

Water oceans on dense exoplanets from outgassing and interior-atmosphere feedback processes

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The search for habitable planets



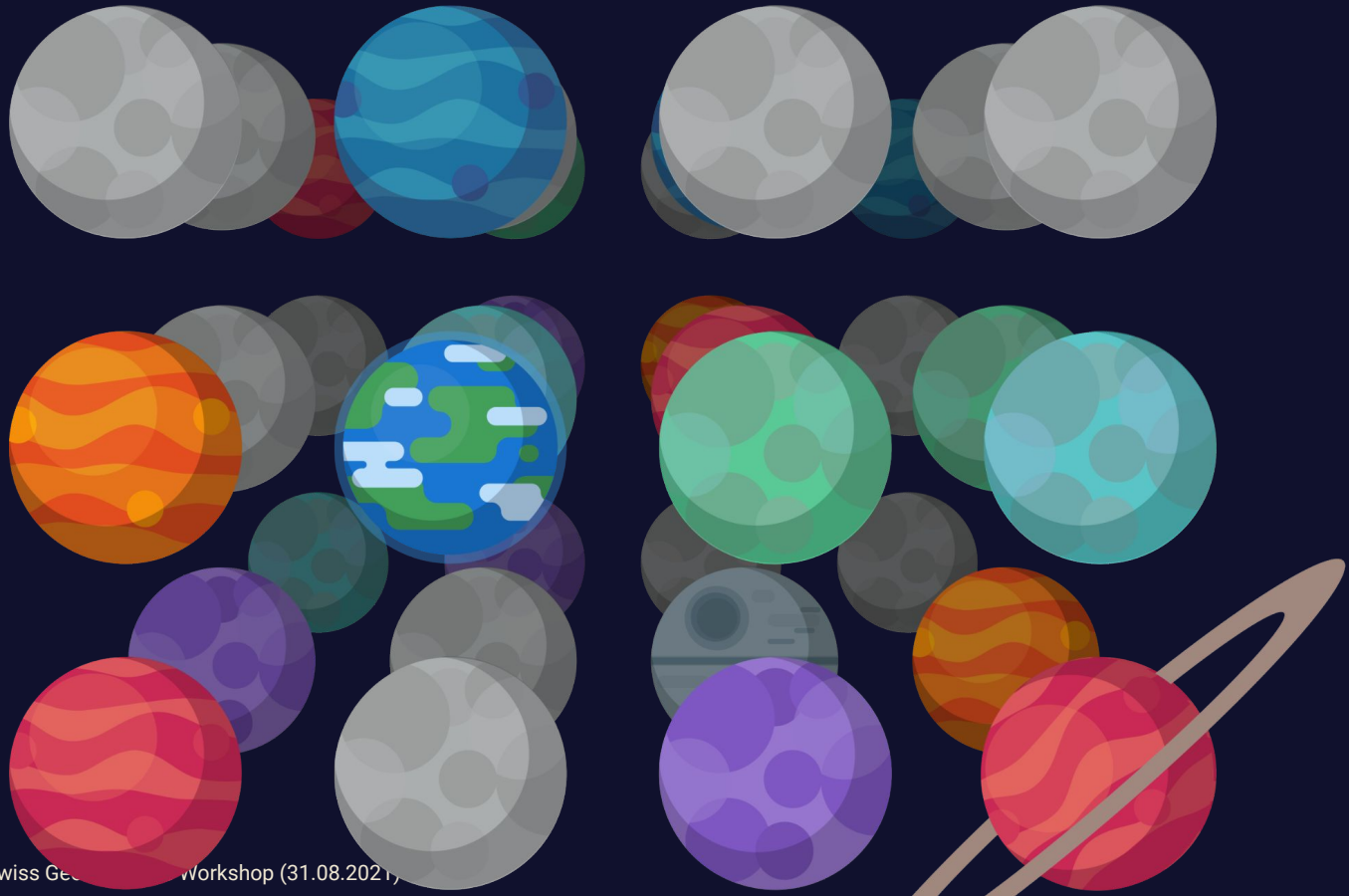
The search for habitable planets

**Atmosphere
measurements can only
give indirect evidence**

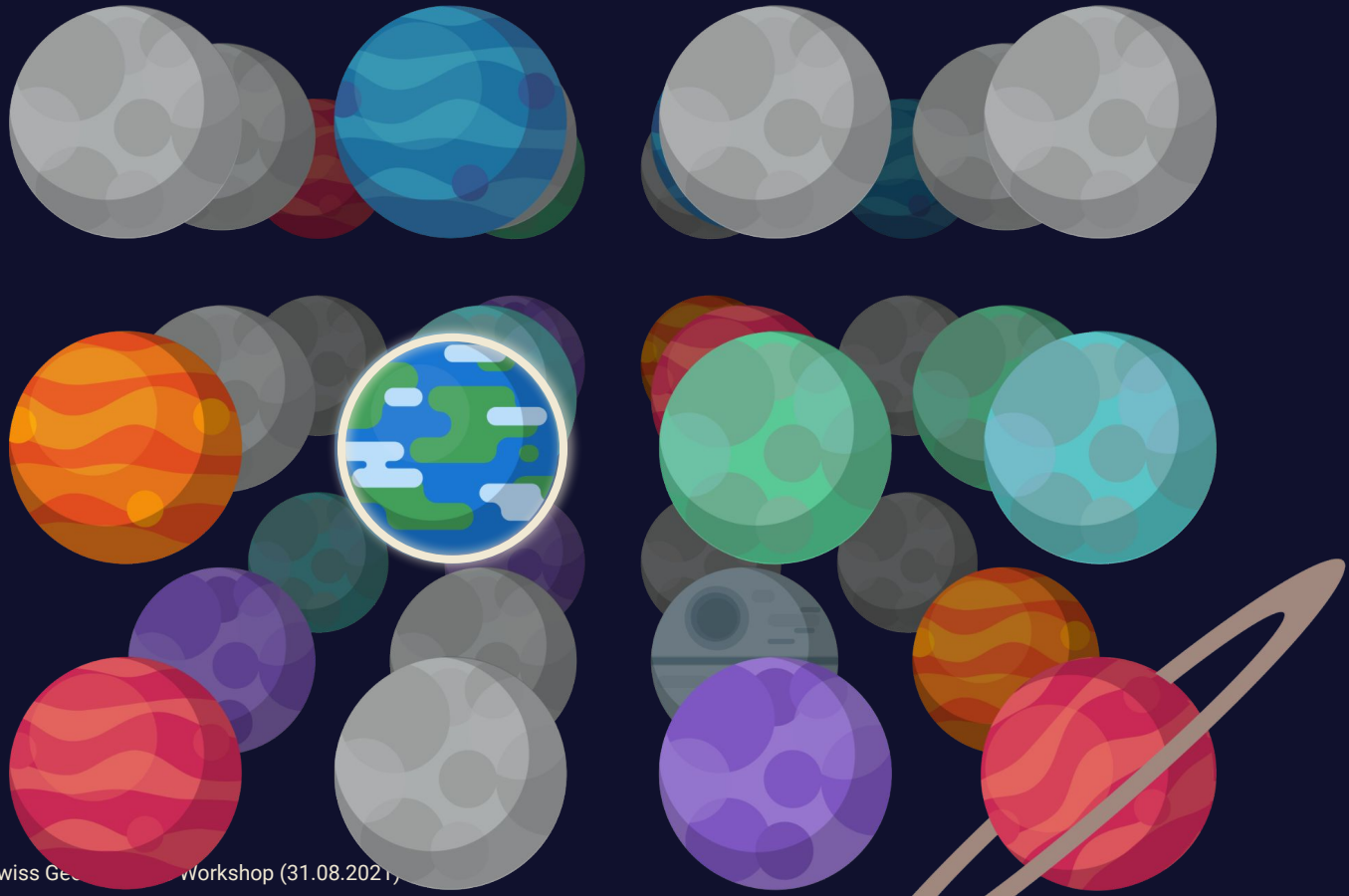


**Direct detection of an ocean
is extremely challenging**

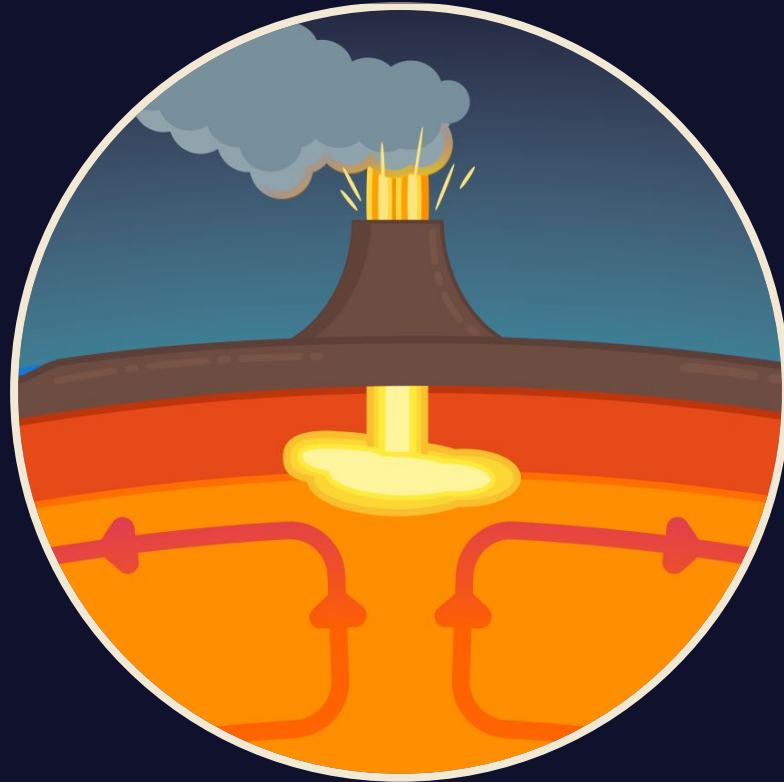
Which planets *can* have oceans?



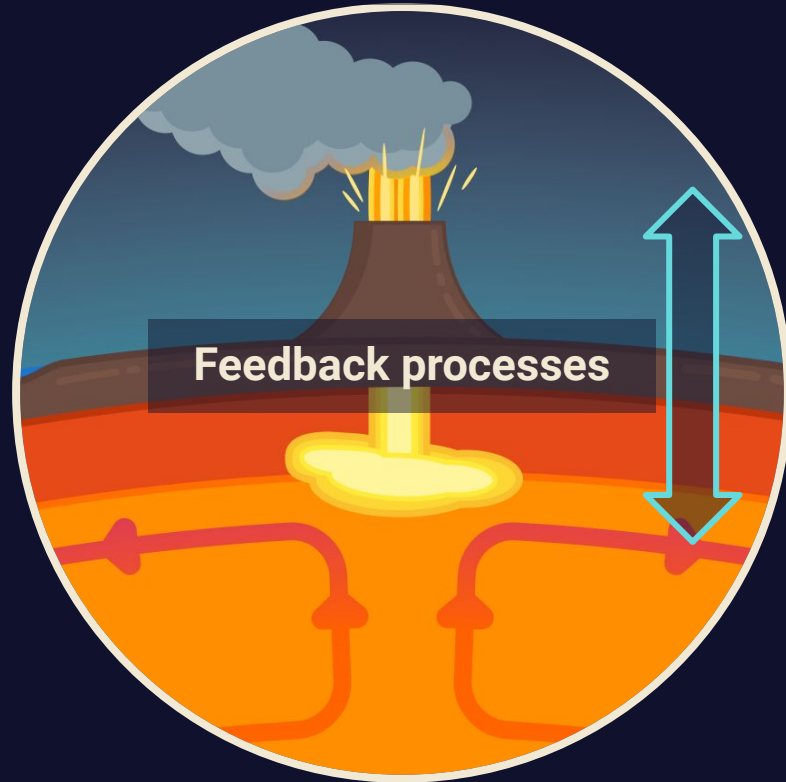
Which planets *can* have oceans?



The planet interior is a major source of water



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Water feedback mechanisms

Outgassing of water only possible at *low atmospheric pressures*

Water is a potent greenhouse gas, controlling *surface temperature*

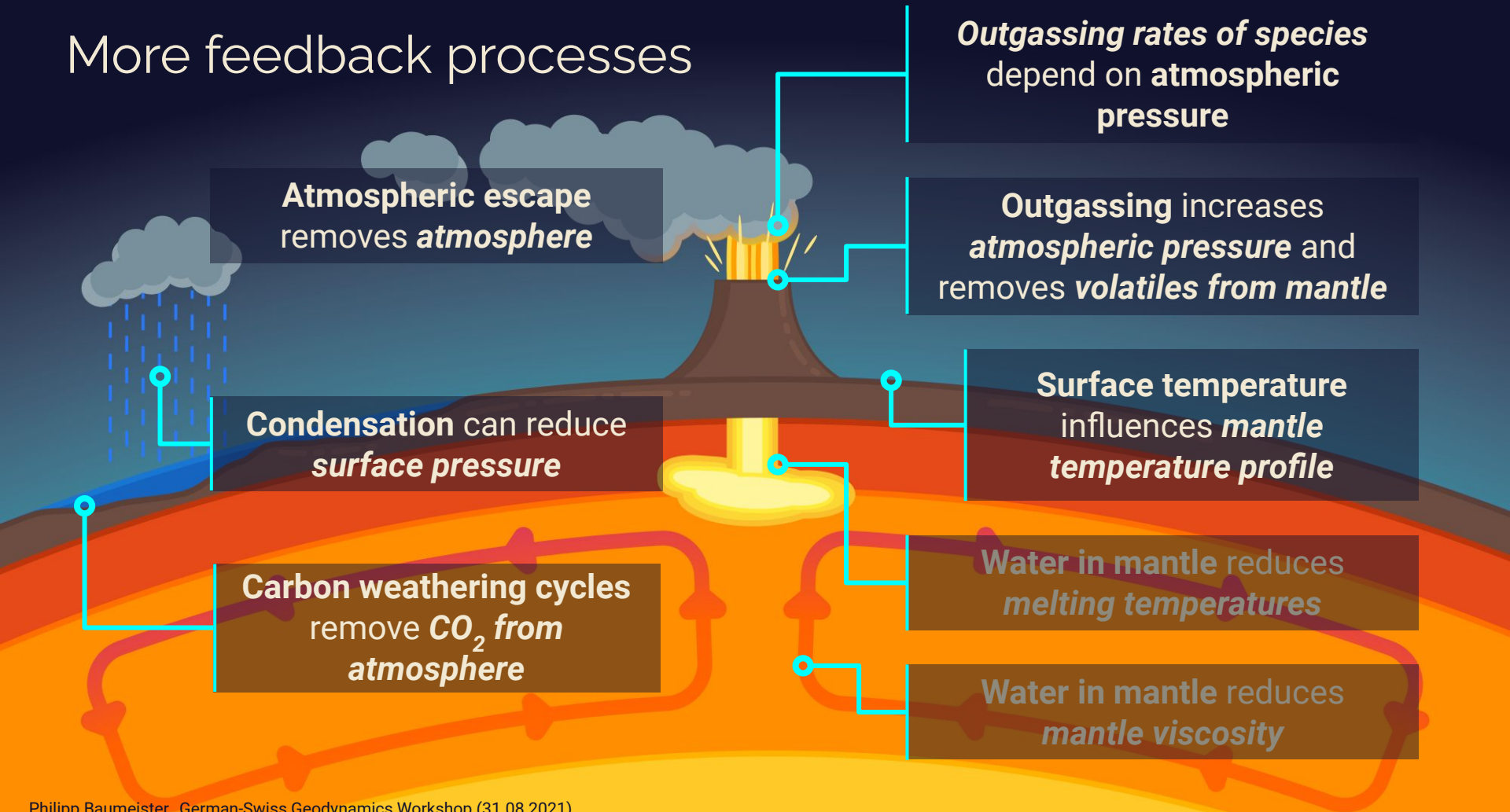
Condensation builds up oceans

Weathering cycles depend on liquid water

Water in mantle reduces *melting temperatures*

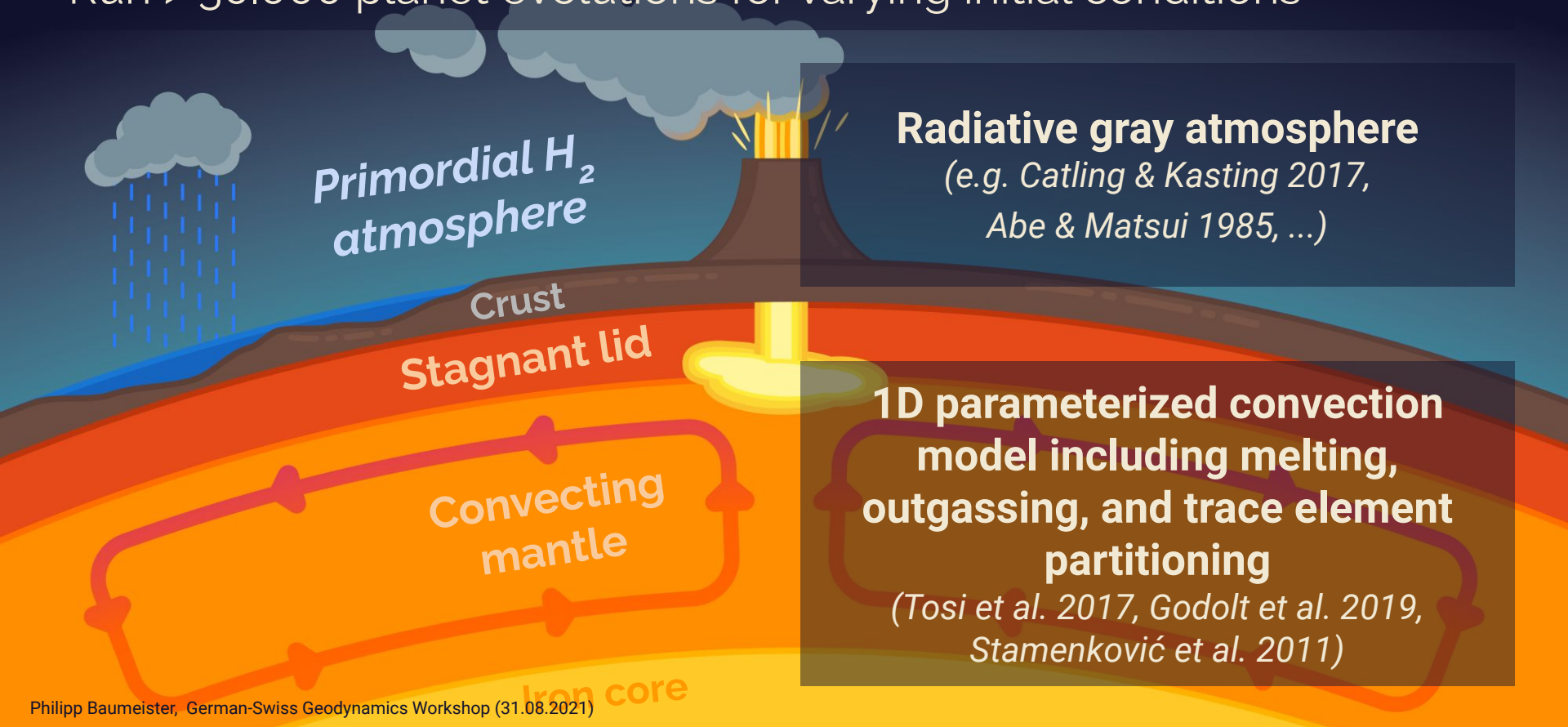
Water in mantle reduces *mantle viscosity*

More feedback processes



Our modeling approach:

Run > 30.000 planet evolutions for varying initial conditions



Primordial H₂
atmosphere

Radiative gray atmosphere

(e.g. Catling & Kasting 2017,
Abe & Matsui 1985, ...)

Crust
Stagnant lid

Convecting
mantle

**1D parameterized convection
model including melting,
outgassing, and trace element
partitioning**

(Tosi et al. 2017, Godolt et al. 2019,
Stamenković et al. 2011)

Our modeling approach:

Outgassing of H_2O and CO_2
(Tosi et al. 2017)

Grey atmosphere model for
surface temperature
(e.g. Abe & Matsui 1985)

Water condensation
(from vapour pressure)

Stagnant lid carbon cycle
(Höning et al. 2019)

H_2 escape

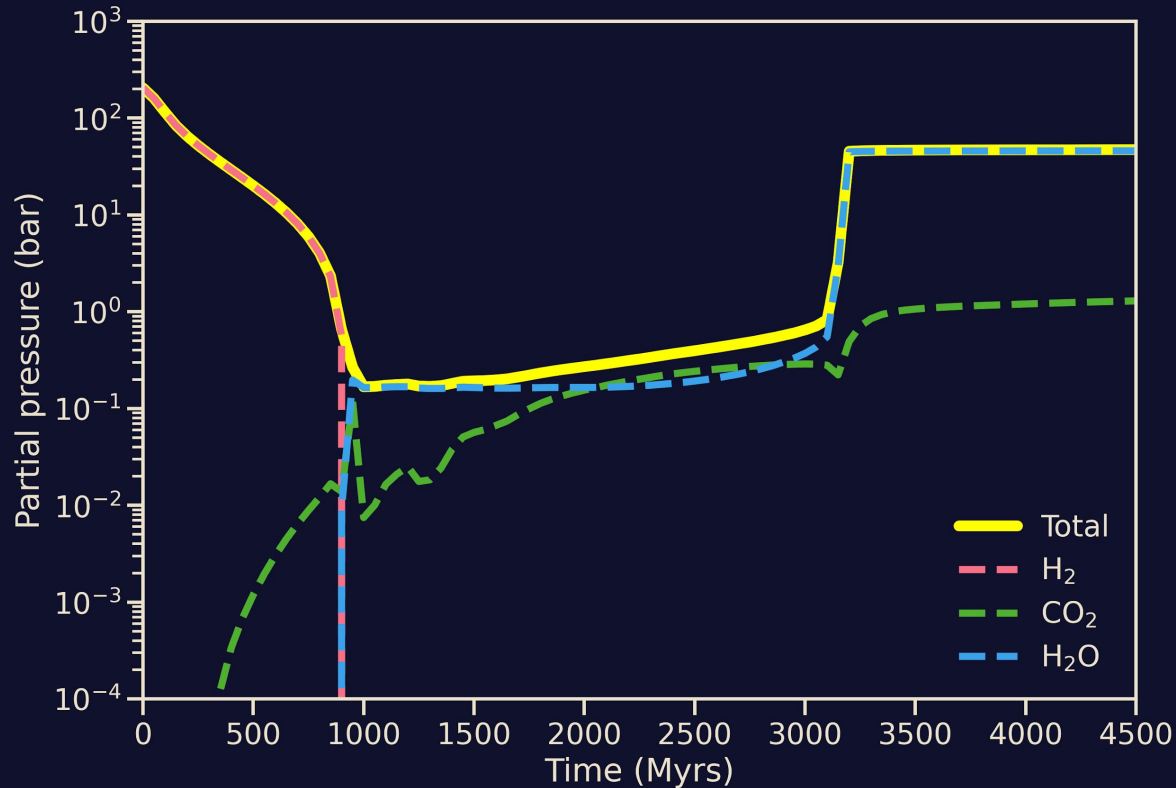
(Katyal et al. 2019, Owen & Wu
2017)

**Stellar luminosity and F_{XUV}
evolution**
(Gough 1981, Owen & Wu 2017)

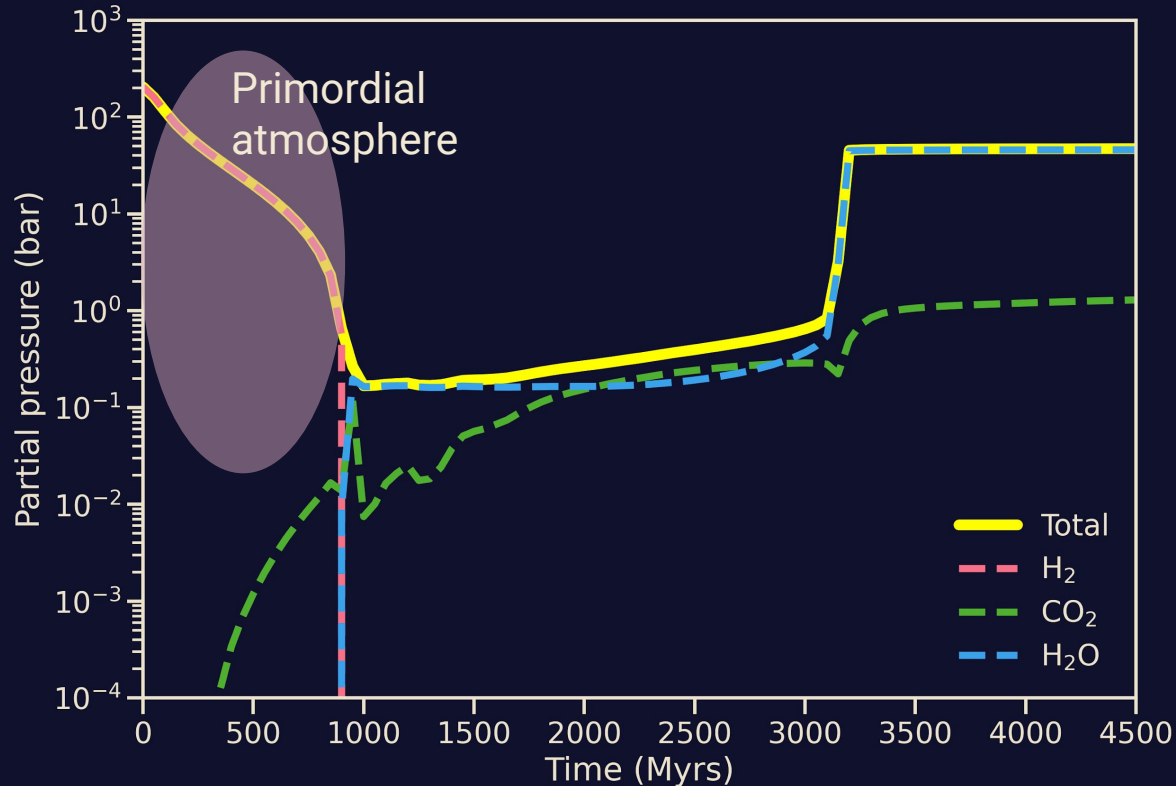
**Melting and trace element
partitioning**
(Tosi et al. 2017)

1D parametrized convection
(Tosi et al. 2017,
Stamenković et al. 2012)

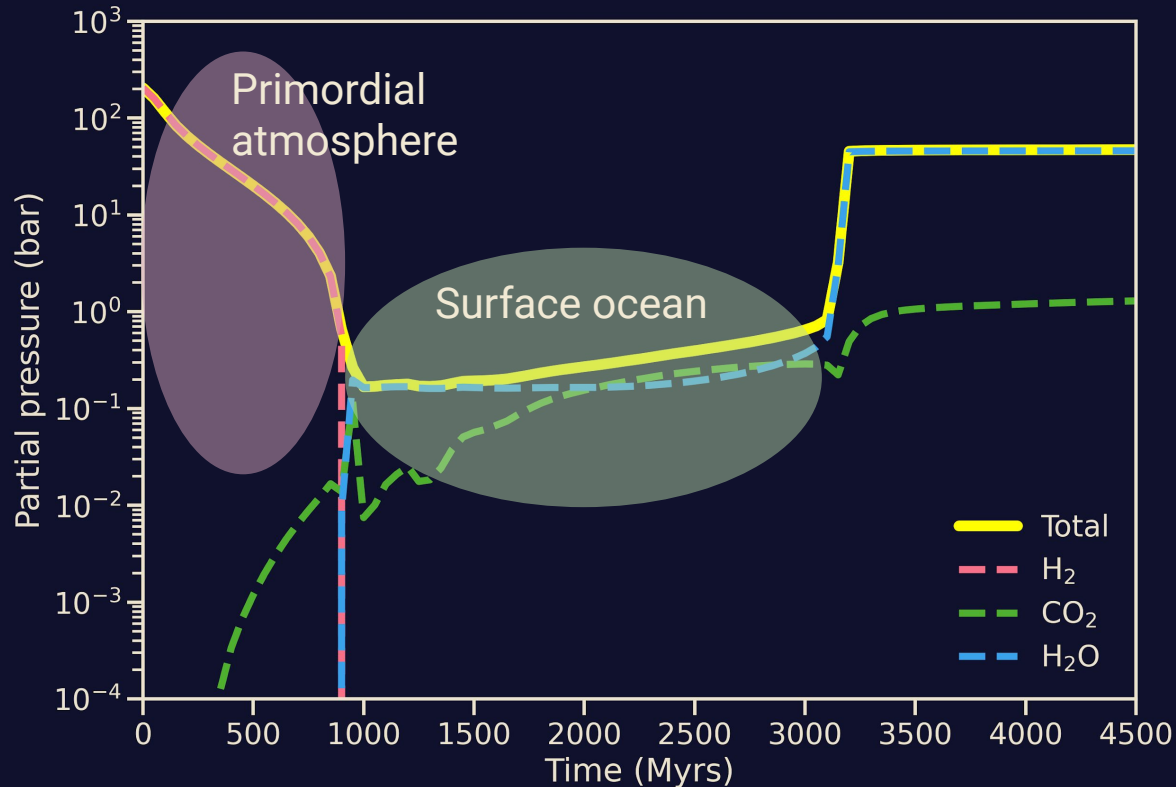
Characteristic outgassing evolution



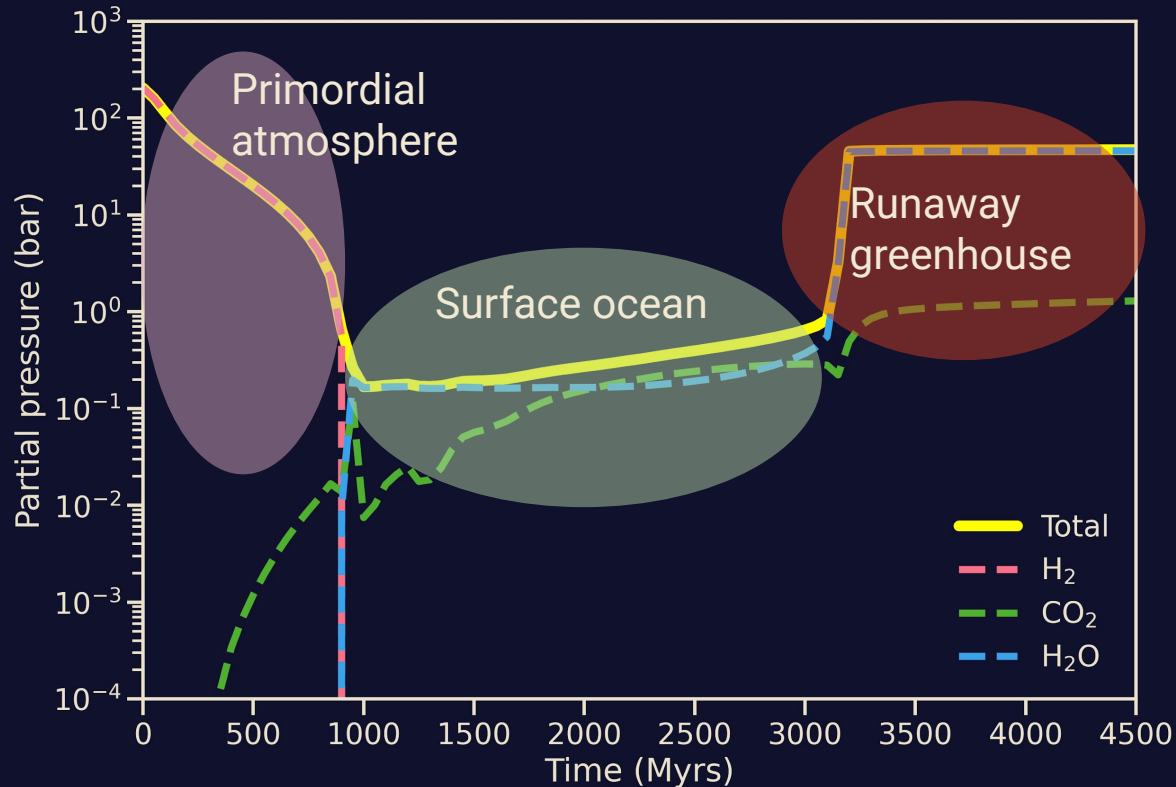
Characteristic outgassing evolution



Characteristic outgassing evolution



Characteristic outgassing evolution



Investigated parameters

Evolution time t
(8 Gyrs)

Initial surface pressure P_0
(0 - 500 bar)

Primordial H_2
atmosphere

Orbital distance
(G type star)
(0.3 - 2 au)



Mantle water
concentration X_{H_2O}
(100 - 1000 ppm)

Mantle redox state
(oxygen fugacity f_{O_2})
(IW-1 - IW+1)

Planet mass
(0.5 - 5 M_J)

Iron core size
(20% - 80%)

Investigated parameters

Initial surface pressure P_0
(0 - 500 bar)

Evolution time t
(0 Gyrs)

Orbital distance
(G type star)
(0.3 - 2 au)

We ran 30.000 planet evolutions for randomly chosen parameters, then selected snapshots at random ages

Mantle iron concentration X_{Fe}
(100 - 1000 ppm)

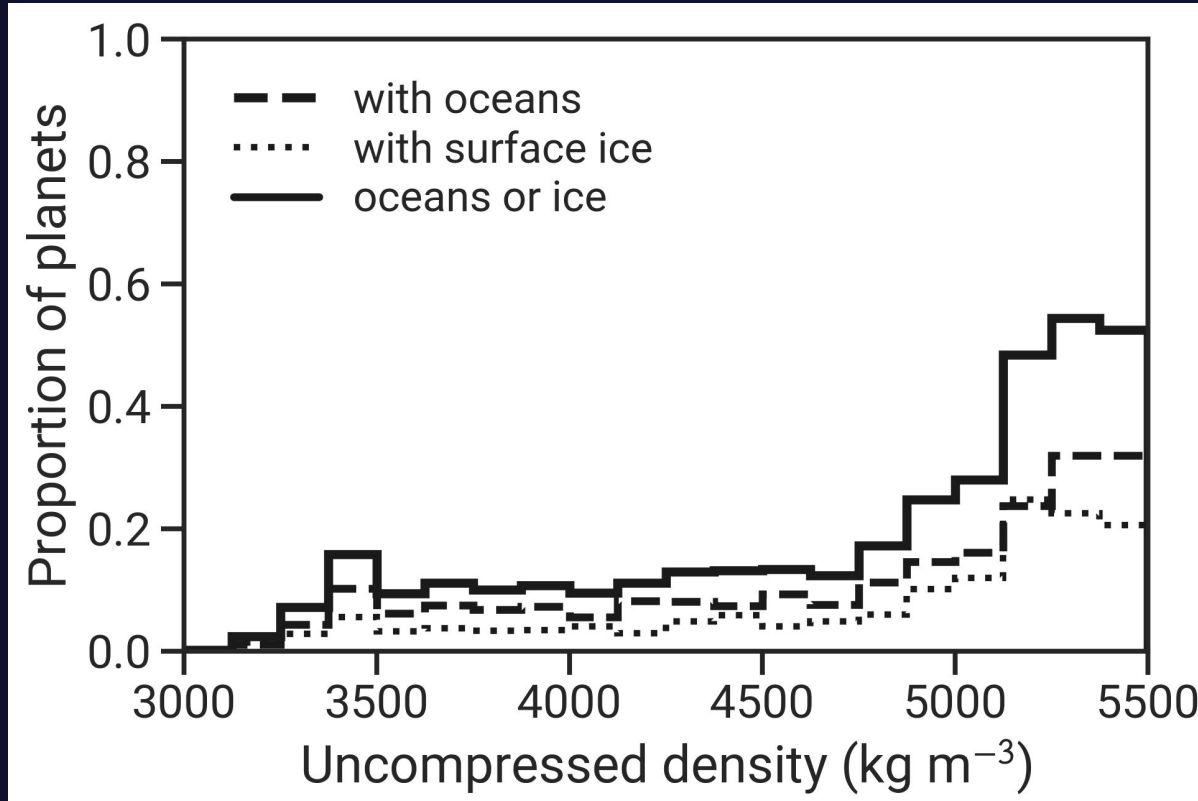
Mantle redox state
(oxygen fugacity f_{O_2})
(10^{-1} - 10^{+1})

Planet mass
(0.5 - 3 M_J)

Iron core size
(20% - 80%)

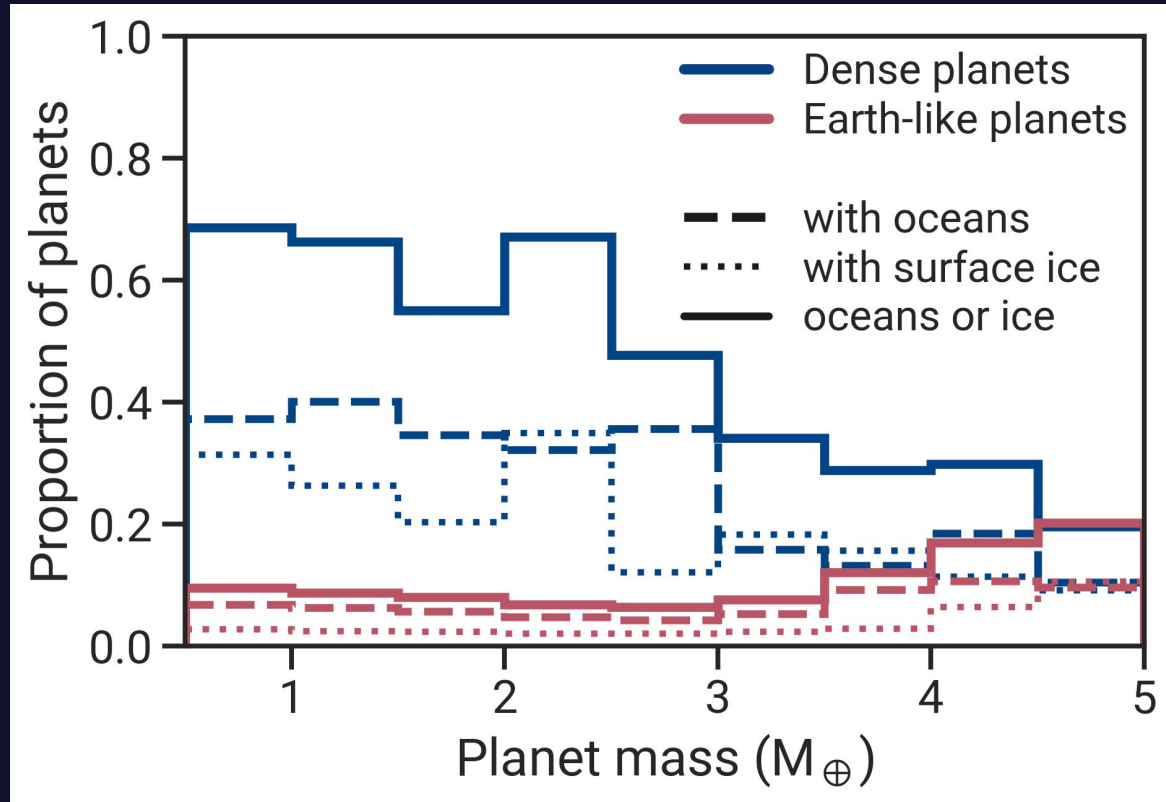
Most dense planets have oceans ...

Baumeister et al. 2021,
under review.



...especially at low masses

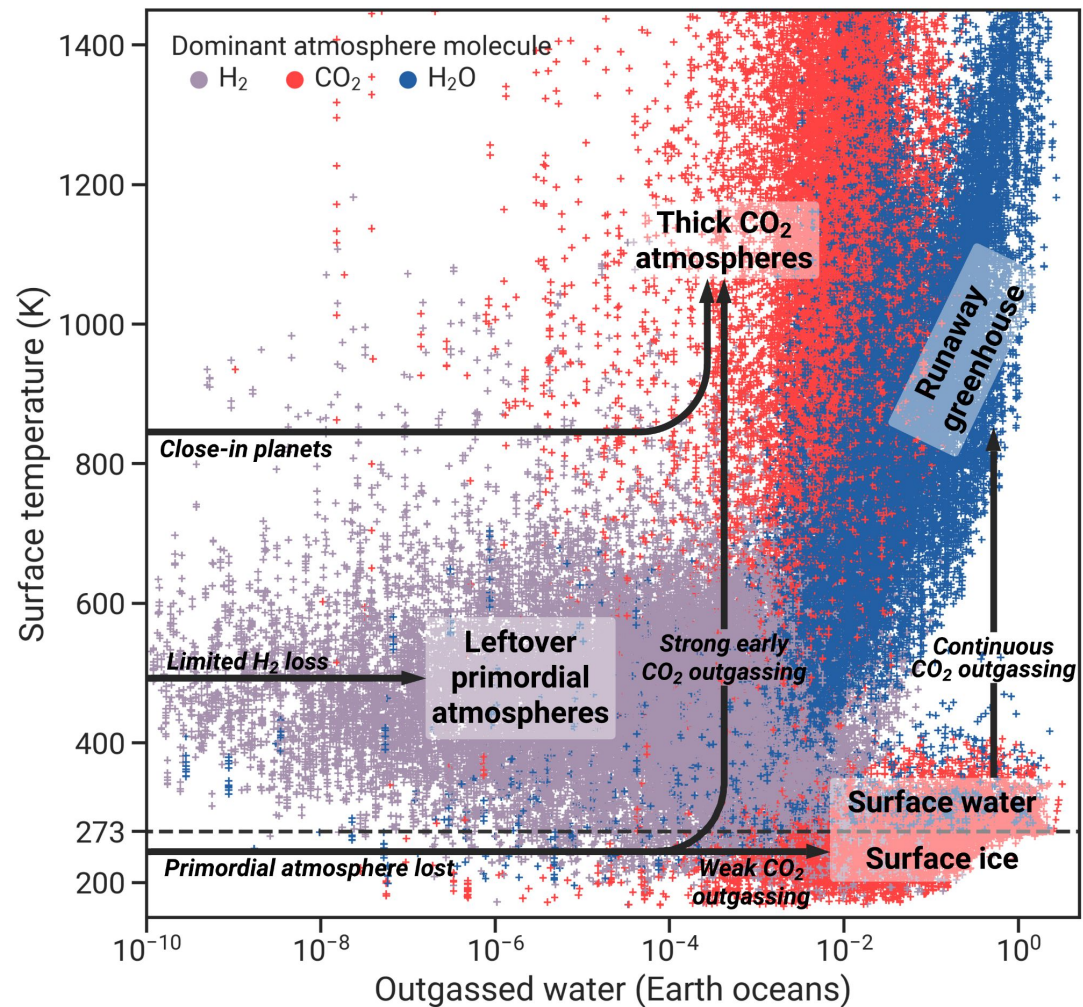
Baumeister et al. 2021,
under review.

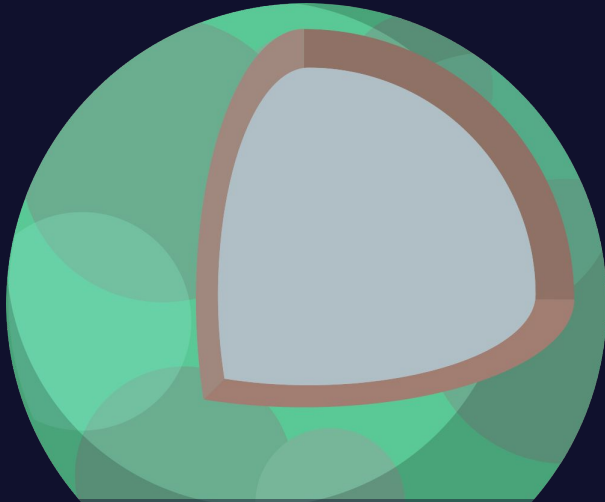


CO₂ outgassing rate determines ocean evolution

- Stagnant-lid planets lack efficient process for long-term CO₂ removal
- For water outgassing, surface pressure needs to be low
- For surface water, CO₂ outgassing needs to be low
- Otherwise: Runaway greenhouse

Baumeister et al. 2021,
under review.





- **Less volcanic activity due to large pressure gradients**
(see also e.g. Noack et al. 2017)
- **Faster mantle cooling**
- **Water outgassing is favoured**



- **Long-lived, stronger volcanic activity**
- **CO₂ outgassing is favoured**



Dense planets planets may offer a better chance at detecting an ocean than Earth-like planets

Conclusions

- A majority of high-density planets have water oceans/surface water
- Rate of CO₂ outgassing drives the coupled interior-atmosphere evolution
- Water outgassing is favored on planets with large cores
- Planets with small cores tend to transition into a runaway greenhouse regime

Thank you for your attention!

Dense planets planets may offer a better chance at detecting an ocean than Earth-like planets