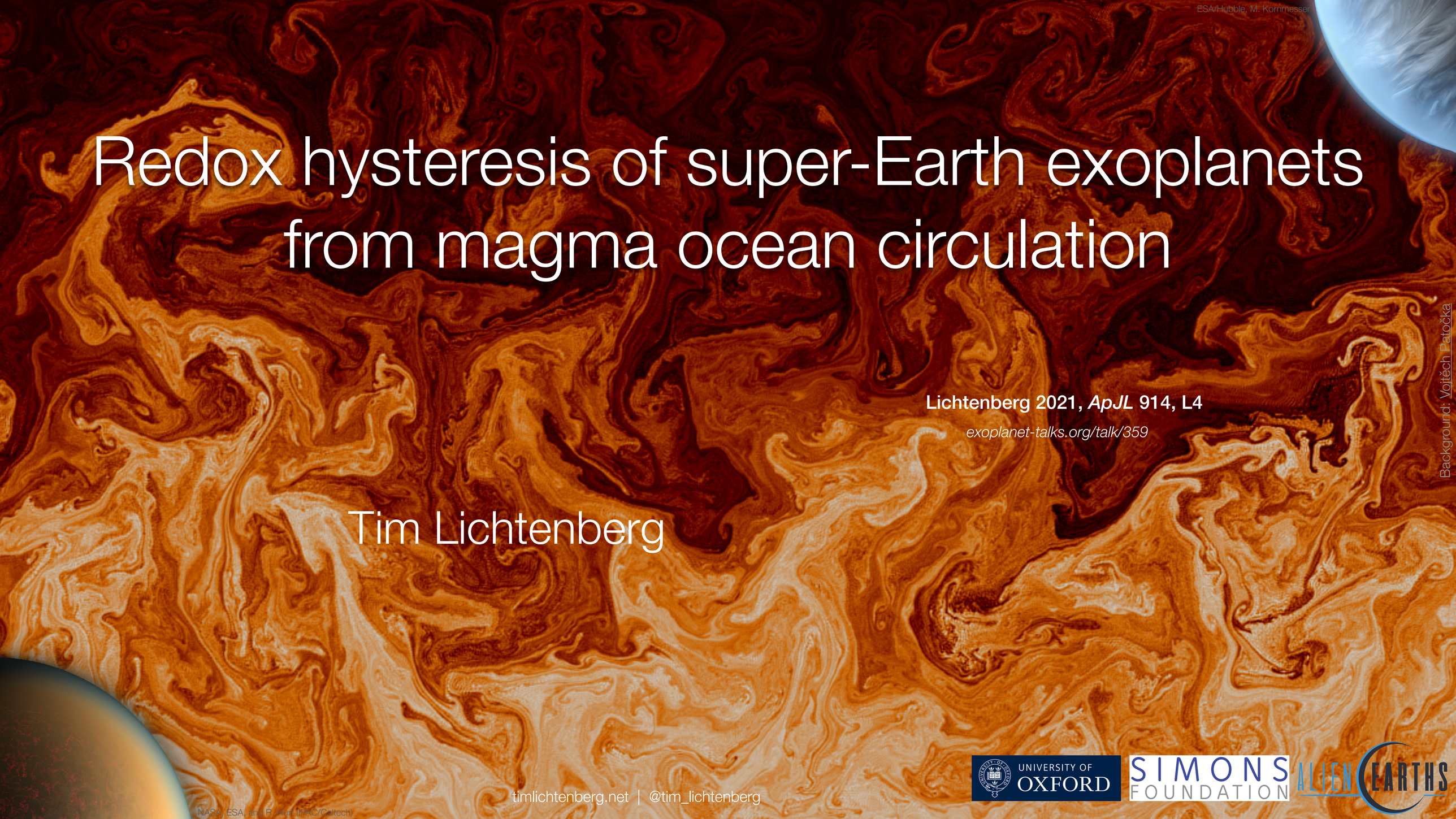


Redox hysteresis of super-Earth exoplanets from magma ocean circulation

Lichtenberg 2021, *ApJL* 914, L4

exoplanet-talks.org/talk/359

Tim Lichtenberg

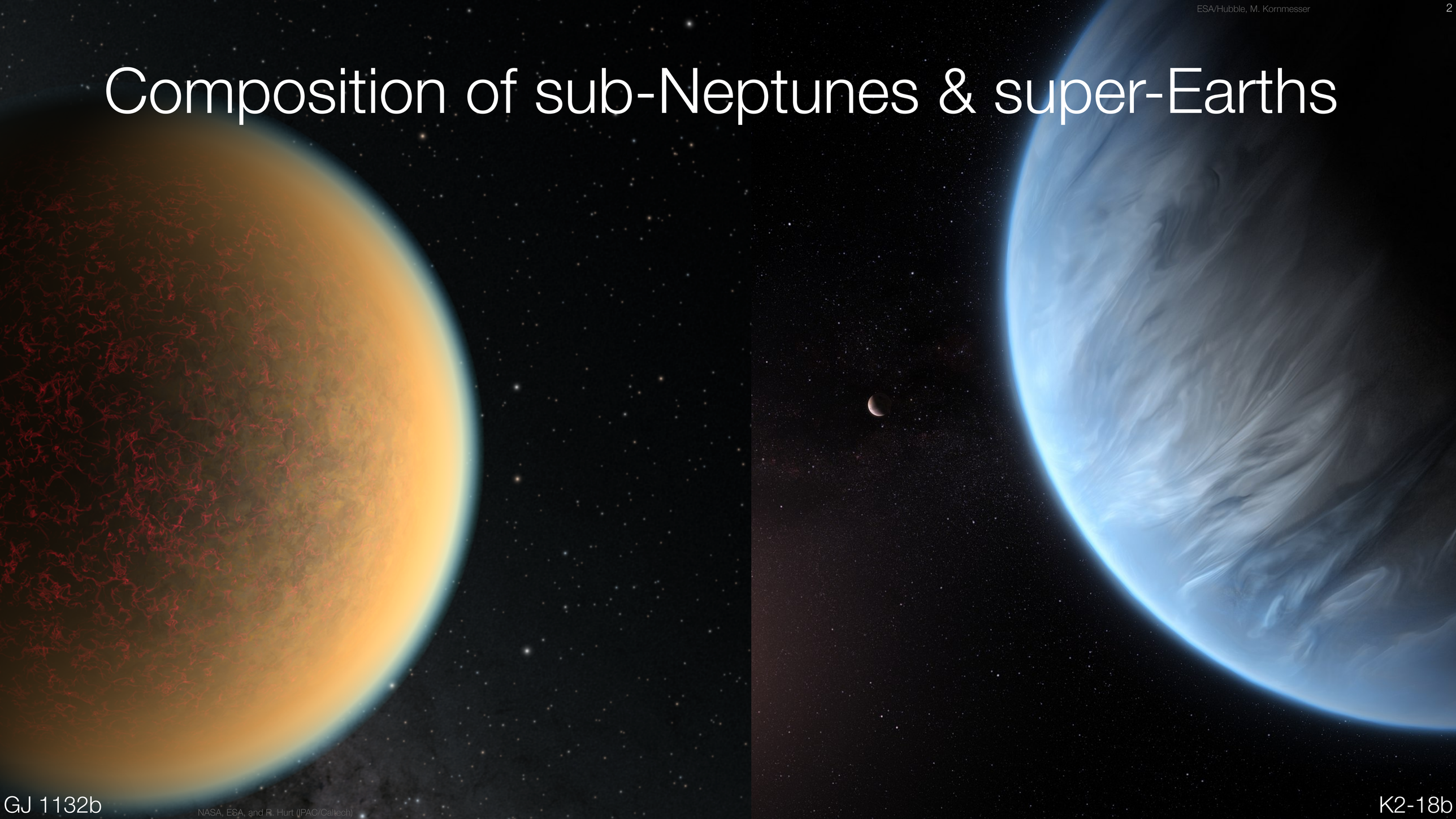
timlichtenberg.net | @tim_lichtenberg

ESA/Hubble, M. Kornmesser

Background: Vojtěch Patočka

NASA, ESA, and R. Hurt (IPAC/Caltech)

Composition of sub-Neptunes & super-Earths



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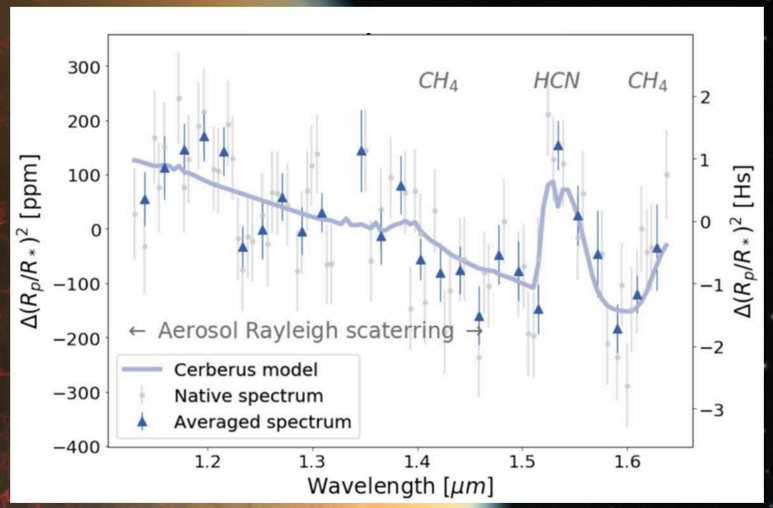
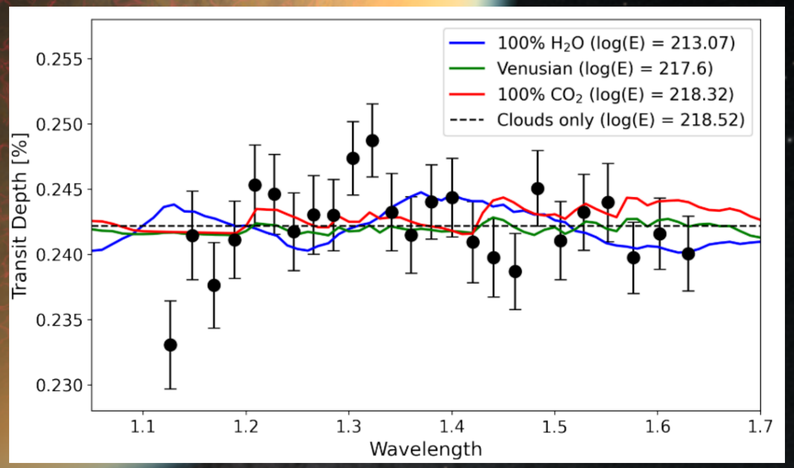


Swain+ 21



Mugnai+ 21

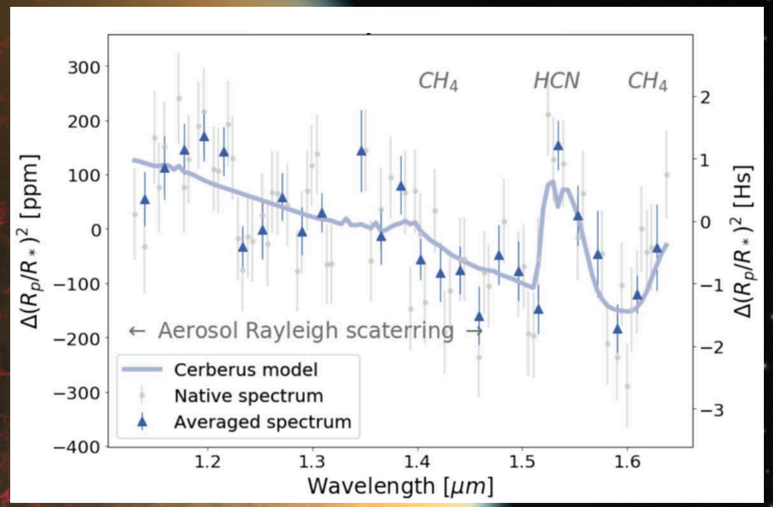
GJ 1132b

NASA, ESA, and R. Hurt (IPAC/Caltech)

ESA/Hubble, M. Kornmesser

K2-18b

Composition of sub-Neptunes & super-Earths



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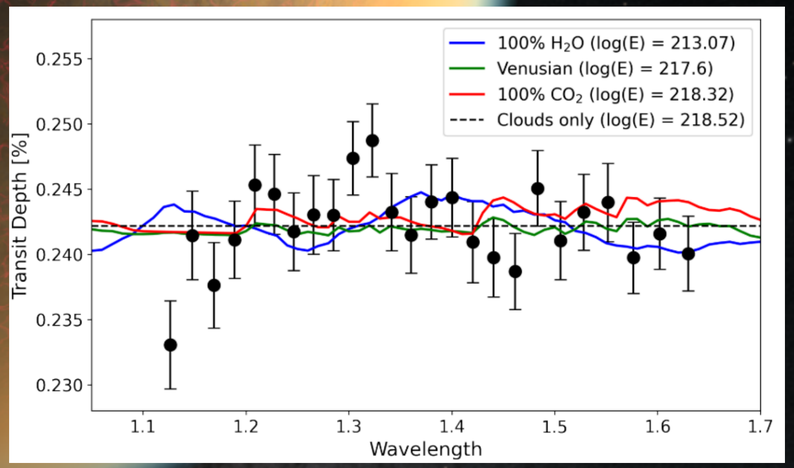

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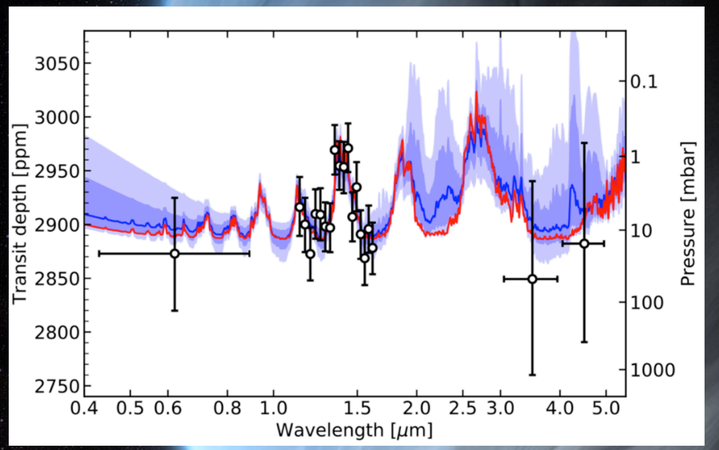
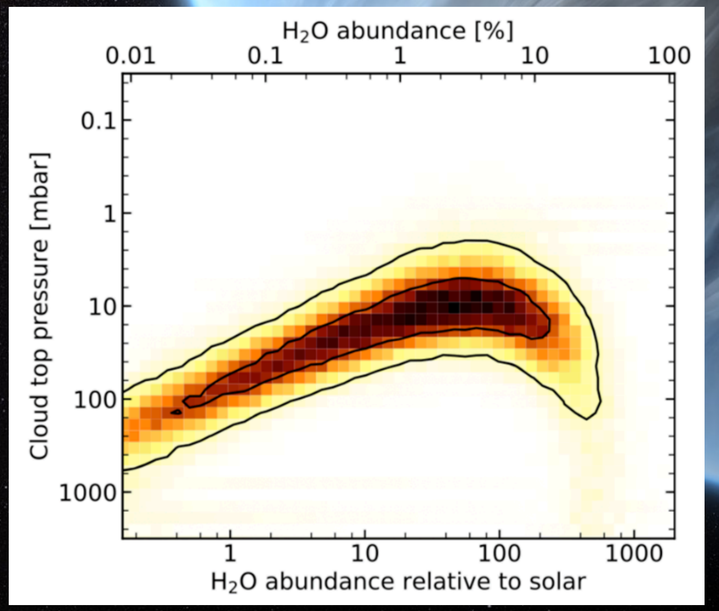
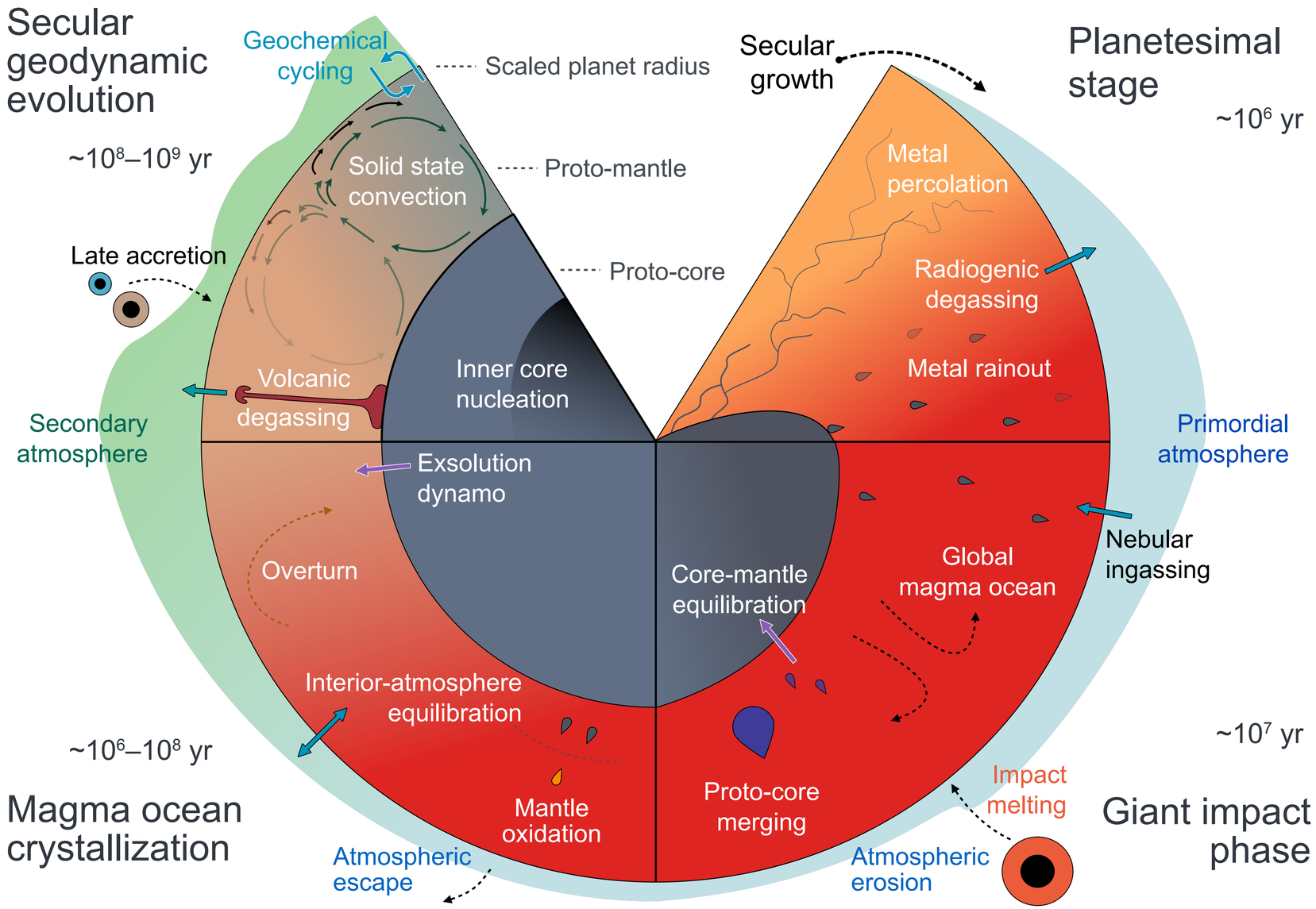




Benneke+ 19

K2-18b

Composition of secondary atmospheres



Lichtenberg, Schaefer, Nakajima, Fischer, *Protostars & Planets VII, in review*

Redox alteration requires reservoir mixing

Iron disproportionation

$$3Fe^{2+} \rightarrow 2Fe^{3+} + Fe^{0}$$

Frost+ 04, Wade & Wood 05, Frost & McCammon 08, Carlson+ 12

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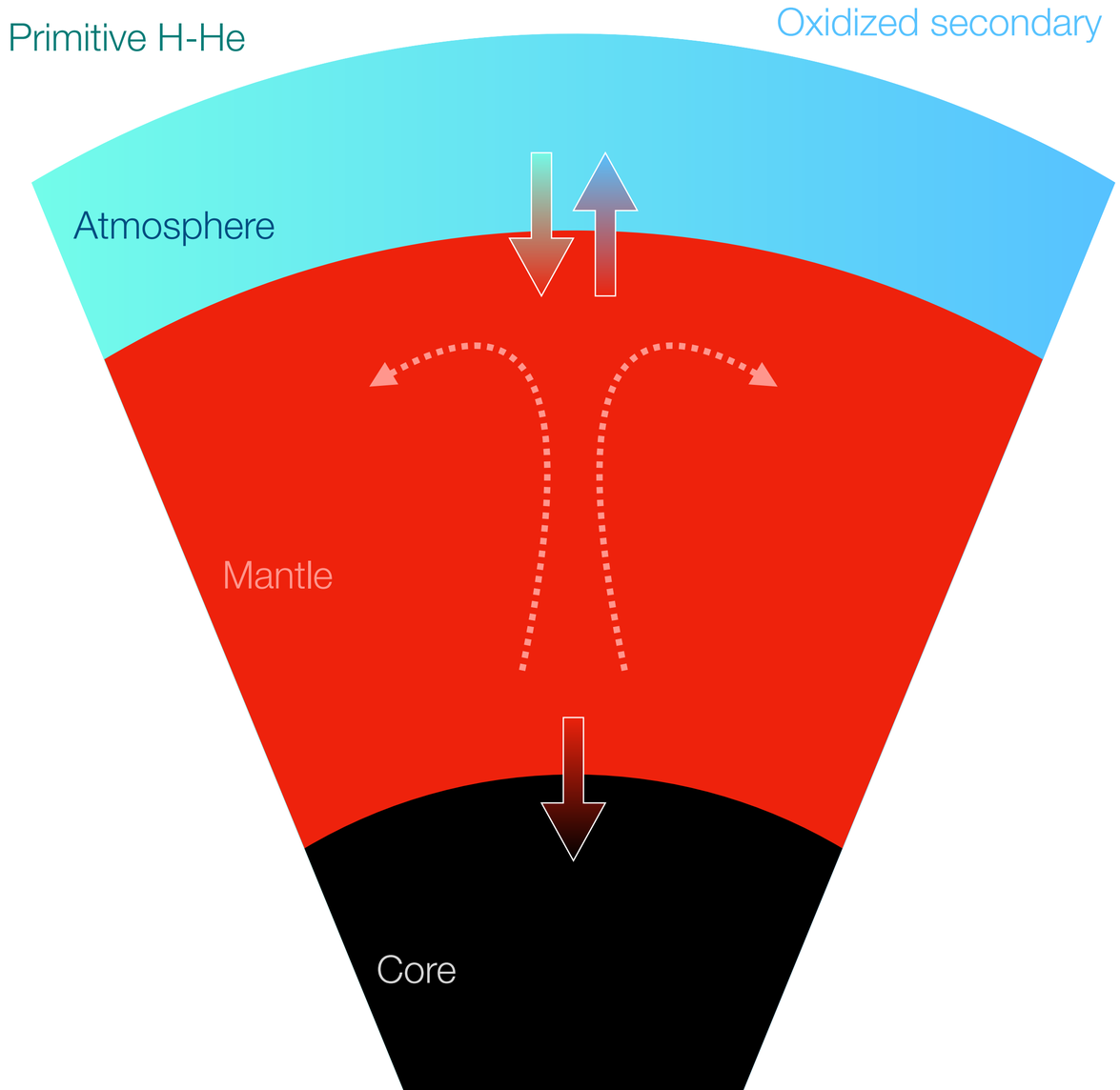
Ikoma & Genda 06, Ikoma+ 18, Olson & Sharp 18, Kite & Schaefer 21



Redox evolution on >terrestrial-sized planets

Iron disproportionation

‘Ferrous iron’ ‘Ferric iron’ ‘Iron metal’

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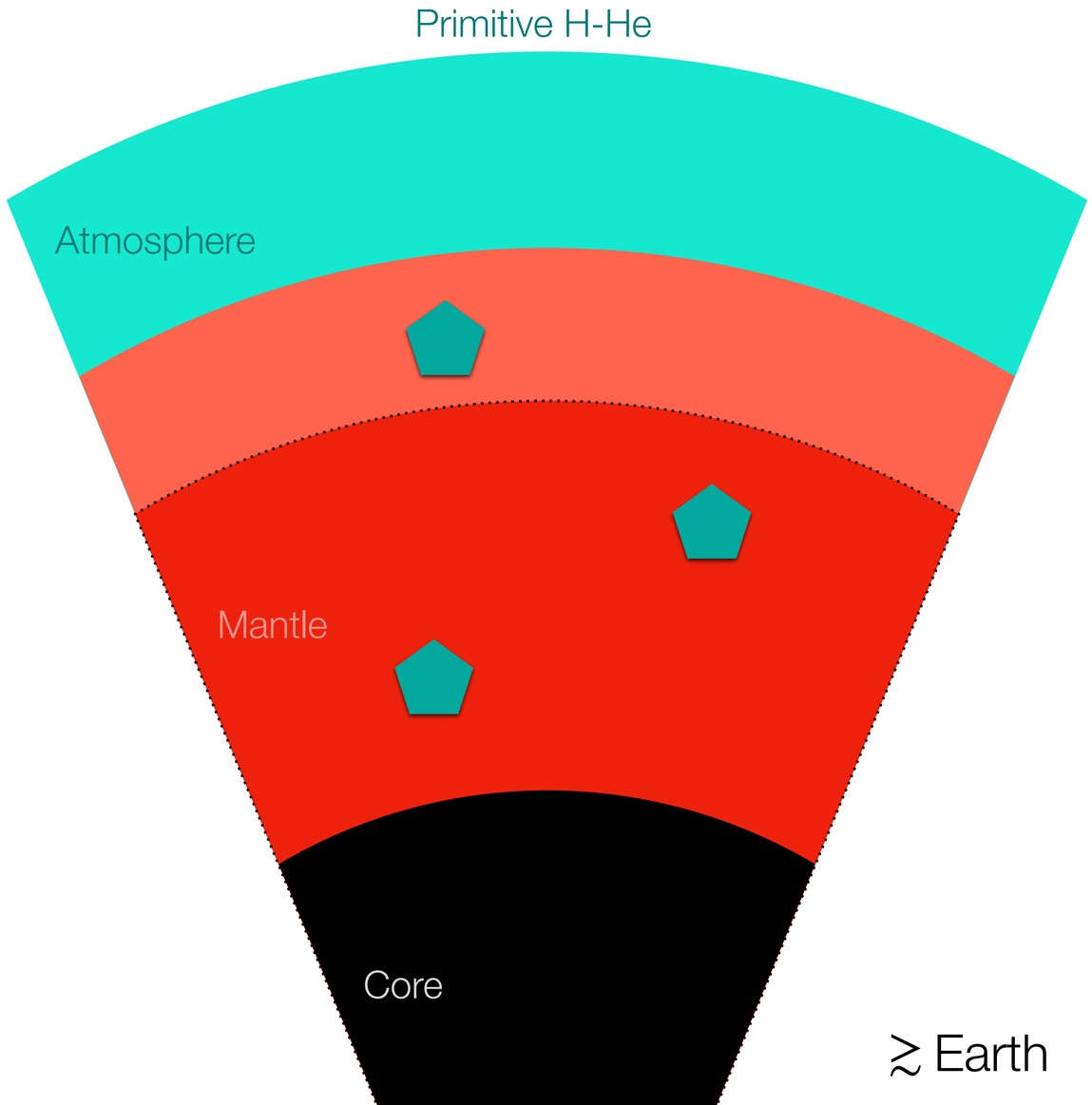
$$\underset{\text{silicate melt}}{3FeO + Al_2O_3} = \underset{\text{perovskite+metal}}{2FeAlO_3 + Fe^0}$$



$\gtrsim$ Earth

Frost & McCammon 08, Carlson+ 12

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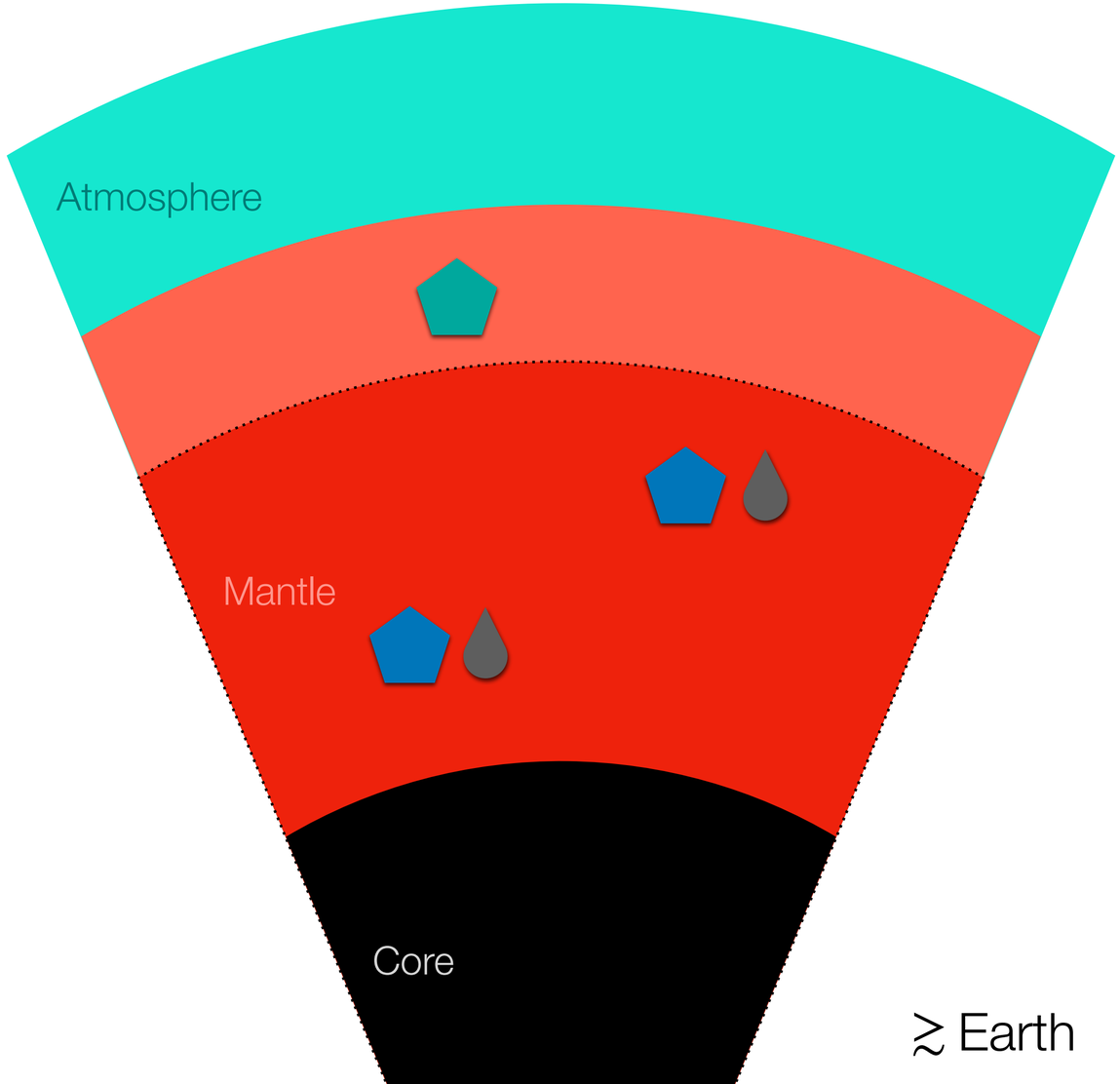

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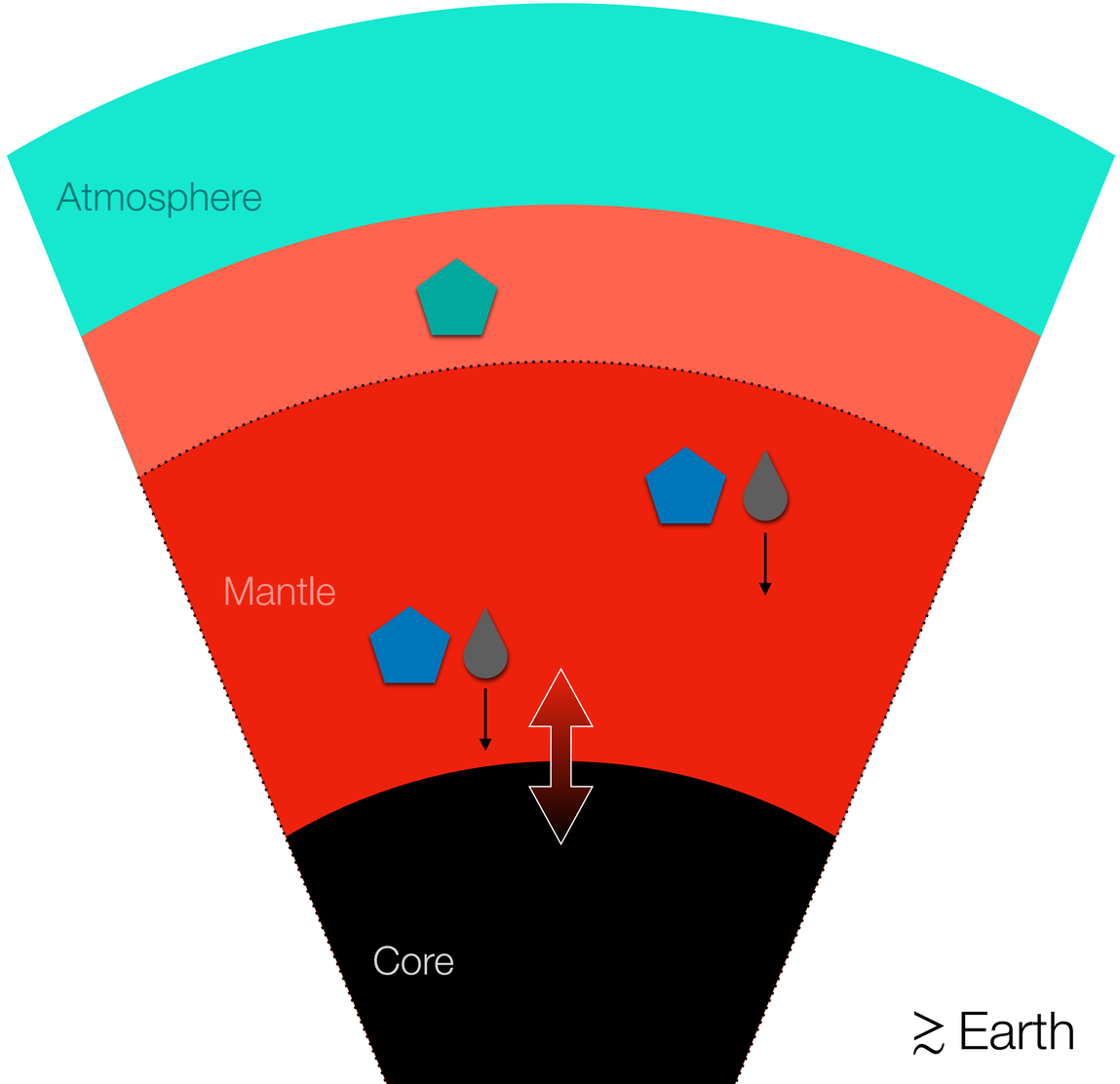

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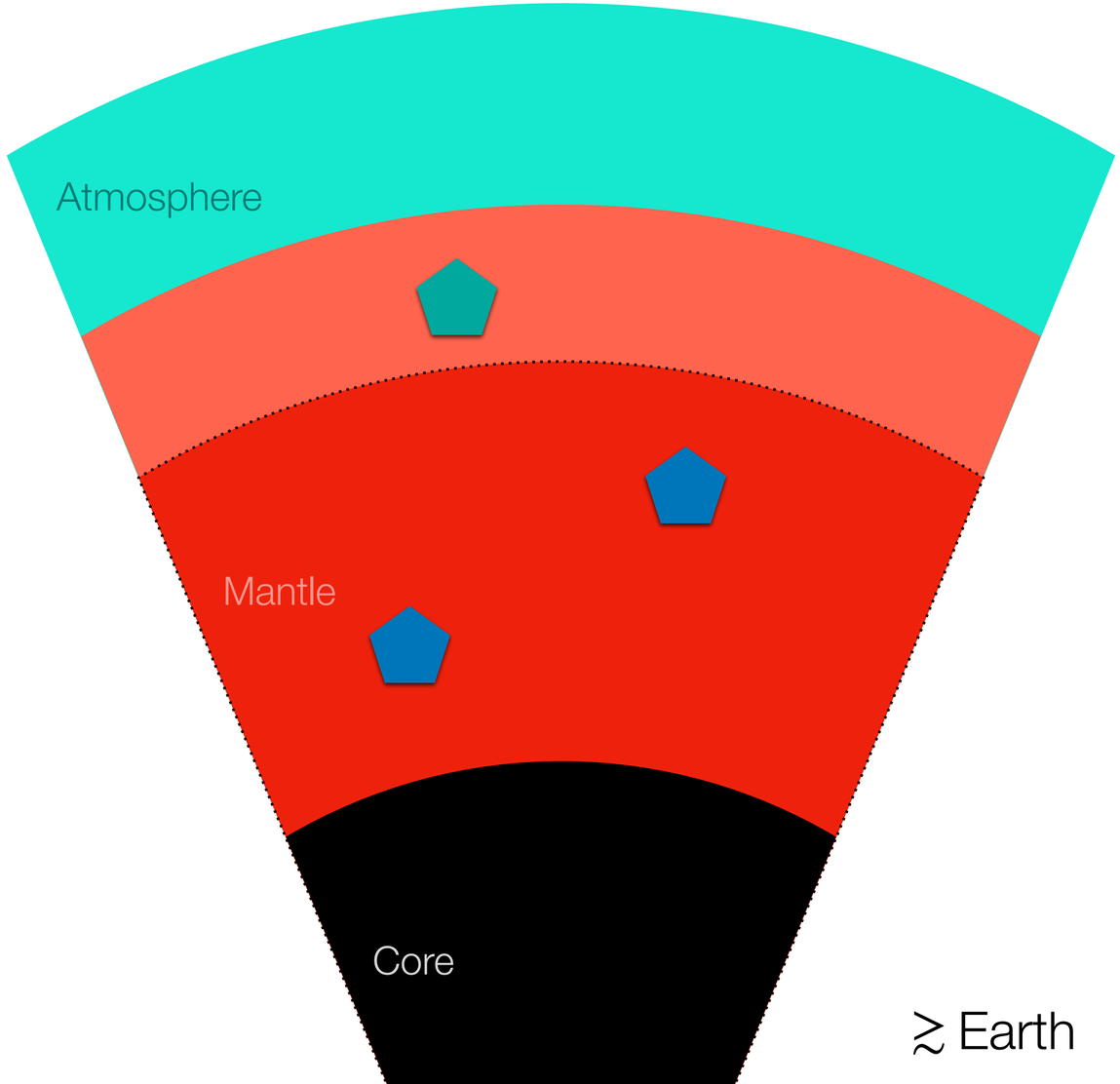

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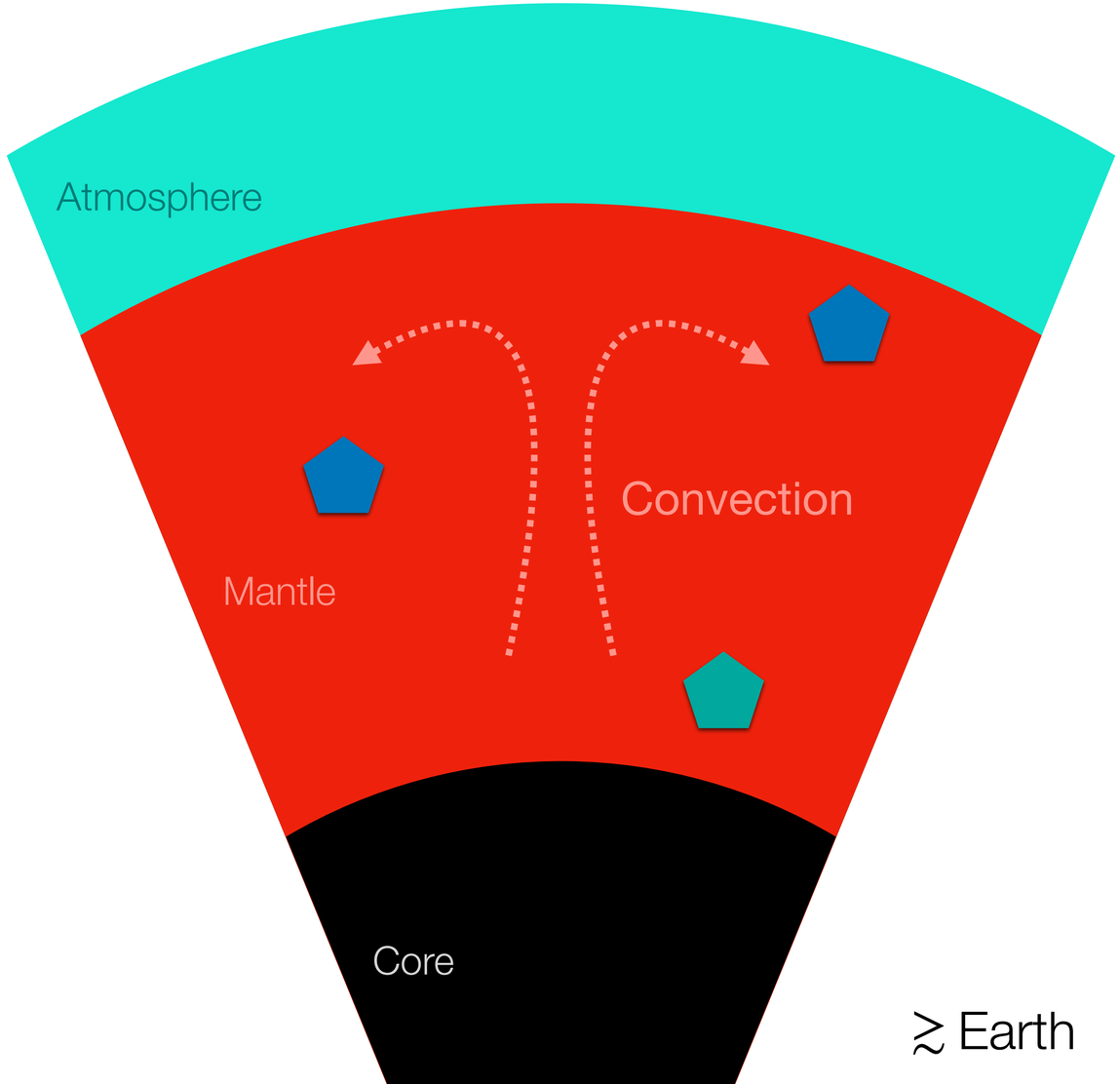

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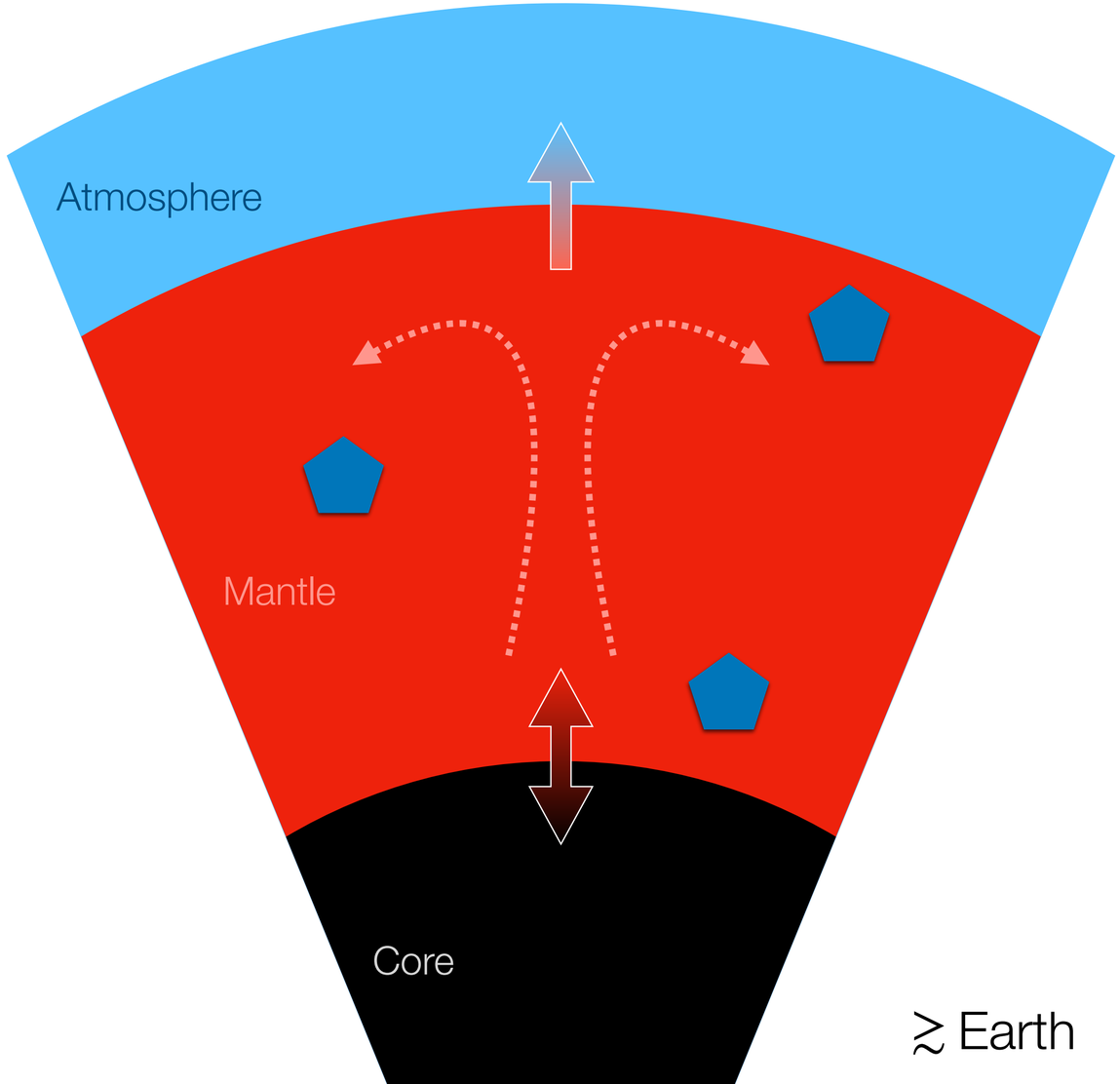


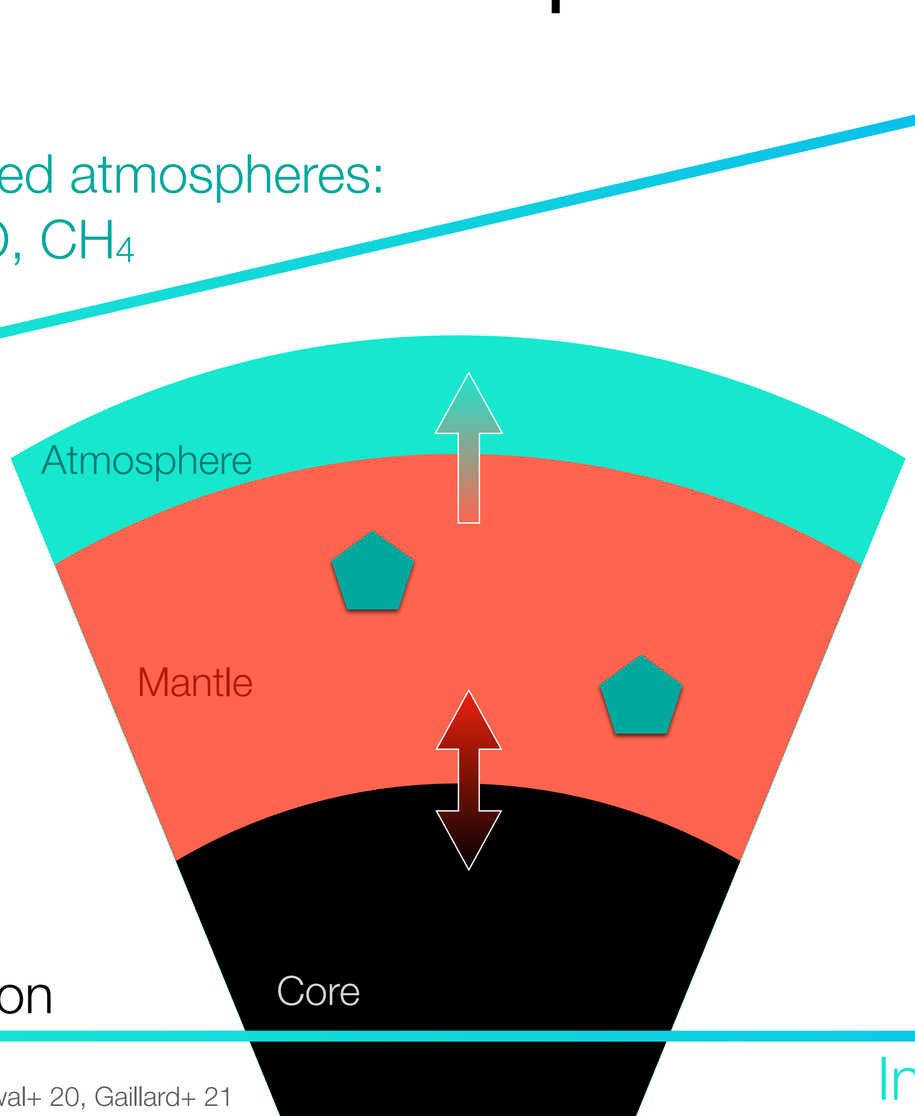
$\gtrsim$ Earth

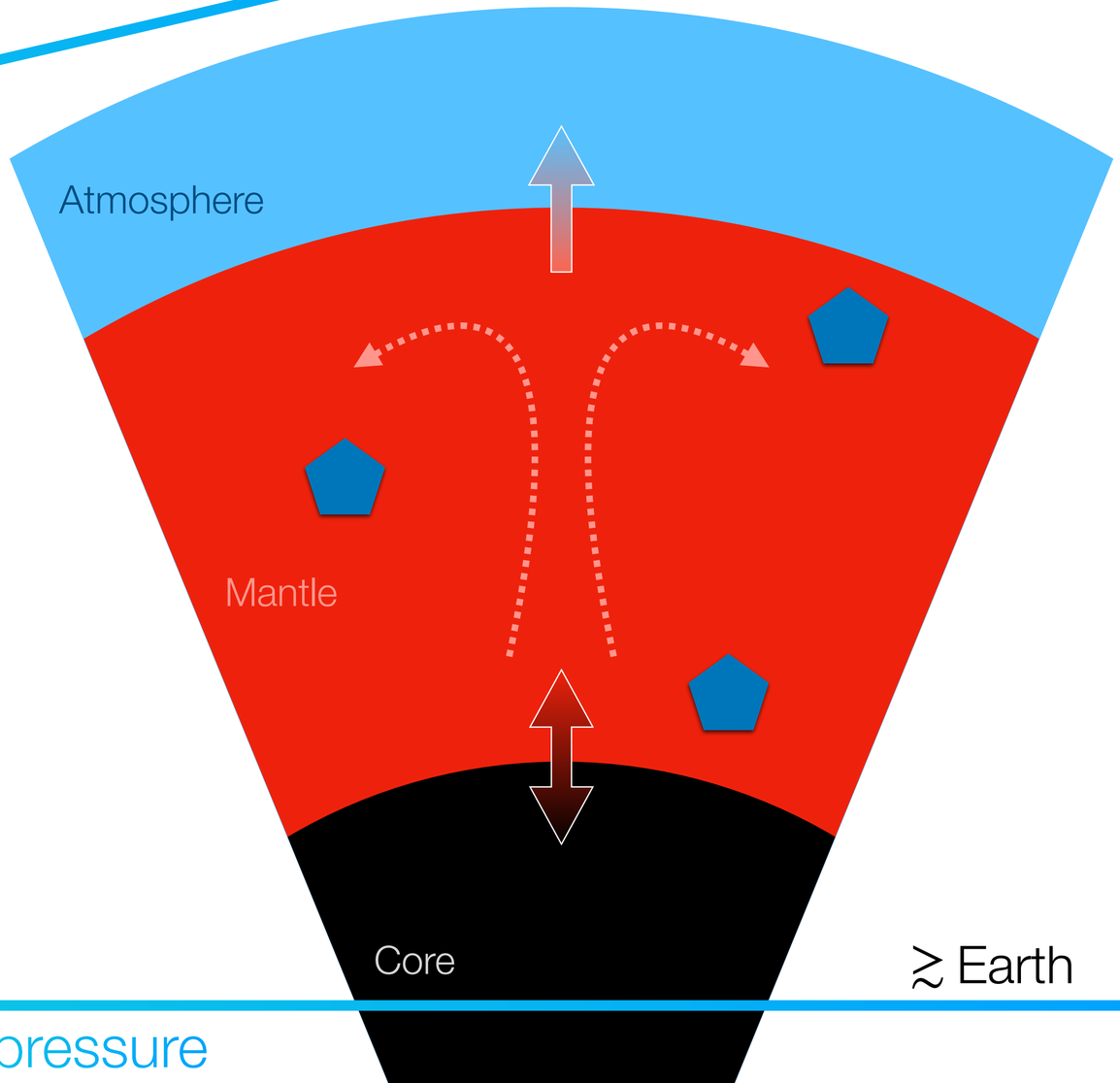
Frost & McCammon 08, Carlson+ 12

Atmosphere composition related to planetary size

Oxidised atmospheres:
H_2O, CO_2, SO_2

Reduced atmospheres:
H_2, CO, CH_4





~Moon

~Mars

$\gtrsim$ Earth

Increasing pressure

Deng+ 20, Grewal+ 20, Gaillard+ 21

Redox alteration requires reservoir mixing

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Frost+ 04, Wade & Wood 05, Frost & McCammon 08, Carlson+ 12

Endogenous water production

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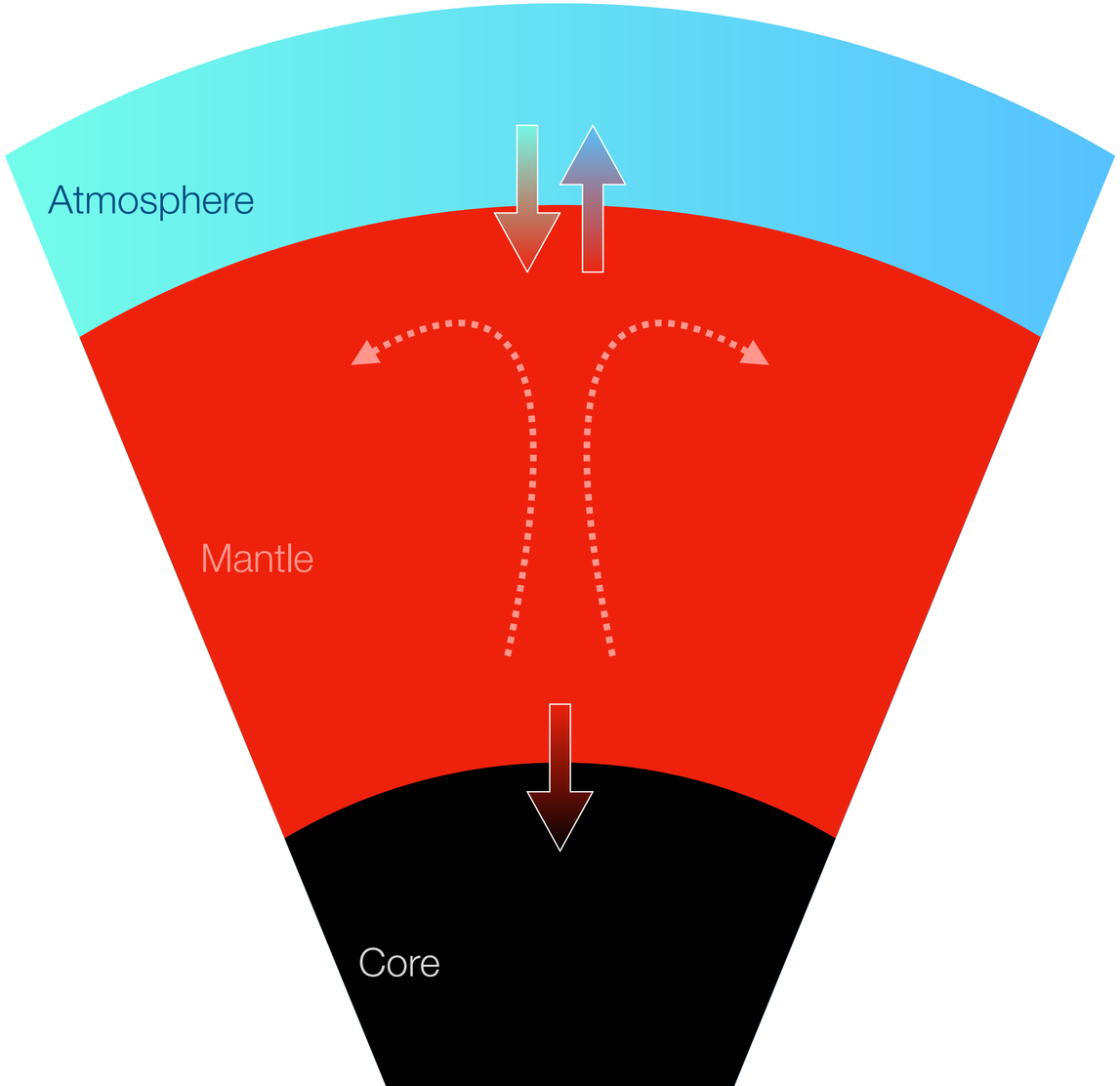
Ikoma & Genda 06, Ikoma+ 18, Olson & Sharp 18, Kite & Schaefer 21

Require:

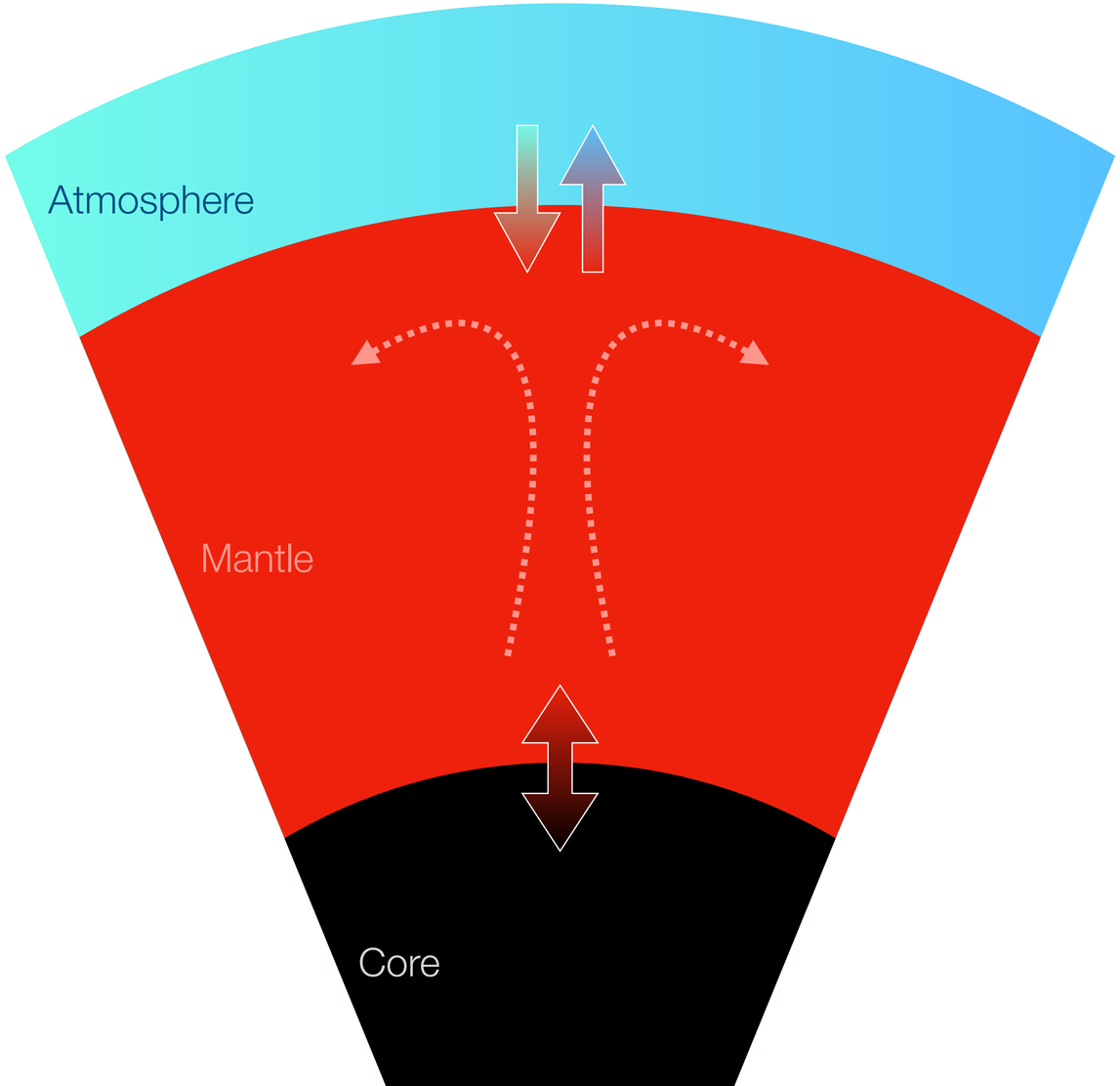
- Mixing: atmosphere-mantle
- Mixing: mantle-core

?



Turbulent convection in sub-Neptunes

$$\mathrm{Ra} = \frac{\alpha \rho g \Delta T D^3}{\kappa \eta}$$



Turbulent convection in sub-Neptunes

Melt density

Thermal gradient

Thermal expansivity

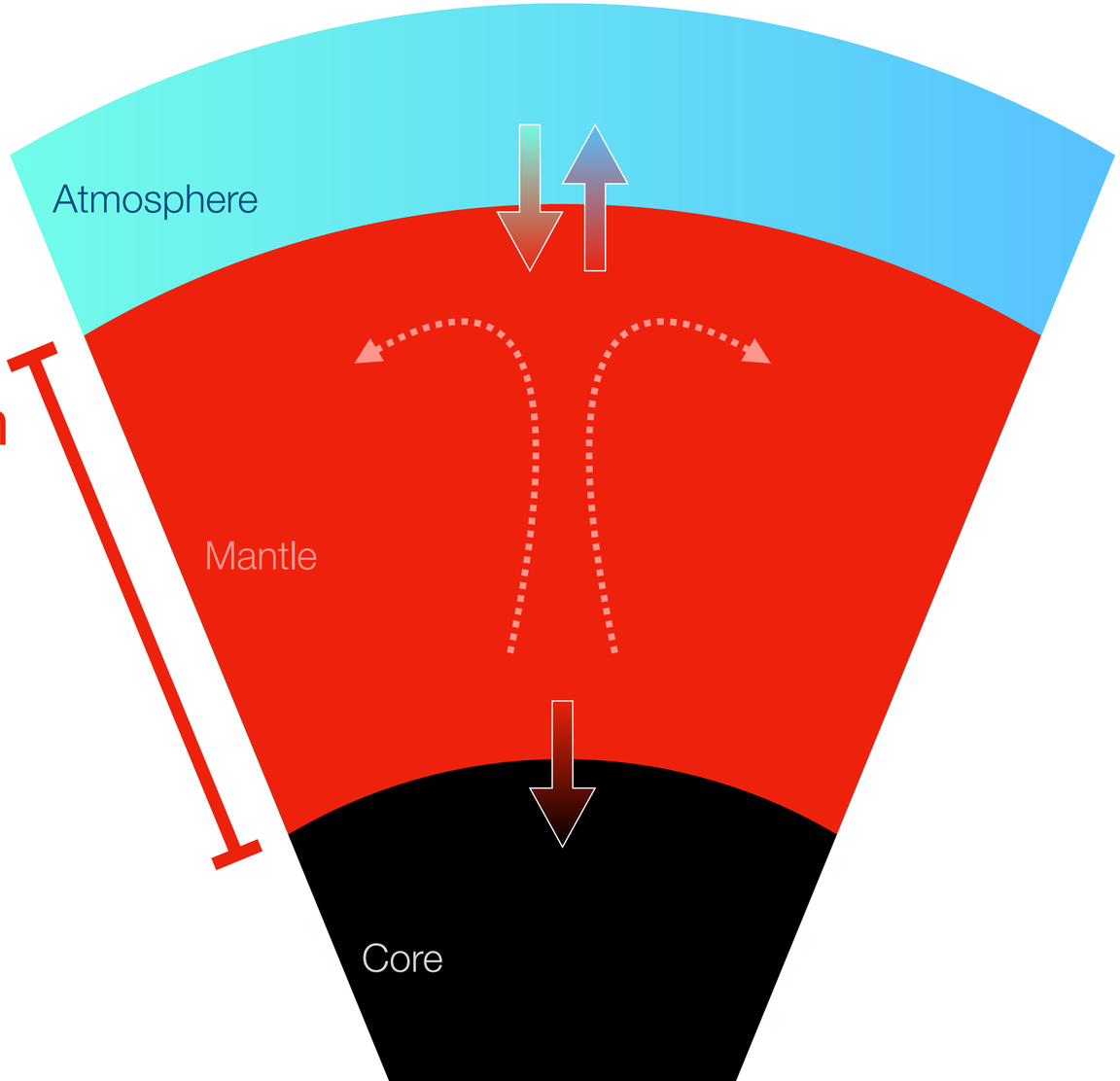
Gravity acceleration

$$\mathrm{Ra} = \frac{\alpha \rho g \Delta T D^3}{\kappa \eta}$$

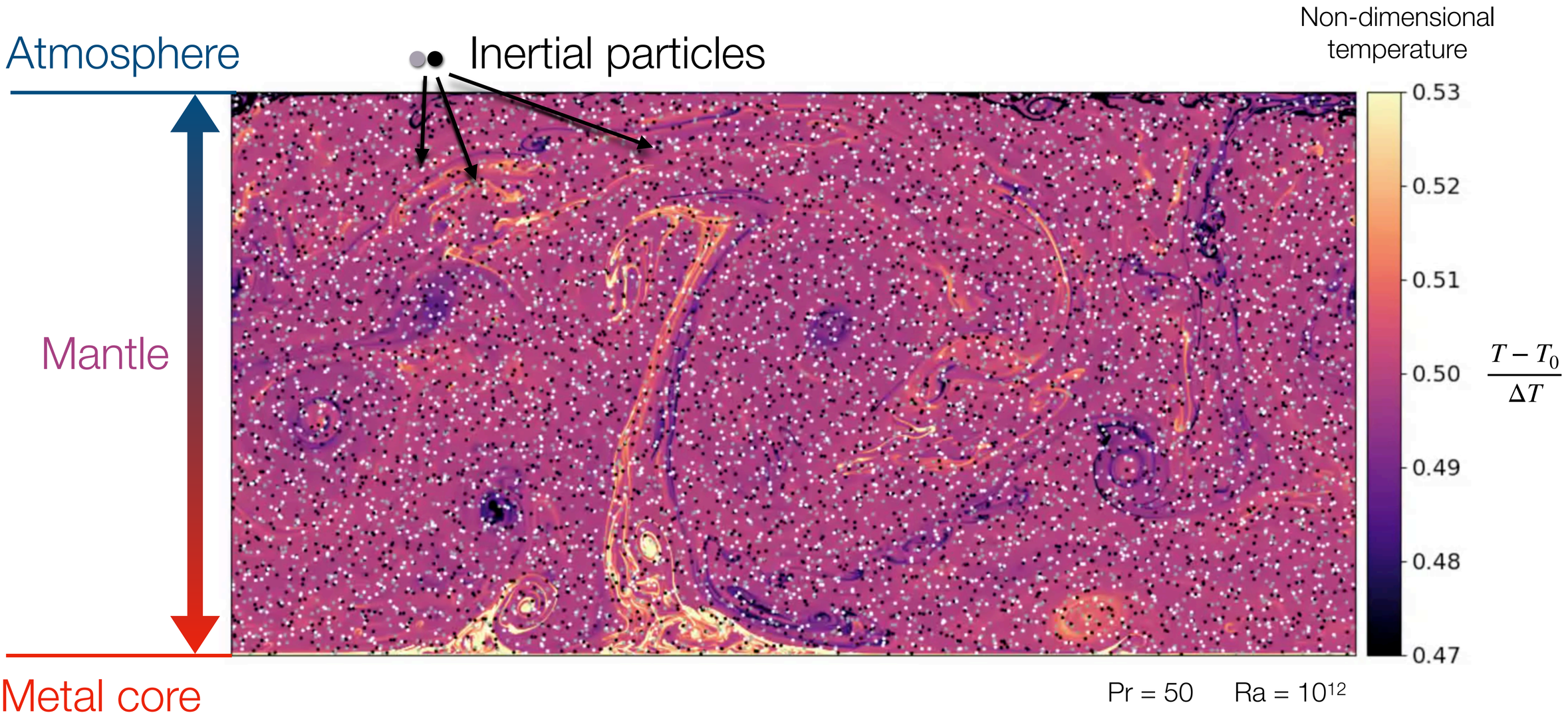
Magma ocean depth

Thermal diffusivity

Melt viscosity



Particle settling in turbulent convection



Patočka+ 20, Phys. Rev. Fluids

Turbulent convection in sub-Neptunes

Expected iron droplet sizes

Surface energy

Weber number

$$d_{\text{droplet}} \approx \frac{\sigma \cdot \text{We}}{\Delta\rho \cdot v_{\text{magma}}^2}$$

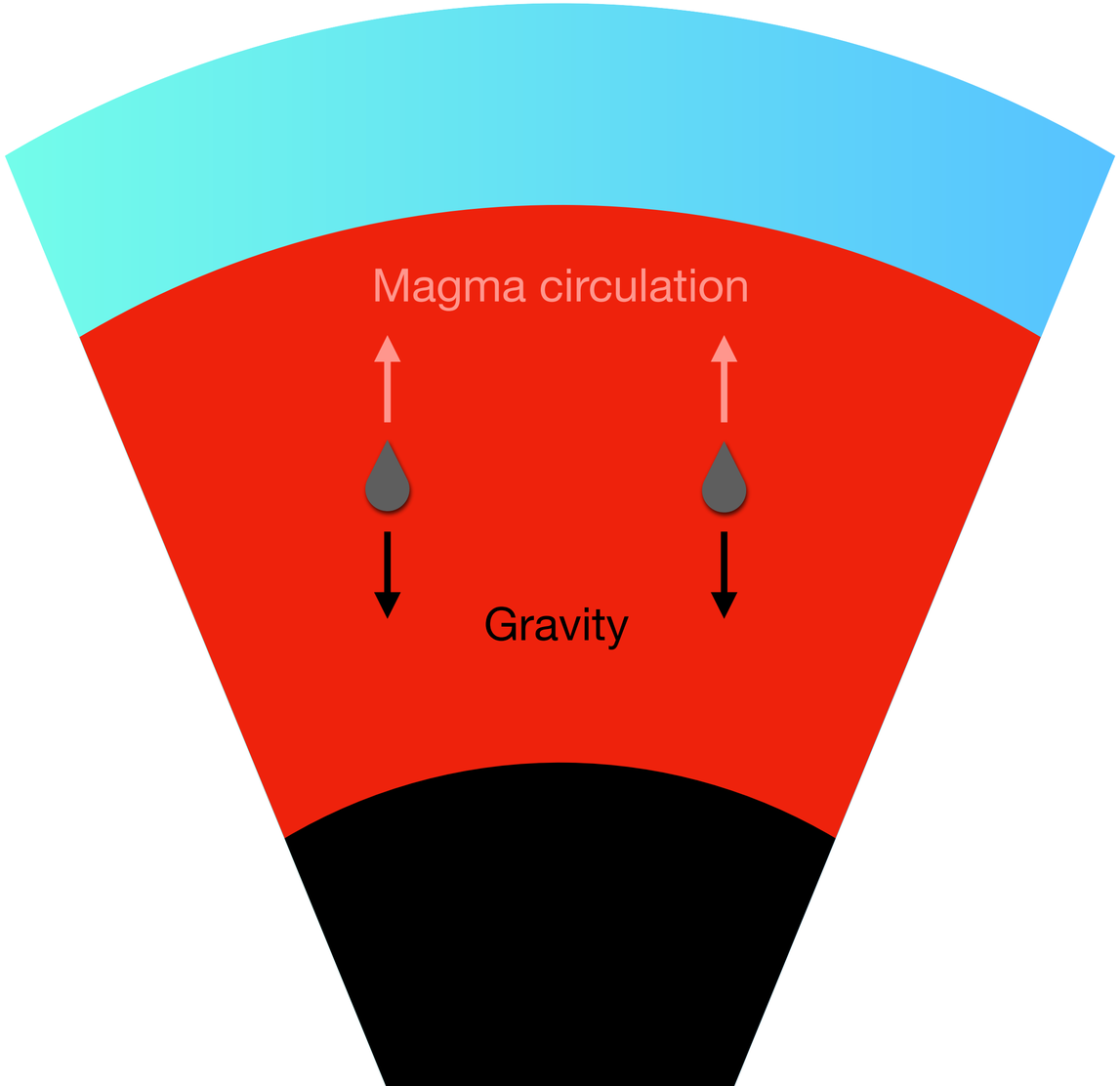
Iron-magma density difference

Fluid velocity

Size threshold for suspension

Magma density

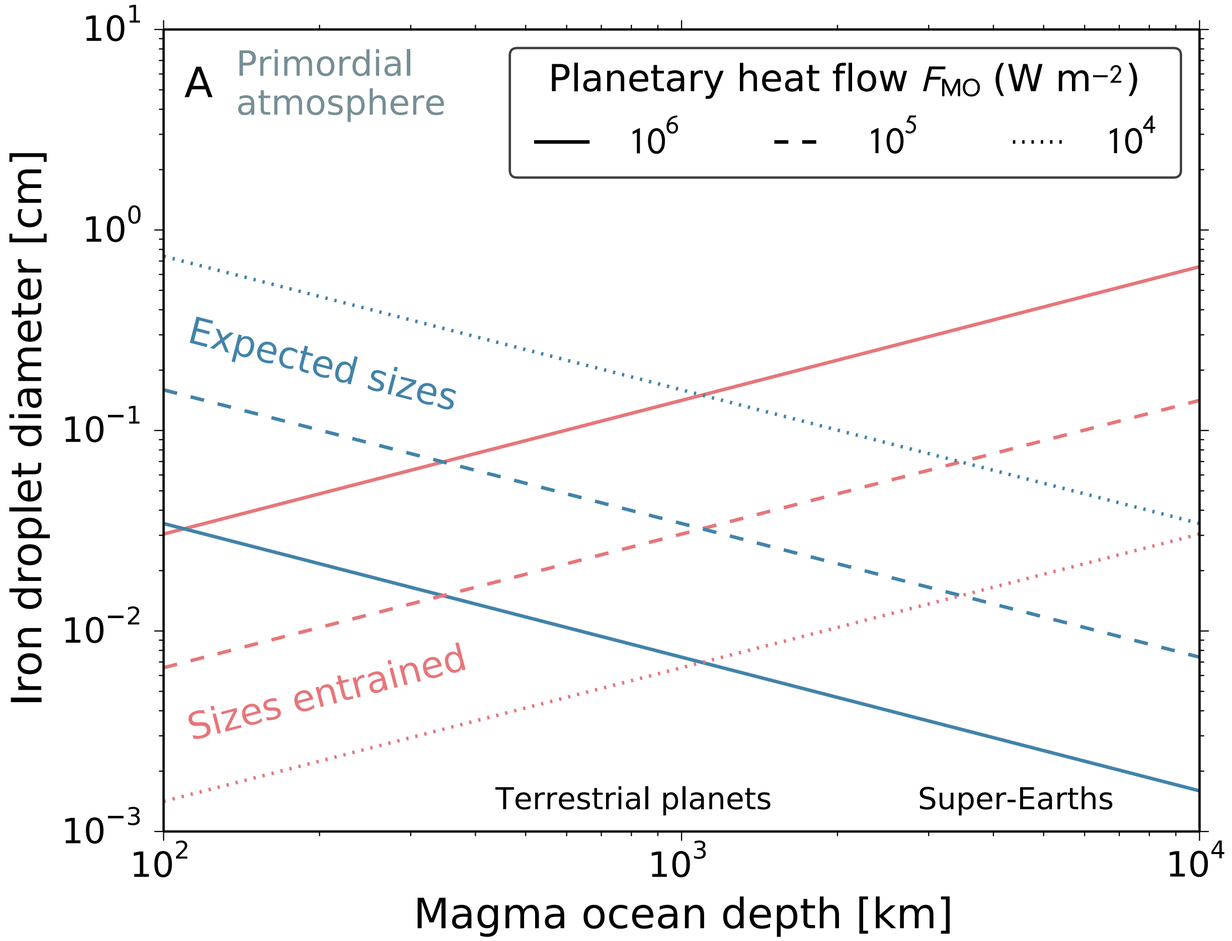
$$d_{\text{crit}} \lesssim \frac{\rho_{\text{magma}} (v_{\text{magma}}/60)^2}{0.1\Delta\rho \cdot g}$$

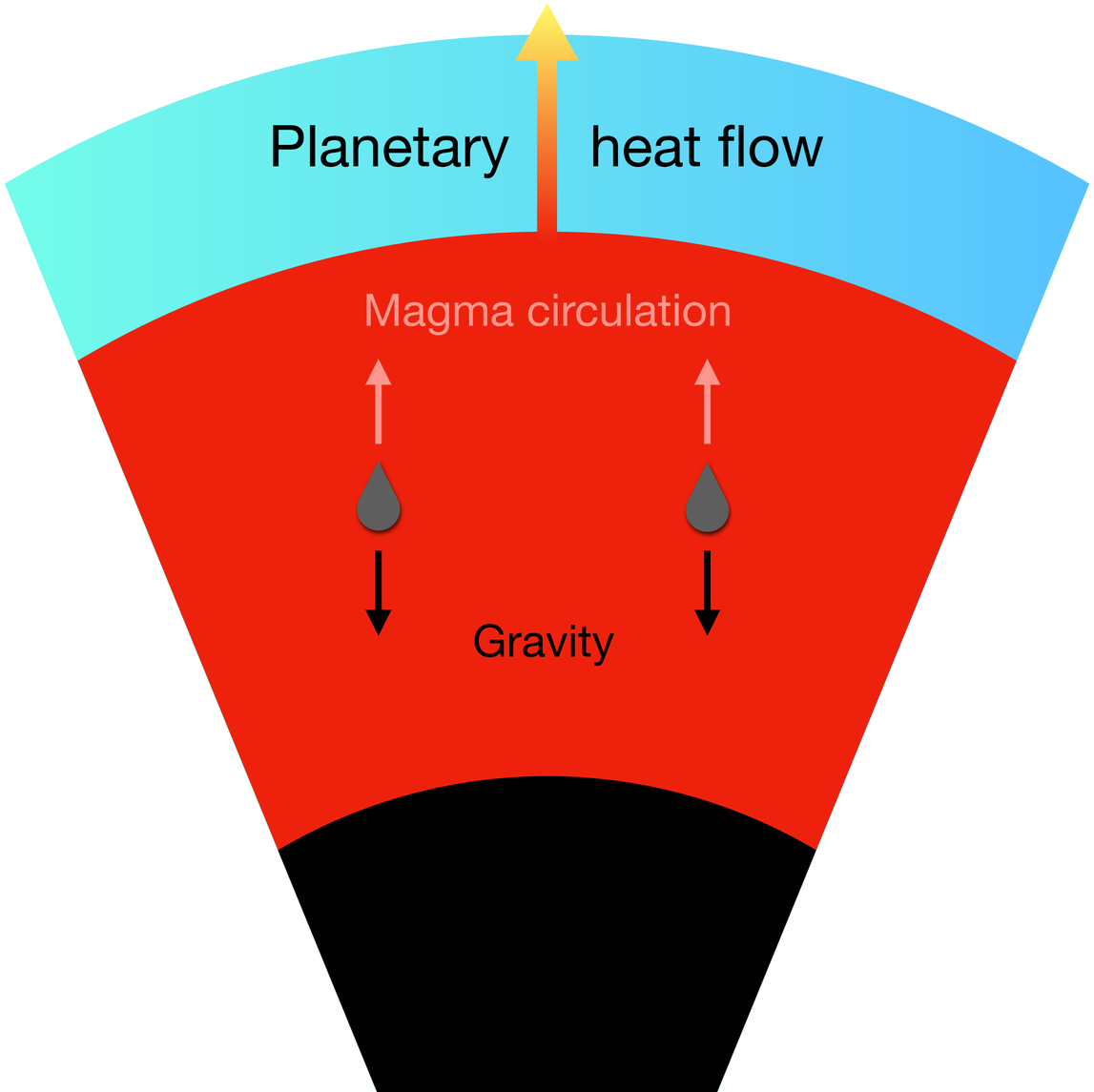


Rubie+ 03, Solomatov 15

Rainout quenching in sub-Neptune interiors

d_{droplet} **vs.** d_{crit}





Lichtenberg, *ApJL 2021*

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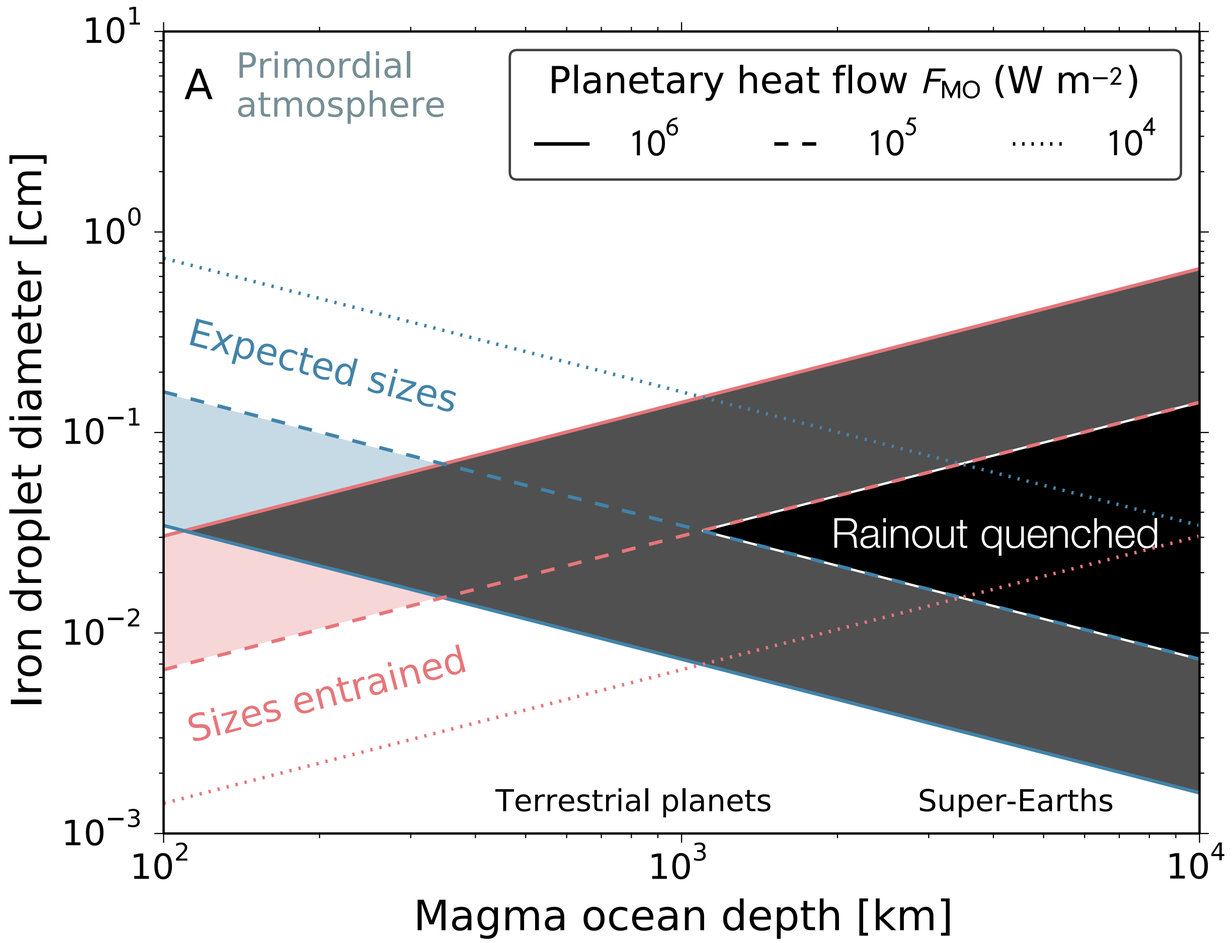
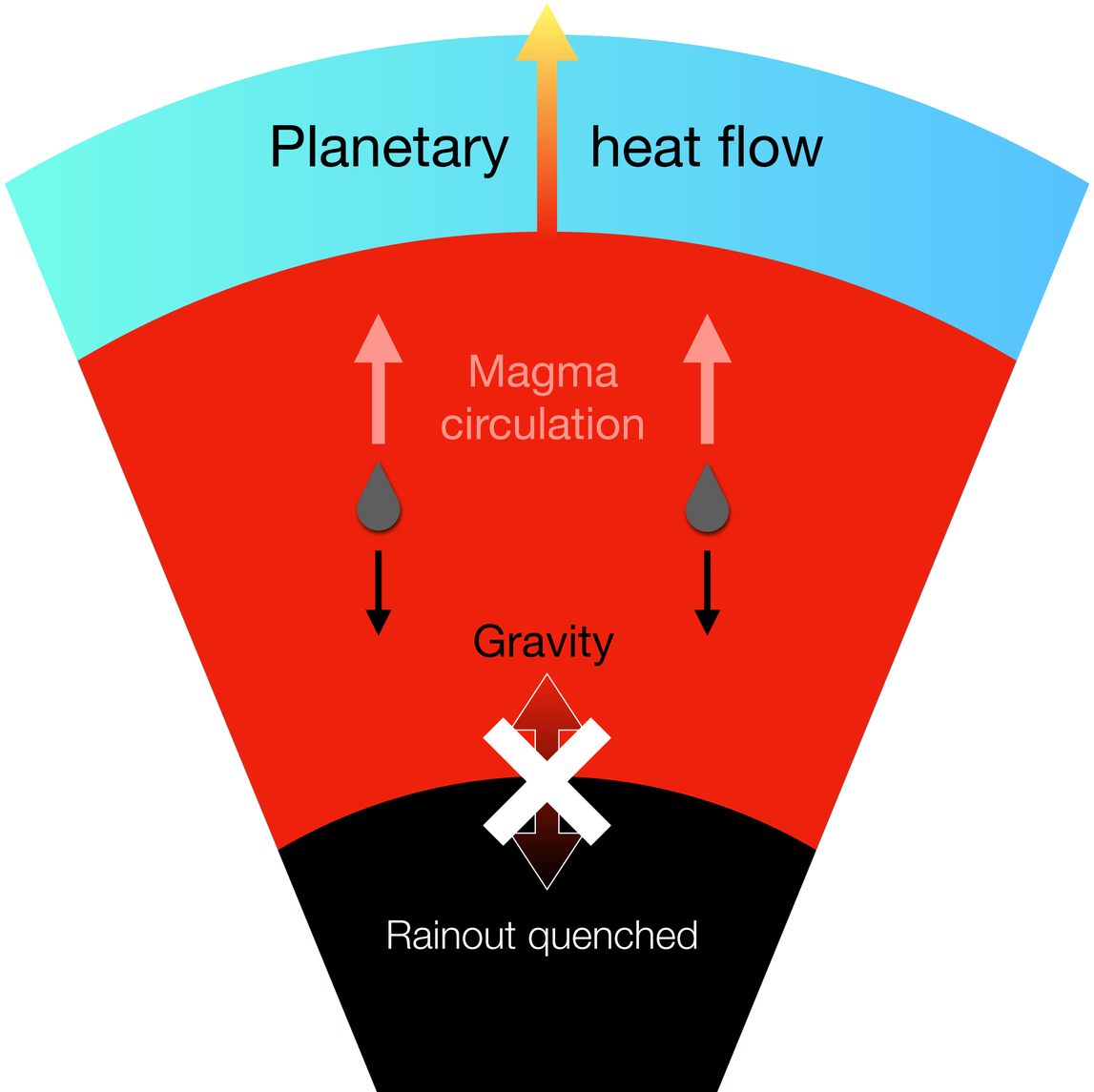
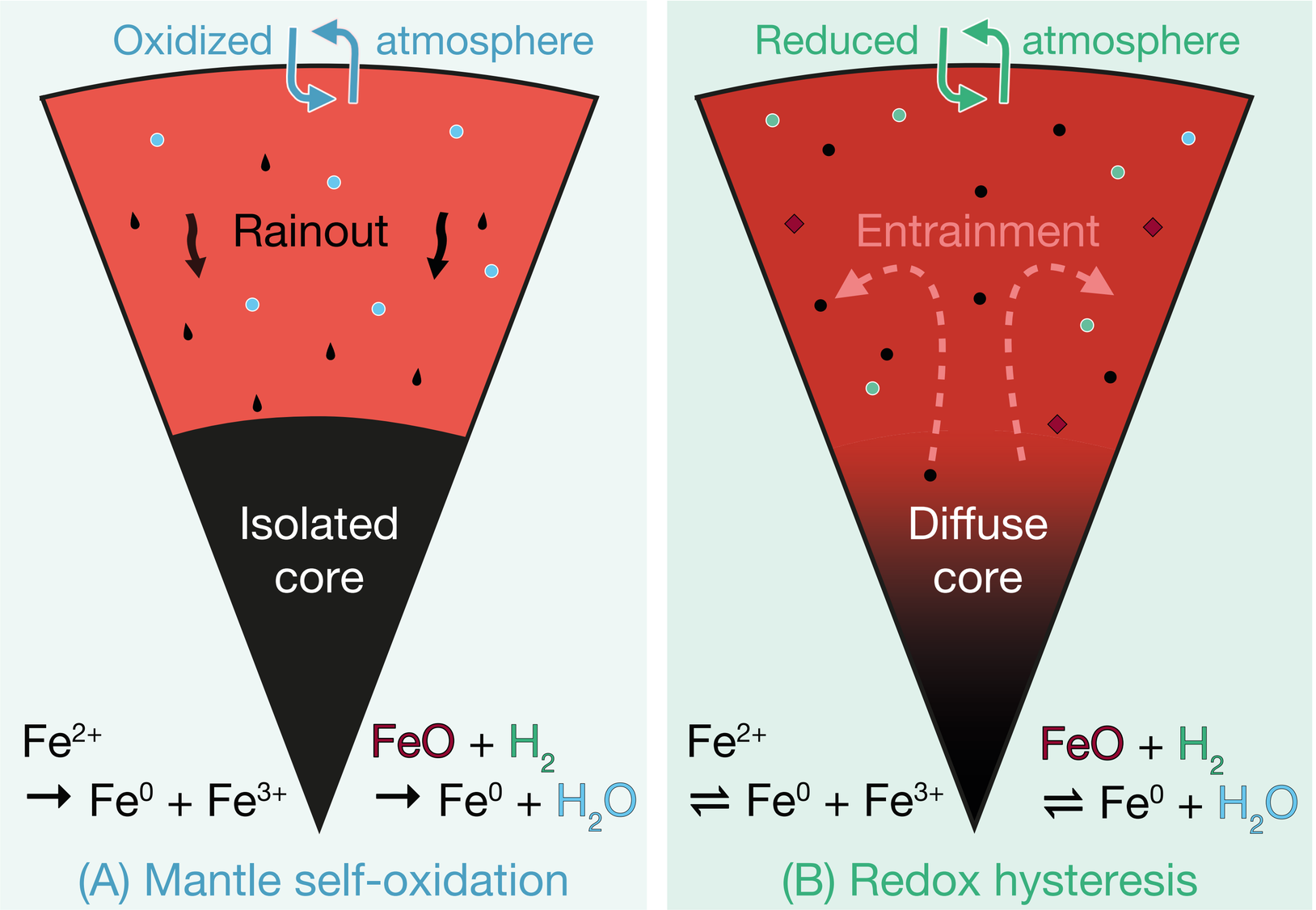




Lichtenberg, *ApJL 2021*

Magma circulation affects *redox balance*



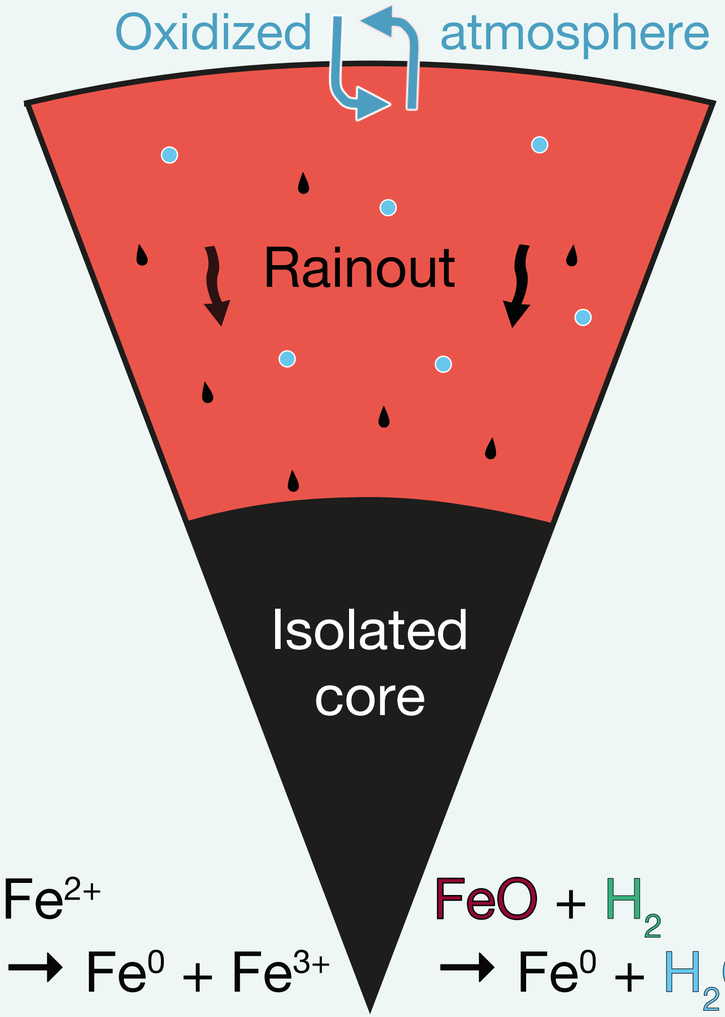
Lichtenberg, *ApJL 2021*

Magma circulation affects *composition*

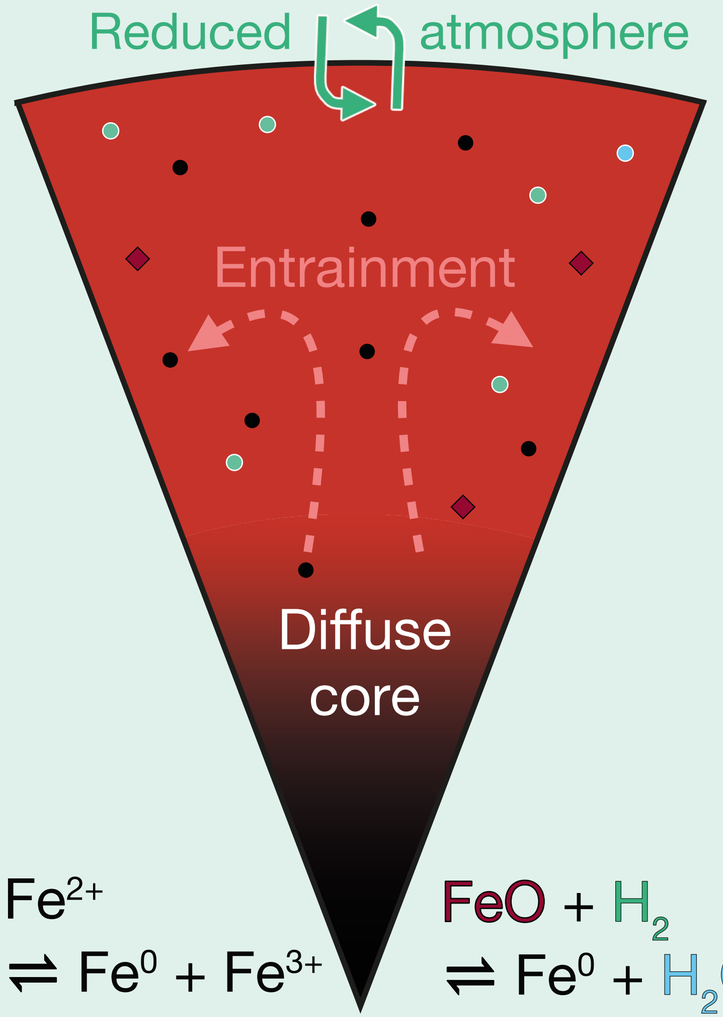
H_2O
CO_2
SO_2

Oxidised surfaces

Prolongs magma ocean phase



(A) Mantle self-oxidation



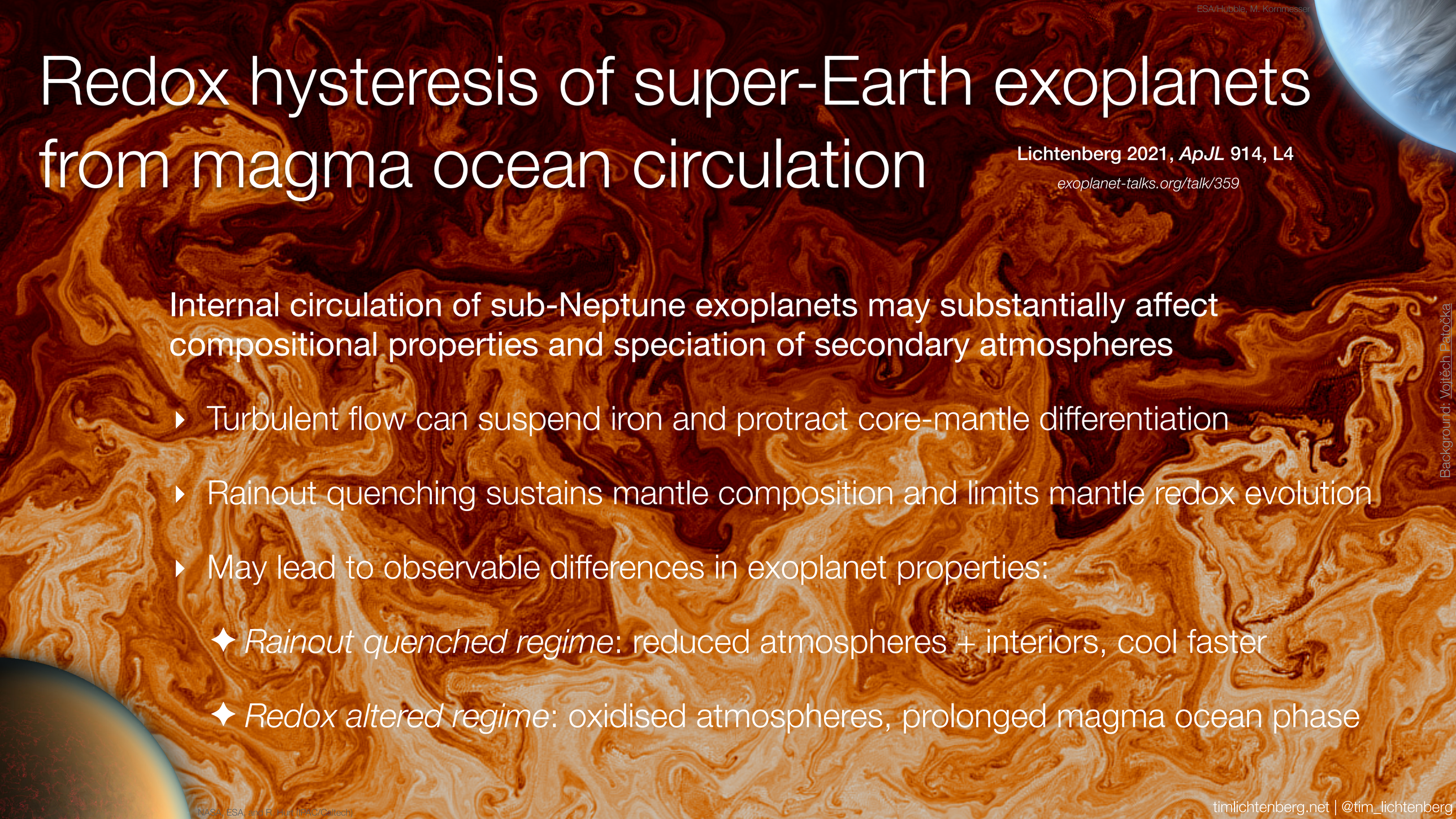
(B) Redox hysteresis

H_2
CO
CH_4

Reduced surfaces

Enhances chances for detection

Lichtenberg, *ApJL 2021*



Redox hysteresis of super-Earth exoplanets from magma ocean circulation

Lichtenberg 2021, *ApJL* 914, L4

exoplanet-talks.org/talk/359

Internal circulation of sub-Neptune exoplanets may substantially affect compositional properties and speciation of secondary atmospheres

- Turbulent flow can suspend iron and protract core-mantle differentiation
- Rainout quenching sustains mantle composition and limits mantle redox evolution
- May lead to observable differences in exoplanet properties:
  - ✦ *Rainout quenched regime*: reduced atmospheres + interiors, cool faster
  - ✦ *Redox altered regime*: oxidised atmospheres, prolonged magma ocean phase