Chondritic meteorites and their components: Constraints on the early Solar System processes

Sasha Krot[1,2]

[1]*Hawai'i Institute of Geophysics & Planetology & NASA Astrobiology Institute, University of Hawai'i at Mānoa, USA*

[2]*Center for Stars & Planets, Natural History Museum of Denmark, Denmark*

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Outline

- I. Introduction: Chondritic meteorites & their classification
- II. Calcium-Aluminum-rich Inclusions (CAIs)

→ constraint on astrophysical setting of Solar System formation
→ constraint on oxygen-isotope reservoirs

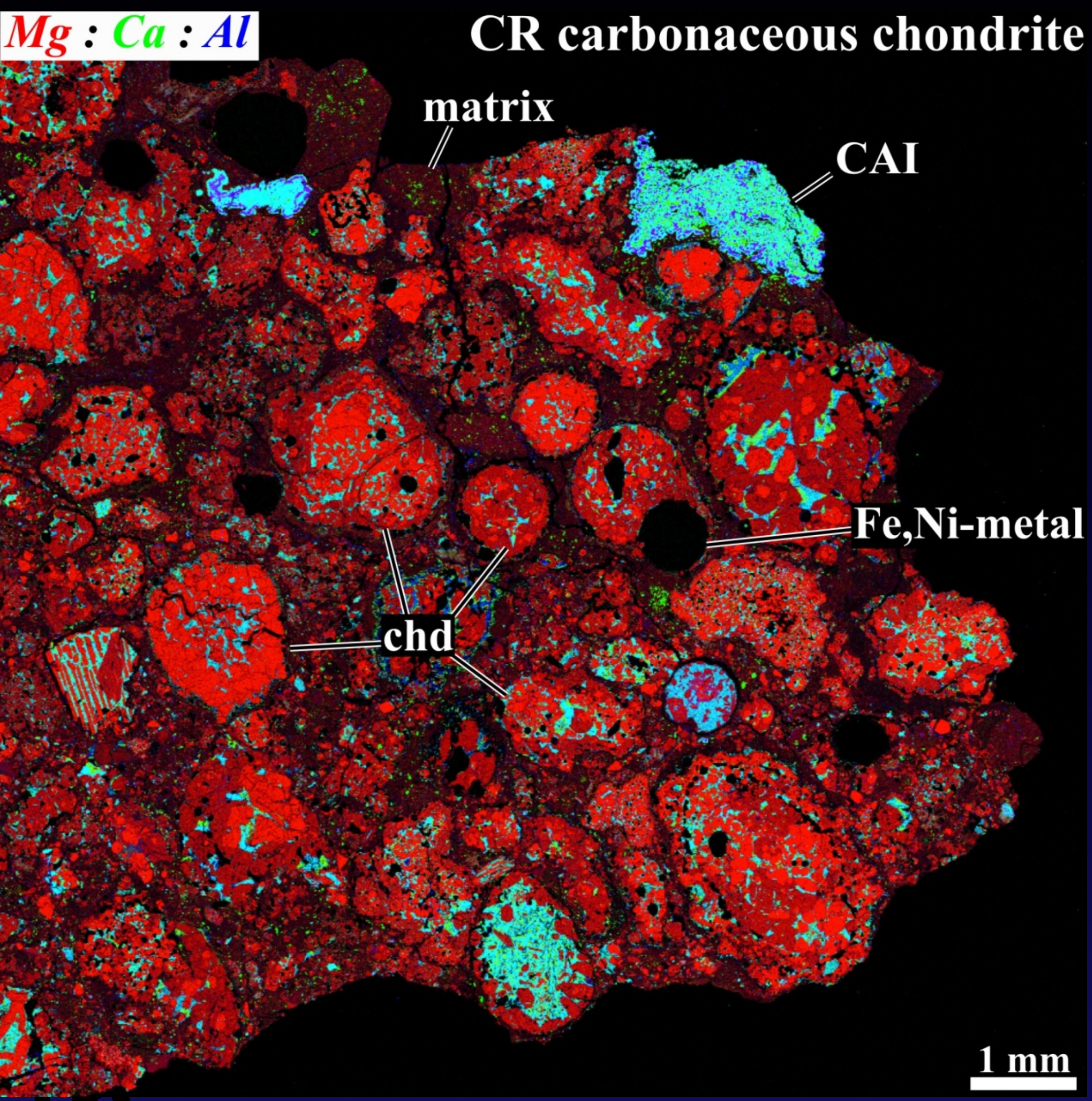
- III. Chondrules & fine-grained matrices

→ constraint on life-time of protoplanetary disk (PPD)
→ constraint on duration of accretion of chondrite parent asteroids

- IV. Aqueous activity on chondrite parent asteroids

→ constraint on sources of asteroidal water

Major chondritic components: Chondrules, matrix, & CAIs



- chondrules + Fe,Ni-metal (30–98 vol%)
- Ca,Al-rich inclusions (CAIs) (<1–5 vol%)
- fine-grained matrix (<2–70 vol%)

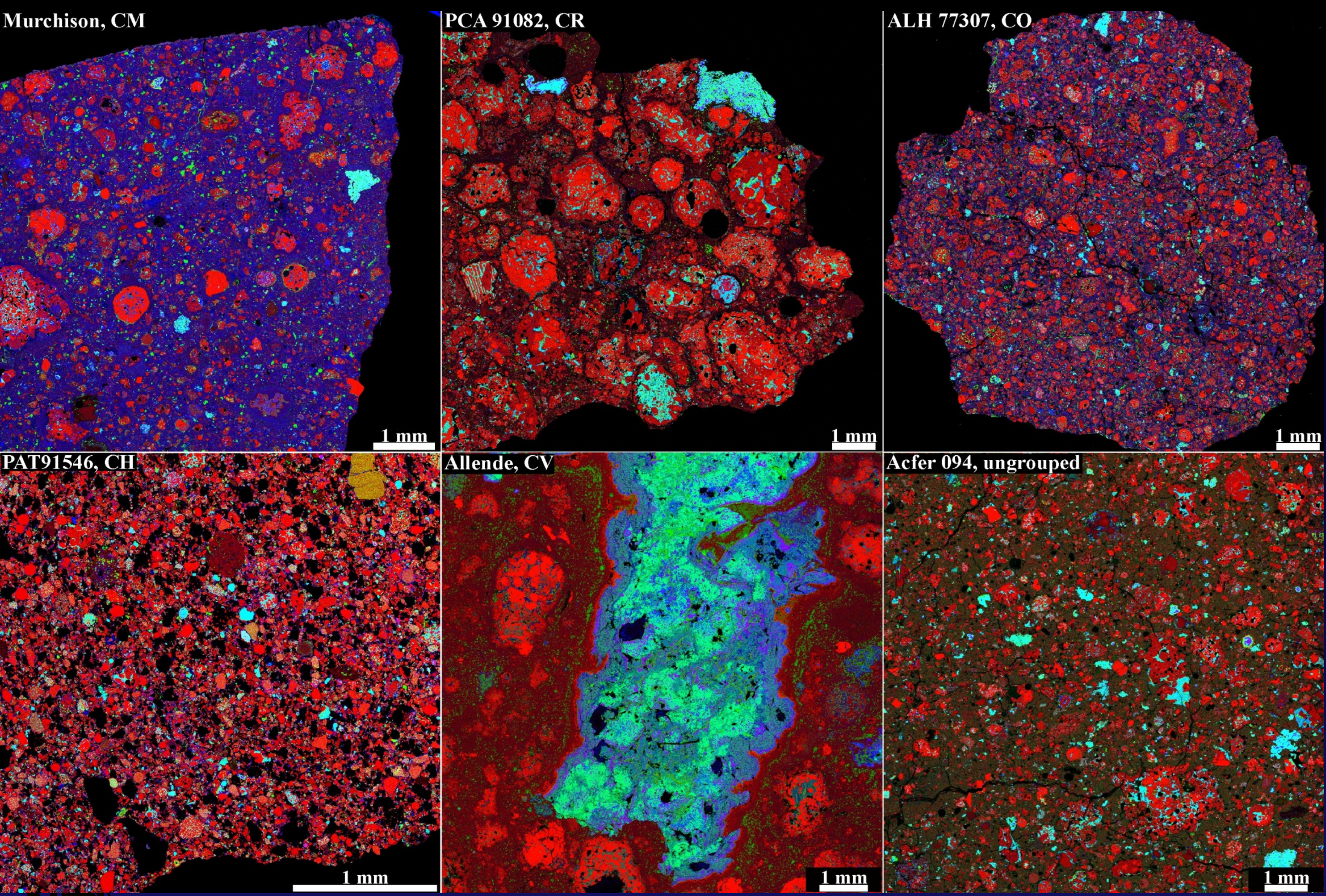
dominated by crystalline material
→ thermal processing in PPD (evaporation, condensation, thermal annealing, & melting)

Classification of chondritic meteorites (chondrites)

- based on mineralogy, petrography, bulk oxygen-isotope & chemical compositions, chondrites are divided into 15 groups & 3 major classes

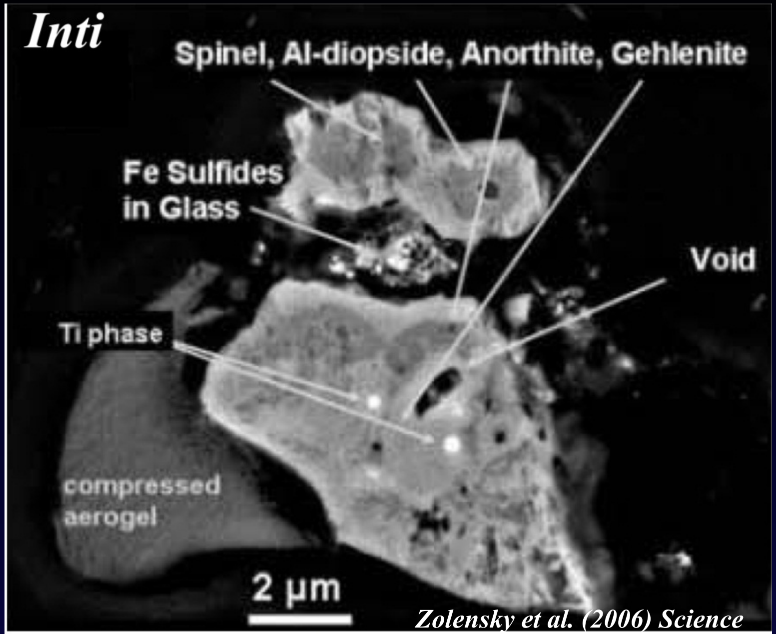
Carbonaceous	*Enstatite*	*Ordinary*	Other
CI CM CR CV CK CO CB CH	EH EL	H L LL	K R

- letters designating groups refer to a prototype meteorite in a group:
  - CI – Ivuna-like (CI chondrite: Orgueil)
  - CM – Mighei-like (CM chondrite: Murchison)
  - CV – Vigarano-like (CV chondrite: Allende)
- some chondrites are ungrouped (e.g., Acfer 094)

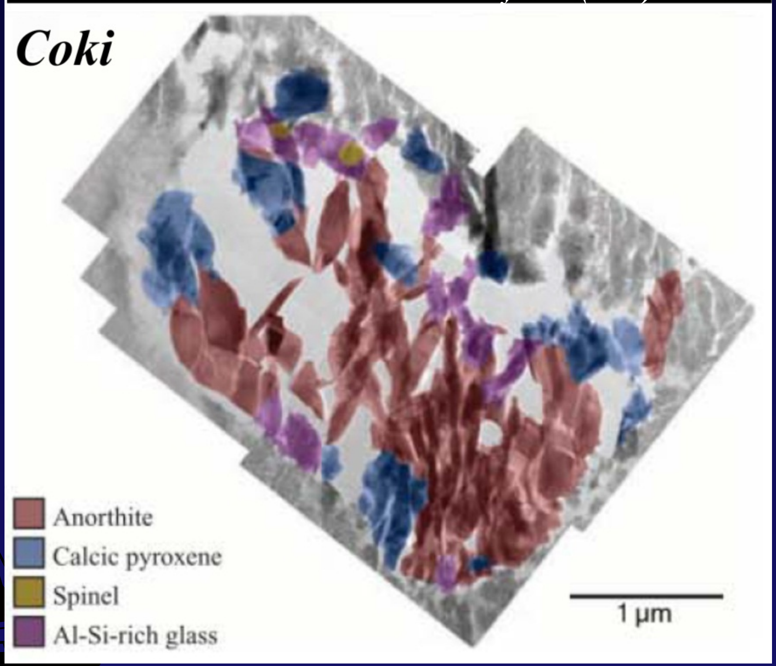


- intergroup variations in textures, mineralogy, sizes & abundances of chondritic components
- CAIs & chondrules present in all chondrite groups & in a comet *81P/Wild 2*

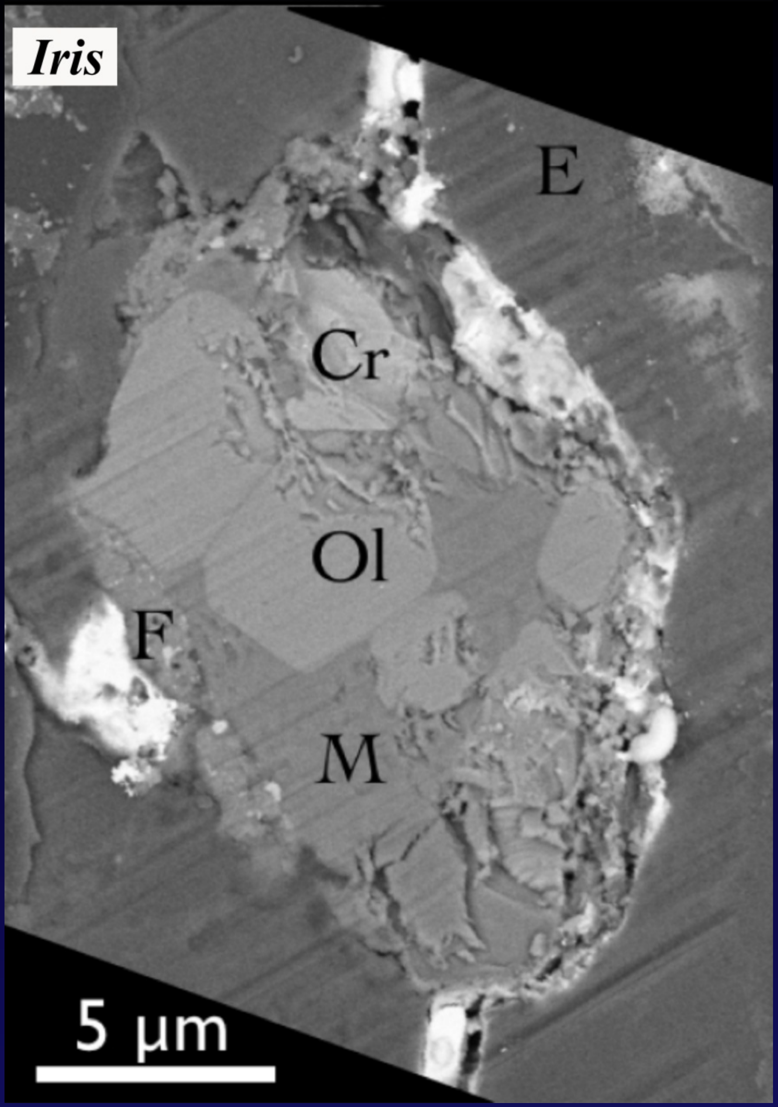
CAIs & a chondrule fragment from *81P/Wild 2* comet



Zolensky et al. (2006) Science

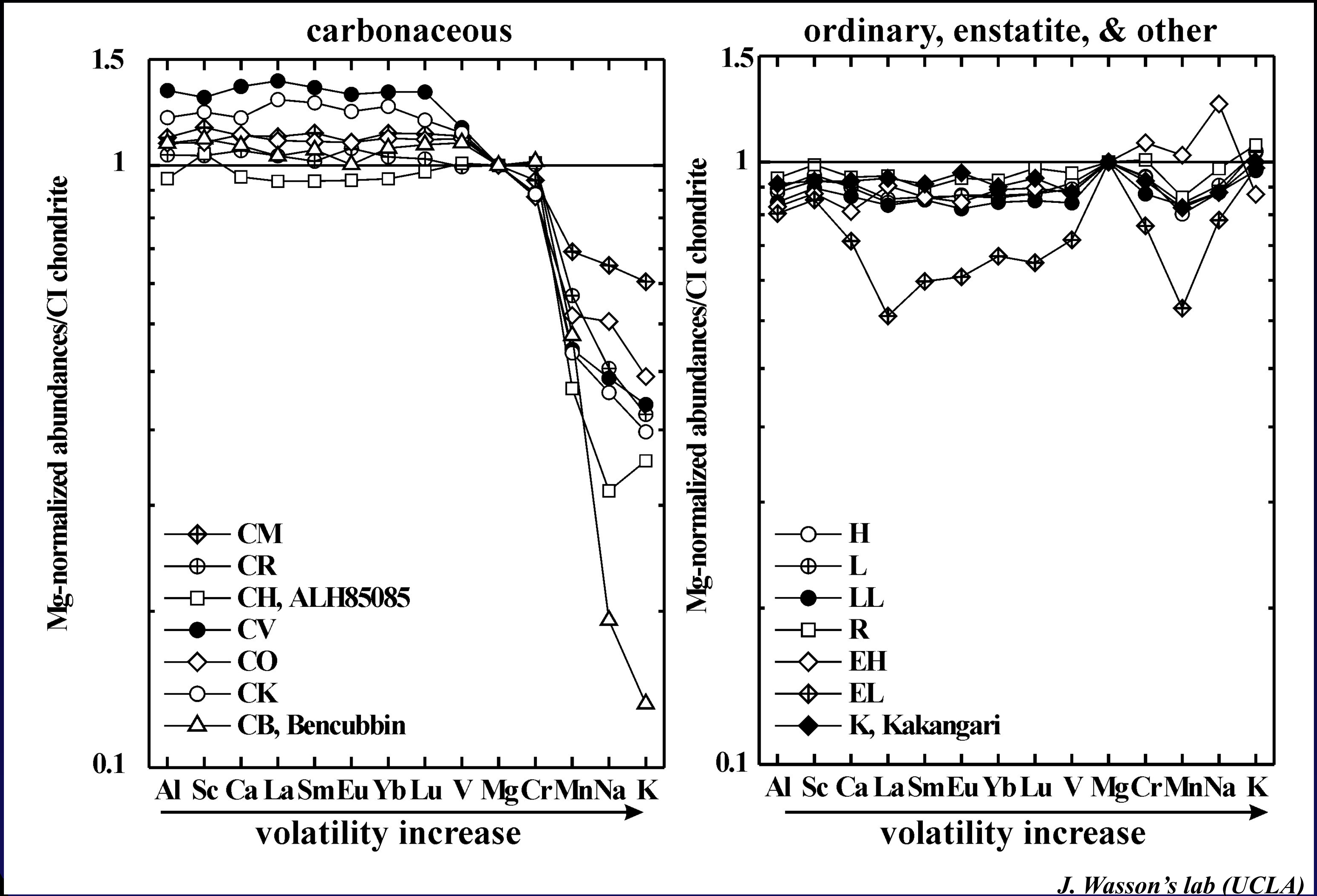


Matzel et al. (2010) Science



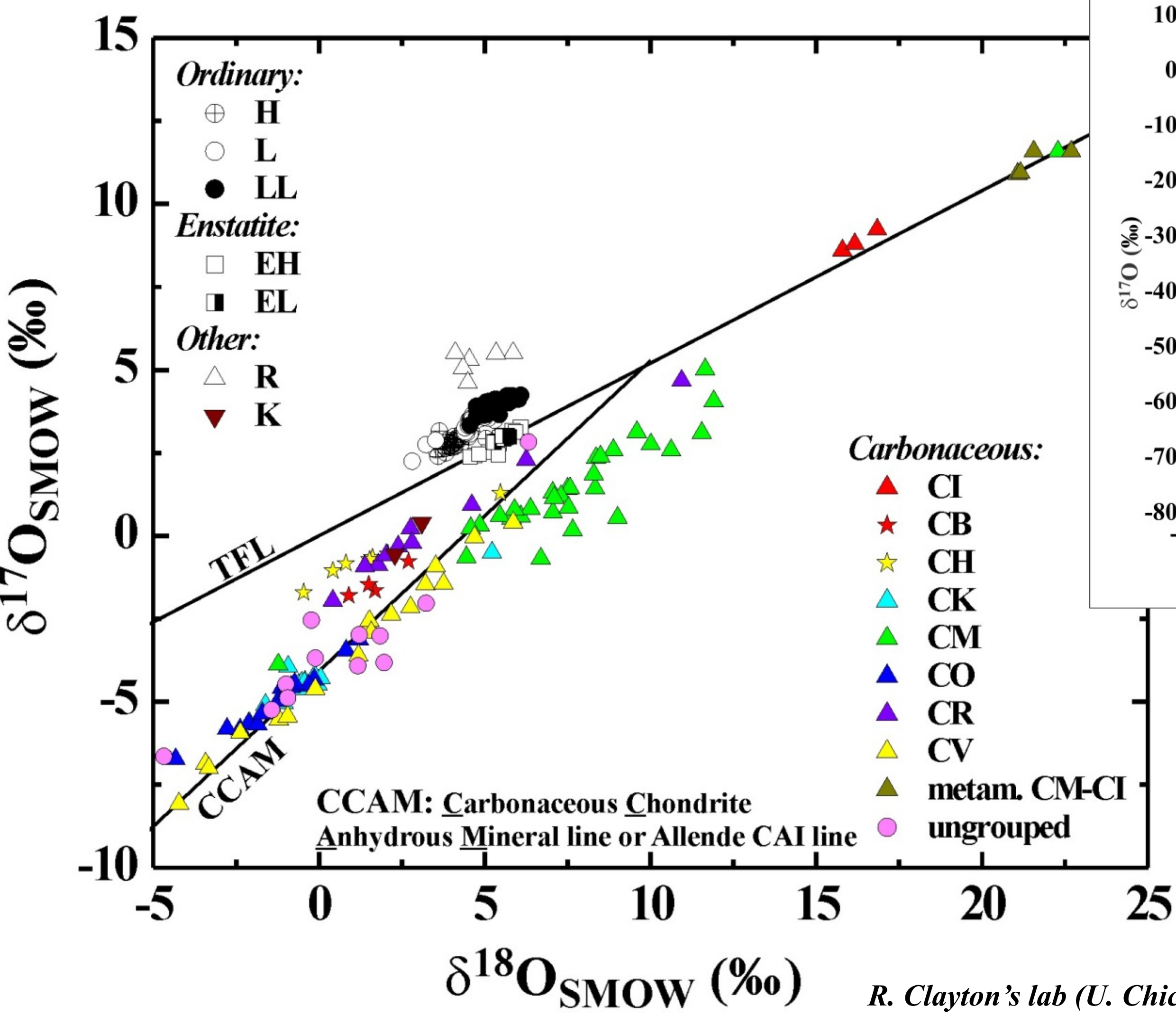
Ogliore et al. (2012) ApJ

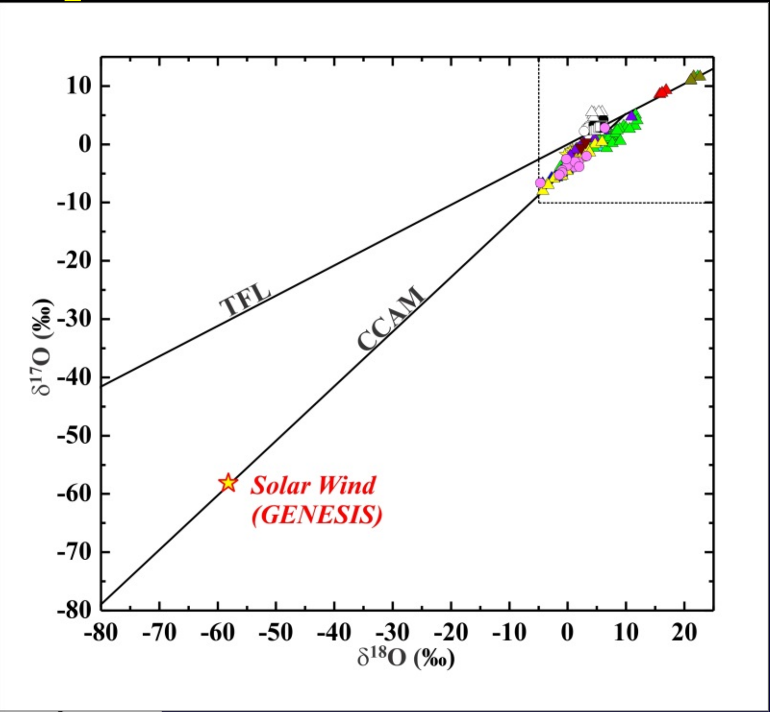
Bulk chemical compositions



- CIs compositionally most similar to solar photosph. & in cosmochemistry CIs ≡ Sun
- chondrite groups have distinct bulk chemical compositions
- chondrites within a group are compositionally similar → sampled same asteroid

Bulk oxygen-isotope compositions

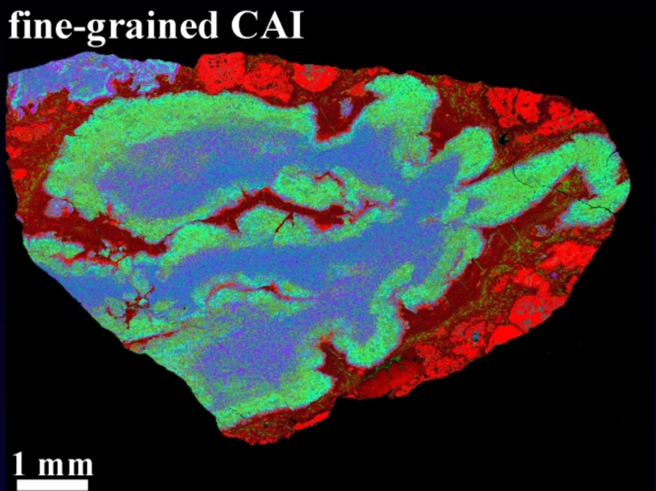


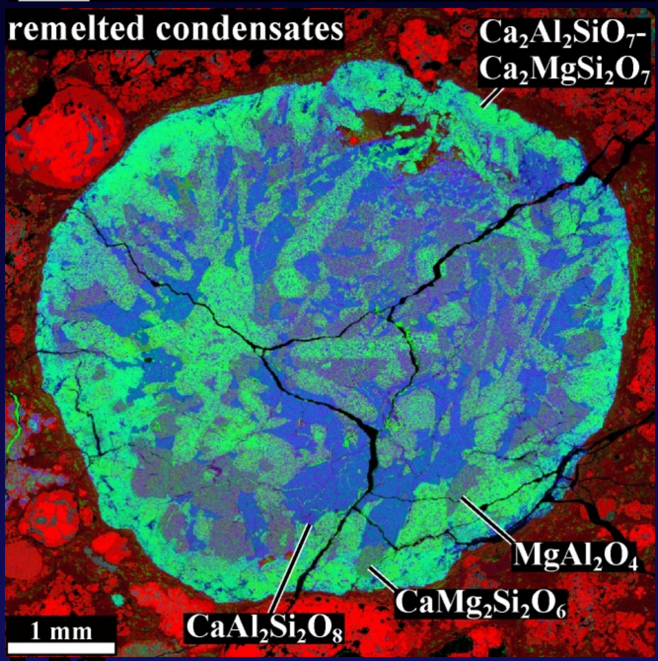


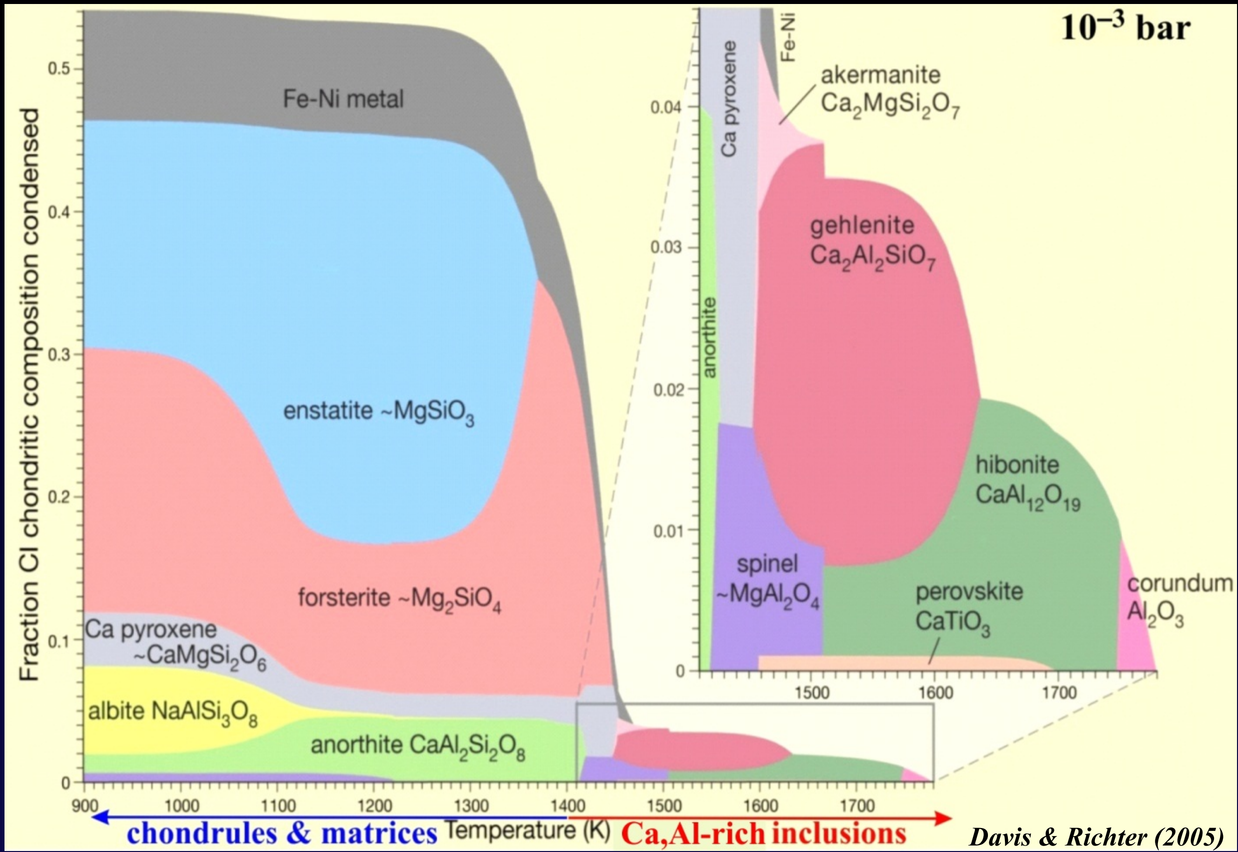
$\delta^{17,18}O = [(^{17,18}O/^{16}O)_{sample}/(^{17,18}O/^{16}O)_{SMOW} - 1] \times 1000$, Standard Mean Ocean Water

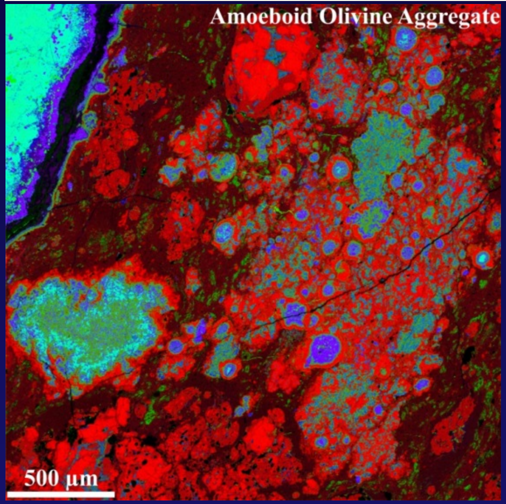
- chondrite groups occupy distinct regions on three-isotope oxygen diagram
- very different from composition of solar wind, $\delta^{17,18}O \approx -60$‰ *(McKeegan et al., 2011)*

II. Ca,Al-rich Inclusions (CAIs)



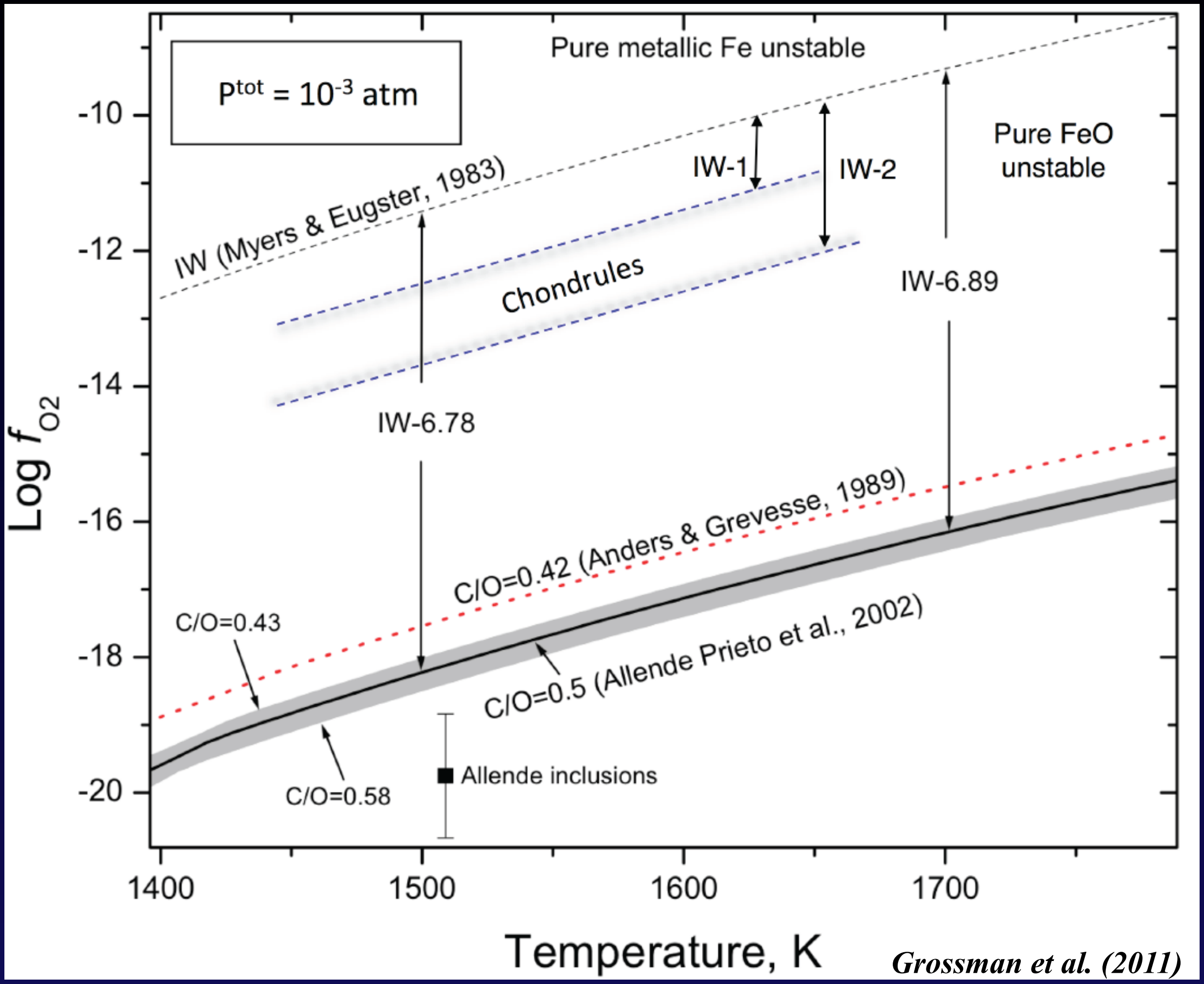






- by multistage evaporation, condensation, aggregation, & melting of solids in region(s) with ambient T > 1400 K
- oldest Solar System solids
- CV CAIs: 4567.3±0.16 Myr ≡ age of Solar System or time 0
- cm-sized CAIs formed at time 0!

Redox conditions in CAI-forming region(s)

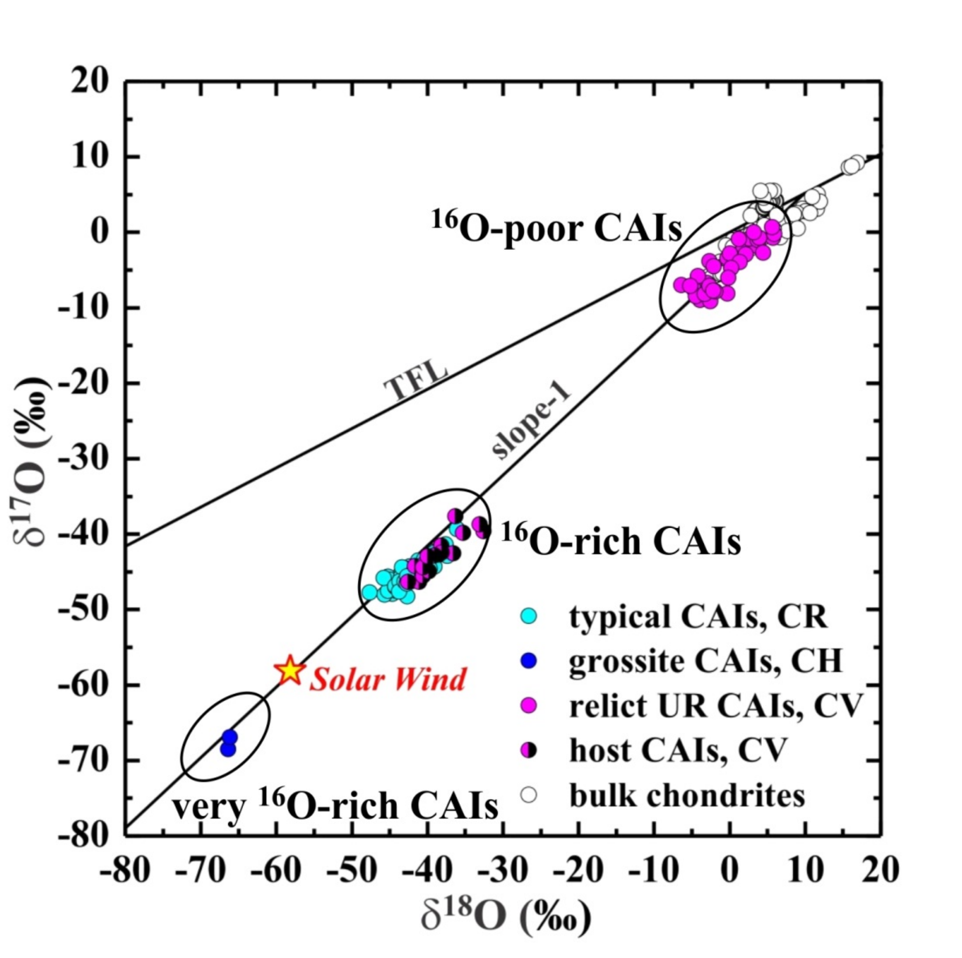


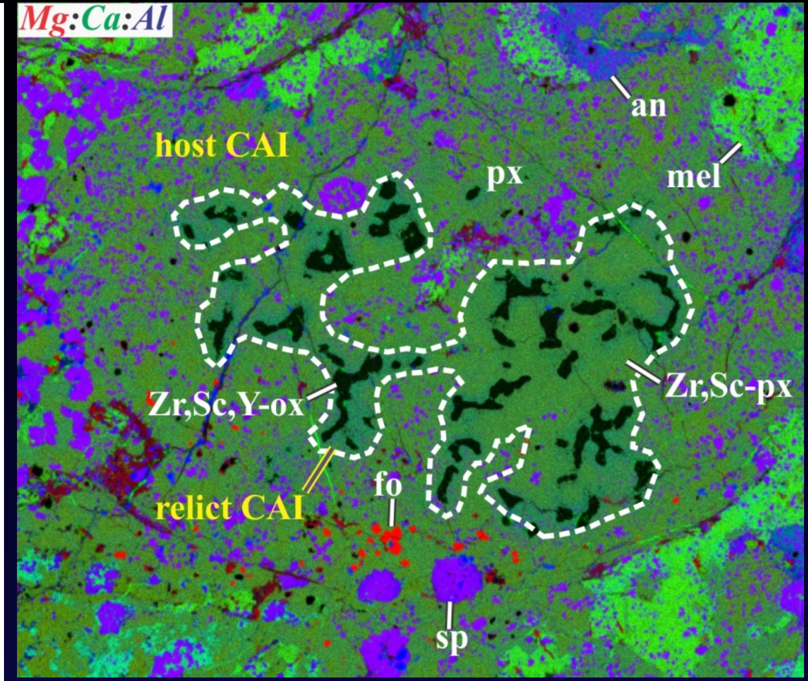
Grossman et al. (2011)

- CAI minerals contain no oxidized Fe (Fe^{2+} or Fe^{3+}) & have high Ti^{3+}/Ti^{4+} ratio

→ formed in highly-reducing, gas-dominated region(s) with a solar $H_2O/H_2 \sim 5\times10^{-4}$

Oxygen-isotope compositions of CAIs





- relict ^{16}O-depleted ultrarefractory CAI inside ^{16}O-rich host CAI

- most CAIs: ^{16}O-rich, close to solar wind value
- some CAIs: ^{16}O-enriched or ^{16}O-depleted relative solar wind

→ early generation of isotopically distinct oxygen reservoirs in PPD

- mechanism of generation of these reservoirs is not understood (CO self-shielding?)
- O-isotope compositions of primordial dust & gas are not known

Short-lived radionuclides (^{53}Mn, ^{60}Fe, ^{182}Hf, ^{10}Be, ^{26}Al, ^{41}Ca)

- ^{53}Mn ($t_{1/2}$ ~ 3.7 Myr), ^{60}Fe (2.6 Myr), ^{182}Hf (9 Myr): uniformly distributed in PPD & inherited from MC

→ ^{53}Mn & ^{182}Hf are used for chronology of SS processes

- ^{10}Be ($t_{1/2}$ ~ 1.5 Myr), ^{26}Al (0.7 Myr), & ^{41}Ca (0.1 Myr): heterogeneous among CAIs
  - ^{10}Be: energetic particle irradiation near protoSun

  → formation of CAIs near protoSun
  - ^{26}Al & ^{41}Ca correlate with each other, but do not correlate with ^{10}Be;
  - ^{26}Al in PPD is too high to be explained by irradiation *Dupra & Tatischeff (2007) ApJ*

  → external, stellar origin

  → Solar System formed near massive star(s) (SN*, AGB, Wolf-Rayet)

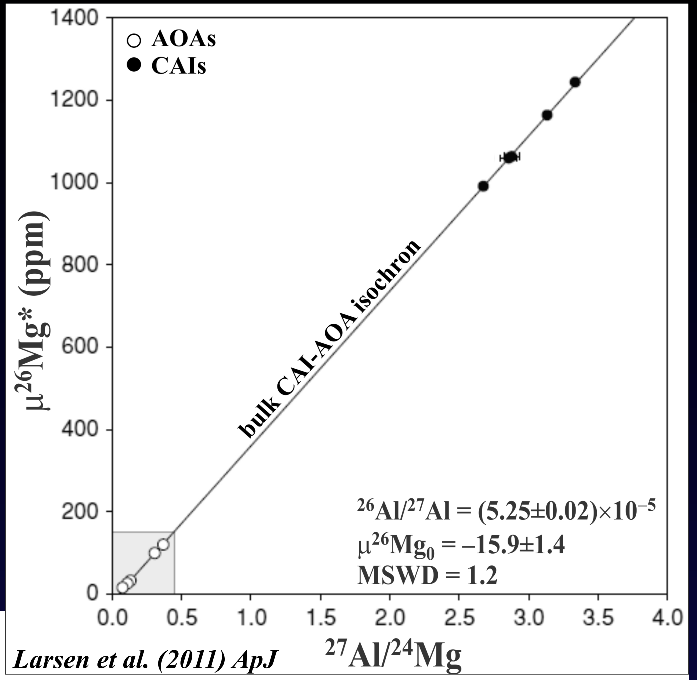
  *previously inferred high abundance of ^{60}Fe requiring SN source has not been confirmed *(check poster #43 by M. Telus)*

^{26}Al heterogeneity during epoch of CAI formation

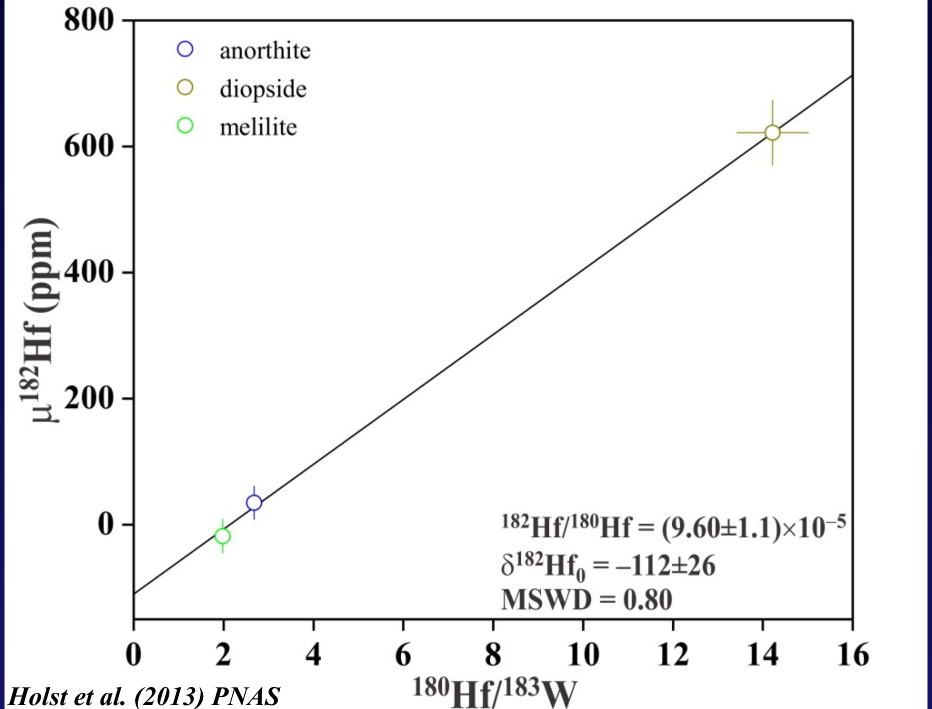
- CV CAIs: $^{26}Al/^{27}Al = (5.25\pm0.02)\times10^{-5}$, "canonical"
  - uniform distribution of ^{26}Al in PPD
  - brief (<0.002 Myr) duration of CAI formation
- incorrect:
  - some CAIs: $^{26}Al/^{27}Al < 5\times10^{-6}$ & formed before or contemporaneously with canonical CAIs

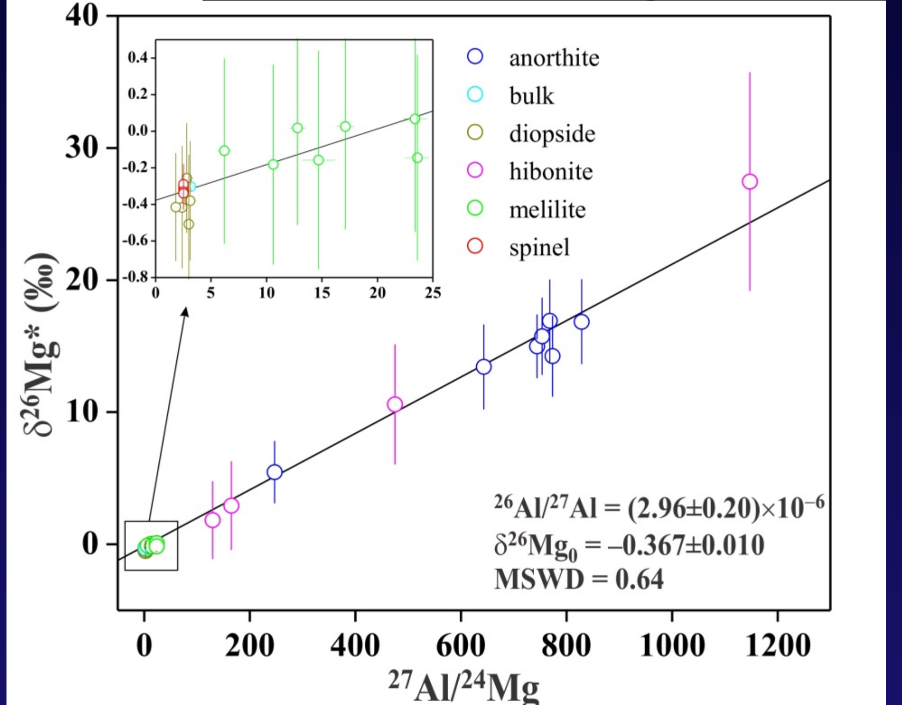
  → ^{26}Al heterogeneity in protosolar MC

  → recent injection of ^{26}Al into MC core or PPD



CAIs with diff. $^{26}Al/^{27}Al$ have similar $^{182}Hf/^{180}Hf$





CAIs: Summary

- earliest SS solids dated: ~4567.3 Ma ≡ age of SS ≡ time 0 in cosmochemistry
- evaporation, condensation, aggregation, irradiation (^{10}Be) & ±melting processes in a gas of solar composition (reduced & ^{16}O-rich) in region(s) with ambient T >1400K
- early generation of isotopically distinct oxygen reservoirs in PPD
- heterogeneous distribution of ^{26}Al & ^{41}Ca in PPD

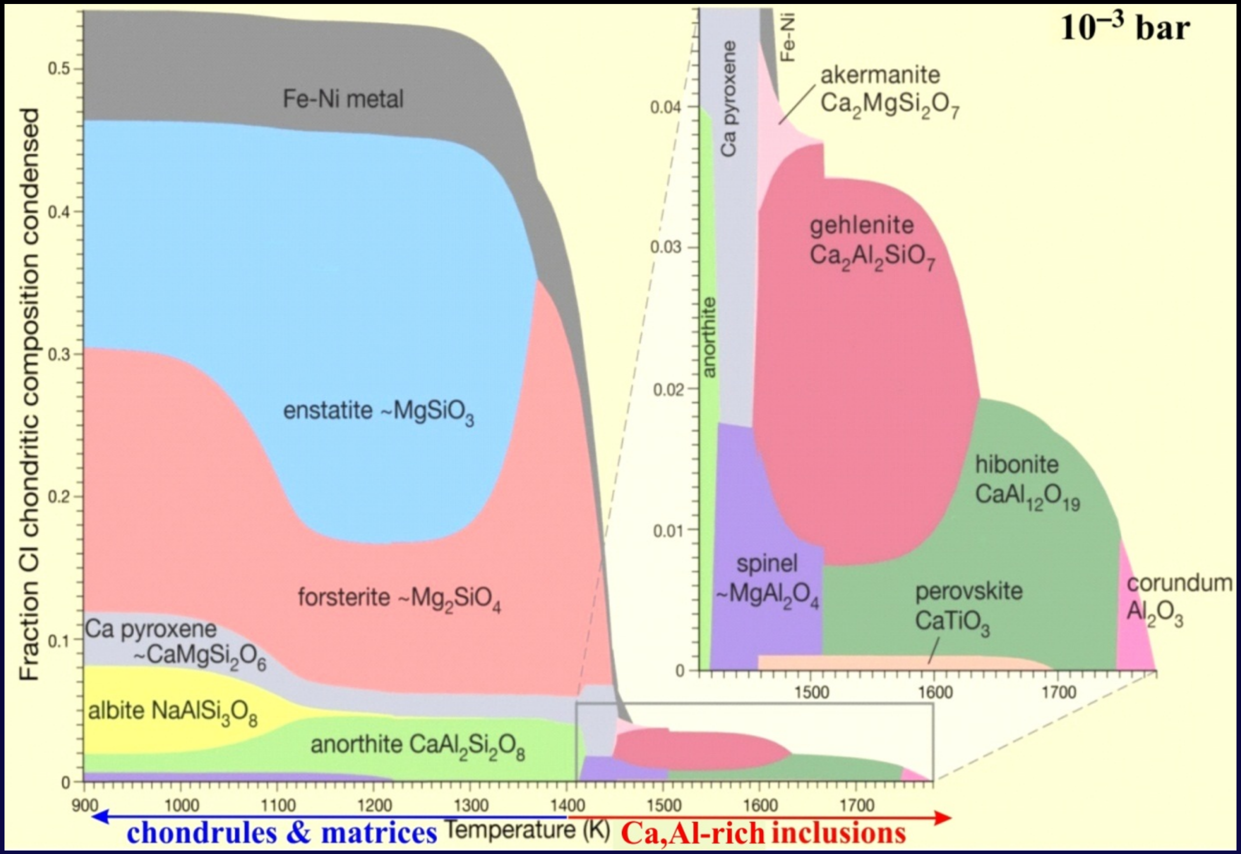
    → recent injection of ^{26}Al into ^{26}Al-poor MC core by massive star(s)

    → duration of CAI formation is not known & cannot be inferred from ^{26}Al

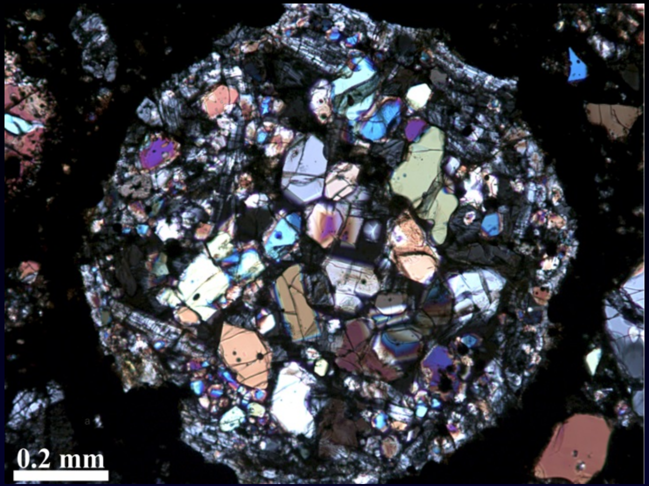
    → distribution of ^{26}Al in PPD cannot be inferred from CAIs
- present in all chondrite groups & in a comet *81P/Wild 2*

    → after formation were removed from hot region & dispersed throughout PPD

III. Chondrules & fine-grained matrices



Davis & Richter (2005)

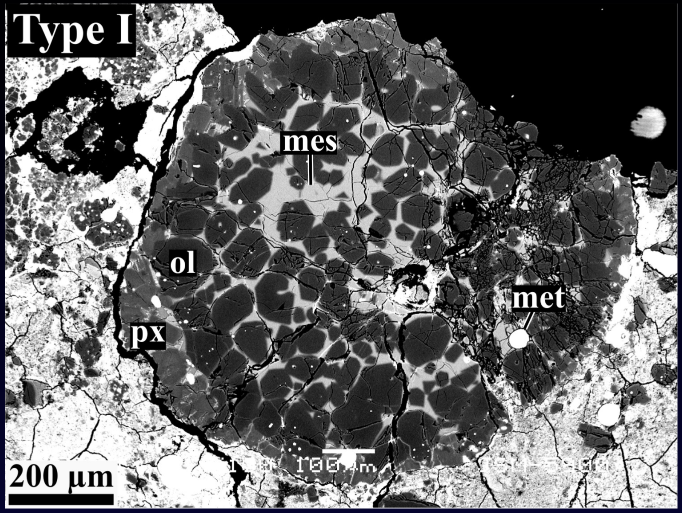


courtesy of D. Lauretta

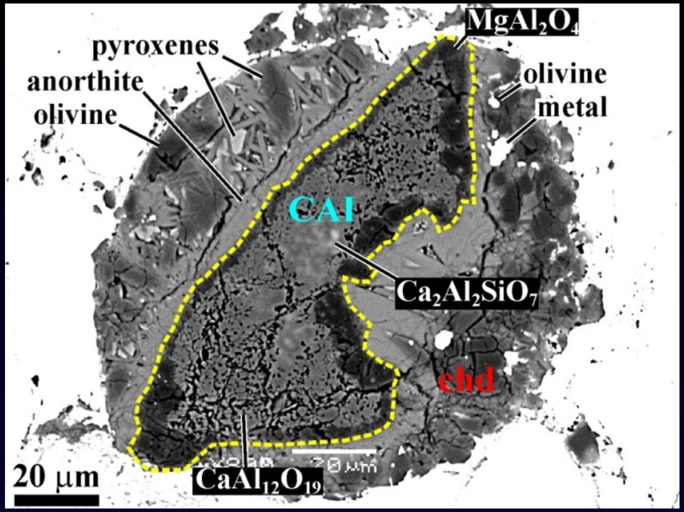
mm-sized molten & rapidly solidified objects once freely floating in space

- less refractory than CAIs
- contain ferromagnesian silicates (Fe^{2+}) & abundant volatiles (Na, K, S)

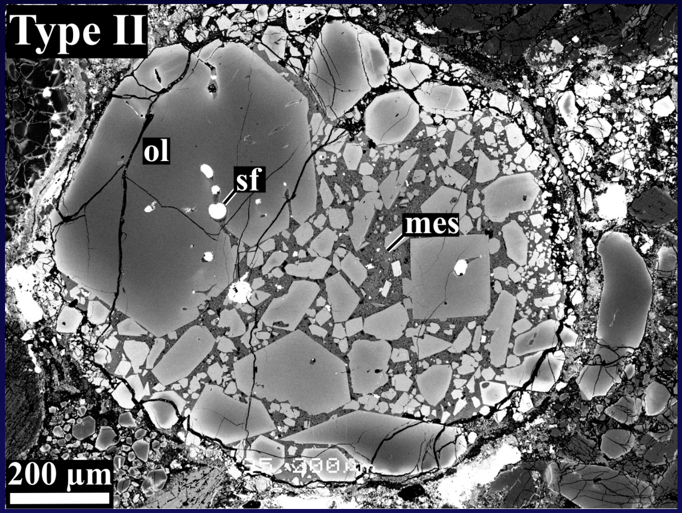
Porphyritic textures & relict grains: Incomplete melting



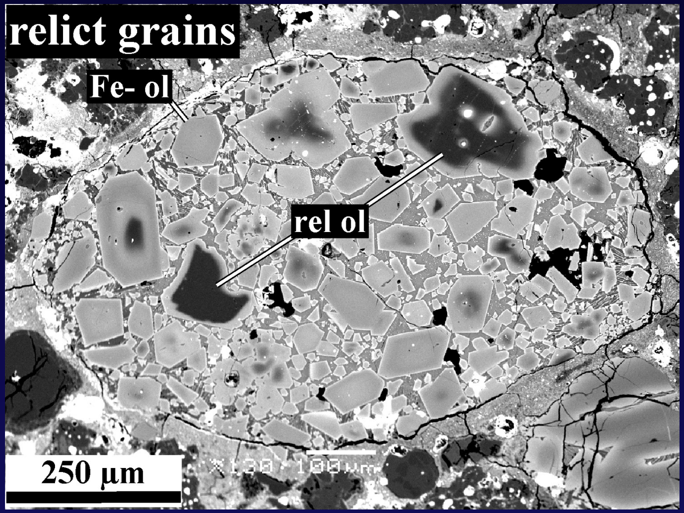
magnesian porphyritic



relict CAI



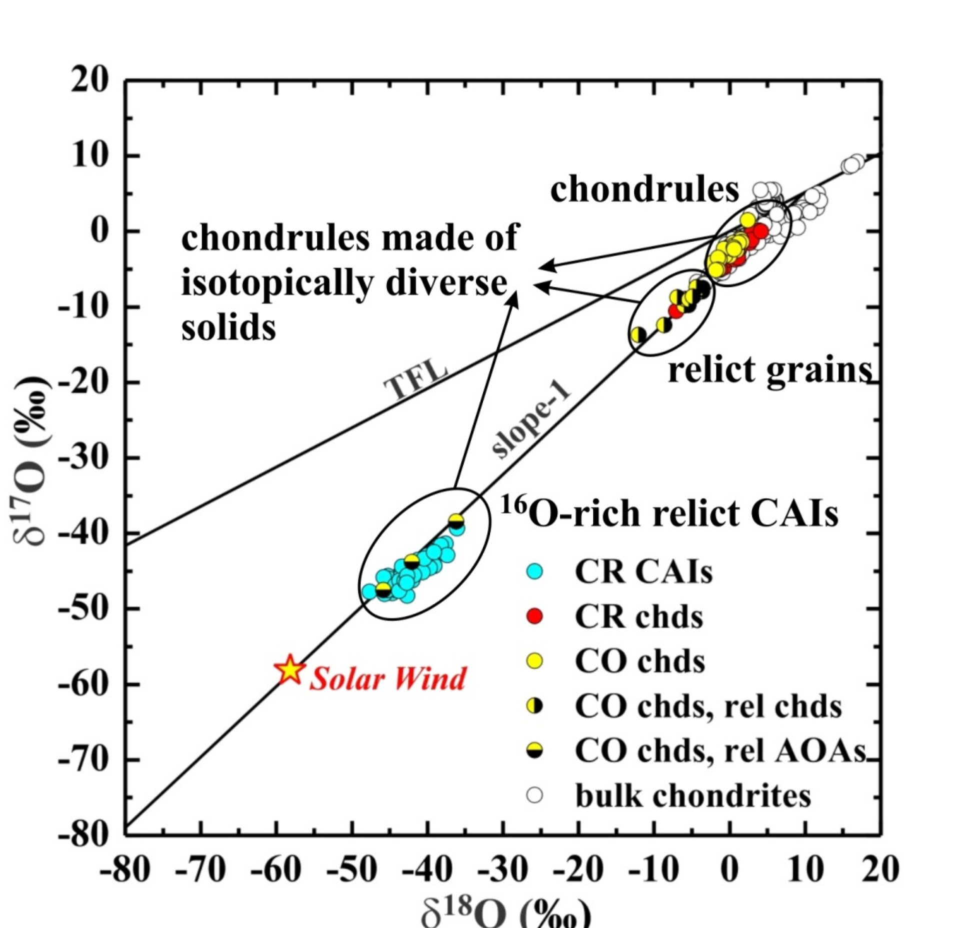
ferroan porphyritic



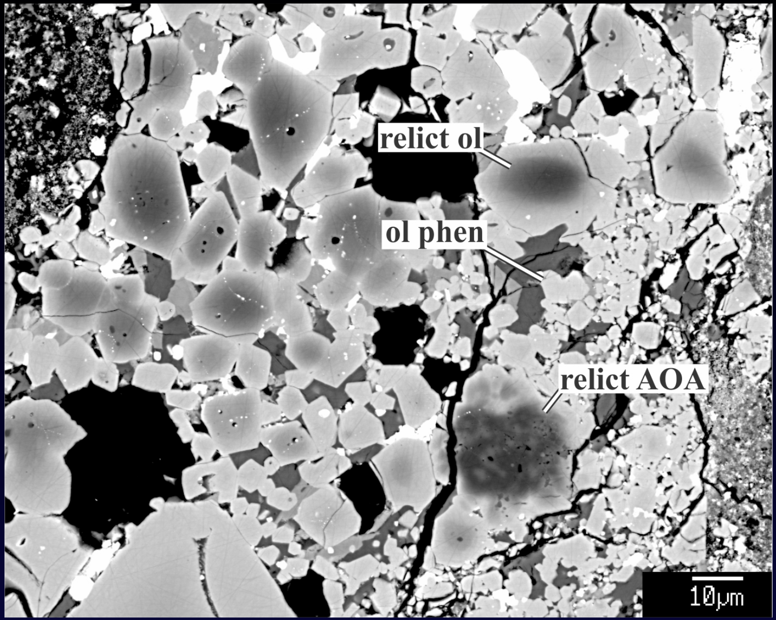
relict chondrule fragments

- melting (often incomplete) of solid precursors, including fragments of earlier formed chondrules & CAIs

Oxygen-isotope compositions of chondrules



Libourel et al. (unpubl.)

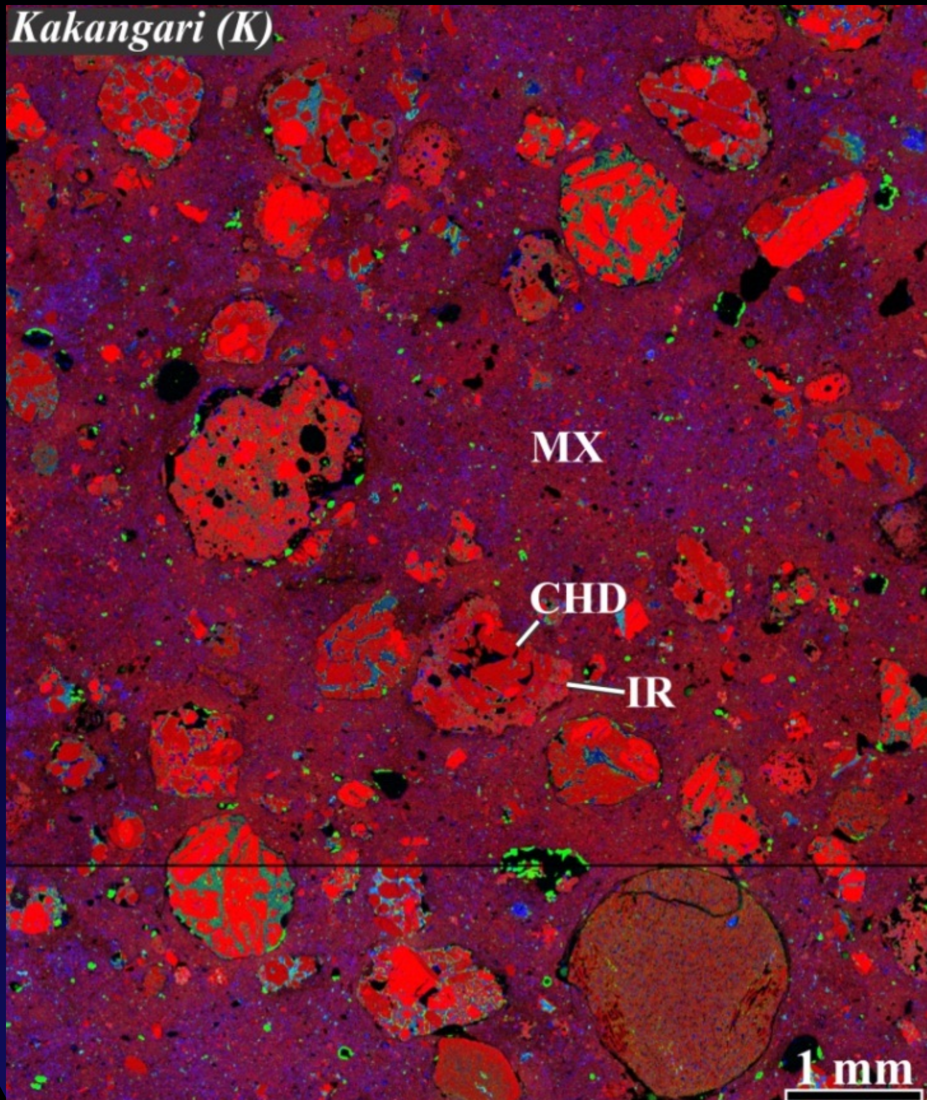


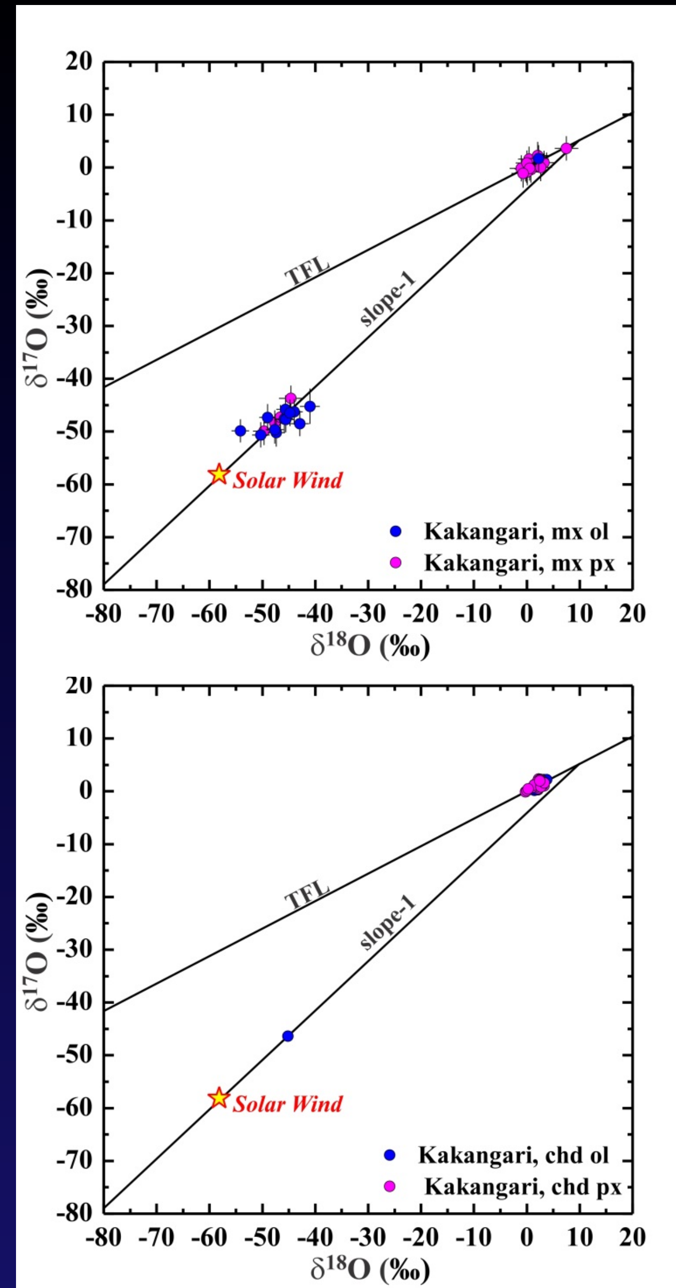
relict AOA & relict chondrule fragments in a ferroan porphyritic chondrule

- chondrules are ^{16}O-depleted relative to CAIs
- relict grains ^{16}O-enriched relative host chondrules

→ chondrules formed by melting of isotopically diverse precursors in ^{16}O-depleted gaseous reservoir

Chondrule-matrix relationship: Insights from oxygen isotopes

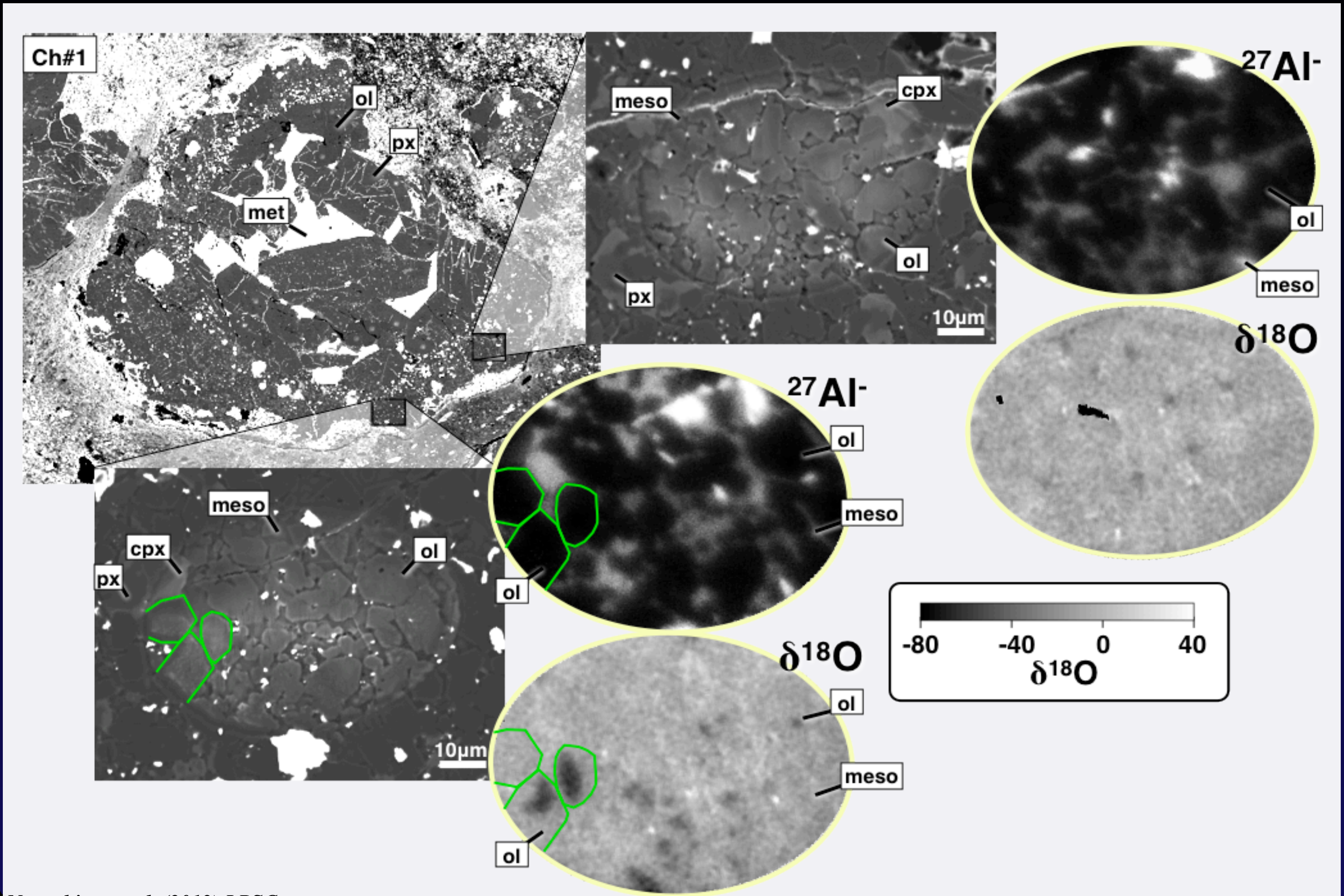




- matrix & chondrules in Kakangari contain isotopically similar olivine & pyroxene

Nagashima et al. (2012) LPSC

Chondrule-matrix relationship: Insights from oxygen isotopes

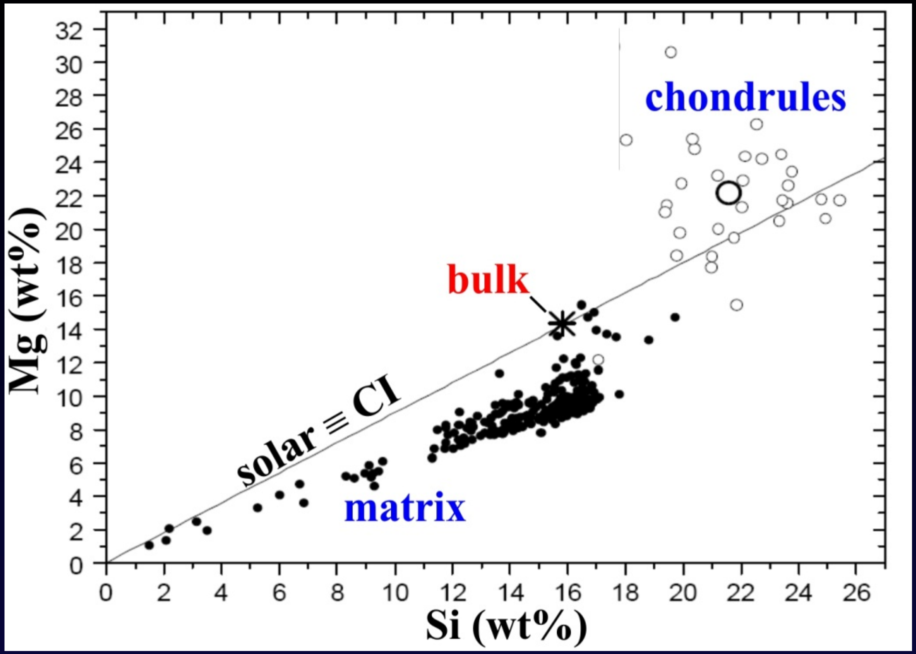


Nagashima et al. (2012) LPSC

- matrix & igneous rims around Kakangari chondrules contain abundant ^{16}O-rich grains

→ matrix grains were among chondrule precursors

Chondrule-matrix relationship: Insights from bulk chemistry



Klerner & Palme (1999) MAPS

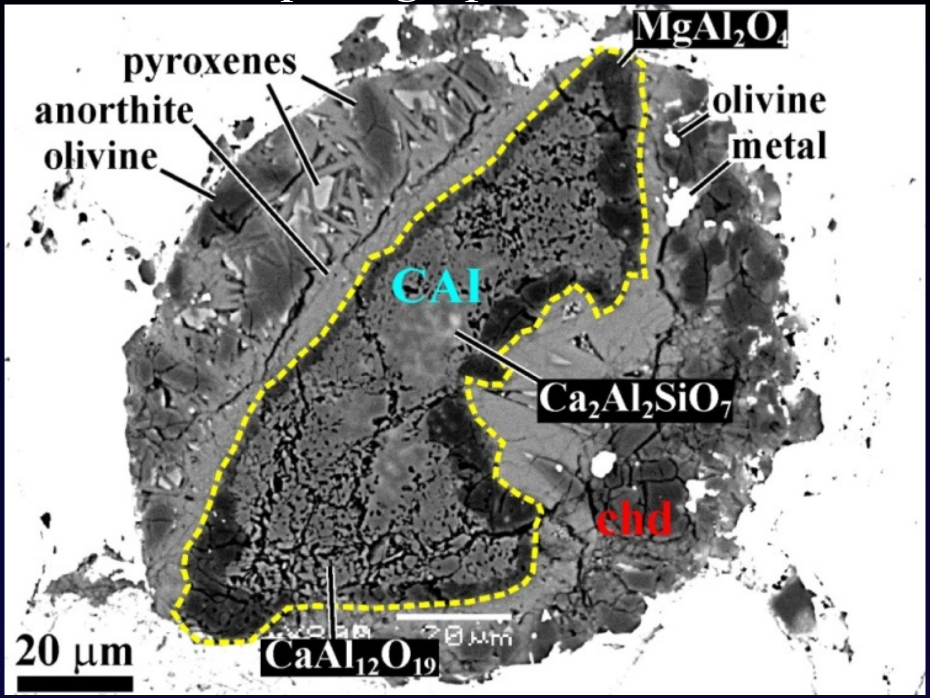
- matrix & chondrules in a chondrite group are chemically complementary: e.g., Mg/Si ratio in Renazzo, CR chondrite

matrix	0.65±0.11
chondrules	1.03±0.20
bulk chondrite	0.91
solar Mg/Si	0.90

→ matrix & chondrules formed in the same nebular regions throughout the PPD, contrary to X-wind model suggesting chondrules formed near the protoSun & were transported to 1-4 AU where they accreted together with thermally unprocessed matrices *(Shu et al. 1996, 1997, 2001)*

Chondrules: Relative & absolute chronology

based on petrographic observations

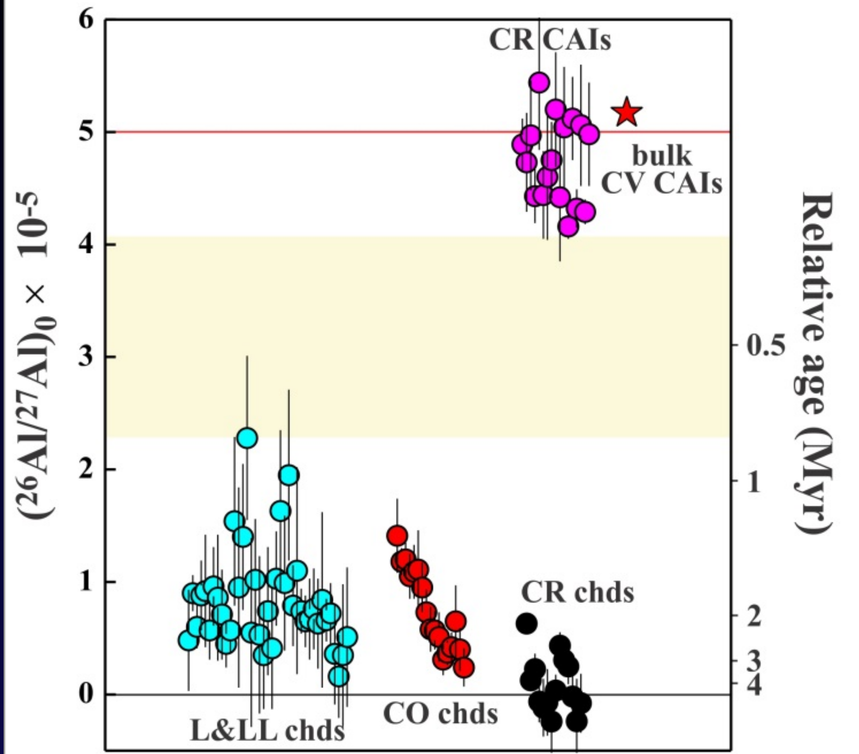


- relict CAIs in chondrules

→ CAIs predated chondrules

→ age difference cannot be inferred

based on short-lived radionuclide ^{26}Al



assumption: uniform $^{26}Al/^{27}Al$ in PPD

Krot et al. (2009) GCA

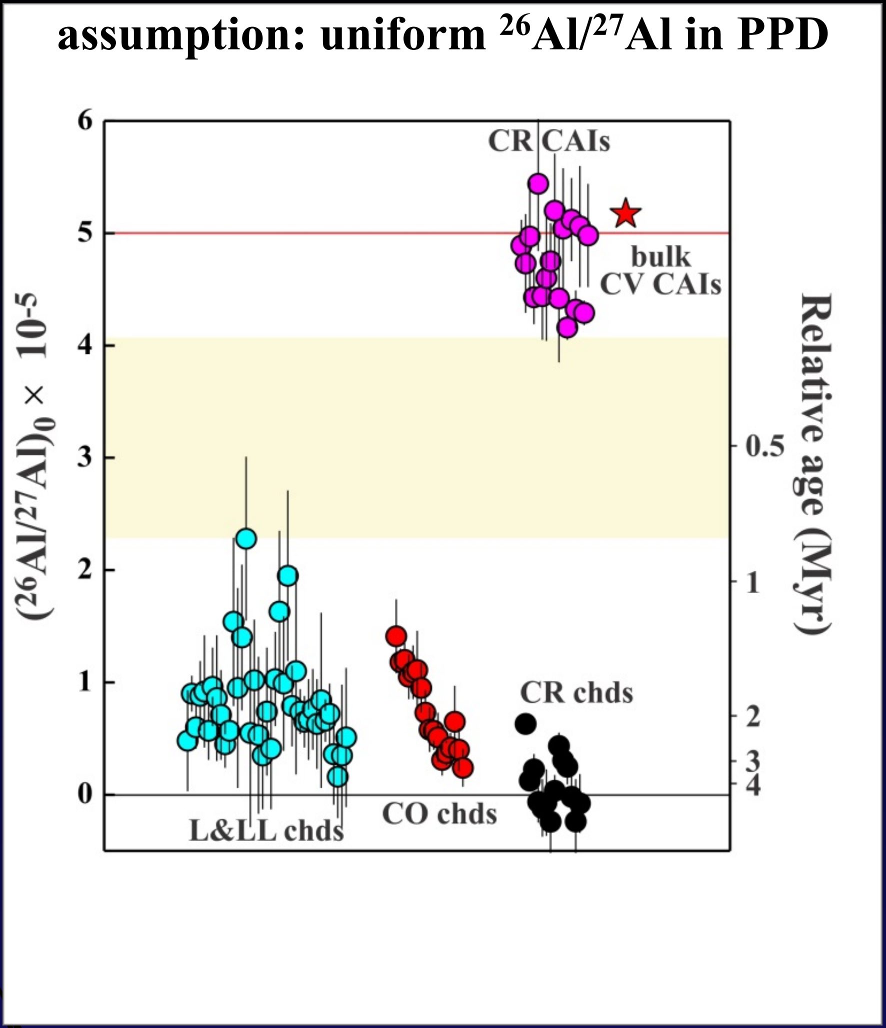
- if $(^{26}Al/^{27}Al)_0$ in PPD was uniform, ~5×10^{-5}

→ 1 Myr age gap between CAIs & chondrules

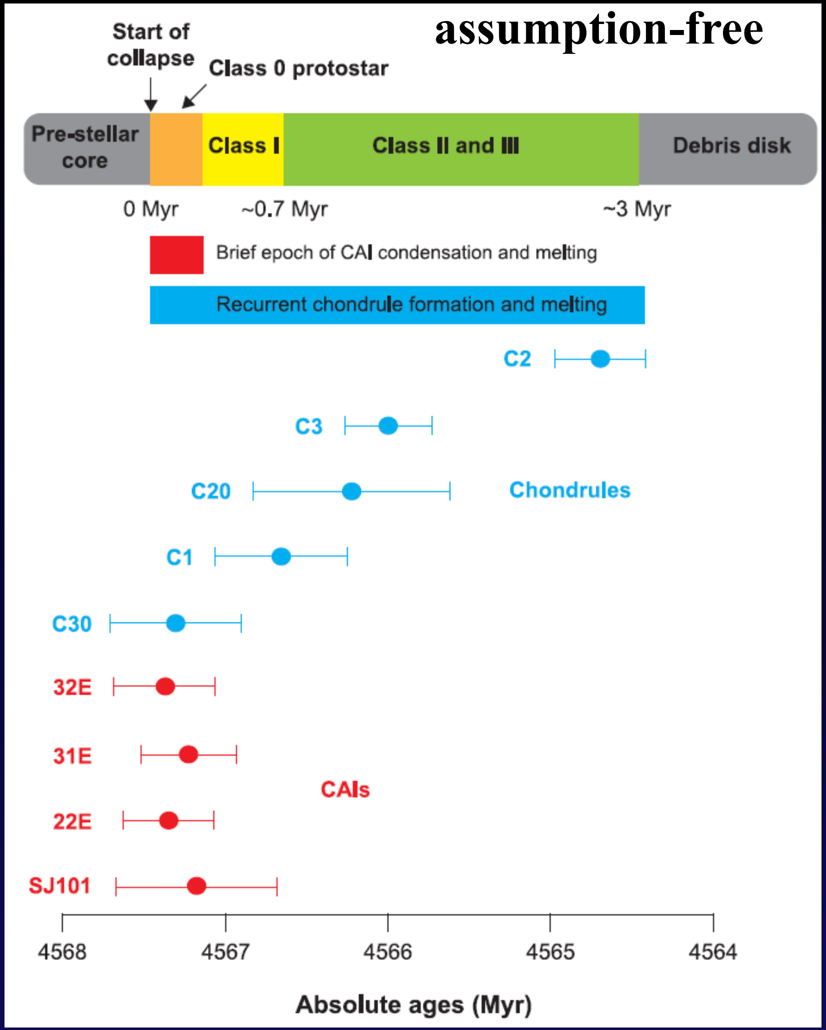
→ chondrule formation lasted for ~3 Myr

→ life-time of PPD is at least 4 Myr

Chondrules: Relative ^{26}Al-^{26}Mg & absolute U-Pb chronology



Krot et al. (2009) GCA



Connelly et al. (2012) Science

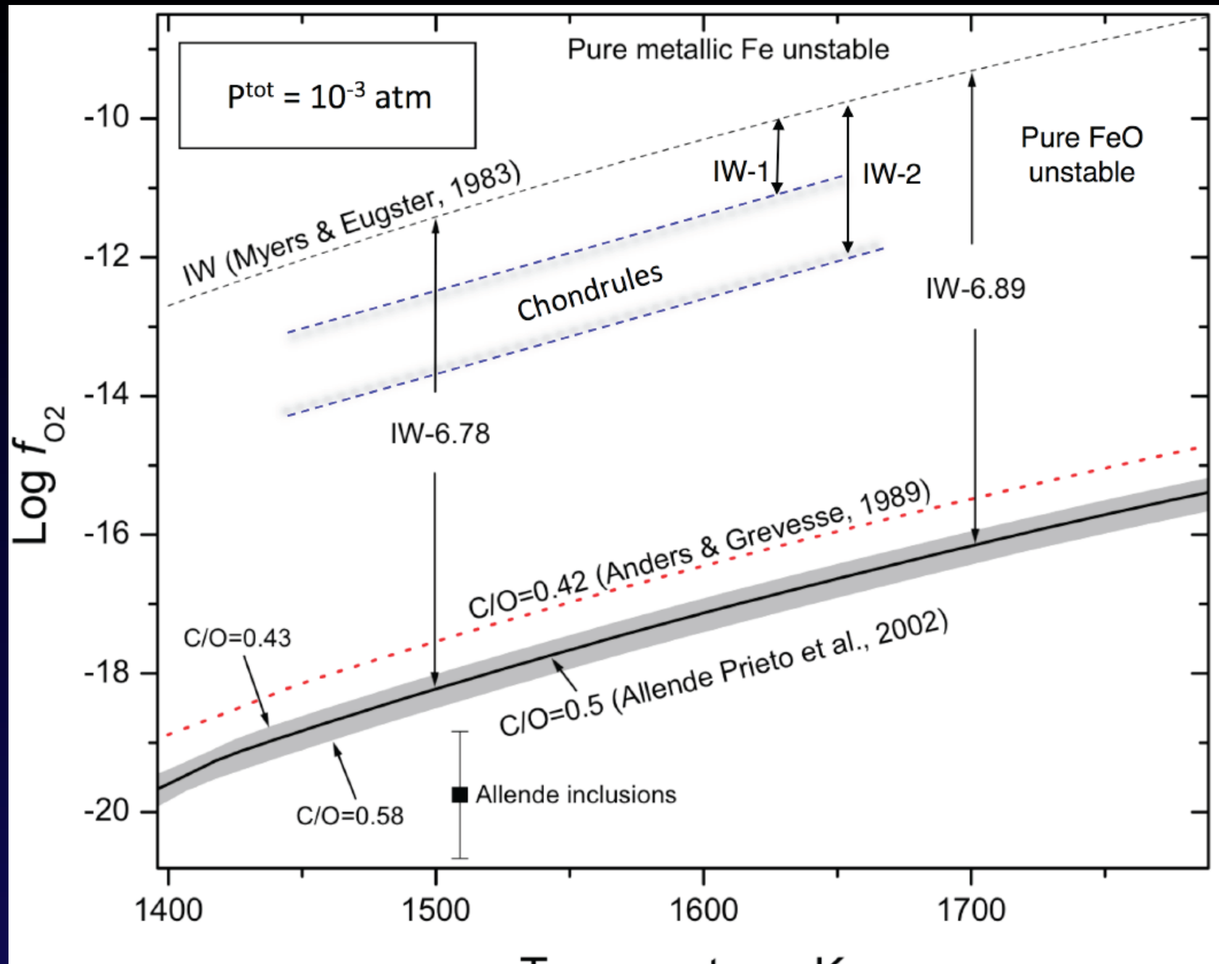
Relative ^{26}Al-^{26}Mg chronology:

- 1 Myr age gap between CAIs & chondrules
- chondrule formation lasted for ~3 Myr
- at least 4 Myr PPD life-time

Absolute U-Pb chronology:

- chondrule formation started contemporaneously with CAIs & lasted for at least 3 Myr

Chondrules formed under oxidizing conditions

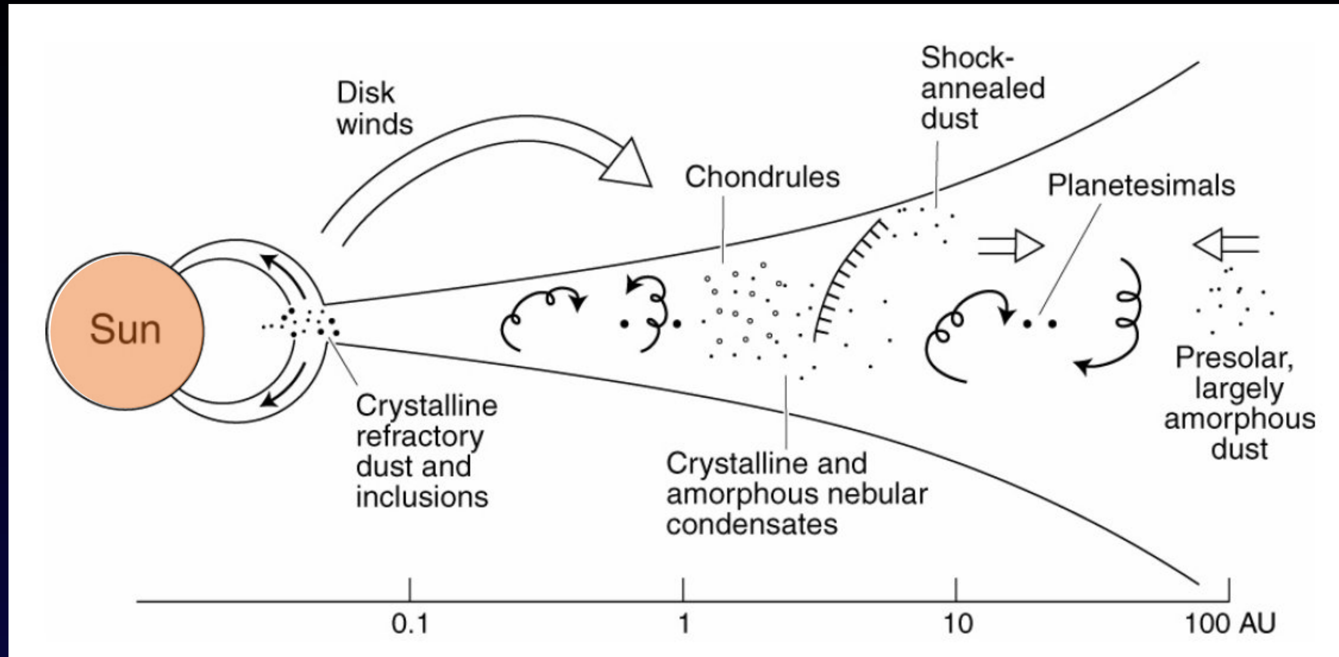


Grossman et al. (2011) MAPS

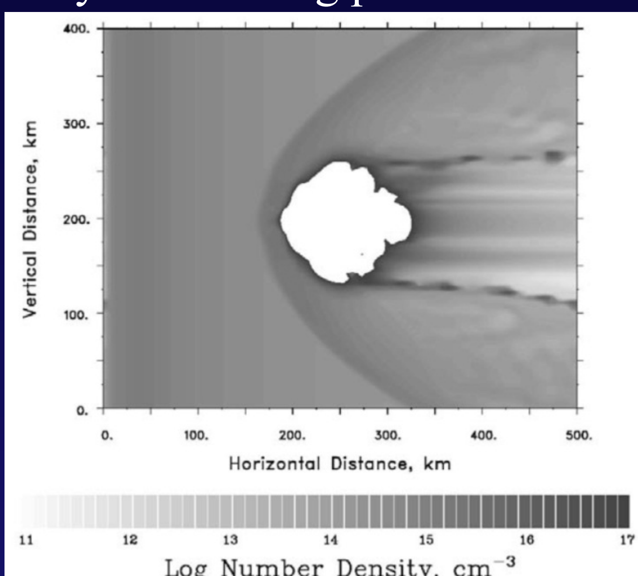
- under much more oxidizing (up to IW-1) conditions than CAIs (up to IW-7)
- high partial pressures of Si, Na, Mg, Fe, & S (were not lost from chondrule melts)

→ formed under <u>non-solar</u> conditions (D/G > 10^4×solar; H_2O/H_2 >10^2×solar)

Models of chondrule formation: Shock waves, impacts, lightning ...

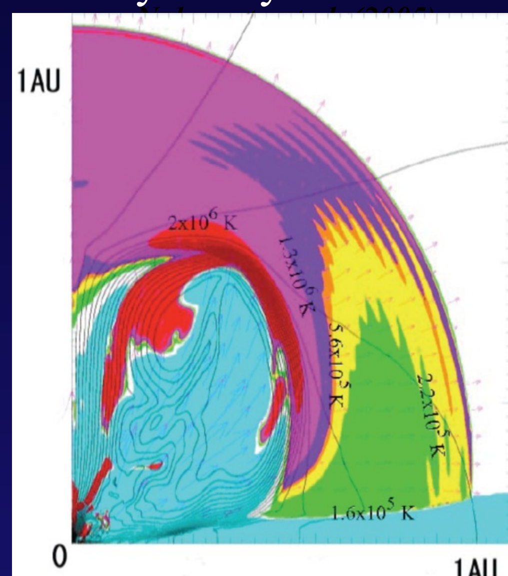


by fast moving planetesimals



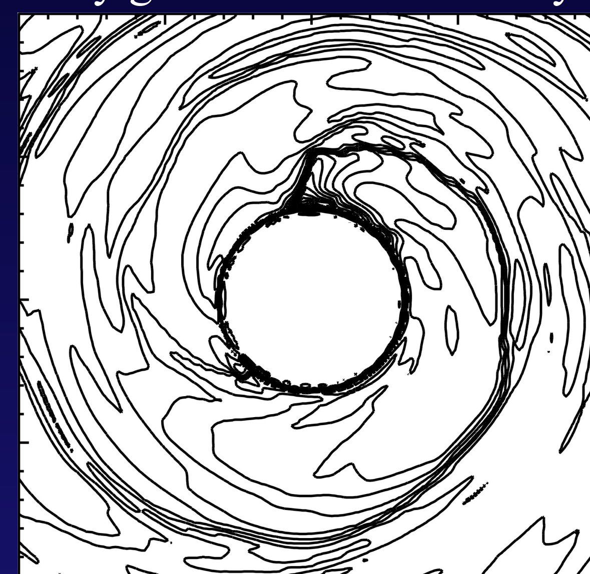
Hood et al. (2005)

by X-ray flares



Nakamoto et al. (2005)

by gravitational instability



Boss & Durisen (2005)

Chondrules & fine-grained matrices: Summary

- in isotopically distinct regions of inner disk dominated by ^{16}O-poor dust & gas
- at lower ambient T (<650 K) & highly non-solar dust/gas & H_2O/H_2 ratios
- rapid heating (up to 1600ºC) & cooling (1-1000ºC hr^{-1}) of isotopically & mineralogically diverse solid precursors (fragments of earlier formed chondrules & CAIs, & matrix)
- most matrix was thermally processed during chondrule & CAI formation
- formation mechanisms are not understood: shock waves, impacts, lightning, …
- started contemporaneously with CAIs & lasted ~ 3-4 Myr

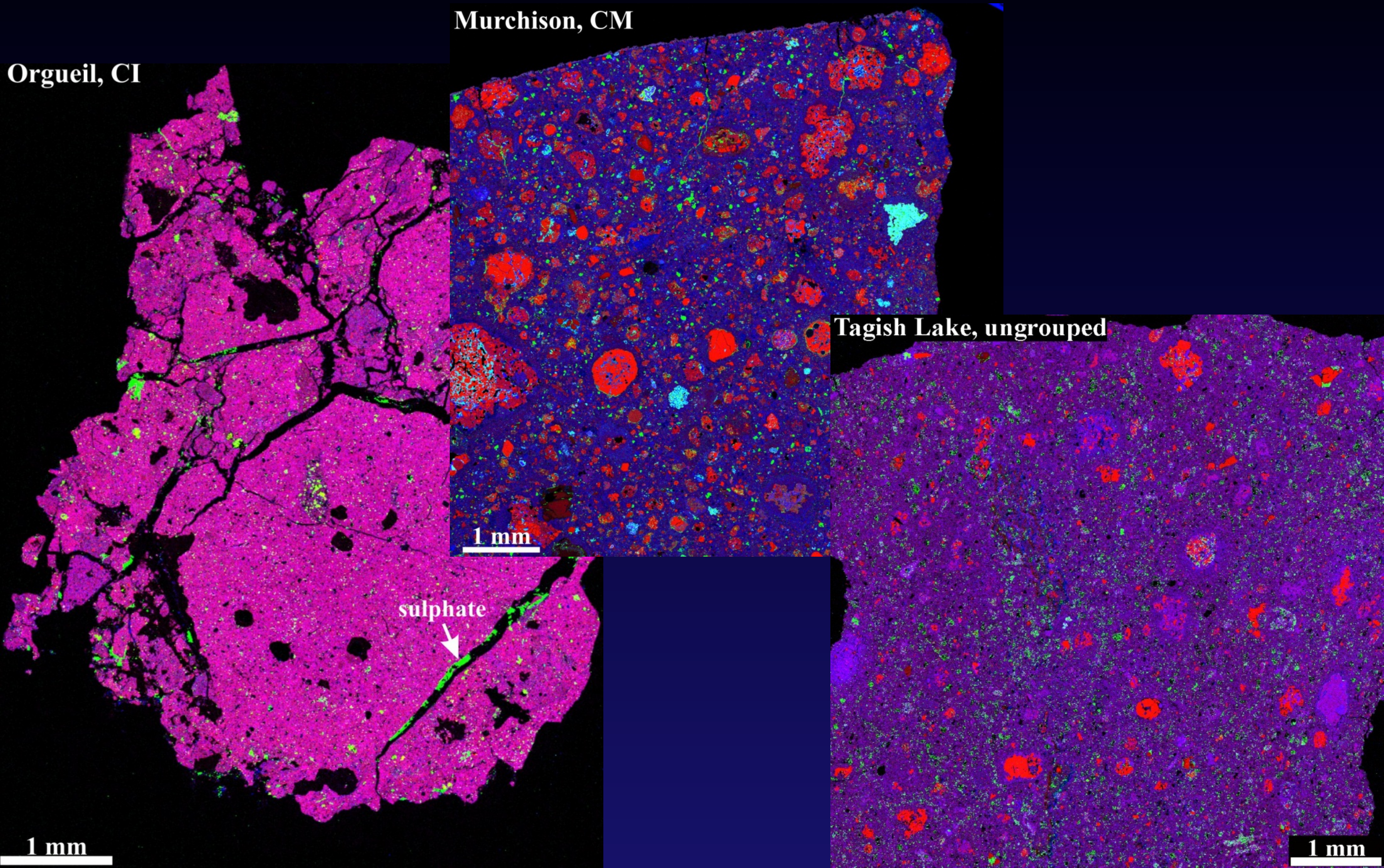
→ life-time of PPD ~ 3-4 Myr

→ duration of accretion of chondrite asteroids ~ 3-4 Myr

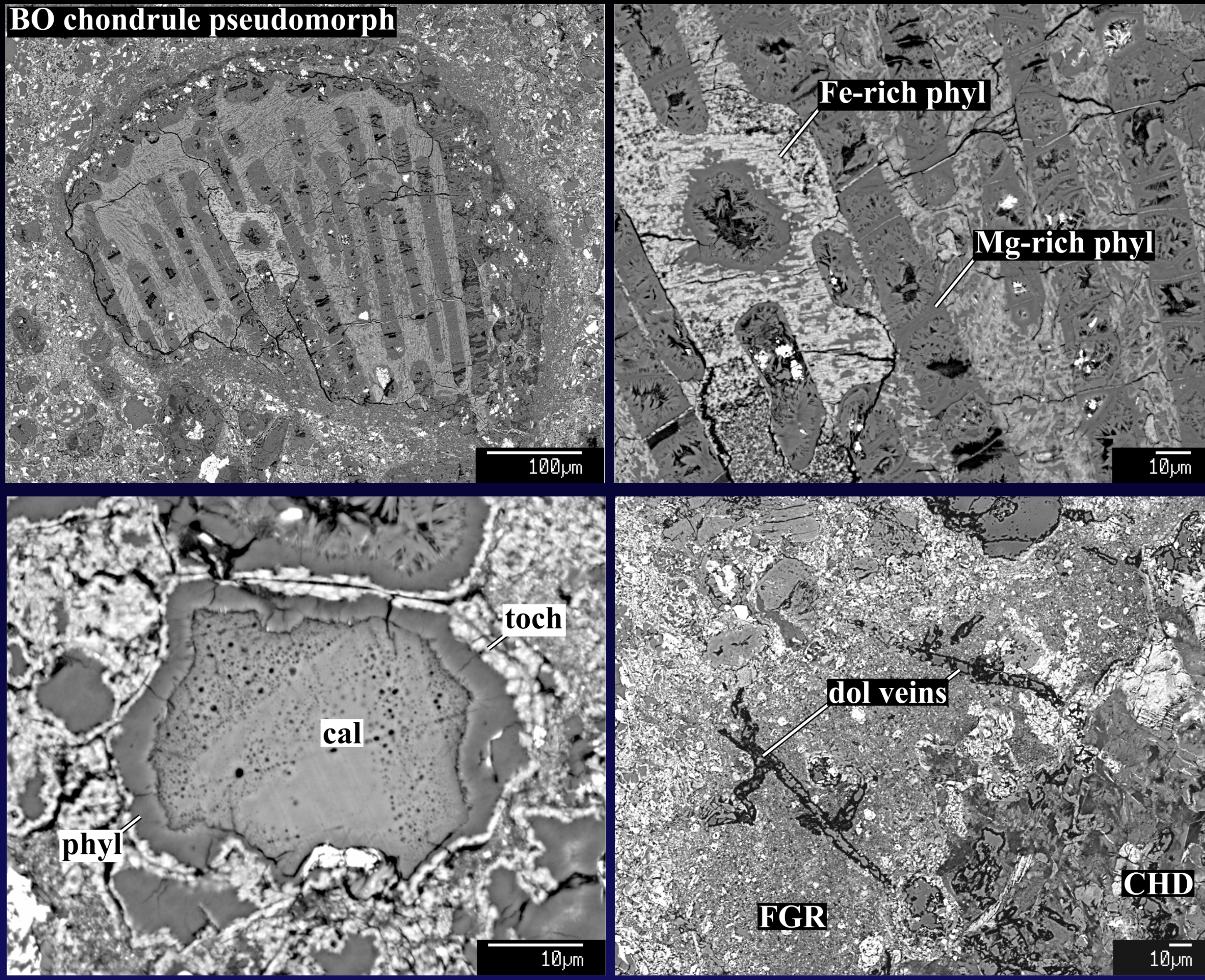
- chondrule formation may have been rapidly followed by chondrite accretion

IV. Aqueous activity on chondrite parent bodies

Carbonaceous	*Enstatite*	*Ordinary*	Other	Ungrouped
CI CM CR CV CK CO CH CB	EH EL	H L LL	K R	Tagish Lake

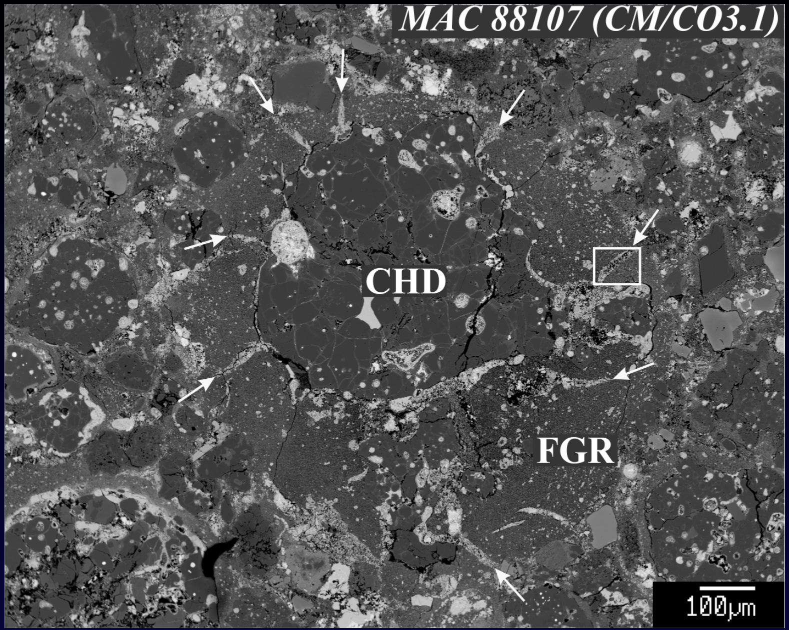


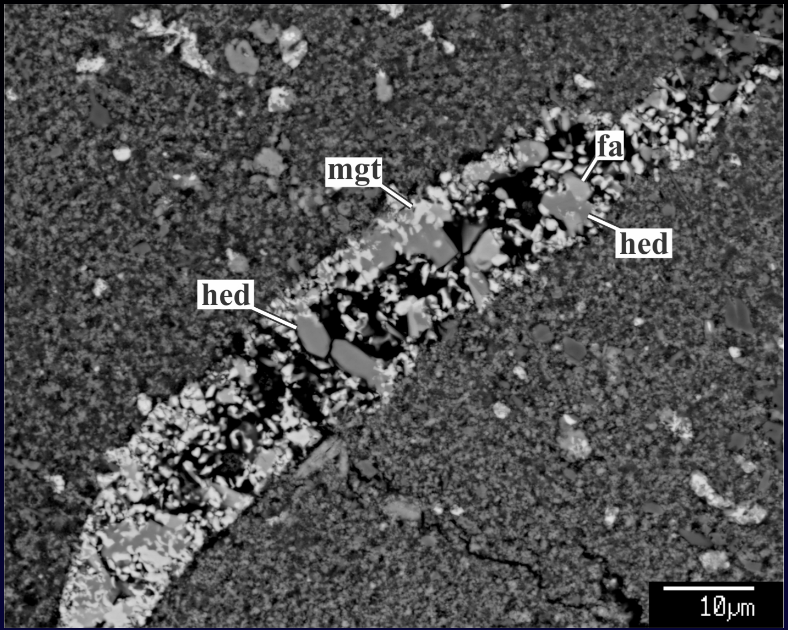
Phyllosilicates, carbonates, veins, chondrule pseudomorphs



- aqueous alteration occurred on chondrite asteroids, <u>not in the nebula</u>
- CMs, CIs, & CRs: low-T aq. alteration ~25-100°C at high W/R vol. ratio: 0.4-1

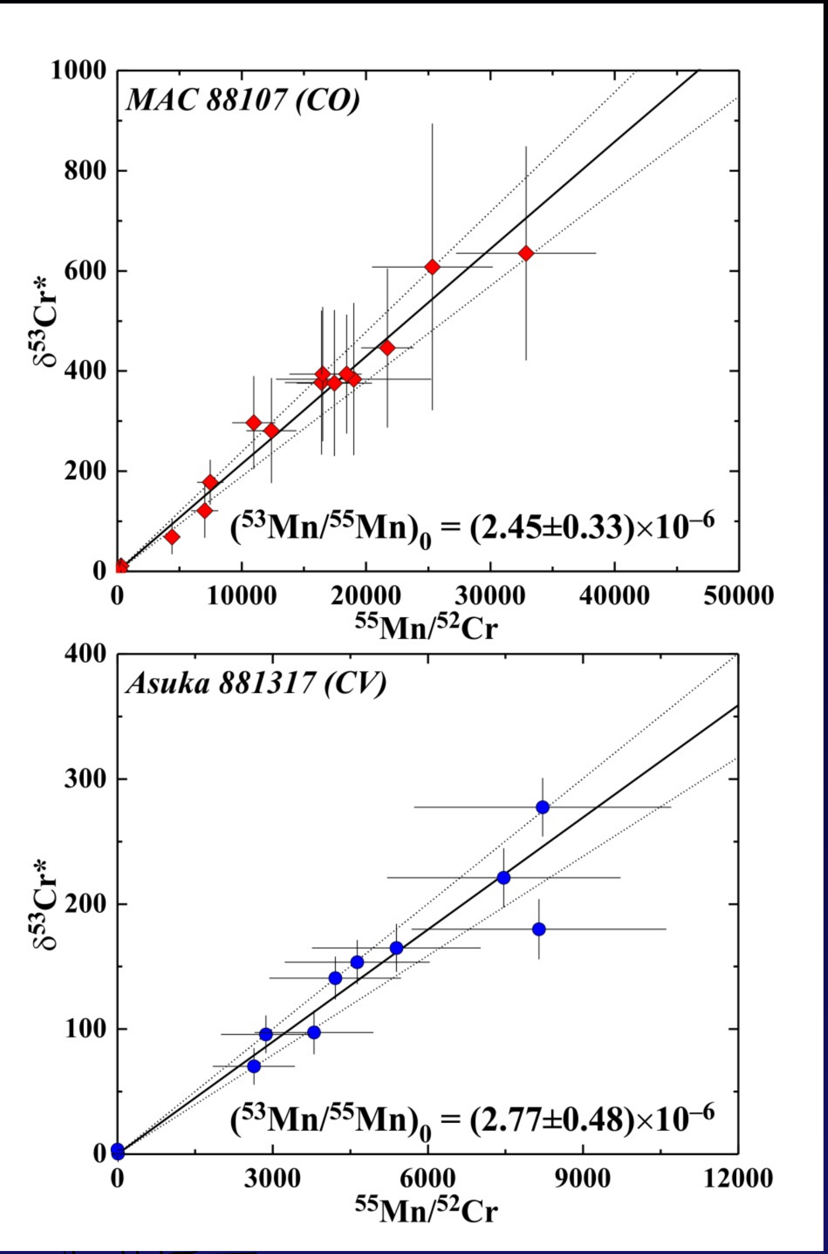
Fayalite-hedenbergite-magnetite veins





- CV, CO, CK, H, L, LL, & R chondrites: T ~ 100-200°C & low W/R <0.2
- aqueous alteration under highly-oxidizing conditions
- phyllosilicates, fayalite ($Fe^{2+}{}_2SiO_4$), magnetite ($Fe^{2+}Fe_2{}^{3+}O_4$), hedenbergite $CaFe^{2+}Si_2O_6$, andradite $Ca_3Fe_2{}^{3+}Si_3O_{12}$

Chronology of aqueous alteration



Doyle et al. (2013) LPSC

^{53}Mn- ^{53}Cr system: $^{53}Mn \rightarrow {}^{53}Cr$, $t_{1/2}$ ~3.7 Myr

^{53}Mn uniformly distributed in PPD with the $(^{53}Mn/^{55}Mn)_0 = 6\times10^{-6}$ *(Kleine et al., 2012, GCA)*

Doyle et al. (2013) LPSC

- fayalite in CVs : 3.7 Myr after t_0
- fayalite in COs : 4.4 Myr after t_0

Fujiya et al. (2012, 2013) EPSL, Nature Comm.

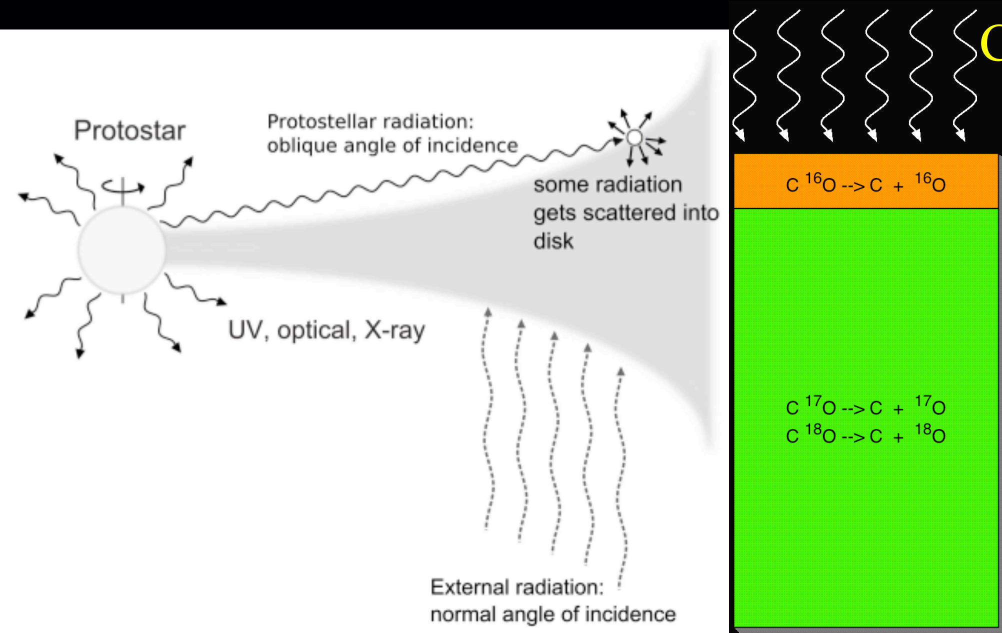
- carbonates in CMs : ~ 4 Myr after t_0
- carbonates in CIs : ~ 3.5 Myr after t_0

→ aqueous alteration on CC parent asteroids started shortly after accretion

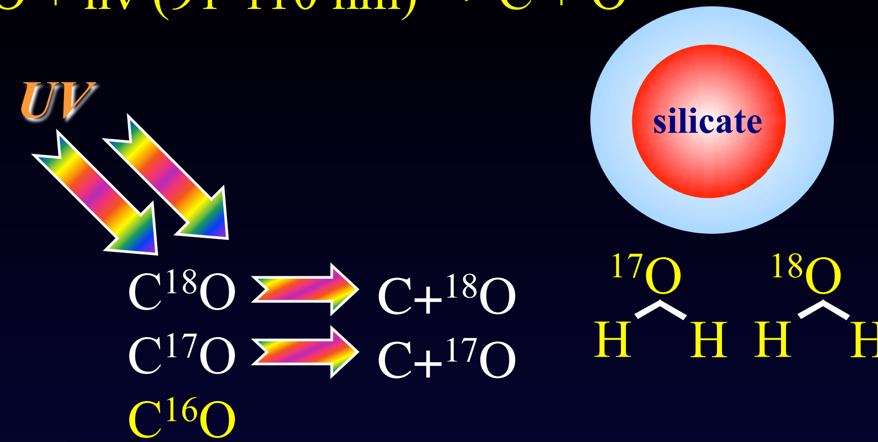
→ chondrites formed near the snow line

→ position of snow line varied with time

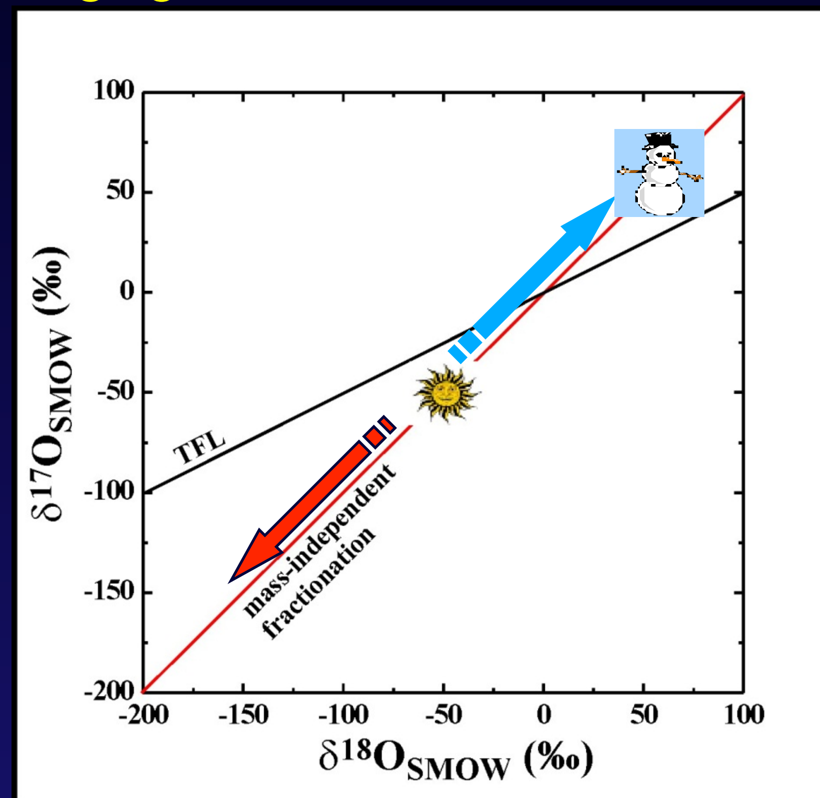
Water as a carrier of heavy oxygen in the molecular cloud & PPD



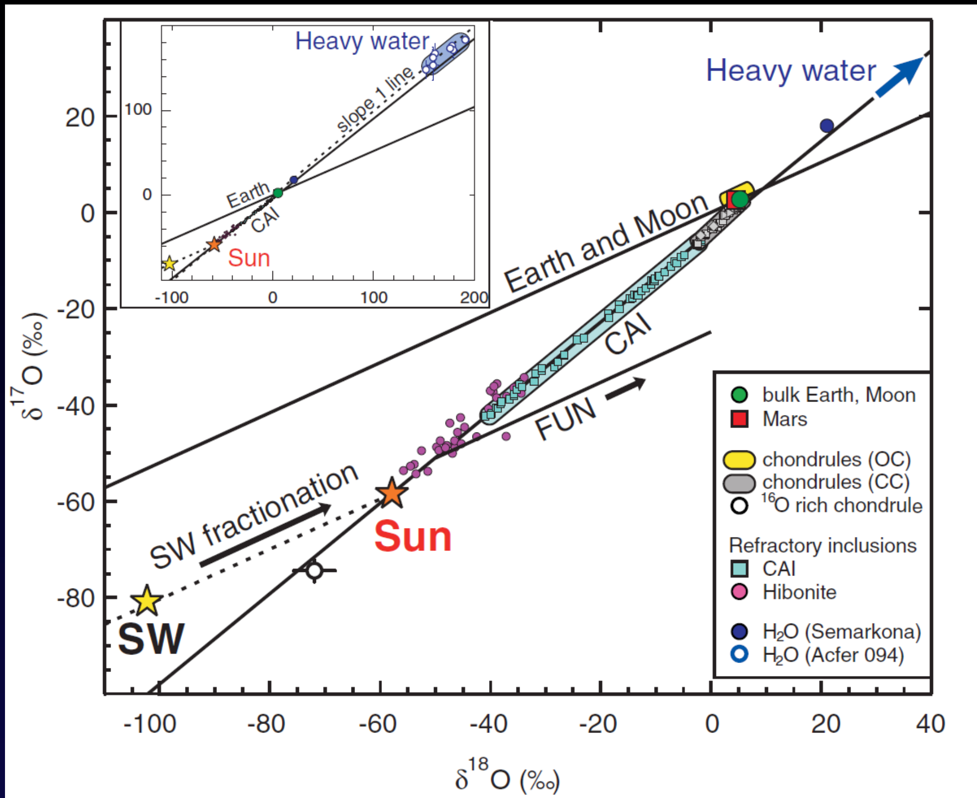
$CO + h\nu$ (91-110 nm) → C + O



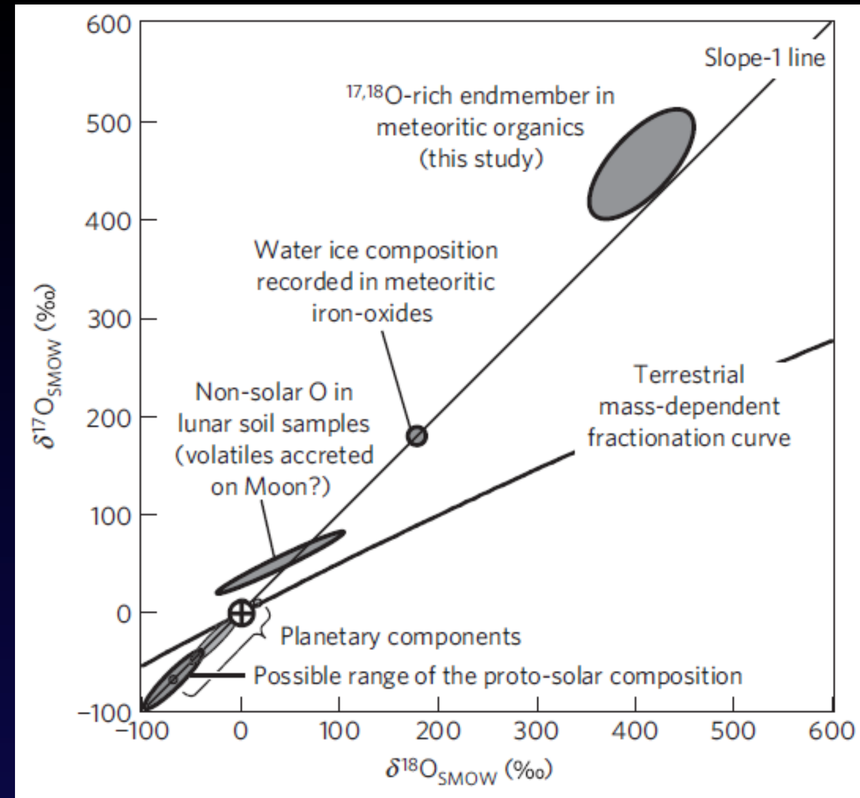
- preferential photodissociation of $C^{17}O$ & $C^{18}O$ in the initially uniformly ^{16}O-rich ($\Delta^{17}O$ ~ -25‰) PPD or MC (assumption)
- released ^{17}O & ^{18}O incorporated into $H_2O_{(s)}$; $CO_{(g)}$ is ^{16}O-enriched
- $H_2O_{(s)}/CO_{(g)}$ enrichment in the midplane of the protoplanetary disk followed by ice evaporation → $^{17,18}O$-enriched gas
- thermal processing of dust in $^{17,18}O$-rich gas → evolution of solids towards the TFL



Oxygen isotopes & water in the Solar System



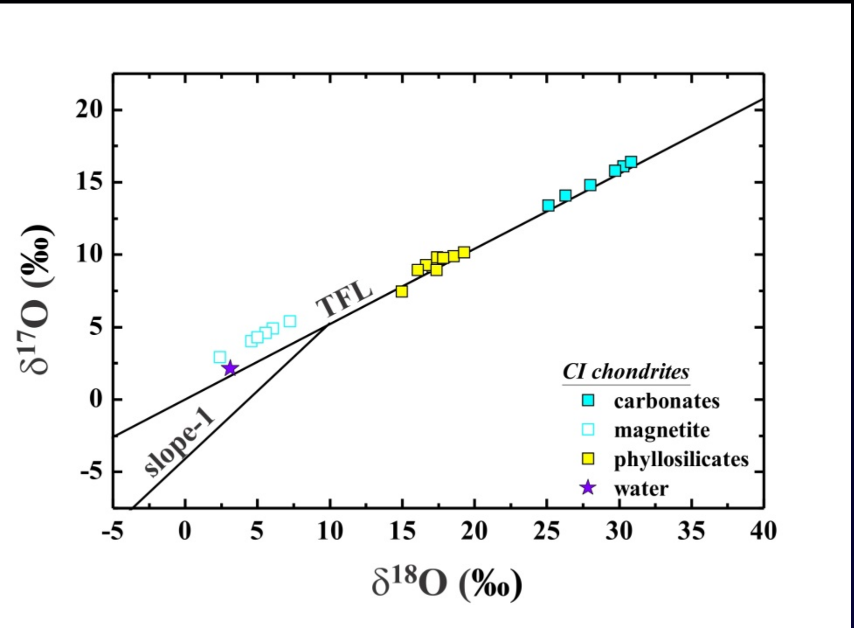
McKeegan et al. (2011) Science

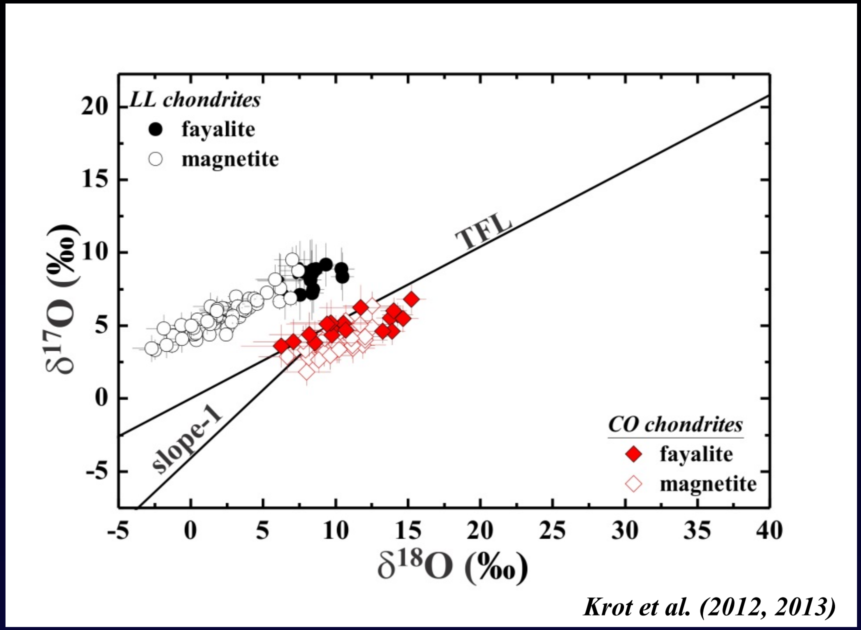


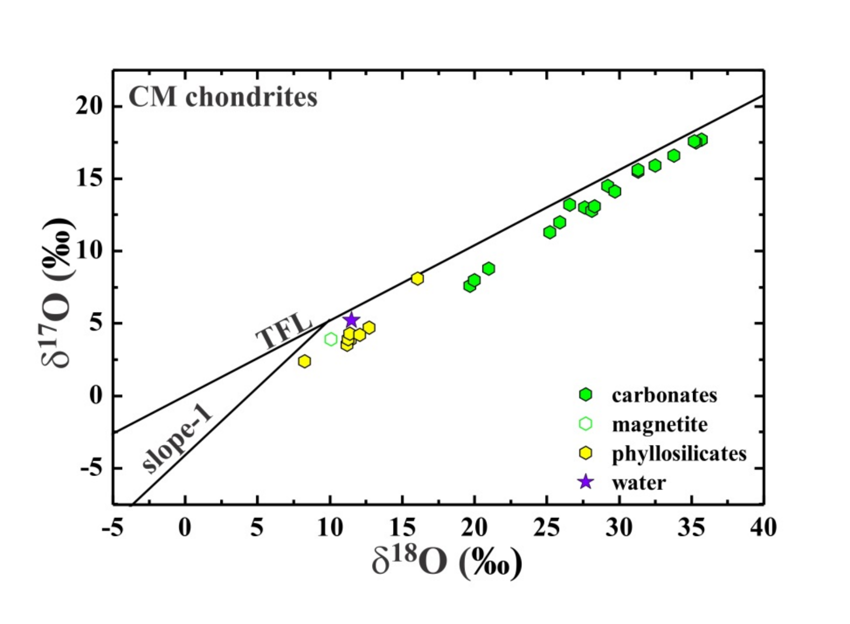
Hashizume et al. (2011) Nature Geoscience

- in the CO self-shielding models *(Yurimoto & Kuramoto, 2004, Science; Lyons & Young, 2005, Nature)*, water in the outer disk (>30 AU) is highly ^{17}O & ^{18}O-enriched relative to the inner disk (testable by ALMA)
  - iron oxides in Acfer 094 (ungr.): $\Delta^{17}O$ ~ +90‰ *(Sakamoto et al., 2007, Science)*
  - grains in IOM from Y-793495 (CR): $\Delta^{17}O$ ~ +500‰ *(Hashizume et al., 2007)*

Oxygen-isotope compositions of aqueously-formed minerals



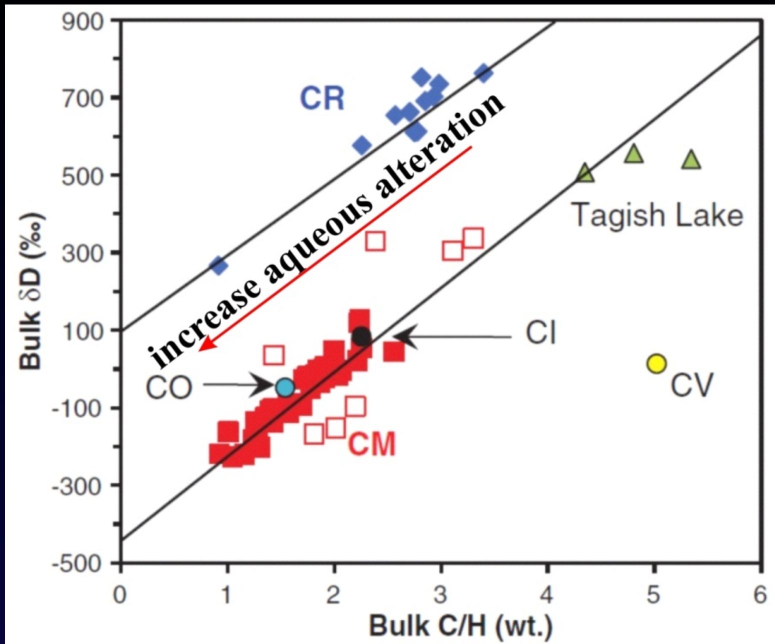


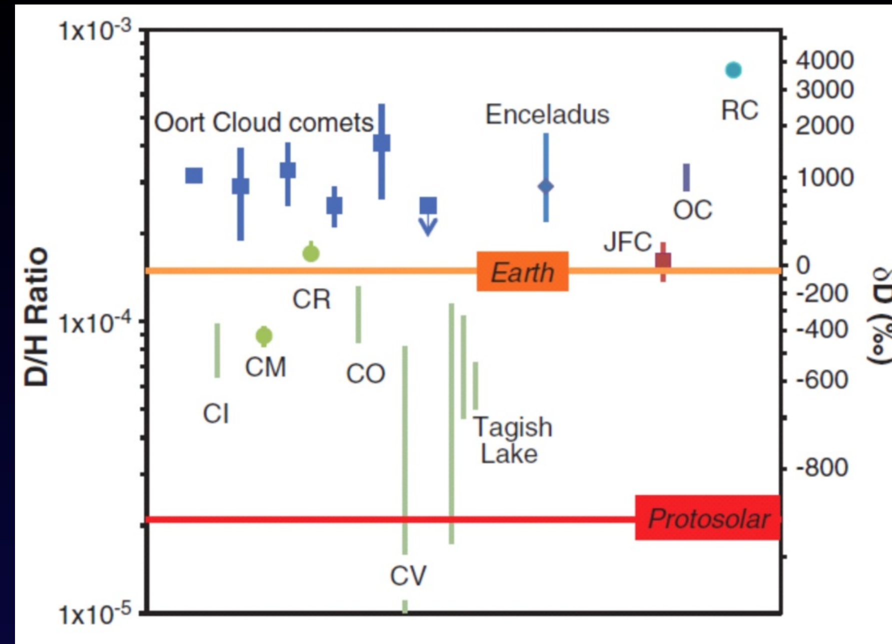


- $\Delta^{17}O$ of aqueously-formed minerals can be used as a proxy for $\Delta^{17}O$ of asteroid water ices; it stays ~constant during alteration
- near terrestrial $\Delta^{17}O$ values of water ices → local, inner SS origin of water

Clayton & Mayedan (1999), Rowe et al. (1994), Leshin et al. (2011), Baker et al. (2002), Benedix et al. (2003)

Sources of water on asteroids: Insights from D/H ratio





Alexander et al. (2012) Science

- $\delta D = (D/H_{sample}/D/H_{SMOW} - 1)\times 1000$
- bulk δD = phyllosilicates + organics
- δD of phyllosilicates at C/H = 0

- δD in chondrites, Oort Cloud & Jupiter Family comets, & Enceladus

→ water in chondrites & comets formed in different SS regions *(contrary to Walsh et al., 2011, Nature)*

→ low influx of water from the outer SS into the inner disk ~2 Myr after t_0 could be due to an early growth of Jupiter that prevented significant radial transport of dust from outside its orbit

Constraints on the early SS processes from chondrites

- ✓ Solar System formed near massive star(s)
- ✓ early generation of ^{16}O-rich & ^{16}O-poor reservoirs in protoplanetary disk
- ✓ inner Solar System solids experienced extensive thermal processing during evaporation, condensation, thermal annealing, & melting
- ✓ thermally processed solids were radially transported to the outer Solar System
- ✓ life-time of the PPD is ~3-4 Myr
- ✓ accretion of cm-sized objects started at t_0
- ✓ accretion of asteroid-sized bodies started < 1 Myr after t_0 & lasted at least 3-4 Myr
- ✓ accretion of individual asteroids may have been very rapid
- ✓ most chondrites accreted water ices, i.e., were close to the Snow Line
- ✓ influx of the outer Solar System material was small during chondrite accretion