

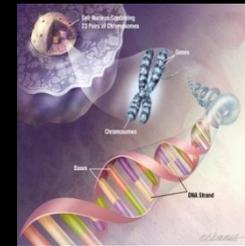
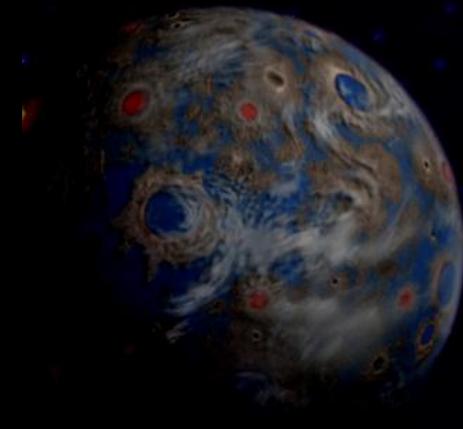
## Planetenatmosphären:

### Implikationen bei der Suche nach einer „Exo-Erde“

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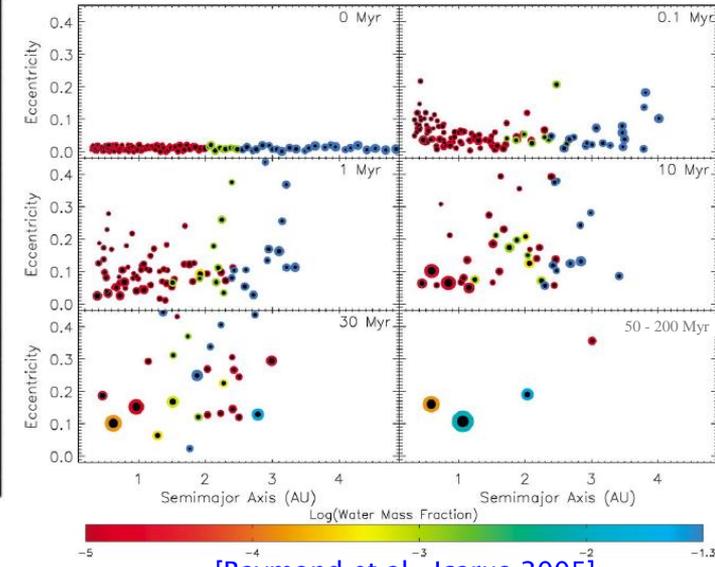
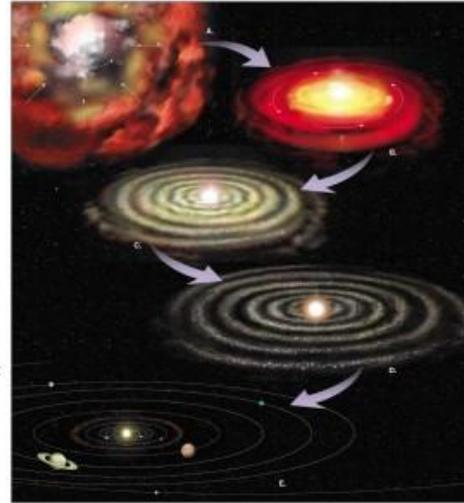
- Entstehung von Protoatmosphären
- Effekte und Stabilität der frühen Atmosphären gegen hoch-energetische Strahlung (X-ray, SXR, EUV, UV) sowie dichten- und energiereichen Teilchenflüssen
  - zeitliche Variationen der stellaren Aktivität
  - stellare Aktivität ist unterschiedlich je nach Spektraltyp des Sterns
  - stellare Aktivität kann sich über Milliarden Jahre bis auf 3 Größenordnungen ändern
- Wie konnte sich die Erdatmosphäre durch diese aktive Phase der frühen Sonne entwickeln?
- Welche Rolle spielen planetare Magnetfelder und Magnetosphären?
- Wie wichtig ist die Zusammensetzung von frühen Planetenatmosphären?
  - Waren die frühen Atmosphären reich an Wasserstoff?
  - Wie wichtig ist CO<sub>2</sub>?
  - Prozesse welche die hohe Atmosphäre kühlen
- Wie stabil sind Stickstoffatmosphären gegen extreme UV Strahlung

Planeten entstehen durch Kollisionen von Planetesimalen und planetaren Embryos  
 Planetare Nebel verschwinden nach ca. 3 bis 10 Millionen Jahren

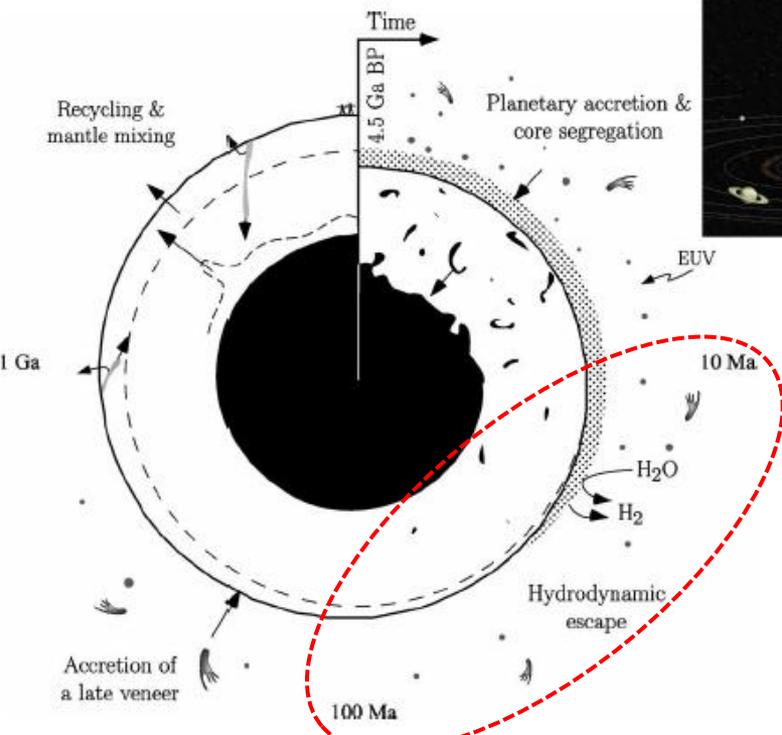
[e.g., Hayashi et al., Earth Pl. Sci. Lett. 1988; Rafikov, ApJ 2006; Ikoma and Hori, ApJ 2012]

Erde war nach 50–60 Myr fertig gewachsen

[e.g., Touboul et al., Nature 2007]



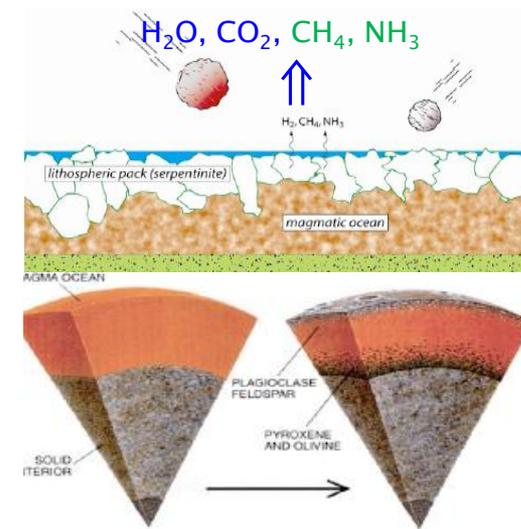
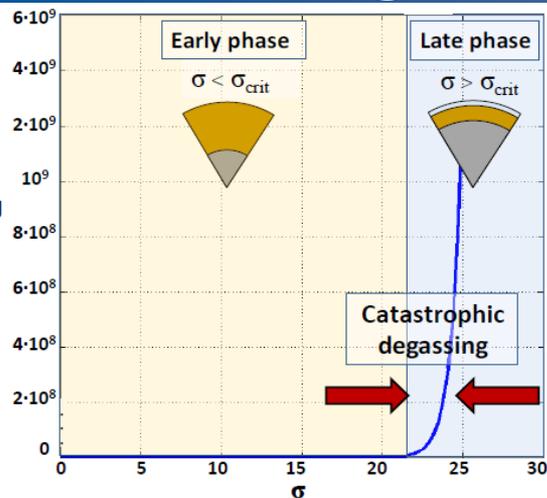
[Raymond et al., Icarus 2005]



[Dauphas, Icarus 2003]

$M/\dot{M}$ [yr]	$M$ [ $M_{\text{Earth}}$ ]	$R$ [ $R_{\text{Earth}}$ ]	$T_s$ [K]	$M_{\text{atm}}$ [g]	$M_{\text{atm}}$ [ $\text{EO}_H$ ]
$10^6$	1.0	$\sim 1.0$	$\sim 4080$	$\sim 1.5 \times 10^{26}$	$\sim 1000$
	0.5	$\sim 0.85$	$\sim 2585$	$\sim 5.3 \times 10^{25}$	$\sim 350$
	0.2	$\sim 0.62$	$\sim 1310$	$\sim 2.0 \times 10^{25}$	$\sim 135$
	0.1	$\sim 0.5$	$\sim 690$	$\sim 8.5 \times 10^{24}$	$\sim 55$
$10^7$	1.0	$\sim 1.0$	$\sim 3980$	$\sim 3.3 \times 10^{26}$	$\sim 2200$
	0.5	$\sim 0.85$	$\sim 2500$	$\sim 7.5 \times 10^{25}$	$\sim 500$
	0.2	$\sim 0.62$	$\sim 1240$	$\sim 2.0 \times 10^{25}$	$\sim 135$
	0.1	$\sim 0.5$	$\sim 625$	$\sim 8.5 \times 10^{24}$	$\sim 55$

[Hayashi et al., Earth Pl. Sci. Lett. 1988; Matsui and Abe, Science 1986]



	0.05 wt %	0.1 wt%	0.5 wt %	1 wt %	3 wt %
$1M_{\text{Earth}}$	~250 bar	~500 bar	~7000 bar	~15000 bar	~23000 bar

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## Linked magma ocean solidification and atmospheric growth for Earth and Mars

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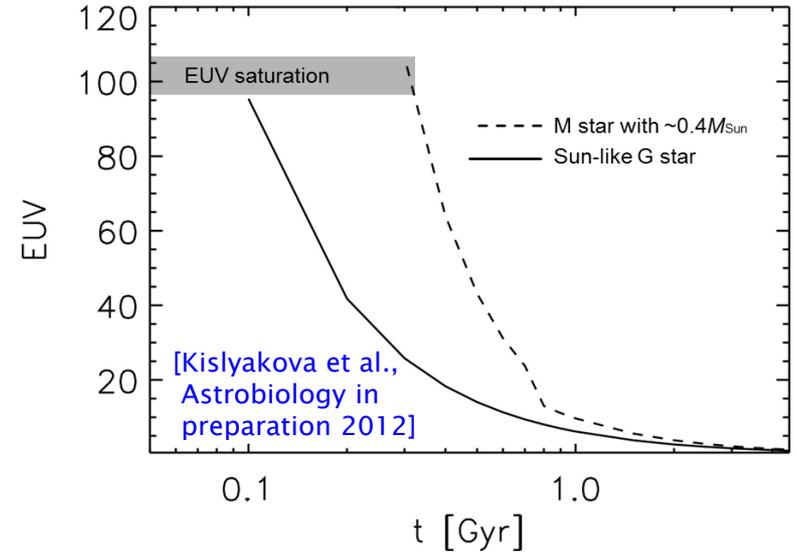
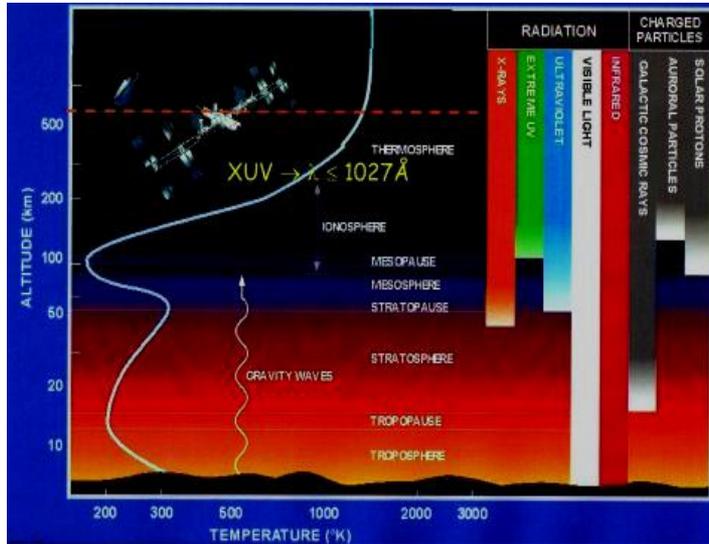
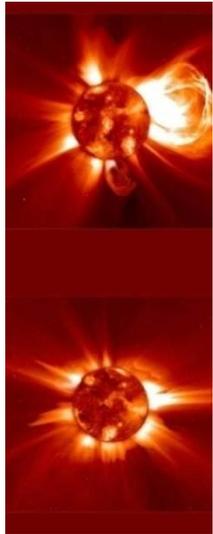
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 atmosphere  
 cement conditions

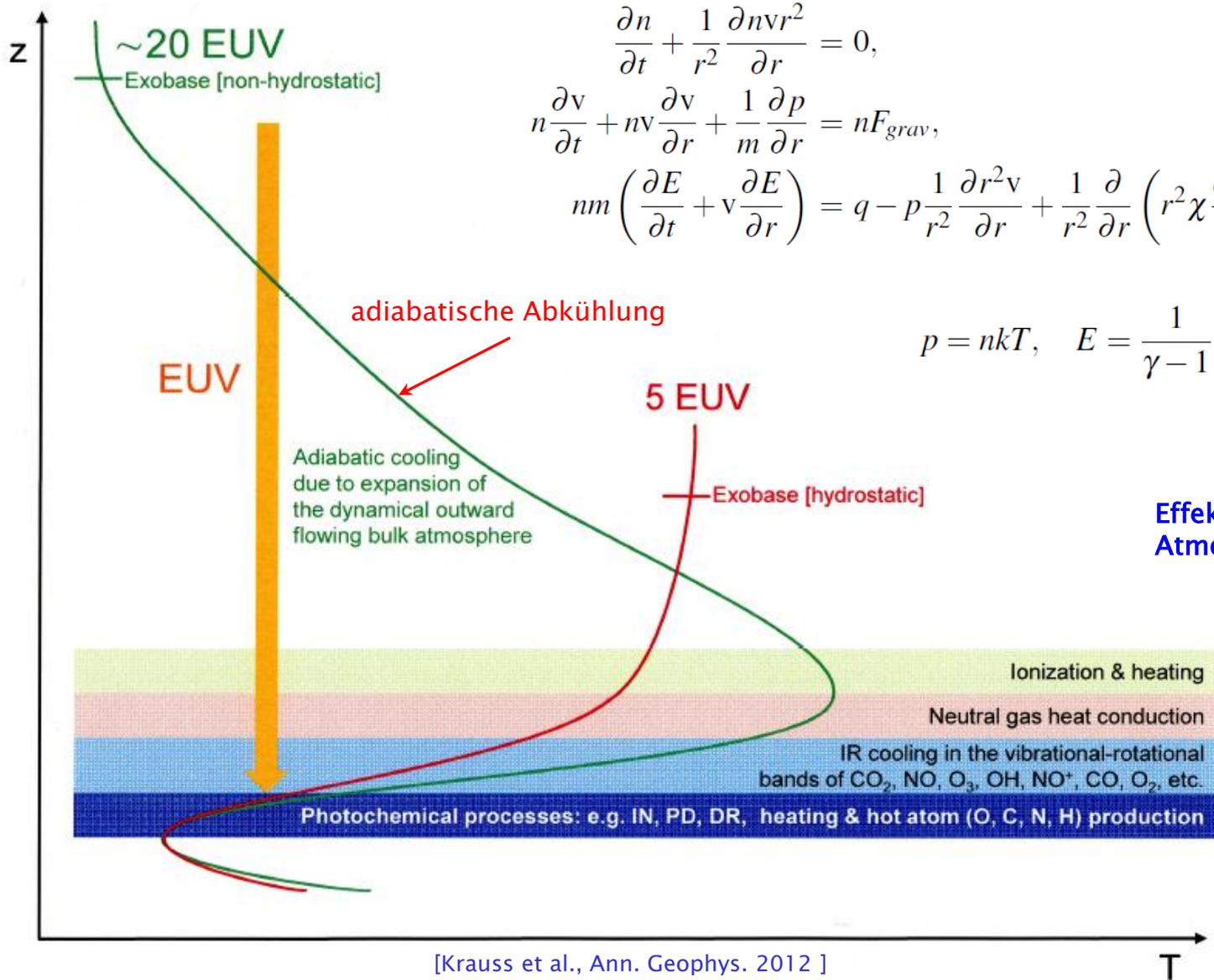
### ABSTRACT

Early in terrestrial planet evolution energetic impact, radiodecay, and core formation may have created one or more whole or partial silicate mantle magma oceans. The time to mantle solidification and then to cement surface conditions allowing liquid water is highly dependent upon heat flux from the planetary surface through a growing primitive atmosphere. Here we model the time to cement conditions for whole and partial magma oceans on the Earth and Mars, and the resulting silicate mantle volatile compositions. Included in our calculations are partitioning of water and carbon dioxide between solidifying mantle cumulate mineral assemblages, evolving liquid compositions, and a growing atmosphere. We find that small initial volatile contents (0.05 wt% H<sub>2</sub>O, 0.01 wt% CO<sub>2</sub>) can produce atmospheres in excess of 100 bars, and that mantle solidification is 98% complete in less than 5 Myr for all magma oceans investigated on both Earth and Mars, and less than 100,000 yr for low-volatile magma oceans. Subsequent cooling to cement surface conditions occurs in five to tens of Ma, underscoring the likelihood of serial magma oceans and punctuated cement conditions in the early planets. Cumulate mantles are volatile-bearing and stably stratified following solidification, inhibiting the onset of thermal convection but allowing for further water and carbon emissions from volcanoes even in the absence of plate tectonics. Models thus produce a new hypothetical starting point for mantle evolution in the terrestrial planets.

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Solar age [Gyr]	$t$ b.p. [Gyr]	X-ray [1–20 Å]	SXR [20–100 Å]	EUV [100–920 Å]	FUV [920–1180 Å]	Lyman- $\alpha$ [1200–1300 Å]	UV [1300–1700 Å]
0.7	3.9	37	11	8.6	5	3.9	—
0.65	3.95	43	12	9.4	5.3	4.1	5.8
0.6	4.0	50	13	10	5.7	4.3	—
0.55	4.05	59	15	11	6.1	4.6	—
0.5	4.1	71	17	13	6.6	4.9	—
0.45	4.15	87	19	14	7.2	5.3	—
0.4	4.2	109	22	17	8	5.8	—
0.35	4.25	141	26	19	9	6.4	—
0.3	4.3	189	32	23	10	7.1	10.6
0.25	4.35	268	40	28	12	8.1	—
0.2	4.4	412	54	37	14	9.6	—
0.15	4.45	715	77	51	18	11.8	—
0.1	4.5	1558	129	82	26	15.8	40.5



$$\frac{\partial n}{\partial t} + \frac{1}{r^2} \frac{\partial nvr^2}{\partial r} = 0,$$

$$n \frac{\partial v}{\partial t} + nv \frac{\partial v}{\partial r} + \frac{1}{m} \frac{\partial p}{\partial r} = nF_{grav},$$

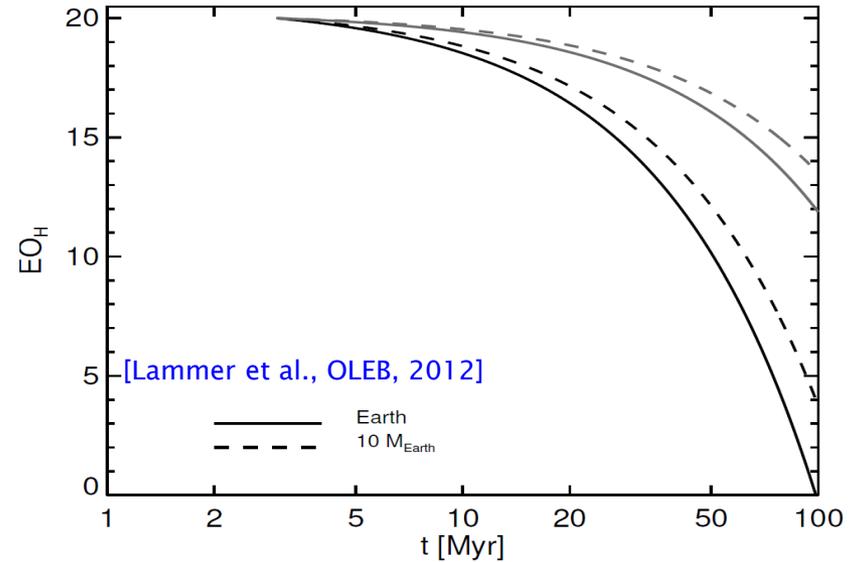
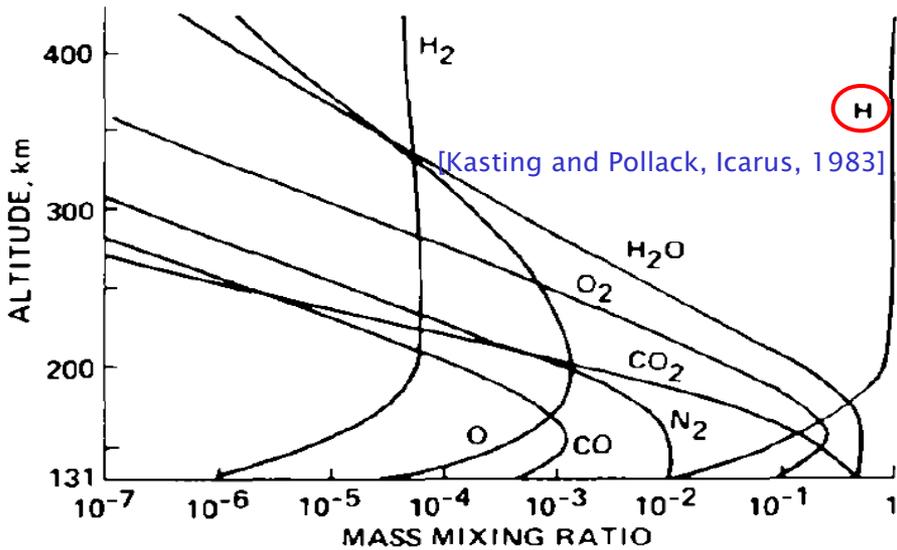
$$nm \left( \frac{\partial E}{\partial t} + v \frac{\partial E}{\partial r} \right) = q - p \frac{1}{r^2} \frac{\partial r^2 v}{\partial r} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \chi \frac{\partial T}{\partial r} \right)$$

$$p = nkT, \quad E = \frac{1}{\gamma - 1} \frac{p}{nm}$$

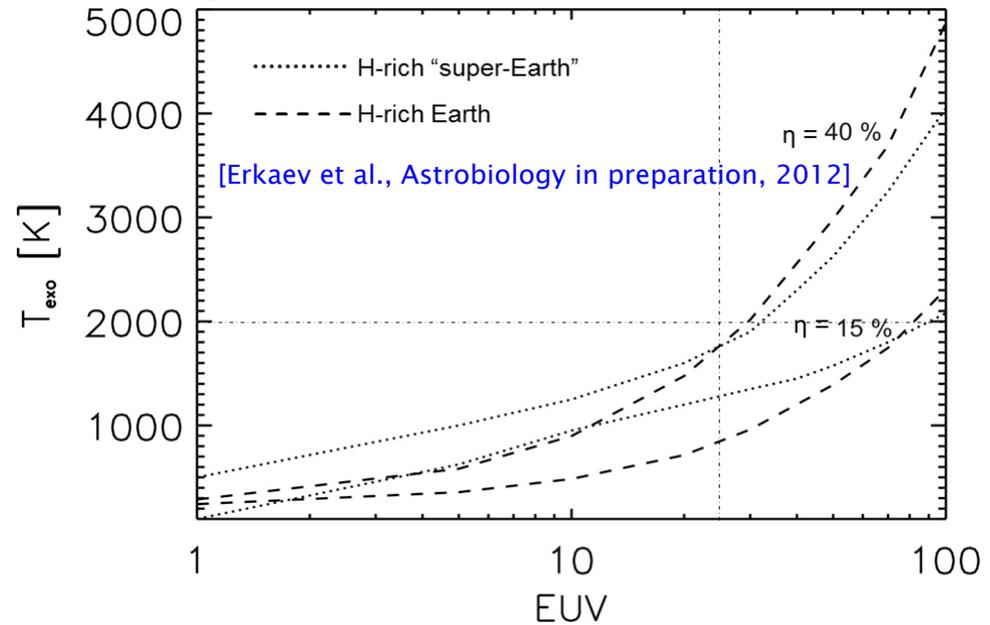
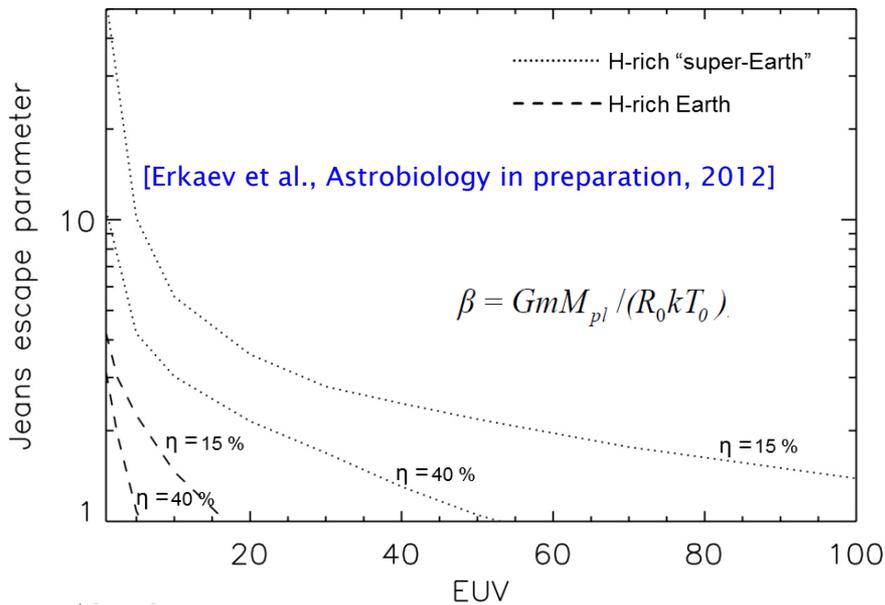
## Effektivität der Atmosphärenflucht

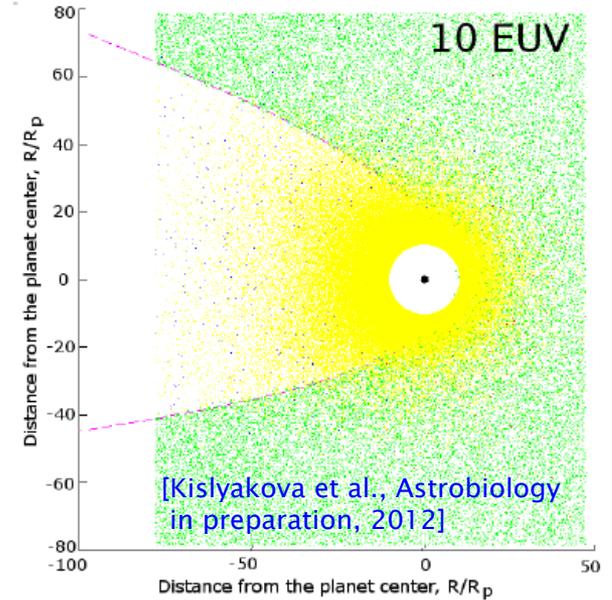
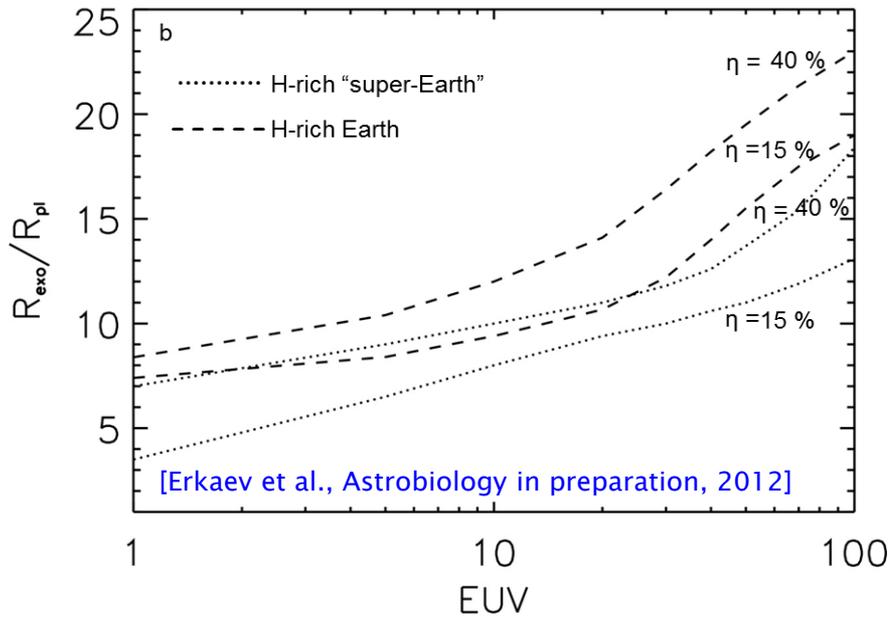
- Temperatur und Dichte in der unteren Atmos.
- Art der Bestandteile
- Kühlung
- Orbit (EUV, X-ray, Sternwind)

[Krauss et al., Ann. Geophys. 2012 ]

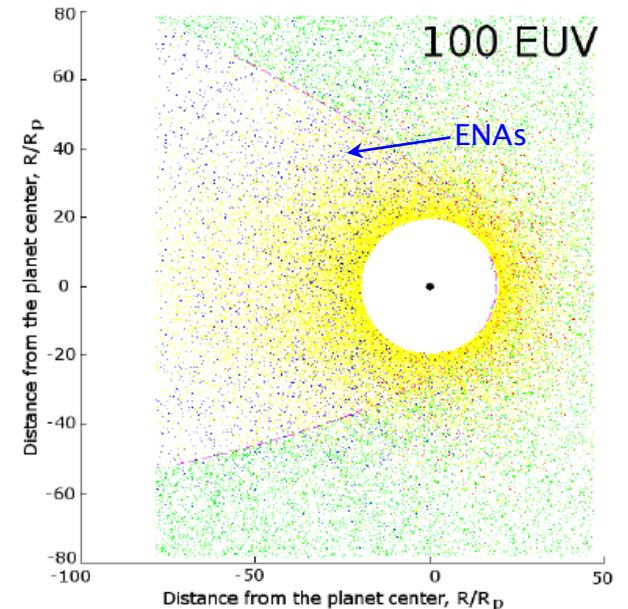
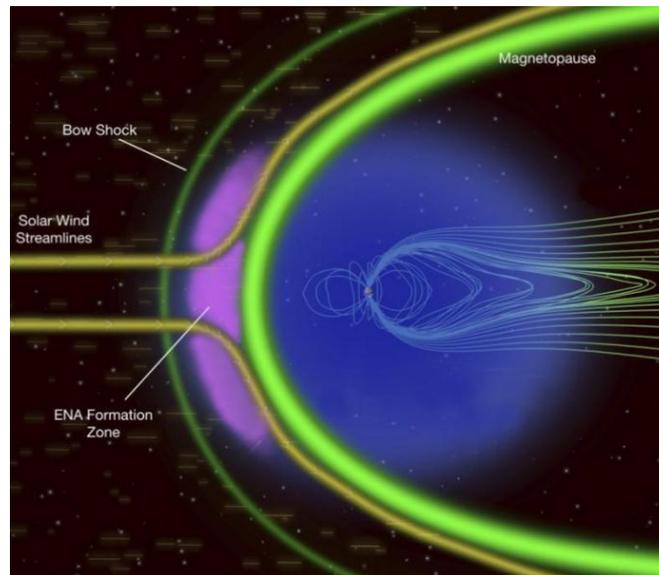
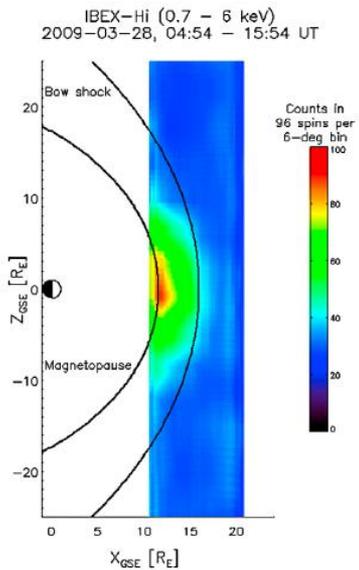


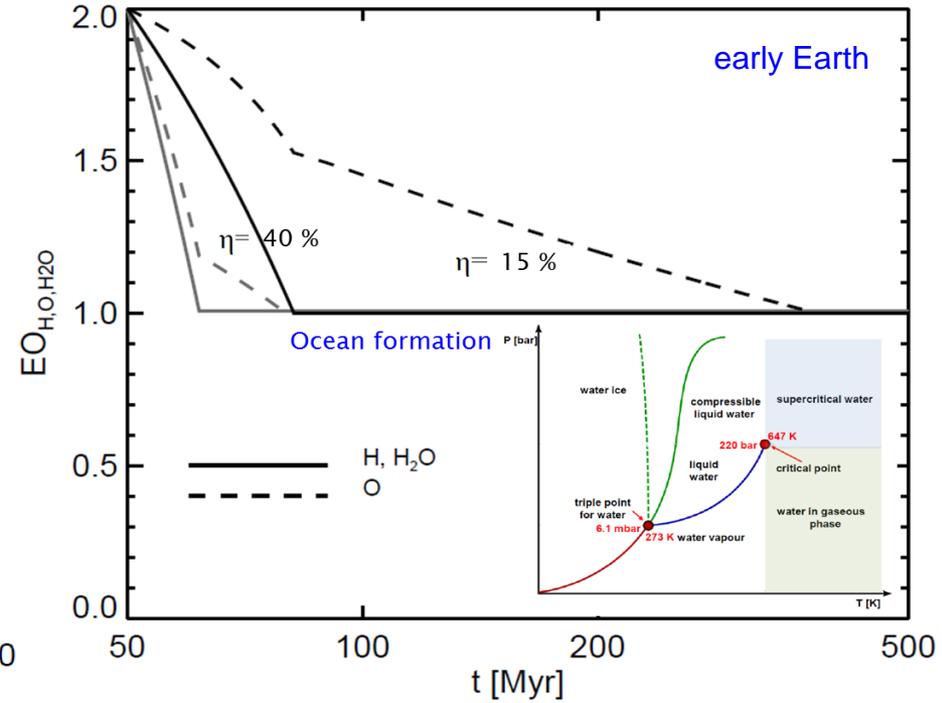
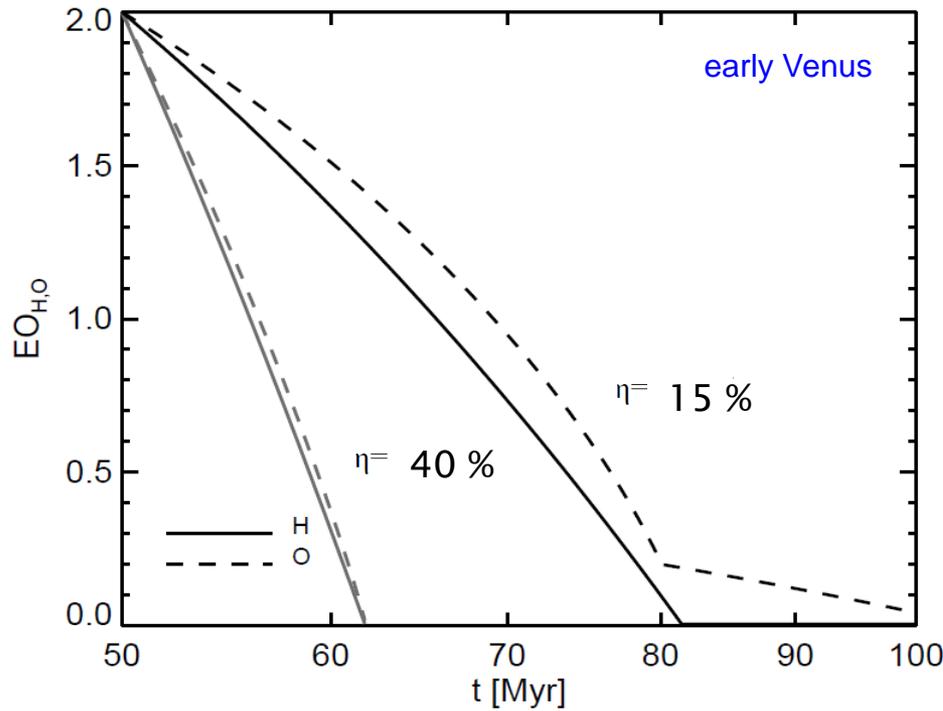
Extremste Bedingungen während der ersten 100 Millionen Jahre  
 → heiße Atmosphären, häufige Kollisionen mit großen Asteroiden





[Fuselier et al., GRL, 2010]





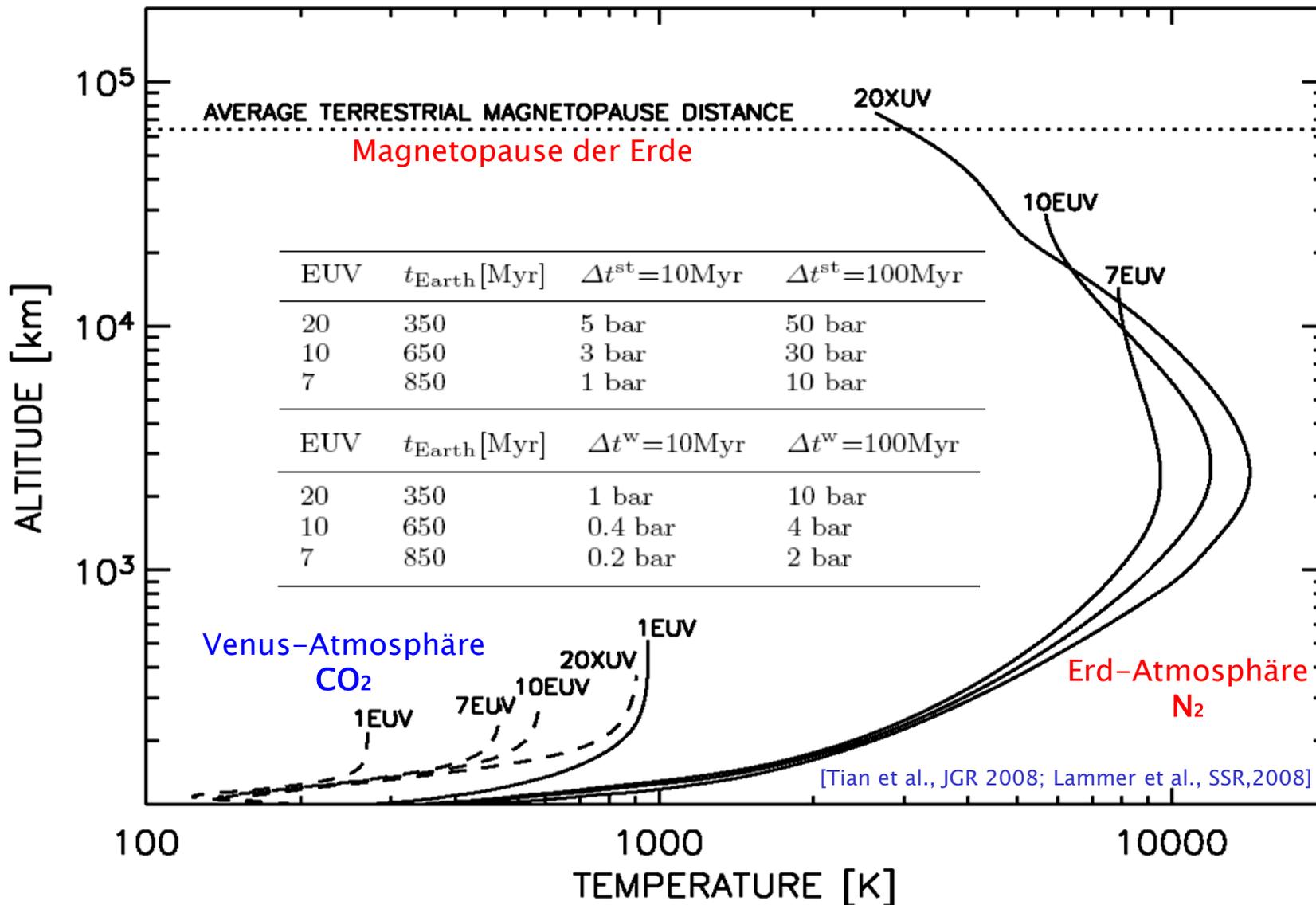
$$F_{O,C,N} = \frac{3\eta S_{EUV} F_{EUV} X_{O,C,N}}{8\pi r_{sv} G \rho_{pl} m_H X_H} \left[ \frac{\left( m_H + \frac{kT \frac{3\eta S_{EUV} F_{EUV}}{8\pi r_{sv} G \rho_{pl} m_H}}{bg X_H} \right) - m_{O,C,N}}{\left( m_H + \frac{kT \frac{3\eta S_{EUV} F_{EUV}}{8\pi r_{sv} G \rho_{pl} m_H}}{bg X_H} \right) - m_H} \right]$$

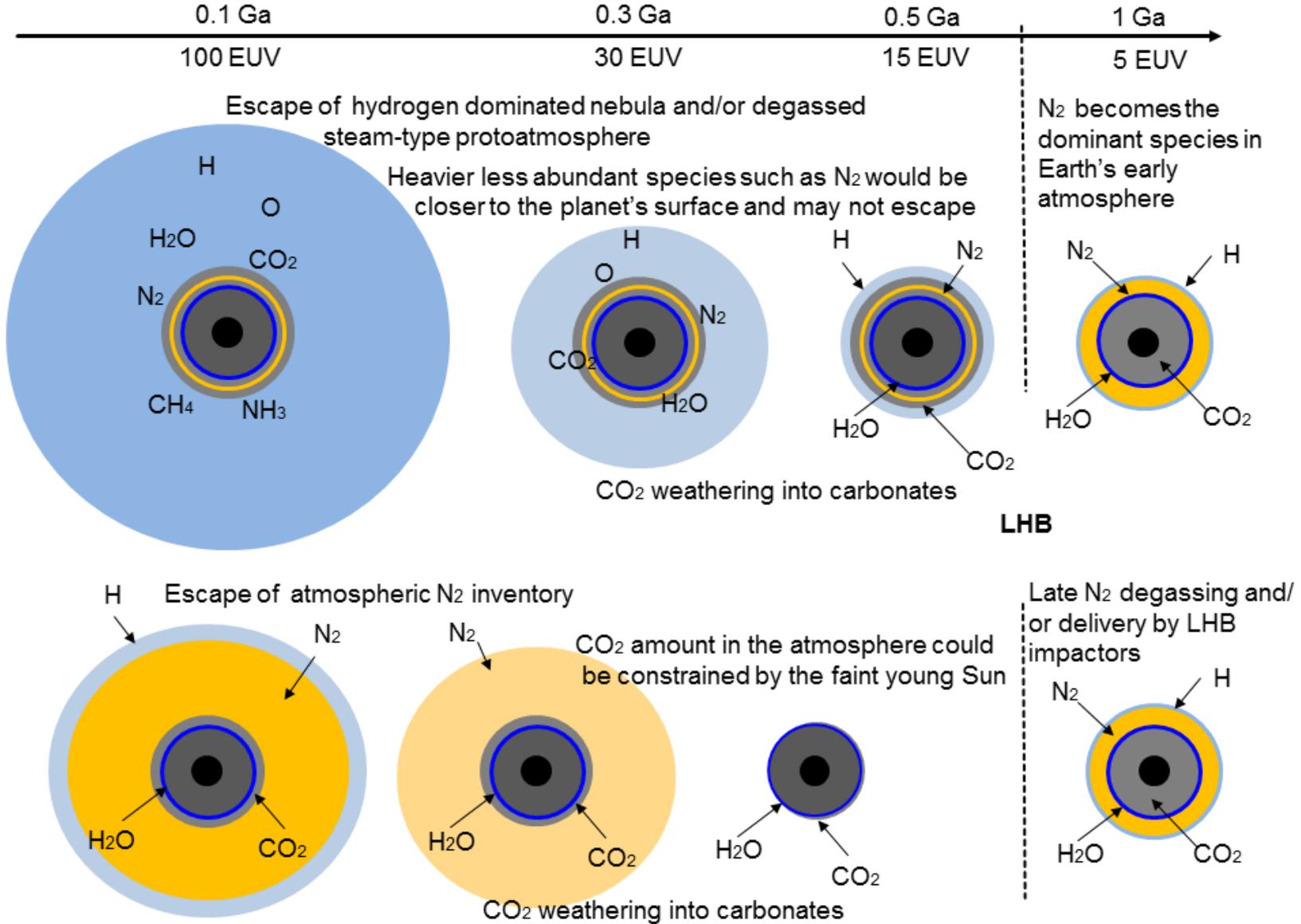
Species	H <sub>2</sub> O	CO <sub>2</sub>	Cl	N <sub>2</sub>	S	Ar, etc.
P [bar]	~250–550	~50–70	~7	≥1	≥0.5	0.03

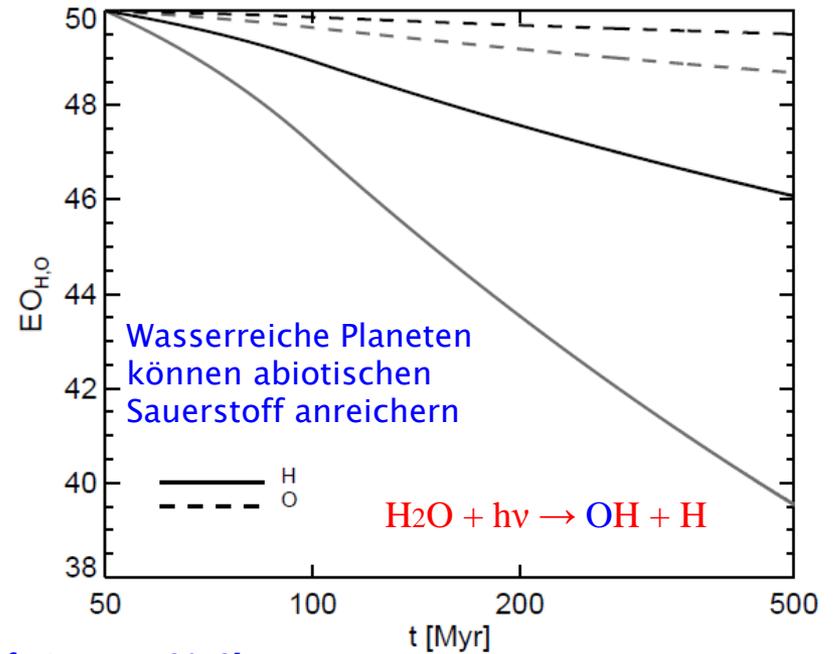
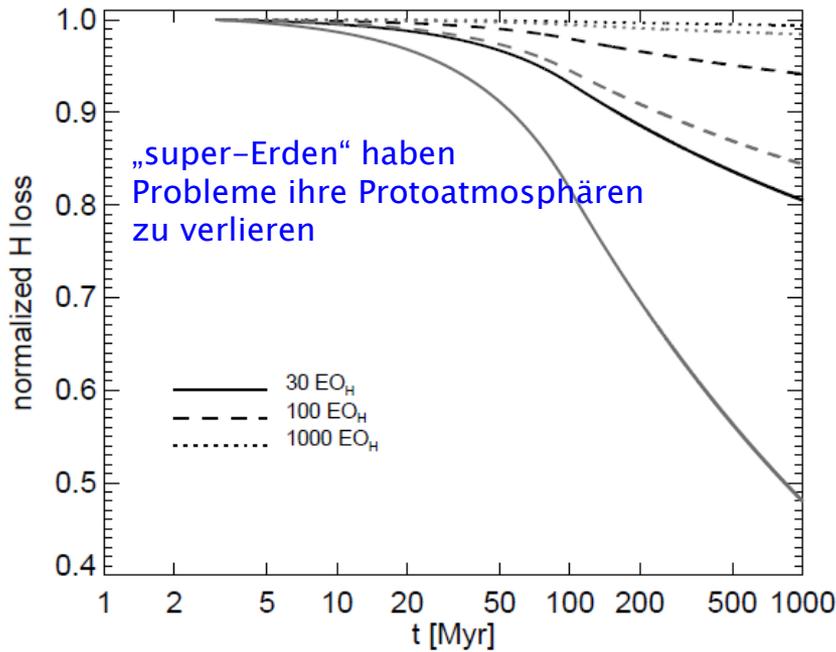
[e.g., Rubey, Bull. Geo. Soc. Am. 1952;  
Elkins-Tanton, Planet. Sci. Lett. 2008]

[Lammer, Springer Briefs, in press, 2012]

[Lichtenegger et al., Icarus 2010; Lammer et al., OLEB 2012]

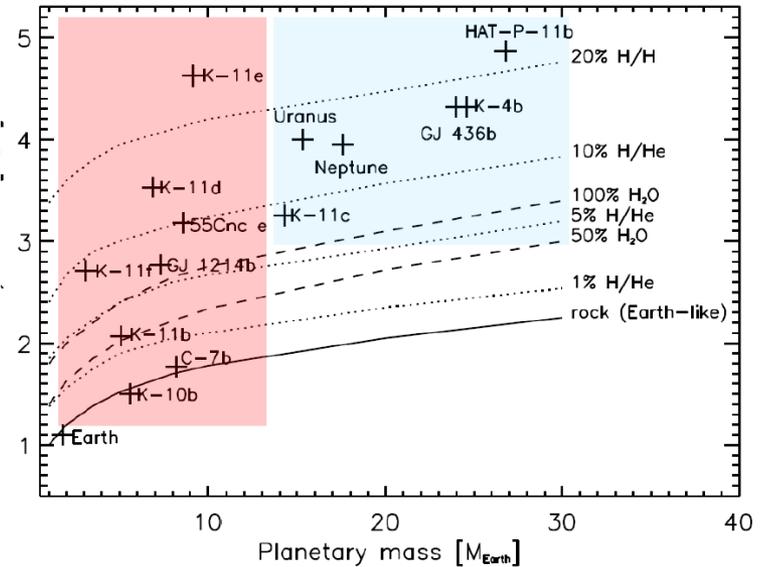




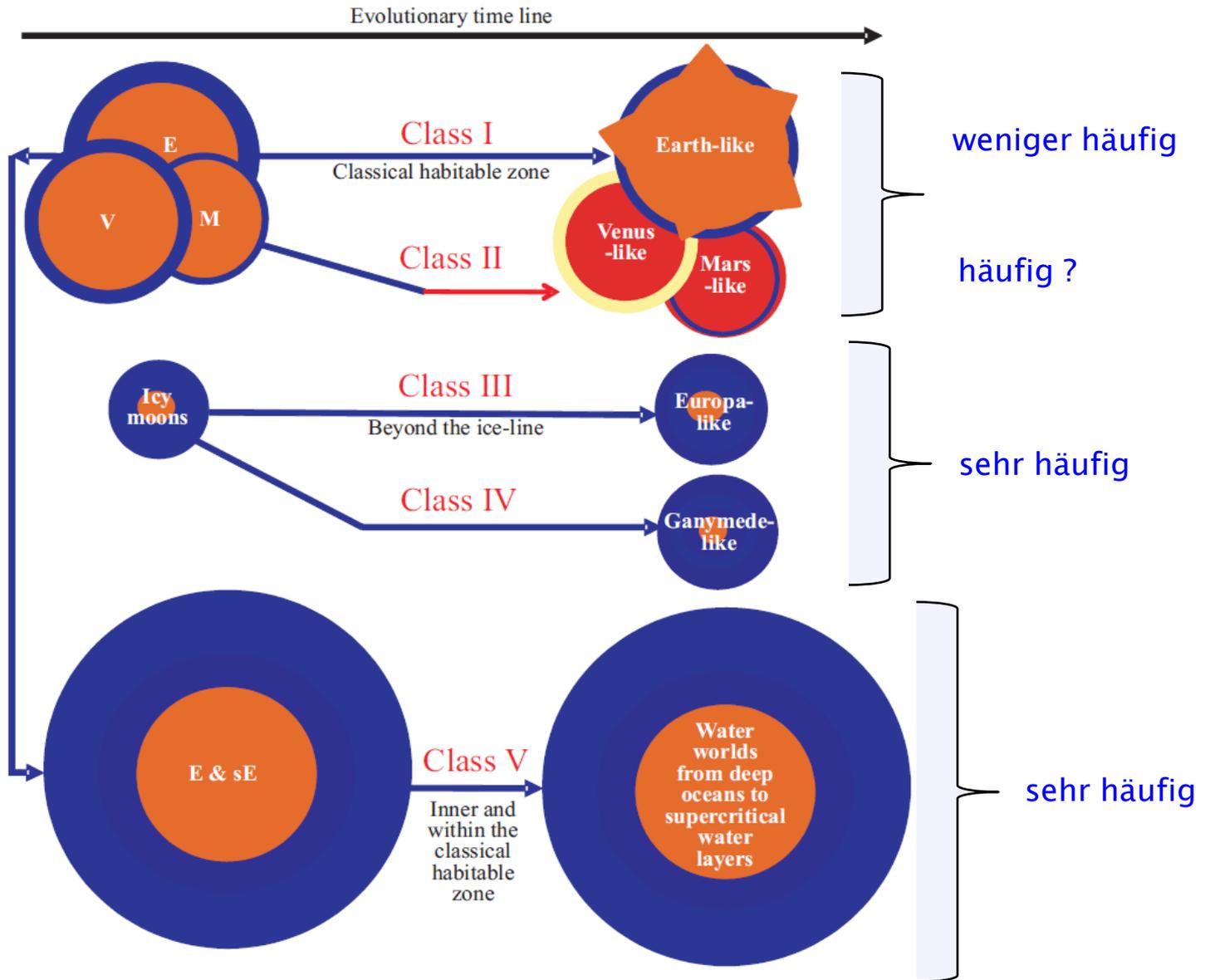


[Lammer, Springer Briefs, in press, 2012]

Planet	$R_{pl}$ [ $R_{Earth}$ ]	$M_{pl}$ [ $M_{Earth}$ ]	Star-type	Star mass [ $M_{Sun}$ ]	$T$ [K]	$d$ [AU]
GJ 1214b	~2.678	~6.55	M	0.153	2949	0.014
GJ 436b	~4.3	~22.2	M2.5	0.452	3684	0.02887
55 Cnc e	~2.0	~8.63	K01V-V	0.905	5196	0.0156
CoRoT-7b	~1.58	~7.42	K0V	0.93	5275	0.0172
HAT-P-11b	~4.58	~26.0	K4	0.81	4780	0.053
Kepler-10b	~1.4	~4.56	G	0.895	5672	0.01684
Kepler-4b	~3.87	~24.47	G0	1.223	5857	0.0456
Kepler-11b	~1.97	~4.3	G	0.95	5680	0.091
Kepler-11c	~3.15	~13.5	G	0.95	5680	0.106
Kepler-11d	~3.43	~6.1	G	0.95	5680	0.159
Kepler-11e	~4.52	~8.4	G	0.95	5680	0.194
Kepler-11f	~2.61	~2.3	G	0.95	5680	0.25



„super-Erden“ mit bekannten Radien und Massen



[Lammer, Springer Briefs, in press, 2012]

- Die habitable Zone ist ein wichtiger Bestandteil für die Evolution von erdähnlichen Planeten – gibt aber keine Garantie dafür ab, dass sich ein Planet sich zu einer zweiten Erde entwickeln muss
- Wann und von wo bekam die Erde ihren Stickstoff?
  - Vulkane?
  - Asteroiden (spätes schweres Bombardement)?
  - Problem bezüglich der Stabilität von Stickstoffatmosphären
- Viele erdähnliche Planeten und „super-Erden“ können sehr wahrscheinlich ihre Wasserstoffreichen Protoatmosphären nicht verlieren → ineffiziente Atmosphärenflucht
- „Erd-analoge Planeten“ scheinen weniger häufig zu entstehen als „exotische Habitate“
- Diese Hypothesen können durch Beobachtungen und Modellrechnungen in der nahen Zukunft verifiziert werden → siehe nächster Vortrag von K. G. Kislyakova

