

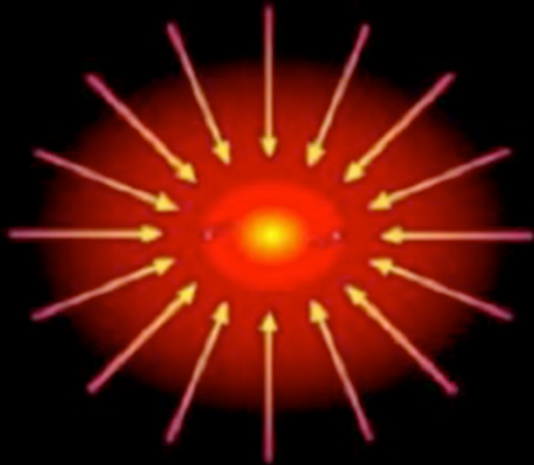
**Formation of First Solids in the
Early Solar System:
Perspectives from Radioactive
and Stable Isotopes**

Ming-Chang Liu

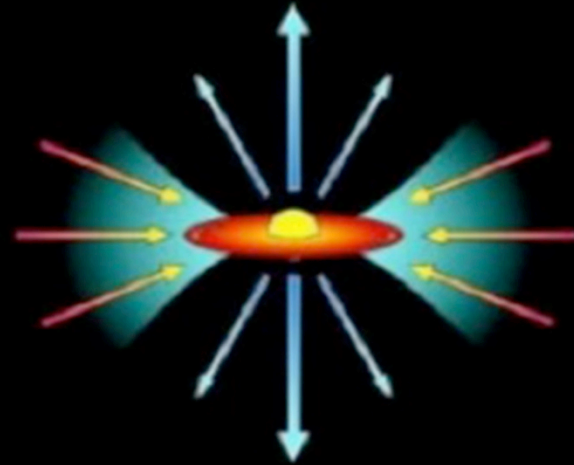
Inst. of Astronomy and Astrophysics

Academia Sinica

Formation of the Solar System



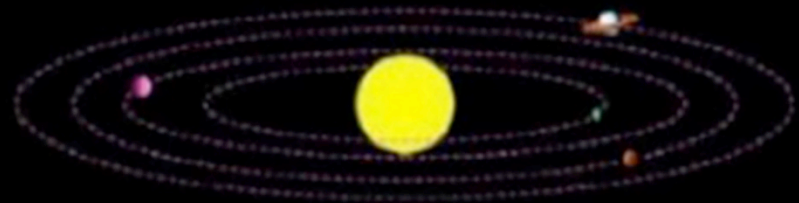
10^4 yrs; $10-10^4$ AU; $10-300$ K



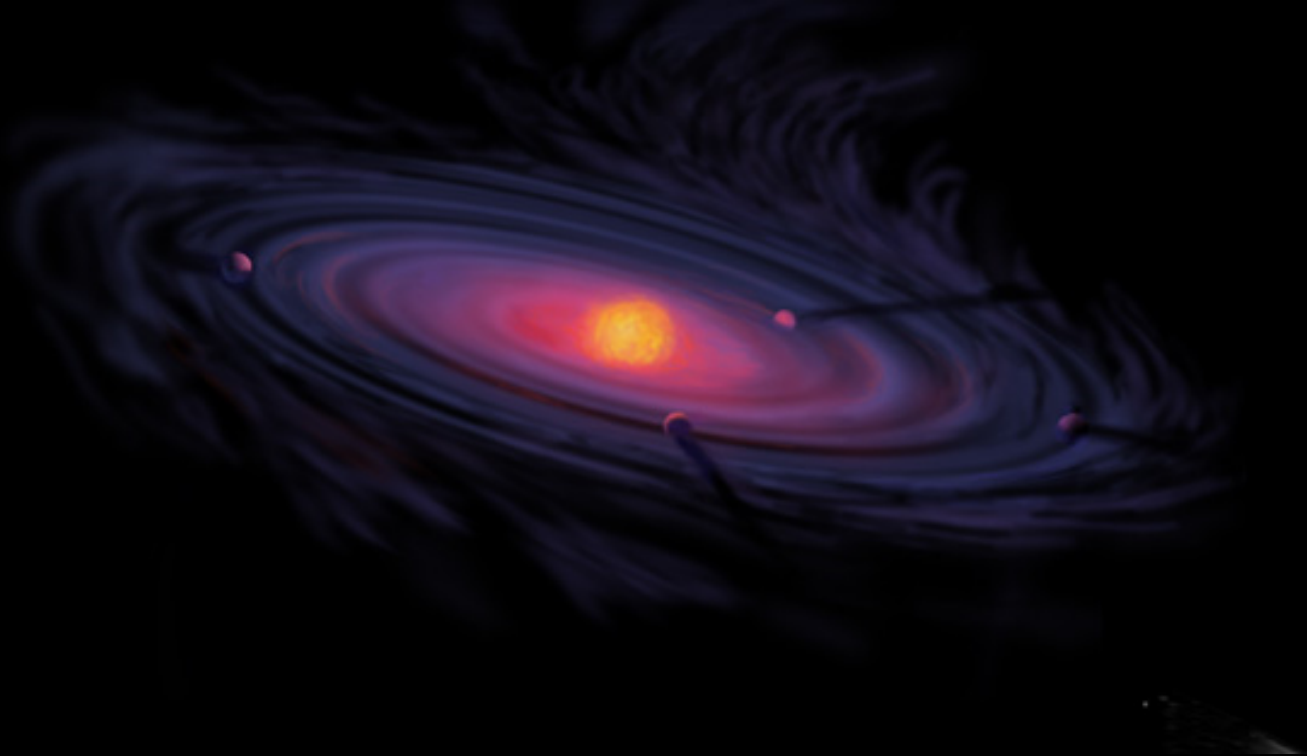
10^{5-6} yrs; $1-1000$ AU; $100-3000$ K

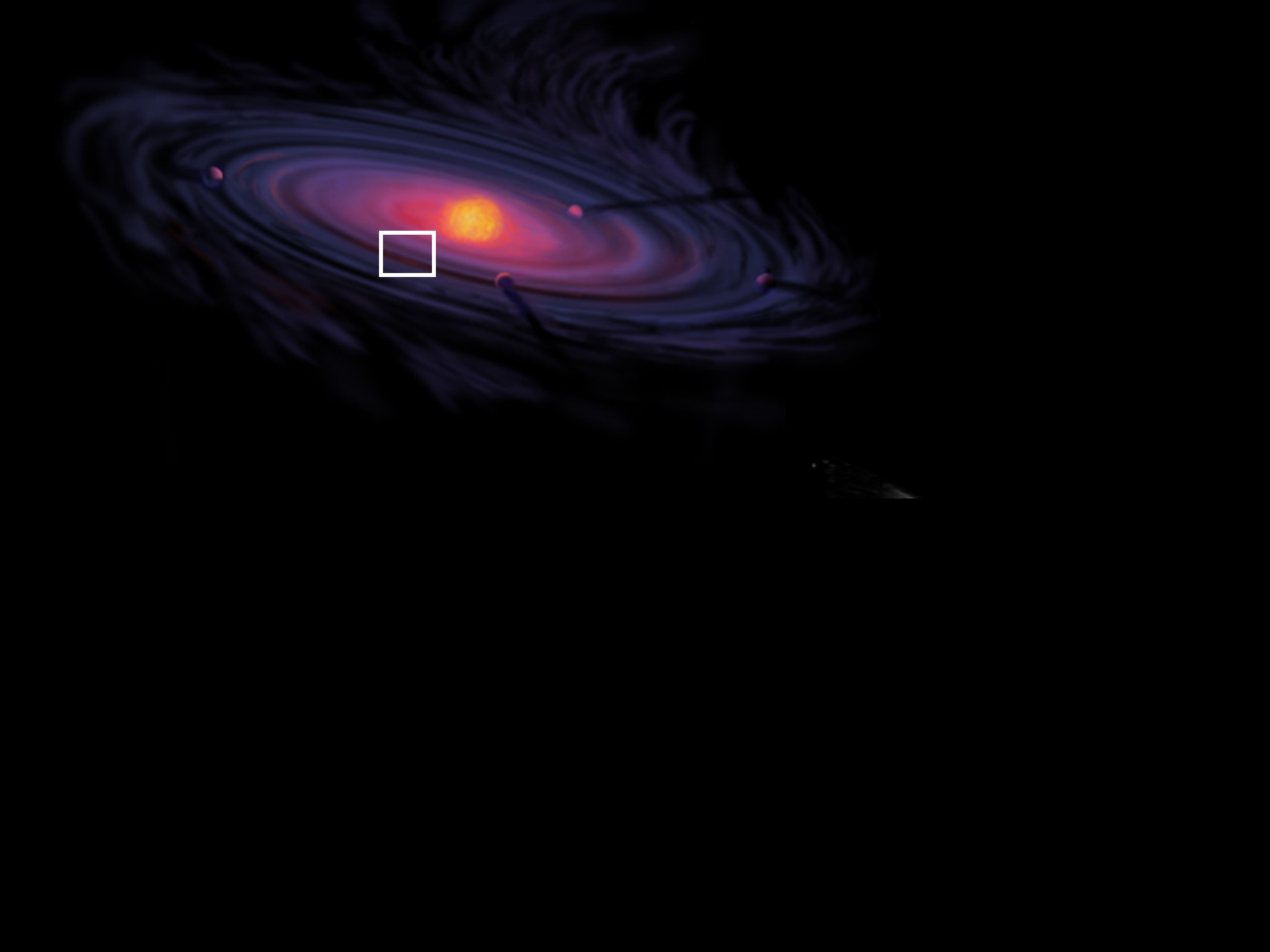


10^{6-7} yrs; $1-100$ AU; $100-3000$ K

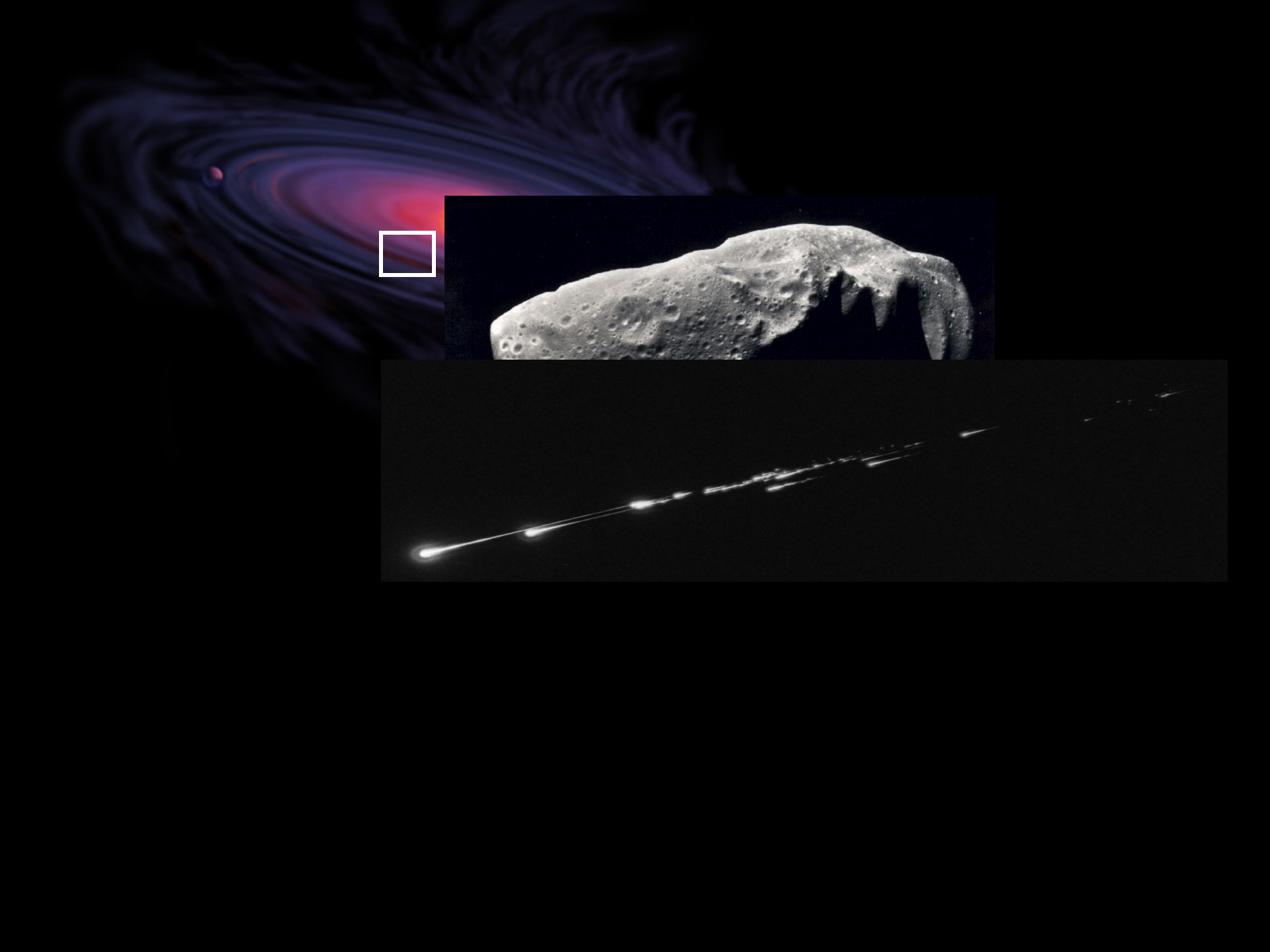


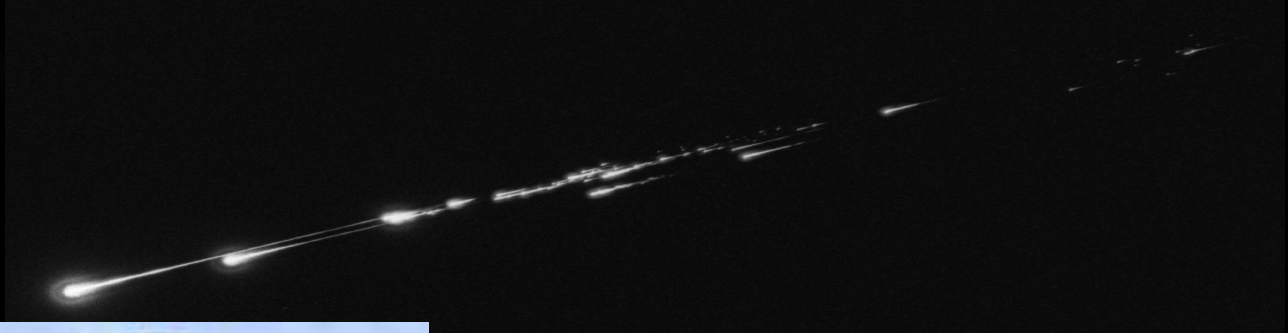
10^{7-9} yrs; $1-100$ AU; $200-3000$ K

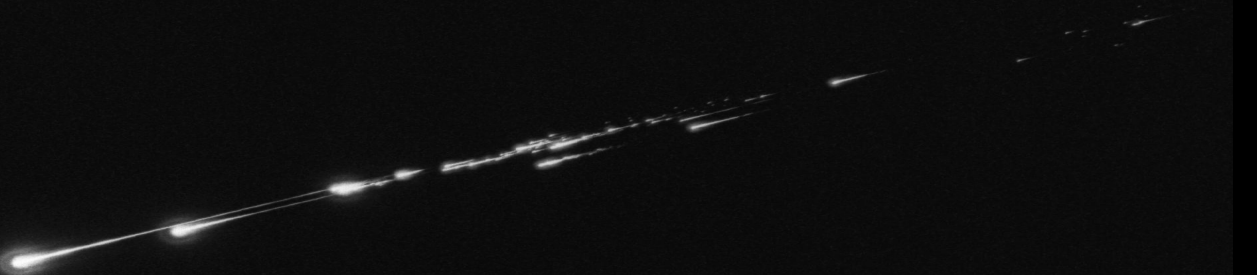




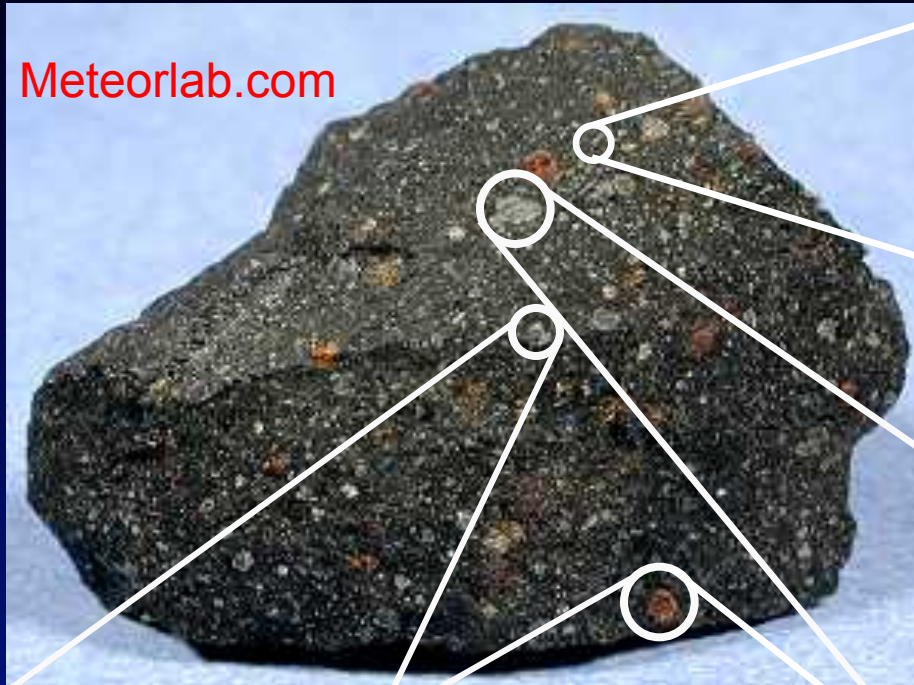




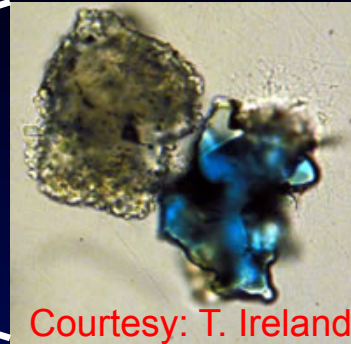




The Solar System "HOTTEST" Phases

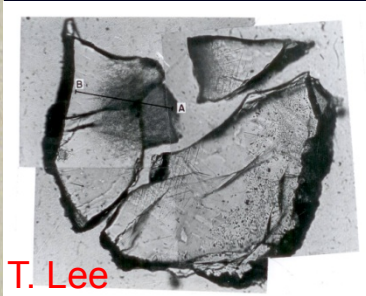


Meteorlab.com



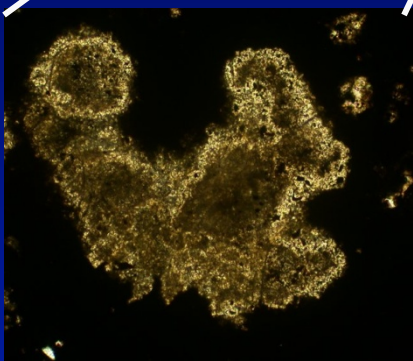
Courtesy: T. Ireland

Hibonite
($\text{CaAl}_{12}\text{O}_{19}$)
($\phi \sim 20\text{--}80 \mu\text{m}$)

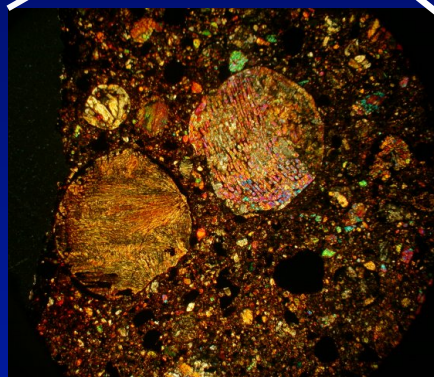


T. Lee

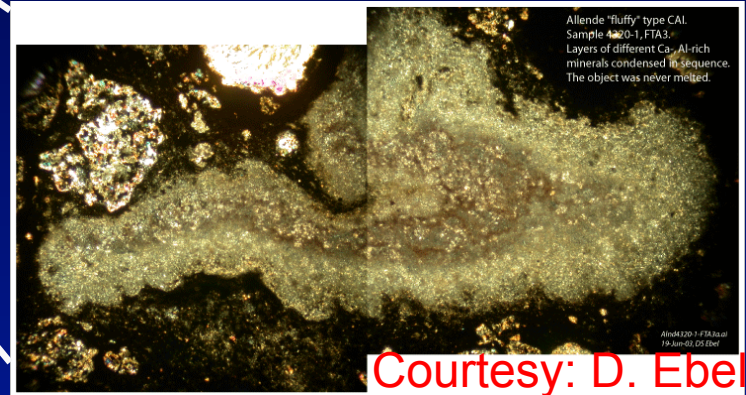
"HAL"
($\phi \sim 1 \text{ mm}$)



Amoeboid olivine
aggregate (AOA)



Chondrule ($\phi \sim 0.5\text{--}20 \text{ mm}$)

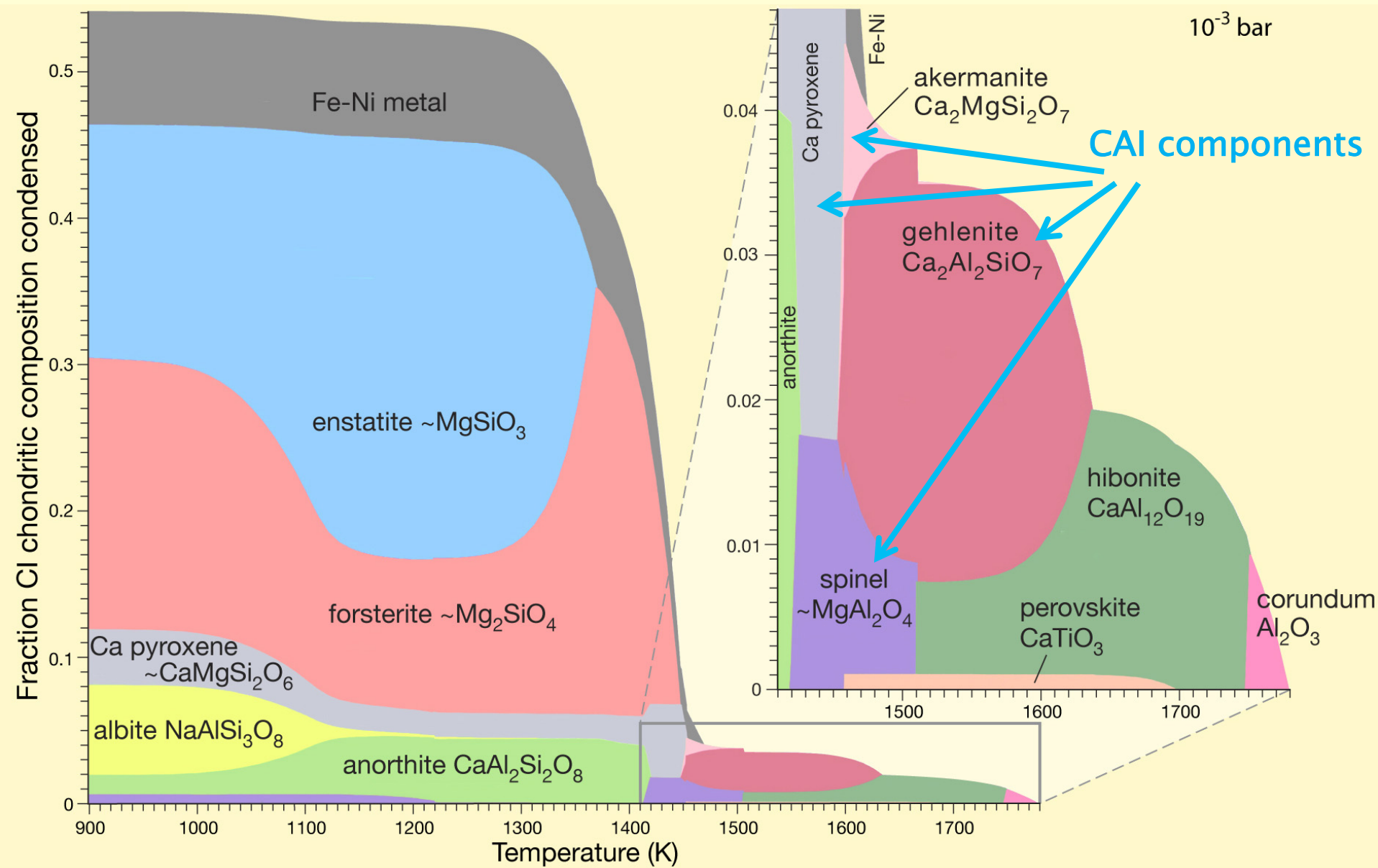


Allende "fluffy" type CAI.
Sample #420-1, FTA 3.
Layers of different Ca-Al-rich
minerals condensed in sequence.
The object was never melted.

Allende 420-1 FTA 3 at
19-Jun-03, DS Eberl

Courtesy: D. Eberl

Ca-Al-rich Inclusion (CAI)
($\phi \sim 0.5\text{--}10 \text{ mm}$)
Oldest "datable" solid =
4.568 Gyr



Davis and Richter (2005)

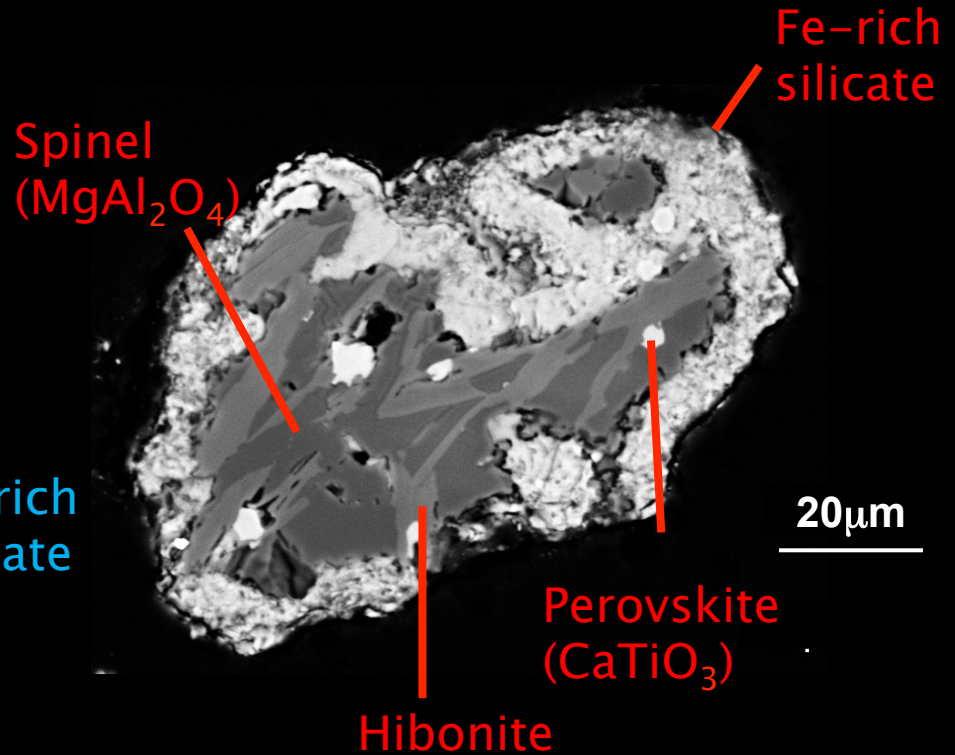
Condensate

Recrystallized solid

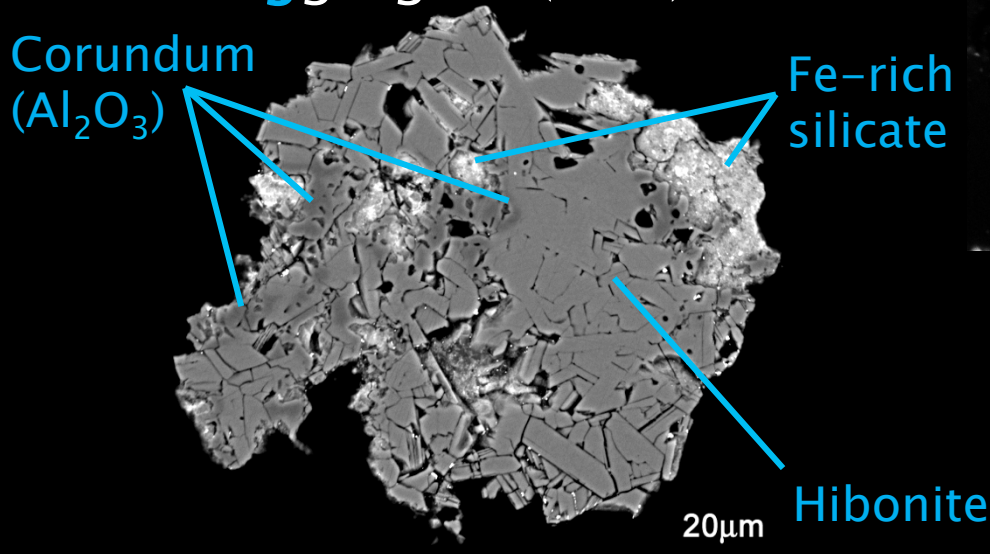
PLAty-hibonite Crystal (PLAC)



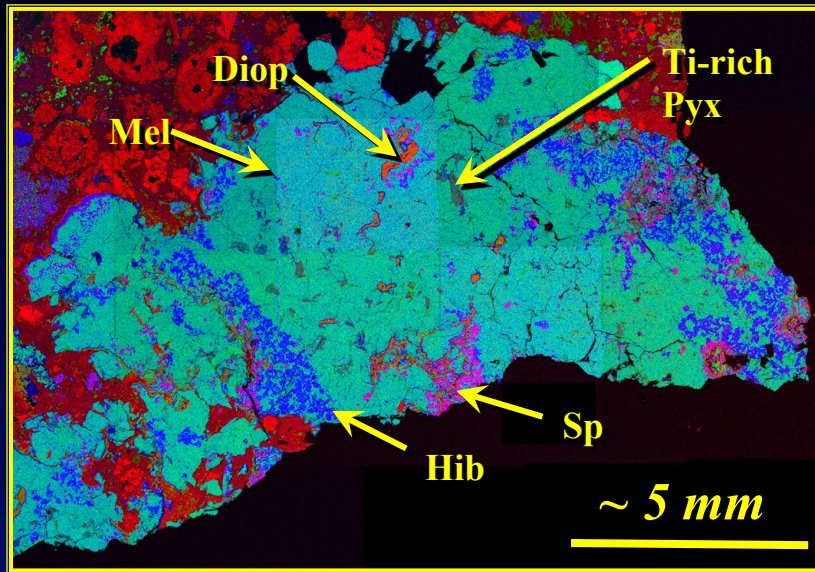
Spinel-HIBonite Spherule (SHIB)



Blue-Aggregate (BAG)

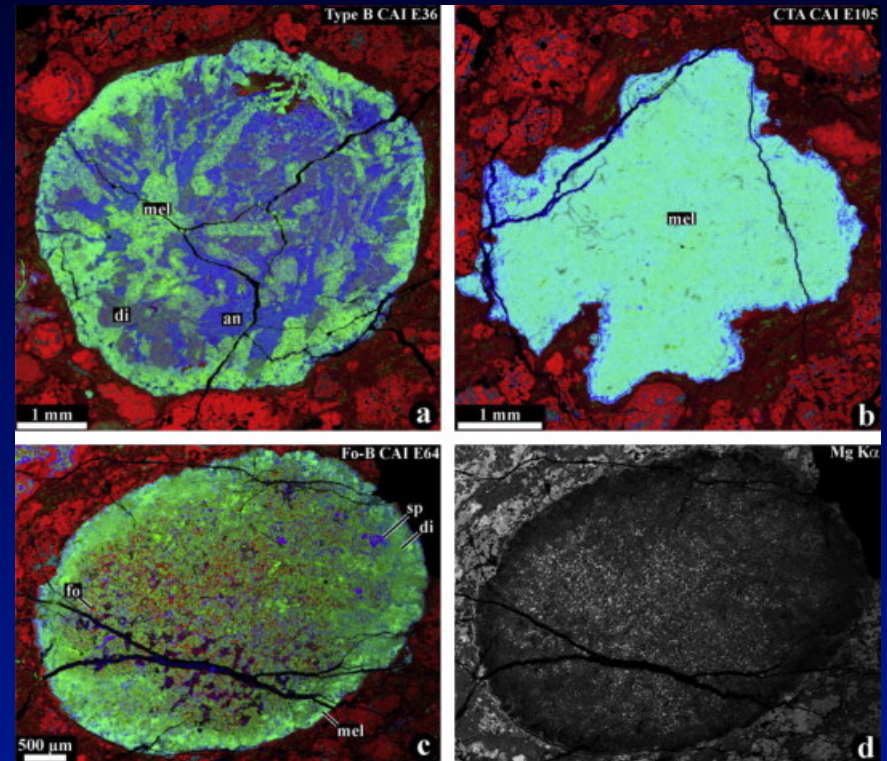


Condensate

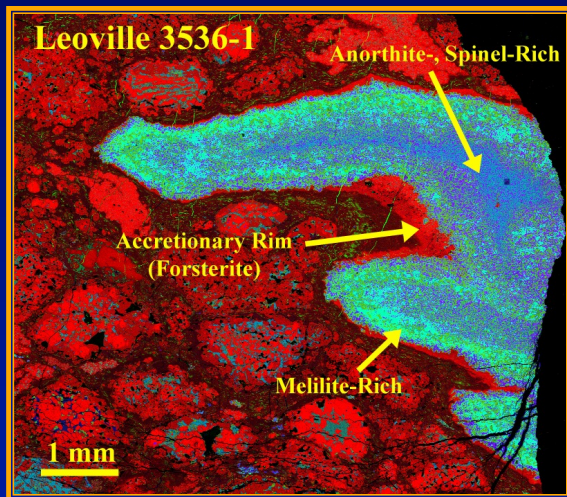


MacPherson et al. (2012)

Recrystallized solid



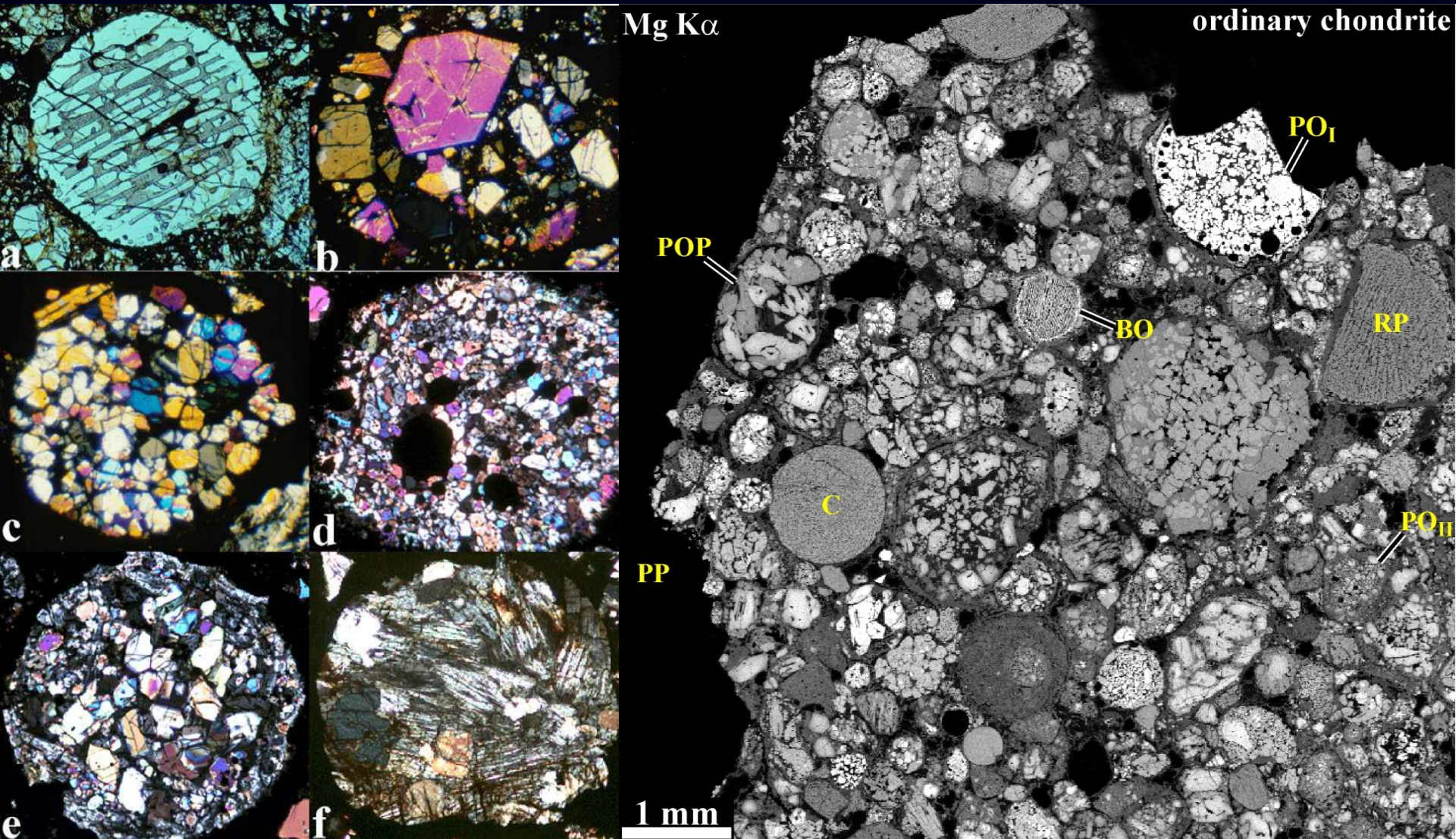
Krot et al. (2009)



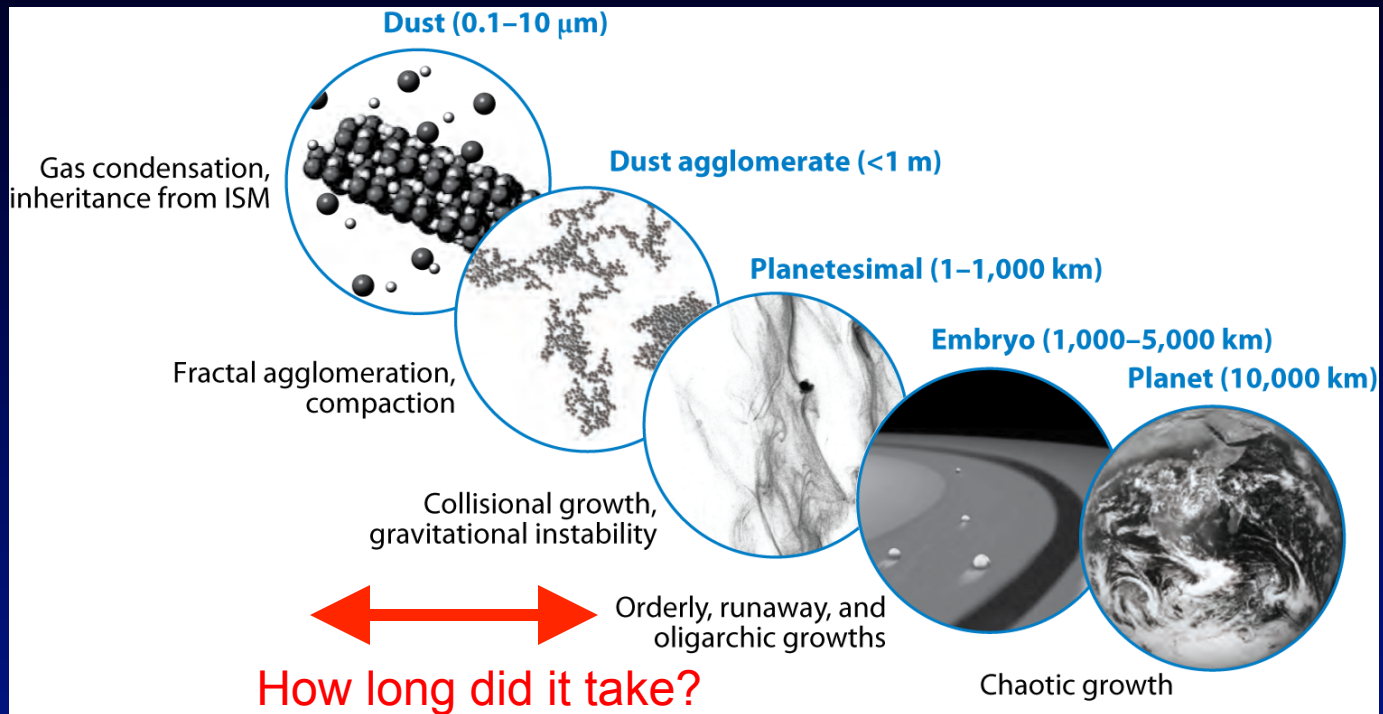
Krot et al. (2009)

Ca-Al-Mg composite X-ray map

Chondrules are all igneous



Courtesy: Sasha Krot

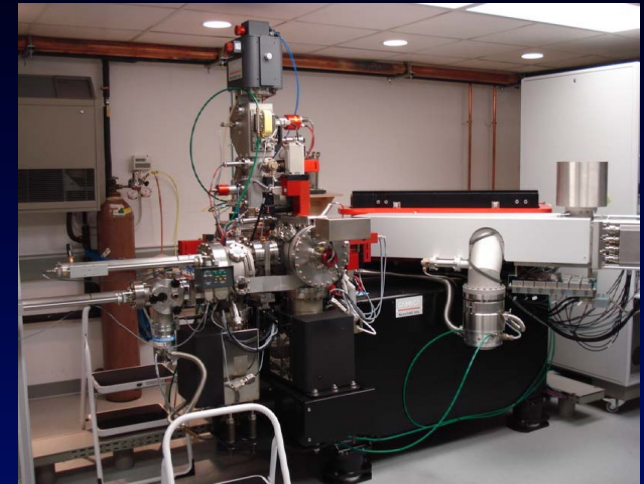


AR Dauphas N, Chaussidon M. 2011.
 Annu. Rev. Earth Planet. Sci. 39:351–86

Cosmochemists' telescopes



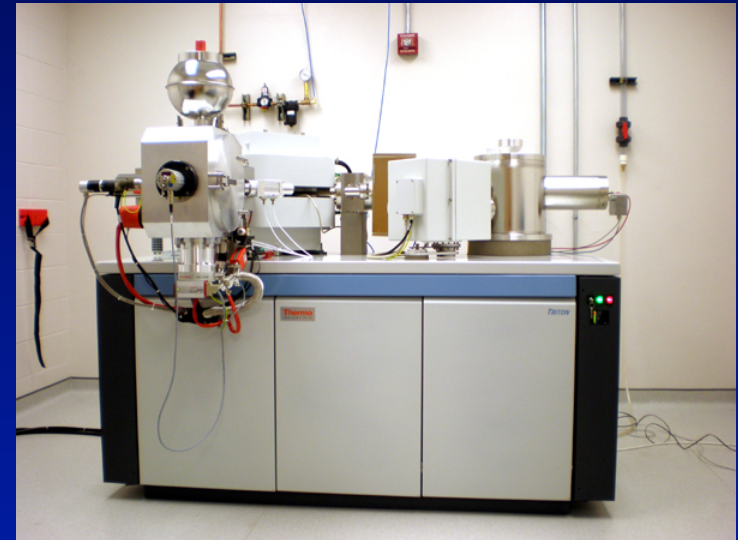
Secondary Ion Mass Spectrometer (SIMS)



NanoSIMS



Inductively Coupled Plasma Mass Spectrometer



Thermal Ionization Mass Spectrometer

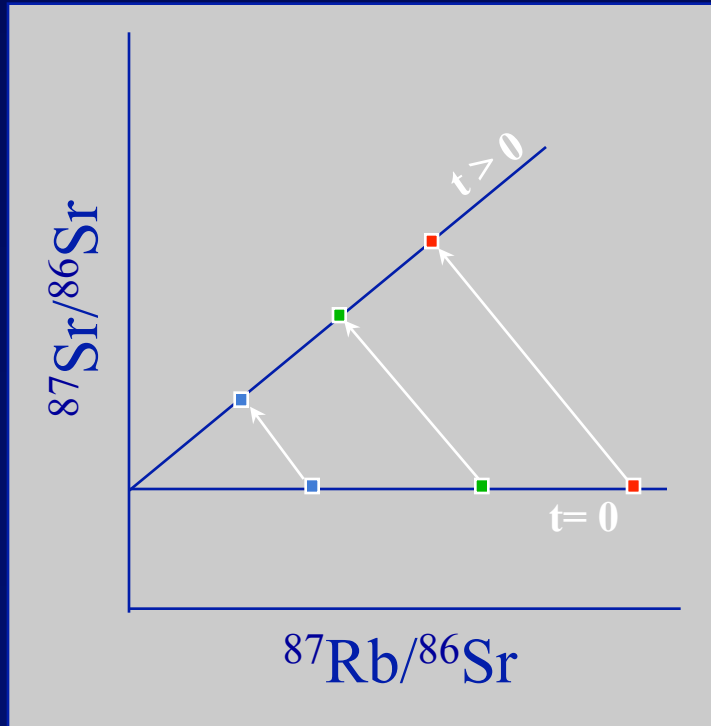
δ -notation

$$\delta = \left(\frac{r_m}{r_{ref}} - 1 \right) \times 1000$$

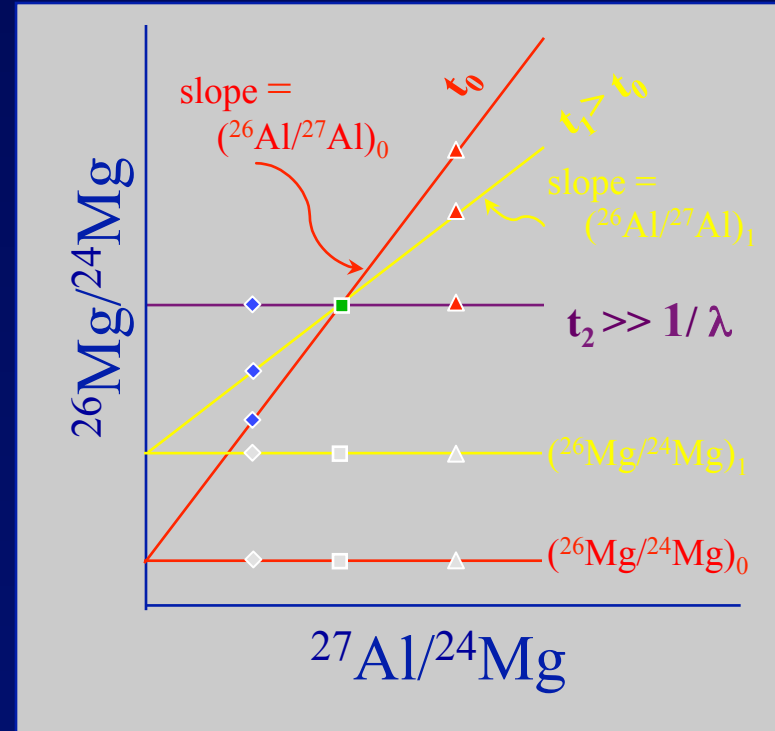
“permil”

isochrons

Long-lived:

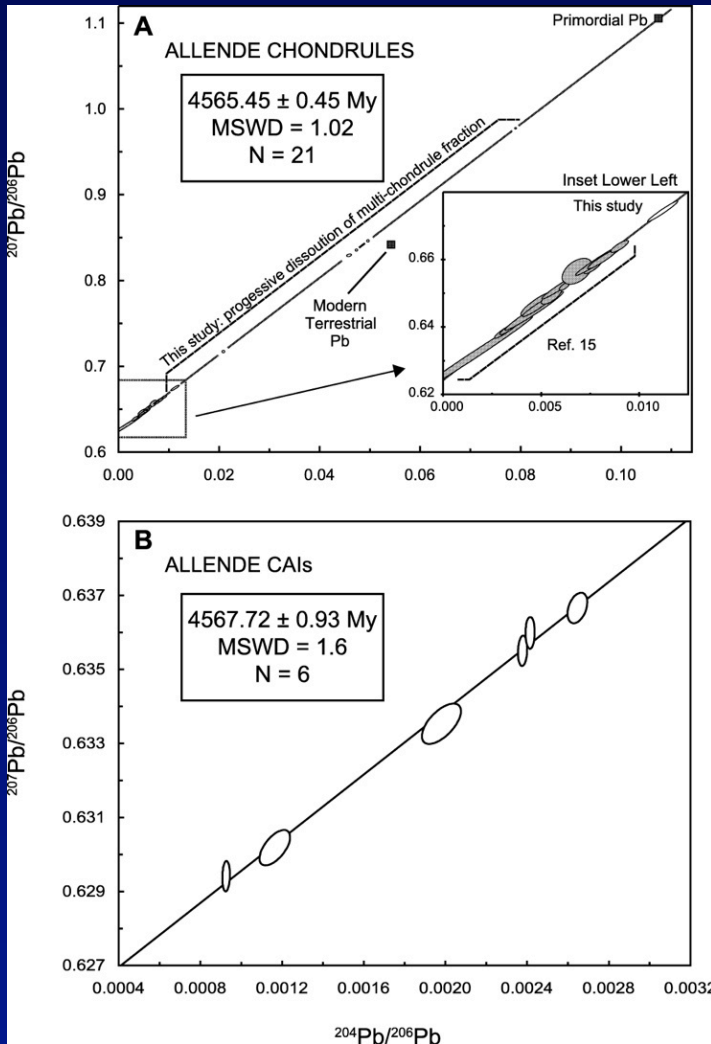


Short-lived ($t_{1/2} < 100$ Myr):



- Extinct isotopes can provide relative dates with high-resolution
 - time following a chemical (parent-daughter) fractionation from an initially isotopically homogeneous reservoir
 - requires cogenetic mineral assemblage - isotopic closure
 - to infer relative time, requires initially uniform abundance of radionuclide

Absolute Pb-Pb ages of first solids



- $^{238}\text{U} \rightarrow ^{206}\text{Pb}$ ($t_{1/2} = 4.5$ Gy)
- $^{235}\text{U} \rightarrow ^{207}\text{Pb}$ ($t_{1/2} = 703$ My)
- CAIs and chondrules formed $\sim 2\text{--}3$ Myr apart
- Temporal resolution with Pb-Pb dating $\sim 0.5\text{--}1$ Myr

Connelly et al. (2008)

Resolution is key



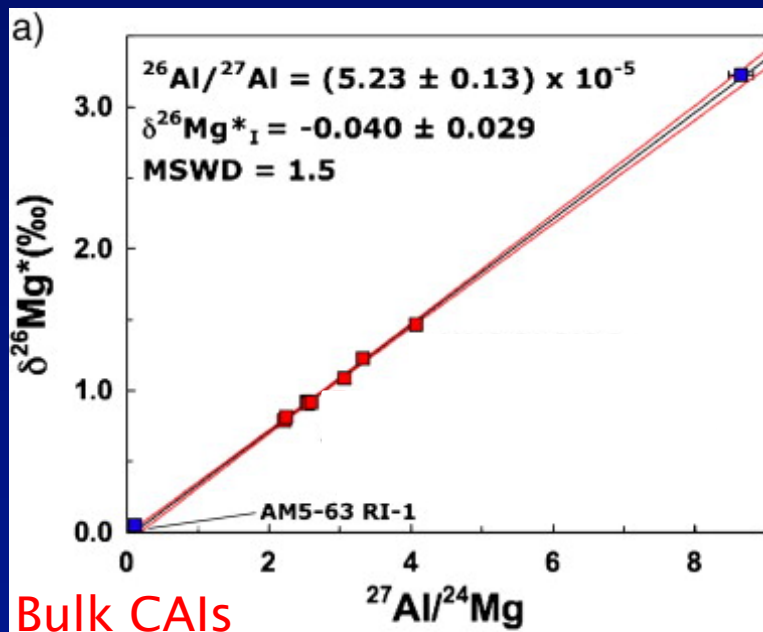
A blunt knife



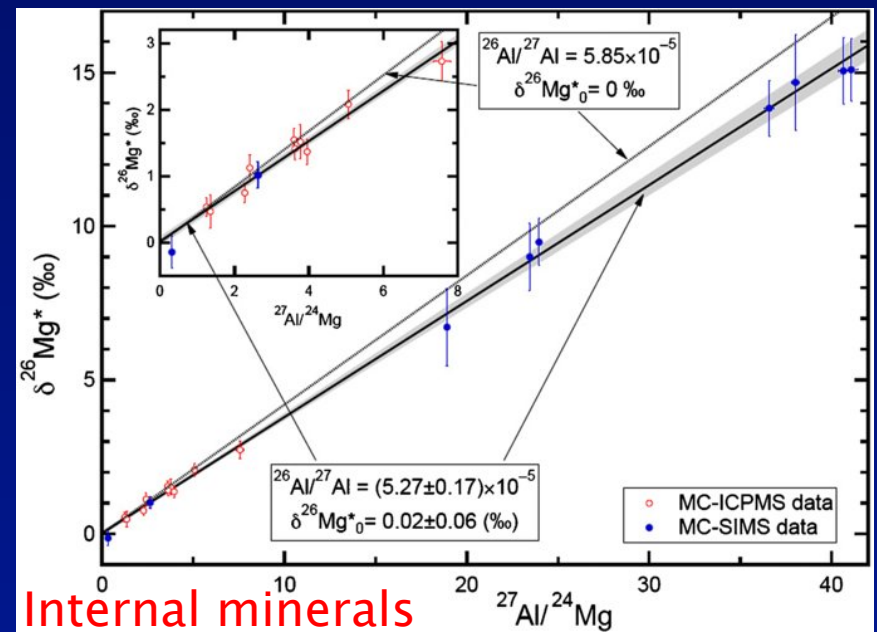
A fine chain saw

^{26}Al in the Solar Nebula

- $^{26}\text{Al} \rightarrow ^{26}\text{Mg}$ ($t_{1/2} = 0.73$ My)
- Initial $^{26}\text{Al}/^{27}\text{Al} = 5.2 \times 10^{-5}$ (e.g., Lee et al. 1977)
 - Determined in many CAIs – Homogeneity of ^{26}Al in disk
 - c.f. galactic $^{26}\text{Al}/^{27}\text{Al} \sim 8 \times 10^{-6}$ (Diehl et al 2006)
 - Last-minute input required for high solar system abundance, most likely from a star

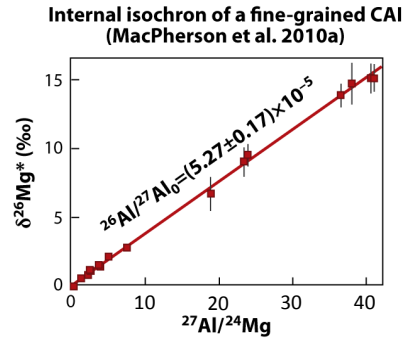
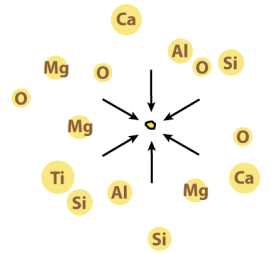
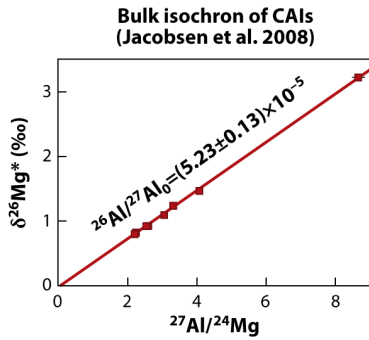


Jacobsen et al. (2008)

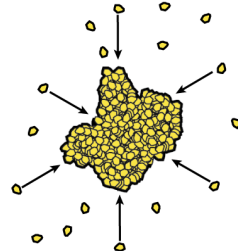


MacPherson et al. (2010)

Condensation of 1–10- μm dust from nebular gas



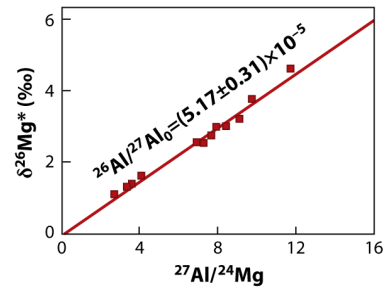
Agglomeration into mm–cm-sized objects



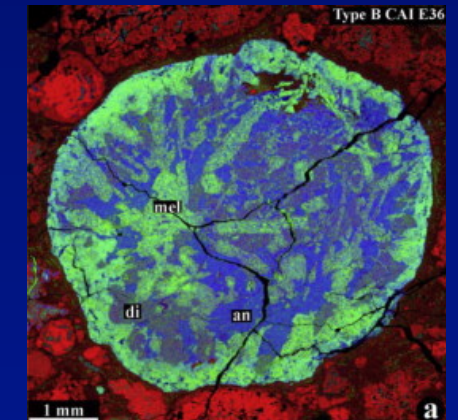
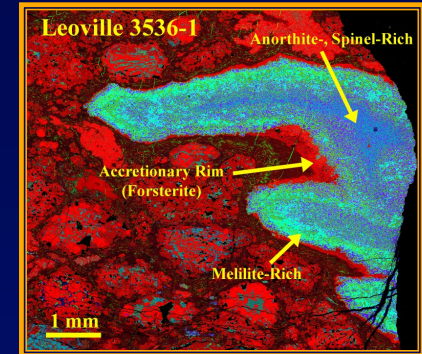
Melting and crystallization

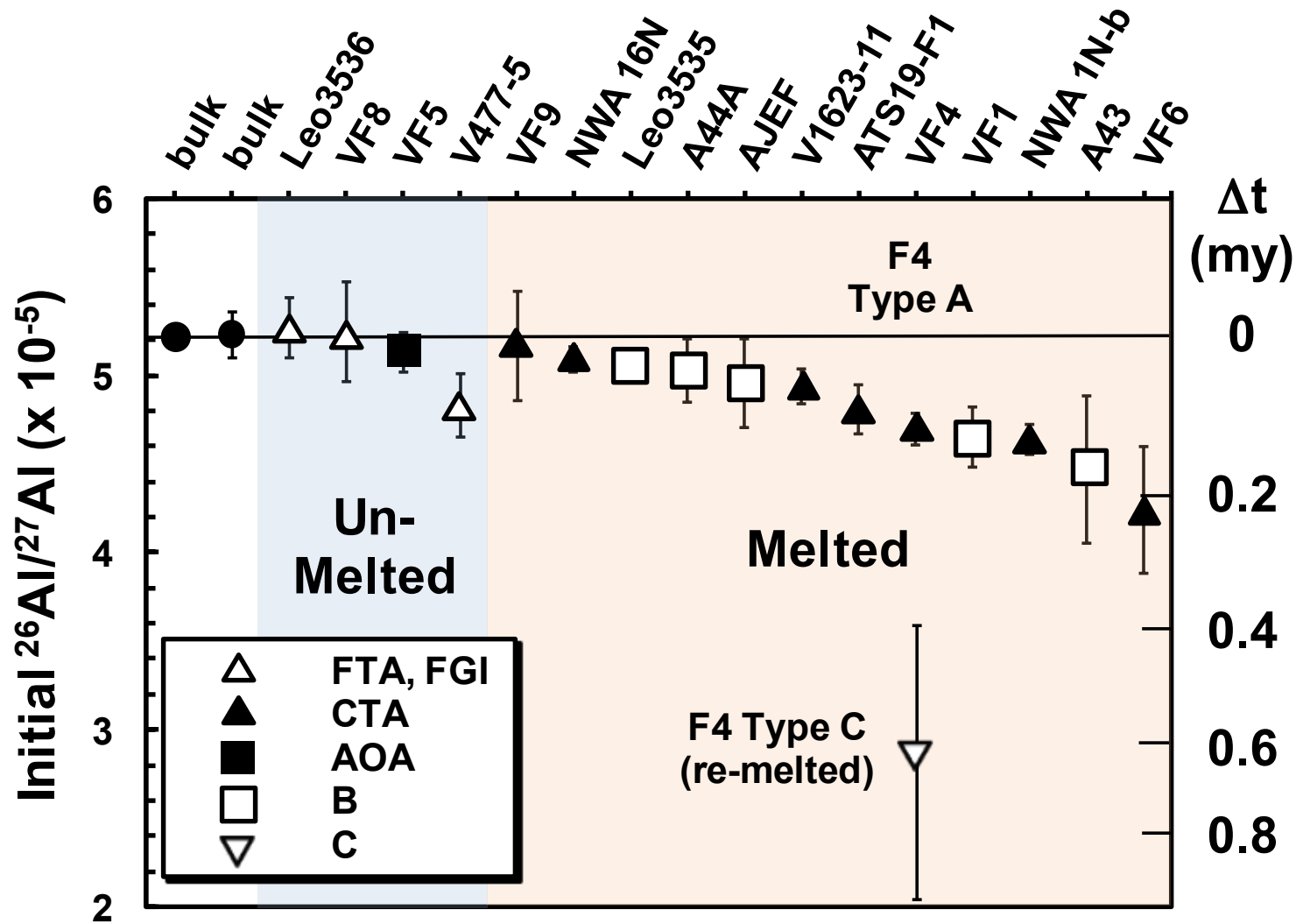


Internal isochron of an igneous CAI
(MacPherson et al. 2010b)

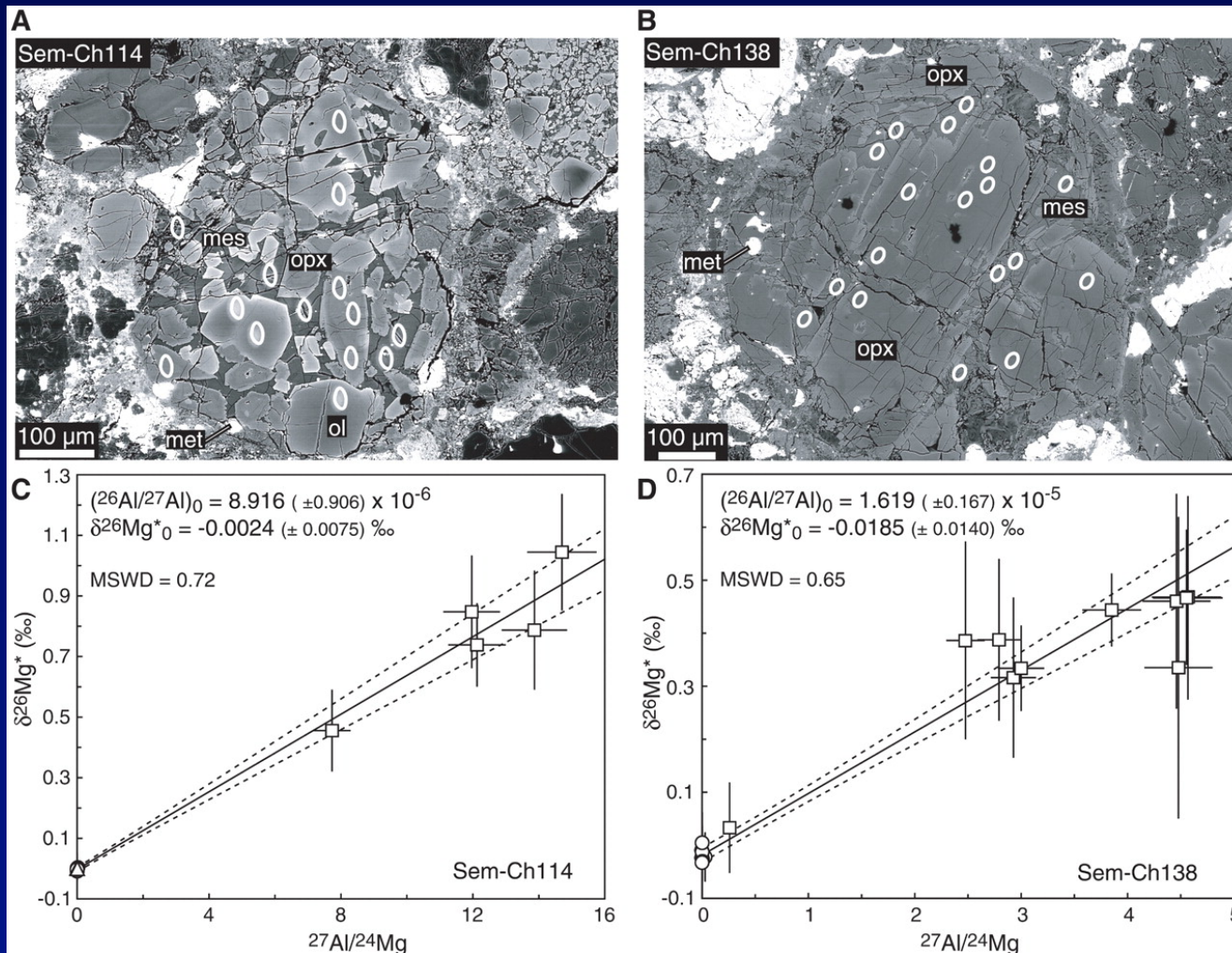


< 50 kyr



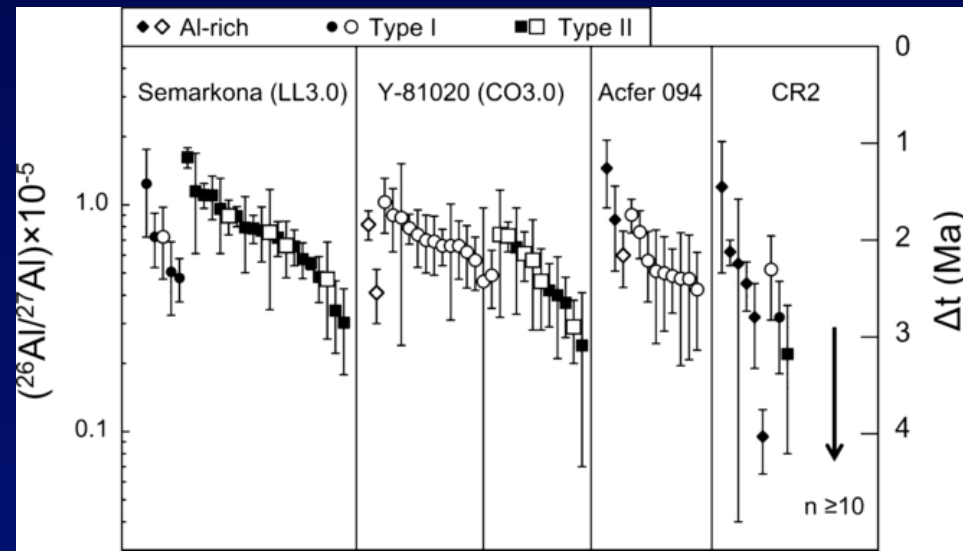


^{26}Al in Chondrules



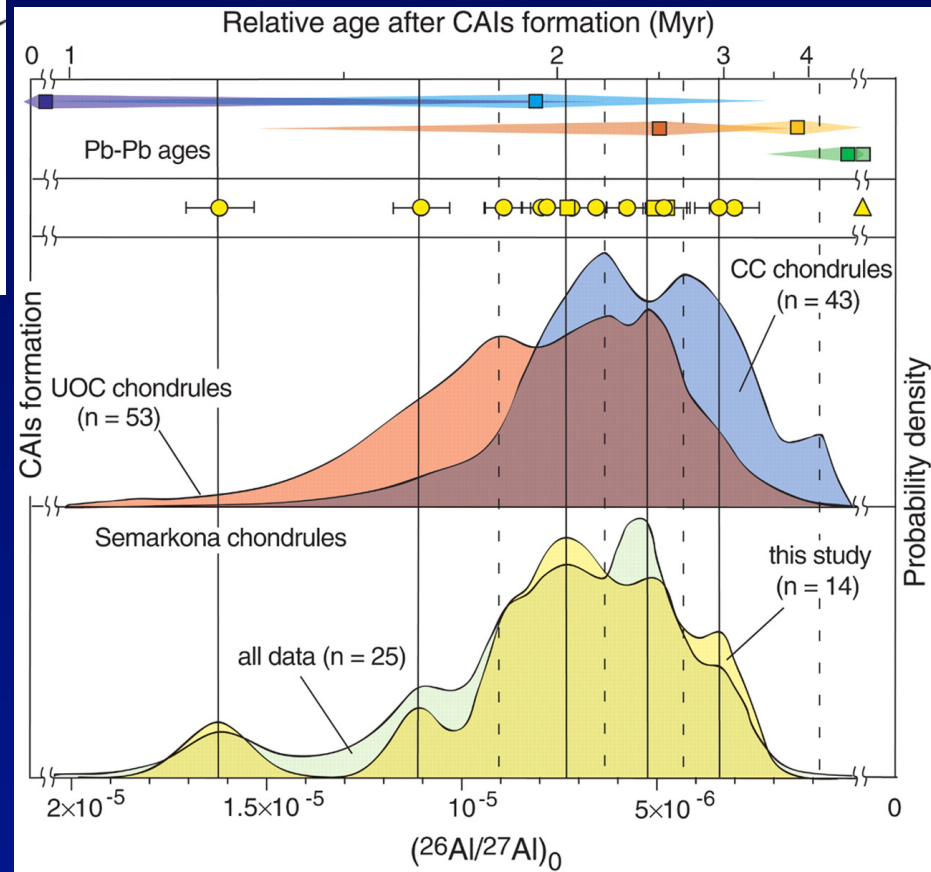
Villeneuve et al. (2009)

Protracted Chondrule Formation



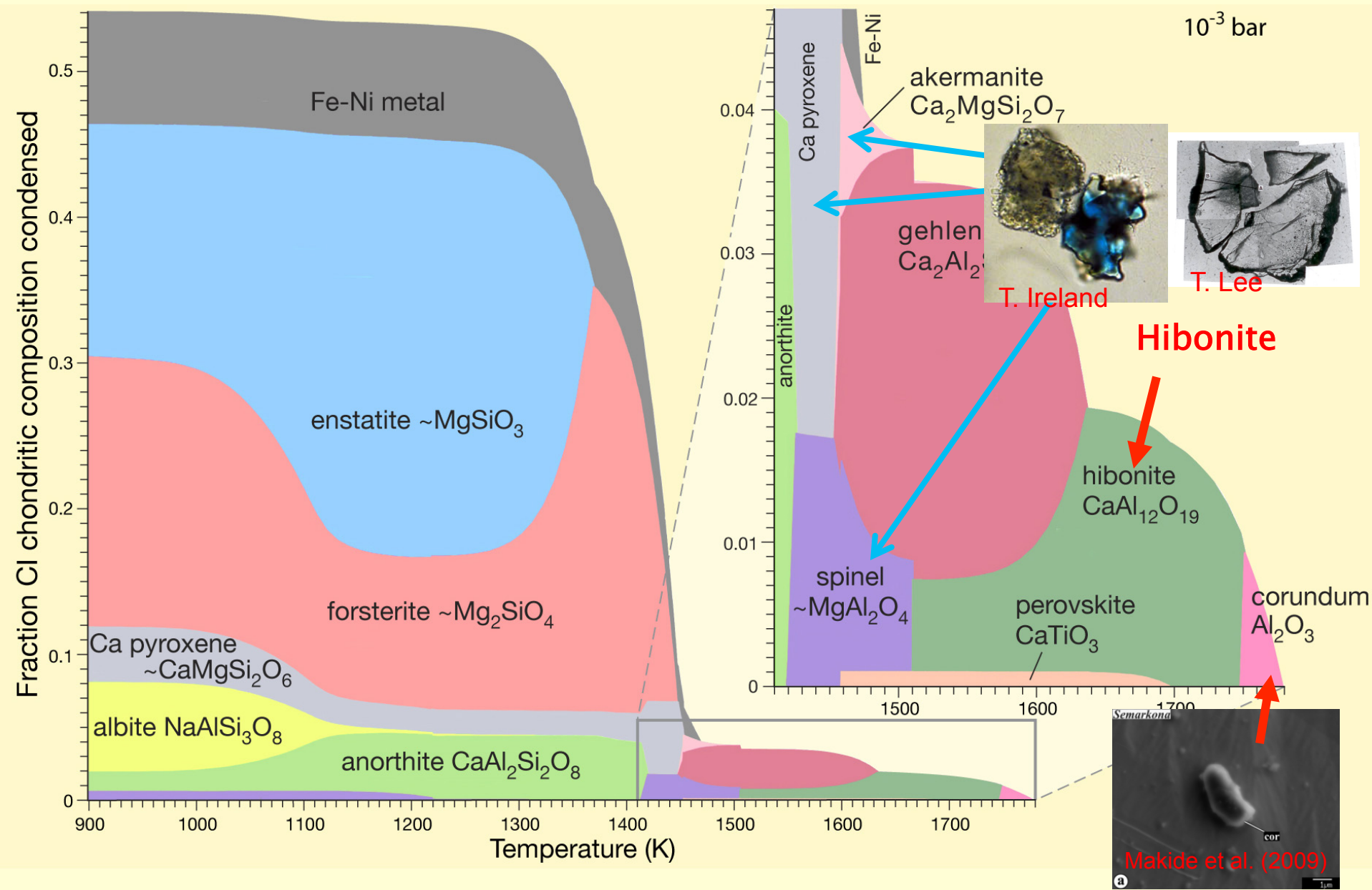
Kita et al. (2012)

Chondrule formation appears to have started $\sim 1-2$ Myr after $t = 0$ (defined by CAIs) and lasted for 2-3 Myrs



Villeneuve et al. (2009)

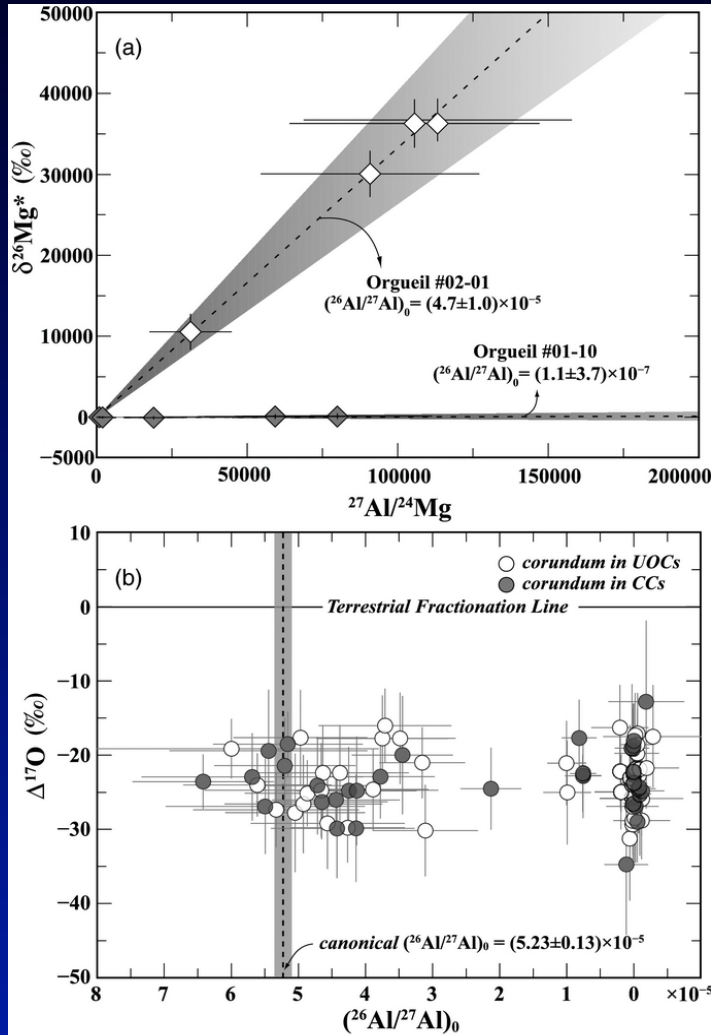
**Anything formed before
 $t = 0$ defined by CAIs?**



Davis and Richter (2005)

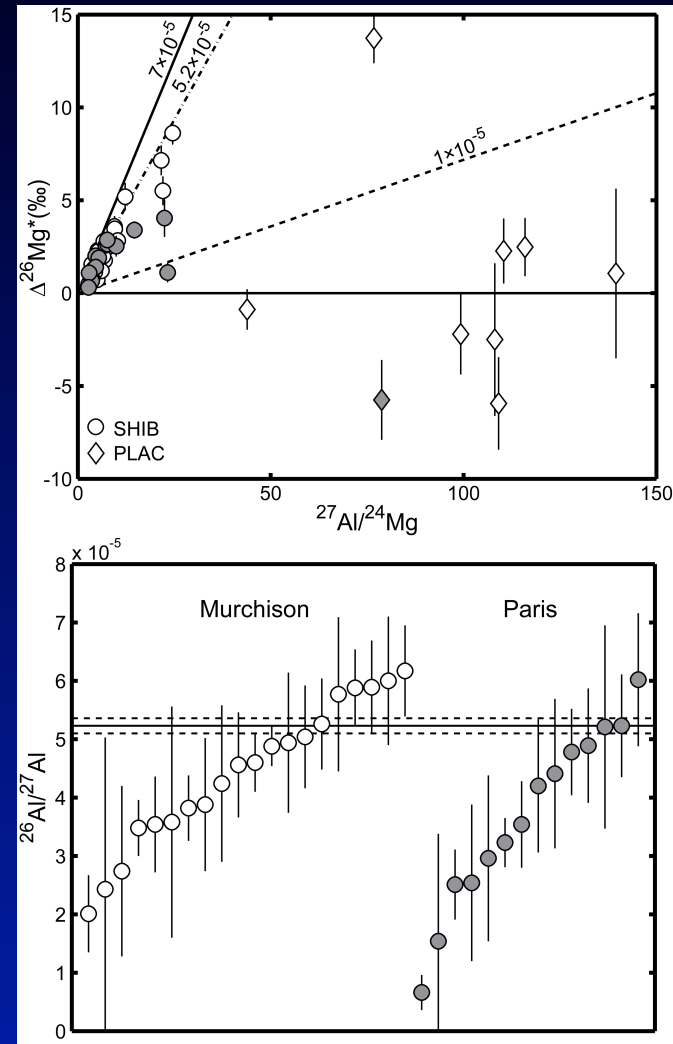
^{26}Al in Corundum and Hibonite

Corundum



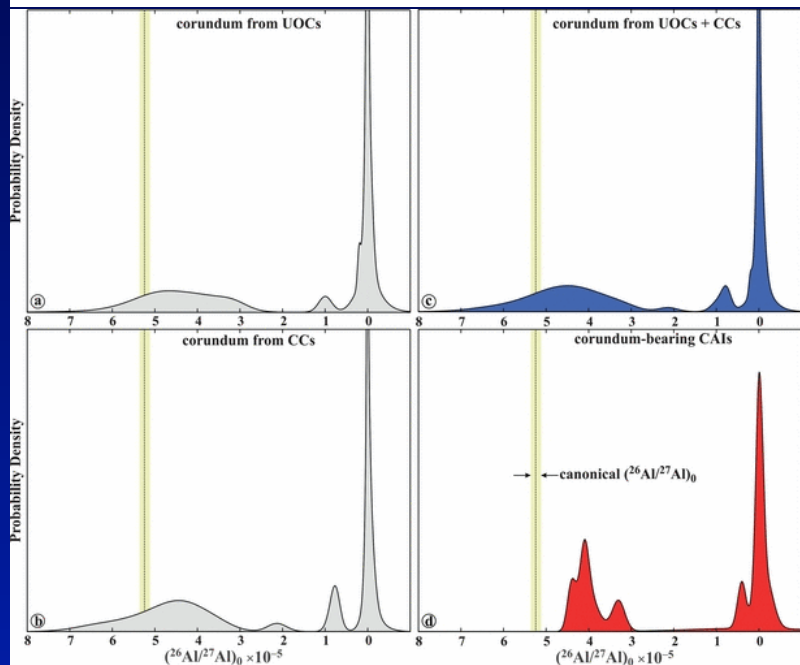
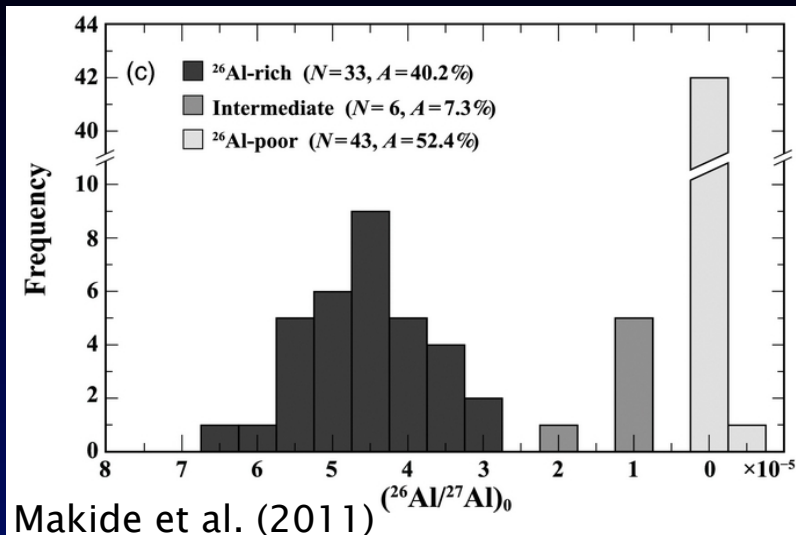
Makide et al. (2011)

Hibonite



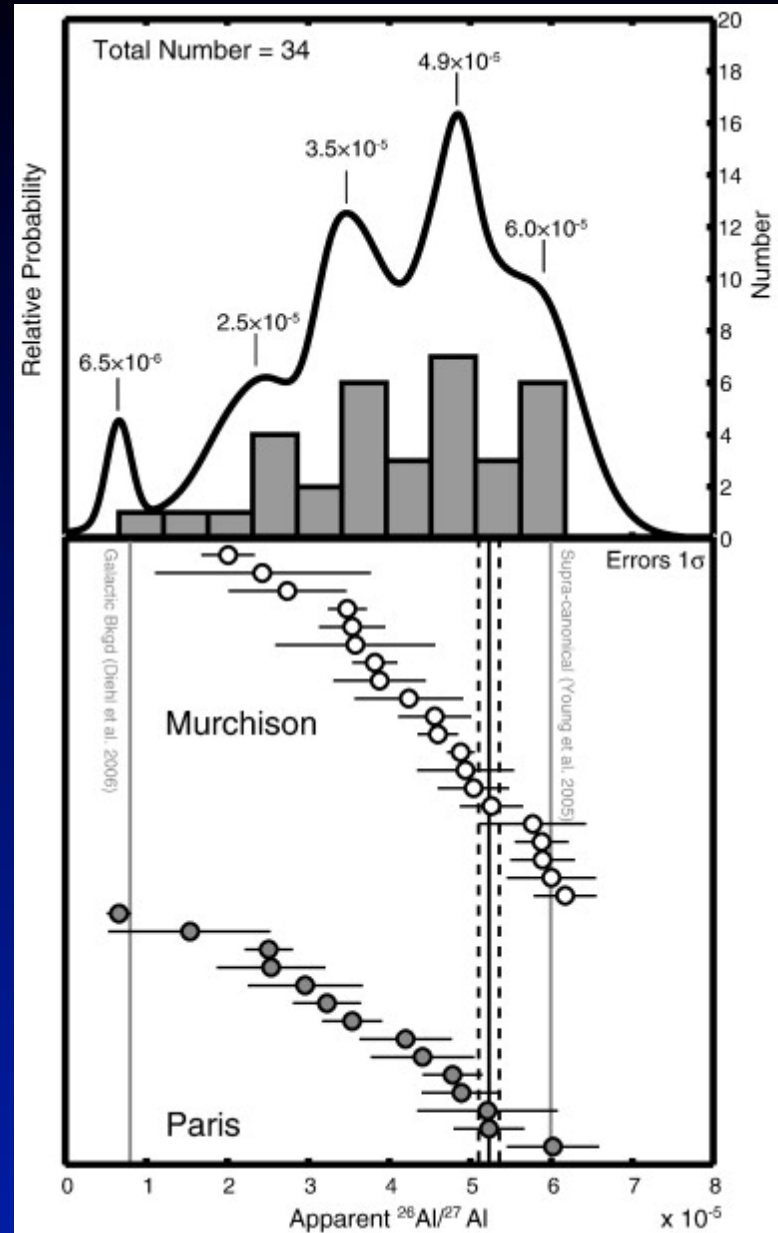
Liu et al. (2012)

Corundum

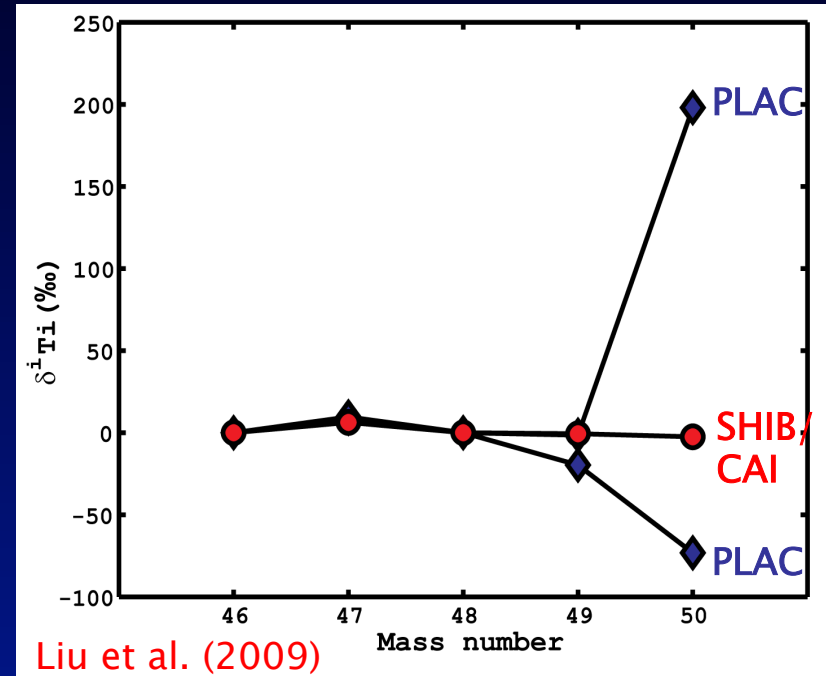
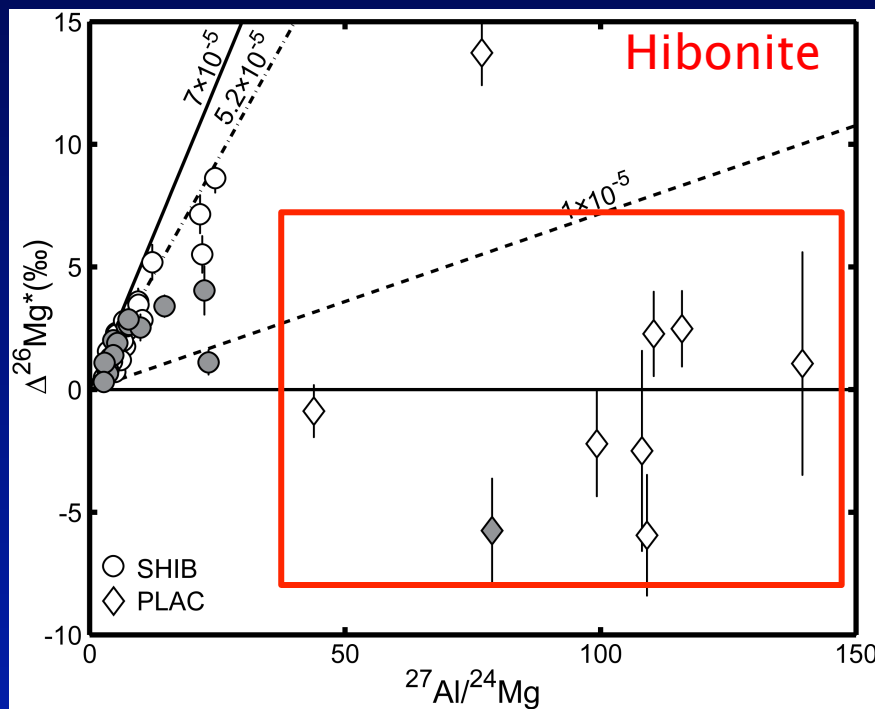
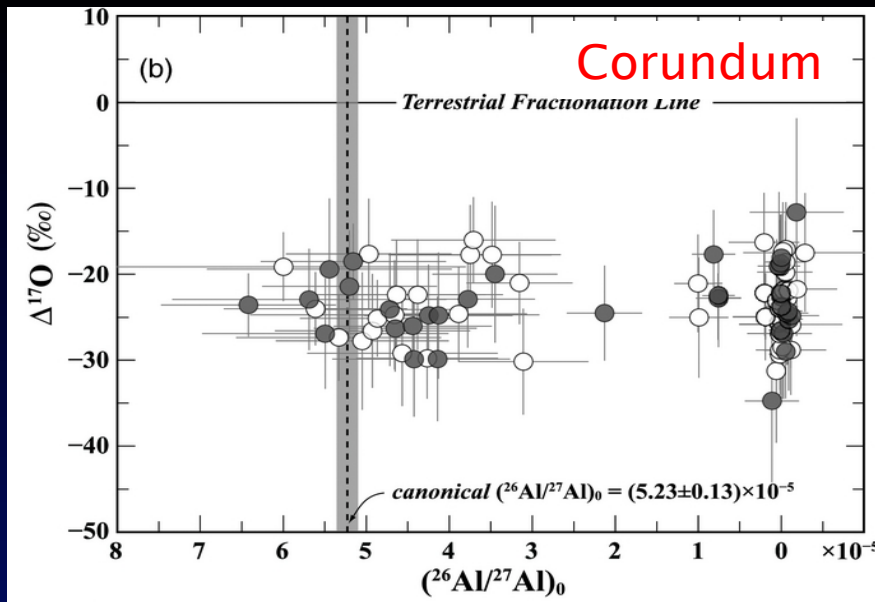


Krot et al. (2012)

Hibonite



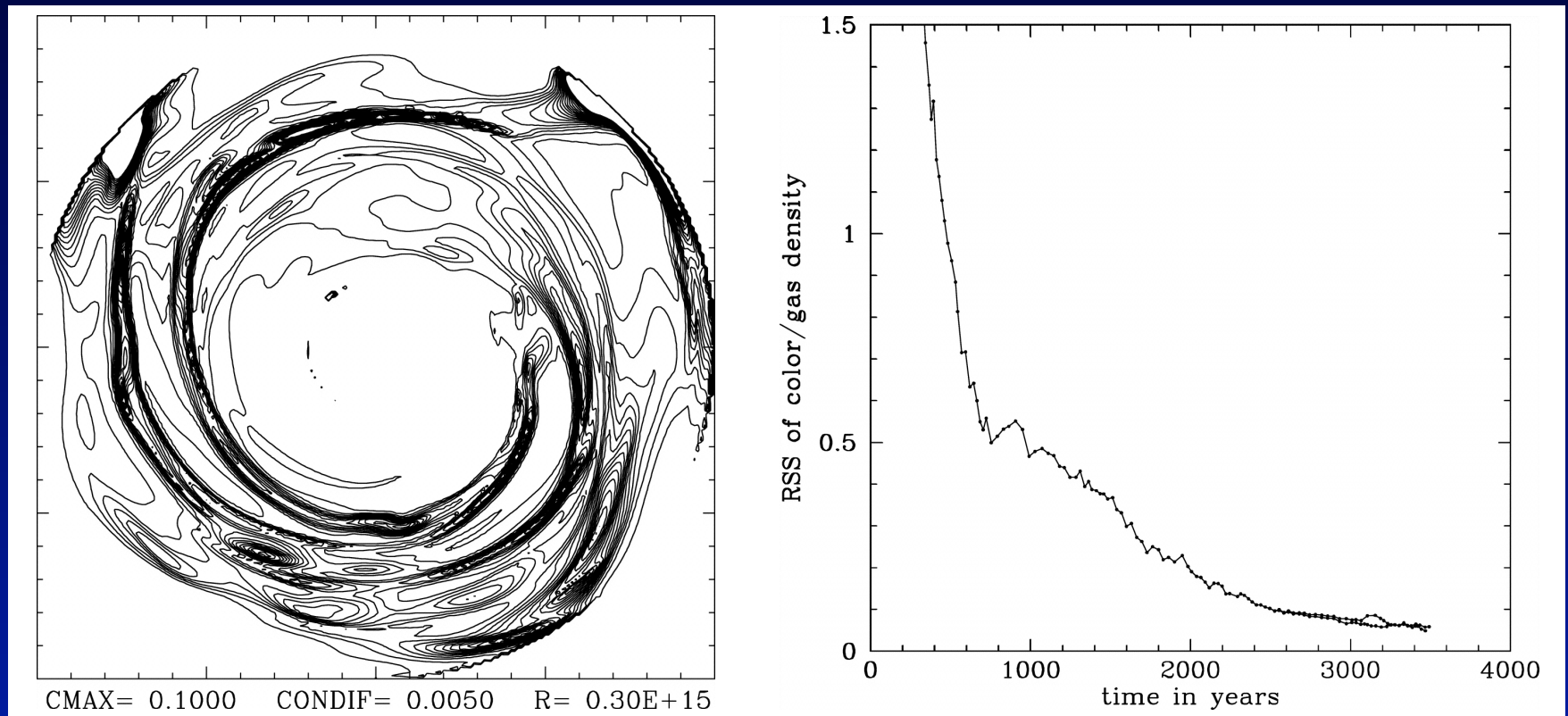
Liu et al. (2012)



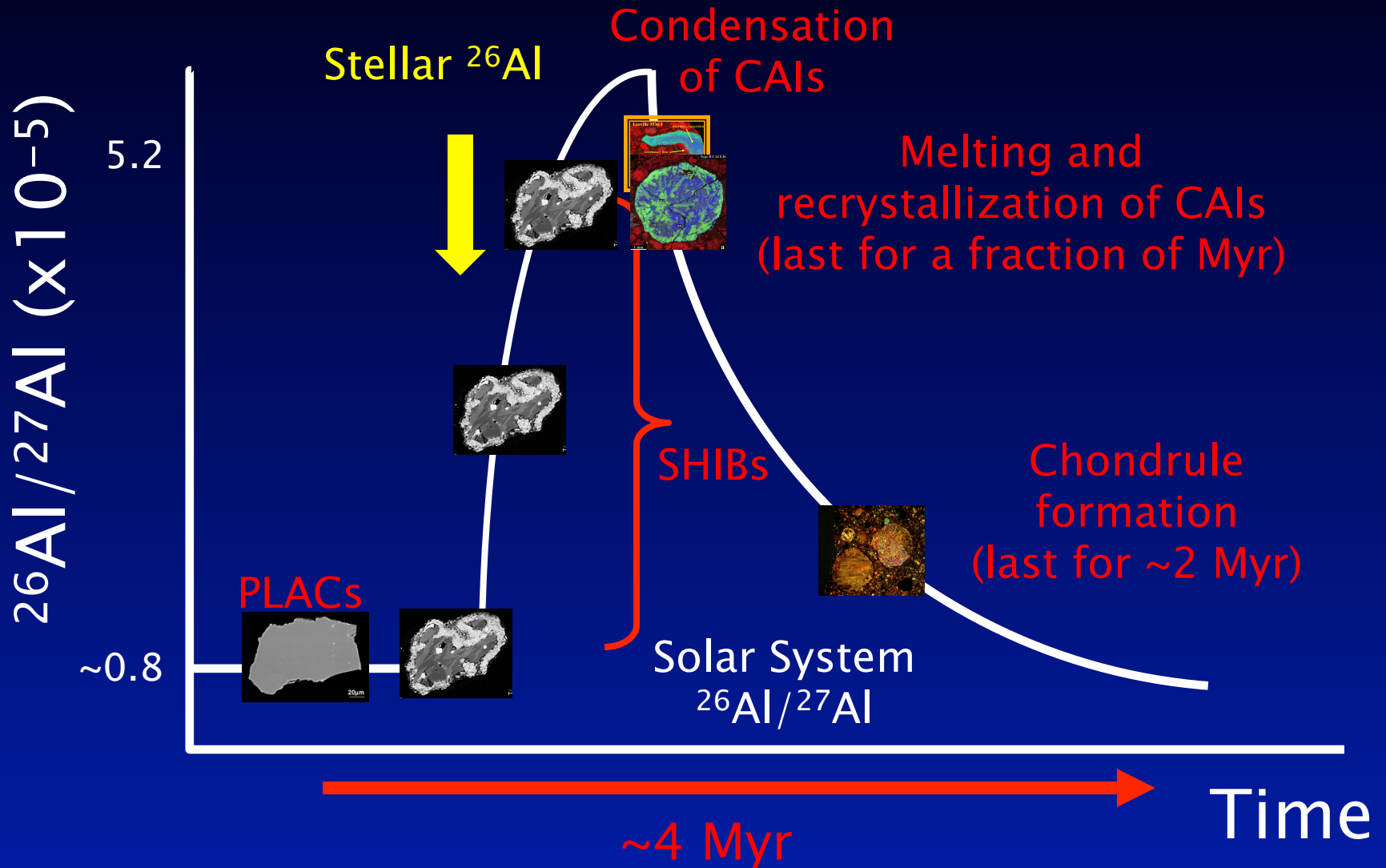
Hibonite condensates are probably older than (condensed and igneous) CAIs and recrystallized hibonite grains

A Heterogeneous Disk

- Mixing by chaotic fluid motions in a marginally gravitationally unstable disk

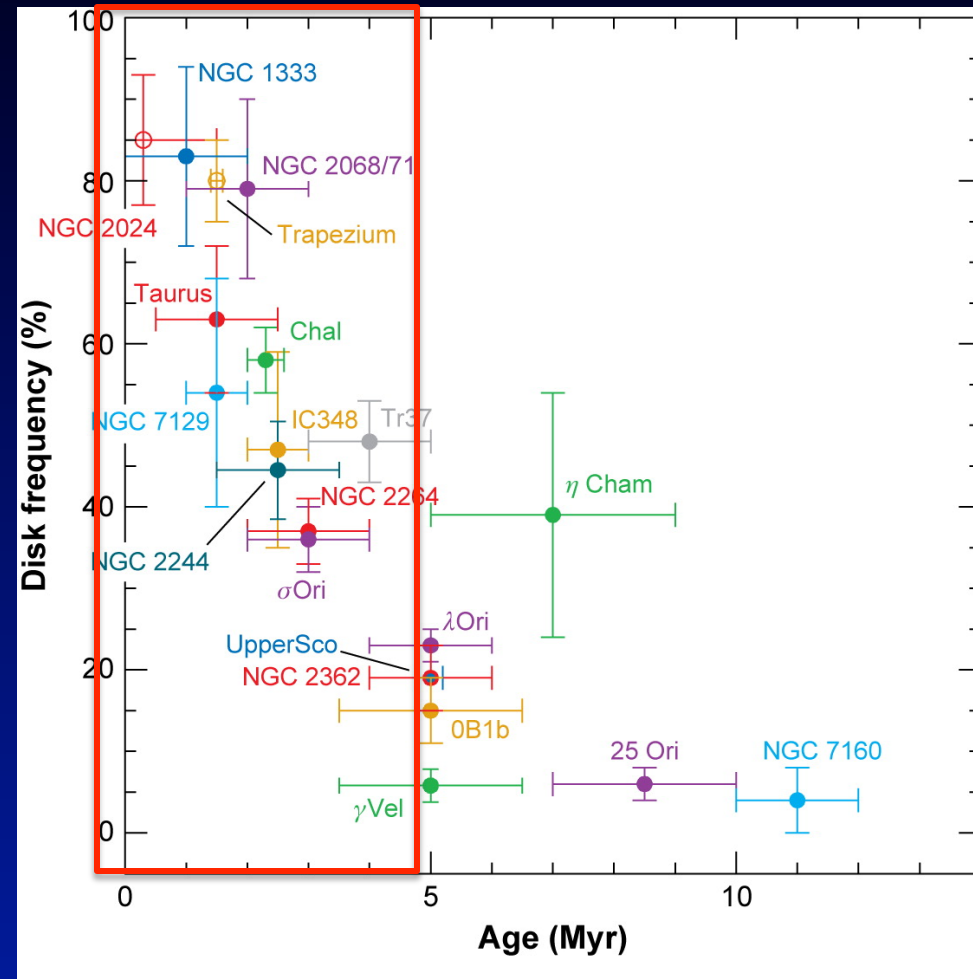


Synthesis



Chronology of Solid Formation

- High-T phases in chondrites formed in the gas-rich disk
 - Solar nebula should have been present for a few Myr
 - Such a timescale is consistent with that inferred from observations of YSOs



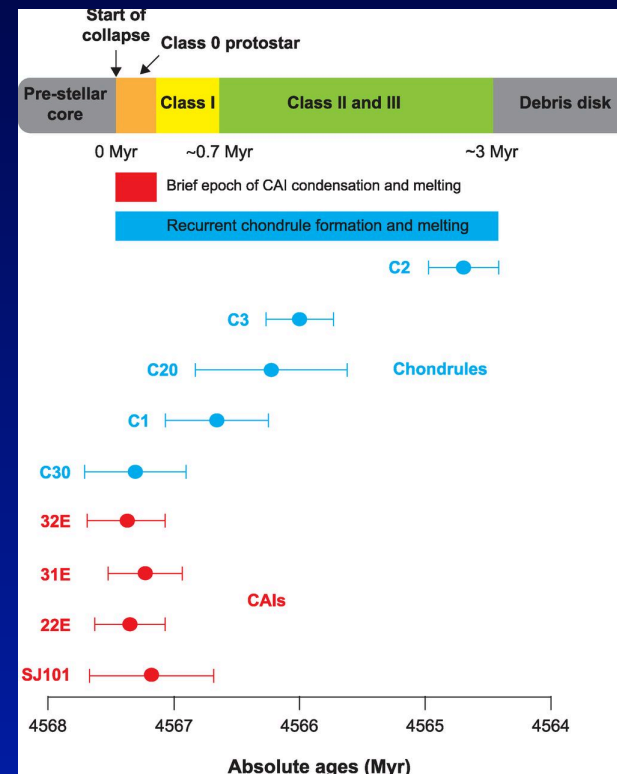
Wyatt (2008)

Link to any specific stage?

- Which stage in the formation of the Sun does “cosmochemical time zero” correspond to?

Can we observe active dust formation at high temperatures in other YSOs?

→ ALMA will tell us



Connelly et al. (2012)

A37

