M Dwarf Evolution

and Effects on Habitability

Luger, R. and Barnes, R. (2015) **Extreme water loss and abiotic O_2 buildup on planets throughout the habitable zones of M dwarfs.** Astrobiology 15, doi:10.1089/ast.2014.1231

Luger, R., Barnes, R., Lopez, E., Fortney, J., Jackson, B., and Meadows, V. (2015) **Habitable evaporated cores: transforming mini-Neptunes into super-Earths in the habitable zones of M dwarfs.** Astrobiology 15:57-88, doi:10.1089/ast.2014.1215

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The Bad News

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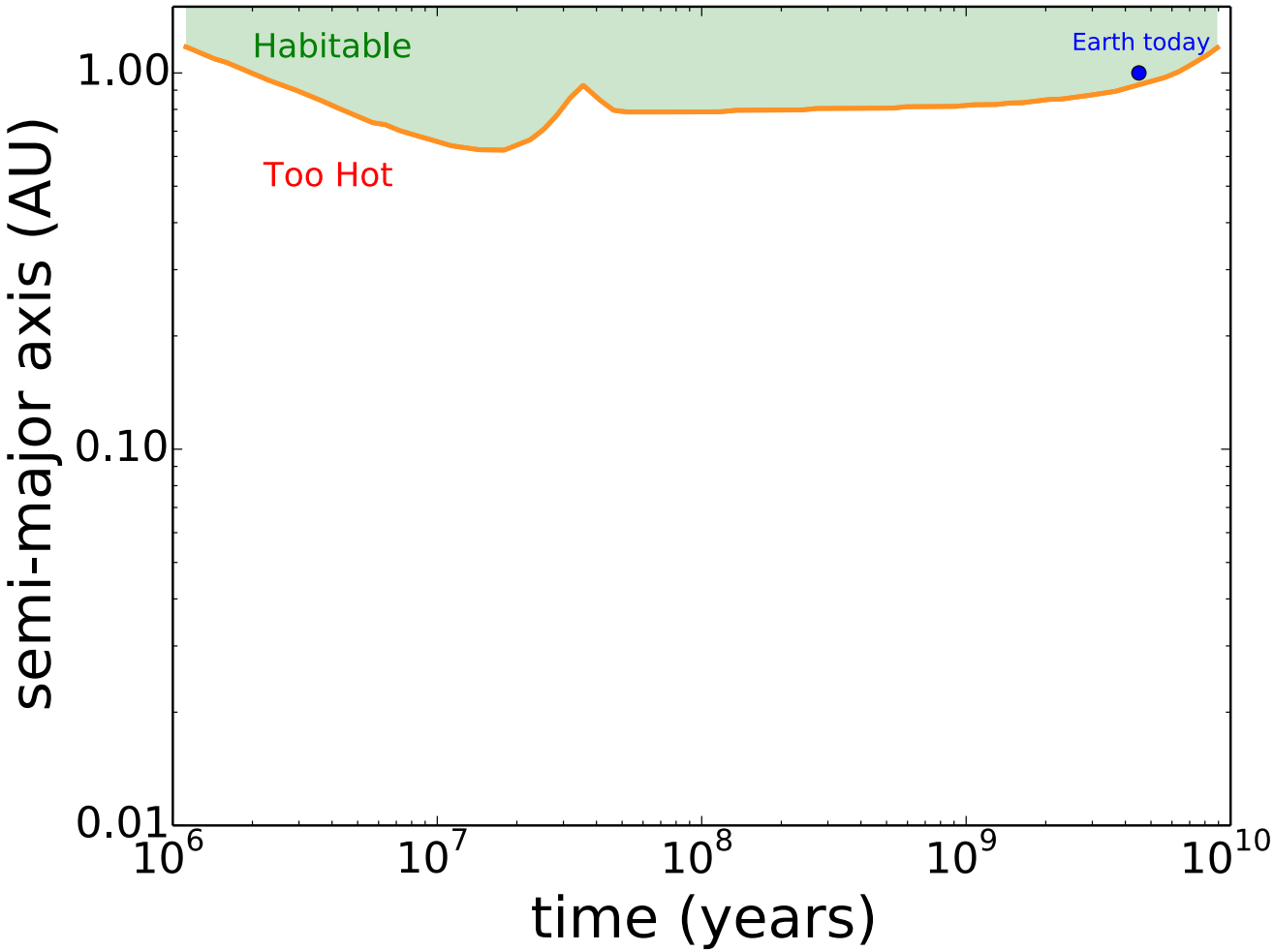
Pre-Main Sequence Evolution



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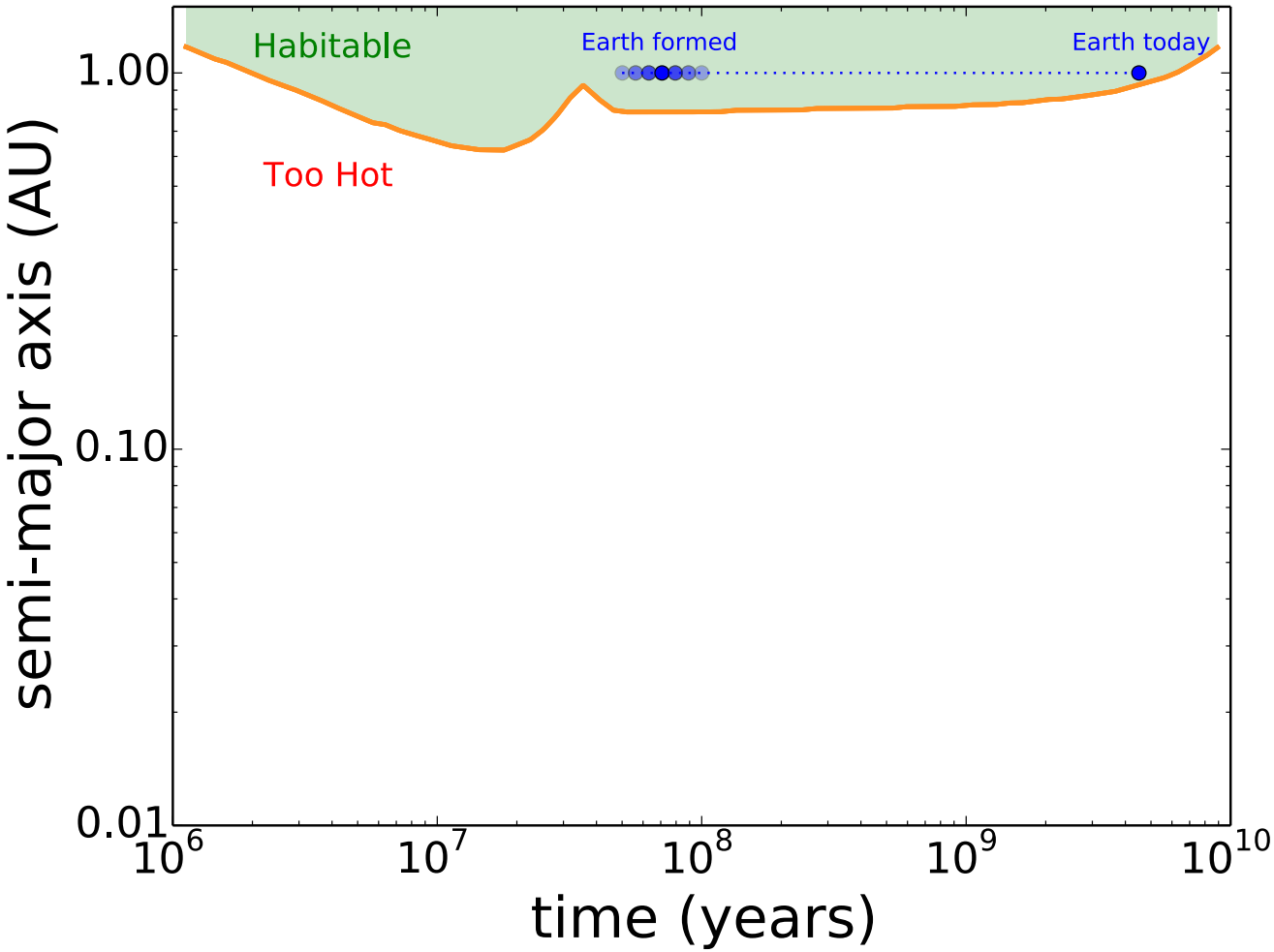
Pre-Main Sequence Evolution



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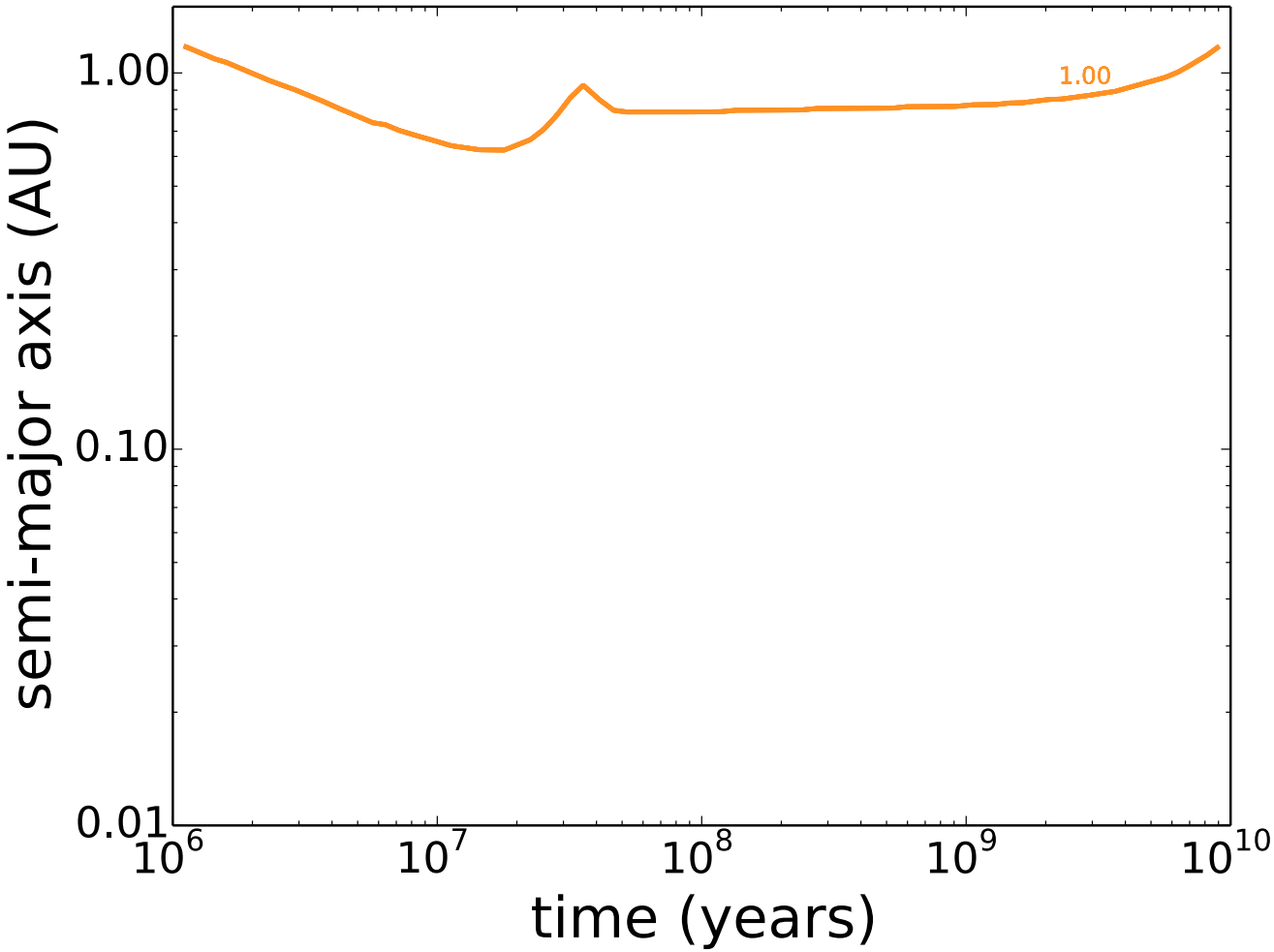
Pre-Main Sequence Evolution



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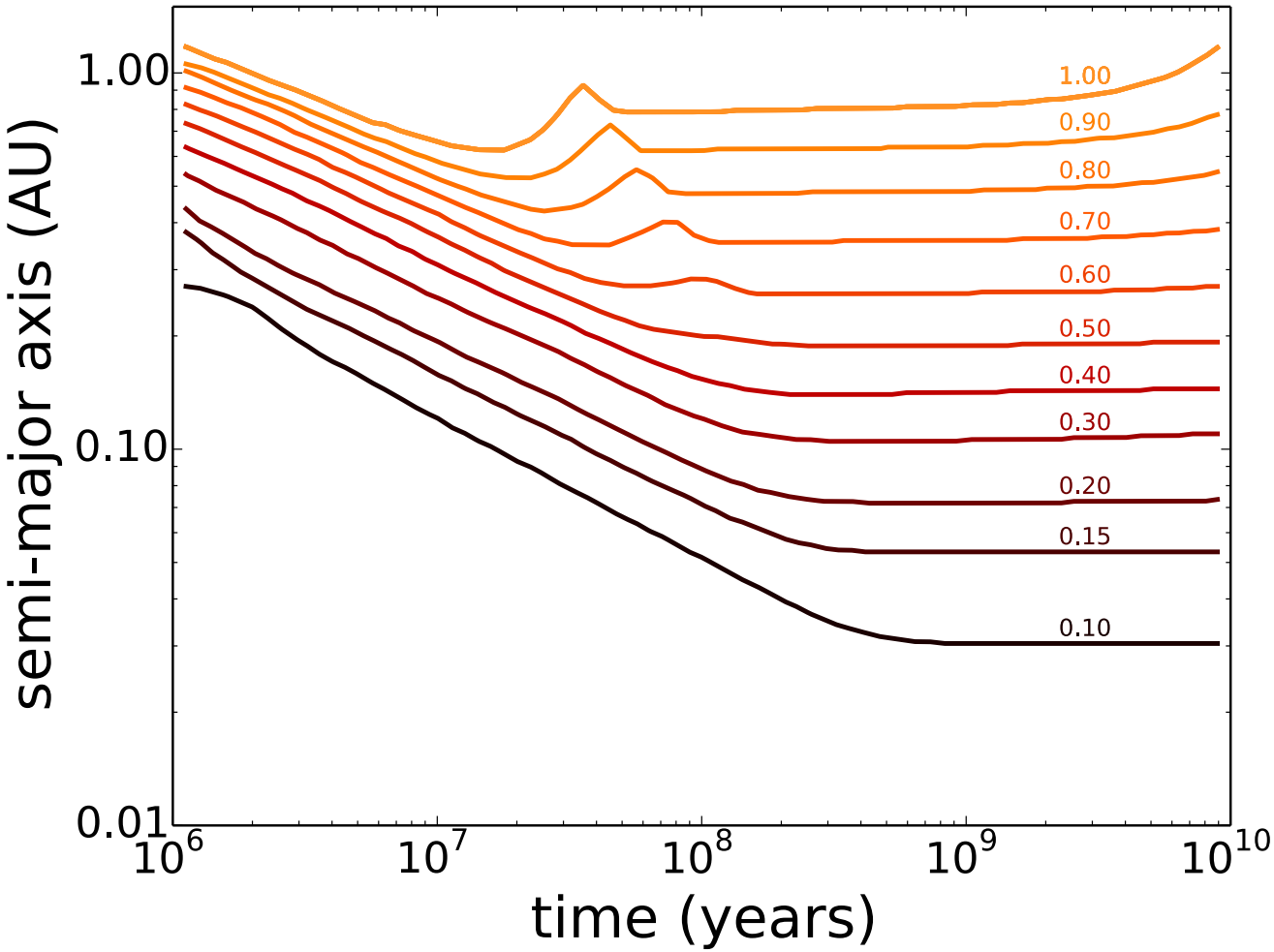
Pre-Main Sequence Evolution



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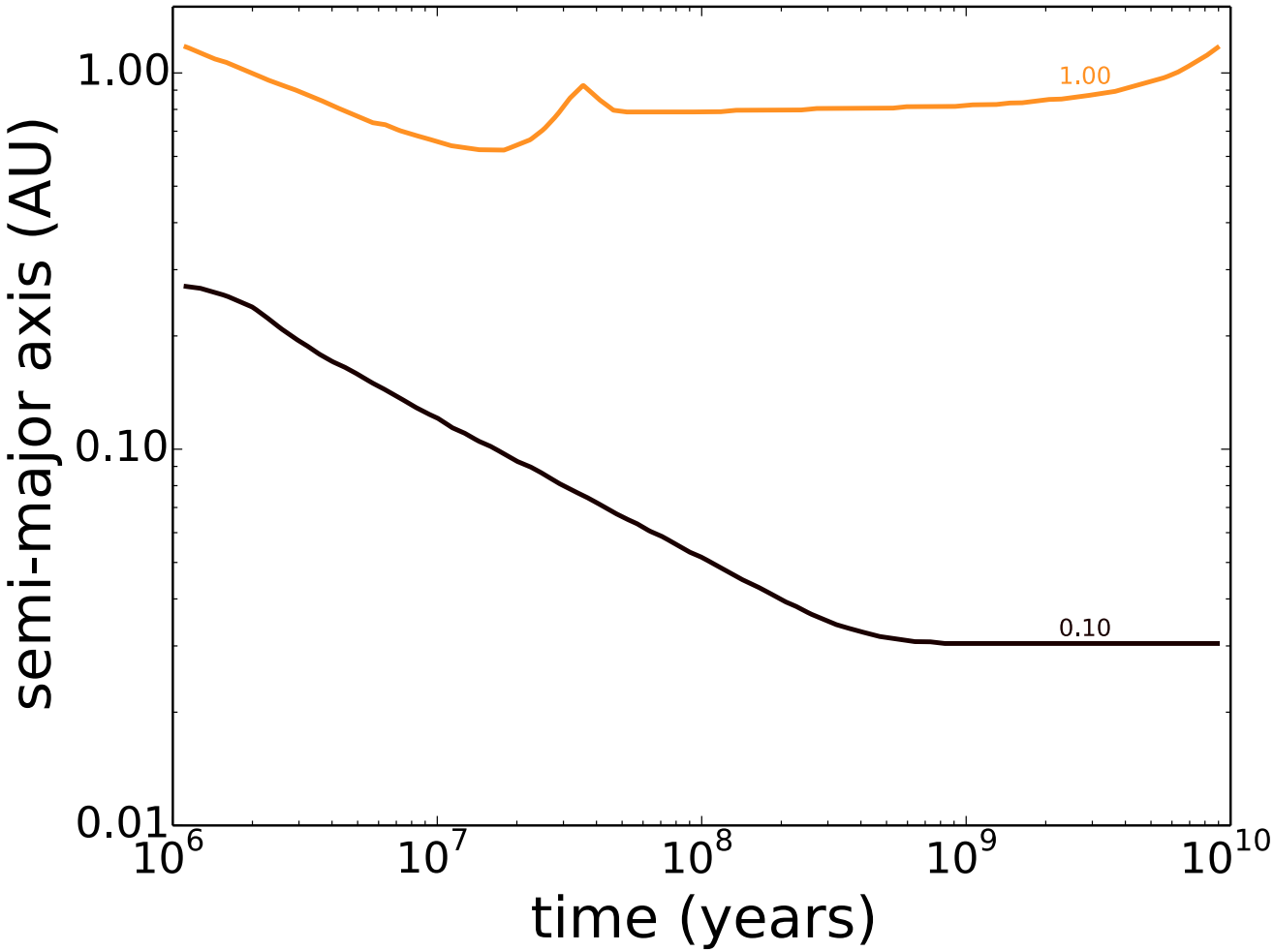
Pre-Main Sequence Evolution



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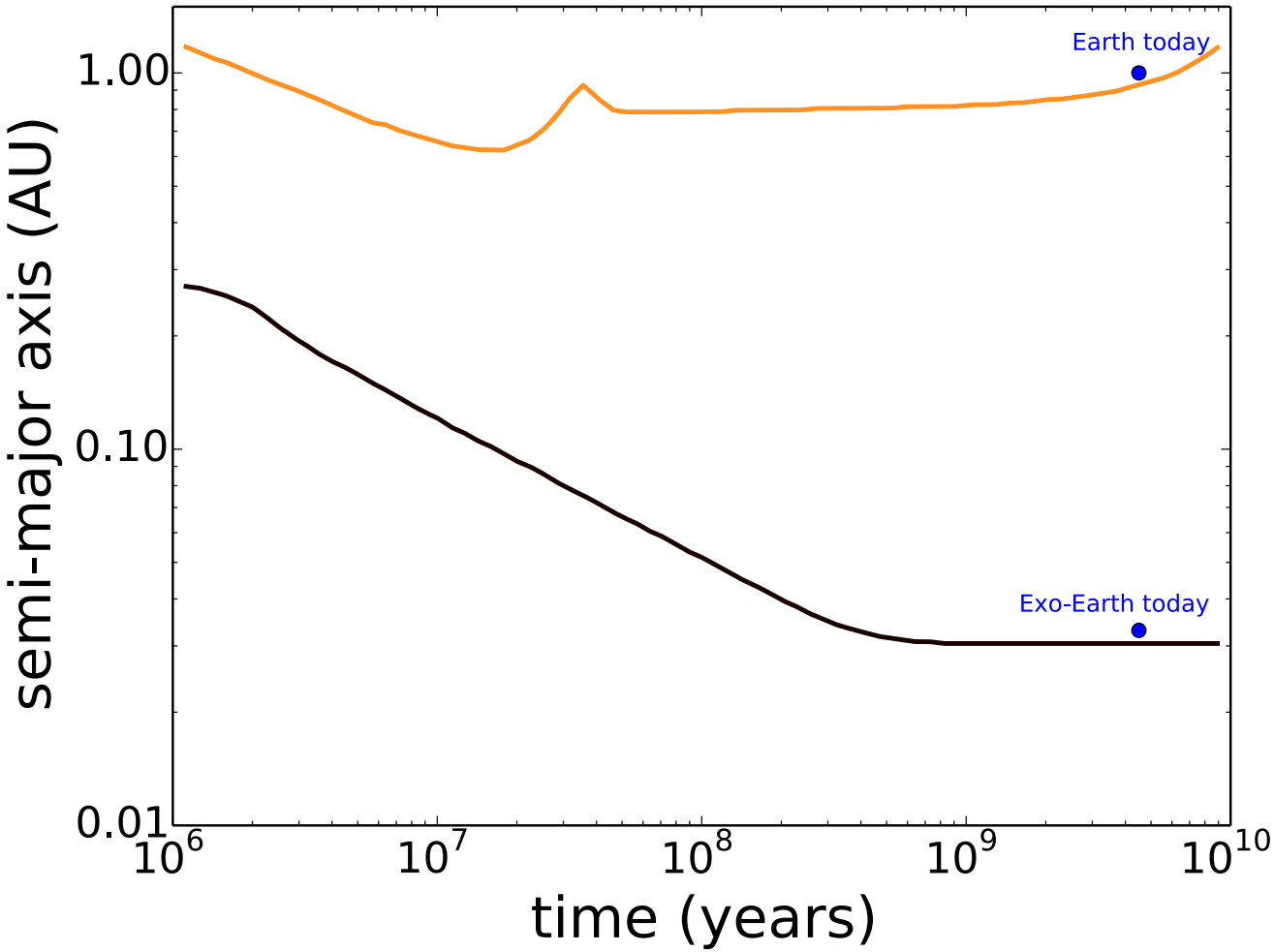
Pre-Main Sequence Evolution



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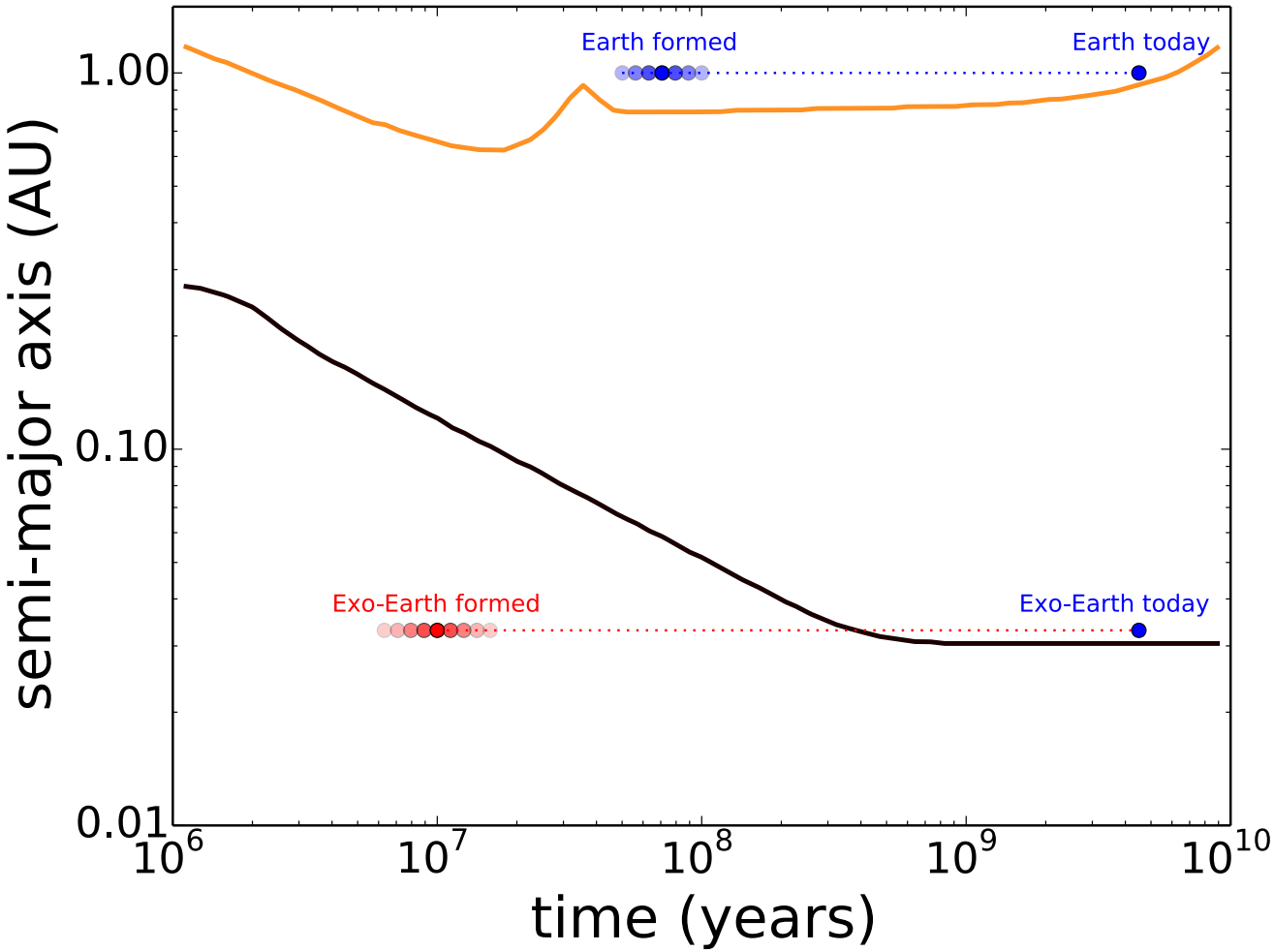
Pre-Main Sequence Evolution



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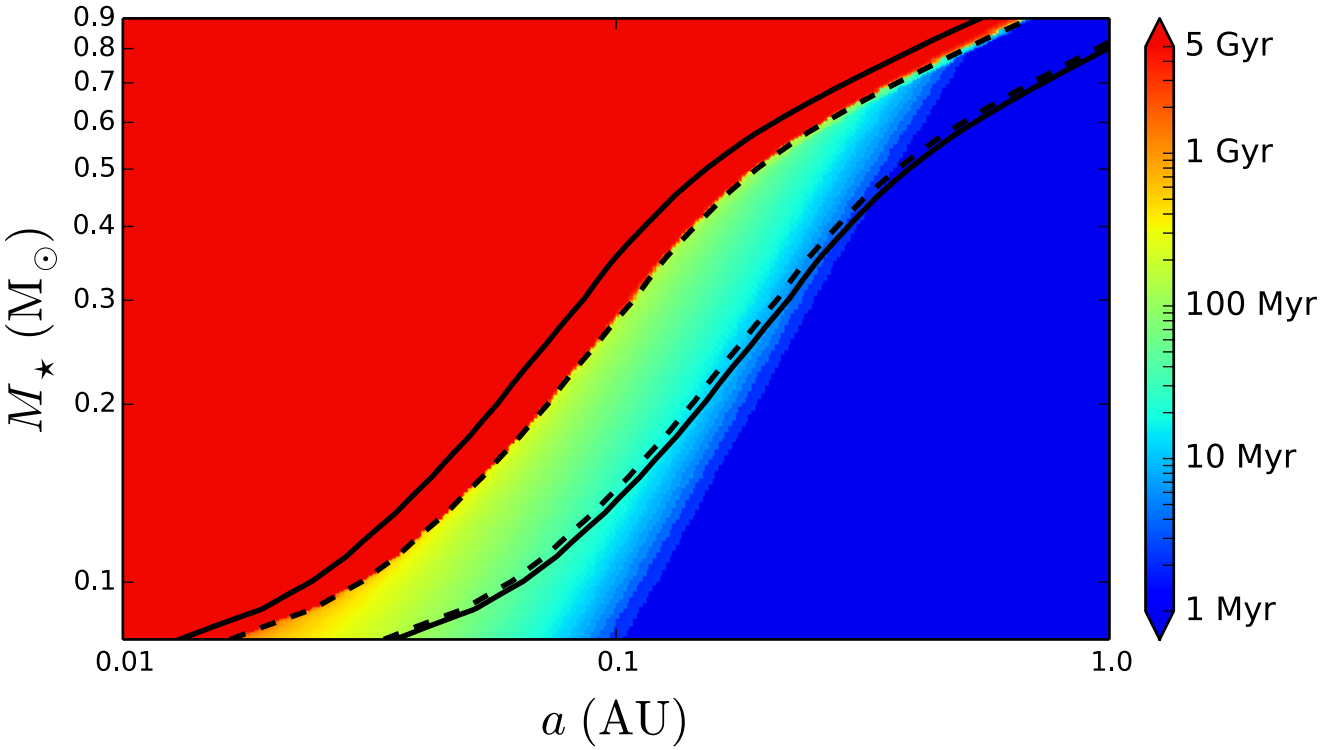
Duration of the Runaway Greenhouse



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Atmospheric Escape Model

- XUV power law decline (Ribas et al. 2005)

$$\frac{L_{\mathrm{XUV}}}{L_{\mathrm{bol}}} = \begin{cases} f_0 & t \leq t_0 \\ f_0 \left(\frac{t}{t_0}\right)^{-\beta} & t > t_0 \end{cases} \tag{1}$$

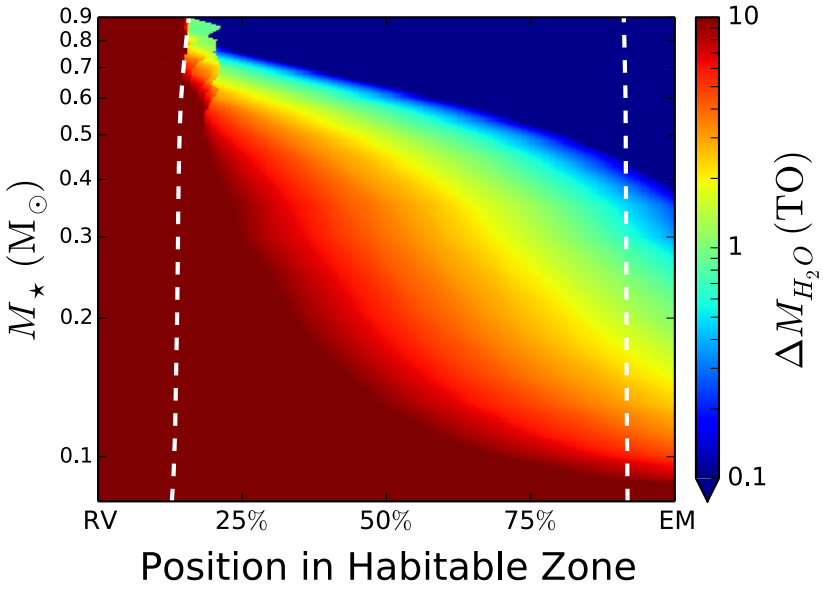
- XUV-driven energy-limited escape (Erkaev et al. 2007)

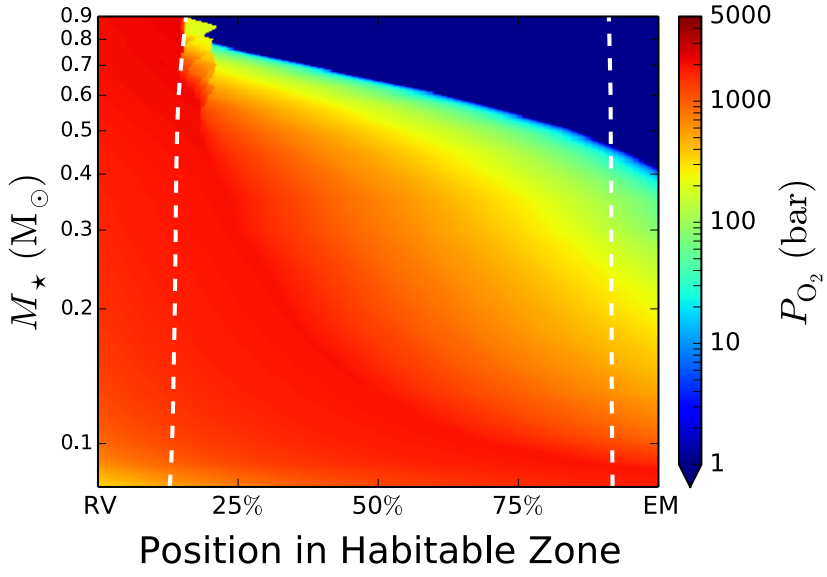
$$F_{\mathrm{H}} = \frac{\epsilon_{\mathrm{XUV}} \mathcal{F}_{\mathrm{XUV}} R_{\mathrm{p}}}{4 G M_{\mathrm{p}} K_{\mathrm{tide}} m_{\mathrm{H}}} \tag{2}$$

- Hydrodynamic mass fractionation (Hunten et al. 1987)

$$F_{\mathrm{O}} = \frac{X_{\mathrm{O}}}{X_{\mathrm{H}}} F_{\mathrm{H}} \left(\frac{m_{\mathrm{c}} - m_{\mathrm{O}}}{m_{\mathrm{c}} - m_{\mathrm{H}}}\right) \tag{3}$$

Water Loss & O_2 Buildup





A 5 $M_\oplus$ super-Earth can lose up to a few tens of Earth oceans of water and build up several thousands of bars of O_2, particularly near the inner HZ of low-mass M dwarfs.

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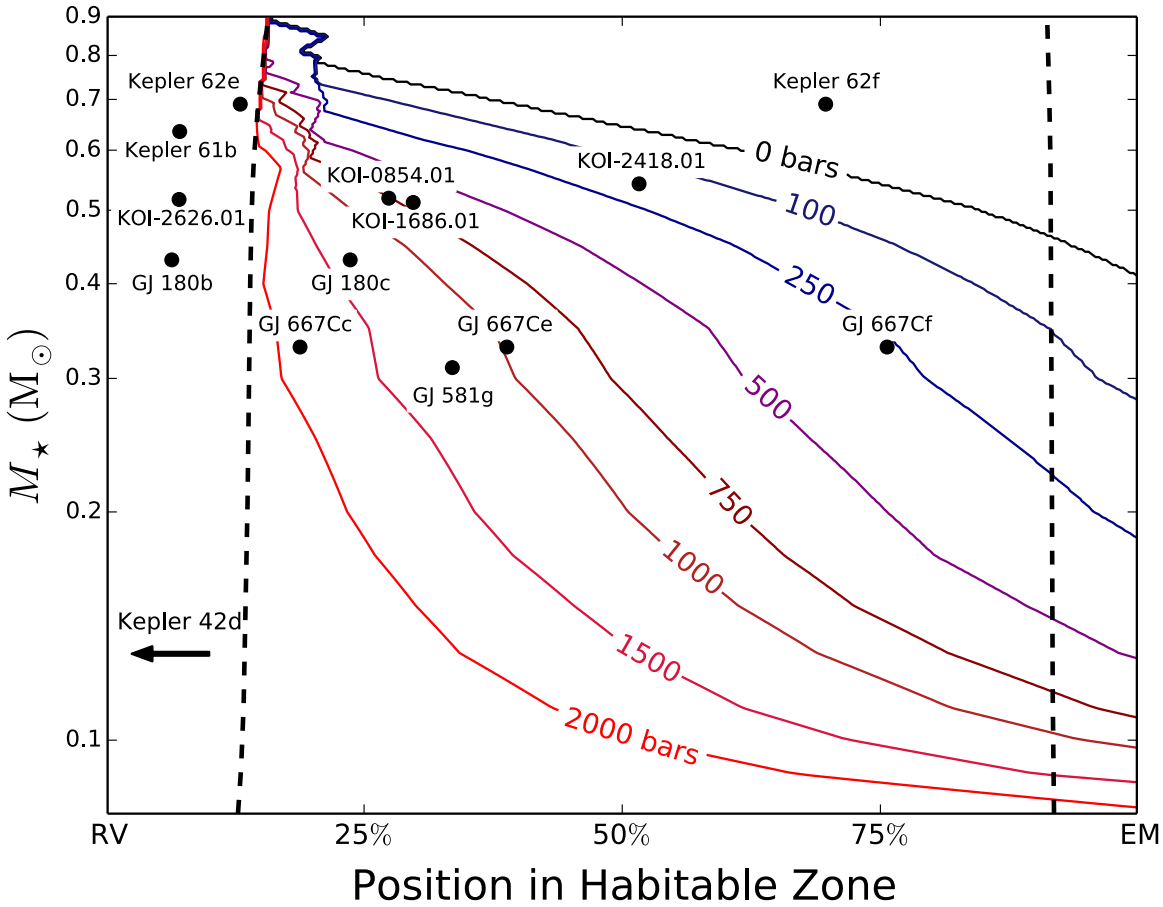
O_2 Buildup on Known Exoplanets



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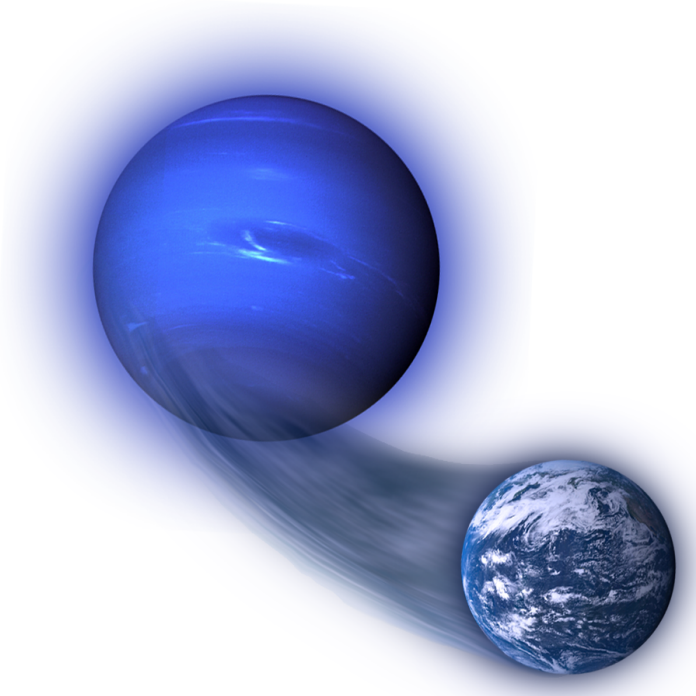
Habitable Evaporated Cores



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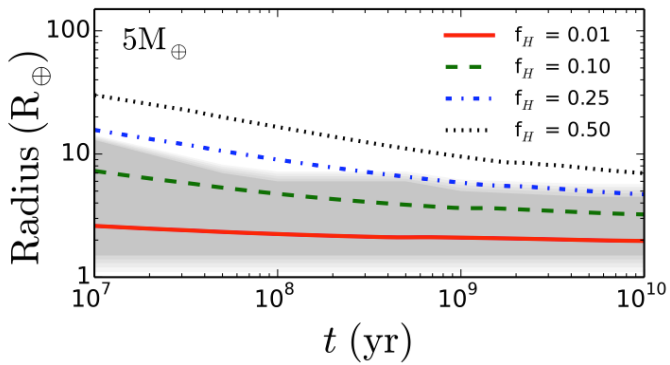
Mini-Neptune Evolution Model

- Quick formation/migration (Raymond+ 2007, Ogihara & Ida 2009)
- Thermal evolution models (Lopez and Fortney 2014)



- Energy and RR-limited escape (Erkaev+ 2007, Murray-Clay+ 2009)

$$\frac{dM_p}{dt} \approx \frac{\epsilon_{\rm XUV}\pi F_{\rm XUV} R_p R_{\rm XUV}^2}{G M_p K_{\rm tide}(\xi)} \qquad \dot{M}_{\rm RR} \approx 7.11\times10^7 {\rm g/s} \left(\frac{F_{\rm EUV}}{\rm erg/cm^2/s}\right)^{1/2} \left(\frac{R_p}{R_\oplus}\right)^{3/2}$$

- Tidal Evolution (Heller+ 2011)

$$\frac{da}{dt} = \frac{2a^2}{GM_\star M_p} \sum_{i\neq j} Z_i \left(\frac{f_2(e)}{\beta^{12}(e)} \frac{\omega_i}{n} - \frac{f_1(e)}{\beta^{15}(e)} \right)$$

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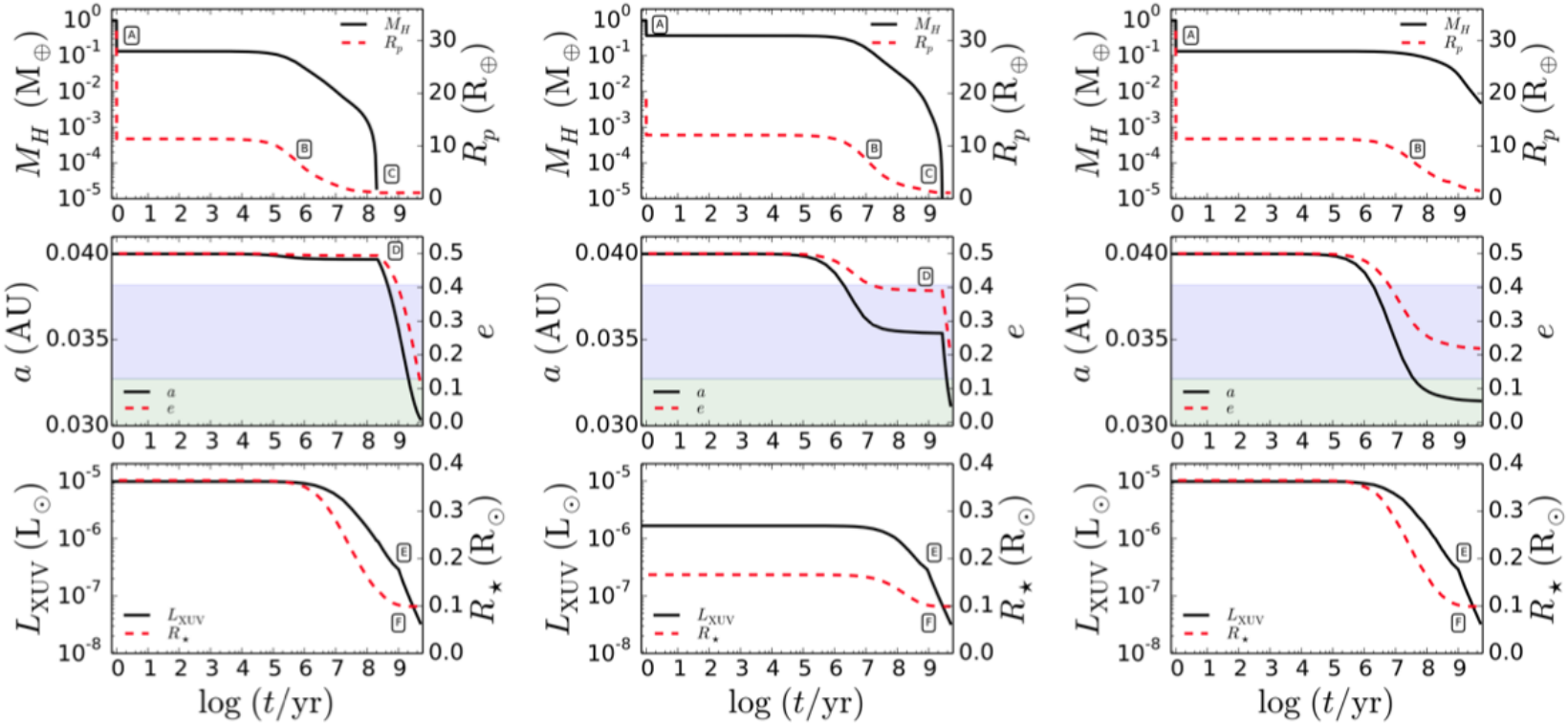
Typical Evolution



(a) Energy-Limited

(b) Energy-Limited, $t_0 = 100$ Myr

(c) Radiation/Recombination Limited

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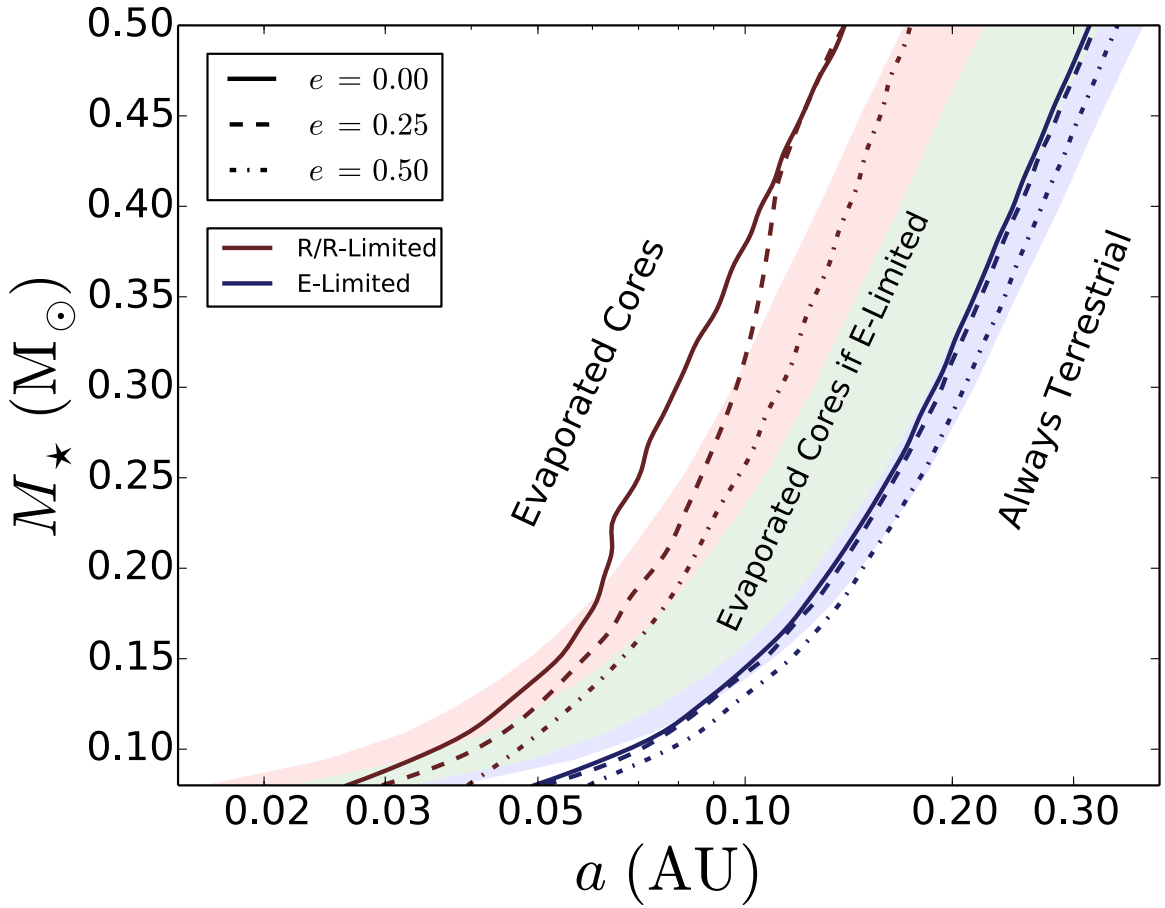
1 $M_\oplus$ Cores



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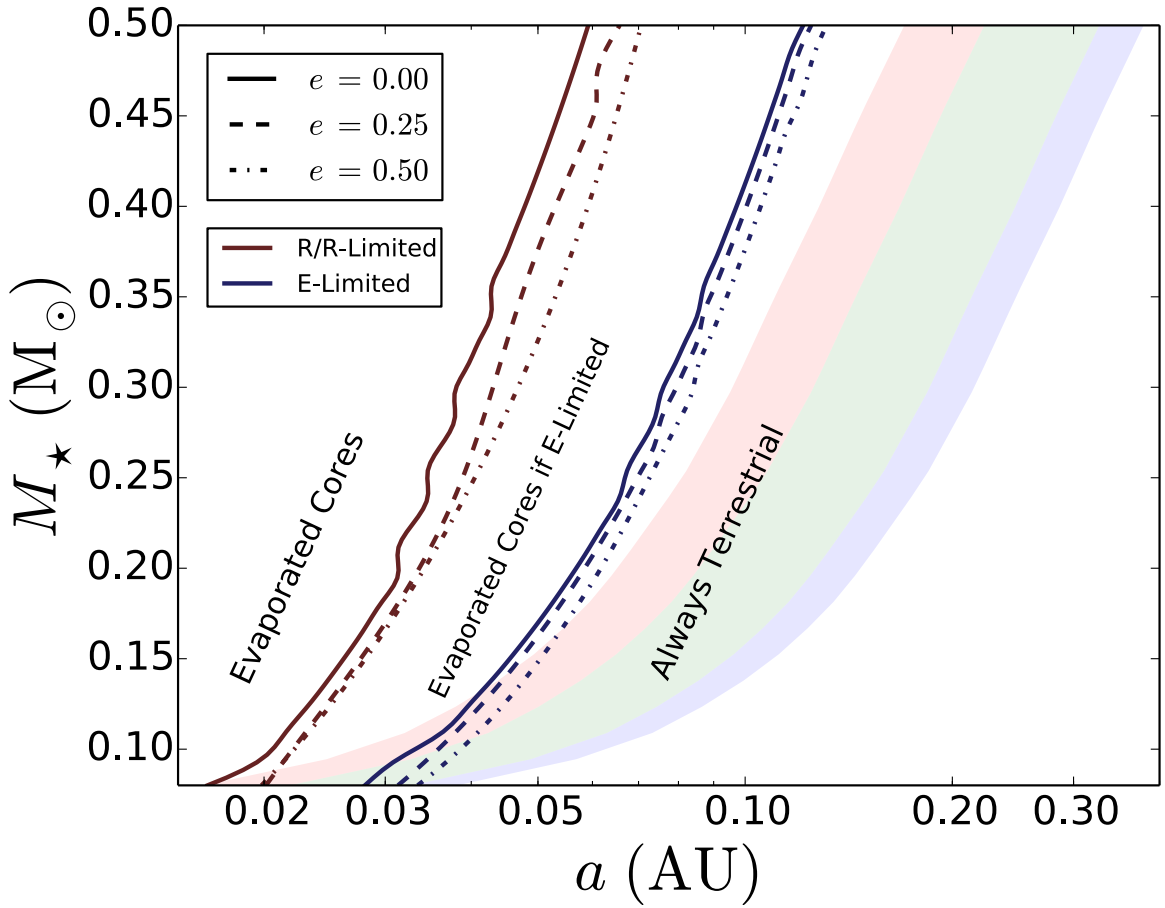
2 $M_\oplus$ Cores



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Summary & Conclusions

- Planets in the HZs of *all* M dwarfs can lose **several oceans of water** and build up **hundreds to thousands of bars** of O_2.
- **Water loss and O_2 buildup scale with planet mass.** This is essentially controlled by diffusion.
- Fast O_2 production (5–25 bars/Myr) could overwhelm surface sinks, leading to detectable levels of atmospheric O_2. **Oxygen may not be a reliable biosignature on M dwarf planets.**
- On the upside, mini-Neptunes in the HZ can **shed their hydrogen envelopes during the star's pre-main sequence phase** for core masses $\lesssim 2M_\oplus$.
- These **"habitable evaporated cores"** could exist throughout a large fraction of the HZ of low mass M dwarfs.

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