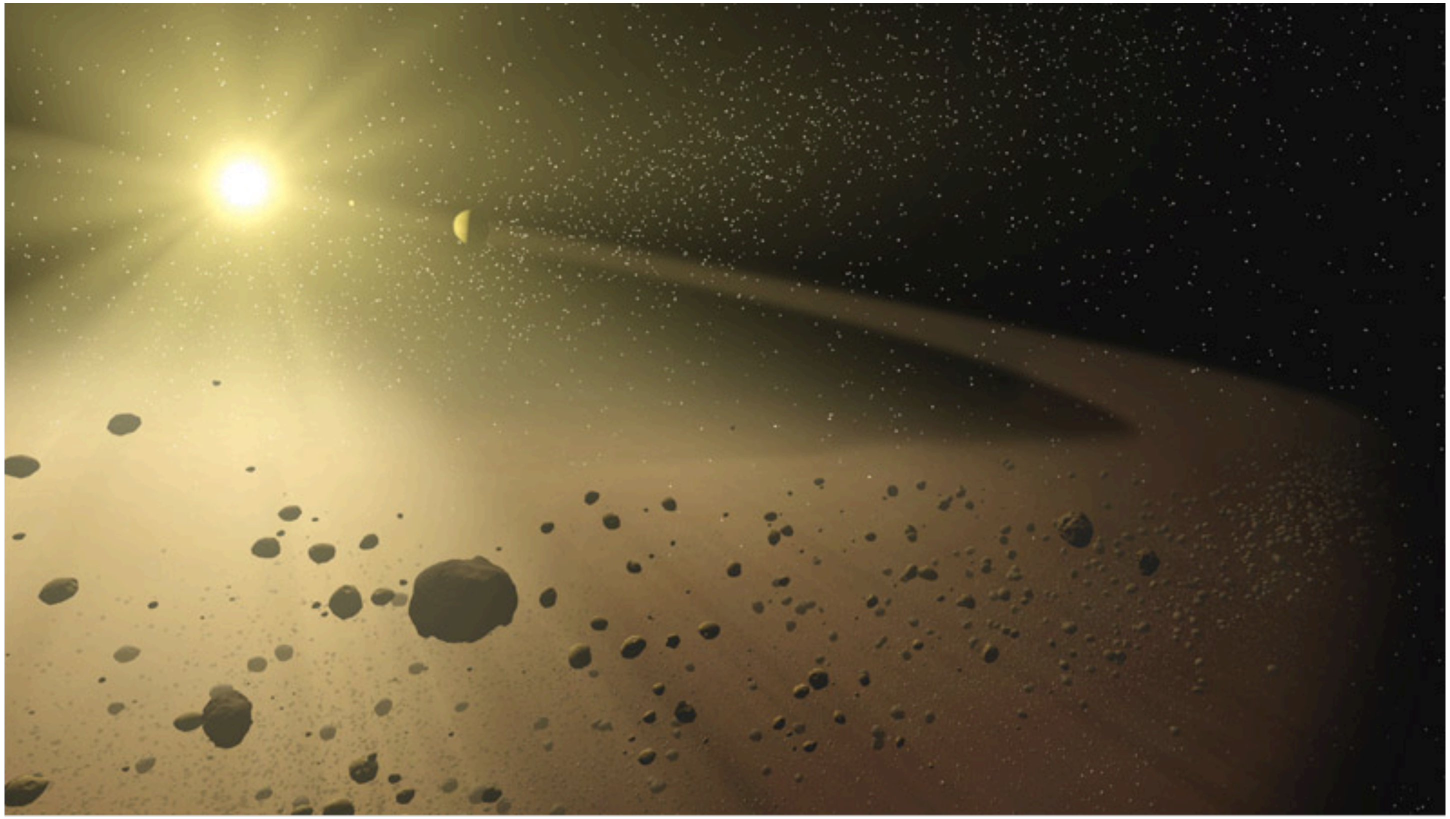
Constraints on the early evolution of the Solar System's protoplanetary disk from asteroid compositions



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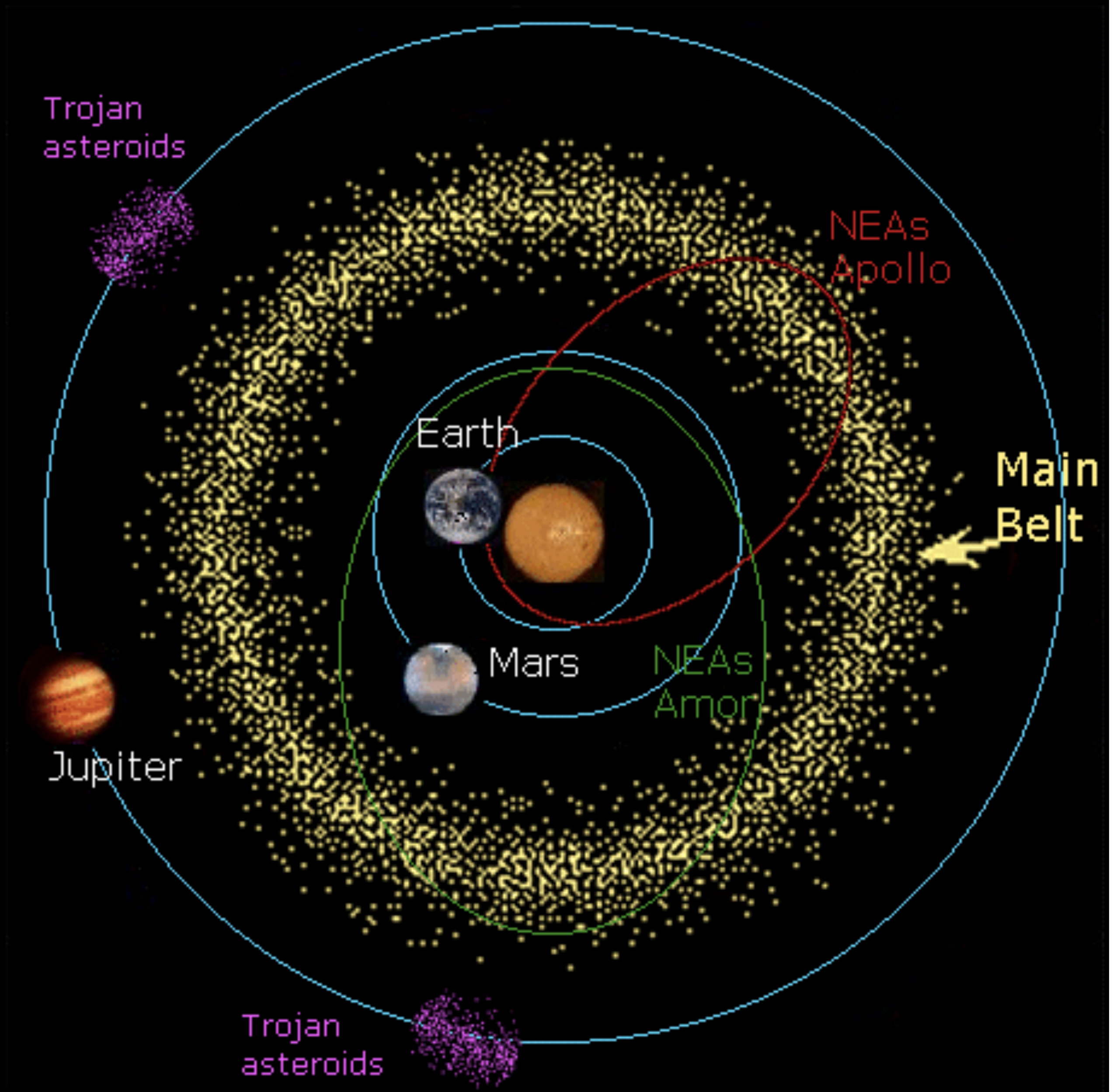
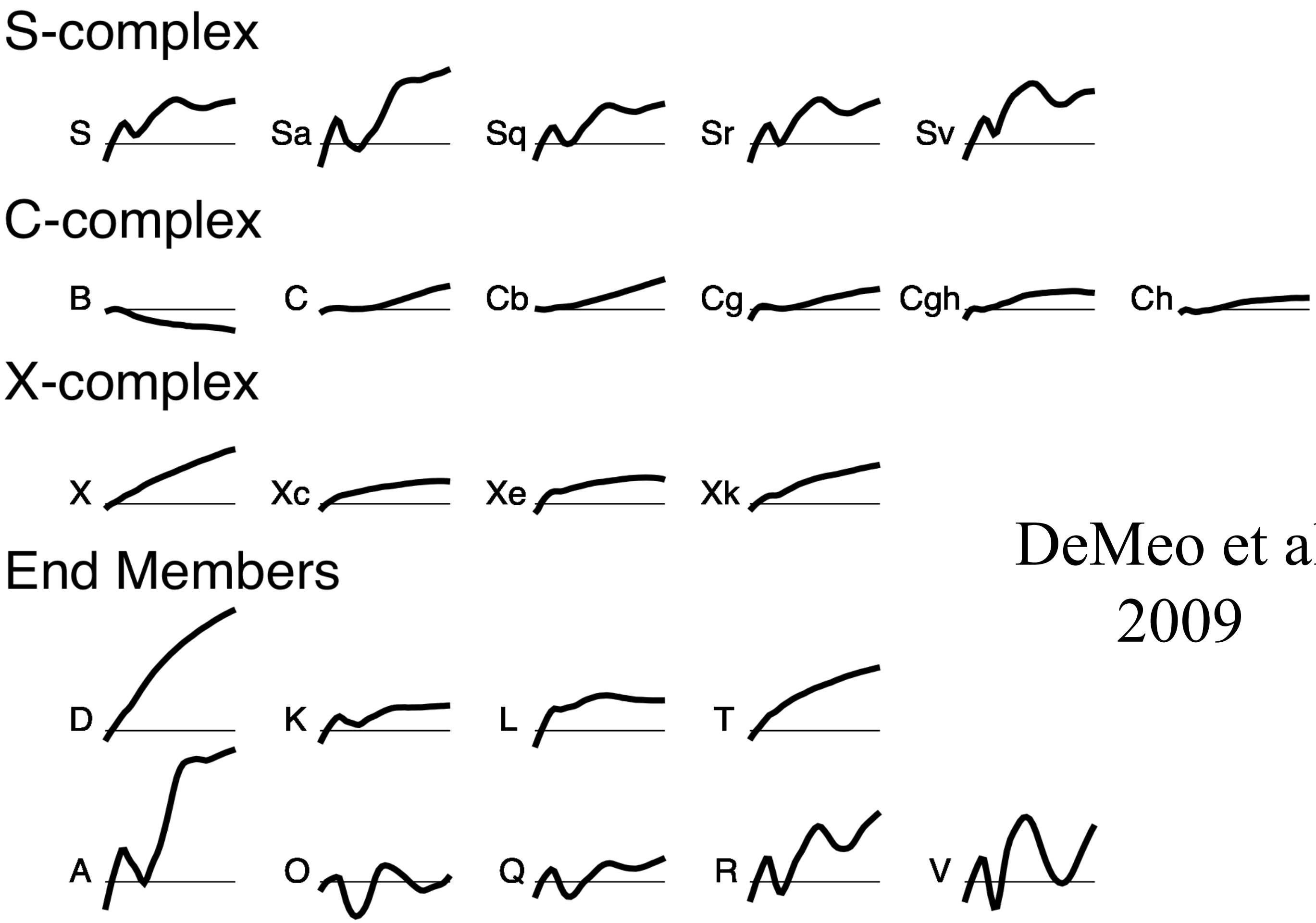
Asteroid Facts:

- **Most are in the main asteroid belt (between Mars and Jupiter).**
- **Largest is Ceres, discovered 1801 (~ 950 km across).**
- **More than 300,000 asteroids known.**
- **Estimated one-million main-belt asteroids larger than 1 km.**

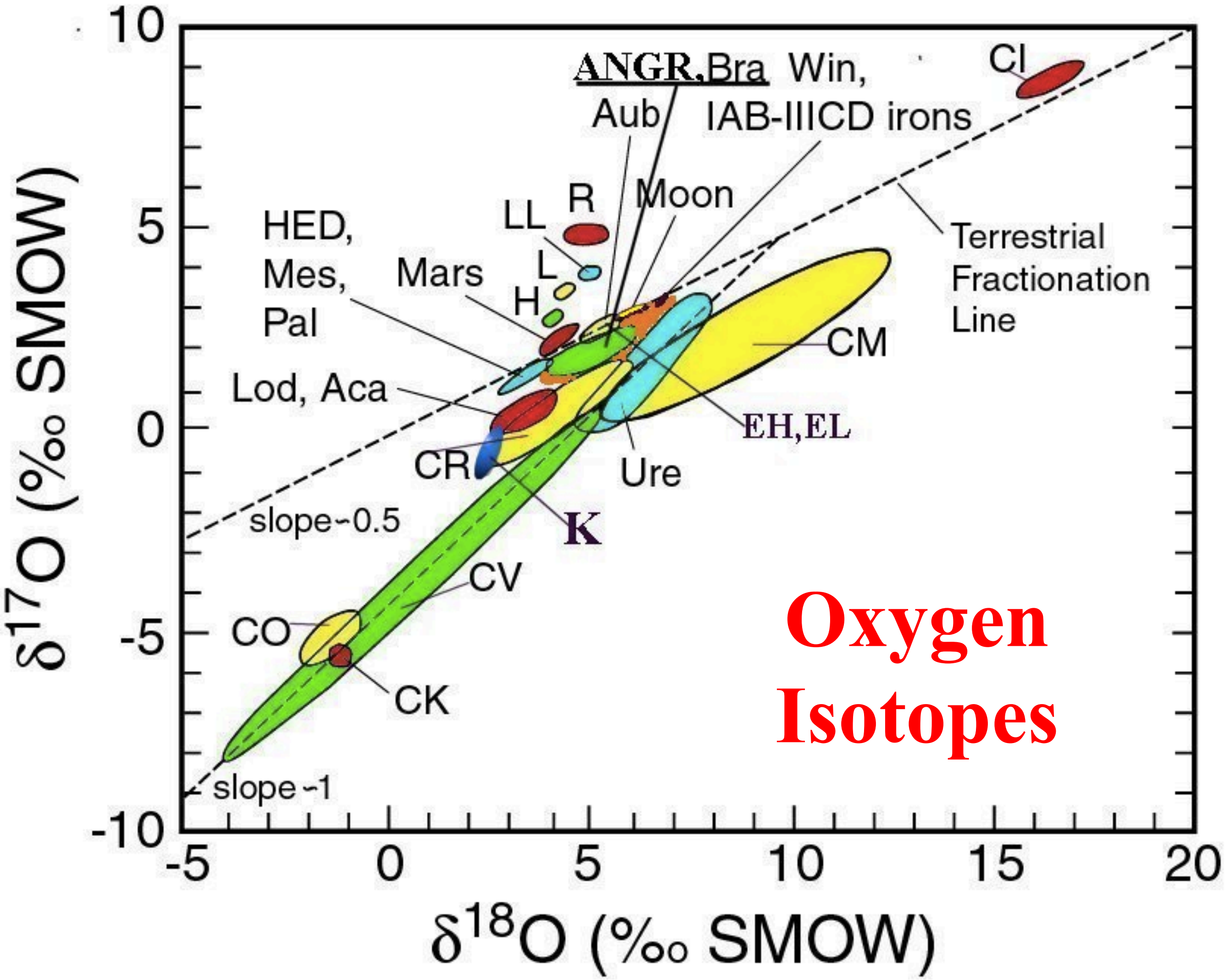


Compositional diversity & clones among asteroids



DeMeo et al. 2009

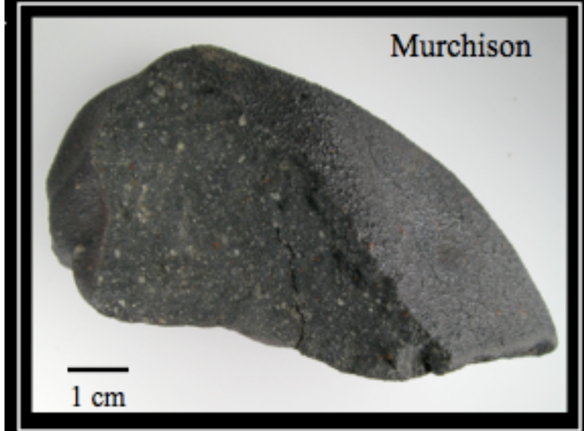
Compositional diversity & clones among meteorites (1)



Oxygen Isotopes

Compositional diversity & clones among meteorites (2)

Carbonaceous chondrites



Density: 2.1 - 2.4 g/cm^3
Porosity: 16 - 29 %
H_2O: 10 %

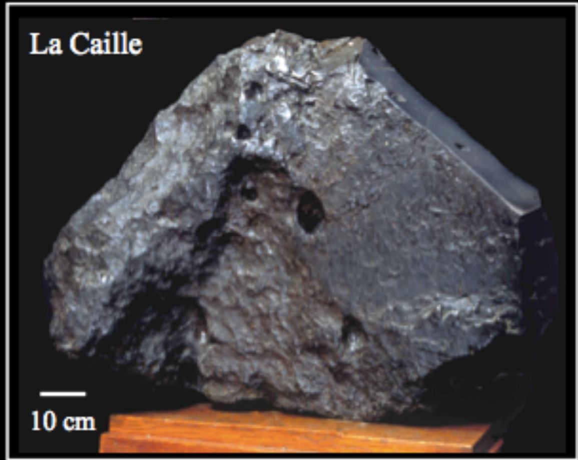
Ordinary chondrites

Density:
2.6 - 3.7 g/cm^3

Porosity:
5 - 20 %

H_2O: 0 %

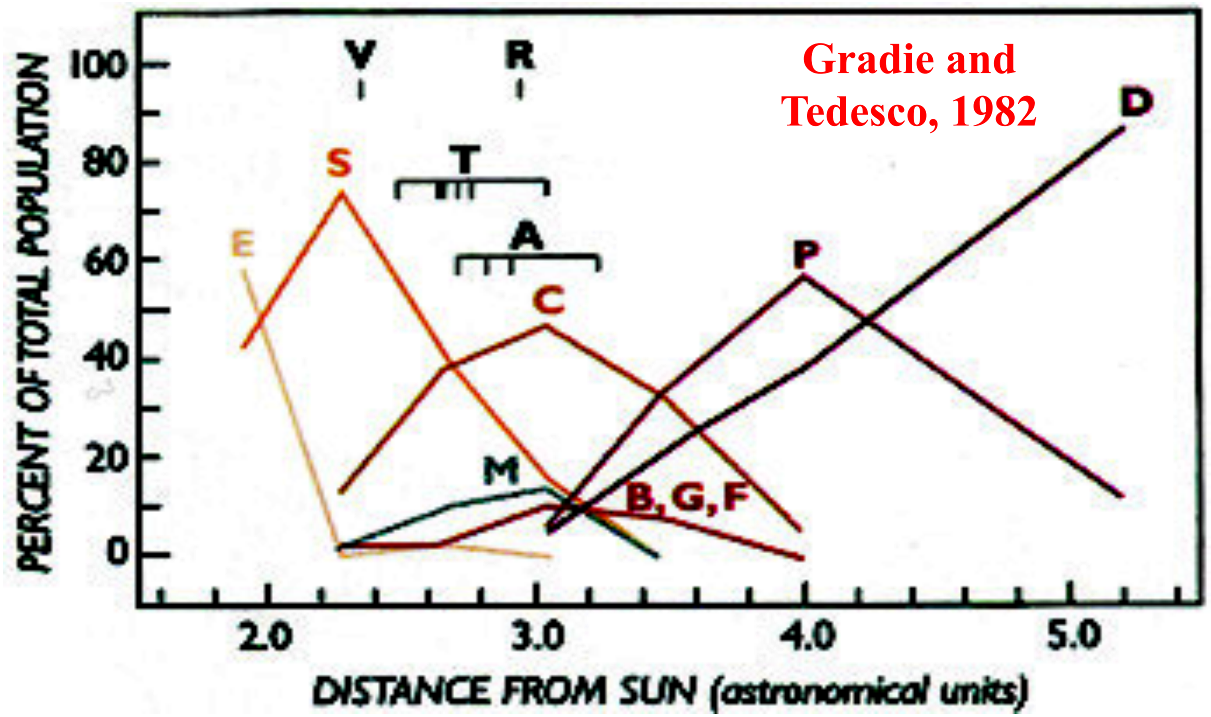
Iron meteorites



Density: 7.0 - 7.6 g/cm^3
Porosity: ~ 0 %
H_2O: 0 %

Compositional gradient & radial mixing

Class	Density (g/cm^3)	Mineralogy
E, M, S	3.0 - 7.0	metal, silicates, sulfides
C	2.0 - 3.0	hydrated silicates, silicates
P, D	1.5 – 2.0	hydrated silicates

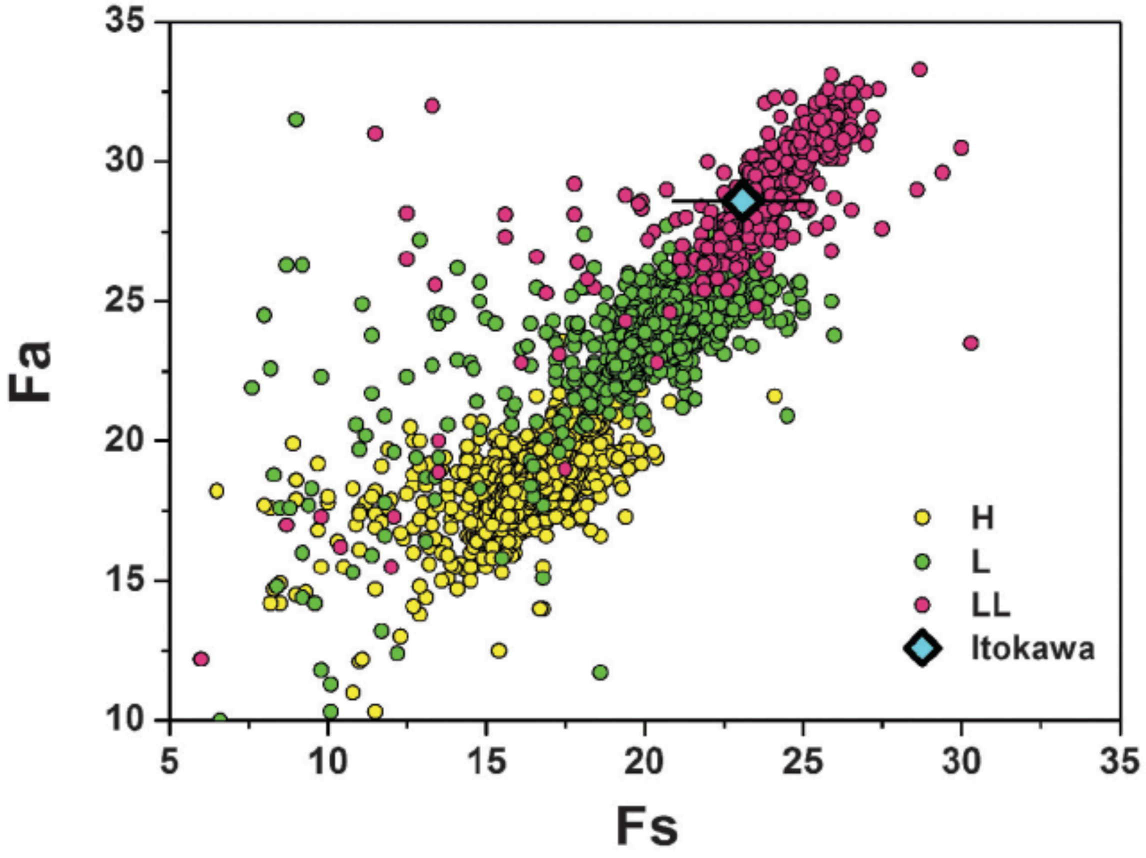


Formation process of S-type asteroids & Ordinary chondrites

- S-type asteroids ~ 30% of all Main Belt Asteroids
- Ordinary chondrites (H, L, LL) ~ 80% of all falls

The Hayabusa mission has ended a 40 years long debate :

S-type asteroids are the parent bodies of Ordinary chondrites !



Nakamura et al. 2011, *Science*

Science questions

- Can we locate the exact source location of the H, L, and LL parent bodies? (provided that the latter one is unique for the H, L, and LL?)

- Did H chondrites form closer to the Sun than LL chondrites (as suggested by their more reduced state) or is it the opposite?

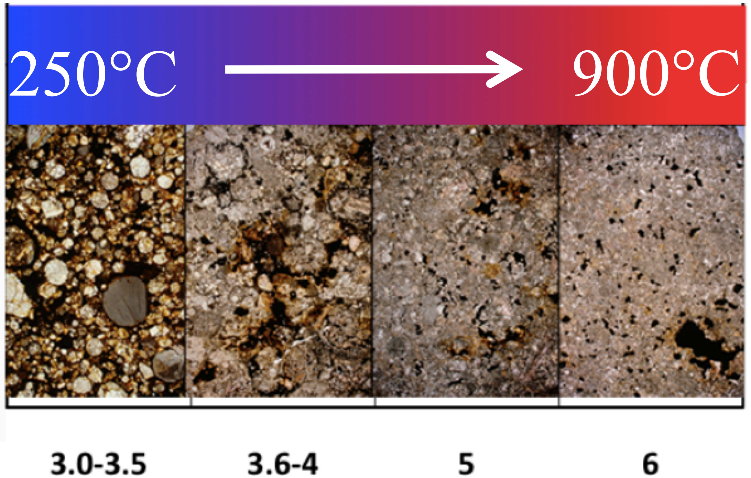
- Did H chondrites form before or after LL chondrites?

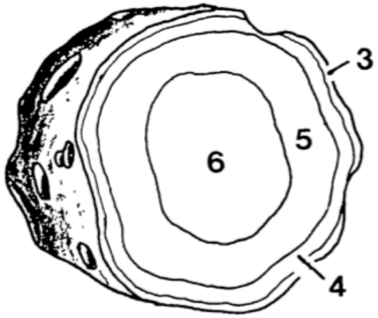
Input Data

Meteorites

(laboratory measurements)

- >100 **ordinary chondrite** spectra (0.4-2.5 μm)





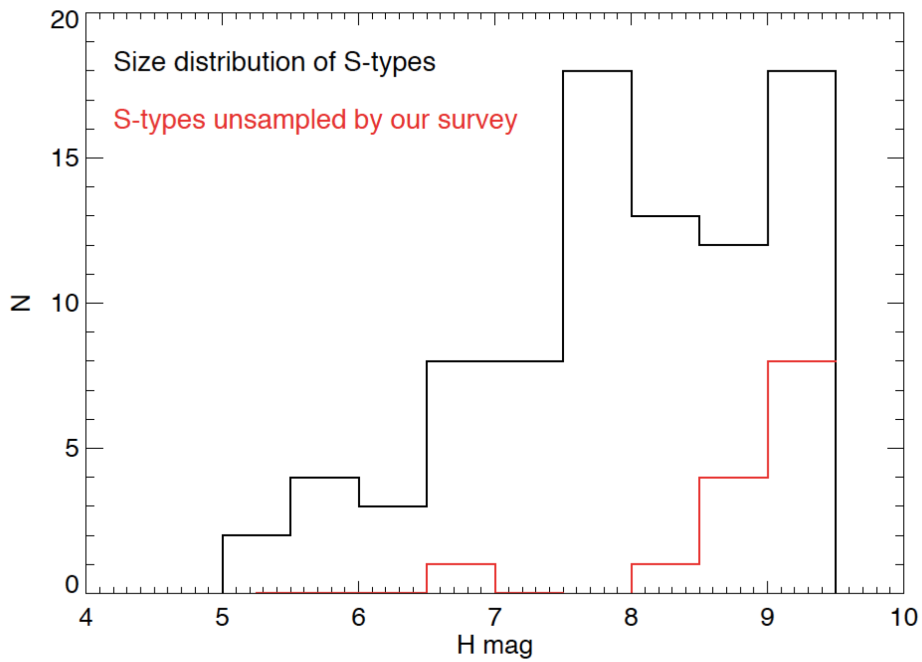
Expected structure via ^{26}Al & ^{60}Fe heating

Main BeltAsteroids

(ground-based observations)

- 93 **S-type** asteroid spectra (0.4-2.5 μm)

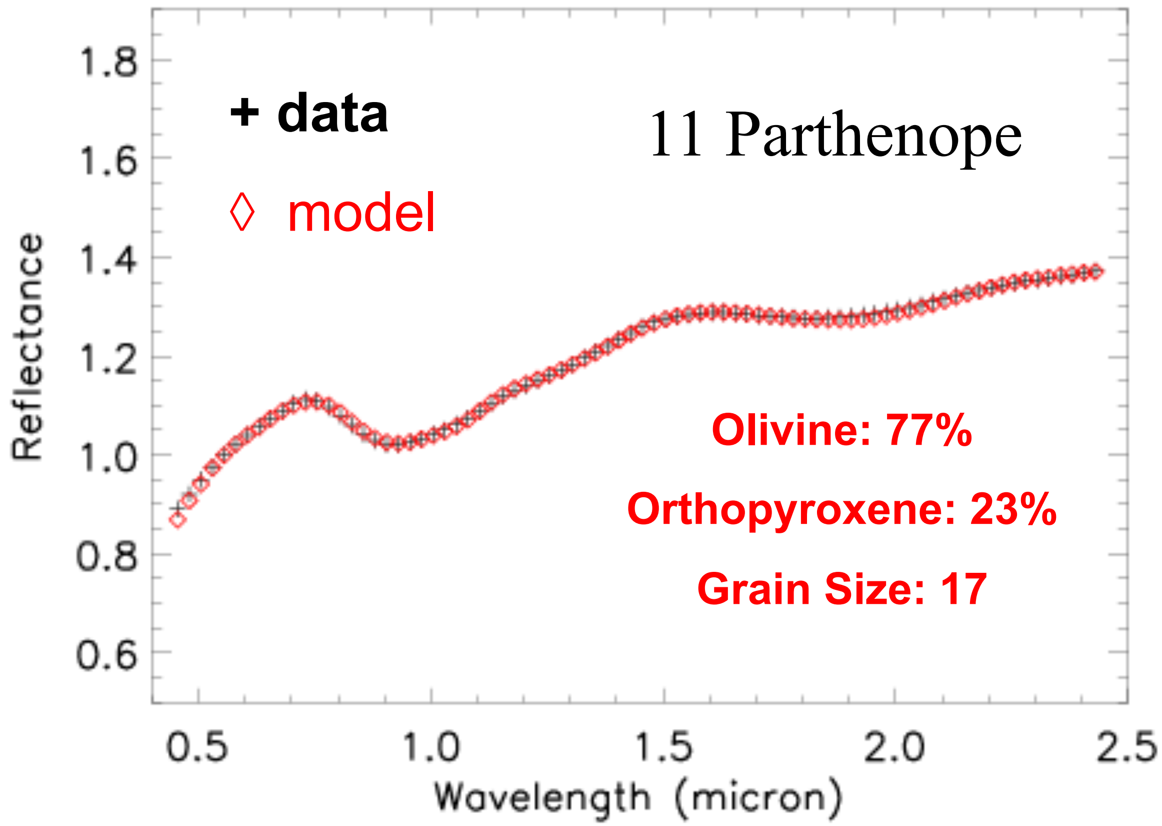
Survey almost complete down to H=8.5 (D~60km)



Compositional Modeling

Compositional model of Shkuratov et al. (1999).

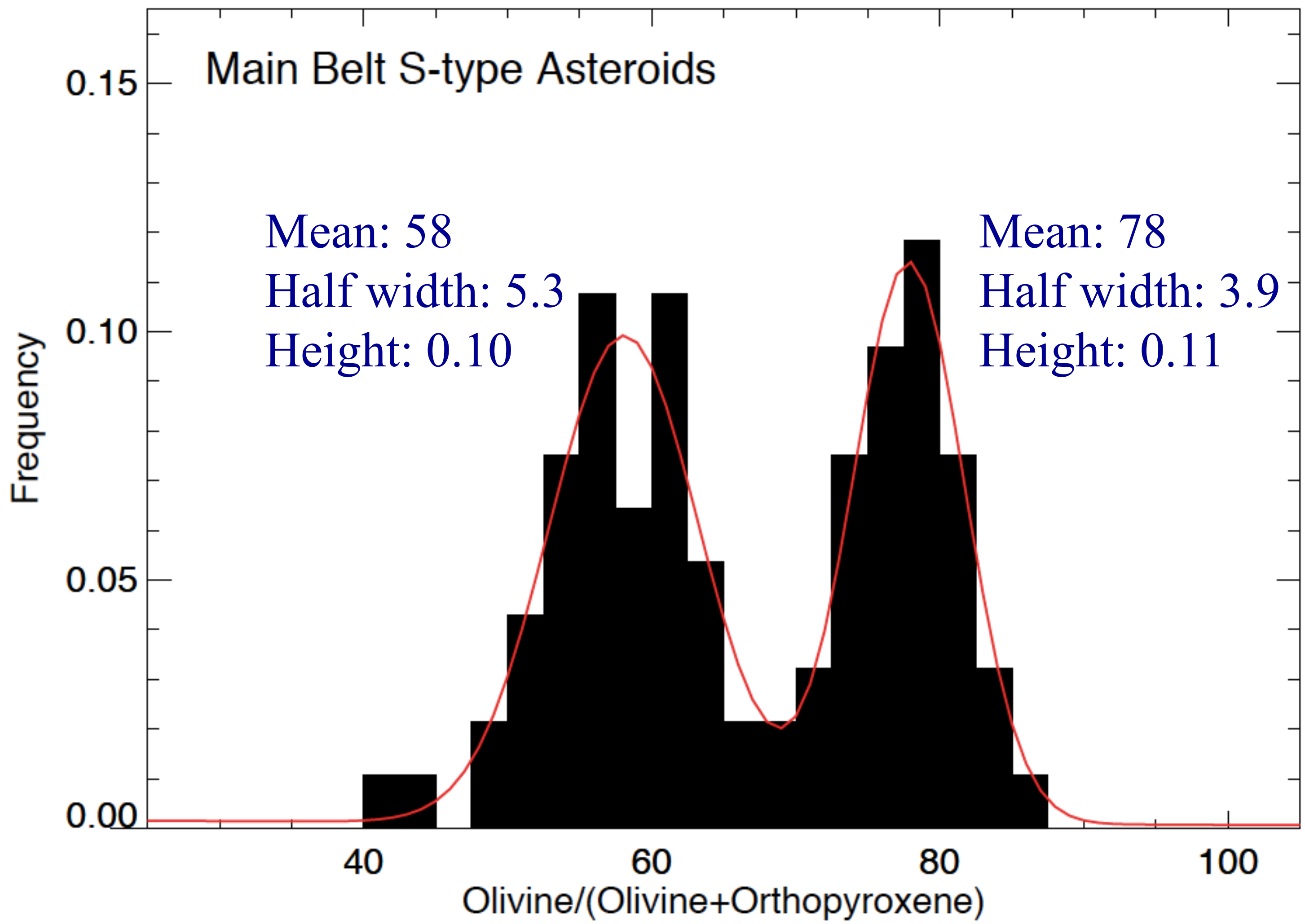
Olivine (Ol), Orthopyroxene (Opx), Clinopyroxene (Cpx)



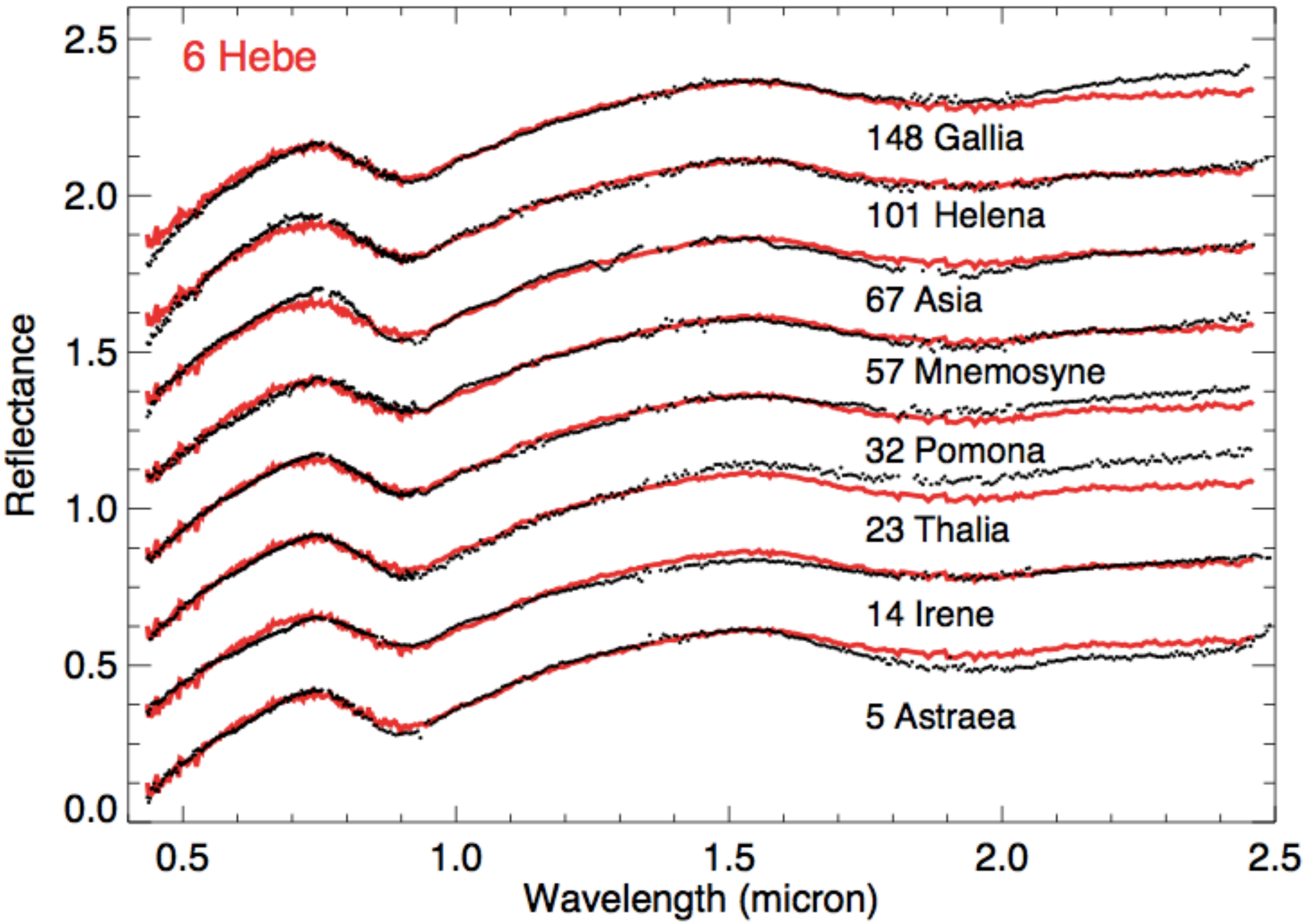
Model predicted the recently confirmed link (Nakamura et al. 2011) between 25143 Itokawa and LL chondrites (Vernazza et al. 2008)

Asteroid slopes accounted for using weathering model of Brunetto et al. (2006).

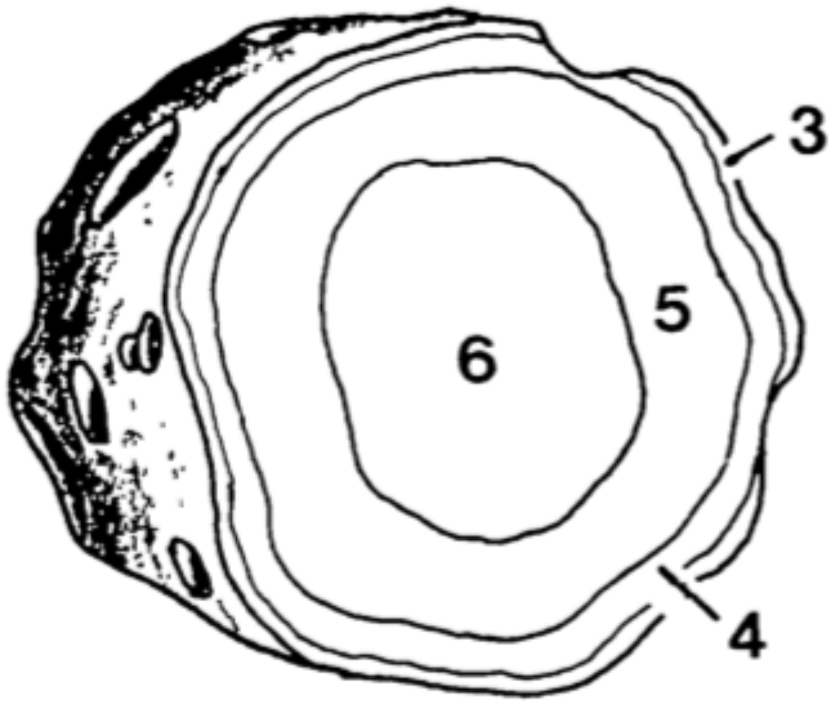
Two compositional groups



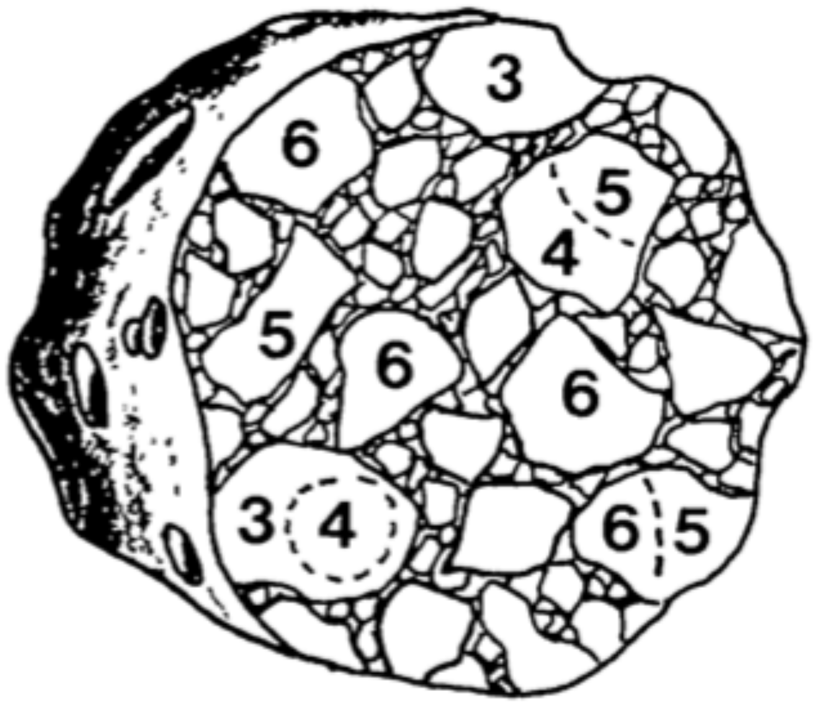
Example of clones !



Is this a primordial signature or the result of collisions ?

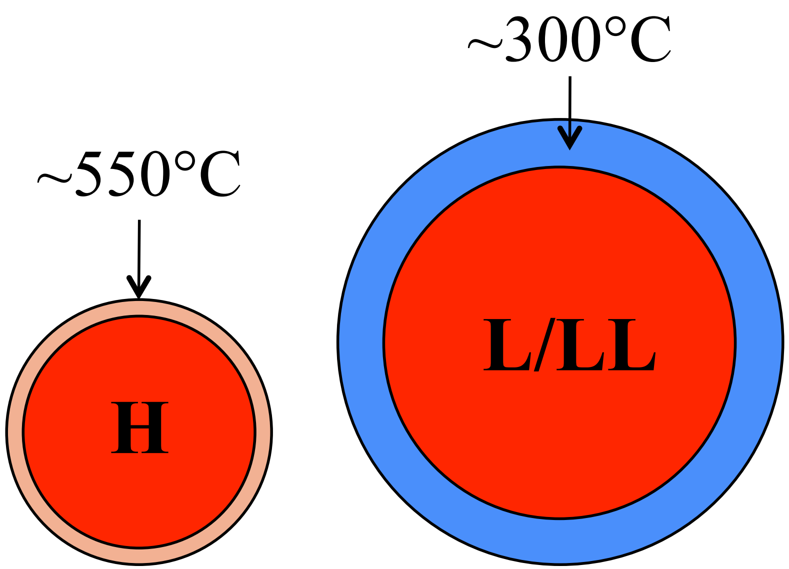


Onion – shell

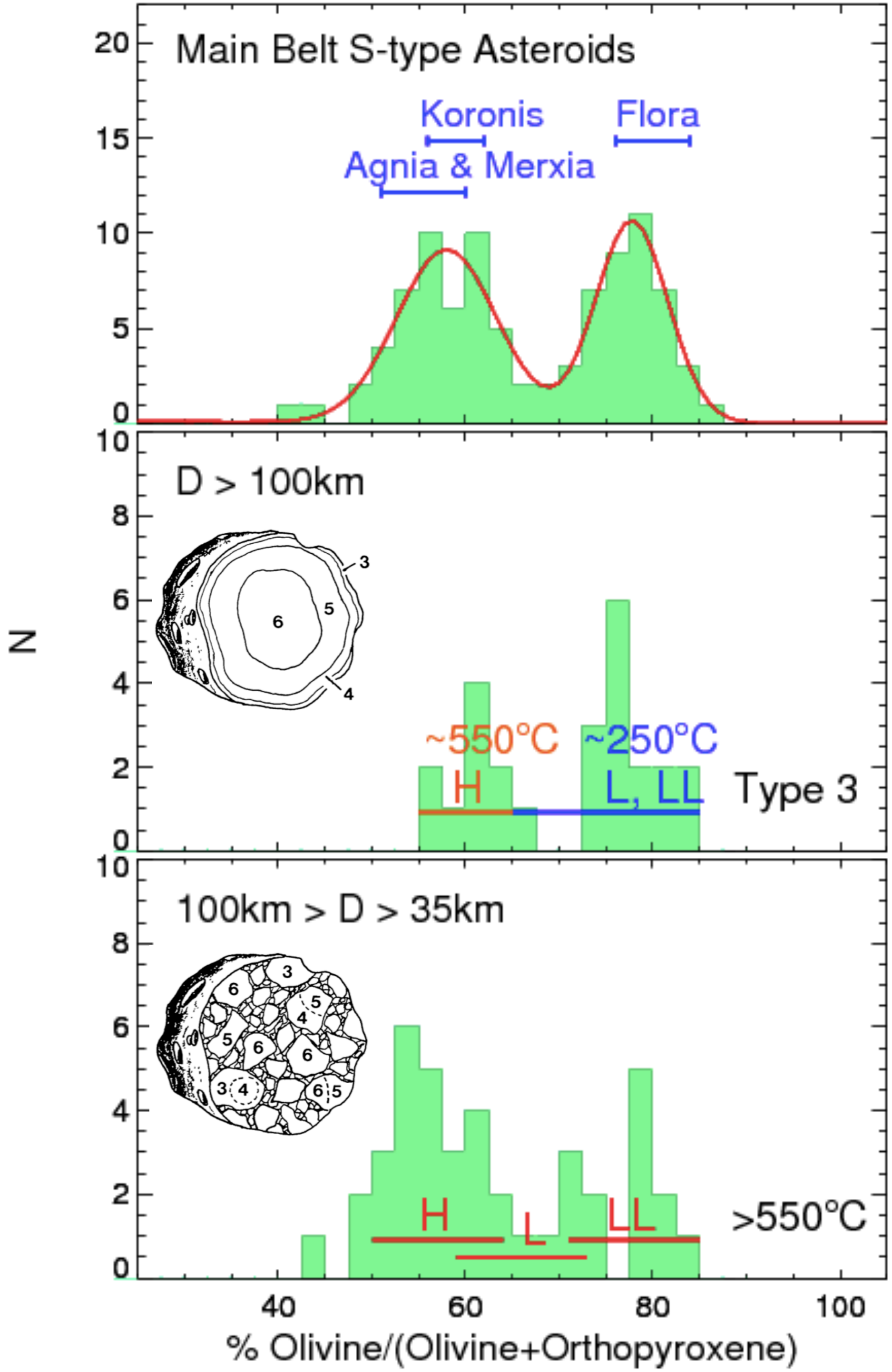


Rubble – pile

Primordial signature & H parent bodies have warmer surfaces than L/LL ones while being likely smaller



≠ Sizes supported by the size distribution and cooling rates of H, L and LL



Possible causes for this bimodality

Investigation among the three variables that define the composition of a planetesimal:

A) Different formation locations ?

B) Different formation time ?

C) Different durations of accretion ?

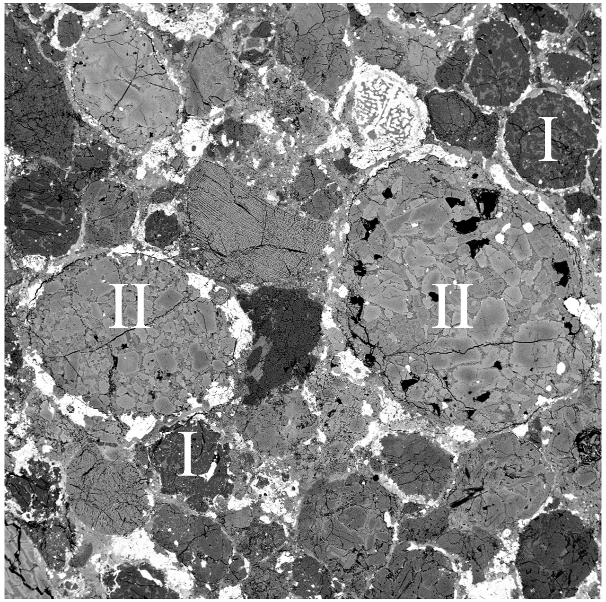
A) Different formation locations?

No correlation between composition and distance to the Sun (using various size ranges, yet insensitive to the Yarkovsky effect, D>35km):

Olivine-rich peak (LL): 2.59±0.24 AU

Olivine-poor peak (H): 2.64±0.24 AU

=> Nearly identical formation location for these bodies



B) Different formation times?

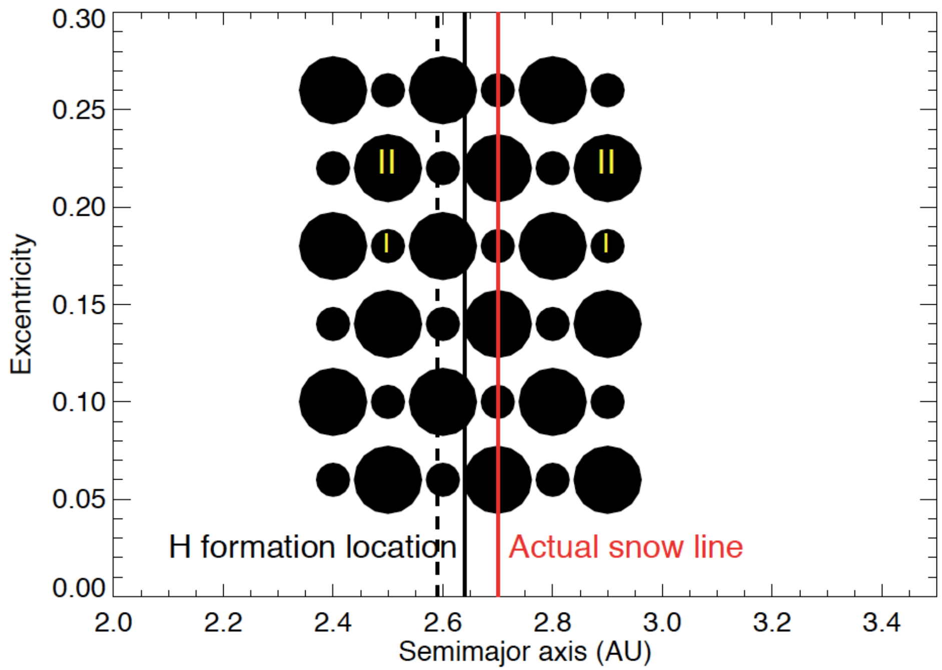
- H, L and LL are all made of volatile-poor type I and volatile-rich type II chondrules that most likely formed from precursors condensed on each side of the snowline

- H chondrites = ~55% Type I + ~45% Type II
- LL chondrites = ~25% Type I + ~75% Type II

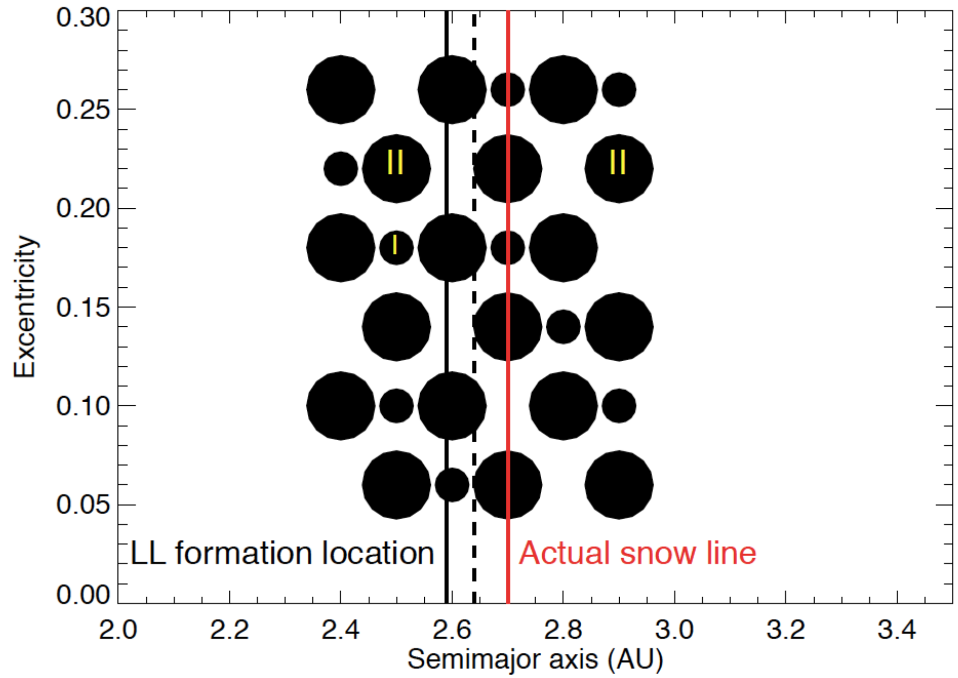
An identical formation time for H and LL parent bodies is a priori excluded, considering that they formed at the same place.

B) Different formation times!

Chondrule population at the time of H formation

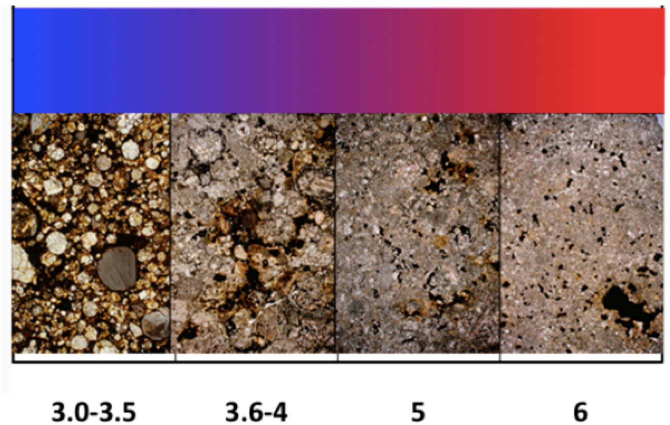


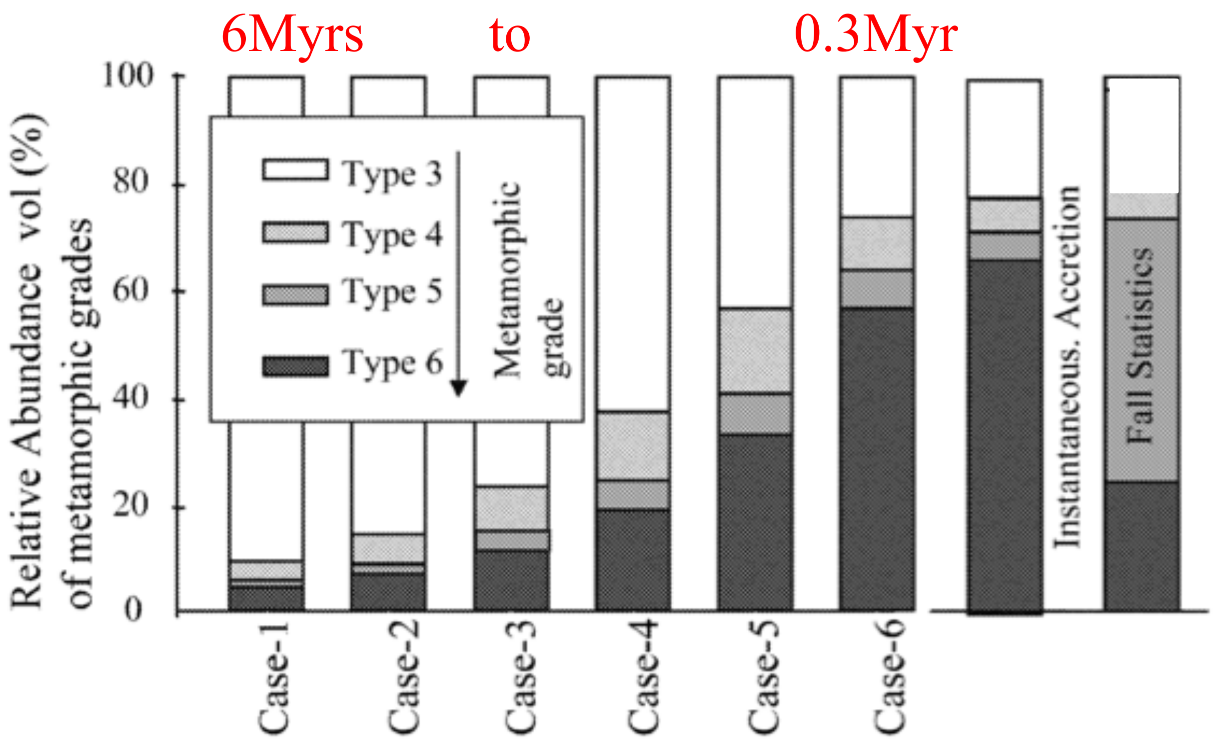
Chondrule population at the time of LL formation



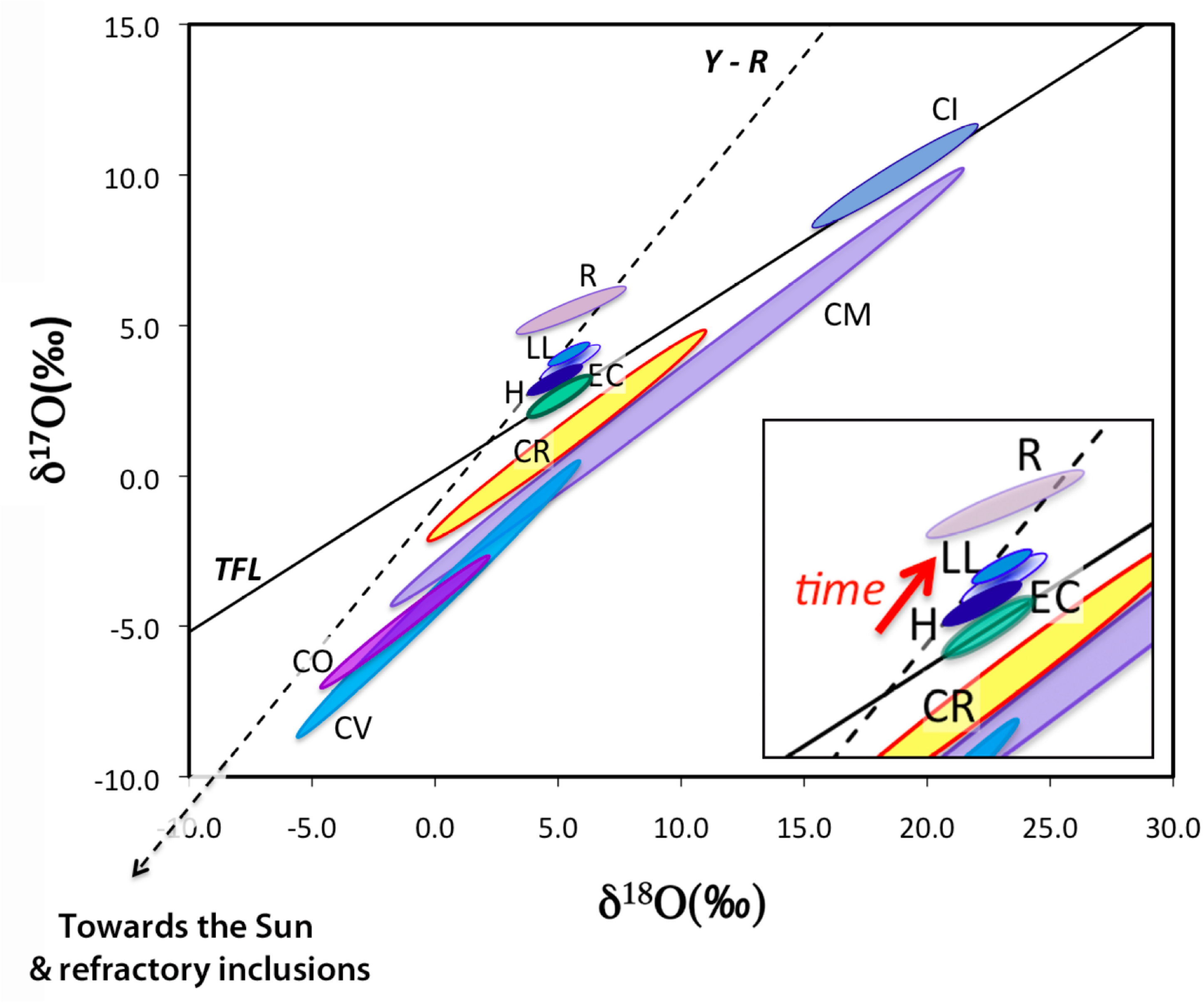
C) Different duration of accretion ?

Following current thermal models, both a ‘warm’ surface for the H parent bodies and fall statistics for H, L and LL type 3 material imply instantaneous accretion.





Not Distance, thus time !



Conclusion

Planetesimal formation must occur from a ring of homogenized chondrule populations: otherwise, how would we get compositional clones?

Planetesimal fromation must be a discrete event in time, otherwise we would not observe compositional gaps.

This study illustrates the importance of both radial mixing and formation time on the actual heliocentric compositional gradient observed among small bodies.