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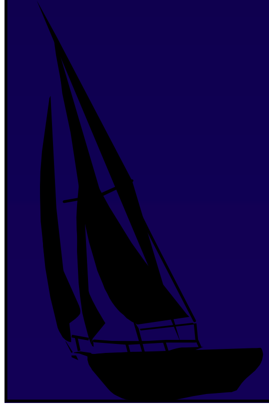
Lecture 2: Chondrites & chondritic components: Implications for understanding processes in the solar nebula

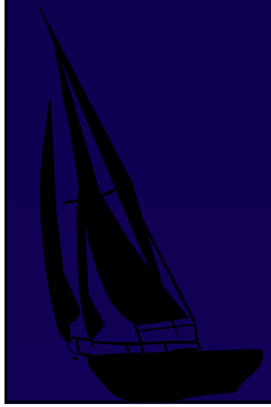
Part I: Chronology of chondritic components

Part II: Origin & evolution of O-isotopic reservoirs in the Solar System



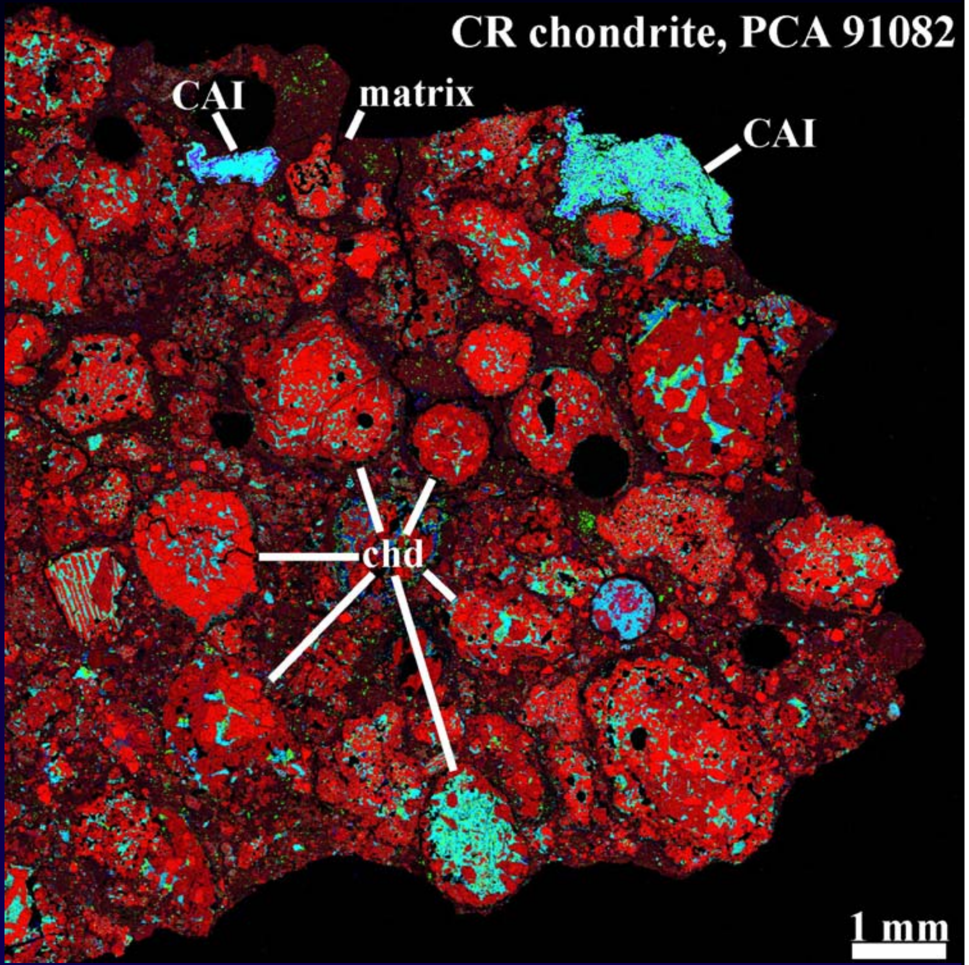
Outline

- *Part I:* Chronology of chondritic components
  - Introduction
  - X-wind model of CAI & chondrule formation
  - Absolute chronology of CAI & chondrule formation
  - Relative chronology of CAI & chondrule formation
    - ^{26}Al-^{26}Mg systematics
    - additional constraints from mineralogy, oxygen isotopes & trace elements
    - ^{53}Mn-^{53}Cr systematics
    - ^{60}Fe-^{60}Ni systematics
  - Conclusions



Chondrites & chondritic components

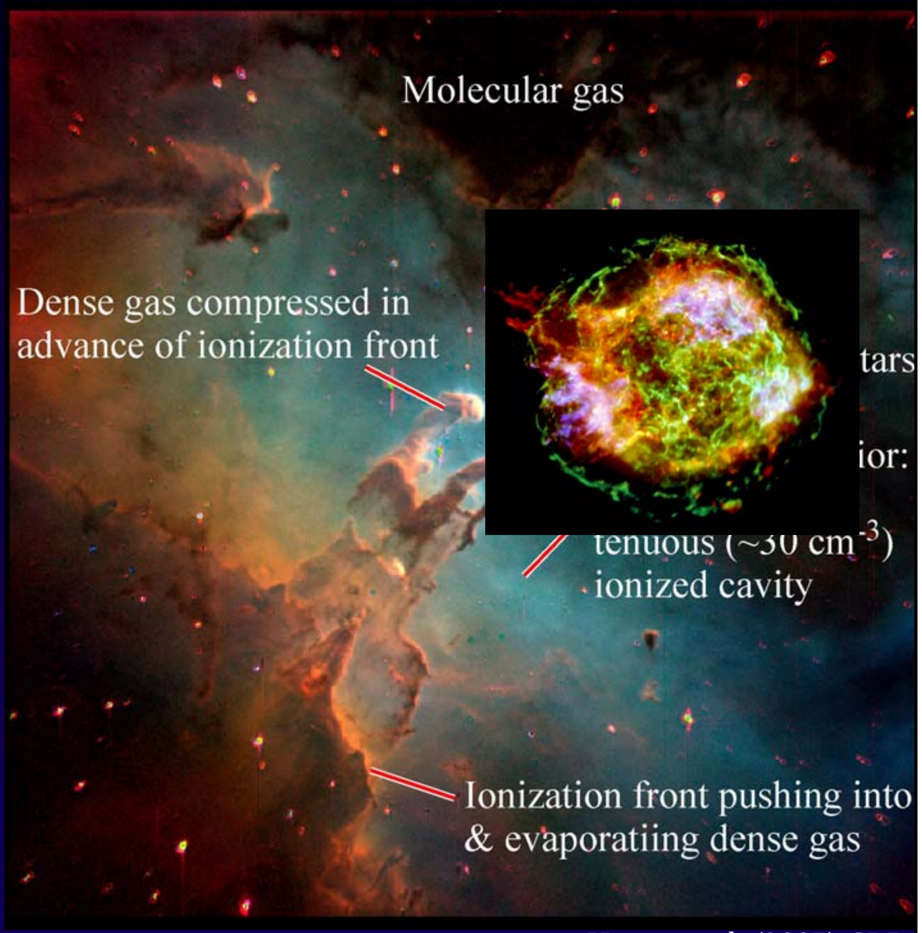
- major chondritic components:
  - ✓ refractory incls: CAIs & AOAs
  - ✓ chondrules
  - ✓ matrix
  - ✓ Fe,Ni-metal
- formed in the protoplanetary disk by high-temperature processes such as evaporation, condensation, & melting
- experienced thermal processing on asteroids (thermal metamorphism & aqueous alteration)



Astrophysical setting of early Solar System formation

- Sun formed in *H II* region near a massive ($>25M_\odot$) star(s)

- Star exploded as supernova & injected short-lived nuclides (^{60}Fe, ^{26}Al*, ^{41}Ca)* into the molecular cloud or protoplanetary disk & the nuclides were quickly homogenized → can be used for early Solar System chronology



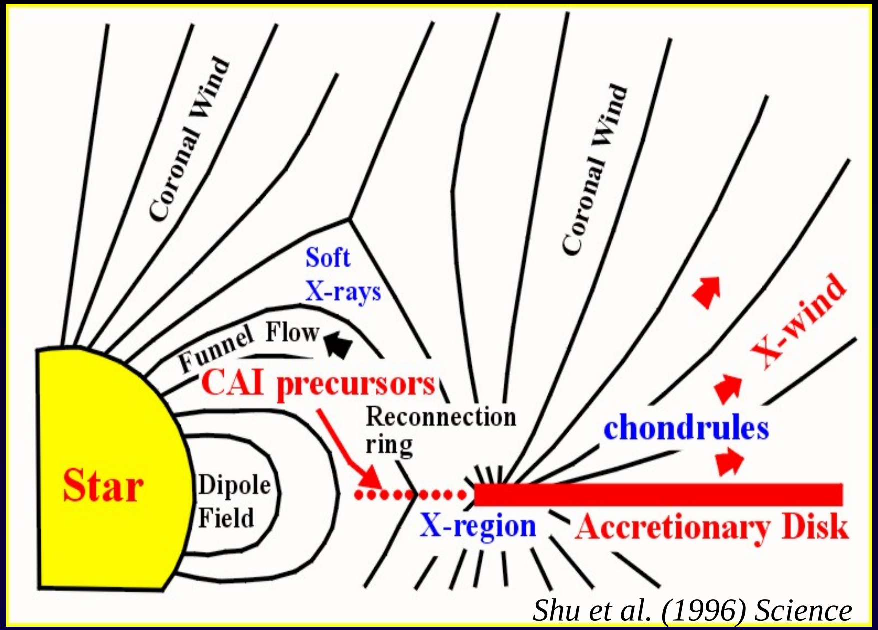
Hester et al. (2005) CPD

* ^{26}Al was may have been injected with the wind, not SN explosion *(Bizzarro et al., 2007, Science; Krot et al., 2007, ApJ)*

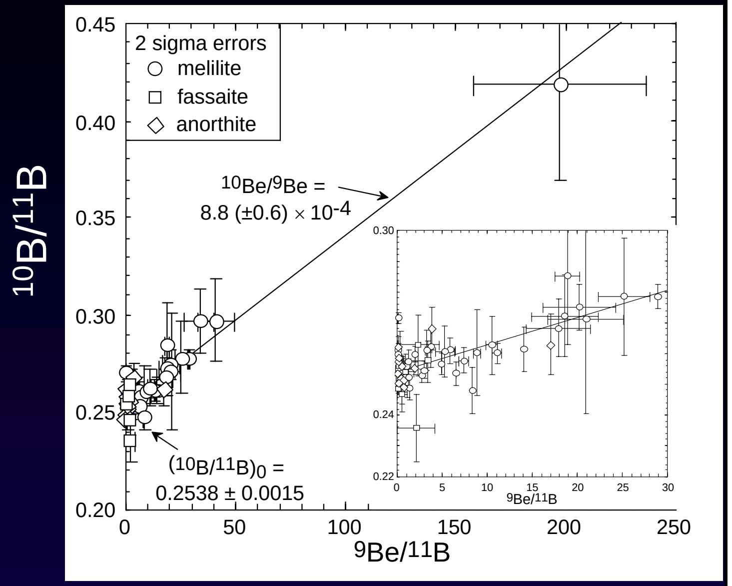
* some short-lived nuclides – ^{10}Be, ^{7}Be(?), & some (or all) of ^{26}Al, ^{41}Ca, ^{53}Mn – may have formed by irradiation

* ^{53}Mn could have resulted from Galactic chemical evolution (i.e., no injection or irradiation would be required)

Formation of CAIs, chondrules & matrices: X-wind model



Shu et al. (1996) Science

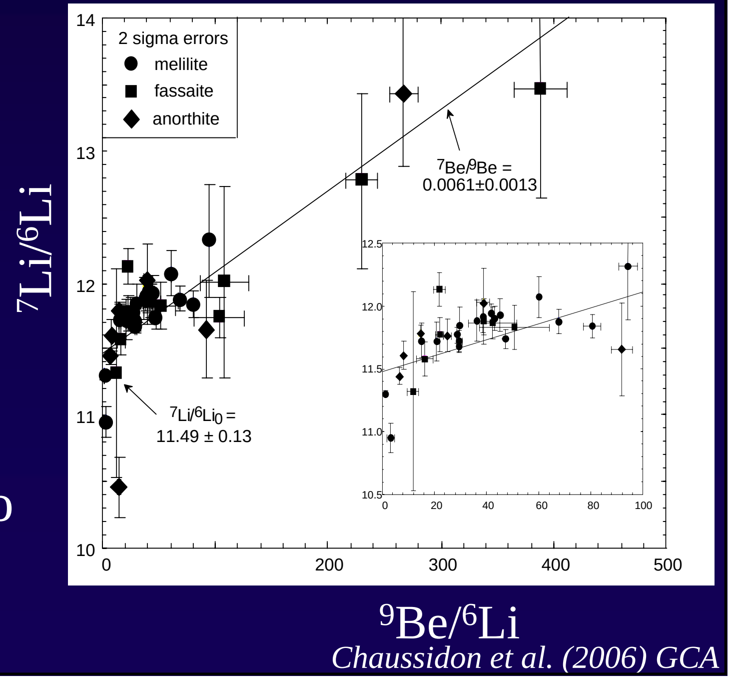


McKeegan et al. (2000) Science

- CAIs contain decay products of ^{10}Be ($t_{1/2}$ = 1.5 Myr) & possibly ^{7}Be ($t_{1/2}$ = 53 days) → evidence for irradiation in the Solar System
- CAIs contain high abundance of ^{26}Al compared to chondrules

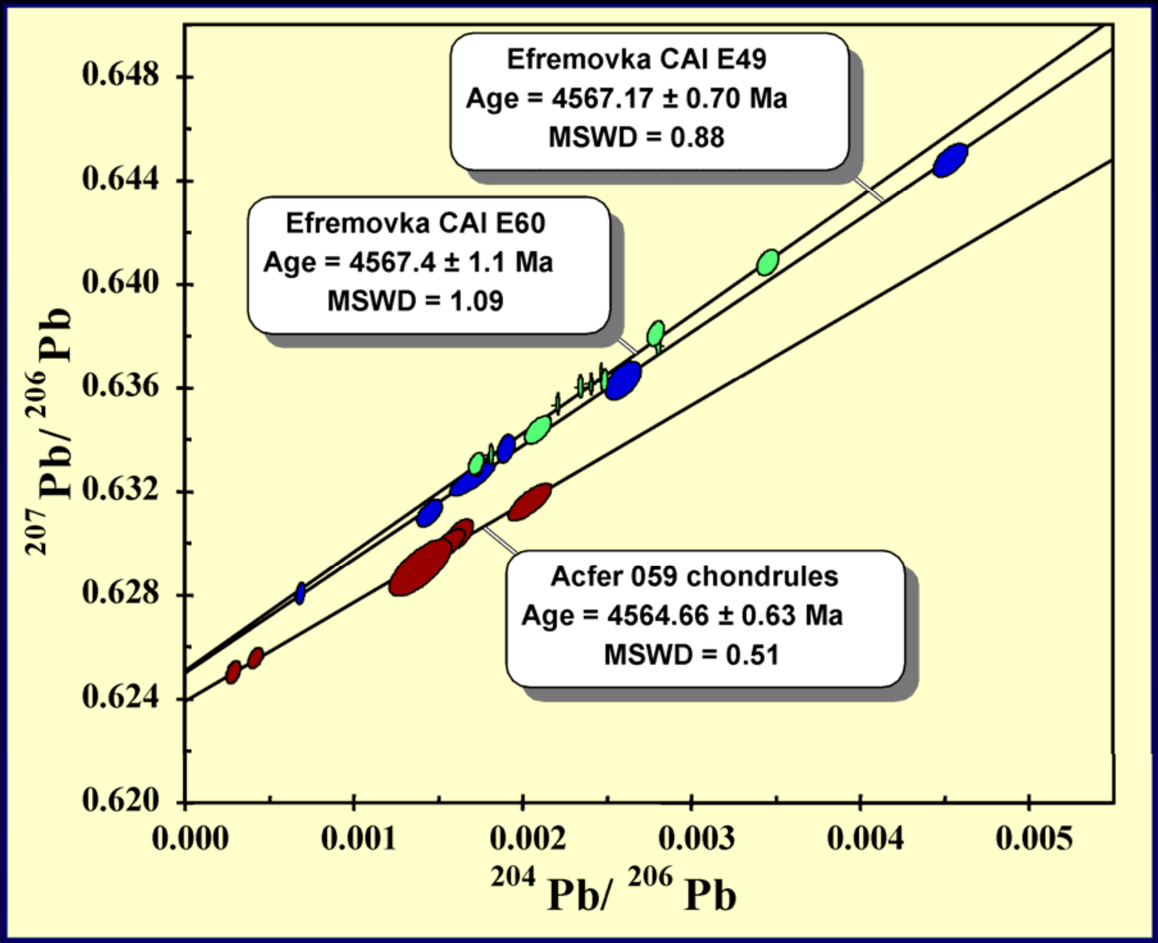
✓ CAIs formed in reconnection ring (<0.1 AU); chondrules formed at the edge of the disk contemporaneously with CAIs

✓ CAIs & chondrules were subsequently transported to 1-5 AU, where they accreted together with matrix which escaped thermal processing



Chaussidon et al. (2006) GCA

Absolute (^{207}Pb-^{206}Pb) ages of CAIs & chondrules

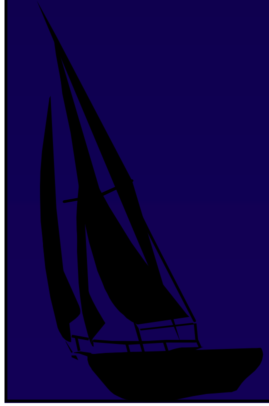


Efremovka CAI E49
Age = 4567.17 ± 0.70 Ma
MSWD = 0.88

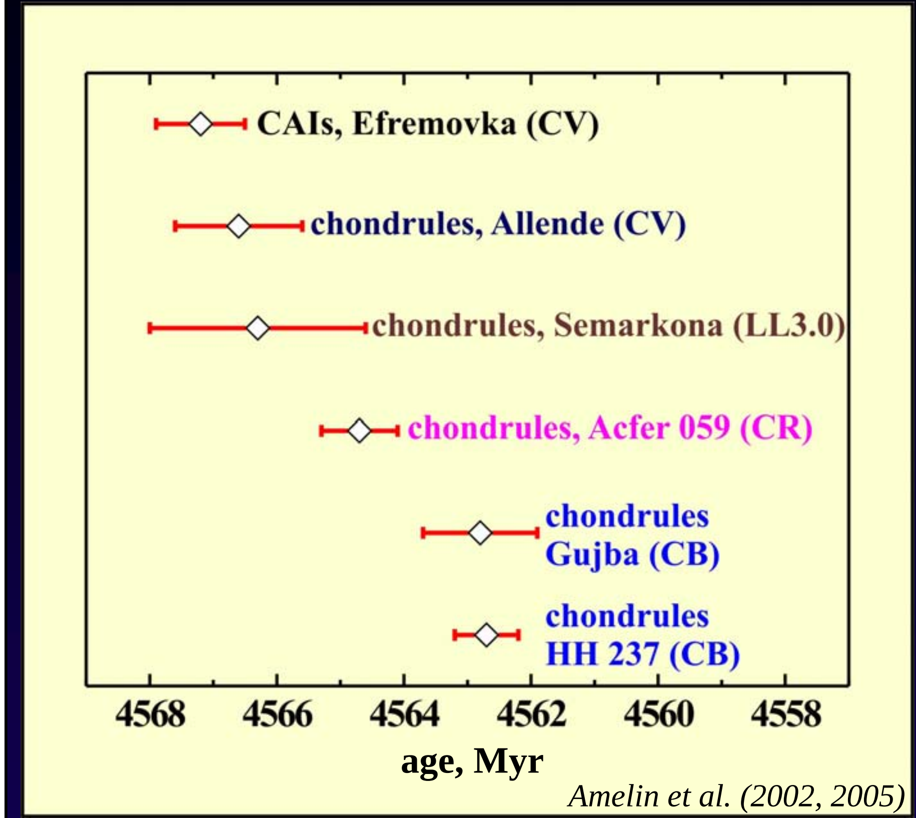
Efremovka CAI E60
Age = 4567.4 ± 1.1 Ma
MSWD = 1.09

Acfer 059 chondrules
Age = 4564.66 ± 0.63 Ma
MSWD = 0.51

Amelin et al. (2002) Science

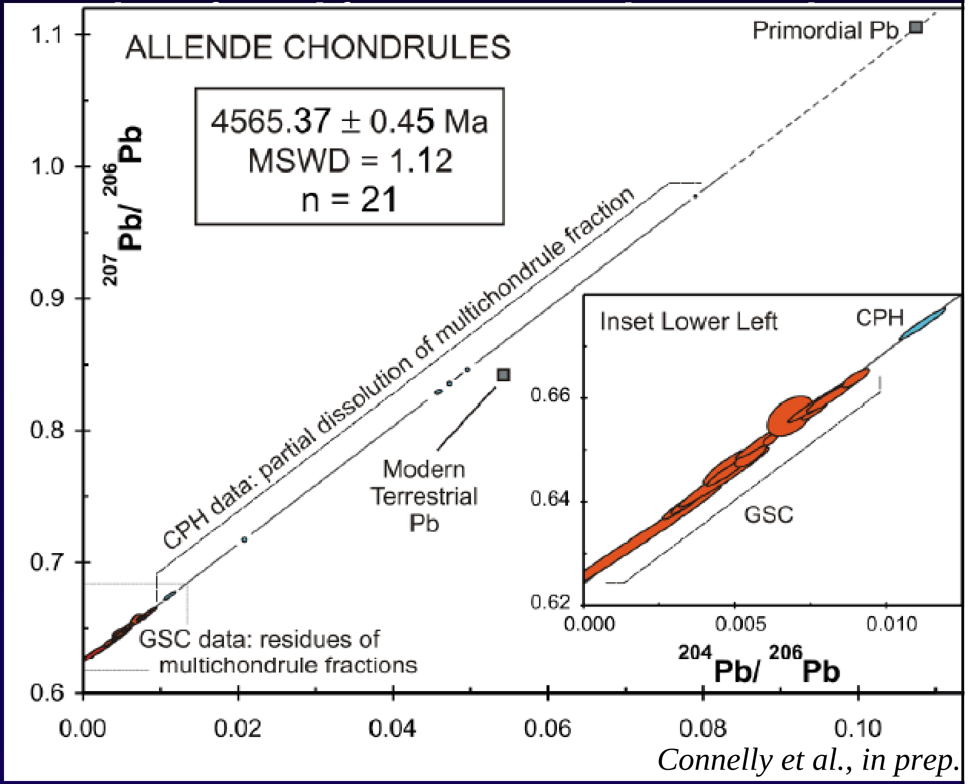


Absolute (^{207}Pb-^{206}Pb) ages of CAIs & chondrules



Amelin et al. (2002, 2005)

CV CAIs	4567.2±0.2 Myr
CV chds	4565.4±0.4 Myr
OC chds	4566.3±1.7 Myr
CR chds	4564.7±0.6 Myr
CB chds*	4562.7±0.5 Myr



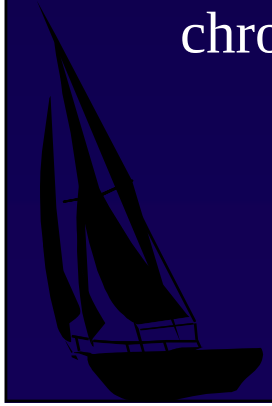
Connelly et al., in prep.

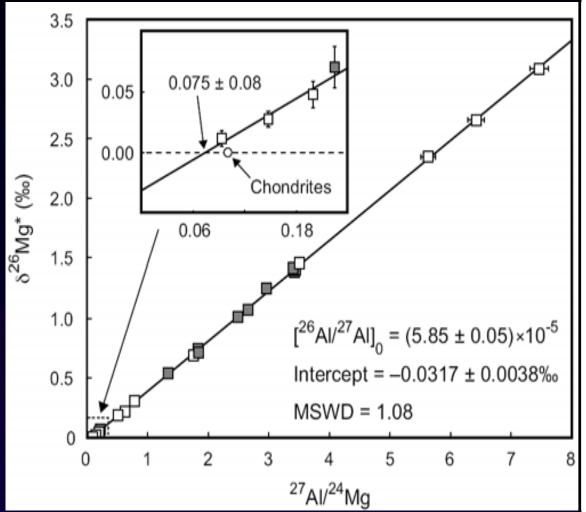
- CAIs formed first; chondrule formation started ~1 Myr later & lasted for 3-4 Myr
- chondrules within a chondrite group might have formed within 1 Myr

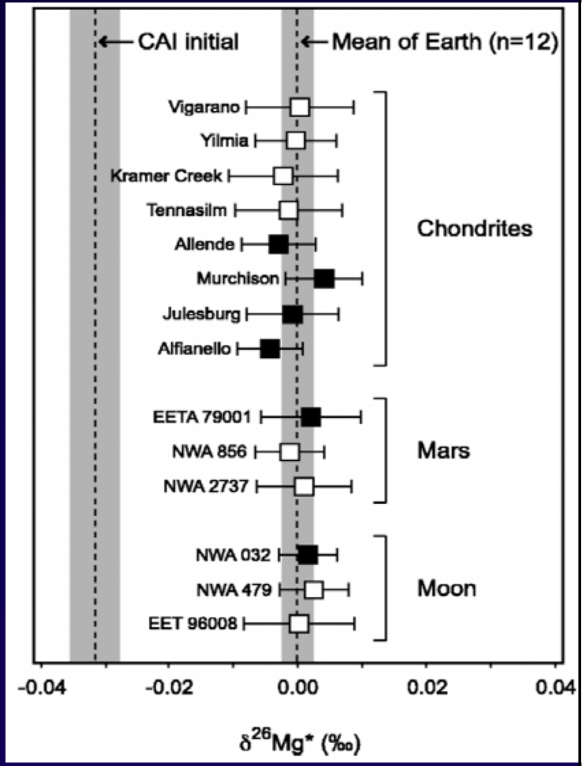
✓ resolved age difference between CAIs & chondrules in CV chondrites contradicts X-wind hypothesis of their contemporaneous formation

Relative chronology of CAI & chd formation: ^{26}Al-^{26}Mg system

- $^{26}\text{Al} \rightarrow {}^{26}\text{Mg}$ ($t_{1/2} = 0.73$ Myr)
- use of ^{26}Al as a chronometer for dating CAI & chondrule formation used to require the <u>assumption</u> on its uniform distribution in the inner solar nebula
- this assumption <u>has been tested</u> by
  - high-precision Mg-isotope measurements of bulk chondrites, Earth & Mars
    - bulk CAIs define a regression line corresp. to $(^{26}\text{Al}/^{27}\text{Al})_I = (5.85 \pm 0.05) \times 10^{-5}$
    - intercept –0.0317 ± 0.0038‰
  - cross-calibrating ^{26}Al-^{26}Mg & ^{207}Pb-^{206}Pb chronometers



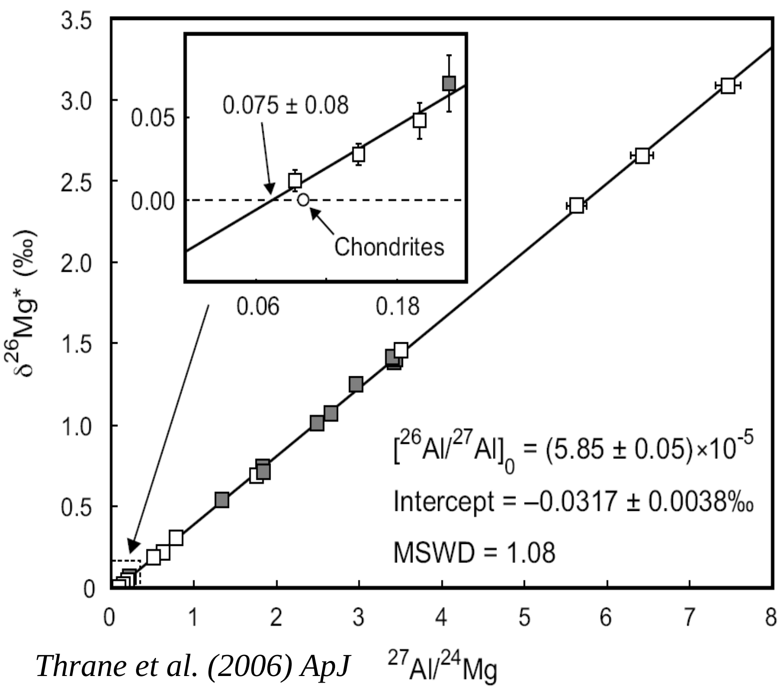




Thrane et al. (2006) Ap

Relative chronology of CAI & chd formation: ^{26}Al-^{26}Mg system

- ✓ bulk CAIs define a regression line corresponding to $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_I = (5.85 \pm 0.05) \times 10^{-5}$; error on slope ±20,000 yrs, which may represent formation interval of CAIs or their precursors
- chondrule formation started shortly after CAIs/AOAs & lasted for ~3-4 Myr



Thrane et al. (2006) ApJ

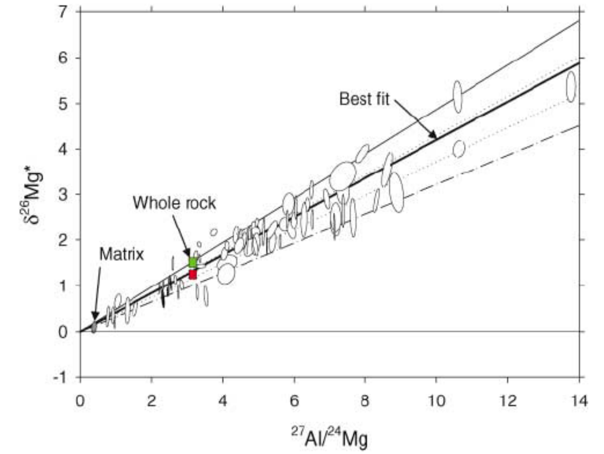
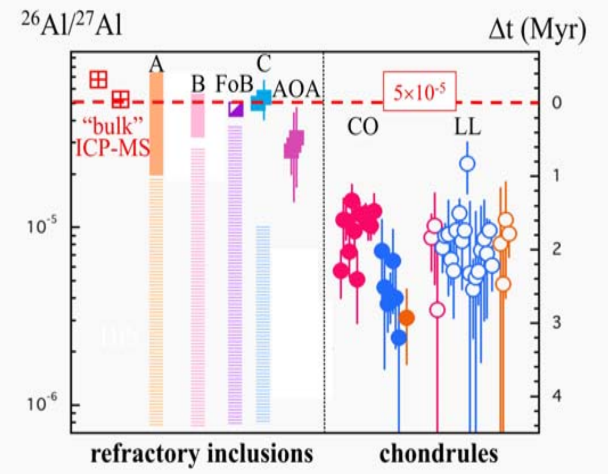
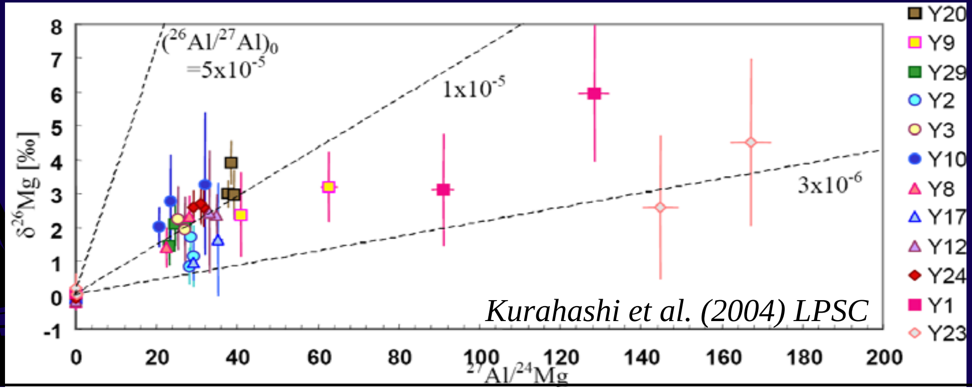


Fig. 2. Plot of δ^{26}Mg* versus ^{27}Al/^{24}Mg values for CAI 144A (compact type A) from the Leoville CV3 meteorite obtained by laser-ablation MC-ICPMS. Each datum is shown as a 1σ error ellipse. Most data are above the canonical line (dash-dot line), and many are on or just below the 7×10^{-5} line (upper solid line) defined by some bulk CAI data. The data show a strong correlation with a best-fit slope corresponding to $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_o = 5.9 \times 10^{-5}$ (heavy black line). Also shown is the whole-rock datum for 144A calculated for two different reference fractionation lines (green square and red square as in Fig. 1). The $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_o$ values of the reference lines are the same as in Fig. 1.

Young et al. (2005) Science



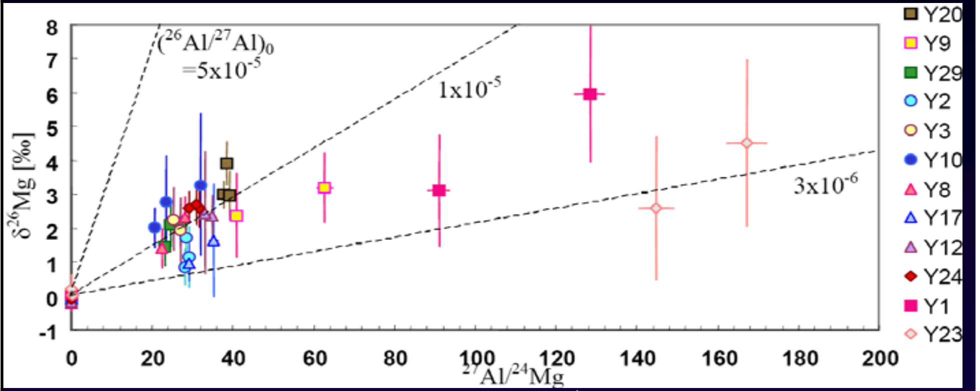
Kita et al. (2005) CPD



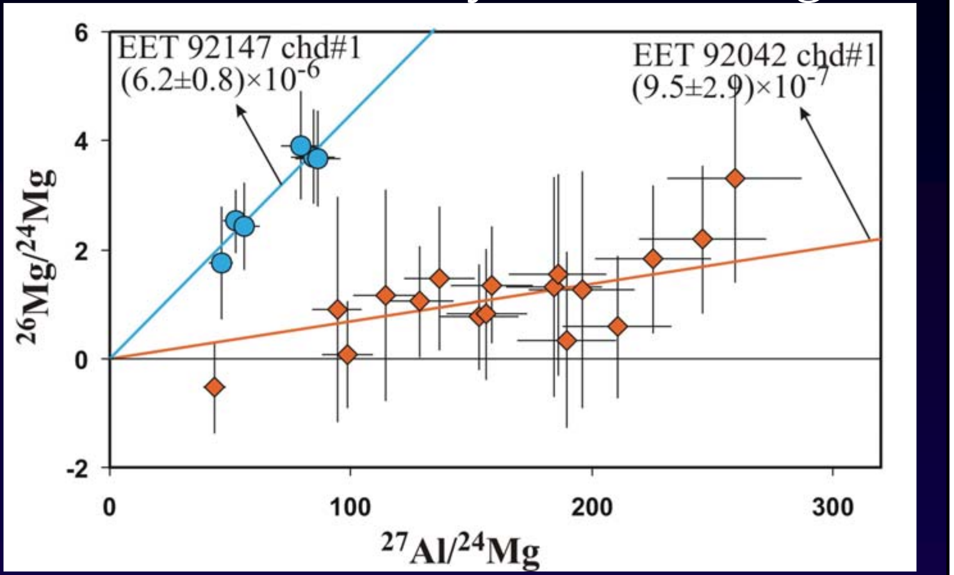
Kurahashi et al. (2004) LPSC

Relative chronology of CAI & chd formation: ^{26}Al-^{26}Mg system

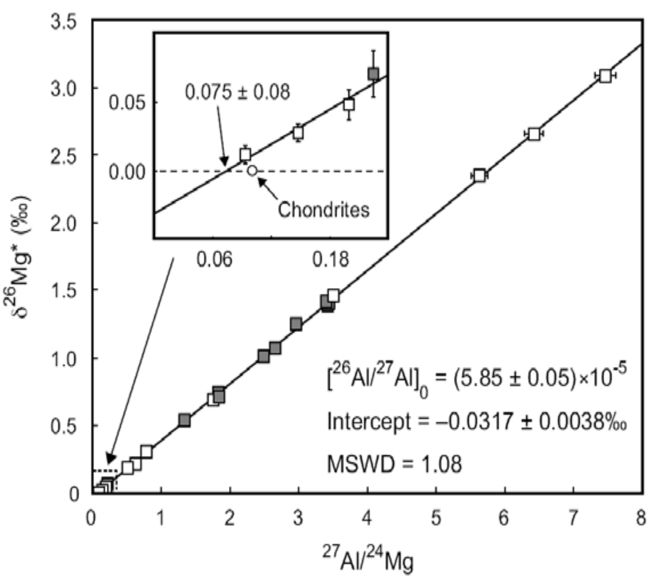
- young crystallization ages of chondrules are inferred from internal isochrons
- model Al-Mg isochrons of bulk chondrules do not date crystallization ages



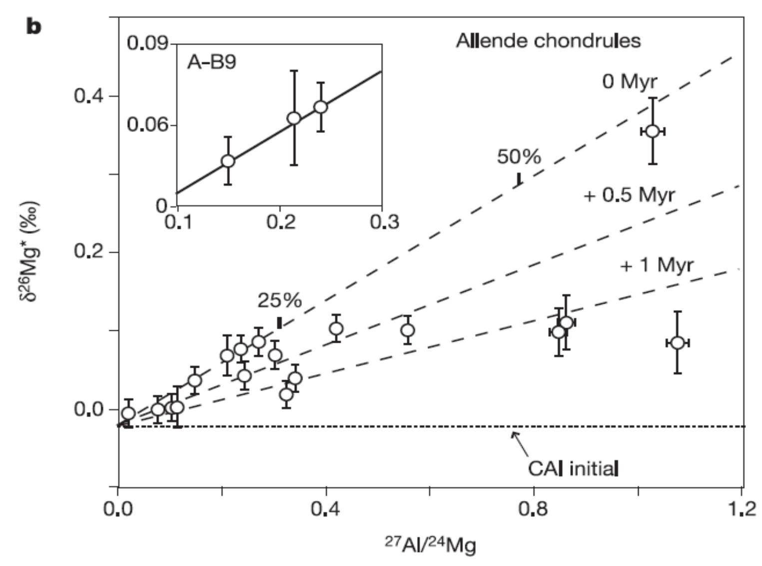
↑*Kurahashi et al. (2004) LPSC*



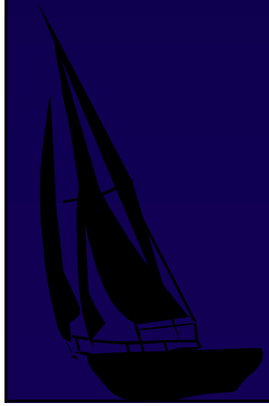
→ *Nagashima et al. (2007) MAPS*



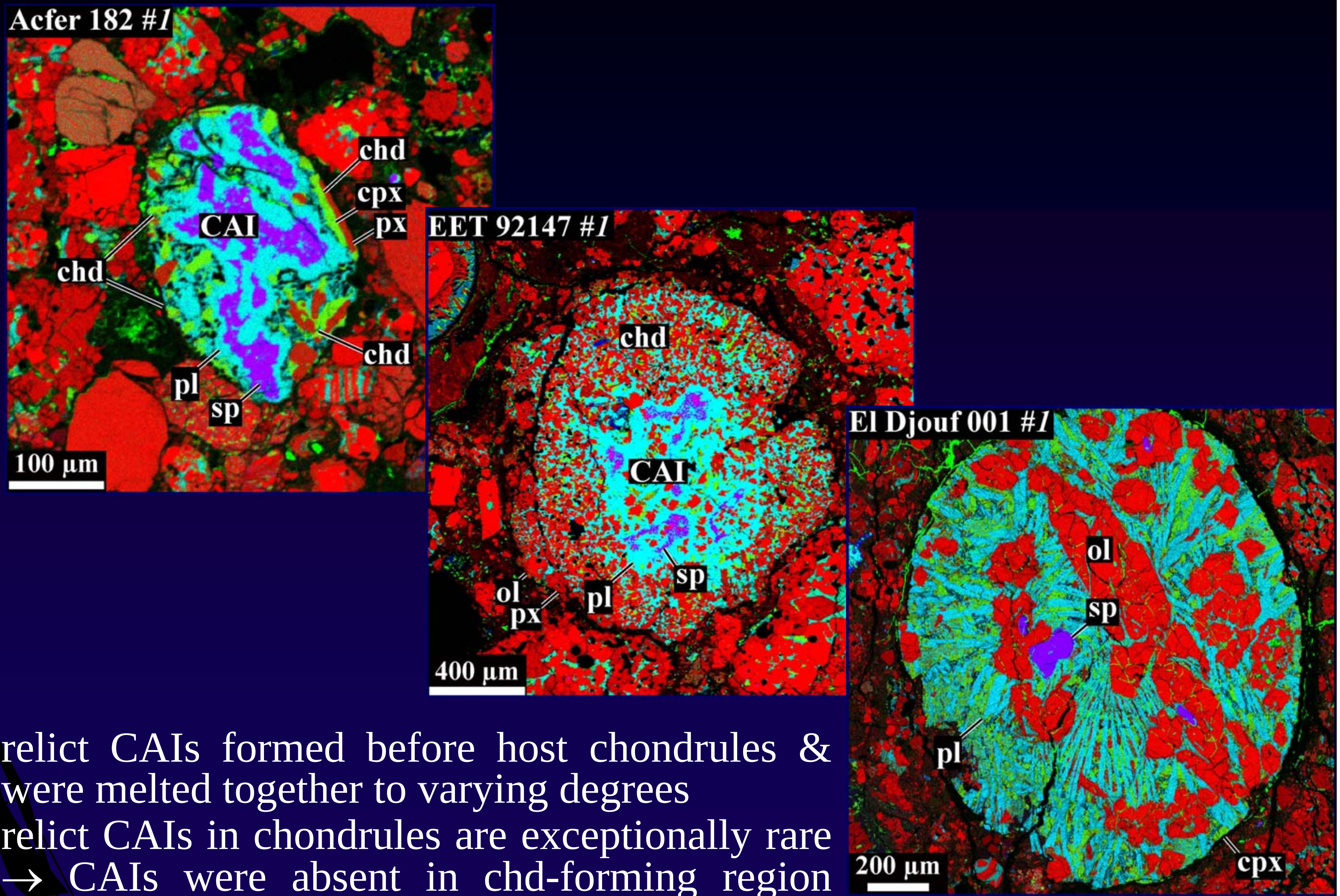
Thrane et al. (2006) ApJ



Bizzarro et al. (2004) Nature

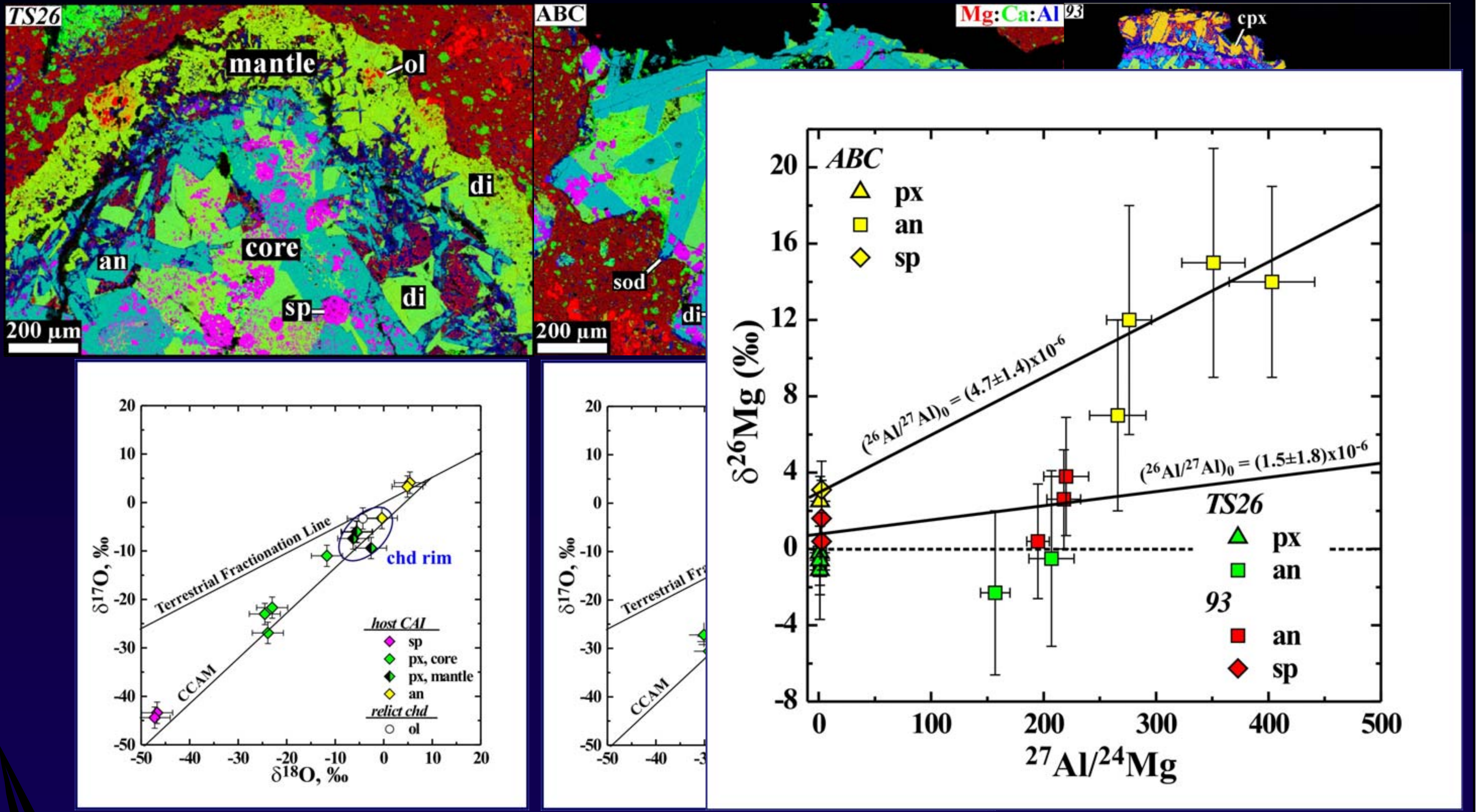


Relative chronology of CAI & chd formation: Relict CAIs



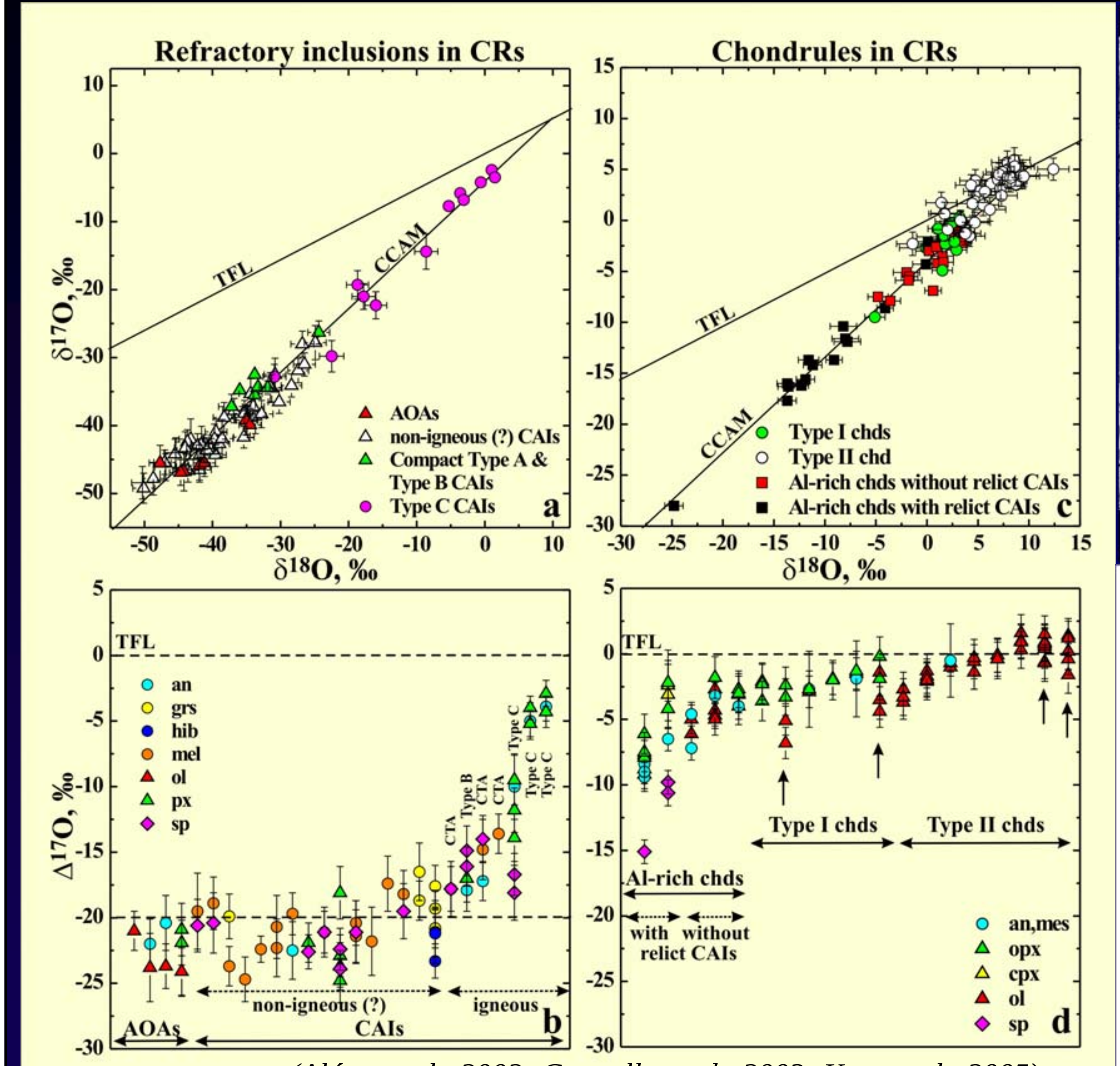
- relict CAIs formed before host chondrules & were melted together to varying degrees
- relict CAIs in chondrules are exceptionally rare → CAIs were absent in chd-forming region (consistent with X-wind model)

Relative chronology of CAI & chd formation: Igneous rims

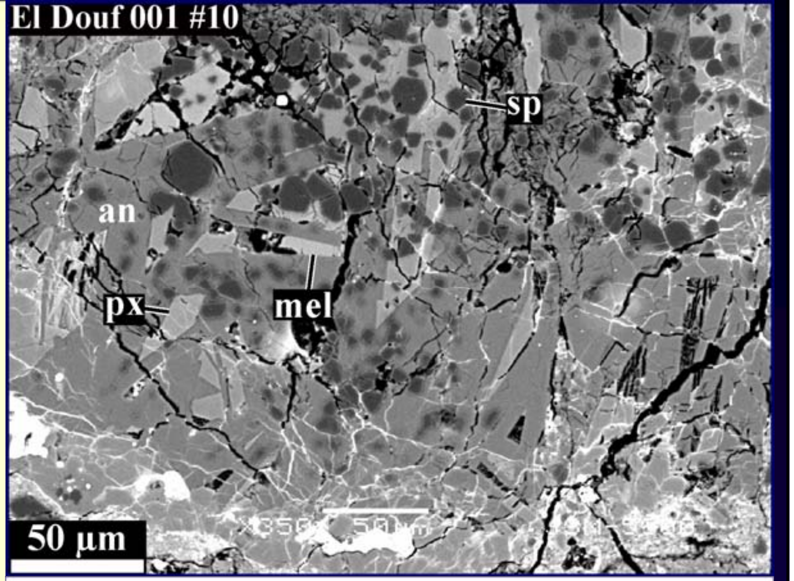


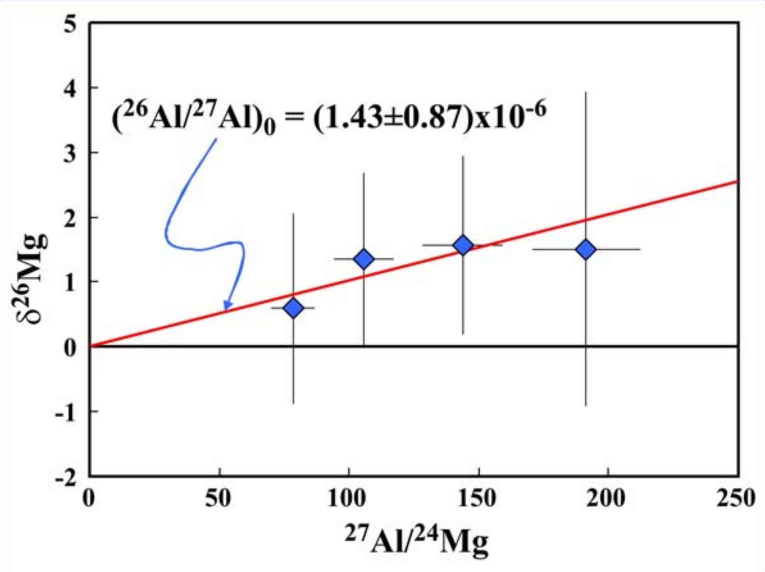
- CAIs remelted in an ^{16}O-poor gaseous reservoir with small addition of chondrule material
- ^{26}Al-^{26}Mg system was reset during host chondrule melting

Relative chronology of CAI & chd formation: Remelted CAIs



(Aléon et al., 2002; Connolly et al., 2003; Krot et al., 2005)

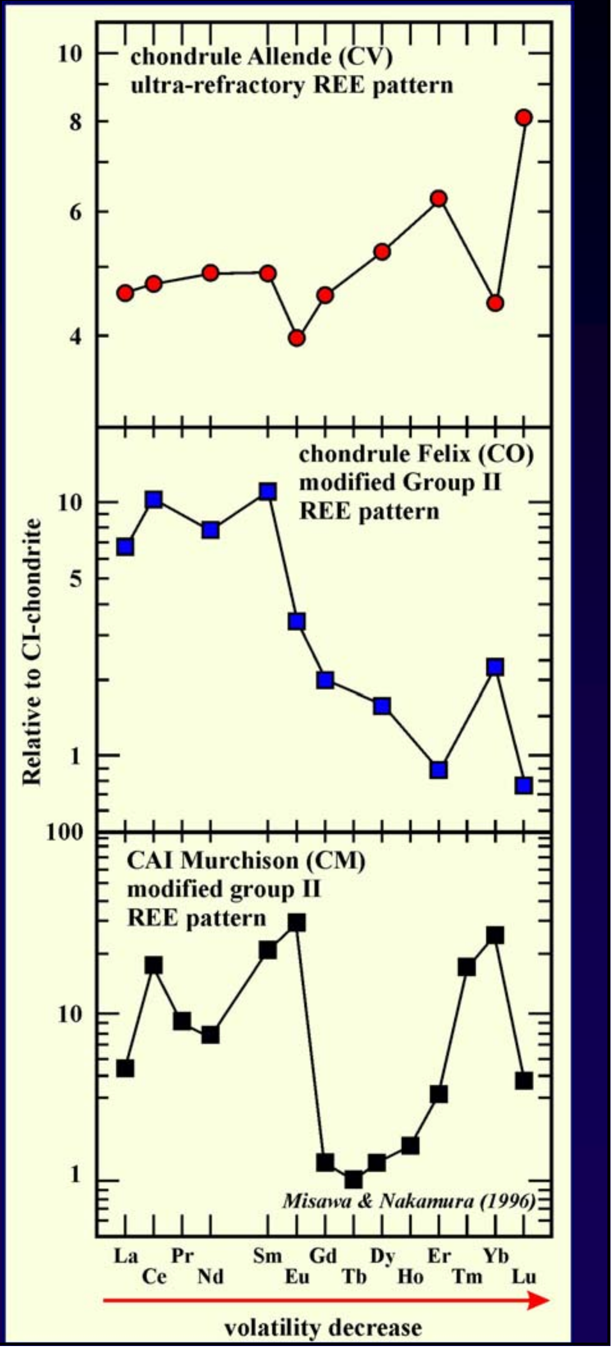


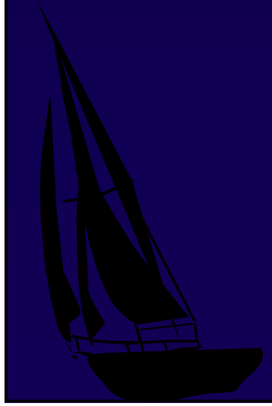


- CAIs were remelted in an ^{16}O-poor gaseous reservoir & their ^{26}Al-^{26}Mg system was reset, most likely during chondrule melting

Relative chronology of CAI & chd formation: REE patterns

- most CAIs
  - ✓ fractionated REE patterns indicating gas-solid fractionation during evaporation-condensation processes
- most chondrules
  - ✓ unfractionated REE patterns
- some chondrules
  - ✓ fractionated REE patterns suggesting presence of CAIs among their precursors



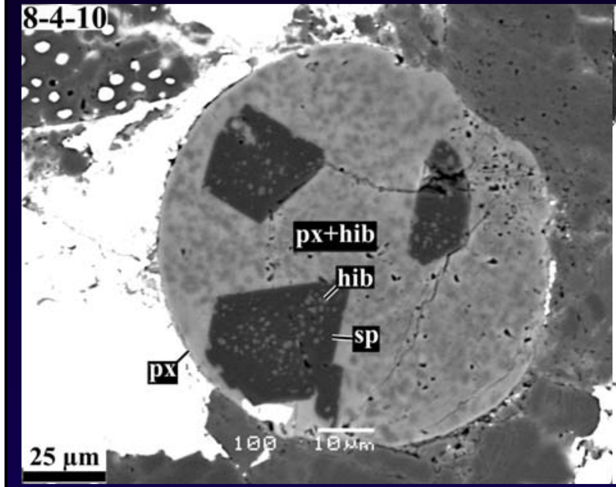


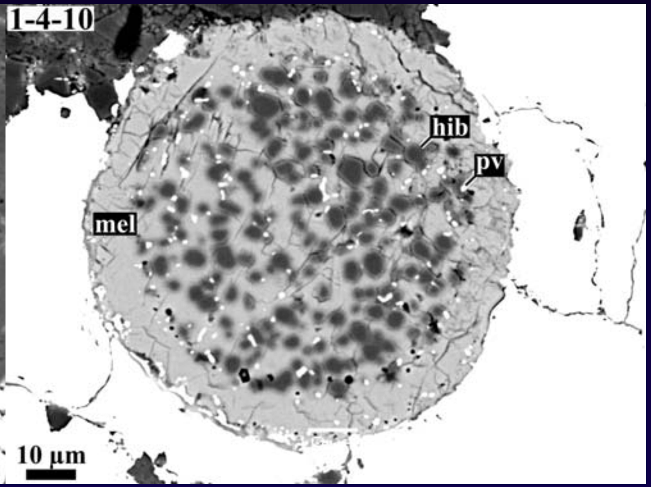
Chronology of ^{26}Al-poor CAIs

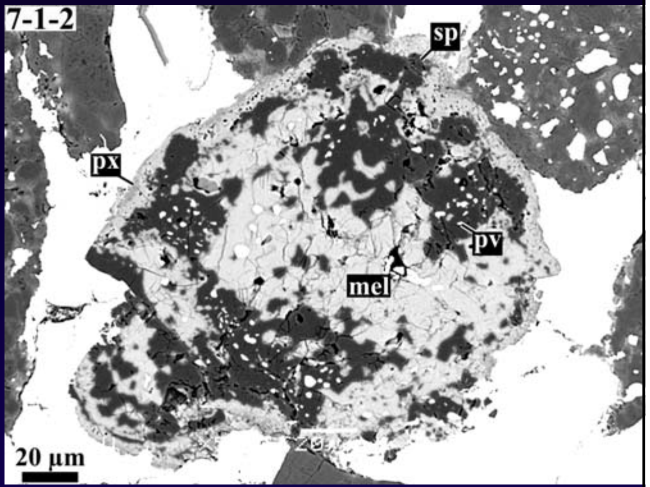
- CAIs in most chondrite groups are dominated by spinel-pyroxene-melilite types & characterized by ^{16}O-rich compositions & canonical ^{26}Al/^{27}Al ratio
- two populations of CAIs in CH-like chondrites Isheyevo & Acfer 182/214

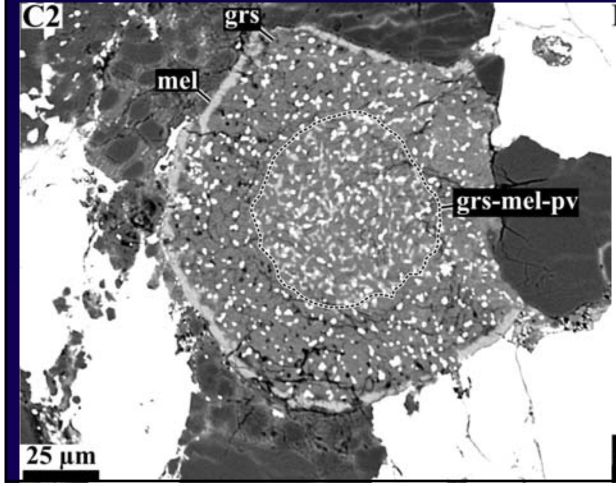
✓ *Very refractory: rich in grossite* ($CaAl_4O_7$)*, hibonite* ($CaAl_{12}O_{19}$)*, Al-pyroxene, ghl-melilite*

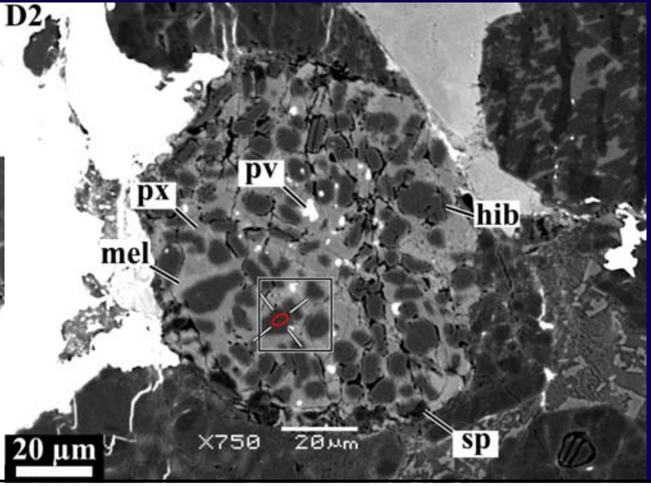
✓ *Less refractory: melilite, spinel, pyroxene, anortite*

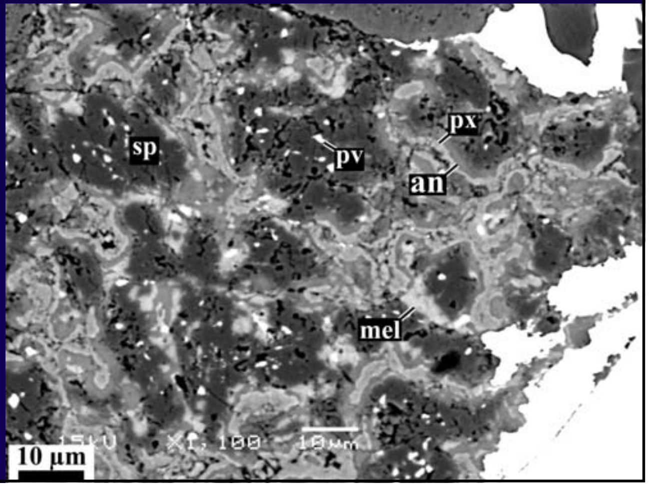




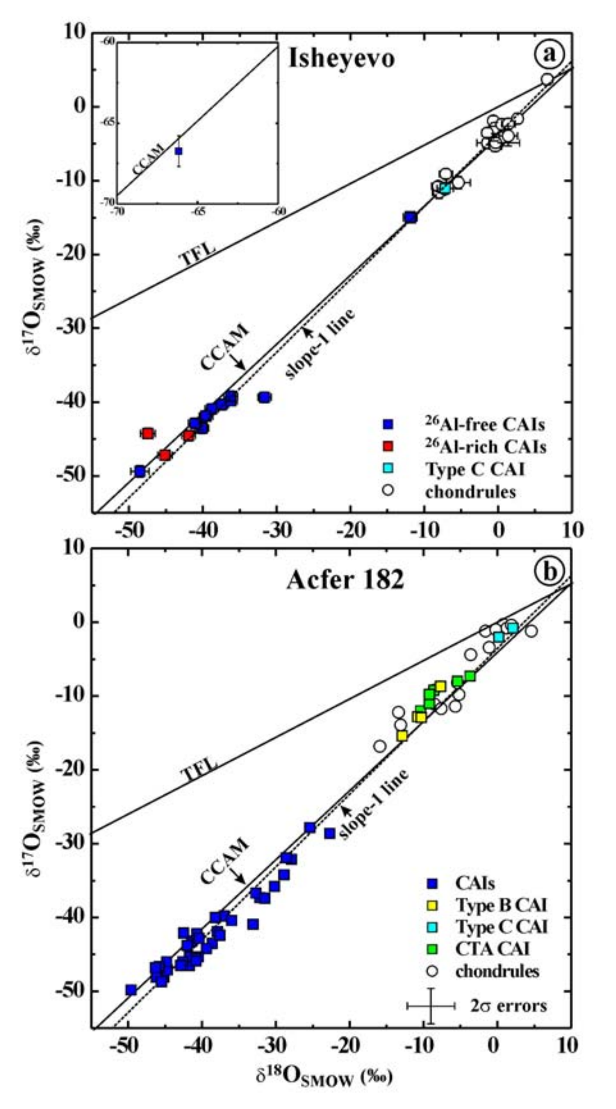


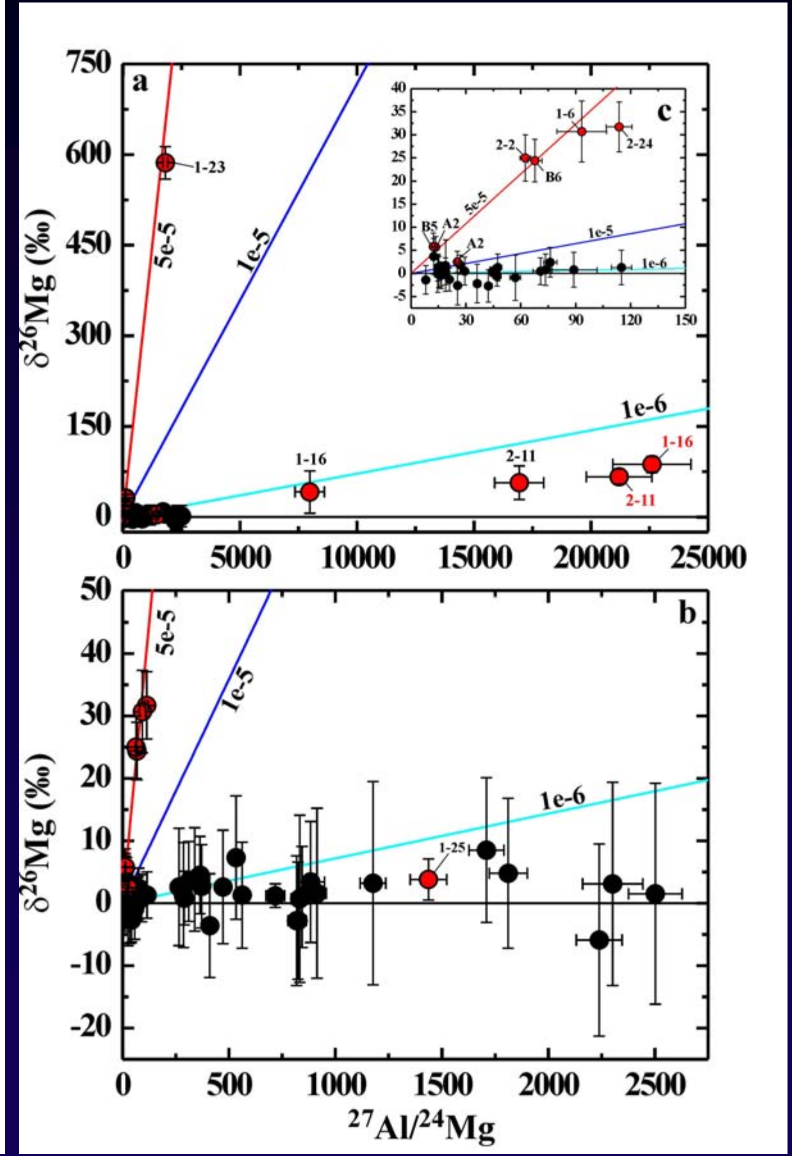


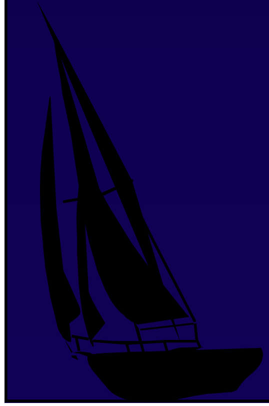




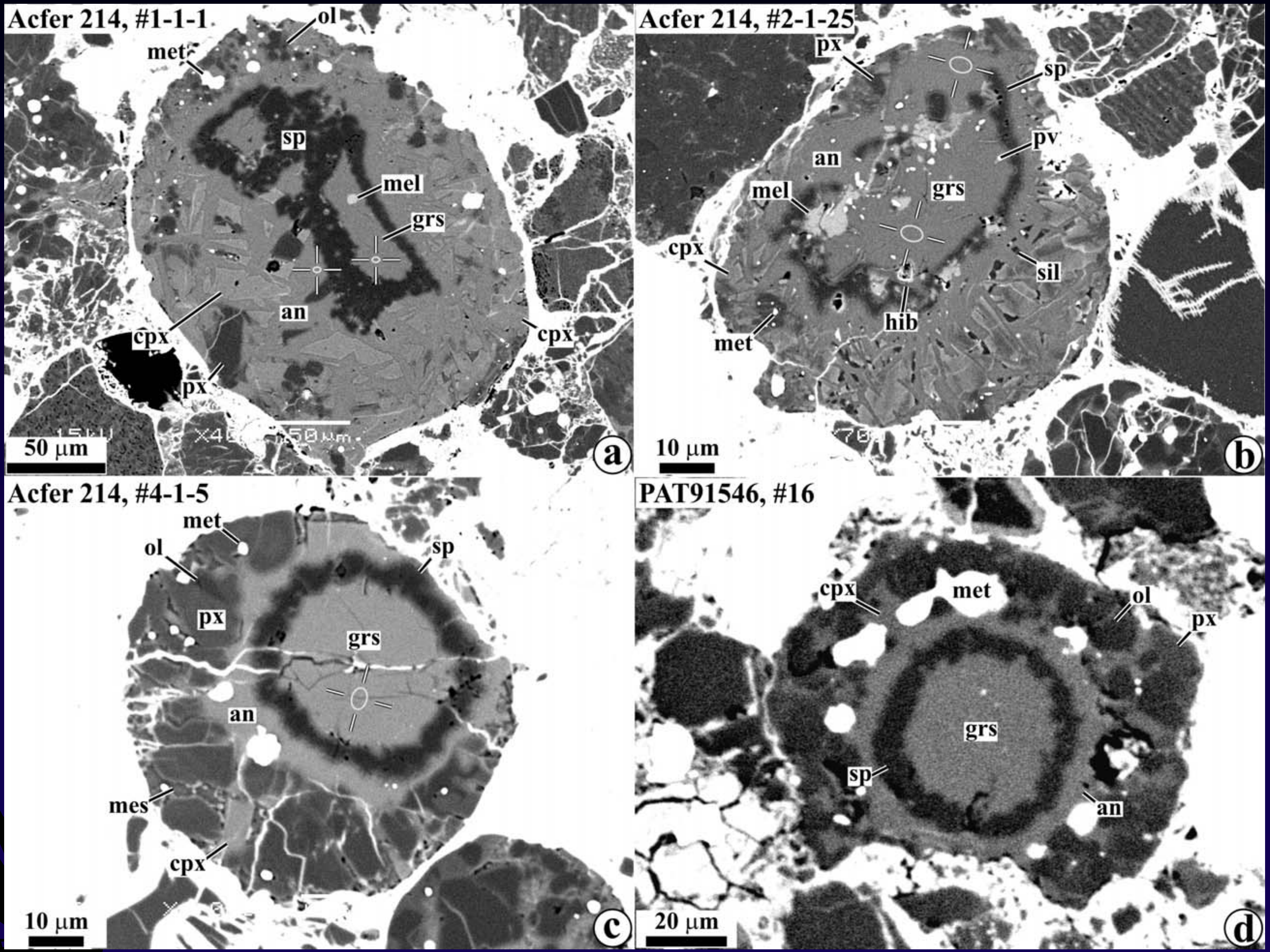
- both populations are ^{16}O-rich, but show bi-modal distribution in ^{26}Al/^{27}Al:
  - ✓ ~ 5 × 10^{-5} (less refractory) & <10^{-6} (more refractory)
  - ✓ ^{26}Al-poor CAIs formed either very early or very late (testable)



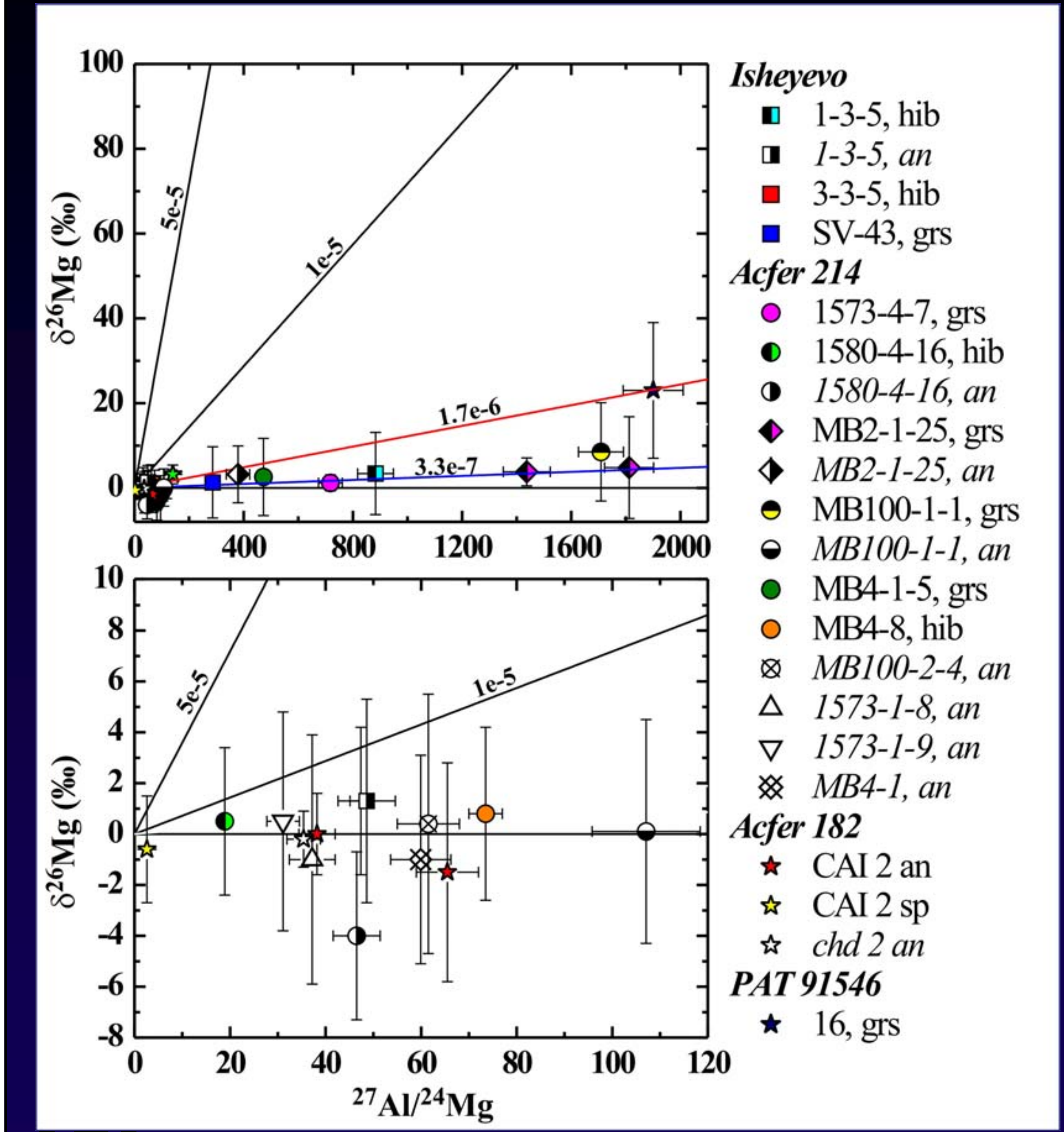


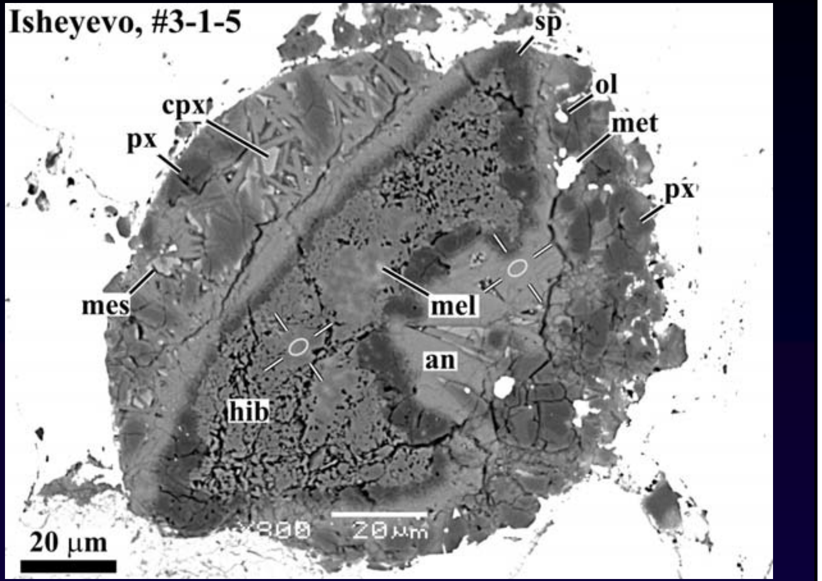


Relict CAIs inside & outside CH chondrules are similar



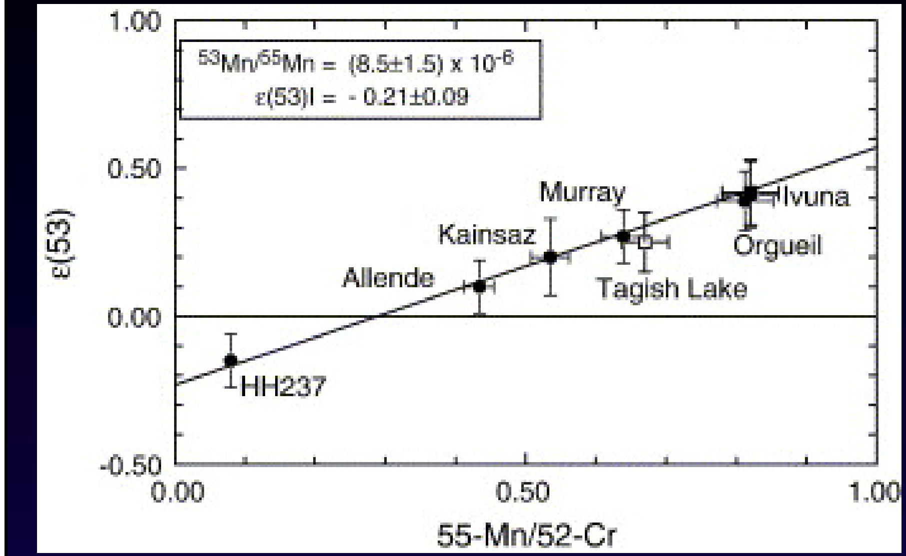
Relict CAIs inside & outside CH chondrules are similar





- ✓ CH CAIs were present in region(s) where CH chondrules formed, but many of them were unaffected by chondrule melting events

Relative chronology of CAI & chd formation: ^{53}Mn-^{53}Cr system

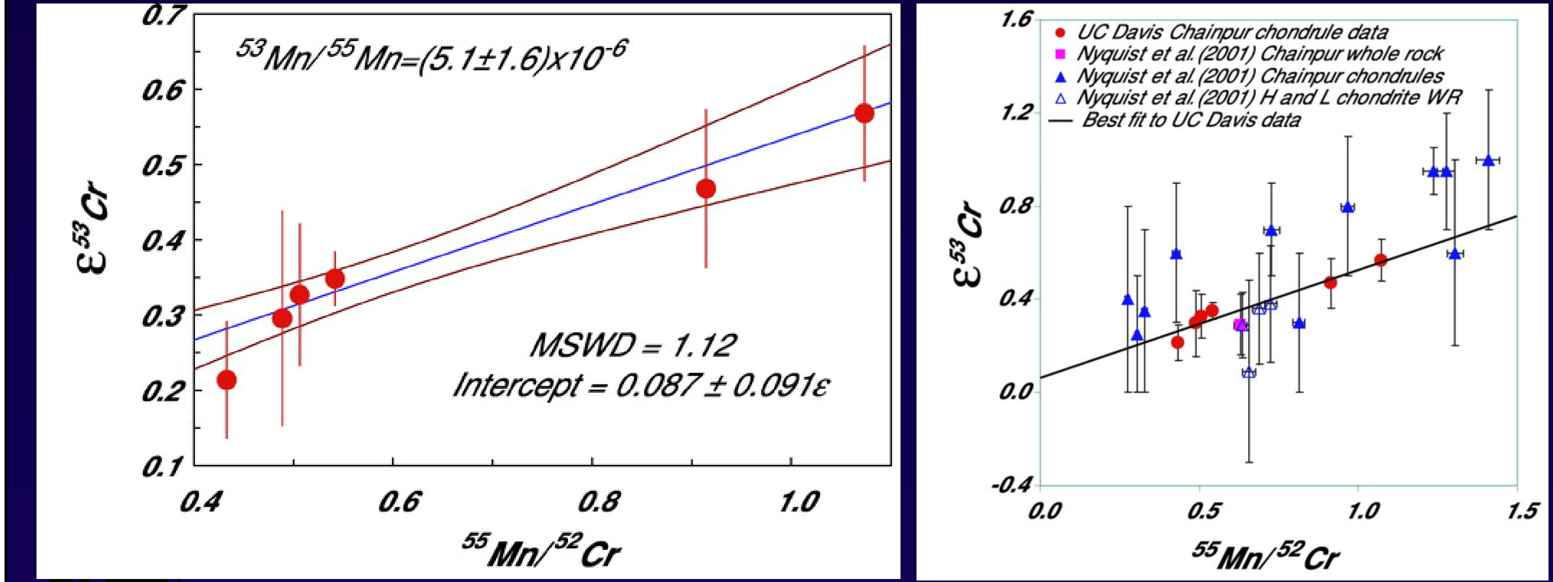


Shukolyukov & Lugmair (2006) GCA

^{53}Mn-^{53}Cr system of bulk CCs

- ^{53}Mn→^{53}Cr ($t_{1/2}$ = 3.7 Myr)
- (^{53}Mn/^{55}Mn)$_0$ is unknown because Mn-Cr isotope systematics in CAIs is disturbed, but can be inferred from bulk carbonaceous chondrites

✓ Chainpur chondrules are 2.73 Myr younger relative to the "initial" ^{53}Mn/^{55}Mn in the Solar System

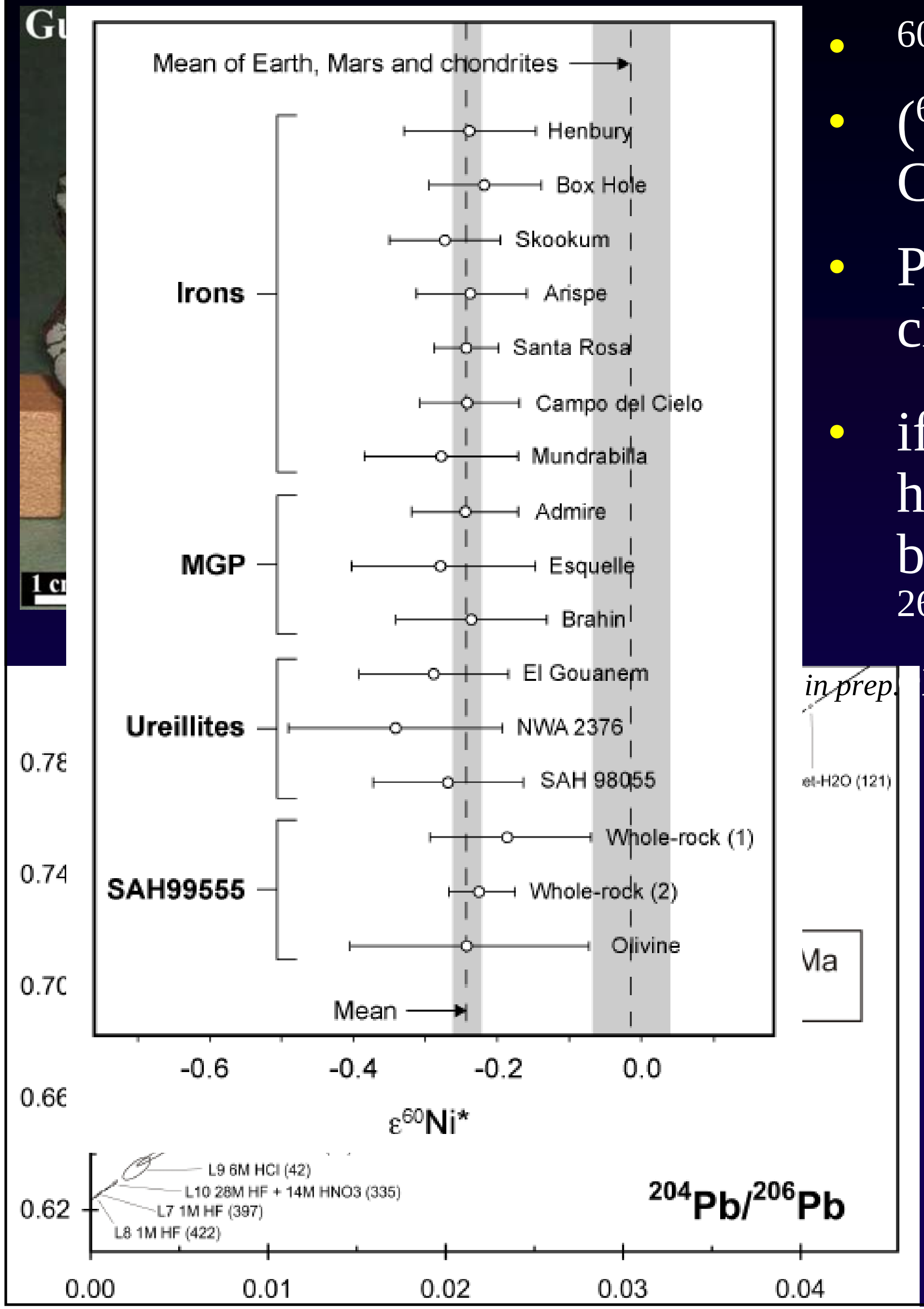


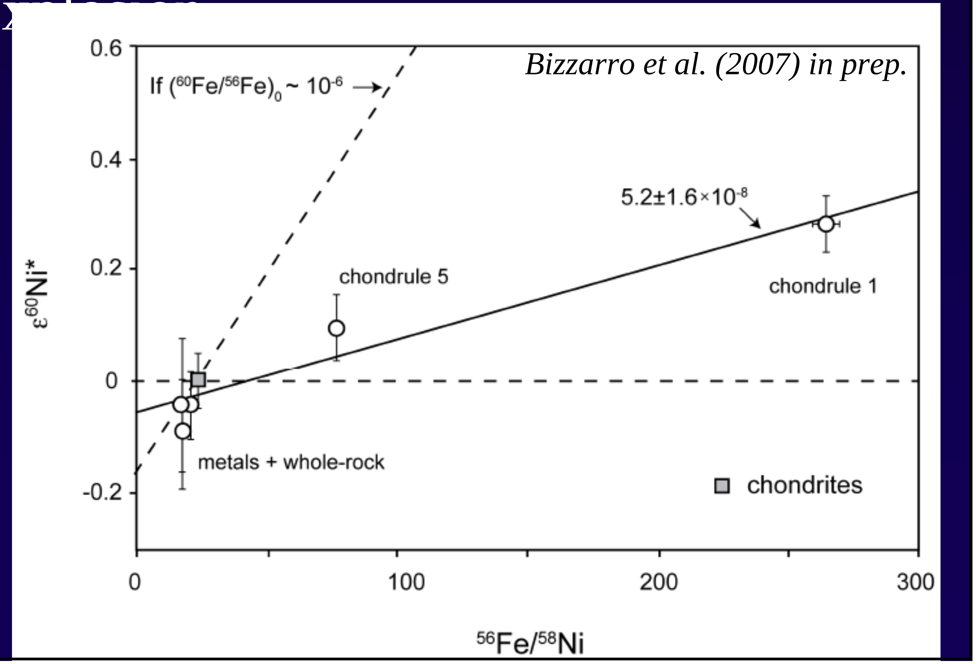
Yin et al. (2007) ApJL

^{53}Mn-^{53}Cr system of Chainpur chondrules

Relative chronology of CAI & chd formation: ^{60}Fe-^{60}Ni system

- $^{60}Fe \rightarrow {}^{60}Ni$ ($t_{1/2}$ = 1.49 Myr)
- $(^{60}Fe/^{56}Fe)_0$ is unknown because Ni in CAIs shows nuclear isotopic anomalies
- Pb-Pb & Fe-Ni chronology of CB chondrites
- if ^{60}Fe & ^{26}Al are decoupled, ^{60}Fe-^{60}Ni has limited chronological implication, but important astrophysical implication: ^{26}Al can not be injected with SN explosion




Bizzarro et al. (2007) in prep.

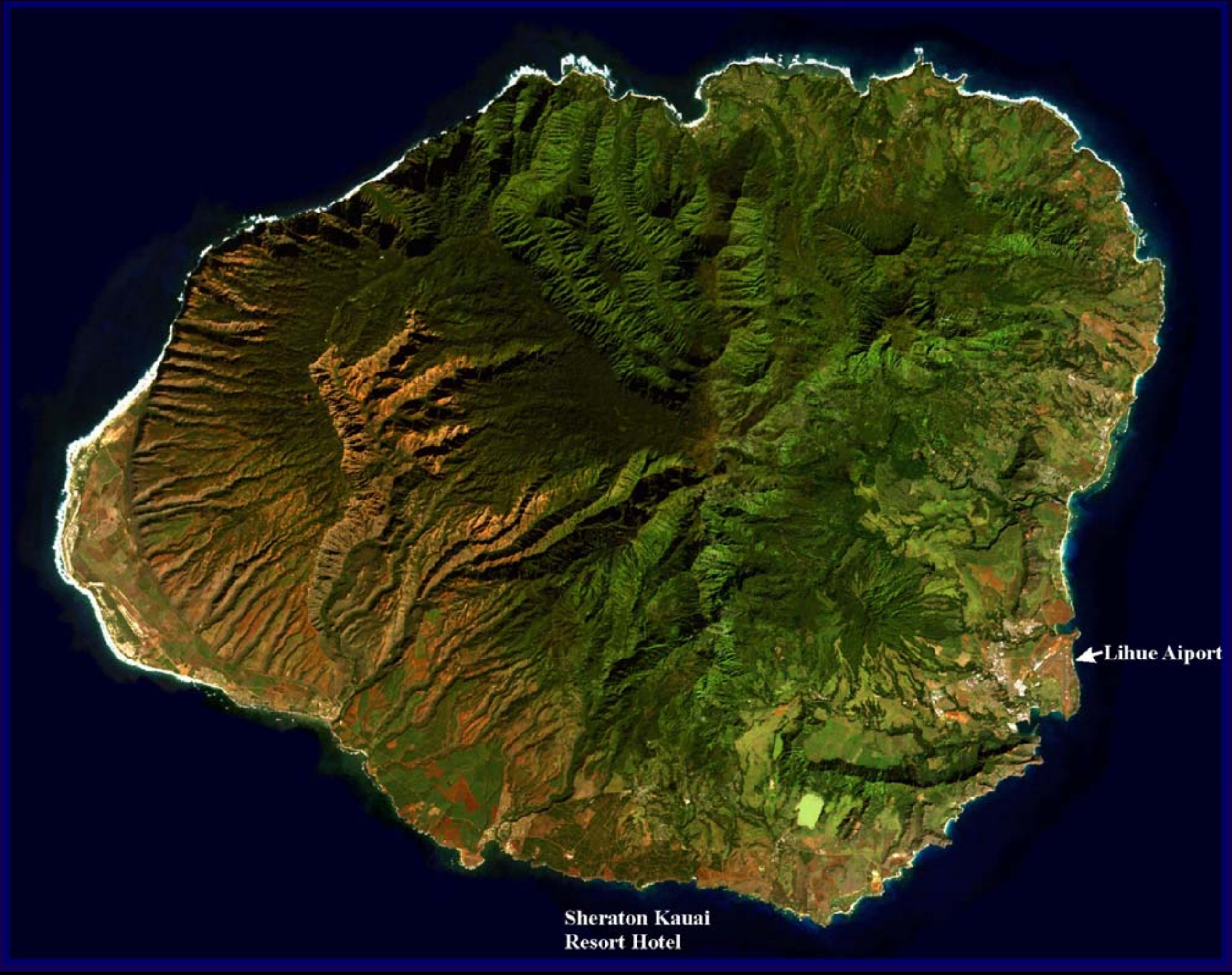
Conclusions: Part I

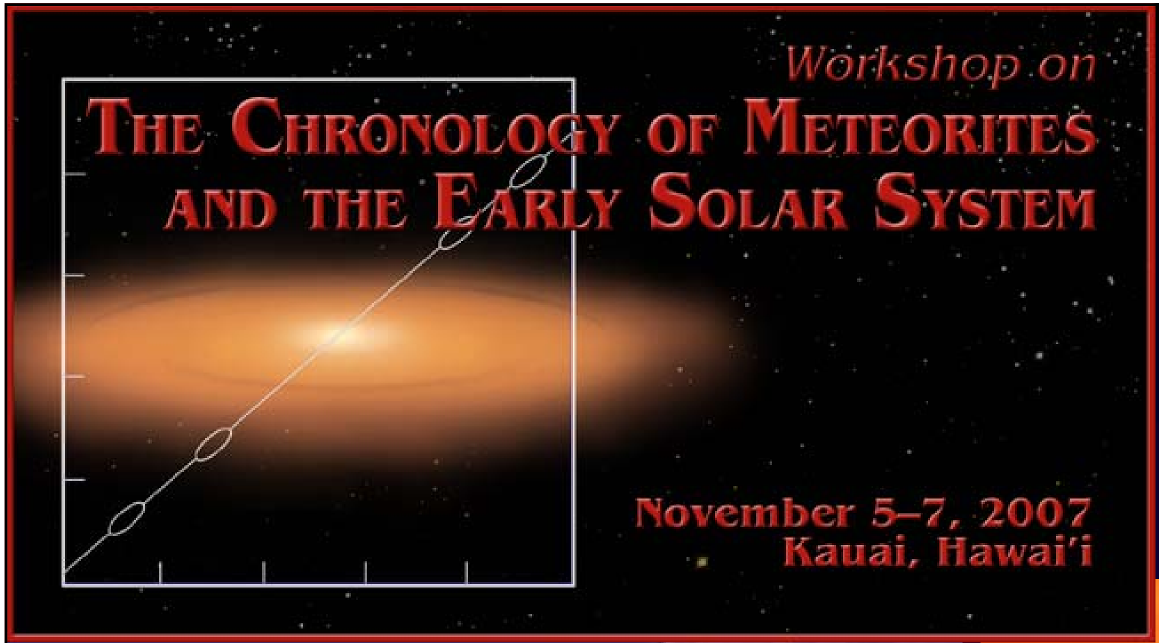
- evidence from short-lived (^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr) & long-lived (^{207}Pb-^{206}Pb) isotope systematics, oxygen isotopes & mineralogy all suggest that CAIs & AOAs were the first solids to form in the solar nebula, possibly within a period of <0.1 Myr, when the Sun was accreting rapidly as a class 0 or I protostar
- CAIs & AOAs formed multiple times either throughout the inner solar nebula or in a localized nebular region & were subsequently dispersed around the Sun
- most chondrules & matrices formed throughout the inner solar nebula 1-3 Myr after CAIs, when the Sun was accreting more slowly
- majority of chondrules in a chondrite group may have formed over a much shorter period (<0.5-1 Myr)
- CAIs were probably present in the chondrule-forming regions at the time of chondrule formation, but have been largely unaffected by chondrule melting events

Workshop *Chronology of Meteorites and the Early Solar System*

- Sheraton Kauai Resort Hotel, Kauai
- November 5-7, 2007

http://www.lpi.usra.edu/meetings/metchron2007

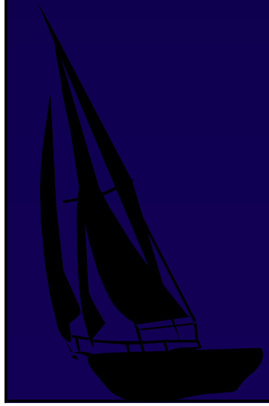




The workshop will honor the outstanding contributions of
C. Allégre, G. Lugmair, L. Nyquist, D. Papanastassiou, & G. Wasserburg
to our understanding of the chronology of the early solar system

http://www.lpi.usra.edu/meetings/metchron2007

- *Part II.* Origin & evolution of O-isotopic reservoirs in the Solar System
  - Introduction
  - Bulk O-isotopic compositions of asteroidal & planetary meteorites
  - O-isotopic composition of the Sun
  - Thermal processing of chondritic components in the early Solar System, their chronology & O-isotopic compositions
  - CO self-shielding model
  - Conclusions



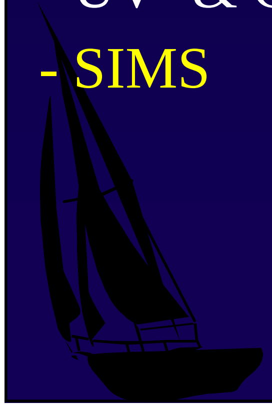
Definitions & Analytical Techniques

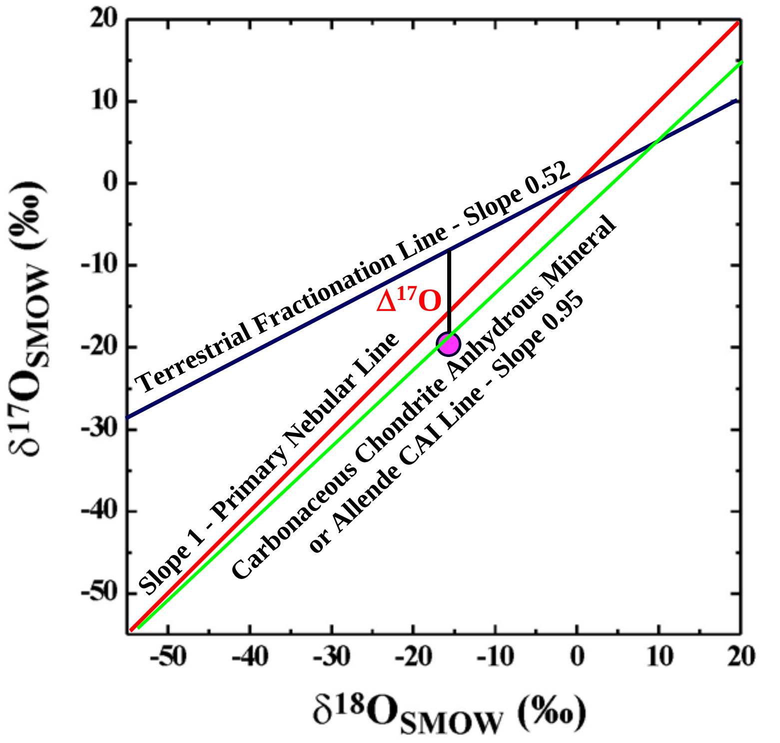
- O - third most abundant element in the Solar System
- major oxygen species in the solar nebula - CO : H_2O : silicates = 3 : 2 : 1
- $^{16}O = 99.76\%$, $^{17}O = 0.039\%$, $^{18}O = 0.202\%$
- $\delta^{17}O = [(^{17}O/^{16}O)_{sample}/(^{17}O/^{16}O)_{SMOW} - 1]\times1000$
- $\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW} - 1]\times1000$

SMOW = *Standard Mean Ocean Water*

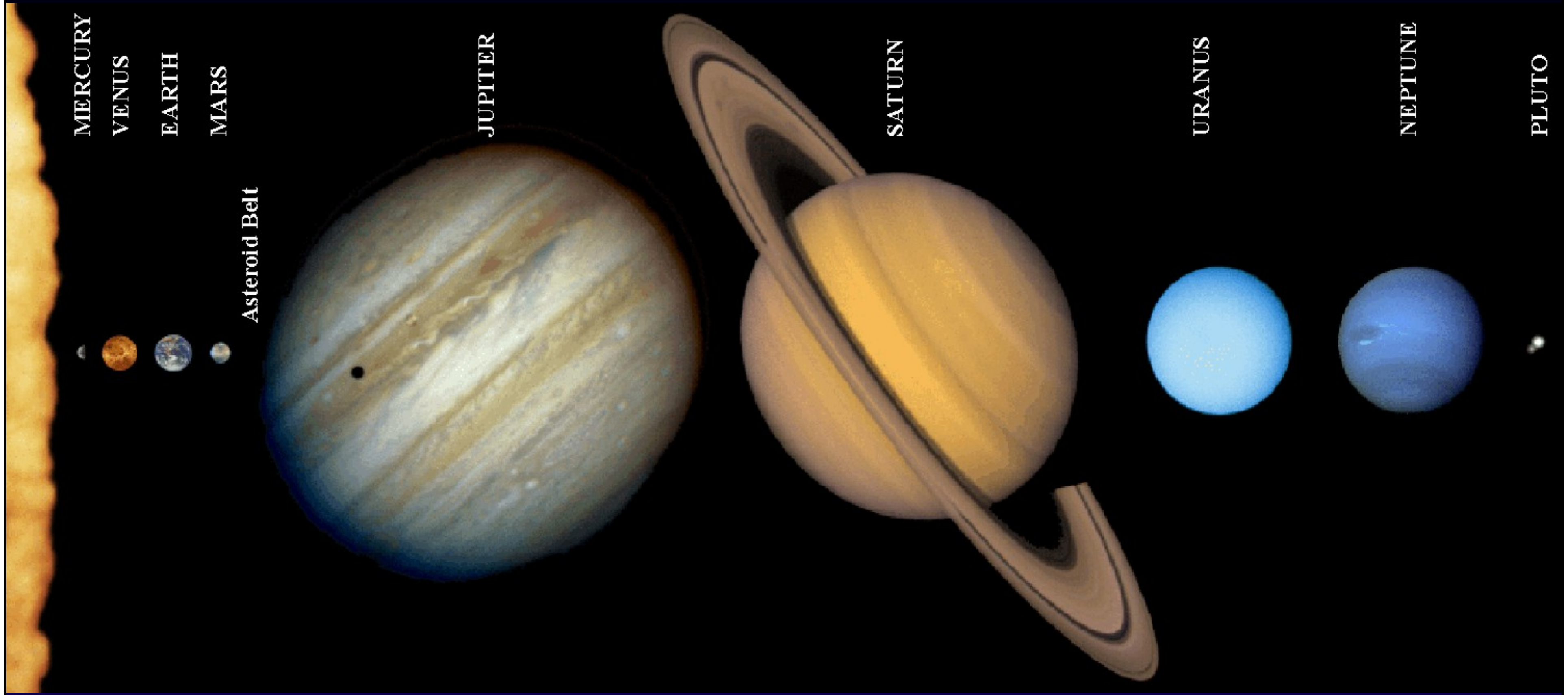
- $\Delta^{17}O = \delta^{17}O - 0.52 \times \delta^{18}O$

analytical techniques	ncertainty, 2σ, $\Delta^{17}O$
- fluorination+MS	0.16‰
- UV- & CO_2 LF+MS	0.04 – 0.4‰
- SIMS	<0.5‰





Oxygen isotopic compositions of the Solar System bodies

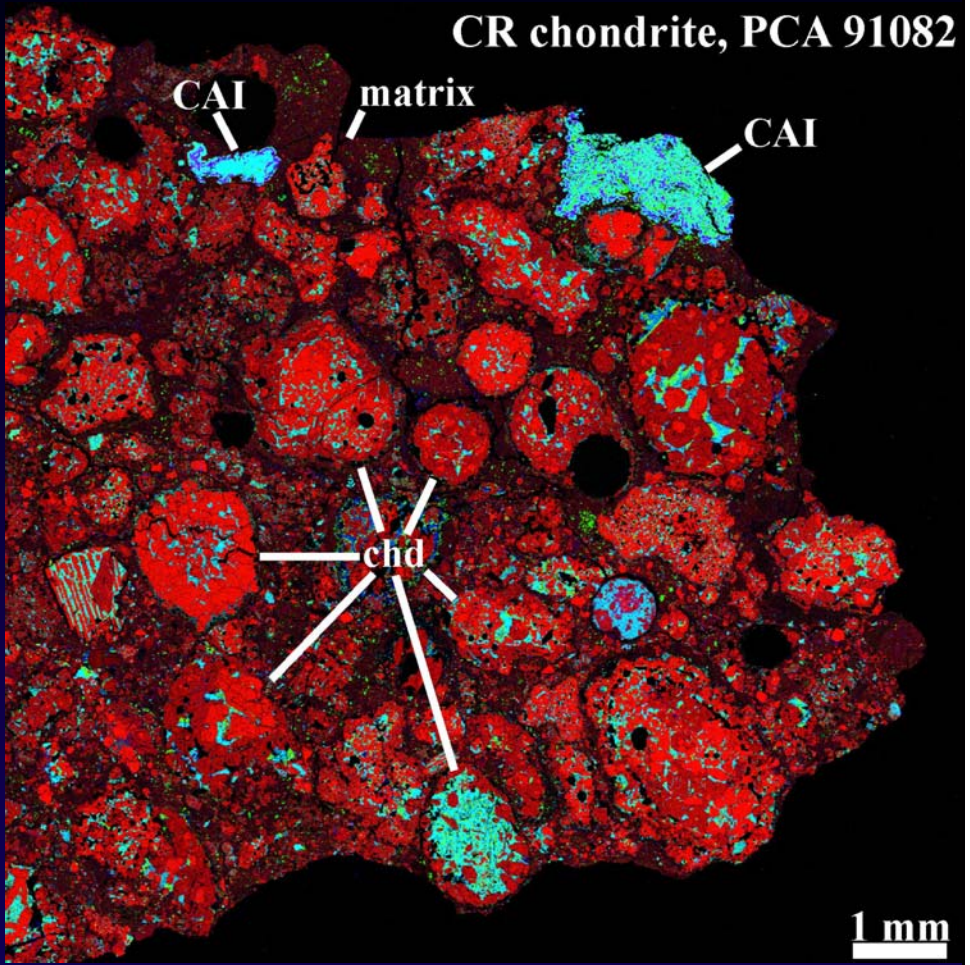


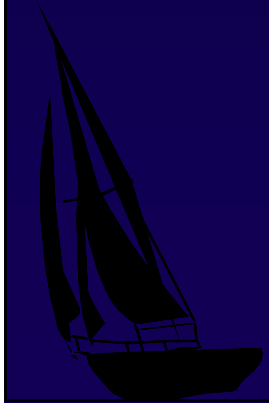
- ✓ Sun* - ? Δ^{17}O = 0‰, < -20‰, > +20‰ (*Genesis)
- Mercury - ?
- Venus - ?
- ✓ Earth, Moon: Δ^{17}O = 0‰
- ✓ Mars: Δ^{17}O = +0.32‰
- ✓ poorly sampled Asteroid Belt: Δ^{17}O = -5.7‰ to +3.4‰

- Jupiter - ?
- Saturn - ?
- Uranus - ?
- Neptune - ?
- Comets - ?

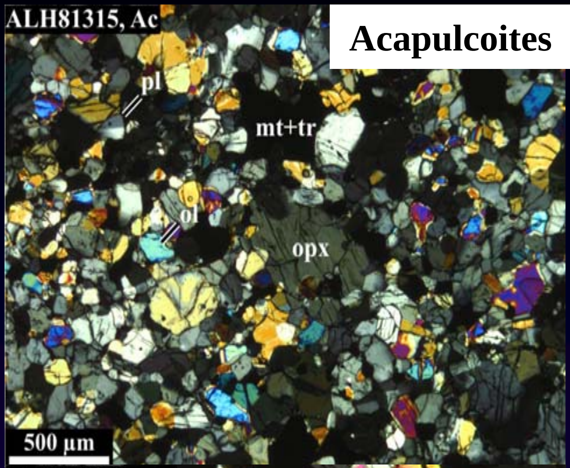
Chondrites & their components

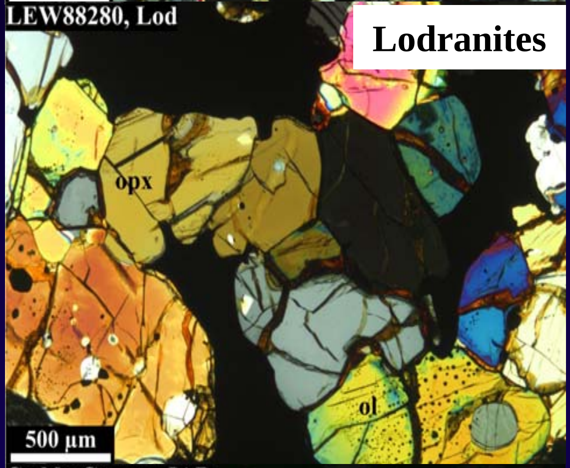
- major chondritic components:
  - ✓ chondrules
  - ✓ refractory inclusions
  - ✓ fine-grained matrix
- formed in the PPD by high-temperature processes (evaporation, condensation, & melting)
- may have recorded O-isotopic composition of PPD at different times & places

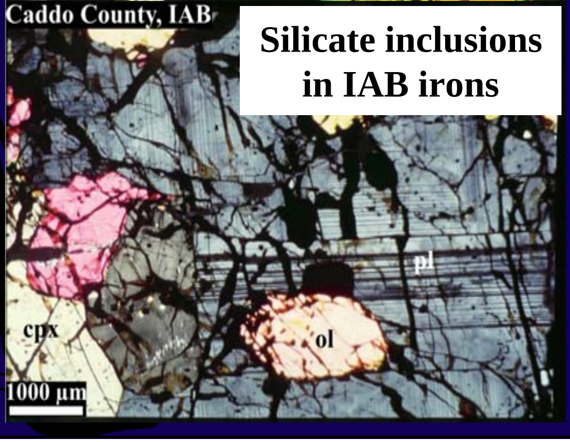




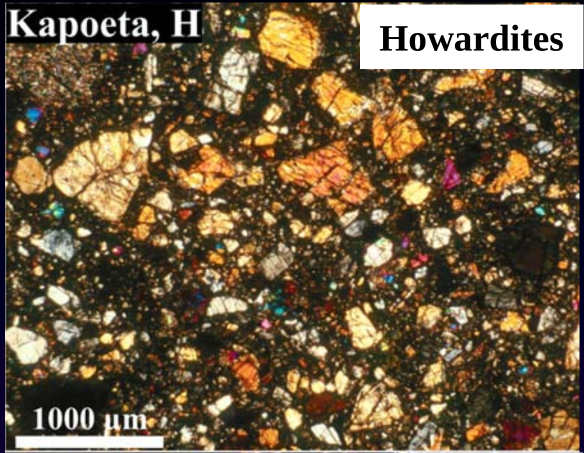
Primitive achondrites

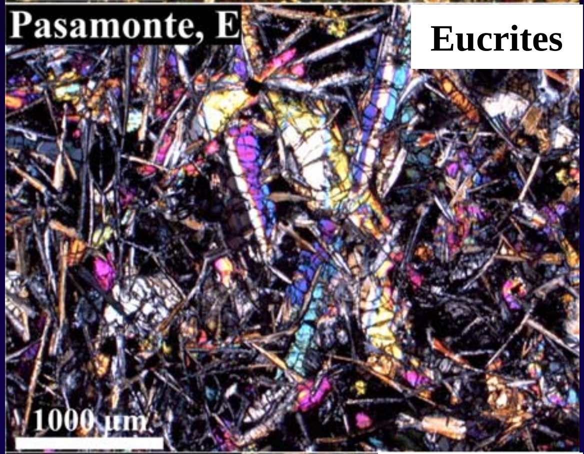

Acapulcoites


Lodranites

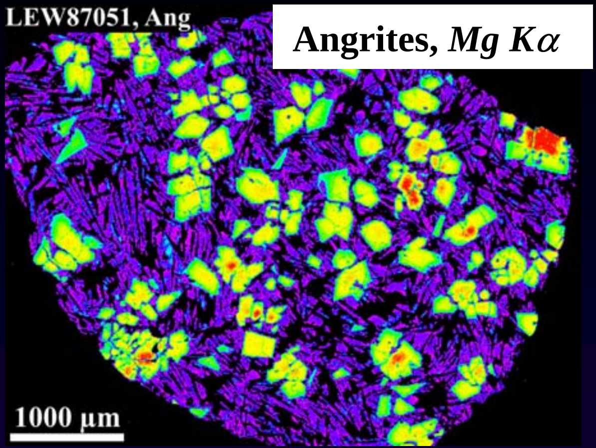

Silicate inclusions in IAB irons

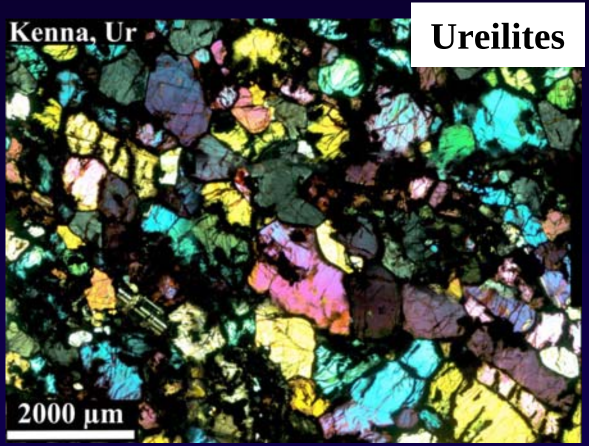
Differentiated achondrites

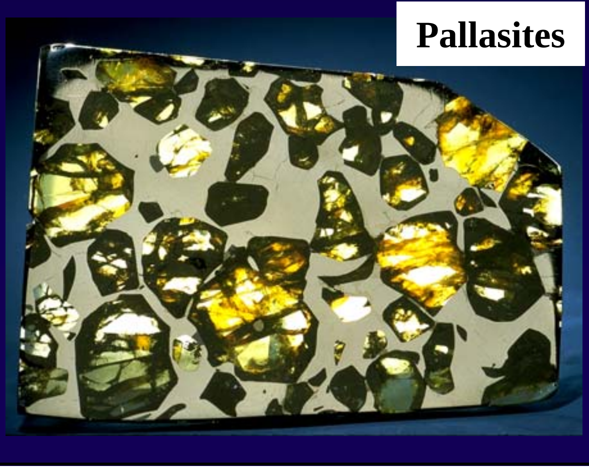

Howardites


Eucrites


Diogenites


Angrites, *Mg* $K\alpha$

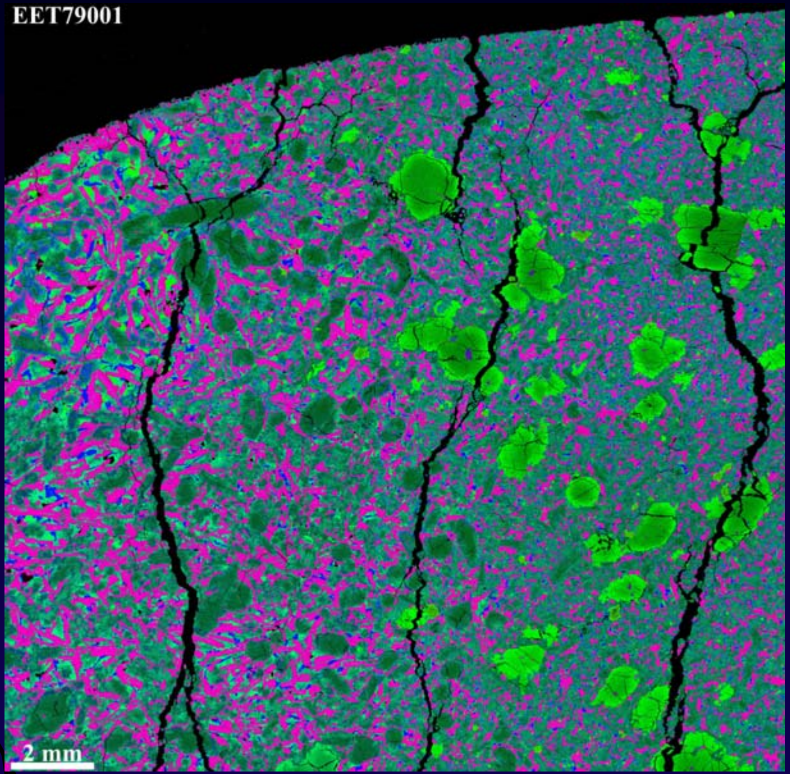

Ureilites


Pallasites

Planetary differentiated achondrites (cont.)

Martian meteorites

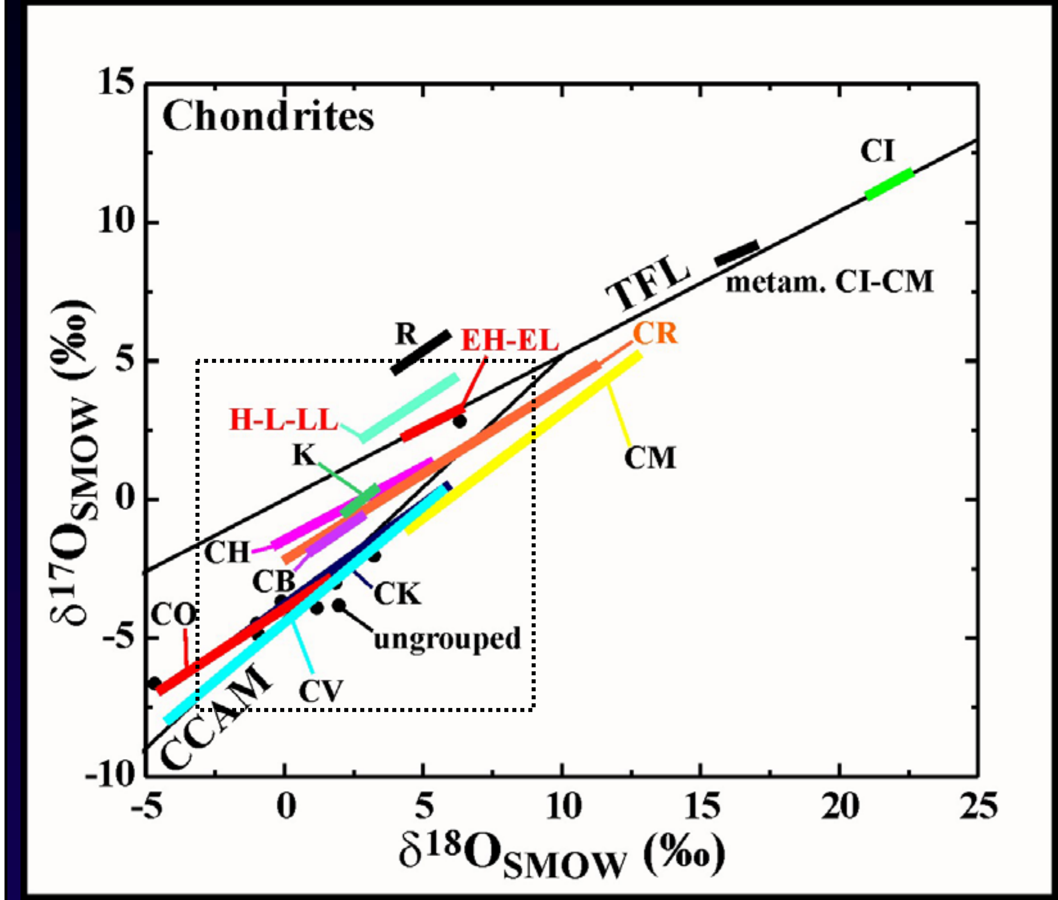
Lunar meteorites & samples

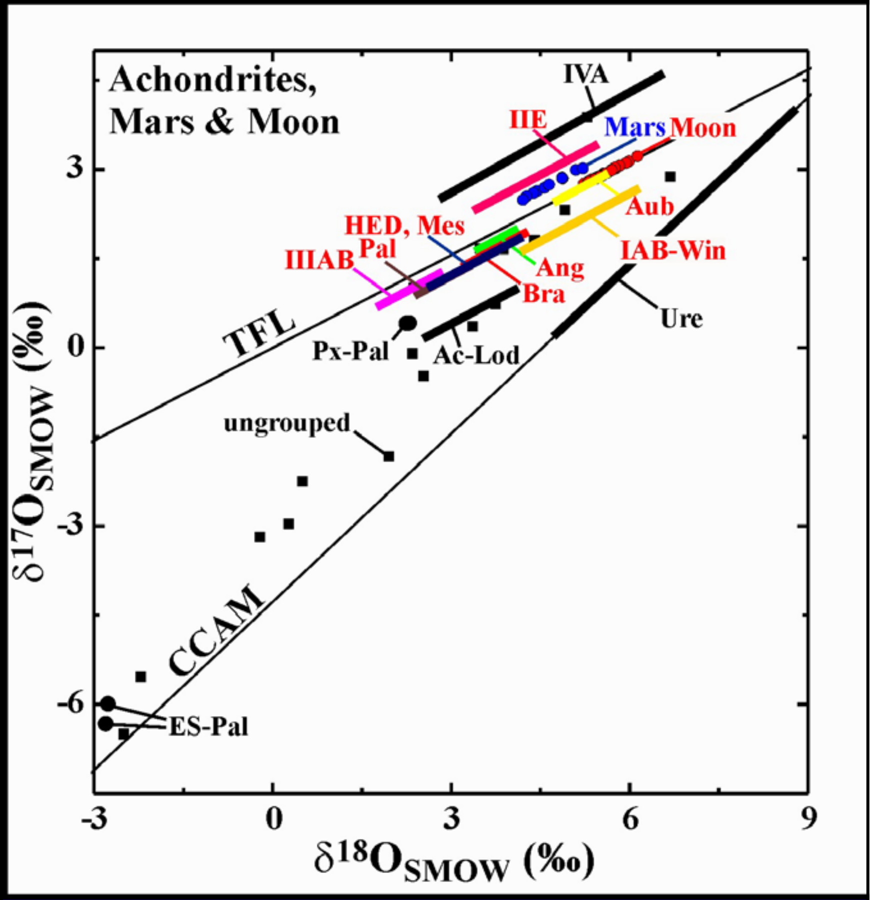


Courtesy of C. Goodrich

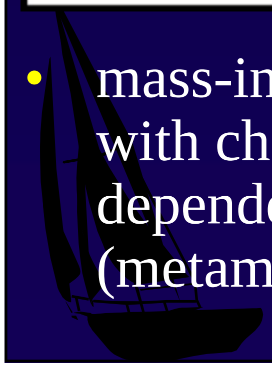
Courtesy of M. Kilgore

Bulk oxygen isotopic compositions of meteorites





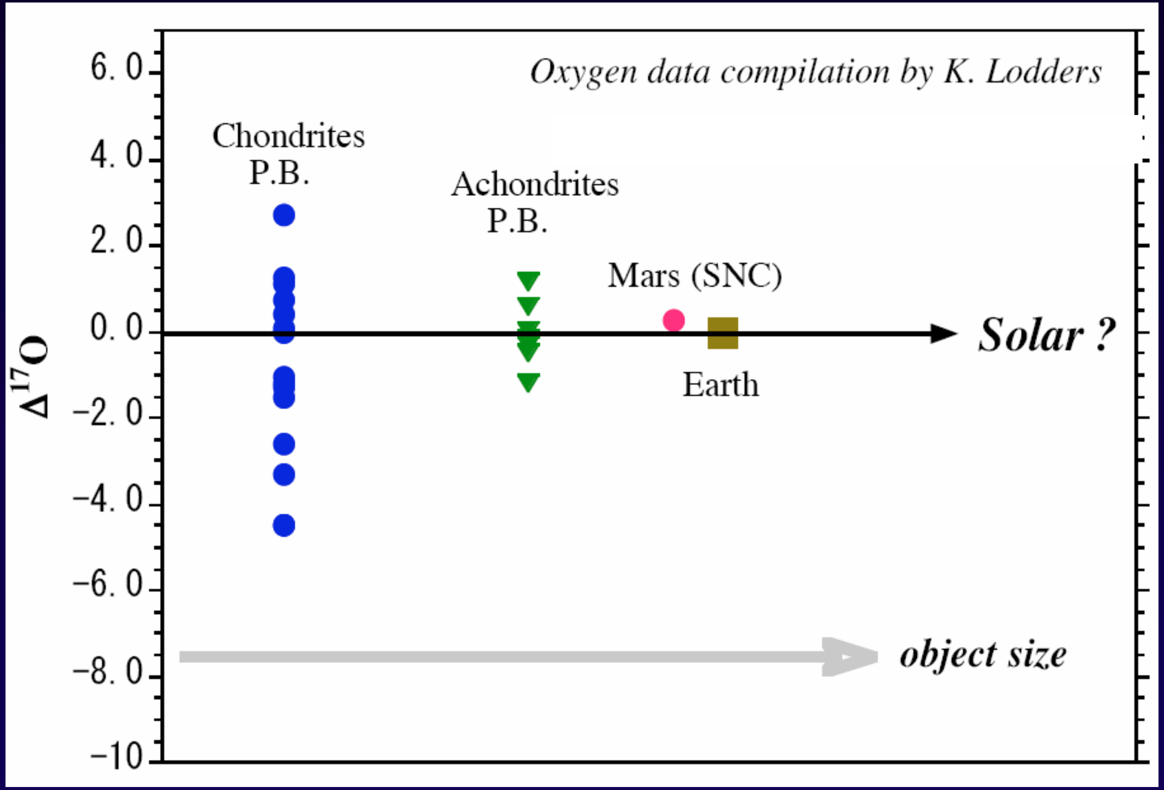
data from R. Clayton's lab



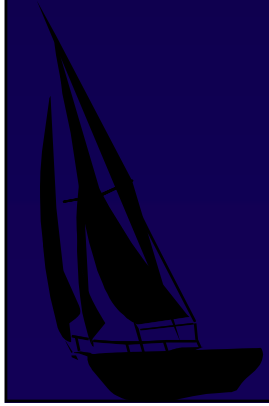
- mass-independent effects associated with chondritic components + mass-dependent asteroidal prosesses (metamorphism & aqueous alteration)
- varying degree of melting & isotope homogenization

Oxygen isotopic composition of the Sun: I. $\Delta^{17}O \sim 0‰$

- chondrite & achondrite parent bodies, Mars, & Earth formed from progressive random accretion of planetesimals, & hence, should have the same $\Delta^{17}O$ as the solar nebula, which represents the average $\Delta^{17}O$ of a whole planetesimal population



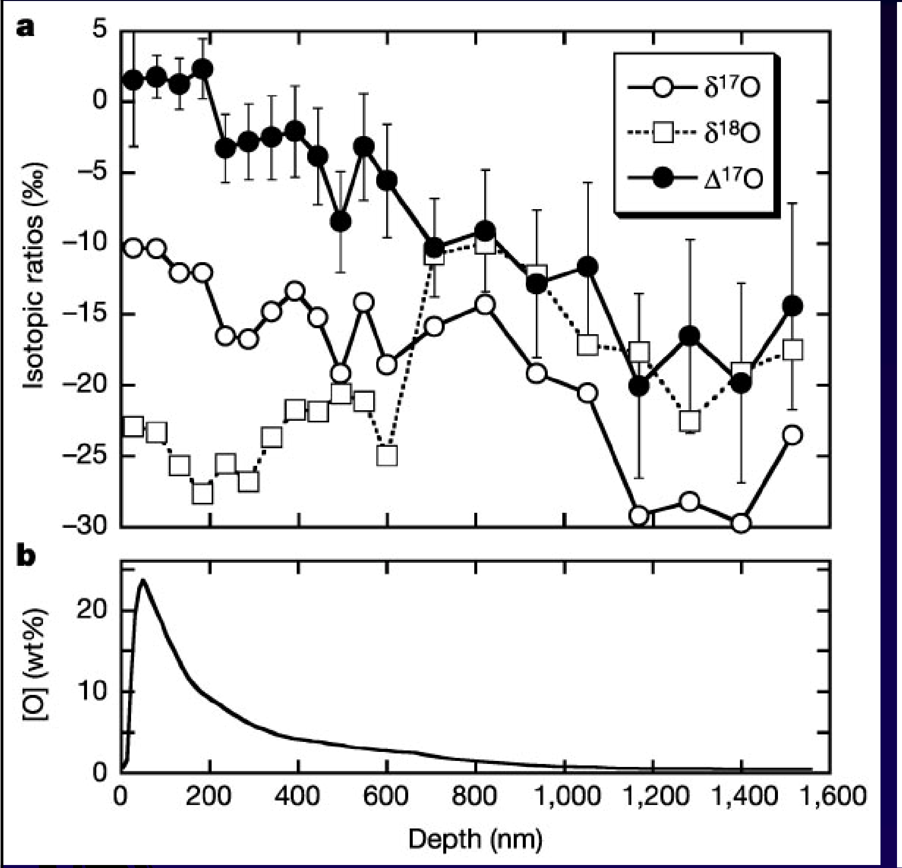
Ozima et al. (2006) LPSC

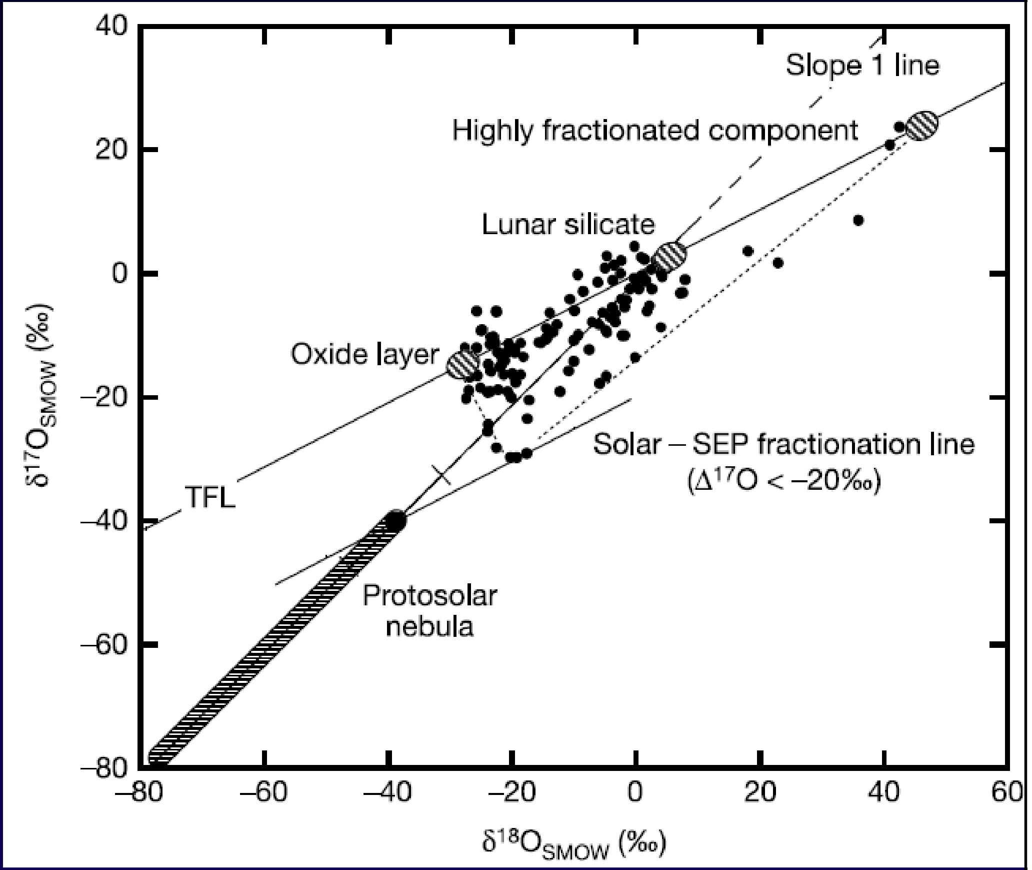


Oxygen isotopic composition of the Sun: II. $\Delta^{17}O < -20‰$

A non-terrestrial ^{16}O-rich isotopic composition for the protosolar nebula

Ko Hashizume[1] **& Marc Chaussidon**[2] *(Nature, 2005, 619-622)*

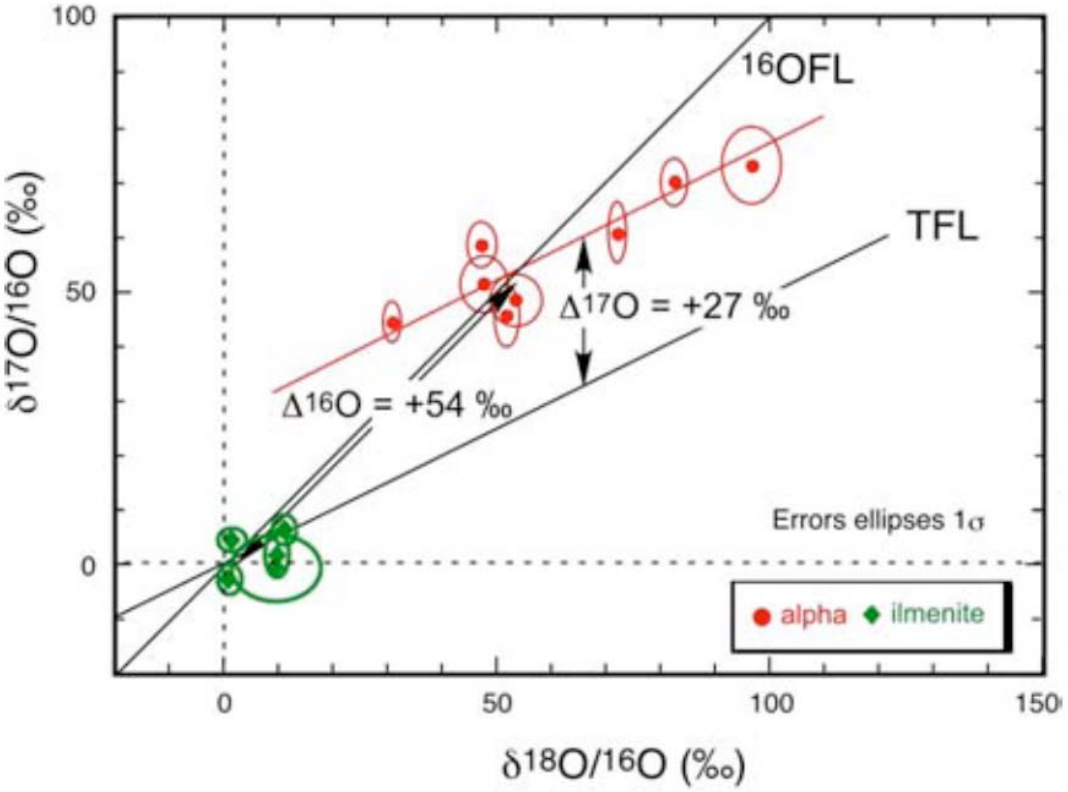


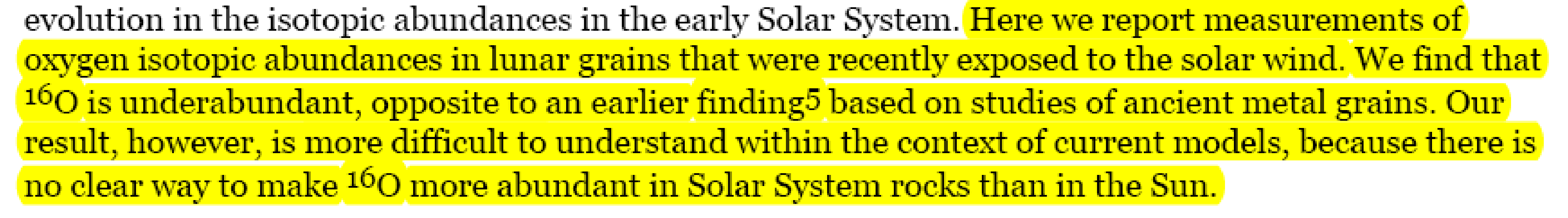


Oxygen isotopic composition of the Sun: III. $\Delta^{17}O > +20‰$

Isotopic enhancements of ^{17}O and ^{18}O from solar wind particles in the lunar regolith

(Ireland, Holden, Norman, & Clarke, 2006, Nature, 440, 776-778)



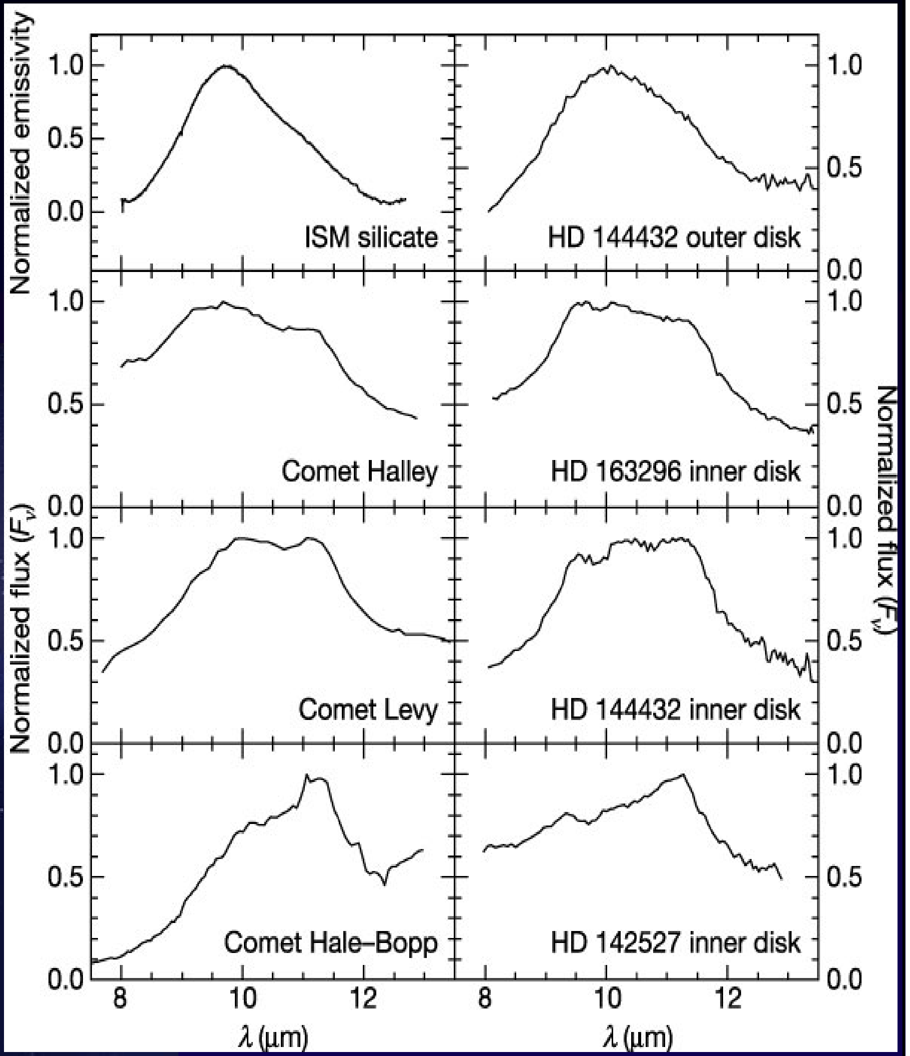

evolution in the isotopic abundances in the early Solar System. Here we report measurements of oxygen isotopic abundances in lunar grains that were recently exposed to the solar wind. We find that ^{16}O is underabundant, opposite to an earlier finding5 based on studies of ancient metal grains. Our result, however, is more difficult to understand within the context of current models, because there is no clear way to make ^{16}O more abundant in Solar System rocks than in the Sun.

Thermal processing of solids in the protoplanetary disks

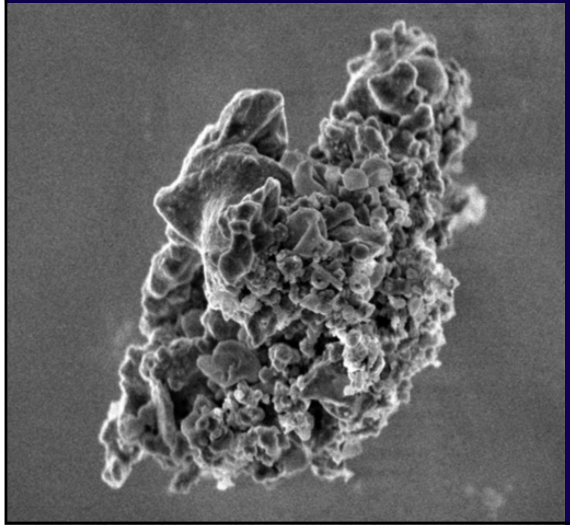
- silicates in ISM & outer part of the PPDs are largely amorphous
- inner disks, comets, & matrices of primitive chondrites contain abundant crystalline silicates (*Scott Messenger*)

→ crystalline silicates formed by thermal processing in the inner PPDs

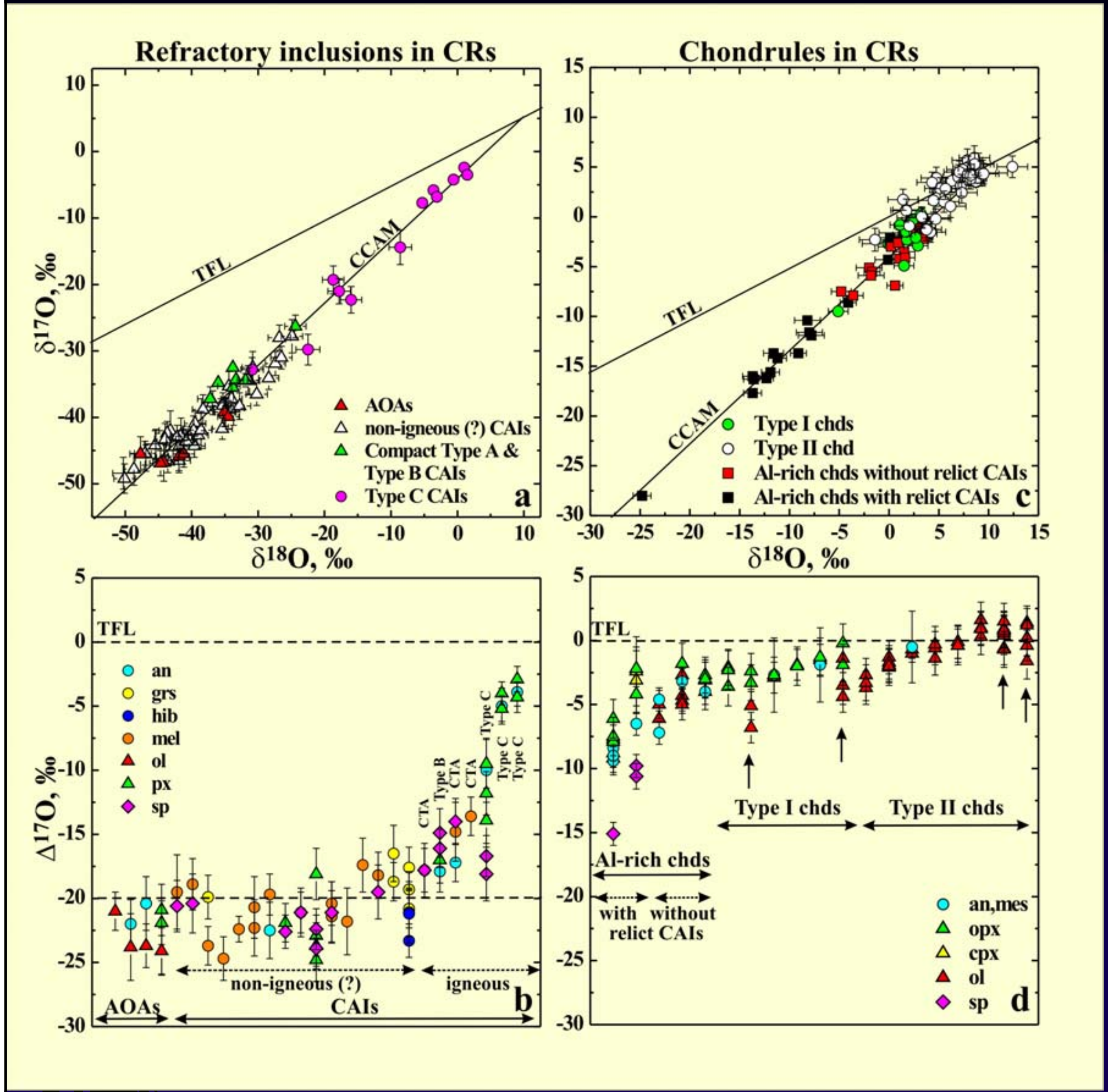
→ radial mixing



van Boekel et al. (2004) Nature



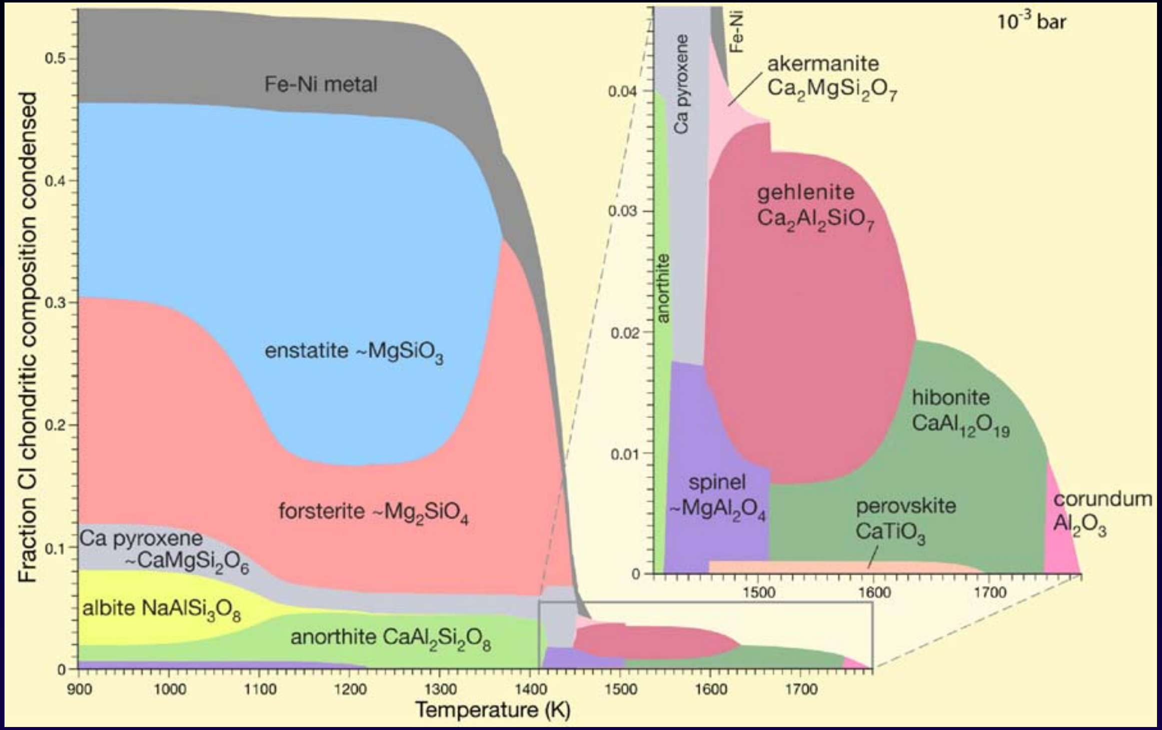
O-isotopic compositions of CAIs, AOAs & chondrules in CRs



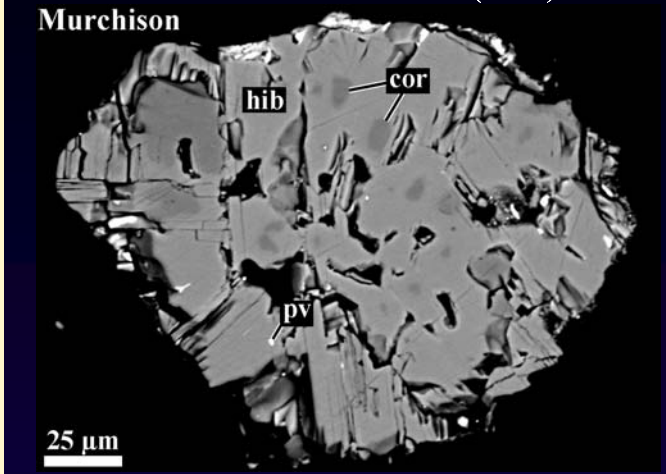
Aléon et al. (2002) GCA; Connolly et al. (2003) LPSC; Krot et al. (2005) GCA

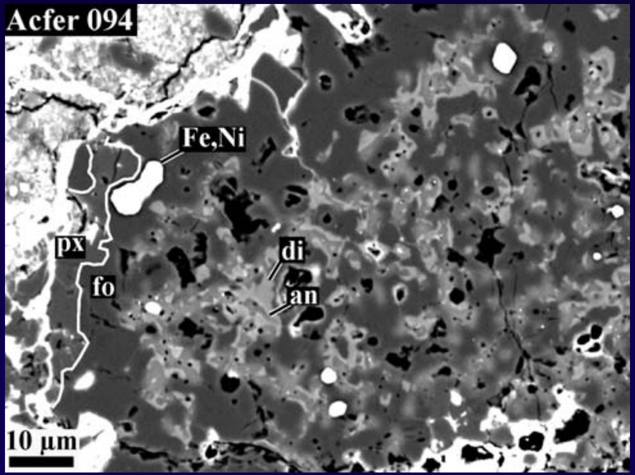
- chondrules, CAIs & AOAs plot along slope-1 line
- AOAs & most CAIs are ^{16}O-rich ($\Delta^{17}O \leq -20$‰)
- chondrules are ^{16}O-depleted ($\Delta^{17}O > -5$‰)
- some igneous CAIs are ^{16}O-depleted like chondrules

^{16}O-rich gaseous reservoir in the early Solar System



Simon et al. (2002) MAPS

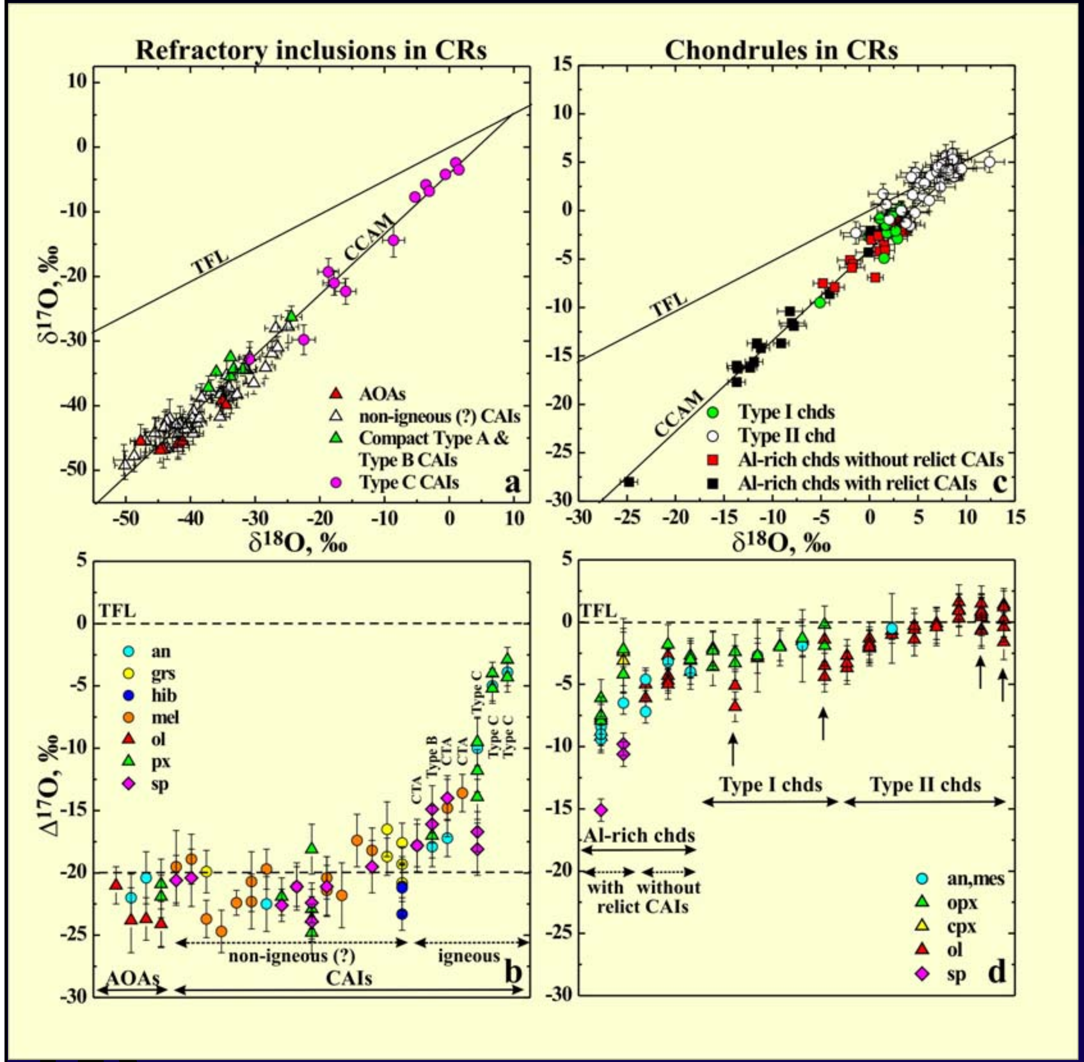


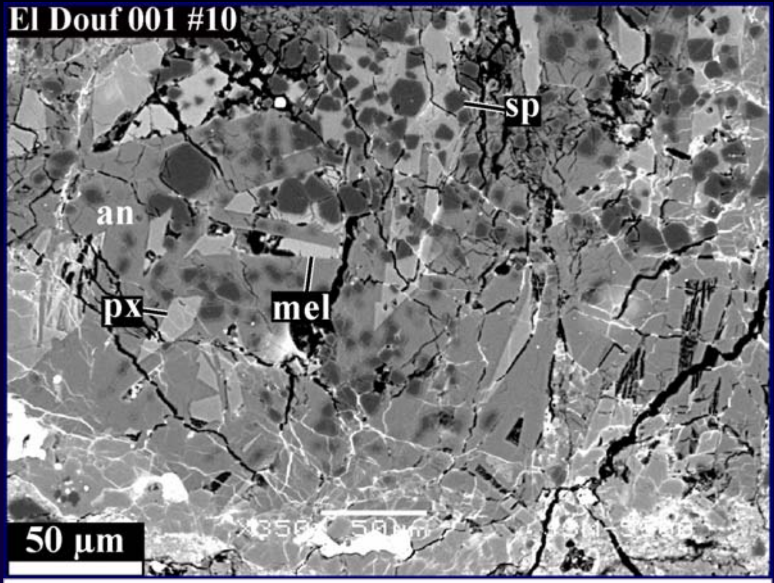


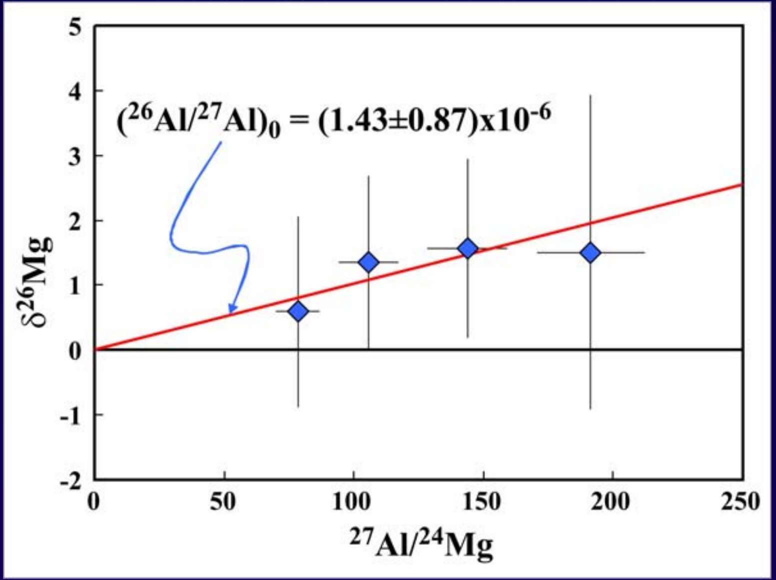
Krot et al. (2005) GCA

- ✓ CAIs & AOAs formed in the presence of ^{16}O-rich nebular gas (Δ^{17}O ~ -20‰), consistent with ^{16}O-rich inferred composition of the Sun
- ✓ ^{16}O-rich gas was dominant through the entire condensation sequence (from corundum to enstatite) recorded by CAIs & AOAs

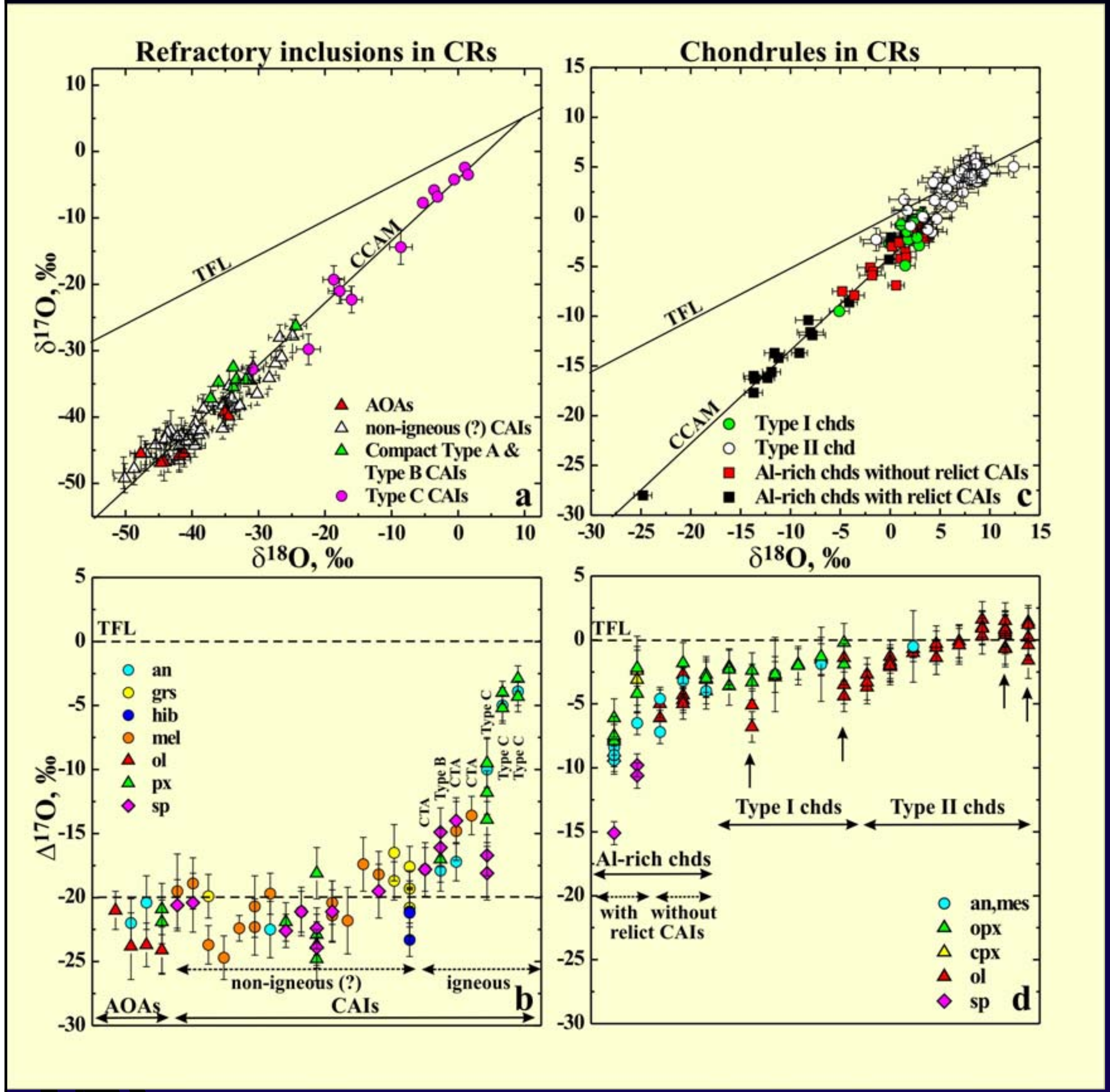
^{16}O-depleted CAIs: Isotopic exchange during late-stage melting







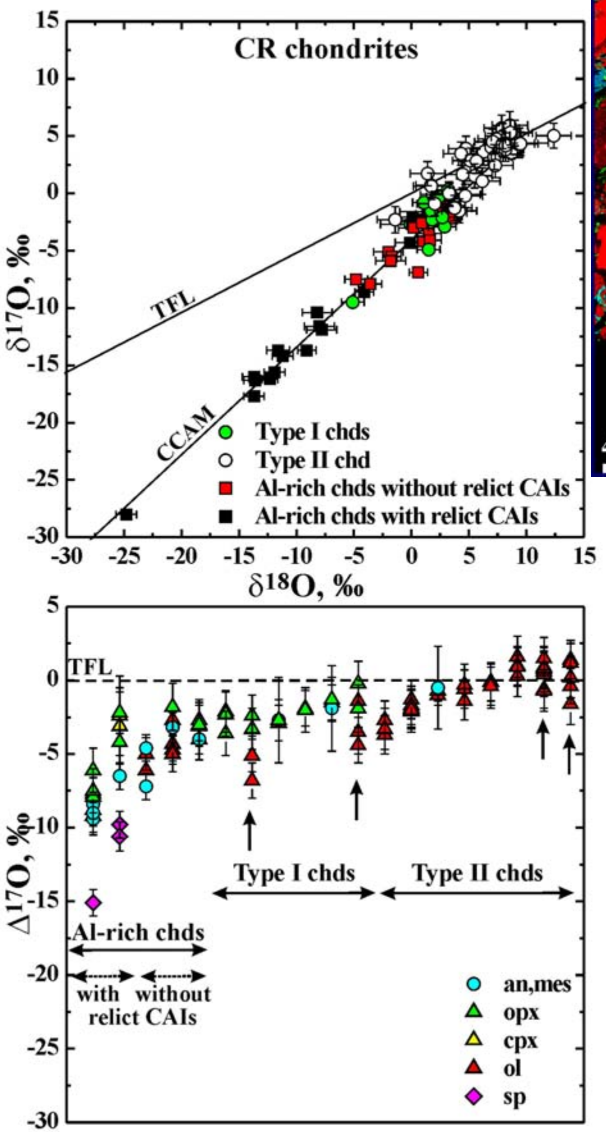
O-isotopic compositions of chondrules

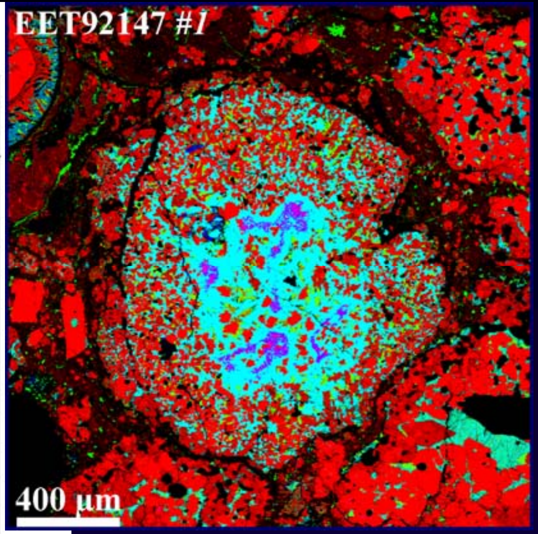


(Aléon et al., 2002; Connolly et al., 2003; Krot et al., 2005)

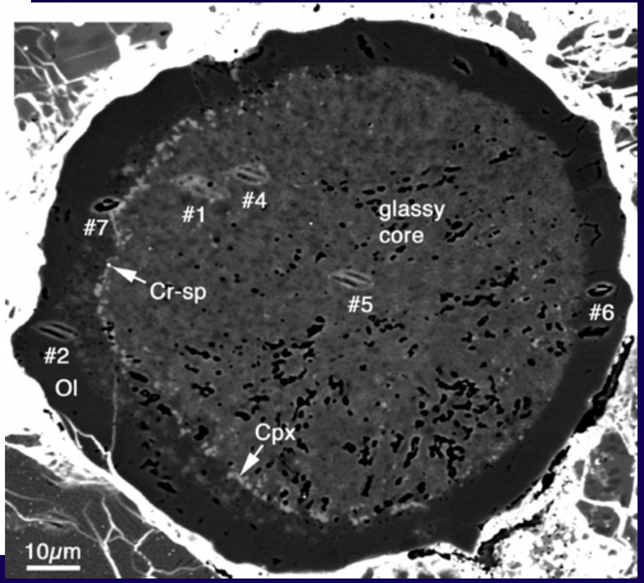
- chondrules are ^{16}O-depleted relative to AOAs & most CAIs
- ^{16}O-depletion decreases in order Al-rich → Type I → Type II chondrules
- FeMg-chondrules are isotopically uniform (±3-4‰)
- Al-rich chondrules are more heterogeneous

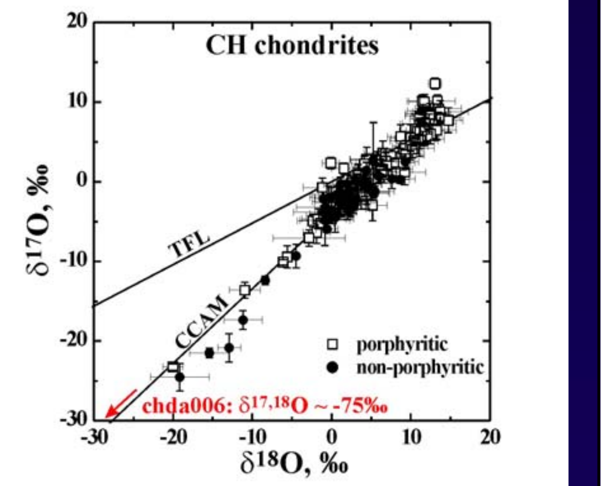
O-isotopic compositions of chondrules





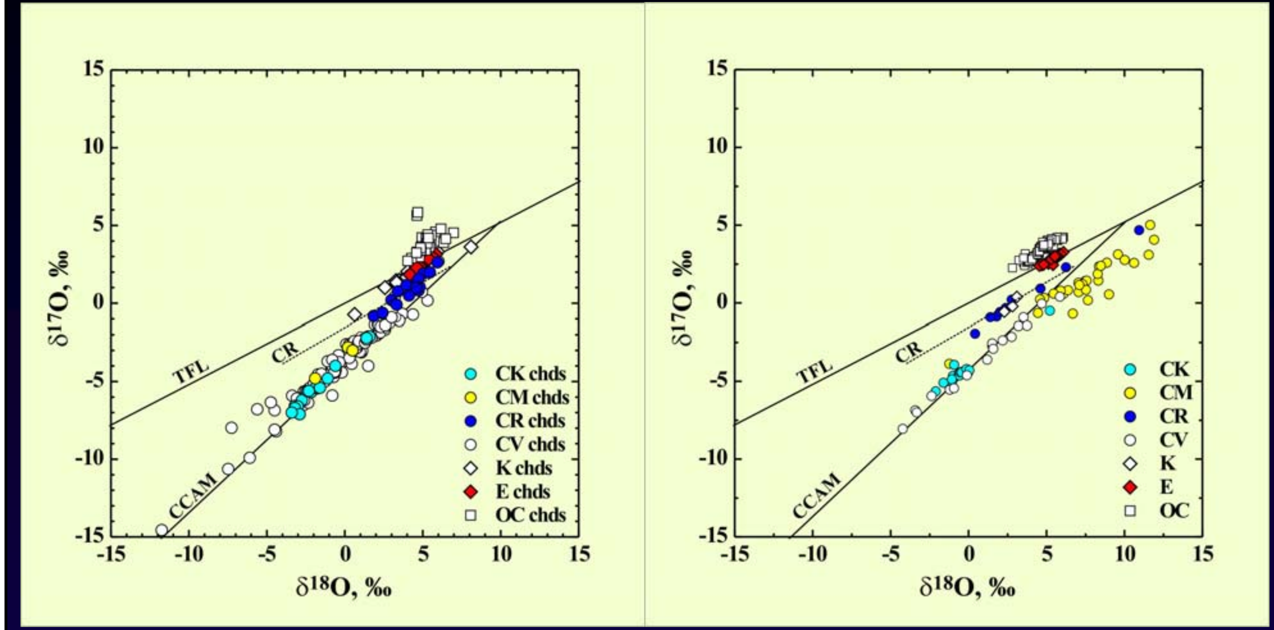
- O-isotopic heterogeneity is due to relict grains melted to varying degrees
- ^{16}O-depletion correlates with oxidation state
- no evidence that chondrules formed from ^{16}O-rich solids or in ^{16}O-rich gas
- the only exception is a unique chondrule from CH

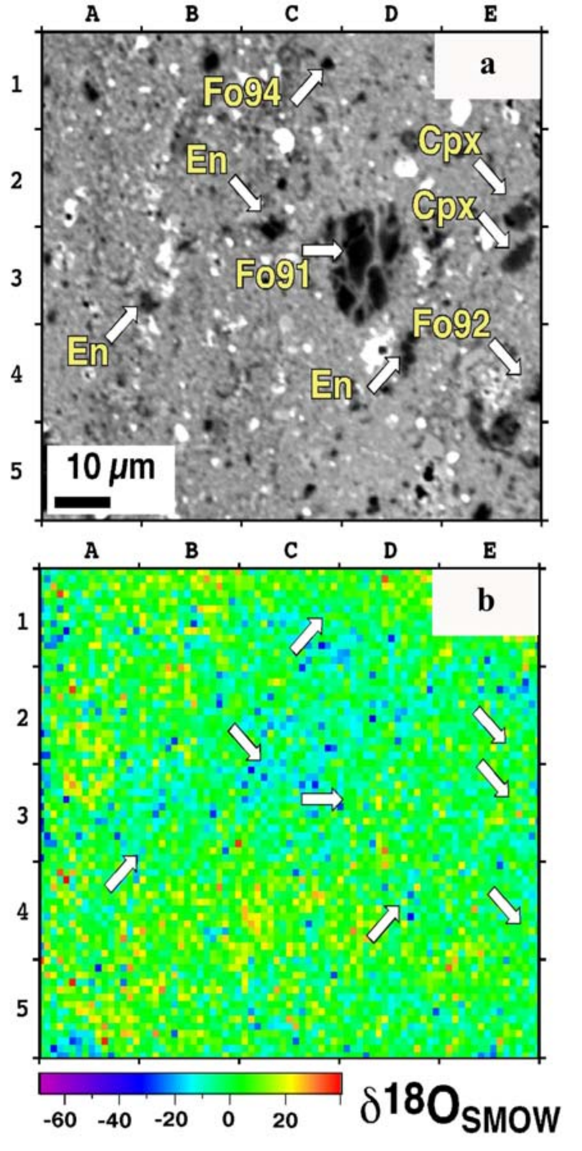




(Kobayashi et al., 2003; Yoshitake et al., 2004)

Chondrule-matrix relationship: Evidence from O-isotopes





Kunihiro et al. (2005) GCA

- bulk O-isotopic compositions of chondrules & their host meteorites are similar
- chondrules & matrices are the dominant components of chondrites → chds & matrices of primitive chondrites have similar O-compositions
- matrices are chemically complementary to chondrules → experienced extensive evaporation & recondensation during chondrule formation, which contradicts X-wind model of chondrule & CAI formation

Summary of SIMS O-isotope measurements

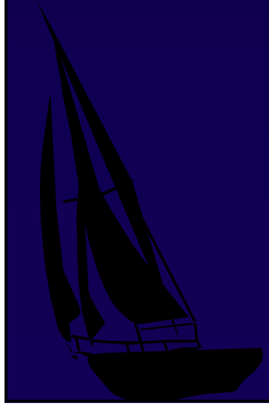
- AOAs & most CAIs are uniformly ^{16}O-rich (Δ^{17}O < -20‰), suggesting formation in the presence of ^{16}O-rich nebular gas
  - O-isotopic heterogeneity in CAIs is due to their late-stage remelting in the presence of ^{16}O-poor gas
- most chondrules are ^{16}O-depleted (Δ^{17}O > -5‰) relative to AOAs & CAIs & isotopically uniform (within 3-4‰)
  - O-isotope heterogeneity in chondrules is due to relict grains, which are ^{16}O-enriched relative to host chondrules

→ most chondrules formed from isotopically heterogeneous, but ^{16}O-depleted solid precursors & experienced isotopic exchange with ^{16}O-poor gas during melting

- CAI & AOA formation started first & may have lasted <0.1 Myr; chondrule started ~ 1 Myr later & lasted for ~3-4 Myr

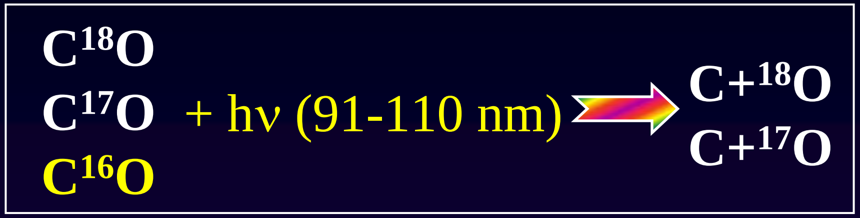
Origin of mass-independent fractionation

- inherited O-isotopic heterogeneity in the solar nebula (^{16}O-rich solids & ^{16}O-poor gas), resulting from nucleosynthesis in stars (*Clayton, 1973*)
- chemical mass-independent fractionation effects during gas-phase ($O + MO \rightarrow MO_2$; *Thiemens, 2006*) or grain-surface condensation reactions (*Marcus, 2004*)
- isotopic self-shielding during UV photolysis of CO in the initially ^{16}O-rich protoplanetary disk or protosolar molecular cloud
  - inner protoplanetary disk (*Clayton, 2002, Nature*)
  - molecular cloud (*Yurimoto & Kuramoto, 2004, Nature*)
  - outer protoplanetary disk (*Lyons & Young, 2005, Science*)

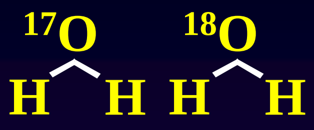


Photochemical self-shielding of CO gas irradiated by UV

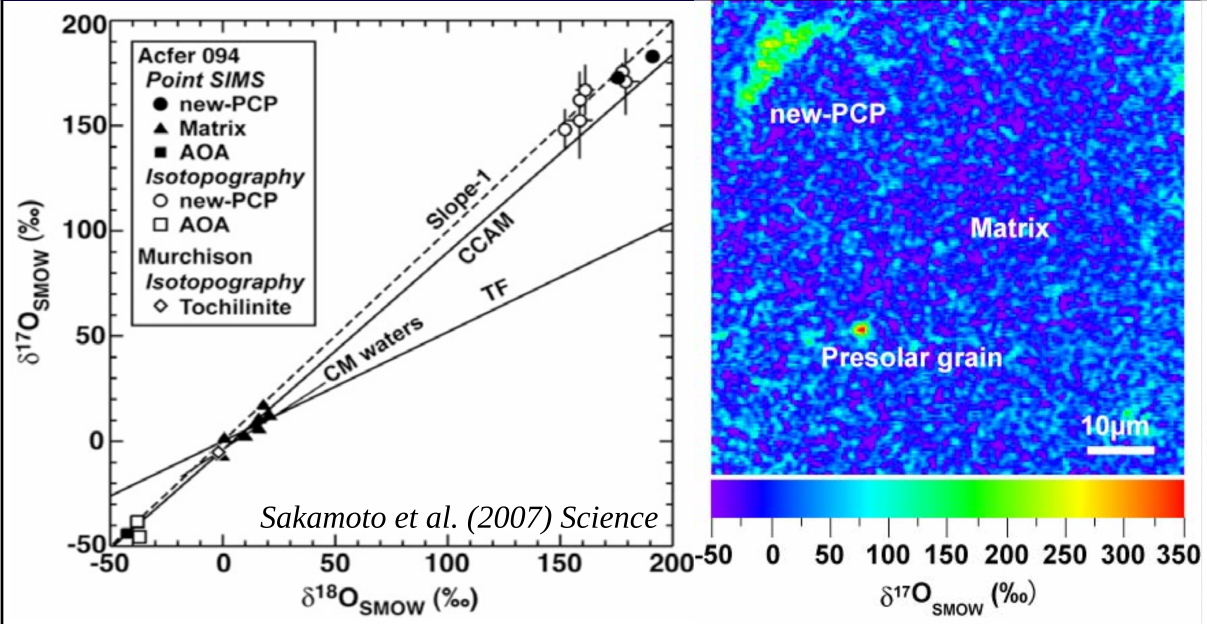
- preferential photodissociation of $C^{17}O$ & $C^{18}O$ in initially ^{16}O-rich ($\Delta^{17}O$ = -25‰) MC or PPD; released ^{17}O & ^{18}O are incorporated into $H_2O_{(s)}$



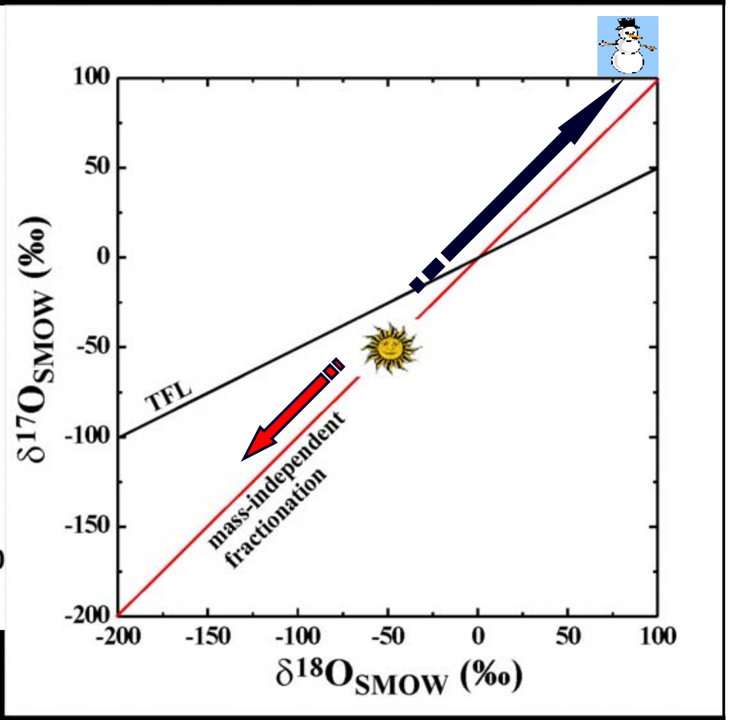
$C^{18}O$, $C^{17}O$, $C^{16}O$ + hν (91-110 nm) → $C + ^{18}O$, $C + ^{17}O$



- ^{16}O-rich $CO_{(g)}$; ^{16}O-poor $H_2O_{(s)}$



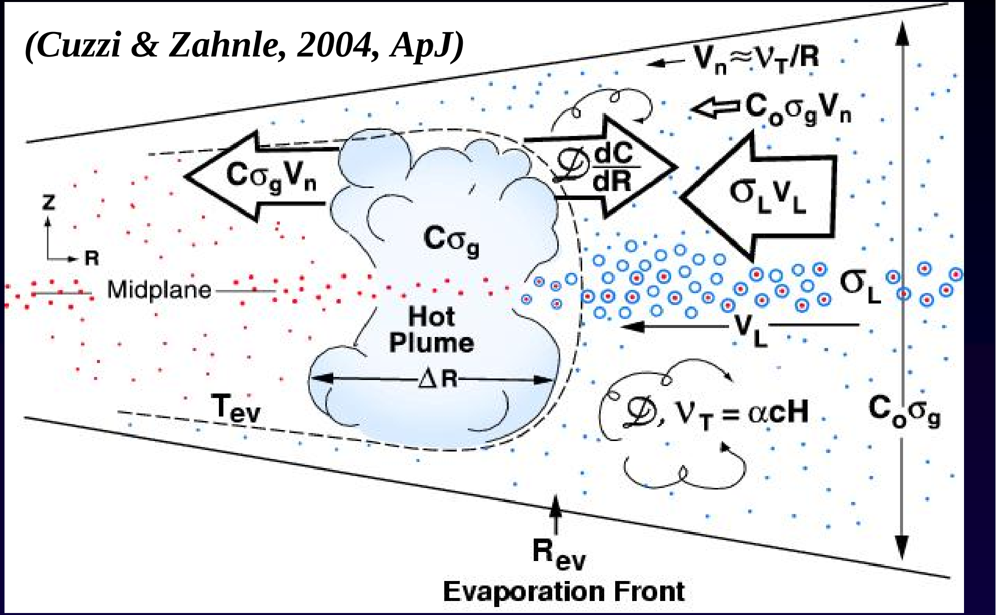
Sakamoto et al. (2007) Science



Yurimoto & Kuramoto (2004) Nature

- $H_2O_{(s)}/CO_{(g)}$ enrichment in the midplane of PPD followed by ice evaporation → ^{16}O-poor gas

Evolution of oxygen isotope reservoir in the inner solar nebula


(Cuzzi & Zahnle, 2004, ApJ)

C_o - solar abundance of water
C - abundance of water in the cloud
σ_g - disk surface mass density
σ_L - surface density of meter-sized icy bodies
V_n - advection velocity
$\mathcal{D}$ - turbulent diffusivity
α - nebular viscosity parameter

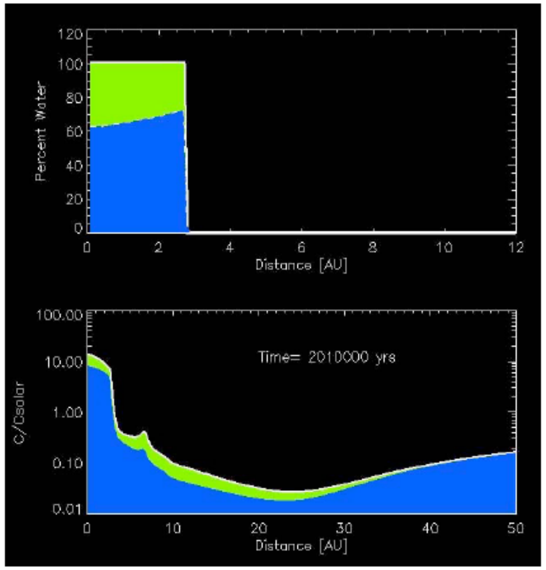
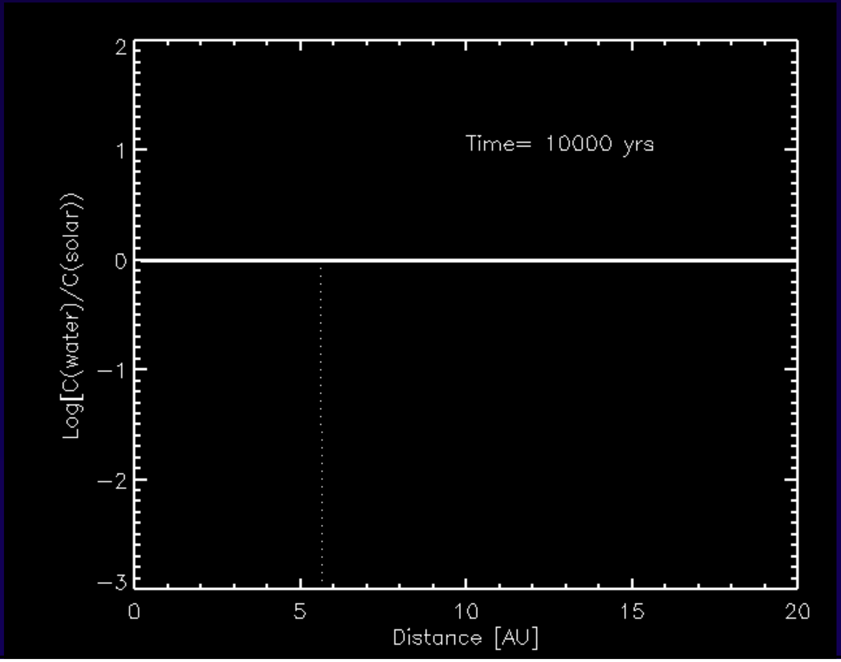
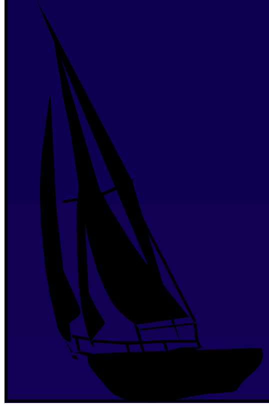
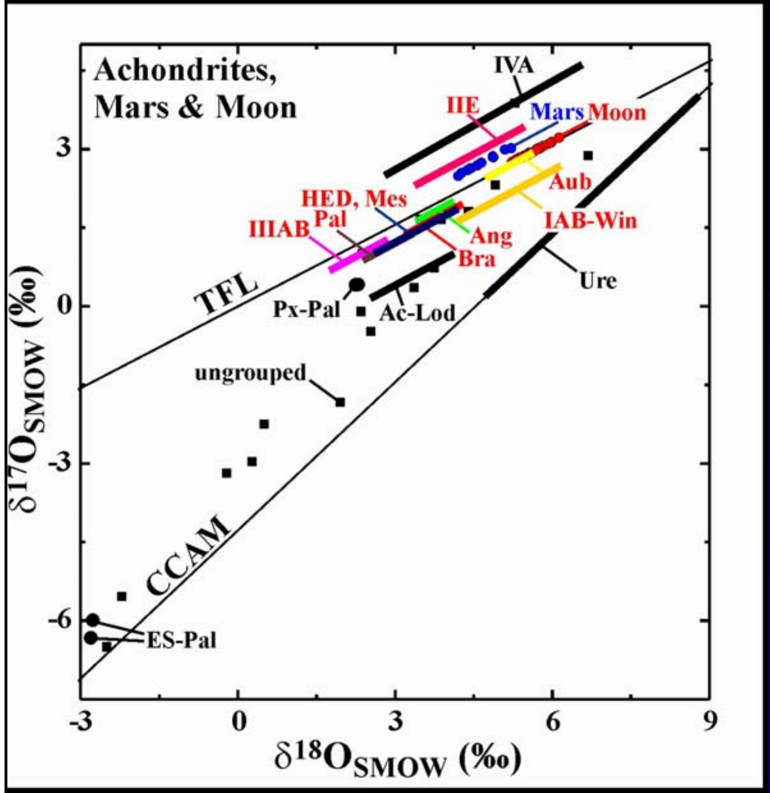


Figure 1: Snapshot after ~2 million years of evolution of the distribution of water inside the snowline (top panel) and its concentration throughout the disk (bottom panel). Green represents ^{17,18}O-poor water while blue is ^{17,18}O-rich based on the model of Lyons and Young [5].





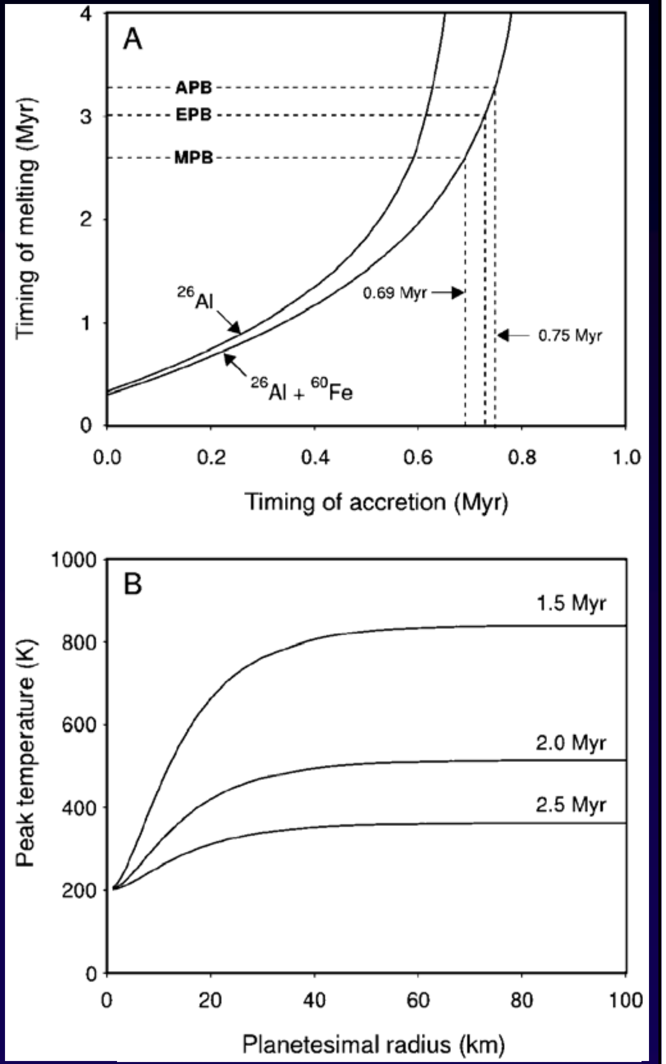
When did nebular gas become ^{16}O-poor?



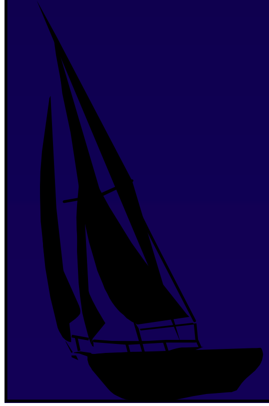
data from R. Clayton's lab

Achondrites	Δ^{17}O,‰
IVA*	+1.2
IIE	+0.6
Aubrites*	0.0
Angrites*	-0.1
Brachinites	-0.3
HED*	-0.3
Mesosiderites*	-0.3
MG Pallasites*	-0.3
IIIAB*	-0.3
IIICD	-0.4
IAB	-0.5
Winonaites	-0.5
Px Pallasites*	-0.8
Acapulcoites	-1.1
Lodranites	-1.2
Ureilites*	-2.5 – -0.2
ES Pallasites	-4.7

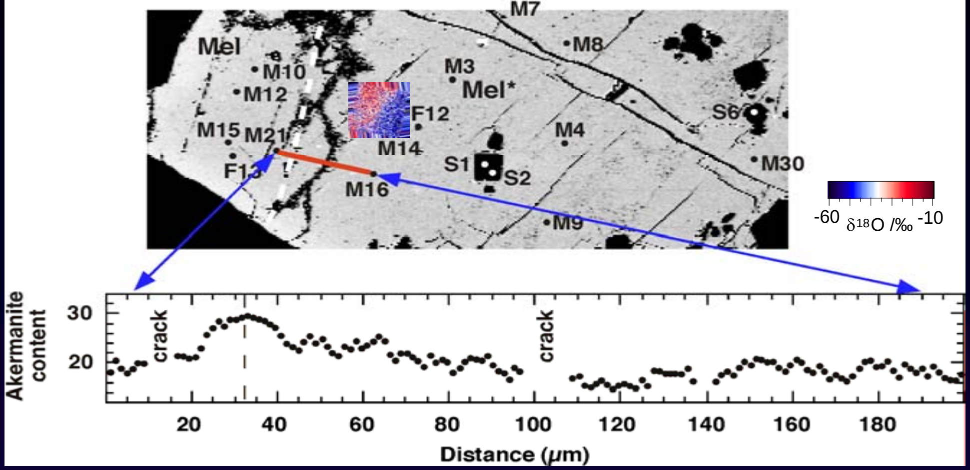
* *experienced early differentiation based on Al-Mg & Hf-W isotope systematics*

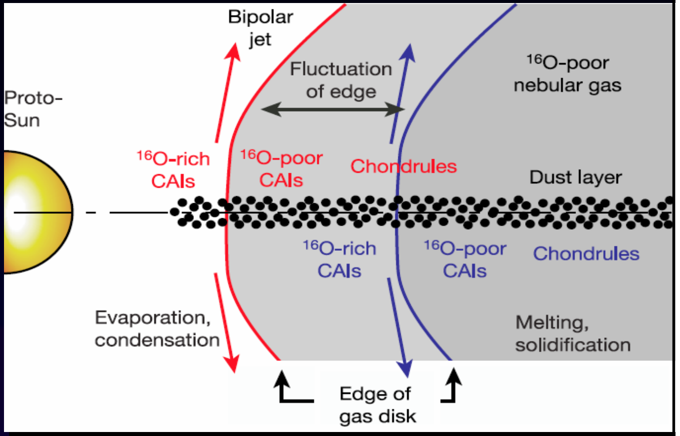


Bizzarro et al. (2005) ApJ

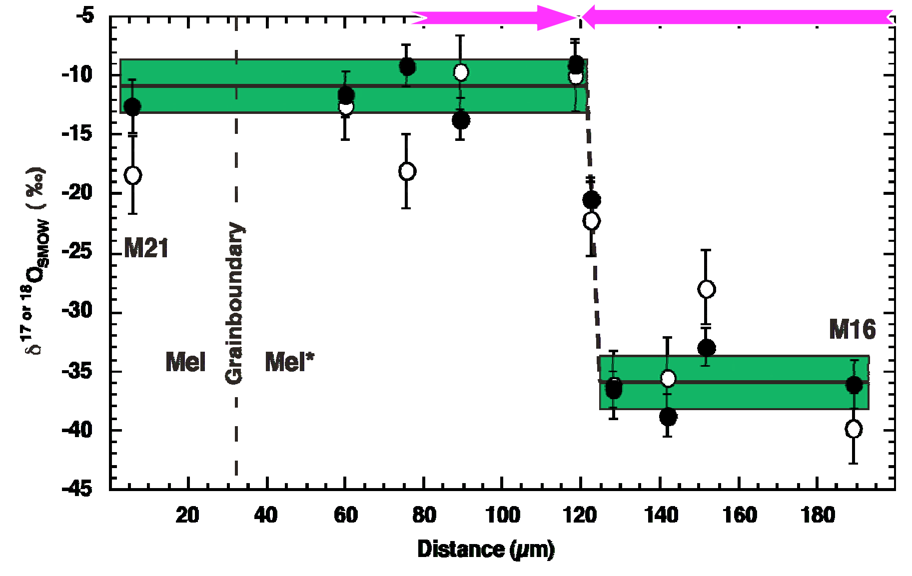


When did nebular gas become ^{16}O-poor? (cont.)

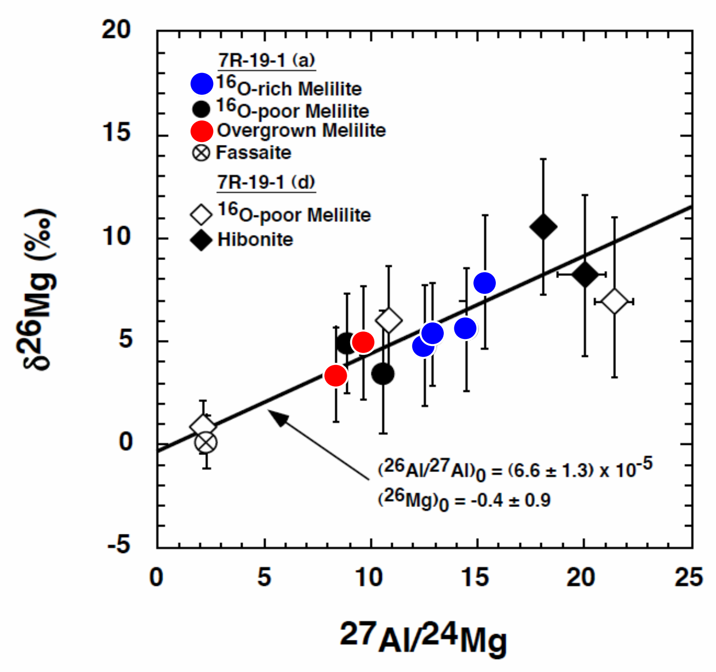




Itoh & Yurimoto (2003) Nature



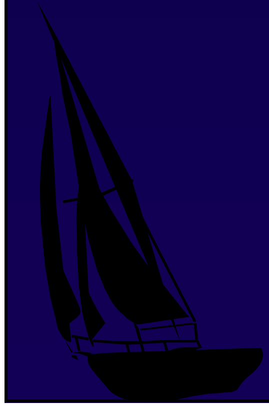
Yurimoto et al. (1998) Science

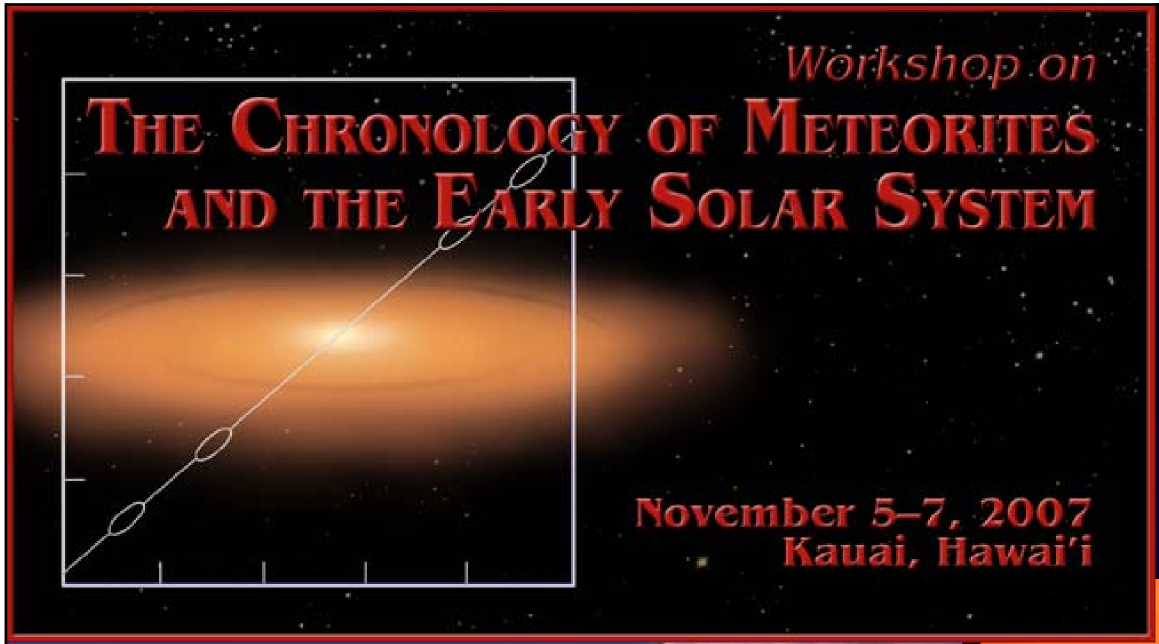


Ito et al. (2005) GCA

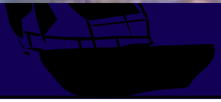
Conclusions

- O-isotope composition of the inner solar nebula may have globally evolved from ^{16}O-rich (Δ^{17}O $\leq$ -20‰) to ^{16}O-poor (Δ^{17}O ~ 0‰) on a timescale < 1 Myr
- ^{16}O-poor nebular gas could have resulted from CO self-shielding & subsequent enrichment of the inner solar nebula in water vapor
- thermal processing of dust in an ^{16}O-poor gas was a fundamentally important process in the inner solar nebula





The workshop will honor the outstanding contributions of
C. Allégre, G. Lugmair, L. Nyquist, D. Papanastassiou, & G. Wasserburg
to our understanding of the chronology of the early solar system



http://www.lpi.usra.edu/meetings/metchron2007