

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

Philipp Baumeister, Nicola Tosi, John Lee Grenfell, Jasmine MacKenzie

PLATO Mission Conference 2021

13.10.2021



# The search for habitable planets



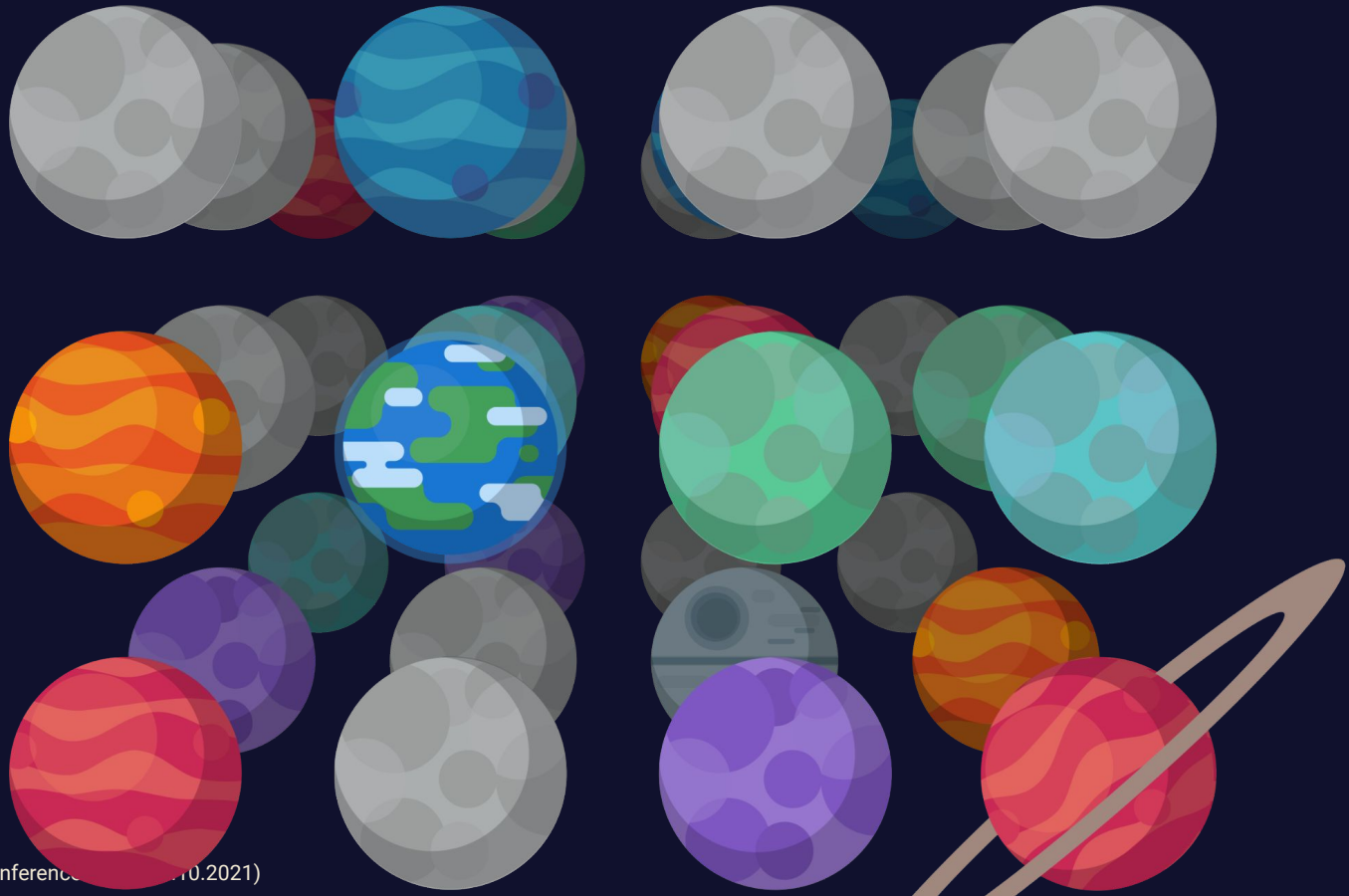
# The search for habitable planets

**Atmosphere  
measurements can only  
give indirect evidence**

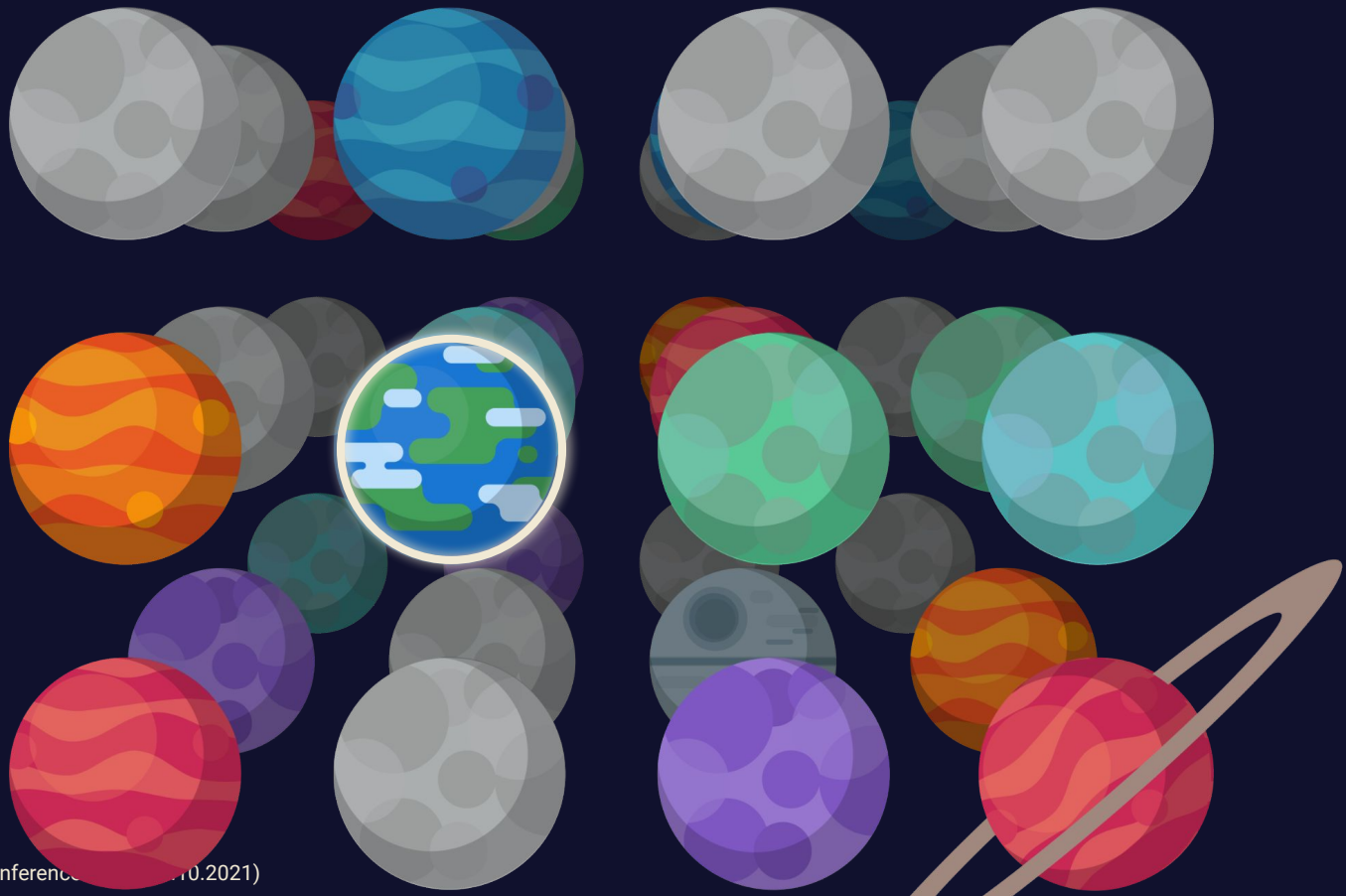


**Direct detection of an ocean  
is extremely challenging**

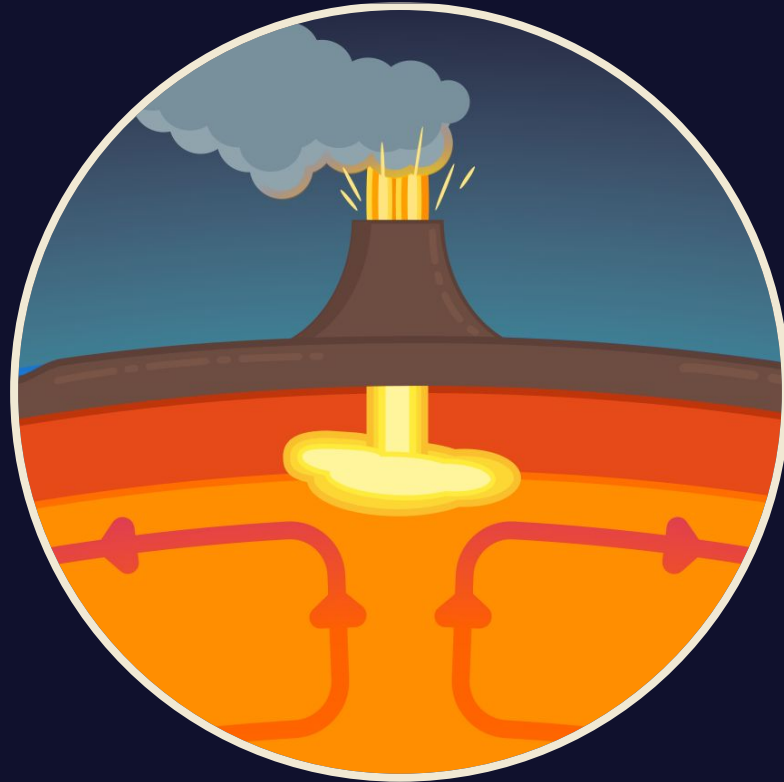
# Which planets *can* have oceans?



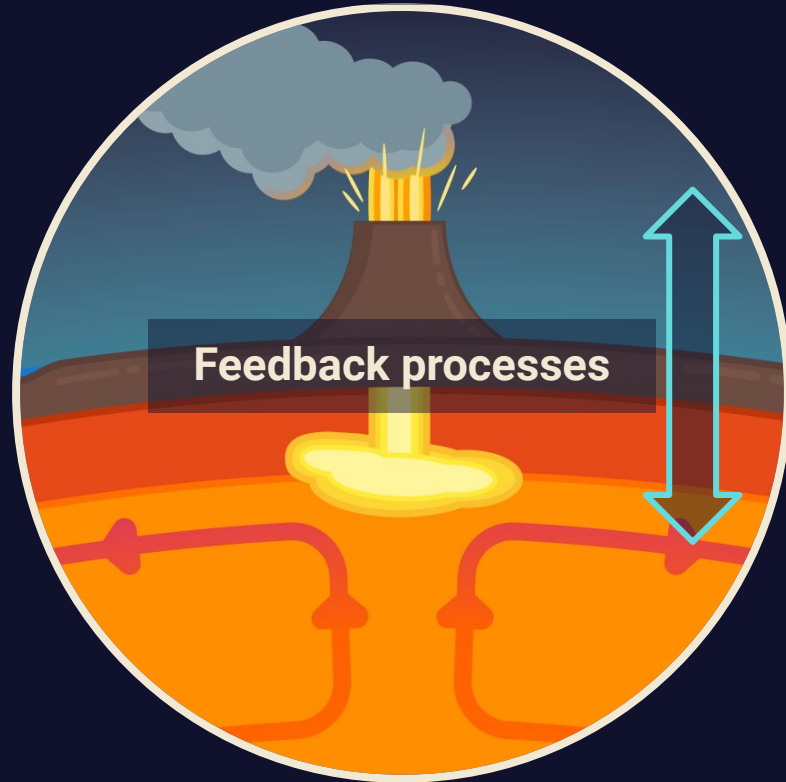
# Which planets *can* have oceans?



# The planet interior is a major source of water



# The planet interior is a major source of water



# 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

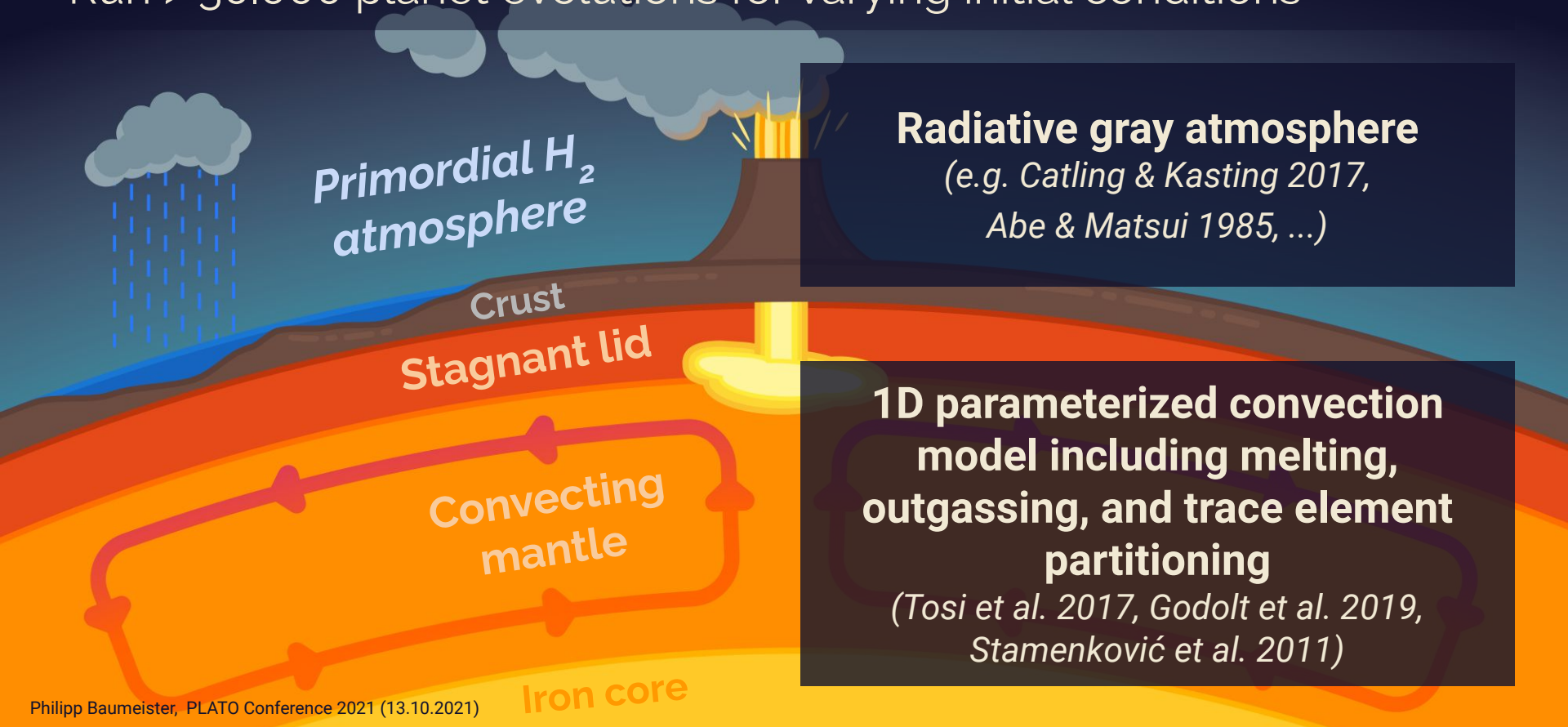
Water in mantle reduces *melting temperatures*

Water in mantle reduces *mantle viscosity*



# Our modeling approach:

Run > 30.000 planet evolutions for varying initial conditions



Primordial H<sub>2</sub>  
atmosphere

Crust

Stagnant lid

Convecting  
mantle

Iron core

## Radiative gray atmosphere

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

## 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:

Run > 30.000 planet evolutions for varying initial conditions

## Stellar luminosity and $F_{\text{XUV}}$ evolution

(Gough 1981, Owen & Wu 2017)

## $\text{H}_2$ escape

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

## Outgassing of $\text{H}_2\text{O}$ and $\text{CO}_2$

(Tosi et al. 2017)

## Water cycle between surface and atmosphere

## Stagnant lid carbon cycle

(Höning et al. 2019)

## Radiative gray atmosphere

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

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

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

# 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)



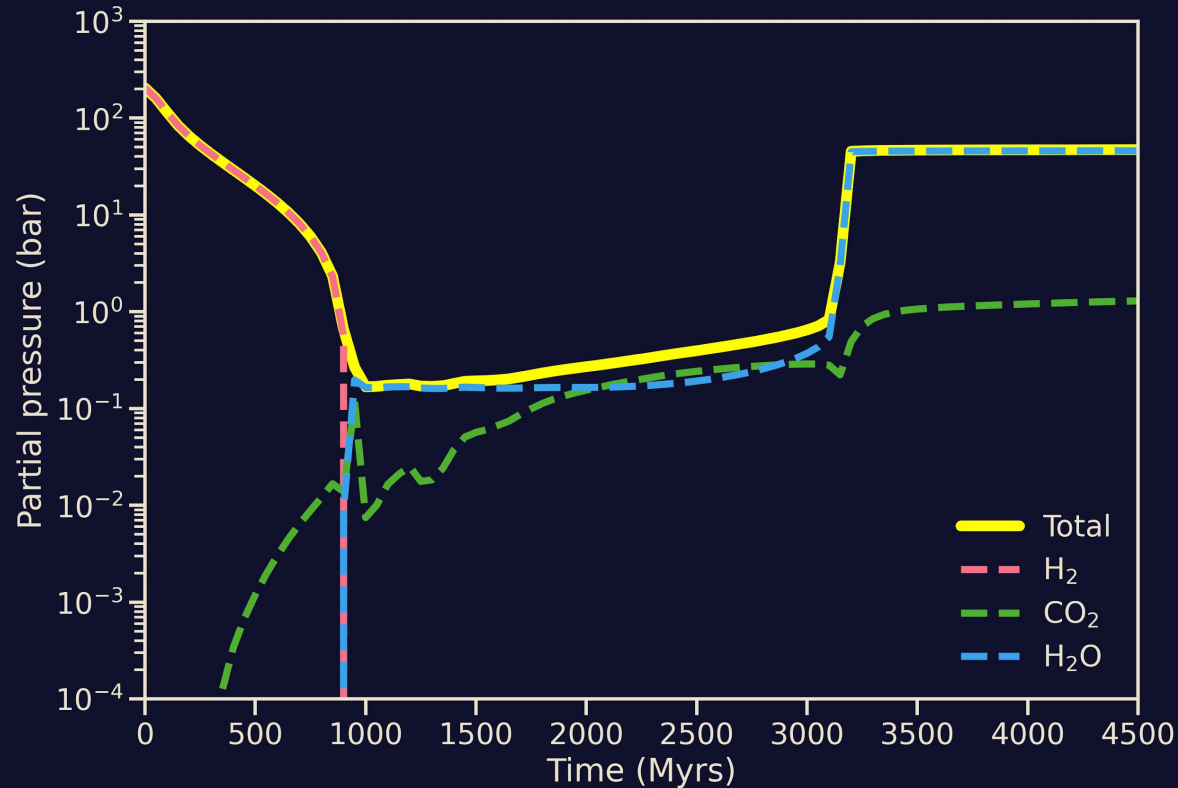
Mantle water  
concentration  $X_{H_2O}$   
(100 - 1000 ppm)

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

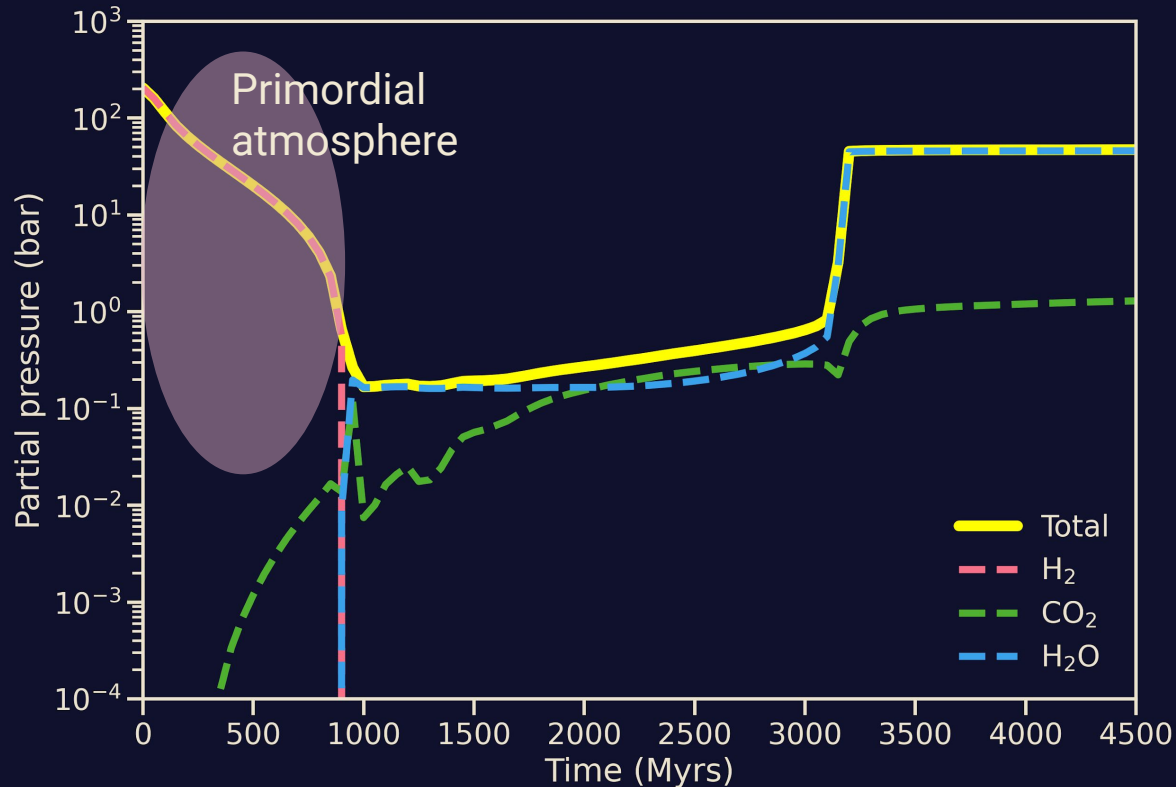
Planet mass  
(0.5 - 5  $M_J$ )

Iron core size  
(20% - 80%)

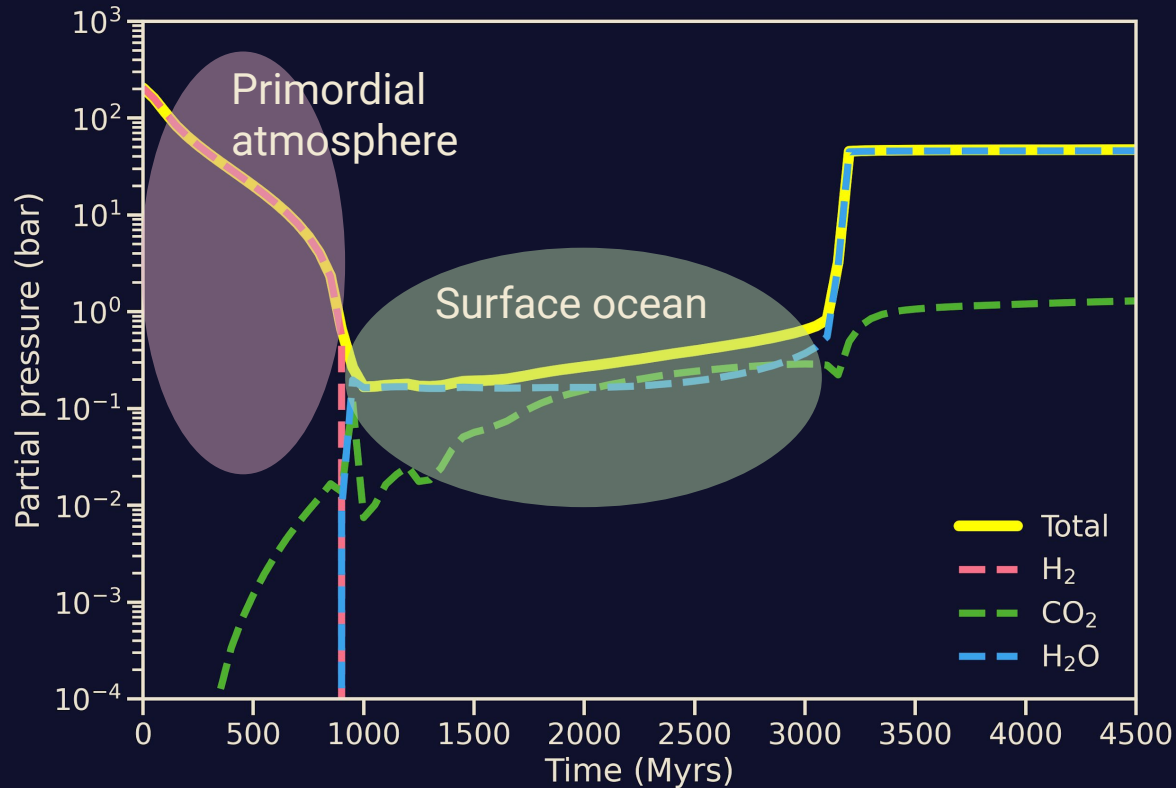
# Characteristic outgassing evolution



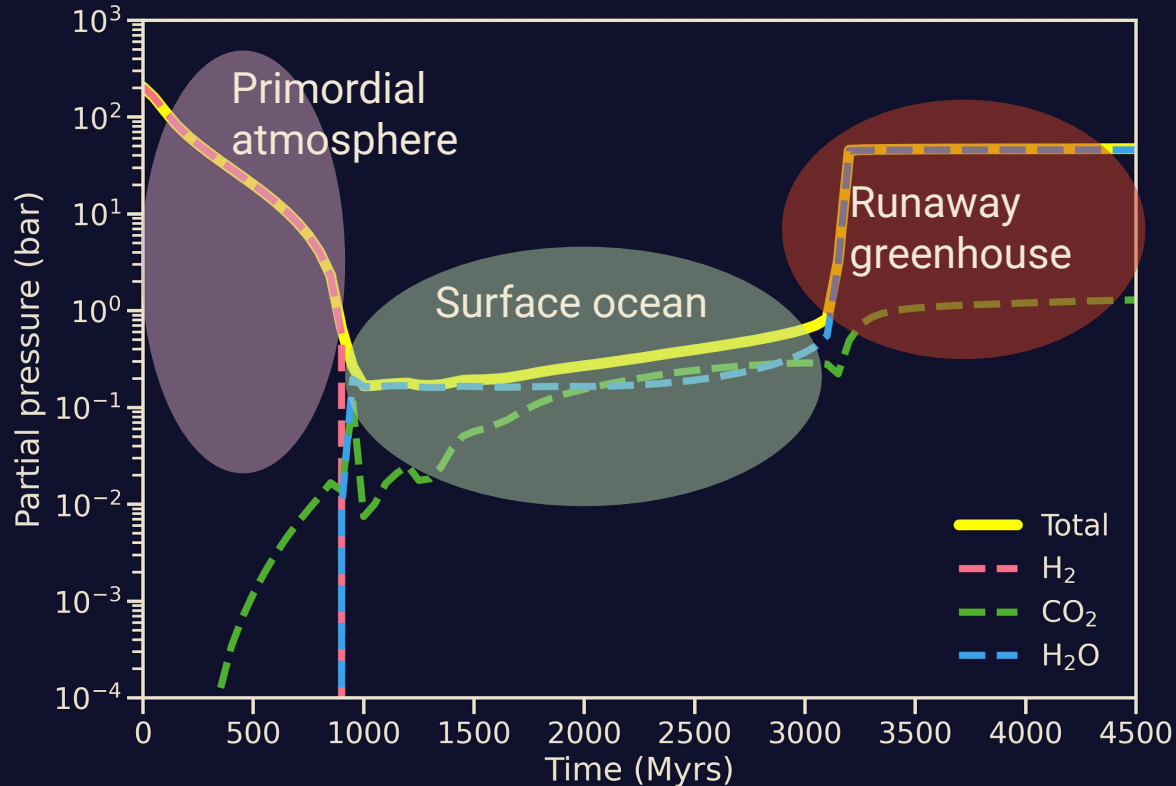
# Characteristic outgassing evolution



# Characteristic outgassing evolution

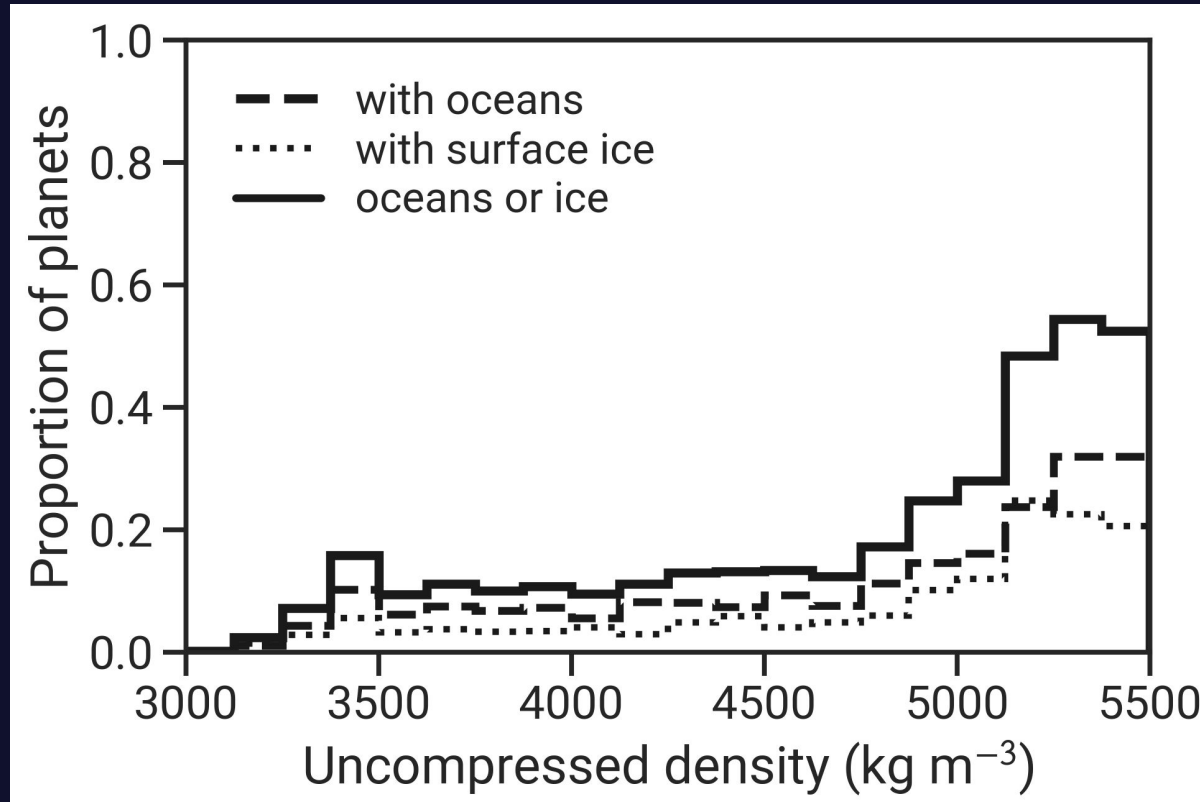


# Characteristic outgassing evolution



# Most dense planets have oceans ...

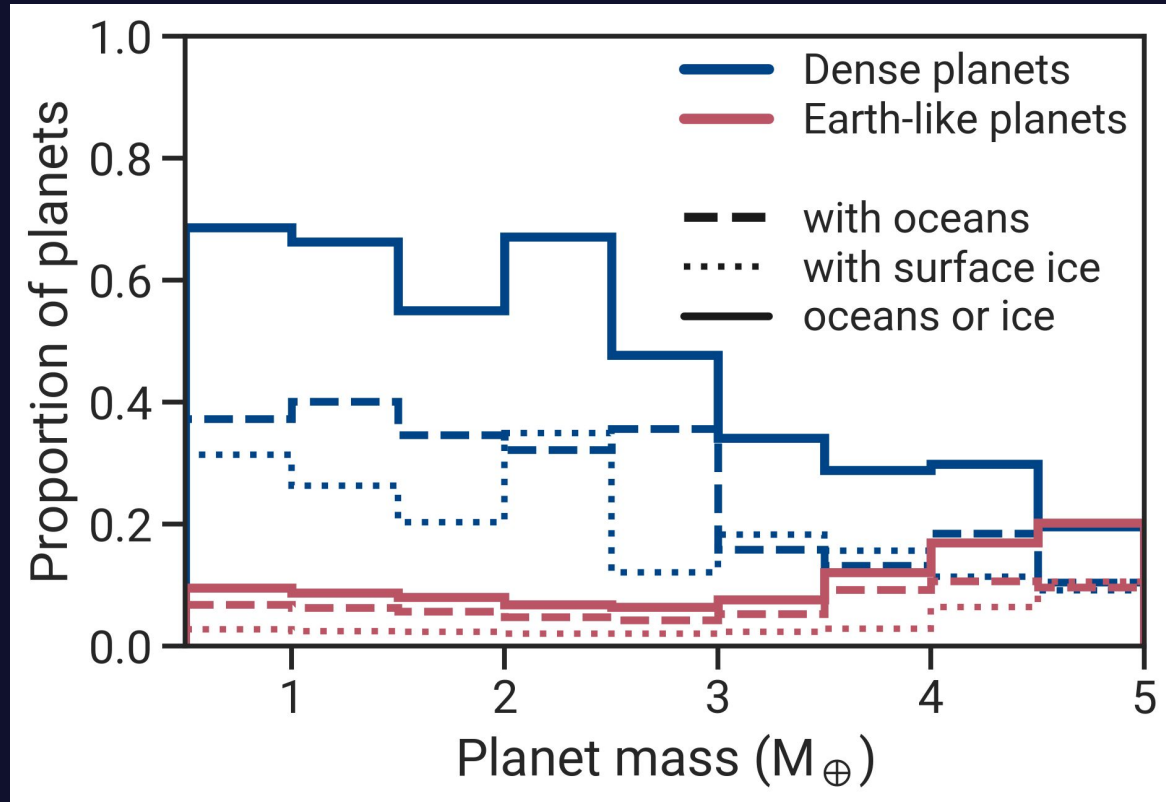
Baumeister et al. 2021,  
under review.





...especially at low masses

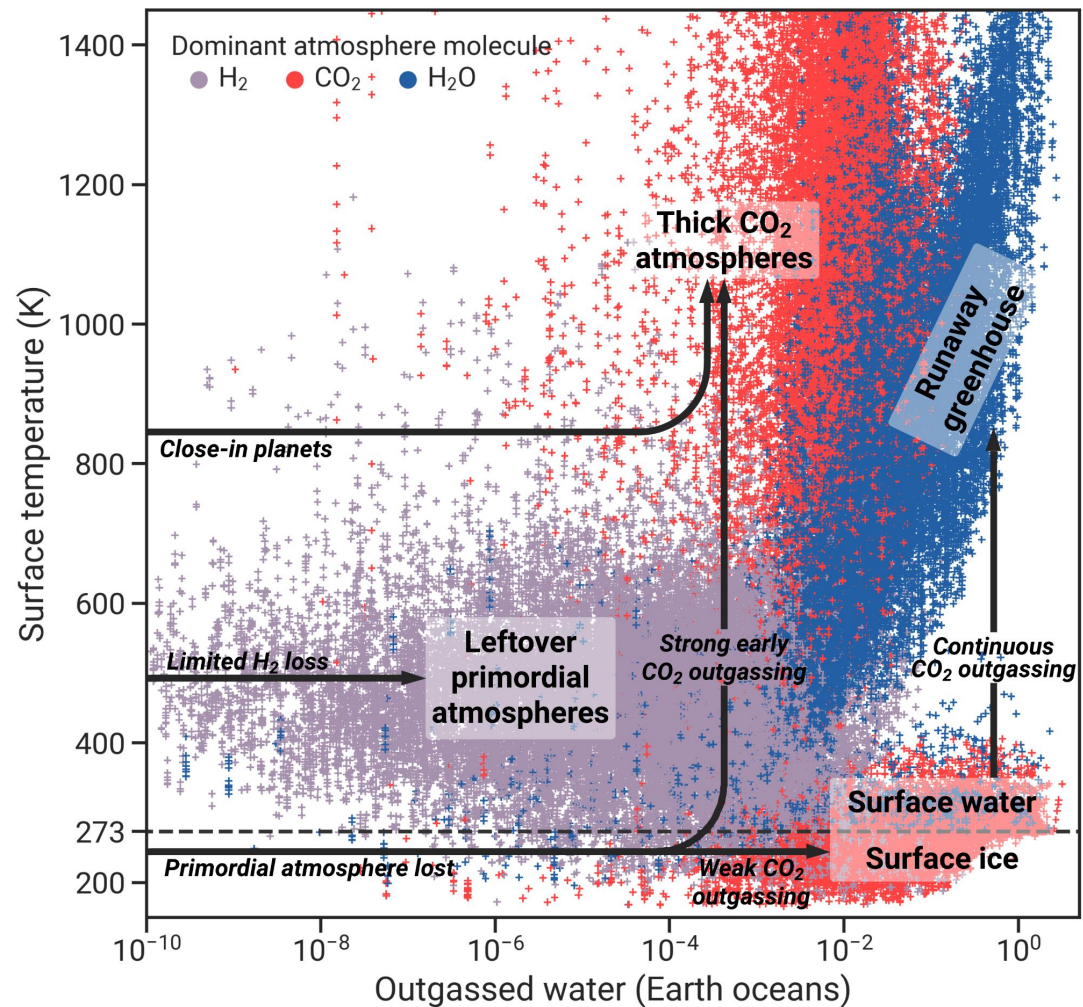
Baumeister et al. 2021,  
under review.

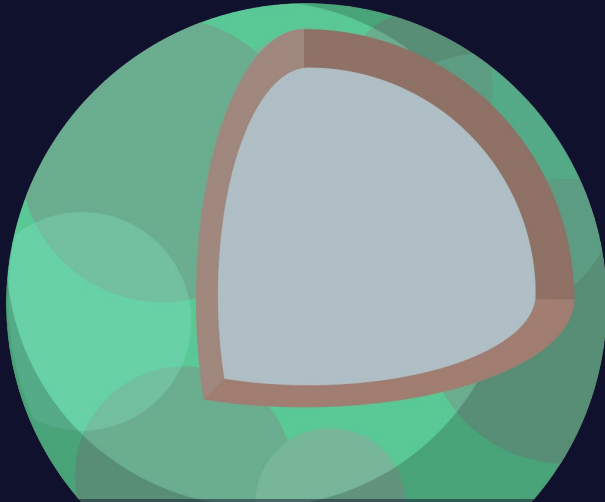


# CO<sub>2</sub> outgassing rate determines ocean evolution

- Stagnant-lid planets lack efficient process for long-term CO<sub>2</sub> removal
- For water outgassing, surface pressure needs to be low
- For surface water, CO<sub>2</sub> 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**
- **CO<sub>2</sub> outgassing is favoured**



**High-density 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 CO<sub>2</sub> 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!**

**High-density planets may offer a better chance at detecting an ocean than Earth-like planets**