MAX PLANCK INSTITUTE
FOR SOLAR SYSTEM RESEARCH

Isotopic anomalies in meteorites: an introduction

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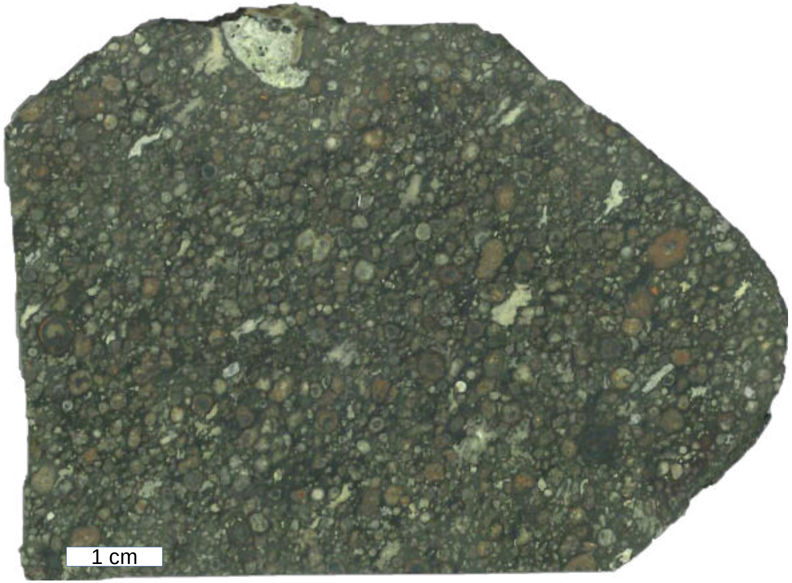
Planetary Science Department
MPI for Solar System Research

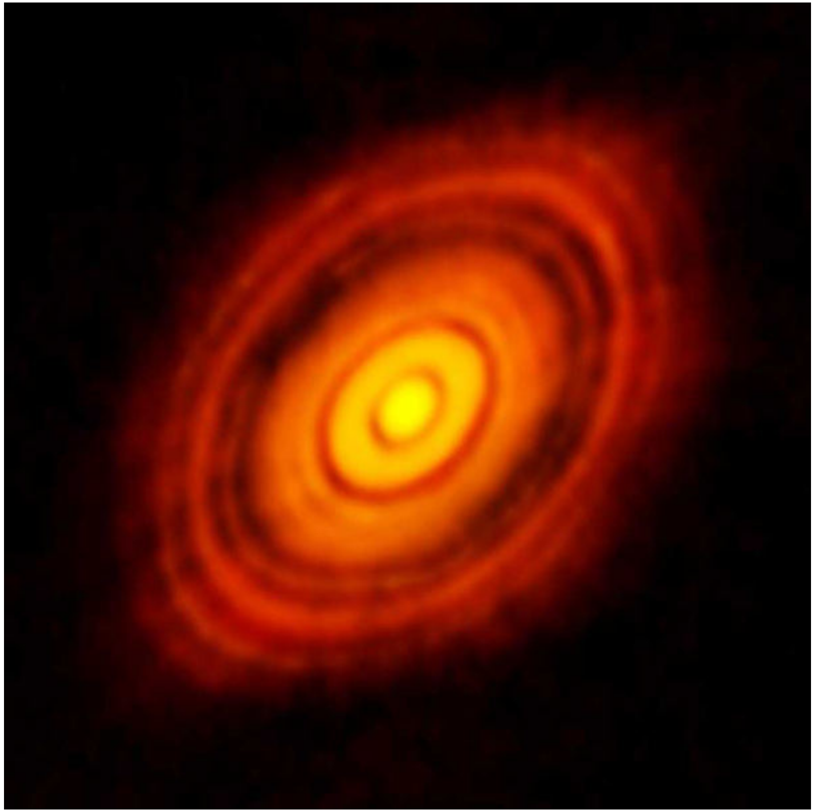
Geologists use fossils to reconstruct paleo-environments

Rußbach fossil wall

Cretaceous reef fauna

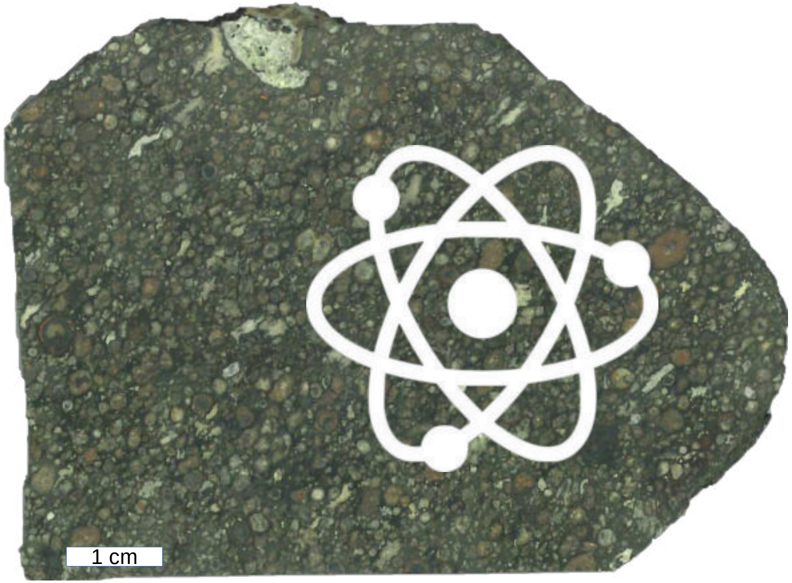
Meteorites as fossils of solar accretion disk





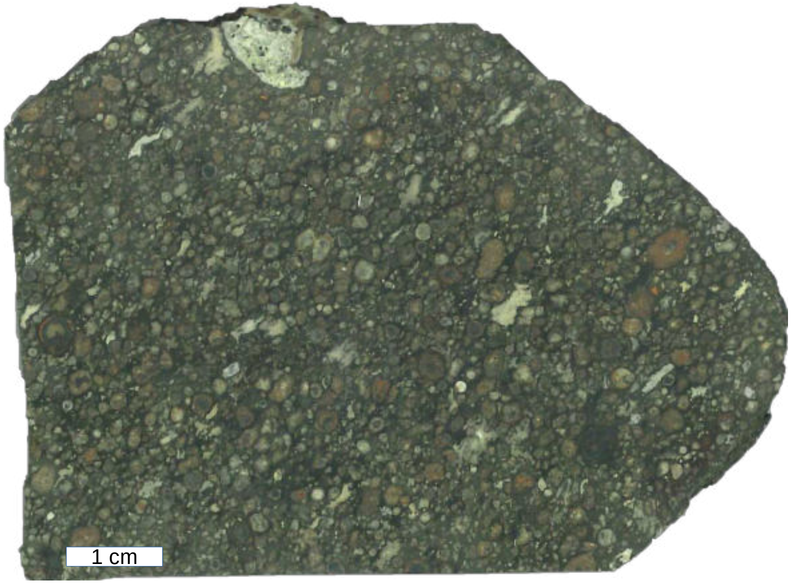
ESO ALMA, HL Tau

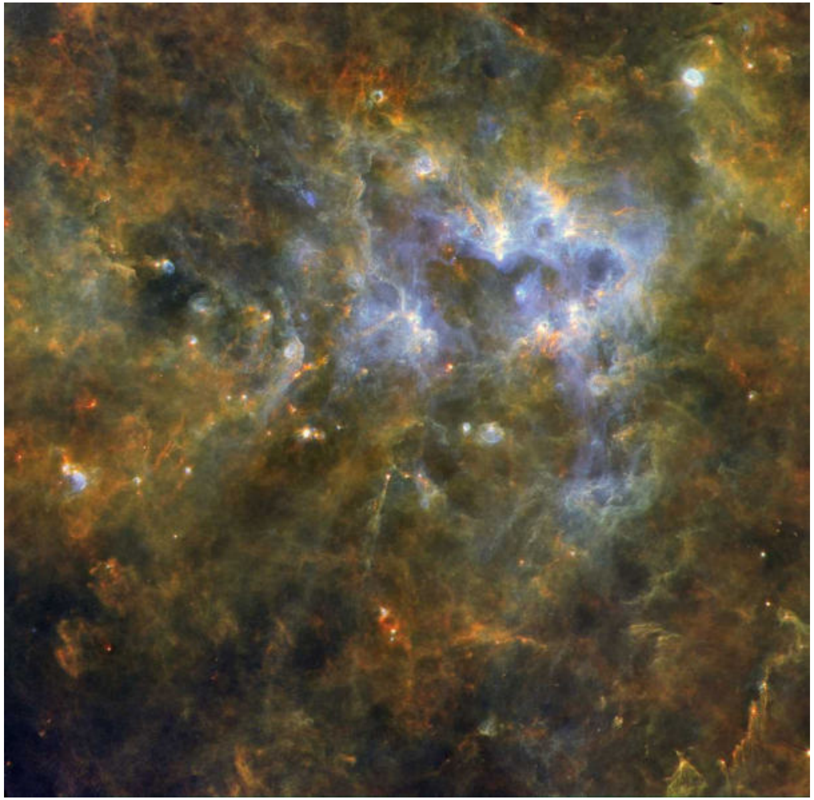
Isotopic anomalies in meteorites



Tracer of solar system evolution

Isotopic anomalies in meteorites

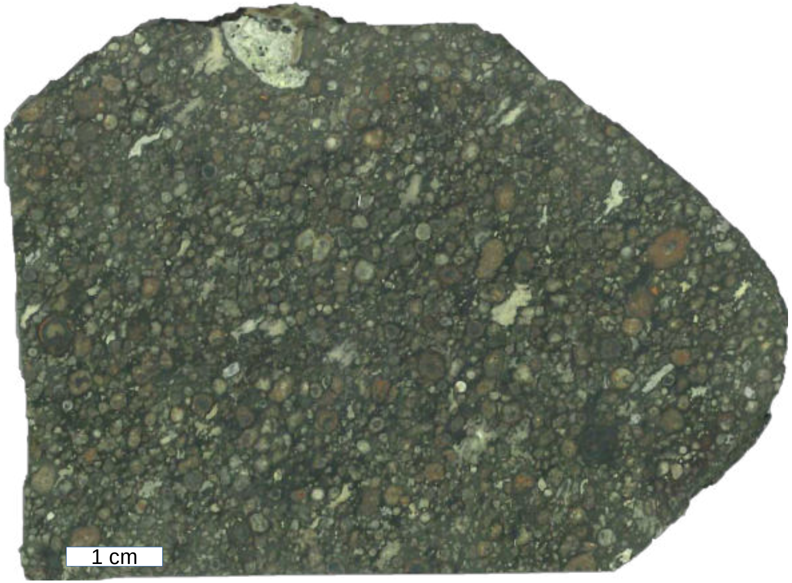




What is the solar system made of?

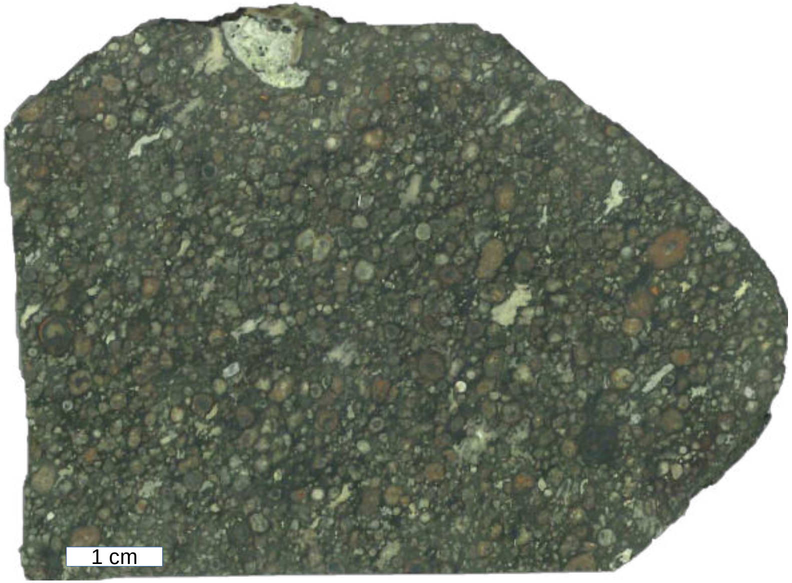
ESA/Herschel/PACS, G305

Isotopic anomalies in meteorites



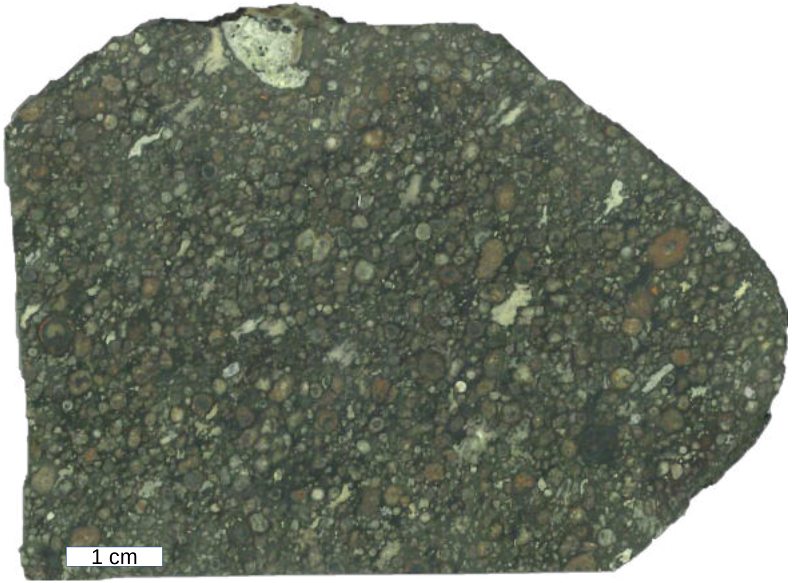
How did the disk form/disk dynamics?

Isotopic anomalies in meteorites



What is the Earth made of/How did it form?

Isotopic anomalies in meteorites



Heritage of Earth's volatiles?

Meteorites 1o1

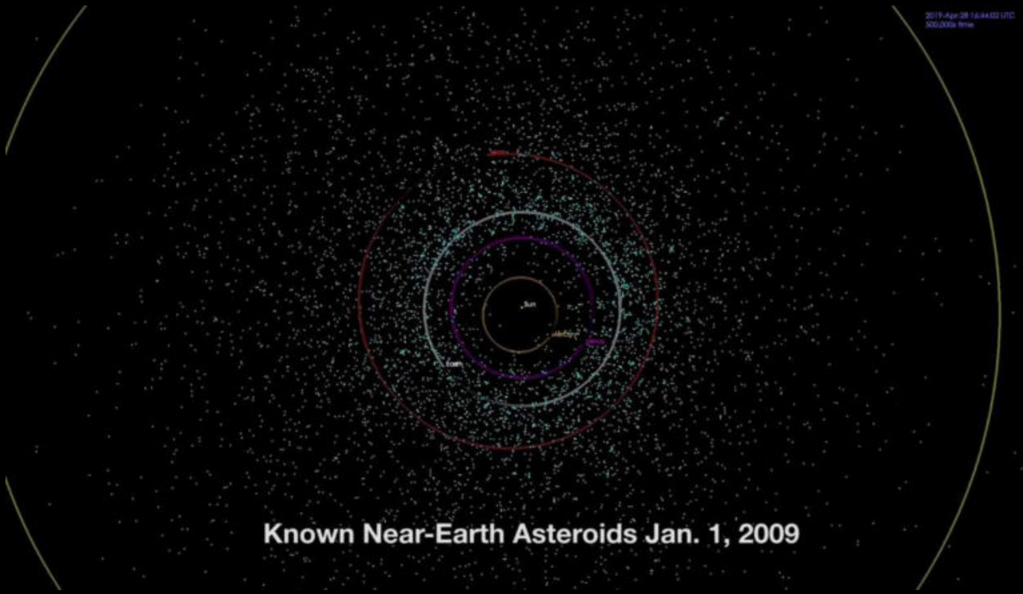
Meteor, meteoroid

Meteorite

Meteorites 1o1

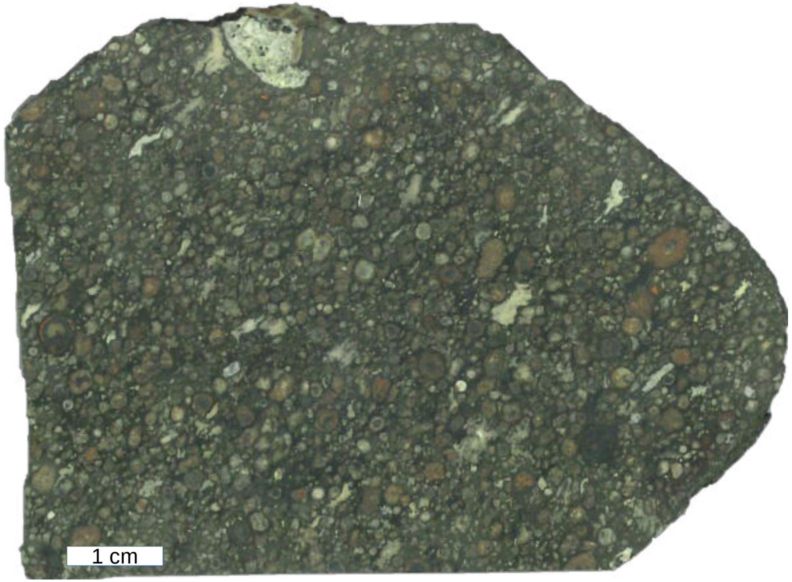
73665 official meteorites

- 473 falls
- 379 Mars
- 666 Moon



Meteorite 1o1: phenomenological classification

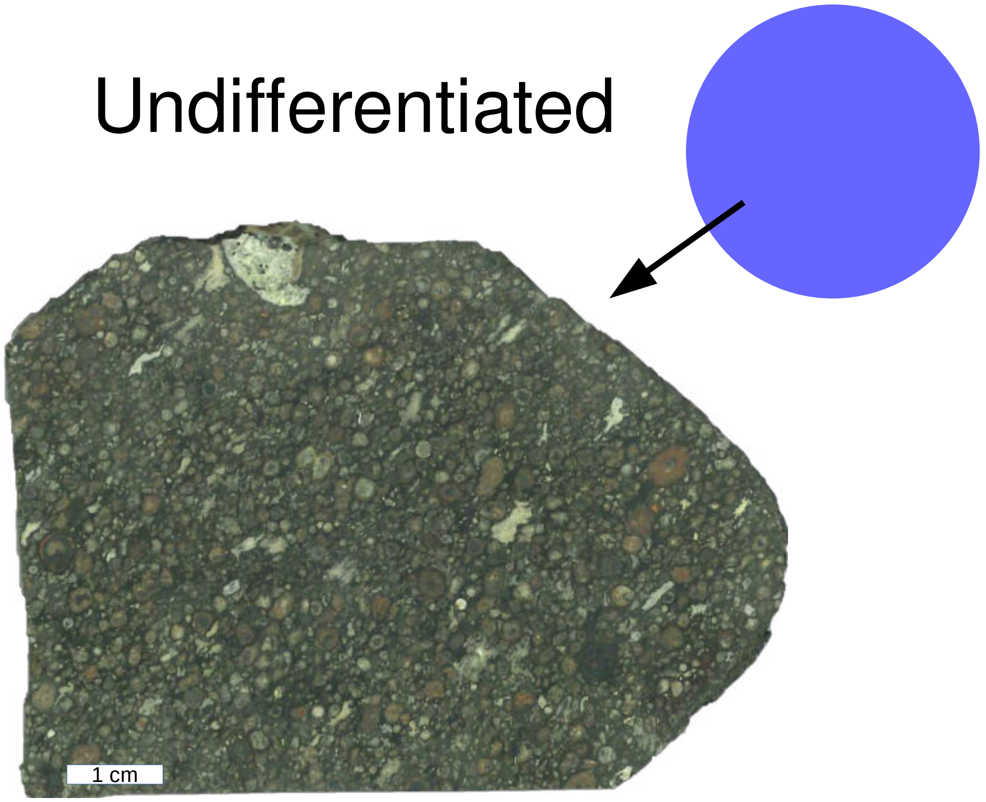
Undifferentiated



Chondrites: “nebular sediment”

Meteorite 1o1: phenomenological classification

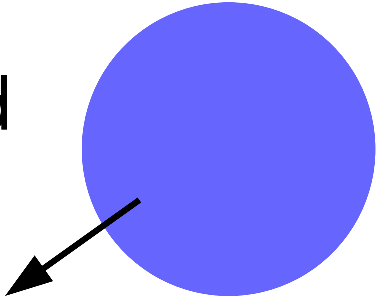
Undifferentiated

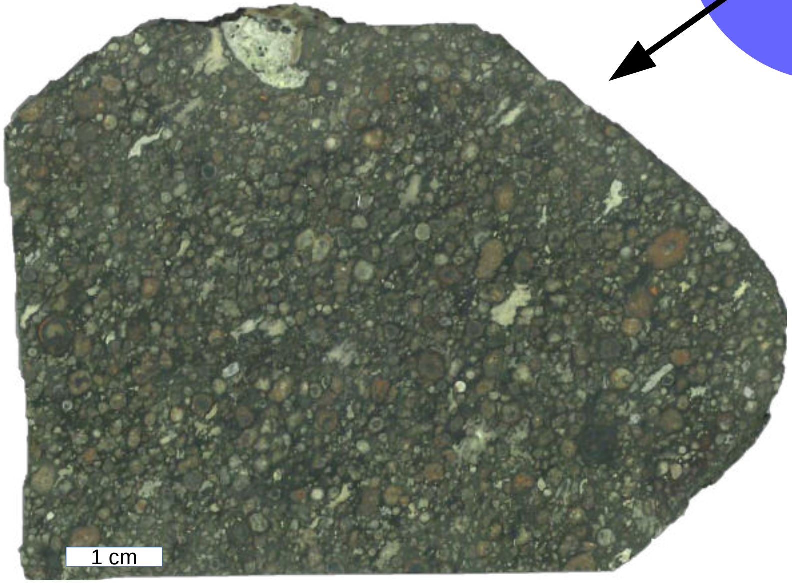


Chondrites: “nebular sediment”

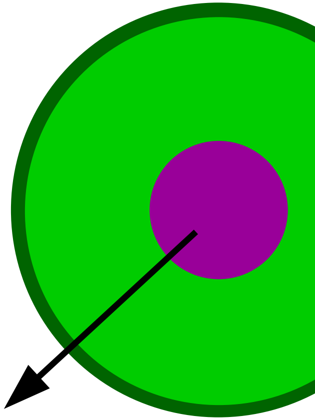
Meteorite 1o1: phenomenological classification

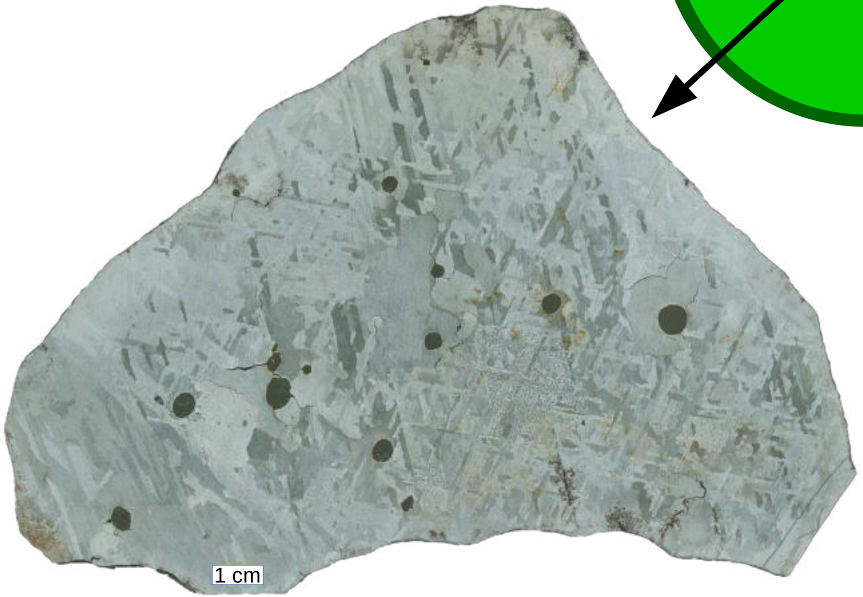
Undifferentiated





Differentiated

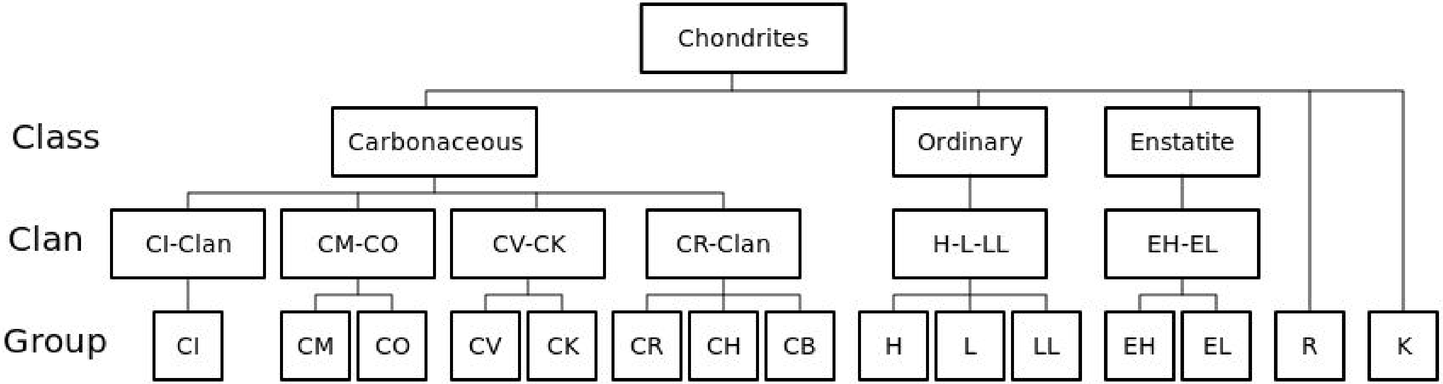




Chondrites: “nebular sediment”

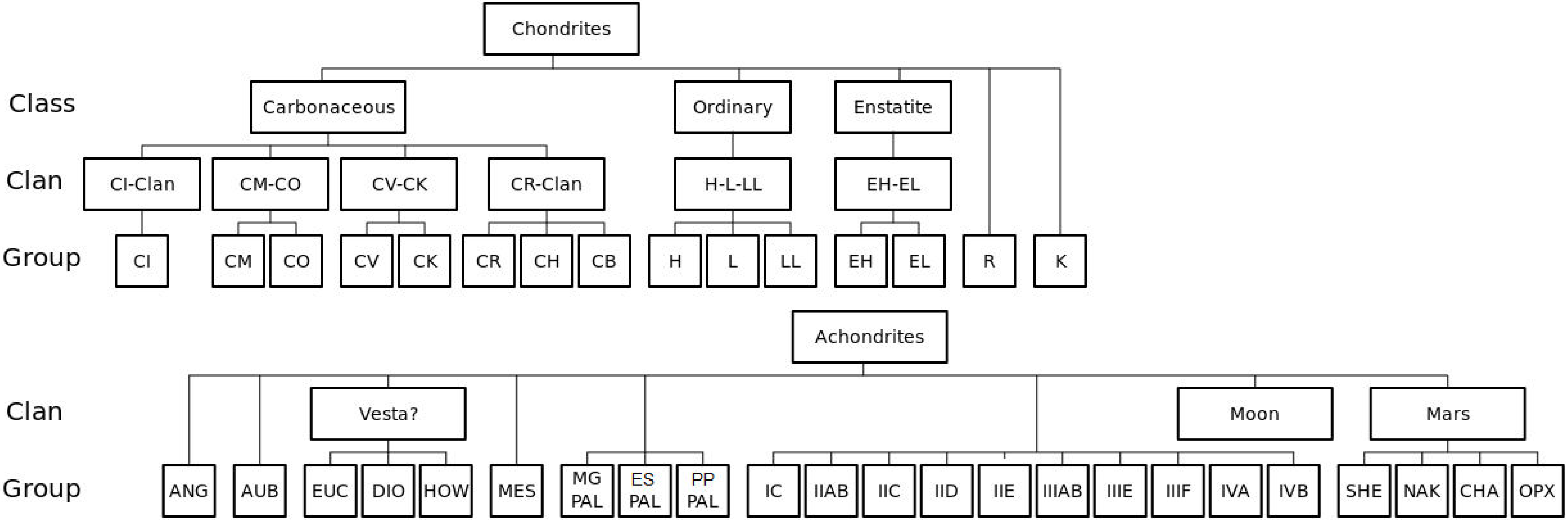
Achondrites: crystallized from a melt

Meteorite 1o1: phenomenological classification



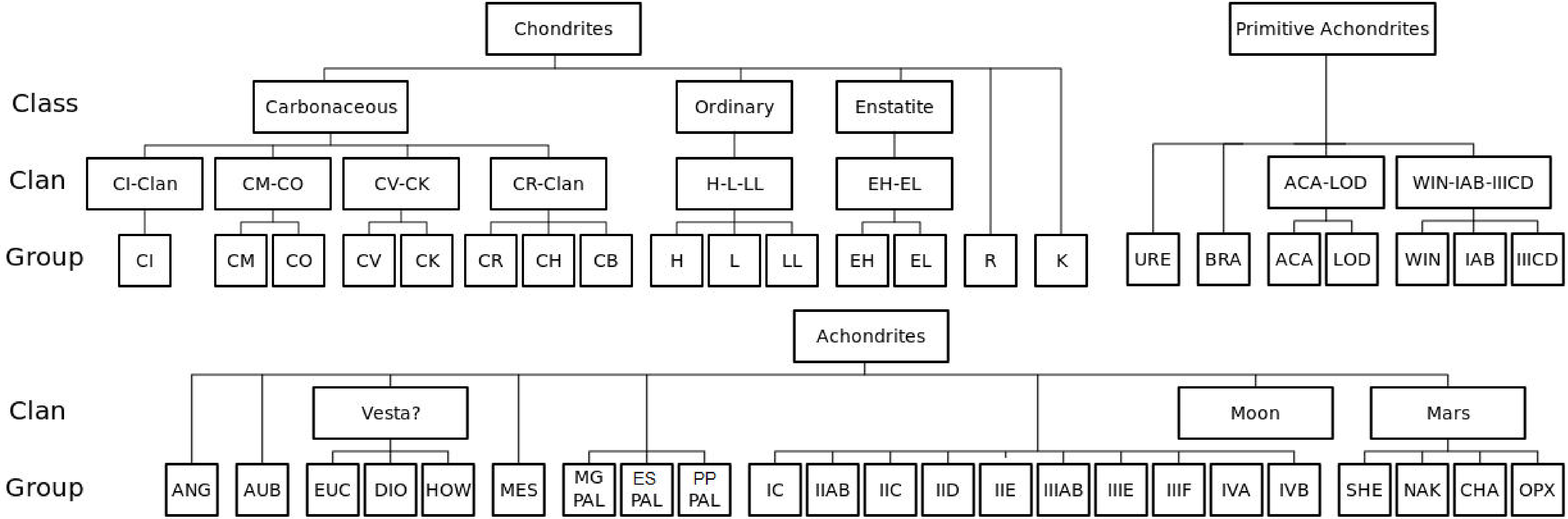
Weisberg, 2006

Meteorite 1o1: phenomenological classification



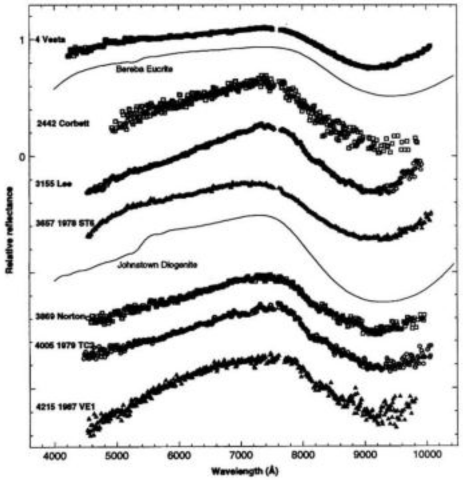
Weisberg, 2006

Meteorite 1o1: phenomenological classification



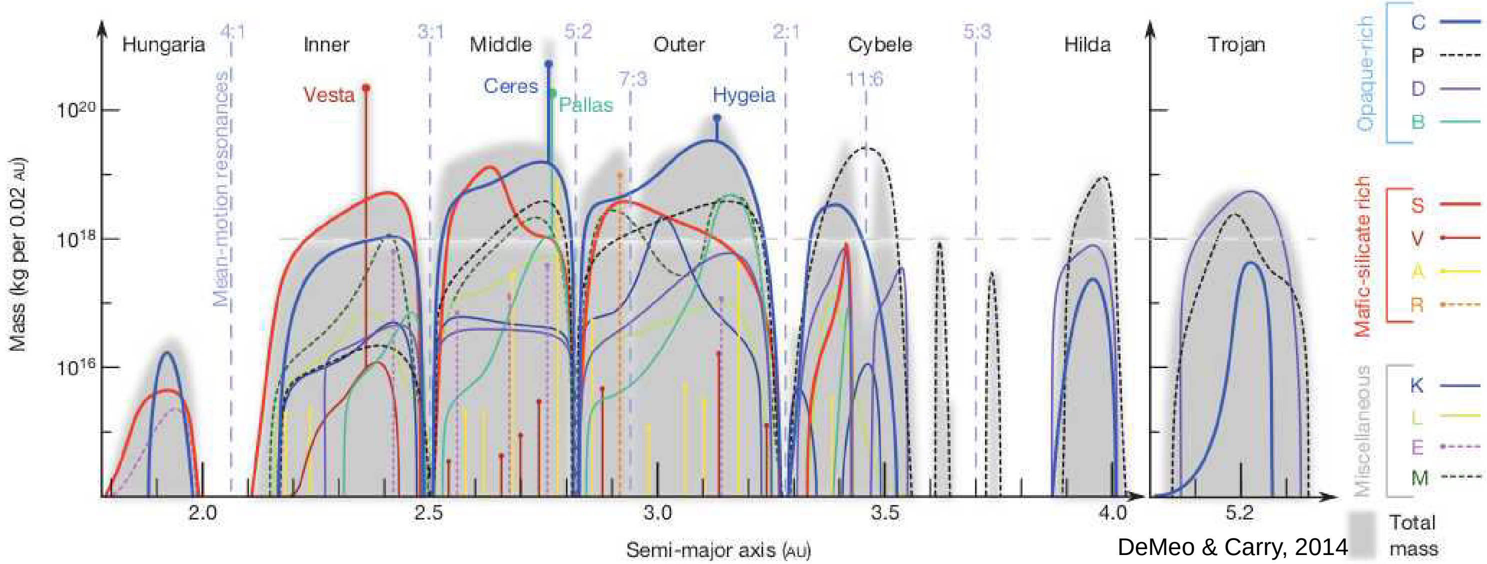
Weisberg, 2006

Meteorite - asteroid links



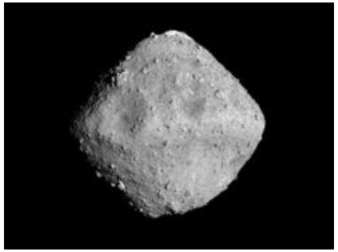
HED meteorites – 4Vesta

Binzel & Xu, 1993



DeMeo & Carry, 2014

Ordinary chondrites –
S-type Itokawa



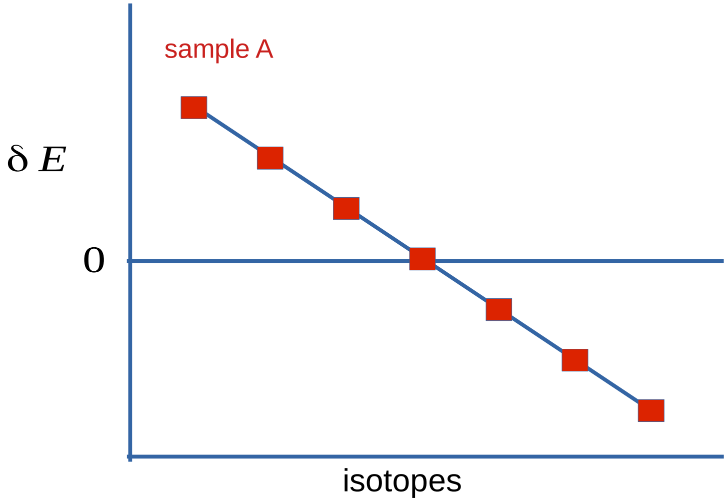
CI chondrites –
Cb-type Ryugu / (B-type Bennu)

Isotope variations

mass-dependent	mass-independent
PROCESSES	**AGES, TRACER**

Isotope variations

mass-dependent

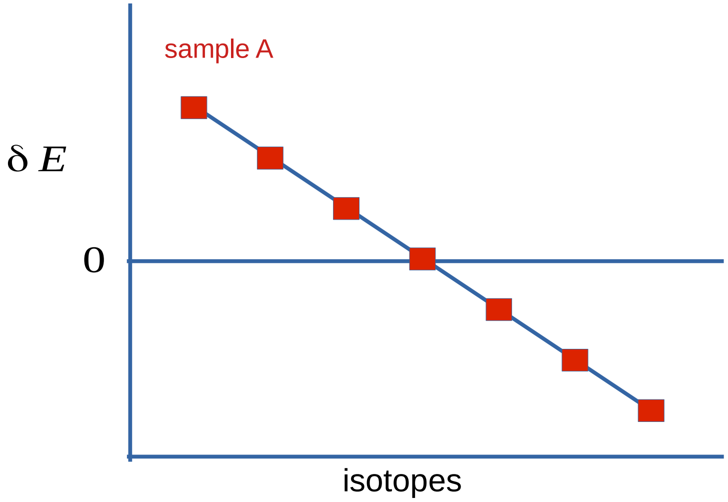


$$\delta^i E = \left[\frac{R^{i,j}_{sample}}{R^{i,j}_{standard}} - 1 \right] \times 10^3$$

mass-independent

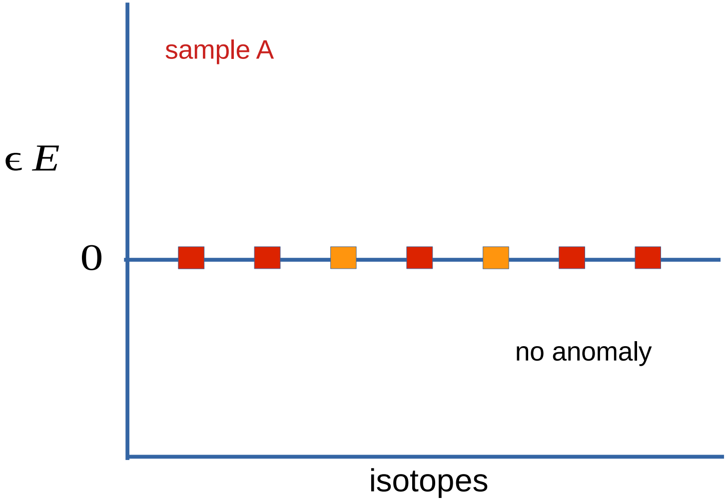
Isotope variations

mass-dependent



$$\delta^i E = \left[\frac{R^{i,j}_{sample}}{R^{i,j}_{standard}} - 1 \right] \times 10^3$$

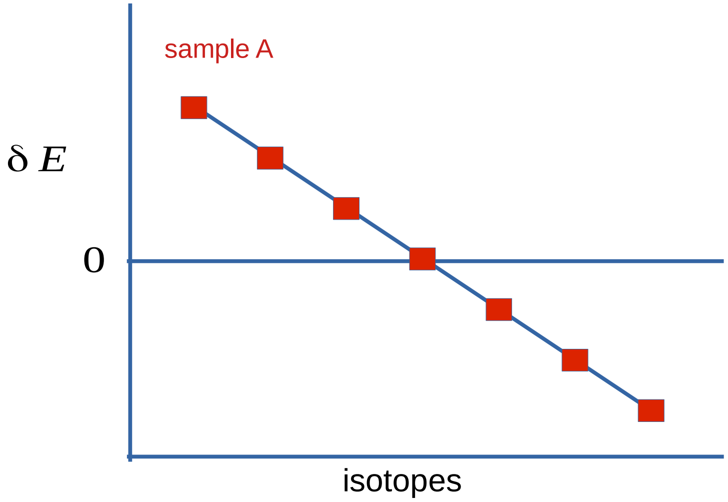
mass-independent



$$\epsilon^i E = \left[\frac{R^{i,j}_{sample}}{R^{i,j}_{standard}} - 1 \right] \times 10^4$$

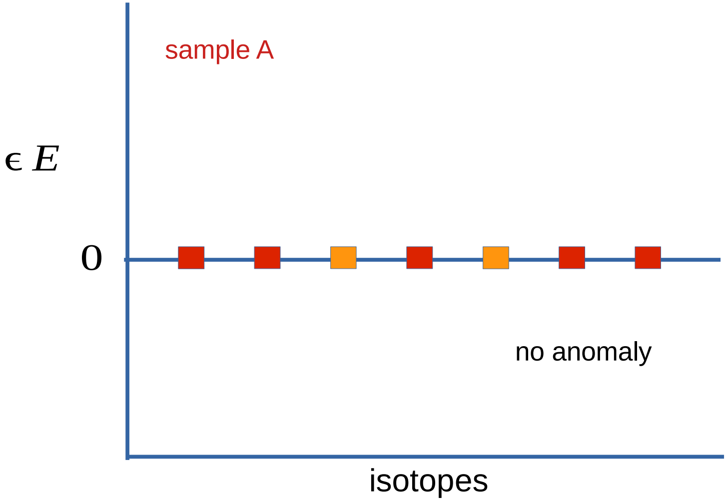
Isotope variations

mass-dependent



$$\delta^{i}E = \left[\frac{R^{i,j}_{sample}}{R^{i,j}_{standard}} - 1 \right] \times 10^{3}$$

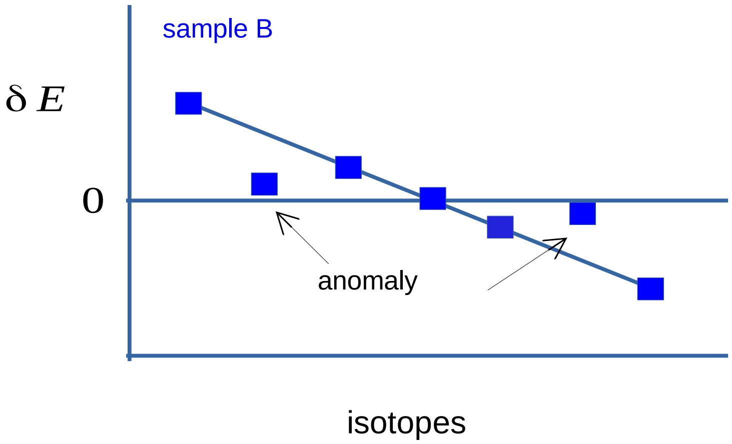
mass-independent



$$\epsilon^{i}E = \left[\frac{R^{i,j}_{sample} \times \left(\frac{m_i}{m_j} \right)^{\beta_{smp}}}{R^{i,j}_{standard} \times \left(\frac{m_i}{m_j} \right)^{\beta_{std}}} - 1 \right] \times 10^{4}$$

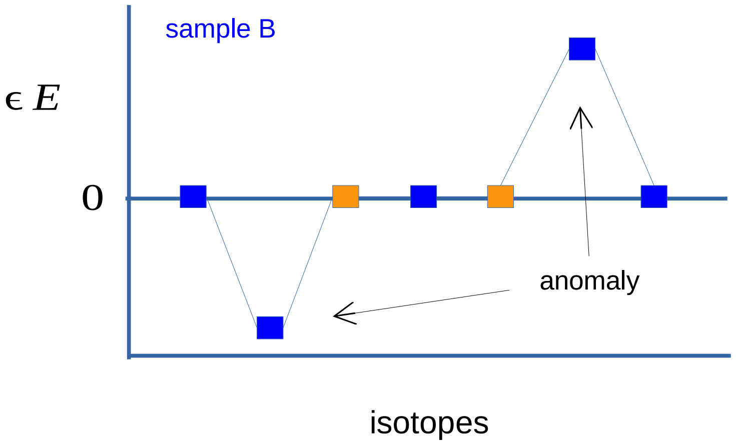
Isotope variations

mass-dependent



$$\delta^{i} E = \left[\frac{R^{i,j}_{sample}}{R^{i,j}_{standard}} - 1 \right] \times 10^{3}$$

mass-independent



$$\epsilon^{i} E = \left[\frac{R^{i,j}_{sample} \times \left(\frac{m_i}{m_j} \right)^{\beta_{smp}}}{R^{i,j}_{standard} \times \left(\frac{m_i}{m_j} \right)^{\beta_{std}}} - 1 \right] \times 10^{4}$$

Isotope variations

mass-dependent

mass-independent

Except presolar grain data all meteorite isotope anomaly data is internally normalized and hence may not show you the true absolute anomaly!

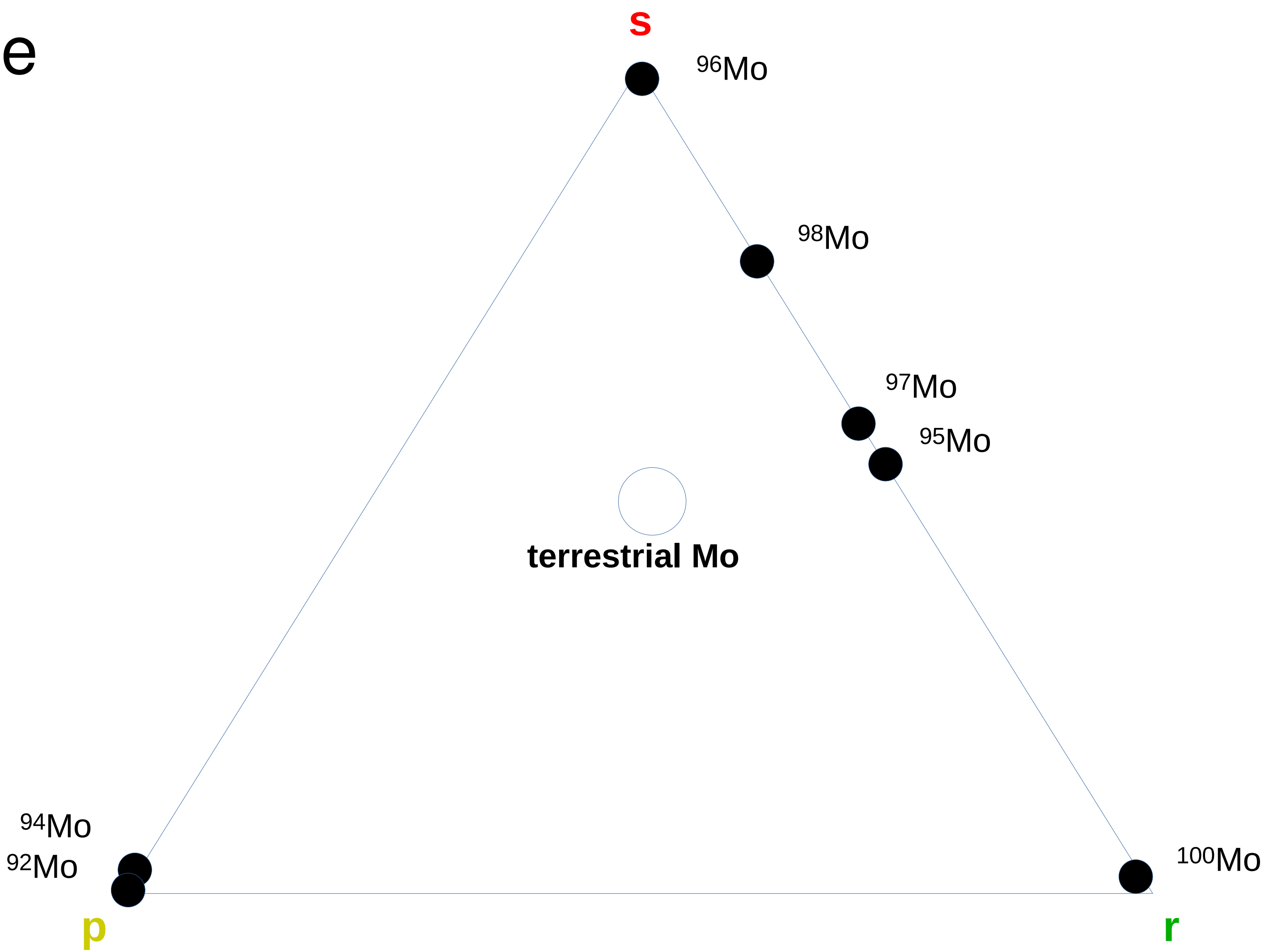
$$\delta^{i}E = \left[\frac{R^{i,j}_{sample}}{R^{i,j}_{standard}} - 1 \right] \times 10^{3}$$

$$\epsilon^{i}E = \left[\frac{R^{i,j}_{sample} \times \left(\frac{m_i}{m_j} \right)^{\beta_{smp}}}{R^{i,j}_{standard} \times \left(\frac{m_i}{m_j} \right)^{\beta_{std}}} - 1 \right] \times 10^{4}$$

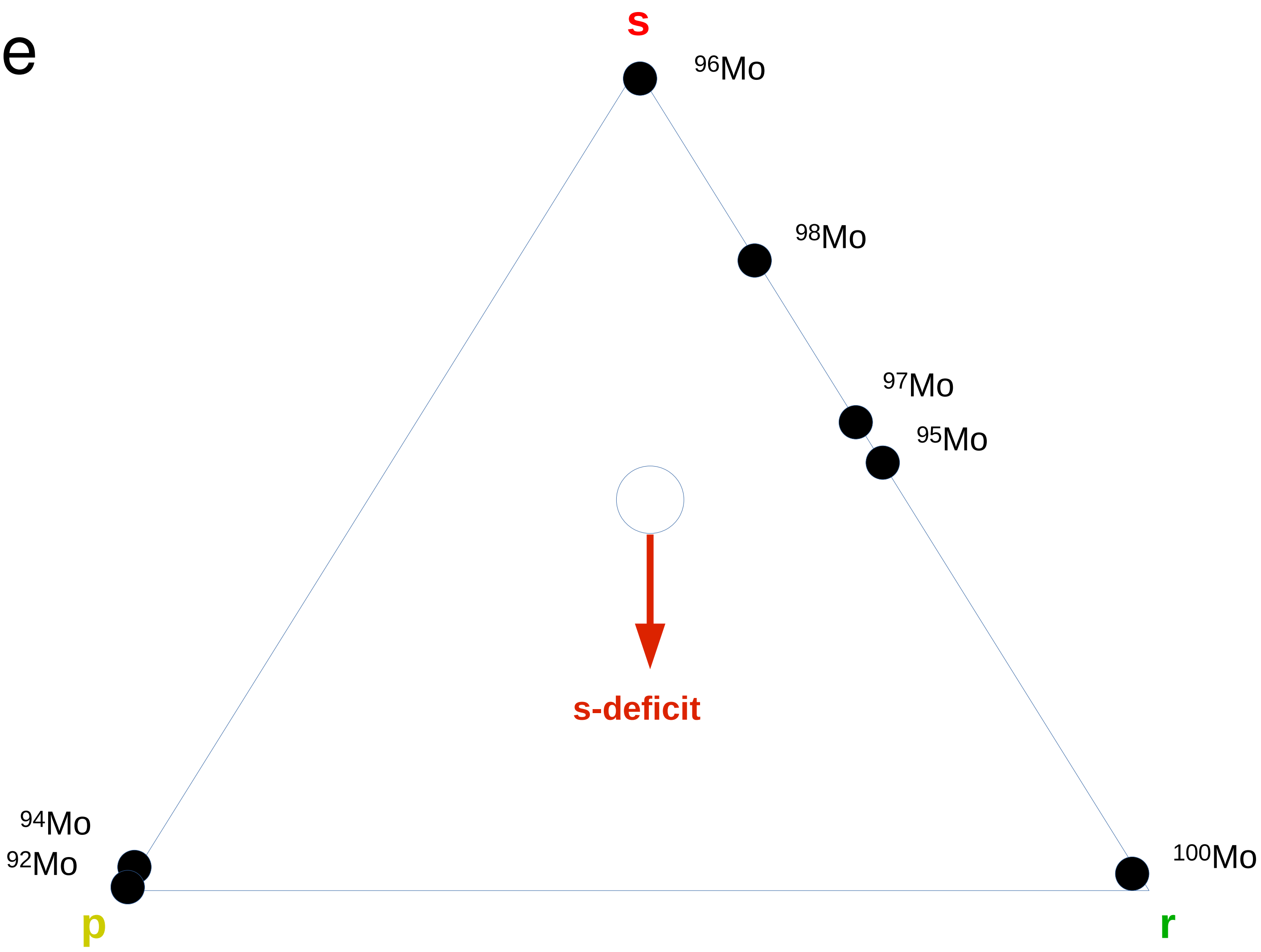
Example

Ru93	Ru94	Ru95	Ru96 5.52	Ru97 2.9d	Ru98 1.88	Ru99 12.7	Ru100 12.6	Ru101 17.0	Ru102 31.6	Ru103 40d	Ru104 18.7
Tc92	Tc93	Tc94	Tc95	Tc96 4.3d	Tc97 4.0E6a	Tc98 4.2E6a	Tc99 2.1E5a	Tc100	Tc101	Tc102	Tc103
Mo91	Mo92 14.84	Mo93 3.5E3a	Mo94 9.25	Mo95 15.92	Mo96 16.68	Mo97 9.55	Mo98 24.13	Mo99 2.8d	Mo100 9.63 1.1E19a	Mo101	Mo102
Nb90	Nb91 680a	Nb92 3.6E7a	Nb93 100	Nb94 2E4a	Nb95 35d	Nb96 1d	Nb97	Nb98	Nb99	Nb100	Nb101
Zr89 3d	Zr90 51.45	Zr91 11.22	Zr92 17.15	Zr93 1.5E6a	Zr94 17.38	Zr95 64d	Zr96 2.80 3.9E19a	Zr97	Zr98	Zr99	Zr100

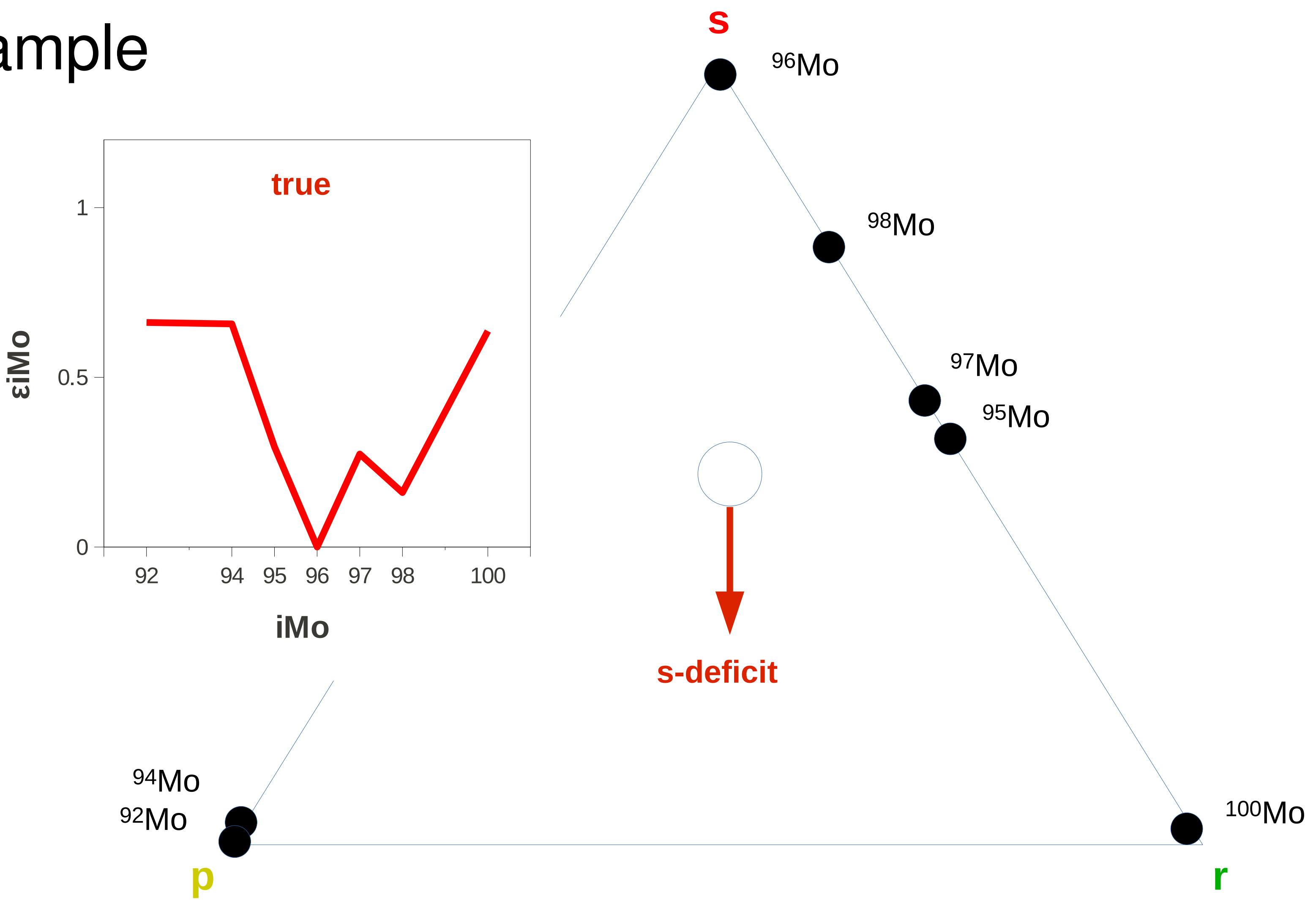
Example



Example



Example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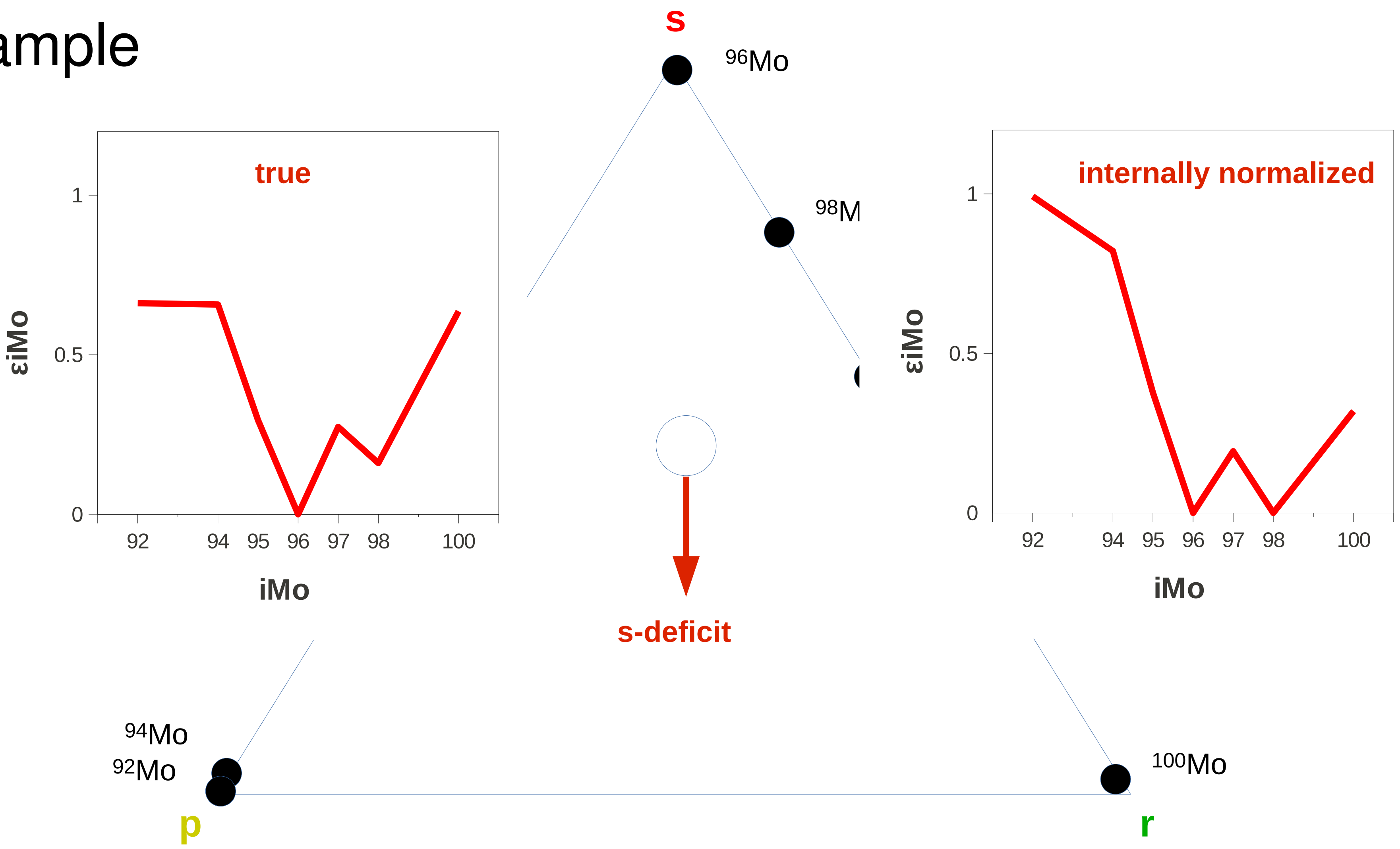
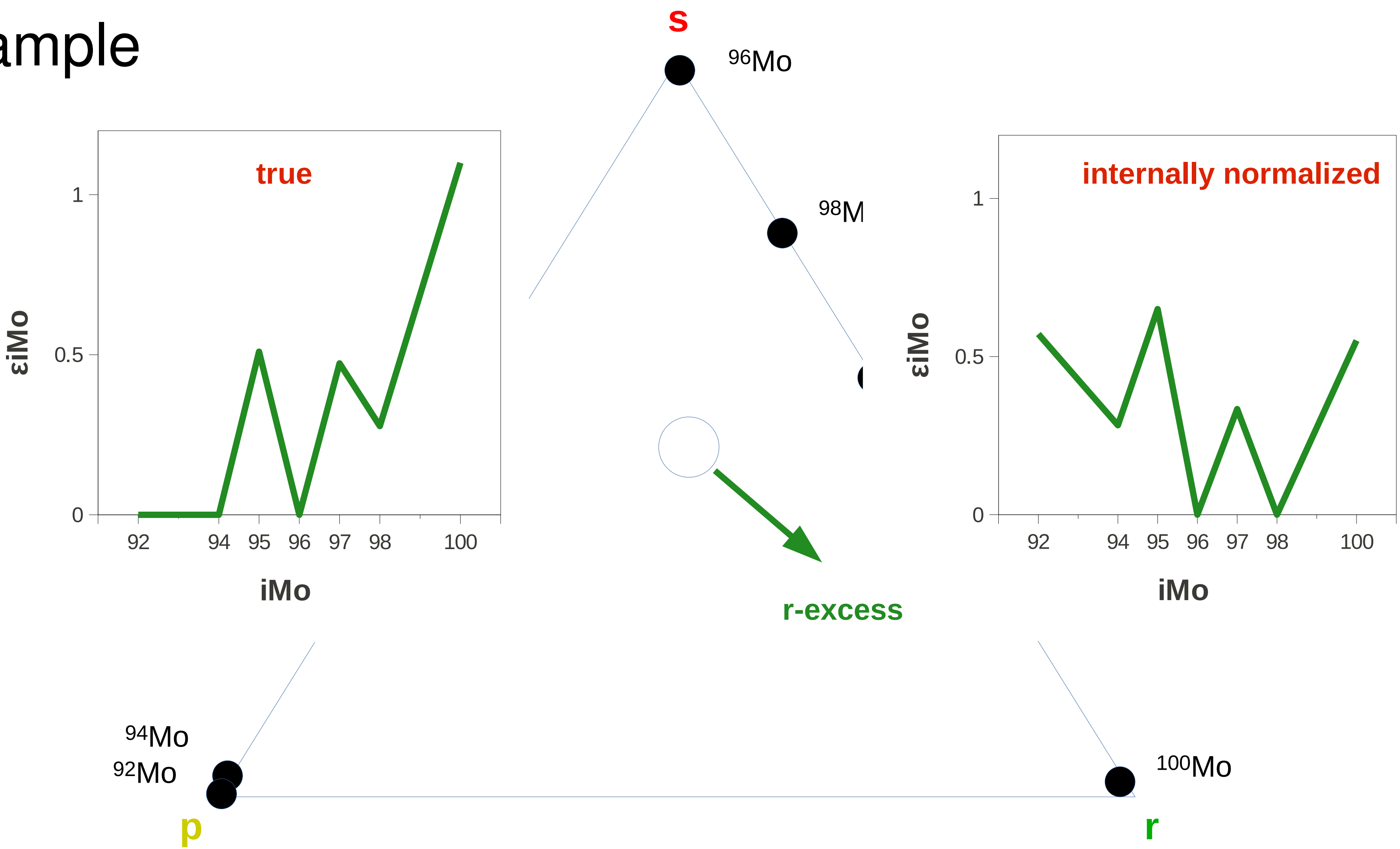
96Mo
98Mo
97Mo
95Mo
94Mo
92Mo
100Mo
p
r
s-deficit
true
εiMo
1
0.5
0
92
94
95
96
97
98
100
iMo

Example



s
96Mo
98M
true
1
0.5
0
εiMo
92
94
95
96
97
98
100
iMo
internally normalized
s-deficit
94Mo
92Mo
100Mo
p
r

Example



s
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98M
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0
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98
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internally normalized
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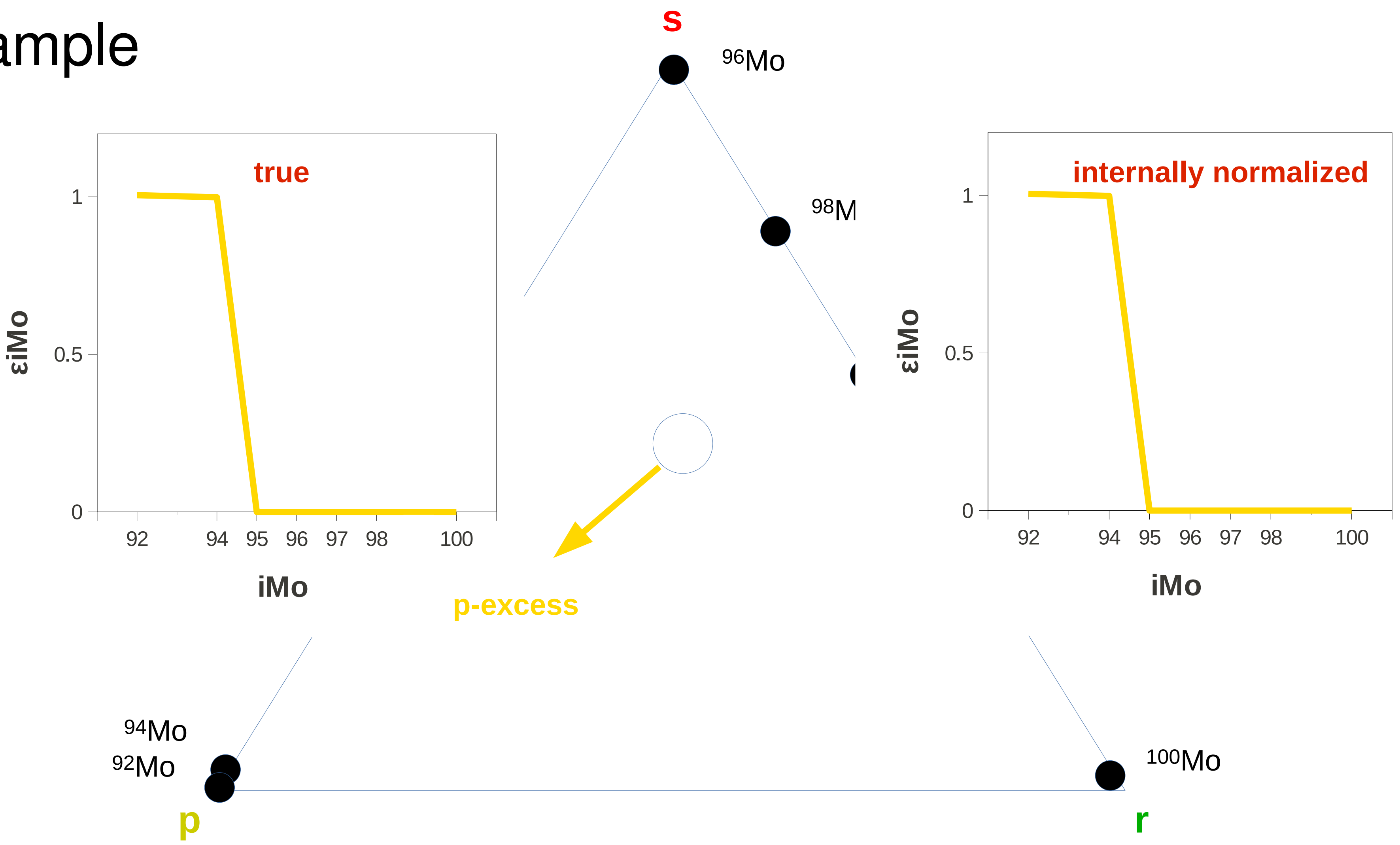
Example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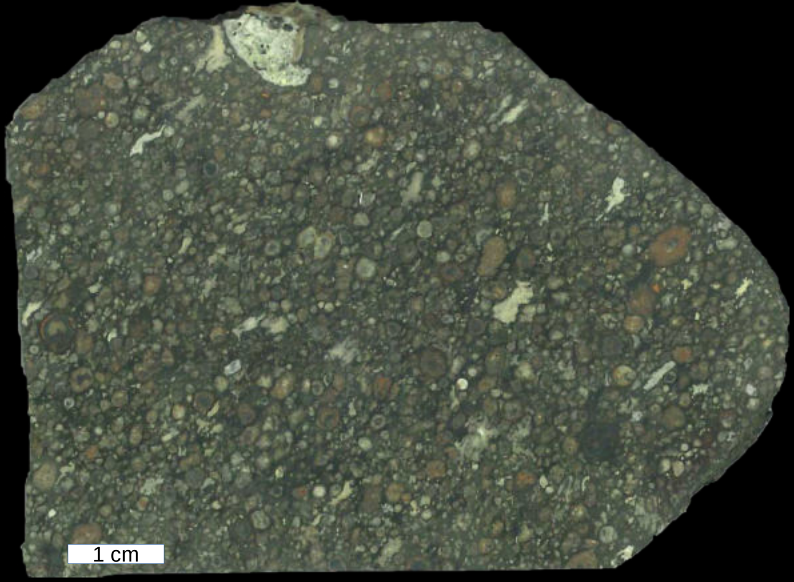
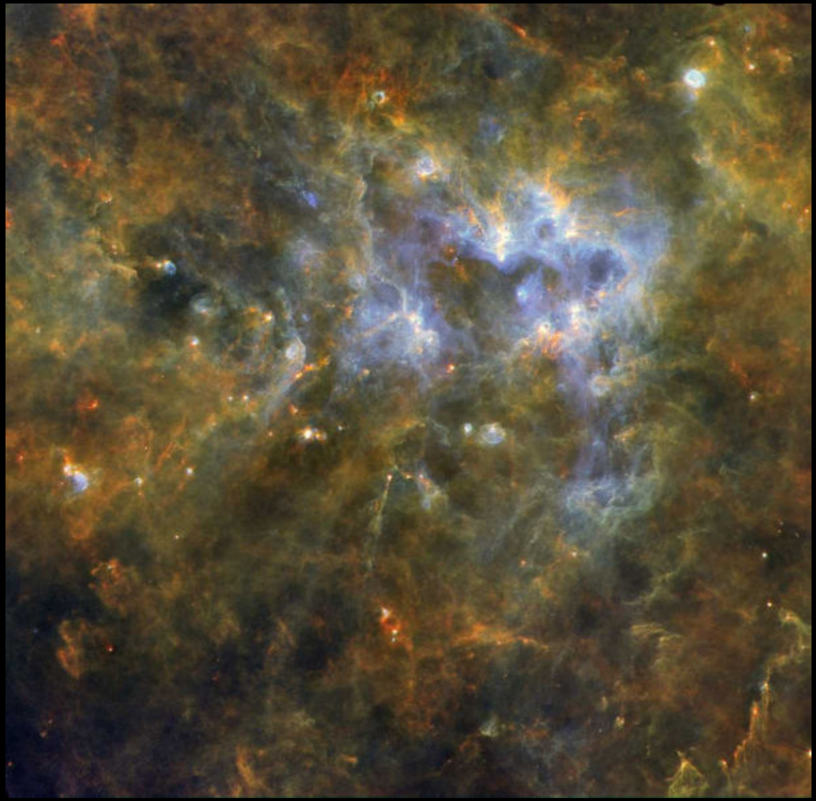
Isotopic anomalies in meteorites

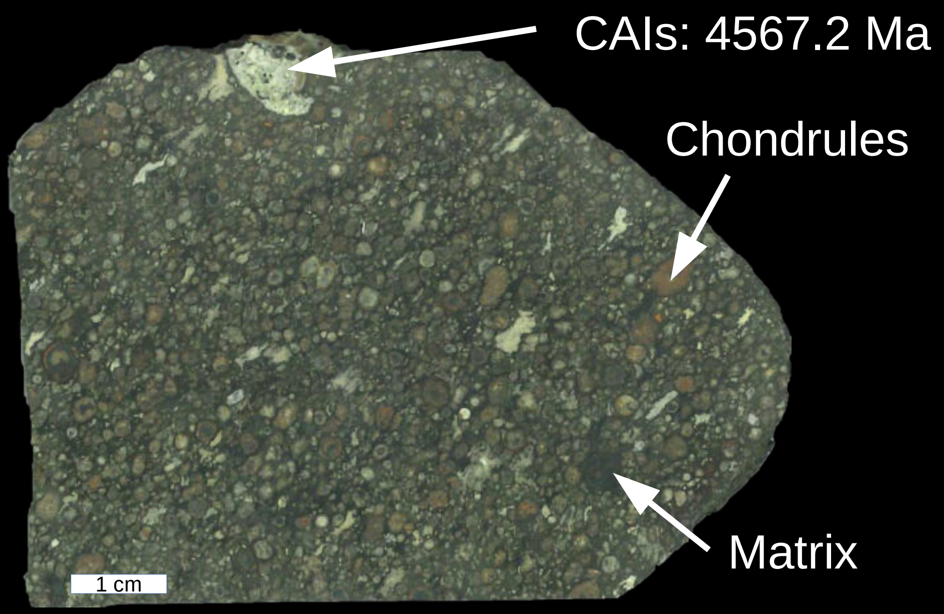


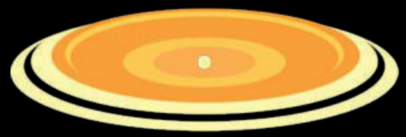


What is the solar system made of?

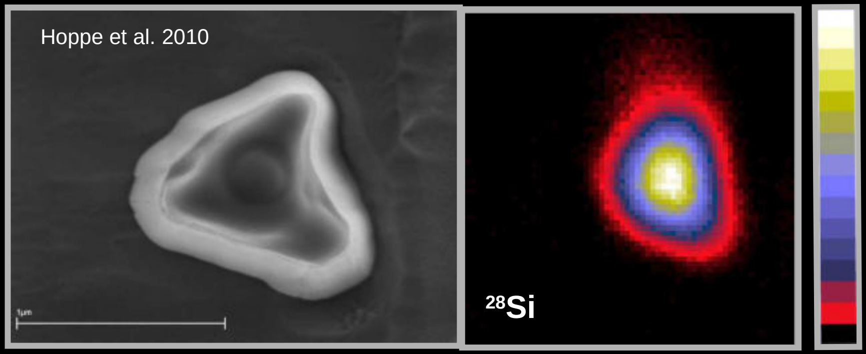
ESA/Herschel/PACS, G305

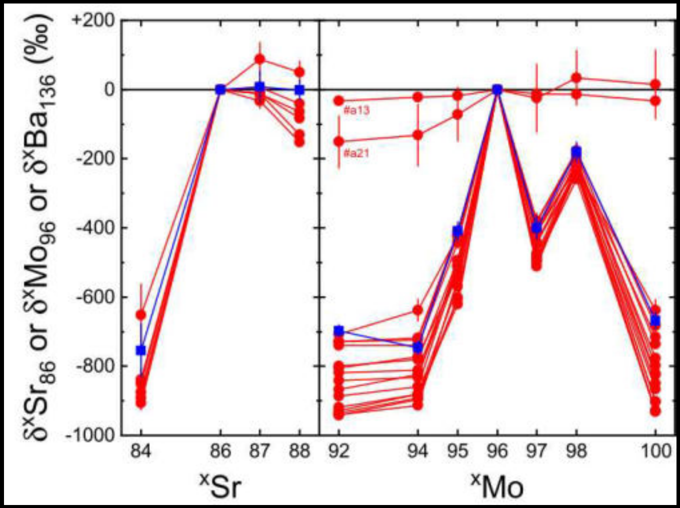
Chondrites



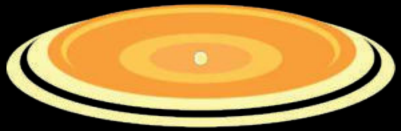


Presolar grains (Lewis et al., 1987)





Stephan et al. 2019



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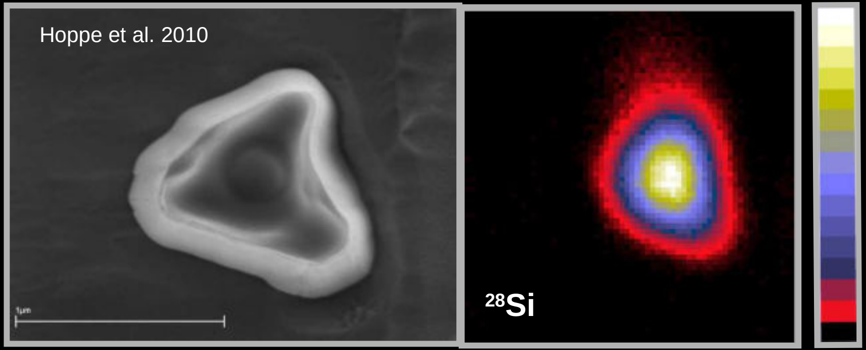

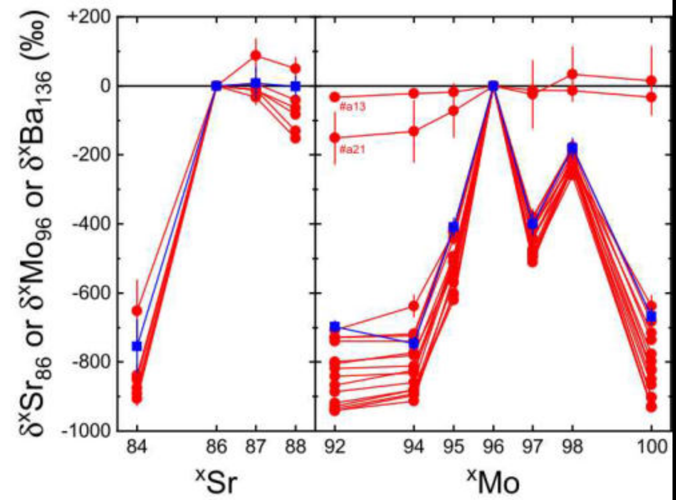

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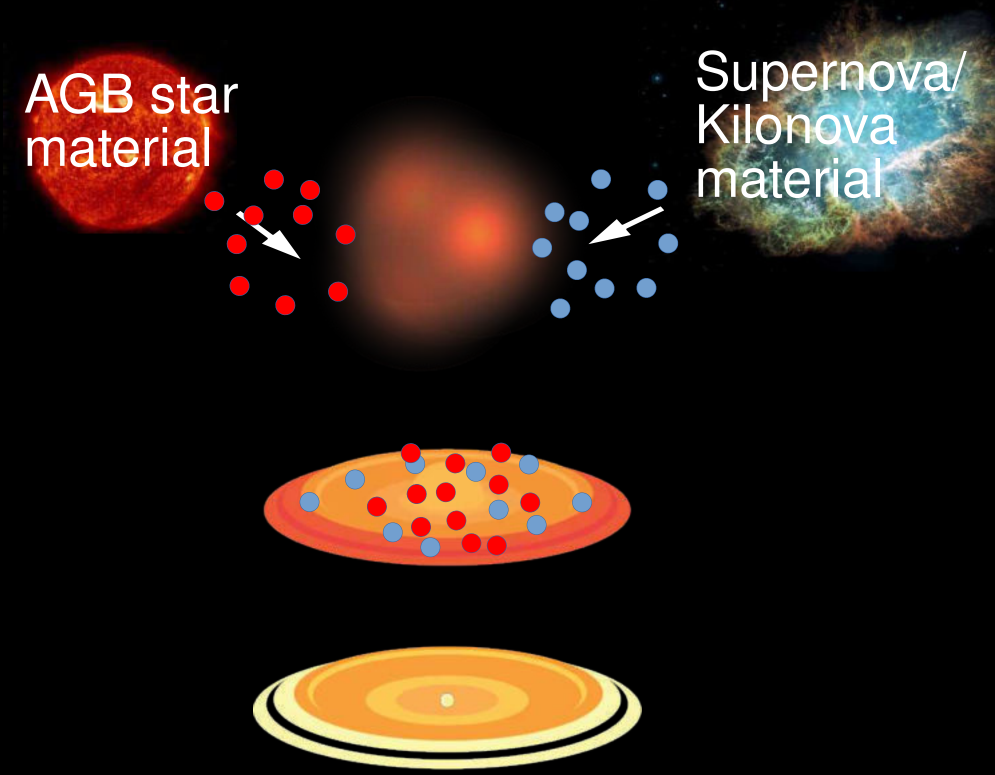
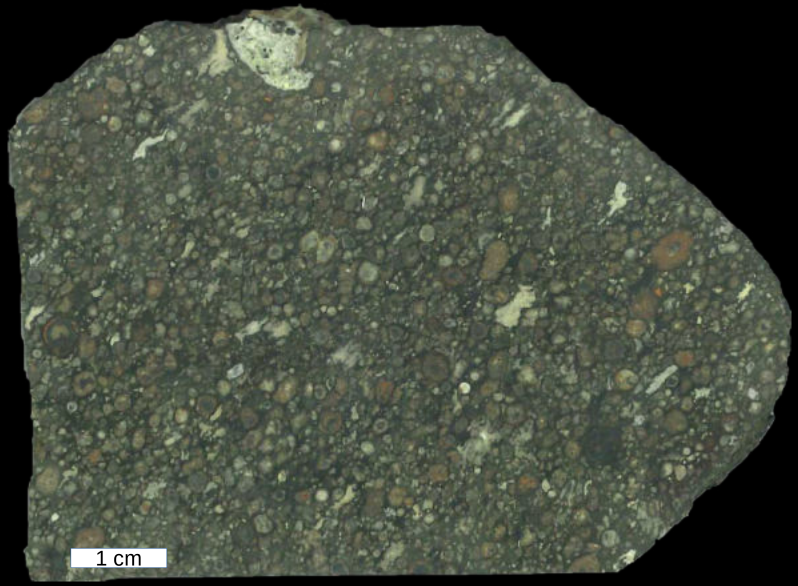
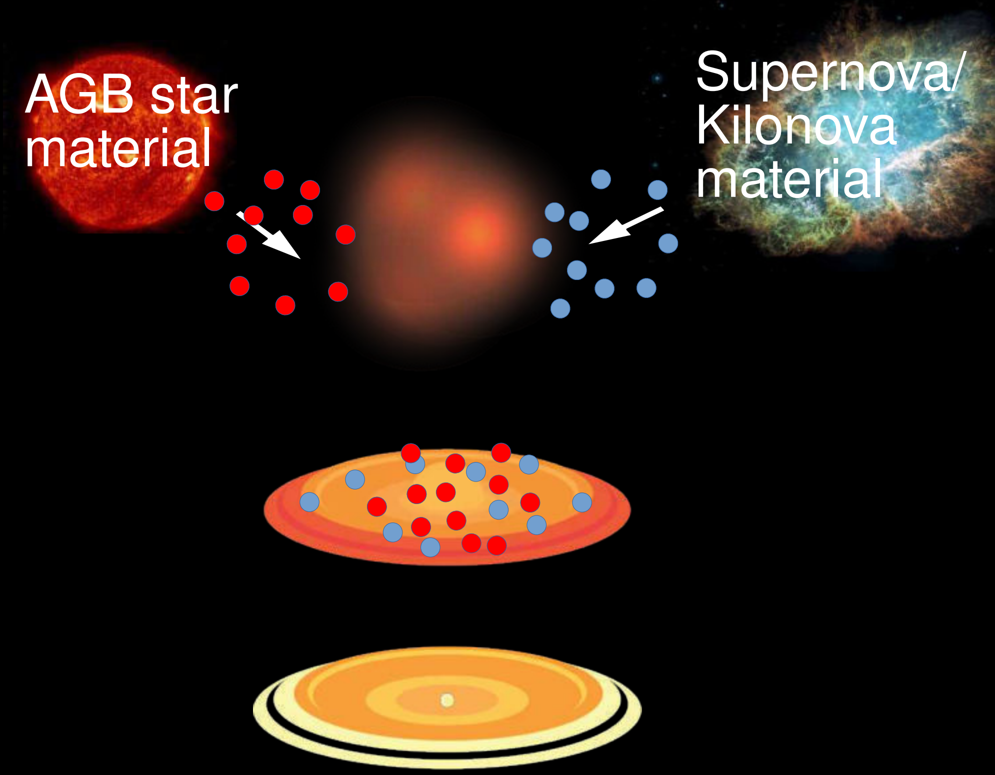
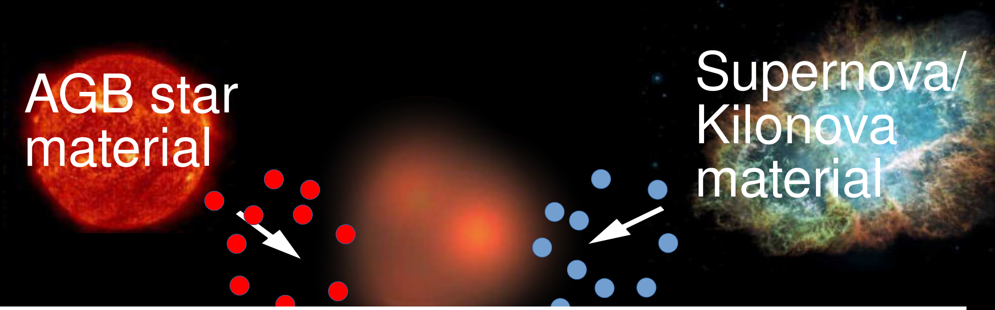


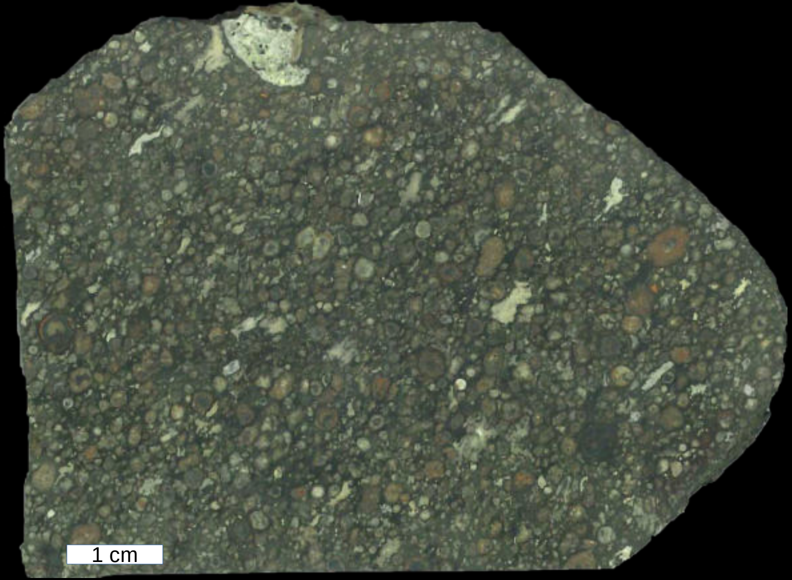
Short-lived nuclides

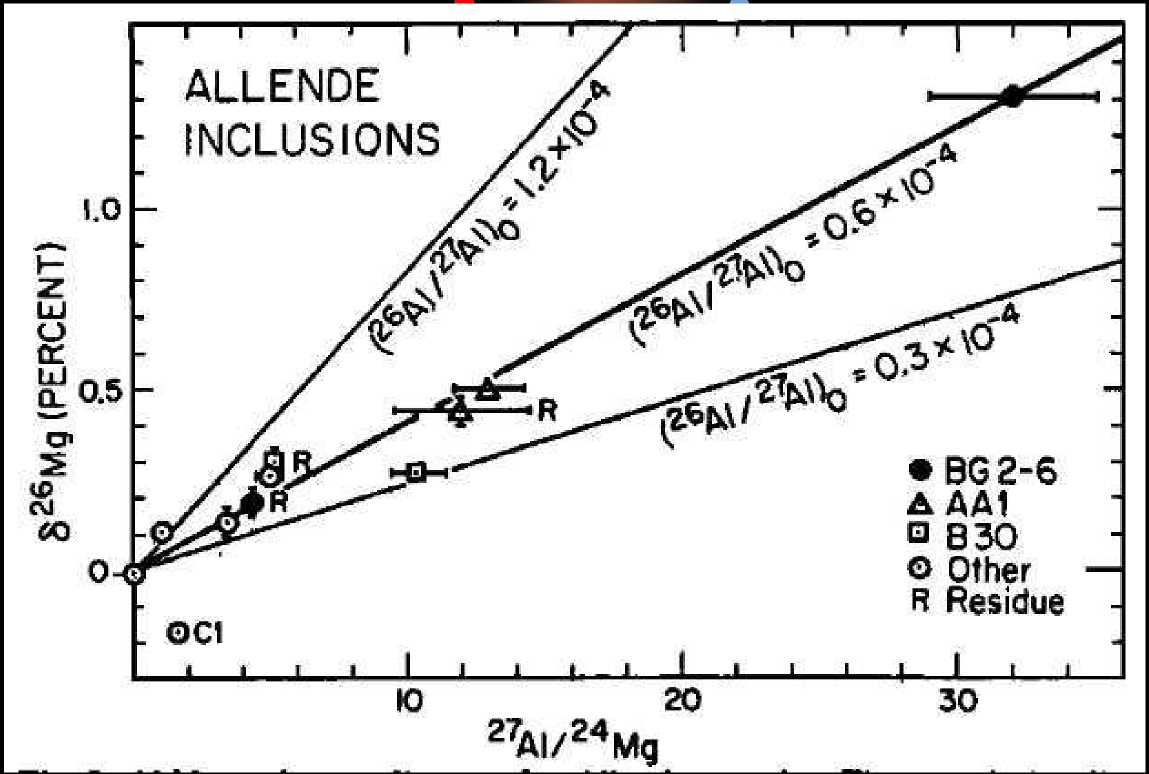




Short-lived nuclides

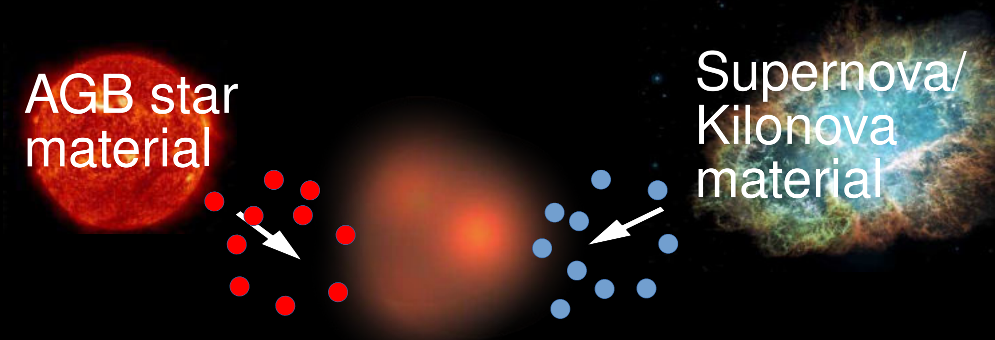






Lee et al. 1976

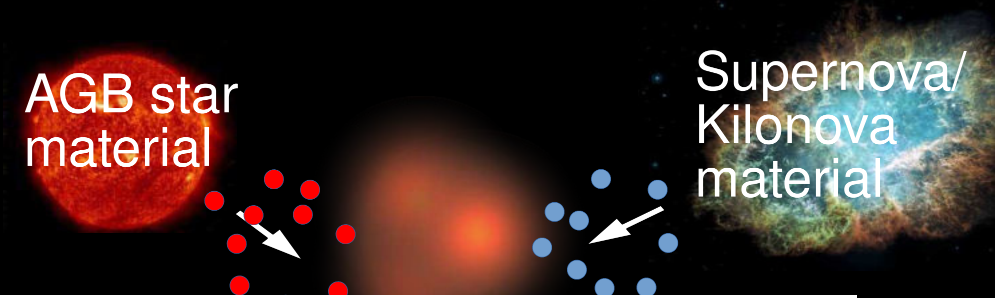
Short-lived nuclides

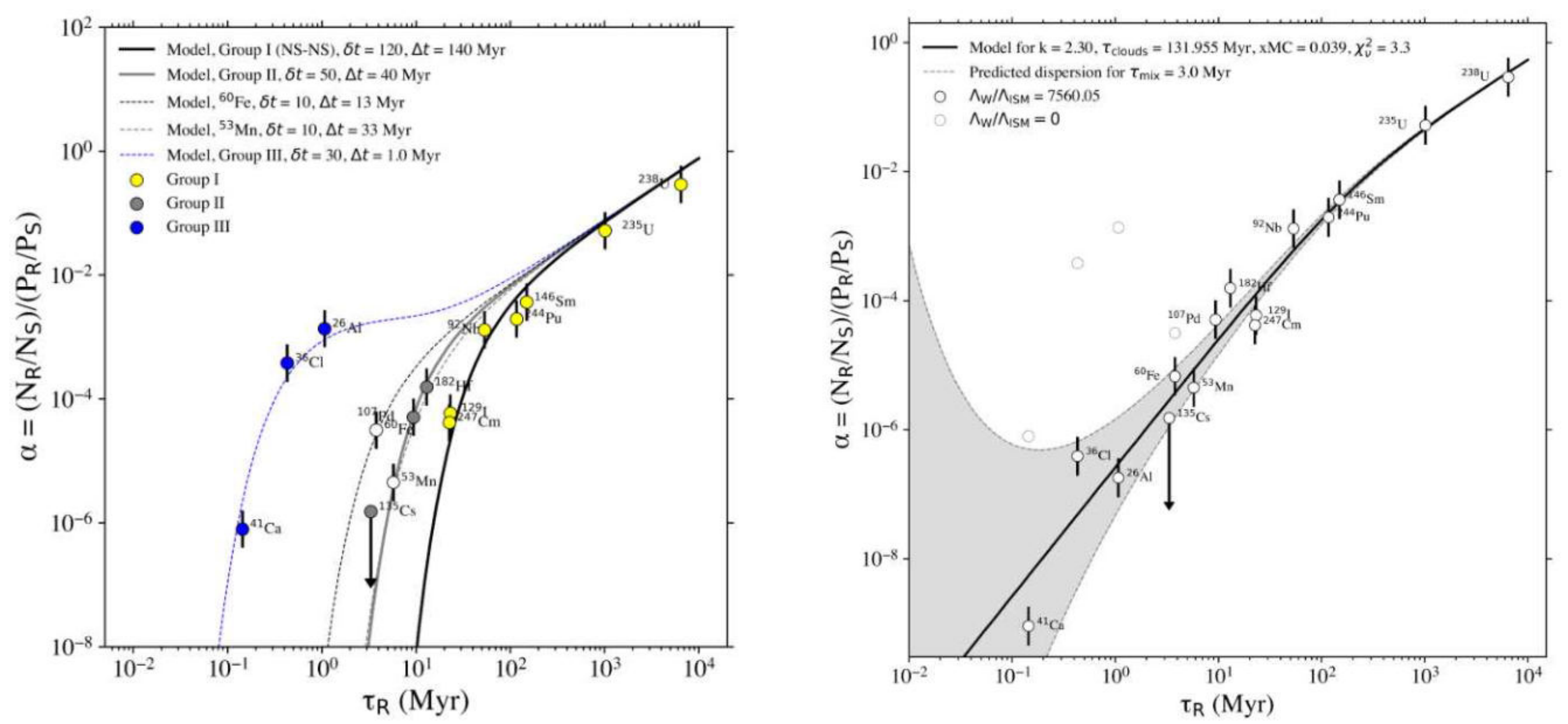


SLR	Daughter	Half-life (Myr)	Ref.	Solar System Abundance at t=0	Ref.	ISM Production Ratios	Ref.
^{41}Ca	^{41}K	0.0994 ± 0.0015	[1]	$^{41}\mathrm{Ca}/^{40}\mathrm{Ca} \approx 4.2 \times 10^{-9}$	[2]	$^{41}\mathrm{Ca}/^{40}\mathrm{Ca} = 2.3 \times 10^{-3}$	[3]
^{36}Cl	^{36}Ar, ^{36}S	$0.301 \pm 0.002^{\dagger}$		$^{36}\mathrm{Cl}/^{35}\mathrm{Cl} \approx (1.7-3) \times 10^{-5}$	[4]	$^{36}\mathrm{Cl}/^{35}\mathrm{Cl} = 2.63 \times 10^{-2}$	[5]
^{26}Al	^{26}Mg	0.717 ± 0.017	[6]	$^{26}\mathrm{Al}/^{27}\mathrm{Al} = 5.23 \times 10^{-5}$	[7]	$^{26}\mathrm{Al}/^{27}\mathrm{Al} = 1.667 \times 10^{-2}$	[8]
^{10}Be	^{10}B	1.387 ± 0.012	[9]	$^{10}\mathrm{Be}/^{9}\mathrm{Be} = (7.1 \pm 0.2) \times 10^{-4}$	[10]		
^{60}Fe	^{60}Fe	2.62 ± 0.04	[11]	$^{60}\mathrm{Fe}/^{56}\mathrm{Fe} = (0.9 \pm 0.1) \times 10^{-8}$	[12]	$^{60}\mathrm{Fe}/^{56}\mathrm{Fe} = 1.23 \times 10^{-4}$	[13]
^{53}Mn	^{53}Cr	3.98 ± 0.11	[14]	$^{53}\mathrm{Mn}/^{55}\mathrm{Mn} = (7.8 \pm 0.4) \times 10^{-6}$	[15]	$^{53}\mathrm{Mn}/^{55}\mathrm{Mn} = 7.52 \times 10^{-1}$	[16]
^{107}Pd	^{107}Ag	6.5 ± 0.3	[17]	$^{107}\mathrm{Pd}/^{108}\mathrm{Pd} \approx (7.7 \pm 0.5) \times 10^{-5}$	[18]	$^{107}\mathrm{Pd}/^{108}\mathrm{Pd} = 6.5 \times 10^{-1}$	[19]
^{182}Hf	^{182}W	8.896 ± 0.089	[20]	$^{182}\mathrm{Hf}/^{180}\mathrm{Hf} = (1.04 \pm 0.1) \times 10^{-4}$	[21]	$^{182}\mathrm{Hf}/^{180}\mathrm{Hf} = 2.9 \times 10^{-1}$	[22]
^{247}Cm	^{235}U	$15.6 \pm 0.5^{\dagger}$		$^{247}\mathrm{Cm}/^{235}\mathrm{U} = (5.6 \pm 0.3) \times 10^{-5}$	[23]	$^{247}\mathrm{Cm}/^{232}\mathrm{Th} = 1.01 \times 10^{-1}$	[24]
^{129}I	^{129}Xe	16.14 ± 0.12	[25]	$^{129}\mathrm{I}/^{127}\mathrm{I} = (1.74 \pm 0.02) \times 10^{-4}$	[26]	$^{129}\mathrm{I}/^{127}\mathrm{I} = 1.25 \times 10^{0}$	[27]
^{205}Pb	^{205}Tl	$17.3 \pm 0.7^{\dagger}$		$^{205}\mathrm{Pb}/^{204}\mathrm{Pb} = (1.4 \pm 0.3) \times 10^{-4}$	[28]		
^{92}Nb	^{92}Zr	$34.7 \pm 0.7^{\dagger}$		$^{92}\mathrm{Nb}/^{93}\mathrm{Nb} = (1.7 \pm 0.6) \times 10^{-5}$	[29]	$^{92}\mathrm{Nb}/^{93}\mathrm{Nb} = 5.65 \times 10^{-3}$	[30]
^{146}Sm	^{142}Nd	103 ± 5	[31]	$^{146}\mathrm{Sm}/^{144}\mathrm{Sm} = (8.28 \pm 0.44) \times 10^{-3}$	[32]	$^{146}\mathrm{Sm}/^{144}\mathrm{Sm} = 9.5 \times 10^{-1}$	[33]
^{244}Pu	^{236}U, ^{232}Th	$80.0 \pm 0.9^{\dagger}$		$^{244}\mathrm{Pu}/^{238}\mathrm{U} = (7 \pm 1) \times 10^{-3}$	[34]	$^{244}\mathrm{Pu}/^{232}\mathrm{Th} = 6.67 \times 10^{-1}$	[35]
^{135}Cs	^{135}Ba	2.3 ± 0.3^{a}		$^{135}\mathrm{Cs}/^{133}\mathrm{Cs} = (4.8 \pm 0.8) \times 10^{-4}$	[36]	$^{135}\mathrm{Cs}/^{133}\mathrm{Cs} = 8.0 \times 10^{-1}$	[37]
				$^{135}\mathrm{Cs}/^{133}\mathrm{Cs} < 2.8 \times 10^{-6}$			

Desch et al. 2023

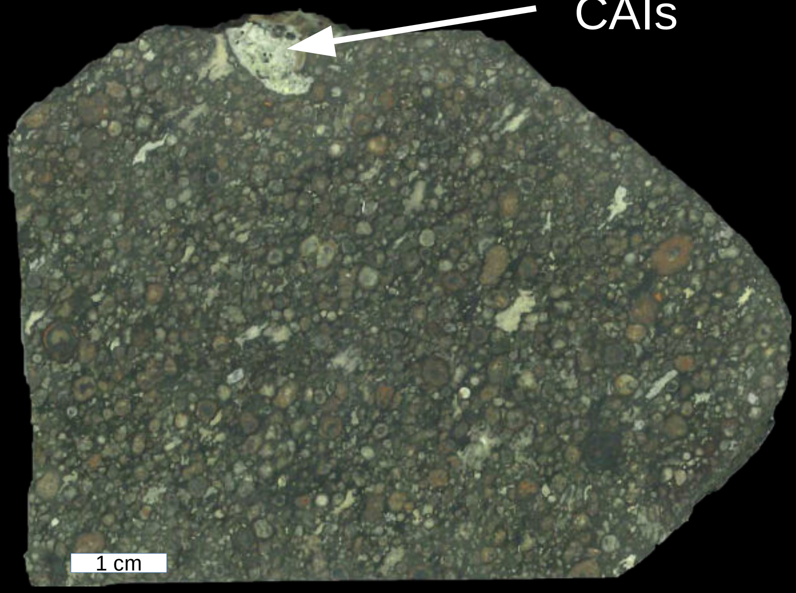
Short-lived nuclides

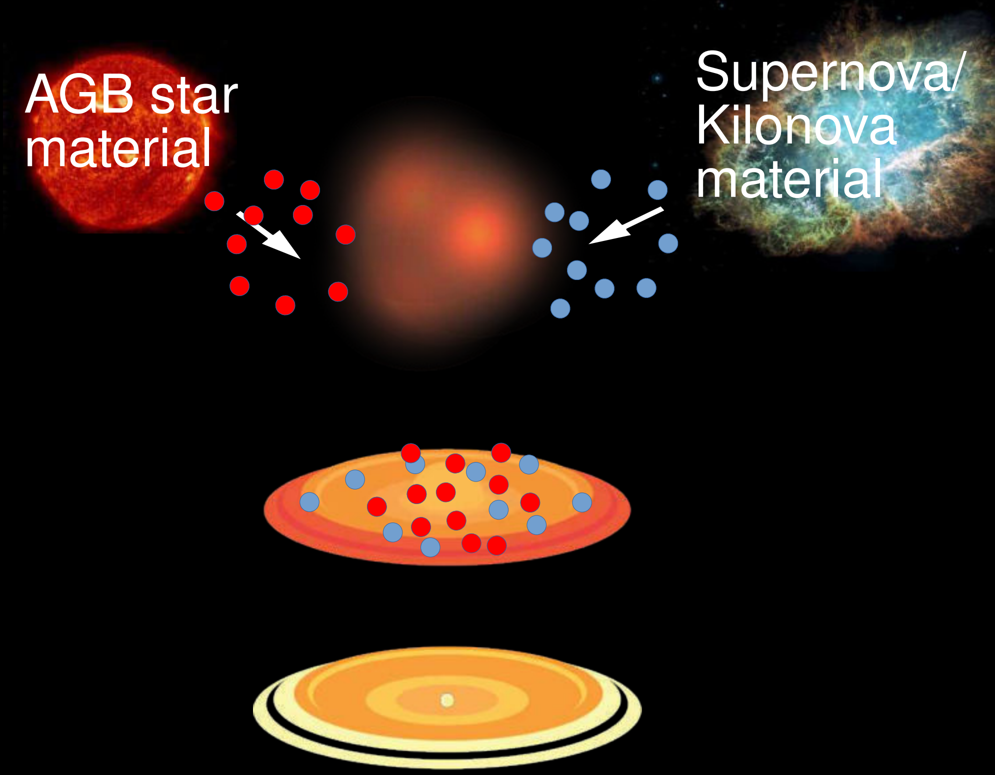




Desch et al. 2023

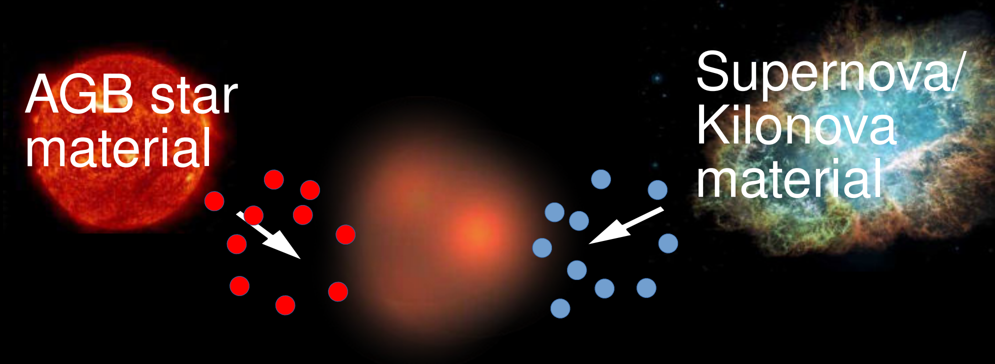
Isotopic anomalies

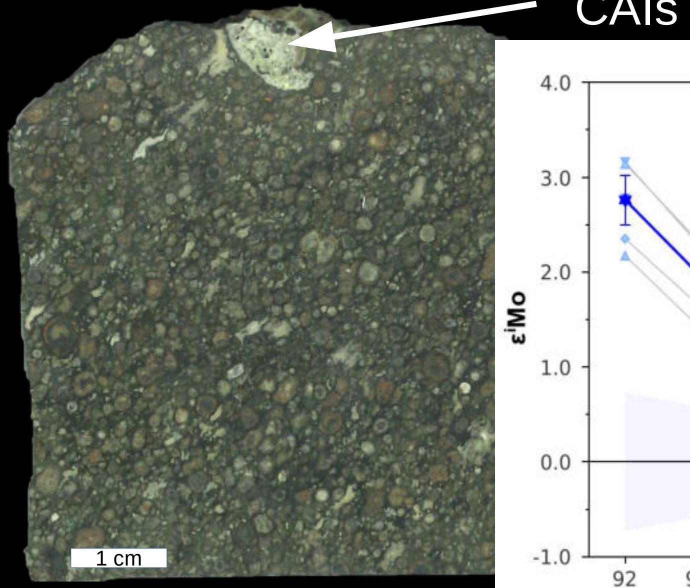


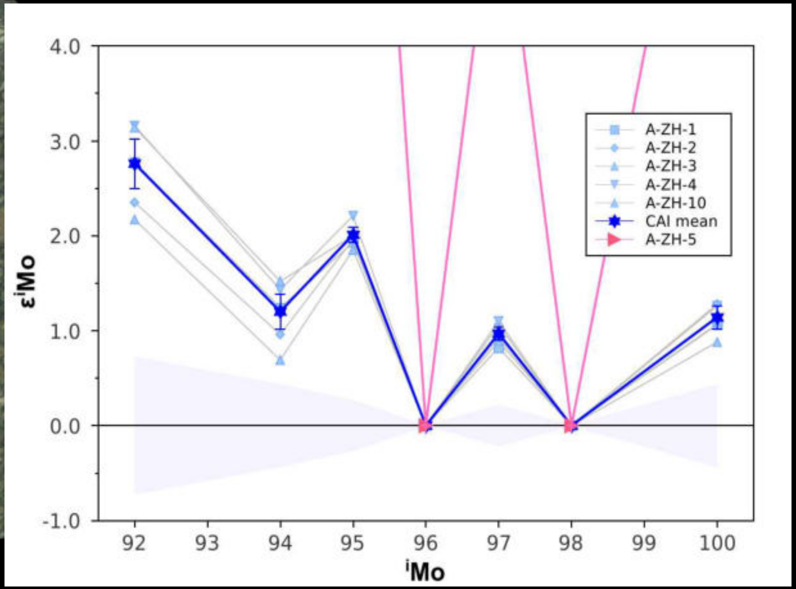


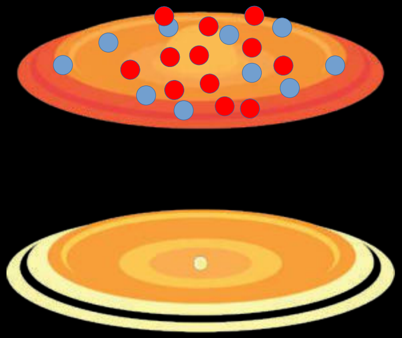
How did disk form? /disk dynamics?

Isotopic anomalies



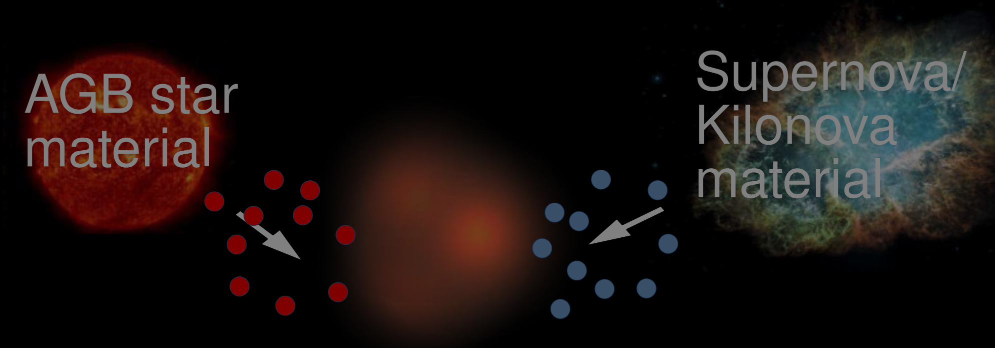


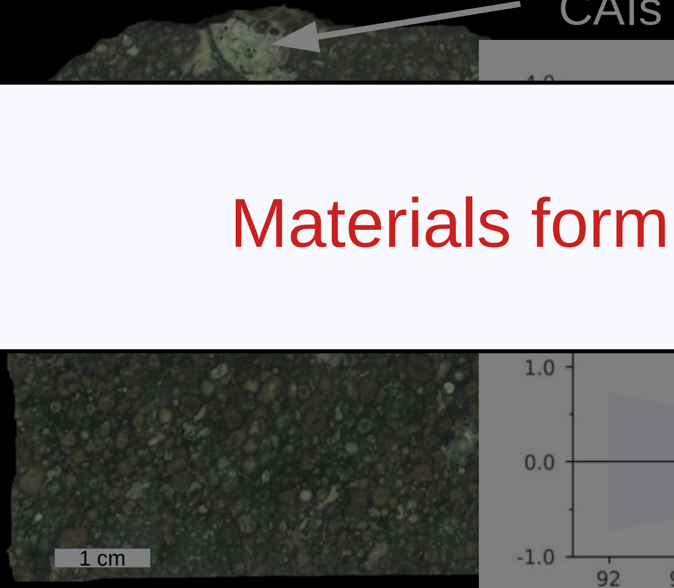


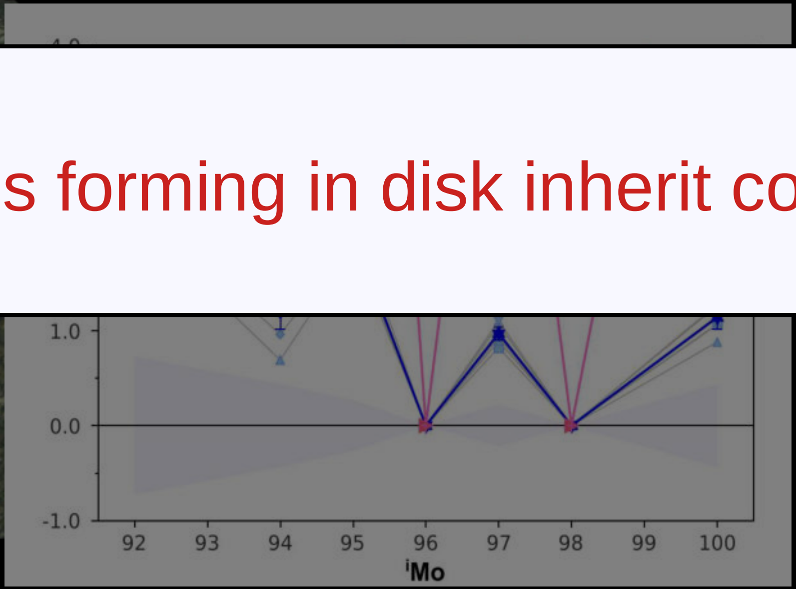


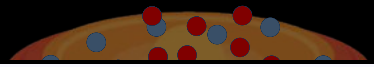
SN/r-process enrichment in CAIs

Isotopic anomalies





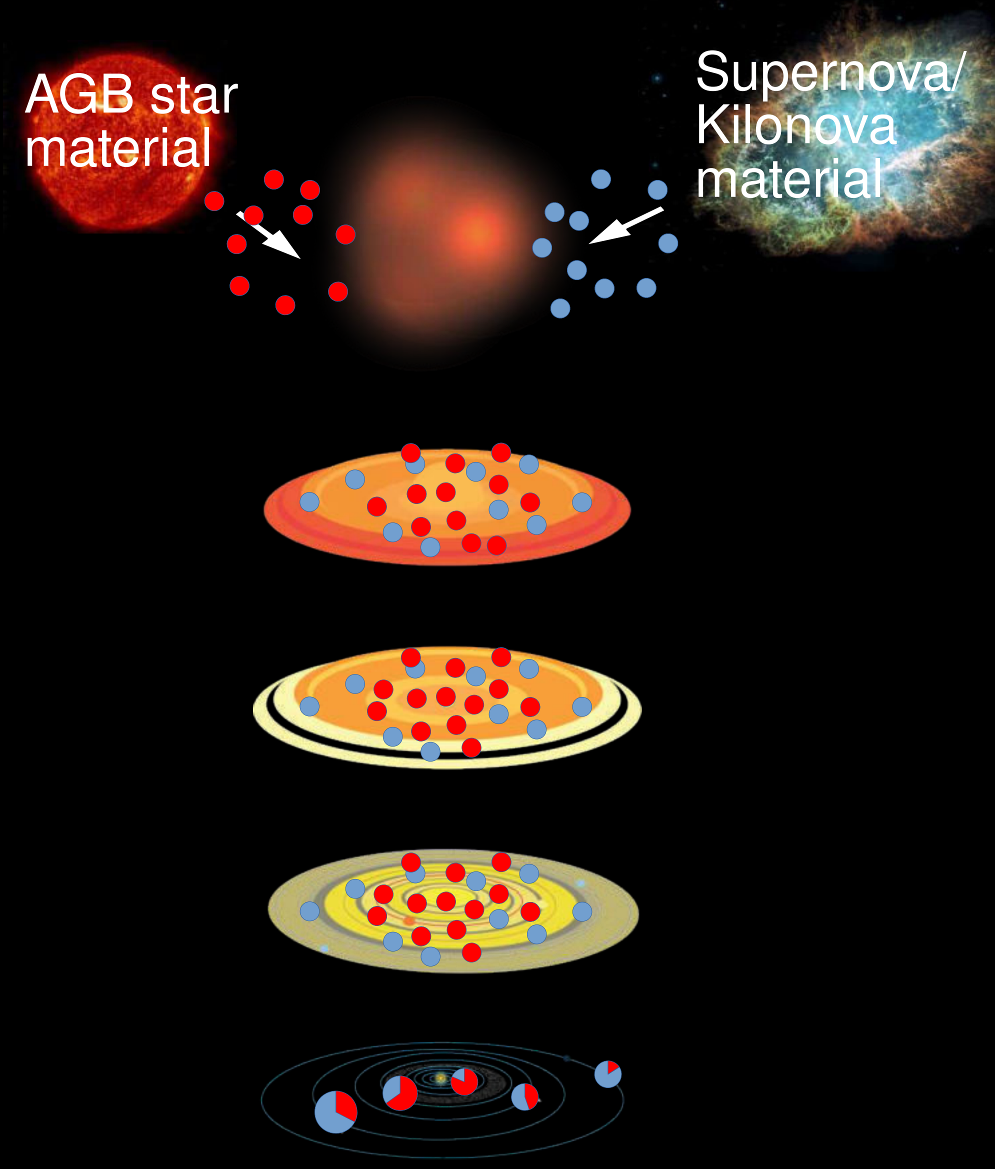




Materials forming in disk inherit cosmic memory!

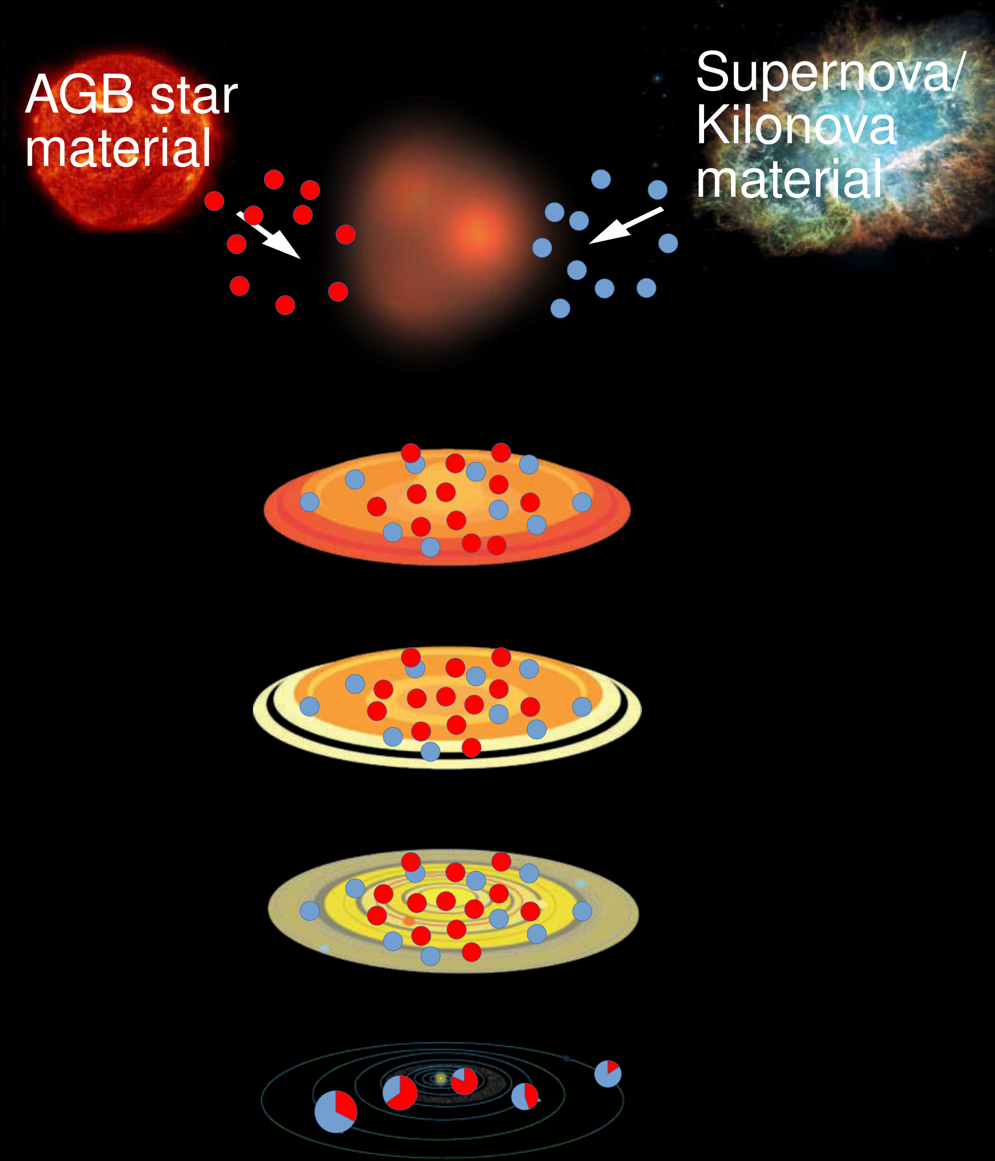
SN/r-process enrichment in CAIs

Distribution

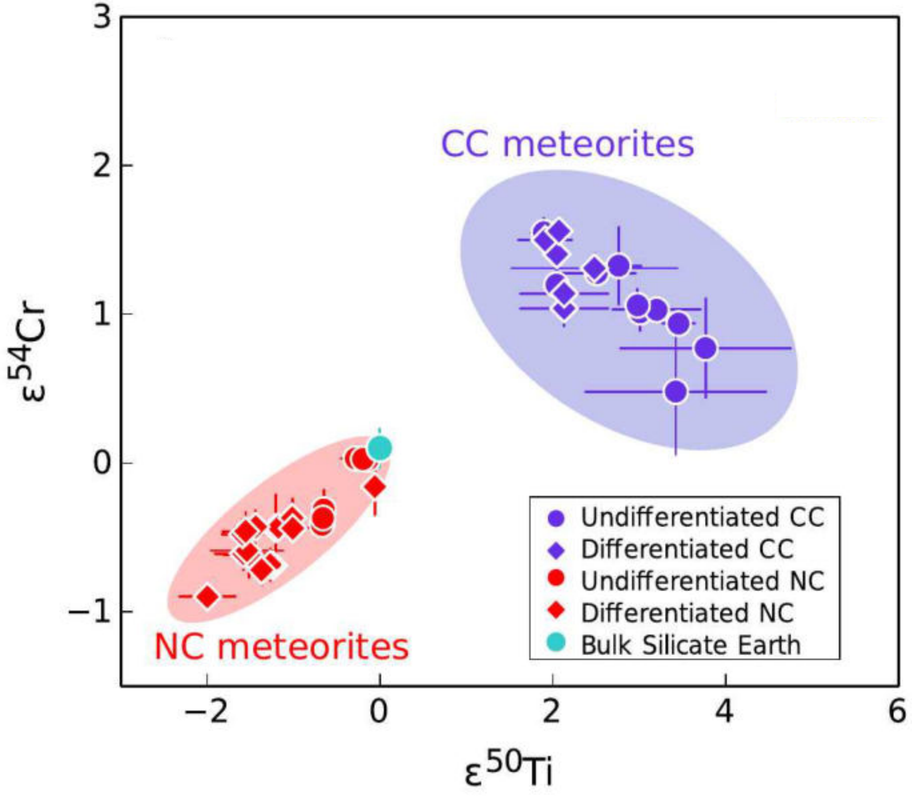


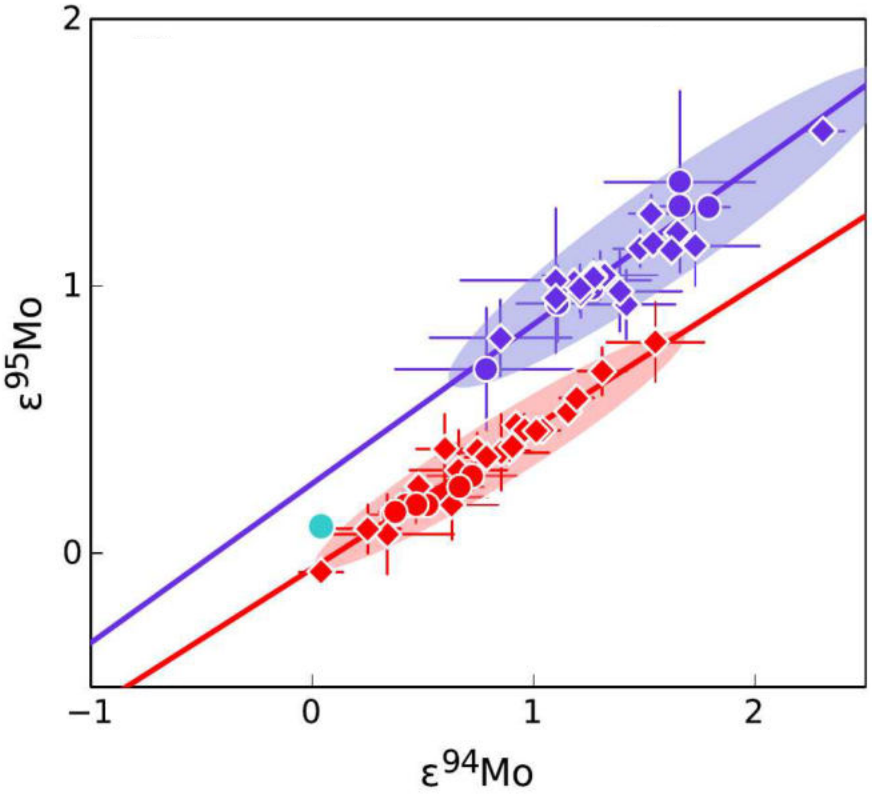
Distribution

Different bodies have distinct isotopic compositions



Planetary-scale nucleosynthetic isotope anomalies

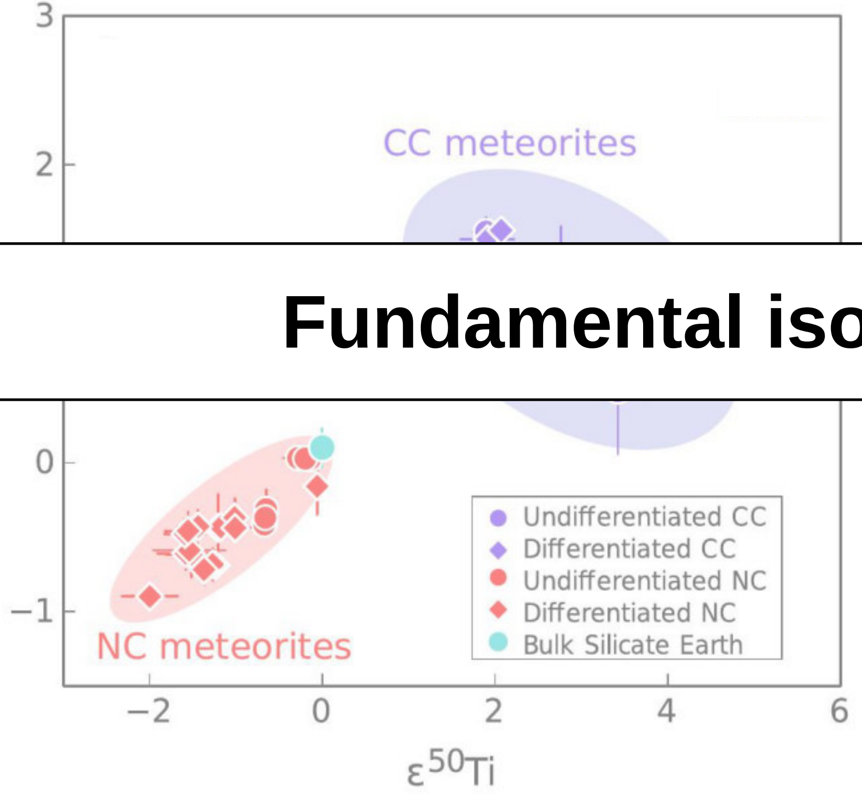


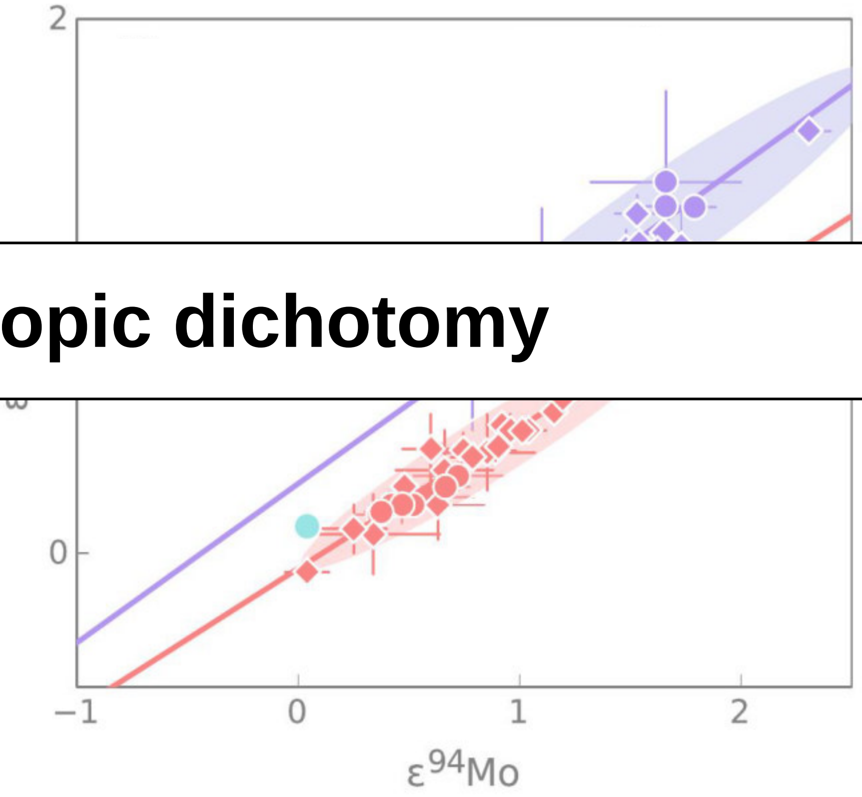


Warren 2011 EPSL

Burkhardt 2021 Elements

Planetary-scale nucleosynthetic isotope anomalies



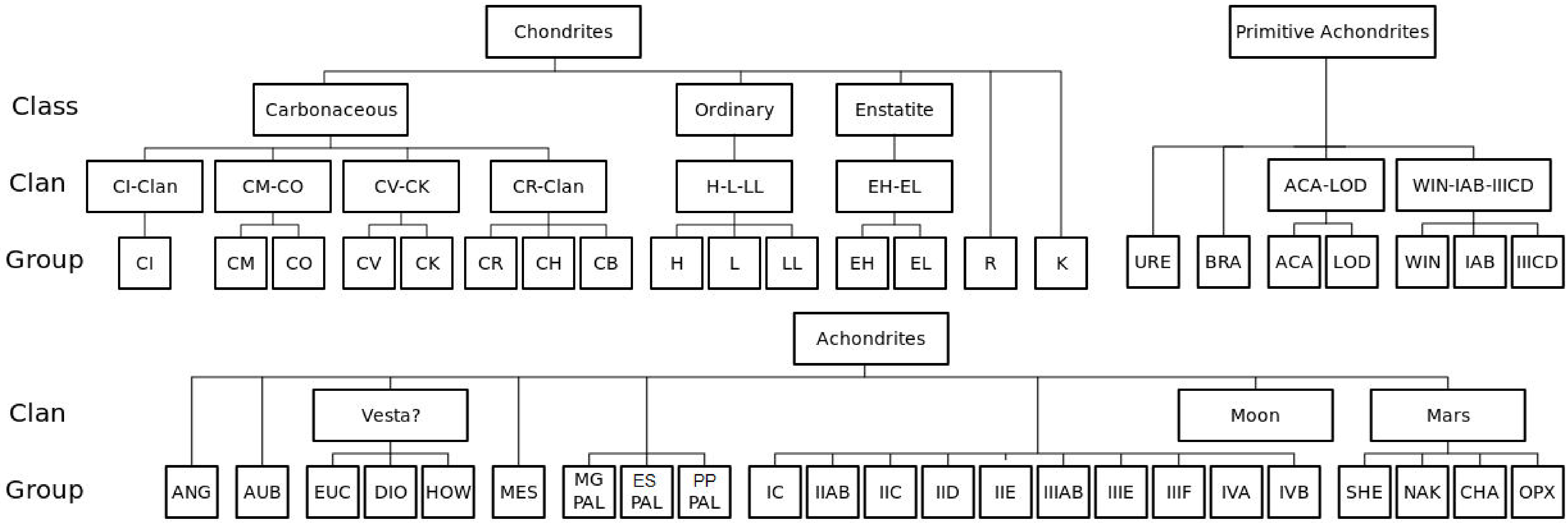


Fundamental isotopic dichotomy

Warren 2011 EPSL

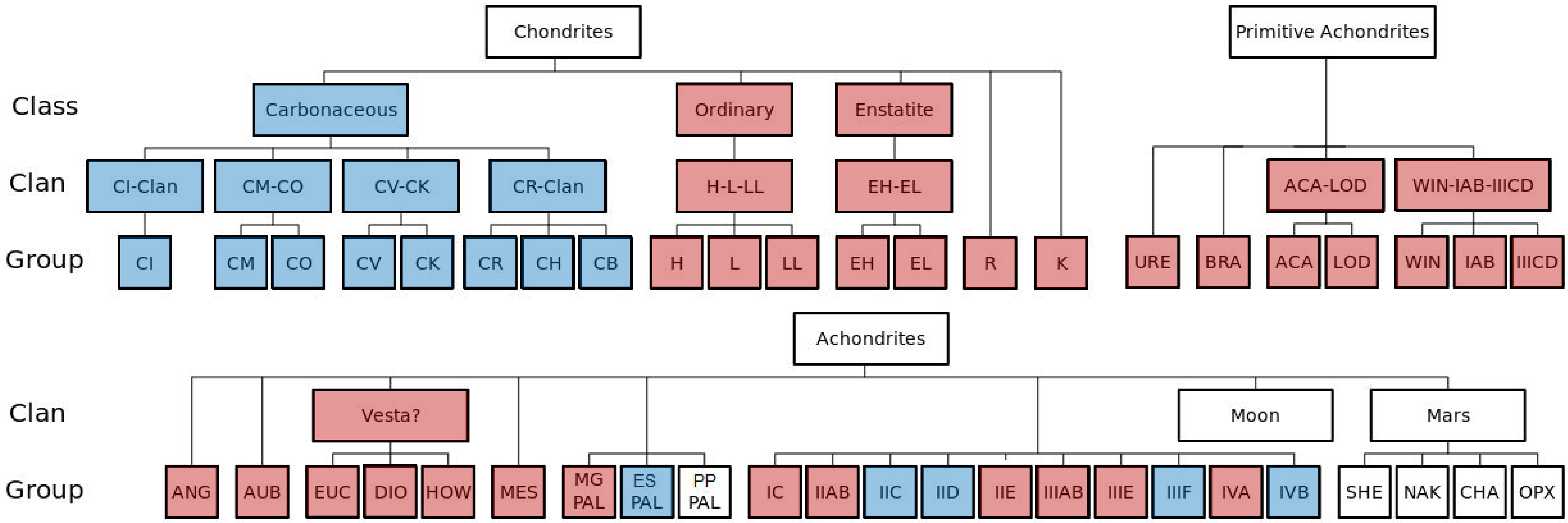
Burkhardt 2021 Elements

Phenomenological classification

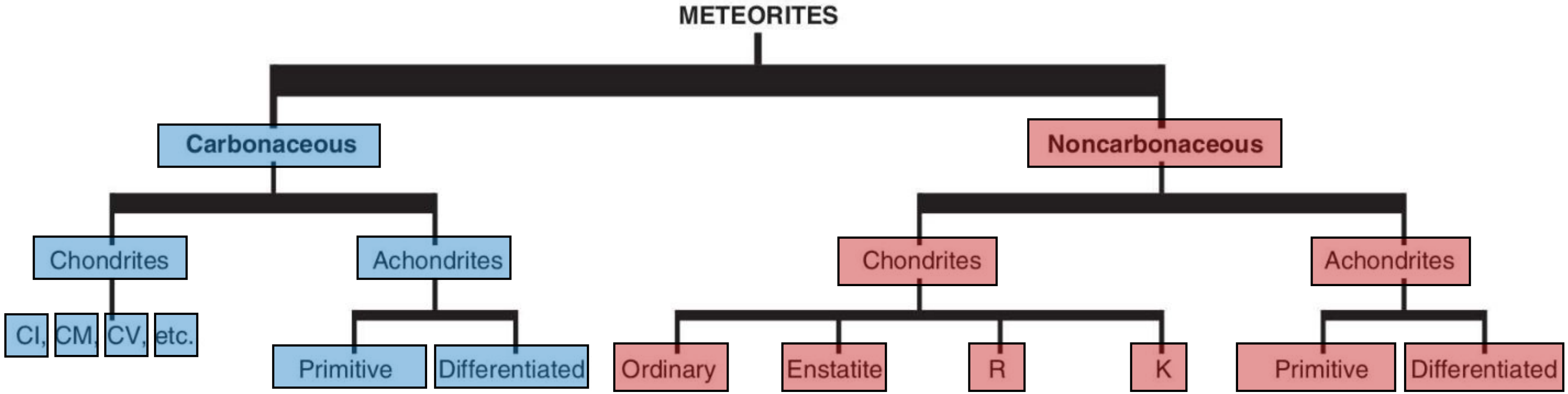


Weisberg, 2006

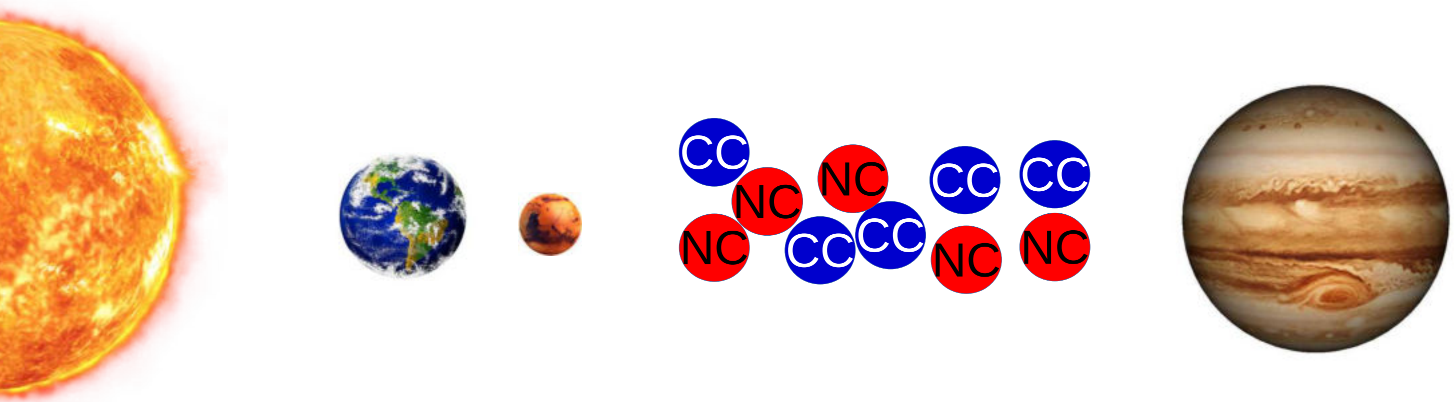
Genetic classification



Genetic classification



Warren, 2011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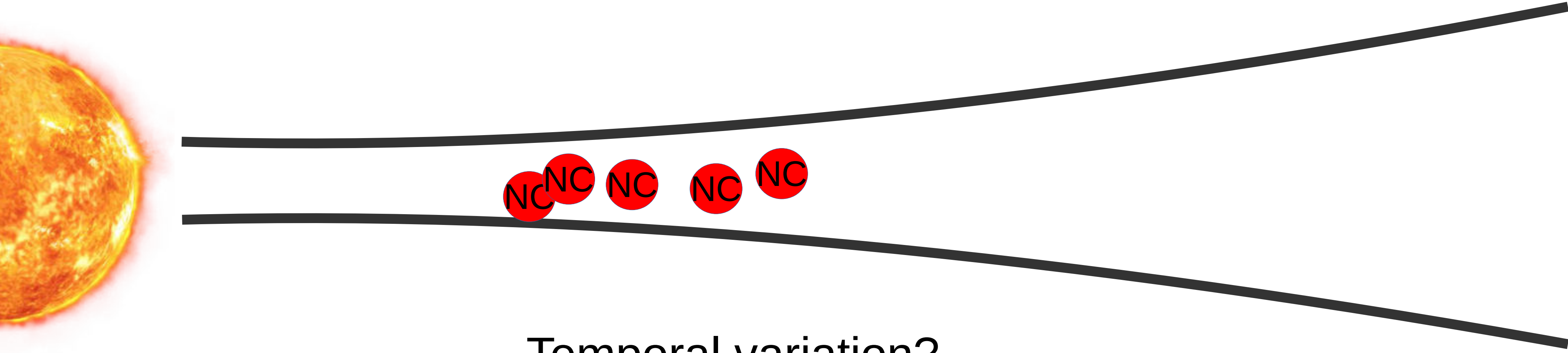
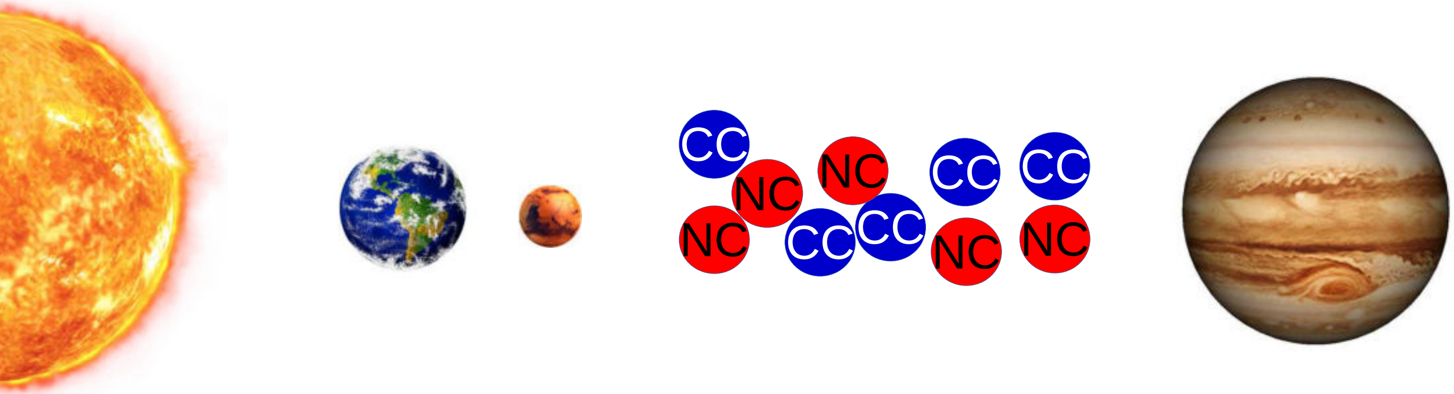
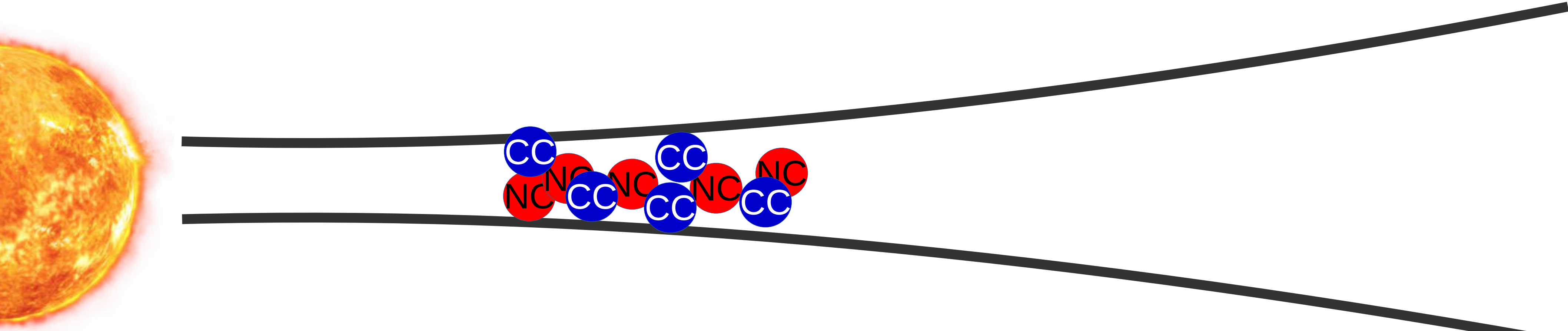
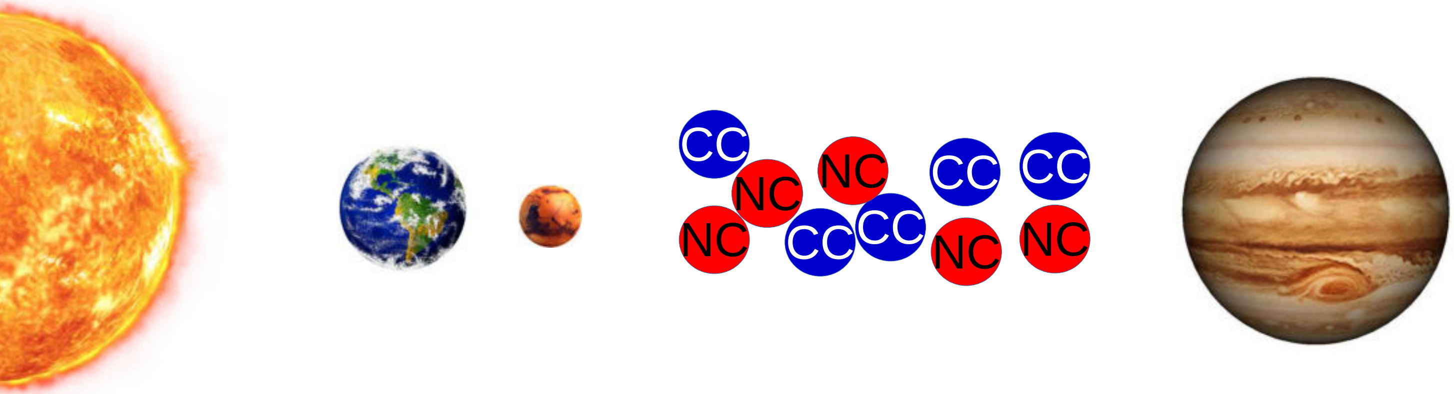


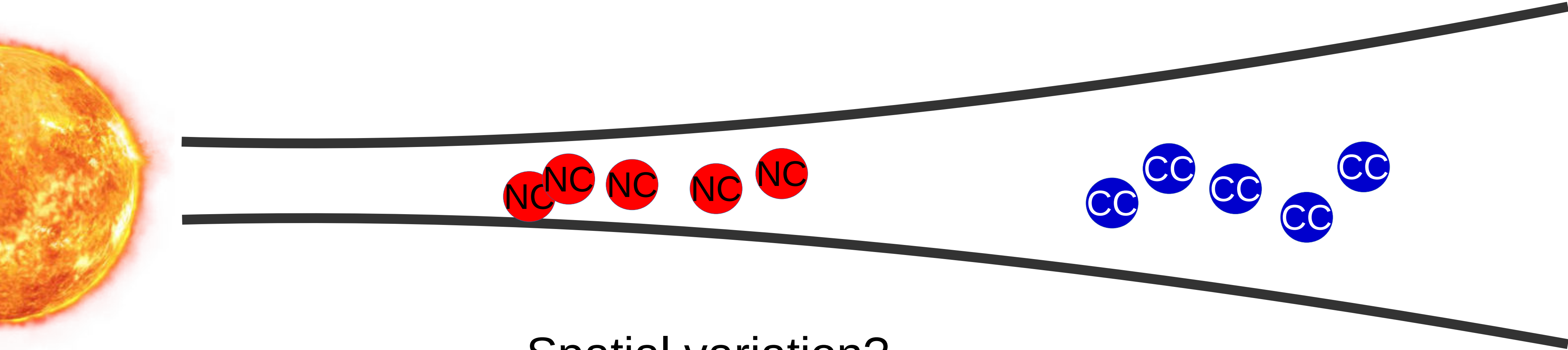
Temporal variation?



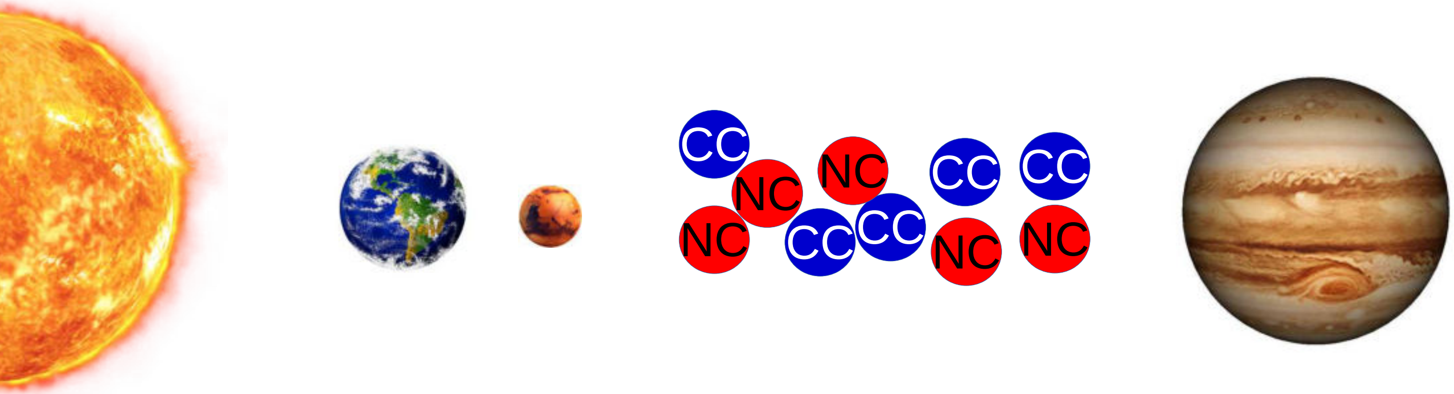


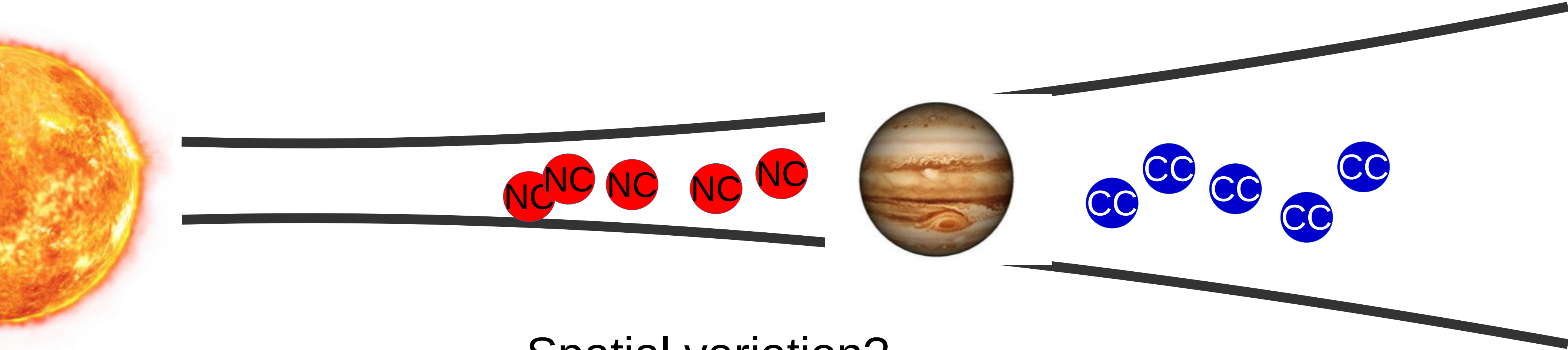
Temporal variation?



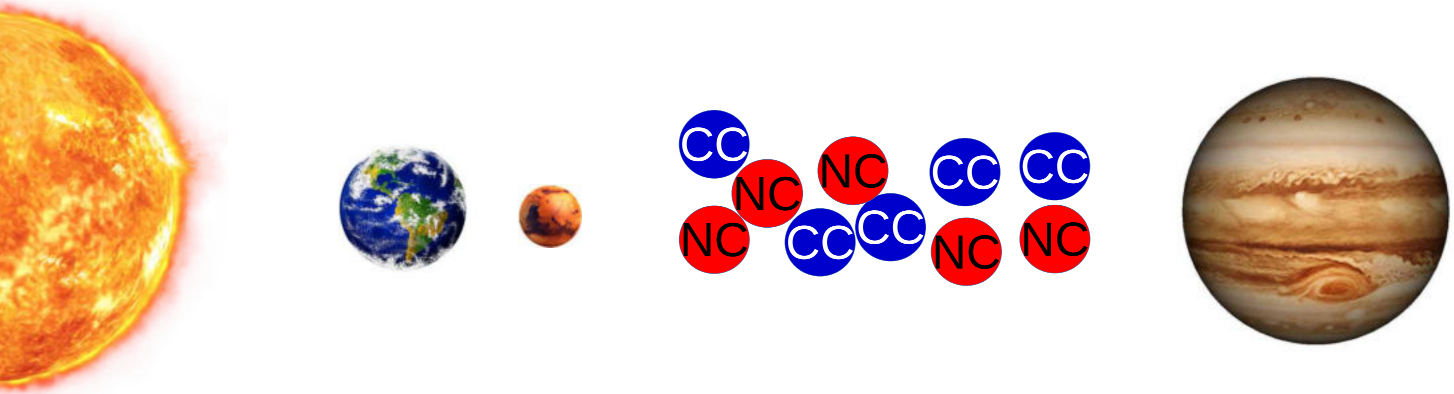


Spatial variation?



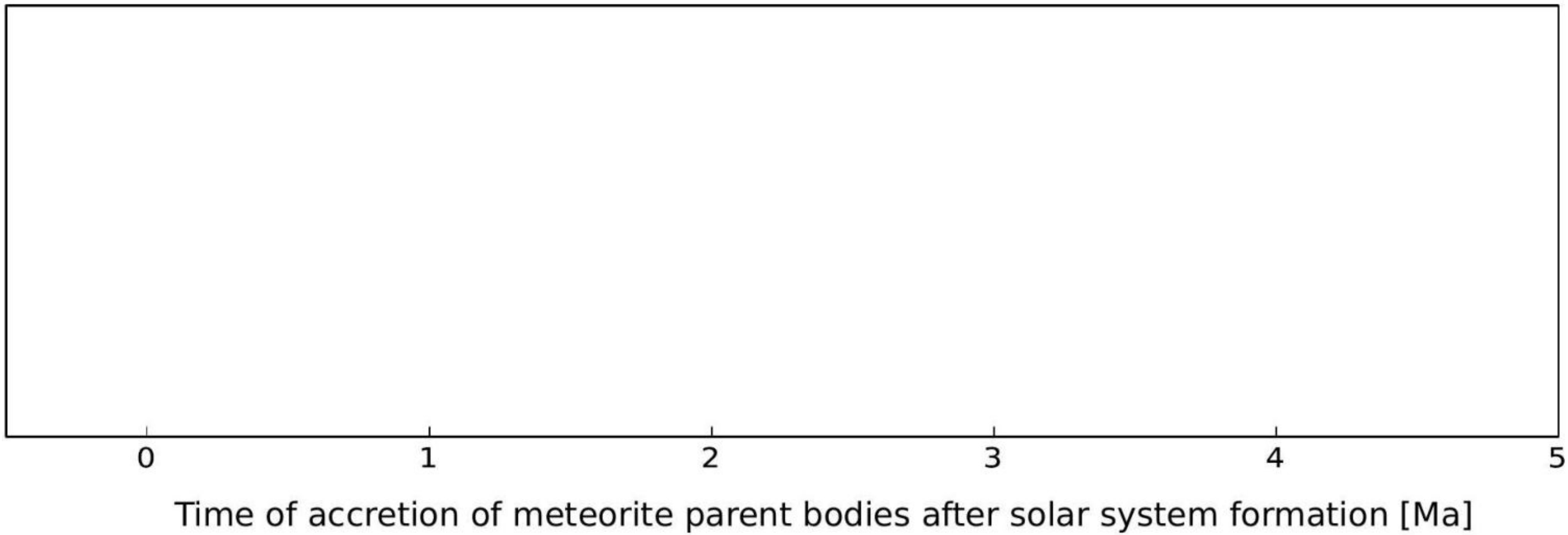


Spatial variation?

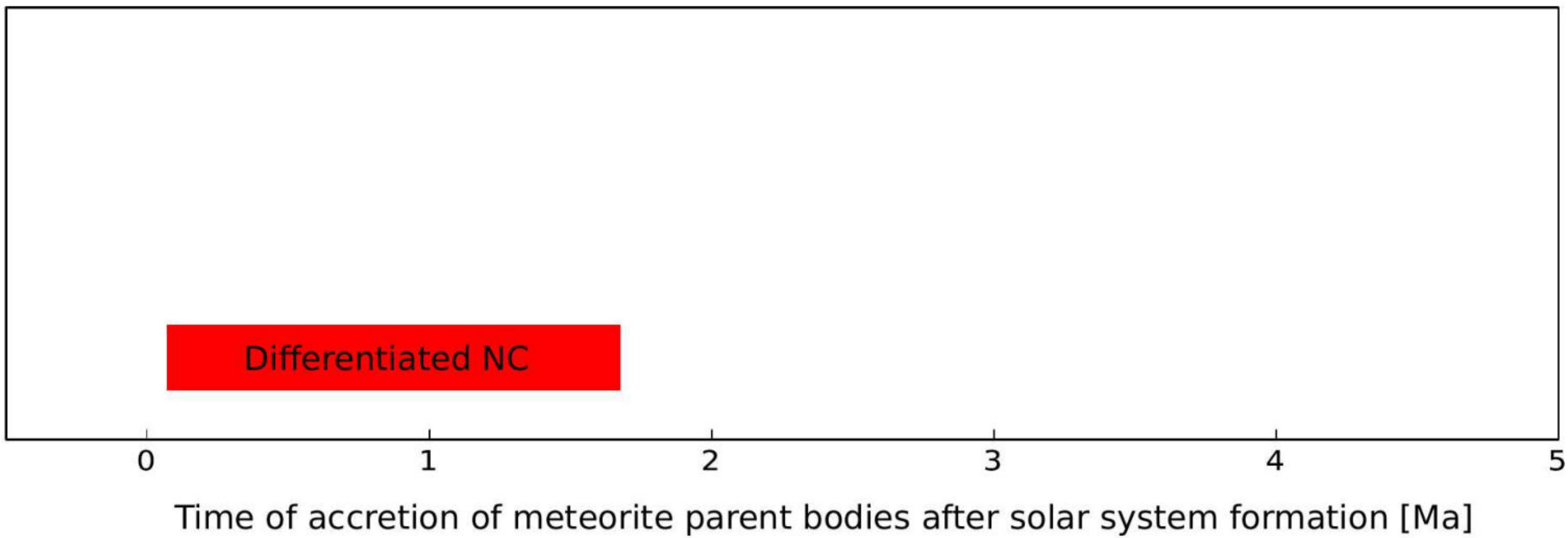


Kruijer, Burkhardt, Budde, Kleine (2017) PNAS

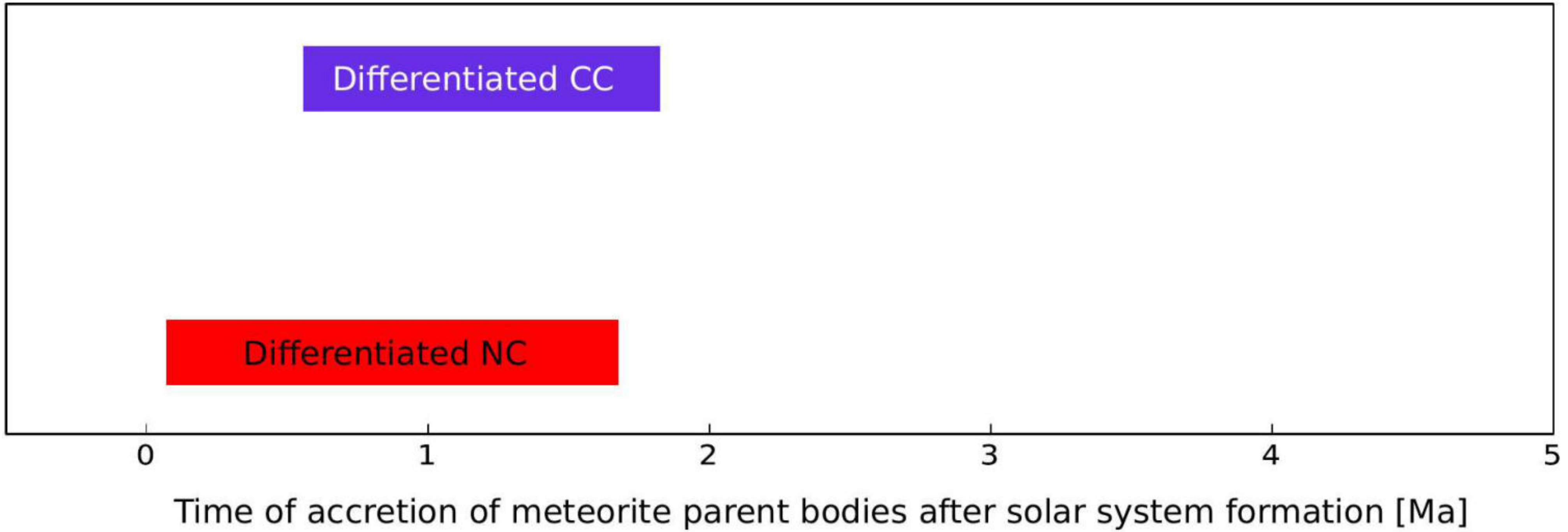
Approach: Combining age + anomaly information



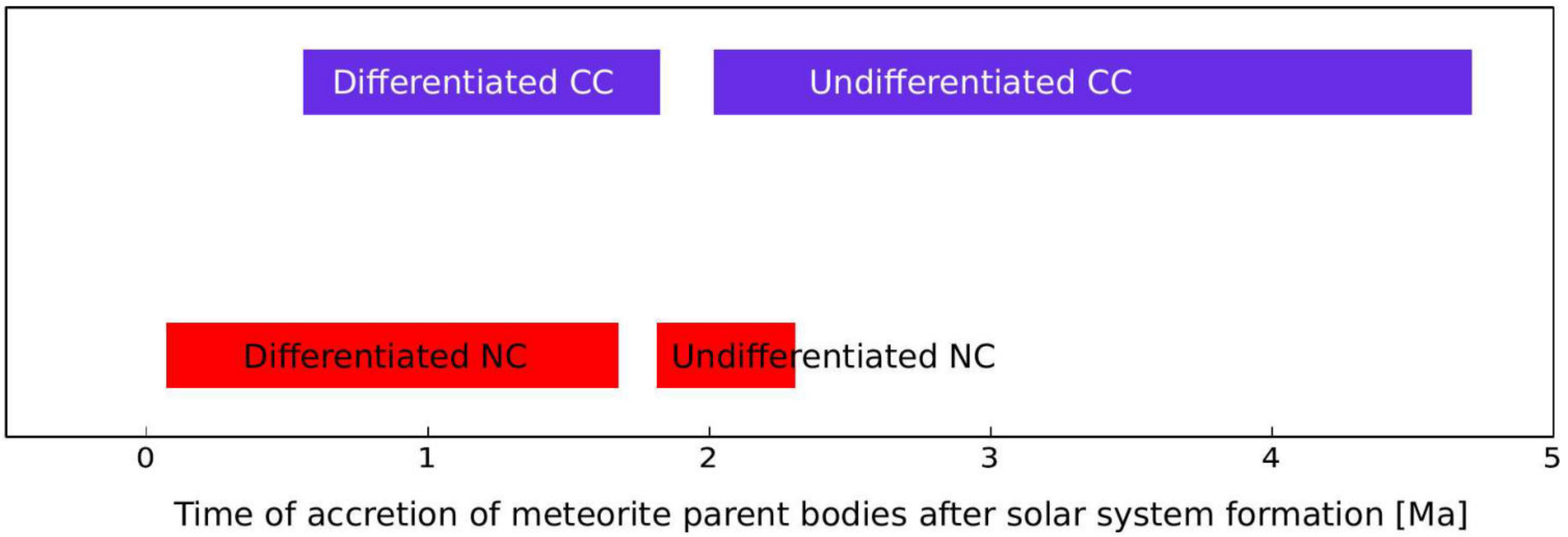
Combining age + anomaly information



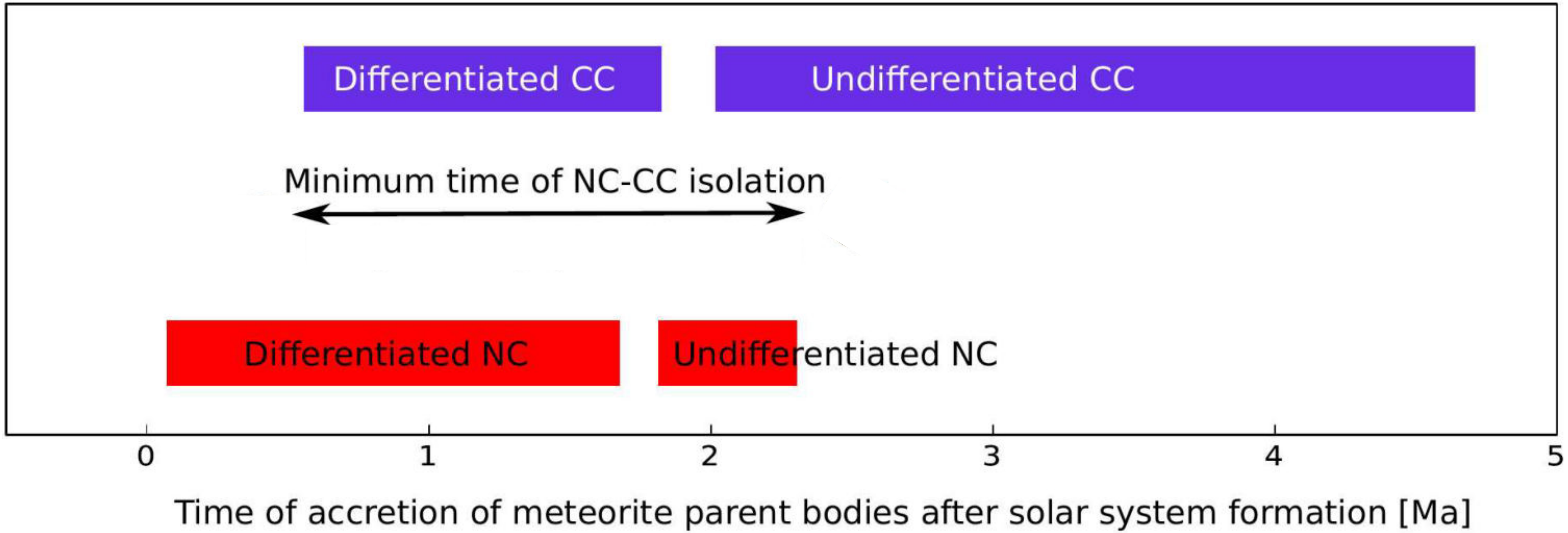
Combining age + anomaly information



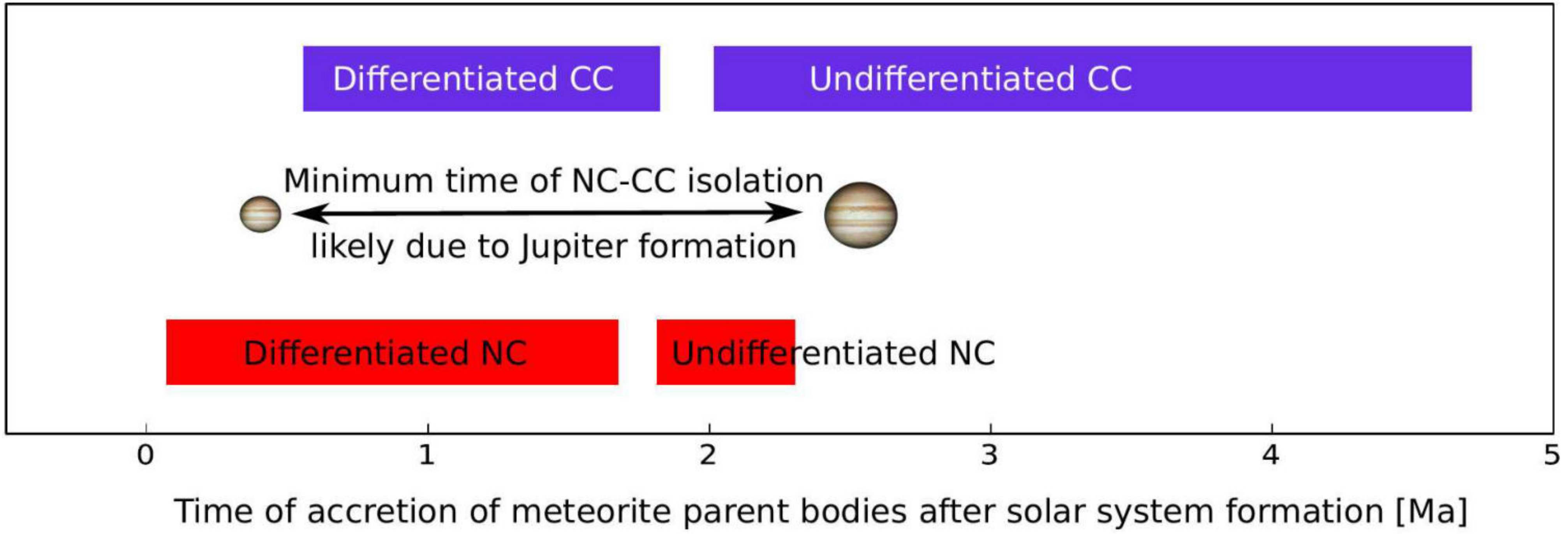
Combining age + anomaly information

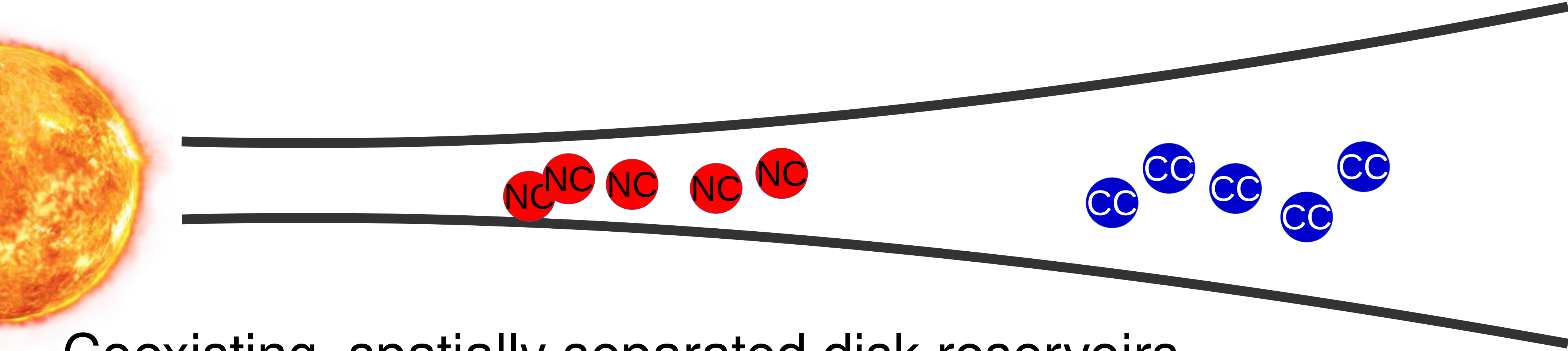


Combining age + anomaly information



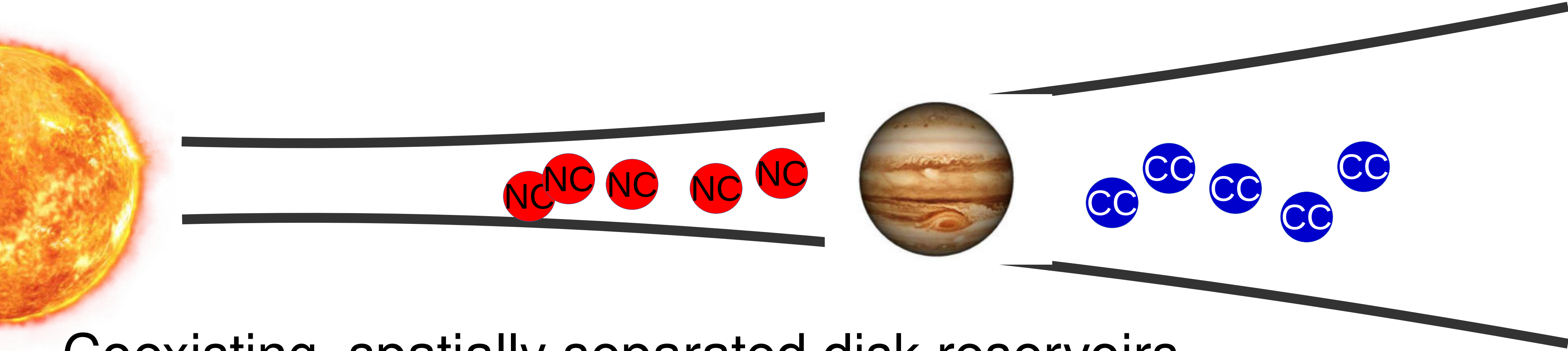
Combining age + anomaly information



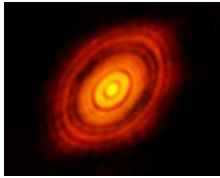


- Coexisting, spatially separated disk reservoirs

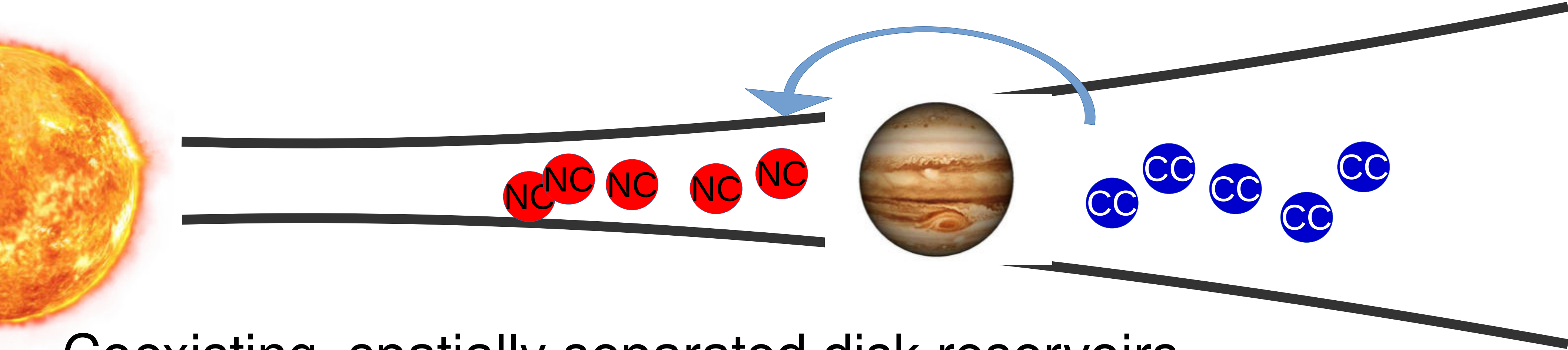
Kruijer, Burkhardt, Budde, Kleine 2017 PNAS



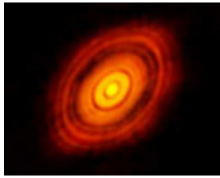
- Coexisting, spatially separated disk reservoirs
- Core of Jupiter (~$20M_E$) within 1 Ma
- Consistent with core accretion model and disk observations



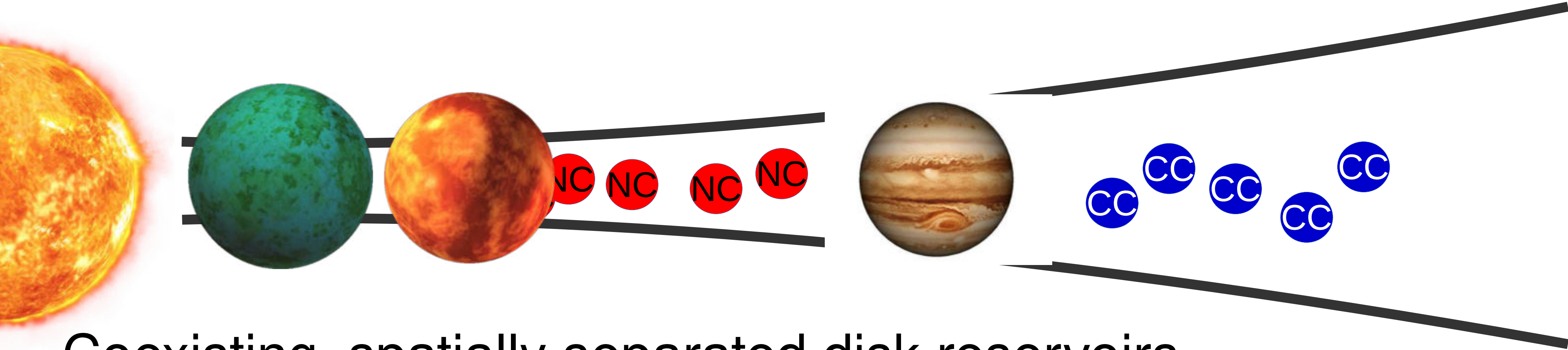
Kruijer, Burkhardt, Budde, Kleine 2017 PNAS



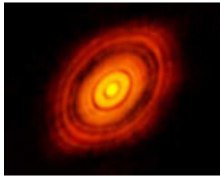
- Coexisting, spatially separated disk reservoirs
- Core of Jupiter (~20M_E) within 1 Ma
- Consistent with core accretion model and disk observations
- Naturally explains scattering of CC bodies into inner solar system



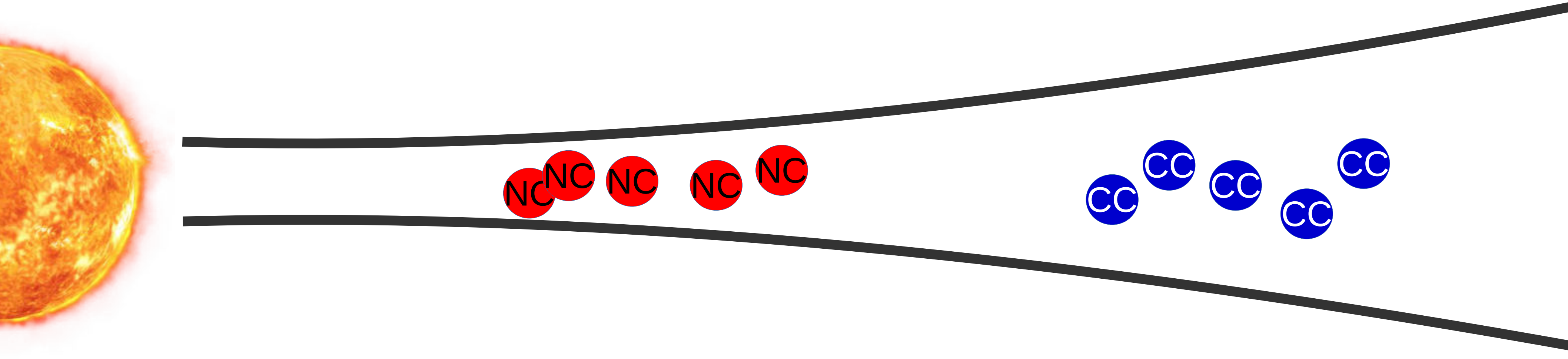
Kruijer, Burkhardt, Budde, Kleine 2017 PNAS



- Coexisting, spatially separated disk reservoirs
- Core of Jupiter (~$20M_E$) within 1 Ma
- Consistent with core accretion model and disk observations
- Naturally explains scattering of CC bodies into inner solar system
- Jupiter formation explains why solar system lacks super-Earth



Kruijer, Burkhardt, Budde, Kleine 2017 PNAS


NC
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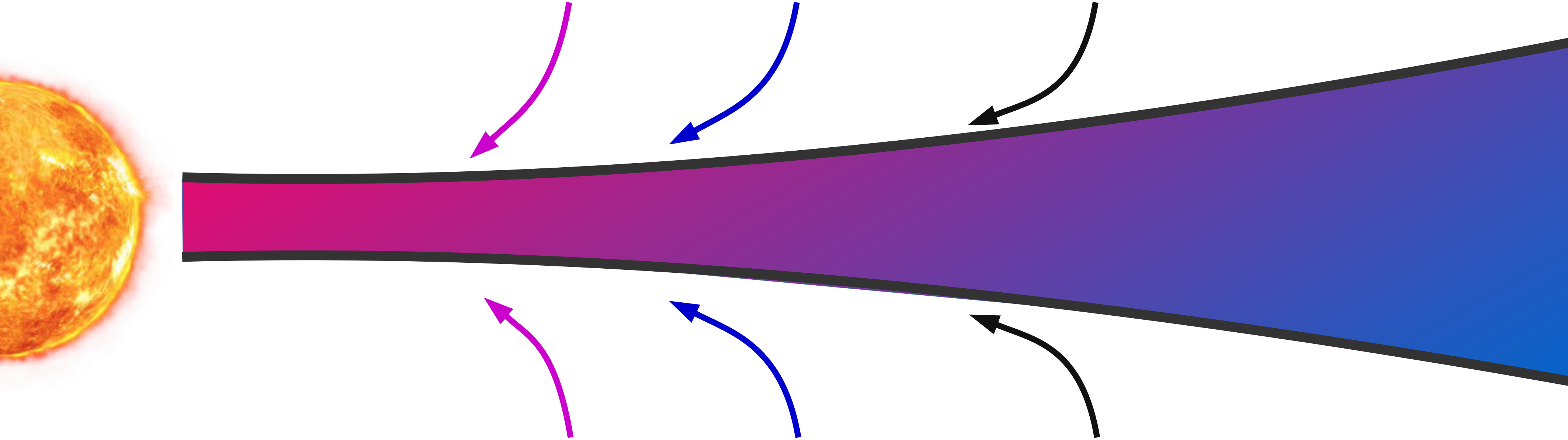
WHAT CONTROLS PLANETARY SCALE ANOMALIES?

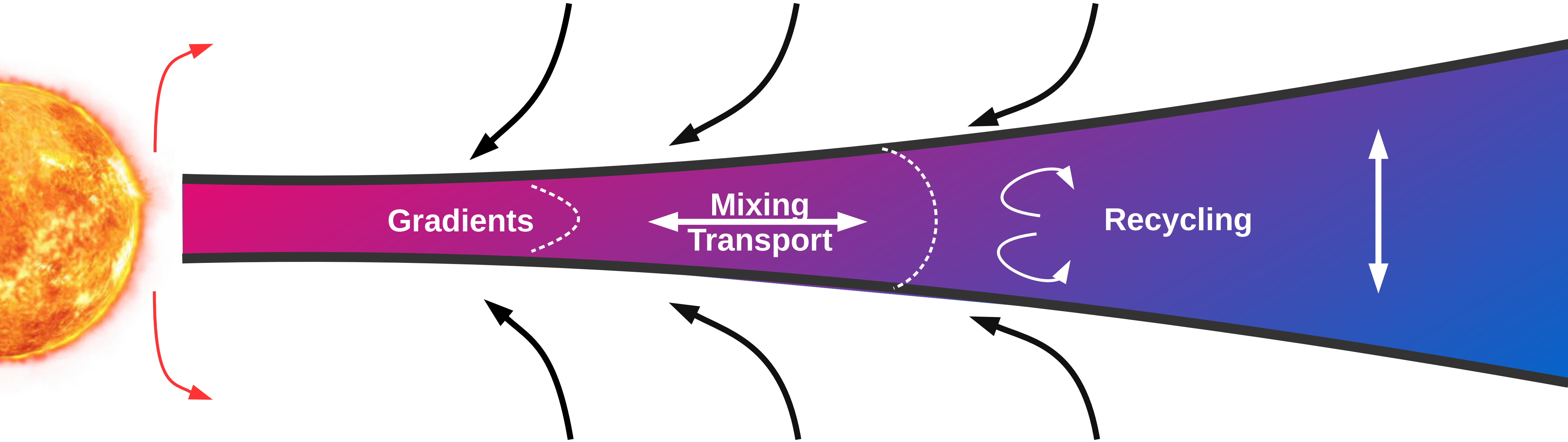
Burkhardt et al. (2019) GCA

Heterogeneous infall?

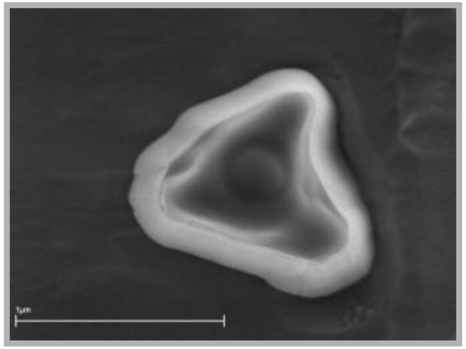


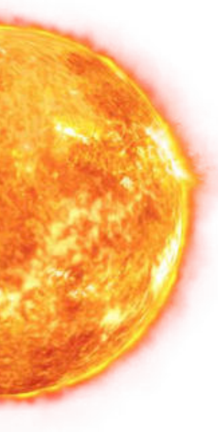
Burkhardt et al. (2019) GCA

Disk processing?



Burkhardt et al. (2019) GCA





Control by presolar grains or disk products?

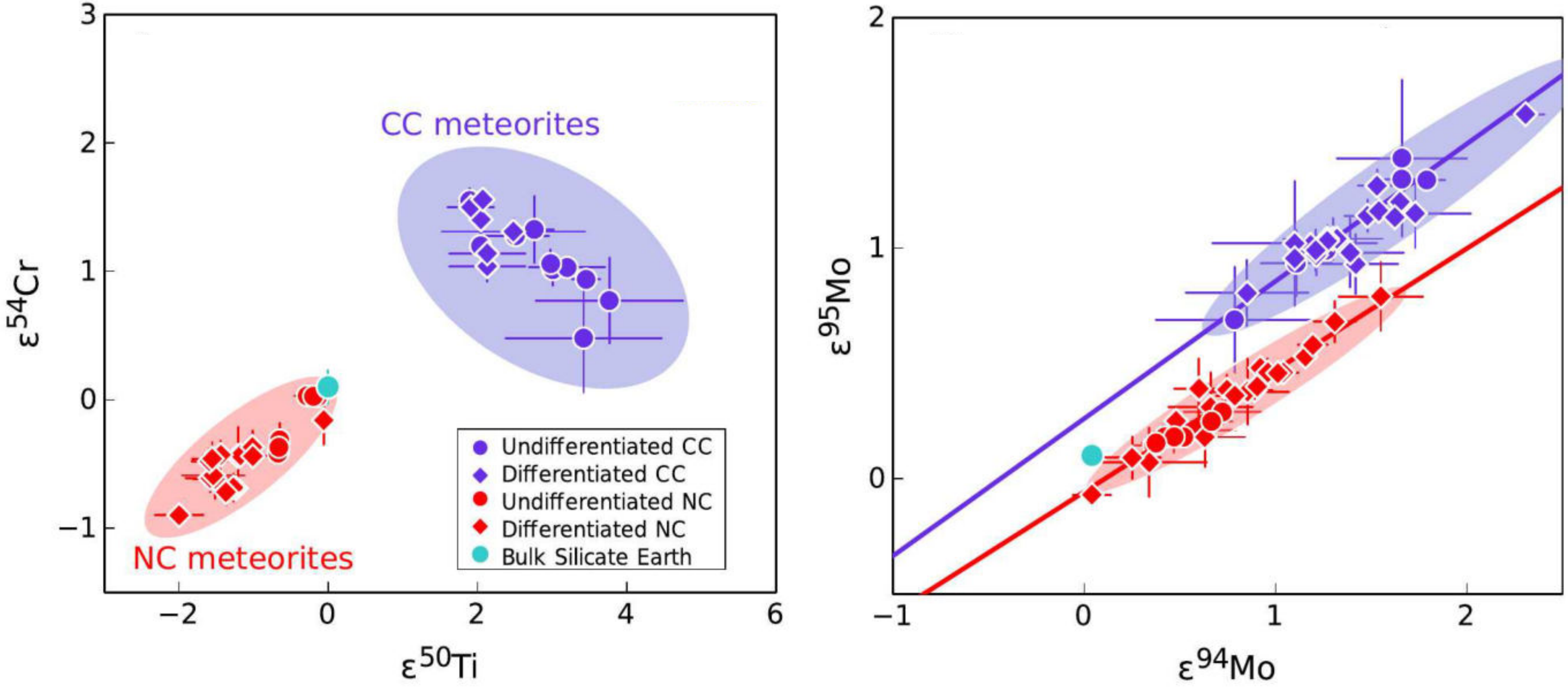
Burkhardt et al. (2019) GCA

Approach

Investigate multi-element anomaly relations between:

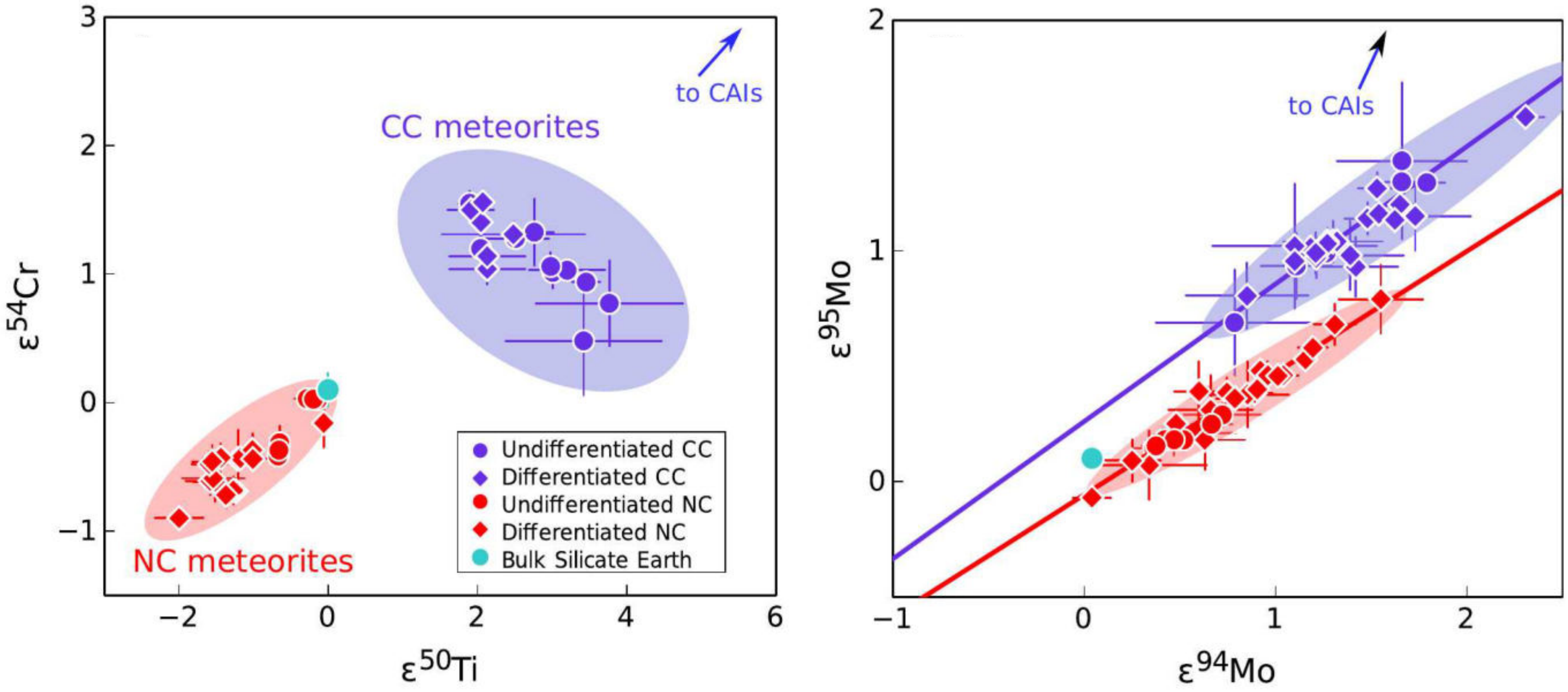
- Presolar grains
- CAIs
- Chondrules
- Matrix
- Bulk bodies

Burkhardt et al. (2019) GCA



Burkhardt 2021 Elements

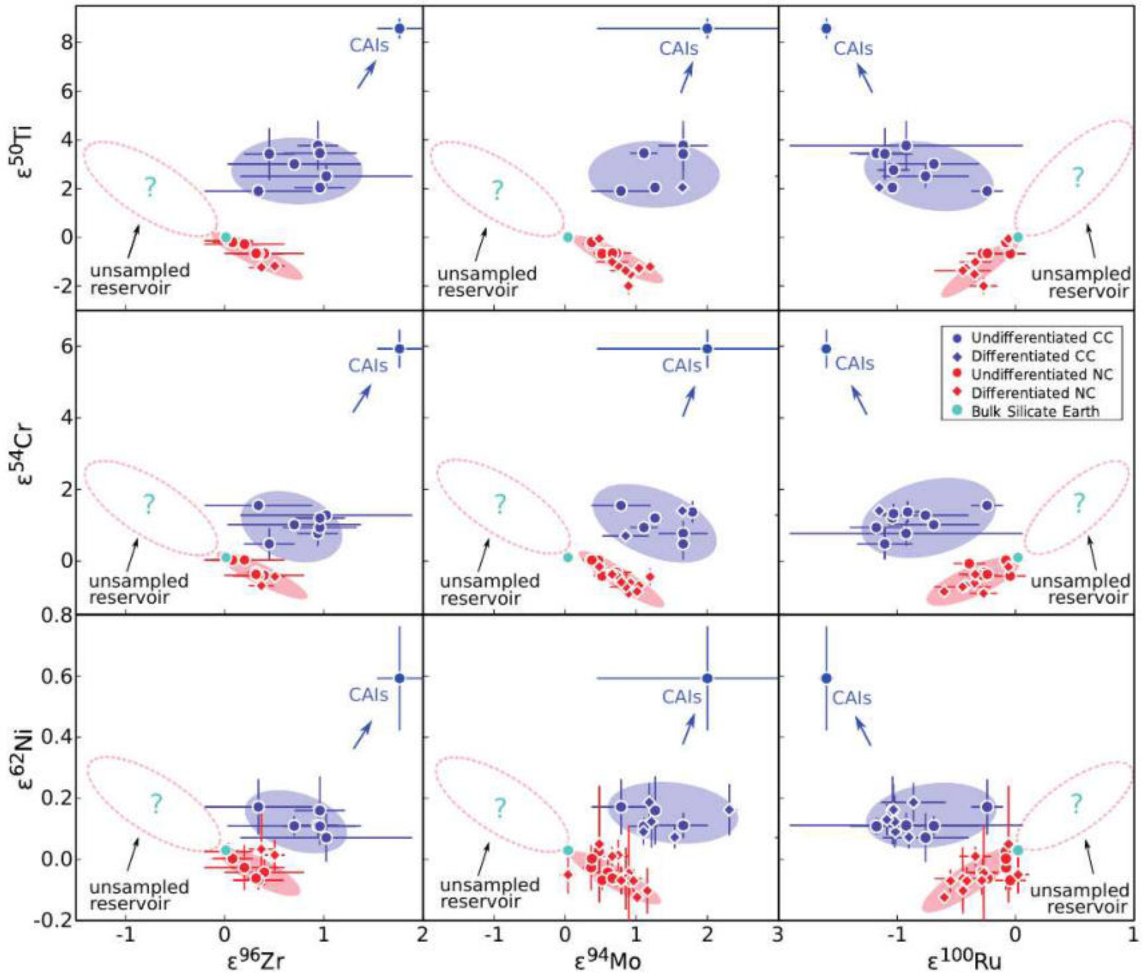
CC offset from NC towards CAI



Offset not limited to refractory elements!

Burkhardt 2021 Elements

CC offset from NC towards CAI

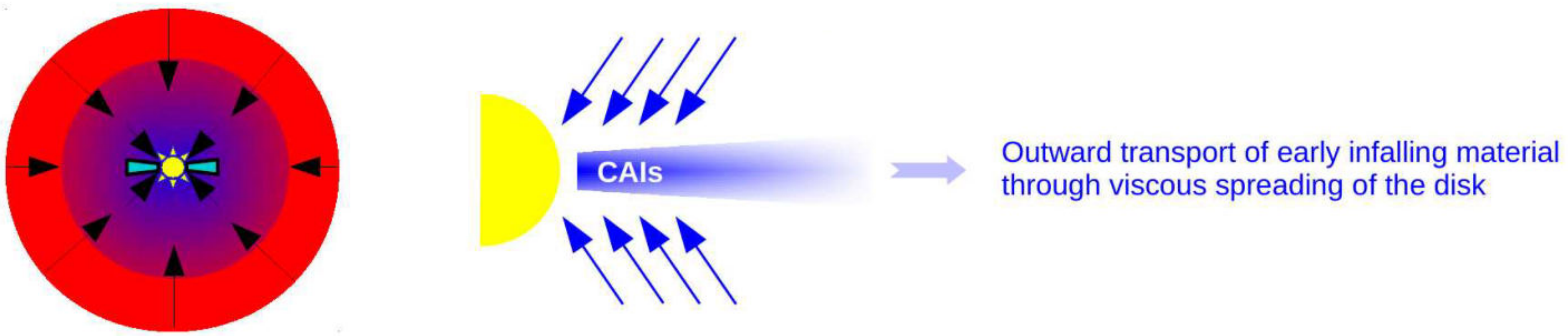


Burkhardt 2021 Elements

Variable mixing of disk materials!

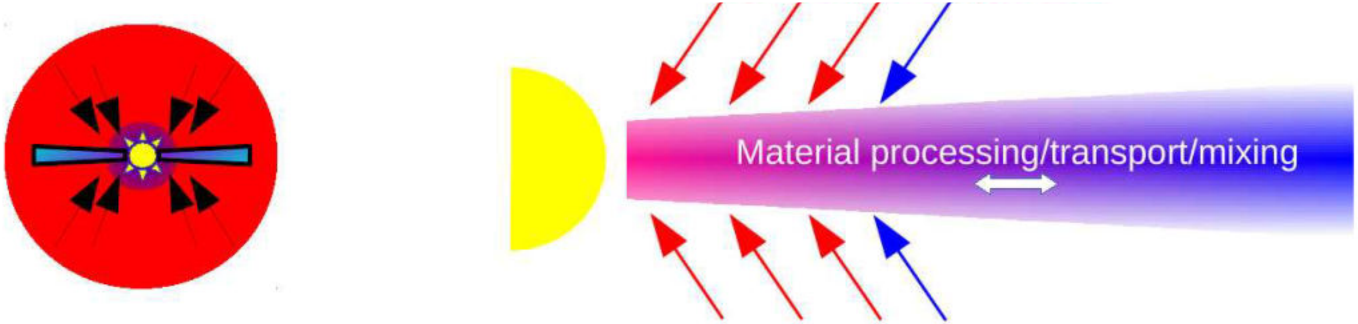
CC = NC + inclusion-like chondritic (IC) reservoir

Model for the formation of the solar system



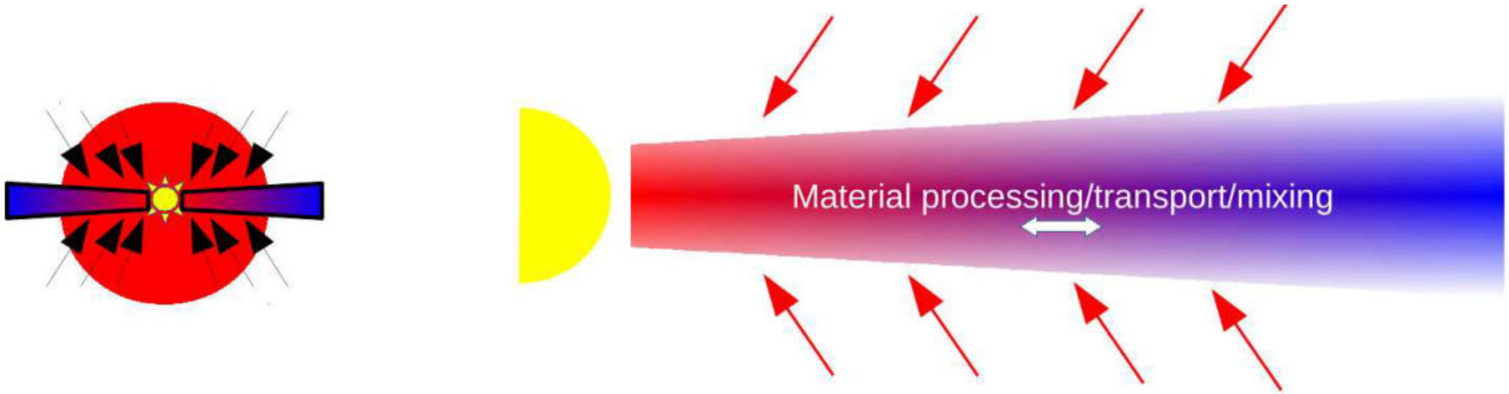
Burkhardt et al. (2019) GCA

Model for the formation of the solar system



Burkhardt et al. (2019) GCA

Model for the formation of the solar system

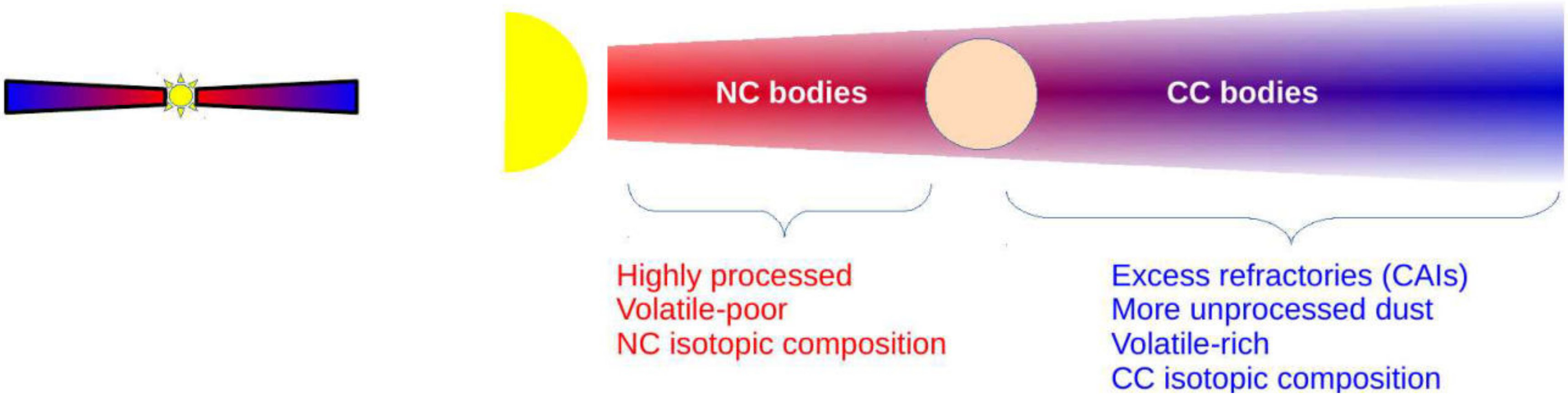


Burkhardt et al. (2019) GCA

Model for the formation of the solar system

Burkhardt et al. (2019) GCA

Model for the formation of the solar system



Burkhardt et al. (2019) GCA

Model for the formation of the solar system

Isotopic variability set very early!

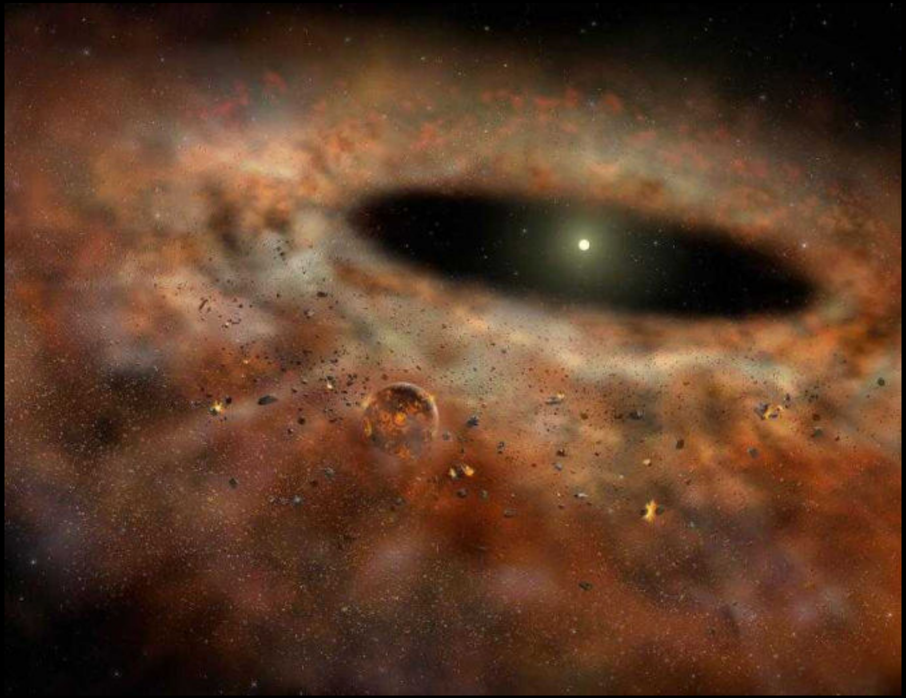
→ Reinforces usability of anomalies for tracing genetics

Burkhardt et al. (2019) GCA

How did the terrestrial planets form?

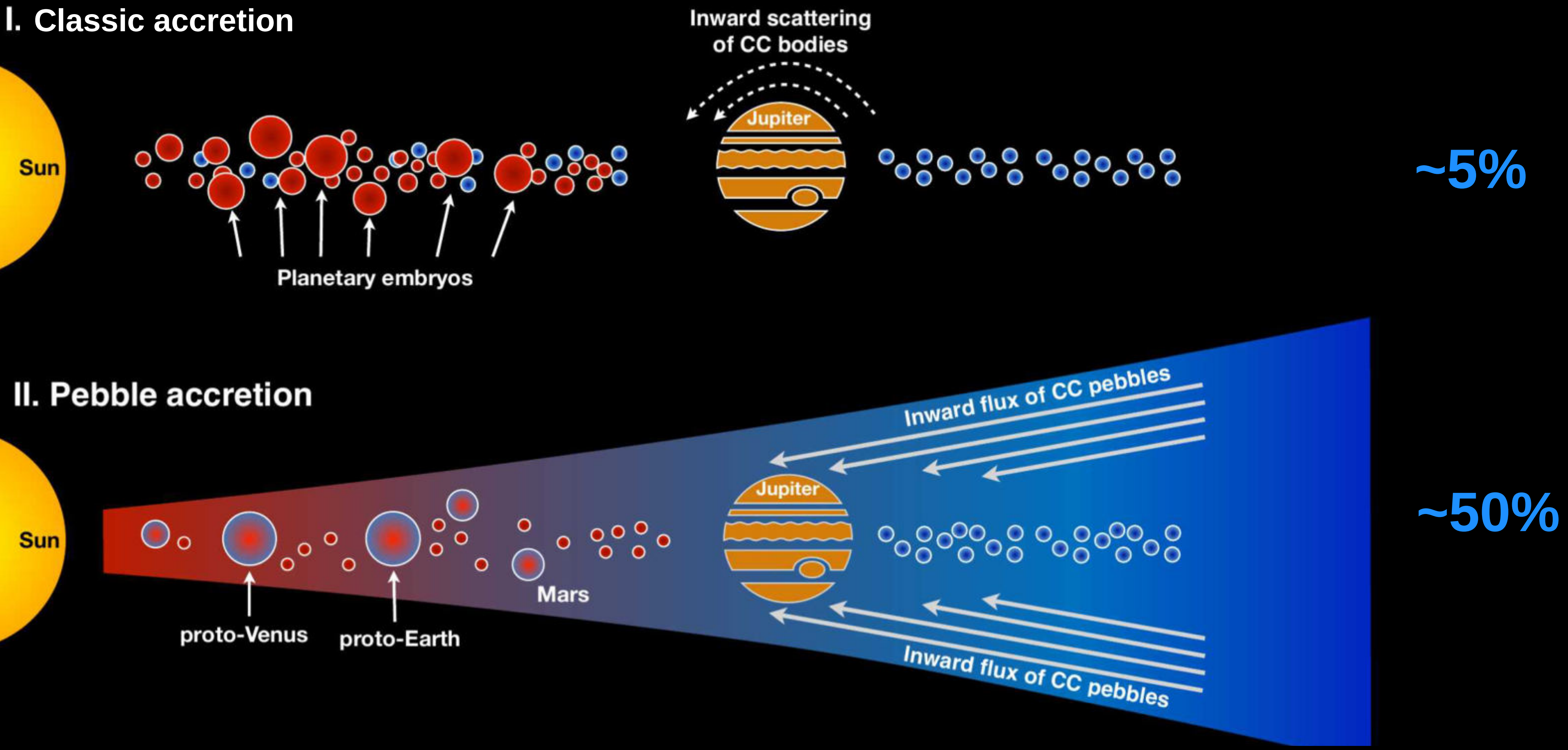
Oligarchic growth in 10s to 100s Ma

Limited outer solar system input

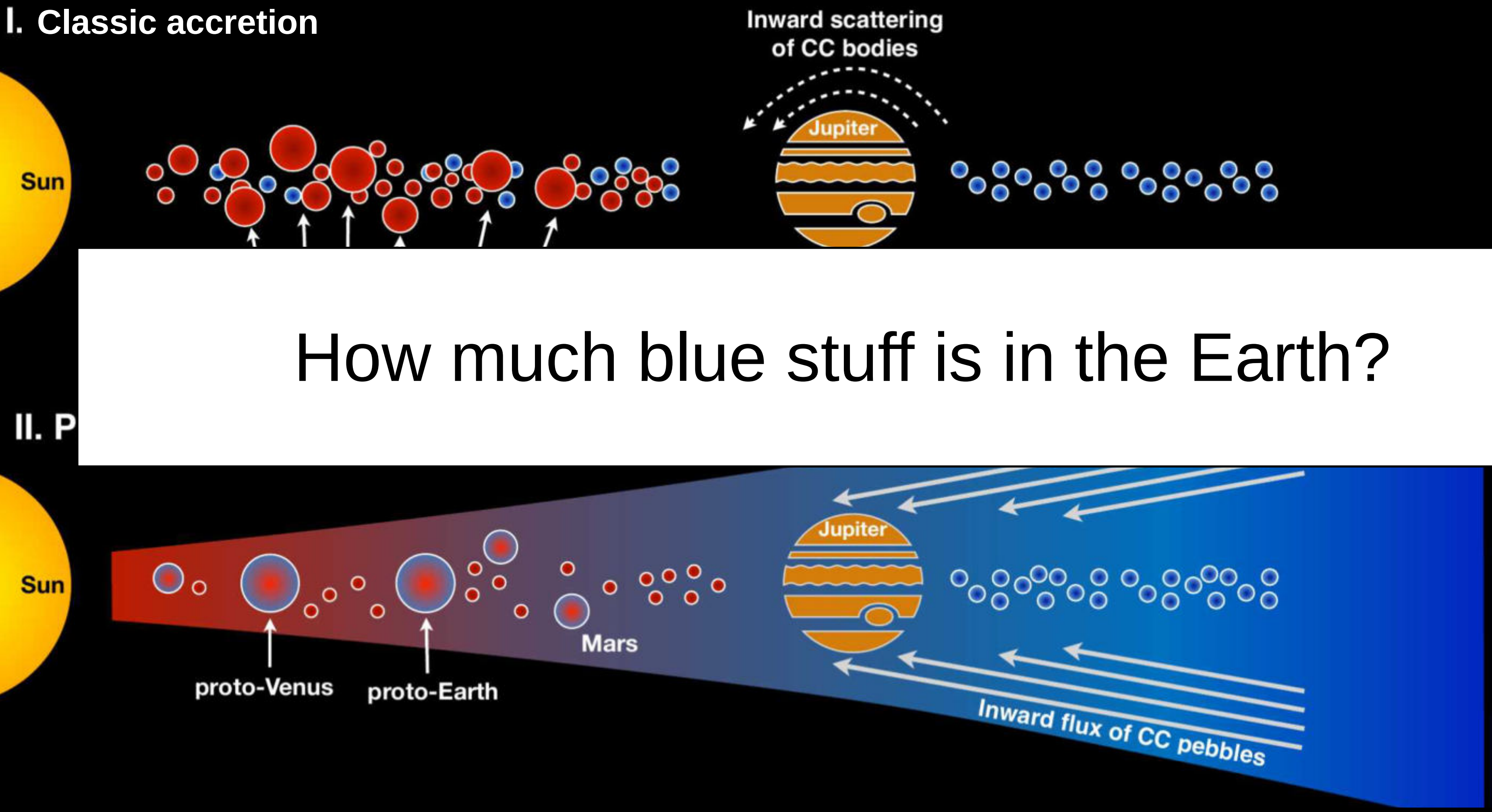


Pebble accretion in < 5 Ma

Significant outer solar system input



Burkhardt et al. 2021 Sci. Adv.



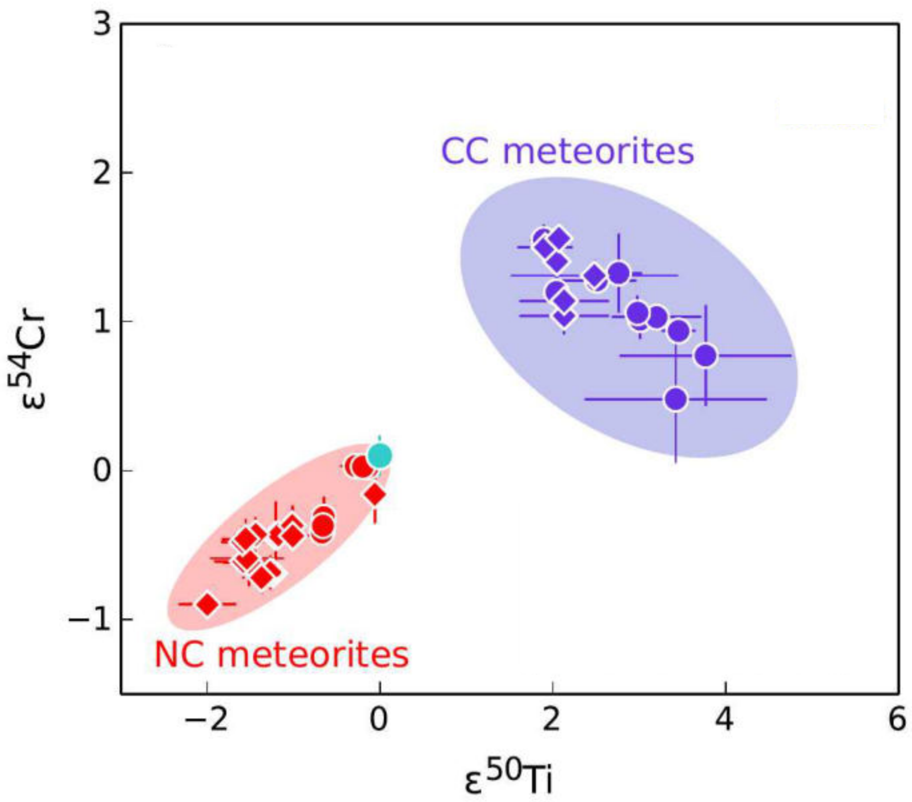
~5%

How much blue stuff is in the Earth?

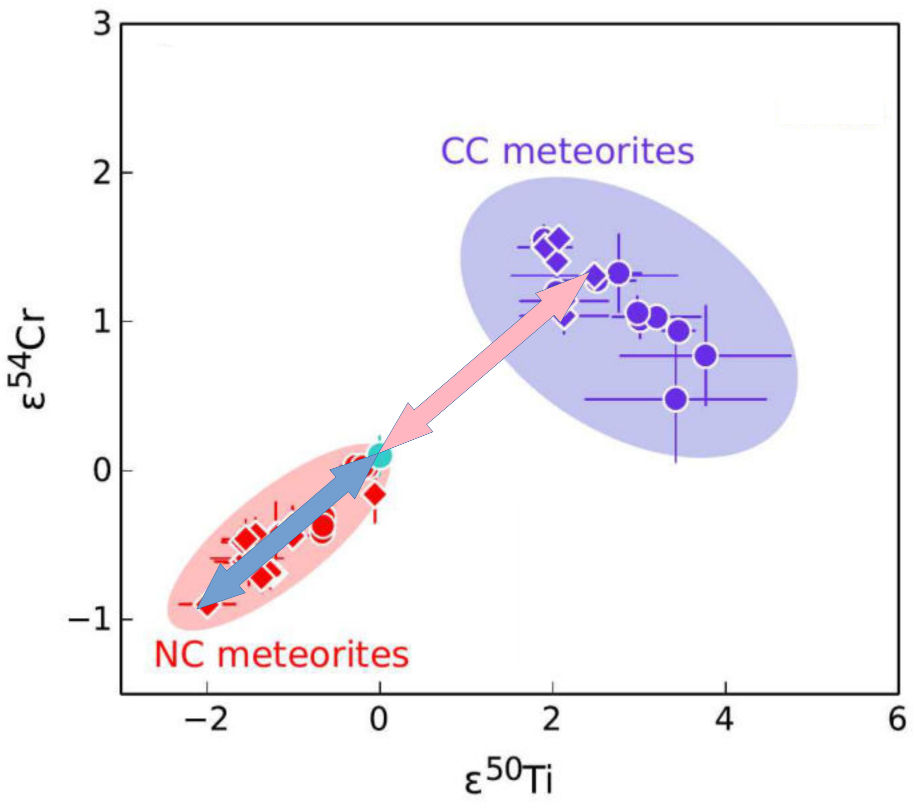
~50%

Burkhardt et al. 2021 Sci. Adv.

CC amount in Earth, Mars



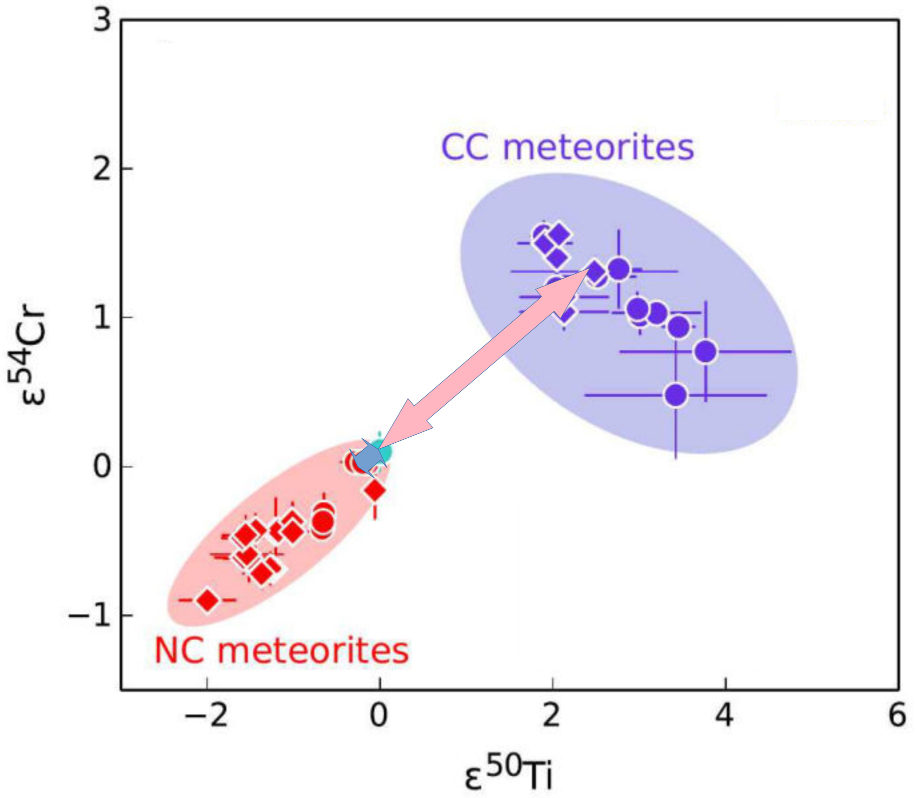
CC amount in Earth, Mars



~40% CC

Warren 2011 EPSL, Schiller et al. 2018, Nature, 2020 Sci Adv.

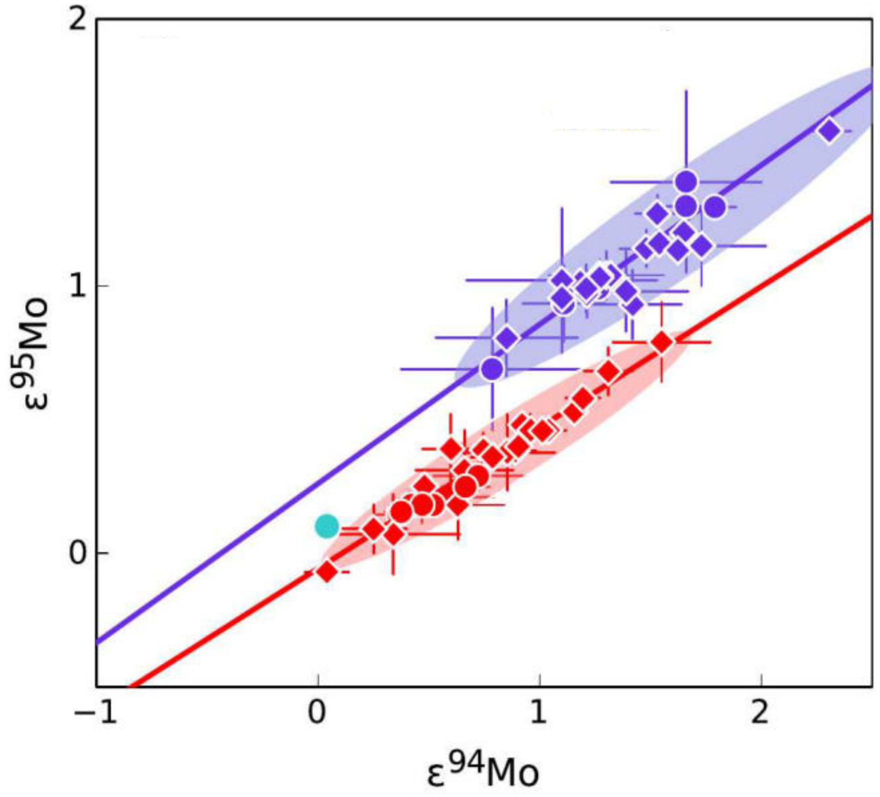
CC amount in Earth, Mars



<5% CC

Dauphas 2017 Nature

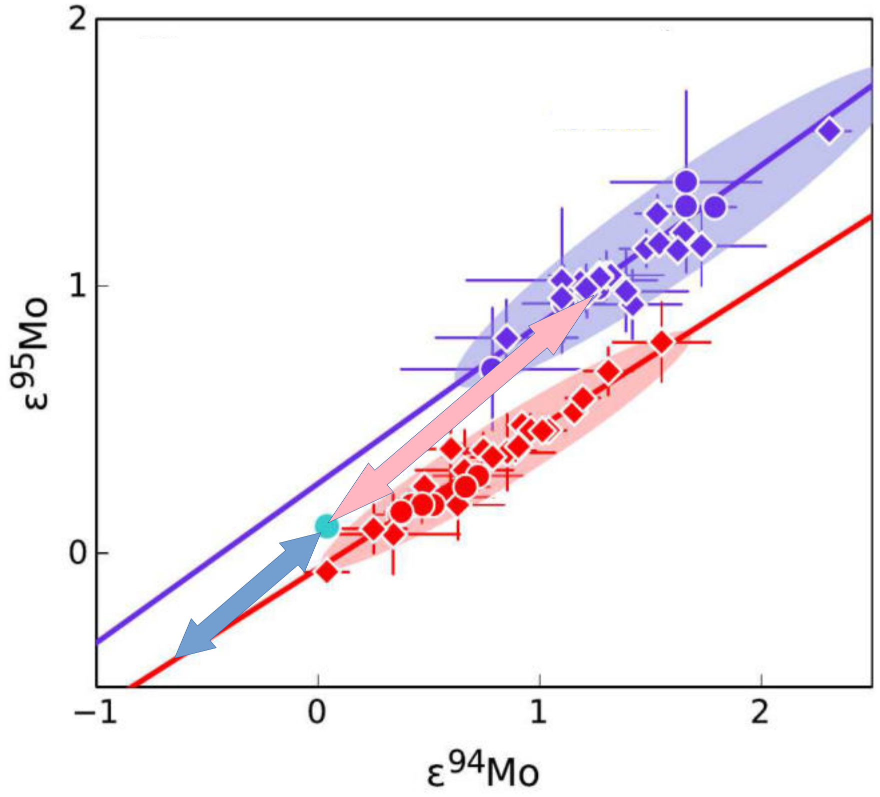
CC amount in Earth, Mars



Earth contains material unsampled by meteorites!

Burkhardt et al. 2011 EPSL; Budde, Burkhardt et al. 2019 Nat. Astro

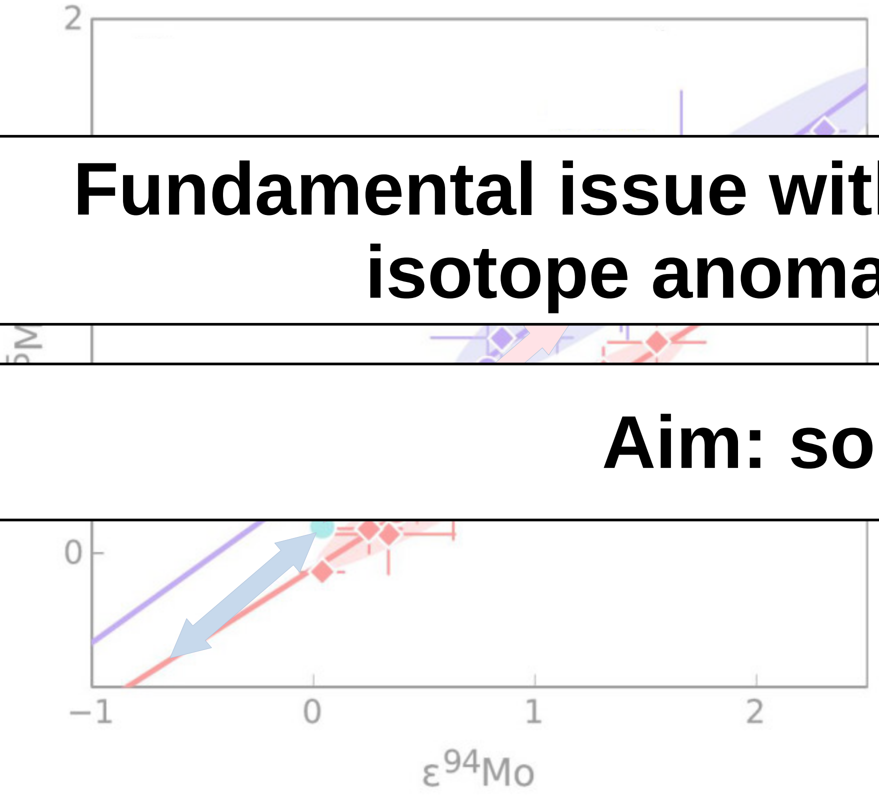
CC amount in Earth, Mars



Earth contains material unsampled by meteorites!

Burkhardt et al. 2011 EPSL; Budde, Burkhardt et al. 2019 Nat. Astro

CC amount in Earth, Mars



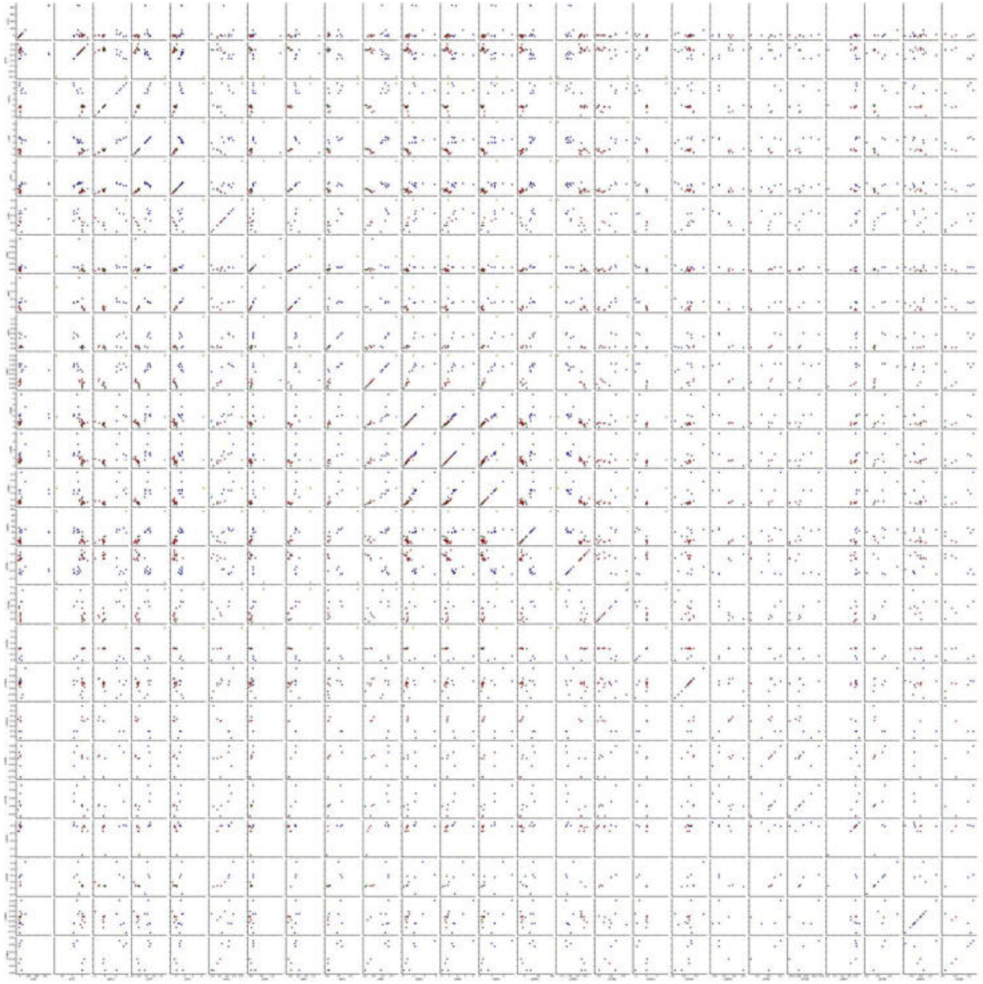
Fundamental issue with use of nucleosynthetic isotope anomalies / meteorites

Aim: sort this out

Burkhardt et al. 2011 EPSL; Budde, Burkhardt et al. 2019 Nat. Astro

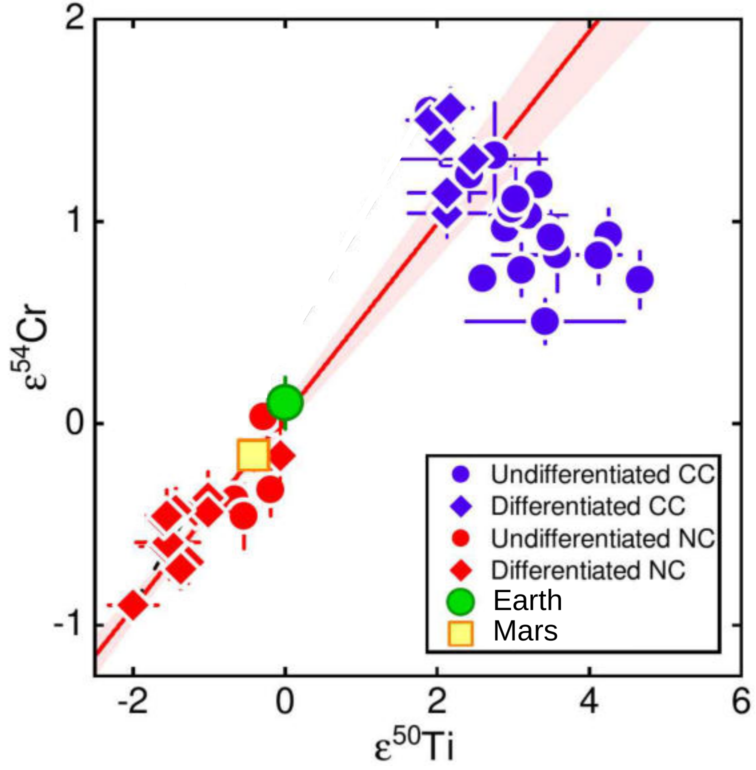
Approach

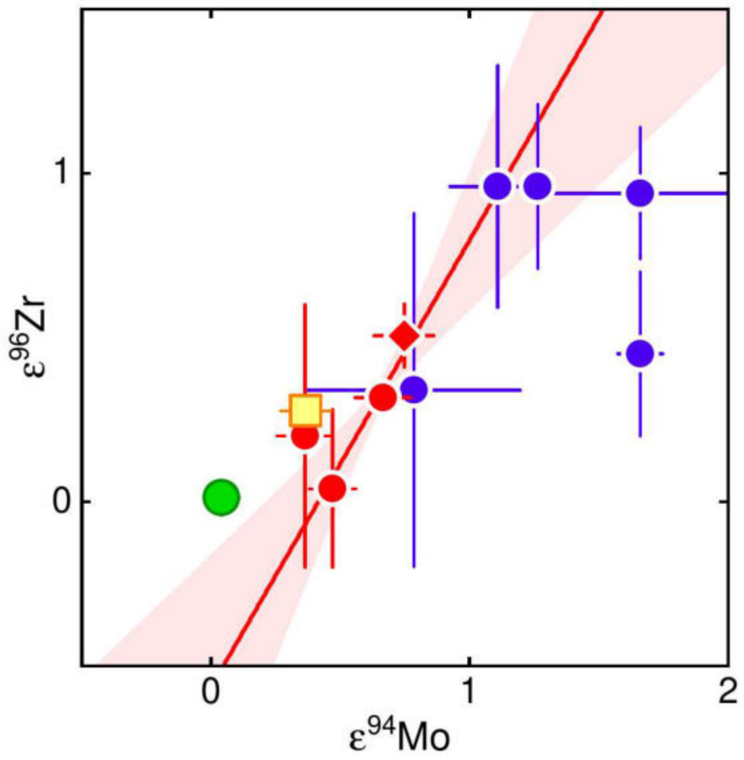
- Look at *all* anomalies in multi-elemental space
- Constrain composition and origin of unsampled component
- New data for Mars



Burkhardt et al. 2021 Sci. Adv.

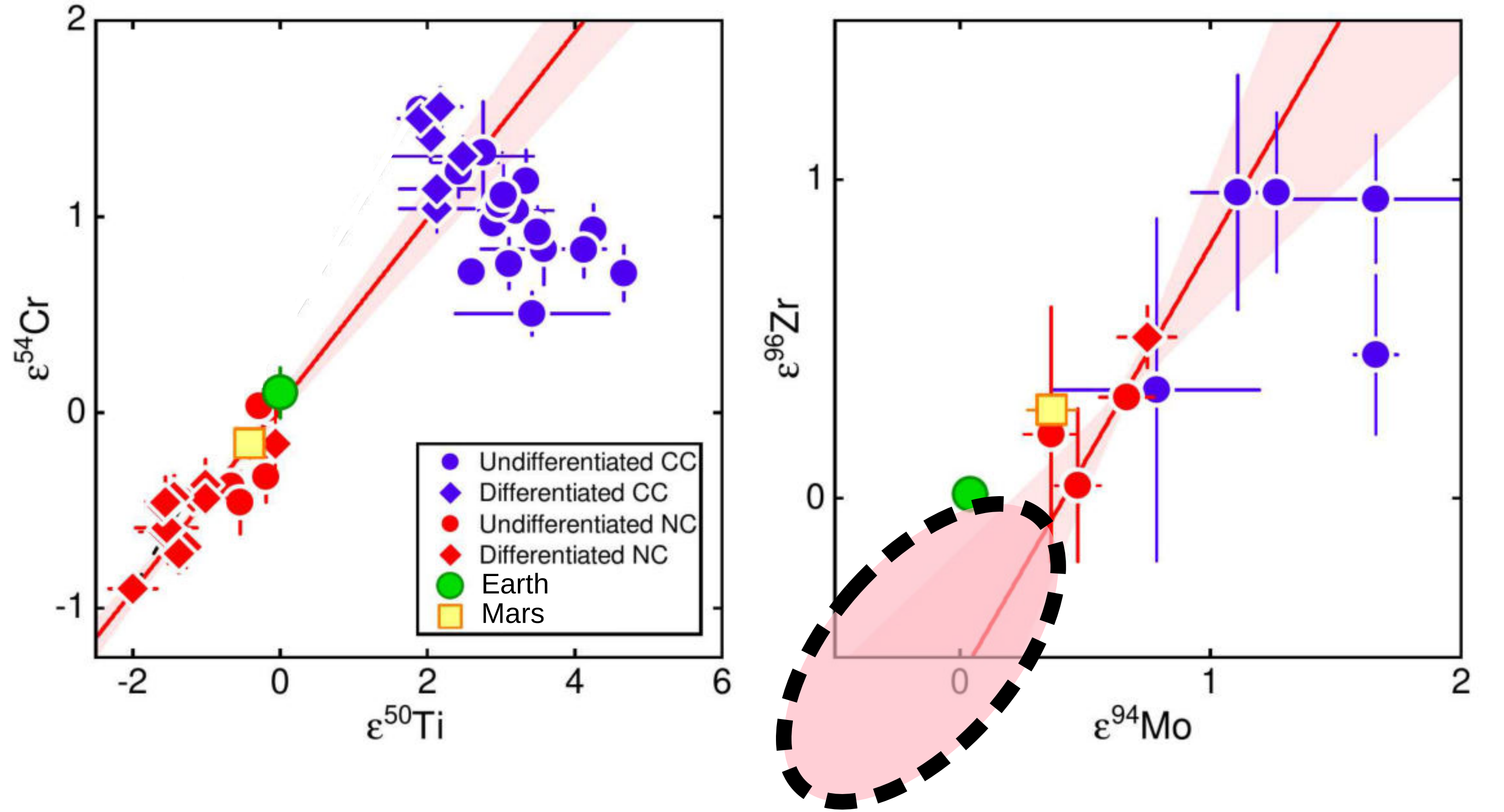
Results





Burkhardt et al. 2021 Sci. Adv.

Results



Burkhardt et al. 2021 Sci. Adv.

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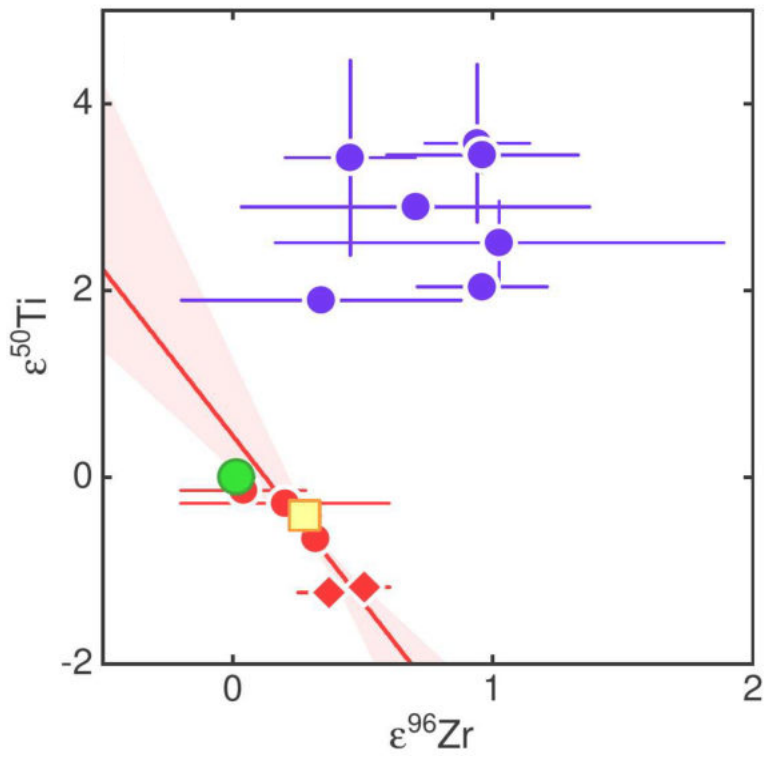
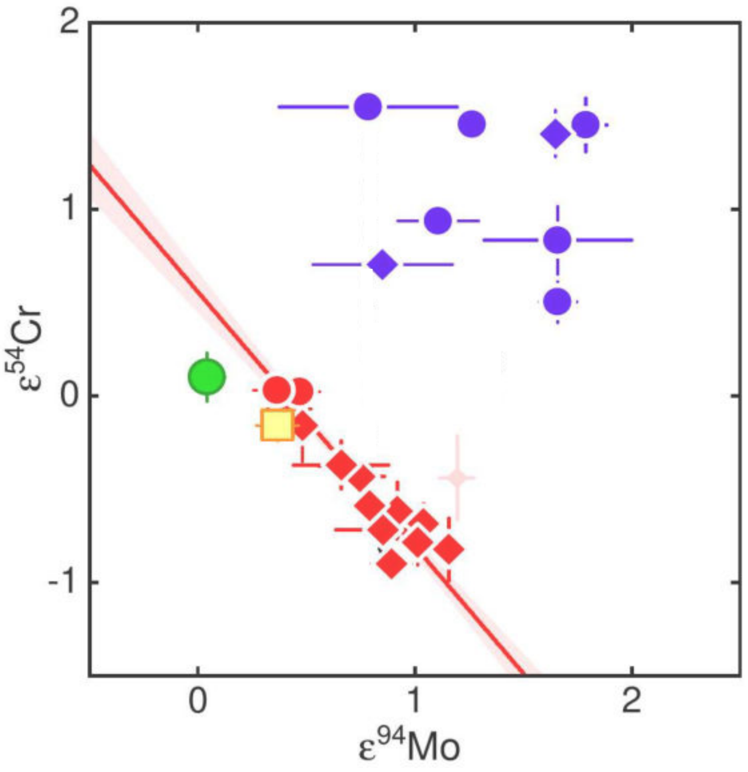
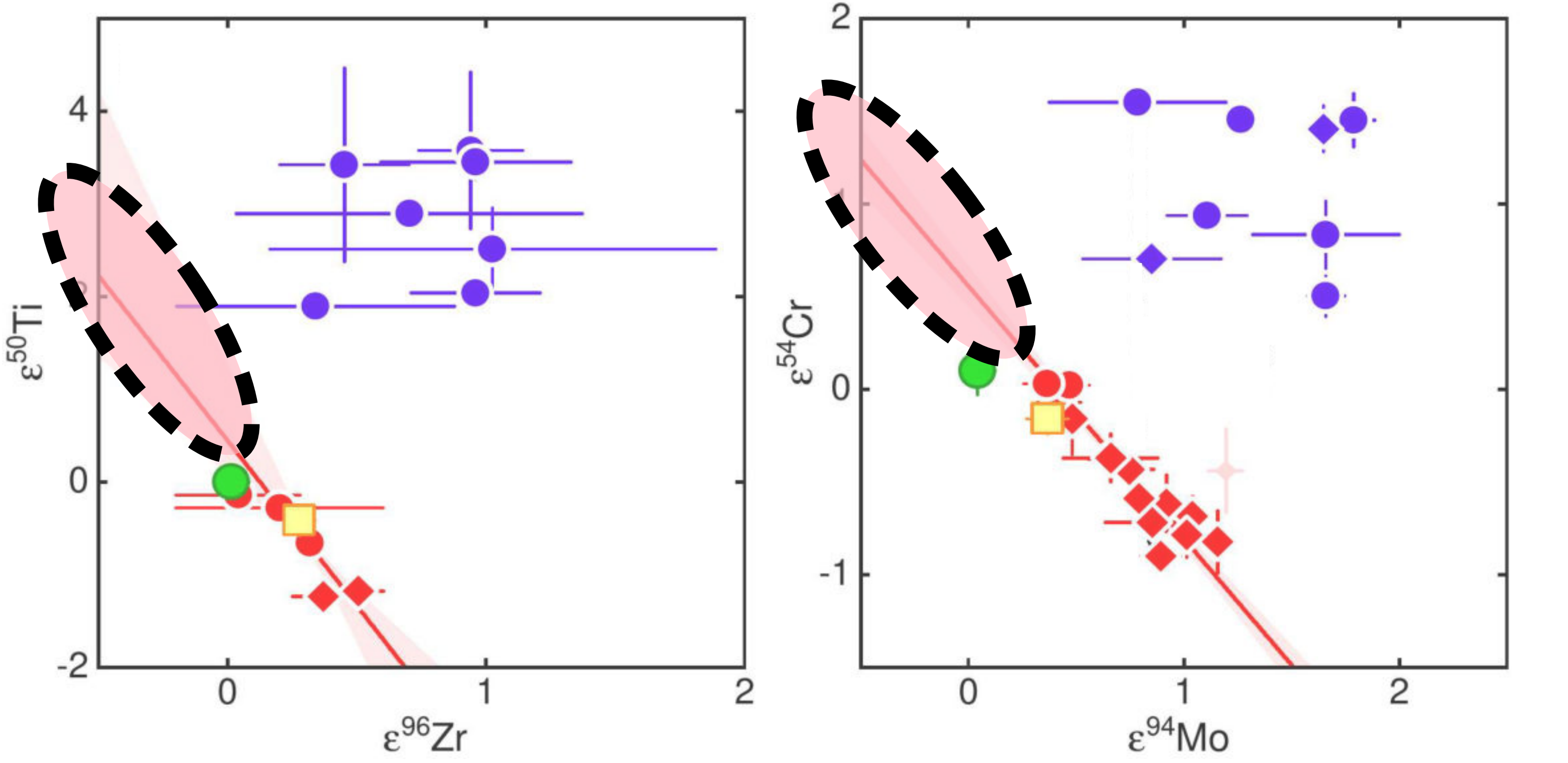




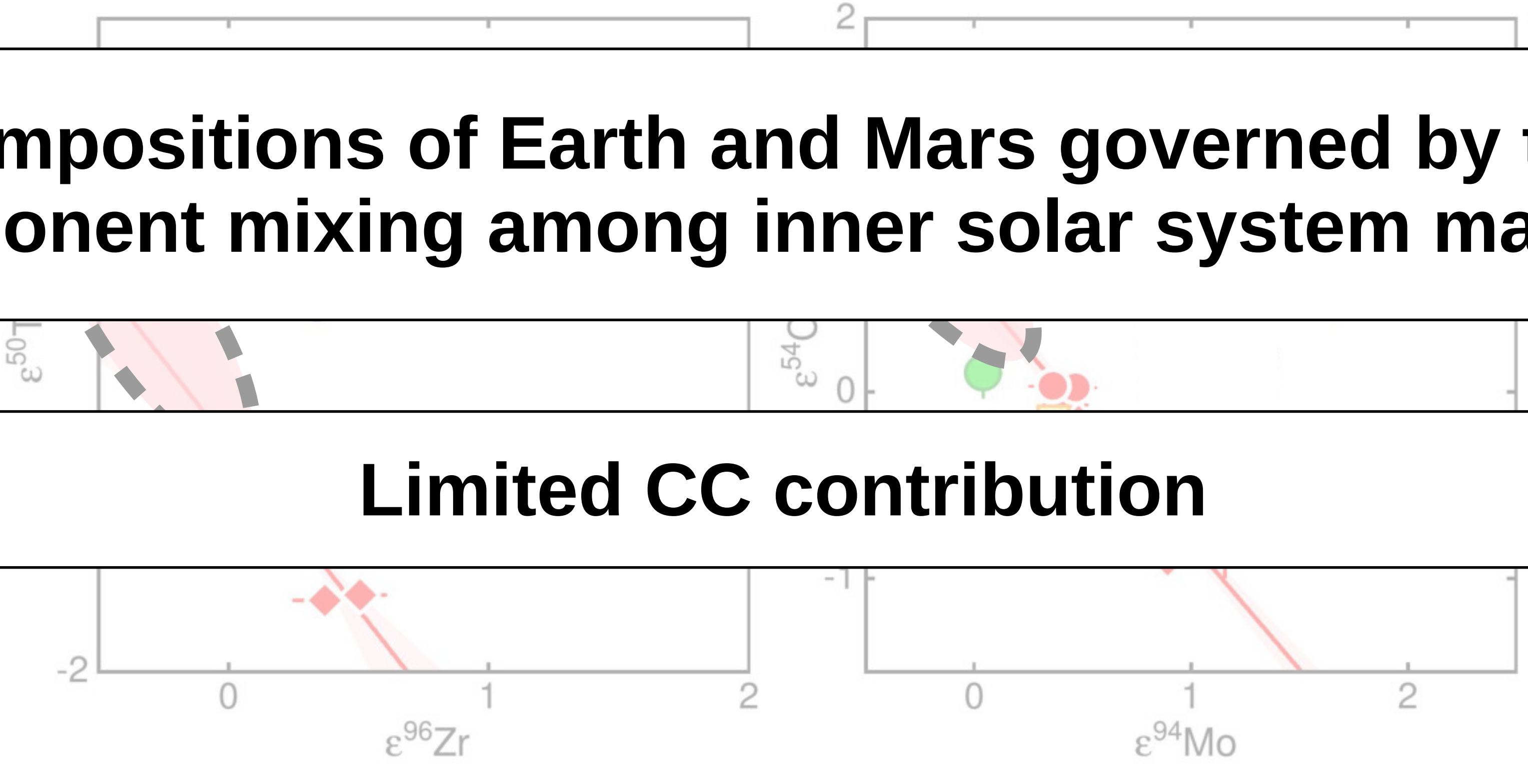
Burkhardt et al. Sci. Adv.

Results



Burkhardt et al. Sci. Adv.

Results



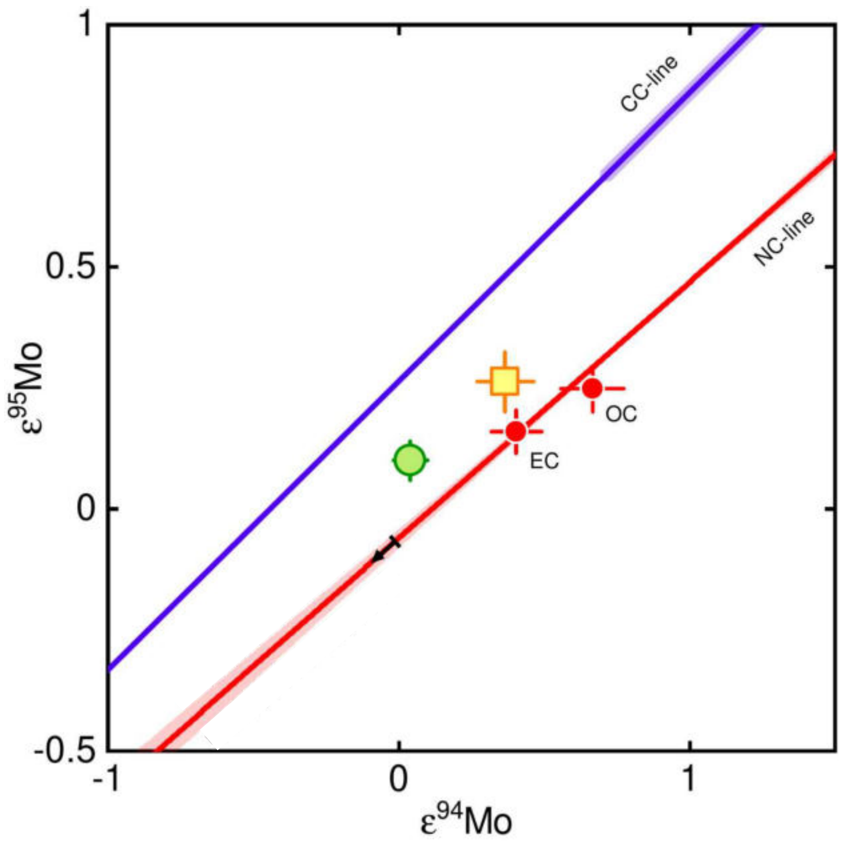
Compositions of Earth and Mars governed by two-component mixing among inner solar system materials

Limited CC contribution

Burkhardt et al. Sci. Adv.

Results

Earth & Mars must contain some CC material



Burkhardt et al. Sci. Adv.

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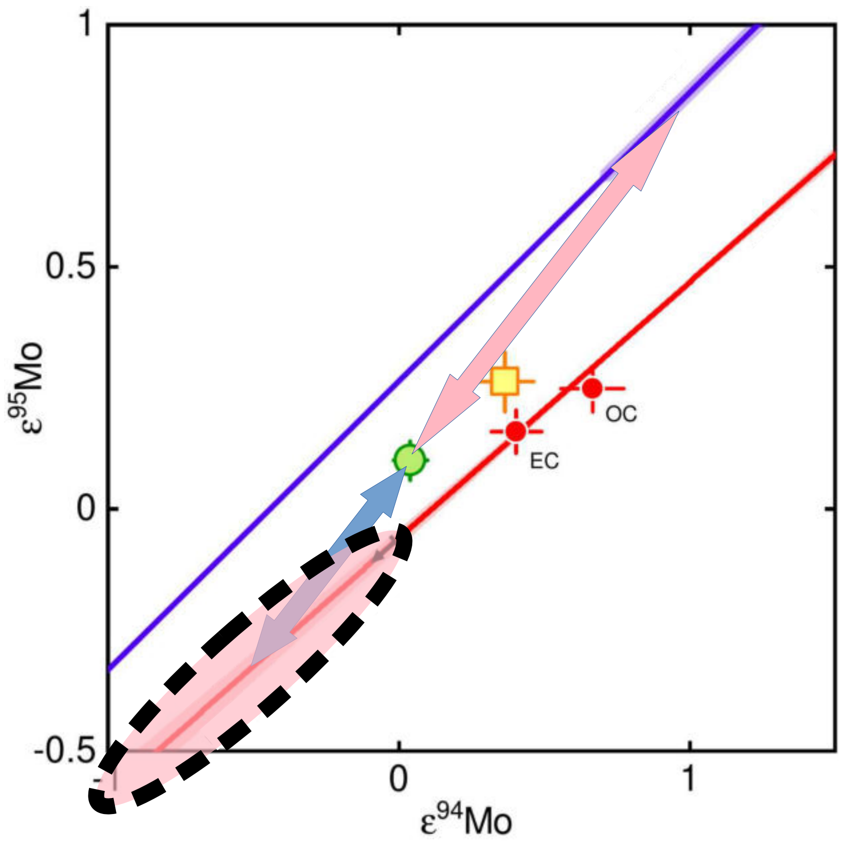
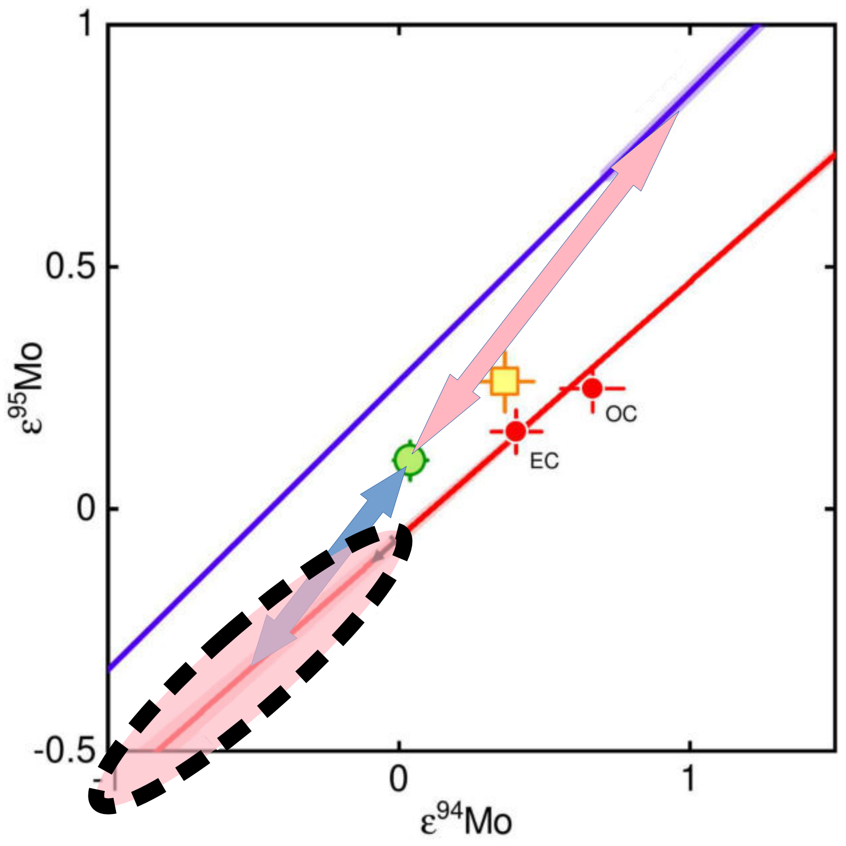


Burkhardt et al. 2021 Sci. Adv.

Results

Earth & Mars must contain some CC material

Model:
Mo in Earth, Mars mixture:
$NC_{Late} + NC_{Early} + CC$



Burkhardt et al. 2021 Sci. Adv.

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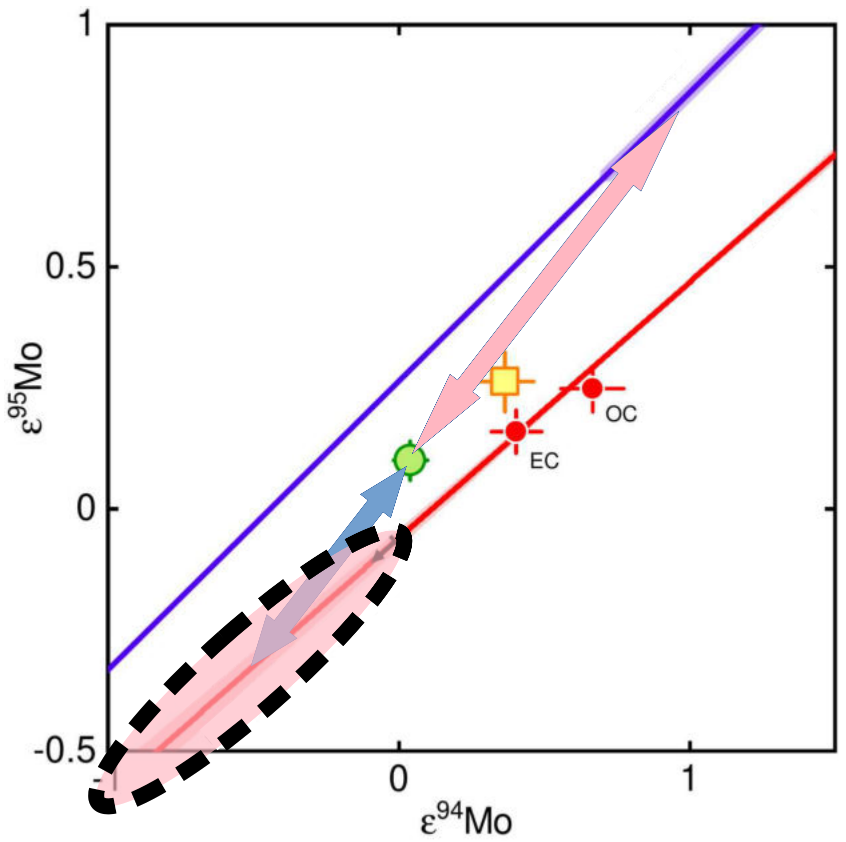
$f_{MoNCLate}$, f_{BulkCC}, $f_{BulkNCLate}$



Burkhardt et al. 2021 Sci. Adv.

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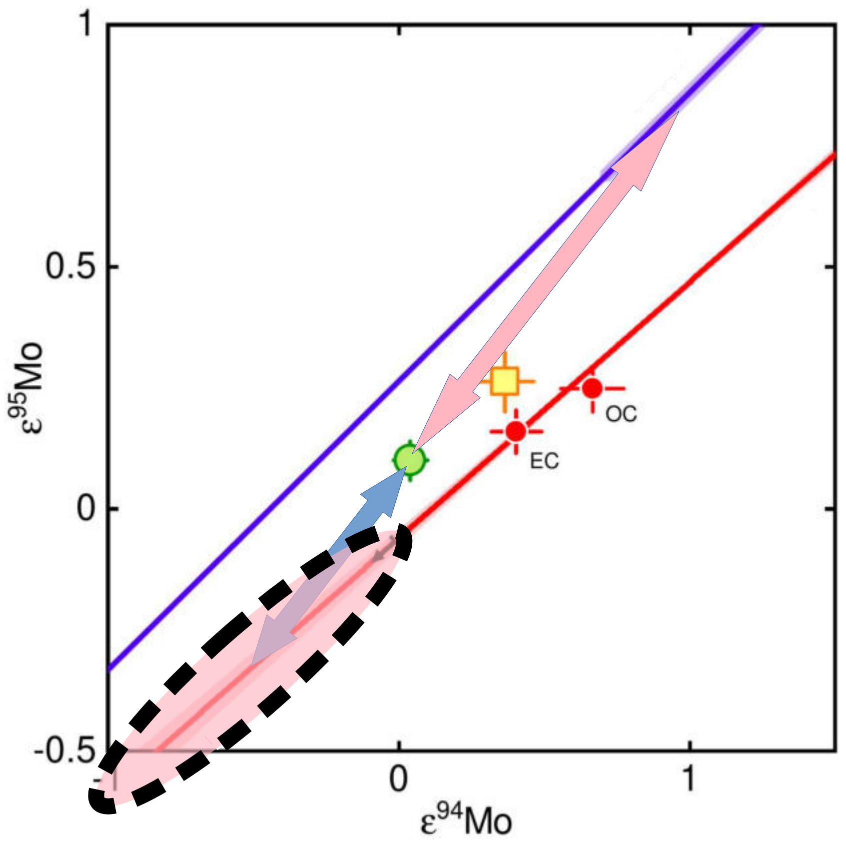

Burkhardt et al. 2021 Sci. Adv.

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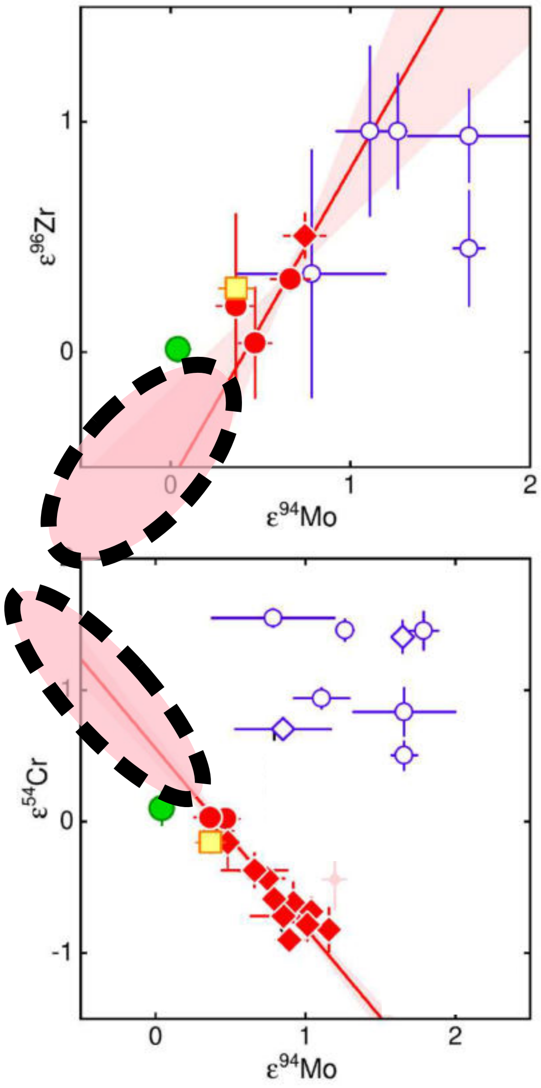

Burkhardt et al. 2021 Sci. Adv.

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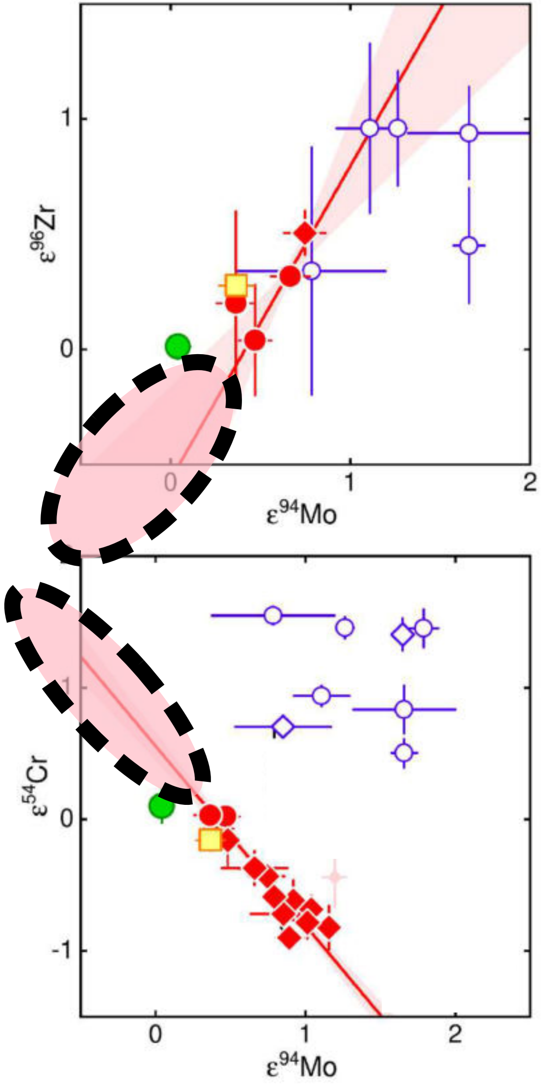

Burkhardt et al. 2021 Sci. Adv.

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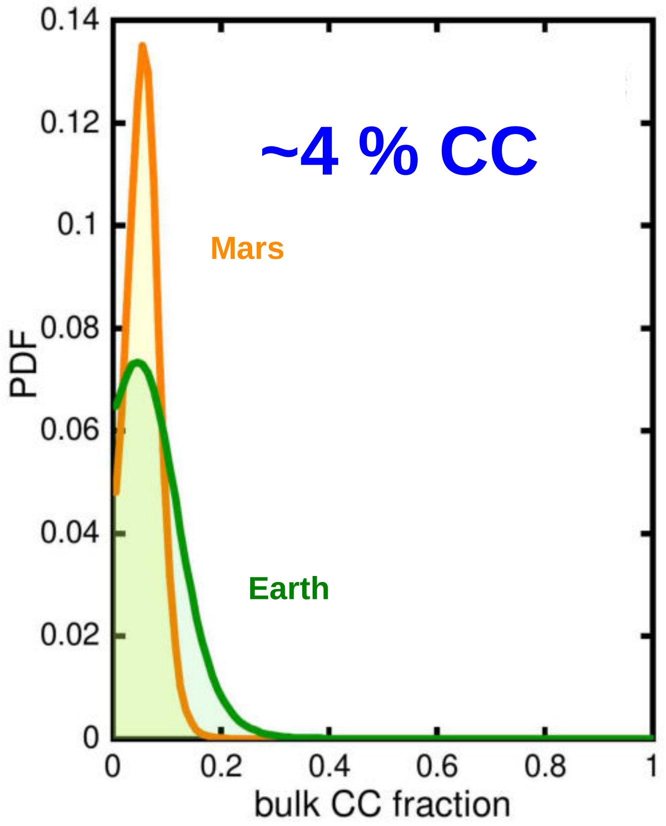
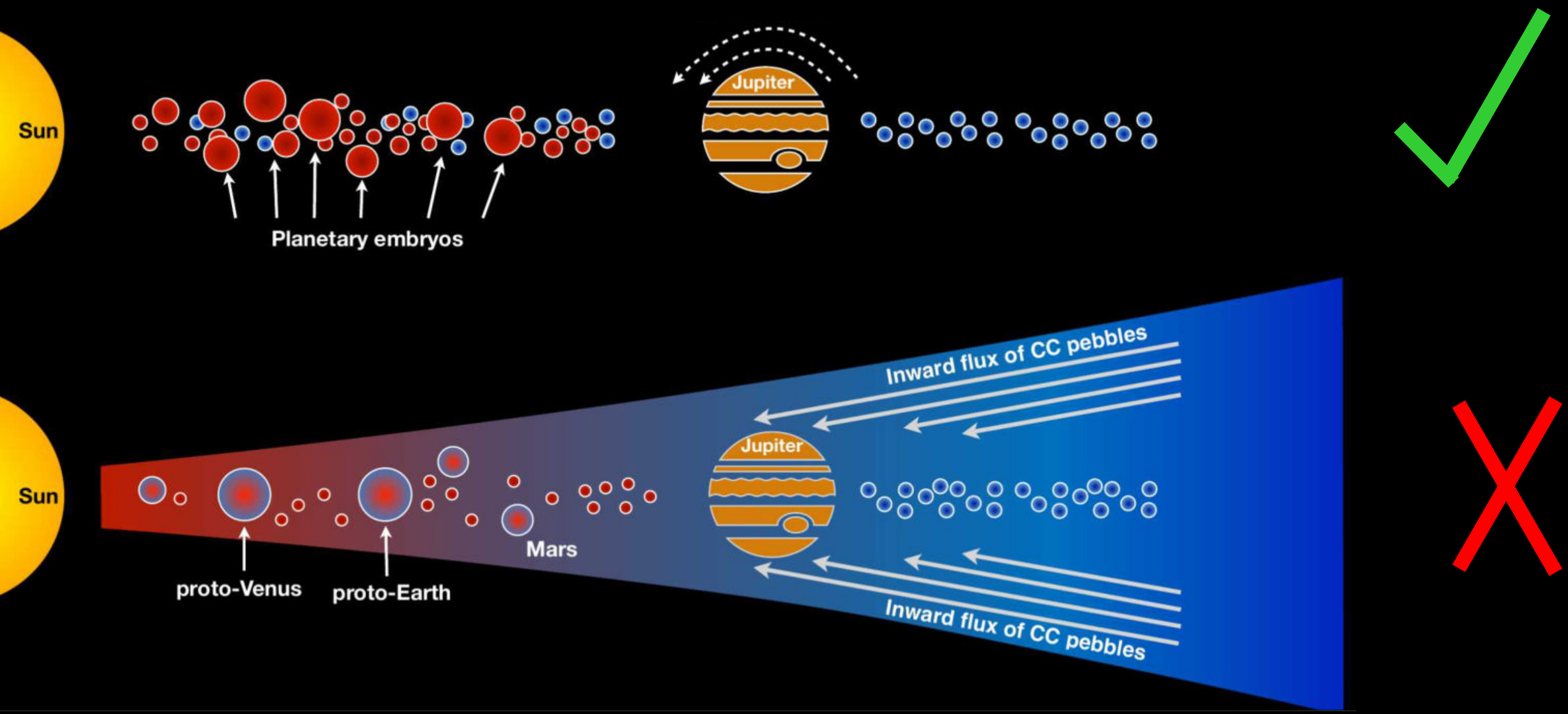


Burkhardt et al. 2021 Sci. Adv.

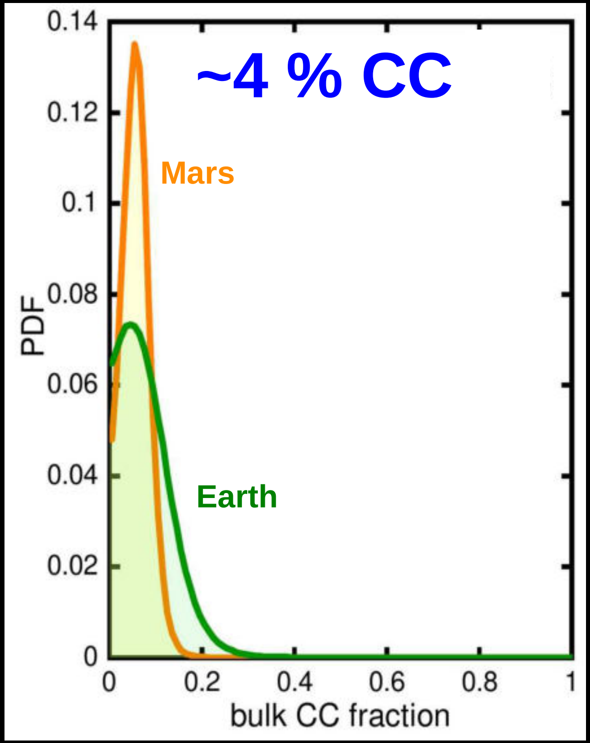
Mode of terrestrial planet formation



Burkhardt et al. 2021 Sci. Adv.

Heritage of Earth’s volatiles

Few % CC in Earth, Mars



Heritage of Earth's volatiles

Few % CC in Earth, Mars

Valid for refractory elements

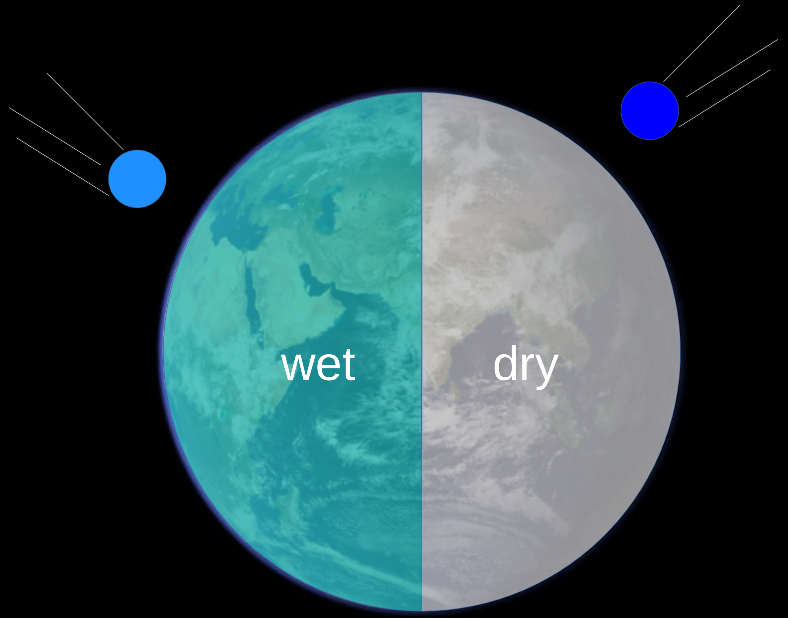
Heritage of Earth’s volatiles

Few % CC in Earth, Mars

Valid for refractory elements

Suffice to explain all of Earth’s & Mars’ volatiles by CC addition

Heritage of Earth's volatiles



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Can't differentiate between wet & dry accretion ($f_{\text{CC volatiles}}$)

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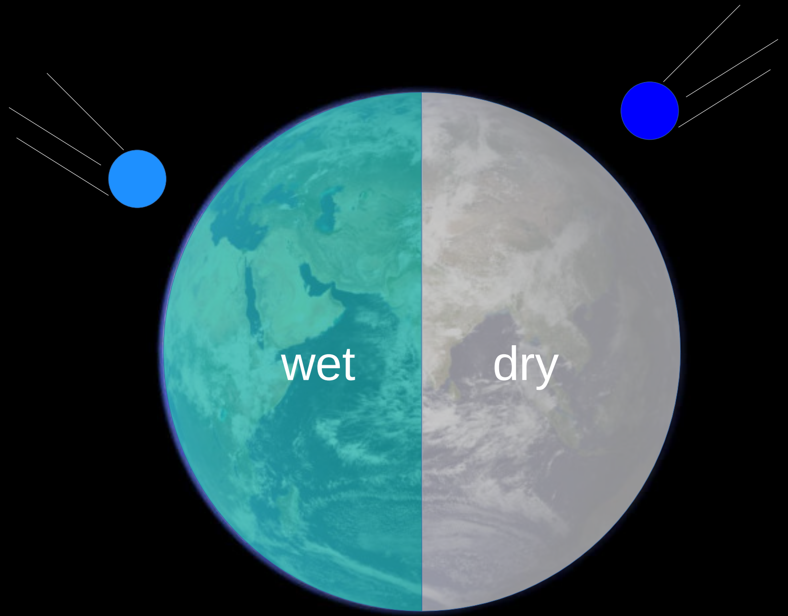

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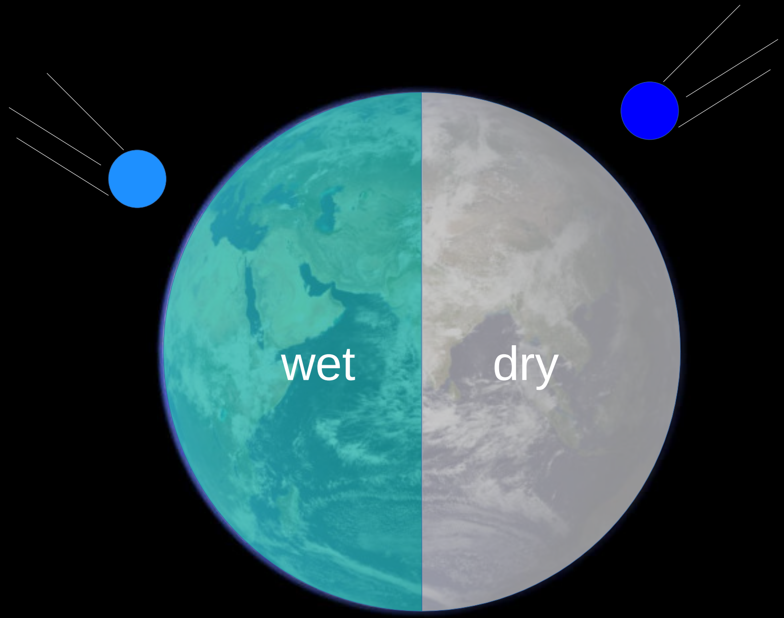
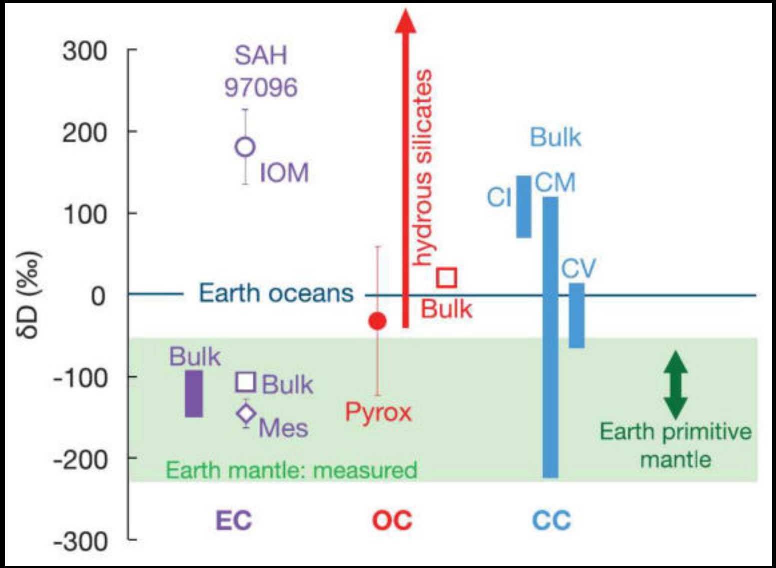
→ Data from volatile elements

Heritage of Earth's volatiles



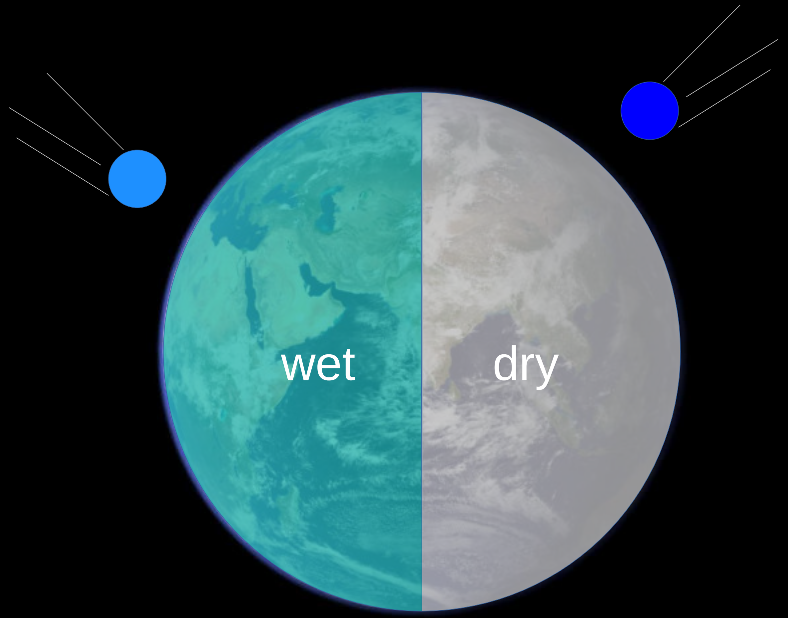
H, C, N only 2 isotopes!



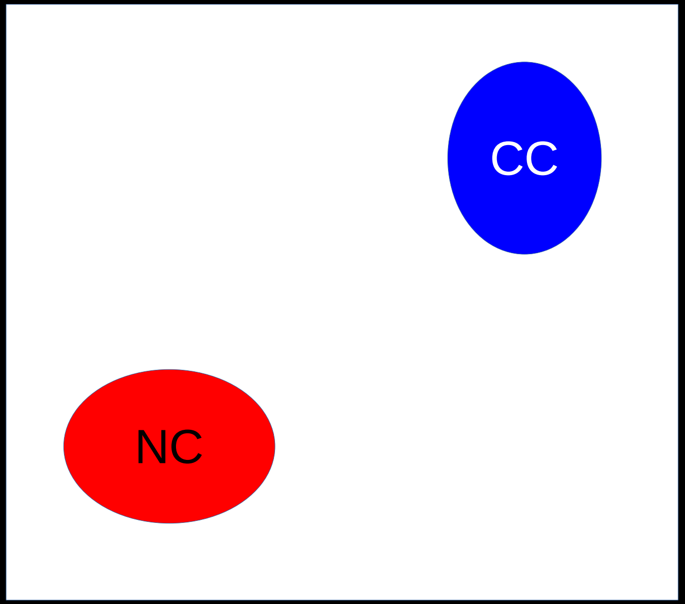
→ Data from volatile elements

(Piani et al. 2020 Science)

Heritage of Earth's volatiles

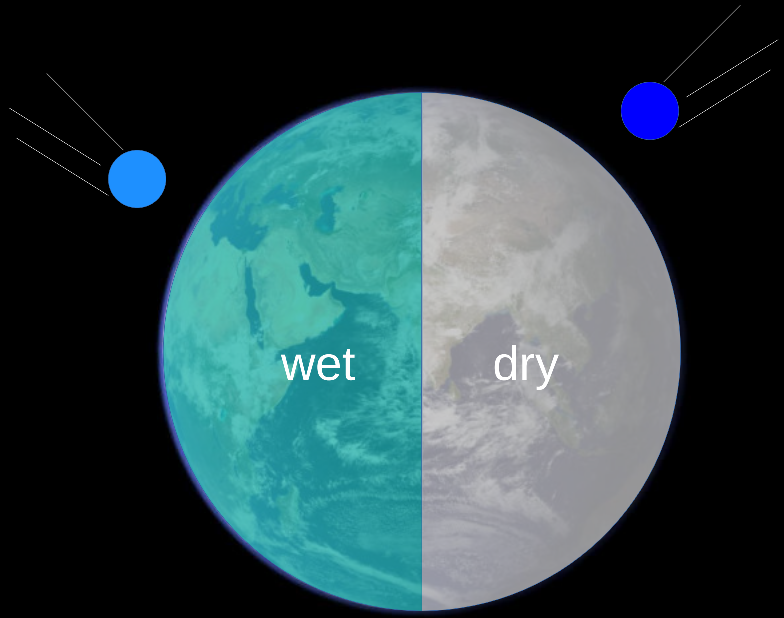


X 4+ isotopes, NC CC distinct



→ Data from volatile elements

Heritage of Earth's volatiles



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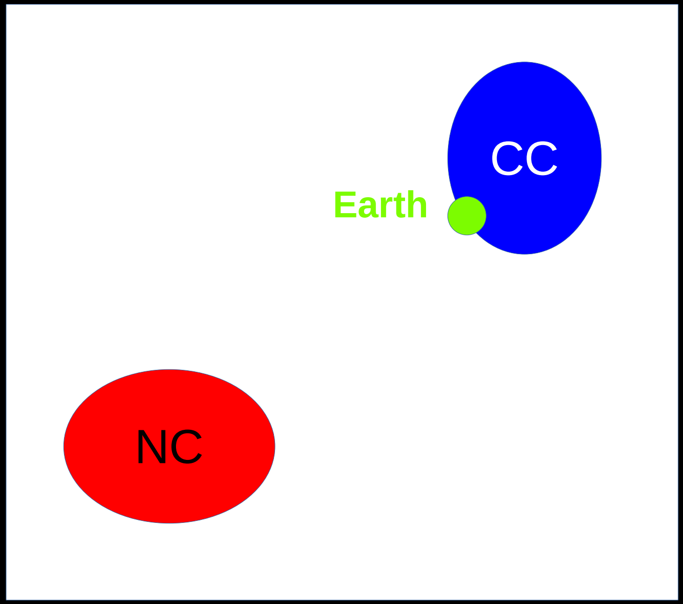

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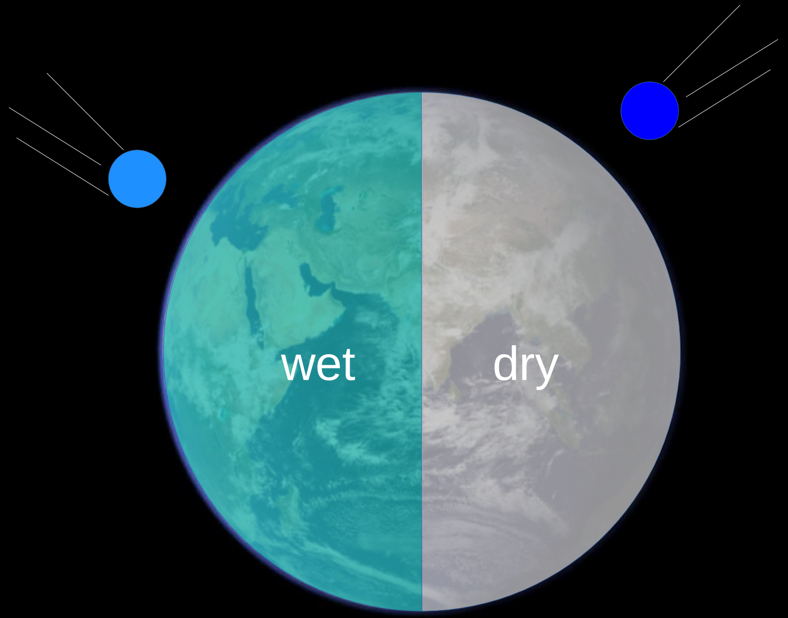
Heritage of Earth's volatiles



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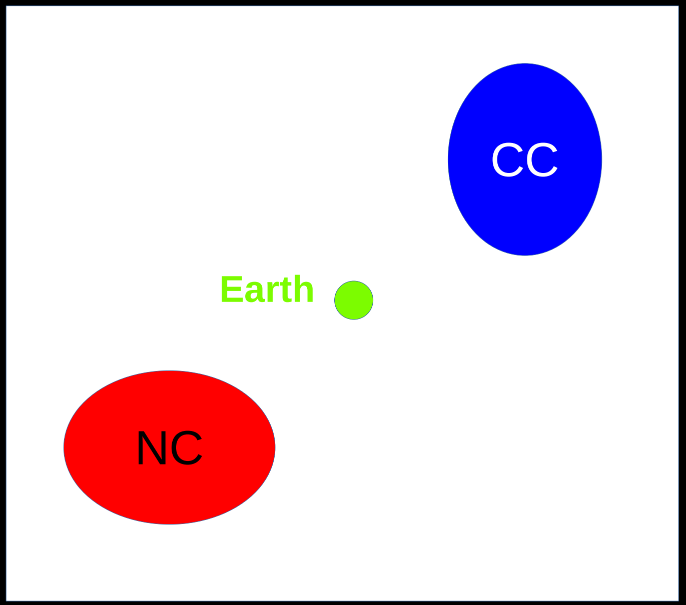

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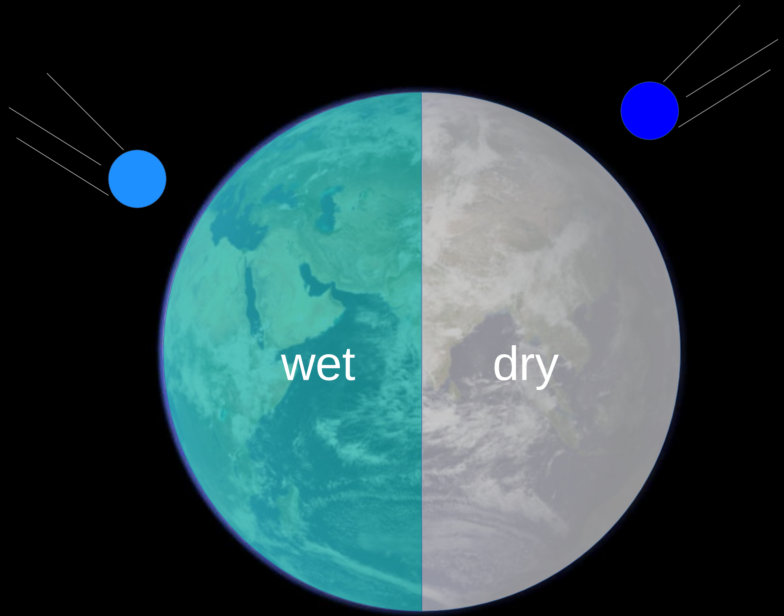
Heritage of Earth's volatiles



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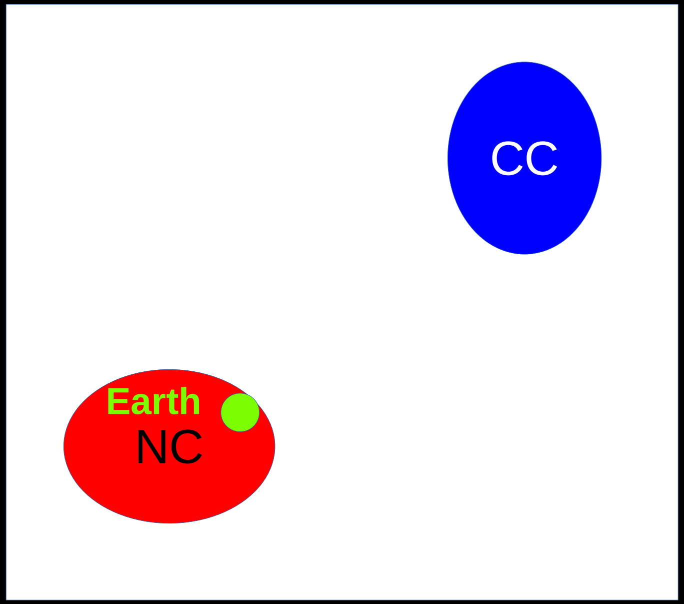


→ Data from volatile elements

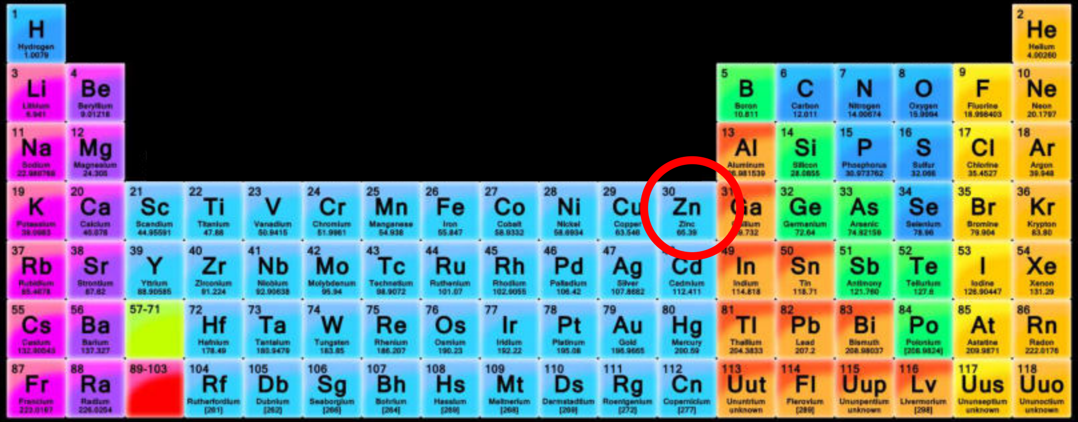
Zinc

$T_{C,50\%} = 704$ K

lithophile

abundant in meteorites

Fe-peak element



Zinc

$T_{C,50\%} = 704$ K

lithophile

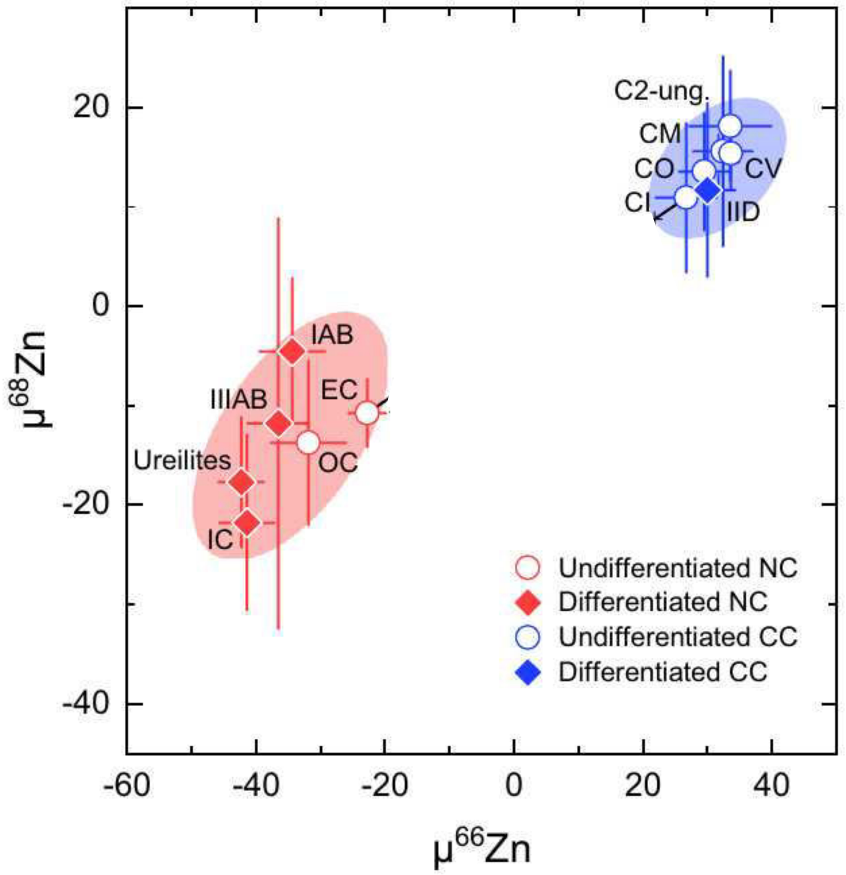
abundant in meteorites

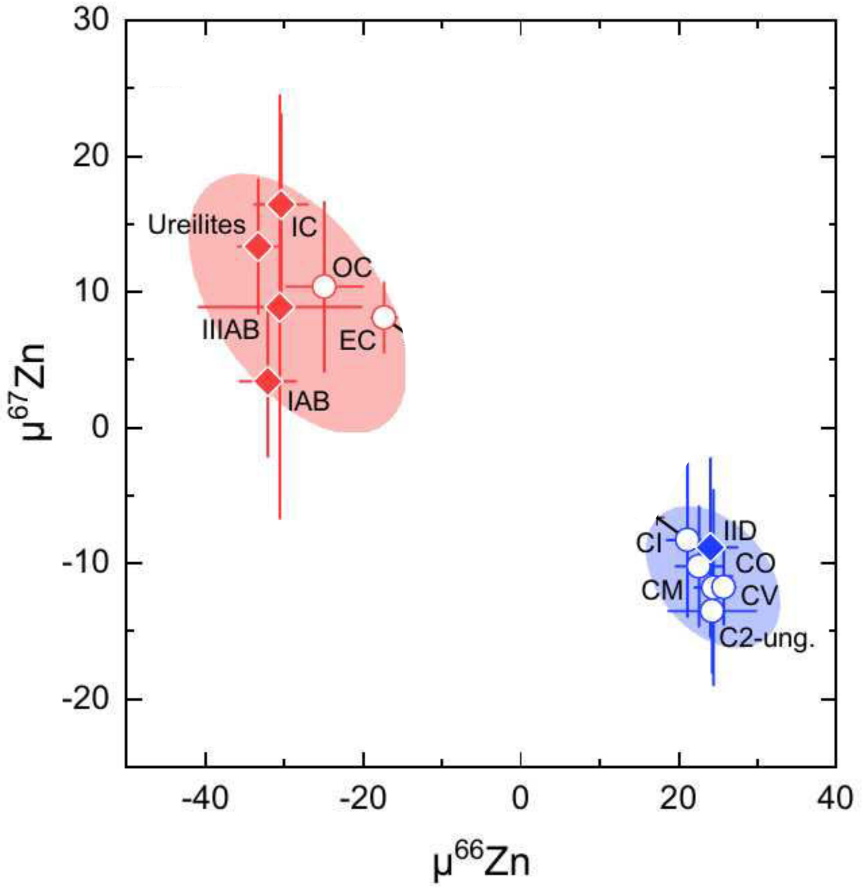
Fe-peak element

5 isotopes

^{64}Zn	^{66}Zn	^{67}Zn	^{68}Zn	^{70}Zn
48.6	27.9	4.1	4.1	0.6

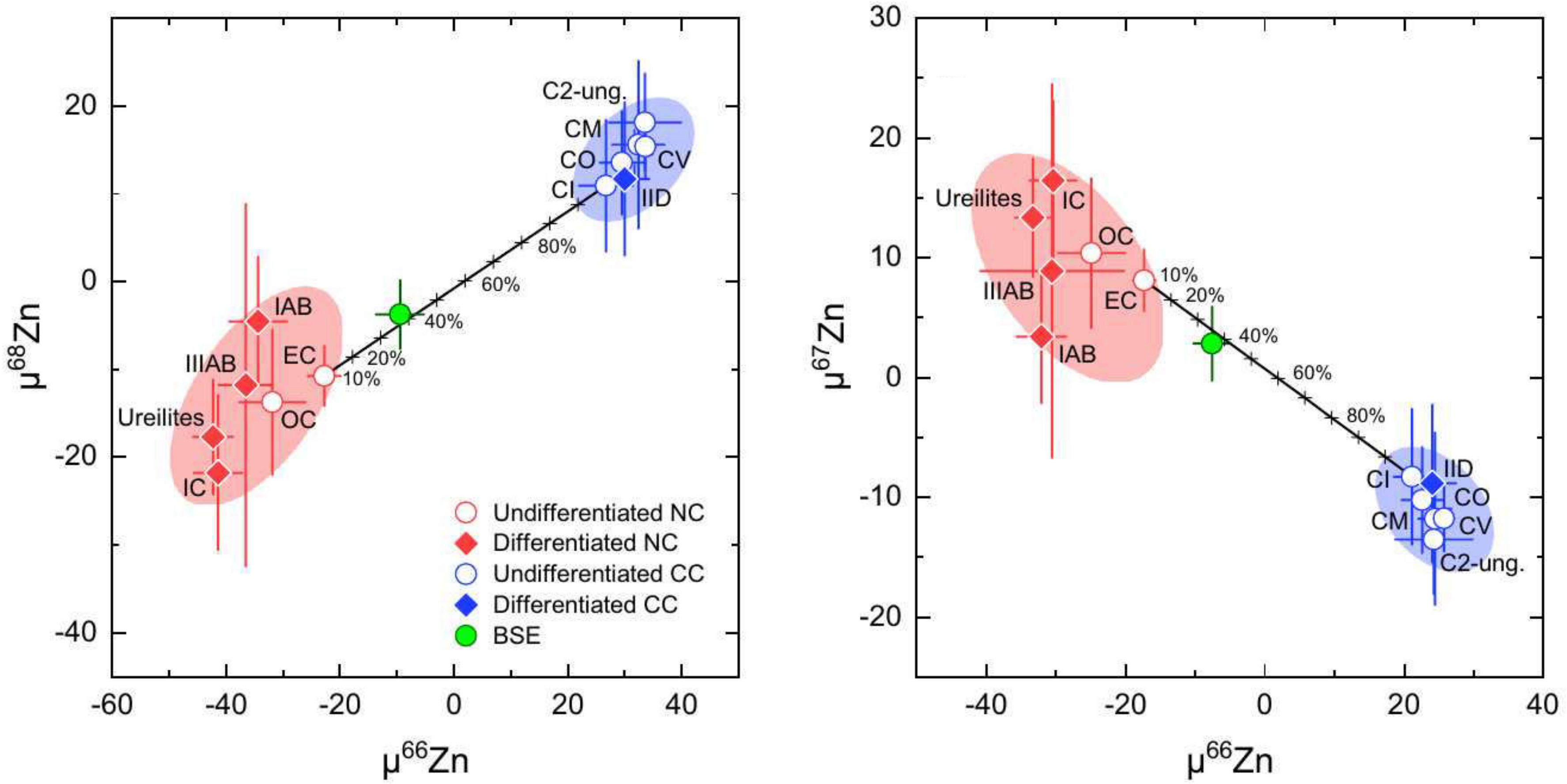
Results





Steller et al. 2022 Icarus

Results



Steller et al. 2022 Icarus

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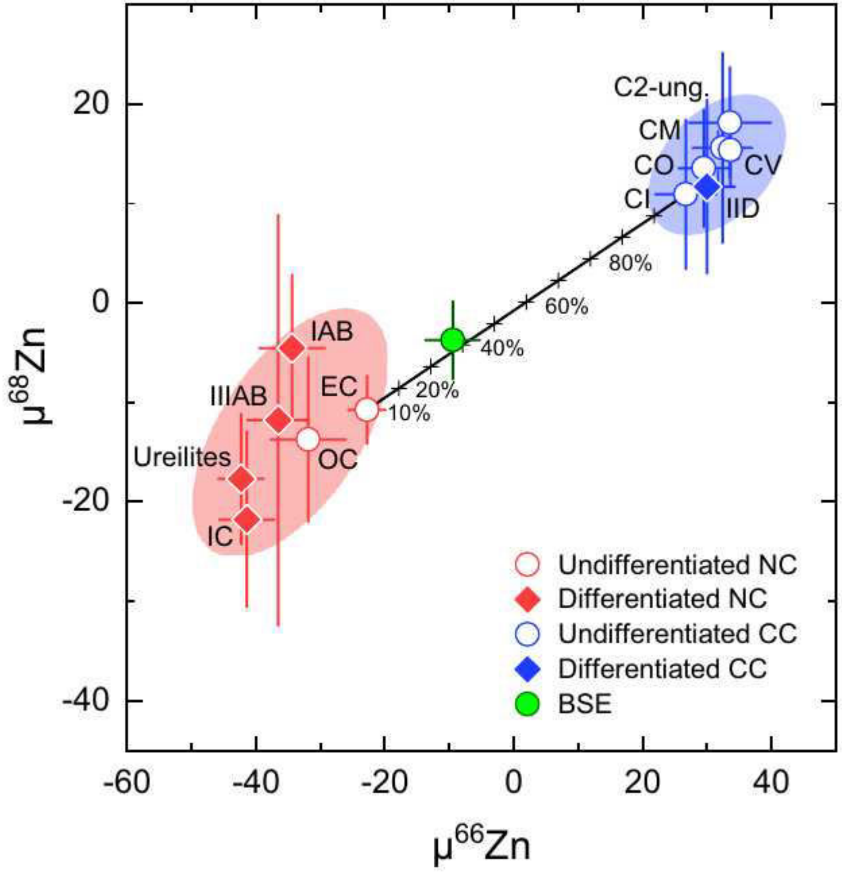
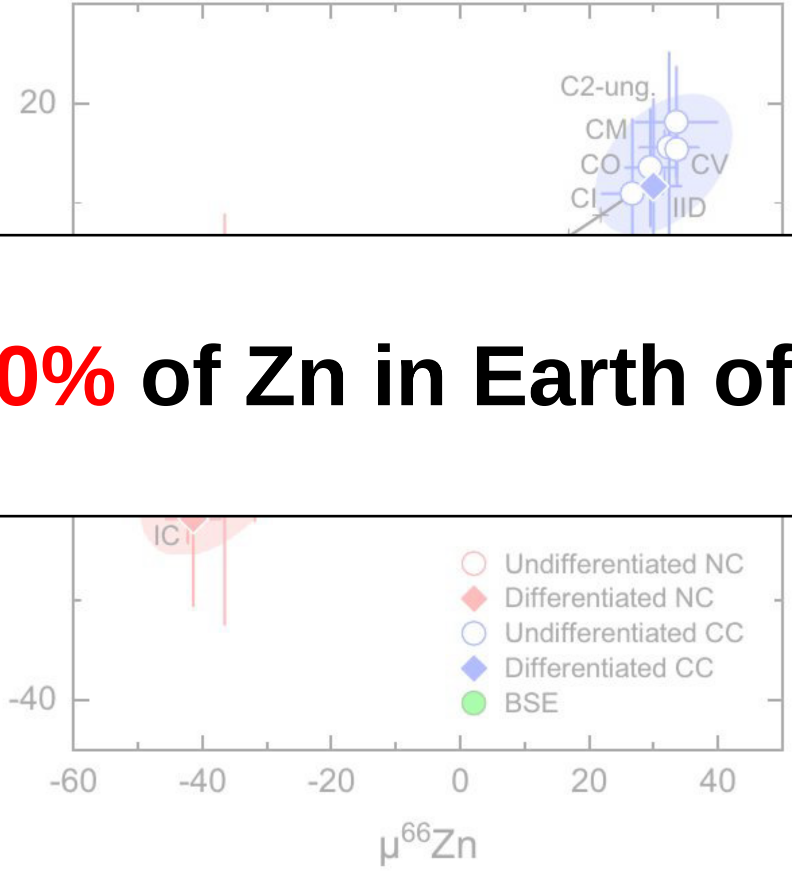


$$f_{CC}(Zn)_{BSE} = \frac{\mu^{66}Zn_{BSE} - \mu^{66}Zn_{NC}}{\mu^{66}Zn_{CC} - \mu^{66}Zn_{NC}}$$

Steller et al. 2022 Icarus

Results



~70% of Zn in Earth of NC heritage, 30% CC

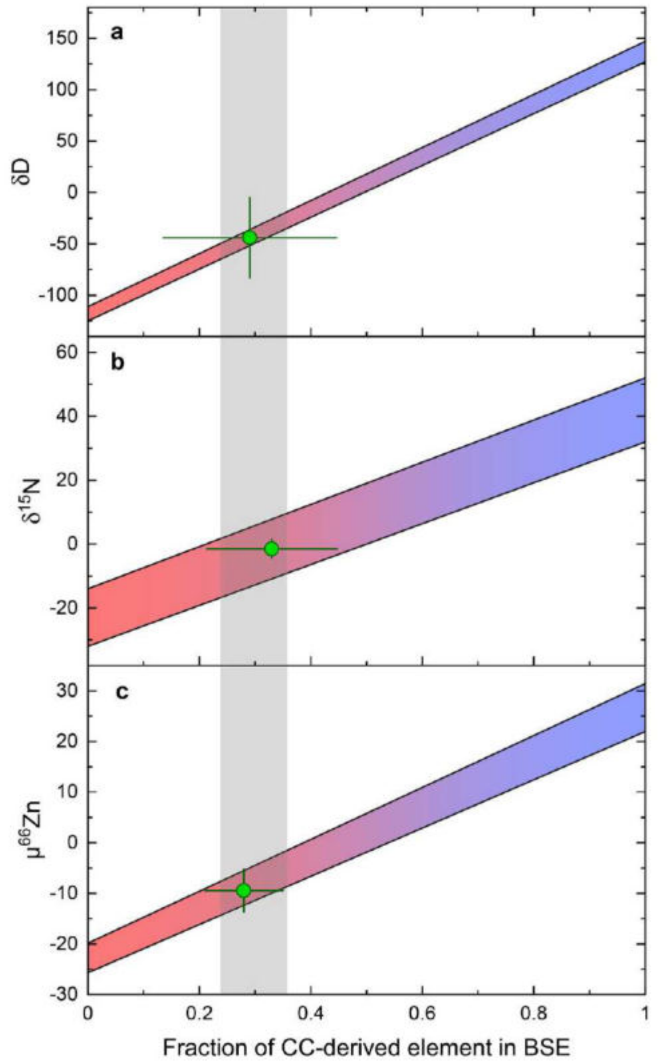
Steller et al. 2022 Icarus

Results

$$f_{CC}(H)_{BSE} = \frac{\delta D_{BSE} - \delta D_{NC}}{\delta D_{CC} - \delta D_{NC}}$$

$$f_{CC}(N)_{BSE} = \frac{\delta^{15} N_{BSE} - \delta^{15} N_{NC}}{\delta^{15} N_{CC} - \delta^{15} N_{NC}}$$

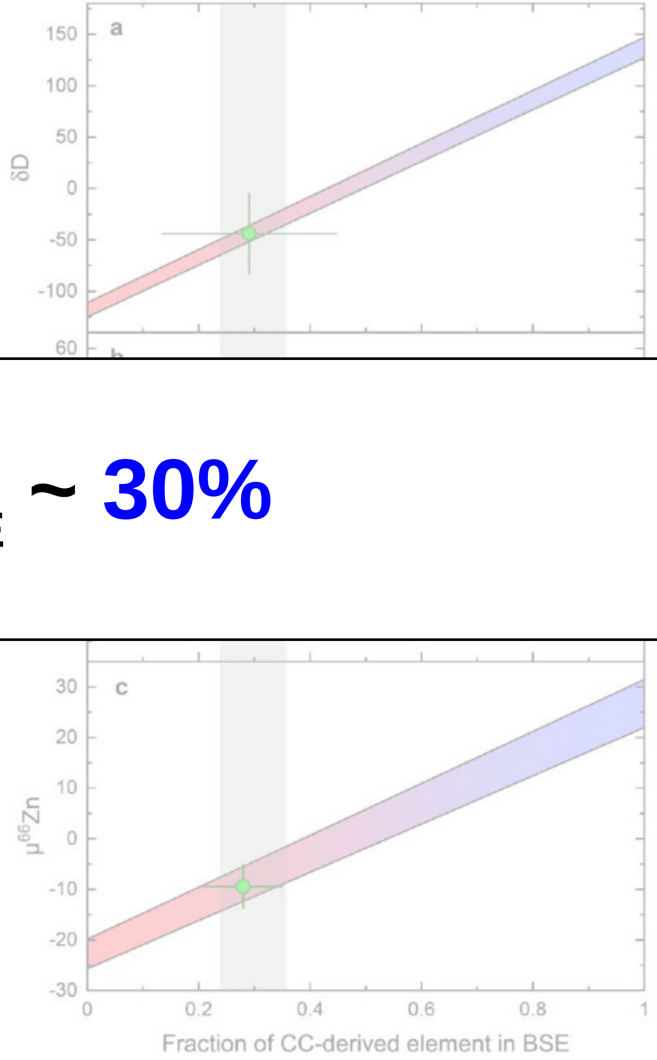
$$f_{CC}(Zn)_{BSE} = \frac{\mu^{66} Zn_{BSE} - \mu^{66} Zn_{NC}}{\mu^{66} Zn_{CC} - \mu^{66} Zn_{NC}}$$



Steller et al. 2022 Icarus

Results

$$f_{CC}(H)_{BSE}=\frac{\delta D_{BSE}-\delta D_{NC}}{\delta D_{CC}-\delta D_{NC}}$$



f_{cc}volatiles $_{BSE}$ ~ 30%

$$f_{CC}(Zn)_{BSE}=\frac{\mu^{66}Zn_{BSE}-\mu^{66}Zn_{NC}}{\mu^{66}Zn_{CC}-\mu^{66}Zn_{NC}}$$

Steller et al. 2022 Icarus

Fraction of **CC** in bulk Earth?

$$f_{CC}(Earth) = f_{CC}(\mathrm{Zn})_{BSE} \cdot \frac{[Zn]_{BSE}}{[Zn]_{CC}}$$

Fraction of **CC** in bulk Earth?

$$f_{CC}(Earth) = f_{CC}(Zn)_{BSE} \cdot \frac{[Zn]_{BSE}}{[Zn]_{CC}}$$

CI chondrites: 5 ± 2 %

CV chondrites: 12 ± 4 %

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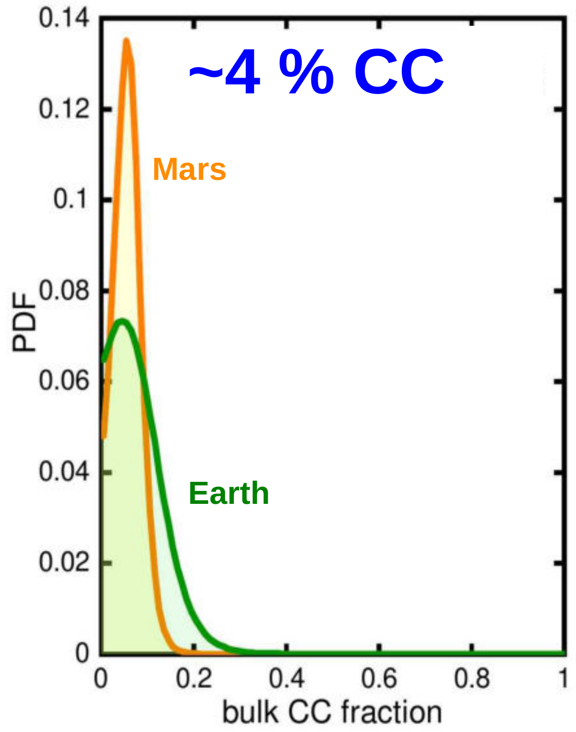
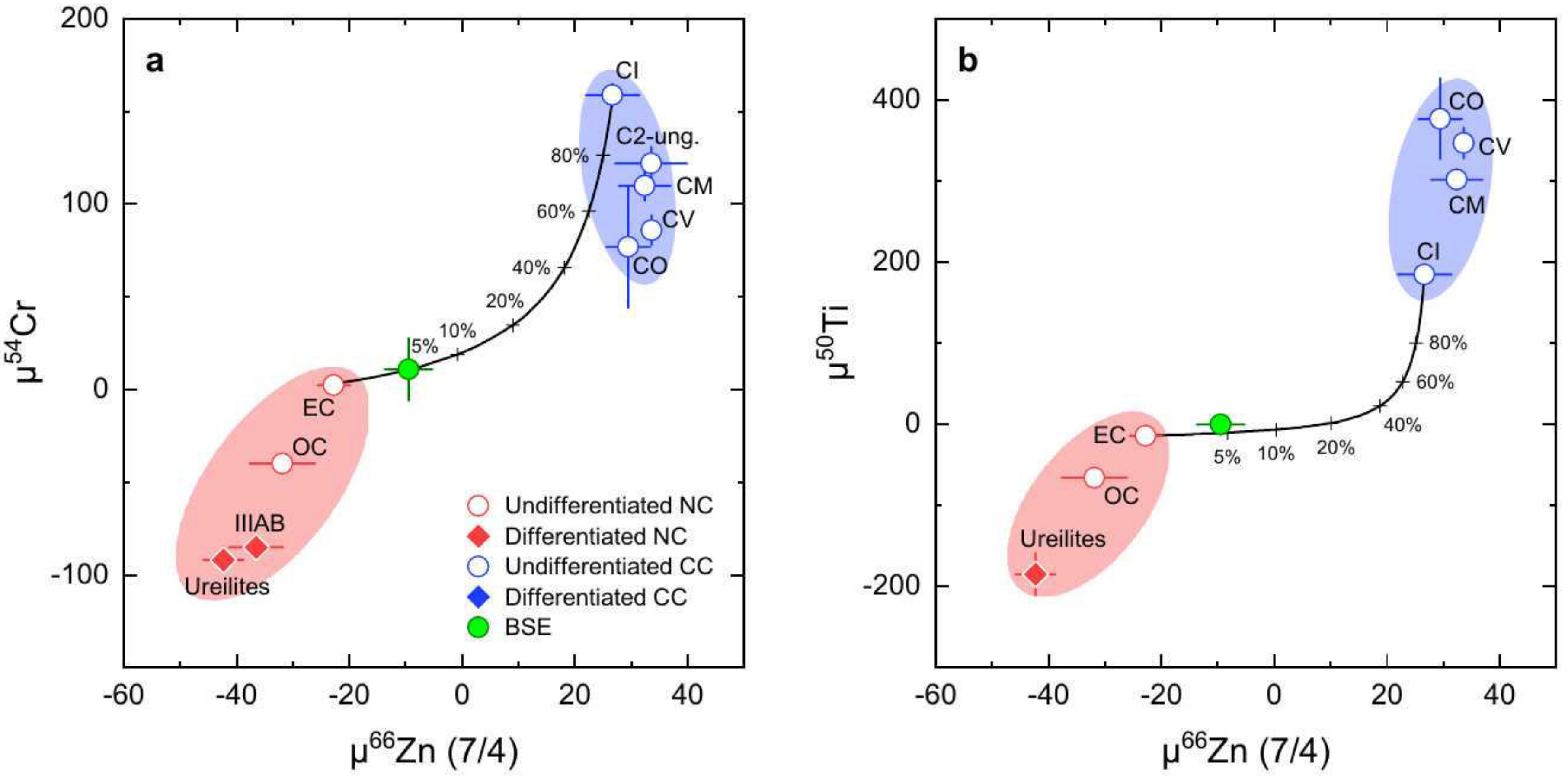


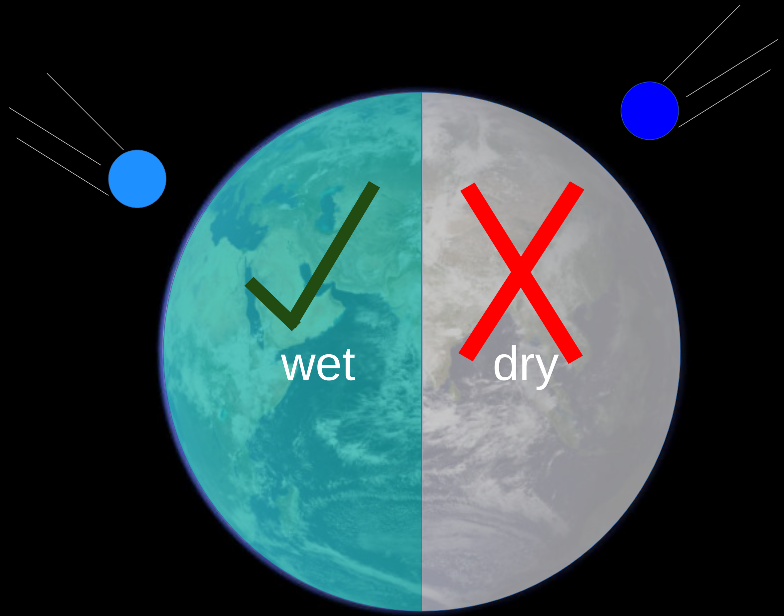
Burkhardt et al. 2021 Sci. Adv.

Fraction of CC in bulk Earth



Steller et al. 2022 Icarus

Heritage of volatiles



Identification of NC CC isotopic dichotomy for volatile element Zn

Heritage of BSE volatiles 70:30

Volatiles present in inner solar system
→ Wet accretion!

Isotopic anomalies in meteorites

What is Solar System made of?

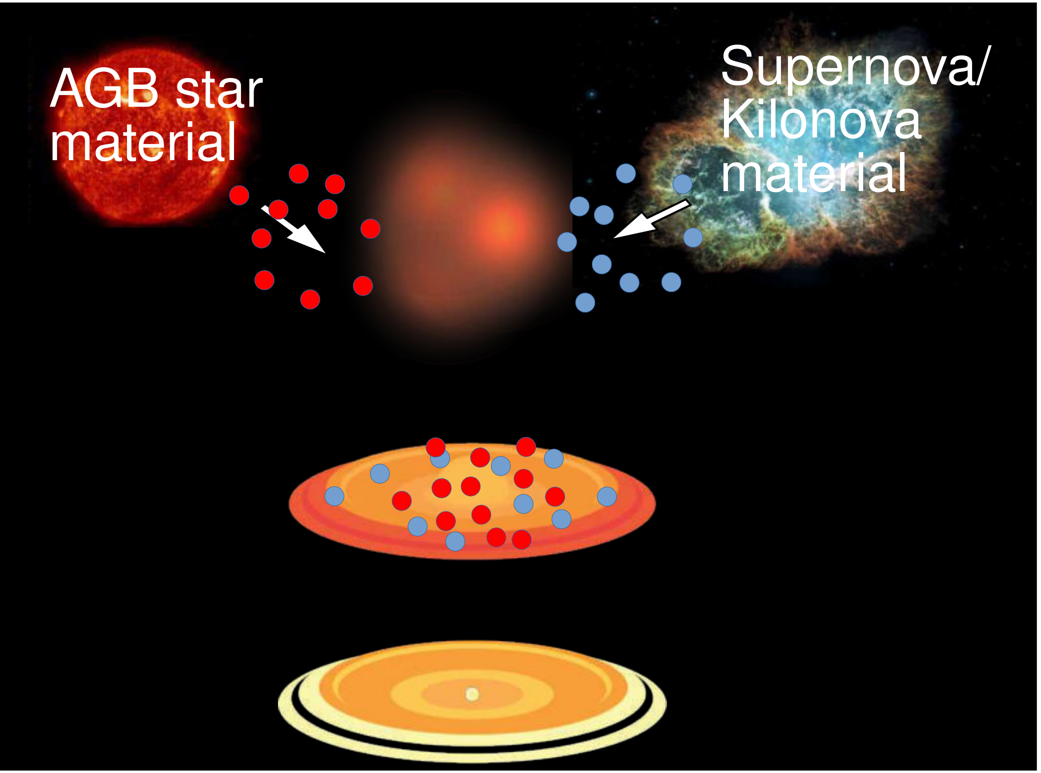
How did disk form/disk dynamics?

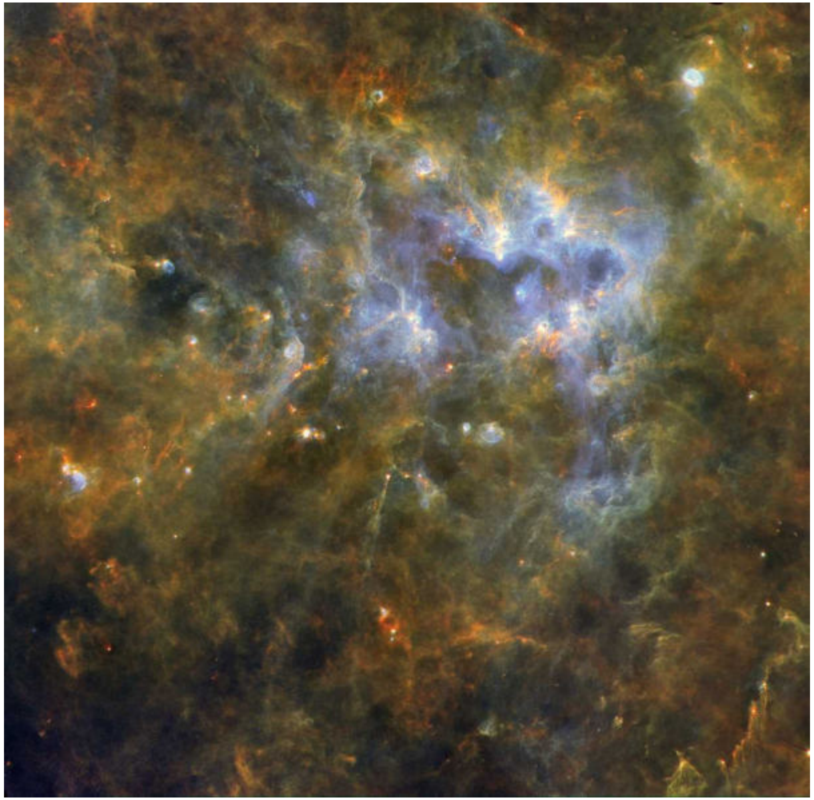
What is Earth made of?

How did Earth form?

Heritage of Earth volatiles?

Isotopic anomalies in meteorites

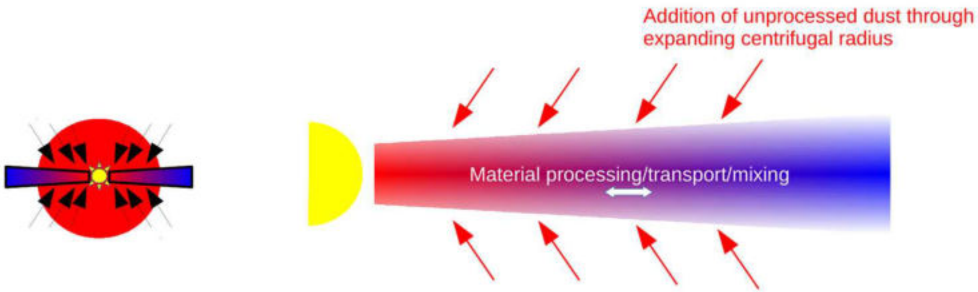




What is the solar system made of?

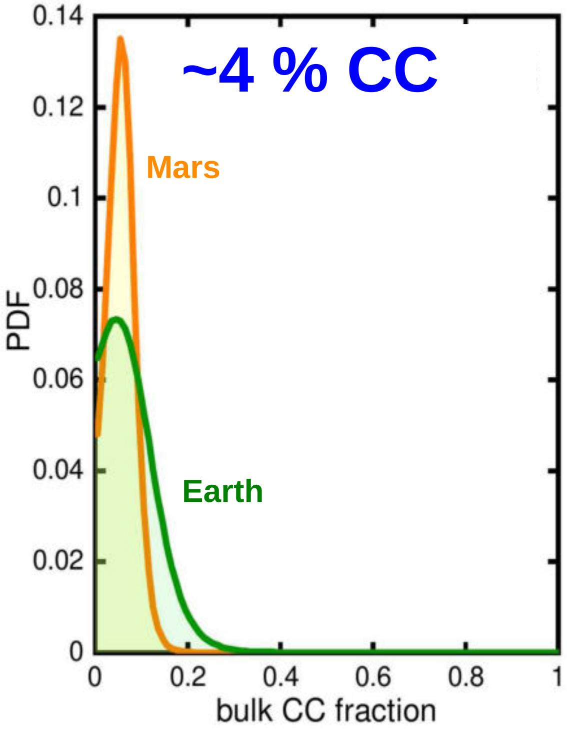
ESA/Herschel/PACS, G305

Isotopic anomalies in meteorites



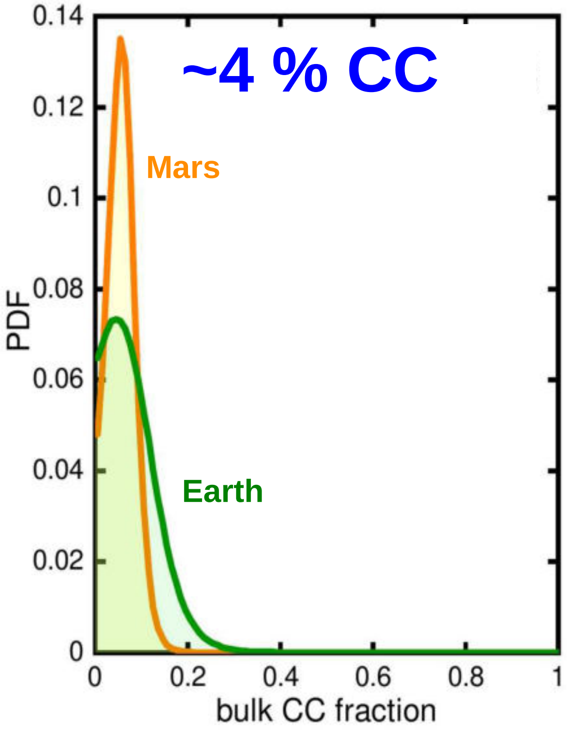
How did the disk form/disk dynamics?

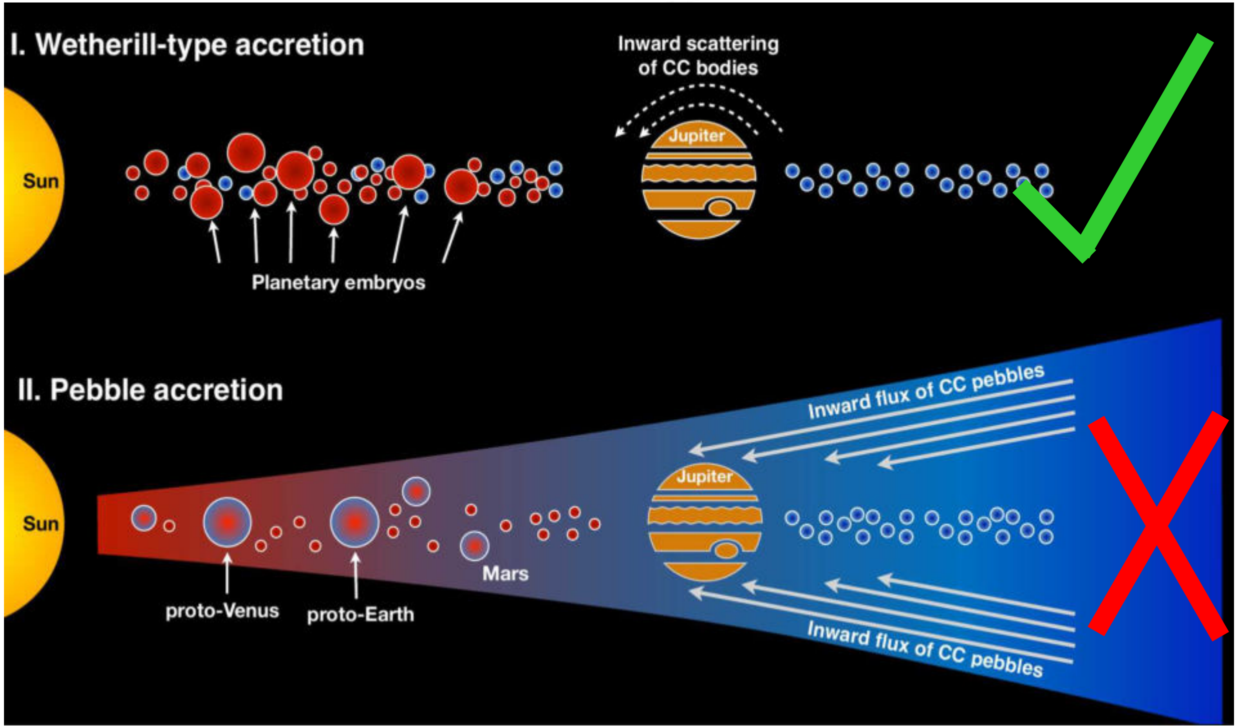
Isotopic anomalies in meteorites



What is the Earth made of?

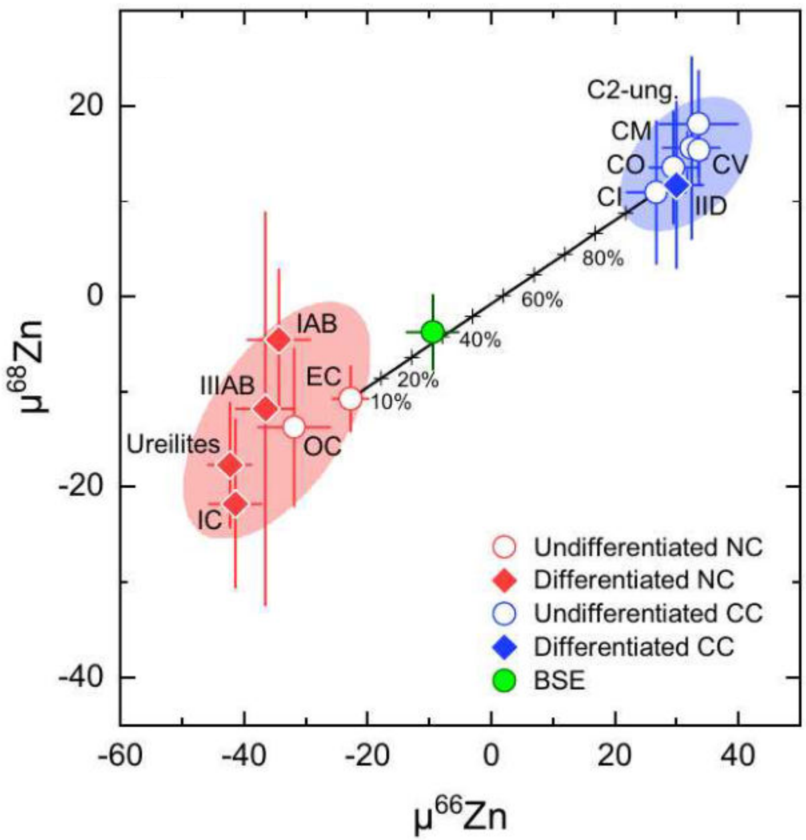
Isotopic anomalies in meteorites





What is the Earth made of? /How did it form?

Isotopic anomalies in meteorites



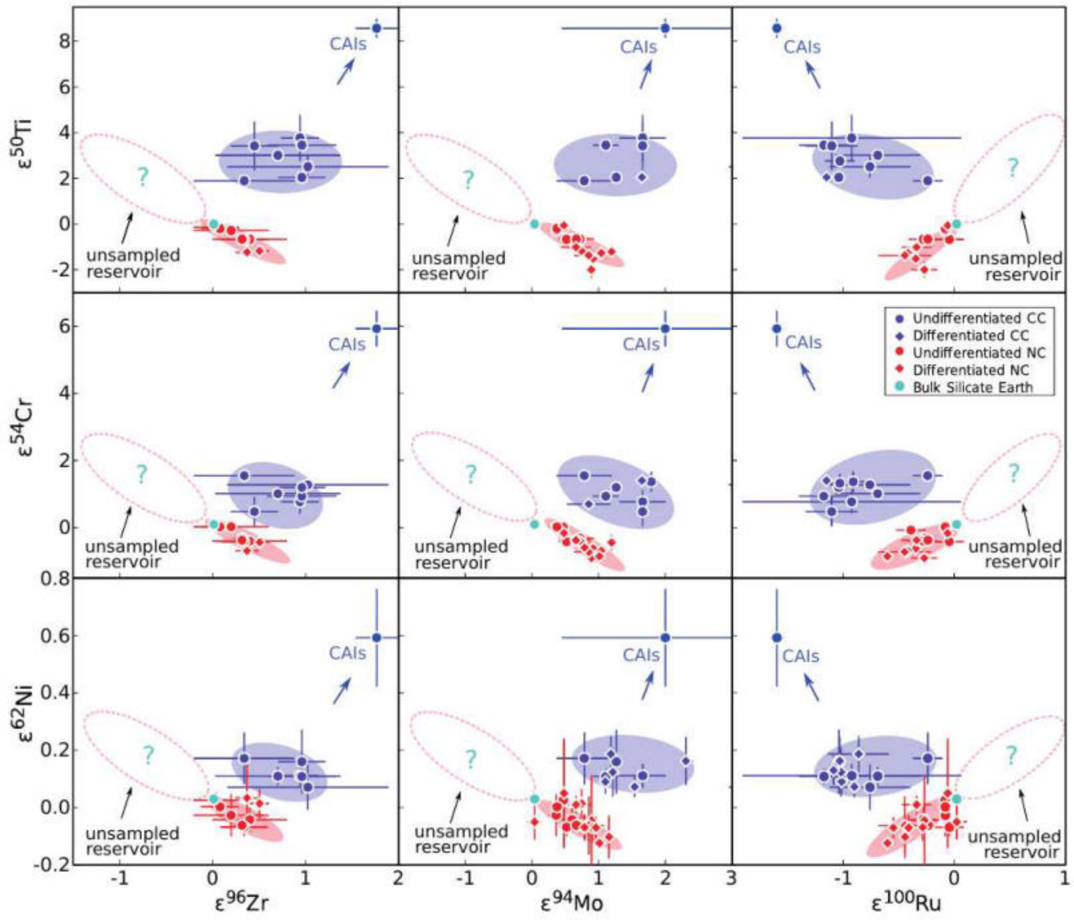
Heritage of Earth’s volatiles?

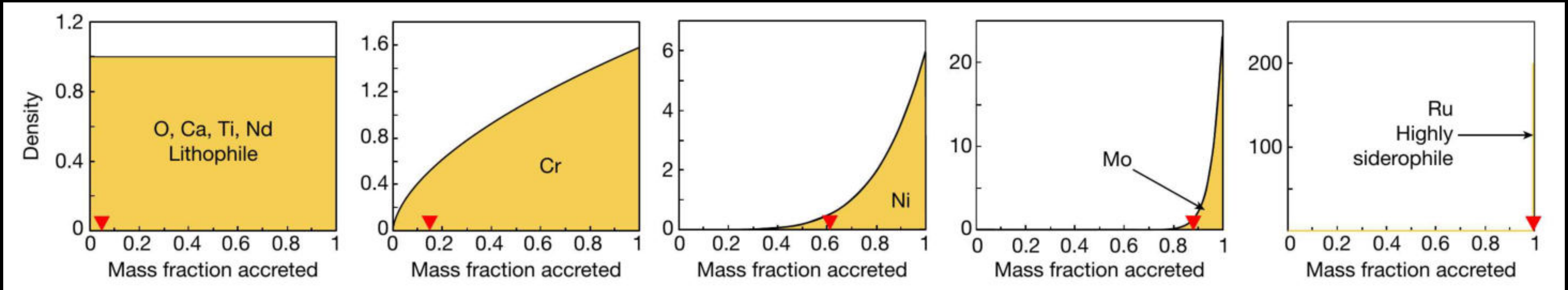
Open questions

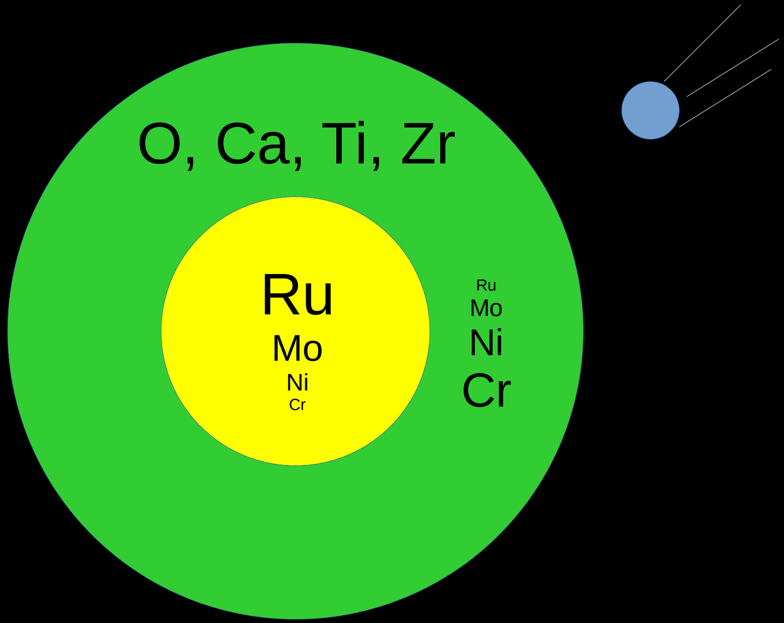
Origin NC trend?

Nature of unsampled reservoir?

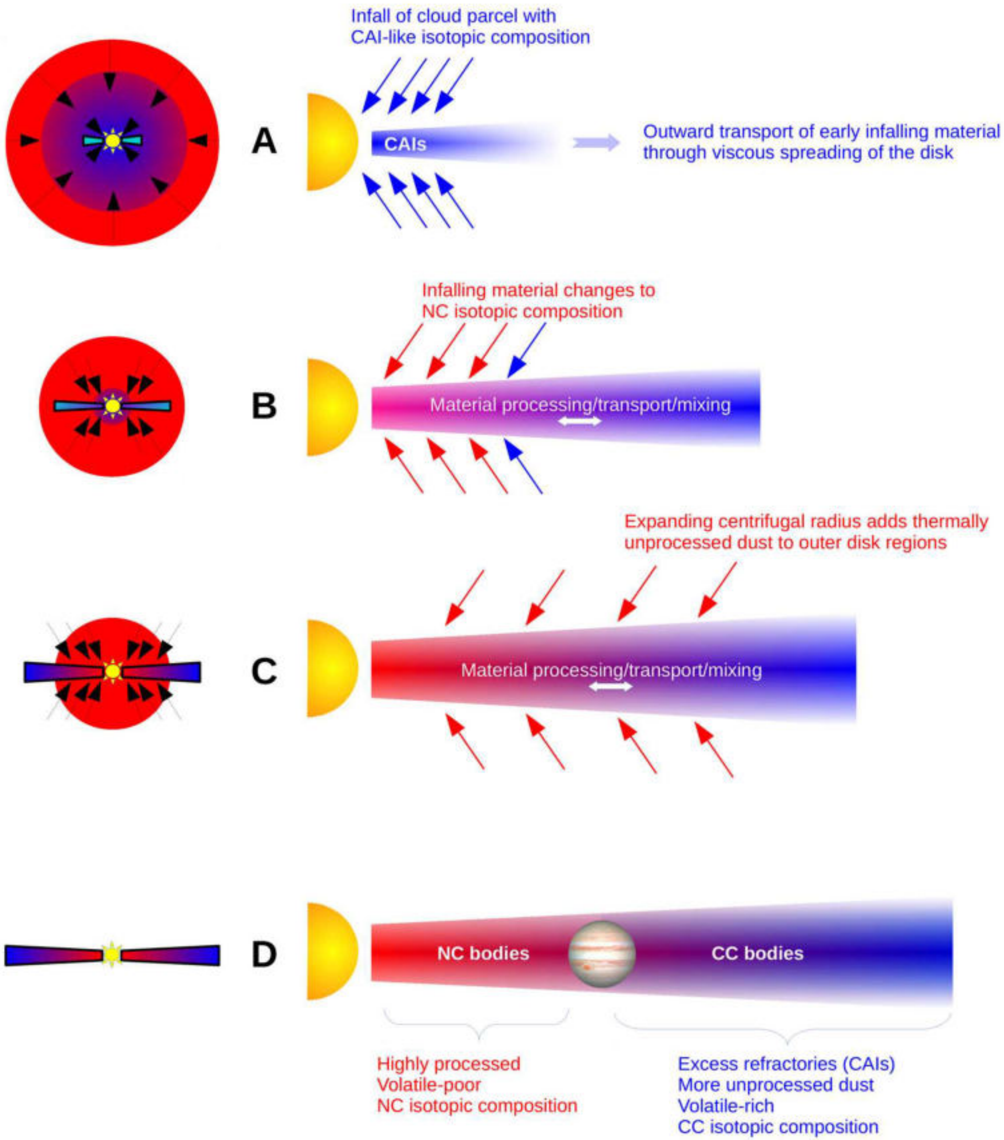
Inheritance vs. disk processing?





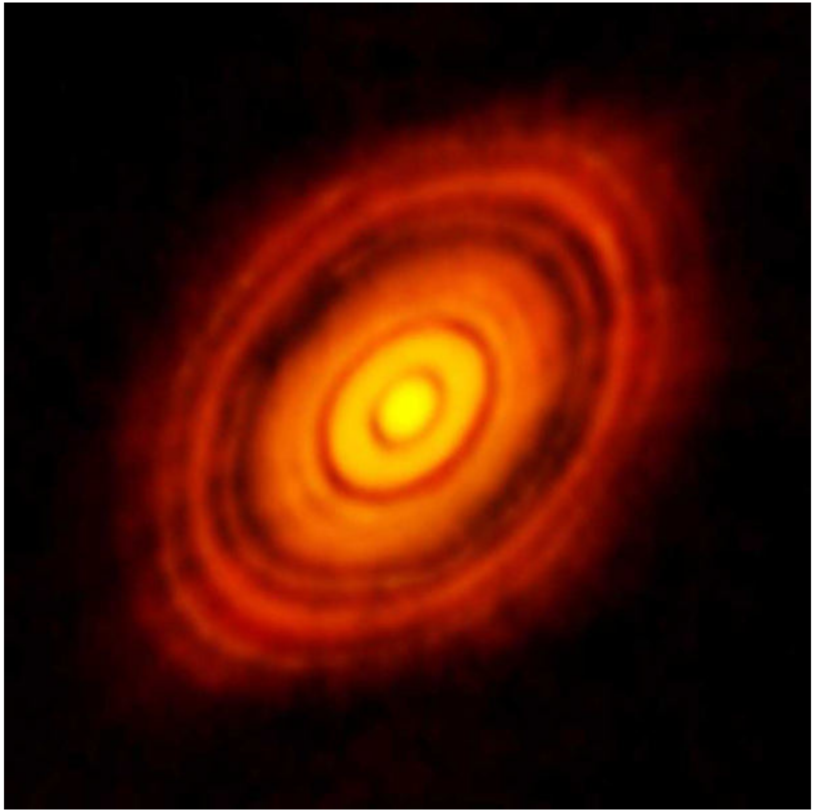


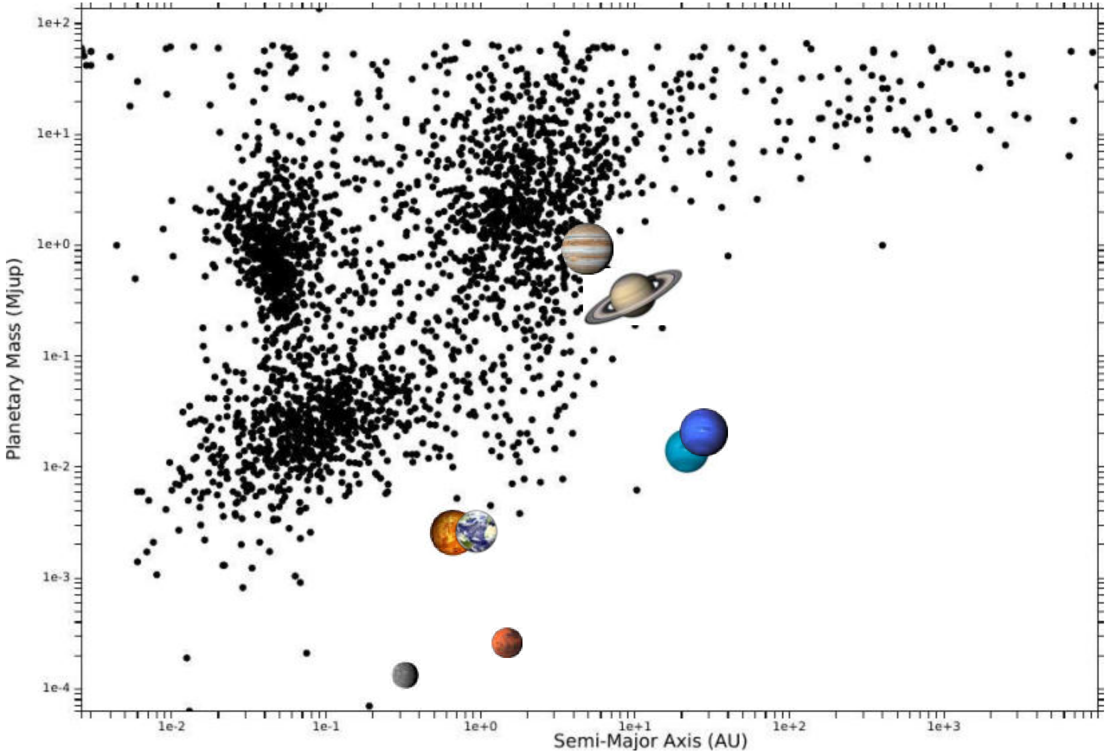
Dauphas 2017 Nature



Infall of cloud parcel with
CAI-like isotopic composition
A
CAIs
Outward transport of early infalling material
through viscous spreading of the disk
Infalling material changes to
NC isotopic composition
B
Material processing/transport/mixing
Expanding centrifugal radius adds thermally
unprocessed dust to outer disk regions
C
Material processing/transport/mixing
D
NC bodies
CC bodies
Highly processed
Volatile-poor
NC isotopic composition
Excess refractories (CAIs)
More unprocessed dust
Volatile-rich
CC isotopic composition

Star and planet formation is diverse!





ESO ALMA, HL Tau

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