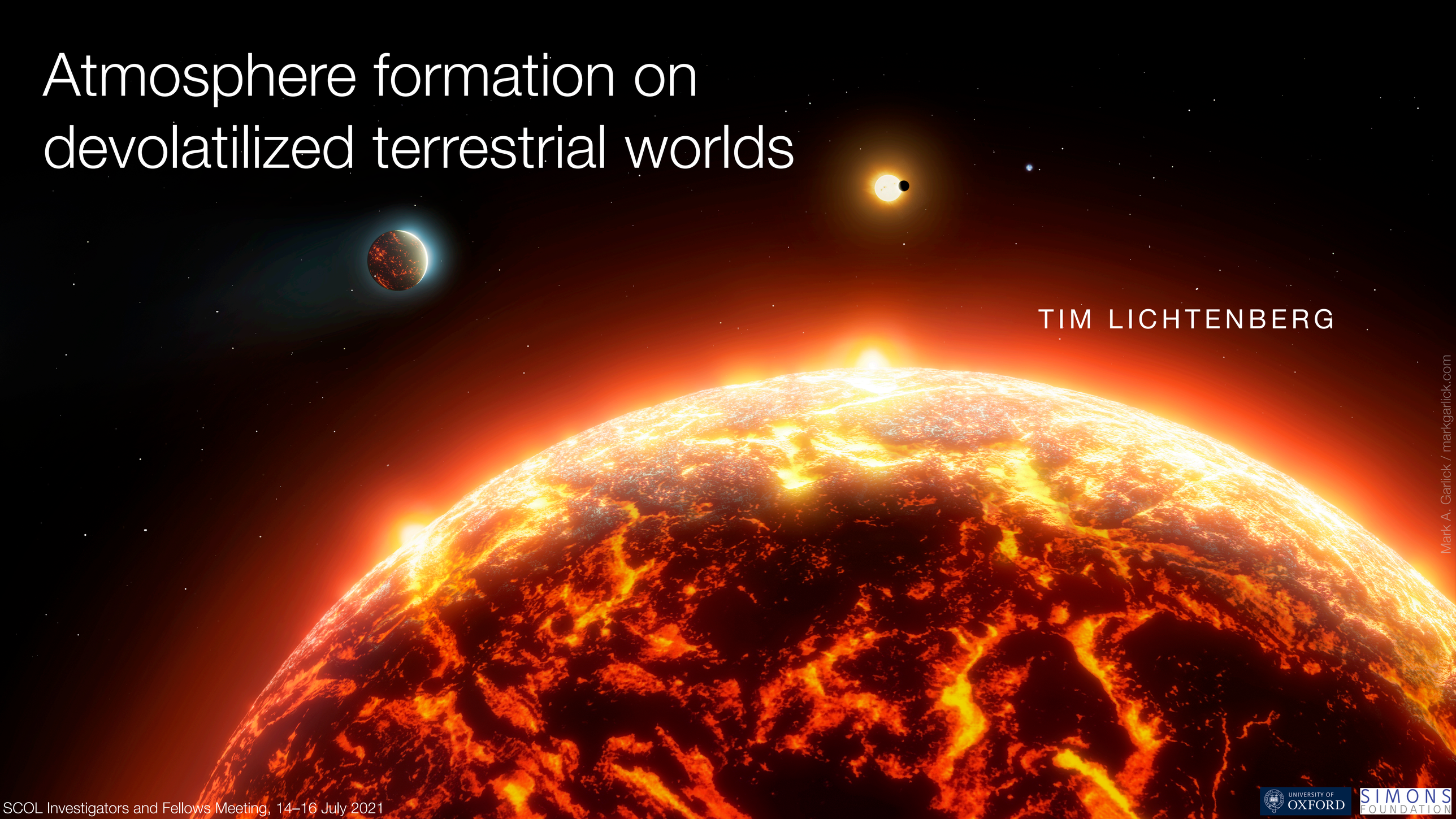
Atmosphere formation on devolatilized terrestrial worlds



TIM LICHTENBERG

Mark A. Garlick / markgarlick.com

SCOL Investigators and Fellows Meeting, 14–16 July 2021

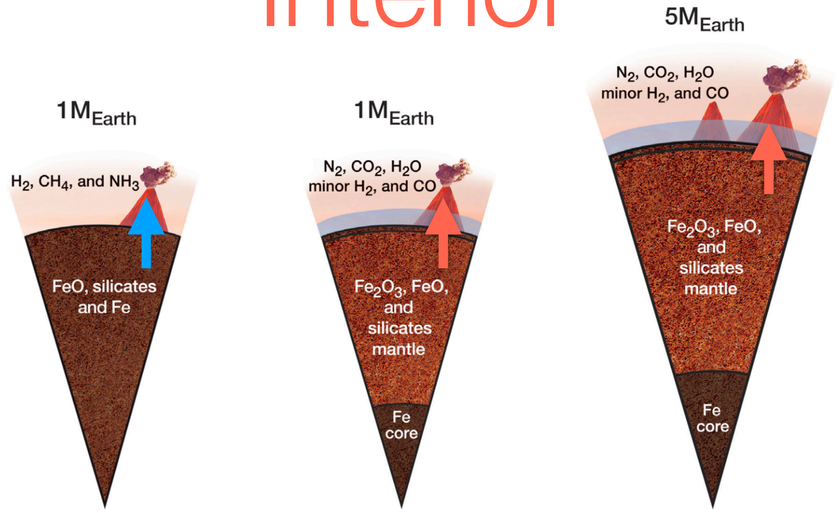
UNIVERSITY OF OXFORD
SIMONS FOUNDATION

What kind of world was the prebiotic Earth?

- What is the climate and atmospheric composition?
- What is the geochemistry of the mantle?
- How do external factors (like impacts) alter the volatile inventory?
- Can Hadean Earth analog exoplanets inform our understanding?

Science Photo Library/Corbis

Interior

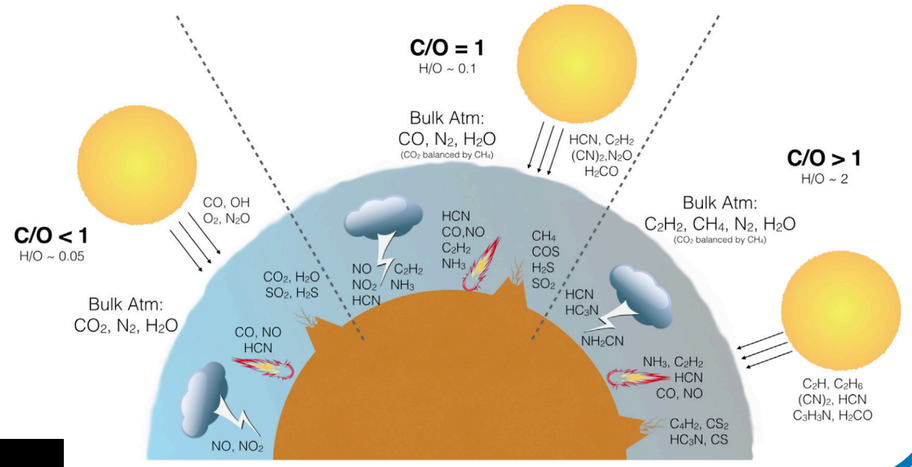


Forming Earth
Reduced atmosphere

Earth
Oxidized atmosphere

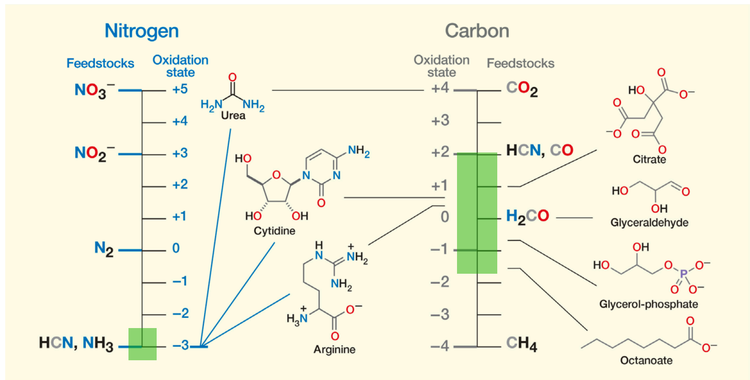
Super-Earth
Oxidized atmosphere

Atmosphere



Rimmer & Rugheimer 19, *Icarus*

Redox state

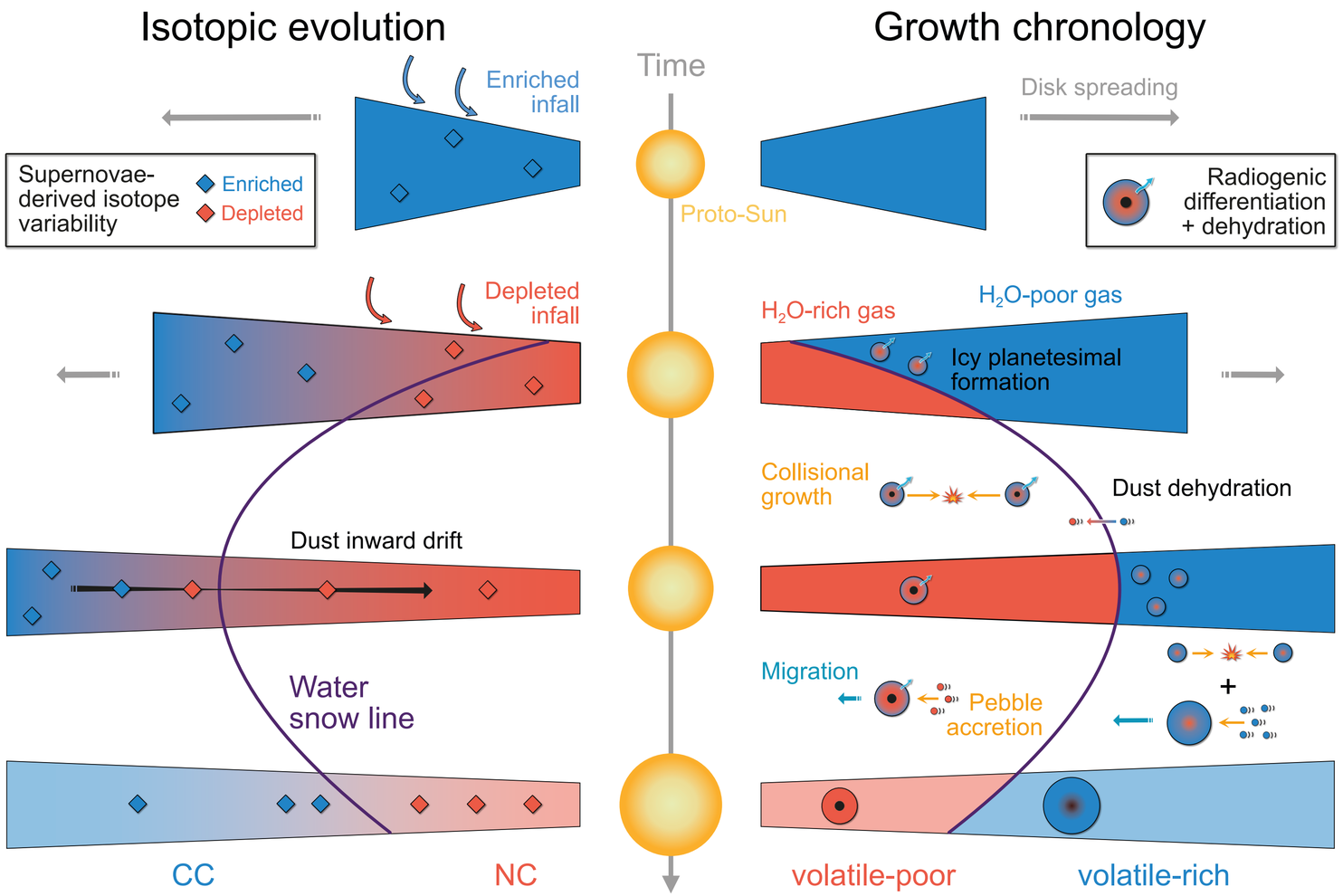


Feedstocks

e.g., nitriles, formaldehyde, phosphate, ammonia

Sasselov, Grotzinger, Sutherland 2020, *Science Advances*

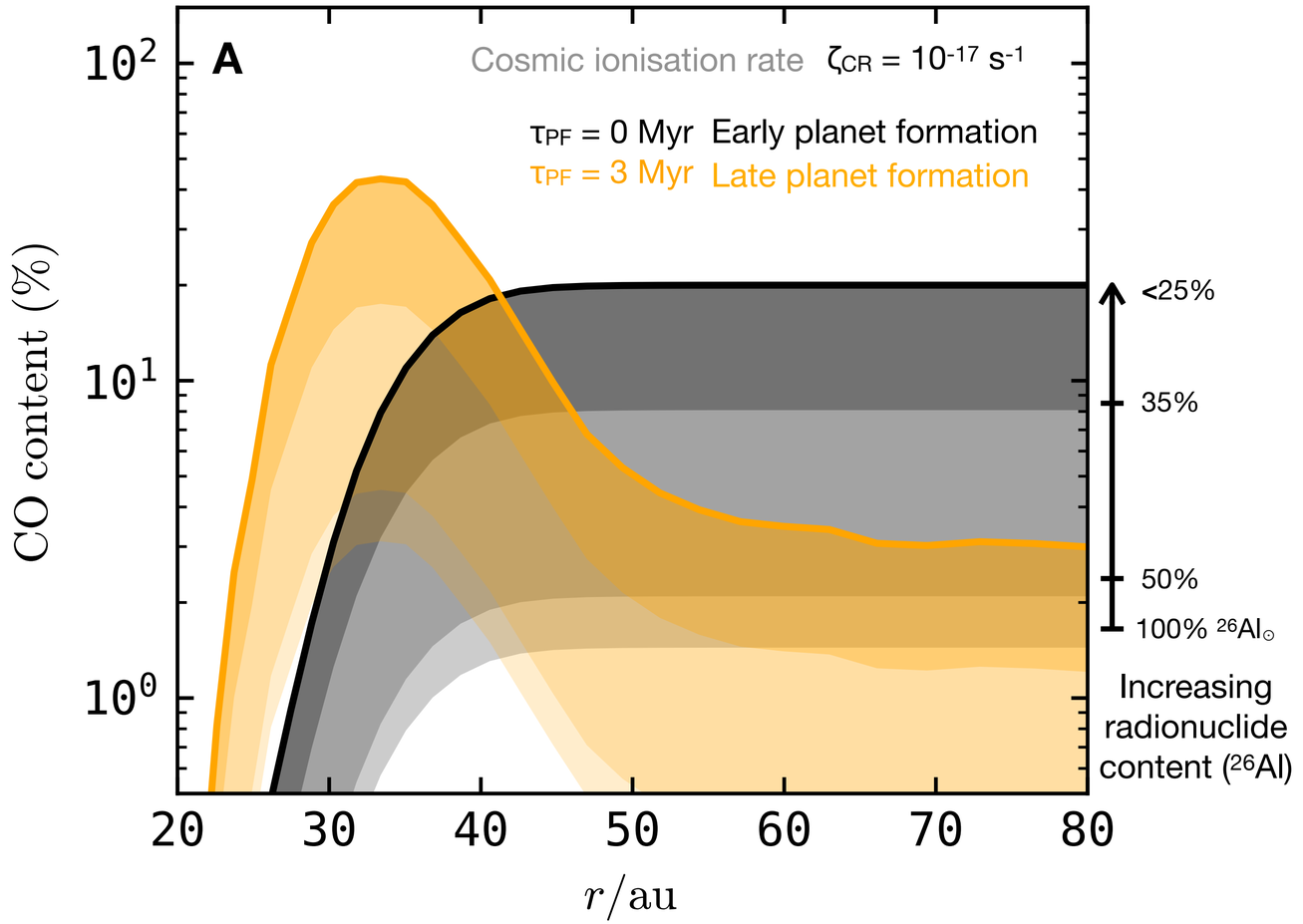
(1) The inner Solar System is dry because it formed from devolatilized building blocks



- Earth is dry because precursors dried out from radioactive heat
- Volatile inventory primarily due to accretion chronology, not location
- Physical explanation for Hf-W & Mn-Cr meteoritic chronology
- Mechanism for highly and moderately volatile depletion of NC meteorites
- Late veneer type impactors <u>not</u> typically reduced

Lichtenberg et al. 2021a, *Science*

(2) Radioactive heating systematically depletes carbon compounds on terrestrial worlds during accretion

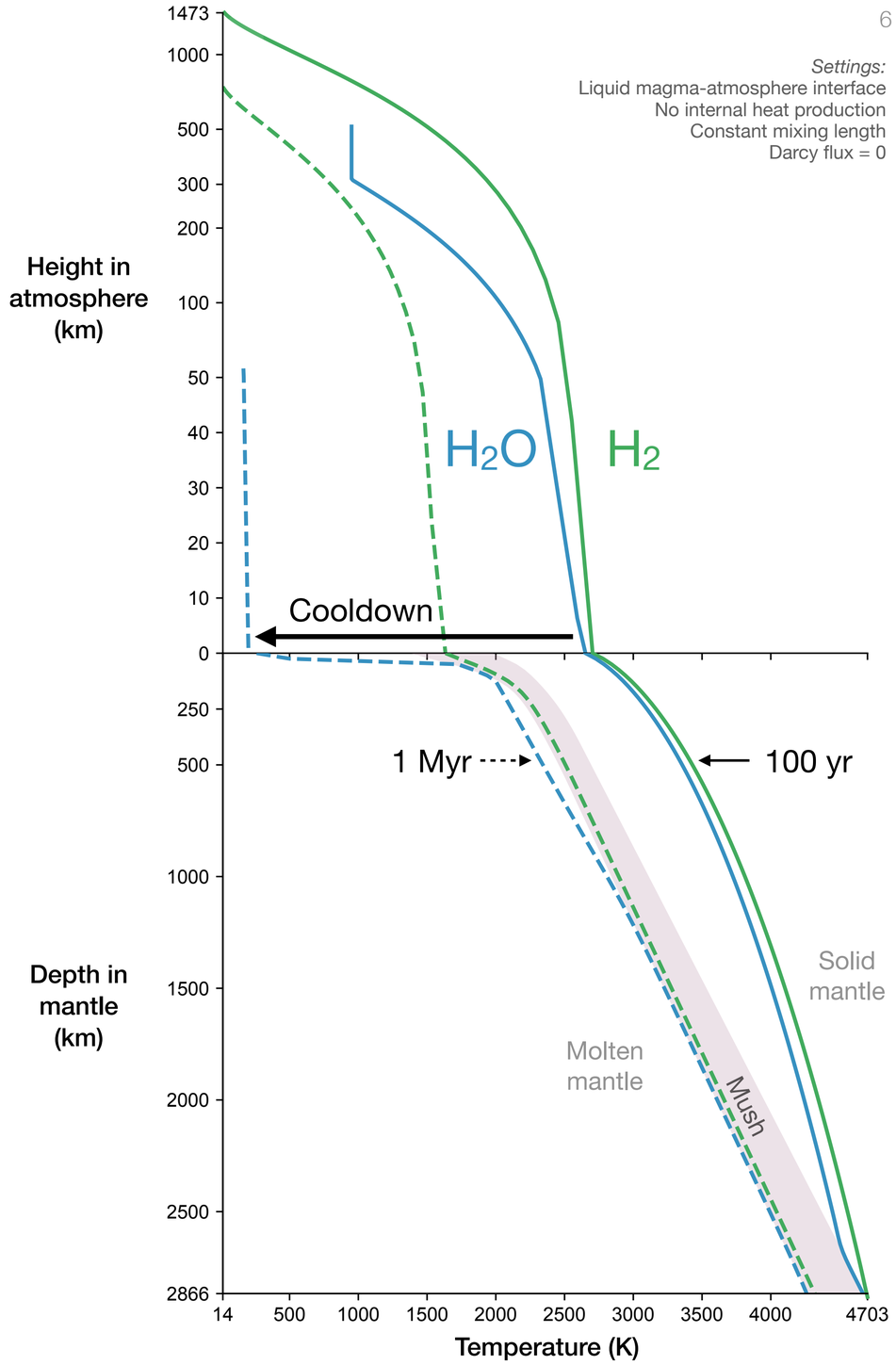


- Planetary C/O, CO, CO_2, and H_2O scale with radionuclide abundances
- Step-function-like abundance of C and H_2O across planetary systems
- Late veneer type impactors typically carbon-rich in exoplanet systems?

Lichtenberg & Krijt 2021, *ApJL*

(3) Worlds with varying volatiles *solidify in distinct fashion*

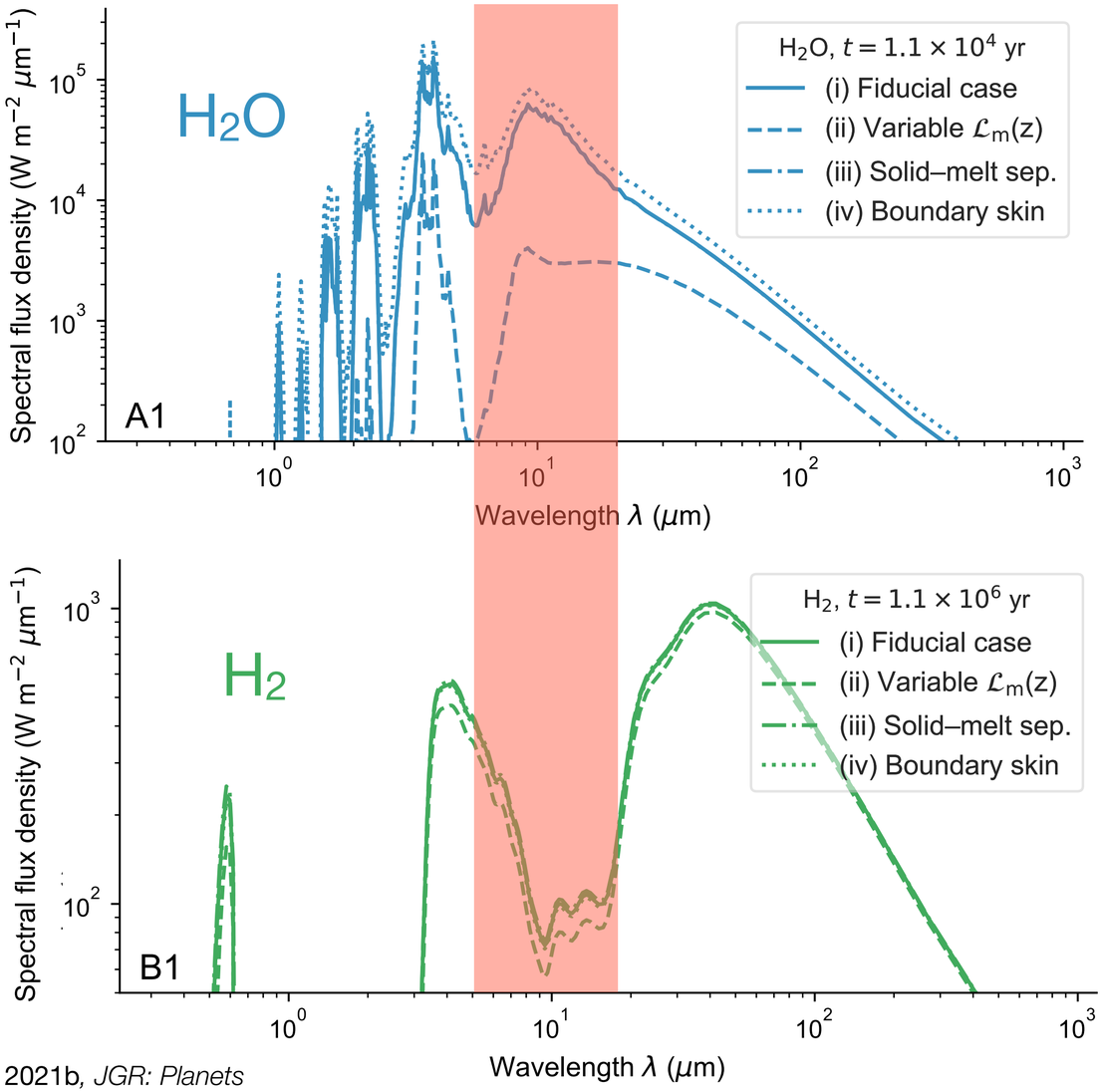
- Magma ocean solidification defines initial conditions of lithosphere
- Crystallization timescale affects volatile storage and redox state of mantle

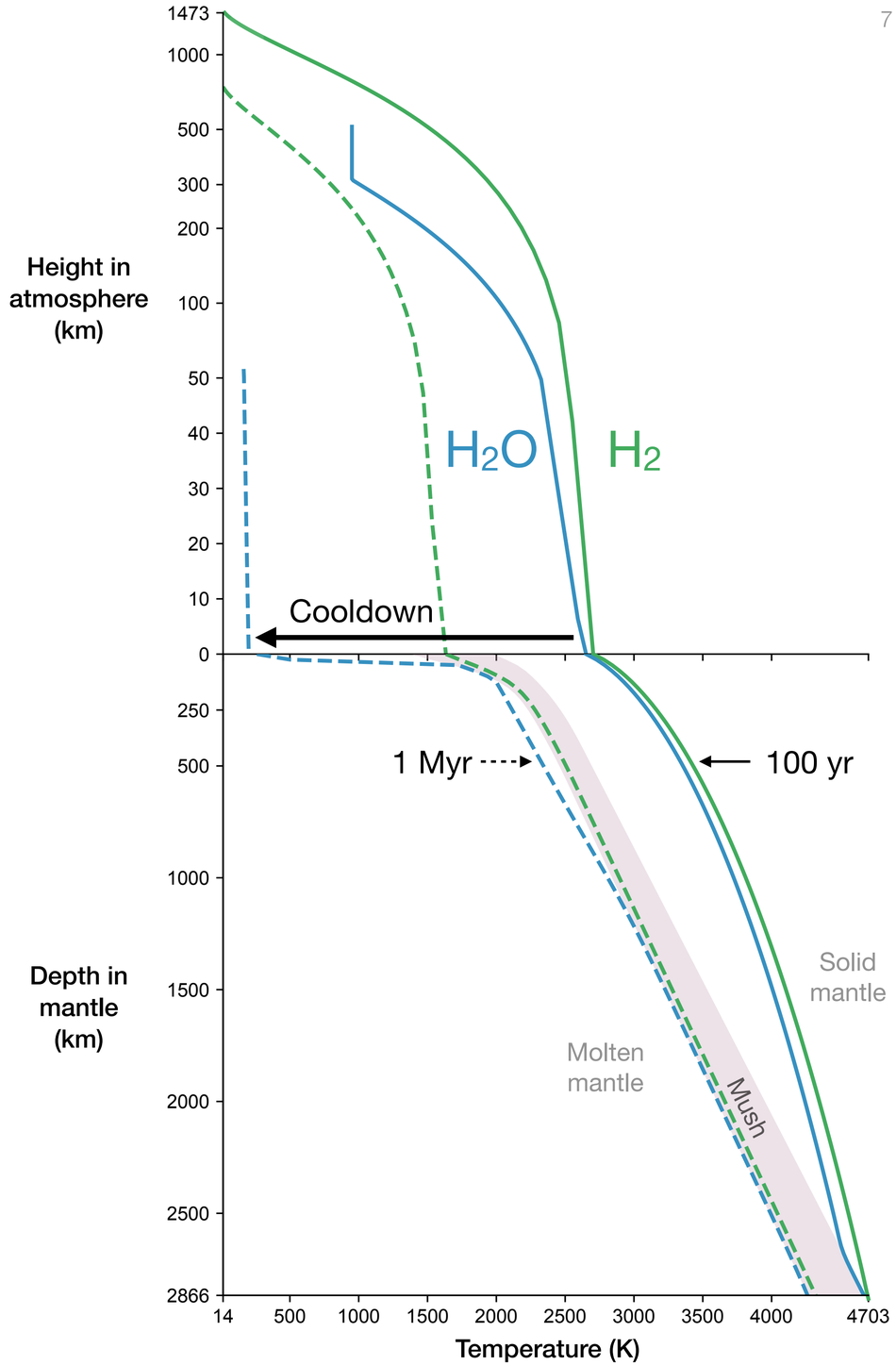


Lichtenberg et al. 2021b, *JGR: Planets*

(3) Worlds with varying volatiles *look differently*

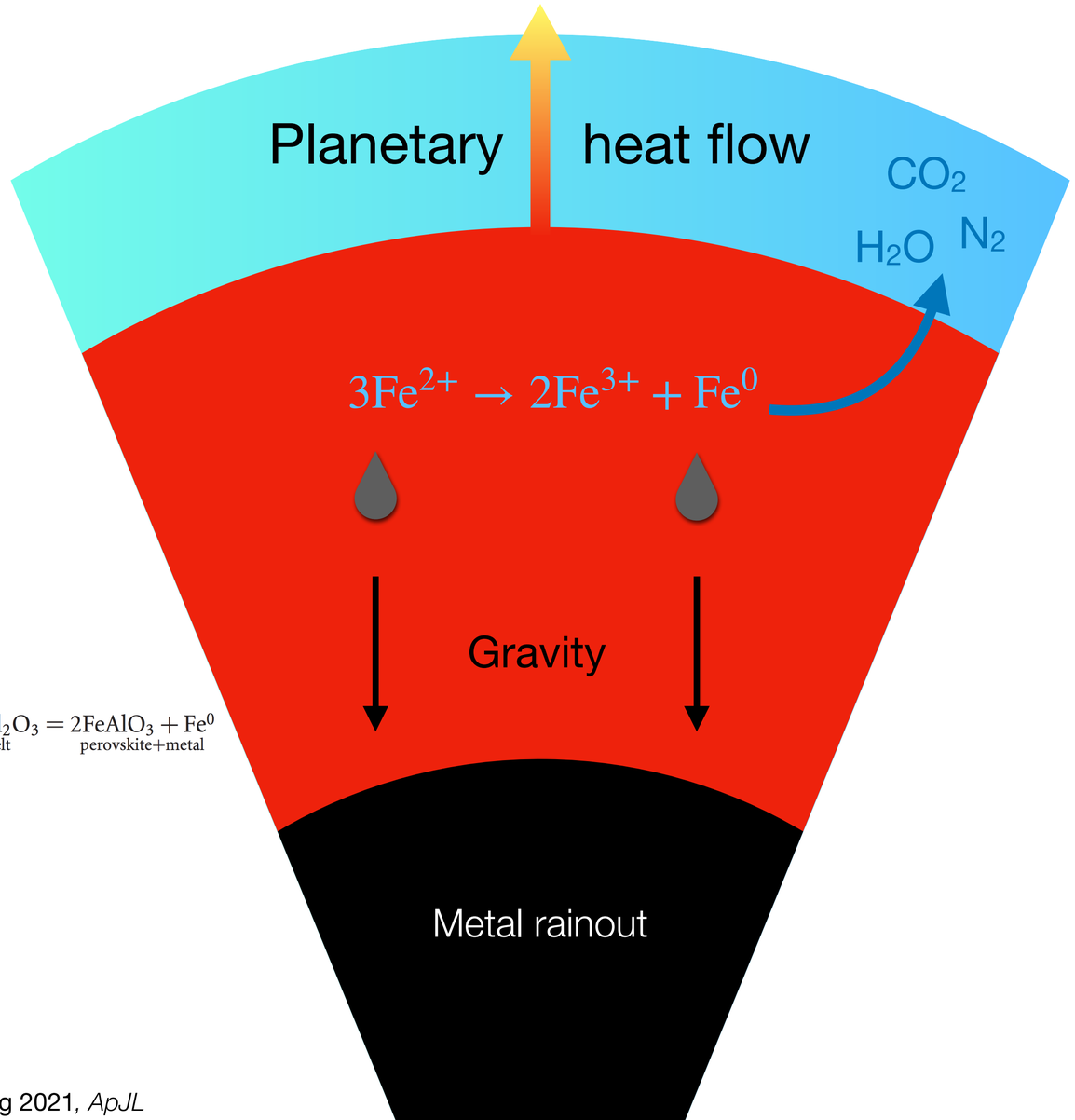
Spectral coverage **Large Interferometer for Exoplanets** *(Quanz et al. 2019, 2021)*





Lichtenberg et al. 2021b, *JGR: Planets*

(4) Super-Earths can host reduced atmospheres

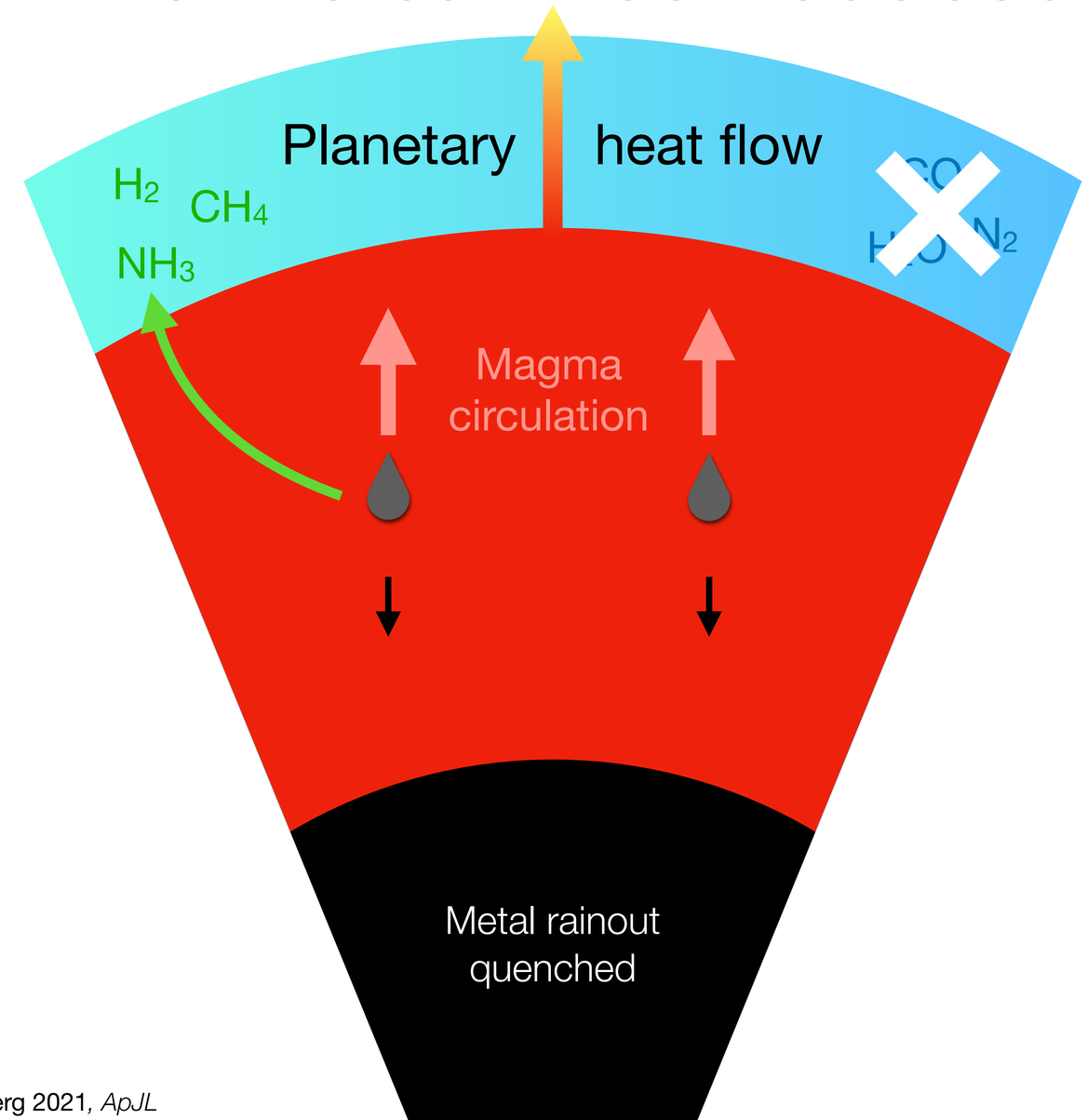


$$3FeO + Al_2O_3 = 2FeAlO_3 + Fe^0$$
silicate melt — perovskite+metal

- Mantle self-oxidation dependent on Fe removal to the core

Lichtenberg 2021, *ApJL*

(4) Primary envelope-stripped super-Earths can host reduced atmospheres

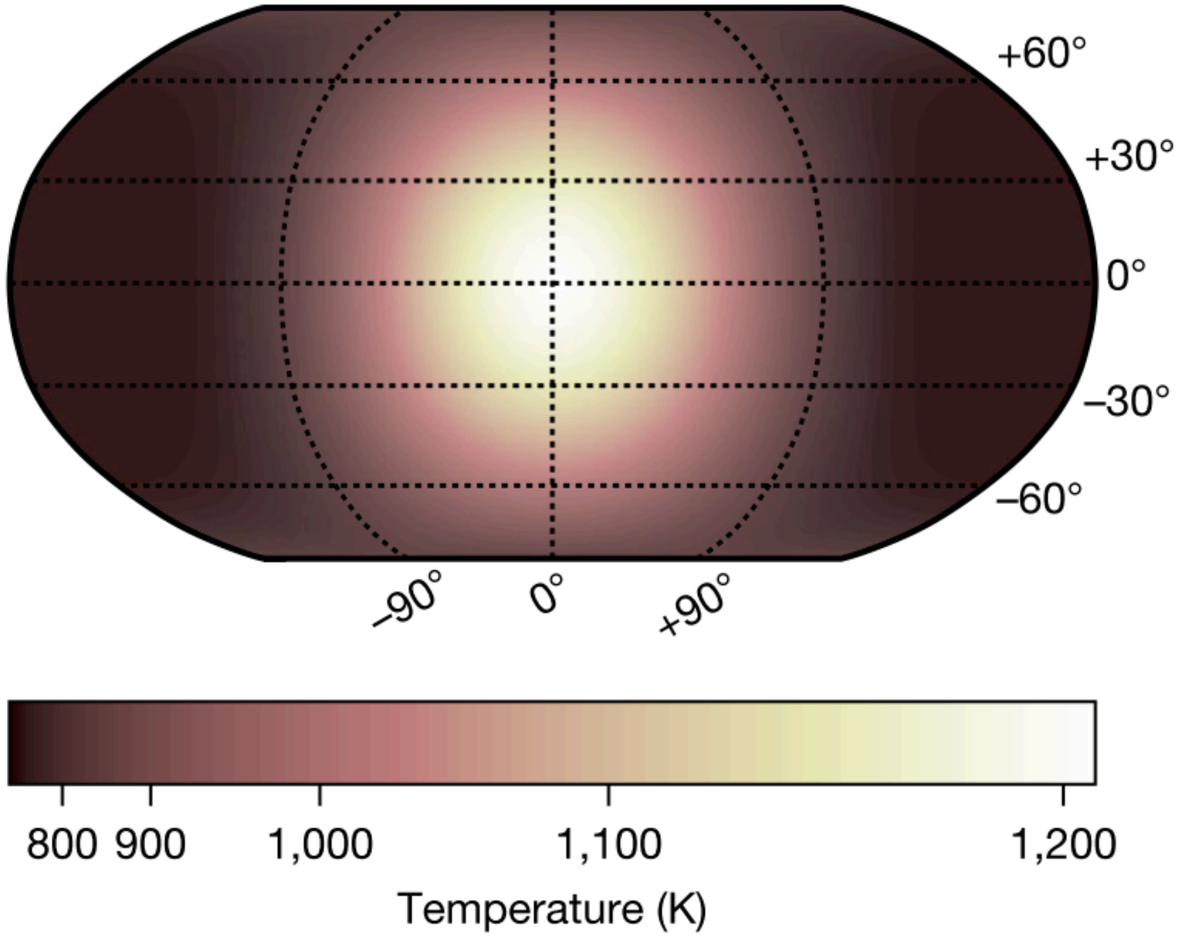


- Mantle self-oxidation dependent on Fe removal to the core
- Vigorous convection in molten super-Earths can prevent iron rainout
- Reduced atmospheres on super-Earths remain viable

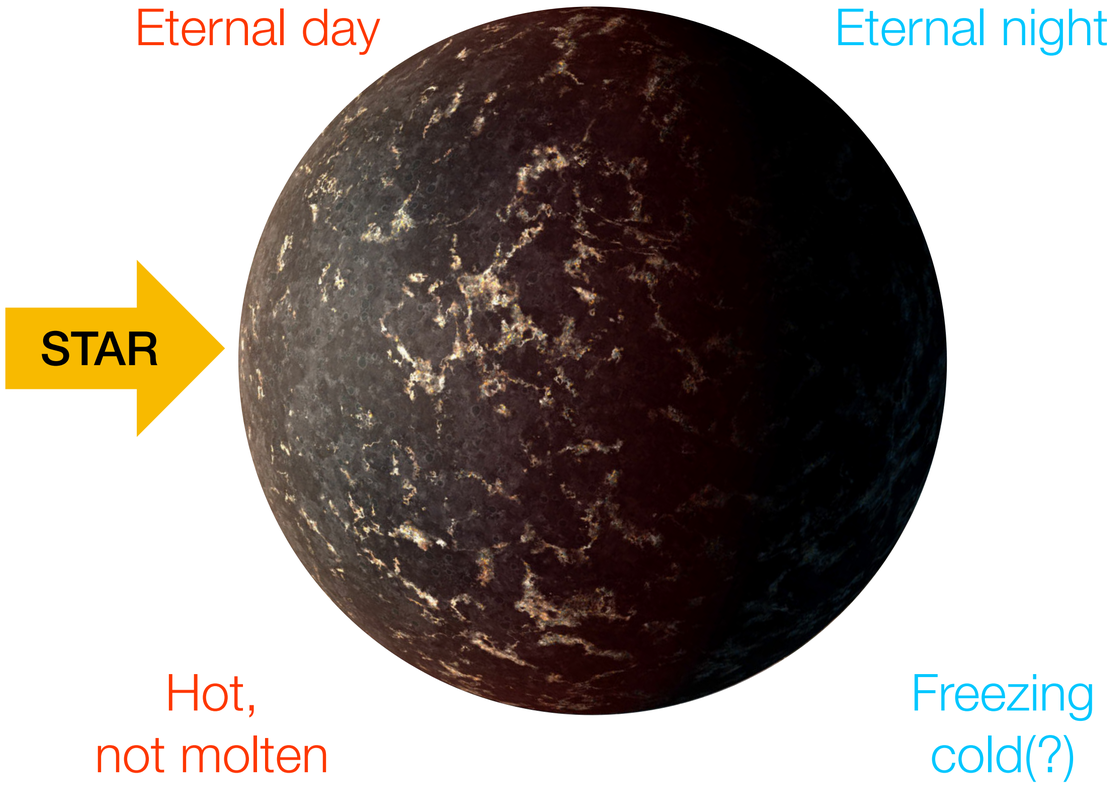
Lichtenberg 2021, *ApJL*

(5) Tectonics of hot, partially molten mantles: insights from exoplanets

Surface temperature map of LHS 3844b

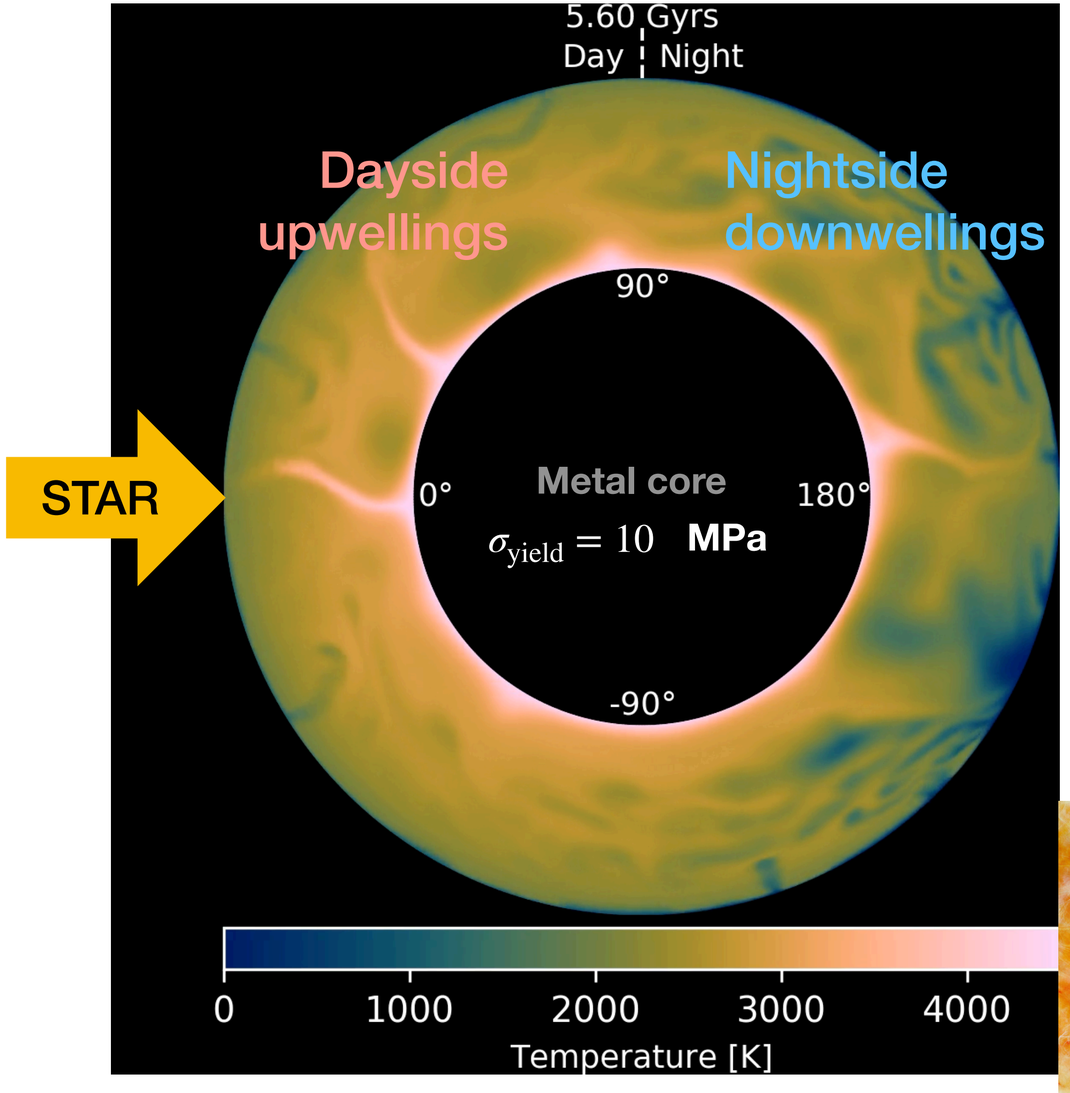


Kreidberg et al. 2019, *Nature*

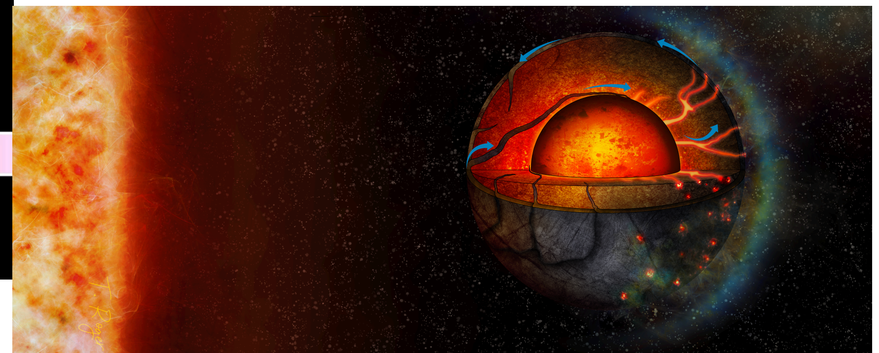


NASA / JPL-Caltech / R. Hurt, IPAC

(5) Tectonics of hot, partially molten mantles: insights from exoplanets

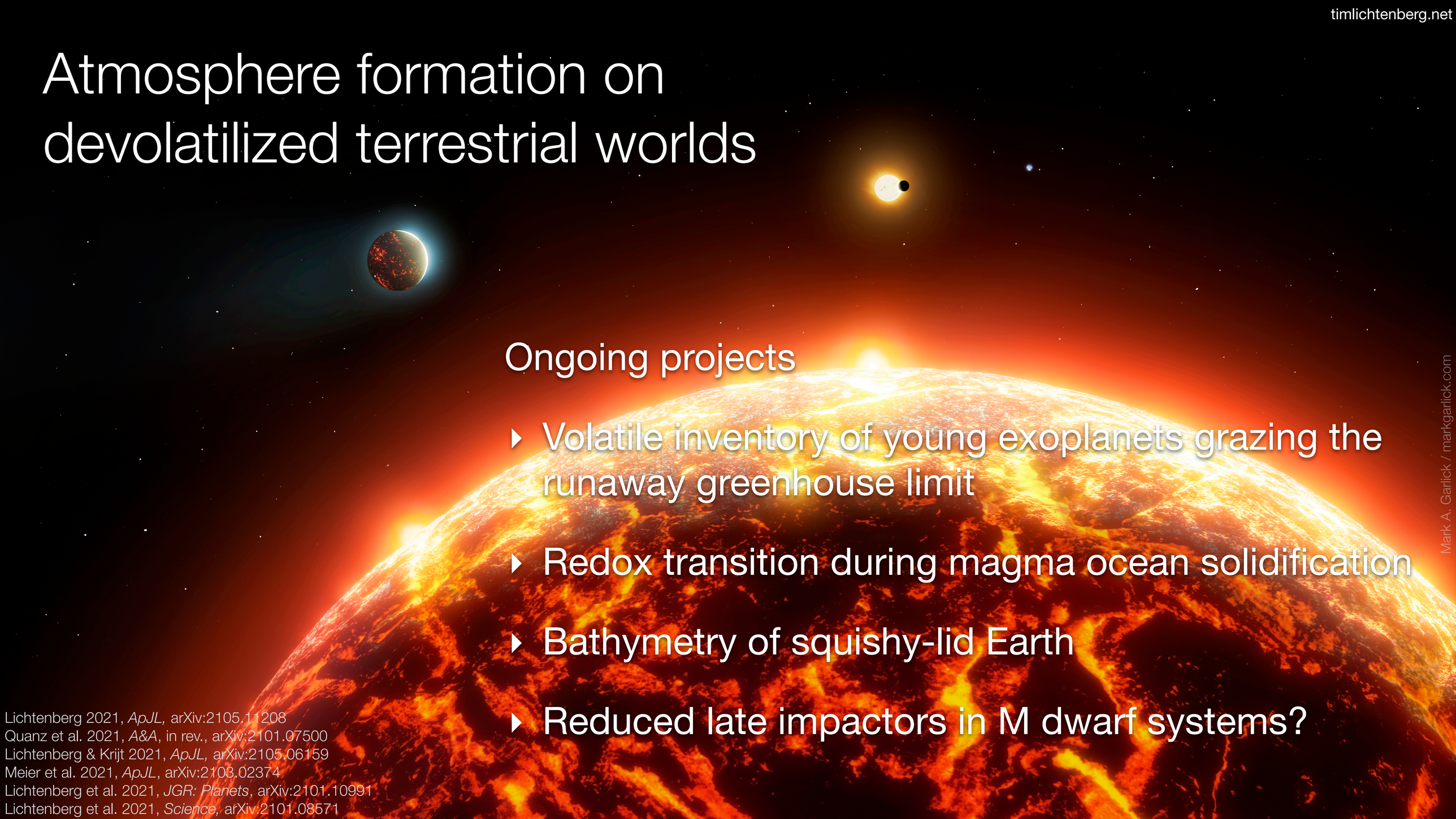


- First evidence of tectonic activity on rocky exoplanet
- Hemispherically-split tectonics, *unknown from Solar System*
- Mixed mobile-lid regime
- Outgassing patterns informs geodynamic diversity of super-Earths



Meier, Bower, **Lichtenberg** et al. 2021, *ApJL*

Atmosphere formation on devolatilized terrestrial worlds



Ongoing projects

- Volatile inventory of young exoplanets grazing the runaway greenhouse limit
- Redox transition during magma ocean solidification
- Bathymetry of squishy-lid Earth
- Reduced late impactors in M dwarf systems?

Lichtenberg 2021, *ApJL,* arXiv:2105.11208
Quanz et al. 2021, *A&A*, in rev., arXiv:2101.07500
Lichtenberg & Krijt 2021, *ApJ,* arXiv:2105.06159
Meier et al. 2021, *ApJ*, arXiv:2103.02374
Lichtenberg et al. 2021, *JGR: Planets*, arXiv:2101.10991
Lichtenberg et al. 2021, *Science,* arXiv:2101.08571