Stages in the acquisition and loss of volatiles during Earth's accretion

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Origins of Volatiles in Habitable Planets

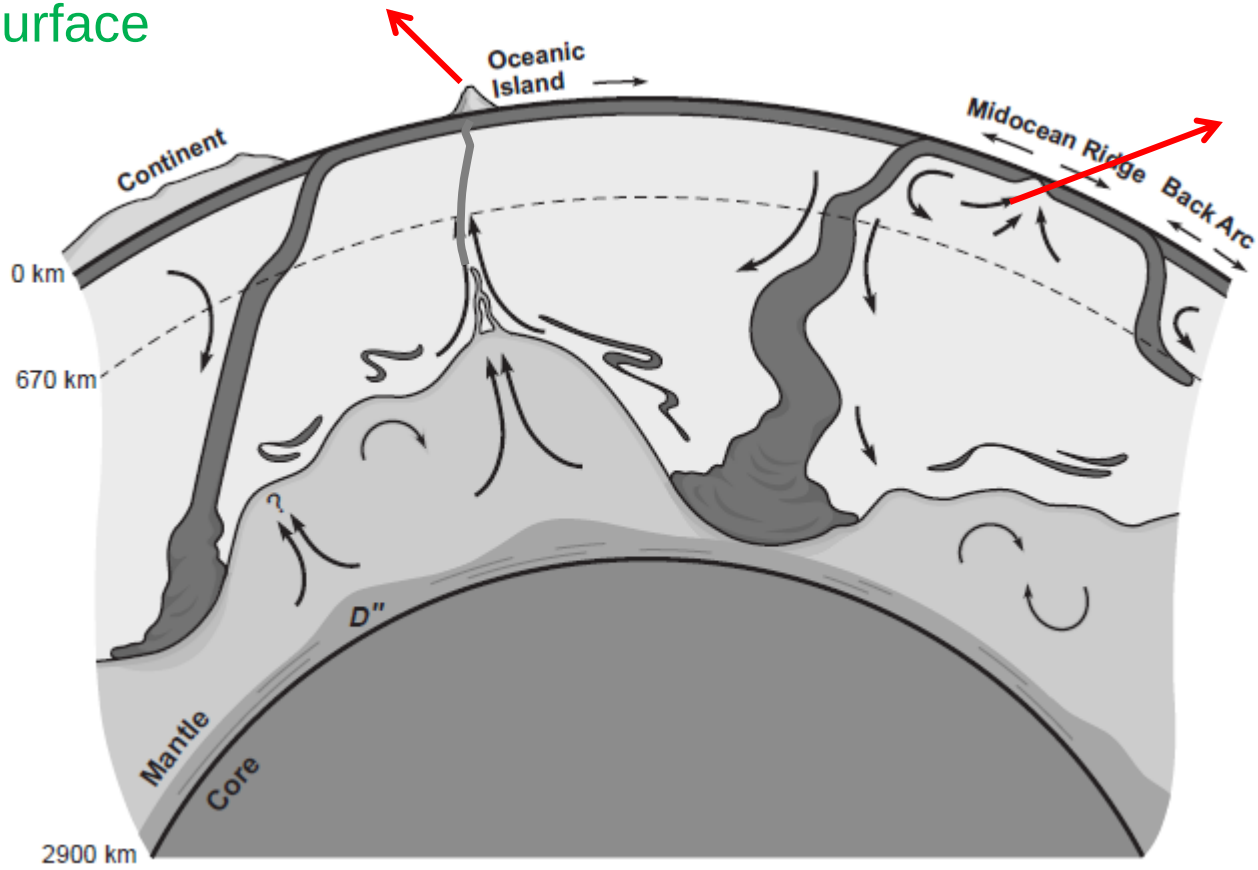
Talk Outline

- Accretion of volatiles during the main phase of accretion.
  - Evidence from Neon isotopes and Neon/Argon ratios
- Evidence of volatile loss from Earth
  - Sources changed and the signal is still preserved
- Earth's atmosphere
  - Volatiles mostly acquired during main phase, sculpted by loss and supplemented post Moon-forming impact
- Comparison of Venus, Earth and Mars
  - differences related to impacts?

Use tracers that are inert (noble gases)
a memory of early events

The Broad Structure of the Earth

OIB (Mantle plumes) → Ocean Island Basalt
Plumes bring material from near core-mantle boundary to the surface

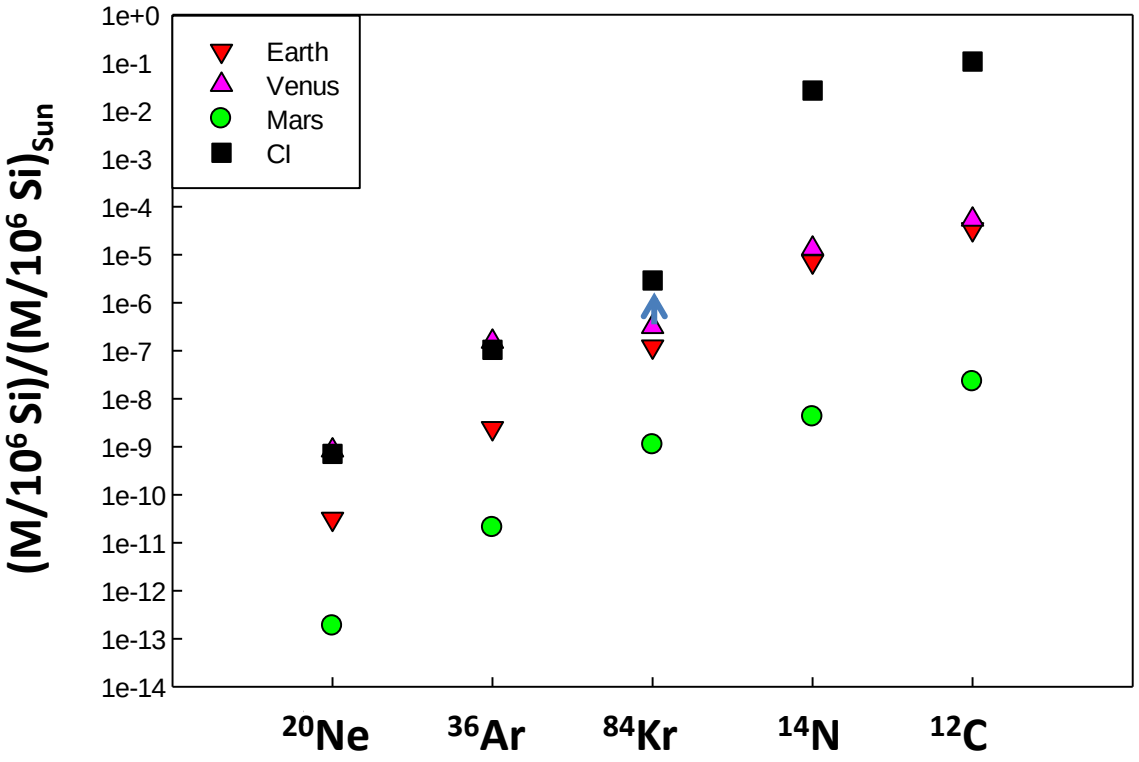


From Kellogg et al., 1999

MORB →
Mid Ocean Ridge Basalt
Comes from the shallow mantle = depleted mantle

We do not really know where the boundary between the deep and shallow mantle lies.

Comparison of volatile abundance patterns



Modified from Halliday (2012)

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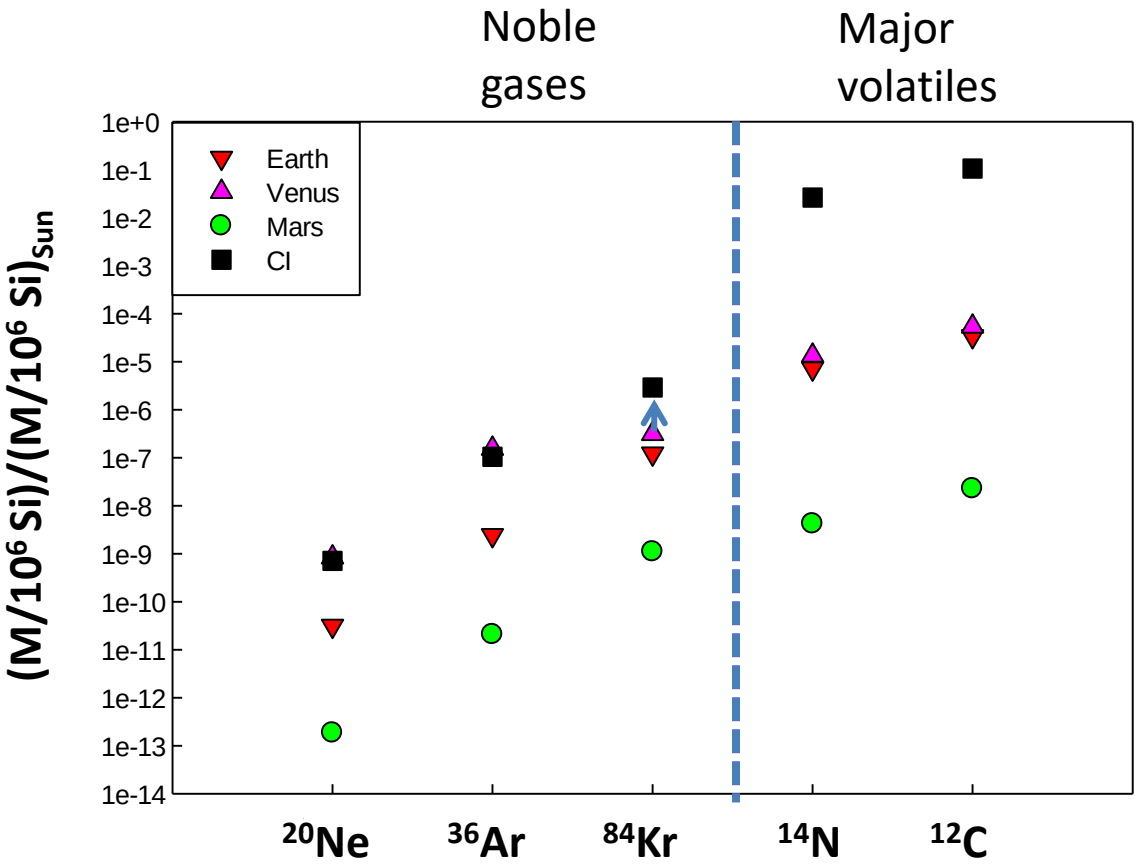
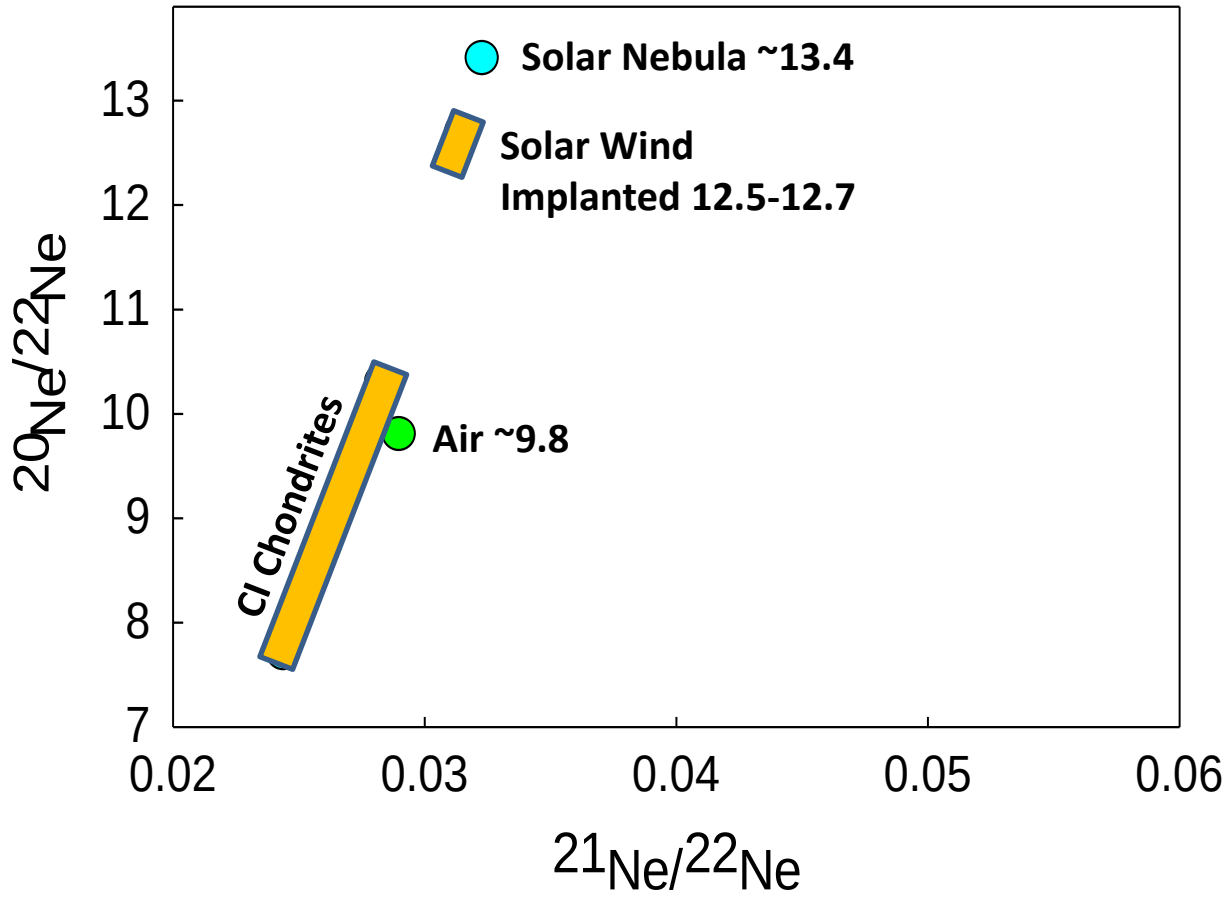


Modified from Halliday (2012)

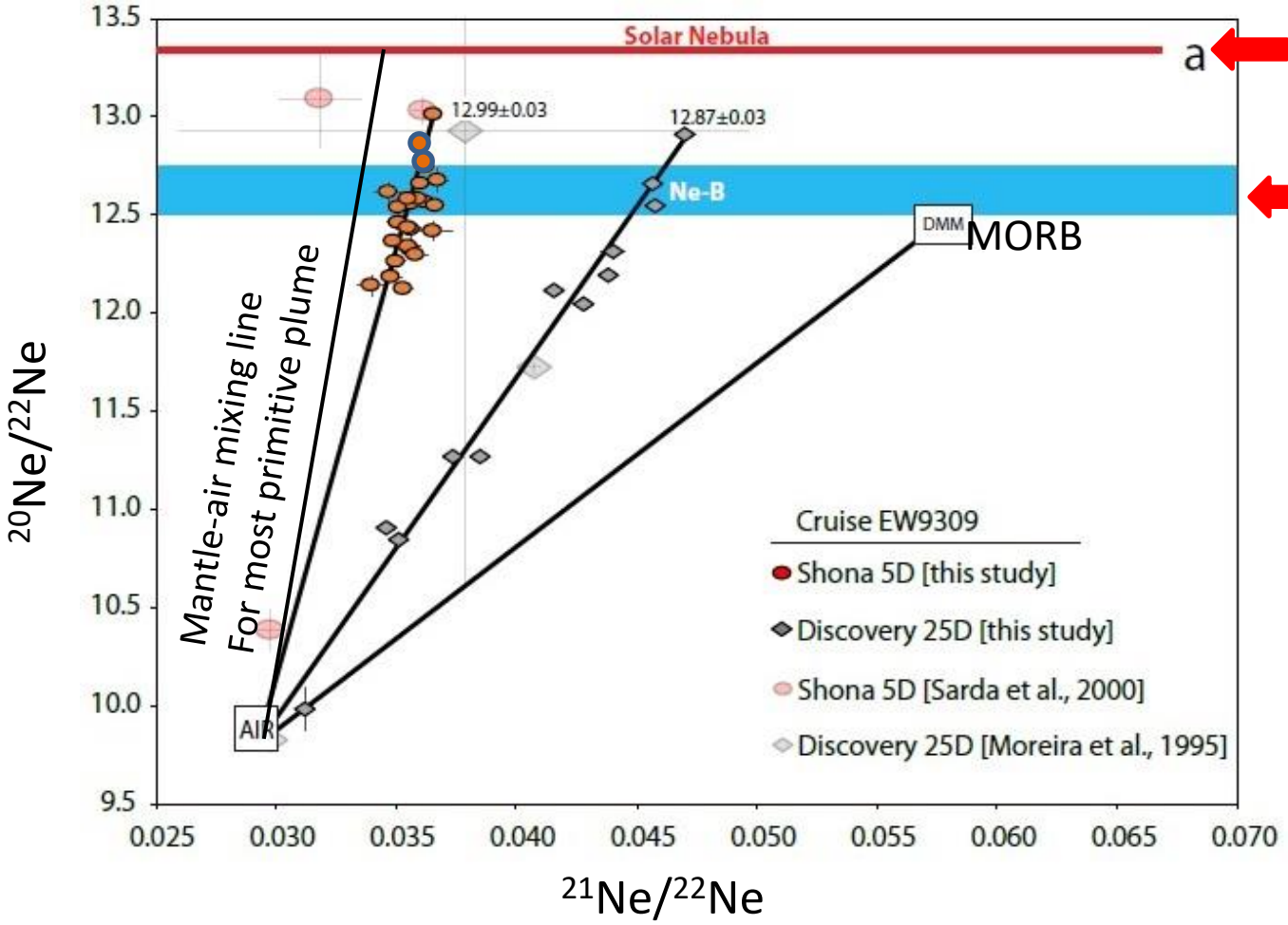
How are (noble) gases incorporated into the terrestrial planets?

- Solar wind irradiation of dust – noble gases
  - How to you preserve the signature from micron-sized dust through formation and differentiation of planetesimals.
- Dissolution of nebular gases into magma ocean H, C, N, He, Ne
  - Challenge is to grow the embryos to a large enough size in the presence of a nebula
- Delivery of chondrites – major volatile and noble gases
  - signature seen in some but not all gases
- Delivery of comets – signature might be seen only in some noble gases
  - signature seen in some but not all gases

Fingerprinting the Neon sources



Different flavors of solar Neon in the mantle



Solar nebula

Implanted Solar wind

Williams and Mukhopadhyay, to be submitted

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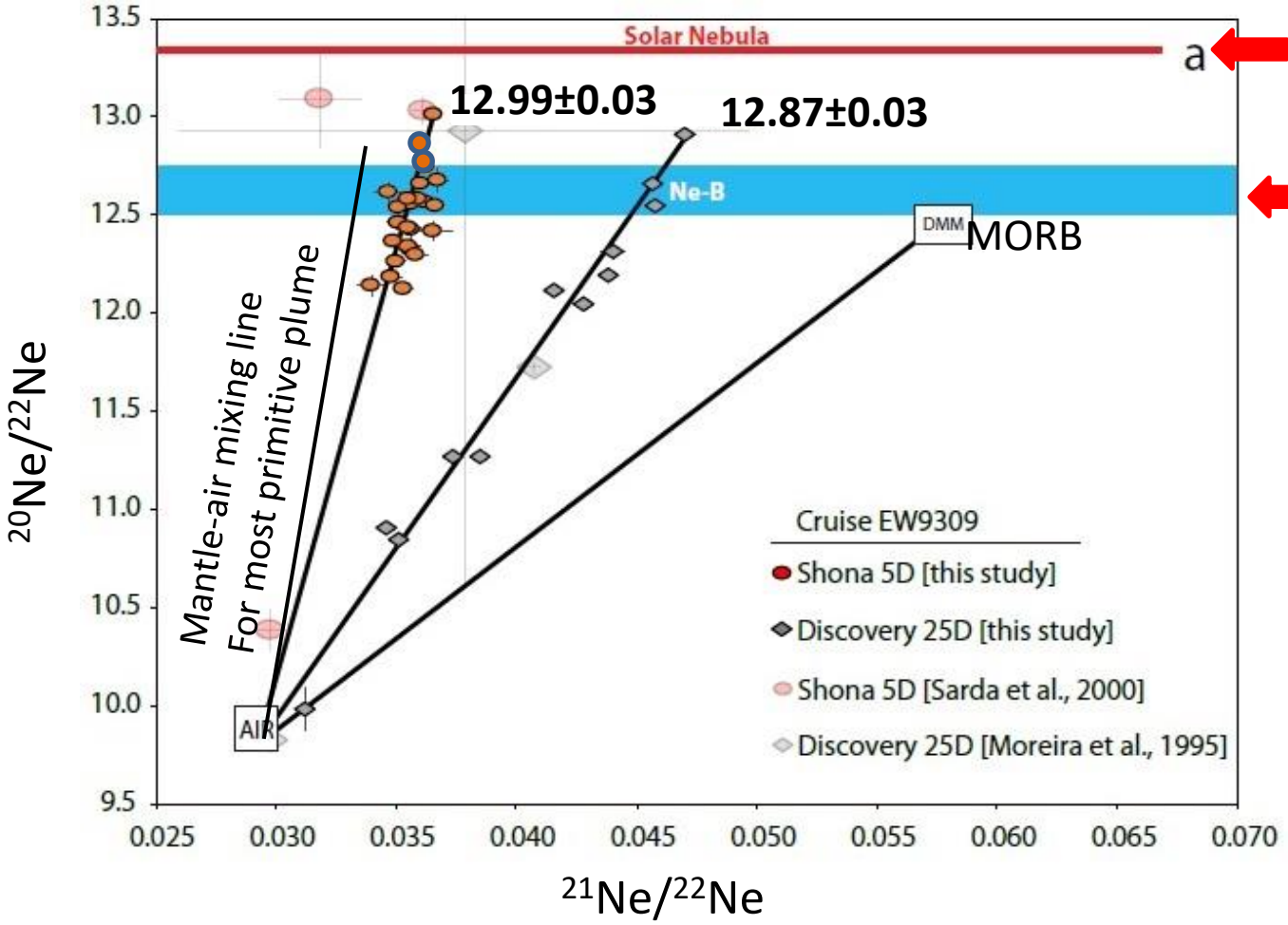

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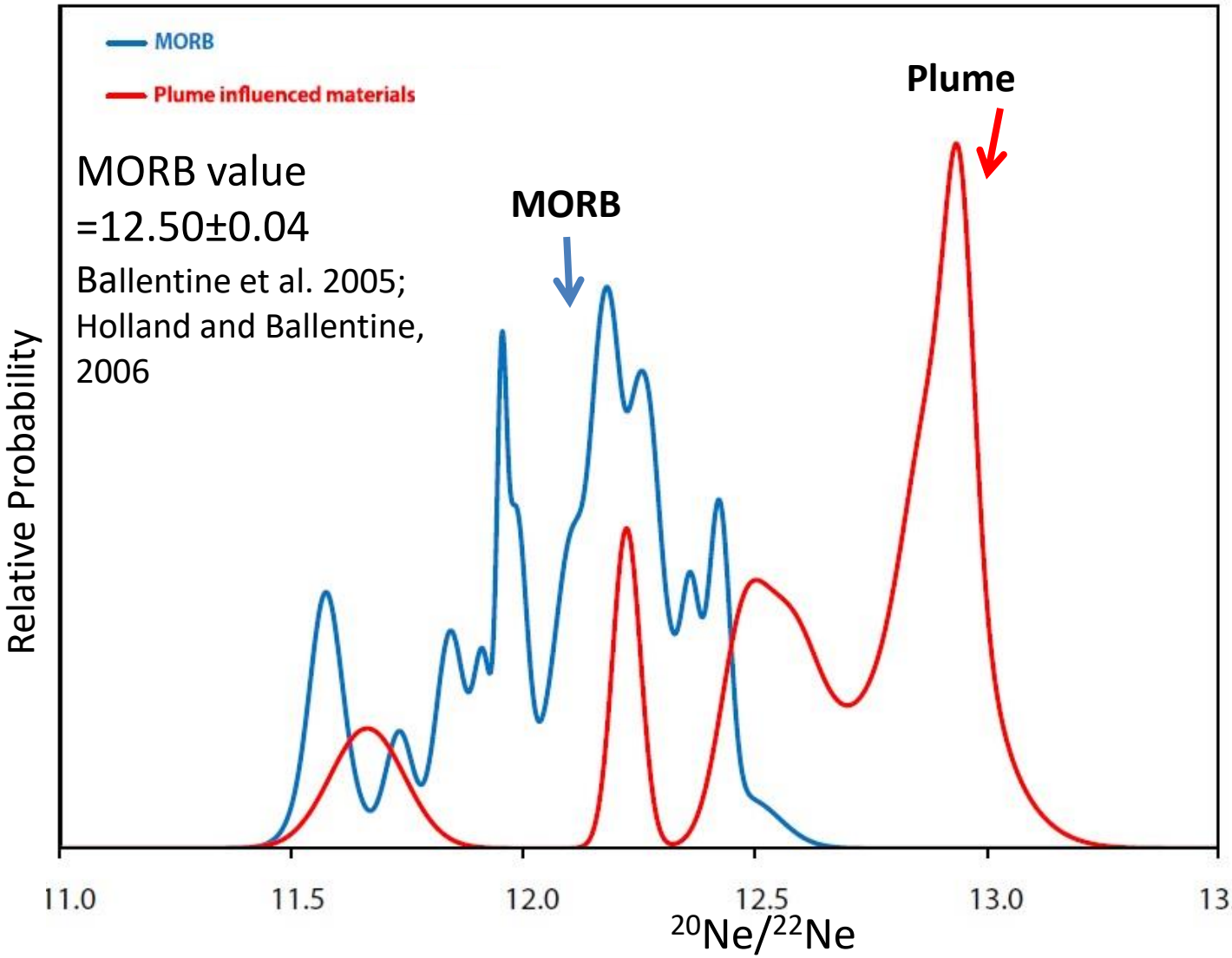


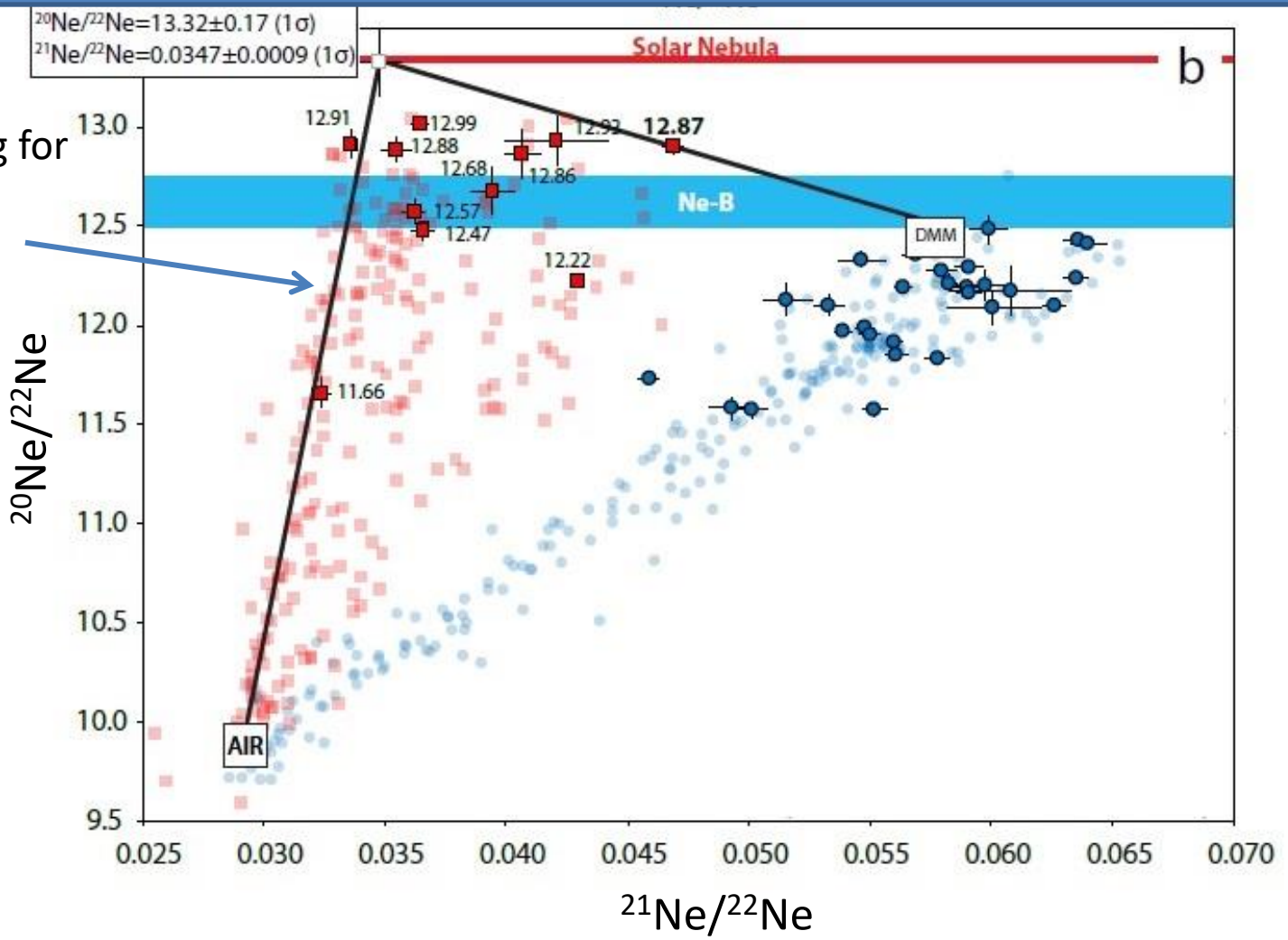
OIB data from:
Yokochi & Marty, 2004;
Mukhopadhyay, 2012
Peron et al. 2016
This study

A statistical difference between the highest measured $^{20}Ne/^{22}Ne$ values between deep and shallow mantle

Williams and Mukhopadhyay, to be submitted

Different flavors of solar Neon in the mantle

Air-mantle mixing for most primitive Galapagos plume



Suggest deep mantle $^{20}Ne/^{22}Ne = 13.32 \pm 0.17$, indistinguishable from nebular values

Williams and Mukhopadhyay, to be submitted

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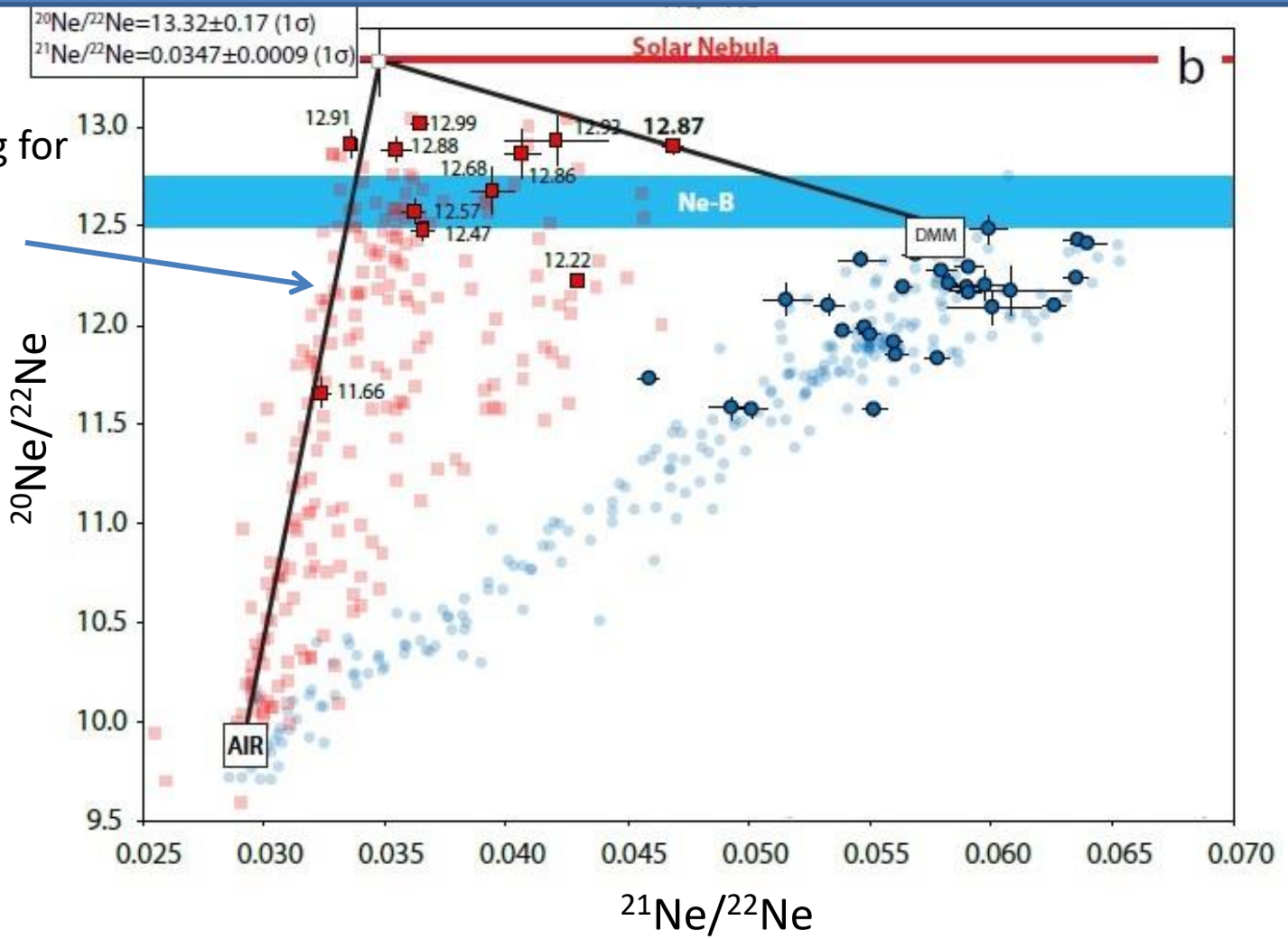
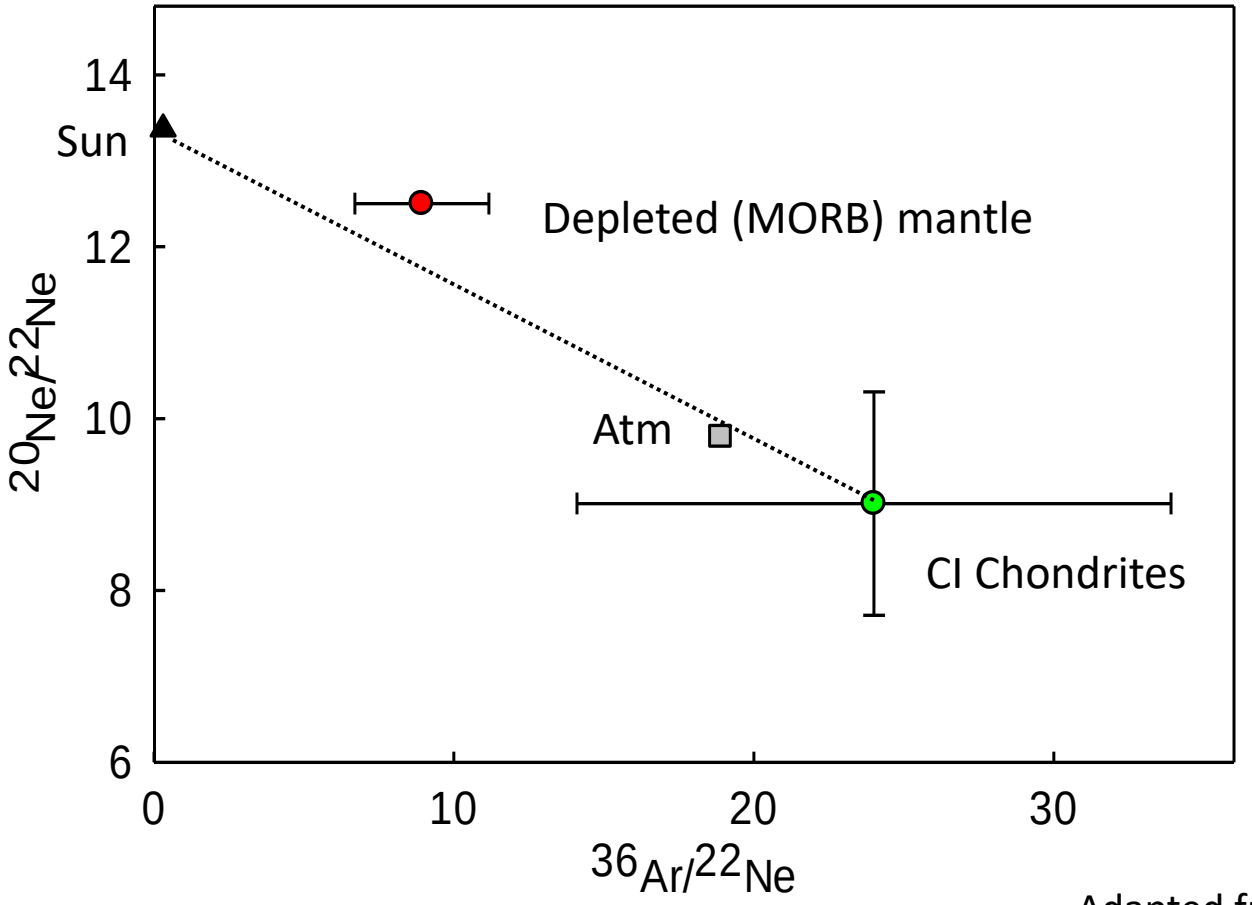


But cannot dispute that Neon in the mantle is Solar

→ We do not see such clear evidence of a solar component in other major volatiles or heavier noble gases

Different components in different parts of the Earth



Adapted from Marty, 2012

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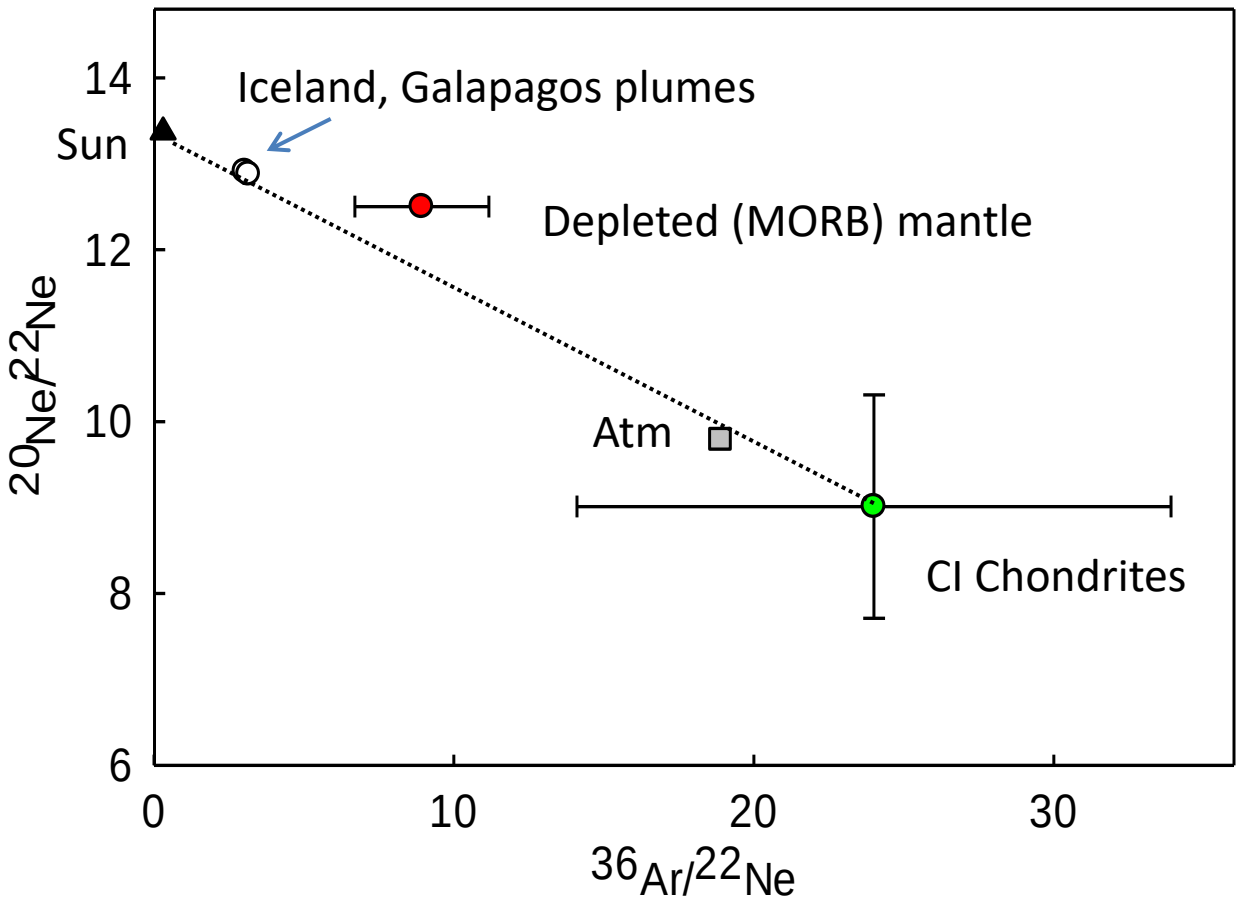

Mantle solar, atmosphere closer to chondrites

Mukhopadhyay et al., in prep

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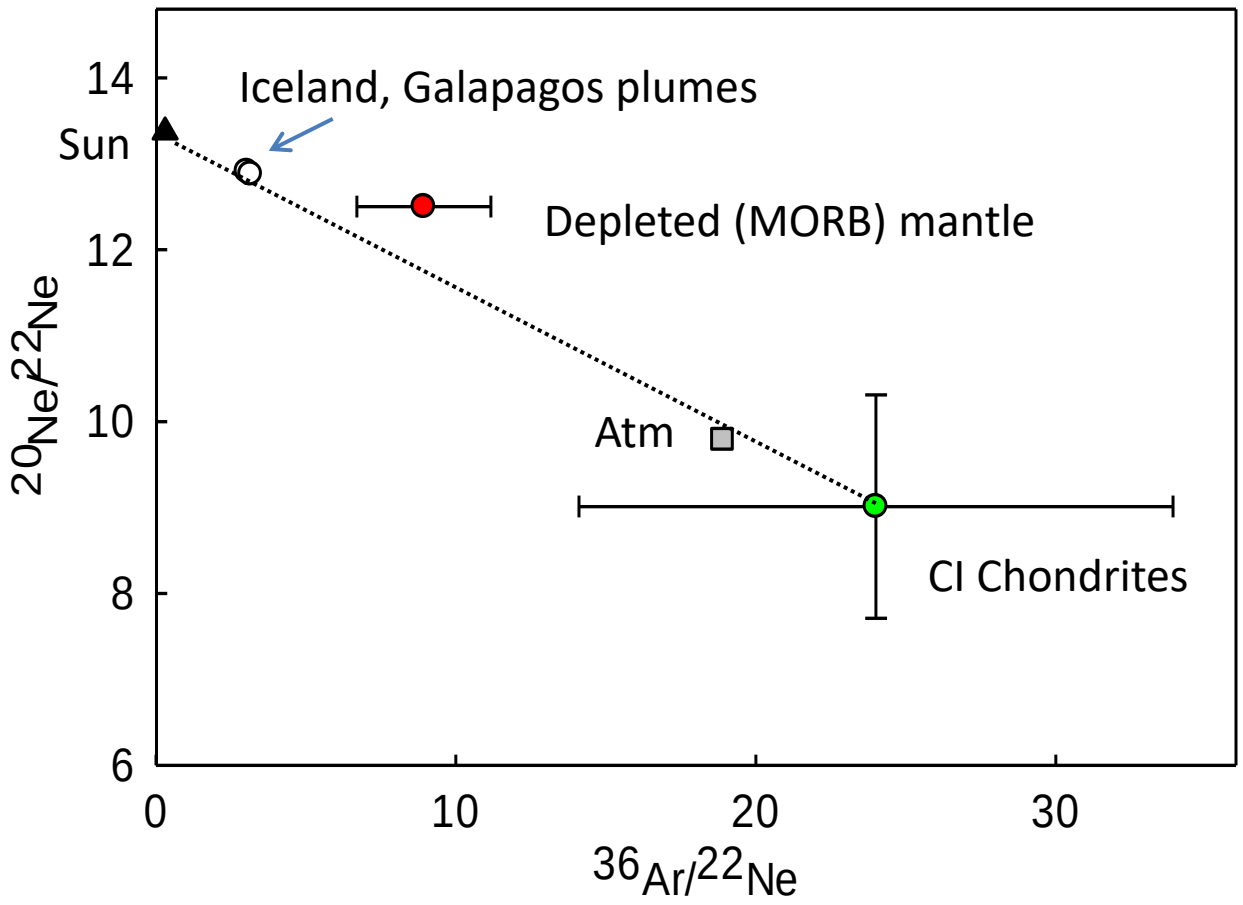

Atmosphere and mantle have very different noble gas composition
Atmospheric gases delivered after last giant impact?

Mukhopadhyay et al., in prep

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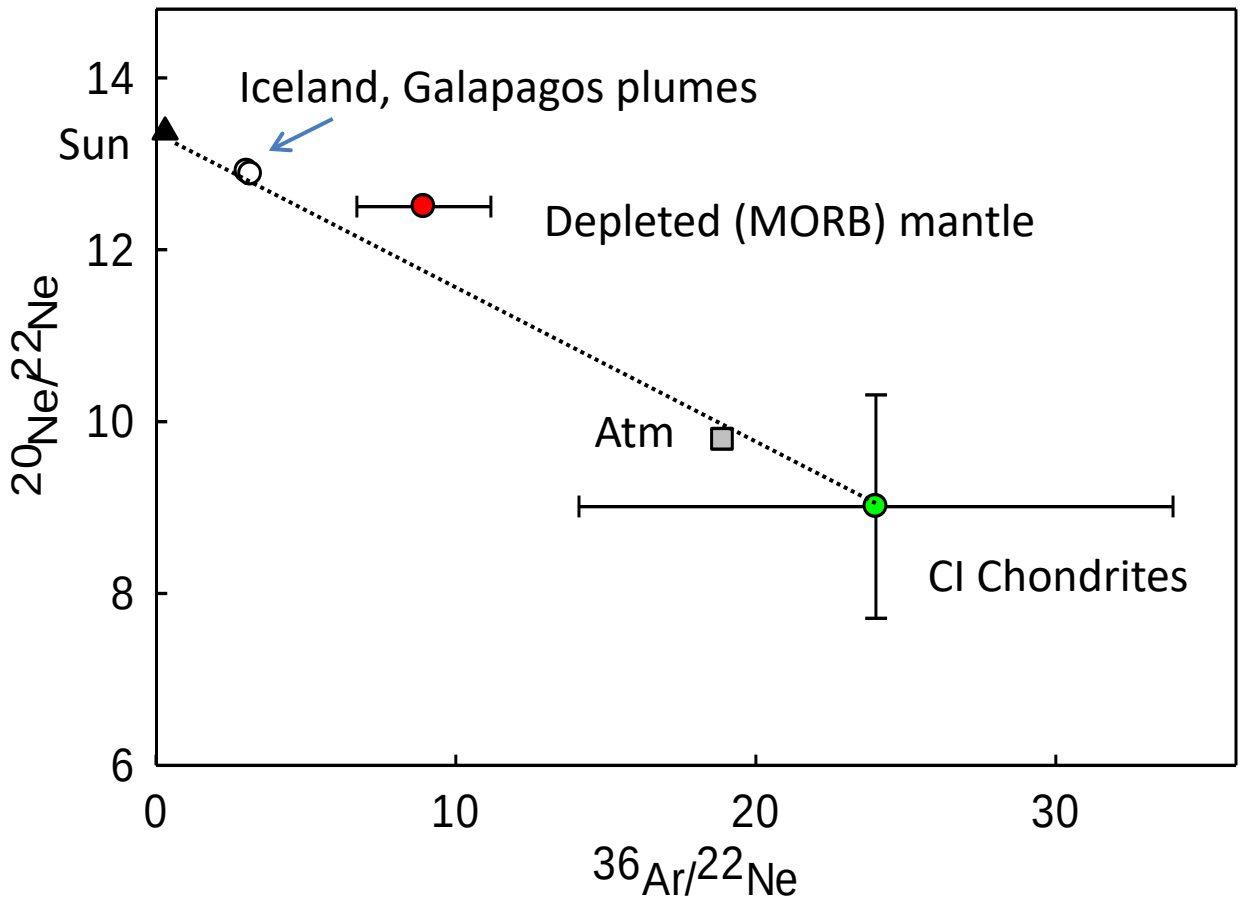
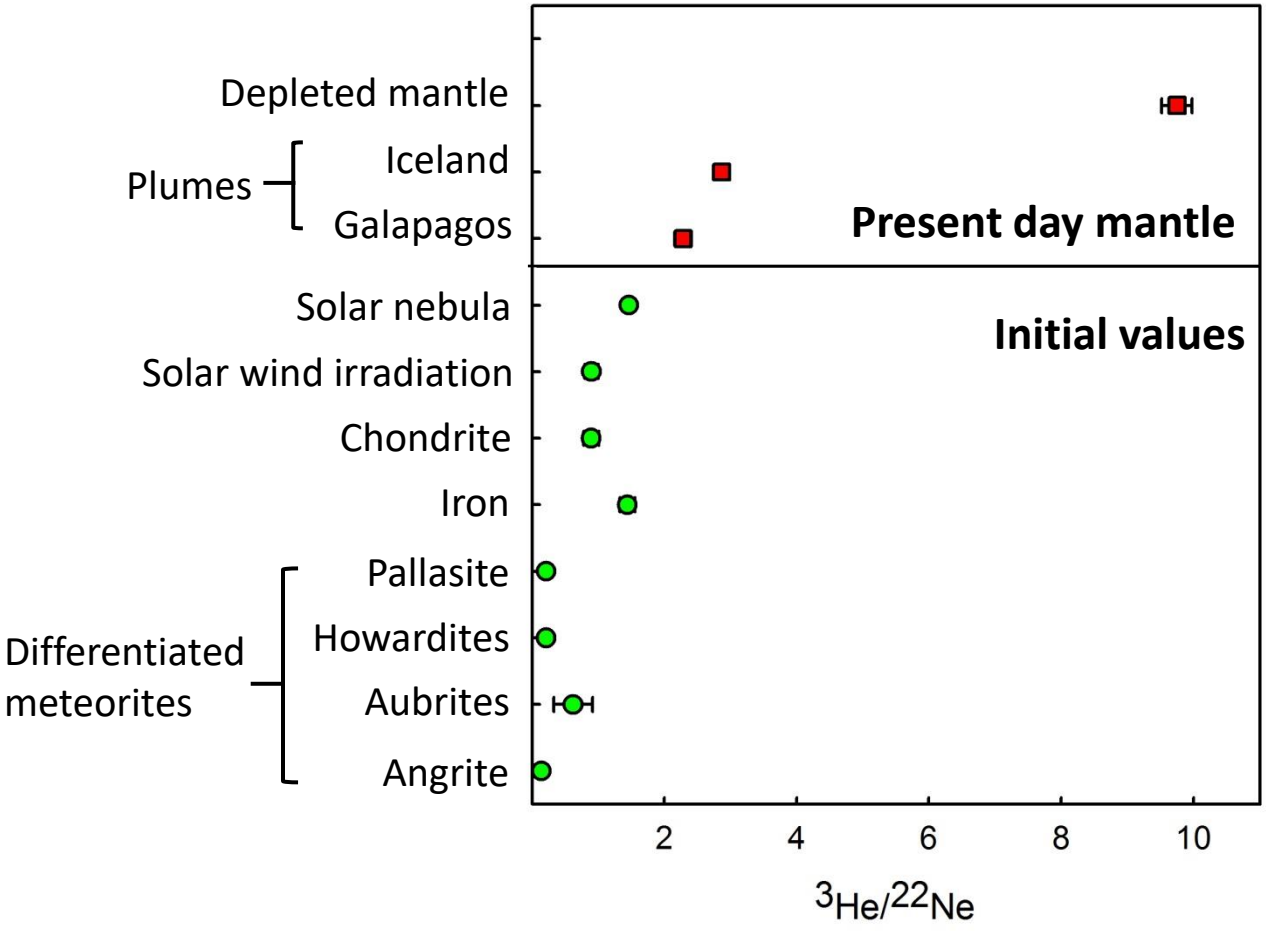


Atmosphere and mantle have very different noble gas composition
Atmospheric gases delivered after last giant impact?

Ar, Kr, Xe from comets (≤ 1 % of late veneer mass); but, hard to do trap Ne in ices…….

Earth is enriched in ^{3}He relative to ^{22}Ne compared to potential parent bodies



Tucker and Mukhopadhyay, 2014

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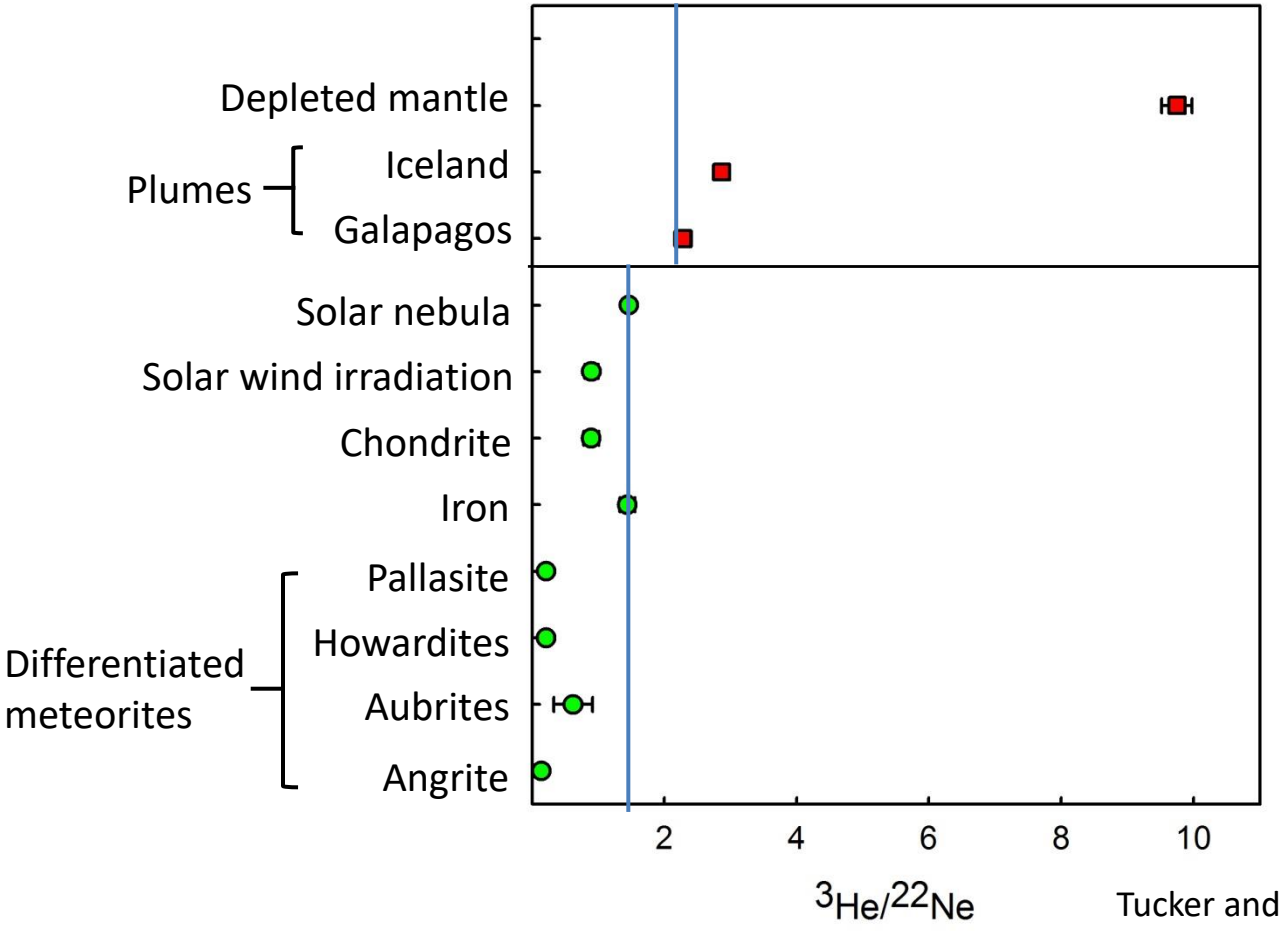

Present day mantle

Initial values

Tucker and Mukhopadhyay, 2014

Compared to potential sources, entire mantle enriched in ^{3}He compared to ^{22}Ne

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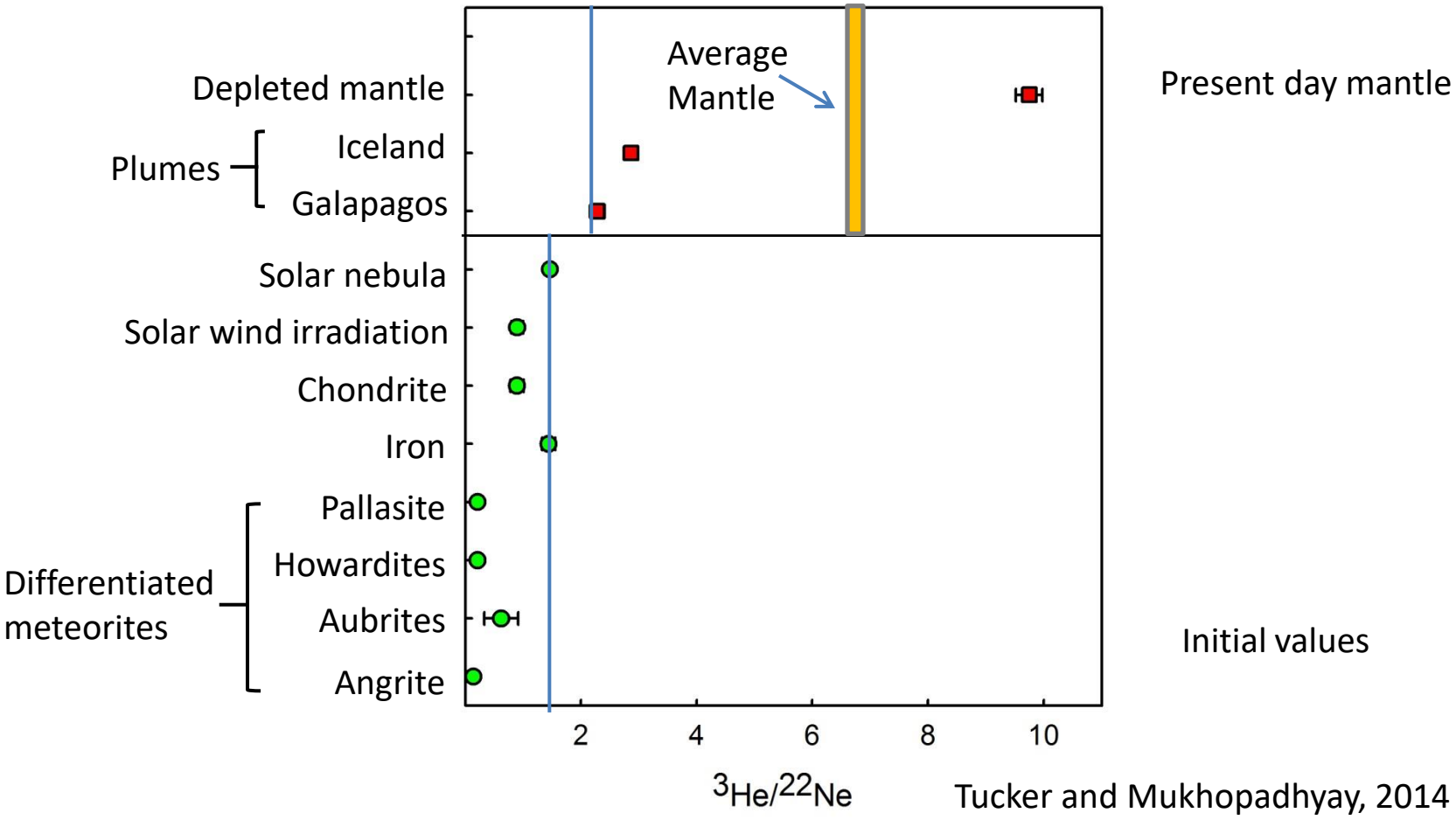


Tucker and Mukhopadhyay, 2014

Compared to potential sources, entire mantle enriched in ^{3}He compared to ^{22}Ne

Mantle on average ~5X higher value than deep mantle

Magma ocean and atmospheric blow-off

He is twice as soluble as Ne in magma

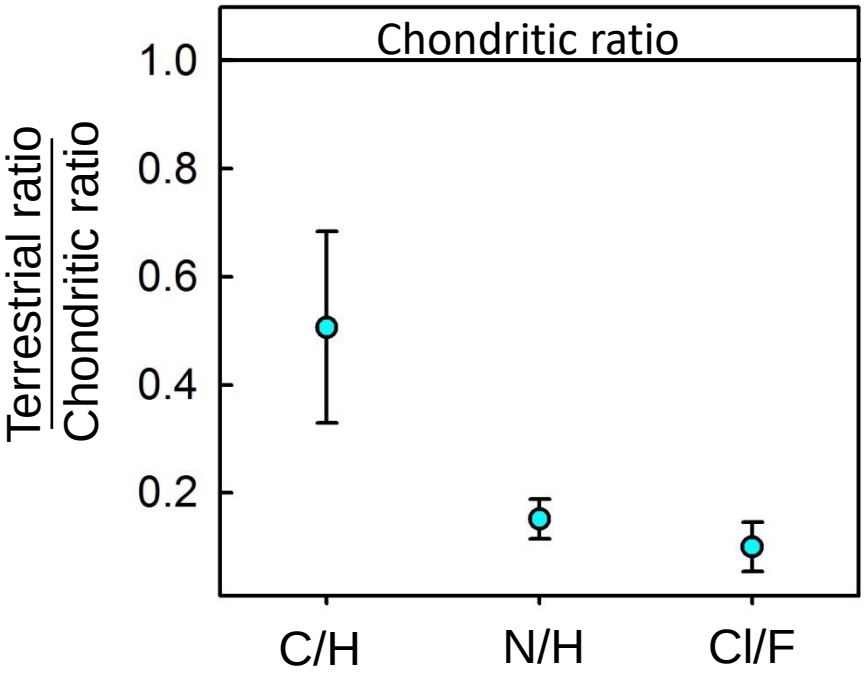
To go from $^{3}He/^{22}Ne \leq 1.5$ to $^{3}He/^{22}Ne \geq 7$: outgas a liquid planet, aka magma ocean

Requires atm. blow-off and atm-mantle equilibration x 2 at minimum

Tucker and Mukhopadhyay, EPSL, 2014

Earth's volatile budget: primarily acquired during main phase of accretion and sculpted by impacts

Isotopic ratios of H, C, N, Cl are chondritic
Elemental abundance ratios are not

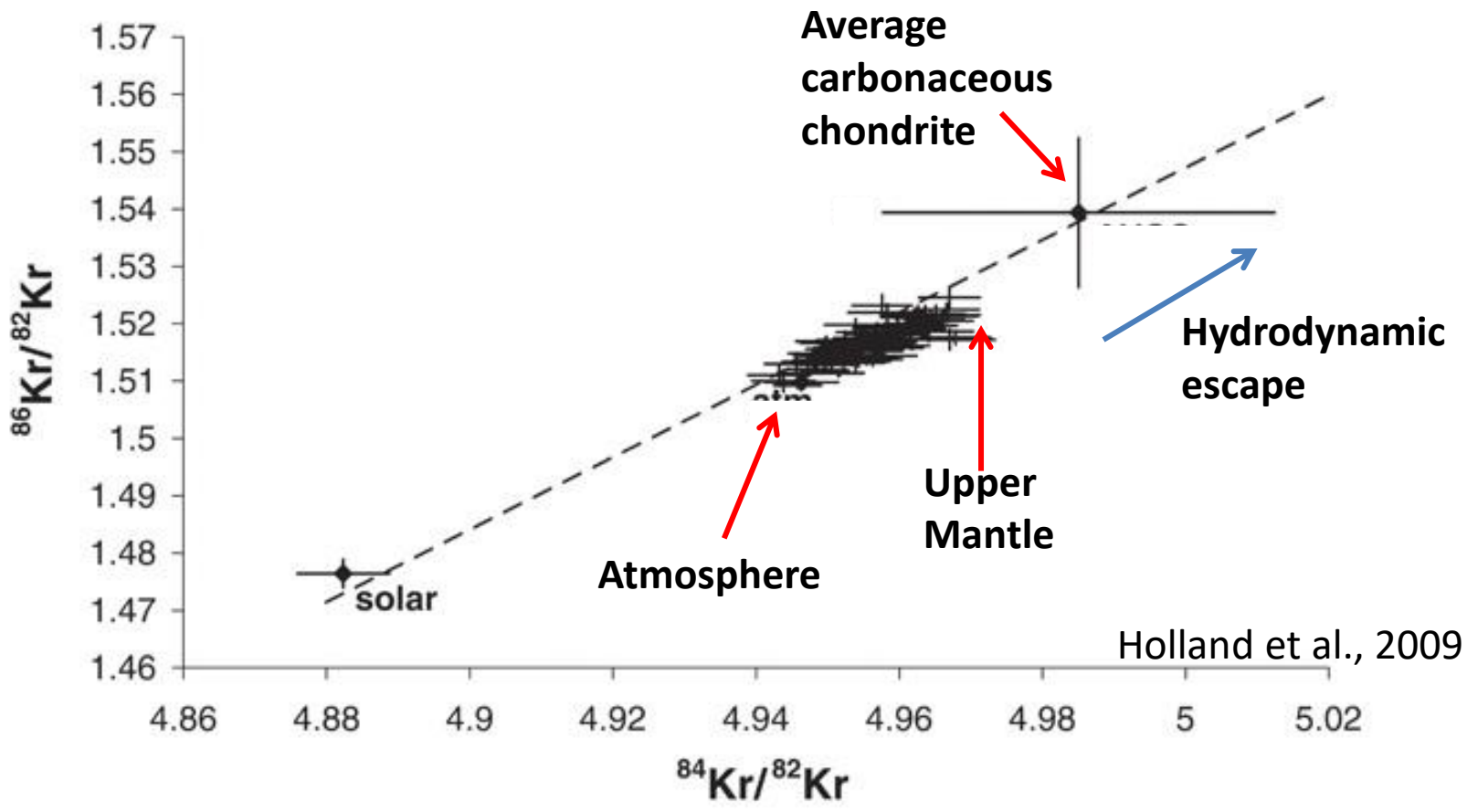


Significant percentage of present day water budget (~80%) accreted prior to the last giant impact

Data from Marty 2012; Halliday 2013;
Sharp and Draper 2013, McDonough and Sun 1995

Tucker and Mukhopadhyay, 2014

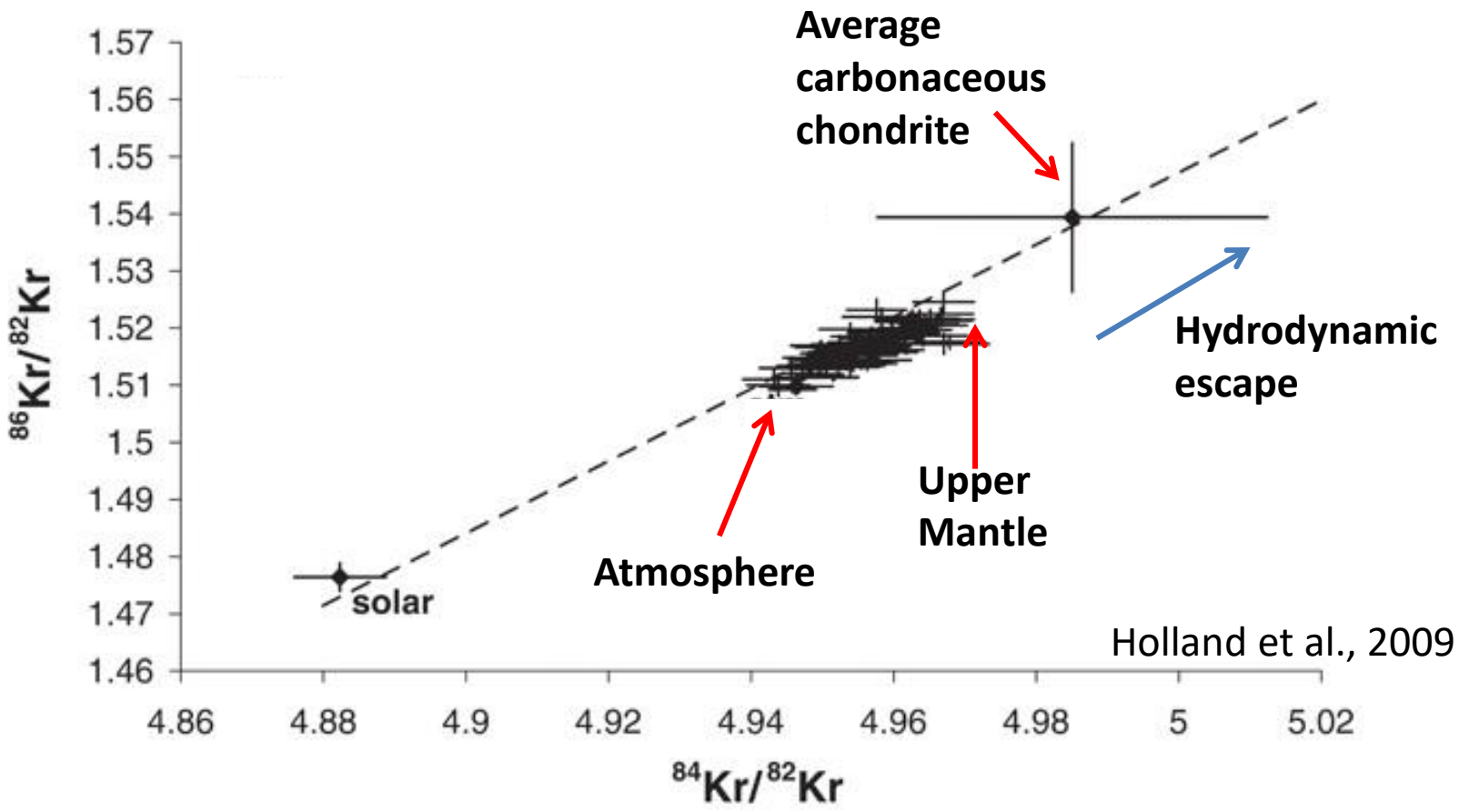
Different components in different parts of the Earth



No indication that hydrodynamic escape processes have played a major role in shaping the atmosphere

Atmospheric Kr delivered after mantle received its Kr budget – late veneer

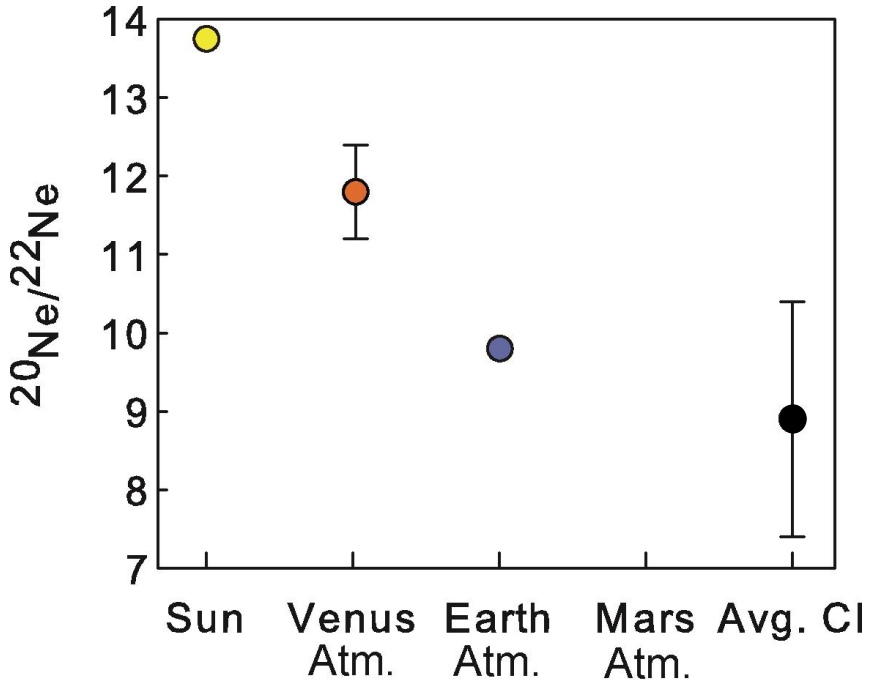
Different components in different parts of the Earth



Primordial noble gases in Earth's atmosphere is not from outgassing of the solid Earth during its main accretionary stage or subsequently

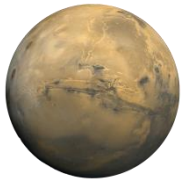
Comparing atmospheric noble gas composition Venus, Earth and Mars

Venus Ne = 20X Earth; Venus Ar = 70X Earth



Venus

Earth



Mars

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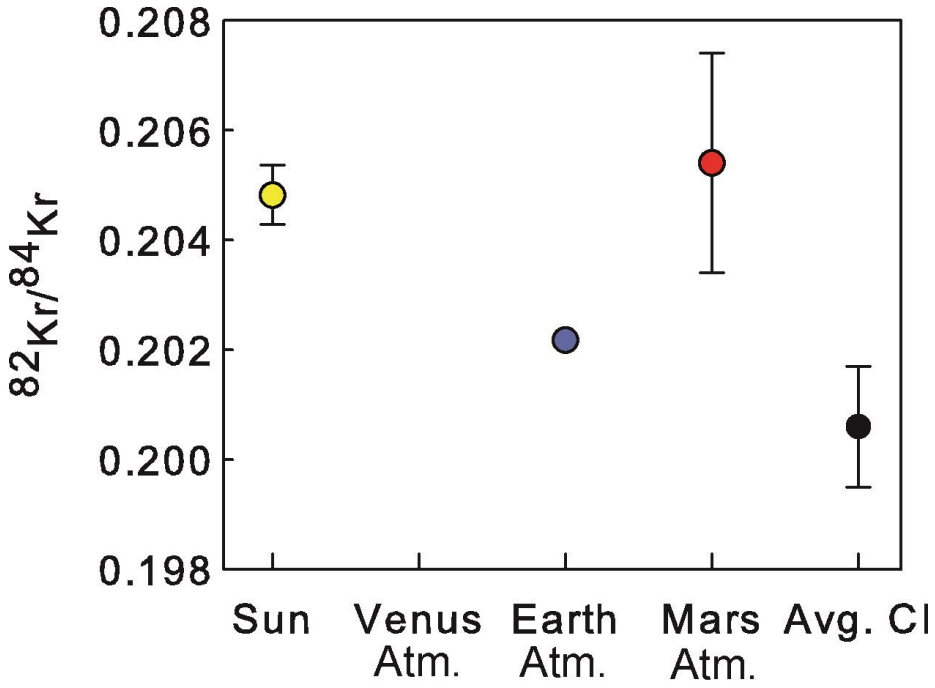

Venus

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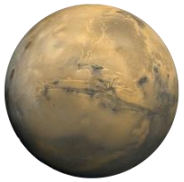


Mars

The Noble Gas Data

Venus

Atm closer to solar than Earth ($^{20}Ne/^{22}Ne$)

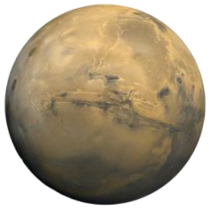
Greater noble gas abundance than Earth (e.g., 20×[Ne]; 70×[^{36}Ar])

Need more data

Earth

Atm not solar; more similar to chondritic

Deep mantle plumes near solar Ne; shallow mantle has evidence for multiple magma oceans



Mars

Atm is solar (Kr)

Mantle is solar (Xe)

Atm Ne, Ar fractionated by on going escape due to solar wind sputtering

Tucker & Mukhopadhyay 2013; Mukhopadhyay 2012; Pepin & Porcelli 2002; Halliday 2013; Marty 2012; Mukhopadhyay et al. in prep.; and refs therein

Conclusions

- Different volatiles tell us about different processes.

  Noble gases tell us about processes and sources not captured by major volatiles and vice versa

- When where volatiles accreted?
  - Throughout accretion
  - Most of the volatile budget during main stage of accretion and abundance pattern sculpted by impacts
  - Some fraction after the last giant impact; comets could have been important for some of the noble gases

- Did the sources stay the same or did they change?
  - Sources changed; volatile poor early and volatile rich later and signal is still preserved in the Earth's mantle-atmosphere system