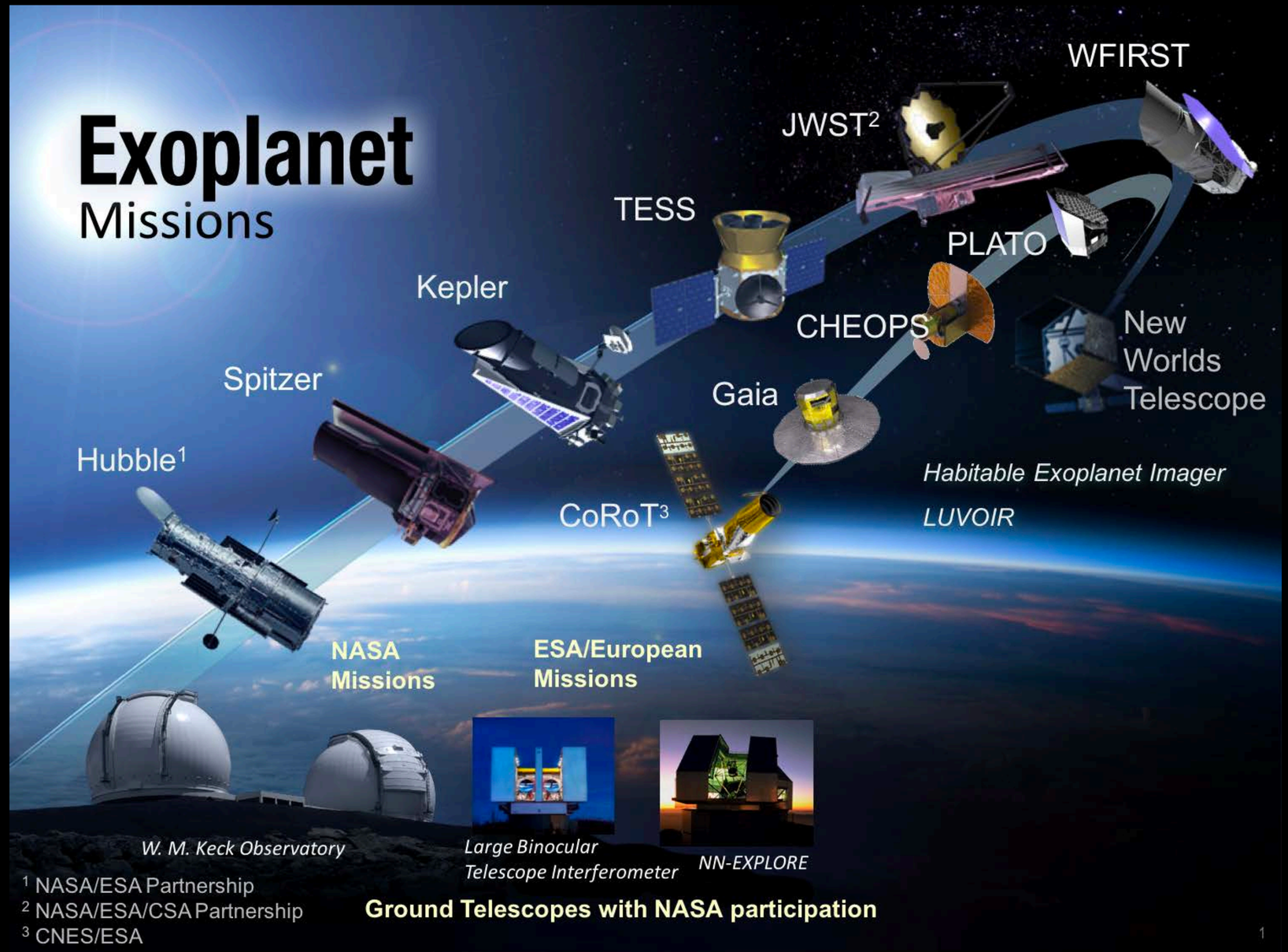
Kraus *et al.*, *Science* **375**, 202–205 (2022) 14 January 2022

PLANETARY SCIENCE

Measuring the melting curve of iron at super-Earth core conditions

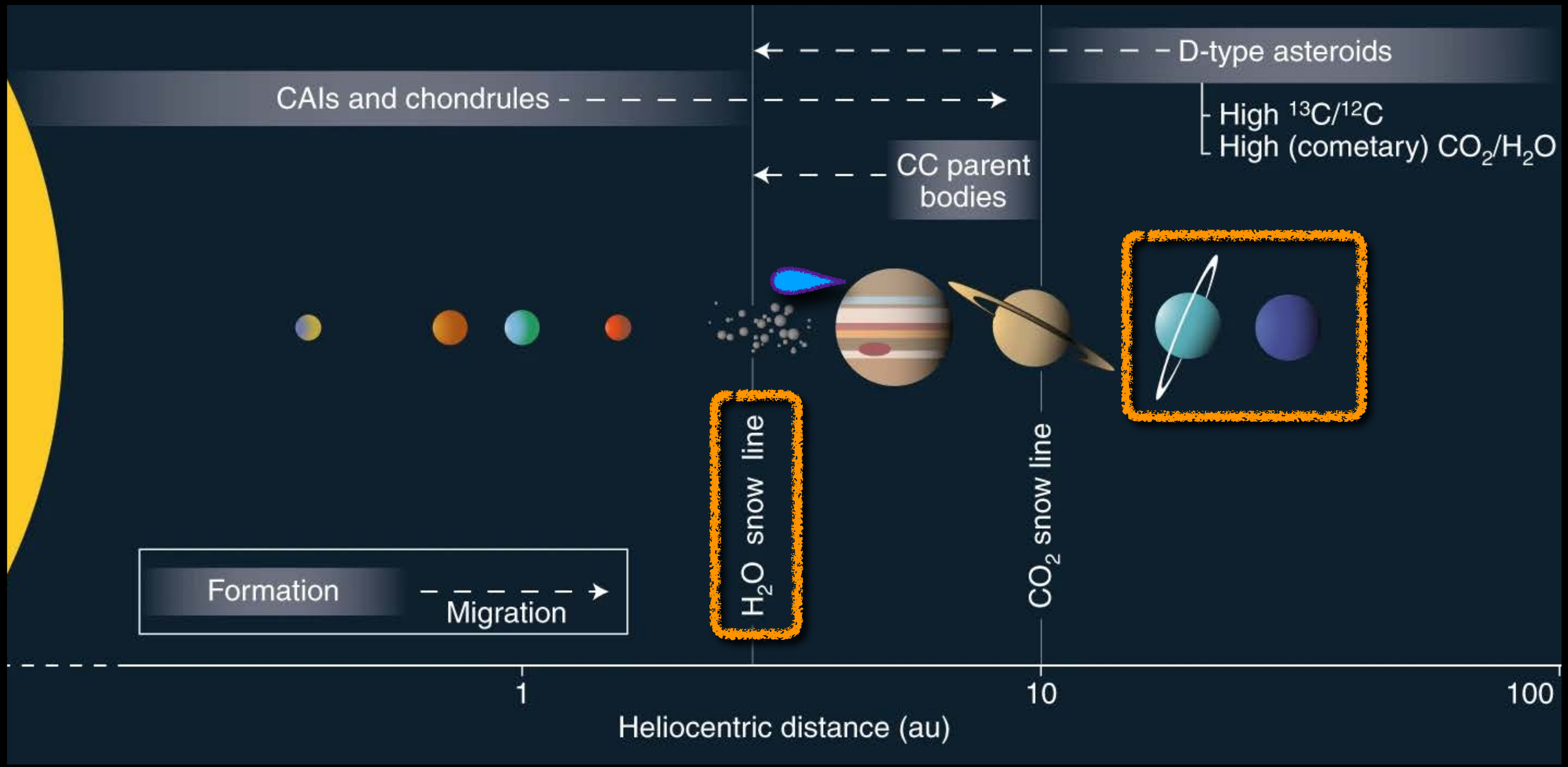
Richard G. Kraus[1]*, Russell J. Hemley[2], Suzanne J. Ali[1], Jonathan L. Belof[1], Lorin X. Benedict[1], Joel Bernier[1], Dave Braun[1], R. E. Cohen[3], Gilbert W. Collins[4], Federica Coppari[1], Michael P. Desjarlais[5], Dayne Fratanduono[1], Sebastien Hamel[1], Andy Krygier[1], Amy Lazicki[1], James Mcnaney[1], Marius Millot[1], Philip C. Myint[1], Matthew G. Newman[6], James R. Rygg[4], Dane M. Sterbentz[1], Sarah T. Stewart[7], Lars Stixrude[8], Damian C. Swift[1], Chris Wehrenberg[1], Jon H. Eggert[1]

Atmosphere-Interior Interactions



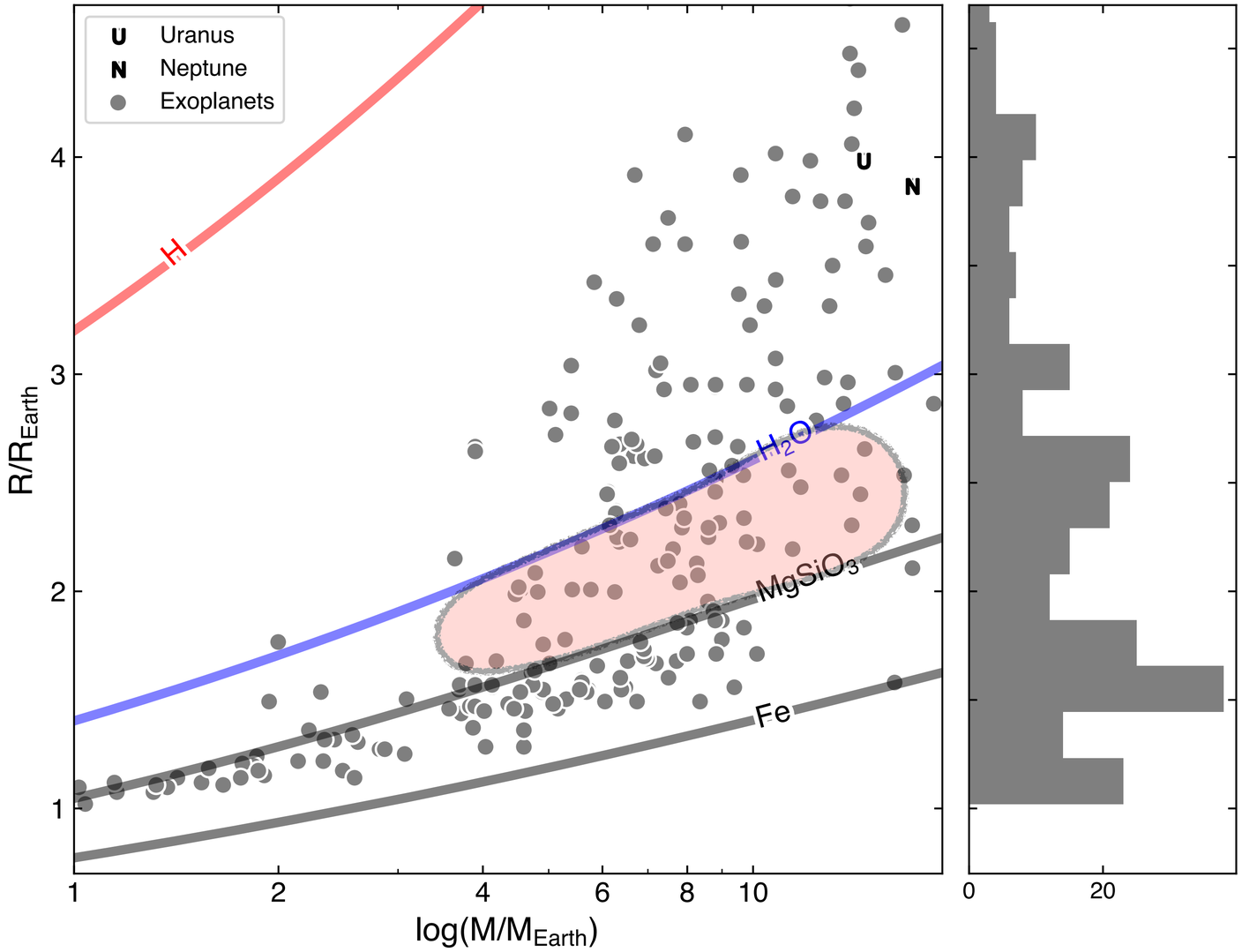
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA

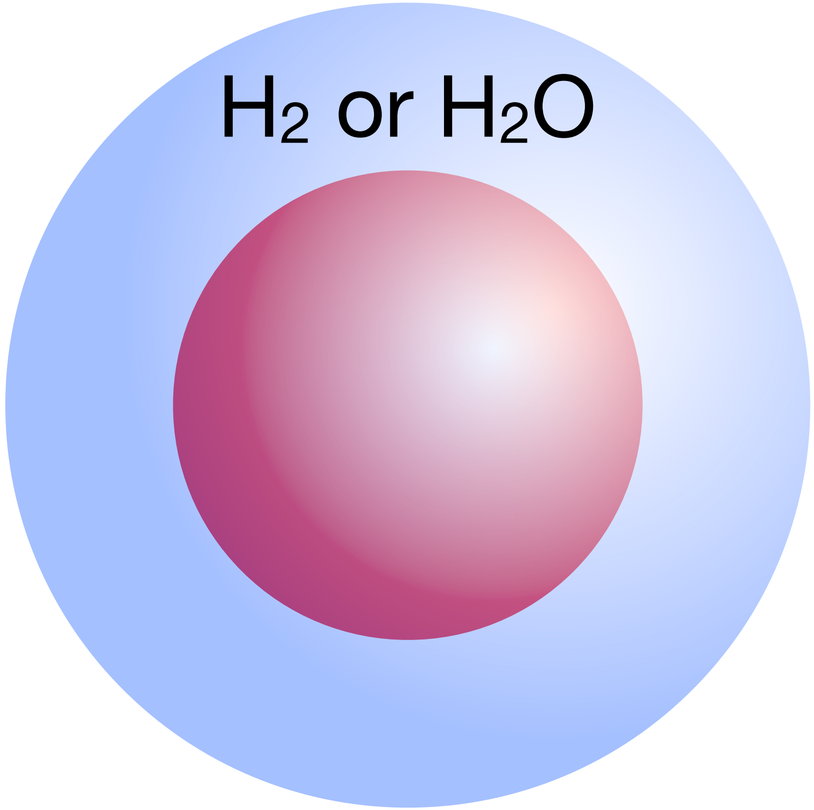
- $H_2 + 1/2\ O_2 = H_2O$
- Mixing-Demixing



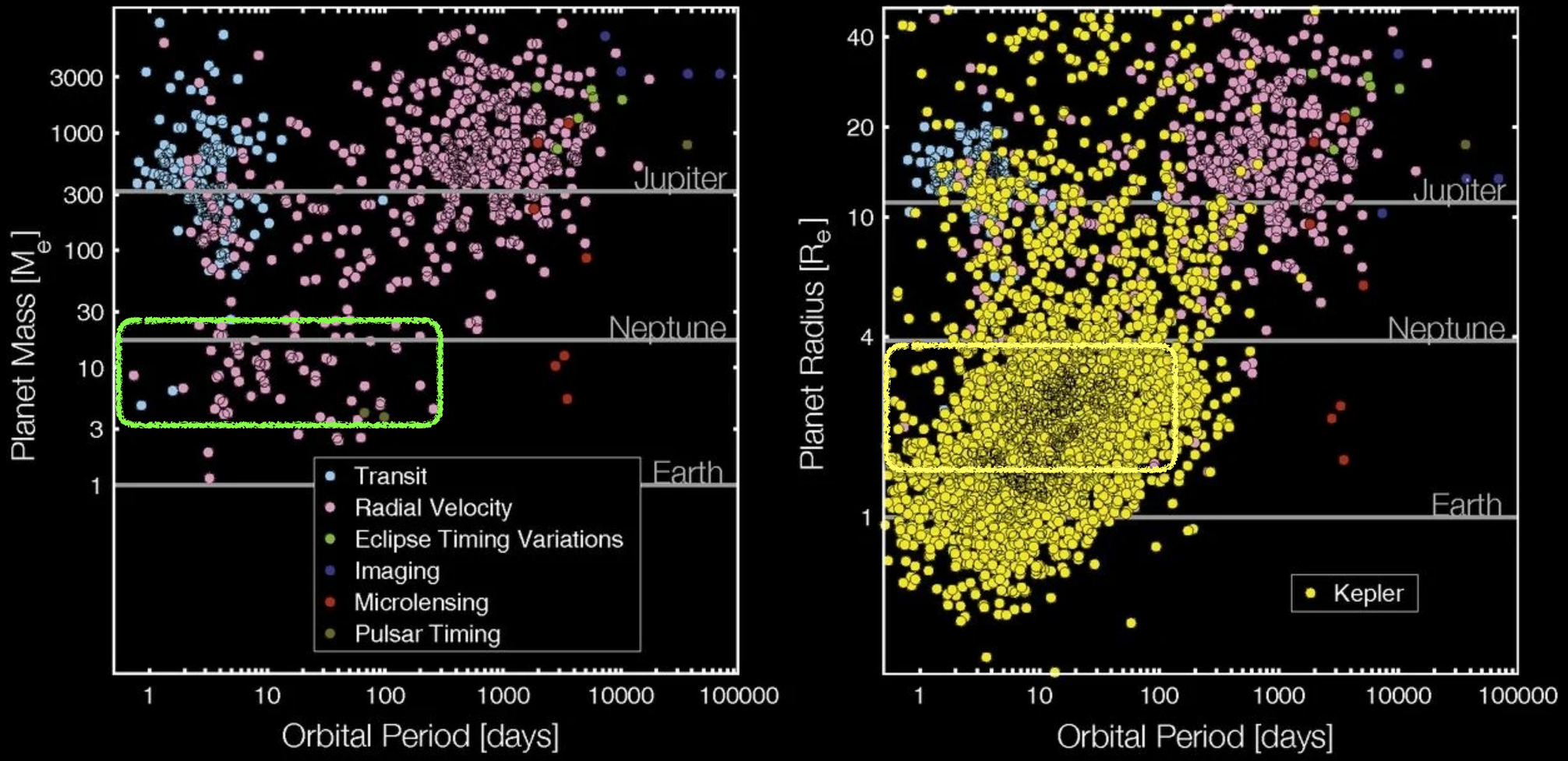
Marrocchi and Piani (2019) Nat. Astro.

Sub-Neptunes



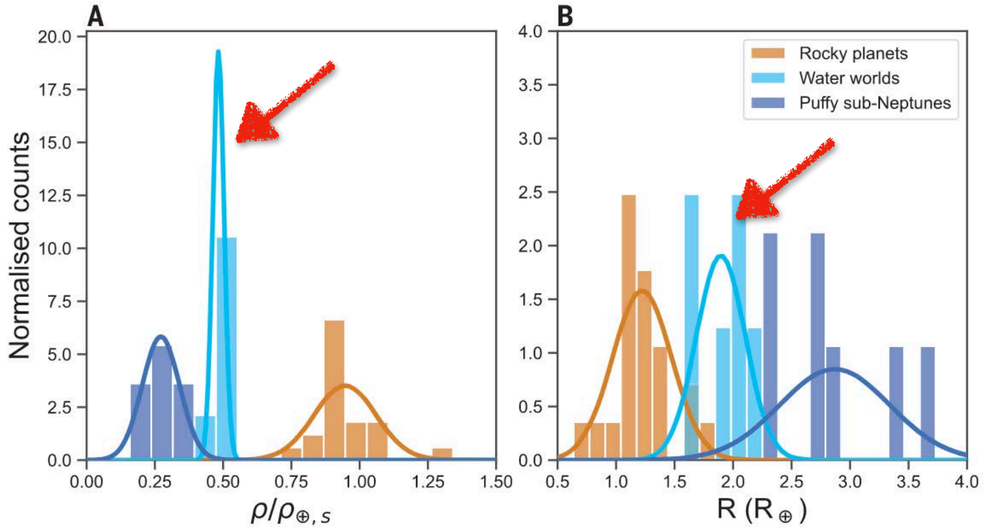


Close-in Sub-Neptunes

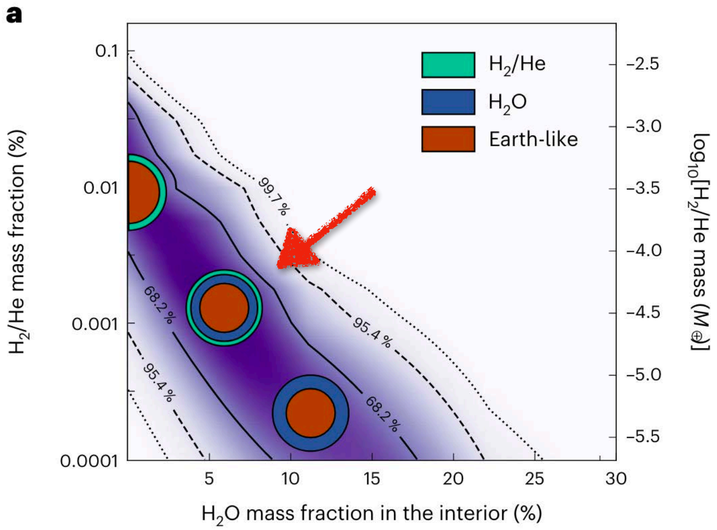


Batalha (2014, PNAS)

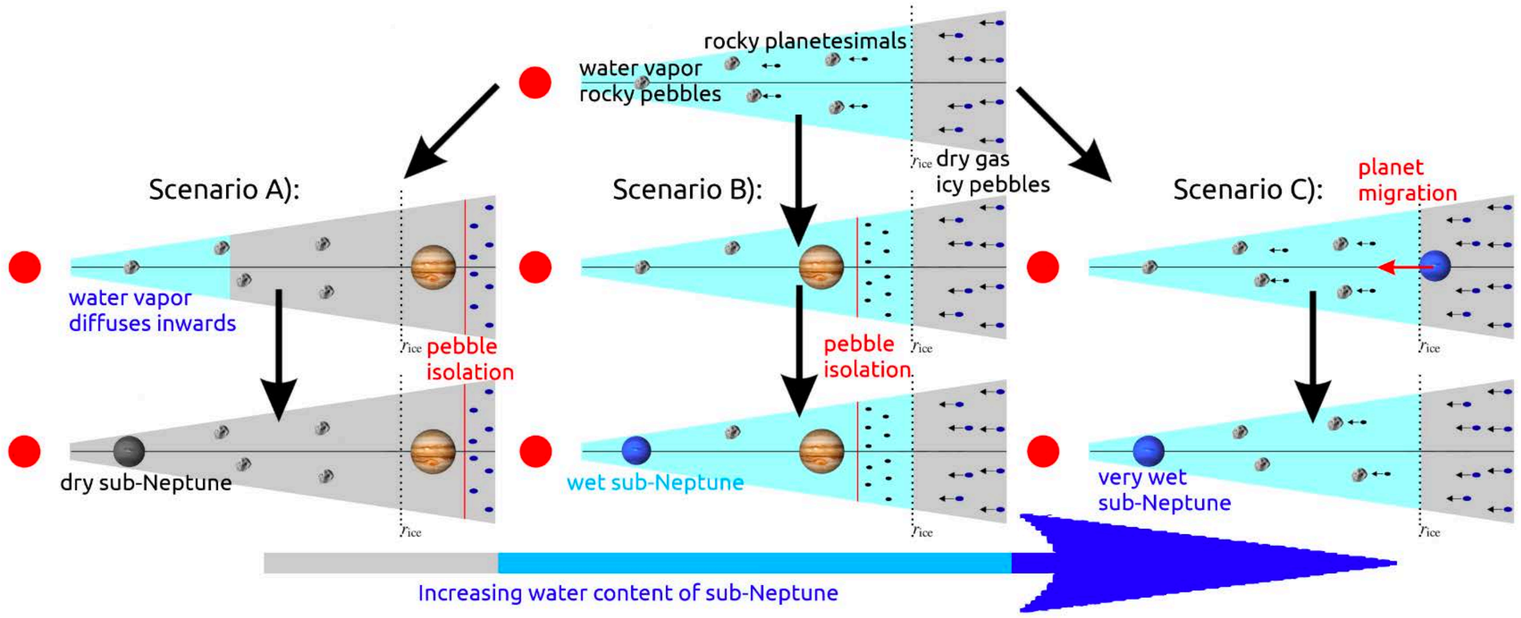
Water-rich Sub-Neptunes



Luque and Palle (2022) Science

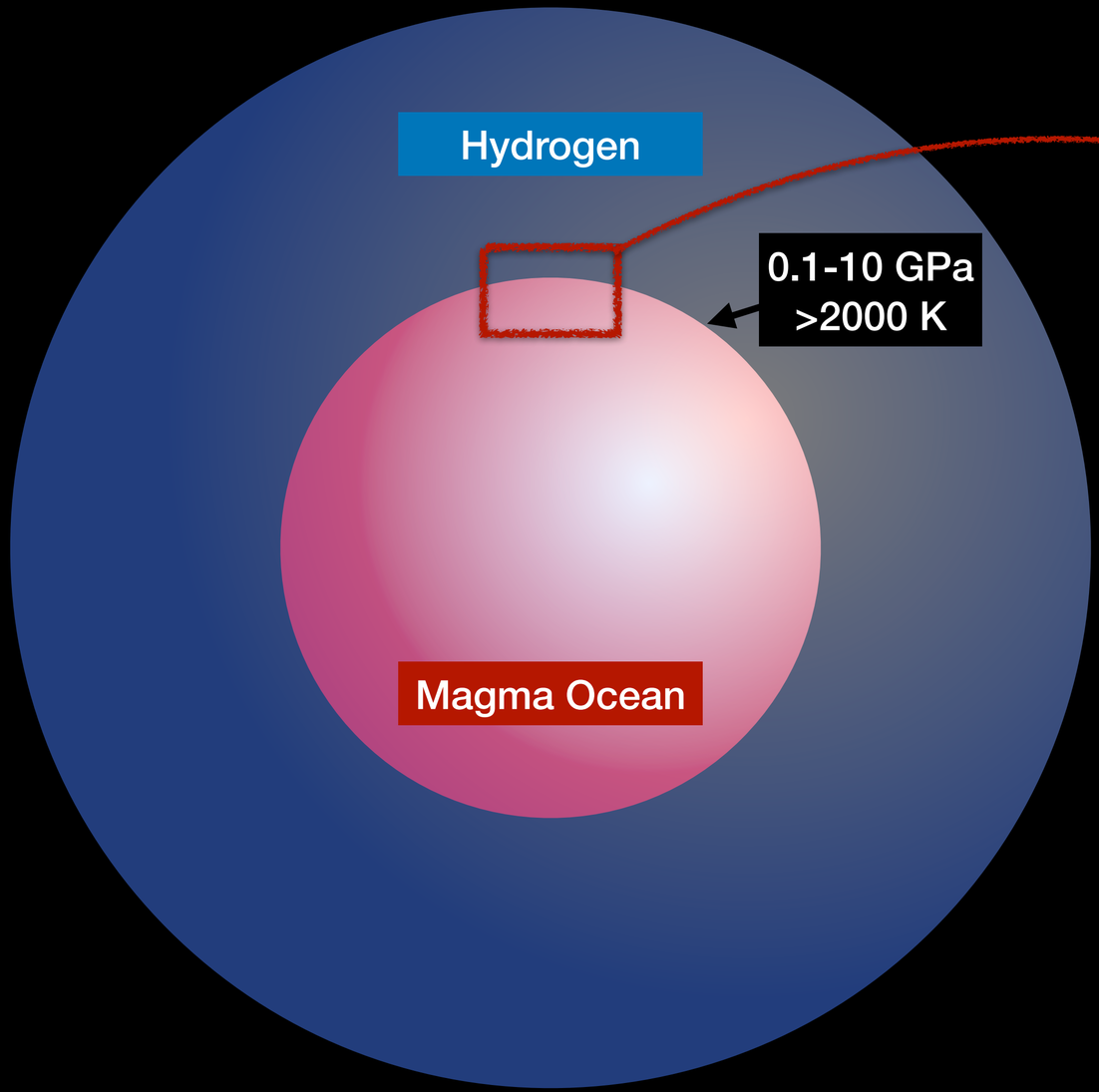


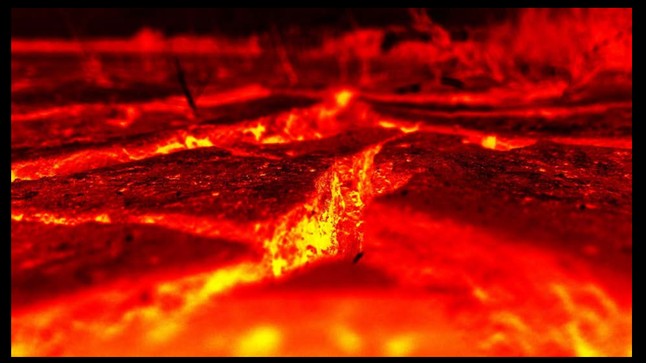
Kepler-138d, Piaulet et al. (2022) Nat. Astro.



Bitsch et al. (2021) Astron. & Astrophys.

Interior Model for Sub-Neptunes

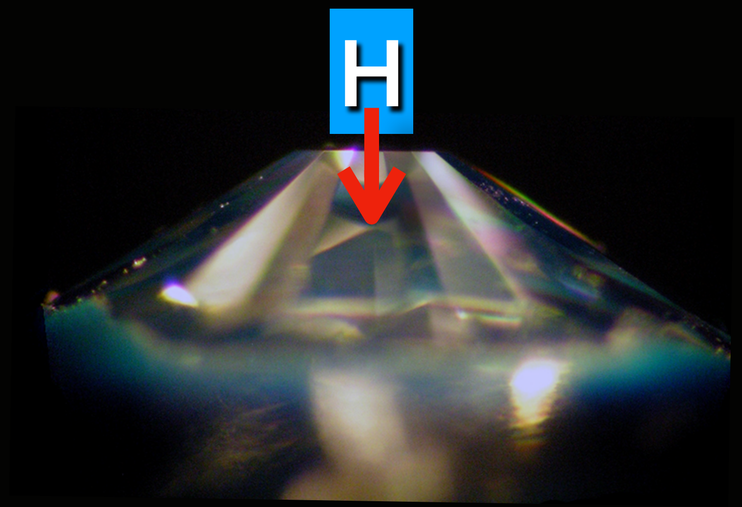


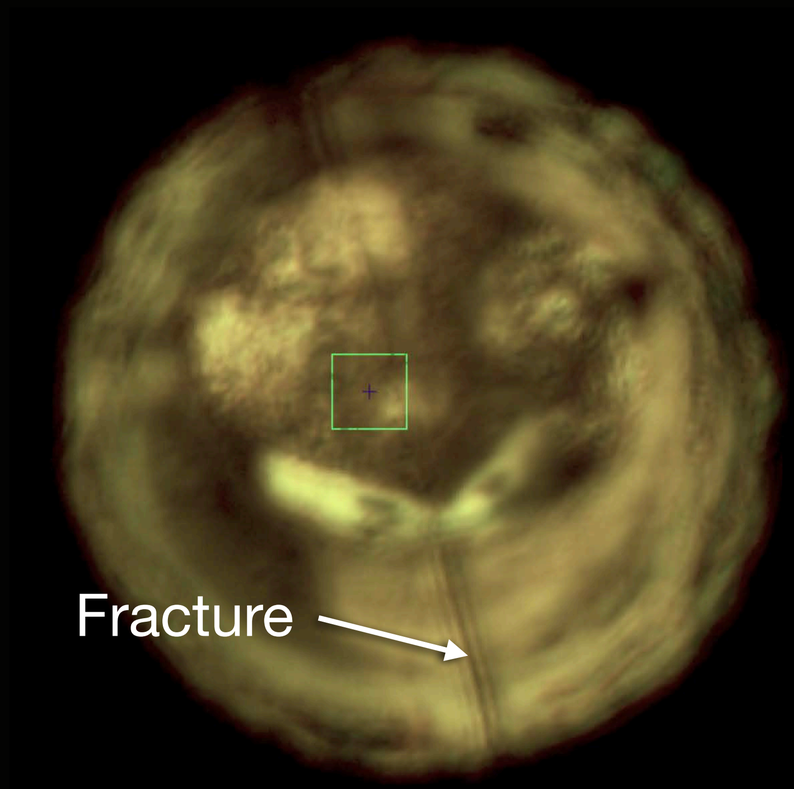


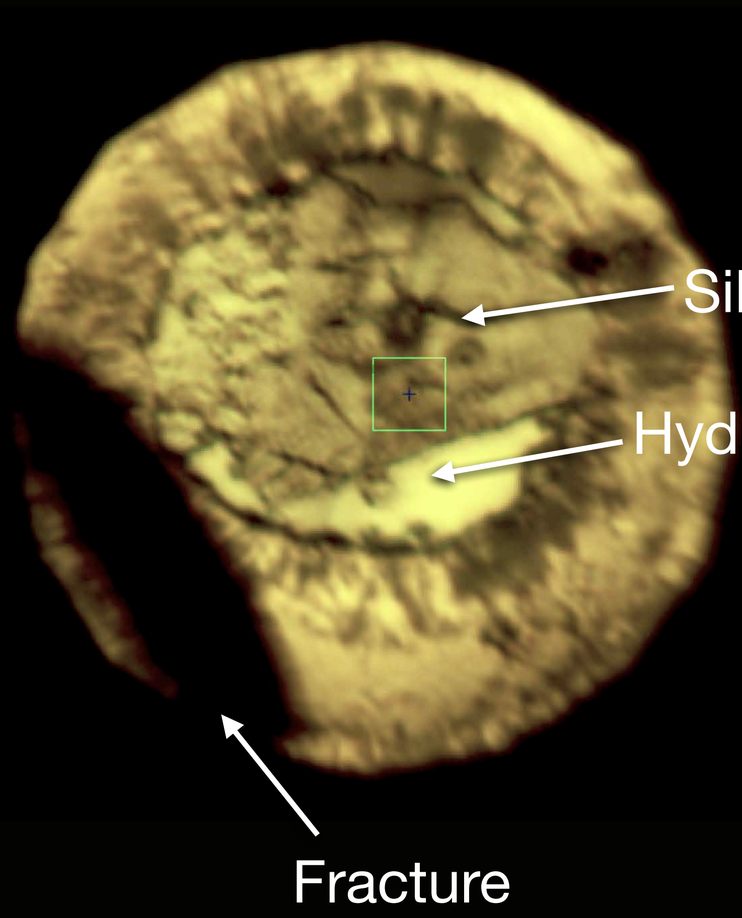
The magma ocean phase may last several gigayears

Vazan et al. (2018) ApJ

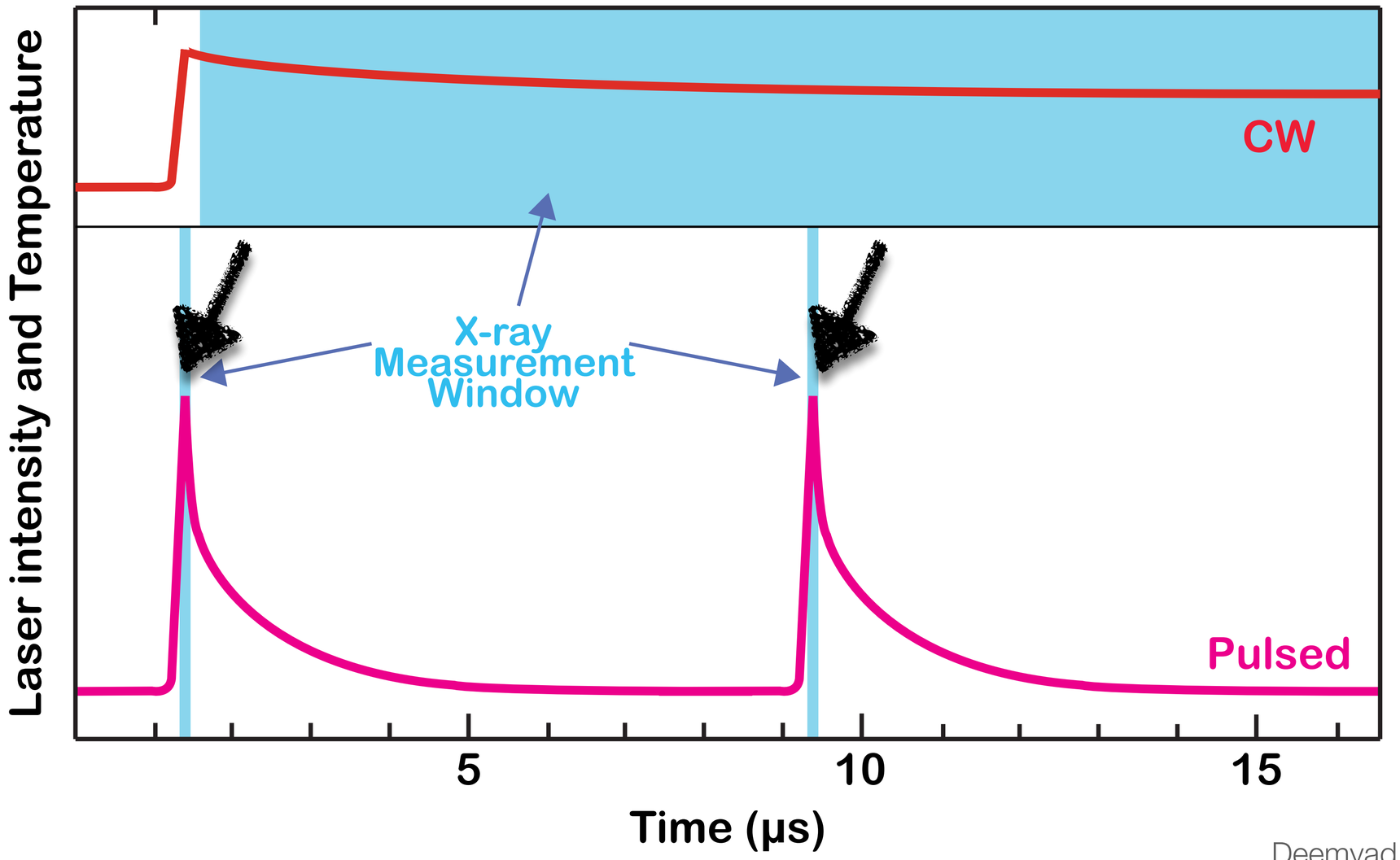
Diamond Embrittlement





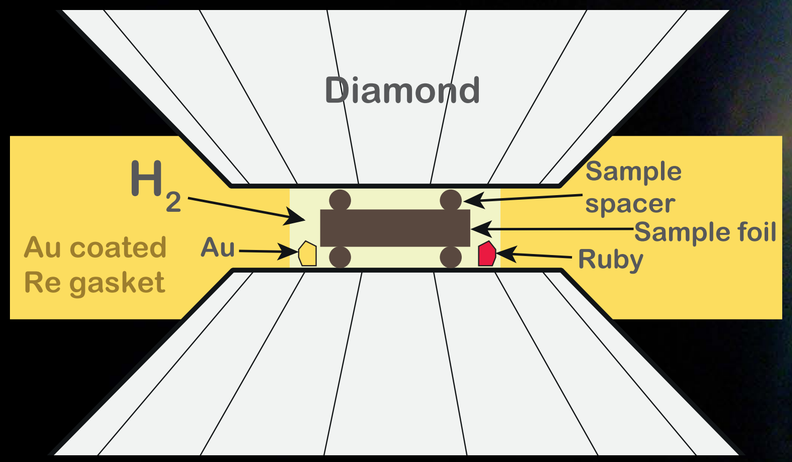


Pulsed Laser Heating



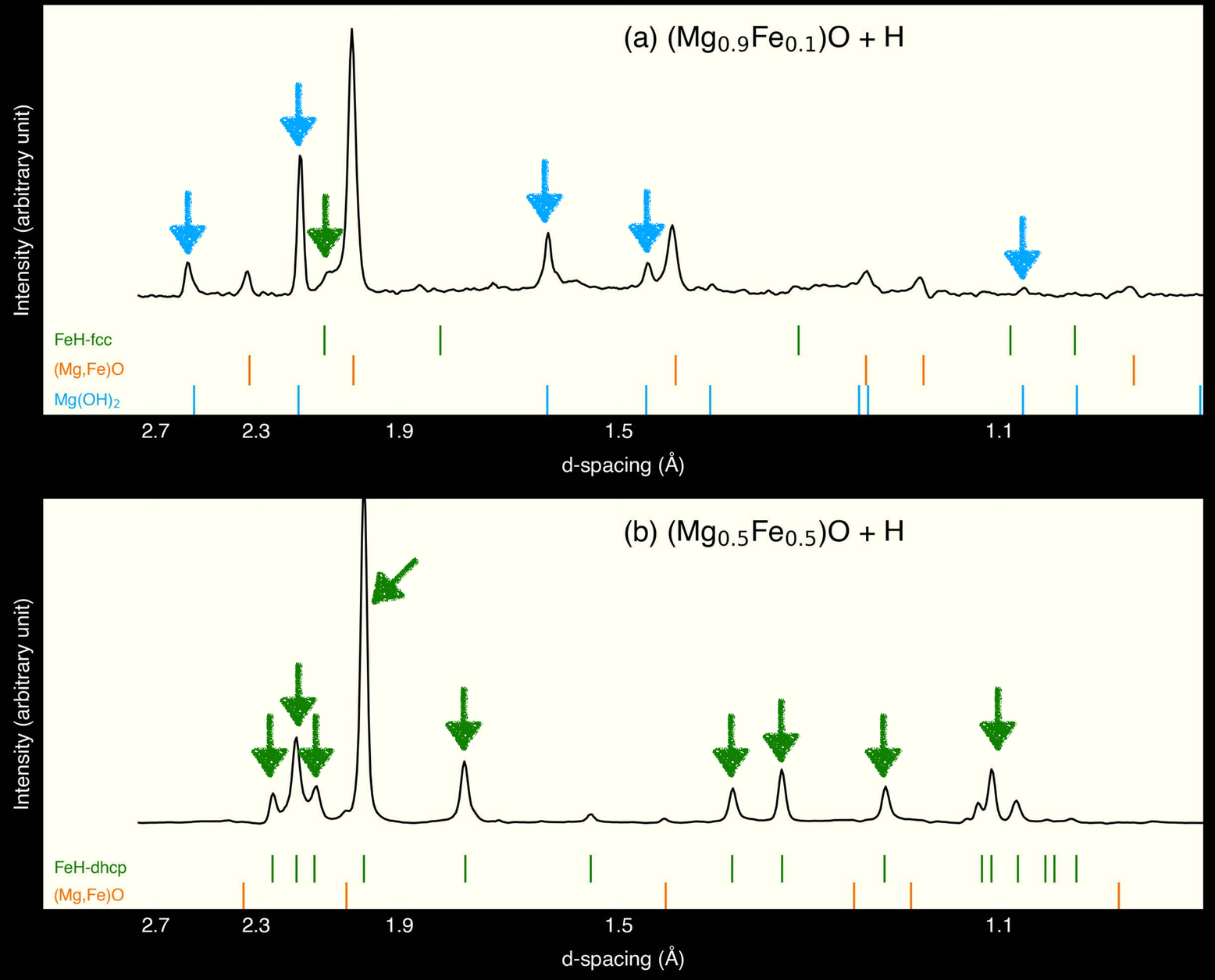
Deemyad and Silvera (2008) PRL
Goncharov et al. (2010) RSI

Diamond Anvil Cell



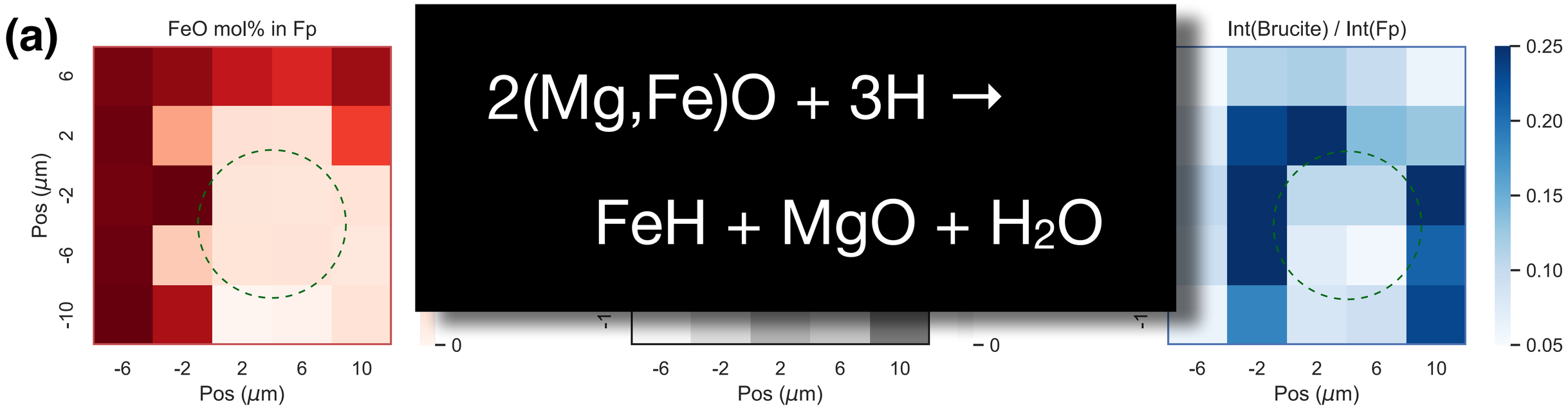
(Mg,Fe)O + H

22-30 GPa, 1500-2000 K



Allen-Sutter and Shim, in press, PSJ

(Mg,Fe)O + H



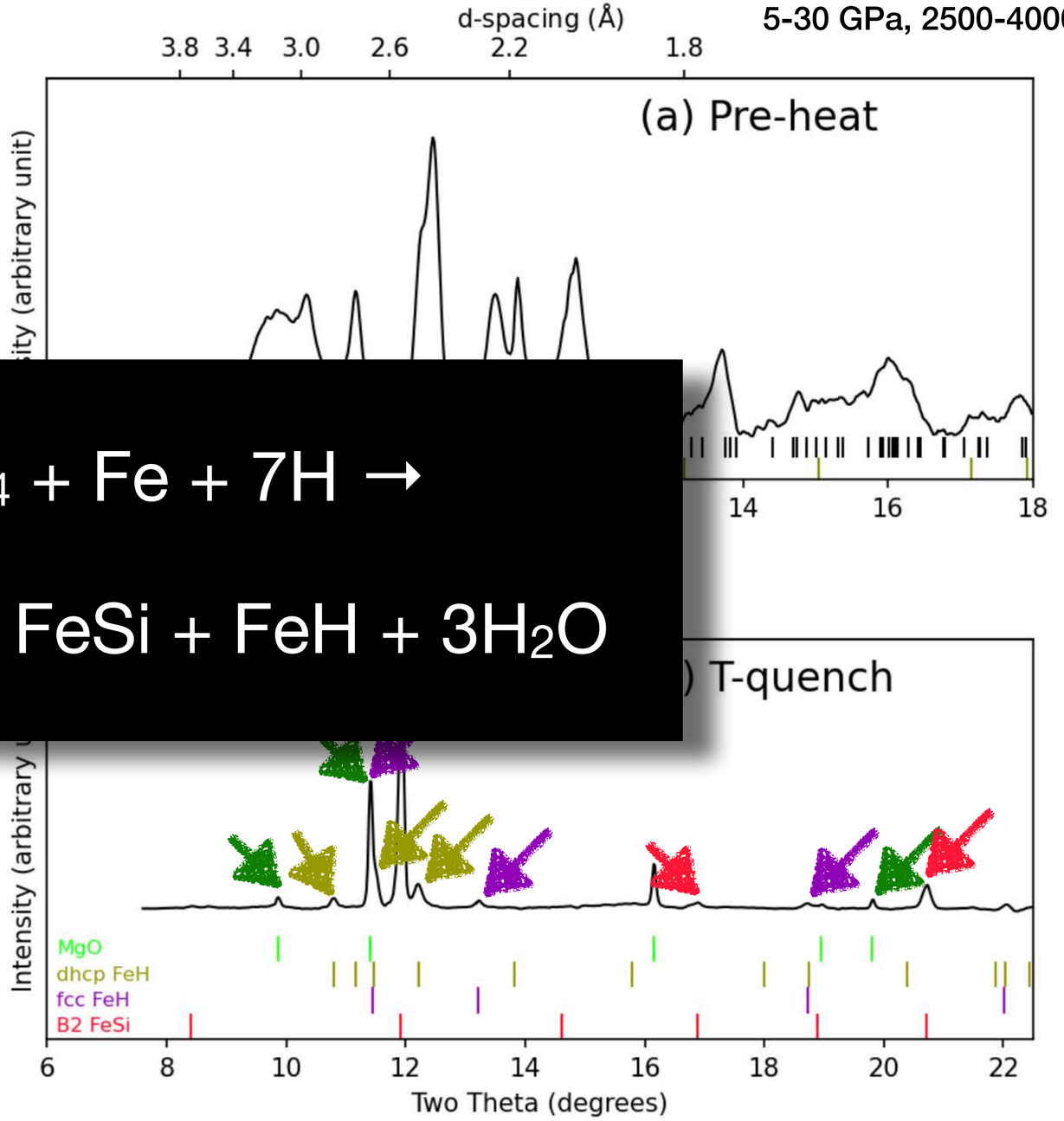
Allen-Sutter and Shim, in press, PSJ

5-30 GPa, 2500-4000 K

$(Mg,Fe)_2SiO_4$

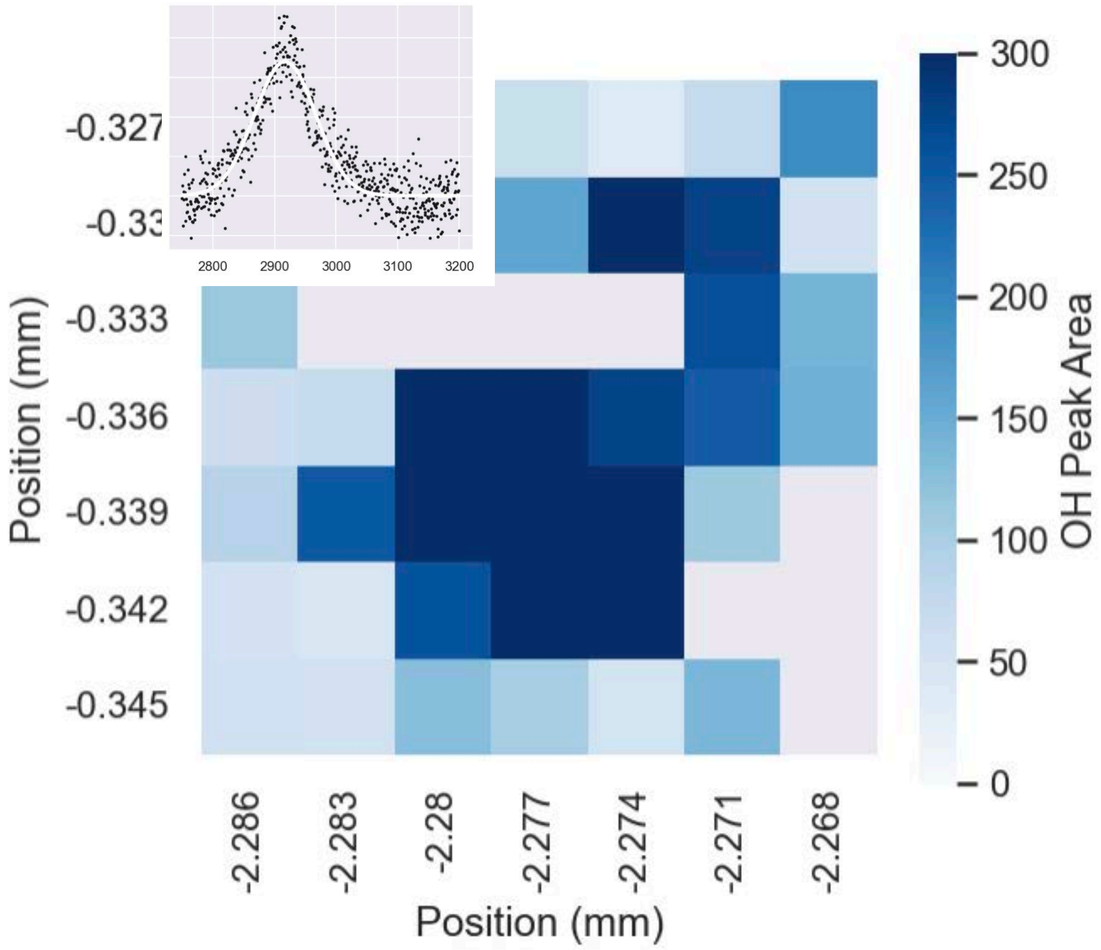
$(Mg,Fe)_2SiO_4 + Fe + 7H \rightarrow$

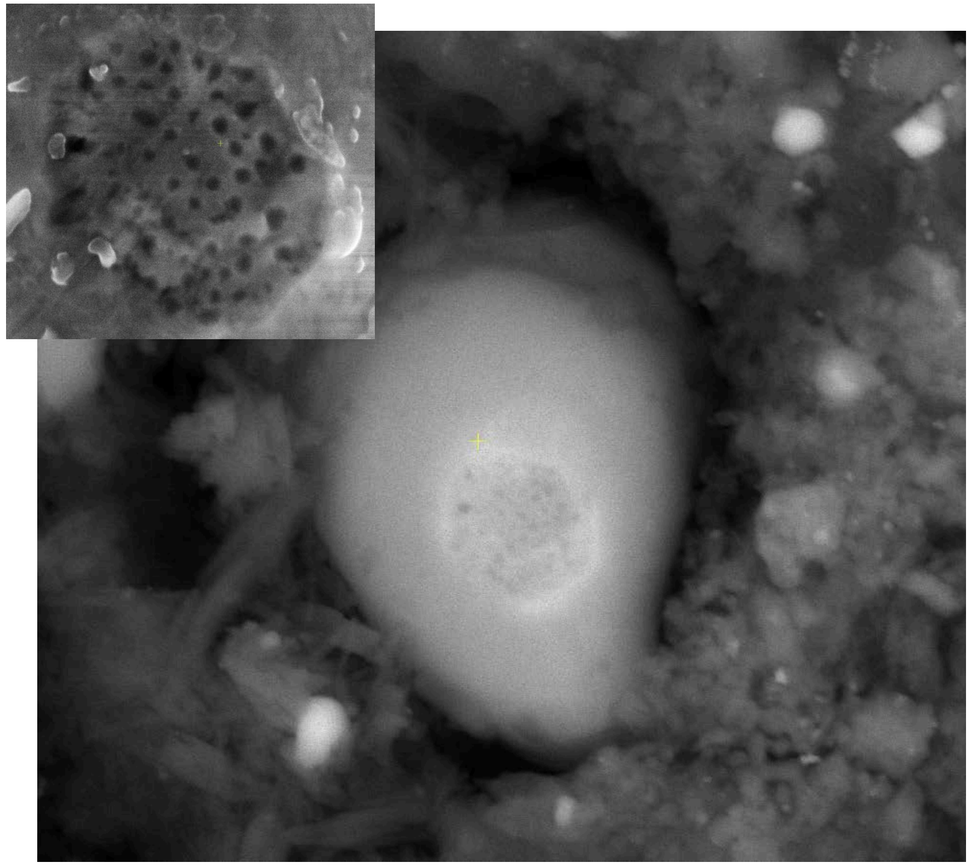
$MgO + FeSi + FeH + 3H_2O$



Allen-Sutter and Shim, in prep

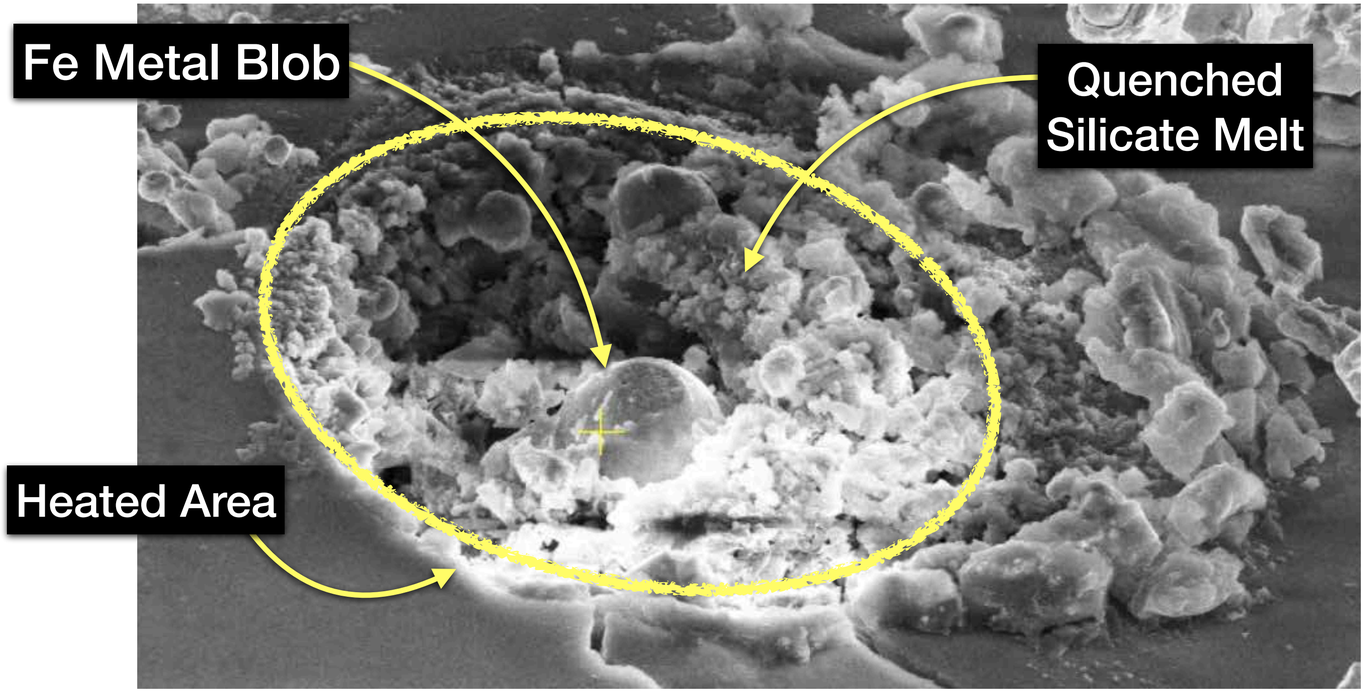
$(Mg,Fe)_2SiO_4 + H$





Fayalite in a H medium at 12 GPa and 3000 K

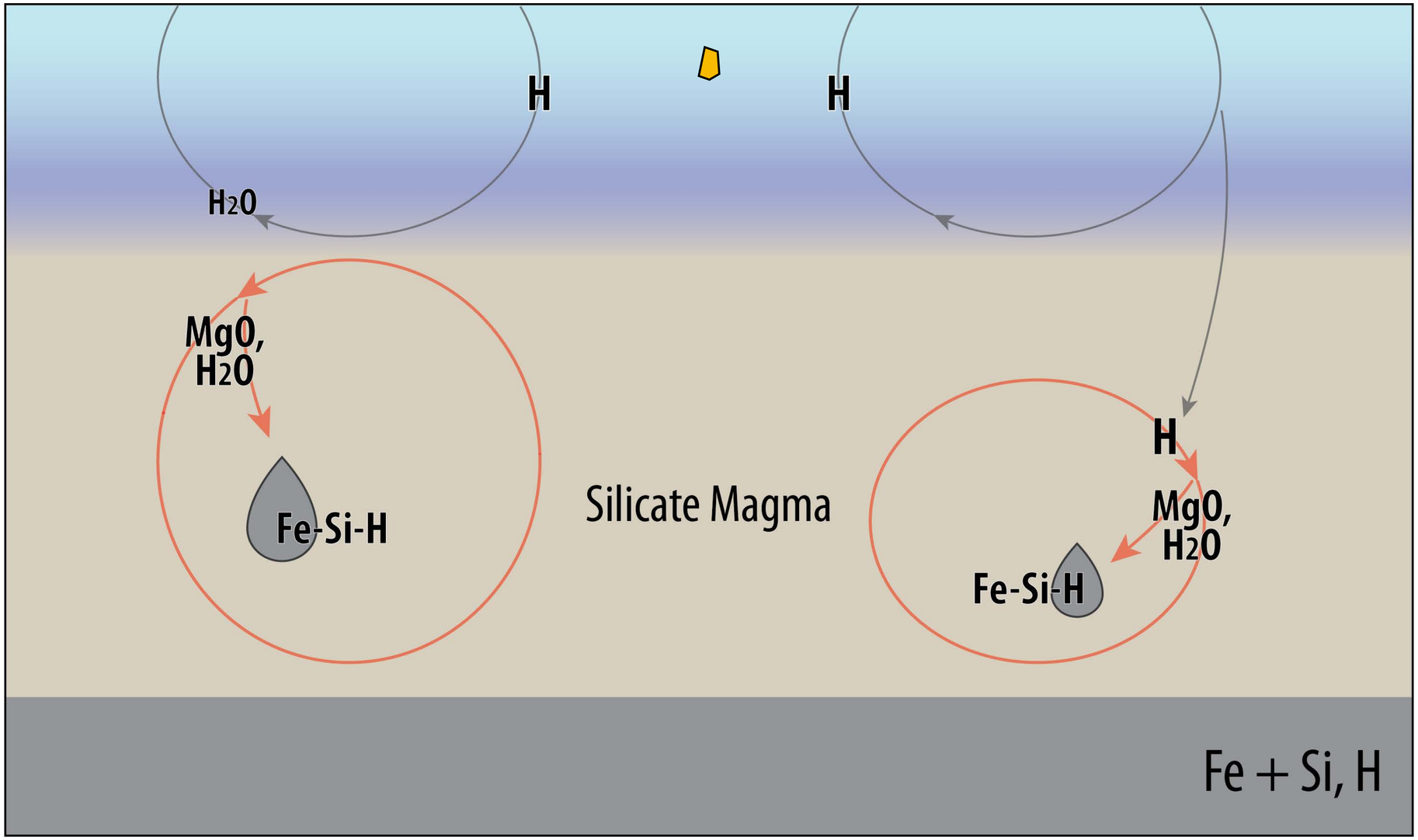
Electron Microscopy



Fayalite in a H medium at 12 GPa and 3000 K.

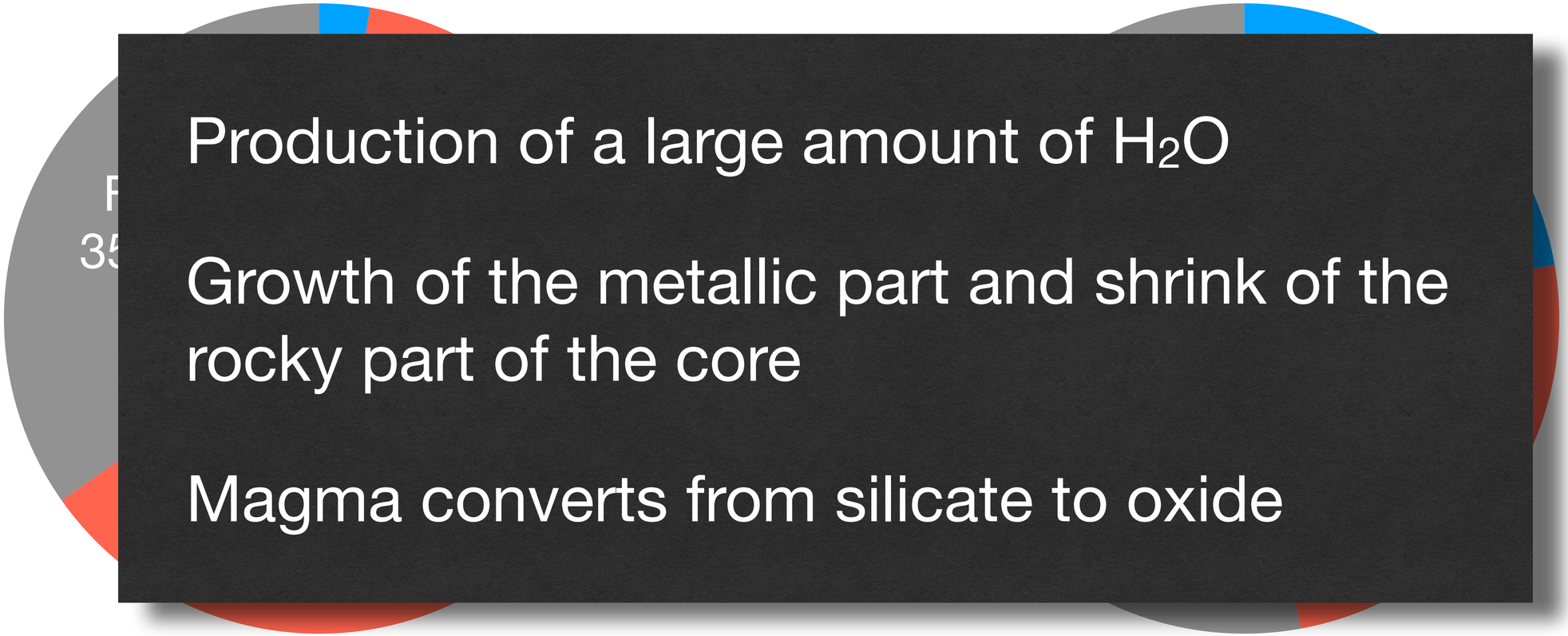
- $FeO + H_2 \rightarrow Fe + H_2O$
- $SiO_2 + 2H_2 \rightarrow Si + 2H_2O$
- $Fe + 0.5H_2 \rightarrow FeH$

Conversion of H to H_2O Planet



Allen-Sutter and Shim, in prep

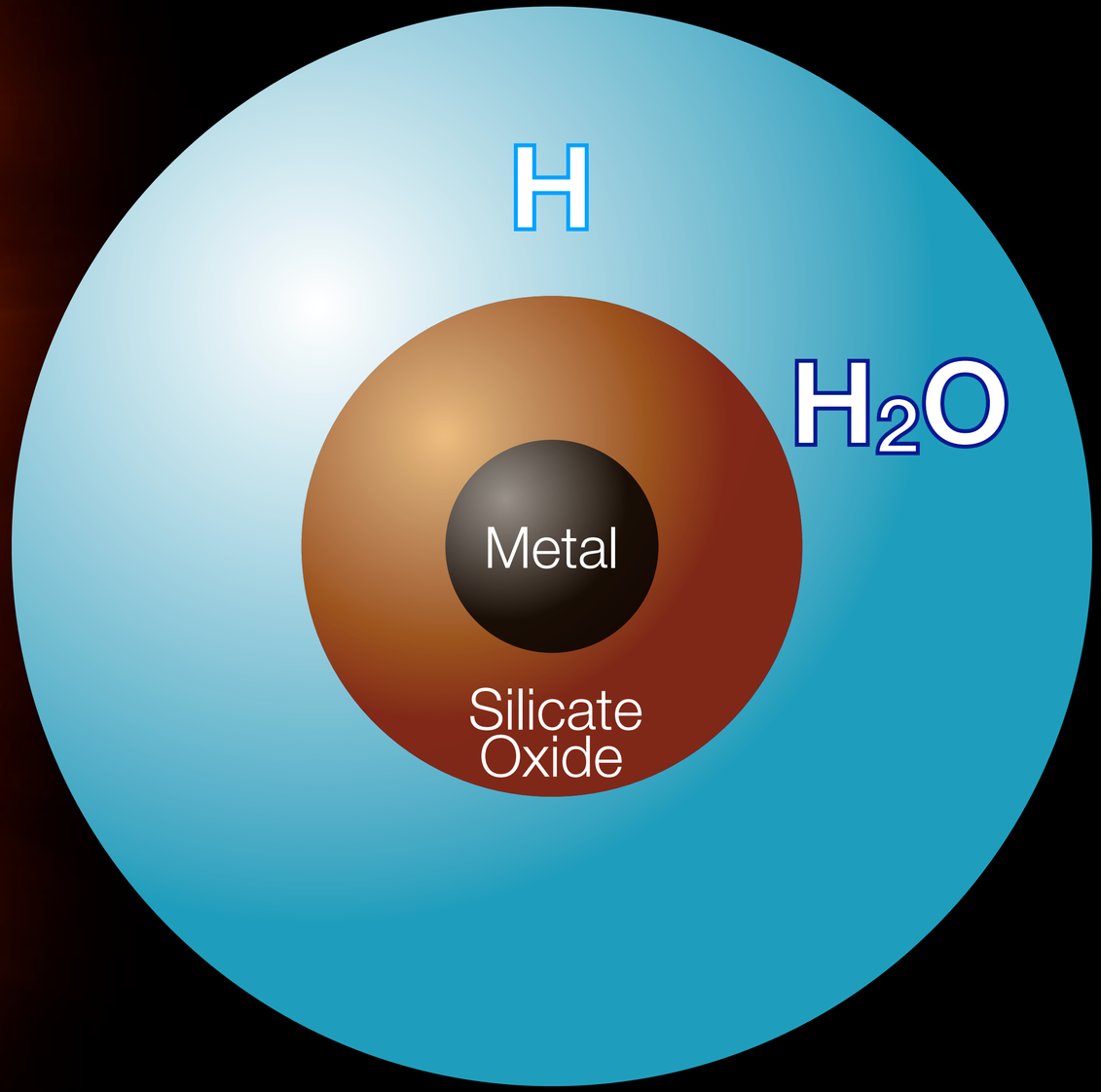
Impact of Si Reduction



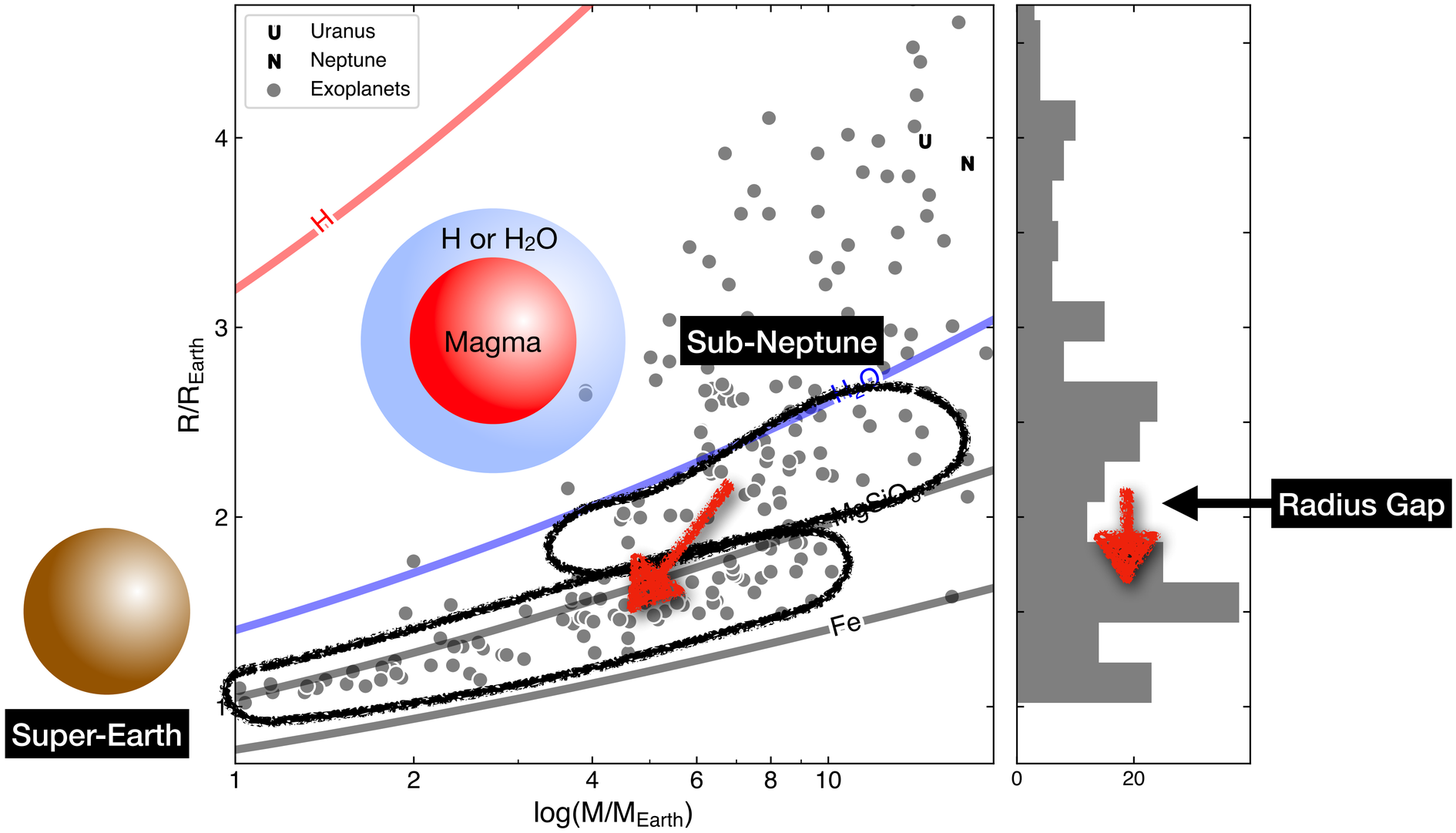
- Production of a large amount of H_2O
- Growth of the metallic part and shrink of the rocky part of the core
- Magma converts from silicate to oxide

Allen-Sutter and Shim, in prep

Planet Conversion

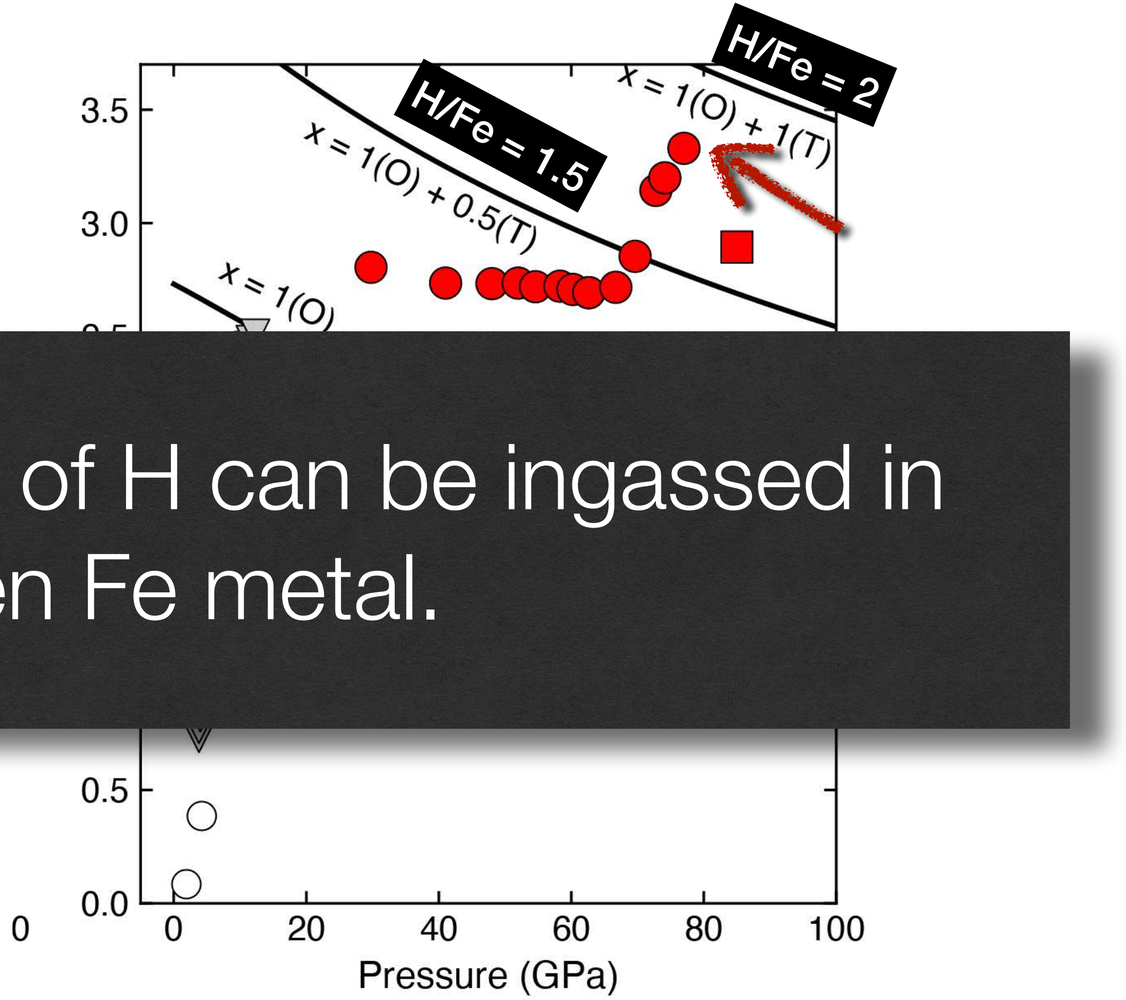


Sub-Neptunes and Super-Earths



Mixing-Demixing

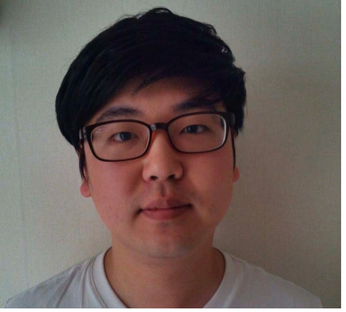
Super-Stoichiometric FeHx Liquid



H

Very large amount of H can be ingassed in molten Fe metal.

Piet et al. (2021) PRB, Piet et al. (2023) in revision



H_2O-Mg_2SiO_4

nature astronomy

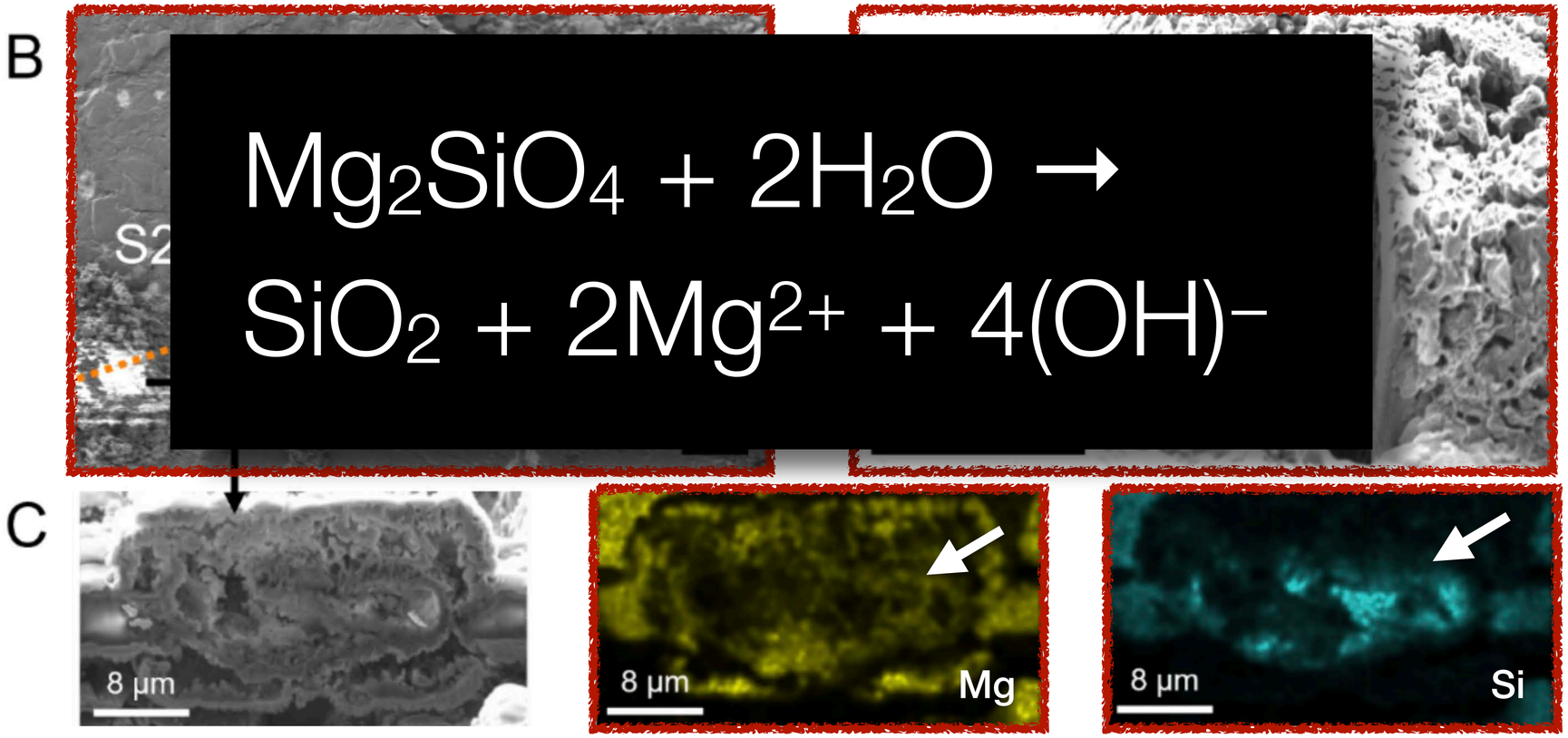
ARTICLES

https://doi.org/10.1038/s41550-021-01368-2

Check for updates

Atomic-scale mixing between MgO and H_2O in the deep interiors of water-rich planets

Taehyun Kim[1], Stella Chariton[2], Vitali Prakapenka[2], Anna Pakhomova[3], Hanns-Peter Liermann[3], Zhenxian Liu[4], Sergio Speziale[5], Sang-Heon Shim[6]✉ and Yongjae Lee[1]✉



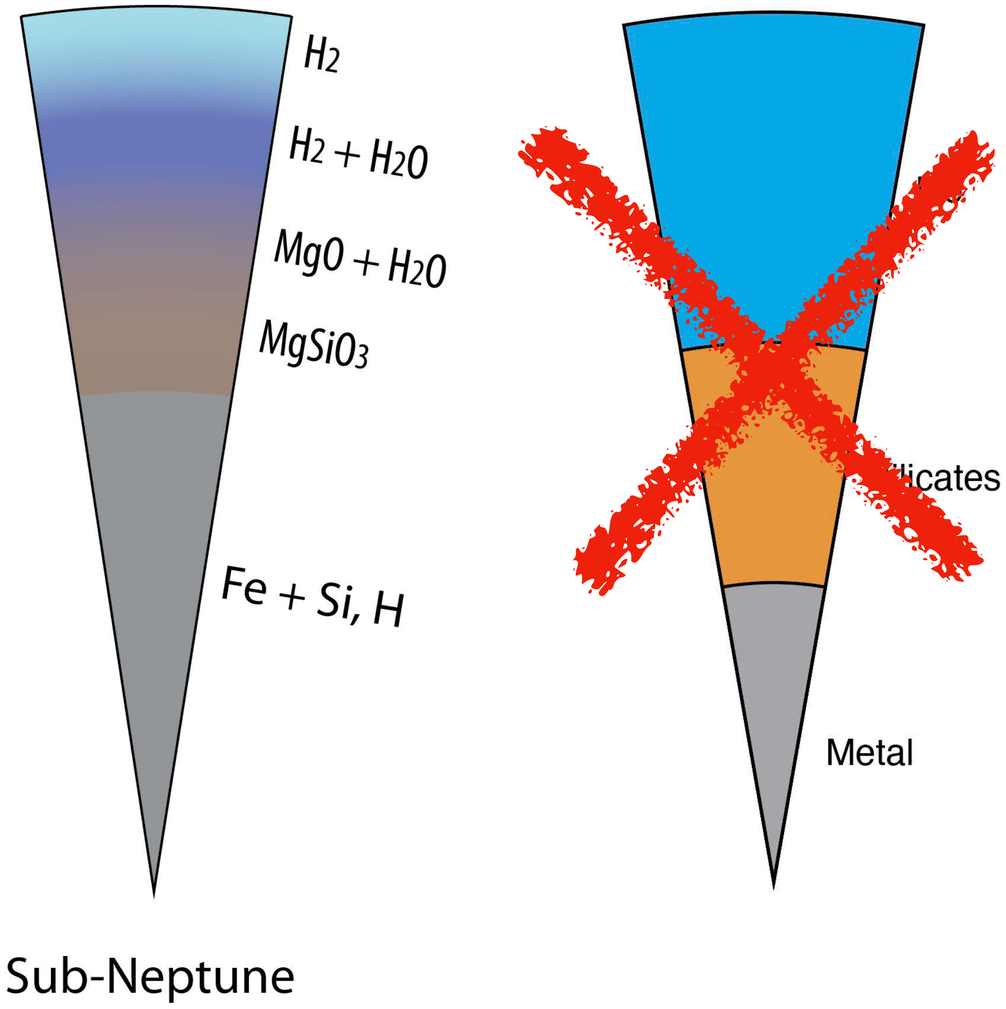
$$Mg_2SiO_4 + 2H_2O \rightarrow SiO_2 + 2Mg^{2+} + 4(OH)^-$$

Mixing-Demixing

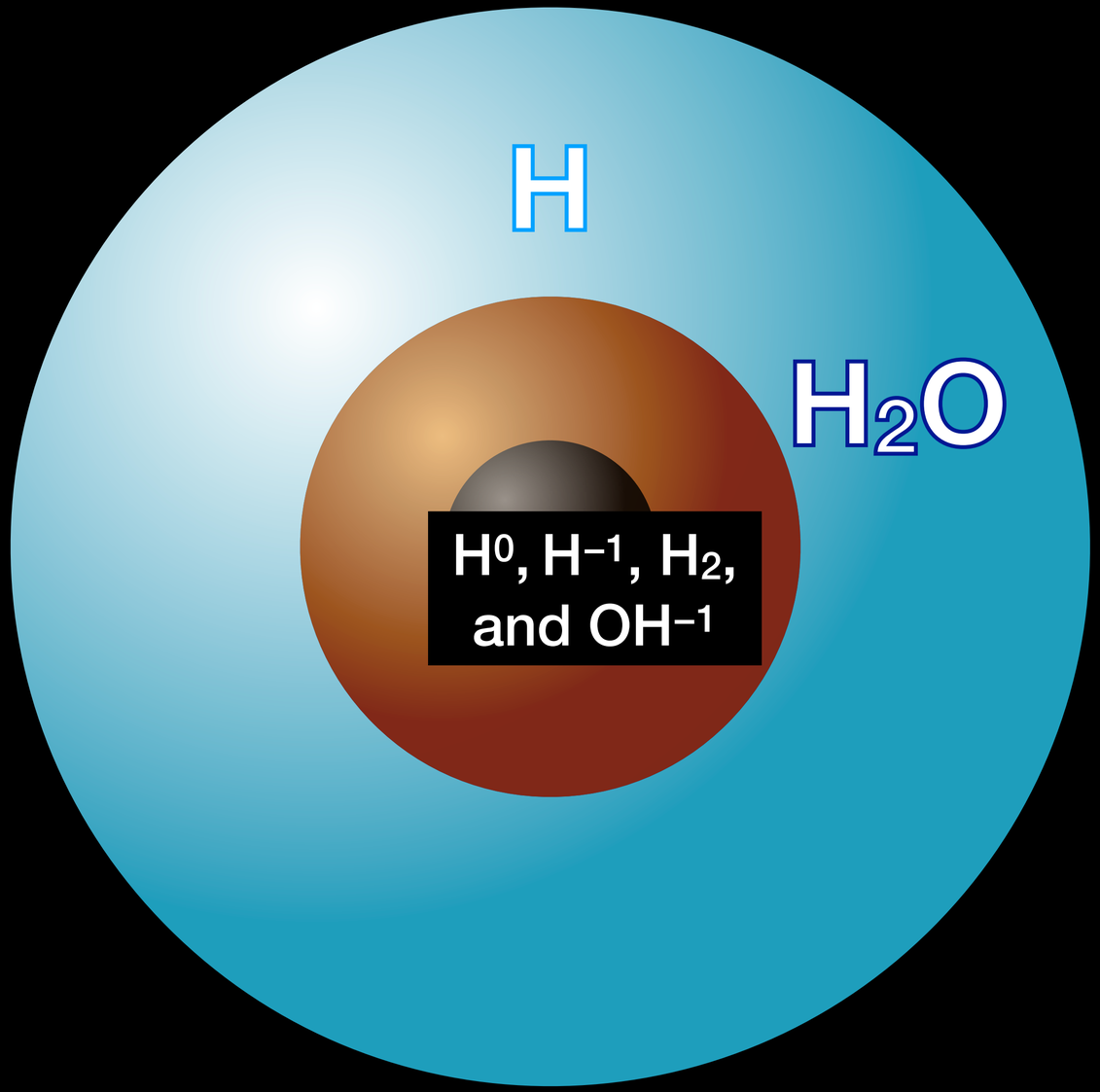
Mixing between Planetary Materials

H_2-H_2O: Lei et al. (2021) JPCL, Soubiran and Militzer (2015) ApJ

H_2O-MgO: Kim et al. (2021) Nat. Astron.

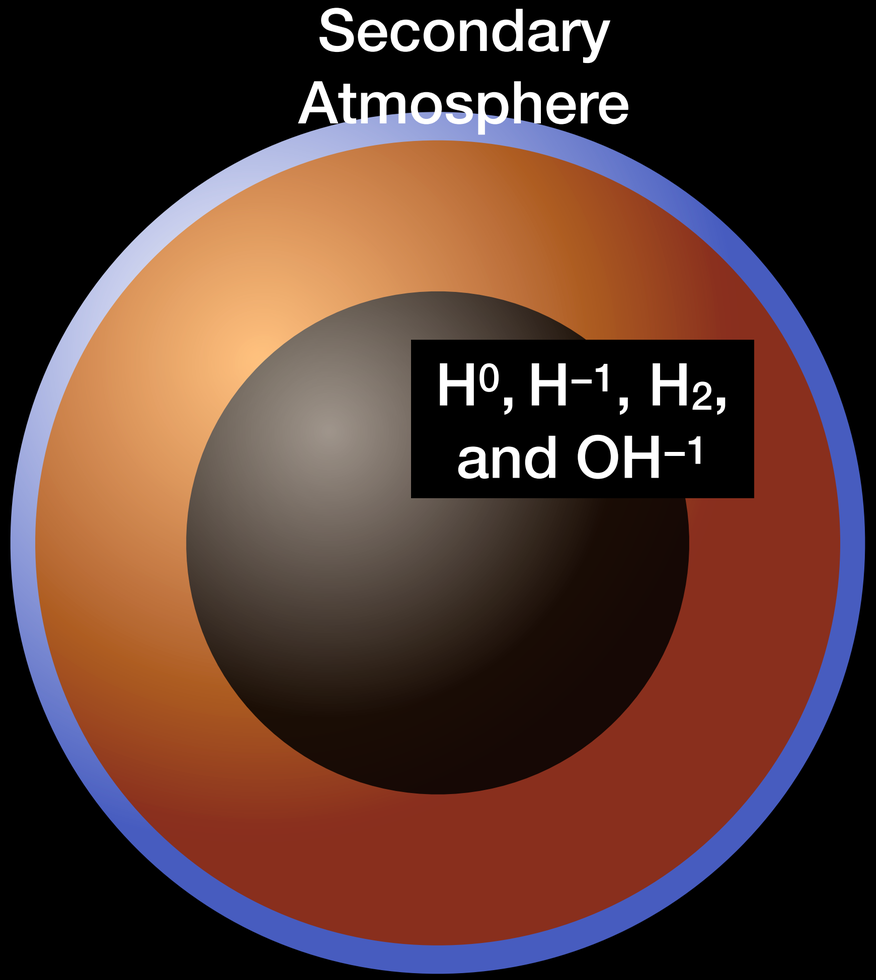


Allen-Sutter and Shim, in prep



Ingassing

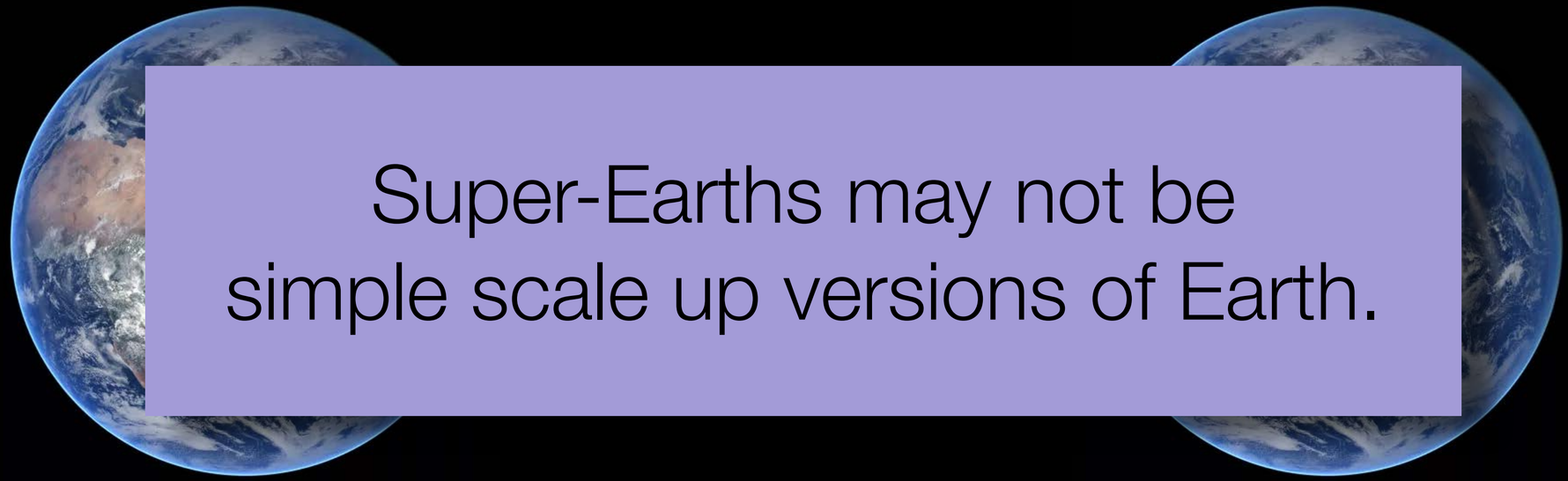
- Ingassing through mixing
- Dynamic processes



Outgassing

- Low H/H_2O solubility in solid silicates and metal.
- Impact of interior processes for the chemical composition of secondary atmosphere

Super-Earths



Super-Earths may not be
simple scale up versions of Earth.

https://wordlesstech.com/super-earth-planet-could-be-our-next-home/#post/0

Summary

- Hydrogen-silicate reaction can produce water, converting a dry hydrogen rich planet to a wet water rich planet.
- Mixing-demixing could play an important role in the formation of secondary atmosphere of super-Earths converted from sub-Neptunes
- High-pressure chemistry will play a key role in advancing our understanding on exoplanets’ atmospheres.

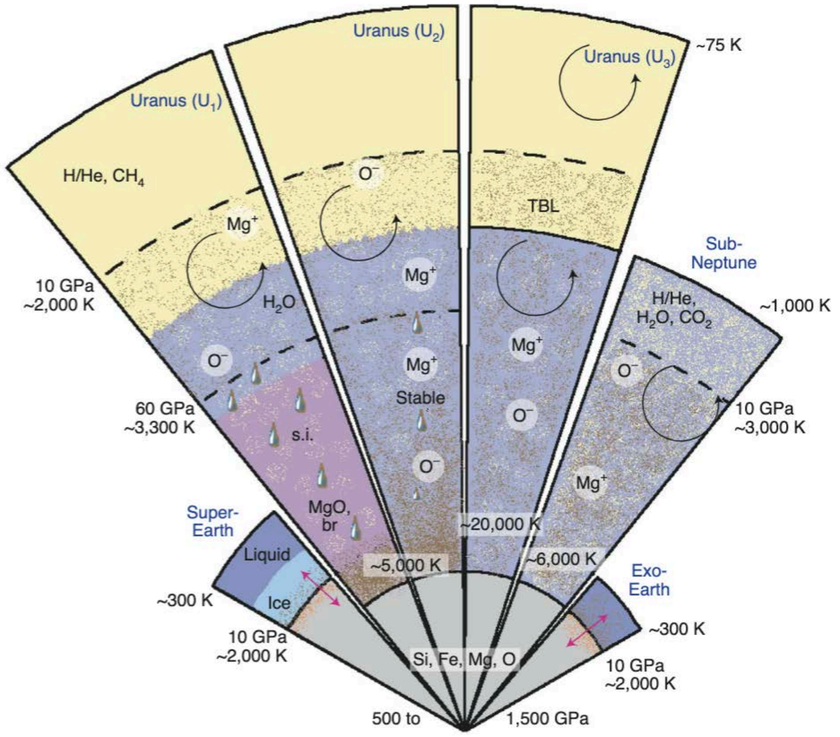
Nature Astronomy, 2021

PLANETARY INTERIORS

Stardust in the deep interior of low-mass planets

The behaviour of minerals under high pressure affects the bulk properties of exoplanets and planets with rocky components, possibly influencing their observable radii. Obtaining a wide range of experimental data is key to understanding observations and informing planetary interior models.

Nadine Nettelmann



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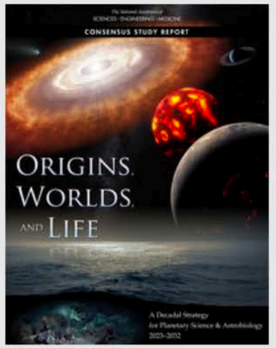
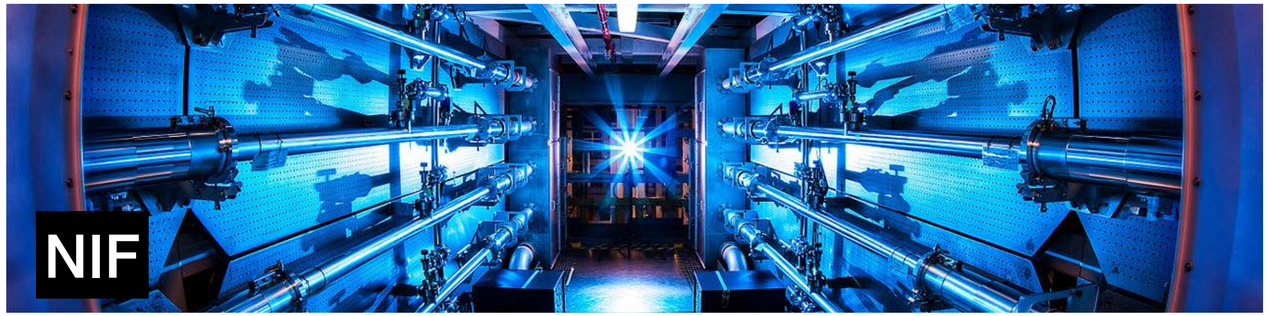


Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032 (2022)

DETAILS

800 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-47578-5 | DOI 10.17226/26522



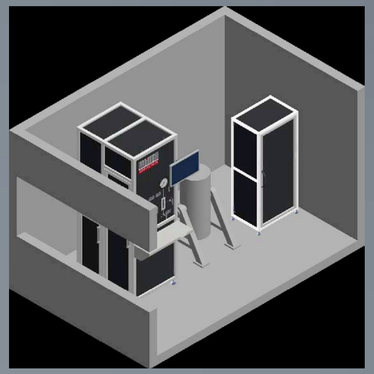
FORCE

Facility for Open Research in a Compressed Environment

6000-t multi-anvil press

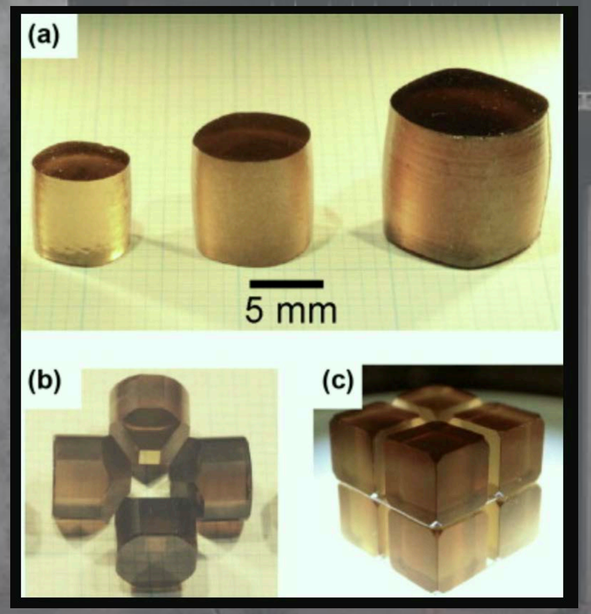
Ultrahigh pressure cubic press

Torsional apparatus



Gas pressure vessel

Dense $FeSiO_3$ Rod



Nano-polycrystalline diamond (Irifune et al., 2014)