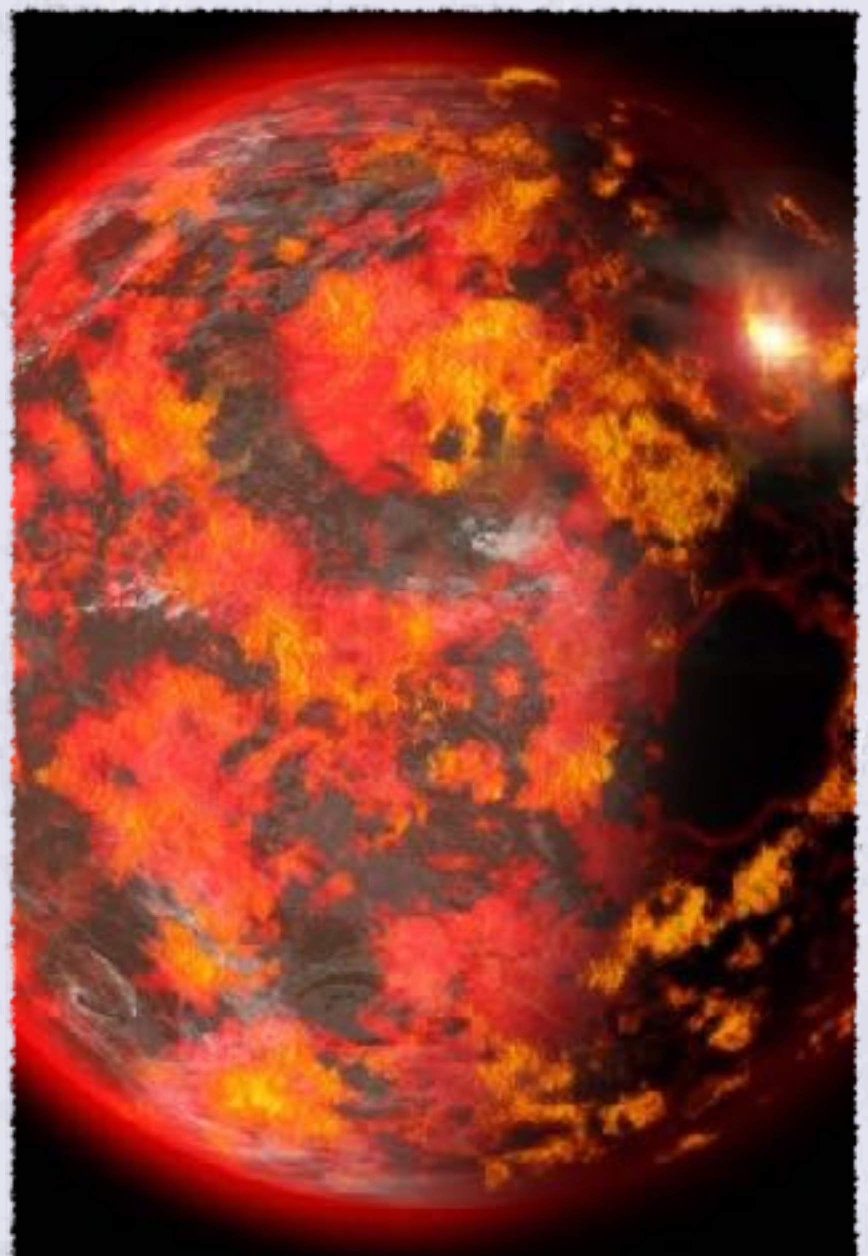




非传统同位素在天体化学中的应用

Washington University in St. Louis

王昆

Image Credit: NASA/JPL-Caltech/Diego Barucco/Shutterstock/

Washington University in St. Louis

Founded in Feb. 22, 1853

Named after
George Washington

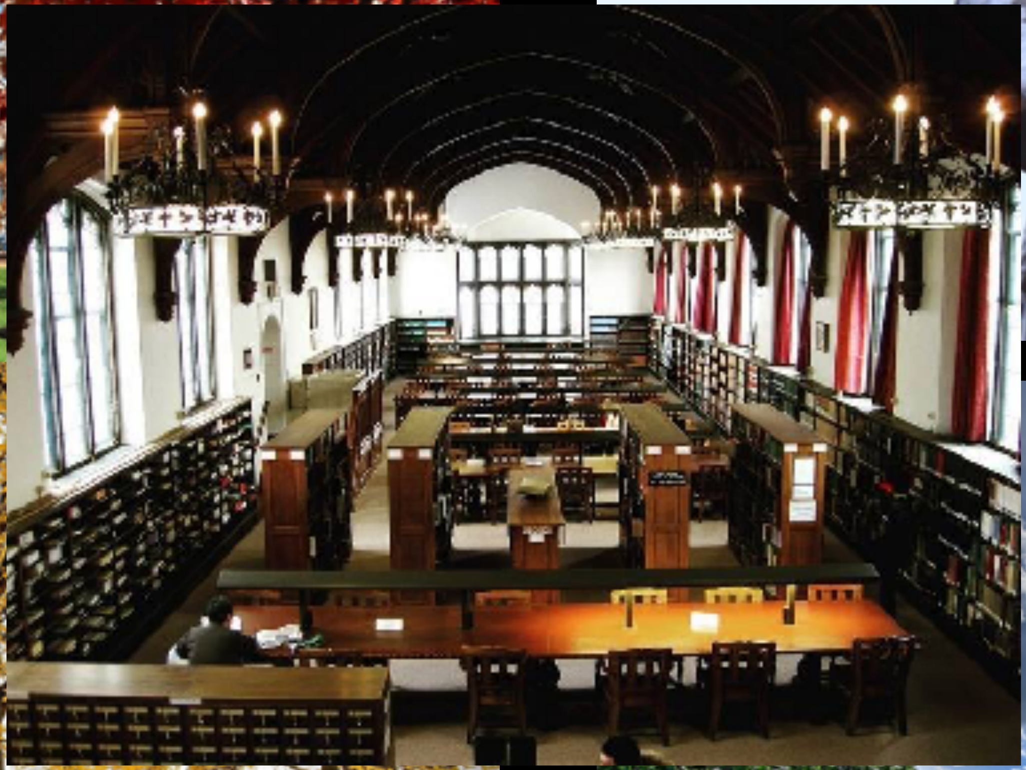
"in St. Louis" added in 1976

Washington University in St. Louis

1904 World's Fair

1904 Olympic Games

Washington University in St. Louis

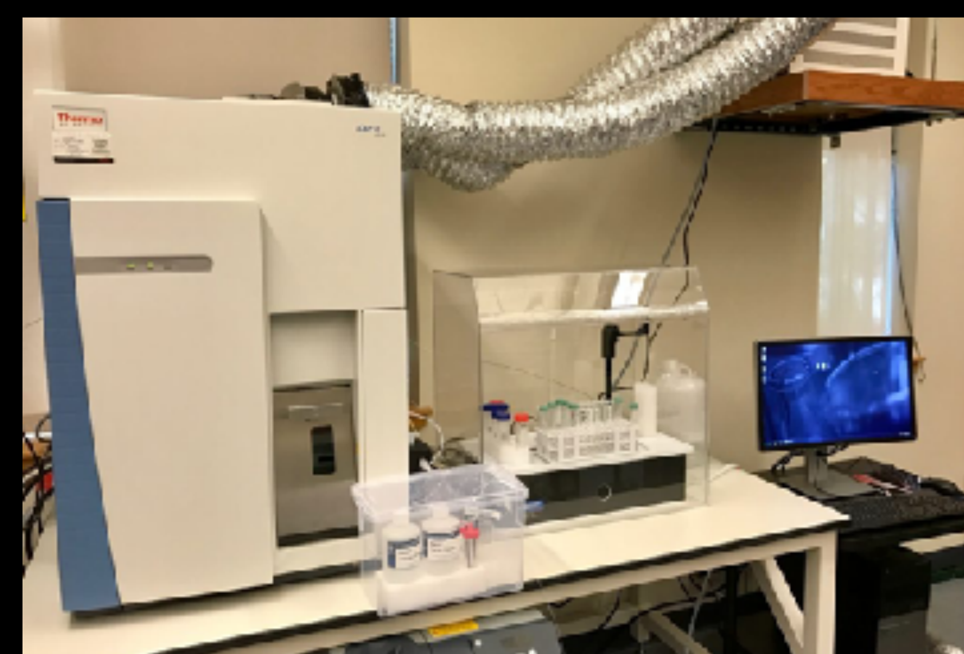


Isotope Cosmochemistry Laboratory

Clean lab
(terrestrial sample prep)

Ultra clean lab
(extraterrestrial sample prep)

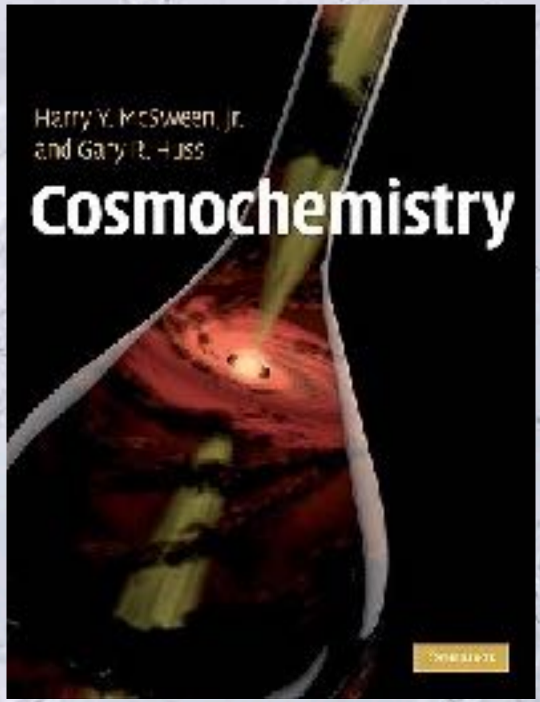
NEPTUNE Plus MC-ICP-MS



iCAP Q ICP-MS

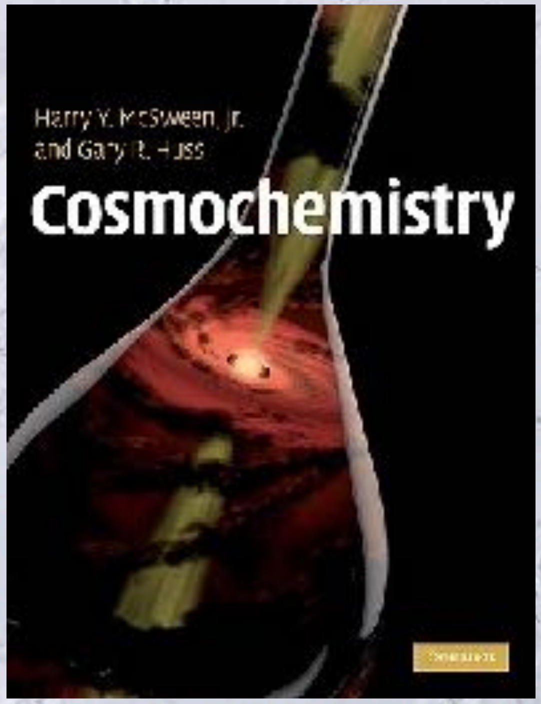
“天体化学旨在通过研究太阳系内包括行星，卫星，小行星等在内的各种天体及宇宙物质的化学组成，以揭示导致化学组成随空间时间演化的物理化学过程。”

Harry Y. McSween
Gary R. Huss



“同位素天体化学旨在通过研究太阳系内包括行星，卫星，小行星等在内的各种天体及宇宙物质的同位素组成，以揭示导致同位素随空间时间演化分馏的物理化学过程。”

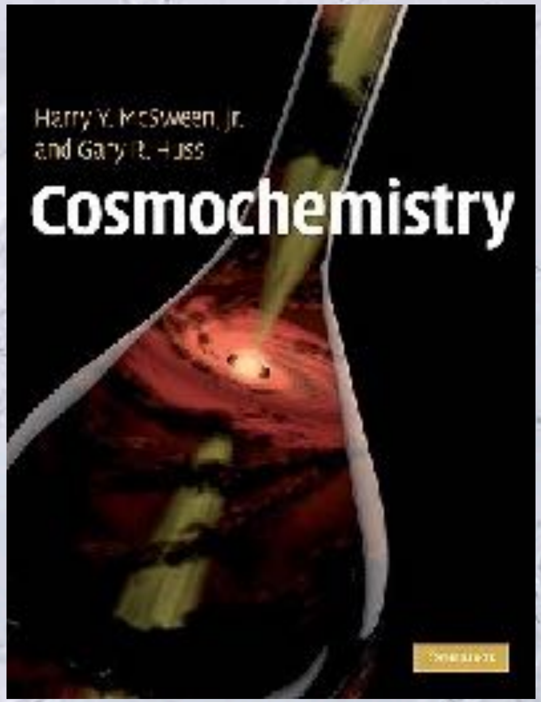
Harry Y. McSween
Gary R. Huss

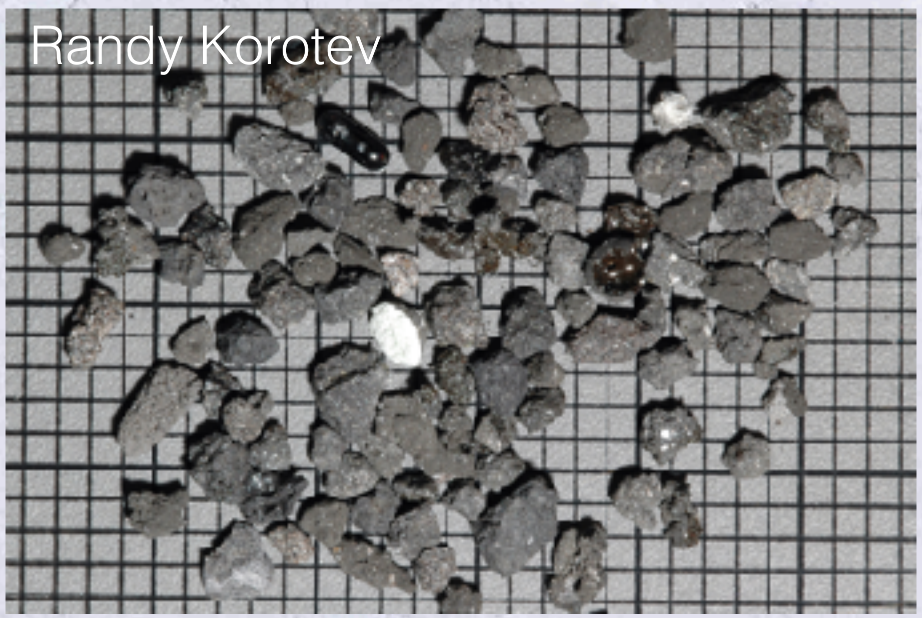


非传统

“同位素天体化学旨在通过研究太阳系内包括行星，卫星，小行星等在内的各种天体及宇宙物质的同位素组成，以揭示导致同位素随空间时间演化分馏的物理化学过程。”

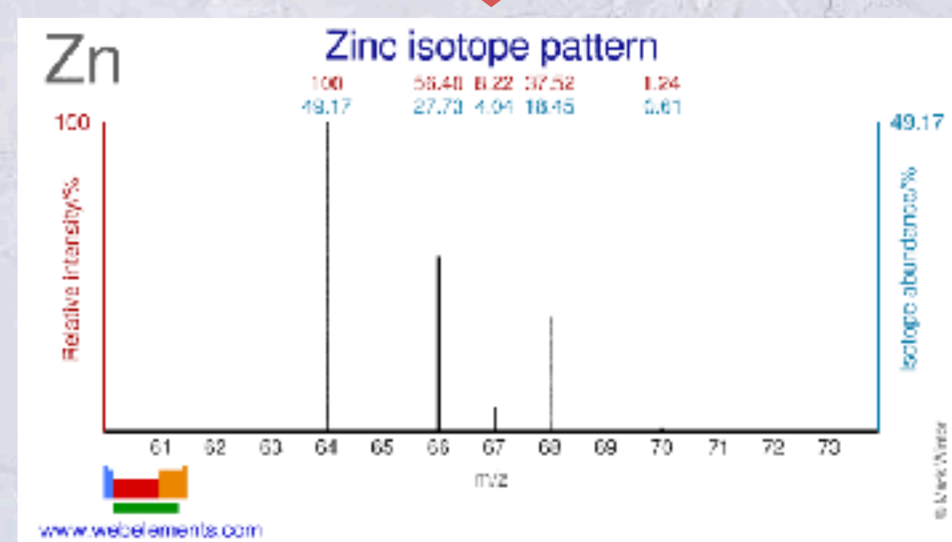
Harry Y. McSween
Gary R. Huss





Meteorites+Apollo
Lunar Samples

Elemental +
Isotopic analysis



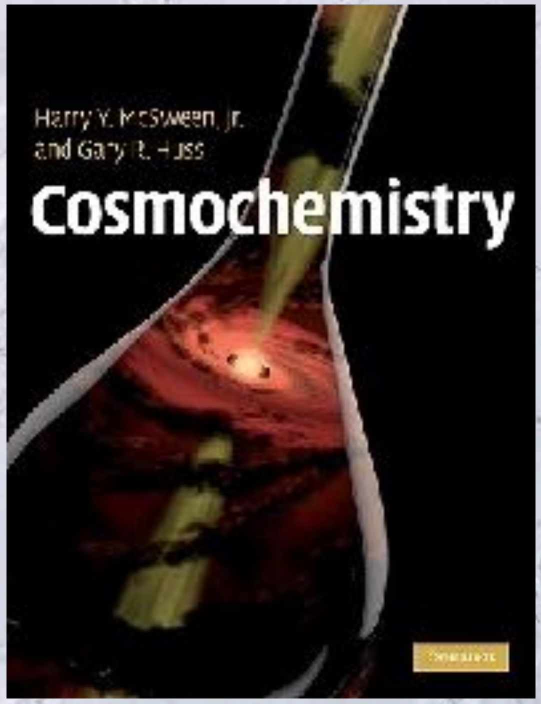
Data

Formation, differentiation,
magmatic process……

“同位素天体化学旨在通过研究太阳系内包括行星，卫星，小行星等在内的各种天体及宇宙物质的同位素组成，以揭示导致同位素随空间时间演化分馏的物理化学过程。”

太阳系本身和
太阳系内天体
的形成和演化

Harry Y. McSween
Gary R. Huss



The age of the Universe:

- **13.787±0.020 Billion years**
- **Hubble's law ($v = H_0 D$): $t_0 = D/v = 1/H_0$**

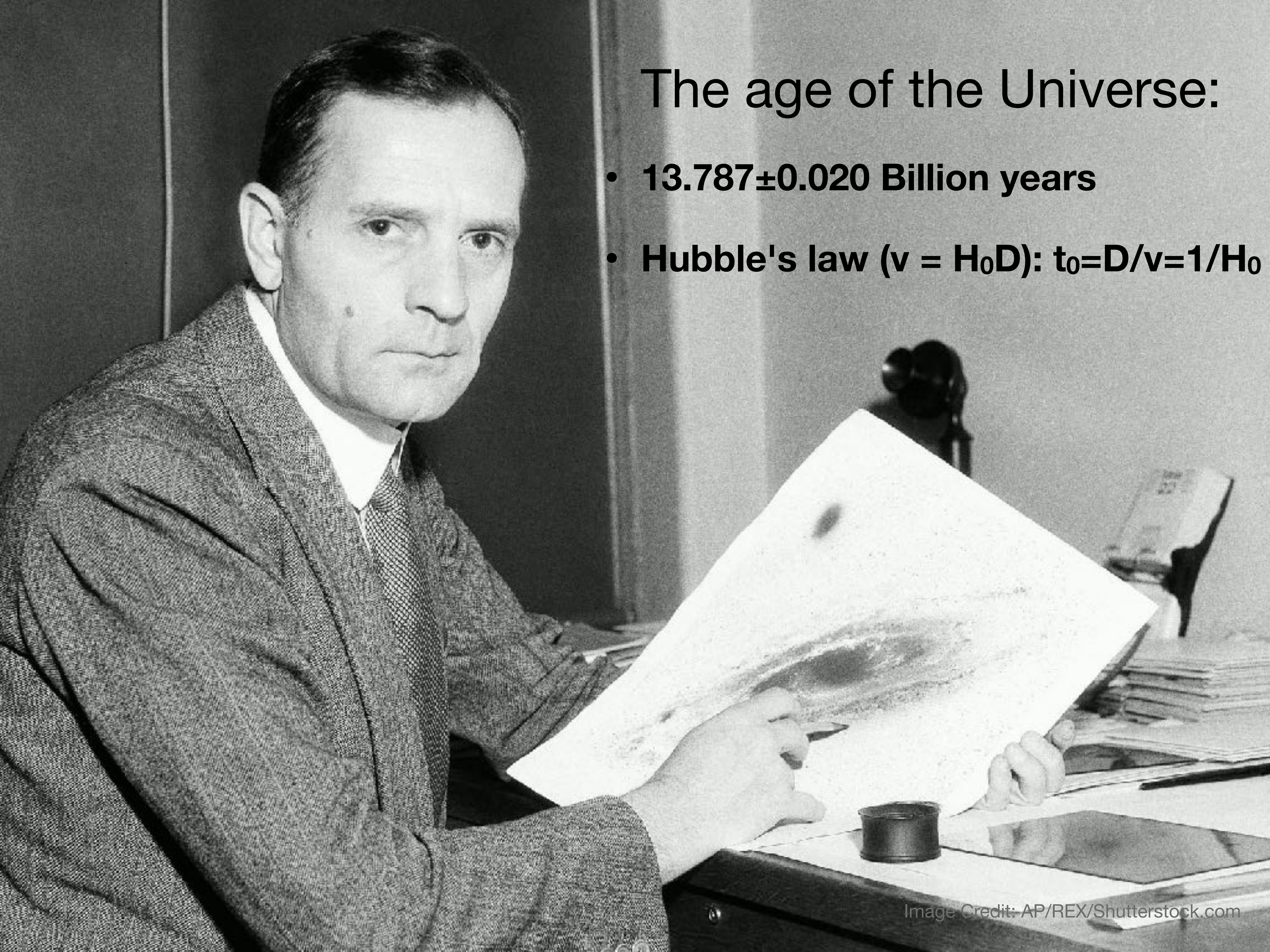
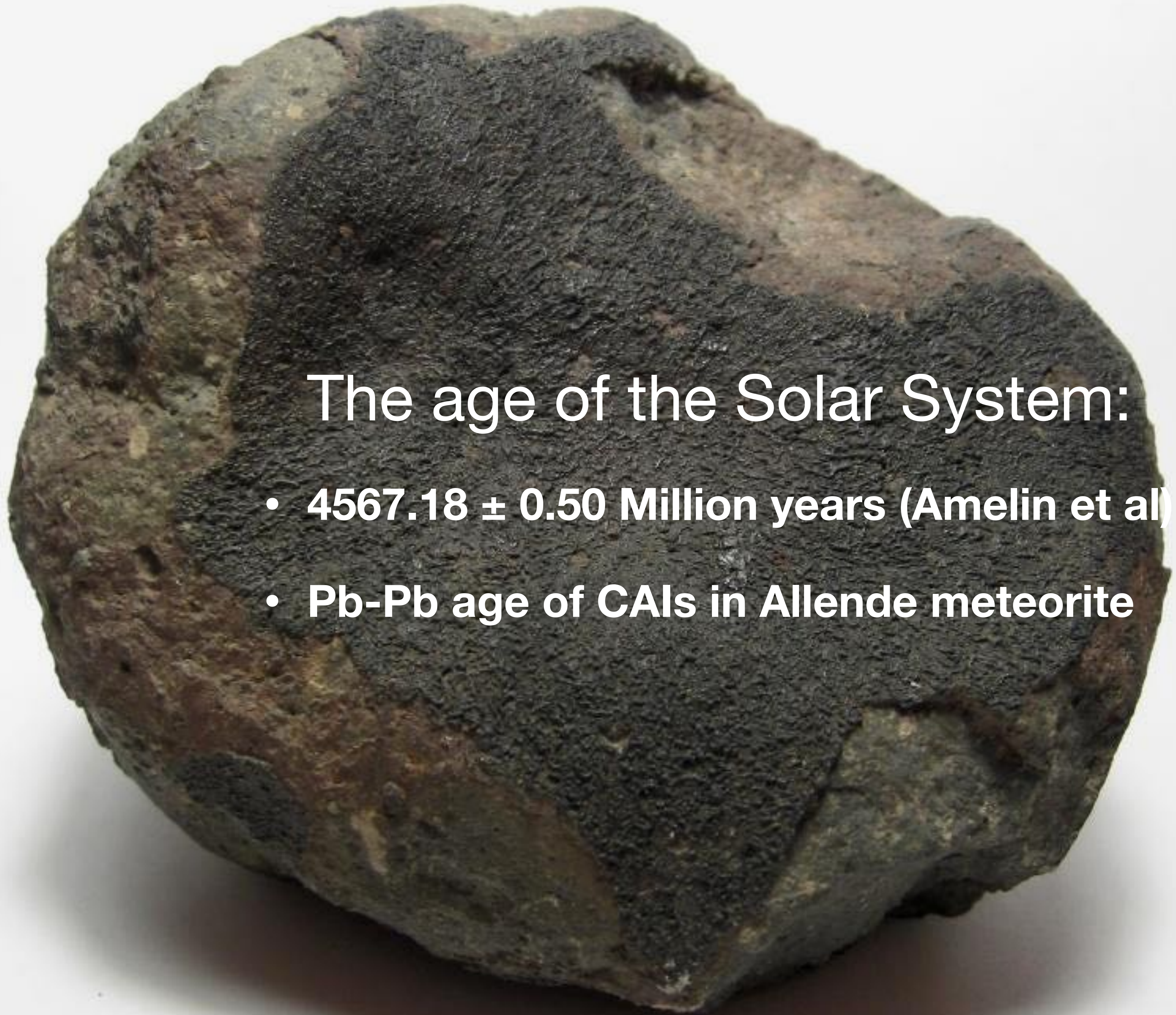


Image Credit: AP/REX/Shutterstock.com

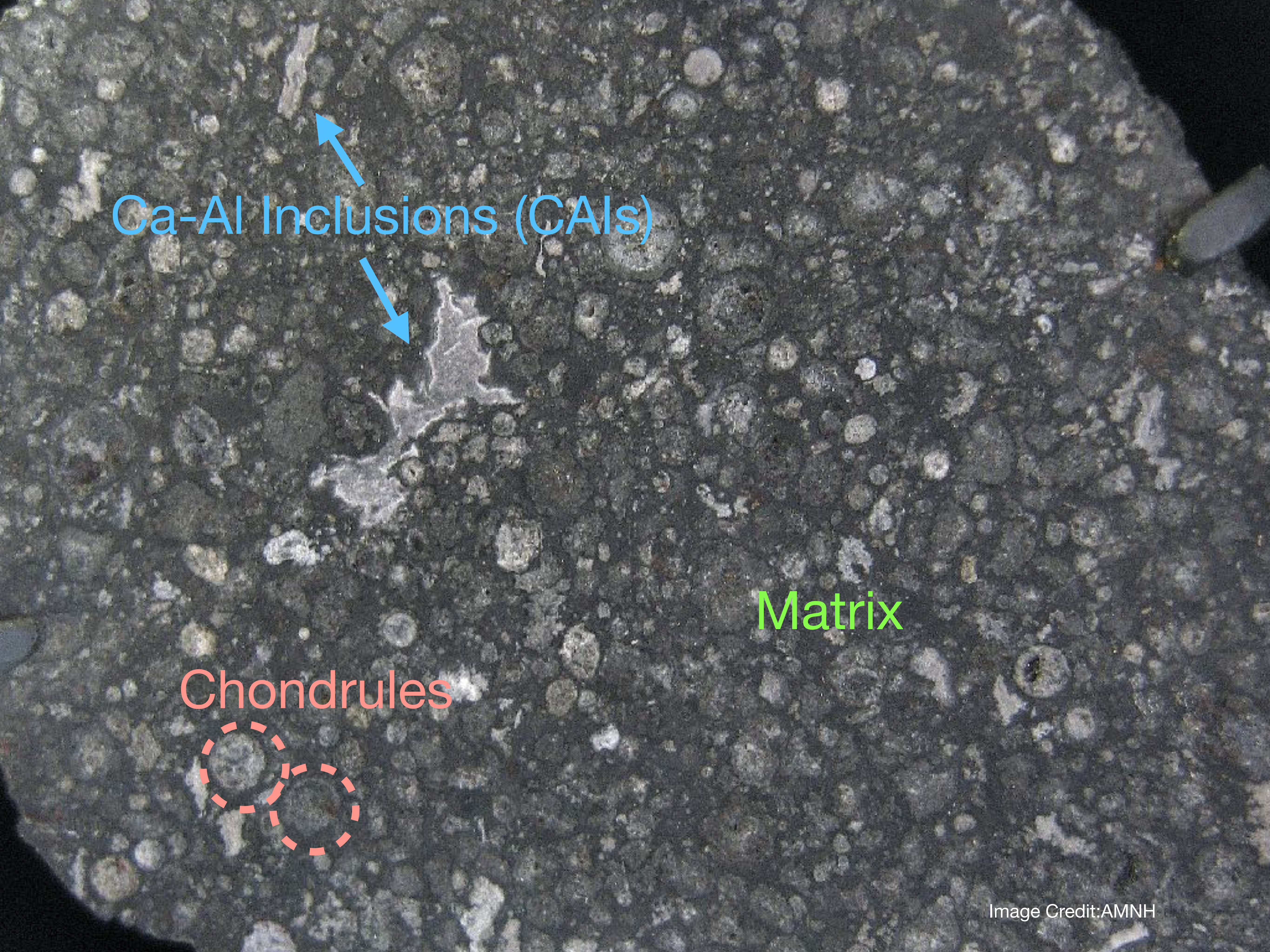


The age of the Solar System:

- **4567.18 ± 0.50 Million years (Amelin et al)**
- **Pb-Pb age of CAIs in Allende meteorite**

Image Credit: H. Raab

Image Credit: Stuart Hay


Ca-Al Inclusions (CAIs)
Matrix
Chondrules
Image Credit:AMNH

The First Solid of the Solar System

NWA 2086

Image Credit: Martin Horejsi

The age of the Earth:

- **4.55±0.07 Billion years**
- **Clair Cameron Patterson**

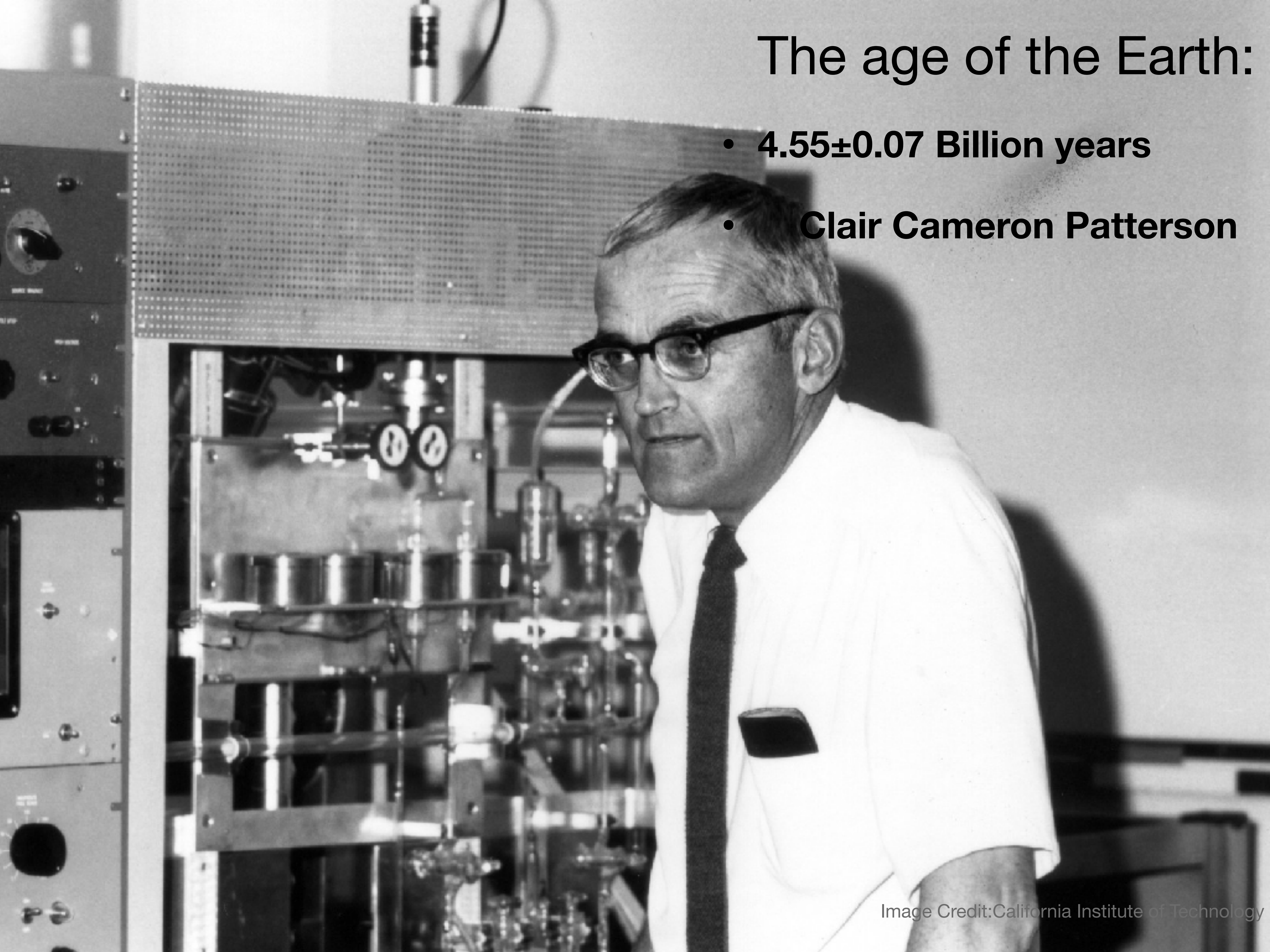


Image Credit:California Institute of Technology

Geochimica et Cosmochimica Acta, 1956, Vol. 10, pp. 230 to 237. Pergamon Press Ltd., London

Age of meteorites and the earth

CLAIRE PATTERSON
Division of Geological Sciences
California Institute of Technology, Pasadena, California

(*Received* 23 *January* 1956)

Abstract—Within experimental error, meteorites have one age as determined by three independent radiometric methods. The most accurate method (Pb^{207}/Pb^{206}) gives an age of $4{\cdot}55 \pm 0{\cdot}07 \times 10^9$ yr. Using certain assumptions which are apparently justified, one can define the isotopic evolution of lead for any meteoritic body. It is found that earth lead meets the requirements of this definition. It is therefore believed that the age for the earth is the same as for meteorites. This is the time since the earth attained its present mass.

The Formation of the Solar System

- The age of the Universe: 13.787±0.020 Billion years
- The age of the Solar System: 4.567 ± 0.0005 Billion years
- The age of the Earth: 4.55±0.07 Billion years

The Formation of the Solar System

- The age of the Universe: 13.787±0.020 Billion years

~9 Billion years

- The age of the Solar System: 4.567 ± 0.0005 Billion years

~0 Billion years

- The age of the Earth: 4.55±0.07 Billion years

The Formation of the Solar System

- The age of the Universe: 13.787±0.020 Billion years

↓ ~9 Billion years

- The age of the Solar System: 4.567 ± 0.0005 Billion years

↓ ~30-100 Million years (Hf-W)

- The age of the Earth: 4.55±0.07 Billion years

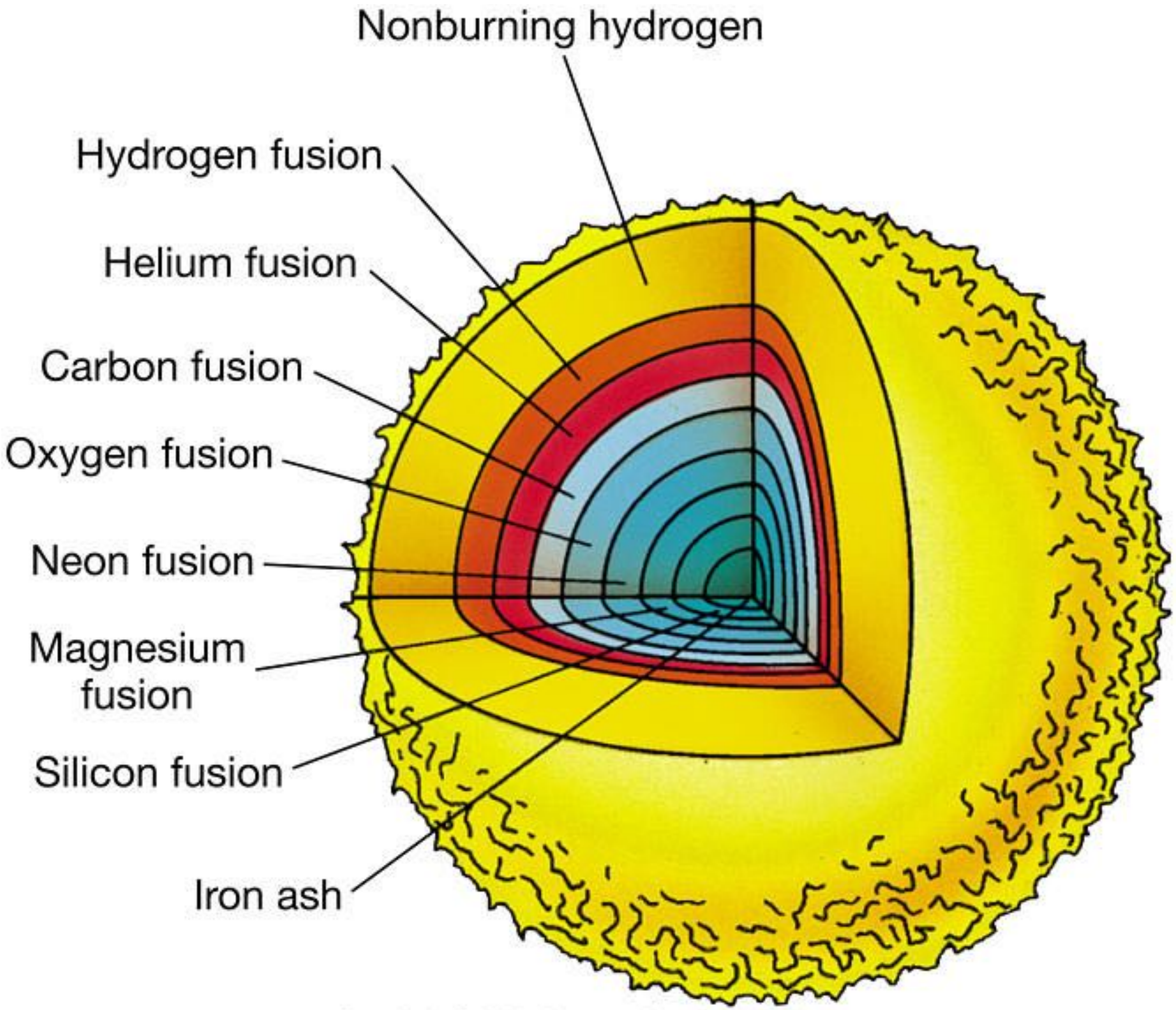

13.787±0.020 Billion years
“Big Bang”
produced hydrogen,
helium and lithum
© Siloto/Alamy

After “Big Bang”

First-Generation Stars Formed

Image Credit:Science Photo Library/Getty

Stellar nucleosynthesis creates heavier elements (up to Fe)



Supernova produced elements heavier than Fe

Image Credit: NASA

Nucleosynthesis periodic table

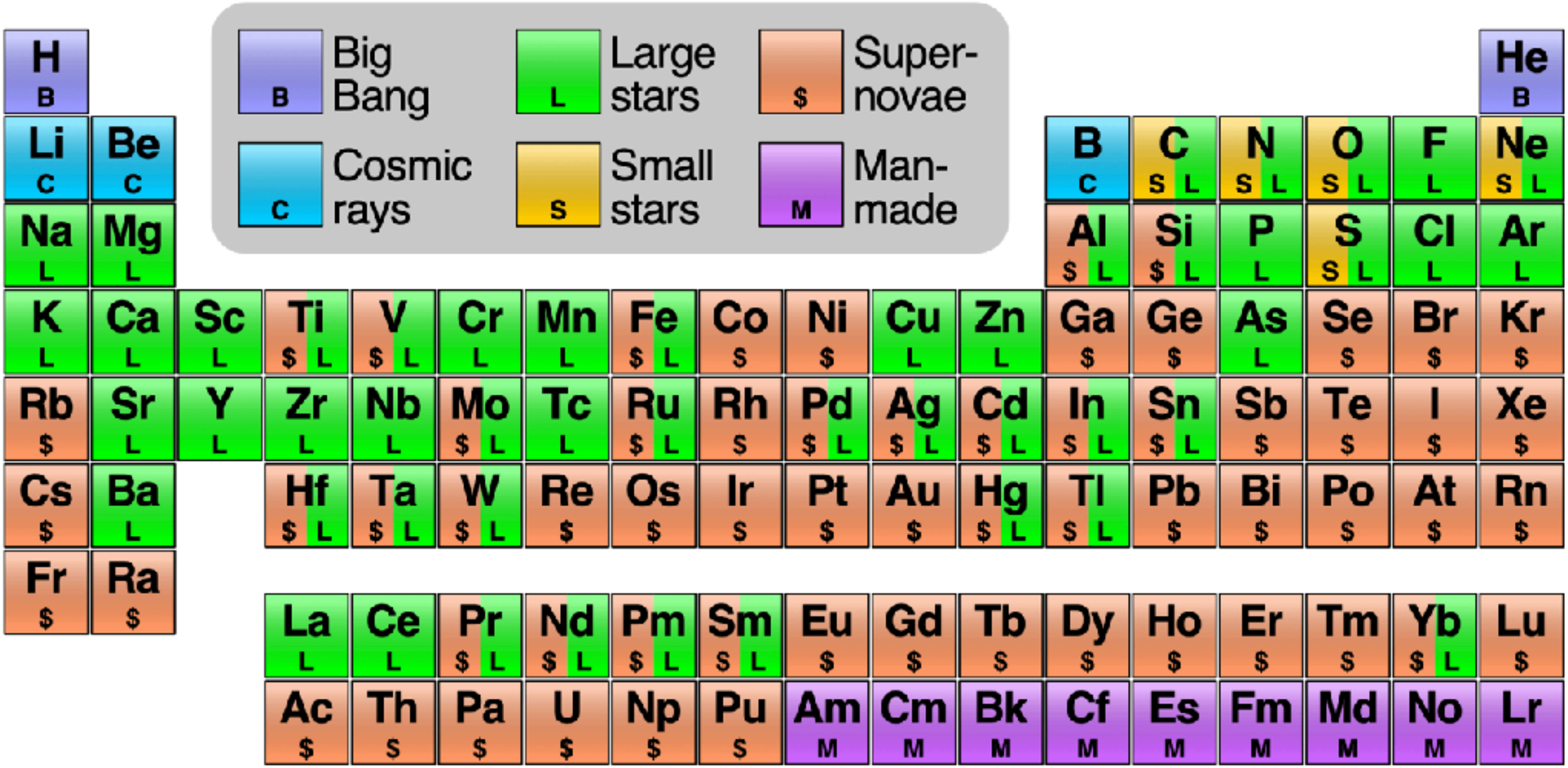


Image Credit: Cmglee

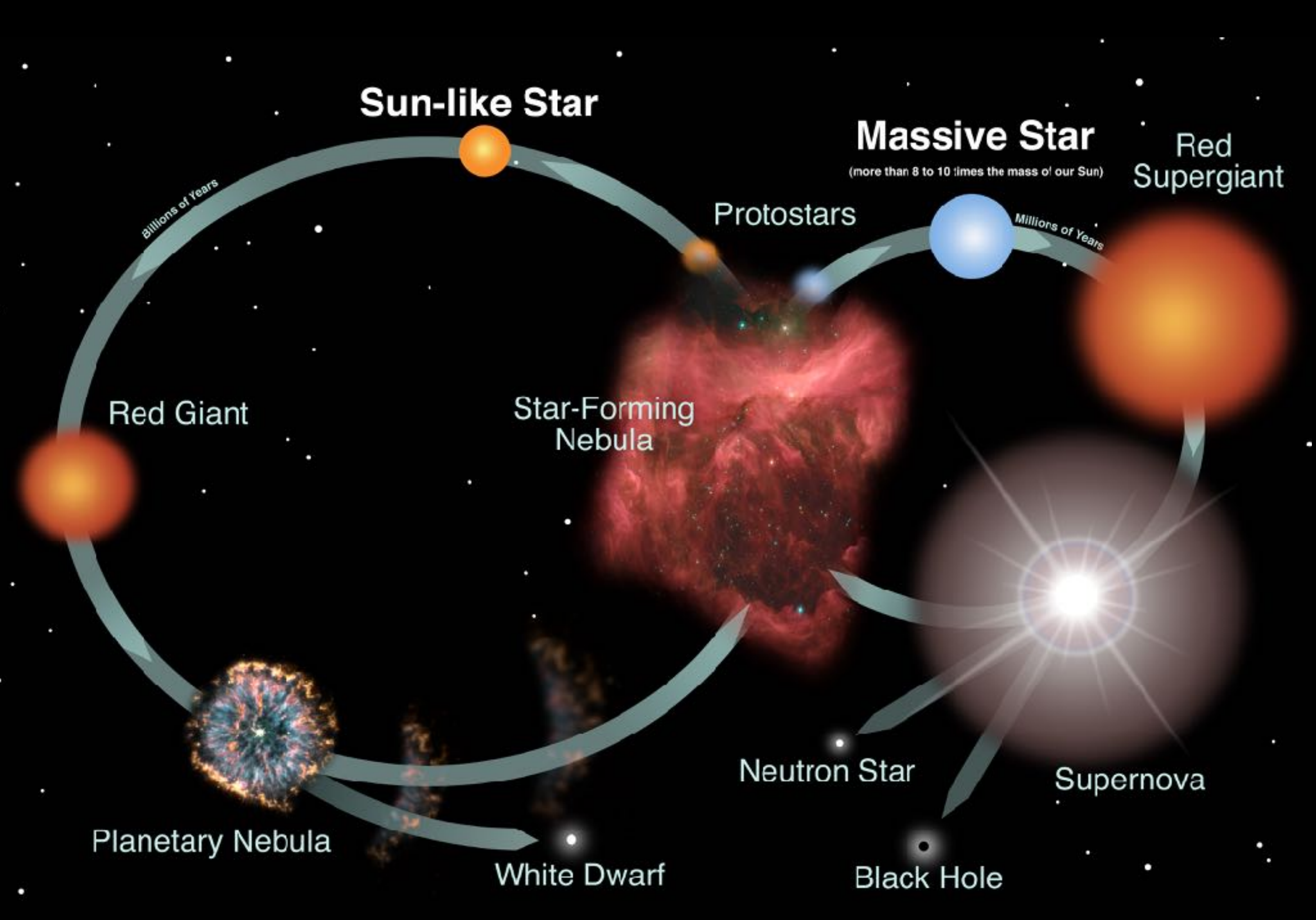


Image Credit: NASA and the Night Sky Network

The Formation of the Solar System

- The age of the Universe: 13.787±0.020 Billion years

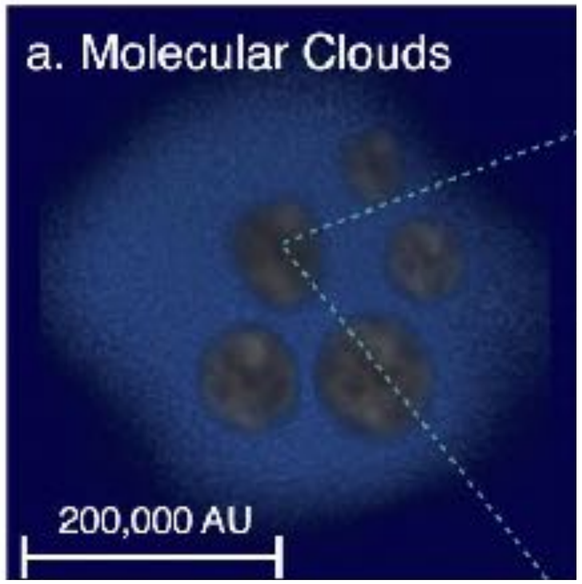
~9 Billion years

- The age of the Solar System: 4.567 ± 0.0005 Billion years

~30-100 Million years (Hf-W)

- The age of the Earth: 4.55±0.07 Billion years

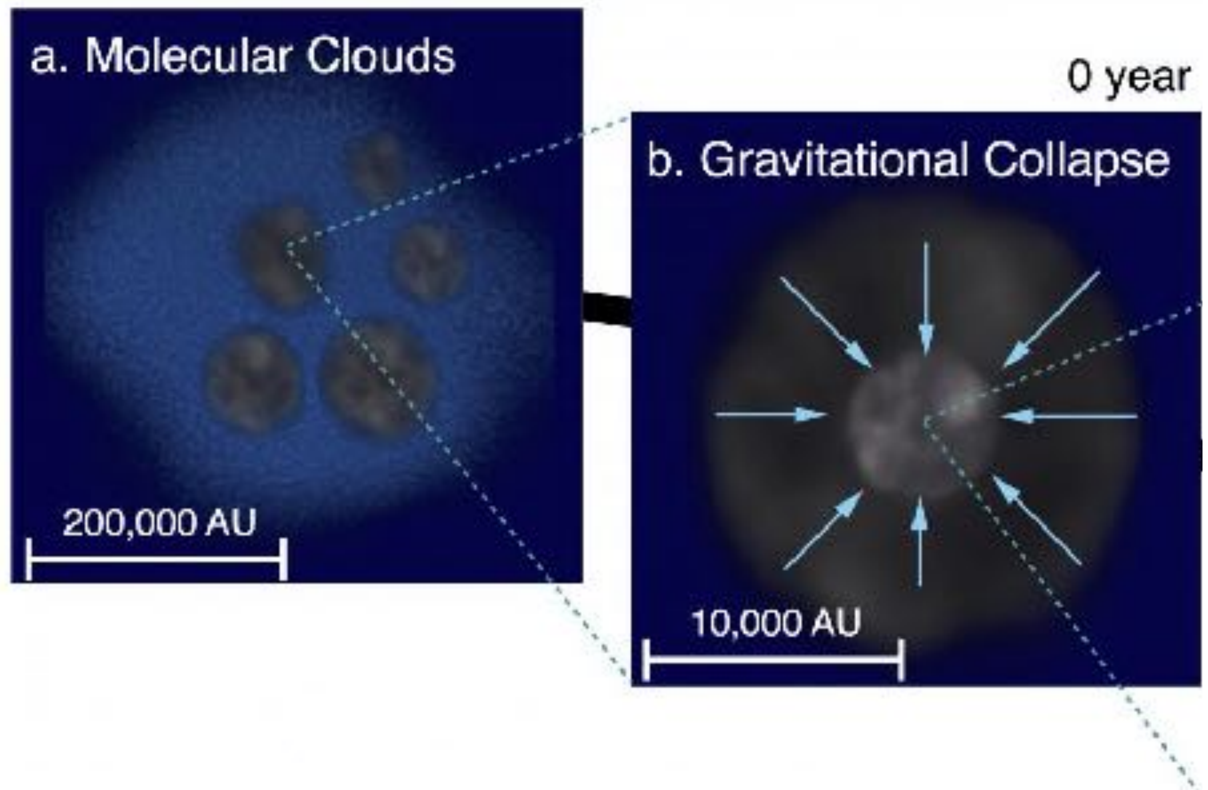
The Formation of the Solar System



Clouds of gas and dust are disturbed and form clumps

Image Credit: ASIAA

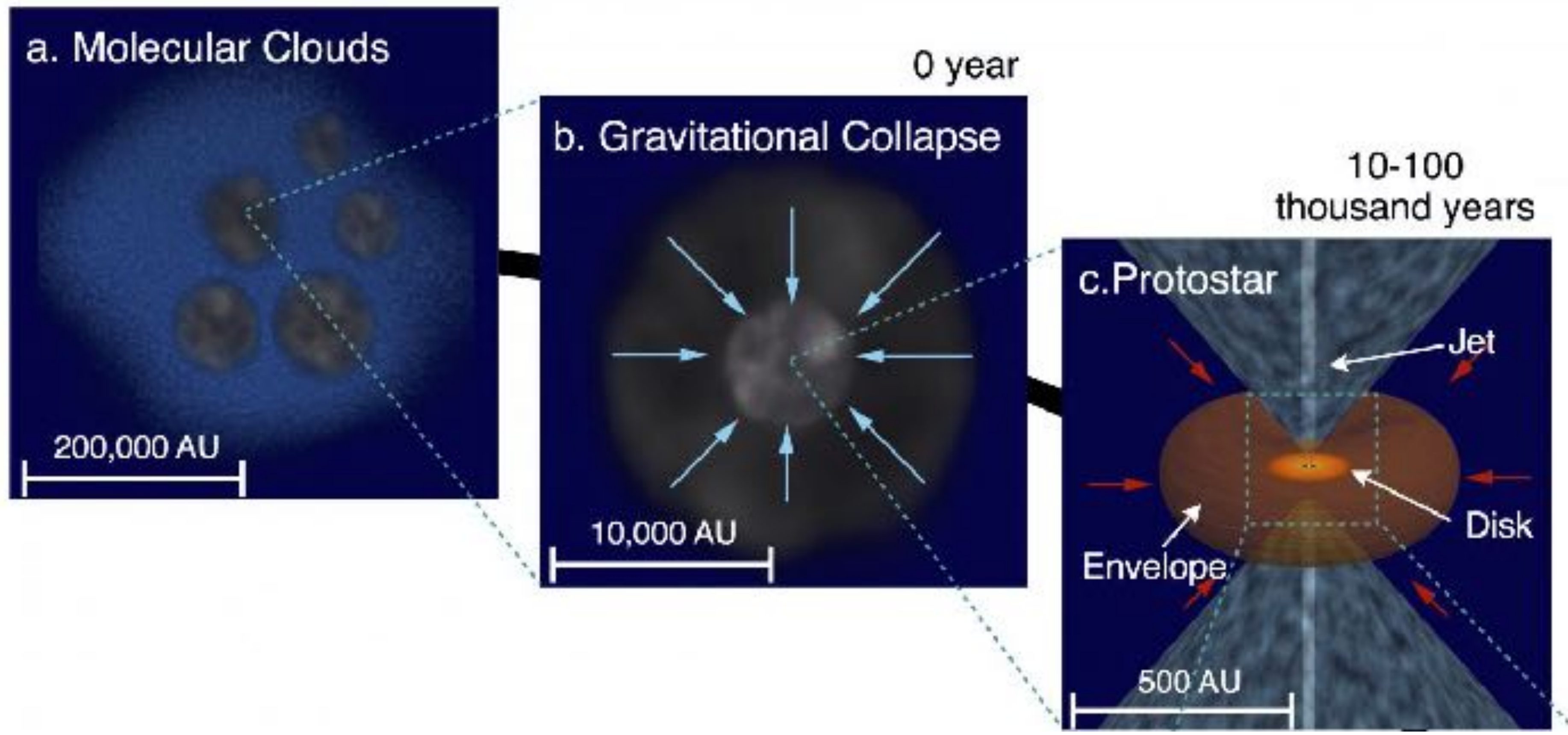
The Formation of the Solar System



Gravity increases
and the cloud collapses

Image Credit: ASIAA

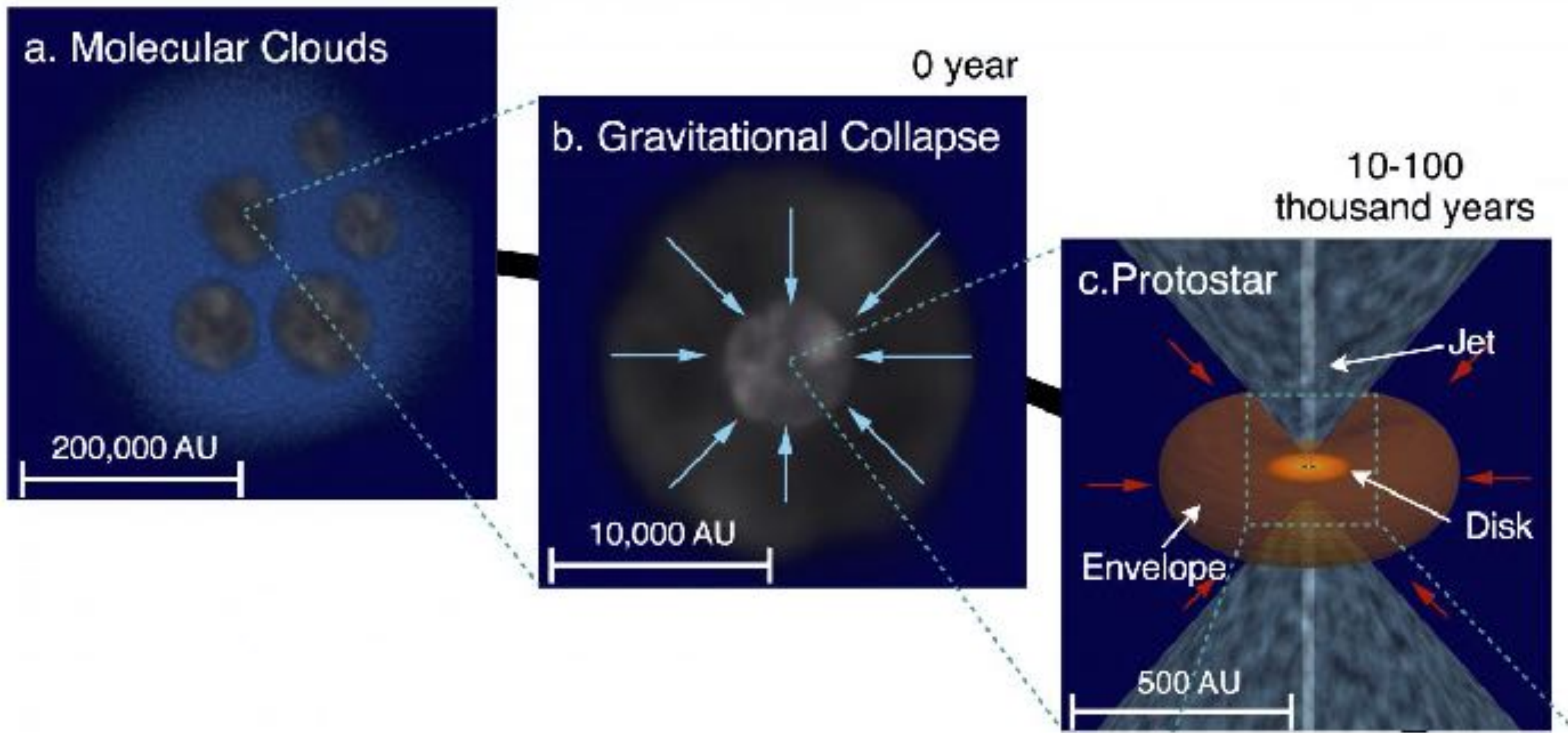
The Formation of the Solar System



Collapse of rotating clouds
forms a disk

Image Credit: ASIAA

The Formation of the Solar System



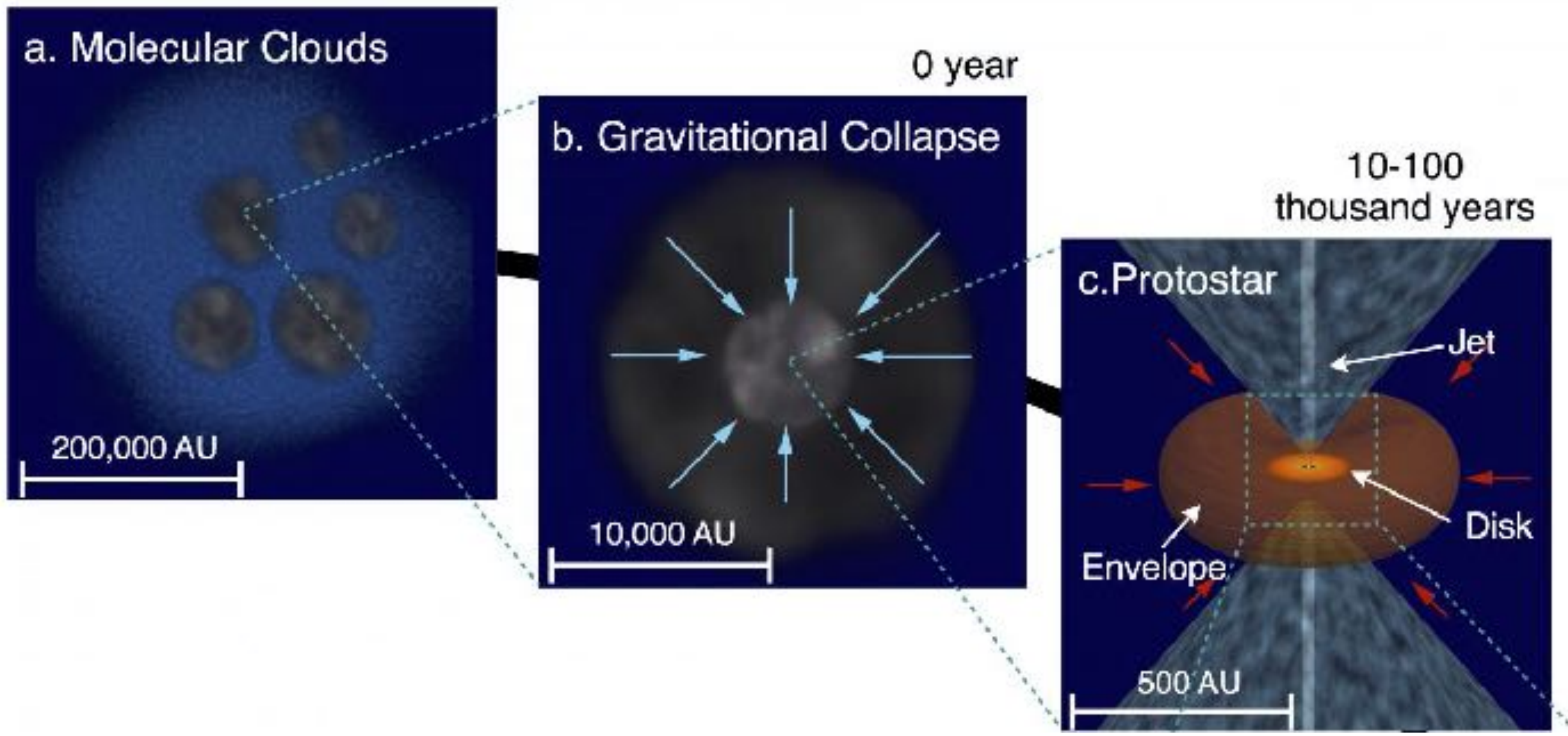
hot, dense core ignites
hydrogen fusion and becomes protostar

Image Credit: ASIAA

Image Credit: Hubble Space Telescope

Image Credit: Hubble Space Telescope

The Formation of the Solar System



T Tauri stars with bipolar outflows

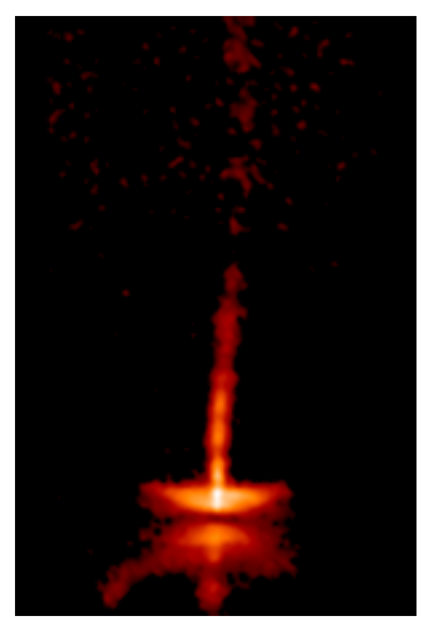


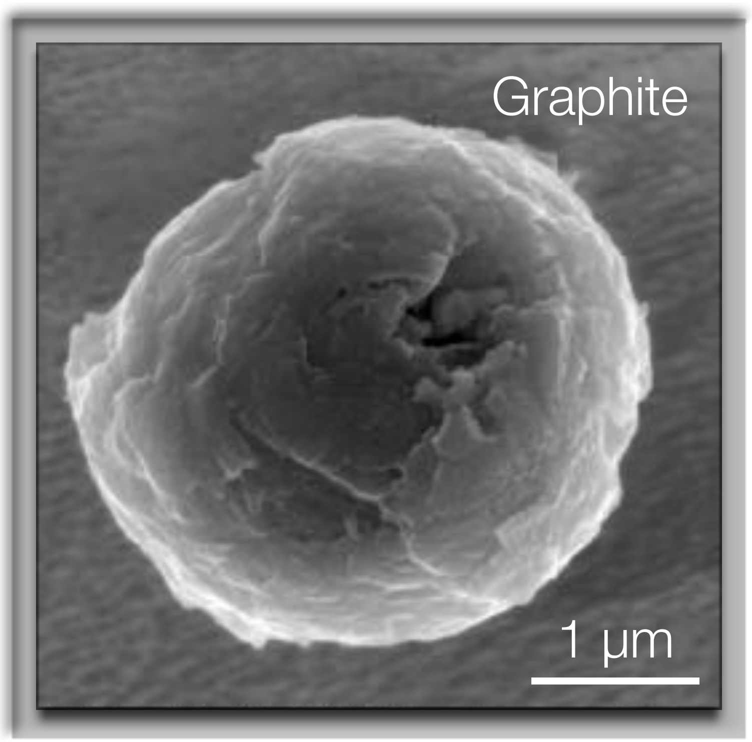
Image Credit: ASIAA/ NASA, A. Watson (UNAM), K. Stapelfeldt (JPL), J. Krist (STScI) and C. Burrows (ESA/ STScI)

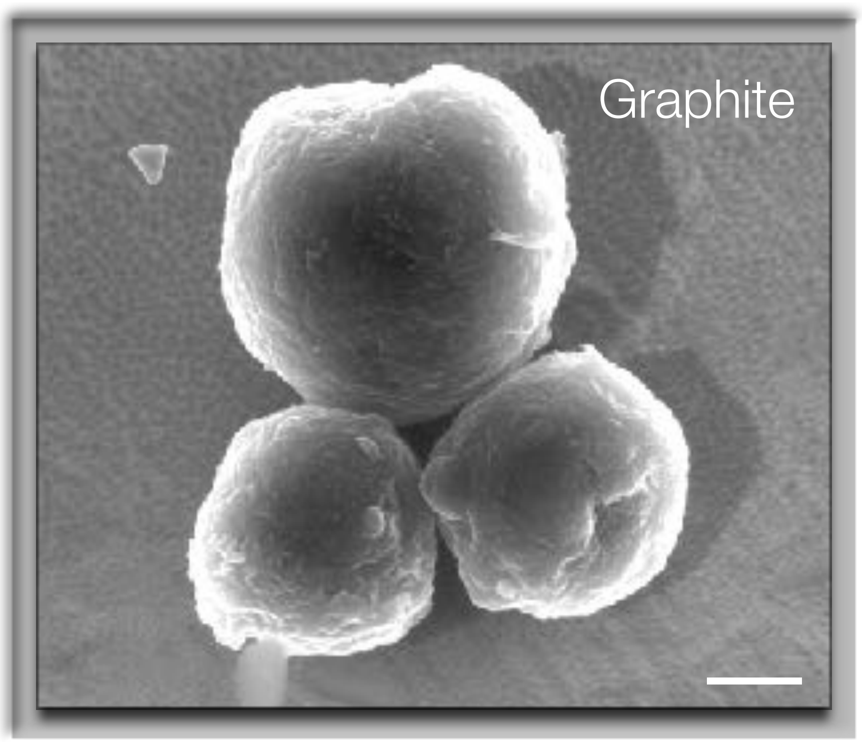
The Source of the Solar System

Presolar grains

- = star dust ➜ formed in other stars and remained intact throughout its journey into the solar system where it was preserved in primitive extraterrestrial materials.

- (characterized by large isotopic anomalies): C, N, O, Al (Mg), Si, Ca (K), Ti, V…..





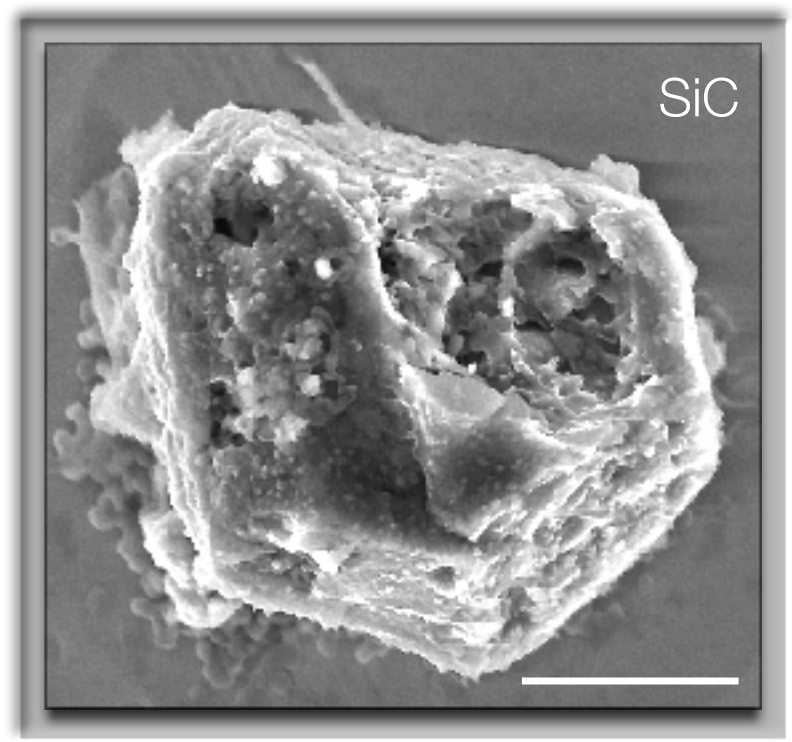


Image Credit: Pierre Haenecour

The Source of the Solar System

Presolar grains

- = star dust ➜ formed in other stars and remained intact throughout its journey into the solar system where it was preserved in primitive extraterrestrial materials.

- (characterized by large isotopic anomalies)

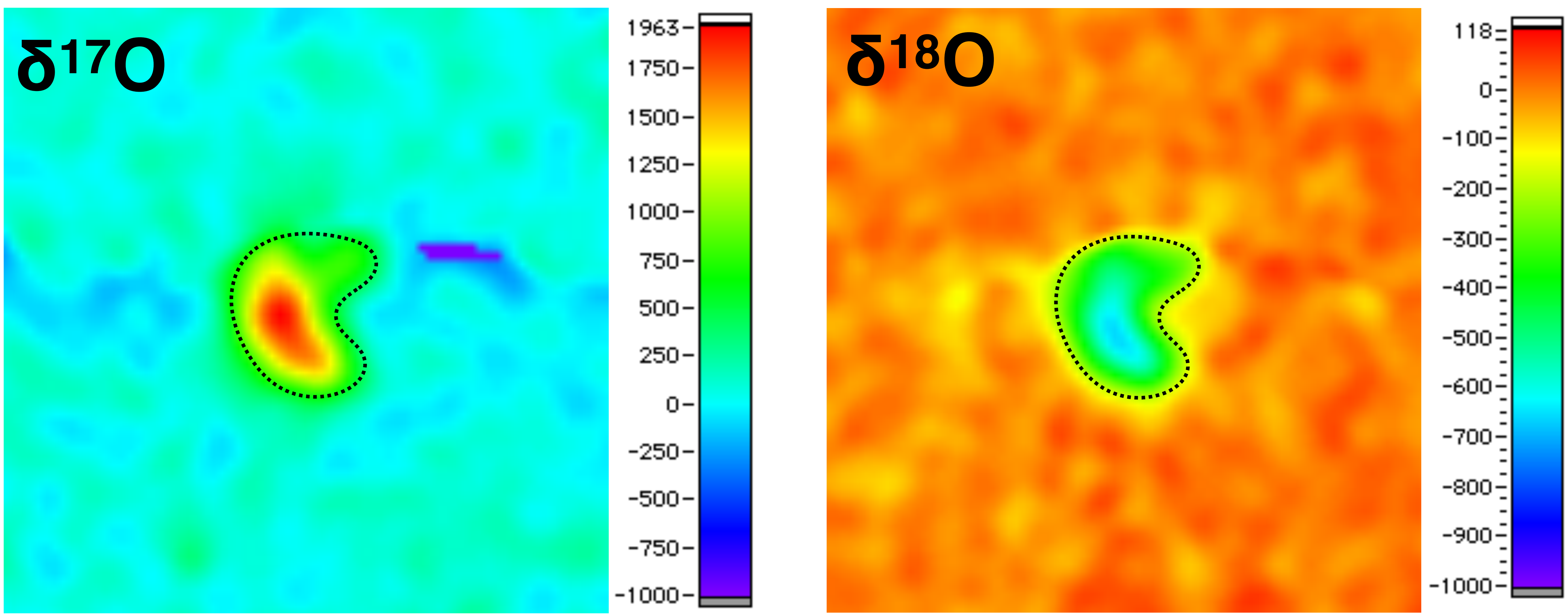


Image Credit: Pierre Haenecour

The Source of the Solar System

Presolar grains

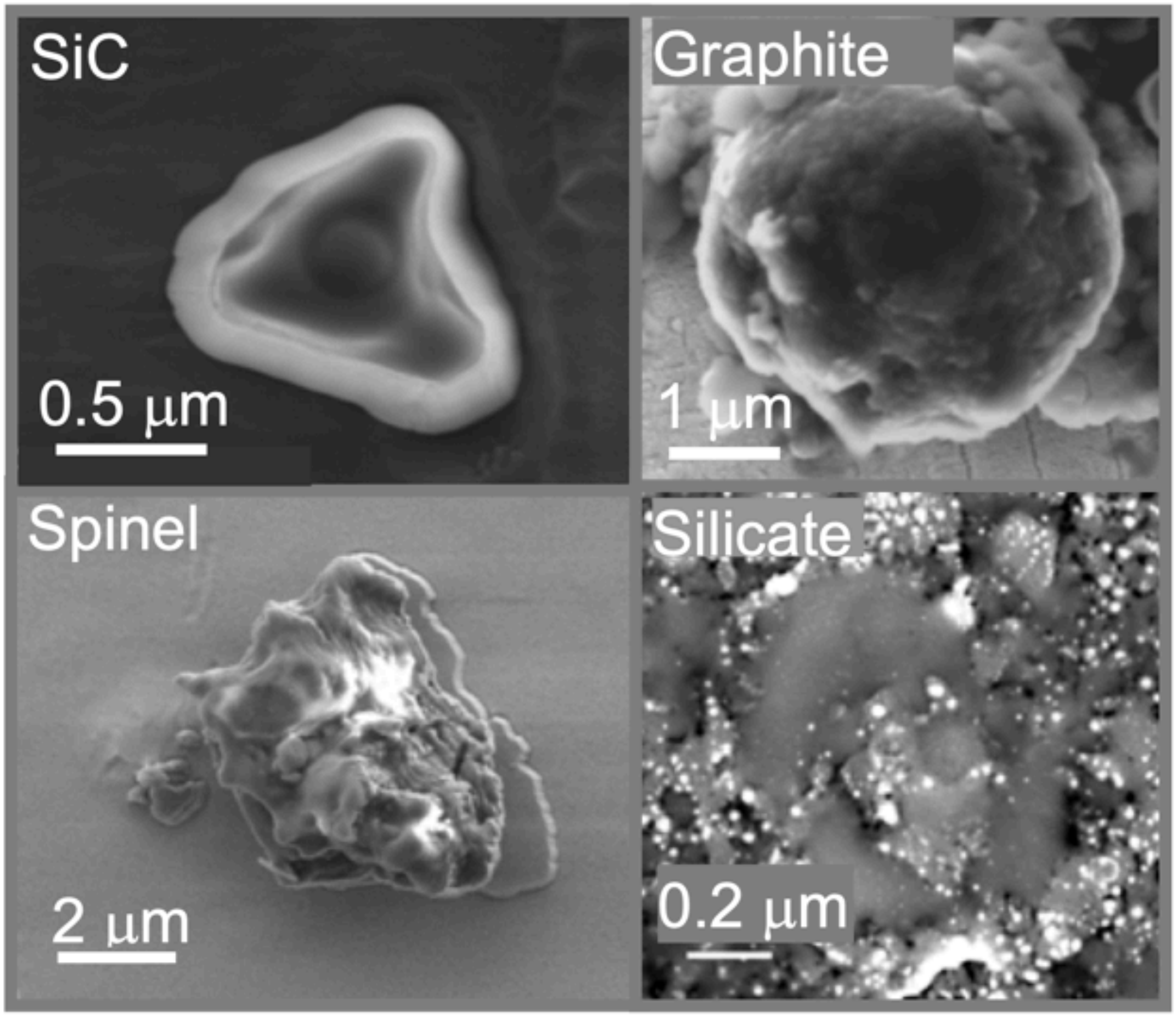


Image Credit: Hoppe (2010)

The Source of the Solar System

Presolar grains

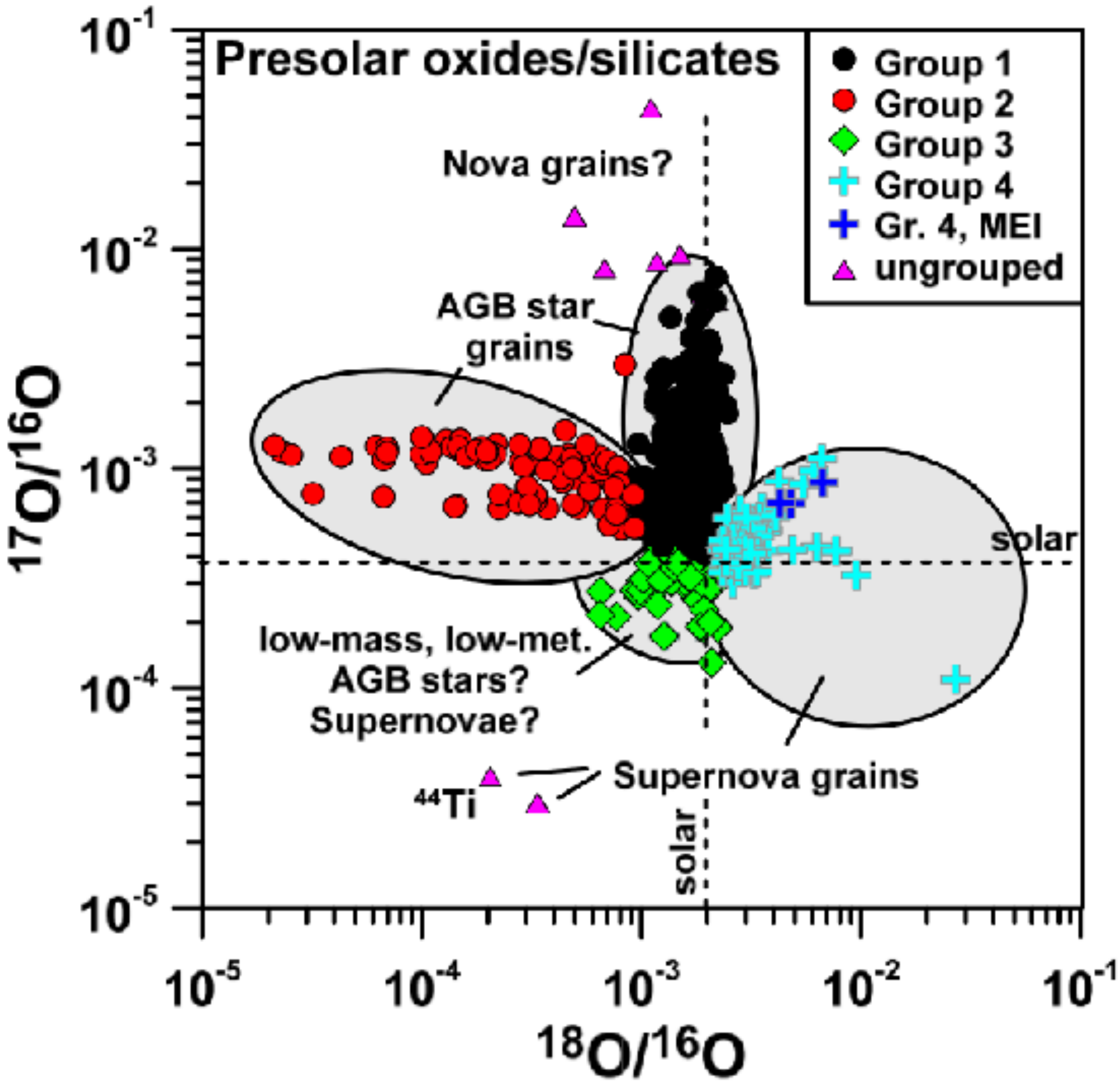


Image Credit: Hoppe (2010)

The Source of the Solar System

Presolar grains

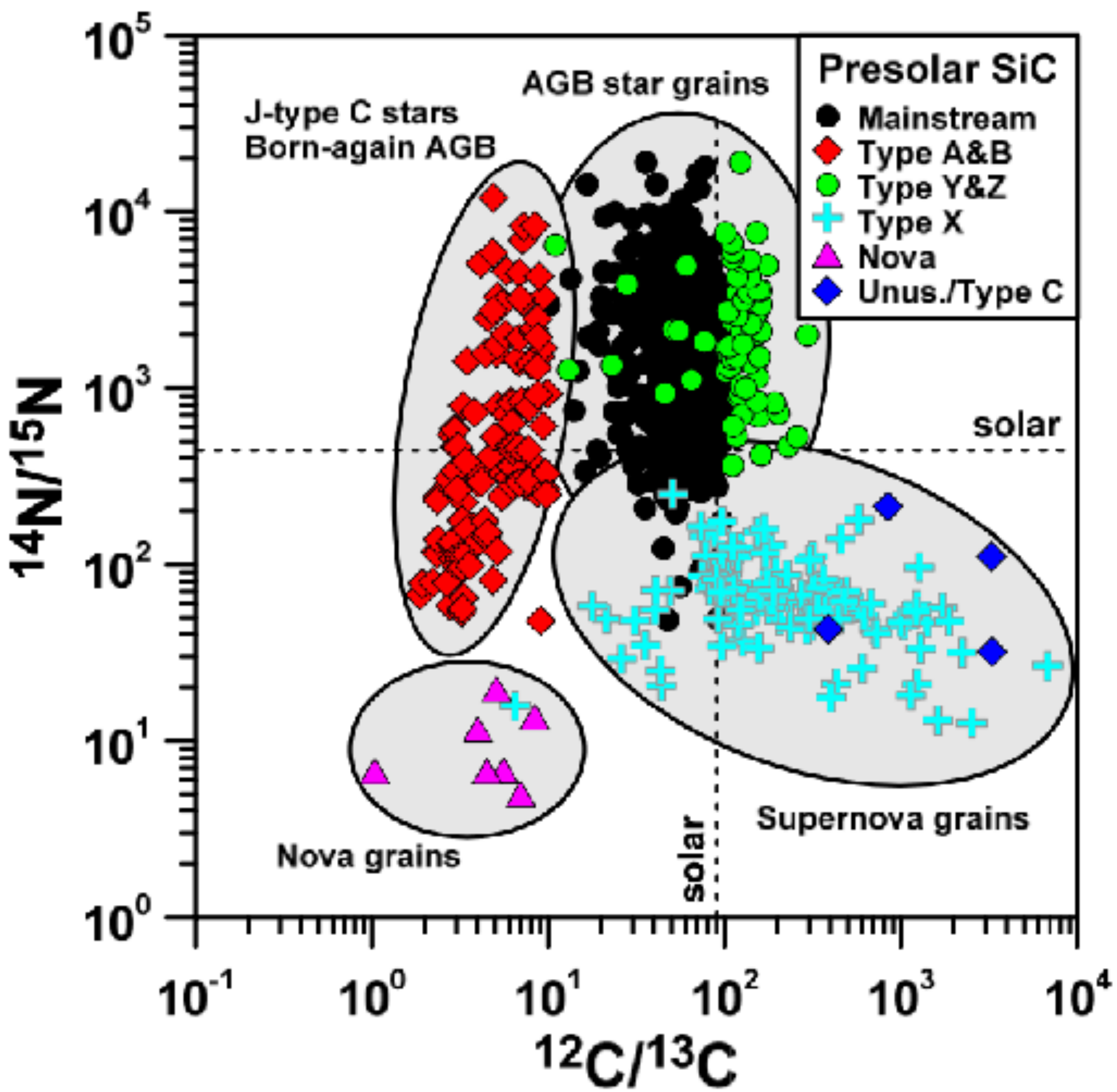


Image Credit: Hoppe (2010)

The Source of the Solar System

Presolar grains

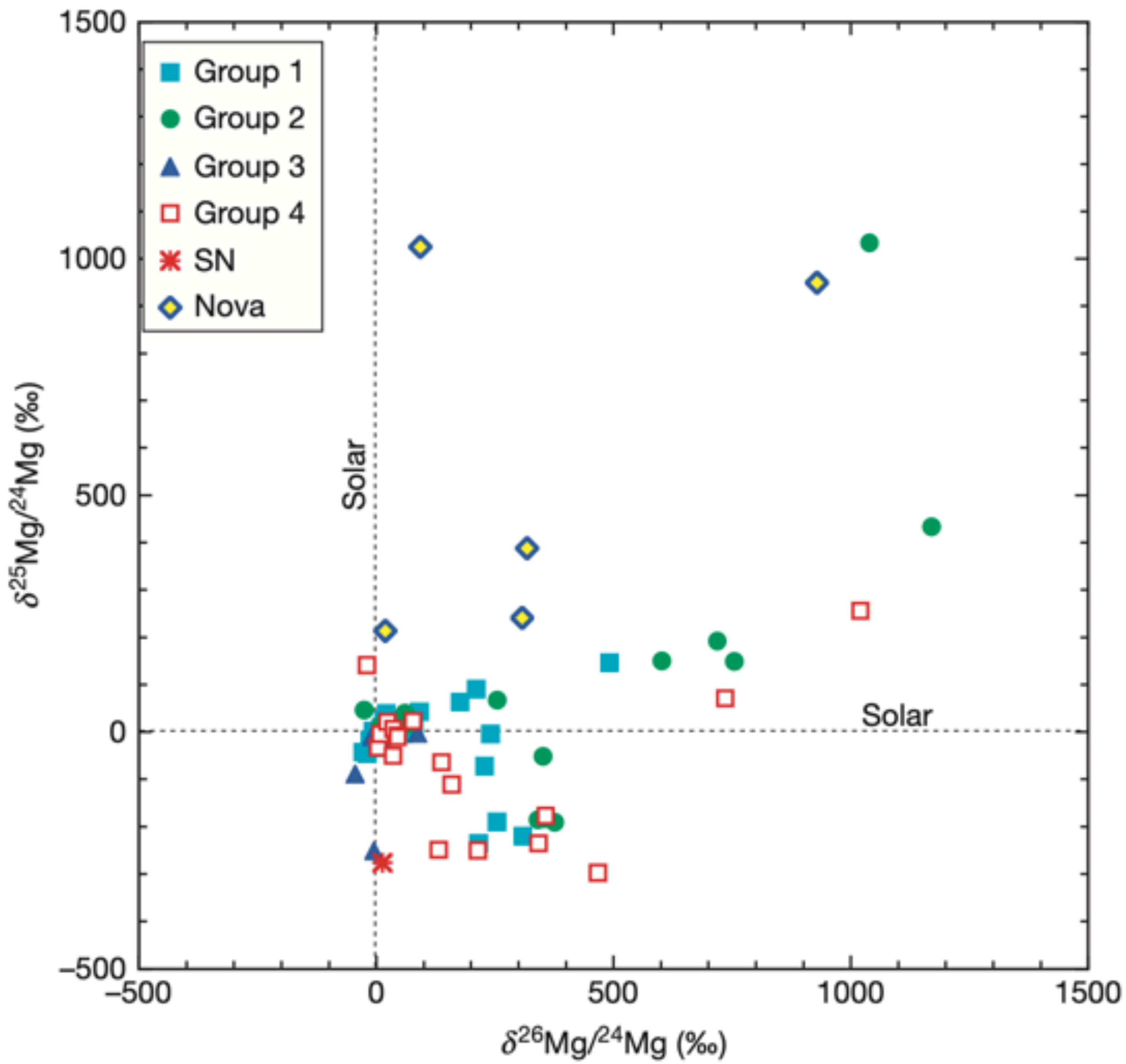


Image Credit: Zinner (2014)

The Source of the Solar System

Presolar grains

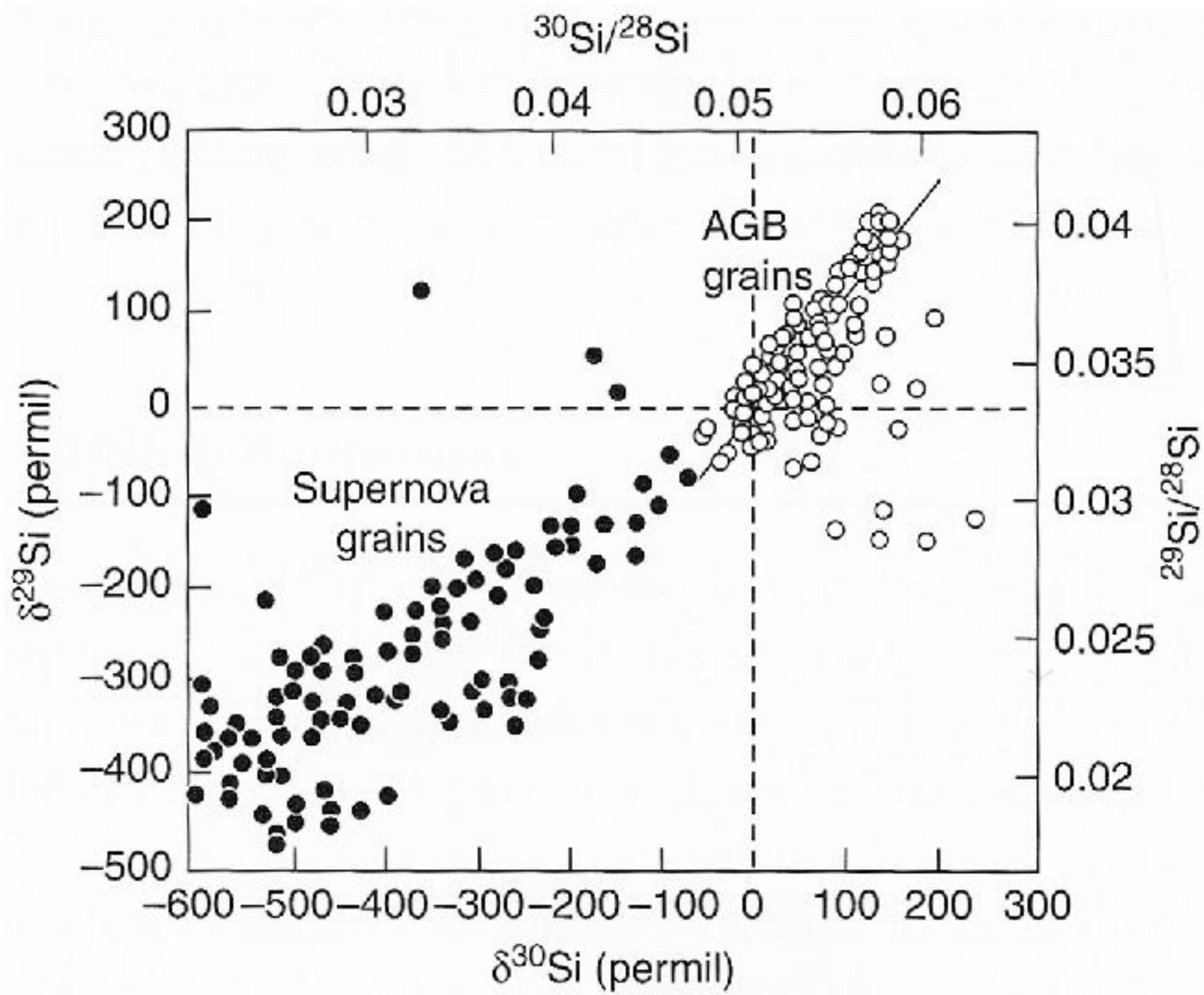
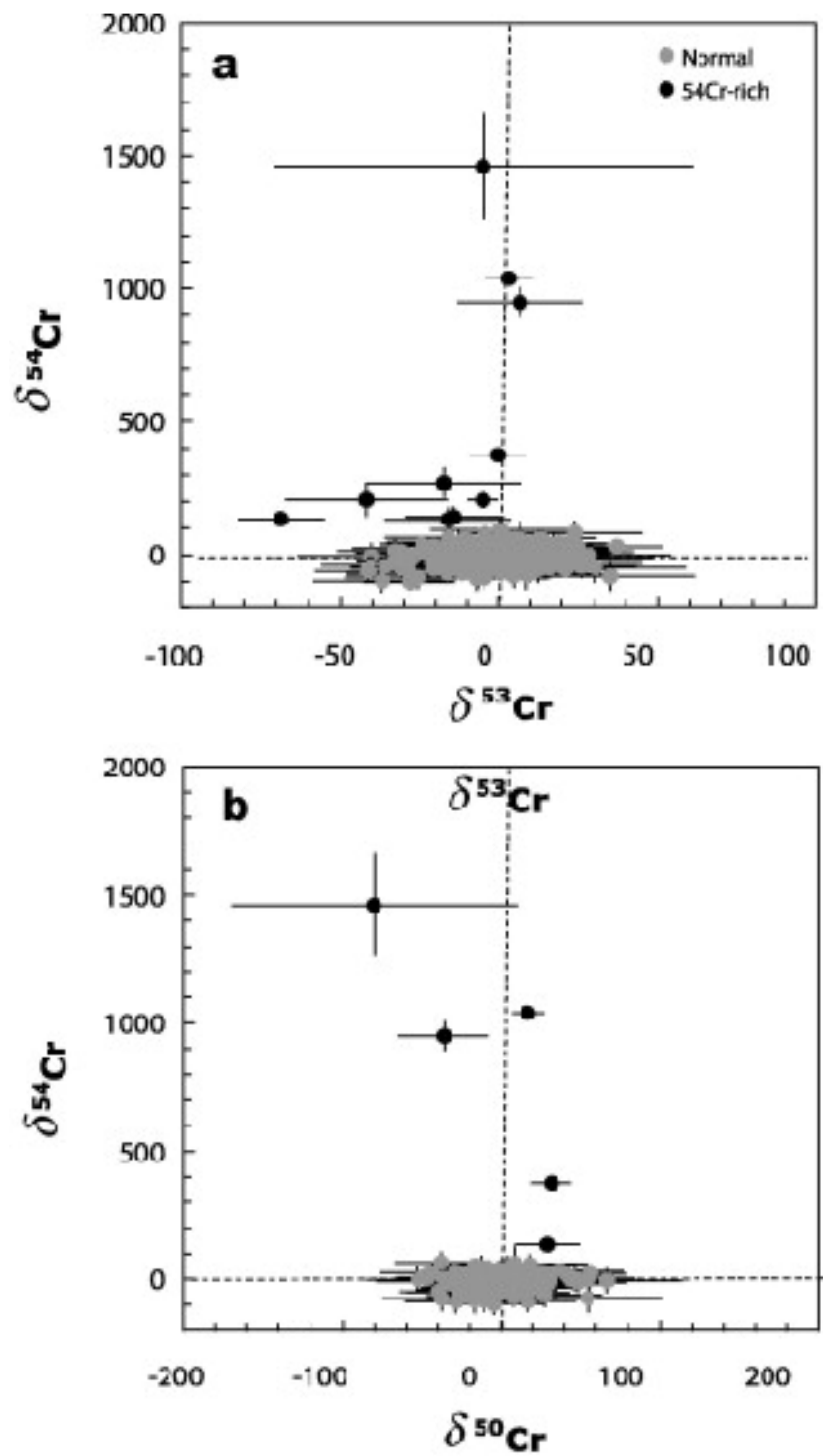


Image Credit: Zinner (2014)

The Source of the Solar System

Presolar grains



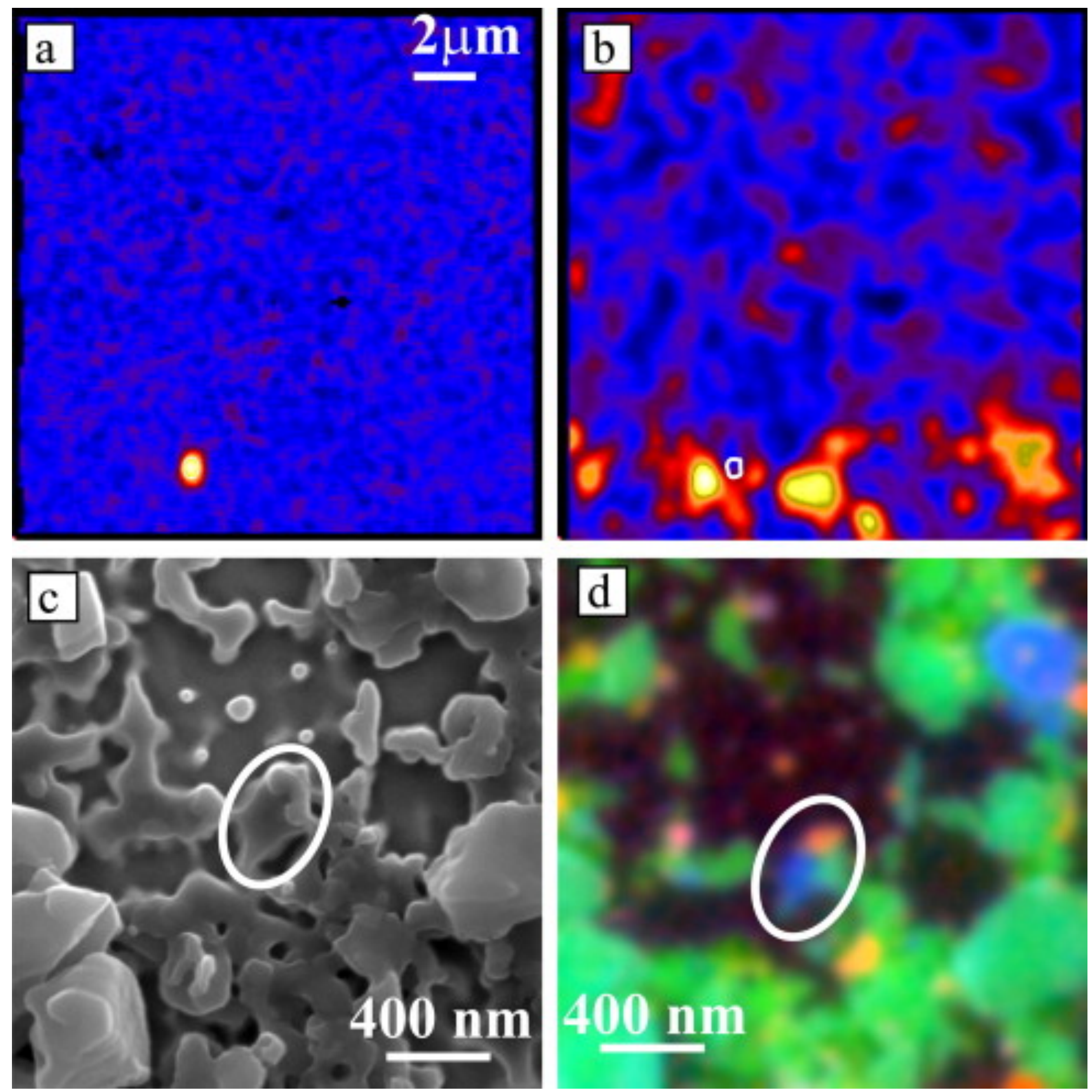


Image Credit: Qin et al. (2014)

The Source of the Solar System

Presolar grains

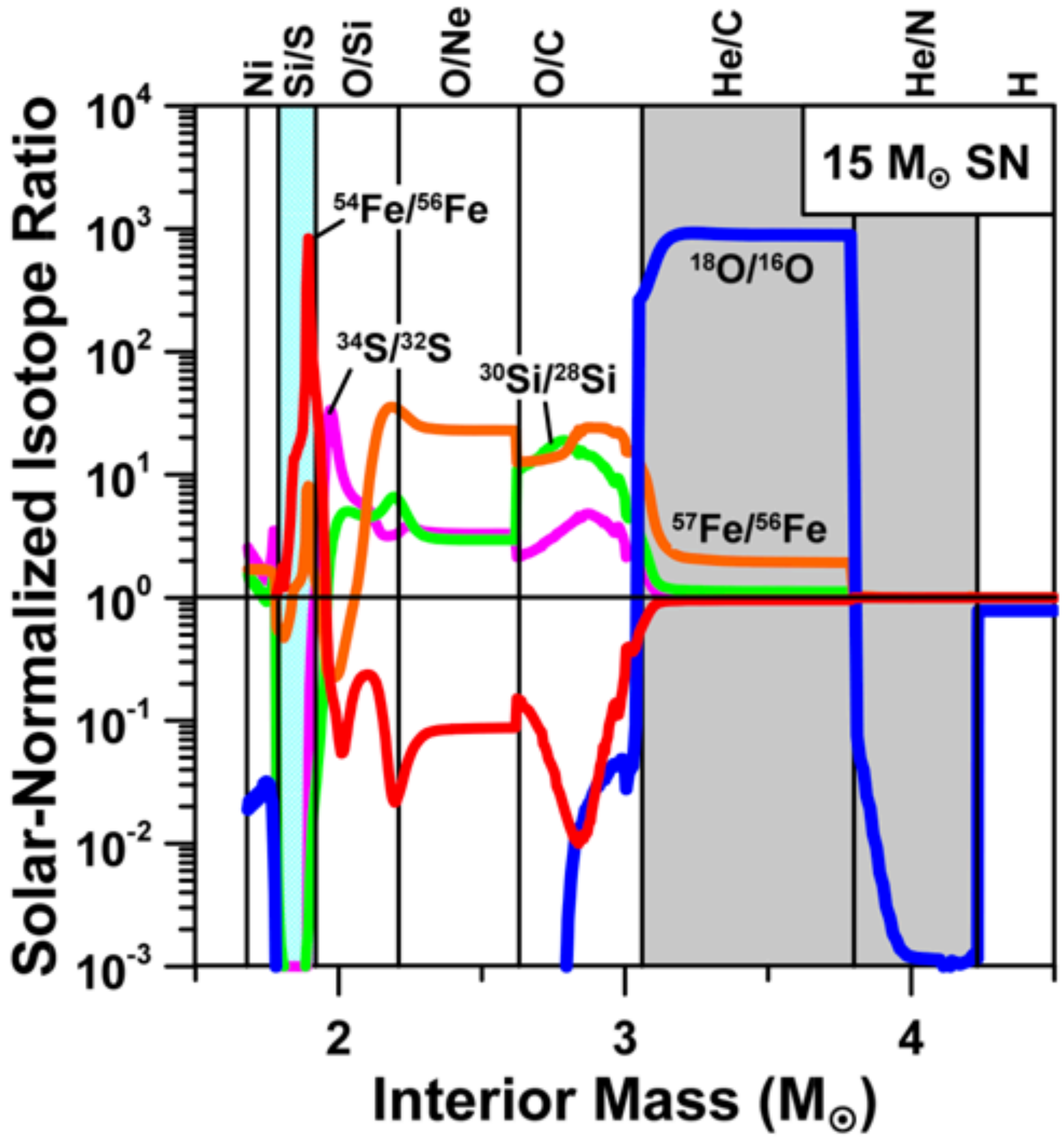


Image Credit: Hoppe (2010)

The Source of the Solar System

Presolar grains

Mineral	Abundance (ppm)	Stellar Source	%
SiC	30	**AGB (1.5-3M)** J-type C stars SNII Novae	**>90** <5 1 0.3
Graphite	10	**SNII** AGB J-type C stars Novae	**60** 30 10 2
Si_3N_4	0.002	SNII	100
Oxides/silicates	50/200	**AGB (1-2.2M)** AGB (<1M) AGB (low M&Z) SNII Novae	**70** 15 5 10 <1

Image Credit: Hoppe (2010)

The Source of the Solar System

Presolar grains

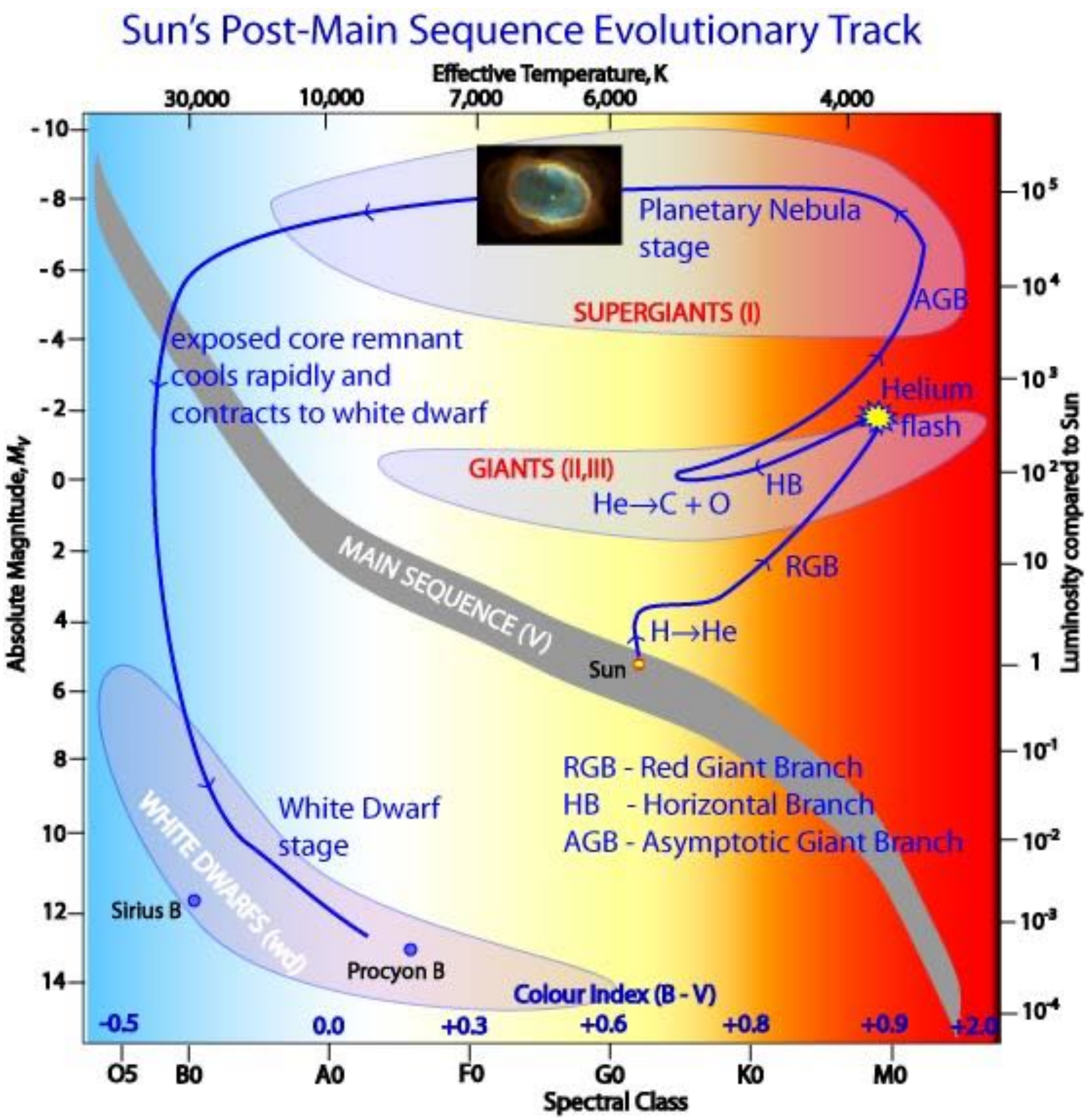


Image Credit: Australia Telescope National Facility

The Source of the Solar System

Presolar grains

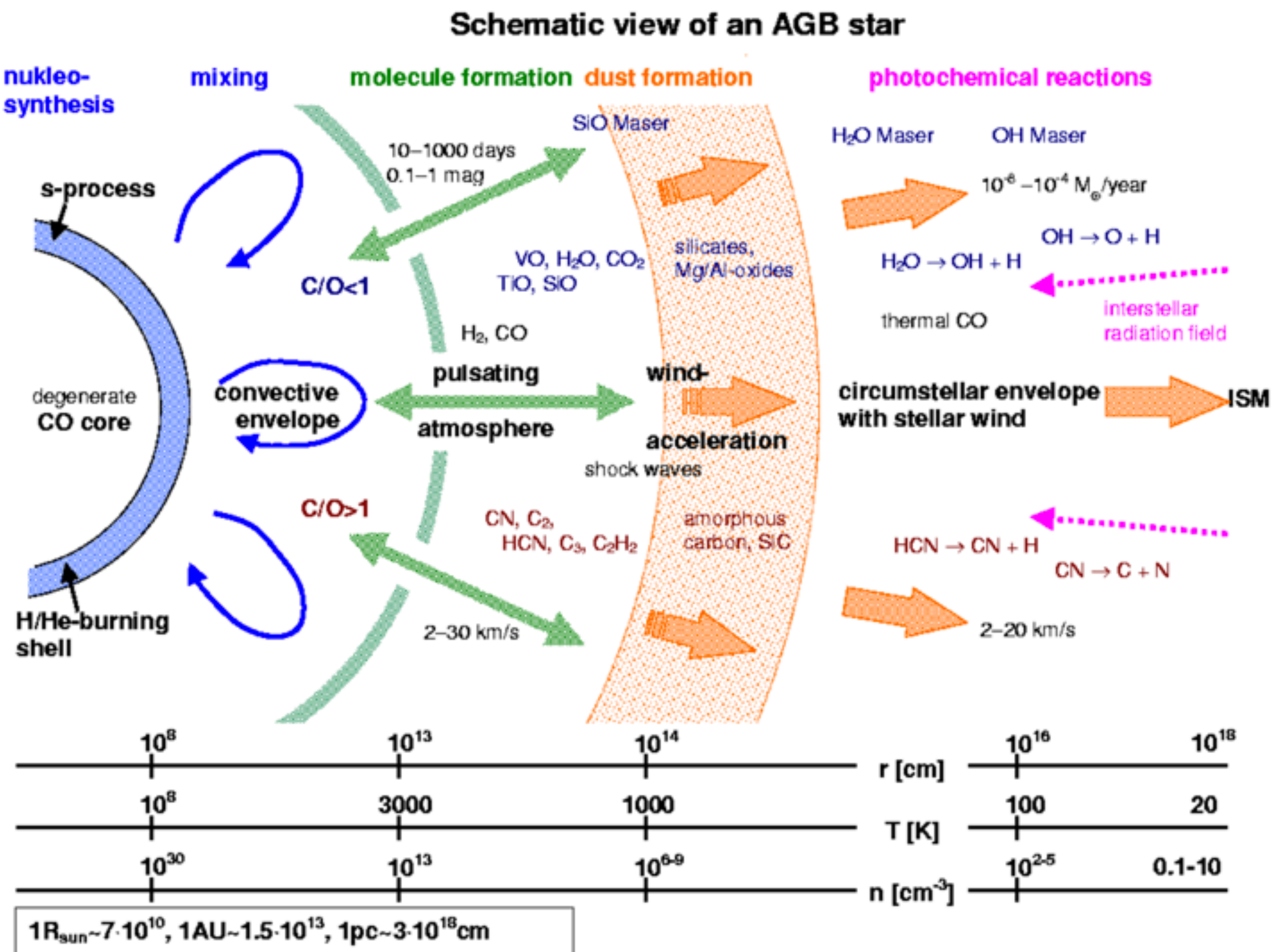
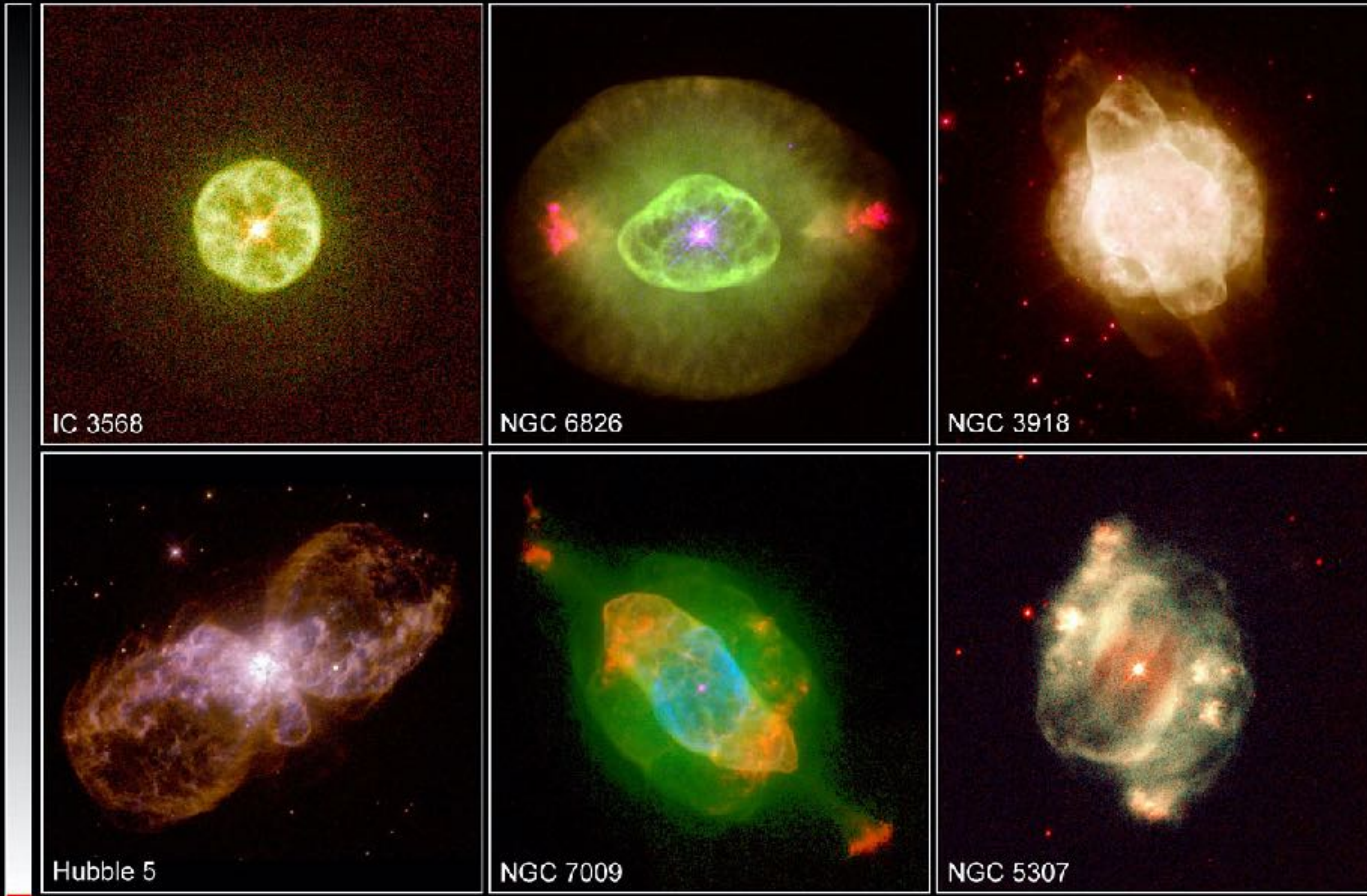


Image Credit: J. Hron

J. Hron, Inst. for Astronomy, Univ. of Vienna



Planetary Nebula Gallery
Hubble Space Telescope • WFPC2

PRC97-36b • ST ScI OPO • December 17, 1997 • H. Bond (ST ScI), B. Balick (University of Washington) and NASA

The Source of the Solar System

Presolar grains

Mineral	Abundance (ppm)	Stellar Source	%
SiC	30	**AGB (1.5-3M)** J-type C stars SNII Novae	**>90** <5 1 0.3
Graphite	10	**SNII** AGB J-type C stars Novae	**60** 30 10 2
Si_3N_4	0.002	SNII	100
Oxides/silicates	50/200	**AGB (1-2.2M)** AGB (<1M) AGB (low M&Z) SNII Novae	**70** 15 5 10 <1

Image Credit: Hoppe (2010)

Supernova Triggered the Formation of the Solar system?

ICARUS 30, 447–461 (1977)

The Supernova Trigger for Formation of the Solar System

A. G. W. CAMERON

Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, Cambridge, Massachusetts 02138

AND

J. W. TRURAN

Department of Astronomy, University of Illinois at Urbana–Champaign, Urbana, Illinois 61801

Received July 27, 1976

It is suggested that the explosion of a Type II supernova triggered the collapse of a nearby interstellar cloud and led to the formation of the solar system. Estimates of the abundances resulting from nuclear processing of the supernova ejecta are presented. It appears promising that nucleosynthesis in this single supernova event can account for most isotopic anomalies and traces of extinct radioactivities in solar system material.

Supernova Triggered the Formation of the Solar system?

Evidence: short-lived (~<10Myr) radionuclides: ^{26}Mg, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{10}Be

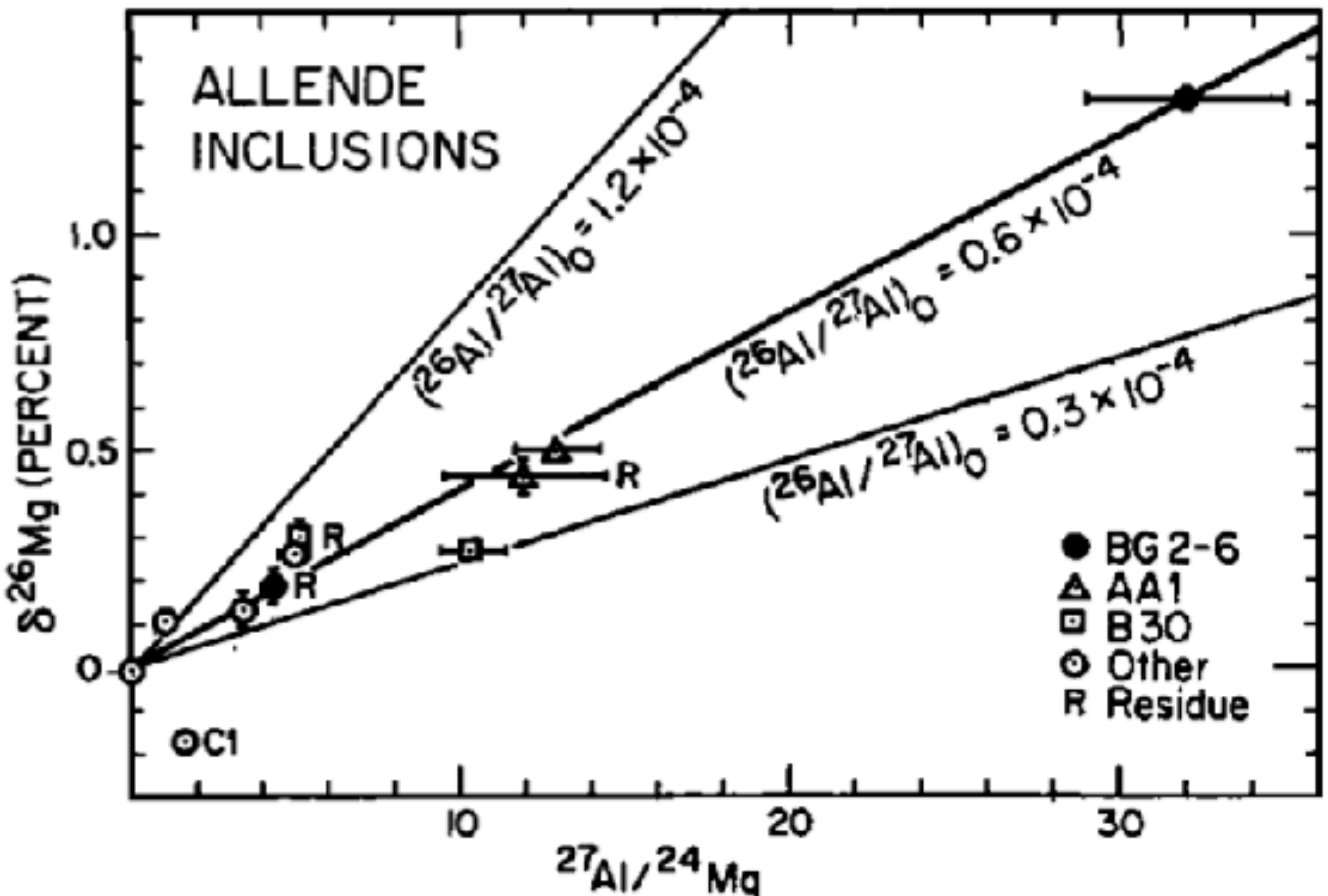


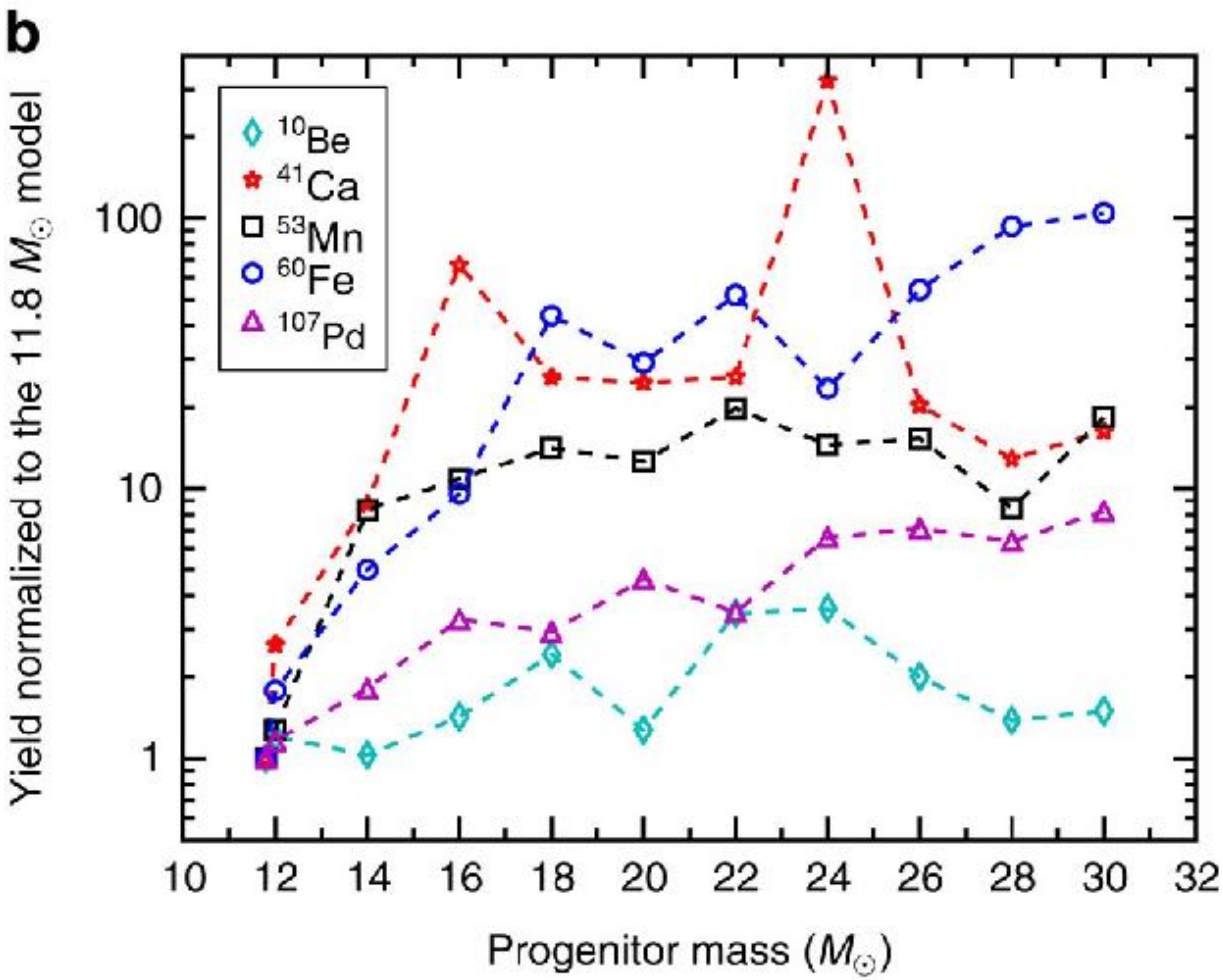
Fig. 2. Al-Mg evolution diagram for Allende samples. The correlation line for BG2-6 yields $(^{26}Al/^{27}Al)_0 = 0.6 \times 10^{-4}$ and contrasts sharply with the correlation line for B30 which has essentially zero slope and much higher initial $^{26}Mg/^{24}Mg$.

李太枫

Image Credit: Lee et al. (1976)

Supernova Triggered the Formation of the Solar system?

Evidence: short-lived (~<10Myr) radionuclides: ^{26}Mg, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{10}Be



钱永忠

Image Credit: Banerjee et al. (2016)

Supernova Triggered the Formation of the Solar system?

Evidence: short-lived (~<10Myr) radionuclides: ^{26}Mg, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{10}Be

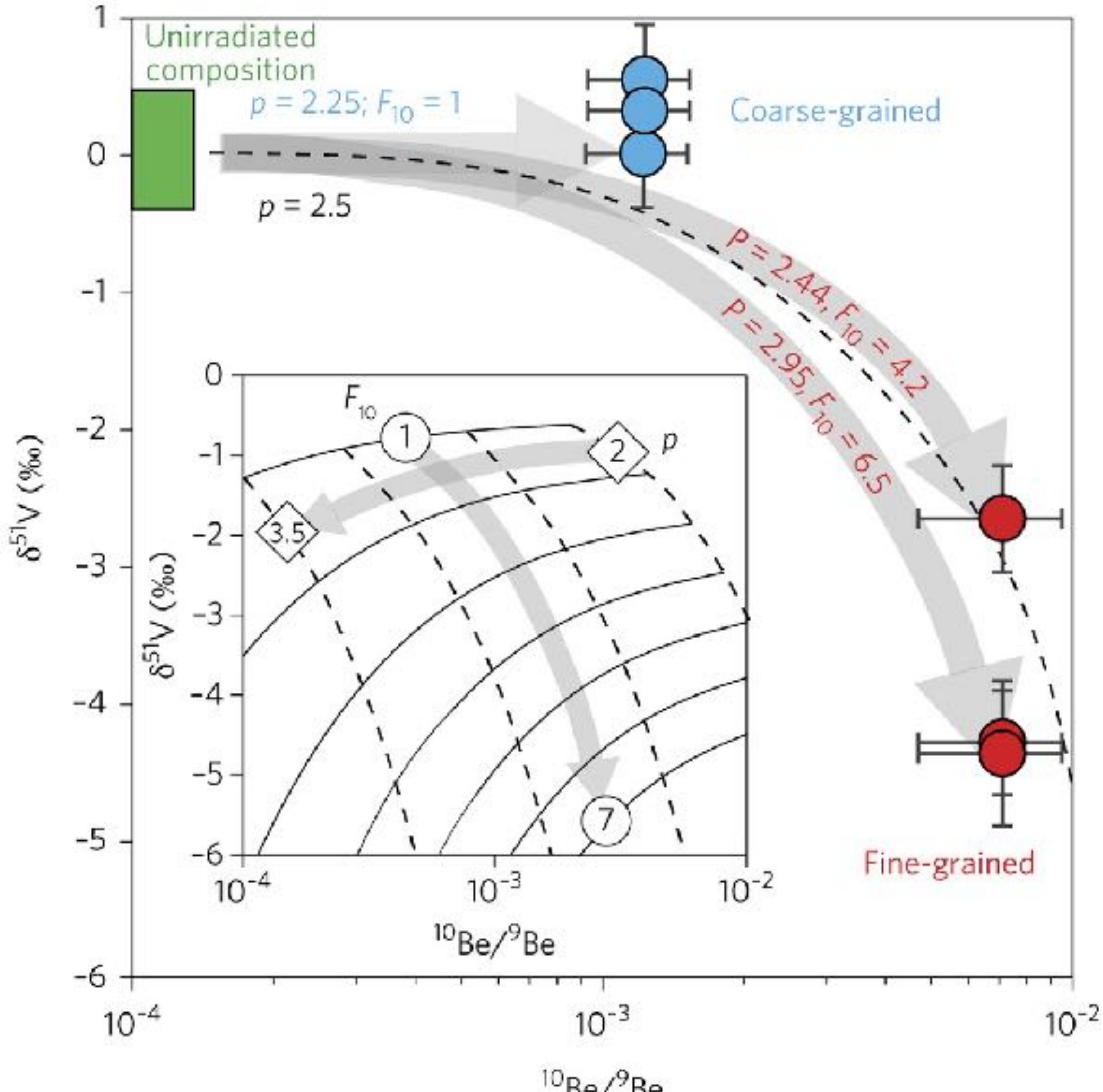


Image Credit: Sossi et al. (2017)

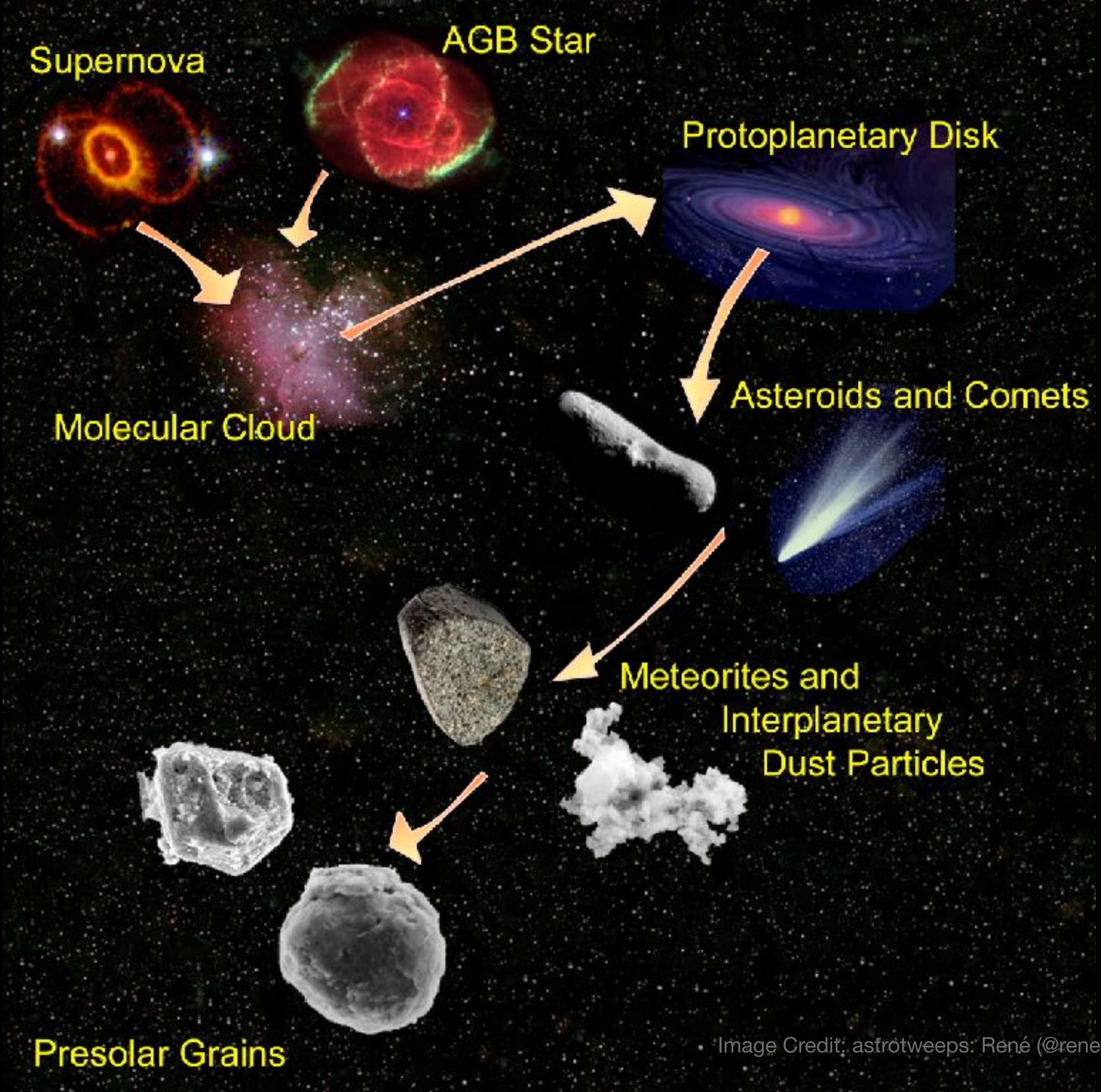
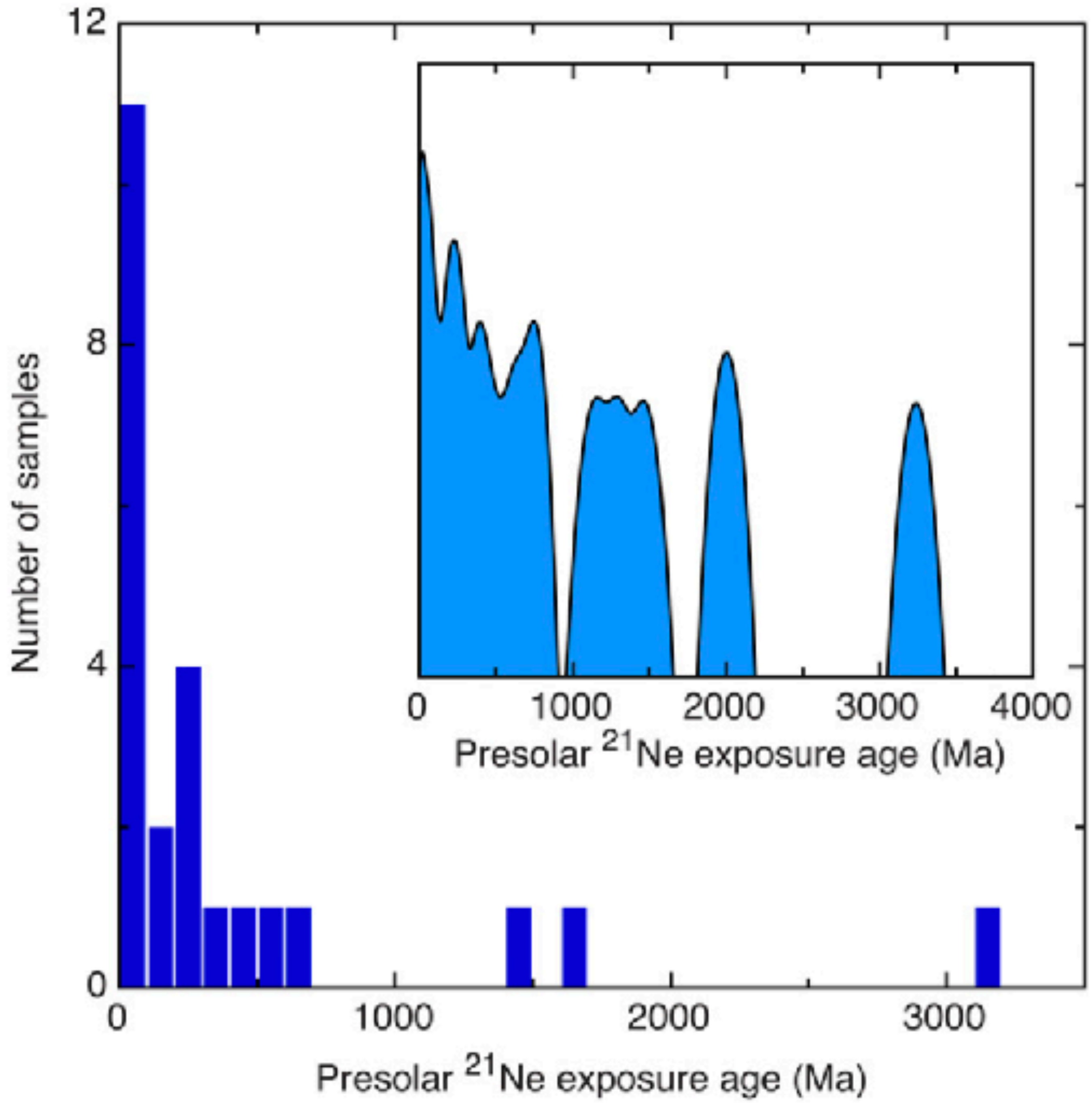


Image Credit: astrotweeps: René (@rene_ortega_m)

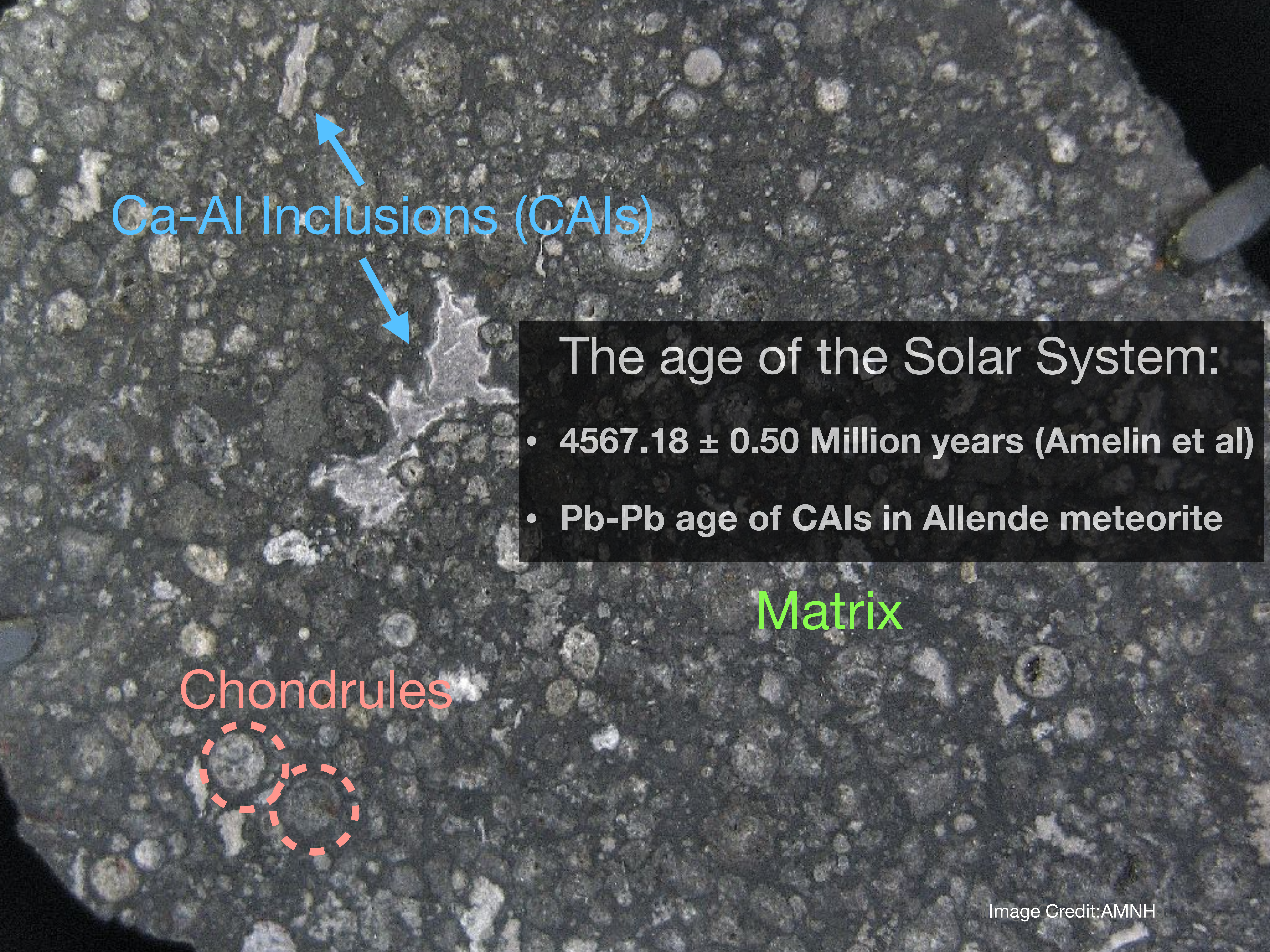
How old are presolar grains?

Presolar grains



- Exposure ages to Galactic cosmic rays (e.g., ^{3}He, ^{21}Ne isotopes)
- time that the grains spent floating in ISM and solar nebula
- 60% of SiC grains have exposure ages of < 300 Myrs
- (~8% of grains ≥ 1 Gyr)

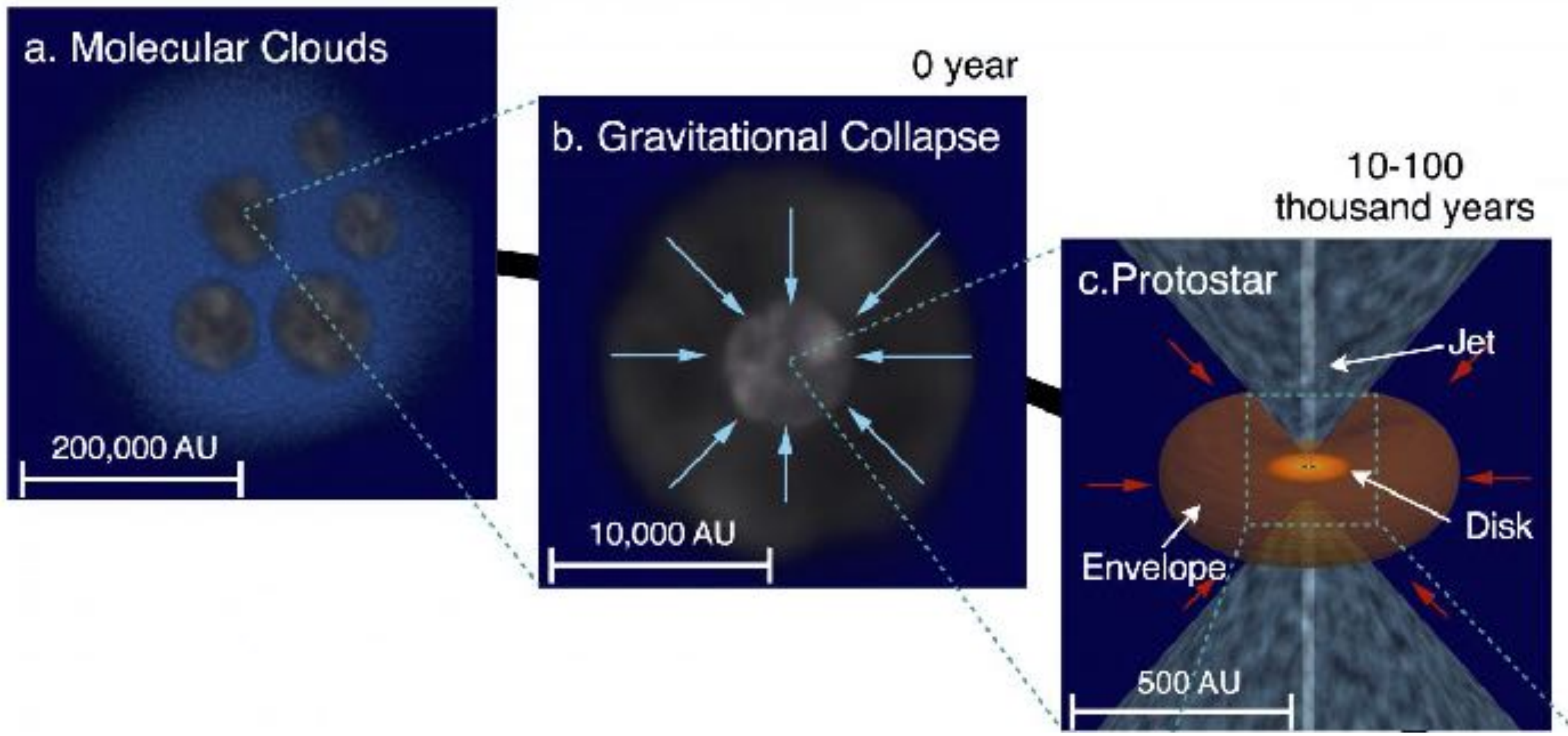
Image Credit: Heck et al. (2020)



The age of the Solar System:

- **4567.18 ± 0.50 Million years (Amelin et al)**
- **Pb-Pb age of CAIs in Allende meteorite**

The Formation of the Solar System



hot, dense core ignites
hydrogen fusion and becomes protostar

Image Credit: ASIAA

The First Solid of the Solar System

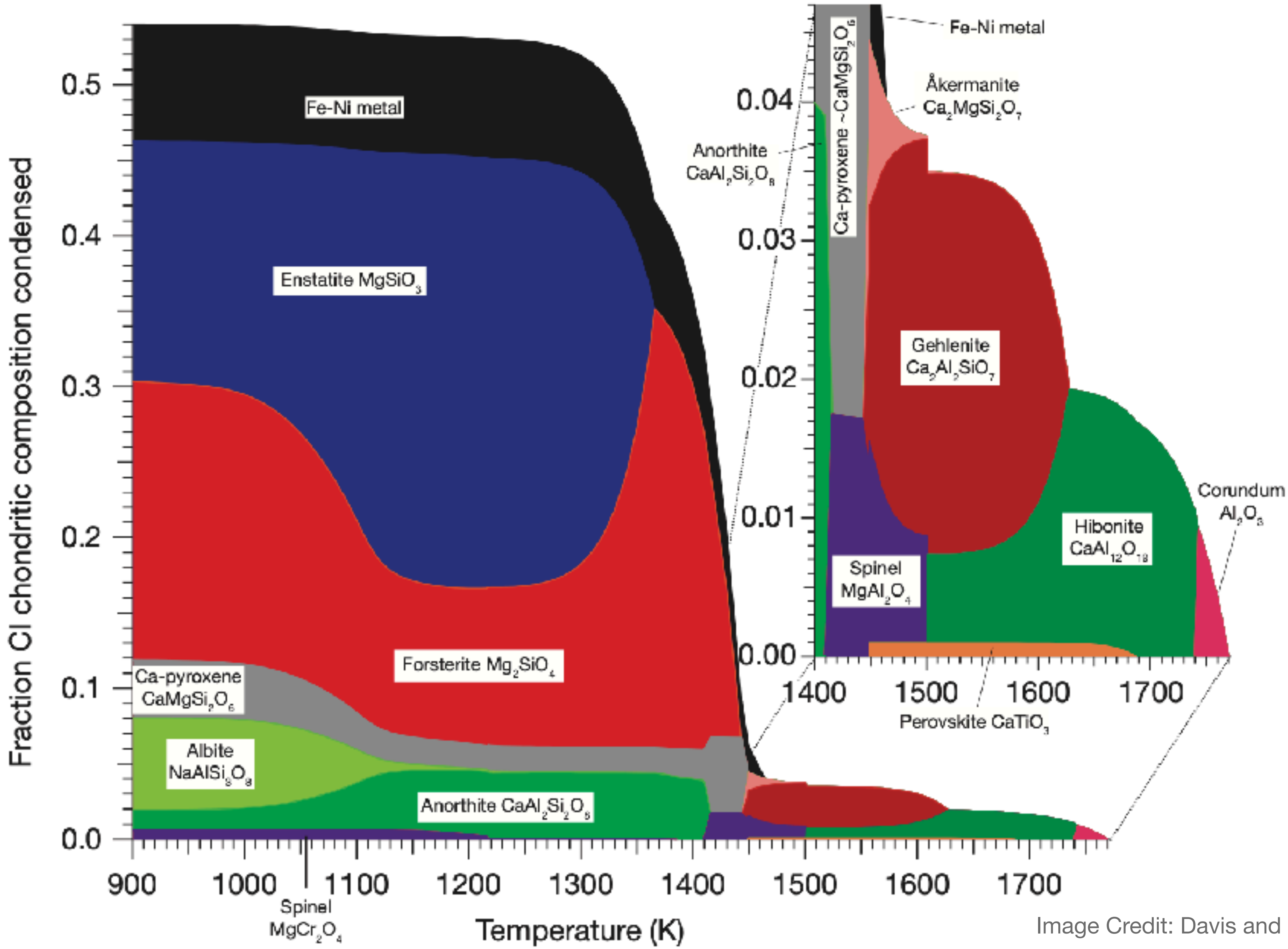


Image Credit: Davis and Richter (2014)

The First Solid of the Solar System

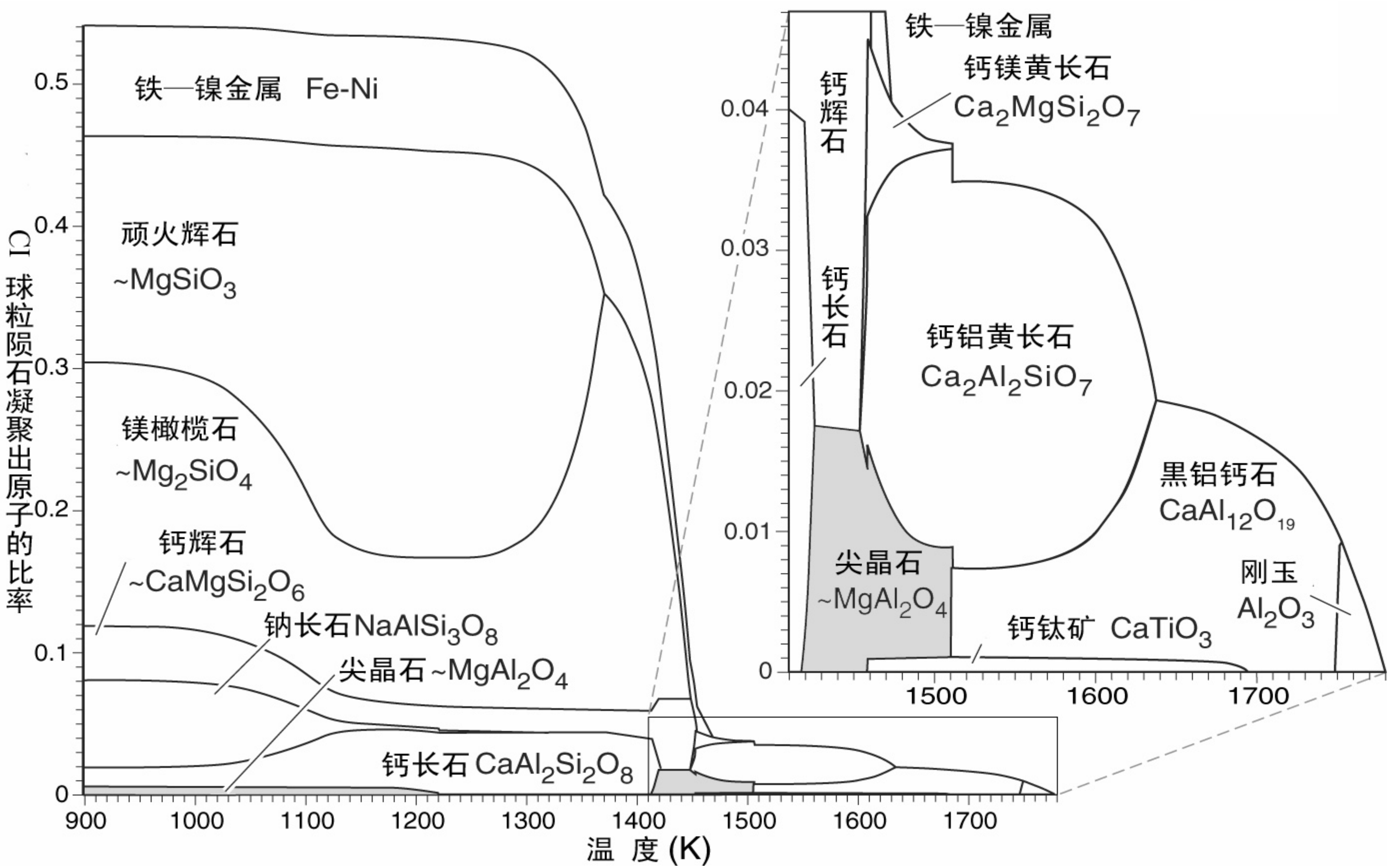
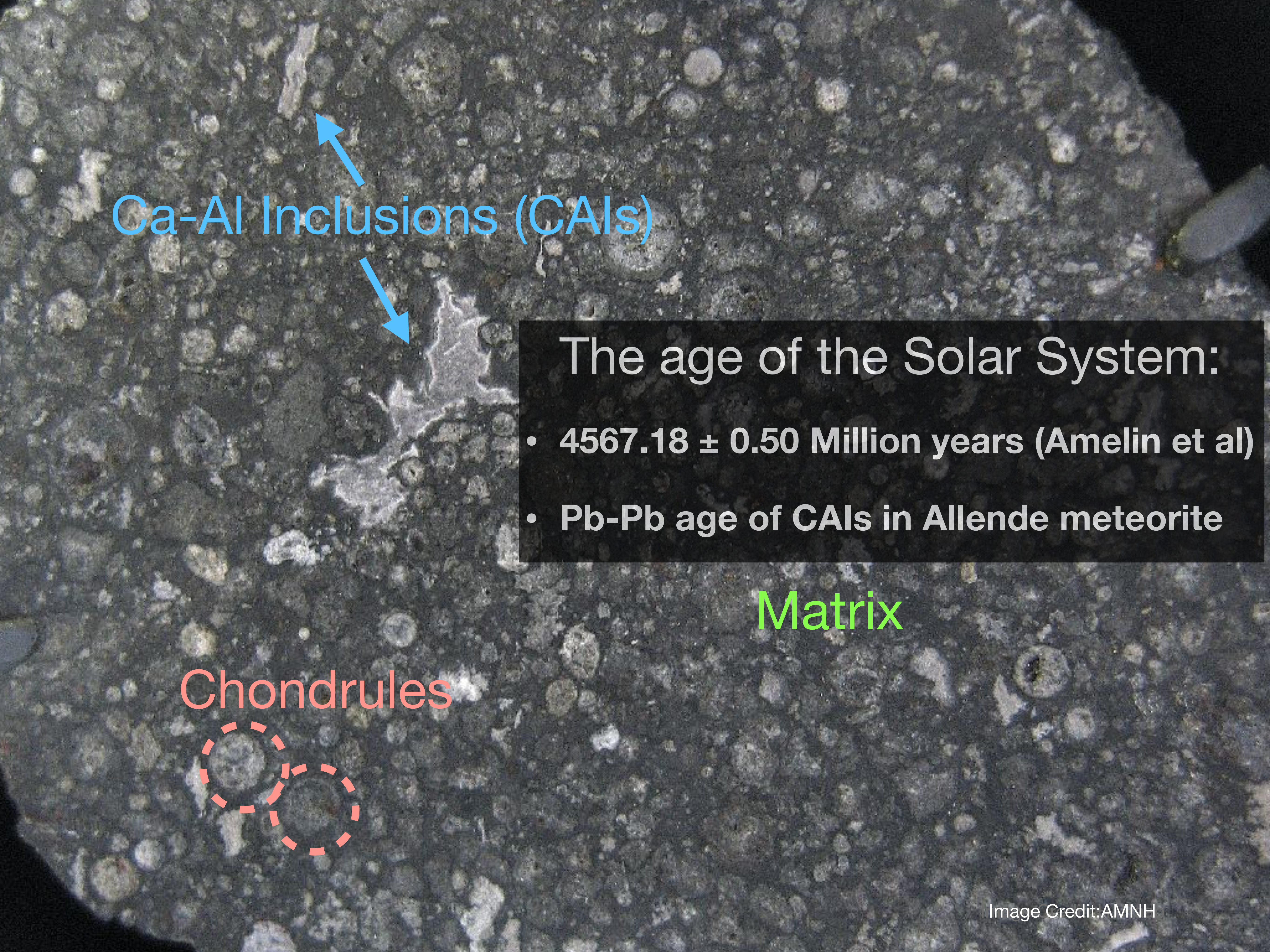


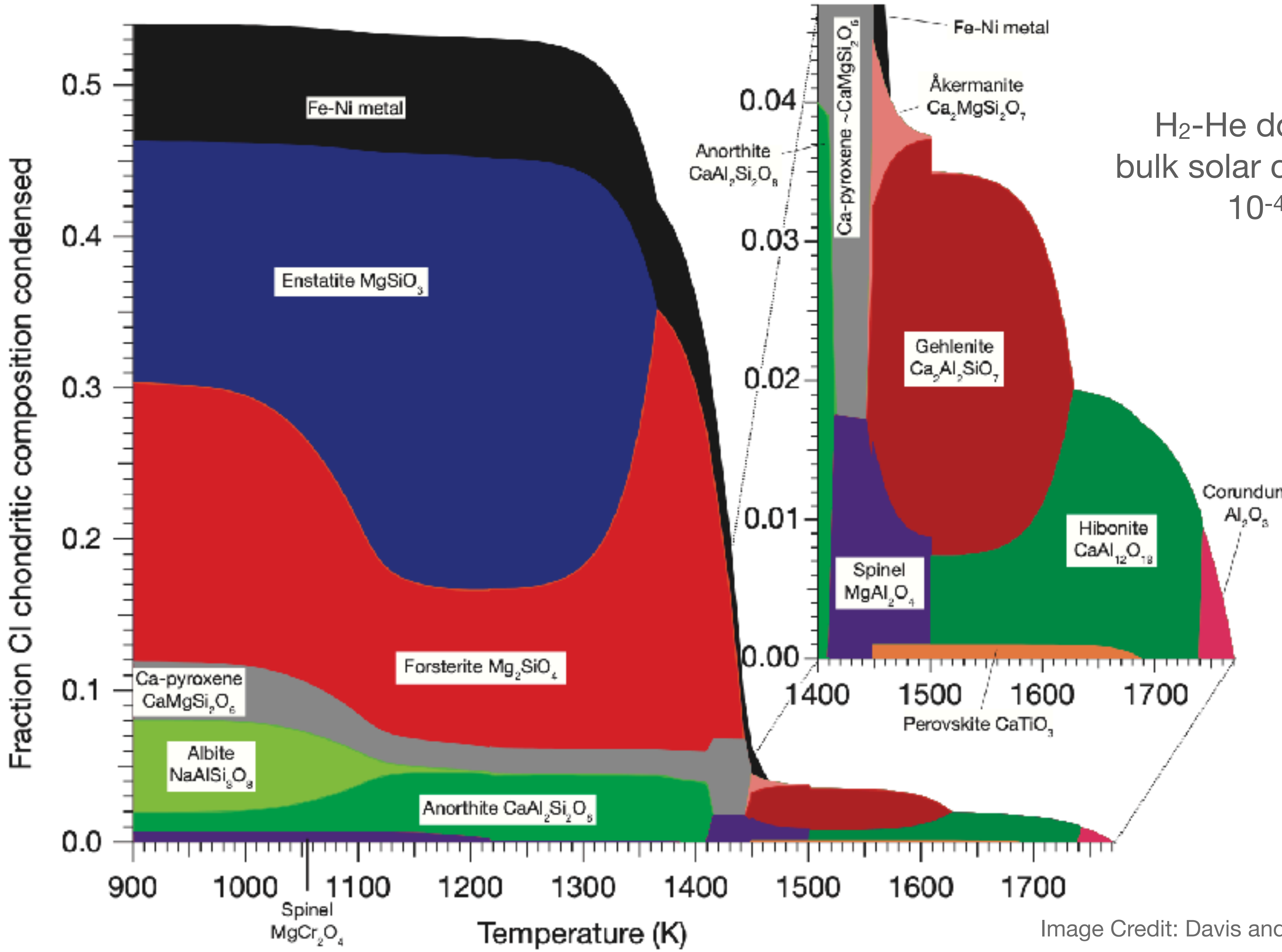
Image Credit: Davis and Richter (2014)

The age of the Solar System:

- **4567.18 ± 0.50 Million years (Amelin et al)**
- **Pb-Pb age of CAIs in Allende meteorite**



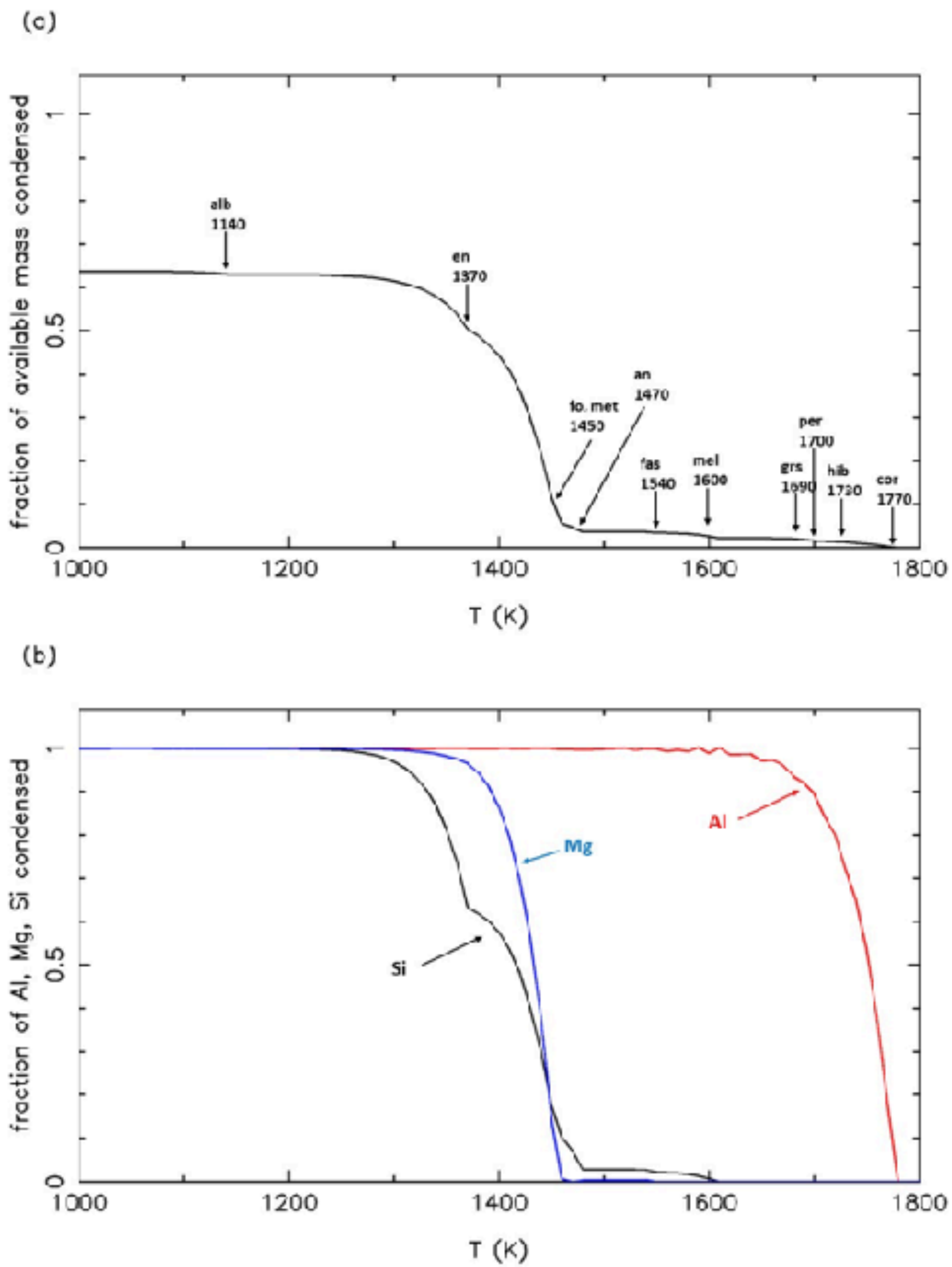
The First Solid of the Solar System



H2-He dominated bulk solar composition 10^{-4} bar

Image Credit: Davis and Richter (2014)

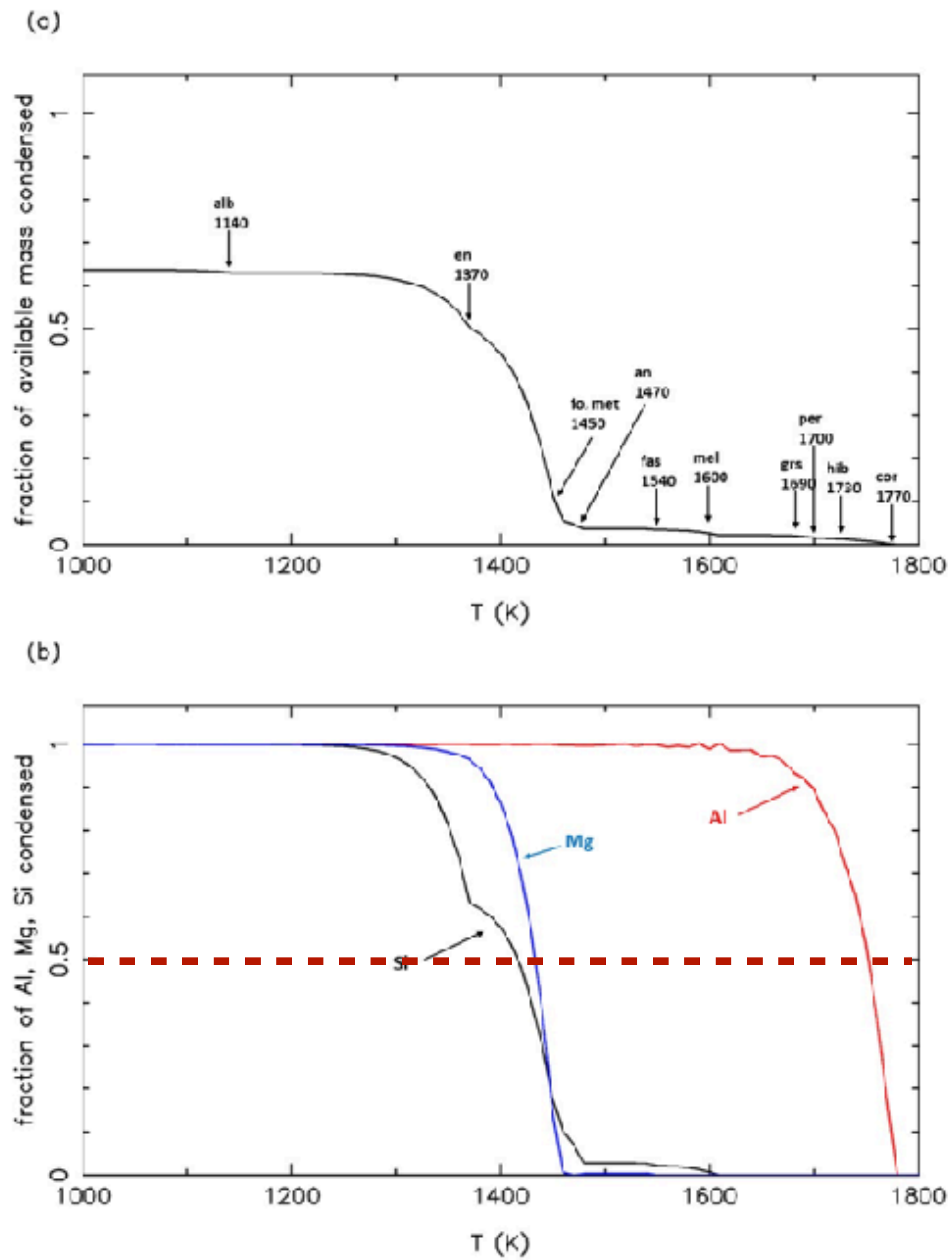
Cosmochemical Classification of Elements



H_2-He dominated
bulk solar composition
10^{-3} bar

Image Credit:Morbidelli et al. (2020)

Cosmochemical Classification of Elements

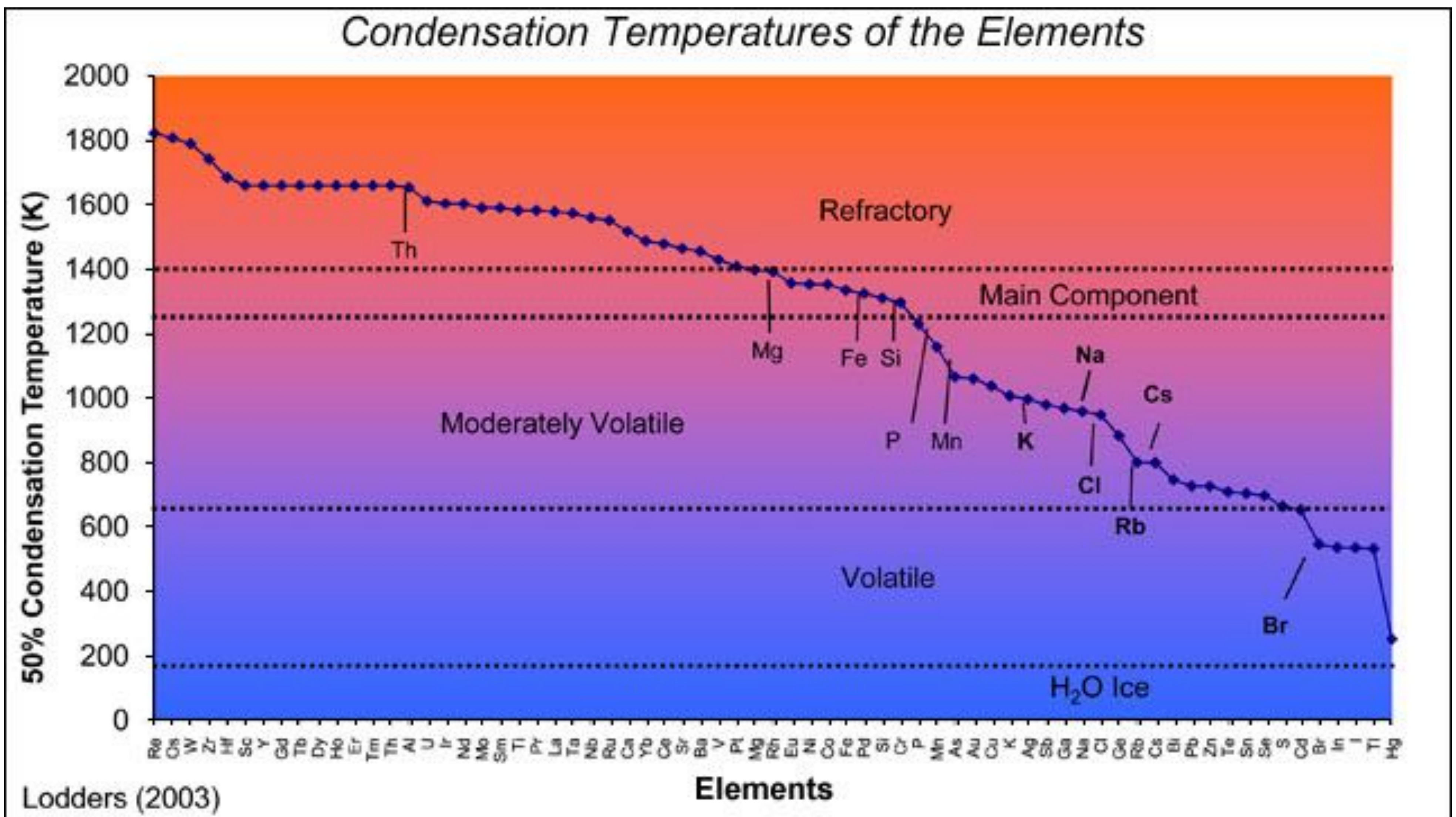


H_2-He dominated
bulk solar composition
10^{-3} bar

50% solar nebula condensation temperature

Image Credit:Morbidelli et al. (2020)

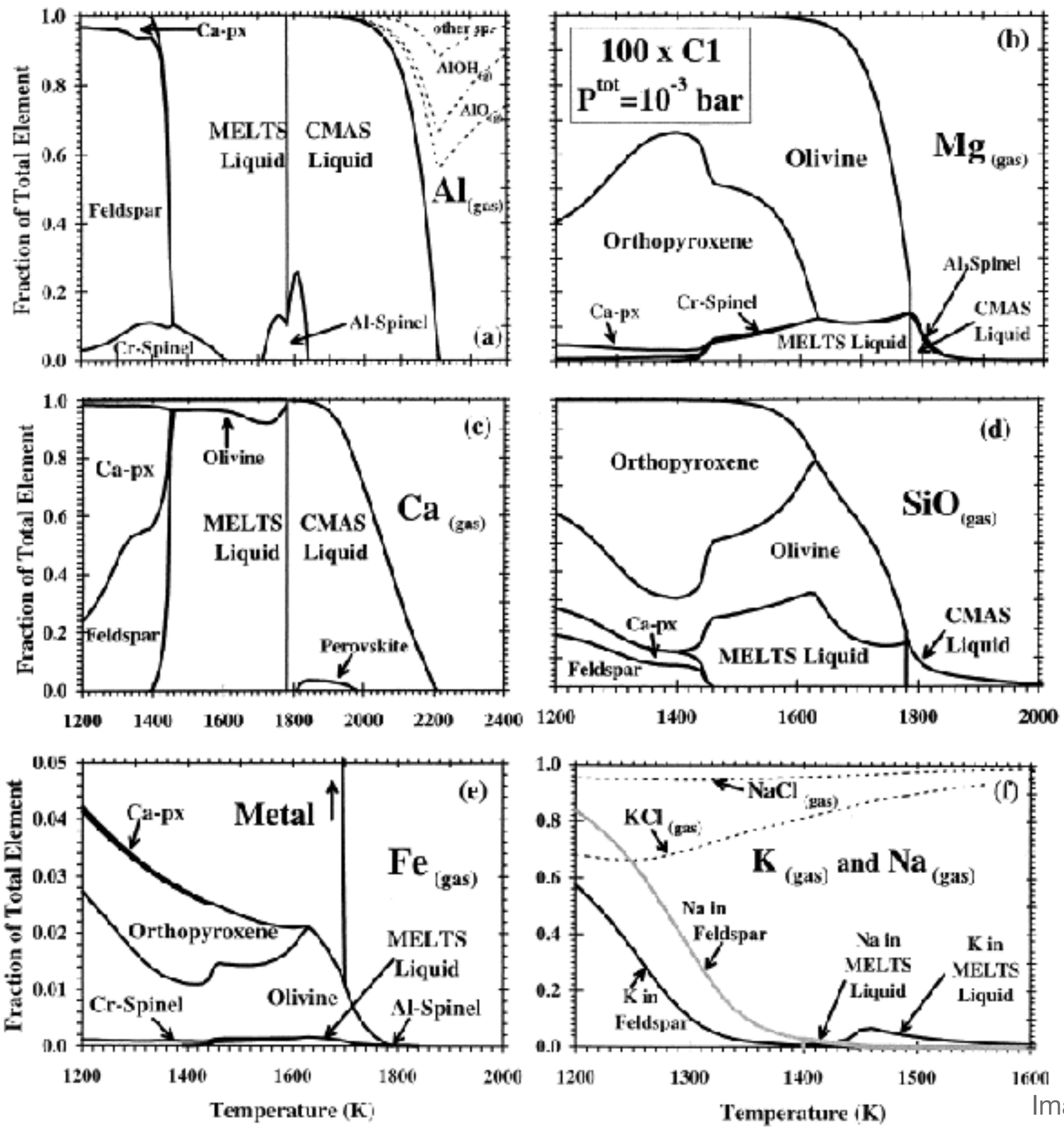
Cosmochemical Classification of Elements



(PSRD graphic based on calculations done by Katarina Lodders, Washington University in St. Louis.)

Katharina Lodders

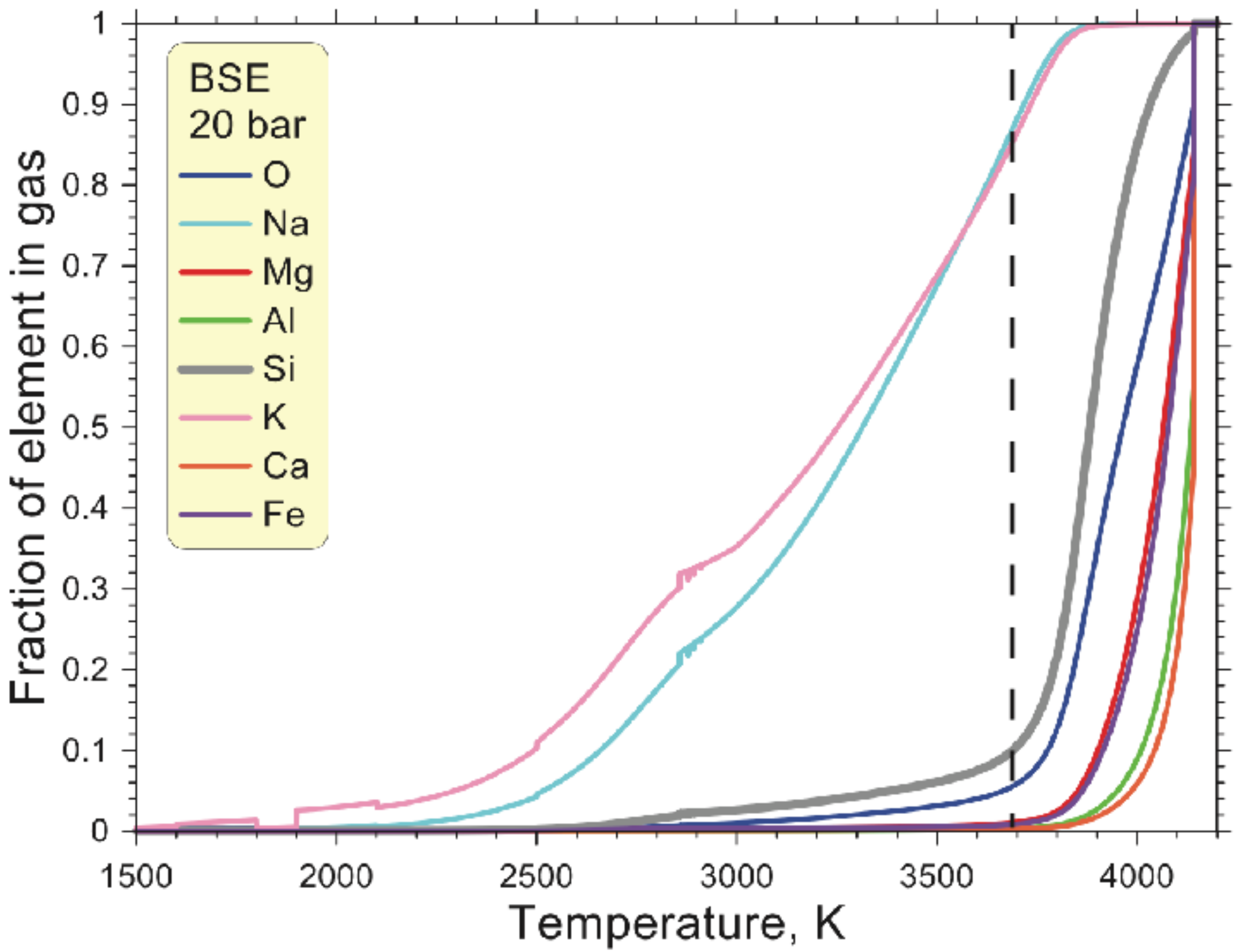
Cosmochemical Classification of Elements



dust-rich
100xCl
10^{-3} bar

Image Credit: Ebel and Grossman (2010)

Cosmochemical Classification of Elements



BSE
20 bar

Image Credit: (Petaev et al., LPSC, 2016)

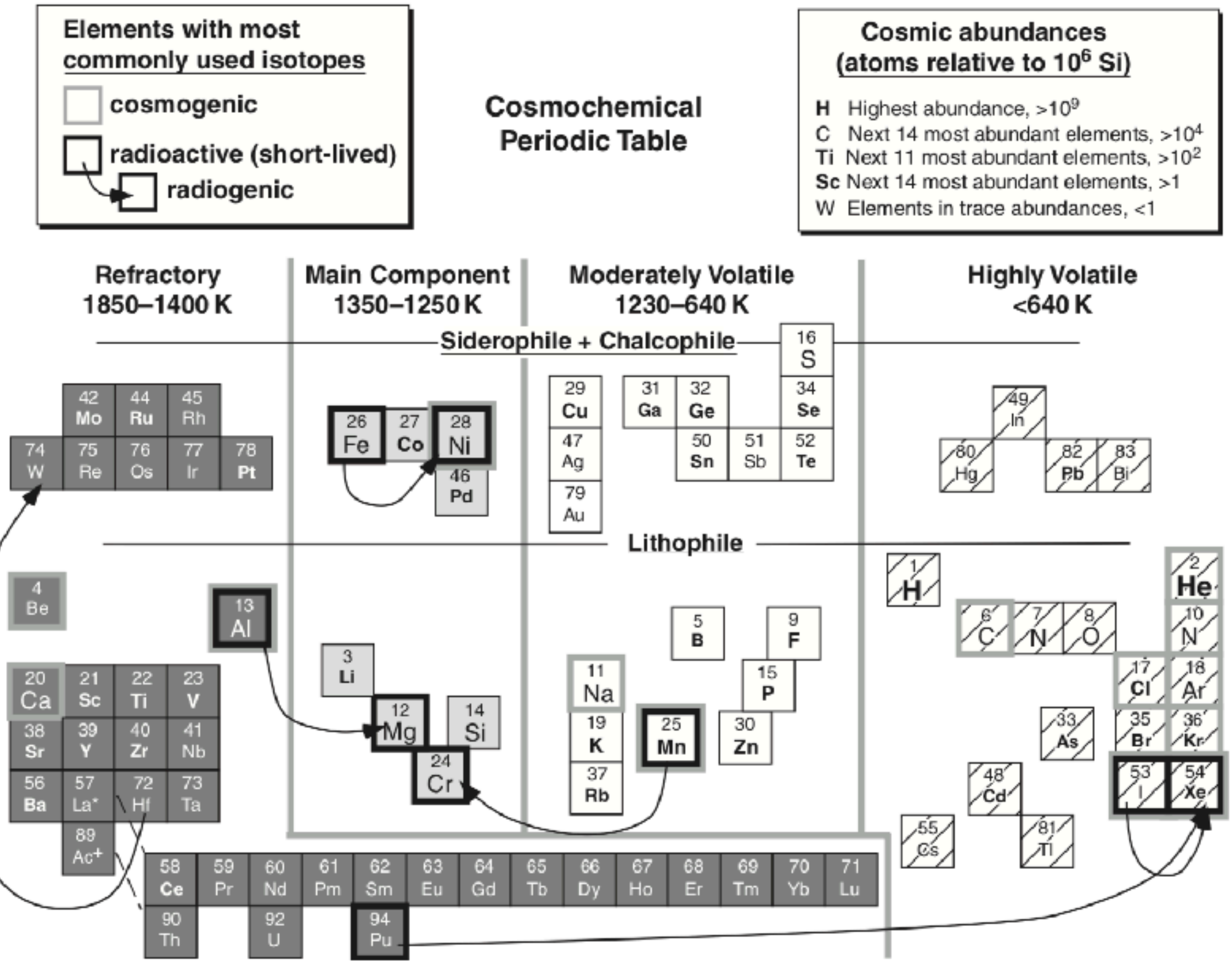
Cosmochemical Classification of Elements

- 1850-1400K **Refractory Elements**
- Calcium, Aluminum, and Titanium Oxide
- 1250-1350K **Major Elements**
- Magnesium and Silicon -> Forsterite/enstatite
- Fe, Ni, Co ->Metal
- 640 -1230K **Moderately Volatile Elements**
- Alkalis and moderately volatile elements (Cl, K, Zn)
- Below 640K **Highly Volatile Elements**
- Halogens and inert gases

Cosmochemical Classification of Elements

	Lithophile	**Siderophile + chalcophile**
Refractory (50%Tc=1850-1400K)	Al, Ca, Ti, Be, Ba, Sc, V, Sr, Y, Zr, Nb, Ba, REE, Hf, Ta, Th, U, Pu	Mo, Ru, W, Re, Os, Ir, Pt
Main component (50%Tc=1350-1250K)	Mg, Si, Cr, Li	Fe, Ni, Co, Pd
Moderately volatile (50%Tc=1230-640)	Mn, P, Na, B, Rb, K, F, Zn	Au, As, Cu, Ag, Ga, Sb, Ge, Sn, Se, Te, S
Highly volatile (50%Tc<640K)	Cl, Br, I, Cs, Tl, H, C, N, O, He, Ne, Ar, Kr, Xe	In, Bi, Pb, Hg

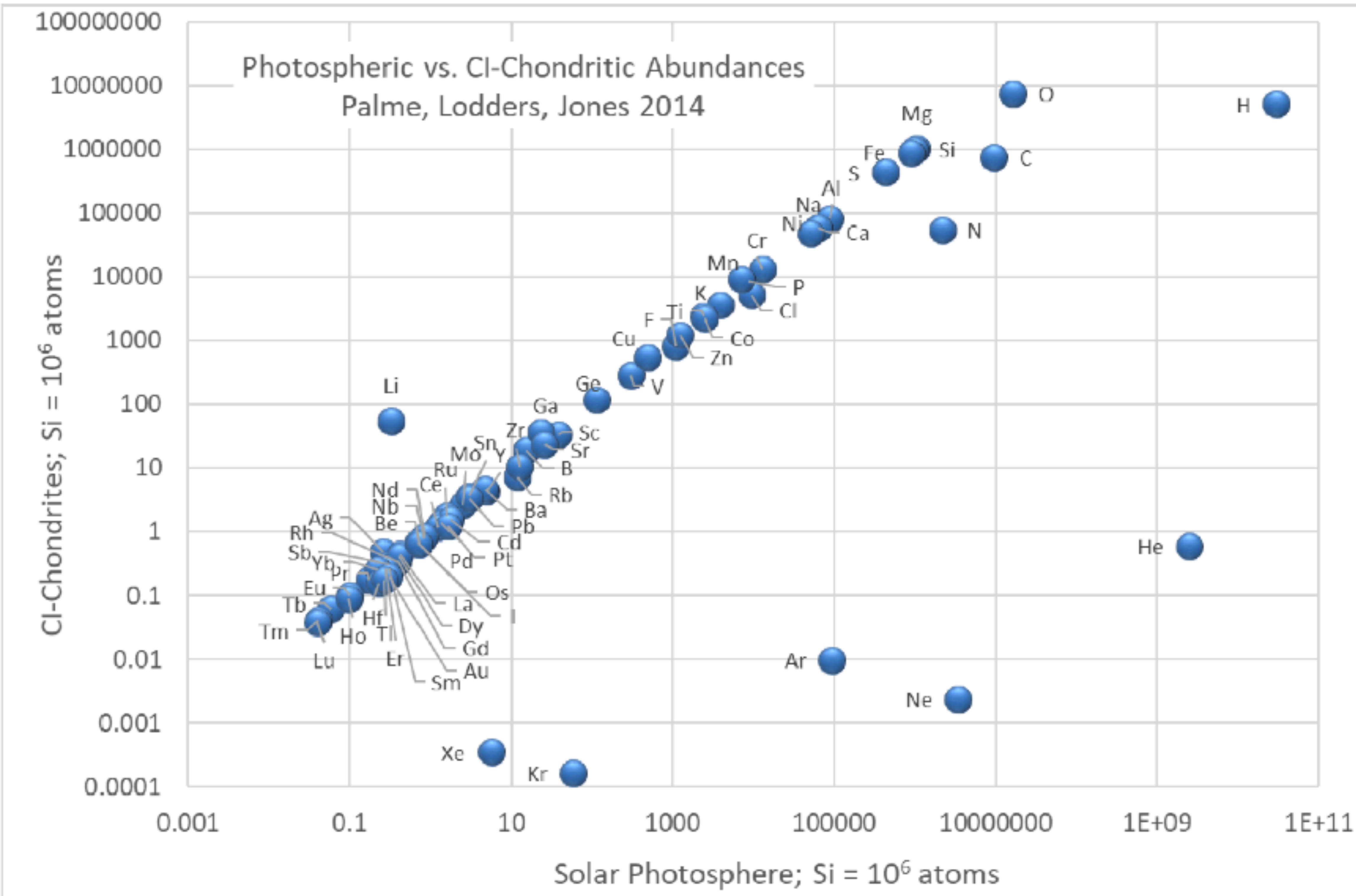
Cosmochemical Classification of Elements



(McSween and Huss, 2010)

CI carbonaceous chondrites

vs. solar photosphere



CI carbonaceous chondrites

vs. solar photosphere

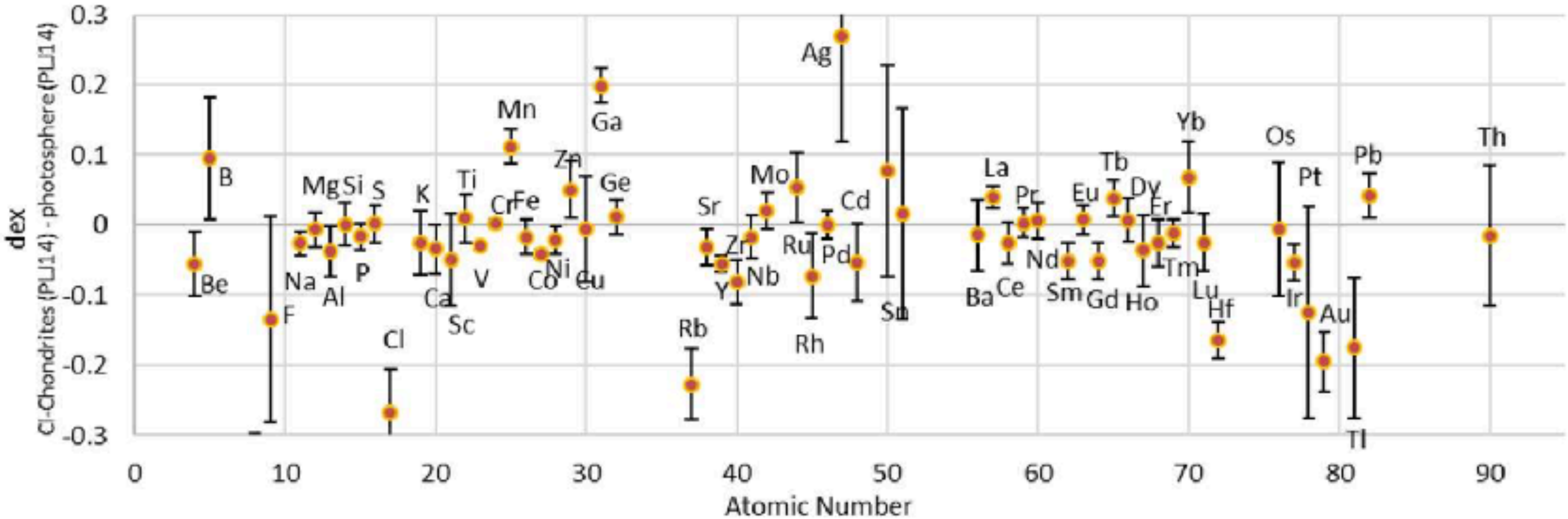
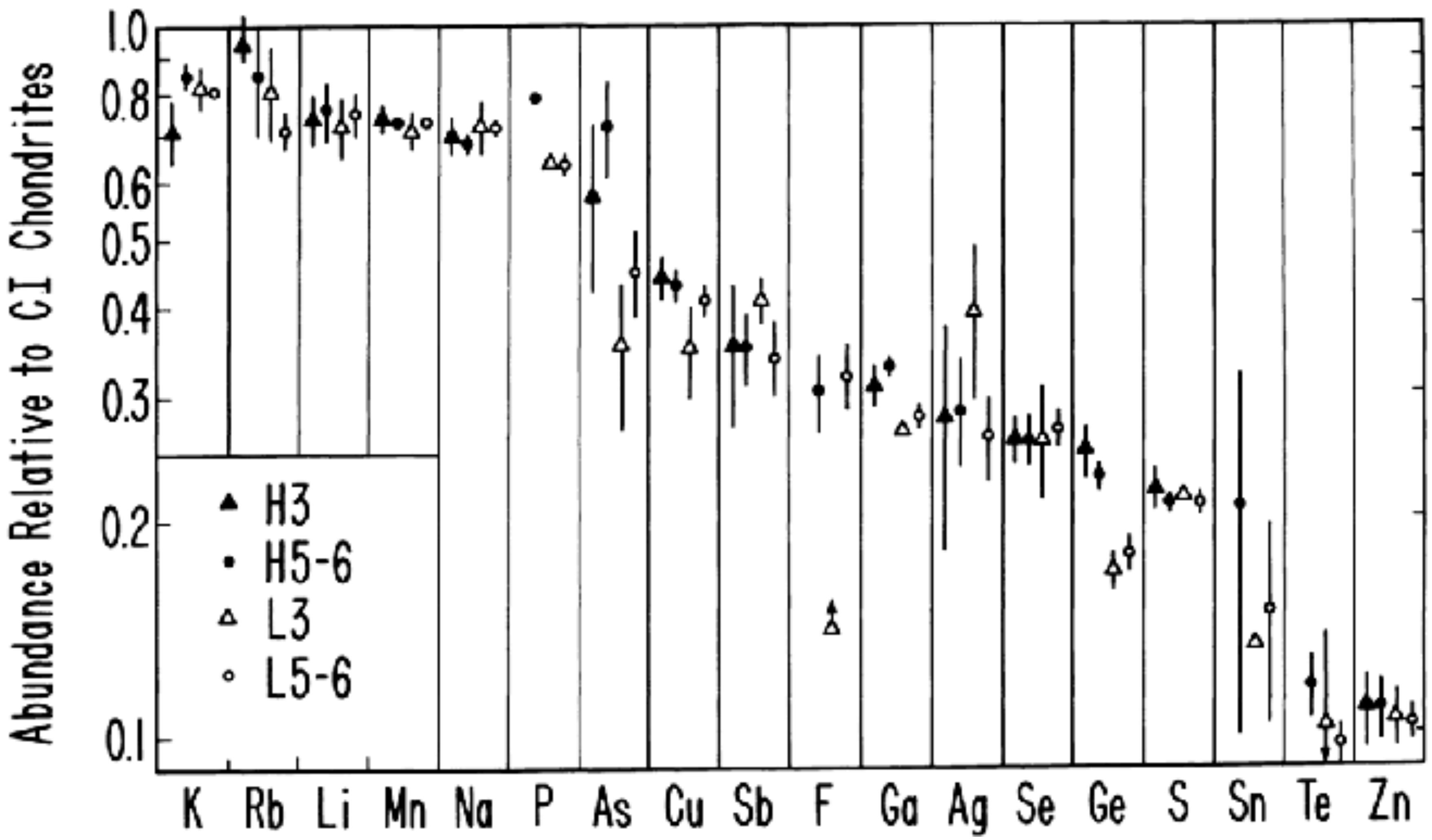


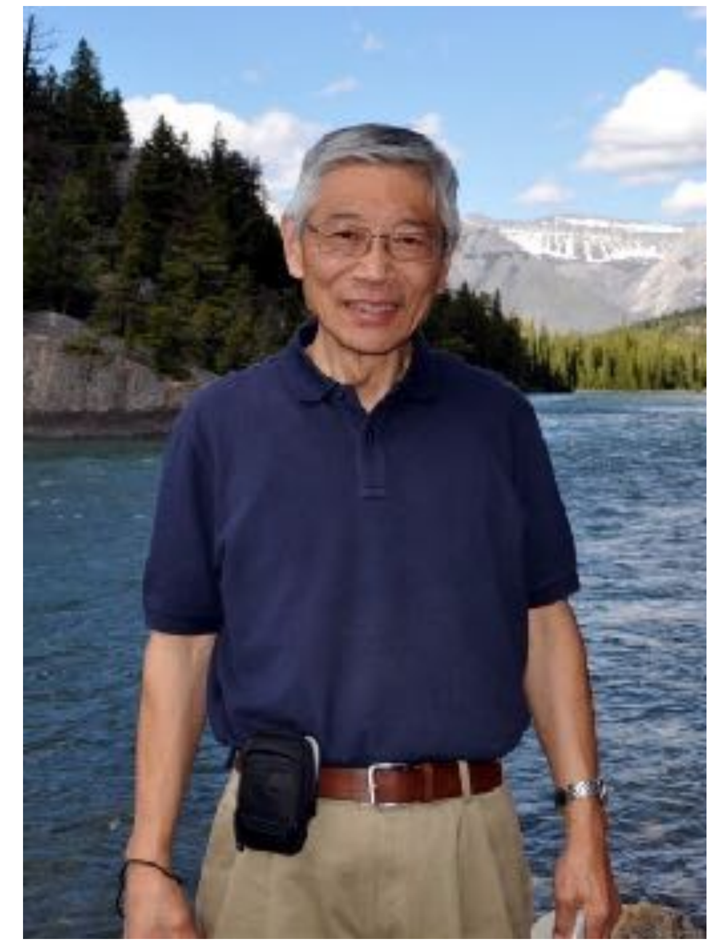
Image Credit: Lodders (2018) and NHM, Paris

CI carbonaceous chondrites

vs. other chondrites



50% solar nebula condensation temperature



周诚林 （1943-2019）

李春辉博客 http://blog.sciencenet.cn/blog-509459-1193509.html

Image Credit: Wasson and Chou (1974)

CI carbonaceous chondrites

vs. other chondrites

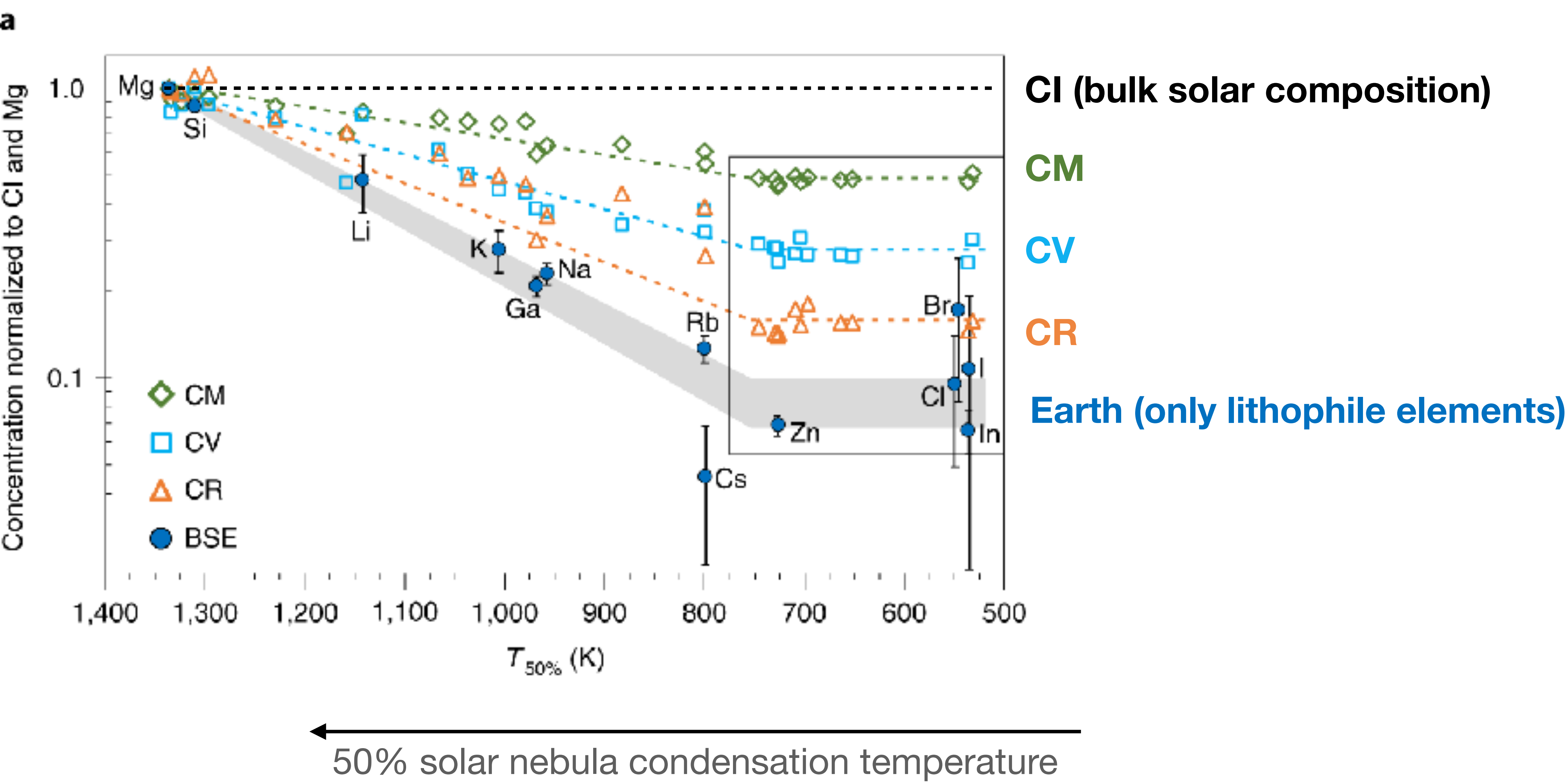


Image Credit: Braukmüller et al. (2019)

CI carbonaceous chondrites

vs. other chondrites

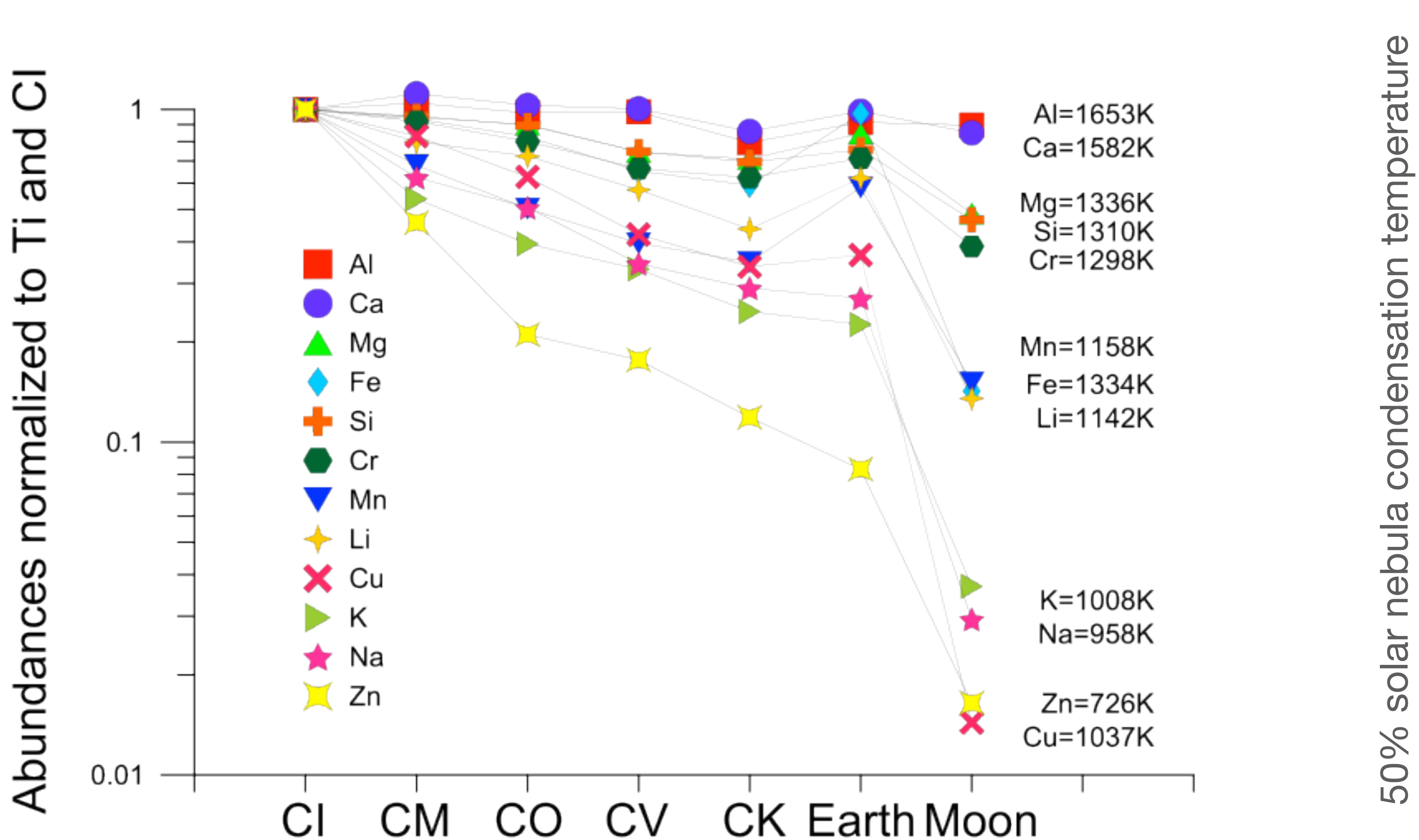


Image Credit: Braukmüller et al. (2019)

Processes to explain these progressive depletion patterns

- 1) initial incomplete condensation from the solar nebula
- 2) partial evaporation of interstellar dusts prior to incorporation into the solar nebula
- 3) mixing of chondrite components formed in distinct volatile-rich and volatile-poor reservoirs of the early Solar System

CI carbonaceous chondrites

vs. other chondrites

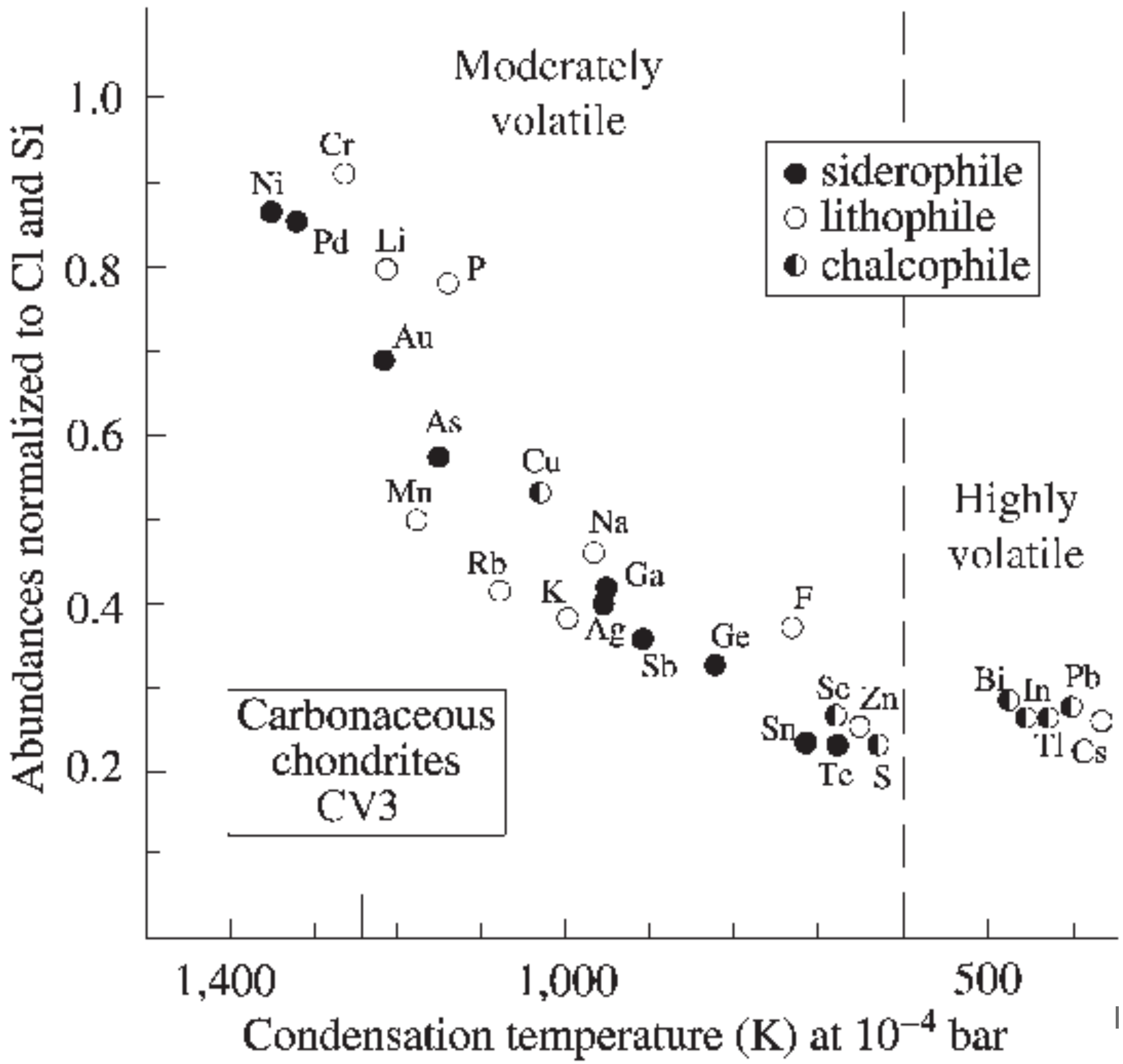
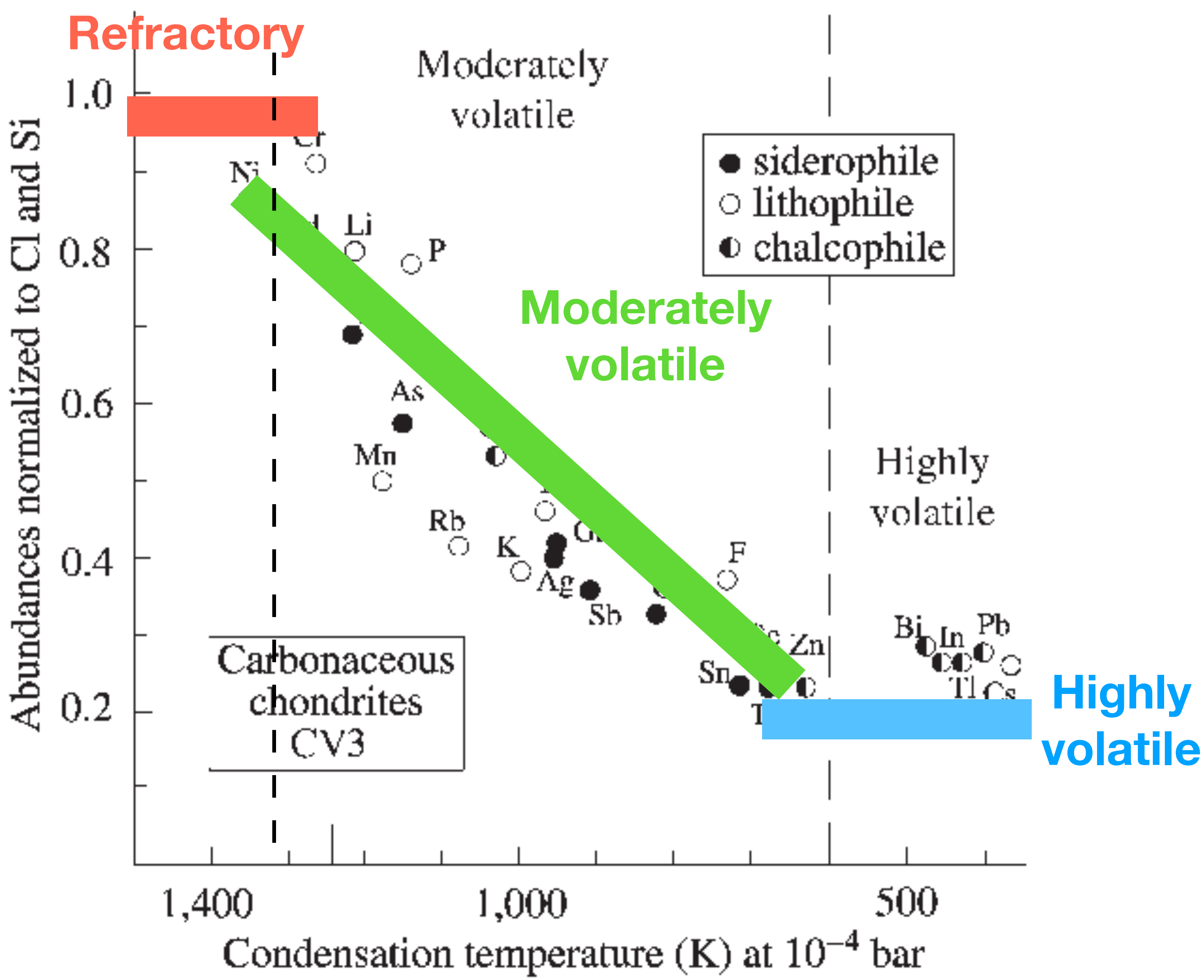


Image Credit: Palme et al. (2014)

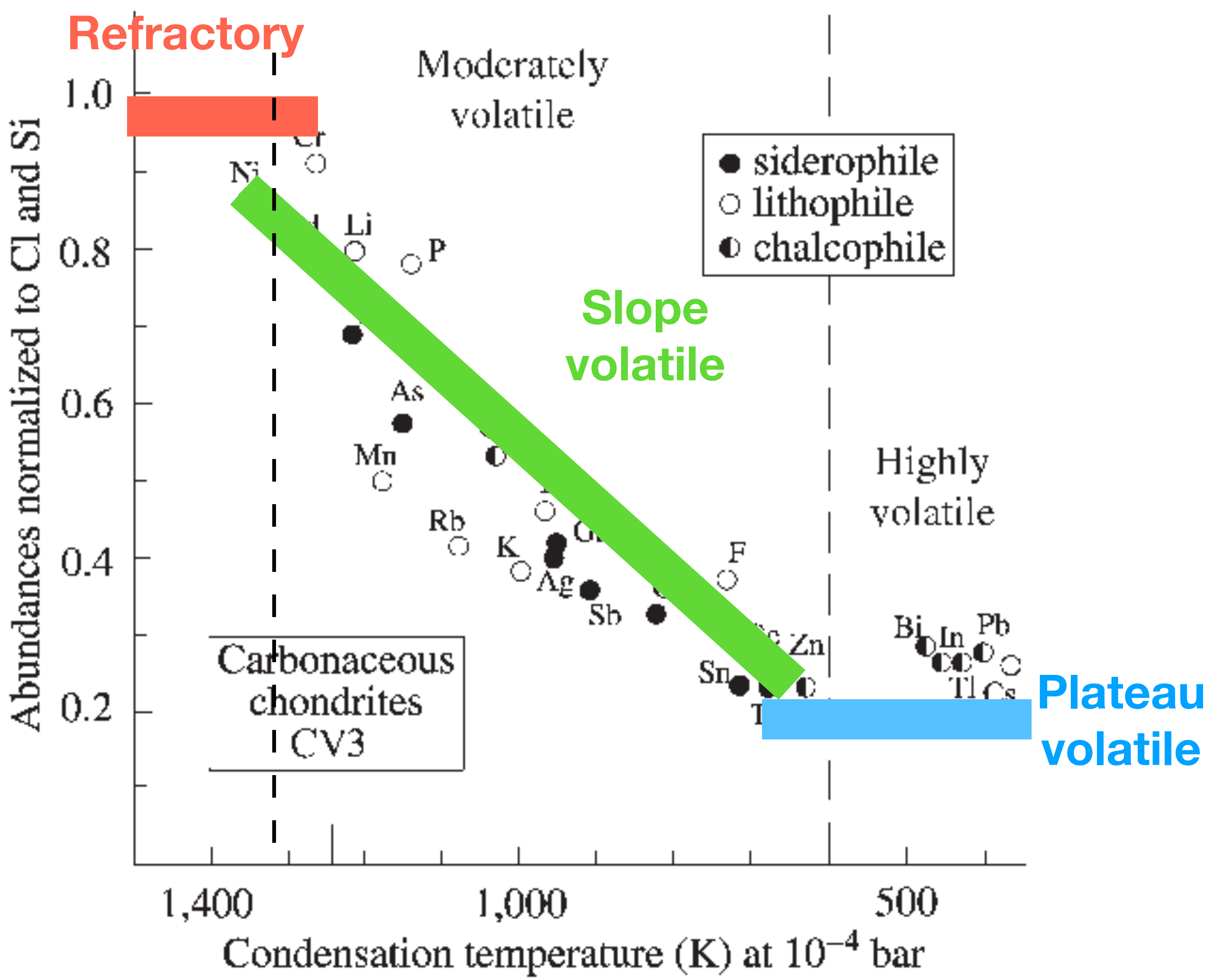
CI carbonaceous chondrites

vs. other chondrites



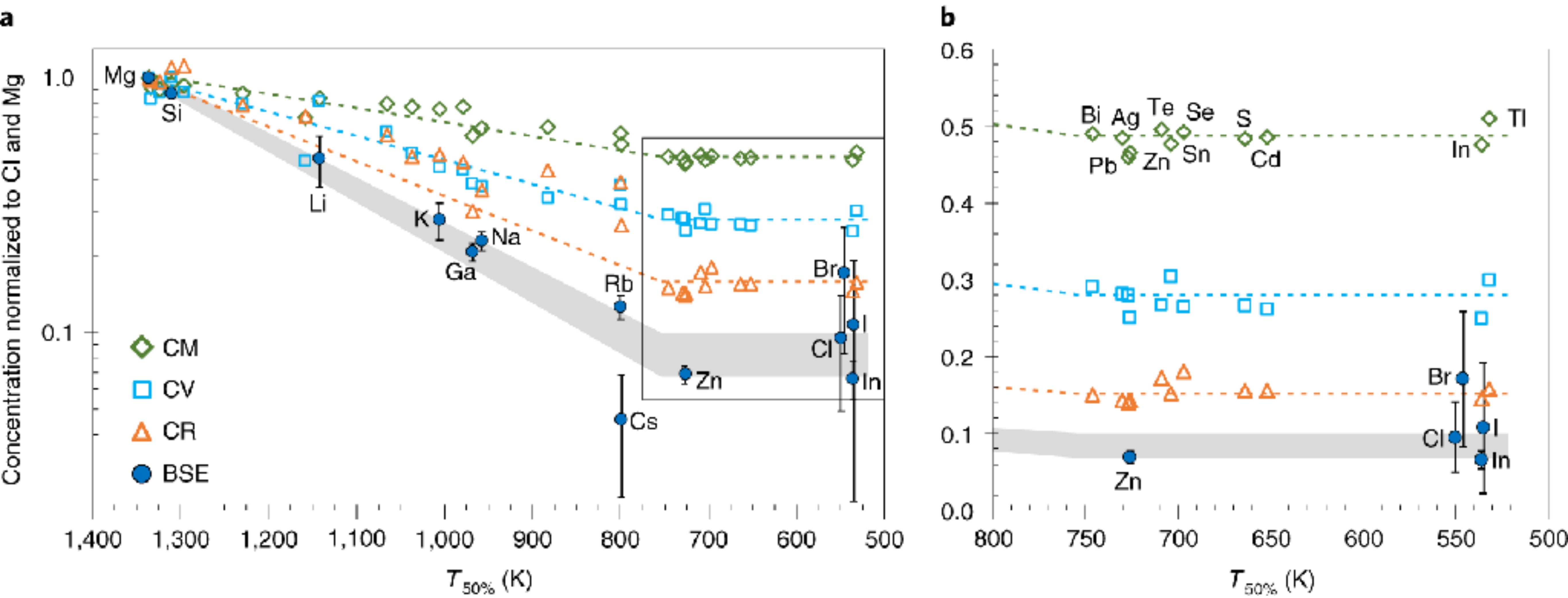
CI carbonaceous chondrites

vs. other chondrites



CI carbonaceous chondrites

vs. other chondrites

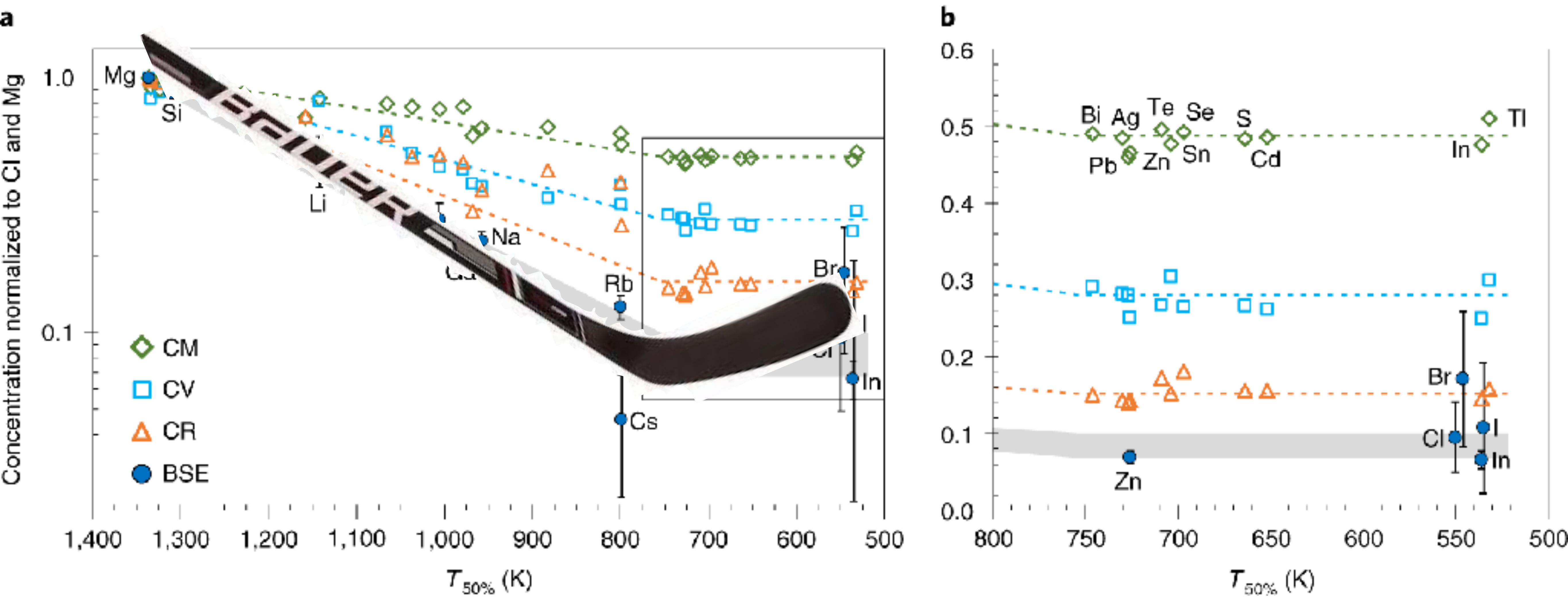


50% solar nebula condensation temperature

Image Credit: Braukmüller et al. (2019)

CI carbonaceous chondrites

vs. other chondrites



50% solar nebula condensation temperature

Image Credit: Braukmüller et al. (2019)
Purehockey

Carbonaceous chondrite mixing model

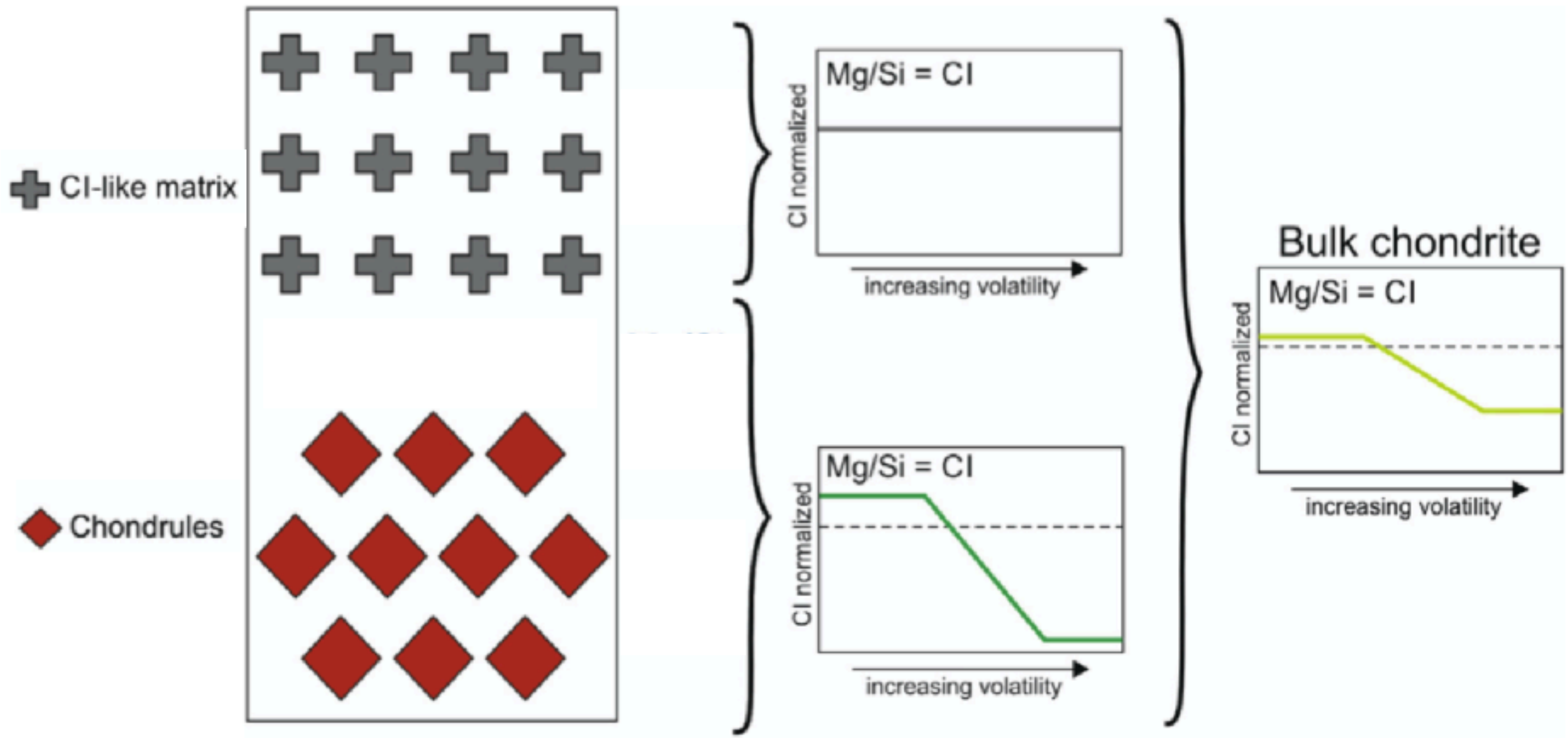
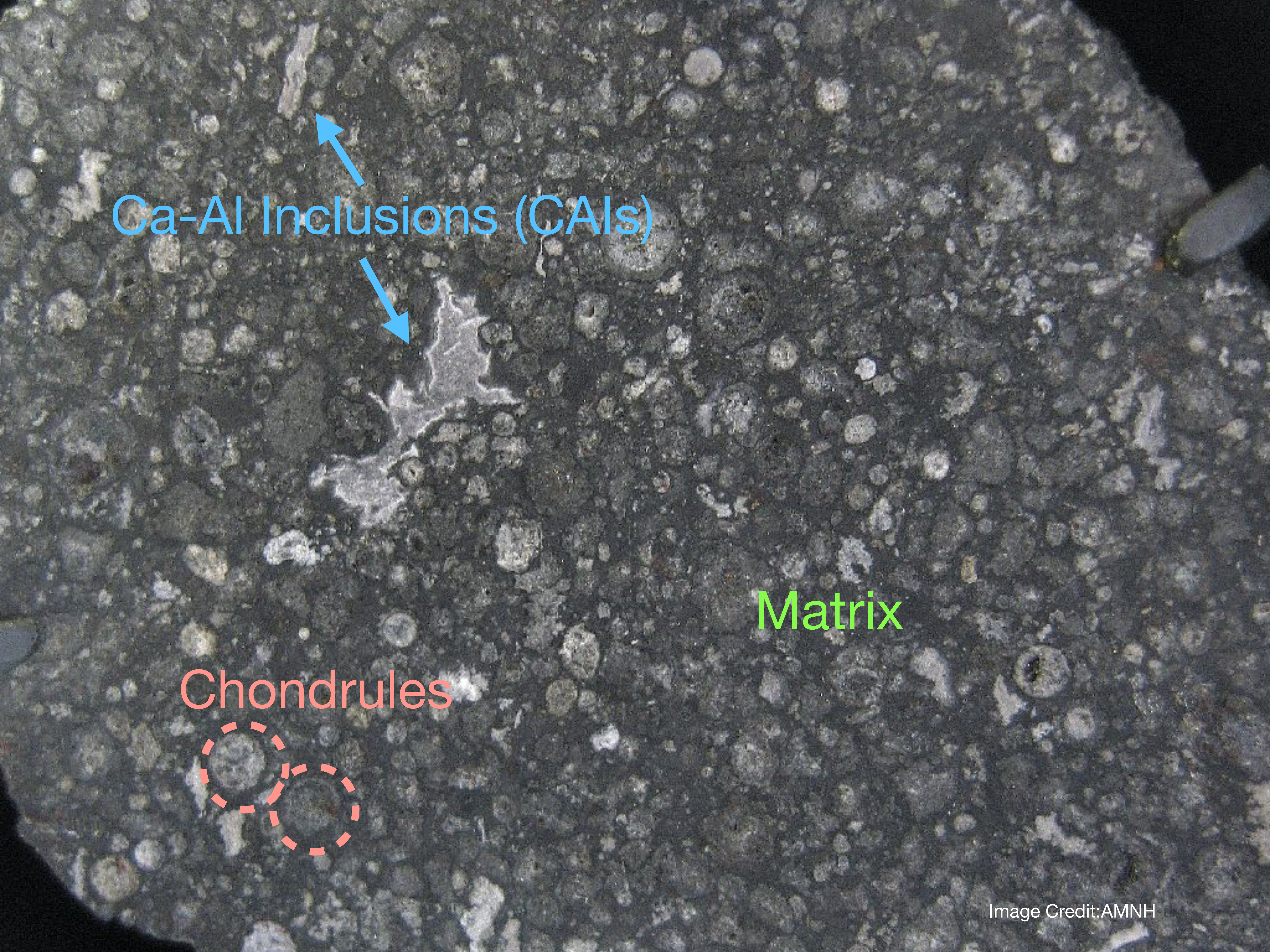
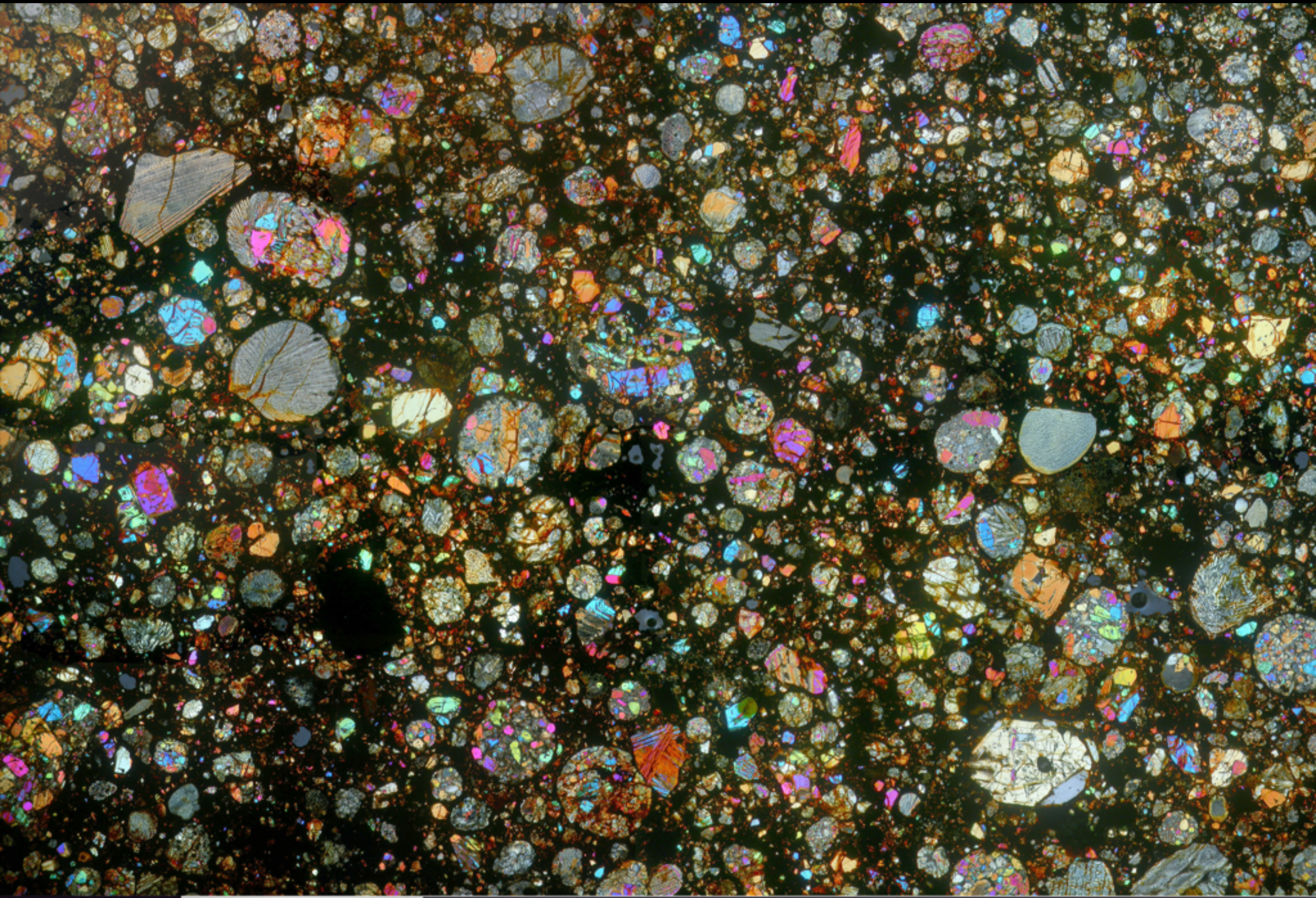


Image Credit: Braukmüller et al. (2018)


Ca-Al Inclusions (CAIs)
Matrix
Chondrules
Image Credit:AMNH



Carbonaceous chondrite mixing model

	Matrix (vol.%)	AOA+CAIs (vol.%)	Matrix (wt.%)	cc-RI (wt.%)	'Chond.' (wt.%)	H_2O (wt.%)	fcc-RI (wt.)
CI	100		72.5			27.5	
T.L.	49–83[5]		53.5	3.0	25.0	18.5	
CM	61[9], 47[8]	8.5[9], 5[7], >0.8[10]	46.5	4.3	35.4	13.8	<0.092
CO	33.8[4]	12.1[4], 13[7], 5.8[3], >1[10]	24.5	5.2	67.6	2.7	<0.059
CV	38.5[2]	9.7[2], 10[7], 6.7[3], >5[10]	23.9	8.3	59.7	8.1	<0.053
CK	75[7]	4[7], >5.7[10]	19.3	11.7	62.0	7.0	
CR	38[1]	0.5[7], 1.5[1], >0.1[10]	21.1	1.7	67.2	10.1	<0.023

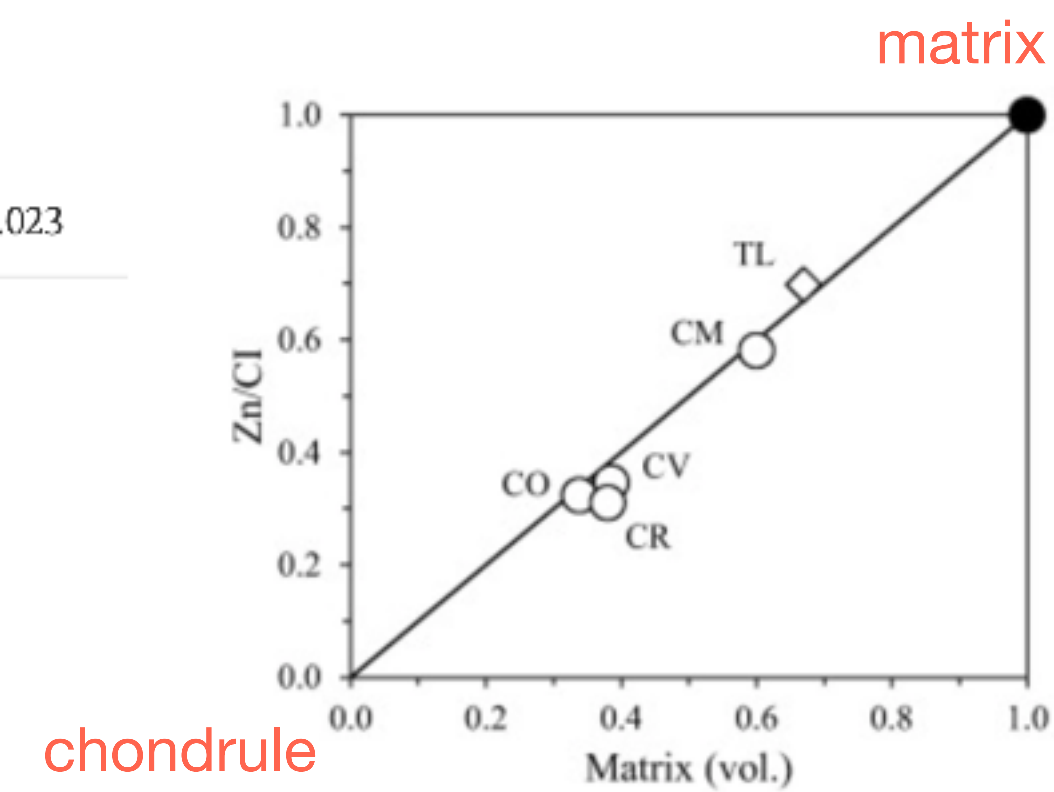


Image Credit: Alexander (2019)

Carbonaceous chondrite mixing model

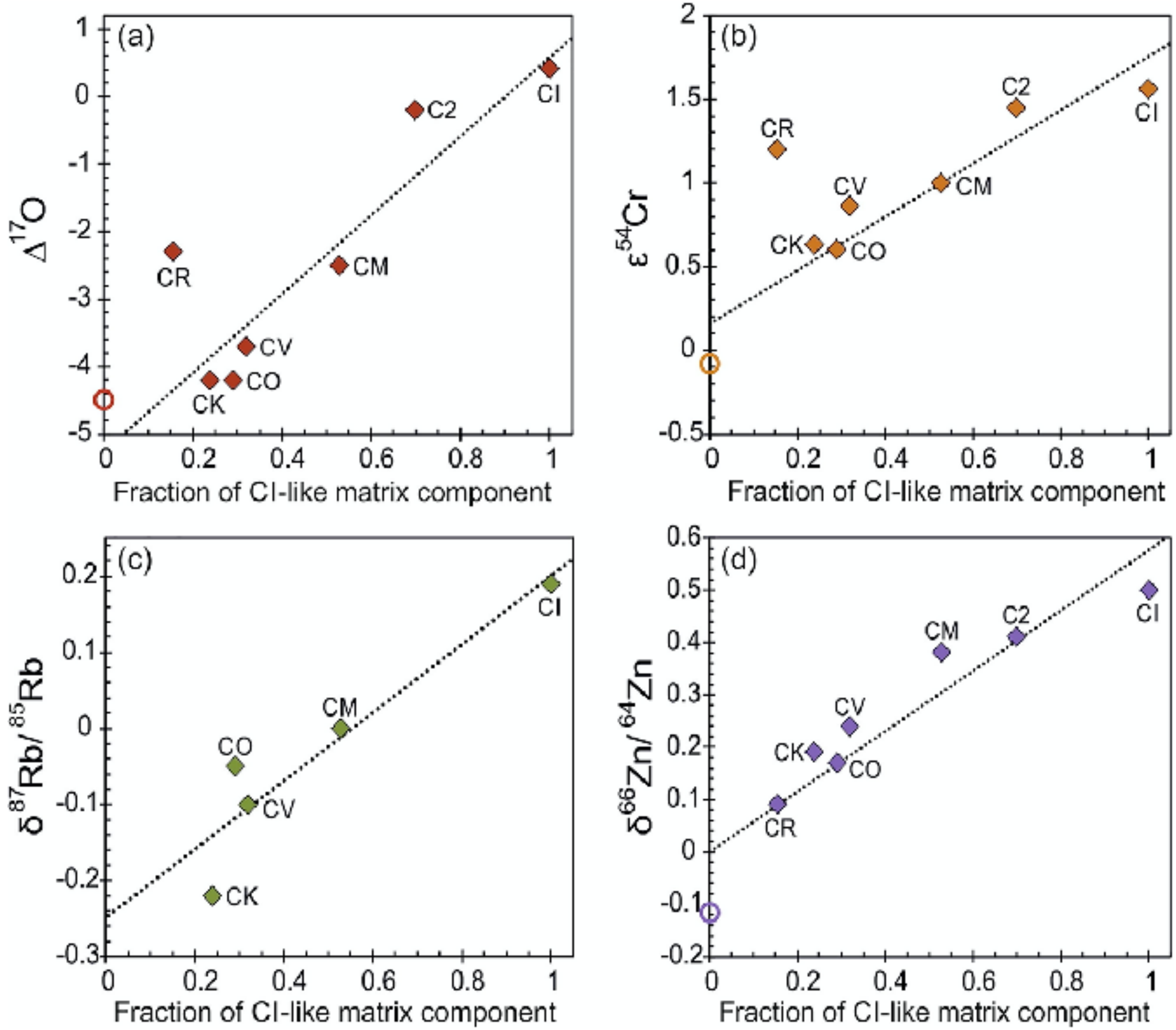
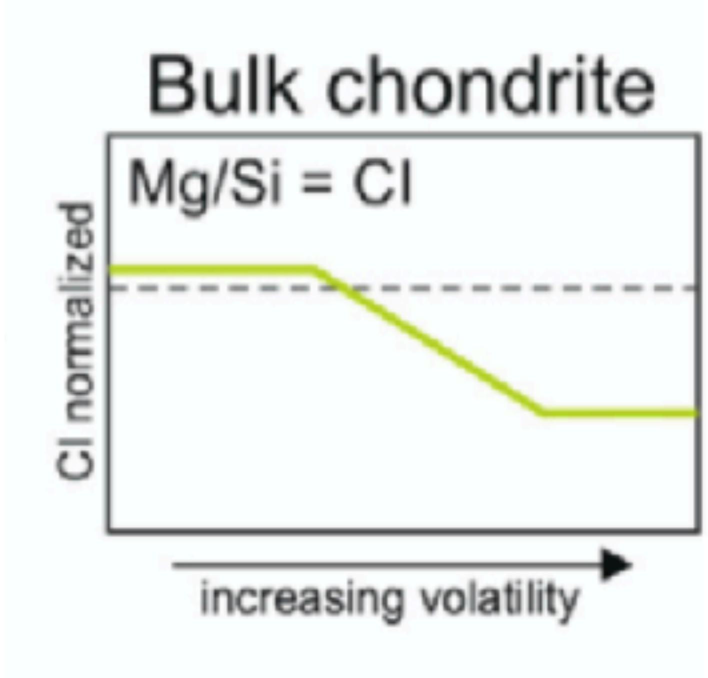


Image Credit: Braukmüller et al. (2018)
Pringle and Moynier, (2017)

Carbonaceous chondrite mixing model



Refractory/main component elements

- Ca, Mg, Fe, Si show no isotope fractionation

Slope volatile elements

- Zn, Cu, Ga, Rb and K show significant isotope fractionation

Plateau volatile elements

- Sn, Tl, Te, Se, and Cd show no isotope fractionation

Image Credit: Braukmüller et al. (2018)

Carbonaceous chondrite mixing model

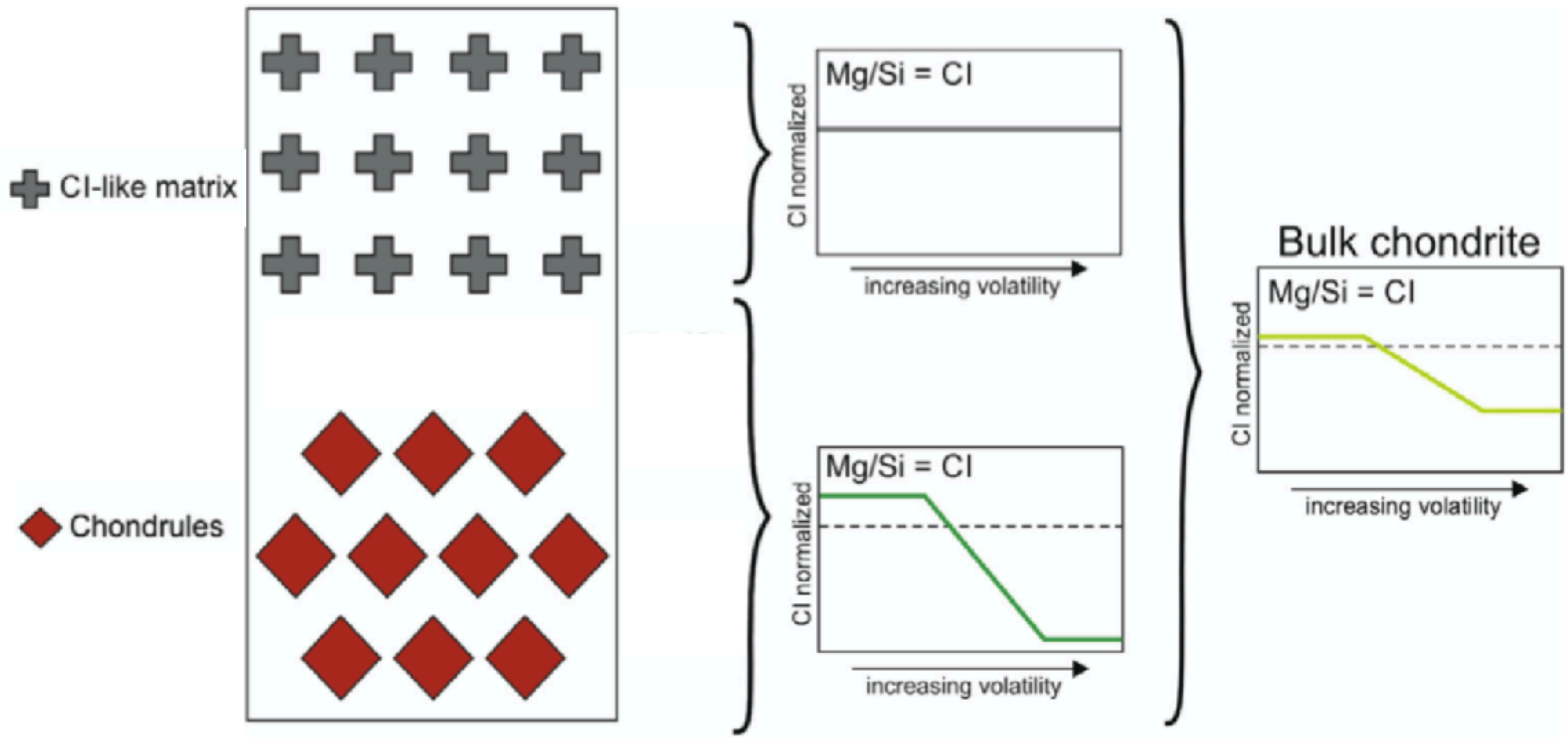


Image Credit: Braukmüller et al. (2018)

Carbonaceous chondrite mixing model

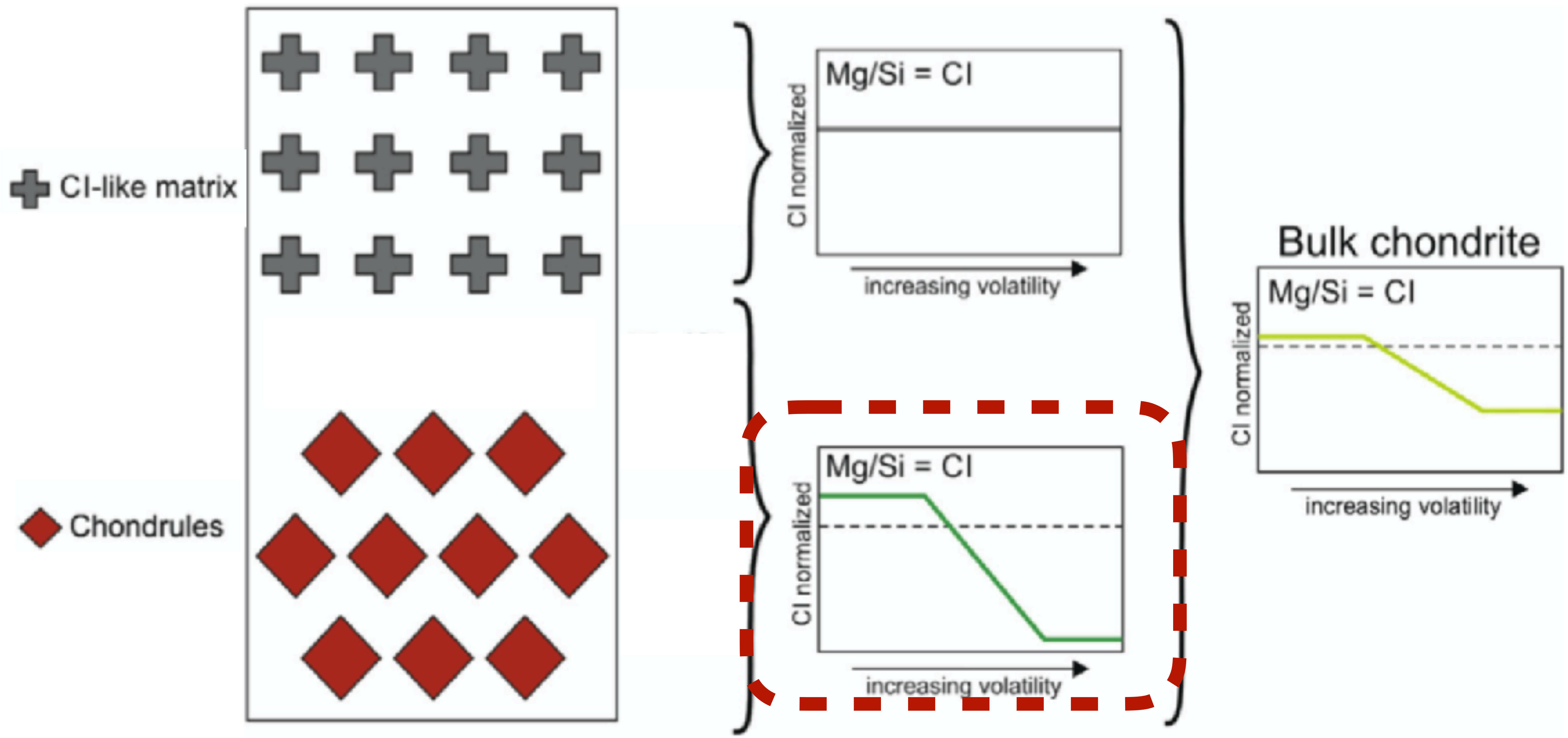


Image Credit: Braukmüller et al. (2018)

Carbonaceous chondrite mixing model

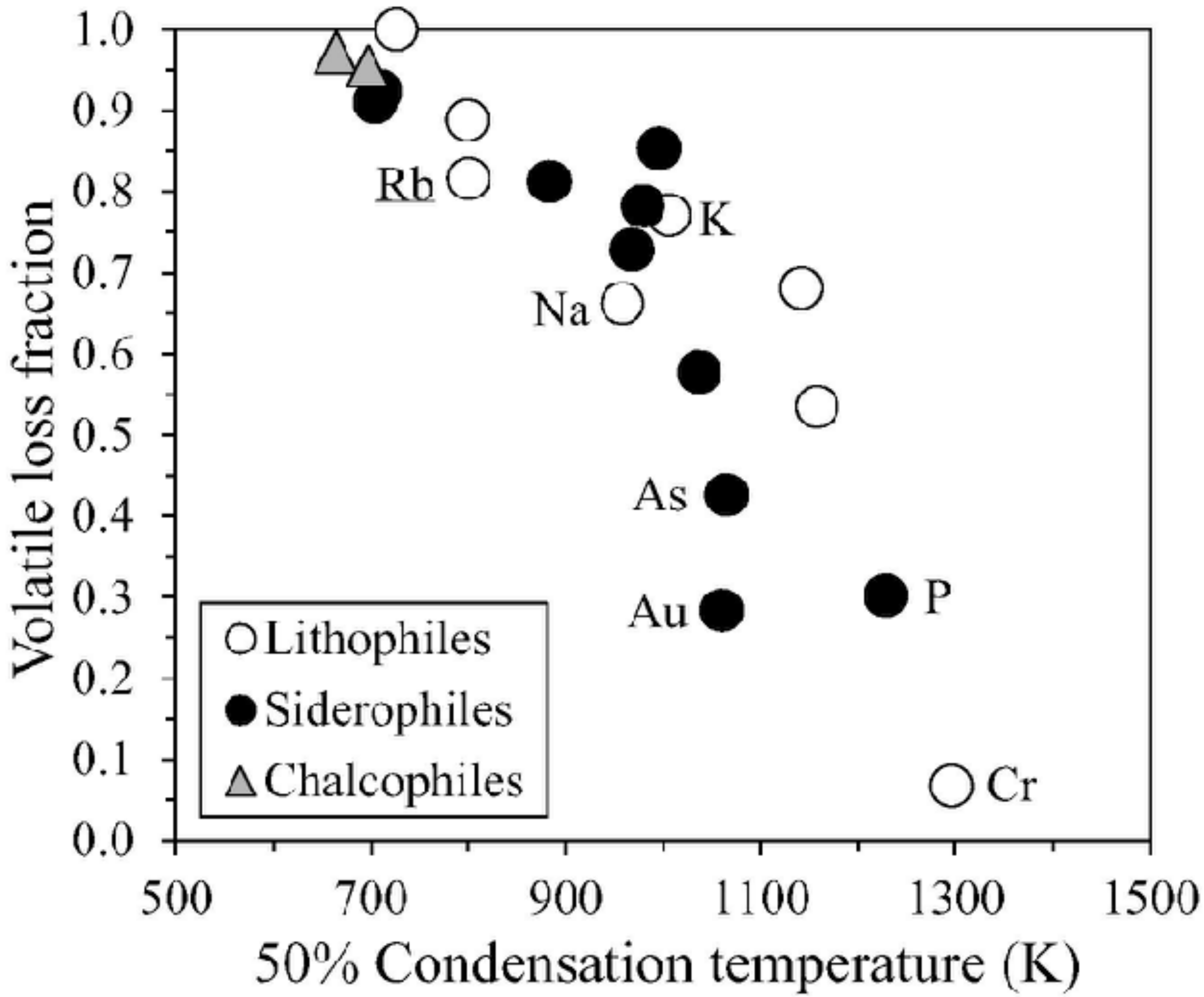


Image Credit: Alexander (2019)

Carbonaceous chondrite mixing model

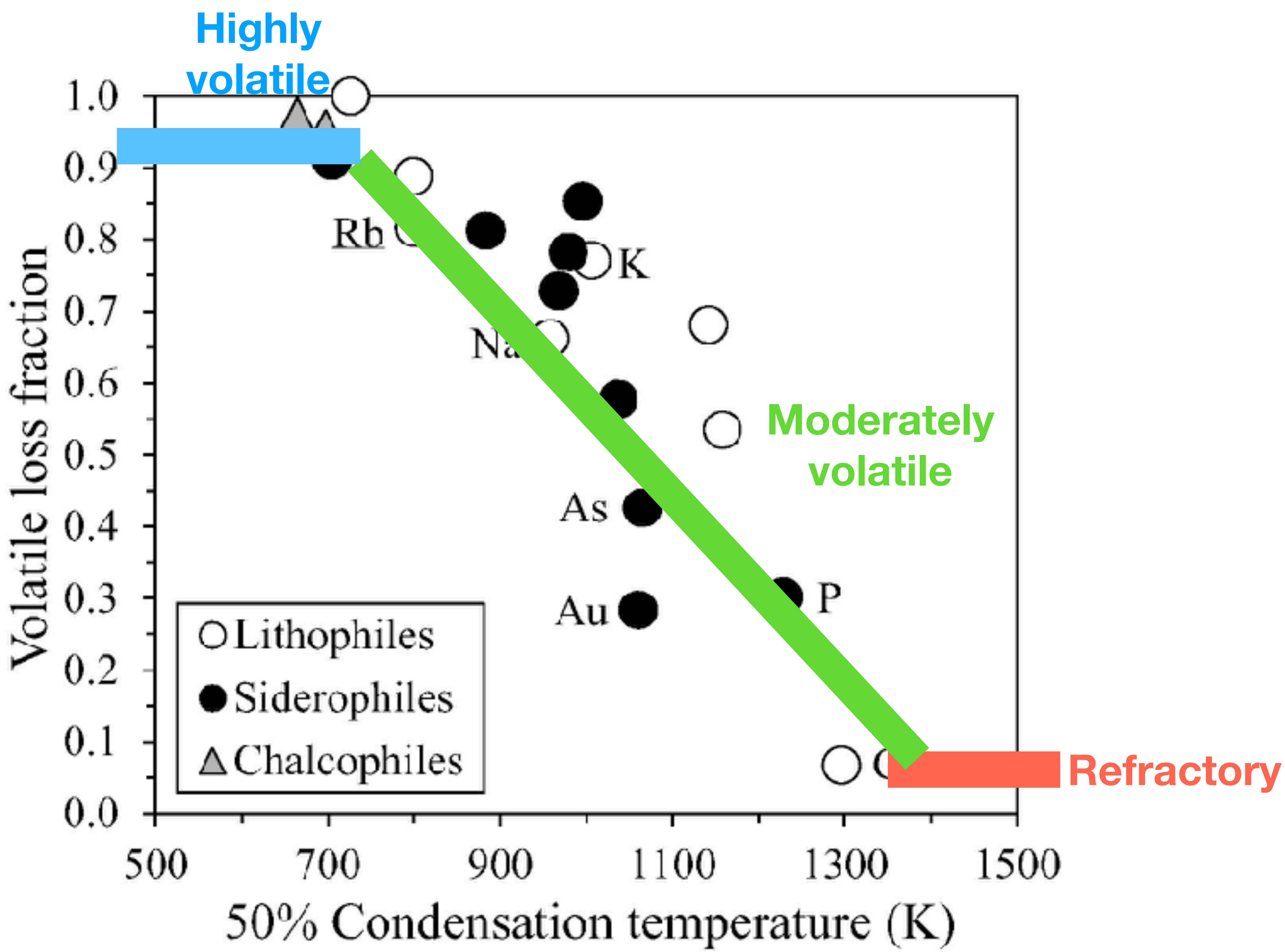
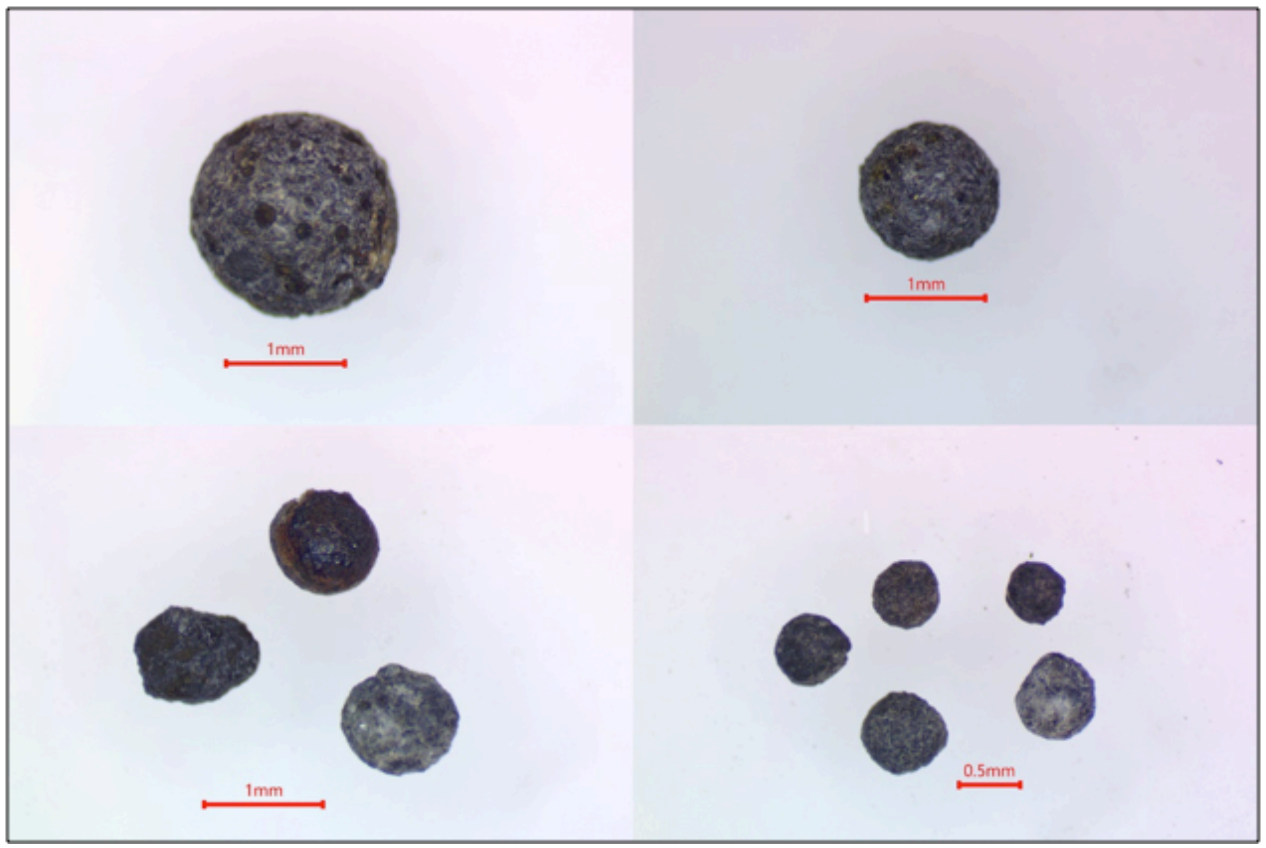
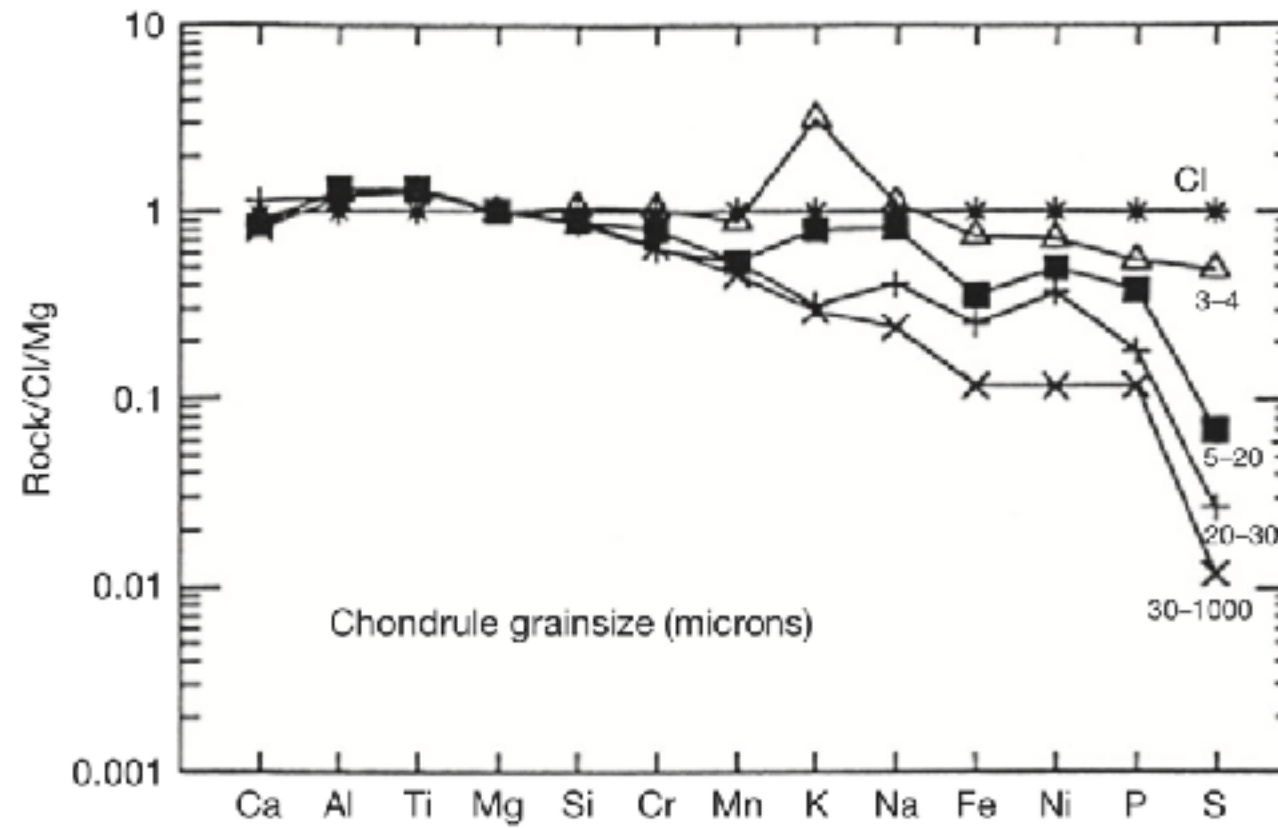


Image Credit: Alexander (2019)

Chondrule Formation

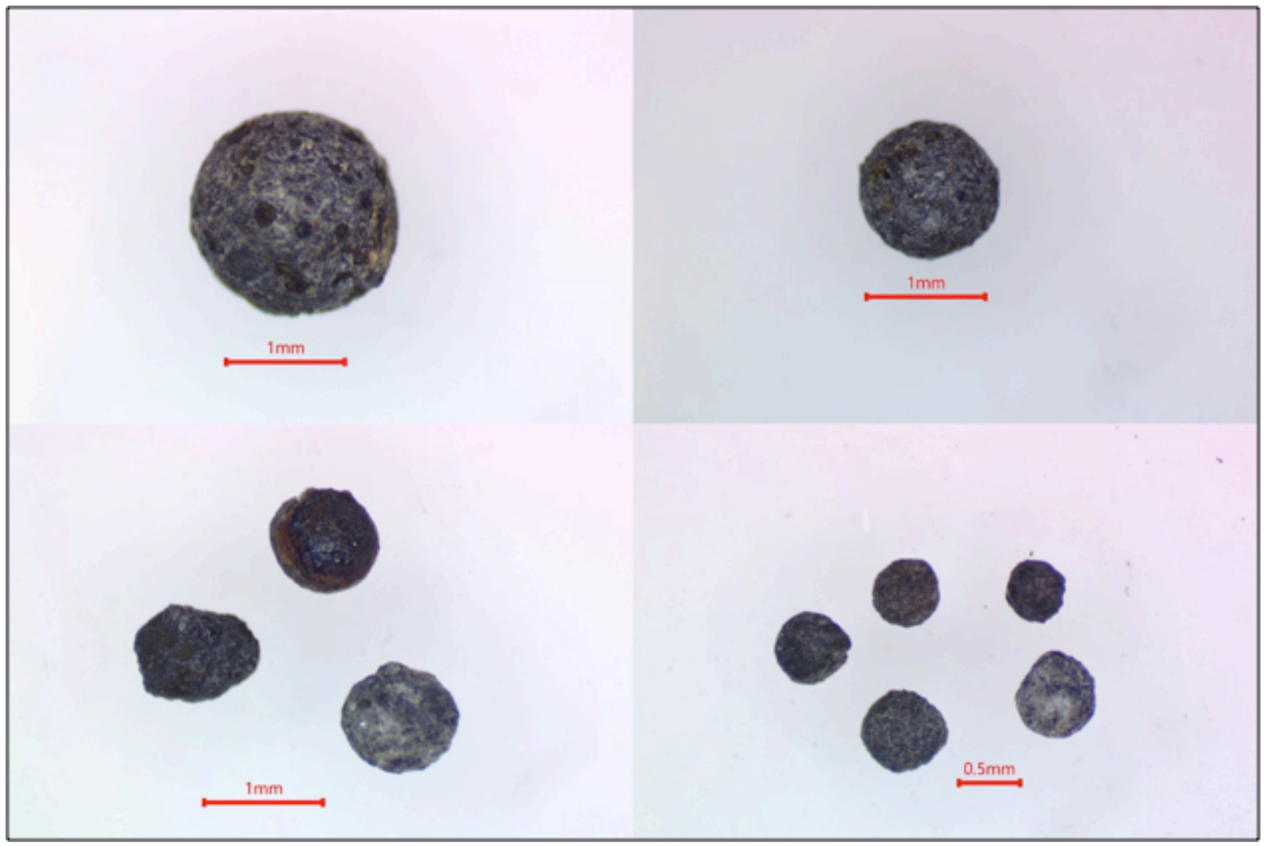




50% solar nebula condensation temperature

Image Credit: (Hewins et al., 1997)

Chondrule Formation



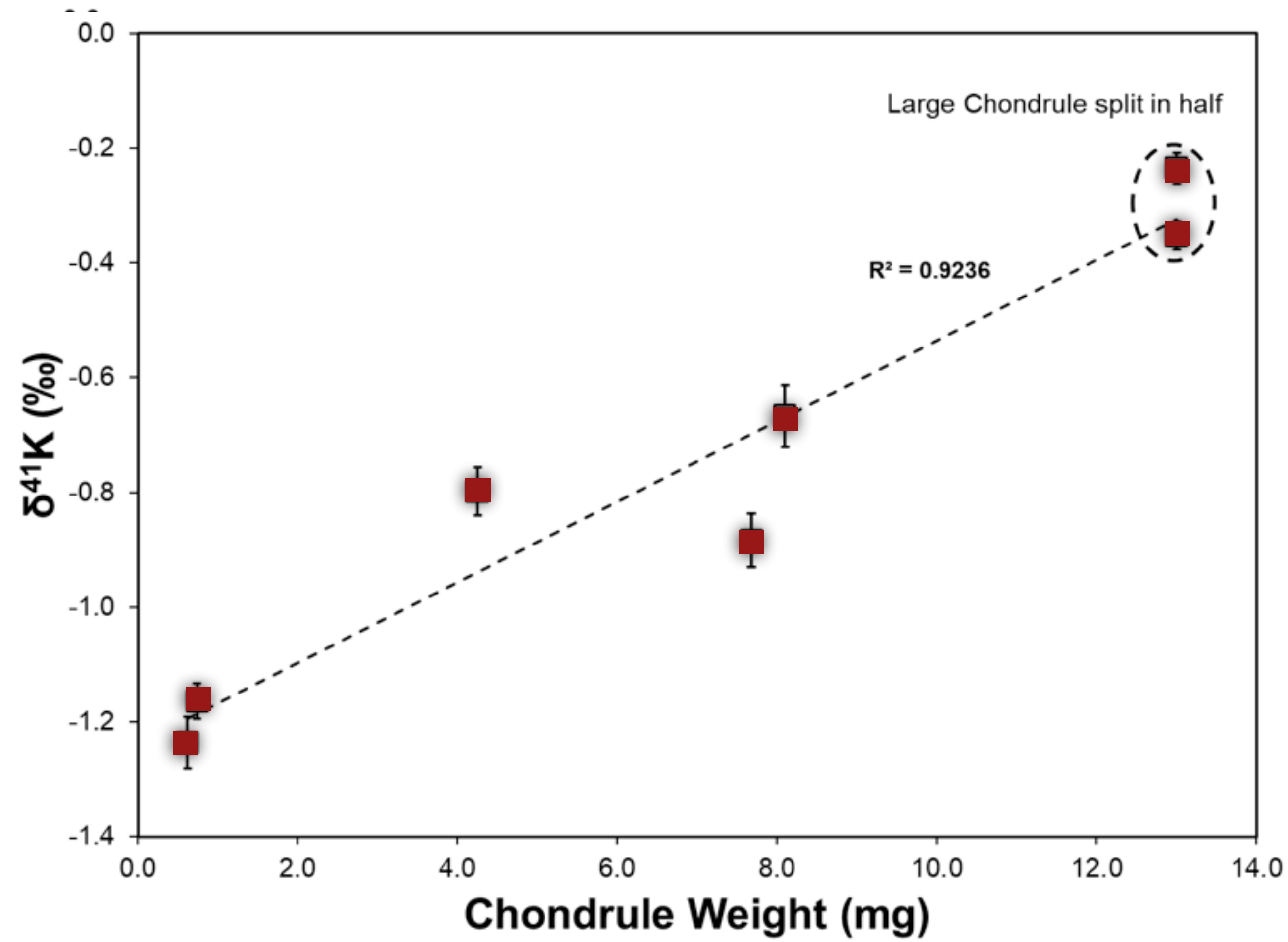


Image Credit: Koefoed et al. (2020)

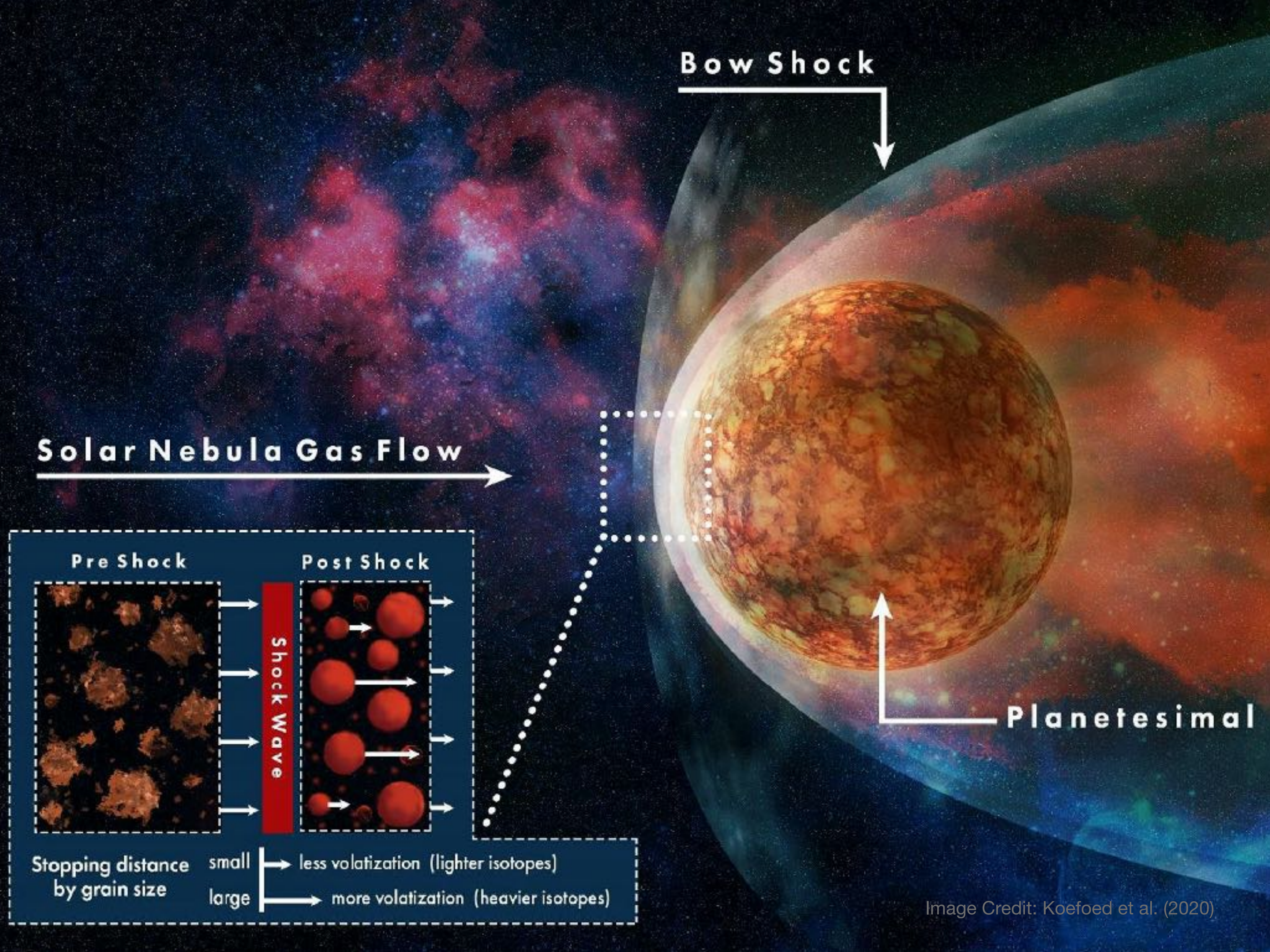
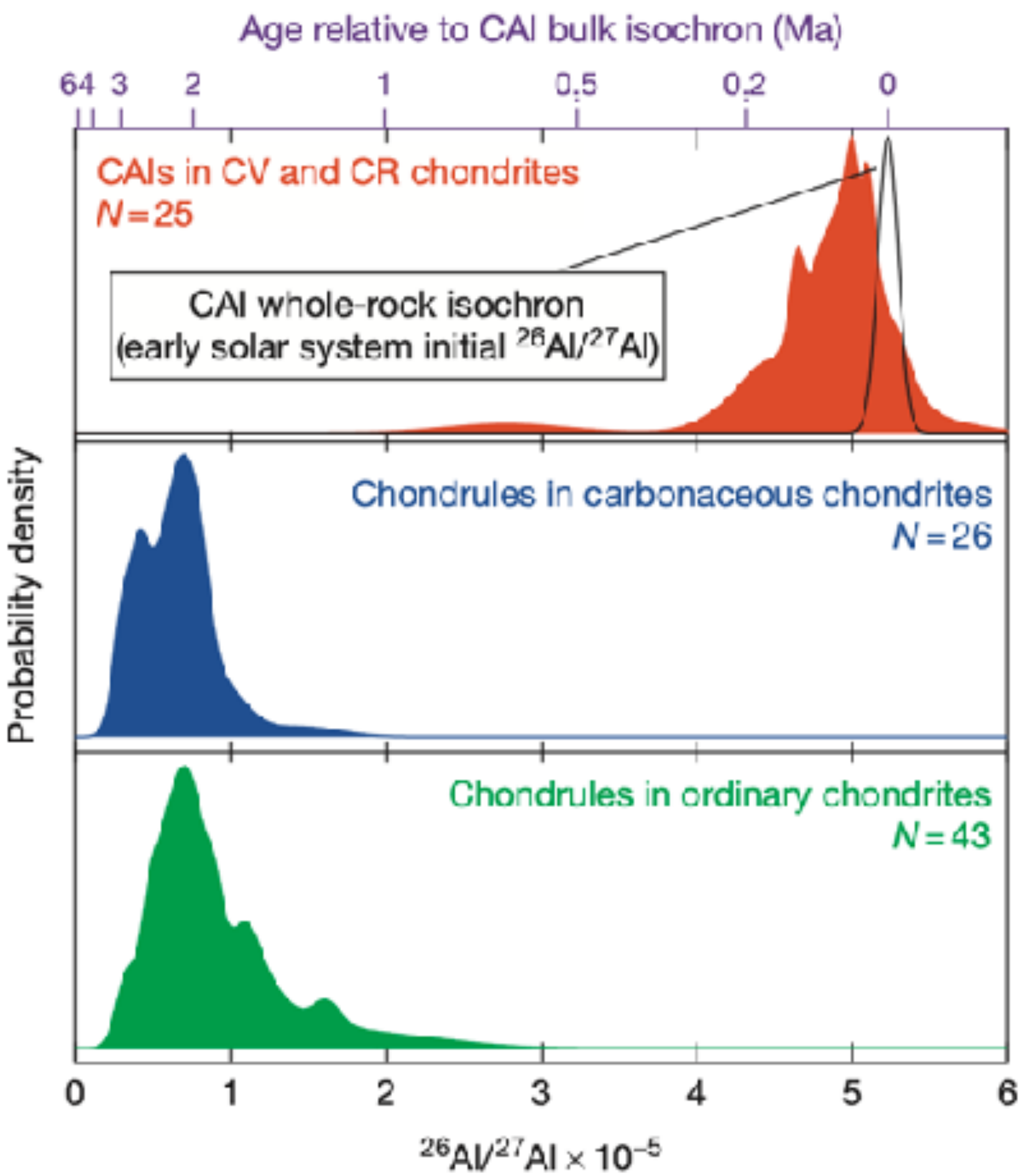


Image Credit: Koefoed et al. (2020)

The timing of events in the early Solar System



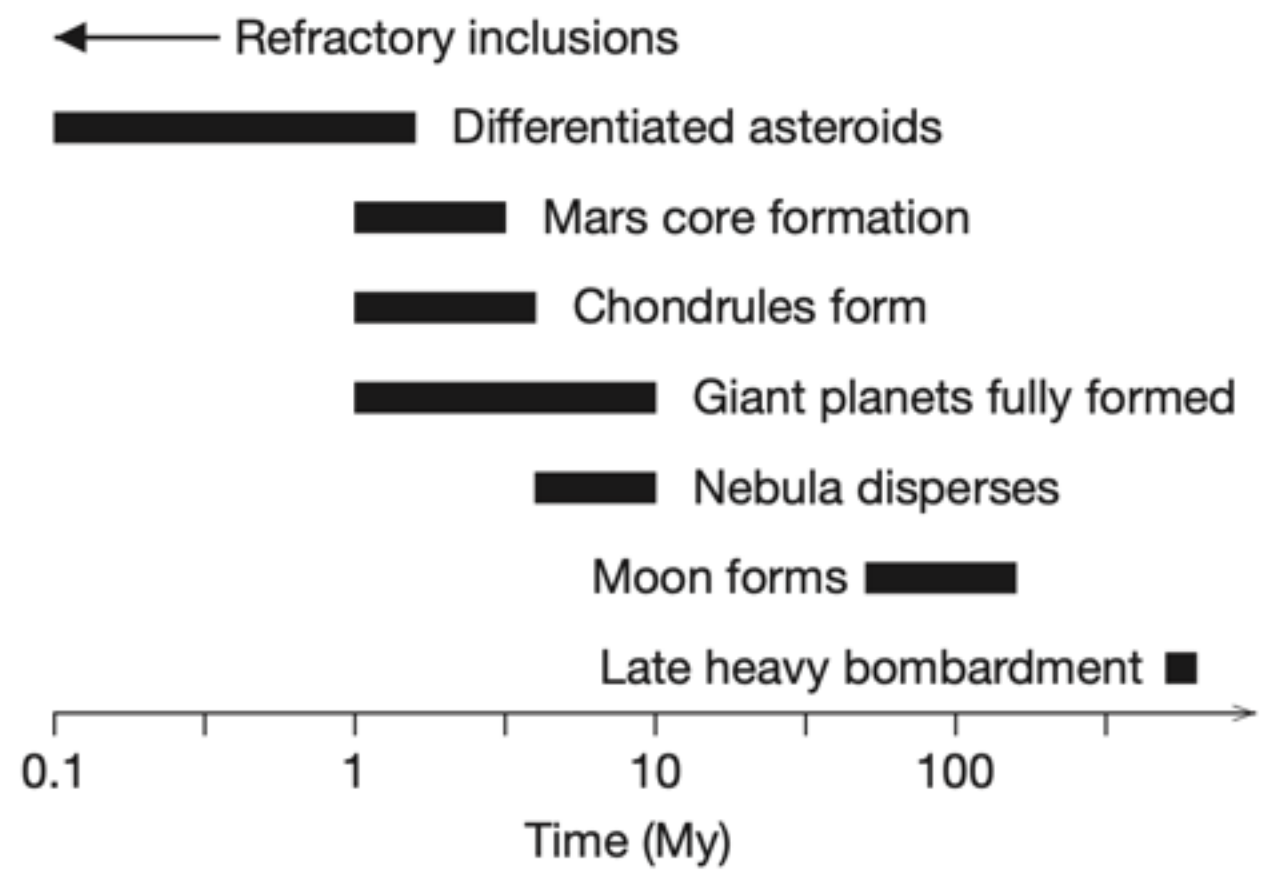


Image Credit: Davids and McKeegan (2014)
Chambers (2014)

The great isotopic dichotomy of the early Solar System

Isotopic anomalies (mass-independent isotope systems): refractory elements

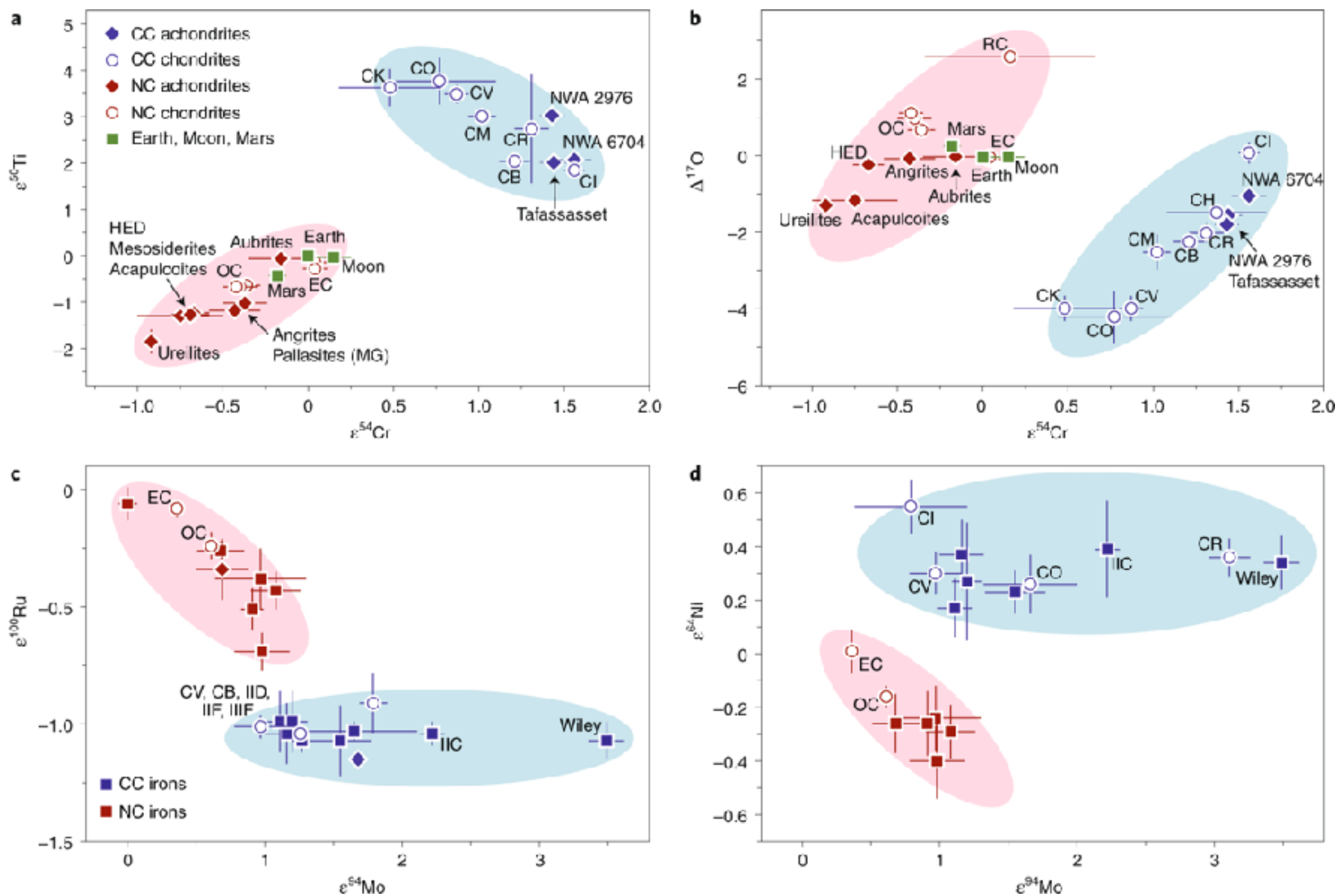
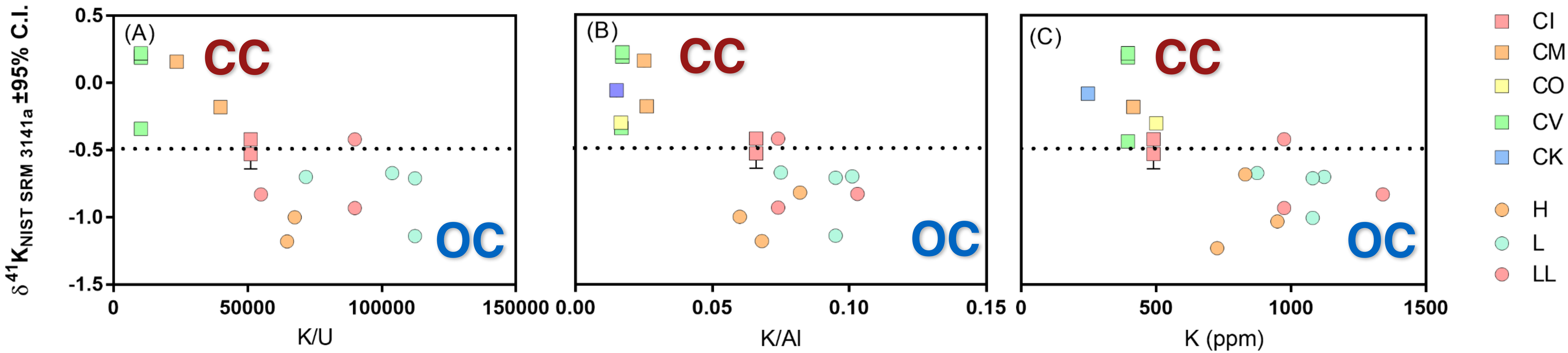
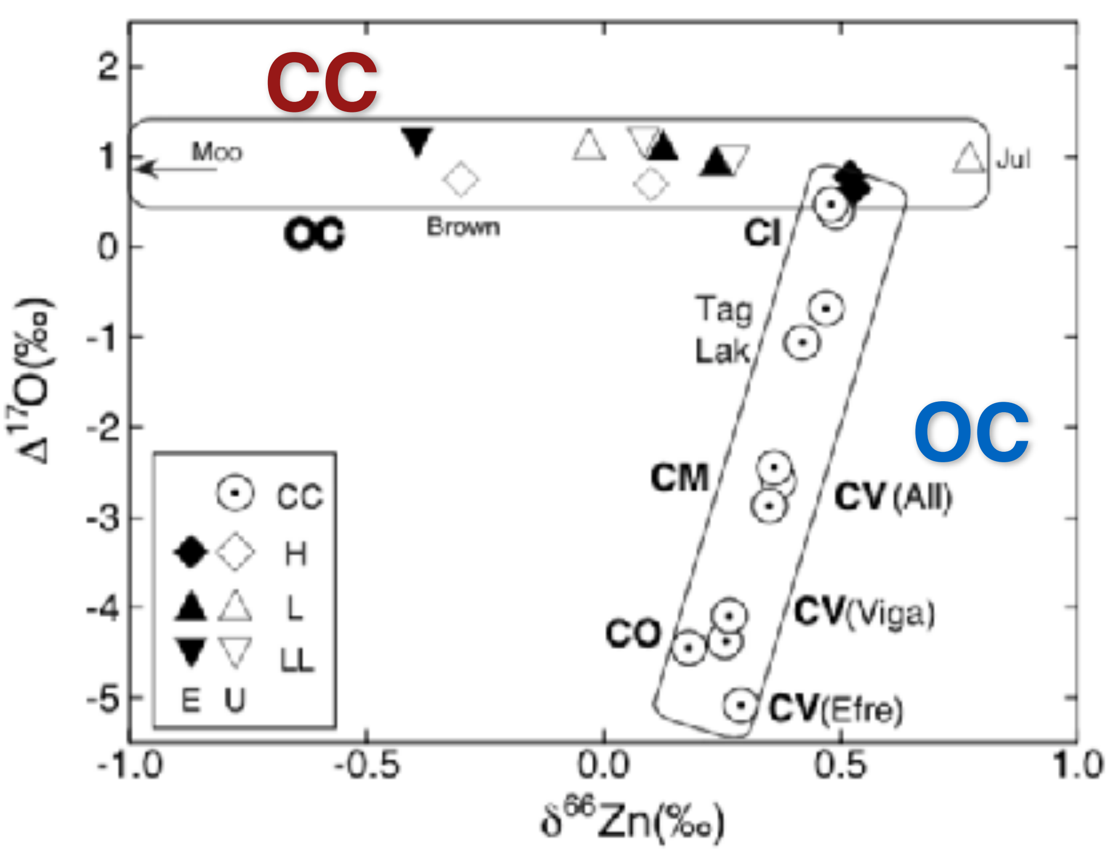


Image Credit: Kruijer et al (2020)

The great isotopic dichotomy of the early Solar System

mass-dependent isotope systems): moderately volatile elements





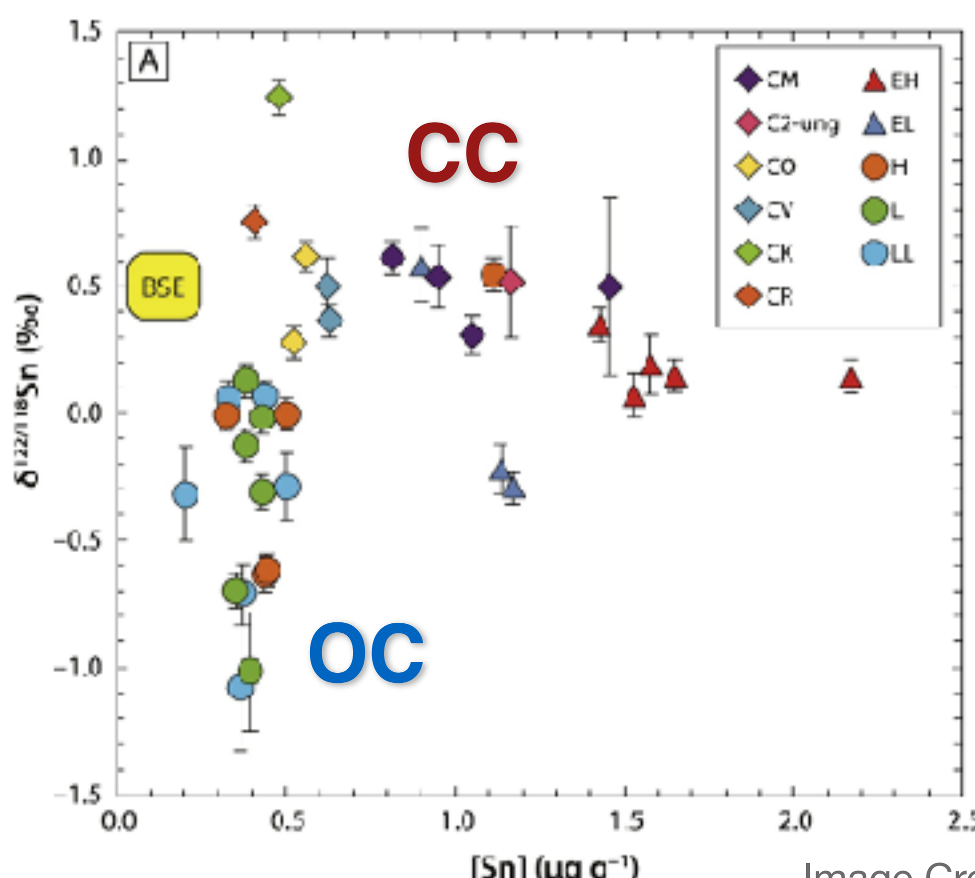


Image Credit: Luck et al. (2015)
Bloom et al (2020)
Creech and Moynier (2019)

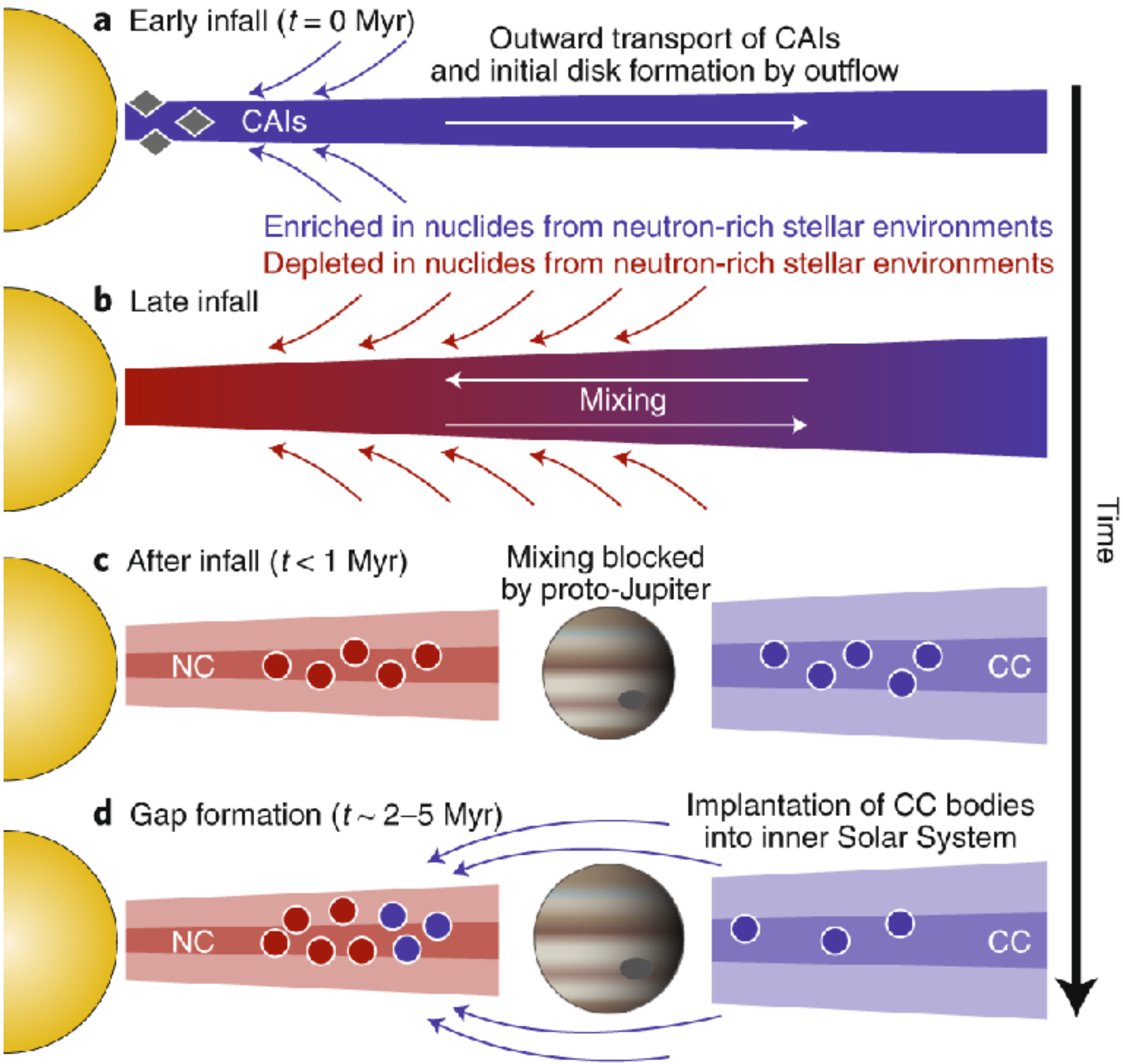


Image Credit: Kruijer et al (2020)

ALMA image of the planet-forming disk around the young Sun-like star

Image Credit: The Atacama Large Millimeter/
submillimeter Array (ALMA)

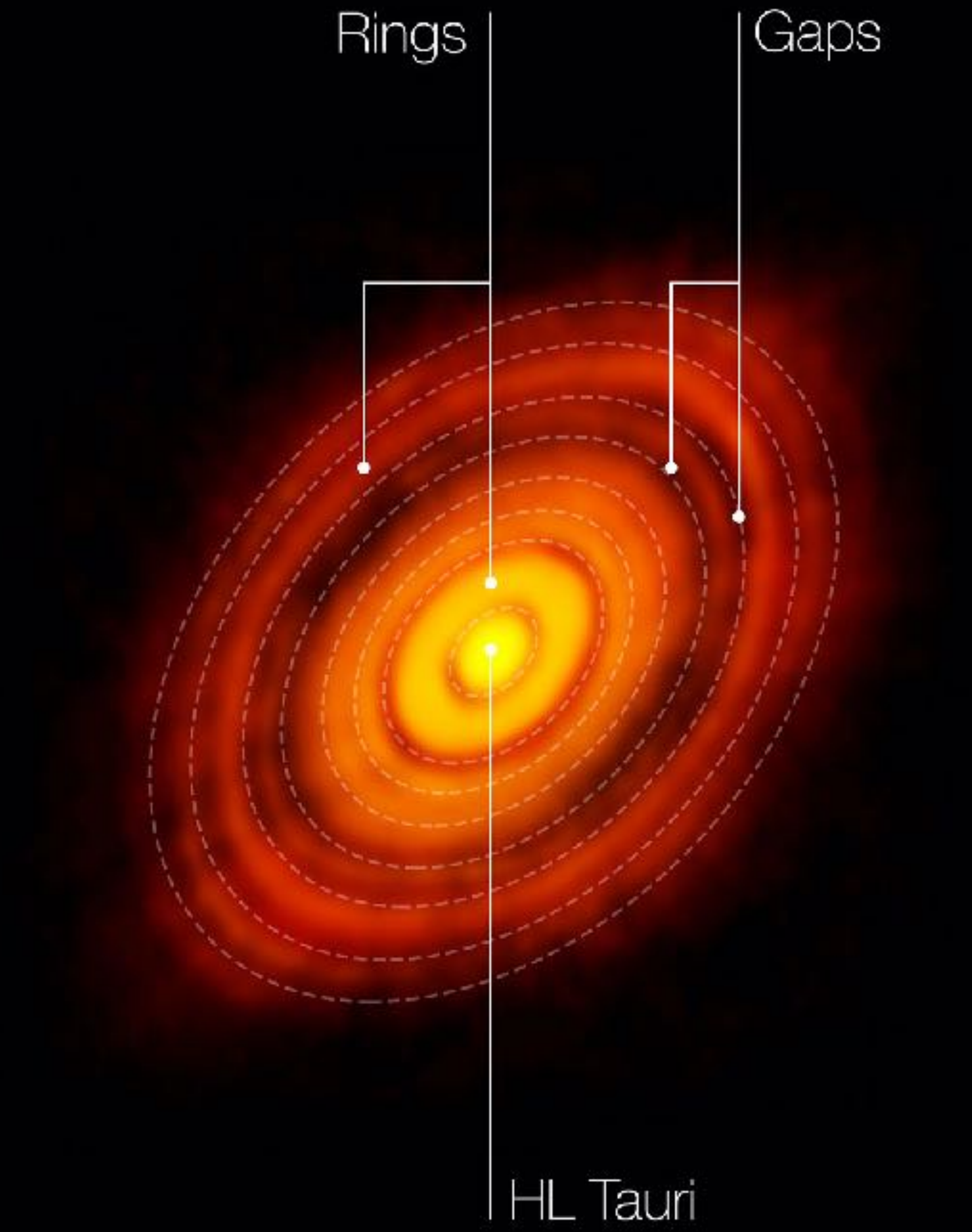


Image Credit: The Atacama Large Millimeter/
submillimeter Array (ALMA)

ALMA high-resolution images of nearby protoplanetary disks

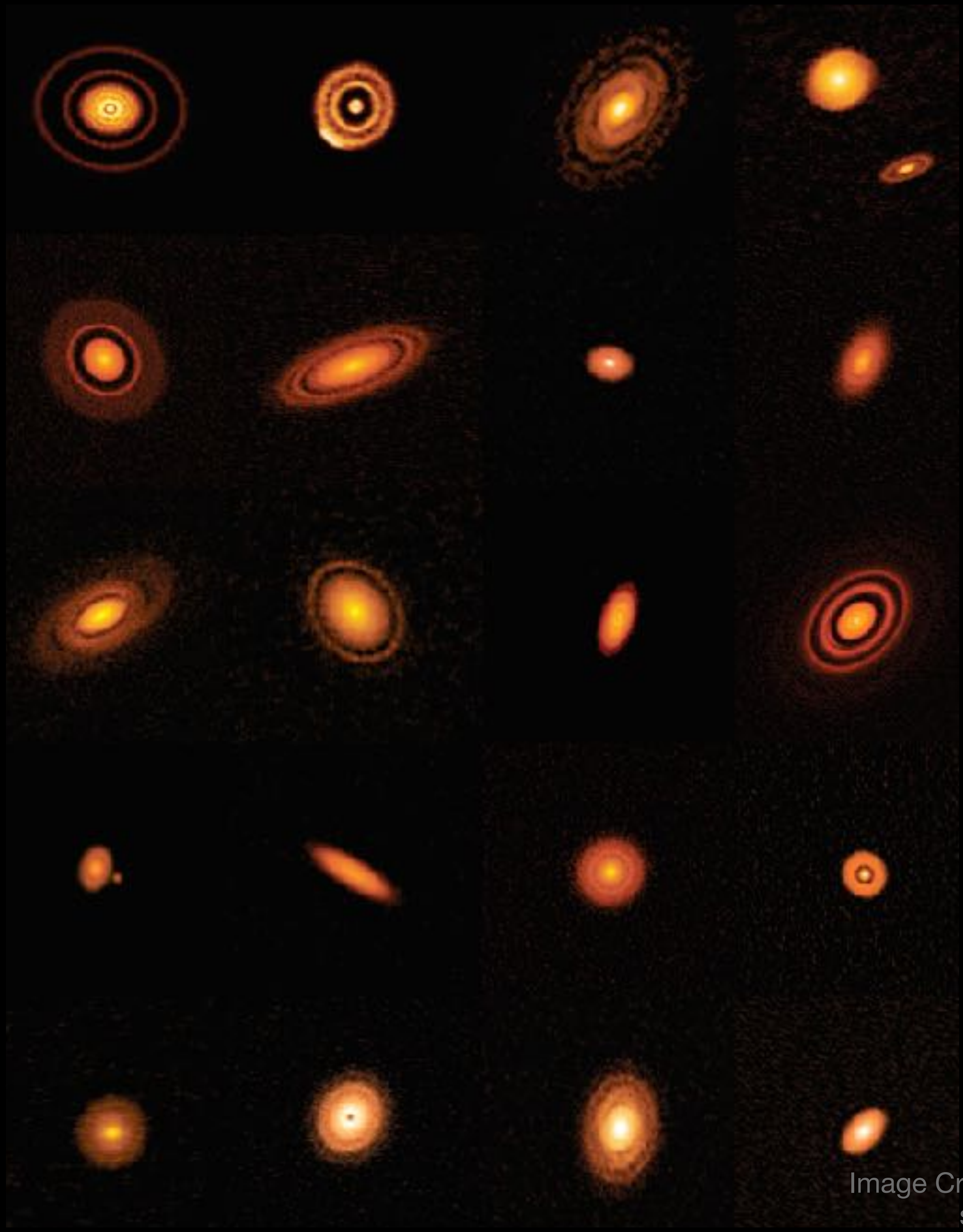
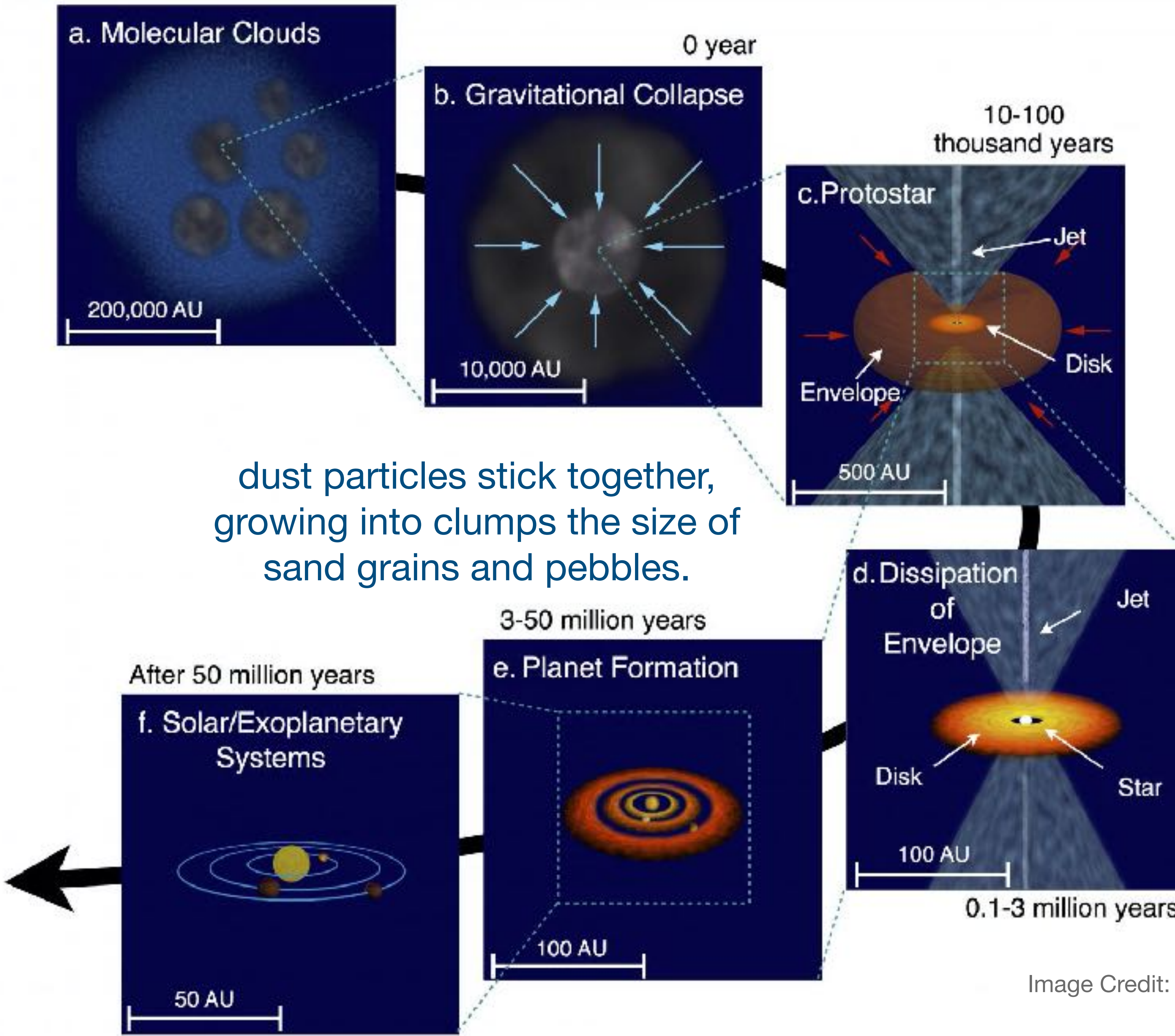


Image Credit: The Atacama Large Millimeter/
submillimeter Array (ALMA)

The Formation of Planets



dust particles stick together, growing into clumps the size of sand grains and pebbles.

Image Credit: ASIAA

The Formation of Planets

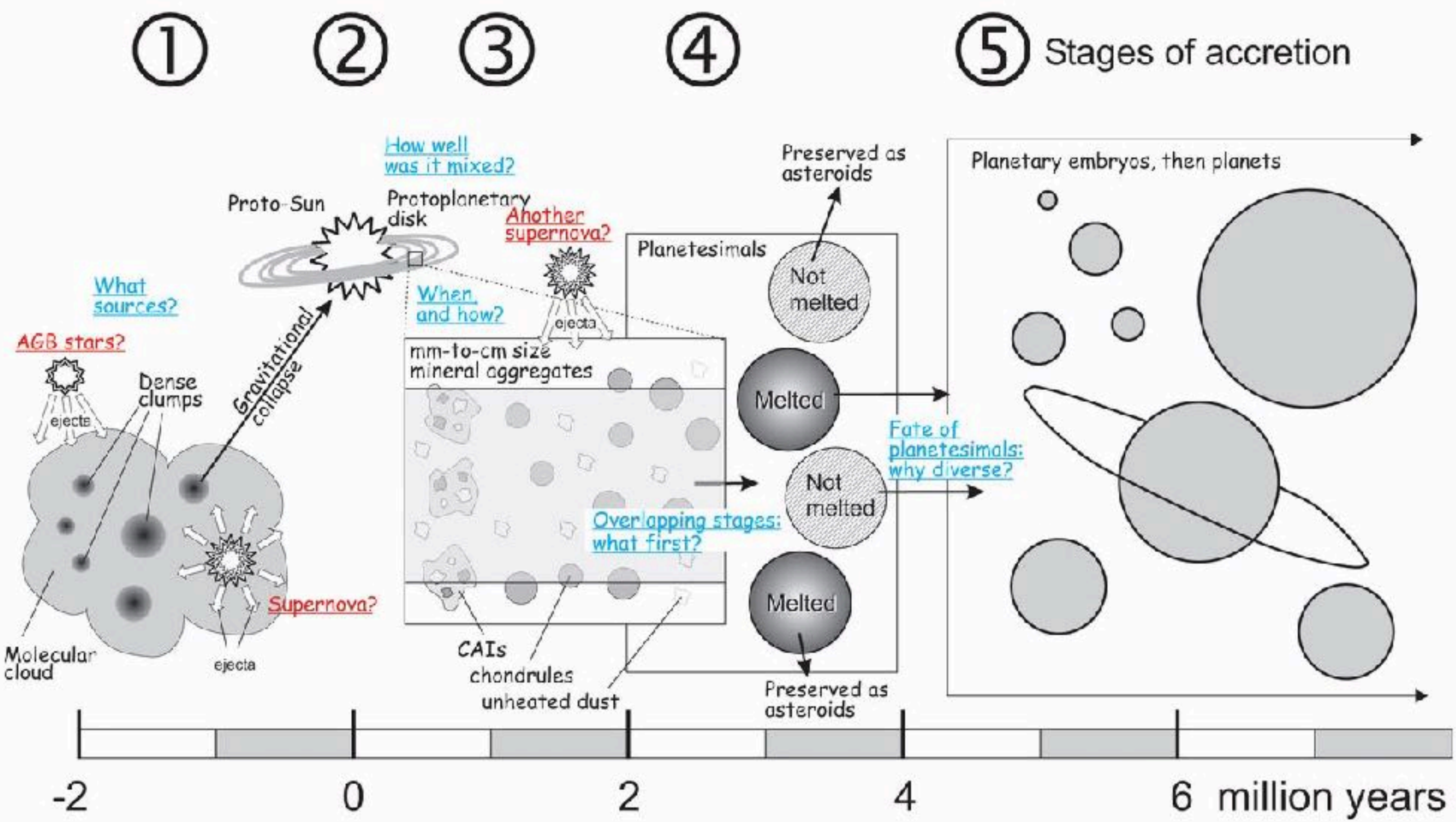


Image Credit: Amelin and Ireland (2013)

The Formation of the Solar System and Planets

- The age of the Universe: 13.787±0.020 Billion years

~9 Billion years

- The age of the Solar System: 4.567 ± 0.0005 Billion years

~30-100 Million years (Hf-W)

- The age of the Earth: 4.55±0.07 Billion years


Thanks!