The origin of short-lived radionuclides

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Why are extinct short-lived radionuclides important?

- Fact
  - Extinct **short-lived radionuclides** were present in the protoplanetary disk

- Questions
  - Constraints on the **astrophysical environment** of the protoSun
  - Constraints on the **irradiation conditions** in the protoplanetary disk
  - Possibility to build a **chronology** for the radionuclides whose initial distribution is well known
  - <u>Is our Solar System typical ?</u>

- Extinct short-lived radioactivities within meteorites

La décroissance radioactive: rappels

- Découverte par Becquerel en 1896
- Radioactivité α: ${}^{A}_{Z}P$ ◊ ${}^{A-4}_{Z-2}F + {}^{4}He$
- Radioactivité β⁻: ${}^{A}_{Z}P$ ◊ ${}^{A}_{Z-1}F + e^{-} + \bar{\nu}_e$ (n ◊ p+e⁻+ν̄)
- Radioactivité β⁺: ${}^{A}_{Z}P$ ◊ ${}^{A}_{Z+1}F + e^{+} + \nu_e$ (n ◊ p+e⁻+ν)

$$F(t) = F(0) \times \exp[-\lambda \, . \, t] \text{ ou } F(t) = F(0) \times (1/2)^{-t/T}$$

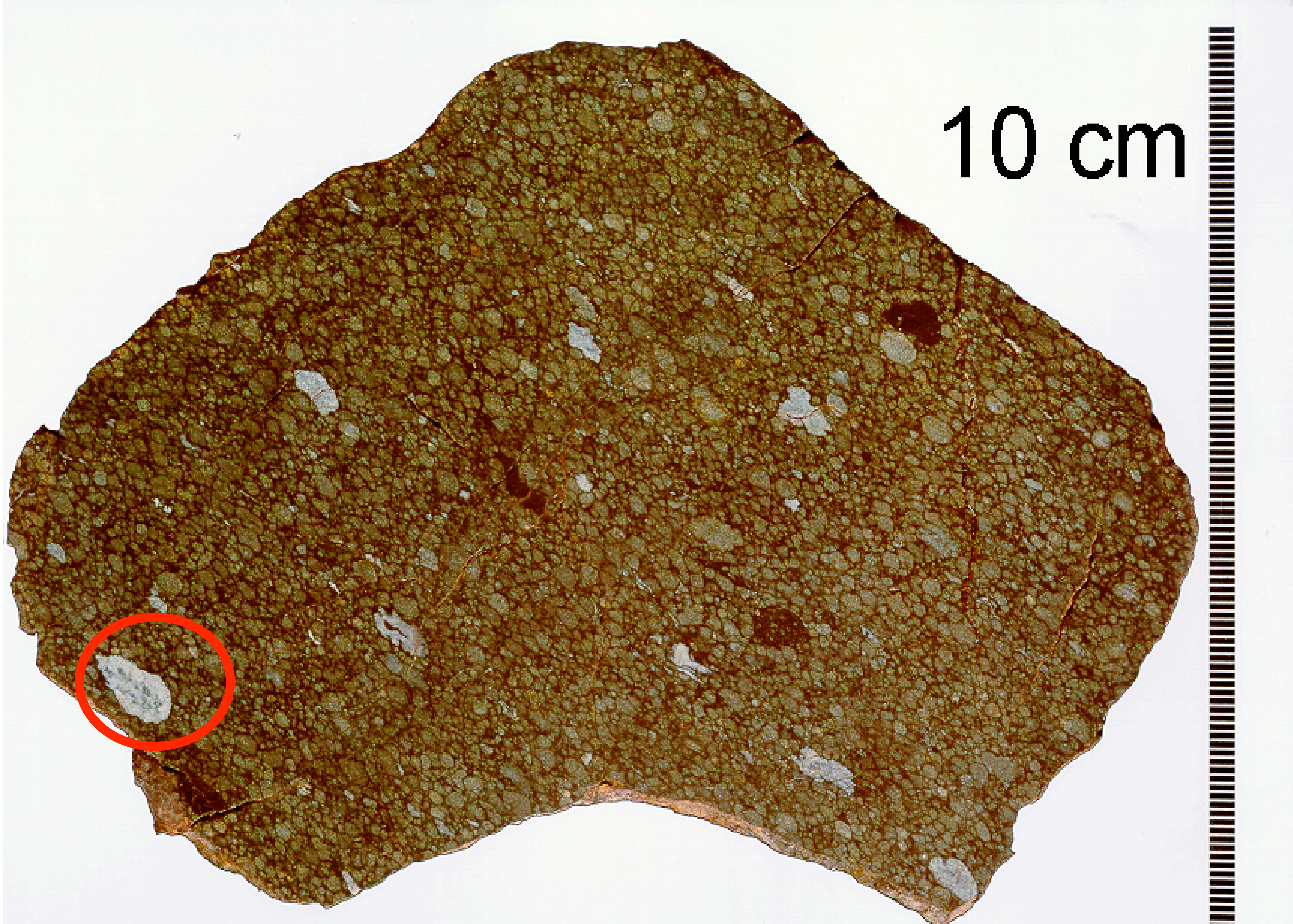
- Décroissance radioactive caracterisée par **la constante de décroissance radioactive (λ)** ou la **période ($T_{1/2}$)**

- **Exemples:**
  - ${}^{14}C$ ◊ ${}^{14}N + e^{-} + \nu_e$ (β^{-})
    - Utilisé pour les datations en archéologie ($T_{1/2}$ = 5730 ans)
  - ${}^{26}Al$ ◊ ${}^{26}Mg^{*} + e^{+} + \bar{\nu}_e$ (β^{+}) ($T_{1/2}$ = 0.73 Ma)
    - Mg^{*} se désexcite en émettant un **rayon γ** (1.809 MeV)

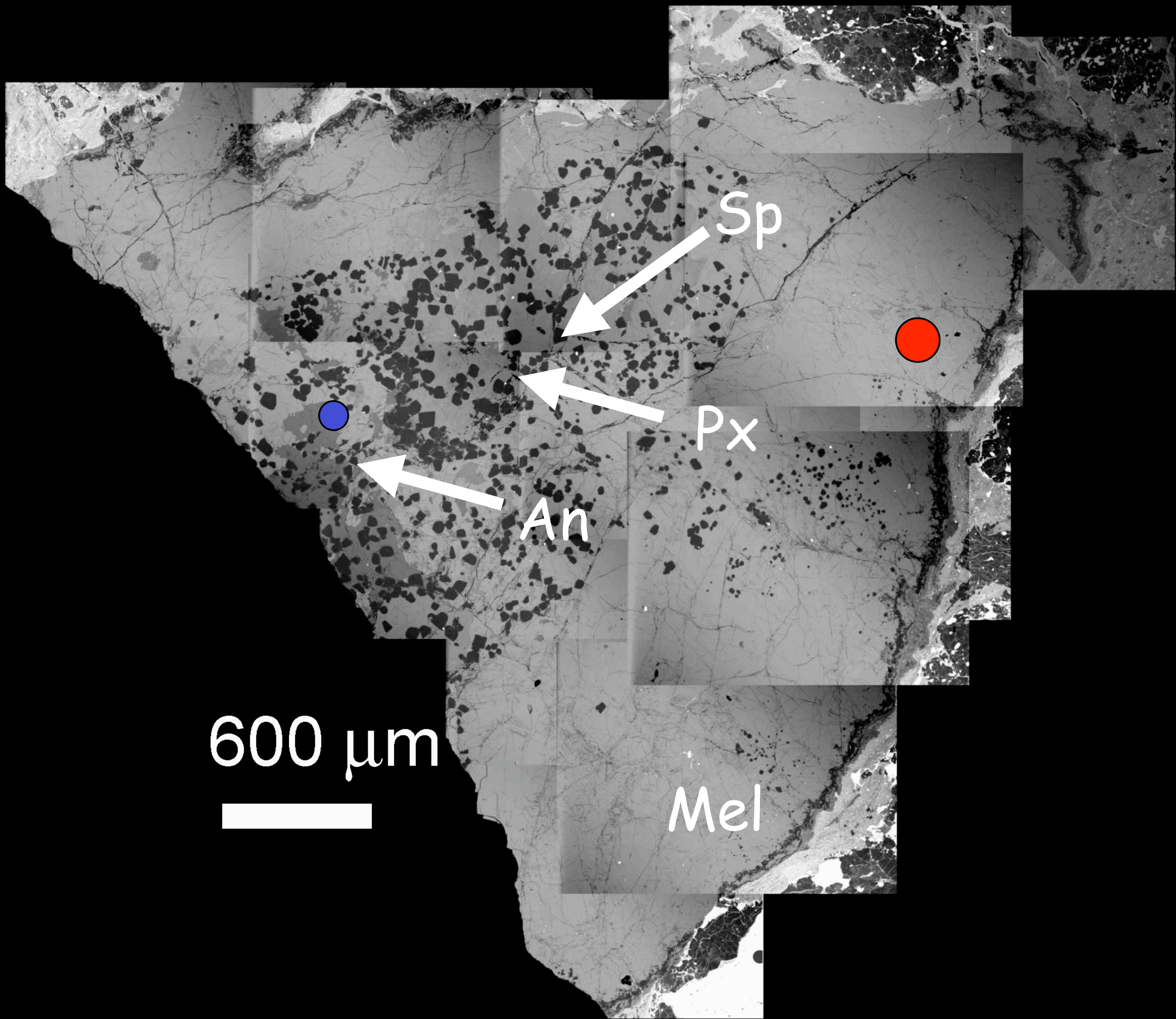
Extinct short-lived radioactivities (ESRs)

- Because their half-life (52 days - 103 Ma) is short compared to the age of the Solar System (~4.6 Ma), they are **now decayed**
- What is detected in meteorite are the daughter isotopes
- Evidence for extinct short-lived radionuclides has been found in
  - Primitive objects (CAIs, chondrules...)
    - Presumed to be young
    - Formed in the accretion disk
  - Differentiated objects (achondrites)
    - Older than CAIs and chondrules
    - Made of the agglomeration of primitive objects ?

Differentiated meteorite: Esquel (pallasite)



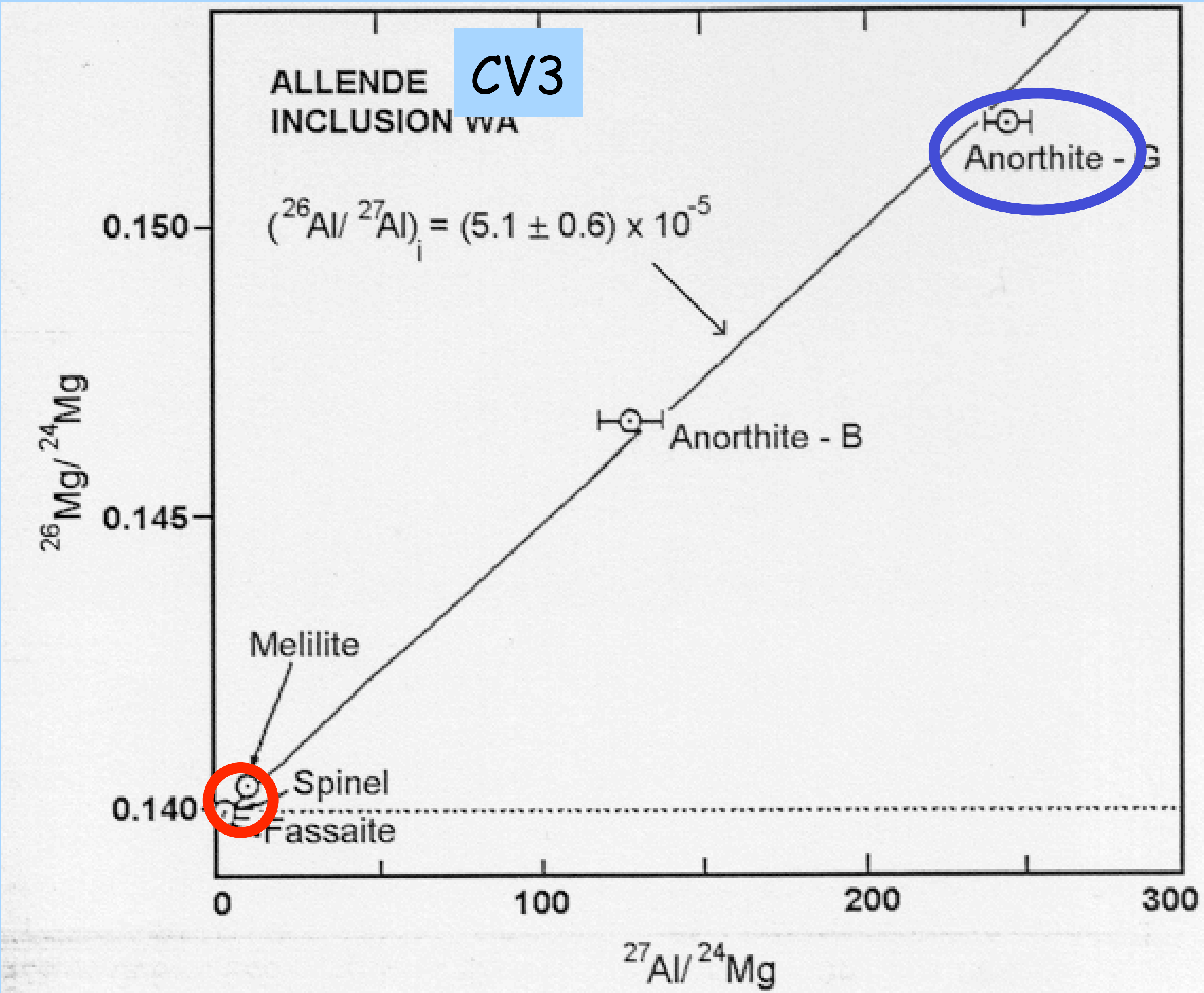
Météorite primitive: chondrite carbonée (Leoville, CV3)



Mélilite
Anorthite
Spinel
Pyroxène

Inclusion réfractaire MRS6 (Leoville, CV3)

Formée il y a ~ 4.567 Ga

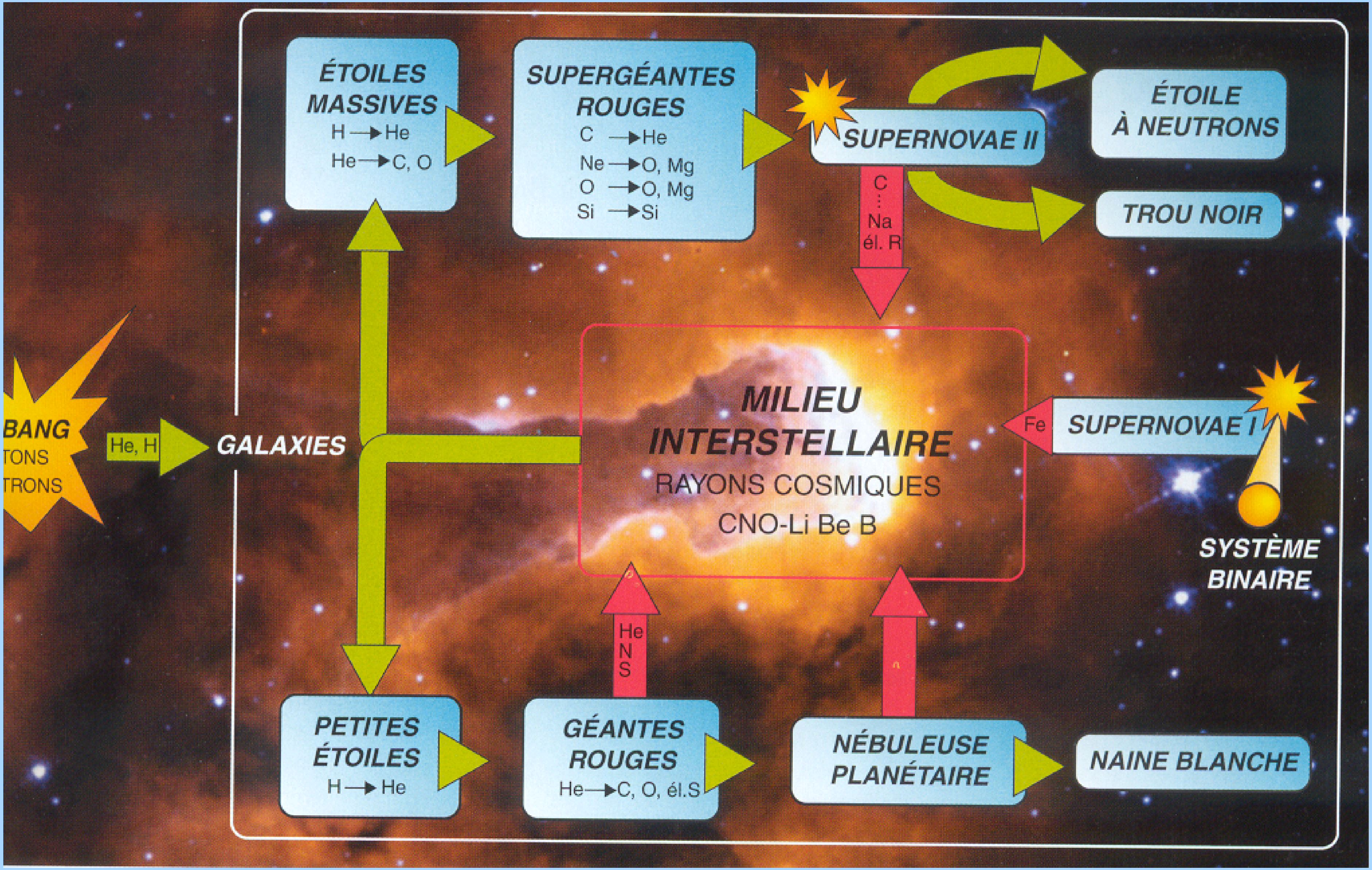


Isochrone révélant la présence passée d'^{26}Al (Lee et al. 1976) au moment de la cristallisation de l'inclusion réfractaire

Radioactive Isotope (R)	T (Ma)	Daughter Isotope	Stable Isotope (S)	Objects
^{7}Be	52 days	^{7}Li	^{9}Be	CAIs
^{41}Ca	0.1	^{41}K	^{40}Ca	CAIs
^{26}Al	0.74	^{26}Mg	^{27}Al	CAIs, CHs, DIFF
^{10}Be	1.5	^{10}B	^{9}Be	CAIs
^{60}Fe	1.5	^{60}Ni	^{56}Fe	CAIs, DIFF
^{53}Mn	3.7	^{53}Cr	^{55}Mn	CAIs, CHs, DIFF
^{107}Pd	6.5	^{107}Ag	^{108}Pd	DIFF
^{182}Hf	9	^{182}W	^{180}Hf	CHs, DIFF
^{129}I	16	^{129}Xe	^{127}I	CAIs, CHs, DIFF
^{92}Nb	36	^{92}Zr	^{93}Nb	CHs, DIFF
^{244}Pu	81	Fission products	^{238}U	CAIs, DIFF
^{146}Sm	103	^{142}Nd	^{144}Sm	DIFF

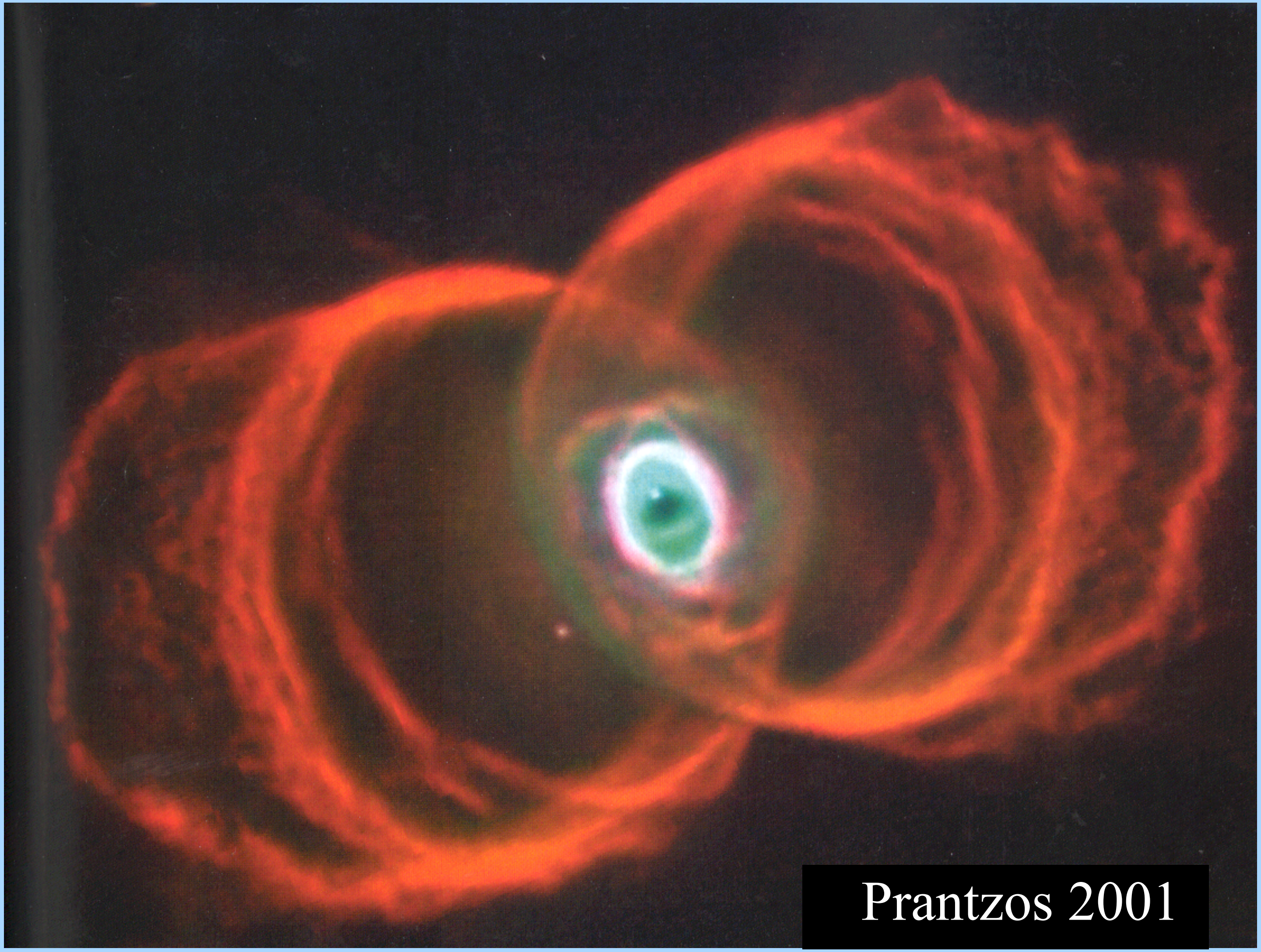
- The origin of the elements in the Galaxy

Évolution chimique de la galaxie



Prantzos 2000

Nébuleuse du sablier (MyCn18)



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L'Évolution chimique de la Galaxie

WOOSLEY & WEAVER

TABLE 19

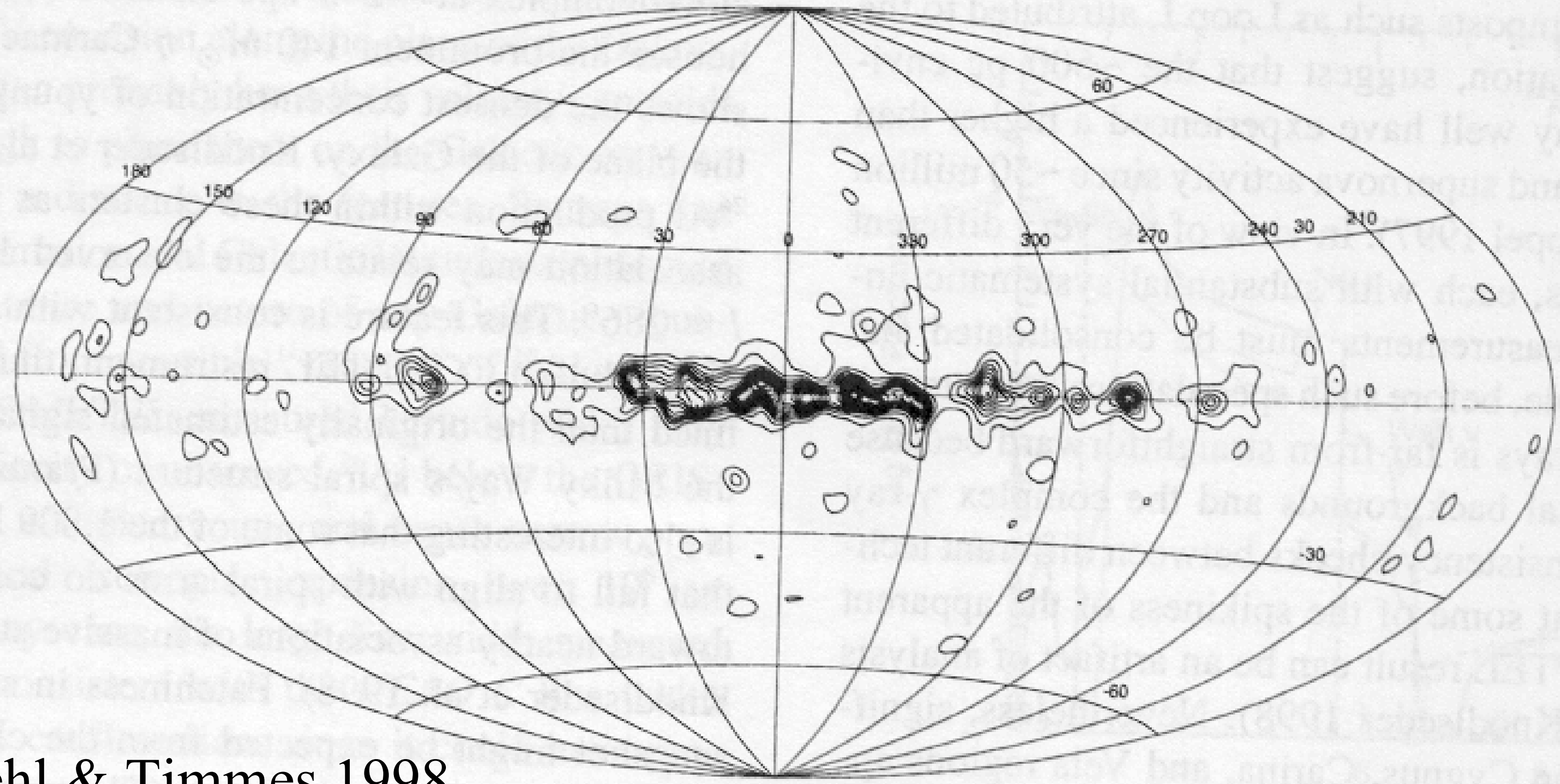
THE ORIGIN OF THE LIGHT AND INTERMEDIATE-MASS ELEMENTS

Species	Origin	Species	Origin	Species	Origin
^{1}H	BB	^{29}Si	Ne,xNe	^{50}Ti	nse-Ia-MCh
^{2}H	BB	^{30}Si	Ne,xNe	^{50}V	Ne,xNe,xO
^{3}He	BB,L*	^{31}P	Ne,xNe	^{51}V	α,Ia-det,xSi,xO,ν
^{4}He	BB,L*,H	^{32}S	xO,O	^{50}Cr	xSi,xO,α,Ia-det
^{6}Li	CR	^{33}S	xO,xNe	^{52}Cr	xSi,α,Ia-det
^{7}Li	BB,ν,L*,CR	^{34}S	xO,O	^{53}Cr	xO,xSi
^{9}Be	CR	^{36}S	Ne,xNe	^{54}Cr	nse-Ia-MCh
^{10}B	CR	^{35}Cl	xO,xNe,ν	^{55}Mn	Ia, xSi, [illegible]
^{11}B	ν	^{37}Cl	xO,xNe	^{54}Fe	[illegible],xSi
^{12}C	L*,He	^{36}Ar	xO,O	^{56}Fe	xSi,Ia
^{13}C	L*,H	^{38}Ar	xO,O	^{57}Fe	xSi,Ia
^{14}N	L*,H	^{40}Ar	C,Ne	[illegible]	He(s),nse-Ia-[illegible]
^{15}N	Nova,ν	^{39}K	xO,O.ν	^{59}Co	He(s),α,Ia,ν
^{16}O	He	^{40}K	C,Ne	^{58}Ni	α,Ia
^{17}O	H	^{41}K	xO	^{60}Ni	α, He(s)
^{18}O	He	^{40}Ca	xO,O	^{61}Ni	α,Ia-det,He(s)
^{19}F	ν,He	^{42}Ca	xO	^{62}Ni	α,He(s)
^{20}Ne	C	^{43}Ca	C,Ne	^{64}Ni	He(s)
^{21}Ne	C,He(s)	^{44}Ca	α,Ia-det	^{63}Cu	He(s), α
^{22}Ne	He	^{46}Ca	C,Ne	^{65}Cu	He(s)
^{23}Na	C,He(s),H	^{48}Ca	nse-Ia-MCh	^{64}Zn	He(s),α
^{24}Mg	C,Ne	^{45}Sc	α,C,Ne,ν	^{66}Zn	He(s),α,nse-Ia-MCh
^{25}Mg	C,Ne,He(s)	^{46}Ti	xO, Ia-det	^{67}Zn	He(s)
^{26}Mg	C,Ne,He(s)	^{47}Ti	xO, xSi, Ia-det	^{68}Zn	He(s)
^{27}Al	C,Ne	^{48}Ti	xSi,Ia-det		
^{28}Si	xO,O	^{49}Ti	xSi,He(s)		

^{26}Al and ^{60}Fe are gamma ray emitters

- ^{26}Al $T_{1/2}$ = 0.73 Ma; γ = 1.809 MeV
- ^{60}Fe $T_{1/2}$ = 1.5 Ma; γ = 1.332 MeV
- ^{60}Fe not seen yet by a gamma-ray satellite
- M_{26Al} = 3.1 ± 0.9 Mo (COMPTEL)
- M_{26Al} = [2.6 ± 0.4 – 4.5 ± 0.7] Mo (GRIS)
- Most important sources for ^{26}Al are massive stars (Knodleseder 1999)
  - SNII
  - Wolf-Rayet stars
- Minor contribution of AGB stars (Busso et al. 1999) and novae

Distribution de l'^{26}Al dans la Galaxie



Diehl & Timmes 1998

2.2 Masses solaires d '^{26}Al dans le milieu interstellaire - essentiellement produit par des supernovae

Origin of the extinct short-lived radionuclides

- Short-lived radionuclies are indeed produced within stars belonging to the Galaxy
- The question: is the abundance of short-lived radionuclides observed in the early Solar System compatible with expectations of Galactic evolution ?
- Two important exceptions: ^{7}Be, ^{10}Be
  - ^{7}Be has too short a half-life (compared to the timescale of star formation of 1 Ma) to have been introduced alive within the Solar System
  - ^{10}Be as all Be isotopes is destroyed in stars, and is formed via spallation reactions
- Two steps
  - Identify the initial abundance in early Solar System (CAIs ?)
  - Compare this initial abundance to the Galactic evolution models

Early Solar System abundances of ESRs

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

- **$^{41}Ca/^{40}Ca = 1.5 \times 10^{-8}$**
  - Srinivasan, Ulyanov and Goswami (1994)
  - Found in CAIs from CV3 and CM2 chondrites

- **$^{53}Mn/^{55}Mn = 4.4 \times 10^{-5}$**
  - 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
  - Found only in CV3 chondrites
  - Variable initial abundance ?

NEW

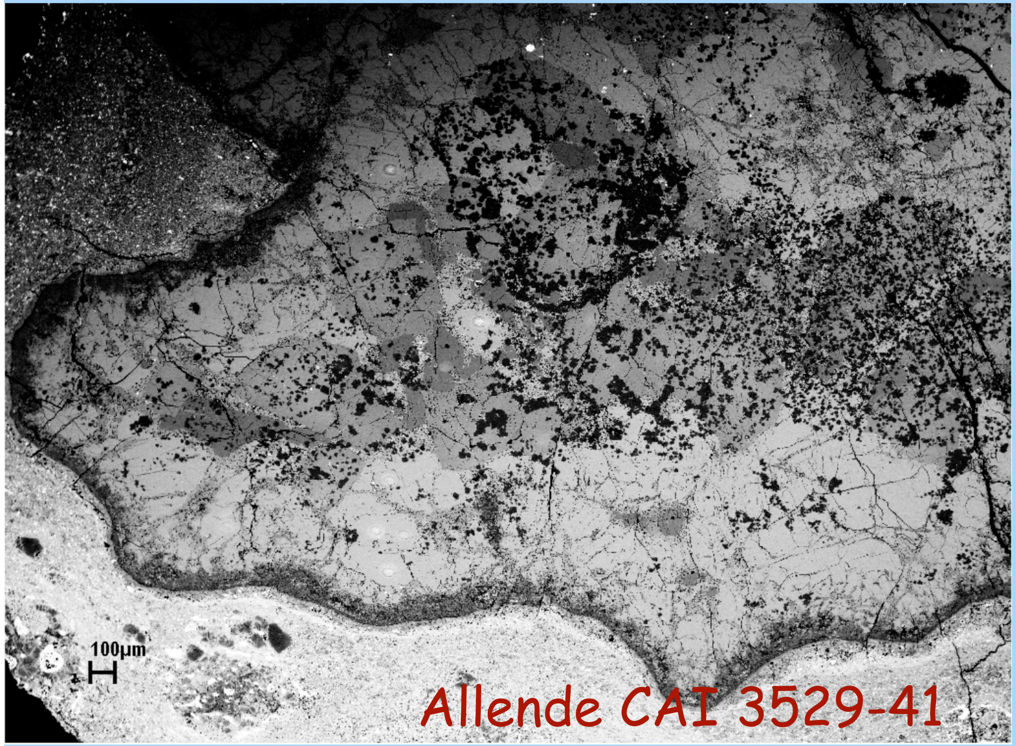
Early Solar System abundances of ESRs 2

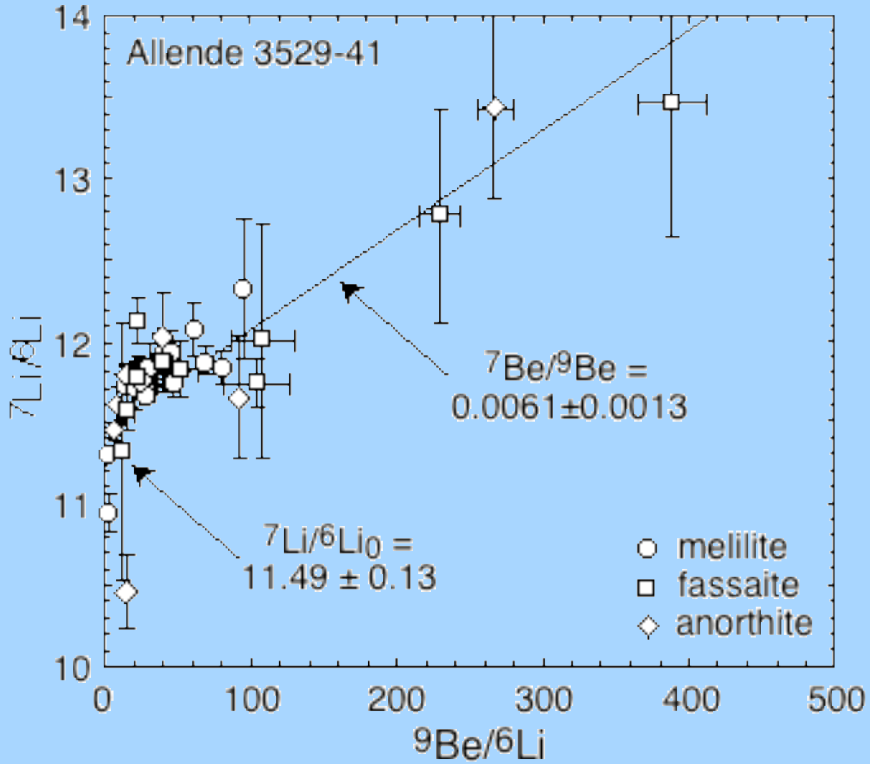
- **$^{10}Be/^{9}Be = 0.87 \times 10^{-3}$**
  - McKeegan, Chausidon & Robert (2000)
  - Now found in CAIs from CV3 and CM2 chondrites
  - Average value from 17 CAIs

VERY NEW

- **$^{36}Cl/^{35}Cl = (5\text{-}11) \times 10^{-6}$**
  - Lin et al. (2004 – LPSC)
  - Alteration phases in Ningqiang (CV-an) CAIs
  - True initial Solar System ratio unknown yet

Discovery of ^7Be (Chaussidon et al. 2004)





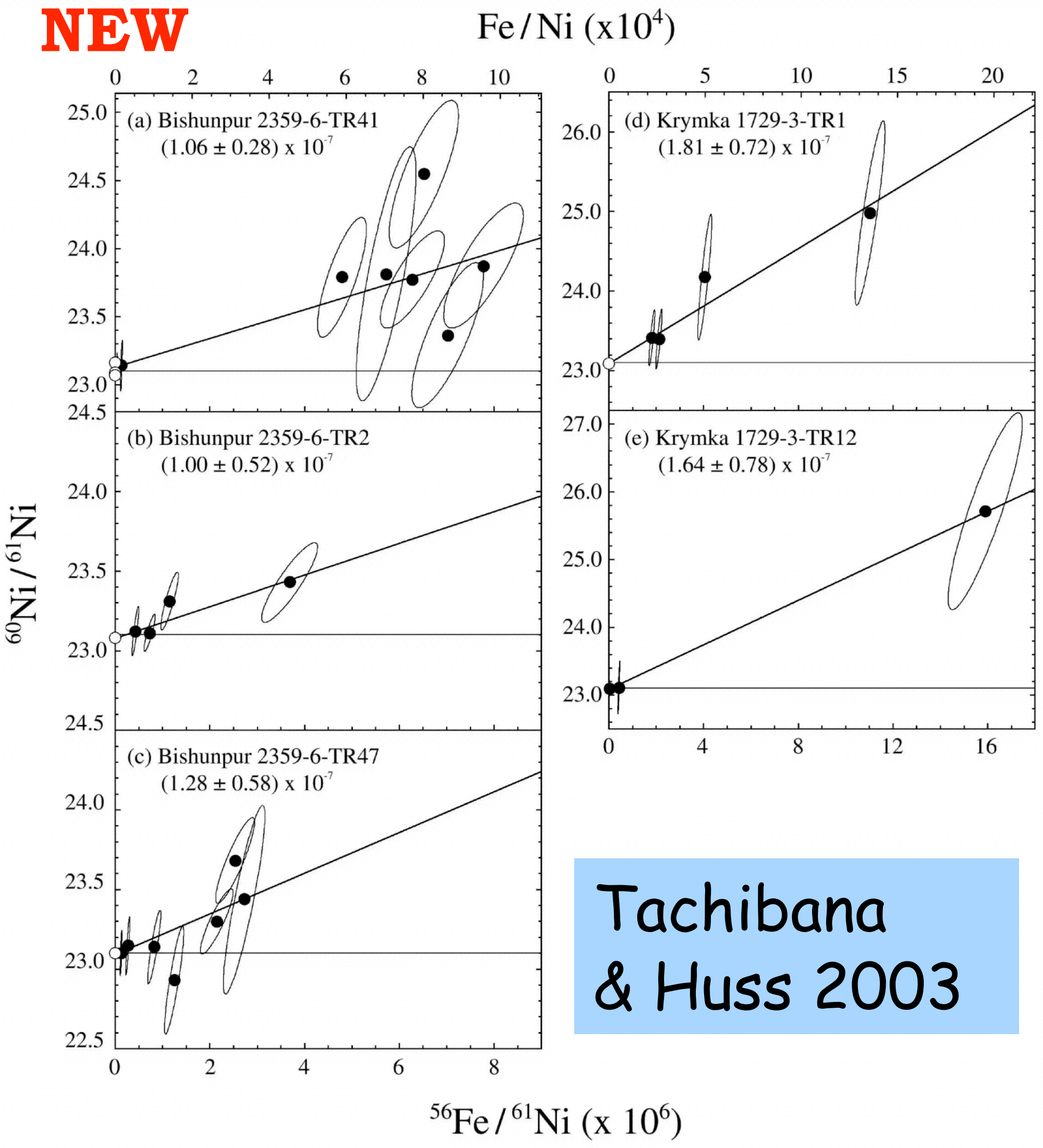
- $^7Be/^9Be = 6.1 \times 10^{-3}$
  - Chausidon, Robert and McKeegan (2004)
  - Allende CAI USNM 3529-41

NEW

- **Previously $^7Be/^9Be$ = [0-220±130]** $\times 10^{-3}$
  - Chaussidon, Robert & McKeegan (2002)
  - Allende CAI USNM 3515

The $^{60}Fe/^{56}Fe$ ratio of ordinary chondrites

- $(1.08 \pm 0.23) \times 10^{-7}$
  - ☆ Krymka LL3.1
  - ☆ Tachibana & Huss 2003
- $(1.73 \pm 0.53) \times 10^{-7}$
  - ☆ Bishunpur LL3.1
  - ☆ Tachibana & Huss 2003
- $(7.5 \pm 2.6) \times 10^{-7}$
  - ☆ Semarkona LL3.0
  - ☆ Mostefaoui et al. 2003



Tachibana & Huss 2003

The previous $^{60}Fe/^{56}Fe$ data

- CAIs
  - ☆ < 1.6×10^{-6} (Birck & Lugmair 1988)
  - ☆ < 1.7×10^{-6} (Choi et al 1999)

- Chondrules
  - ☆ < 1.4×10^{-7} (Kita et al 2000)

- Planetary differentiates (eucrites)
  - ☆ $(3.9 \pm 0.6) \times 10^{-9}$ (Chervony Kut, Shokolyukov & Lugmair 1993)
  - ☆ $(4.3 \pm 1.5) \times 10^{-10}$ (Juvinas, Shokolyukov & Lugmair 1993)

☆ The initial $^{60}Fe/^{56}Fe$ was poorly constrained

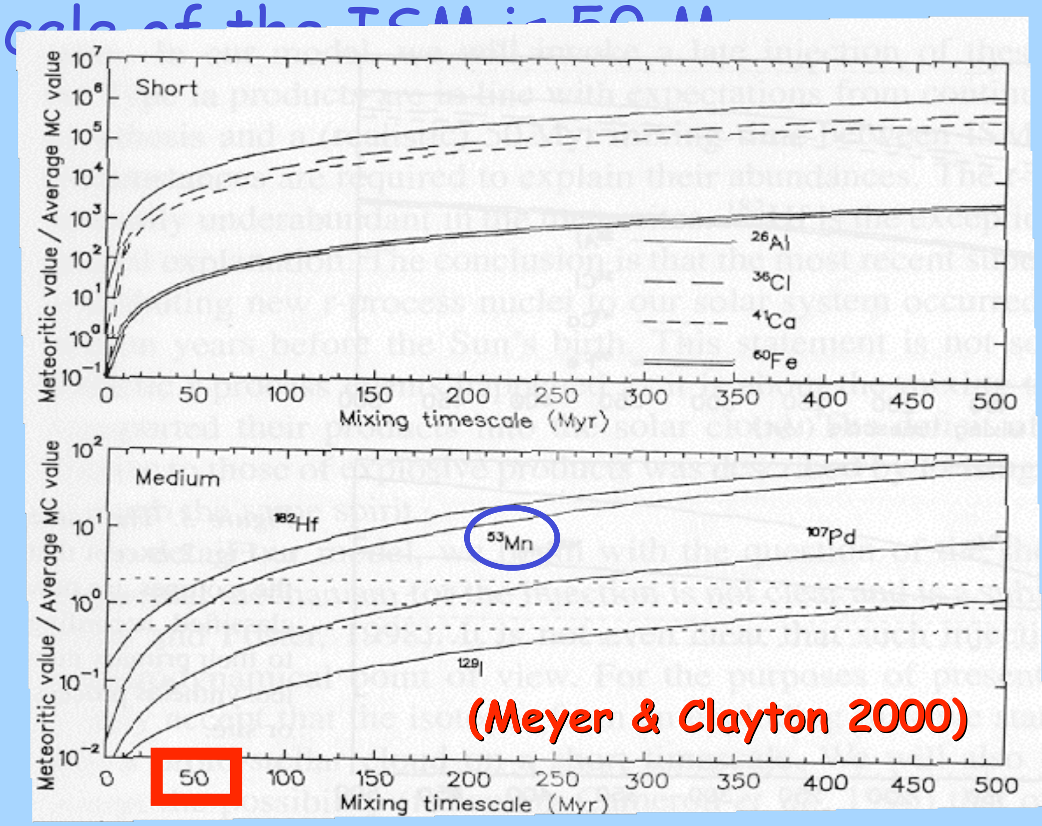
☆ Estimates were marginally compatible with continuous galactic nucleosynthesis

☆ **New data are incompatible with continuous galactic nucleosynthesis**

A model of Galactic evolution for ESRs

The abundance of ESRs in the ISM is a balance between stellar production and decay

For example, in Clayton chemical model of the Galaxy, the mixing timescale of the ISM is 50 M



Galactic evolution for ESRs

☆Some ESRs are underabundant in the Solar System compared to the continuous galactic production (^{107}Pd,^{129}I)

☆Some ESRs have an early Solar System abundance compatible with the continuous galactic production (^{182}Hf)

☆Some ESRs are overabundant in the Solar System compared to the continuous galactic production (^{26}Al, ^{41}Ca)

☆Some cases are unclear (^{53}Mn)

Two observations

☆**Granularity** of nucleosynthesis: the stellar production sites of ^{107}Pd and ^{129}I are rarer and different than the stellar production sites of ^{182}Hf (2 r-processes ? Wasserburg et al. 1996)

☆ESRs with shorter half-lifes are more likely to be surabundant because **« decay wins »**

Radioactive Isotope (R)	T (Ma)	Daughter Isotope	Stable Isotope (S)	Initial Abundance (R/S)	Continuous Galactic Production
^{7}Be	52 days	^{7}Li	^{9}Be	6×10^{-3}	no
^{41}Ca	0.1	^{41}K	^{40}Ca	1.5×10^{-8}	no
^{26}Al	0.74	^{26}Mg	^{27}Al	5×10^{-5}	no
^{10}Be	1.5	^{10}B	^{9}Be	$4\text{-}14 \times 10^{-3}$	no
^{60}Fe	1.5	^{60}Ni	^{56}Fe	$0.1\text{-}1.6 \times 10^{-6}$	no
^{53}Mn	3.7	^{53}Cr	^{55}Mn	1.2×10^{-4}	?
^{107}Pd	6.5	^{107}Ag	^{108}Pd	$> 4.5 \times 10^{-5}$	yes
^{182}Hf	9	^{182}W	^{180}Hf	$> 1.0 \times 10^{-4}$	yes
^{129}I	16	^{129}Xe	^{127}I	1.0×10^{-4}	yes
^{92}Nb	36	^{92}Zr	^{93}Nb	10^{-5} - 10^{-3}	yes
^{244}Pu	81	Fission products	^{238}U	$4\text{-}7 \times 10^{-3}$	yes
^{146}Sm	103	^{142}Nd	^{144}Sm	$4\text{-}15 \times 10^{-3}$	yes

Galactic production from Meyer and Clayton (2000) and Busso, Gallino and Wasserburg (1999)

The last minute origin of some ESRs

- ^{7}Be, ^{10}Be, ^{26}Al, ^{41}Ca, ^{60}Fe and possibly ^{53}Mn are overabundant compared to expected galactic nucleosynthesis

- They have a specific origin

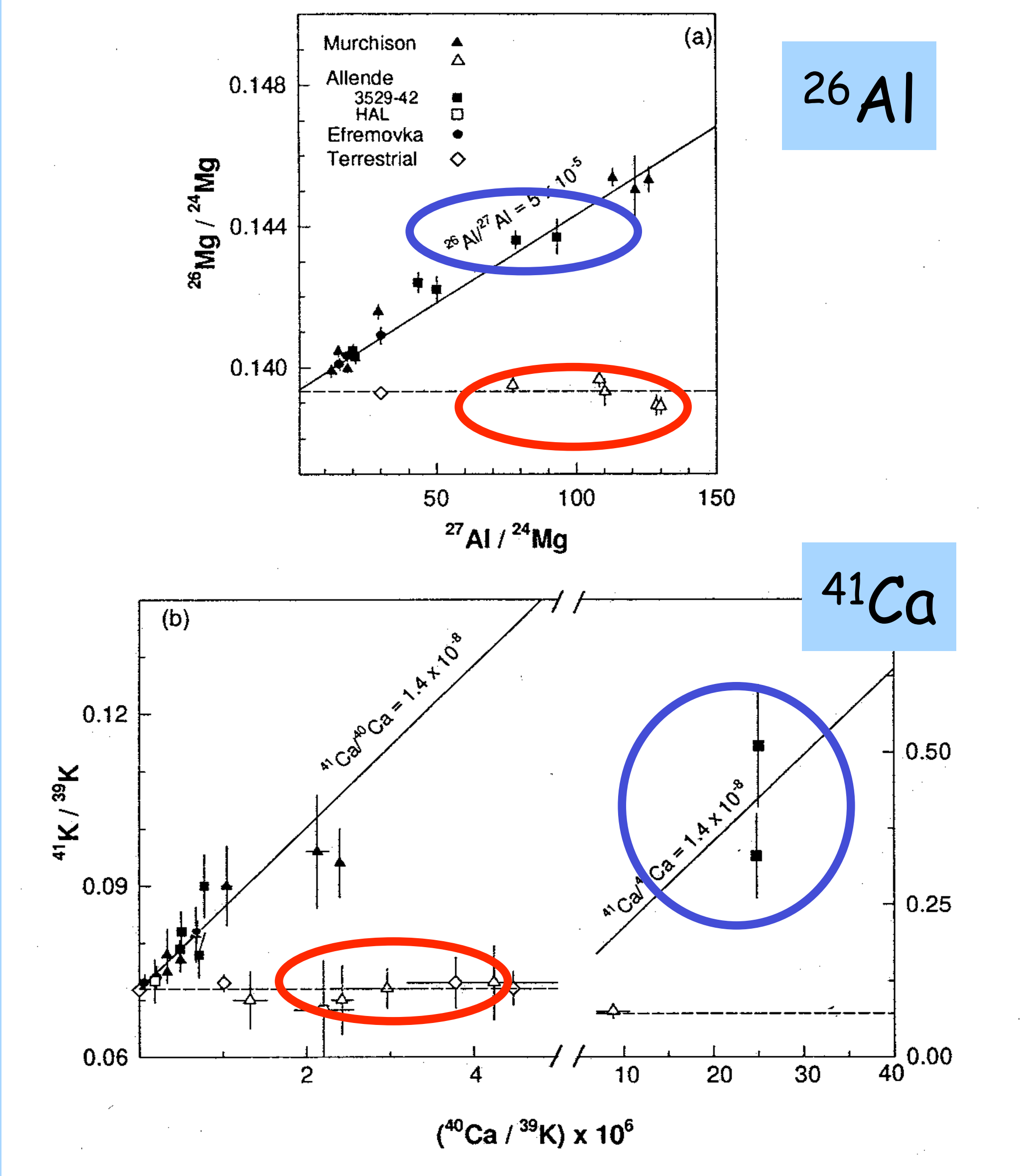
- This is a last minute origin (to counteract decay)
  - External stellar origin (all but Be isotopes)
  - In situ irradiation origin (all but ^{60}Fe)
  - GCR trapping (^{10}Be only)

- Is it possible to build a coherent astrophysical and cosmochemical scenario to acoount for ALL ESRs ?

- The origin of ESRs

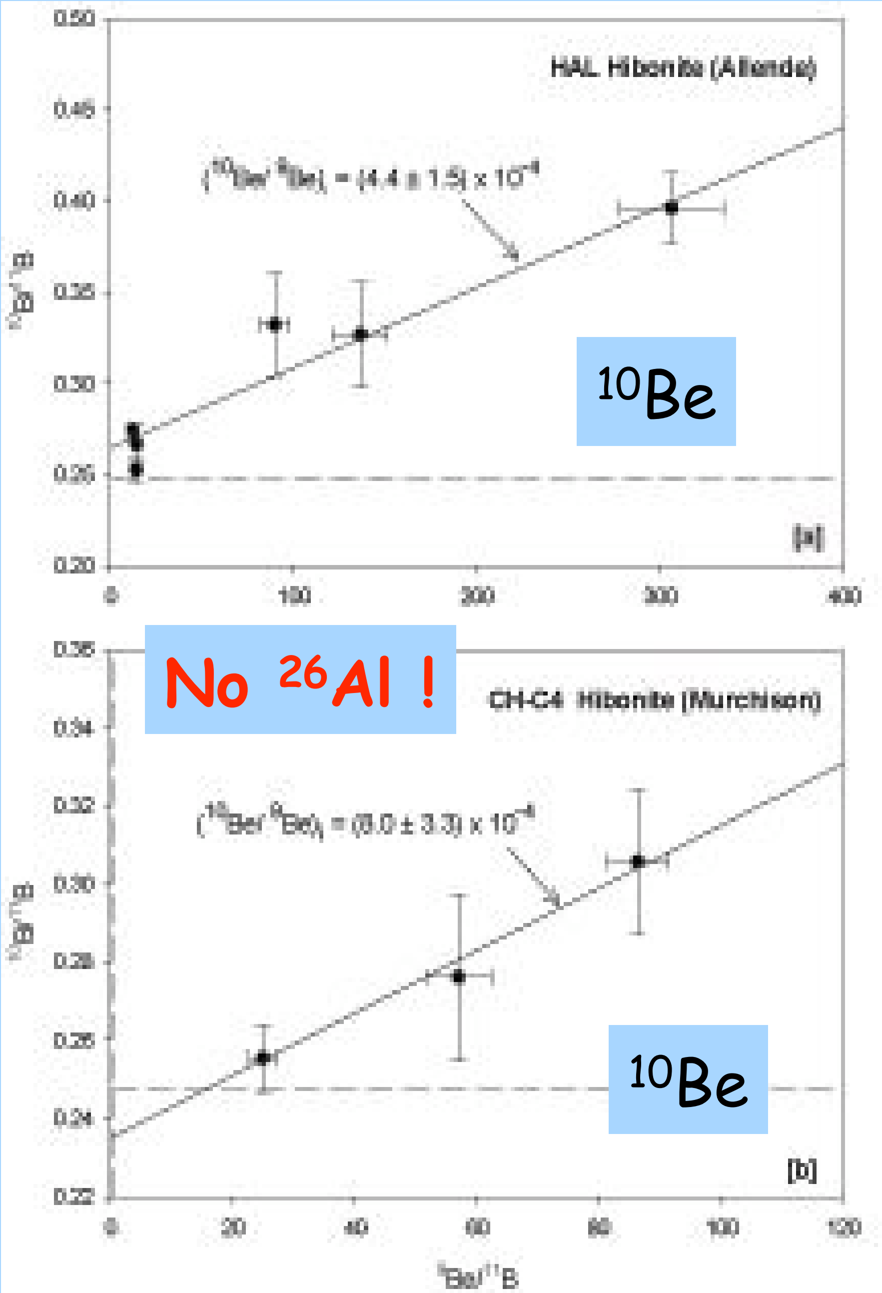
additional constraints

Coupling of short-lived radionuclides 1: ^{26}Al and ^{41}Ca



Sahjipal et al. 1998

Decoupling of short-lived radionuclides 2: ^{26}Al and ^{10}Be



- ^{26}Al and ^{41}Ca coupled
- ^{26}Al and ^{10}Be decoupled

From these observations, Marhas et al. suggest that:

^{10}Be is produced via irradiation

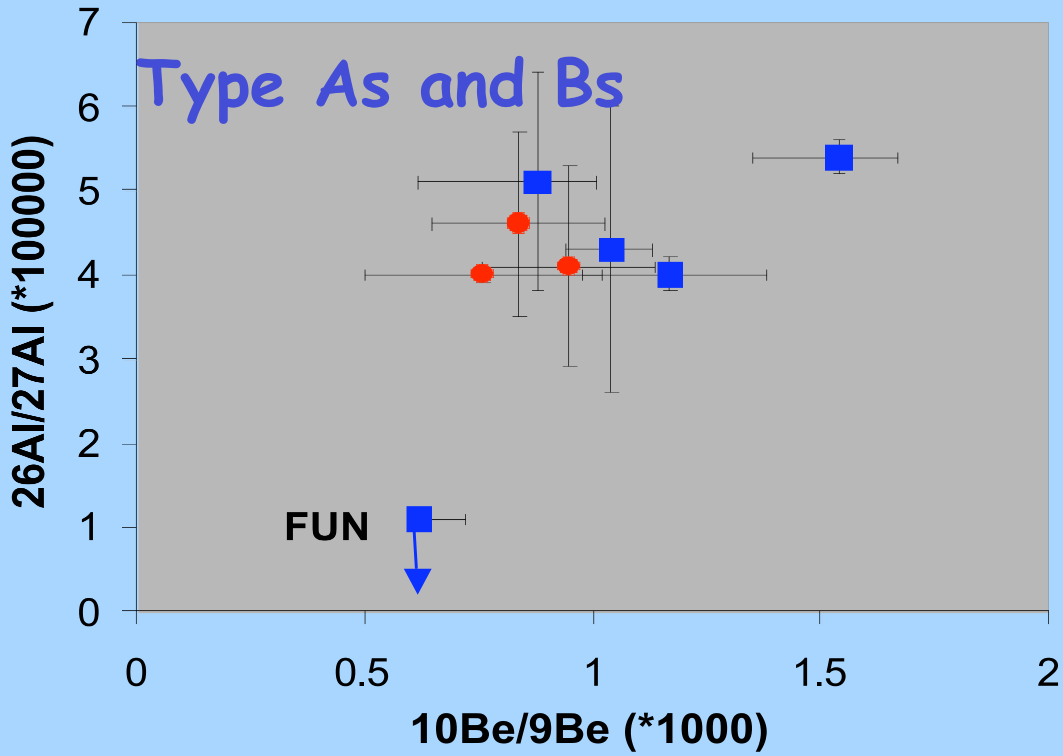
^{26}Al, ^{41}Ca have a stellar source

Mahras et al. 2002

(De)coupling of short-lived radionuclides 3: ^{26}Al and ^{10}Be

- **BUT** the hibonites are not "typical" CAIs: linked to FUN inclusions (^{48}Ca, ^{50}Ti anomalies) ?

- Type A and B CAIs have both ^{26}Al & ^{10}Be (within the disturbance of the Al-Mg system)



McKeegan et al. 2001
McPherson & Huss 2001

The FUN CAIs

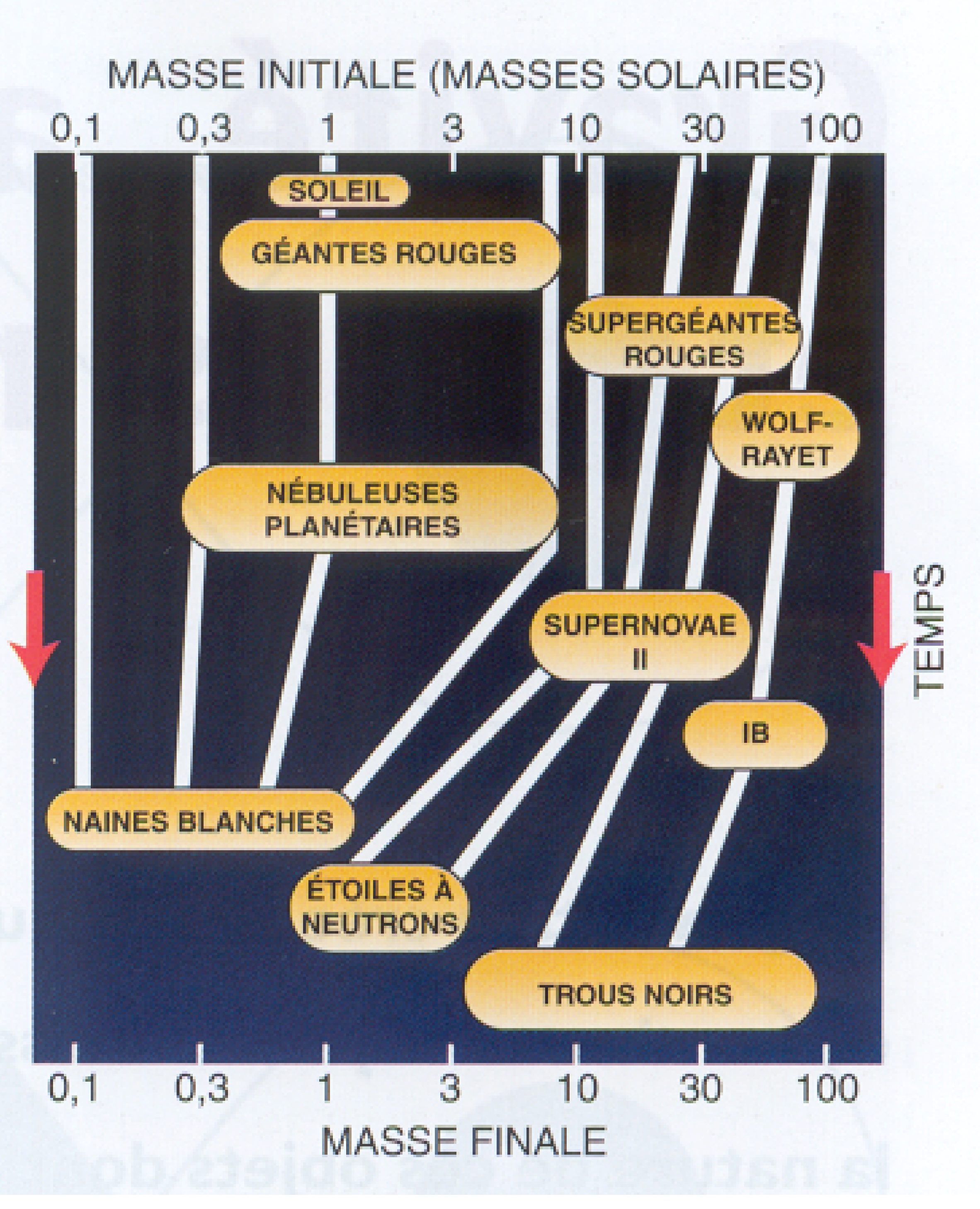
- CAIs having large isotopic anomalies
  - **F: Fractionated isotopic anomalies**
    - Oxygen
    - Silicium
  - **UN: Unidentified Nuclear isotopic anomalies** (mass independant)
    - ^{50}Ti
    - ^{48}Ca
    - ^{54}Cr
    - Ni, Ba, Fe...
- Most FUN CAIs did not contain ^{26}Al
- Petrographically, FUN inclusions are similar to normal inclusions (but **HAL**...)

- The external stellar models

External stellar origin for ESRs, possible sources

- Late-type stars because you need to inject the nucleosynthesis products in the Interstellar Medium (ISM)
  - Wolf-Rayet stars
  - AGB stars
  - Type II Supernovae **(SNII)**
- For SNII, the injection of ESRs is closely linked to the trigger of the gravitational collapse (Cameron & Truran 1977)

- Stars cannot produce ^{7}Be and ^{10}Be



Évolution des étoiles en fonction de la masse

Prantzos 2001

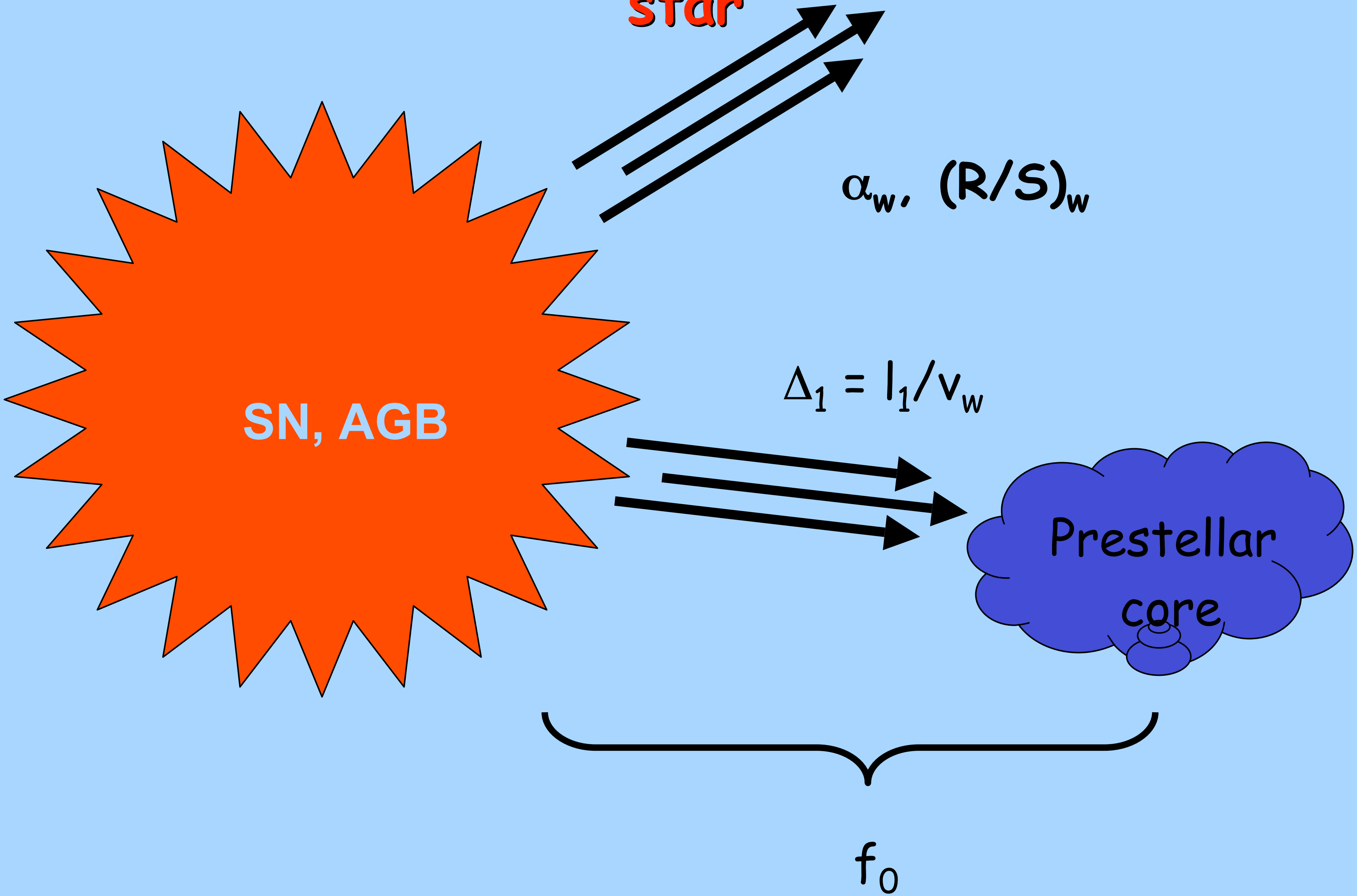
ESR enrichment of the Solar System by a nearby star

$$(R/S)_{ESS} = \alpha_w \times (R/S)_w \times f_0 \times \exp(-\Delta_1/\tau)$$

- **Parameters of the model**
  - ☆ a_w = enrichment factor (relative to ISM) of the stable isotope in the wind
  - ☆ $(R/S)_w$ = abundance ratio (radioactive to stable) in the wind
  - ☆ f_0 = mixing ratio between the wind and the progenitor ISM
  - ☆ $\Delta 1$ = time between the nucleosynthesis in the star and the cristallisation
  - ☆ τ = mean life of the ESR

- **Adopted parameters**
  - ☆ a_w depends on nucleosynthetic models [very complicated]
  - ☆ $(R/S)_w$ depends on nucleosynthetic models [very complicated]
  - ☆ f_0 = free parameter (within certain limits)
  - ☆ $\Delta 1$ = free parameter (within certain limits ?)

ESR enrichment of the Solar System by a nearby star



Wolf-Rayet stars
Arnould et al. 1997

- **Late stage for very massive stars**
  - ☆ Precursor of SNIs
- **Huge mass loss through winds of ~10^{-5} Mo/yr**
  - ☆ A lot of nucleosynthesis products injected on the interstellar medium
- **Simple stars compared to Supernovae and AGB stars**
  - ☆ Nucleosynthesis calculations better constrained
- **Range of parameters explored by Arnould et al. (1997)**
  - ☆ $25 < M < 120$ Mo
  - ☆ $0.001 < Z < 0.04$
- **Can synthetise the right abundances of ^{26}Al and ^{41}Ca**
- **Cannot synthetise the right abundances of ^{53}Mn, ^{60}Fe**

Radioactivités éteintes dans les supernovae
Wasserburg et al. (1998)

- Basé sur les **taux de production des SNII** de masse comprise entre 10 et 40 masses solaires (Timmes 1995)

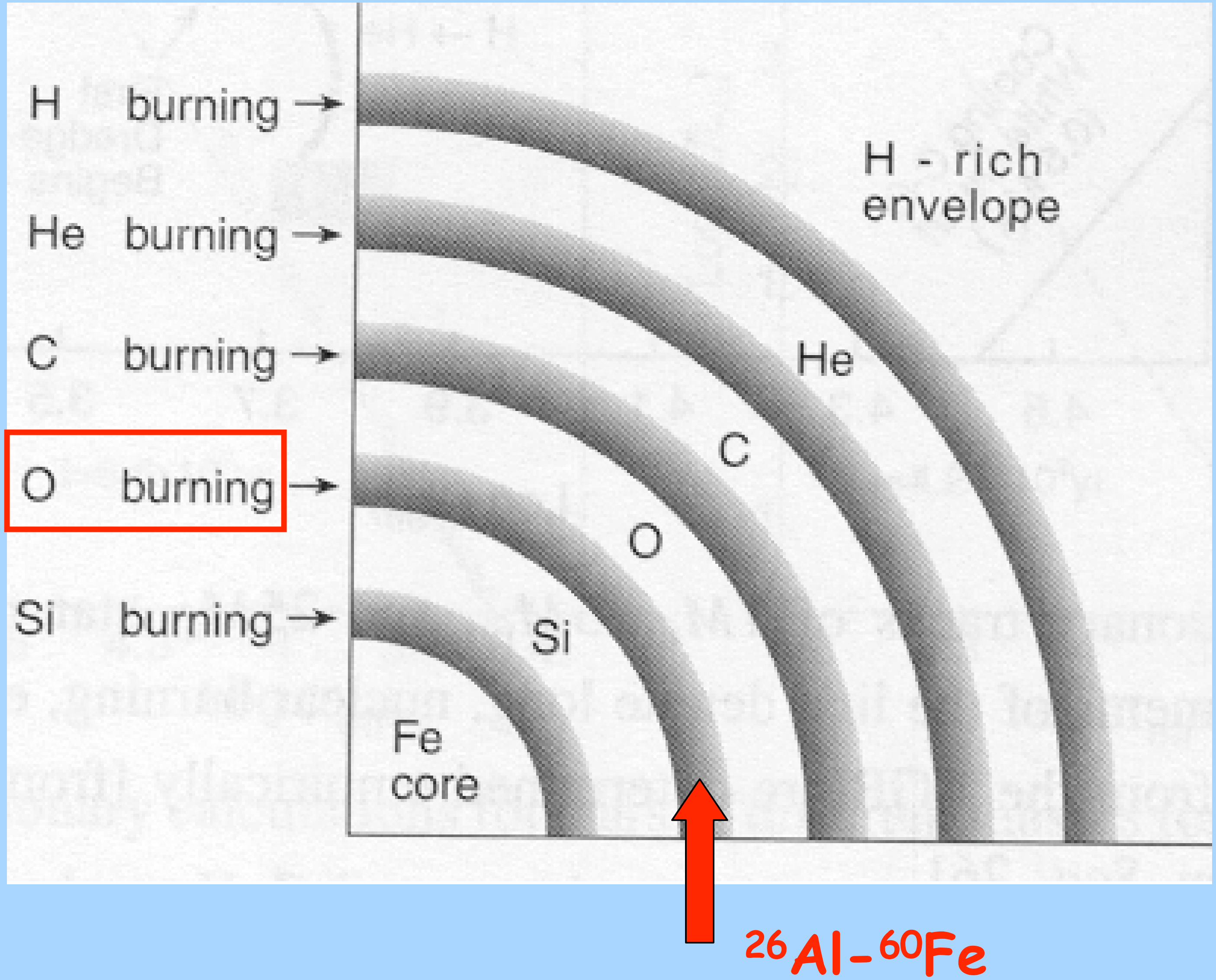
- ^{26}Al et ^{60}Fe produits dans la même zone (O/Ne) de la SN

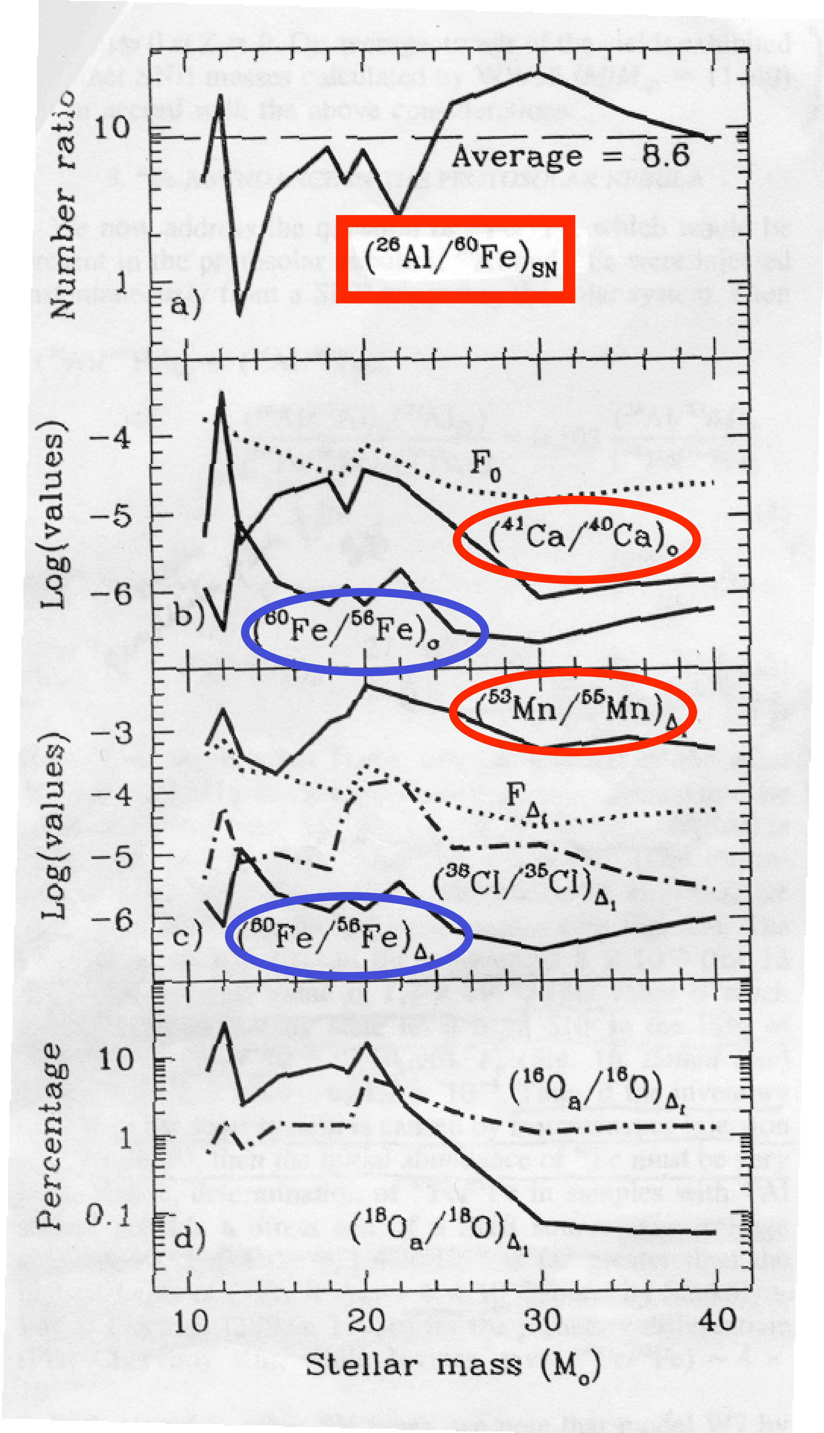
- $^{26}Al/^{60}Fe$ = [0.6-23], **valeur moyenne $^{26}Al/^{60}Fe = 8.5$**

- Ce rapport dépend de la masse du progéniteur, peu de la métallicité (Z/Z_0)

- Variations faibles autour de la valeur moyenne
  (sauf pour M= 13 Mo)

Structure de l'étoile progénitrice d'une Supernova





Wasserburg, Gallino & Busso (1998)

On attend, pour

^{26}Al/^{27}Al = 5 x 10^{-5},

une valeur moyenne

^{60}Fe/^{56}Fe = 1.4x10^{-6}

☆Compatible with the upper limits for CAIs

☆Overproduction of ^{41}Ca & ^{53}Mn

- ☆^{41}Ca/^{40}Ca ~ 10^{-6}
- ☆ ^{53}Mn/^{55}Mn ~ 10^{-3}

Updated supernova model

Busso, Gallino, Wasserburg (2003)

		? $_1$ = 1.09 Myr	
	mean life	**15 Mo**	**25Mo**
		fo=3 x 10^{-4}	**fo=1.3 x 10^{-4}**
26Al	1.05	**5.00E-05**	**5.00E-05**
41Ca	0.15	**1.50E-08**	**1.50E-08**
53Mn	5.3	3.50E-03	3.00E-03
60Fe	2.2	4.70E-05	9.00E-06

- Mo = Sun Mass determines the isotopic abundance $(R/S)_w$ and the elemental abundance α_w
- **New nucleosynthetic data of Rauscher et al. 2000**
  - **Up-to-date set of reaction rates**
  - **Upgrades in the evolutionary code**
- $\Delta 1$ = free decay interval calculated by Busso et al. (2003) to have ^{26}Al and ^{41}Ca at the meteoritic level
- Overproduction of ^{53}Mn and ^{60}Fe

AGB stars

Busso, Gallino & Wasserburg 2003

- Extreme AGB star models can reproduce the abundance of ^{26}Al, ^{41}Ca, ^{60}Fe
  - M = 1.5Mo,
  - Metallicity = 1/6 solar
- More

$M = 1.5\ M_\odot$, Z=0.02

$f_0 = 5.1 \times 10^{-3}$, $\Delta_1 = 0.76$ Myr

Rad.	Ref.	α_w	$(N_R/N_S(w))$	$(N_R/N_S)_{\Delta_1}$
^{26}Al	^{27}Al	1.02	2.0×10^{-2}	5.0×10^{-5}
^{41}Ca	^{40}Ca	0.99	4.5×10^{-4}	1.4×10^{-8}
^{60}Fe	^{56}Fe	0.99	1.6×10^{-5}	5.7×10^{-8}
^{107}Pd	^{108}Pd	1.02	9.9×10^{-3}	4.6×10^{-5}

FUN-like inclusions in external stellar models

- **Remember**: they did contain ^{10}Be but no ^{26}Al
- The formed before ^{26}Al and other stellar radionuclides entered the molecular cloud core
- This explanation is compatible with the isotopic anomalies observed in FUN CAIs (mixing less efficient)

Stellar models: Summary

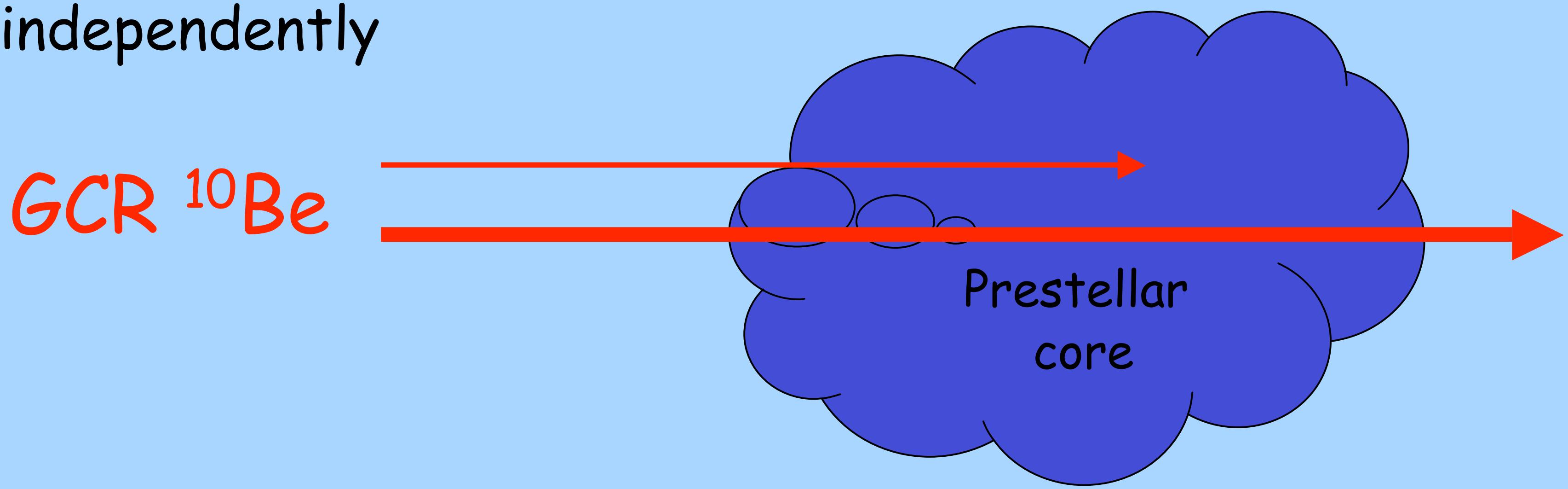
- Wolf-Rayet stars cannot reproduce the relative abundance of ESRs
- Latest supernovae models fail to reproduce the relative abundance of ESRs
- Extreme AGB star models can reproduce the abundance of ^{26}Al, ^{41}Ca, ^{60}Fe
  - ^{53}Mn could result from the continuous Galactic production
  - Impossible to account for the ^{7}Be presence in early Solar System
  - Impossible to account for the ^{10}Be presence in early Solar System
- Is an **external source** for ^{10}Be possible?

- A possible GCR origin for ^{10}Be

A possible GCR origin for ^{10}Be

Desch, Connolly and Srinivasan (ApJ 2004 to appear)

- **Trapping** of 1-100 MeV ^{10}Be GCR in the protostellar core
- Claim they can make the meteoritic value, model-independently



- All the ^{10}Be GCR below a certain energy (E_c) will be stopped in the prestellar core

^{10}Be trapping in the prestellar core

Ignoring the magnetic focusing and mirroring which does not change the final result by more than 10 % (Desch et al. 2004).

$$F_{trap} = 4\pi \int_0^{E_c(\Sigma(t))} F_{^{10}Be}(E)dE \qquad (1)$$

F_{trap} is the number of ^{10}Be nuclei stopped per unit of time and surface (s^{-1} cm^{-2})
F_{10Be} is the number flux of ^{10}Be nuclei in the GCR

All the nuclei between E=0 MeV and E=Ec (MeV) are trapped

Desch et al. 2004

^{10}Be GCR flux

2 The GCR flux

$F_{^{10}Be}(E)$ is the number flux of 10Be GCR, it reads (equation 12 of DCS):

$$F_{^{10}Be}(E) = \psi_{10Be} \times \psi_H \times 4.6 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1} (\mathrm{MeV/A})^{-1} \quad (2)$$

where ψ_{10Be} and ψ_H quantify the increase of ^{10}Be and proton GCR respectively 4.5 Ga.

The ^{10}Be GCR flux 4.5 Ga ago is estimated from contemporary observations of the GCR flux

Desch et al. 2004

Trapping ^{10}Be nuclei: the Bethe formula

$$E_c = E_{10}\left(\frac{\Sigma(t)}{\Sigma(E_{10})}\right)^{\frac{1}{a+1}}$$

The maximum trapping energy (Ec) depends on the surface density of the cloud Σ(t) (in $g.cm^{-2}$)

Desch et al. 2004 - MODIFIED

The final F_{trap} expression

Combining equations (1), (2) and (4), one gets:

$$F_{trap} = 4\pi \times \psi_{10Be} \times \psi_{H} \times 4.6 \times 10^{-9} \times E_{10} \times \left(\frac{\Sigma(t)}{\Sigma(E_{10})}\right)^{\frac{1}{r+1}} \qquad (5)$$

Desch et al. 2004 -MODIFIED

The $^{10}Be/^{9}Be$ ratio (R) in the core

$$\frac{dR}{dt} = F_{trap}\left(\frac{x_{9Be}\Sigma(t)}{1.4m_H}\right)^{-1} - \frac{R}{\tau} \qquad (6)$$

$$R(t) = R(0)e^{-\frac{t}{\tau}} + e^{-\frac{t}{\tau}}\int_0^t f(t')e^{+\frac{t'}{\tau}}dt' \qquad (7)$$

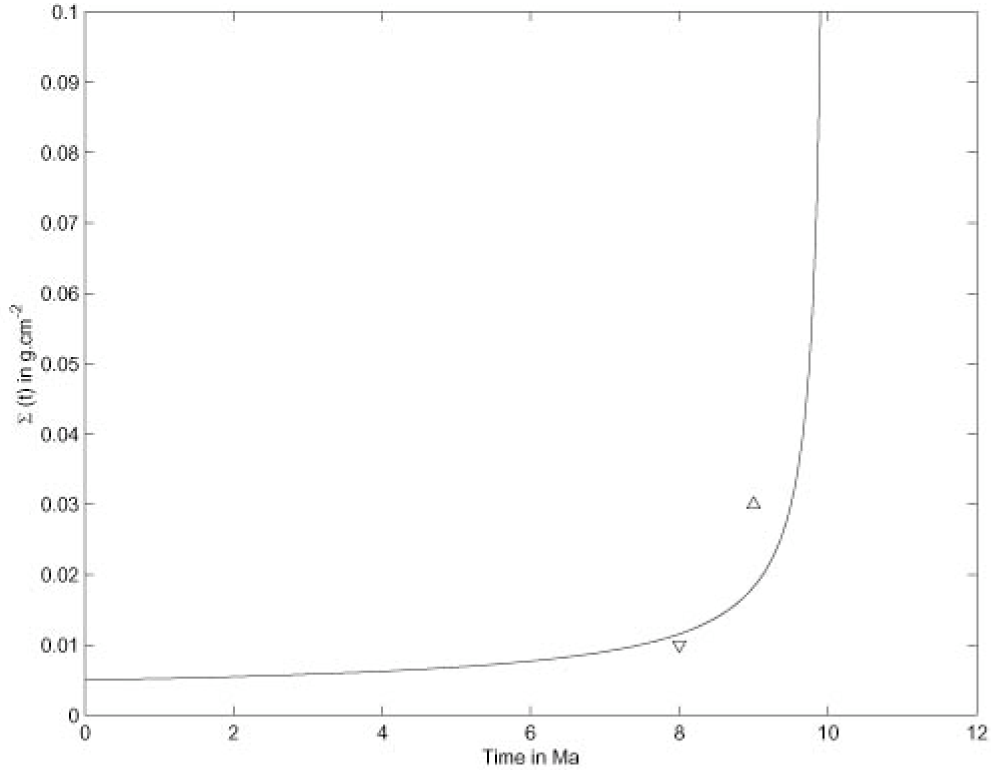
$$f(t) = 4\pi \times \psi_{10Be} \times \psi_H \times 4.6 \times 10^{-9} \times E_{10} \times \left(\frac{\Sigma(t)}{\Sigma(E_{10})}\right)^{\frac{1}{q+1}}\left(\frac{x_{9Be}\Sigma(t)}{1.4m_H}\right)^{-1} \qquad (8)$$

The parameters given by DCS are: $E_{10} = 10MeV$, $\Sigma(E_{10}) = 0.003$ g.cm^{2}s^{-1}, $\psi_H = 2$, $\psi_{10Be} = 0.83$, R(0) = 1×10^{-4}.

I adopt $q \sim 0.8$ from Clayton & Jin (1995).

τ is the mean life of ^{10}Be, m_H the mass of the hydrogen atom, and x_{9Be} the abundance fraction of ^{9}Be

Desch et al. 2004 -MODIFIED



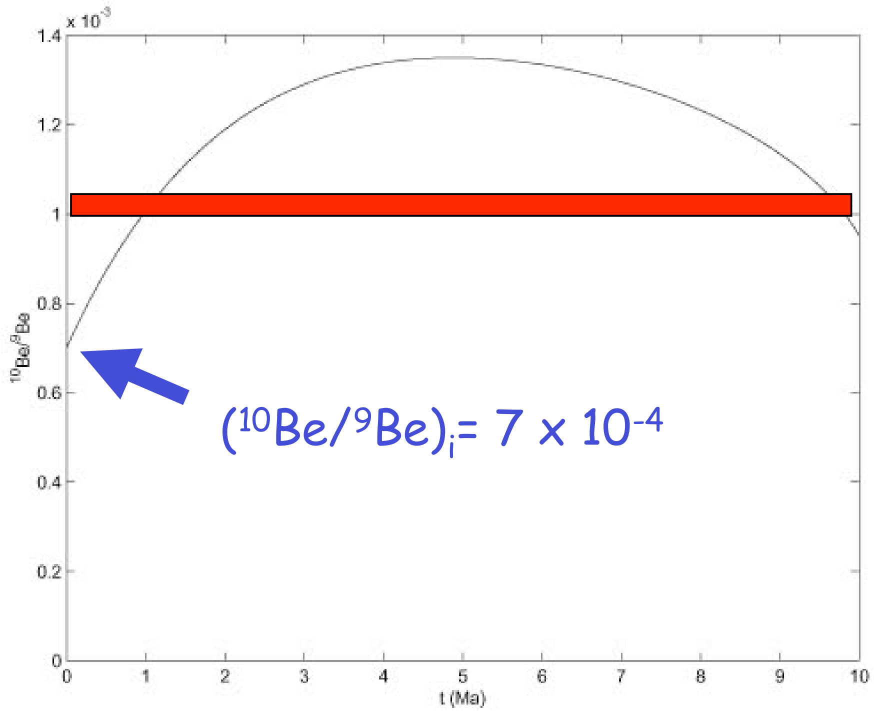
Surface density of a 45 Mo prestellar core

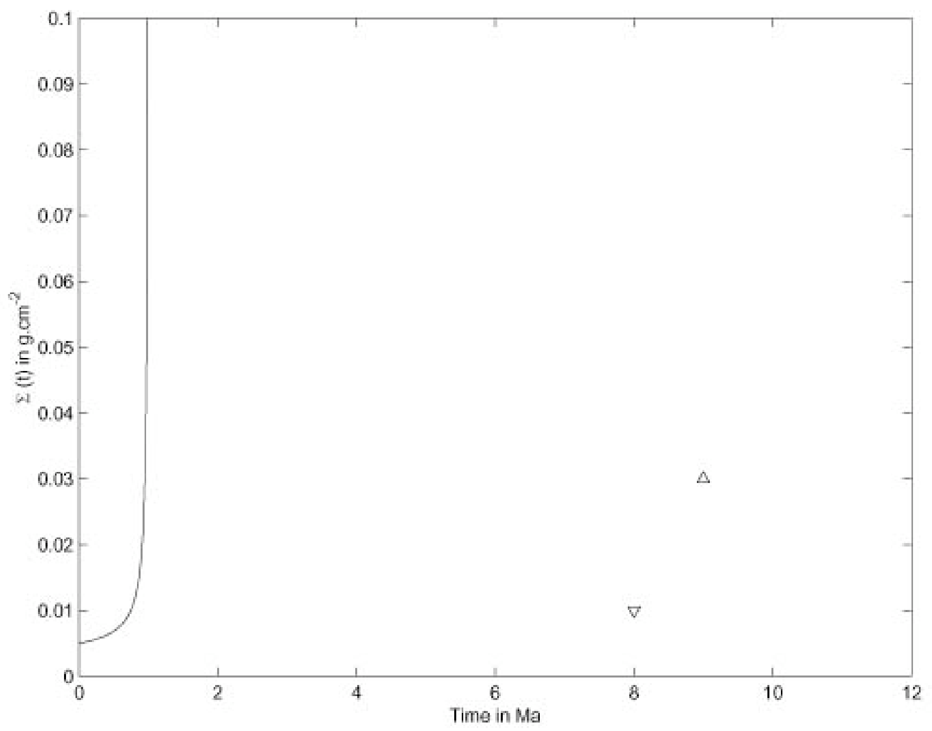
-Desch et al. 2004

-Desch & Mouschovias 2001

Evolution of the $(^{10}Be/^{9}Be)_{trapped}$

-Desch et al. 2004





Toy "Surface density" with a 1 Ma timescale

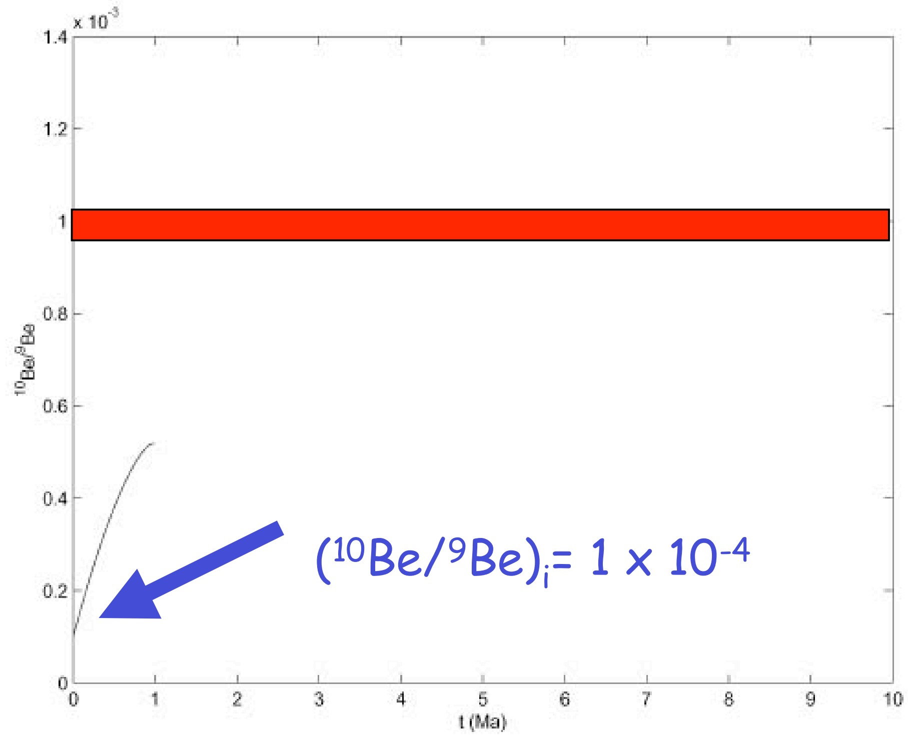
-See P. Andre's talk

More realistic $(^{10}Be/^{9}Be)_i = 1 \times 10^{-4}$

-McKeegan et al (2000)

Evolution of the $(^{10}Be/^{9}Be)_{trapped}$

-Calculations of Desch et al. 2004



A possible GCR origin for ^{10}Be
Desch et al. 2004

- **The model depends on**
  - $\Sigma(t)$, the column density of the core
    - ☆ 45 Mo molecular cloud core
    - ☆ From Desch & Mouschovias 2001
  - The duration of the core collapse phase
    - ☆ 10 Ma
  - The initial $^{10}Be/^{9}Be$ ratio in the core
    - ☆ $^{10}Be/^{9}Be = 7 \times 10^{-4}$
  - The increase of the GCR flux 4.5 Ga ago
    - ☆ Factor 2 increase compared to now

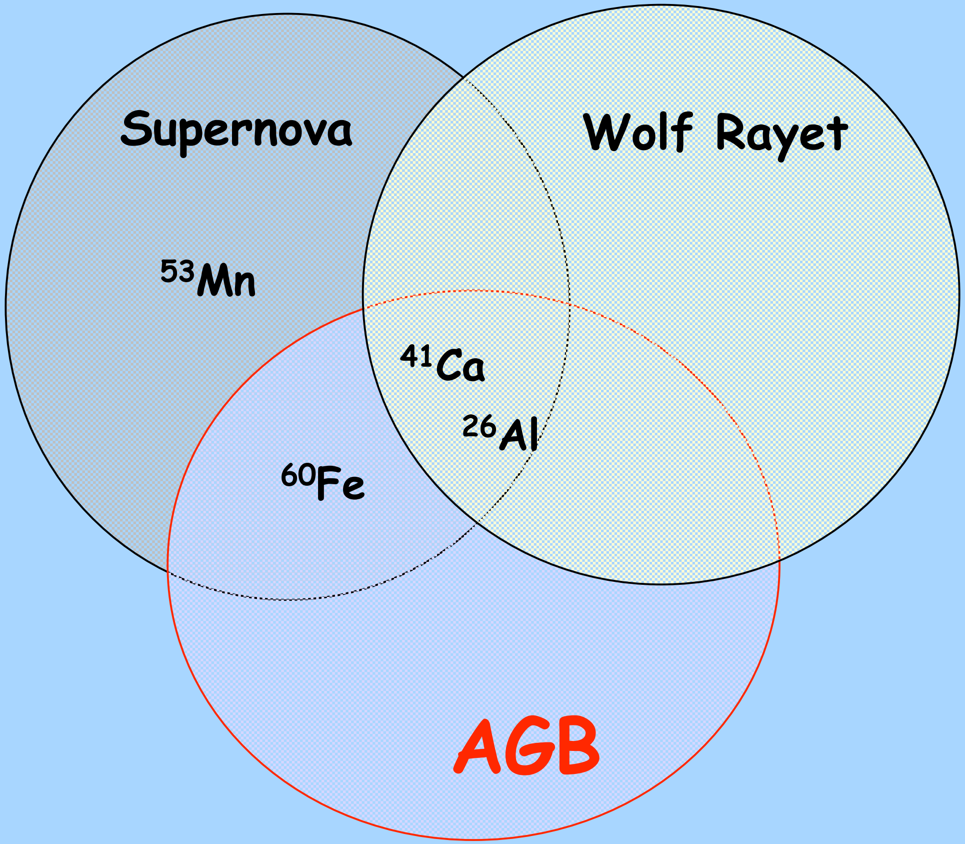
Why are extinct short-lived radionuclides important?

- Fact
  - Extinct **short-lived radionuclides** were present in the protoplanetary disk

- Questions
  - Constraints on the **astrophysical environment** of the protoSun
  - Constraints on the **irradiation conditions** in the protoplanetary disk
  - Possibility to build a **chronology** for the radionuclides whose initial distribution is well known
  - <u>Is our Solar System typical ?</u>

ESRs in stellar models - Summary again

^{10}Be trapped from the GCR ? - No solution for ^{7}Be



- Irradiation models:

the basics

Irradiation model: the basics 0

Short-lived radionuclides are produced via nuclear reactions

Target (T) + Cosmic Ray (CR) → Radionuclide (R)

e.g. $^{16}O + p \rightarrow {}^{10}Be$

- Because projectiles are p, ^{3}He, ^{4}He, **irradiation fail to produce ^{60}Fe**, a neutron-rich isotope by orders of magnitude (e.g. Lee et al. 1998)

- Irradiation has long been known to be the source of Be isotopes

Irradiation model: the basic equation

For a nuclear reaction Target(T) + Cosmic Ray(CR) → Radionuclide (R)

$$\frac{N_R}{N_S} = F_0 \Delta t \sum_i y^i{}_{CR} \sum_j \frac{x^T{}_j}{x_S} \int \sigma(E) N(E) dE$$

- **N_R is the number of radionuclides (e.g. ^{10}Be)**
- **N_S is the number of stable isotopes (e.g. ^{9}Be)**

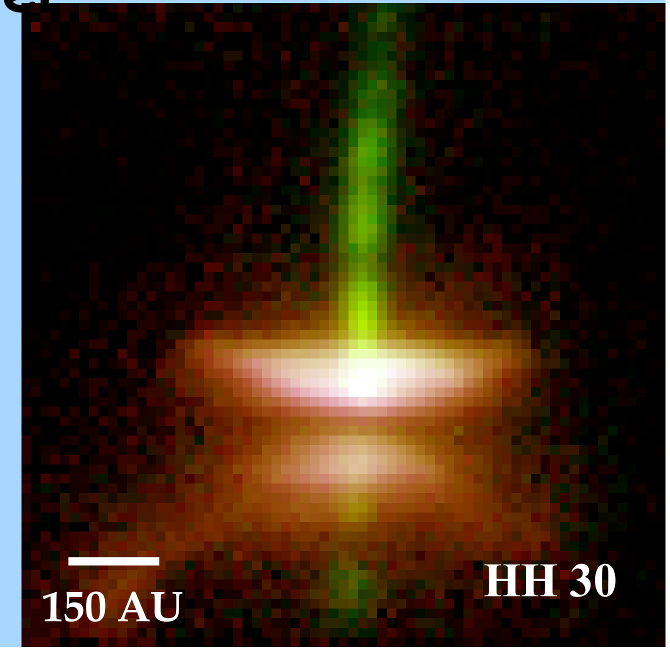
- F_0 is the proton flux (in $cm^{-2}.s^{-1}$)
- **y_{CR}^i is the abundance relative to proton of the CR i (^{4}He, ^{3}He)**
- **x_j is the abundance of the target T**
- x^T_s is the abundance of the reference stable isotope (e.g. ^{9}Be)
- σ is the nuclear cross section
- N(E)dE is the differential number of accelerated protons
- Δt is the irradiation time

Irradiation model: the astrophysical context

- **Location of the irradiated matter relatively to the source of Cosmic Rays (the SUN) and to nebular gas**
  - Asteroidal distances (~3 AU) - shielding ?
  - Edge of the accretion disk (~0.06 AU)

- **Physical state of the irradiated matter**
  - Gas phase - shielding ?
  - Solid phase ($n(r) = r^{-\alpha}$)

- **Chemistry of the target**
  - CI (cosmic) composition
  - CAI composition
  - Core-mantle structure



The recent irradiation models

- **Clayton & Jin (1995)**
  - In the molecular cloud
  - **Undeproduces ^{26}Al**
- **Goswami et al. (1997, 2001), Marhas, Goswami & Davis (2002)**
  - At asteroidal distances (2-4 AU) -**ignoring the nebular gas**
  - Solid targets
  - CI chemistry
  - Proton and ^{4}He reactions only
  - **Undeproduces ^{26}Al, ^{41}Ca, ^{53}Mn, produces ^{10}Be at the meteoritic level**

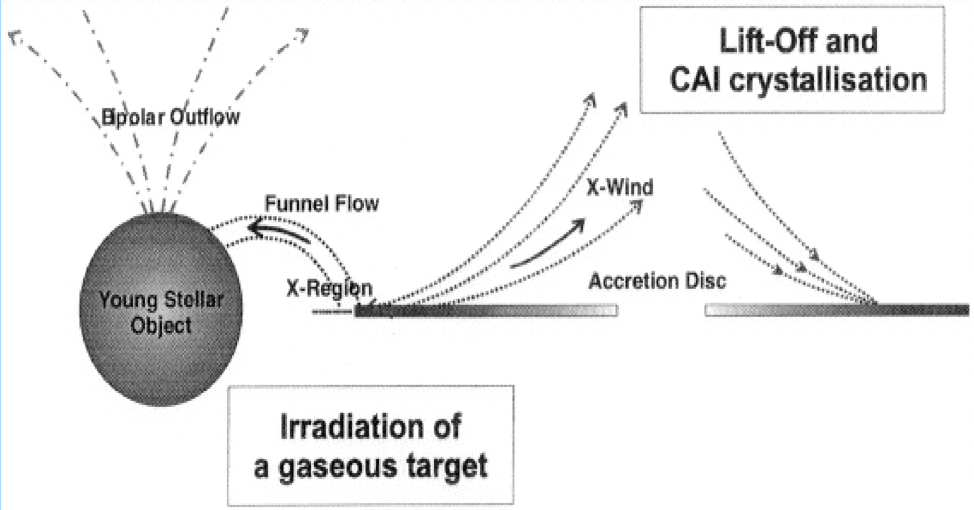
The recent irradiation models

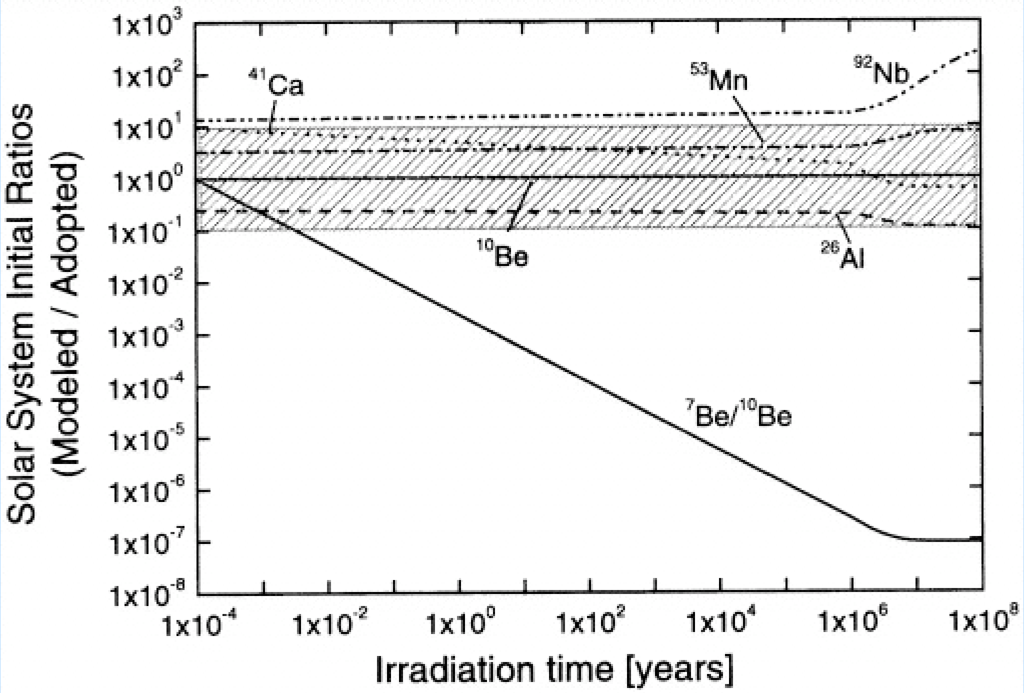
- **Lee, Shu et al. (1998)**
  - Close to the Sun (0.06 AU) - in the context of the x-wind theory
  - In a **gas-free region**
  - Solid targets
  - CI chemistry
  - Takes into account the ^{3}**He reactions (in addition to proton and alphas)**
  - **Produces ^{26}Al and ^{53}Mn at the right level but overproduces ^{41}Ca**

- **Gounelle, Shu et al. (2001) and Shu, Shang et al. (2001)**
  - Similar to Lee et al. (1998)
  - Introduces self-shielding - CI chemistry with a core-mantle structure
  - **Produces ^{10}Be, ^{26}Al, ^{41}Ca, ^{53}Mn at the right level (within a factor of 2)**

The recent irradiation models

- **Leya et al. (2003)**
  - In the context of the x-wind model ?
  - Gaseous targets
  - CI and CAI chemistry
  - p, ^{3}He and ^{4}He reactions
  - Calculates ^{22}Na, ^{44}Ti, ^{92}Nb...





- **Produces ^{7}Be, ^{10}Be, ^{26}Al, ^{41}Ca and ^{53}Mn at the right level**

- **Results contradictory with Lee et al. (1998)?**

- Irradiation model in the context of the x-wind theory

MG

F. Shu

S.Shang

A.E. Glassgold

E.Rehm

T. Lee

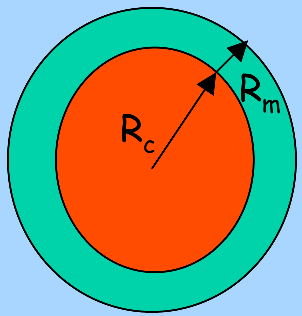
Irradiation model in the context of the x-wind theory: parameters

❶ **Irradiation close to the Sun (~0.06 AU) of a solid target**

- Similar to Lee et al. (1998)

❷ **ProtoCAIs have a core-mantle structure**

- The total population has a chondritic composition
- Mantle (R_m) size is fixed (Shu et al. 2001)
- Core size (R_c) varies between 50 μm and 2.5 cm
- $N(R_c)dR_c = R_c^{-2.5}\, dR_c$



❸ **Irradiation time (Δt) proportional to protoCAIs' size (R)**

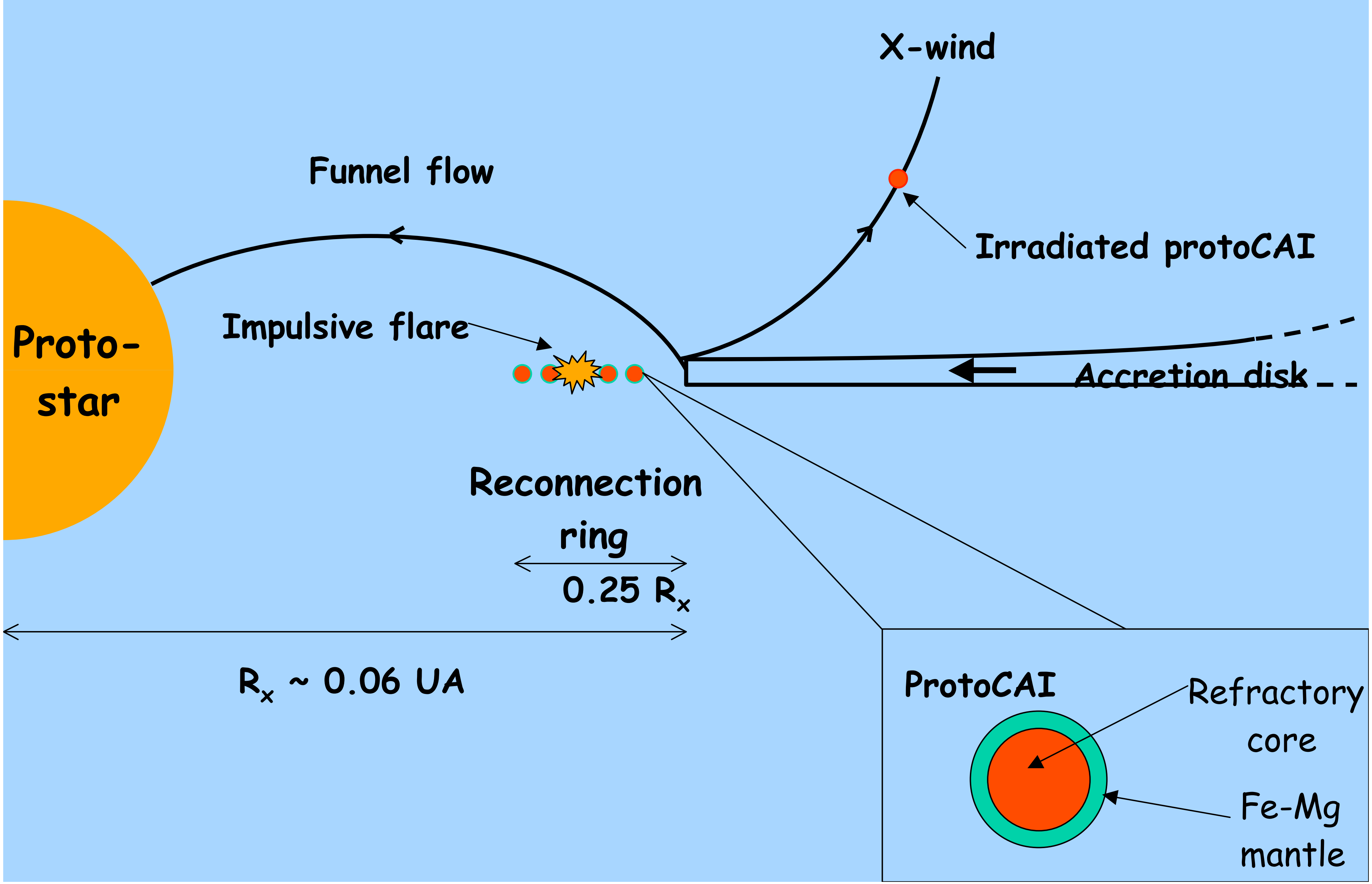
$$\Delta t = 2 \times R \times \frac{t_{10}}{L}$$

t_{10} = 10 yr
L = 1 cm

❹ **Cross sections σ(E)**

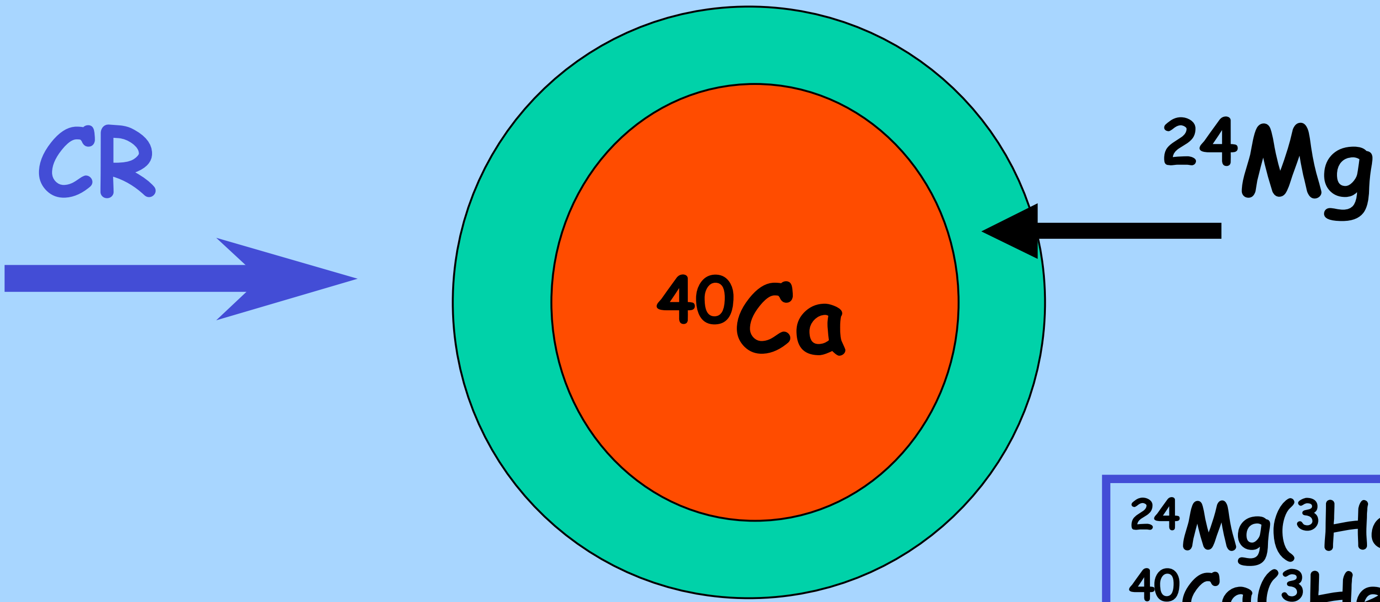
- Experimental measurements
- Numerical simulations

1- The astrophysical setting



2-The core-mantle chemistry

- **Justification provided by Shu et al. (2001)**
  - Condensation, evaporation and agglomeration in the reconnection ring



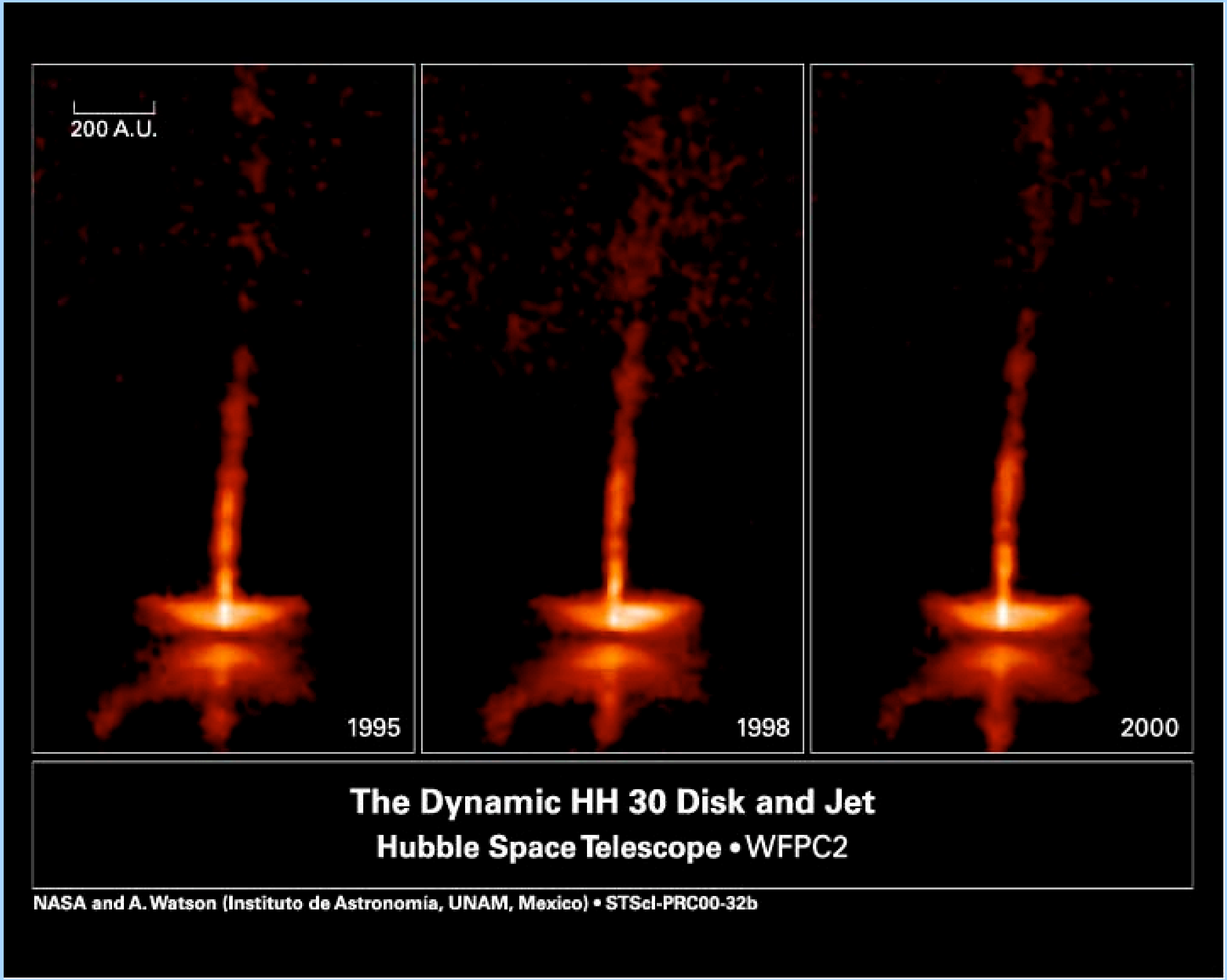
$^{24}Mg(^{3}He,p)^{26}Al$
$^{40}Ca(^{3}He,pn)^{41}Ca$

- **Self-shielding of the core**
  - Decreases the production of ^{41}Ca

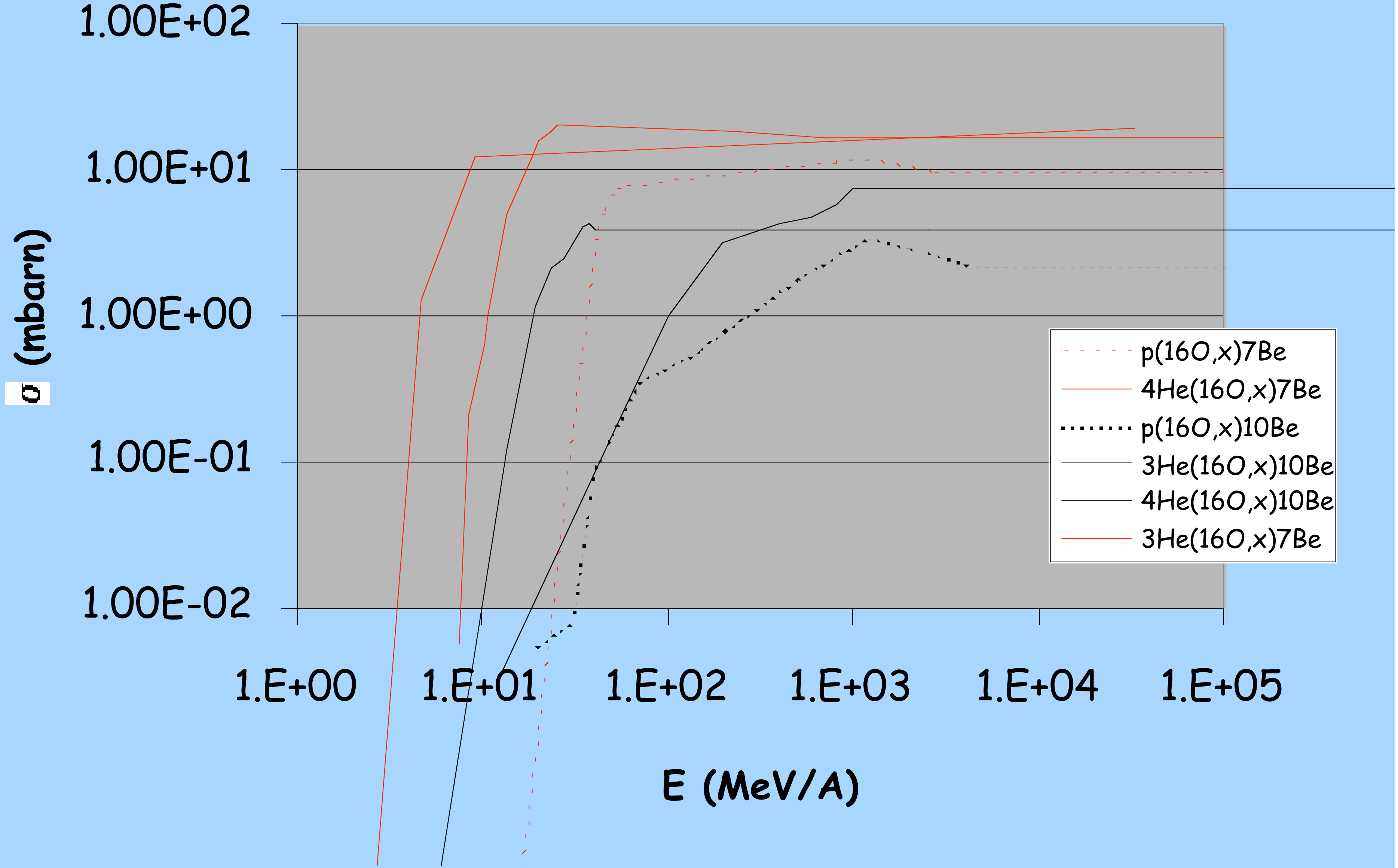
3-Timescales in steady-state

- **Step 1**
  - Formation and irradiation of protoCAIs
    - ☆ Timescale ~ 2-20 yr
  - Periodic volatilization due to large flares (Lx = 10^{34} erg.s^{-1}, e.g. Grosso et al. 1997) assures **homogeneisation of the irradiation products** (short-lived radionuclides)
    - ☆ Timescale << 2 yr
- **Step 2**
  - Fluctuation of the x-point
  - Transport of protoCAIs in the wind to asteroidal distances
  - Volatilisation of the mantle exposed to sunlight

3- Year variability of jets structure



4 7Be -10Be cross sections



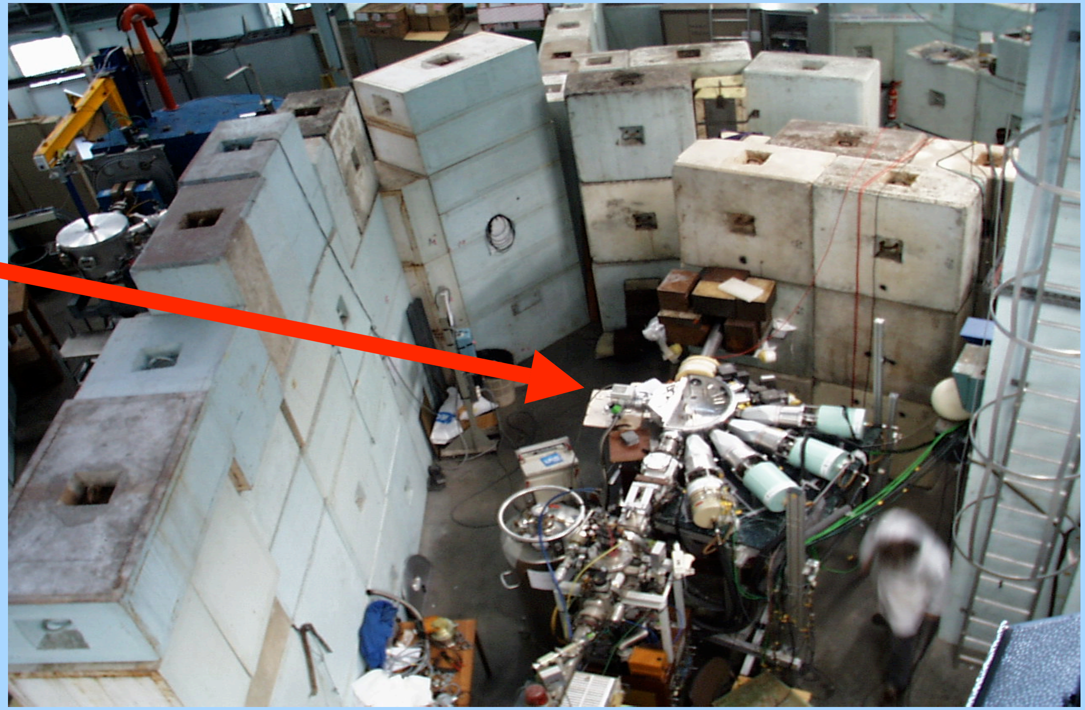
4– The measure of σ $^{24}Mg(^{3}He,p)^{26}Al$

Tandem Orsay

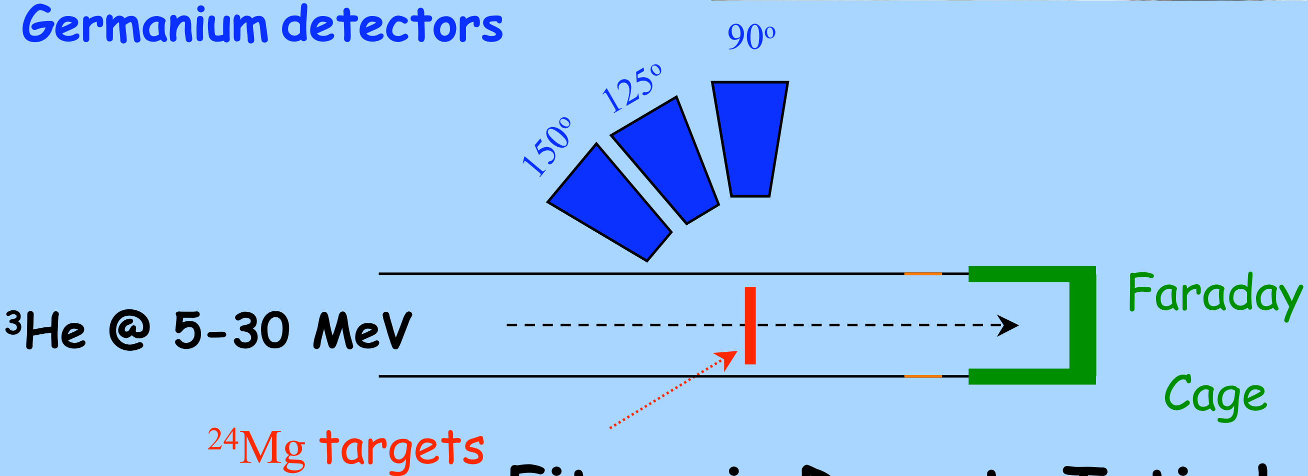
-irradiation

Tandetron Orsay

-^{26}Al counting

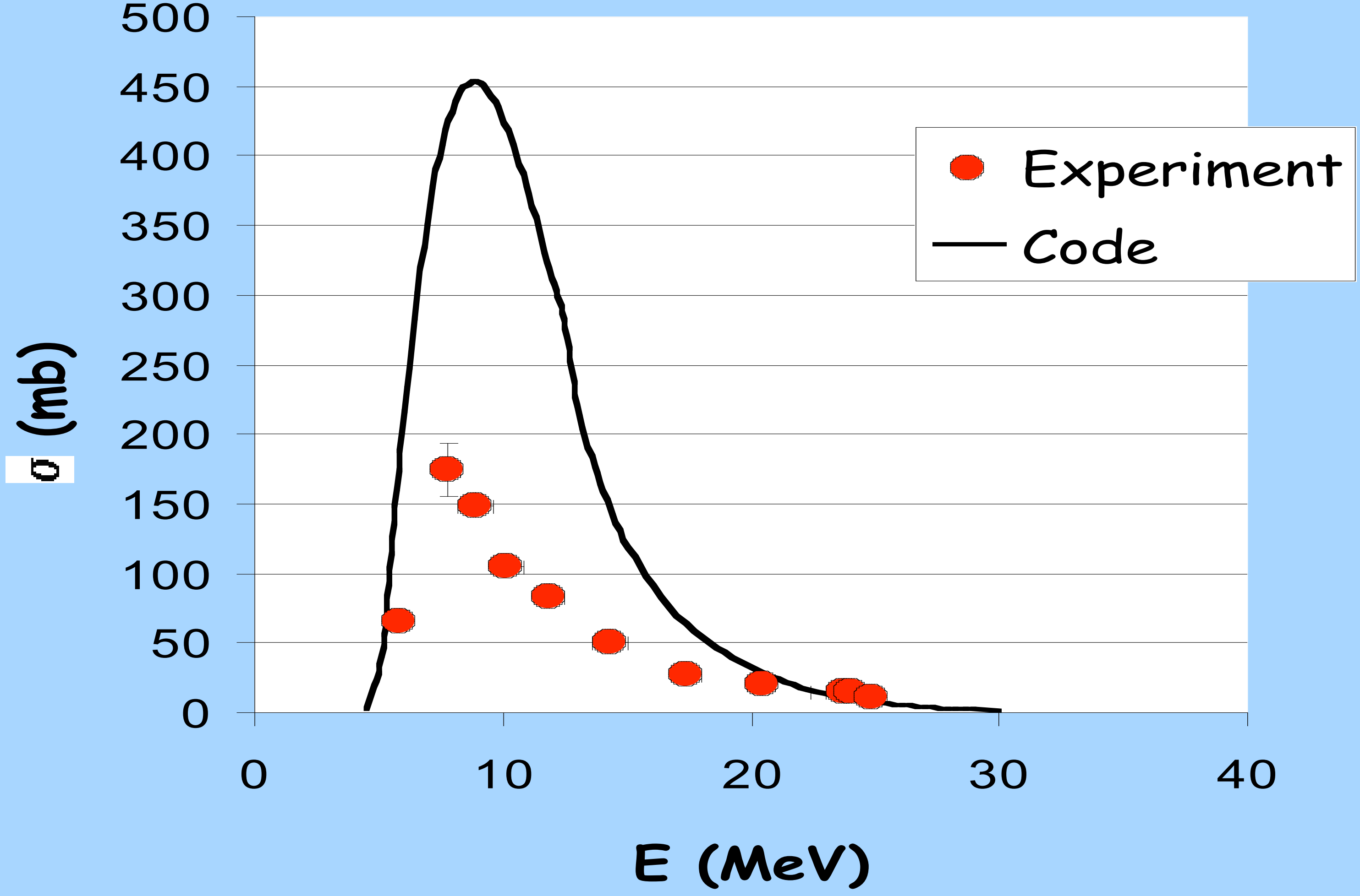


Germanium detectors



Fitoussi, Duprat, Tatischeff et al. (2004)

$^{24}Mg(^{3}He,p)^{26}Al$: Comparison of code (Rehm) & experiment (Fitoussi, Duprat et al. 2004)



Irradiation model: the cosmic-ray parameters

- **Scaling of protostars to the contemporary sun**

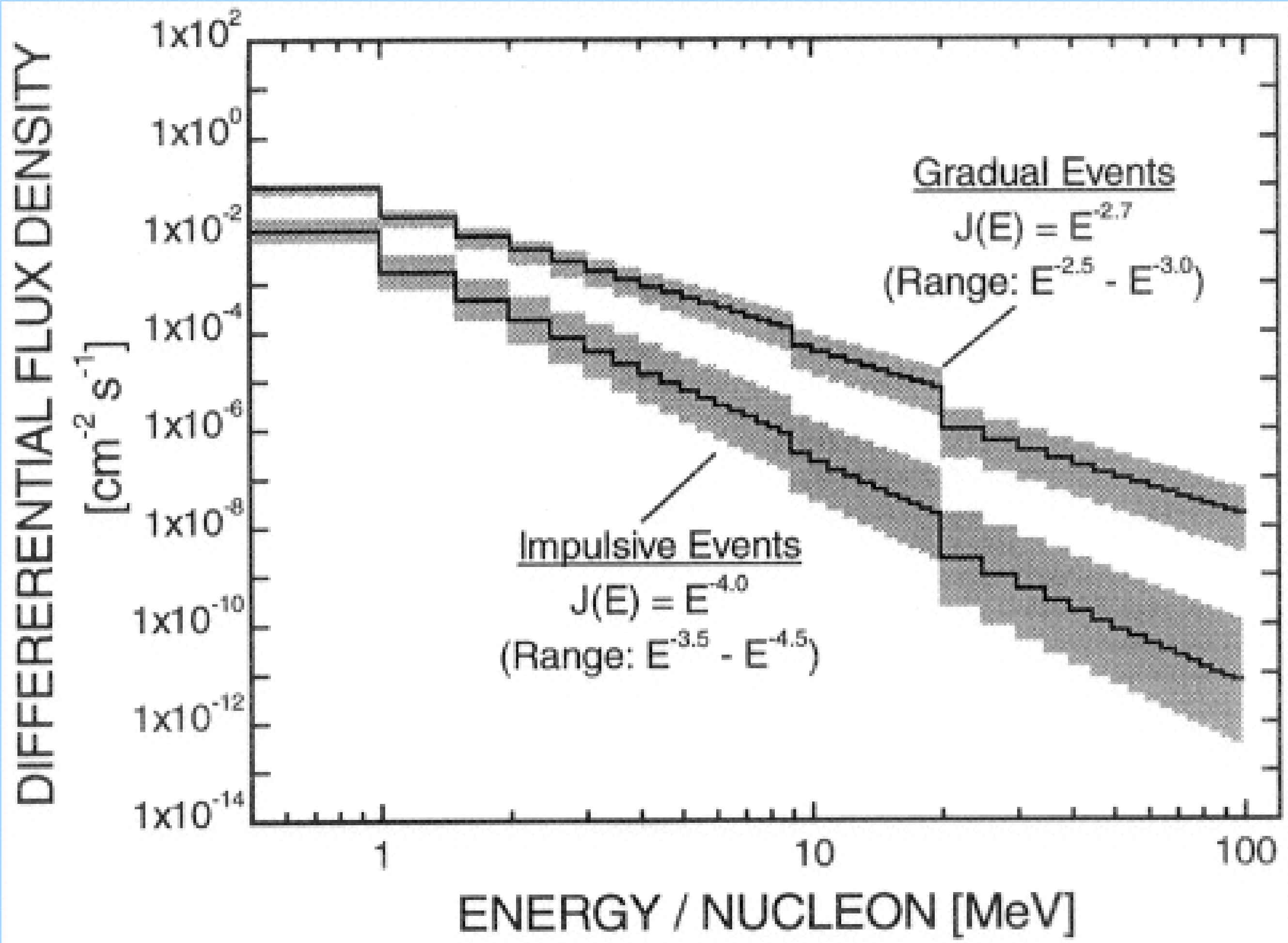
- **Cosmic Rays accelerated in the irradiation region**
  - For the Sun, L_p (E>10 MeV) ~ 0.09 L_X^{hard}
  - For protostars, $L_x^{hard} = 5 \times 10^{30}$ erg.s^{-1}
  - Scaling protostars to the Sun, L_p (E>10 MeV) ~ 4.5×10^{29} erg.s^{-1}
  - $F_p \sim L_p/A \sim 2 \times 10^{10}$ cm^{-2}.s^{-1}

- **Proton energy spectra** : $N(E) = E^{-p}$
  - p varies between 2 and 5

- **CR abundances**
  - ^{4}He/alpha = 0.1
  - ^{3}He/p varies between 0 and 1

The proton energy spectrum

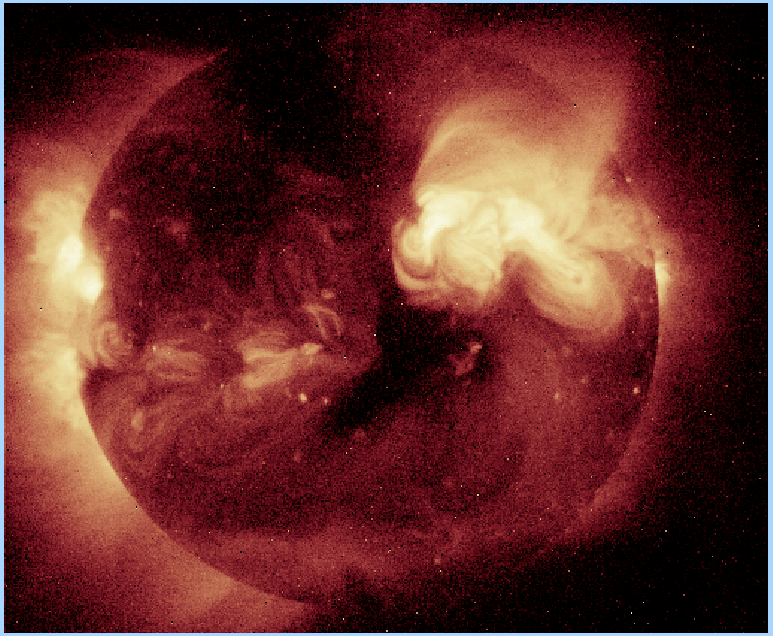
- **Proton energy spectra** : $N(E) = E^{-p}$



Leya et al. 2003

Irradiation model: the cosmic-ray parameters 2

In the contemporary Sun, there are <u>2 types of flares</u>



❶ **Impulsive flares**

- **^{3}He-**rich (^{3}He/p up to 3)
- Steep energy spectra (p ~ 4)
- Electron-**rich**
- Hard X-rays
- Frequent

❷ **Gradual flares**

- ^{3}He-poor
- Shallower energy spectra (p ~ 3)
- Electron-poor
- Soft X-rays
- Rare

- New results in the context of the x-wind model

Irradiation model: the novelties

❶ **Use of a new EXPERIMENTALLY measured $^{24}Mg(^{3}He,p)^{26}Al$ cross section**

- TANDEM and AMS at Orsay
- Duprat, Tatischeff et al. (2004)
- Other measurements ?

❷ **Calculations made for ^{7}Be**

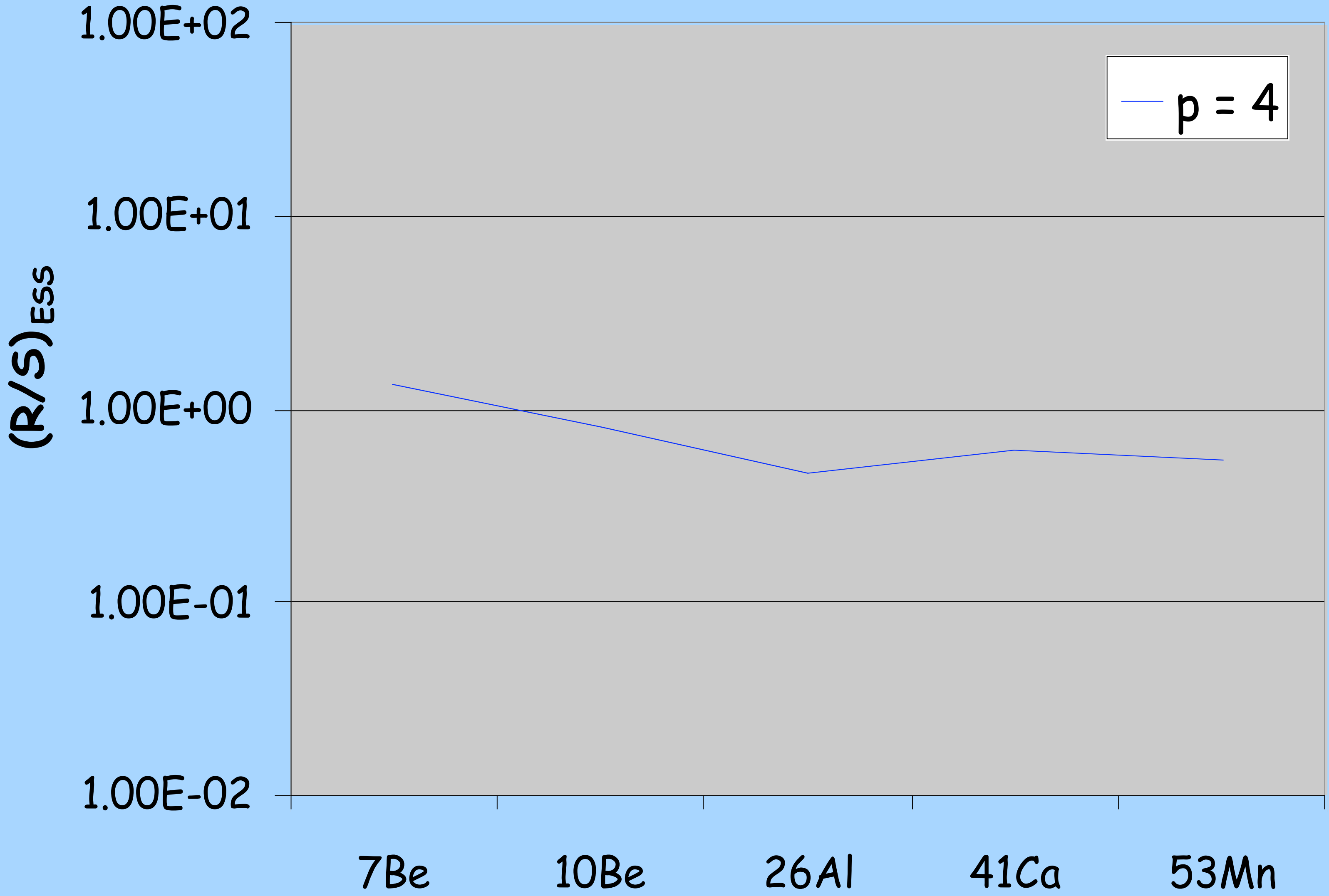
- Taking into account its short half-life (53 days) compared to the irradiation time (20 yr for a cm-sized protoCAI)
- What matters is the ^{7}Be produced over the **last mean-life** (0.21 yr)

❸ **Possibility of using a chondritic chemistry**

- Comparison with previous version of the model (Lee et al. 1998)
- Comparison with other models (Mahras et al. 2002. Leya et al. 2003)

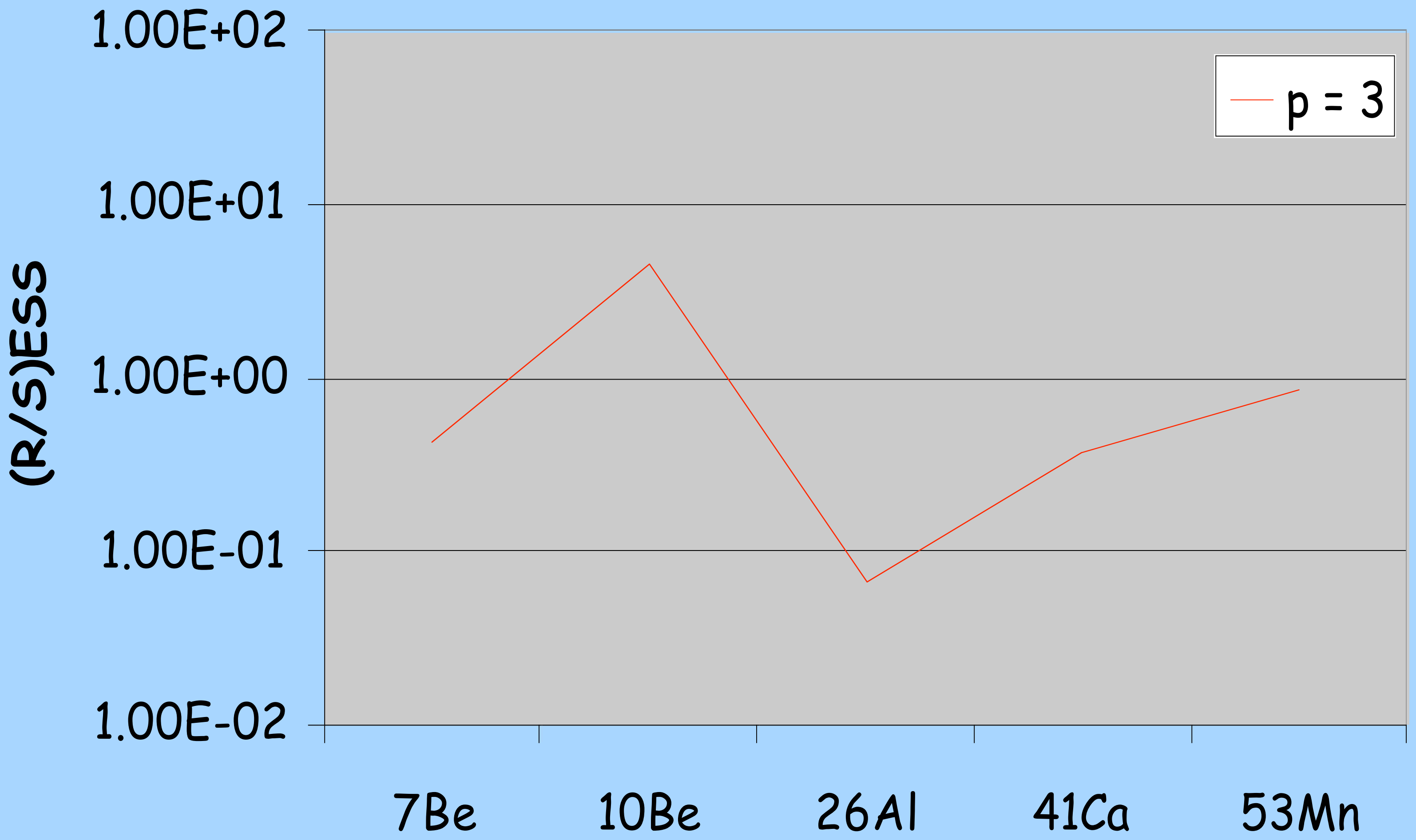
Core-mantle protoCAIs

Impulsive flares (3He/p = 0.3, p ~ 4)



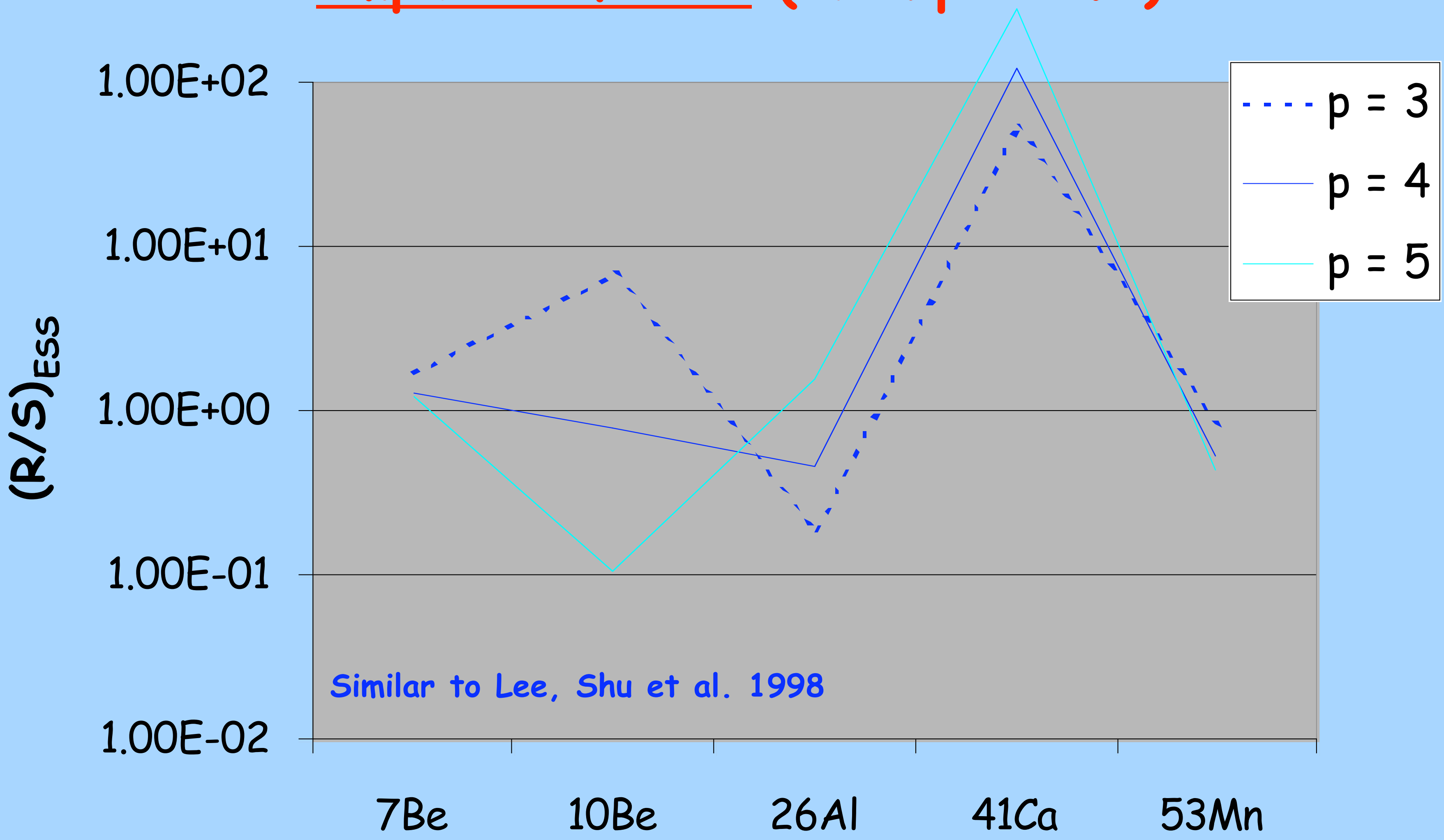
Core-mantle protoCAIs

Gradual flares (3He/p=0, p ~ 3)



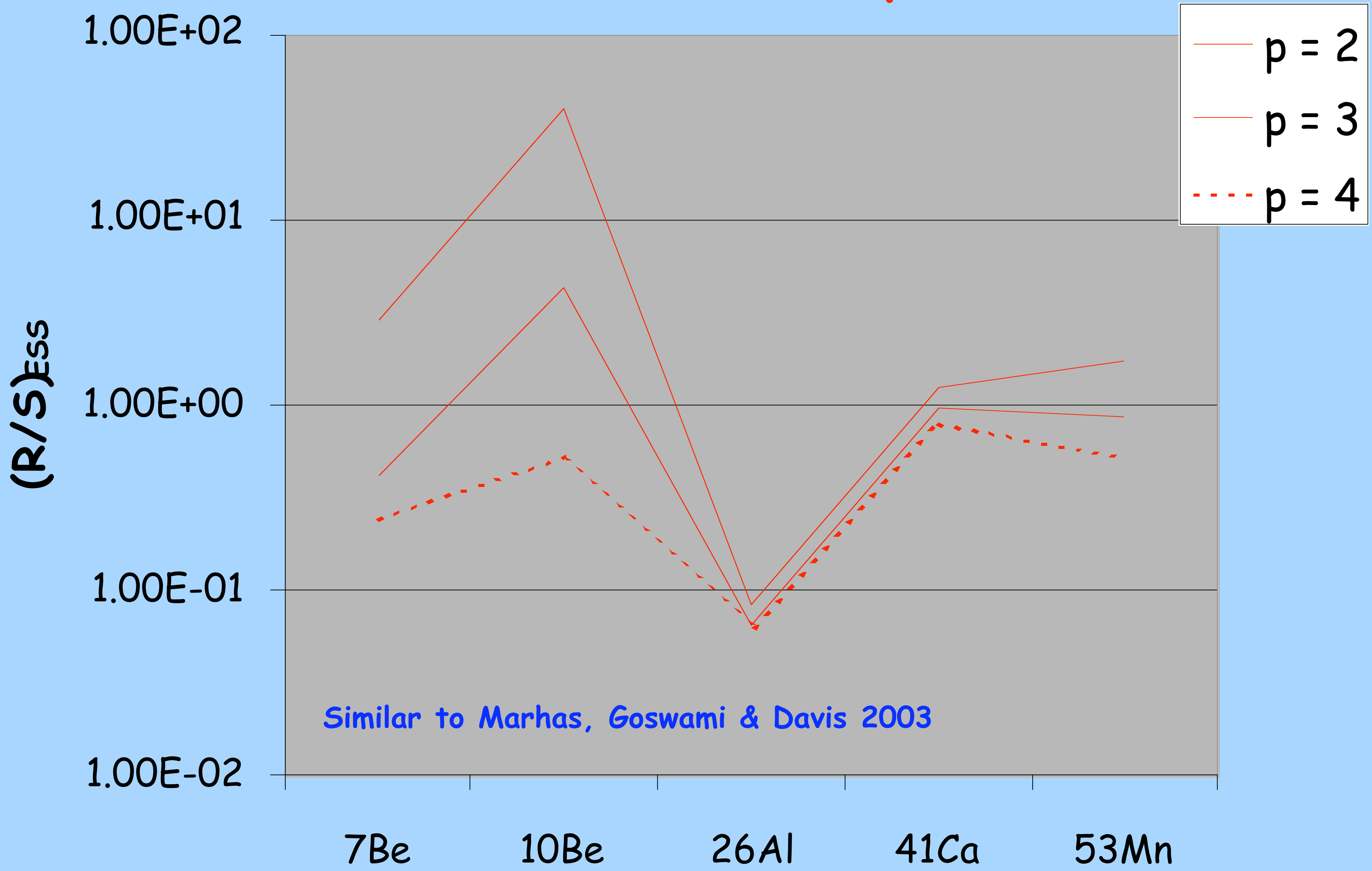
Chondritic protoCAIs

Impulsive flares (3He/p = 0.3)



Chondritic protoCAIs

Gradual flares (3He/p = 0)



The irradiation model: Summary 1

- ^{7}Be can only be produced by in situ irradiation

- Impulsive flares can reproduce the observed abundance of ^{7}Be in CAIs, as well as ^{10}Be, ^{26}Al, ^{41}Ca, ^{53}Mn

- This is with **the same parameters** as in our 2001 work

- Note: The measured ^{7}Be value ($^{7}Be/^{9}Be = 0.0061 \pm 0.0013$) is within a factor of two of what we calculated in 2003 ($^{7}Be/^{9}Be \sim 0.003$ LPSC abstract)

Decoupling of ^{10}Be and ^{26}Al: a possible solution

- Gradual flares can produce ^{10}Be without producing ^{26}Al nor ^{41}Ca
- We propose that: **Isotopically anomalous hibonites produced during gradual flares**
- Gradual flares in the contemporary sun are rarer than impulsive flares (factor of 100, Reames 1995): coherent with the fact that hibonites (and FUN inclusions) are rarer than normal inclusions

Decoupling of ^{10}Be and ^{26}Al: a possible solution

- **Does it work quantitatively?**
  - HAL is the only FUN CAI for which we have ^{26}Al and ^{10}Be data – no ^{53}Mn or ^{41}Ca data
  - Note that what is observed for other FUN CAIs are upper limits not **zero**
    - $(^{10}Be/^{9}Be)/(^{26}Al/^{27}Al) = 8.1 \pm 4 \times 10^3$ for HAL
    - $(^{10}Be/^{9}Be)/(^{26}Al/^{27}Al) = 4.7 \times 10^3$ **calculated in gradual flares**

The $^{60}Fe/^{56}Fe$ "problem" 1

- The Solar System initial ratio not known (~ 1-16 x 10^{-7})

- Expected abundance of Galactic nucleosynthesis ~ 2.6 x 10^{-8}
  - ☆ Busso, Gallino & Wasserburg 1999
  - ☆ At best the early "Solar System value" is a factor of 4 lower
  - ☆ ^{60}Fe not a product of the Galactic evolution

- ^{60}Fe is not made by irradiation
  - ☆ Lee, Shu et al. 1998
  - ☆ Too neutron-rich a radionuclide to be made with p, ^{3}He, ^{4}He

- ^{60}Fe has a "last minute" stellar origin

The $^{60}Fe/^{56}Fe$ "problem" 2

Output of the Busso, Gallino, Wasserburg (2003) SN model

		?$_1$ = 1.09 Myr		?$_2$ = 8 Myr	?$_2$ = 4 Myr
	mean life	**15 Mo**	**25Mo**	**15 Mo**	**25Mo**
		fo=3 x 10^{-4}	**fo=1.3 x 10^{-4}**	**fo=3 x 10^{-4}**	**fo=1.3 x 10^{-4}**
26Al	1.05	**5.00E-05**	**5.00E-05**	2.5E-08	1.1E-06
41Ca	0.15	**1.50E-08**	**1.50E-08**	1.0E-31	3.9E-20
53Mn	5.3	3.50E-03	3.00E-03	7.7E-04	1.4E-03
60Fe	2.2	4.70E-05	9.00E-06	**1.2E-06**	**1.5E-06**

- Mo = Sun Mass determines the isotopic abundance (R, S)
- f_0 = dilution of the SN ejecta with ISM
- $\Delta 1$ = free decay interval calculated by Busso et al. (2003) to have ^{26}Al and ^{41}Ca at the meteoritic level
- $\Delta 2$ = additional free decay interval calculated by us to have ^{60}Fe at the meteoritic level

The $^{60}Fe/^{56}Fe$ solution

- **If ^{60}Fe is produced at the meteoritic level**
  - ^{26}Al and ^{41}Ca are far below the early Solar System abundance,
  - ^{53}Mn is slightly overproduced using Busso et al. (2003) parameters

- The ^{53}Mn production in supernovae models can be decreased by changing the mass cut (Meyer & Clayton 2000)
- We can change f_0 to get ^{53}Mn right

- **A supernova can deliver ^{60}Fe without delivering the other short-lived radionuclides**
  - ☆ Not surprising since SN produce copious amounts of ^{60}Fe
  - ☆ This supernova exploded ~ 8 Myr ago: **no collateral effects**

The irradiation model - summary

- Can reproduce the observed abundance of ^{7}Be together with ^{10}Be, ^{26}Al, ^{53}Mn
- Can account for the rare CAIs having ^{10}Be and no ^{26}Al
- A "late" minute supernova can account for the abundance of ^{60}Fe
- **Problems**
  - There is no evidence for any ferromagnesian mantle in meteorites
  - Need of a high ^{3}He abundance to make ^{26}Al

- The astrophysical context of the Sun's birth

The birth of a star

- **Stars are born in Molecular Clouds (MC)**

- **They can be born**
  - In isolation (single or binary stars)
  - In groups ($N < N^*$)
  - In clusters ($N > N^*$)

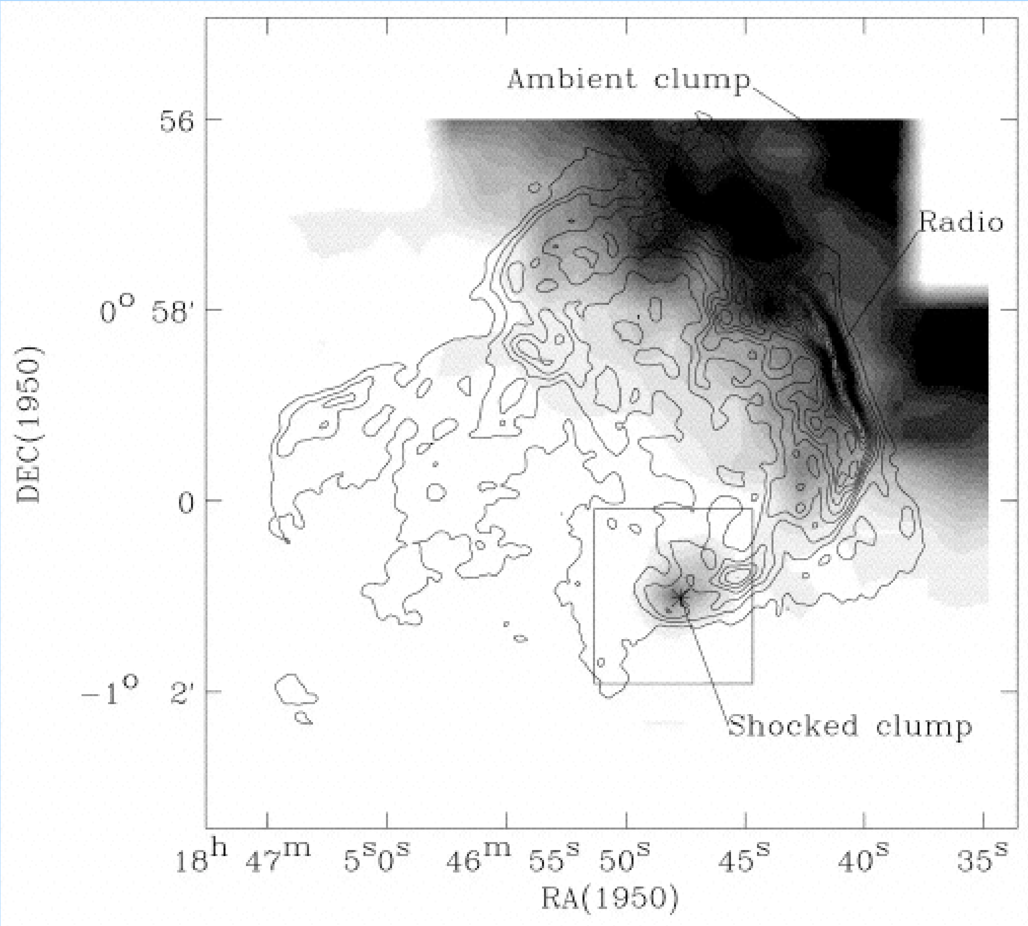
- **N^* is difficult to estimate, but $N^* \sim 100$ (Adams & Myers 2001)**

- **Most stars (90 %) are born in isolation or in groups ($N<100$) (Adams & Myers 2001)**

What about our SUN ?

- **It is a low-mass star (1Mo = 10^{30} kg)**
- **Low-mass stars are observed to be born**
  - In small molecular clouds (~few 100 stars, e.g. Taurus)
  - In giant molecular clouds (~2300 stars, e.g. Trapezium in Orion)
- **The Sun has drifted in position since its birth 4.5 Ga**
  - Analysis based on the Sun's metallicity (Z = [Fe/H])
  - From 6.6 ± 0.9 kpc to 8.5 kpc to the Galactic Center
  - Wieden et al. 1996
- **We do not know where and in which environment our Sun was born**

Has triggered stellar formation been observed?



Excitation and disruption of a GMC by the Supernova Remnant 3C 391
Reach and Rho ApJ 511 836-846

- **Shocked clump v ~ 20 km.s^{-1}**
- **Post shock T>100 K, n ~ 3 x 10^{5} cm^{-3}**
- **Supernova was estimated to be 3 pc away from the core**
- **High mass core**

Likehood and occurrence of such encounters

- **Only very few known cases of interaction between a Molecular Cloud core and a Supernova Remnant**
  - 3C 391 (Reach and Rho 1999)
  - IC 443 (van Dishoeck et al 1993)

- **If the Sun was born in a molecular cloud as Taurus, the chance to be associated with a Supernova is low, because Initial Mass Function (IMF) “favours” low-mass stars**
  - $dN/dM \sim M^{-2.4}$

- **No known case of encounter between an AGB and a MC**

- **The probability of encounter for an AGB star is low (~1% Kastner & Myers 1994)**

Constraints on the birth aggregate of the Solar System

Adams & Laughlin Icarus 150 151-162 (2000)

- **Enhanced UV flux leading to photoevaporation of the disk**
  - From 5 AU outwards, the UV flux of the environment is larger than that of the Sun
  - Photoevaporation at a rate dM/dt = 10^{-7} Mo/y
  - If a minimum solar nebula (0.01 Mo) is lost in 10^5 yr, problems with giant planet and chondrule formation

- **Gravitational interaction leading to orbit disruption**
  - Orbit stability of the outer planet ?
  - Survival of the Kuiper belt ?

Summary of "astrophysical" arguments

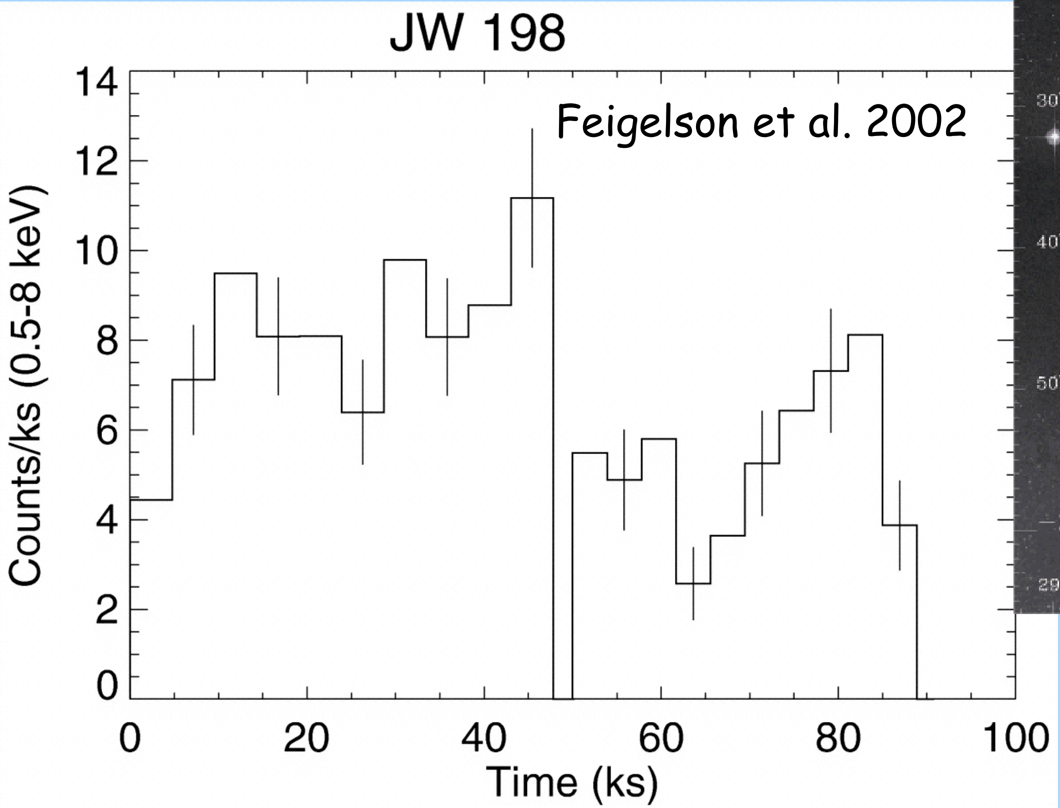
- **Orion environment is not the rule**
  - Stars are rather born in clusters
- **Orion environment is agressive for a protoplanetary System**
  - Disruption of the disk ?
  - Stability of orbits ?
- **SN-MC encounters observed but rare**
- **AGB-MC encounters not observed, estimated to be rare**
- **Improbable event does not mean impossible event**
  - Is our Solar System typical?

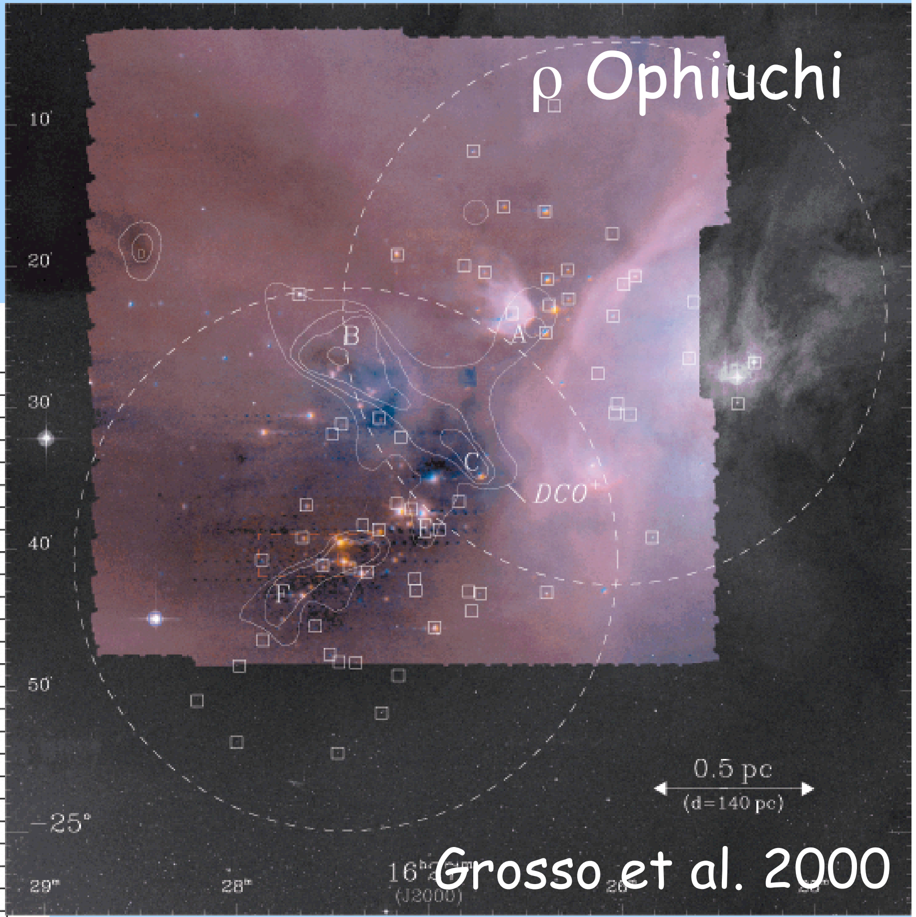
- X-Rays in protostars

  & Cosmic Rays

Flares in protostars and the Sun

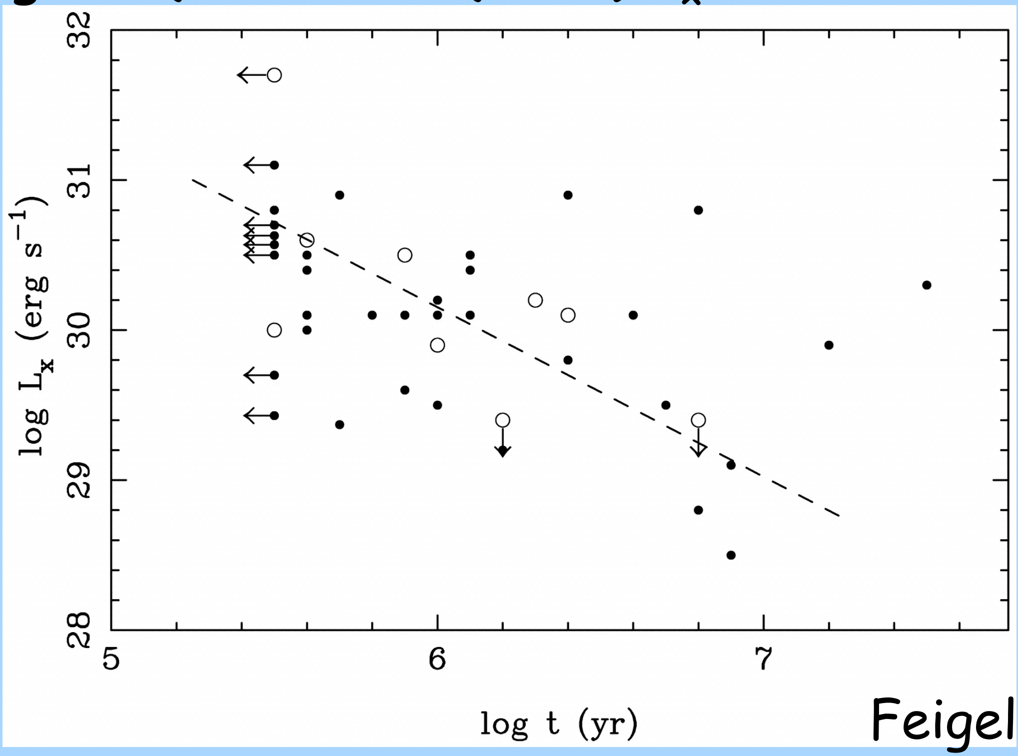
- **Observations of Protostars with X-Ray satellites**
  - Ubiquitous activity
  - Variable activity
  - Hard X-rays (up to 12 KeV)
  - ➲ Impulsive flares ?





X-Ray luminosity in protostars

- CHANDRA Survey (Feigelson et al. 2002)
- 43 stars with masses 0.7 -1.4 Mo
- $L_x = 10^{30.3}$ erg.s^{-1} (Lee et al. (1998) $L_x = 5 \times 10^{30}$ erg.s^{-1})



Feigelson et al. 2002

X-Ray luminosity in protostars

- In the Sun, acceleration of proton, 3He and 4He is seen in flares together with X-rays

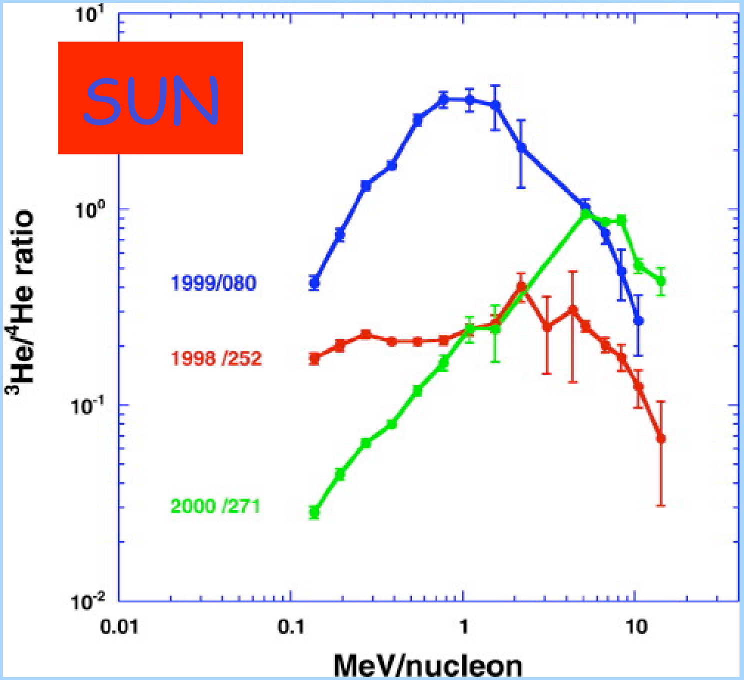
Ubiquity of hard X-Rays in protostars

=

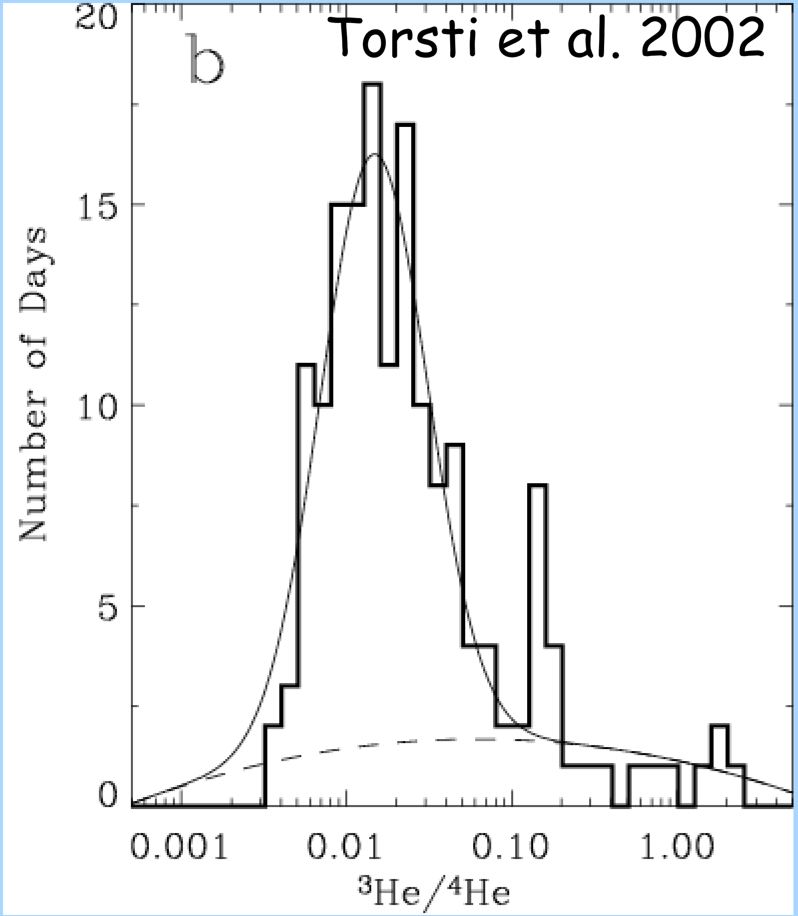
Ubiquity of irradiation processes

?

^3He in the contemporary Sun

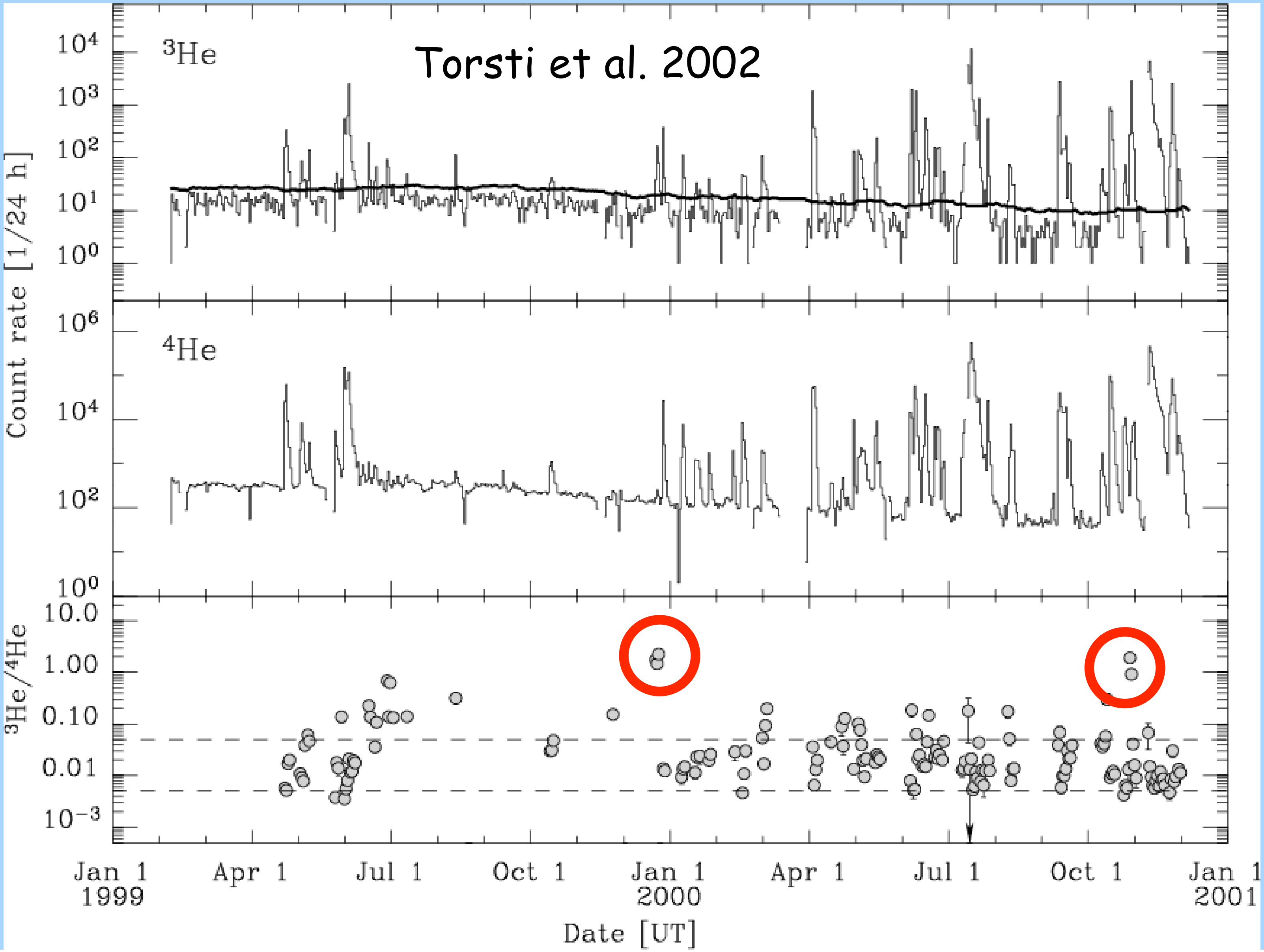


Mason et al. 2002



Note: the present SUN is teh best analog we have of the protoSun, but the actual physics might have been quite different

^3He in the contemporary Sun



- The origin of short-lived radionuclides: Summary

Summary 1

- ^{7}Be, ^{10}Be, ^{26}Al, ^{41}Ca, ^{60}Fe, (^{53}Mn) need a last minute origin
- Latest SN models fail to account for the ESR abundance
- Some **AGB stars** can account for **^{26}Al, ^{41}Ca and ^{60}Fe** (Busso et al 2003) while **GCR trapping** might account for ^{10}Be (Desch et al 2004)
  - ☆ A MC-AGB encounter is an unlikely event
  - ☆ Parameters for GCR trapping might not be adapted to our Sun
  - ☆ Cannot make ^{7}Be

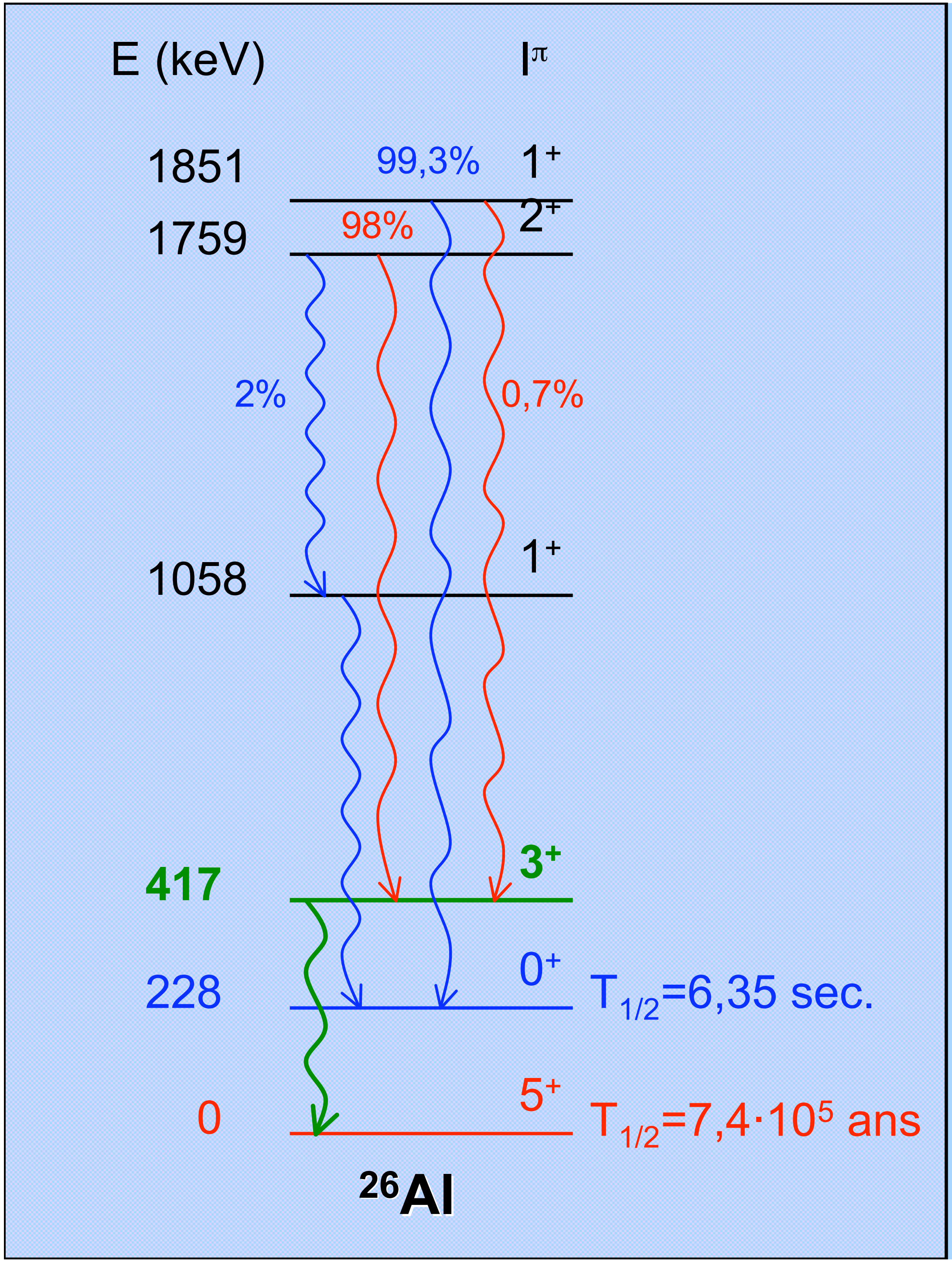
Summary 2

- **If ^{7}Be was present** in the early Solar System, there was some **irradiation**

  - The irradiation model in the context of the x-wind theory can account for ^{10}Be, ^{26}Al, ^{41}Ca, ^{53}Mn abundances
  - It reproduces the ^{7}**Be** abundance without parameters tuning
  - It gives a straightforward explanation for FUN-like CAIs
  - The presence of ^{60}Fe is **not** a problem
  - The ferromagnesian mantle is still a problem

- Let us await for some more data and be patient!

Energy levels of ^{26}Al



Beware: not the gamma ray seen in space

The 1809 keV γ ray comes from the $^{26}Mg^{*}$ desintegration