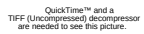
# THE ABUNDANCES AND ISOTOPIC RATIOS OF NOBLE AND LIGHT GASES: CLUES TO THE ORIGIN AND EVOLUTION OF VENUS, EARTH AND MARS

Kevin H. Baines, Alistair Bargery, Sushil K. Atreya, David Grinspoon, and Kevin Zahnle

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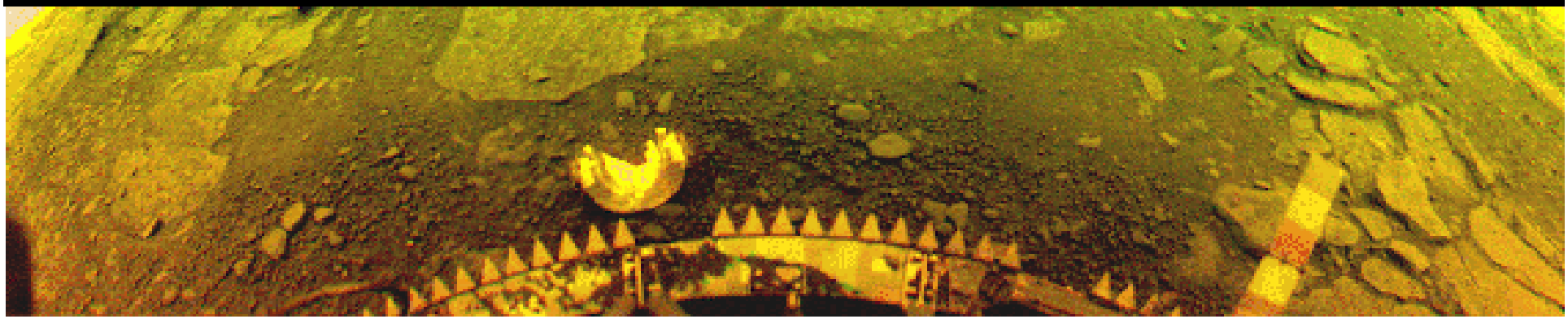
# OUTLINE

-Noble Gas Characteristics
-Origin: Clues from Neon
-Early Evolution: Clues from Xenon
-Subsequent Evolution: Clues from Xenon, Argon, Krypton, Helium, and Light Isotopes
-Venus: Possible Measurements from Future In-Situ Missions



# Noble Gas Characteristics

Chemically and Spectroscopically Inert

Good News: Preserves record of the past

Bad News: Can not be sensed remotely

Must be measured in-situ

Two flavors: Non-Radiogenic and Radiogenic Isotopes

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- Neither created nor destroyed in the planet itself
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  - Plus: What has been delivered/released by impacts (comets, planetesimals, asteroids, impact de-gassing)
  - Minus: What has been lost, for example:
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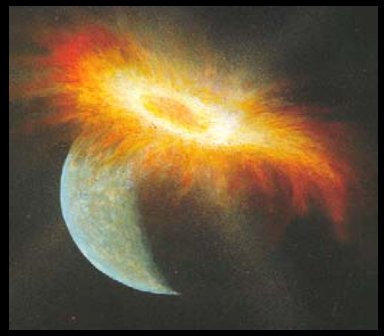

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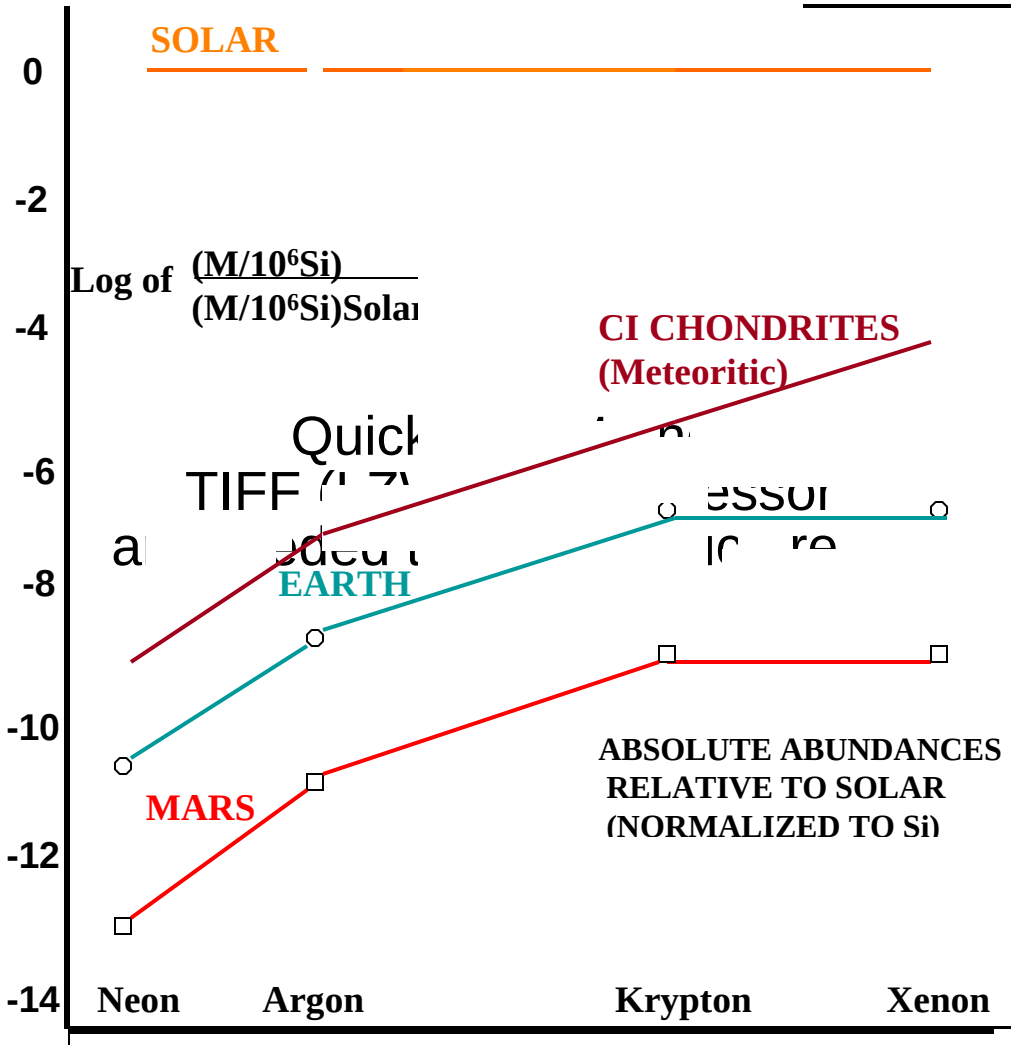
## Radiogenic Isotopes

- Formed by radioactive decay of parent species (e.g., $^{40}Ar$ from $^{40}K$, 1.3 Gyr half-life; $^{129}Xe$ from $^{129}I$, 15.7 Myr half-life)
- Yields timing constraints on major global events (eg., atmospheric loss)
- Indicates average rate of degassing from the interior - Volcanism

# Non-Radiogenic Noble and Light Gas Summary

## Earth vs Mars

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Pepin, *Icarus* **92**, 2-79, 1991

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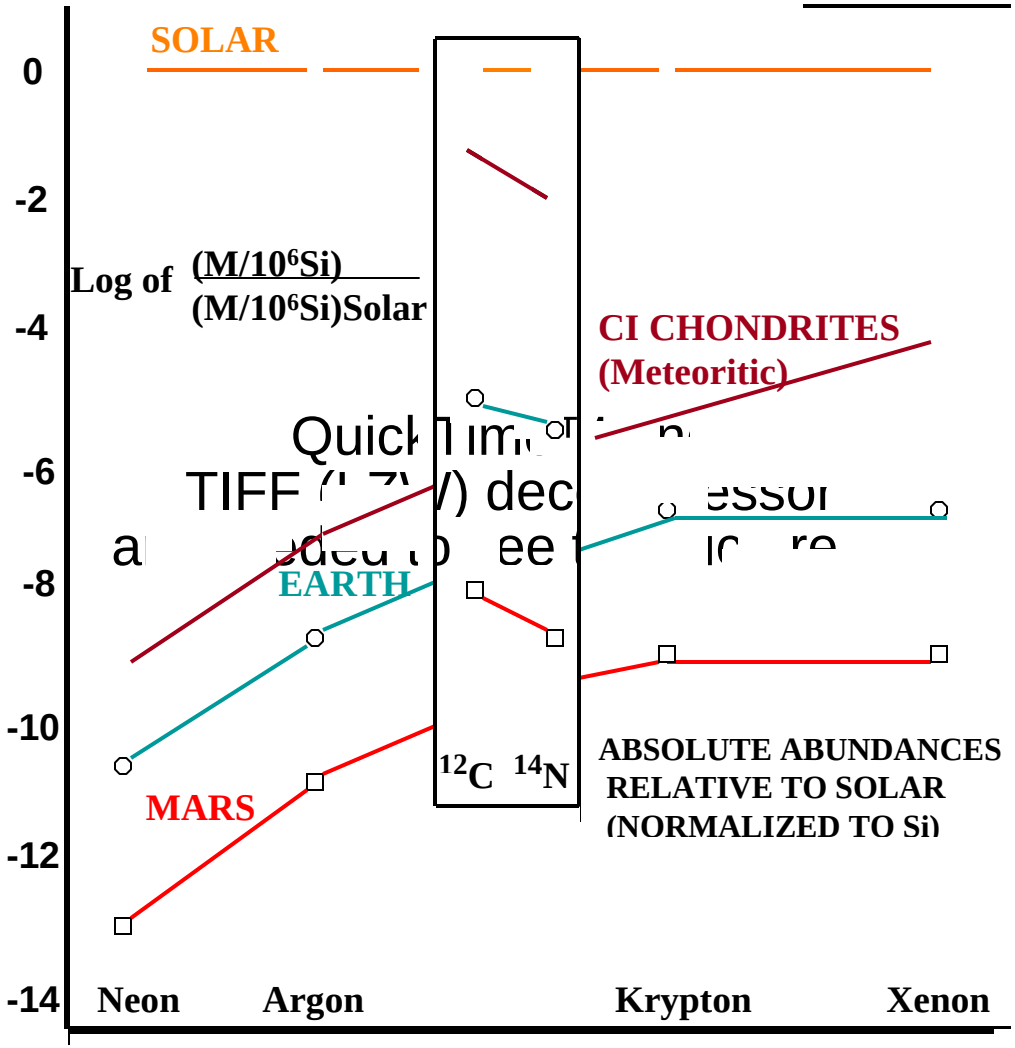


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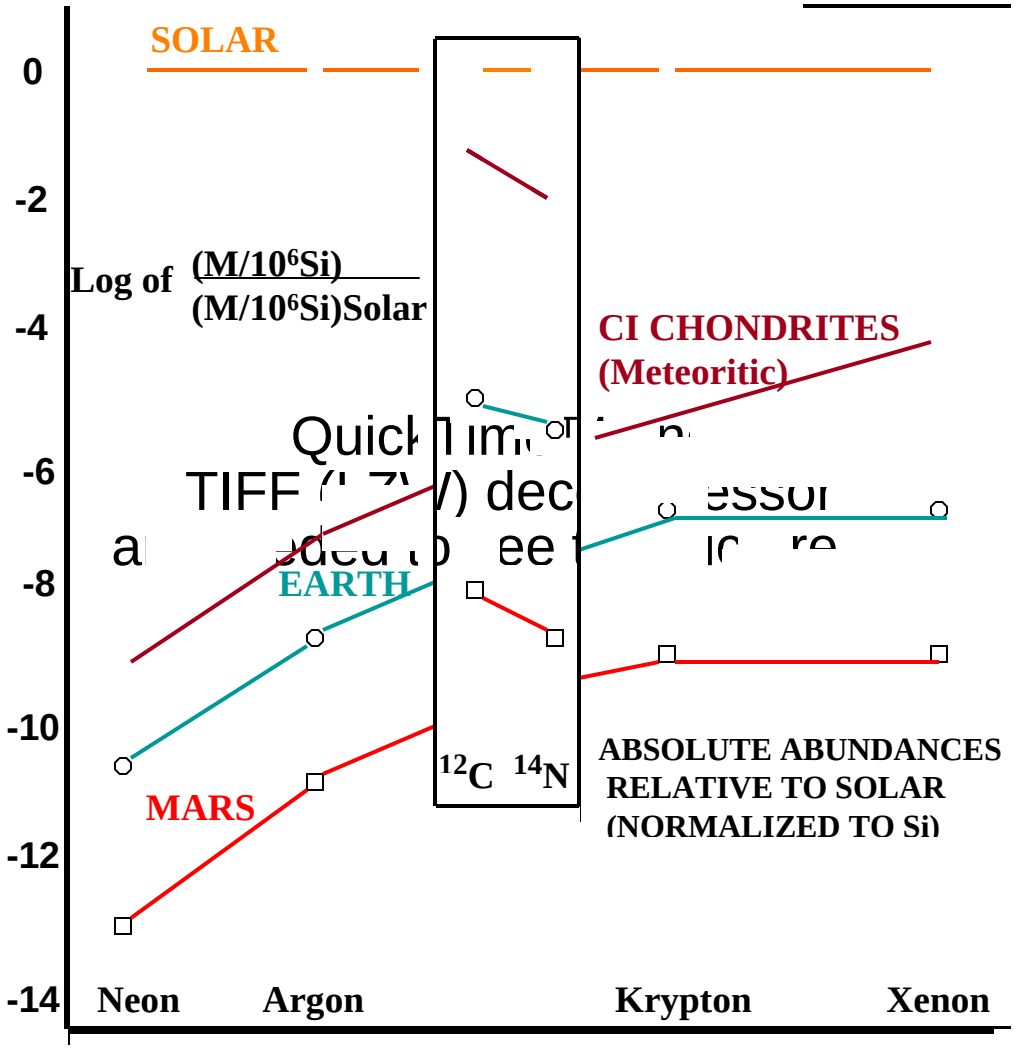


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- **Earth and Mars: Ne:Ar:Kr looks Meteoritic, BUT: Xenon more depleted, more Solar-like**
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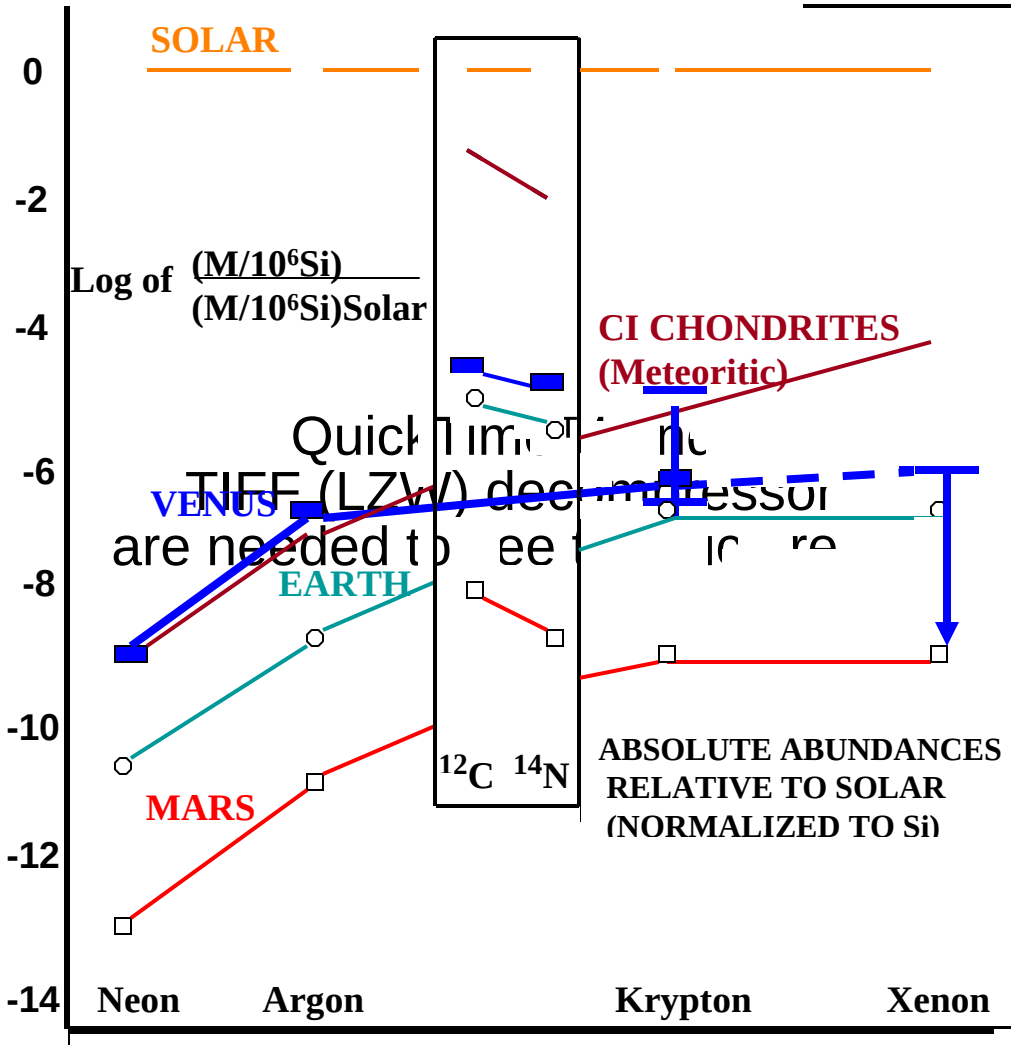
**What about Venus?**

# Non-Radiogenic Noble and Light Gas Summary

## Venus vs Earth vs Mars




- **All terrestrial planets depleted relative to Solar, by > $10^4$**
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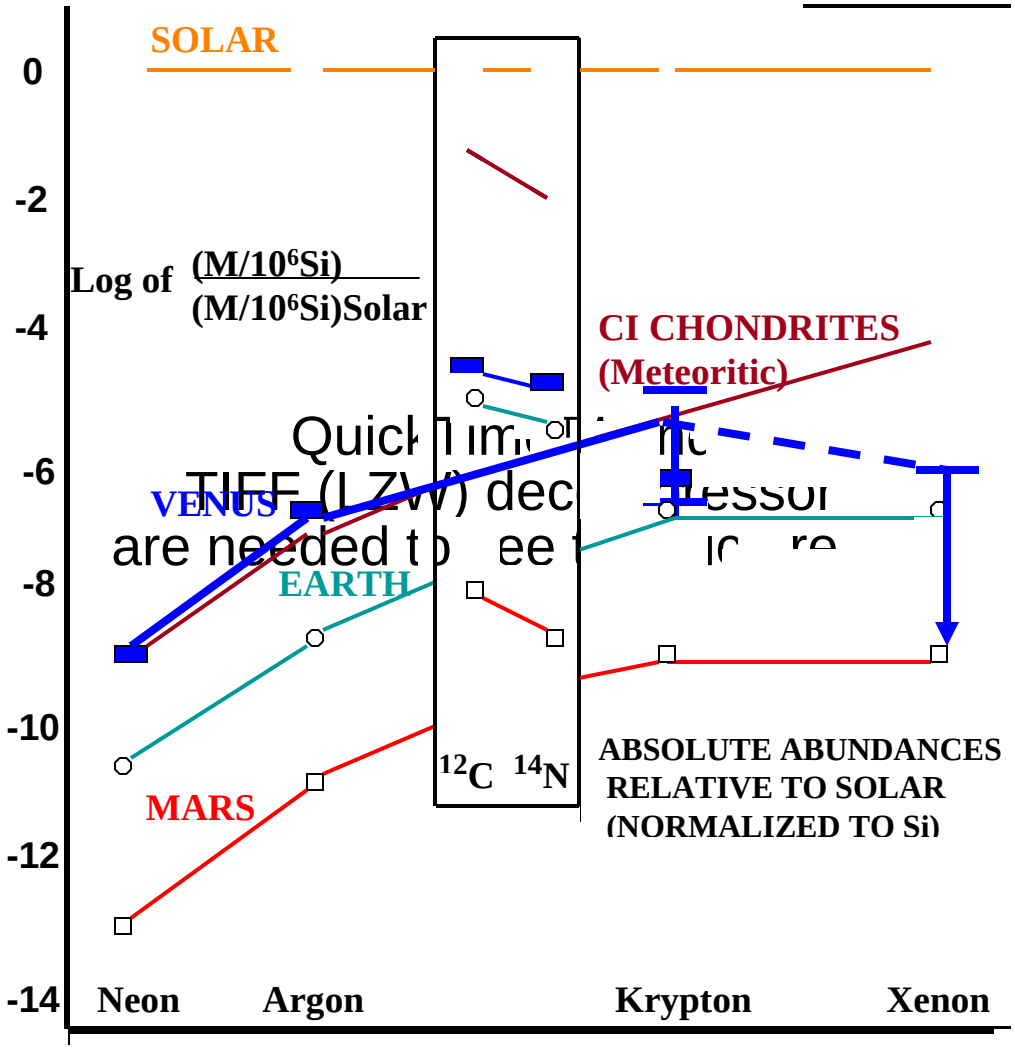


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  **BUT: Venera 11/12 results suggest Kr:Ar could still be meteoritic**

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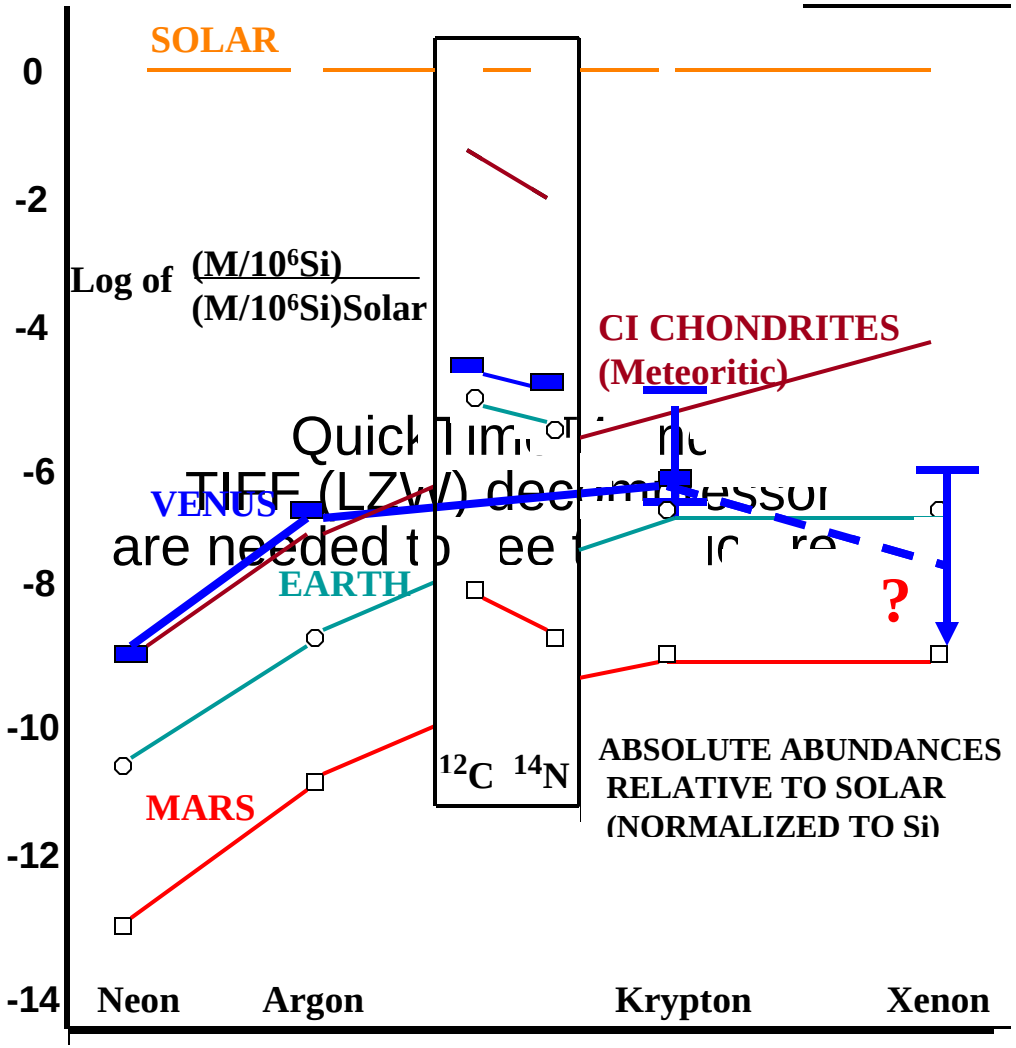


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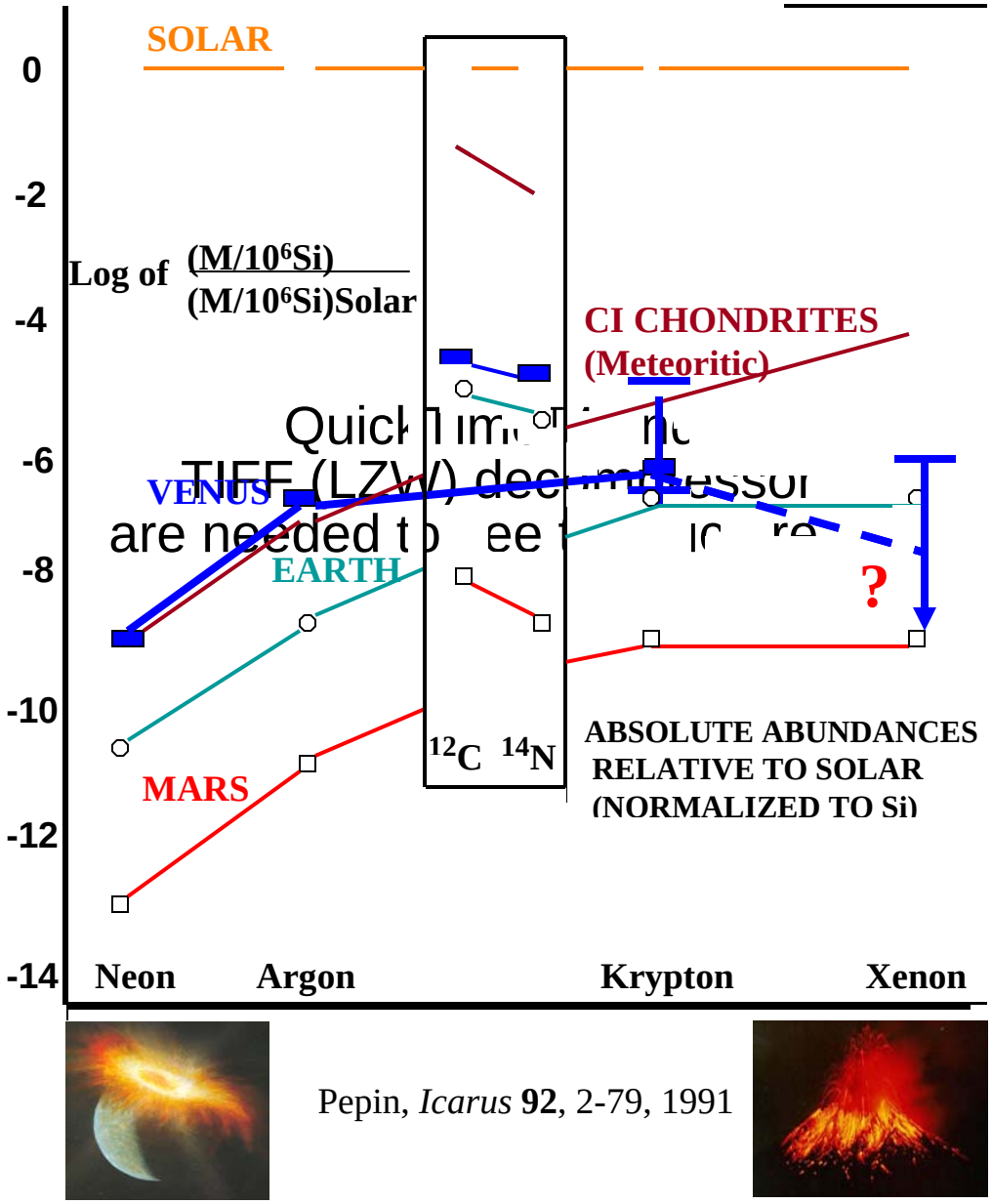


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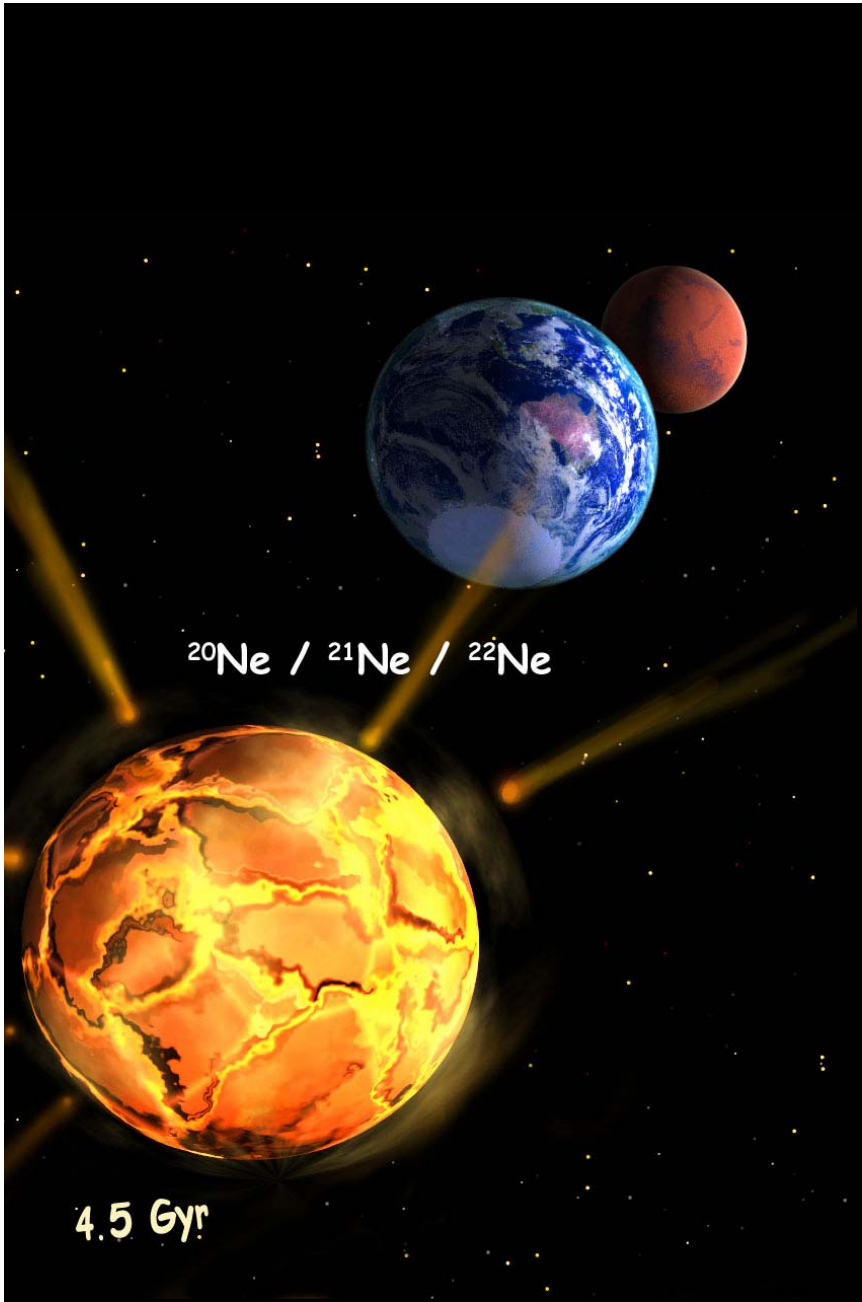
**Altogether: Eventful Histories**
**Variety of External Sources**
**Impacts? Escape? Volcanism?**
**Slow Degassing? Sequestering?**




# A Common Birth?

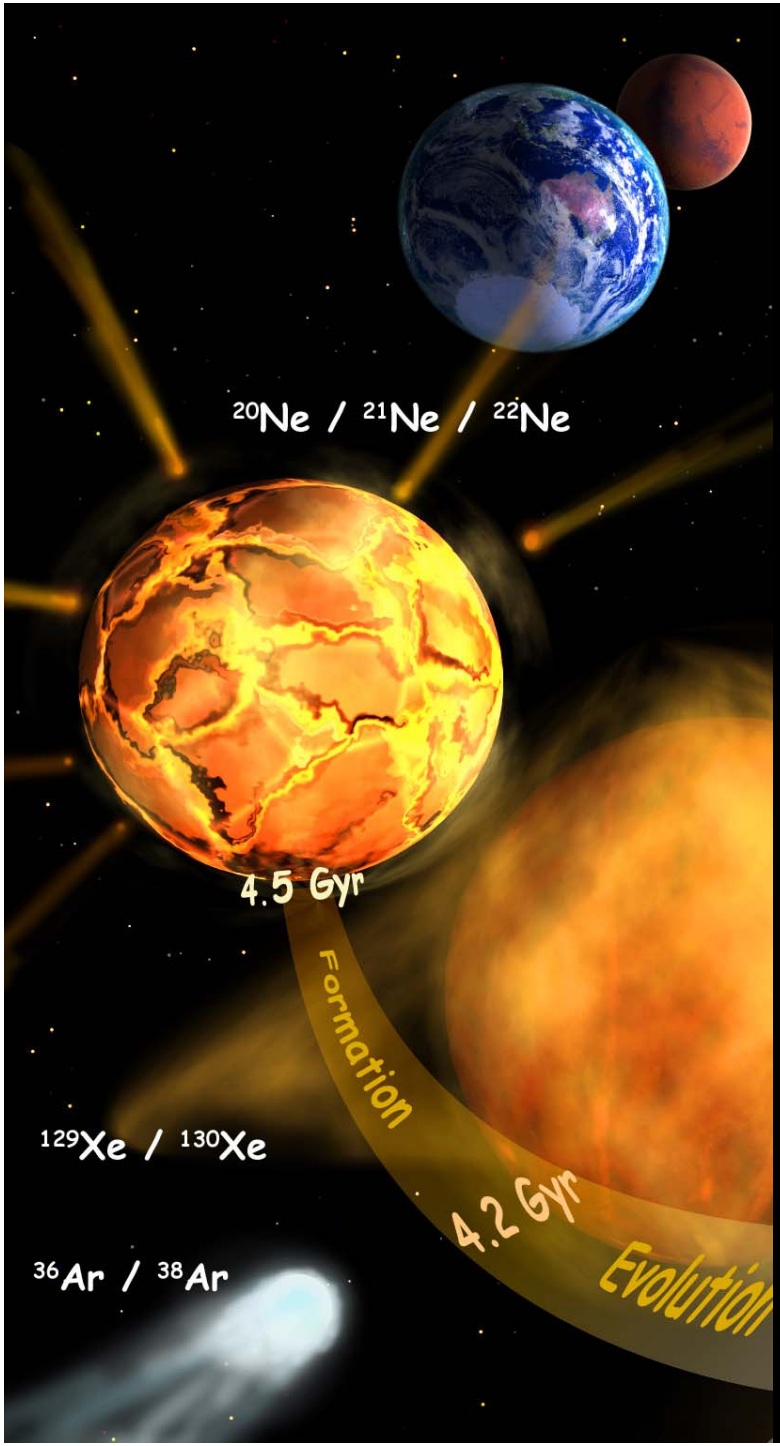
## Were Earth, Venus and Mars formed from the same source?

Despite evident loss of much of Earth's original atmosphere, we can still tell whether a common nebular source gave birth to Venus, Earth and Mars

Measure the ratios of Ne isotopes $^{22}$Ne/$^{20}$Ne and $^{21}$Ne/$^{20}$Ne

Do Venus and/or Mars fall on the same escape-fractionation curves as Earth? If so, then born as planetary twins/triplets

Present status: $^{21}$Ne/$^{20}$Ne not yet measured on Venus and Mars



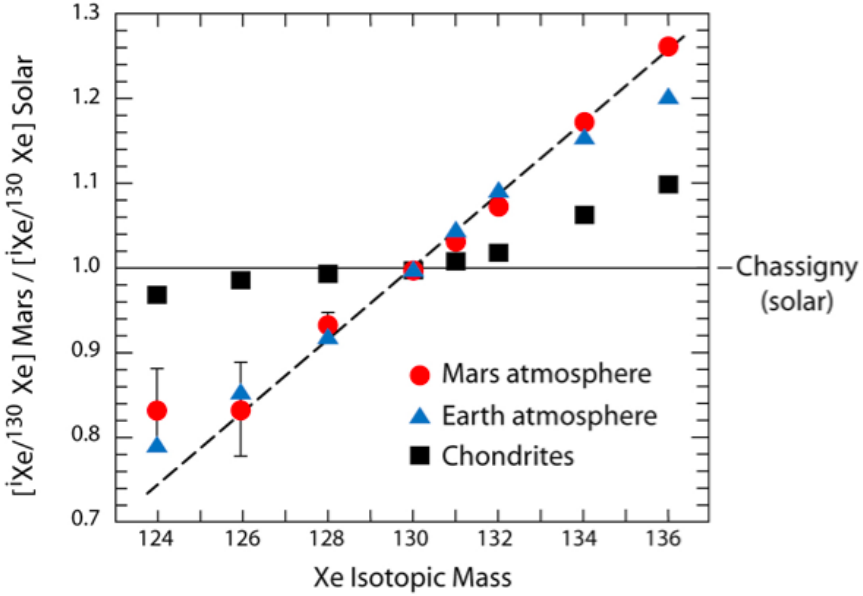

# A Troubled Youth for Venus, Like Earth and Mars?

Evidence strongly suggests that Earth and Mars lost much of their early atmospheres during their first ~ 0.25 to ~ 0.5 Gyr

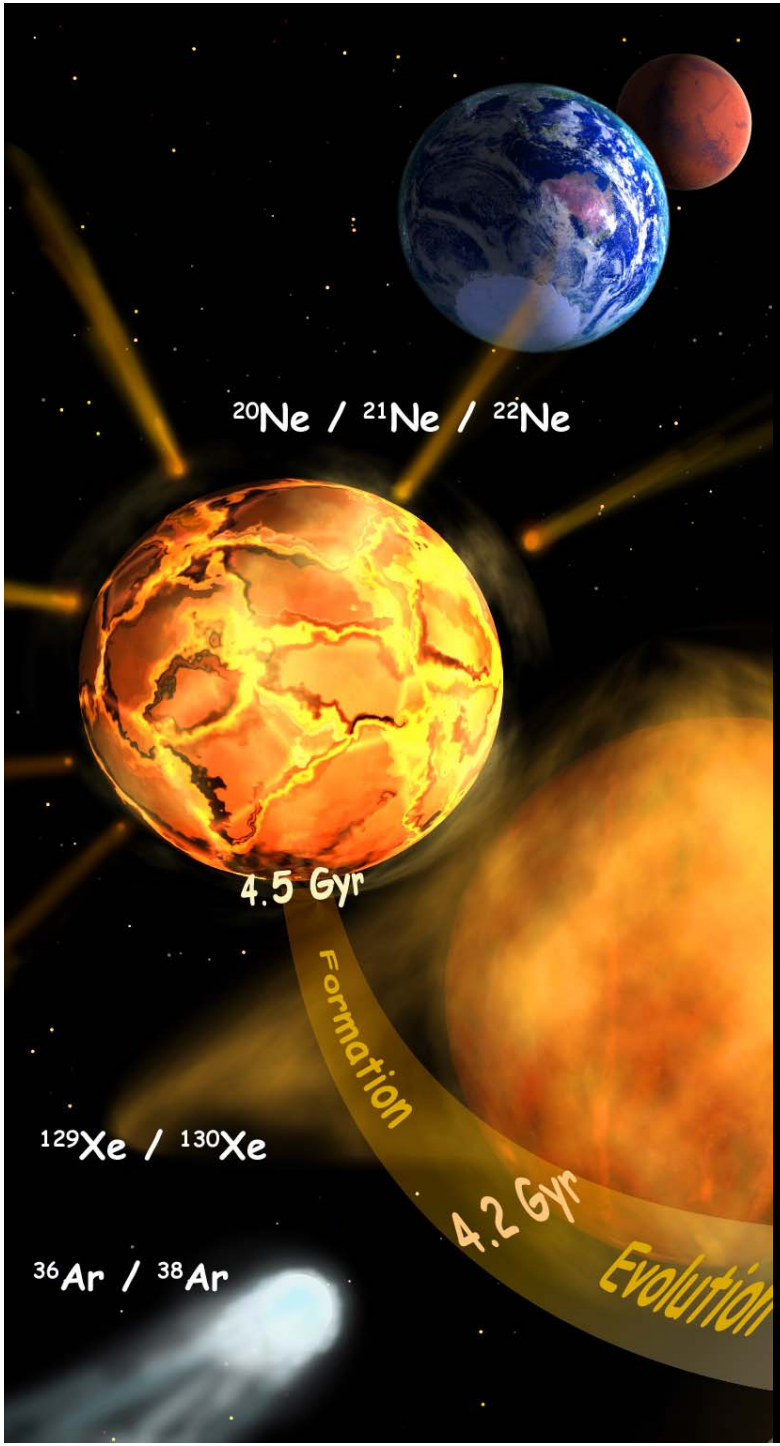
- Low fraction of light Xenon isotopes (gradient of 4% per AMU across the 9 isotopes, compared to Sun)

Mars = Earth!

Gradients differ from Sun =>
Loss of Original Atmospheres
[And/or similar sources (comets(?), not meteorites)]




**Bogard et al.,2001, Martian Volatiles, SSR 96, 425-458**

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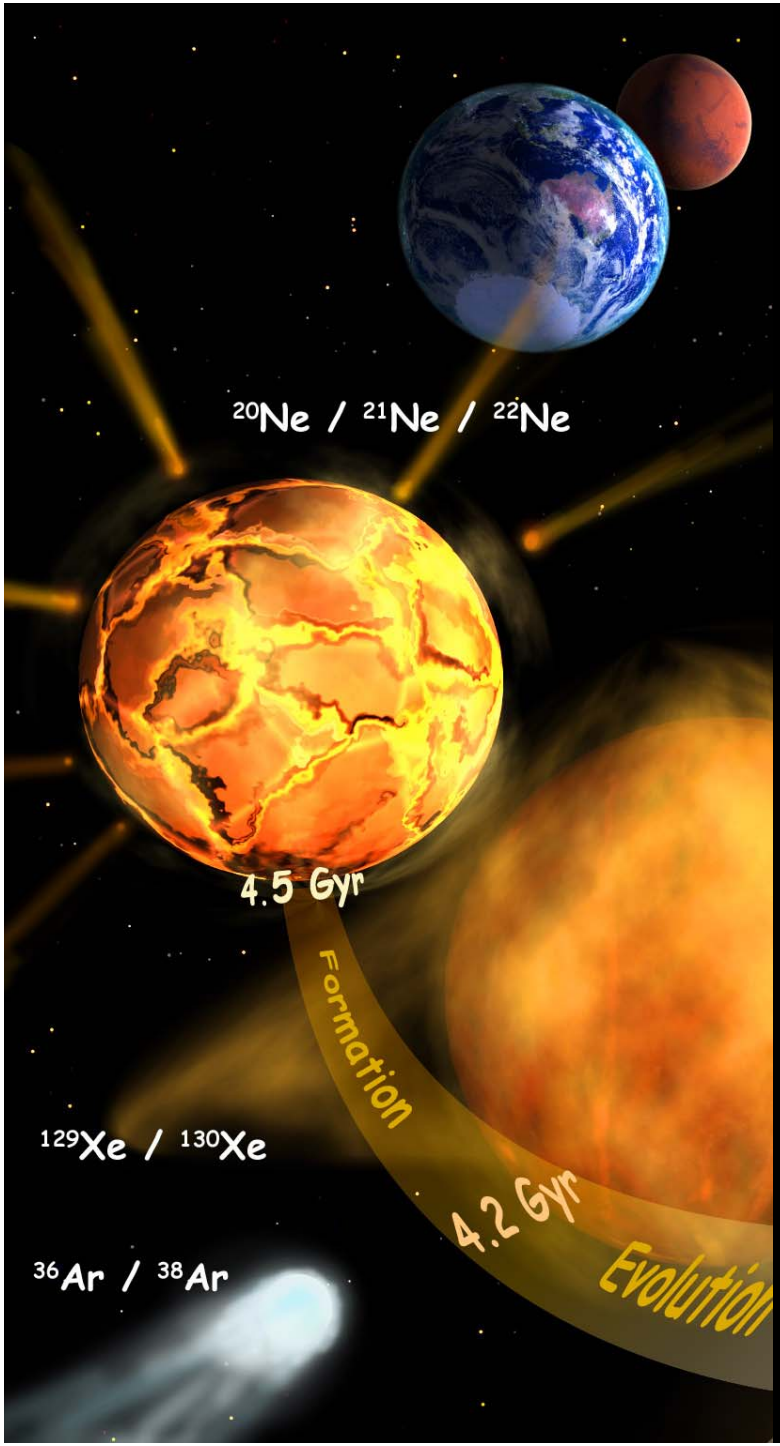


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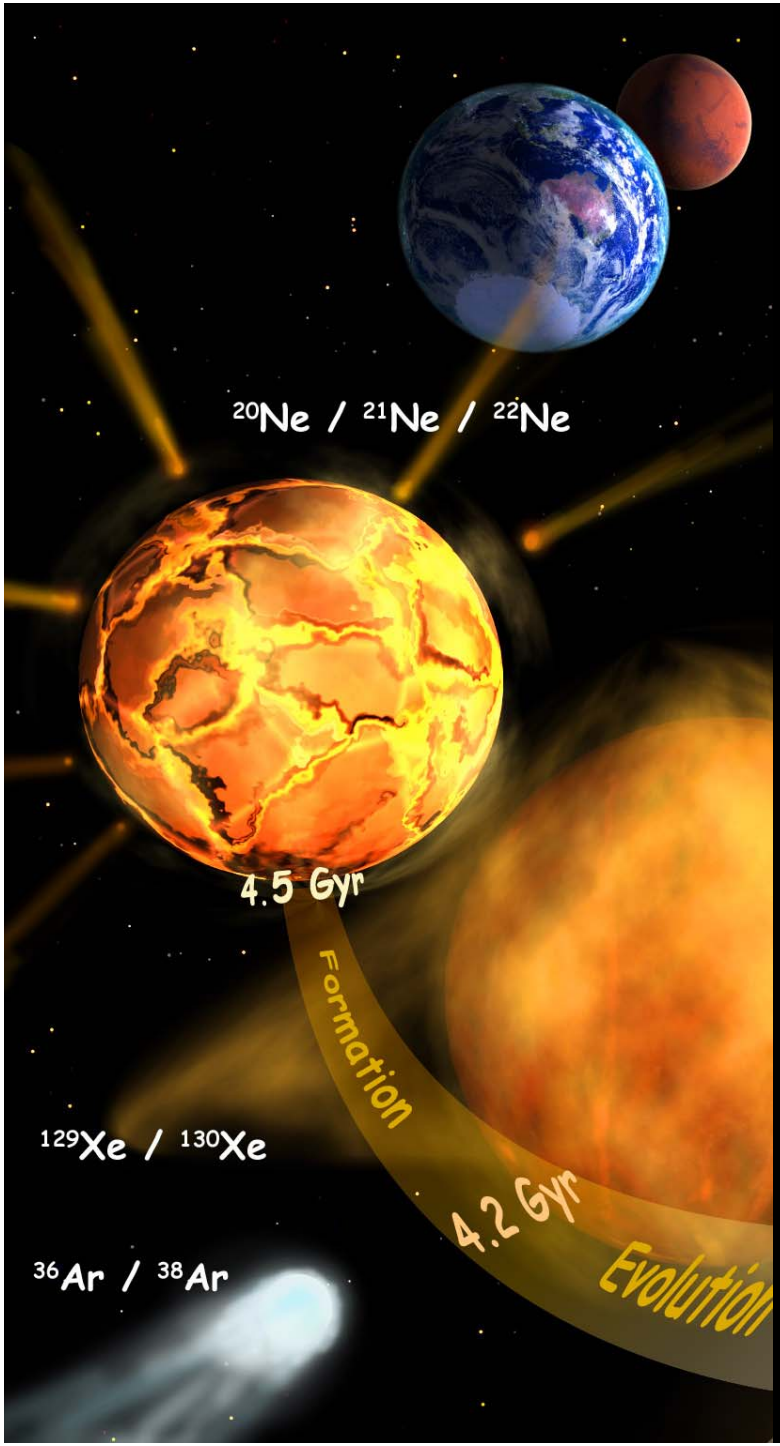


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- Global atmospheric loss looks favored
- But lack of tell-tale Xe data, both bulk value and isotopic distribution

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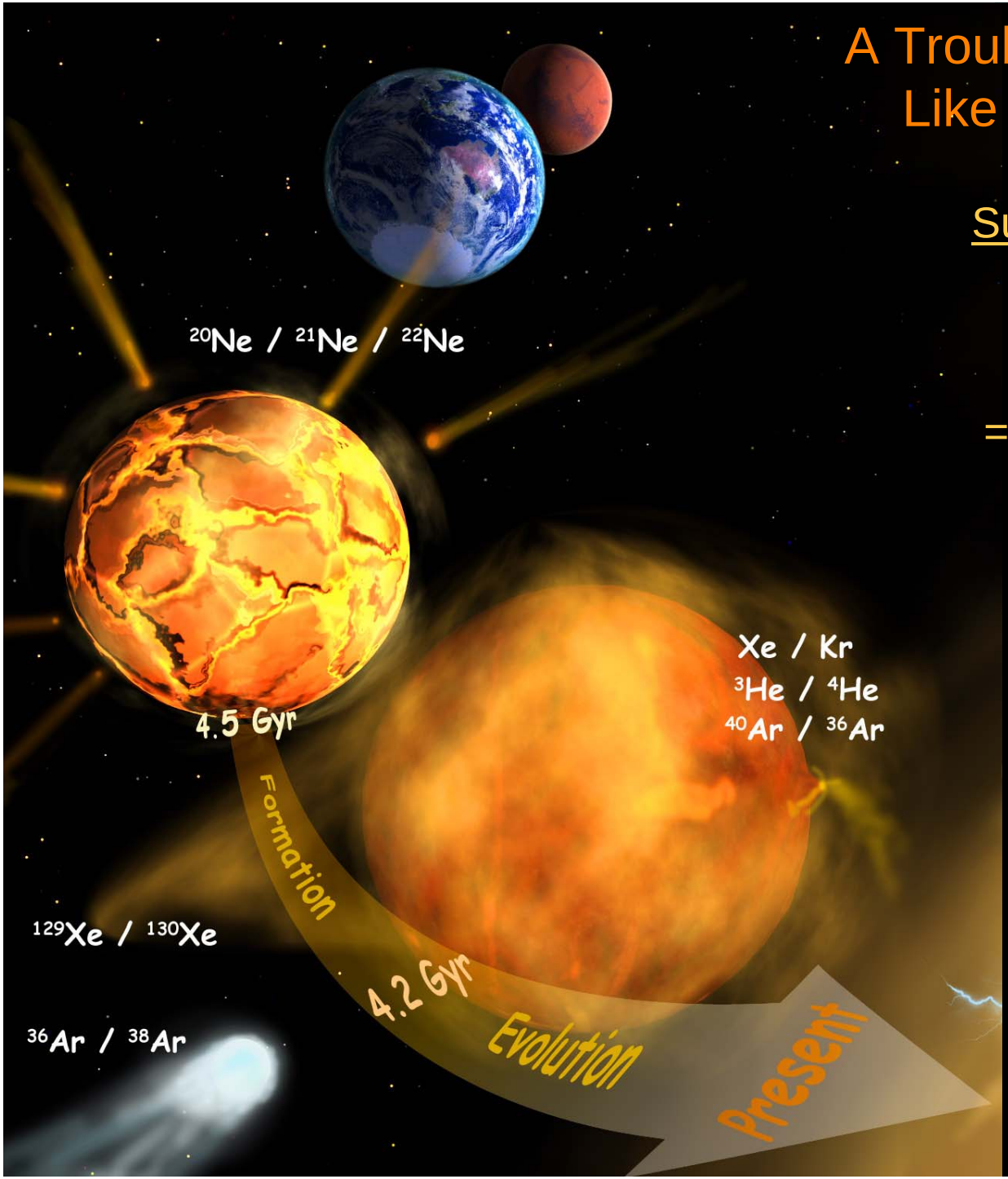


Supersonic blowoff ?

Driven by EUV solar flux

> 100 times today

=> Venus would experience it too, but much stronger

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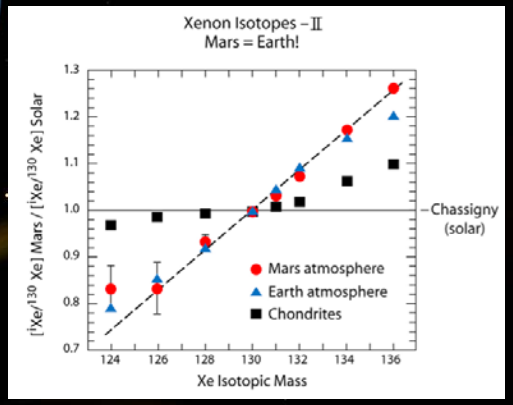





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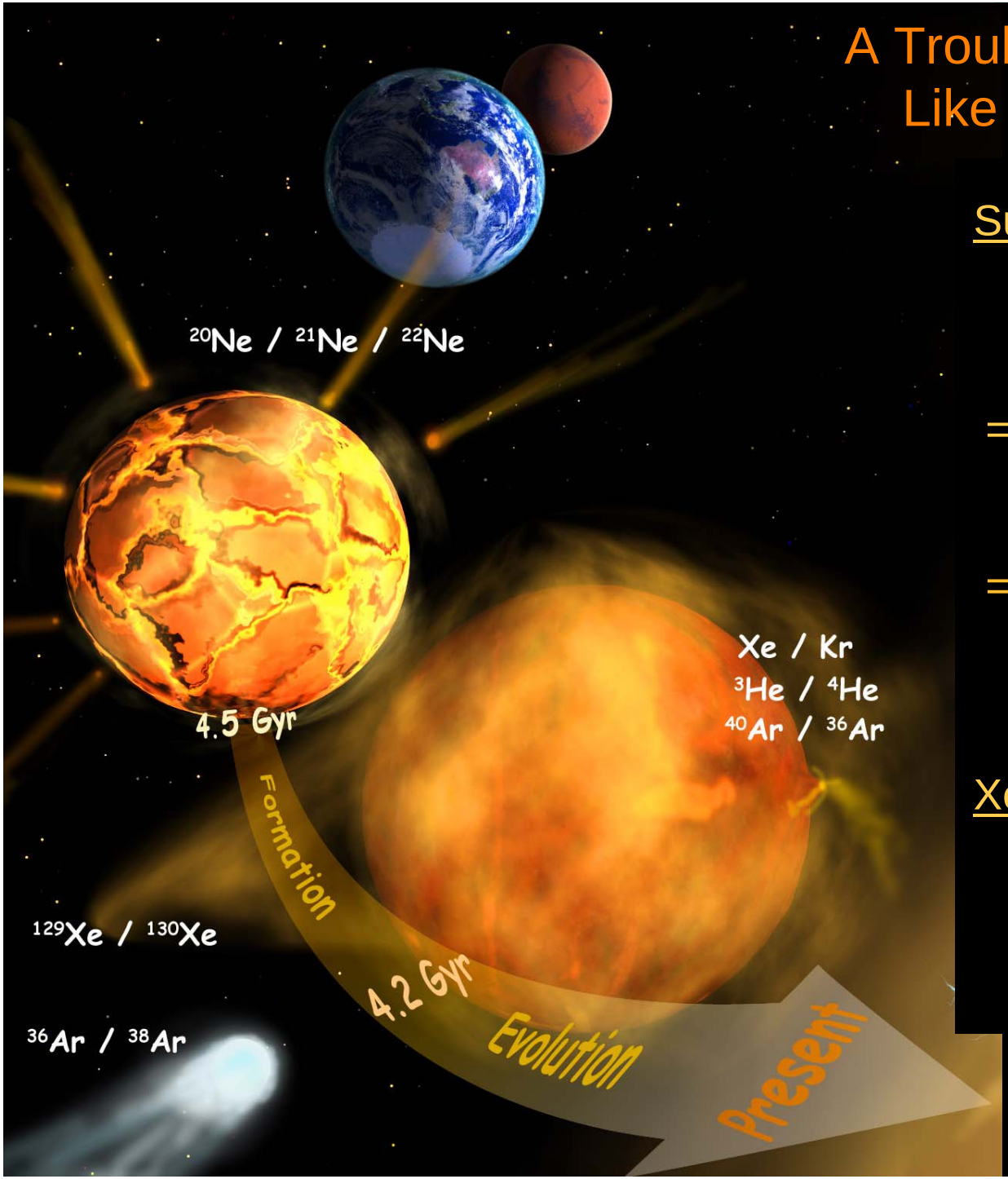


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<u>Xe ionization and enhanced escape in EUV blowoff?</u>

Ionized hydrogen in blowoff drags off preferentially ionized Xe
=> Low Xe/Kr

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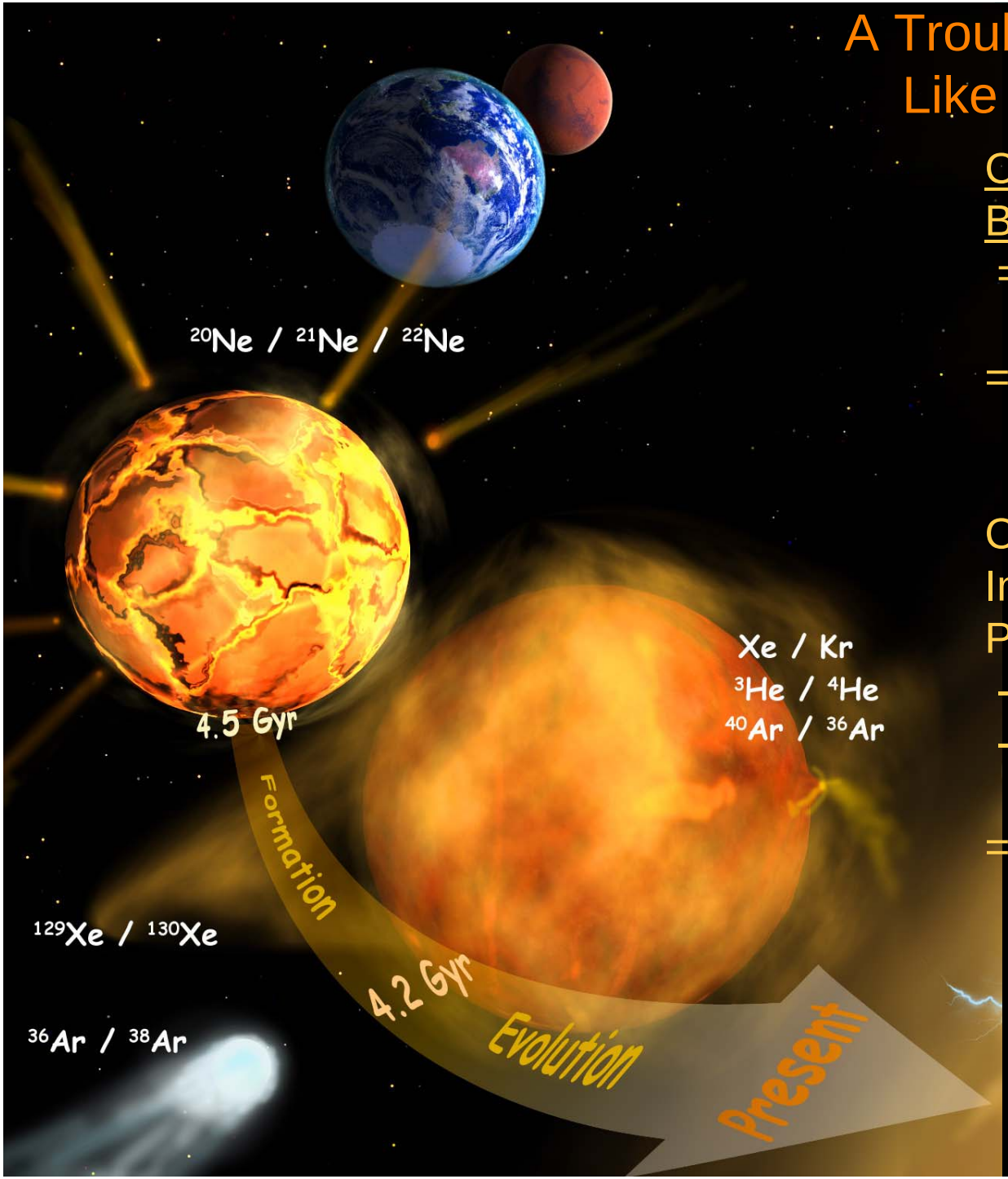



<u>Comet Bombardment/Erosion?</u>

=> Venus would experience it too

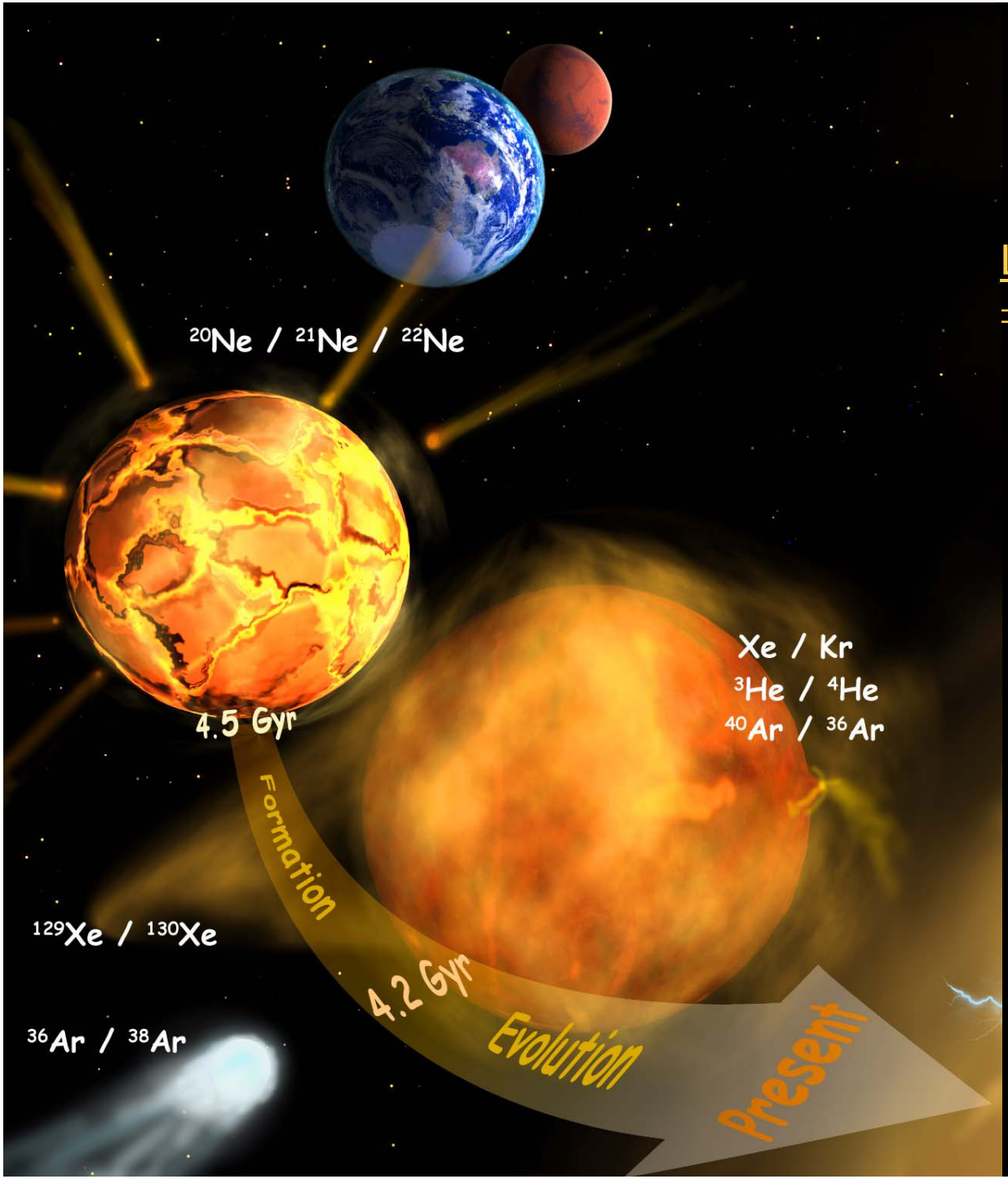
=> Xe isotopic pattern should be similar to Earth/Mars

Cold, solar-like comets Important for Jupiter (Galileo Probe)

- Jupiter has solar Ar:Kr:Xe
- Earth, Mars? Perhaps

=> Venus:Ar:Kr:Xe solar-like

Present Status: Unknown, due to unknown Xe and uncertain Kr (e.g., Kr:Ar could be either solar or meteoritic)



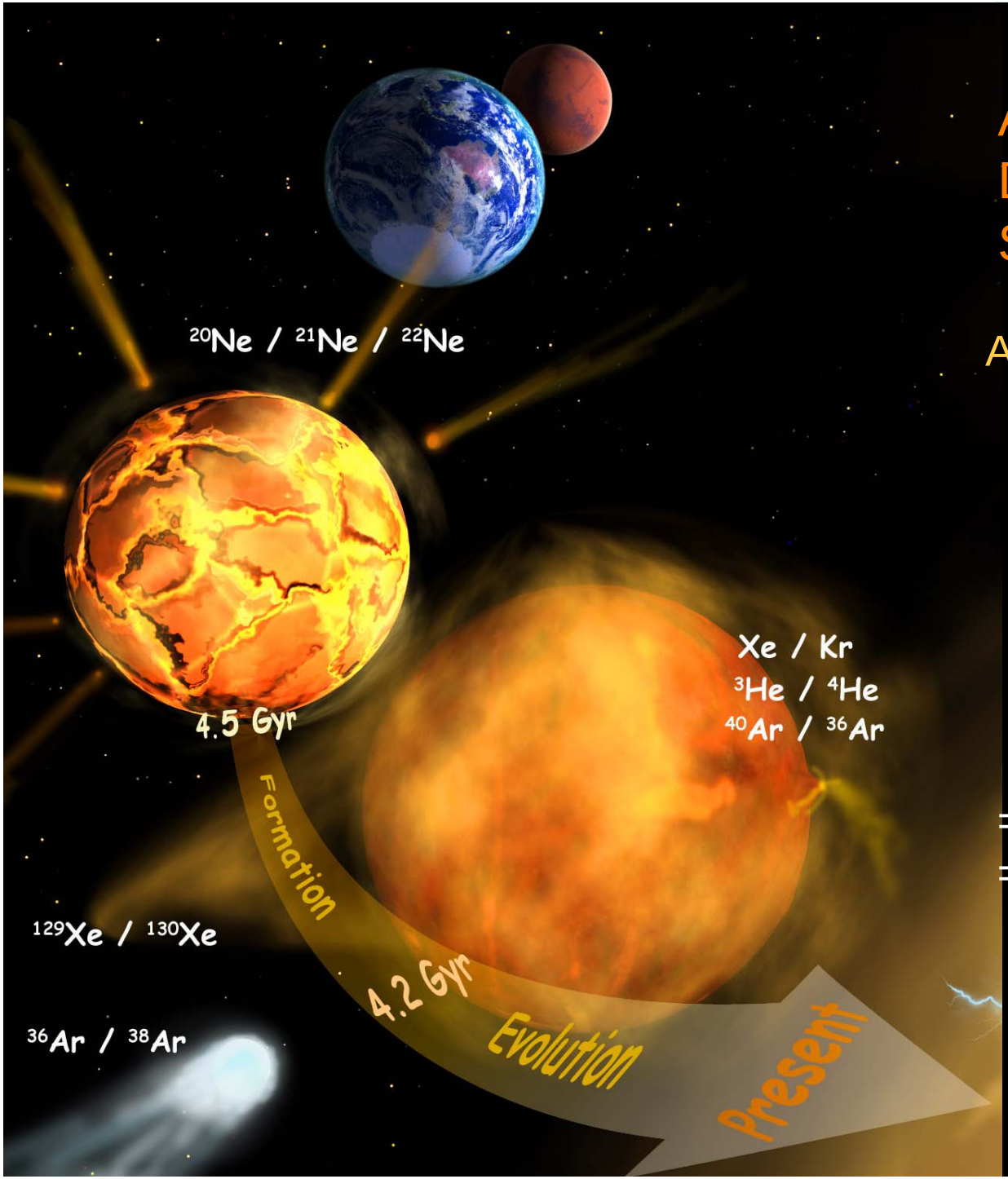

# A Late Cataclysm: Did Venus, like Earth, Suffer a Large Impact?

Large Moon-forming impact ?

⇒If did not occur on Venus, then Xe pattern should be different than Earth, perhaps similar to original (near-Solar) complement

But: Large amounts of non-radiogenic $^{36}$Ar, $^{38}$Ar and Neon seen by PV indicates a large impact on Venus, which delivered the exotic amounts of Ar and Neon

Impactor: > 200 km diam. from the outer solar system




# A Late Cataclysm: Did Venus, like Earth, Suffer a Large Impact?

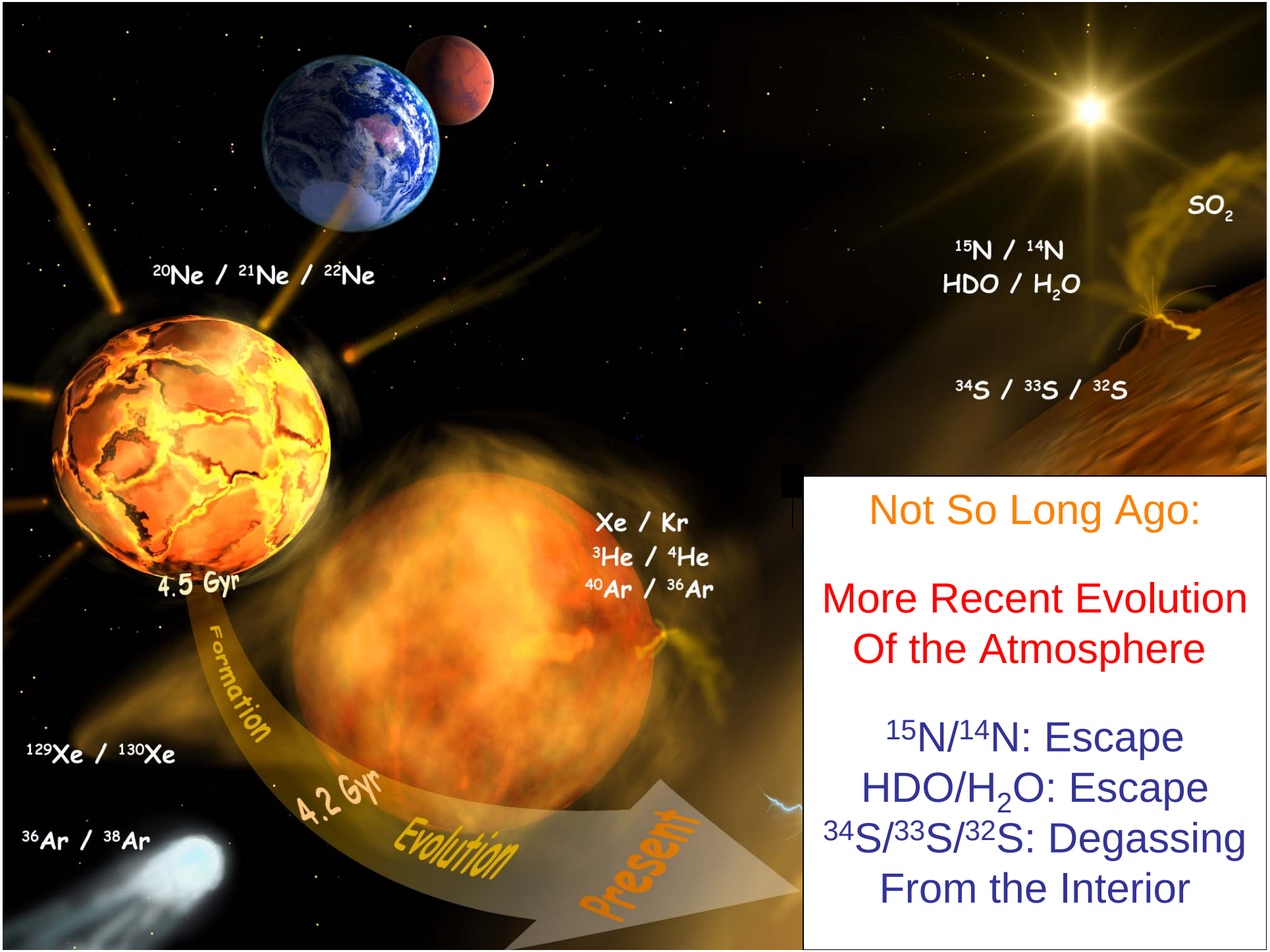
Alternatively:

Venus's thick atmosphere protects against catastrophic loss by giant impacts (Genda and Abe, 2005)

=> Nebula Ar preserved on Venus, lost on Earth

=> Different Ar abundances

=> Large Ar abundance on Venus



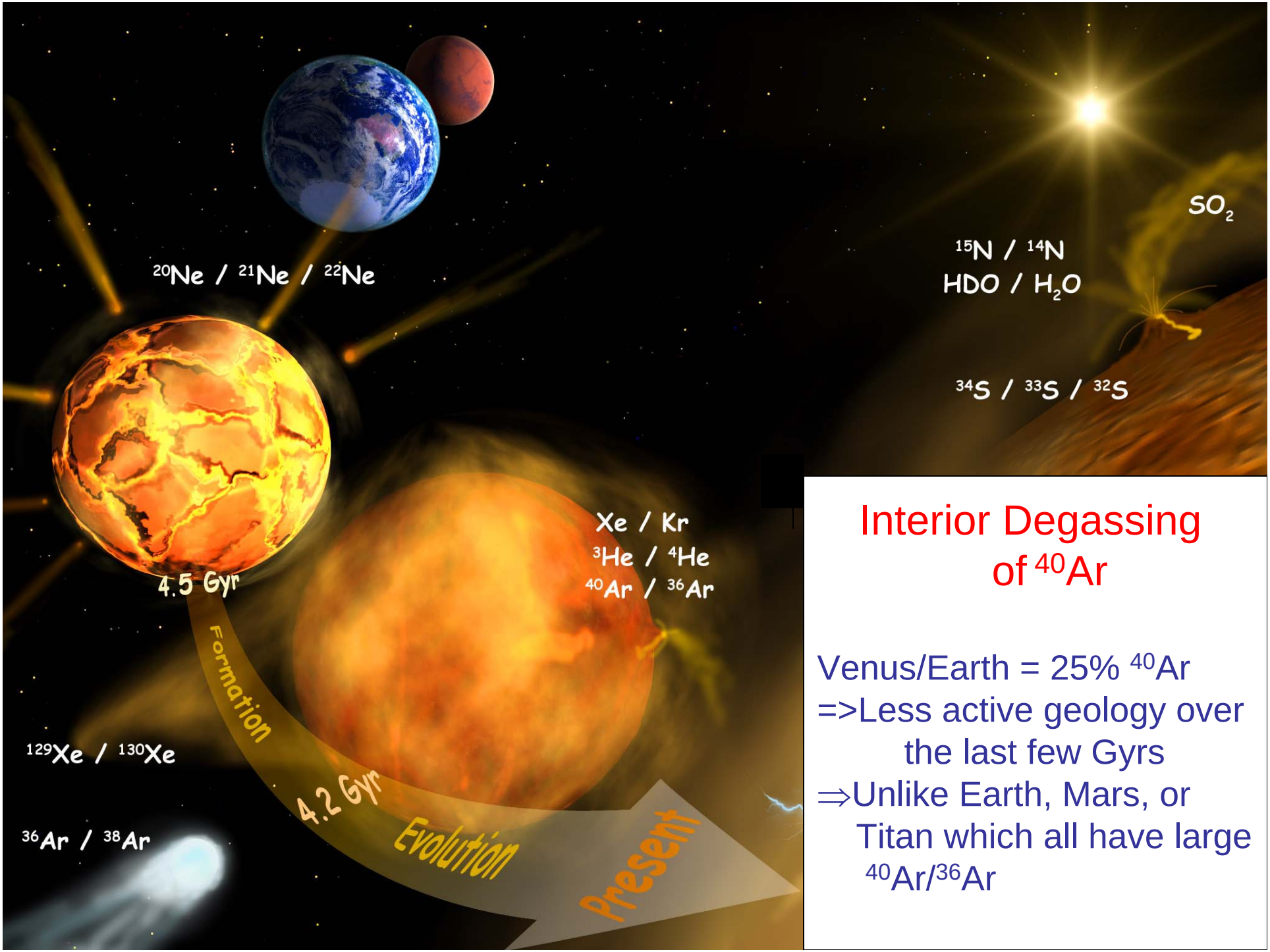

Not So Long Ago:

More Recent Evolution Of the Atmosphere

$^{15}N/^{14}N$: Escape

$HDO/H_2O$: Escape

$^{34}S/^{33}S/^{32}S$: Degassing From the Interior

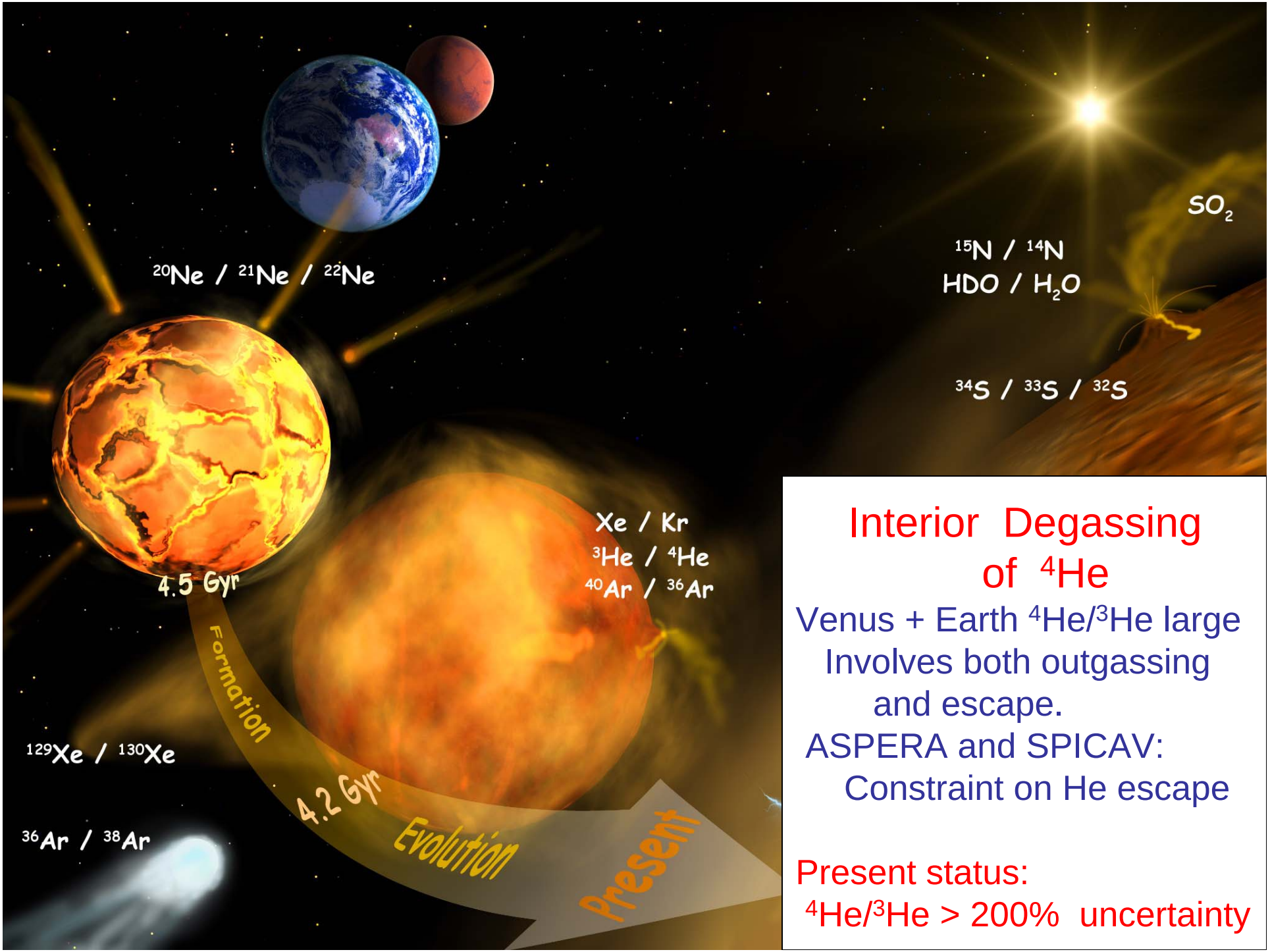



# Interior Degassing of $^{40}Ar$

Venus/Earth = 25% $^{40}Ar$

=>Less active geology over the last few Gyrs

⇒Unlike Earth, Mars, or Titan which all have large $^{40}Ar/^{36}Ar$




# Interior Degassing of $^{4}He$

Venus + Earth $^{4}He/^{3}He$ large

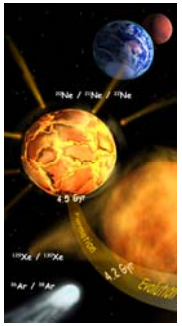
Involves both outgassing and escape.

ASPERA and SPICAV: Constraint on He escape

Present status:

$^{4}He/^{3}He$ > 200% uncertainty

# In-Situ Missions To Venus



## Salient Science Measurements Needed

- Noble Gases and Their Isotopes: Formation/Evolution
- Isotopes of Light Gases: Formation/Evolution

| Constituent | Primary Science Objective | Current Measurements | Implied Uncertainty | Mission |
|---|---|---|---|---|
| **Noble Gases** | | | | |
| $^{132}Xe$ | Origin/evolution of terrestrial planets: Roles of blowoffs, comets, and planetesimals | ~1.9 ppb | >200% | |
| $^{84}Kr$ | Origin/evolution: Cold comets as atmospheric gas supplier | 0.7 ± 0.35 ppm or 0.05 ± 0.025 ppm | >100% (average) | Venera Pioneer Venus |
| $^{36}Ar$ | Planetary origin: Roles of comets and planetesimals | 31 ± 9 ppm | 33% | |
| $^{20}Ne$ | Planetary origin: Earth and Venus, a common kinship? | 7 ± 3 ppm | 43% | |
| $^{4}He$ | Early evolution: Interior outgassing | 12 (+24/-8) ppm | >60% | |
| **Noble Gas Isotopic ratios** | | | | |
| $^{129}Xe/^{130}Xe$ | Early evolution: Large atmospheric blow-off | ~3 | >100% | |
| $^{136}Xe/^{130}Xe$ | Origin/evolution: U-Xe hypothesis | ~1 | >100% | |
| $^{40}Ar/^{36}Ar$ | Early history: Interior outgassing | 1.03 ± 0.04 or 1.19 ± 0.07 | 12% (average) | Pioneer Venus Venera 11/12 |
| $^{36}Ar/^{38}Ar$ | Late formation: Large impact | 5.56 ± 0.62 or 5.08 ± 0.05 | 12% (average) | Pioneer Venus Venera 11/12 |
| $^{21}Ne/^{22}Ne$ | Earth/Venus origins: Twin planet hypothesis | <0.067 | >200% | |
| $^{20}Ne/^{22}Ne$ | Earth/Venus origins: Hydrodynamic escape | 11.8 ± 0.7 | 6% | |
| $^{3}He/^{4}He$ | Evolution: Impact of solar wind | $< 3 \times 10^{-4}$ | >200% | |
| **Light-Element Isotopic Ratios** | | | | |
| $HDO/H_2O$ | Atmospheric loss, past/current volcanic activity | 0.019 ± 0.006 | 32% | |
| $^{15}N/^{14}N$ | Atmospheric loss since planetary formation | 0.0037 ± 0.008 | 22% | PV |
| $^{34}S/^{32}S$ | Past/current volcanic activity, magmatic composition | ~0.04 | >100% | |