What we will cover in this lecture

- Estimating Earth's composition
- Extinct radionuclides, the early differentiation of the Earth and its preservation in the present day mantle
- Early atmosphere – where did it come from and how did the gases get into the mantle

Classification of elements

NEBULAR ENVIRONMENT:

- condensation temperatures at which 50% the mass of an element precipitates out of a nebular gas (typical assumption 10^{-4} atm of H)

>1400 K	refractory:	Ca, Al, Ti, Th, U, REE, Re, Os
1350 – 1250 K	major components:	Mg, Fe, Ni, Co, Si
1250 – 800 K	moderately volatile:	K, Pb, S, Rb, Au, Cd, halides
<800 K	volatile:	H, C, N, some halogens, noble gases

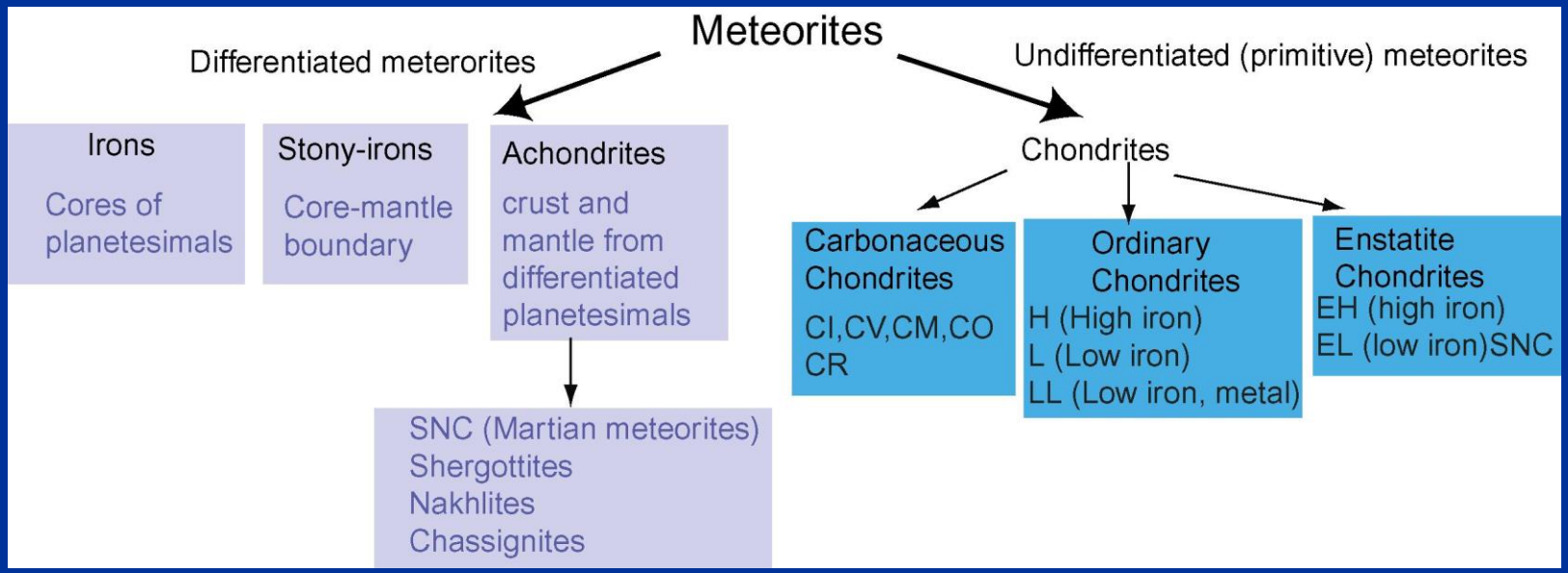
PLANETARY ENVIRONMENT:

- what's in the core, mantle and atmosphere/hydrosphere

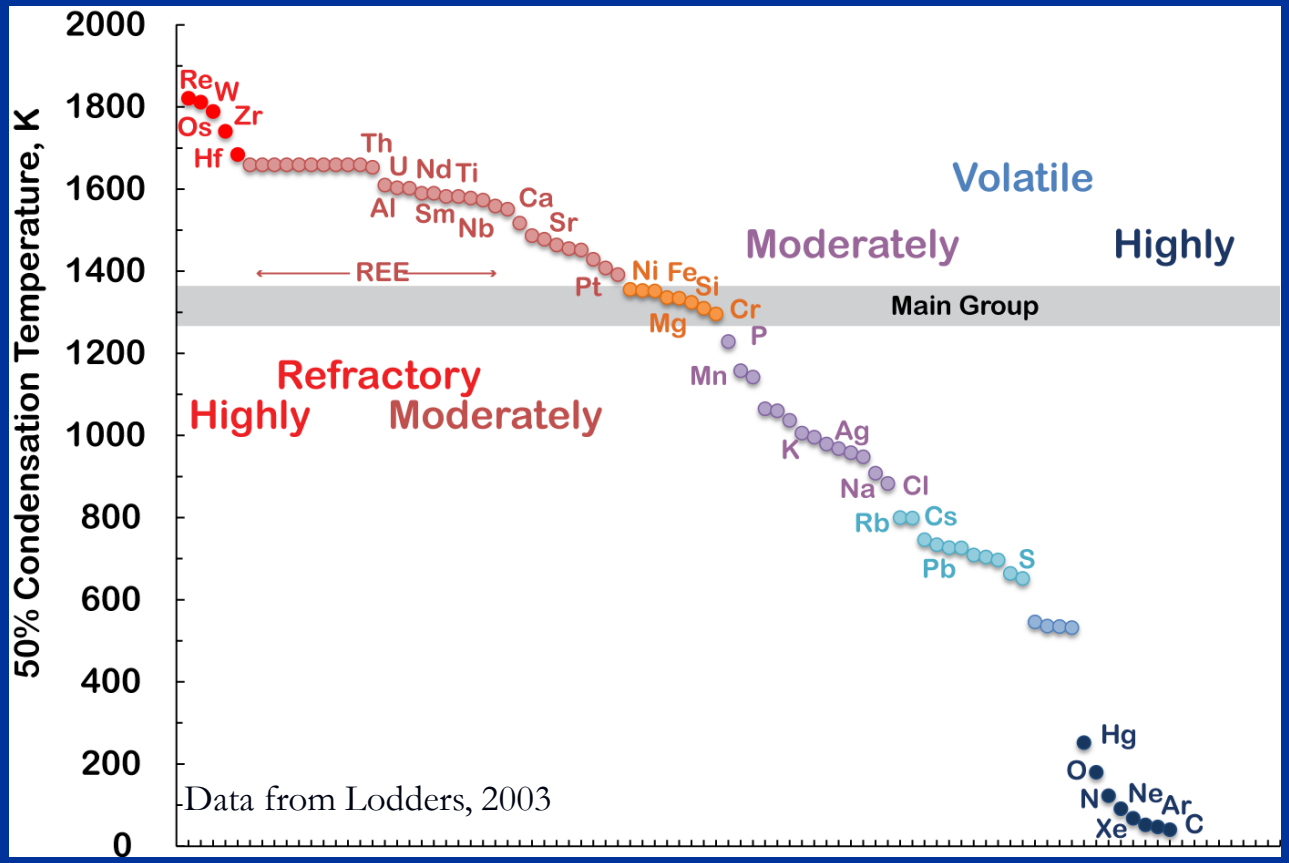
Silicate liquid	lithophile:	Mg, Ca, Al, Ti, Th, U, REE
Fe liquid	siderophile:	Ni, Fe, Co, Ir, Au, Os
Sulfide liquid	chalcophile:	S, Cu, Pb,
Gas phase	atmophile:	N, H, C, noble gases

Earth composition
Meteorites – the building blocks

Meteorite classification

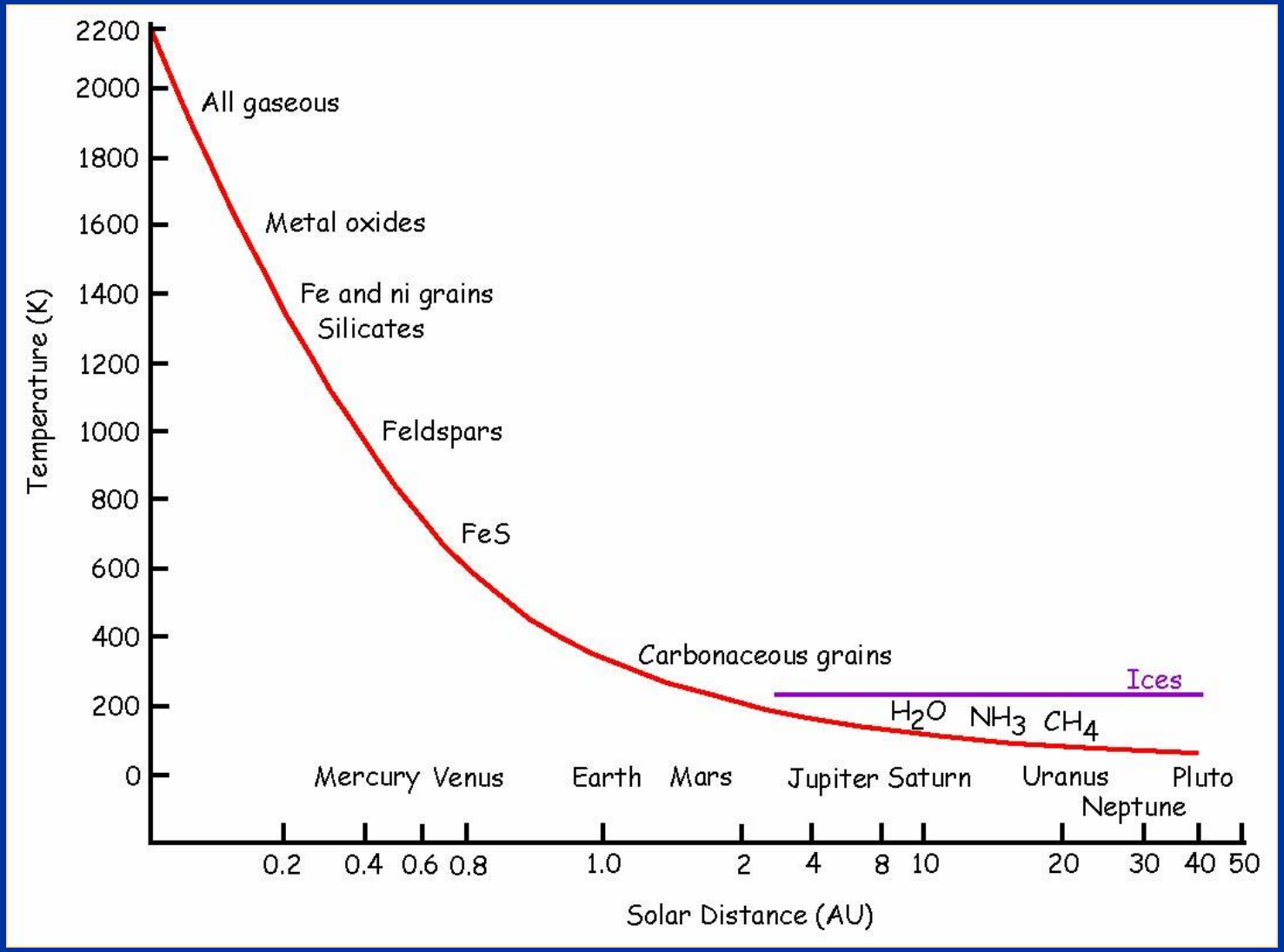


Cooling of a Hot, Gaseous, Solar Nebula Can Cause Element Fractionation According to Condensation Temperature



50% Condensation temperatures of the elements from a low pressure nebula of solar composition.

The outer solar system contained condensates of all kinds, and since ice was nearly three times more abundant, ice dominated the mixture.

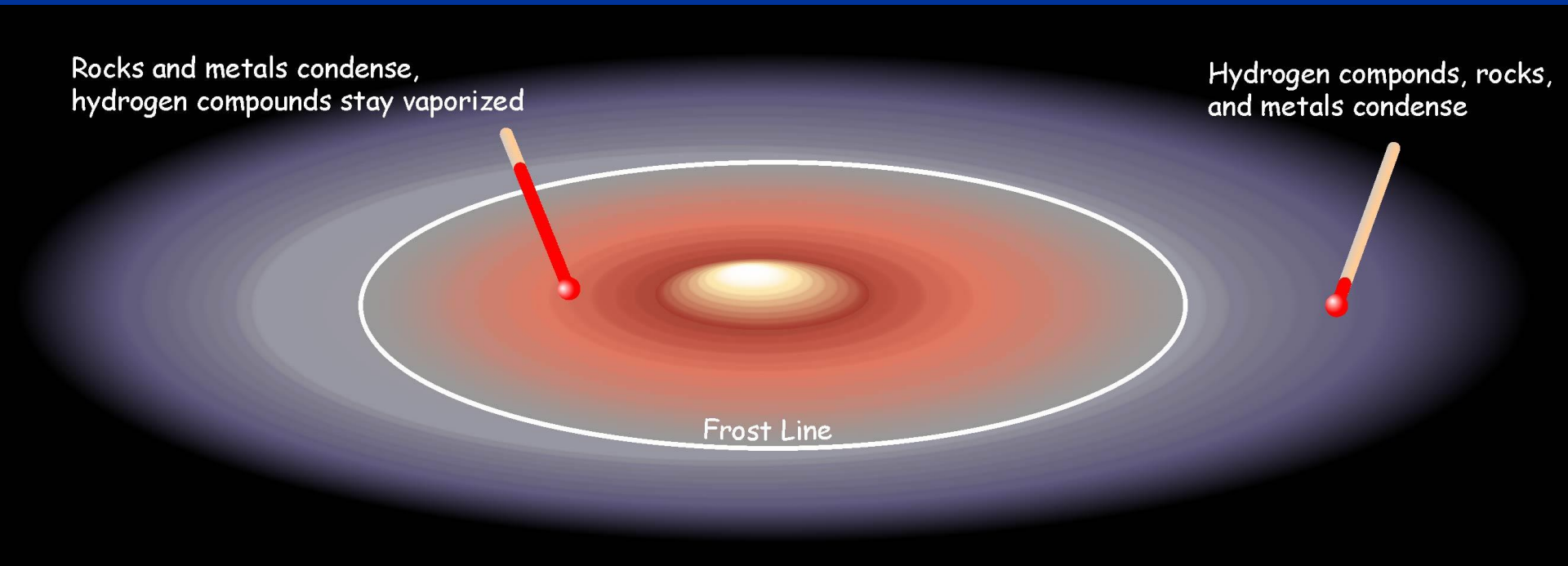


Planet Formation in the Solar Nebula

The great temperature differences between the hot inner regions and the cool outer regions of the nebula determined what kinds of condensates were available to form planets.

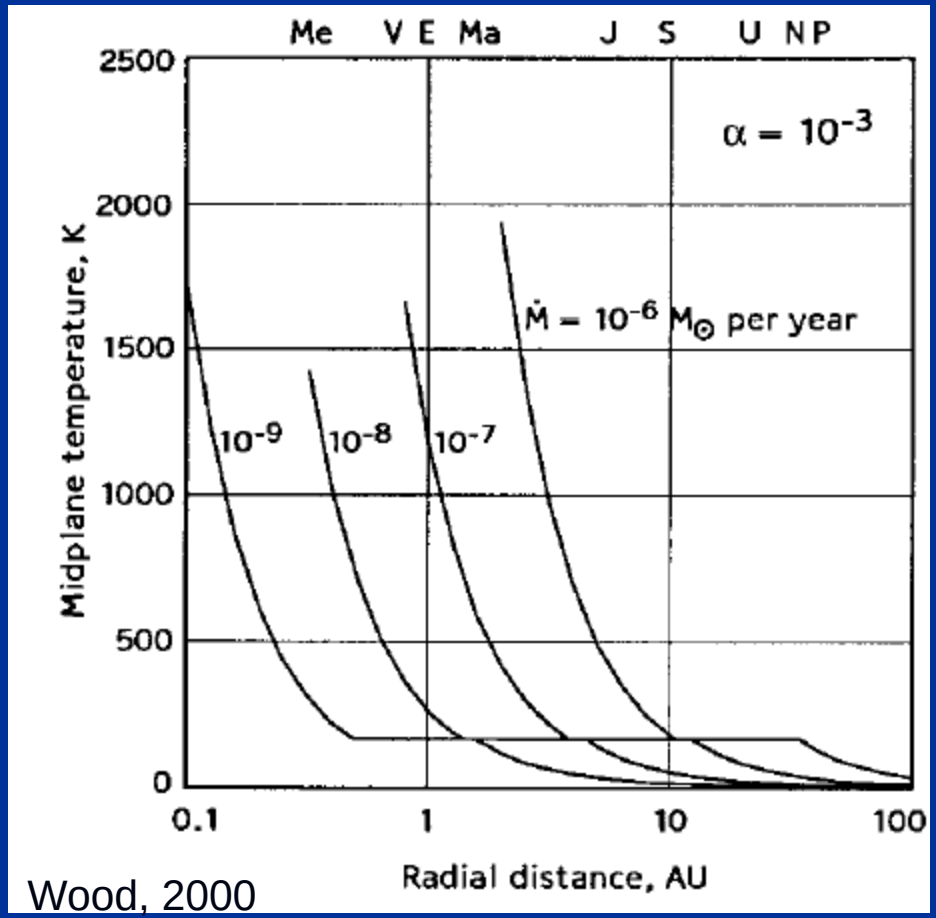
Near Mercury's orbit, refractory oxides and metal will condense. Moving outwards to Venus and Earth, more silcates condensed

Beyond the frost line, which lay between the present-day orbits of Mars and Jupiter, temperatures were low enough for hydrogen compounds to condense into ices.



Complications:

1) Disk temperature is NOT static

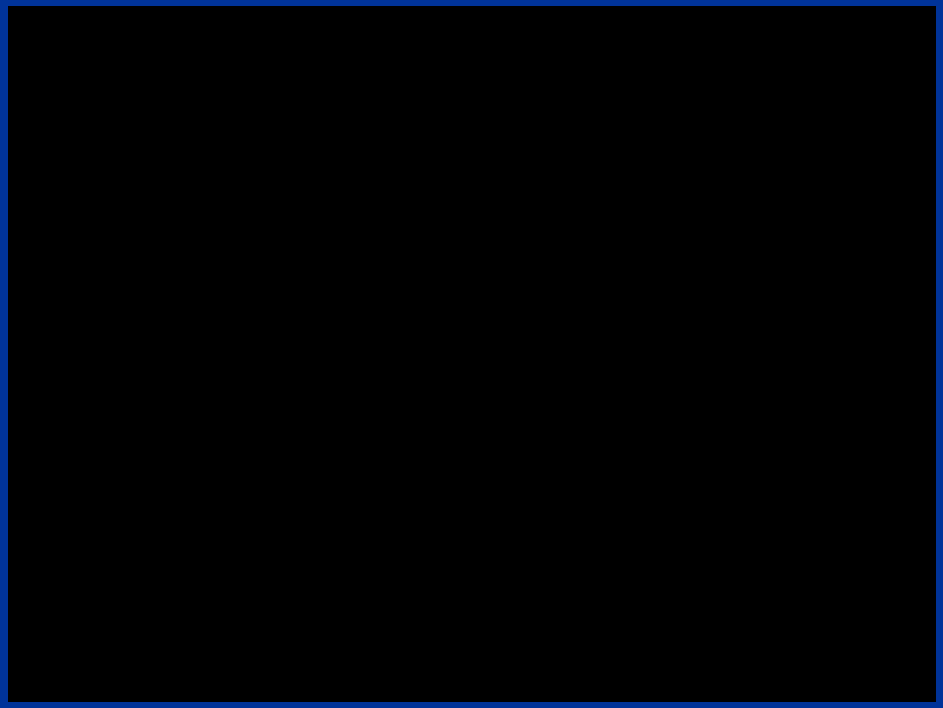


Wood, 2000

SeeBoss and Ciesla, 2014 for a recent review

Complications:

2) Material flows in and out -> feeding zones of embryos and planets will be large



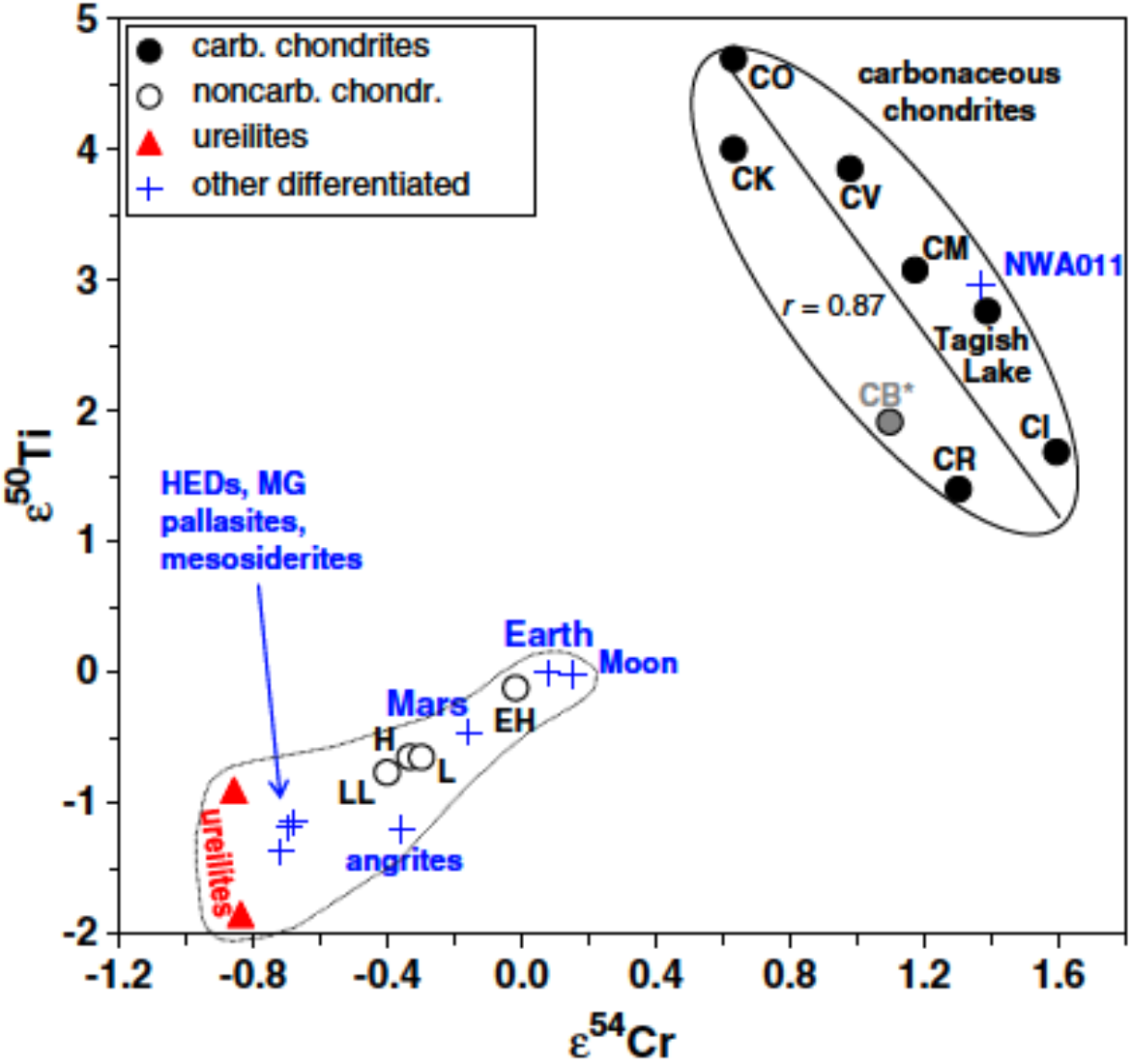
Raymond and Izidoro, 2017

No single body in the solar system may be identical to Earth

Some isotope terminology

- Radioactive isotope → isotopes that will undergo radioactive decay
- Radiogenic isotope → isotope generated from radioactive decay
- Non-radiogenic isotope → stable isotopes not affected by decay; variations in ratios involving non-radiogenic isotopes reflect nucleosynthetic anomalies

No known objects have the same isotopic DNA as the Earth



Enstatite chondrites are the closest analogues but are NOT identical in composition (e.g., Ti, Cr, O, Nd, Mo, Ru)

Warren, 2011

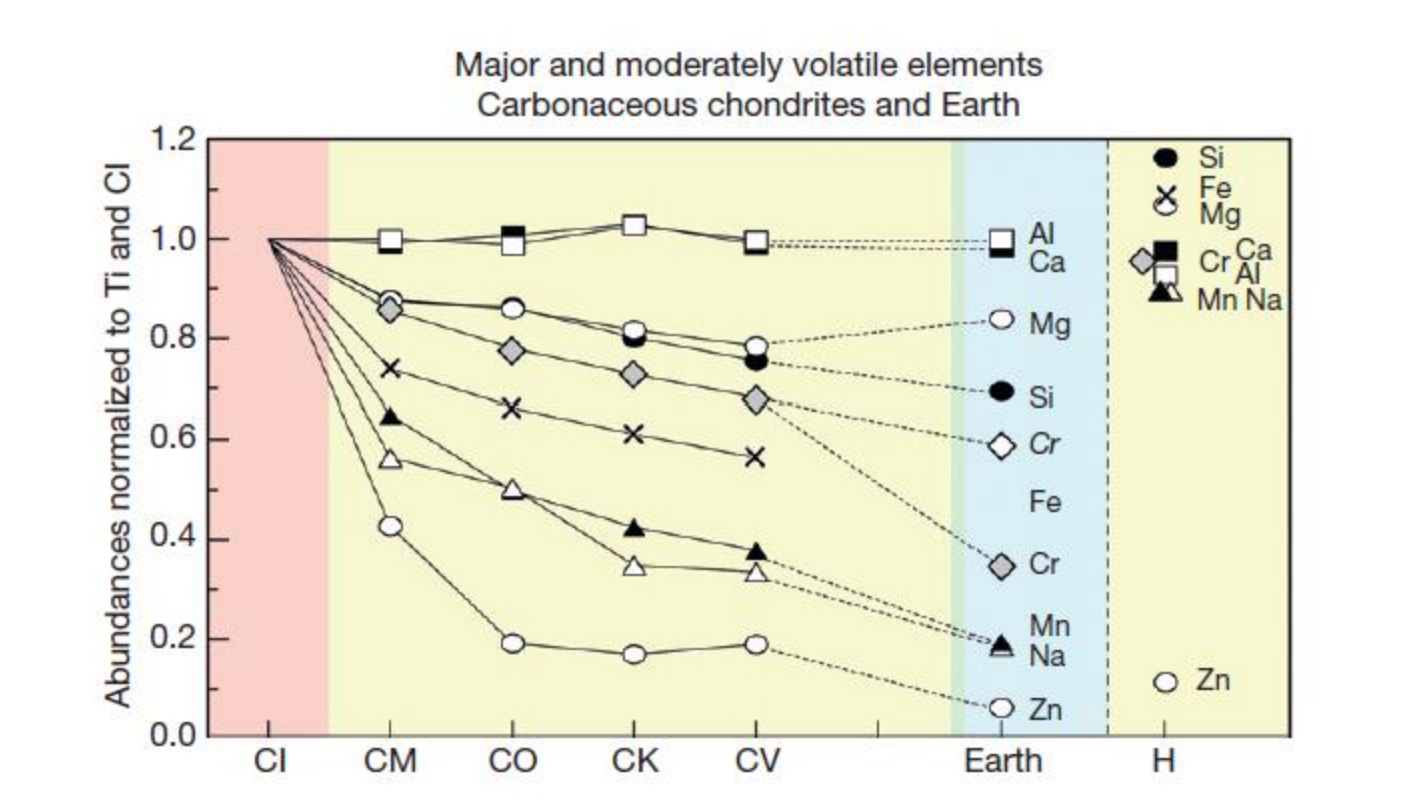
1) Estimating Earth composition

Use mantle peridotites, knowledge of melt extraction and assume earth has certain refractory element ratios in the same proportion as that of CI chondrites

-- the "chondritic Earth model"

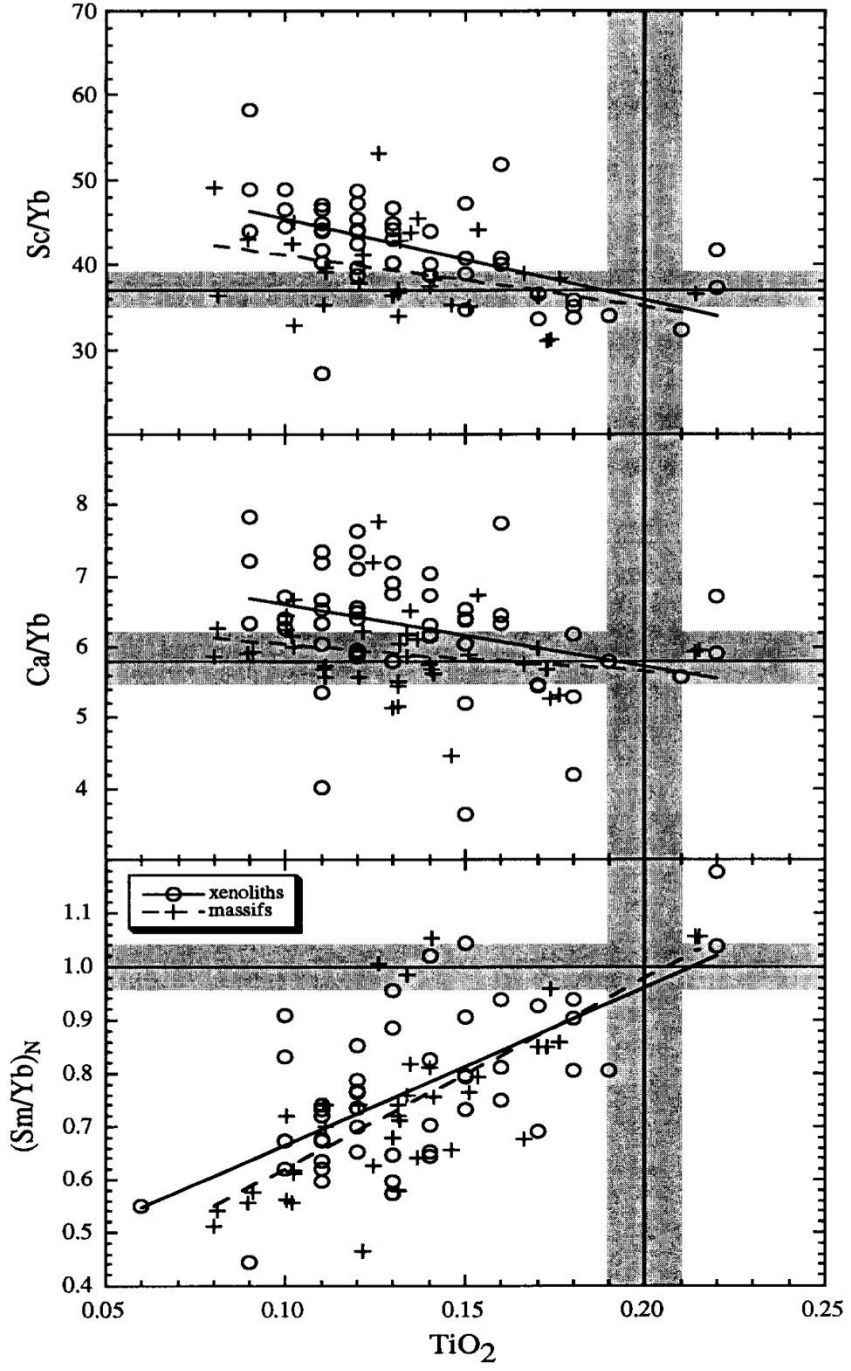
Simply assuming that all elements are present in chondritic proportions will lead to erroneous results

So why is the assumption that Earth has certain refractory element ratios in the same proportion as CI chondrites not terrible?



Palme and O'Neil, 2014

Bulk composition of the Earth

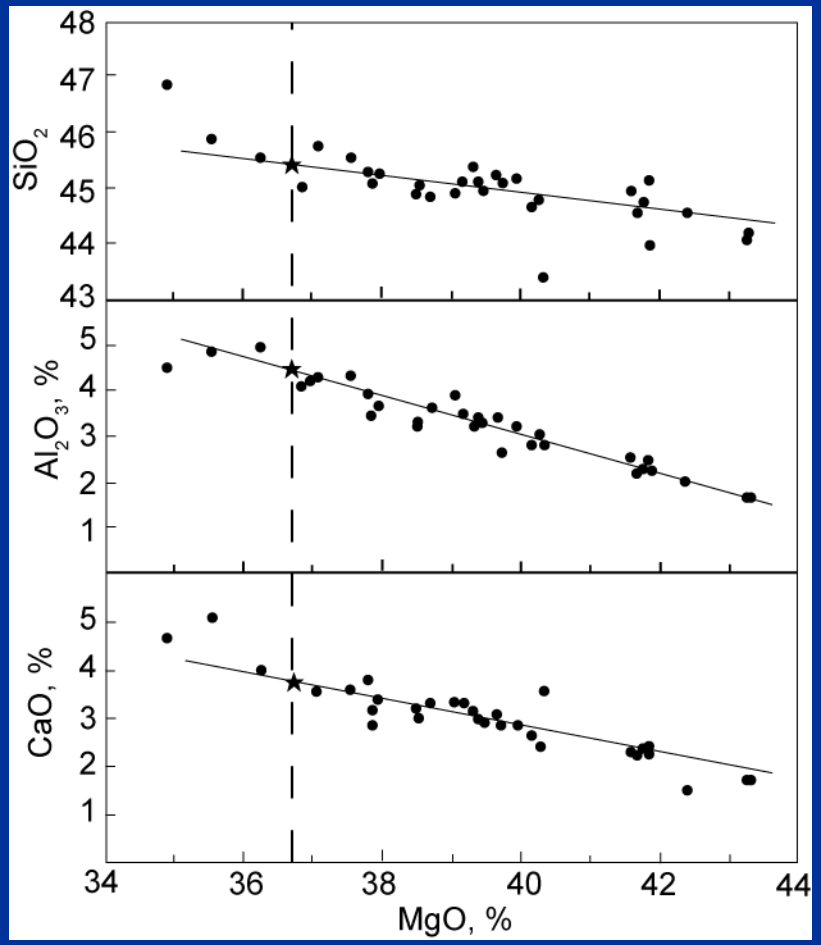


Geochemical models of Earth's composition begin by estimating a major element concentration from a suite of mantle peridotites

McDonough and Sun, 1995

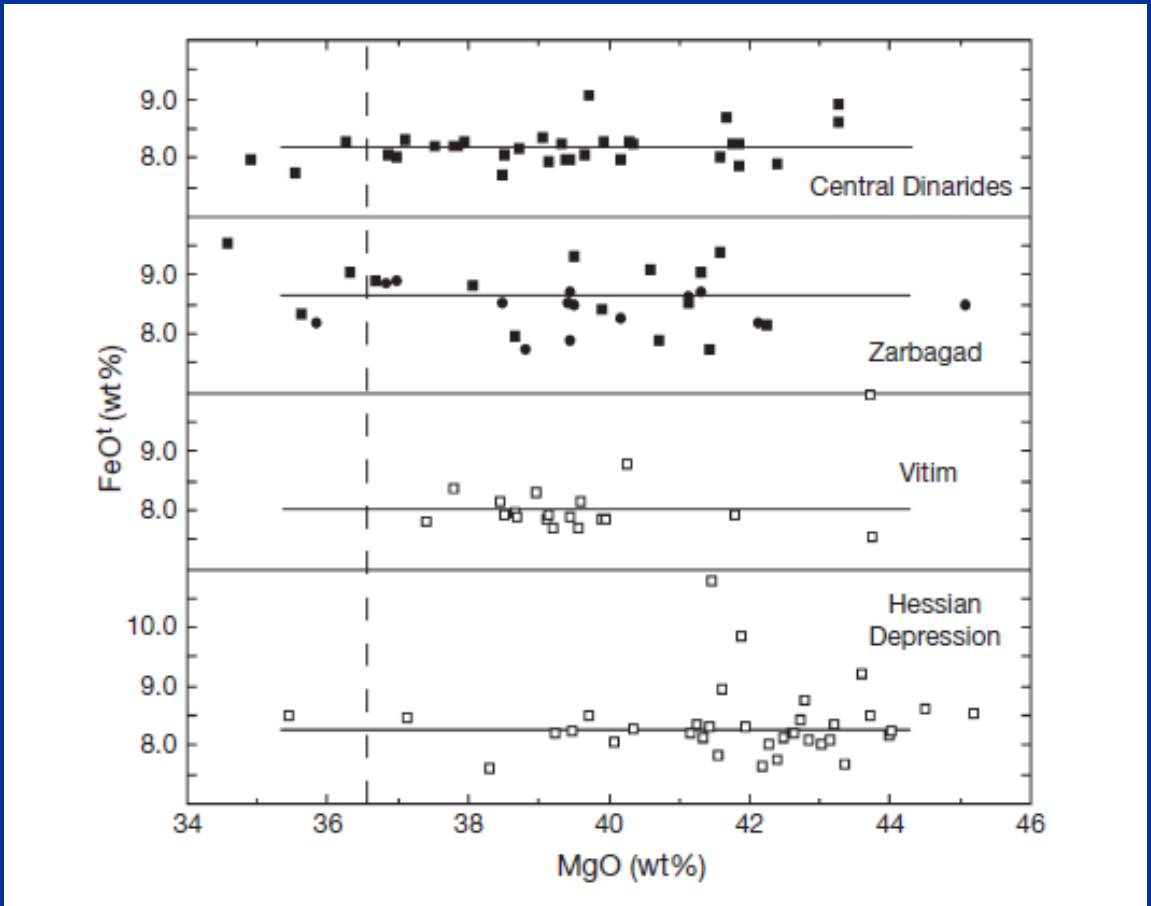
Bulk composition of the Earth

Once a major element concentration is determined, concentrations of other major elements estimated from x-y regression plots of mantle peridotites.



Palme and O'Neil, 2014

Bulk composition of the Earth

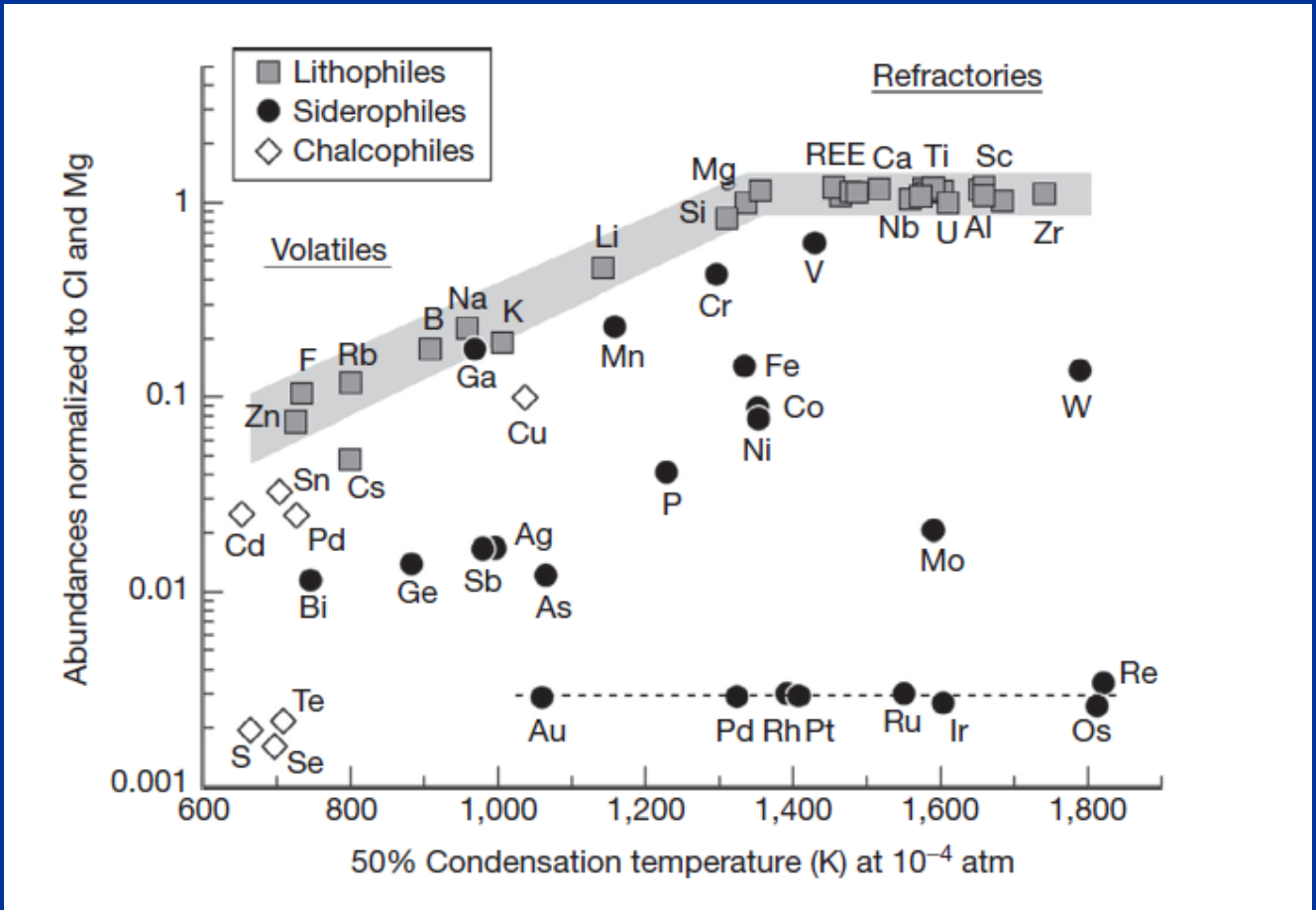


Sets the FeO content of the mantle to 8.1± 0.05 wt %

Get Mg from Mg-number of 0.89 for mantle

Palme and O'Neil, 2014

Estimating Earth Composition



Elemental abundance versus 50% condensation temperature (Halliday and Wood 2015, after McDonough and Sun, 1995)

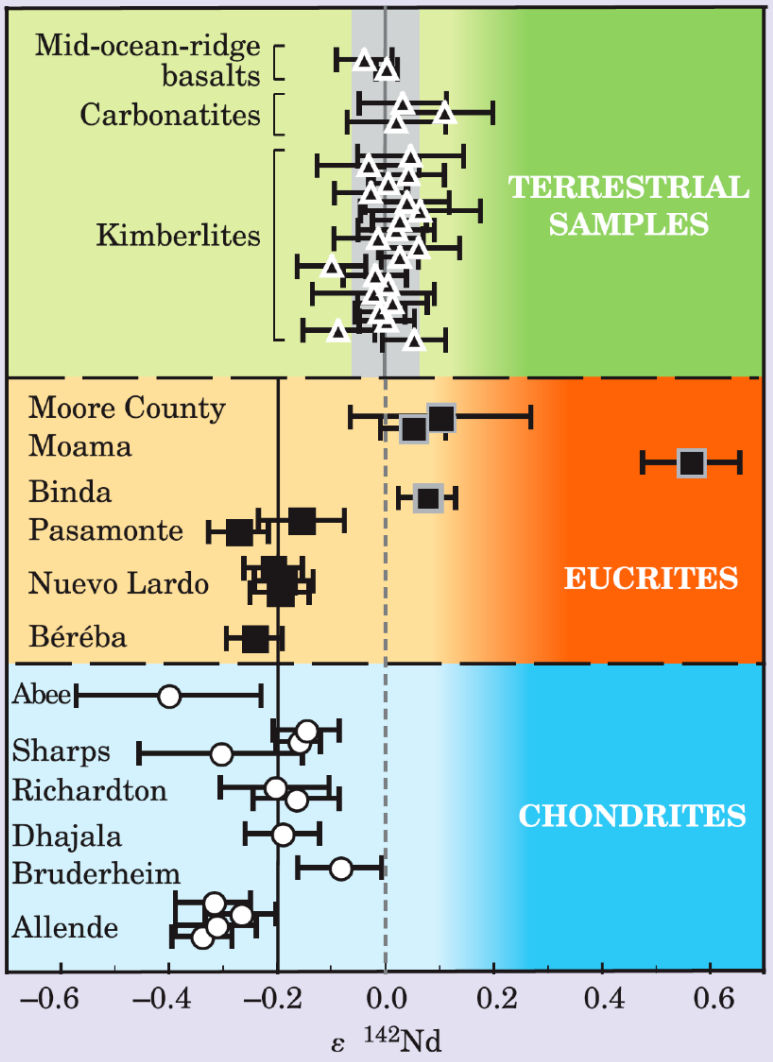
Relative to volatility trend, some elements are grossly depleted in silicate portion of the earth

Some isotope terminology

- Radioactive isotope → isotopes that will undergo radioactive decay
- Radiogenic isotope → isotope generated from radioactive decay
- Non-radiogenic isotope → stable isotopes not affected by decay; variations in ratios involving non-radiogenic isotopes reflect nucleosynthetic anomalies

A challenge to Earth having the same refractory element ratios as CI chondrites

$^{146}Sm \rightarrow {}^{142}Nd$; $t_{1/2} = 103$ My $\quad \varepsilon = \left(\frac{^{142}Nd/^{144}Nd_{sample}}{^{142}Nd/^{144}Nd_{std}} - 1 \right) \times 10000$



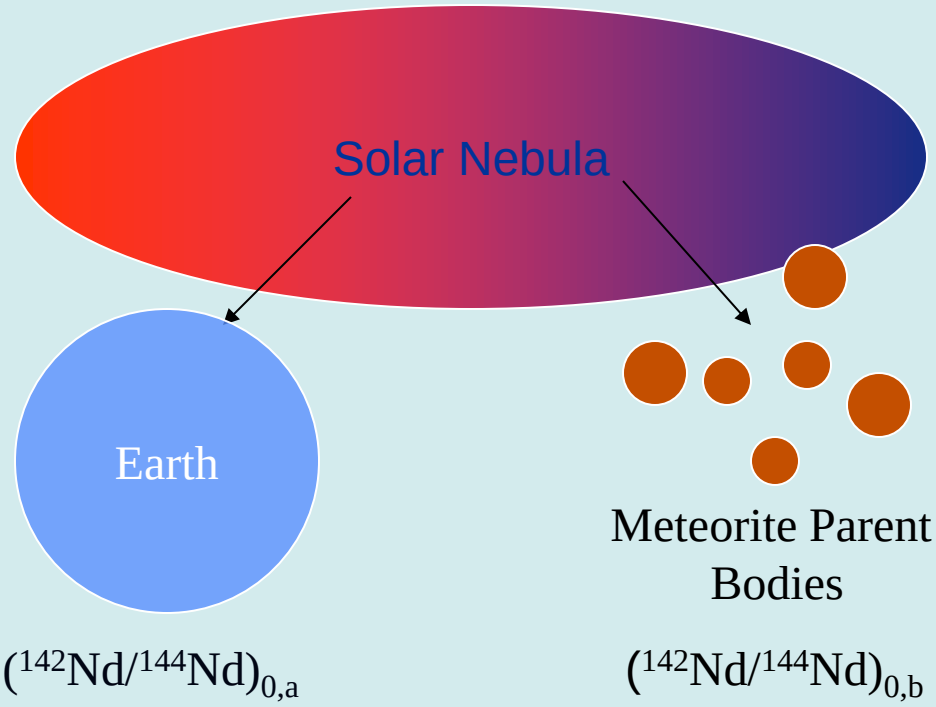
If starting $^{142}Nd/^{144}Nd$ in different objects were the same:
compared to chondrites, accessible silicate Earth has an excess of decay product (^{142}Nd) relative to the parent (^{146}Sm)

Or, silicate mantle could have a higher Sm/Nd ratio than chondrites

Boyet and Carlson (2005)

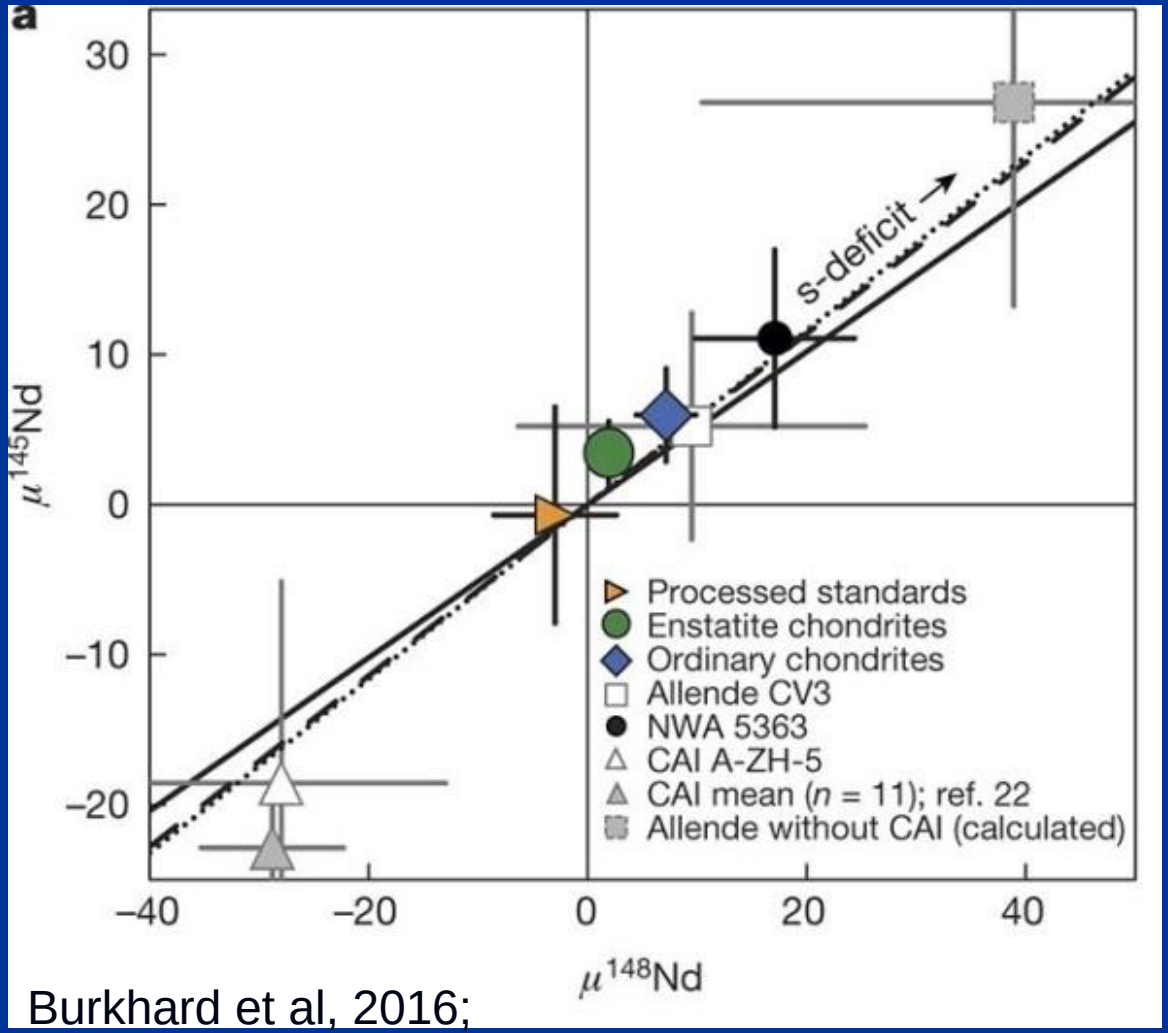
But what if the different objects did not have the same $^{142}Nd/^{144}Nd$?

Is it possible that because of incomplete mixing of r- and s- process components Earth and meteorites had different starting $^{142}Nd/^{144}Nd$ values?



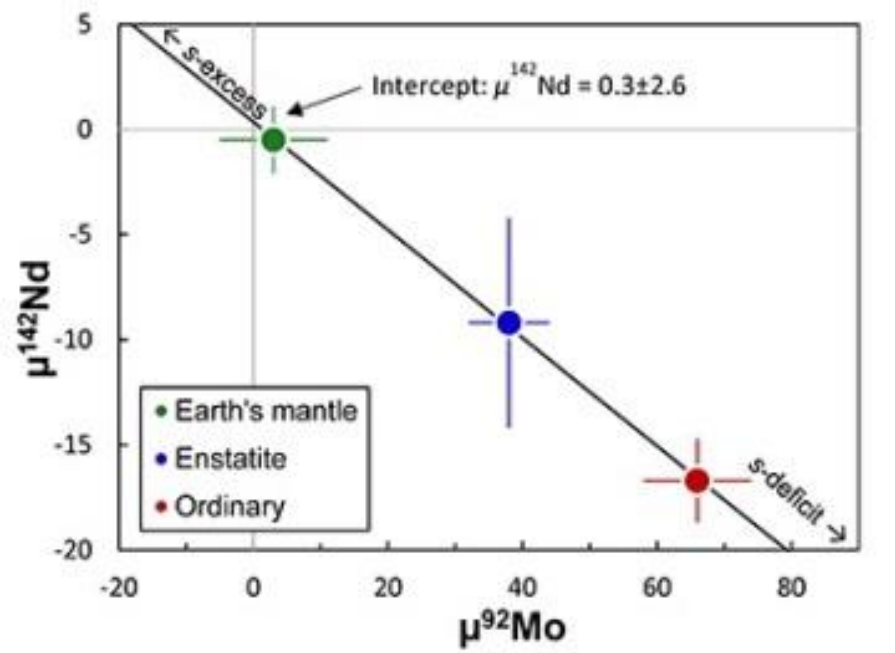
To test this idea one needs to find isotopes produced by both the r- and s-process nucleosynthesis but not having contribution from radioactive decay (e.g., ^{148}Nd)

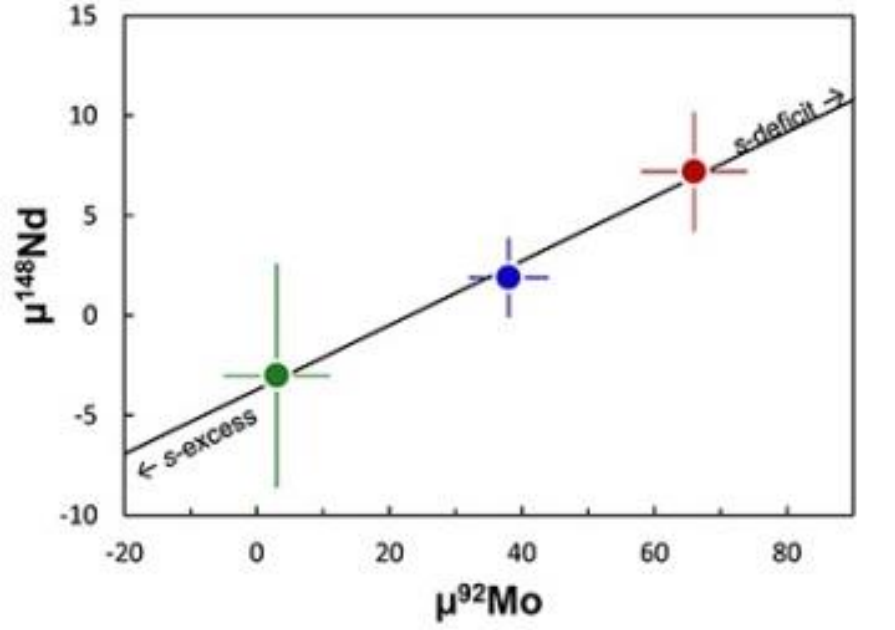
Earth and chondritic meteorites may not have same initial isotopic compositions



Burkhard et al, 2016;

And also Bouvier and Boyet, 2016; Boyet et al., 2018





Earth and meteorites do not have same initial isotopic compositions

What does this mean for interpreting the ε^{142}Nd?

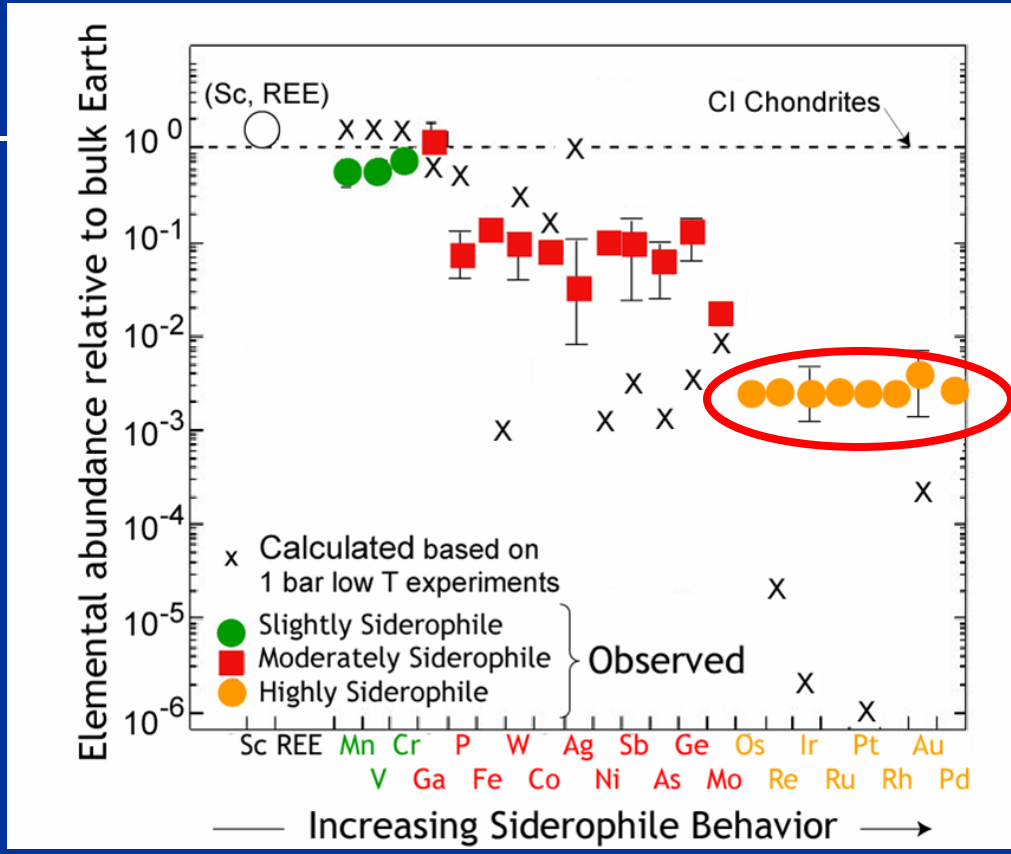
Inference for the bulk composition of the Earth?

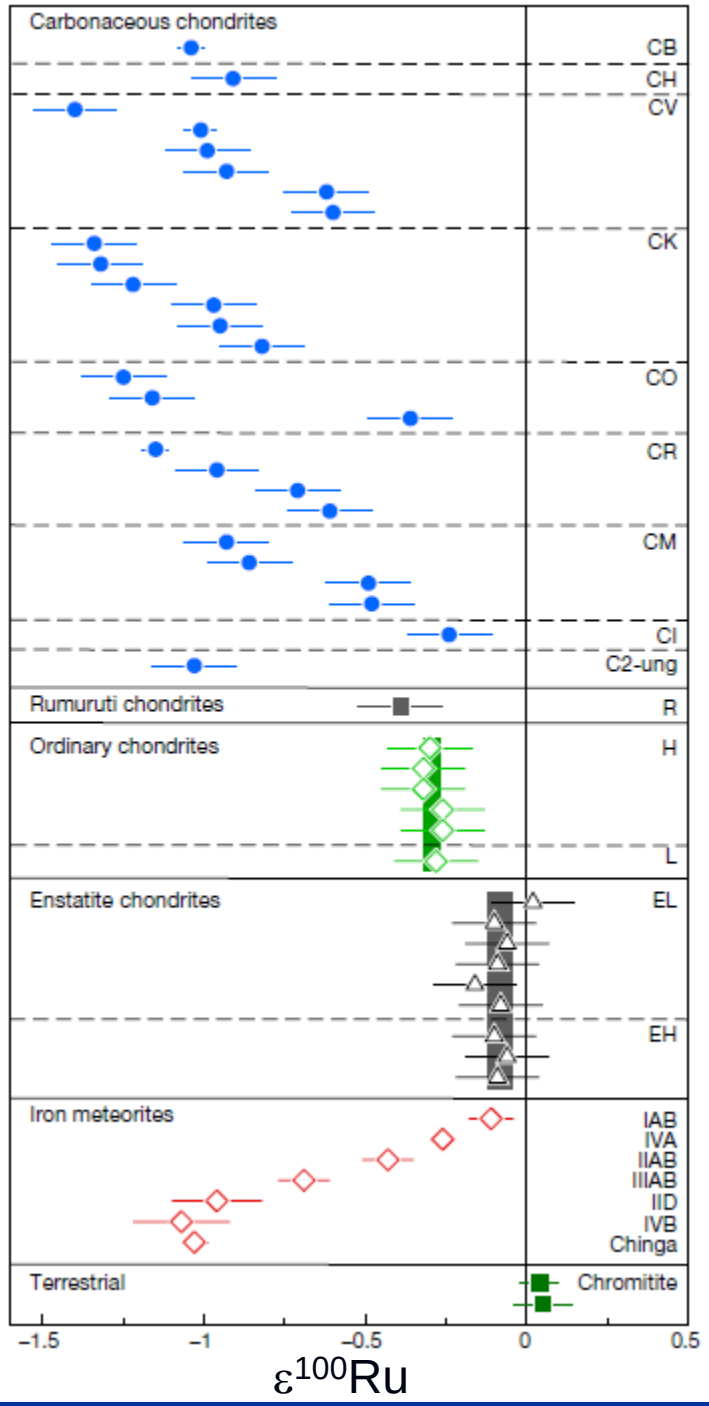
Render et al., 2017

Highly Siderophile Elements (HSE) and the late veneer

Abundances of HSE in mantle higher than predicted by metal-silicate partitioning and abundances are in chondritic relative proportions

Mantle abundances of these elements set after core formation – the so called late venner





The nature of the late veneer

Not a carbonaceous or ordinary chondrite parent body

Mo-Ru correlations indicate that the late veneer material looks similar to the rest 99.1-99.5% of accretion.

(Dauphas, 2017)

Fischer-Gödde et al., 2017

2) Extinct radionuclides and early Earth history ($^{182}Hf \rightarrow {}^{182}W$, $^{146}Sm \rightarrow {}^{142}Nd$, $^{129}I \rightarrow {}^{129}Xe$)

Age equation for a long-lived radioactive element

$$\left(\frac{D_r}{D_s}\right)_{today} = \left(\frac{D_r}{D_s}\right)_{initial} + \left(\frac{P_r}{D_s}\right)_{today}(e^{\lambda t} - 1)$$

Measurable quantities

For an extinct radionuclide we have

$$\left(\frac{D_r}{D_s}\right)_{today} = \left(\frac{D_r}{D_s}\right)_{initial} + \left(\frac{P_r}{D_s}\right)_{initial}$$

But P_r does not exist anymore…..

$$\left(\frac{D_r}{D_s}\right)_{today} = \left(\frac{D_r}{D_s}\right)_{initial} + \left(\frac{P_r}{P_s}\right)_{initial}\left(\frac{P_s}{D_s}\right)$$

P_r is radioactive parent
D_r is radiogenic daughter produced from radioactive decay of P_r
D_s is stable non-radiogenic isotope of D_r and not produced by radioactive decay
P_s stable non-radiogenic isotope of P_r
λ is the decay constant

Hafnium –Tungsten (^{182}Hf-^{182}W) systematics; $t_{1/2}$ = 9 M.y

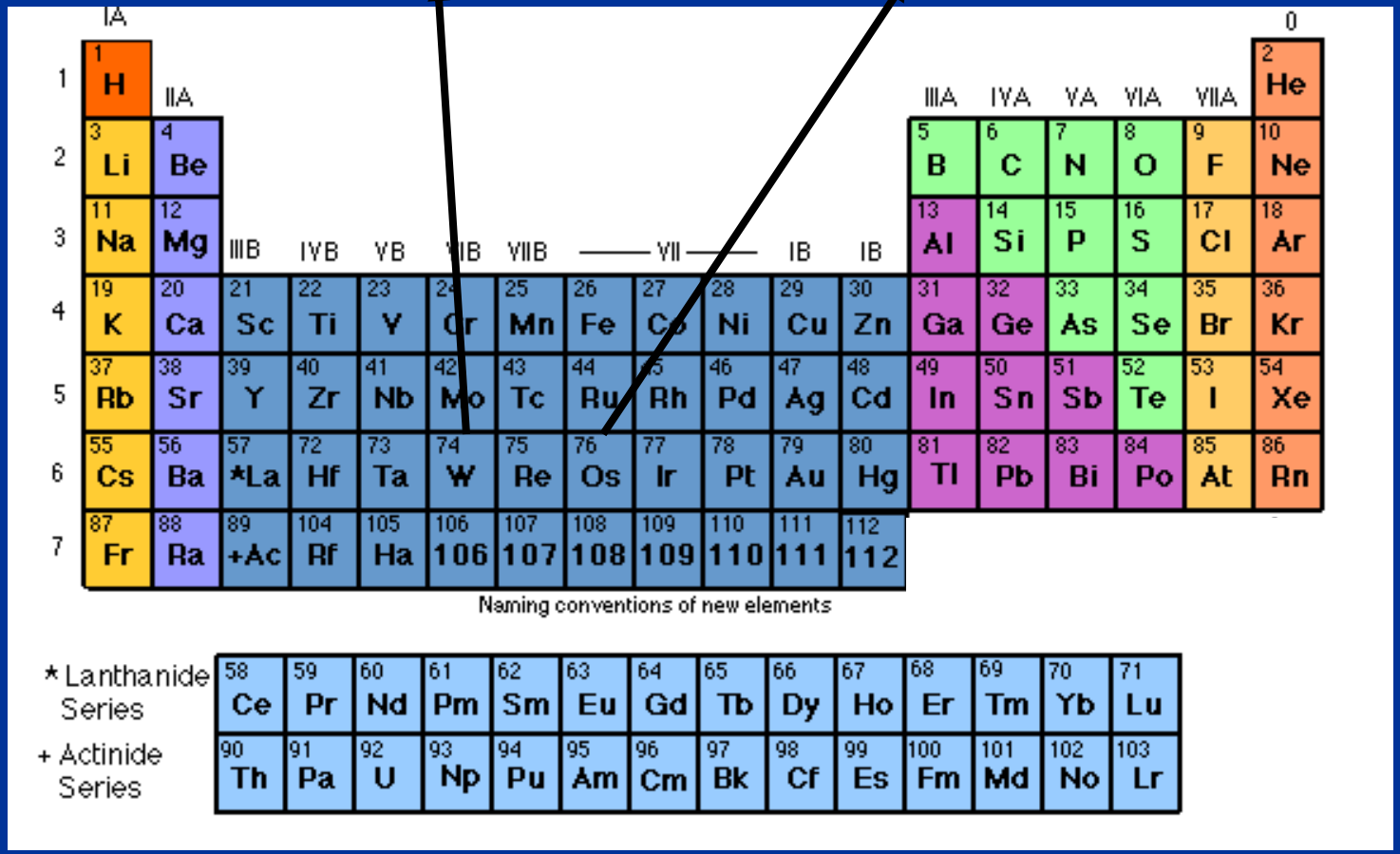
Hf is highly *lithophile*, retains in the silicate portion of the Earth.

W is *moderately siderophile*, some enters core, some retained in the silicate mantle.

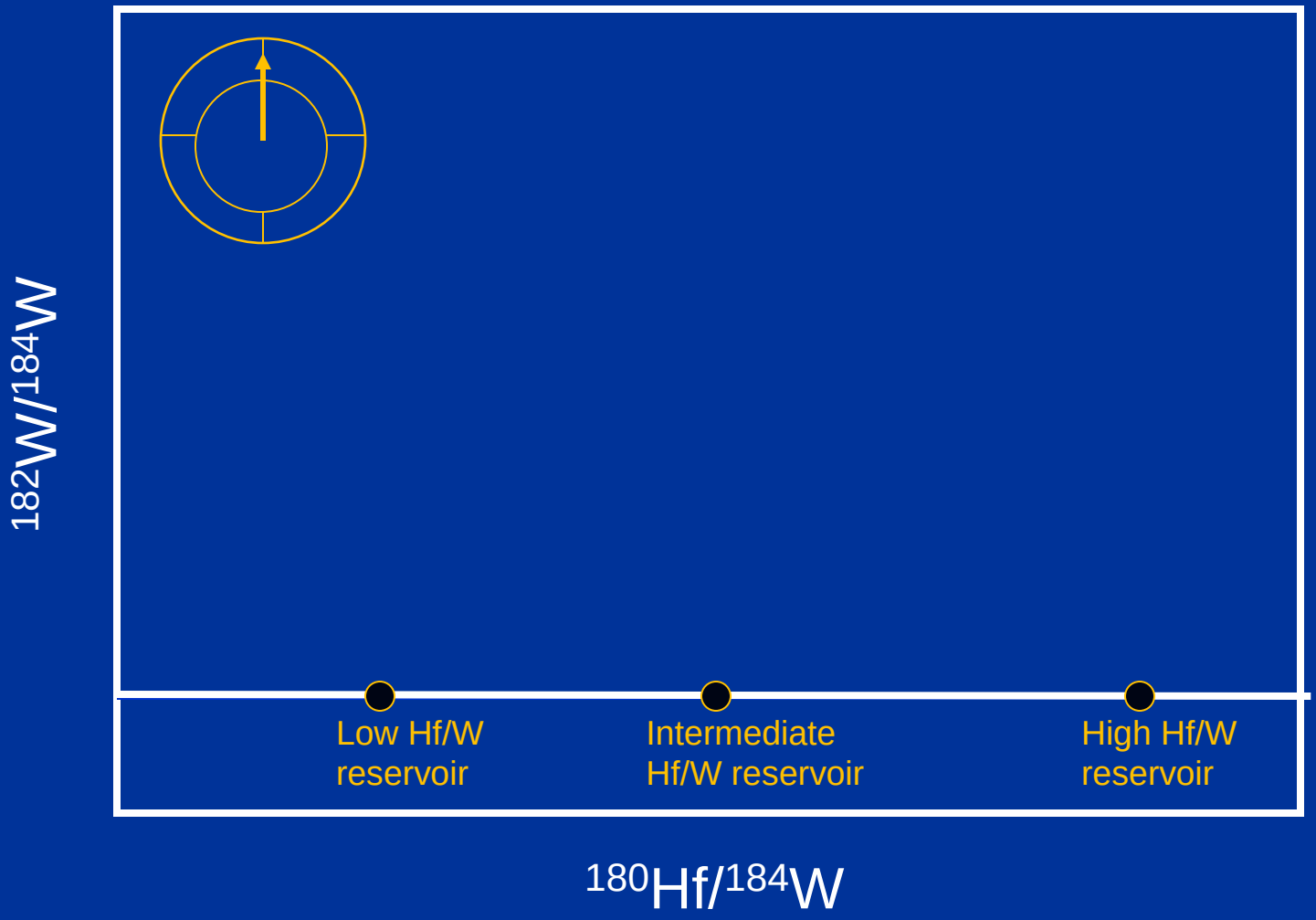
So ideal for tracking core formation

Silicate mantle

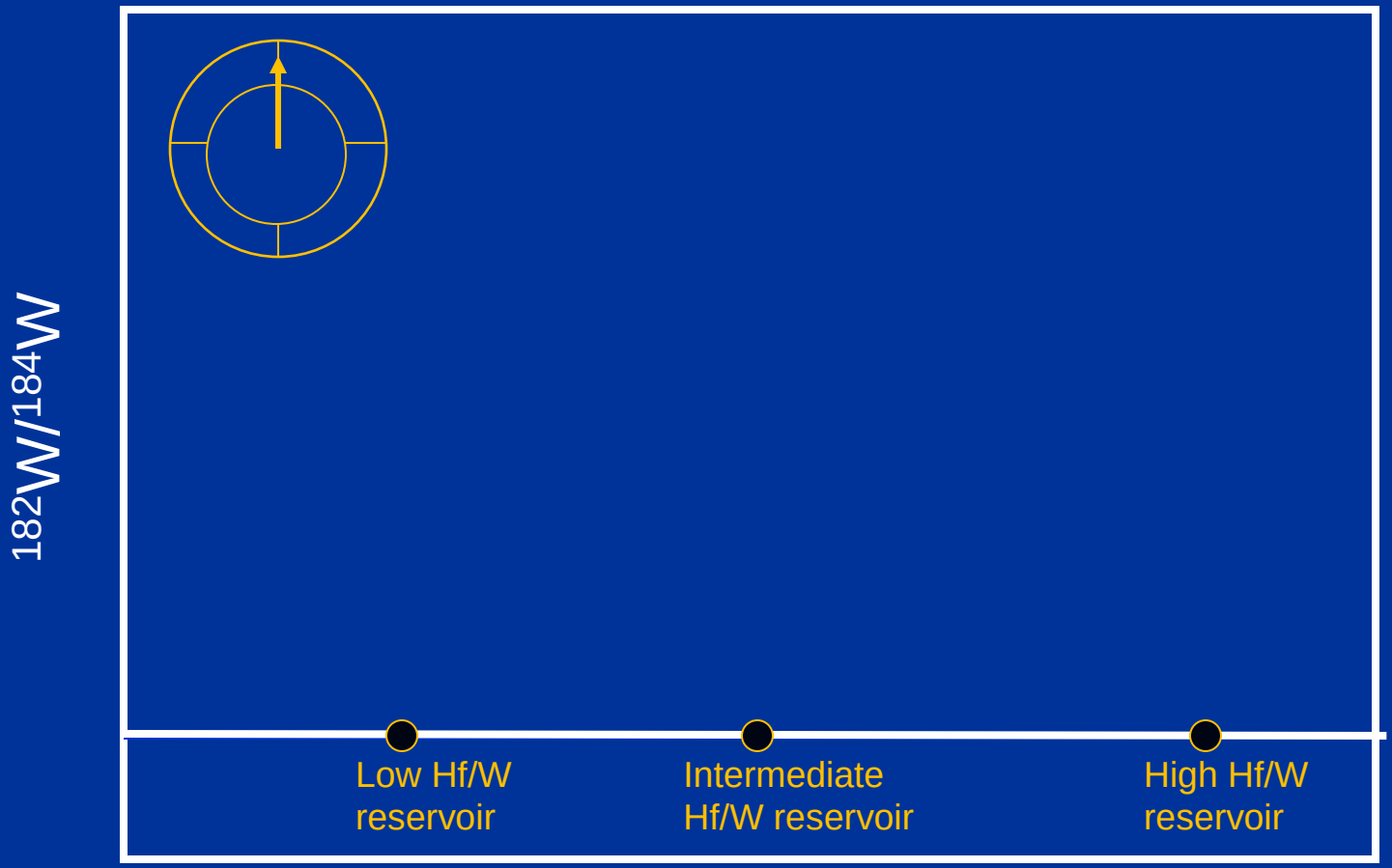
Core



Extinct radionuclides: ^{182}Hf decays to ^{182}W half-life of 9 Myrs

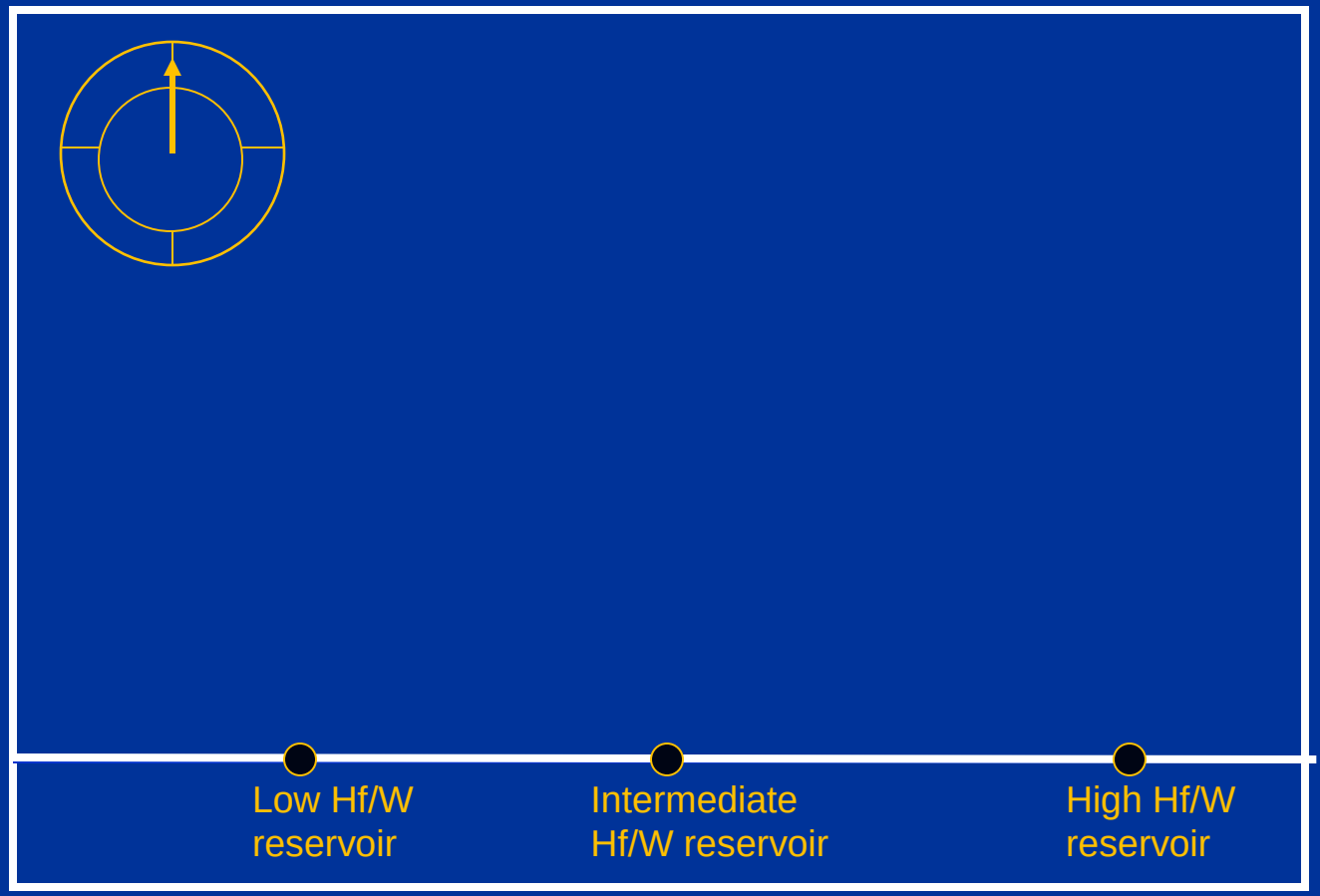


Extinct radionuclides: ^{182}Hf decays to ^{182}W half-life of 9 Myrs

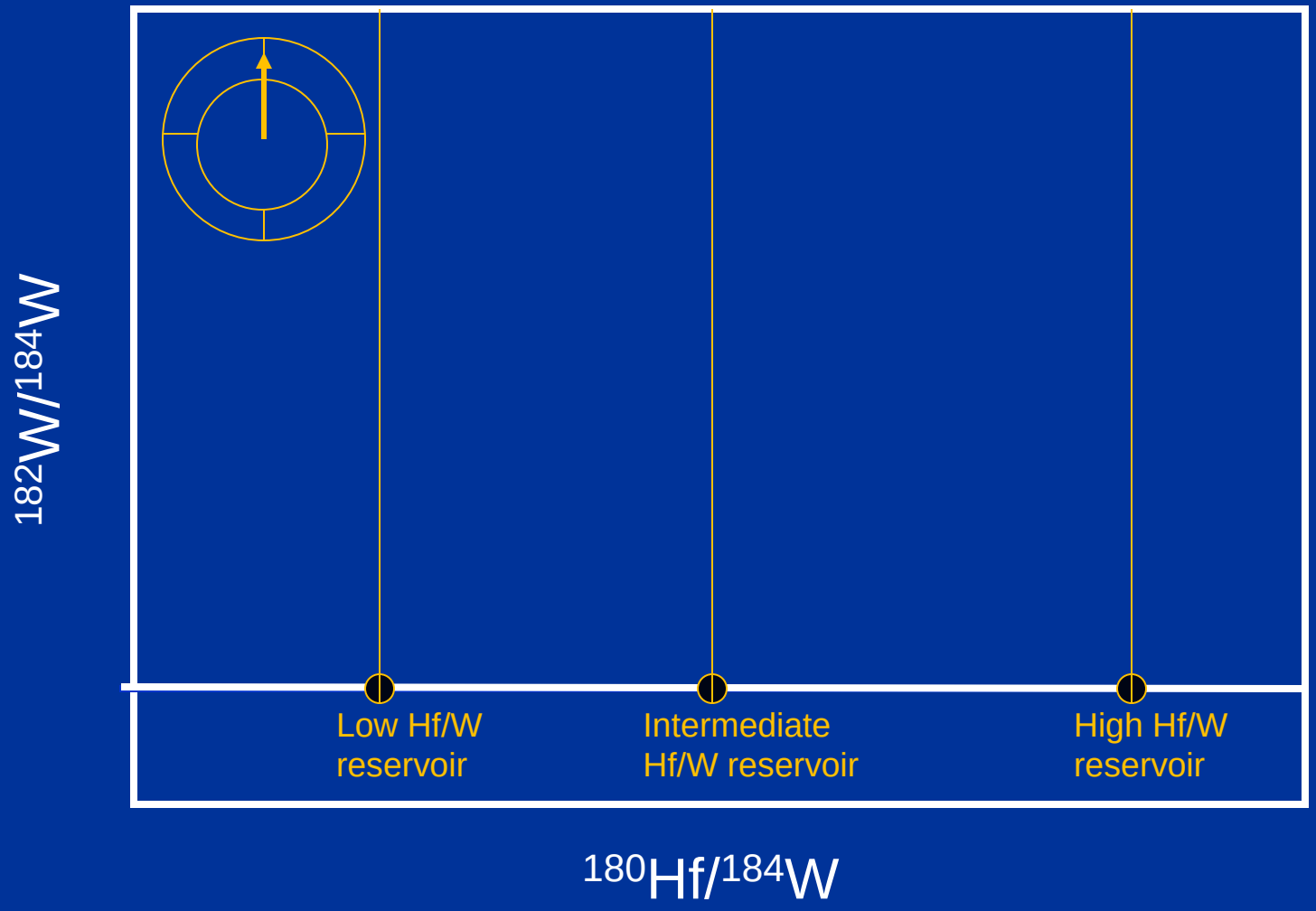


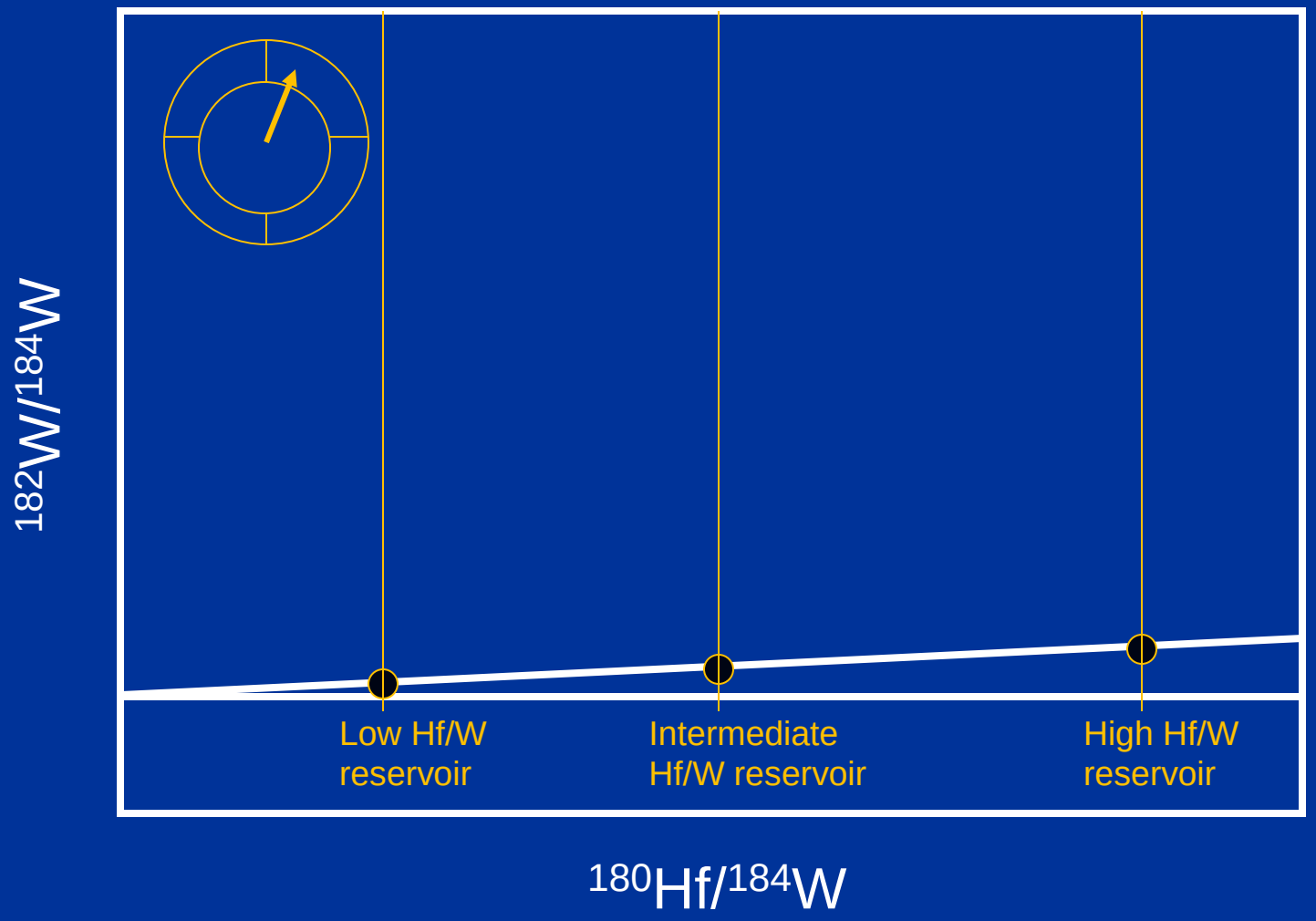
Stable non-radiogenic isotope of extinct nuclide

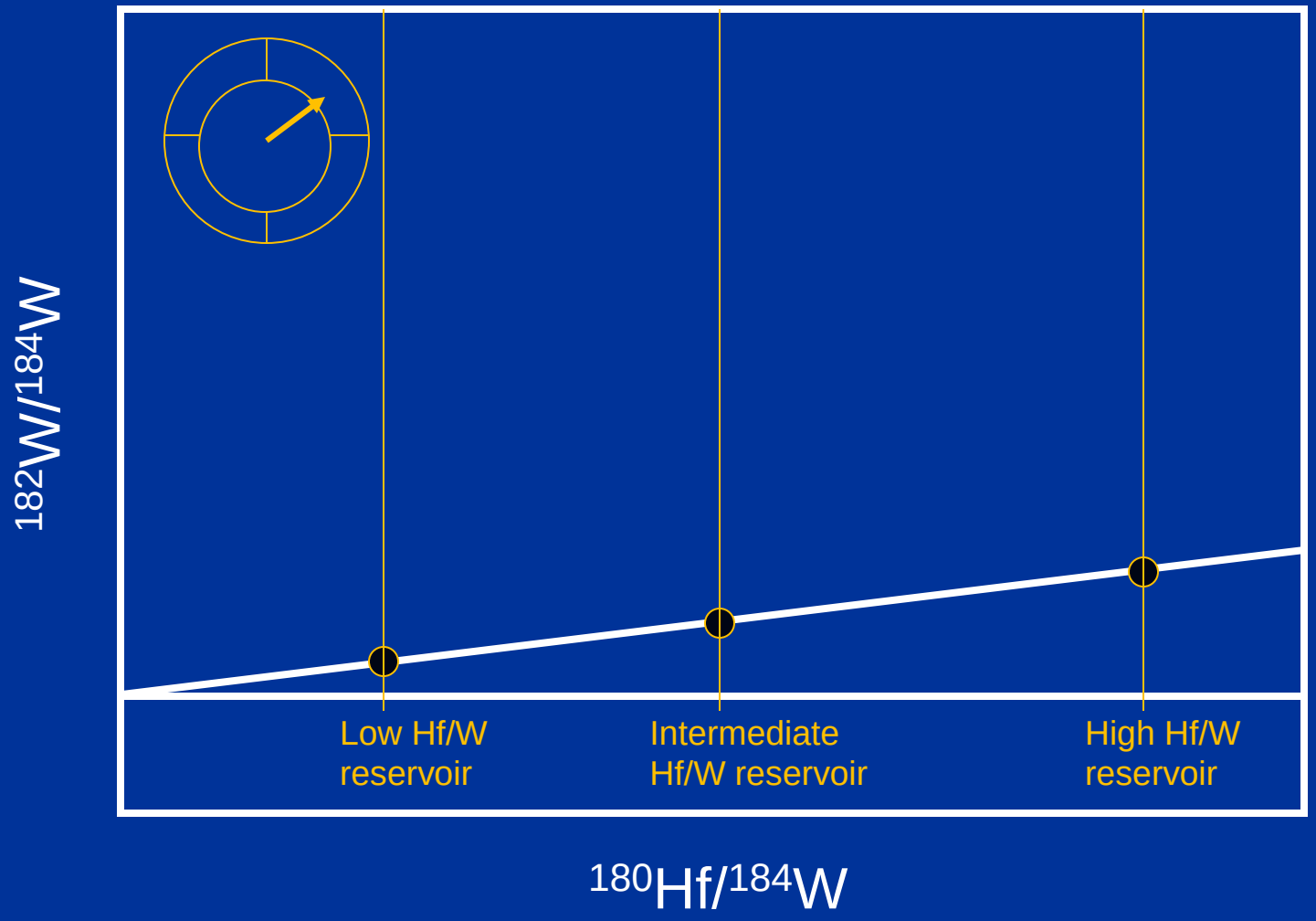
Extinct radionuclides: ^{182}Hf decays to ^{182}W half-life of 9 Myrs

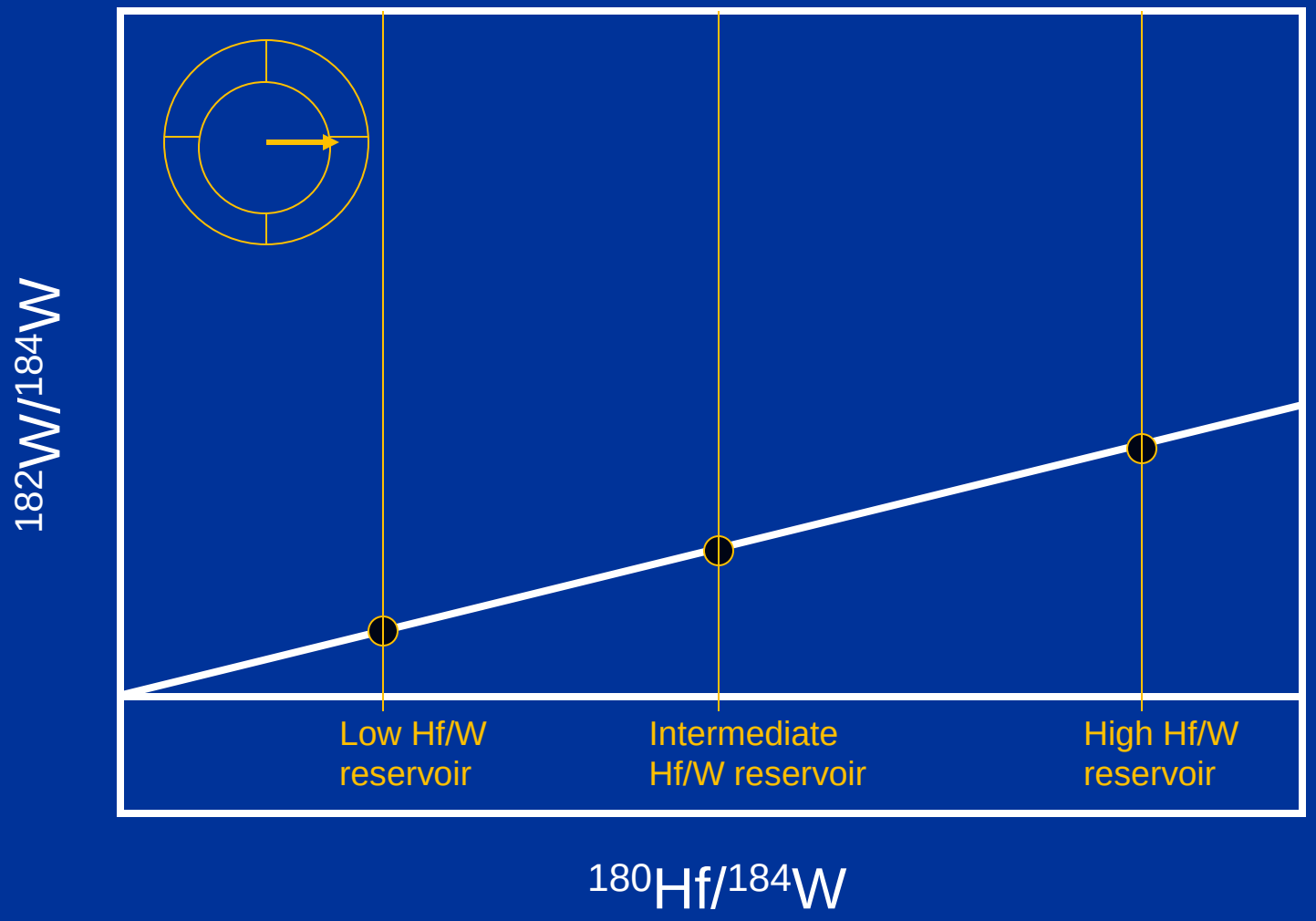


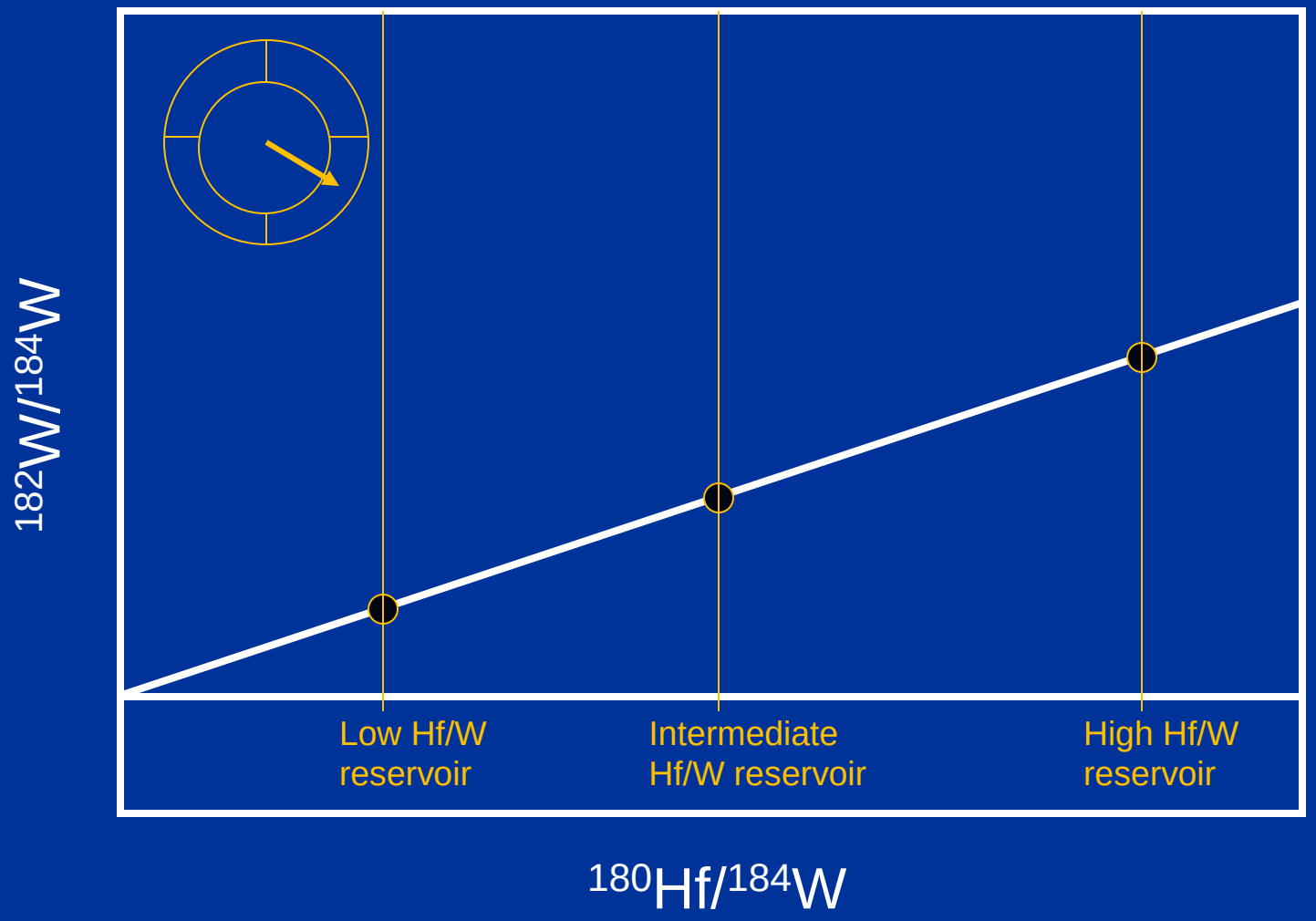
Extinct radionuclides: ^{182}Hf decays to ^{182}W half-life of 9 Myrs

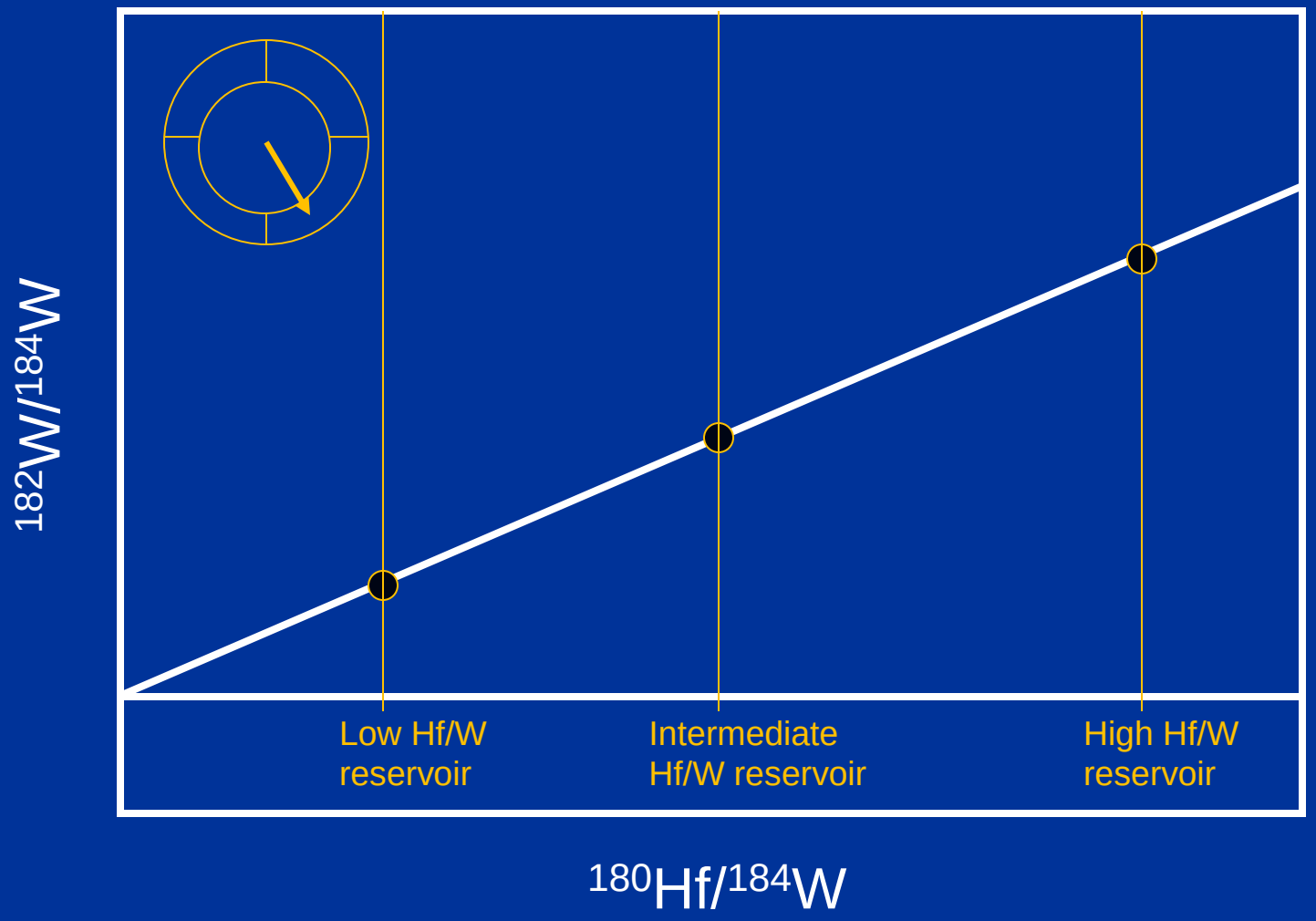


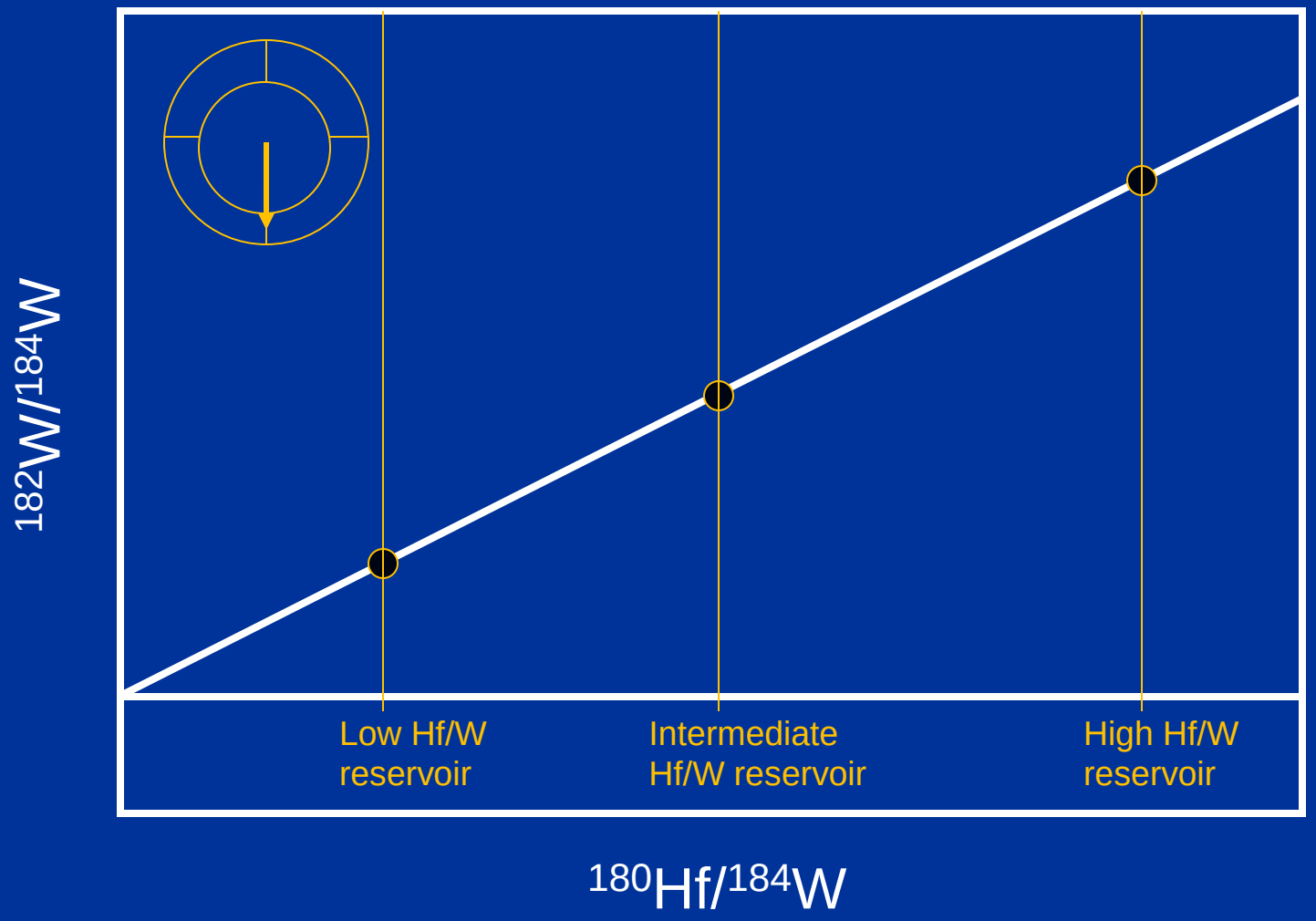

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

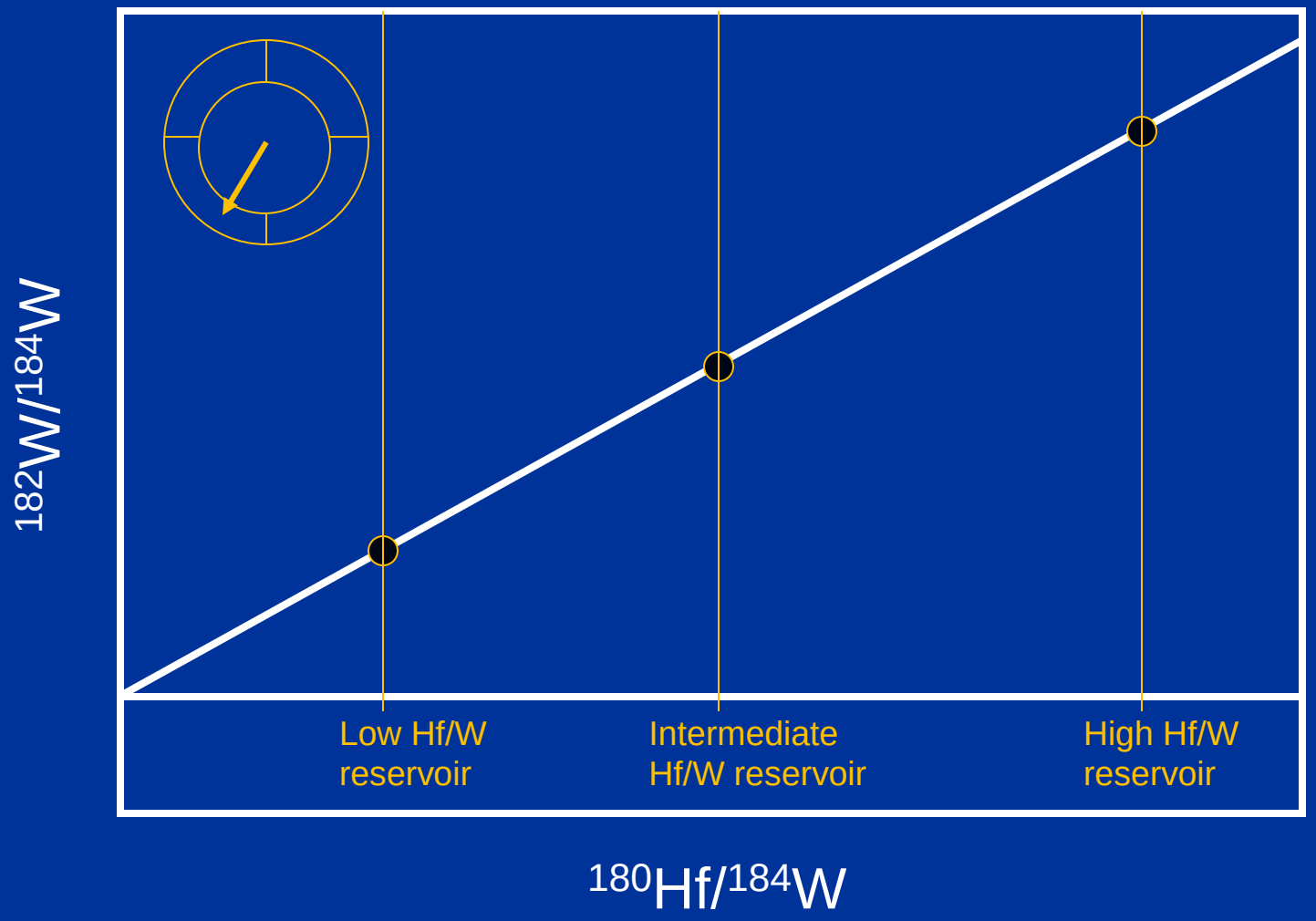

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

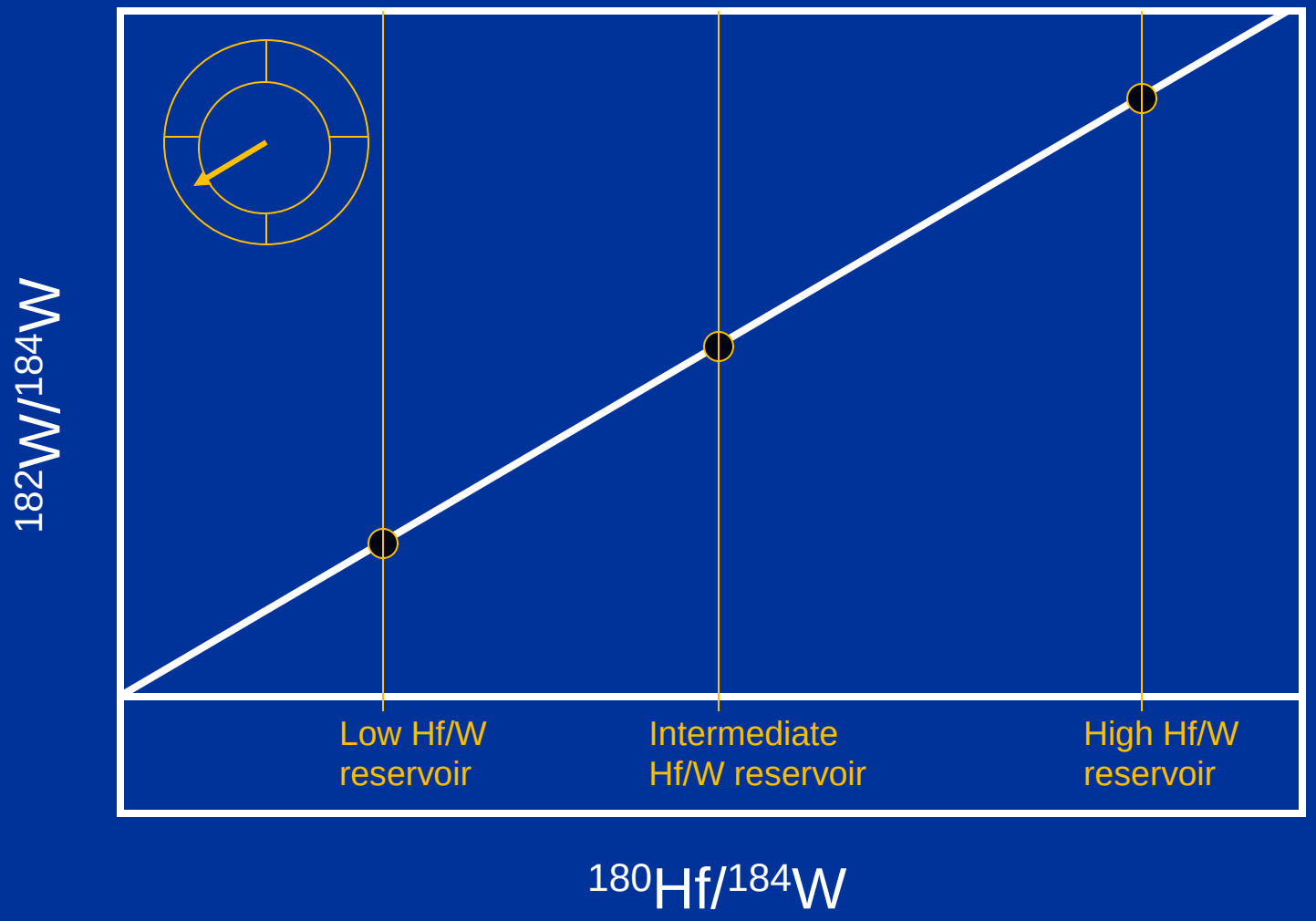

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

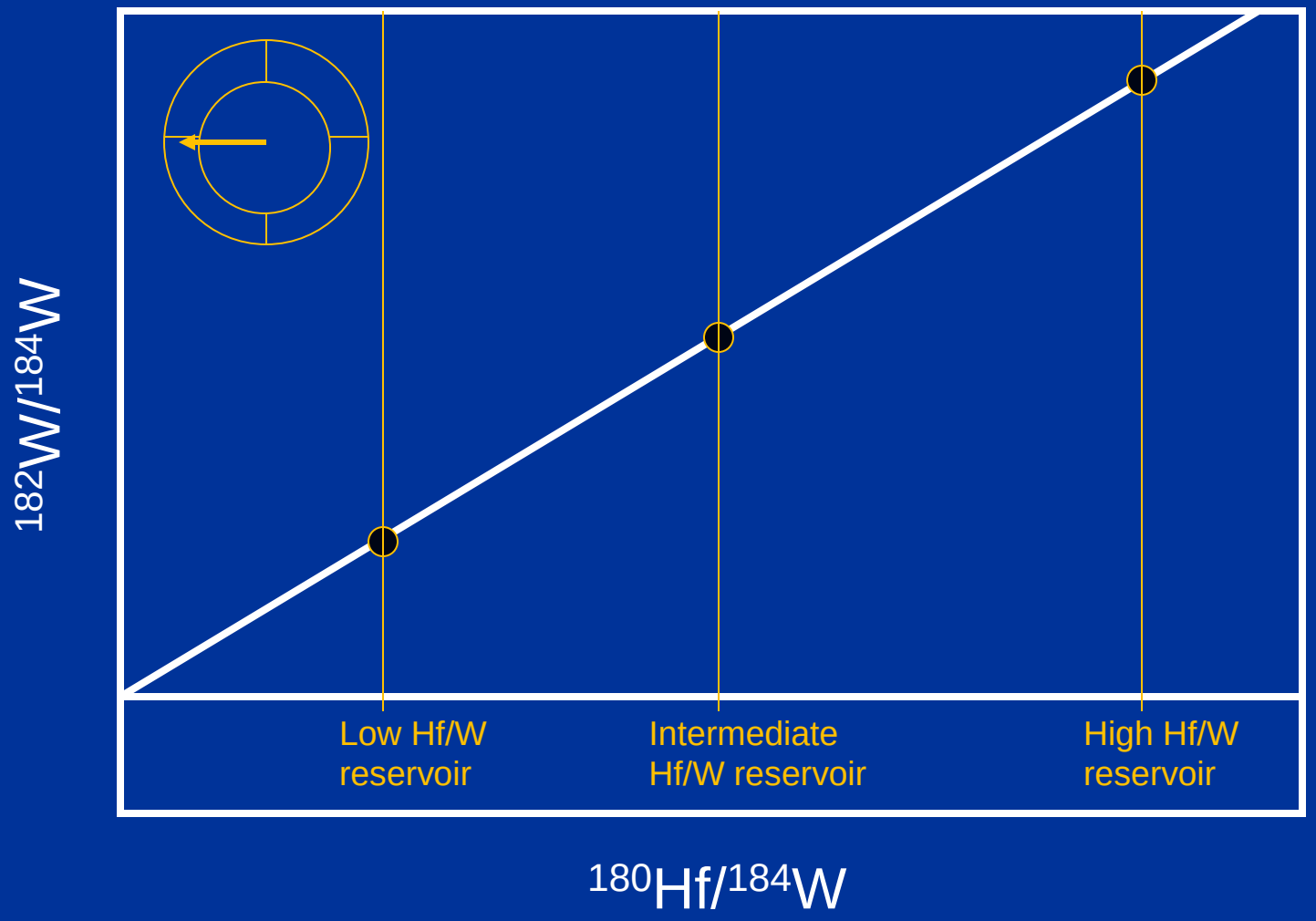

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

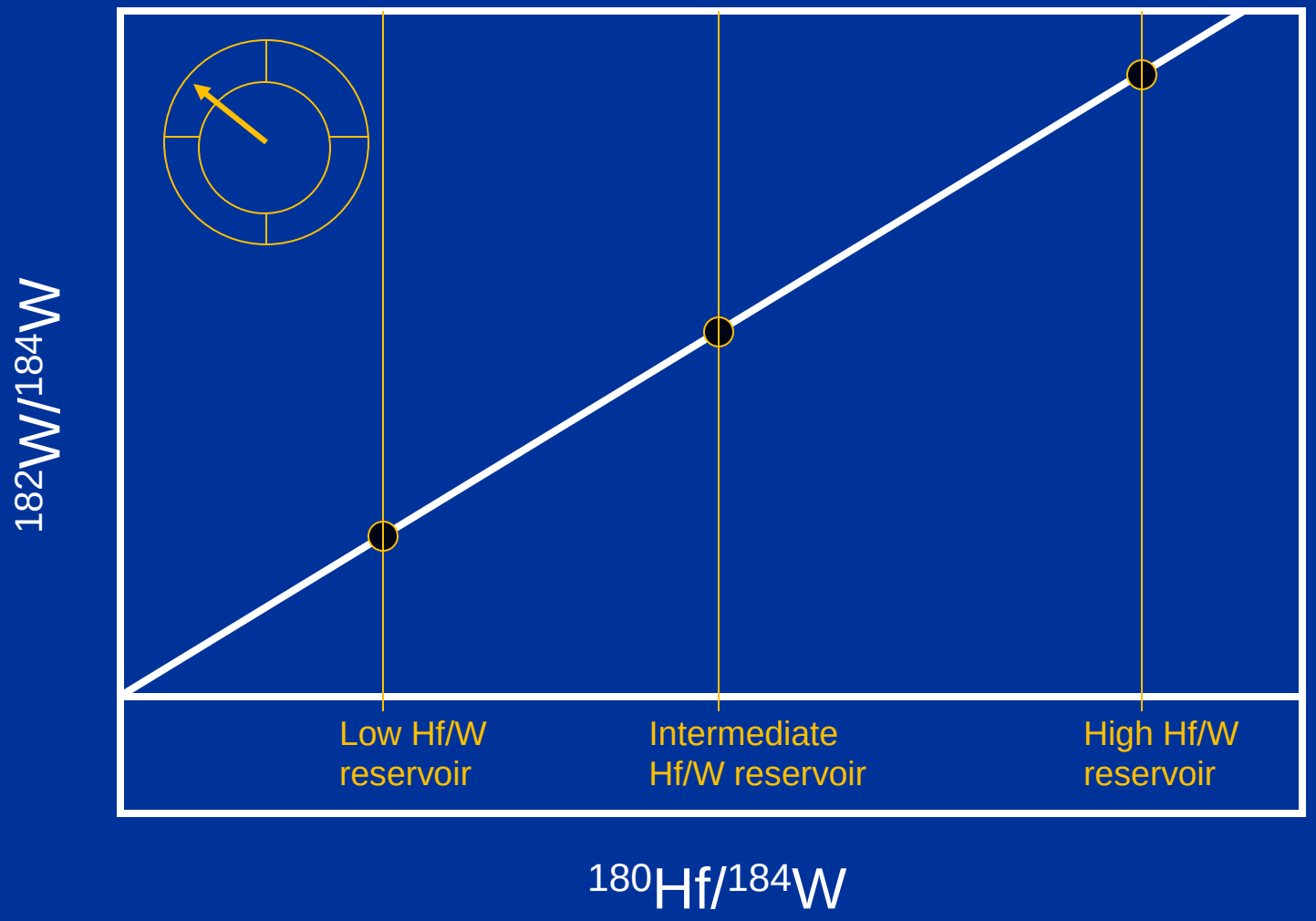

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

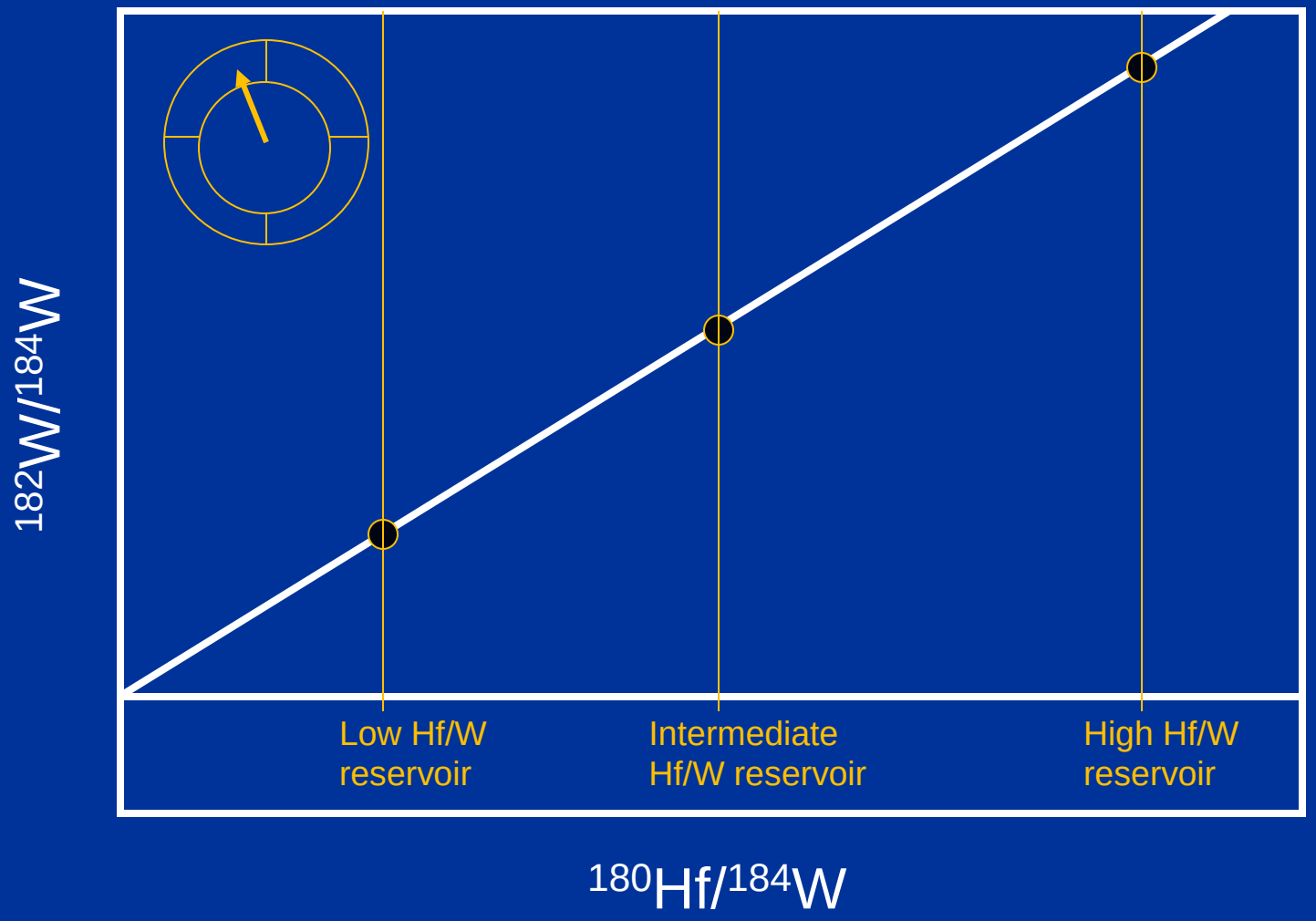

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

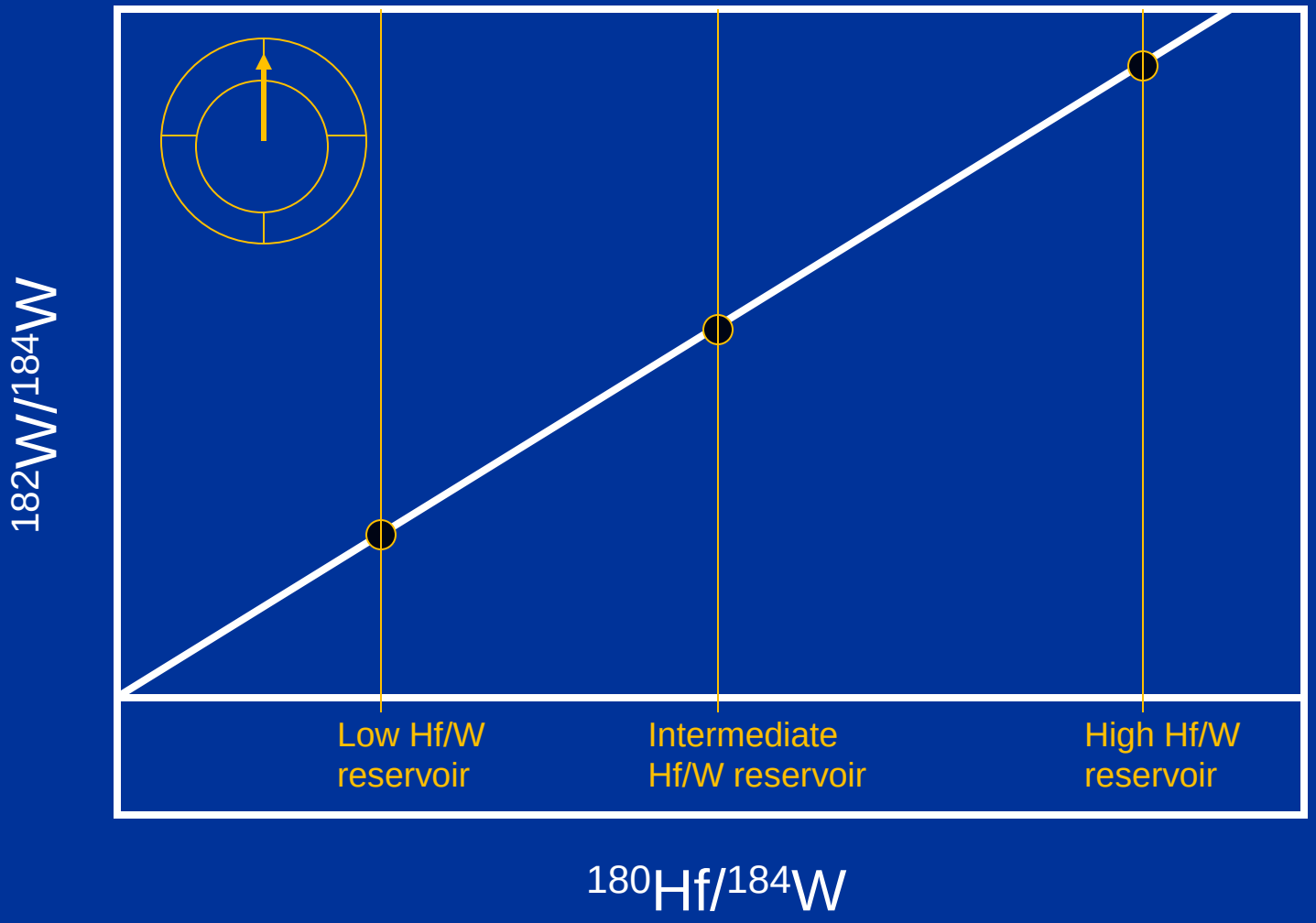

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

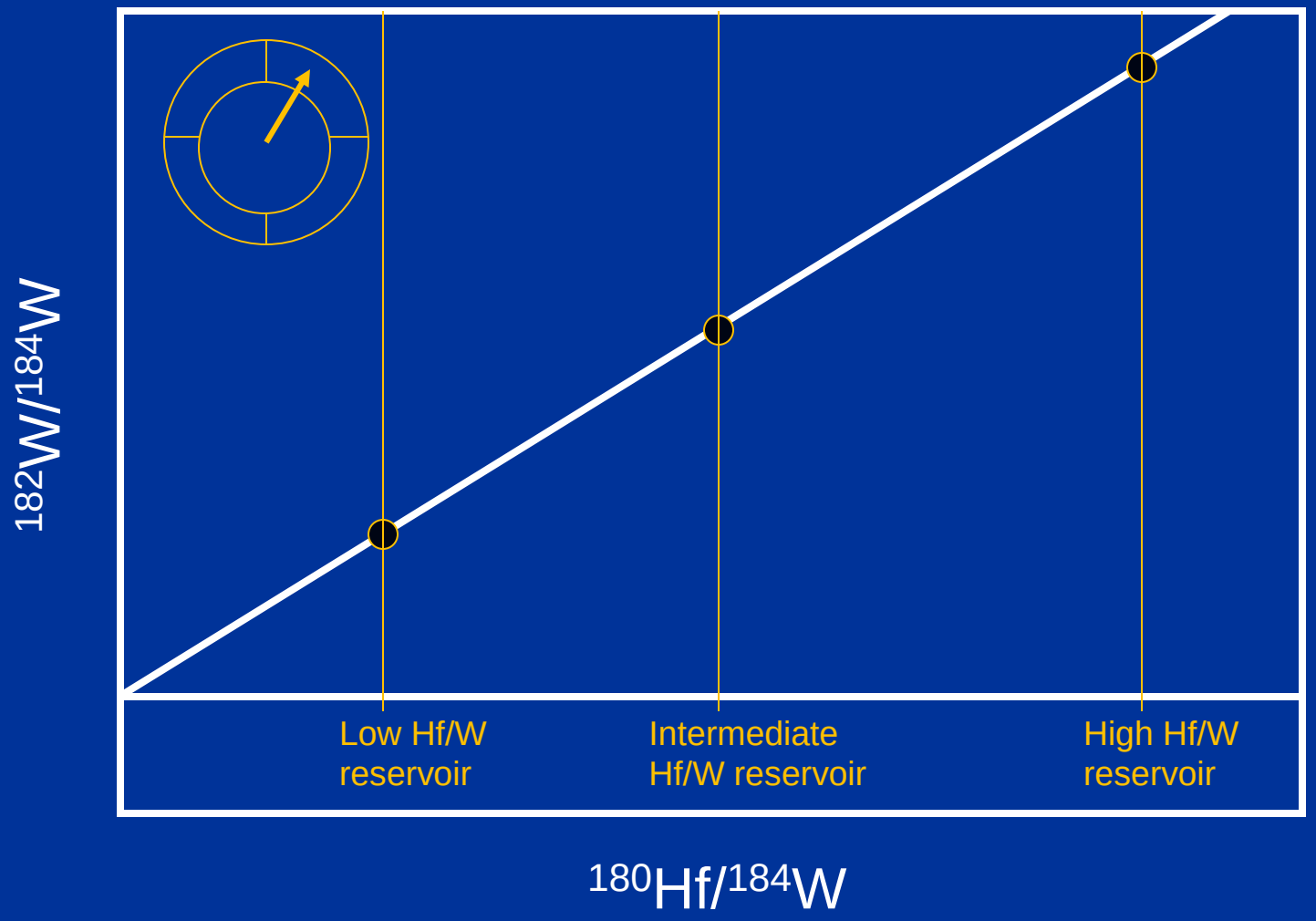

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

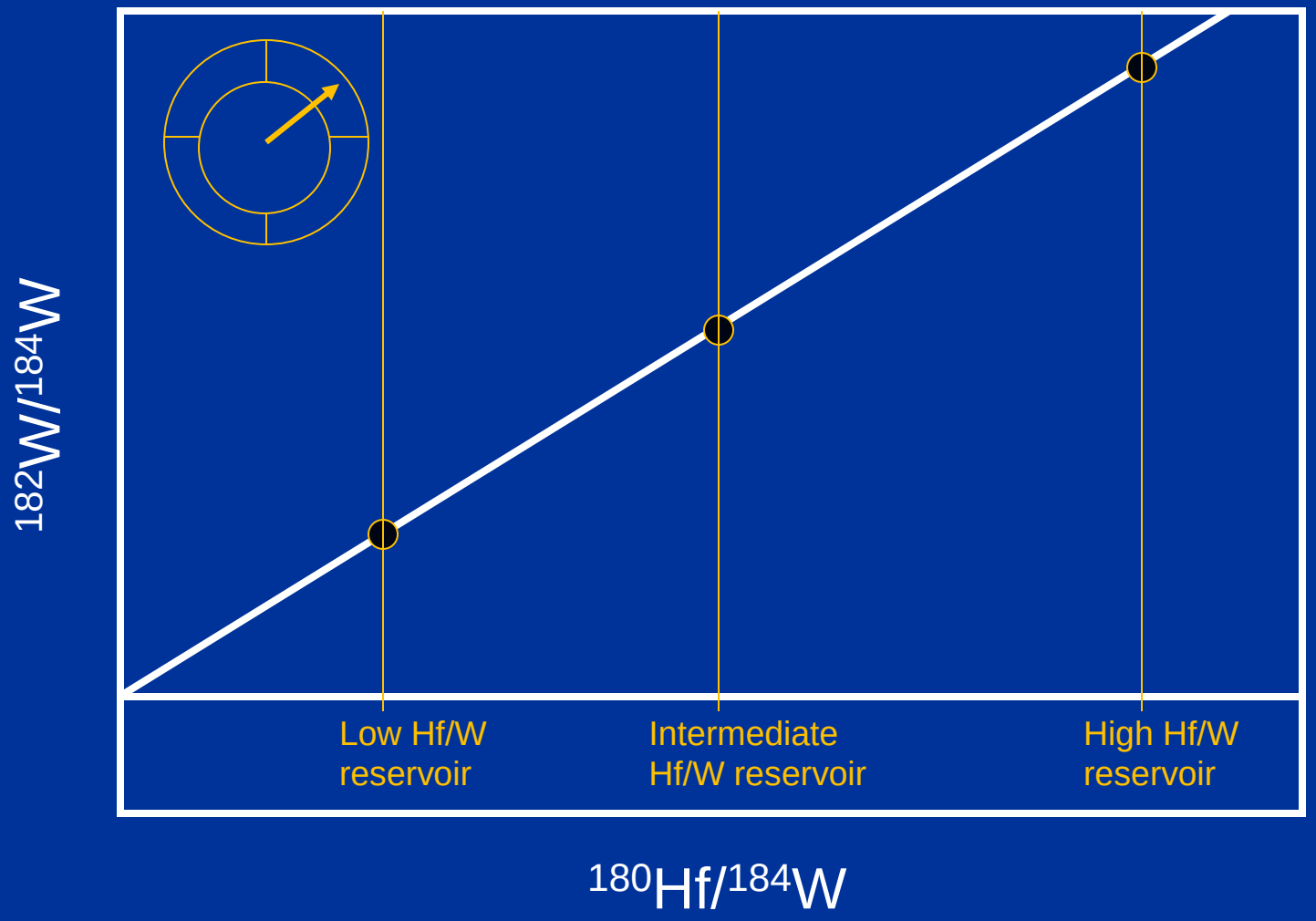

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

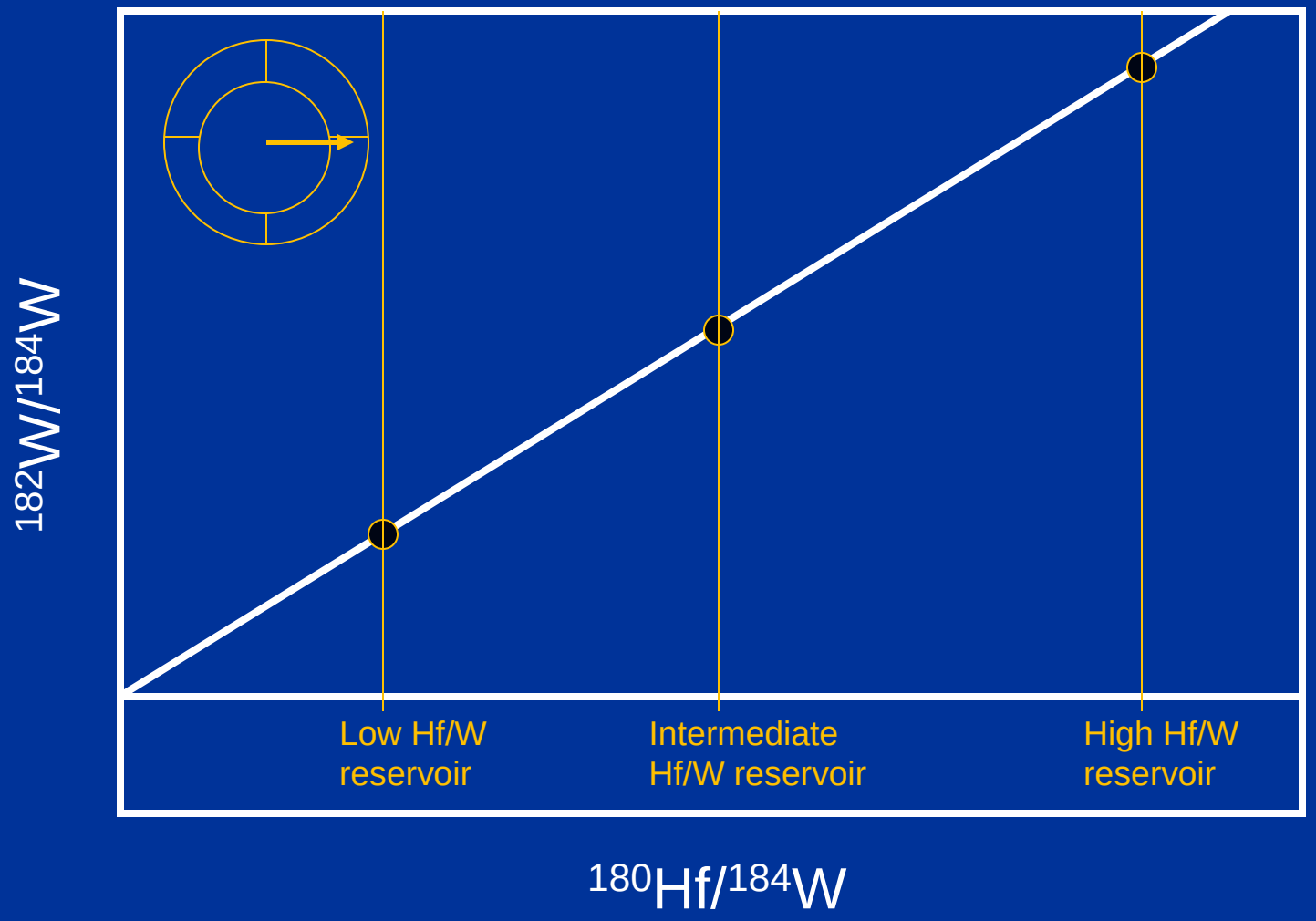

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

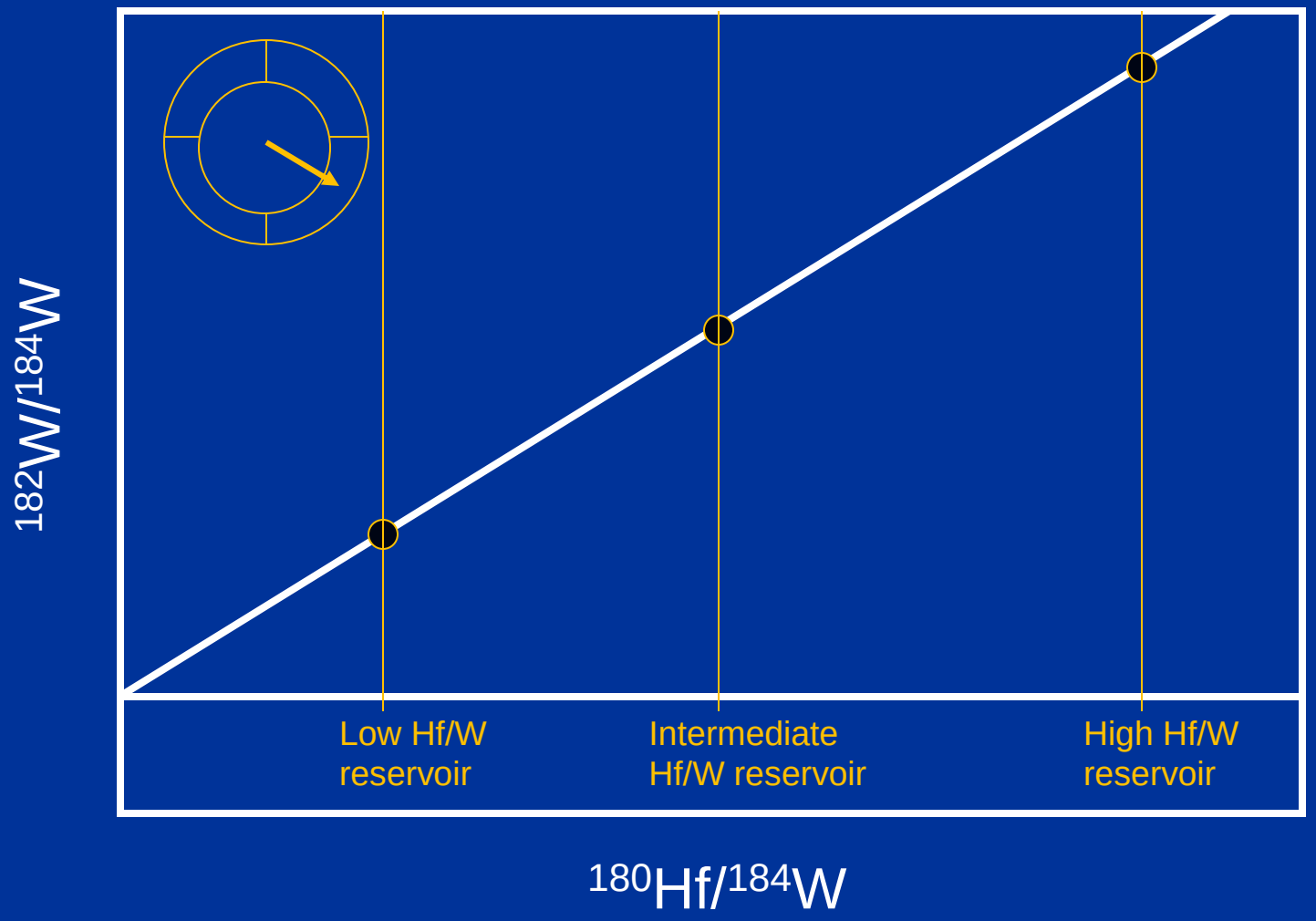

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

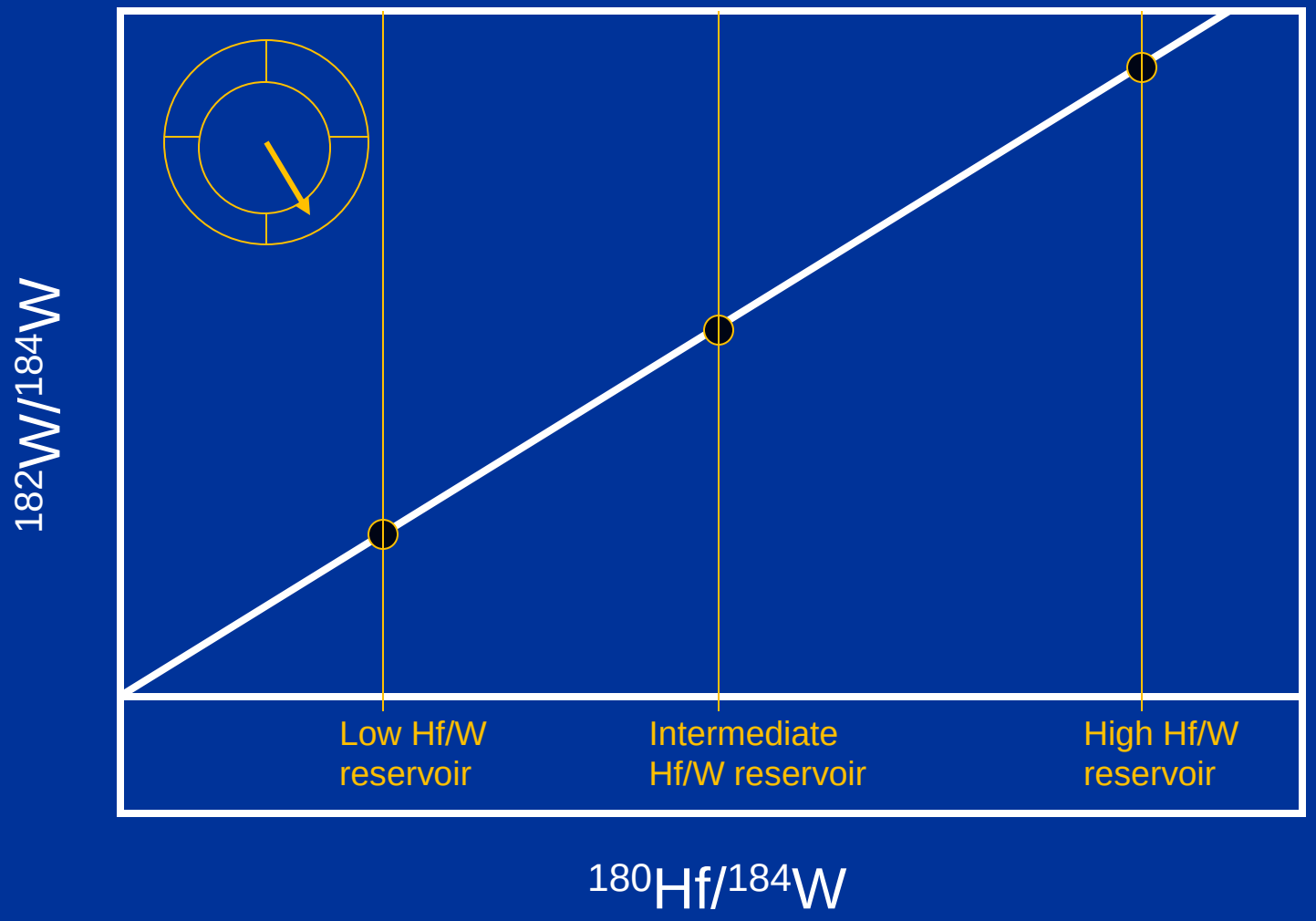

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

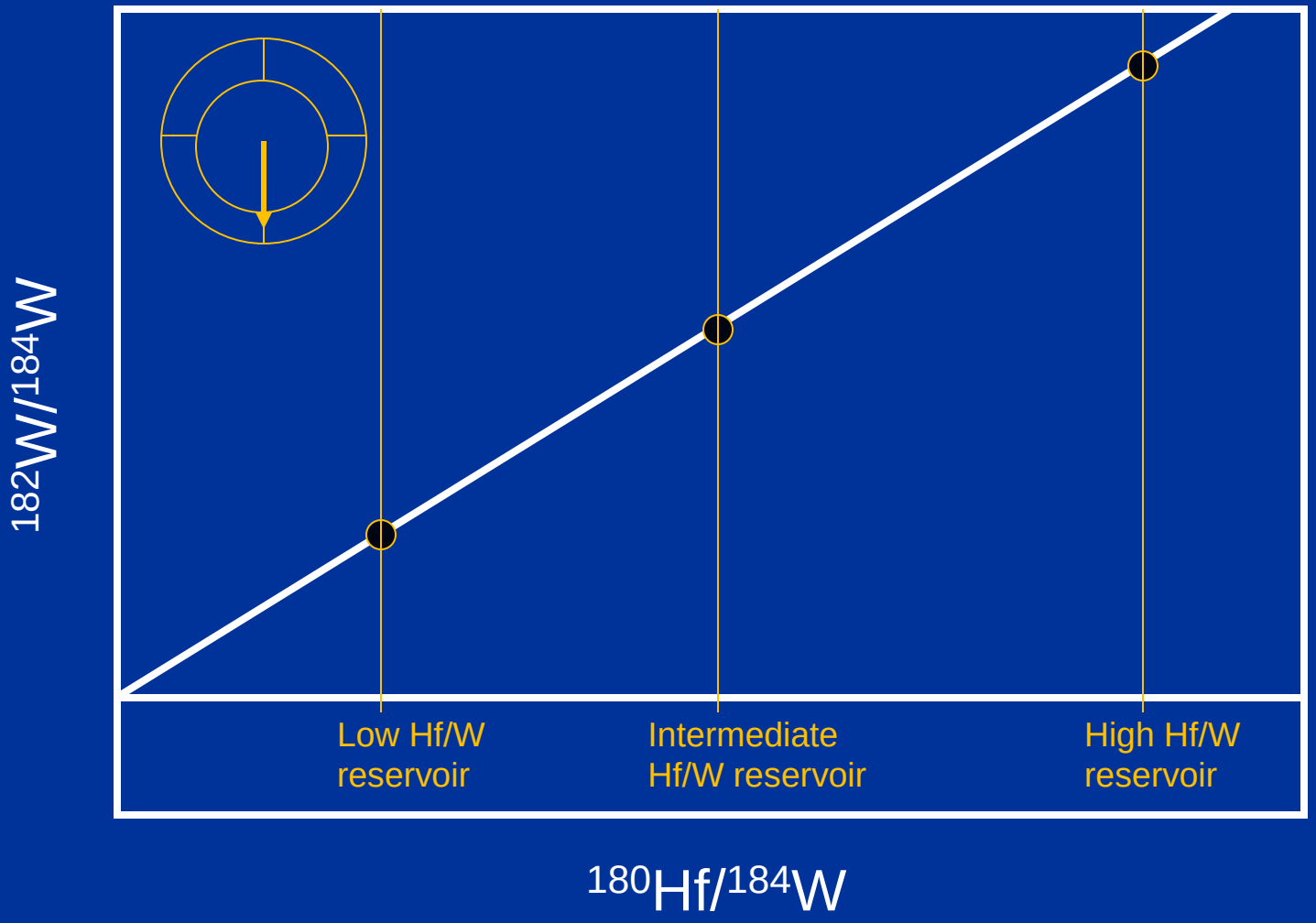

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$


$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$


$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$


$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

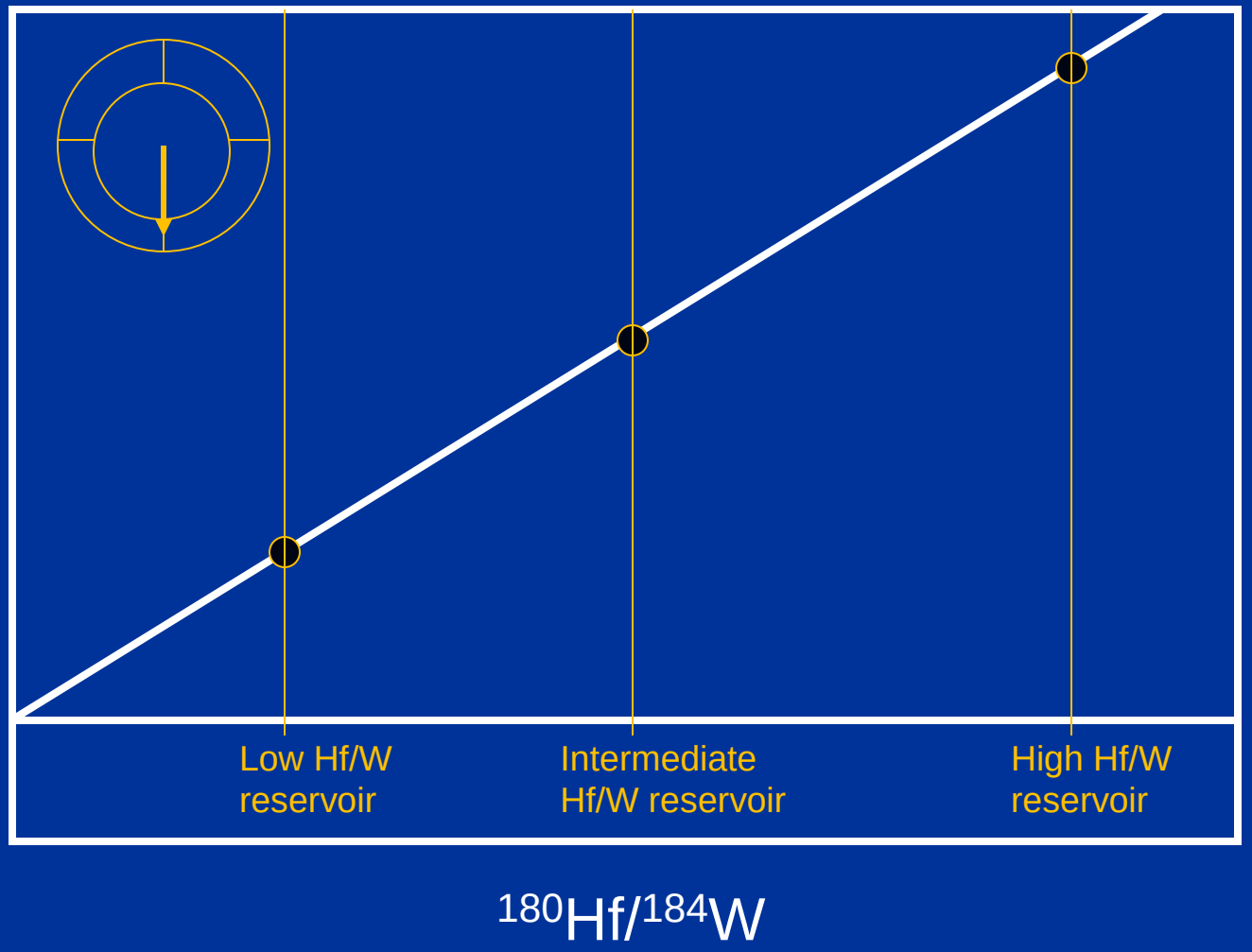

$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$


$^{182}W/^{184}W$
Low Hf/W reservoir
Intermediate Hf/W reservoir
High Hf/W reservoir
$^{180}Hf/^{184}W$

A fossil isochron:

Slope of line is = Extinct Radiogenic Parent/Non-radiogenic stable isotope

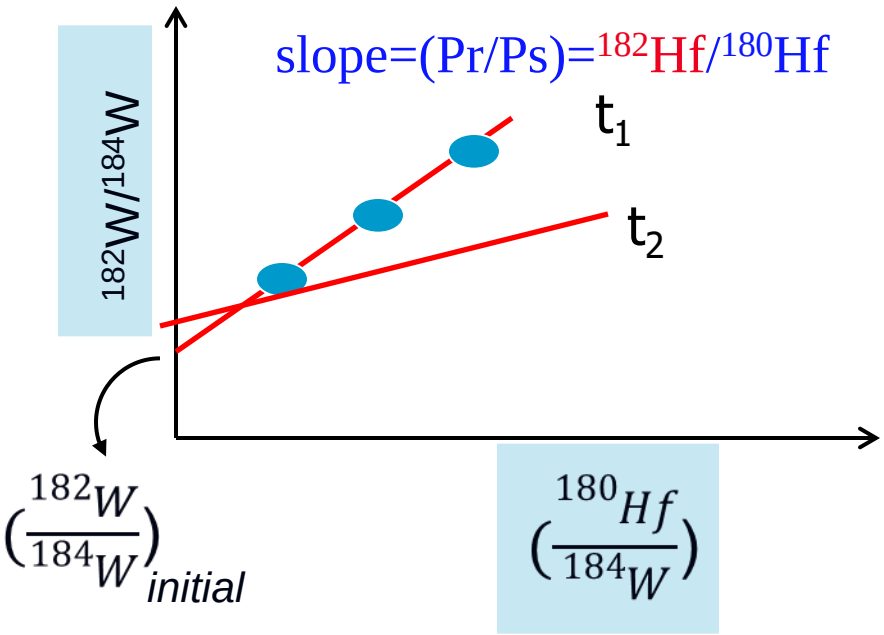
$^{182}Hf/^{180}Hf$



Extinct radionuclides: $^{182}Hf \rightarrow {}^{182}W$

$$\left(\frac{D_r}{D_s}\right)_{today} = \left(\frac{D_r}{D_s}\right)_{initial} + \left(\frac{P_r}{P_s}\right)_{initial}\left(\frac{P_s}{D_s}\right)$$

$$\left(\frac{^{182}W}{^{184}W}\right)_{today} = \left(\frac{^{182}W}{^{184}W}\right)_{initial} + \left(\frac{^{182}Hf}{^{180}Hf}\right)_{initial}\left(\frac{^{180}Hf}{^{184}W}\right)$$



$$\left(\frac{^{182}Hf}{^{180}Hf}\right)_2 = \left(\frac{^{182}Hf}{^{180}Hf}\right)_1 \exp[-\lambda\Delta t]$$

$$\Delta t = t_2 - t_1$$

$^{182}W^*$ Evolution due to decay of ^{182}Hf

$t_{1/2}$ = 9 m.y

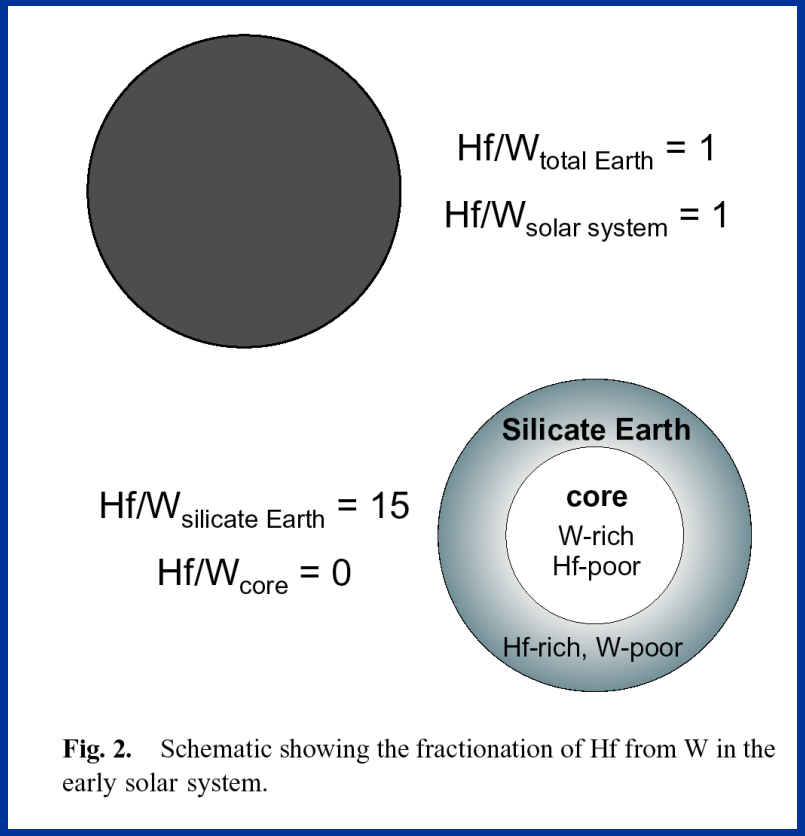
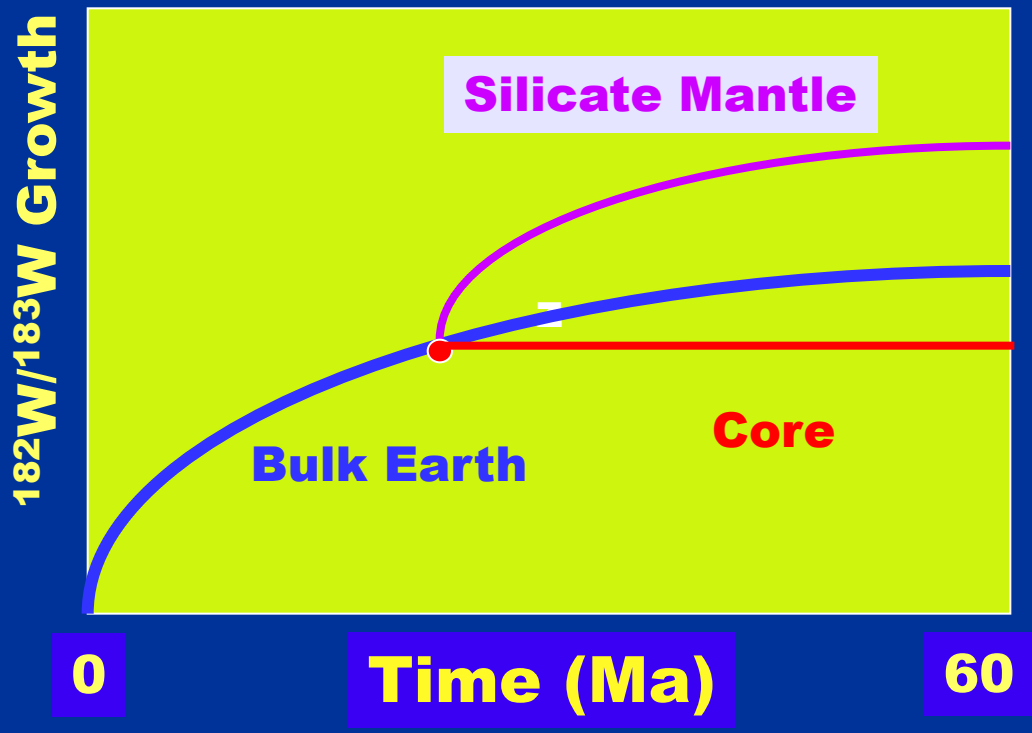
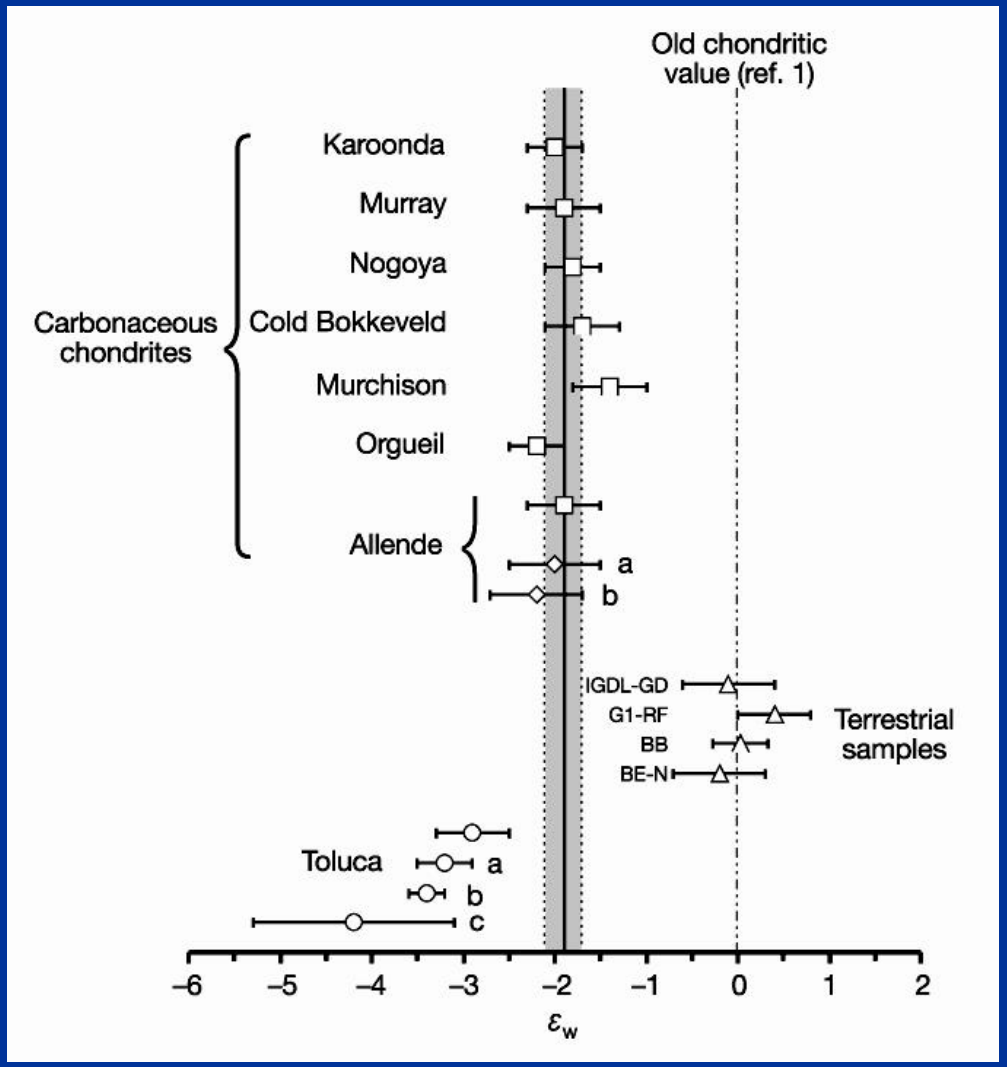


Fig. 2. Schematic showing the fractionation of Hf from W in the early solar system.



So what do the data look like?



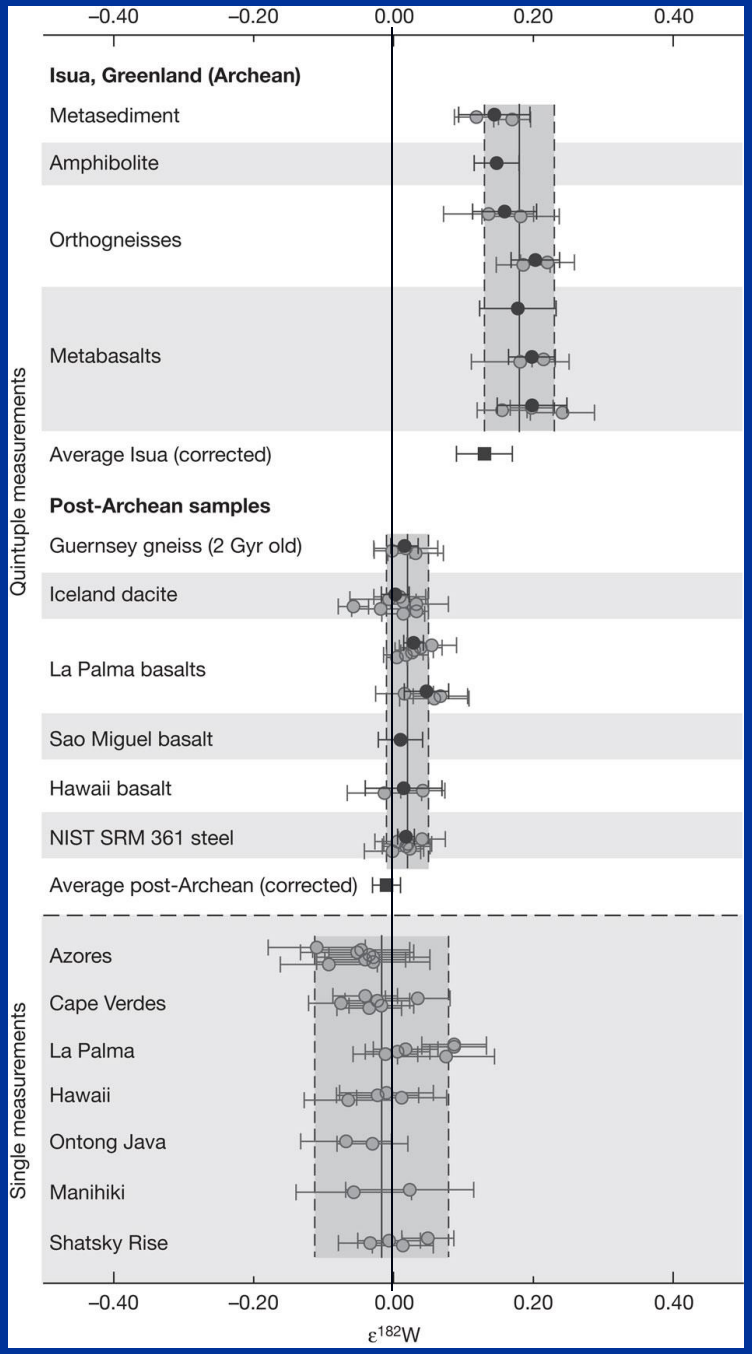
Yin et al. 2002; Kleine et al. 2002

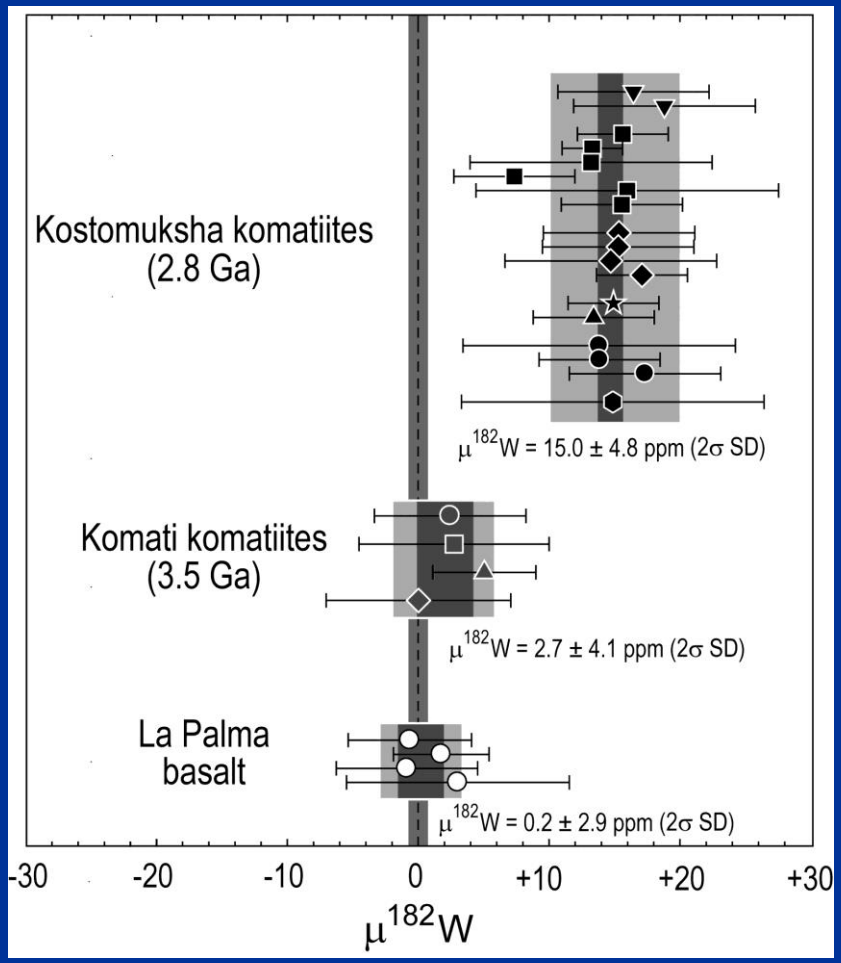
ε is the deviation of a sample from a reference or standard in parts per 10,000

Core formation must have happened when ^{182}Hf was still alive.

For perfect metal-silicate equilibration, mean time of core formation was 11 Myr

Incomplete equilibration leads to longer accretional timescales → Hf-W in N-body simulations to provide constraints on planet formation timescales





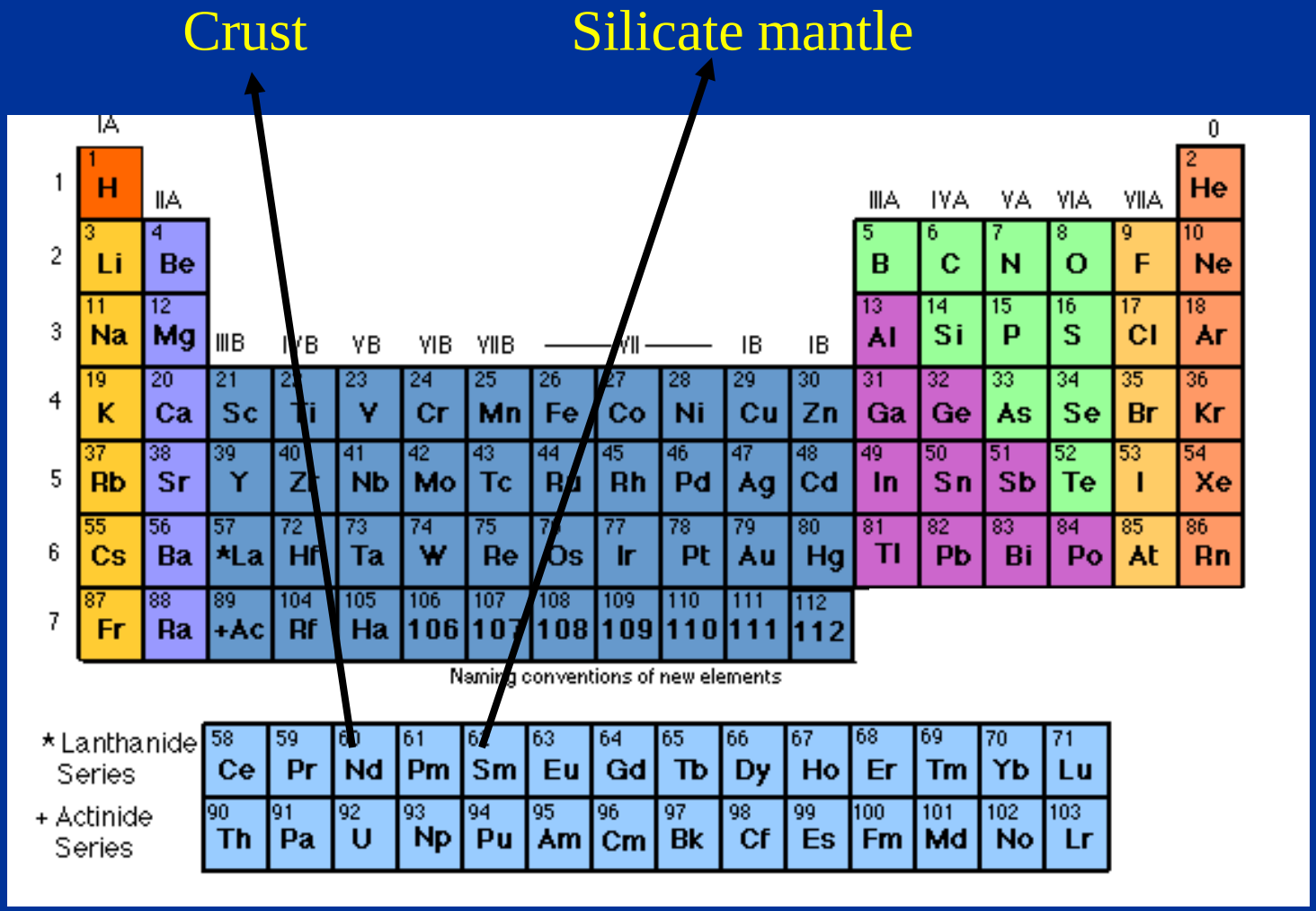
Touboul et al., 2012

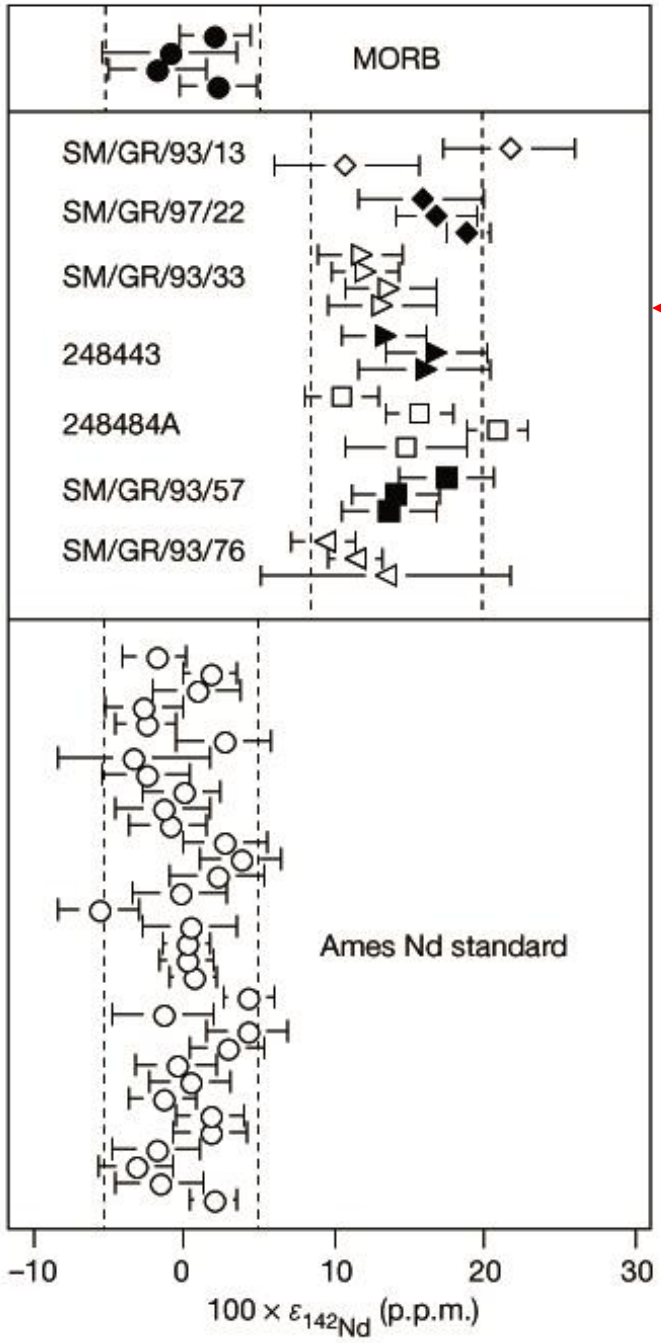
Willbold et al., 2011

W heterogeneities present in the mantle at 2.8 Ga but not seen in modern mantle

Samarium –Neodymium (^{146}Sm-^{142}Nd) systematics; $t_{1/2}$ = 103 M.y

Both Sm and Nd are *lithophile*. Both are incompatible. However Nd is more incompatible than Sm. So ideal for tracking crust-mantle differentiation.

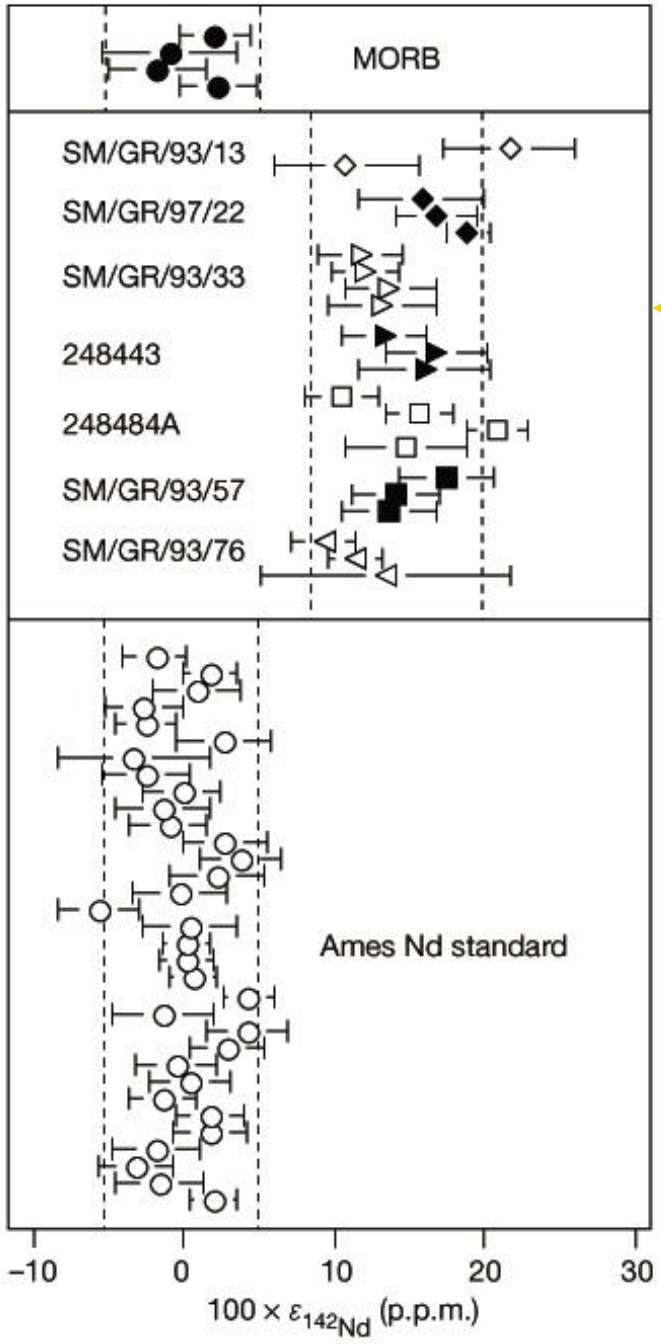




{3.7-3.8 Ga Isua metasediments

(Caro et al.,2003)

Evidence of Early Crust

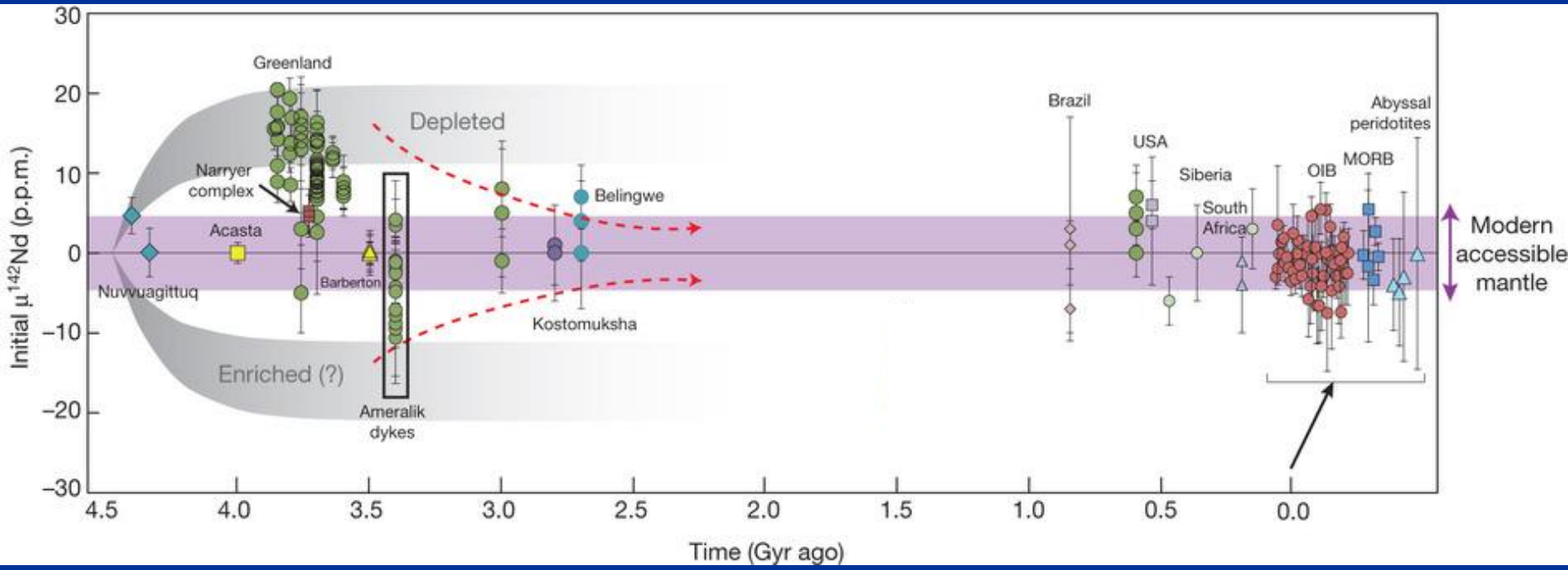


{3.7-3.8 Ga Isua metasediments

Crust derived from a mantle source that has already depleted in incompatible elements

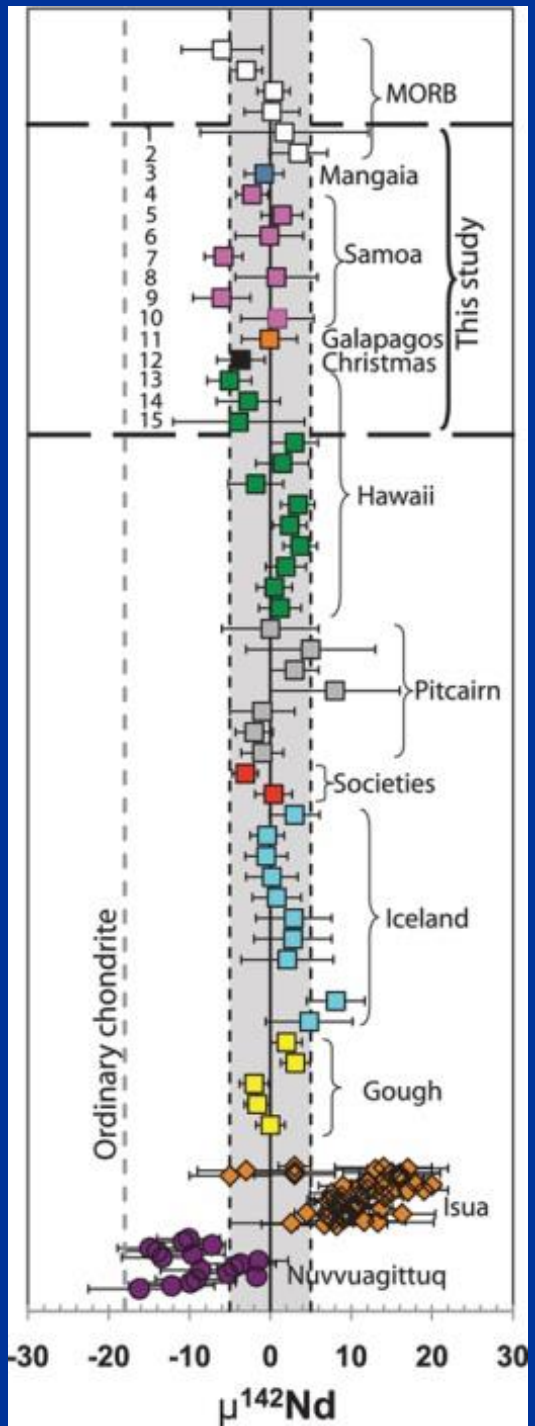
(Caro et al.,2003)

^{142}Nd anomalies over time



Rizo et al., 2012

Nd heterogeneities from early Earth mixed away by 2.5 Ga?



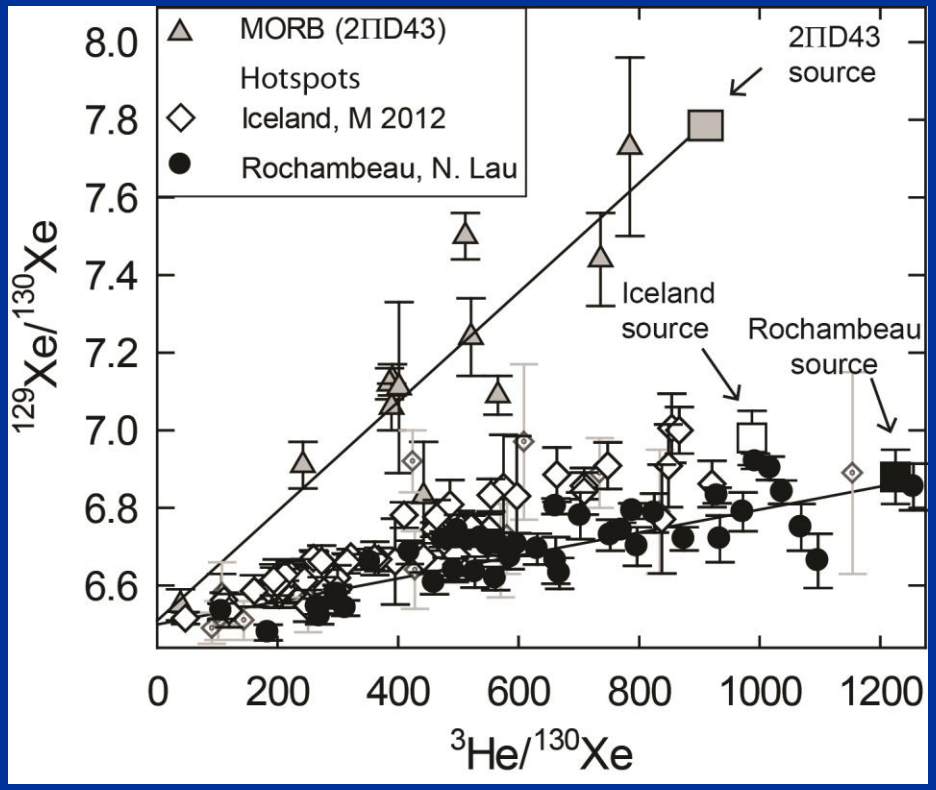
No Nd heterogeneities appear to be present in modern day mantle

Jackson and Carlson, 2012

But, heterogeneities from early Earth preserved in xenon isotopes in modern day mantle

Correlation between Xe isotopes and He/Xe ratios

^{129}I → ^{129}Xe; ^{129}Xe/^{130}Xe can only evolve for first 100Ma



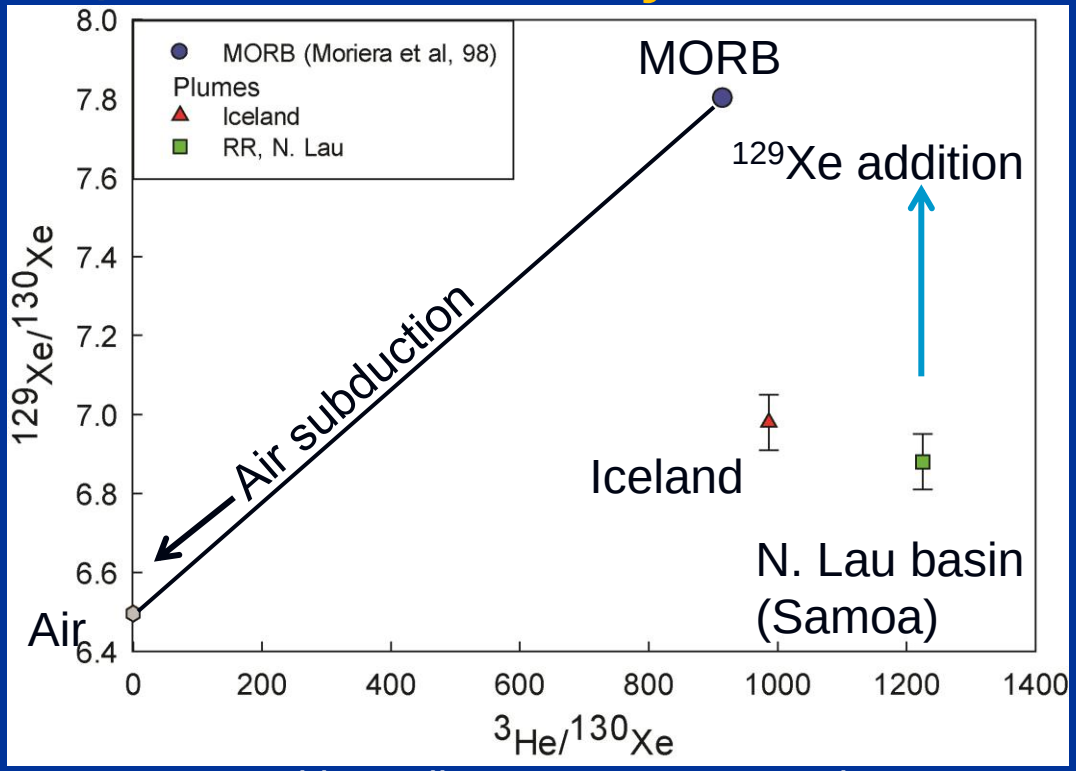
Mukhopadhyay, 2012

Peto, Mukhopadhyay and Kelley, 2013

But, heterogeneities from early Earth preserved in xenon isotopes in modern day mantle

Correlation between Xe isotopes and He/Xe ratios

$^{129}I \rightarrow {}^{129}Xe$; $^{129}Xe/^{130}Xe$ can only evolve for first 100Ma

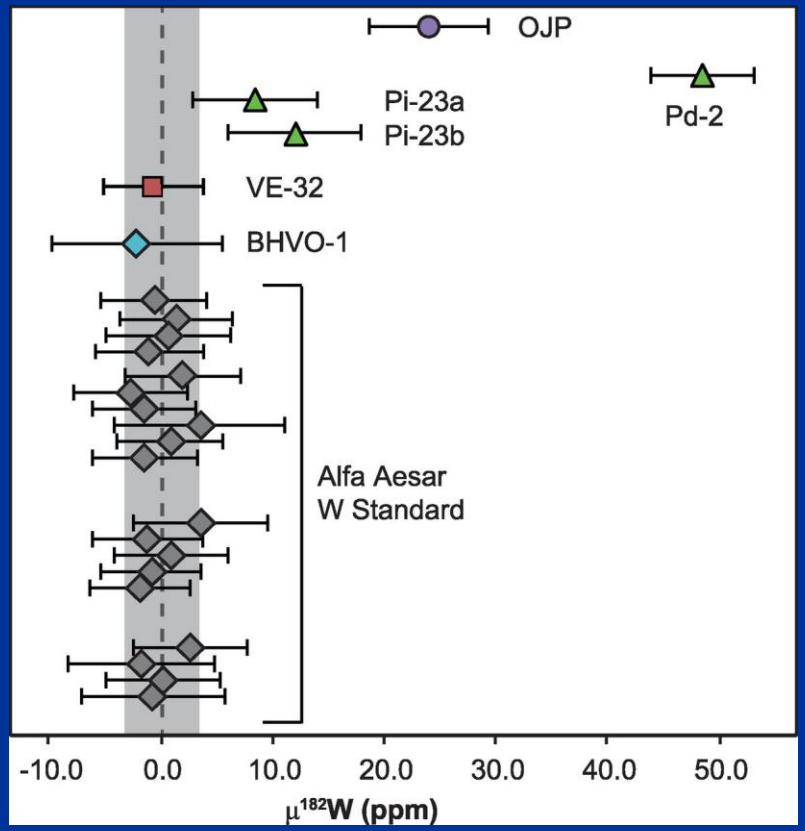


Mukhopadhyay, 2012; Peto et al., 2013

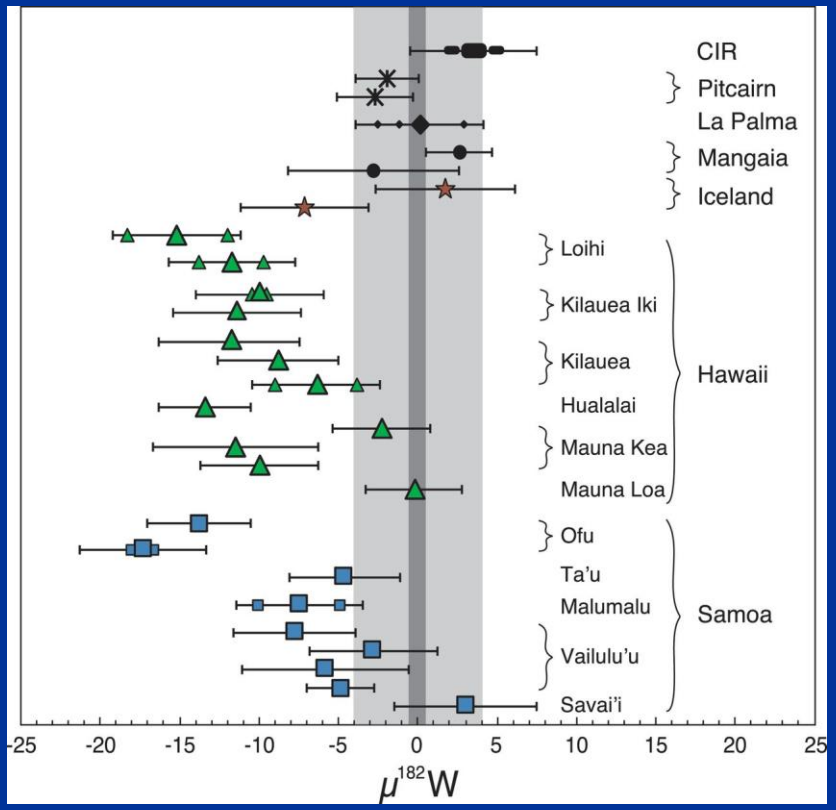
Reservoir supplying noble gases to mantle plumes had differentiated from MORB reservoir very early (pre 4.45 Ga)

Subsequent to 4.45 Ga the two sources have not been homogenized.

Heterogeneities from early Earth also preserved in tungsten isotopes in modern day mantle

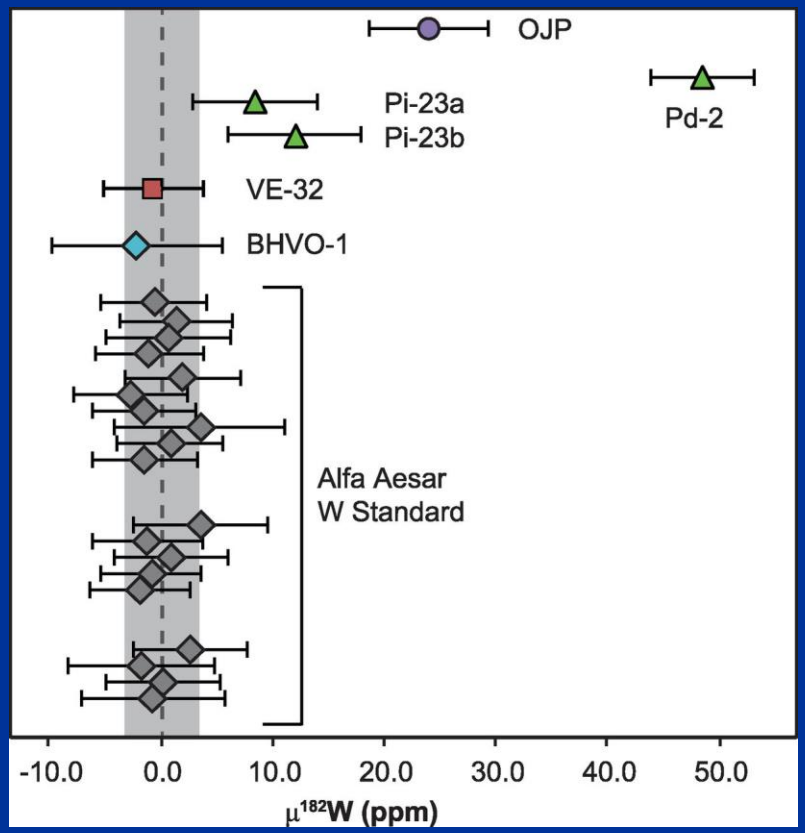


Rizo et al., 2016

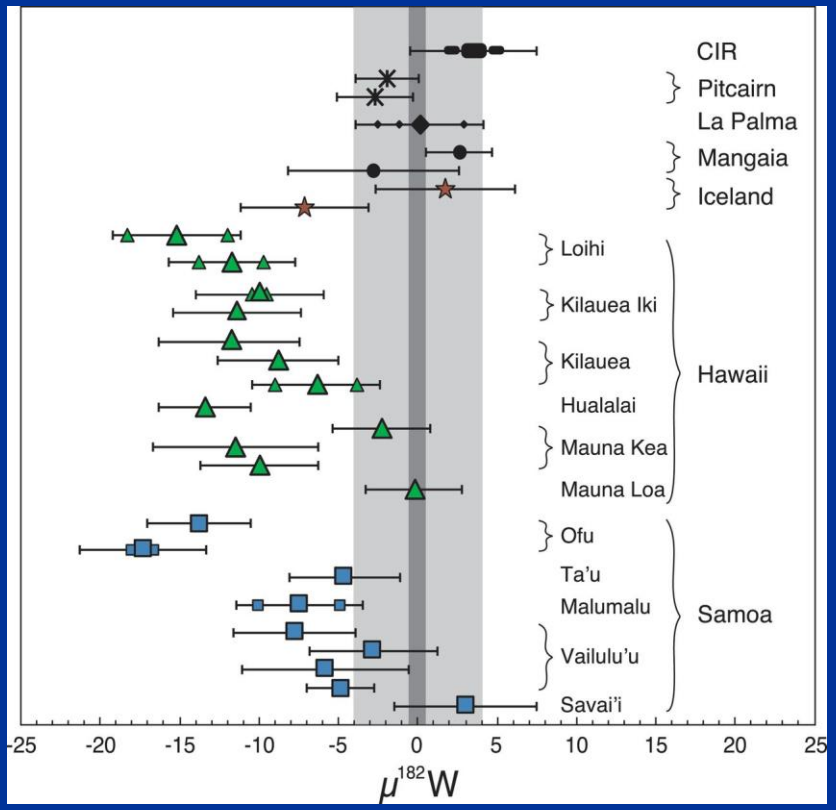


Mundl et al., 2017

Heterogeneities from early Earth also preserved in tungsten isotopes in modern day mantle



Rizo et al., 2016



Mundl et al., 2017

And small ^{142}Nd anomalies may also be present in the modern day plume mantle (Peters et al. 2018)

Where do we stand on the extinct nuclide anomalies?

- The extent of heterogeneity in the Hadean and Archean mantle not yet fully established
- The extent of heterogeneity in the modern day mantle is also not yet fully established
- Characteristic timescales over which the extinct nuclide anomalies are attenuated not yet established.