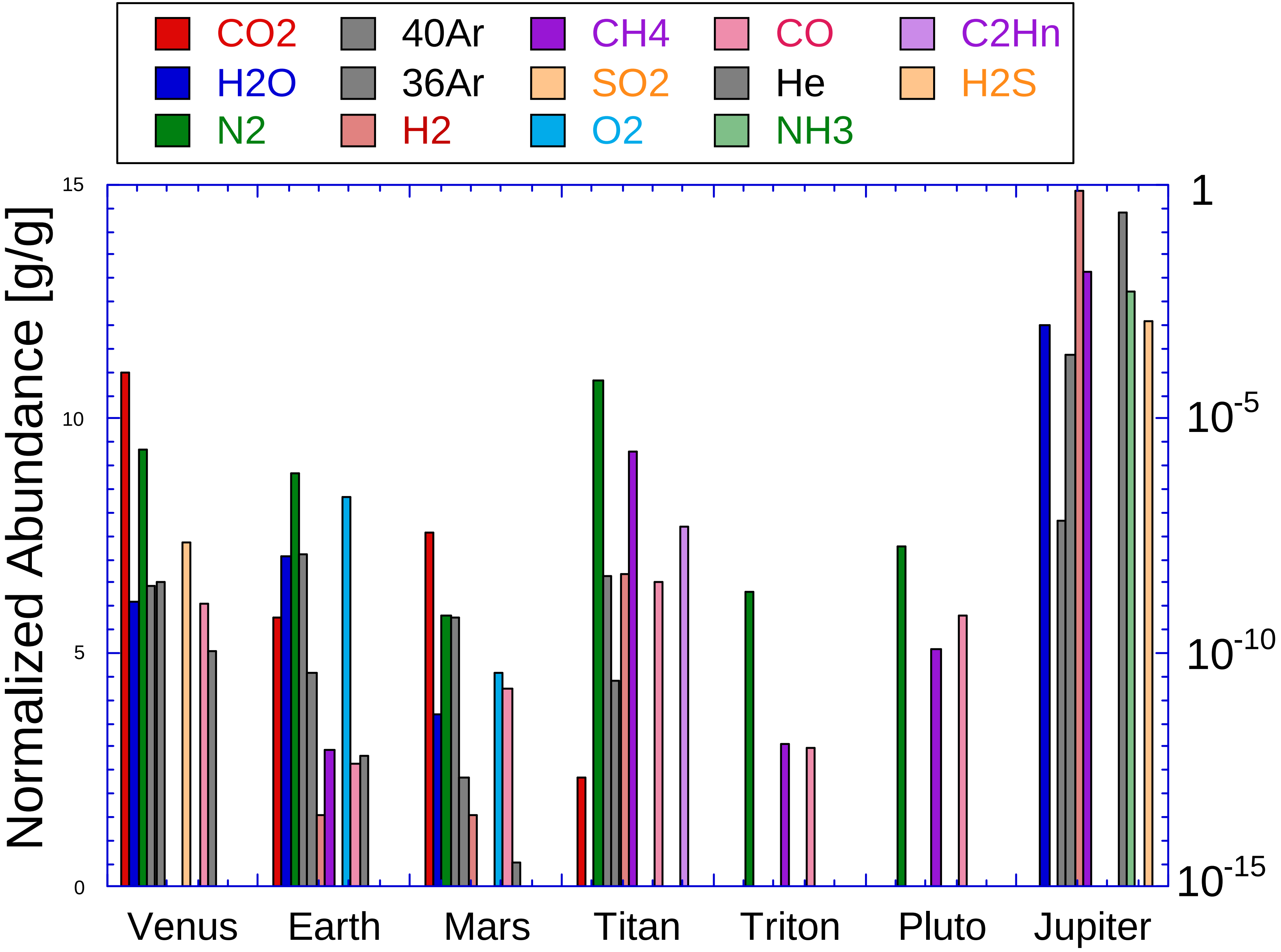
Origins and Evolutions of Planetary Atmospheres

What are they made of?

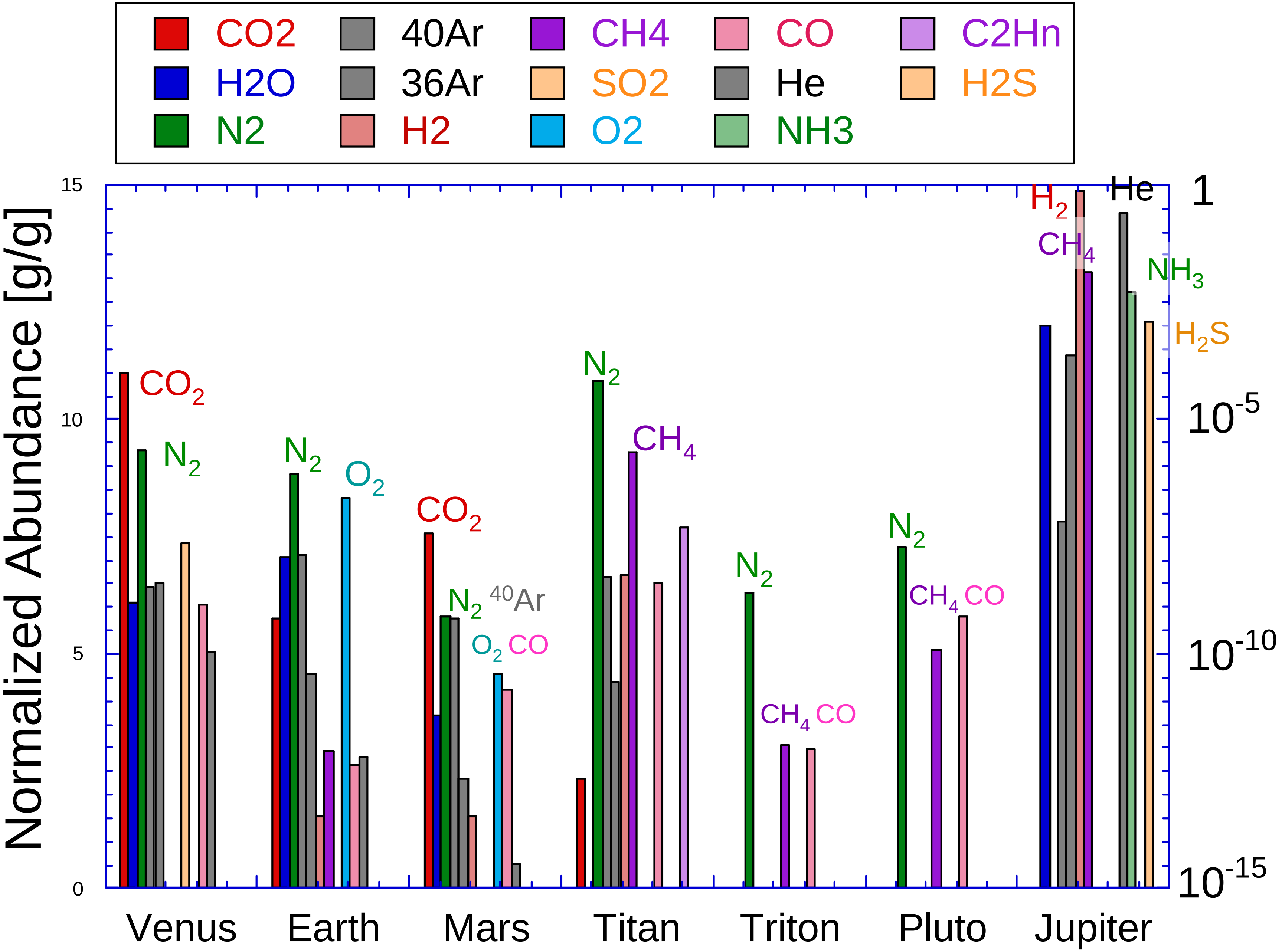
Origins: Sources and Sinks

Evolutions of Atmospheres
- Mostly Earth
- Others if time permits

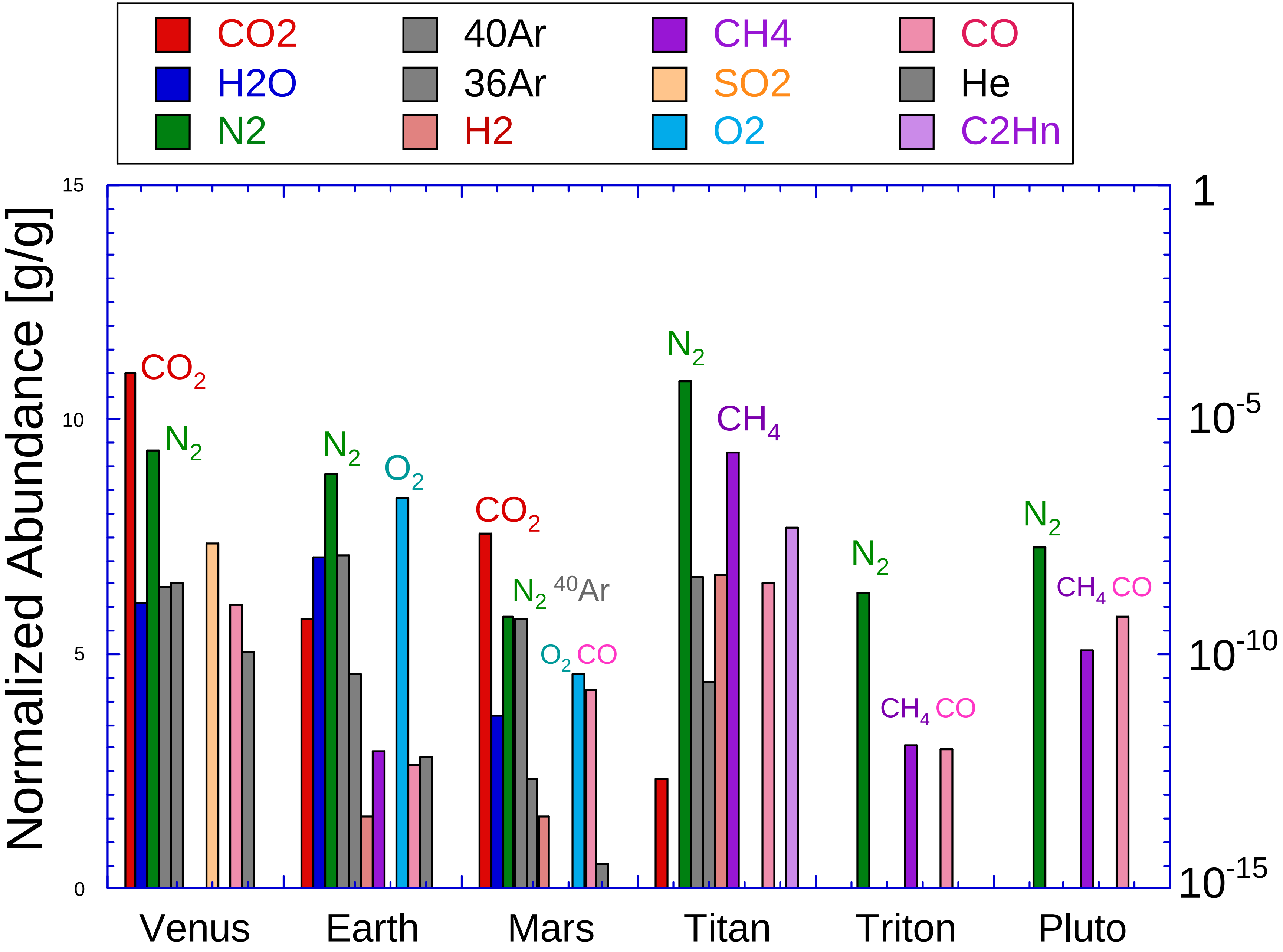
Atmospheric Inventories



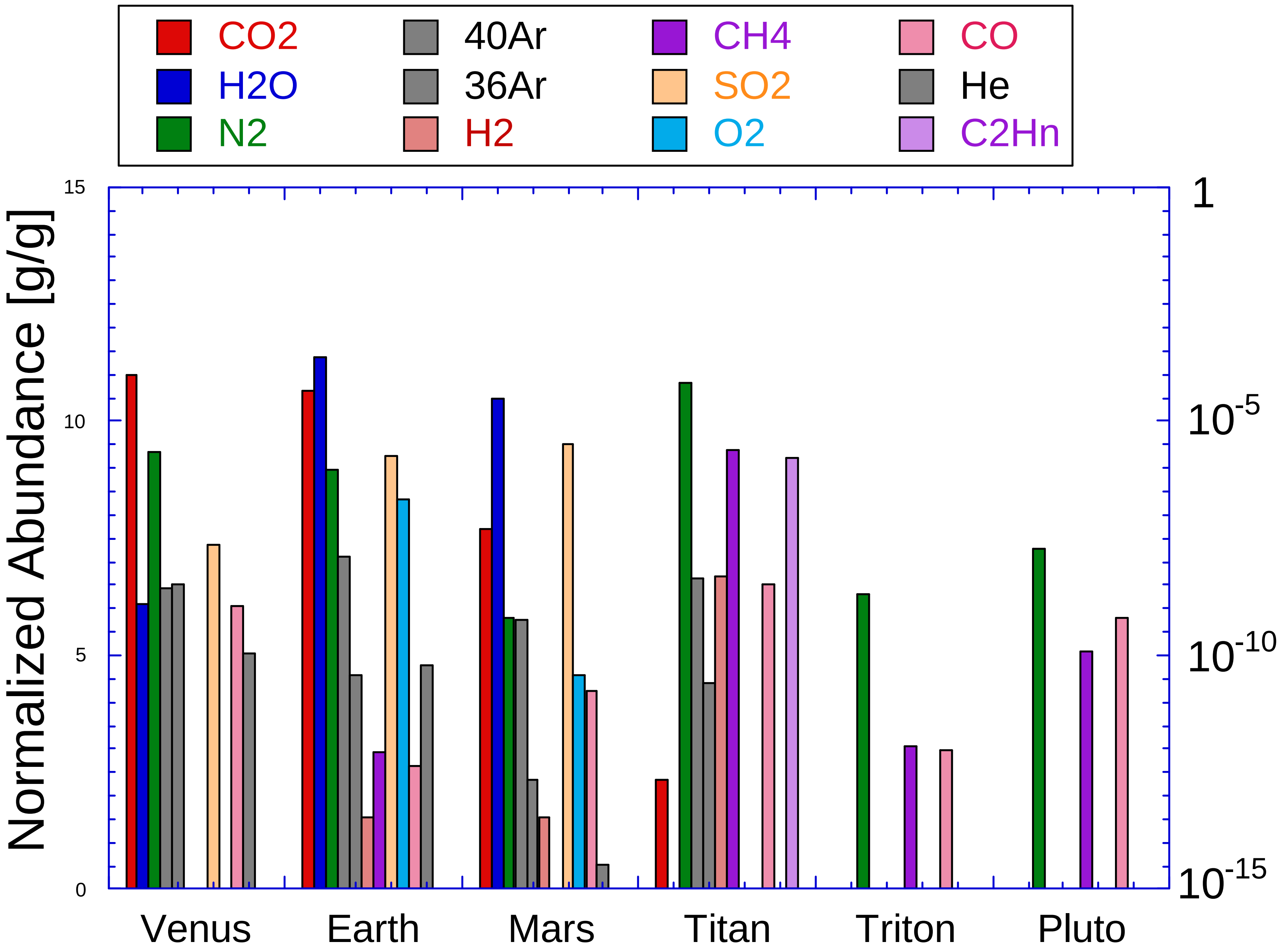
Atmospheric Inventories



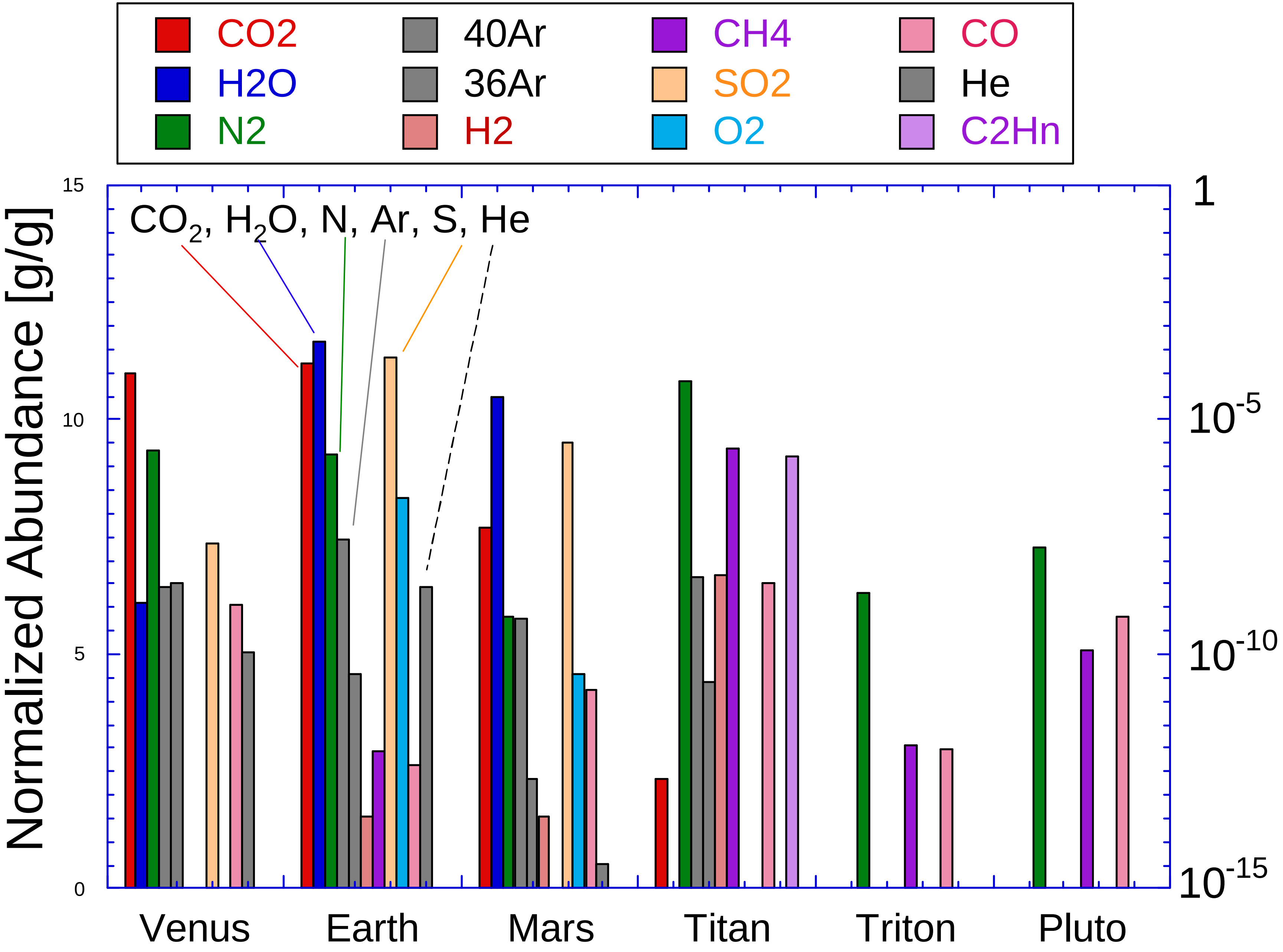
Atmospheric Inventories of ordinary atmospheres



Supplemented by known crustal inventories



Supplemented by known mantle inventories (Earth only)



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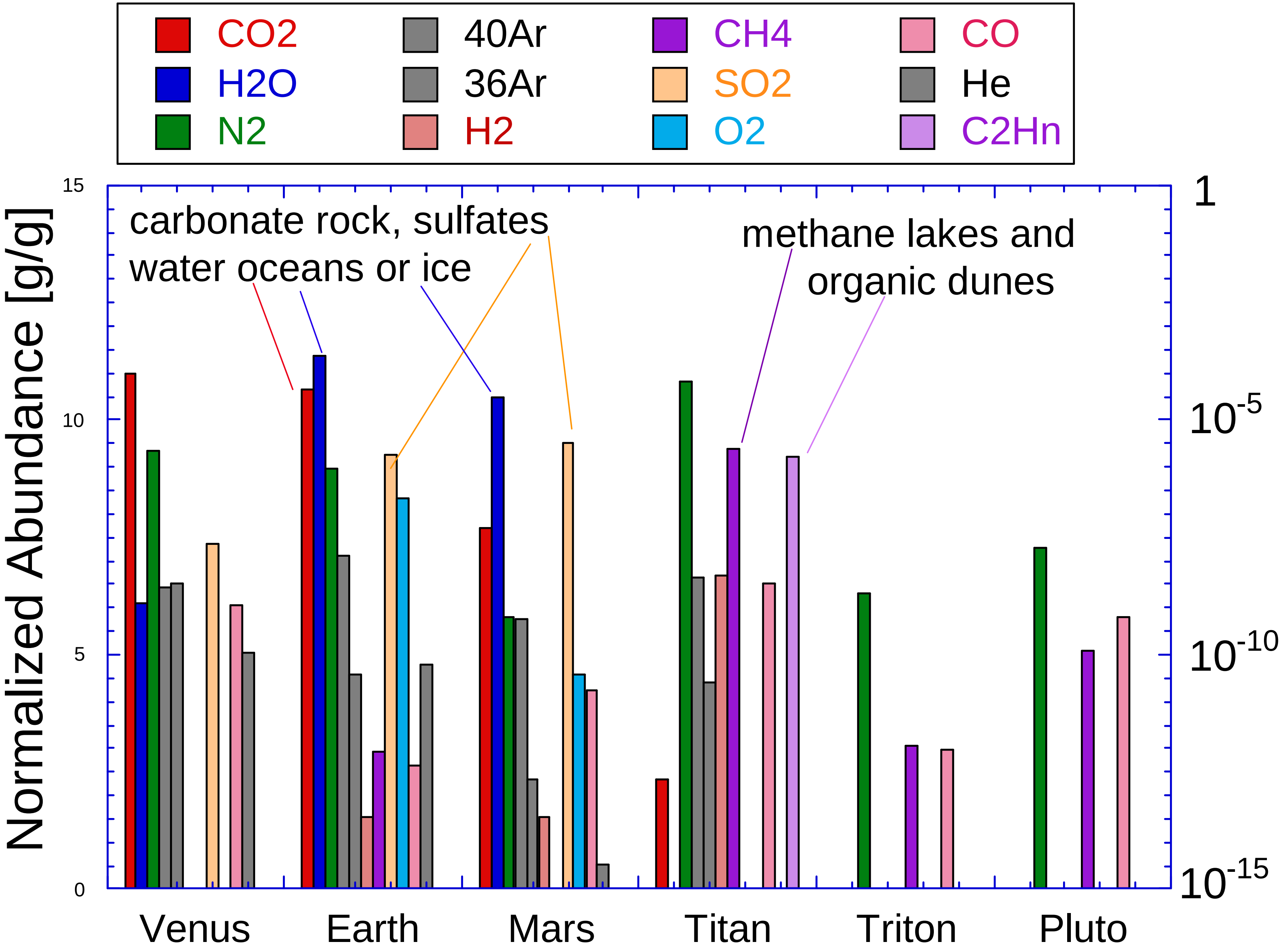

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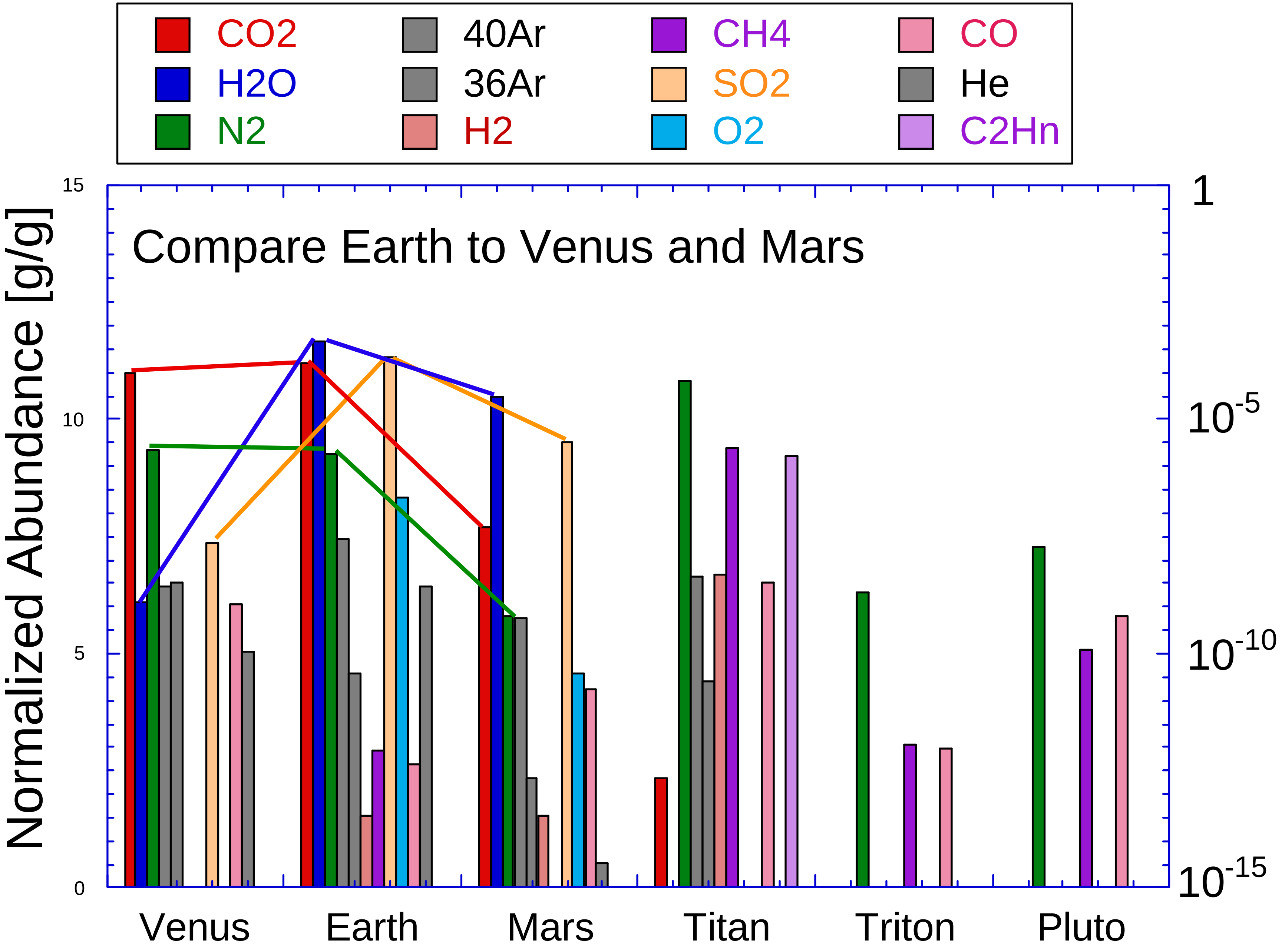
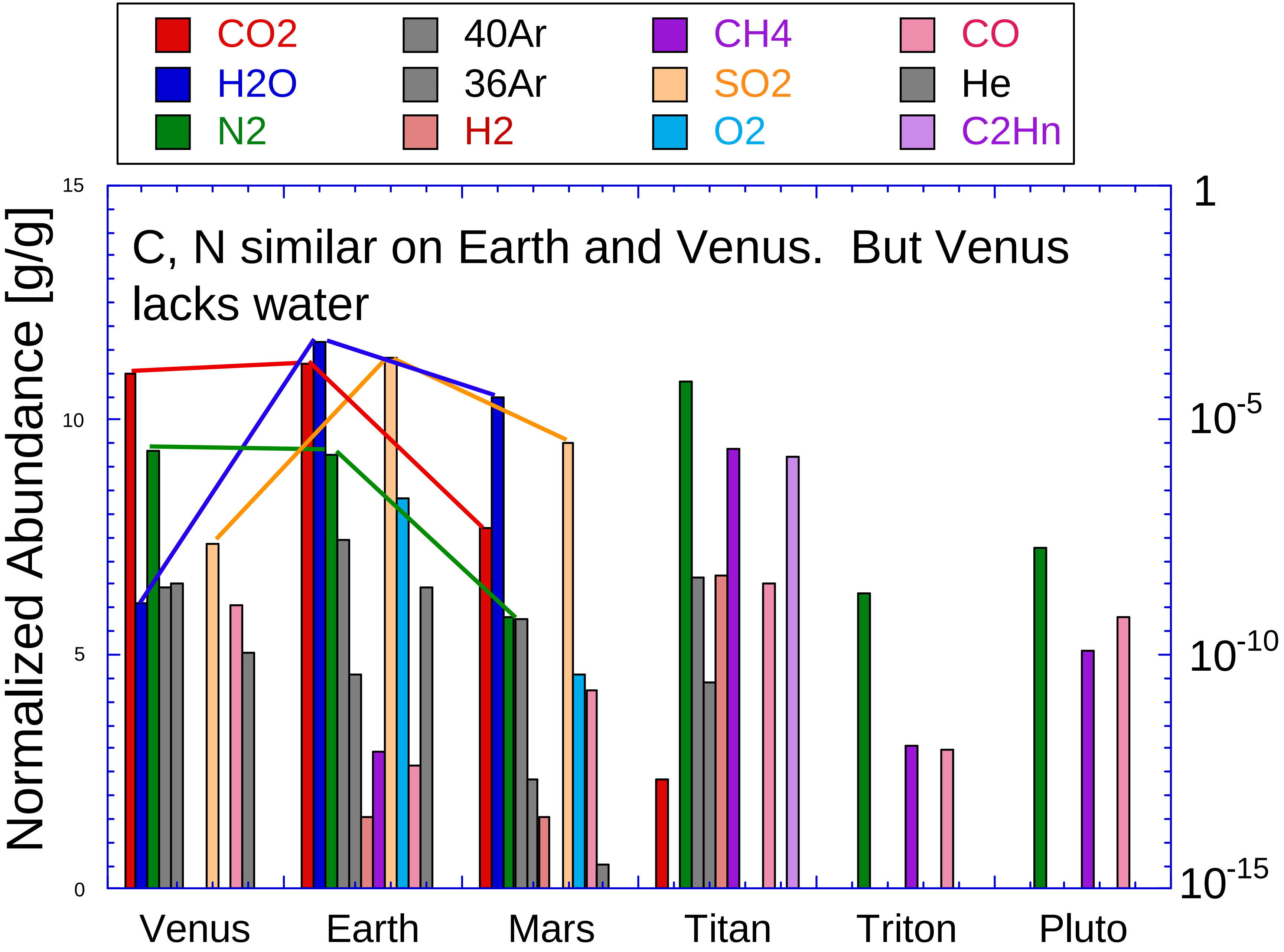


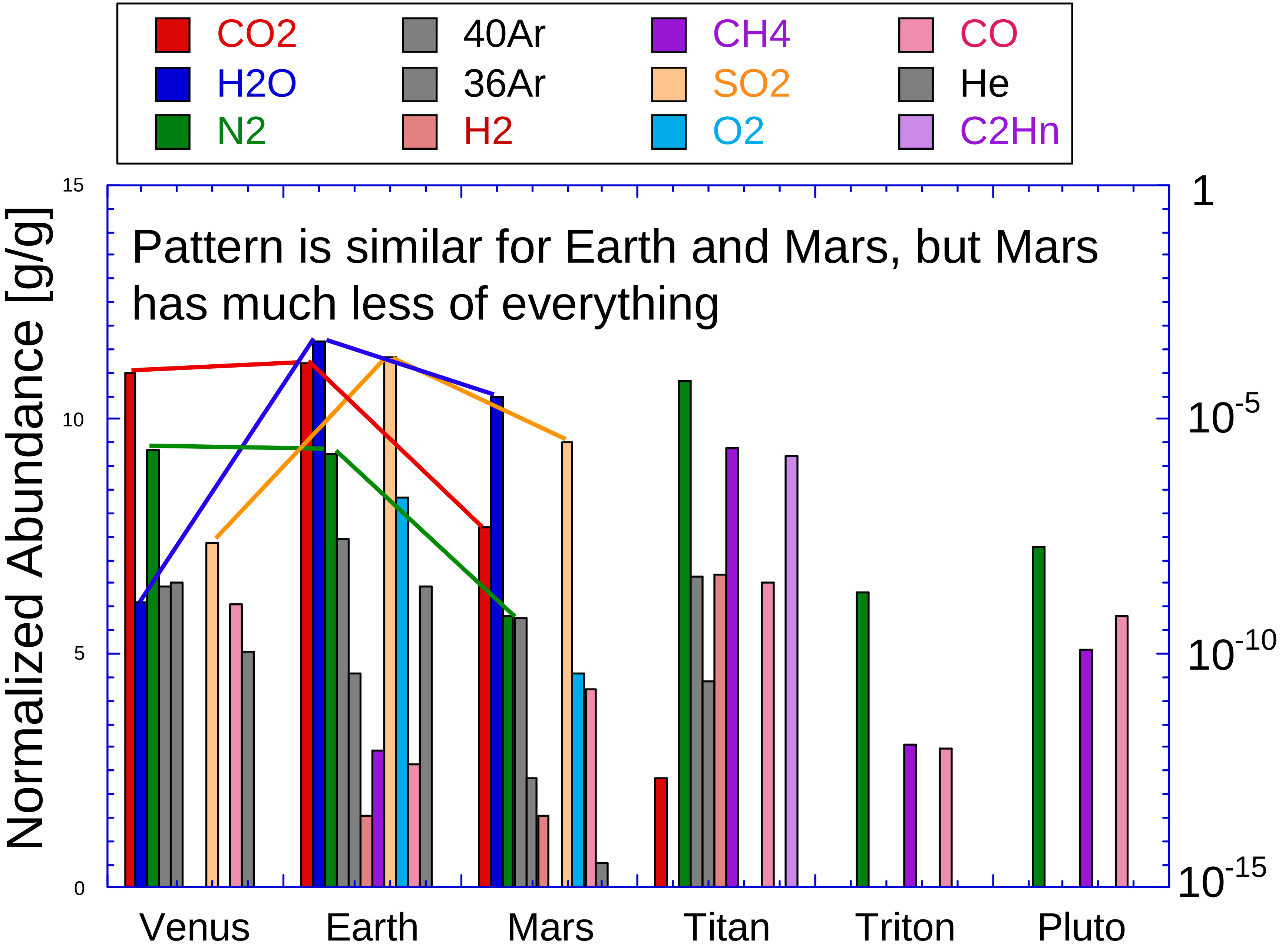
Compare Earth to Venus and Mars

Supplemented by known mantle inventories (Earth only)



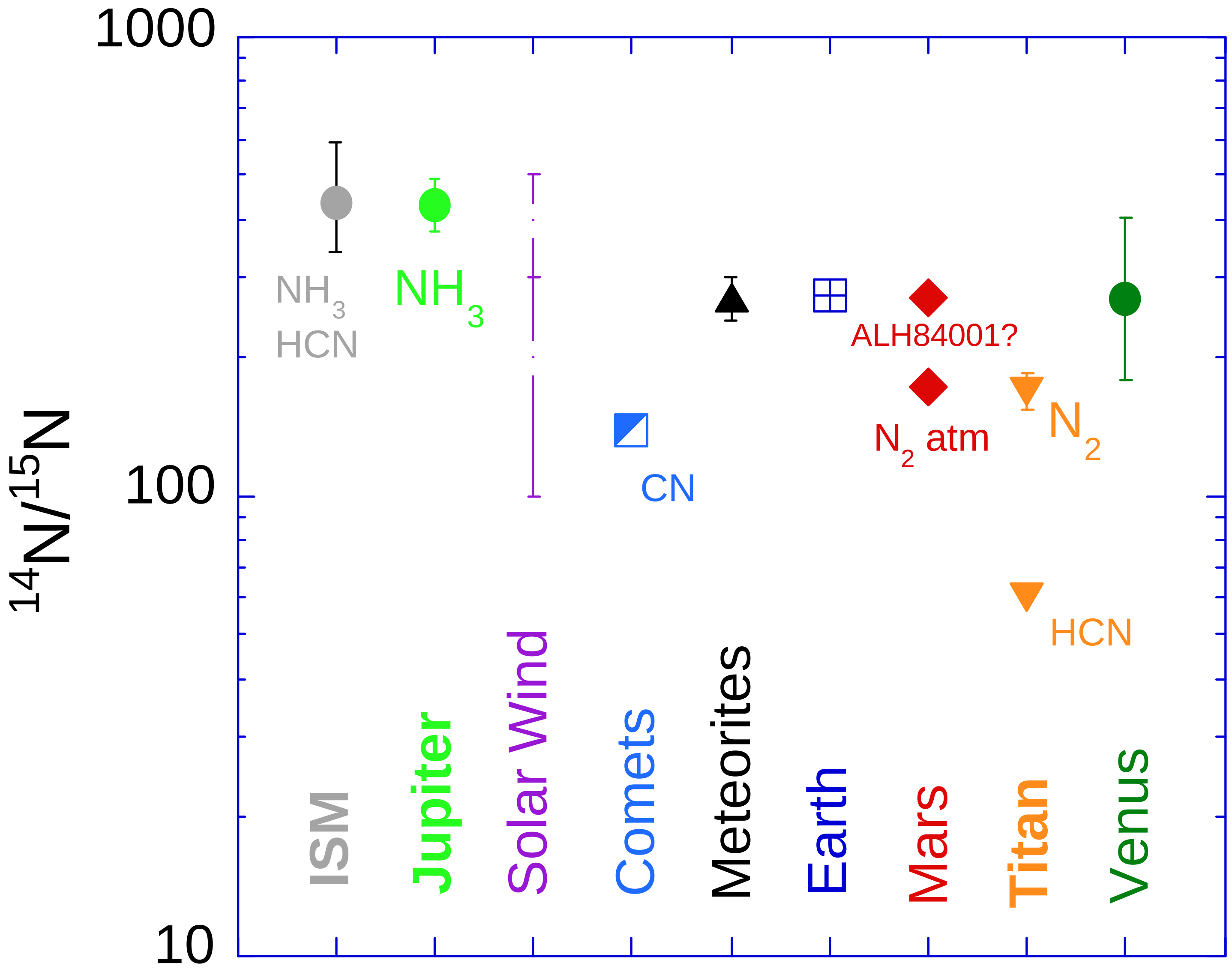
C, N similar on Earth and Venus. But Venus lacks water

Supplemented by known mantle inventories (Earth only)

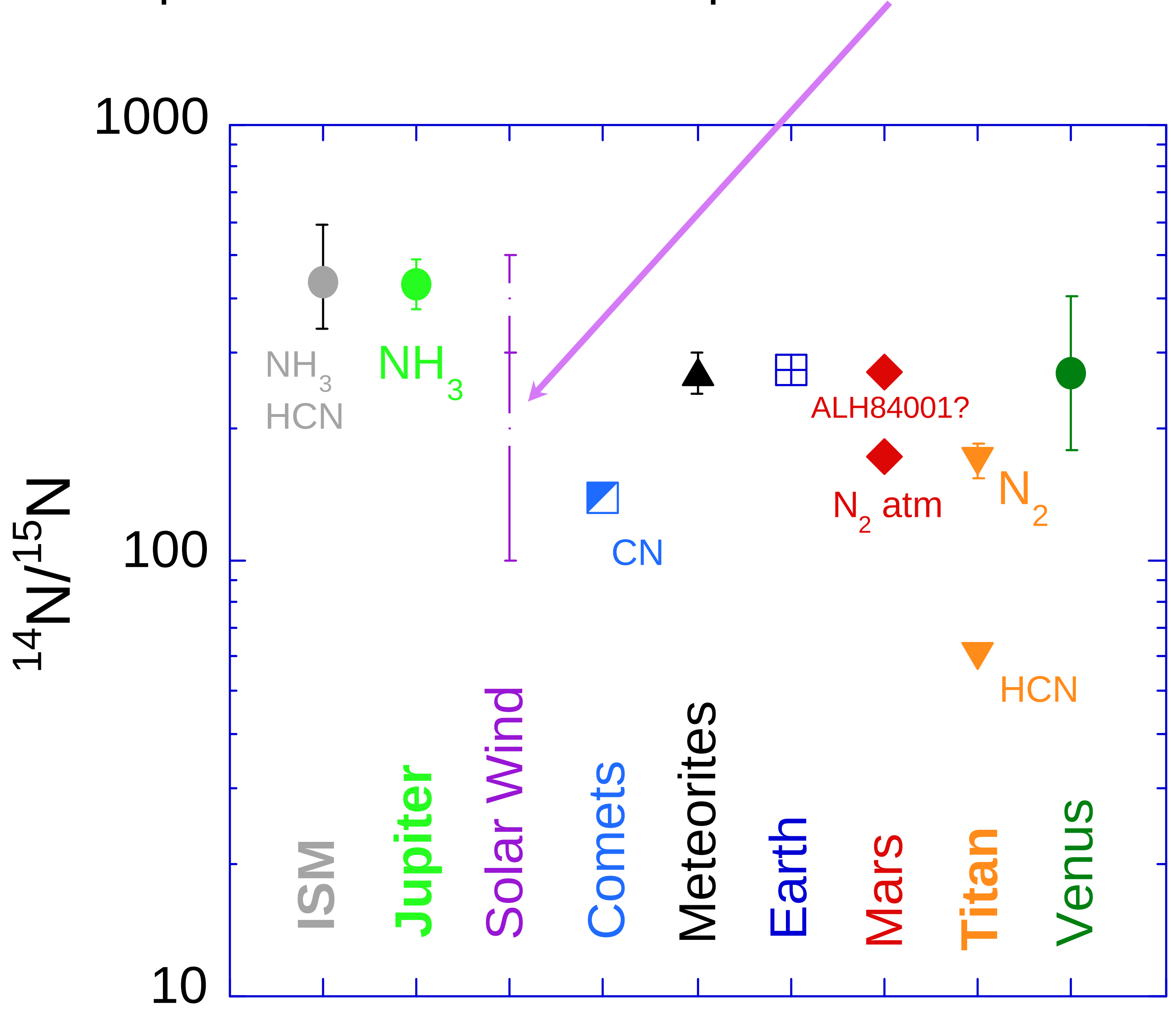


Pattern is similar for Earth and Mars, but Mars has much less of everything

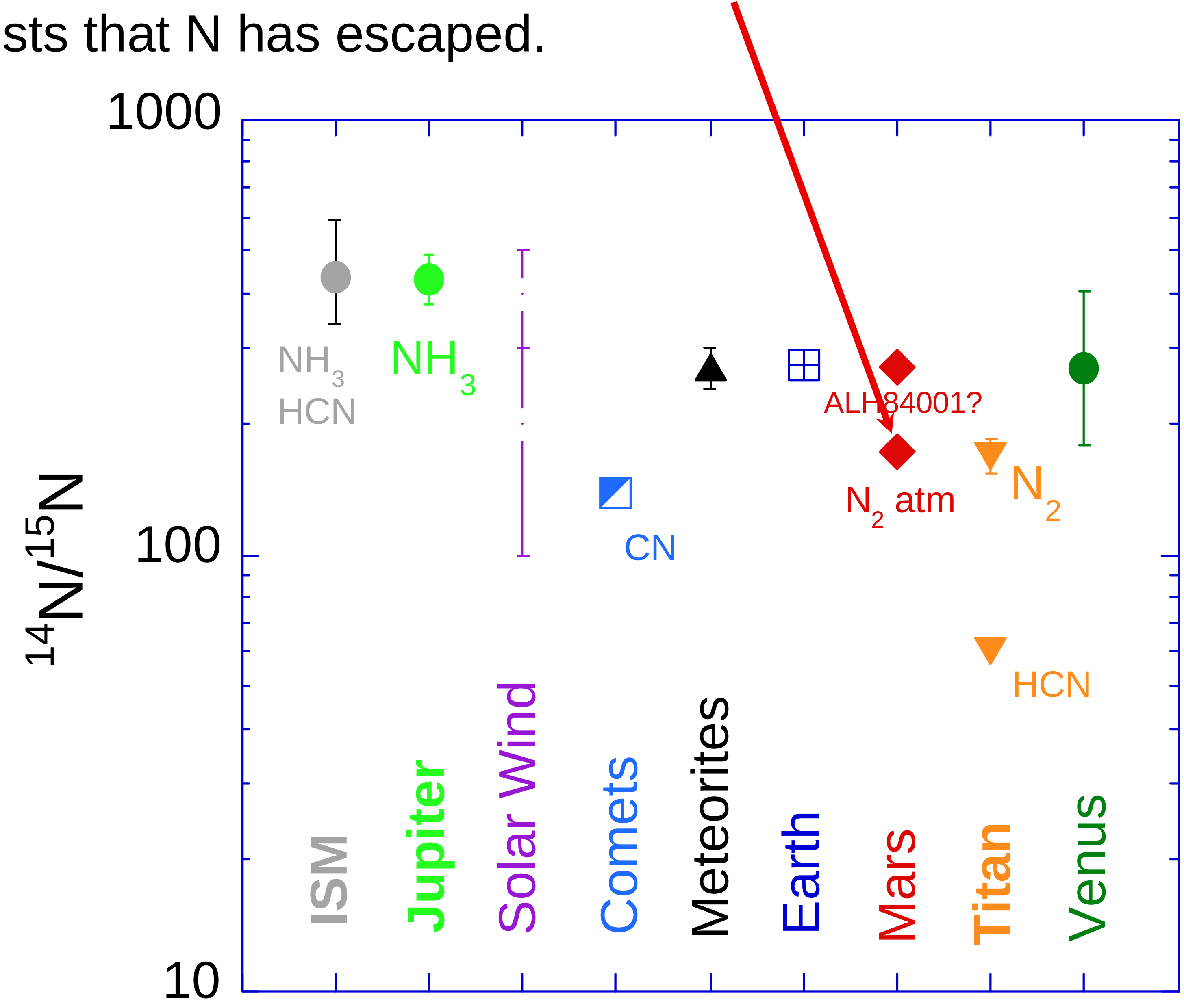
Nitrogen Isotopes: unsettled because primordial ratio is uncertain



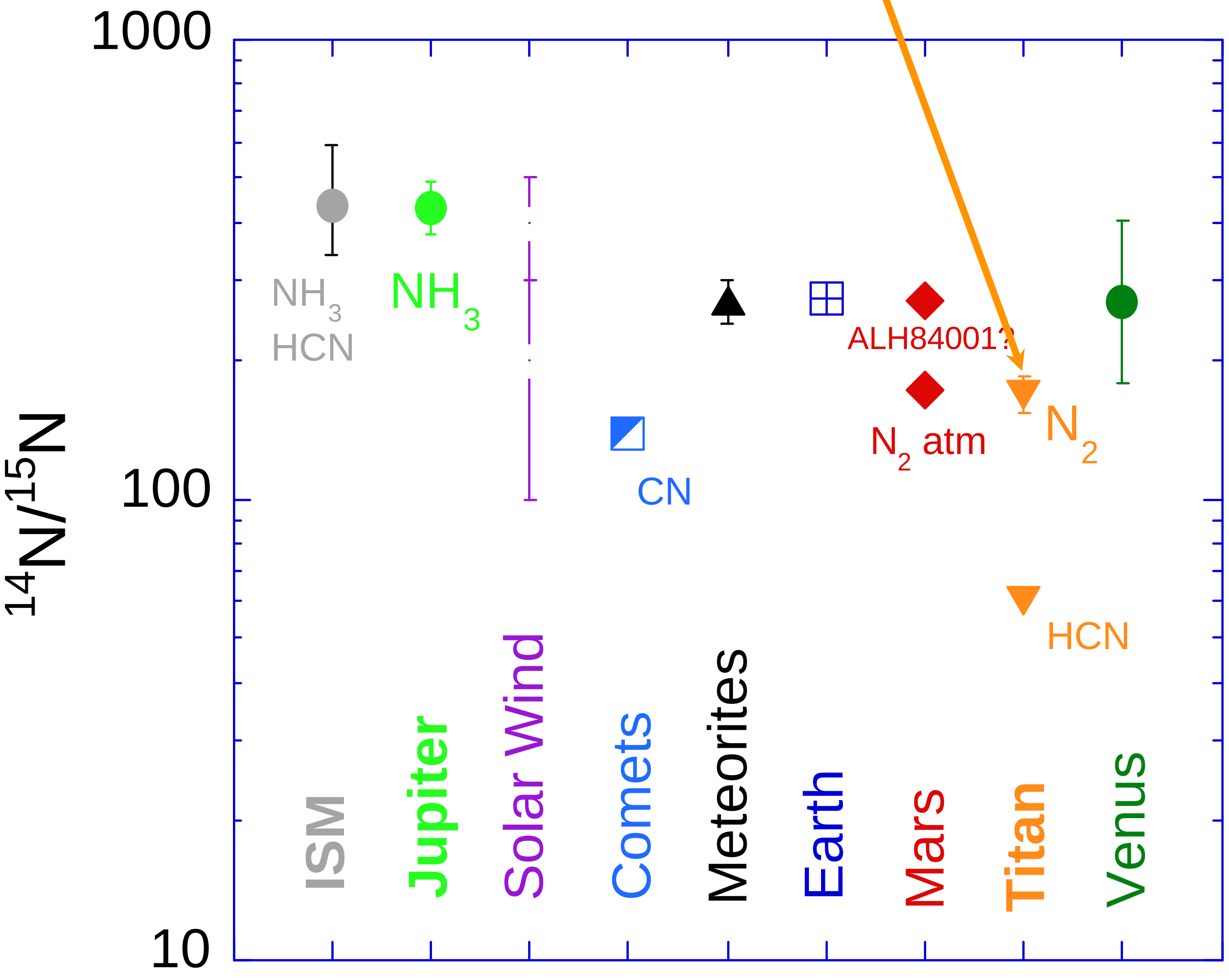
Nitrogen Isotopes: unsettled because primordial ratio is uncertain



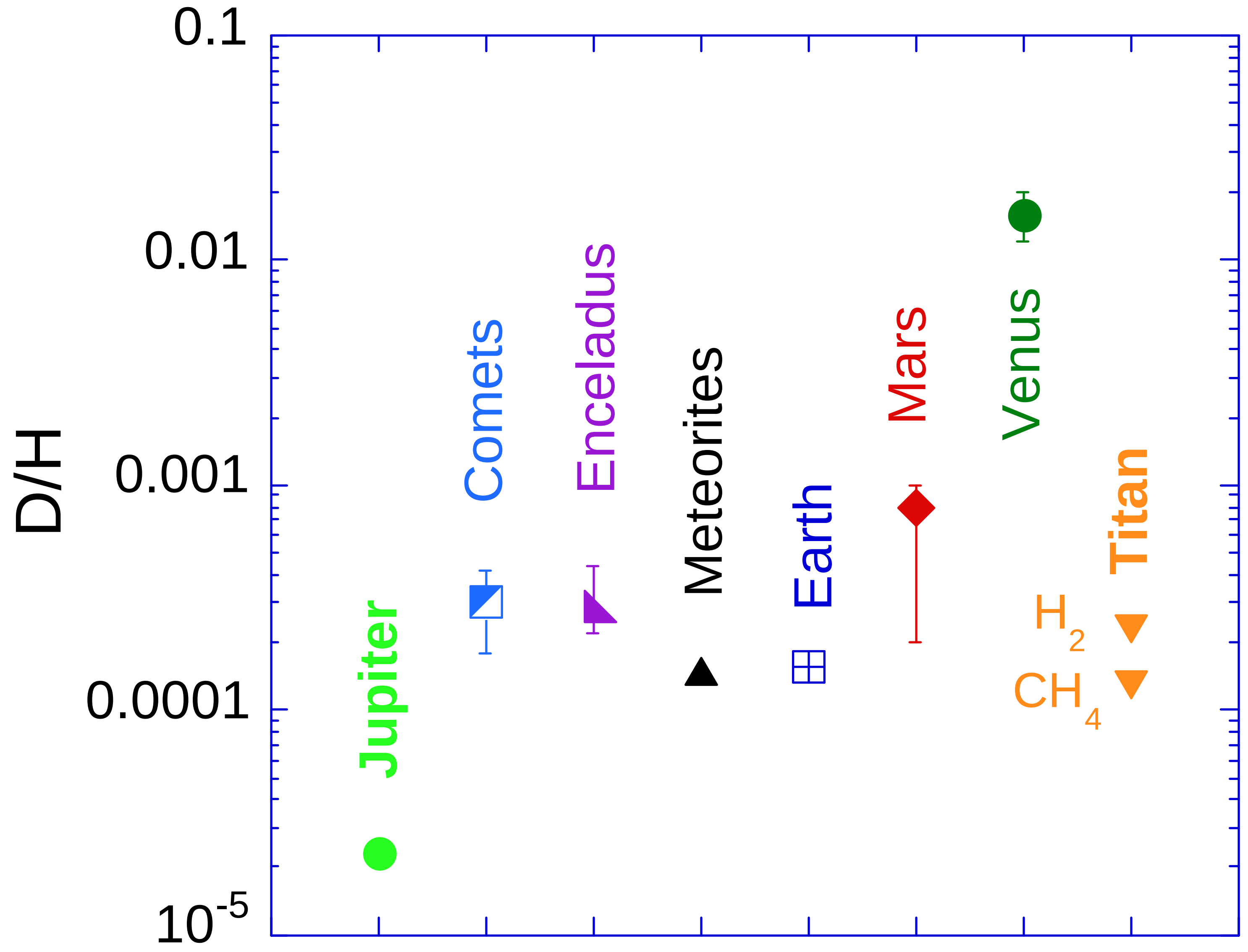
Nitrogen Isotopes. Mars atmosphere. Excess ^{15}N suggests that N has escaped.



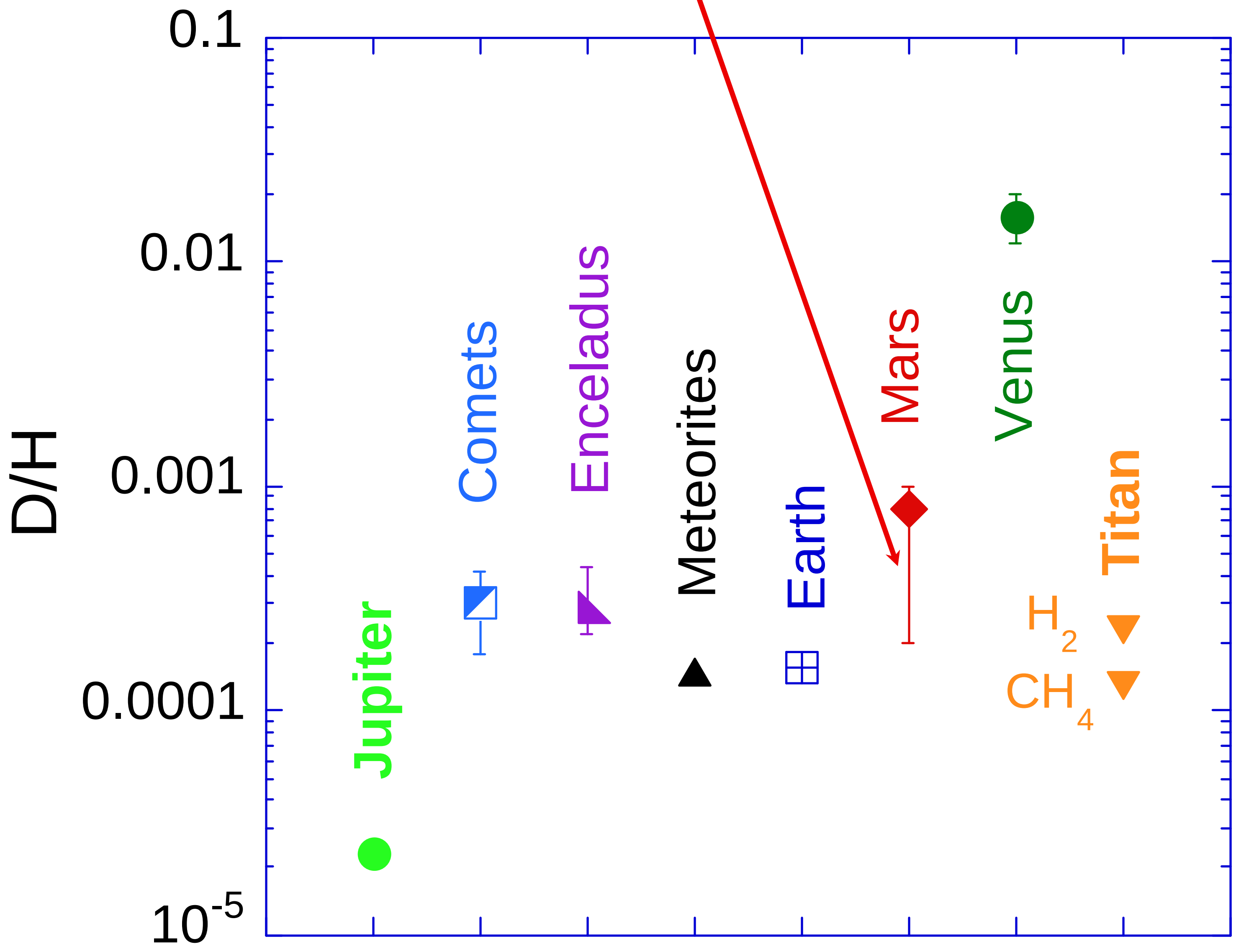
Nitrogen Isotopes. Titan's excess ^{15}N also suggests escape. If so, there must have been a **huge** amount of N initially



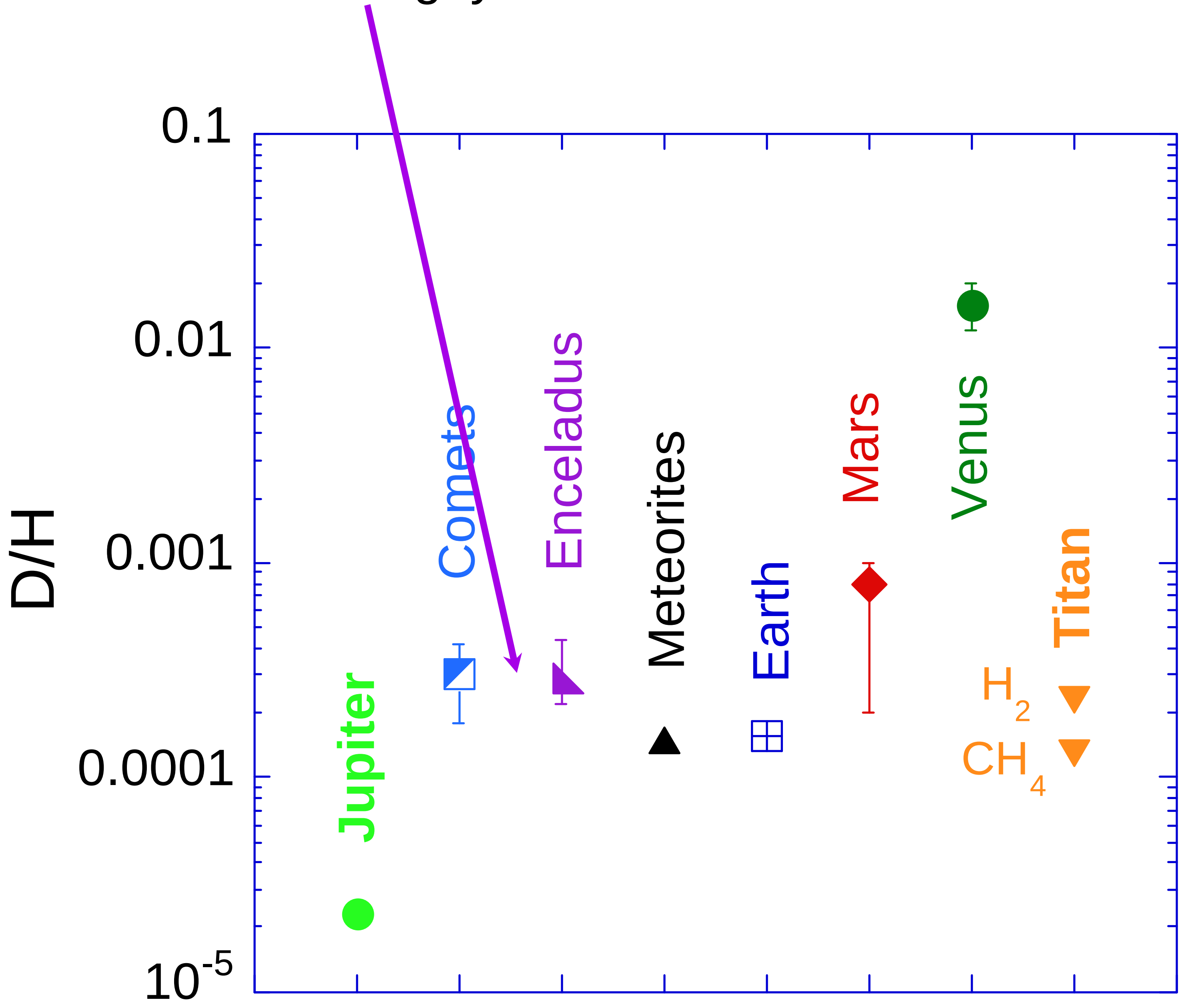
Deuterium. Earth (=SMOW=Standard Mean Ocean Water)



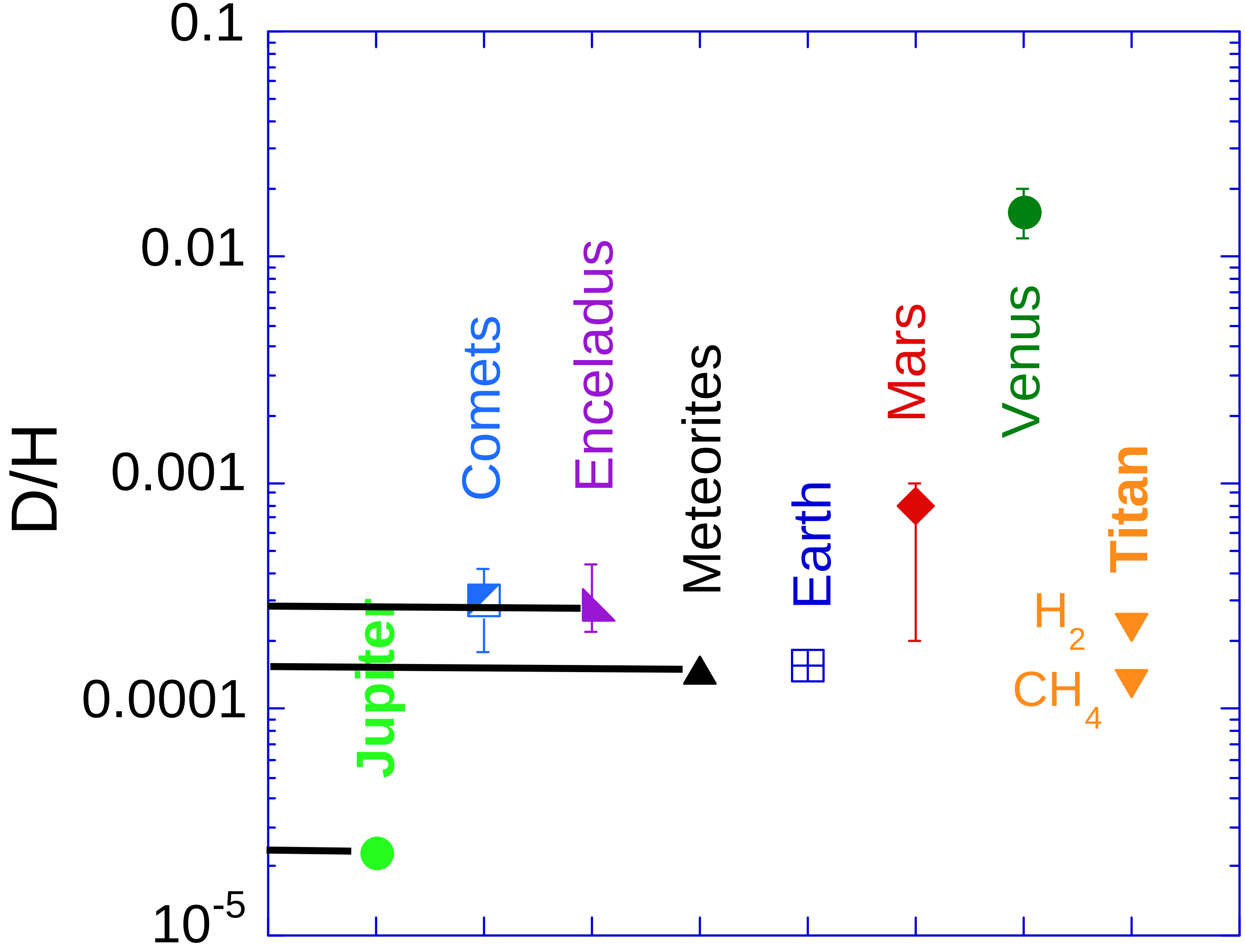
Deuterium. Mars D/H is heavy and is reported to vary.
Different H2O-ice reservoirs with different escape histories?



Deuterium. Enceladus's geysers = comets?



Deuterium. Implies three different source reservoirs? Titan's place unclear. (nb H_2 escape from Titan *lowers* Titan's D/H)



Carbon

Two stable isotopes ^{12}C, ^{13}C.

$^{12}C/^{13}C = 90$ in most solar system materials.

organic matter typically has a little more ^{12}C (2.5-6%).

In Earth air $^{12}CH_4/^{13}CH_4 = 95$

Only other interesting data in Solar System are for Titan:

$^{12}C/^{13}C = 90$ in C_2H_n

while

$^{12}C/^{13}C = 82$ in CH_4

This can be interpreted as evidence that CH_4 is a remnant of an evolved reservoir (i.e., there might not be a lot of CH_4 left)

Noble gases

Helium

- ^{4}He is mostly radiogenic
  - ^{232}Th ($t_{1/2}$=12 Gyr)
  - ^{235}U ($t_{1/2}$=0.7 Gyr)
  - ^{238}U ($t_{1/2}$=4.5 Gyr)
- ^{3}He is mostly primordial
  - ^{3}He flux Earth 1000 moles/yr
  - ~10% of Earth's ^{4}He is primordial

Noble gases

Neon - 3 isotopes ^{20}Ne, ^{21}Ne, ^{22}Ne

^{20}Ne and ^{22}Ne are mostly primordial

^{21}Ne is very rare, partly radiogenic

Ne in the mantle is isotopically lighter
than Ne in air or meteorites

Ne, He, and H_2 do not condense

N/Ne = 1 in the Sun

but Ne/N = 10^{-5} on Earth

Argon - 3 isotopes ^{36}Ar, ^{38}Ar, ^{40}Ar

^{36}Ar and ^{38}Ar are primordial.

^{36}Ar/^{38}Ar = 5.3

Ar might condense at ~25 K

^{40}Ar is almost entirely radiogenic

^{40}K ($t_{1/2}$=1.25 Ga)

Earth is 50% degassed

Venus is 12% degassed

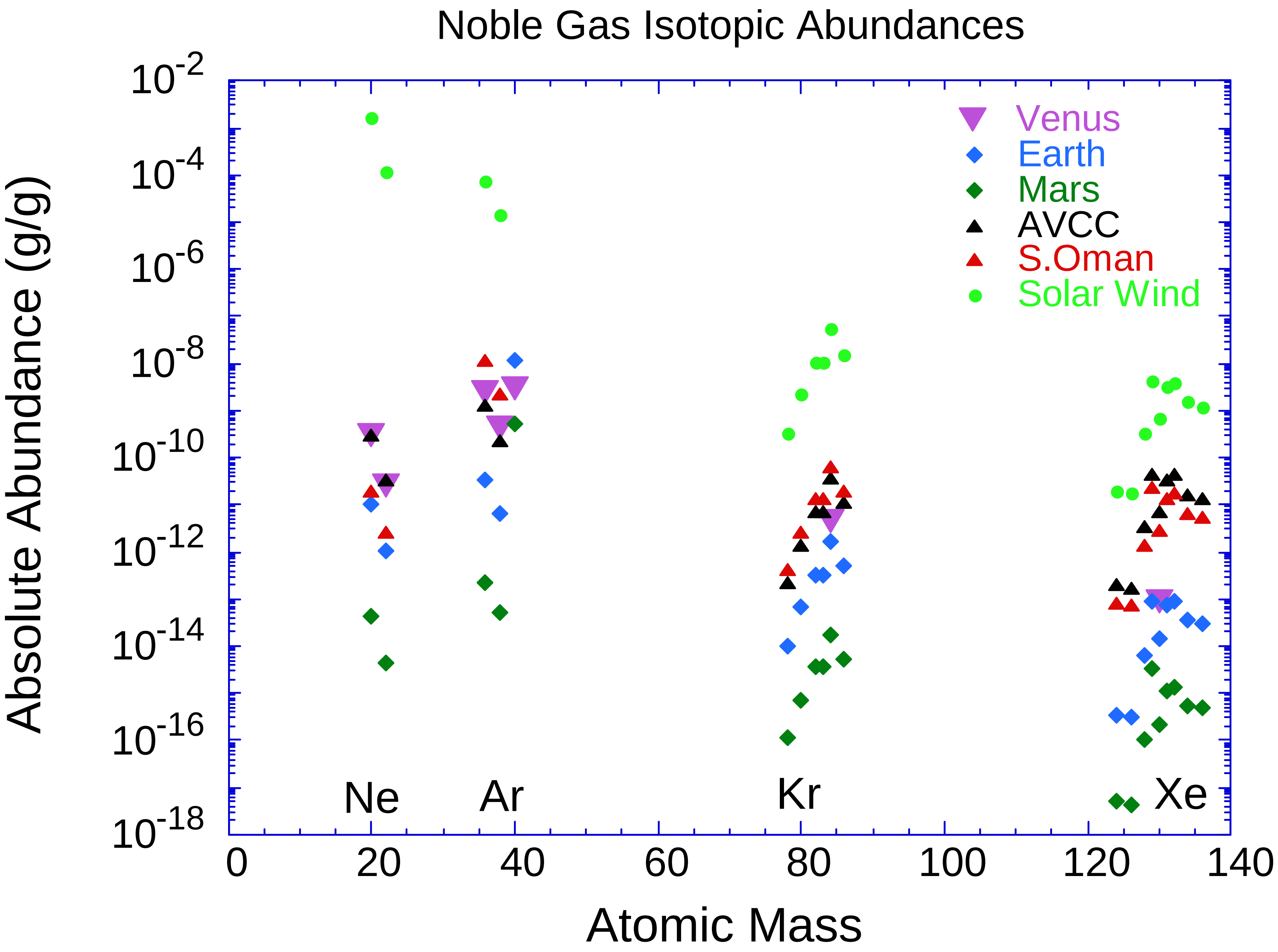
Mars is >0.5% degassed

^{36}Ar/^{38}Ar = 3.9 -> Ar has escaped!

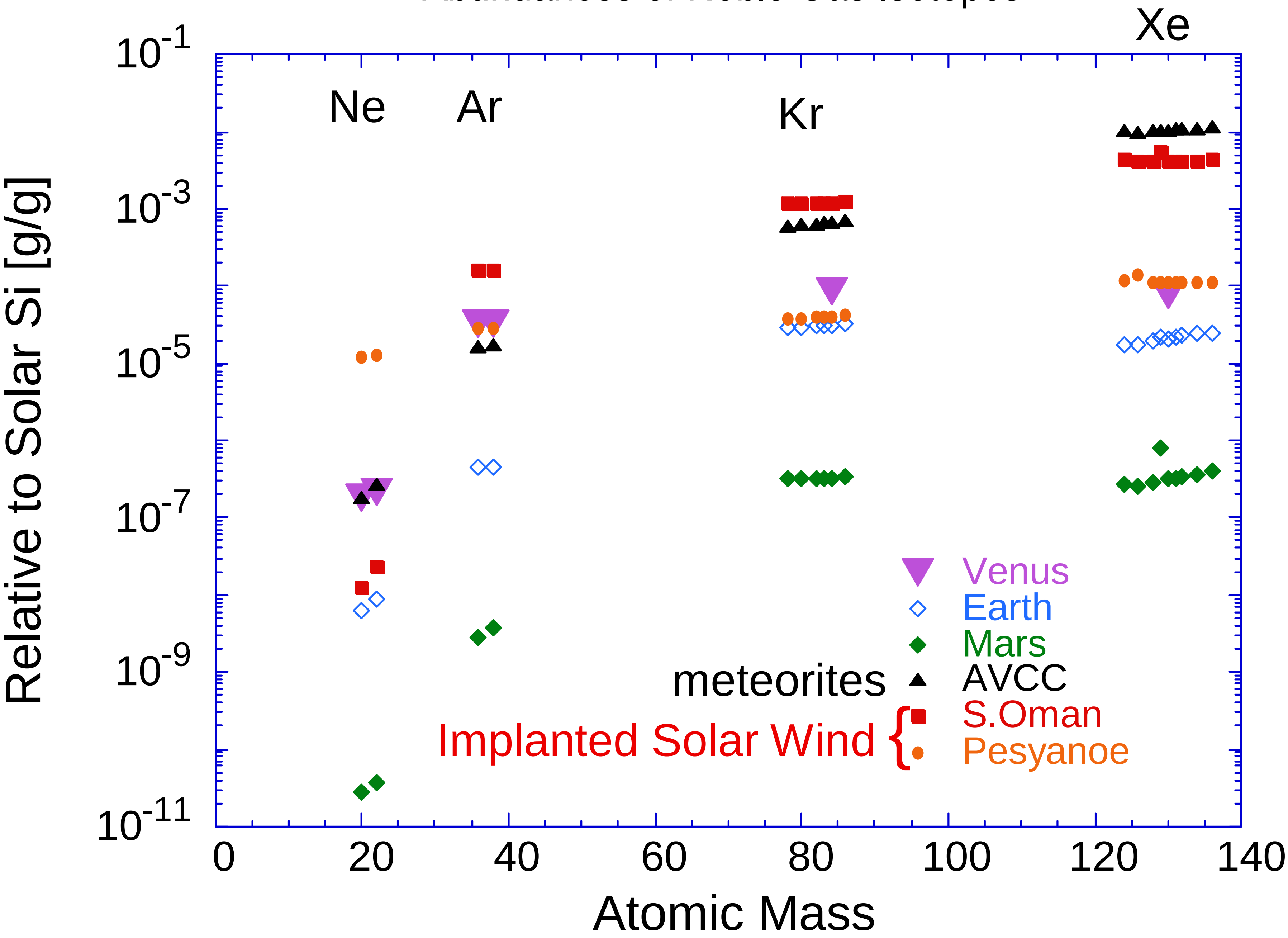
Titan is ~7% degassed

Xenon, Lord of the Isotopes

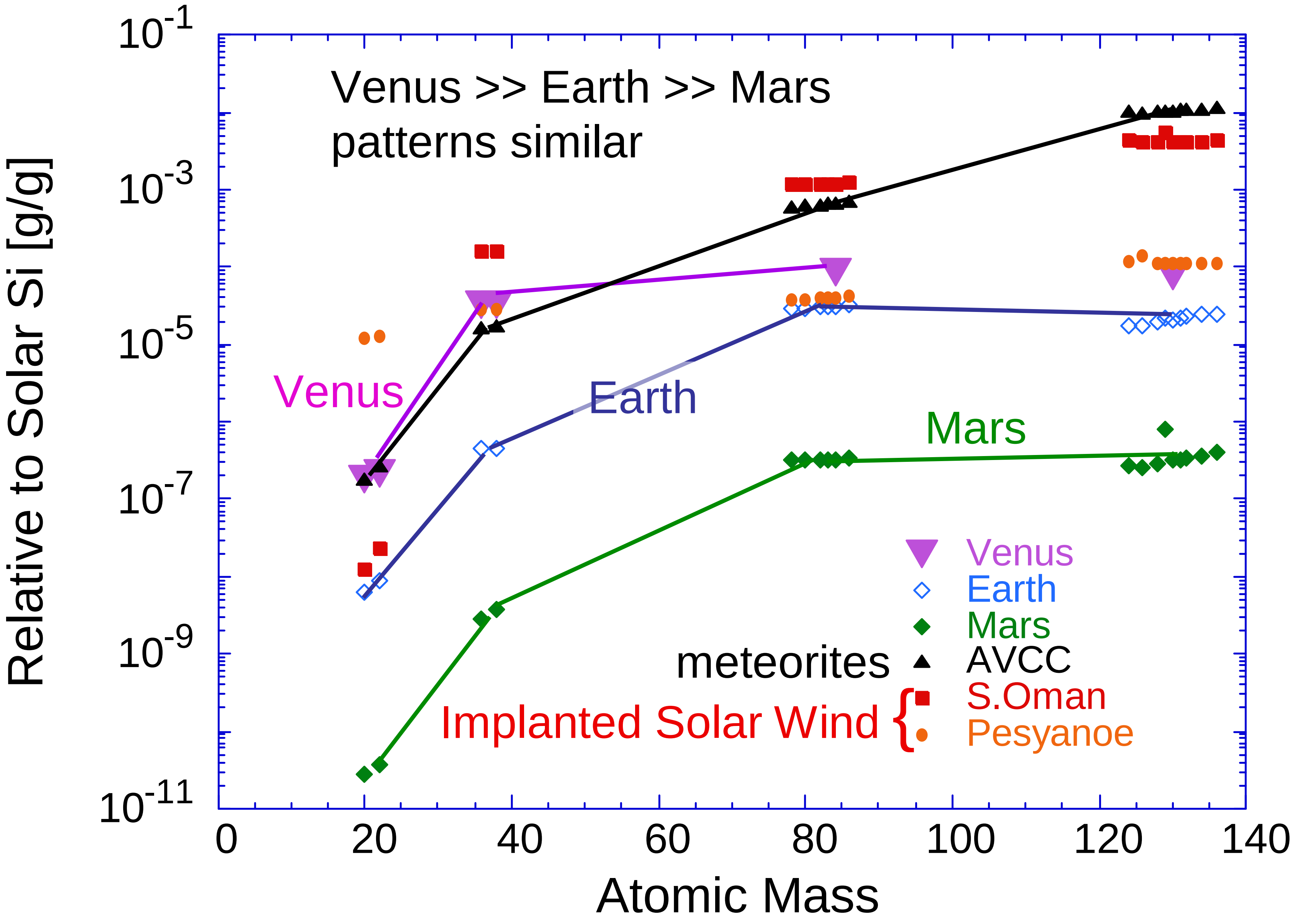
- 9 stable isotopes !
- Profound Mass Fractionations !!
- ^{129}Xe is partly radiogenic
  - ^{129}I ($t_{1/2}$ = 15.7 Myr)
- ^{131,132,134,136}Xe are partly fissogenic
  - ^{238}U ($t_{1/2}$ = 4.5 Gyr)
  - ^{244}Pu ($t_{1/2}$ = 81 Myr)
- all Xe isotopes have some radiogenic
  - e.g., ^{130}Xe can be made from ^{130}Ba


Noble Gas Isotopic Abundances
Absolute Abundance (g/g)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
0
20
40
60
80
100
120
140
Atomic Mass
Venus
Earth
Mars
AVCC
S.Oman
Solar Wind
Ne
Ar
Kr
Xe

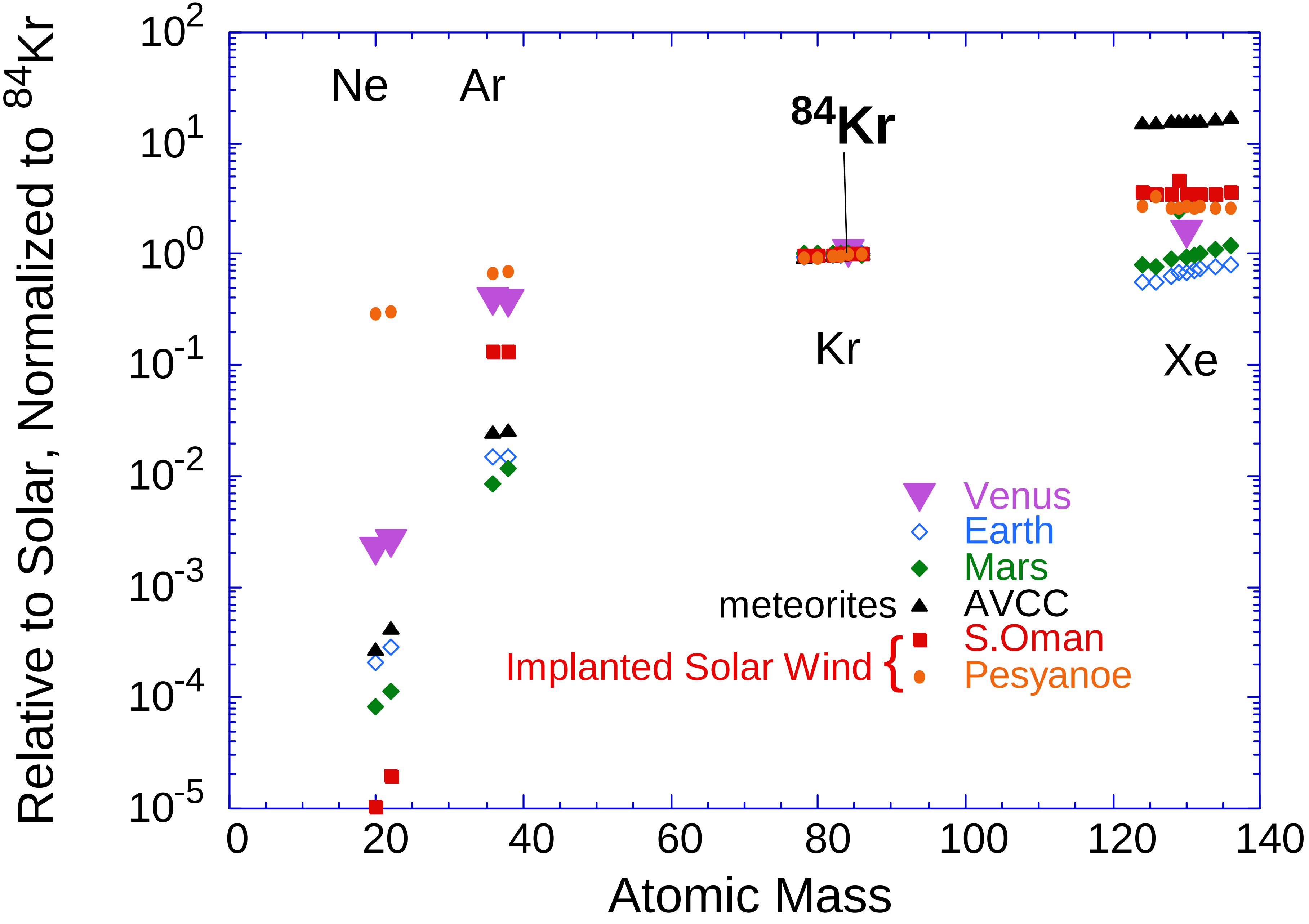
Normalized Abundances of Noble Gas Isotopes



Normalized Abundances of Noble Gas Isotopes



Twice Normalized Abundances of Stable Noble Gas Isotopes



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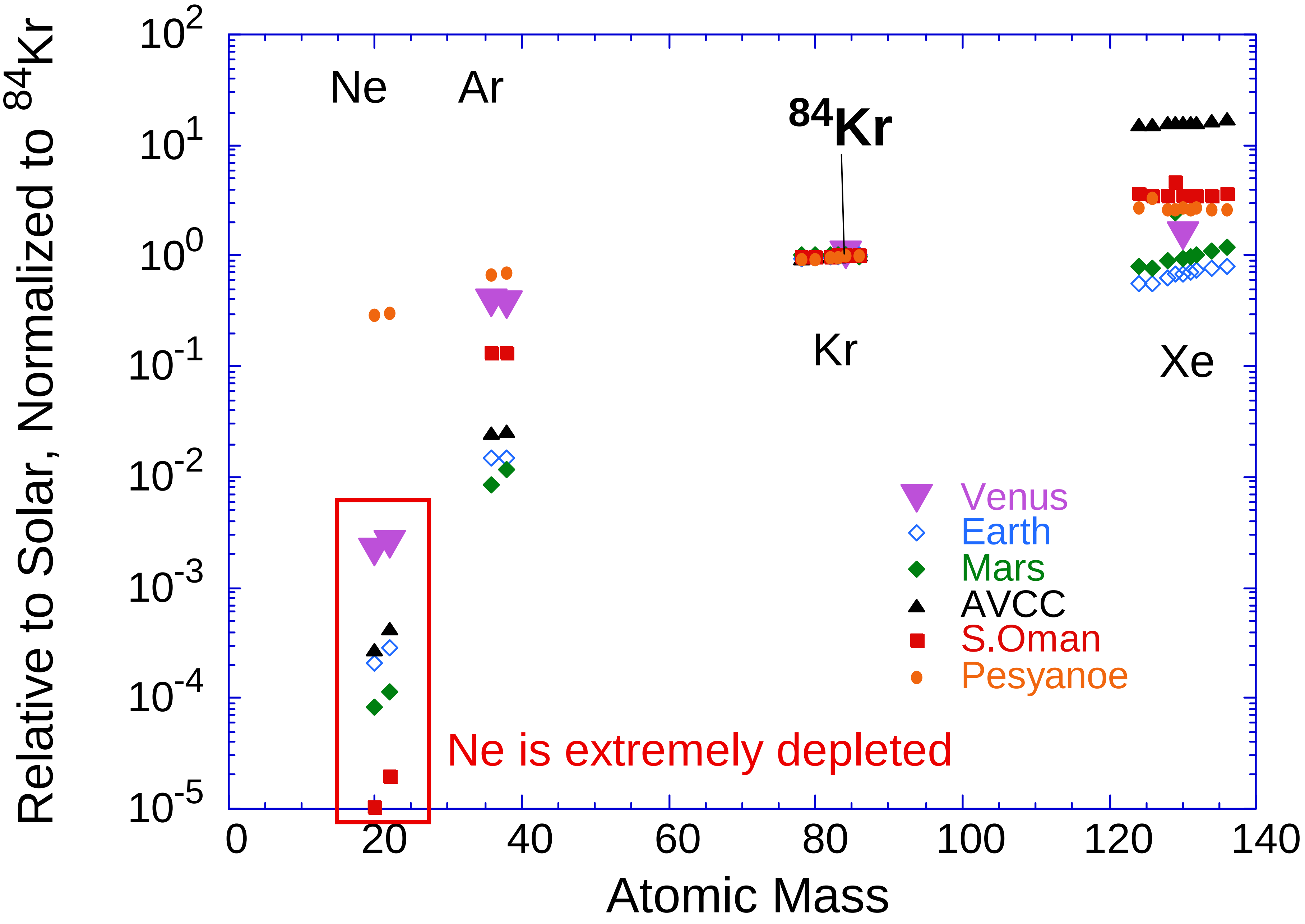
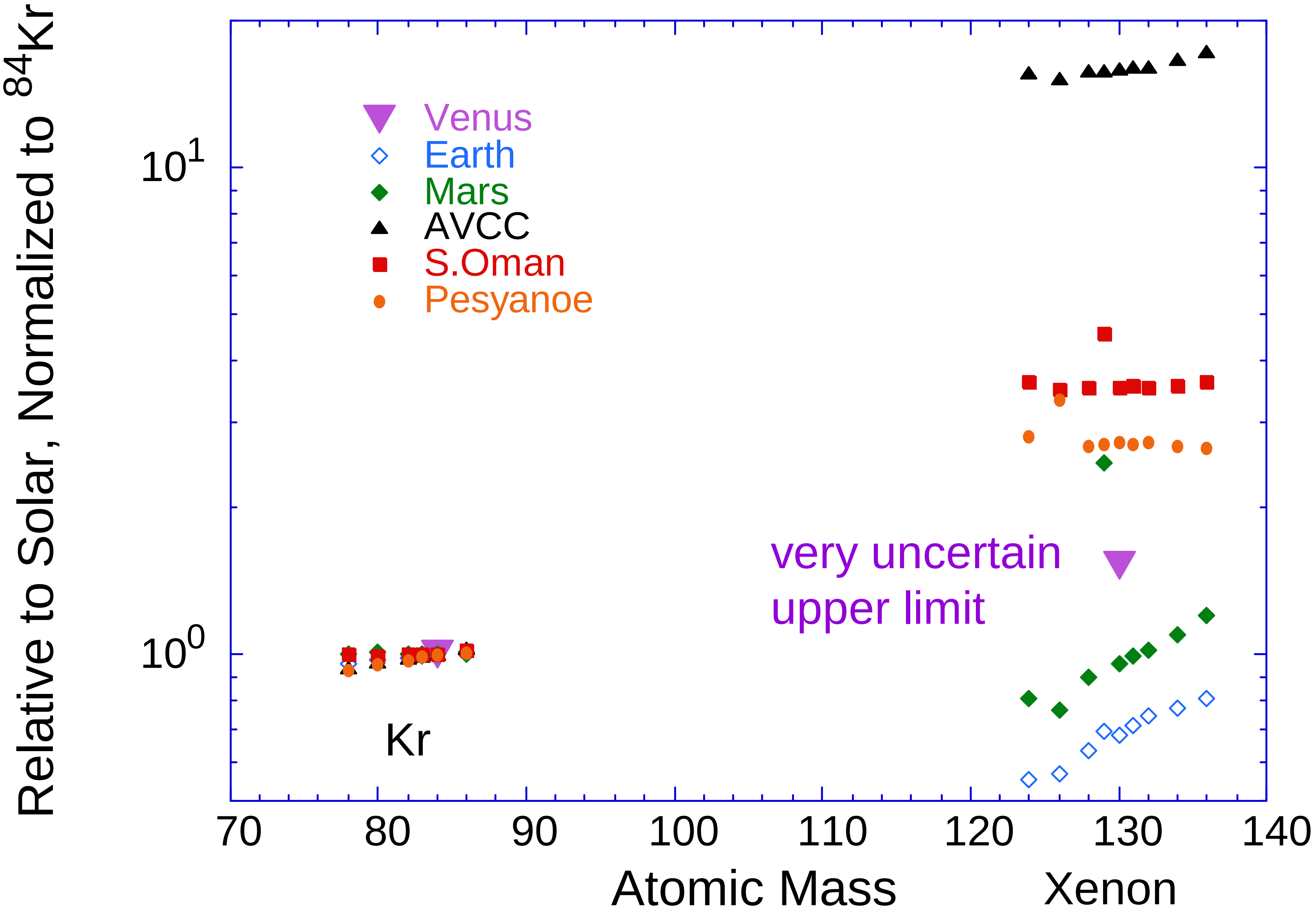
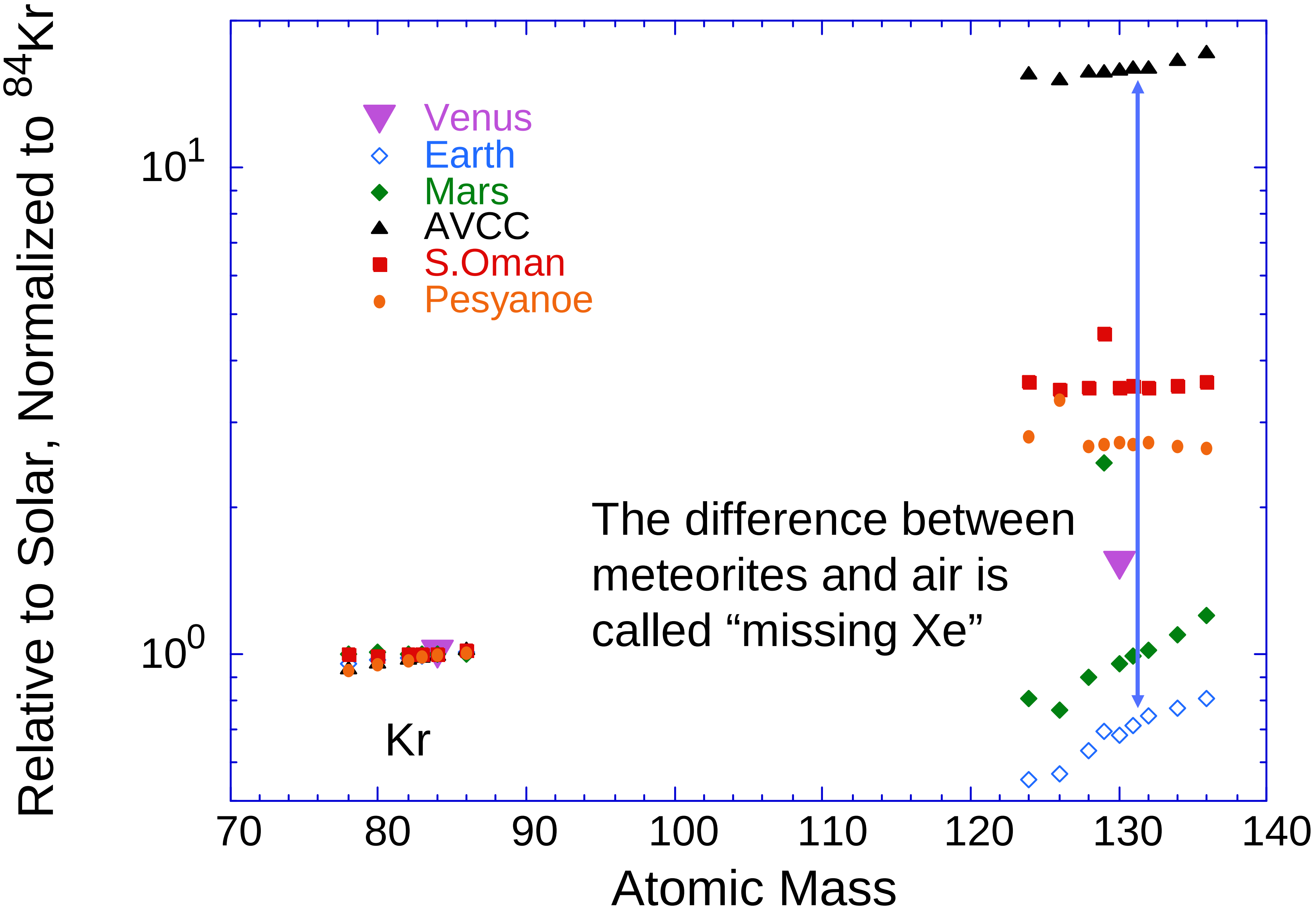


Twice normalized Abundances of Stable Noble Gas Isotopes

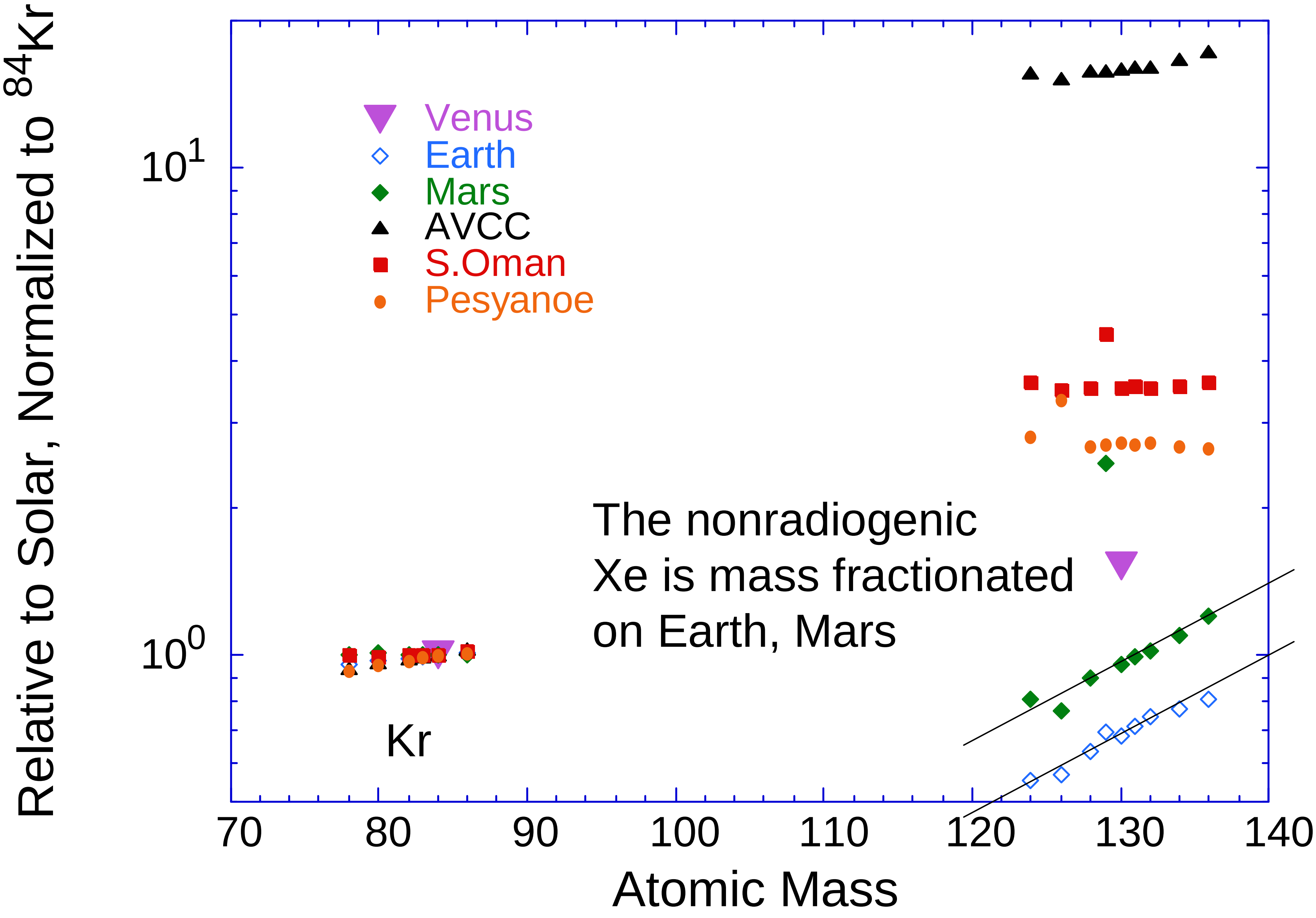


Twice normalized Abundances of Stable Noble Gas Isotopes



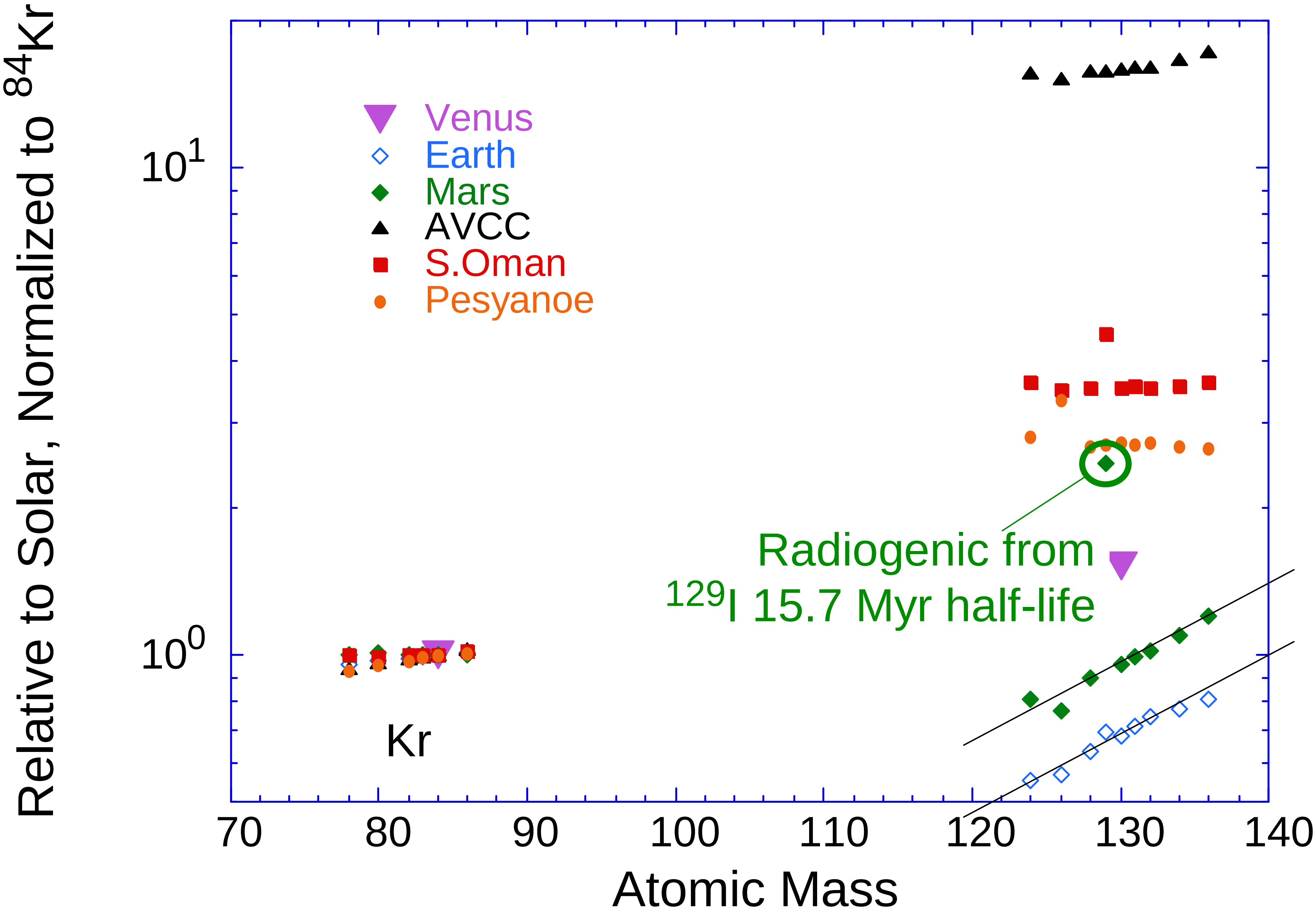
The difference between meteorites and air is called “missing Xe”

Twice normalized Abundances of Stable Noble Gas Isotopes

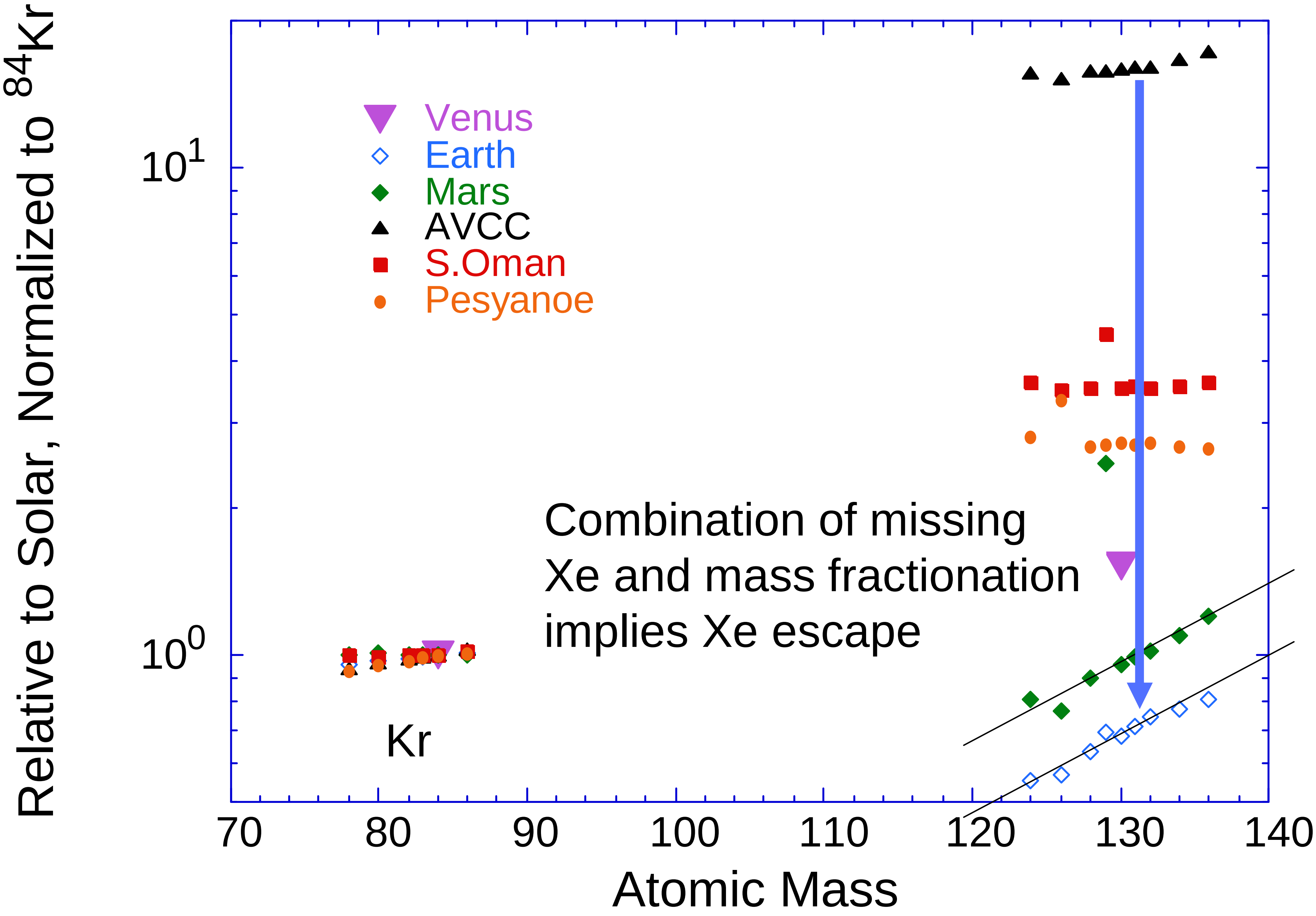


The nonradiogenic
Xe is mass fractionated
on Earth, Mars

Twice normalized Abundances of Stable Noble Gas Isotopes



Twice normalized Abundances of Stable Noble Gas Isotopes



Combination of missing Xe and mass fractionation implies Xe escape

More fun Xenon Facts - Radiogenic Xe is missing

$$^{129}\mathrm{I} \longrightarrow \ ^{129}\mathrm{Xe}^{*} \qquad \tau_{1/2} = 15.7 \text{ Ma}$$

using $\dfrac{^{129}\mathrm{I}}{^{127}\mathrm{I}} = 1 \times 10^{-4}$ and $\left(^{127}\mathrm{I}\right)_{\mathrm{BSE}} = 11$ ppb

We expect $3\mathrm{x}10^{13}$ moles of $^{129}\mathrm{Xe}^*$

Earth Air contains $4.2\mathrm{x}10^{12}$ moles of $^{129}\mathrm{Xe}$

7% of $^{129}\mathrm{Xe}$ in air is radiogenic

= $2.9\mathrm{x}10^{11}$ moles of $^{129}\mathrm{Xe}^*$

Hence 99% of $^{129}\mathrm{Xe}^*$ is missing.

Seven half-lives = 110 Ma.

But wait… There's More!

$$^{244}\mathrm{Pu} \rightarrow {}^{129,131,132,134,136}\mathrm{Xe}^* \qquad \tau_{1/2} = 81\ \mathrm{Ma}$$

using $$\frac{^{244}\mathrm{Pu}}{^{238}\mathrm{U}} = 0.008 \quad \text{and} \quad \left(^{238}\mathrm{U}\right)_{\mathrm{BSE}} = 21\ \mathrm{ppb}$$

$7\text{x}10^{-5}$ of ^{244}Pu decays produce ^{136}Xe*

- We expect $2\text{x}10^{11}$ moles of ^{136}Xe*

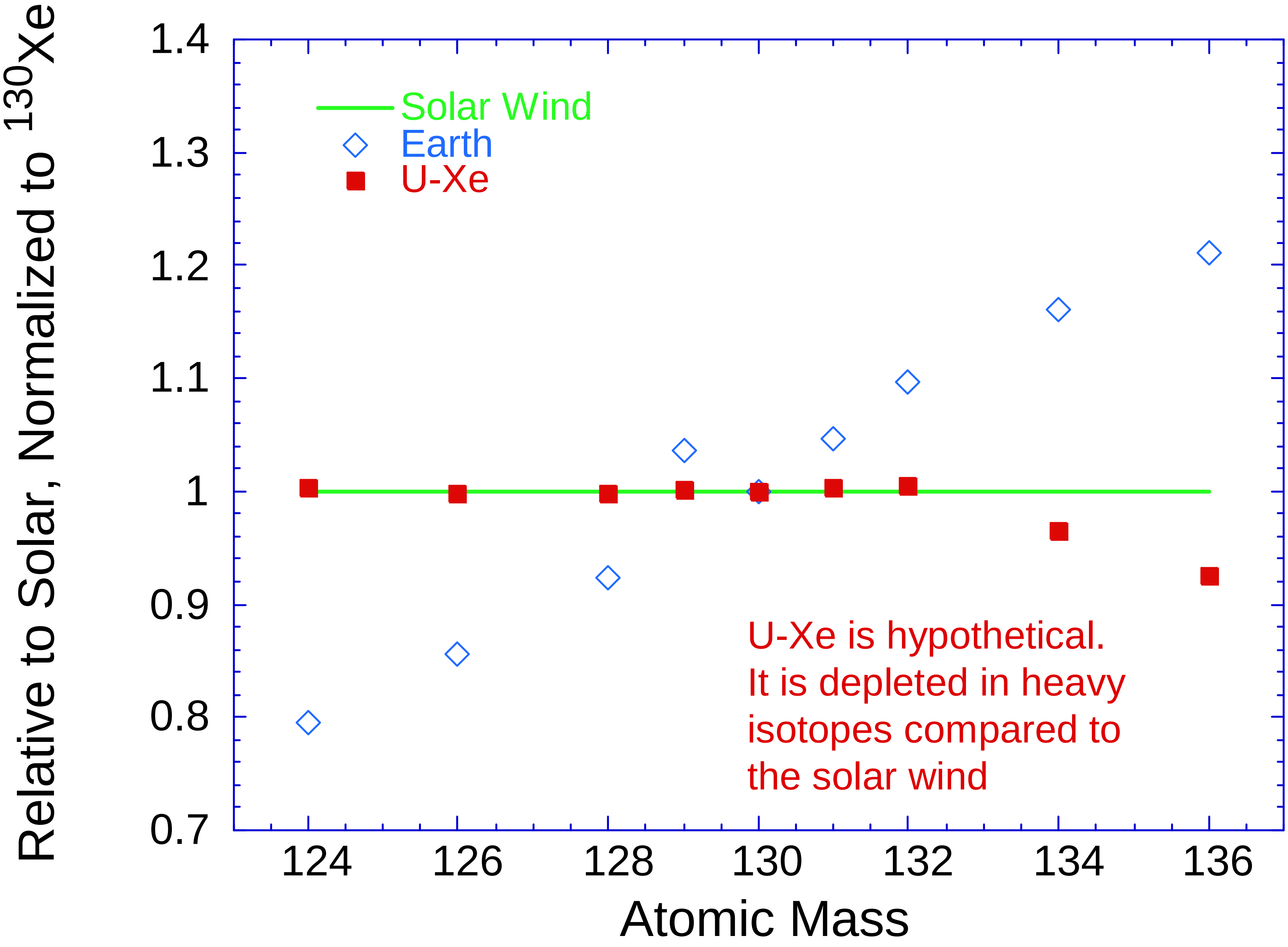
Earth Air contains $1.34\text{x}10^{12}$ moles of ^{136}Xe

< 4% is radiogenic (upper limit, consistent with 0)

< $5\text{x}10^{10}$ moles of ^{136}Xe*

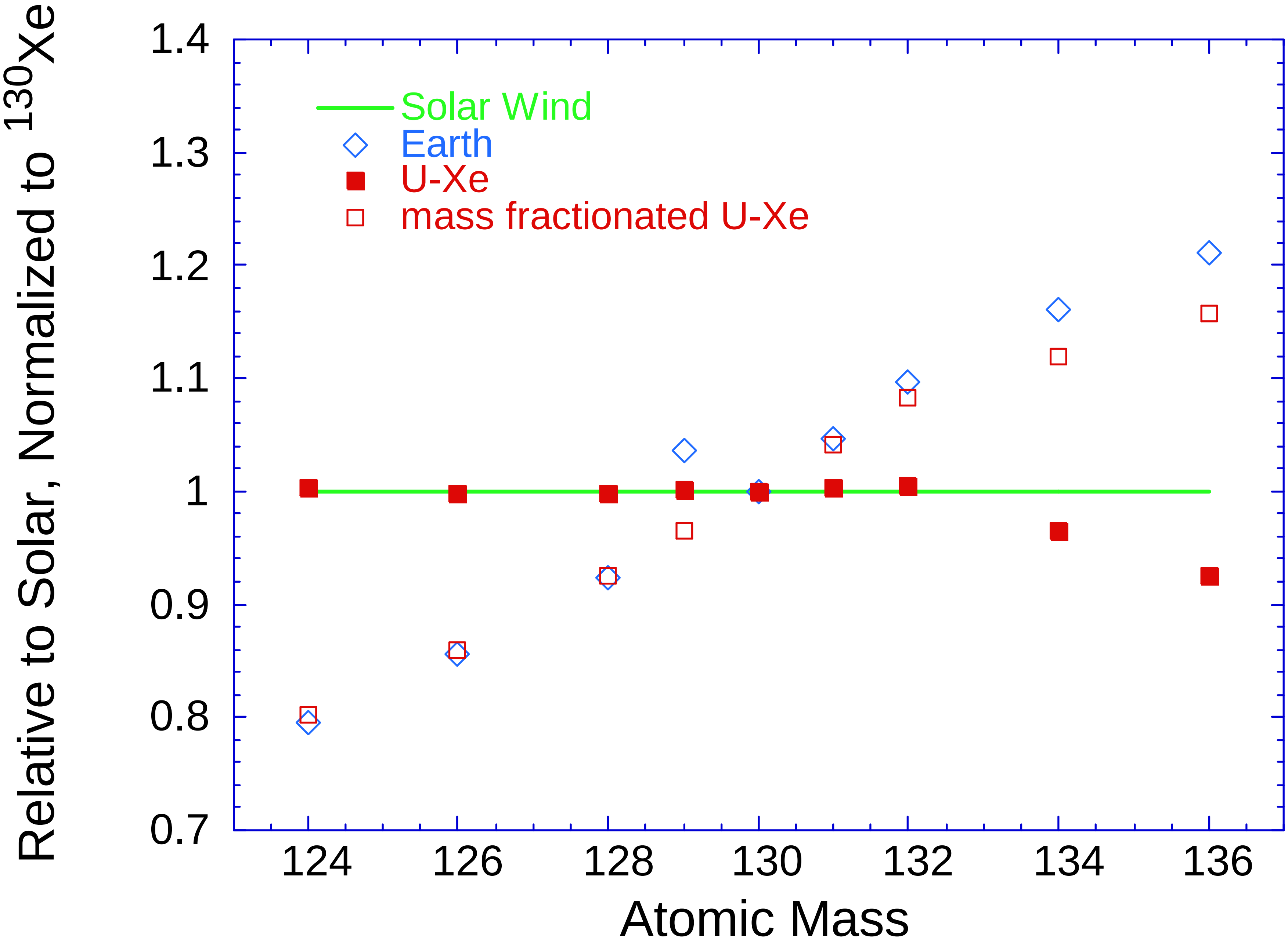
At least 75% of ^{136}Xe* is missing. Did it escape?
if it did, it did so >200 Ma after Earth formed.
For Mars, >96% of ^{136}Xe* is missing.

Twice Normalized Xenon Isotopic Abundances

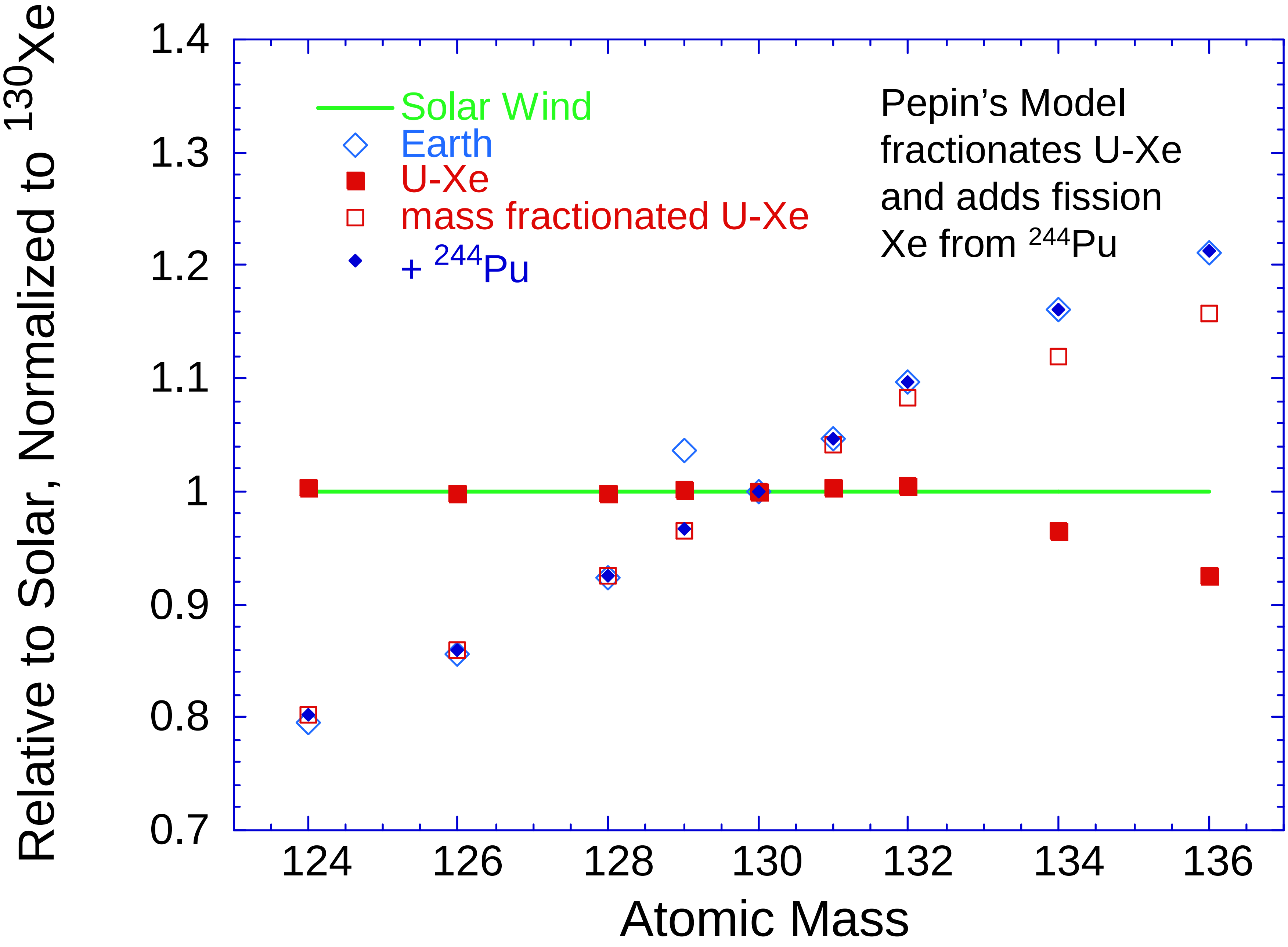


U-Xe is hypothetical.
It is depleted in heavy
isotopes compared to
the solar wind

Twice Normalized Xenon Isotopic Abundances

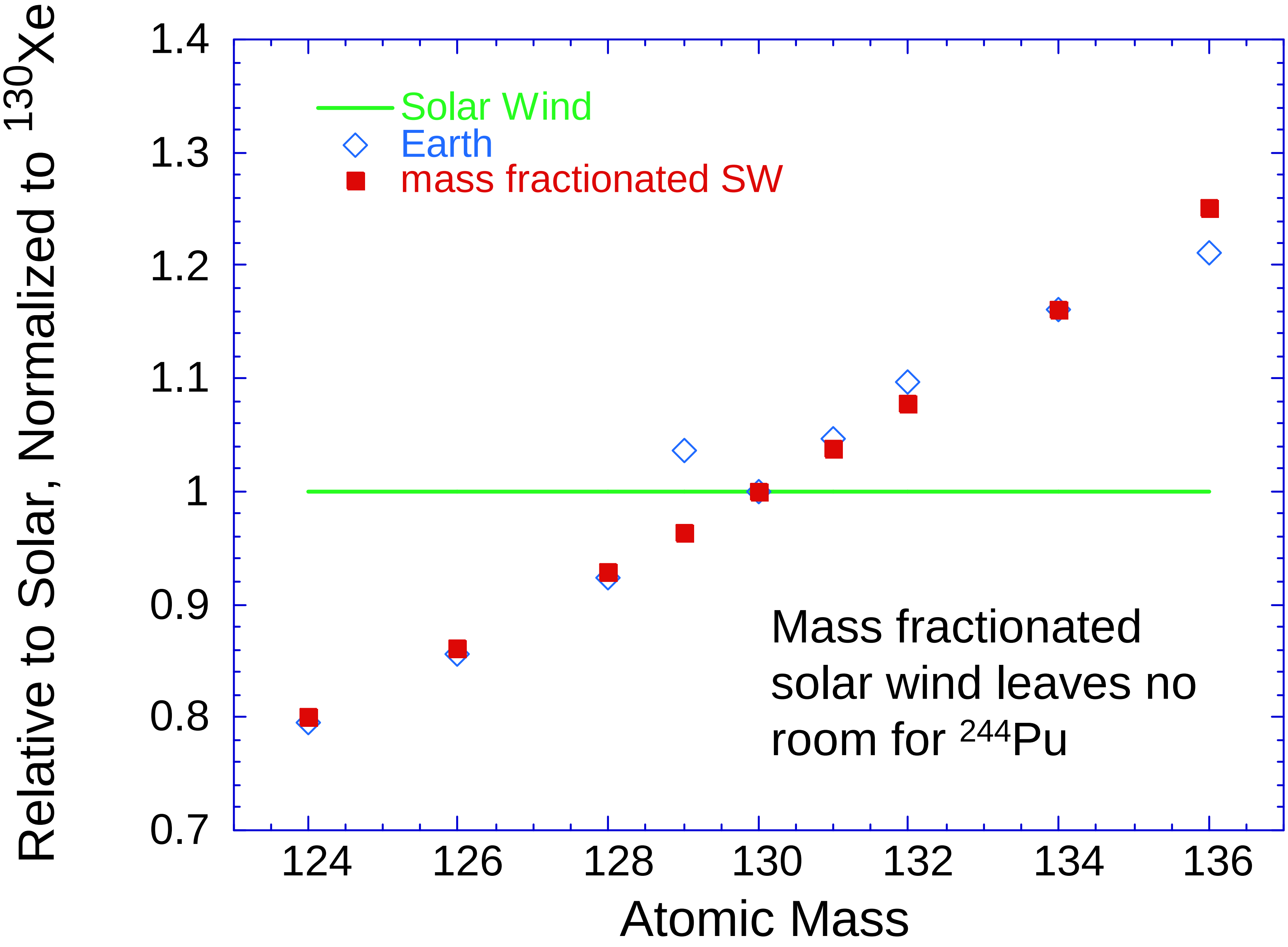


Twice Normalized Xenon Isotopic Abundances



Pepin’s Model fractionates U-Xe and adds fission Xe from ^{244}Pu

Twice Normalized Xenon Isotopic Abundances



Mass fractionated solar wind leaves no room for ^{244}Pu

Sources

Primary Atmospheres

gravitational capture of nebular gases, mostly H_2 & He

Jupiter and Neptune are examples of this

Earth's ^{3}He may be primary

but Earth's Ne/N = 10^{-5} means that Earth's primary atmosphere escaped.

escape is easy if the solar nebula dispersed when the planets were not much bigger than Mars

exercise:

compare thermal velocity of H_2 to escape velocity

do same for H_2O and for silicate vapors (with mean molecular weight of ~40)

Sources

Secondary Atmospheres

degassed from condensed materials.
condensation probably took place in the solar nebula

There are two basic variants:

1. gases are released from the interior of the planet as it heats up (by impact or by radioactivity).
   Giant impacts are an important special case.
   Radiogenic Noble gases are another.
2. gases are released from meteorites on impact for V>5 km/s. They can also be released by ablation when meteorites comets etc strike an atmosphere. This will work for ices with V>1.5 km/s.

sources: an embarrassment of riches

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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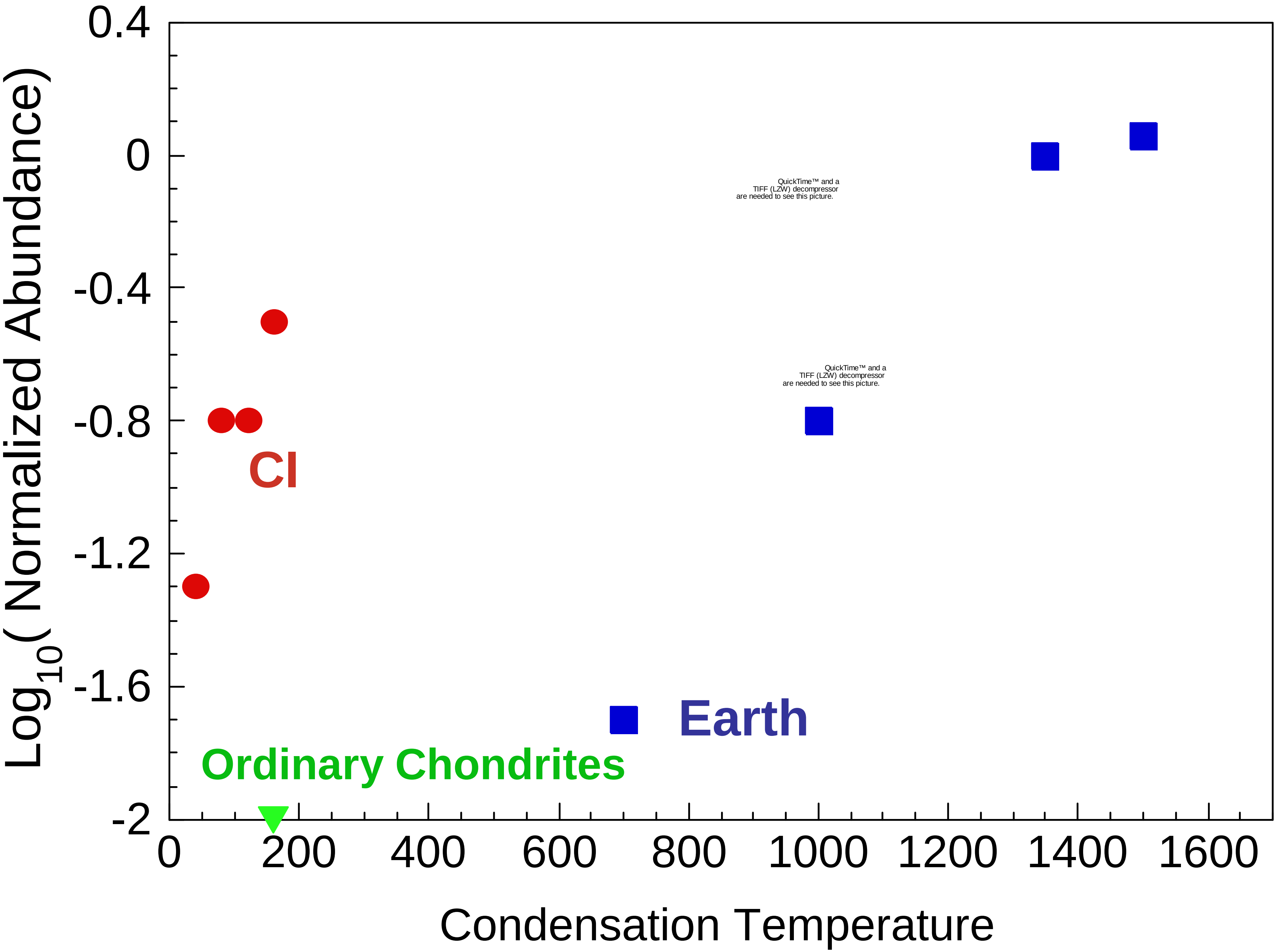
Q.Yin 2004


0.4
0
-0.4
-0.8
-1.2
-1.6
-2
0
200
400
600
800
1000
1200
1400
1600
Log10(Normalized Abundance)
Condensation Temperature
CI
Earth
Ordinary Chondrites
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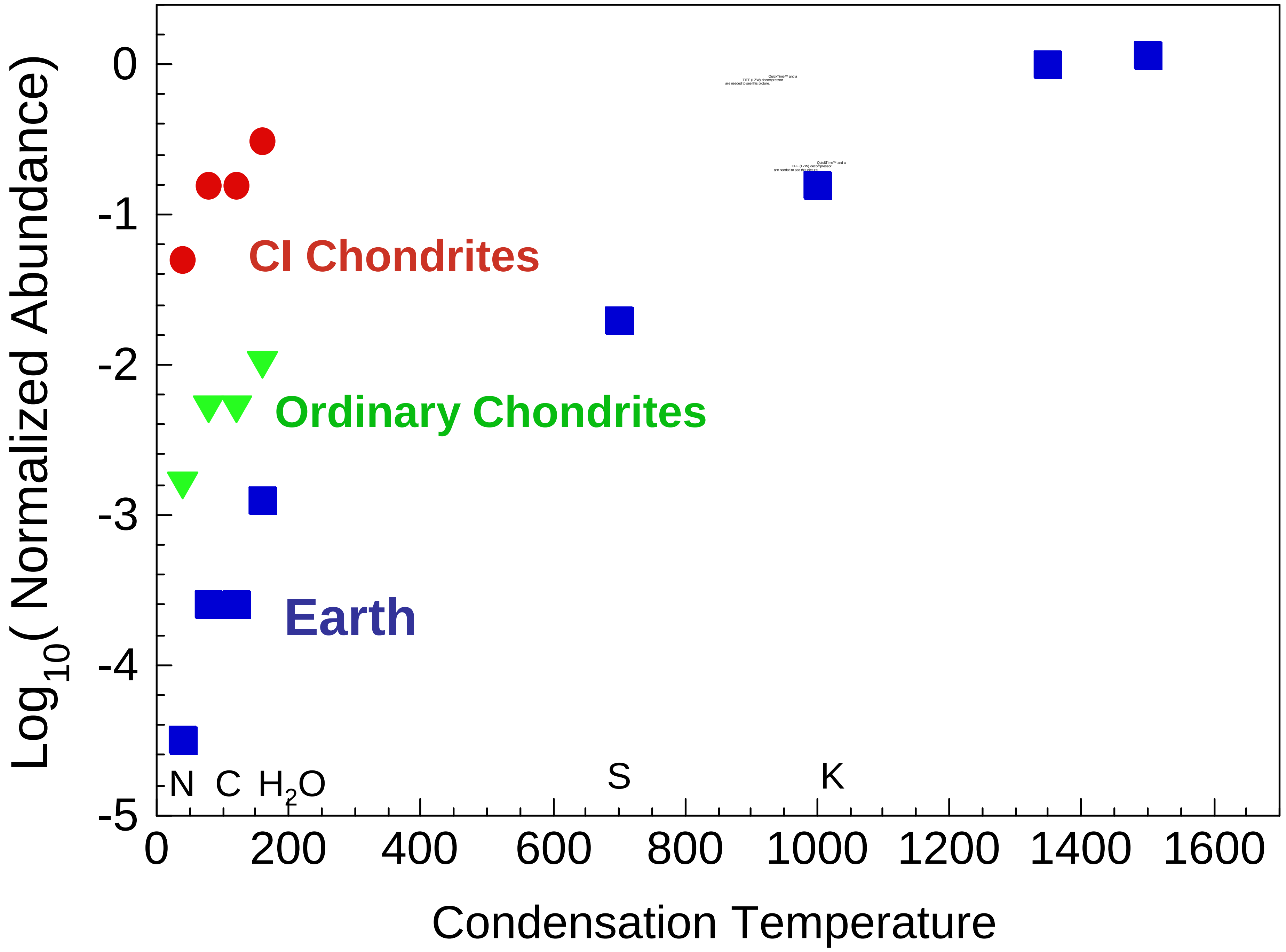
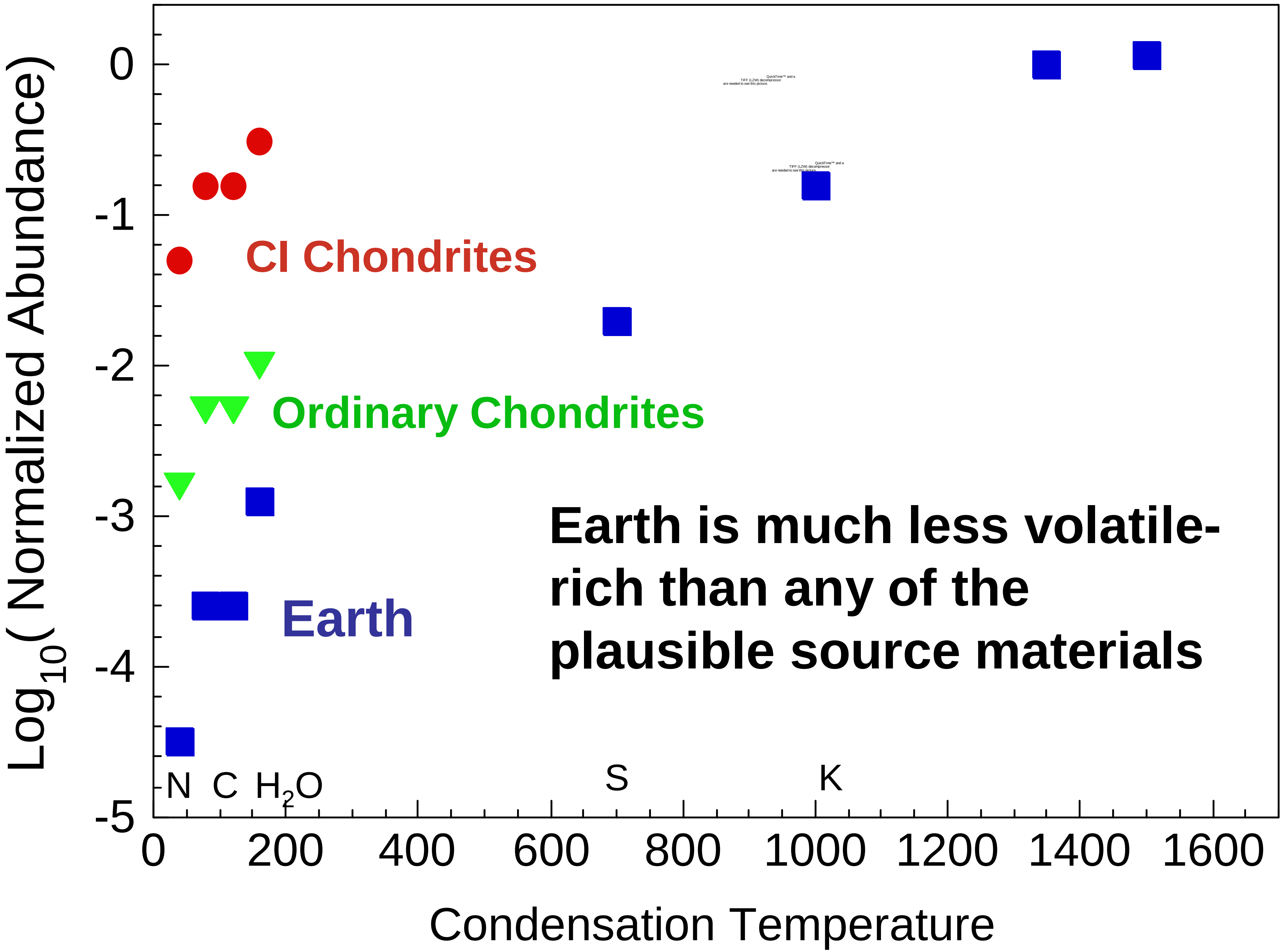

Log$_{10}$(Normalized Abundance)
0
-1
-2
-3
-4
-5
CI Chondrites
Ordinary Chondrites
Earth
N
C
H_2O
S
K
0
200
400
600
800
1000
1200
1400
1600
Condensation Temperature



Earth is much less volatile-rich than any of the plausible source materials

The Sources are Big. What about Escape?

Some Escape Processes

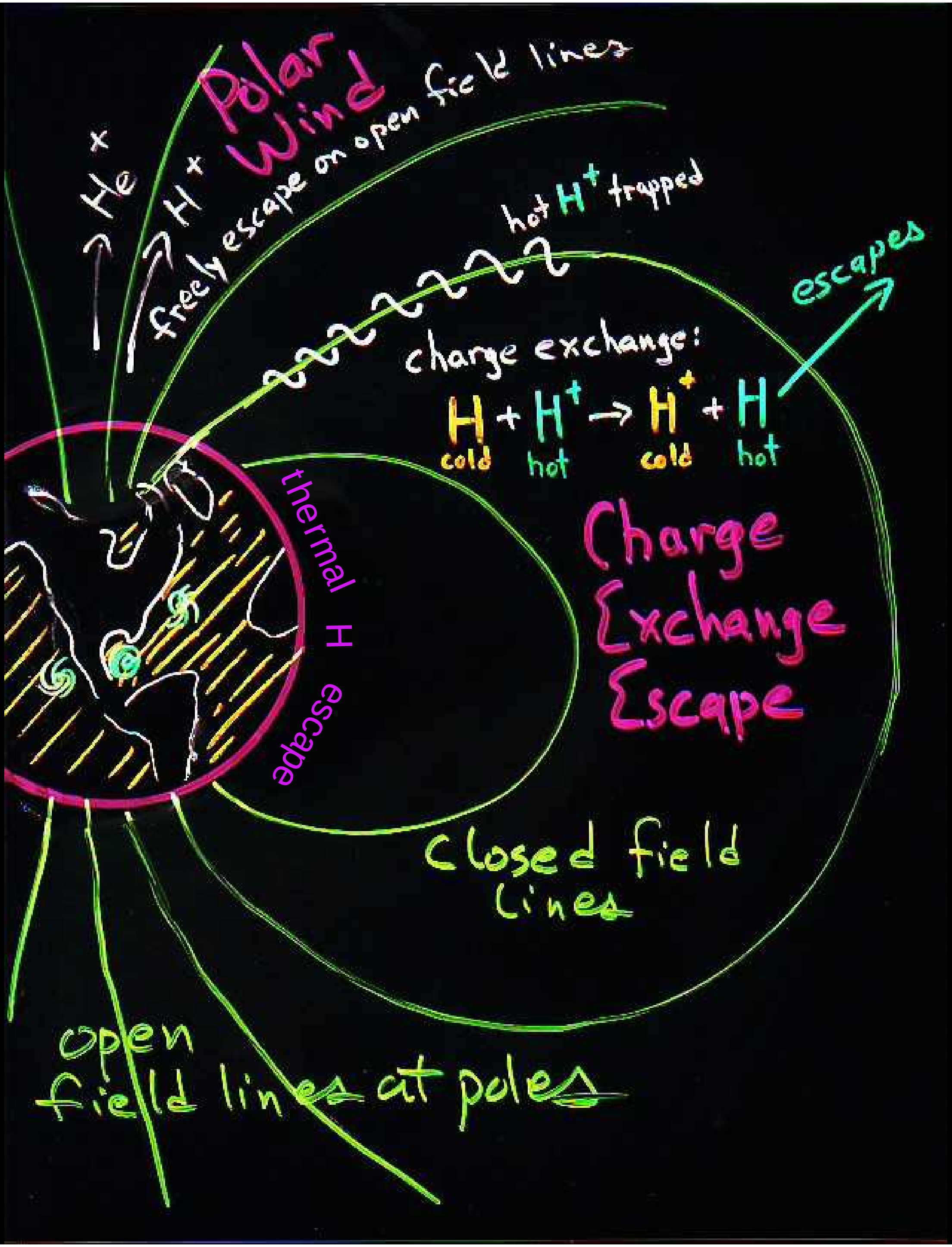
Thermal Escape

- Jeans escape. one molecule at a time. slow.
  - H on Earth, Mars
- hydrodynamic escape. Pressure gradient flow. fast.
  - solar wind, Pluto? Titan?? Ancient Venus, future Europa?
- “kinetic models.” post-Maxwellian “Jeans” escape. fast.
  - solar breeze, electrostatic polar wind, Titan?

Nonthermal Escape. one atom at a time. slow.

- charge exchange
  - H on Earth, Venus
- dissociative recombination
  - N, O, C on Mars
- solar wind sweeping, sputtering, etc.
  - Ar, O on Mars; S & O on Io; etc

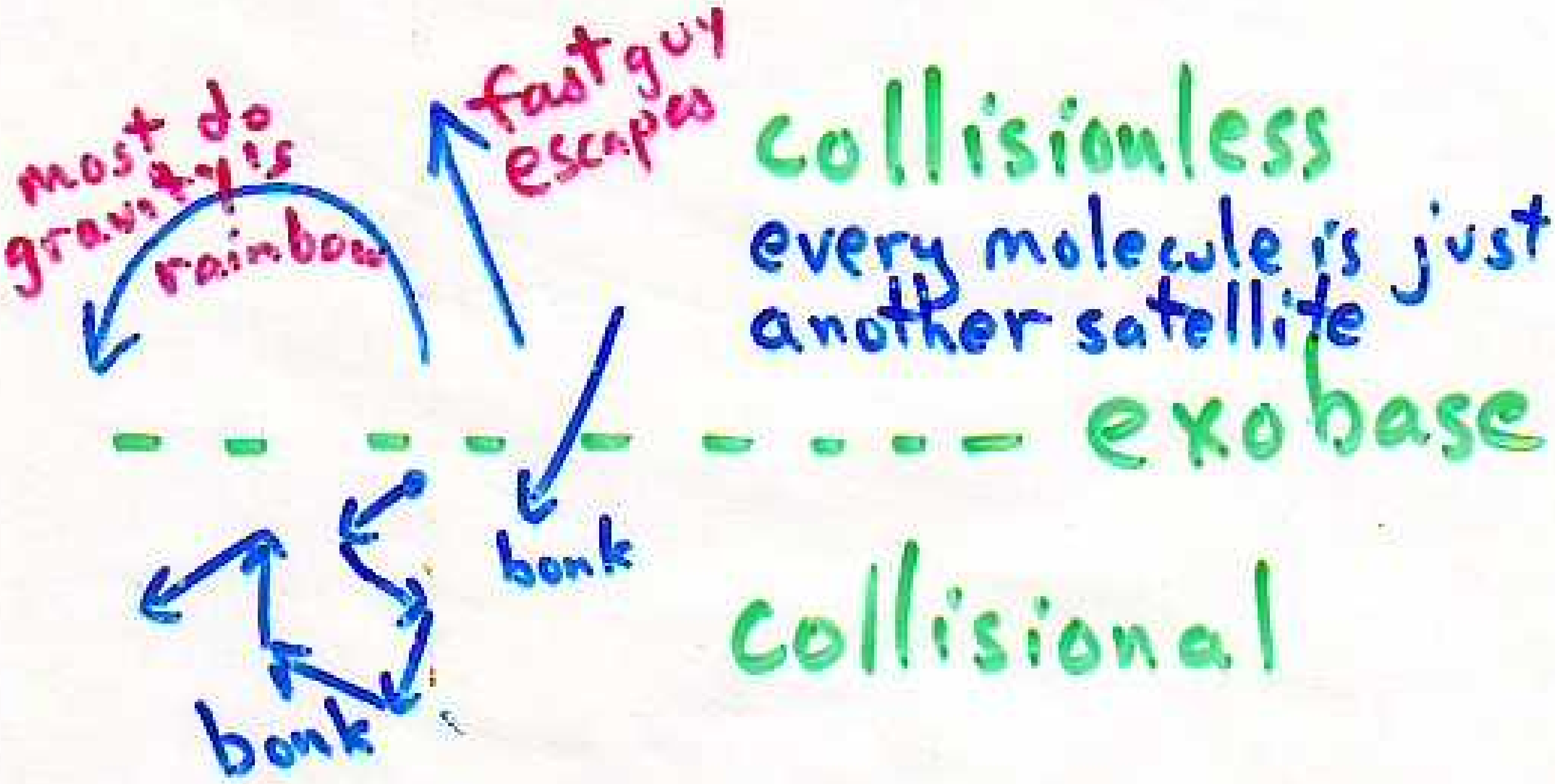
Impact Erosion could be fast



thermal H escape

Exobase (aka "critical level")

what goes up, may come down



collisionless

every molecule is just another satellite

exobase

collisional

Jeans Escape (thermal escape one atom at a time)

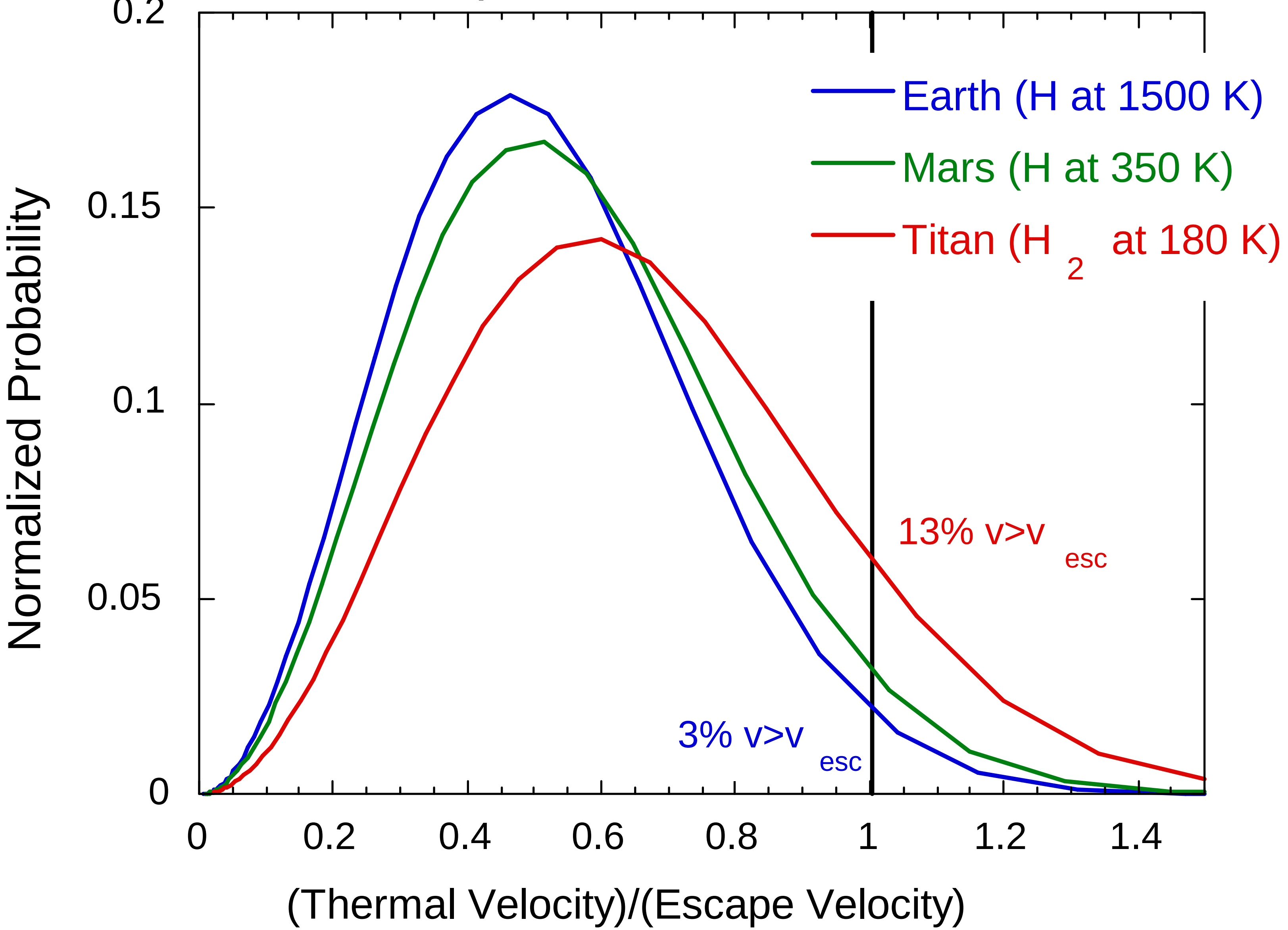
Jeans (1904) integrates the Maxwell-Boltzmann velocity distribution to obtain total flux of outbound atoms that exceed the escape velocity at the exobase

$$\phi_J = n_e\, a \left(1 + \frac{r_e}{H}\right) \exp\left(-\frac{r_e}{H}\right) \frac{B}{\sqrt{2\pi}} \ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

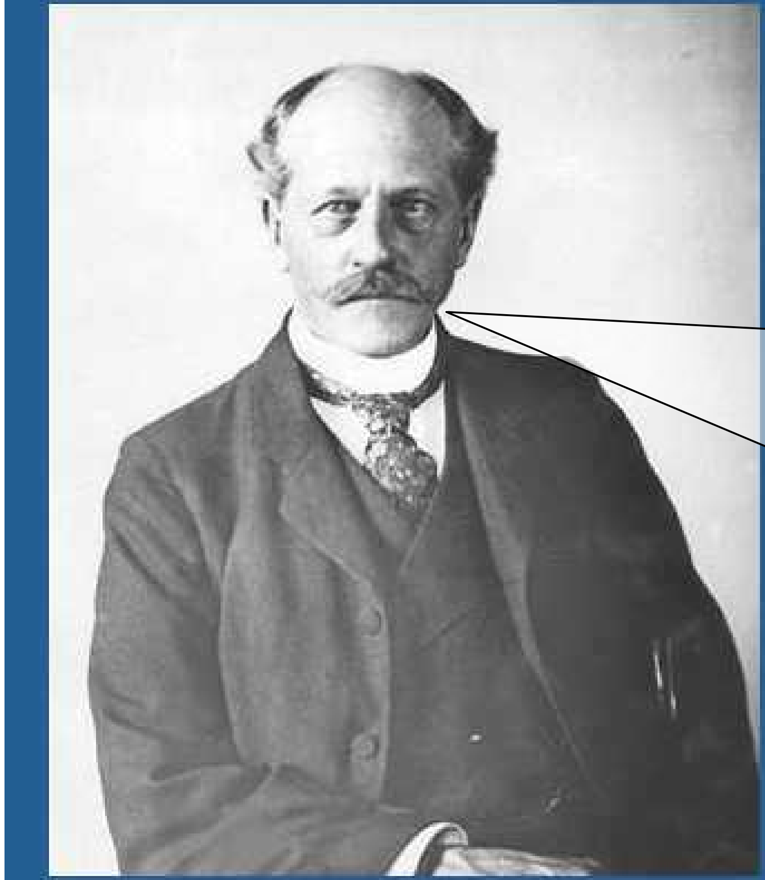
where n_e is the density at the exobase,
H is the scale height,
a is the isothermal sound speed, and
B is a factor of order unity.

$$\frac{r}{H} = \frac{GM}{a^2 r} = \frac{v_{\mathrm{esc}}^2}{2a^2} \approx \frac{\text{escape energy}}{\text{thermal energy}}$$

Jeans escape - the tail of the Maxwellian



And gases escape to space:



Our Plutocrat

"the maximum speed [a molecule] may attain Clerk-Maxwell deduced from the doctrine of chances to be seven-fold the average. What may happen to one, must eventually happen to all."

Bottlenecks to thermal escape

- Condensation
  - water on Earth at tropopause
  - water on Venus in sulfuric acid
  - water on Mars at the surface
  - methane on Titan?
- Solar Energy
- Photolysis (chemical creation of H, H_2)
  - methane to H_2 on Titan?
- Diffusion
  - H, H_2 on Earth, Titan, Mars
  - CH_4 on Titan?

Energy limited escape (the blunt instrument)

- pretty simple - all EUV energy goes into escape.

this applies if there is a lot of H in the atmosphere

$$\frac{GM \times \dot{M}_{\mathrm{EL}}}{R} = \epsilon F_{\mathrm{EUV}} \times \pi R^2$$

- today solar EUV flux at Earth is ~3 erg/cm^2/s. The heating efficiency is between 15-60%. The current energy-limited flux would be ~8x10^{13} g/yr,
- or ~3x10^{11} H atoms cm^{-2} s^{-1}

The diffusion-limited flux

This applies when escape from the exobase is easy. Escape flux is then limited by how quickly the H can diffuse through the thermosphere

$$\phi_i < \phi_{\mathrm{lim}} \equiv b_{ia}\left(\frac{1}{H_a} - \frac{1}{H_i}\right)\frac{f_i}{1+f_i}$$

where $f_i \equiv \frac{n_i}{n_a}$ (=mixing ratio if f_i is small)

and b_{ia} is the binary diffusion coefficient [$\mathrm{cm}^{-1}\mathrm{s}^{-1}$]
= [thermal velocity] ÷ [collision cross section]

between two species i and a

Evaluated for Earth and N_2:

$$\phi_{\mathrm{lim}} = 2.5\times 10^{13}\, f_{\mathrm{tot}}(\mathrm{H})\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Hydrodynamic escape

continuity

$$\rho u r^2 = \text{constant}$$

momentum

$$u\frac{\partial u}{\partial r} + \frac{1}{\rho}\frac{\partial p}{\partial r} = -\frac{GM}{r^2}$$

isothermal + perfect gas

(combines energy eqn and eqn of state)

$$p = a^2\rho$$

Hydrodynamic escape

arrange as one equation for flow velocity u:

$$\left(u^2 - a^2\right) \frac{1}{u} \frac{\partial u}{\partial r} = \frac{2a^2}{r} - \frac{GM}{r^2}$$

This is the isothermal solar wind equation.

There is a critical distance r_c where both sides of the equation equal zero.

Hydrodynamic escape

$$\left(u^2 - a^2\right) \frac{1}{u} \frac{\partial u}{\partial r} = \frac{2a^2}{r} - \frac{GM}{r^2}$$

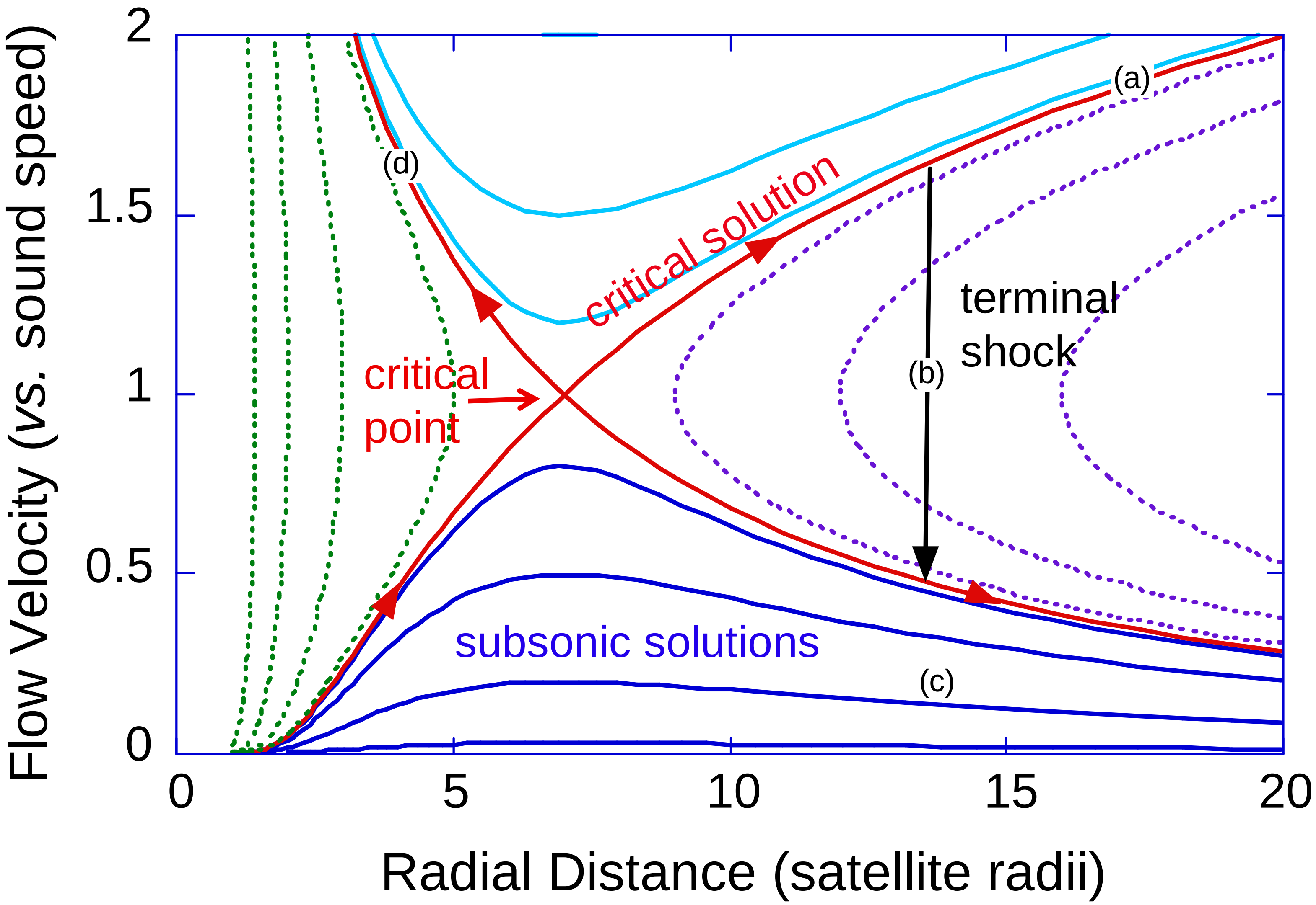
The unique “critical solution” is the one where

$$u_c = a \quad \mathrm{at} \quad r_c = \frac{GM}{R^2}$$

The mean flow *u* increases indefinitely and pressure goes to zero as *r* goes to infinity.

Equations like this one describe thermal escape when escape is vigorous.

Hydrodynamic escape: a constructed example



Isothermal planetary wind. The specific example shown here is for Europa held at 301.6 K for which $R_c = 7R_s$. The sound speed is 373 m/s.

Fractionation during hydrodynamic escape

The relative escape velocity of a heavy species to H is

$$w_j = x_j w_{\mathrm{H}}$$

where the fractionation factor

$$x_j = 1 - \frac{g b_{j\mathrm{H}}}{\phi_{\mathrm{H}} kT}\left(m_j - m_{\mathrm{H}}\right) \qquad \left(0 \le x_j < 1\right)$$

The remaining *j* scales with the remaining Hydrogen as

$$\frac{N_j(t)}{N_j(0)} = \left(\frac{N_{\mathrm{H}}(t)}{N_{\mathrm{H}}(0)}\right)^{x_j}$$

Rayleigh fractionation

Fractionation during hydrodynamic escape

The relative escape velocity of a heavy species to H is

$$w_j = x_j w_{\mathrm{H}}$$

where the fractionation factor

$$x_j = 1 - \frac{g b_{j\mathrm{H}}}{\phi_{\mathrm{H}} k T}\left(m_j - m_{\mathrm{H}}\right) \qquad \left(0 \le x_j < 1\right)$$

The resulting fractionation between two isotopes of the same element is approximately linear in mass

$$\frac{N_i(t)}{N_i(0)} \div \frac{N_j(t)}{N_j(0)} = \left(\frac{N_{\mathrm{H}}(t)}{N_{\mathrm{H}}(0)}\right)^{x_i - x_j}$$

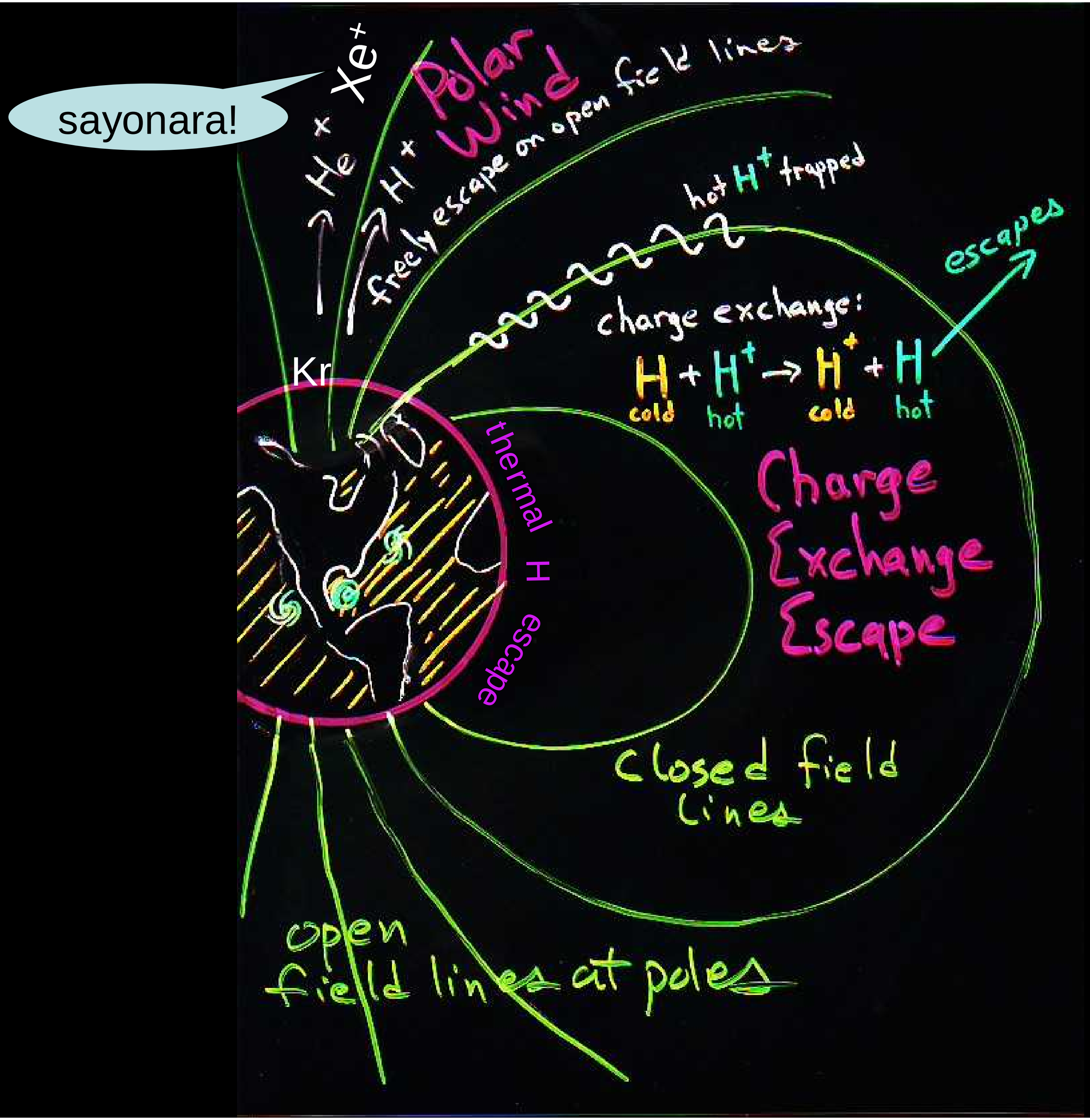
Hydrodynamic H Escape has been suggested as cause of Xe fractionation many times, beginning with Sekiya et al 1981.

Because Xe is the heaviest gas in the atmosphere, this should happen to everything else in the atmosphere.

But Kr and Ar are not strongly mass fractionated.

A possibility is that Xe is present as Xe^+, because Xe is the only noble gas that ionizes more easily than H.

The huge cross-section of Coulomb interaction allows Xe^+ to be dragged along open magnetic field lines by escaping H^+


sayonara!
Xe+
He+
H+
Polar Wind
freely escape on open field lines
hot H+ trapped
charge exchange:
H + H+ → H+ + H
cold hot cold hot
escapes
Kr
Charge Exchange Escape
thermal H escape
Closed field lines
open field lines at poles

Are atmospheres determined by escape?

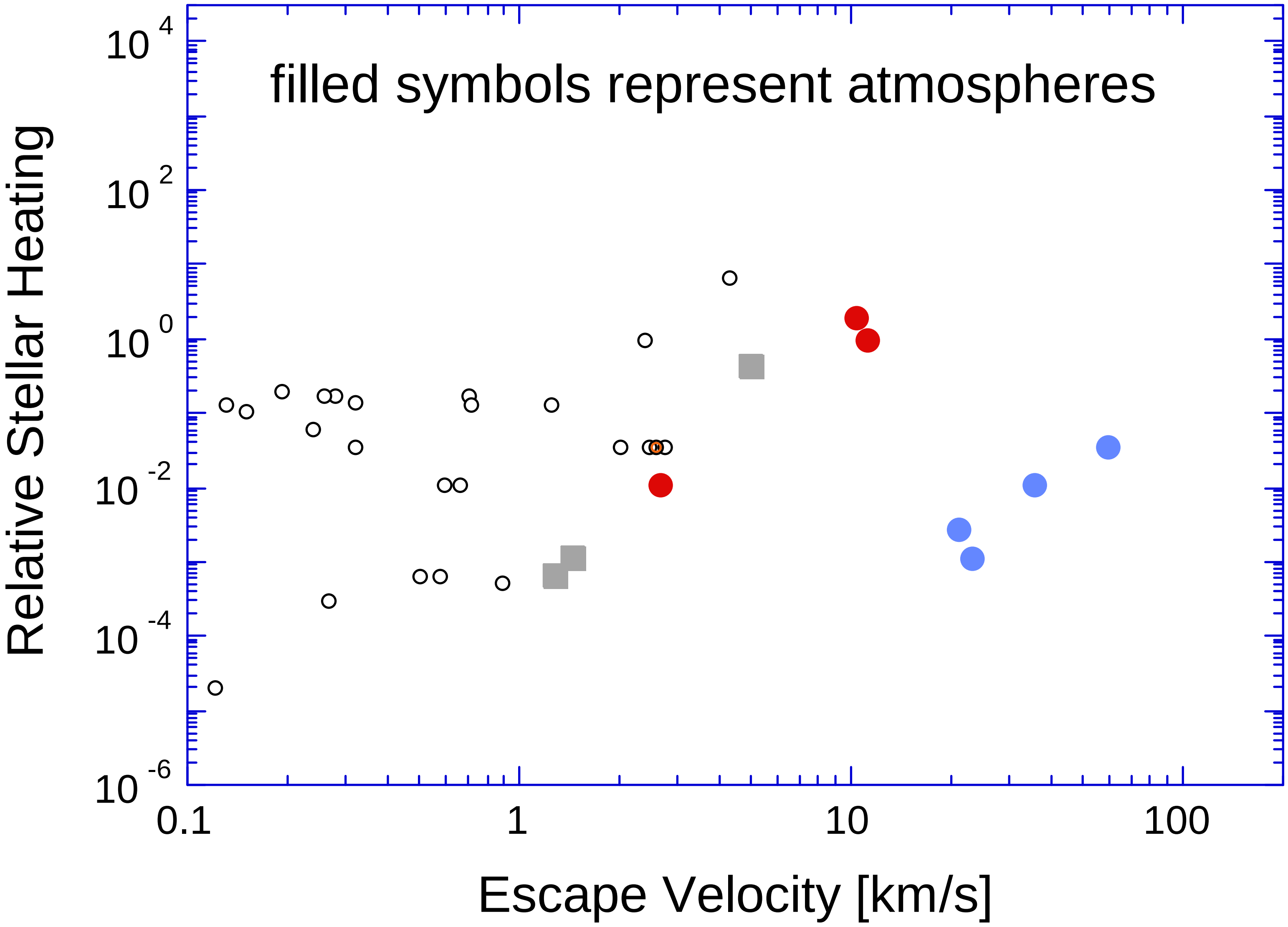
Big Picture: plot Insolation against escape velocity for all planets

Insolation measures how strongly the Sun attacks the atmosphere.

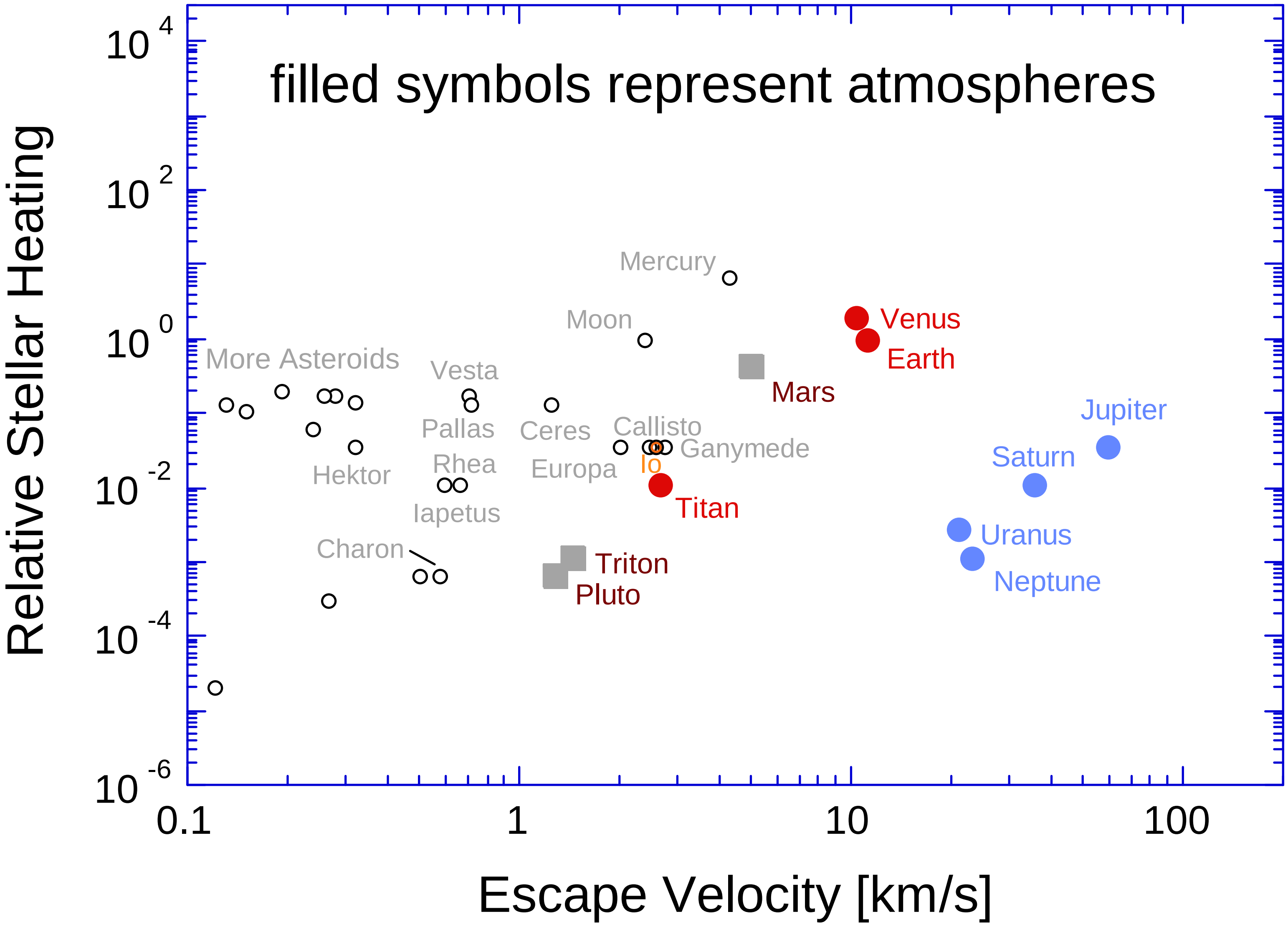
examples:
- UV or X-ray heating
- Solar Wind

Escape velocity is a measure of how strongly a planet can hold its volatiles

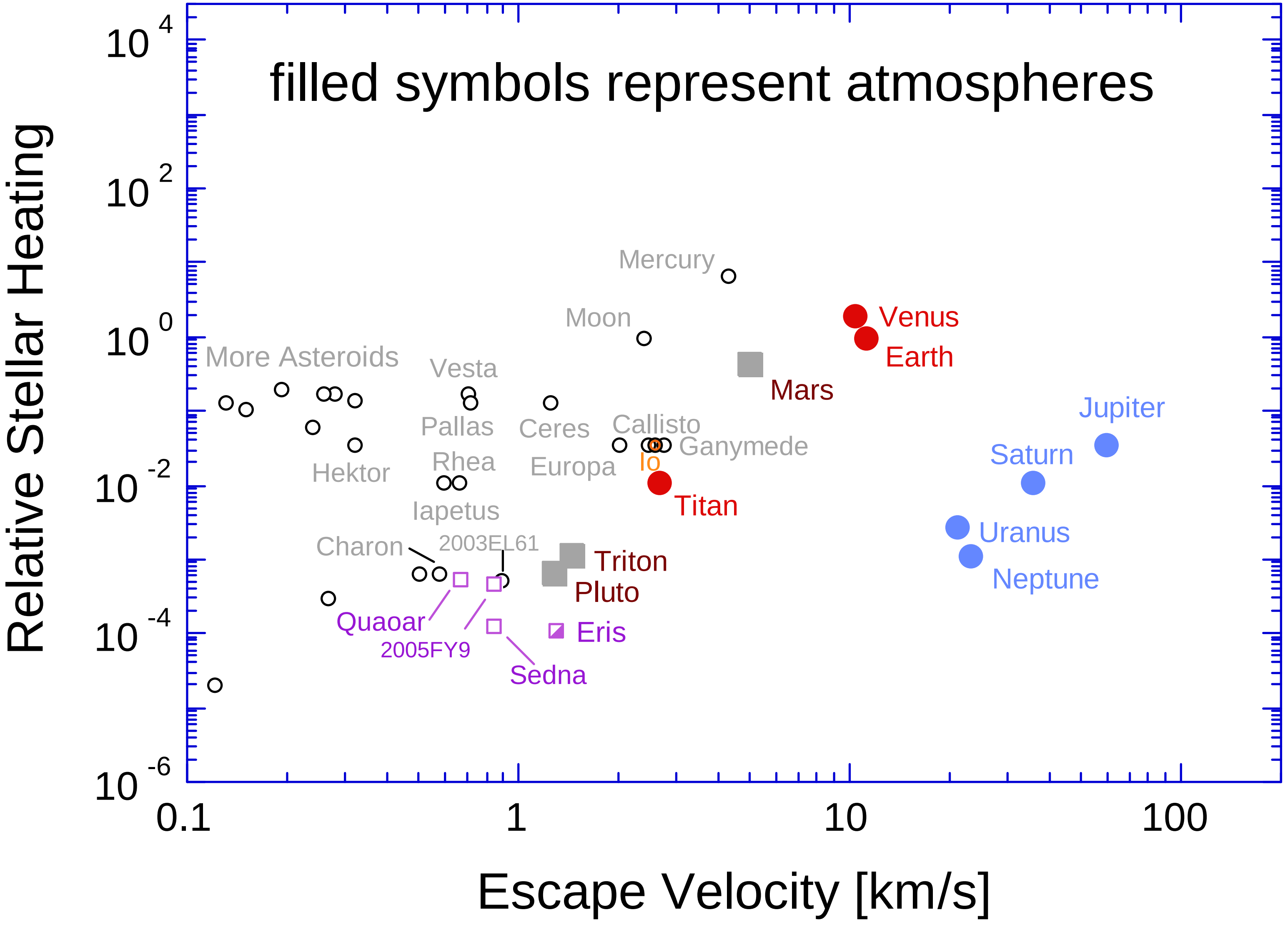
Our Solar System



Our Solar System

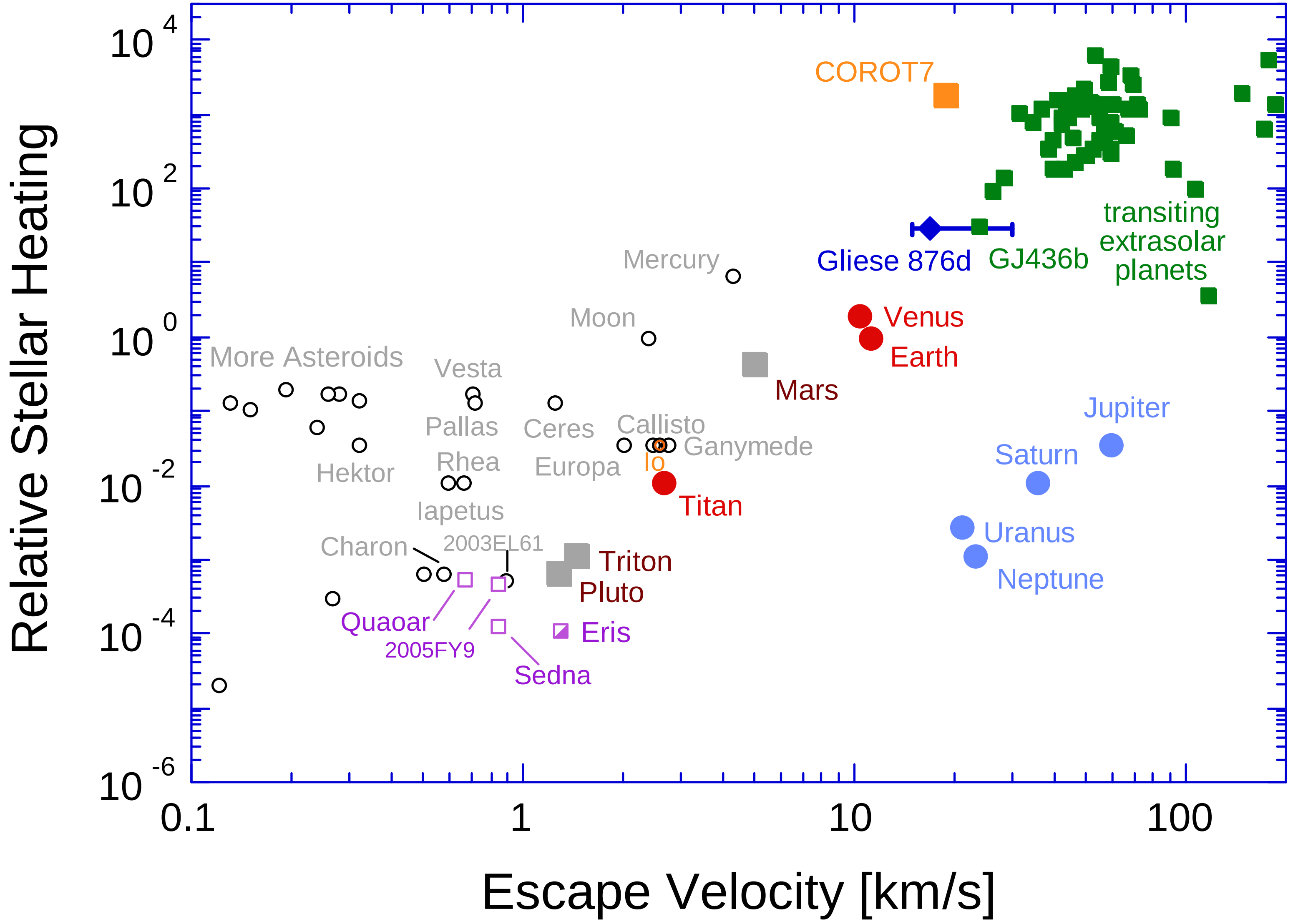


Our Solar System

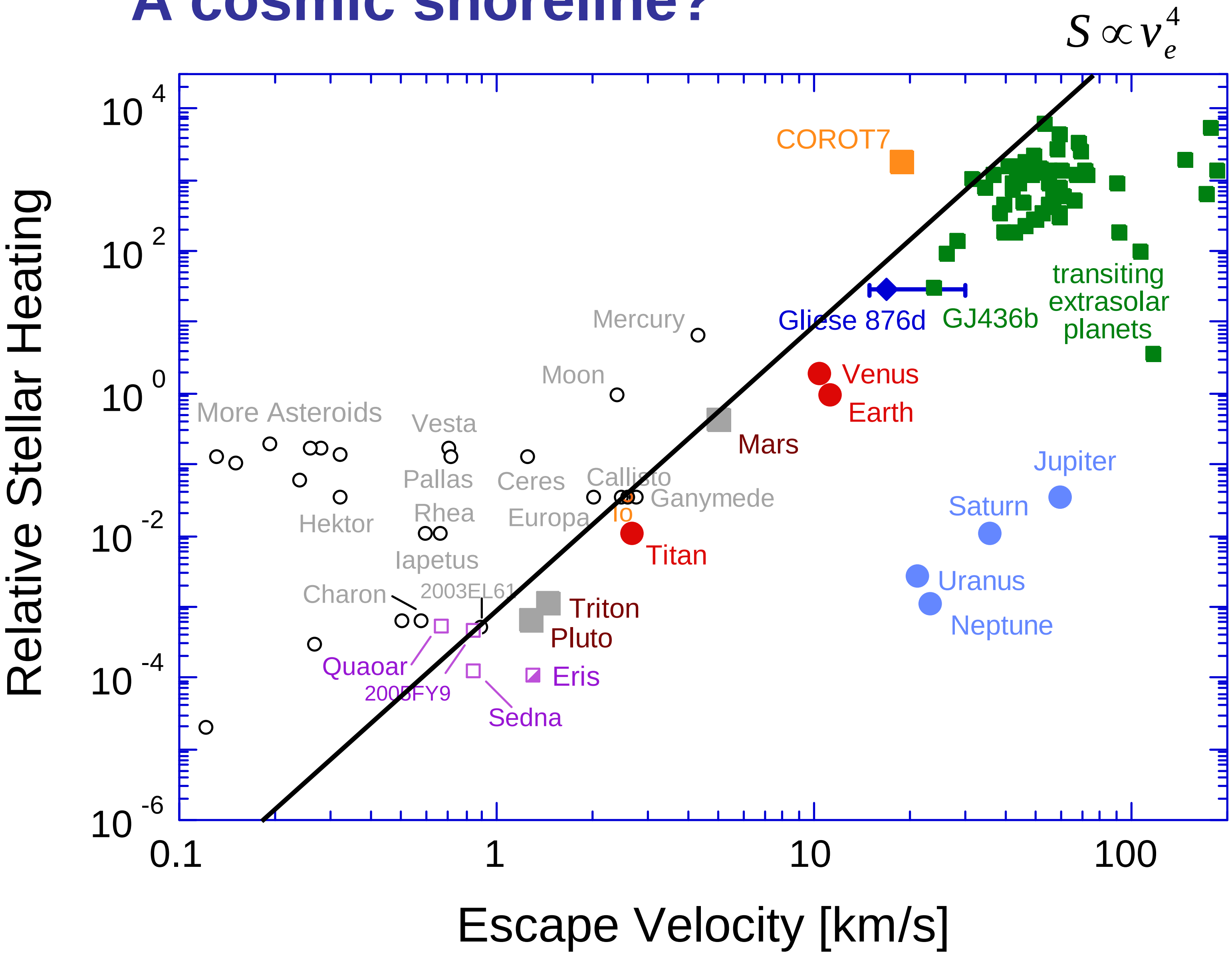


filled symbols represent atmospheres

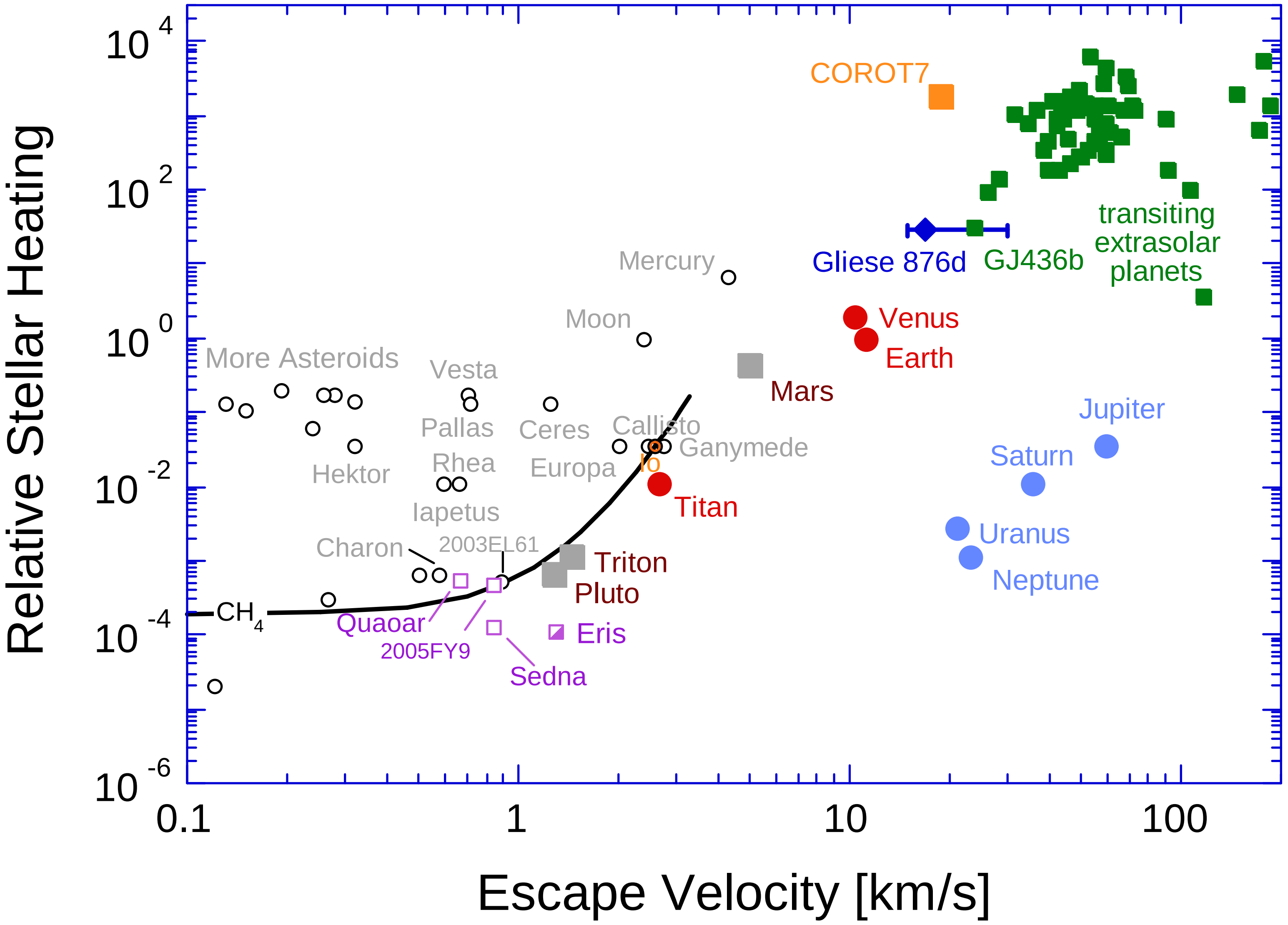
add the transiting extrasolar planets



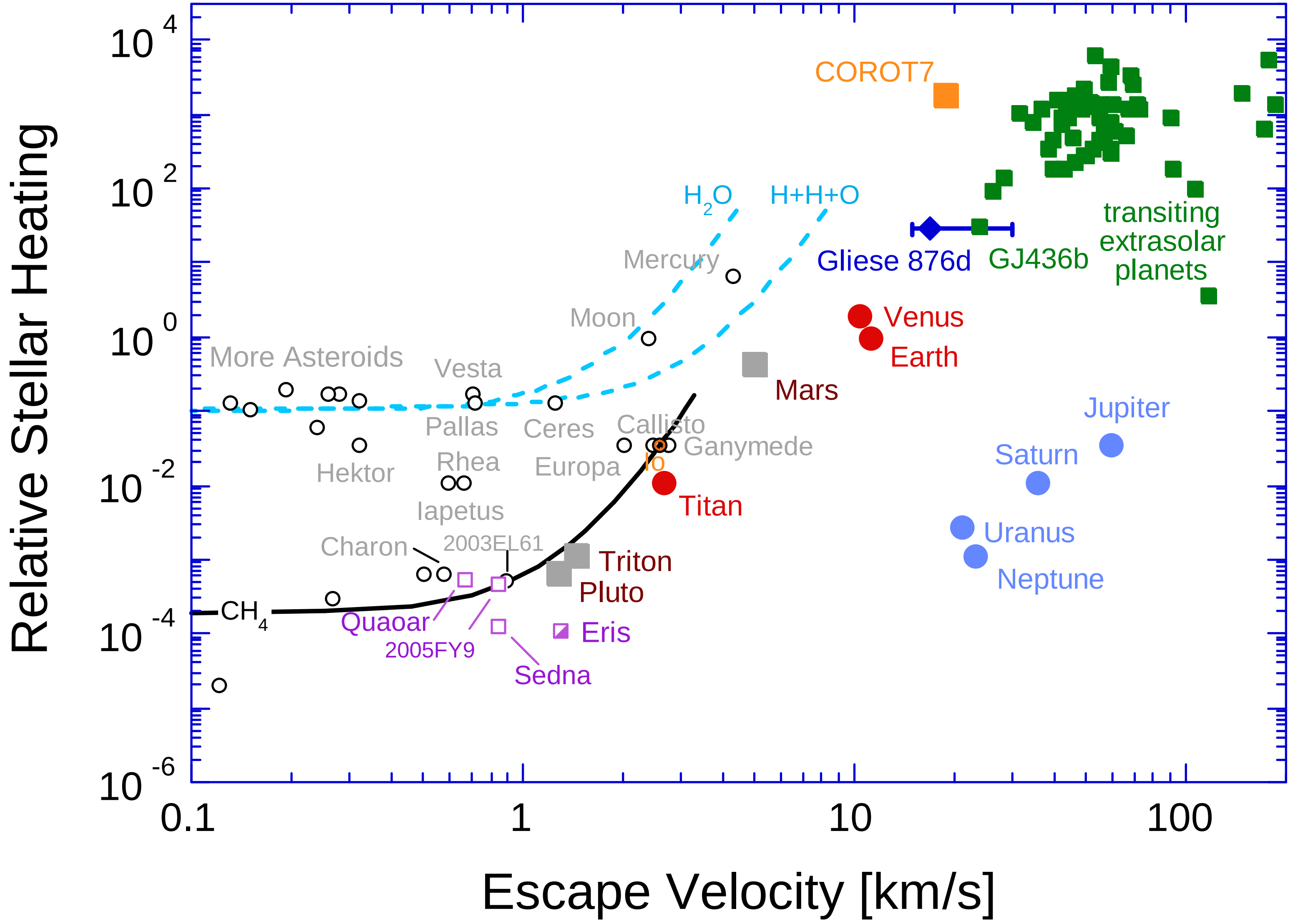
A cosmic shoreline?



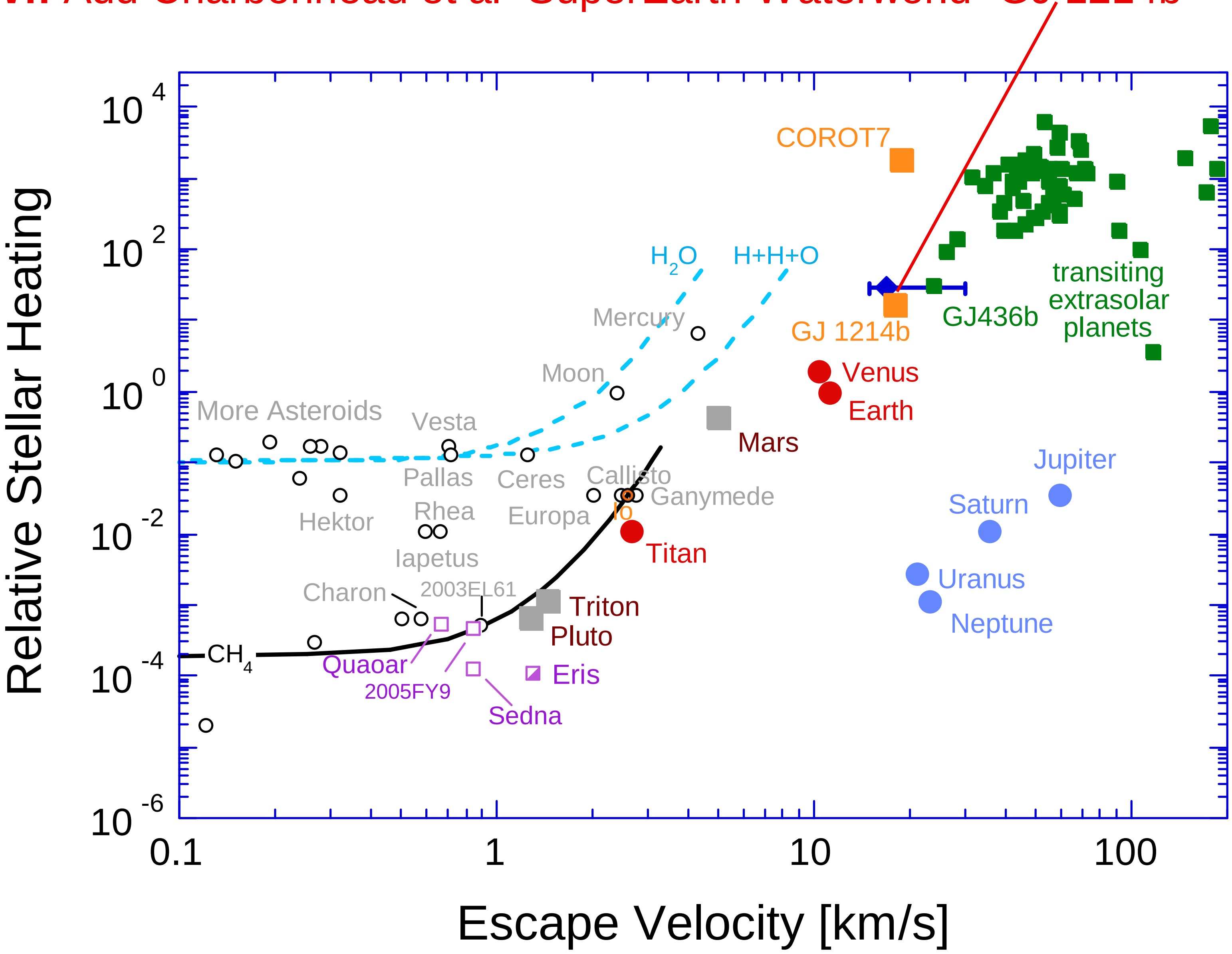
e.g., 5 Gyr lifetimes for evaporating Methane planets [cf Schaller and Brown 2007]



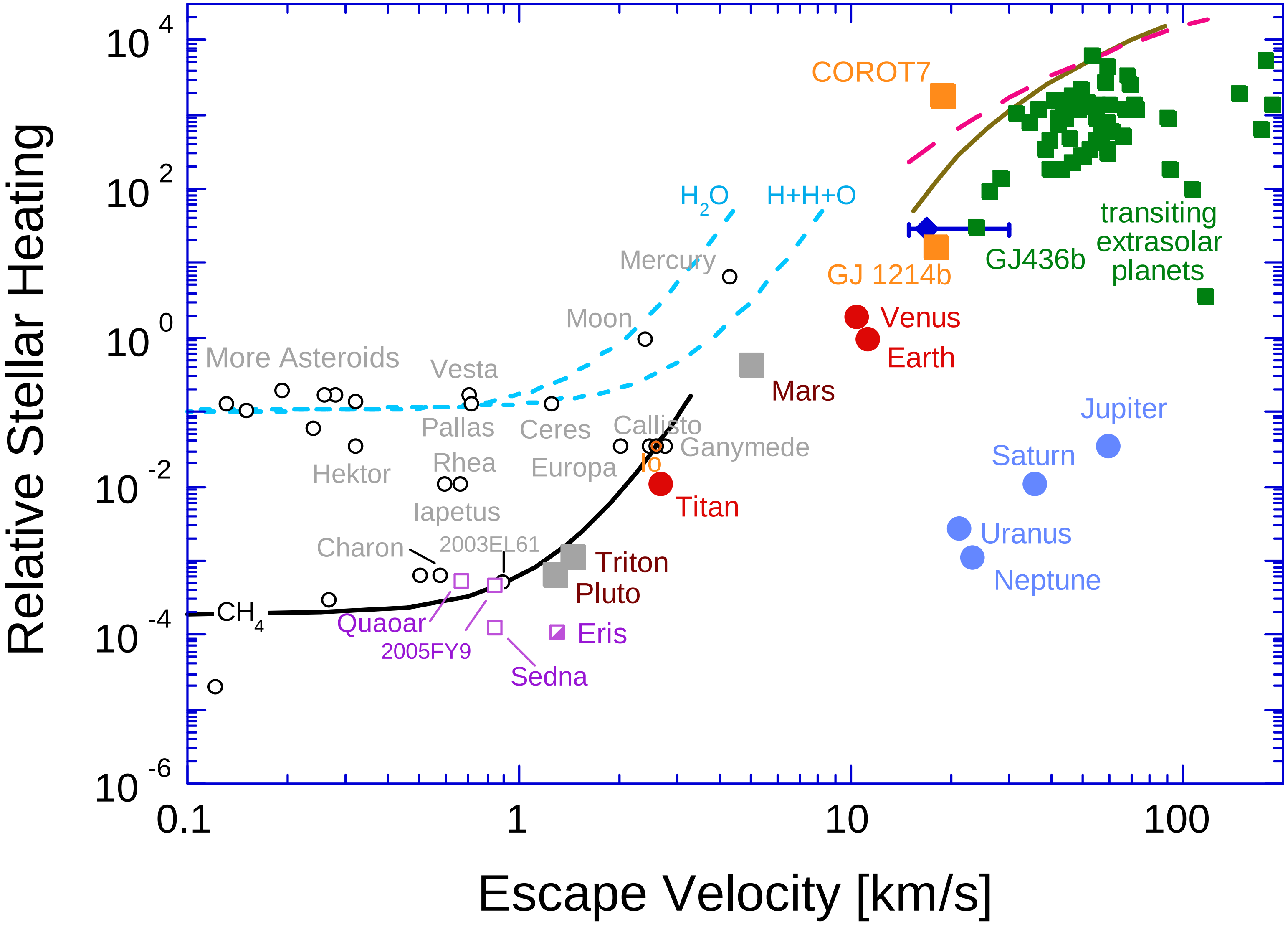
The same thing doesn’t work as well for water ice



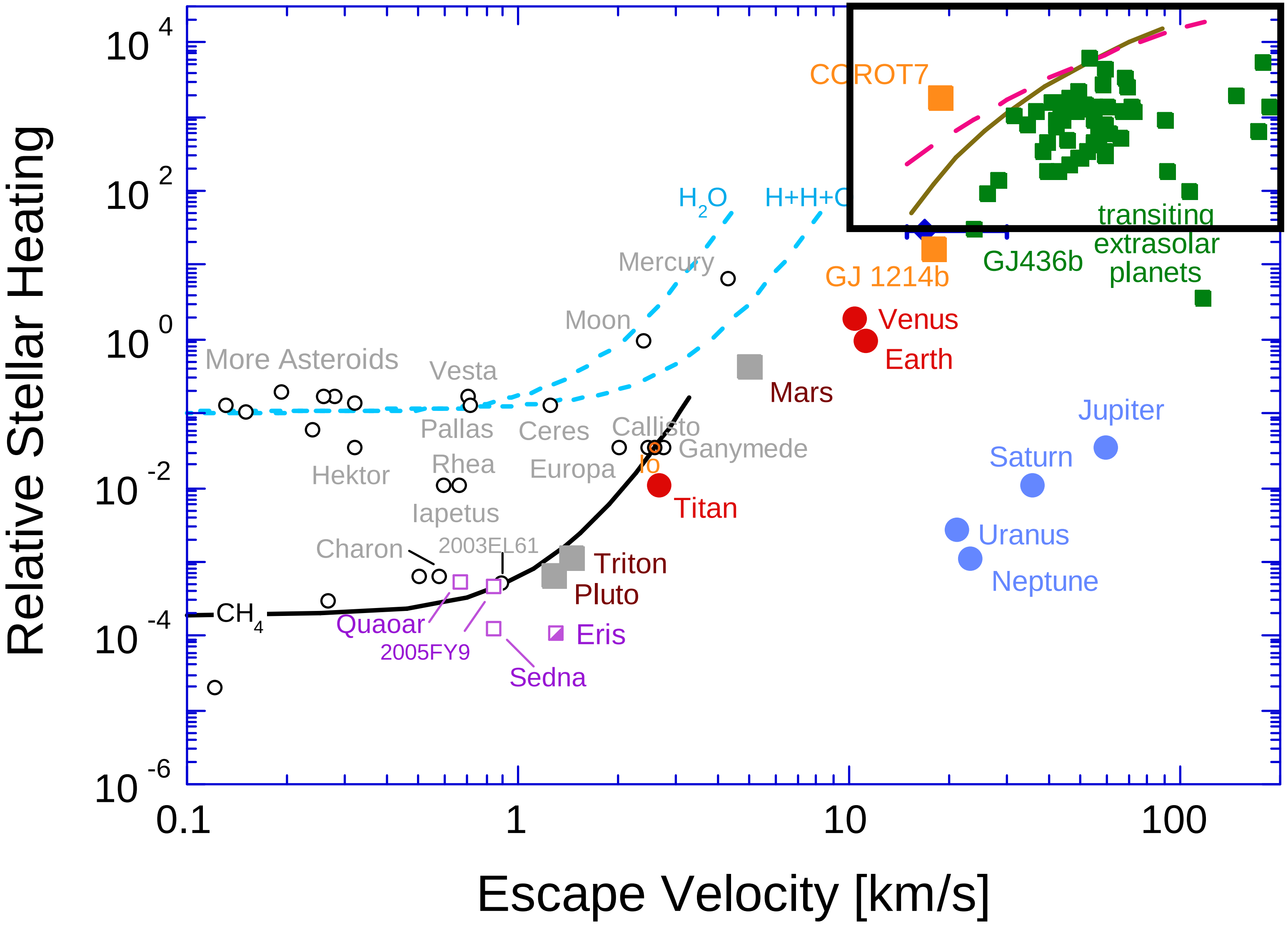
NEW!! Add Charbonneau et al “SuperEarth-Waterworld” GJ 1214b



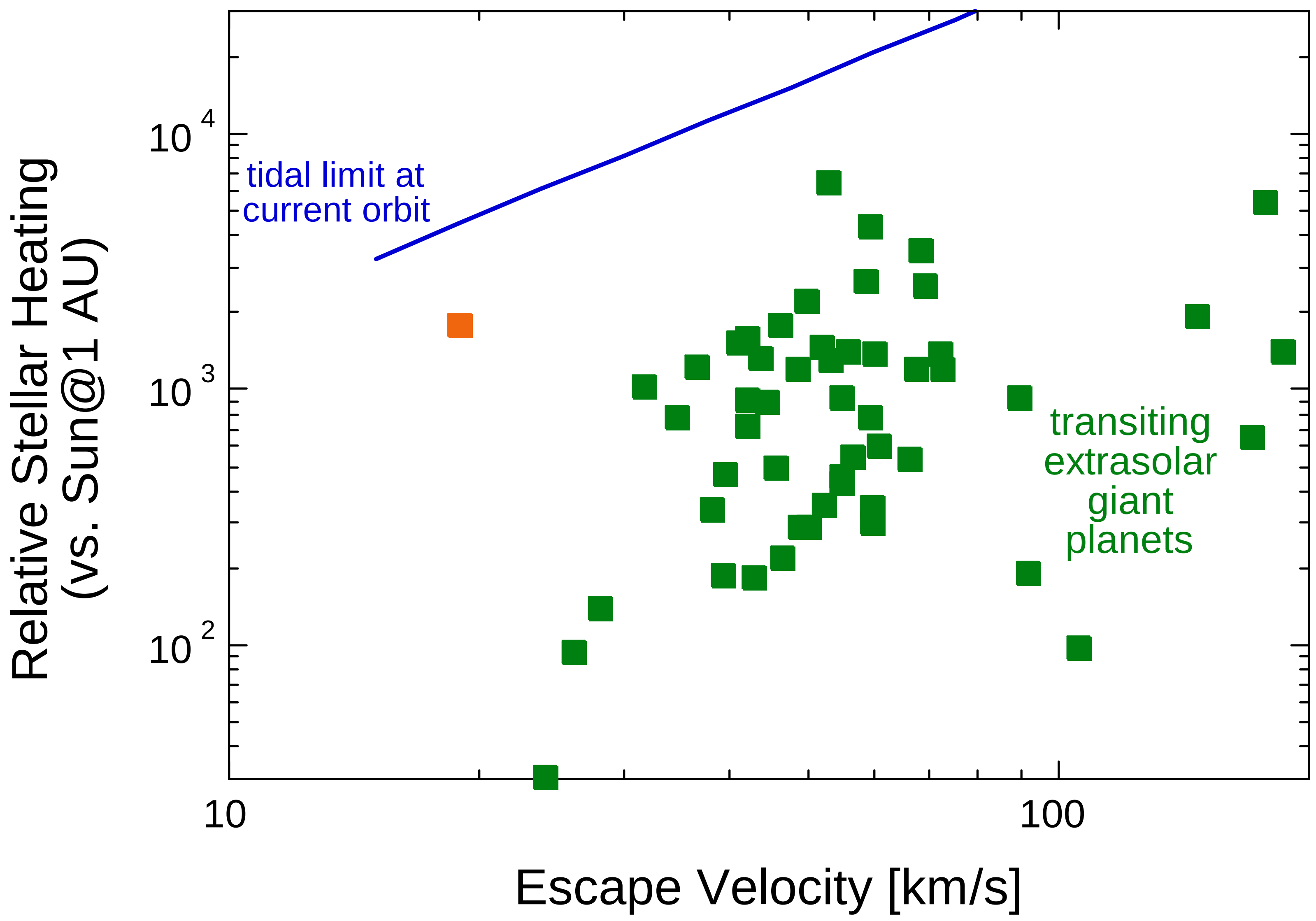
Hydrodynamic Thermal escape can also be applied to giant planets



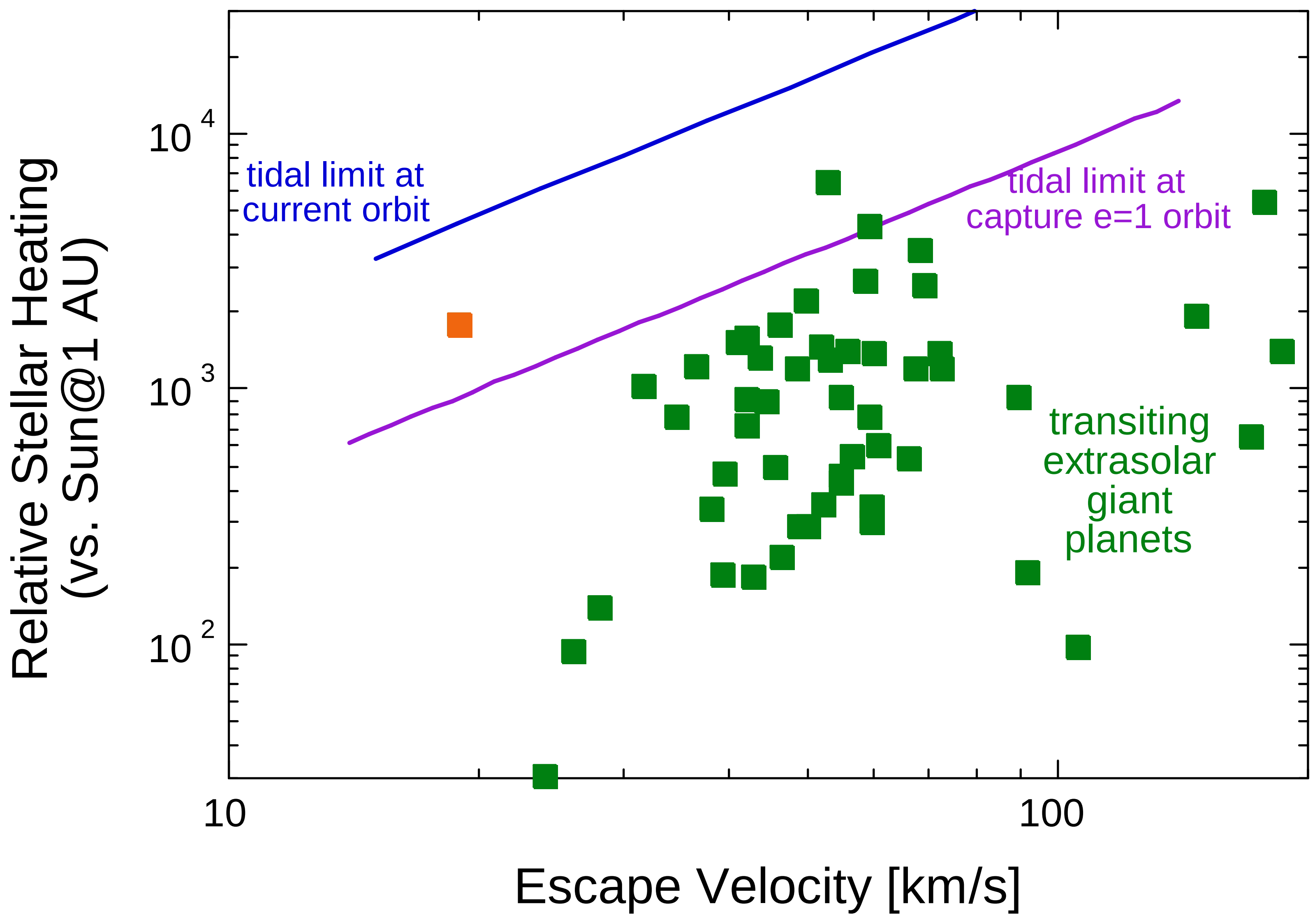
Hydrodynamic Thermal escape can also be applied to giant planets



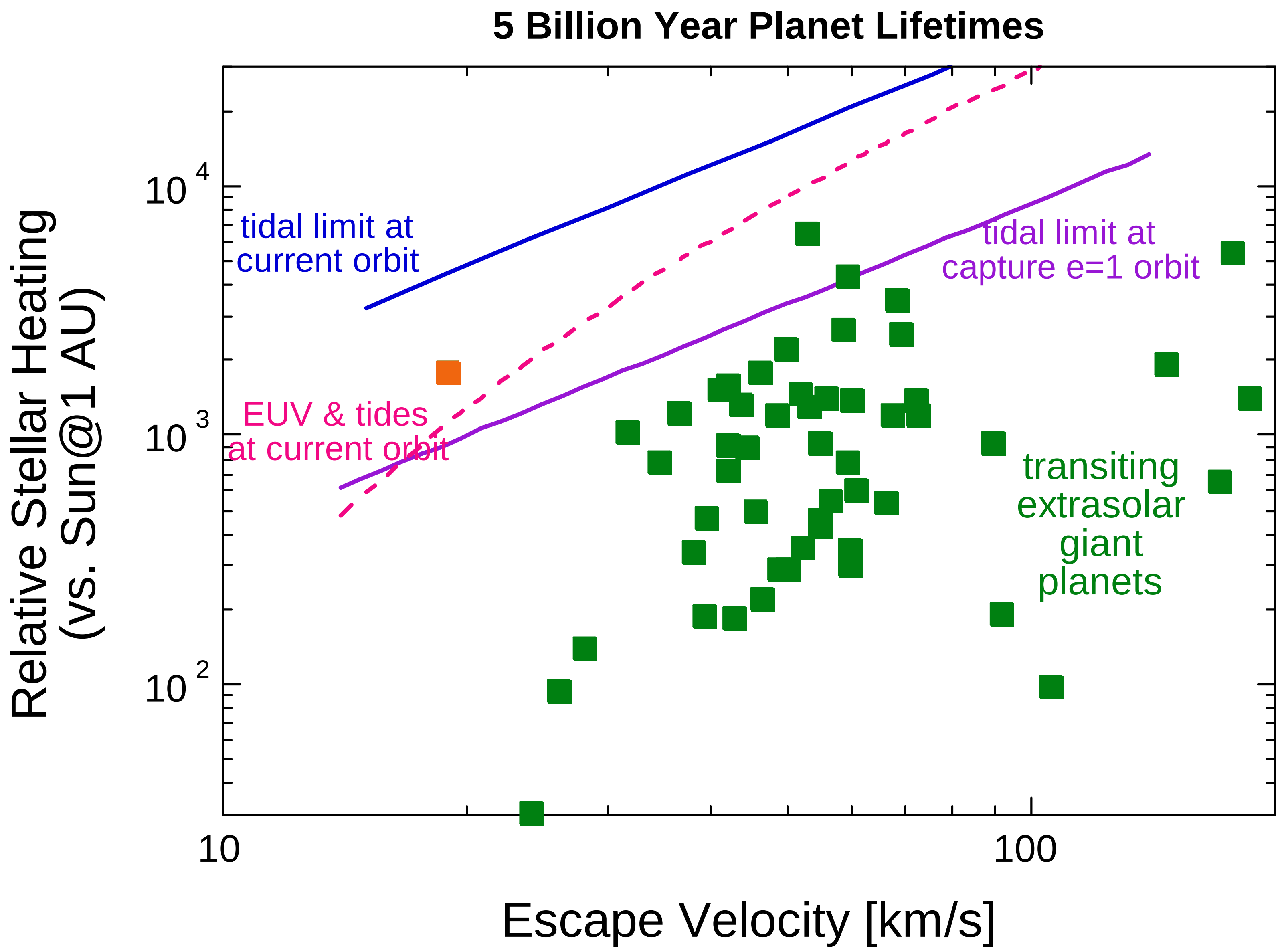
Tidal disruption (Roche Limit) does not work for current orbits



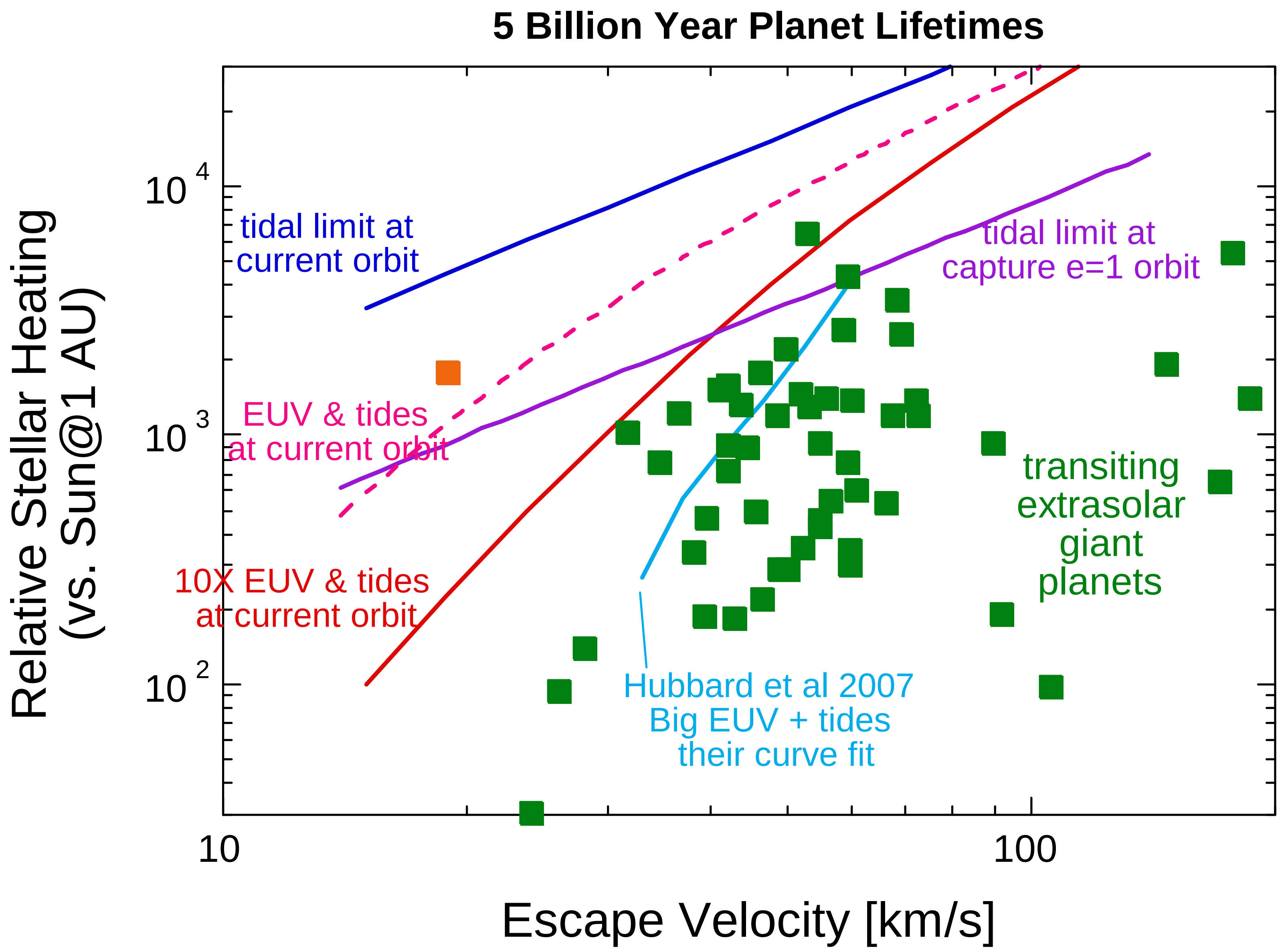
but it does work well for very elliptical capture orbits



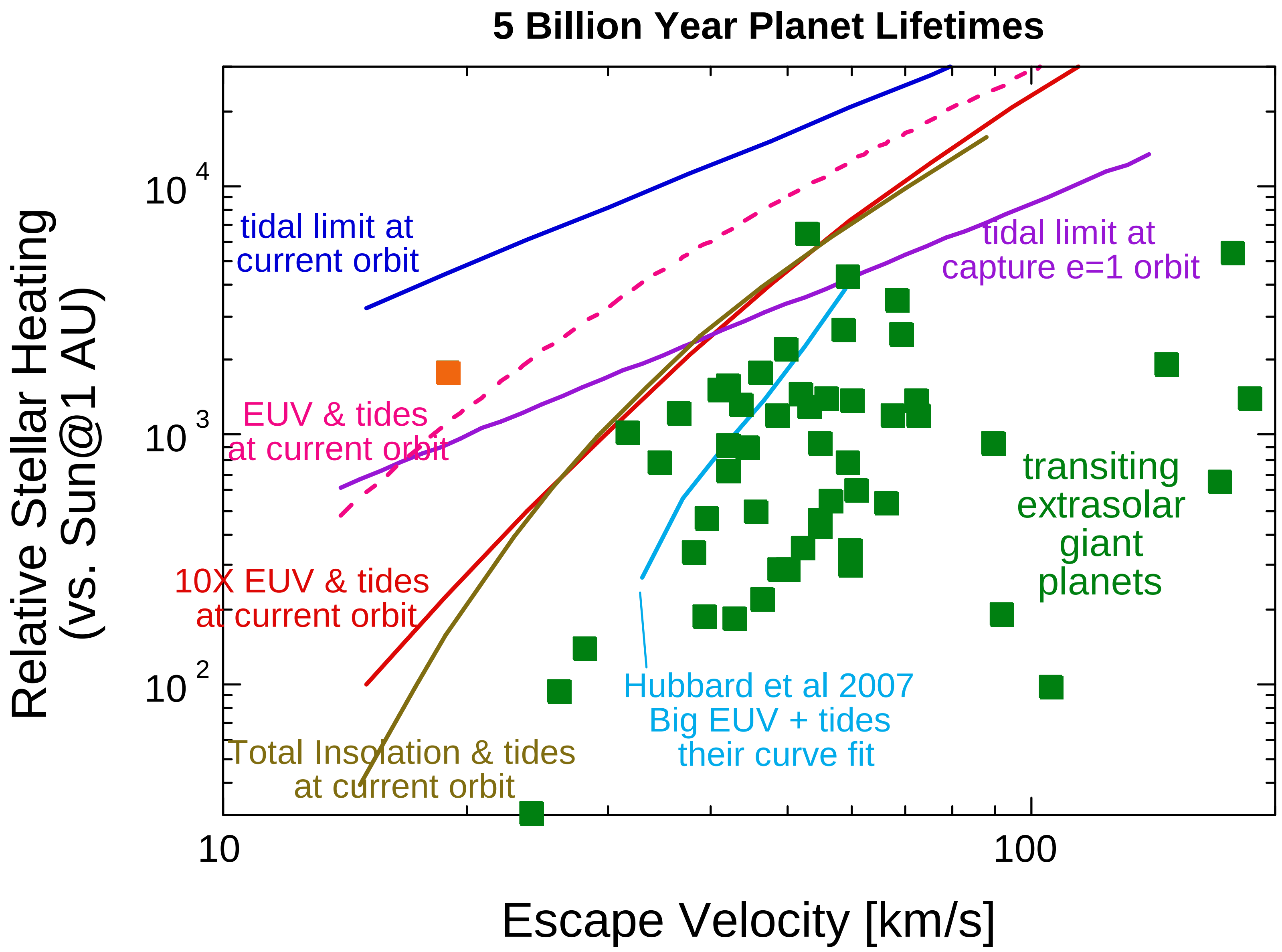
EUV-driven thermal escape can supplement tides

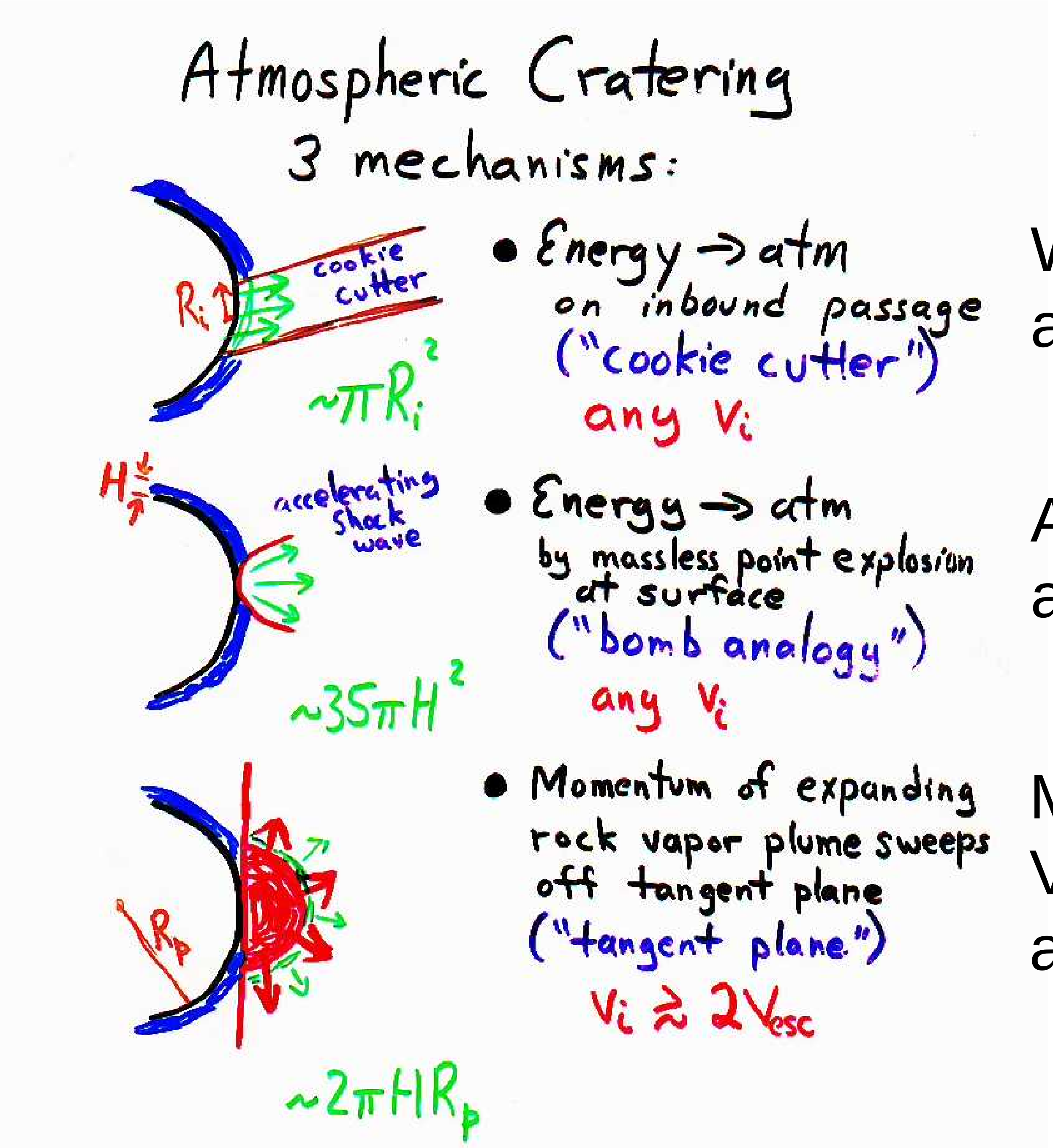


especially early when EUV was big and the planets puffy



but the planets may also be thermally unstable, EUV or no





Atmospheric Cratering
3 mechanisms:

- Energy → atm on inbound passage ("cookie cutter") any V_i

$\sim \pi R_i^2$

Walker's approximation

- Energy → atm by massless point explosion at surface ("bomb analogy") any V_i

$\sim 35\pi H^2$

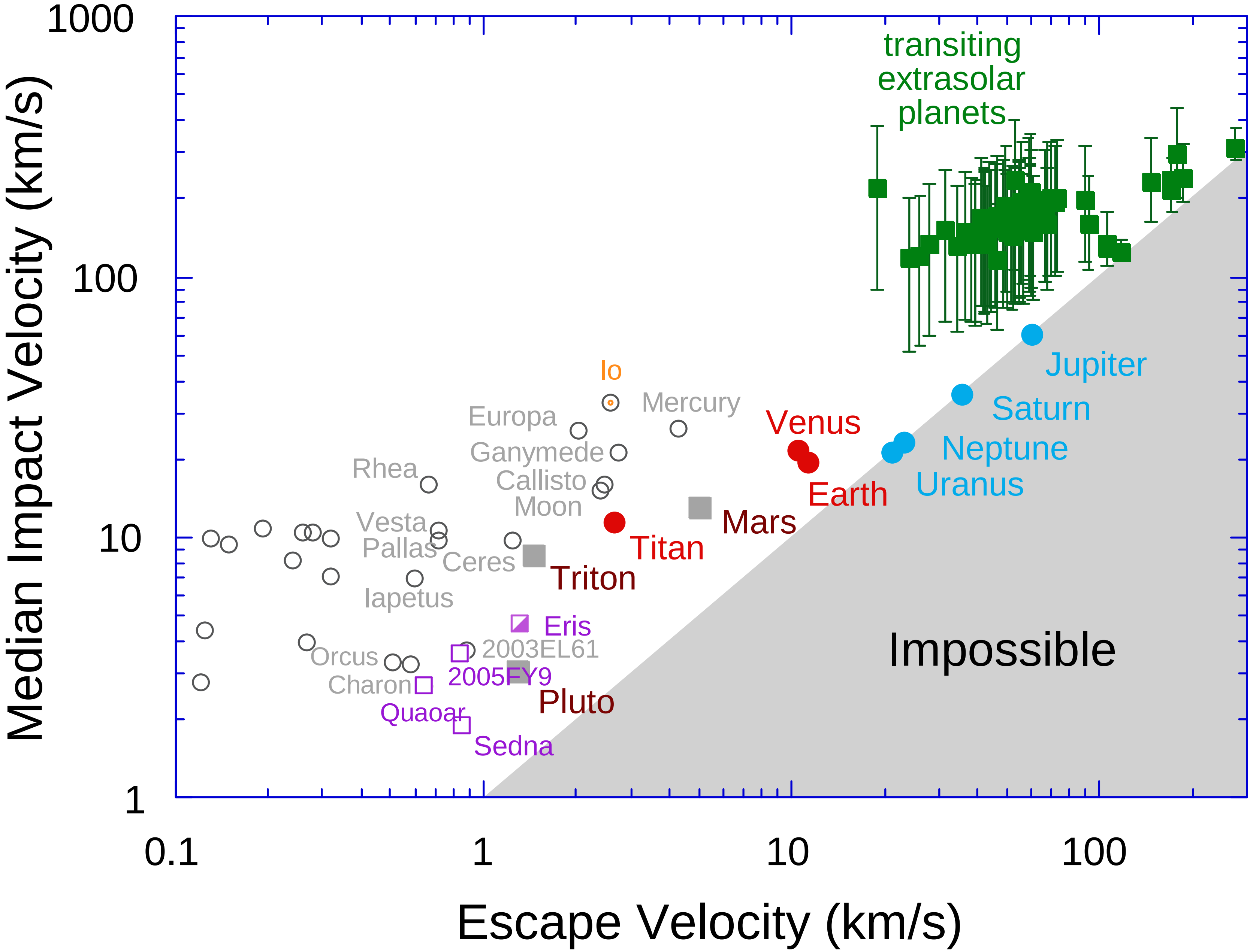
Ahrens's approximation

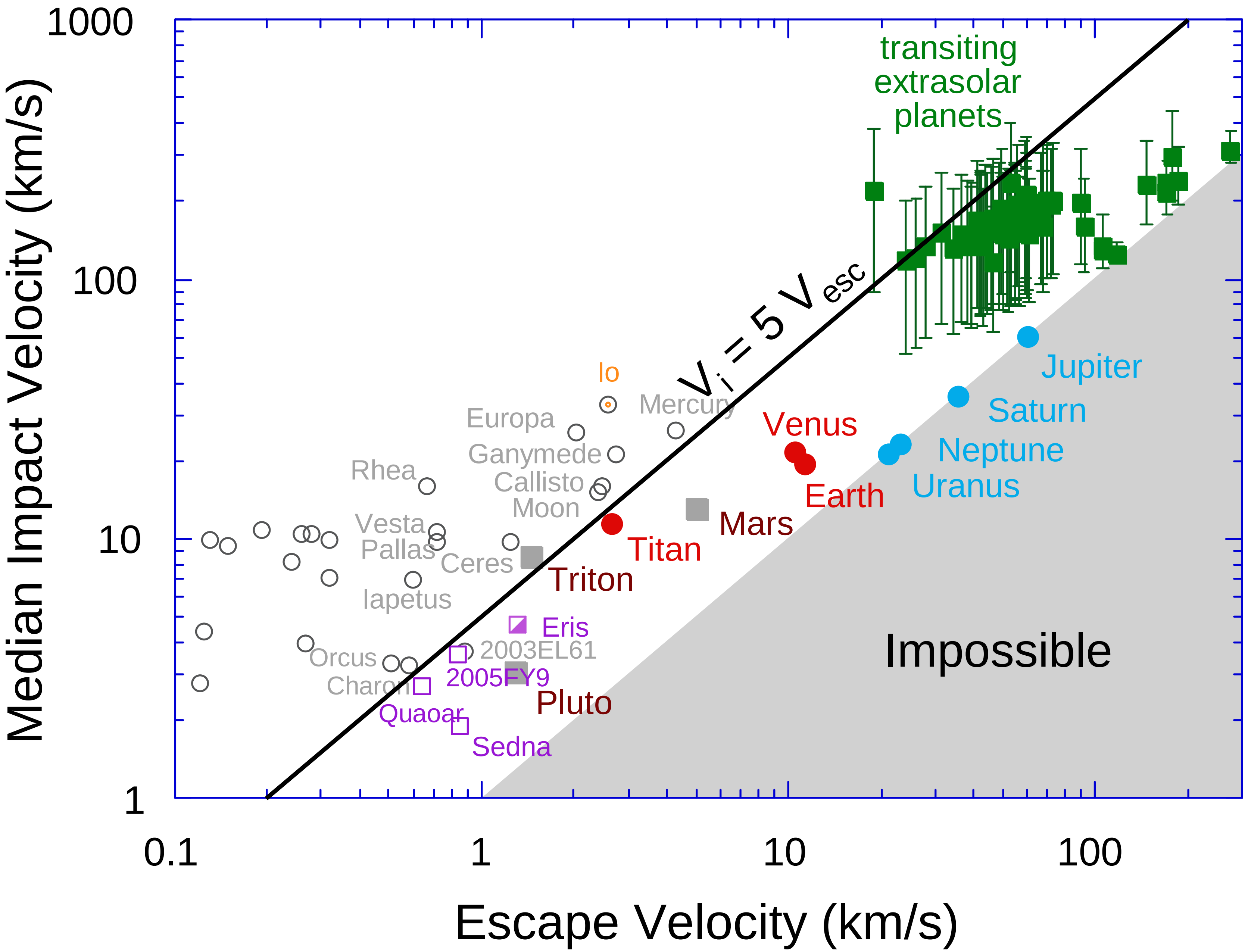
- Momentum of expanding rock vapor plume sweeps off tangent plane ("tangent plane") $V_i \gtrsim 2V_{esc}$

$\sim 2\pi H R_p$

Melosh Vickery approximation

Impact velocity is a measure of the specific energy available to erode the atmosphere


transiting extrasolar planets
Jupiter
Saturn
Neptune
Uranus
Venus
Earth
Mars
Titan
Triton
Io
Mercury
Europa
Ganymede
Callisto
Moon
Rhea
Vesta
Pallas
Ceres
Iapetus
Eris
2003EL61
Orcus
2005FY9
Charon
Quaoar
Pluto
Sedna
Impossible
Median Impact Velocity (km/s)
1000
100
10
1
Escape Velocity (km/s)
0.1
1
10
100



1000
100
10
1
0.1
1
10
100
Median Impact Velocity (km/s)
Escape Velocity (km/s)
transiting extrasolar planets
$V_i = 5\ V_{esc}$
Io
Europa
Mercury
Ganymede
Rhea
Callisto
Moon
Vesta
Pallas
Ceres
Iapetus
Venus
Earth
Mars
Titan
Triton
Jupiter
Saturn
Neptune
Uranus
Eris
2003EL61
Orcus
2005FY9
Charon
Quaoar
Pluto
Sedna
Impossible

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