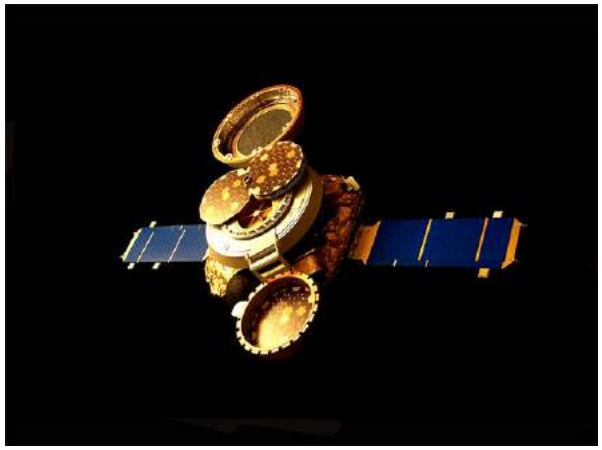
Origin(s) and early evolution of the terrestrial atmosphere

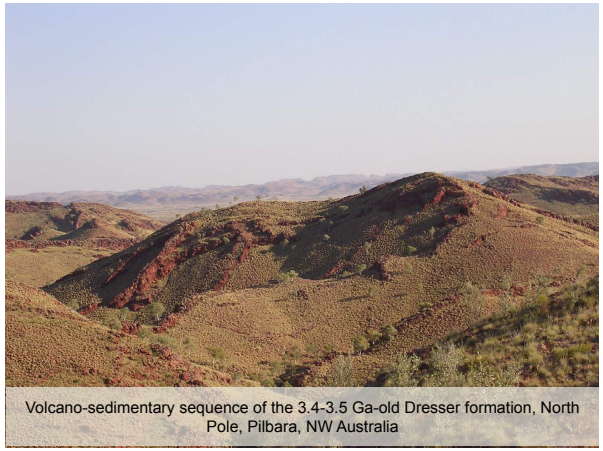


Bernard Marty

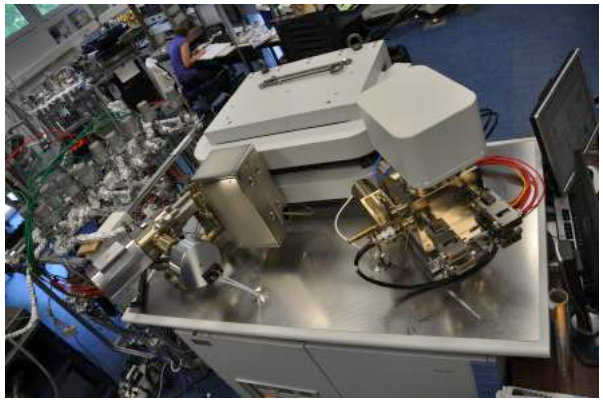
N. Arndt, G. Avice, R. Burgess, P.G. Burnard, D.S. Burnett, M. Chaussidon, E. Hébrard, A. Hofmann, S. Jacobson, M. Kuga, P. Michel, A. Morbidelli, M. Pujol, P. Philippot, L. Zimmermann

Centre de Recherches Pétrographiques et Géochimiques - CRPG-CNRS
Université de Lorraine, Nancy, France

Collab.: IPGP, Univ. Grenoble, Caltech, Univ. Manchester, Univ. Nice, Univ. Johannesburg



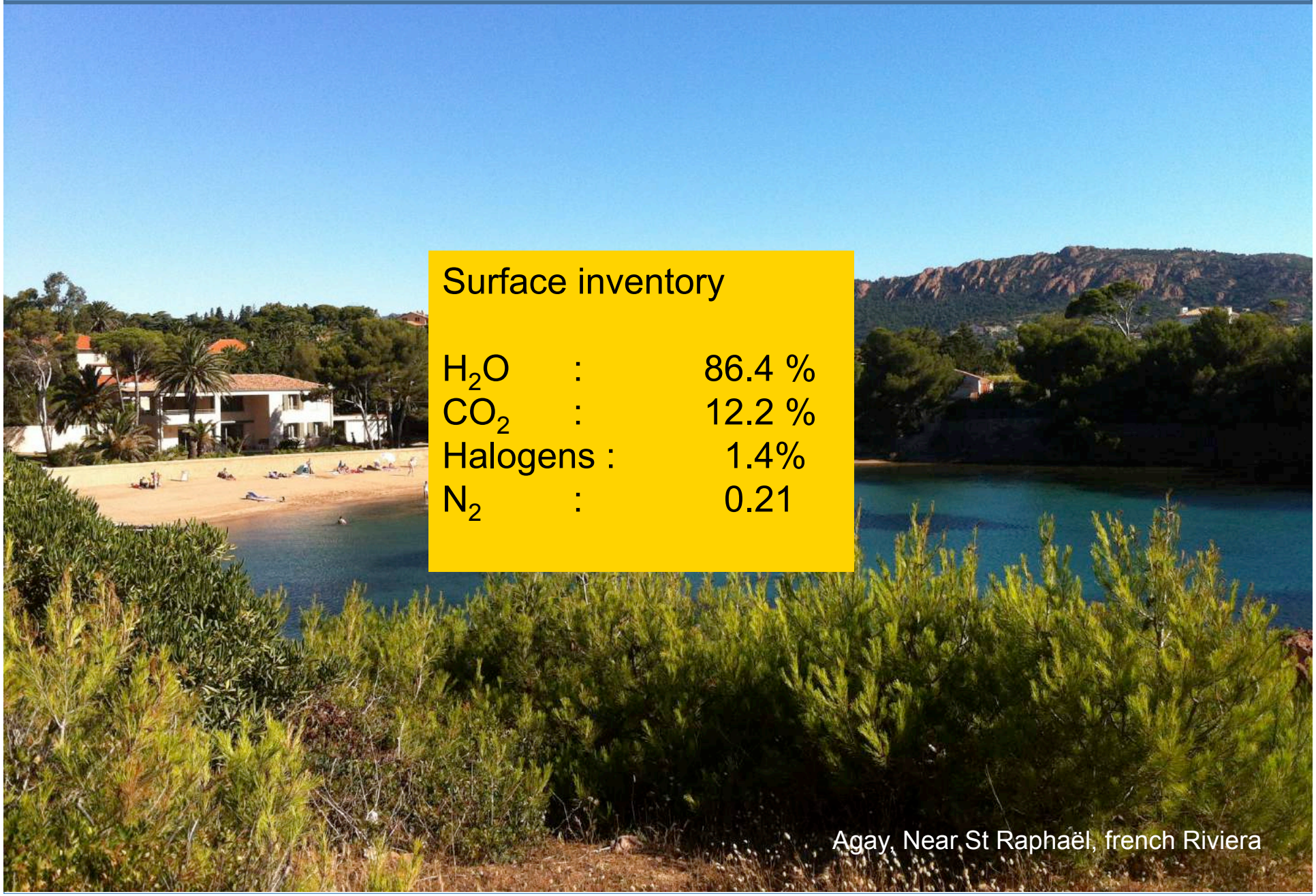
Volcano-sedimentary sequence of the 3.4-3.5 Ga-old Dresser formation, North Pole, Pilbara, NW Australia



UniVersS Oct. 17, 2014

Earth's atmosphere : 15°C, 1 bar, 0.04 % CO_2, 78 % N_2, 21% O_2, liquid water, signs of life

Earth's surface inventory : P > 100 bar

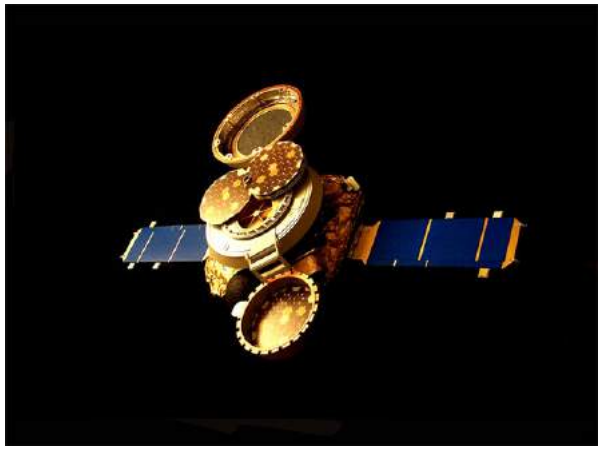


Venus' atmosphere : 96 bar, 460°C, 96% CO_2, 3.5 % N_2, HCl, H_2S …
Water gone (D/H…)

Photo taken by the Russian Venera 13 lander, 1982

Mars' atmosphere : -40°C, 0.006 bar, 96% CO_2, 2.7 % N_2
Very little water (ice at the poles)

Photo taken by the Curiosity lander
Credit: NASA/JPL-Caltech/MSSS



1. Origins
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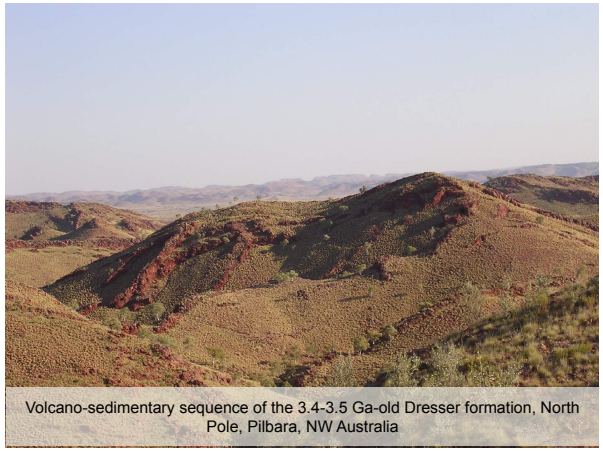

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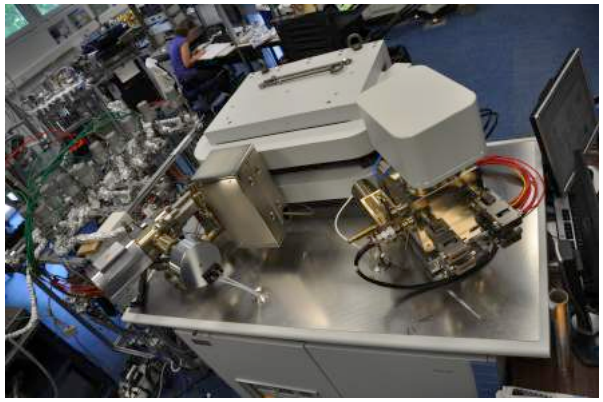
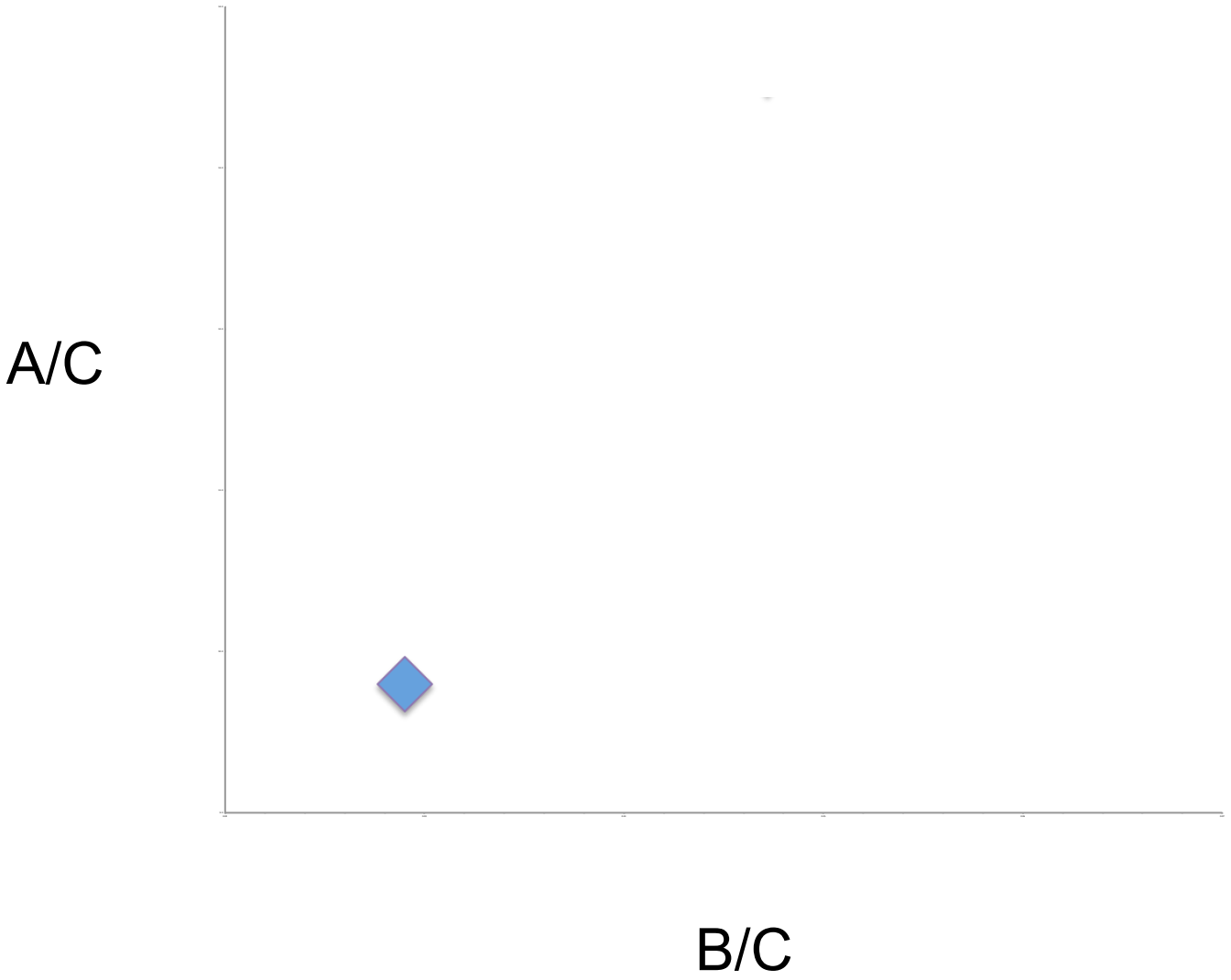


Isotope/element : two-component mixing



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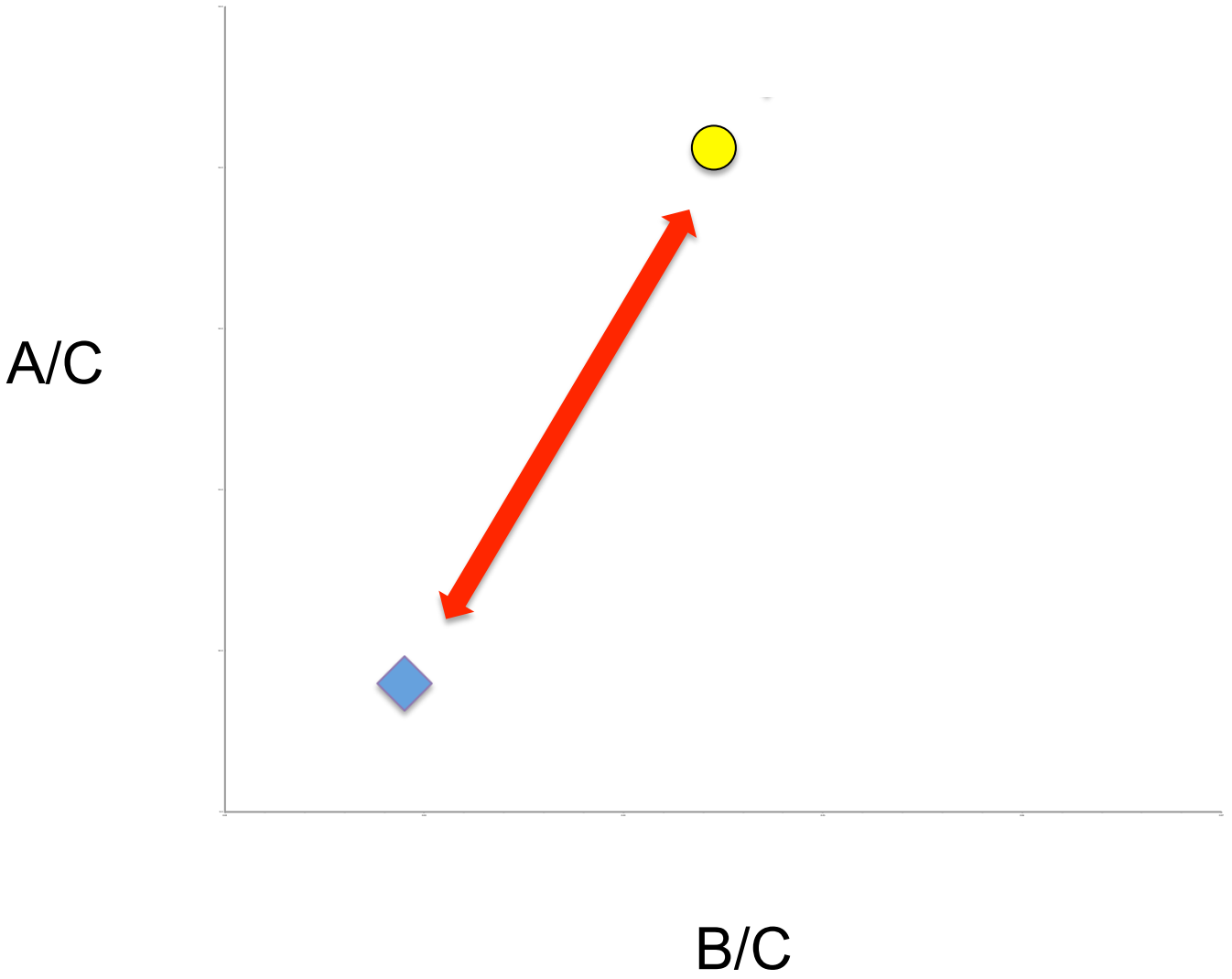

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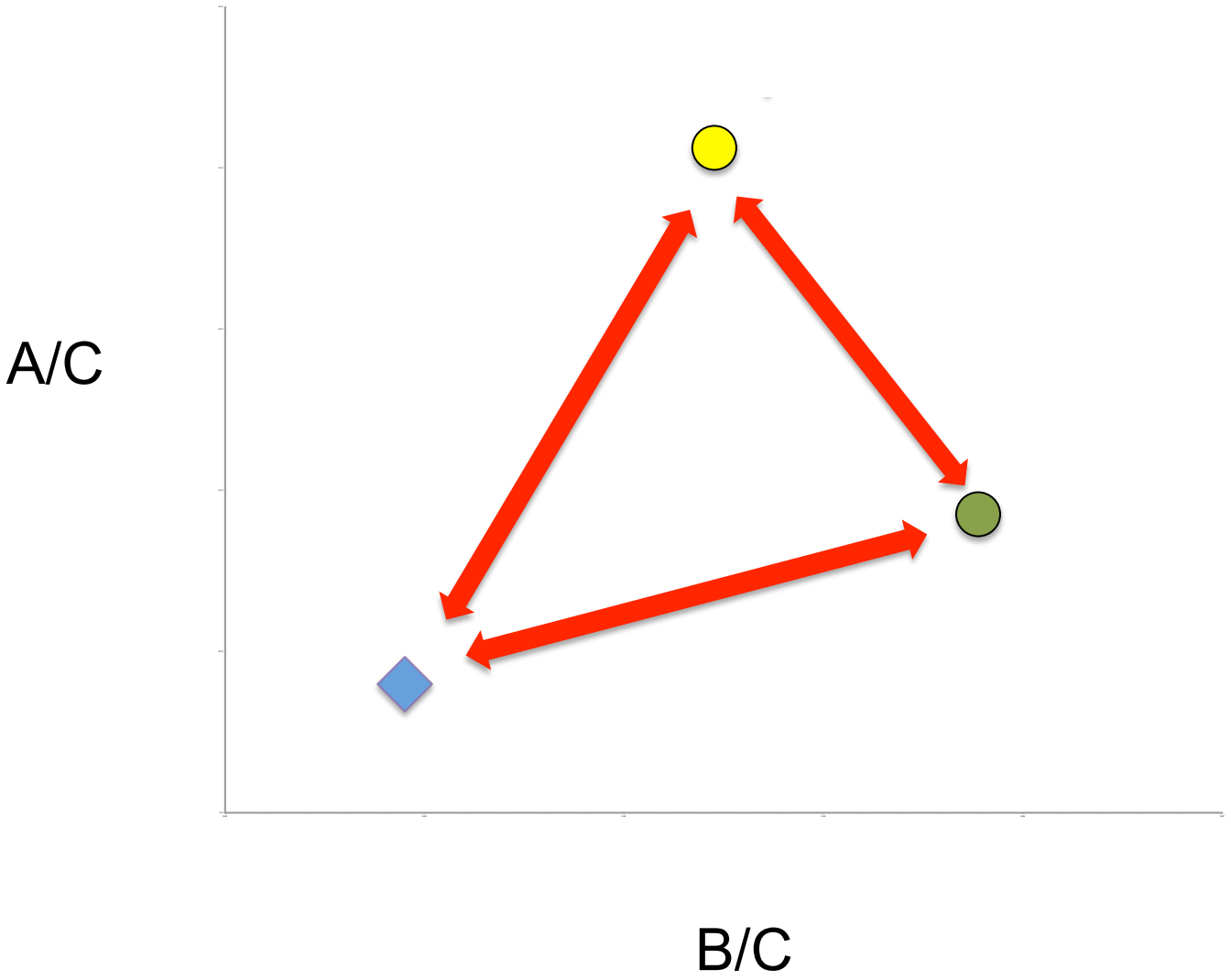
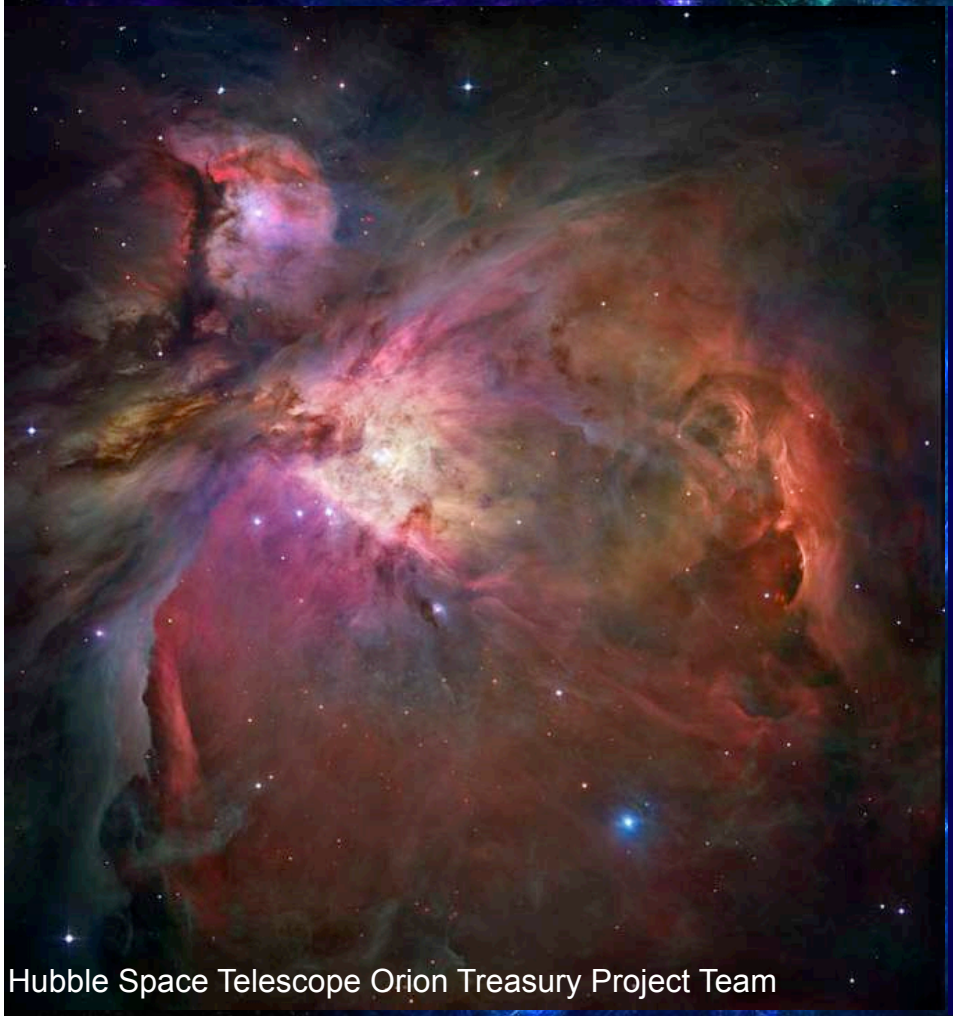
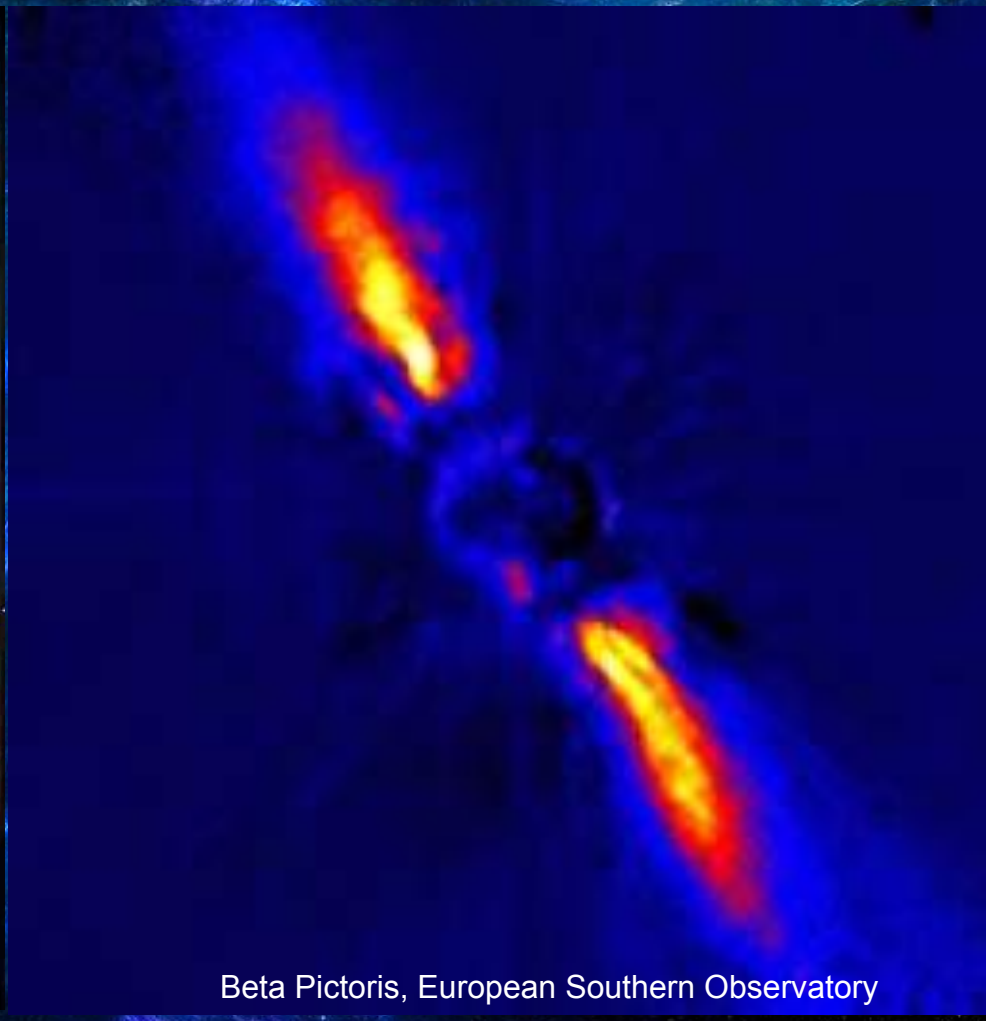


Formation & Evolution of the Solar System

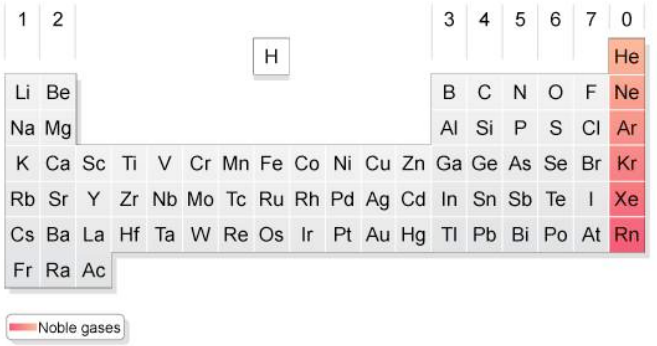


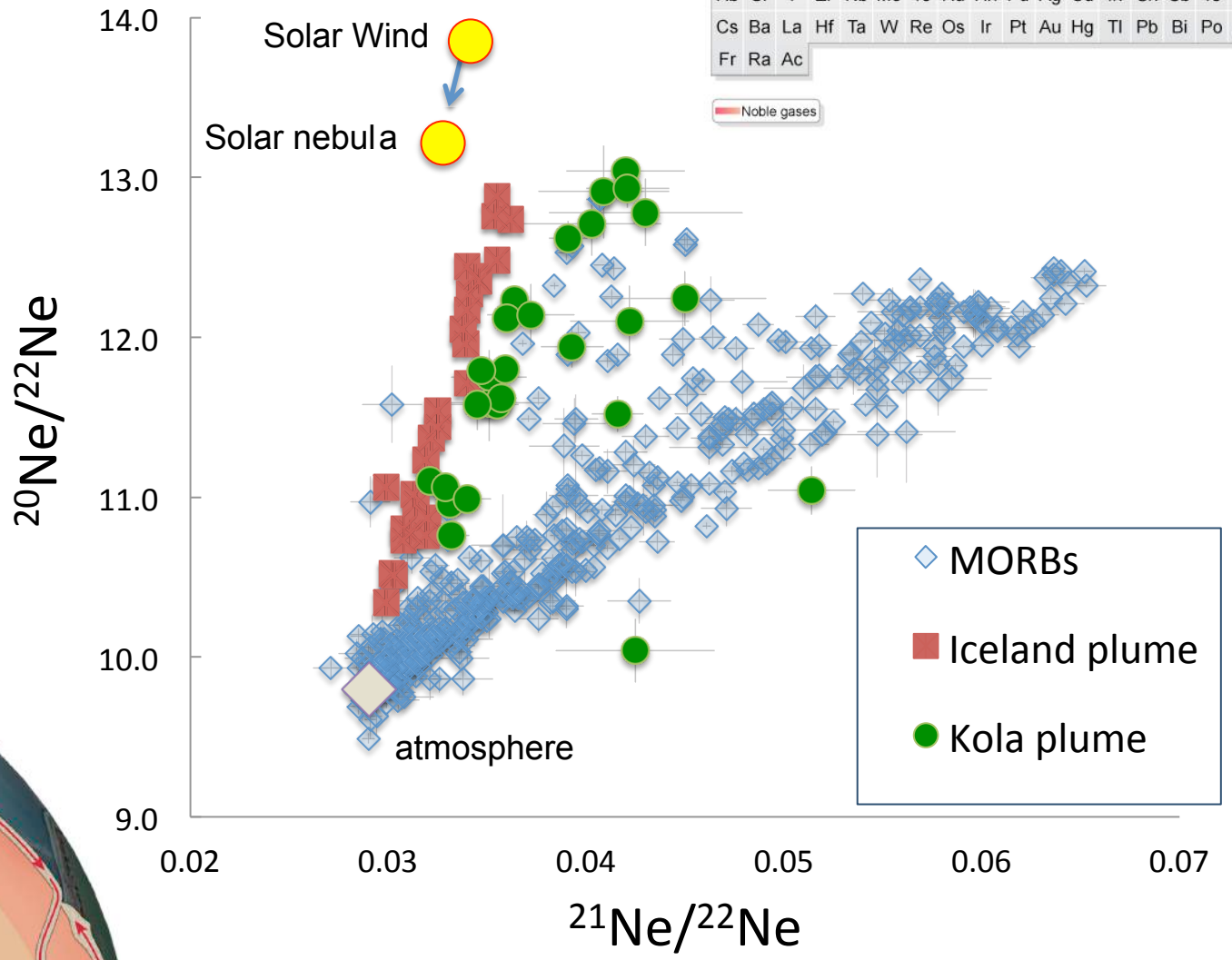
Hubble Space Telescope Orion Treasury Project Team

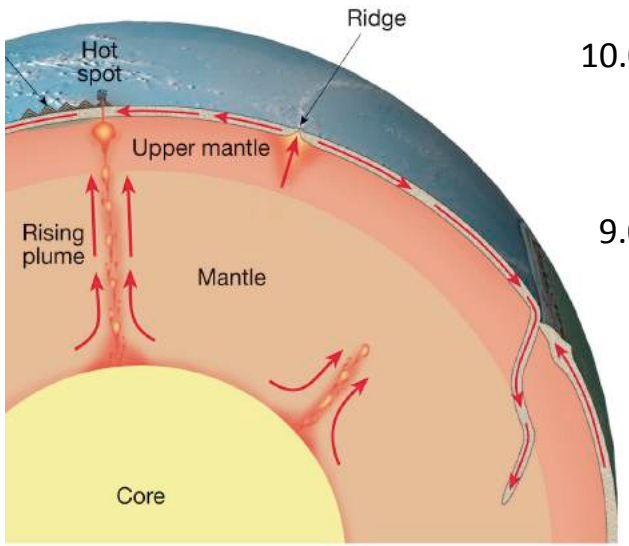


Beta Pictoris, European Southern Observatory

Solar-like neon in the mantle

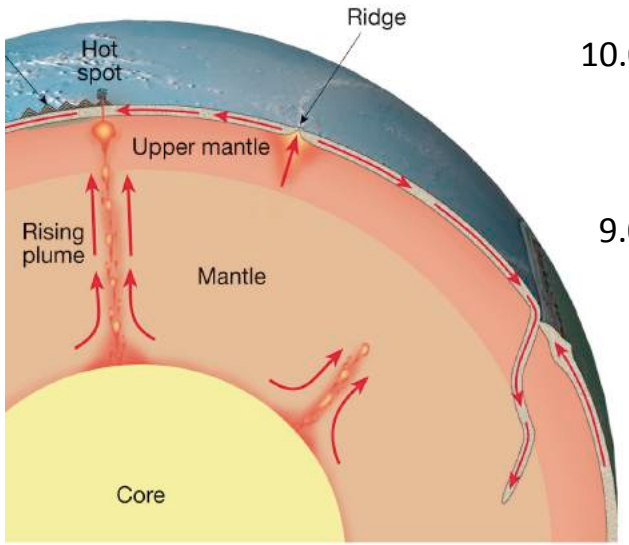


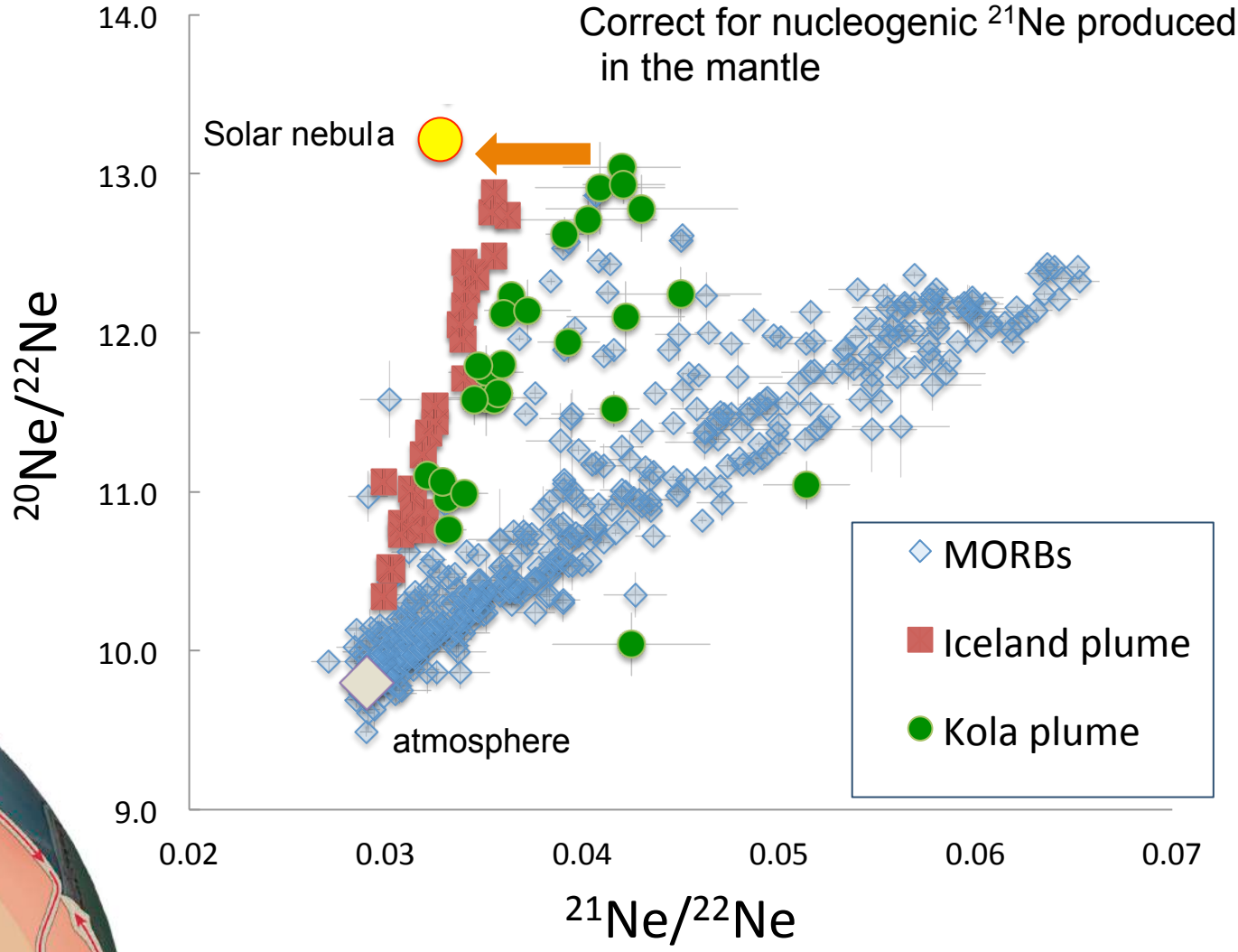




Solar wind : Heber et al. 2013
MORBs : compilation by M. Moreira
Iceland: Mukhopadyay, 2012
Kola: Yokochi & Marty, 2005

Solar-like neon in the mantle





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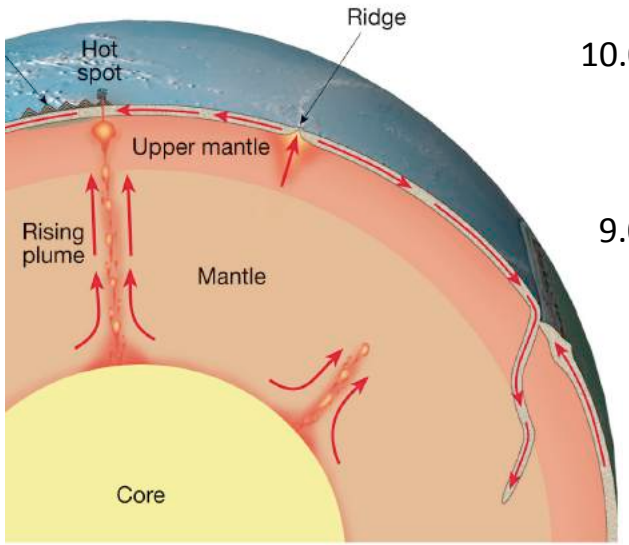

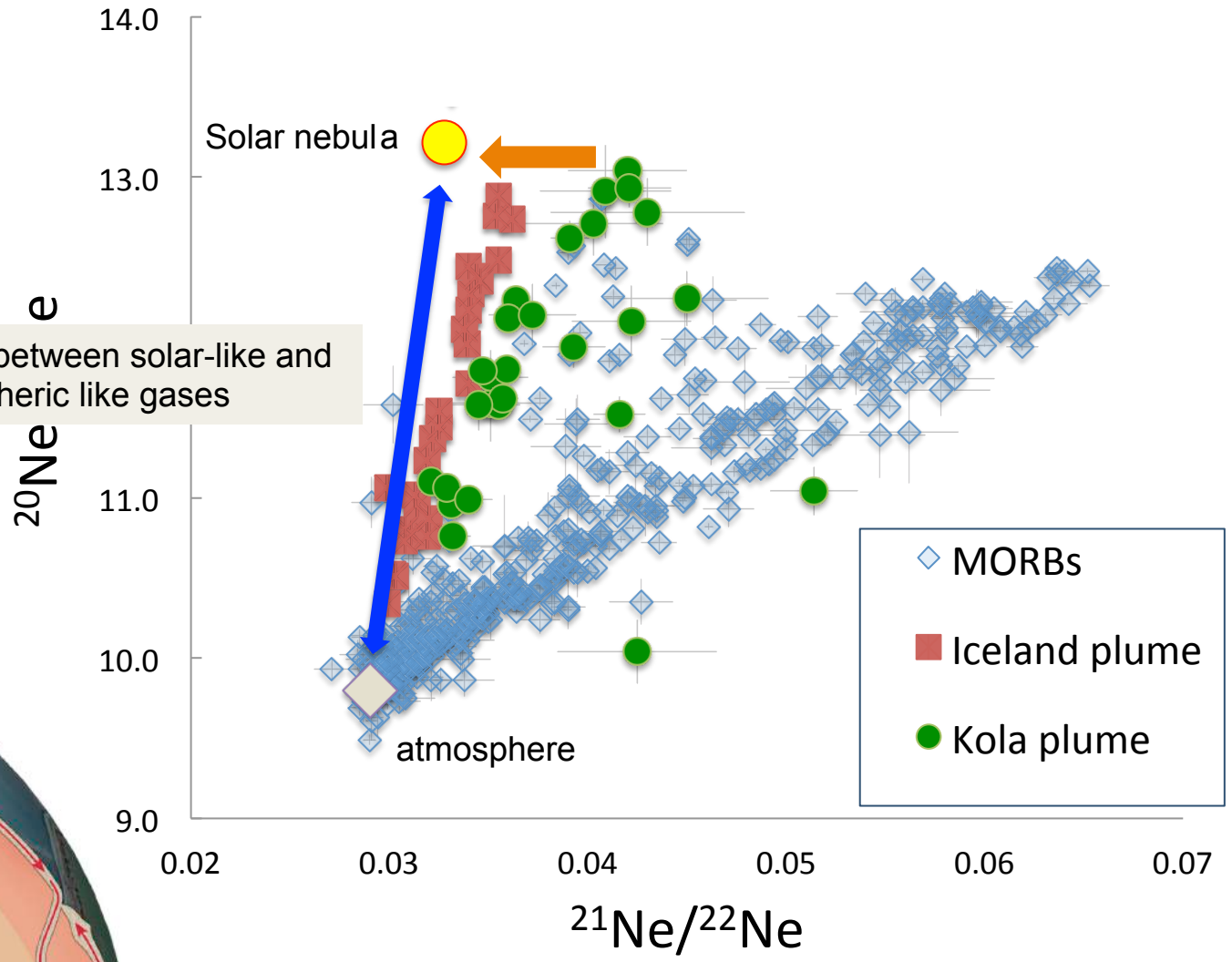

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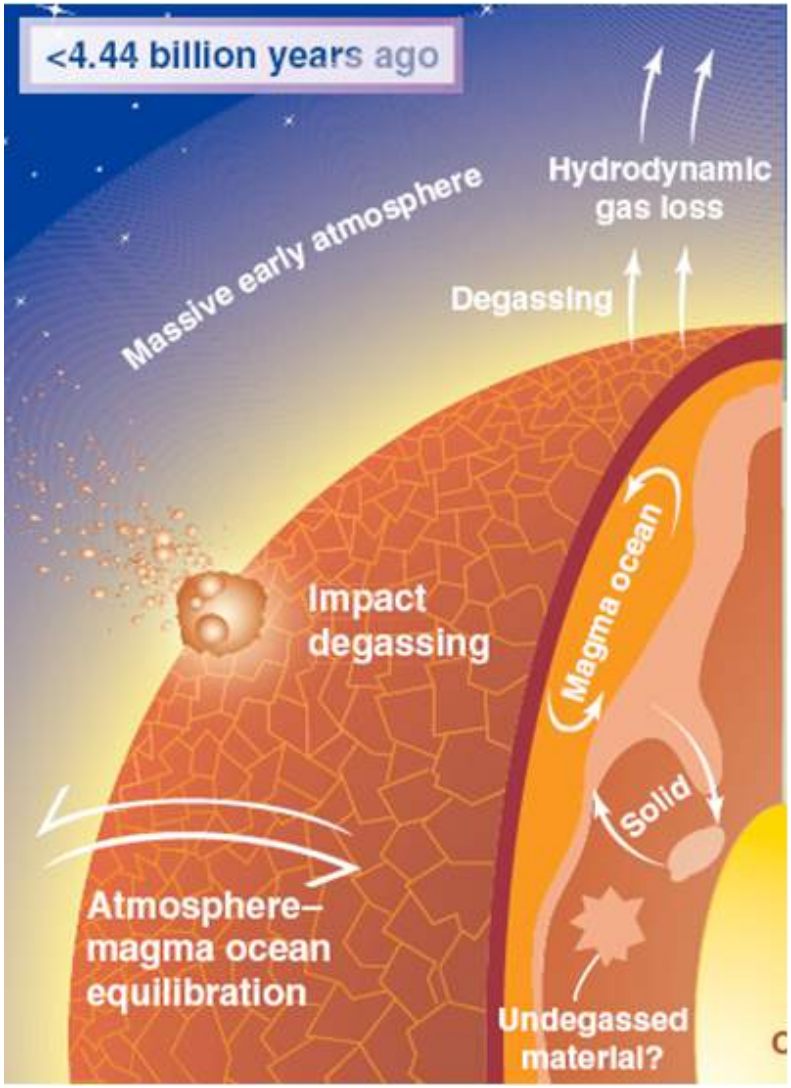
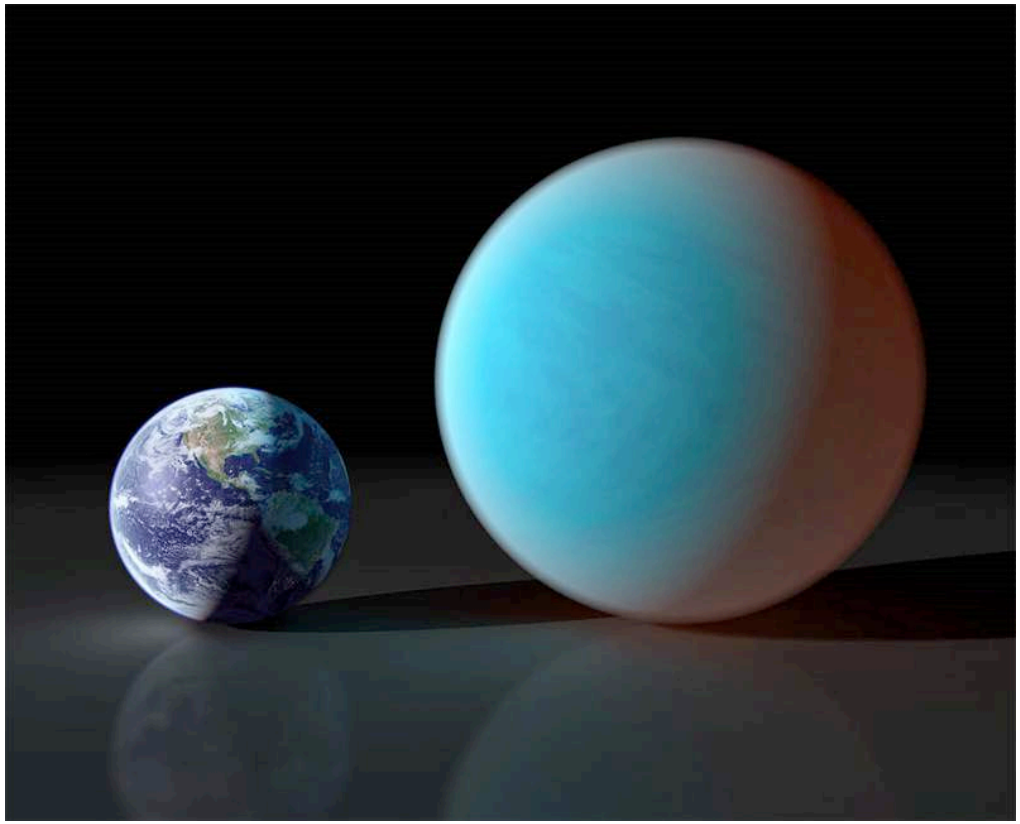
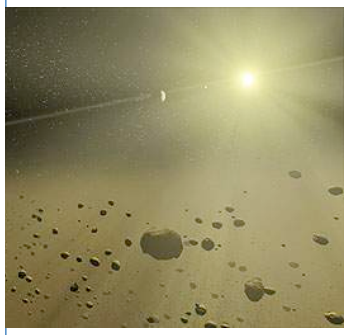
Solar gas : solution of a primitive H_2-rich atmosphere in molten proto-earth

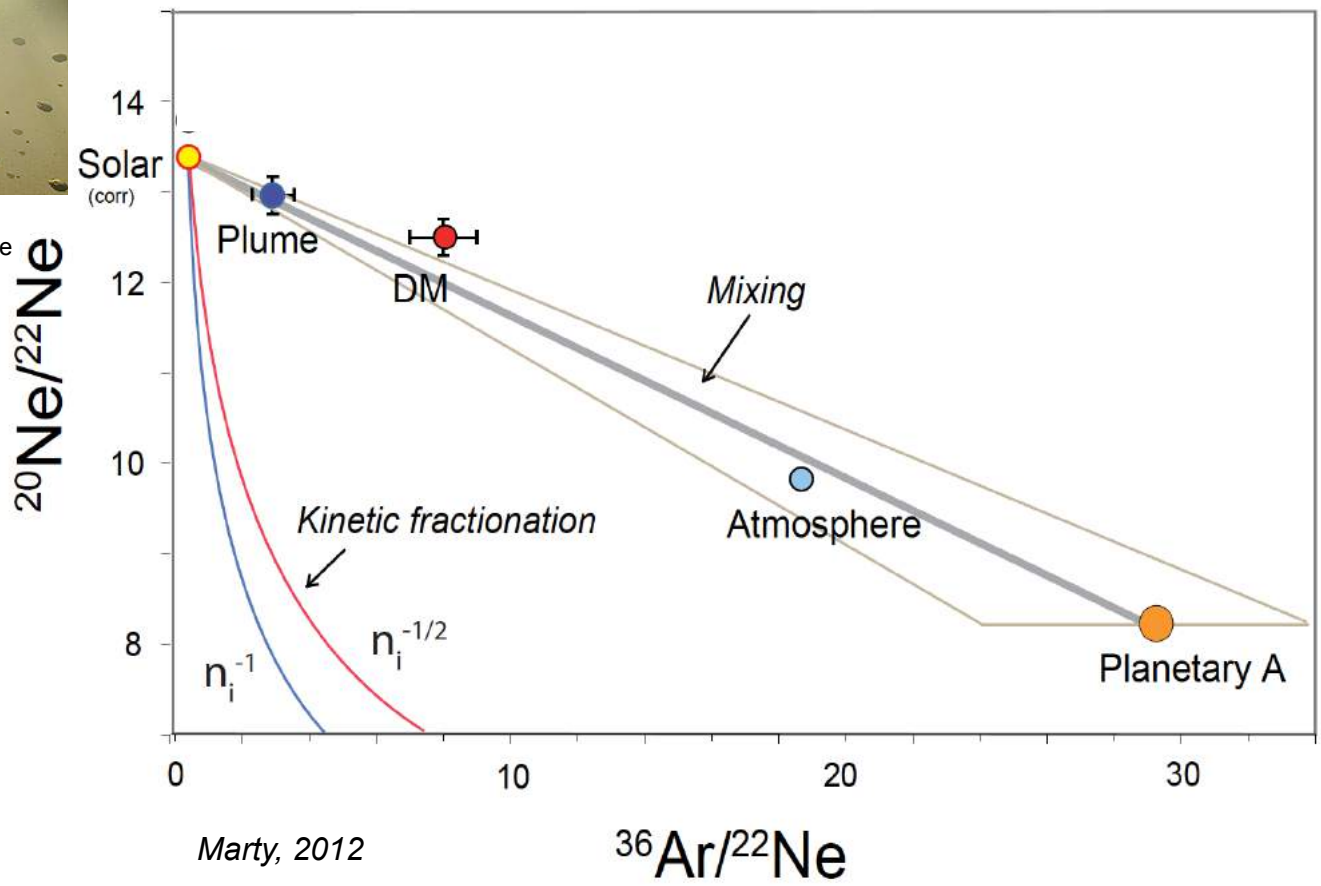




Ballentine, 2004



Proto solar nebula:
Spitzer Space Telescope

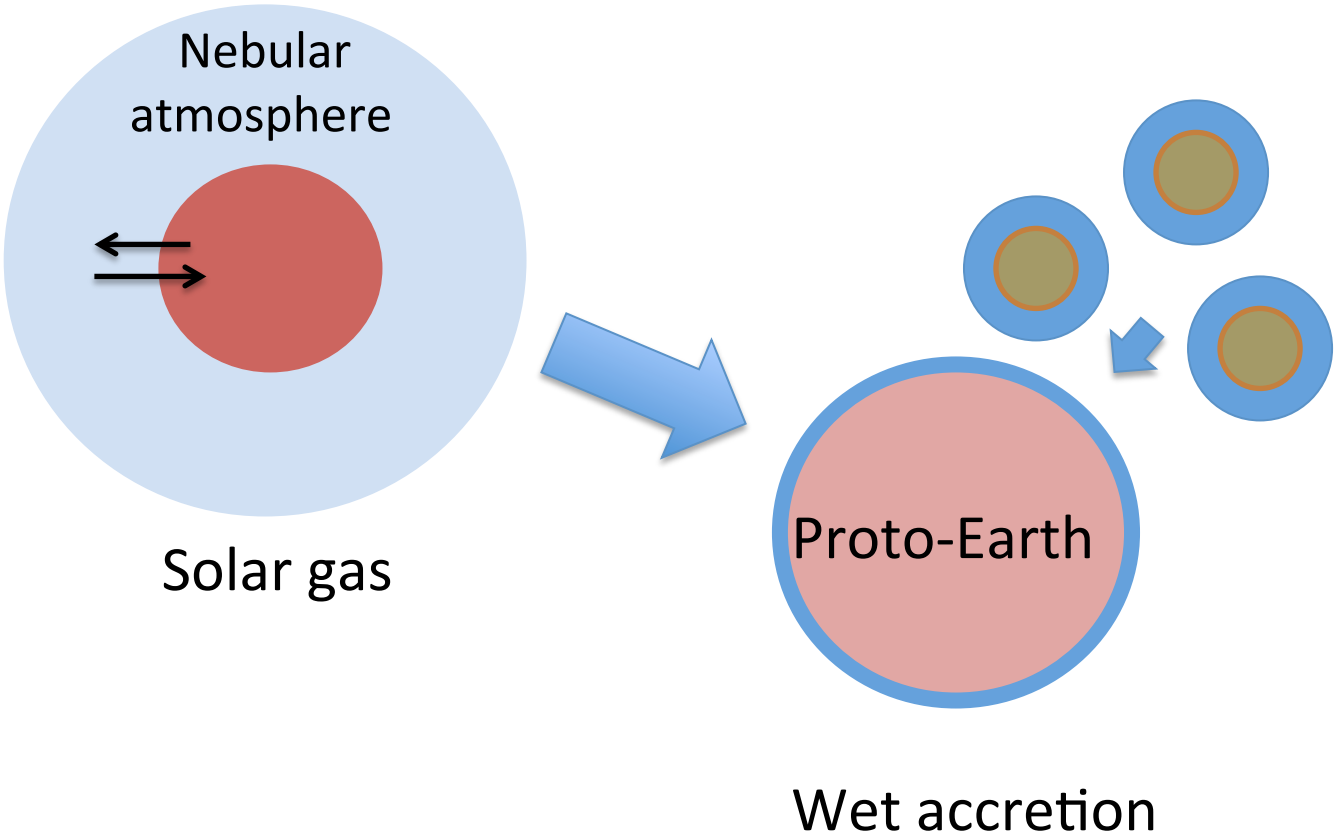


Marty, 2012

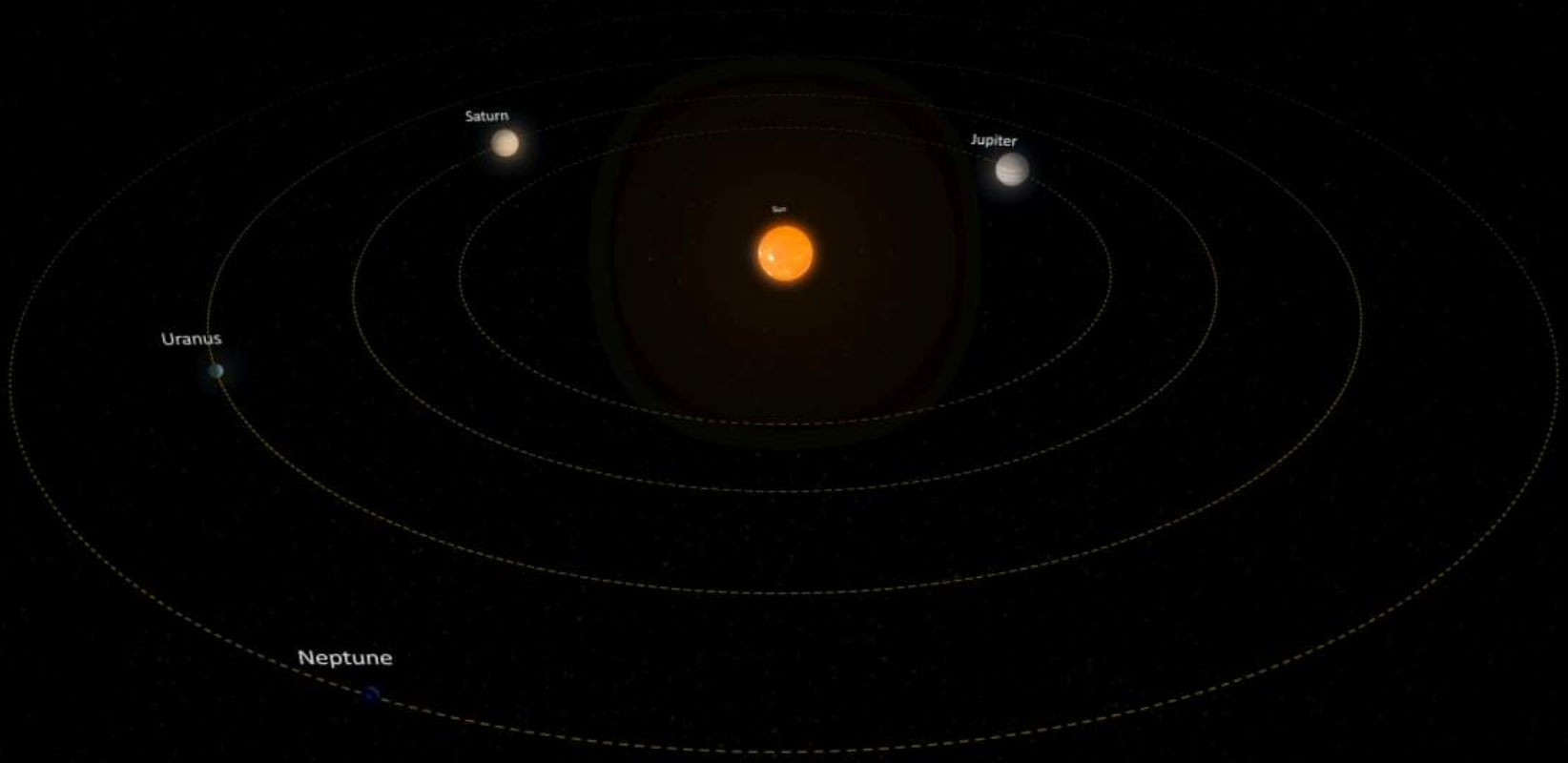
Carbonaceous chondrites

Terrestrial noble gases : mixing between Solar and Chondritic

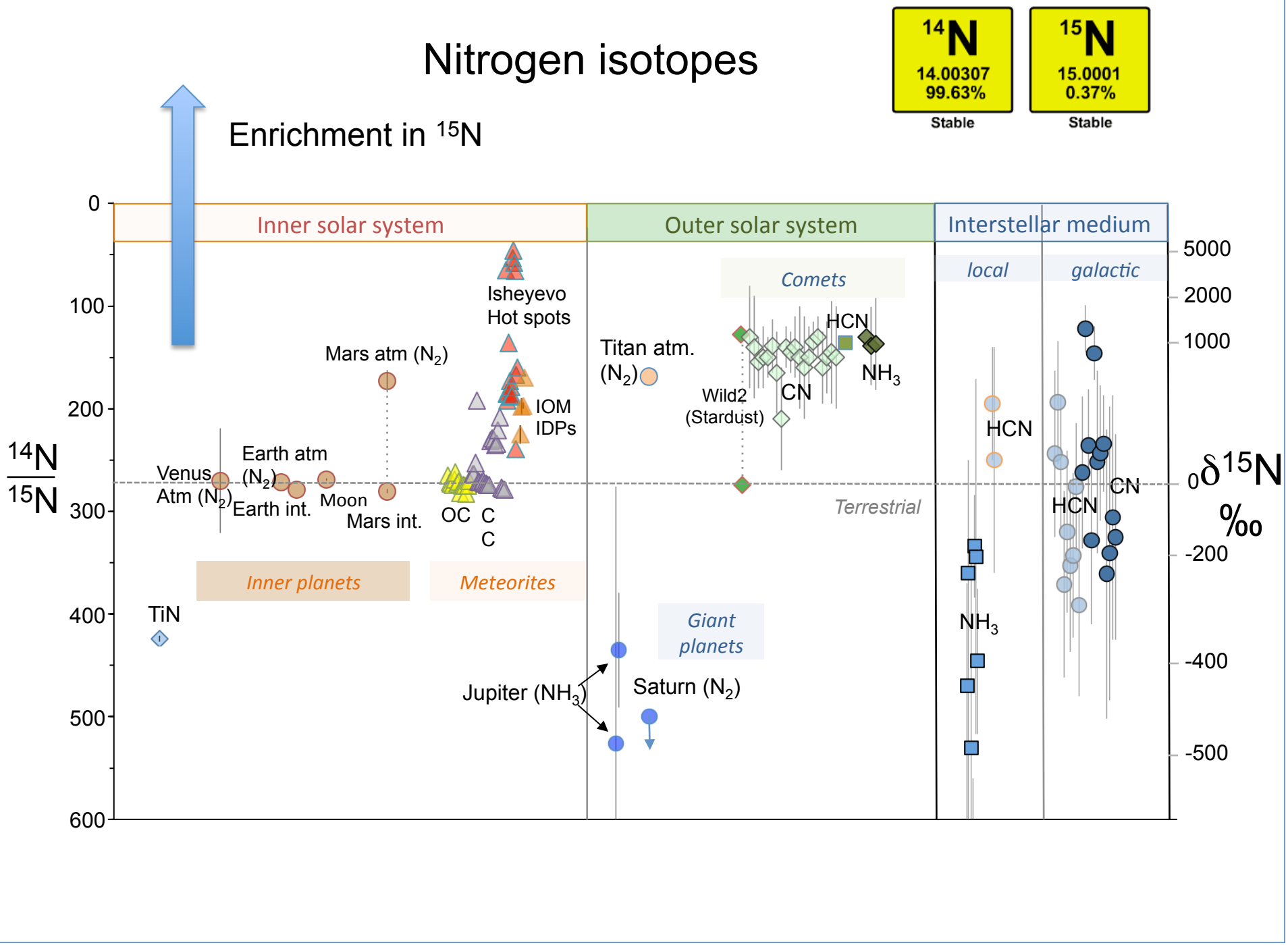
Chondrites:meteorites fragments of primitive asteroids


Nebular
atmosphere
Solar gas
Proto-Earth
Wet accretion

Delivery of volatile elements to inner planets –
the Grand-Tack scenario: the asteroid belt contains primitive material formed in the outer Solar System (Walsh et al. 2011)



Nitrogen isotopes

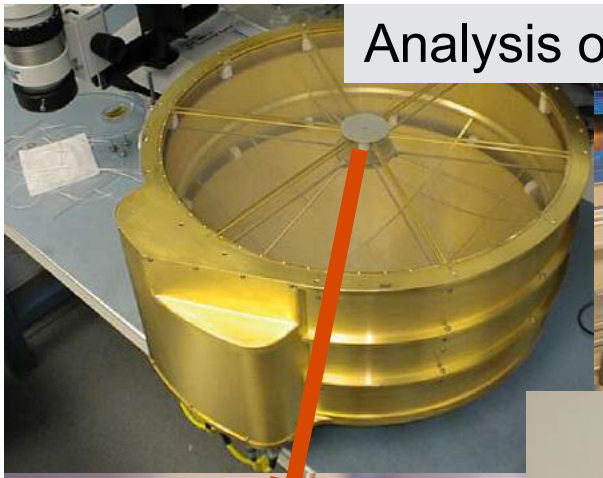


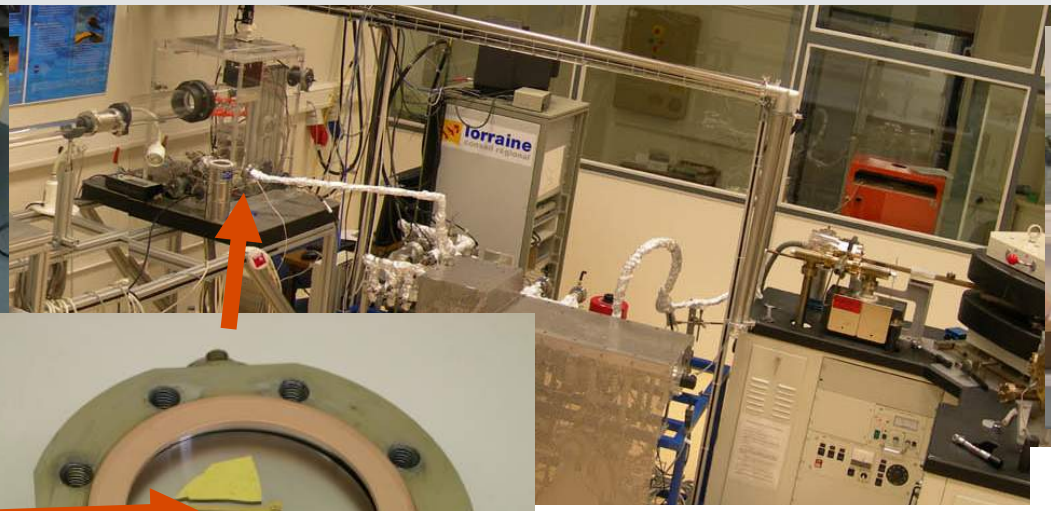
Genesis : the composition of the solar nebula from solar wind measurement
NASA discovery
PI: D.L. Burnett (Caltech)

GENESIS
SEARCH FOR ORIGINS

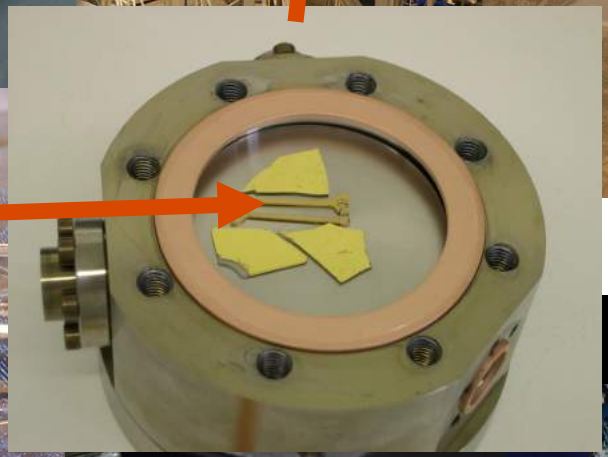
September 8th 2004

Analysis of N isotopes in Genesis Concentrator at Nancy



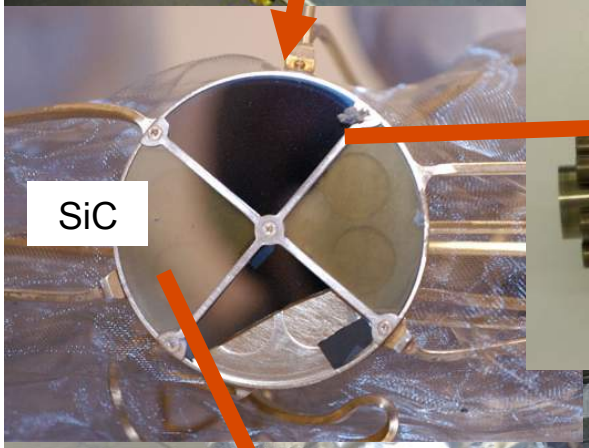


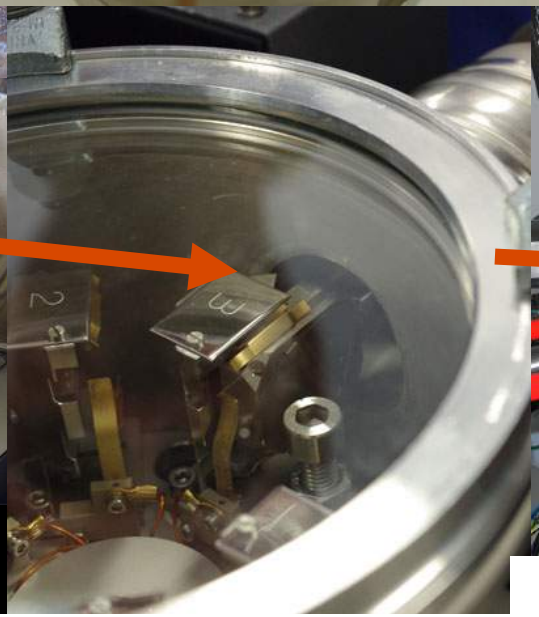
Pete Burnard & Laurent Zimmmermann



Laser ablation – static mass spectrometry

SiC

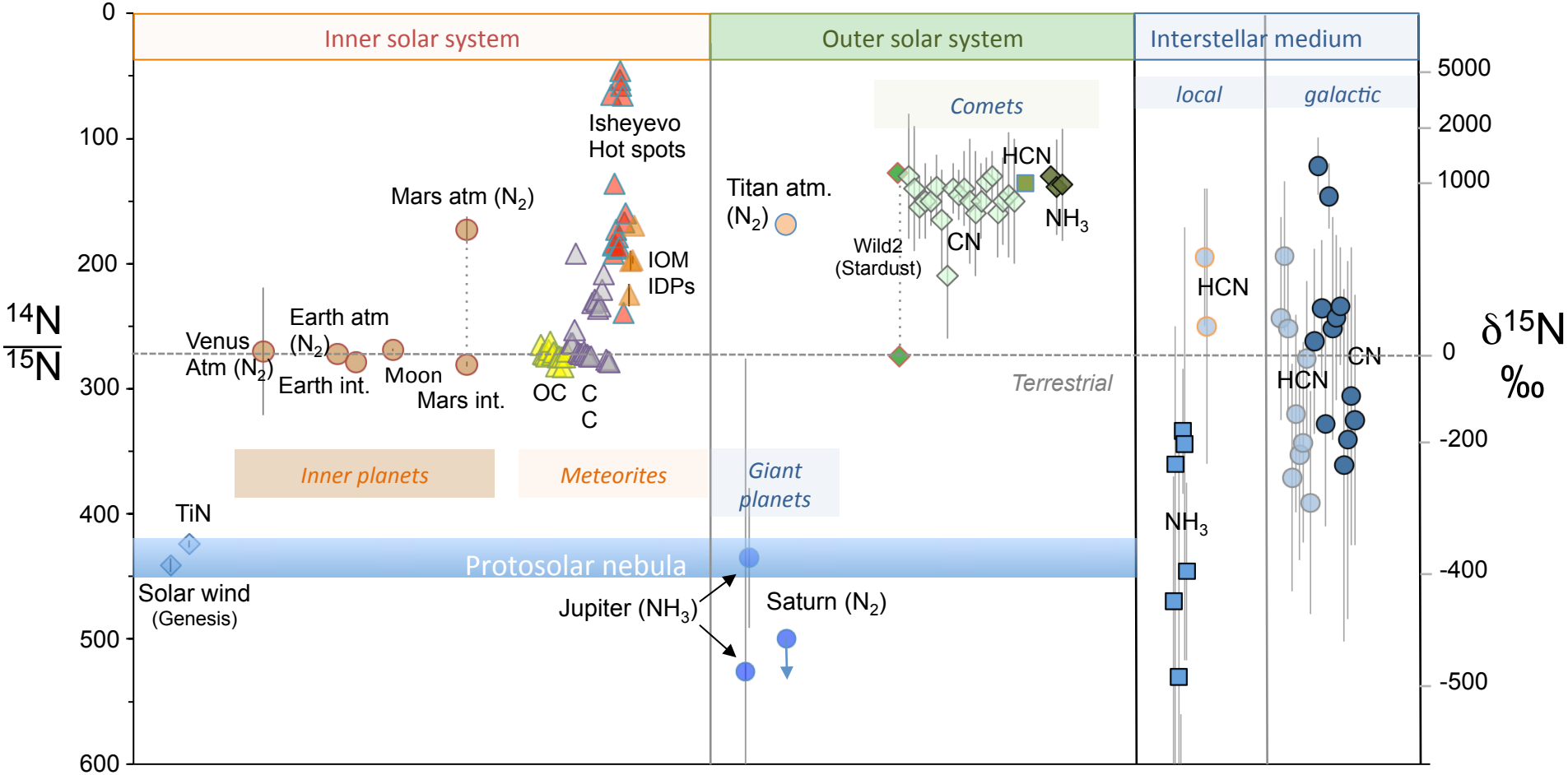




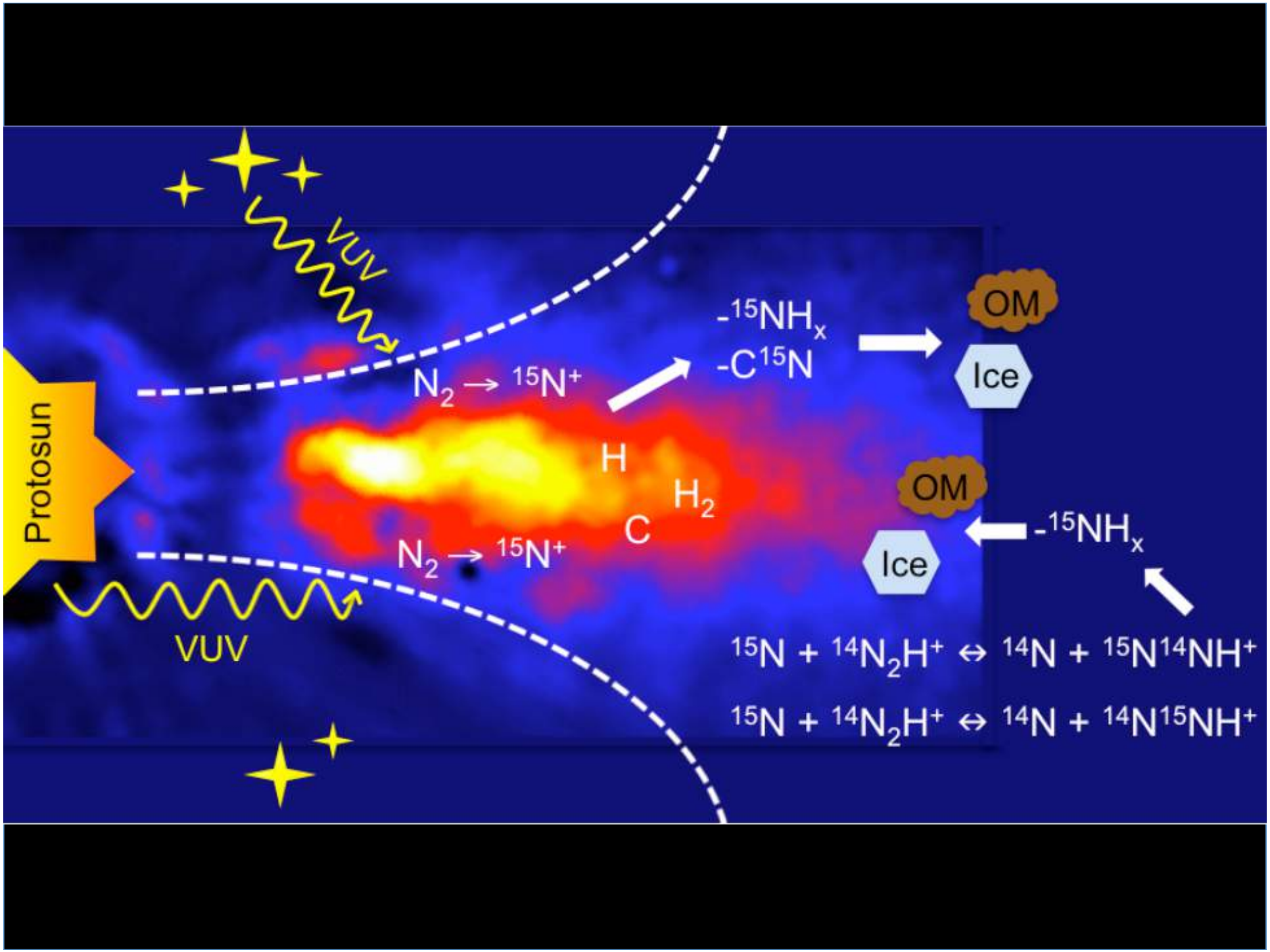
Marc Chaussidon

Ims 1280 HR2 ion probe

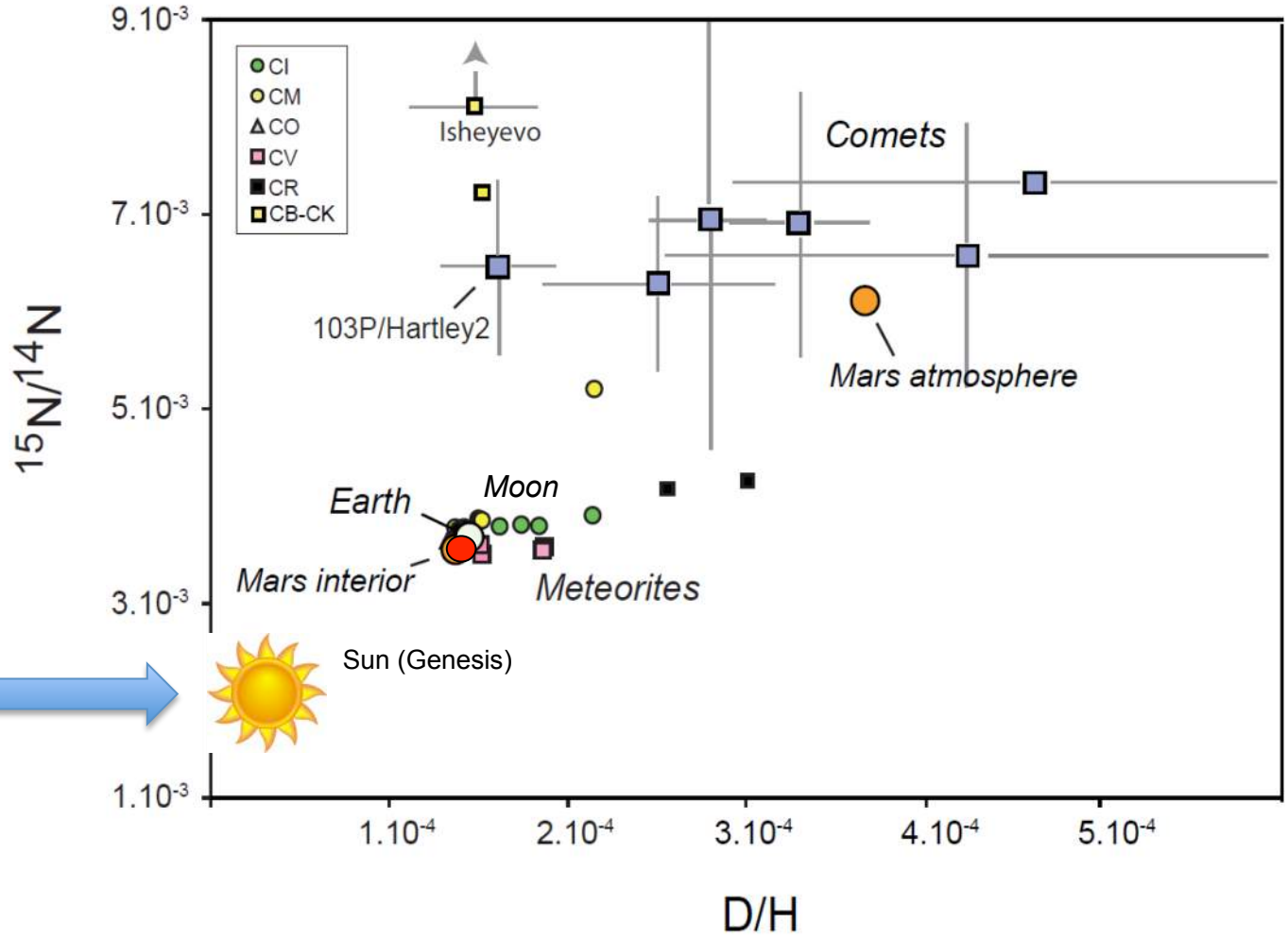
Protosolar nebula : $^{14}N/^{15}N = 441 \pm 6\ (2\sigma)$
$^{15}N/^{14}N = 2.27 \pm 0.03 \times 10^{-3}$
$\delta^{15}N = -383 \pm 7‰$



Marty, Chaussion, Jurewitz, Wiens and Burnett, 2011

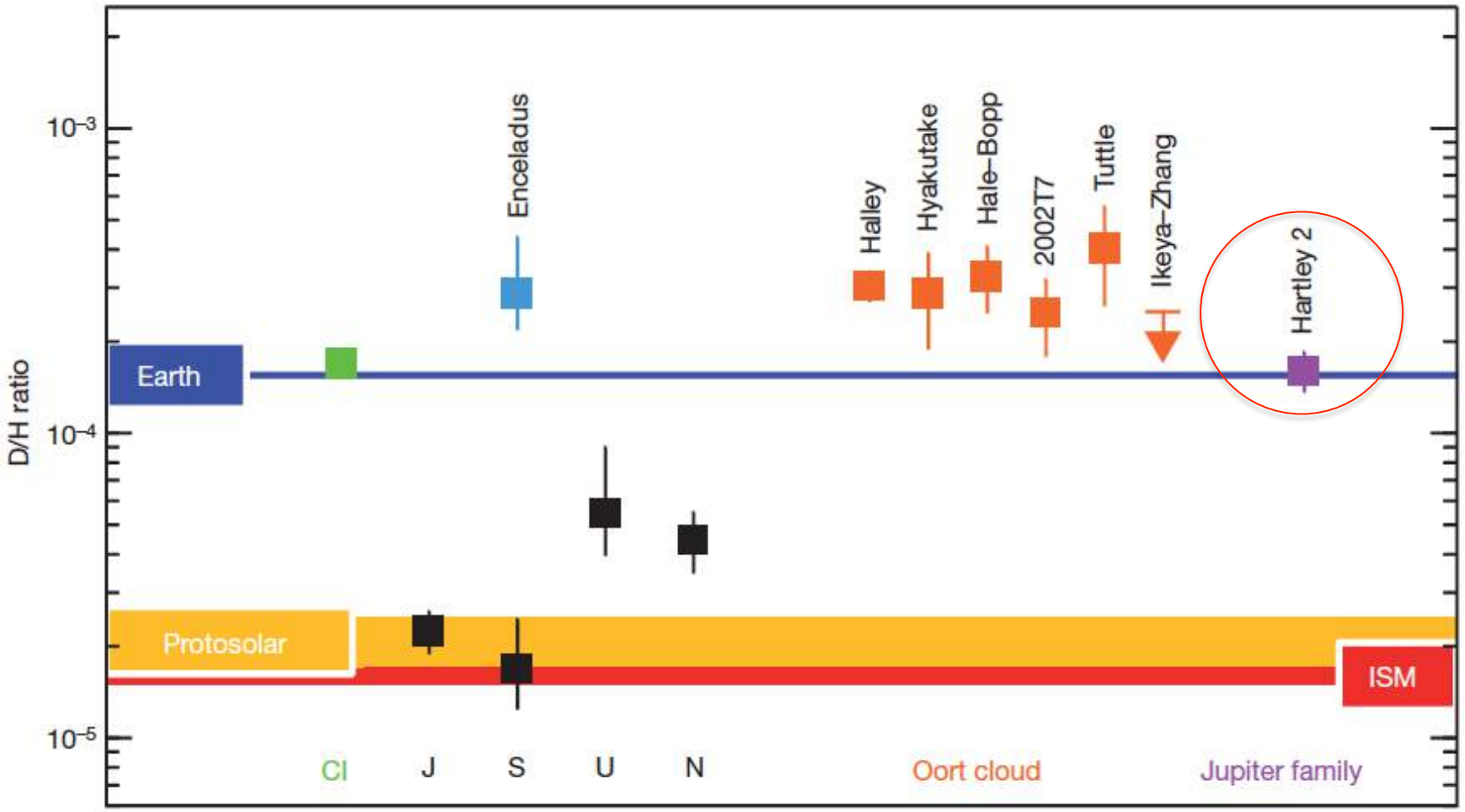

VUV
Protosun
$N_2 \rightarrow {}^{15}N^+$
$-{}^{15}NH_x$
$-C^{15}N$
OM
Ice
H
H_2
C
OM
Ice
$-{}^{15}NH_x$
$N_2 \rightarrow {}^{15}N^+$
VUV
${}^{15}N + {}^{14}N_2H^+ \leftrightarrow {}^{14}N + {}^{15}N^{14}NH^+$
${}^{15}N + {}^{14}N_2H^+ \leftrightarrow {}^{14}N + {}^{14}N^{15}NH^+$

Stable isotopes suggest that terrestrial volatiles originated from a cosmochemical reservoir that also supplied volatile elements to asteroids



Comets : Bockelée Morvan et al., 2007; Hartogh et al., 2011
Genesis : $^{15}N/^{14}N$ in the solar wind, Marty et al., 2011

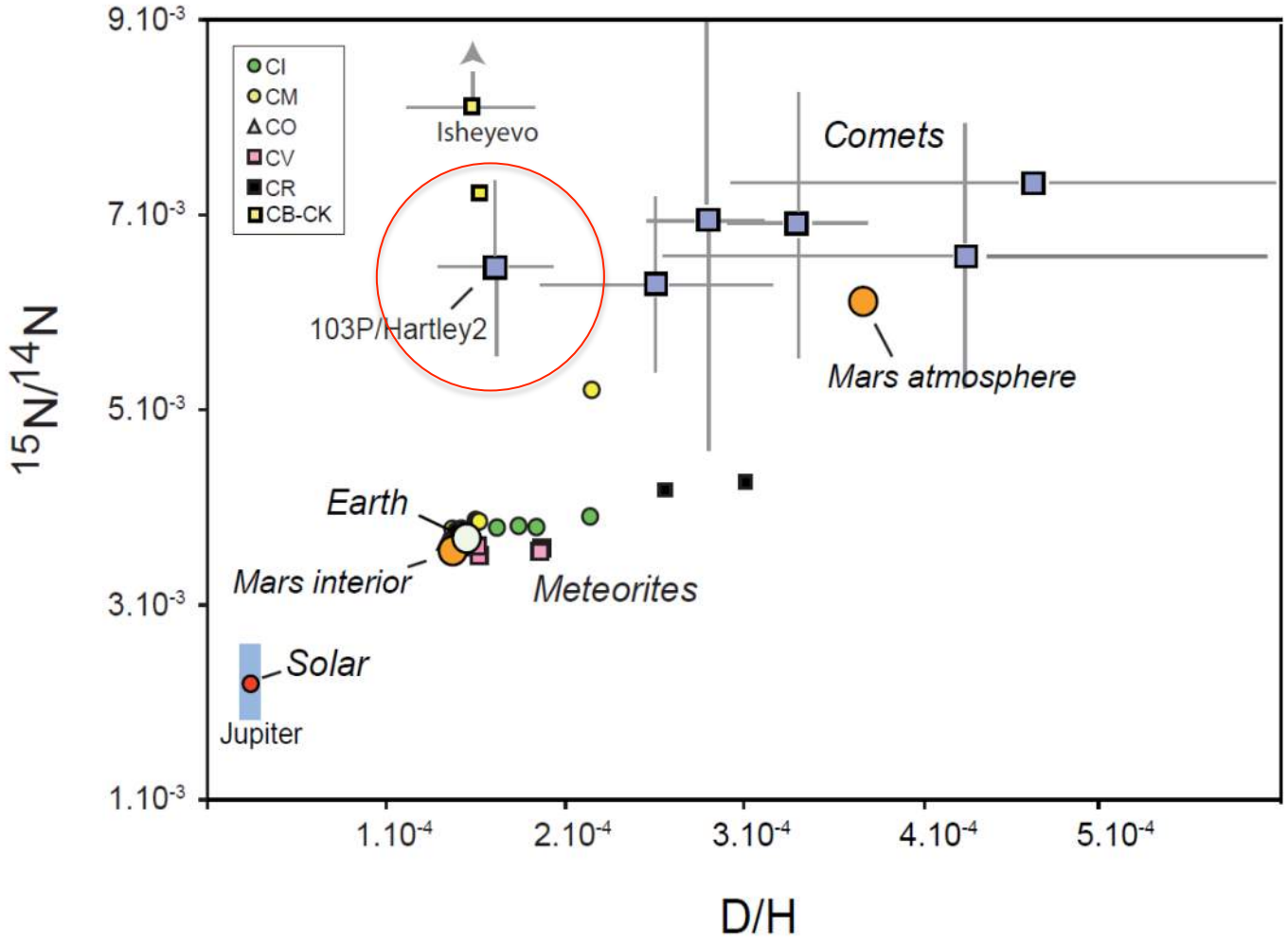
JFC Comet 103P/Hartley2 with ocean-like D/H



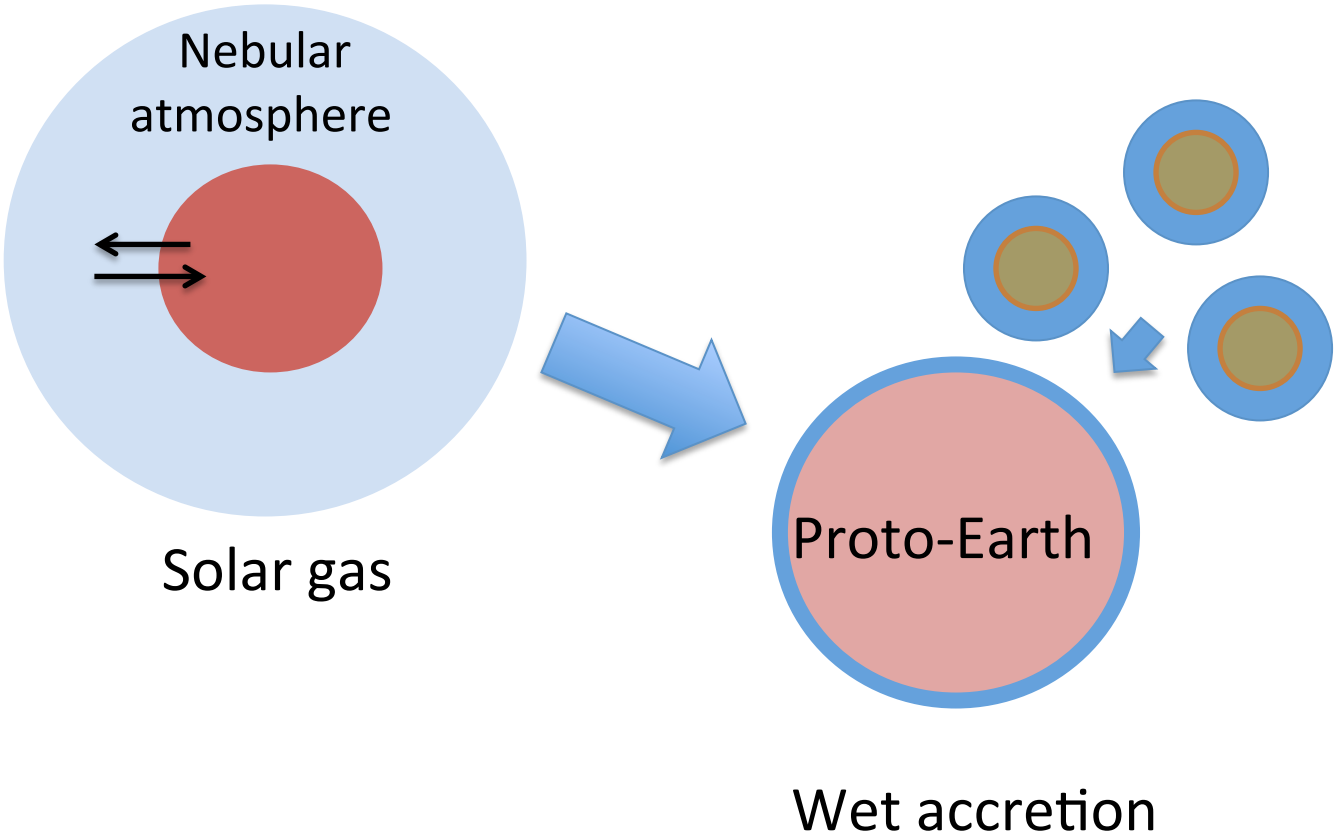
Ocean-like water in the Jupiter-family comet 103P/Hartley 2

Hartogh et al., Nature 2011

JFC Comet 103P/Hartley2 with ocean-like D/H is rich in ^{15}N compared to Earth




Possible caveat : only CN/HCN/NH_2 analyzed on comets, is ^{15}N-poor protosolar N_2 also trapped in cometary ice ?
Rosetta ! D/H, $^{15}N/^{14}N$…


Nebular
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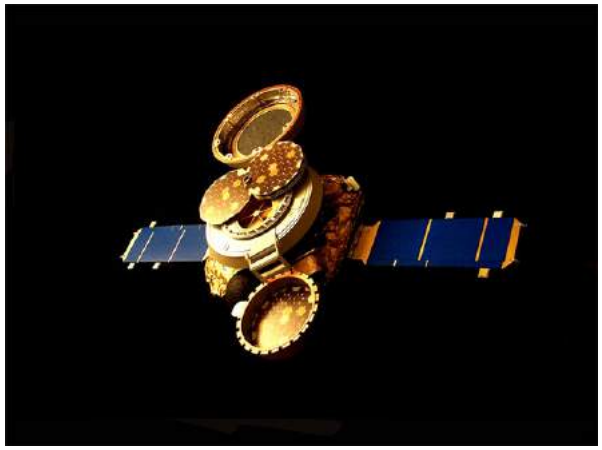

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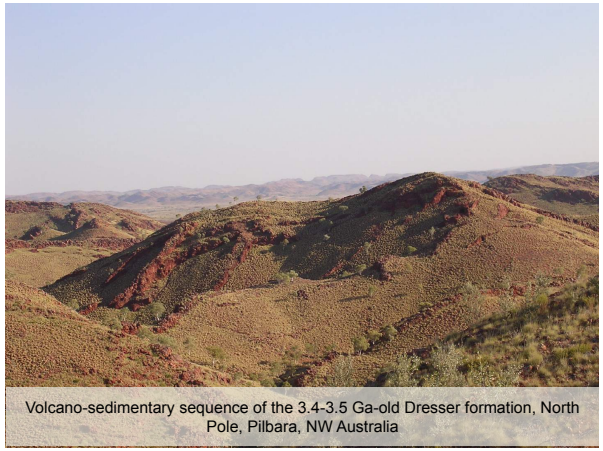

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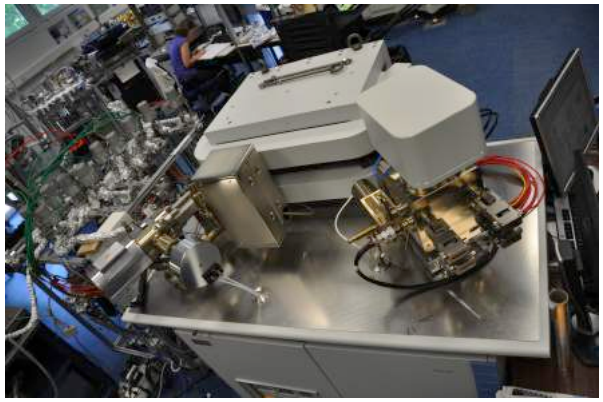
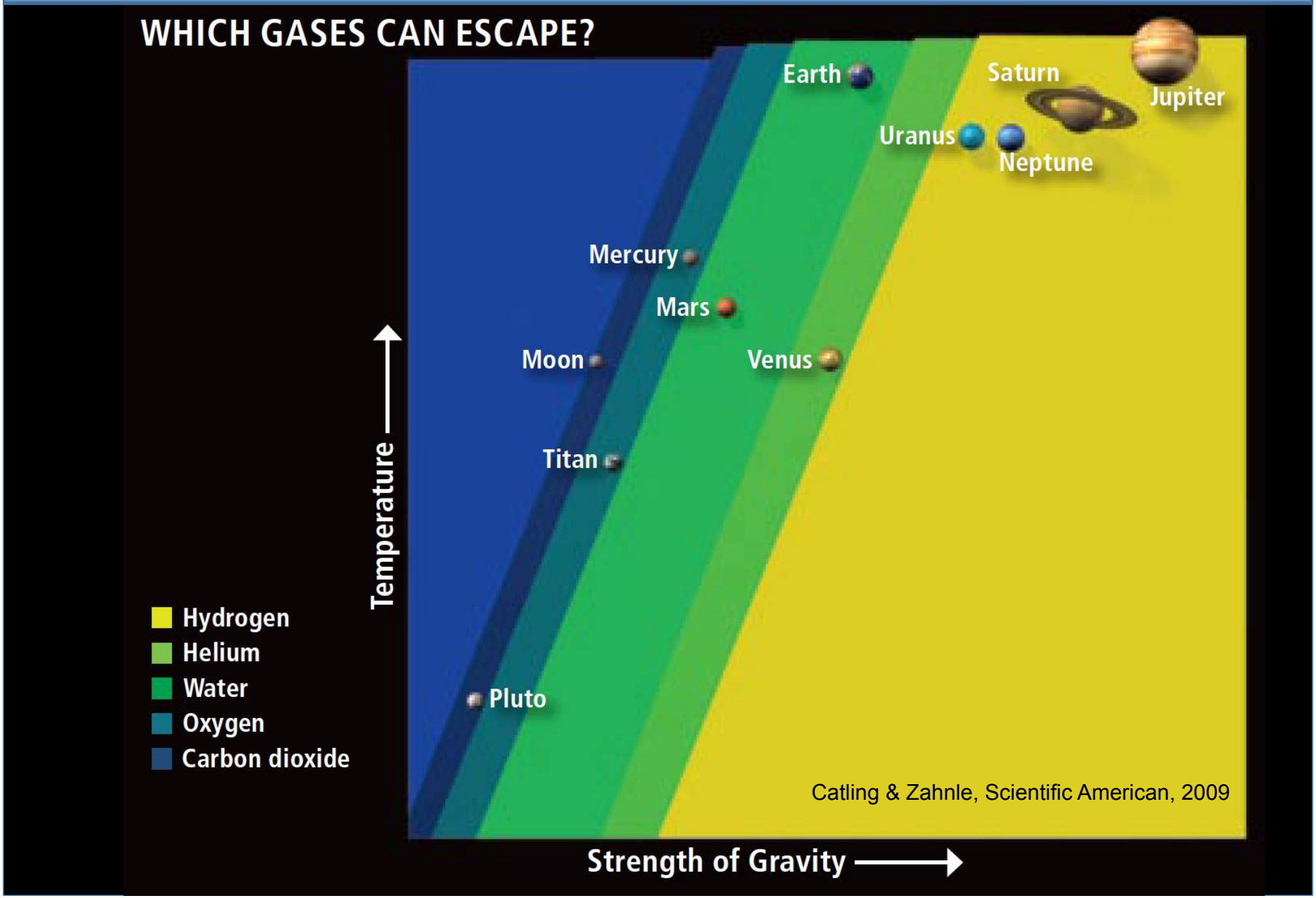
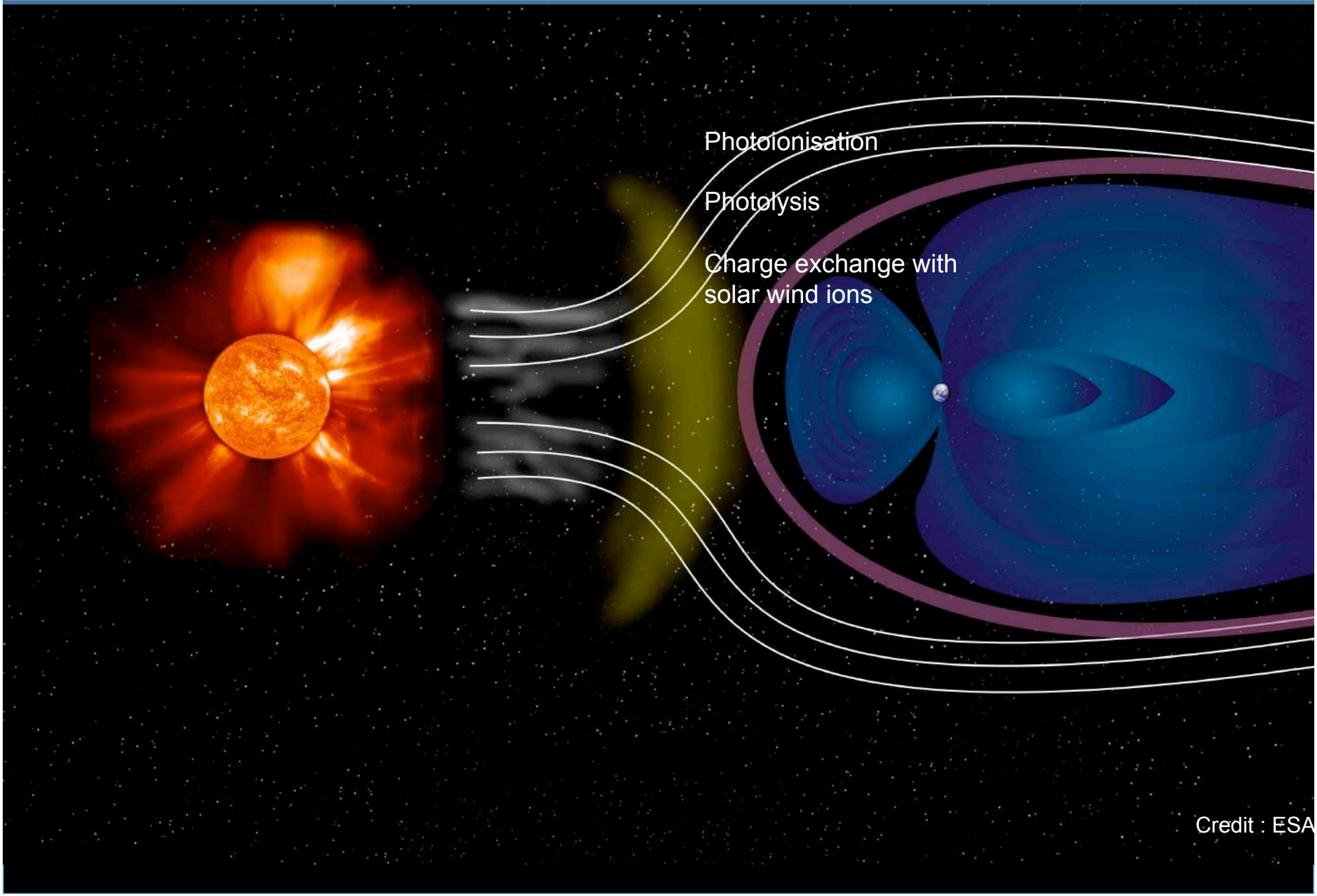


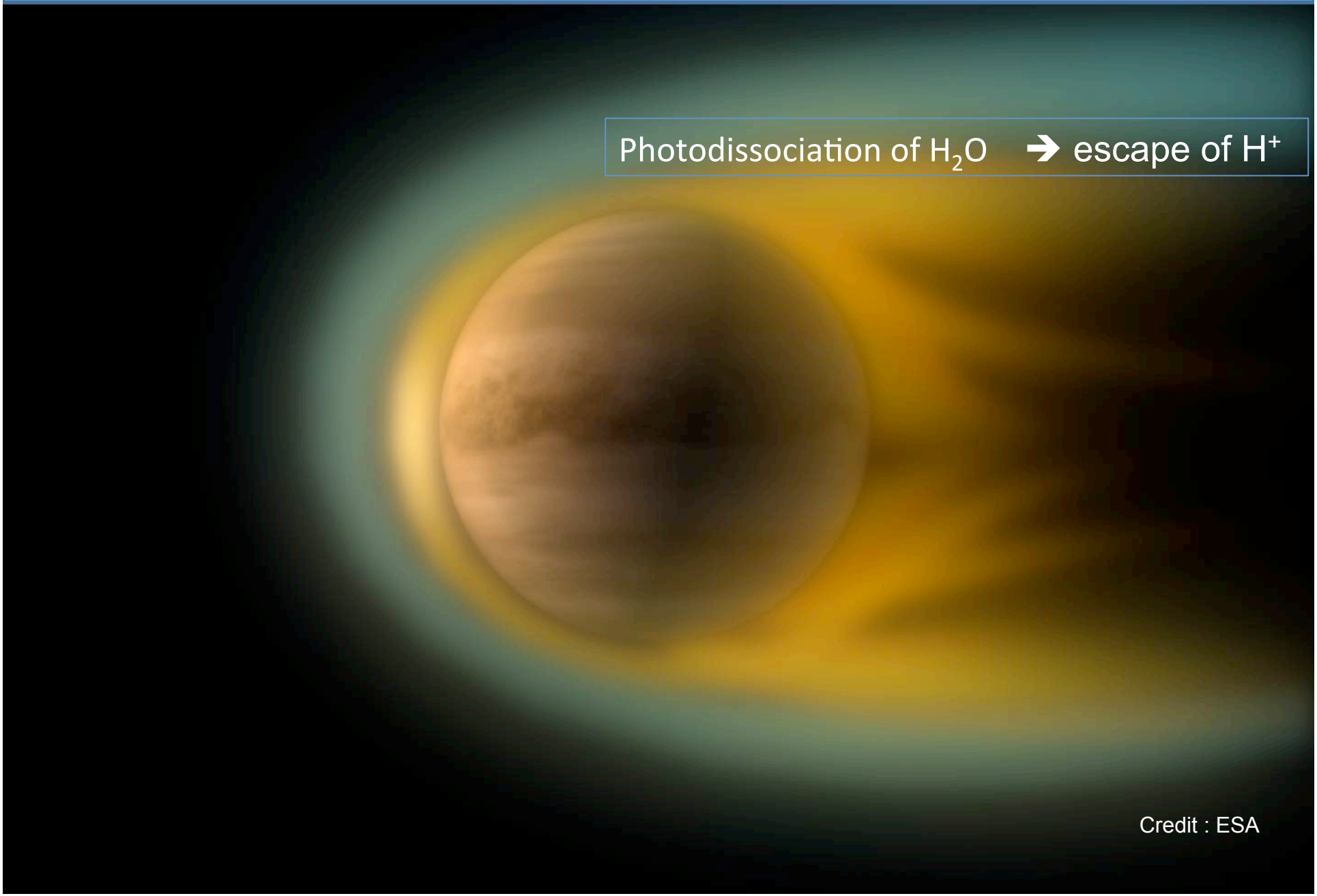
Thermal (mass-related) escape



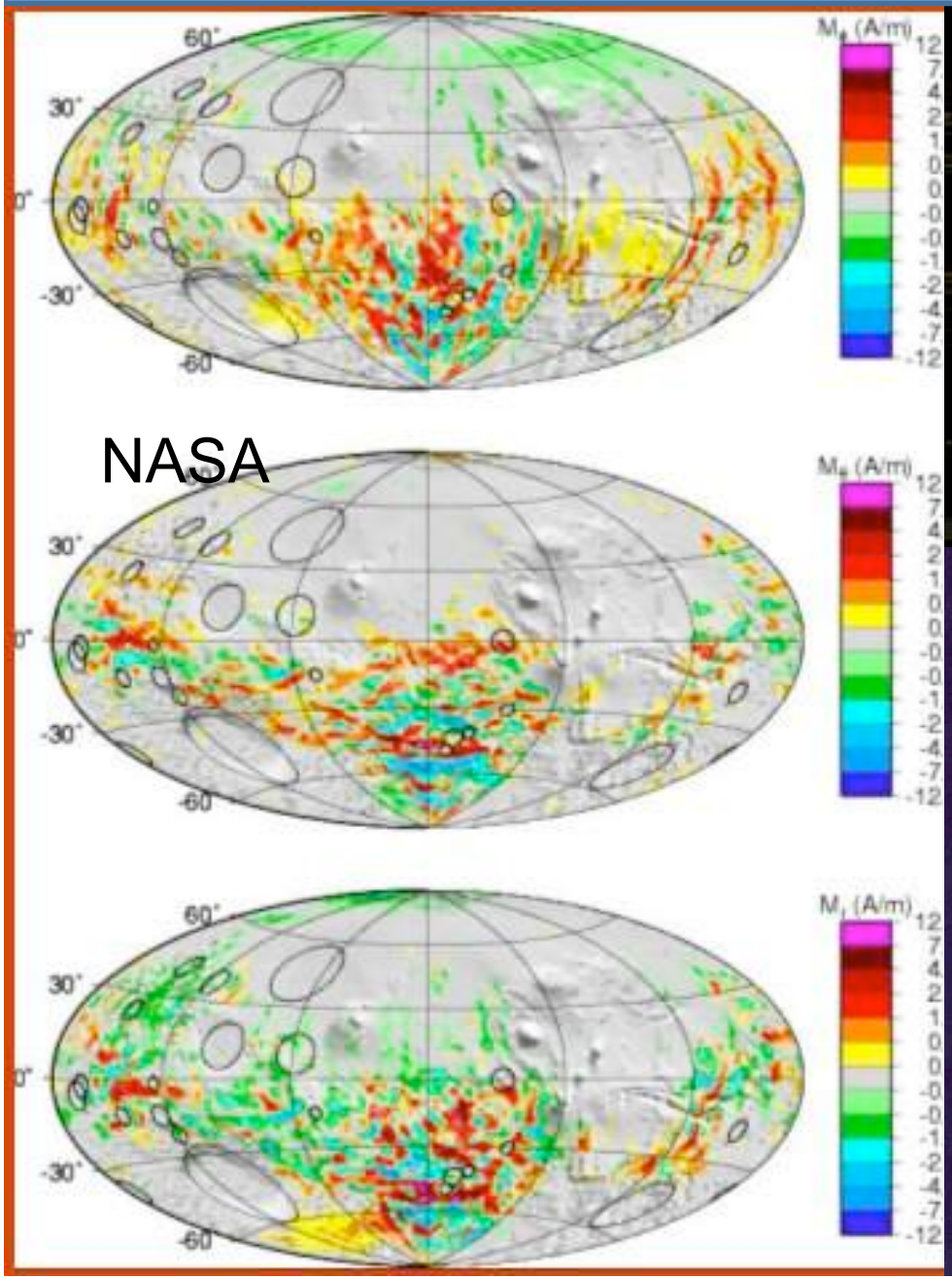
Non-thermal (charge-related) escape

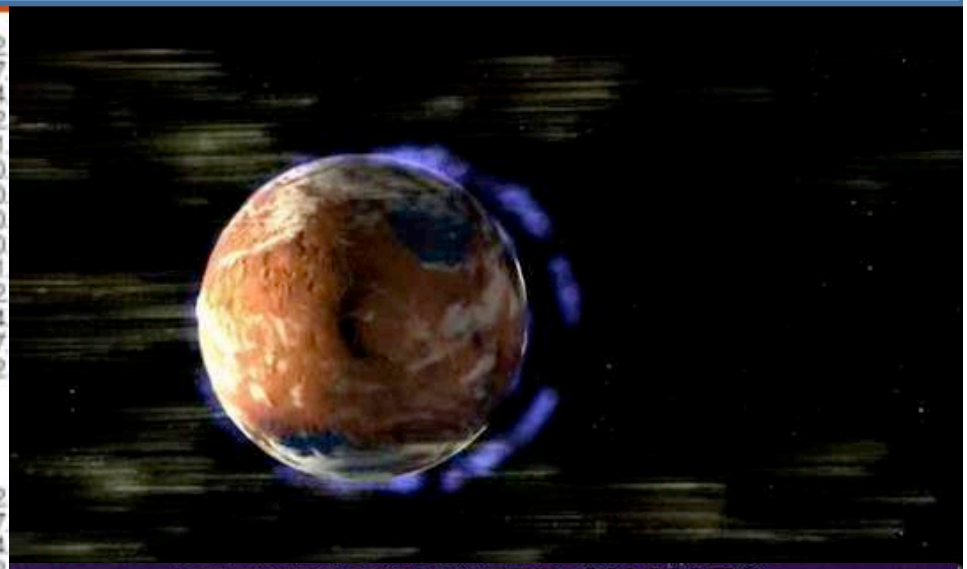


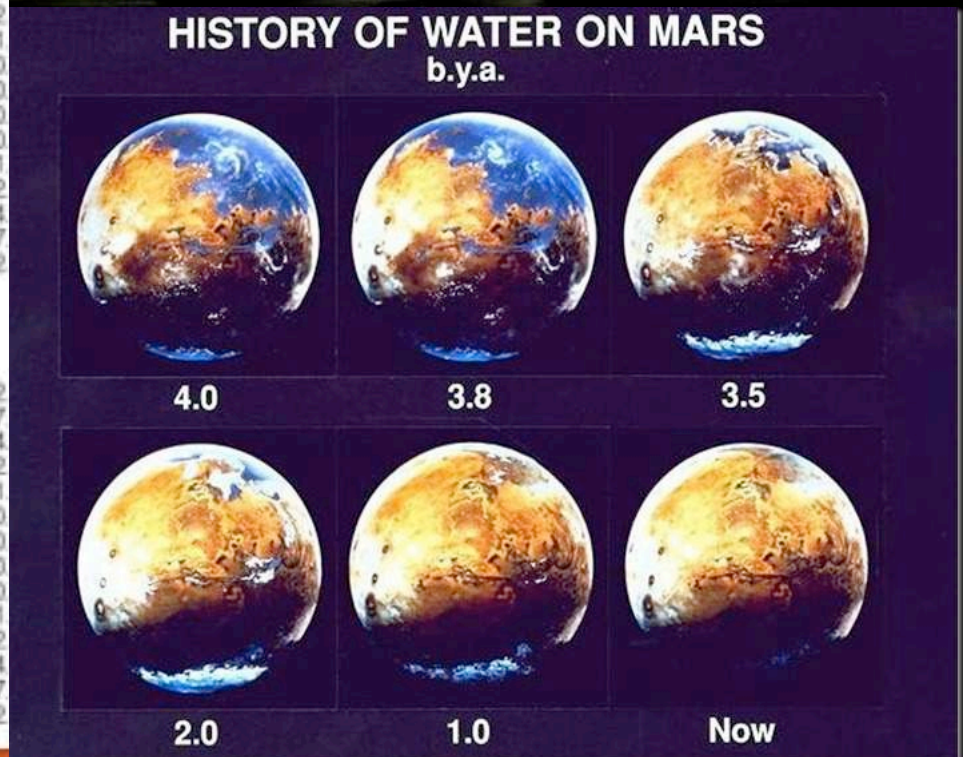
Venus : interactions with solar wind, photodissociation of H_2O by Solar light



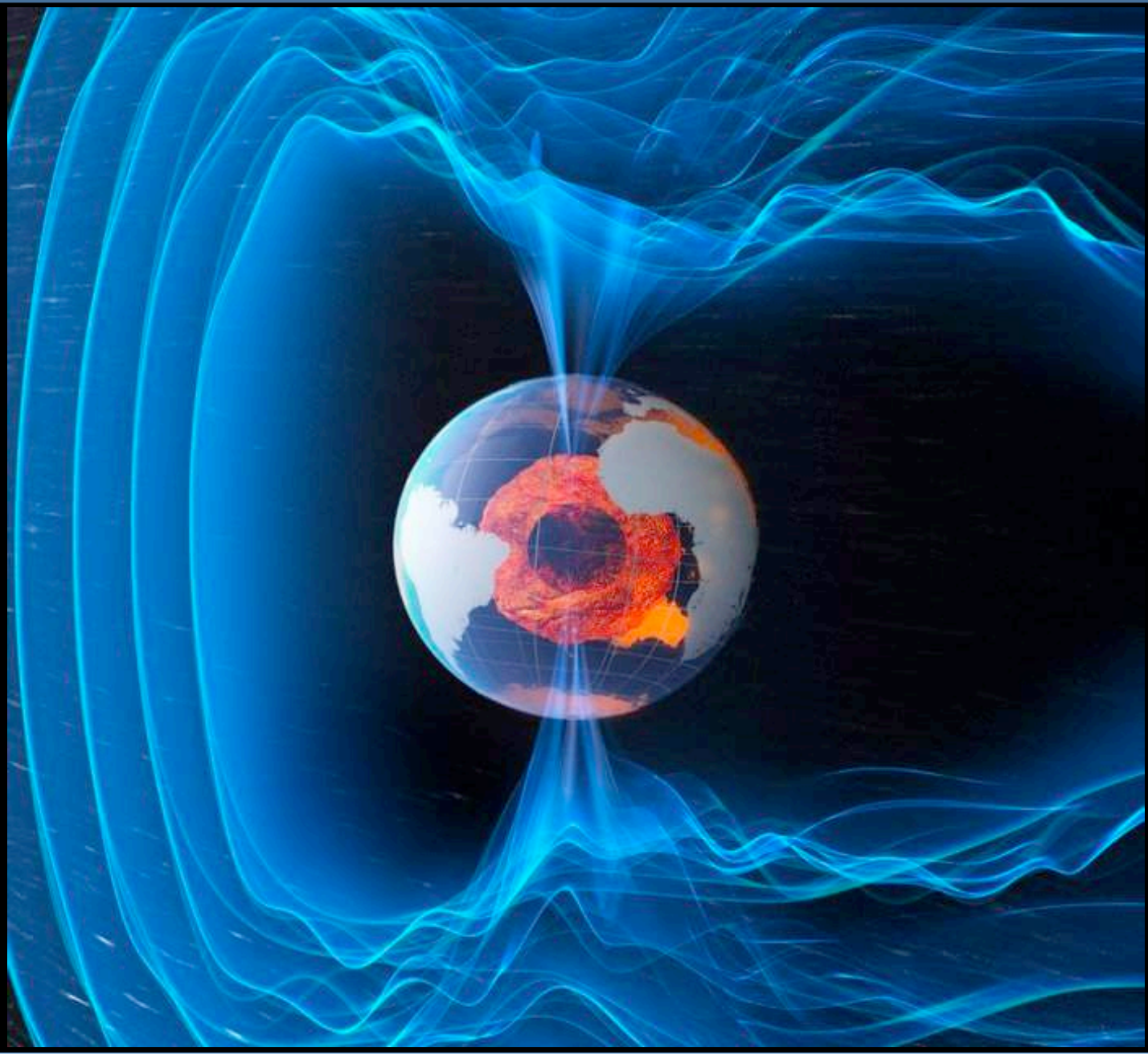
Mars' ancient magnetic field dead







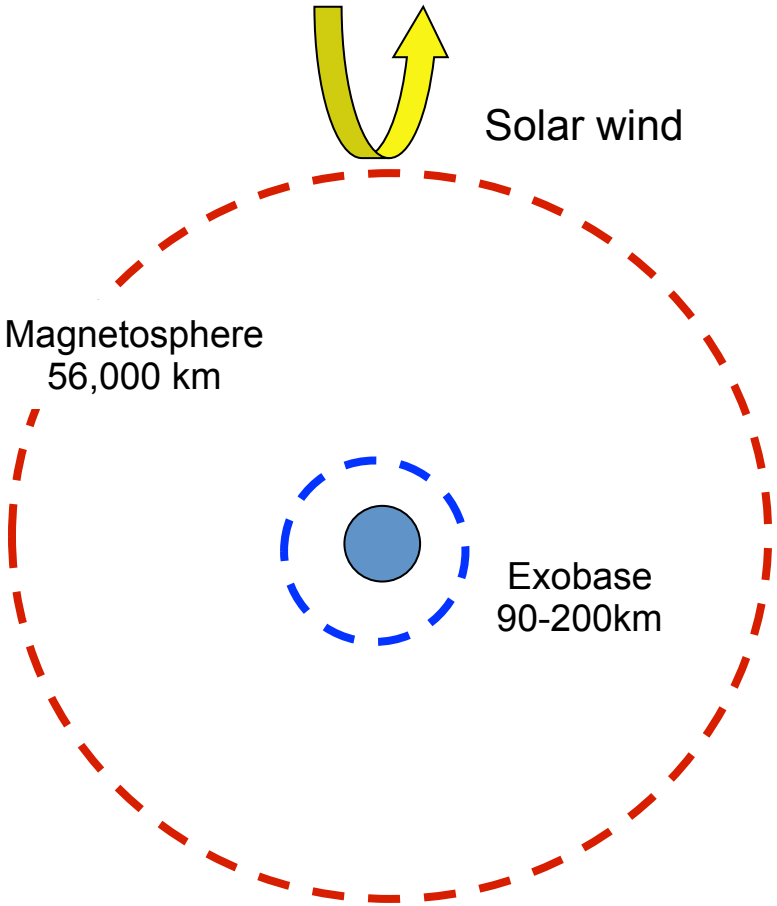
Earth’s magnetic field : active, since when ?



ESA

Ancient atmosphere in Archean (3.5 Ga) rocks

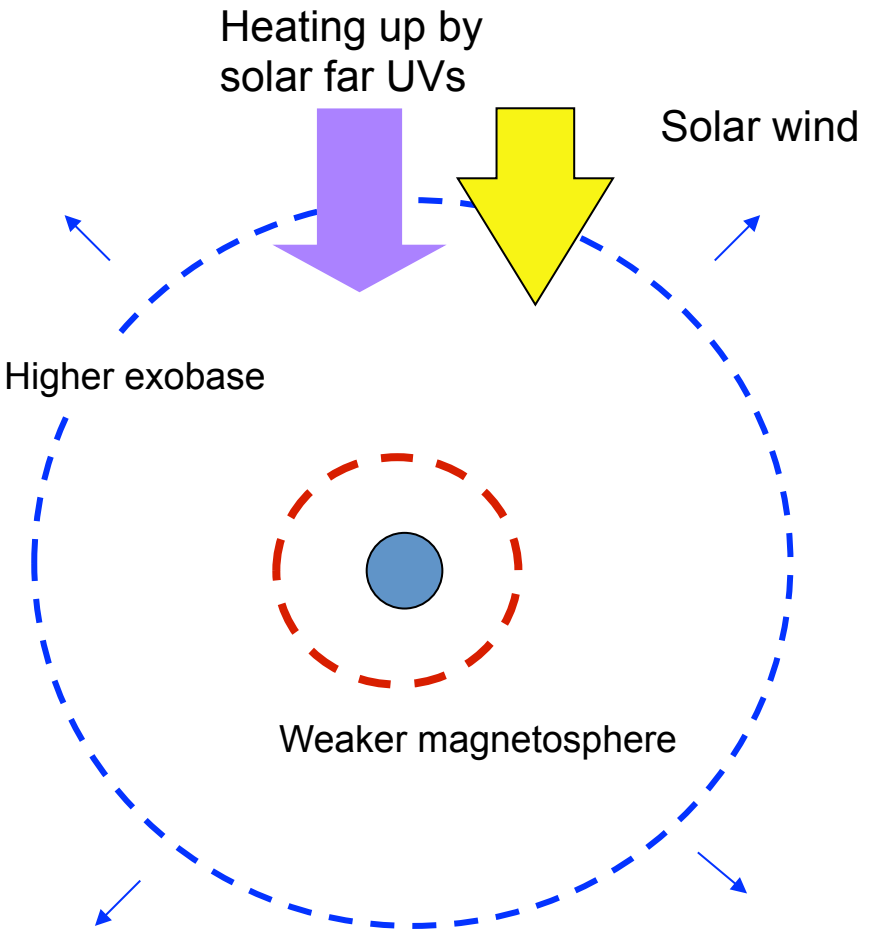
Volcano-sedimentary sequence of the
3.4-3.5 Ga-old Dresser formation,
North Pole, Pilbara, NW Australia



Earth Today

atmosphere shielded from interactions (e.g., charge exchange) with solar wind)

Thermal escape negligible but for H, He



Ancient Earth

- FUVs x 6-10 times, ionization of atm. species
- heating up and expansion of exobase
- weaker/no magnetosphere
- Interactions (e.g., charge exchange) with solar wind
- Thermal / non thermal escape ?

See Lichtenegger et al., 2010, Tarduno et al., 2014

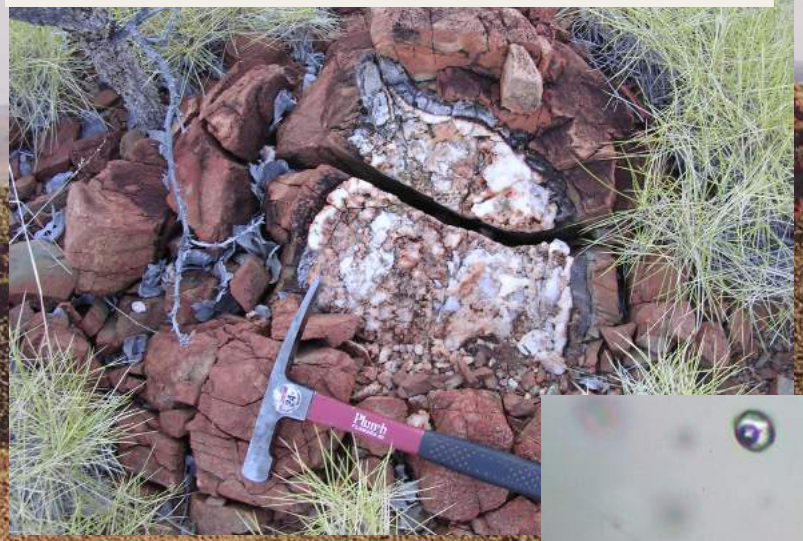
Ancient atmosphere in Archean (3.5 Ga) rocks

Paleo-atmospheric gases trapped in ancient chemical sediments

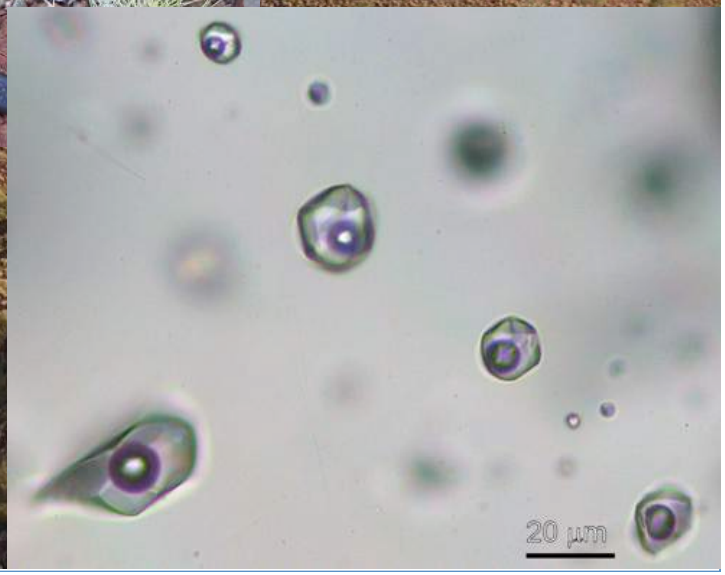
Archean barite

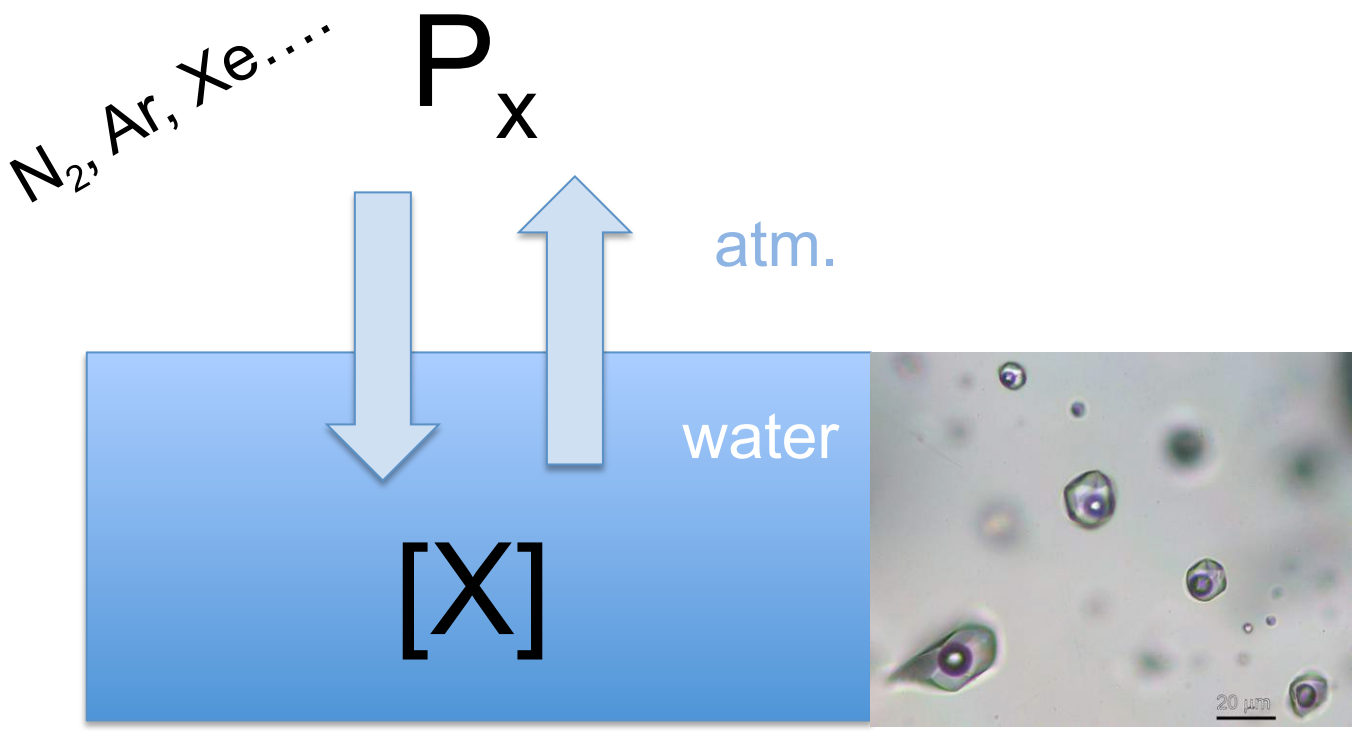
U-Xe age : 3.5±0.2 Ga

Fluid inclusions in hydrothermal quartz



- Age : 3.48 Ga (Sm-Nd, U-Pb)
- Ar-Ar plateau age at 3.0±0.2 Ga





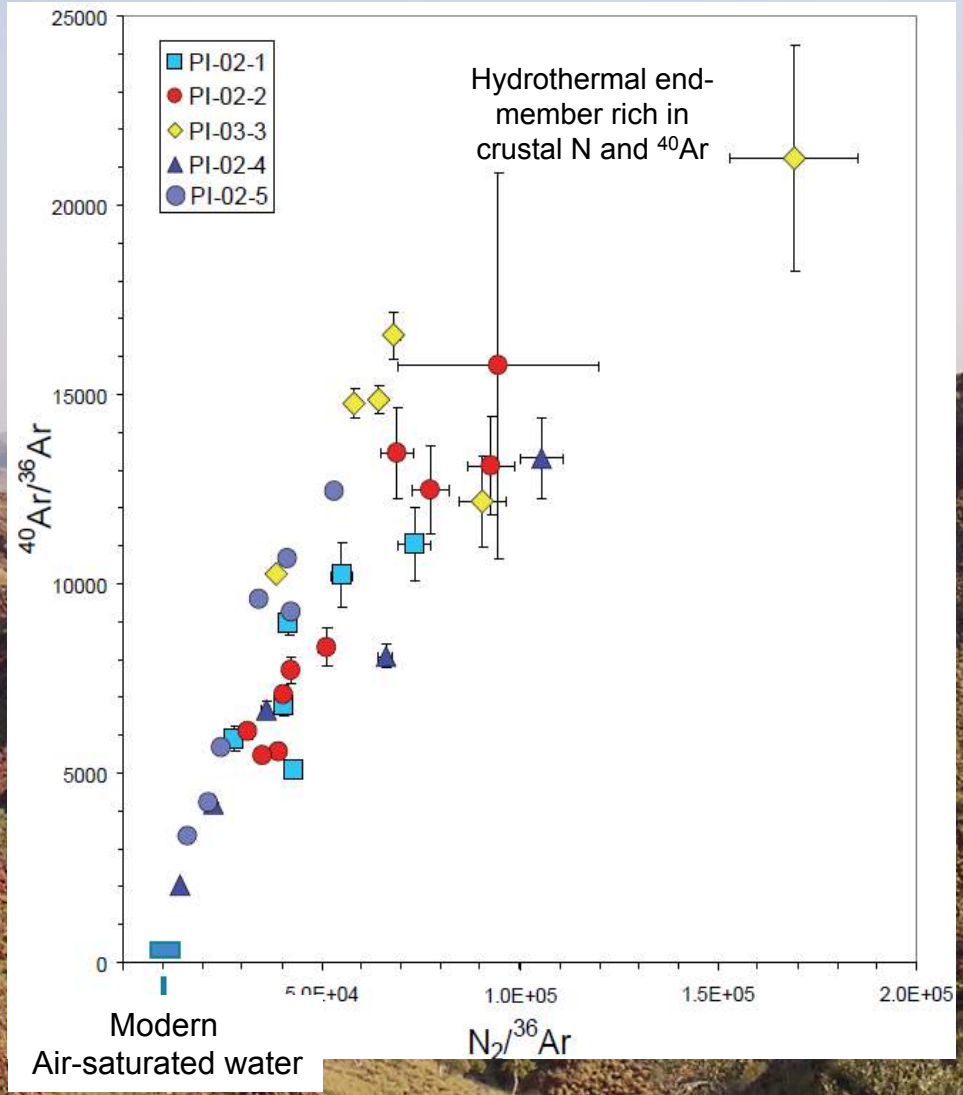
Elements :

$$[X/Y]_{water} = (K_x/K_y) \times (P_x/P_y)_{atm}$$

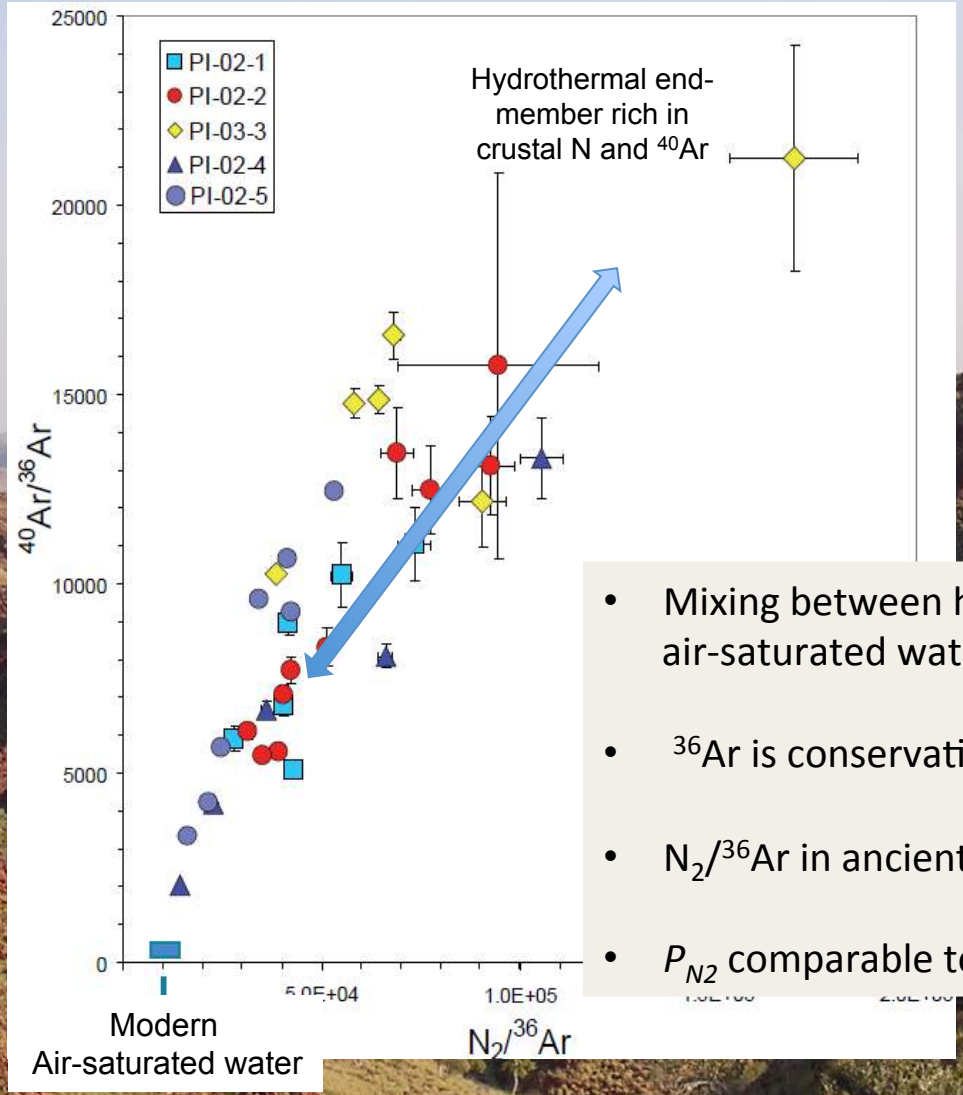
Isotopes :

$$[^iX/^jY]_{water} \approx (^iX/^jY)_{atm}$$

1- Nitrogen: onset of terrestrial magnetic field ?

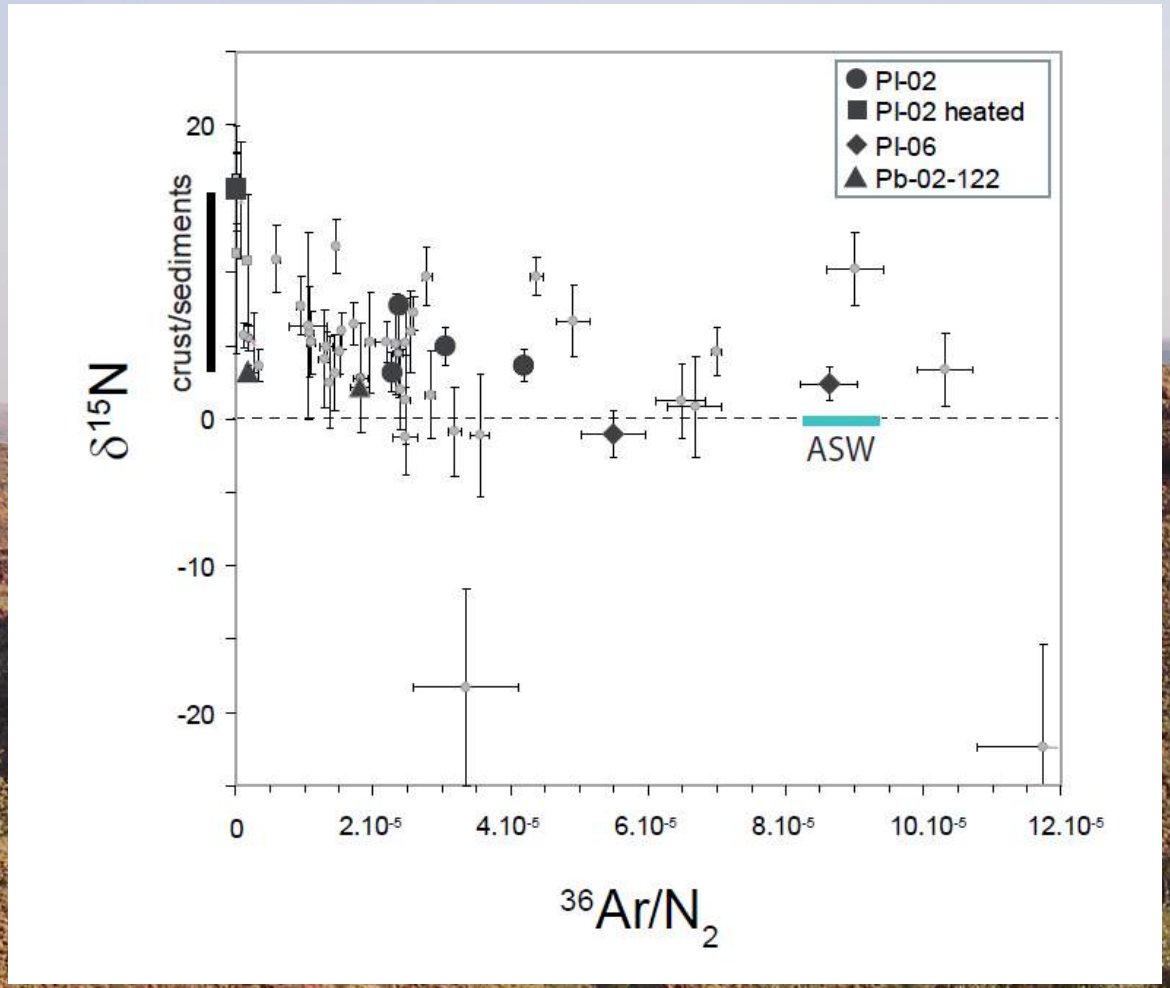


Nitrogen: onset of terrestrial magnetic field ?

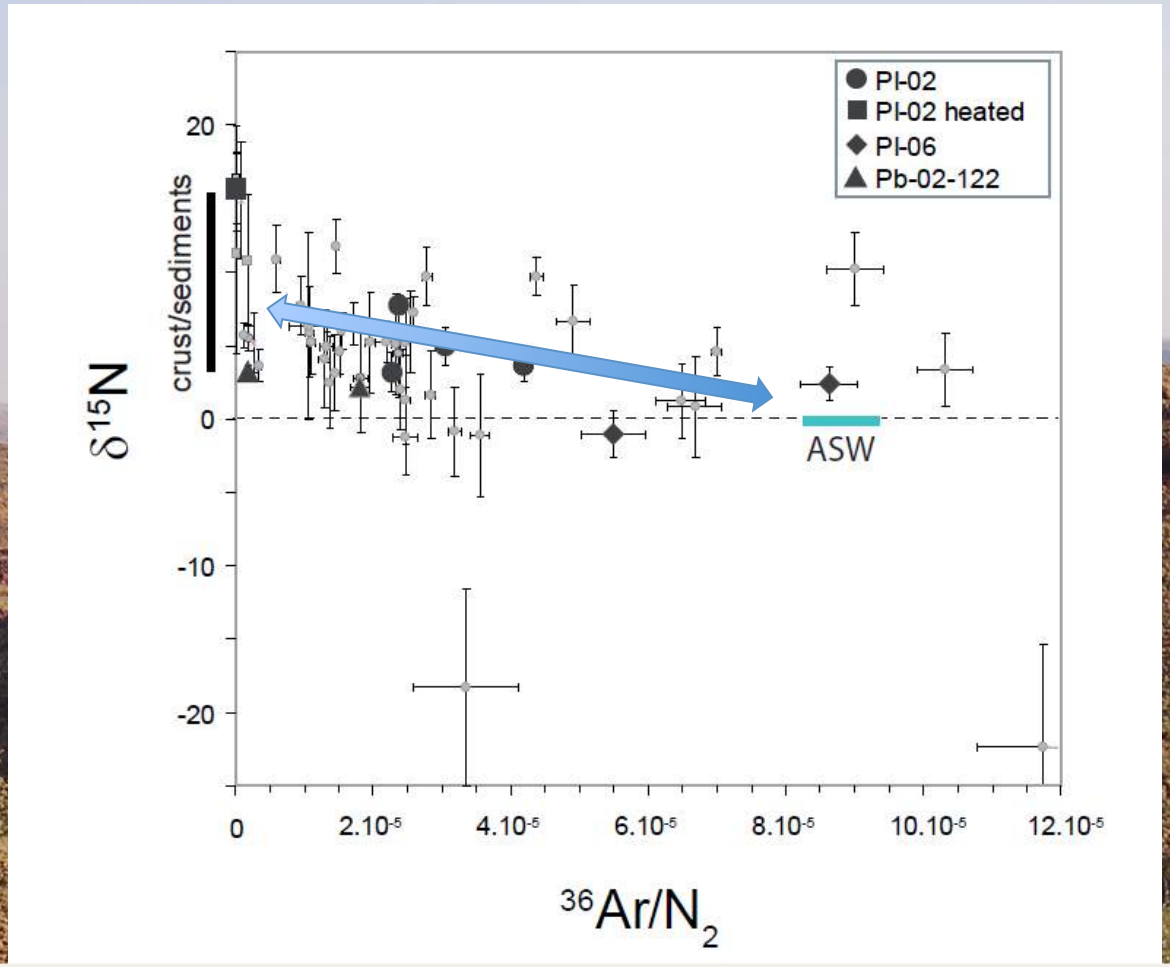


- Mixing between hydrothermal end-member and air-saturated water
- ^{36}Ar is conservative in the atmosphere (isotopes)
- $N_2/^{36}Ar$ in ancient air-saturated water ≅ modern
- P_{N2} comparable to modern

Nitrogen: onset of terrestrial magnetic field ?



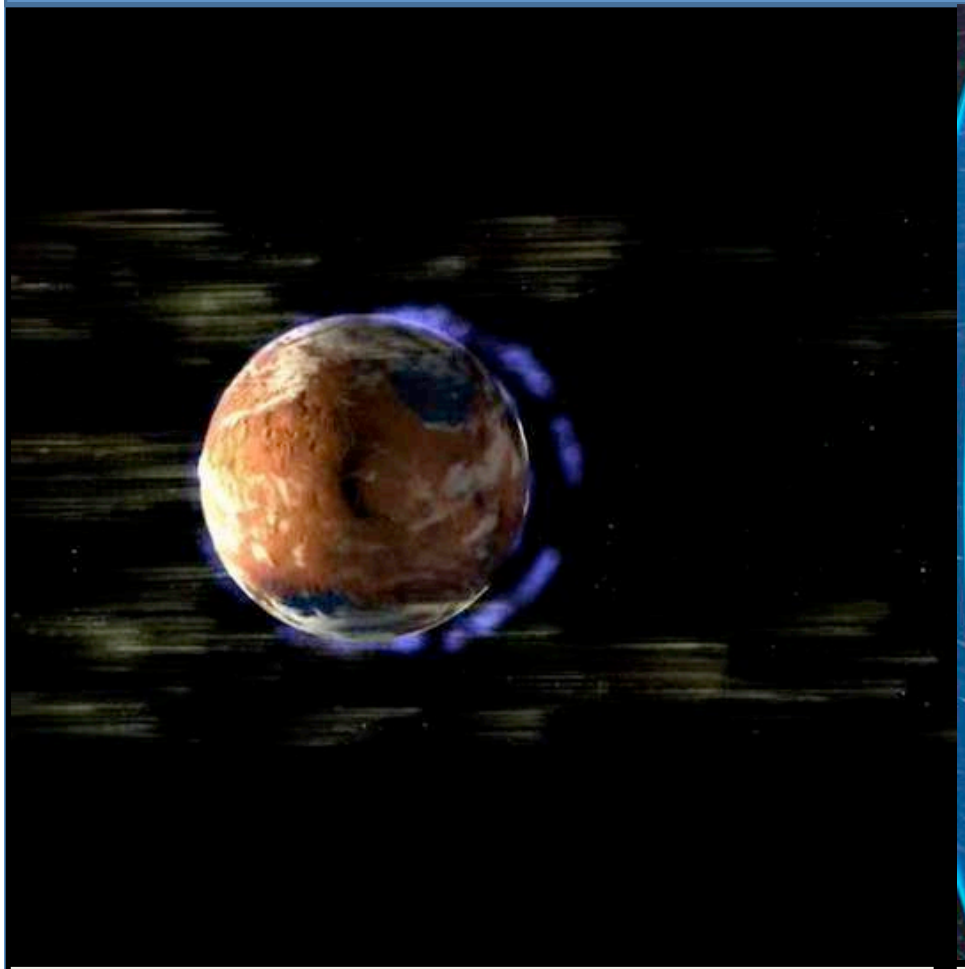
Nitrogen: onset of terrestrial magnetic field ?



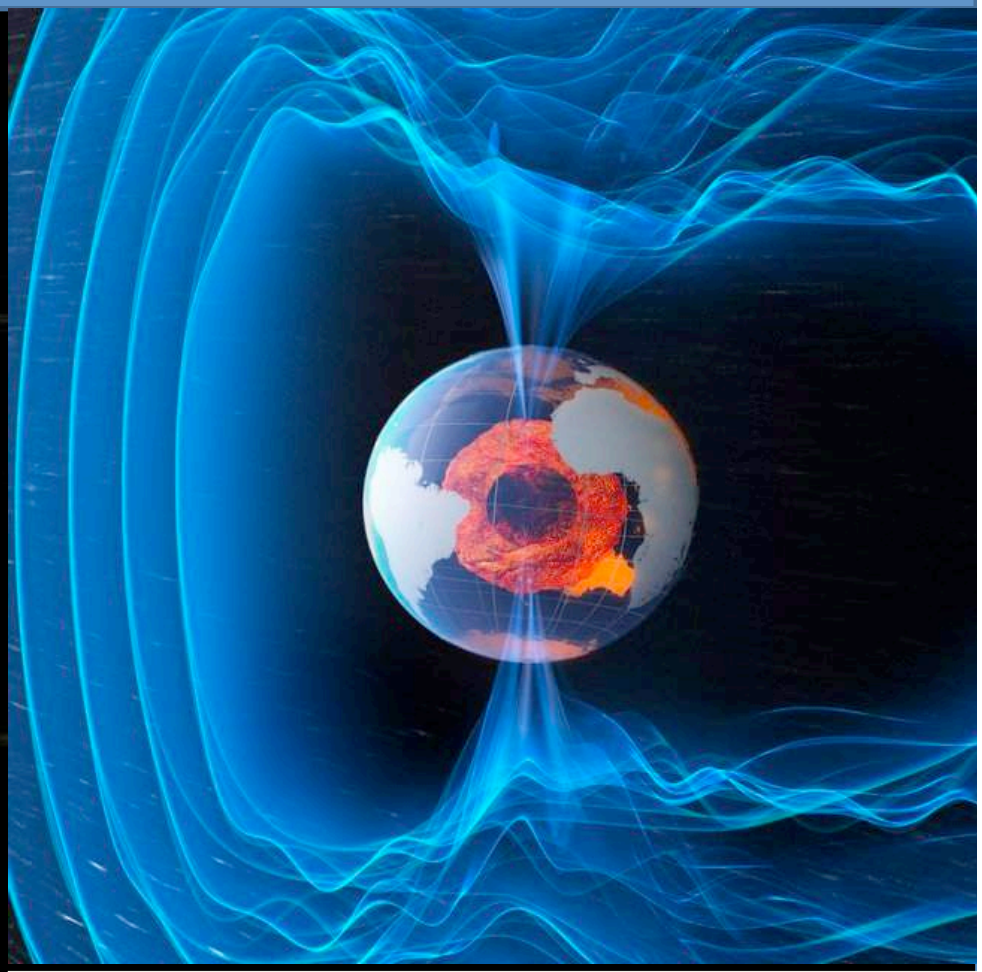
- Nitrogen isotopes : mixing between a crustal end-member and air-saturated water $^{15}N/^{14}N$ in the Archean atm. 3.5 Ga ago ~ modern value

- P_{N2} comparable to Modern ➔ no atm. Escape for N since 3.5 Ga

1- Nitrogen: onset of terrestrial magnetic field



Mars: atmospheric nitrogen enriched in ^{15}N by 60 % relative to Earth : evidence for atmospheric escape through time, no magnetic field



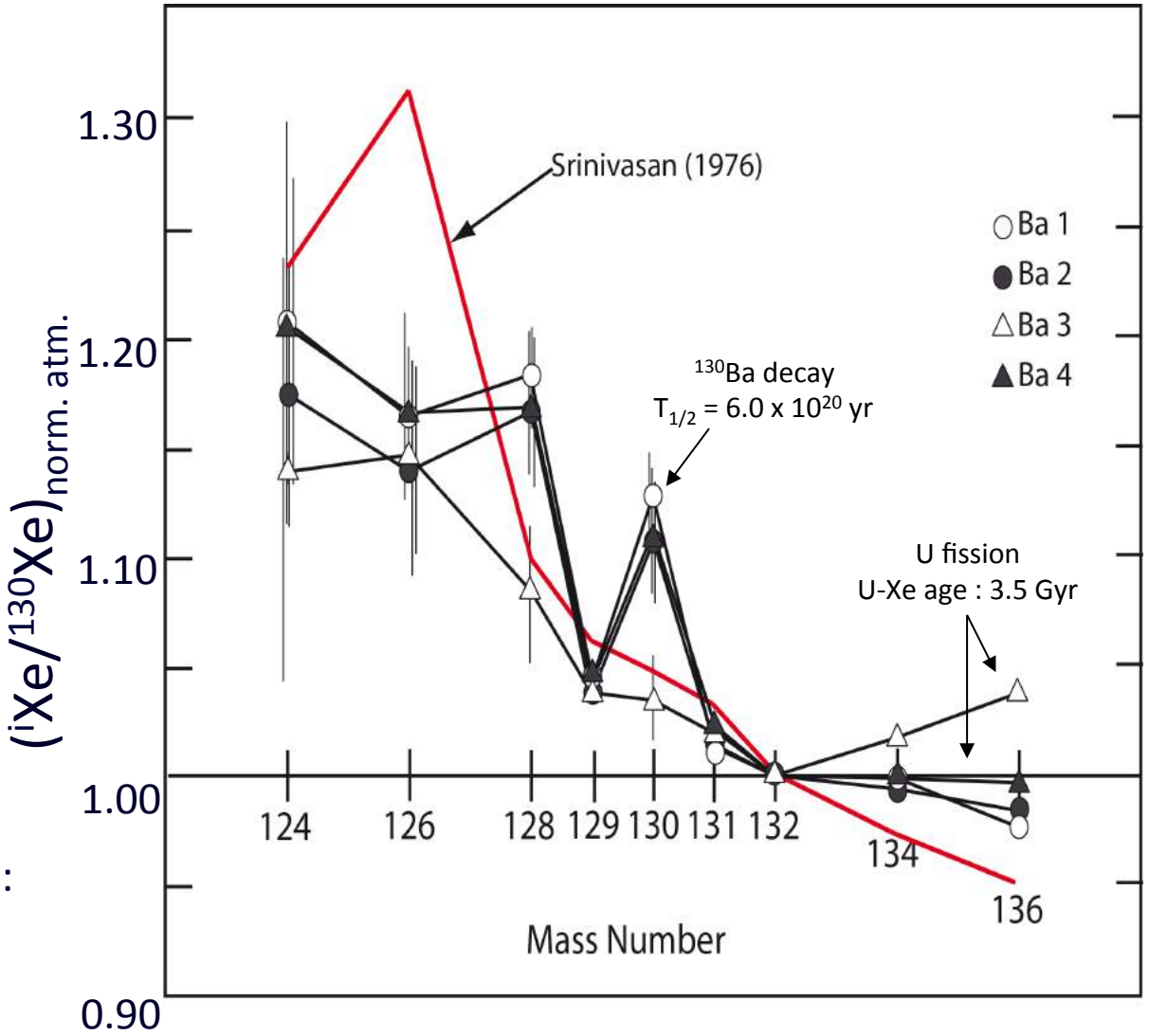
Earth: $^{15}N/^{14}N$ in the Archean atm. 3.5 Ga ago ~ modern value : magnetic field since at least 3.5 Ga

(Marty et al., Science 2013)

Xenon isotopes and the evolution of the solar UV flux through time

U-Xe age : 3.5±0.2 Ga

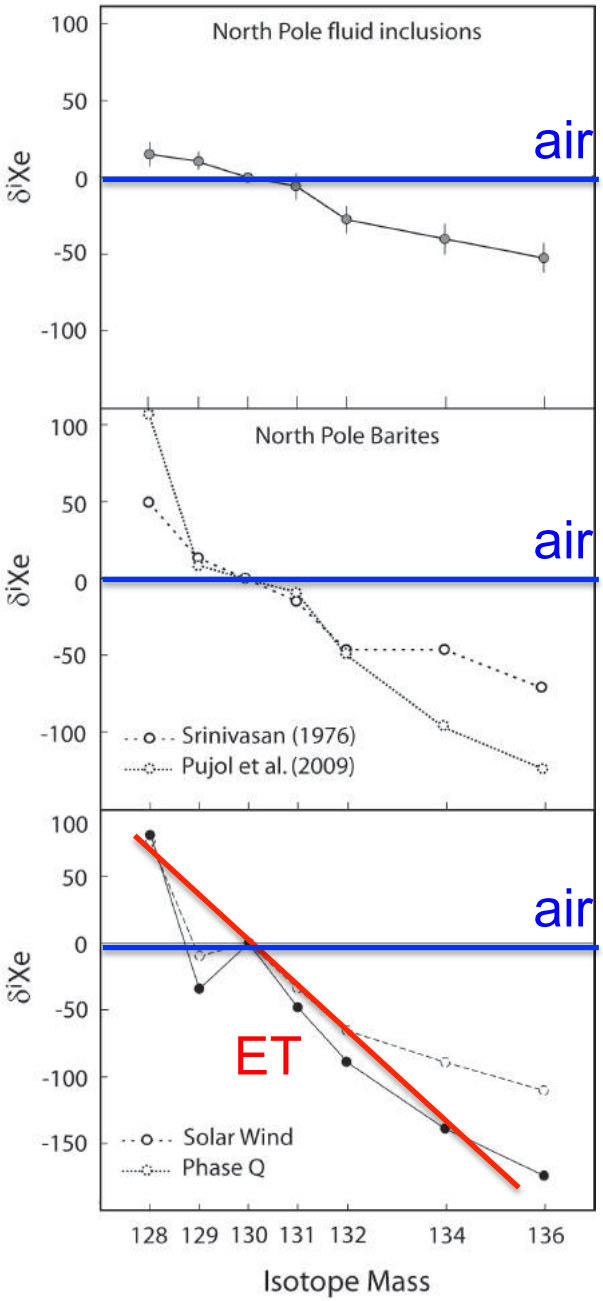
Xenon in Archean samples : 3.5 Ga-old barite, North Pole, Pilbara

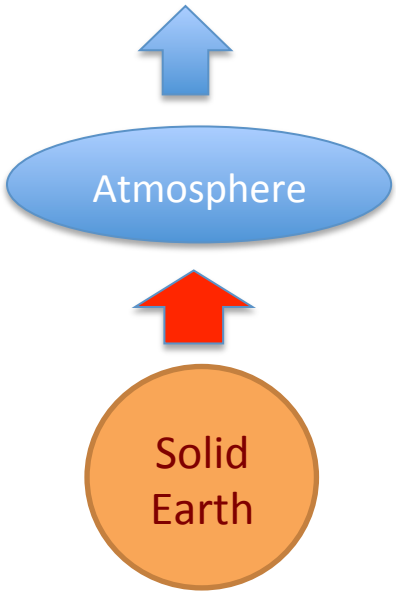


Pujol et al., GCA, 2009

Xenon isotopes and the evolution of the solar UV flux through time

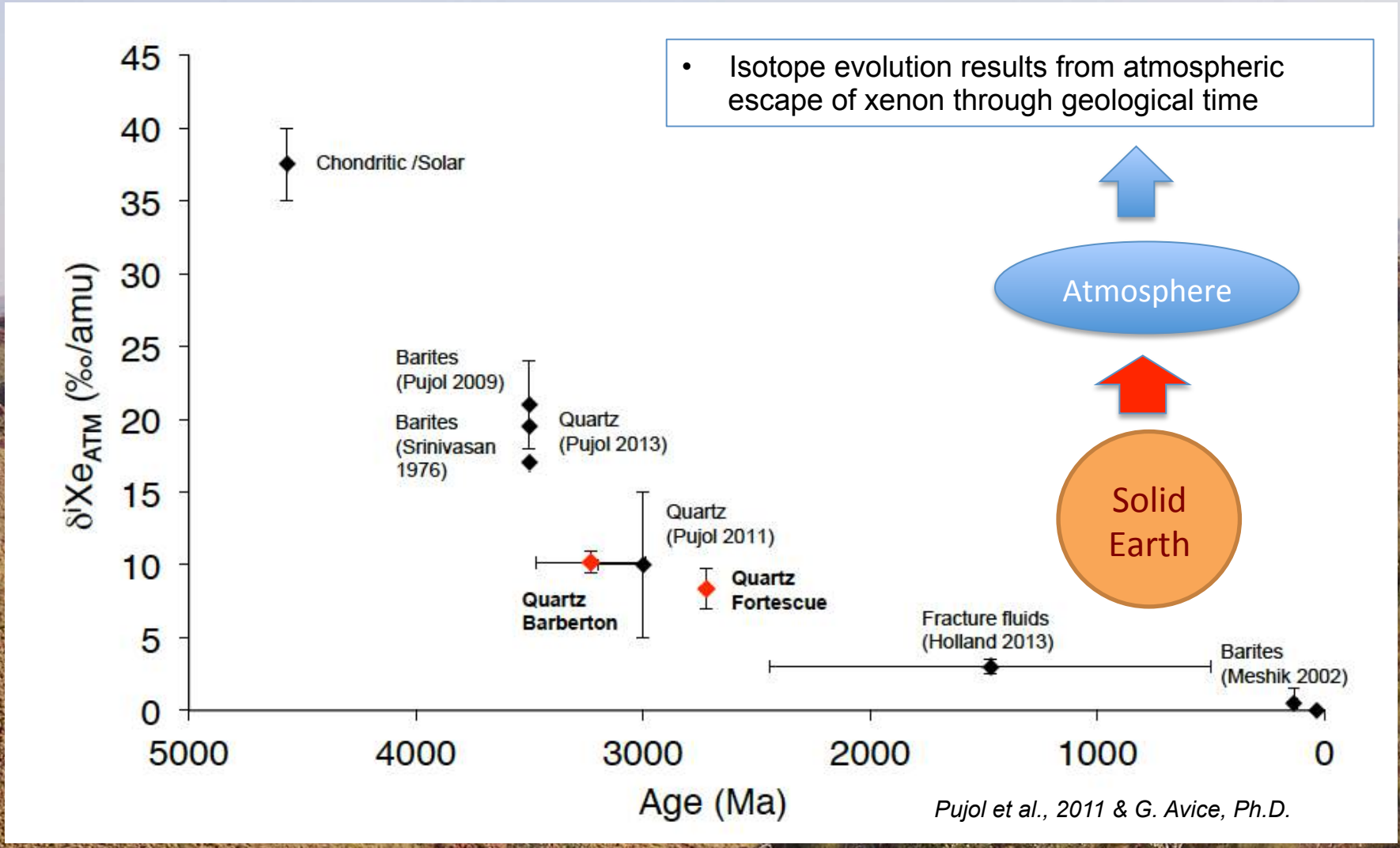
Ne, Kr isotopic compositions similar to modern ones





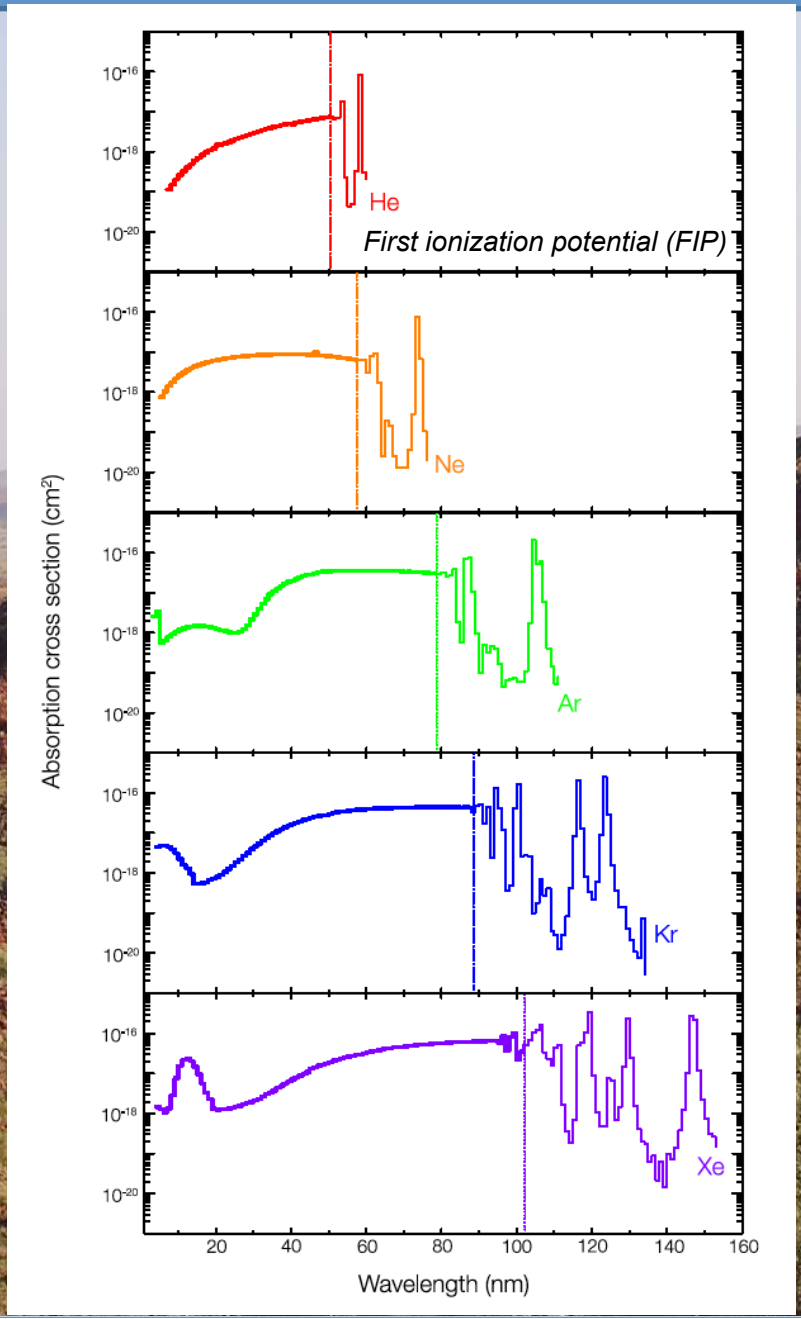
Pujol et al., EPSL 2011

Xenon isotopes and the evolution of the solar UV flux through time

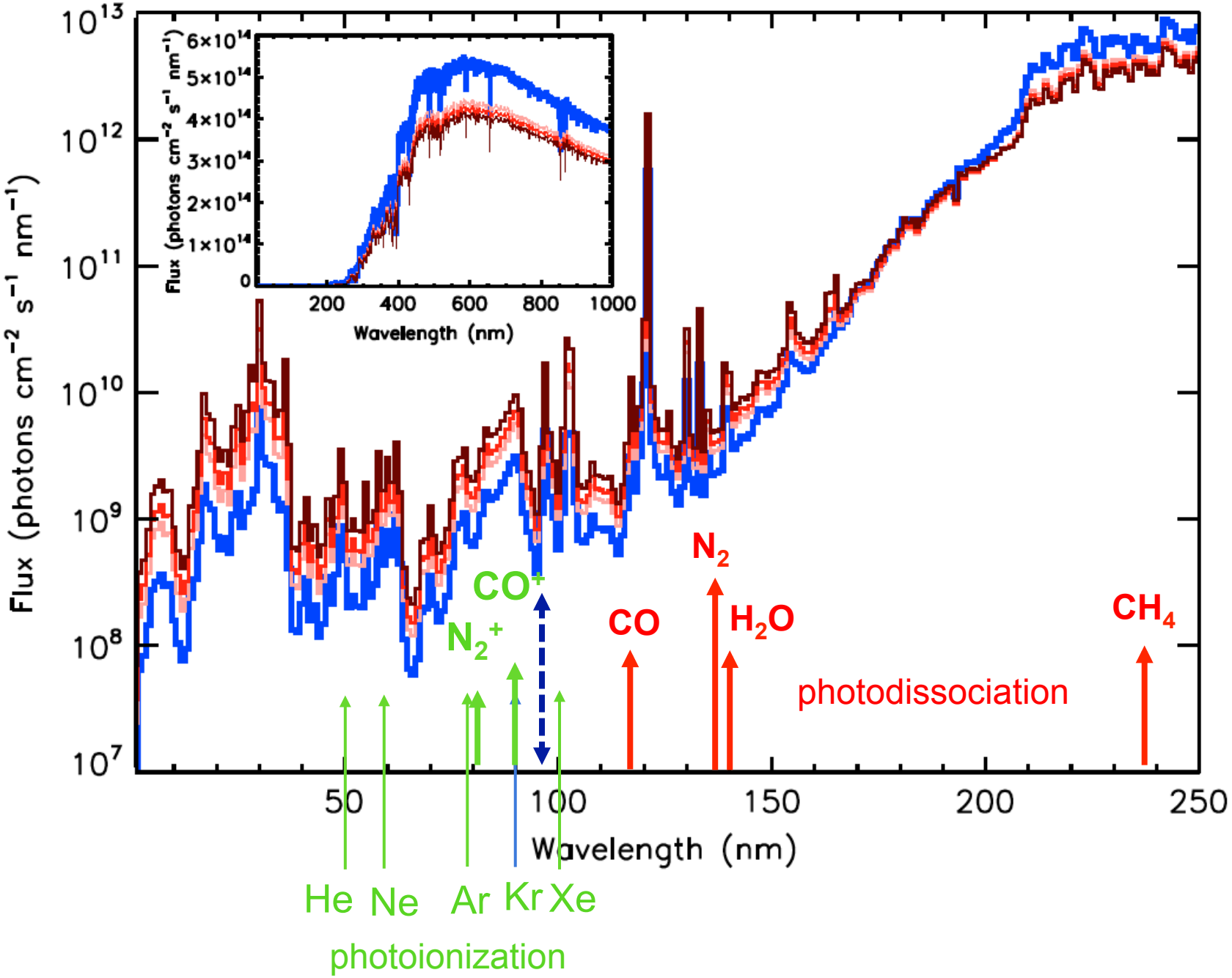


Pujol et al., 2011 & G. Avice, Ph.D.

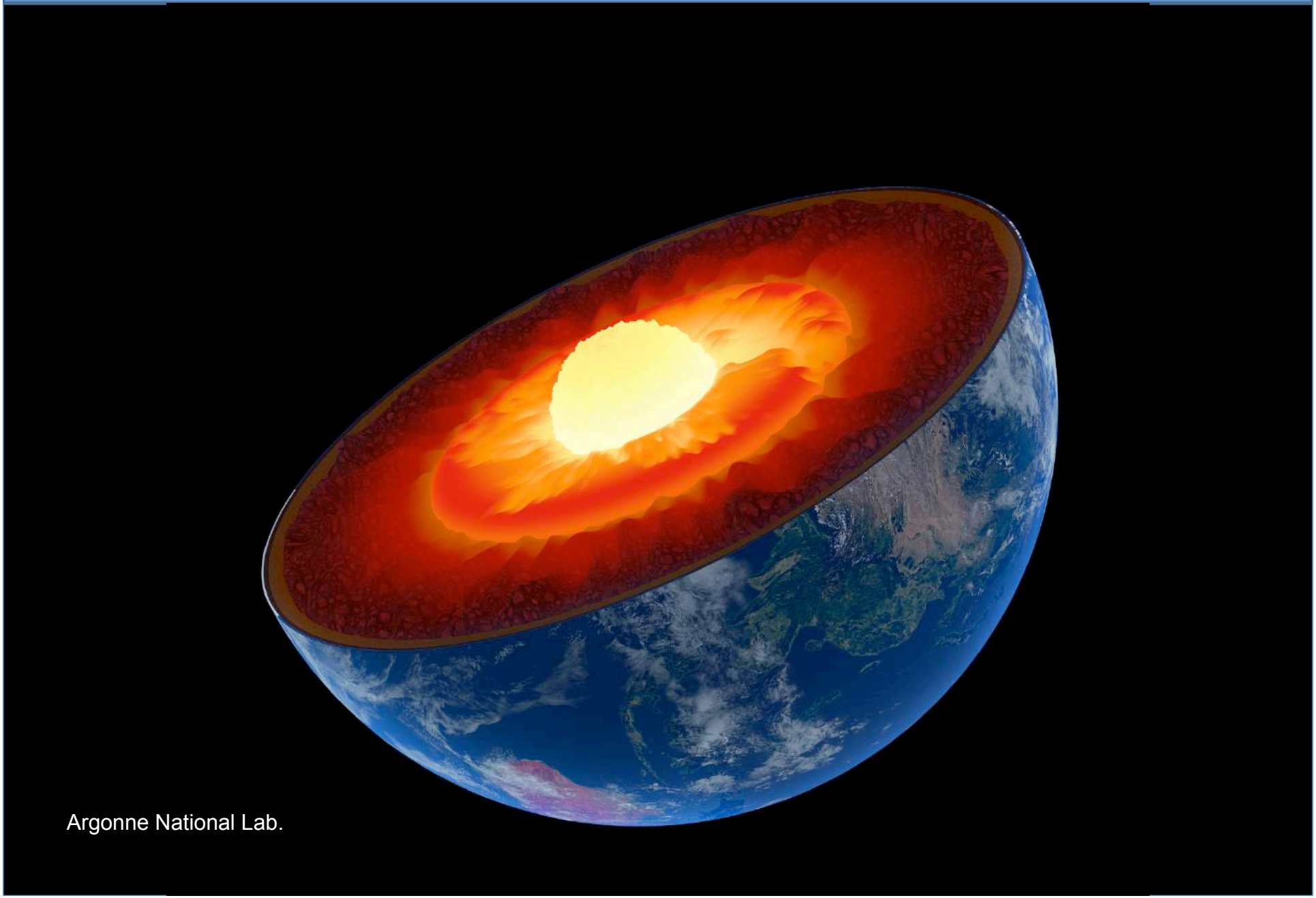
Xenon isotopes and the evolution of the solar UV flux through time



Hébrard & Marty, 2014

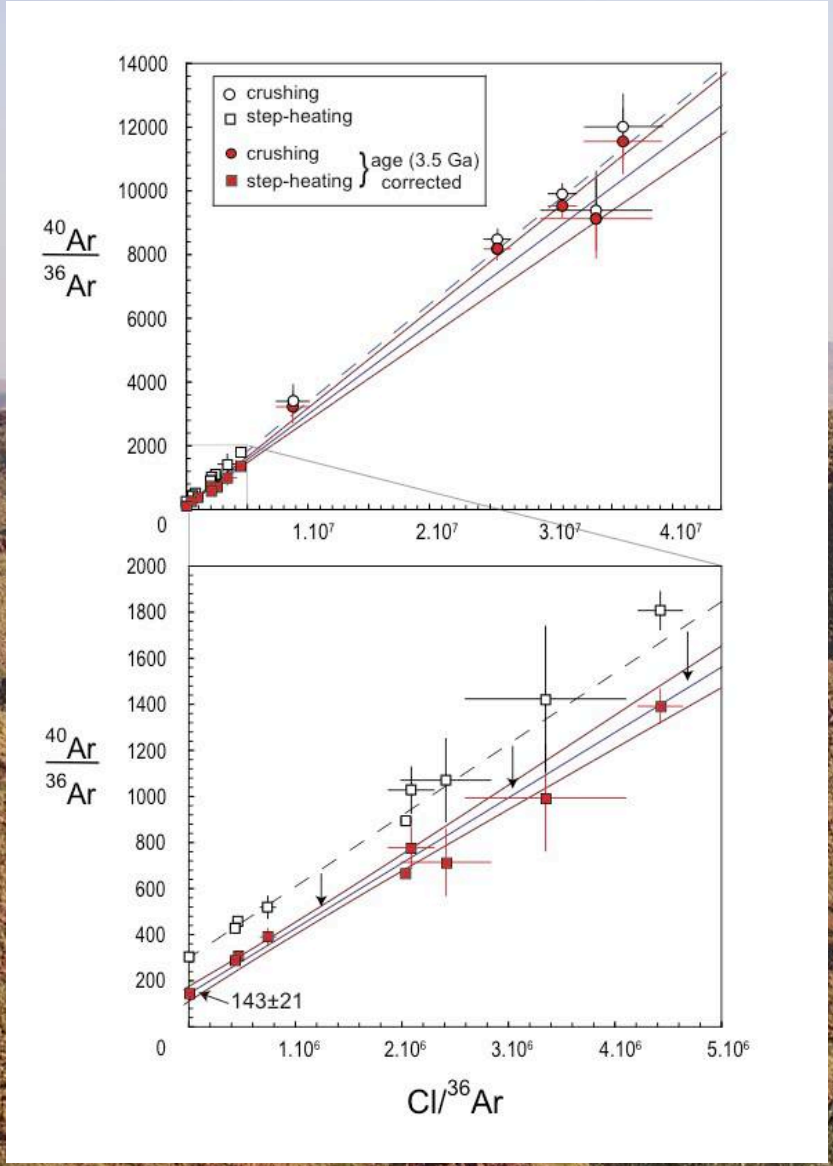

Flux (photons cm^{-2} s^{-1} nm^{-1})
Wavelength (nm)
Flux (photons cm^{-2} s^{-1} nm^{-1})
Wavelength (nm)
CO^+
N_2^+
CO
N_2
H_2O
CH_4
photodissociation
He Ne Ar Kr Xe
photoionization

Earth : dynamically active planet, exchange of volatile elements between interior and surface



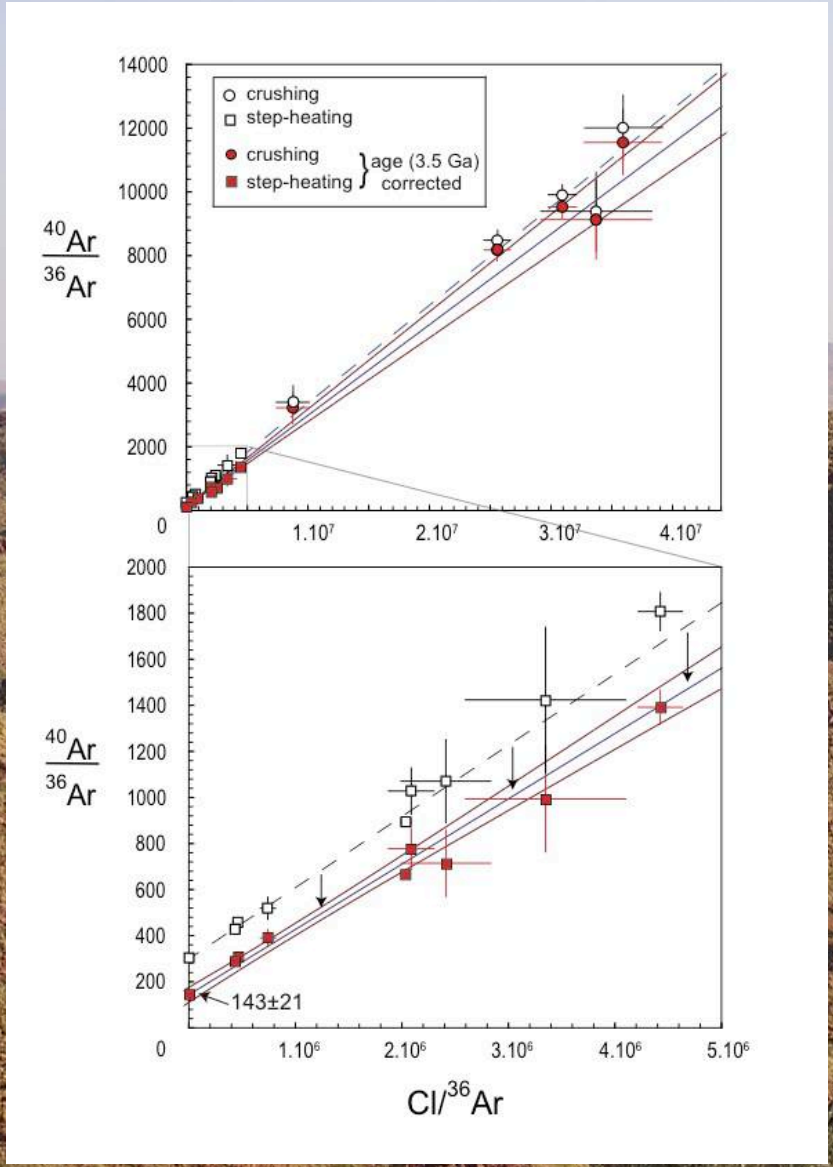
Argonne National Lab.

Argon isotopes and crustal evolution



- Mixing correlation between surface water and hydrothermal fluid rich in ^{40}Ar and Cl

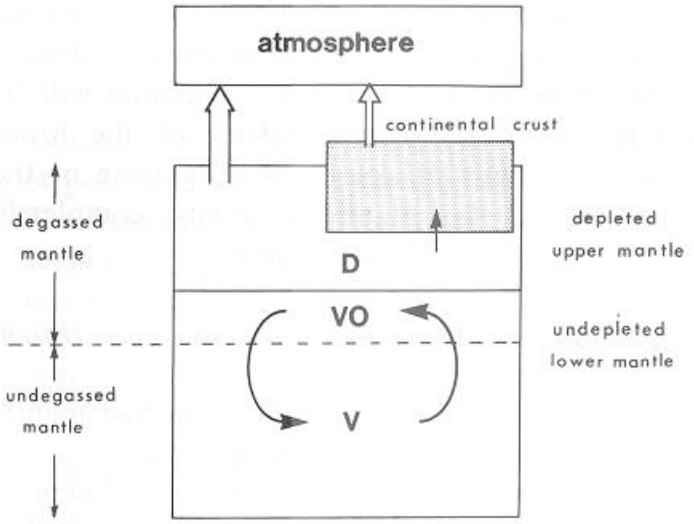
Argon isotopes and crustal evolution



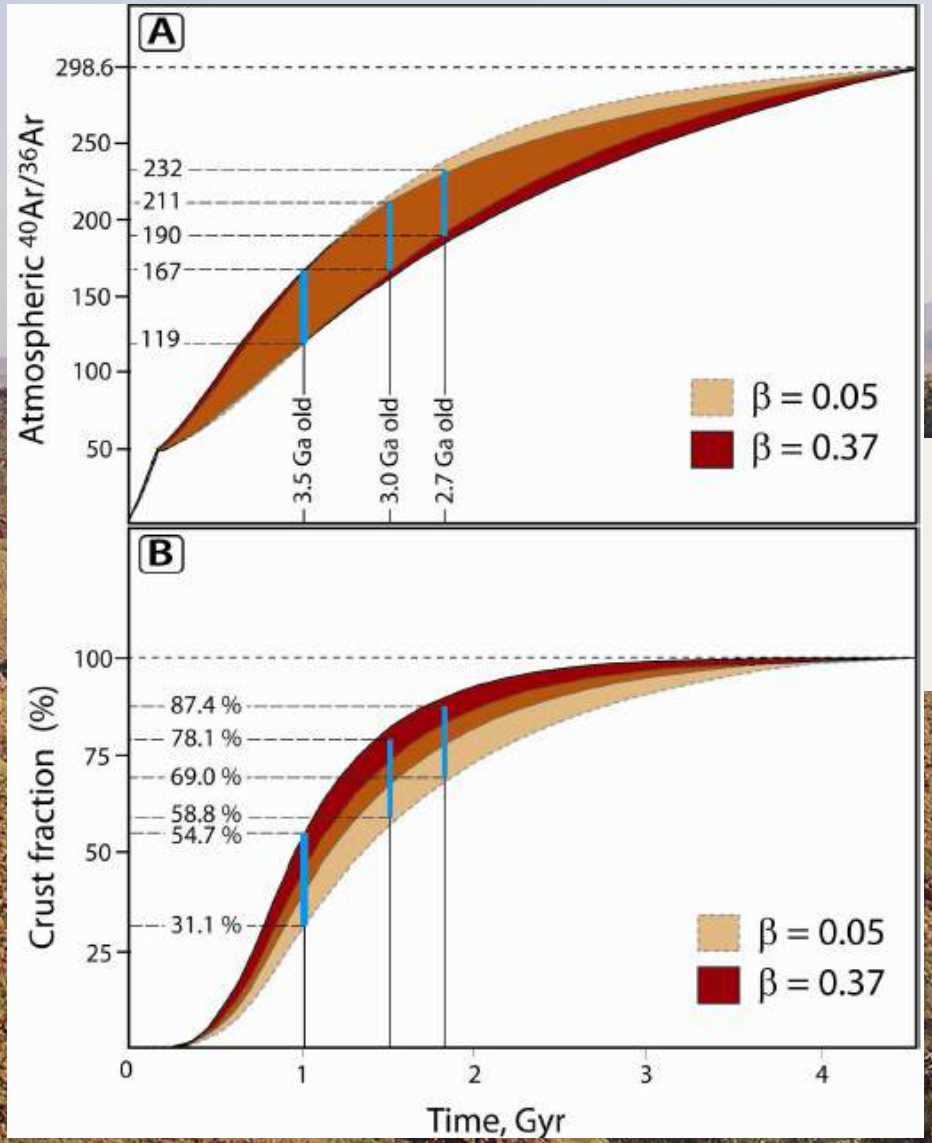
- Mixing correlation between surface water and hydrothermal fluid rich in ^{40}Ar and Cl

- $^{40}K \rightarrow {}^{40}Ar$ ($T_{1/2}$ = 1.25 Ga)
- $^{40}Ar_{initial} \approx 0$

- Atmospheric $^{40}Ar/^{36}Ar$ = 143±34
  3.5 billion years ago (now 298)



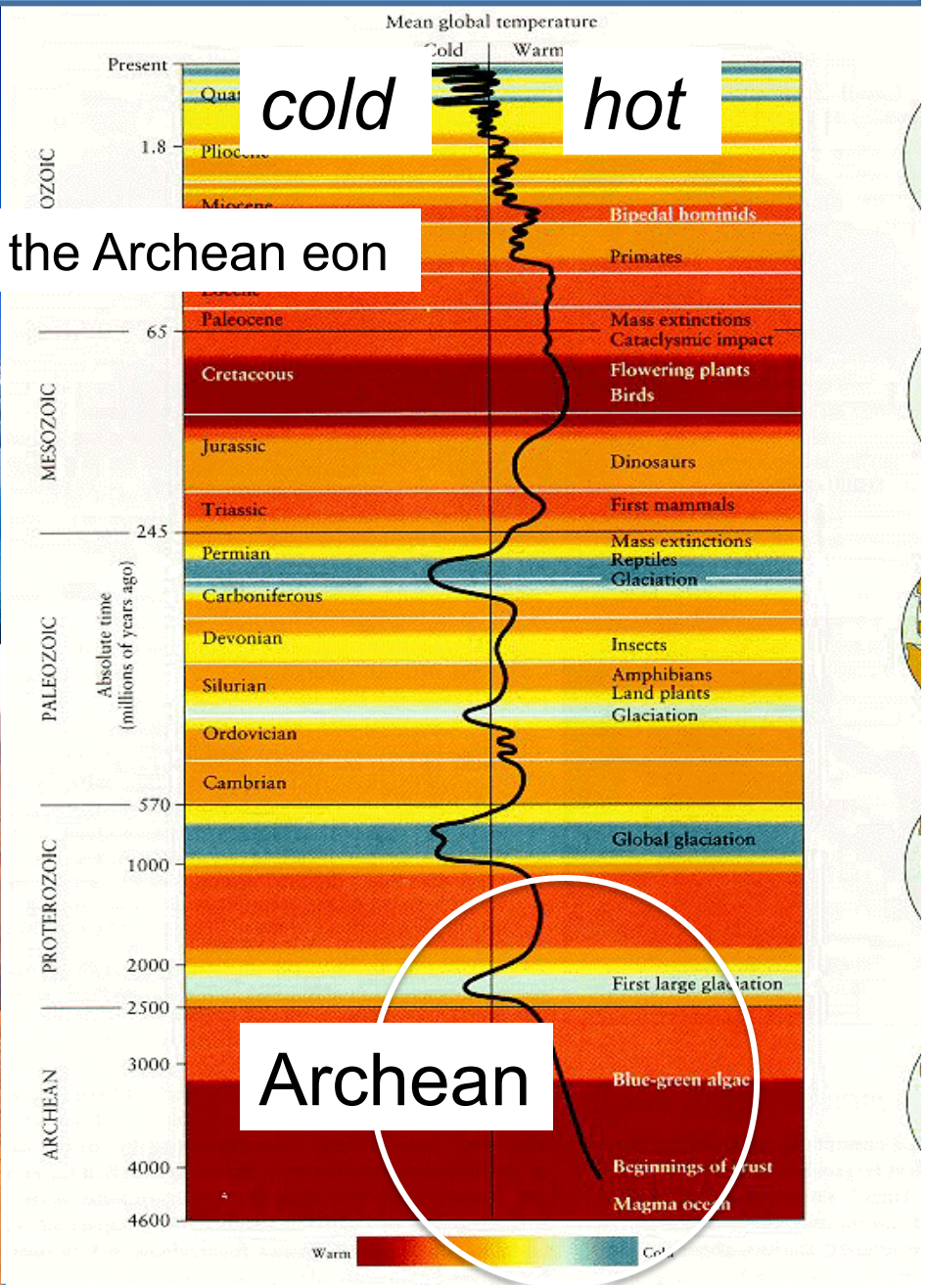
Argon isotopes and crustal evolution



$^{40}Ar/^{36}Ar$ = 143±34, indicates enhanced crustal growth (40-85 % modern crust) during the time interval 3.5-2.7 Ga ago *(Pujol et al., Nature 2013)*

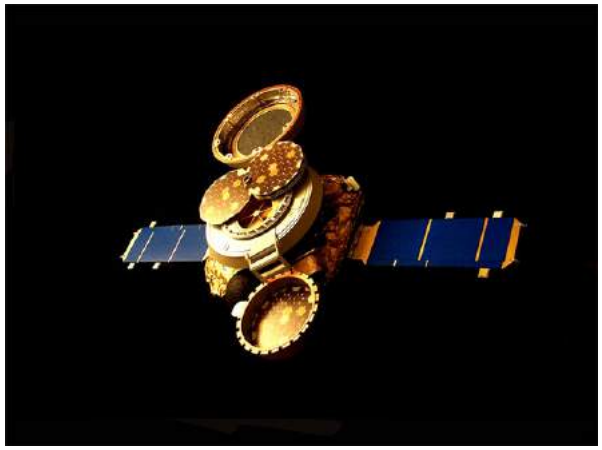
Argon isotopes and crustal evolution

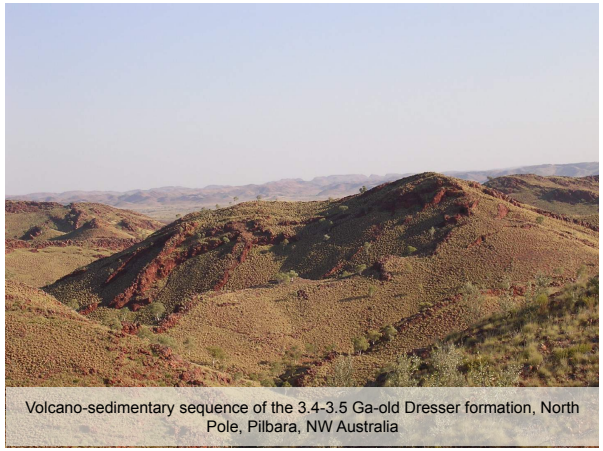
First global glaciation towards the end of the Archean eon



Conclusions

- Solar gases present in the mantle of Earth
- Inner planet volatiles : asteroidal origin (but wait for Rosetta data for possible cometary contribution)
- Differences between Venus, Mars and Earth's atmospheres from ≠ interactions between SW and CR ions and magnetic fields
- On Earth, building and preservation of conditions for life emergence appear accidental





Volcano-sedimentary sequence of the 3.4-3.5 Ga-old Dresser formation, North Pole, Pilbara, NW Australia