U-Pb Chronology of the Early Solar System

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Acknowledgements:
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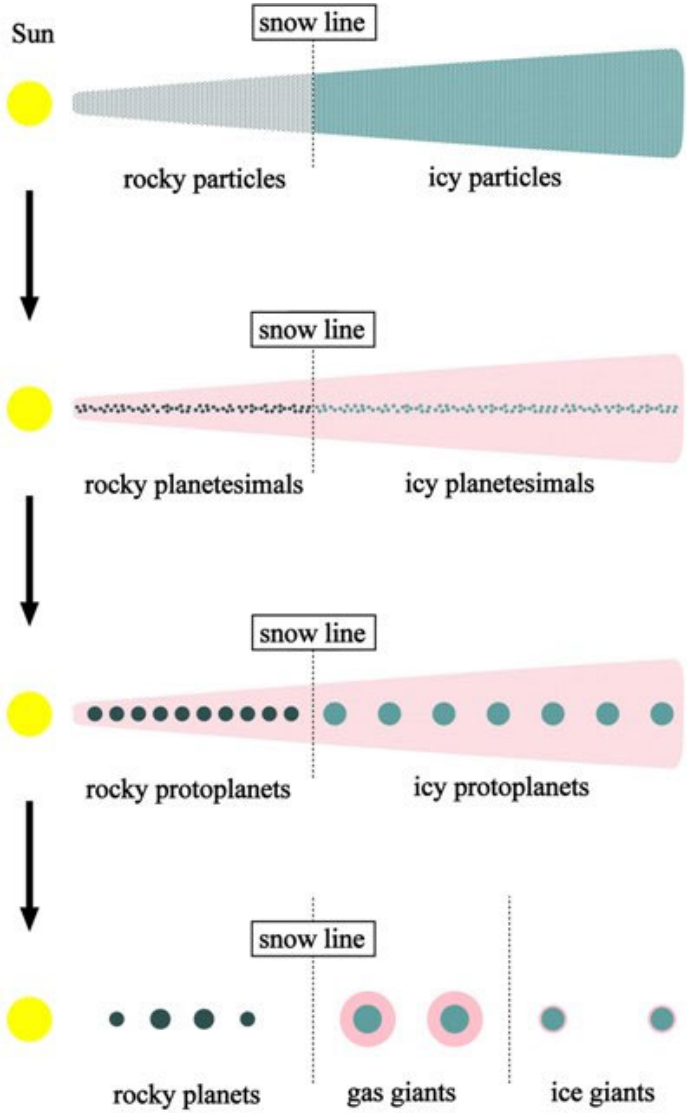
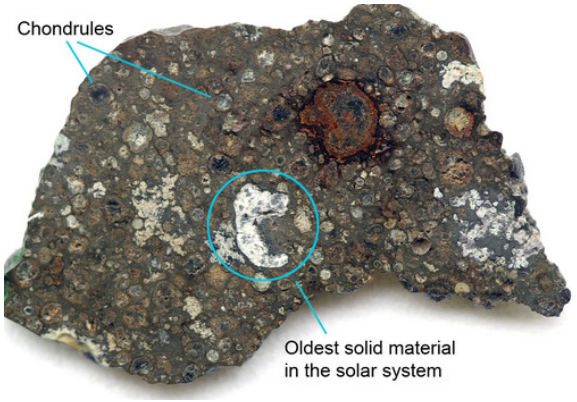
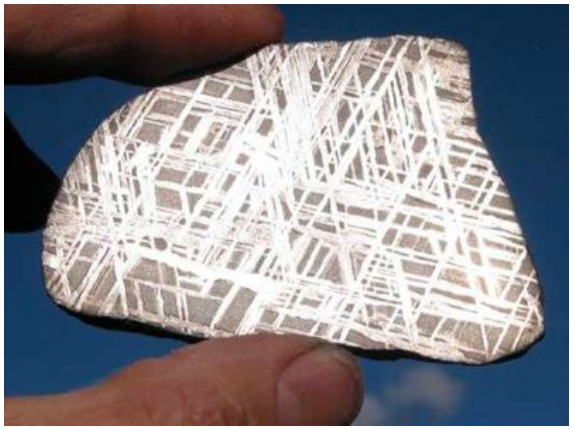
Planet Formation & Meteorites



From https://www.subarutelescope.org/Pressrelease/2009/



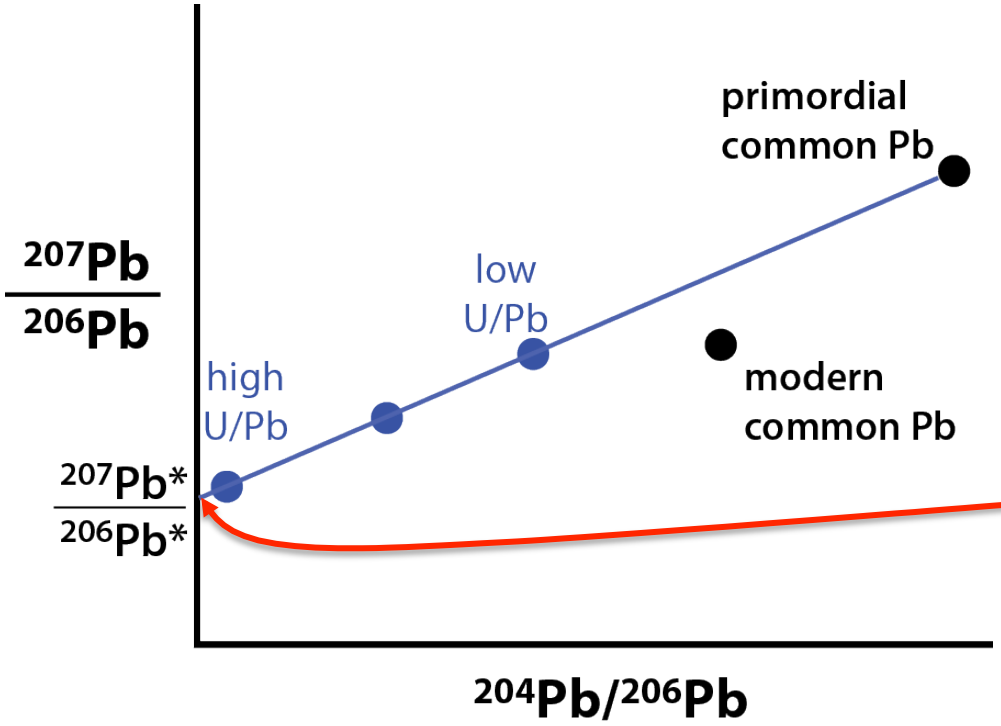
Chondrite



Iron meteorite

Achondrite

U-Pb Chronology



$$^{238}U \rightarrow {}^{206}Pb^{*} \; (t_{1/2}=4468 \text{ Ma})$$

$$^{235}U \rightarrow {}^{207}Pb^{*} \; (t_{1/2}=704 \text{ Ma})$$

$$\frac{^{207}Pb^{*}}{^{206}Pb^{*}} = \frac{^{238}U}{^{235}U} \times \frac{(e^{\lambda 235 t} - 1)}{(e^{\lambda 238 t} - 1)}$$

Age determination using only isotope ratios (not elemental ratios).

- Providing most precise (± 0.1-0.5 Ma) absolute meteorite ages.

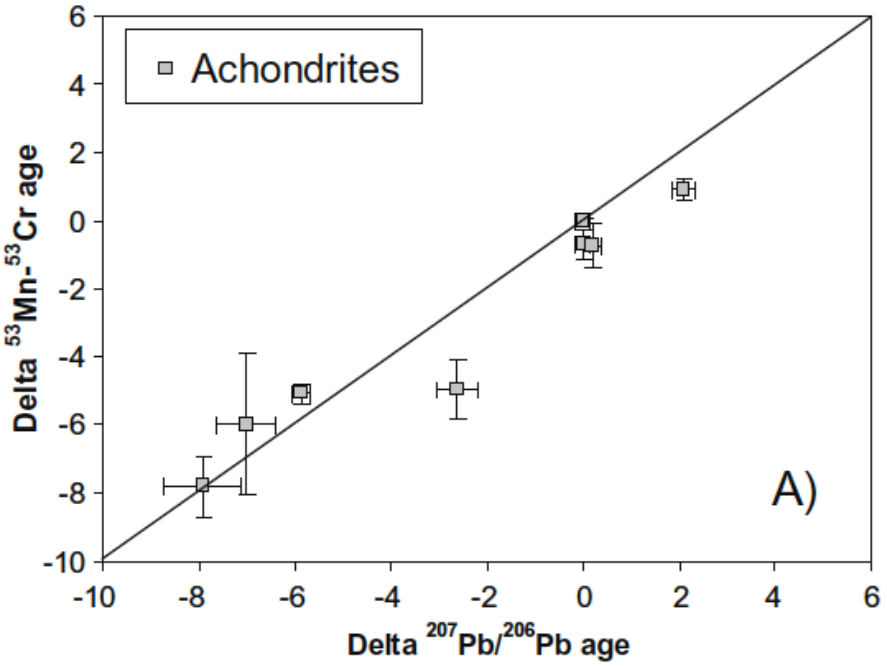
Short-lived Isotope Chronology

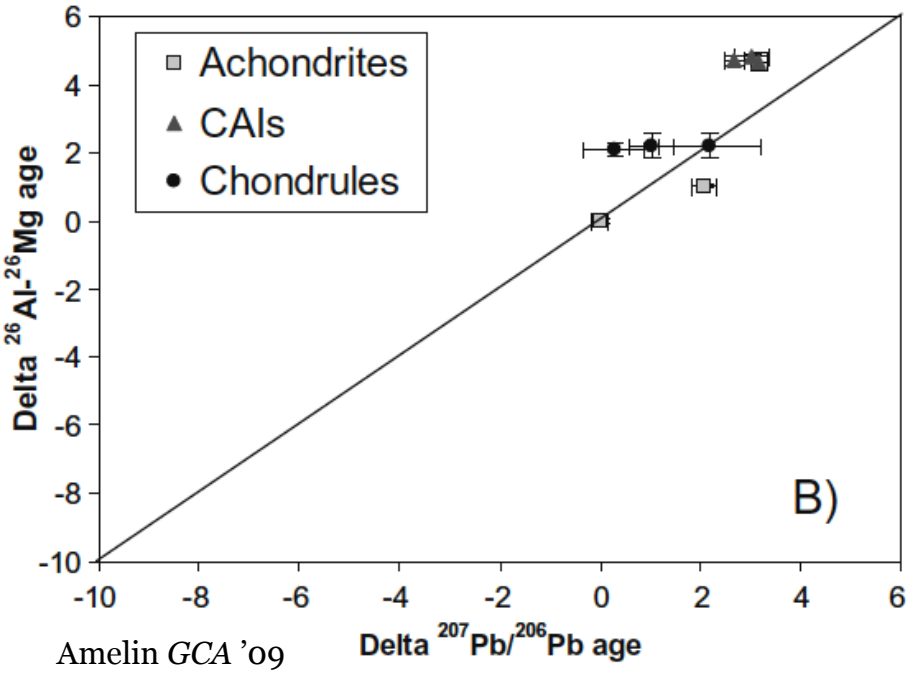
Short-lived Isotope Systems

Par. → Dau.	$T_{1/2}$	Carrier
$^{26}Al \rightarrow {}^{26}Mg$	717 Kyr	Pl-Olv,Px
$^{60}Fe \rightarrow {}^{60}Ni$	1.5 Myr	Px,FeS-Mt
$^{53}Mn \rightarrow {}^{53}Cr$	3.74 Myr	Olv-Chr
$^{182}Hf \rightarrow {}^{182}W$	8.9 Myr	Px-metal

The chronometers provide precise age, BUT requires uniform distribution of the parent-nuclides.

Discrepancy btw U-Pb & Al-Mg/Mn-Cr ages may reflect the non-uniformity.





Amelin *GCA* '09

This Study

Combining U-Pb age & chemical data for meteorites

1. Carbonaceous chondrites

- Thermal events in the proto-planetary disk

2a. Oldest achondrite (A-881394)

- Accretion & differentiation of an asteroid

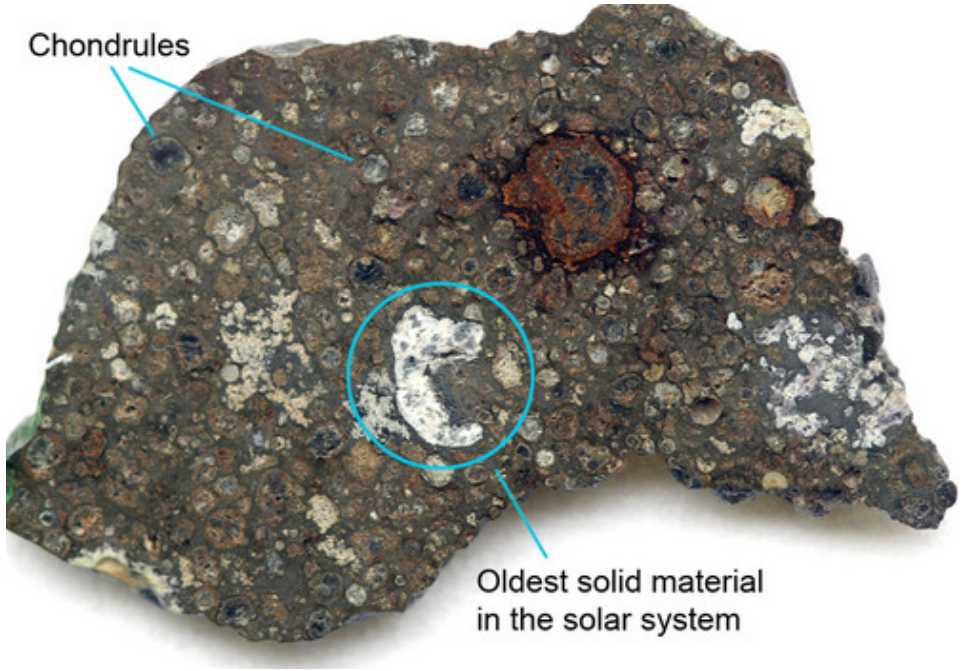
2b. Primitive 'carbonaceous' achondrite (NWA6704)

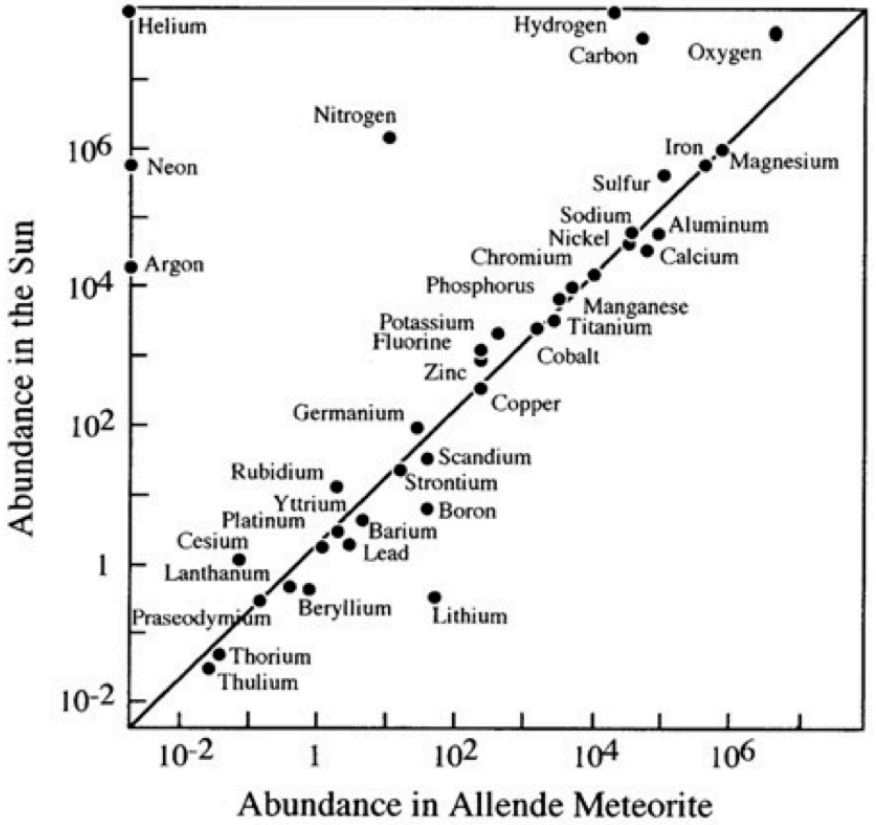
- Accretion & impact of an un-differentiated asteroid

3. Vesicular basaltic achondrites (Ibitira & D'Orbigny)

- H_2O delivery to the terrestrial planet region

Chondrites

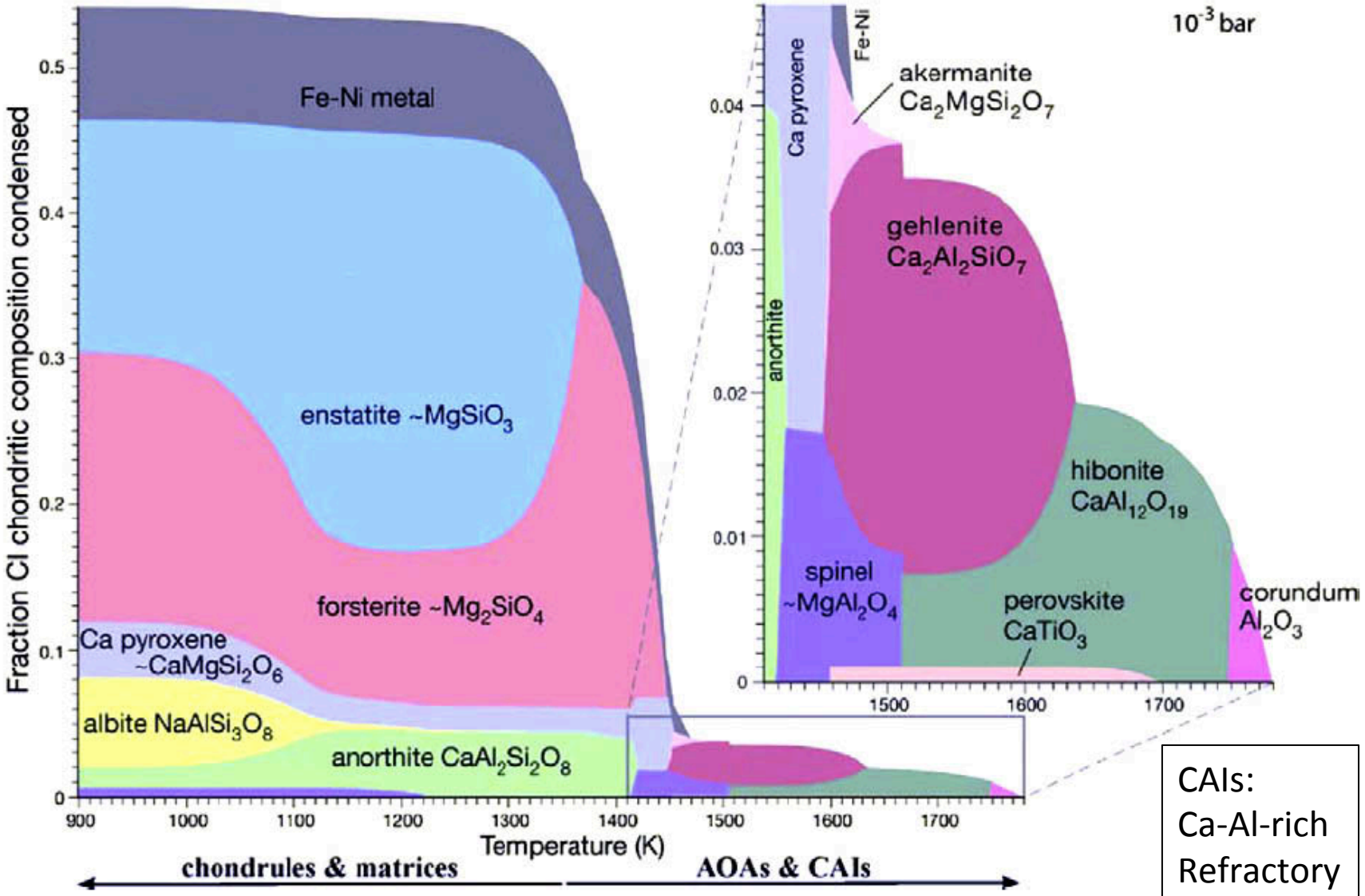




From http://slideplayer.com/slide/9706596/

- Chondrule & metal $_{(30\text{-}98\%)}$ + Ca-Al-Inclusion $_{(<1\sim5\%)}$ + Matrix $_{(<2\sim70\%)}$, likely recording thermal processes in the proto-planetary disk.
- Nearly solar compositions ▶ From un-differentiated parent bodies.

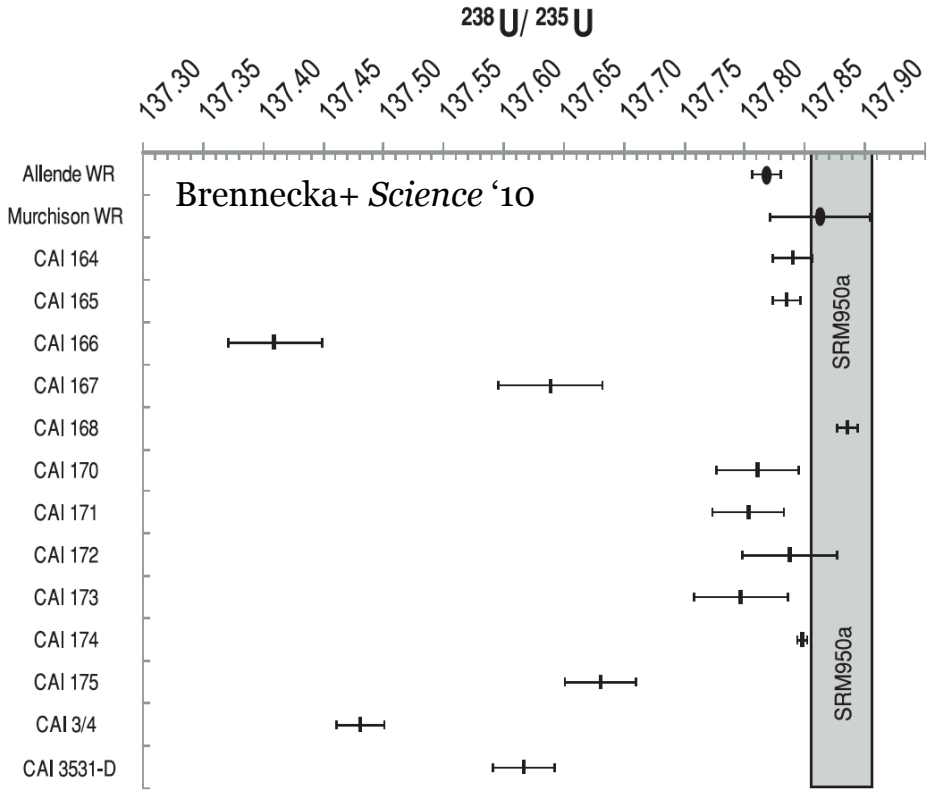
Condensation Sequence

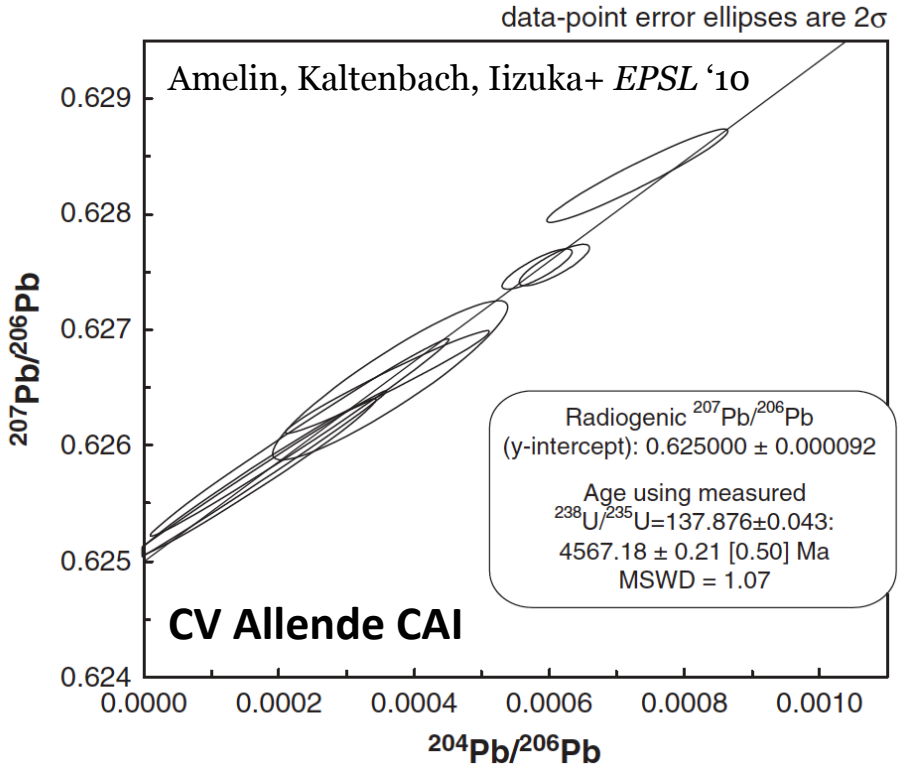


CAIs:
Ca-Al-rich
Refractory
Inclusions

Krot+ *GCA* '09 after Davis & Richter '03

CAI Ages





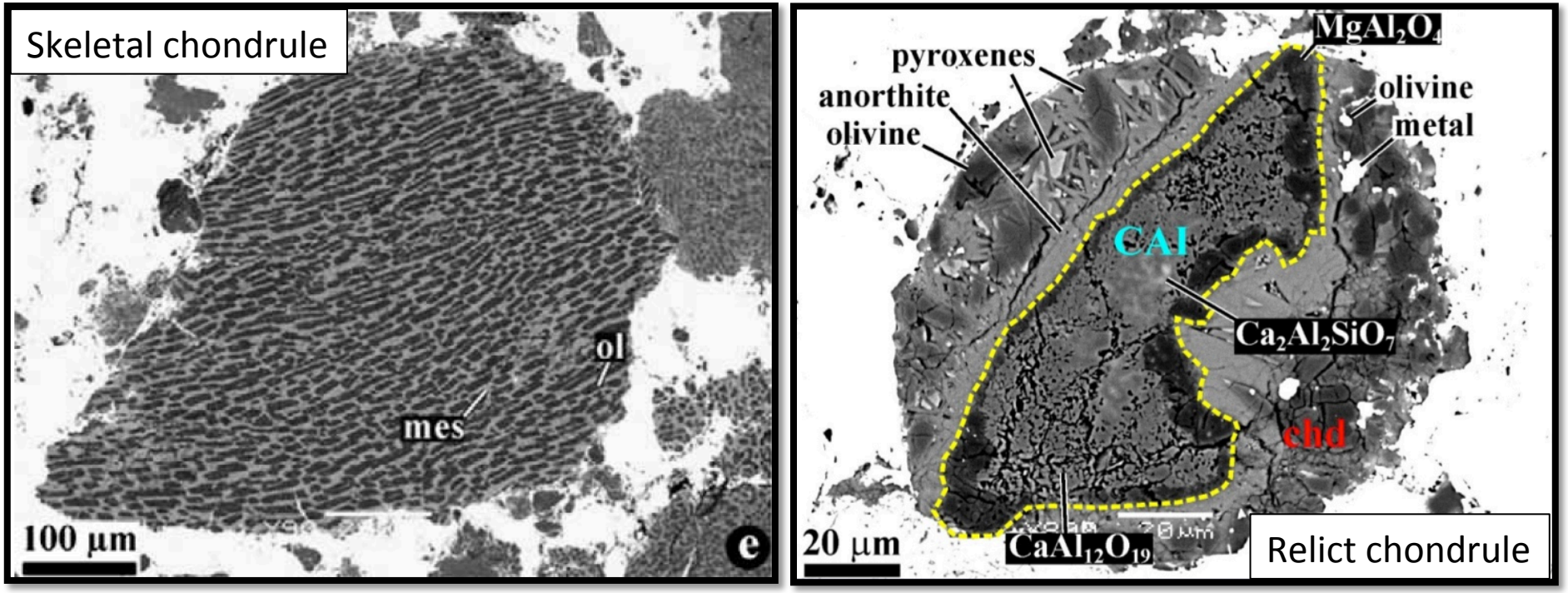
$$\frac{^{207}Pb^*}{^{206}Pb^*} = \frac{^{238}U}{^{235}U} \times \frac{(e^{\lambda 235 t} - 1)}{(e^{\lambda 238 t} - 1)}$$

Used to be assumed 137.88, BUT large variations have been found.

Combined U & Pb isotopic analyses

- CAI formation @ 4567 Ma, representing oldest SS solids.

Chondrules

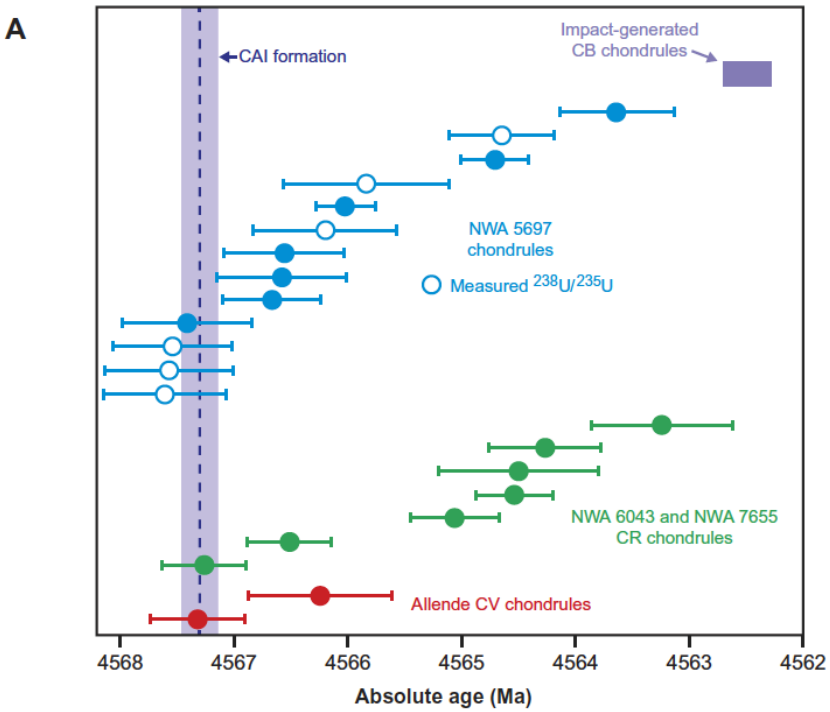


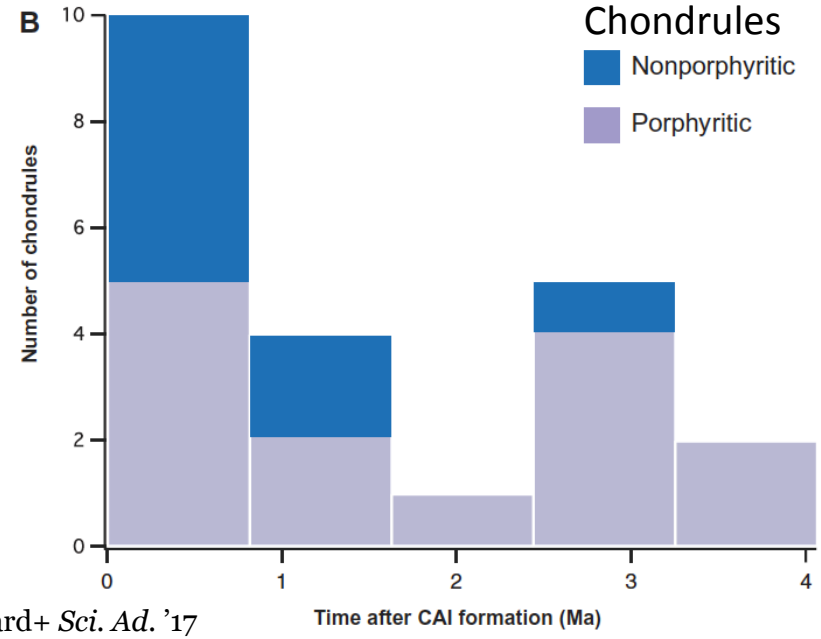
Krot+ *GCA* '09

- mm sized spherules formed by rapid heating (up to 1300 K) & cooling (1-1000 K/hr) of diverse precursors (CAIs, older chondrules, matrix)
- Asteroid growth through gas-drag-assisted accretion of chondrules? (analogous to pebble accretion)

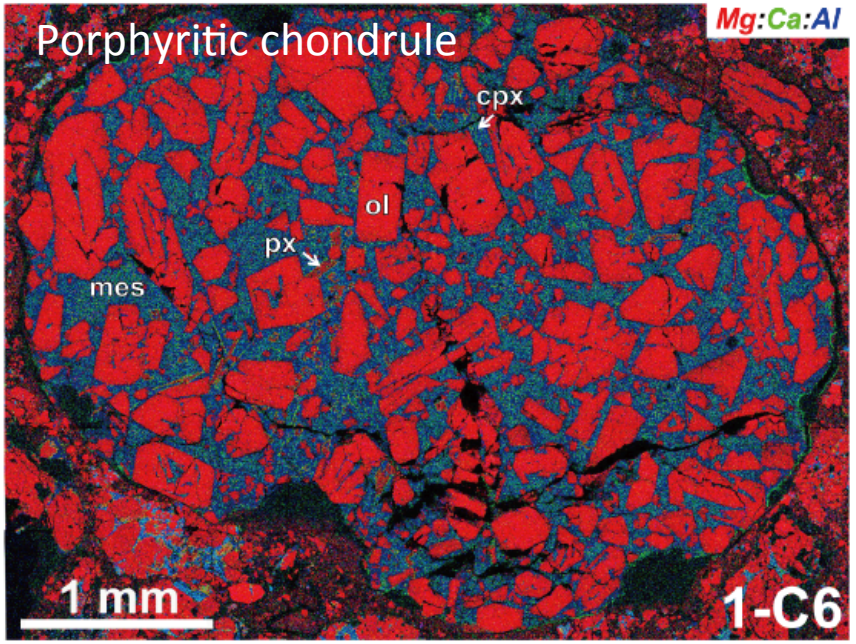
Johansen+ *Sci. Ad.* '15

Chondrule Ages



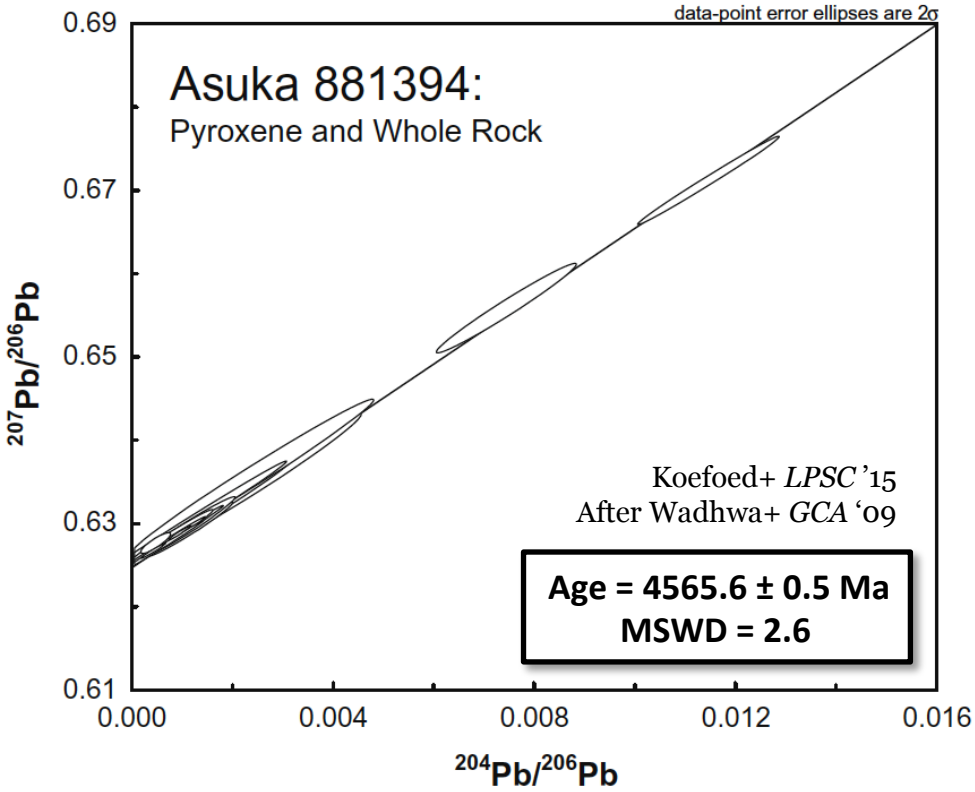


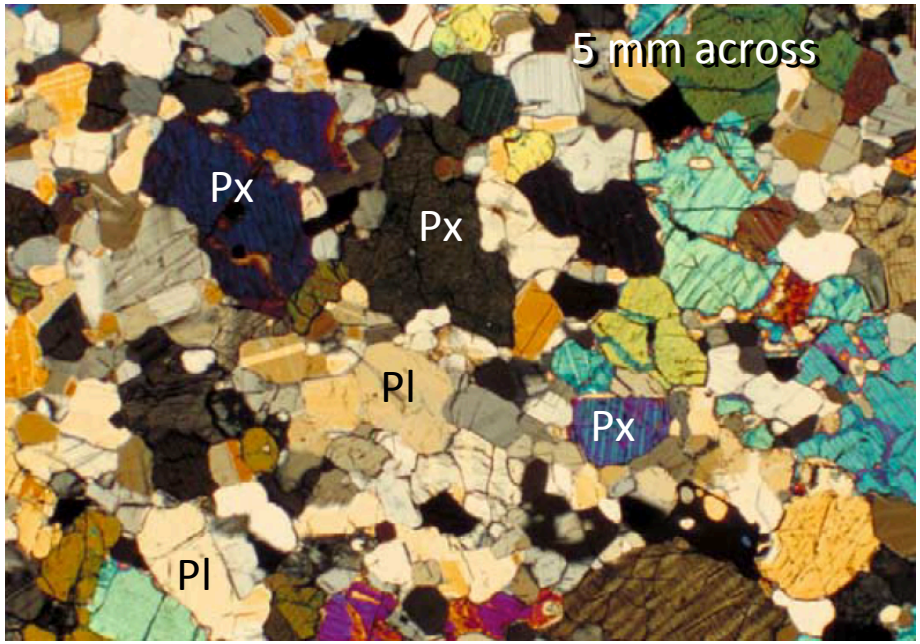
Bollard+ *Sci. Ad.* '17
Connelly+ *Science* '12



- 0-4 Ma after CAIs
- Bimodal age distribution implies
  (i) primary formation @ <1.5 Ma
  (ii) re-melting @ 2.5-4.0 Ma
- Establishment of asteroid seeds by 1.5 Ma

Oldest Achondrite: A-881394



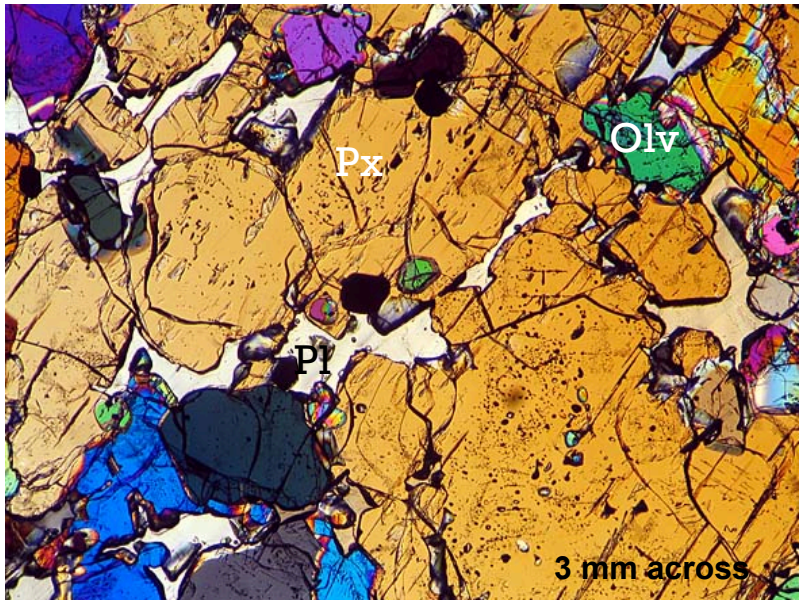


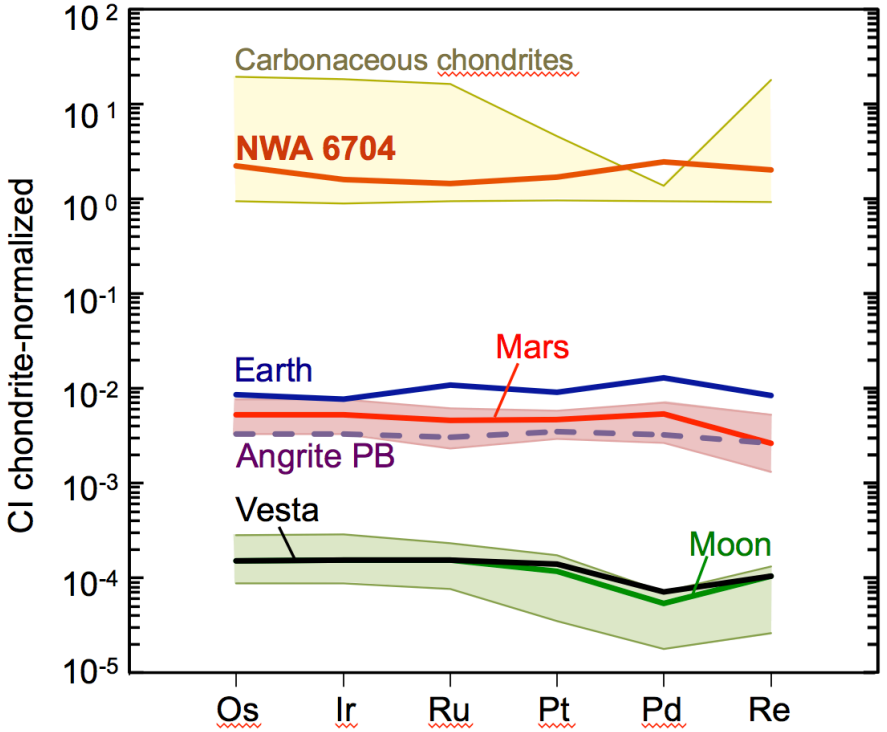
Nyquist+ *EPSL* '09

- Basaltic achondrite composed mainly of Px + Pl, representing crust of the differentiated parent asteroid
- Basalt crystallization @ 1.7 ± 0.5 Ma after CAIs

▶ Accretion & core segregation within ~2 Ma

Primitive Achondrite: NWA6704





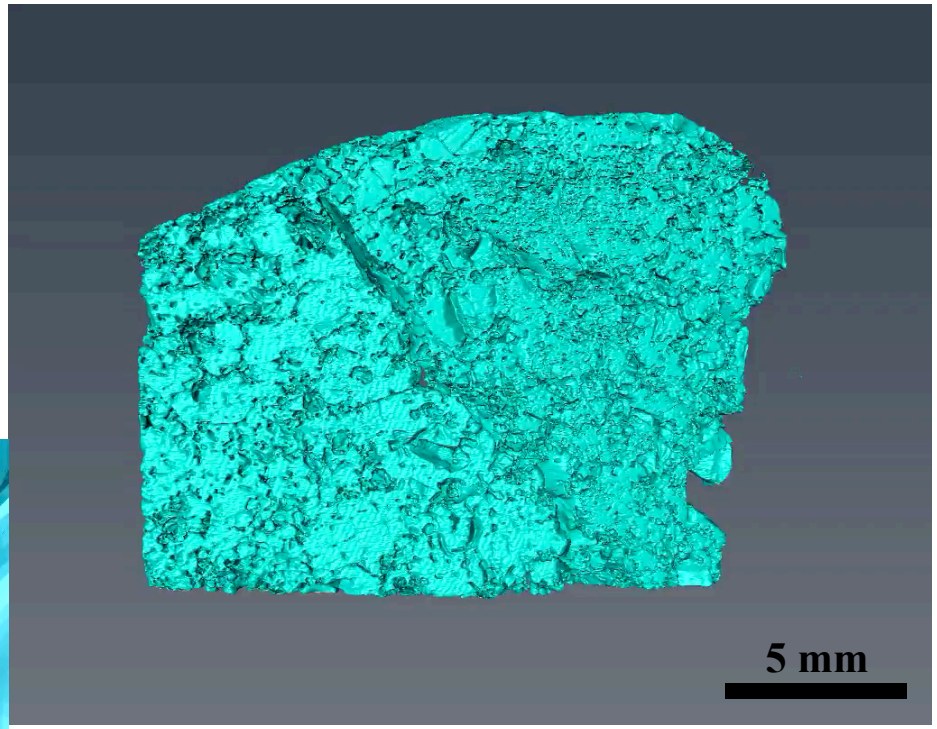
After Hibiya+ *GCA* under review

- Pyroxenite with igneous texture
  - ▶ Magmatism on the parent body
- Chondritic iron-loving element pattern
  - ▶ No metal core in the parent body

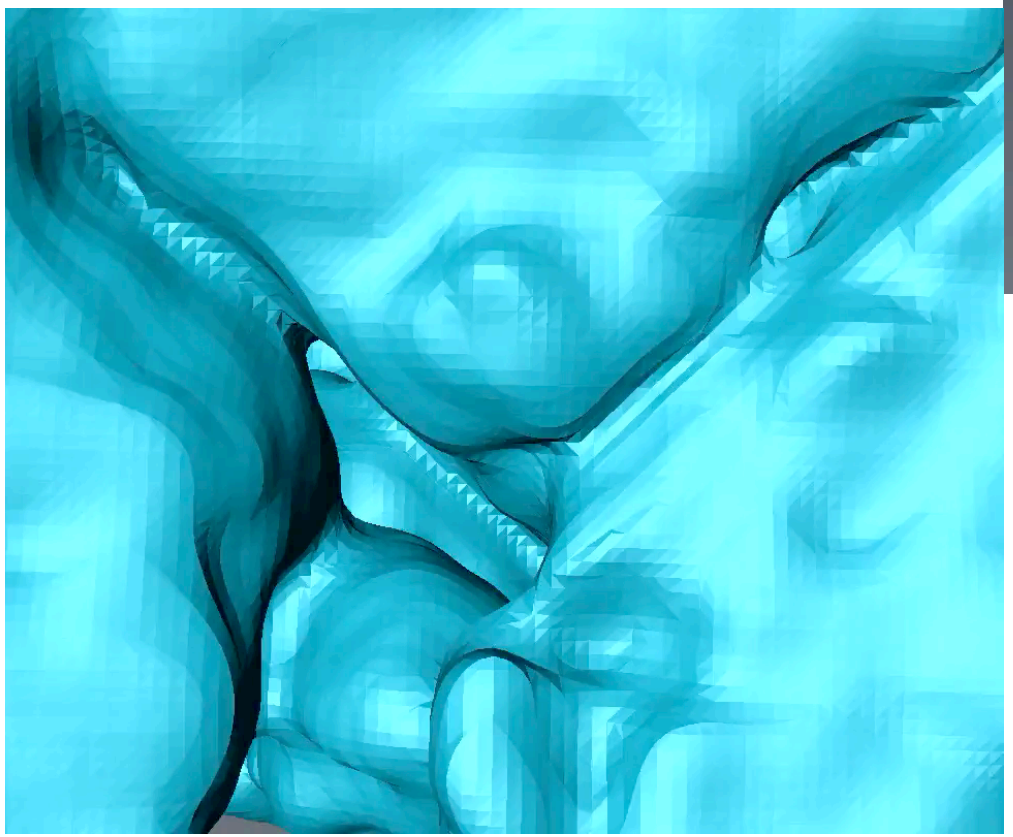
Primitive Achondrite: NWA6704

- Pyroxene shows branching structure
  → Rapid crystallization
- Undifferentiated chemical composition
  → Instantaneous melting

▶ Impact-induced magmatism



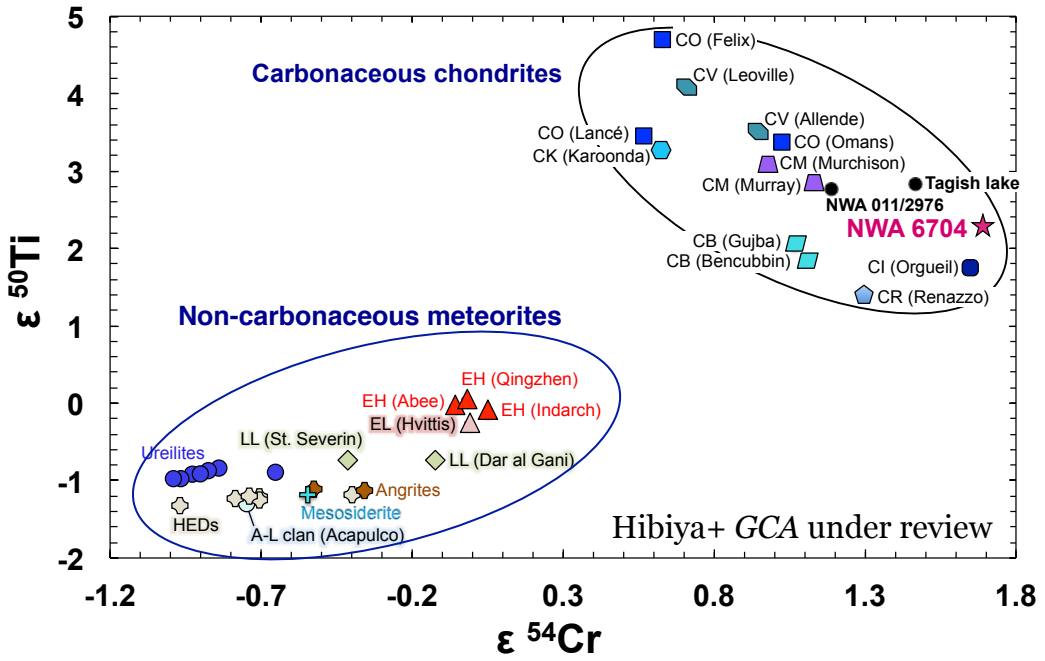
Pyroxene distribution

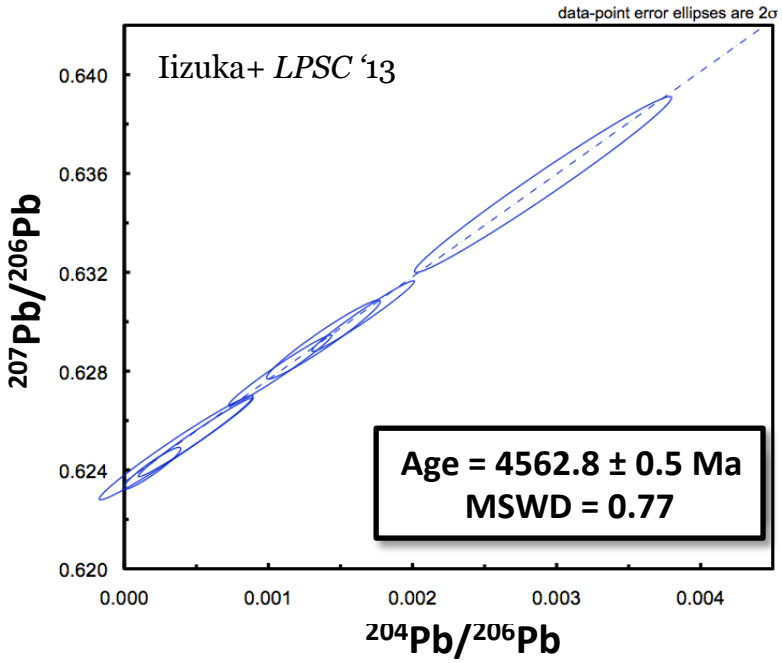


Pyroxene morphology inside NWA6704

- X-ray beam @ 130kV, 120 μA
- Voxels: 0.127 μm

Primitive Achondrite: NAW6704





- Carbonaceous like Ti-Cr isotope compositions
  - ▶ Accretion of the parent body in the outer SS.
- Crystallization @ 4.5 Ma after CAIs
  - ▶ Impact event on the carbonaceous undifferentiated parent body at that time

Timescales for asteroid accretion & differentiation

Inner Solar System:

Oldest achondrite A-881394: ~2.0 Ma

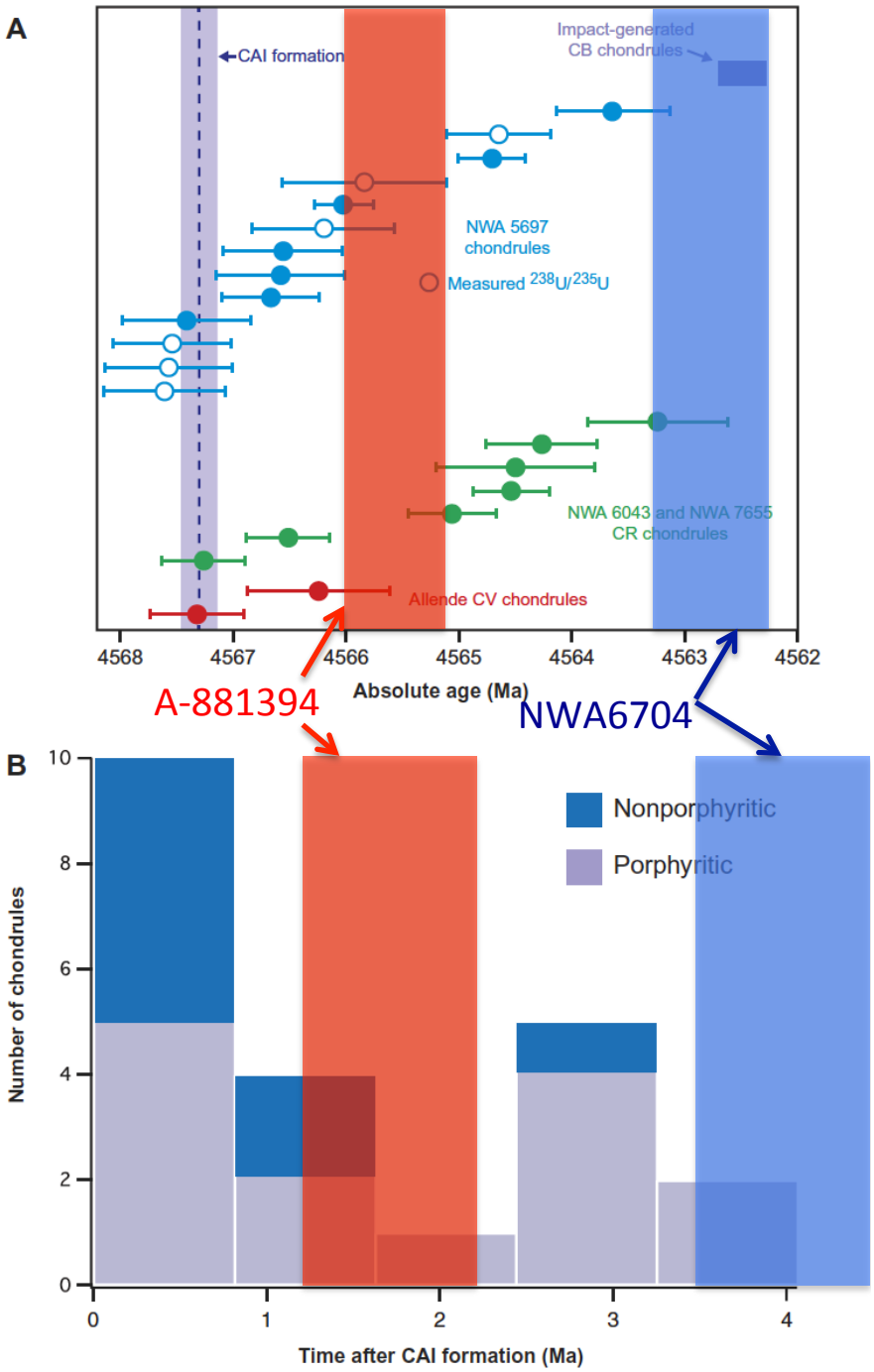
Early-accreted asteroid accretion precedes 2nd chondrule formation peak.

Outer Solar System:

Primitive achondrite NWA6704 : ~4.5 Ma

The age coincides with that of the youngest chondrule considered as impact origin.

Accretion of the un-differentiated parent body by that time.



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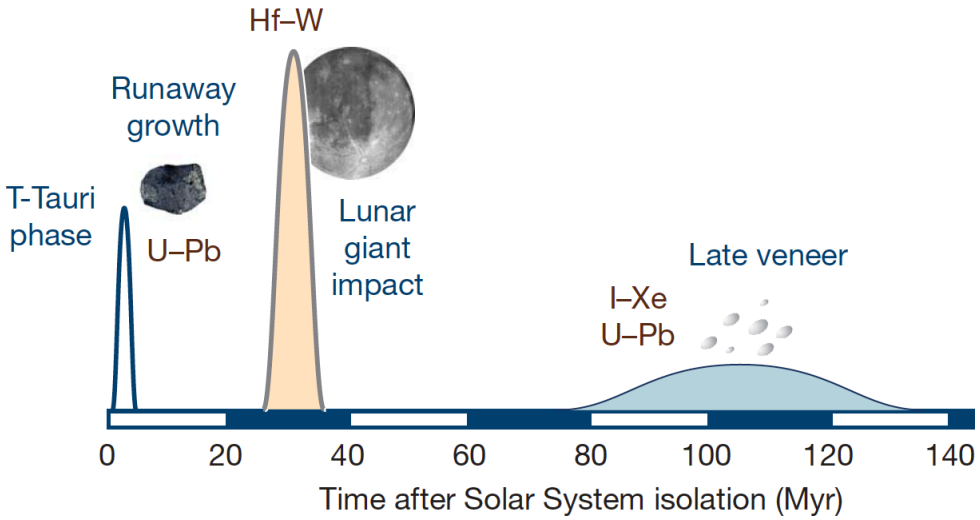
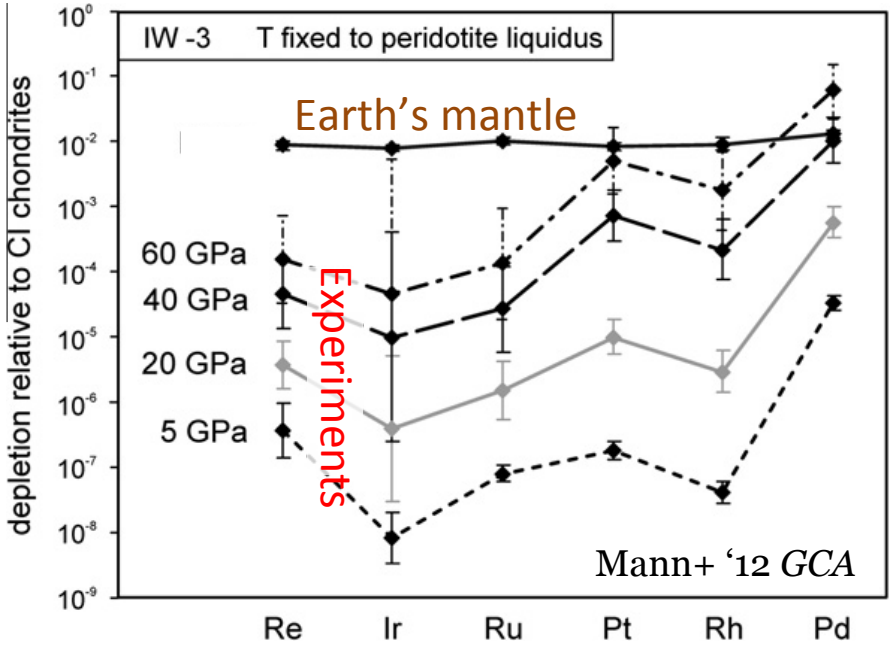
Francis Albarède[1]

PROGRESS

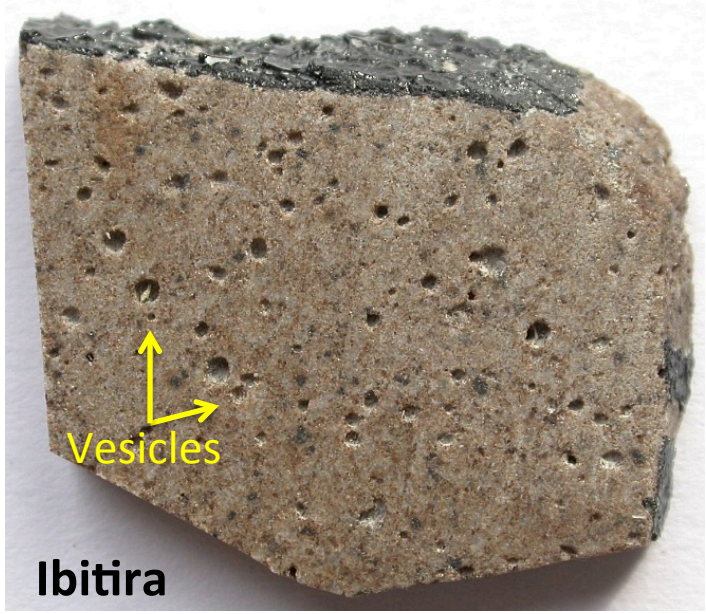
Volatile accretion history of the terrestrial planets and dynamic implications

terrestrial weathering show K/U ratios <20,000 (ref. 17). Depletion of 92–98% is also inferred for Zn, Ag, As, Sb, Sn, Pb and, most importantly, S (refs 18, 19). Planets that lack such large fractions of moderately volatile elements cannot have been endowed with large amounts of water.

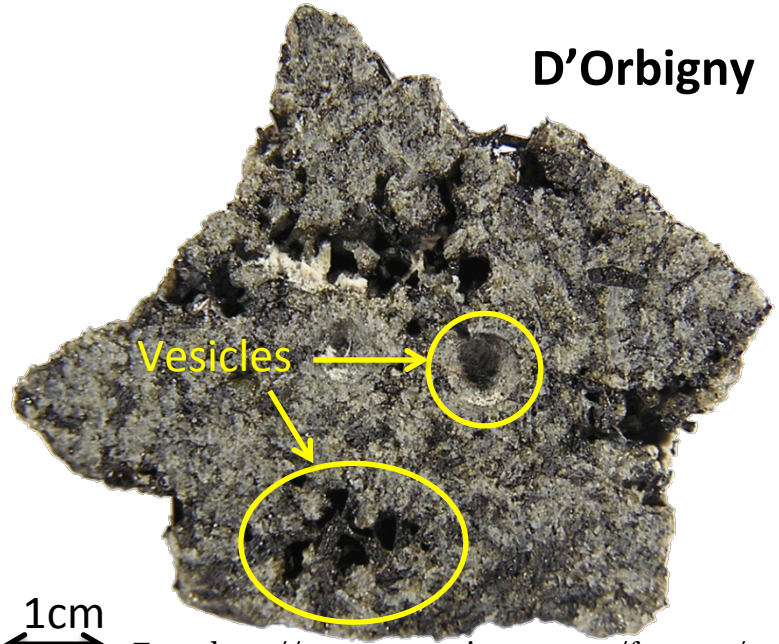




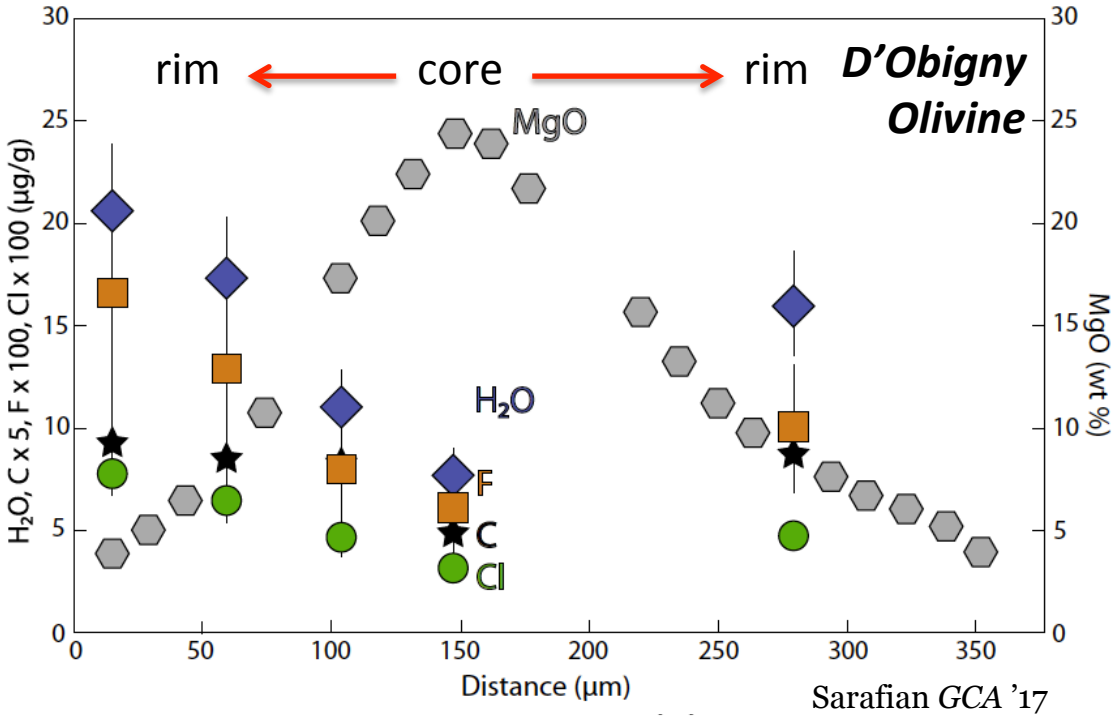
Vesicular Achondrites



From http://imca.cc/insights/2008/IMCA-Insights06.htm



From http://www.meteorites.com.au/features/

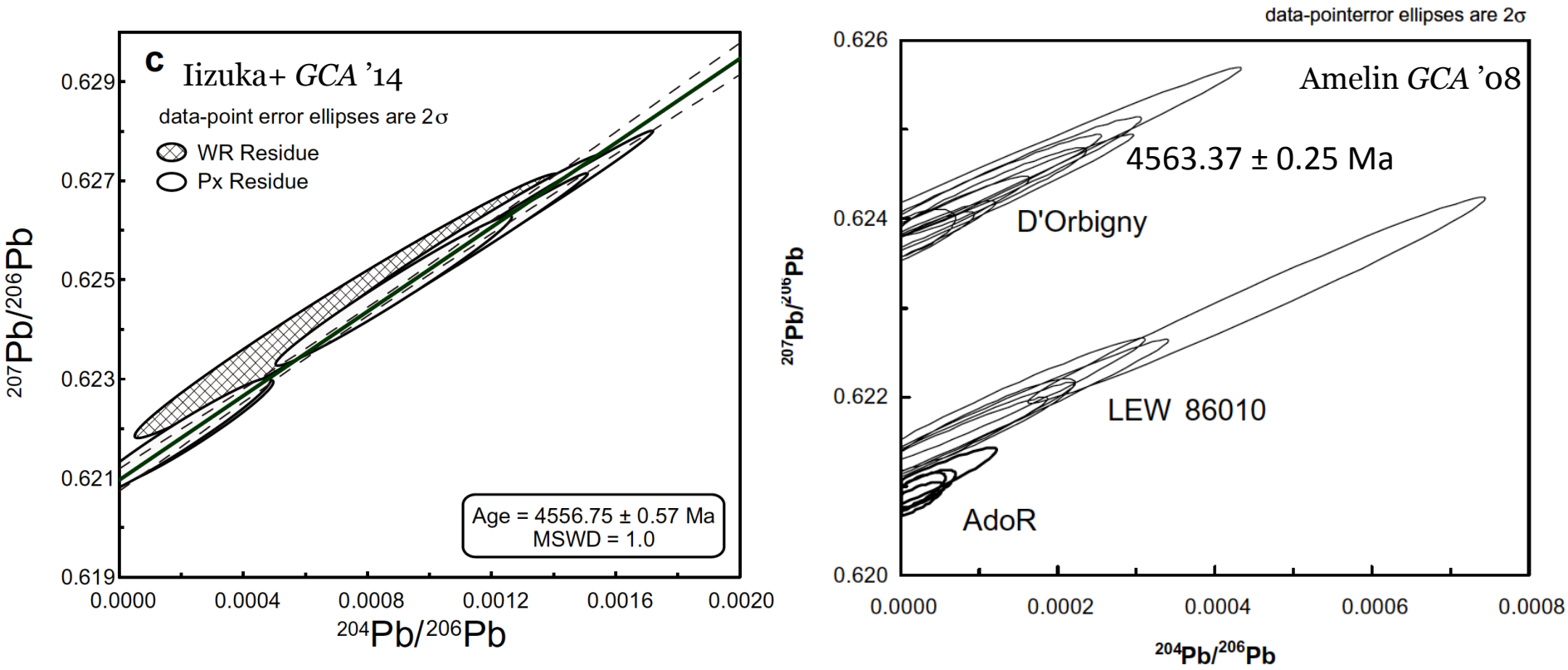


Sarafian *GCA* '17

- Basaltic meteorites depleted in Pb, BUT contain vesicles (volatiles)
- H_2O in D'Obigny Olv = 8-20 ppm, equivalent to ~200 ppm in the mantle c.f. Earth's ocean/bulk = 230 ppm

▶ H_2O delivery before their formation

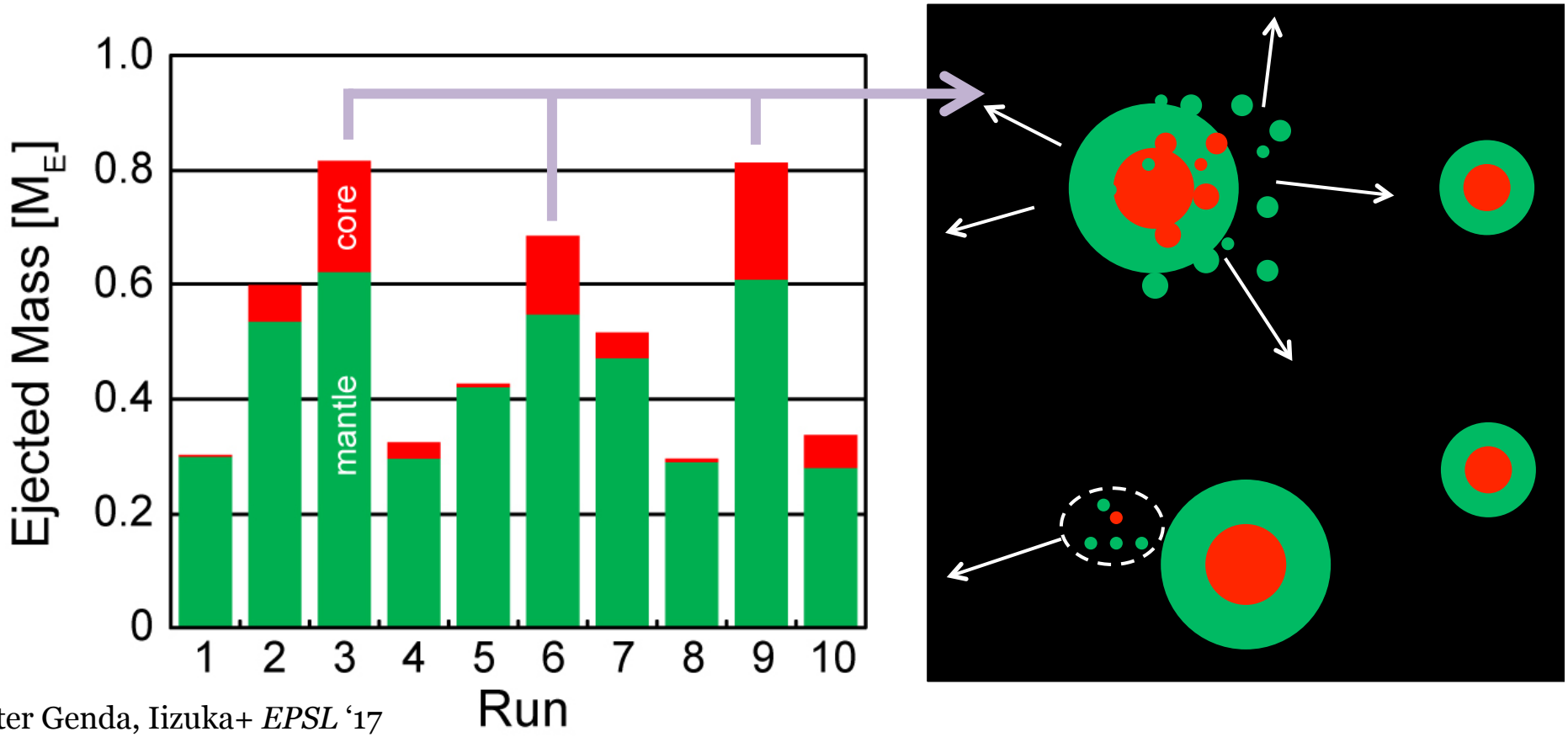
Vesicular Achondrite Ages



Pyroxene crystallization @ 4 & 10 Ma after CAIs, respectively

- H_2O delivery to the terrestrial planet region by that time
- Earth's building blocks would have substantial H_2O before GI

GI Fragment Re-accretion



After Genda, Iizuka+ *EPSL* '17

GIFs would include core materials & re-accrete ~100 Ma after GI

- GIF re-accretion can account for the HSE excess in the mantle.

Take Home Messages

U-Pb choronology of the early Solar System with chemistry:

- CAI age @ 4567 Ma

- Chondrule age @ 0-1.5 & 2.5-4.0 Ma after CAIs

▶ Very early establishment of asteroid building materials (pebbles)

- Oldest achondrite age @ 2 Ma after CAIs

▶ Asteroid accretion & differentiation (core formation) within 2 Ma

- Primitive 'carbonaceous' achondrite age @ 4.5 Ma after CAIs

▶ Impact event on the undifferentiated parent body at that time

- Vesicular basaltic achondrites @ 4 & 10 Ma after CAIs

▶ H_2O delivery to the inner SS by that time (before GI)