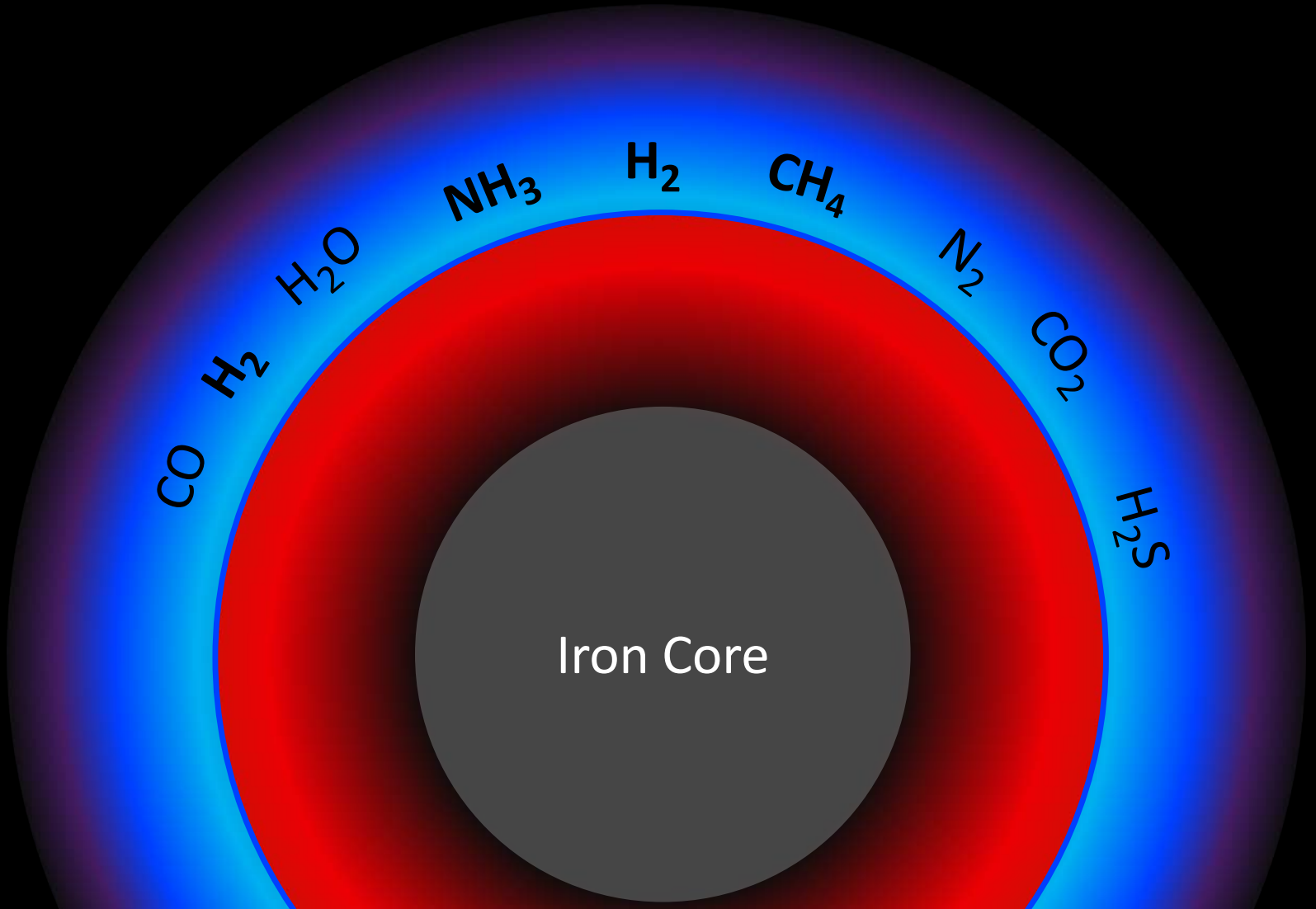
Impact creation of Urey-Miller atmospheres on Earth

Presenter: Kevin Zahnle NASA Ames Research Center
also: Richard Carlson, David Catling, Roxanu Lupu, Nicholas Wogan



September 17, 2020

Outline:

- A paradox
- What is the “Late Veneer” and why do we care?
  (No time to do the subject justice today)
- What is Impact Degassing? What is Quenching?
  (and what are mineral buffers? also another day...)
- Impact processing of pre-existing atmospheres
  Initial conditions, creation, and photochemical evolution of reduced atmospheres
- Recap and a Pretentious Speculation

Since Haldane (1929) and Oparin (1937), most students of the material origin of life have stressed the need for a reduced atmosphere containing H_2, CH_4, and either NH_3 or HCN

Geologists have for nearly as long (e.g, Poole 1951) argued that any atmosphere exhaled from Earth's mantle would be weakly reducing at most, with a strong preference for CO_2 and N_2

Urey (PNAS 1952) sided with Oparin. Our presence means that Earth's early atmosphere was reduced, and any story of Earth's formation in the Solar System must account for this

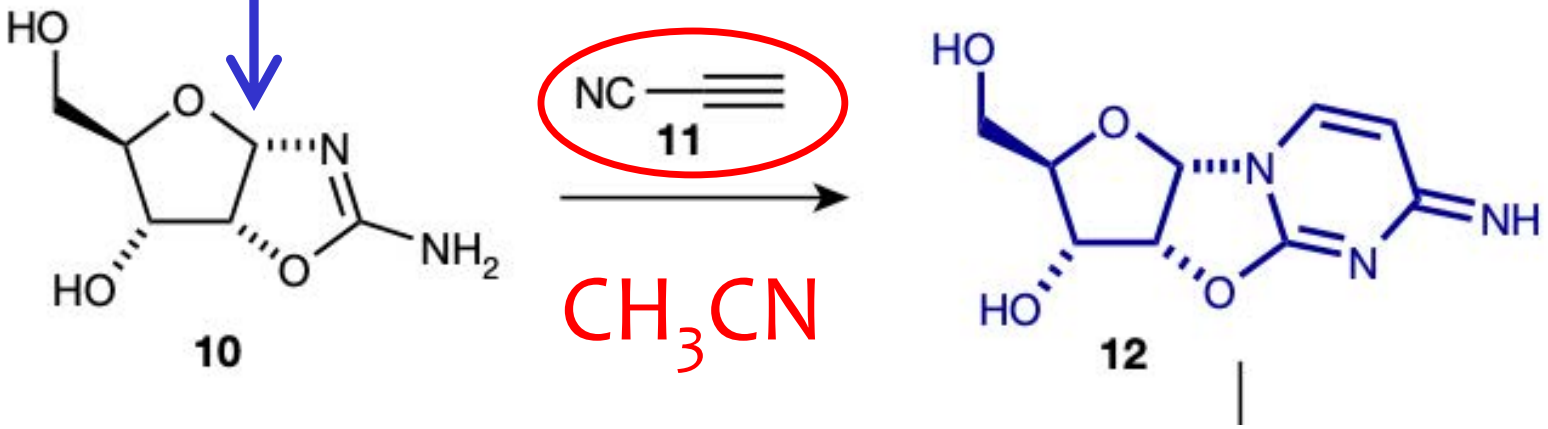
Geologists have dug in. The current idea is FeO disproportionates under high pressure to Fe and Fe2O3, which leaves the mantle oxidized and Fe-depleted

$NH_2CN \leftrightarrow HNCNH$

"**Cyanamide** reacts especially rapidly with **ribose** to form a stable bicyclic adduct ... Furthermore, when employing a racemic mixture of d- and l-ribose, enantiomerically twinned crystals are formed that contain discrete **homochiral** domains. "

Springsteen & Joyce, J Am Chem Soc. 126: 9578-83 (2004).

Previously: pyrimidine ribonucleosides

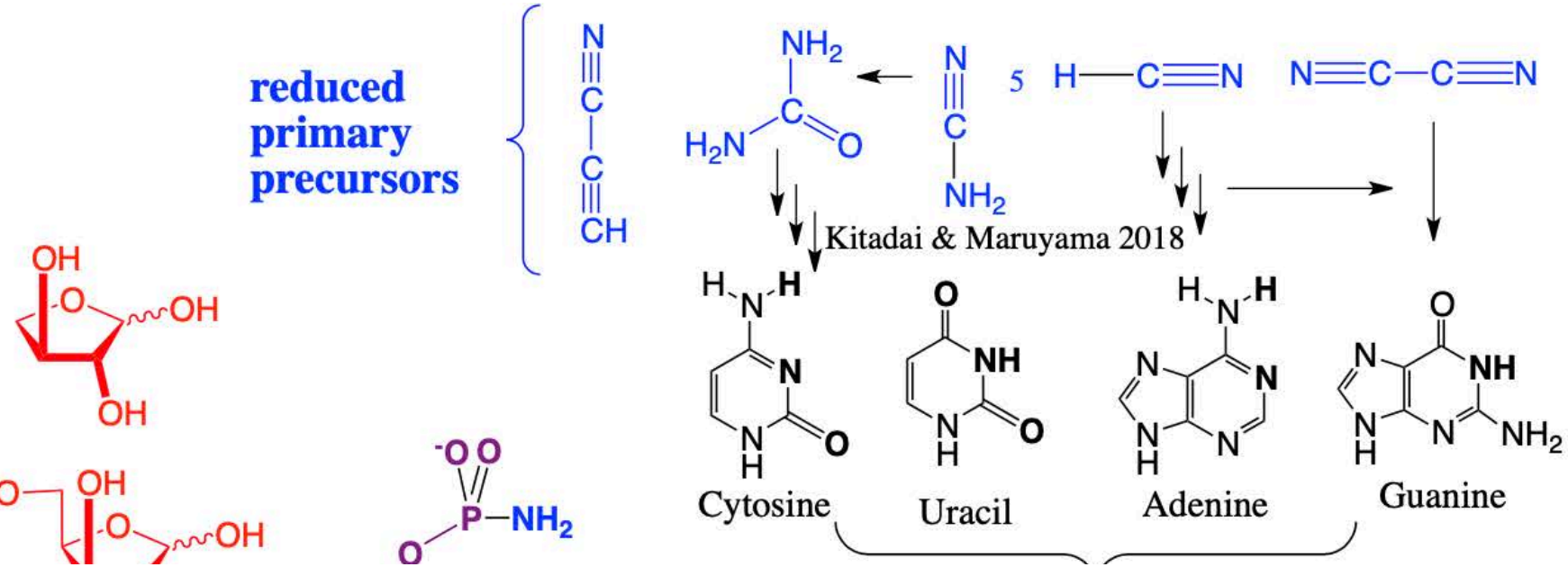


etc.

Selective prebiotic formation of RNA pyrimidine and DNA purine nucleosides

60 | Nature | Vol 582 | 4 June 2020

Jianfeng Xu[1,6], Václav Chmela[1,6], Nicholas J. Green[1], David A. Russell[1], Mikołaj J. Janicki[2], Robert W. Góra[2], Rafał Szabla[3,4], Andrew D. Bond[5] & John D. Sutherland[1]✉



screenshot from Steve Benner and his Templeton gang, 2019

This stuff is made in N2-CH4 atmospheres

Table 2. Retrieved Molecular Abundances at 300 km **on Titan**

	Species	Abundance (ppb)
acrylonitrile, vinyl cyanide	C_2H_3CN	3.03 (0.29)
propionitrile, ethyl cyanide	C_2H_5CN	7.37 (0.32)
cyanoacetylene	HC_3N[a]	4.50 (0.75)
acetonitrile, methyl cyanide	CH_3CN[a]	12.7 (0.3)

Note. Values in parentheses denote 1σ error margins.

Mapping Vinyl Cyanide and Other Nitriles in Titan's Atmosphere Using ALMA

J. C.-Y. Lai[1,2], M. A. Cordiner[1,3], C. A. Nixon[1], R. K. Achterberg[1], E. M. Molter[1,4], N. A. Teanby[5], M. Y. Palmer[1,3], S. B. Charnley[1], J. E. Lindberg[1], Z. Kisiel[6], M. J. Mumma[1], and P. G. J. Irwin[7]

− Hide full author list

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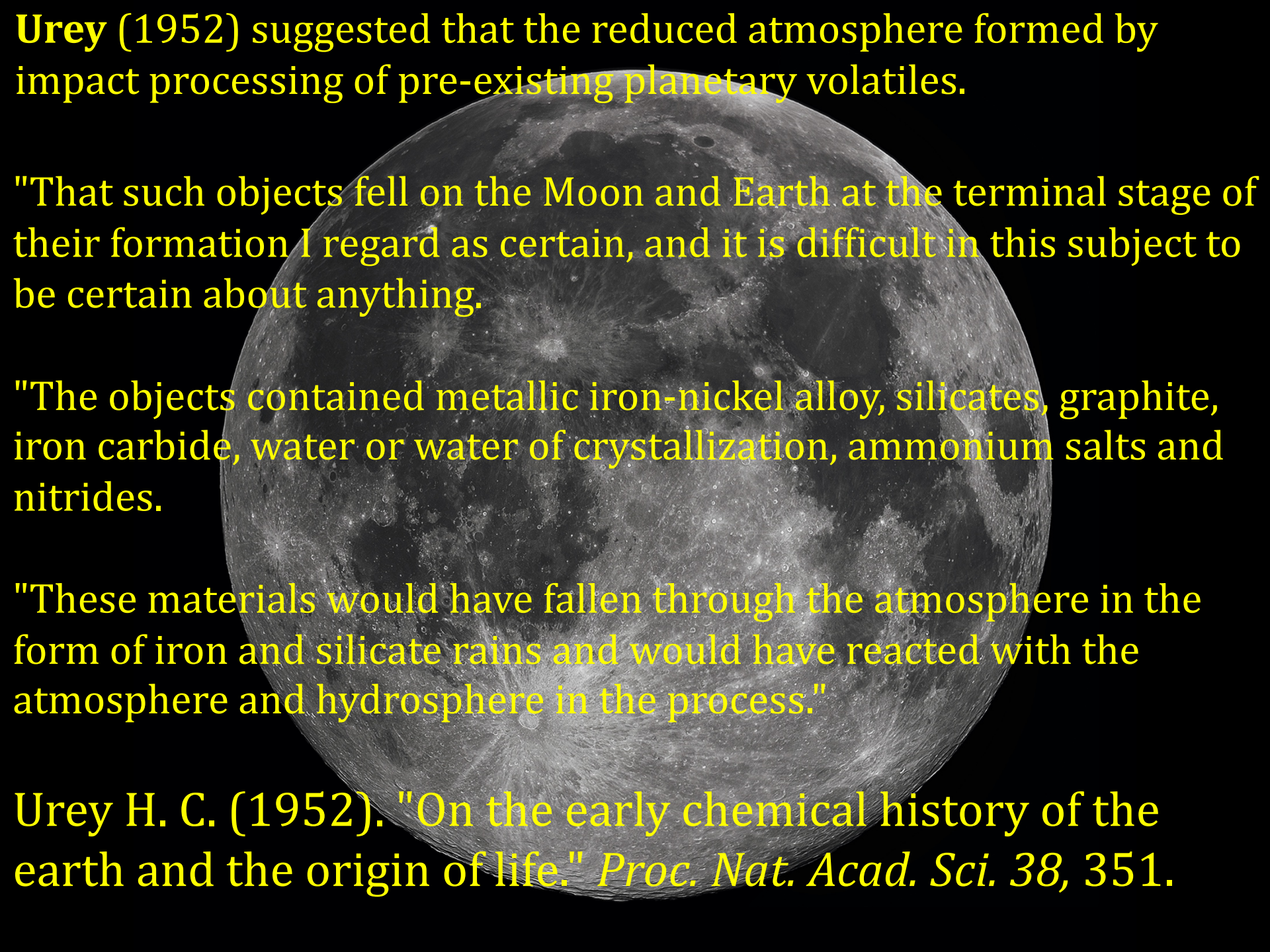
Atmosphere must be Reduced

Atmosphere must be Oxidized

We have a paradox

At this point, Steven Benner quotes Niels Bohr

“Now we have some hope of making progress”



Urey (1952) suggested that the reduced atmosphere formed by impact processing of pre-existing planetary volatiles.

"That such objects fell on the Moon and Earth at the terminal stage of their formation I regard as certain, and it is difficult in this subject to be certain about anything.

"The objects contained metallic iron-nickel alloy, silicates, graphite, iron carbide, water or water of crystallization, ammonium salts and nitrides.

"These materials would have fallen through the atmosphere in the form of iron and silicate rains and would have reacted with the atmosphere and hydrosphere in the process."

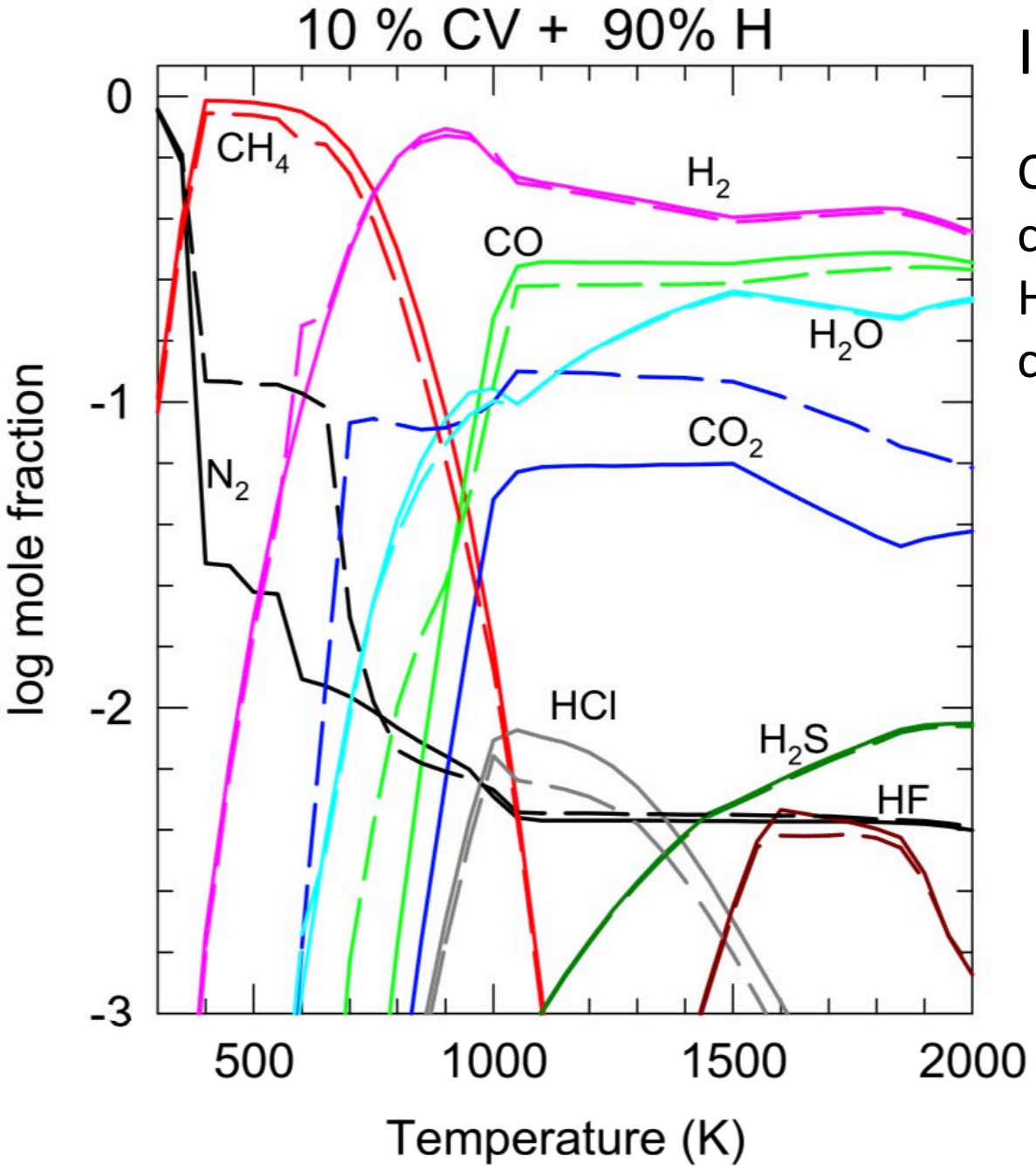
Urey H. C. (1952). "On the early chemical history of the earth and the origin of life." *Proc. Nat. Acad. Sci. 38,* 351.

Impact degassing was addressed by Schaefer and Fegley in a series of studies beginning in 2007

The idea was independently proposed and explored by Hashimoto, Abe, and Sugita 2007

Here I show a screenshot from Schaefer and Fegley

Impact Degassing



CV is a type of carb. chondrite

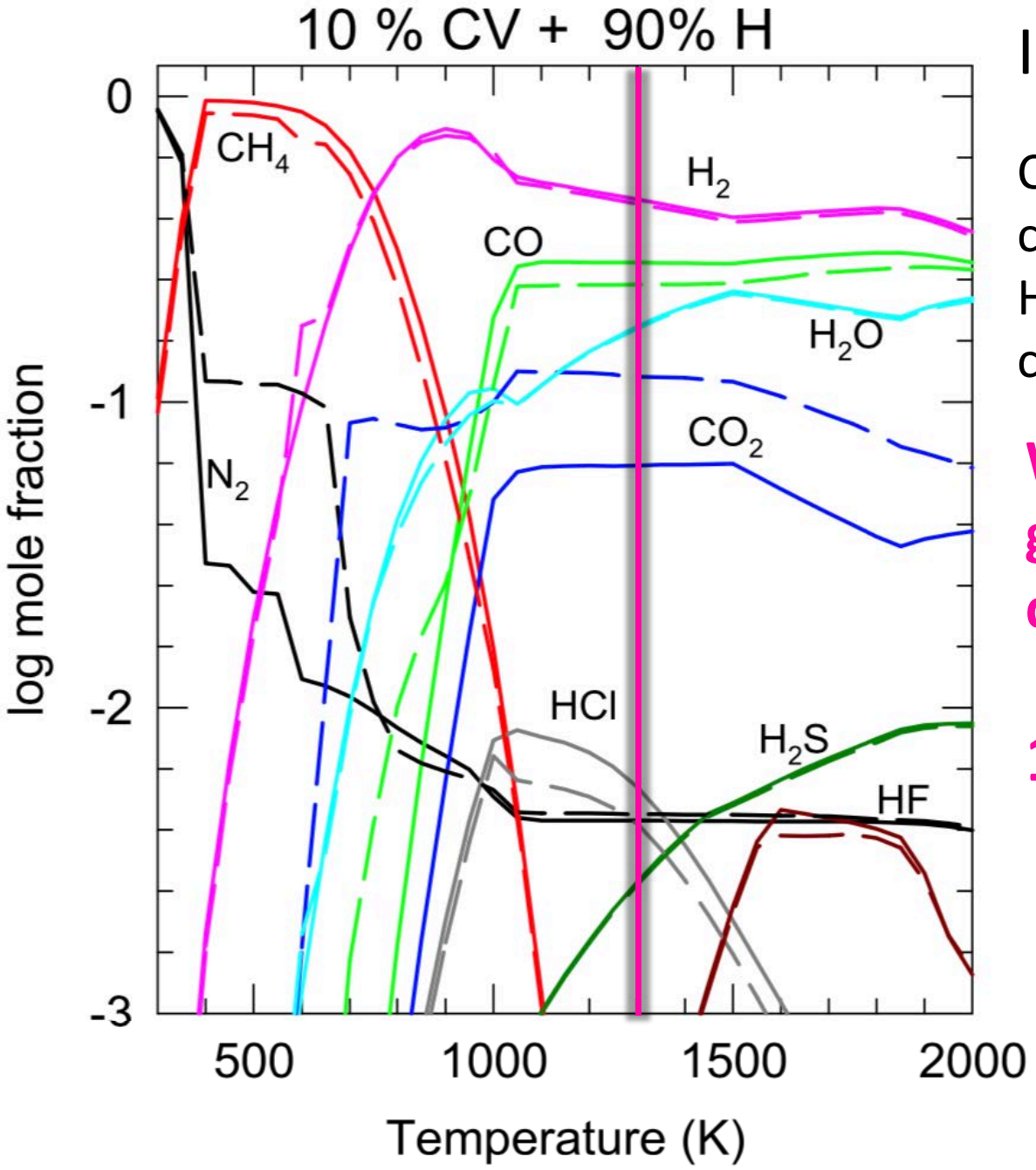
H is a High iron ordinary chondrite

Computed gas compositions at 1 bar

solid - equilibrium

dashed - mixed

Impact Degassing



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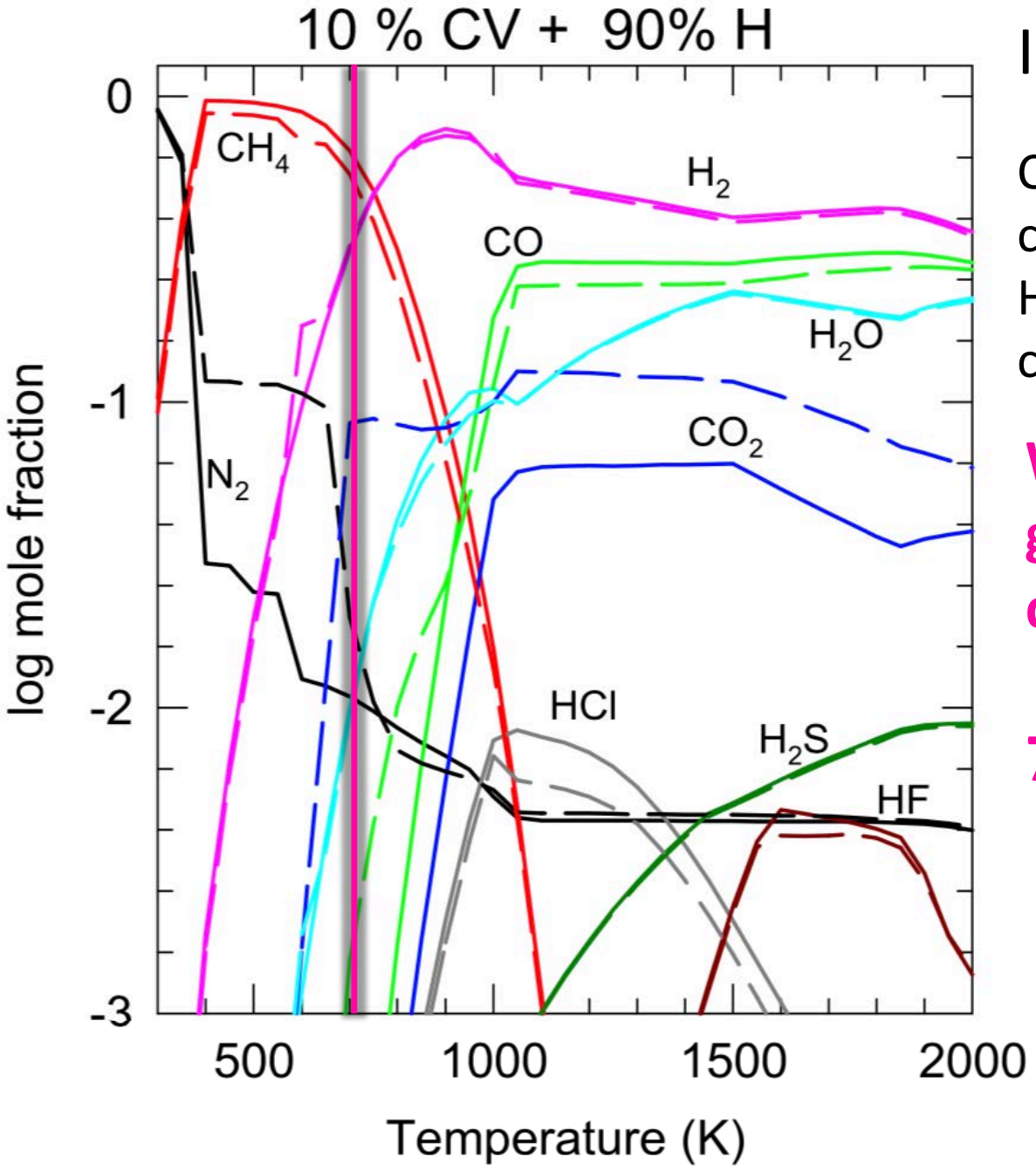
H is a High iron ordinary chondrite

What you actually get depends on the quench temperature

1300 K CO

Schaefer & Fegley THE ASTROPHYSICAL JOURNAL, 843:120 (18pp), 2017 July 10

Impact Degassing



CV is a type of carb. chondrite

H is a High iron ordinary chondrite

What you actually get depends on the quench temperature

700 K CH_4

Schaefer & Fegley THE ASTROPHYSICAL JOURNAL, 843:120 (18pp), 2017 July 10

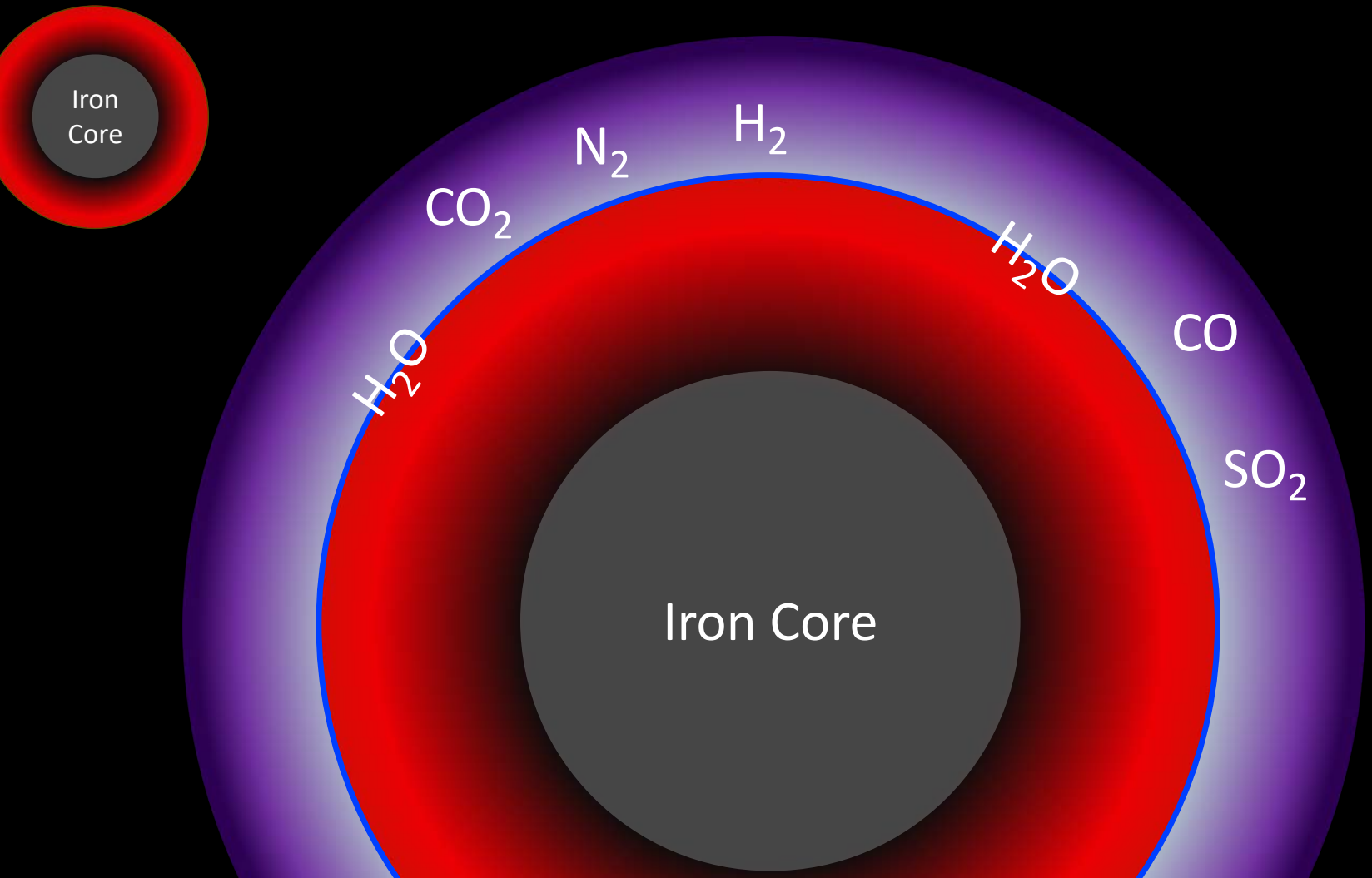
Here we look at impacts reducing Earth's pre-existing atmophiles

Kasting (1990) treated the exogenous reducing source as a continuous flux of small meteors. The atmosphere became CO.

Genda and colleagues considered the reducing power of individual big impacts (2016, 2017). In Benner et al (2019) the focus was on the single biggest impact.

The atmosphere of early Earth was transiently Reducing

Highly reduced bodies striking Earth after the Moon-forming impact turn water into hydrogen, carbon dioxide into methane, and nitrogen into ammonia. This point was made by Urey 1952



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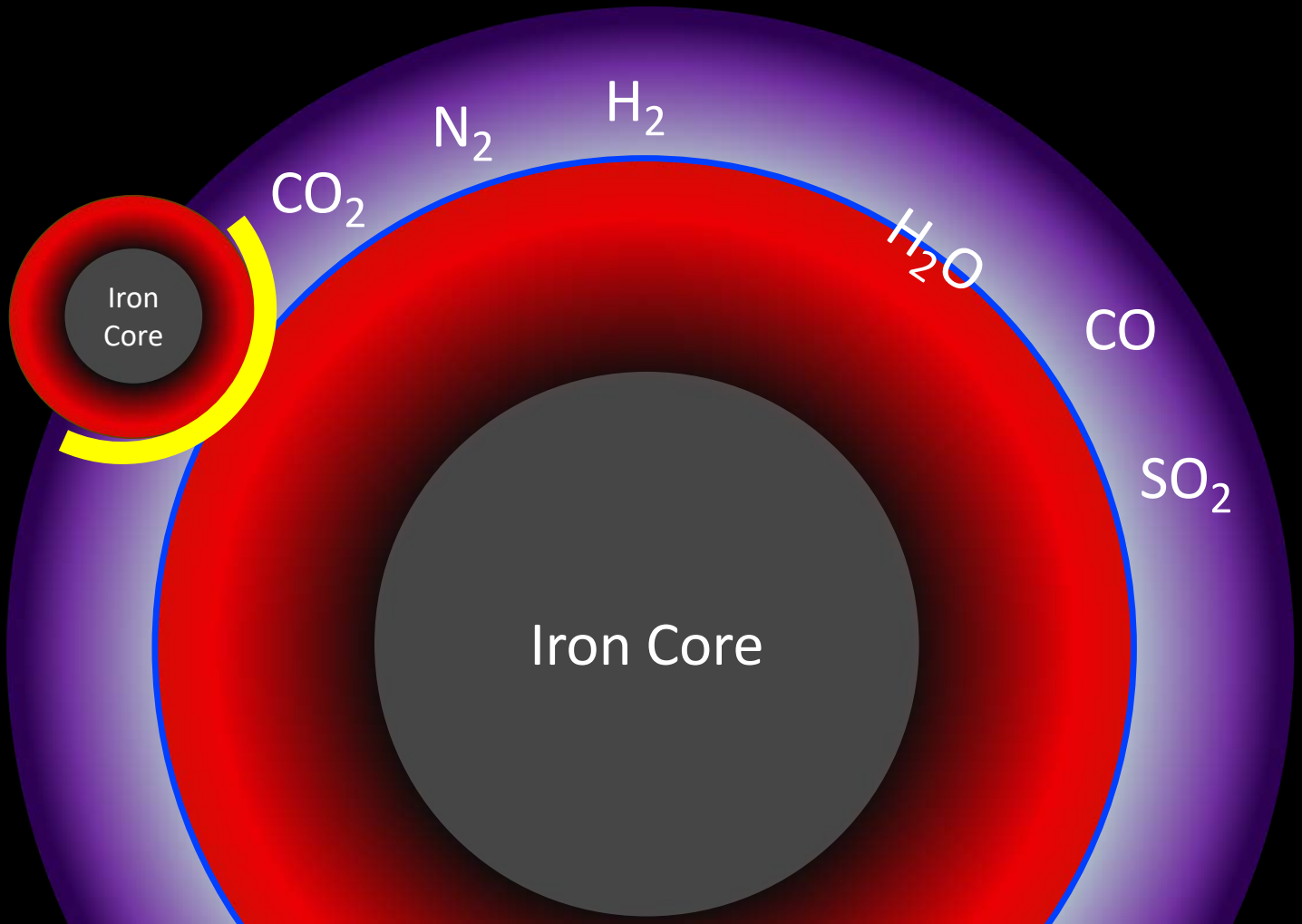

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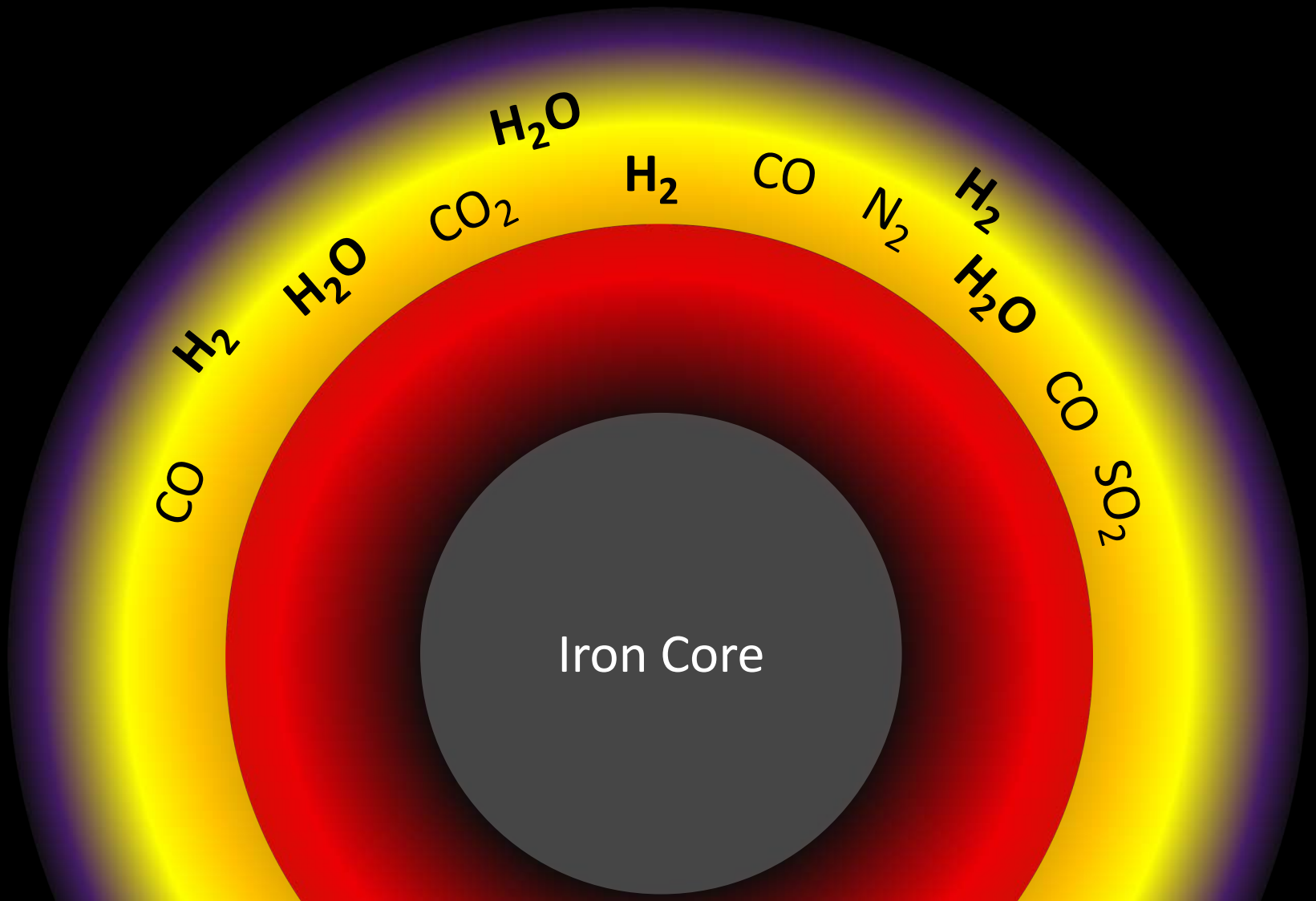

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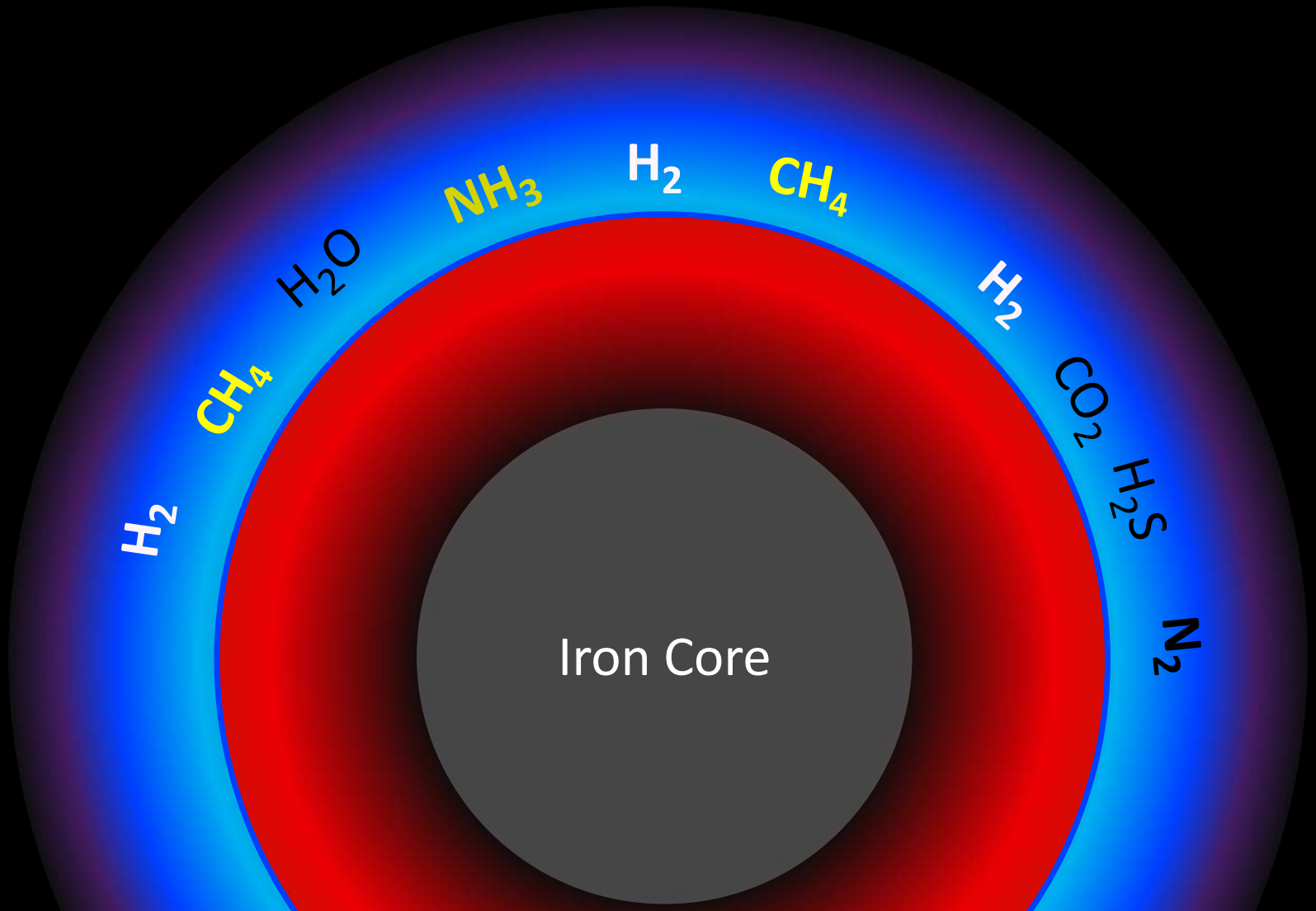


Late Veneer (stub)

Highly Siderophile elements stranded in Earth's mantle suggest that Earth accreted 0.5% of its iron late. Ru isotopes imply that much of this material was dry.

Does the Late Veneer actually matter if doesn't bring water?

Indeed yes! Its even better this way! because the veneer delivers reducing power to the surface. There is enough **Fe** to reduce 1-3 oceans of H_2O to H_2

$$Fe + H_2O > FeO + H_2$$

$$Fe + CO_2 > FeO + CO$$

$$4Fe + 2H_2O + CO_2 > 4FeO + CH_4$$

Big impacts are best because they evaporate the oceans

- pressures are high – 100s of bars – globally
- surface temperatures are high – >1500 K – globally
- cooling is slow, at runaway greenhouse limit

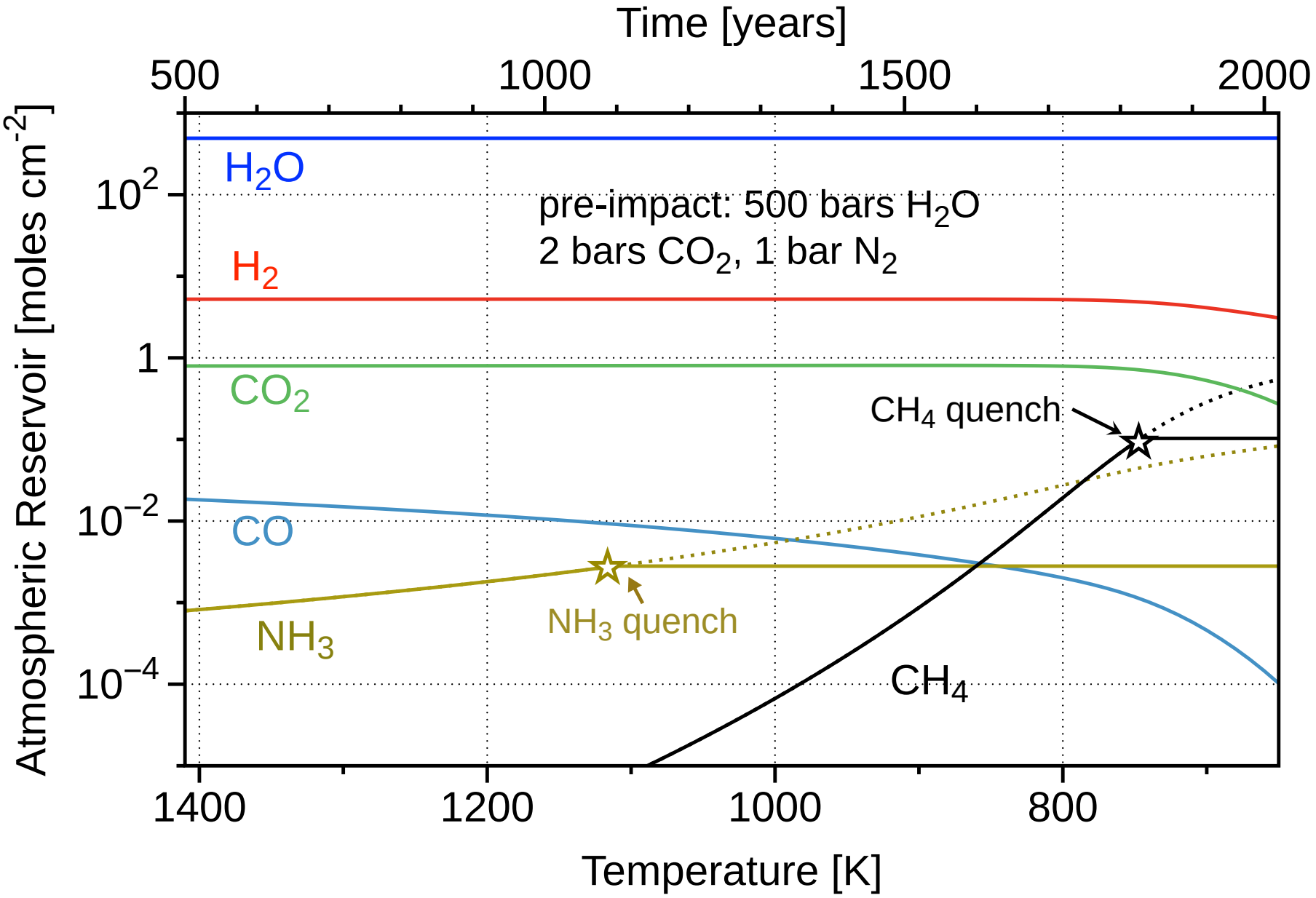
  It takes thousands of years to cool to 800 K

- the long time and high pressure favor **CH_4** and **NH_3**

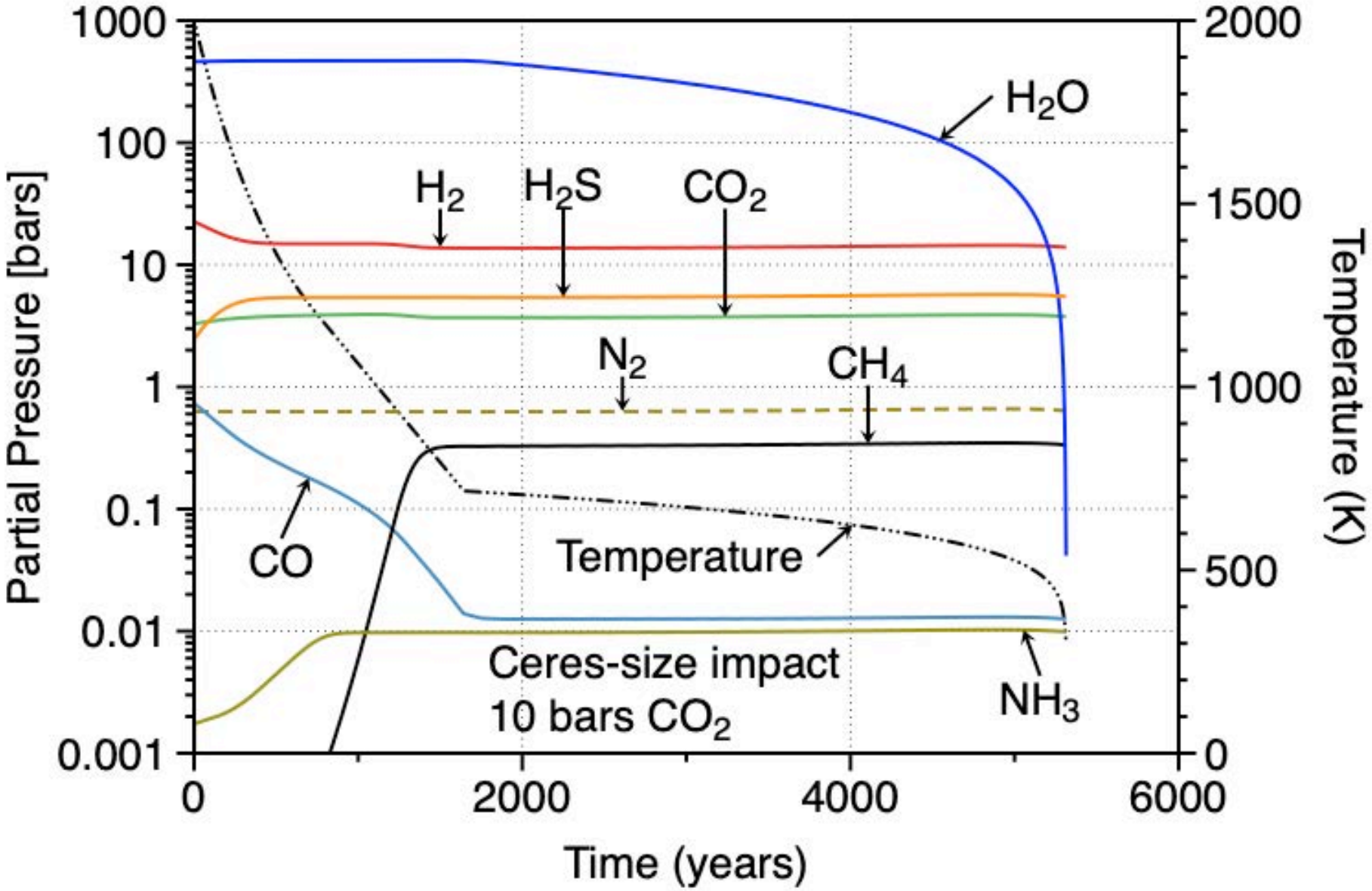
  Methane happens even if there are no catalysts

- supercritical water promotes the oxidation of iron

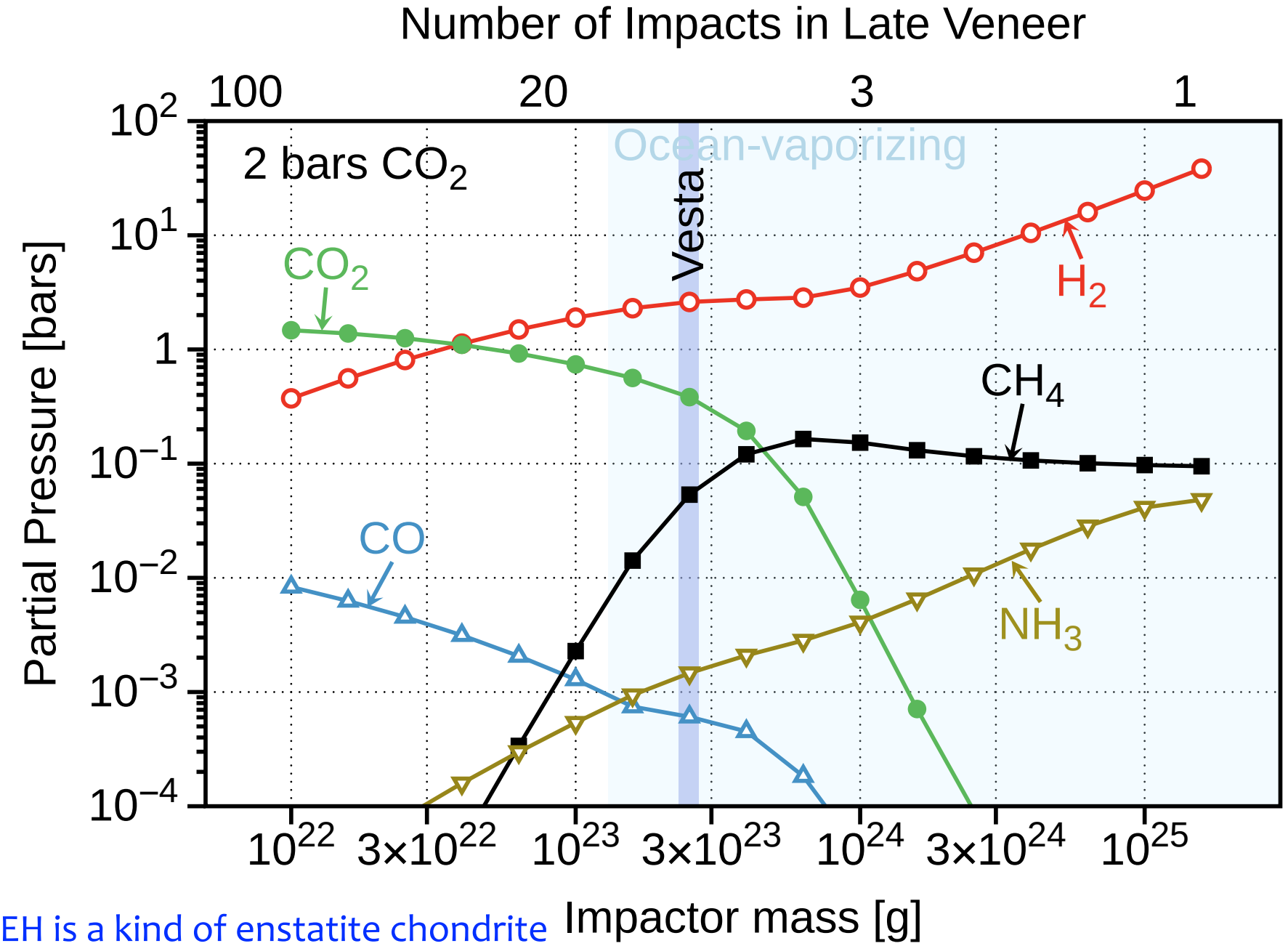
Quenching after a Vesta-sized impact



New! Improved! Time-integrated thermochemistry (here, after a Ceres-sized impact into a 10 bar CO_2 atm)

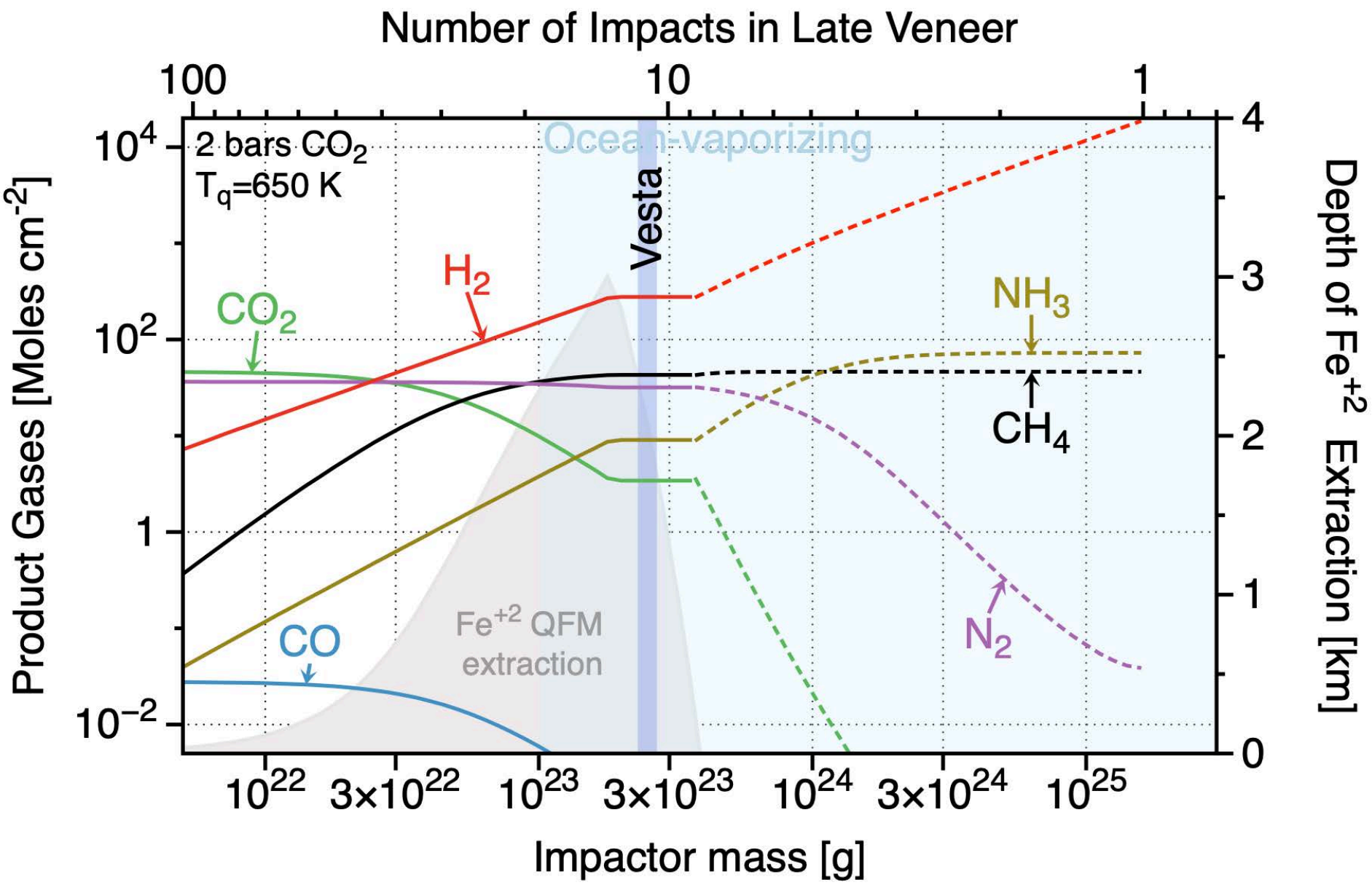


Products of EH* impacts, dry stratosphere



*EH is a kind of enstatite chondrite

Inspired by the previous talk: If the whole world serpentinized…



What happens Next?

Photochemical evolution of transient impact atmospheres:

- CH_4 photolysis makes organics (cf. Titan)
- CH_4, N_2 + UV makes HCN, nitriles
- CO_2 and H_2O + UV oxidizes CH_4
- Hydrogen escapes and organics precipitate
- H_2O is mostly condensed in oceans. Moist

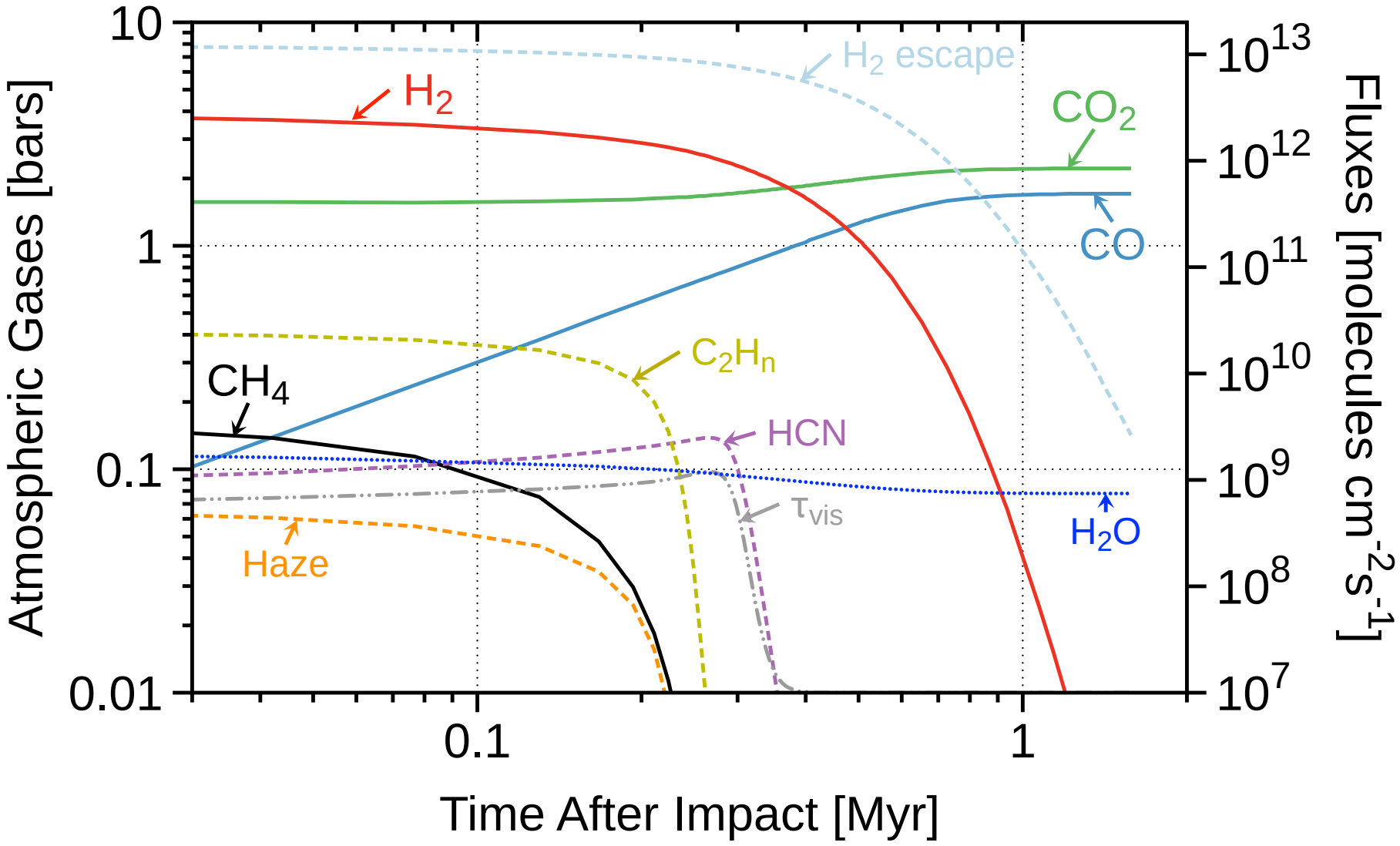
stratospheres are more oxidizing (more CO_2, less tar)

- the oceans are an infinite source of H_2O
- The model runs until the H_2 and CH_4 are gone
- UV optical depths scaled from fractal haze

(Wolf & Toon 2010)

- initial condition is 5 bars of CO_2
- dry stratosphere

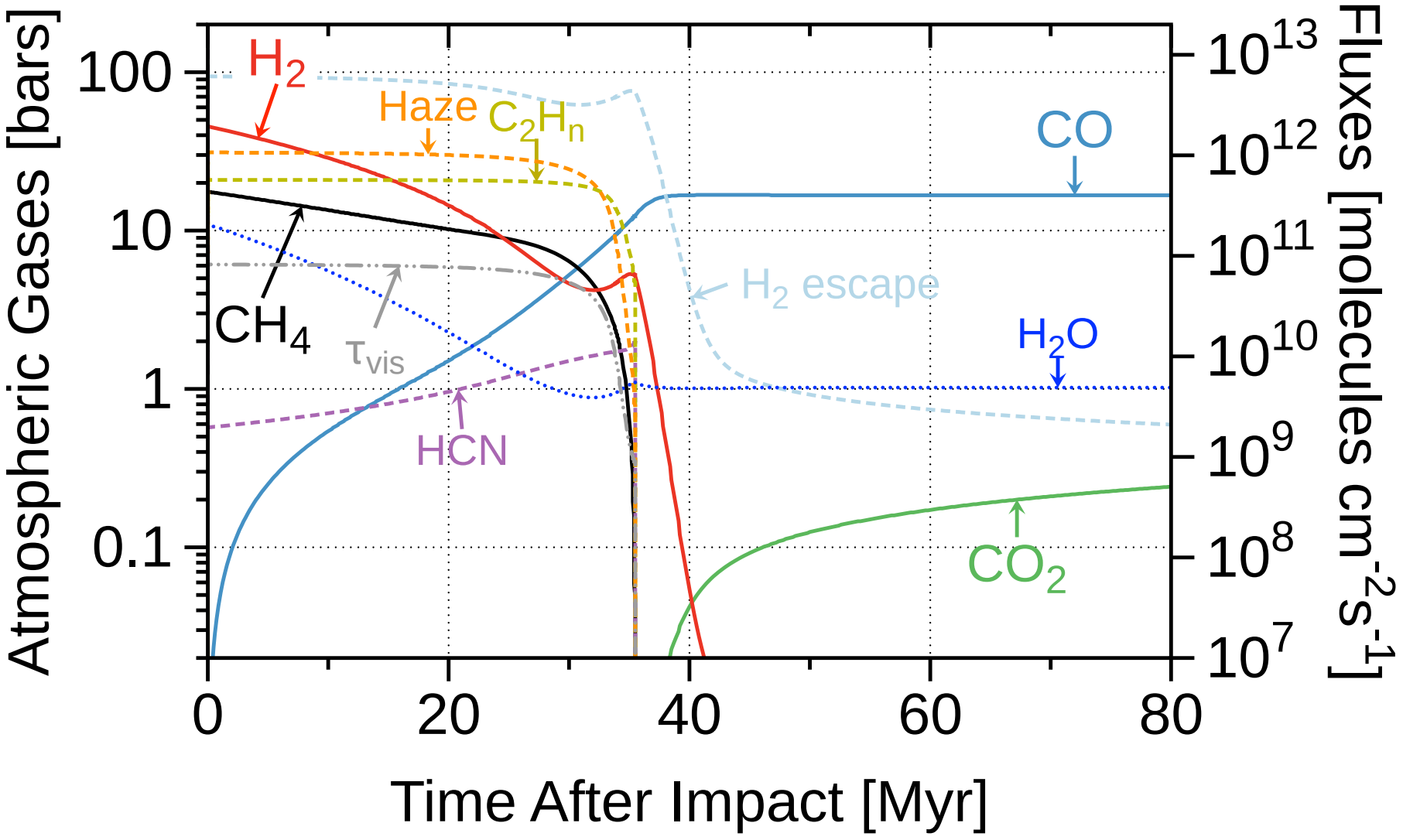
Vesta-sized



H2 from 45 meters of H_2O escape

- initial condition is 100 bars of CO_2
- dry stratosphere

Pluto-sized impact



1.7 km of H_2O escapes. 300-500 m of organics precipitate

Still more words...

Ocean vaporizing impacts by EC-like bodies are effective at making CH_4 and NH_3 from CO_2 and H_2O because the pressure is high and the cooling time is long

Ocean vaporizing impacts leave Earth with a reduced atmosphere fit to evolve

on the other hand...

Ocean vaporizing impacts may annihilate any previous progress toward life

A planet like Earth may get only one roll of the dice