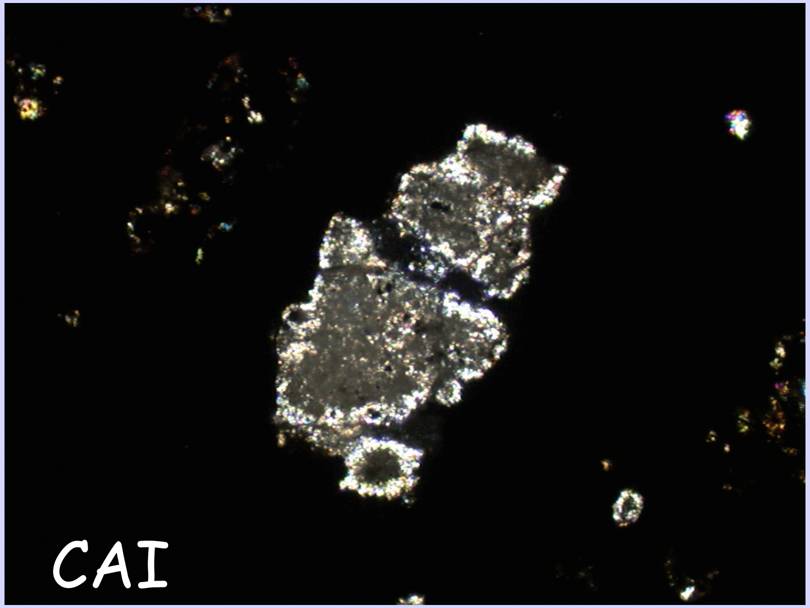
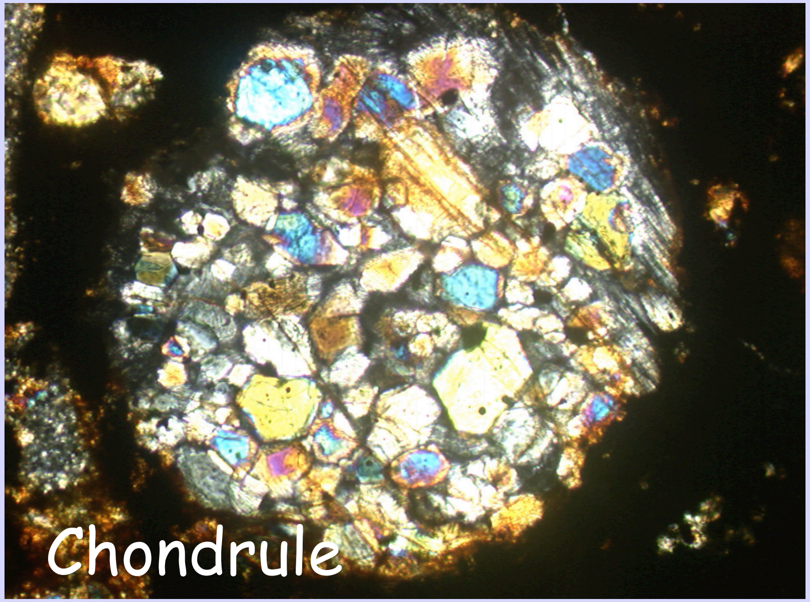
Early Solar System chronology: Implications of a spatially heterogeneous accretion disk

- Chondrule and CAI formation... briefly

A very brief summary of CAIs and chondrules' formation models 1

- Chondrules and CAIs are very complicated objects
- It is crucial to identify the key properties and problems





Transmitted optical light

A very brief summary of CAIs and chondrules' formation models 2

- **What is important?**
  - **Timescales**
    - Was there a 2 Ma gap between the CAIs and chondrules formation?
    - How long did the chondrule formation events last?
  - **Energetics**
    - To make a chondrule, one needs 800 – 21700 J/g
    - 10^{24} g of chondrules in the present asteroid belt -> ~ 10^{28} J = 10^{35} erg
- **Goal: identifying astrophysical processes in the accretion disk accounting for these "facts"**

A very brief summary of CAIs and chondrules' formation models 3

- **Remember:** because of ^{26}Al data, some (most workers believe in a 2 Ma age gap between CAIs and chondrules)

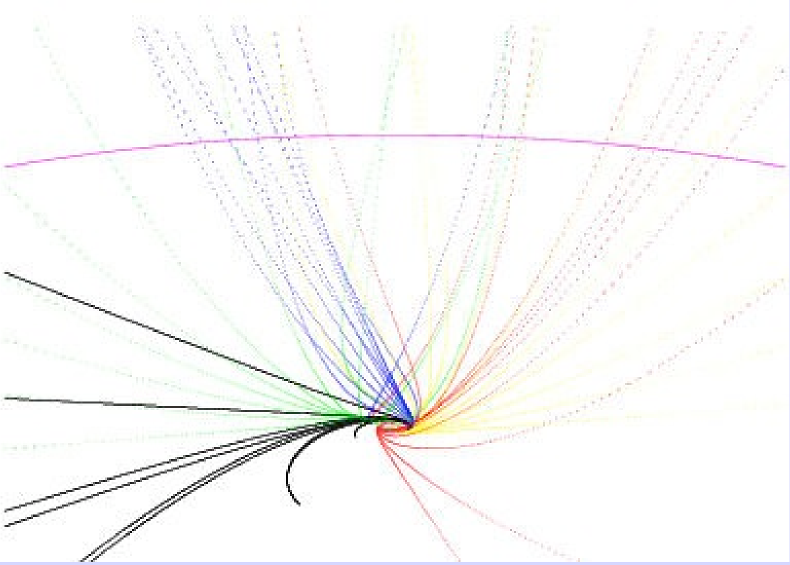
- **The shock wave model** (Desch & Connolly 2002 and others)
  - ☆ Accounts for cooling rates, remanent B, rims...
  - ☆ Has no detailed theory for CAIs (believes in the 2 Ma gap)
  - ☆ Source of the shock wave ? **Gravitational instabilities** (Boss 2000)
  - ☆ If chondrule formation lasts many Ma, how many shock waves?

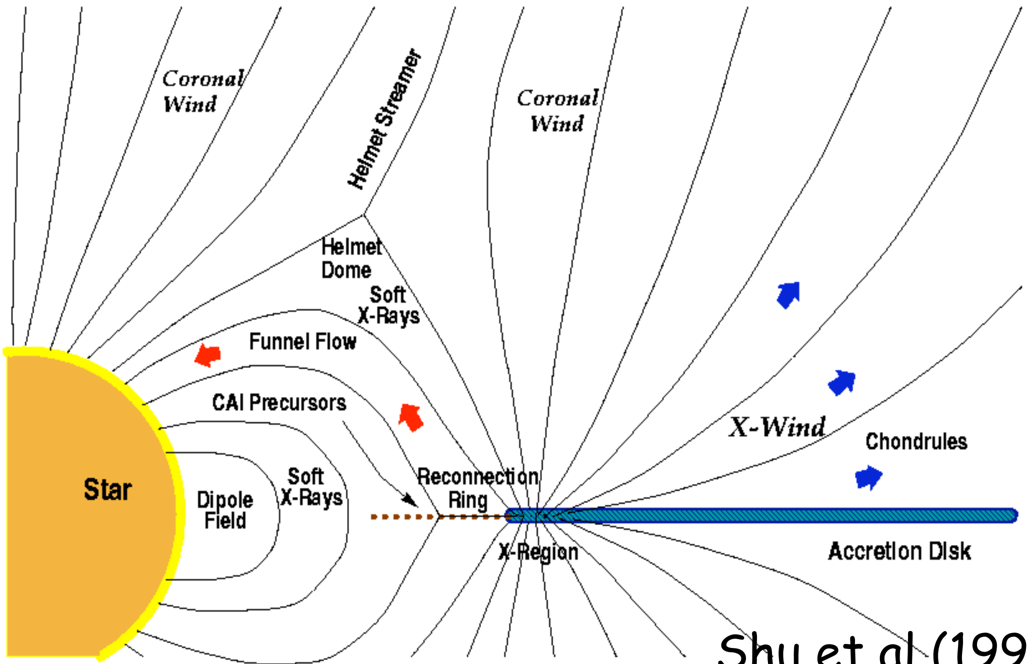
- **The turbulent model for CAIs** (Cuzzi et al. 2003)
  - ☆ Mechanism to account for the 2 Ma age gap
  - ☆ Fine tuning of the sequence of events?

A very brief summary of CAIs and chondrules' formation models 4

- **The x-wind model** (Shu & collaborators 1996, 1997, 2001)
  - ☆ CAIs in the reconnection ring
  - ☆ Chondrules in the x-region or transition region
  - ☆ Transport to asteroidal distances in the x-wind
  - ☆ Contemporary formation of CAIs and chondrules?
  - ☆ **No detailed calculations done for chondrules**

Shang & Shu unpublished





Shu et al (1996)

- Early Solar System chronology: introduction

Early Solar System chronology

- The ESRs content of different objects is different

$^{27}Al/^{27}Al \sim 5 \times 10^{-5}$ and $^{53}Mn/^{55}Mn \sim 4.4 \times 10^{-4}$ for CAIs

$^{27}Al/^{26}Al \sim 1 \times 10^{-5}$ and $^{53}Mn/^{55}Mn \sim 1 \times 10^{-4}$ for chondrules

- ESRs are usually **assumed** to be homogeneously distributed in the accretion disk, and this difference is **interpreted** as a chronological difference

- The chronology based on the homogeneity assumption is a model

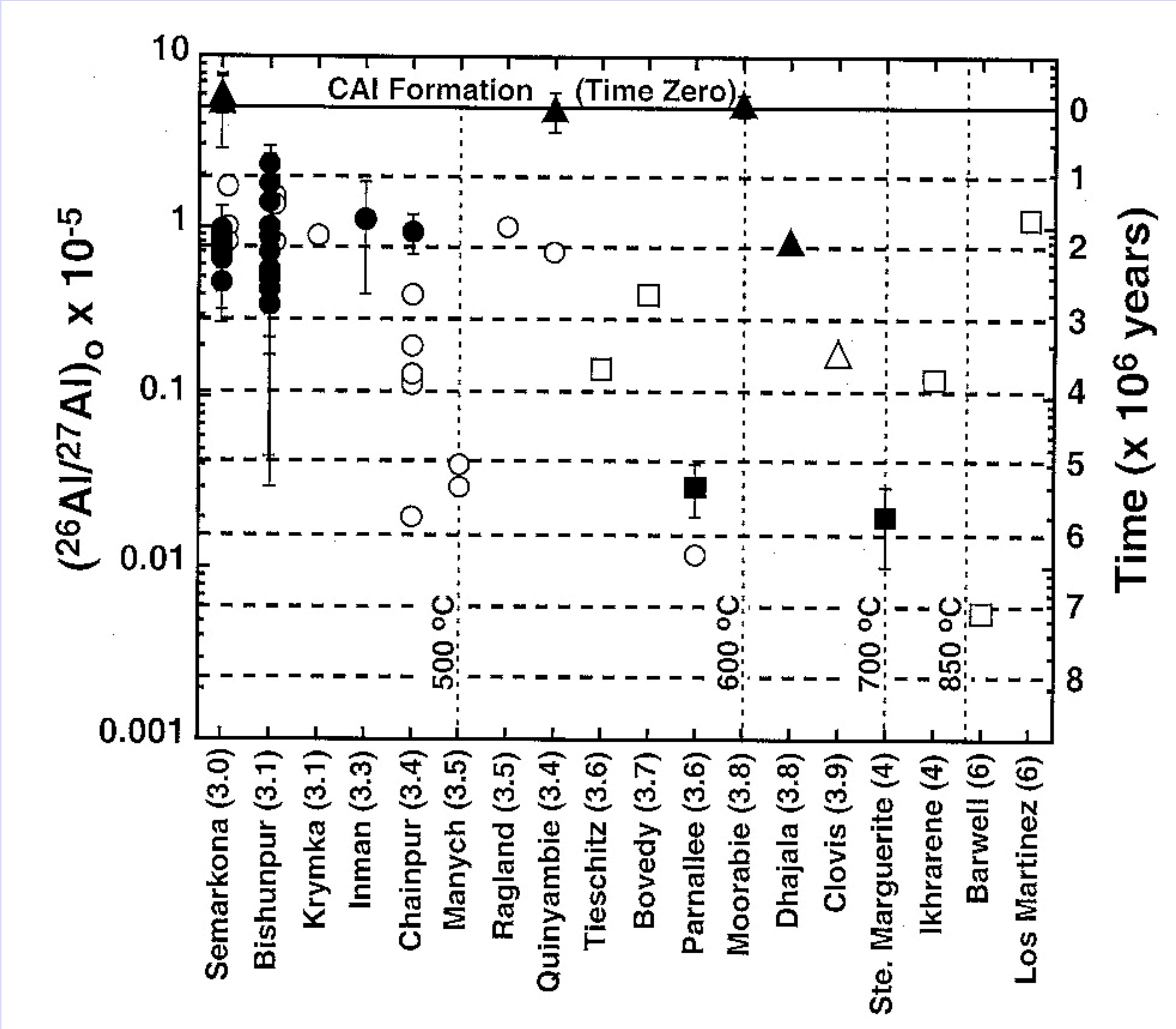
Early Solar System chronology

t_0 origin of time, t_{CAI} and t_{ch} formation time of CAIs and chondrules respectively

$$X_{CAI}(t) = X_{CAI}(0) \times \exp[-(t_{CAI}-t_0)/\tau]$$
$$X_{ch}(t) = X_{ch}(0) \times \exp[-(t_{ch}-t_0)/\tau]$$

- **$\Delta t = - \tau \times \ln [X_{CAI}(t_{CAI})/X_{ch}(t_{ch}) \times X_{CAI}(t_0)/X_{ch}(t_0)]$**
- **Assuming** $X_{CAI}(t_0) = X_{ch}(t_0)$ (**homogeneous distribution**), one builds a chronology and the difference in initial ^{26}Al content is translated into a time (chondrules formed 2-3 Ma after CAIs)

Early Solar System chronology: example



Huss et al. 2001

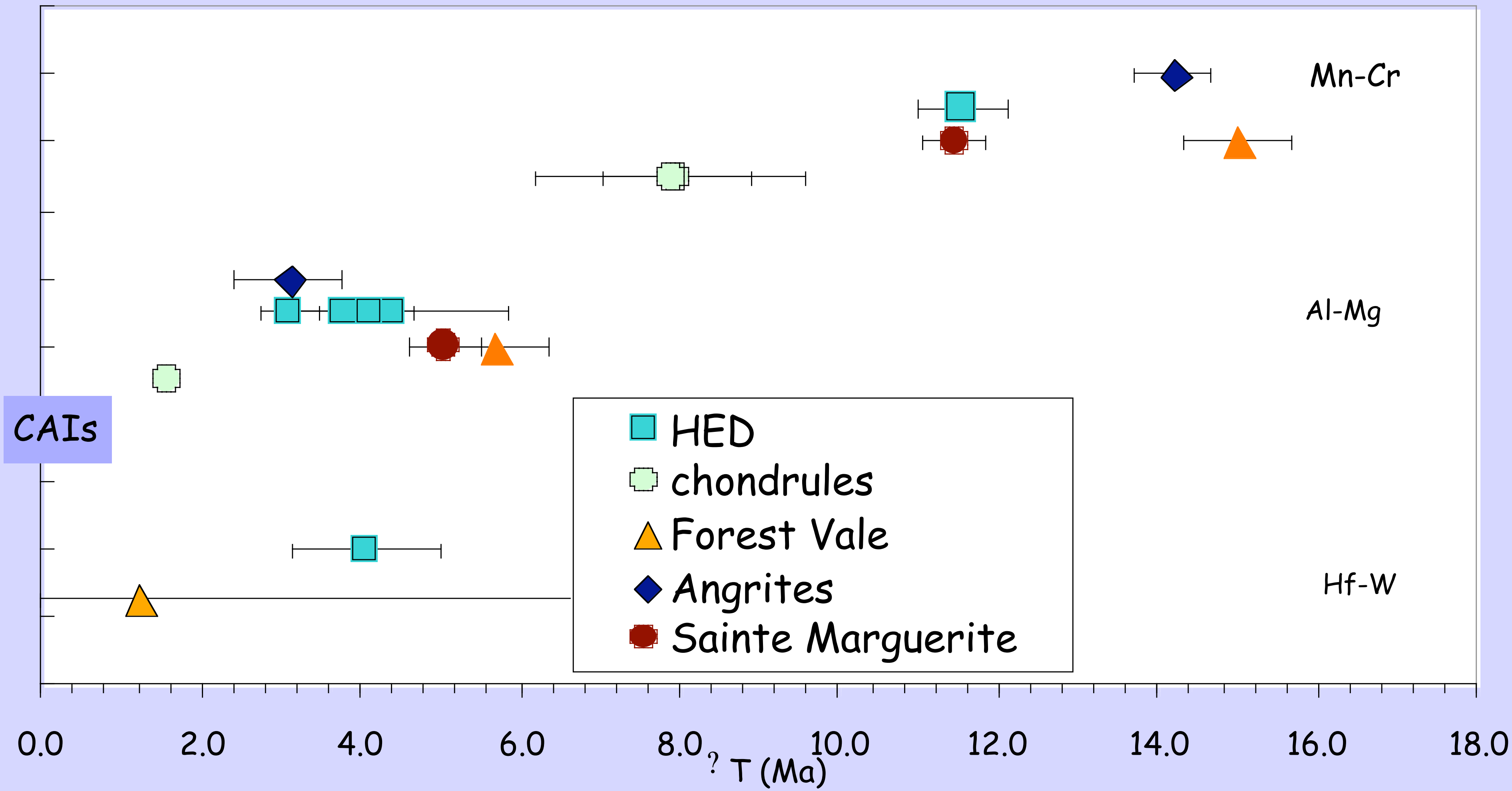
Early Solar System chronology

- Among all radionuclides, only ^{26}Al and ^{53}Mn have being detected in CAIs, chondrules and planetary differentiates

  - ^{182}Hf: no isochron for CAIs and individual chondrules
  - ^{41}Ca, $^{7,10}Be$: only in CAIs
  - ^{60}Fe: no isochron for CAIs
  - ^{107}Pd: only in planetary differentiates
  - ^{129}I probably dates secondary events

  - ^{92}Nb, ^{244}Pu, ^{146}Sm have too long periods to help date Early Solar System events with sufficient precision

- Are the chronologies based on ^{26}Al and ^{53}Mn compatible?



HED: Planetary differentiates (eucrites)
SM & FV: Primitive meteorites
Angrites: Planetary differentiates

Early Solar System chronology: the ^{53}Mn problem

- **The discrepancy for ^{53}Mn has been known for some time**

- Lugmair & Shokolyukov (1998) have proposed that the initial $^{53}Mn/^{55}Mn$ ratio for CAIs is wrong
  - ☆ ^{53}Cr excesses due to nuclear anomalies rather than to ^{53}Mn decay

- Lugmair & Shokolyukov (1998) have proposed an *ad hoc* initial ratio $^{53}Mn/^{55}Mn$ for CAIs to reconcile the ^{53}Mn chronology with others
  - ☆ $^{53}Mn/^{55}Mn = 1.4 \times 10^{-5}$

- New data from Papanastassiou et al. (2002) have confirmed the Birck and Allègre (1985) data
  - ☆ $^{53}Mn/^{55}Mn$ up to 14×10^{-5}

- It is not only a problem with CAIs since relative ages do not work either
  - Sainte Marguerite-Forest Vale
  - HED-angrites

- **Is it possible that there is something wrong in the homogeneity assumption ?**

- The case for spatial heterogeneities in the accretion disk

The case for spatial heterogeneity

- The initial spatial distribution of ESRs in the short-lived radionuclides is unknown

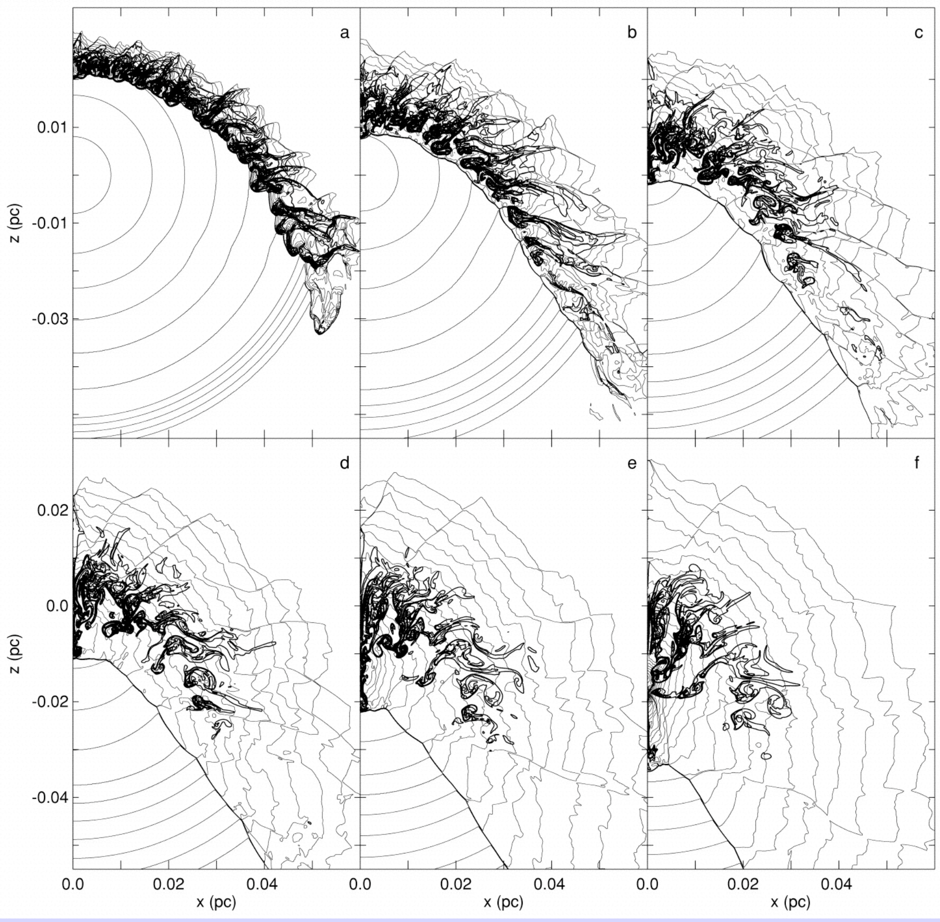
- O isotopes were heterogeneously distributed in the accretion disk

- Isotopic and mineralogical differences between CAIs and chondrules support a spatial heterogeneity in the accretion disk

- **In fine, the spatial homogeneity/heterogenity of ESRs depend on the adopted production model for ESRs**

The origin of ESRs and their spatial distribution in the accretion disk

- **Four possible origins for ESRs**
  - Galactic background : homogeneous spatial distribution
  - Late-minute stellar injection : often assumed homogeneous
  - Irradiation in the Solar System : heterogeneous
  - GCR trapping (only ^{10}Be) : assumed homogeneous ?



Vanhala & Boss 2002
Injection of ESRs from a supernova wind

Is there really a 2 Ma time gap between CAIs and chondrule formation ?

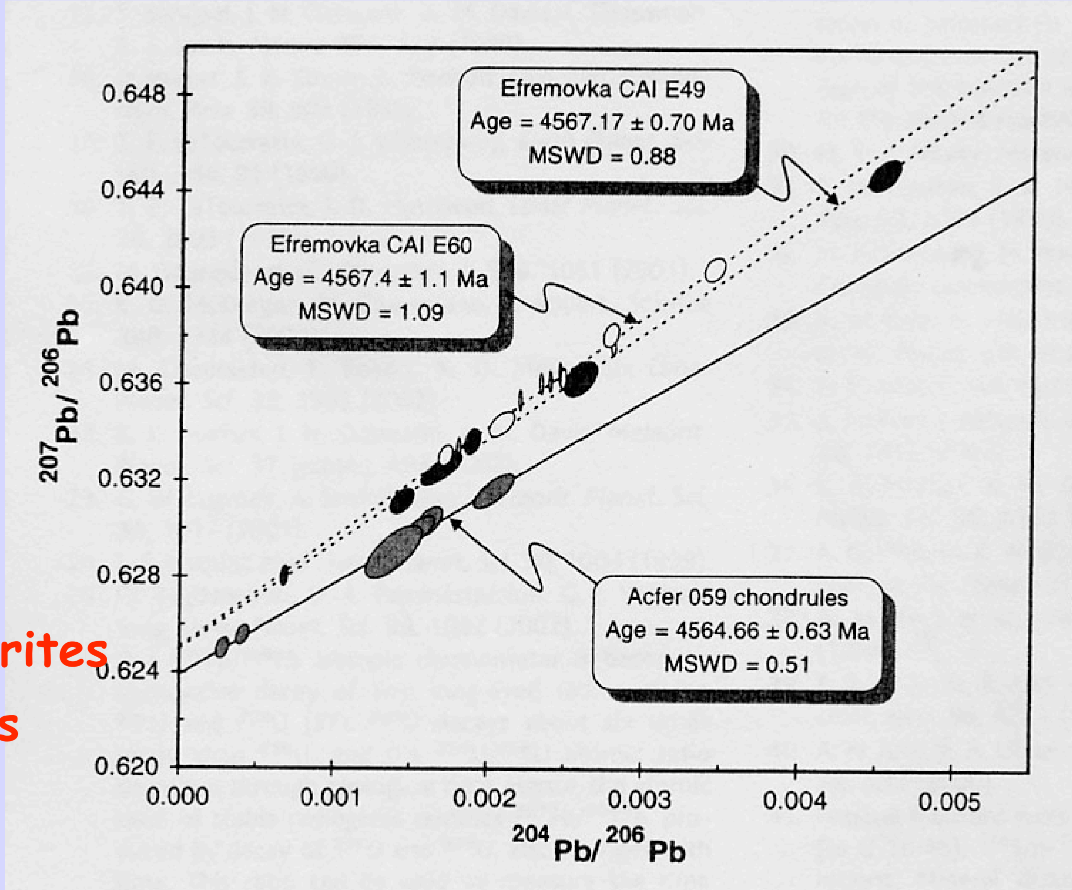
- The **2 Ma gap** is linked to the **homogeneity assumption**
  - If you assume ^{26}Al homogeneity: there is a 2 Ma gap
  - If there is no 2 Ma gap, the ^{26}Al homogeneity hypothesis disappears

- If there is a 2 Ma gap between CAI and chondrule formation, **how do you store CAIs** ?
  - In 10^5 yr CAIs go to the SUN due to **gas drag** (Weidenschiling 1977)

- In addition to storage, you need
  - To prevent CAIs to enter the chondrule formation zone (no CAIs observed within chondrules)
  - To have CAIs mixing with chondrules in the accretion disk just after chondrules formed (chondrites contain chondrules and CAIs…)

The Pb-Pb age of chondrules

- Analytically very difficult
  - Chondrules contain little U
  - Chondrules are small
- Amelin, Krot et al. 2002
  - CAIs: 4567.2 ± 0.7 Ma
  - Chondrules 4564.1 ± 0.6 Ma
- **But**
  - **CAIs belonged to CV3 chondrites**
  - **Chondrules to CR2 chondrites**
- Amelin, Krot et al. **2004**
  - CV3 chondrules: 4566.7 ± 1.0 Ma



Amelin, Krot et al. 2002

- The heterogeneous accretion disk chronological model

Collaborator: Sara S. Russell (NHM)

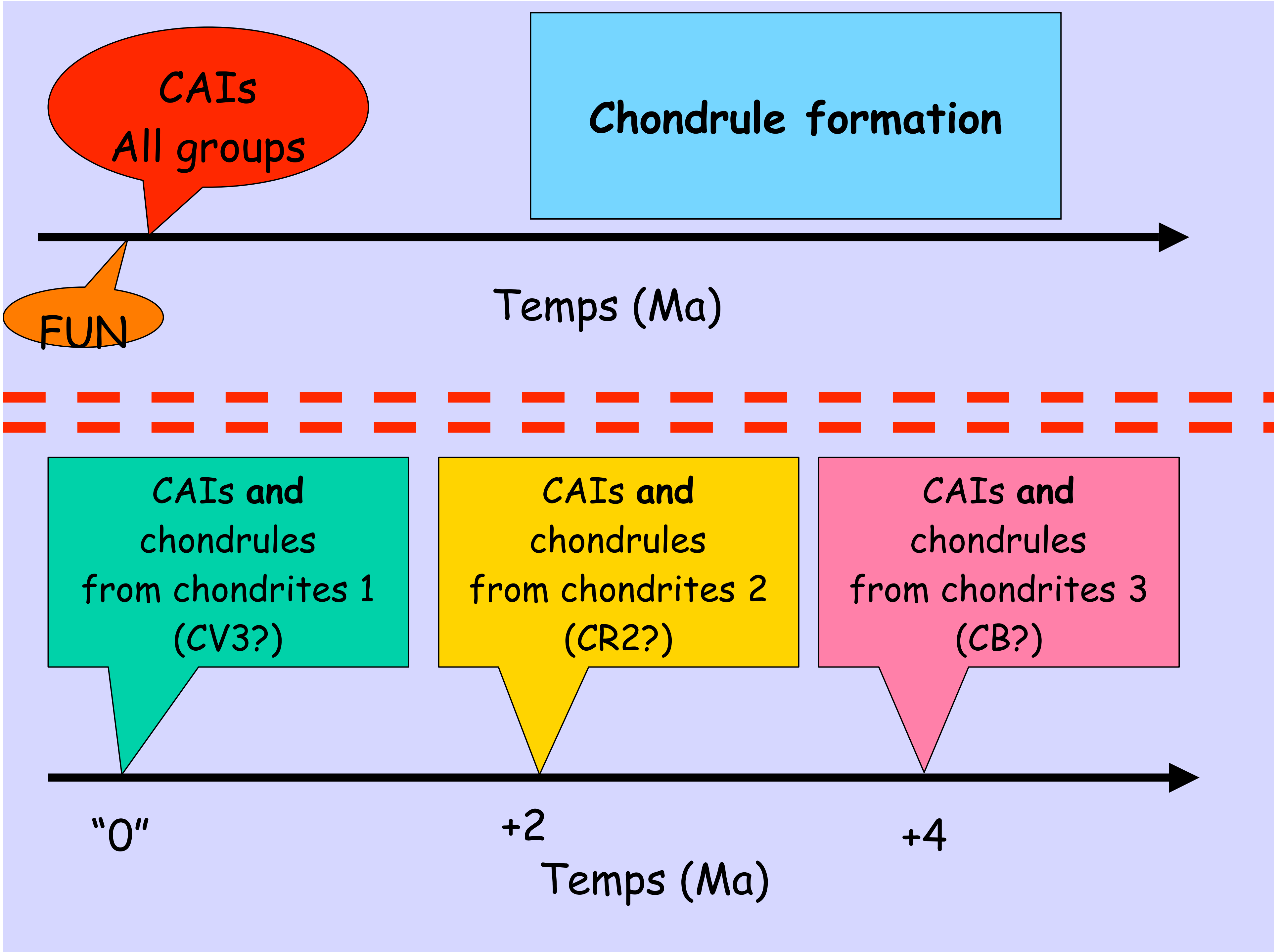
Chronological model in a spatially heterogeneous accretion disk 1

- CAIs and chondrules of the **same chondrite group** formed simultaneously

- CAIs and chondrules from different groups of chondrites formed at different times
  - e.g. CR2 chondrules (**and CAIs**) formed ~ 2 Ma after CV3 chondrules and CAIs

- The ^{26}Al and ^{53}Mn content of CAIs and chondrules are intrinsic properties (compatible with an irradiation origin)

- **Consequence: In this model, there is no ^{26}Al or ^{53}Mn ages of CAIs and chondrules**


CAIs
All groups
Chondrule formation
FUN
Temps (Ma)
CAIs and chondrules from chondrites 1 (CV3?)
CAIs and chondrules from chondrites 2 (CR2?)
CAIs and chondrules from chondrites 3 (CB?)
"0"
+2
+4
Temps (Ma)

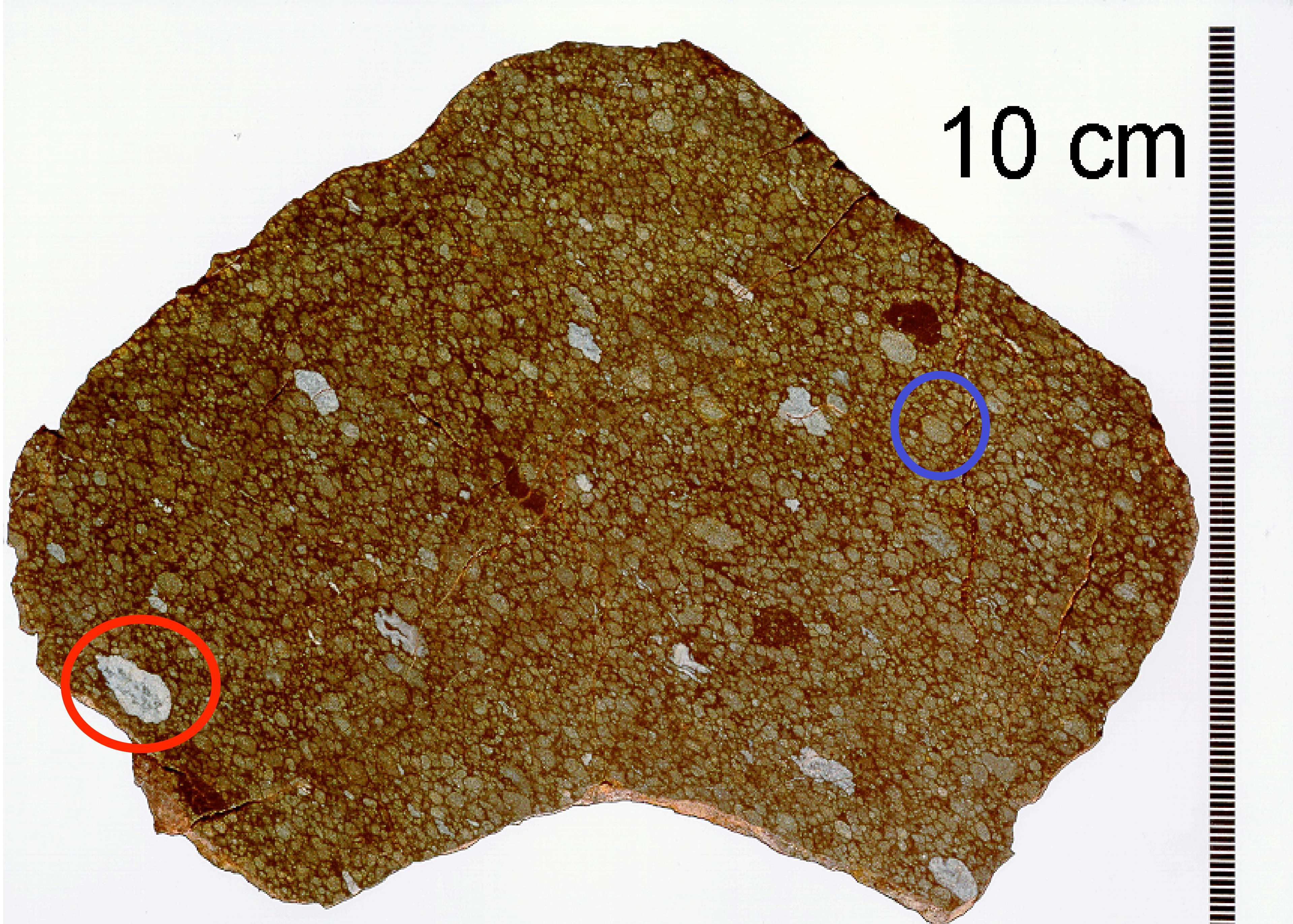
Chronological model in a spatially heterogeneous accretion disk 2

- **Fact:** Chondrites are a **mixture** of CAIs, chondrules and matrix

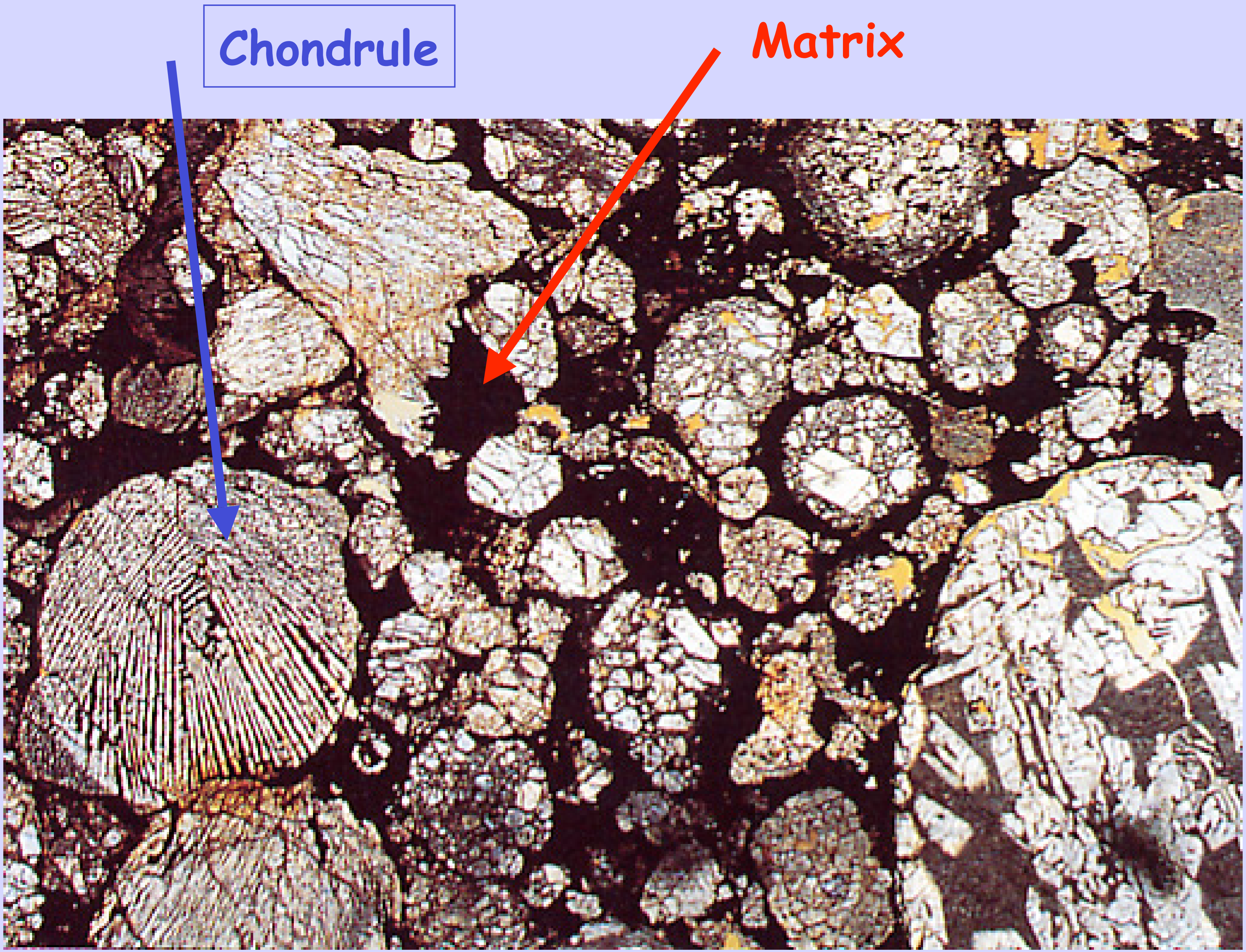
- Existence of 3 distinct isotopic reservoirs
  - CAIs: $^{26}Al/^{27}Al = 5 \times 10^{-5}$ $^{53}Mn/^{55}Mn = 4.4 \times 10^{-5}$
  - Chondres: $^{26}Al/^{27}Al = 1 \times 10^{-5}$ $^{53}Mn/^{55}Mn = 9.4 \times 10^{-6}$
  - Matrix: $^{26}Al/^{27}Al = 0$ $^{53}Mn/^{55}Mn = 0$

- CAIs, chondrules (and matrix) are the **building blocks** of solar system bodies

- **Mixing model:** Many differentiated (achondritic) bodies are believed to originate from a chondritic parent-body



Météorite primitive: chondrite carbonée (Leoville, CV3)



Chainpur (Ordinary chondrite)

Chronological model in a spatially heterogeneous accretion disk 3

- Short-lived radionuclides content of a parent-body made of CAIs, chondrules and matrix evolve following:

$$\Re(t) = \frac{\sum_{i=1}^{i=3} \alpha_i x_i C_i}{\sum_{i=1}^{i=3} \alpha_i C_i} e^{-\lambda t} = \Re(0) e^{-\lambda t}$$

- α_i = abundance of component i (1=CAI, 2=chondrule, 3=matrix)
- C_i = concentration of stable isotope S in component i
- x_i = R/S of component i at the start of accretion

Chronological model in a spatially heterogeneous accretion disk 4

- The age of the parent-body is calculated using

$$t_{PB}^{ESR} = - \tau_{ESR} \times \ln [R_{PB}/R_0]$$

- We search for compatible ages

$$t_{PB}^{26Al} (\alpha_C, \alpha_{CAI}) = t_{PB}^{53Mn} (\alpha_C, \alpha_{CAI})$$

- Only two parameters because $\alpha_C + \alpha_{CAI +} \alpha_M = 1$

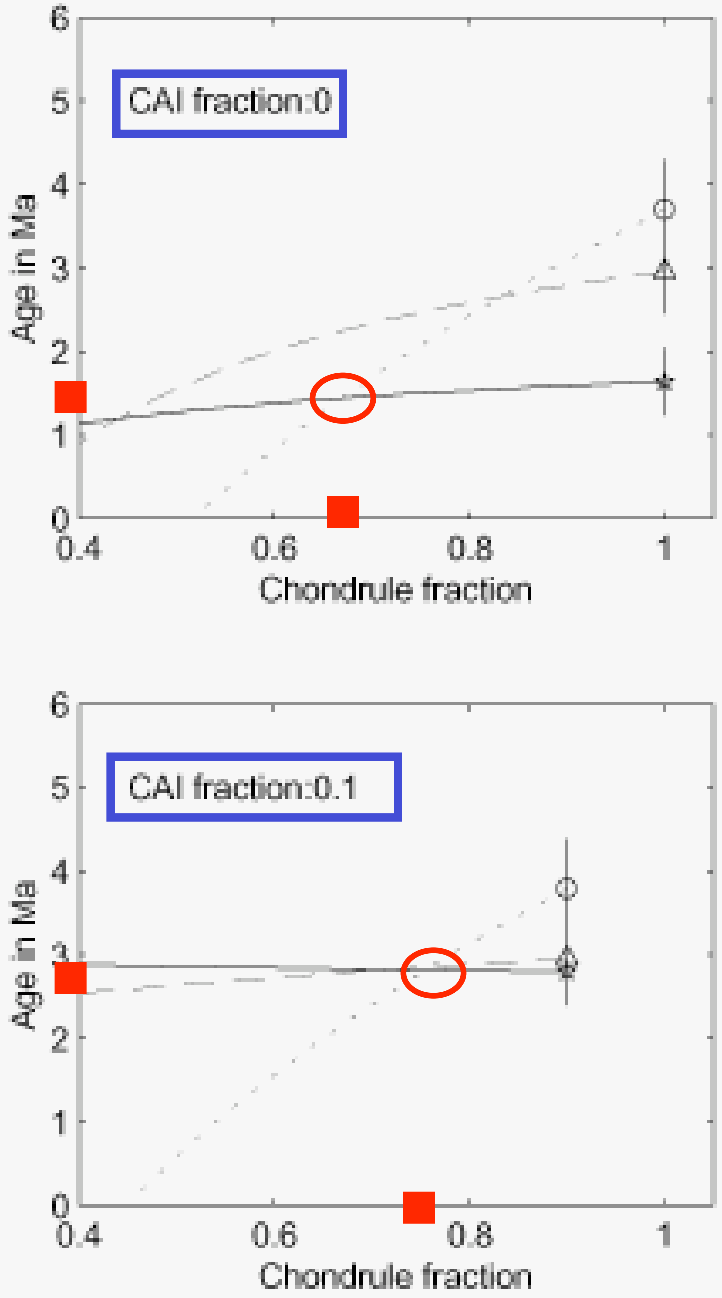
- For a given CAI fraction (α_{CAI}), there will be only one solution (one age and one chondrule fraction)

Chronological model in a spatially heterogeneous accretion disk 5

- Because chondrites have CAIs and chondrule abundances varying between limited quantities, we hope to find well constrained ages
  - No chondrites with CAI abundance > 5 %
  - Chondrule fraction belong to 50-80 % (but CIs ?)

- The age we calculate is the age since the agglomeration of precursors

- We explore 3 possible chemical models (C_M, C_C, C_{CAI})
  - OC: ordinary chondrites (most common meteorites)
  - CV: carbonaceous chondrites (Allende)
  - CM: carbonaceous chondrites (Murchison)



^{26}Al: continuous line
^{53}Mn: dotted line

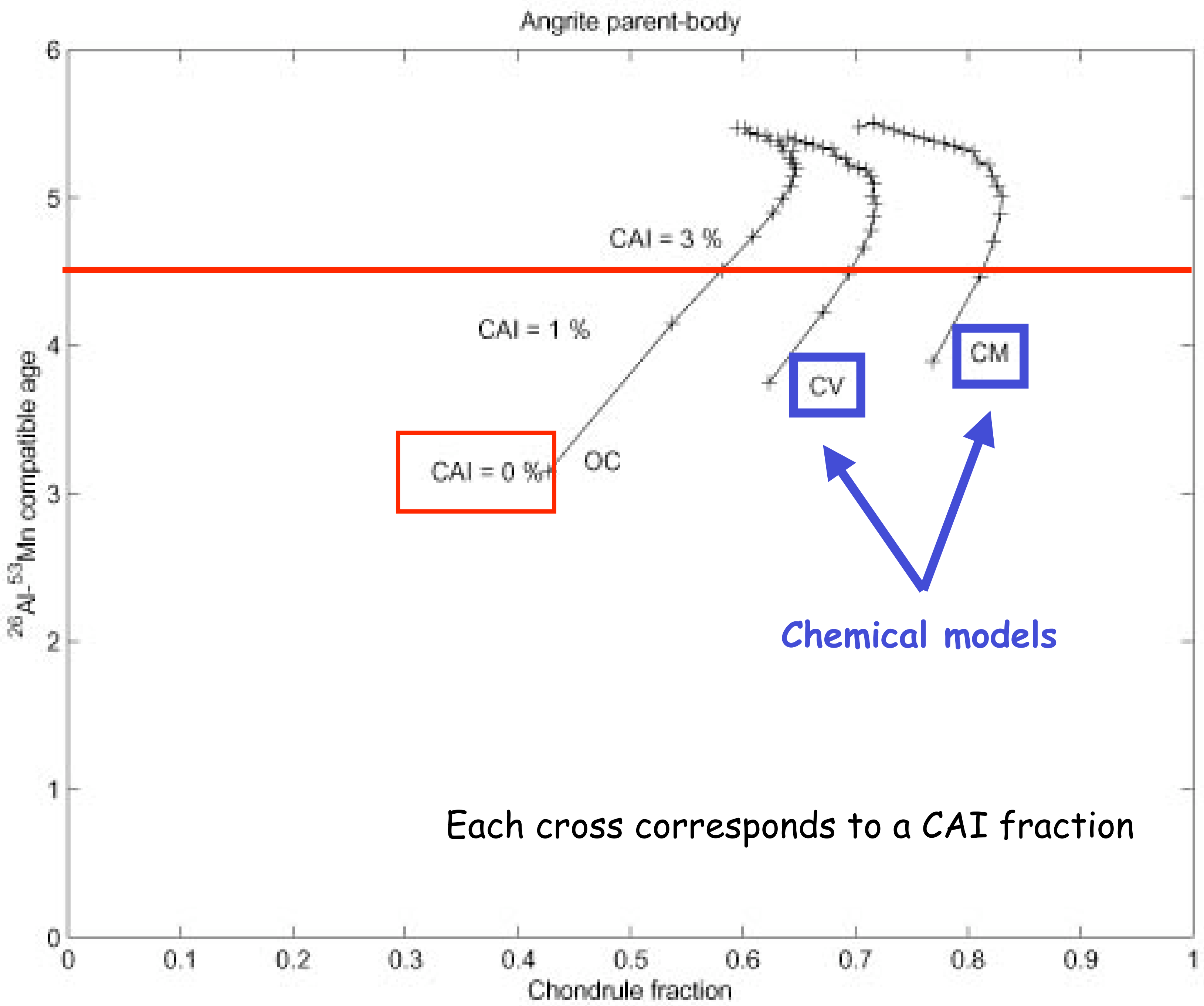
Forget dashed line

For each CAI fraction, there is a **unique compatible** ^{26}Al and ^{53}Mn age

Chronology of Angrites - data

- Angrites are differentiated meteorites
- ^{26}Al and ^{53}Mn data for the **d'Orbigny** angrite
  - $^{26}Al/^{27}Al = (2.3 \pm 0.8) \times 10^{-7}$
  - $^{53}Mn/^{55}Mn = (2.83 \pm 0.25) \times 10^{-6}$

Nyquist et al 2003


Angrite parent-body
^{26}Al-^{53}Mn compatible age
Chondrule fraction
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
CAI = 3 %
CAI = 1 %
CAI = 0 %
OC
CV
CM
Chemical models
Each cross corresponds to a CAI fraction

Chronology of Angrites - results

- Angrites have a **compatible ^{26}Al and ^{53}Mn age of 4.5 ± 1 Ma**
  - Since the formation of their CAIs and chondrules precursors

- This corresponds to a CV parent-body having 5 % CAIs and 70 % chondrules
  - This is compatible with what is really observed
  - Experimental petrology suggests that CV chondrites are teh precursors of angrites (Jurewicz et al. 1995)

Chronology of eucrites - data

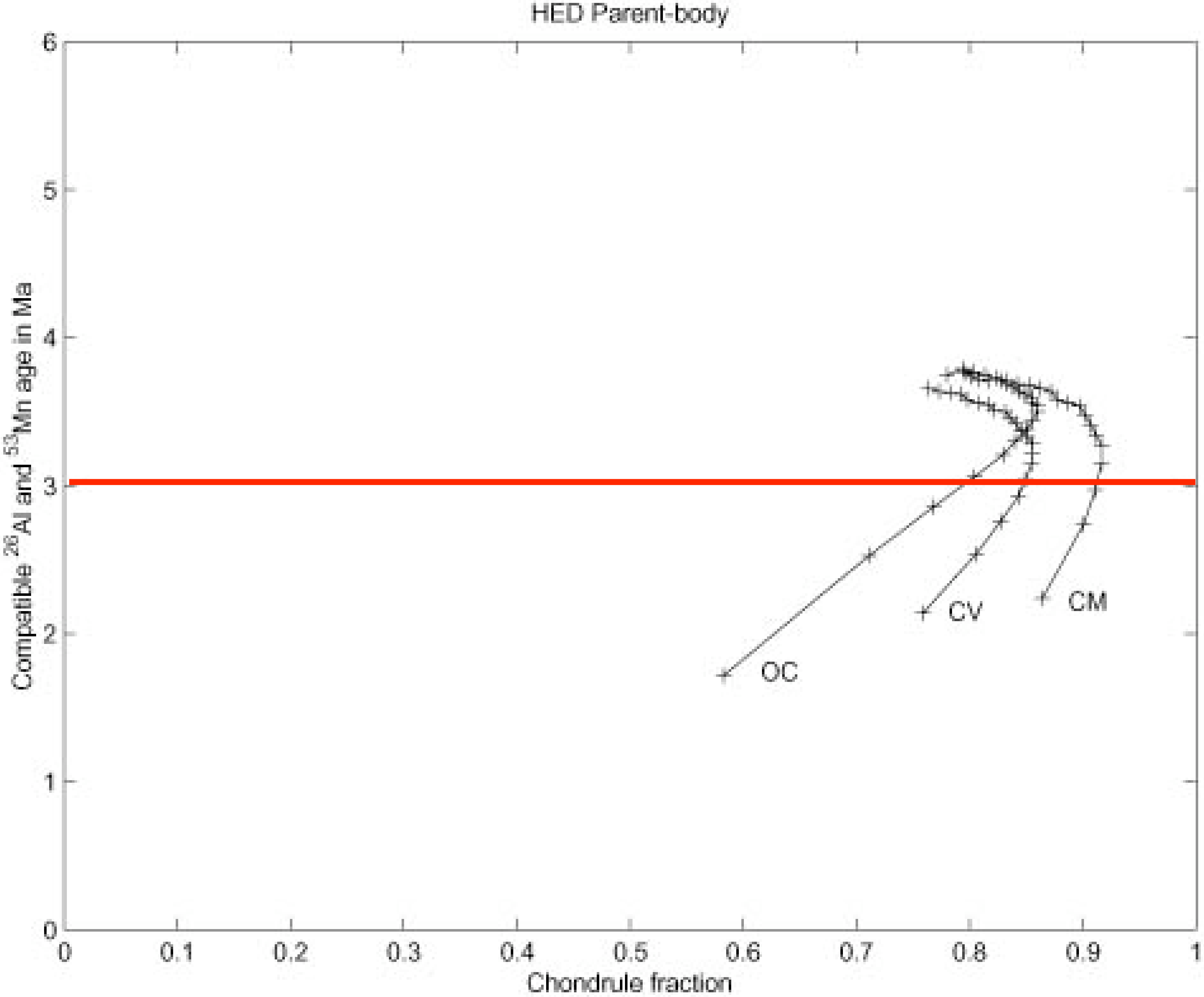
- Eucrites are differentiated meteorites, member of the HED (howardites Eucrites Diogenites) clan

- ^{26}Al and ^{53}Mn data for the **Asuka 881394** eucrite

  - $^{26}Al/^{27}Al = (1.18 \pm 0.14) \times 10^{-7}$

  - $^{53}Mn/^{55}Mn = (4.6 \pm 1.7) \times 10^{-6}$

Nyquist et al 2003


HED Parent-body
Compatible ^{26}Al and ^{53}Mn age in Ma
Chondrule fraction
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
OC
CV
CM

Chronology of eucrites -results

- Eucrites have a **compatible ^{26}Al and ^{53}Mn age of 3 ± 1 Ma**
  - Since the formation of their CAIs and chondrules precursors

- This corresponds to a CM parent-body having 2 % CAIs and 90 % chondrules
- This corresponds to a OC parent-body having 3 % CAIs and 80 % chondrules
  - This does not match perfectly the observed abundances
    - ☆ ***OC***: 0 % CAIs and 80 % chondrules
    - ☆ ***CM:*** 2 % CAIs and 60 % chondrules
- The eucrite parent-body precursor might not be present in our collections
- Mixing between CM and OC matter is supported by some authors (Jurewicz 1993)

Chronology of metamorphosed ordinary chondrites - data

- Sainte Marguerite and Forest Vale are 2 ordinary chondrites that have endured thermal metamorphism (heated but not melted)

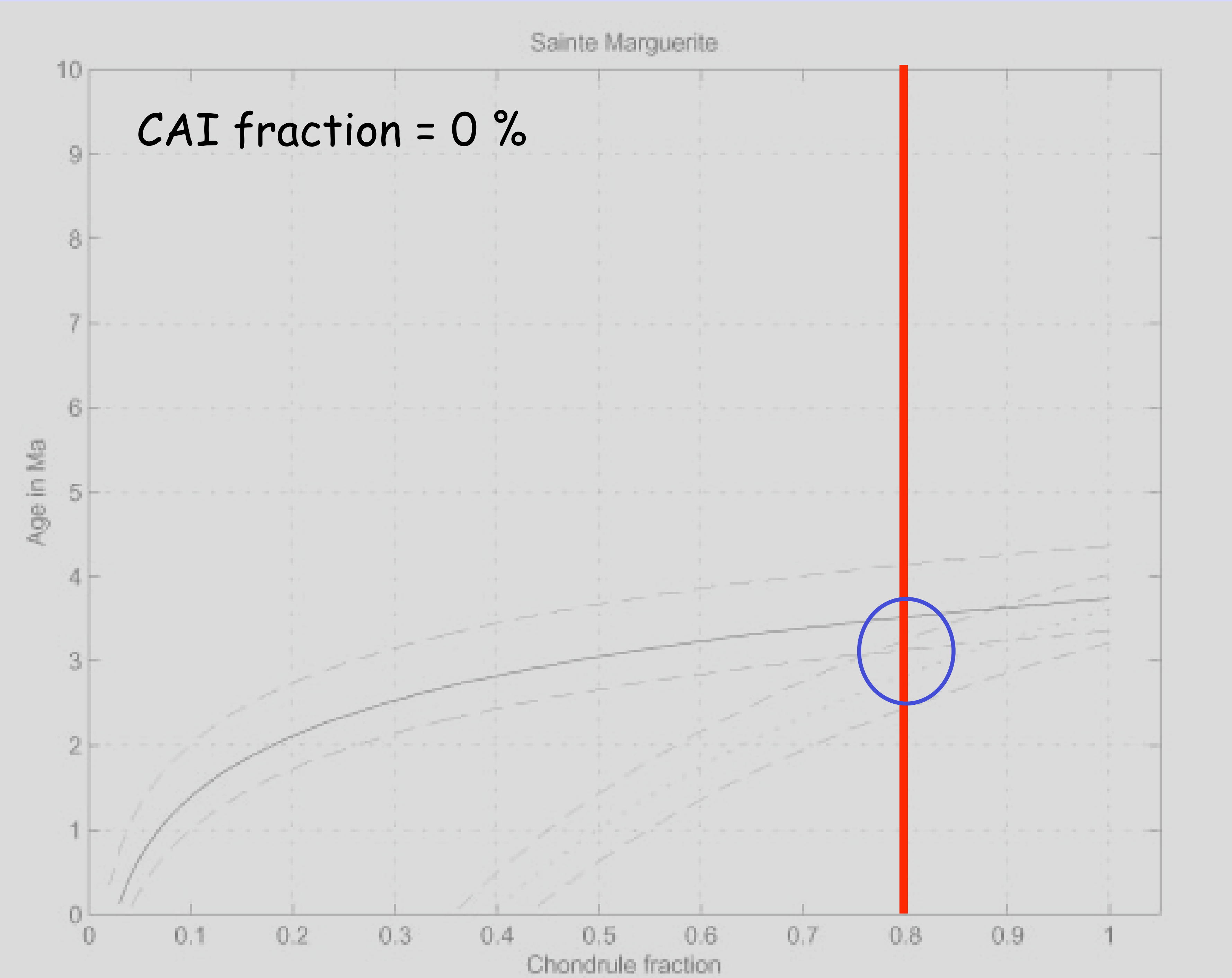
  - $^{26}Al/^{27}Al = (2.87 \pm 0.64) \times 10^{-7}$ Sainte Marguerite
  - $^{53}Mn/^{55}Mn = (4.78 \pm 0.36) \times 10^{-6}$ Sainte Marguerite

  - $^{26}Al/^{27}Al = (1.52 \pm 0.52) \times 10^{-7}$ Forest Vale
  - $^{53}Mn/^{55}Mn = (2.42 \pm 0.31) \times 10^{-6}$ Forest Vale

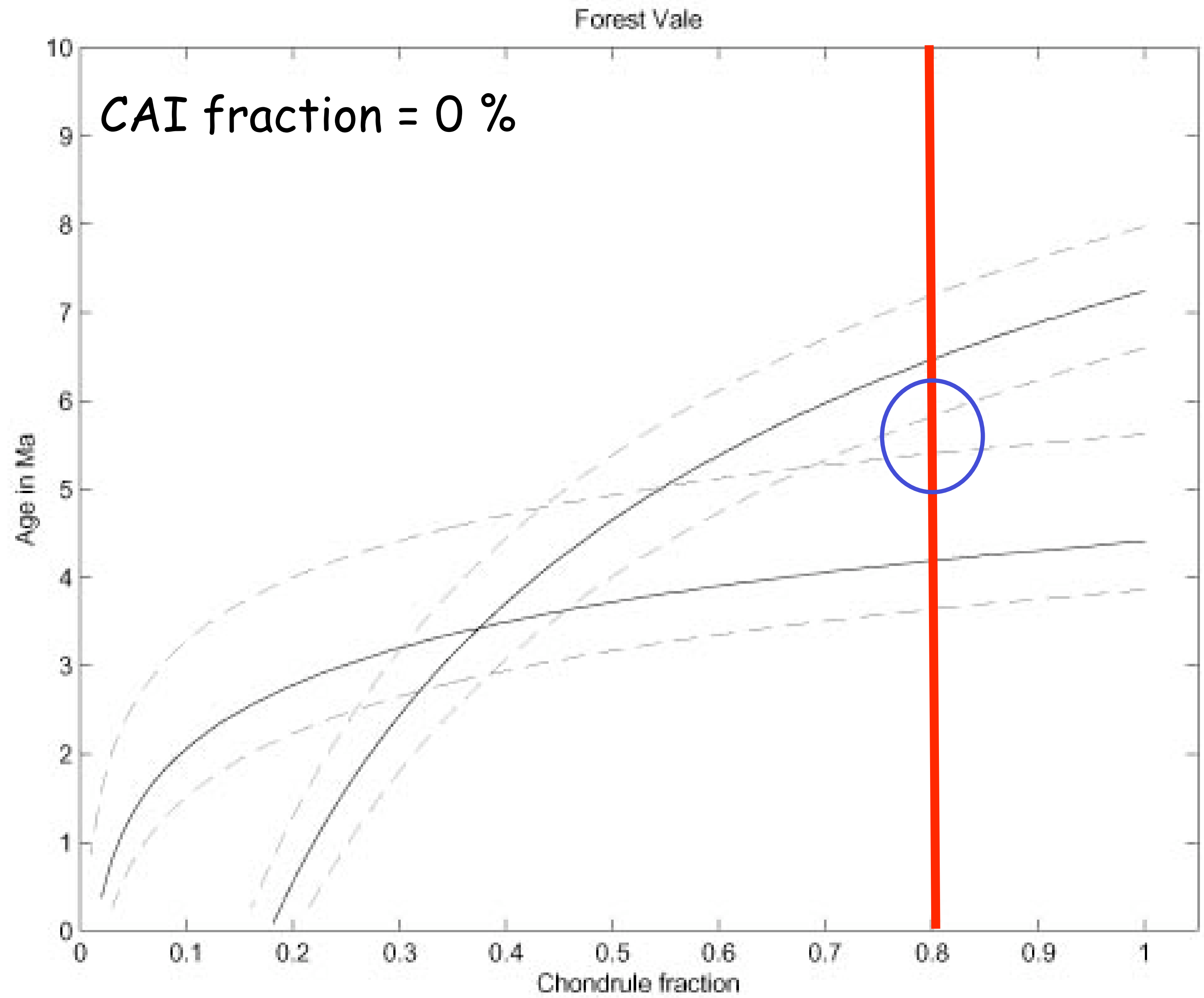
Zinner and Göpel 2002

Chronology of metamorphosed ordinary chondrites – additional constraints

- Sainte Marguerite and Forest Vale have endured thermal metamorphism
- We know the chondritic precursor
  - ~0 % CAIs
  - ~80 % chondrules
- Constraints are a lot tighter



Sainte Marguerite
CAI fraction = 0 %
Age in Ma
Chondrule fraction
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7
8
9
10


Forest Vale
CAI fraction = 0 %
Age in Ma
Chondrule fraction
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1
2
3
4
5
6
7
8
9
10

Chronology of Forest Vale & Sainte Marguerite - results

- For Sainte Marguerite, a 3 ± 1 Ma compatible age is found for a chondrule abundance of 80 %

- For Forest Vale, there is no compatible age found stricto sensu, as within the error bars, the ^{26}Al and ^{53}Mn ages do not intersect at a chondrule abundance of 80 %
  - Mainly because the ^{26}Al age is too high, i.e. the ^{26}Al content too low
  - The mismatch is however very small
  - The ^{26}Al isochron is quite perturbed ?

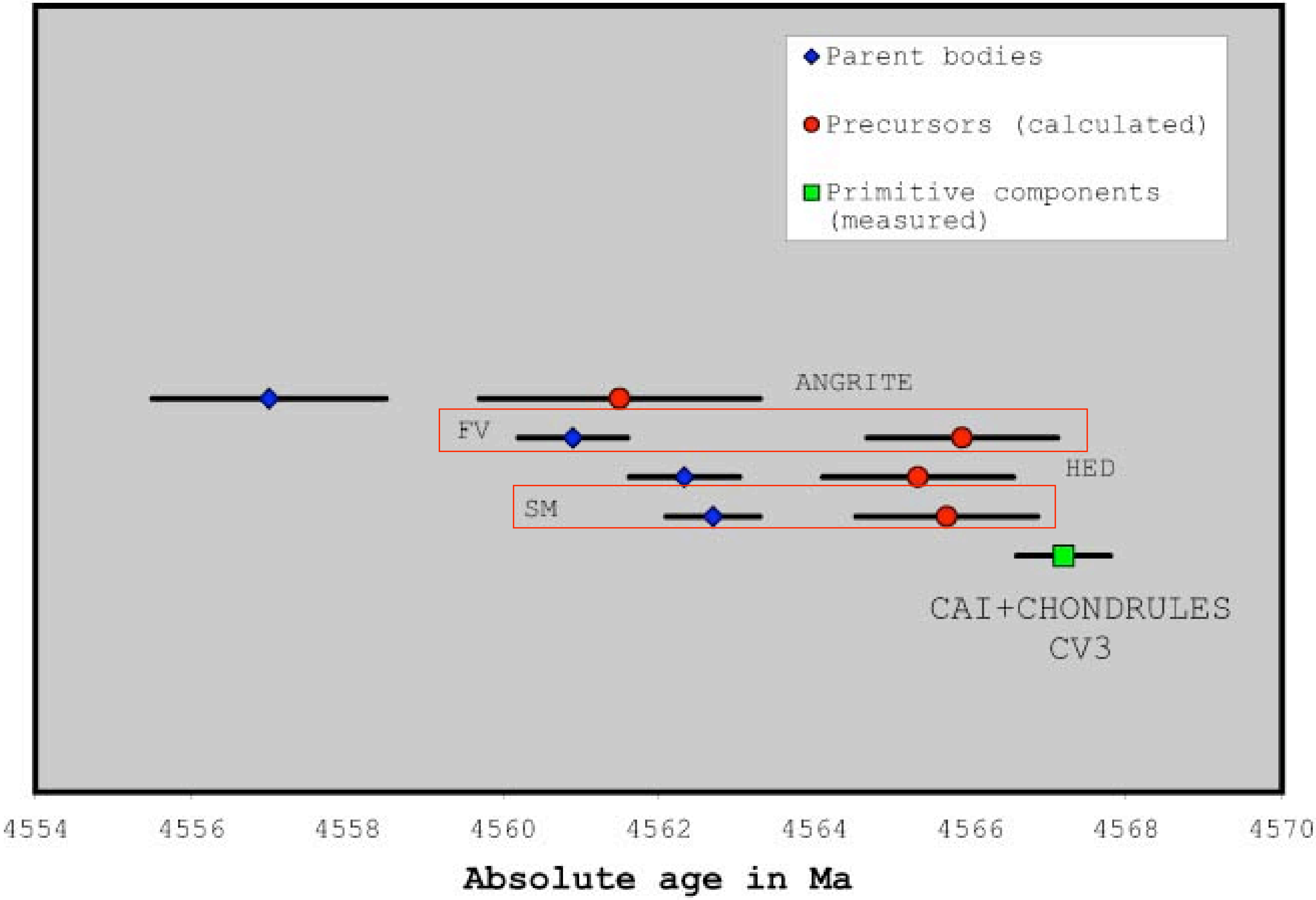
- A 5 ± 1 Ma age for Forest Vale is reasonable

Compatibility with long-lived chronometers (Pb-Pb)

- In our model, ^{182}Hf and U isotopes are homogeneously distributed since they are the product of galactic nucleosynthesis
  - Traditional chronology applies for these systems (Hf-W and Pb-Pb)

- Pb-Pb ages are well characterised for
  - Angrites
  - Sainte Marguerite
  - Forest Vale
  - CV3 CAIs and some chondrules

- The Pb-Pb age of eucrites can be calculated since
  - The initial ^{182}Hf of eucrites is known (Quitté, Birck, Allègre 2001)
  - The initial ^{182}Hf content (Kleine et al. 2003) and the Pb-Pb age of Sainte Marguerite (Zinner & Göpel 2002) is known



Parent bodies
Precursors (calculated)
Primitive components (measured)
ANGRITE
FV
HED
SM
CAI+CHONDRULES
CV3
4554
4556
4558
4560
4562
4564
4566
4568
4570
Absolute age in Ma

Chronology in the context of the heterogeneous accretion disk model

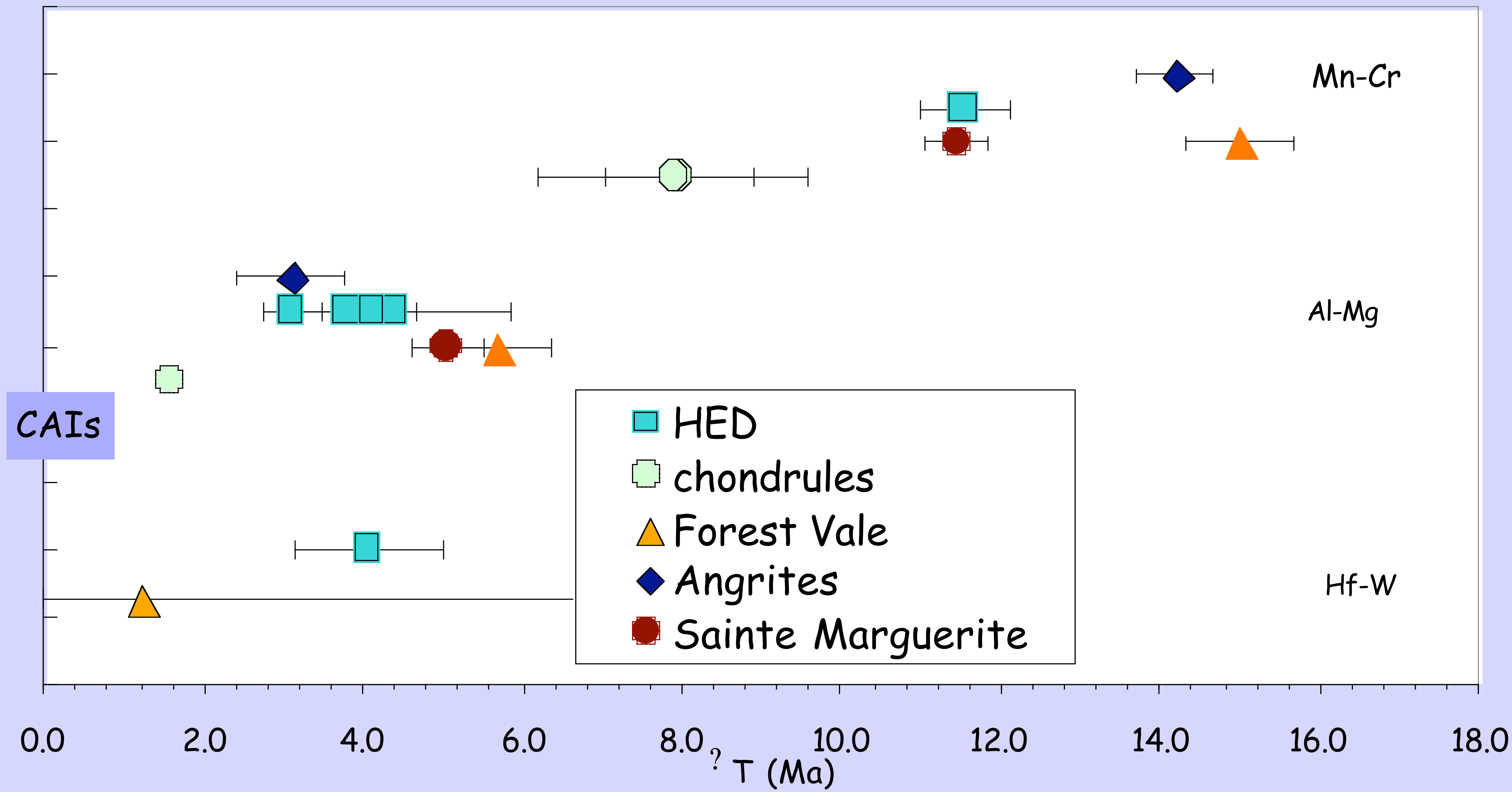
- The problem of the CAIs-chondrule age disappears
  - CAIs and chondrules from the same chondrite group have the same age – **prediction**
  - CAIs and chondrules belonging to different chondrite groups can have the same age
- Ages pretty well constrained (within 1 Ma and “independent” of chemical models)
- Provides compatible ^{26}Al and ^{53}Mn ages for angrites and eucrites (5 and 3 Ma after their respective precursors)

Chronology in the context of the heterogeneous accretion disk model 2

- Provides compatible ^{26}Al and ^{53}Mn ages for the ordinary chondrites Sainte Marguerite and Forest Vale
  - Sainte Marguerite and Forest Vale have compatible precursors

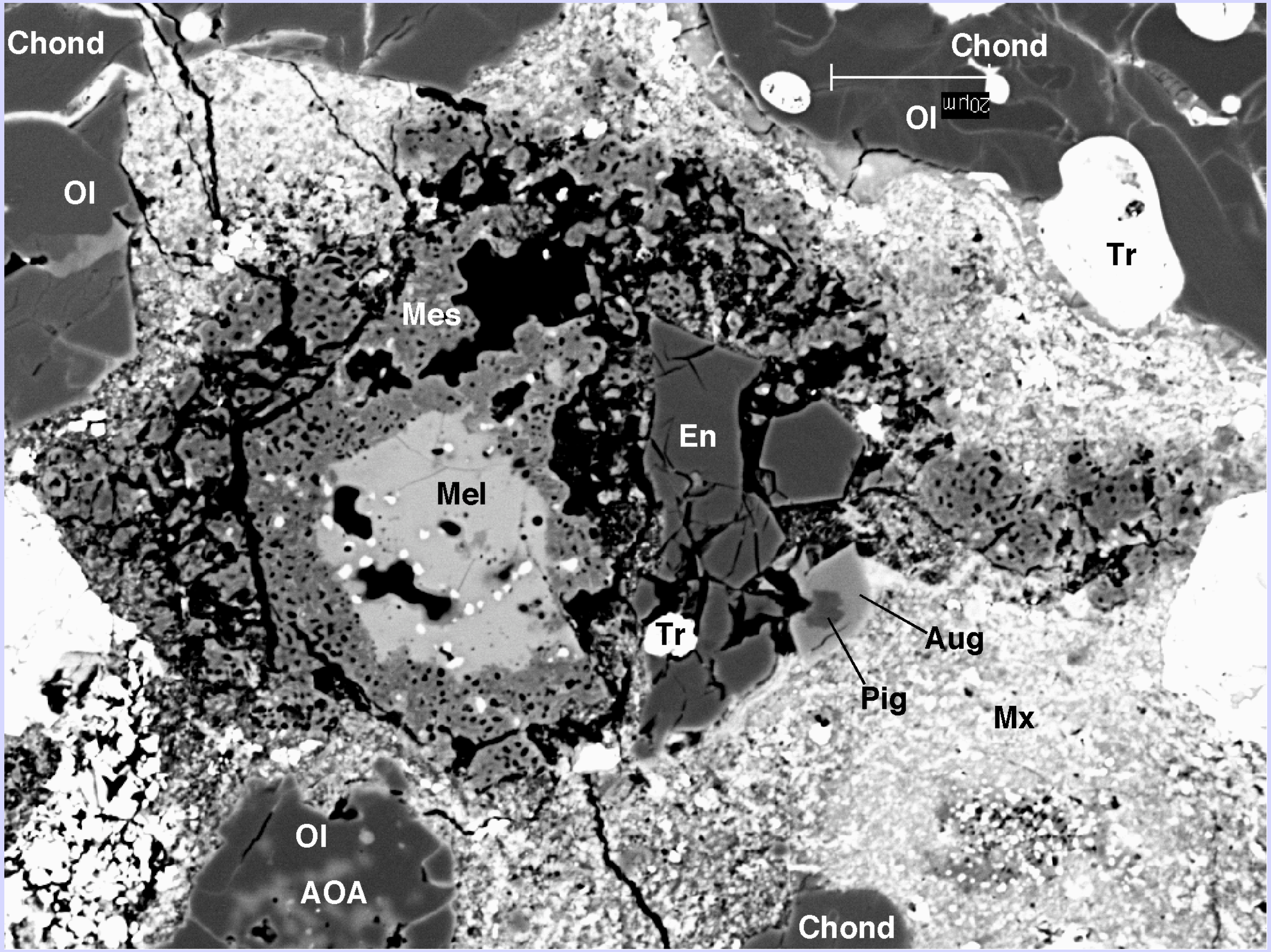
- Unclear how to account for the CI data (Birck et al. 1999)
  - Our model is an **end-member** model (heterogeneous vs homogeneous)
  - The history of CI chondrites unclear?
  - Chondrules from carbonaceous chondrites have different ^{53}Mn initial content than chondrules from ordinary chondrites

- Remember: ^{26}Al is a gamma-ray emitter
  - Proposed to be the heat source for differenciation
  - No delay between ^{26}Al synthesis and incorporation within the parent-body= higher initial ^{26}Al content than in other models
  - Heating and differenciation is less of a problem



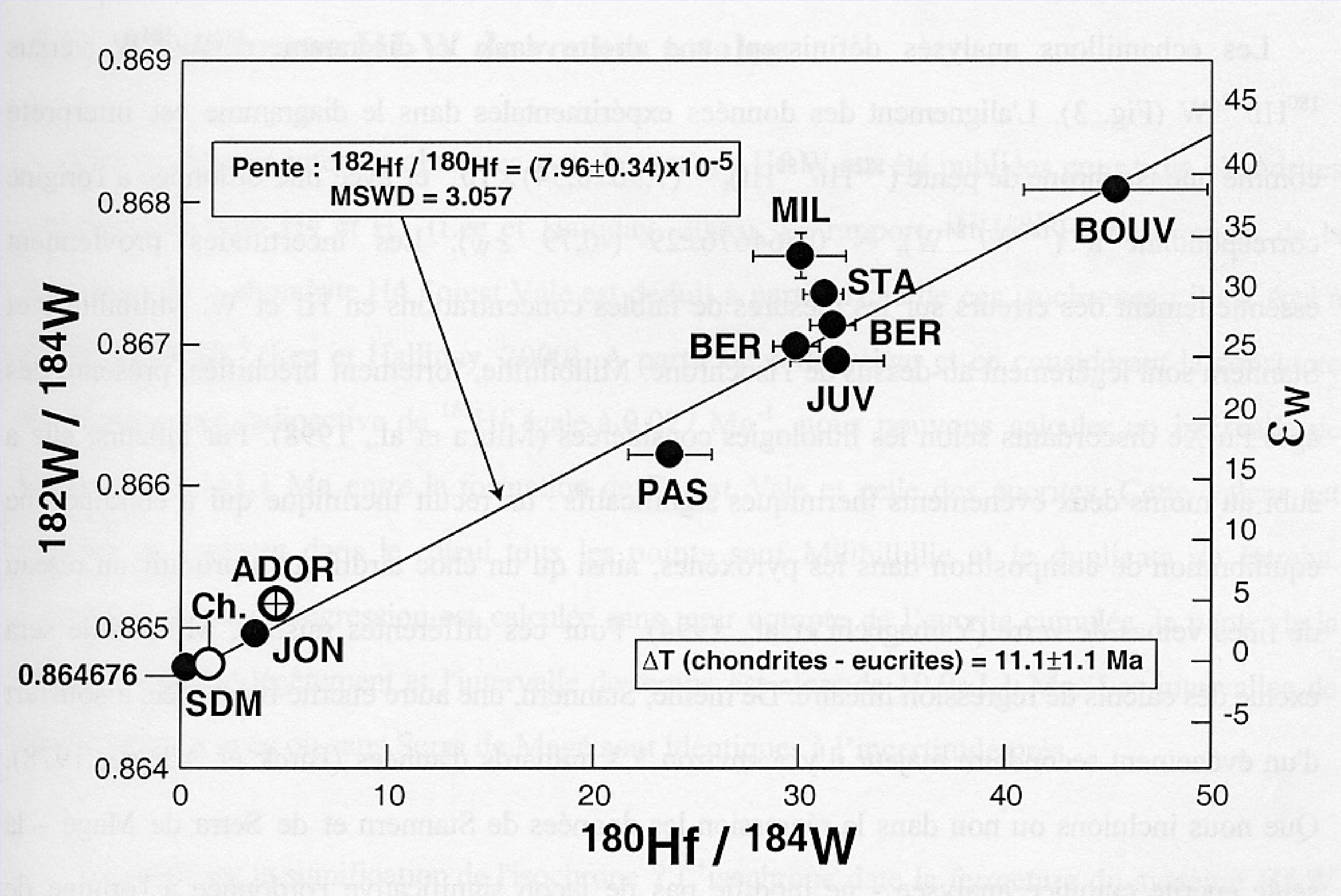
HED: Planetary differentiates (eucrites)
SM & FV: Primitive meteorites

CAI enclosed in a chondrule

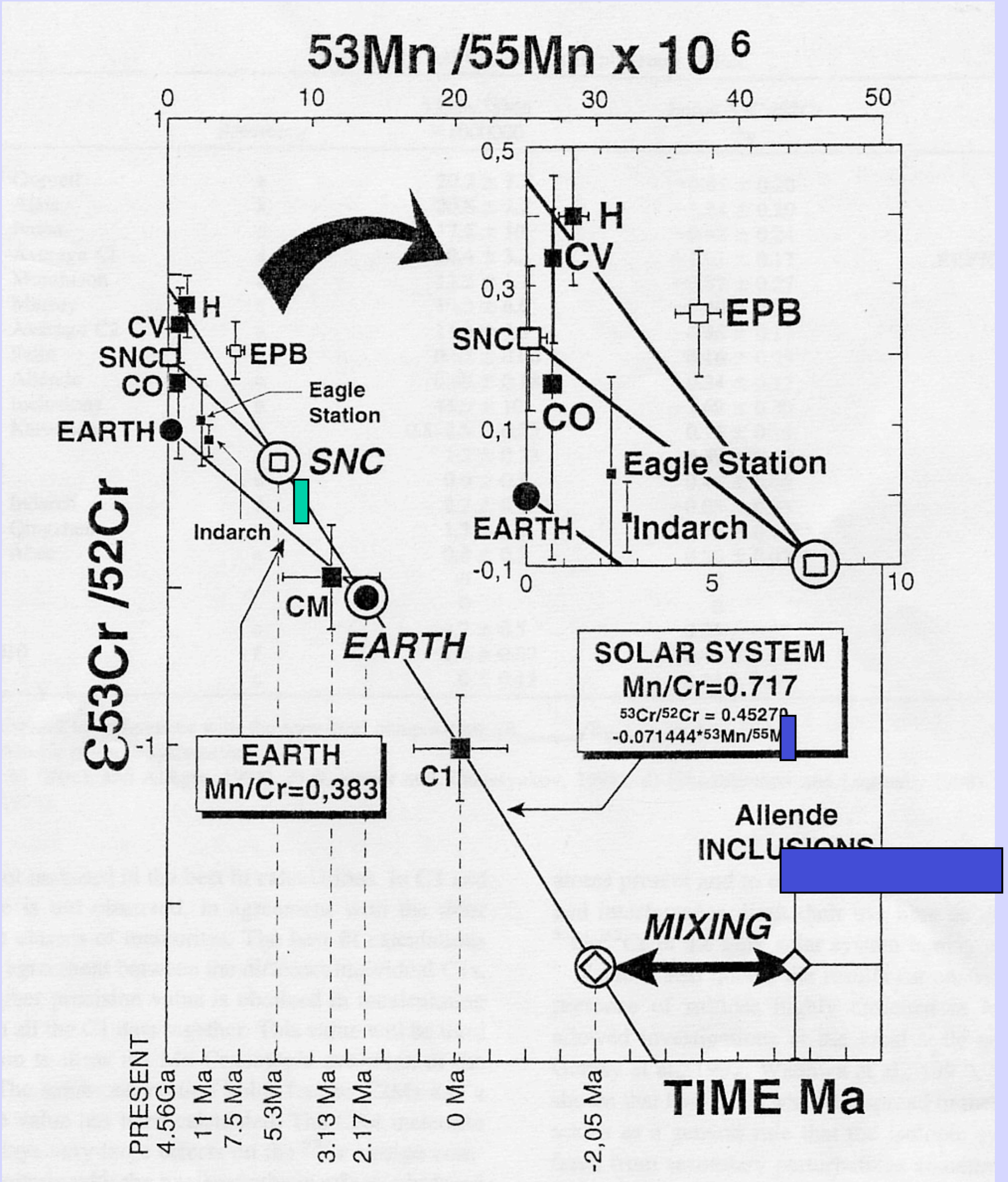


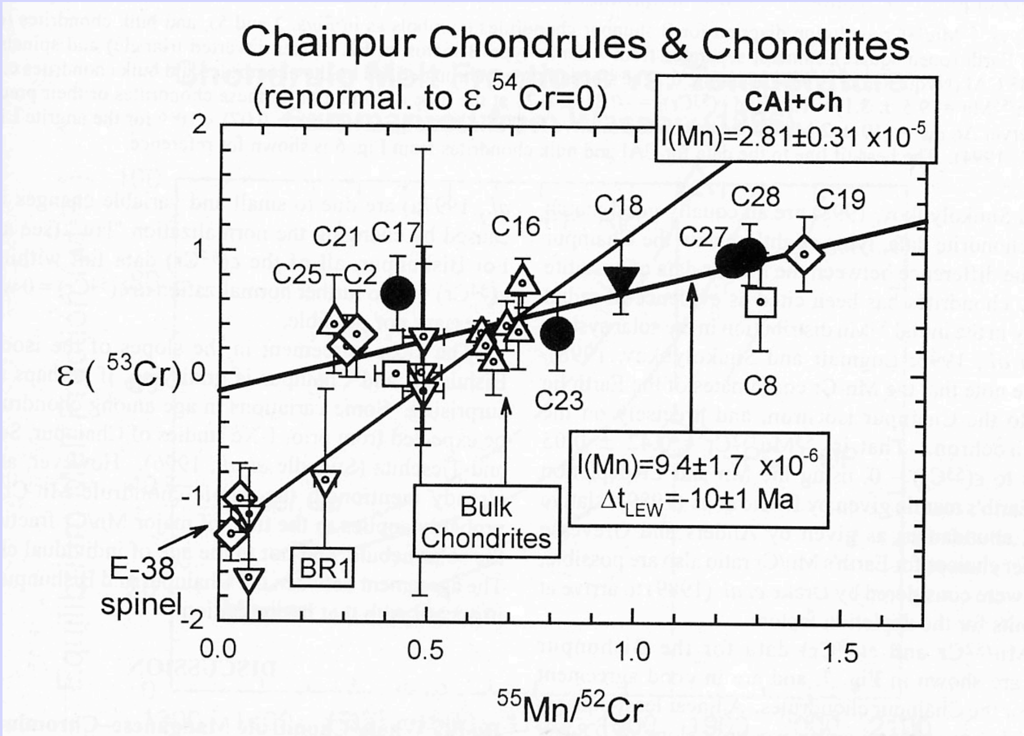
Contemporaneous formation of chondrules and refractory inclusions in the early Solar System

Itoh & Yurimoto (2003) Nature **423** pp728-731



Pente : 182Hf / 180Hf = (7.96±0.34)x10-5
MSWD = 3.057
ΔT (chondrites - eucrites) = 11.1±1.1 Ma
182W / 184W
180Hf / 184W
εW
MIL
STA
BER
BER
JUV
PAS
BOUV
ADOR
Ch.
JON
SDM
0.864676
0.869
0.868
0.867
0.866
0.865
0.864
0
10
20
30
40
50
45
40
35
30
25
20
15
10
5
0
-5


53Mn /55Mn x 10 6
0
10
20
30
40
50
1
-1
ε53Cr /52Cr
H
CV
SNC
EPB
CO
Eagle Station
EARTH
SNC
Indarch
CM
EARTH
C1
EARTH Mn/Cr=0,383
0,5
0,3
0,1
-0,1
0
5
10
H
CV
EPB
SNC
CO
Eagle Station
EARTH
Indarch
SOLAR SYSTEM
Mn/Cr=0.717
53Cr/52Cr = 0.45270
-0.071444*53Mn/55M
Allende
INCLUSIONS
MIXING
PRESENT
4.56Ga
11 Ma
7.5 Ma
5.3Ma
3.13 Ma
2.17 Ma
0 Ma
-2,05 Ma
TIME Ma



Nyquist et al. (2001)

The initial abundances of ^{26}Al and ^{53}Mn

- **$^{26}Al/^{27}Al = 5 \times 10^{-5}$**
  - Lee, Papanastassiou and Wasserburg (1976)
  - Decades of measurements leading to a canonical value

- **$^{53}Mn/^{55}Mn = 4.4 \times 10^{-5}$**
  - Birck & Allègre (1984)
  - Confirmed by Nyquist et al ($^{53}Mn/^{55}Mn = 3 \pm 0.5 \times 10^{-5}$) in 1999
  - Confirmed by Papanastassiou et al. ($^{53}Mn/^{55}Mn = 1\text{-}10 \times 10^{-5}$) in 2002

The initial abundance of ^{182}Hf

$^{182}Hf/^{180}Hf = 1 \times 10^{-4}$

- Yin et al. 2003
- Kleine et al. 2003
- Not a CAI isochron value