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Chronology of the accretion of planetesimals: from the first condensates to the first rocks

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• Temperatures > 1500 C are reached in the inner zone of the disk during dissipation of heat generated by the accretion

(cf talk by Cornelis Dullemond)

• Condensation of solids from the gas takes place over a range of temperature producing liquids and solids with a large range of composition

(cf talk by Joe Nuth)

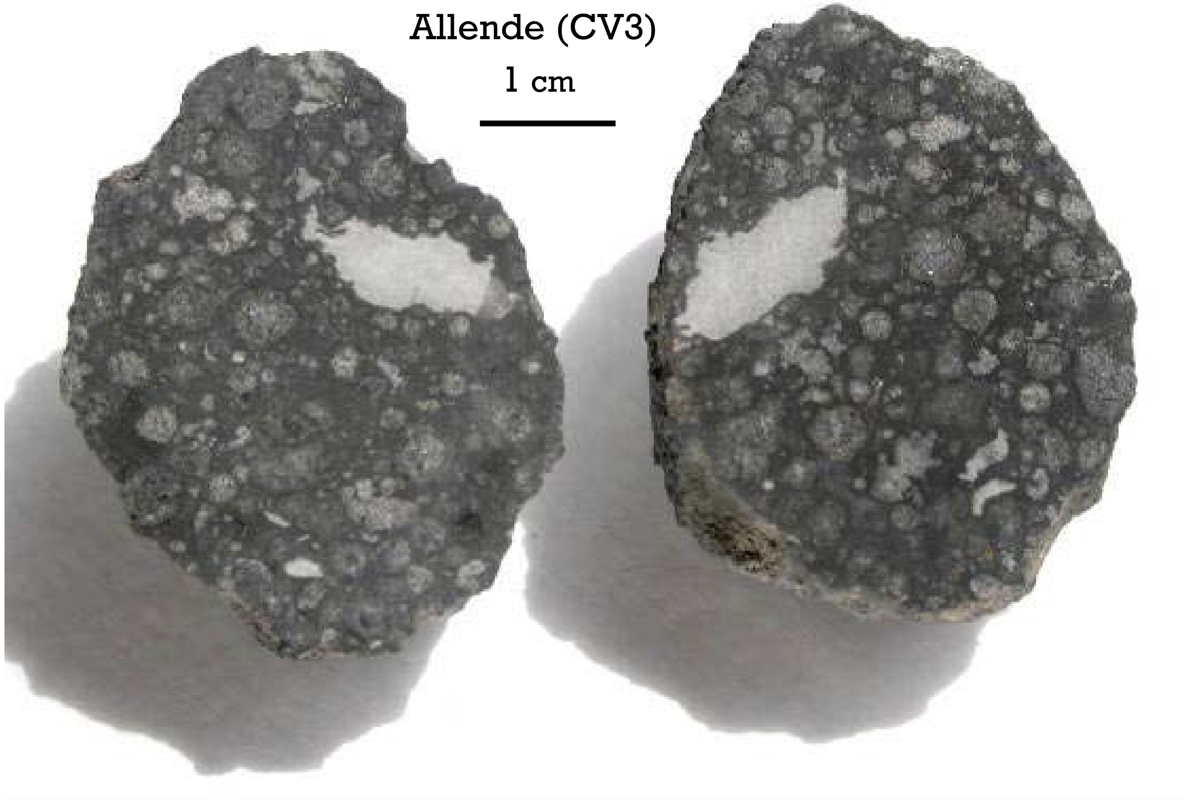
• Recent developments with models of the accretion of planetesimals show that there can be two ways to make 500-1000 km objects, either rapid (a few 0.1 Myr) or slow (a few Myr)

(cf talk by Anders Johansen)

Goal of the talk: summarize constraints on the timing and chronology of these processes from dating of meteorites and their components
(major changes since the first school *Les Houches 2001*)

Primitive meteorites (cf talk by Guy Libourel)

= chondrules (Mg-Fe-rich of types I & II, Al-rich)
+ CAIs (Ca-, Al-rich inclusions)
+ matrix



Important questions, not only for the origin of CAIs and chondrules
but also for the origin of planets and the modelling of their bulk composition

• Processes taking place in the disk during the first few Myrs (or even less ?)

• Chondrites are considered as the “building blocks” of planets, but are they really the building blocks ?
(chondrites accreted late (?), after the formation of Mars)

• What was the composition of the “protoplanets” ? Did they survive ? Were their fragments part of the “building blocks” of chondrites and planets ?

1) Isotopic dating and its limitation

2) ^{26}Al-^{26}Mg: chronology of formation and
evolution of CAIs and chondrules in the disk
(caveats, age of chondrites, fragments of protoplanets, …)

3) U-Pb: the absolute age of CAIs and chondrules
(consistency or not with ^{26}Al)

4) ^{182}Hf-^{182}W: age of iron meteorites and Mars
(last developments since the talk by Bernard Bourdon
at les Houches 2009)

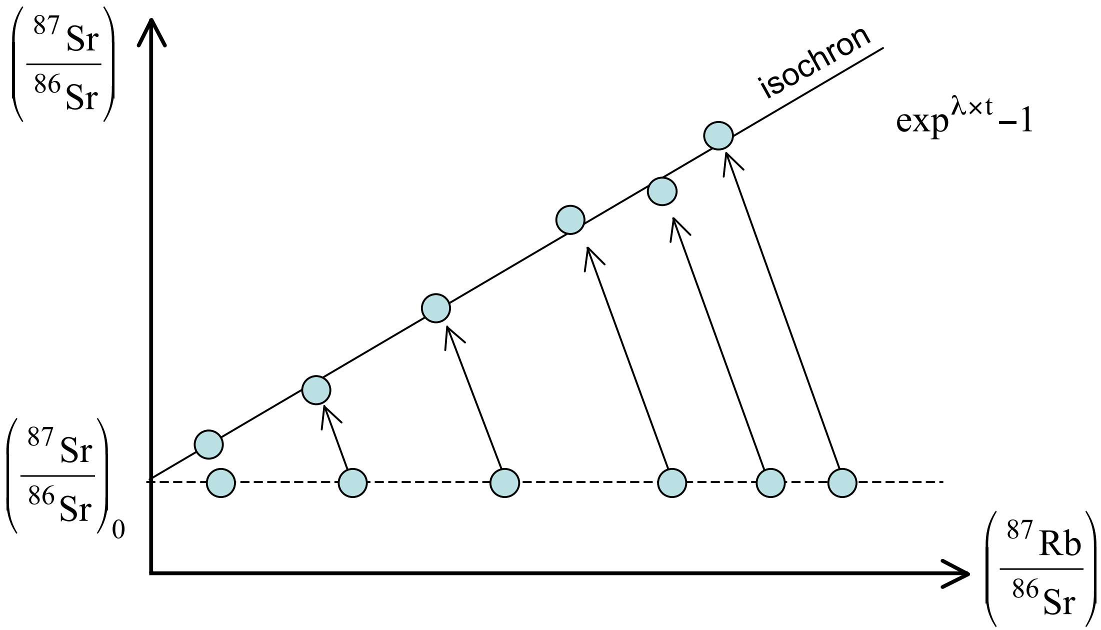
- radioactive decay: $\frac{d\left({}^{87}Rb\right)}{dt} = -\lambda \times {}^{87}Rb$

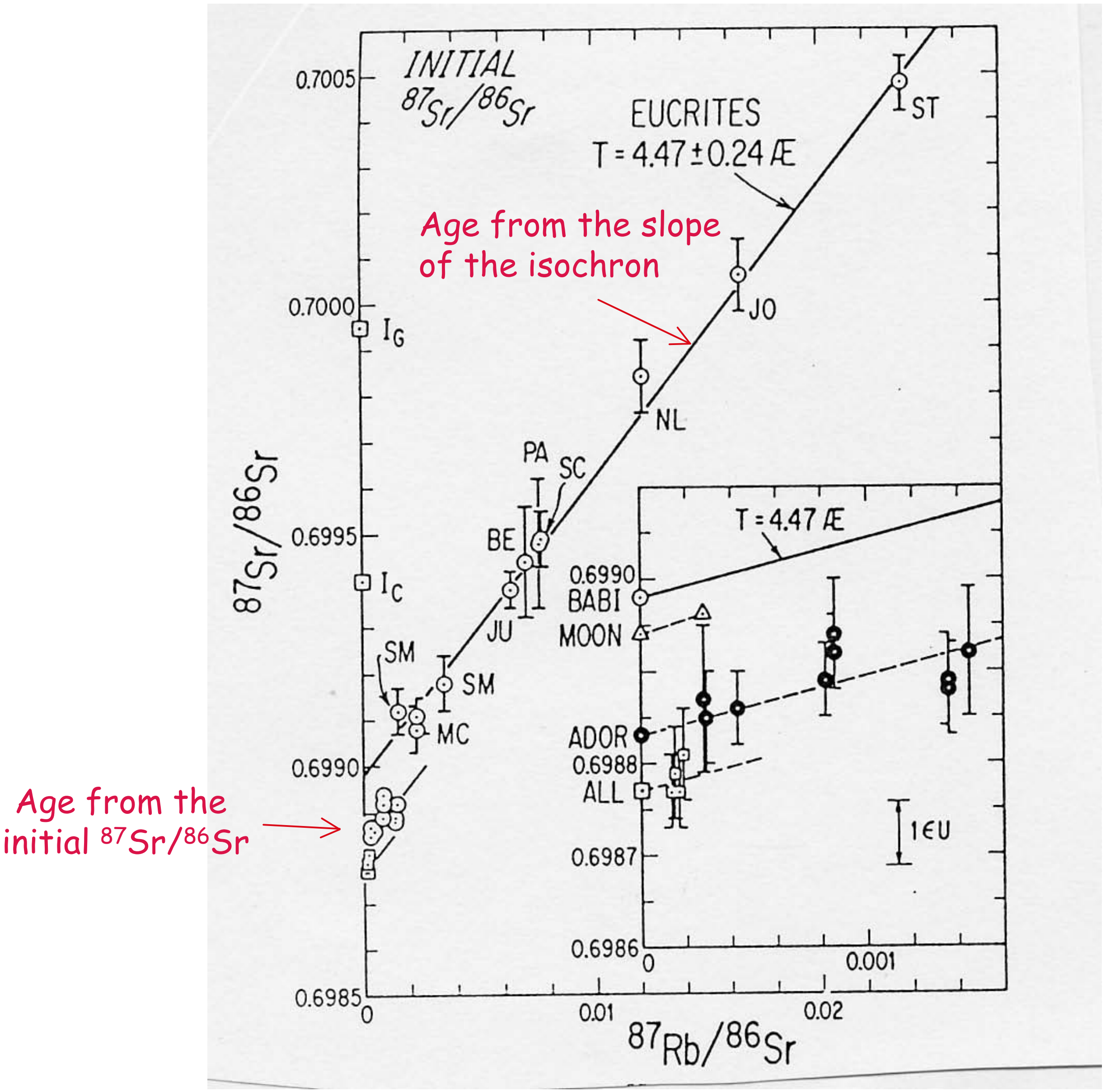
$${}^{87}Rb \rightarrow {}^{87}Sr \quad (T_{1/2} = 48.8 \times 10^{9}\,y)$$

$$\left(\frac{{}^{87}Rb}{{}^{85}Rb}\right) = \left(\frac{{}^{87}Rb}{{}^{85}Rb}\right)_0 \times \exp^{(-\lambda \times t)}$$

- mass balance: $\left({}^{87}Rb\right)_0 - \left({}^{87}Rb\right) = \left({}^{87}Sr\right) - \left({}^{87}Sr\right)_0$

$$\left(\frac{{}^{87}Sr}{{}^{86}Sr}\right) = \left(\frac{{}^{87}Sr}{{}^{86}Sr}\right)_0 + \left(\frac{{}^{87}Rb}{{}^{86}Sr}\right) \times \left(\exp^{(\lambda \times t)} - 1\right)$$





Papanastassiou & Wasserburg (1969)

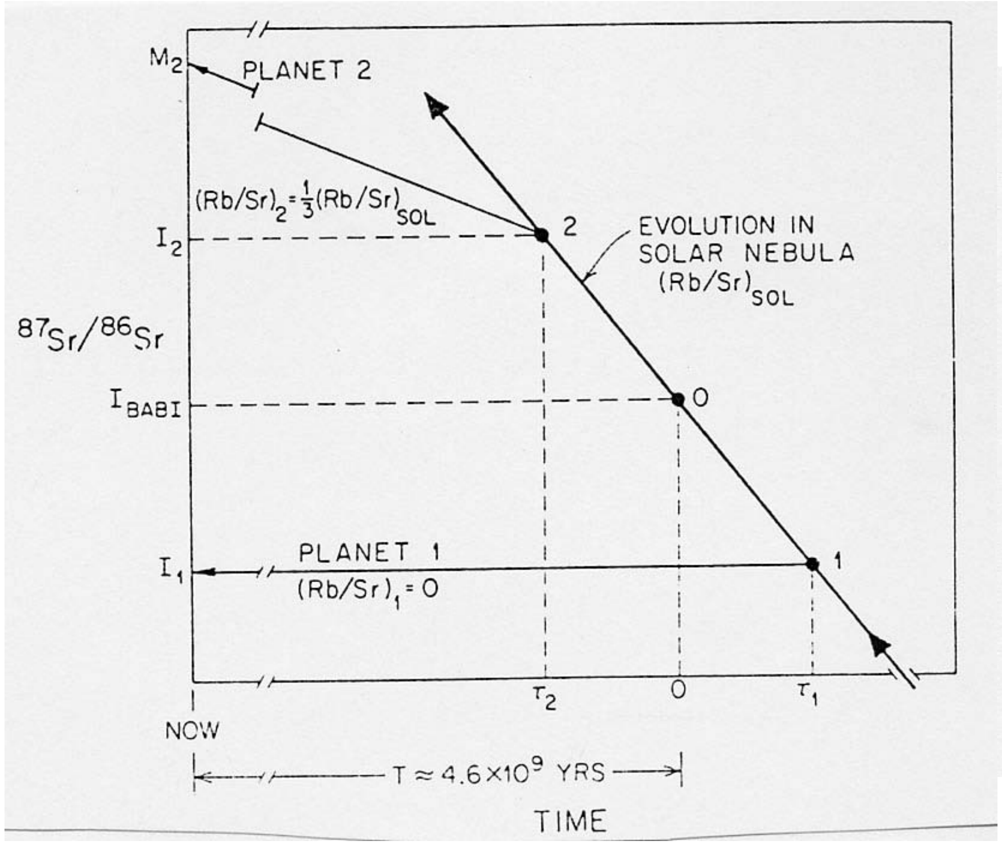


TABLE 1

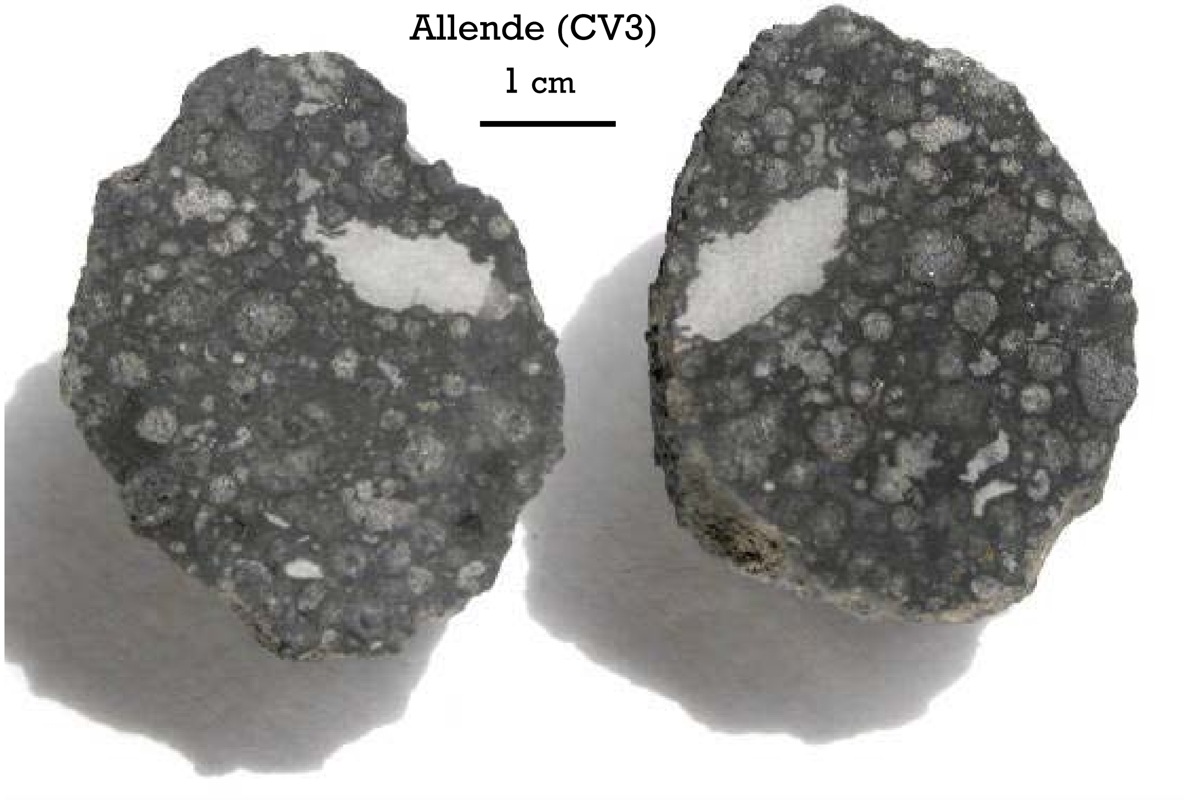
Condensation sequence from initial $^{87}Sr/^{86}Sr$

		ϵ_{BABI} PARTS IN 10^4	ΔT_{SOLAR} 10^6 YEARS
ALL (ALLENDE)		-3.1 ± 0.3	-11
ADOR (ANGRA DOS REIS)		-2.3 ± 0.6	-8
KAPOETA		-1.9 ± 0.6	-7
MOON	60025	-0.6 ± 0.4	-2 to 0
	60015	-0.1 ± 0.4	
	DUNITE	$+0.3 \pm 0.6$	
	TROCTOLITE	$+0.3 \pm 0.6$	
BABI		0.	0
		$(Rb/Sr)_\odot$ =	0.5

Wasserburg (1987)

$$(^{87}Sr/^{86}Sr)_{Allende} - (^{87}Sr/^{86}Sr)_{BABI} = (^{87}Rb/^{86}Sr)_{solar\ nebula} \times (e^{\lambda t} - 1)$$

CAVEATS



Rb/Sr fractionation due to their different volatilities (evaporation/condensation) and different mineral/liquid partioning (cristallisation/melting)

Accretion is a low temperature process which does not produce any fractionation

Age of their youngest component < Age of chondrites < Age of metamorphism

Short-lived radioactive nuclides

$^{10}Be \rightarrow ^{10}B \quad (T_{1/2} = 1.39\ My)$

$^{26}Al \rightarrow ^{26}Mg \quad (T_{1/2} = 0.73\ My)$

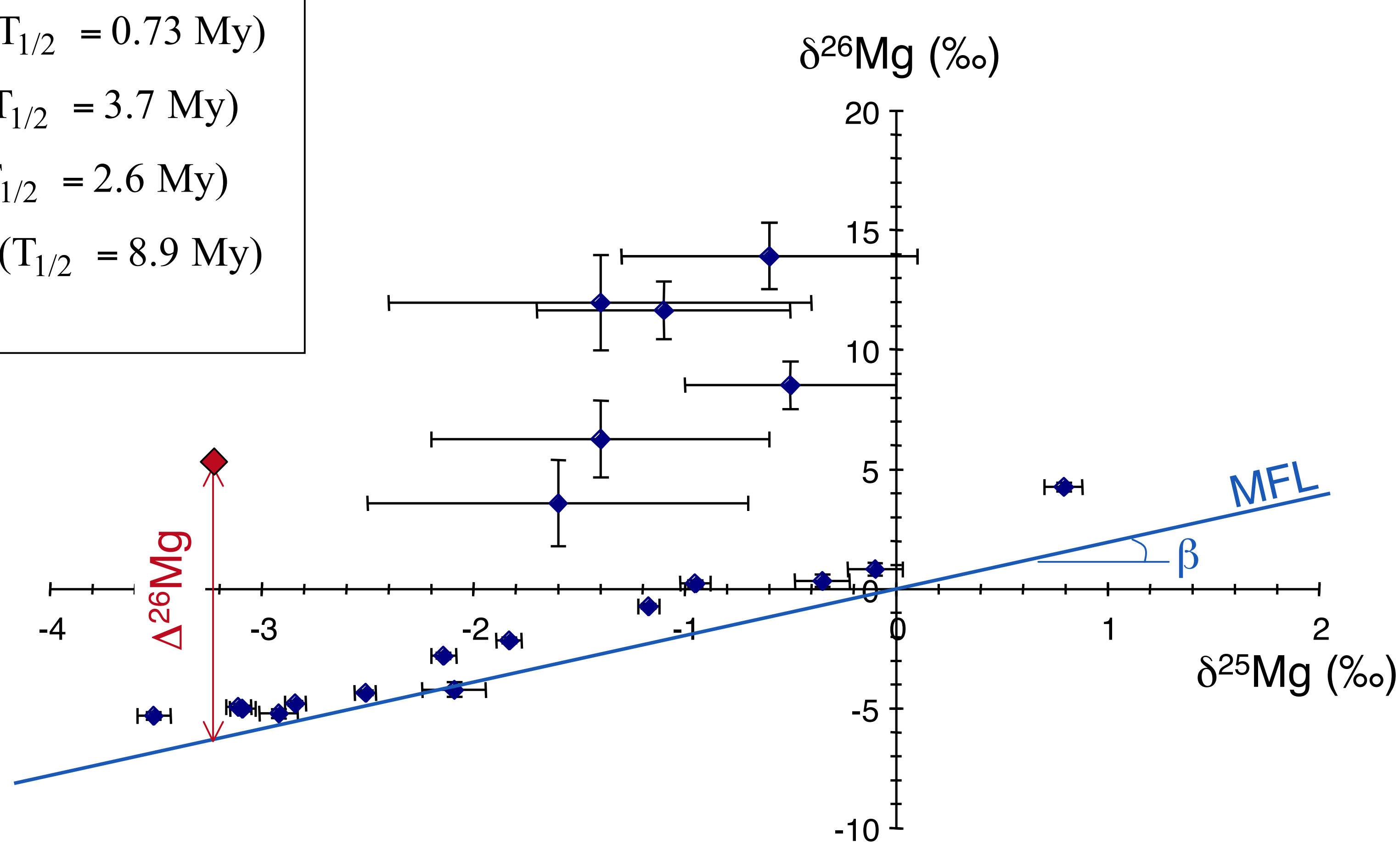
$^{53}Mn \rightarrow ^{53}Cr \quad (T_{1/2} = 3.7\ My)$

$^{60}Fe \rightarrow ^{60}Ni \quad (T_{1/2} = 2.6\ My)$

$^{182}Hf \rightarrow ^{182}W \quad (T_{1/2} = 8.9\ My)$

...

^{26}Al discovered by Lee et al., 1976.
Mass independent variations of Mg isotopes in CAIs
(e.g. data MacPherson et al., 2010)



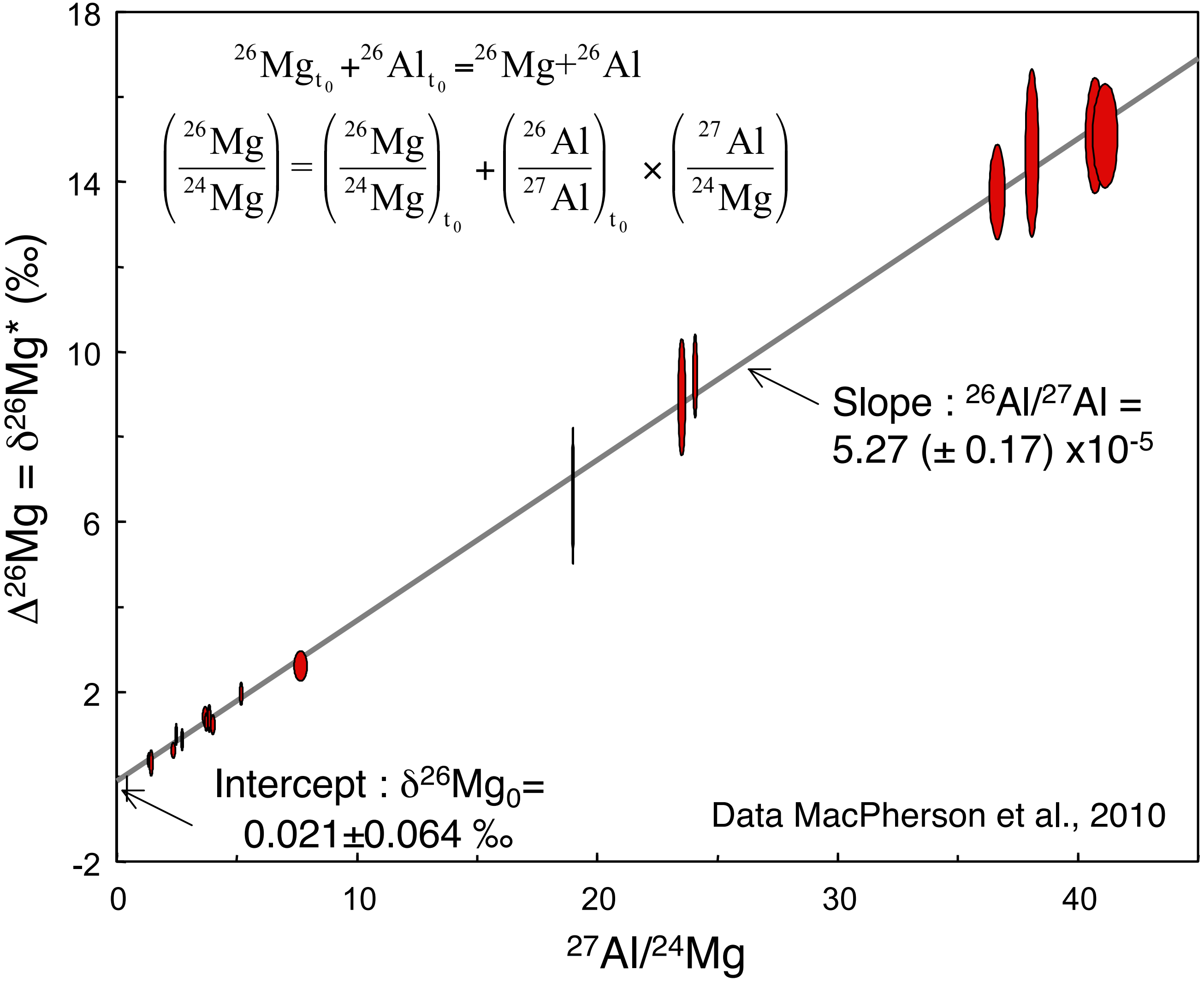
^{26}Mg excess :

$\Delta^{26}Mg \approx \delta^{26}Mg - \delta^{26}Mg / \beta$

$\beta_{equilibrium} = 0.521$

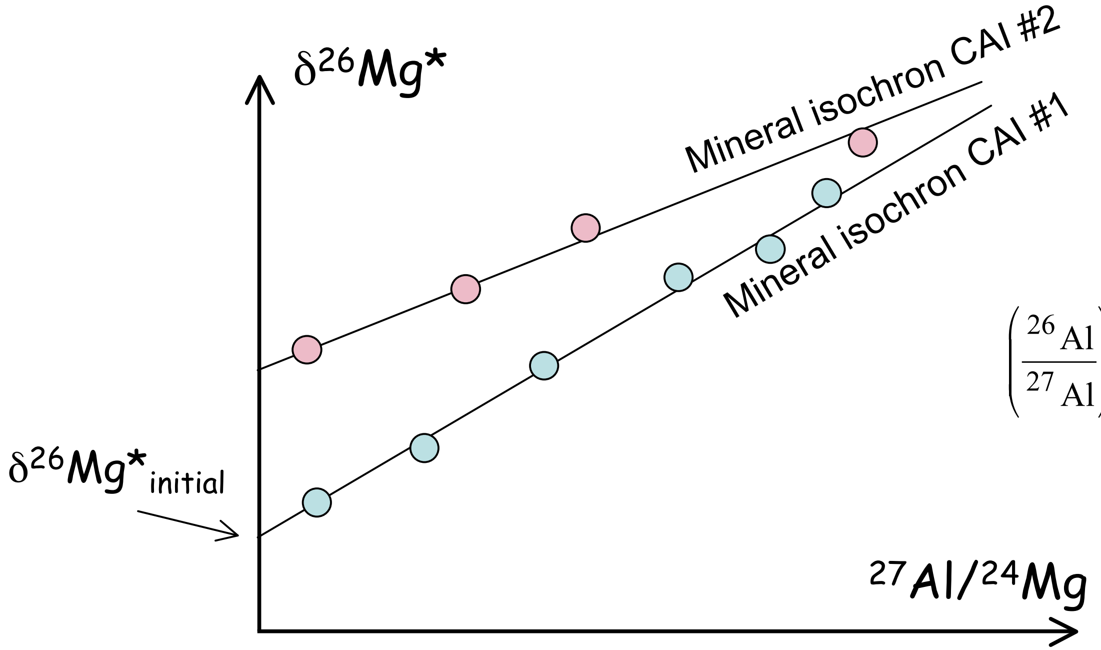
$\beta_{kinetic} = 0.511\text{–}0.514$

The ^{26}Mg excesses are due to the in situ decay of short lived ^{26}Al
(because they are linearly correlated with $^{27}Al/^{24}Mg$ and not $1/^{24}Mg$)



Bulk and mineral ^{26}Al isochrons record (and thus give access to) different processes

- Al/Mg fractionation for mineral isochrons:
  crystal/liquid partitioning during magmatic history of CAIs or chondrules



slopes

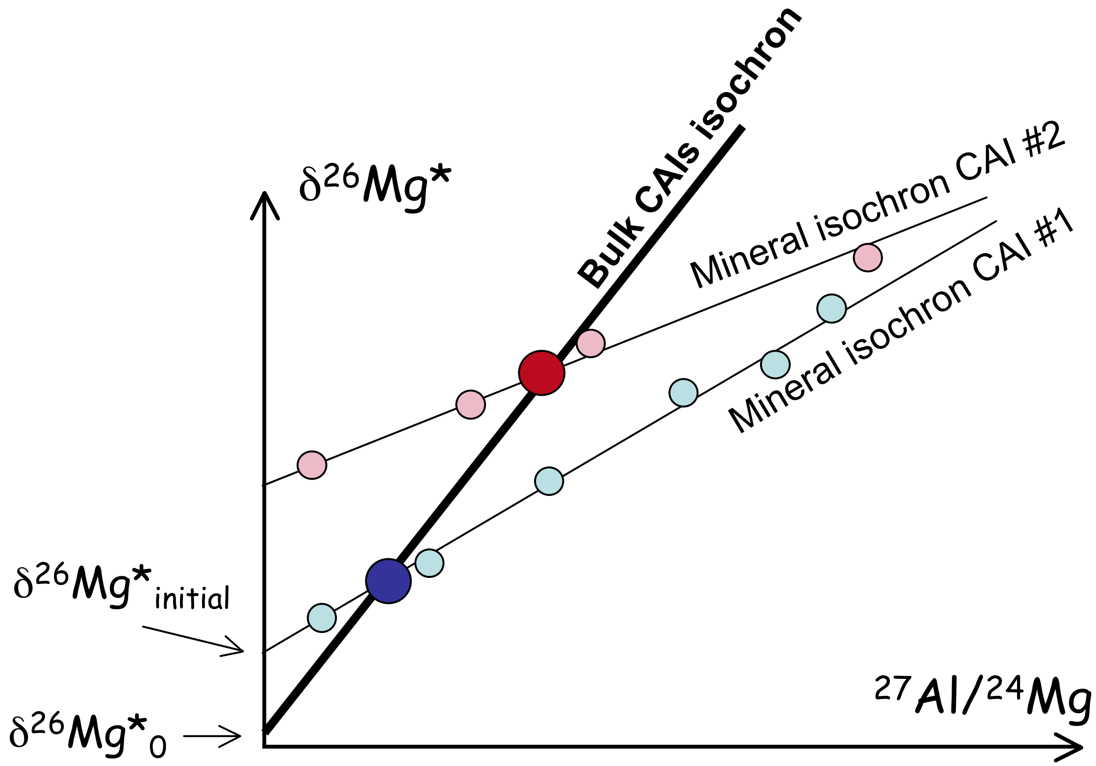
$$\left(\frac{^{26}Al}{^{27}Al}\right)_{initial} = \left(\frac{^{26}Al}{^{27}Al}\right)_0 \times e^{-\lambda(t_0 - t_{initial})}$$

intercepts

$$\delta^{26}Mg^*_{initial} = \delta^{26}Mg^*_0 - \frac{^{27}Al/^{24}Mg}{\left(^{26}Mg/^{24}Mg\right)_{ref}} \times \left[\left(^{26}Al/^{27}Al\right)_0 - \left(^{26}Al/^{27}Al\right)_{initial}\right] \times 1000$$

Bulk and mineral ^{26}Al isochrons record (and thus give access to) different processes

- Al/Mg fractionation for mineral isochrons:
  crystal/liquid partitioning during magmatic history of CAIs or chondrules
- Al/Mg fractionation for bulk isochrons:
  precursors composition, condensation & evaporation of CAI or chondrule melts



1) Isotopic dating and its limitation

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Major questions with ^{26}Al
(see Dauphas & Chaussidon, Ann. Rev. Earth Planet Sci. 2011)

- What is the origin of ^{26}Al in the early solar system ?
(irradiation, dying massive star, not addressed here, see last scenario by Gounelle & Meynet, 2012 and refs therein)

- What is the distribution of ^{26}Al (and of ^{26}Mg) in the disk ? Is ^{26}Al a chronometer ?

  - Level of homogeneity of Mg and Al isotopes and timing of their mixing

    - Is there a common $\delta^{26}Mg^*_0$ and $^{26}Al/^{27}Al_0$ for all CAIs, for all chondrules, for CAIs and chondrules …?

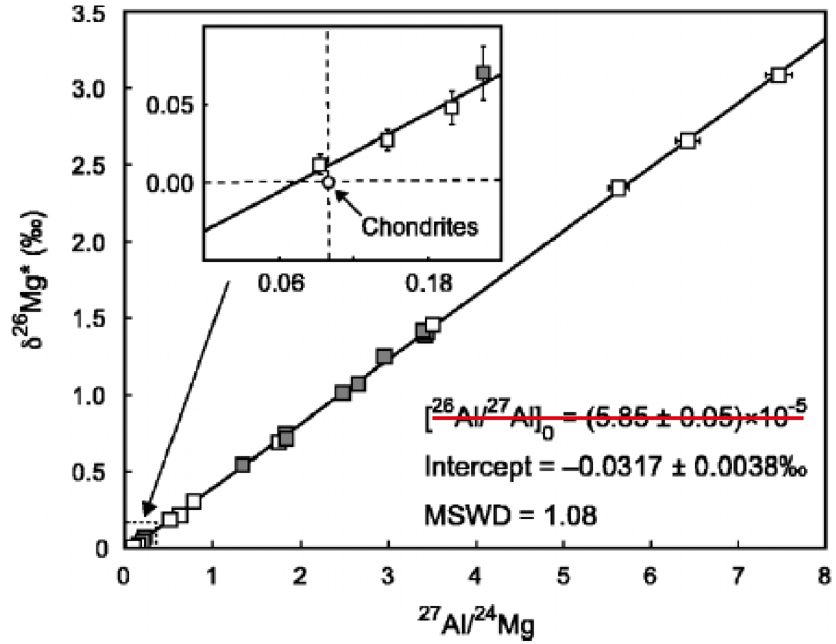
  - Timing of formation of CAIs and chondrules (condensation, melting) and "survival" in the disk

    - What are the $\Delta t=(t_{initial}-t_0)$ for CAIs and chondrules ?
    - Are the $\Delta t=(t_{initial}-t_0)$ calculated for CAIs and chondrules from their $\delta^{26}Mg^*_i$, their $^{26}Al/^{27}Al_i$ (and their $^{207}Pb^*/^{206}Pb^*$) the same ?

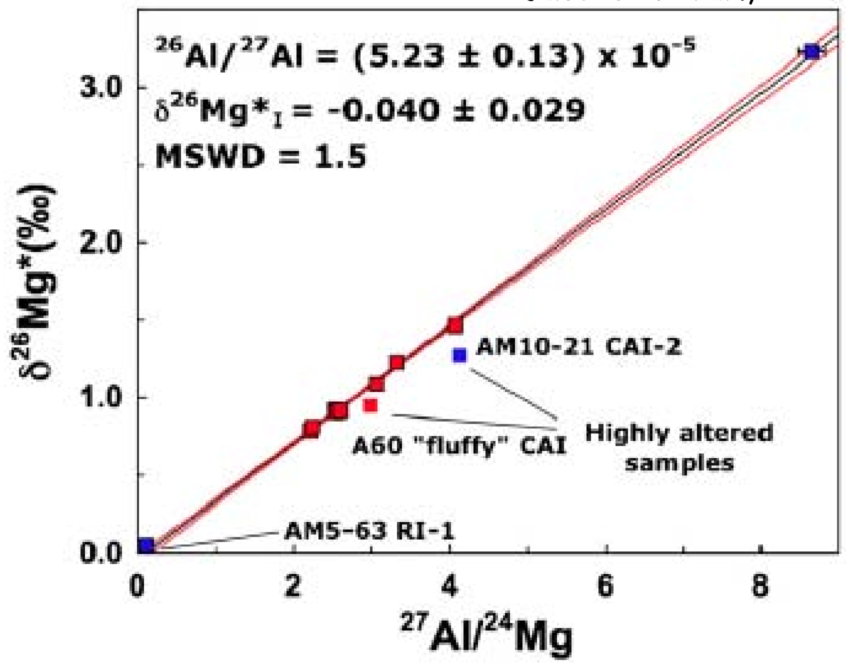
Advances made in the last few years from developments of high-precision Mg isotopes analysis by MC-ICPMS & MC-SIMS

Bulk CAIs from CV chondrites define a very tight bulk ^{26}Al isochron
(Thrane et al. 2006 ; Jacobsen et al. 2008, Larsen et al. 2011)

Thrane et al. 2006



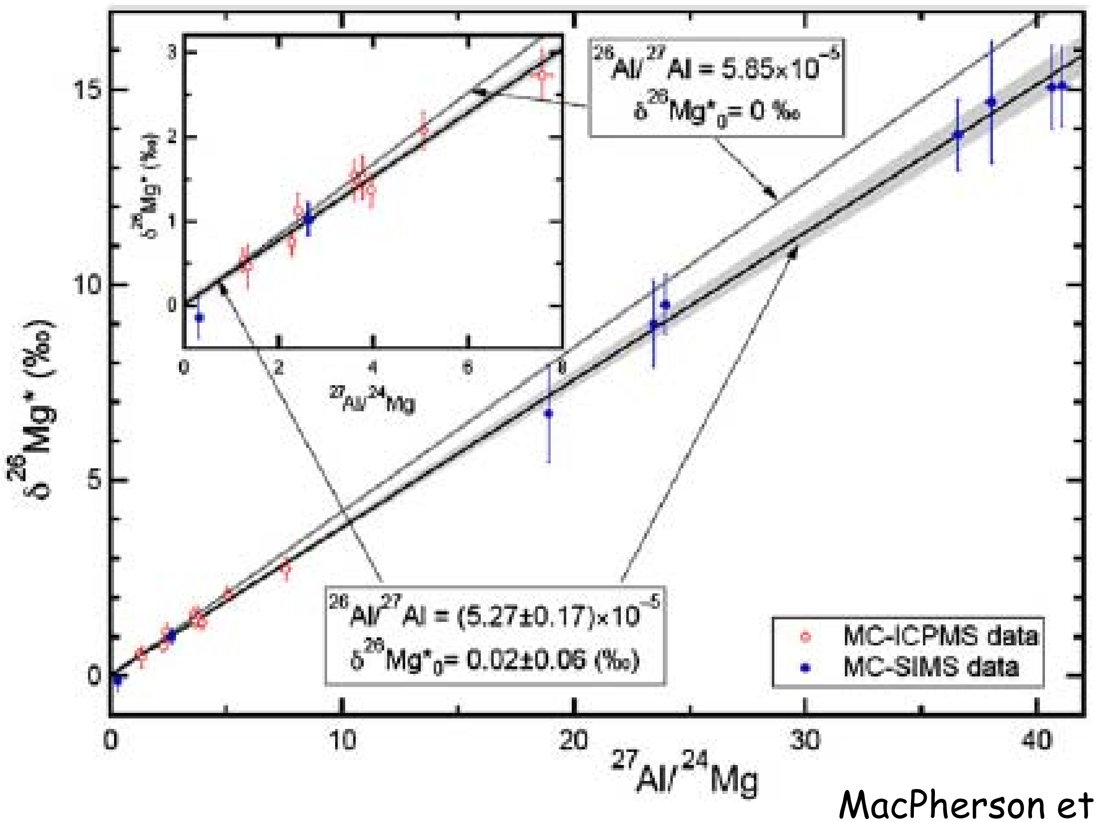
Jacobsen et al., 2008



Very short interval for condensation
$\pm 0.05 \times 10^{-5} \longleftrightarrow \pm 10{,}000$ years

Questions: only one event which lasted 10 000 years, or many events within 10 000 years or formation of CAIs over a much longer period but bias from sample selection ?

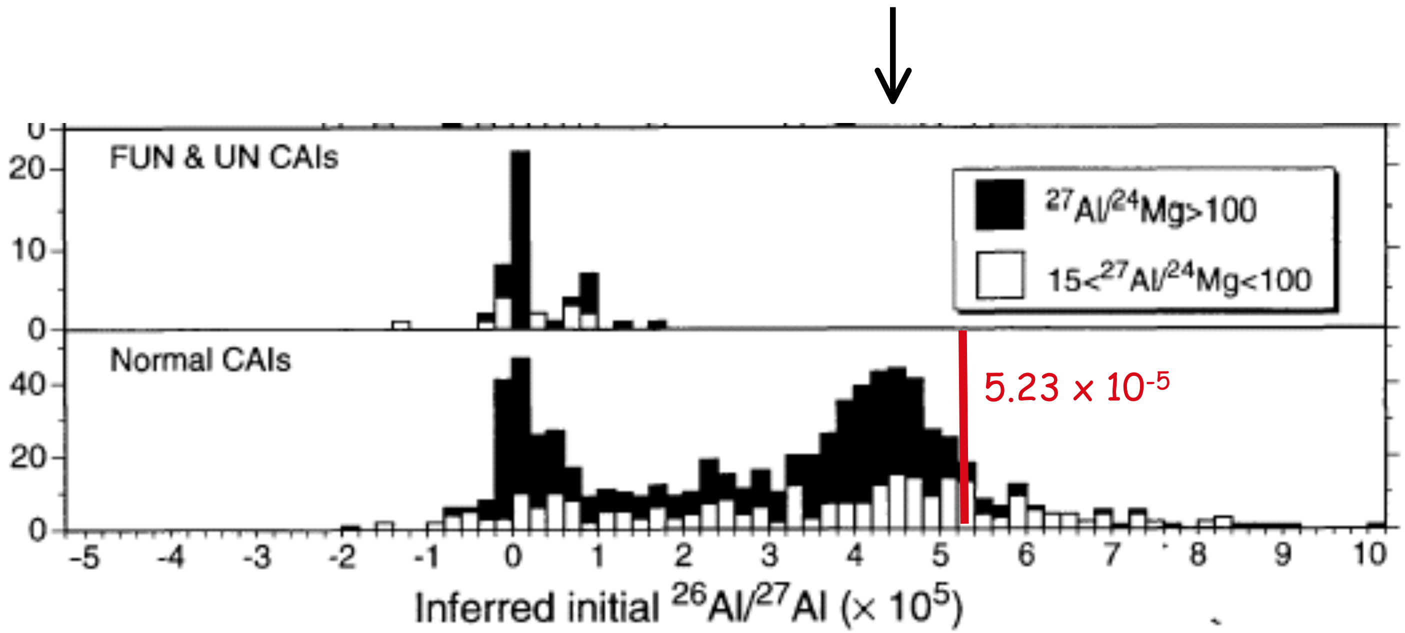
Some CAIs crystallized nearly at the same time and did not undergo any later perturbation



MacPherson et al., 2010

Distribution of initial $^{26}Al/^{27}Al$ in CAIs from "old, low precision" measurements

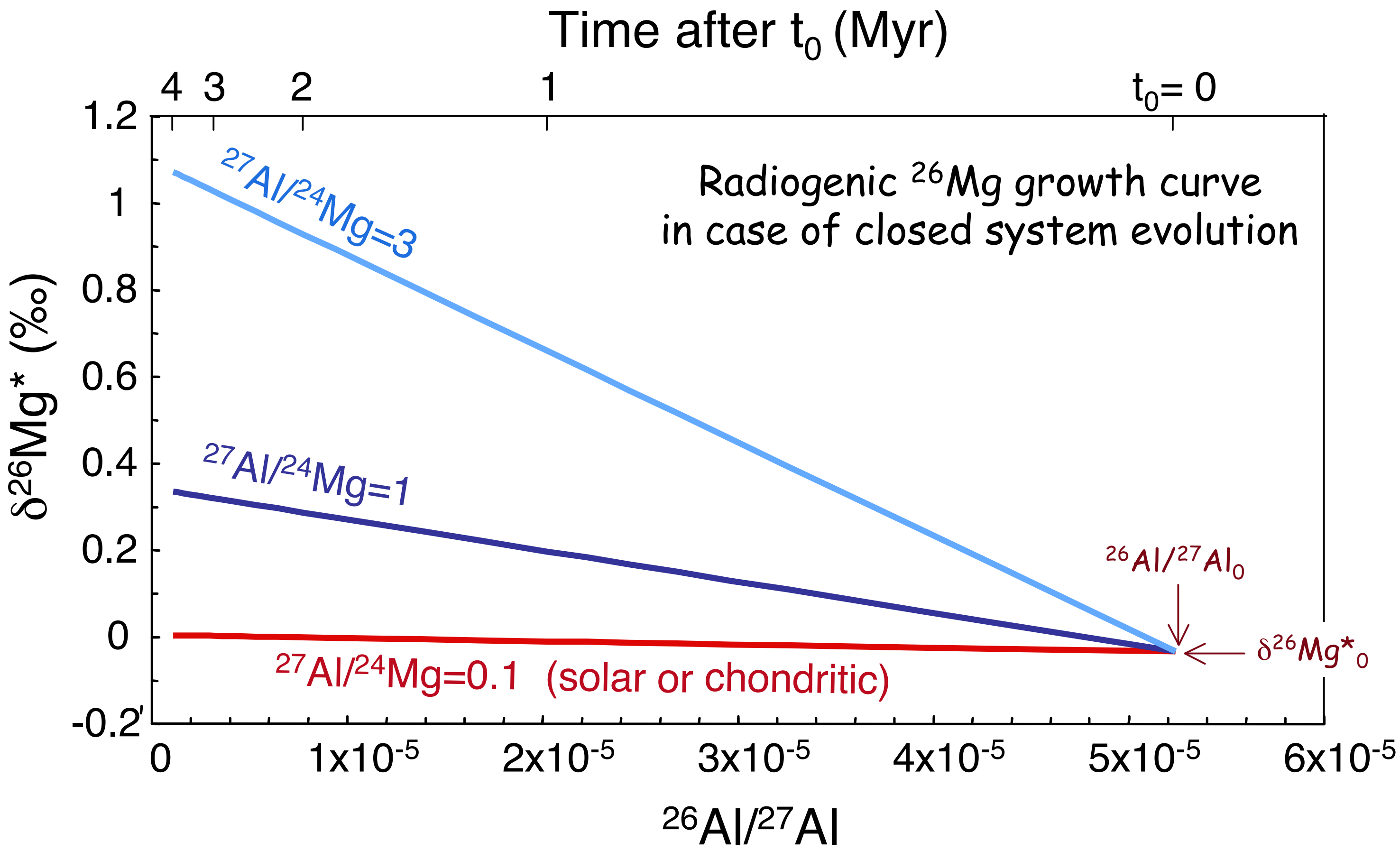
canonic $^{26}Al/^{27}Al$ ratio
of = 4.5×10^{-5}

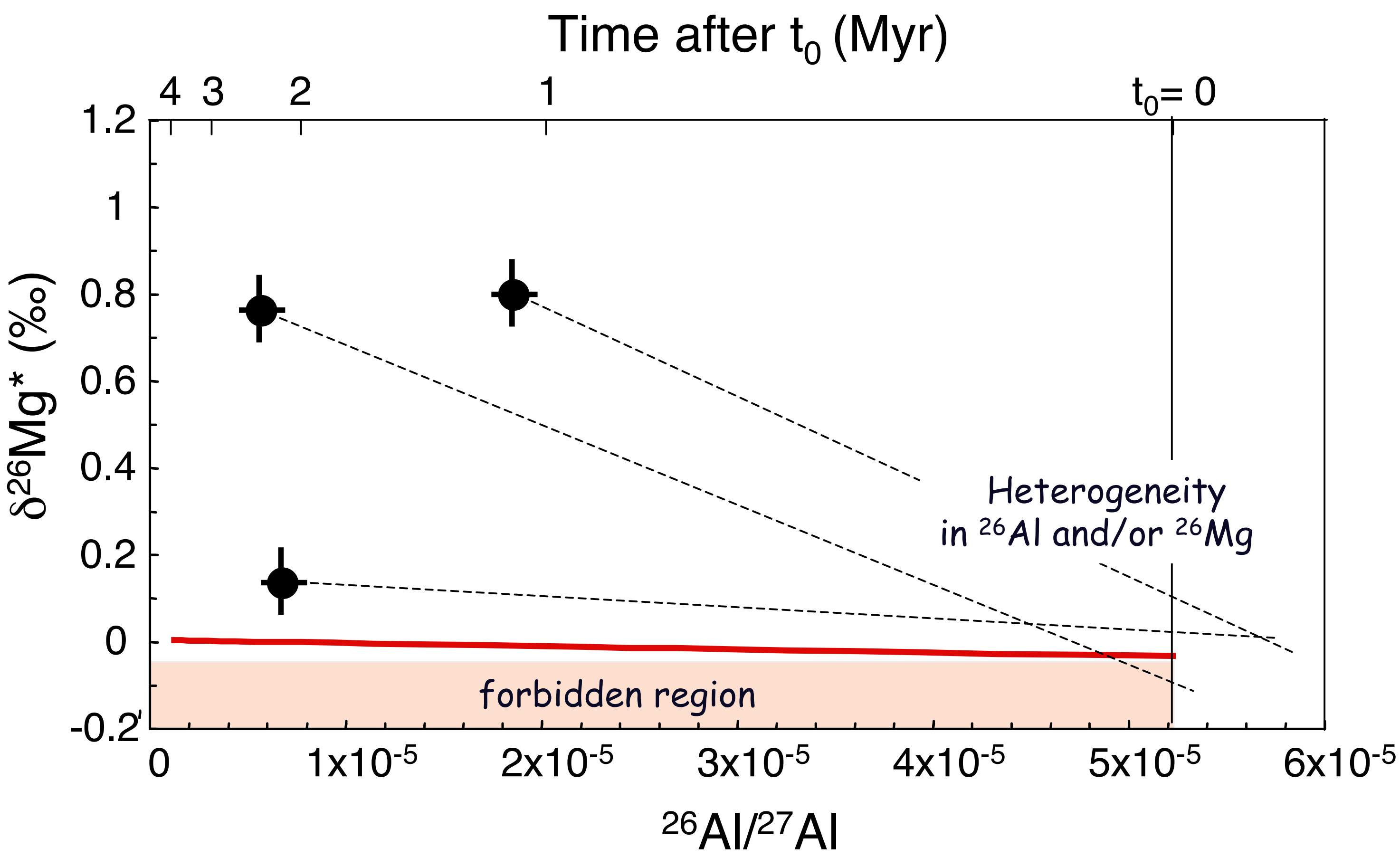


(review by MacPherson et al., 1995)

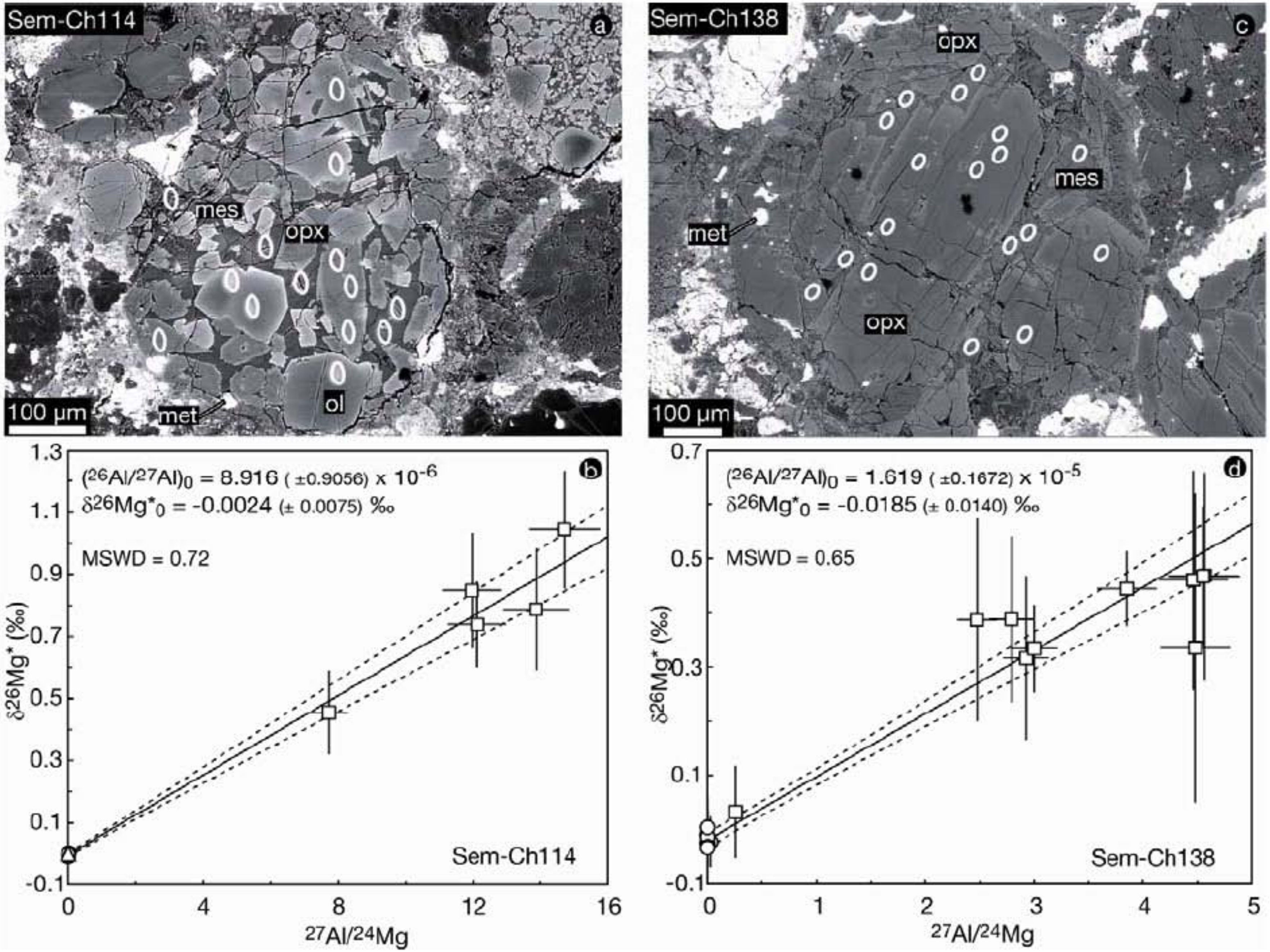
Questions: - what is the meaning of the canonic ratio ?
- what is the meaning of the distribution of $^{26}Al/^{27}Al$ ratios ?

On way to make progress is to compare the $\delta^{26}Mg^*_{initial}$ of different objects with the predictions made from the $^{26}Al/^{27}Al_{initial}$ in case of closed (or open) system evolution of Mg isotopes from a reservoir with a given $\delta^{26}Mg^*_0$ and $^{26}Al/^{27}Al_0$.
(Villeneuve et al., 2009 ; Larsen et al., 2011 ; MacPherson et al., 2012)





Time after t_0 (Myr)
4
3
2
1
t_0= 0
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
δ^{26}Mg* (‰)
Heterogeneity
in ^{26}Al and/or ^{26}Mg
forbidden region
0
1x10^{-5}
2x10^{-5}
3x10^{-5}
4x10^{-5}
5x10^{-5}
6x10^{-5}
^{26}Al/^{27}Al



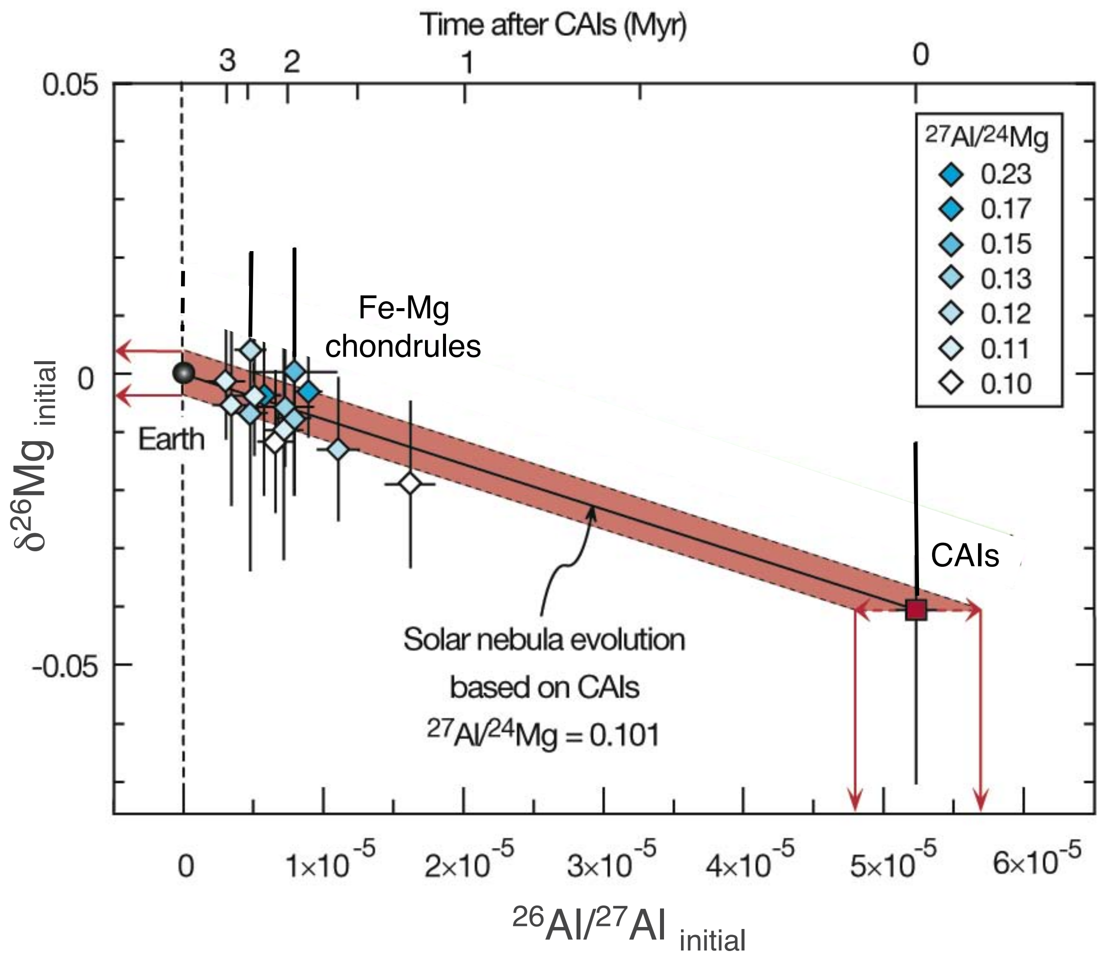
Villeneuve, Chaussidon & Libourel, 2009

The $\delta^{26}Mg^*_{initial}$ and $^{26}Al/^{27}Al_{initial}$ of Semarkona Fe-Mg chondrules are consistent with derivation from $\delta^{26}Mg^*_0$ and $^{26}Al/^{27}Al_0$ established at the time of formation of CAIs,

BUT because Fe-Mg chondrules have $^{27}Al/^{24}Mg$ ratios similar to solar, two scenario:

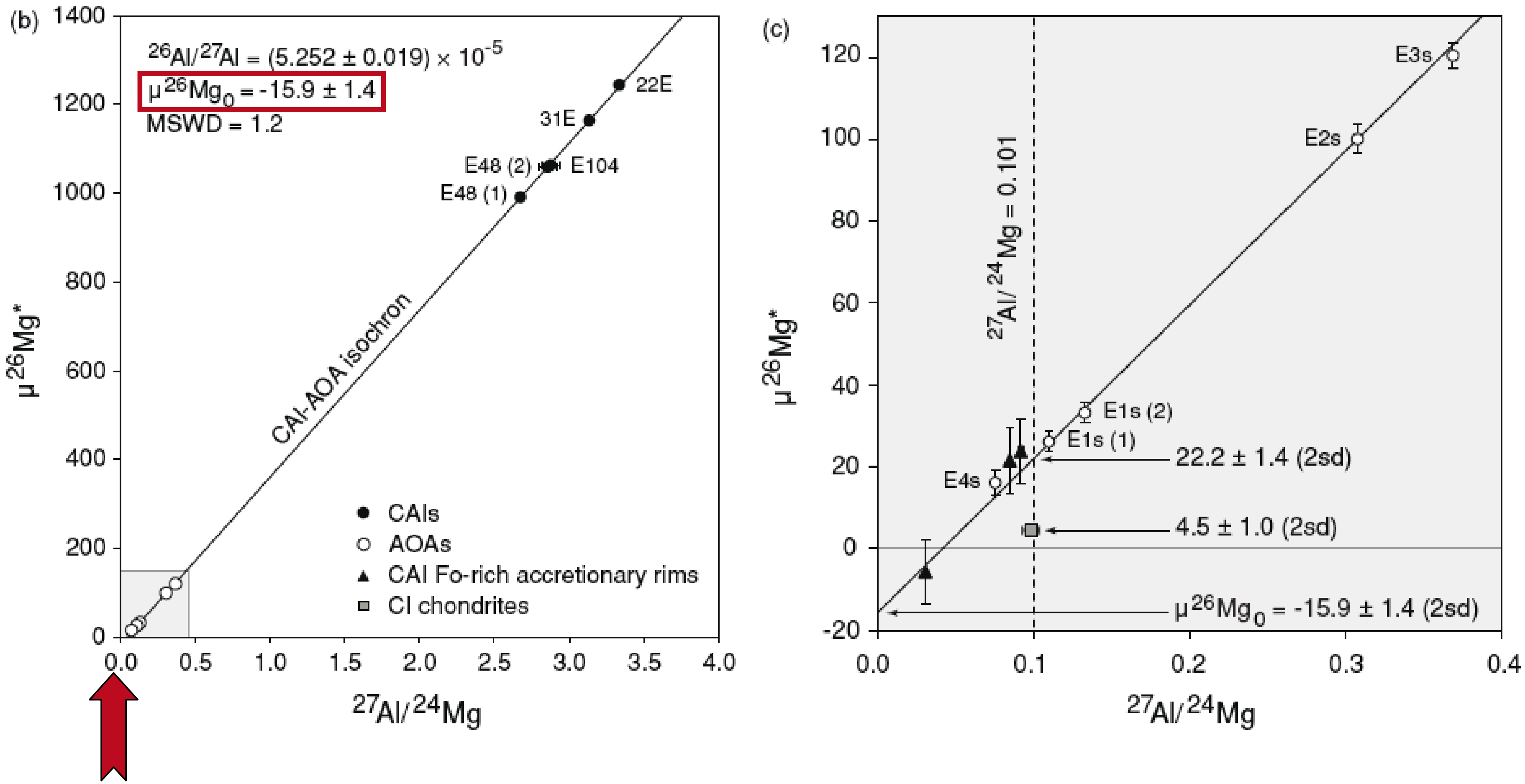
(i) condensation of precursors at t_0 & melting at $t_{initial}$

(ii) nebula gas from t_0 to $t_{initial}$ & condensation of precursors-melting at $t_{initial}$



Villeneuve et al., 2009

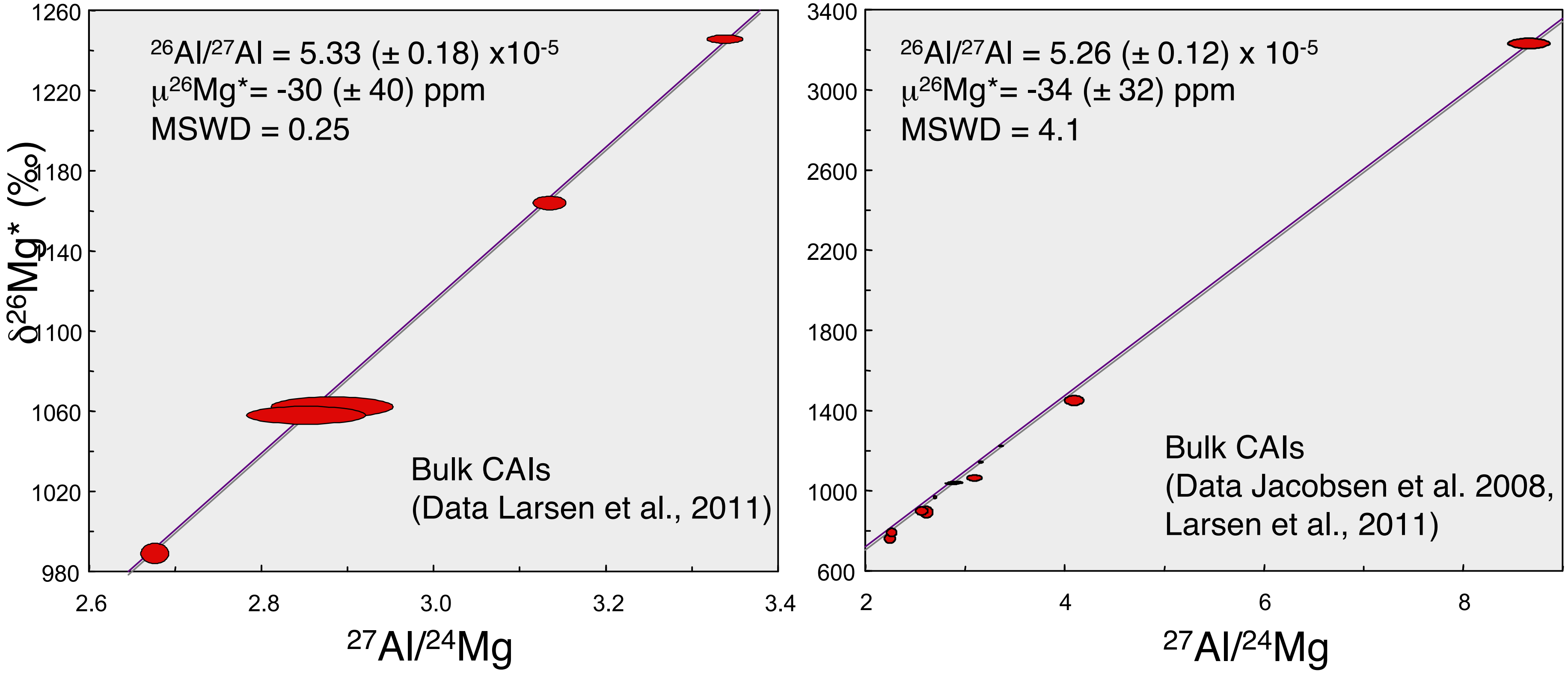
Very high precision Mg isotope work (ppm level, μ^{26}Mg instead of δ^{26}Mg) questions the homogeneity of ^{26}Al and/or Mg isotopes at the time of formation of CAIs



Calculated from CAIs and AOAs (Ameboid Olivine Aggregate) only, assuming that they have exactly the same condensation age and that they originate from the same reservoir

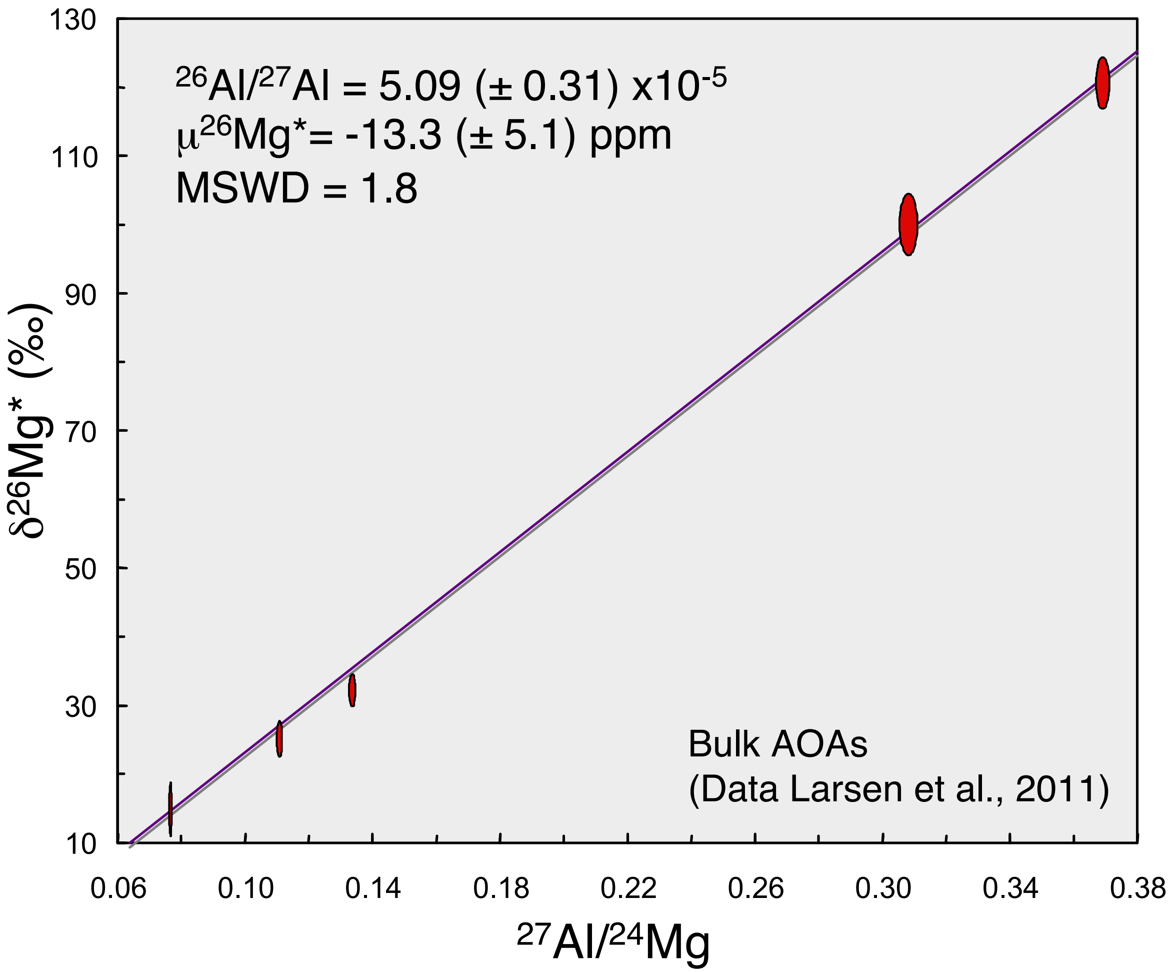
Larsen et al. 2011

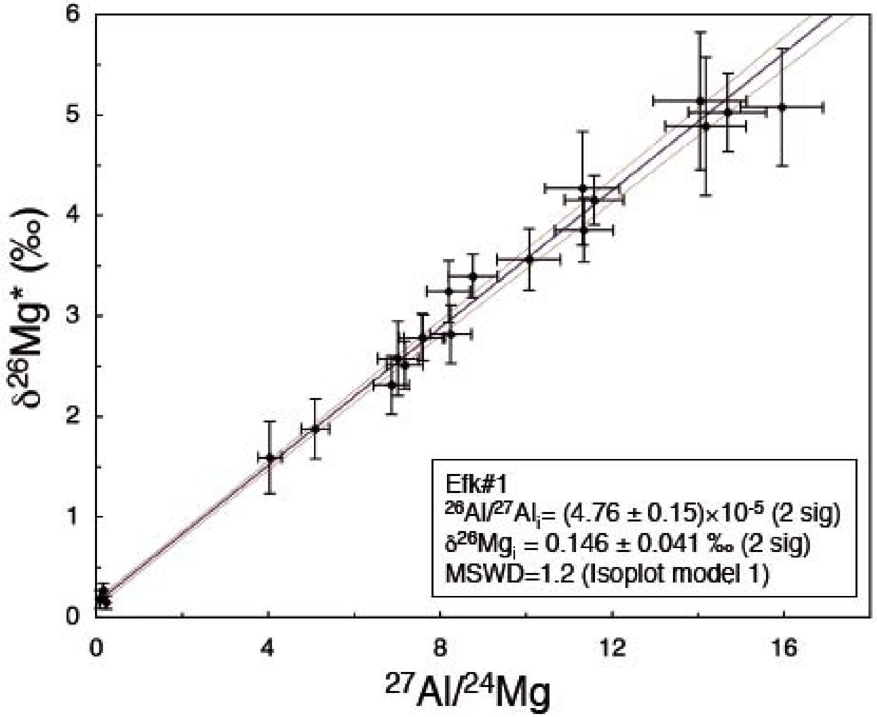
The Larsen et al. data could also be reconciled with previous data in a scenario where ^{26}Al and Mg isotopes are homogenised at ±10% relative ($\mu^{26}Mg_{initial}$ = 40±4 ppm) at the time of type B CAIs from Allende.



In this scenario, formation of AOAs could have taken place later than that of CAIs (≈ 35 000 years later) from a reservoir (refractory in composition) with a $^{27}Al/^{24}Mg \approx 2$.

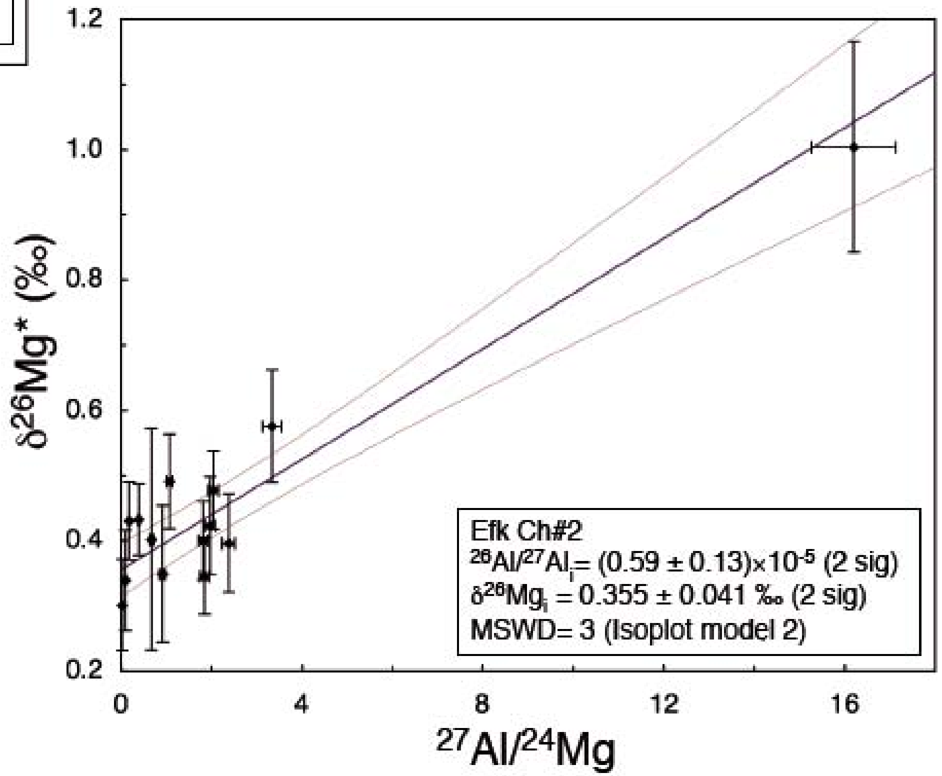
(argument against that : the AOAs are condensate with the same low $\Delta^{17}O$ than the CAIs and they mantle the CAI)





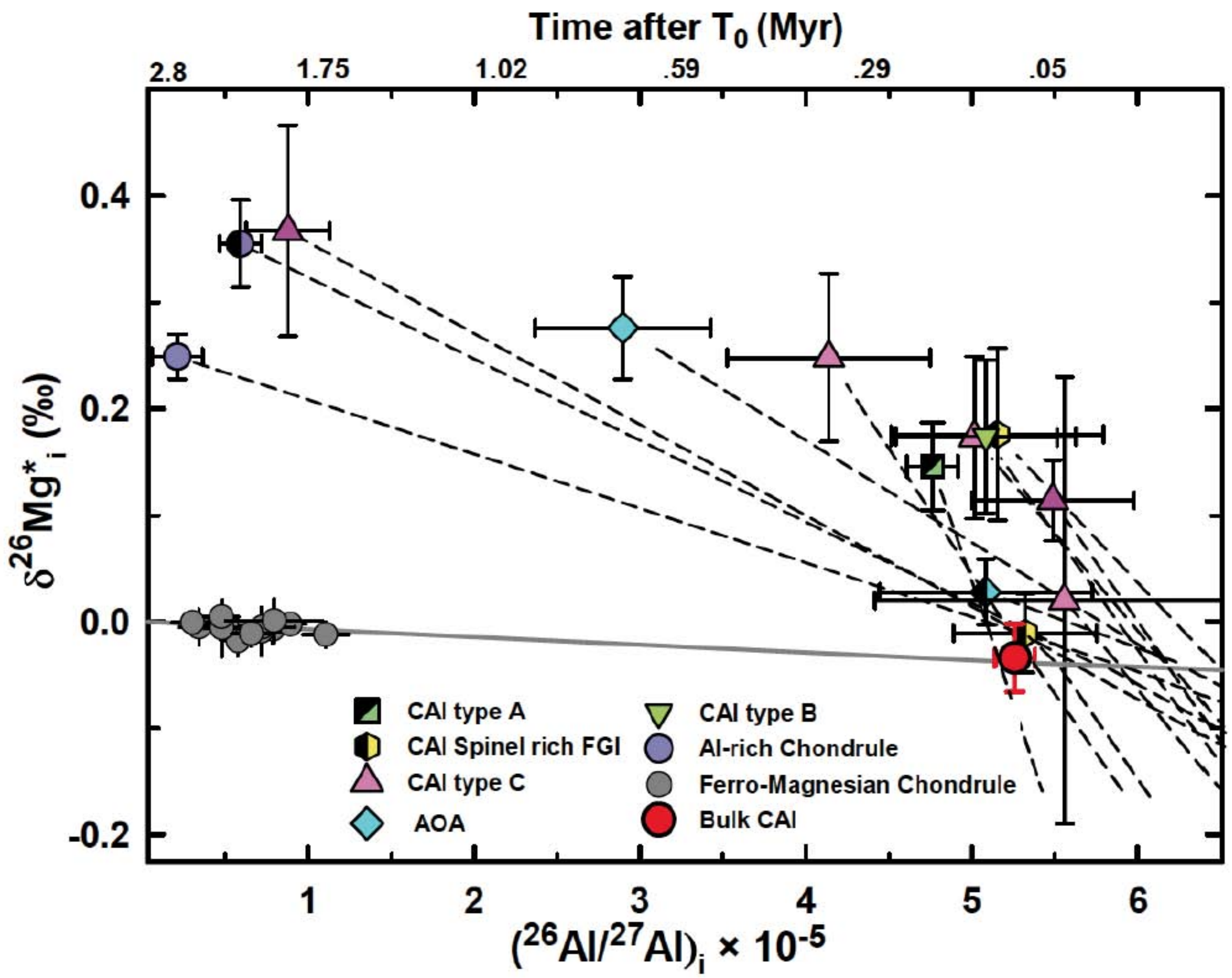
Same approach than for Mg-rih chondrules for 7 CAIs, 2 AOAs and 2 Al-rich chondrules from Vigarano & Efremovka. For each object, the ^{26}Al mineral isochron was determined, as well as its bulk $^{27}Al/^{24}Mg$ ratio, which allowed to calculate:

- the bulk $\delta^{26}Mg^*$ excess
- the radiogenic in-growth of ^{26}Mg (assuming closed system)



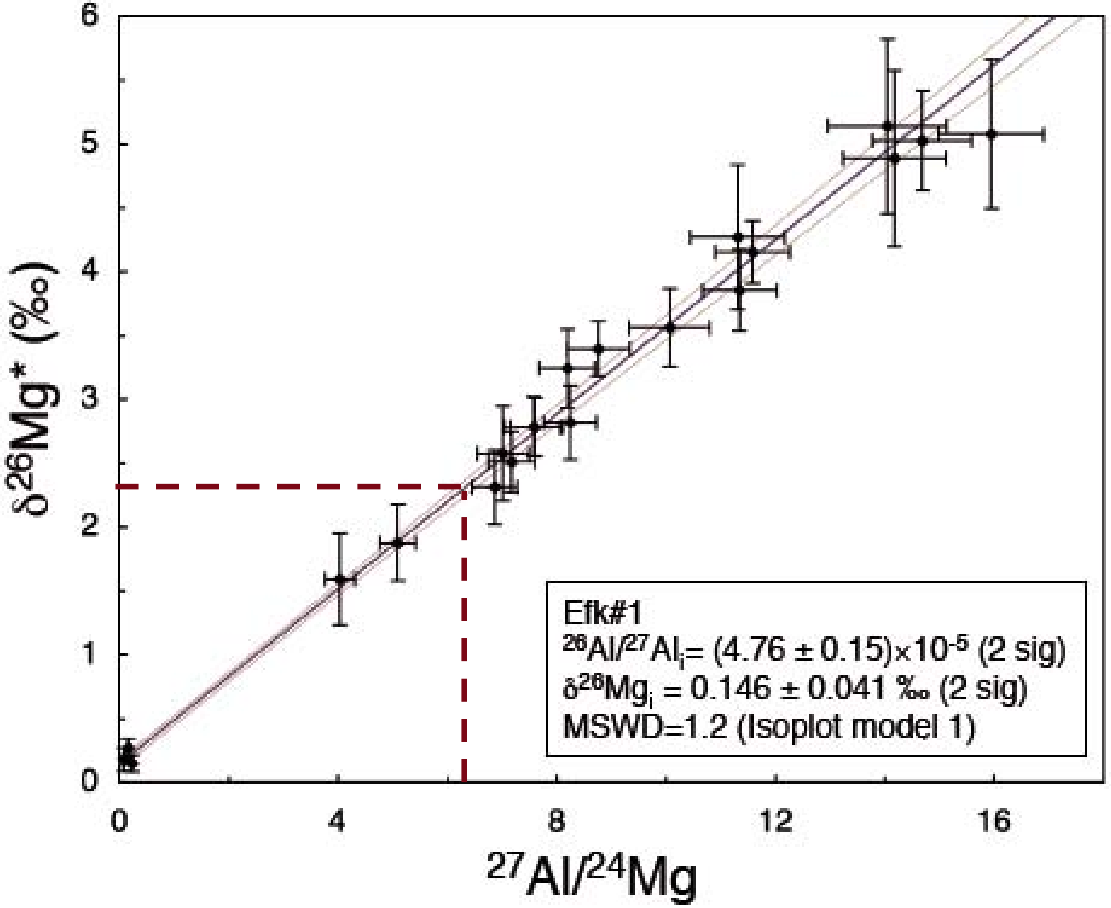
Mishra & Chaussidon (submitted)

All the objects studied have radiogenic ^{26}Al in-growth trajectories which intersect to restricted field



Mishra & Chaussidon (submitted)

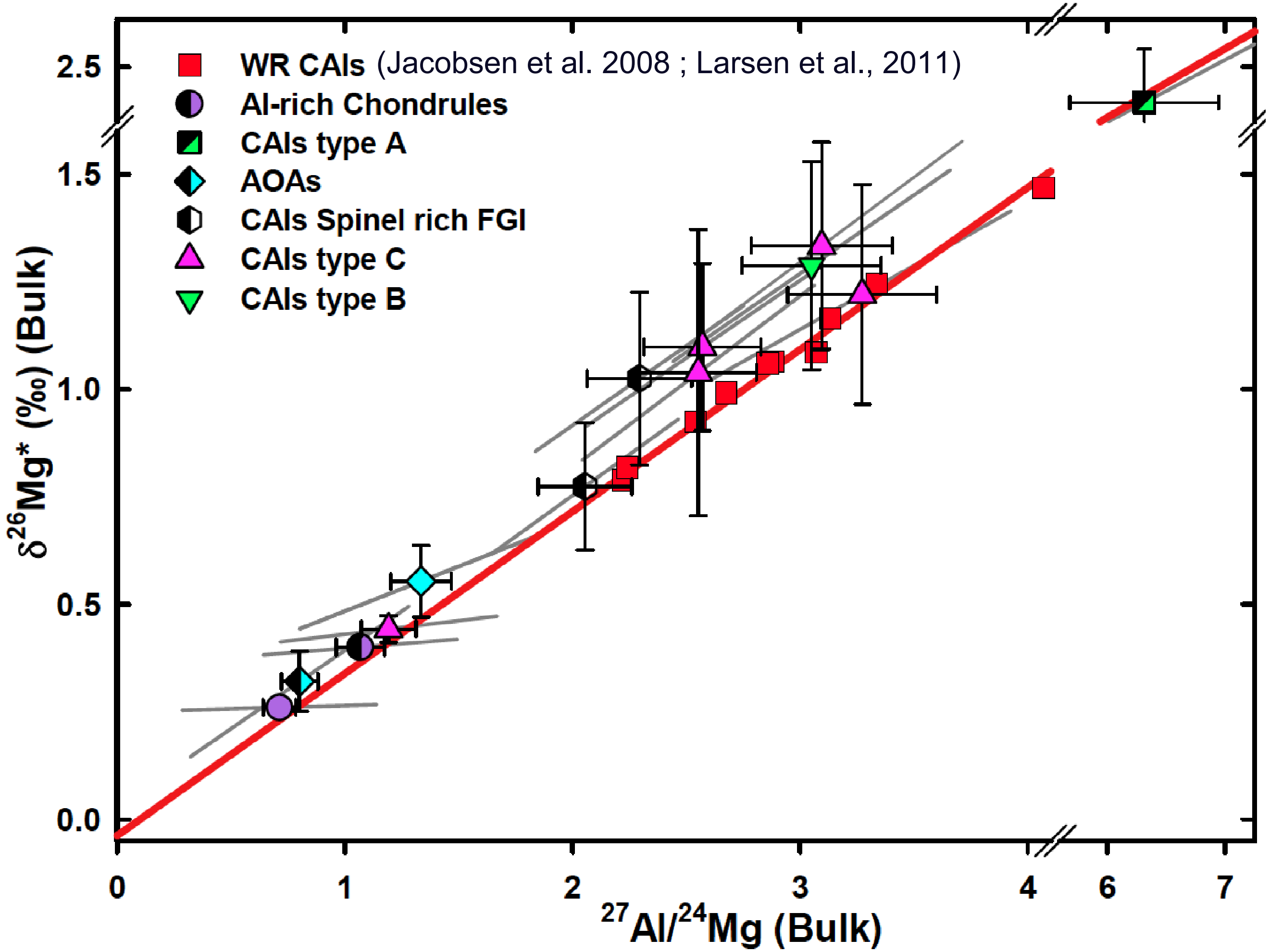
bulk $\delta^{26}Mg^*$
= 2.4‰ (±.15‰)



bulk $^{27}Al/^{24}Mg$
= 6.3 (±10%)

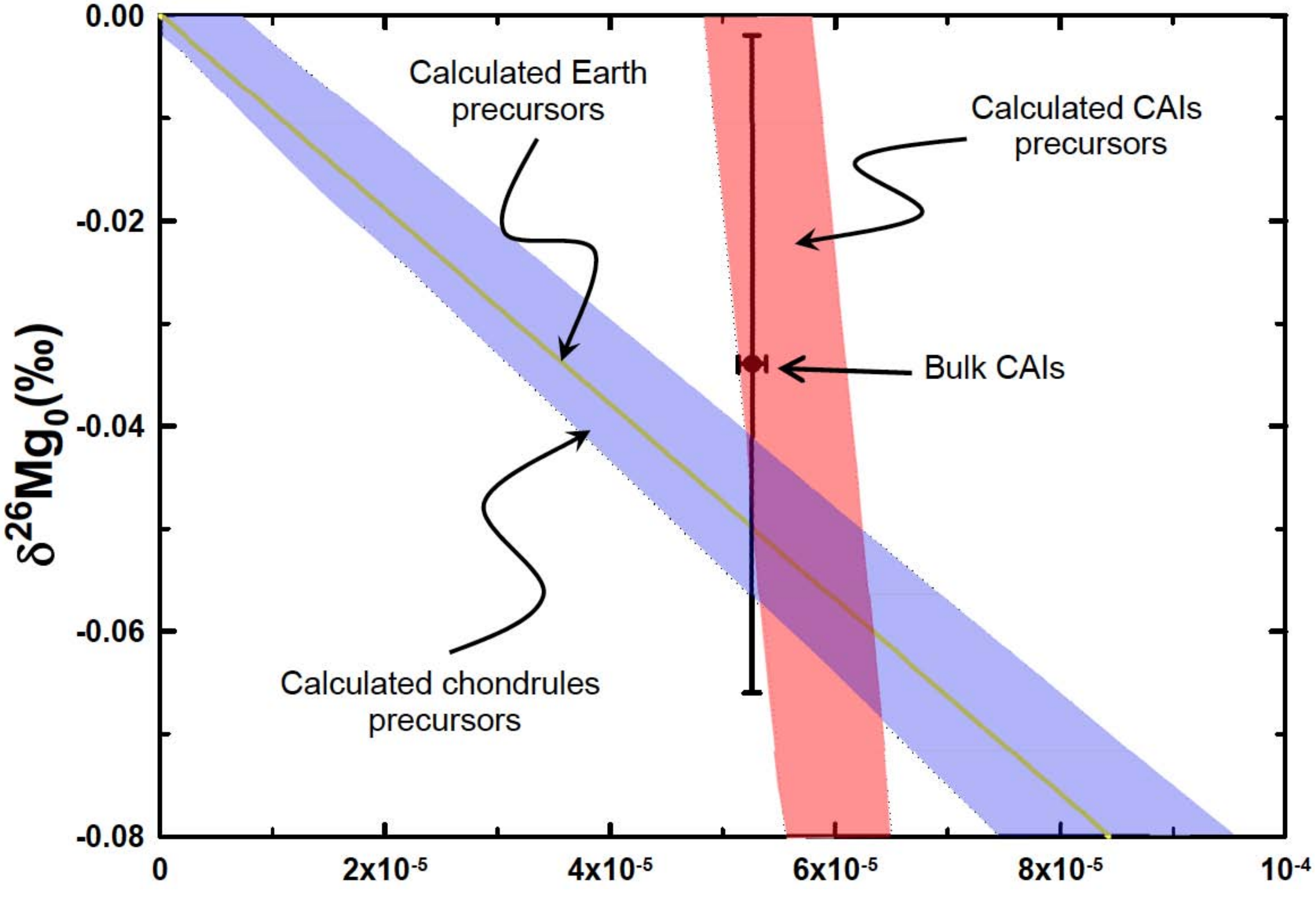
Mishra & Chaussidon (submitted)

Whatever their re-melting age (slope of the mineral isochron) all the objects have reconstructed bulk compositions which fall within errors on the bulk CAI's isochron

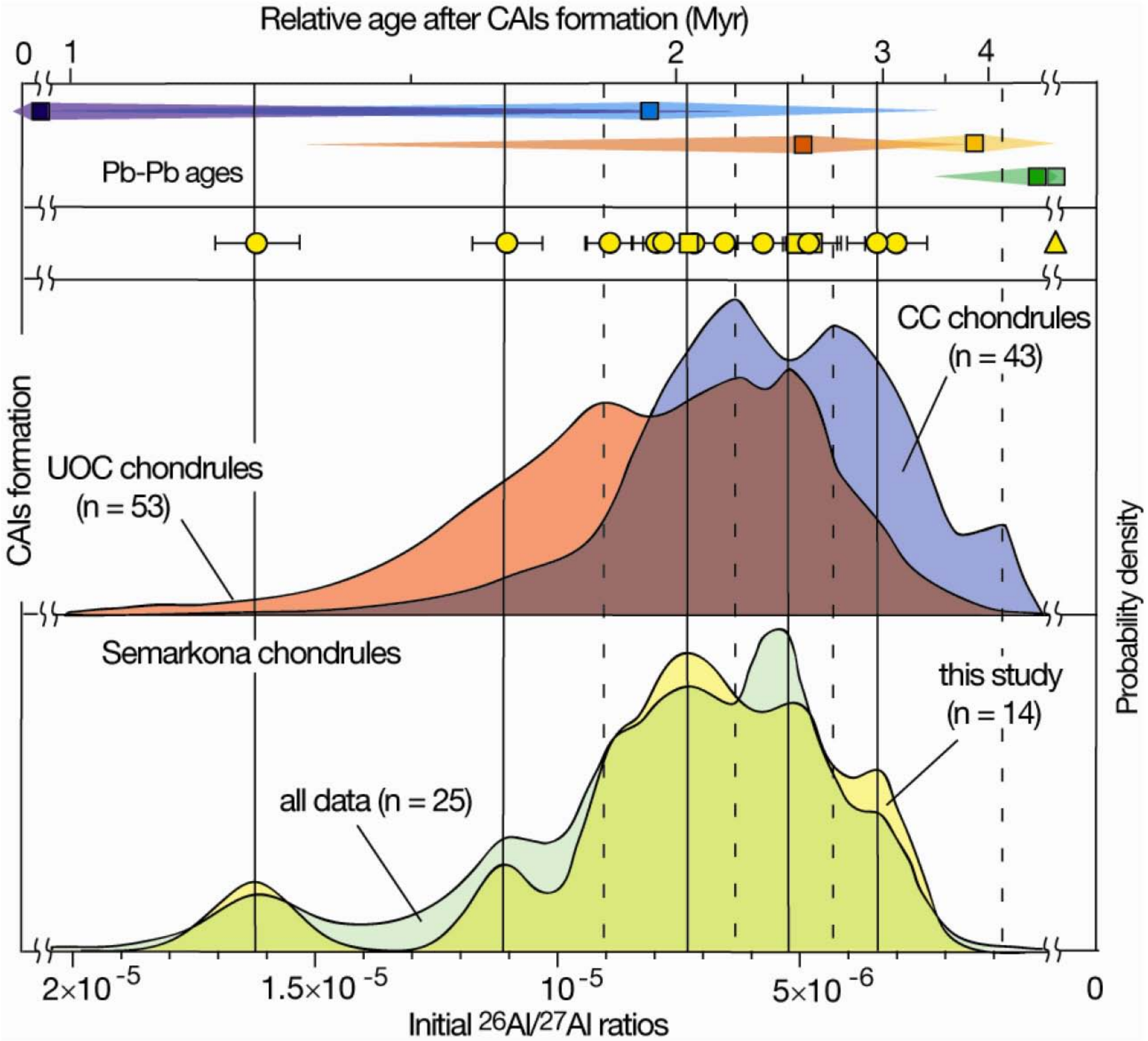


Mishra & Chaussidon (submitted)

Because ferro-magnesian chondrules and refractory objects have very different $^{27}Al/^{24}Mg$ ratios, the composition calculated for their precursors have a well defined intersection

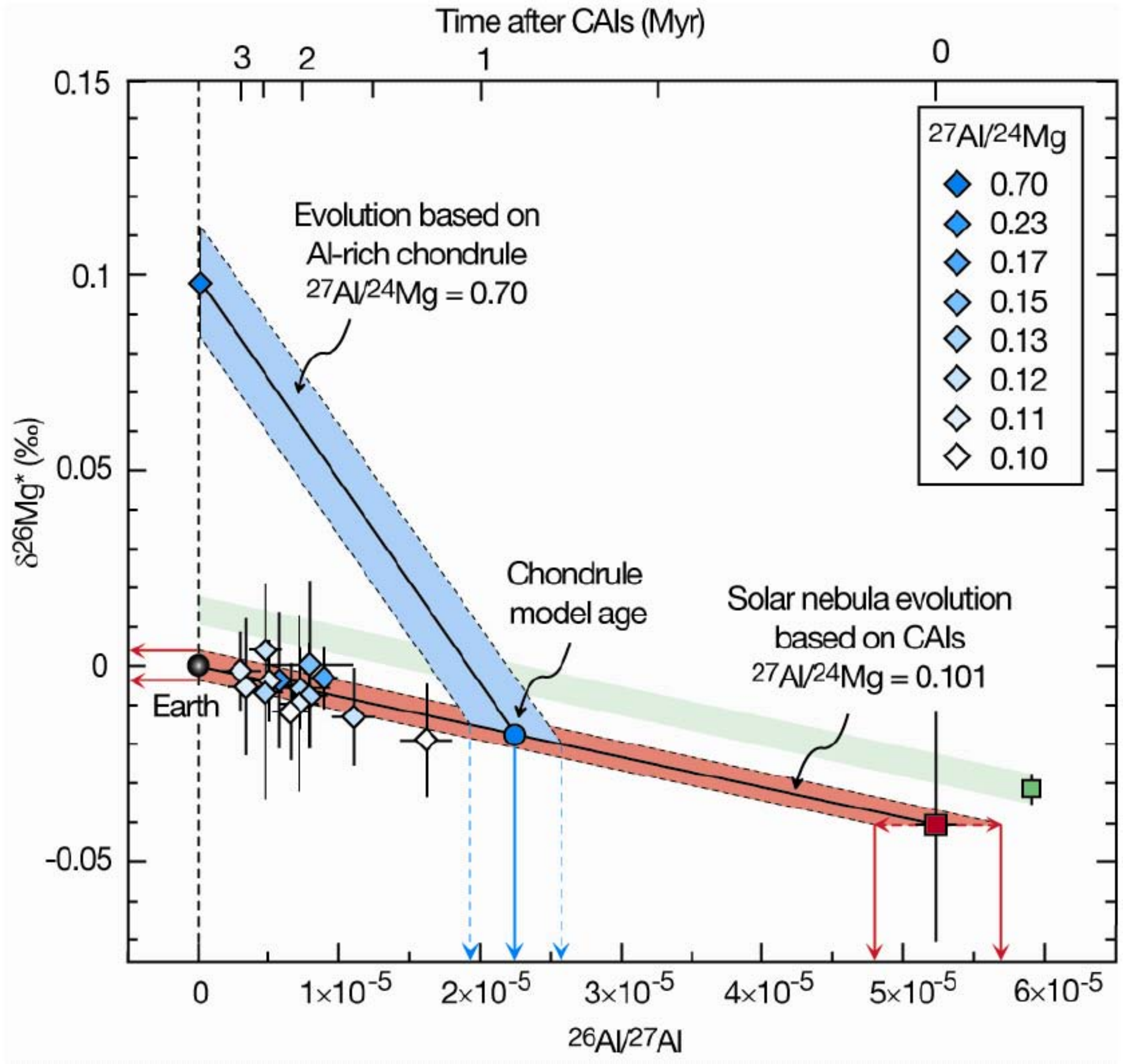


Mishra & Chaussidon (submitted)



Last melting/crystallization of chondrules occurred ≈2-4 Myr after CAIs

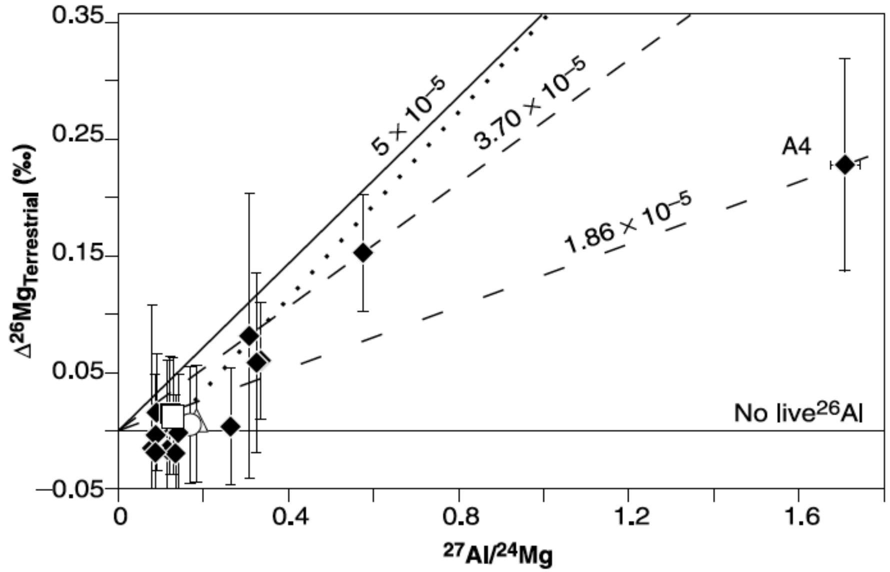
Villeneuve, Chaussidon & Libourel, 2009



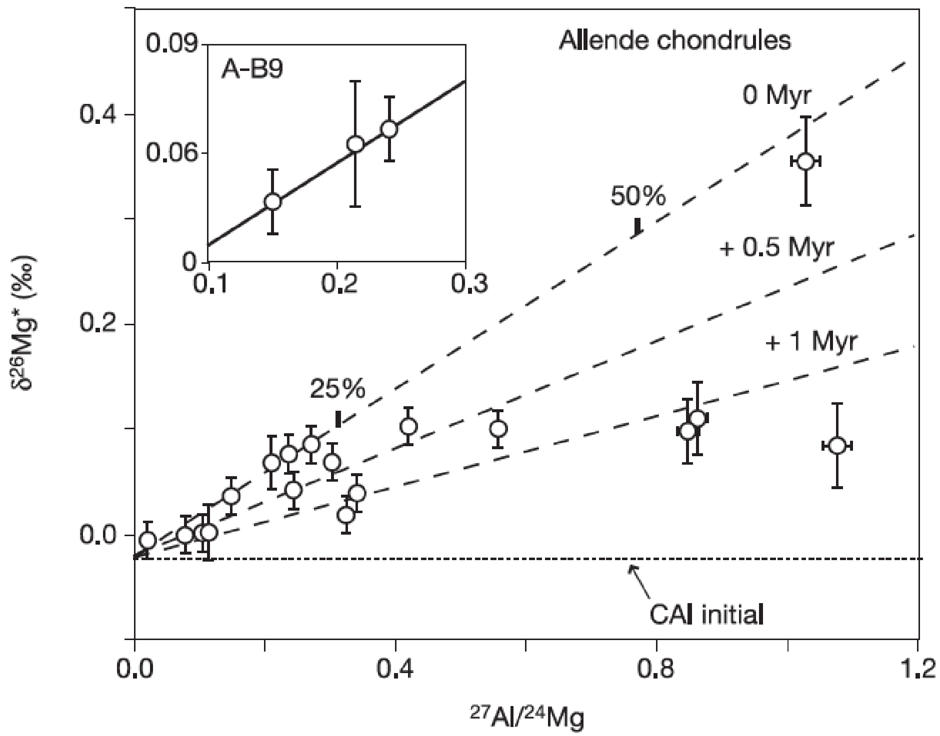
But some chondrules are also much older

Villeneuve, Chaussidon & Libourel, 2009

Bulk $\delta^{26}Mg^*$ of chondrules show that in some cases chondrule precursors may have condensed very early, i. e. contemporaneously to CAIs.

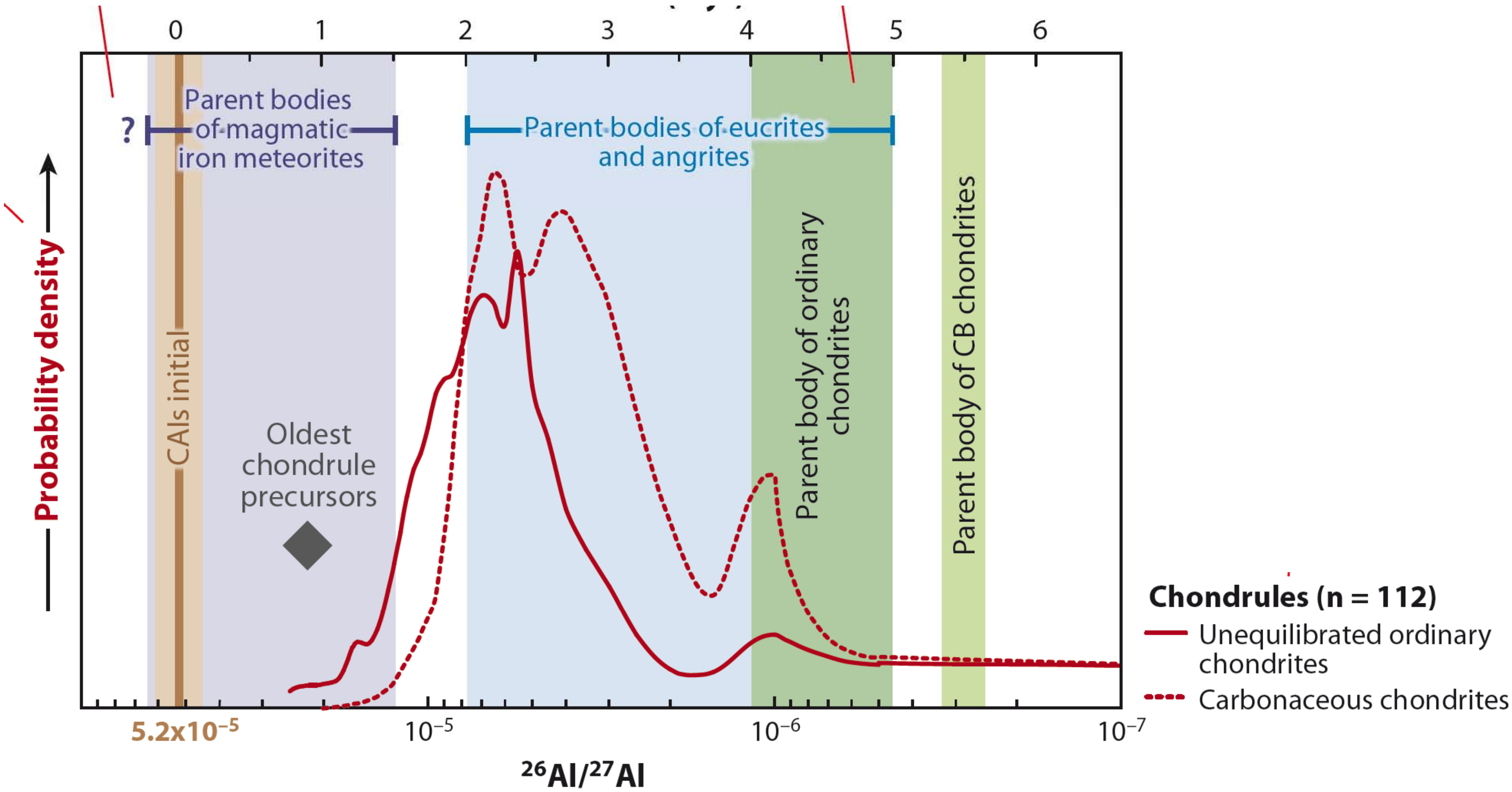


Galy et al., 2000



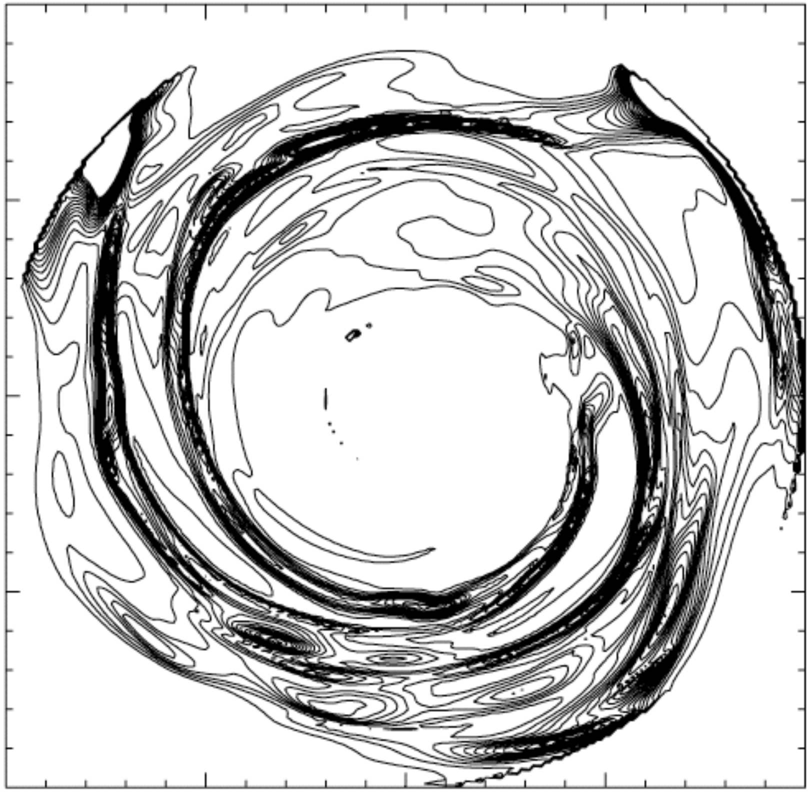
Bizzarro et al., 2004

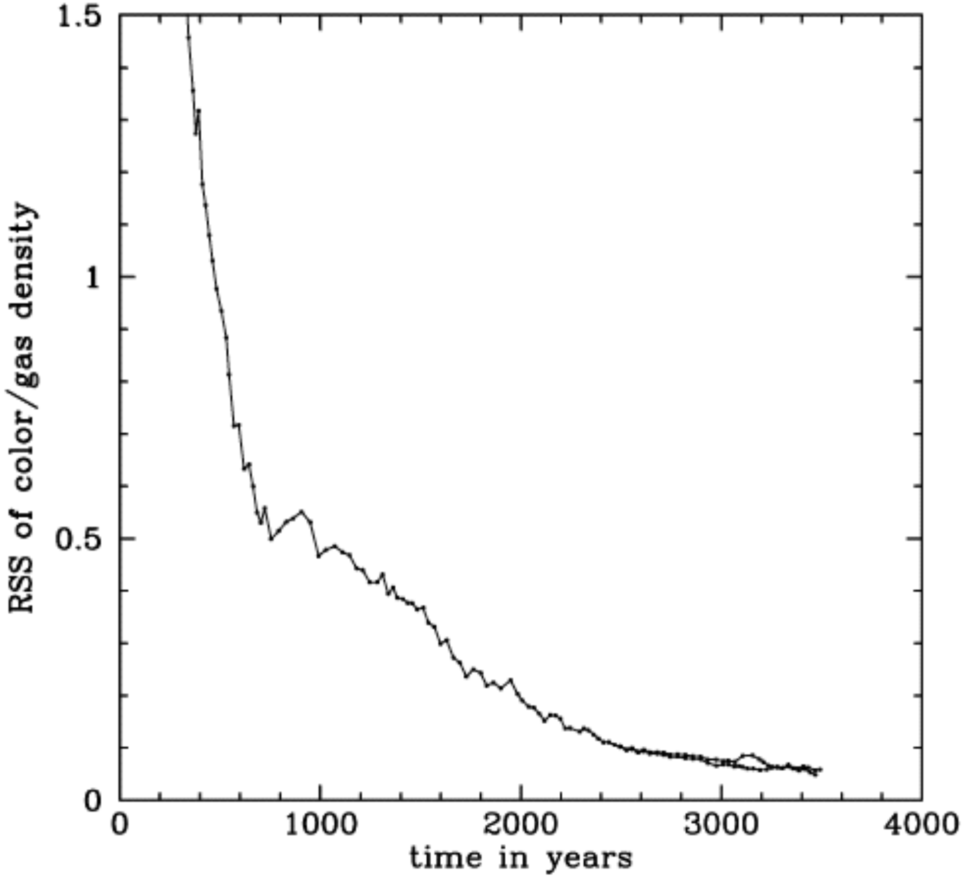
Age of metamorphism of H4 chondrites
Zinner & Göpel 2002



Dauphas & Chaussidon, 2011

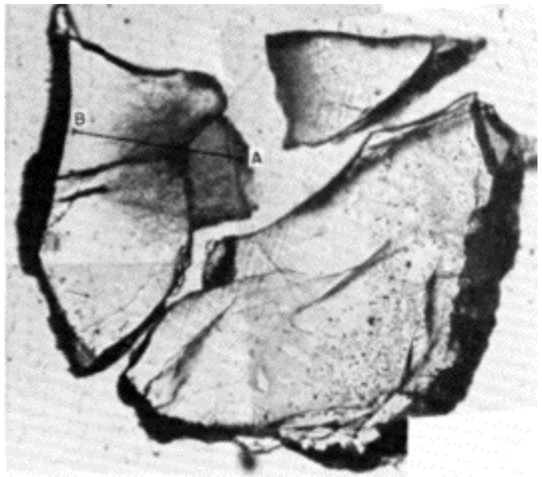
Rapid mixing of supernova products injected in the Solar system (Boss, 2007)





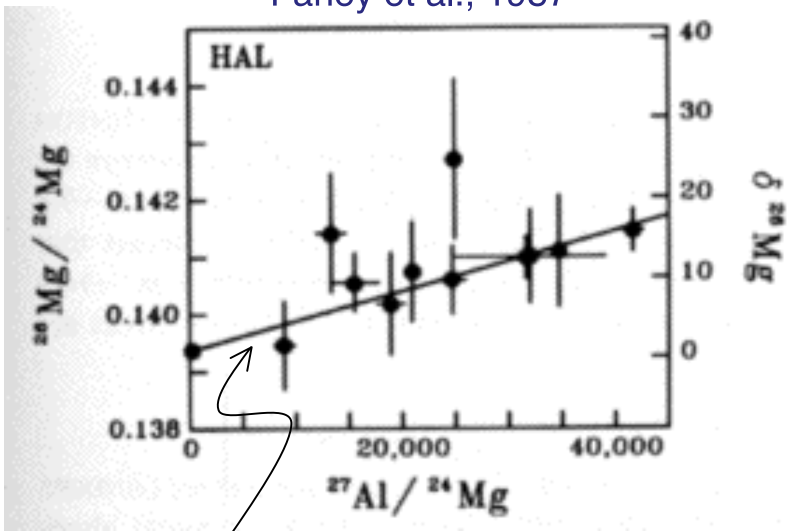
A few ultra-refractory CAIs have no detectable $^{26}Mg^*$
(Fahey et al., 1987 ; Ireland, 1990 ;Weber et al., 1995 ; Sahijpal et al., 2000) :

Formation prior to the introduction of ^{26}Al ?

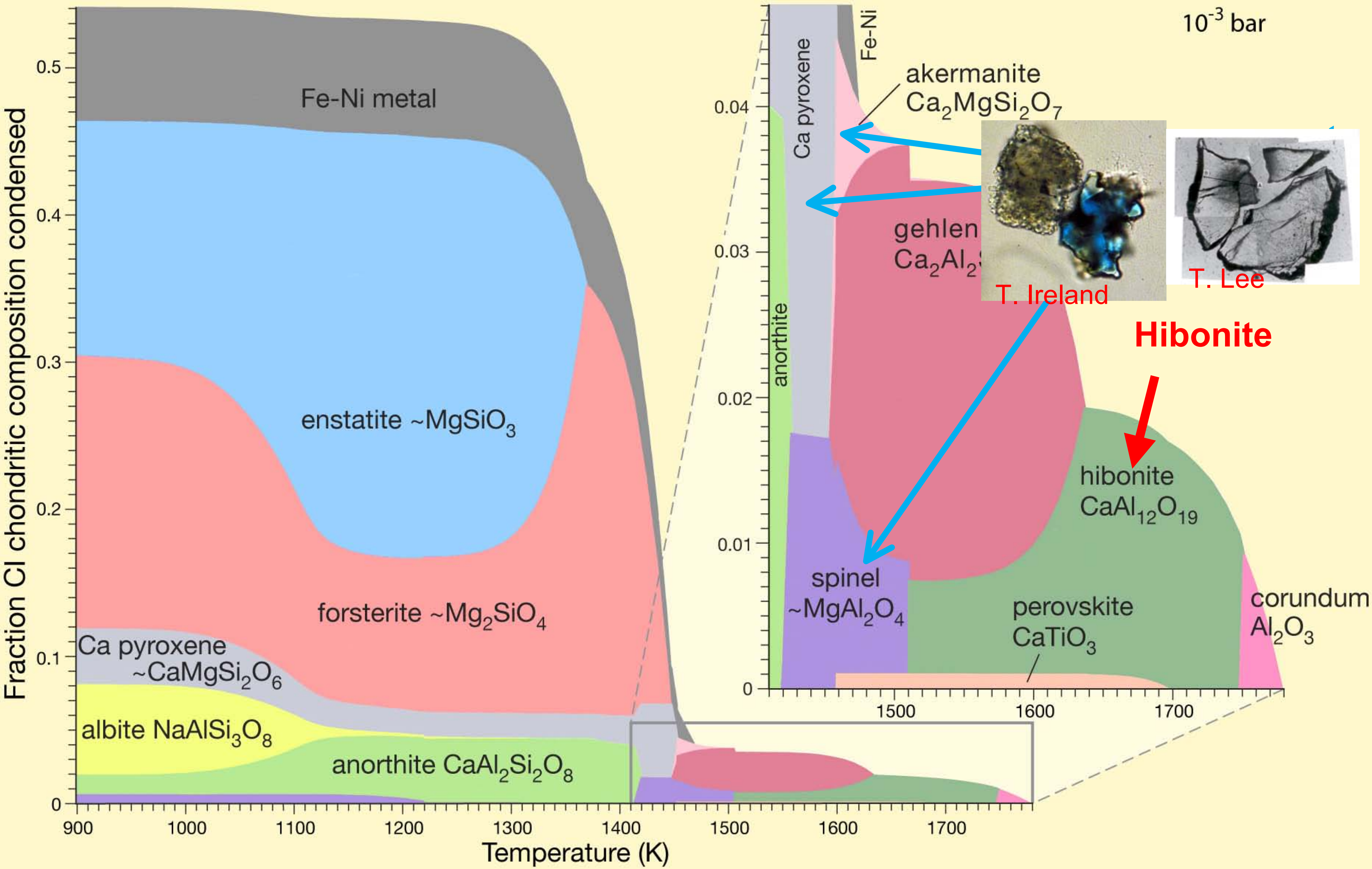


Hibonite-rich CAI named HAL
(Allen et al., 1980)

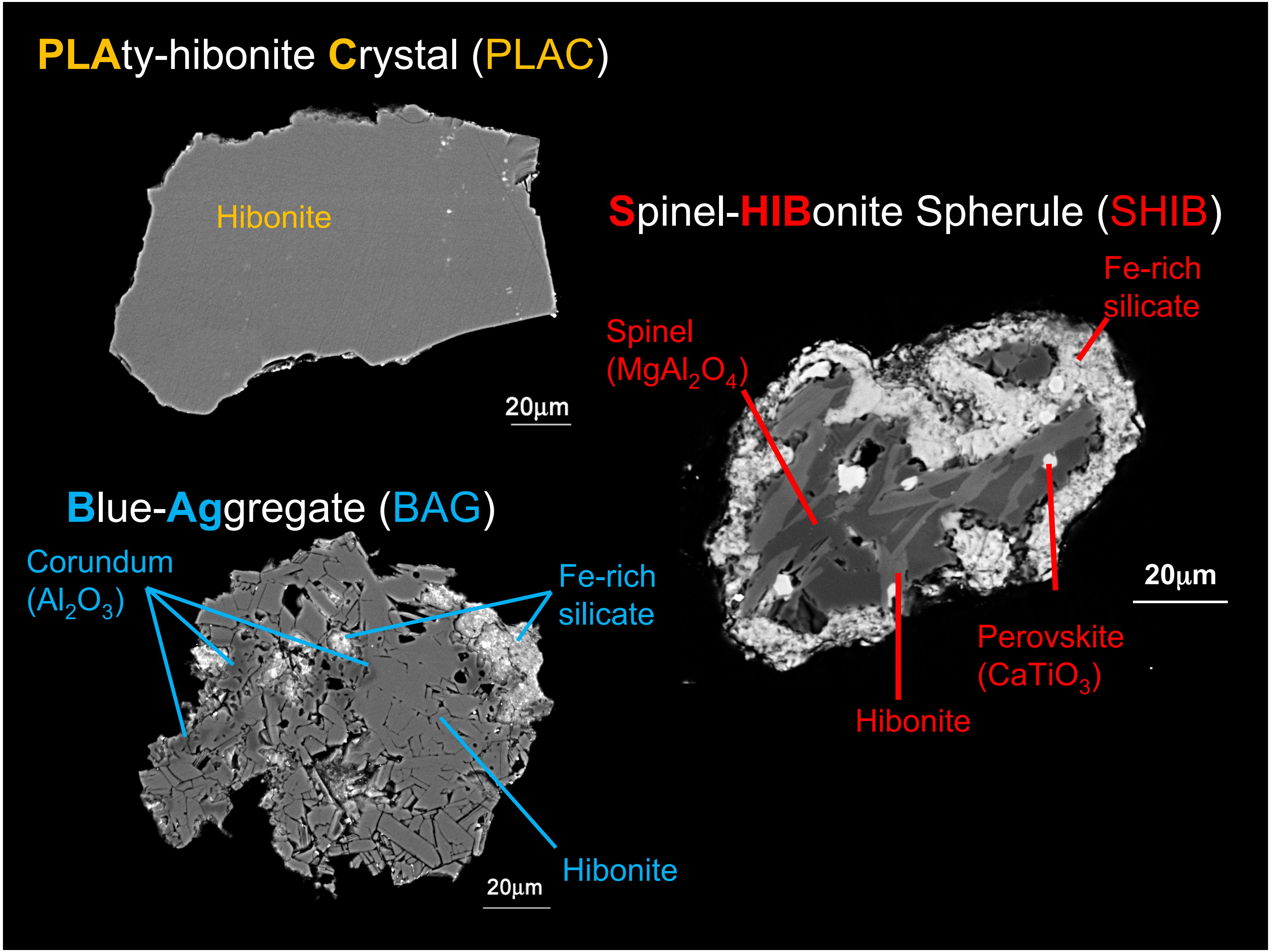
Fahey et al., 1987



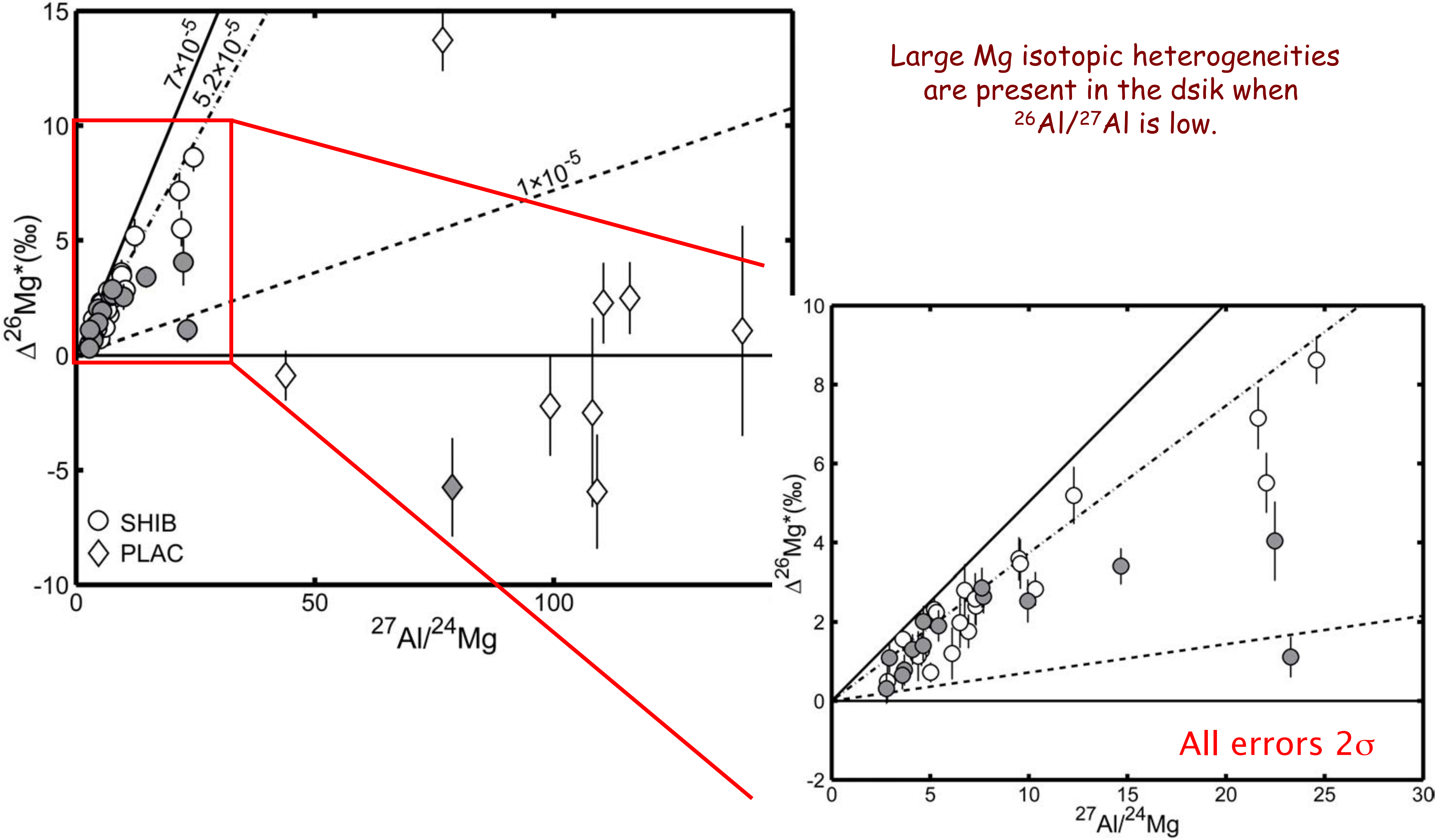
$^{26}Al/^{27}Al = 5.2(\pm 1.7) \times 10^{-8}$
$\delta^{26}Mg^*_0 = +0.3 \pm 2.5‰$



Davis and Richter (2005)


PLAty-hibonite Crystal (PLAC)
Hibonite
20µm
Spinel-HIBonite Spherule (SHIB)
Fe-rich
silicate
Spinel
(MgAl2O4)
20µm
Perovskite
(CaTiO3)
Hibonite
Blue-Aggregate (BAG)
Corundum
(Al2O3)
Fe-rich
silicate
Hibonite
20µm

Mg isotopic compositions of Murchison and Paris hibonites

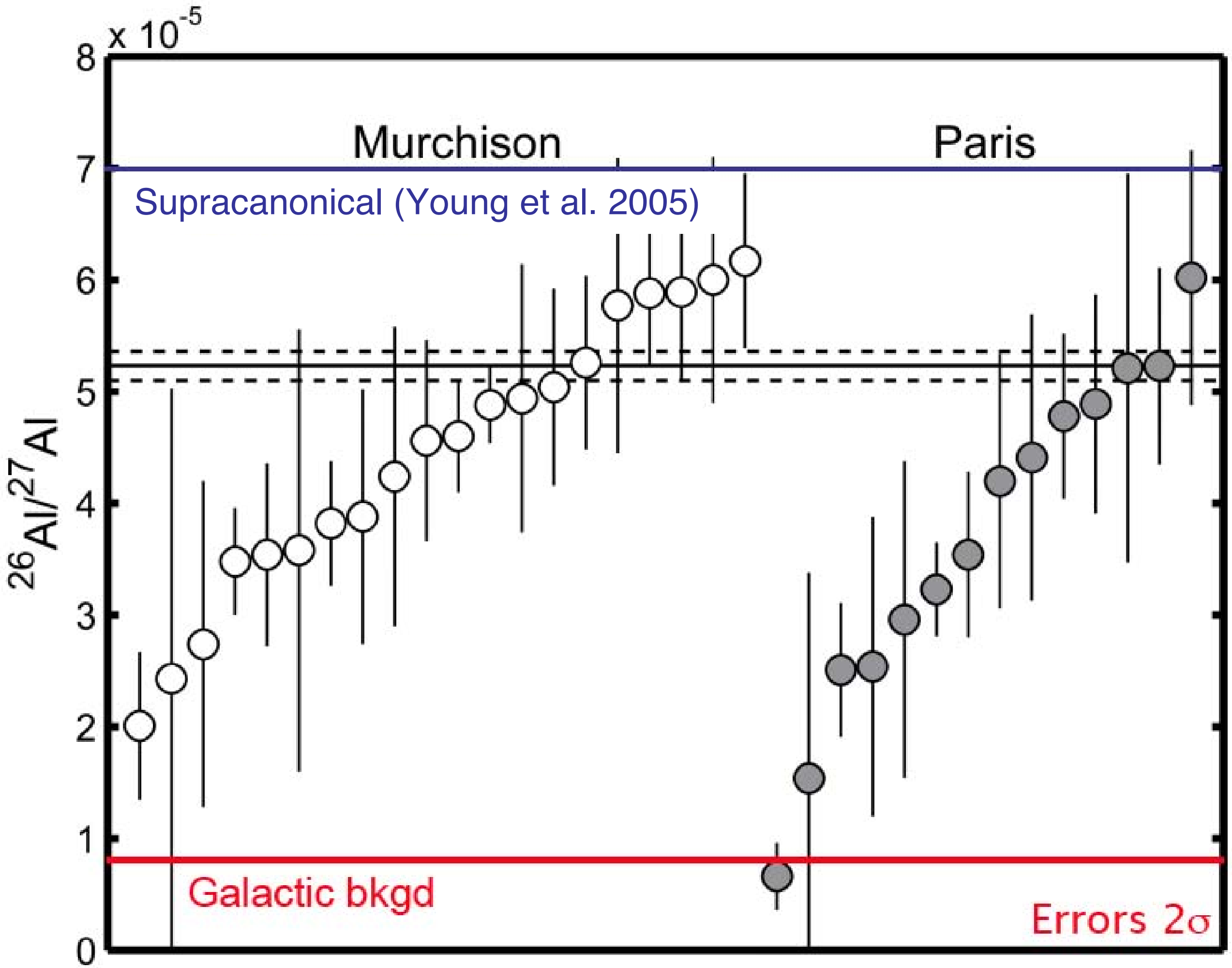


Large Mg isotopic heterogeneities are present in the dsik when $^{26}Al/^{27}Al$ is low.

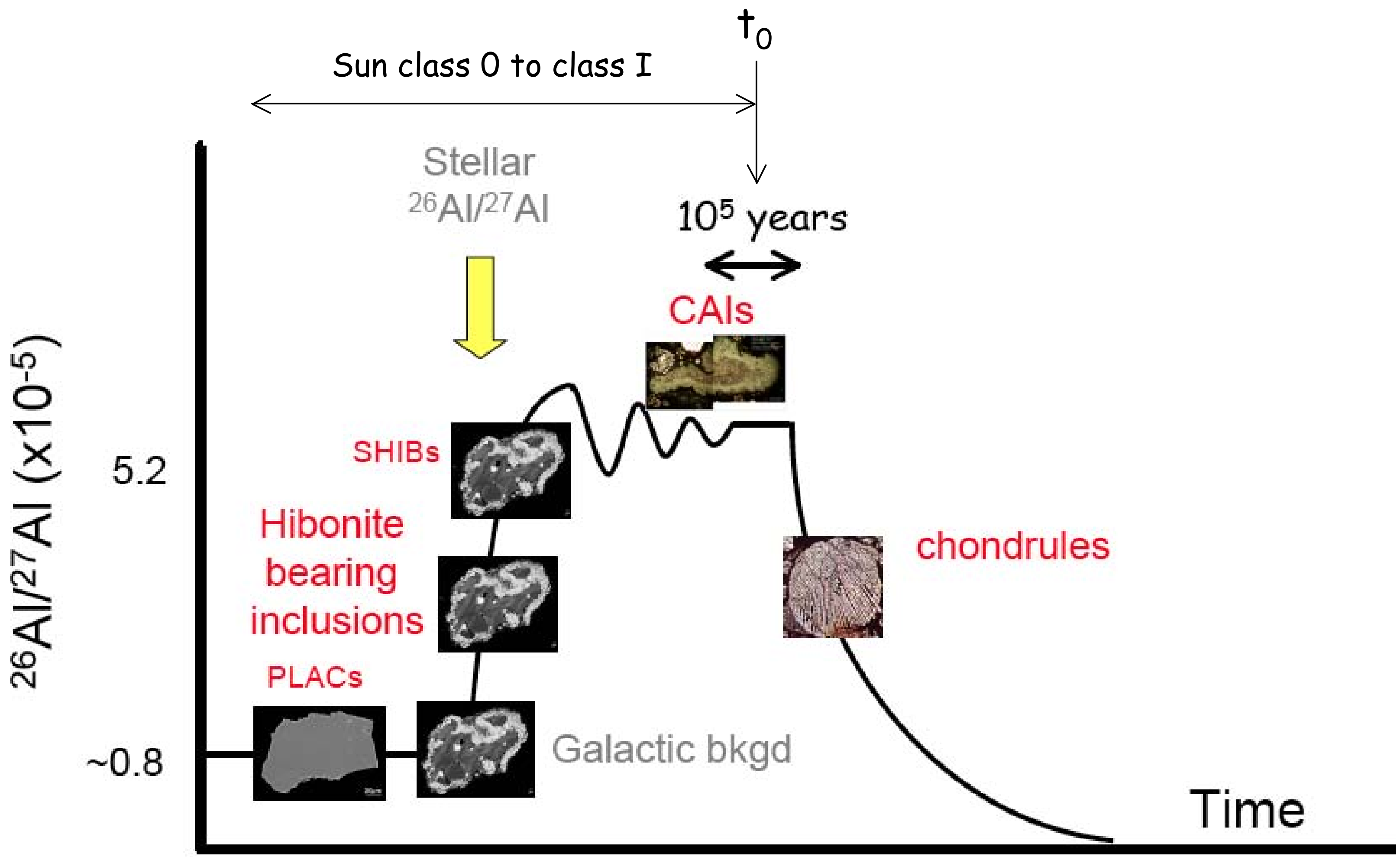
All errors 2σ

Liu, Chaussidon, Gopel & Lee (2012)

$^{26}Al/^{27}Al$ ratios inferred at the time of condensation of hibonites



Liu, Chaussidon, Gopel & Lee (2012)



t0
Sun class 0 to class I
Stellar
26Al/27Al
10^5 years
CAIs
SHIBs
Hibonite bearing inclusions
PLACs
chondrules
Galactic bkgd
26Al/27Al (x10-5)
5.2
~0.8
Time

1) Isotopic dating and its limitation

2) ^{26}Al-^{26}Mg: chronology of formation and evolution of CAIs and chondrules in the disk (caveats, age of chondrites, fragments of protoplanets, …)

3) U-Pb: the absolute age of CAIs and chondrules (consistency or not with ^{26}Al)

4) ^{182}Hf-^{182}W: age of iron meteorites and Mars (last developments since the talk by Bernard Bourdon at les Houches 2009)

Pb-Pb dating

$$^{238}U \rightarrow {}^{206}Pb \quad (T_{1/2} = 4.468 \times 10^9\ y)$$

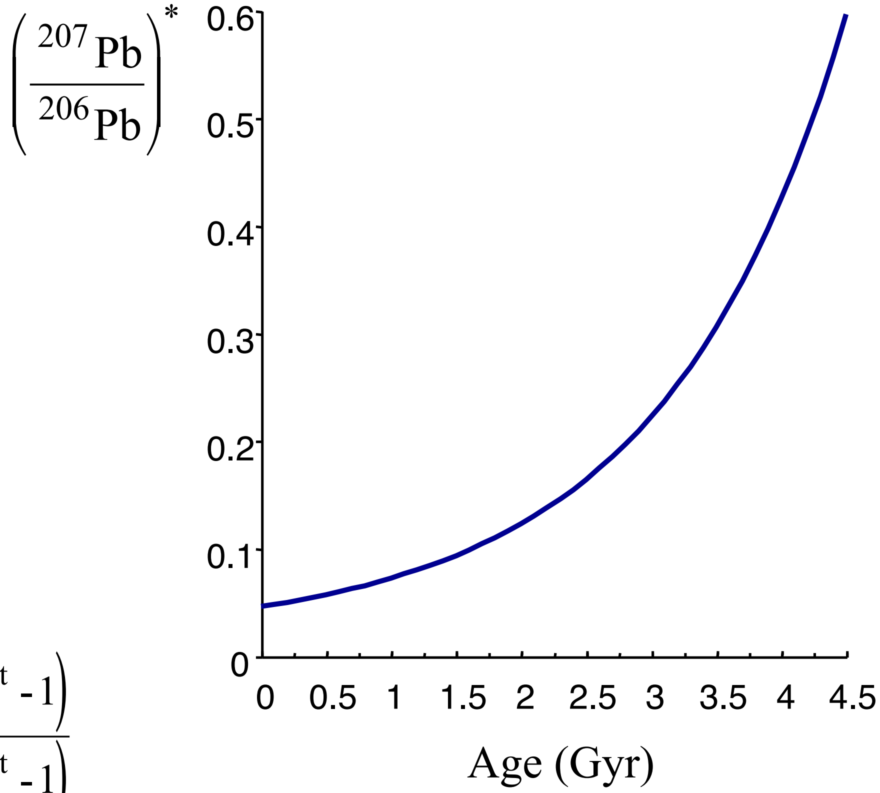
$$\left(\frac{^{206}Pb}{^{204}Pb}\right)_t = \left(\frac{^{206}Pb}{^{204}Pb}\right)_0 + \left(\frac{^{238}U}{^{204}Pb}\right)_t \times \left(e^{\lambda_{238} \times t} - 1\right)$$

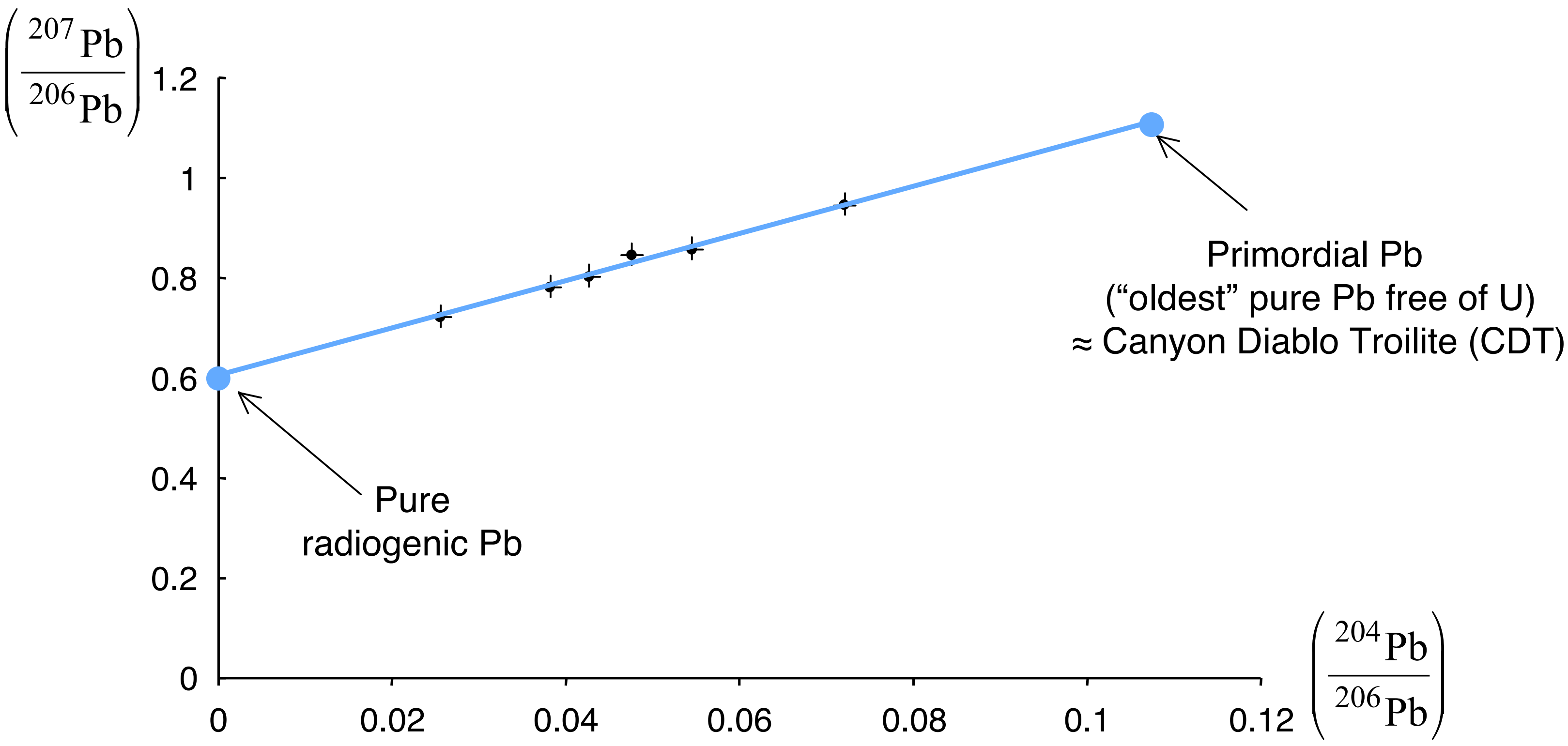
$$^{235}U \rightarrow {}^{207}Pb \quad (T_{1/2} = 0.7038 \times 10^9\ y)$$

$$\left(\frac{^{207}Pb}{^{204}Pb}\right)_t = \left(\frac{^{207}Pb}{^{204}Pb}\right)_0 + \left(\frac{^{235}U}{^{204}Pb}\right)_t \times \left(e^{\lambda_{235} \times t} - 1\right)$$

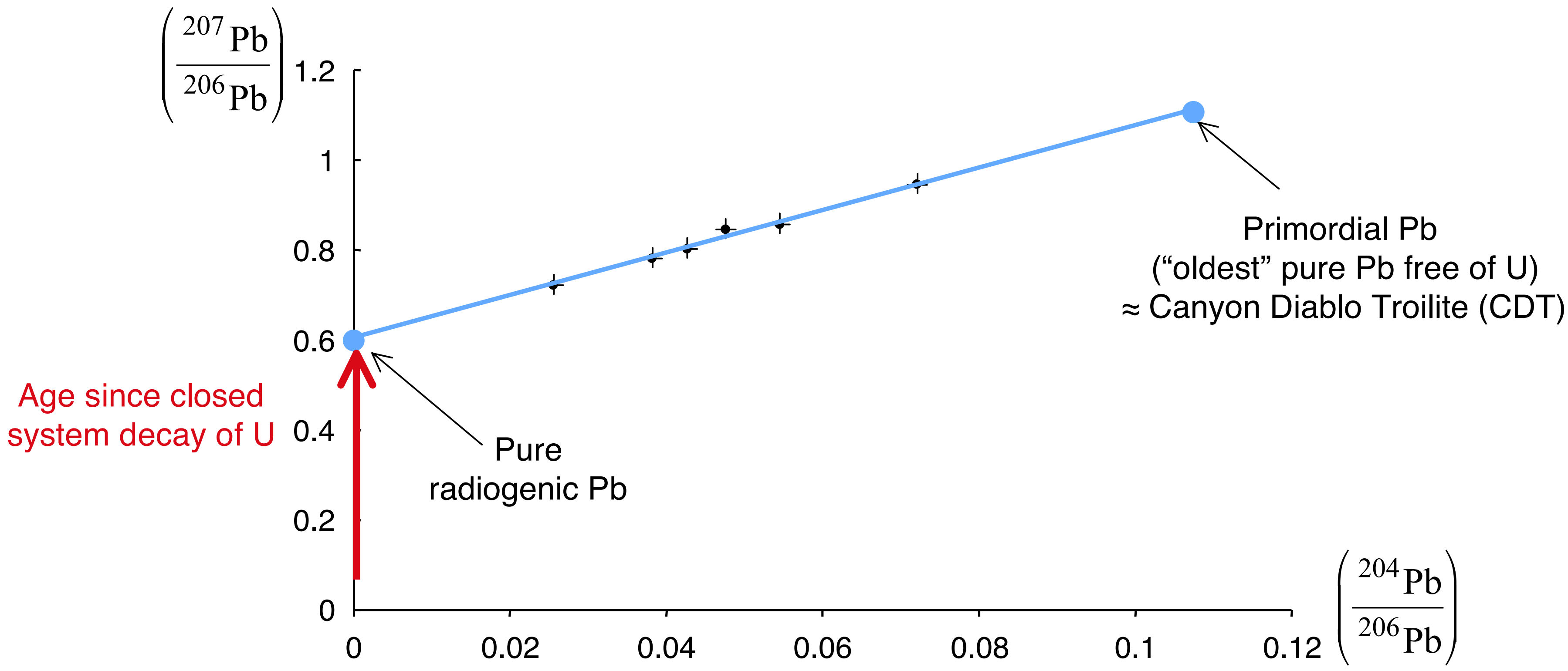
$$\left(\frac{^{207}Pb}{^{206}Pb}\right)^* = \frac{\left(\frac{^{207}Pb}{^{204}Pb}\right)_t - \left(\frac{^{207}Pb}{^{204}Pb}\right)_0}{\left(\frac{^{206}Pb}{^{204}Pb}\right)_t - \left(\frac{^{206}Pb}{^{204}Pb}\right)_0} = \left(\frac{^{235}U}{^{238}U}\right)_t \times \frac{\left(e^{\lambda_{235} \times t} - 1\right)}{\left(e^{\lambda_{238} \times t} - 1\right)}$$

today $\left(\frac{^{235}U}{^{238}U}\right) = \frac{1}{137.88}$

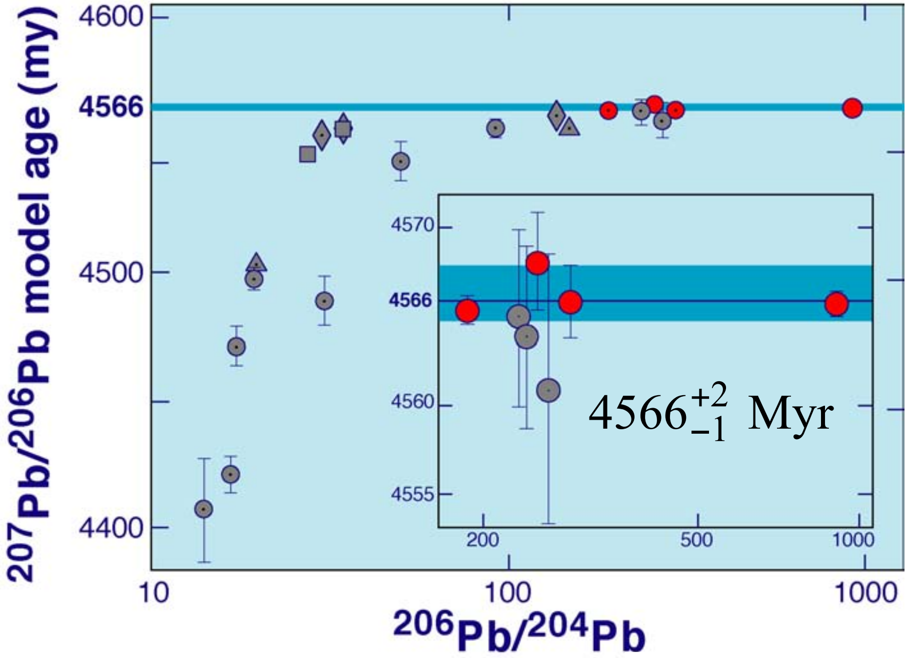




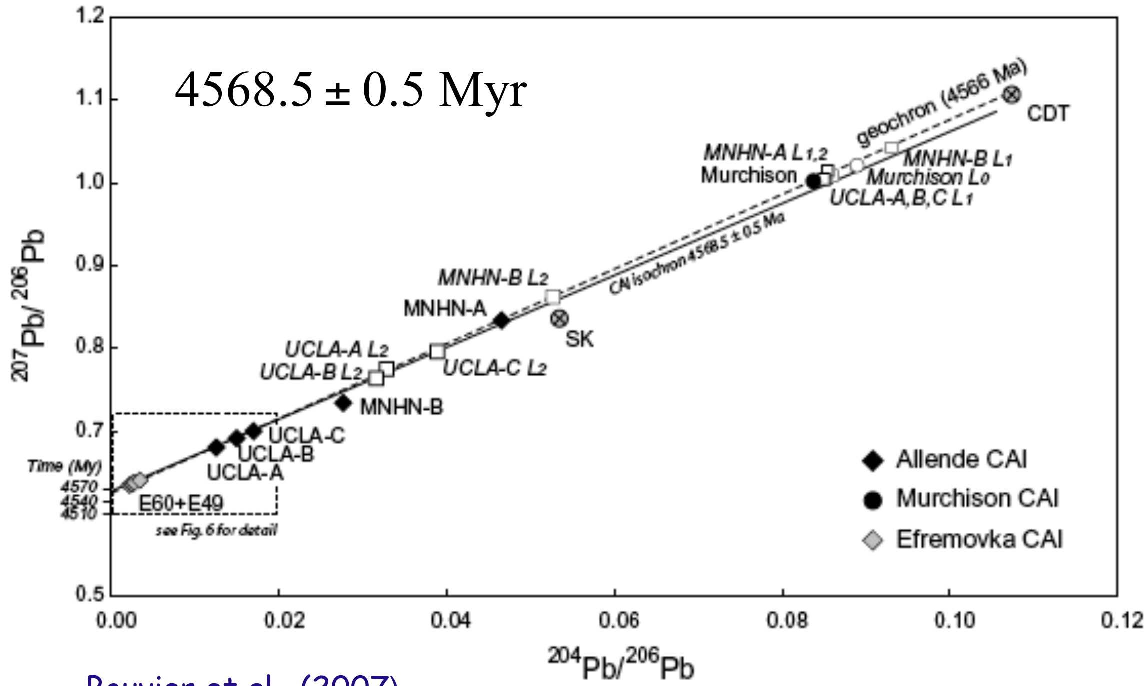
$$\left(\frac{^{207}Pb}{^{206}Pb}\right)^{*} = \frac{\left(\frac{^{207}Pb}{^{204}Pb}\right) - \left(\frac{^{207}Pb}{^{204}Pb}\right)_0}{\left(\frac{^{206}Pb}{^{204}Pb}\right) - \left(\frac{^{206}Pb}{^{204}Pb}\right)_0} = \left(\frac{^{235}U}{^{238}U}\right) \times \frac{\left(e^{\lambda_{235} \times t} - 1\right)}{\left(e^{\lambda_{238} \times t} - 1\right)}$$



$$\left(\frac{^{207}Pb}{^{206}Pb}\right)^{*} = \frac{\left(\frac{^{207}Pb}{^{204}Pb}\right) - \left(\frac{^{207}Pb}{^{204}Pb}\right)_0}{\left(\frac{^{206}Pb}{^{204}Pb}\right) - \left(\frac{^{206}Pb}{^{204}Pb}\right)_0} = \left(\frac{^{235}U}{^{238}U}\right) \times \frac{\left(e^{\lambda_{235} \times t} - 1\right)}{\left(e^{\lambda_{238} \times t} - 1\right)}$$

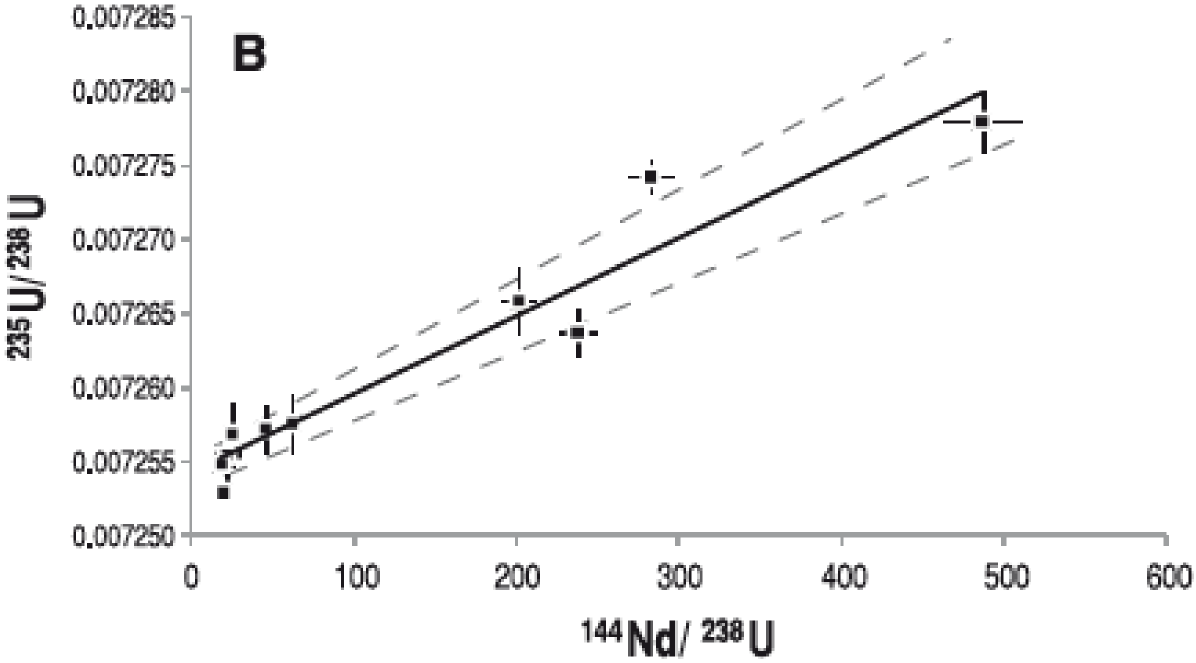


Göpel, Manhès & Allègre (1993)
Allègre, Manhès & Göpel (1995)



Bouvier et al. (2007)

Variations of the $^{238}U/^{235}U$ have been found in CAIs
(Brennecka et al., 2010)

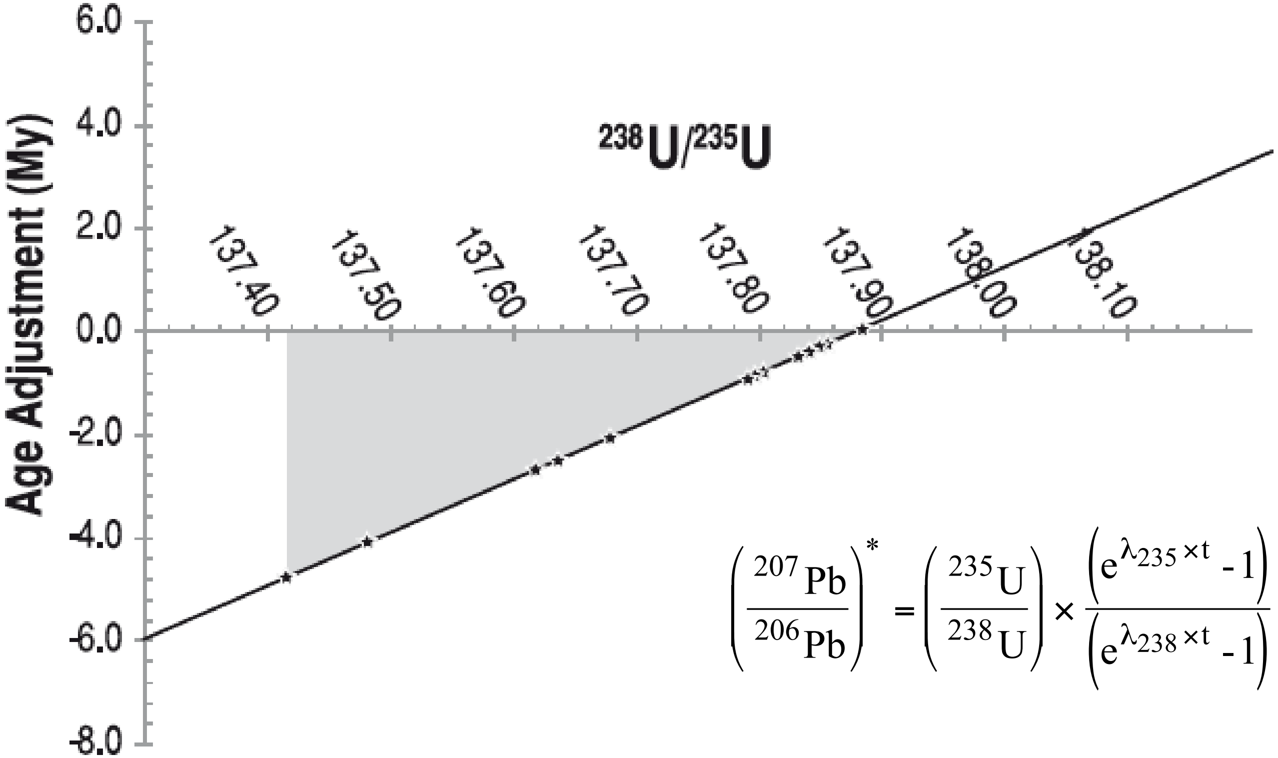


Interpreted as due to the decay of ^{247}Cm (with $^{247}Cm/^{235}U$= 1-2x10^{-4})

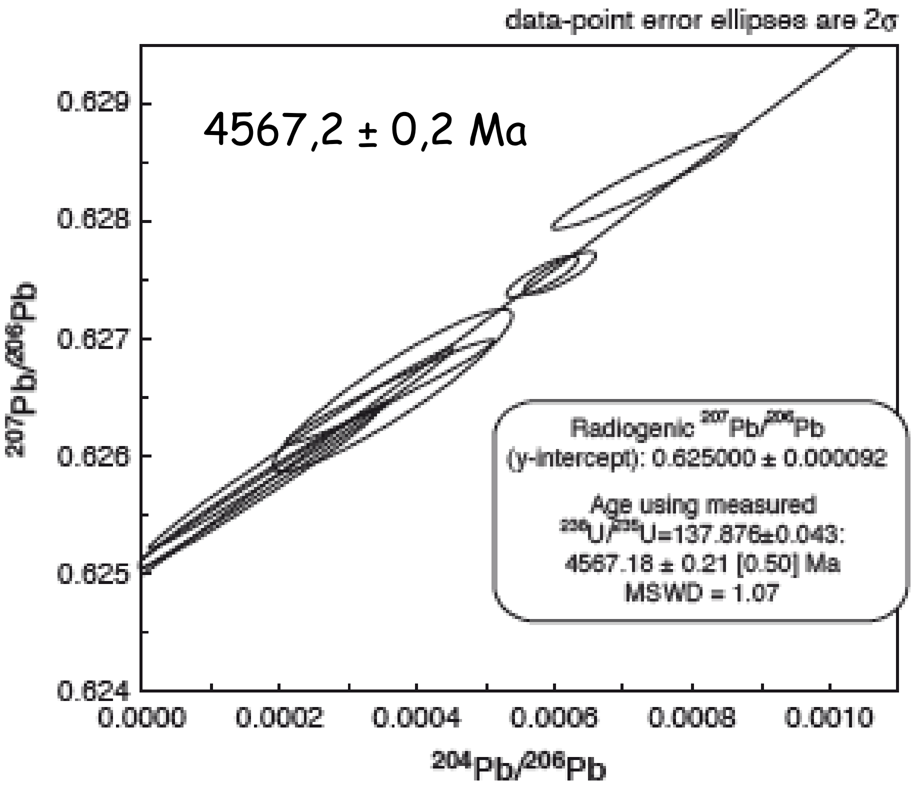
$$^{247}\mathrm{Cm} \rightarrow ^{235}\mathrm{U} \quad (T_{1/2} = 15.6\ \mathrm{My})$$

Alternatively (Connelly et al., 2013), mass fractionation of U isotopes

These variations induce “errors” in the Pb-Pb age of up to 5 Myr
(if the value of 137.88 is taken)

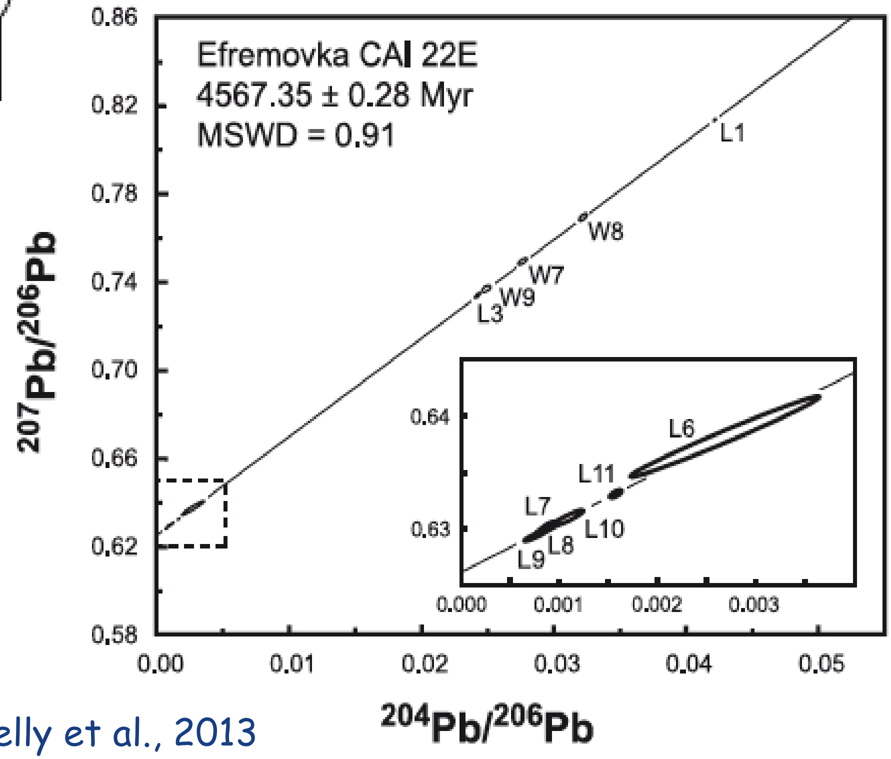


$$\left(\frac{^{207}Pb}{^{206}Pb}\right)^{*} = \left(\frac{^{235}U}{^{238}U}\right) \times \frac{\left(e^{\lambda_{235} \times t} - 1\right)}{\left(e^{\lambda_{238} \times t} - 1\right)}$$

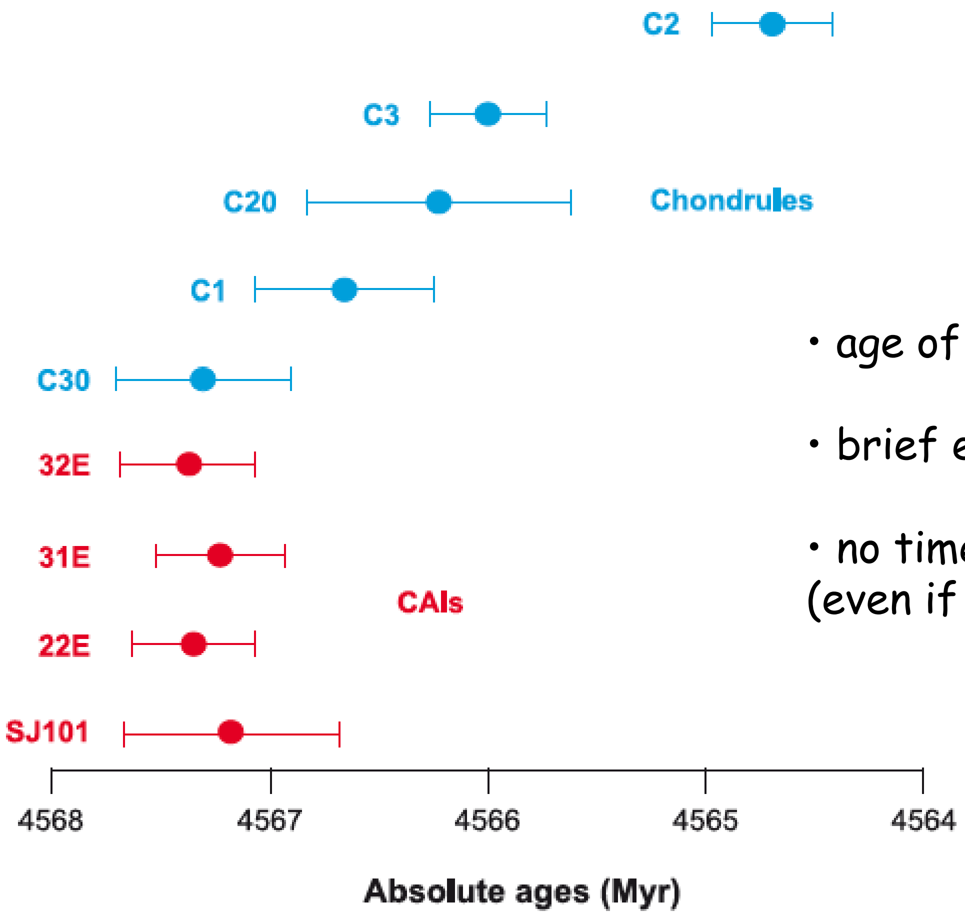


Amelin et al., 2010

It is not clear whether the age of 4568.2±0.2 Myr by Bouvier & Wadhwa (2010) calculated with 137.84 is correct or not

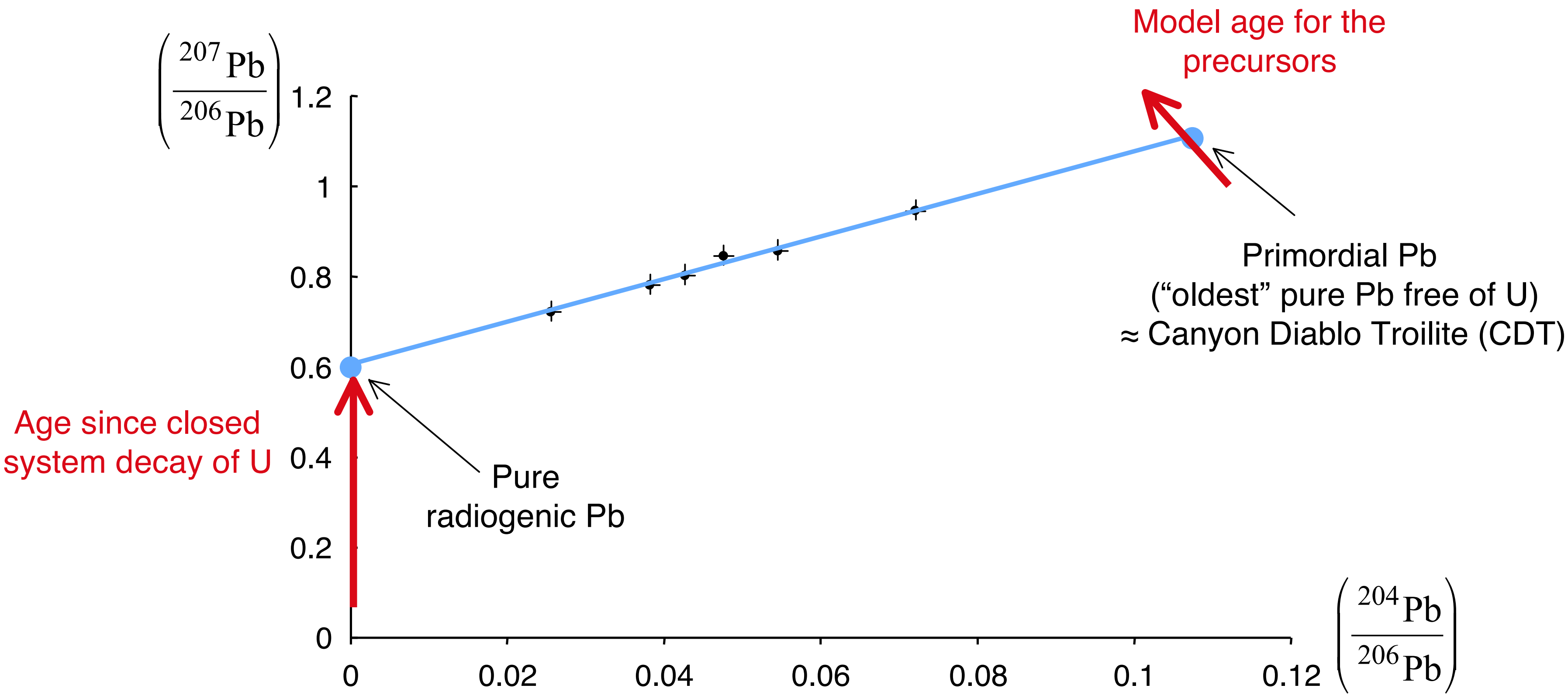


Connelly et al., 2013

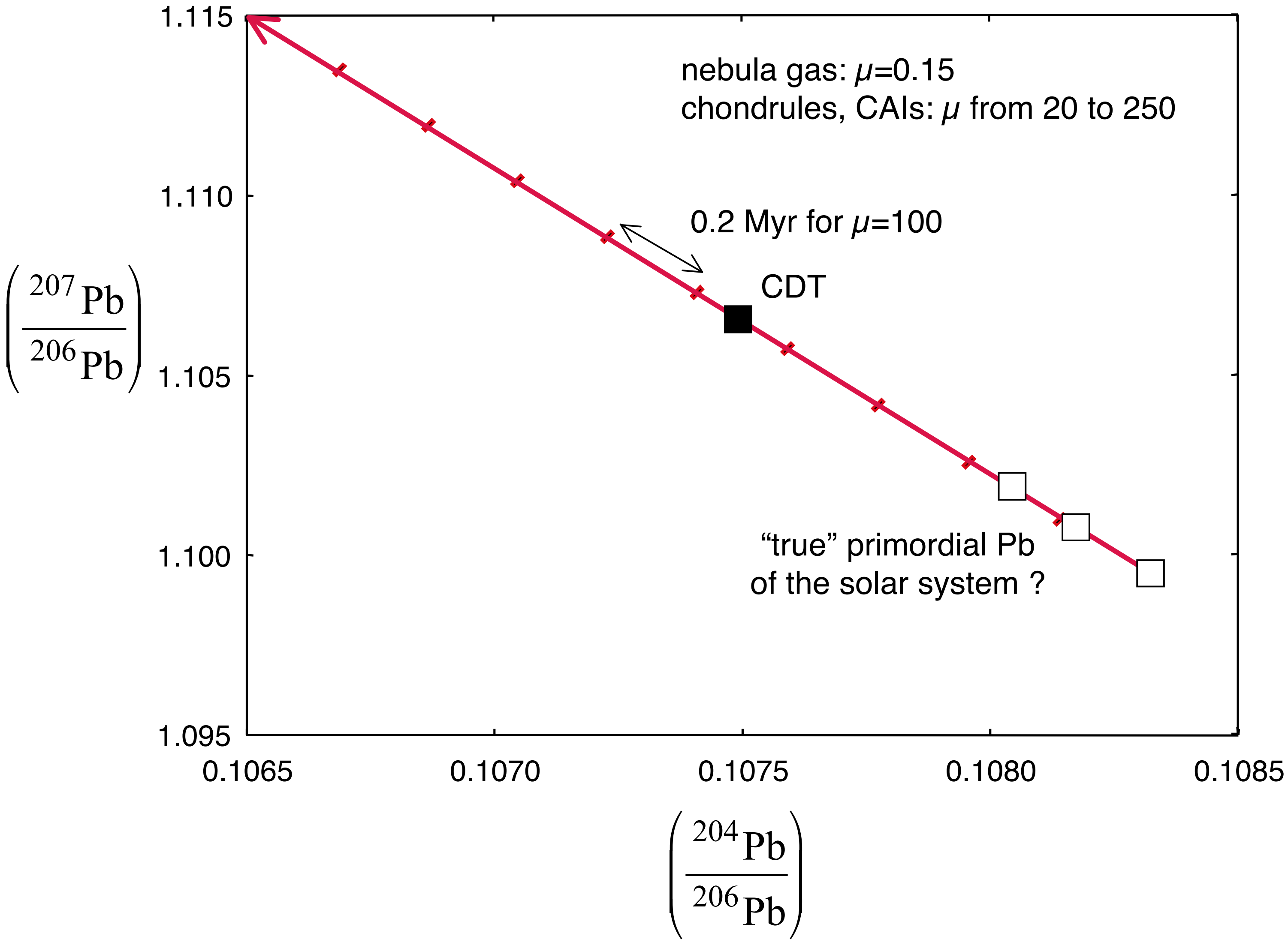


- age of CAI forming event 4567.30 ± 0.16 Myr
- brief event <160 000 years
- no time gap between chondrules and CAIs (even if some chondrules form late)

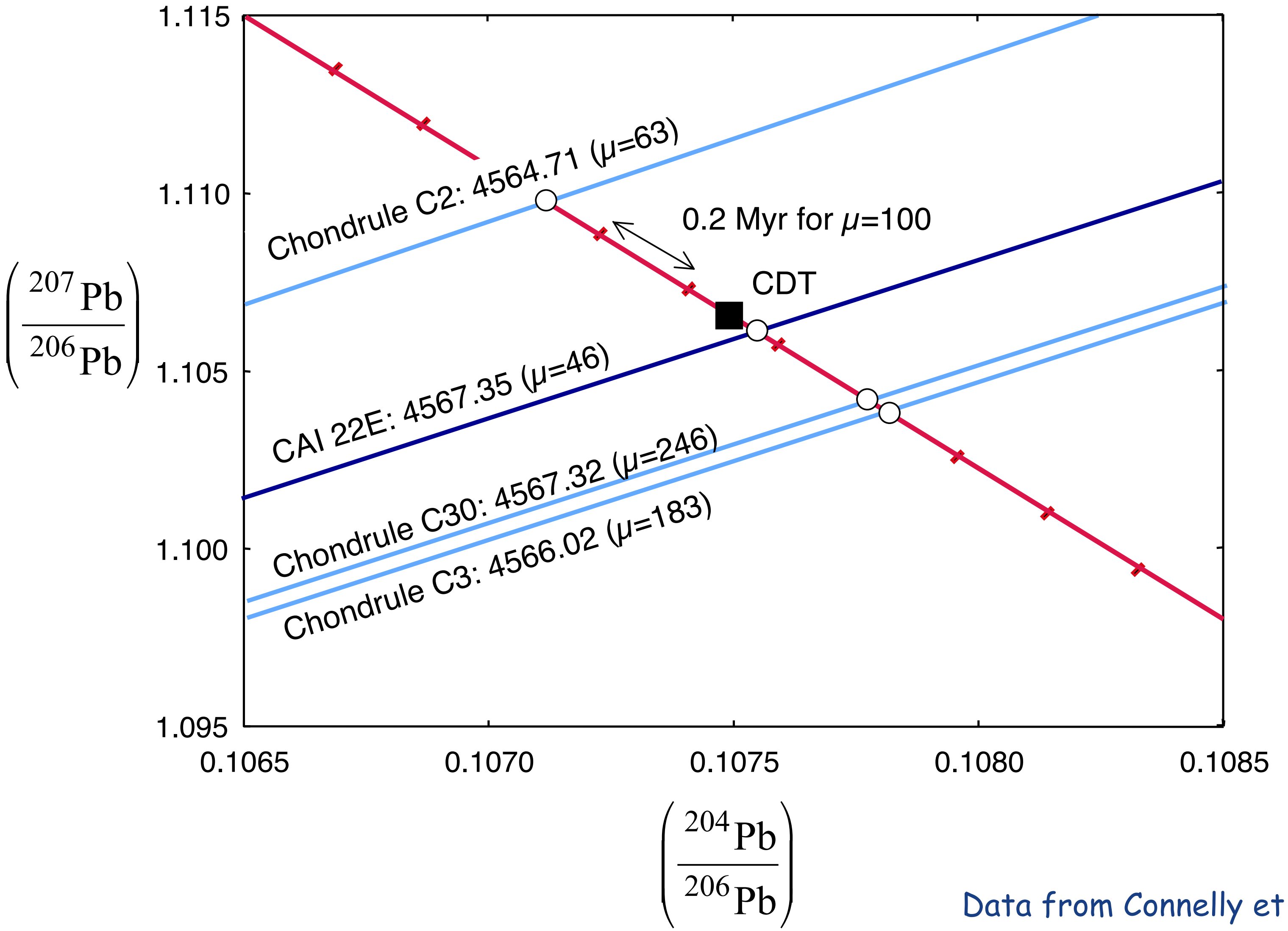
Connelly et al., 2013



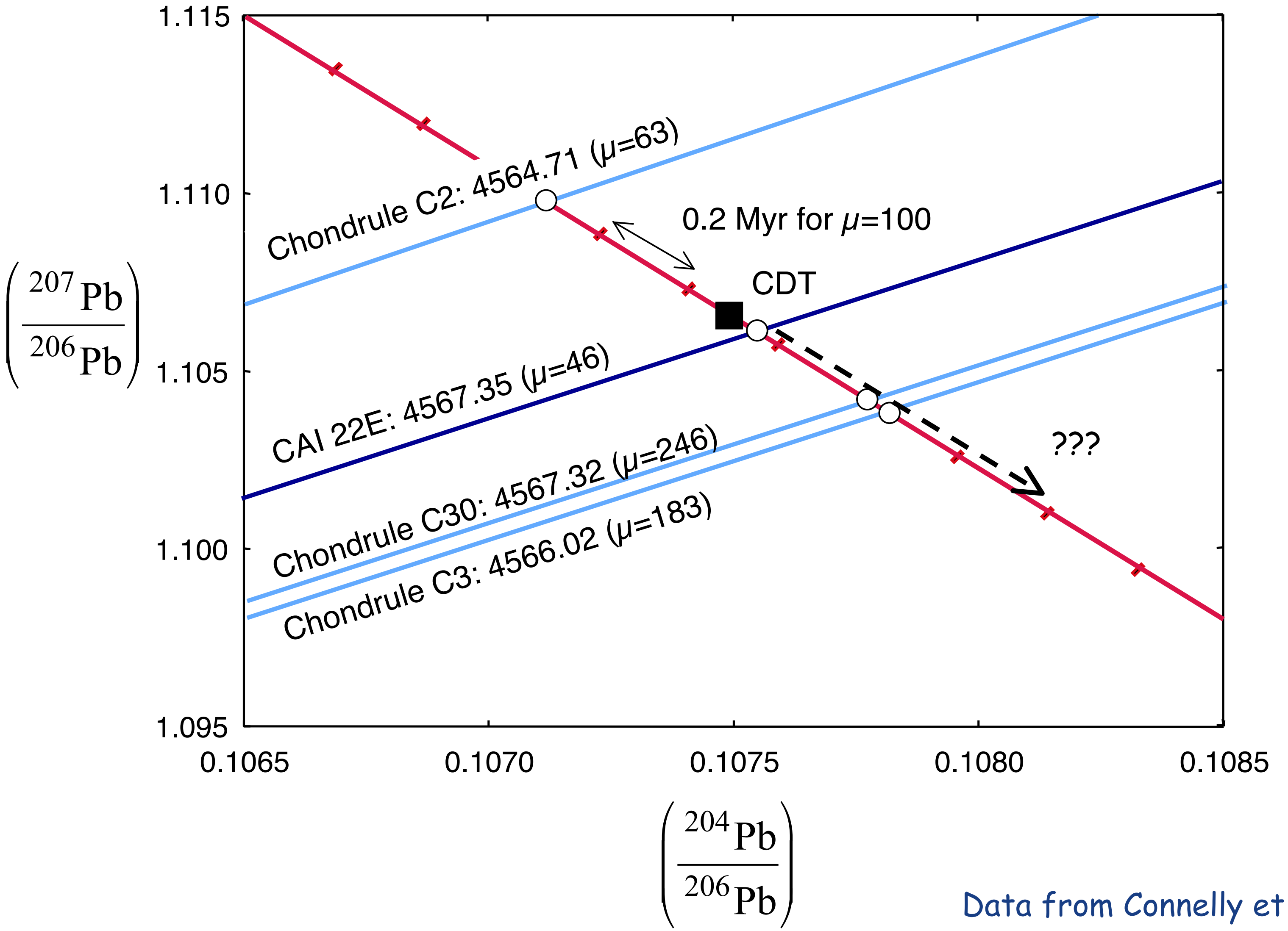
$$\left(\frac{^{207}Pb}{^{206}Pb}\right)^{*} = \frac{\left(\frac{^{207}Pb}{^{204}Pb}\right) - \left(\frac{^{207}Pb}{^{204}Pb}\right)_0}{\left(\frac{^{206}Pb}{^{204}Pb}\right) - \left(\frac{^{206}Pb}{^{204}Pb}\right)_0} = \left(\frac{^{235}U}{^{238}U}\right) \times \frac{\left(e^{\lambda_{235} \times t} - 1\right)}{\left(e^{\lambda_{238} \times t} - 1\right)}$$



1.115
1.110
1.105
1.100
1.095
0.1065
0.1070
0.1075
0.1080
0.1085
$\left(\frac{^{207}Pb}{^{206}Pb}\right)$
$\left(\frac{^{204}Pb}{^{206}Pb}\right)$
nebula gas: μ=0.15
chondrules, CAIs: μ from 20 to 250
0.2 Myr for μ=100
CDT
"true" primordial Pb
of the solar system ?



Data from Connelly et al., 2013



Data from Connelly et al., 2013

Conclusions of the Pb-Pb ages:

- age of CAI forming event 4567.30 ± 0.16 Myr from Pb-Pb

But this can date the last high temperature equilibration ?
(The primordial Pb of the CAIs, is not the "most" primordial ?
or some level of heterogeneities for Pb isotopes ?)

- brief event <160 000 years

in agreement with ^{26}Al systematics, but how many events ???
Is this the same number than the 0.2-0.3 Myrs high-T period seen
from ^{26}Al for CAIs (much more statistics with ^{26}Al)
(and also between CAIs and AOAs ?)

- some chondrules formed at the same time than CAIs,

but why did the CAIs escaped the chondrule forming event ?
and why Pb-Pb is not "seeing" the protracted high-T history of CAIs

1) Isotopic dating and its limitation

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3) U-Pb: the absolute age of CAIs and chondrules (consistency or not with ^{26}Al)

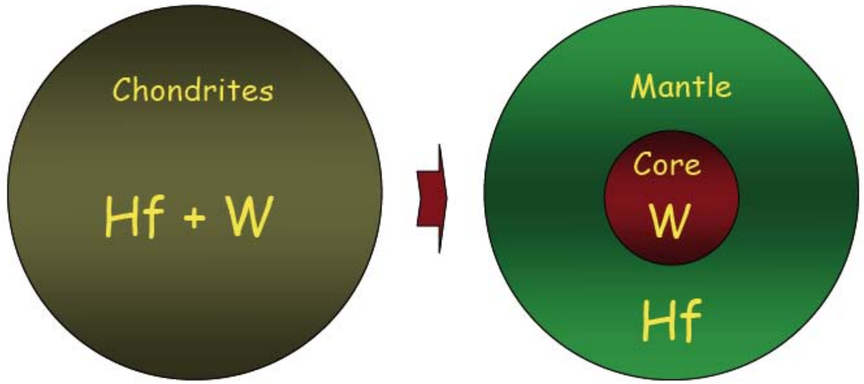
4) ^{182}Hf-^{182}W: age of iron meteorites and Mars (last developments since the talk by Bernard Bourdon at les Houches 2009)

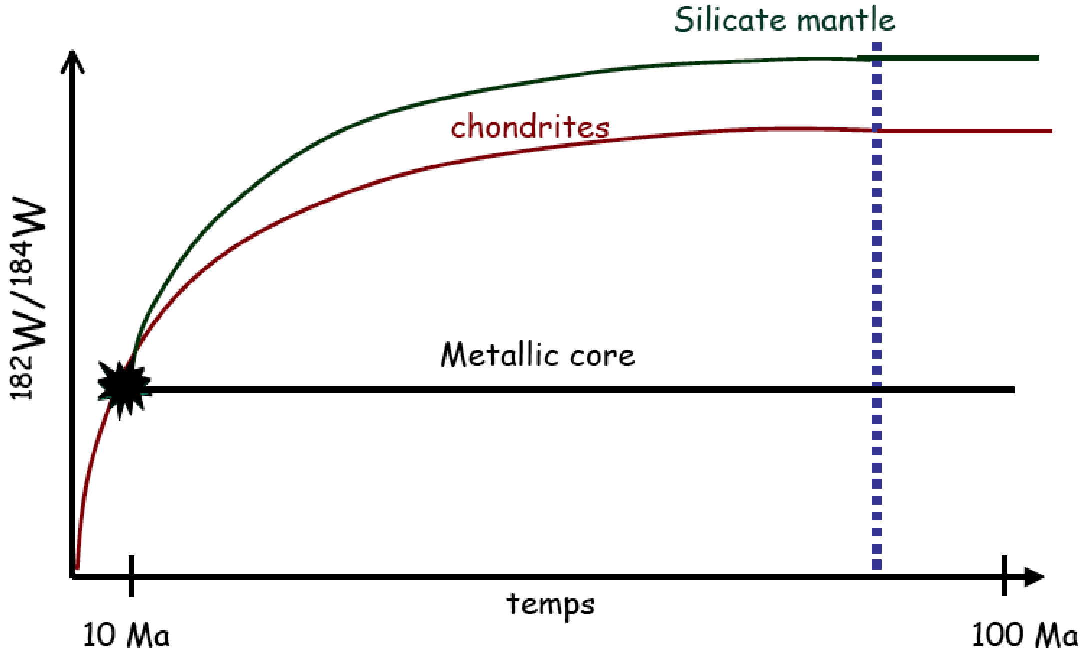
$$^{182}Hf \rightarrow ^{182}W \quad (T_{1/2} = 8.9\ My)$$

$$^{182}Hf_t = ^{182}Hf_0 \times \exp^{-(\lambda \times t)}$$

$$\varepsilon W = \varepsilon^{182}W = \left(\frac{^{182}W/^{184}W_{\text{échantillon}}}{^{182}W/^{184}W_{\text{Terre}}} - 1 \right) \times 10000$$

Hf lithophile & W sidérophile





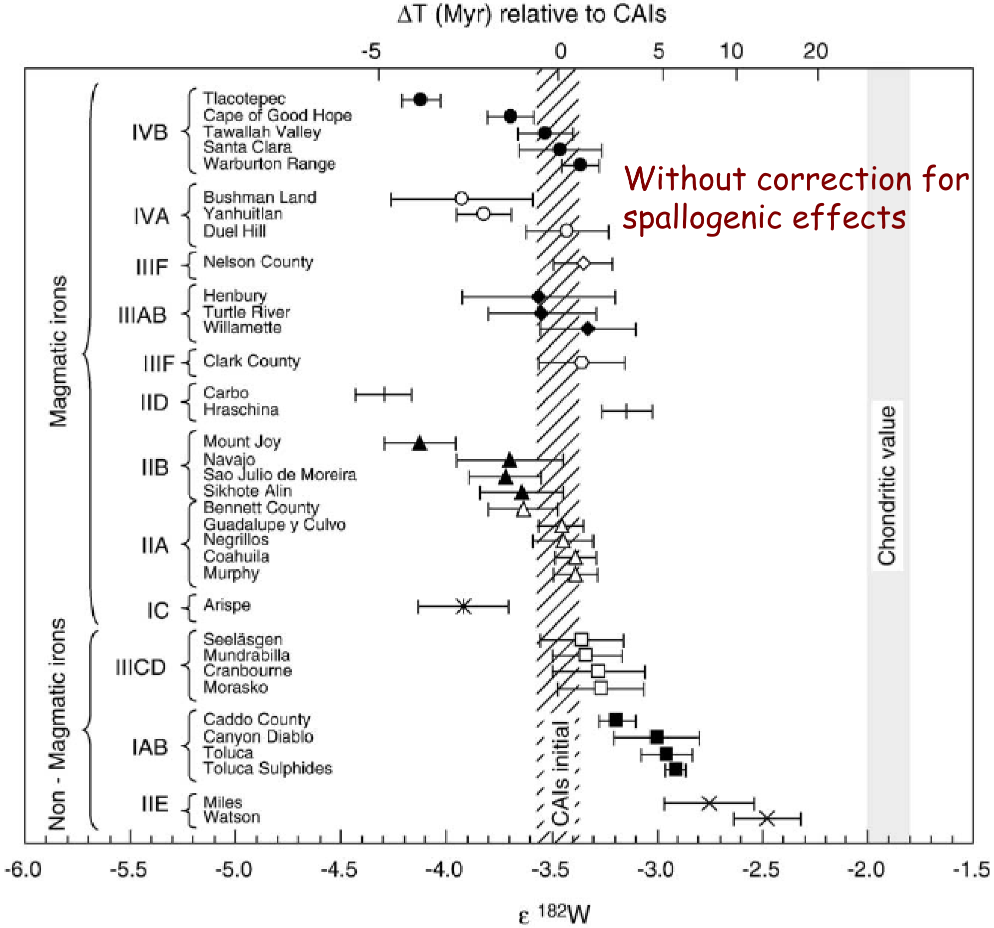
^{182}Hf-^{182}W ($T_{1/2}$=8.9 Myr) story since *Les Houches 2001*

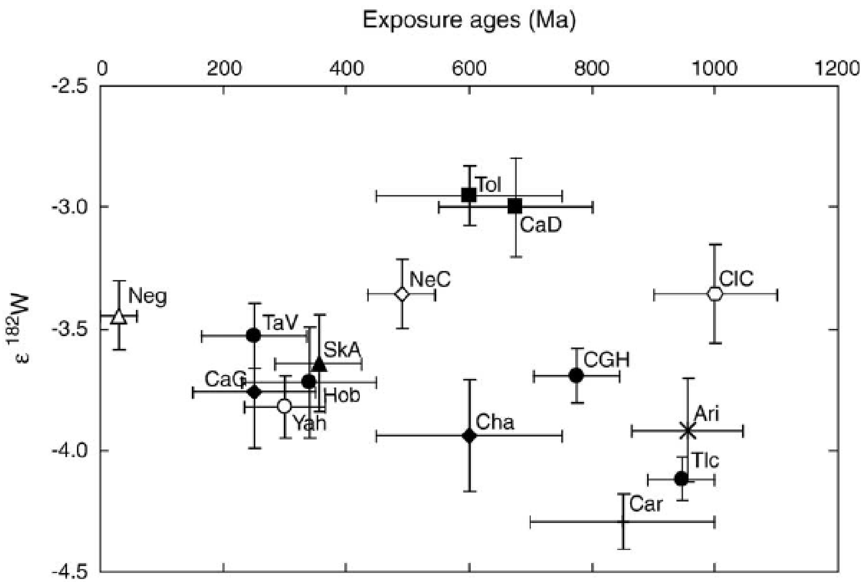
- $\varepsilon^{182}W_{chondrites}$ is -1.9±0.1 (not like the Earth)
  (e.g. Kleine et al., 2002, 2005 ; Yin et al., 2002, …)

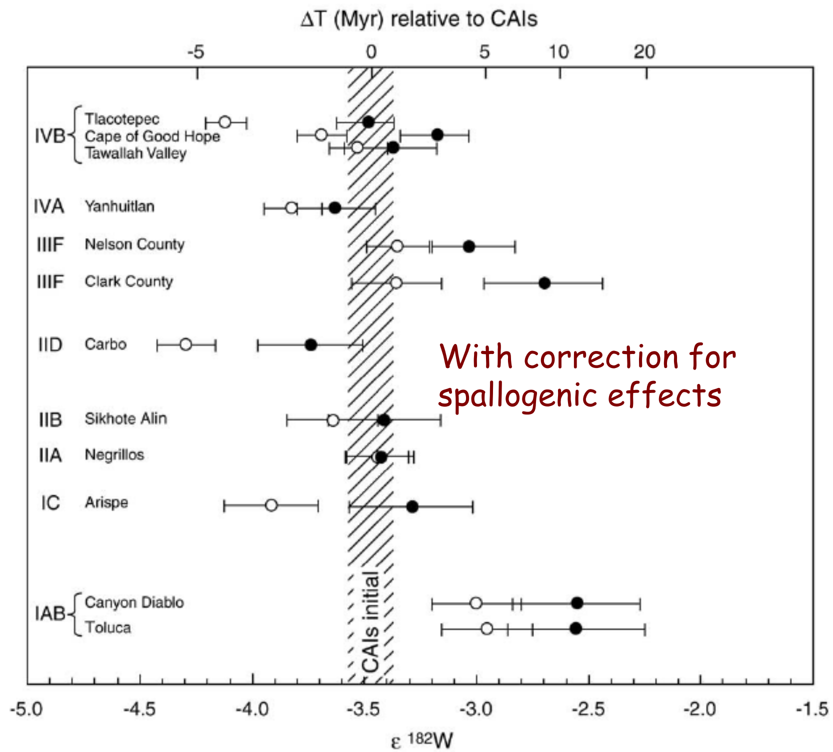
- "Finally" the Earth accreted rather late 50-150 Myr, with the Moon forming event at >60 Myr (cf talk by Bernard Bourdon in *Les Houches* 2009)

- Metal-silicate differentiation in the parent bodies of several magmatic iron meteorites occurred within ≈ 0.5-1 Myr of CAIs (after correction for ^{182}W burnout by low energy thermal neutrons from GCR)
  (Kruijer et al., 2013)

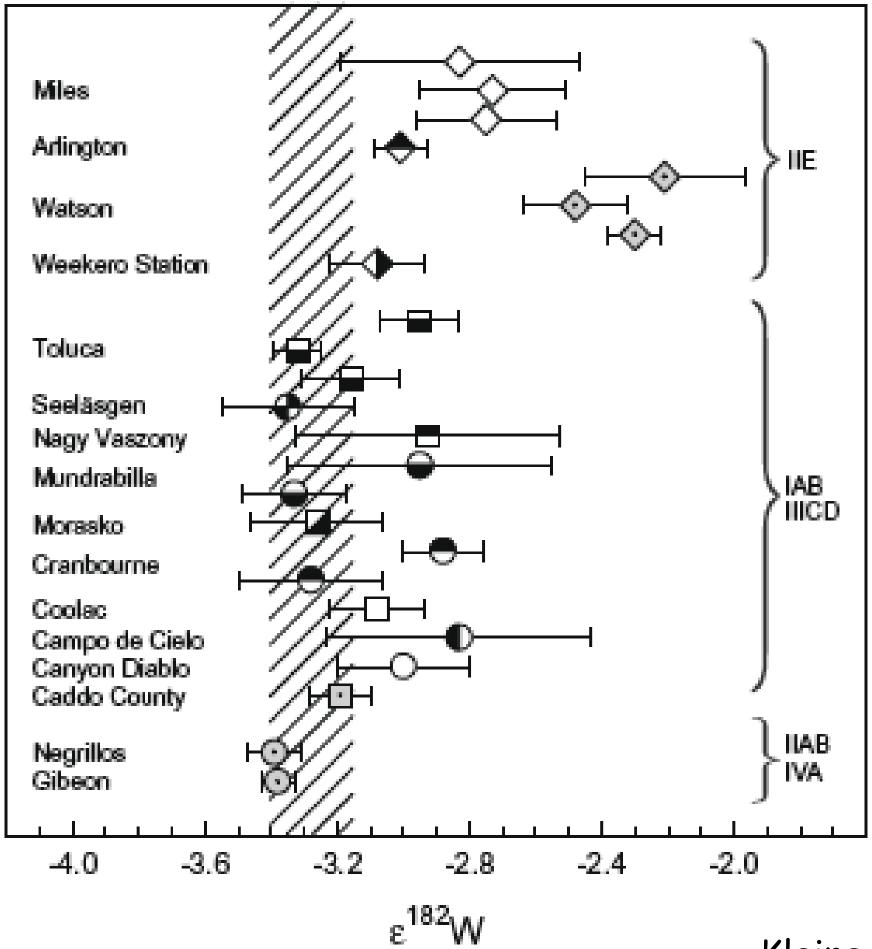
- Mars is a stranded planetary embryo: half of its present size in ≈2 Myr
  (Dauphas & Pourmand, 2011)





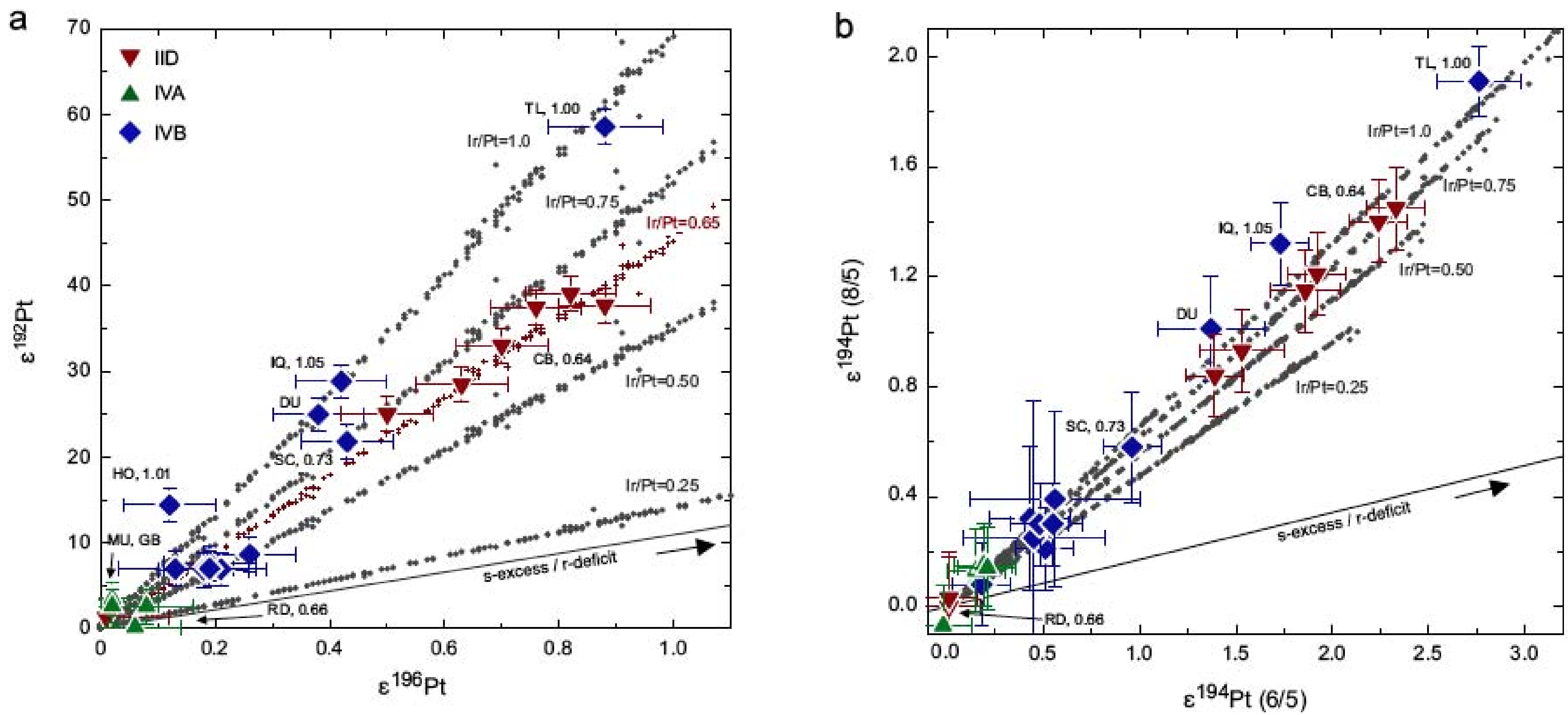


Markowski et al. 2006

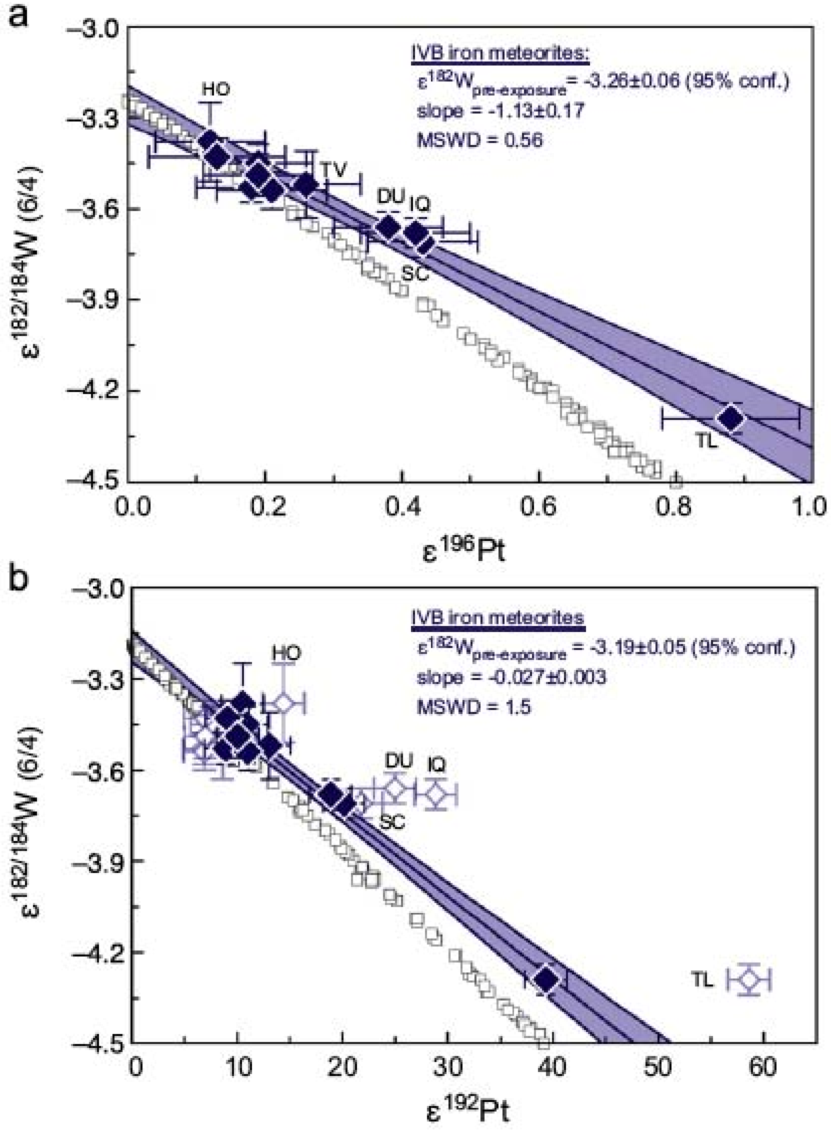


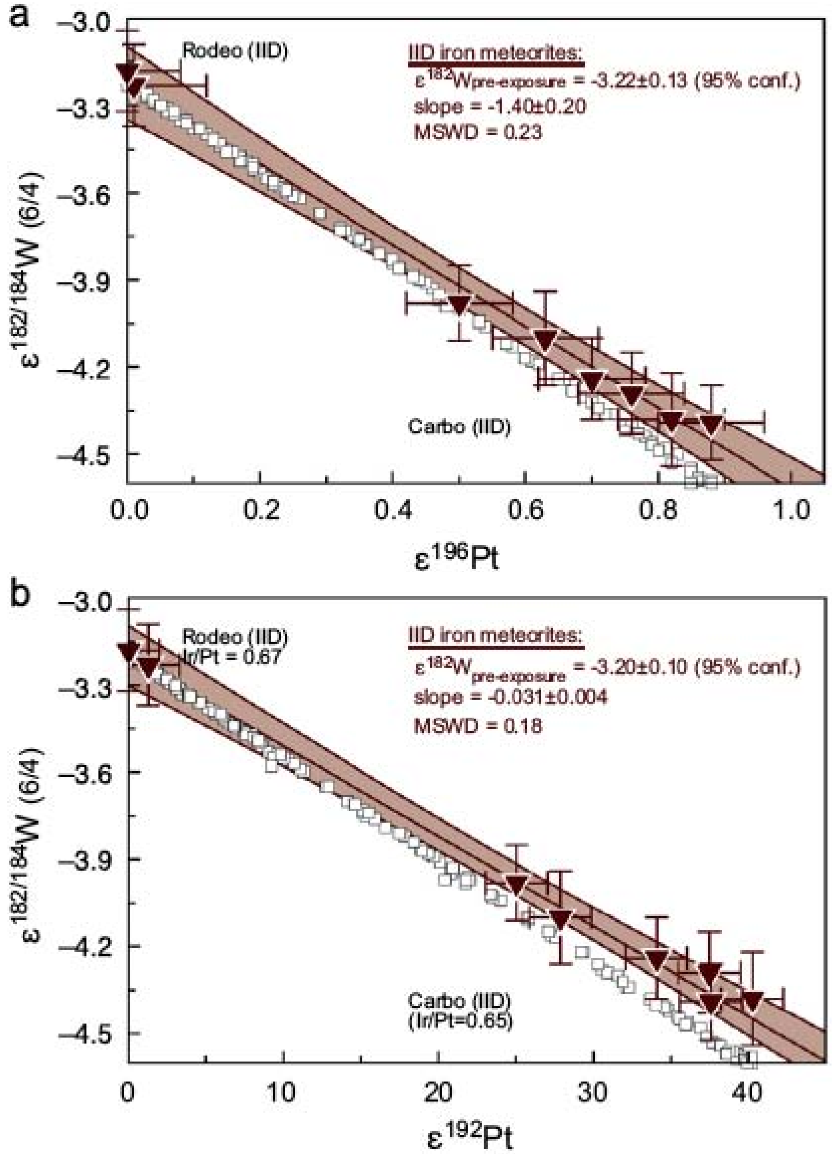
Kleine et al, 2009

Pt isotopes are a better neutron capture monitor
(same depth and energy than for W)



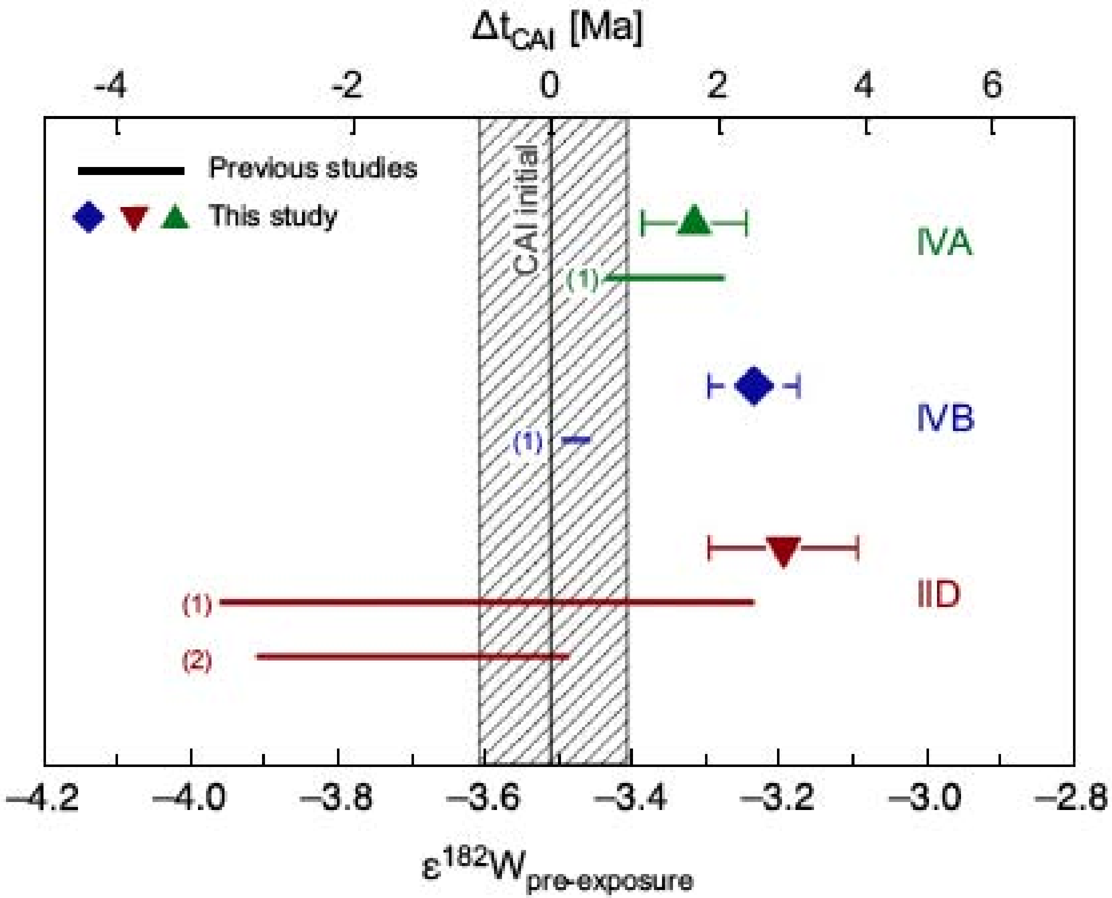
Kruijer et al., 2013





Kruijer et al., 2013

Now parent bodies of magmatic iron meteorite do not form before CAIs



Kruijer et al., 2013

Mars is a stranded planetary embryo: half of its present size in ≈2 Myr
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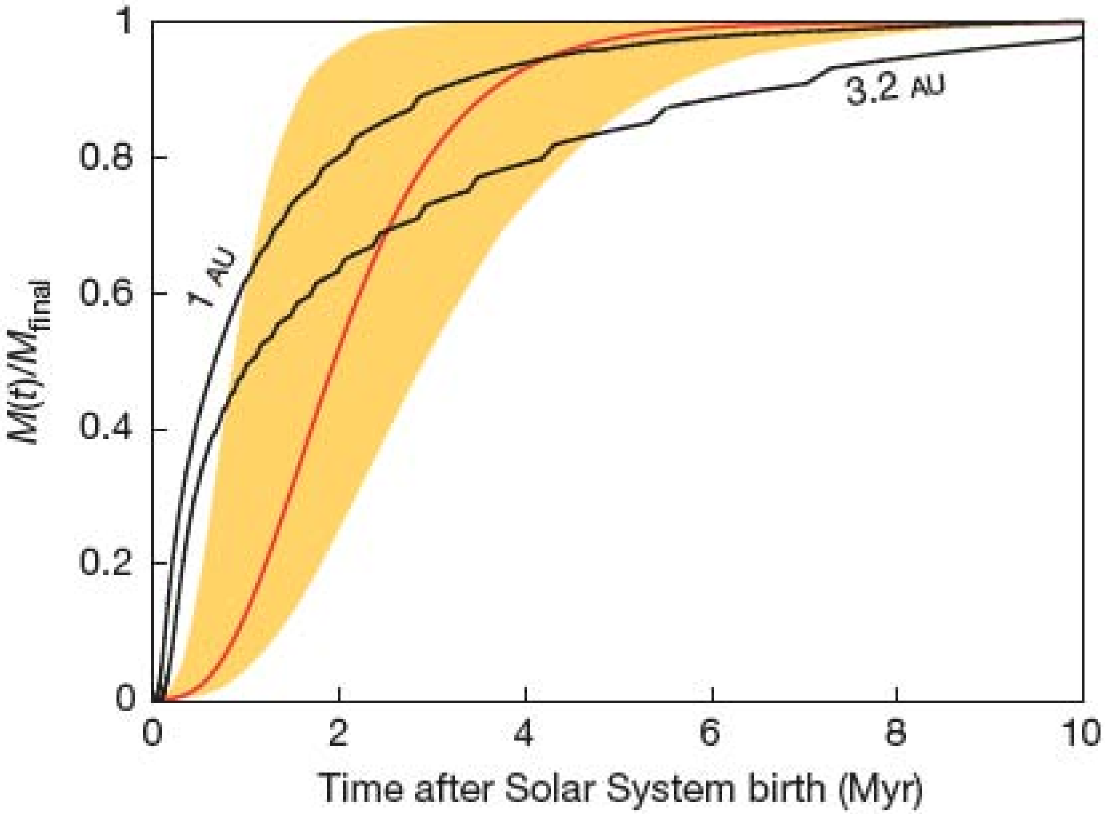

$$f_{mantle}^{Hf/W} = \left(\frac{^{180}Hf}{^{184}W}\right)_m \Big/ \left(\frac{^{180}Hf}{^{184}W}\right)_{CHUR} - 1$$

$$\varepsilon^{182}W_{mantle} = \left(\frac{^{182}Hf}{^{180}Hf}\right)_0 \times \left(\frac{^{180}Hf}{^{182}W}\right)_{CHUR} \times e^{-\lambda_{182} t_c} \times f_{mantle}^{Hf/W} \times 10^4$$

$$\varepsilon^{182}W_{martian\ mantle} = +2.57$$