Les écoles des “Houches”

Chronologie de la formation du Système Solaire

I. Chronologie de la formation du Système Solaire
Février 2001 Les Houches (Petit, Froeschlé, Robert)

II. Des grains présolaires aux objets de Kuiper
Février 2004 Aussois (Froeschlé, Guillot, Morbidelli, Michel)

III. Formation des premiers solides
Mars 2006 Aussois (Guillot, Morbidelli)

IV. L’accrétion et la différentiation des corps planétaires
Février 2009 Les Houches (Michel, Guillot, Morbidelli)

ÉCOLE DE PHYSIQUE
LES HOUCHES

La primitivité n’est plus ce qu’elle était…

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Laboratoire de Minéralogie et de Cosmochimie du Muséum

Muséum National d’Histoire Naturelle

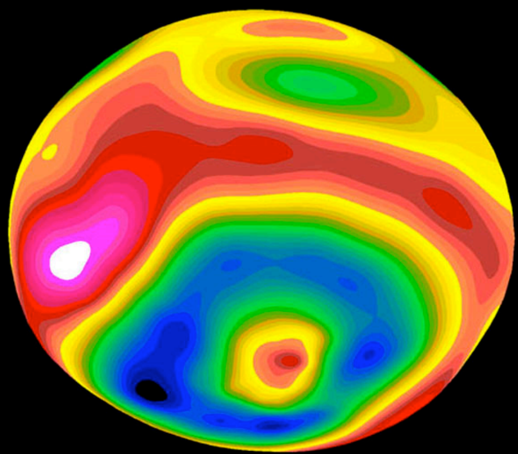
Paris, France

Les Houches, 26 février 2009

1. Le point de vue des livres

Primitives meteorites

(chondrites)

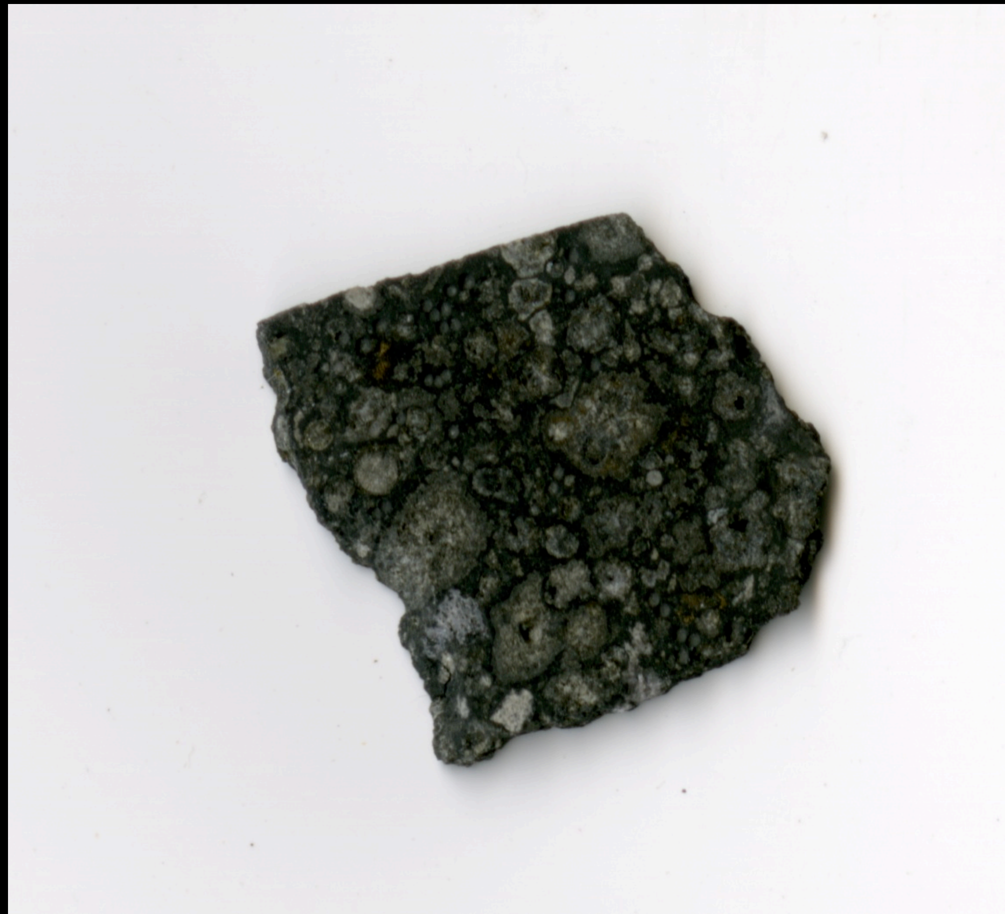


Differenciated meteorites

(achondrites, irons, stony-irons)

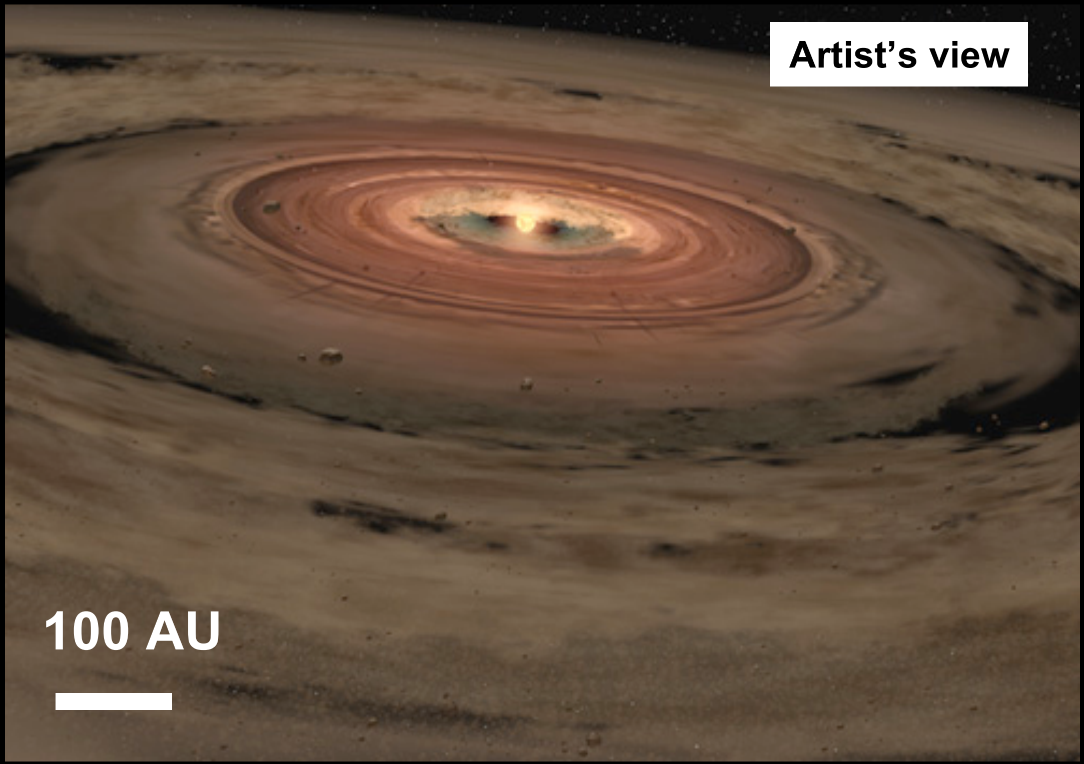
Differentiated & primitive meteorites

PALLASITE (DIFFERENTIATED)



CHONDRITE (PRIMITIVE)

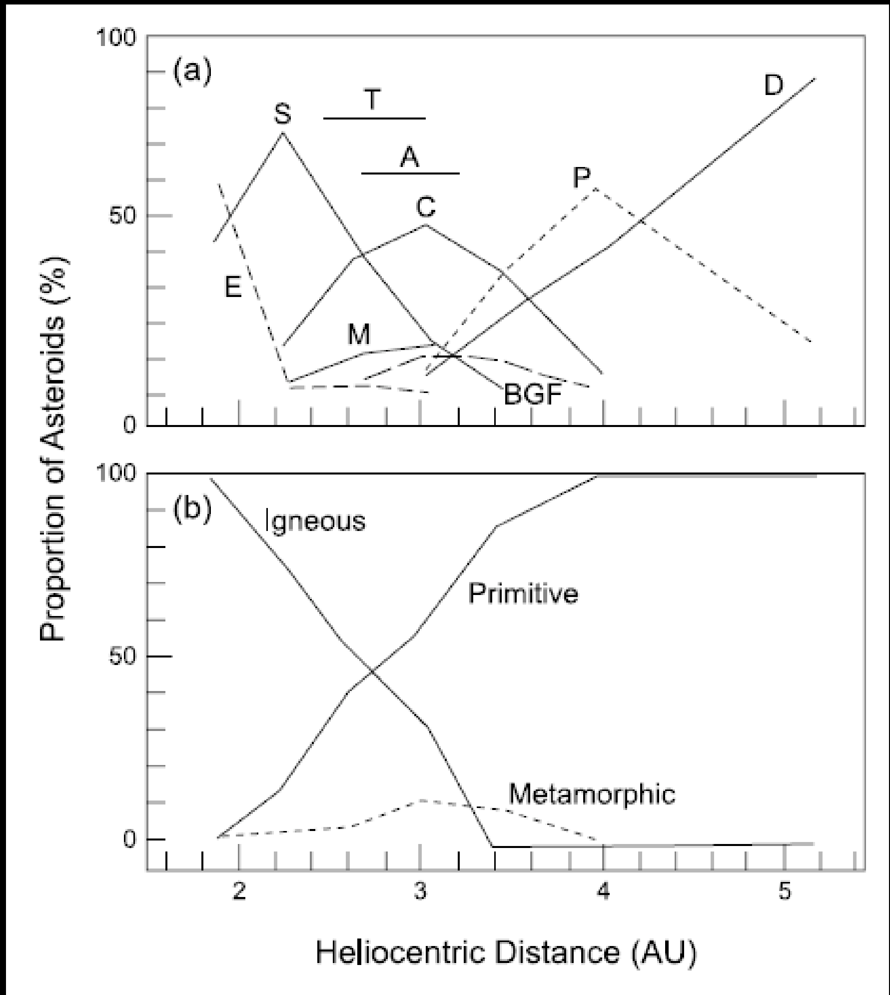
Chondrites and the accretion disk



Chondrites' components formed in the disk

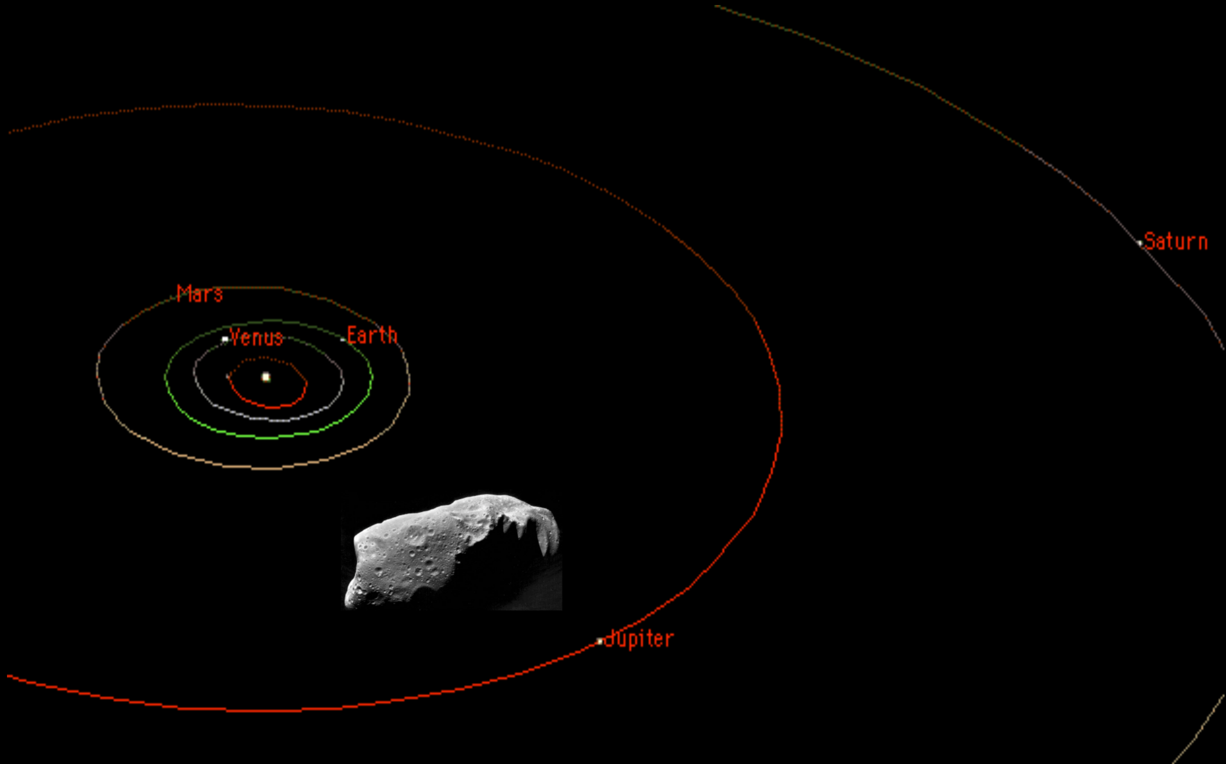
1 AU = Sun-Earth distance = 150 x 10^6 km

Heliocentric zoning in the disk



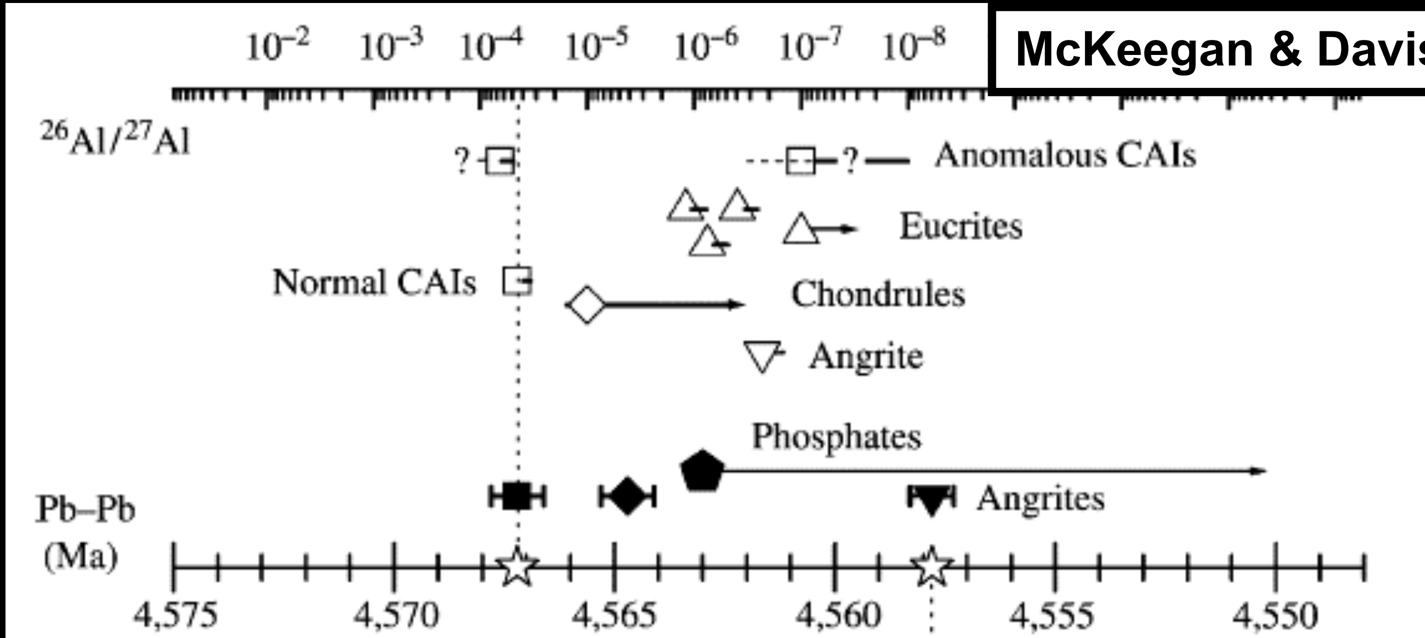
Interpreted as a primordial solar system feature

Comets & asteroids

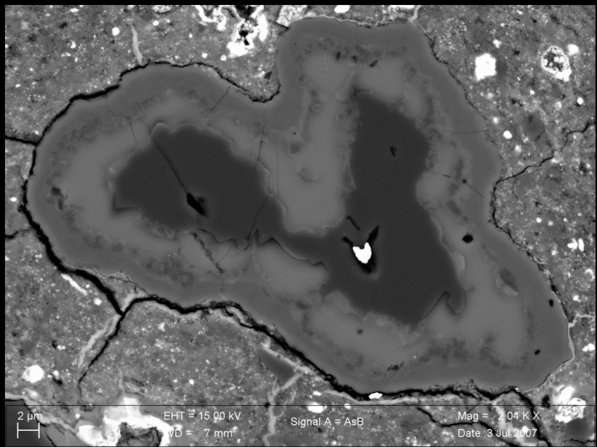


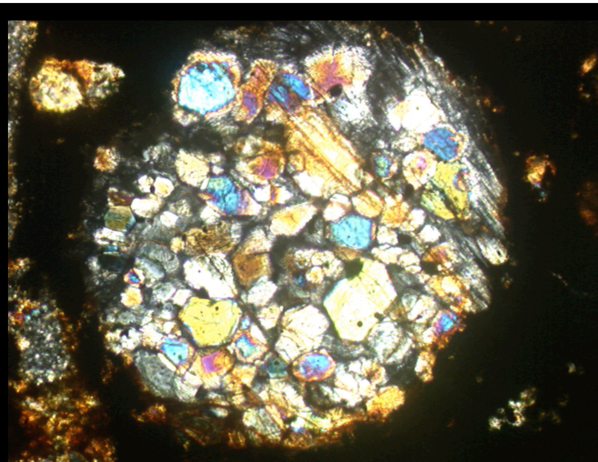
Comets formed further away and were supposed to be more primitive than asteroids (sampling the interstellar matter)

Solar system chronology



McKeegan & Davis 2003

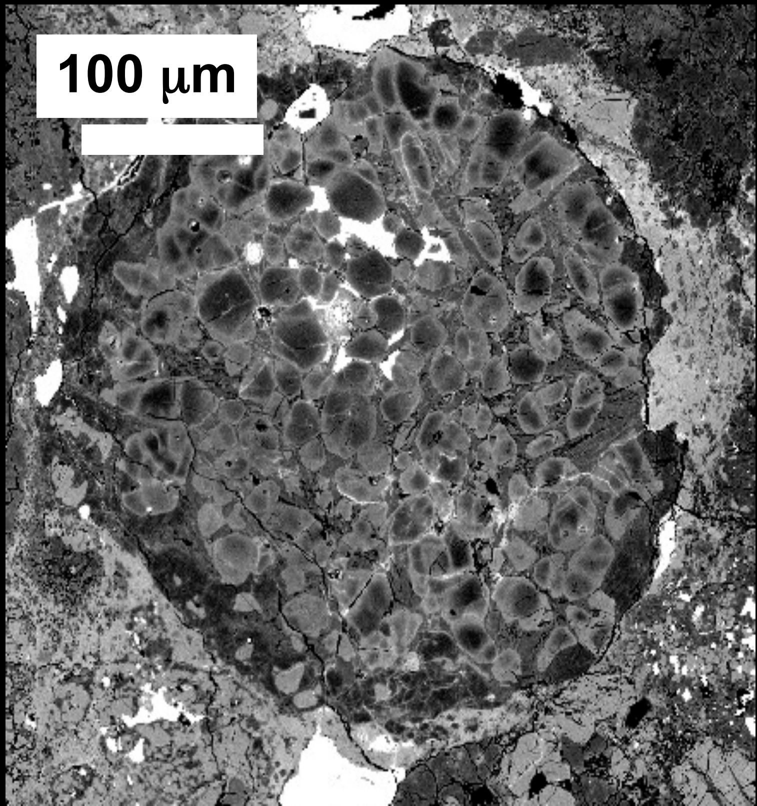




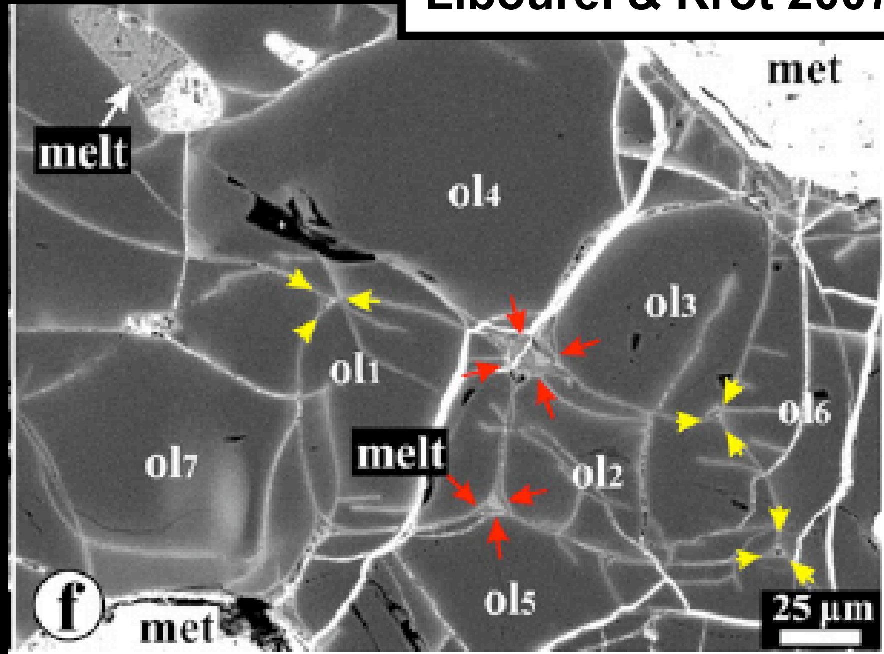
Relative chronology based on the assumption of homogeneous distribution of short-lived radionuclides

2. Matière primitive et matière différenciée: Une histoire de promiscuité

A new view on chondrules

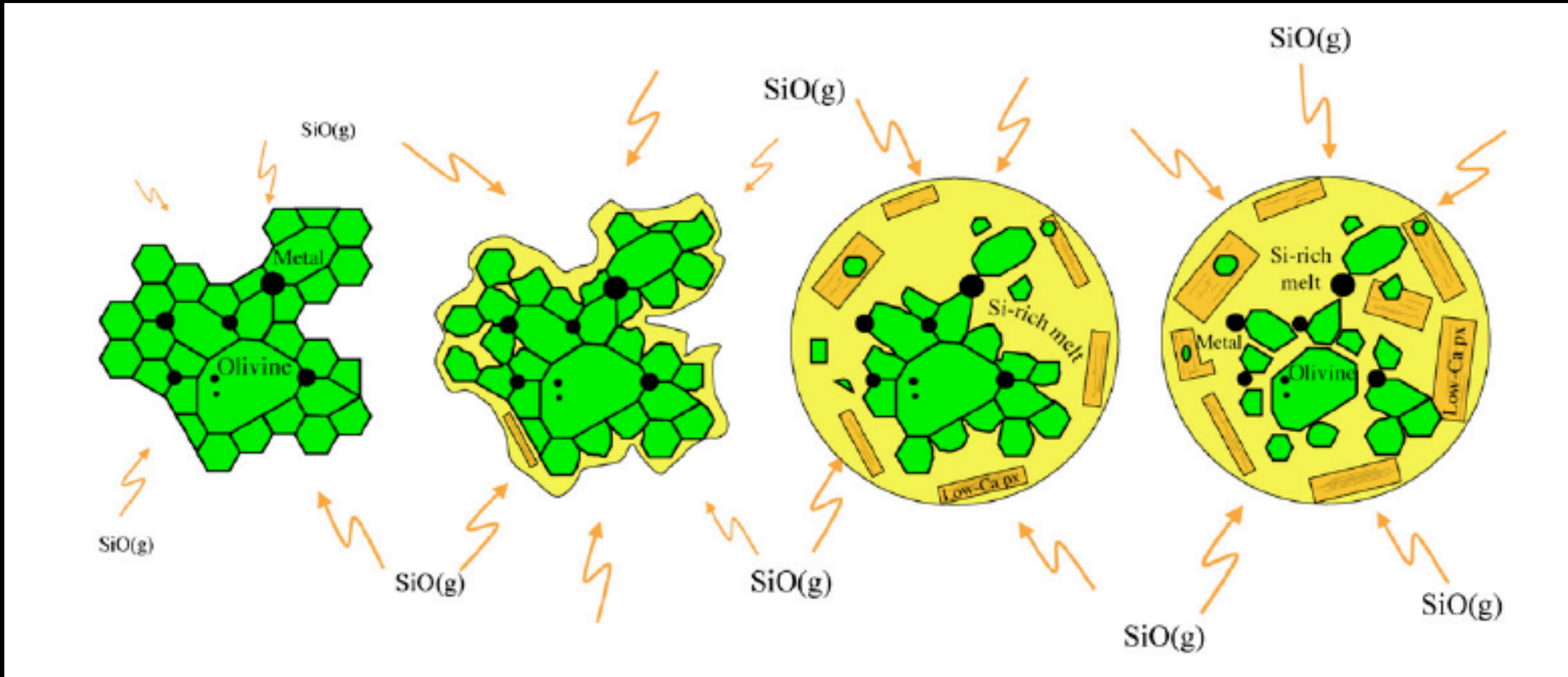


Libourel & Krot 2007



« Evidence for the presence of planetesimal material among the precursors of magnesian chondrules of nebular origin »
Libourel & Krot EPSL 2007

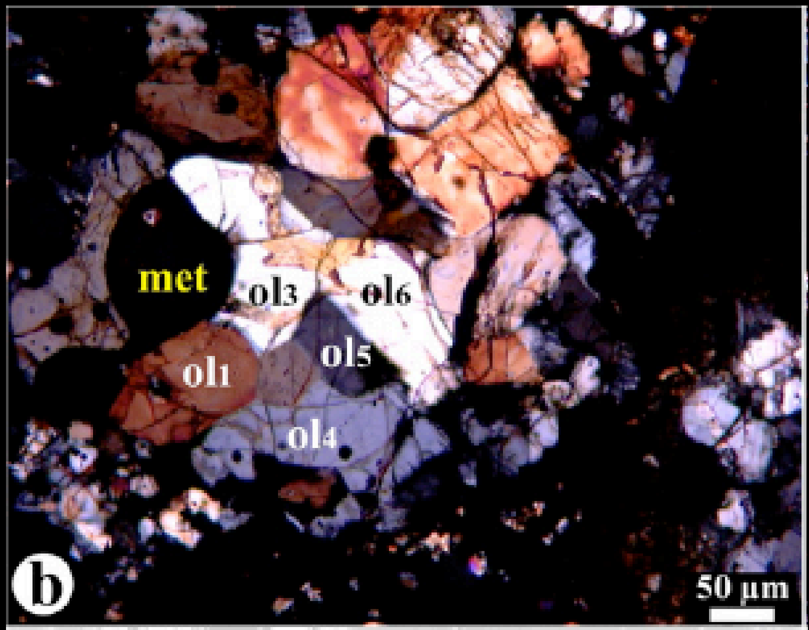
A new view on chondrules



Libourel & Krot 2007

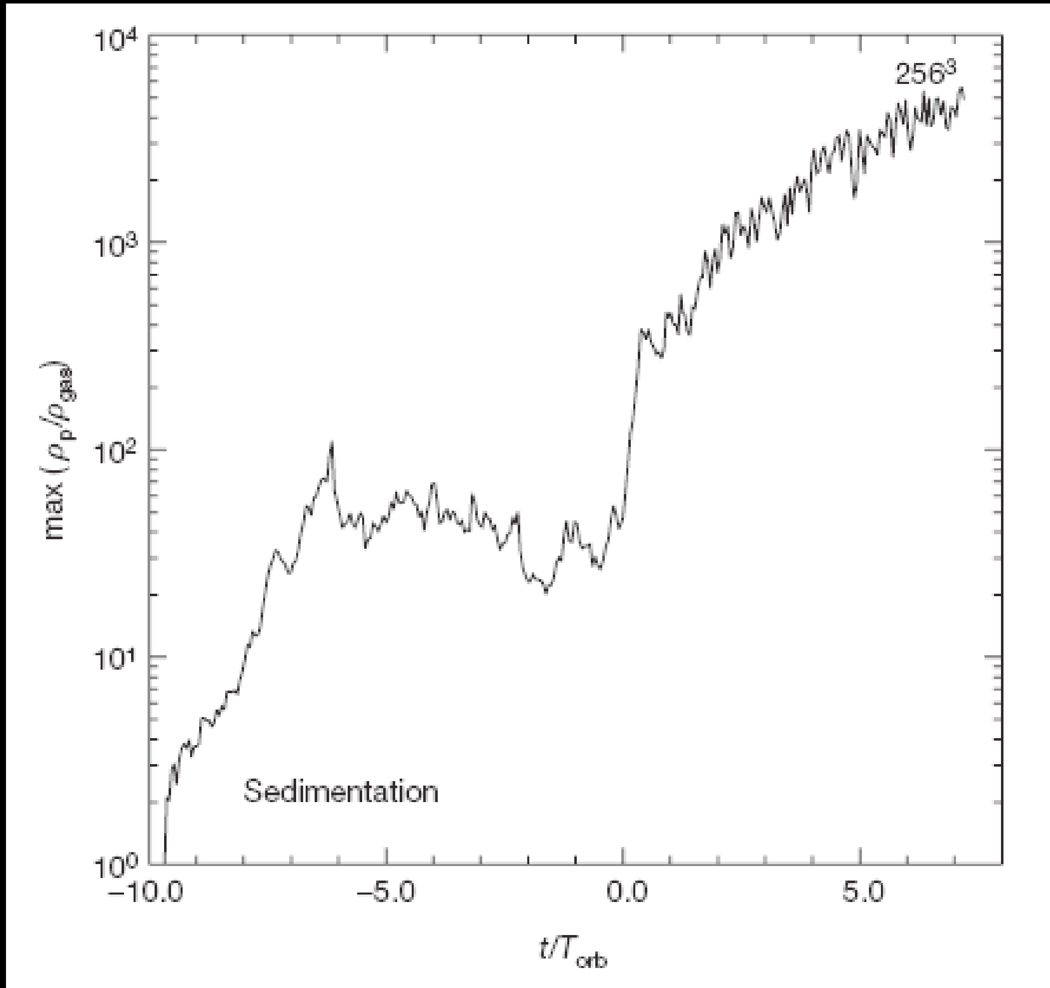
A new view on chondrules

« This implies that Type I chondrules are not as pristine as conventionally viewed [5]; instead, they consist of nebular and <u>asteroidal materials</u> and must have postdated accretion, thermal metamorphism and <u>differentiation of some early generation planetesimals</u>. »



Libourel & Krot 2007

Fast accretion of planetesimals

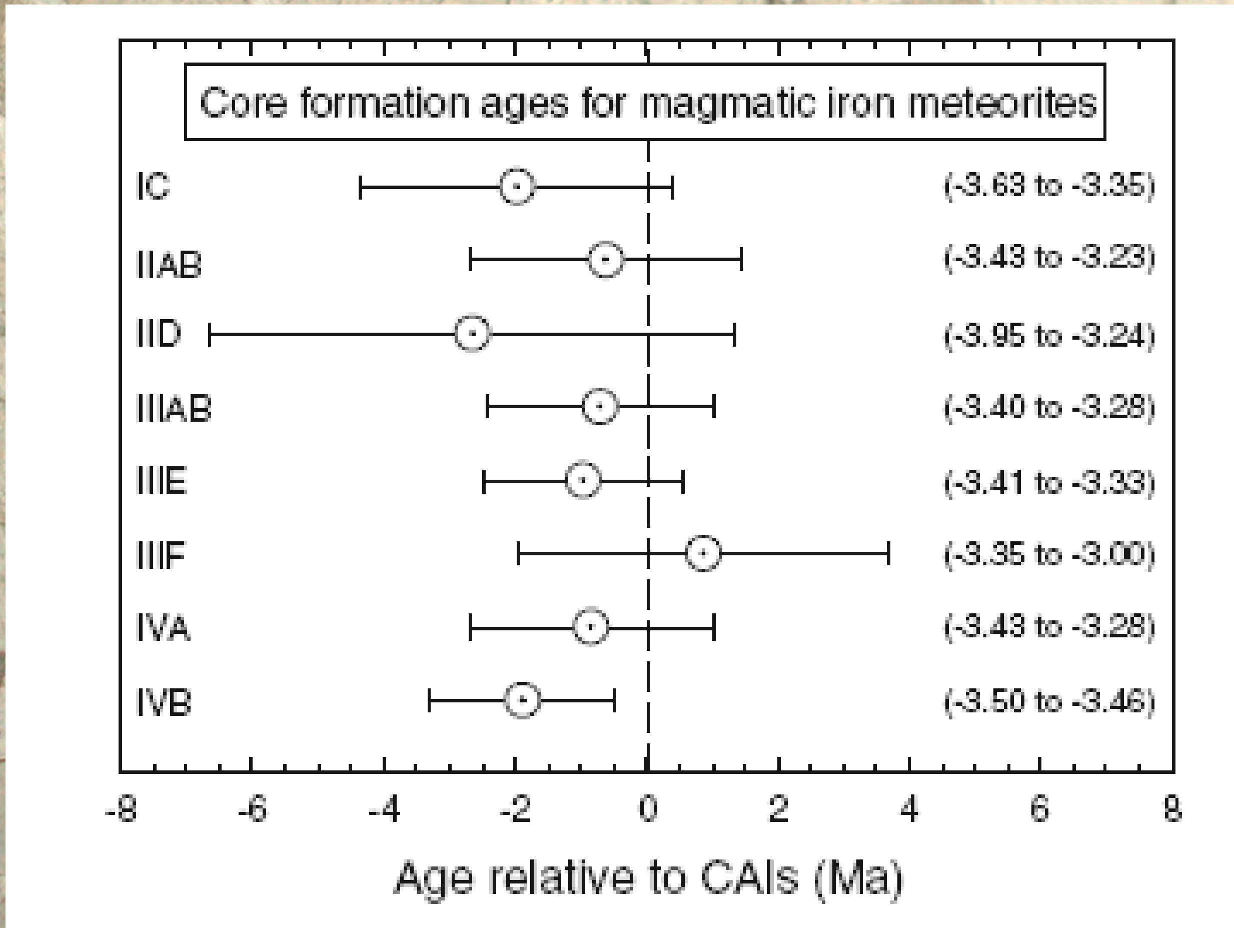


Accretion of 1000 km-size boulders in a few orbital times

- **Gravitational collapse**
- **Turbulence**

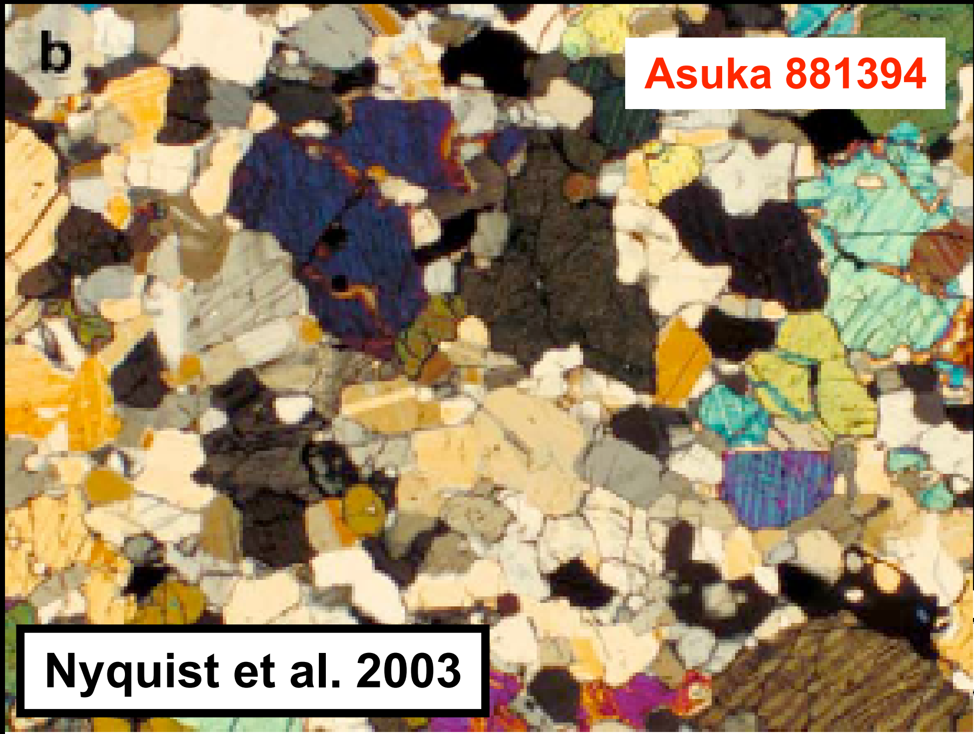
Johansen et al. Nature 2007

Hf-W ages of iron meteorites

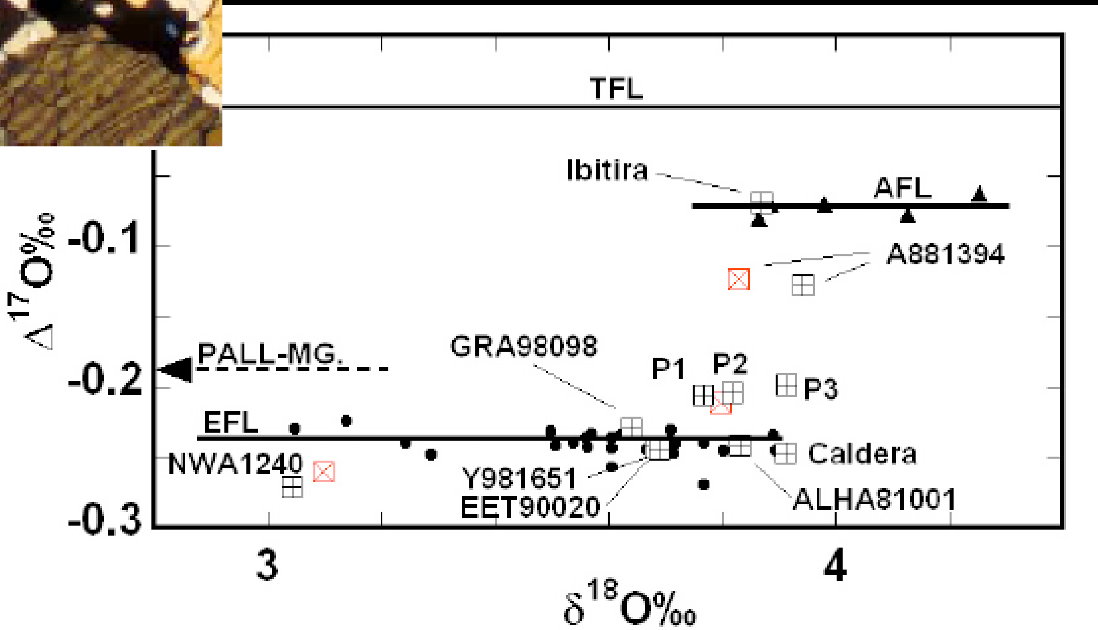


Burkhardt et al. GCA 2008

Pb-Pb age of Asuka 881394

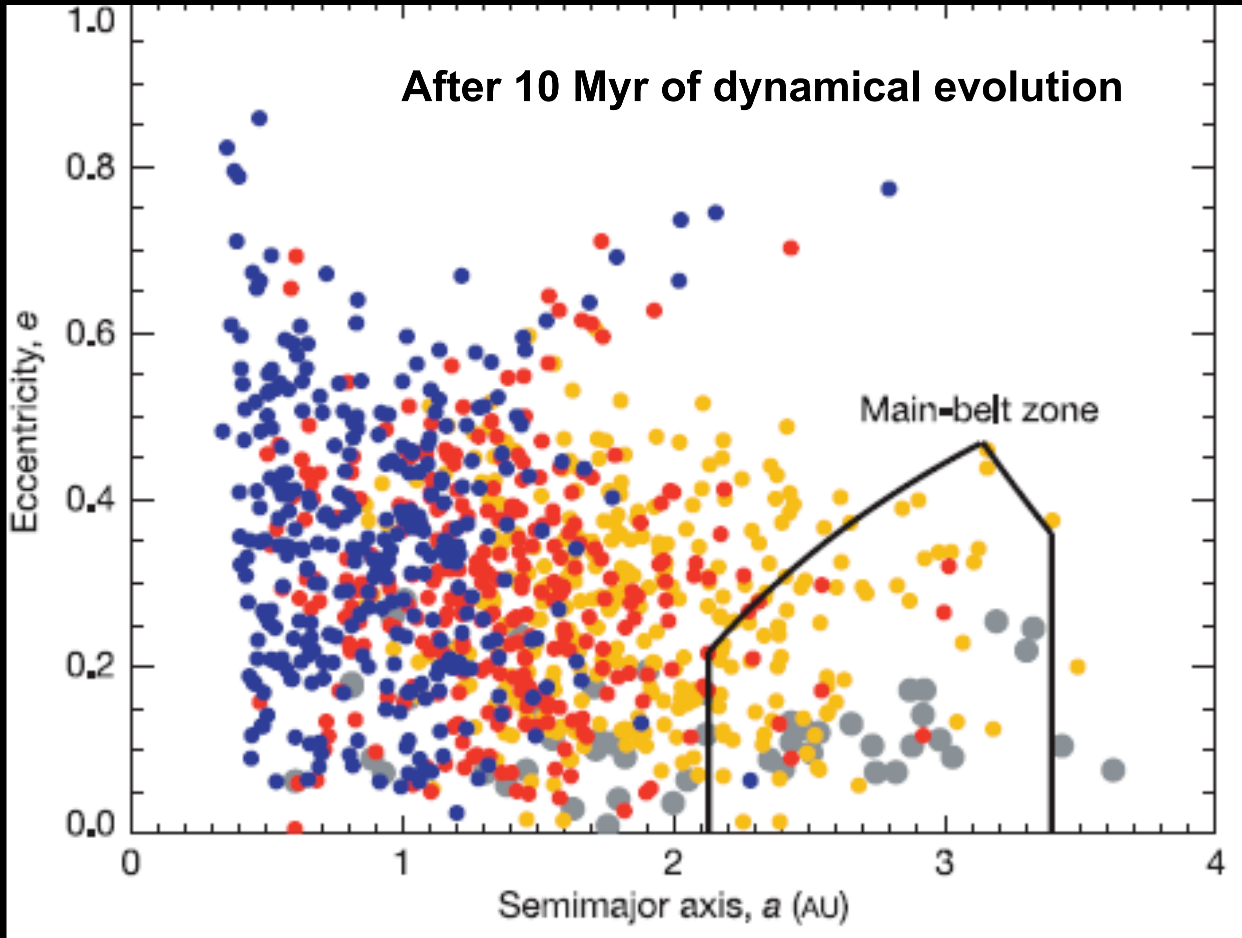


4566.5 ± 0.33 Myr Amelin et al. 2006



Scott et al. 2008

A dynamical model accounting for old planetary objects in the asteroid belt



Bottke et al. Nature 2006

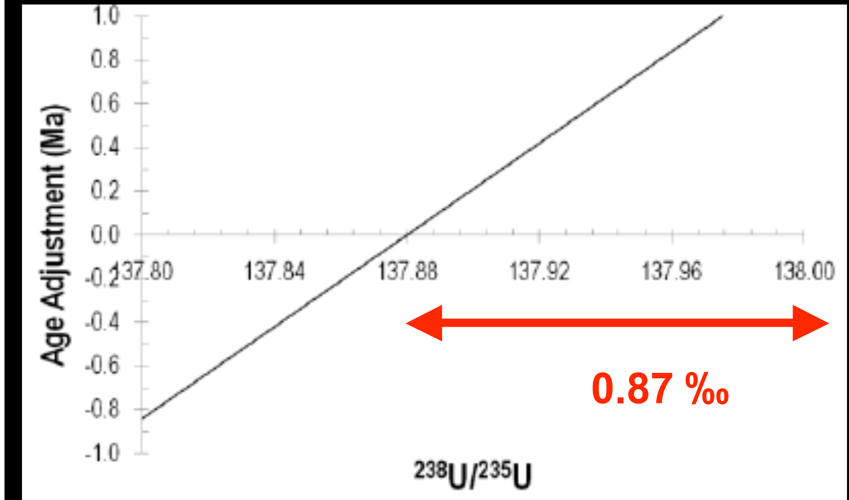
Not that easy to measure Pb-Pb ages

★ Pb-Pb ages might be biased by a serie of analytical/conceptual difficulties (Amelin & Neymark 2008)

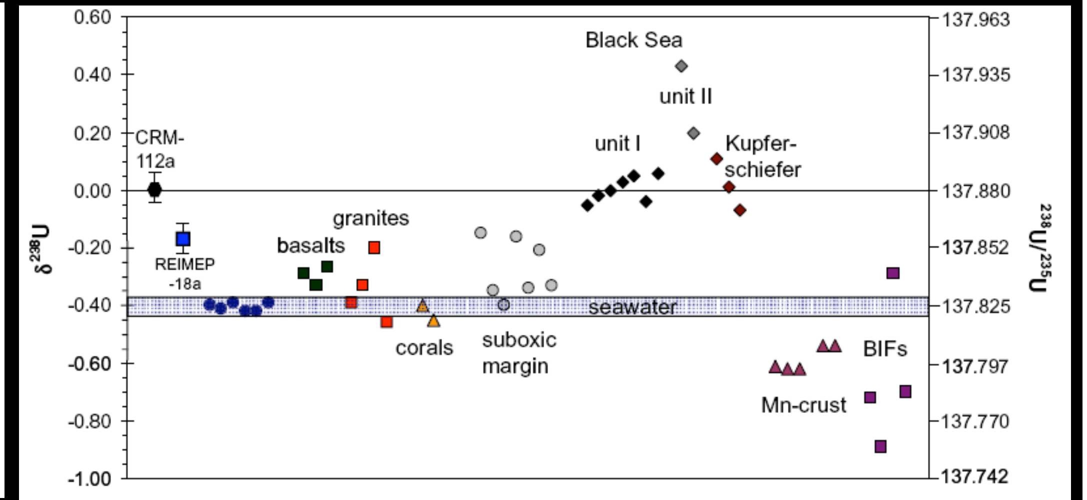
★ …

★ Pb fractionation during leaching (Bouvier & Wadwha 2008)

★ The $^{235}U/^{238}U$ ratio of CAIs, chondrules and others might be different [Pb-Pb ages assume that the $^{235}U/^{238}U$ ratio of CAIs, chondrules and the rest is the same]



Brennecka et al. LPSC 2009



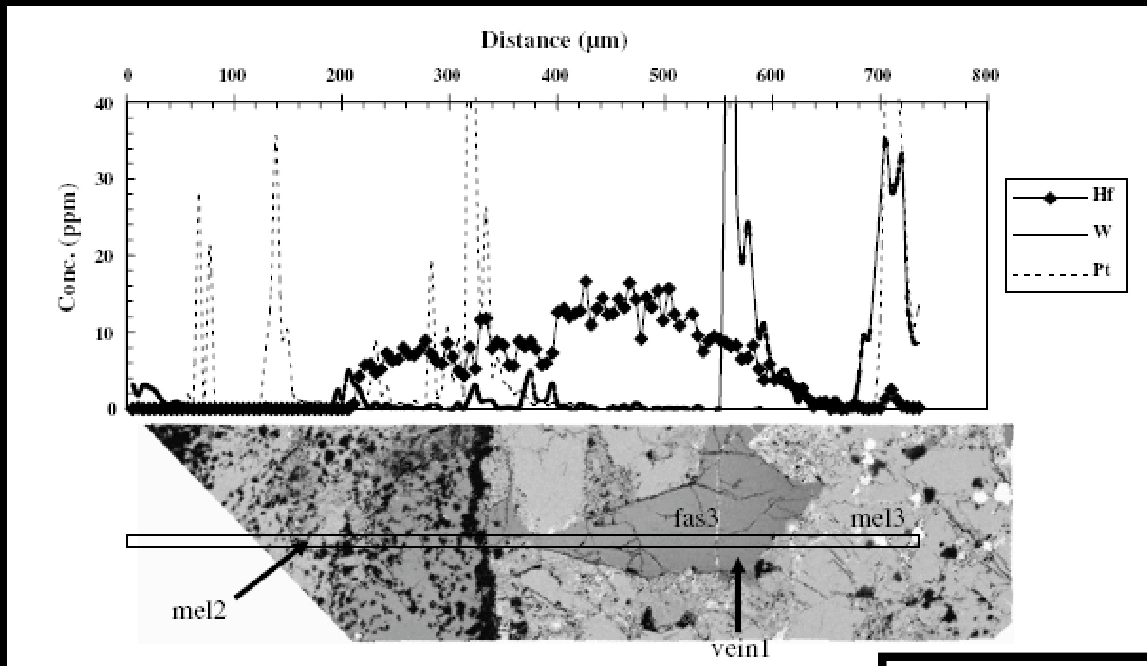
Weyer et al.GCA 2008

Not that easy to interpret Hf-W data

- The Hf-W age of iron meteorites is a model age

- The "old Hf-W age" of iron meteorites is calculated relative to the reference Hf-W age of CAIs

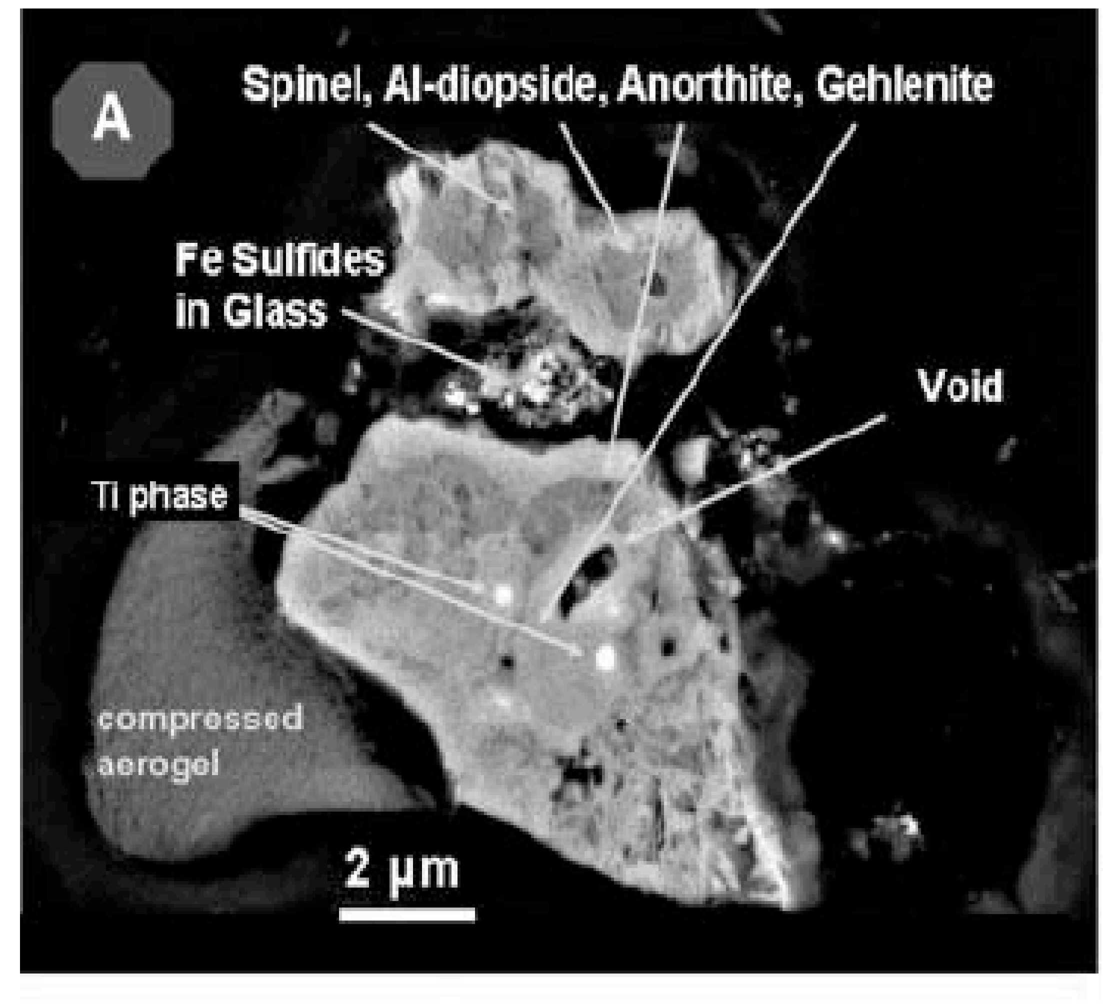
- The Hf-W isochron could be due to redistribution of W (Humayun et al. 2007)



Humayun et al.GCA 2007

3. La primitivité perdue des comètes

Cometary dust looks alike carbonaceous chondrites



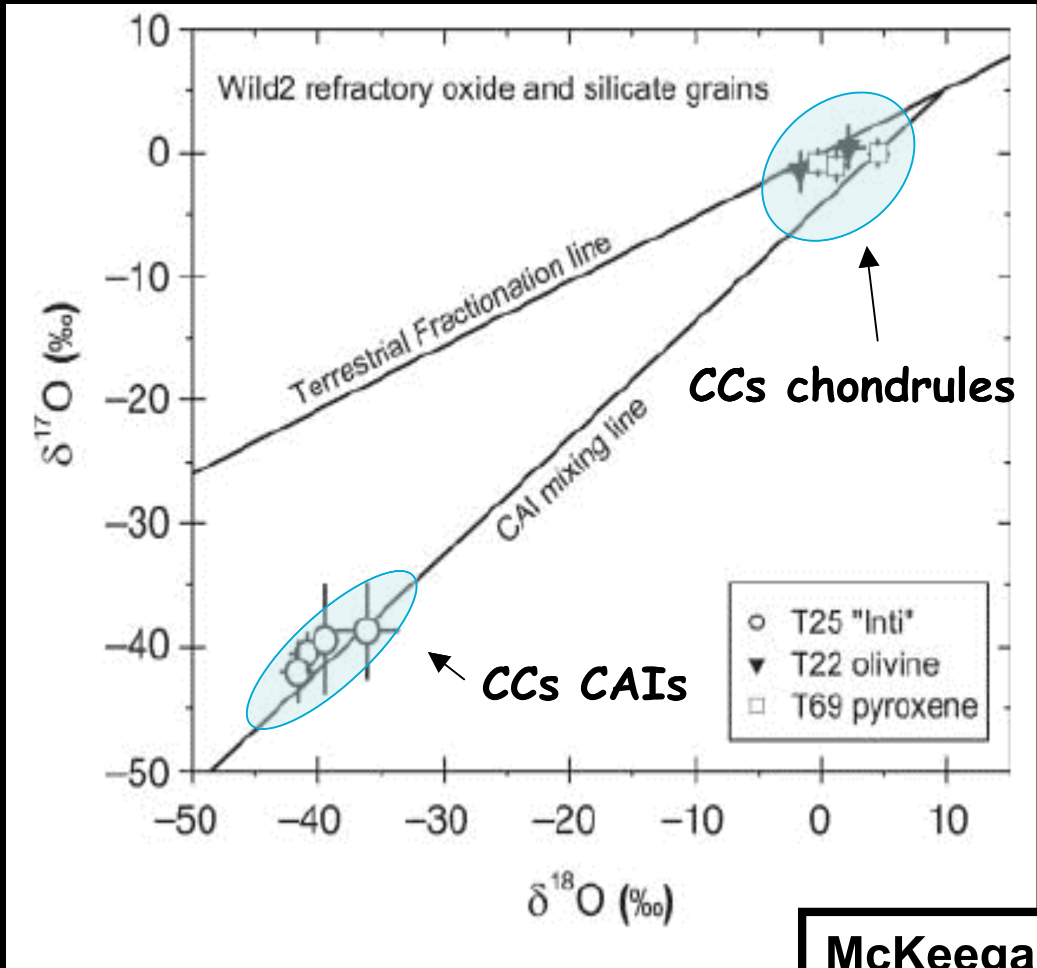
Discovery of CAIs in Wild 2 dust (Stardust mission)

Zolensky et al. Science 2006

Cometary dust looks alike carbonaceous chondrites

Discovery of chondrules in Wild 2 dust (Stardust mission)

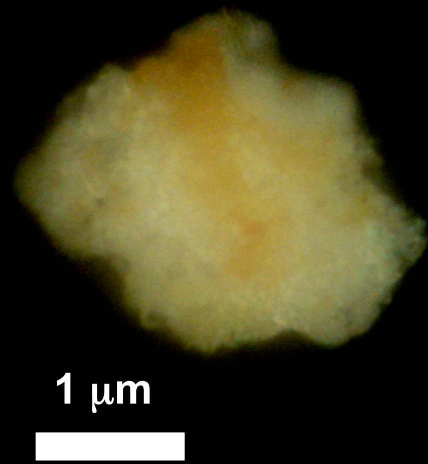
Cometary dust looks alike carbonaceous chondrites



McKeegan et al. Science 2006

The oxygen isotopic composition of Wild 2 CAIs and chondrules matches that of CCs CAIs and chondrules

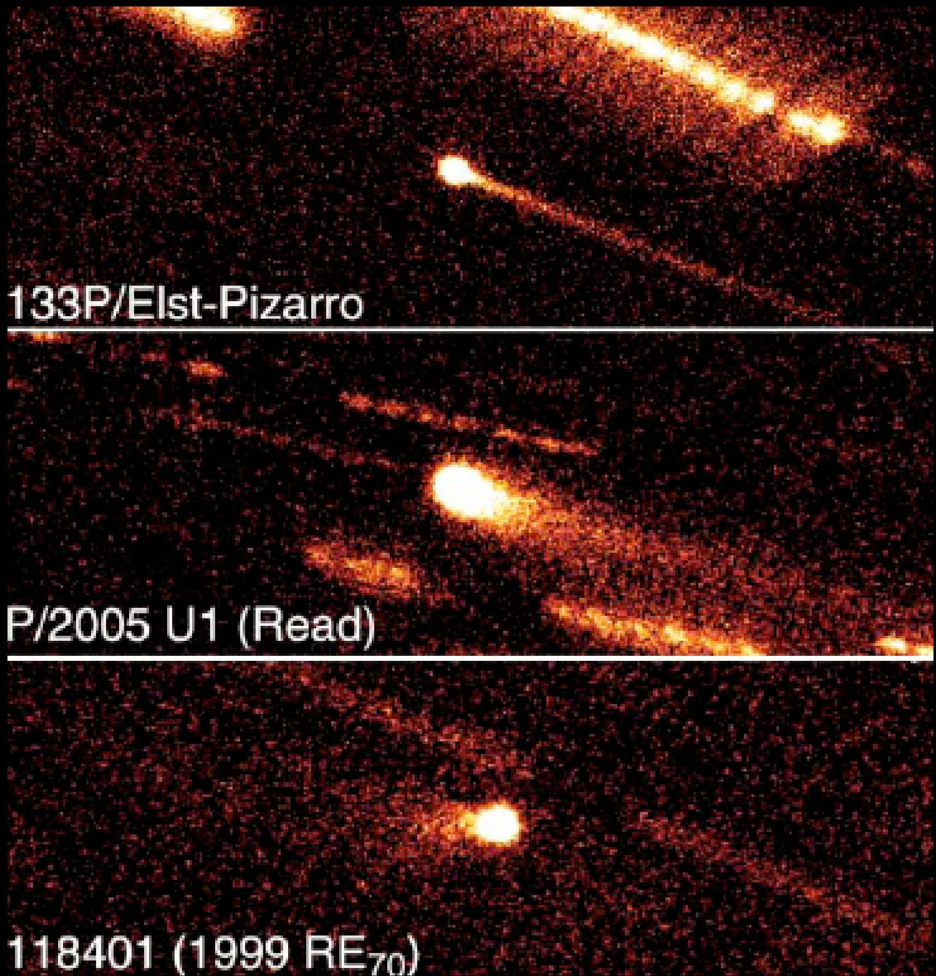
Stardust (partial) summary



Cometary dust was processed in the solar system (NOT interstellar)

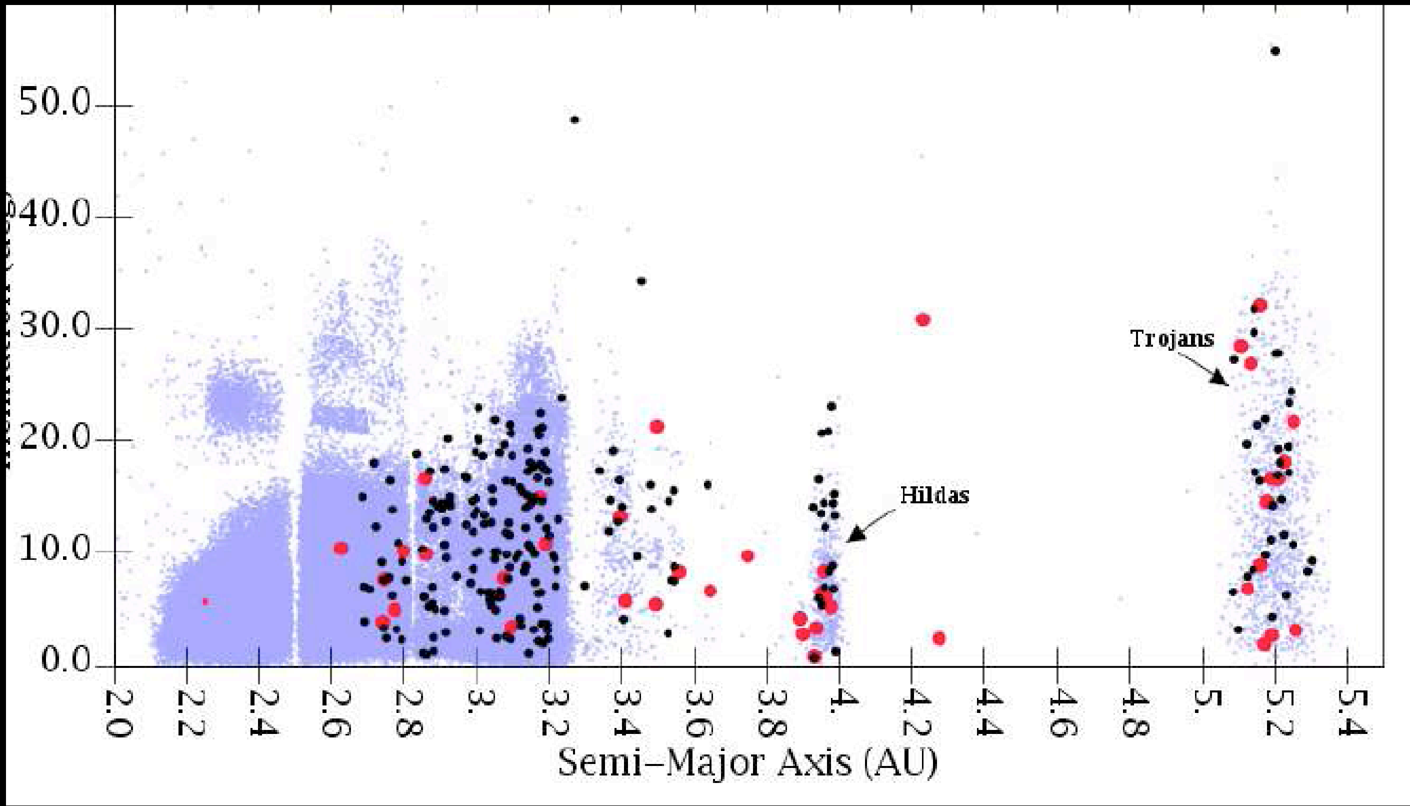
There is a <u>continuum</u> between primitive asteroids and comets

Observed comets in the asteroid belt



Hsieh & Jewitt Science 2006

Embedded comets in the asteroid belt



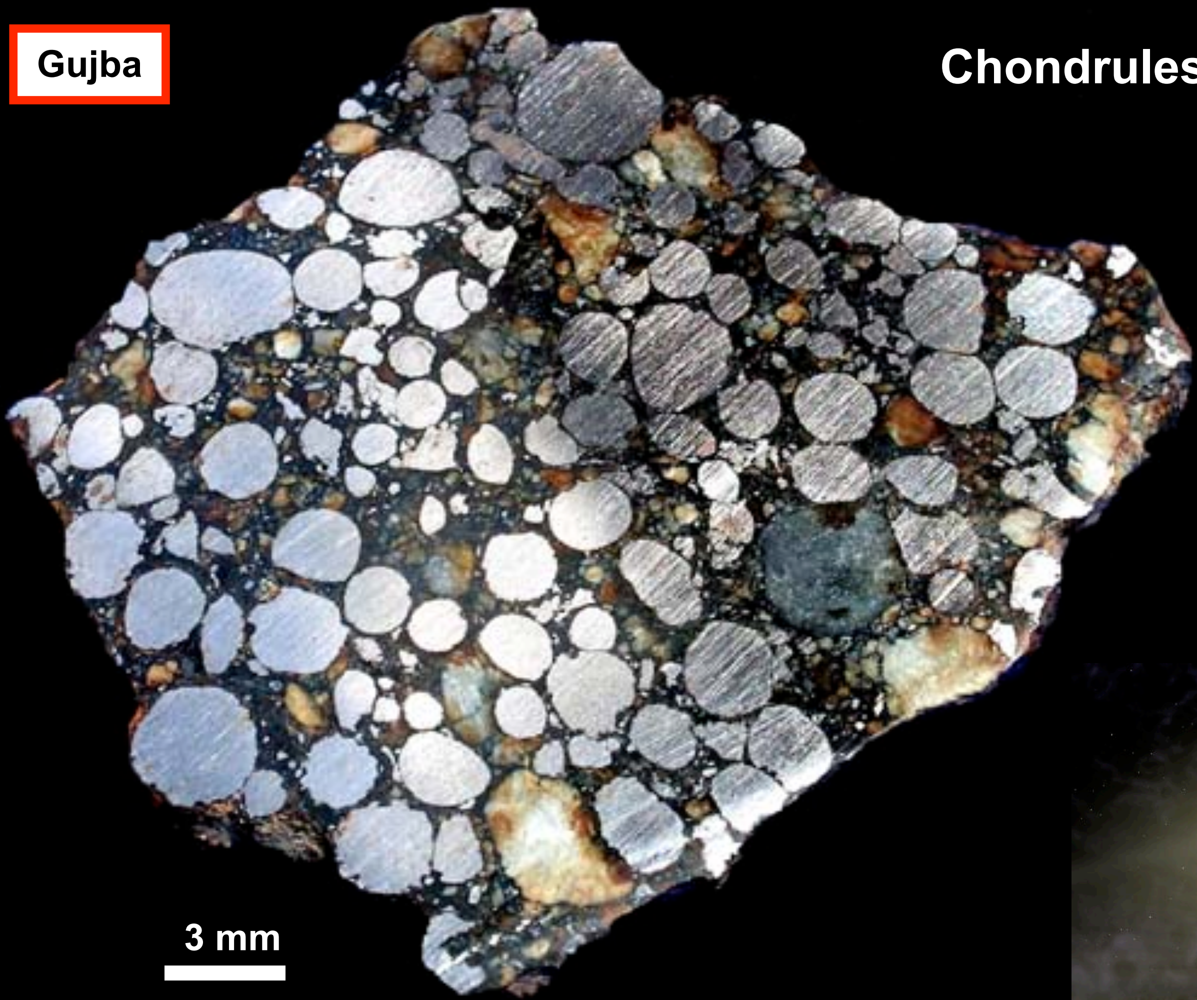
D asteroids (black dots) are <u>implanted comets</u> (red dots) during the Late Heavy Bombardment

Levison et al. Submitted

4. D'autres sujets de perplexité

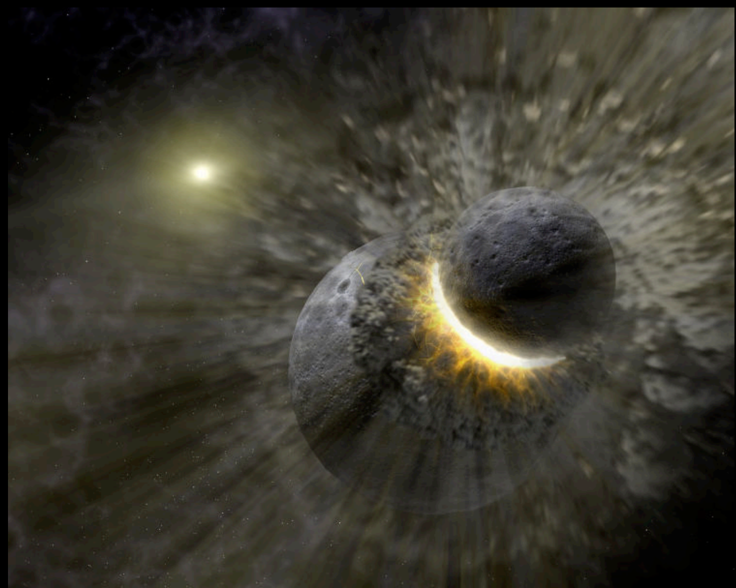
Some chondrites NOT formed in the disk?

Gujba



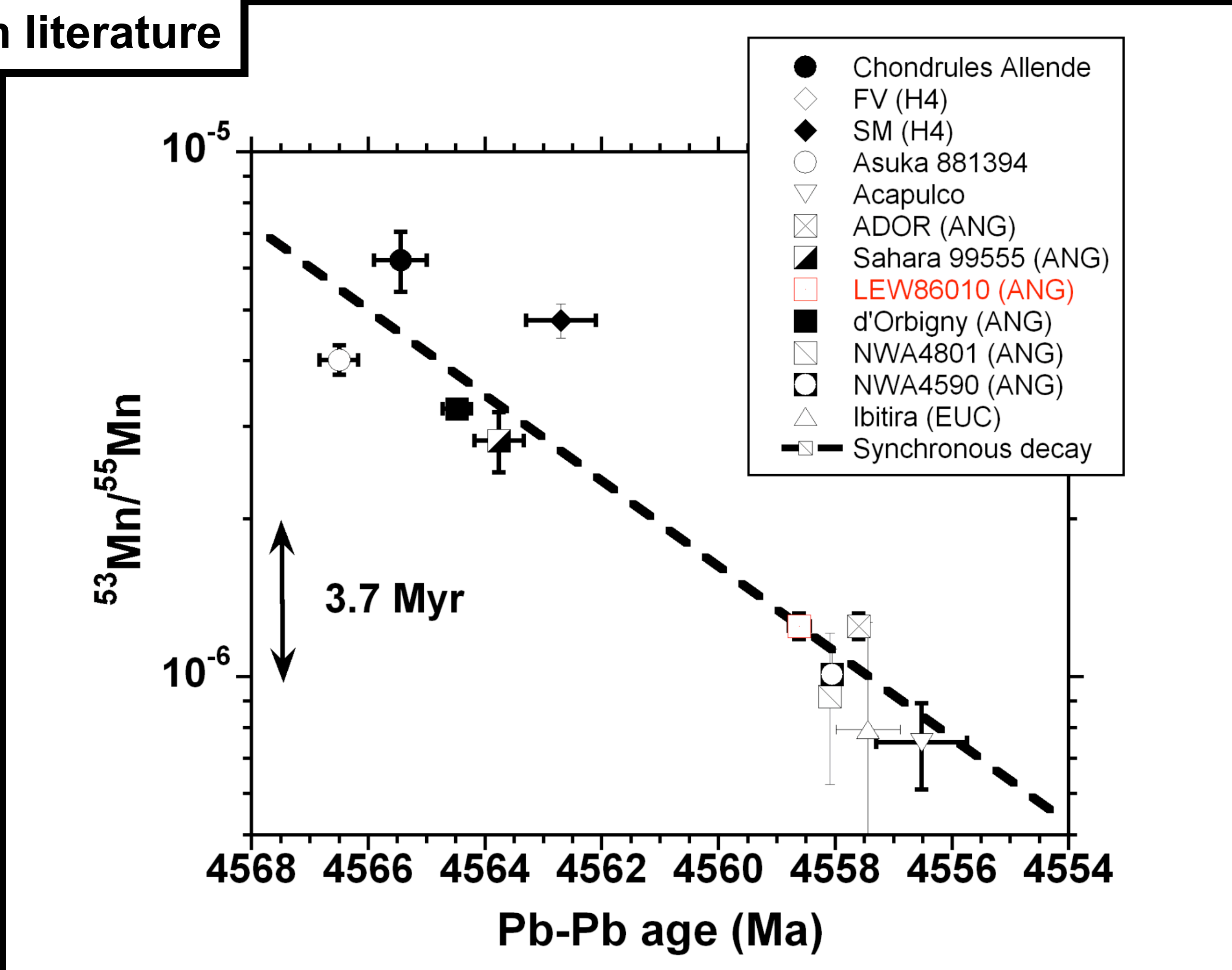
Chondrules' age: 4562.8 ± 0.9Myr

Krot et al. Nature 2005



Non synchronicity

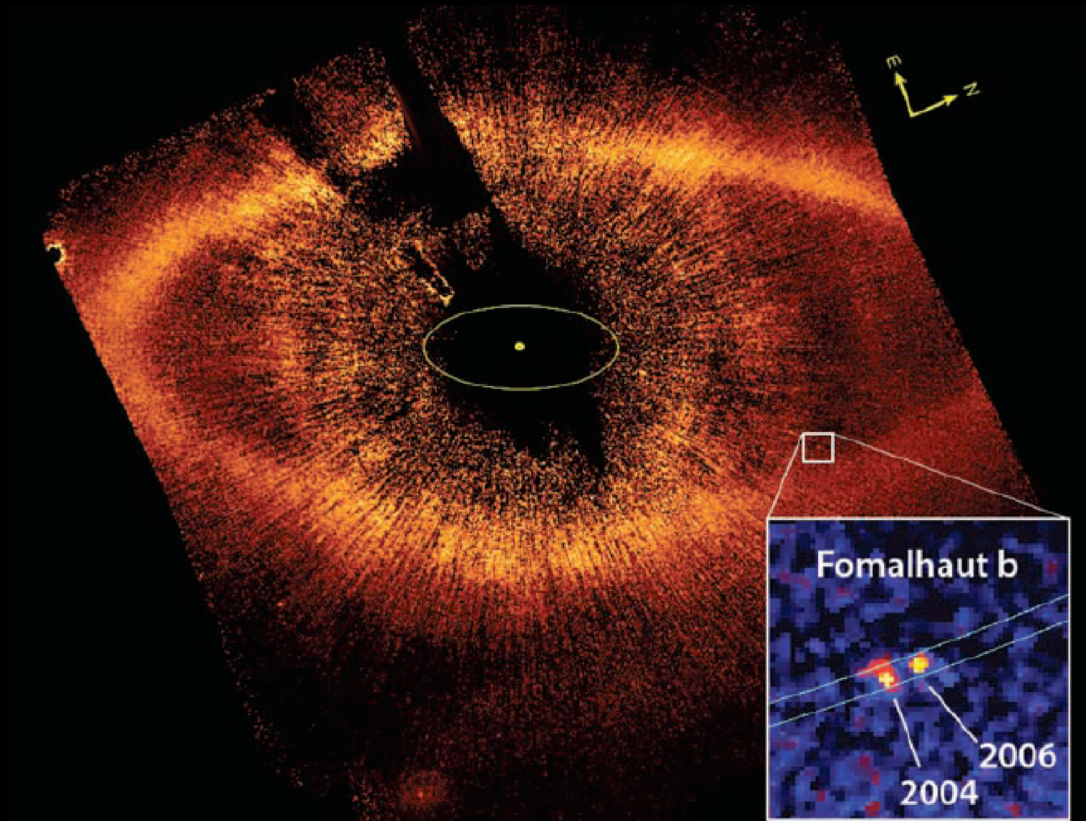
Data from literature



Non synchronicity between Mn-Cr and Pb-Pb ages questions the meaning of radiochronology

The revolution of exoplanets

Giordano Bruno (1548-1600)



Fomalhaut b
$M > 3\ M_J$
~ 119 astronomical units (AU) from the star

Kalas et al. Science 2008

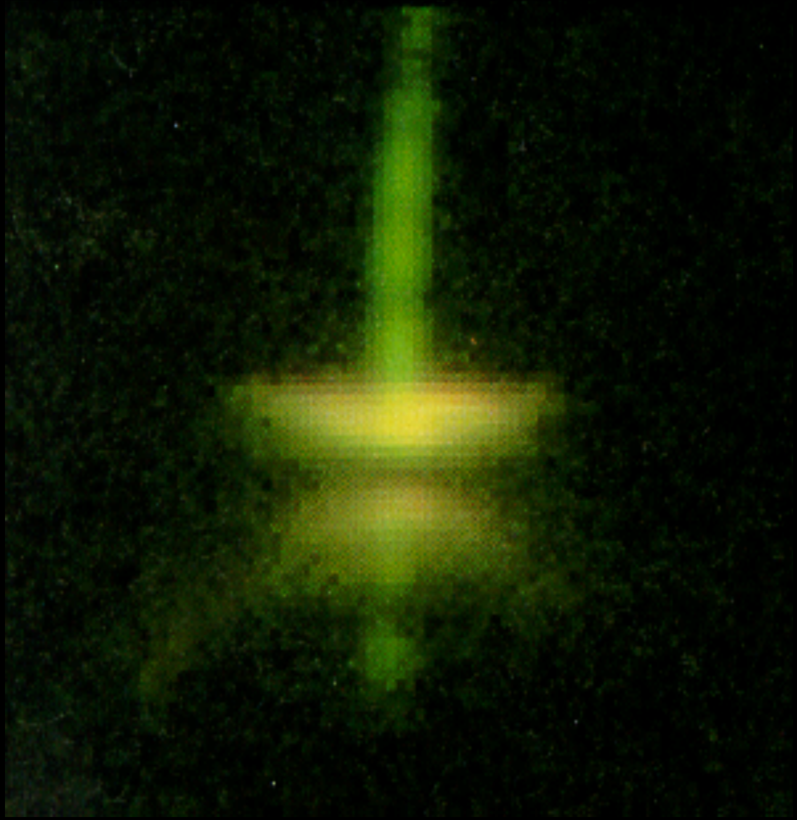
5. Conclusions

Conclusions: À la recherche de la primitivité perdue

- **Differentiated and primitive materials probably coexisted in the disk**
  - Fast accretion
  - What about the 2 Myr CAI-chondrule age difference?
  - The usual time sequence CAIs-chondrules-differentiated asteroids might be revisited
- **Complex dynamical processes have messed up the spatial distribution of bodies**
- **Comets are not very much more primitive than asteroids**

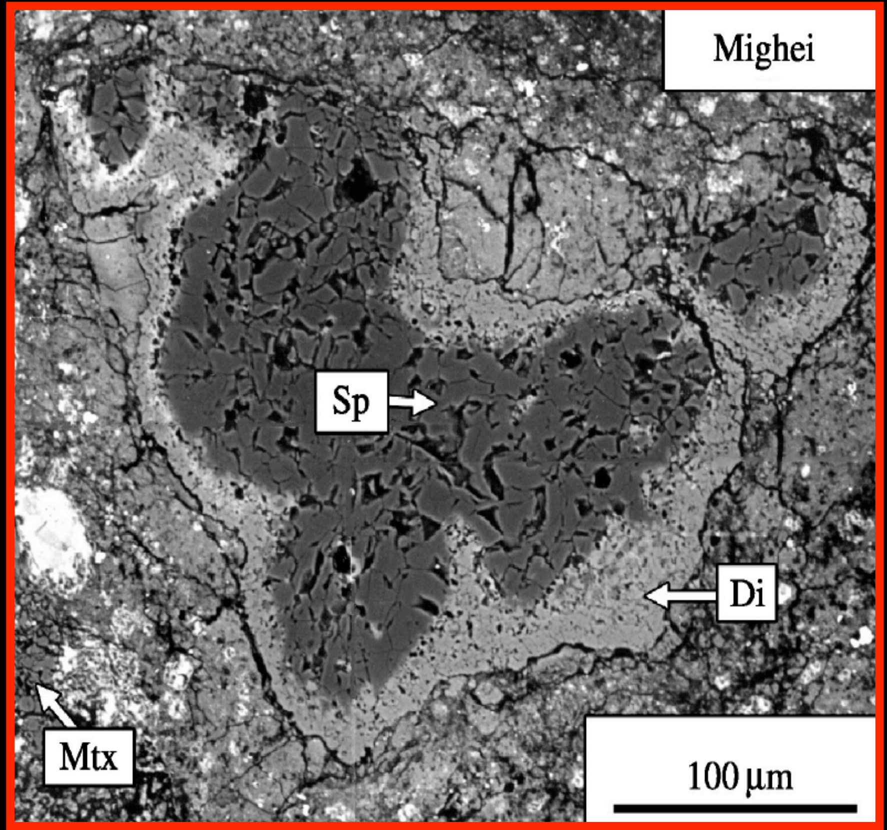
Transparents superfétatoires

What is primitive matter?



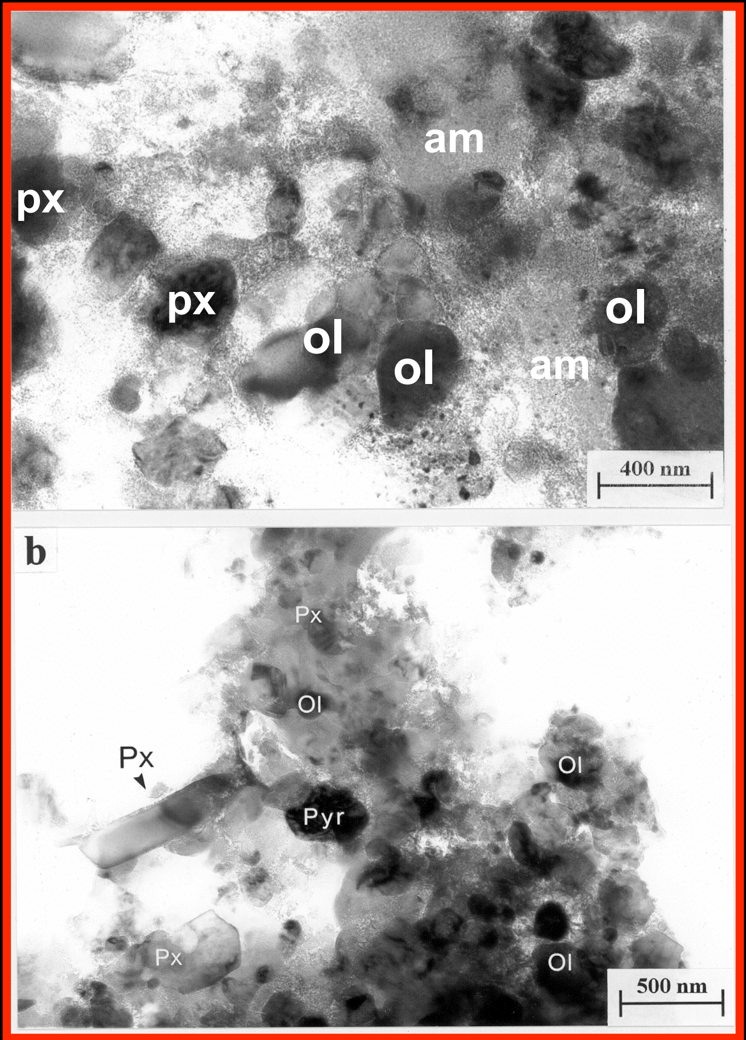
Calcium-, Aluminium-rich Inclusions

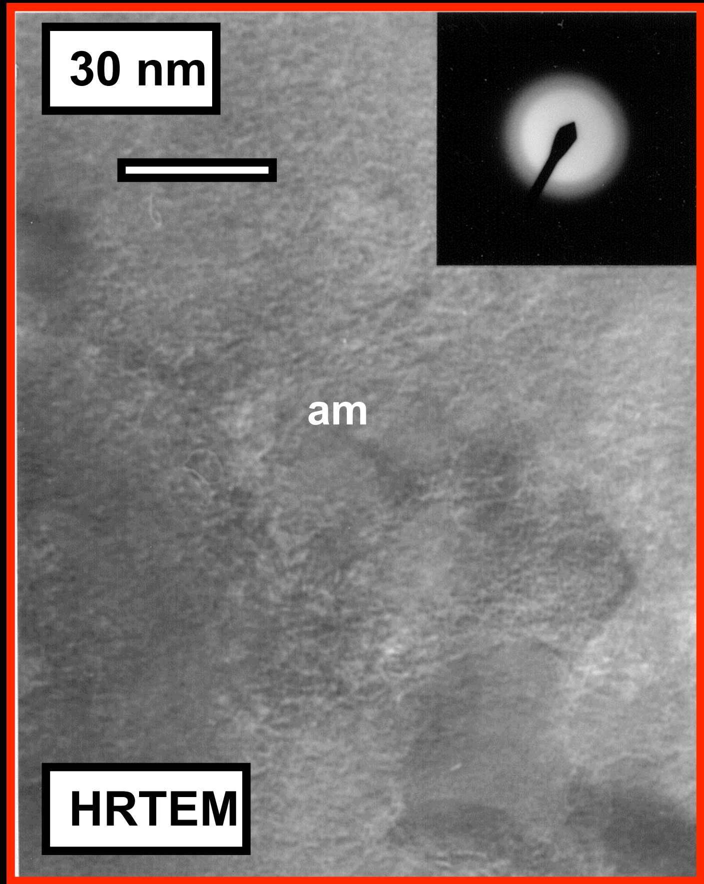
- Acronym is ***CAIs***
- Also named white inclusions or ***refractory inclusions***
- Discovered in 1967 by Madame Christophe in the ***Vigarano*** meteorite (CV3)
- CAIs are made of Ca- and Al-rich oxides and silicates
  - Melilite [$CaAl_{2x}Mg_{1-x}Si_{2-x}O_7$]
  - Spinel [Mg_2AlO_4]
  - Anorthite [$CaAl_2Si_2O_8$]
  - Perovskite [$CaTiO_3$]
  - Diopside [$CaMgSi_2O_6$]
- They are believed to be the first objects to have formed in the accretion disk 4567.1 Ga ago



Matrix

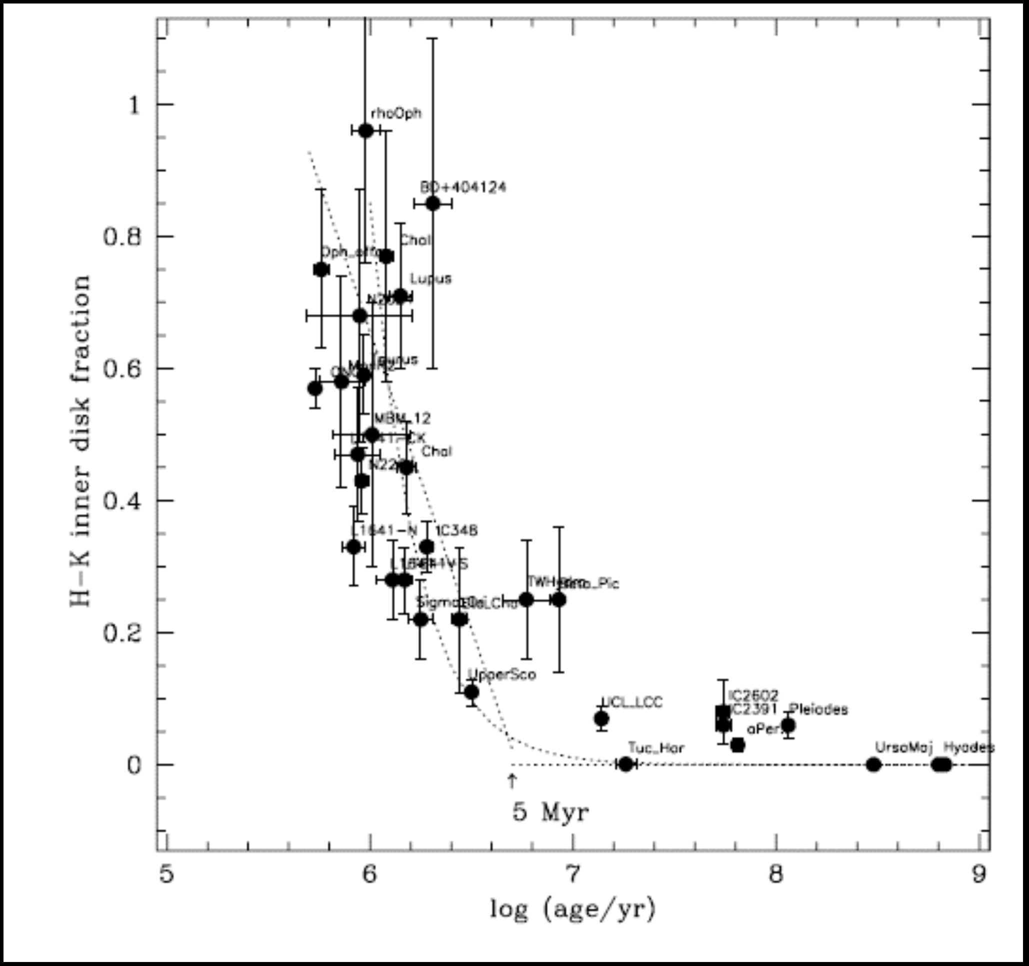
☆ **The matrix consists of small olivines (ol), pyroxenes (px) and sulfides (pyr) embedded in an amorphous groundmass (am)**





Greshake, GCA 1997

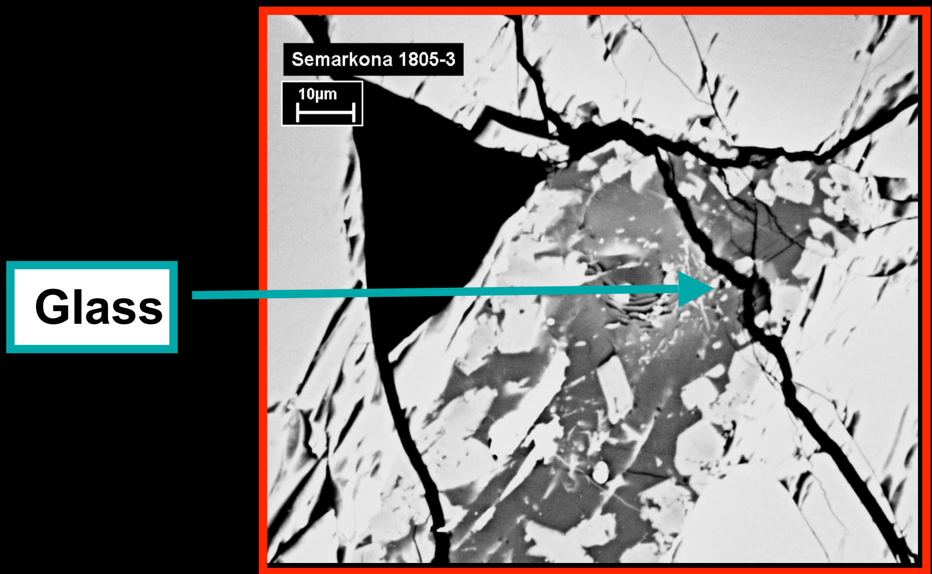
The lifetime of disks

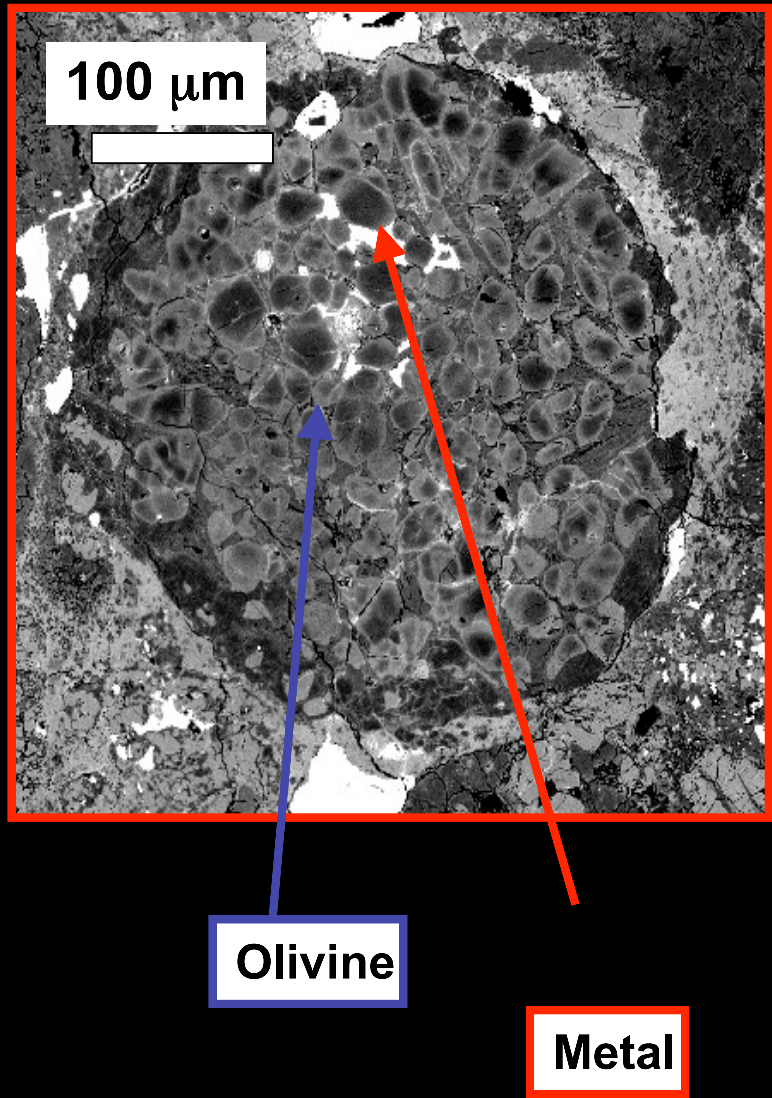


Chondrules

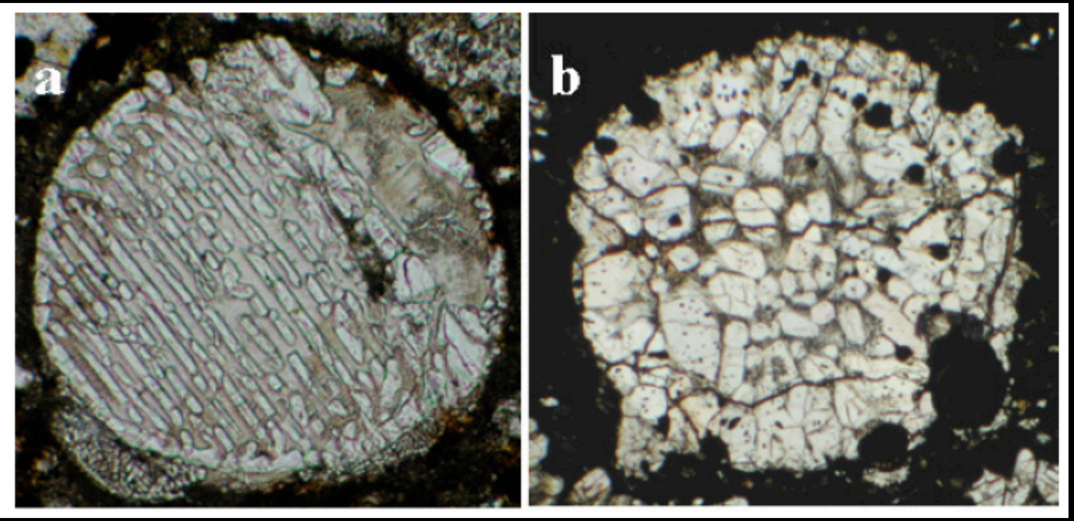
- Chondrules are made of
  - Olivine $(Mg,Fe)Si_2O_4$
  - Pyroxene $(Mg,Fe,Ca)SiO_3$
  - Metal (Fe,Ni)
  - Glass SiO_2- and alkali-rich [K, Na]
  - Iron sulfide FeS

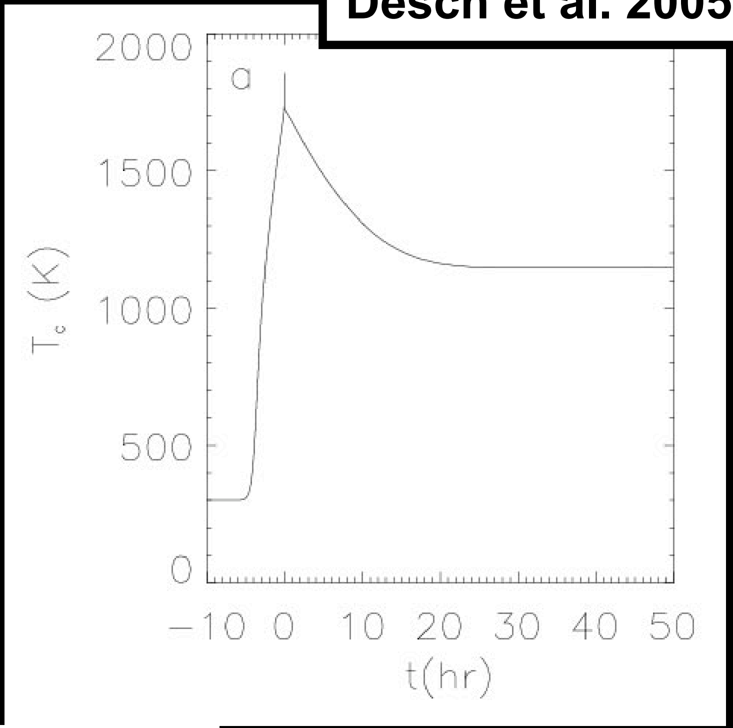
- The glass phase is interstitial
  - Mesostasis



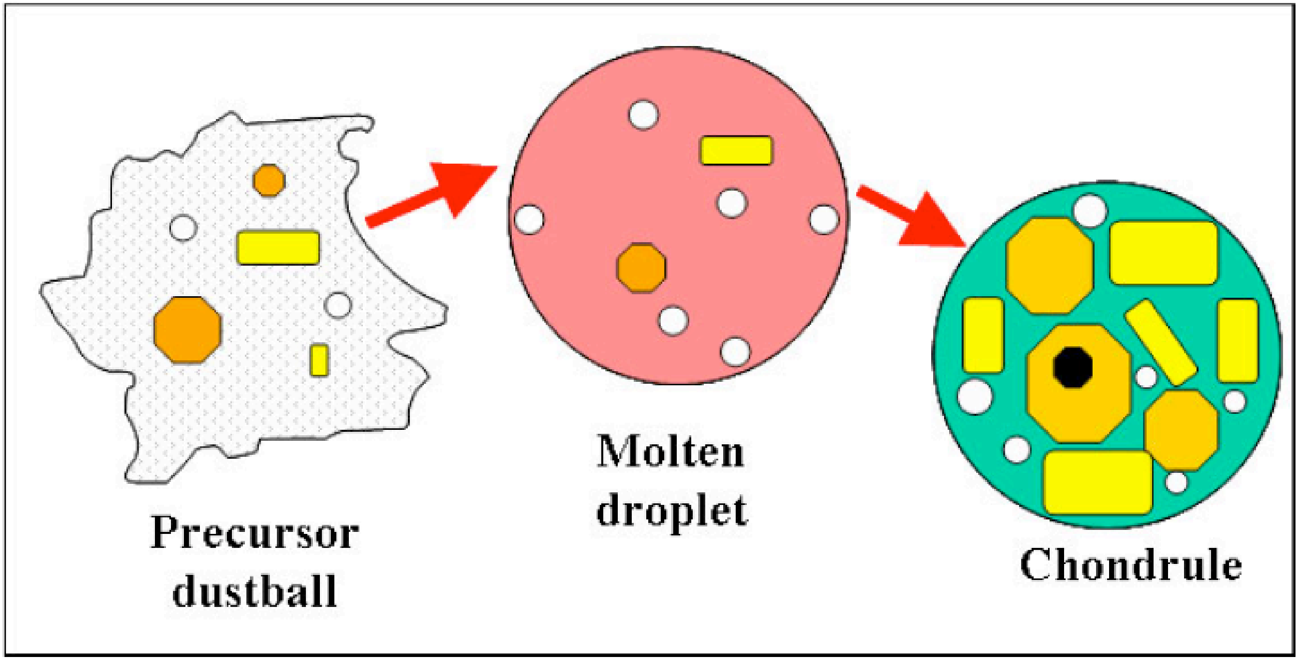


Chondrule formation



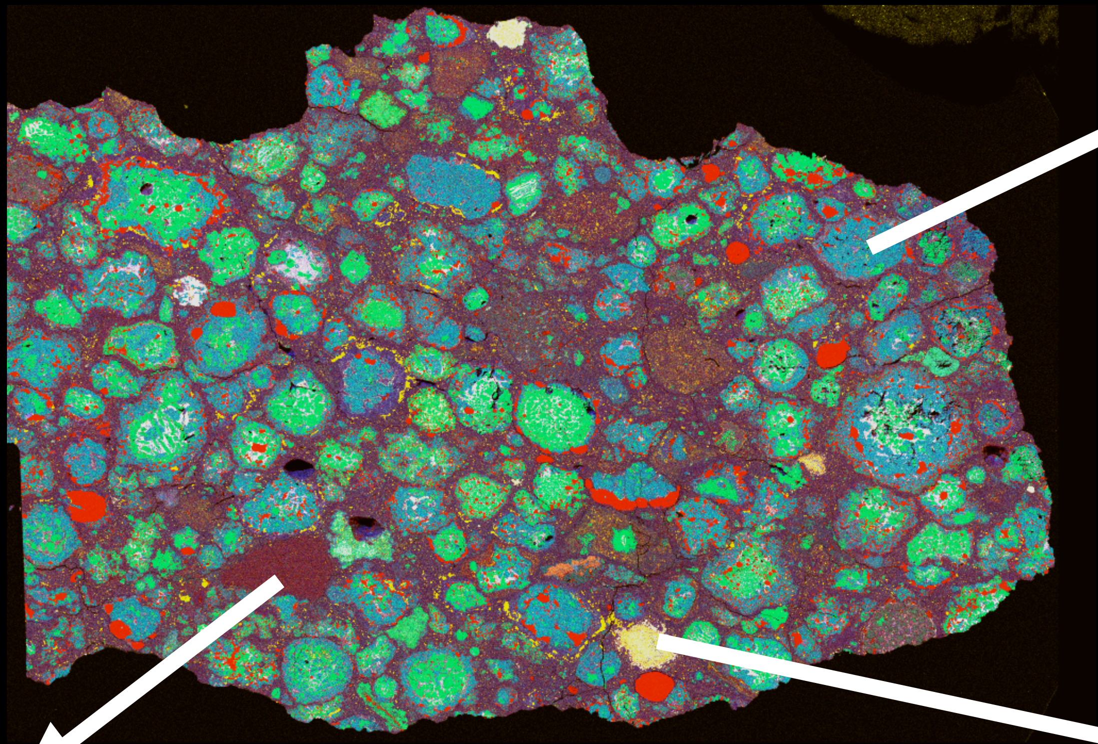


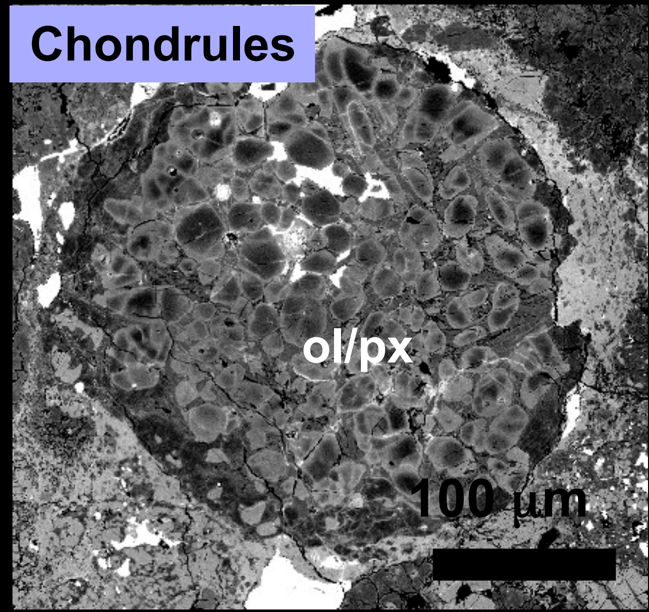
Desch et al. 2005

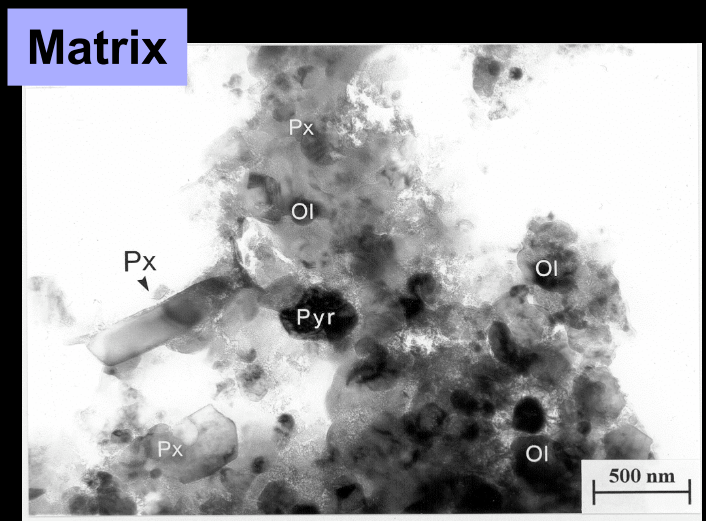


Jones et al. 2005

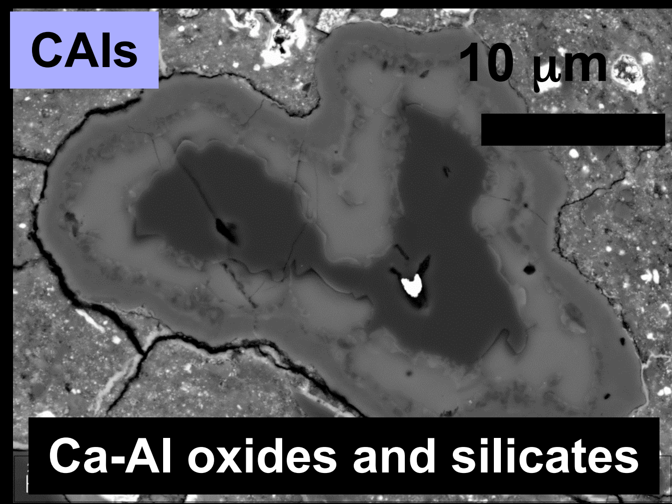
Chondrites' components







olivine: Mg_2SiO_4
pyroxene: $MgSiO_3$



Carbonaceous chondrites and asteroids

Primitive carbonaceous chondrites come from C asteroids

IV. L'accrétion et la différentiation des corps planétaires

La physique de la différentiation

Y. Ricard (ENS, Lyon)

Le chronomètre Hf-W : application à l'âge de la Lune

B. Bourdon (ETH, Zürich, Suisse)

Différentiation des corps parents des météorites de fer et précurseurs des chondres

M. Chaussidon (CRPG, Nancy)

Différentiation des corps de taille intermédiaire à Ceres, Vesta, Japet

C. Sotin (JPL, Pasadena, USA)

Différentiation des planètes telluriques

F. Albarède (ENS, Lyon)

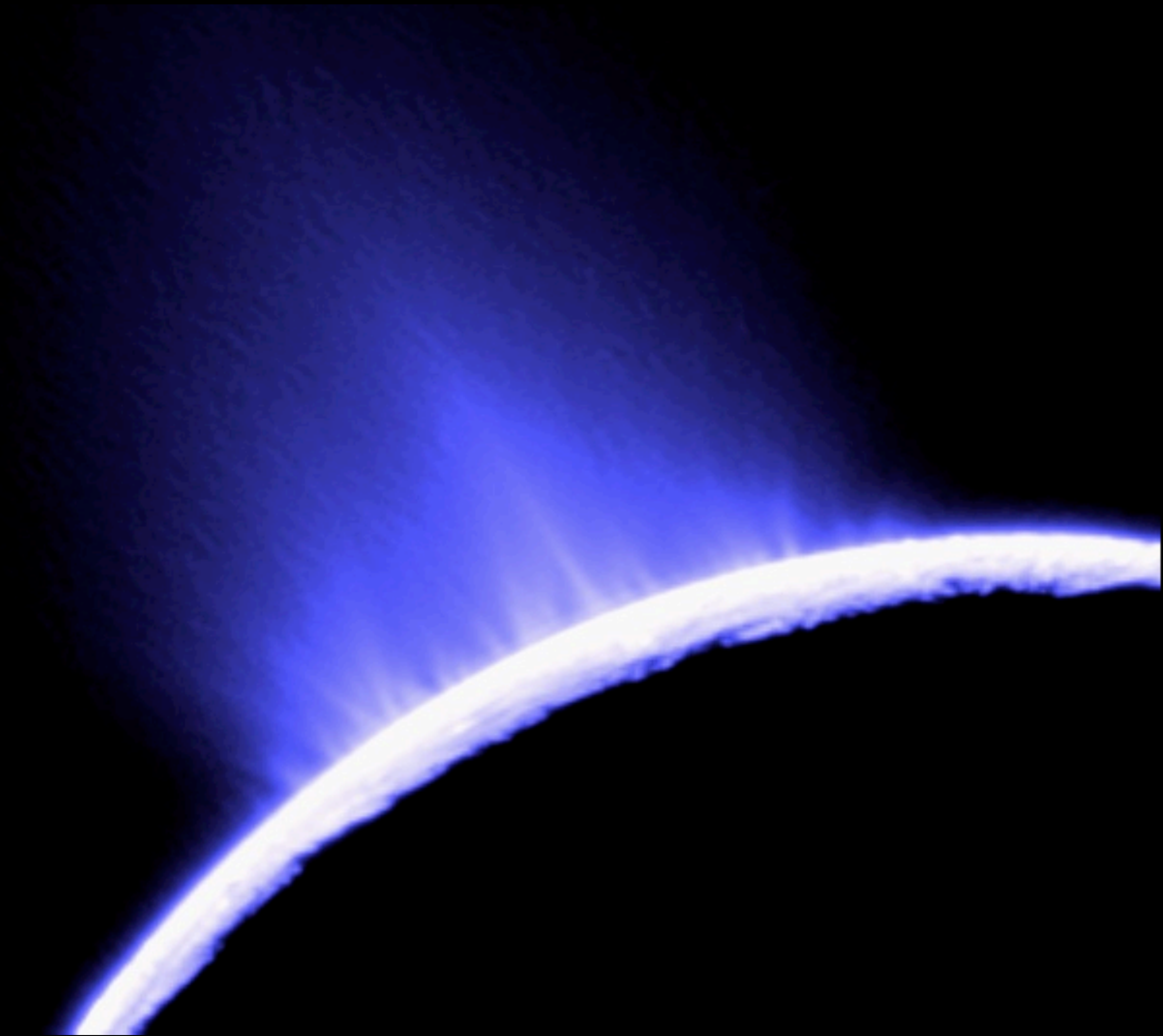
La formation de l'atmosphère

B. Marty (CRPG, Nancy)

Le contexte astronomique : modélisation des collisions et de l'accrétion planétaire

P. Michel (OCA, Nice)

Enceladus' activity



Saturn's Moon. 250 km radius