The Atmospheres of the Terrestrial Worlds

Earth-Venus-Mars-Titan

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Map

- The basics
  - Atmospheres make-up
  - Temperatures
  - Greenhouse now, greenhouse then; aerosols too
- Nitrogen, nitrogen everywhere, but where from?
- Methane only somewhere: does it mean life?
- What next?

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Earth

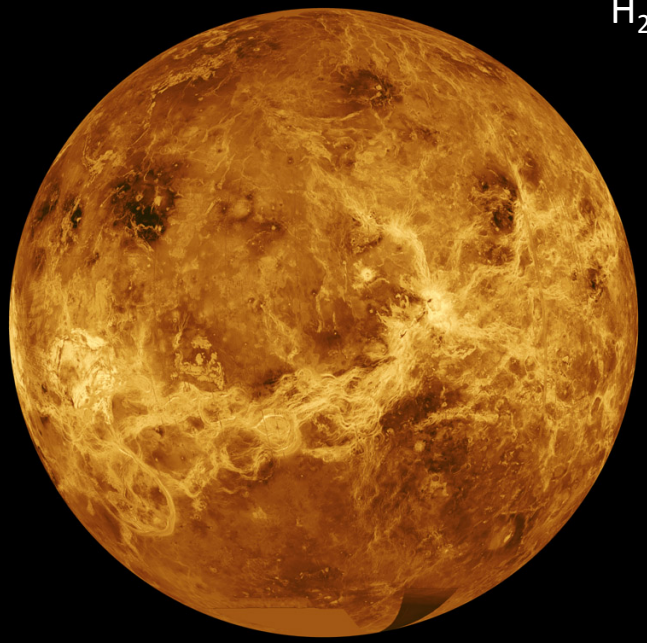
1 AU
288 K
1 bar

N_2 78% by vol
O_2 21%
O_3 0.3 ppm
CH_4 1.78 ppm
H_2O ≤1%
CO_2 400 ppm
SO_2, HCl

Mars

1.5 AU
220 K
6 mb

CO_2 96%
N_2 2%
O_2 0.1%
O_3 0.01-1 ppm
CH_4 0.7-7 ppb
H_2O 150ppm
H_2O_2 0-20 ppb

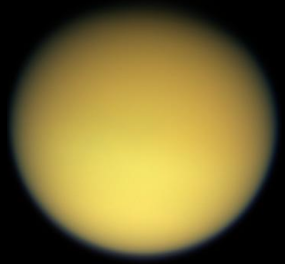


0.72 AU
735 K
92 bar

CO_2 96%
N_2 3%
O_2 ppm
H_2O 10 ppm
SO_2, H_2SO_4
HCl, HF

9.5 AU
94 K
1.5 bar

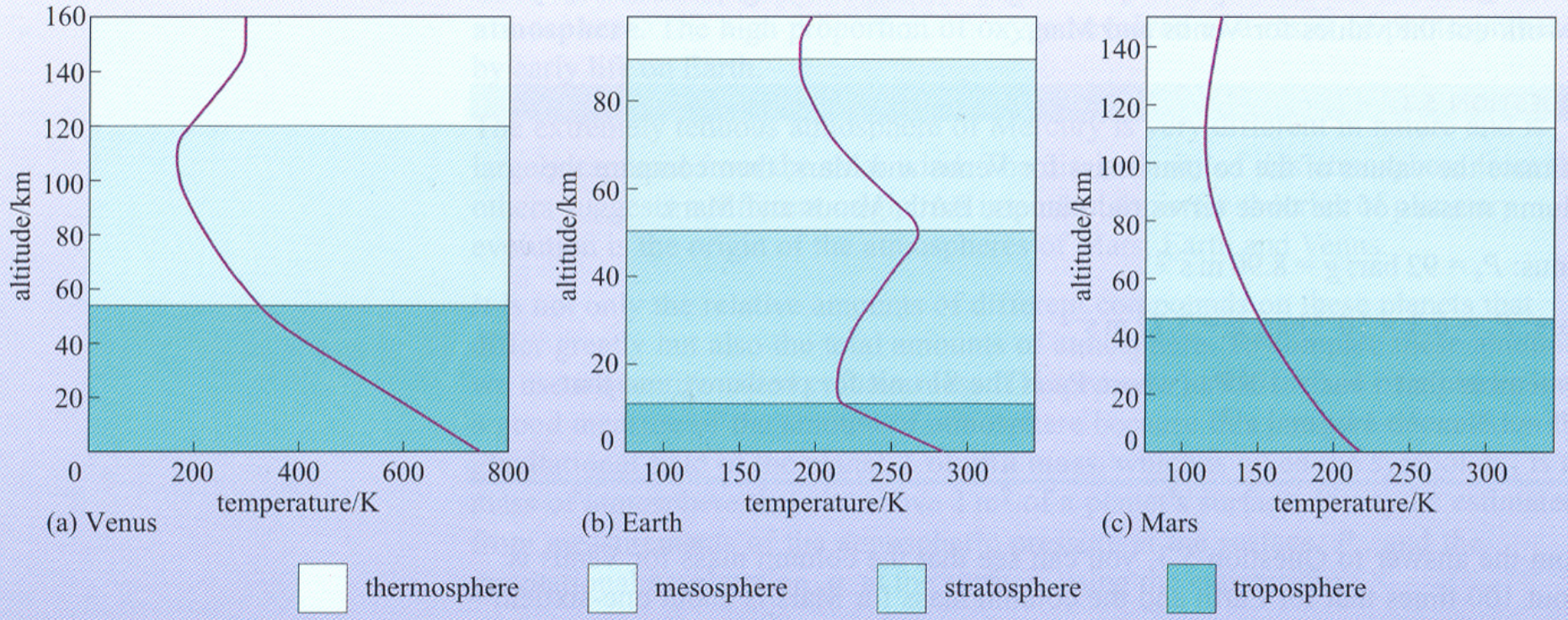
N_2 94%
CH_4 6%
C_xH_y-N_z



Titan

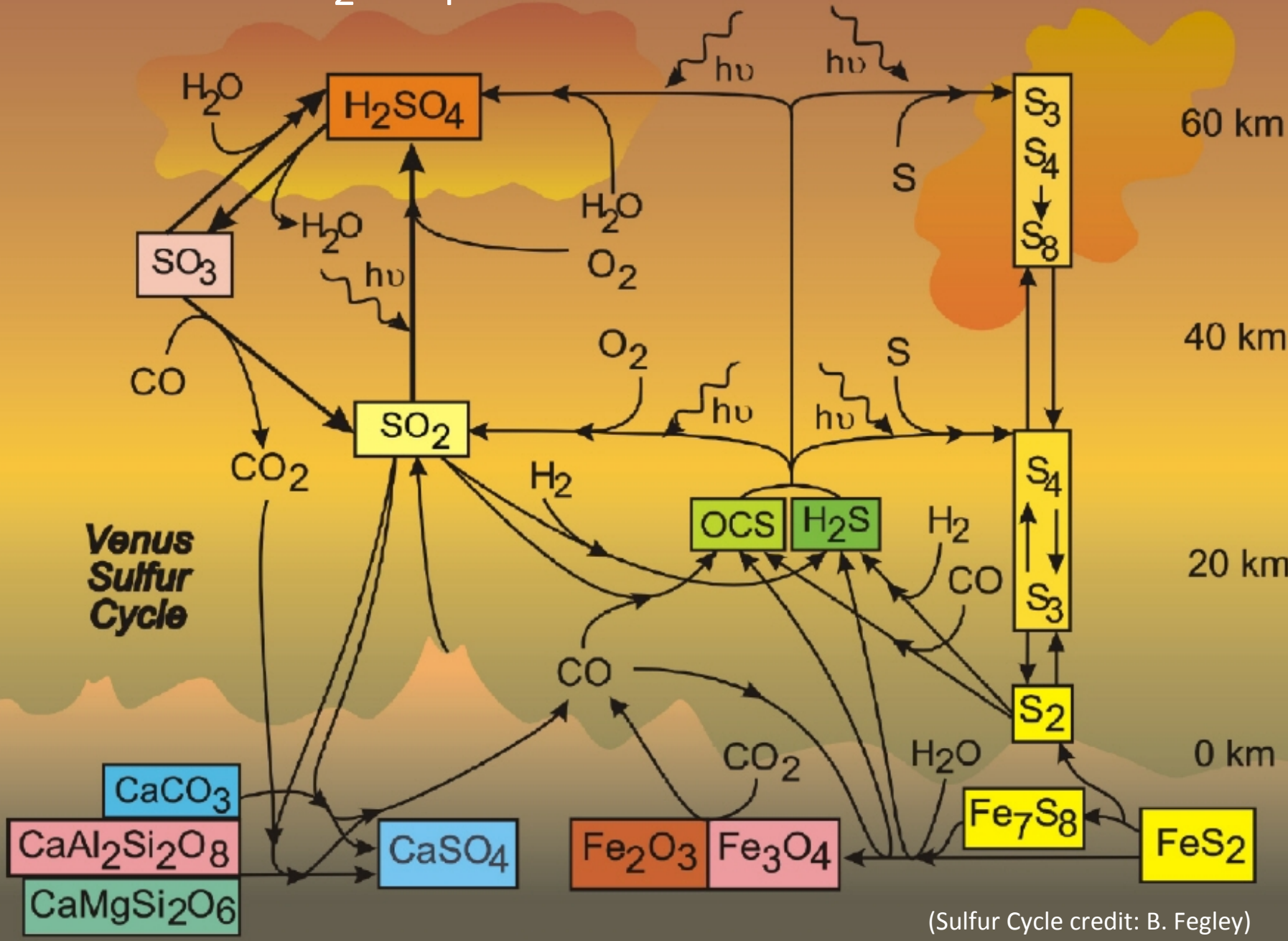
Venus (climate gone wild)

Venus-Earth-Mars Thermal Structure



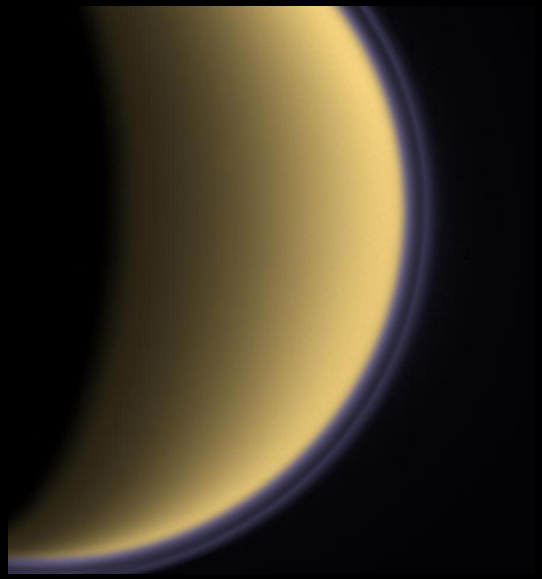
T_{eq}	231 K	253 K	212 K
T_s	735 K	288 K	220 K
Greenhouse:	CO_2 ~500 K	H_2O 30 K, CO_2 5 K	aerosols ~8 K

H_2SO_4 aerosols *cool* Venus

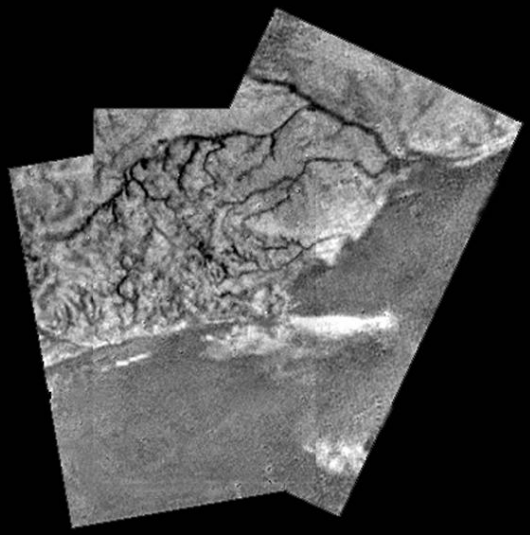


(Sulfur Cycle credit: B. Fegley)

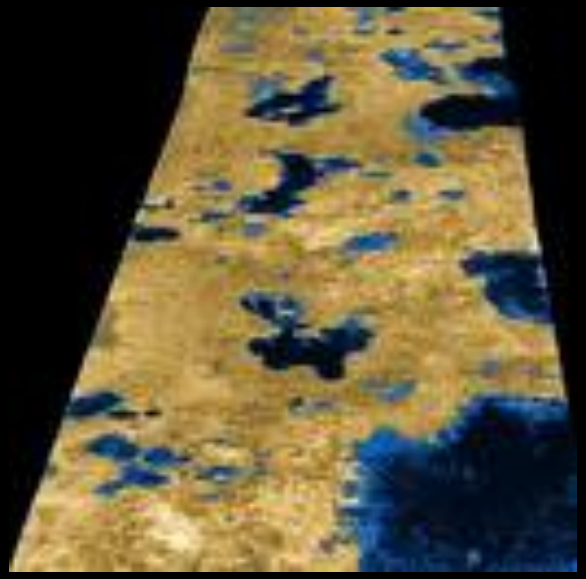
Titan
Aerosols *heat* the atmosphere, and control its fate



haze/Voyager
1980

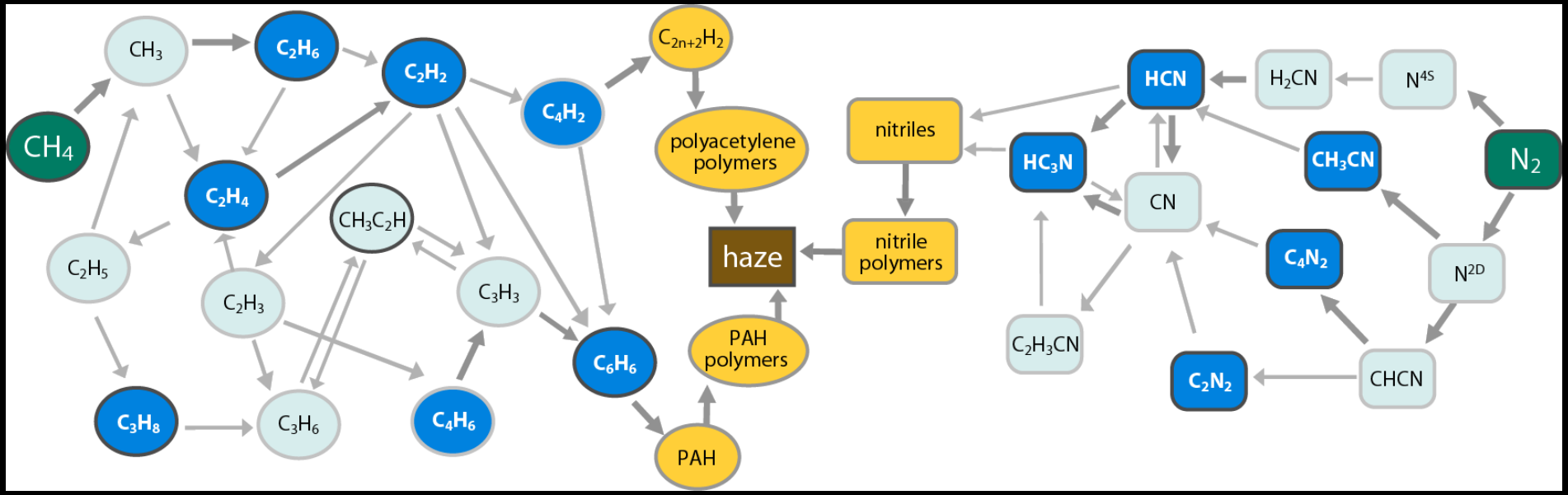


rivers/Huygens
2005



lakes/Cassini
2004-2017

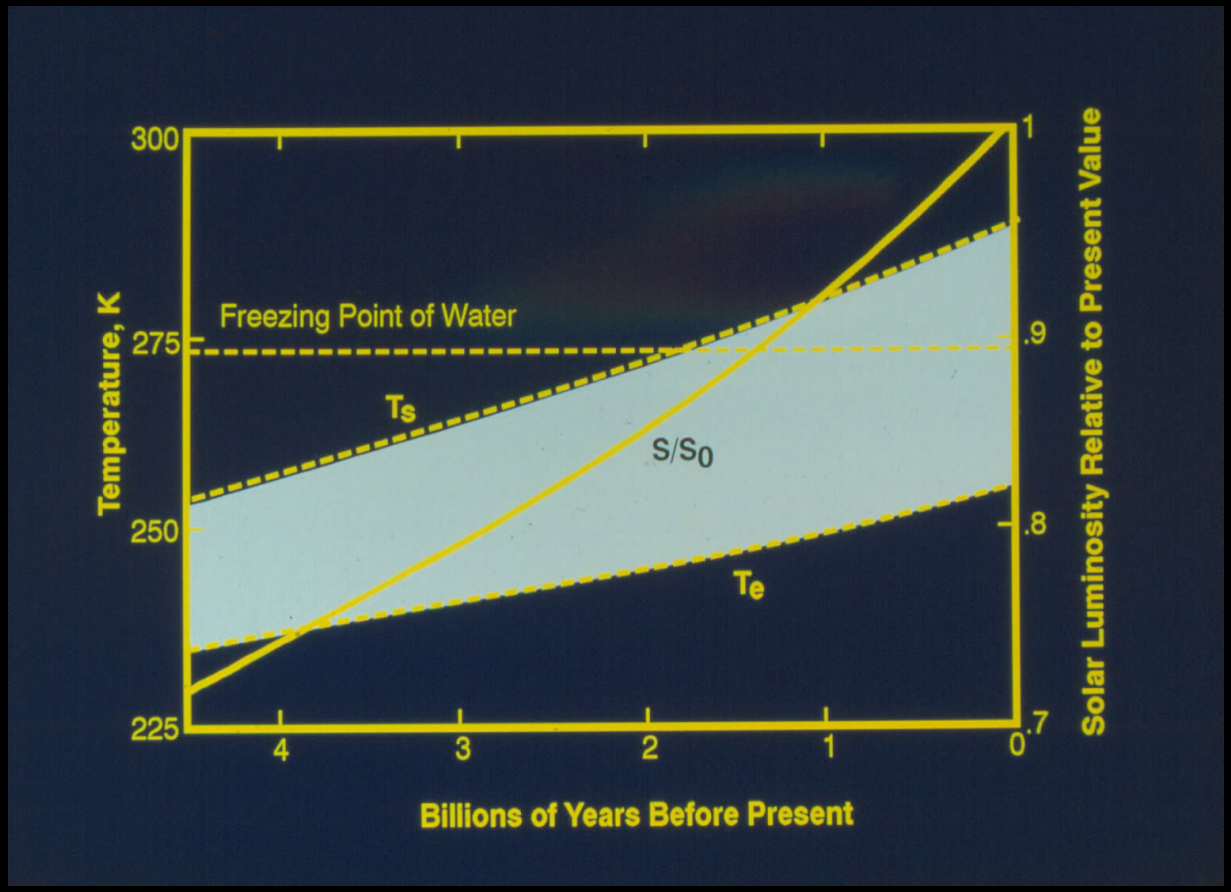
Methane converts *irreversibly* to heavier hydrocarbons, nitriles, hazes in ~30 My by neutral and ion chemistry



No CH_4 -> N_2 condenses -> Little atmosphere!
Hazes from CH_4-N_2 -> 120 K warming in the stratosphere
CIA (CH_4-N_2, CH_4-H_2 …) 20 K warming in the troposphere

(Methane Cycle and Chemistry: Atreya et al., 2006; Wilson and Atreya, 2004, 2009. Greenhouse: Lorenz, 1997)

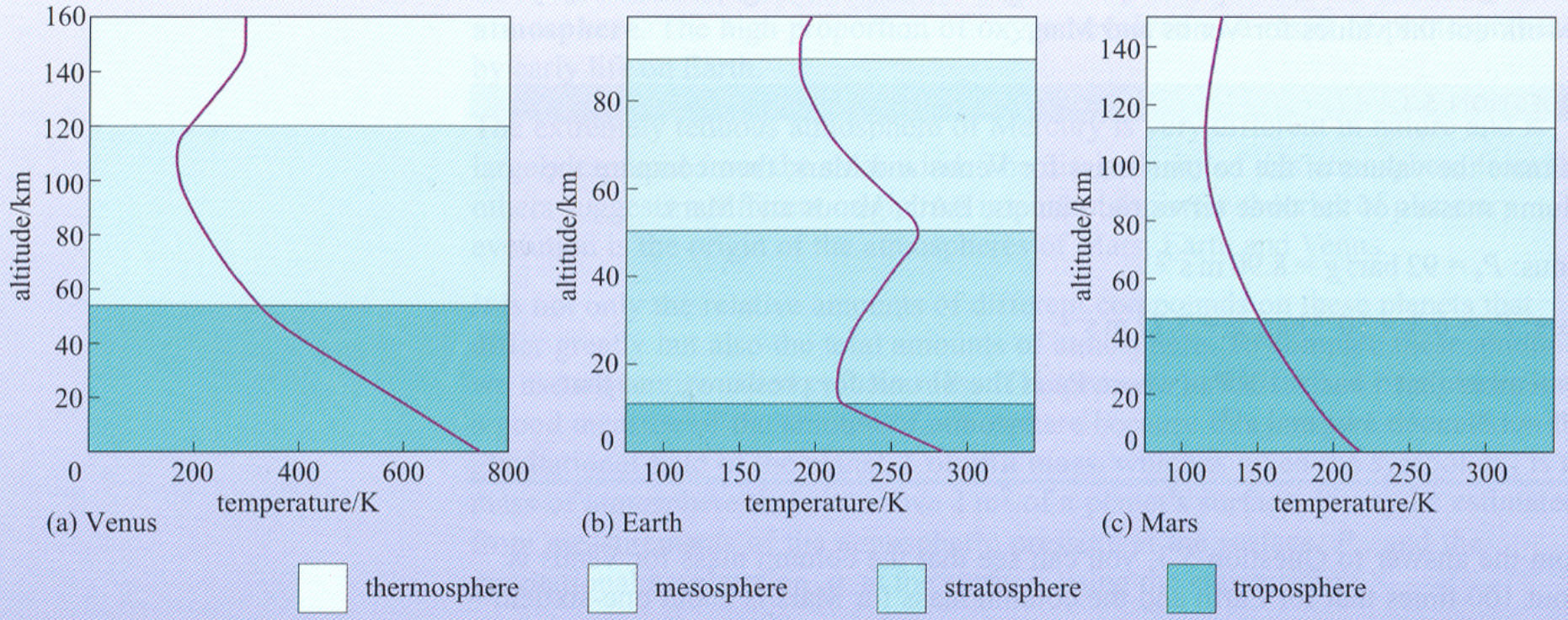
The Faint Young Sun Problem



Earth's surface temperature would have been below freezing prior to 2 Gy, but liquid water has been present from the beginning

(Kasting 1988)

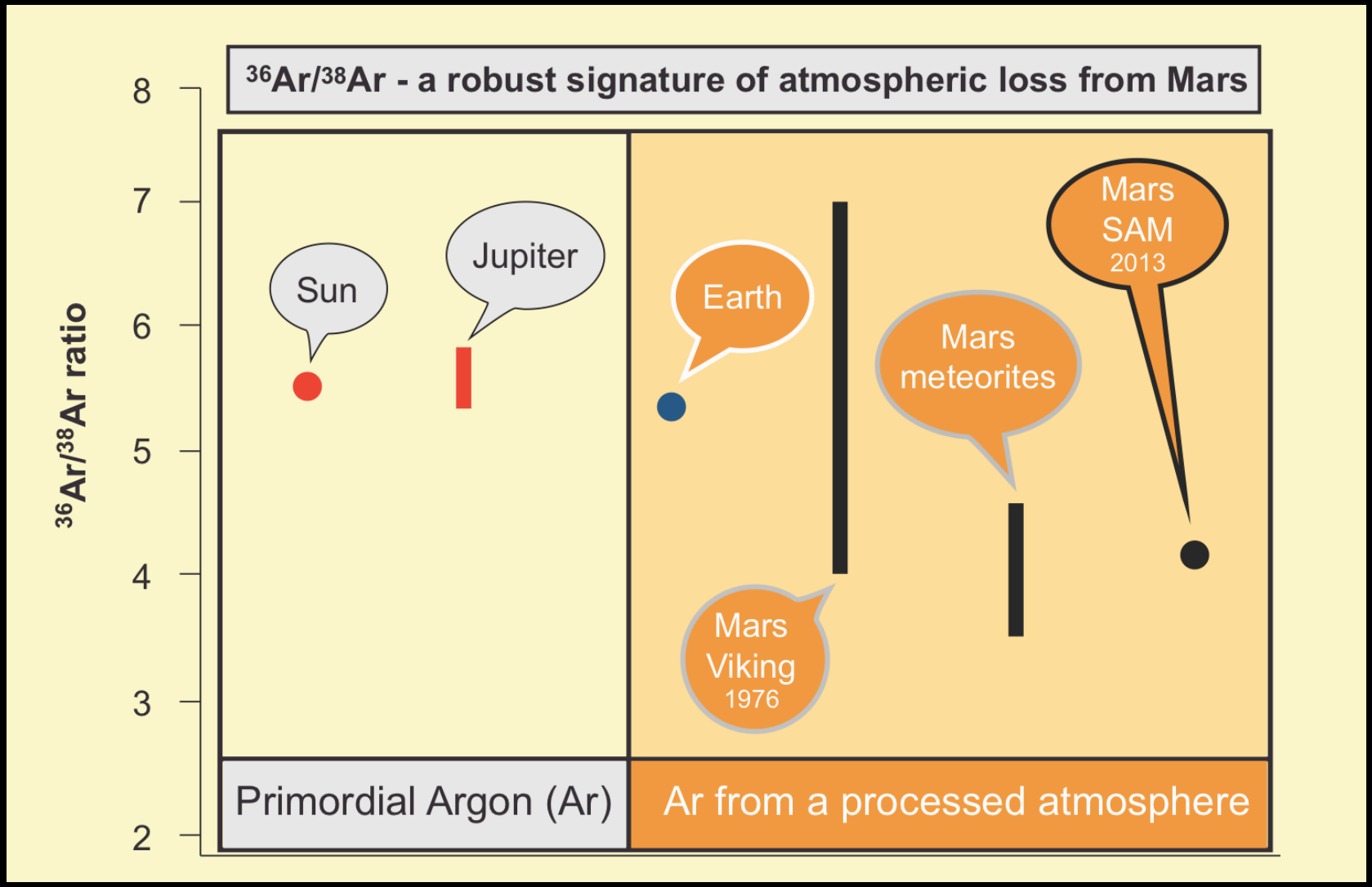
Venus-Earth-Mars Thermal Structure



D/H	**150× SMOW**	**1.6×10^{-4} (SMOW)**	**5-8× SMOW**

Greenhouse gases in the past

H_2O initially, then CO_2	CO_2 (~~NH_3, CH_4~~)	CO_2



Argon isotope ratio gives the most compelling evidence that the so-called "martian" meteorites are indeed rocks from Mars (Atreya et al. 2013)

Isotopes point to atmospheric loss from Mars

Isotopes	Mars value ‰	SAM suite instrument	Reference
$\delta^{38}Ar_{Sun}$	310 ± 31	QMS	Atreya et al. (2013, *GRL*)
$\delta^{40}Ar_{Earth}$	5419 ± 1013	QMS	Mahaffy et al. (2013, *Science*)
$\delta^{15}N_{Earth}$	572 ± 82	QMS	Wong et al. (2013, *GRL*)
$\delta^{13}C_{VPDB}$	45 ± 12	QMS	Mahaffy et al. (2013, *Science*)
$\delta^{13}C_{VPDB}$	46 ± 4	TLS	Webster et al. (2013, *Science*)
$\delta^{18}O_{SMOW}$	48 ± 5	TLS	Webster et al. (2013, *Science*)
δD_{SMOW}	4950 ± 1080	TLS	Webster et al. (2013, *Science*)

Curiosity's SAM measures atmospheric isotope ratios

[δ vs R: e.g. $\delta^{13}C(‰) = 1000\ (R/R_{Std} - 1)$; $R = {}^{13}C/{}^{12}C$]

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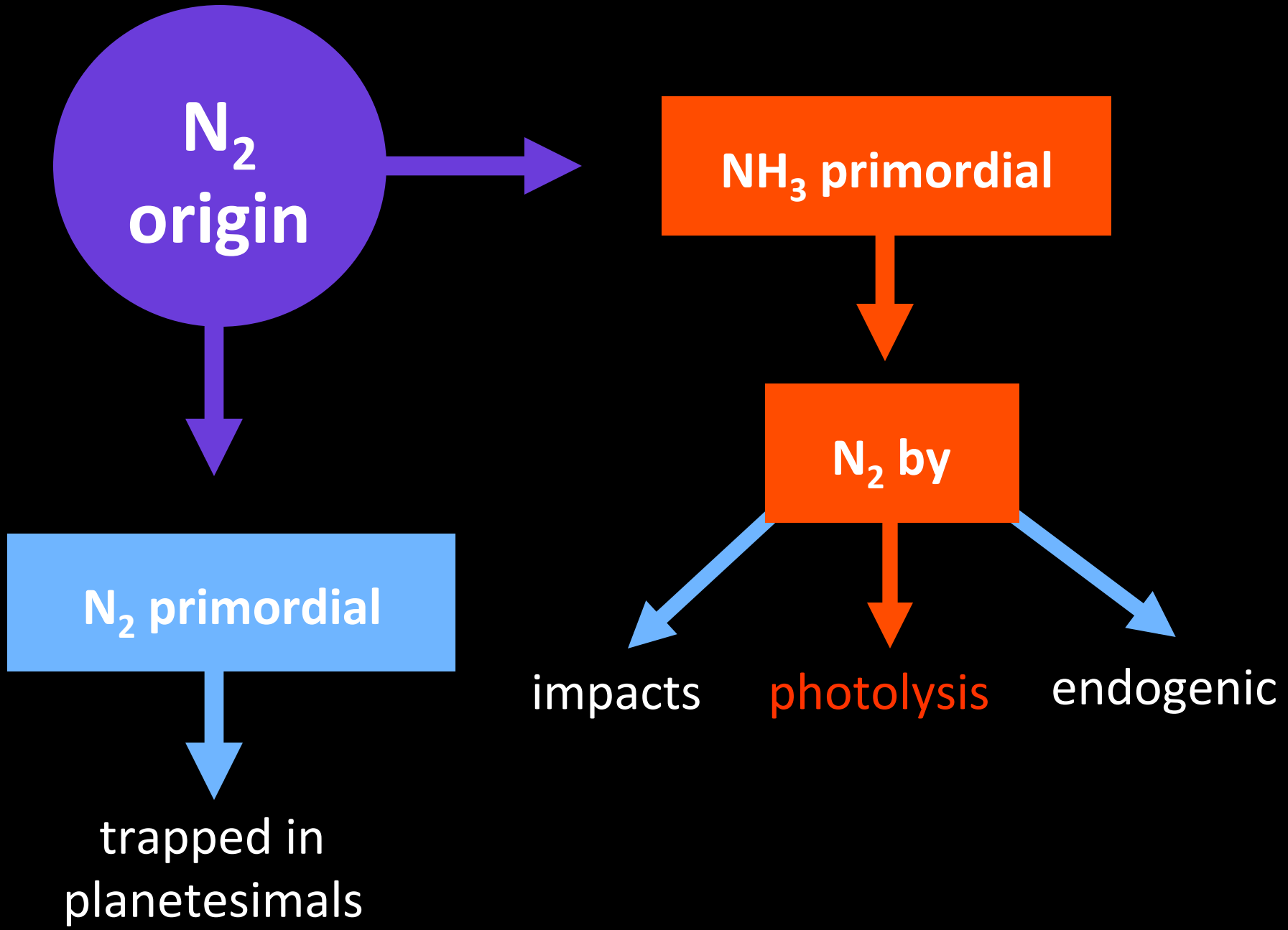
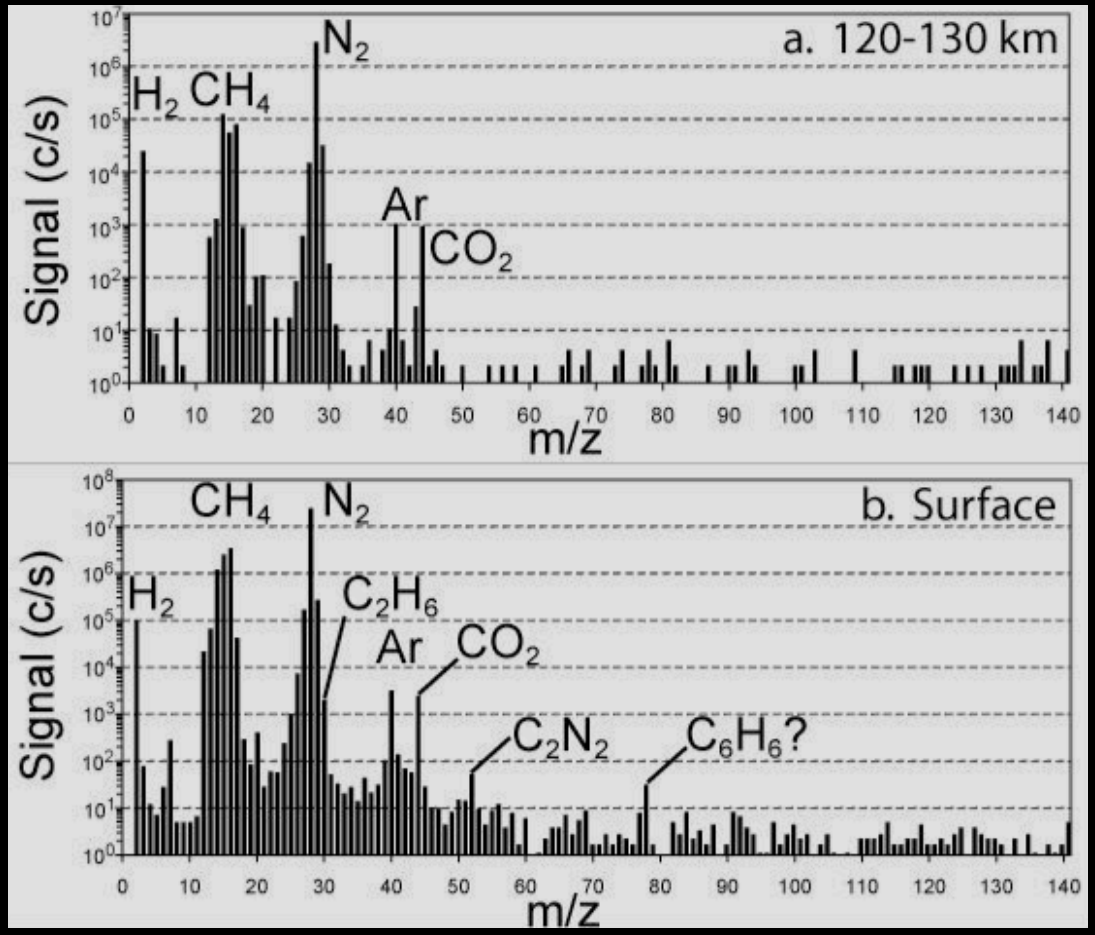

N_2 origin
NH_3 primordial
N_2 by
N_2 primordial
impacts
photolysis
endogenic
trapped in planetesimals

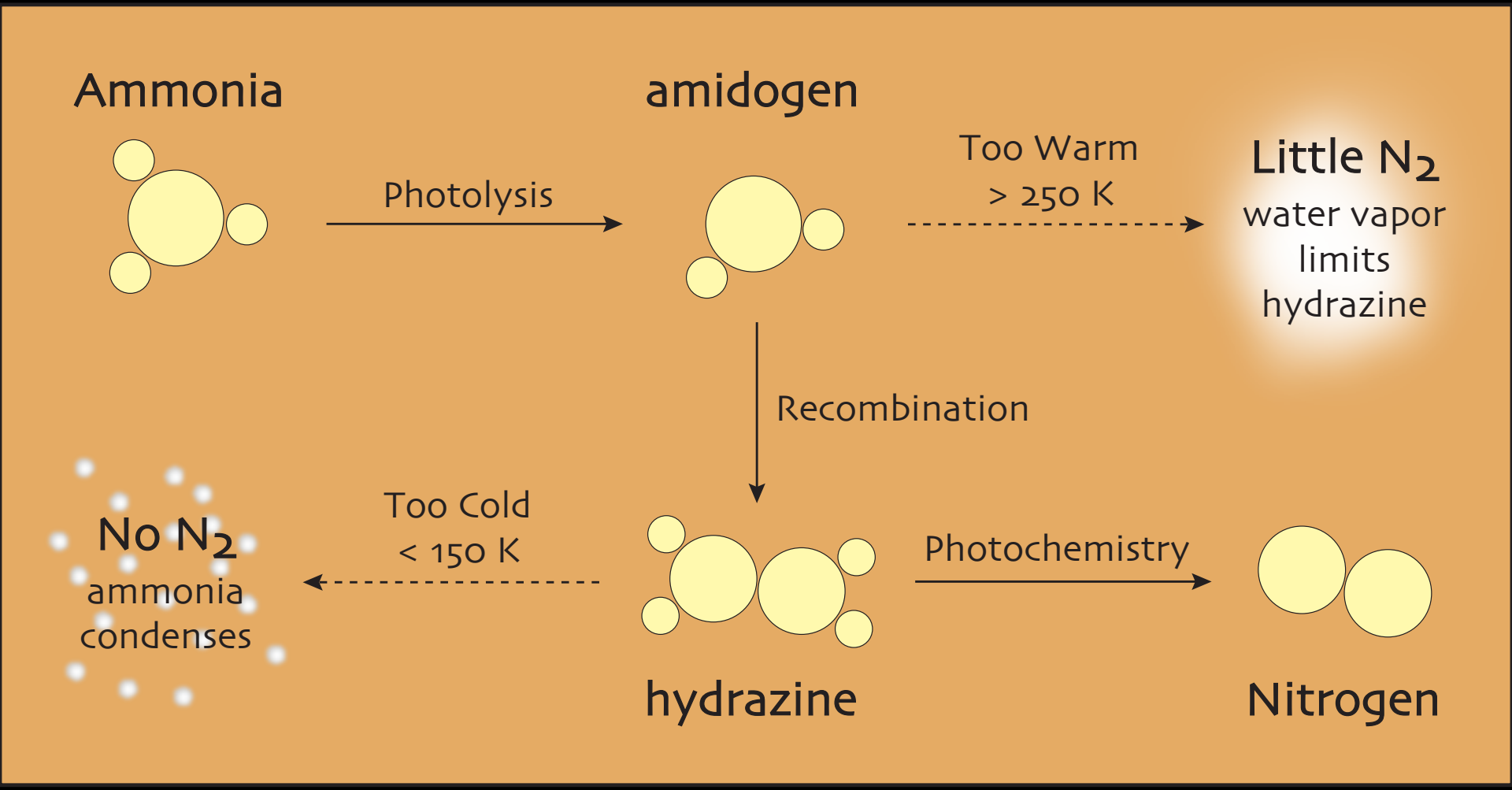
Nitrogen did *not* arrive as N_2 on Titan

$^{36}Ar/N_2$ Titan: 2.1×10^{-7} *solar: 0.11* Titan/Sun = 2×10^{-6}

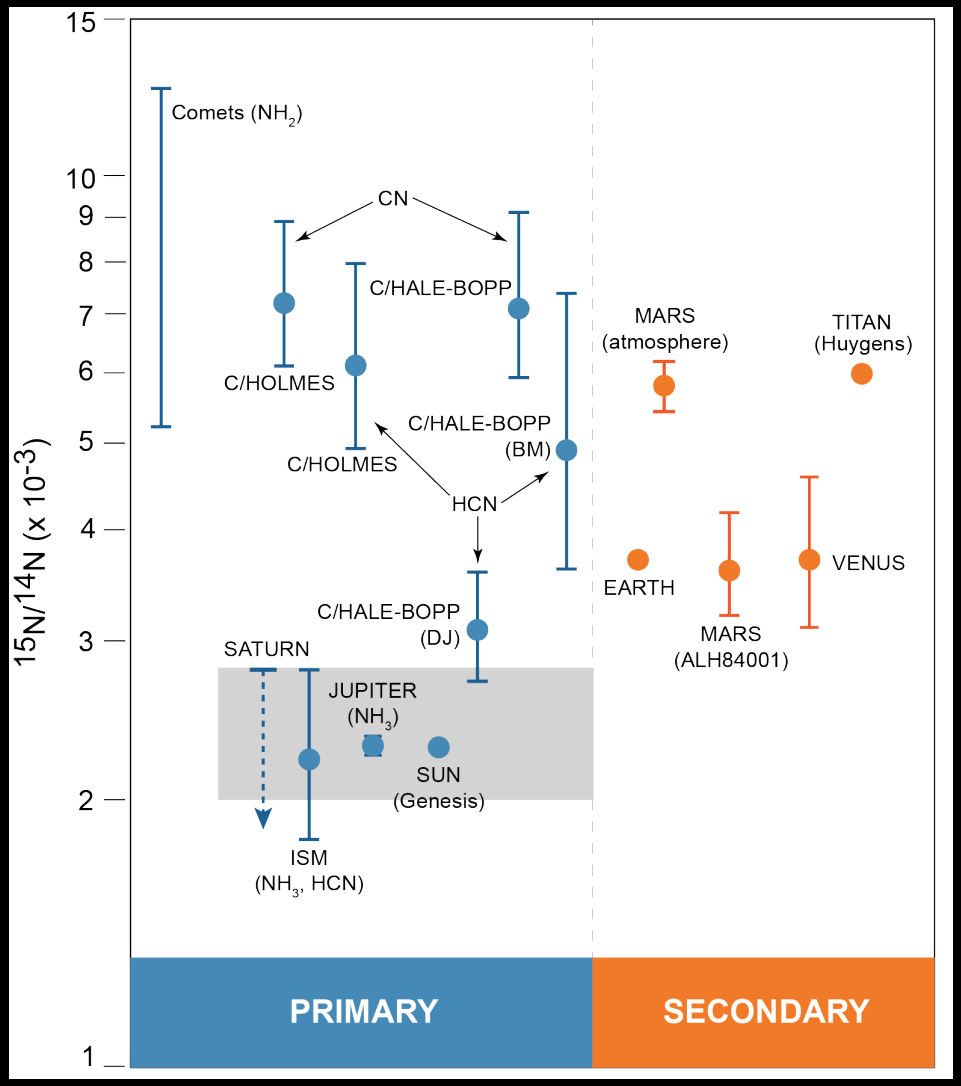


(Niemann et al. 2005, 2010 Huygens GCMS)

N_2 from NH_3 on *primordial* Titan
2 bars in <5 Myr; 10 bars in <20 Myr
(Atreya et al. 1978, 2006; Adams and Atreya, 2005)



Nitrogen isotopes: Titan and the rest



(Atreya et al. 2015)

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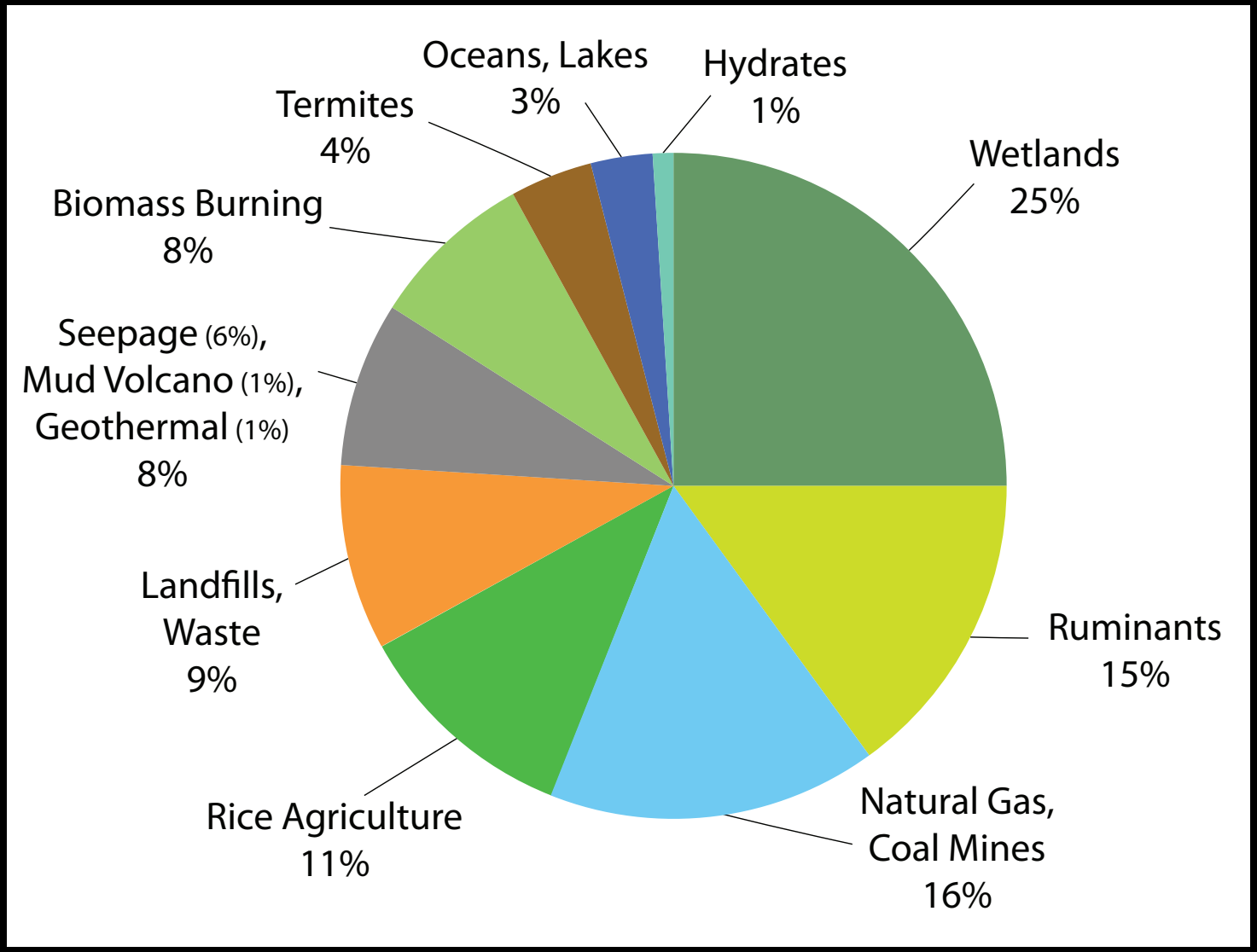
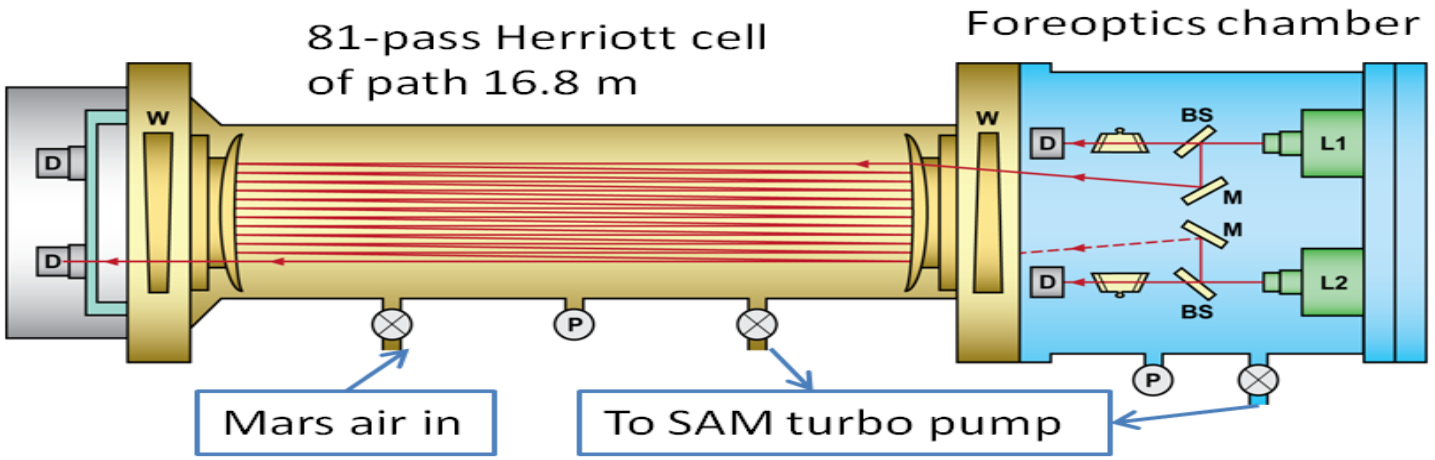
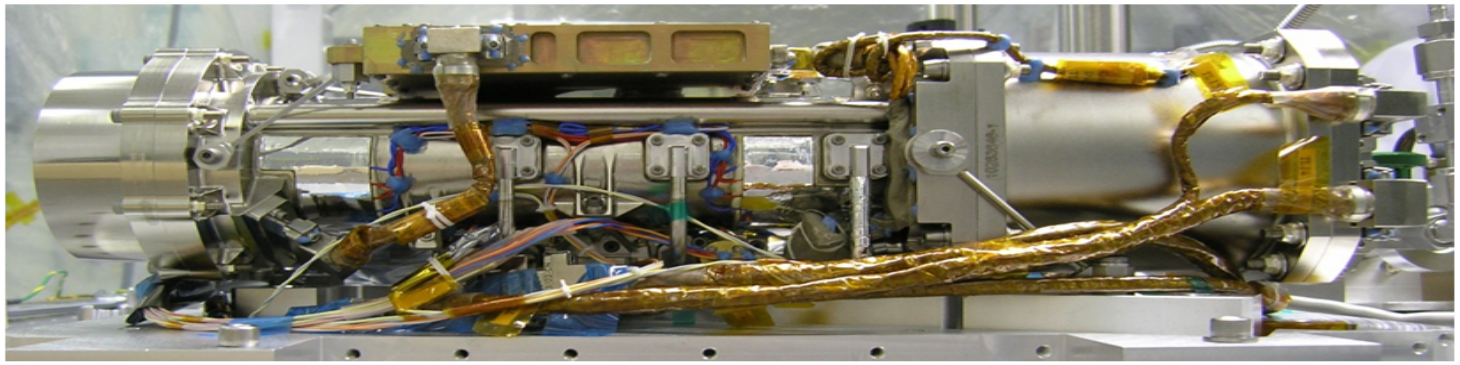


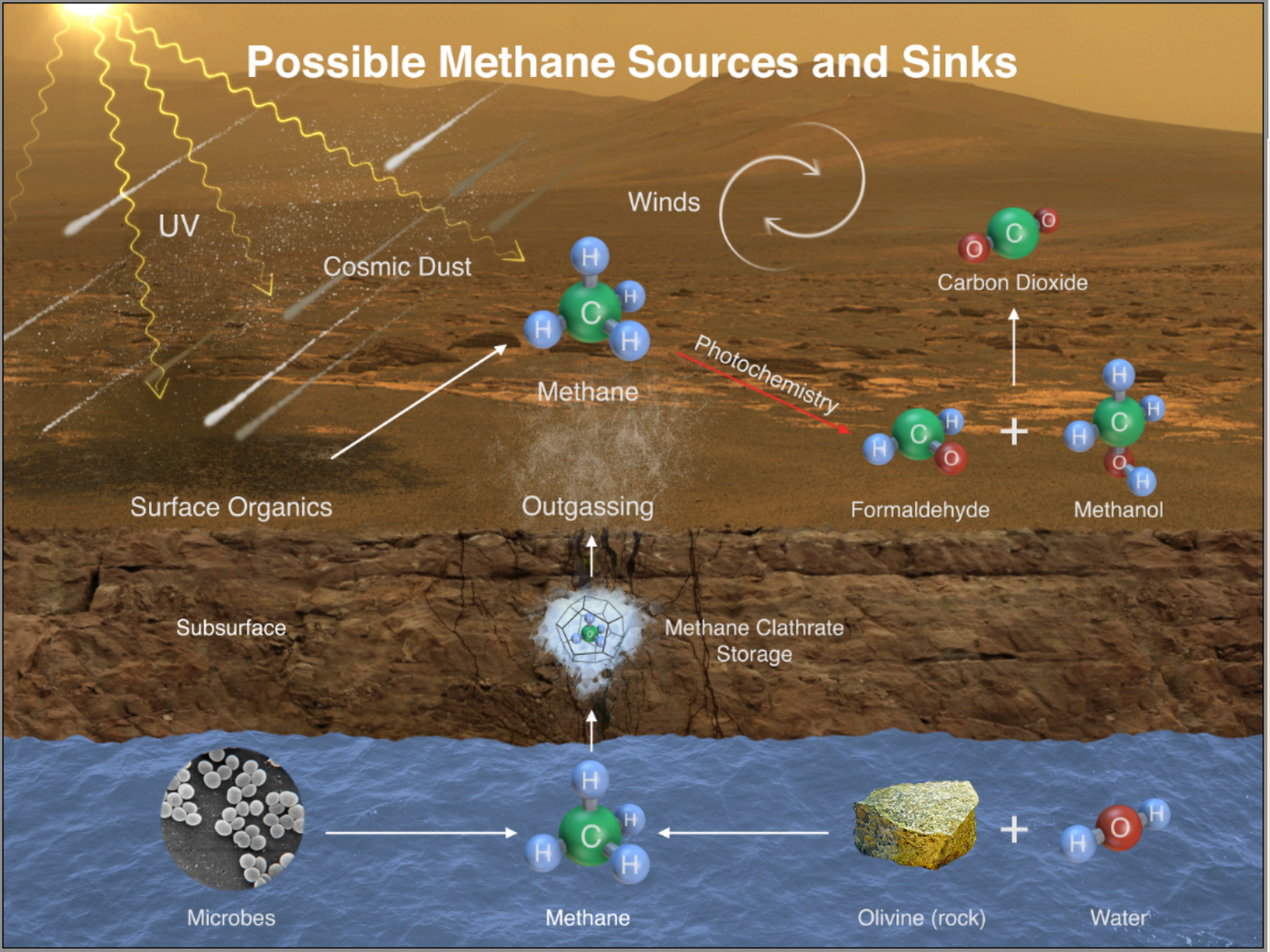
Life as we know it produces methane, 90-95% of the 1775 ppbv on Earth

Tunable Laser Spectrometer measured a constant methane background level of 0.7 ppbv, and a spike of 7 ppbv over two months





(Webster et al. Science 2015)


Possible Methane Sources and Sinks
UV
Cosmic Dust
Winds
Carbon Dioxide
Methane
Photochemistry
Surface Organics
Outgassing
Formaldehyde
Methanol
Subsurface
Methane Clathrate
Storage
Microbes
Methane
Olivine (rock)
Water

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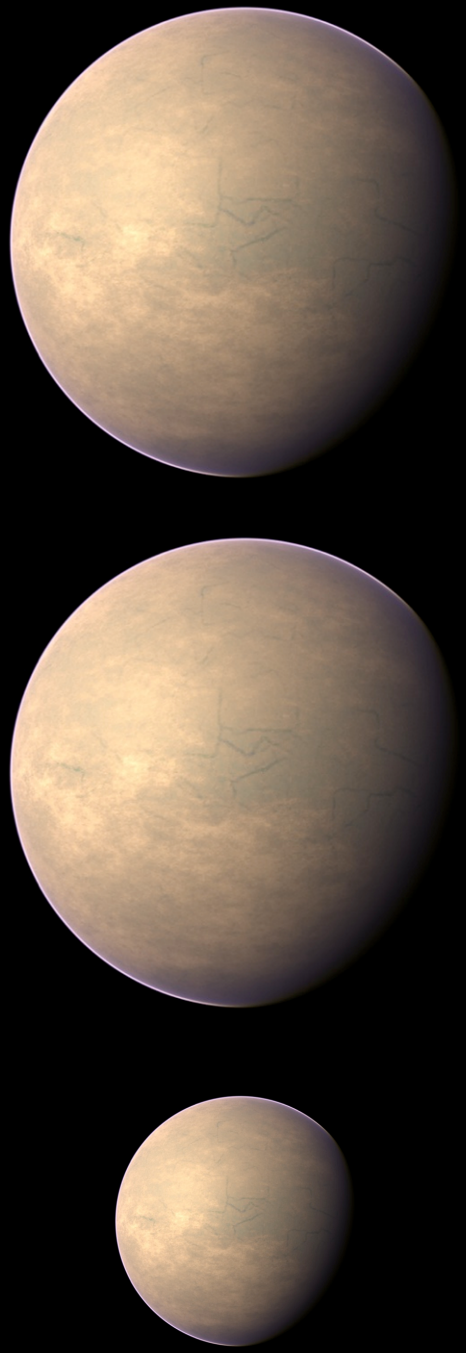
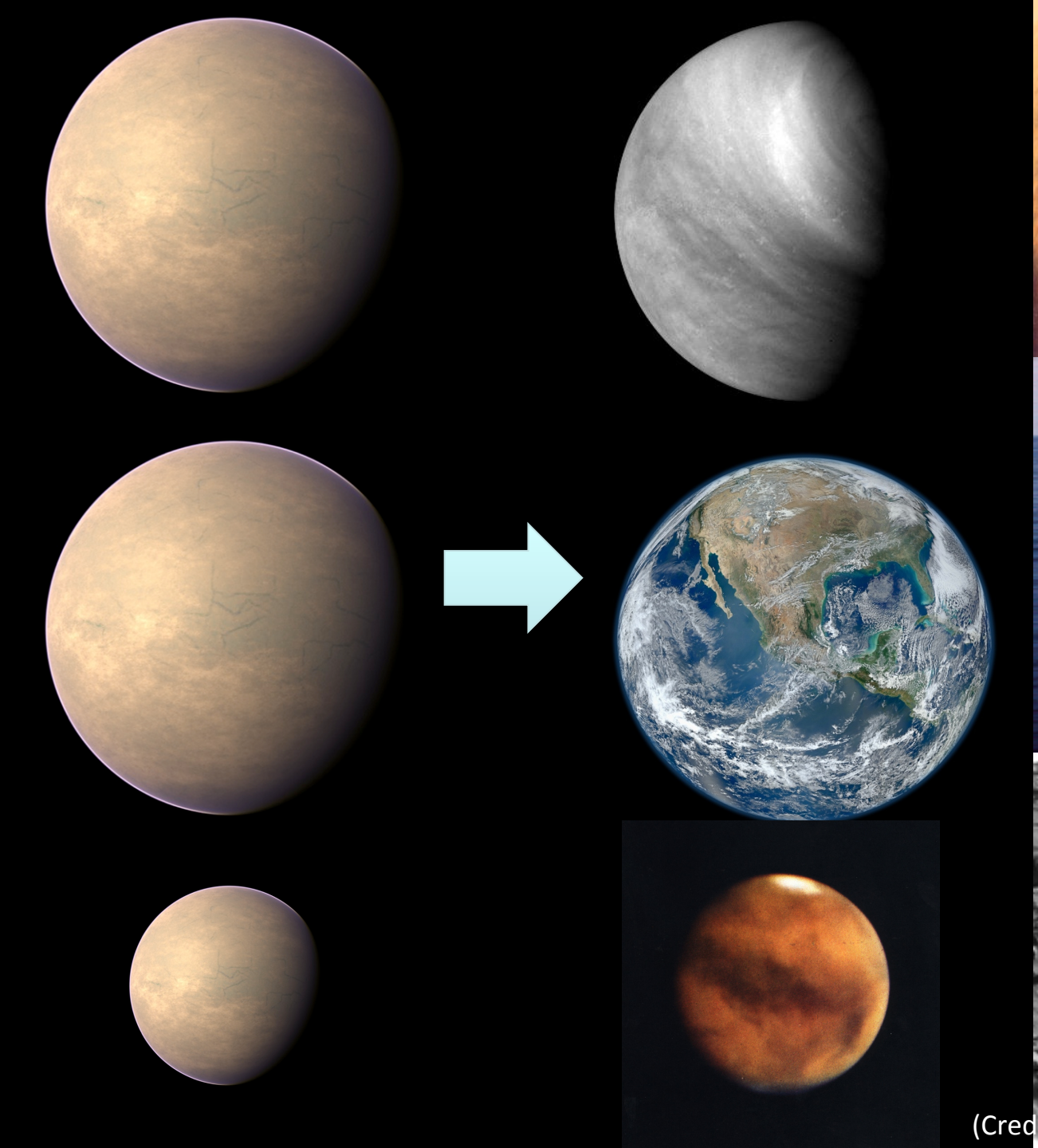
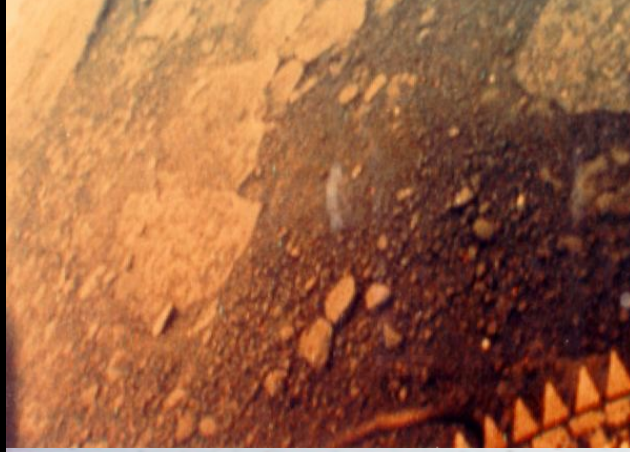
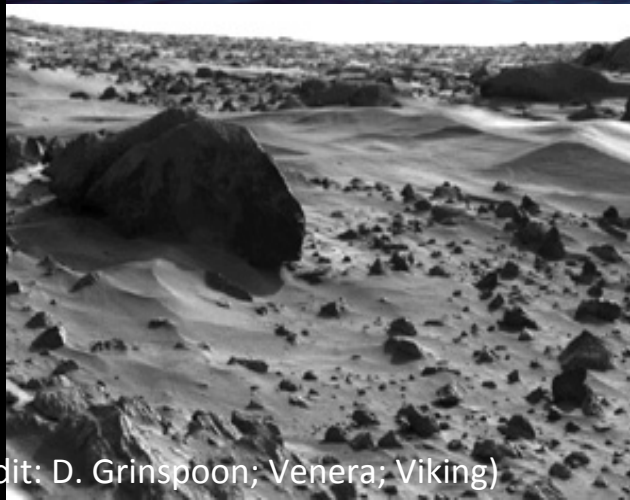


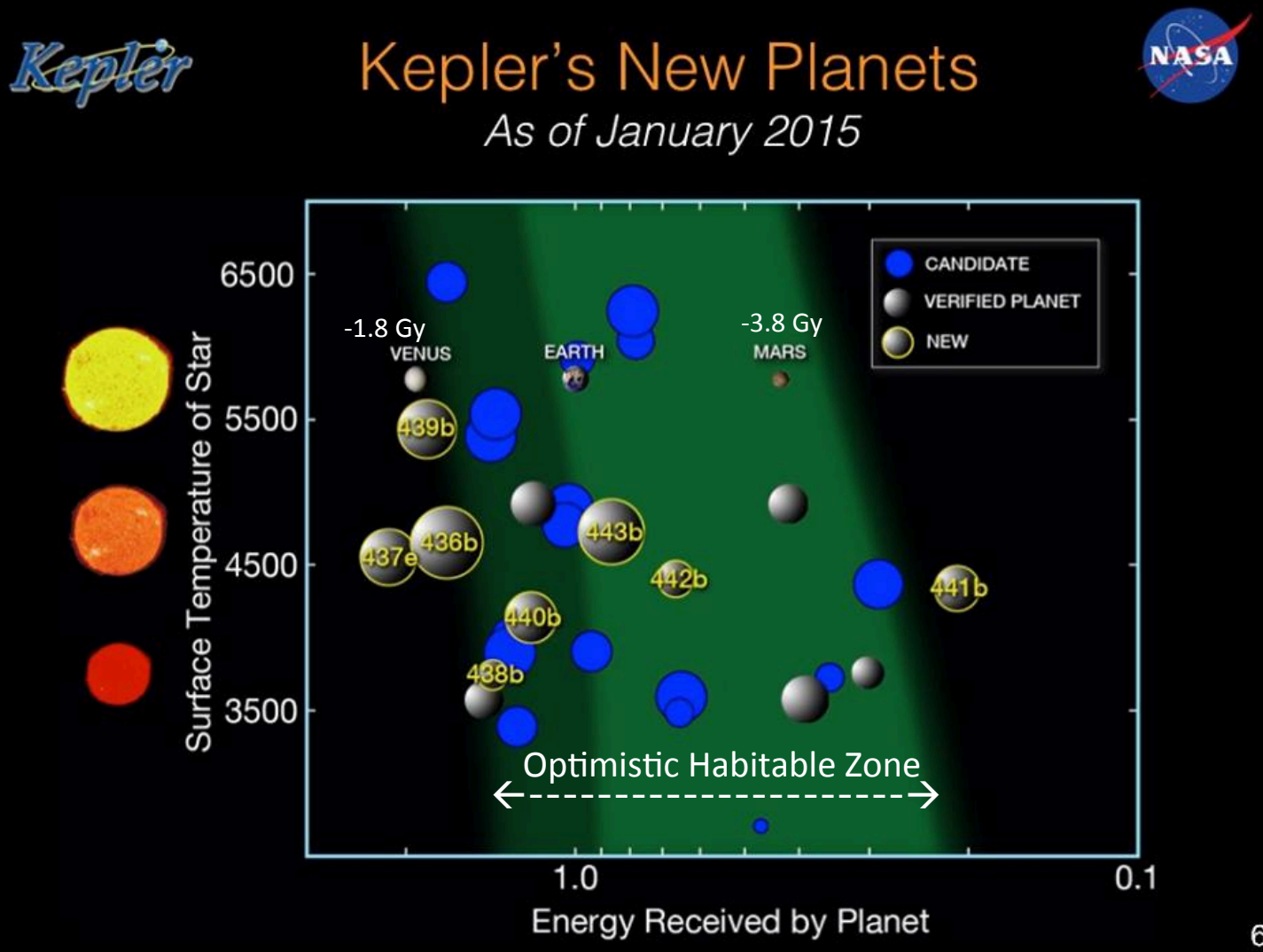






(Credit: D. Grinspoon; Venera; Viking)

Habitable Zone Planets



Looking to the future: from Earth-size to Earth-like, i.e. Habitable Planets

- Life as we know it
  - Is carbon based (RNA, DNA, proteins), and requires
  - Liquid water, for biochem rxns and nutrient transport
  - Nutrients (CHNOPS)
  - Energy (stellar/chemical)
- SLWHZ (surface liquid water habitable zone) is excellent start, and identification of
- H_2O, CH_4, O_2, O_3, CO_2, SO_2, C_nH_m, HCl, $^{13}C/^{12}C$ and the aerosols etc. in the atmospheres of earth-size exoplanets could give clues to their habitability