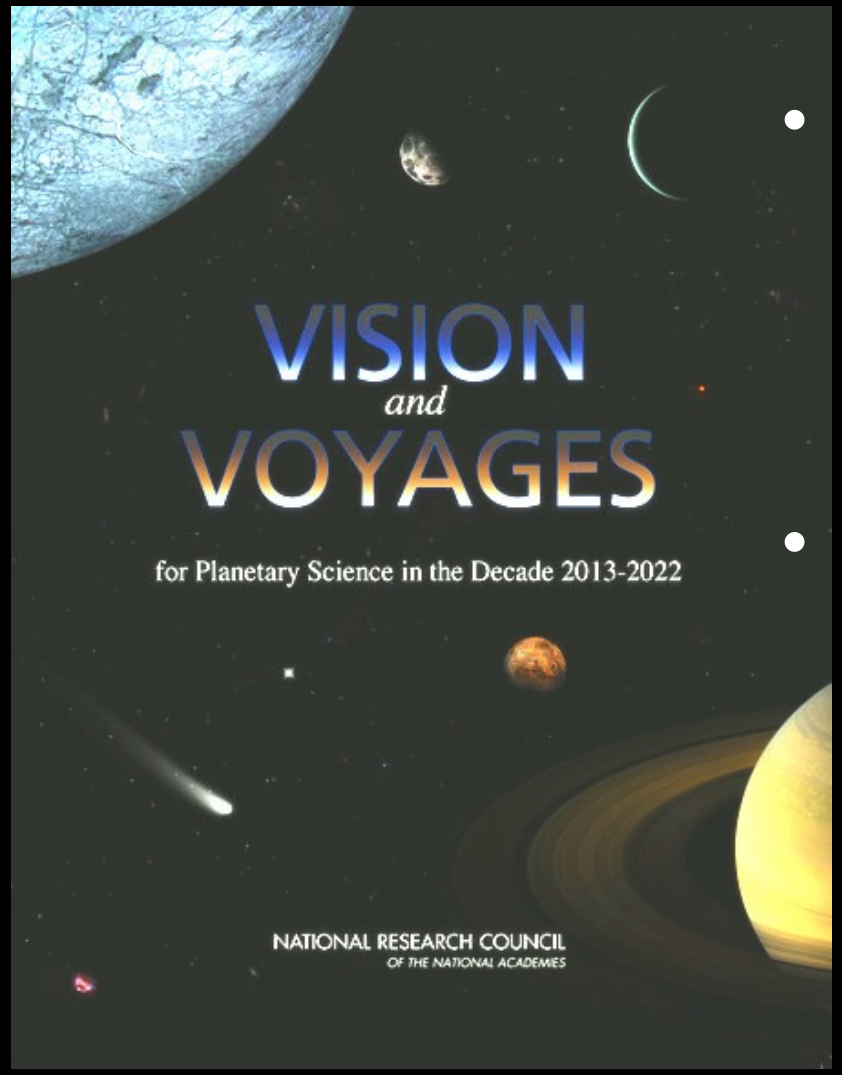
Volatiles on Venus:
A missing link in understanding terrestrial planet evolution

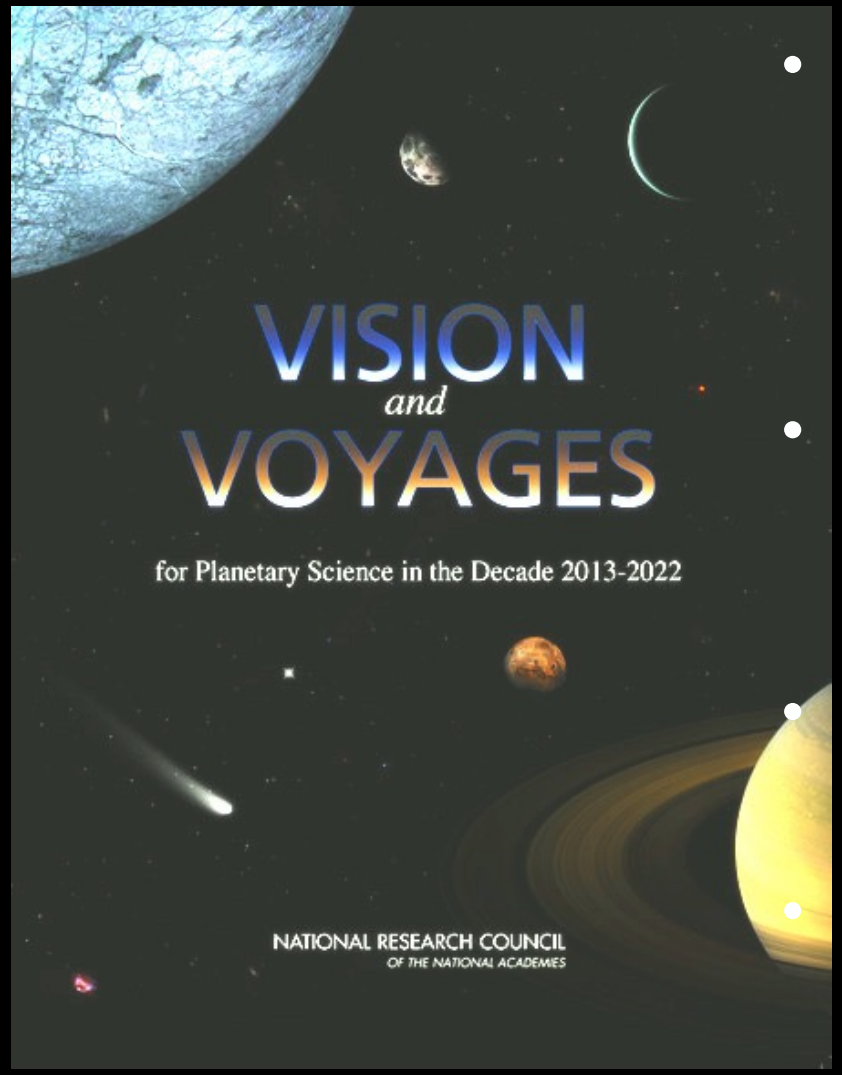
Melissa G. Trainer
Planetary Environments Laboratory
NASA Goddard Space Flight Center

Important questions in the last Decadal Survey [a sampling…]



- How similar or diverse were the original states …and the coupled evolution of interiors and atmospheres on Venus, Earth, and Mars?
- What are the inventories and distributions of volatile elements and compounds …in the mantles and crusts of the inner planets?

Important questions in the last Decadal Survey [a sampling…]



- What are the elemental and isotopic compositions of species in Venus's atmosphere, especially the noble gases and nitrogen-, hydrogen-, carbon- and sulfur-bearing species?
- What was Venus's original volatile inventory and how has this inventory been modified during Venus's evolution?
- How and to what degree are volatiles exchanged between Venus's atmosphere and its solid surface?
- Is there evidence of environments that once were habitable on Venus?

Two major themes

I. Venus is the key to understanding our terrestrial planet system

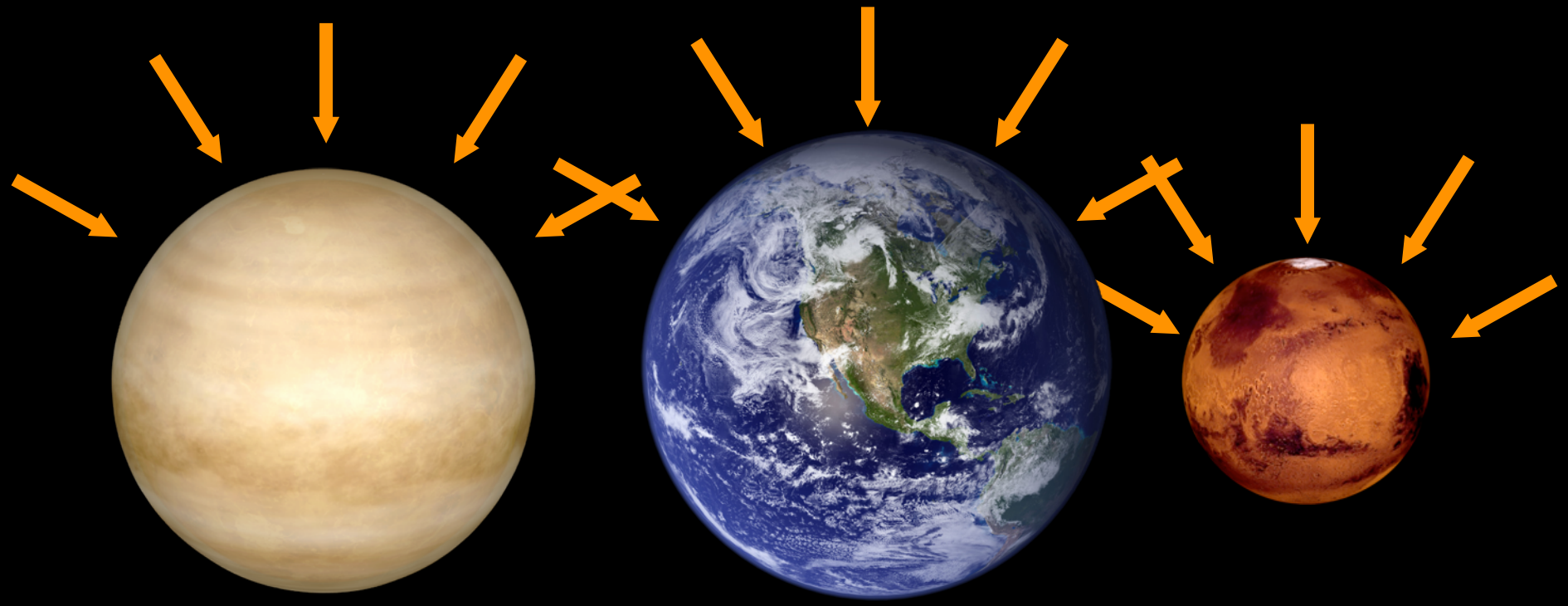
II. Venus is key to understanding formation of habitable systems

Venus is a terrestrial planet

Venus is a terrestrial planet

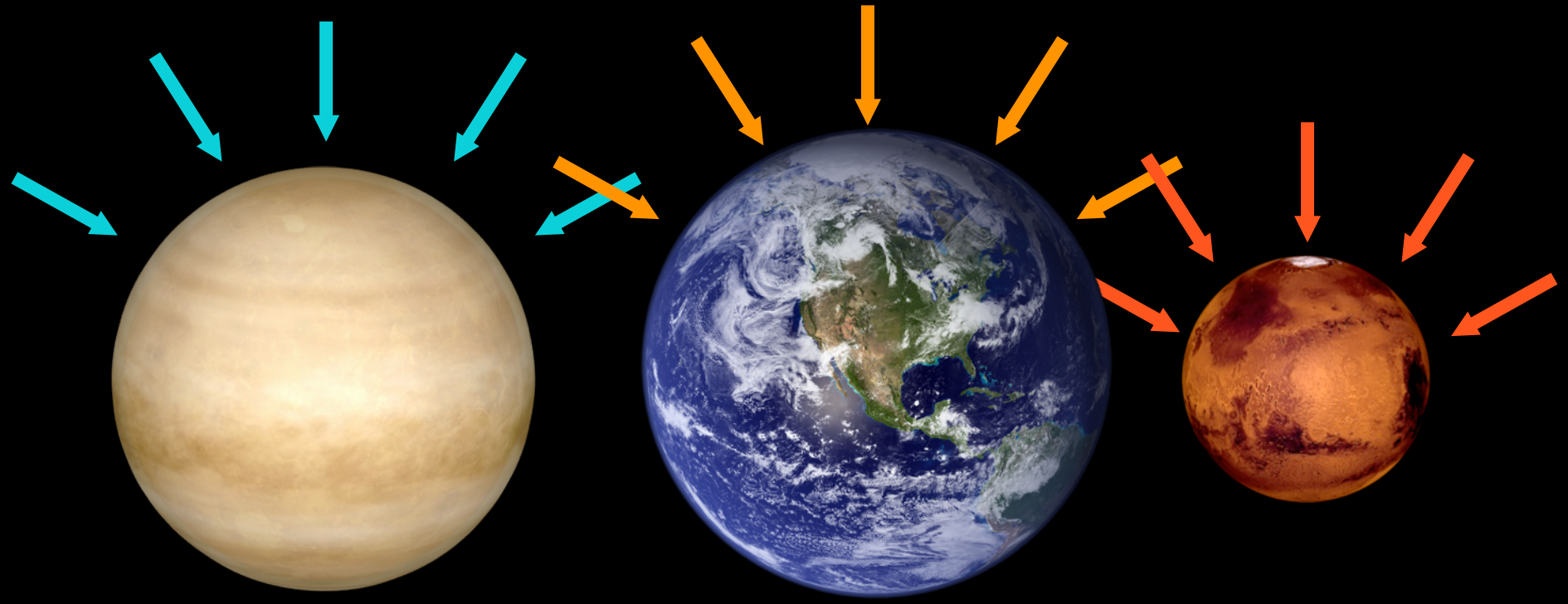
Atmospheres **sourced** from:
1) accretion of volatile material (nebular gas, comets, chondrites)
2) outgassing from the interior after planetary formation

Atmospheres **lost** to:
1) space
2) surface sinks (carbonates)



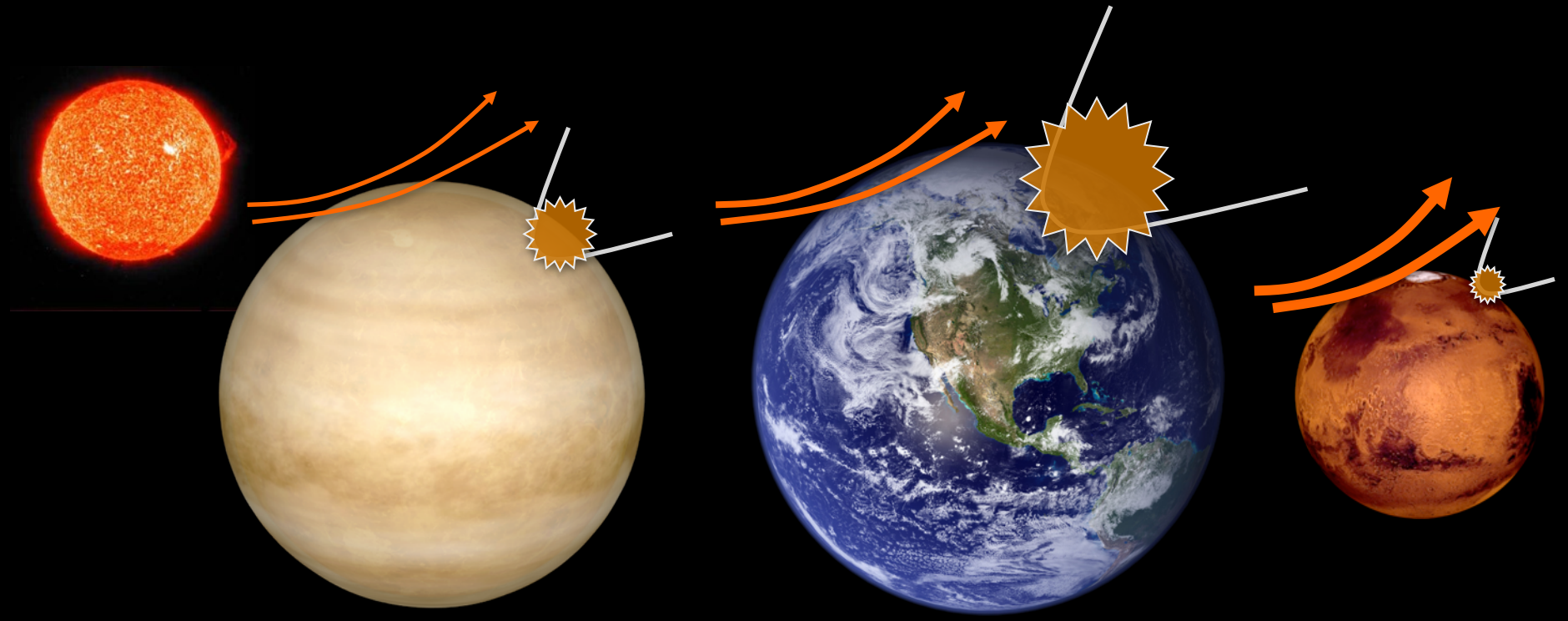
Atmospheres **sourced** from:
1) accretion of volatile material (nebular gas, comets, chondrites)
2) outgassing from the interior after planetary formation

Atmospheres **lost** to:
1) space
2) surface sinks (carbonates)



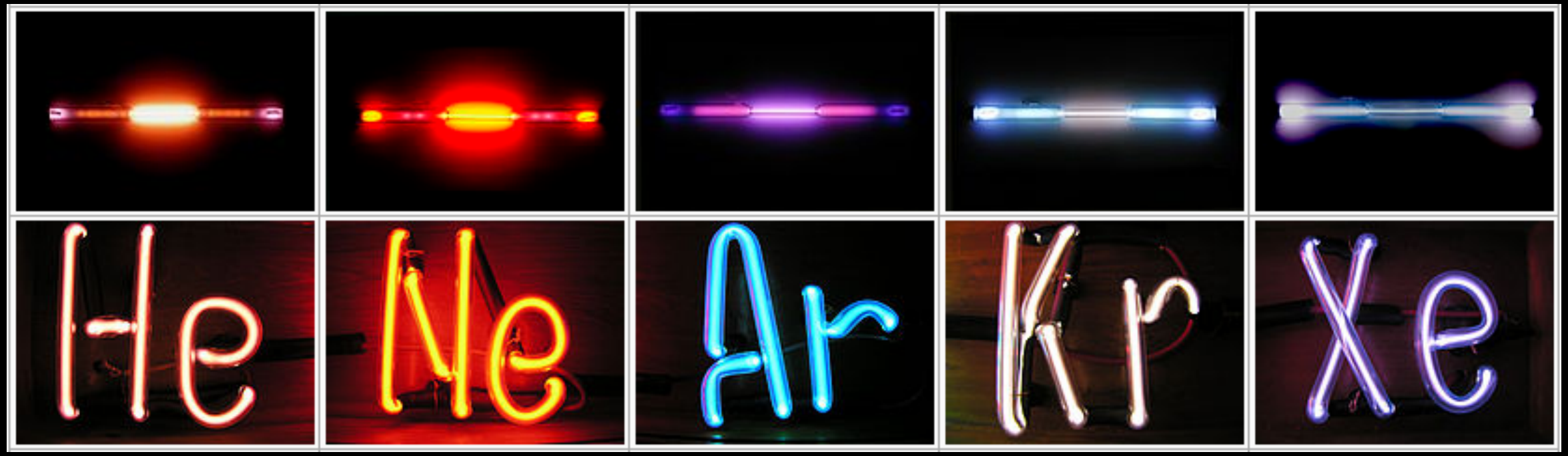
Atmospheres **sourced** from:
1) accretion of volatile material (nebular gas, comets, chondrites)
2) outgassing from the interior after planetary formation

Atmospheres **lost** to:
1) space
2) surface sinks (carbonates)

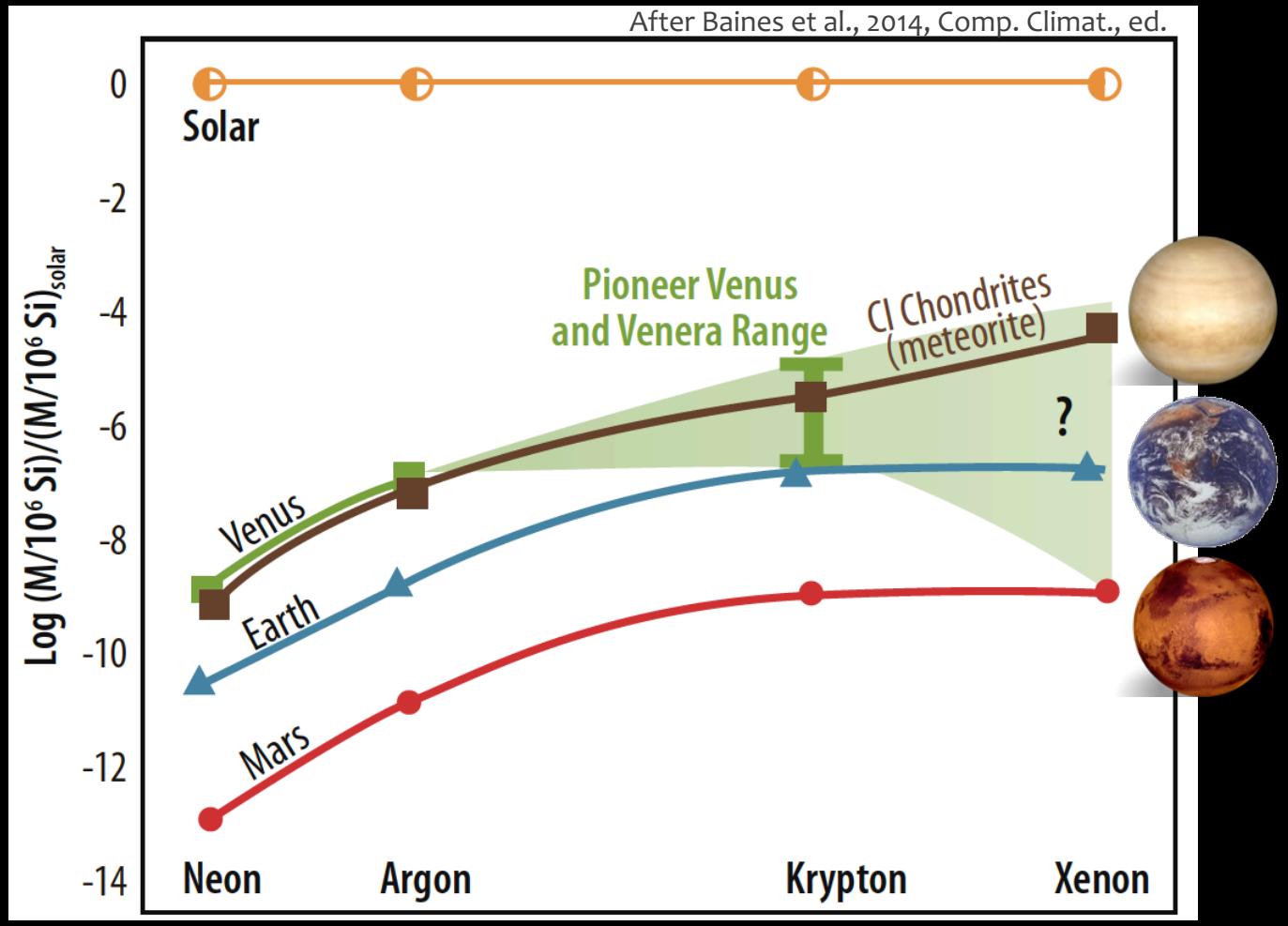


Atmospheres **sourced** from:
1) accretion of volatile material (nebular gas, comets, chondrites)
2) outgassing from the interior after planetary formation

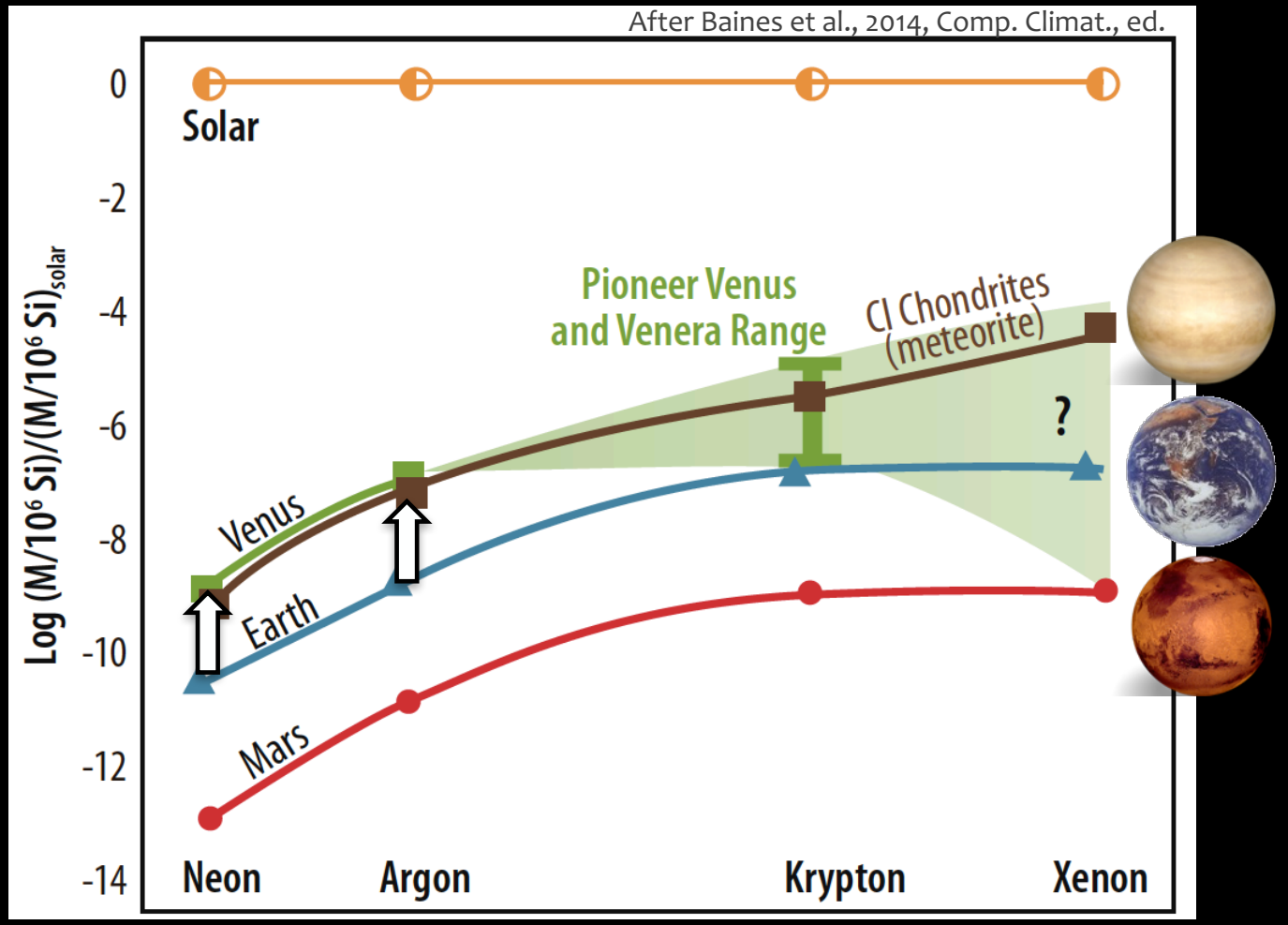
Atmospheres **lost** to:
1) space
2) surface sinks (carbonates)


He
Ne
Ar
Kr
Xe

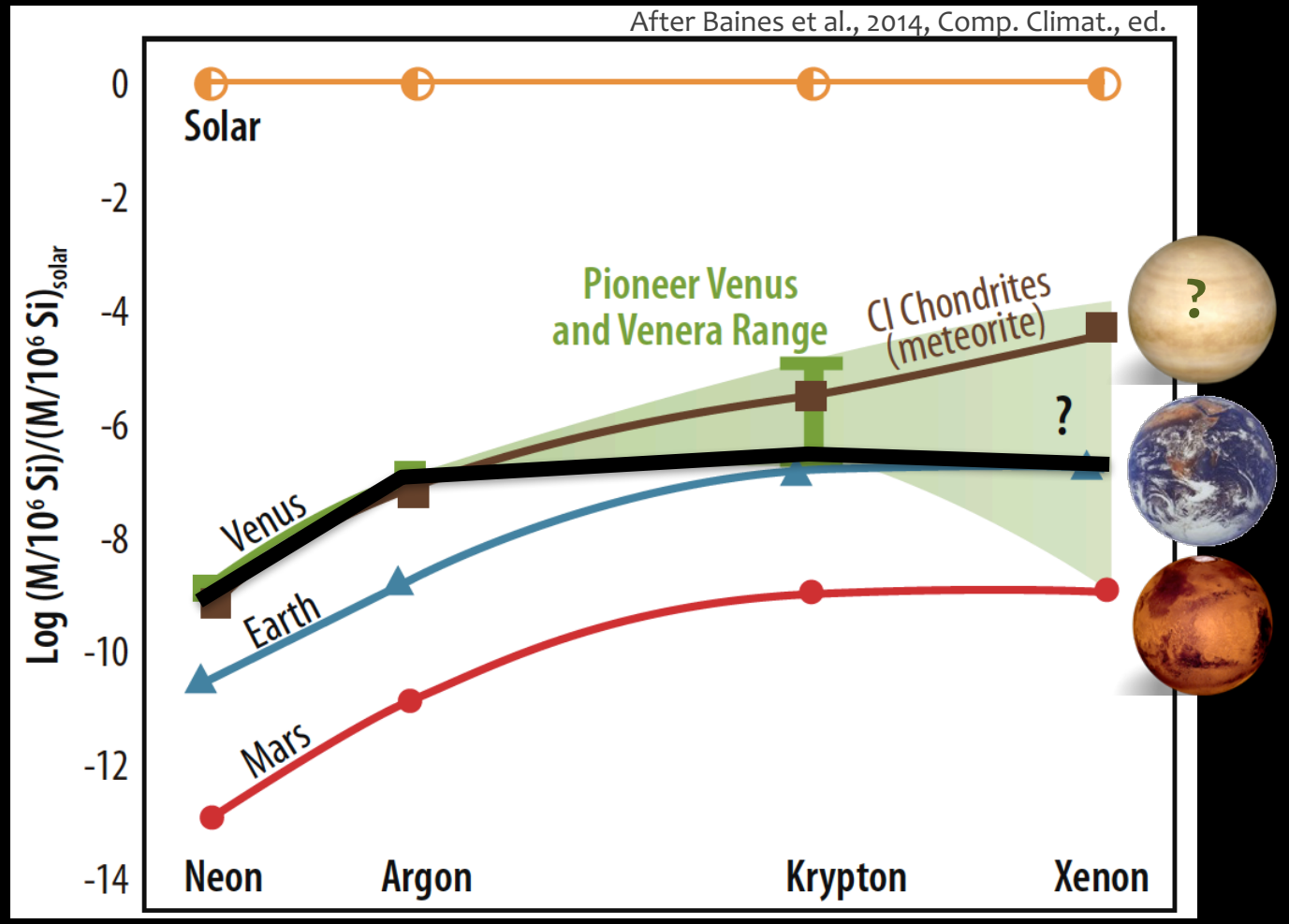
What are the sources of planetary volatiles?



What are the sources of planetary volatiles?

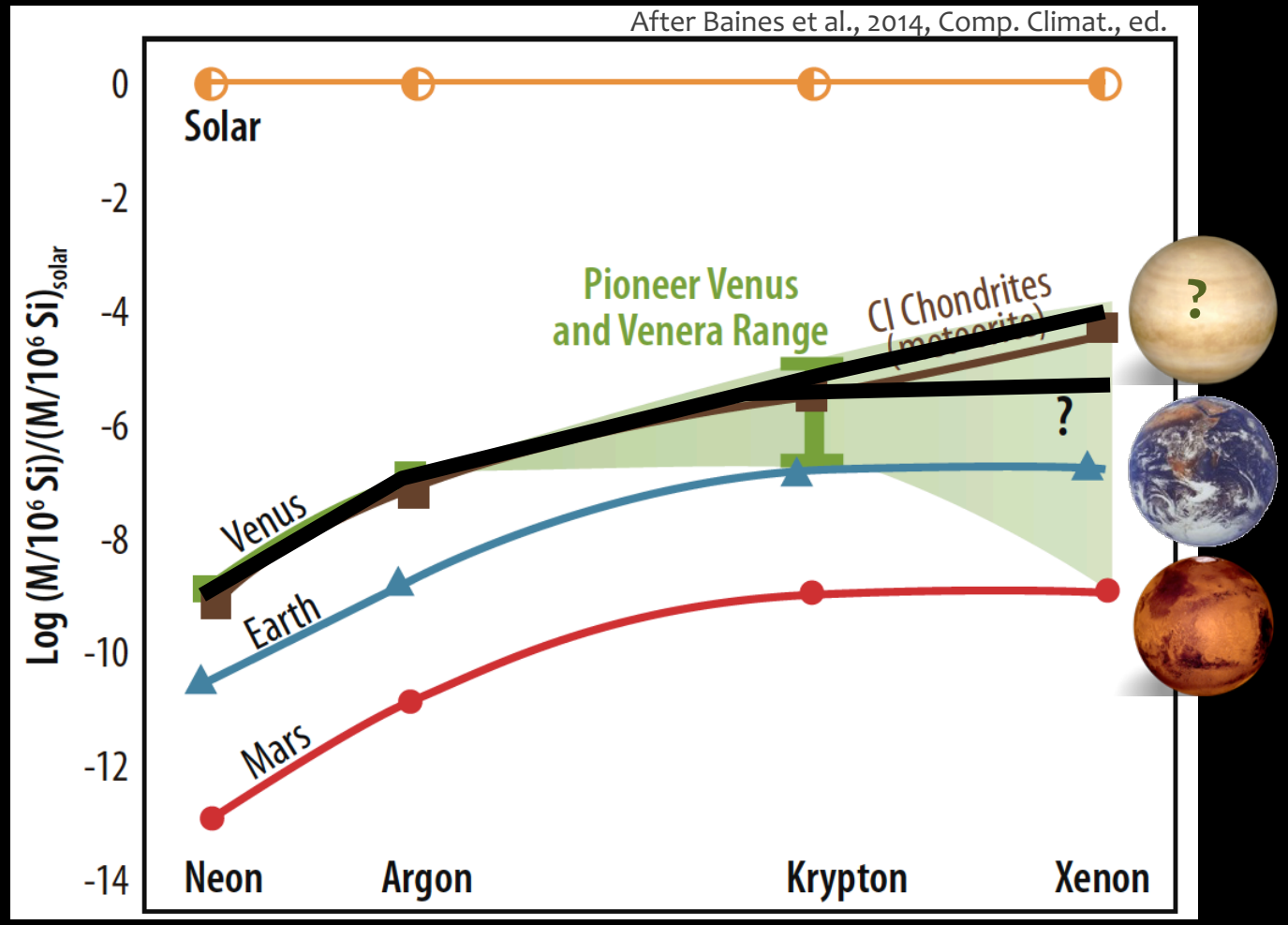


What are the sources of planetary volatiles?

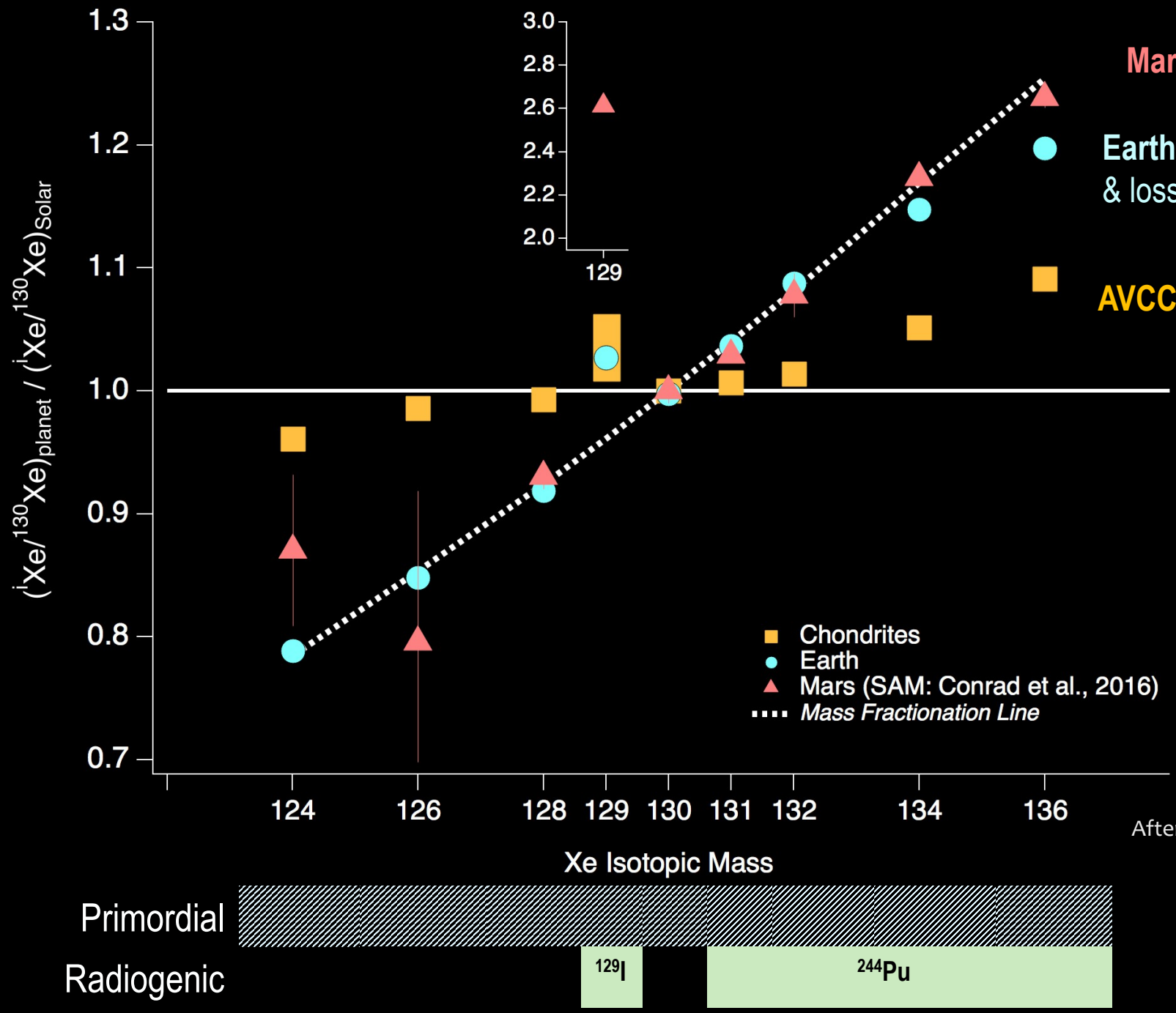


- If Venus is more like solar and Jupiter, supports delivery from planetesimals with solar composition ("cold comet hypothesis")

What are the sources of planetary volatiles?



- If Venus is more like meteorites and planets it supports chondrites as source to inner planets, but without substantial loss as for Earth and Mars



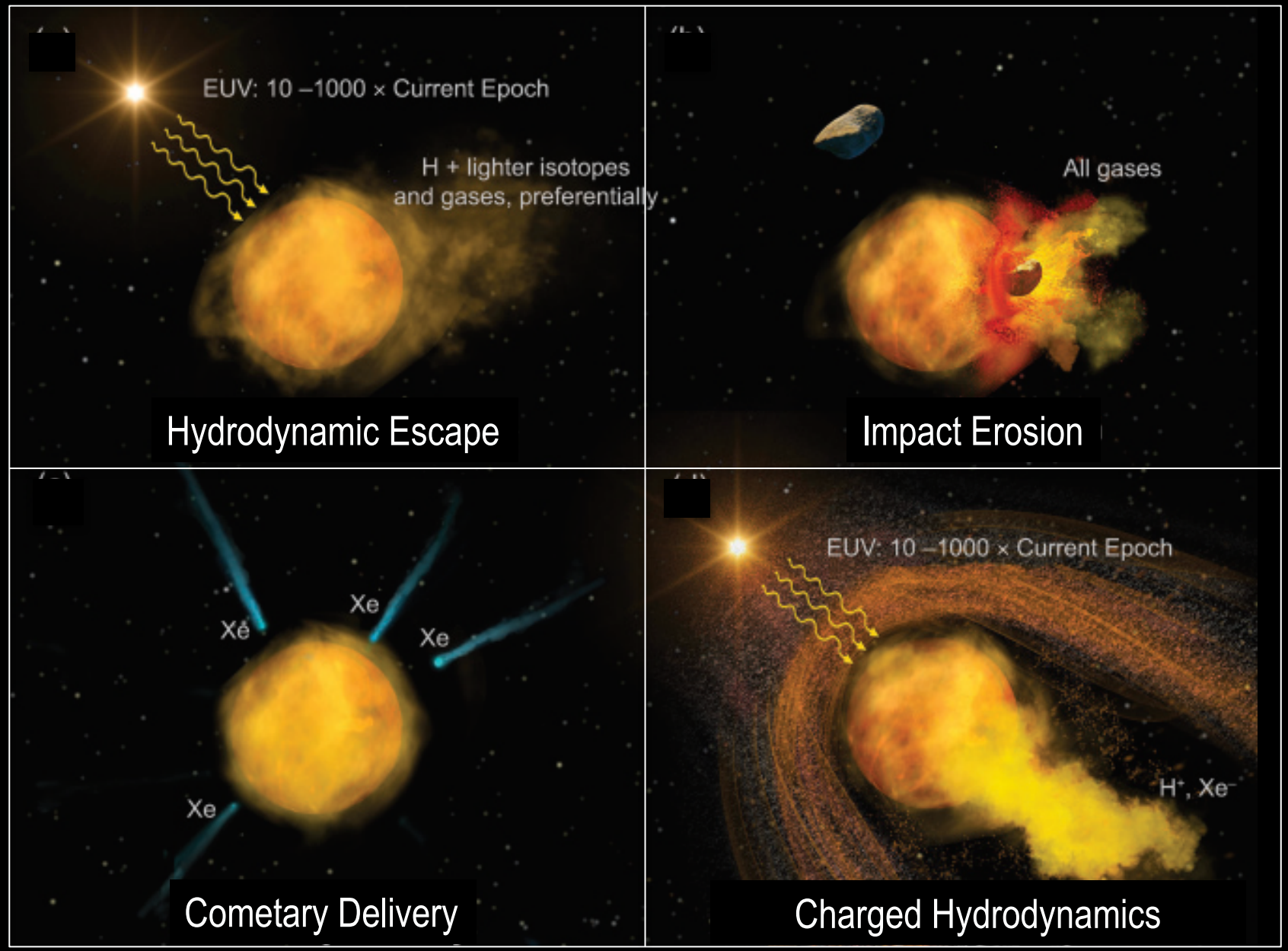
Mars – fractionation from loss

Earth – unique source, "U-Xe"
& loss from major impacts/events

AVCC – combined alteration

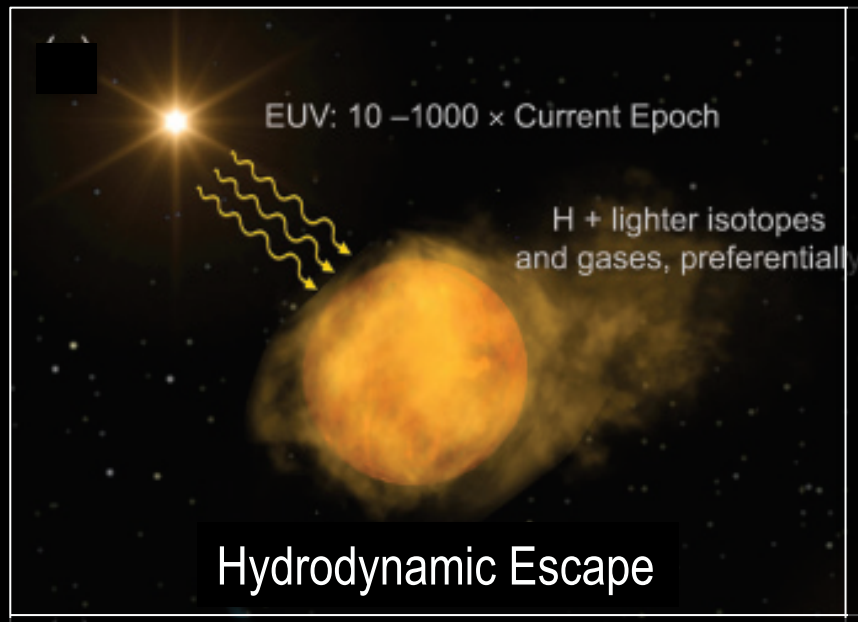
After Baines et al., 2014, Comp. Climat., ed.

Which forces controlled atmospheric evolution? [xenology]



After Baines et al., 2014, Comp. Climat., ed.

Which forces controlled atmospheric evolution? [xenology]



Hydrodynamic Escape

Terrestrial planets lost noble gases to blowoff of atmospheric H by EUV (or Moon-formation)

Lighter gases replenished from interior

Each planet has unique loss rate

Supporting data:

- Mass fractionation
- $[Xe]_T$ depletion relative to $[Ar,Kr]_T$

➢ Venus holds more noble gases

➢ Venus ^{129}Xe greater

Cometary Delivery

Charged Hydrodynamics

After Baines et al., 2014, Comp. Climat., ed.

Which forces controlled atmospheric evolution? [xenology]

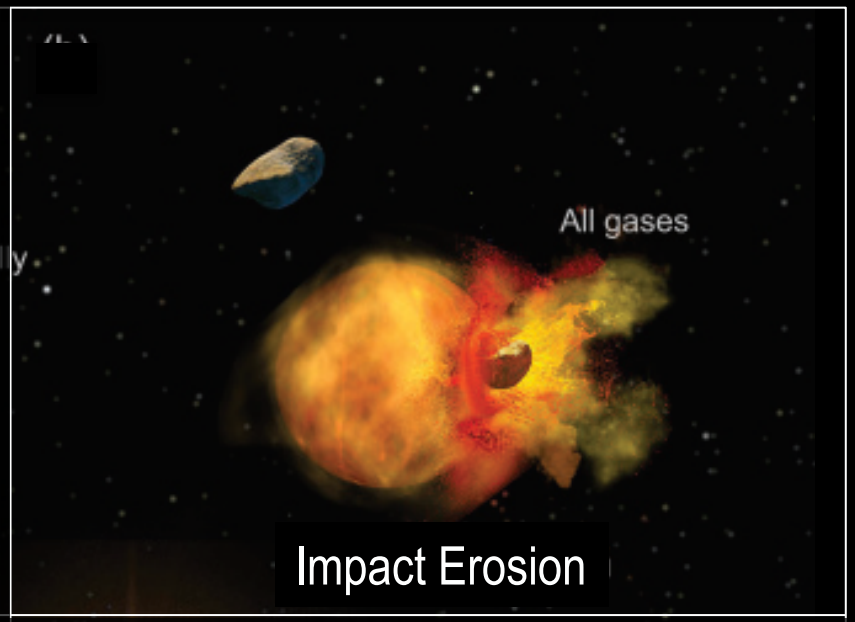
Impacts during accretion would lead to mass-independent fractionation

Phase is controlling factor (i.e., can lose nobles w/o losing ocean)

Not only evolutionary event

Supporting data:

- Loss of bulk noble gases
- ➢ Loss of radiogenic Xe on Venus



Impact Erosion

Hydrodynamic Escape

H + lighter isotopes and gases, preferentially

Xe

Cometary Delivery

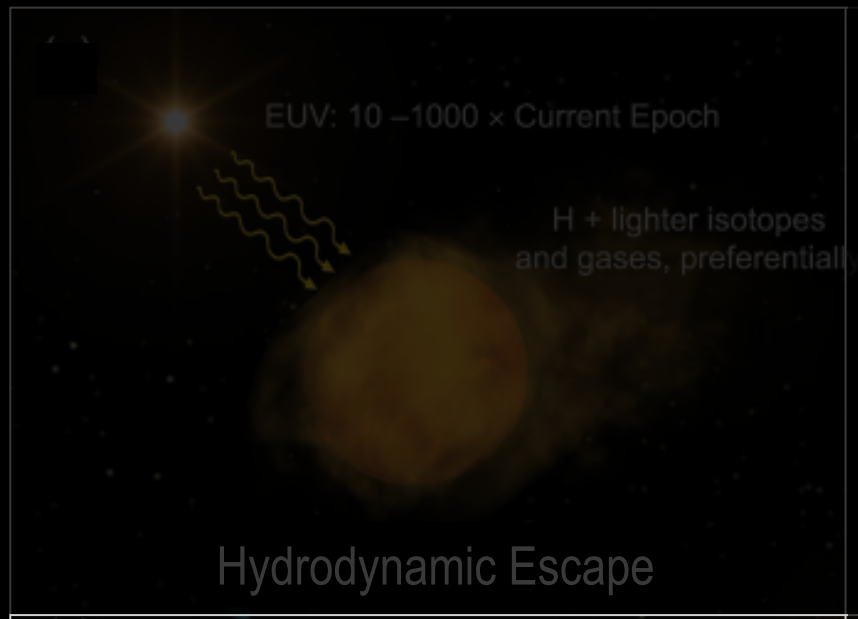
EUV: 10 –1000 × Current Epoch

H⁺, Xe⁻

Charged Hydrodynamics

After Baines et al., 2014, Comp. Climat., ed.

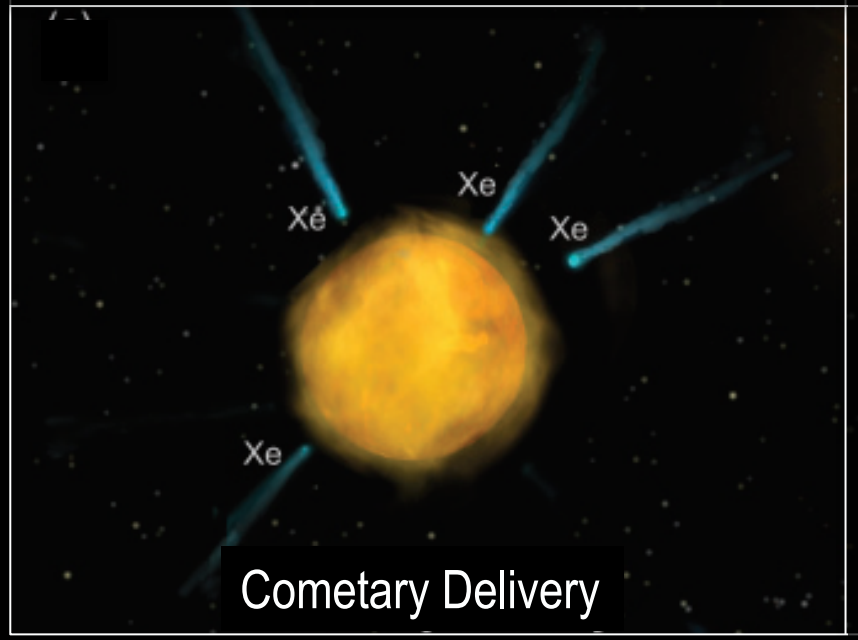
Which forces controlled atmospheric evolution? [xenology]



Outer solar system “cold comets” are source of volatiles

Delivered noble gases are already fractionated

Delivered to other inner solar system bodies

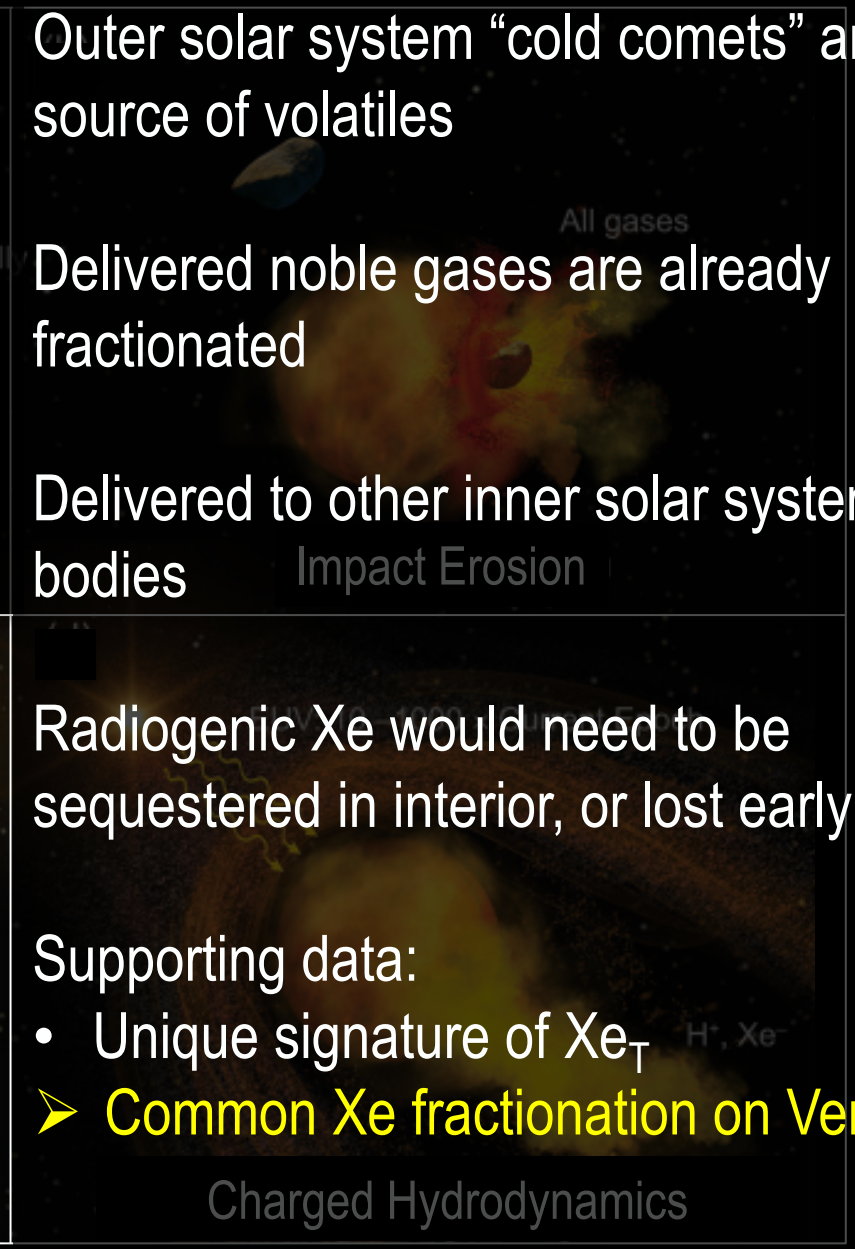


Radiogenic Xe would need to be sequestered in interior, or lost early

Supporting data:

- Unique signature of Xe_T

➢ Common Xe fractionation on Venus



After Baines et al., 2014, Comp. Planet., ed.

Which forces controlled atmospheric evolution? [xenology]

Xe is easily ionized by H- and preferentially escapes with solar wind

Atmospheric blowoff that removes Xe more significantly than other volatiles

Hydrodynamic Escape

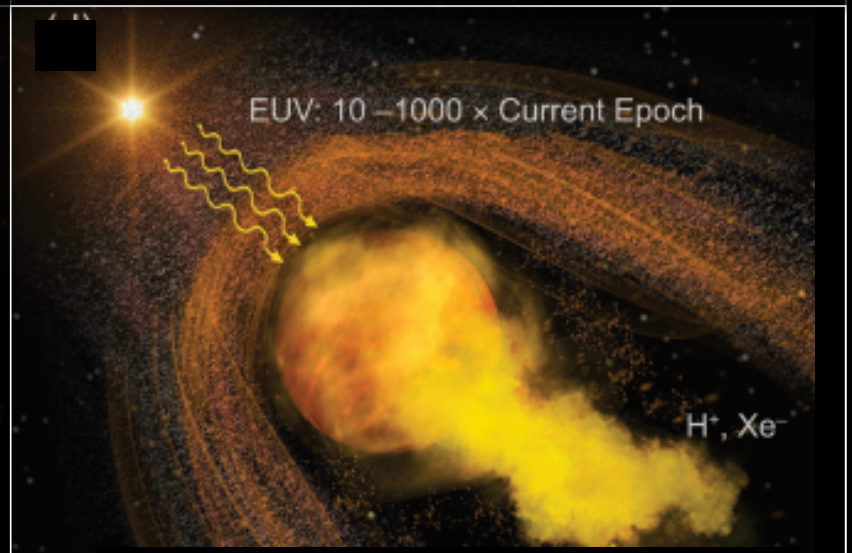
Impact Erosion

Supporting data:

- Earth's and Mars' "missing xenon"

➢ Venus relatively depleted in Xe

Cometary Delivery

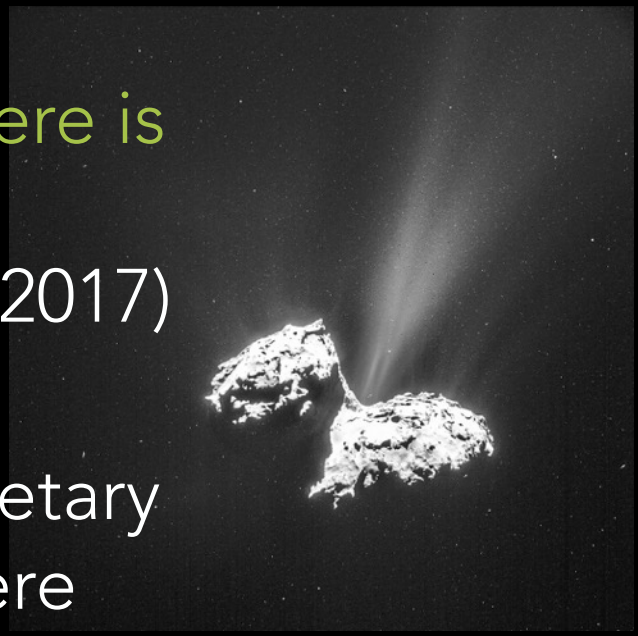


Charged Hydrodynamics

After Baines et al., 2014, Comp. Climat., ed.

Whence the U-Xe?

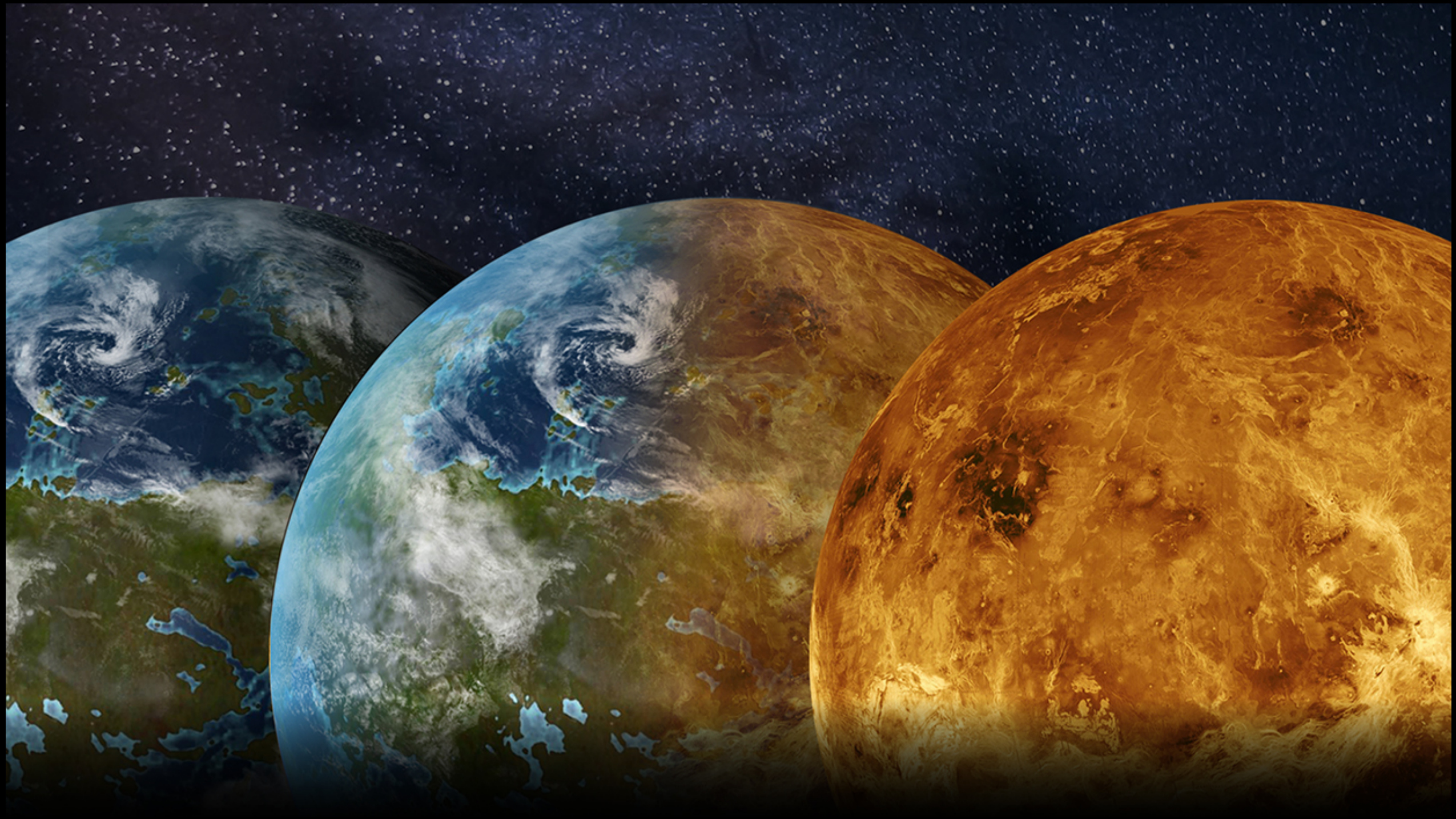
- This theoretical reservoir of isotopically unique Xe required to explain Earth's current atmospheric composition
- Recently published work confirms Archean atmosphere is consistent with less-fractionated U-Xe composition - possibly delivered during late accretion (Avice et al. 2017)
- Rosetta/ROSINA measurements at Comet 67P/C-G suggest detection of U-Xe*, and results imply a cometary contribution of ~22% to Earth's primordial atmosphere (Marty et al. 2017)
- Venus may be only other place to find evidence of U-Xe



* coma measurement: assumes bulk Xe in ice is similar

Which process shaped our habitable planet?

- Likely a combination of multiple processes
  - Example: Cometary delivery of "U-Xe" but unique blowoff rates
- Full complement of bulk and isotopic compositions of noble gases required to disentangle
- The source and alteration of noble gases has implications for other critical volatiles as well: H_2O, C, N
- The relative contributions of "nature" vs "nurture" cannot be discerned without Venus



Evolution of Venus' hydrosphere and surface

- Similar (or not) sources of volatiles to Earth and Venus?
- Timing of loss of ocean
  - Early water loss, as evidenced by relatively low ^{40}Ar: testable hypothesis by comparing to ^{129}Xe (Mikhail et al. 2016)
- Resurfacing of landscape
  - $^{3}He/^{4}He$ ratio – combined with escape rates - provides insight into the timing and magnitude of recent outgassing events


Ar
129I
Kr
Xe
He
40K
Ne

Isotope	Testable hypotheses	Compared with
$^{n}Xe/^{132}Xe$	Source of volatiles to inner solar system	Terrestrial (var.) Jupiter (GPMS) Comet 67P/C-G (ROSINA) Solar wind (Genesis) Mars (SAM)
	Importance of major loss processes	
$^{129}Xe/^{132}Xe$	Timing of major loss events, including impacts	
$^{82}Kr/^{86}Kr$	Source of volatiles to inner solar system: chondritic or solar	
$^{36}Ar/^{38}Ar$	Atmospheric loss since formation	
$^{20}Ne/^{22}Ne$	Sources to atmosphere: nebular, meteoritic, implanted solar wind	Terrestrial Solar wind (var.) Mars (met.) Meteorites (var.)
$^{3}He/^{4}He$	Exogenic and endogenic (volcanic) sources	Escape rates (Venus Express) Terrestrial
$^{40}Ar/^{36}Ar$; With $^{129}Xe/^{132}Xe$	Outgassing rates and timing of ocean loss	Terrestrial

Origin

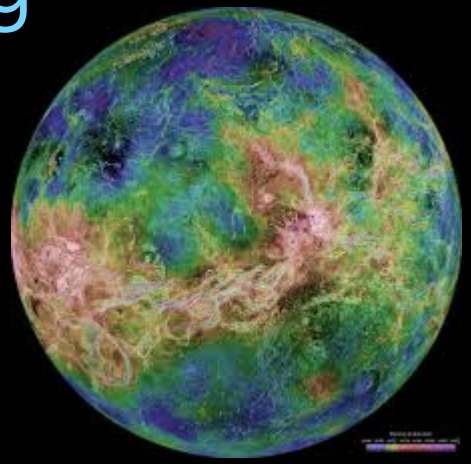
Evolution

Mars
Comet
Venus

What's new since the Decadal Survey?

- Full suite of xenon isotopes in Mars atmosphere with MSL; confirms earlier meteorite measurements of loss-fractionated SW-Xe but with contribution from regolith (Conrad et al. 2016)
- Ar and N isotopes in Mars atmosphere point to substantial loss (Atreya et al. 2013, Wong et al. 2013, Jakosky et al. 2017)
- Measurements of heavier isotopes of Xe (128 – 136) in Comet 67P/C-G suggest a possible source of U-Xe (Marty et al. 2017)
- Magnitude of "electric wind" measured by *Venus Express* strips ions < 18 amu at significantly higher rates than other terrestrial planets (Collinson et al. 2016)

Venus remains the "missing link" to understanding terrestrial planet evolution in our solar system



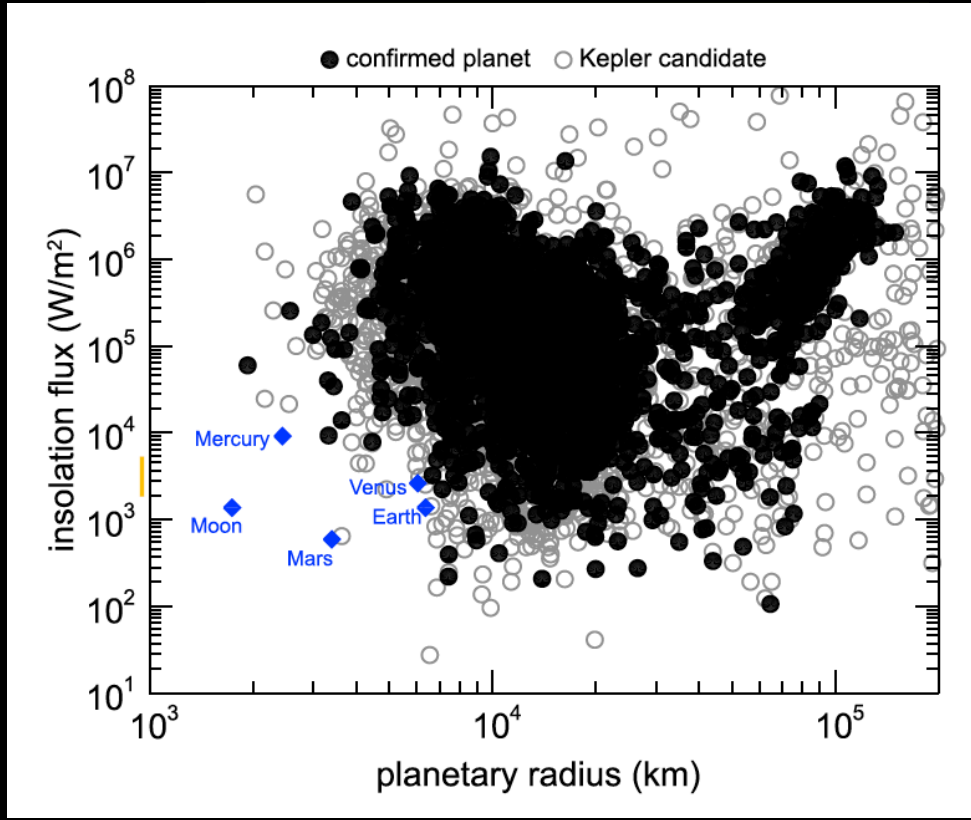
- Noble gases require *in situ* measurement
- Venus has not supplied us with meteorites
- Must be sampled from deep, well-mixed atmosphere
- Present at low abundances (ppm_v to ppb_v)
- Venus environment has not supported long-lived missions

The good news: with an in situ mission these critical measurements could be made using current flight-proven technologies (Galileo, MSL).

These fundamental measurements to reveal the history of our inner solar system are definitive, discernable -- and within reach

Venus provides critical context to our understanding of habitable systems and future exoplanet studies

- What did our inner solar system look like …
  4 Gya? 3 Gya? 1 Gya?
- Venus may have lost its ocean as recently as ~1 Gya
  - Planets like Venus can maintain an extended period of habitability well inside the inner edge of the "habitable zone" *if* they retain H_2O and rotate slowly enough (Way et al., *GRL* 2016)
- Stellar *and* planetary controls on habitability are not fully understood
- Venus and Mars may be two end members of what we are looking for around other stars – yet we are severely lacking data for one of these



Ehlmann et al., *JGR-Planets*, 2016

Acknowledgements and References

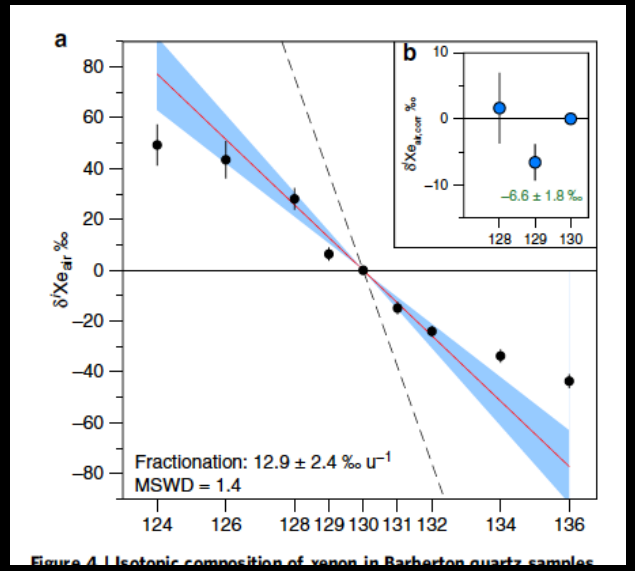
- Thanks to the Committee of the Review of Progress Toward Implementing the Decadal Survey Vision and Voyages for Planetary Science and the National Academy of the Sciences for the opportunity to present
- Thanks to P. Mahaffy, L. Glaze, K. Zahnle, S. Atreya, S. Domagal-Goldman, R. Pepin, and others with whom I've had related conversations

- Avice et al., *Nature Communications*, 8:15455, DOI: 10.1038/ncomms15455, 2017.
- Baines et al., in *Comparative Climatology of Terrestrial Planets*, Univ. Arizona Press, Tucson, pp. 137-160, 2013.
- Collinson et al., *Geophysical Research Letters*, 43, 5926–5934, doi:10.1002/2016GL068327, 2016.
- Conrad et al., *Earth and Planetary Science Letters*, 454: 1-9, 2016.
- Ehlmann et al., *Journal of Geophysical Research – Planets*, 121: 1927–1961, doi:10.1002/2016JE005134, 2016.
- Mahaffy et al., *Journal of Geophysical Research – Planets*, 105(E6): 15,061–15,071, 2000.
- Marty et al., *Science*, 356: 1069–1072, 2017.
- Mikhail et al., *Venus Conference*, Oxford UK, 2016.
- VEXAG, *Goals, Objectives, and Investigations for Venus Exploration*, 2016.
- Pepin, *Icarus* 92: 2-79, 1991.
- Pepin, *Space Science Reviews* 92: 371–395, 2000.
- Pepin, *Earth and Planetary Science Letters* 252: 1–14, 2006.
- Way et al., *Geophysical Research Letters*, 43: 8376–8383, doi:10.1002/2016GL069790, 2016.
- Zahnle, in *Protostars and Planets*, vol. III, Univ. Arizona Press, Tucson, pp. 1305–1338, 1993.

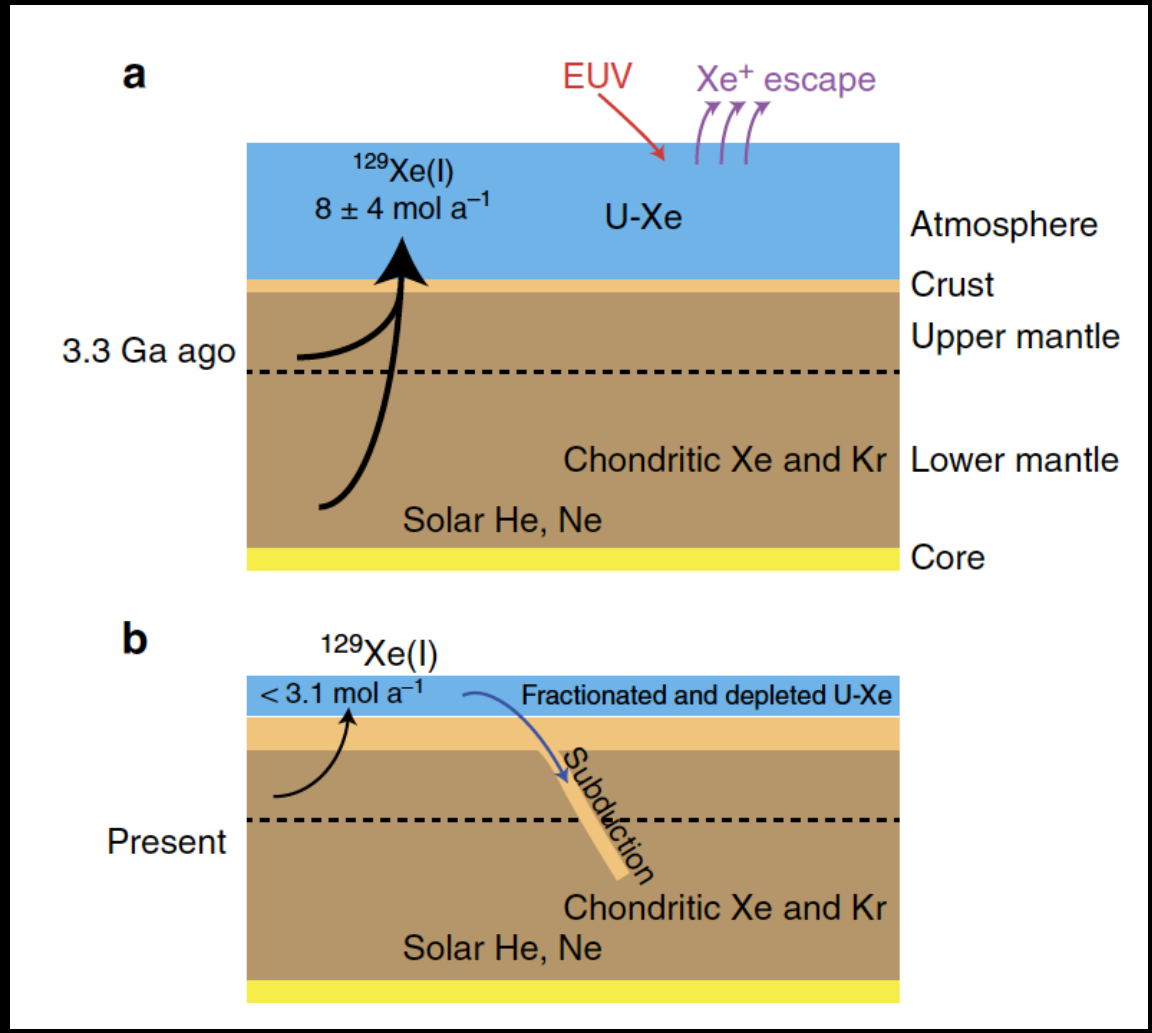
BACKUP SLIDES

Xe isotopes provide information on evolution of Earth's atmosphere and record of major events:

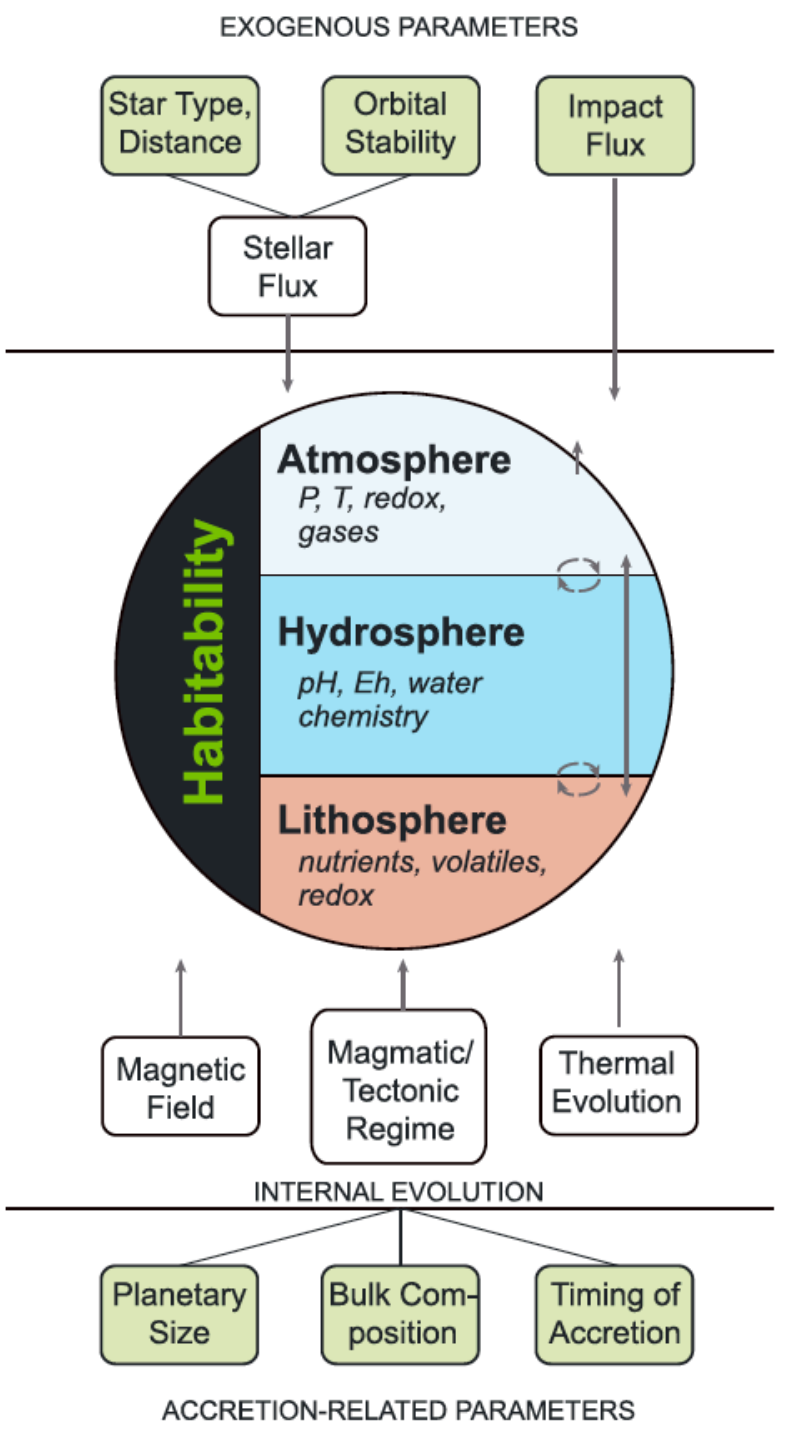
- degassing of mantle
- Moon-forming impact
- delivery of exogenous material

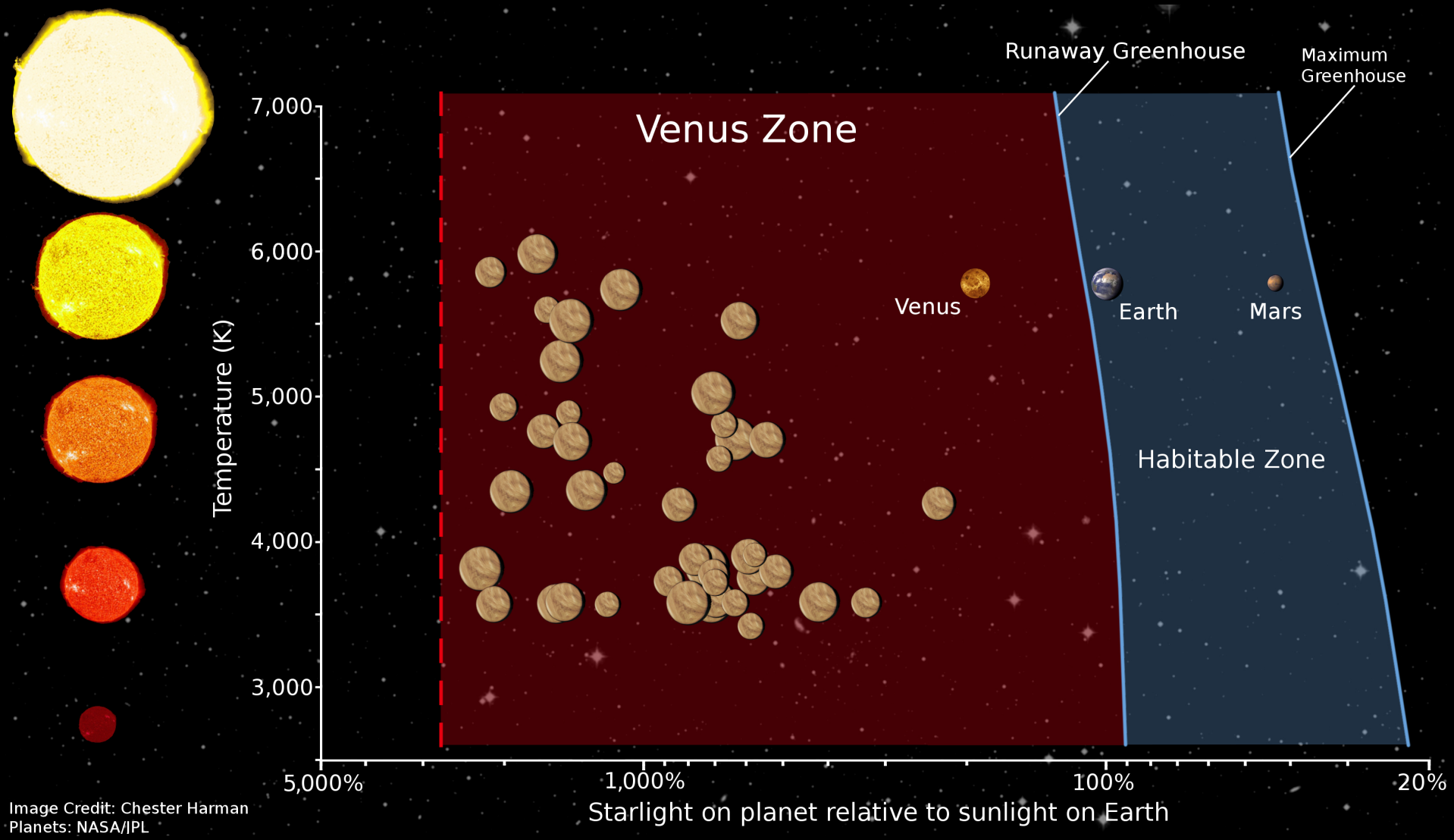


From Avice et al., *Nature Communications*, 2017



From Ehlmann et al., 2016





The 'Venus Zone' represents both confirmed and candidate exoplanets that are expected to have gone through a runaway greenhouse.