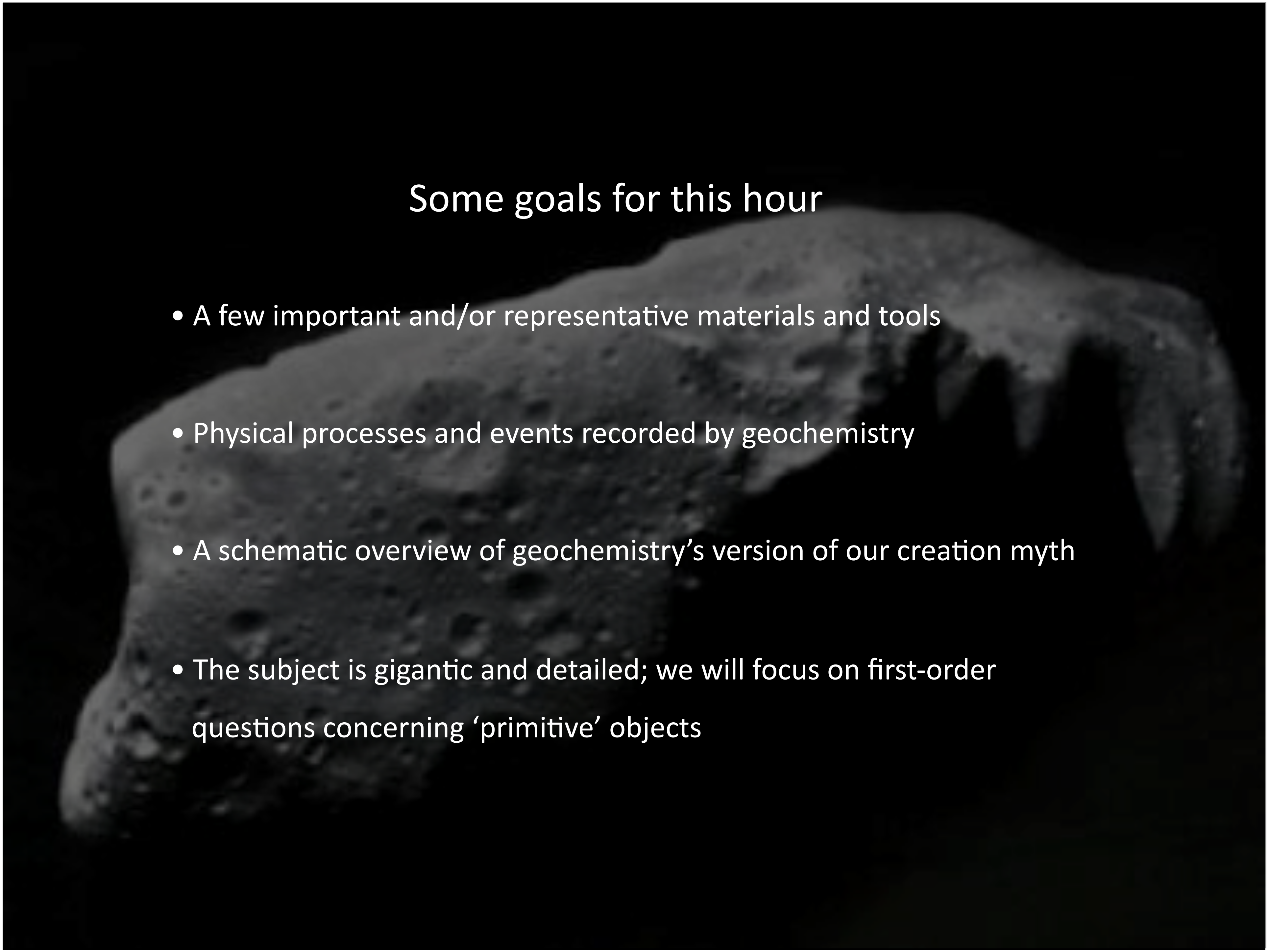
The geochemistry of primitive solar system bodies

John Eiler
Sharp Professor of Geology and Geochemistry

With help from Geoff Blake, Don Burnett, Harold Connolly, Dave Stevenson and Ed Young

Galileo image of 243 Ida



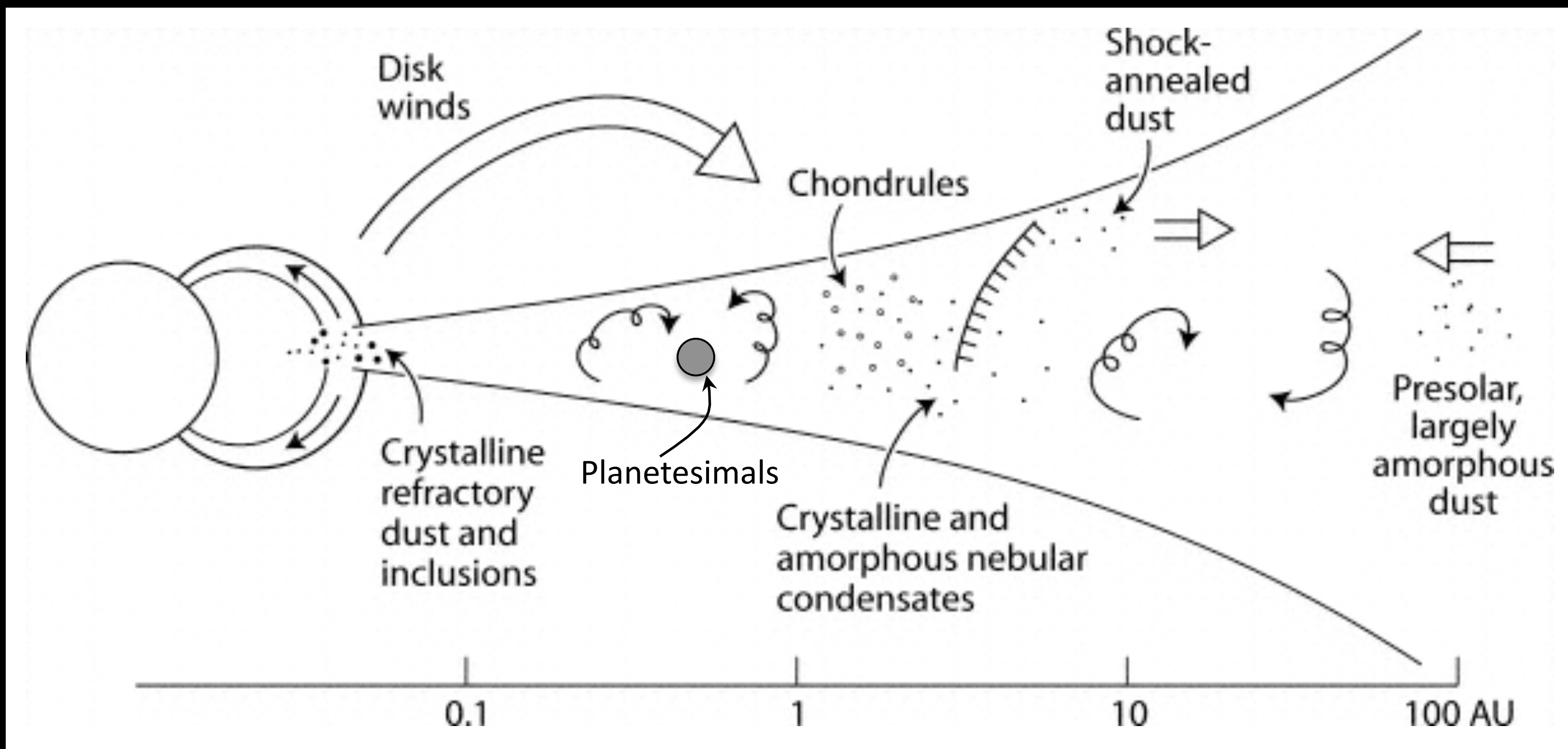
Some goals for this hour

- A few important and/or representative materials and tools
- Physical processes and events recorded by geochemistry
- A schematic overview of geochemistry’s version of our creation myth
- The subject is gigantic and detailed; we will focus on first-order questions concerning ‘primitive’ objects

What do we imagine geochemistry might tell us of the histories of primitive solar system bodies?

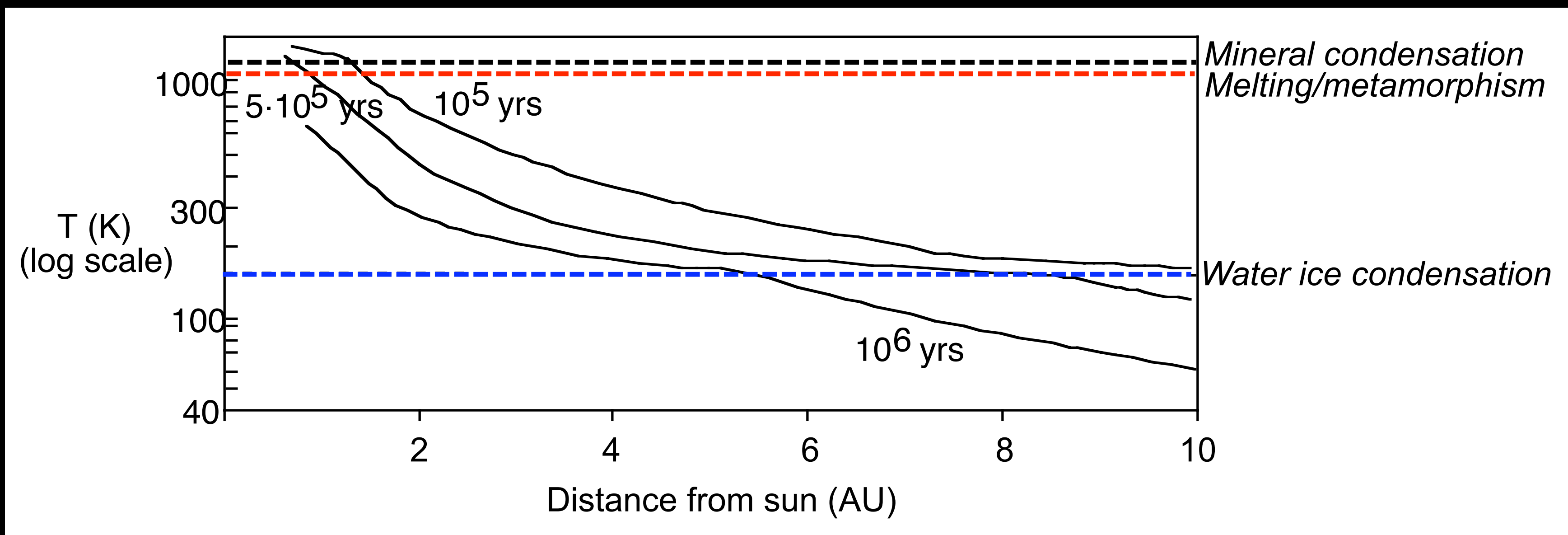
- What?
  - Recognizing primitive bodies for what they are
  - Can we assign a given 'primitive' material to common groups or histories?
- When?
  - Can we prove an object or its constituents formed in the first few million years?
  - Can we rank/order an object within early solar system chronology?
  - Can we recognize and date much later events?
- Where?
  - Inside/outside the 'snow line'?
  - Adjacent to the sun?
  - Prepare to be disappointed if you are hoping for something more subtle….
- How?
  - Mixing of recognized early solar system components (CAI's, chondrules, ice…)
  - Water-rock reaction
  - Metamorphism
  - Metal/silicate differentiation
  - Silicate partial melting

The family of environments in the early solar system



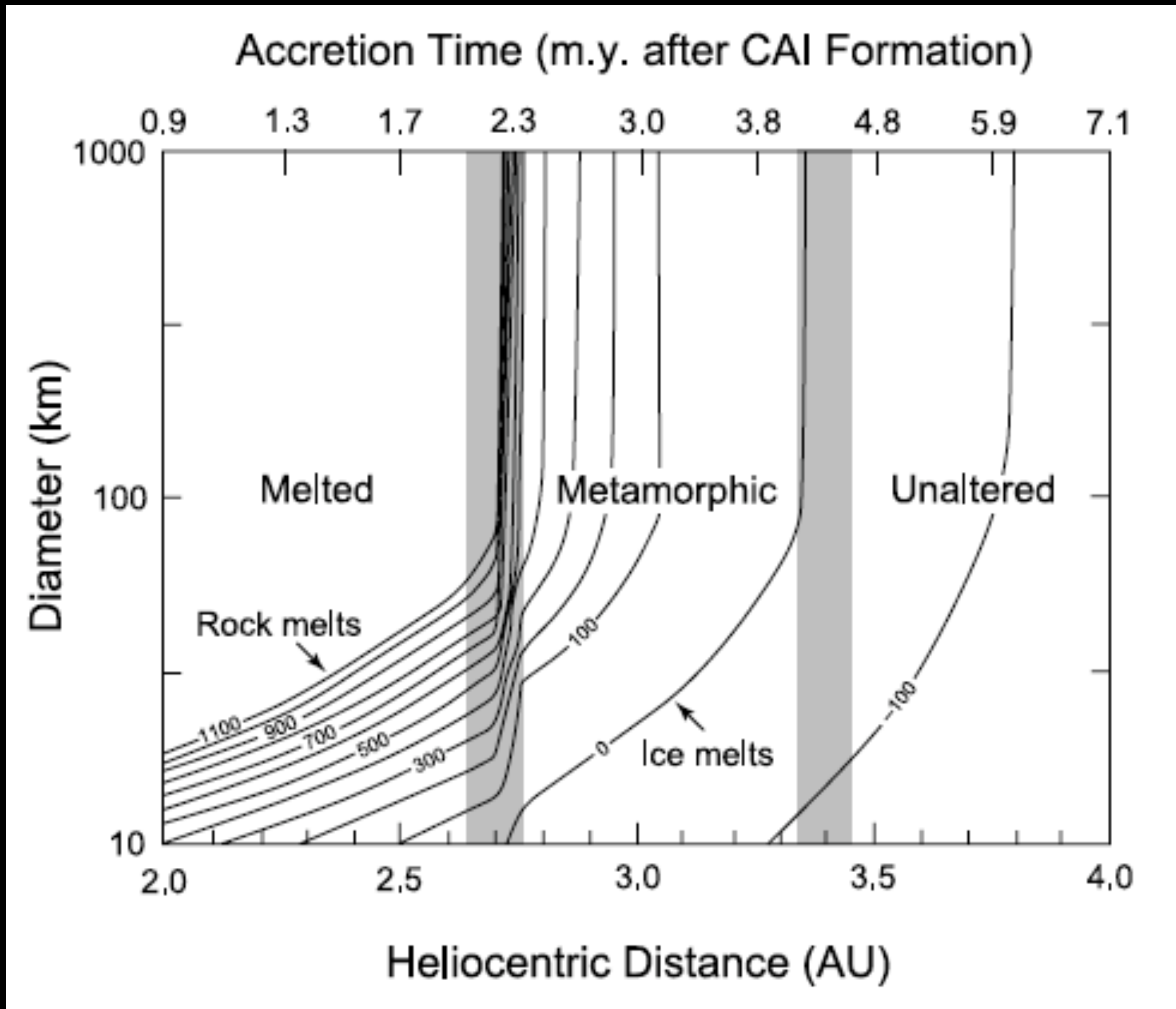
After Krot, 2009

Early temperature history of gas and dust in the disk



After Mousis et al., 2000

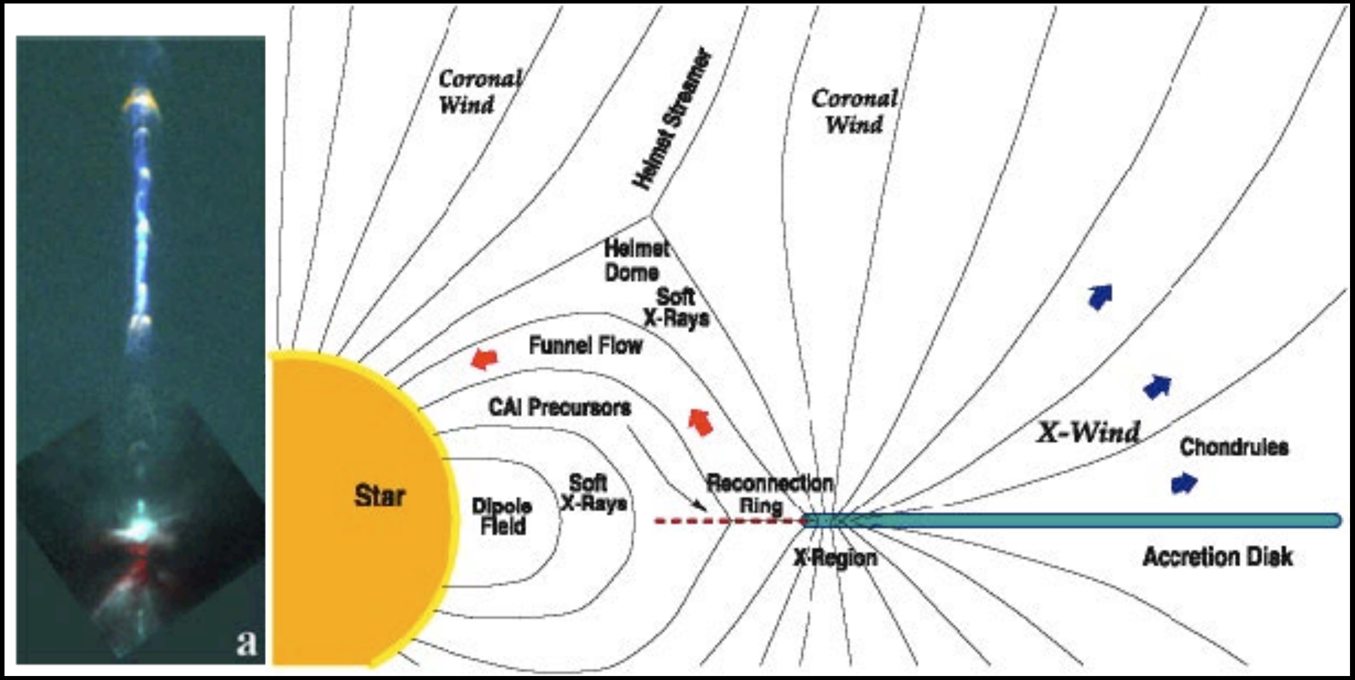
Early temperature history of planetesimals



Ghosh et al., 2006

An end-member 'scenario'

The extended 'X-wind' hypothesis; Shu et al., 1997

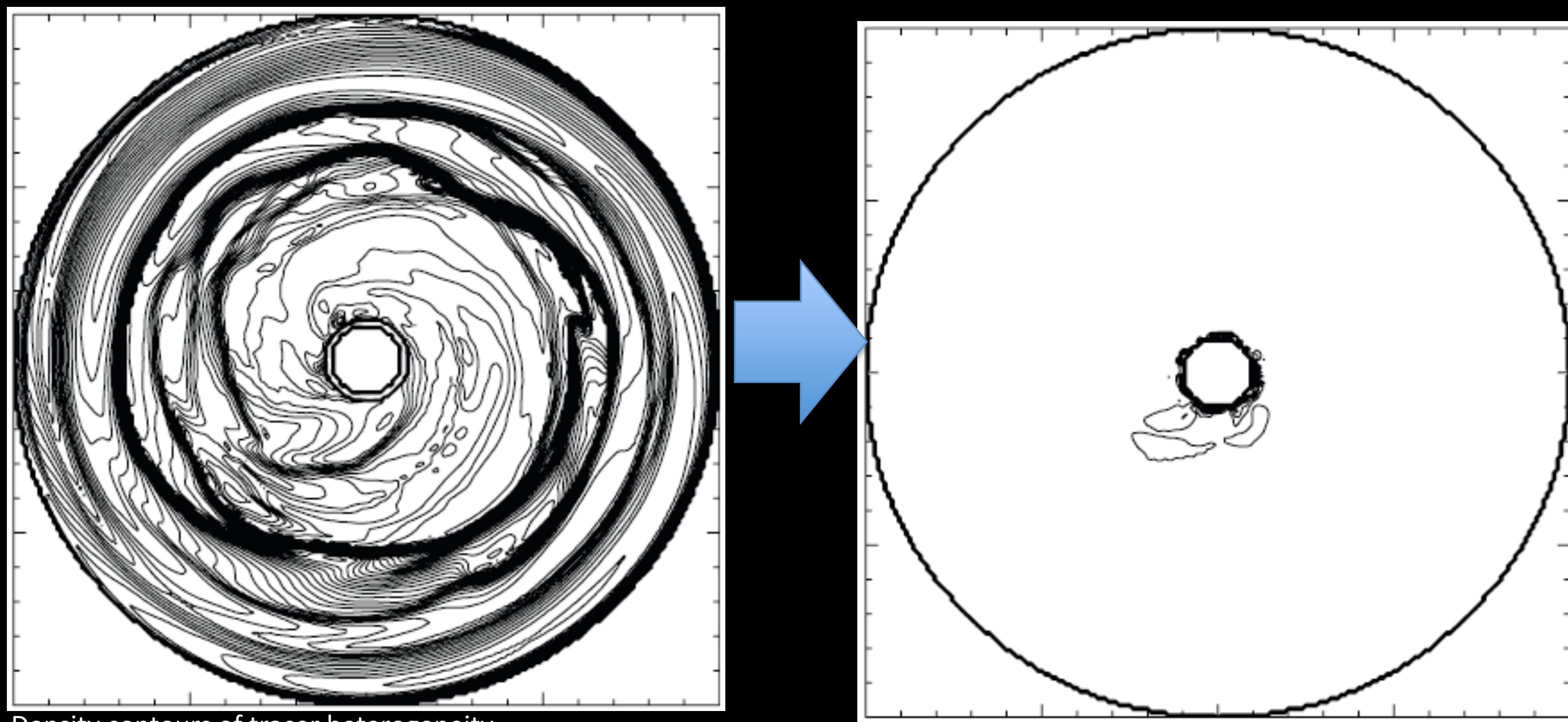


- Intense heat and radiation in innermost disk, and vigorous, focused transport of particles
- Short lived radio-isotopes synthesized near sun
- CAI's form near the sun
- Chondrules in denser inner disk
- Both strewn to snow line and beyond by X-wind
- Heating and short-lived radio-isotope production spatially heterogeneous
- Most of these processes happen simultaneously

Shu et al., 1997; Shang, 2007; Krot, 2009

Another end-member scenario — 'anything-but-X-wind'

A seeded solar system; dynamically mixed; shock-related melting

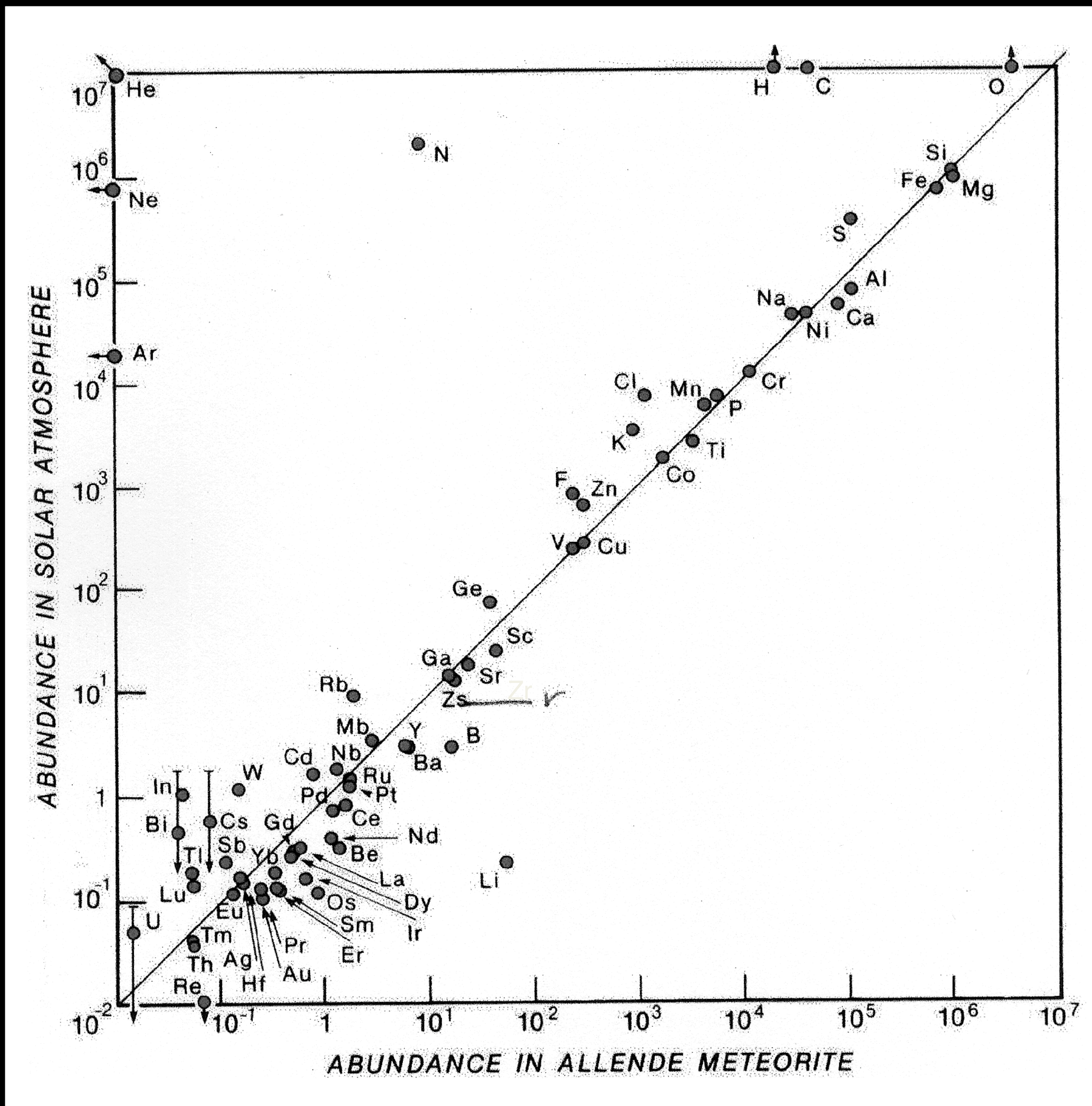


Density contours of tracer heterogeneity

- Pre-solar nebula seeded with short lived radio-isotopes during or just before collapse
- Highly efficient dynamic mixing homogenizes many components
- CAI's form first (likely near the sun)
- Chondrules form after (and repeatedly) in response to shock waves and other local effects
- Redistribution of CAI's and chondrules through complex, somewhat ambiguous dynamics

Boss, 2011

Primitive meteorites look a lot like the sun in elemental abundances (minus the gas and all the hotness)

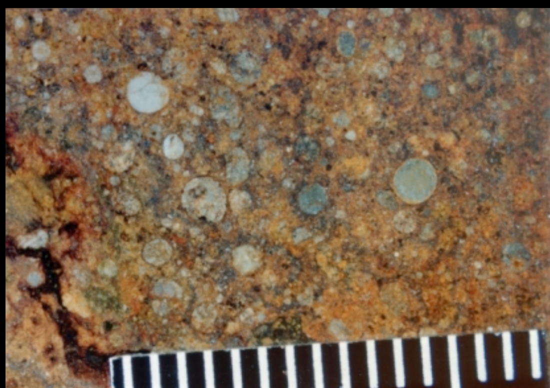


Two options

- They are fairly uniform condensates
- They are statistical samples of a wide variety of things

Chondrites

Chondrules



Grassland meteorite chondrules

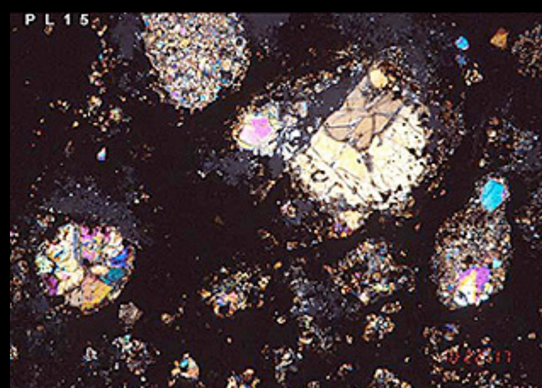
- Silicate melts (possibly multi stage)
- Moderately hot; more oxidizing
- Diverse in age and type

Refractory inclusions

Allende CAI's surrounded by chondrules

- Gas/solid gas/liquid equilibria
- Very hot, reducing environment
- Relatively uniform in age and type

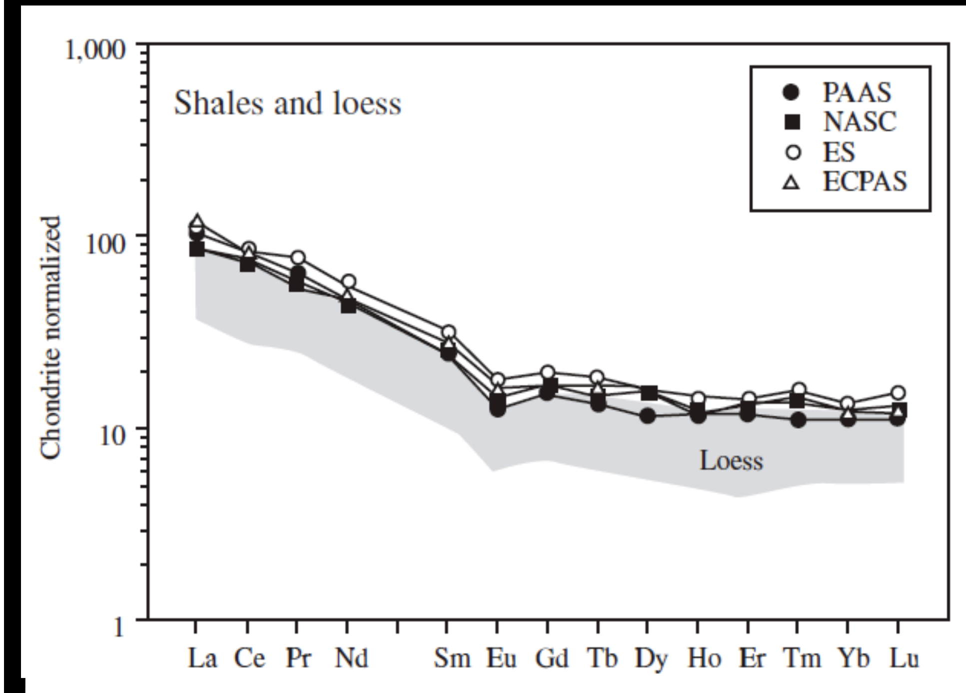
Matrix



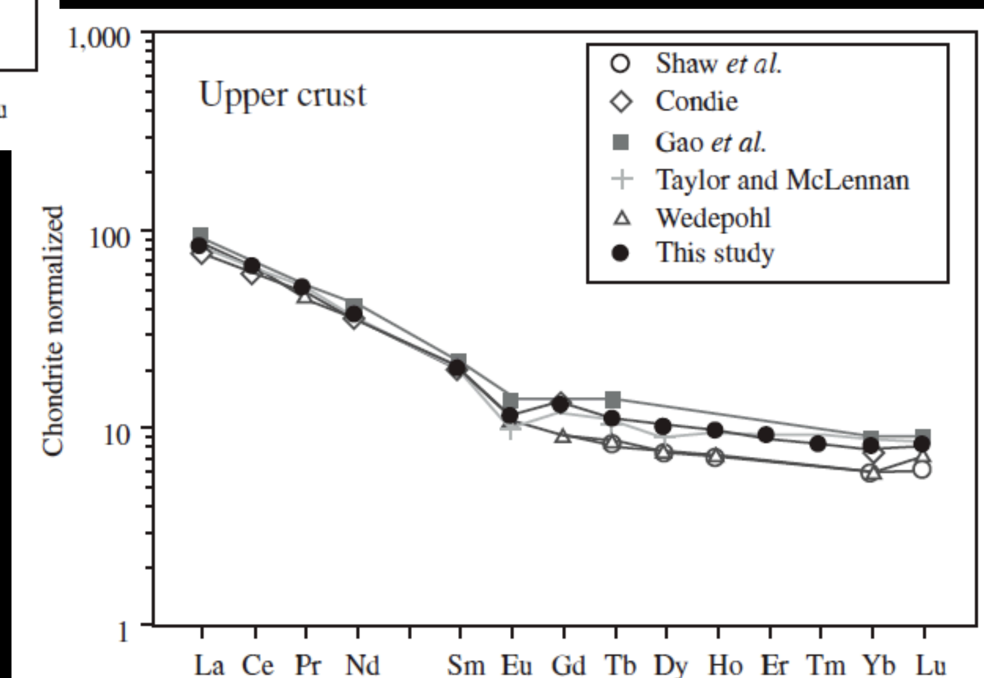
Matrix-rich region of Allende

- Sub-micron silicate, oxide, sulfide, organics
- The petrographic 'mortar' of chondritic materials
- Lots seem processed; like 'mini-chondrules'
- In volatile-rich bodies, altered to hydrous minerals and salts

The carbonaceous chondrites can be thought of as the shales of the early solar system



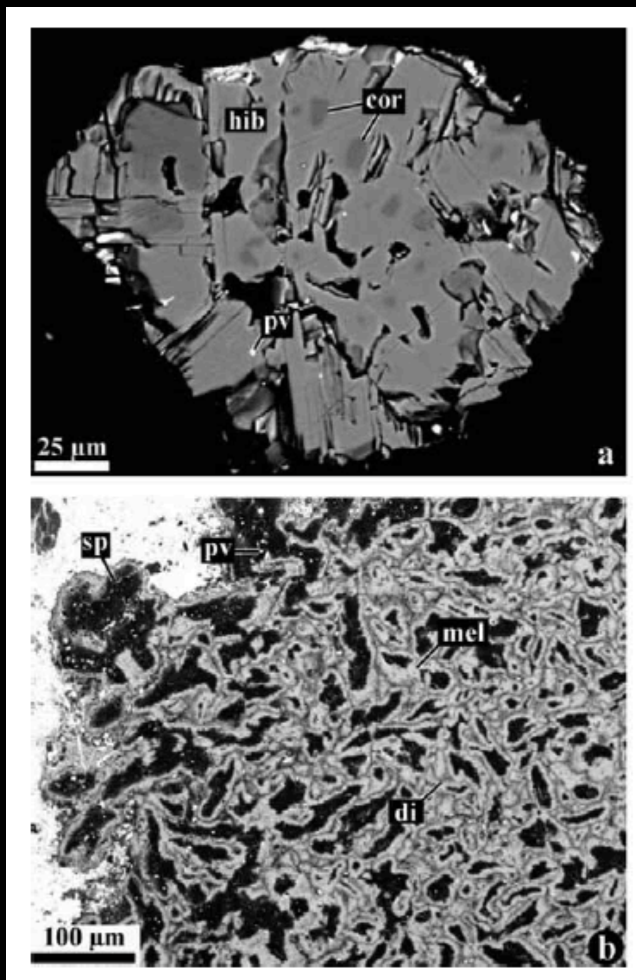
A black shale



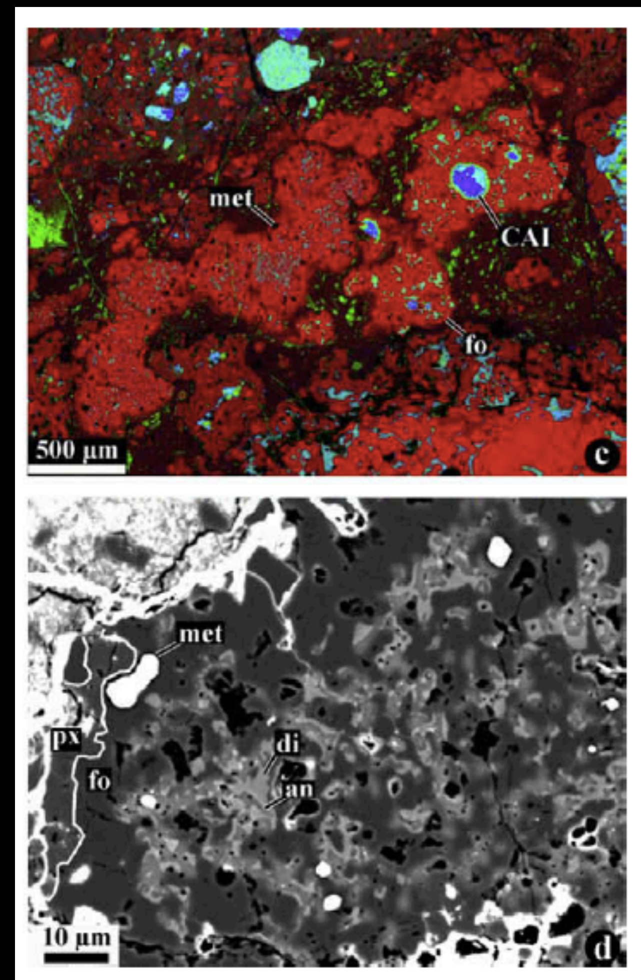
Rudnick and Gao, 2003

Details of refractory inclusions

Calcium-Aluminum Inclusions
Highly refractory condensates



Amoeboid Olivine Aggregates
Somewhat cooler gas/solid reactions

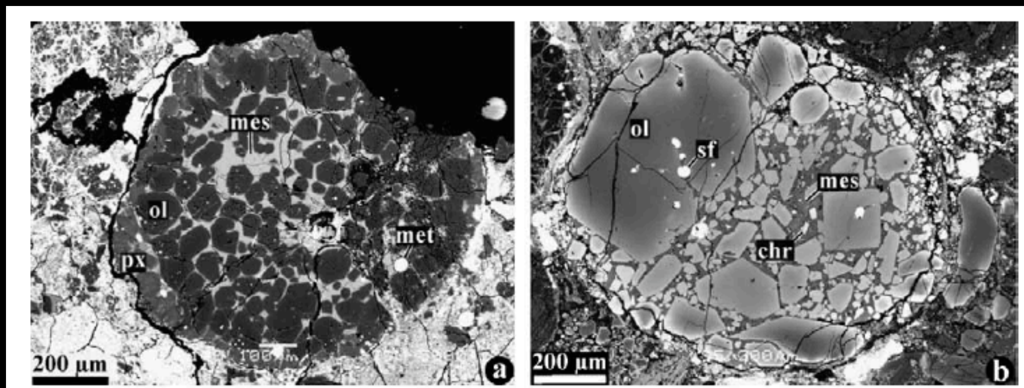


An = anorthite
Cor = corundum
Di = diopside
Fo = forsterite
Hib = hibonite
Mel = melilite
Met = metal
Pv = perovskite
Px = low-Ca pyroxene
Sp = spinel

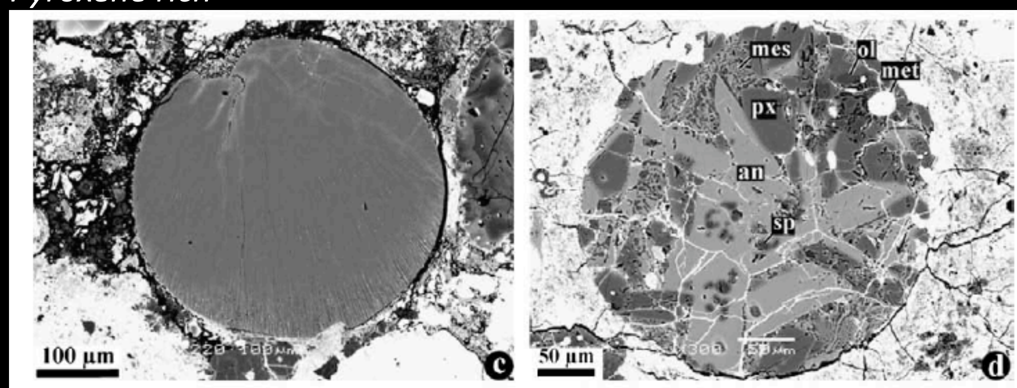
Krot et al., 2009

Details of representative chondrules

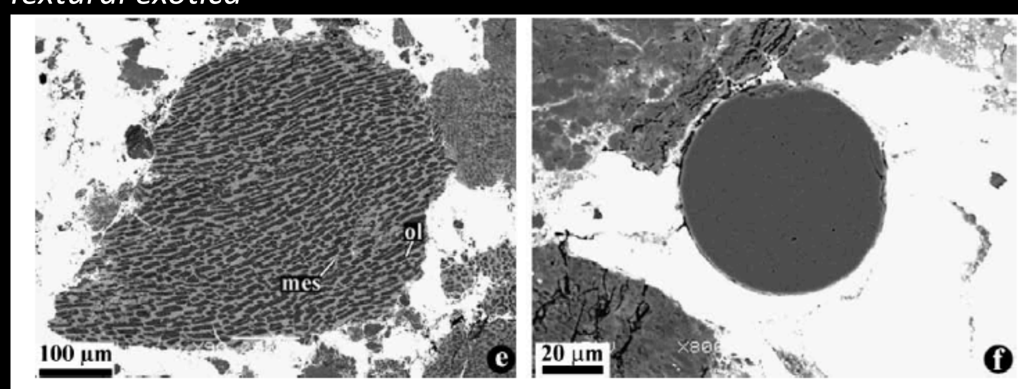
Olivine rich



Pyroxene rich



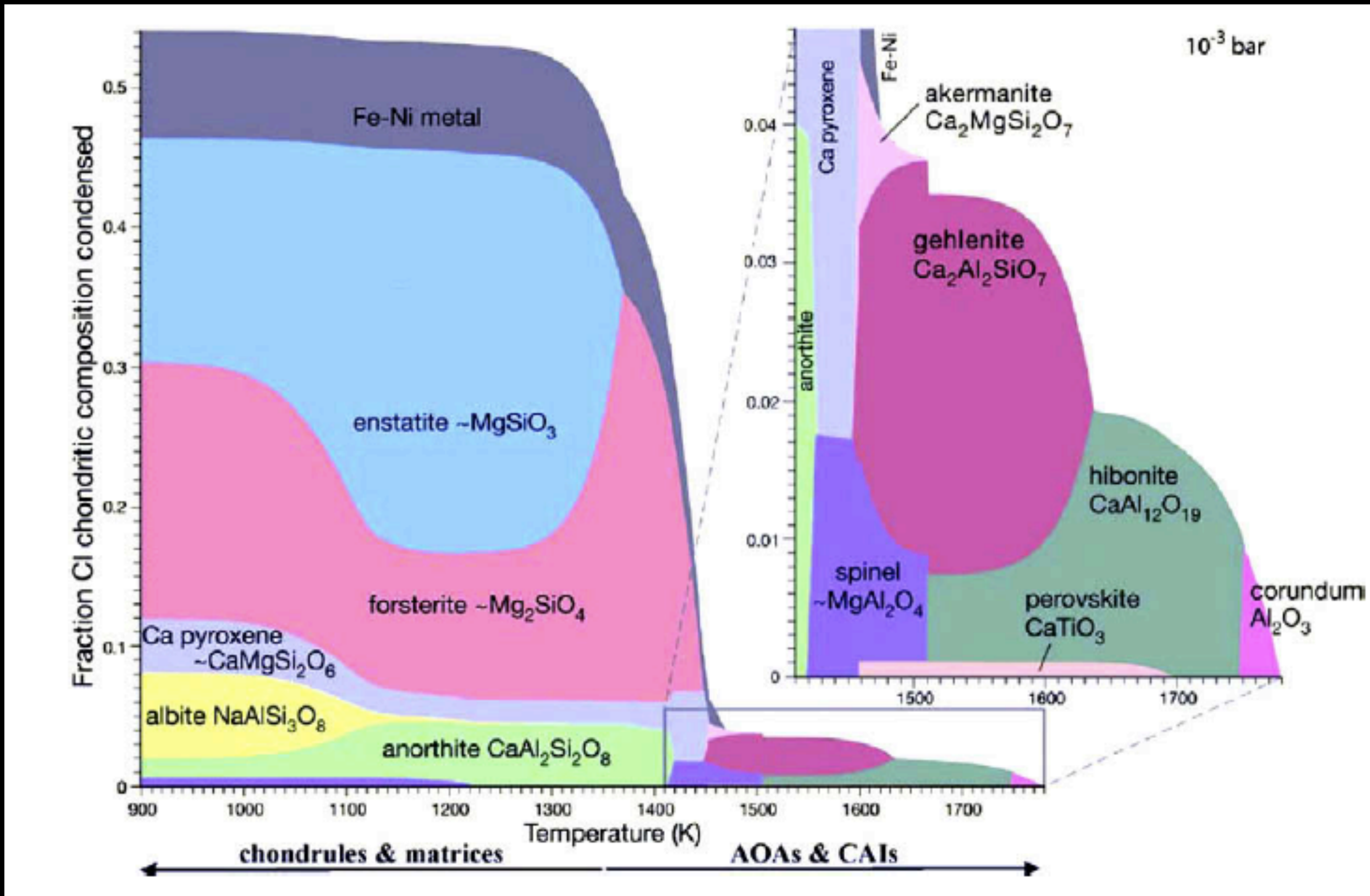
Textural exotica



An = anorthite
Chr = chromite
Mes = mesostatis
Met = metal
Ol = olivine
Px = low-Ca pyroxene
Sf = sulfide
Sp = spinel

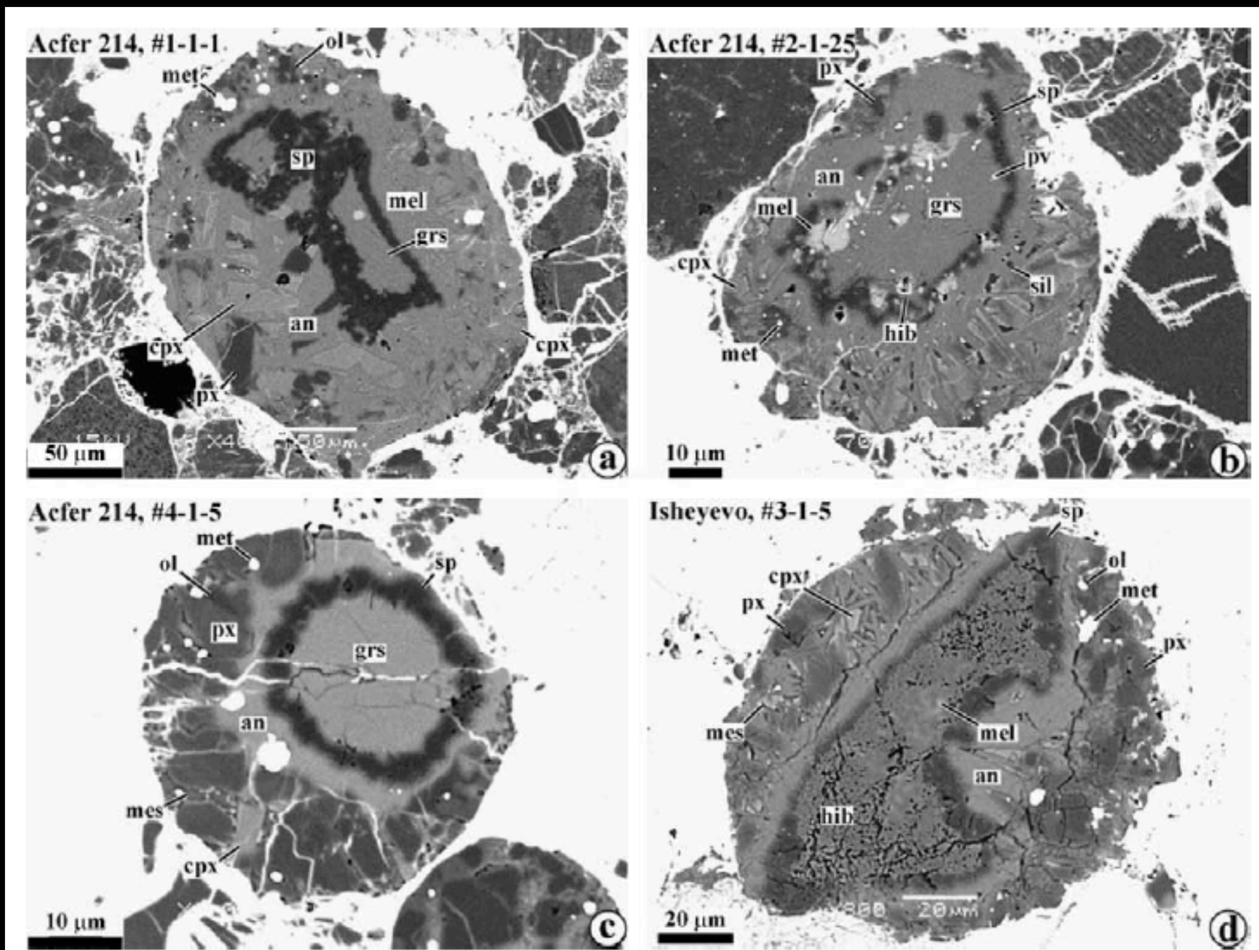
Krot et al., 2009

The temperature significance of CAI and Chondrule components



Davis and Richter, 2003; Krot et al., 2009

CAI's are inclusions in (and thus predate) chondrules

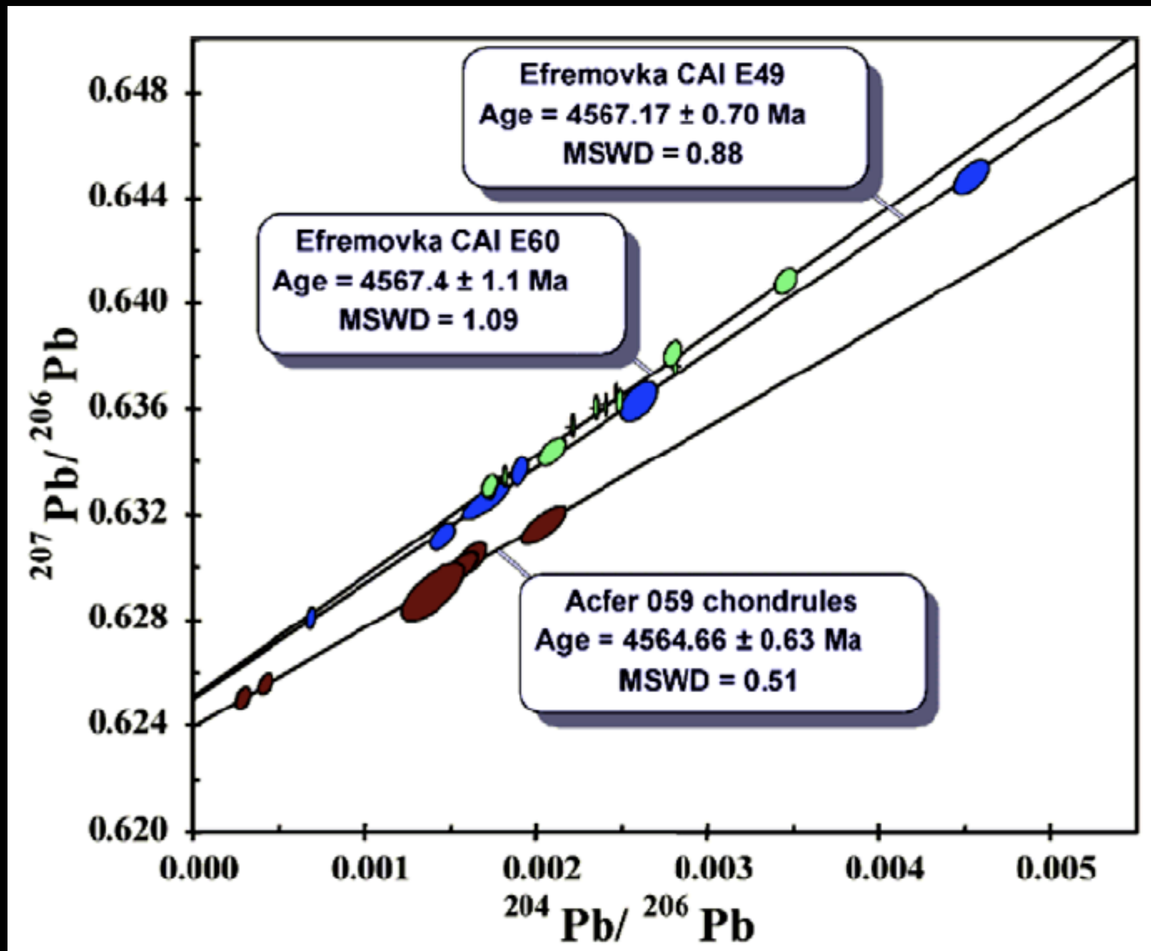


An = anorthite
Cpx = high-Ca pyroxene
Grs = grossite
Hib = hibonite
Mel = melilite
Mes = mesostasis
Met = metal
Ol = olivine
Pv = perovskite
Px = low-Ca pyroxene
Sil = silica
Sp = spinel

I.e., condensation generally preceded igneous reprocessing

Krot et al., 2009

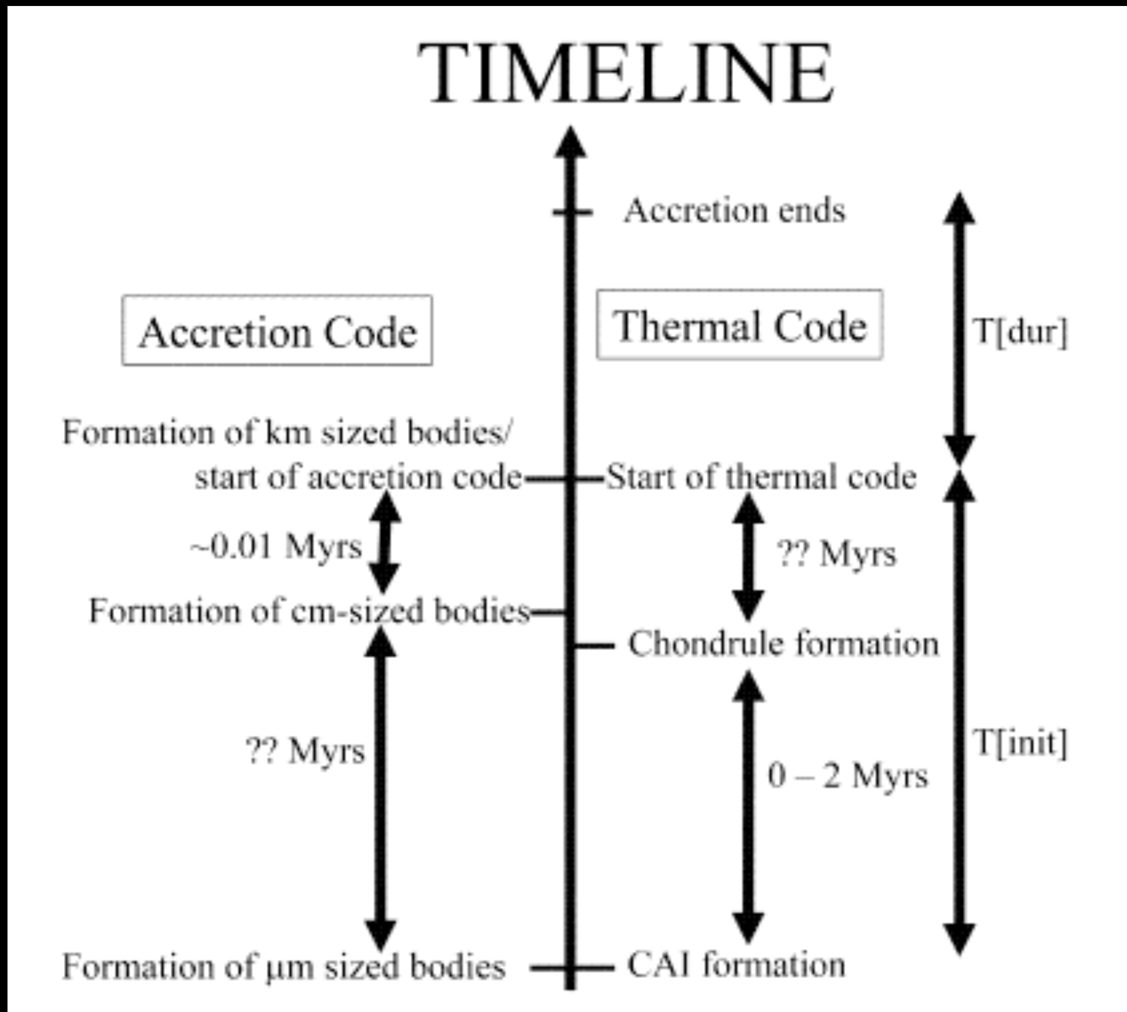
High precision Pb-Pb dating of CAI's and Chondrules



I.e., condensation generally preceded igneous reprocessing, by ~1 Ma

Amelin et al., 2002; Connelly et al., 2008; Krot et al., 2009

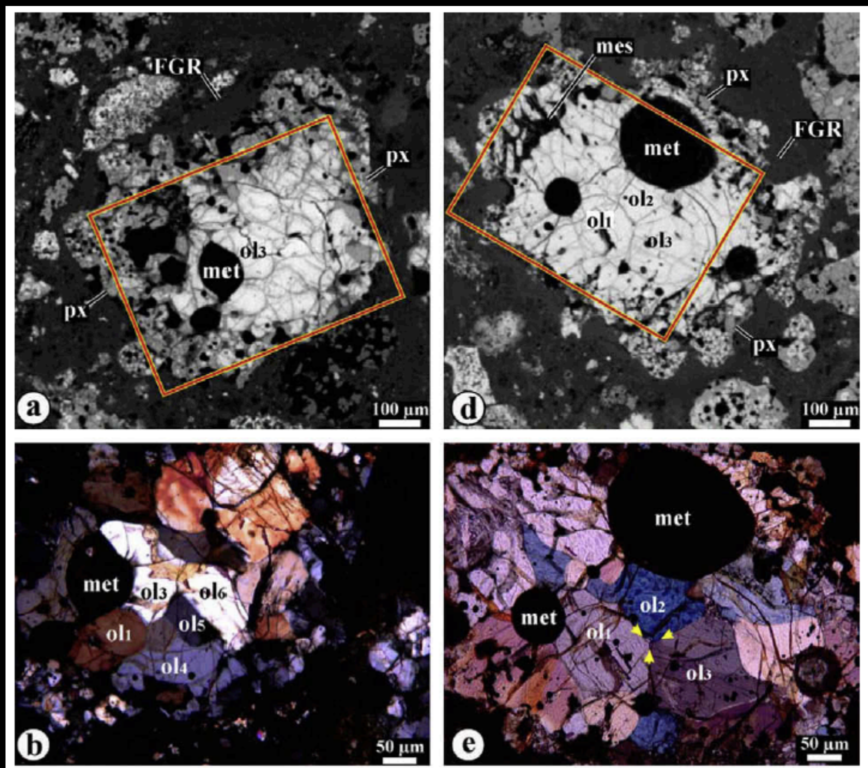
It is sometimes assumed that chondrules preceded accretion of km-scale planetesimals



Seems clearly true in the case of parent bodies of chondrule-rich carbonaceous chondrites

Ghosh, Weidenschilling and McSween, 2003

But some chondrules contain rocky precursors



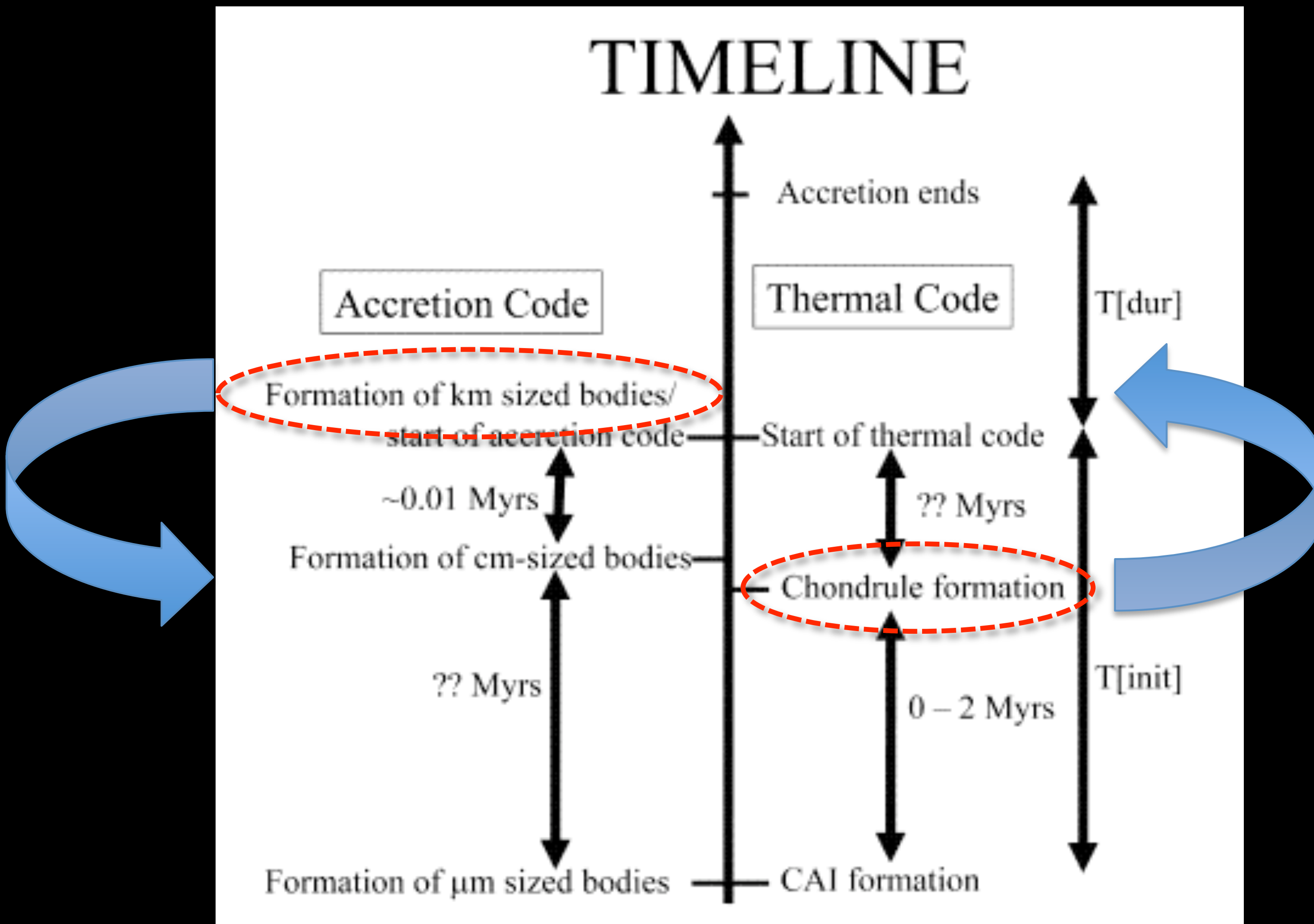
Chondrules in a CV chondrite

Met = metal
Ol = olivine
Px = low-Ca pyroxene

These record recrystallization of igneous or metamorphic rock, likely under some significant pressure

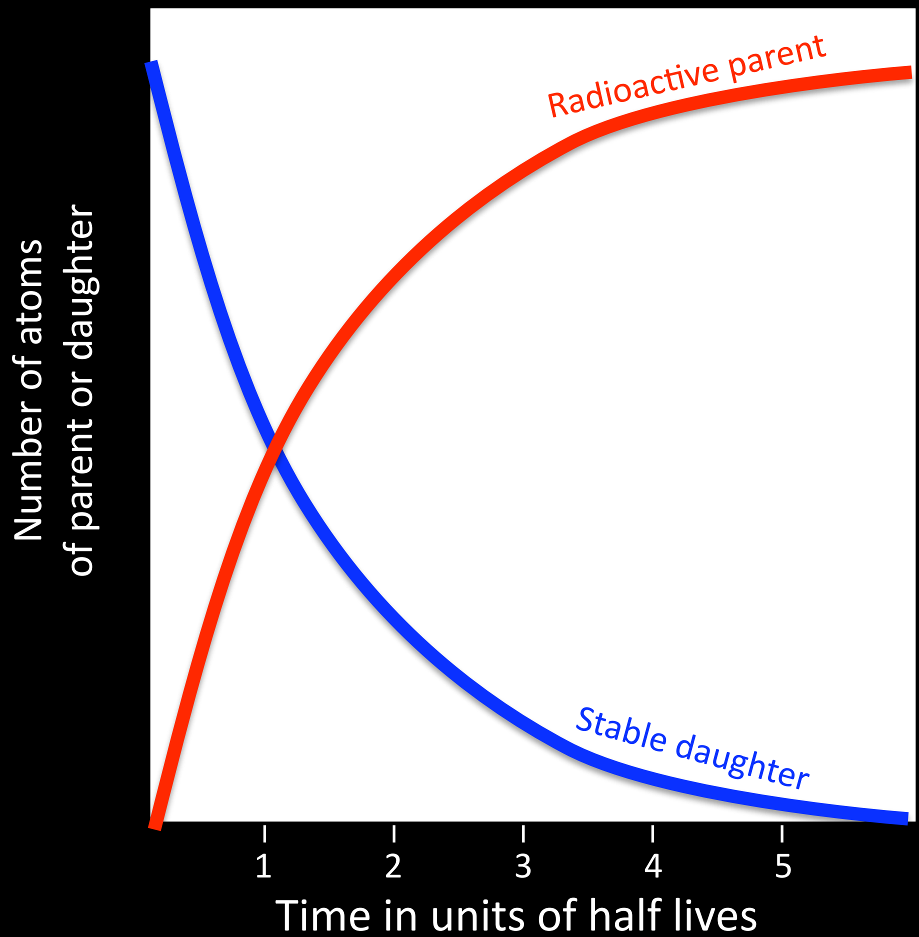
Terrestrial dunnite

Thus at least some planetesimals existed before formation of at least some chondrules



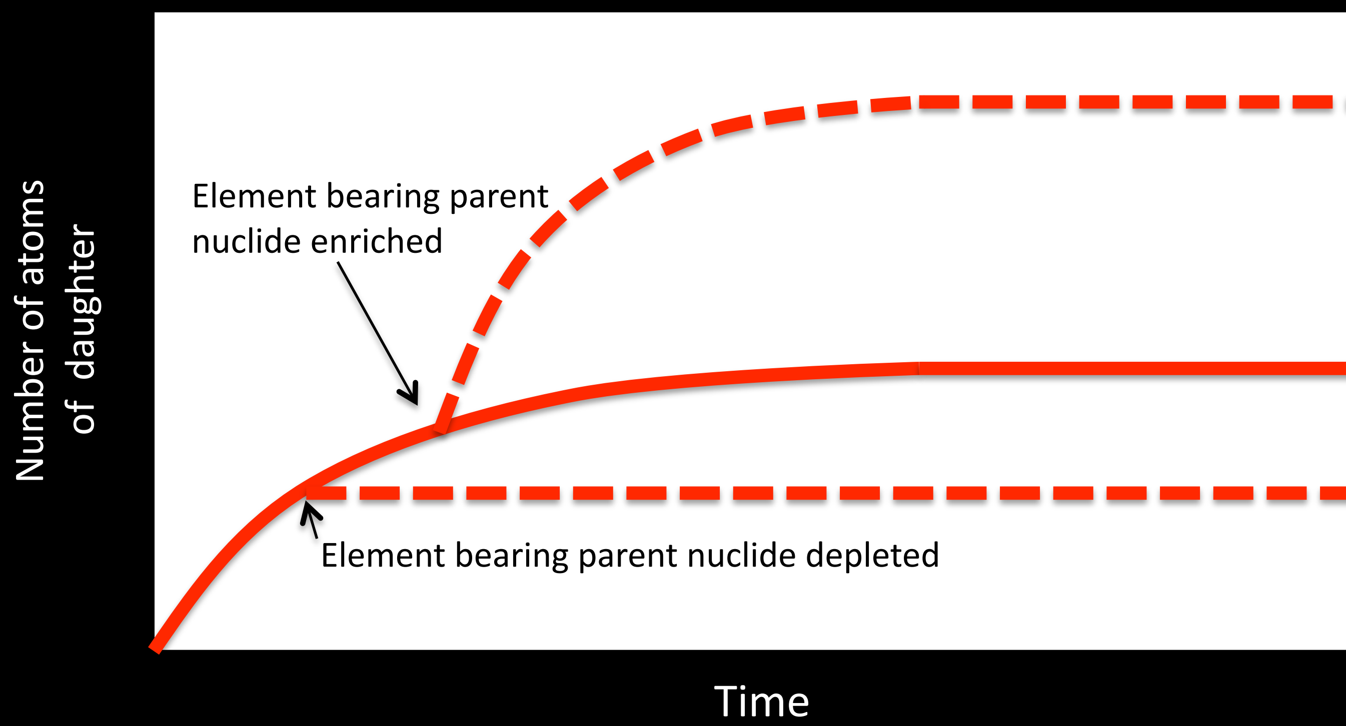
Ghosh, Weidenschilling and McSween, 2003

Short lived radionuclides



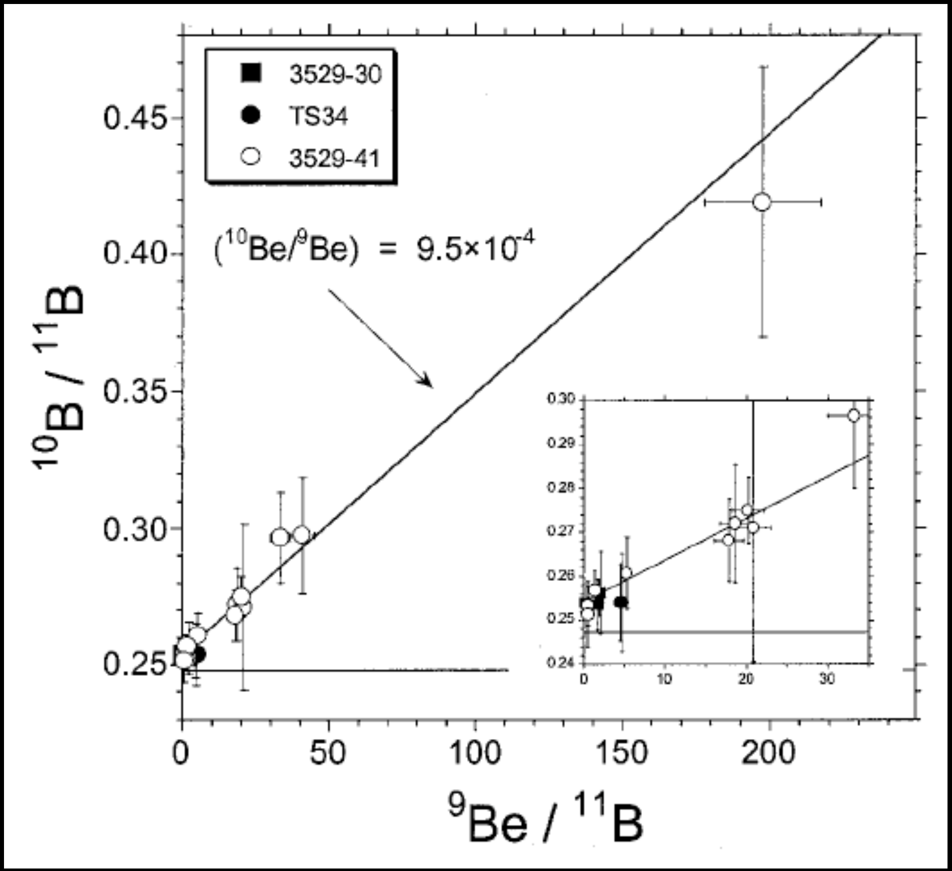
- For half-lives of millions of years or less, the show is long over in all early –
  solar system materials
- All you can measure is the inventory of daughter species accumulated in a sample

Short lived radionuclides



- That inventory can be a time-stamp for chemical differentiation

B and Be in Allende CAI's



- ^{10}Be generated by spallation
- Decays to ^{10}Be, half life = 1.4 My
- Produces anomalies in $^{10}B/^{11}B$ in materials with high Be/B

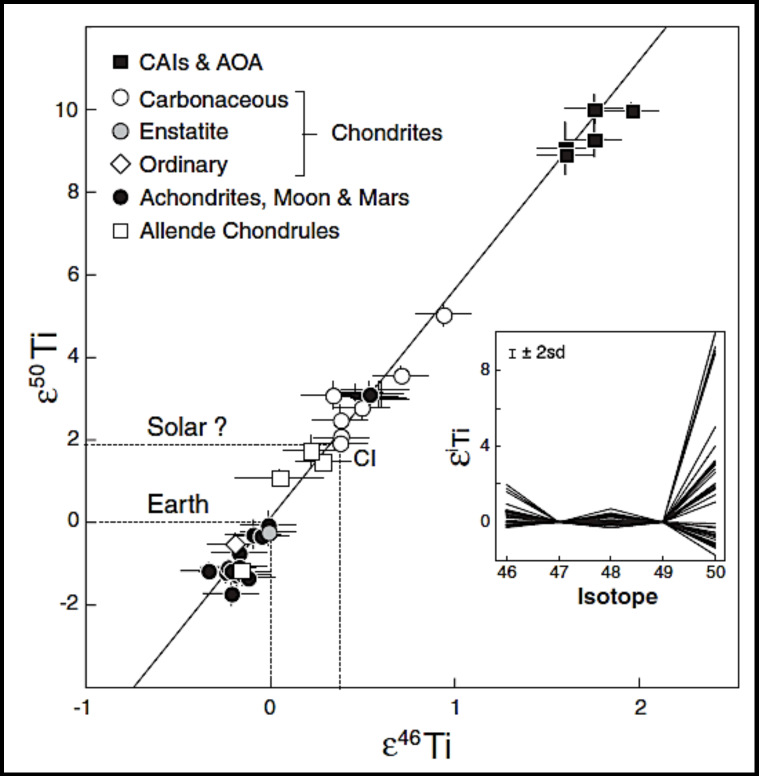
- Implies an irradiated environment at ~0.1 AU broadly resembling inner region of 'X-wind' model
- Similar processes may explain nuclides derived from ^{41}Ca and ^{53}Mn

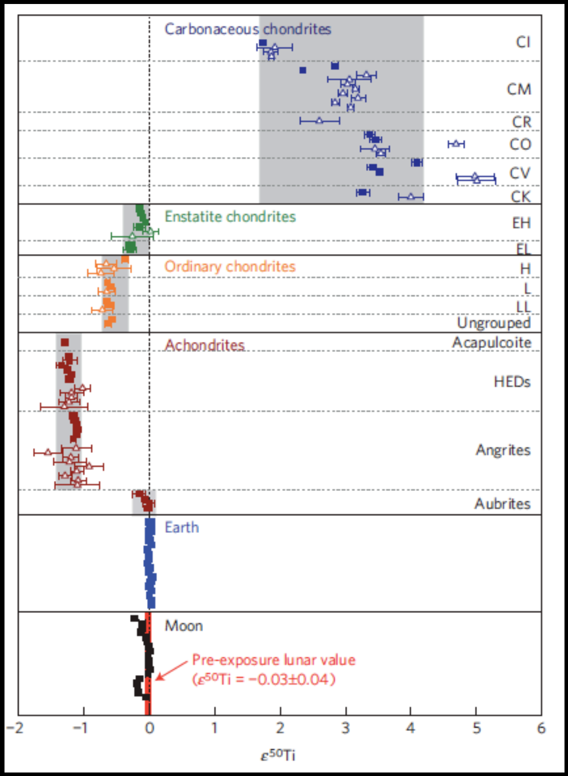
McKeegan et al., 2000

^{50}Ti and ^{46}Ti nucleosynthetic anomalies

A related notion, but isotopes are stable tracers of nucleosynthesis

- Ti is highly refractory and was condensed into the earliest solids in the solar system
- Its isotopic composition was not easily modified during secondary alteration processes.
- Two nuclides with different nucleosynthetic origins

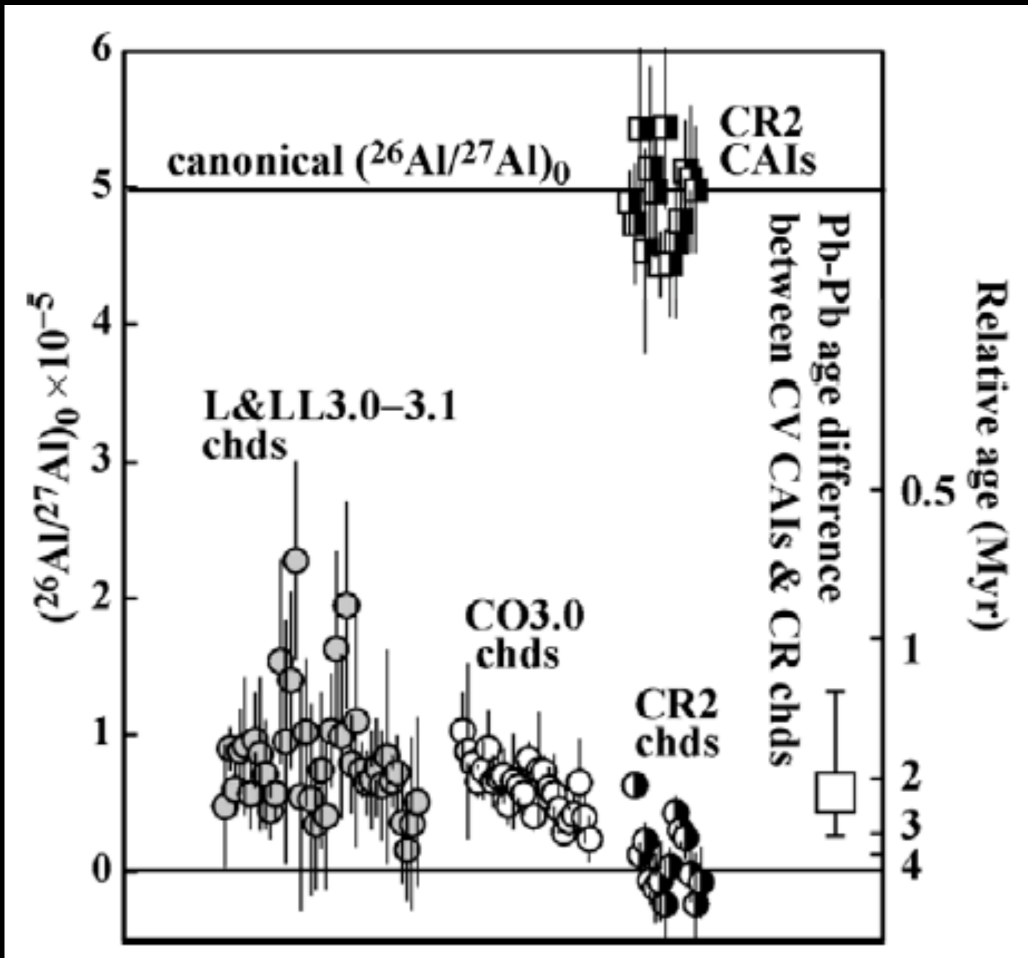




- ^{50}Ti and ^{46}Ti correlate ➔ efficient mixing after nucleosynthesis
- Unevenly distributed today ➔ 'unmixing' by solar system processing

Trinquier et al., 2009; Zhang et al., 2012

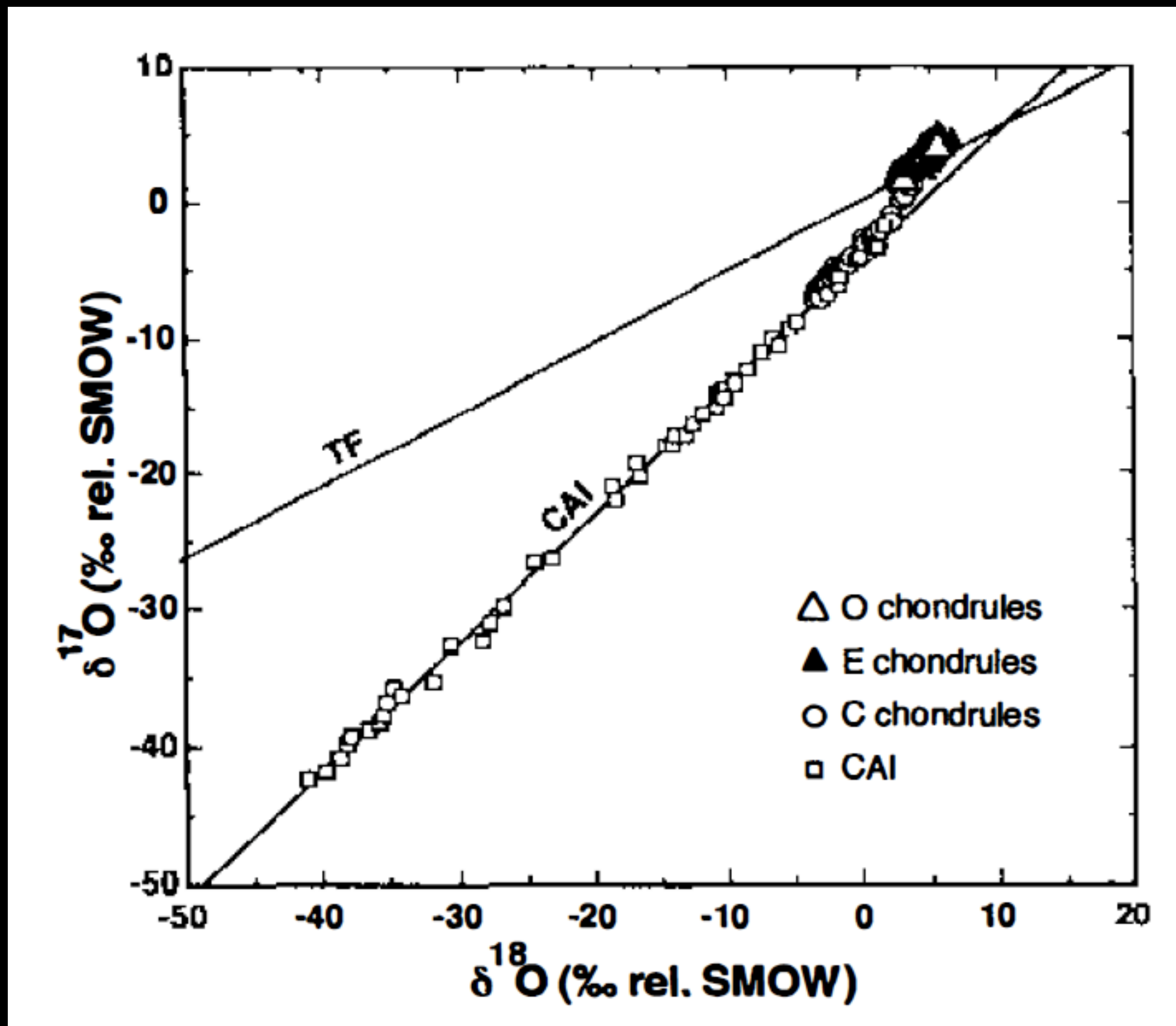
^{26}Al as a chronometer and tracer



- Chronometer assumes ^{26}Al (half life 0.7 Ma) was evenly distributed
- Date by measuring ^{26}Mg accumulated in Al-rich minerals
- But, could be generated in solar system *a la* X-wind models
- Also happens to be an essential heat source for planetesimals

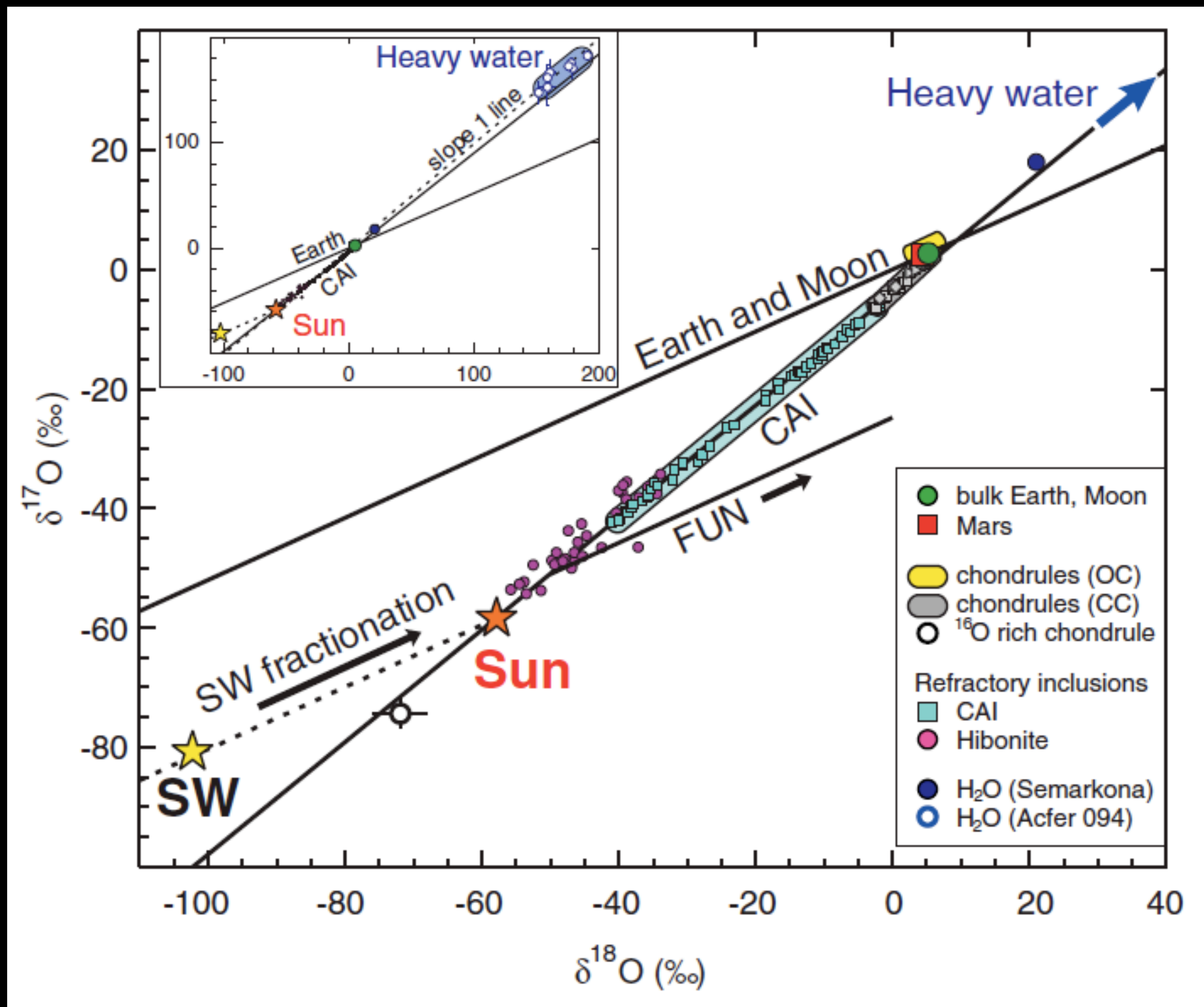
- Chronologies generally consistent and confirm high-precision Pb-Pb dating
- Seems unlikely this could be true unless ^{26}Al was injected as a single 'slug' and then homogenized by very early dynamic mixing

Bulk primitive meteorites do *not* look like the sun in the isotopic composition of their most abundant element (O)



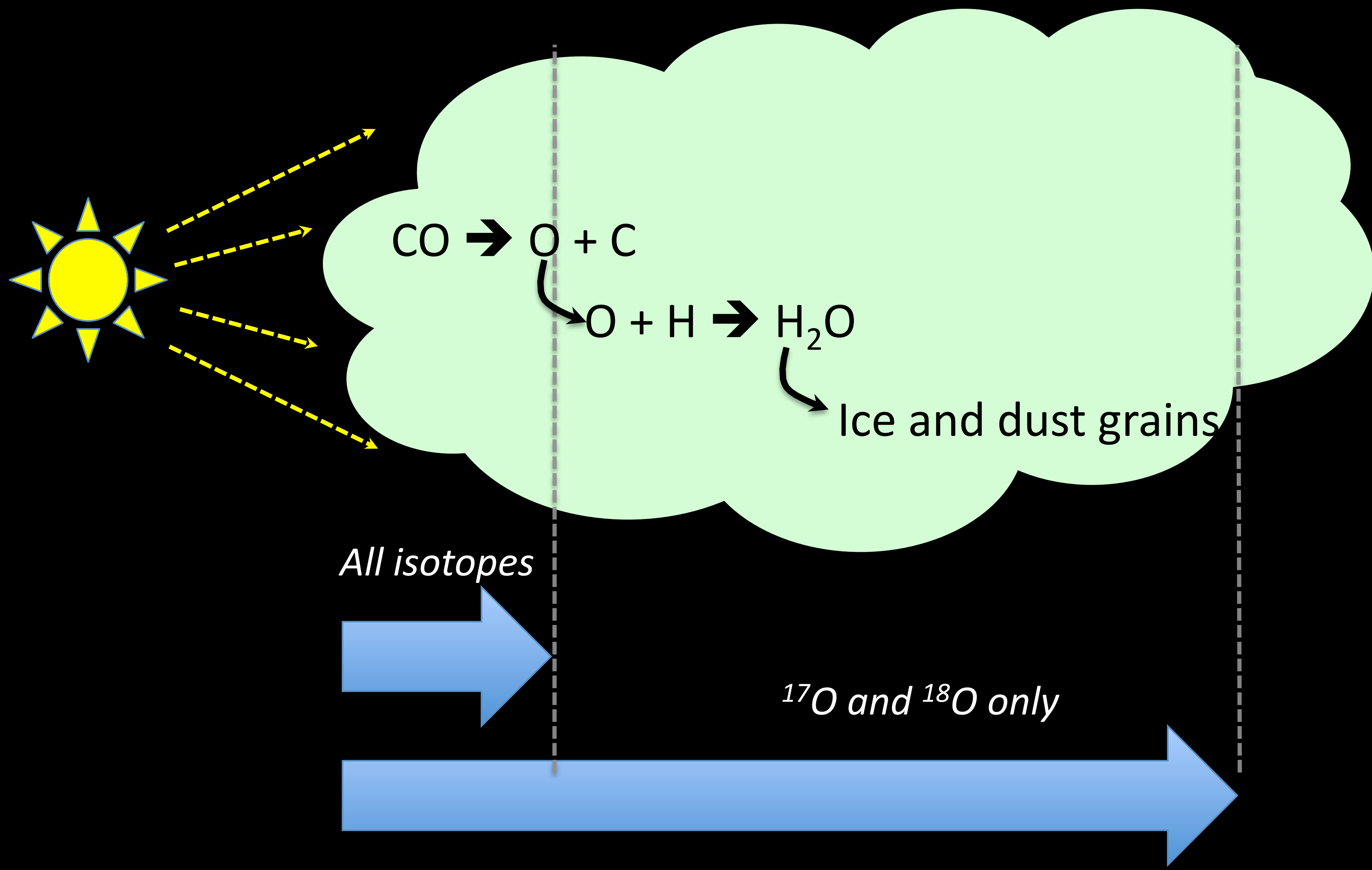
Clayton and Mayeda, 1993

Bulk primitive meteorites lie on a line connecting the sun and water in some primitive meteorites

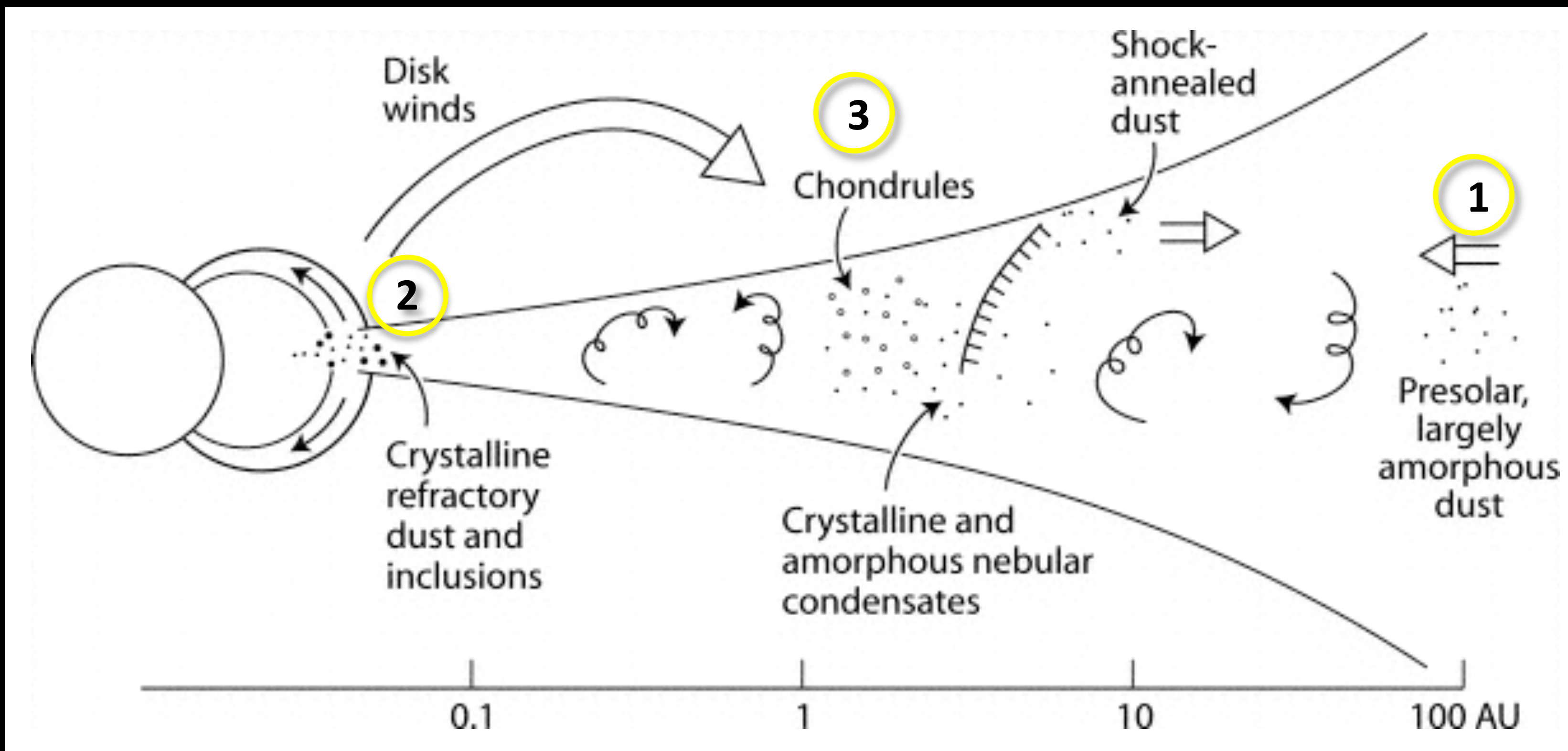


McKeegan et al., 2011

Self shielding: the (currently…) inevitable seeming origin of O isotope anomalies

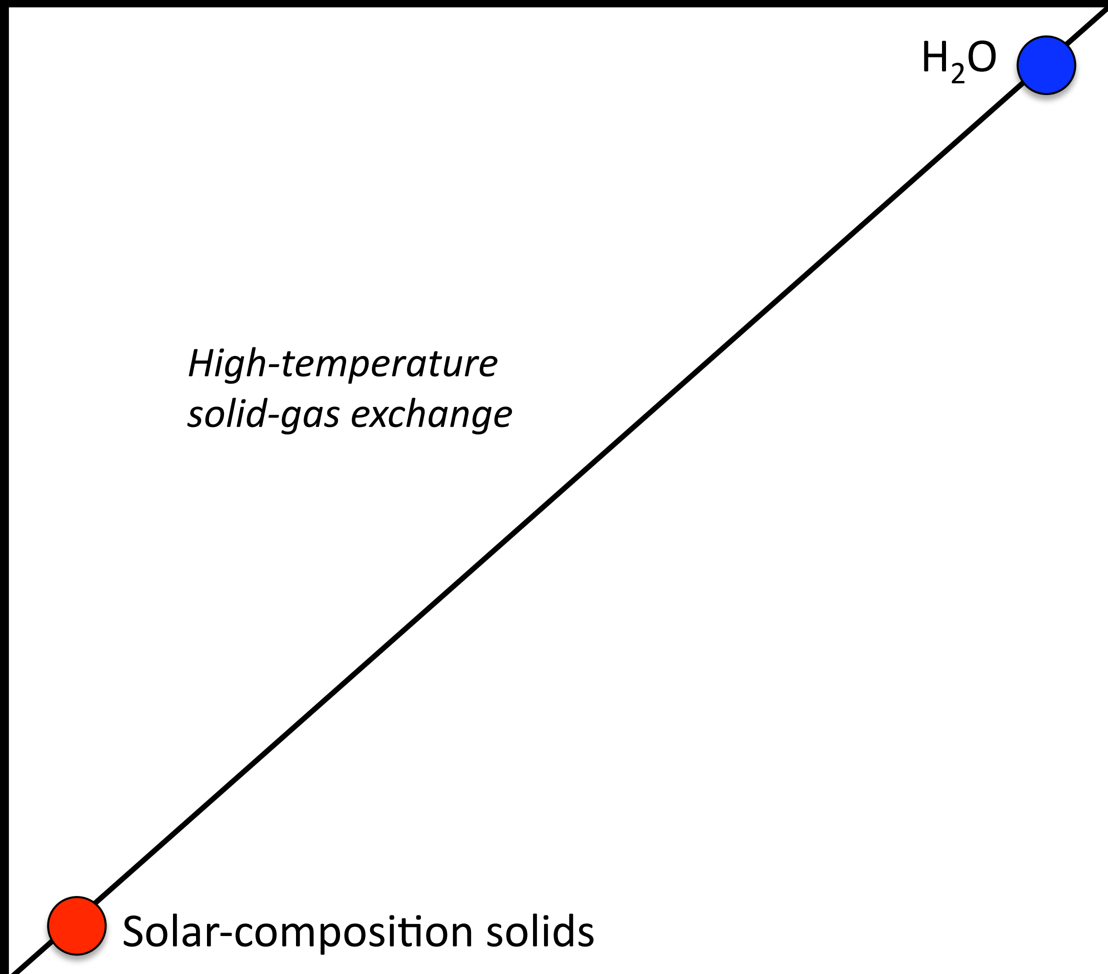


Scenarios for generating the solar-system's ^{16}O-poor water



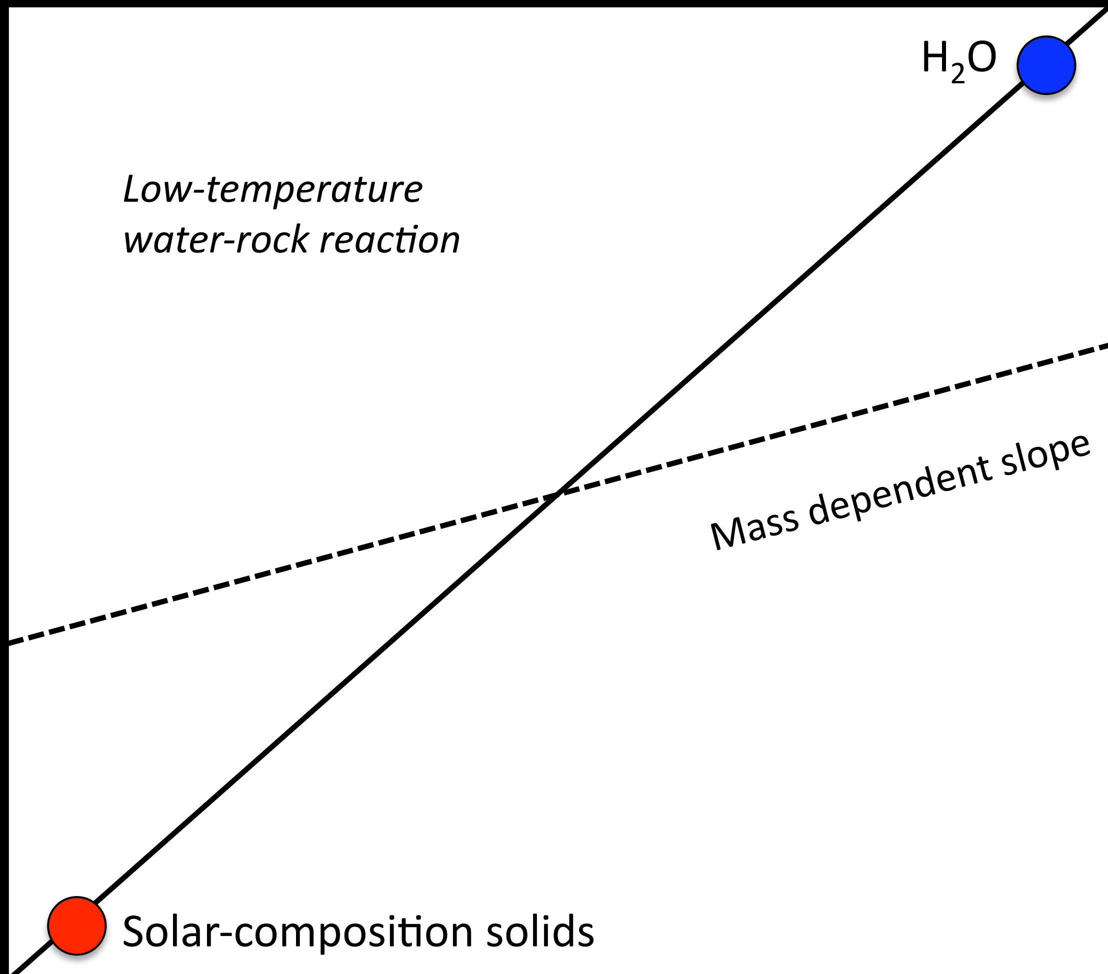
1: Molecular cloud, prior to formation of disk
2: Light from sun, at inner edge of disk
3: Light from nearby star illuminates surface of disk; water-ice particles stir into disk

Ways in which the ^{16}O-poor H_2O can imprint on solids



Note: animated slide

Ways in which the ^{16}O-poor H_2O can imprint on solids

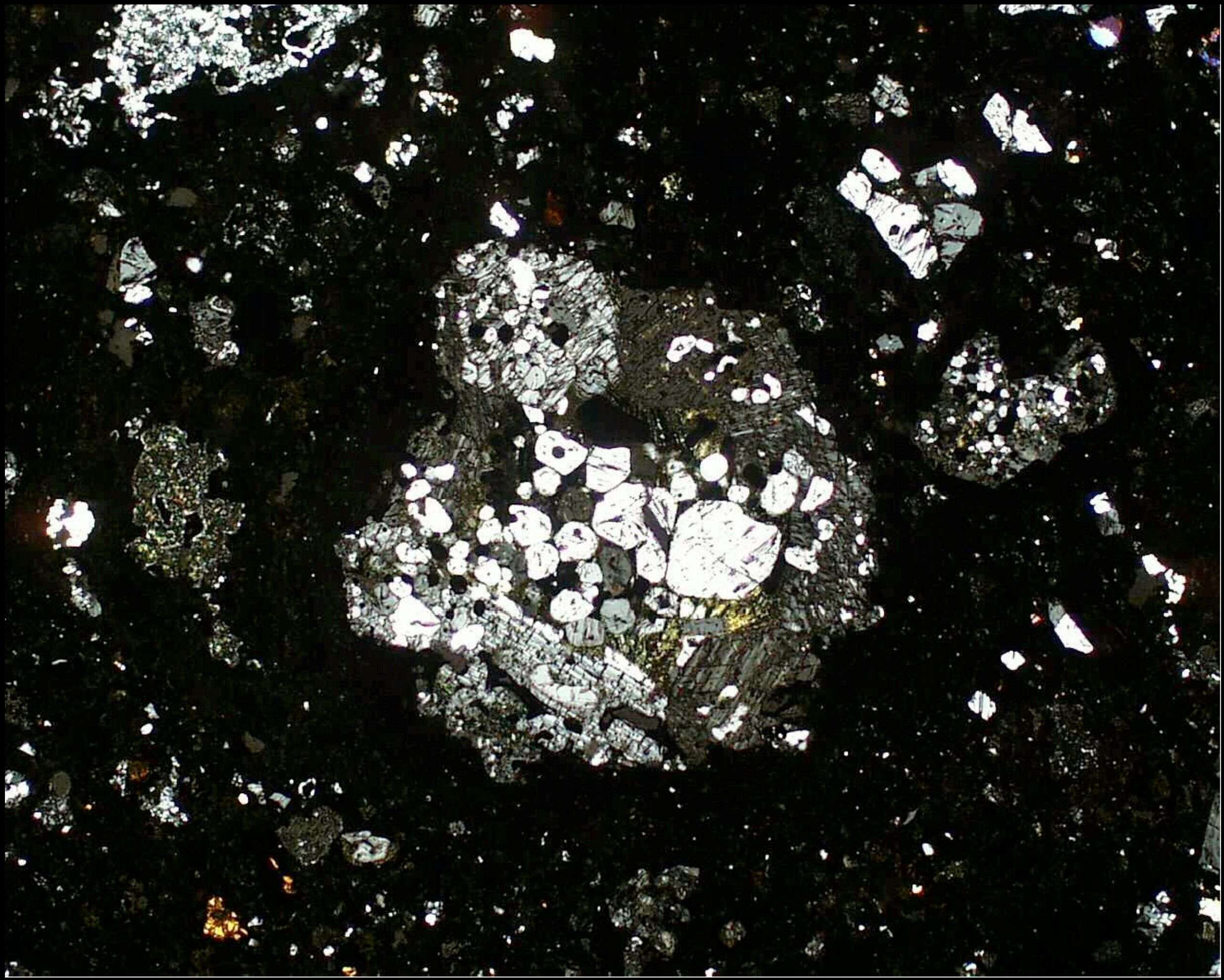


Note: animated slide

The volatile-rich carbonaceous chondrites

Murchison; field of view ca. 2 cm

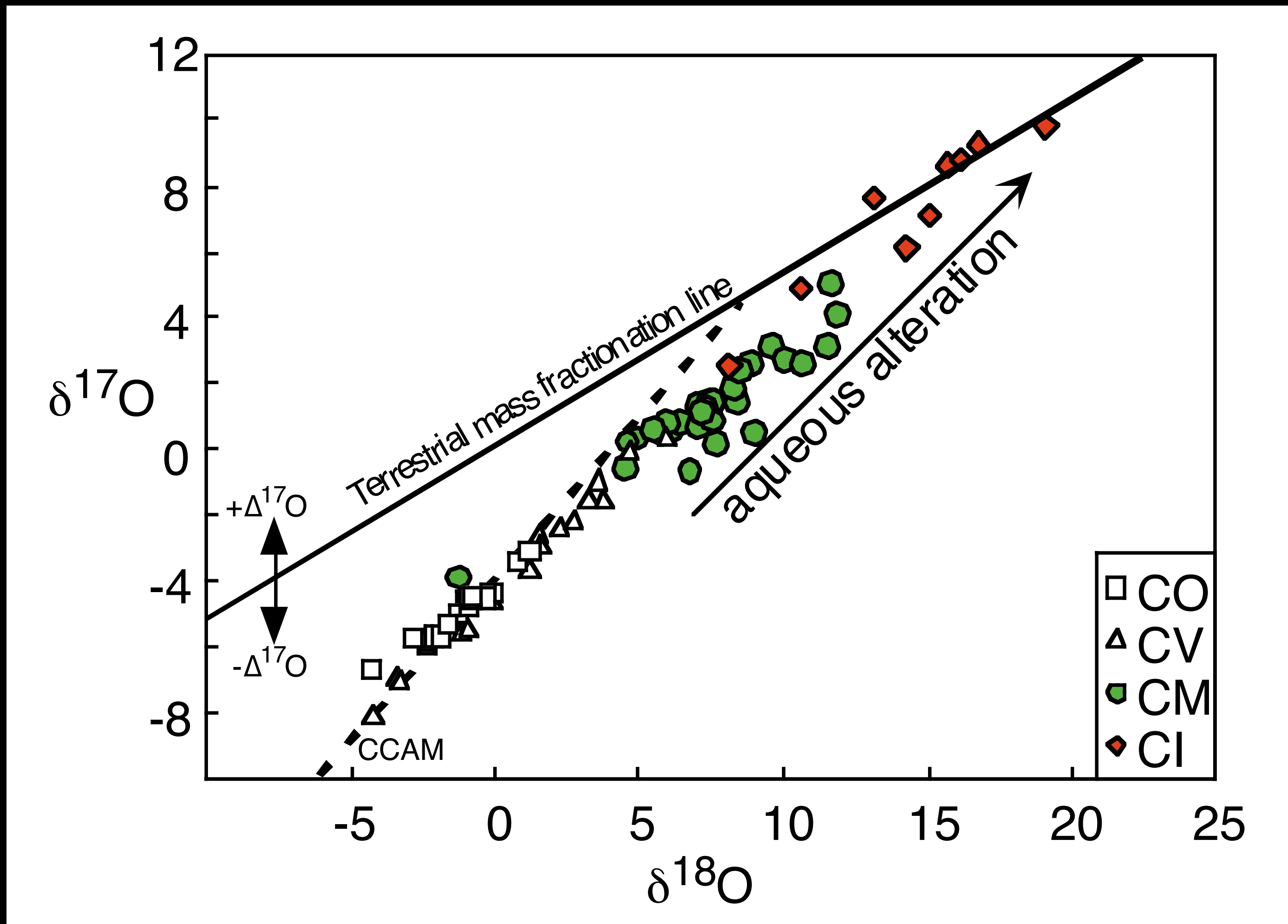
The volatile-rich carbonaceous chondrites



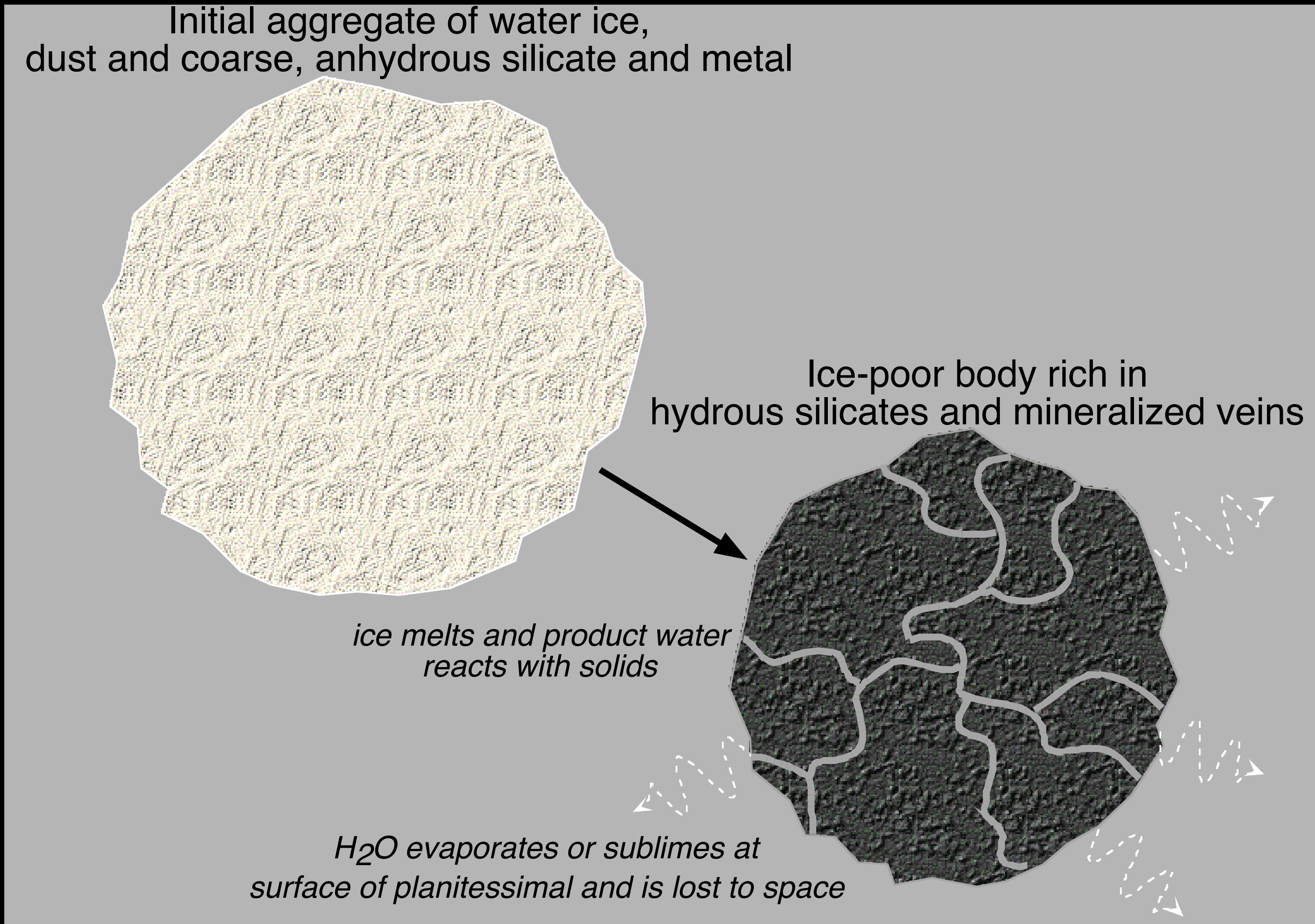
Murchison; field of view ca. 2 mm

Photomicrograph courtesy of A. Brearley

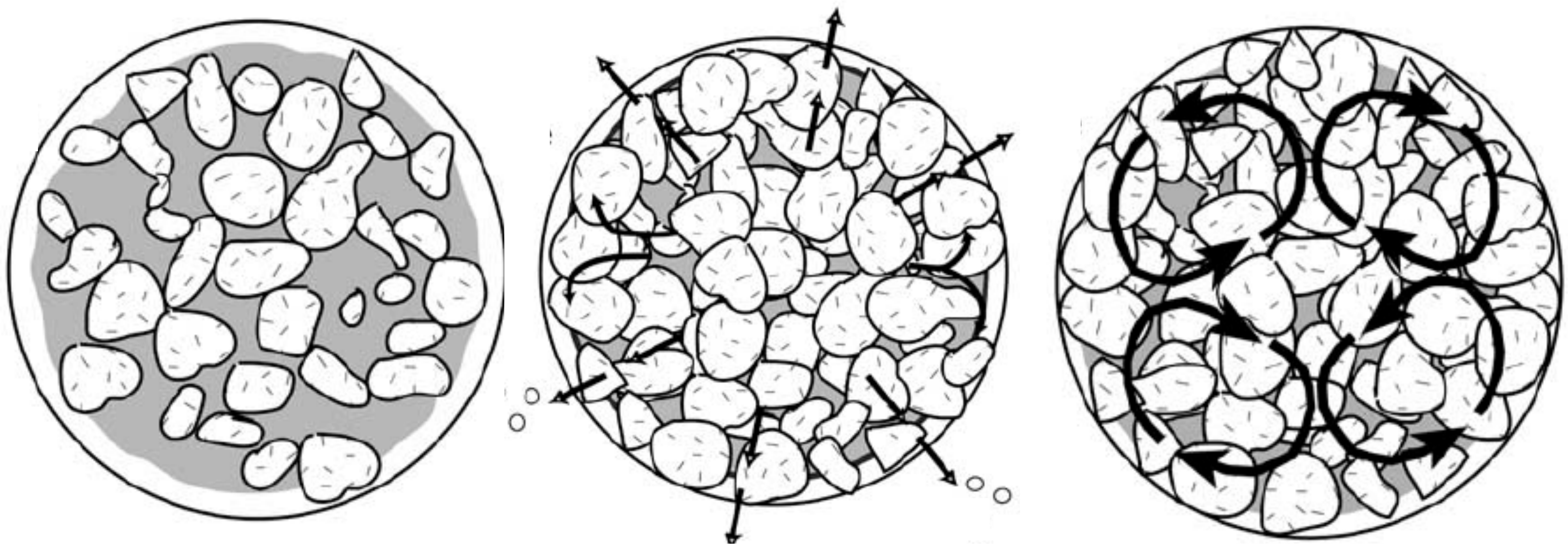
The volatile-rich carbonaceous chondrites



A conceptual model for the secondary origins of volatiles in asteroidal bodies



The seemingly plausible alternatives for the structure and evolution of volatile-rich planetesimals



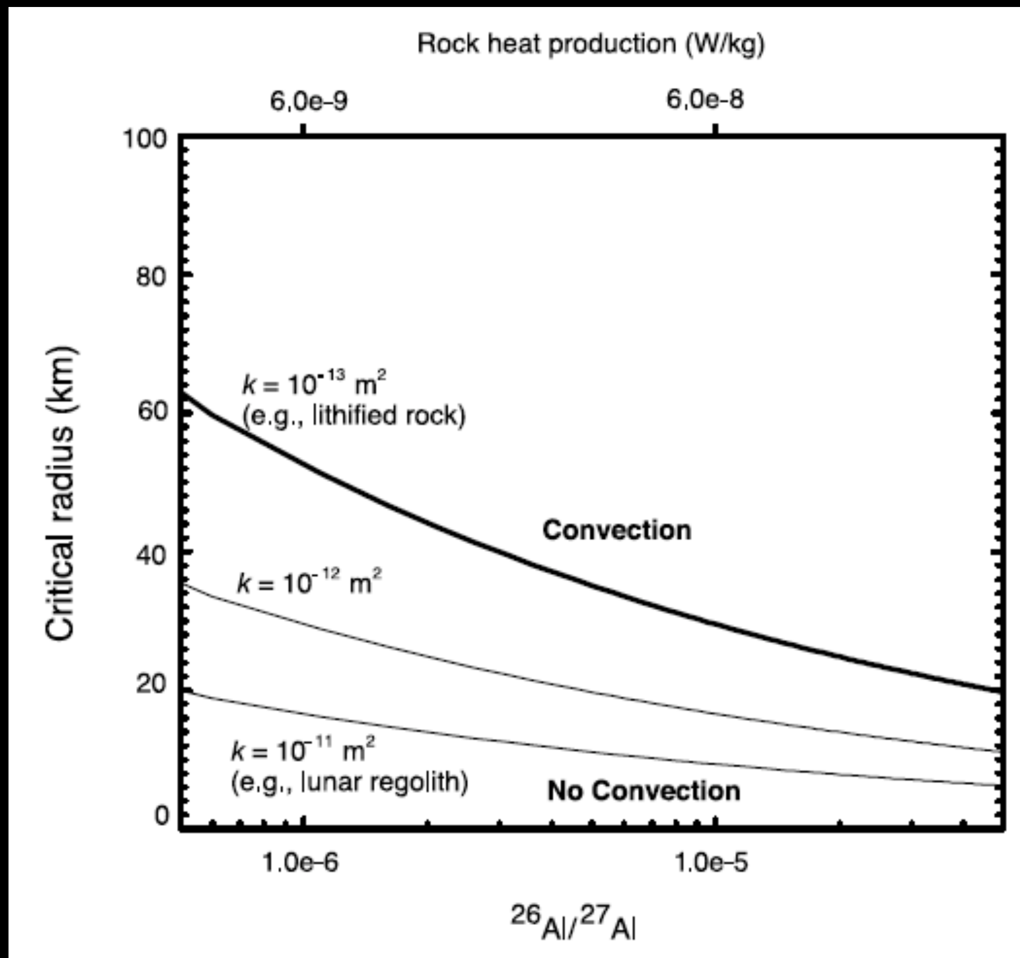
I. Static water II. Water exhalation III. Convection

Small bodies Large bodies

Fast cooling < 20-50 km< *Prolonged cooling*

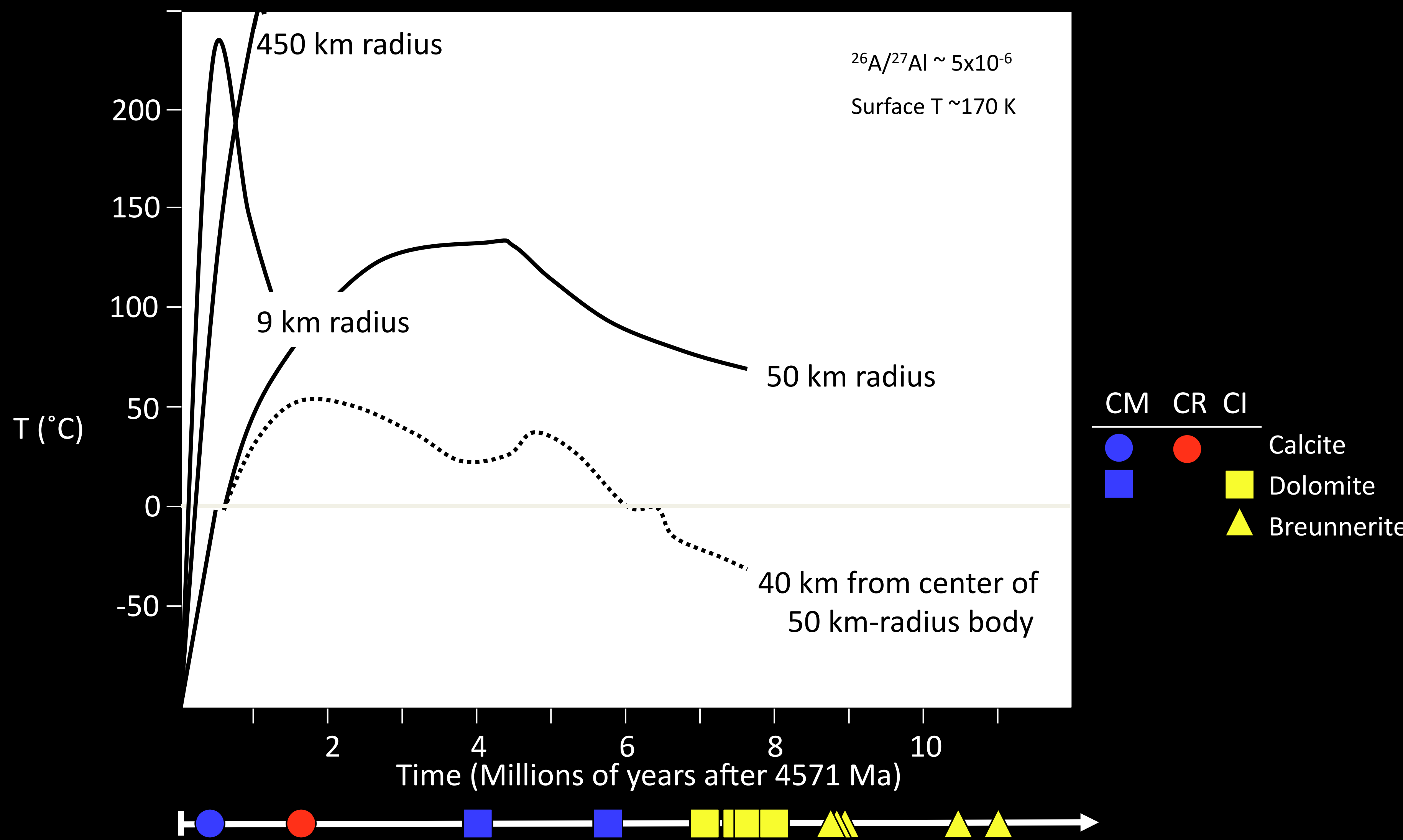
After Young et al. 2003

Potential dynamical significance of recognizing convective water/rock reaction



Young et al., 2003

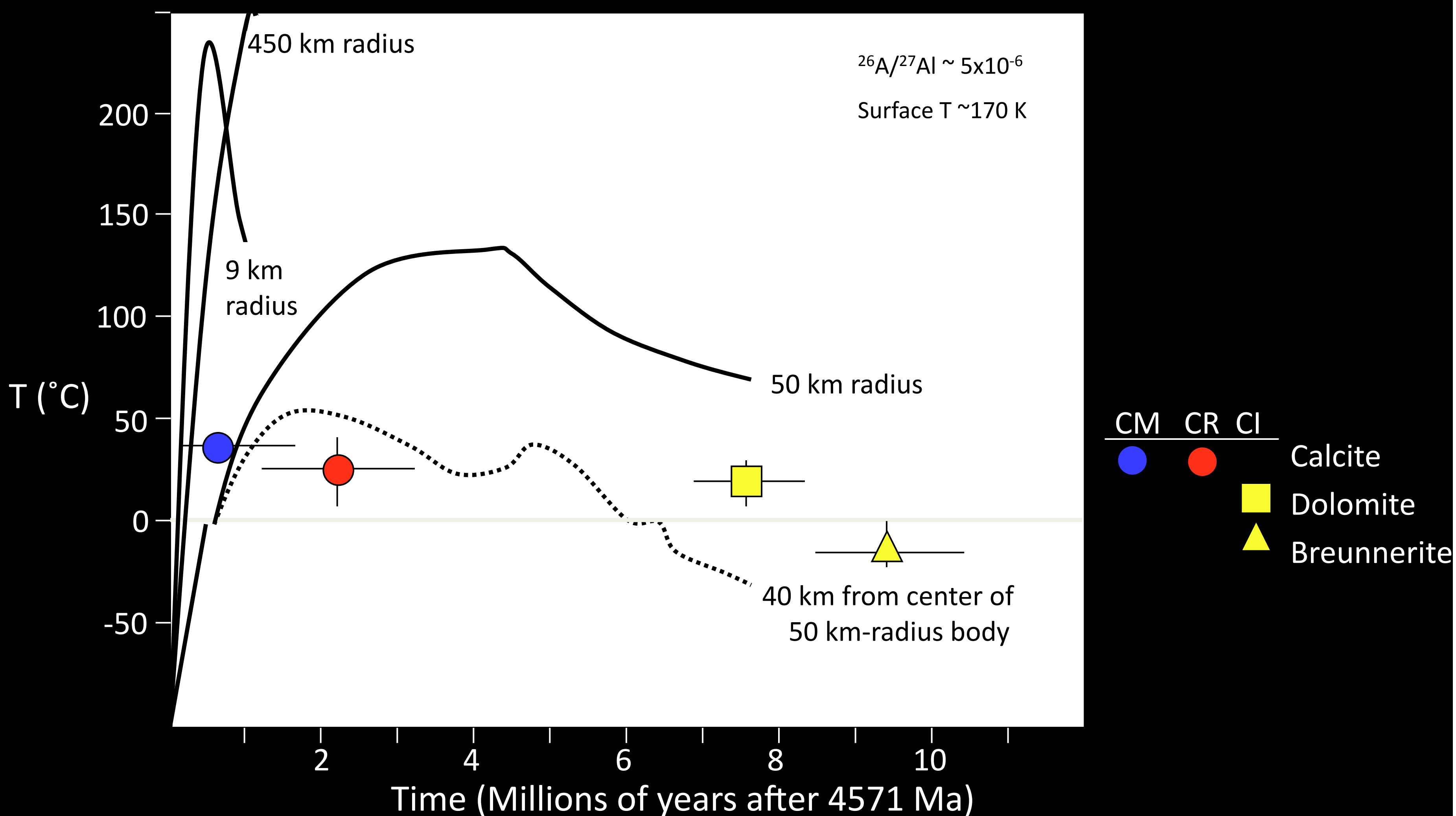
An expected range of thermal histories



Model of Travis and Schubert, 2005 and Young et al., 2003; data from Hutcheon,1999; Brearley, 2000, 2001;Hoppe, 2004

The carbonaceous chondrites come from the 'goldilocks' planetesimals

Big enough to stay cool by convection early; small enough to loose heat by radiation



Models from Young et al., 2003 and Travis and Schubert, 2005; T data from Guo, 2008

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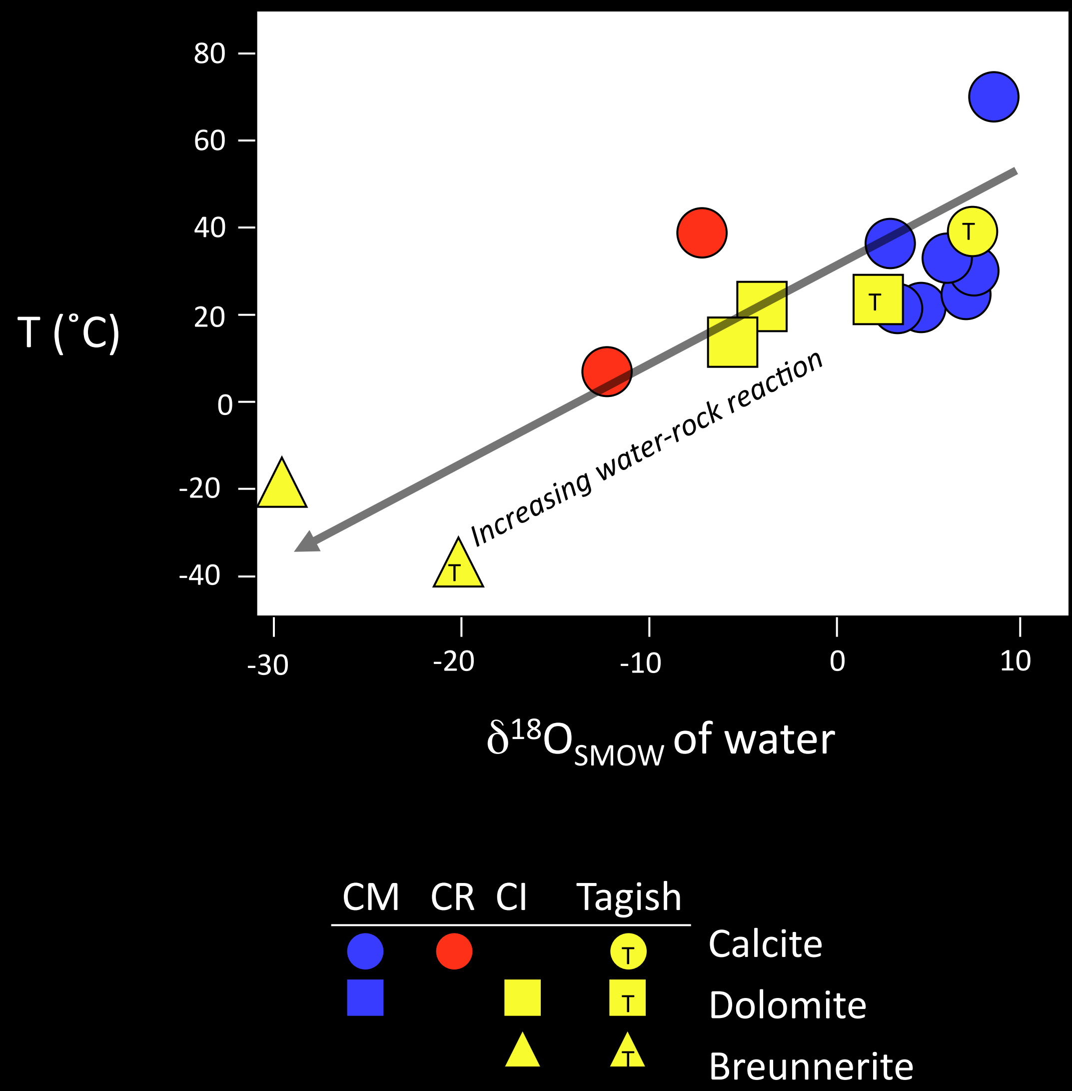
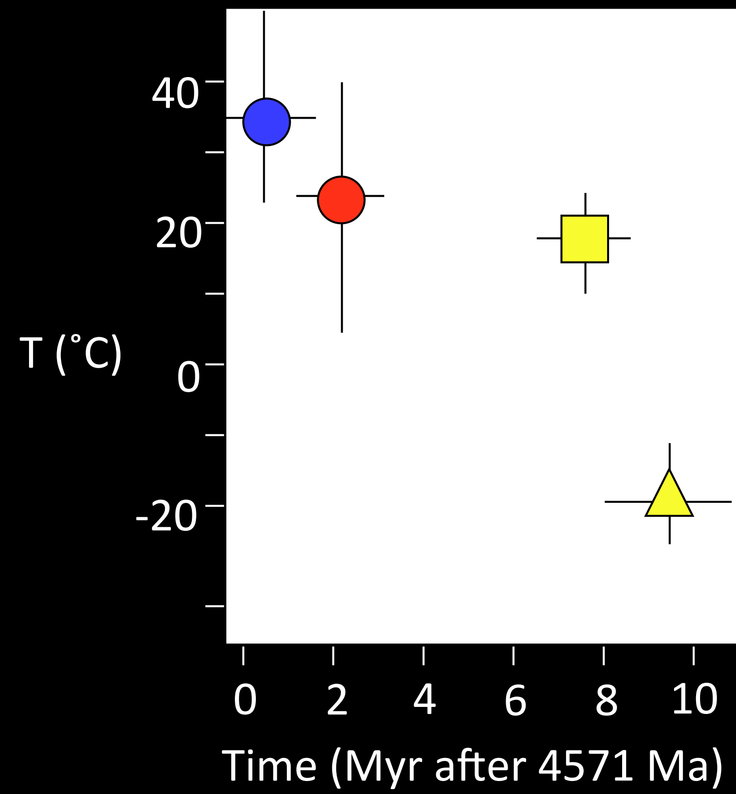
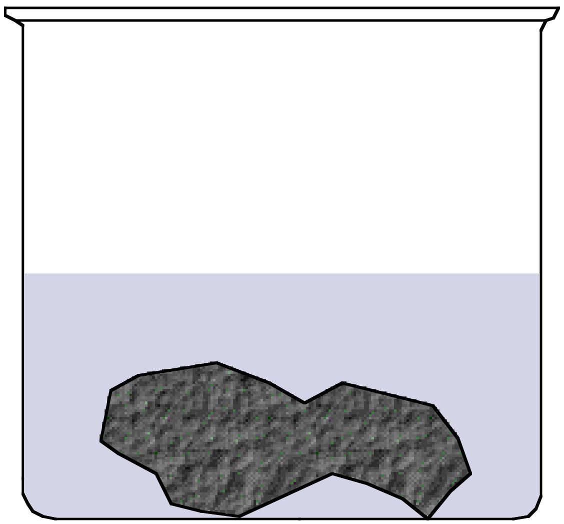




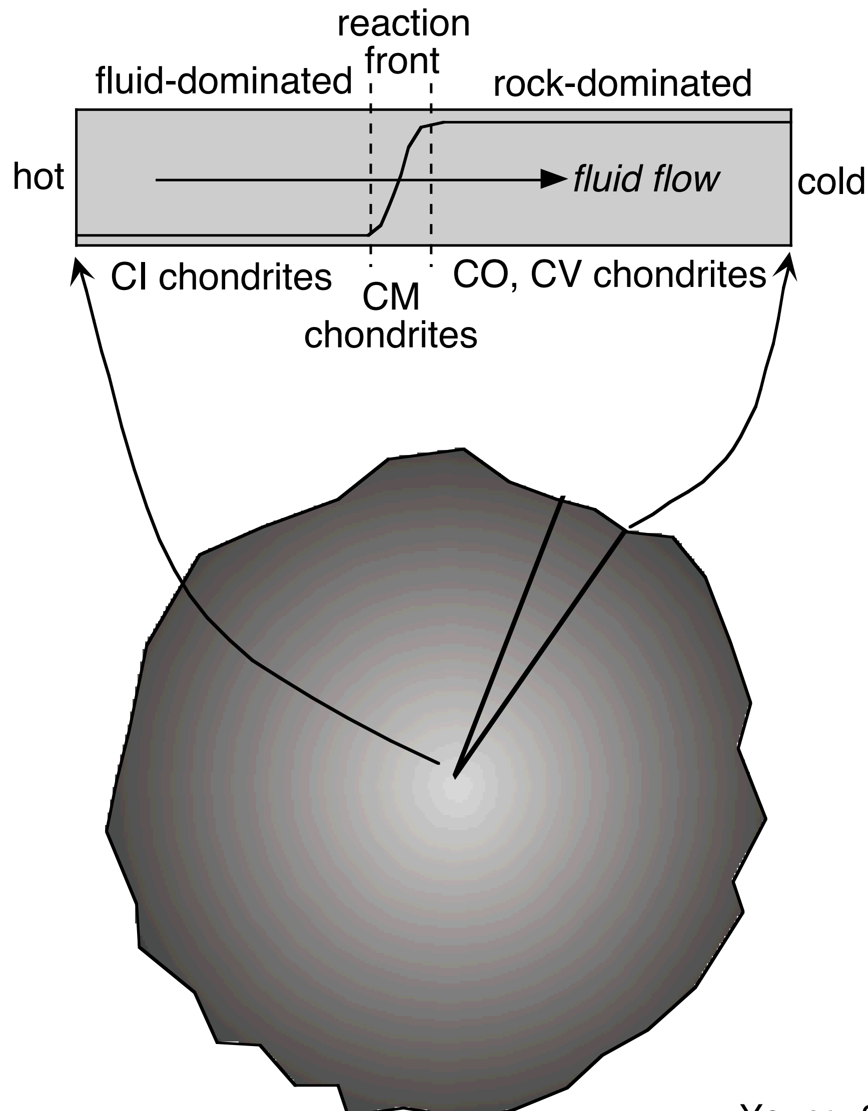
Quantitative models of asteroidal aqueous alteration

Rock in a jar



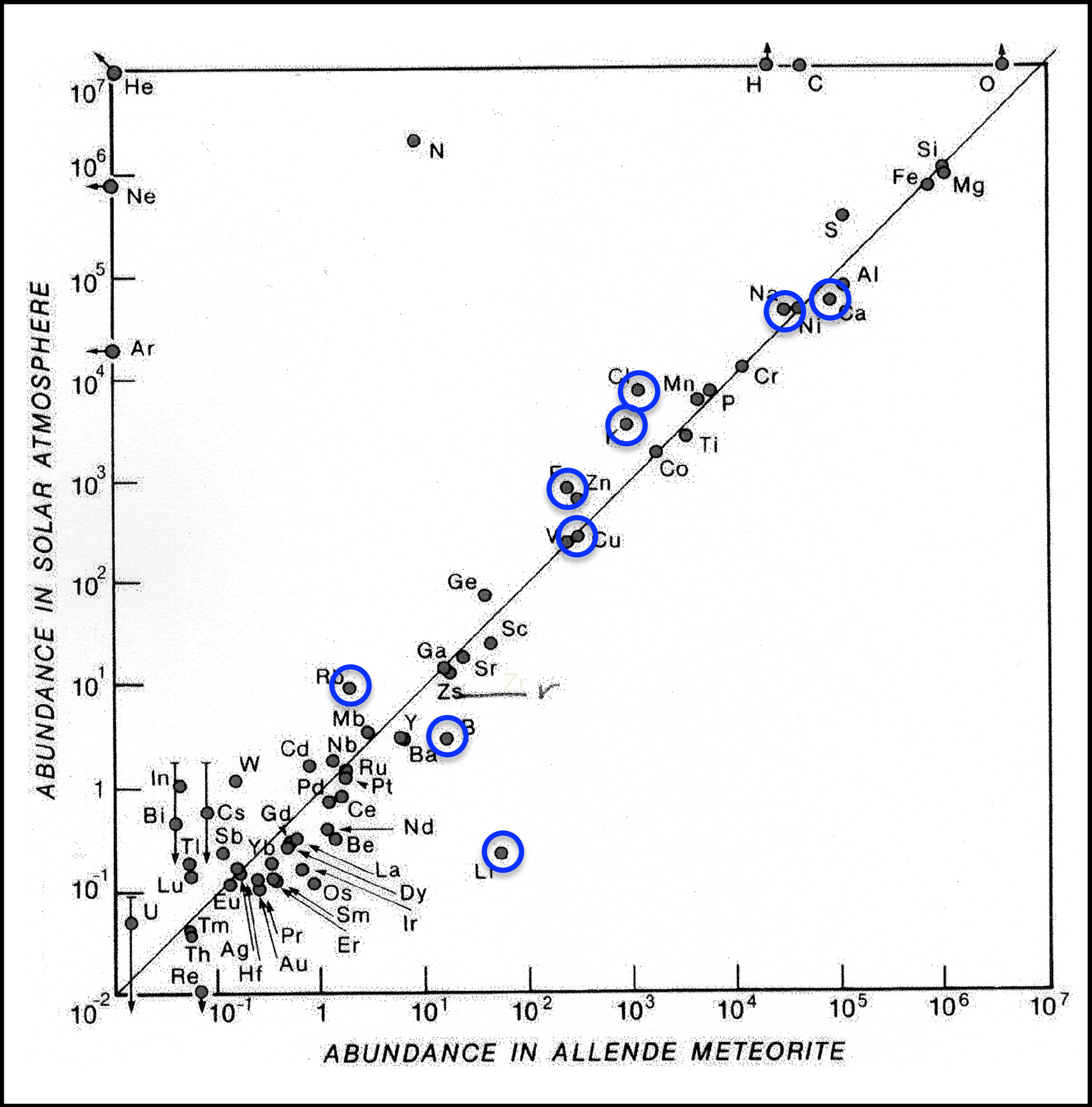
Clayton and Mayeda, 1984; 1999

Soup-to-nuts



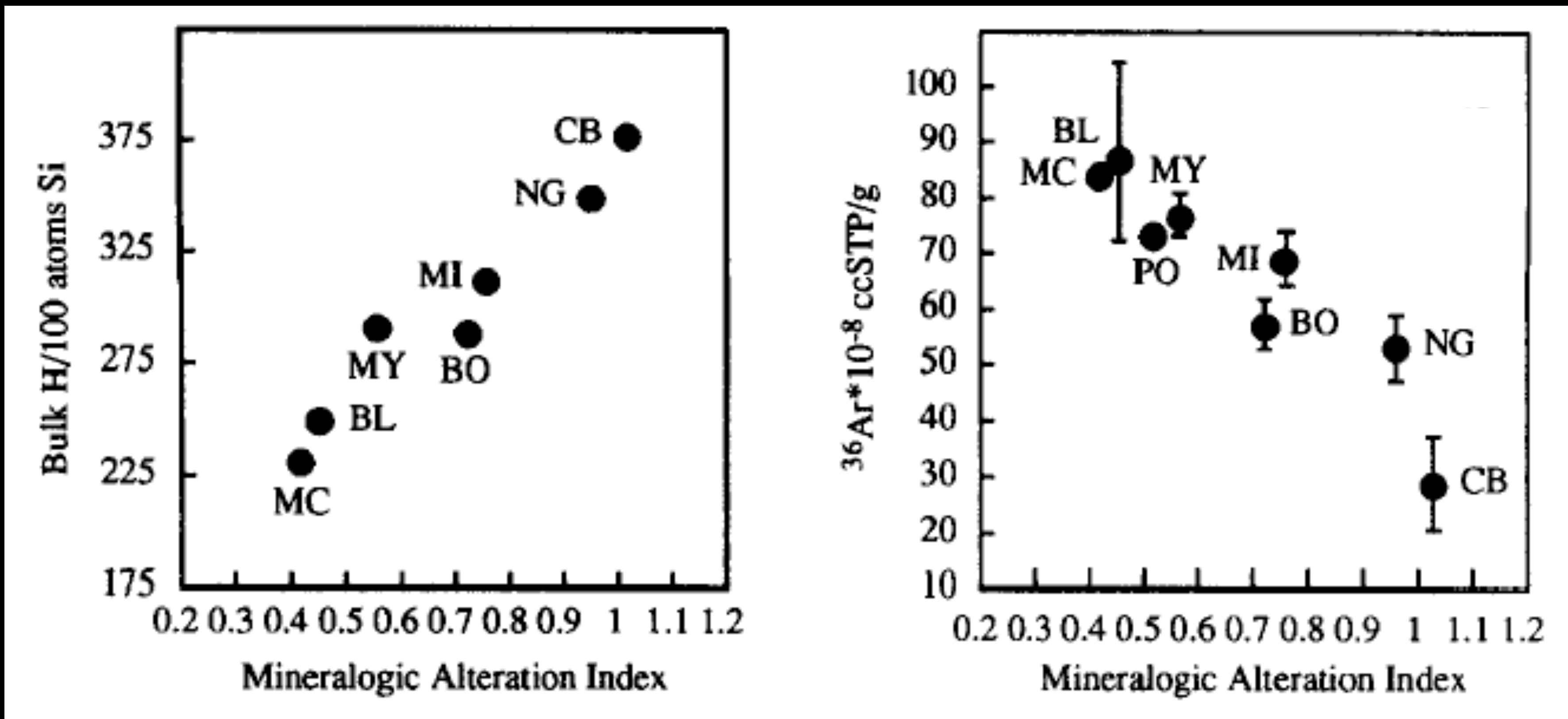
Young, 2000

Can we recognize fluid flow systems in the major element chemistry of chondritic materials?



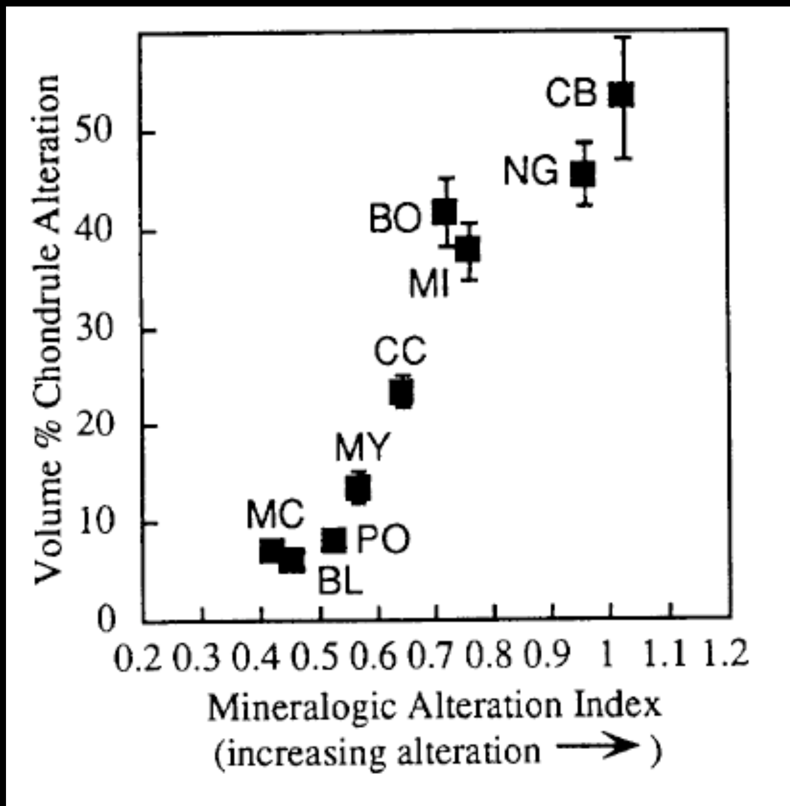
Elements subject to distinctive enrichments or depletions in fluid flow systems

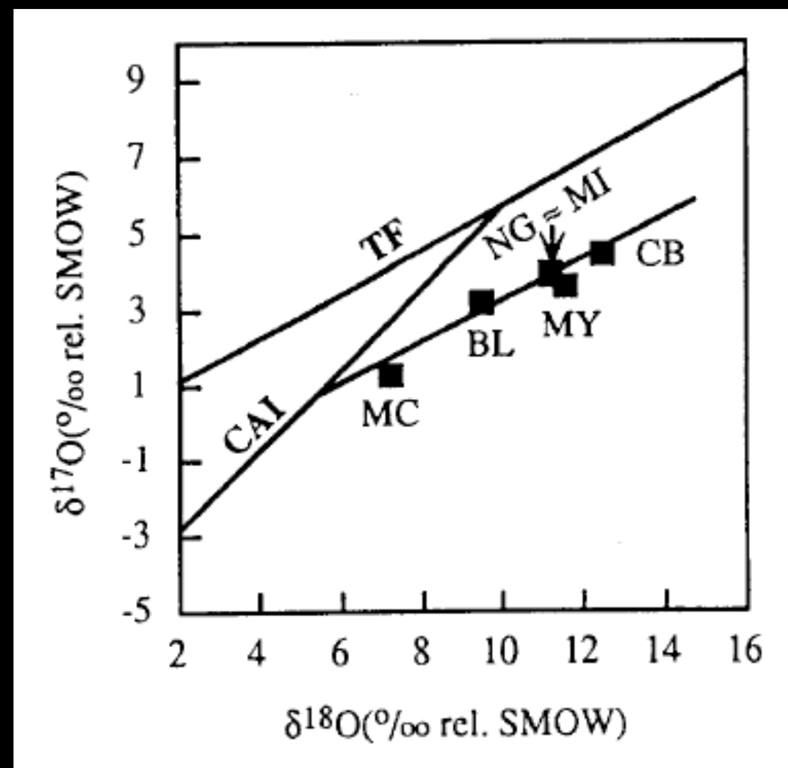
There are clearly systematic 'signals' of water-rock reaction in the elemental abundances of chondrites



Browning et al., 1996

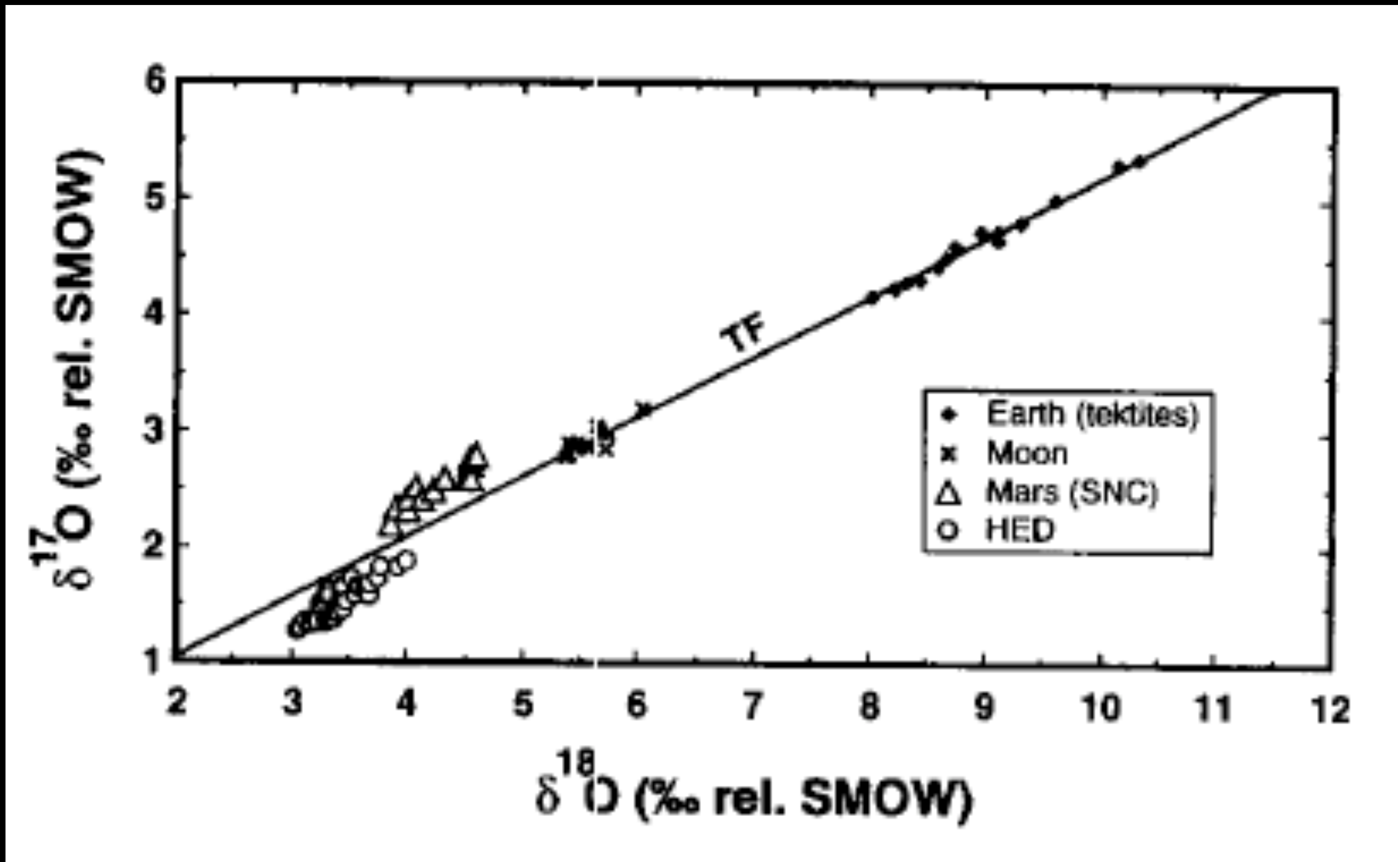
Can we connect simple visual observations to these sorts of geochemical and physical arguments?





Browning et al., 1996

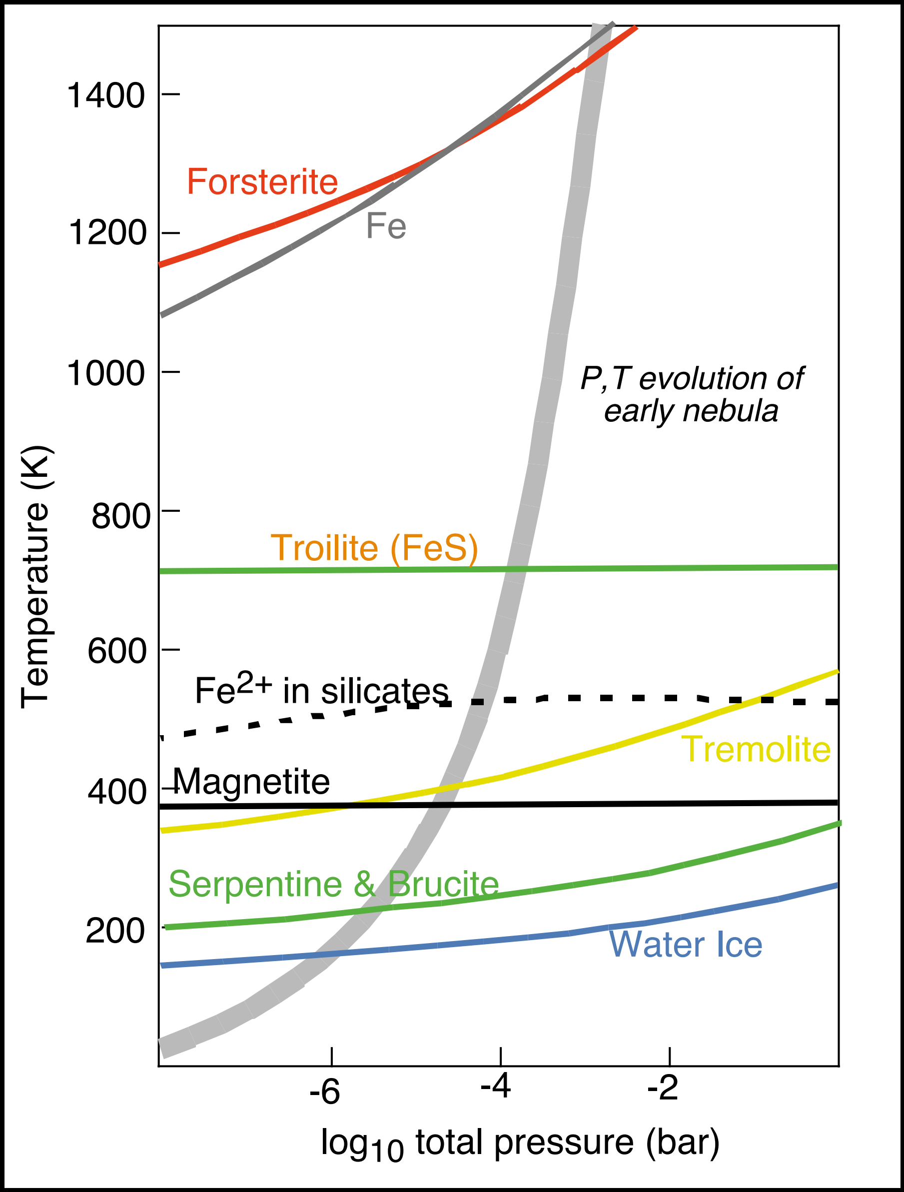
What should we make of subtle differences in ^{16}O depletion between planetary-scale bodies?



- Presumably reflects weighted average H_2O/silicate ratio of 'feeding zone'
- No really meaningful predictions (yet) of spatial/temporal gradients

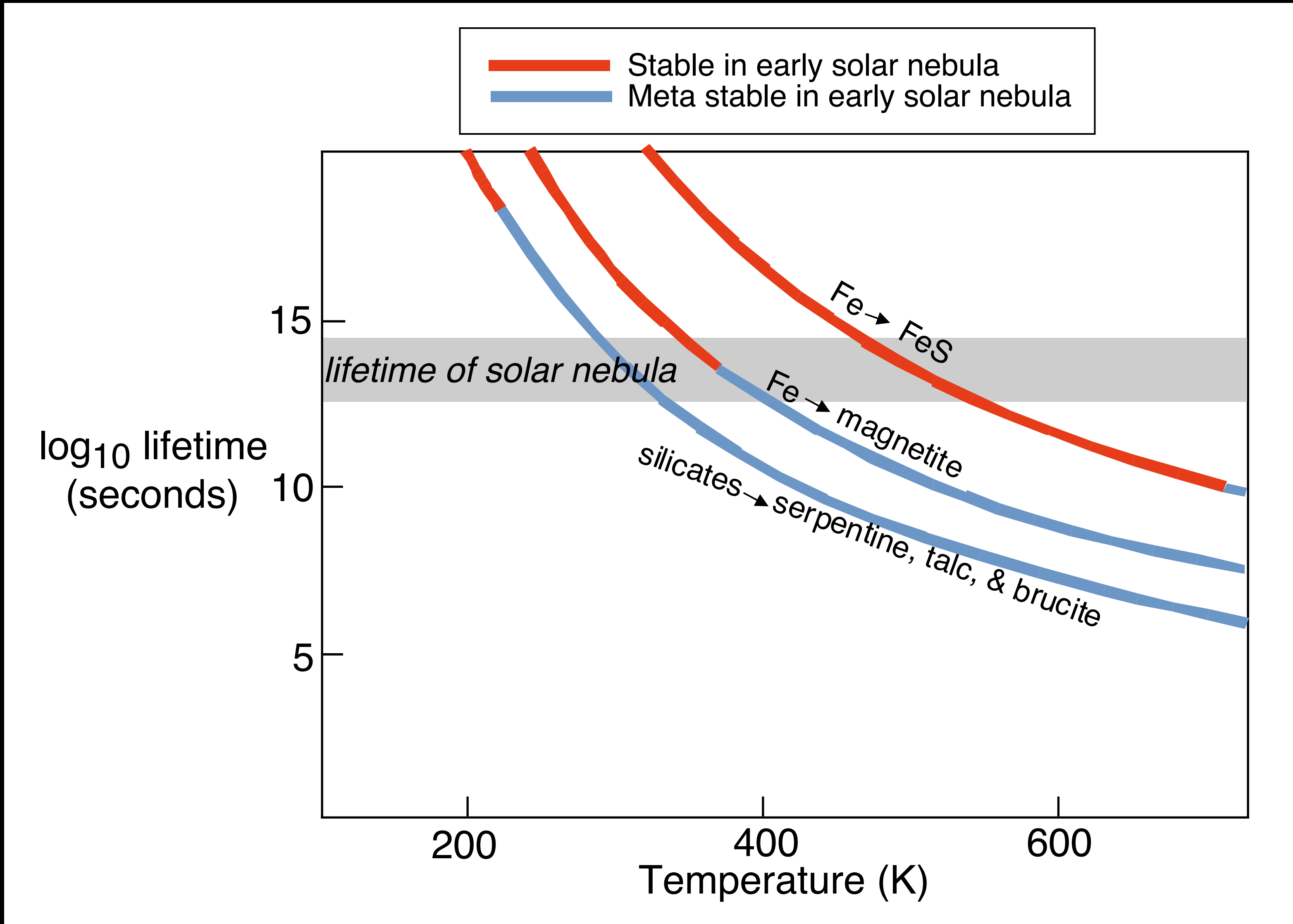
Clayton and Mayeda, 1996

Dust-vapor hydration reactions I: thermodynamics



Fegley, 2000

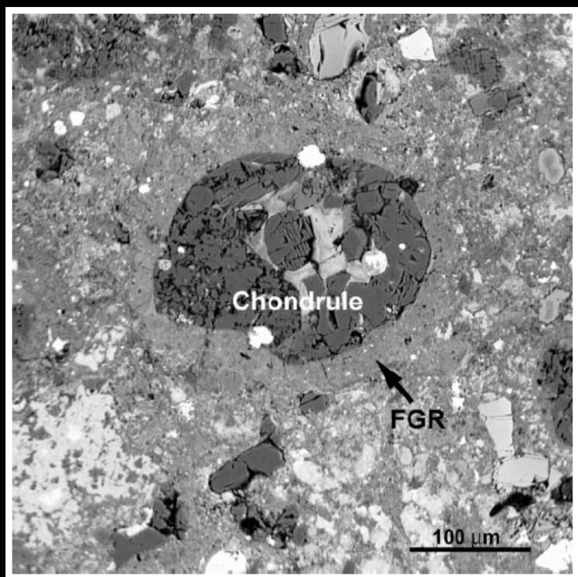
Dust-vapor hydration reactions II: kinetics

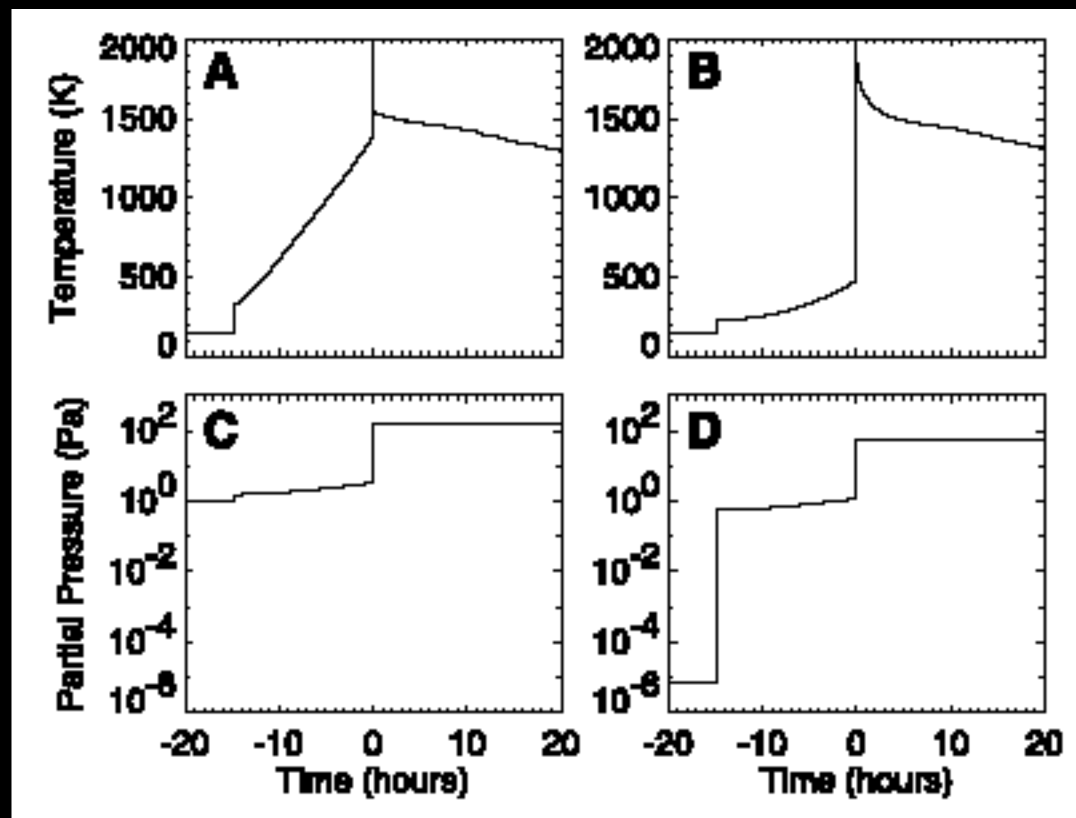


Lifetimes of 100 nm grains w/r to gas-phase reactions

Fegley, 2000

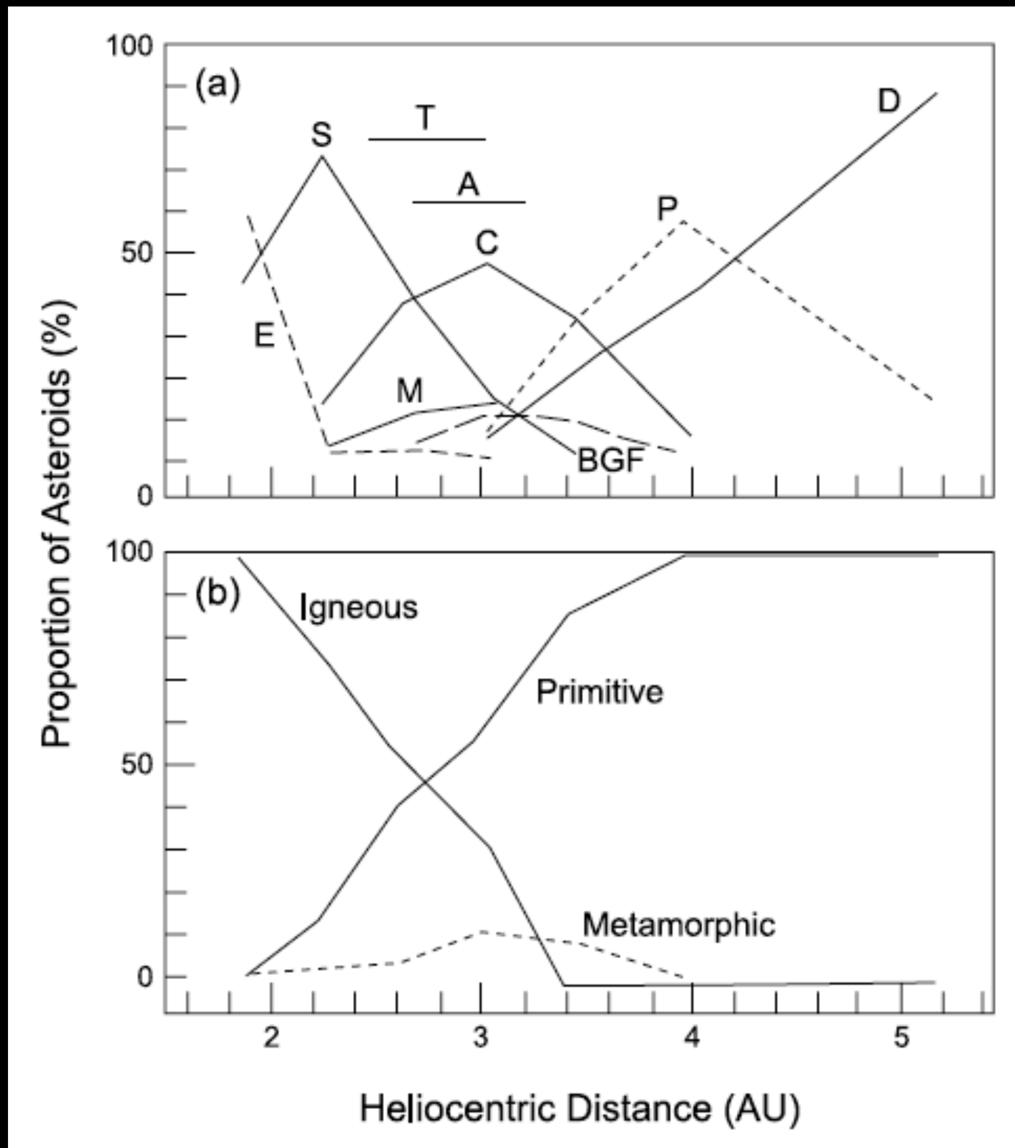
Hydration associated with shock waves?





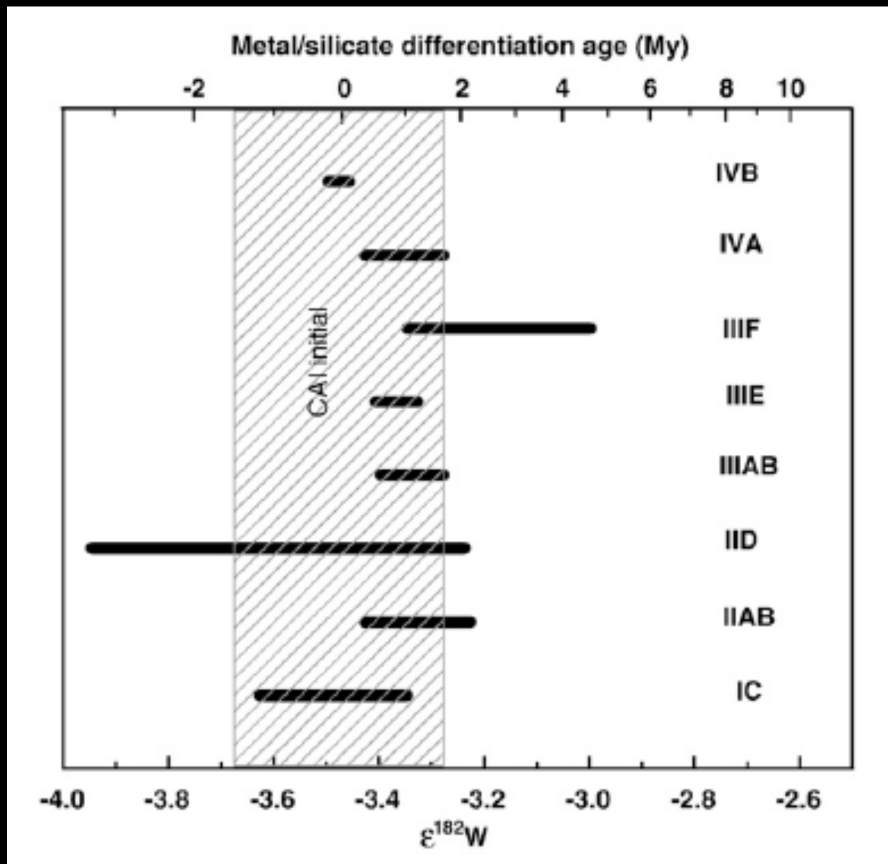
Ciesla et al., 2003

Igneous differentiation of asteroids



Ghosh et al., 2006

Hf-W isotope systematics as a chronometer for metal/silicate differentiation

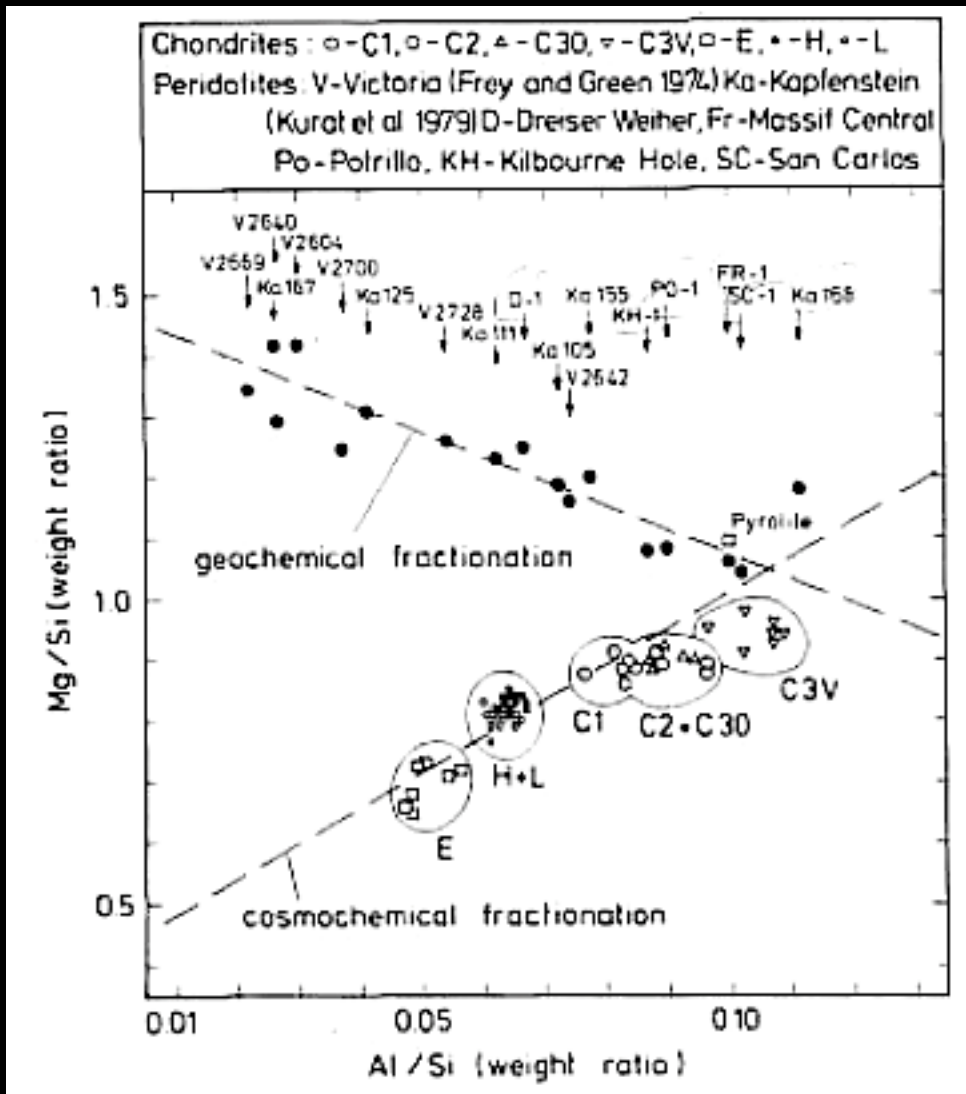


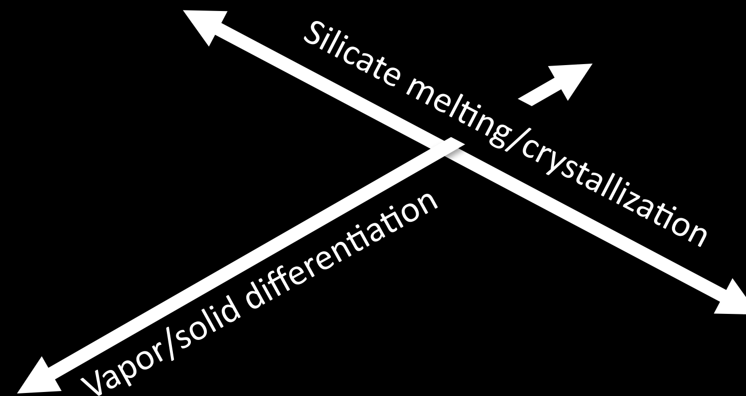
Corrected for cosmic ray W isotope production

- Chronometer assumes ^{182}Hf (half life 8.9 Ma) and its daughter ^{182}W were evenly distributed
- Date by measuring ^{182}W accumulated in high and low Hf/W materials
- Generally dates metal/silicate separation

- Confirms and generalizes petrographic observation that planetesimals differentiated while chondrule formation was still active

Element abundance signatures of silicate differentiation





Granular, cummulate Eucrite

Closing observations and questions

- Laboratory studies of meteorites can establish conditions and timing of
  - condensation
  - melting of dust
  - aqueous alteration
  - metal/silicate separation
  - silicate melting
- What of these do we want to know to address questions of general importance?
- Which things can we figure out remotely? With simple *in situ* observations?
- Is there anything here we want to know so badly that we should invent new instruments or methods to do it?
- O isotopes present a special case; they seem to map a key process of spatially and temporally heterogeneous differentiation. But we don't have any clear ideas about this all connects to planetesimal and larger scales.