Atmospheric Evolution and Loss for M Dwarf Planets

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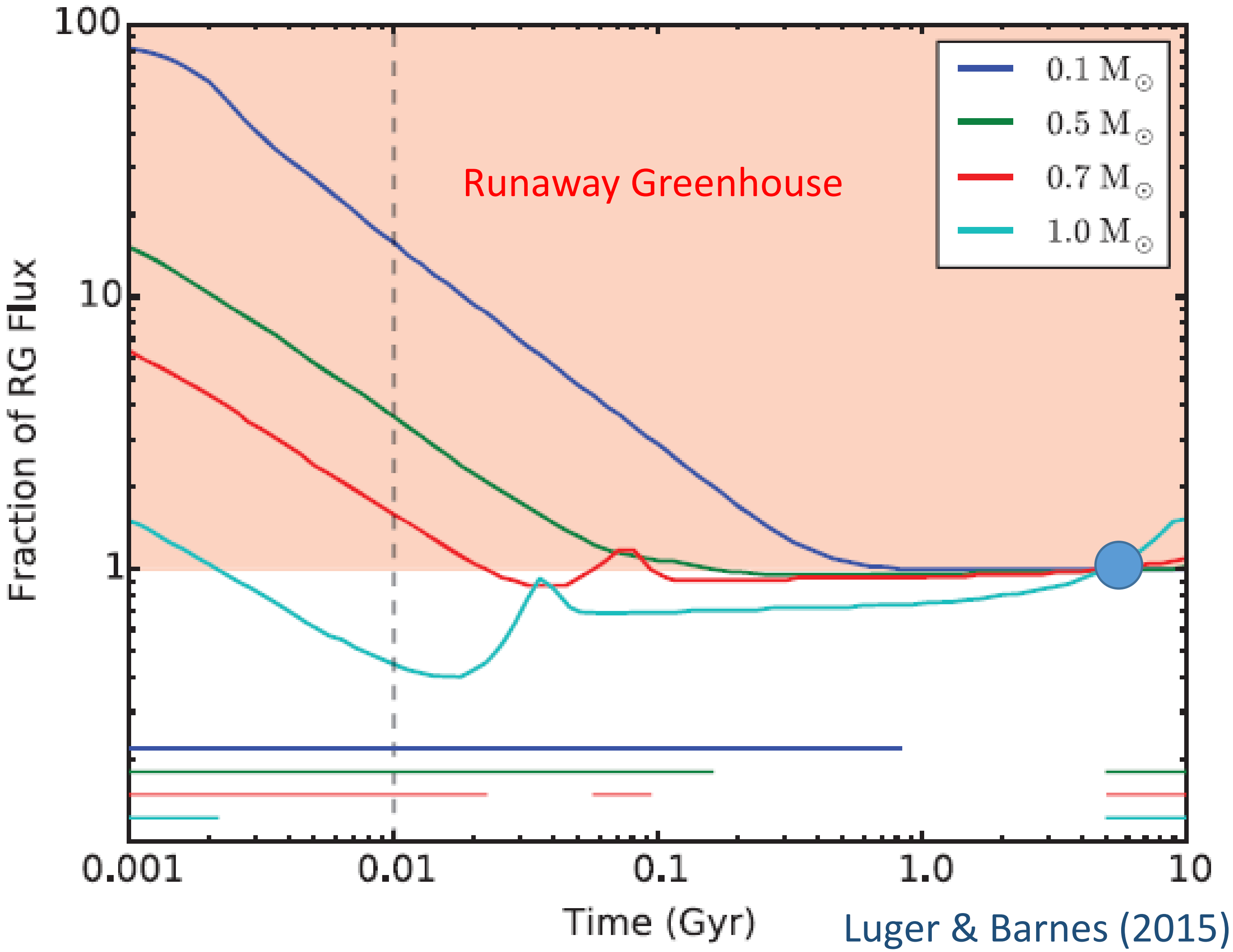
Stellar Radiation Changes with Time & Mass

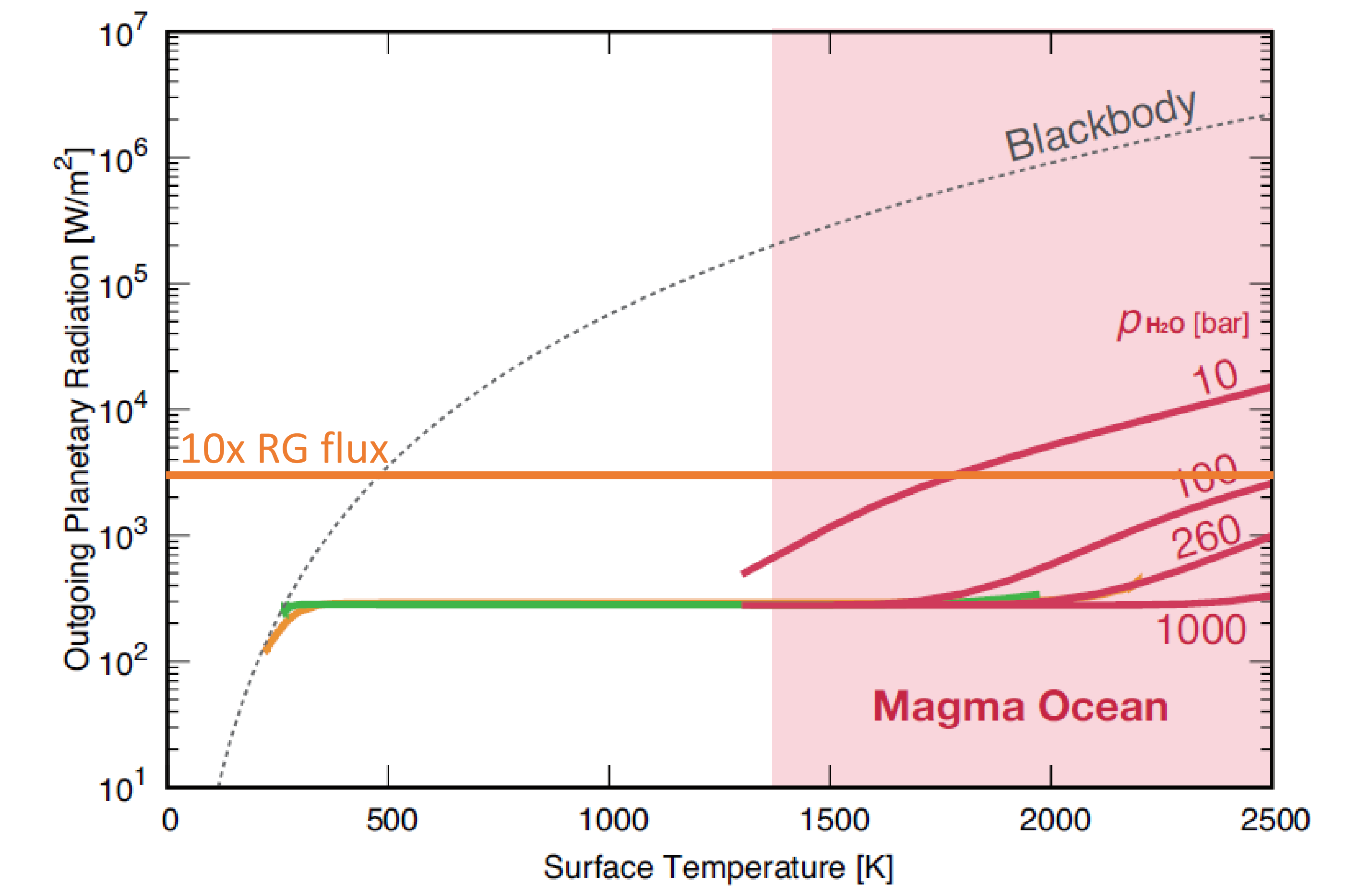


Luger & Barnes (2015)

Outgoing Longwave Radiation

Pure steam atmospheres

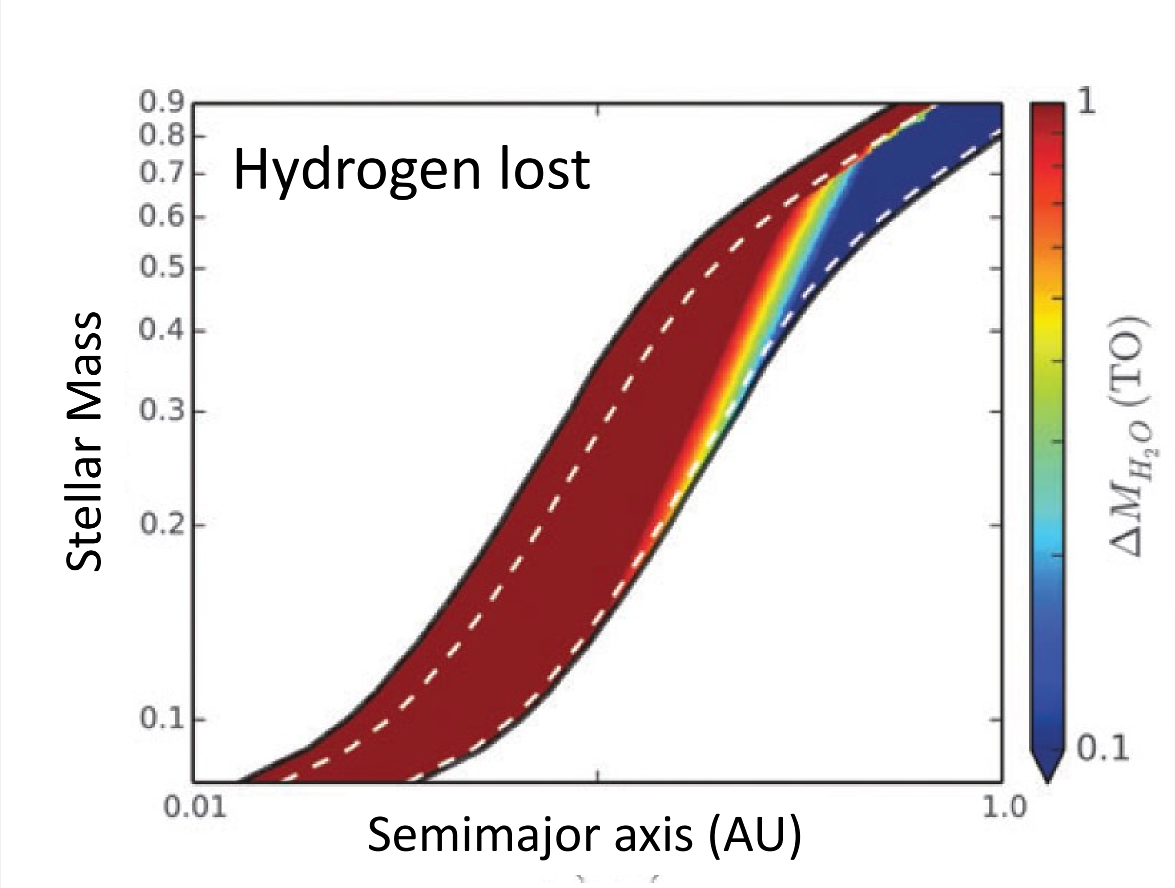
Higher total pressure = lower OLR



1 Ocean Mass (OM) ~ 260 bars on a 1 $M_{\oplus}$ planet

Ikoma et al. (2018)

Escape of H

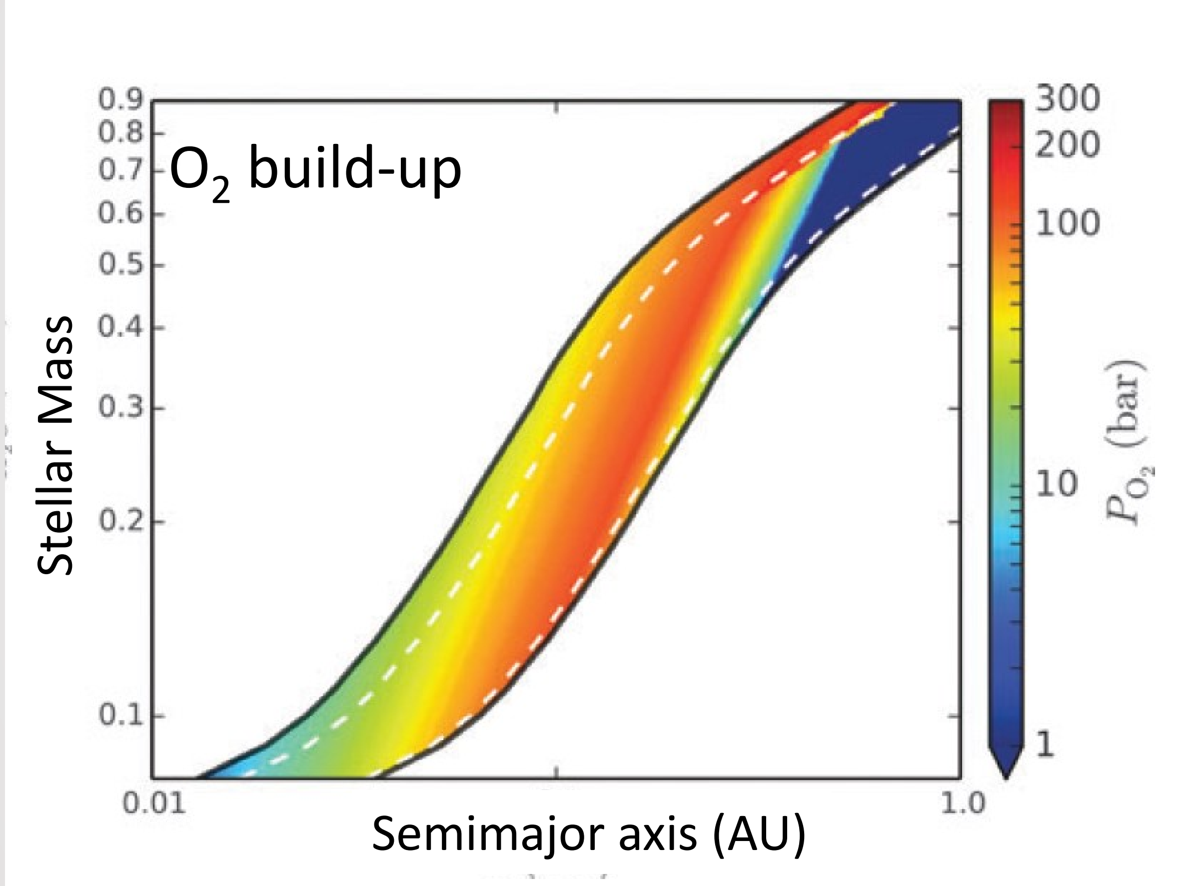


Luger & Barnes (2015)

Energy-limited mass loss

$$\dot{M}_{\rm EL} = \frac{\epsilon_{\rm XUV} \pi \mathcal{F}_{\rm XUV} R_{\rm p} R_{\rm XUV}^2}{G M_{\rm p} K_{\rm tide}}$$

Abiotic O_2 build-up



Luger & Barnes (2015)

Energy-limited mass loss

$$\dot{M}_{\mathrm{EL}} = \frac{\epsilon_{\mathrm{XUV}} \pi \mathcal{F}_{\mathrm{XUV}} R_{\mathrm{p}} R_{\mathrm{XUV}}^2}{G M_{\mathrm{p}} K_{\mathrm{tide}}}$$

Oxygen build-up

$$\dot{M}_{\mathrm{EL}} = \dot{m}_{\mathrm{H}}^{\uparrow} + \dot{m}_{\mathrm{O}}^{\uparrow}$$

$$\dot{m}_{\mathrm{O}}^{\uparrow} + \dot{m}_{\mathrm{O}}^{\mathrm{atm}} = 8\dot{m}_{\mathrm{H}}^{\uparrow}$$

O_2 uptake by magma ocean

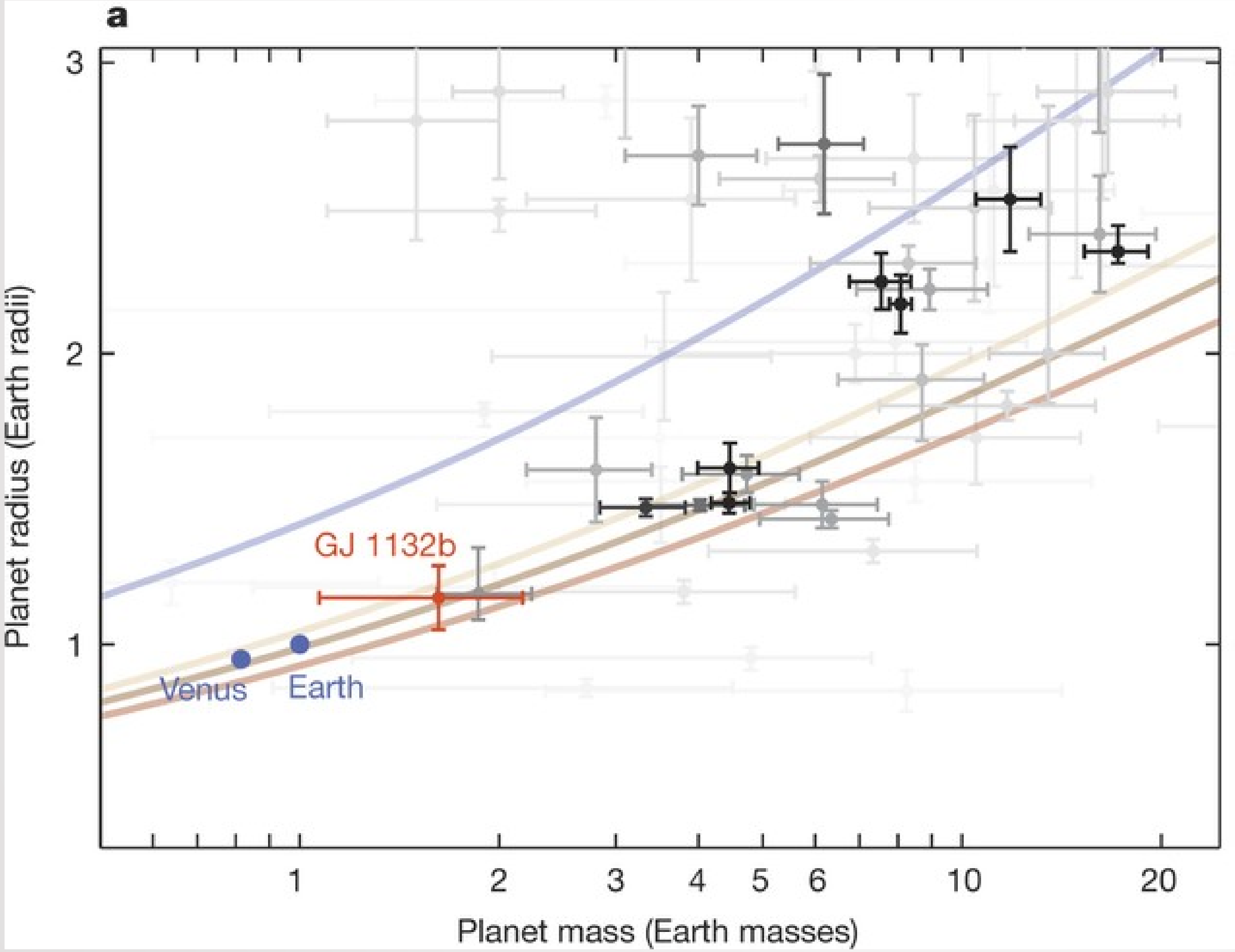
Mantles composed mostly of Mg, Si, Fe, and O

$$\begin{matrix} Mg^{2+} \\ Si^{4+} \\ Fe^{2+} \\ Fe^{3+} \end{matrix} \quad + \quad n\, O^{2-} \quad = \quad \begin{matrix} MgO \\ SiO_2 \\ FeO \\ Fe_2O_3 \end{matrix}$$

$$\ln\left(\frac{X_{Fe_2O_3}}{X_{FeO}}\right) = a \ln(f_{O_2}) + \frac{b}{T} + c + \sum_i d_i X_i + e \left[1 - \frac{T_o}{T} - \ln\left(\frac{T}{T_o}\right)\right] + f\frac{P}{T} + g\frac{(T - T_o)P}{T} + h\frac{P^2}{T}.$$

Kress & Carmichael (1991)

GJ 1132b



Berta-Thompson et al. 2015, Nature

M_{star} 0.181 M_{Sun}

T_{star} 3,270 K

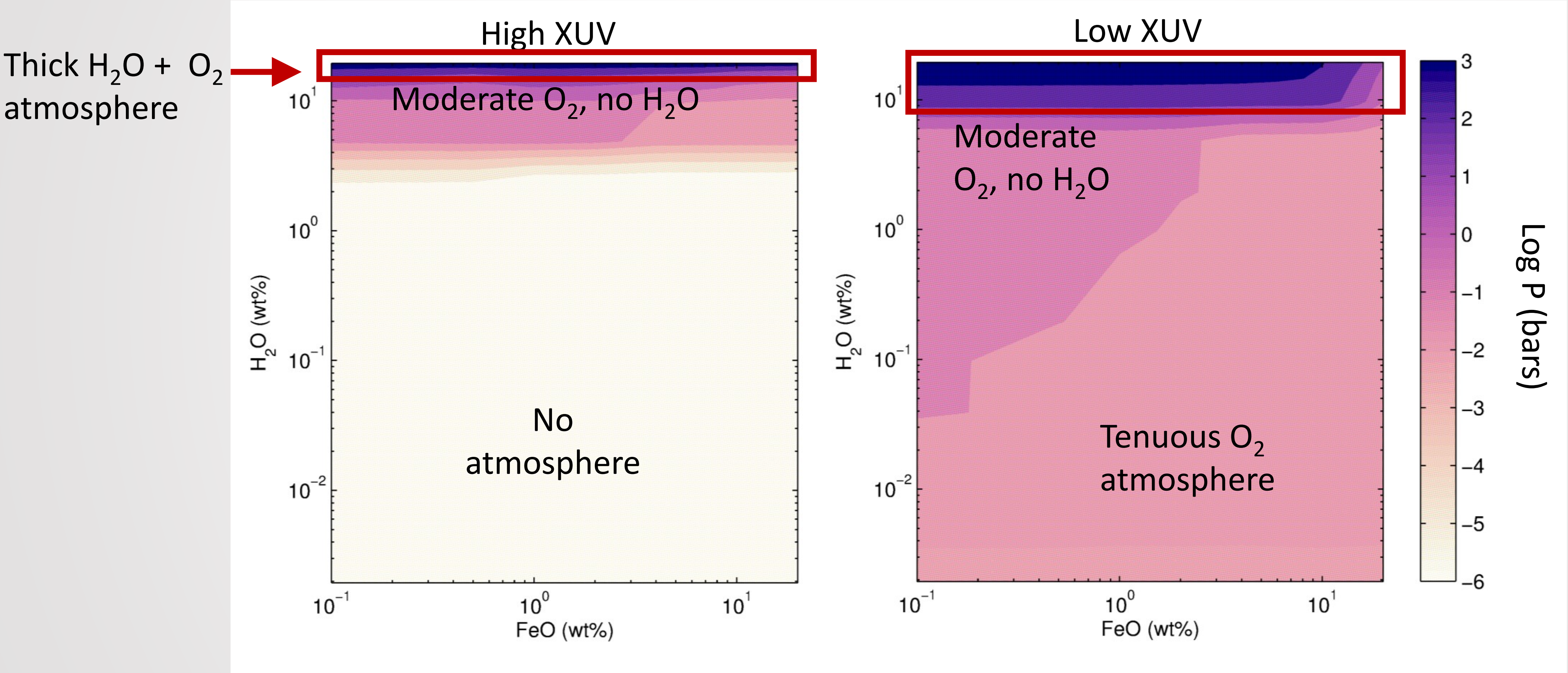
M_p 1.62 ± 0.55 M_{Earth}

R_p 1.16 ± 0.11 R_{Earth}

a 0.0153 AU

T_{eq} 410 K

Atmospheric O_2

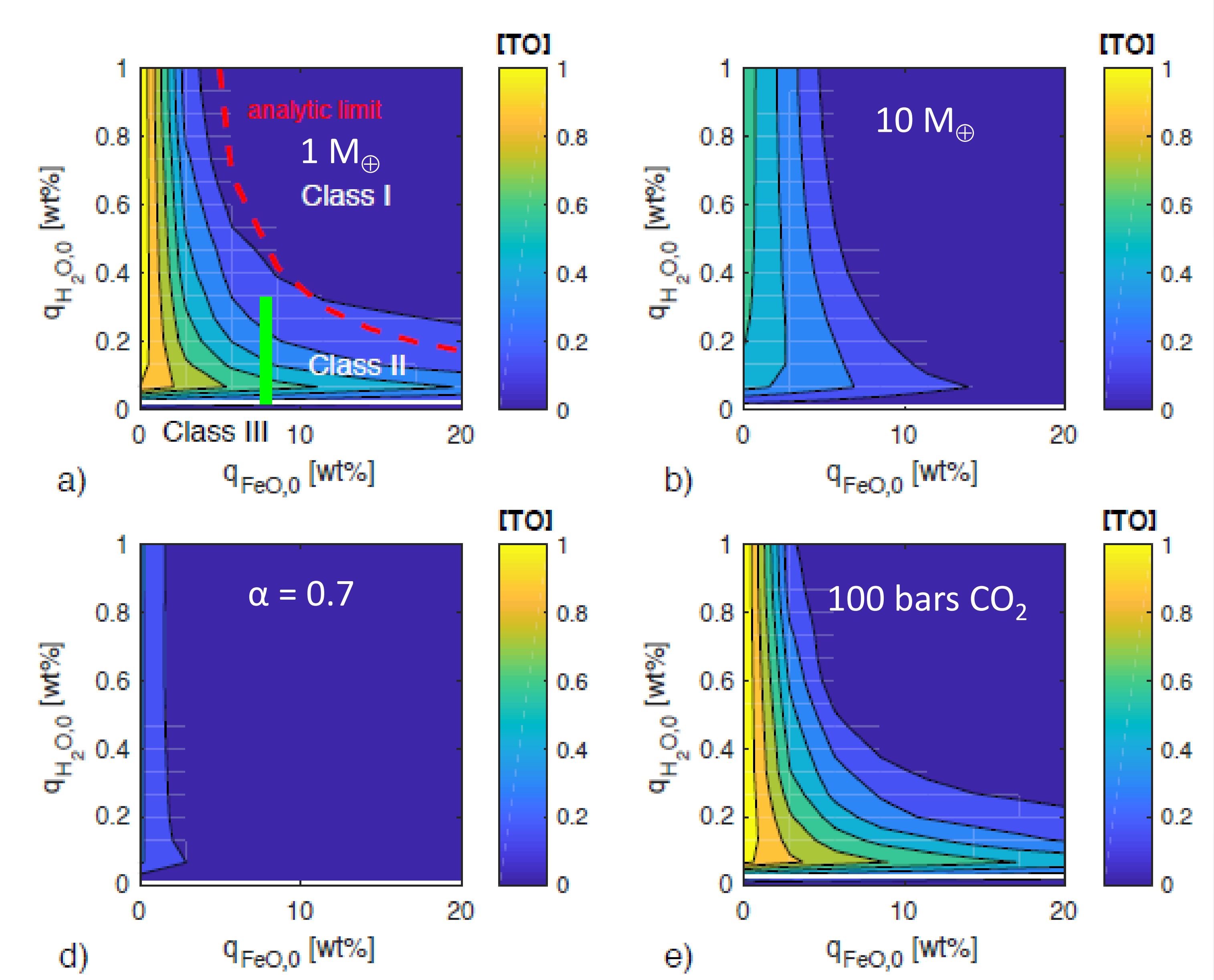


Schaefer et al. (2016) ApJ

The figure shows the final total pressure of O_2 in the atmosphere after 5 Gyr of evolution.

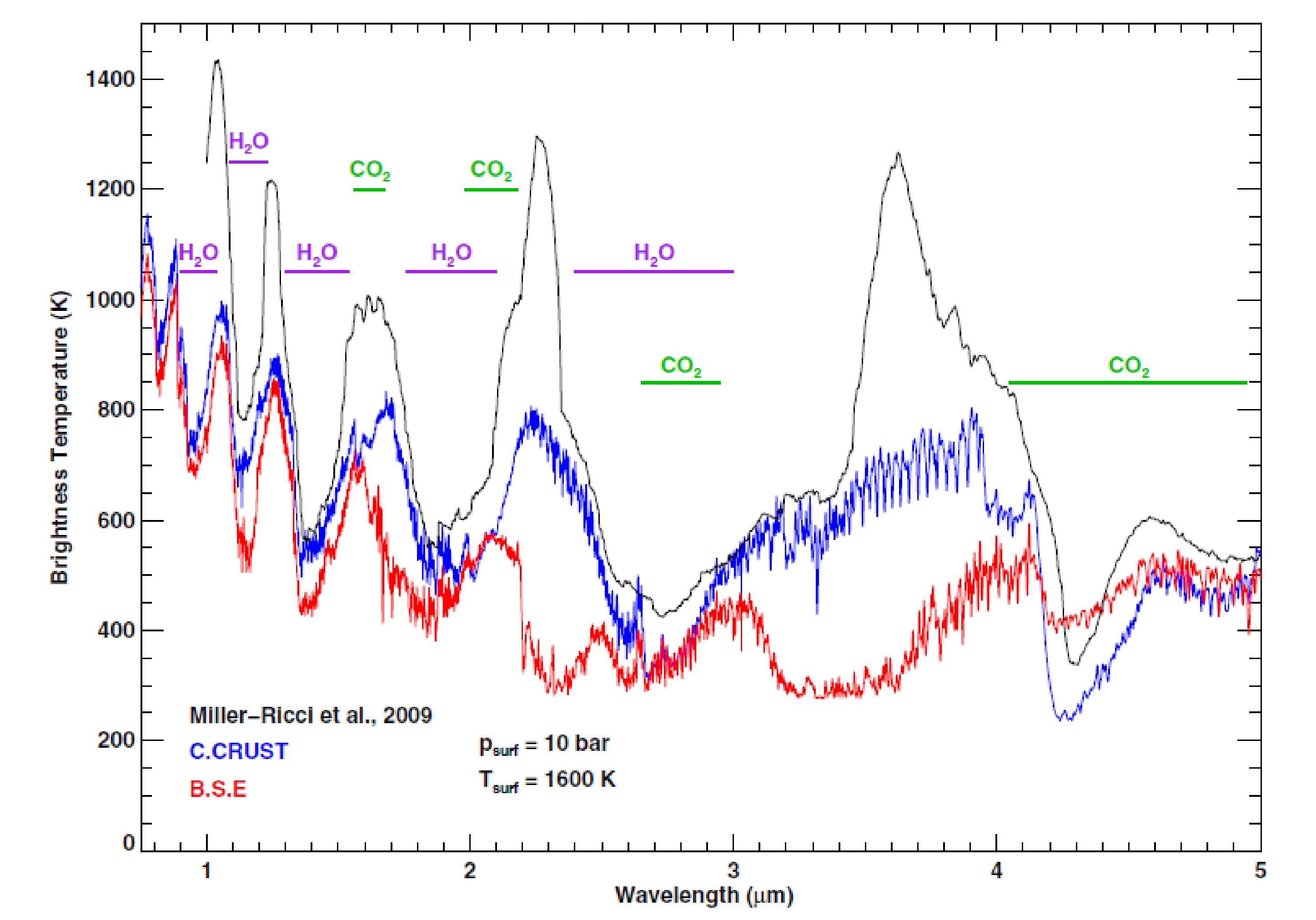
Atmospheric O_2

- most sensitive to
  - Orbit
  - Albedo
  - Planet mass



Wordsworth et al. (2018) ApJ

Emergent Spectra of "Steam" Atmospheres



Lupu et al. (2014)

Previous giant impact models used simple chemical compositions (90% H_2O + 10% CO_2)

Adding additional opacity sources results in lower OLR

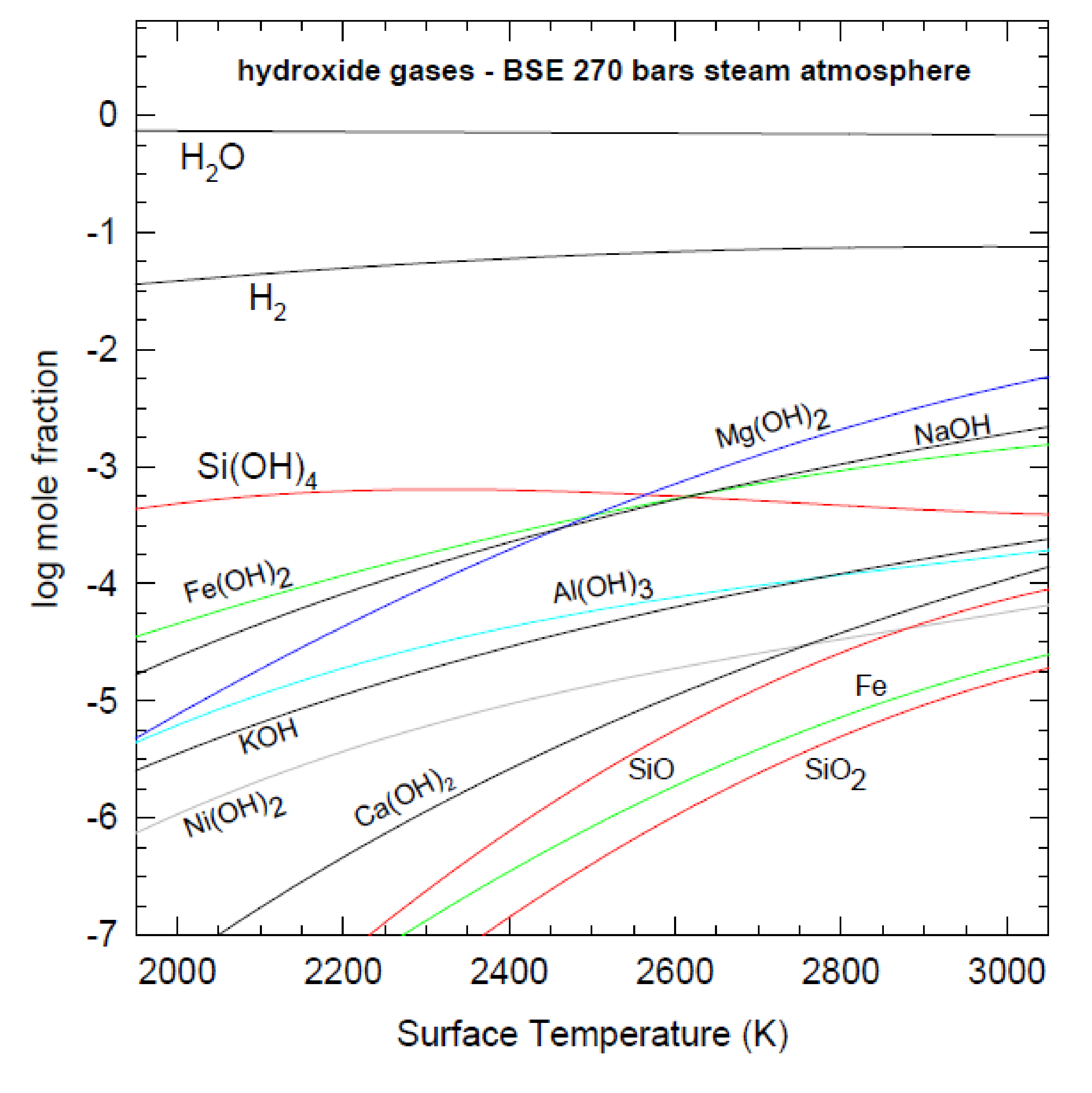
SO_2, HCl, HF, HCN, N_2, NH_3, O_2, OH, SiO, CO, H_2S, etc.

Magma ocean atmospheres…

…contain more than just steam or H_2

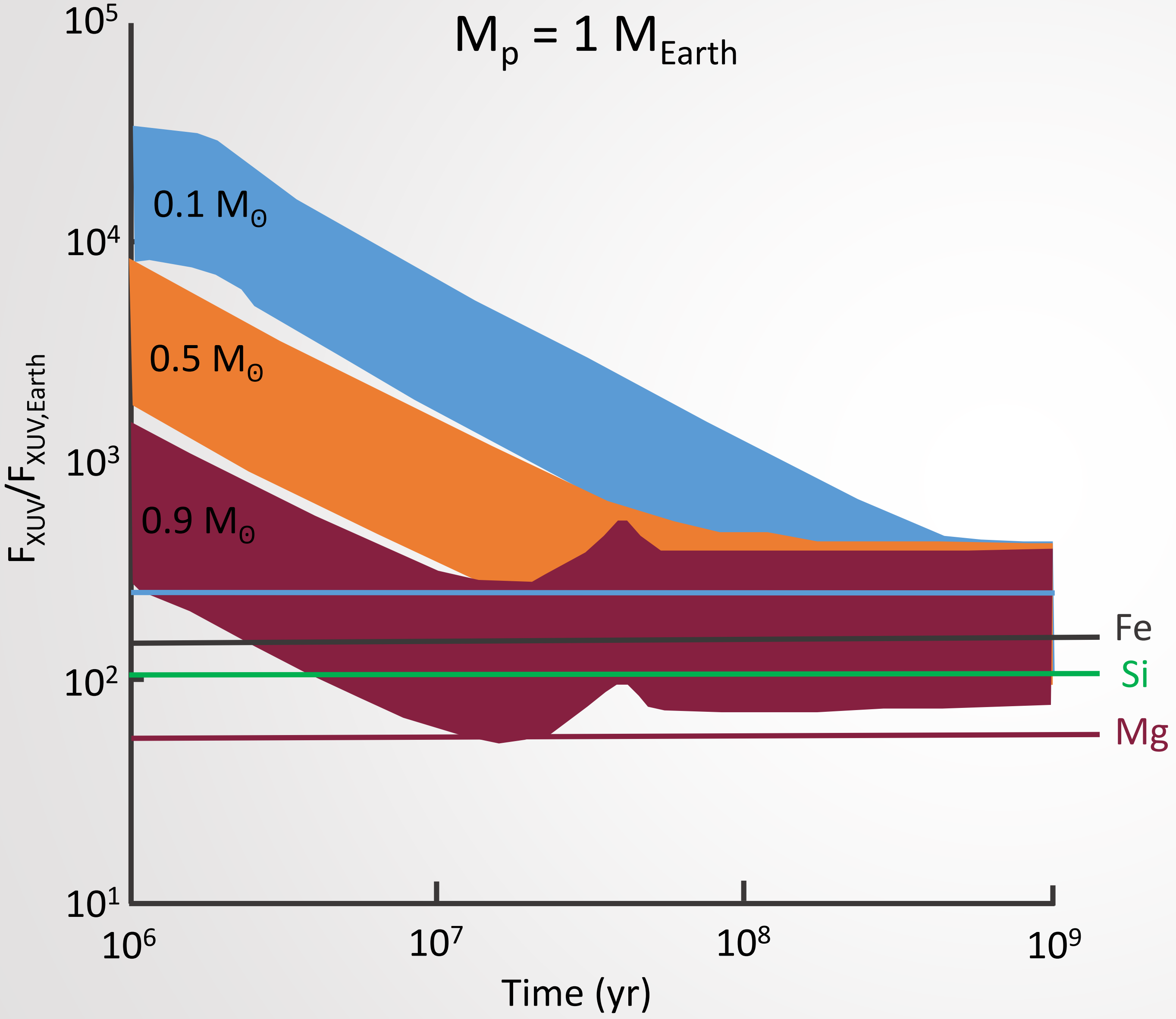
Rock is soluble in water/steam at high water/rock ratios

Hydrodynamic escape of H may pull lithophile elements along for the ride.



Fegley et al. (2016)

XUV fluxes of HZ planets with time



Critical XUV fluxes for escape of Si, Mg and Fe are lower than the runaway greenhouse XUV flux assuming full dissociation

So escape is limited by duration of steam atmosphere rather than by XUV flux

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Summary

- Atmospheres of predominantly rocky planets around M dwarfs will be strongly influenced by processes during the magma ocean stage
- Atmospheres with complex compositions will likely have lower OLR and therefore higher surface temperatures
- At high surface T and P, rock is soluble in steam atmospheres!
  - Models with separate magma ocean/atmosphere may start to break down for water abundances >1 wt%
- Outstanding questions:
  - How do minor atmospheric species affect escape of H?
  - How much of minor species will escape? Can this effect bulk planet composition?