short-lived radioactivity in the early solar system

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what are short-lived (or extinct) radionuclides?

formal definition: short-lived nuclides are *radioactive nuclei with half-lives* ($t_{1/2}$) $\leq$*100 Ma*

in practice: $t_{1/2}$ comparable to “*free decay*” or “*isolation*” time, Δ

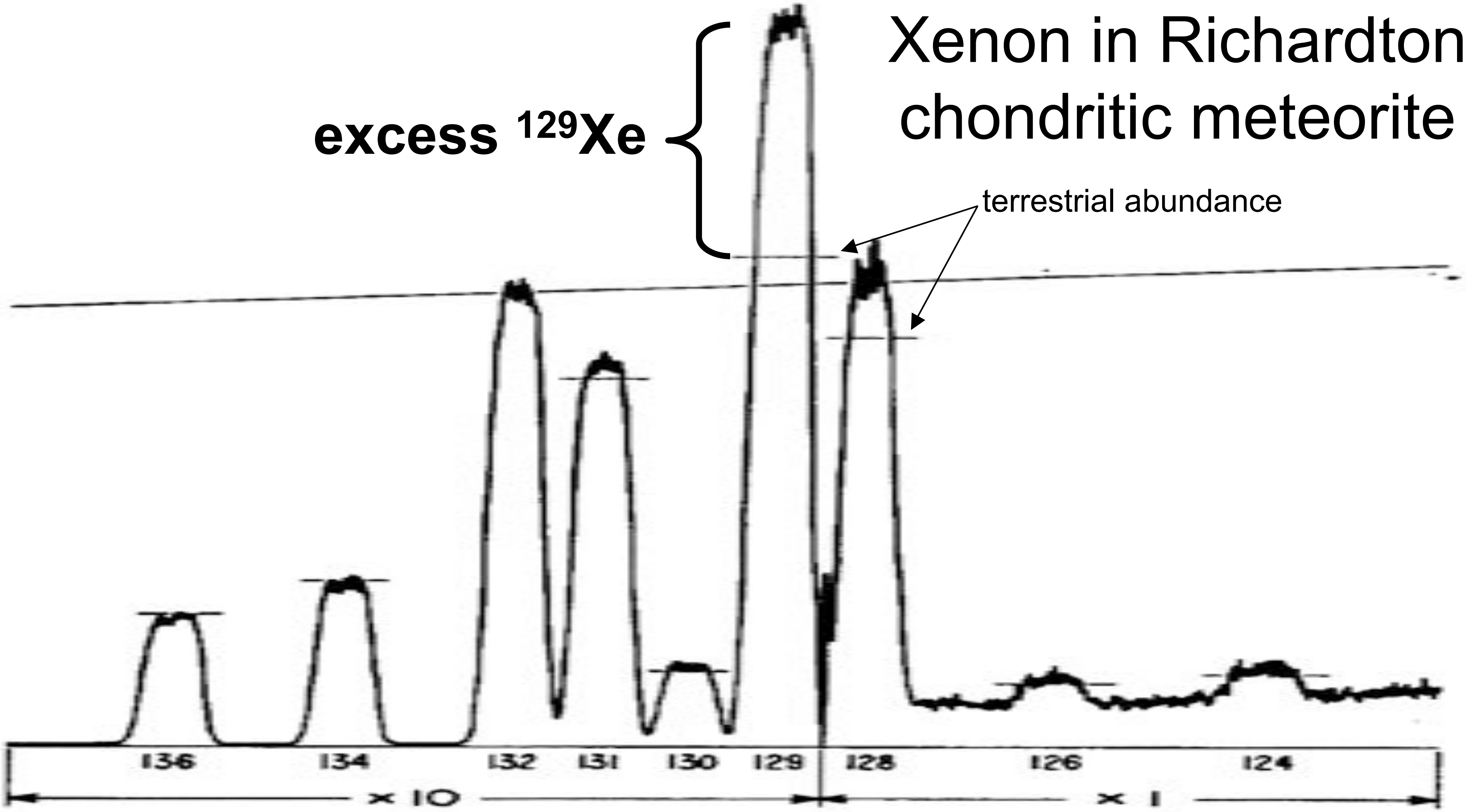
~ 0.1 Ma $< \Delta <$ $\sim$100 Ma

talk overview

Aim: provide an overview of the evidence for short-lived nuclides, abundances and origins, in the early solar system

- historical background
- early solar system inventory
- synthesis models
  - spallation, AGB/WR stars, supernovae, galactic uniform production
  - discriminating between these alternatives: how well do we know the solar accretion disk's initial SLN abundances?
- summary

Reynolds, J.H. (1960) *Determination of the age of the elements.* Physical Review Letters vol. 4, 8-10.



Xenon in Richardton chondritic meteorite

excess ^{129}Xe

terrestrial abundance

^{129}I-^{129}Xe radiogenic decay scheme

$$^{129}\mathrm{I} \rightarrow {}^{129}\mathrm{Xe} + \beta^{-} + \bar{\upsilon}_{e} + Q$$

$$t_{1/2} = 16\ \mathrm{Ma}$$

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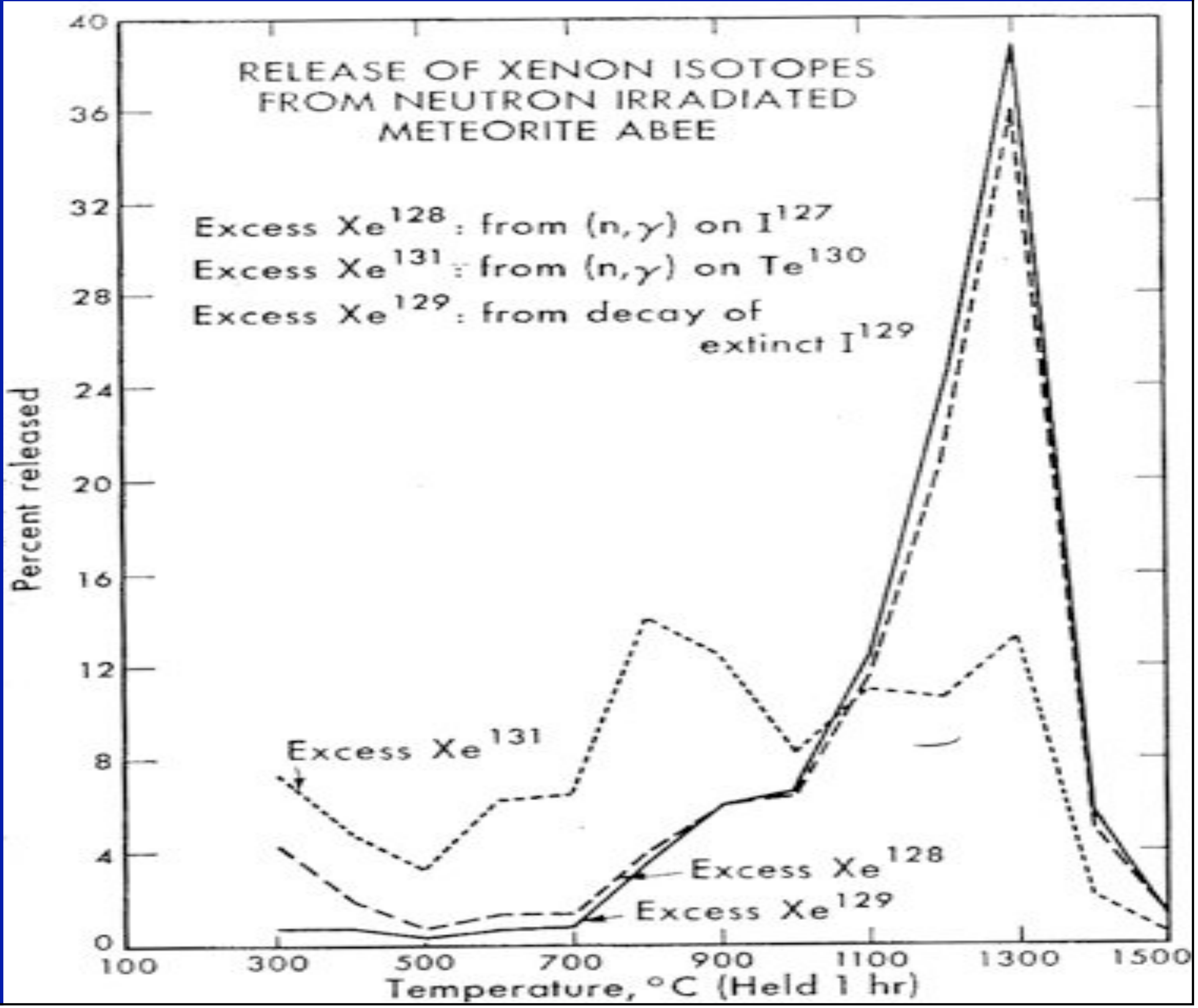
$$t_{1/2} = 16\ \mathrm{Ma}$$

live ^{129}I at time of solar system formation?

Jeffery P.M. and Reynolds J.H. (1961) *Origin of excess Xe^{129} in stone meteorites.* J. Geophysical Research vol. 66, 3582-3583.

in nuclear reactor:

$^{127}\text{I}\ (n,\beta)^{128}\text{Xe}$

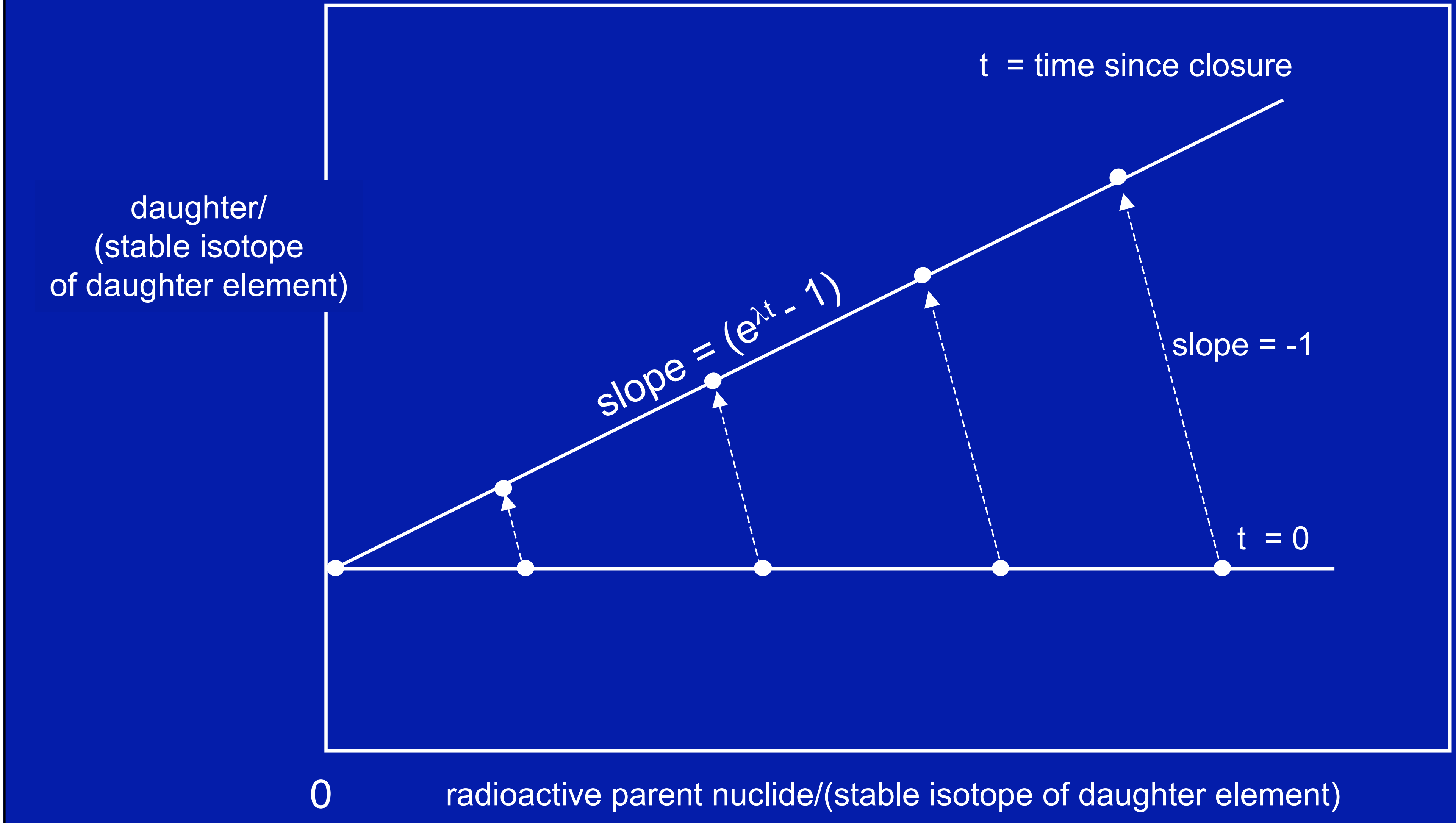


^{26}Al-^{26}Mg radiogenic decay scheme

$$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg} + \beta^{+} + \upsilon_{e} + Q$$

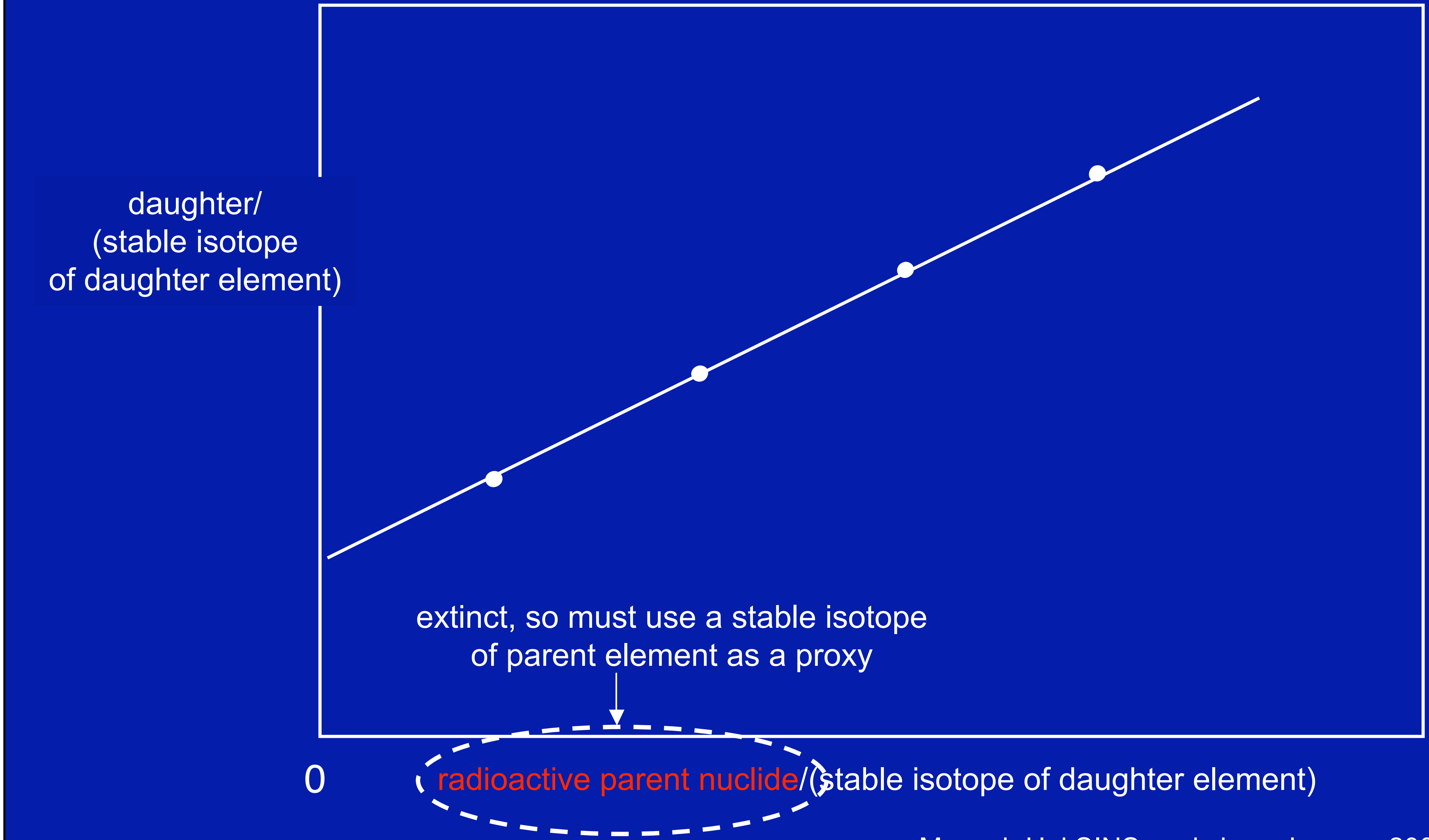
$$t_{1/2} = 0.72\ \mathrm{Ma}$$

isochron diagram



Monash Uni SINS workshop, January 2007

isochron diagram



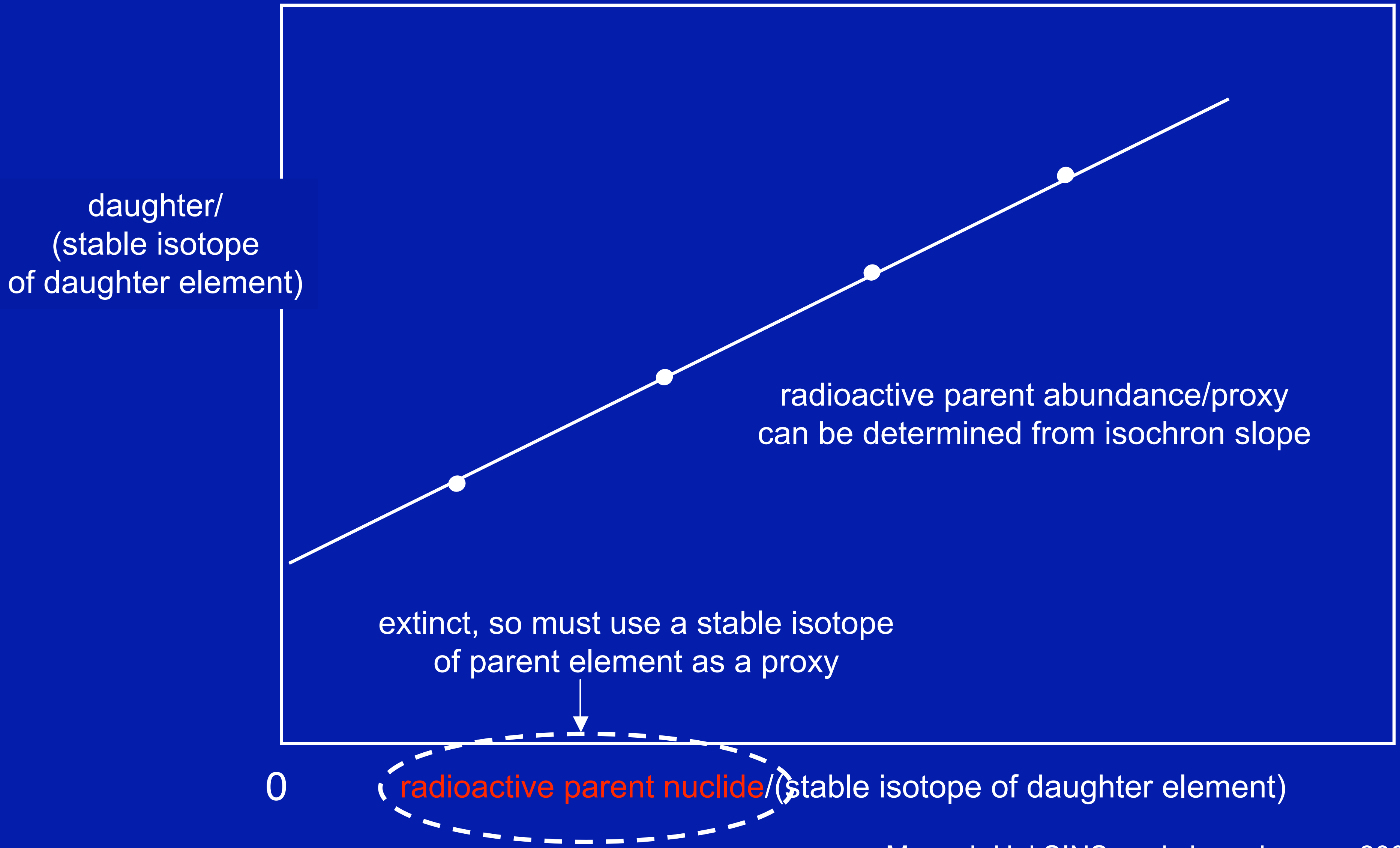
daughter/
(stable isotope
of daughter element)

extinct, so must use a stable isotope
of parent element as a proxy

0 radioactive parent nuclide/(stable isotope of daughter element)

Monash Uni SINS workshop, January 2007

isochron diagram



daughter/
(stable isotope
of daughter element)

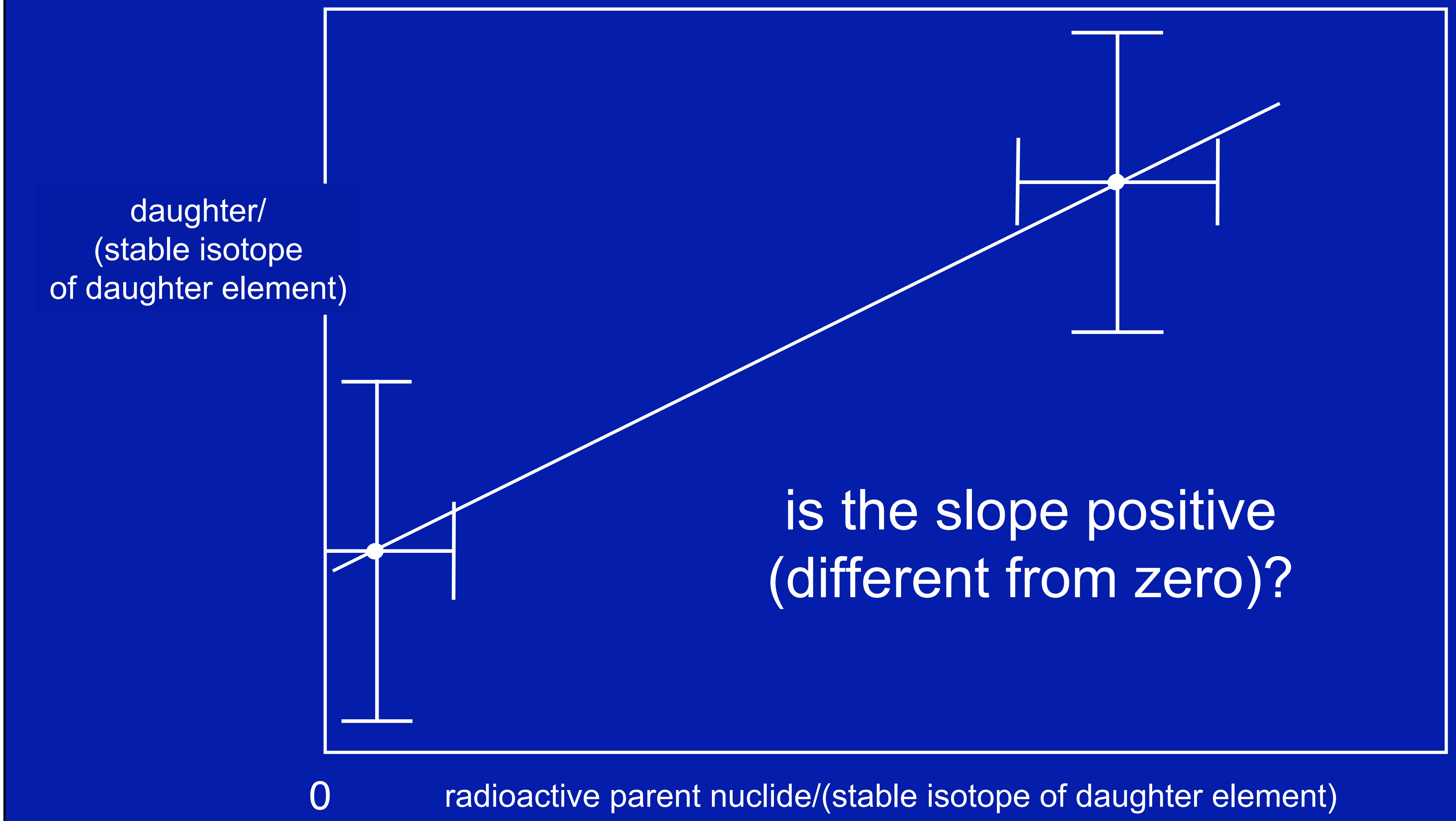
radioactive parent abundance/proxy
can be determined from isochron slope

extinct, so must use a stable isotope
of parent element as a proxy

0 radioactive parent nuclide/(stable isotope of daughter element)

Monash Uni SINS workshop, January 2007

isochron diagram



is the slope positive
(different from zero)?

^{26}Al-^{26}Mg radiogenic decay scheme

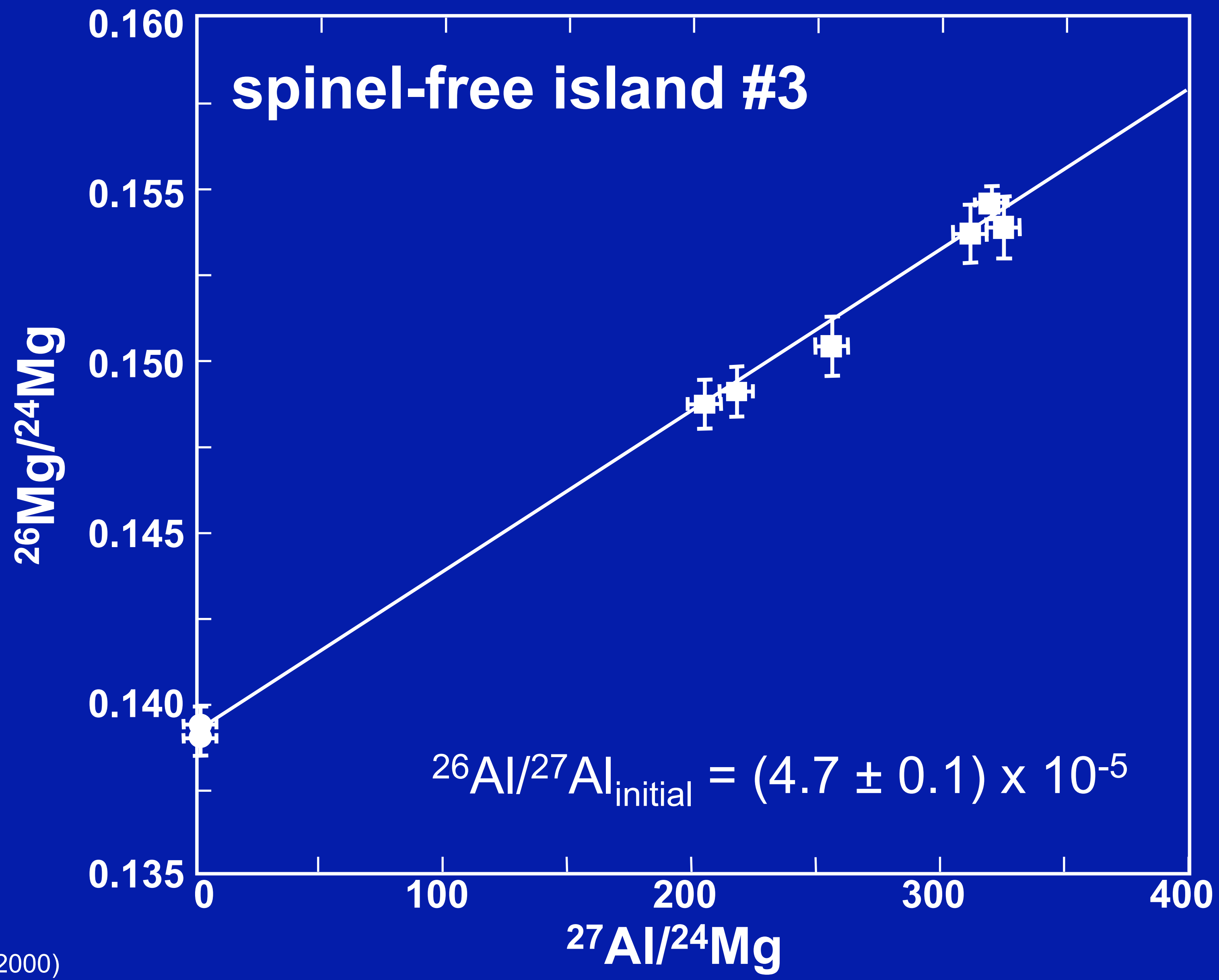
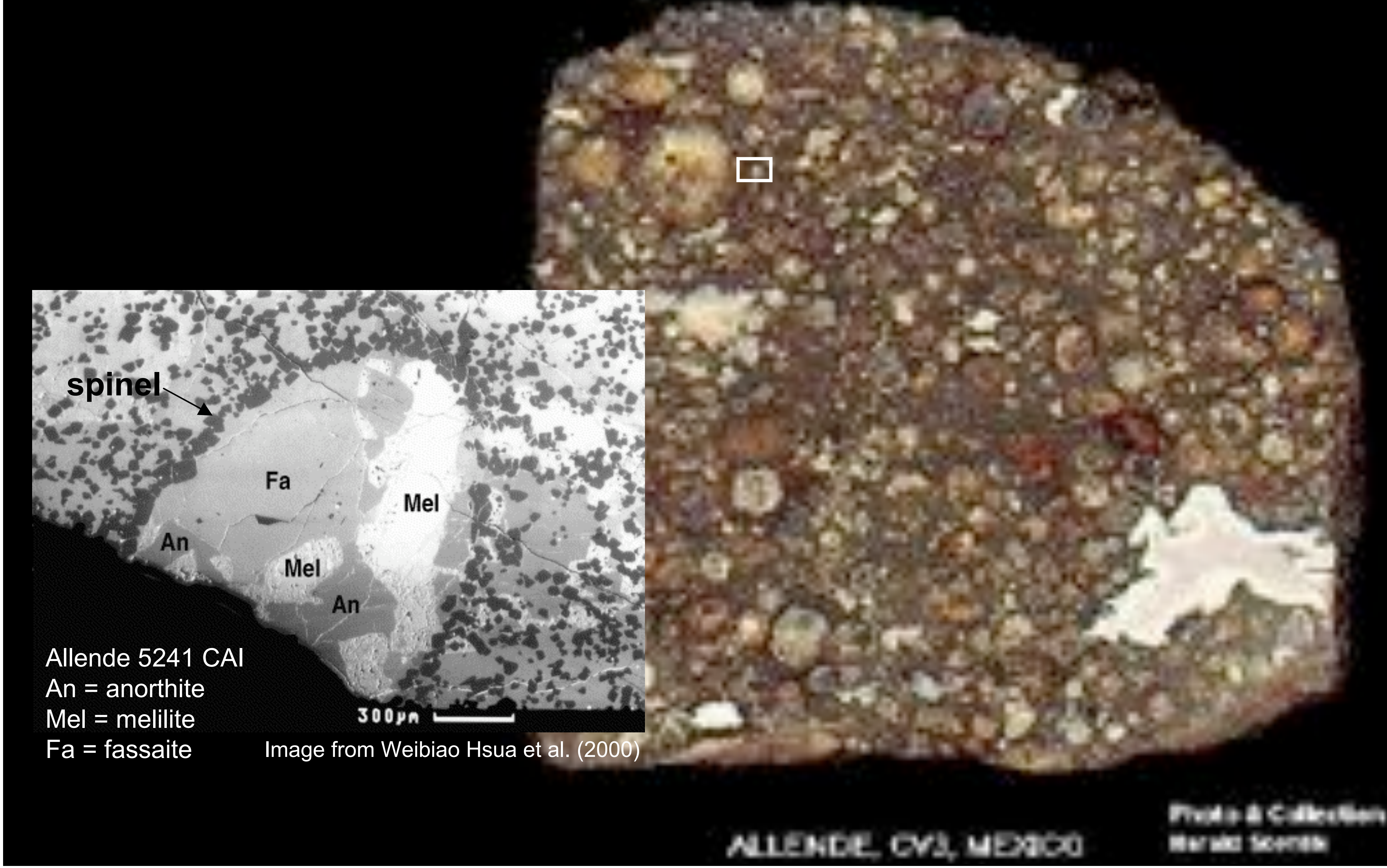


figure adapted from
Weibiao Hsua et al. (2000)

solar system formation



Allende 5241 CAI
An = anorthite
Mel = melilite
Fa = fassaite

Image from Weibiao Hsua et al. (2000)

solar system inventory of short-lived nuclides

radioactive nuclide	**$t_{1/2}$ (My)**	**daughter nuclide(s)**	**reference ratio**	**Initial ratio (I)**
^{10}Be	1.51	^{10}B	^{10}Be/^{9}Be	5.2×10^{-4}
^{26}Al	0.717	^{26}Mg	^{26}Al/^{27}Al	5.5×10^{-5}
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^{92}Nb*	34.7	^{92}Zr	^{92}Nb/^{93}Nb	$<3 \times 10^{-4}$
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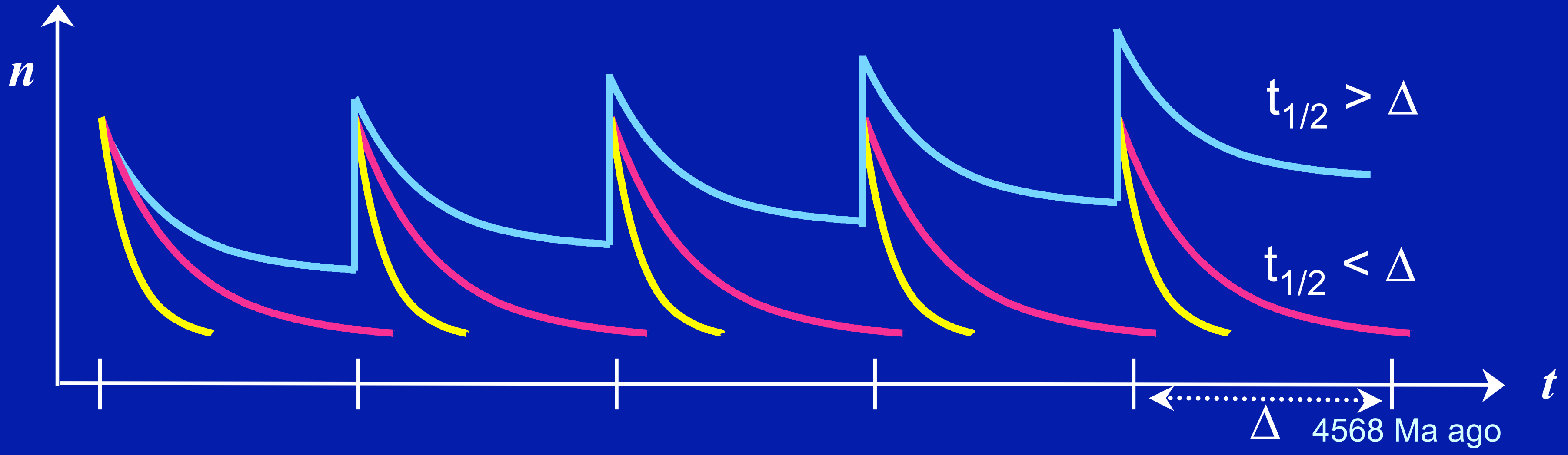
^{247}Cm*	15.6	^{235}U	^{247}Cm/^{235}U	$<8 \times 10^{-5}$

short-lived nuclides: synthesis mechanisms

1. intra- (i.e. post-) solar system
    - spallation induced by early solar (T Tauri phase) x-winds (solar energetic particle irradiation: SEP)

2. extra- (i.e. pre-) solar system
    - multiple stellar sources (continuous galactic production)
    - stellar winds from a TP-AGB or Wolf-Rayet star
    - contamination by core-collapse (type II) supernova ejecta

solar system inventory of short-lived ($t_{1/2} \leq 100$ Ma) nuclides: multiple stellar sources (continuous galactic production)

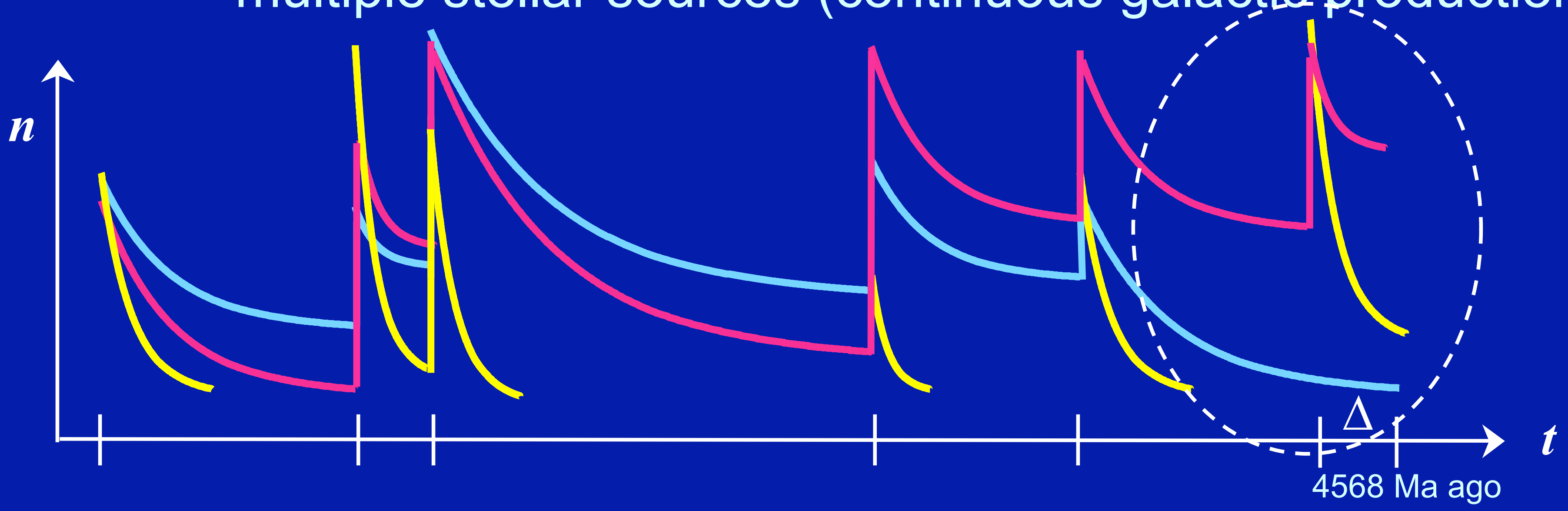


For ~10 $M_\odot$ supernova, ejecta diluted by ~10^{-2} within a 30 pc radius

Type II supernova event rate: ~ 3×10^4 Ma^{-1} (1 every 30 yrs)

⇒ ~20% of galactic disk contaminated by freshly synthesized ejecta every Ma (any point will see new nuclei every ~5 Ma)

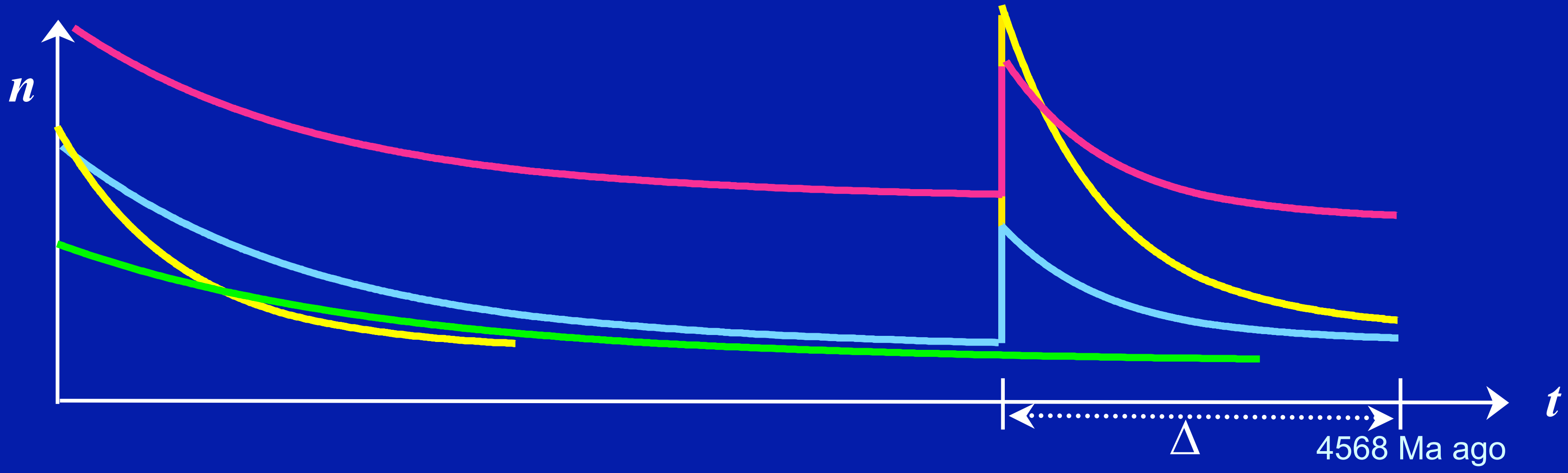
solar system inventory of short-lived ($t_{1/2} \leq 100$ Ma) nuclides: multiple stellar sources (continuous galactic production)



Problems with this analysis:

- nucleosynthesis-ISM events occur randomly, in stellar clusters (OB associations)
- range of masses, pulsing/exploding sources: AGB, W-R, novae, supernovae
- range of ejecta masses/compositions; different cycling rates, ISM mixing and dissemination efficiencies

solar system inventory of short-lived ($t_{1/2} \leq 100$ Ma) nuclides: last nucleosynthesis event



last nucleosynthesis event:

- constraints on Δ provided by SLN with shortest half-life detected
- absence of longer-lived species ⟶ nature of recent event(s)
- more detailed analysis requires comparison of observed SLN abundances with yields for different stellar sources and by spallation

short-lived nuclides:
solar system abundances

Issues:

- a common synthesis process (one Δ for all SLN) and homogeneous distribution within the solar accretion disk is usually assumed
- SLN abundances determined on range of different meteorite materials (CAI's, chondrules, planetary differentiates)
- unconstrained sample formation times and metamorphic disturbance means large SLN abundance uncertainties
- SLN abundance uncertainties will be significantly larger for nuclides with shorter half-lives (i.e. the useful ones)
- SLN abundances are (usually) expressed relative to a stable isotope of same element (i.e. derived from numerous sources); subsequently, these are not easily compared to SLN source yields

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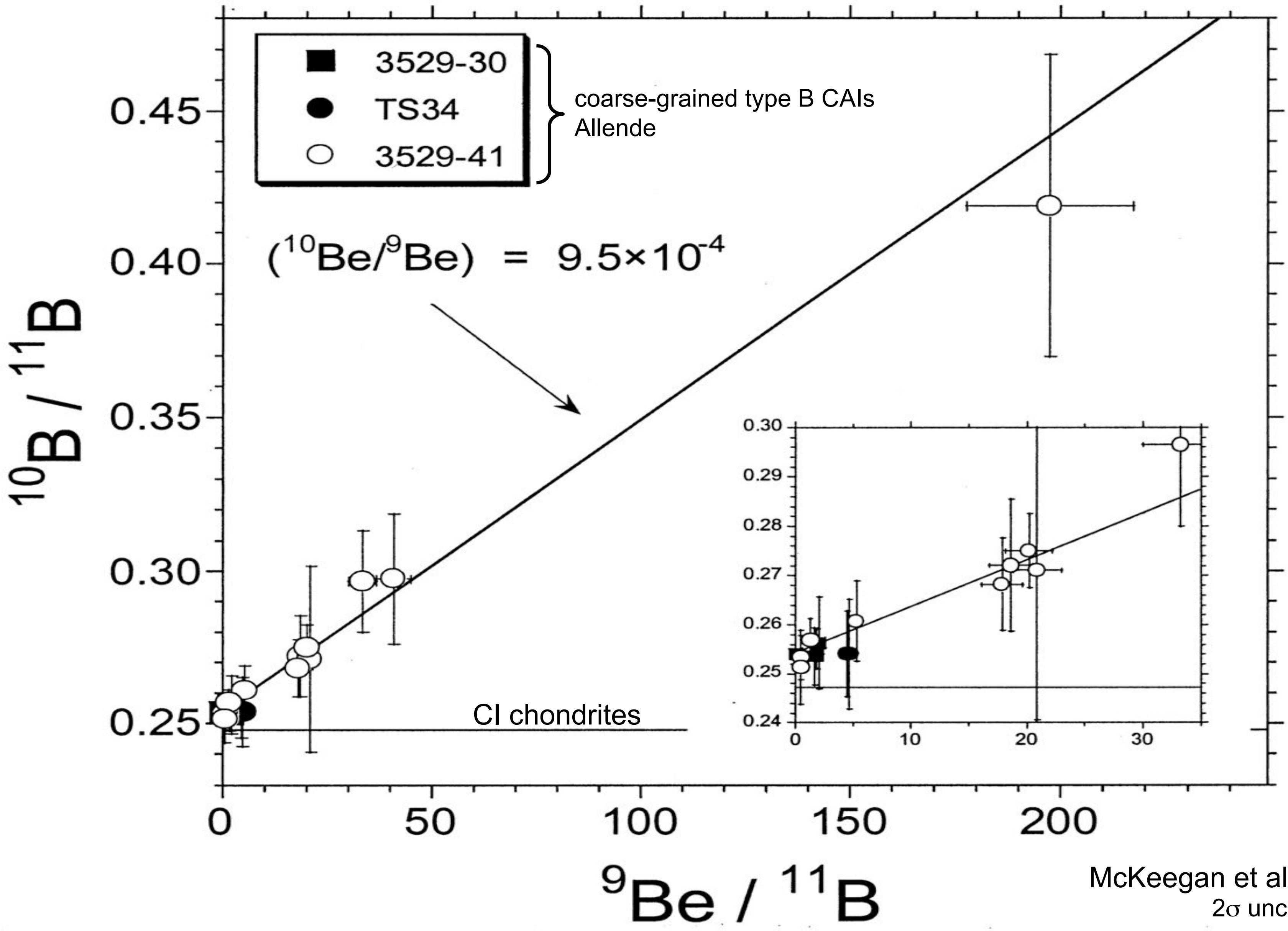
🟥 $t_{1/2} \leq 5$ Ma

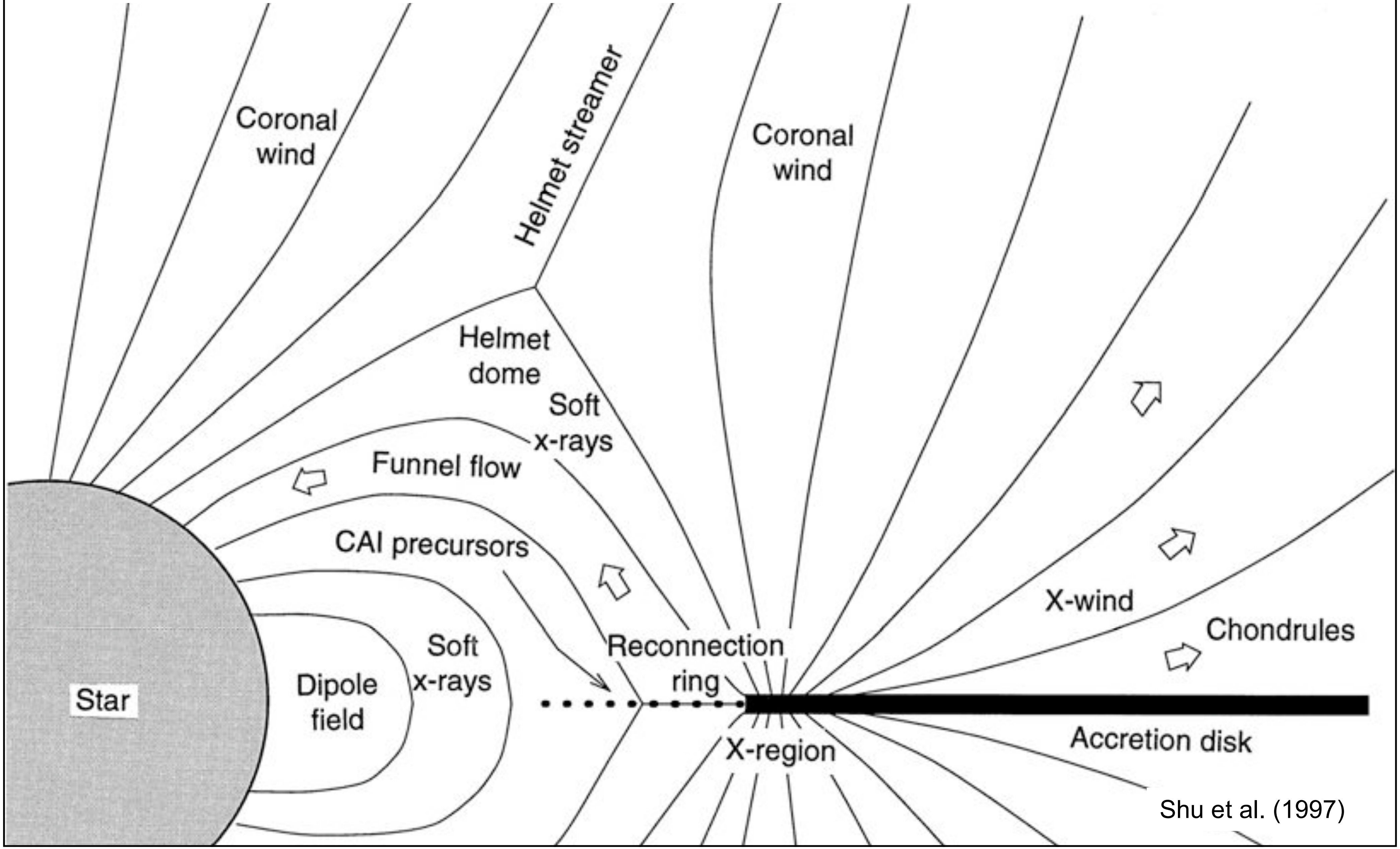
^{10}Be-^{10}B radiogenic decay scheme



coarse-grained type B CAIs
Allende

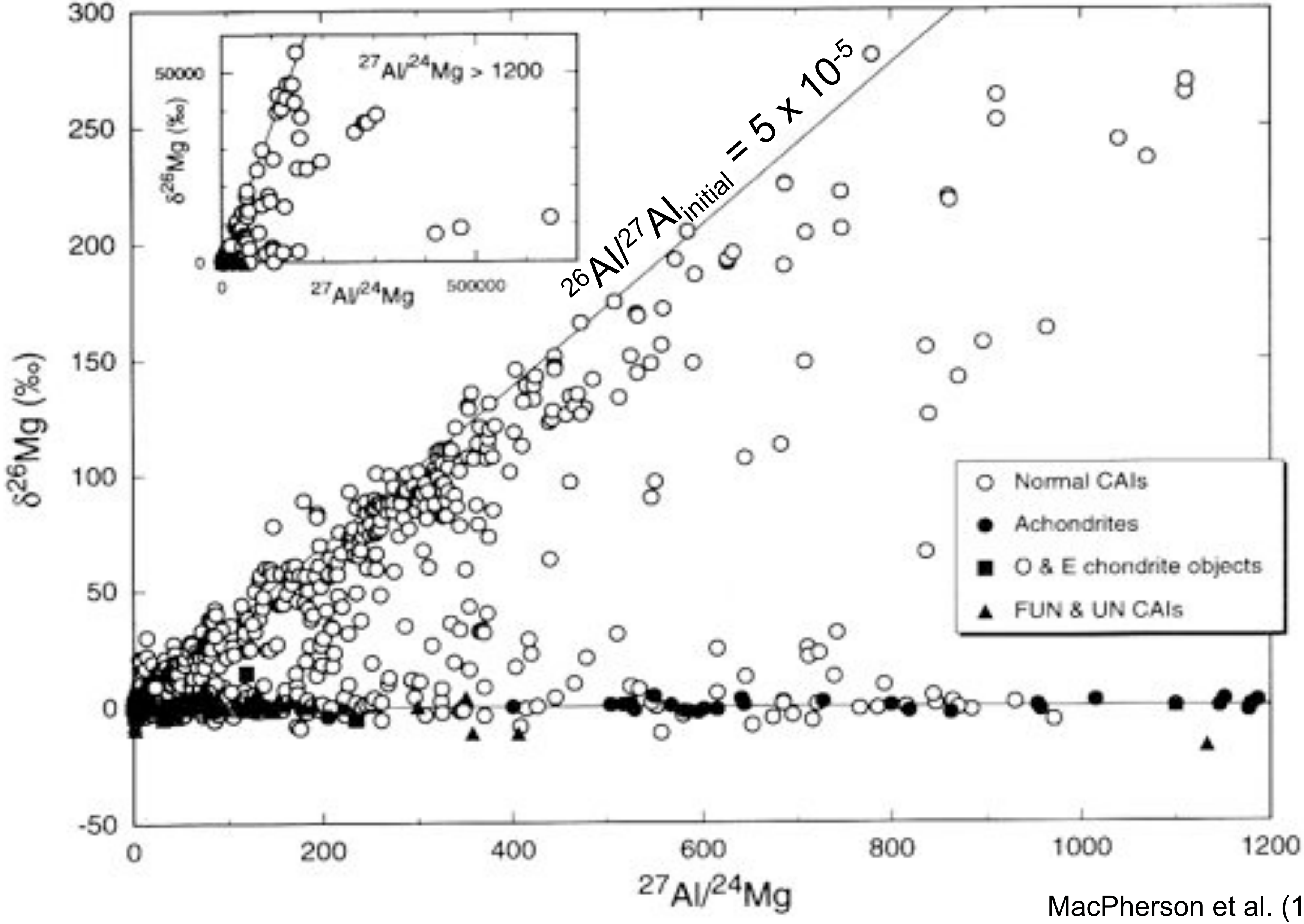
McKeegan et al. (2000)
2σ uncertainties

T-tauri phase sun: solar energetic particle (SEP) irradiation



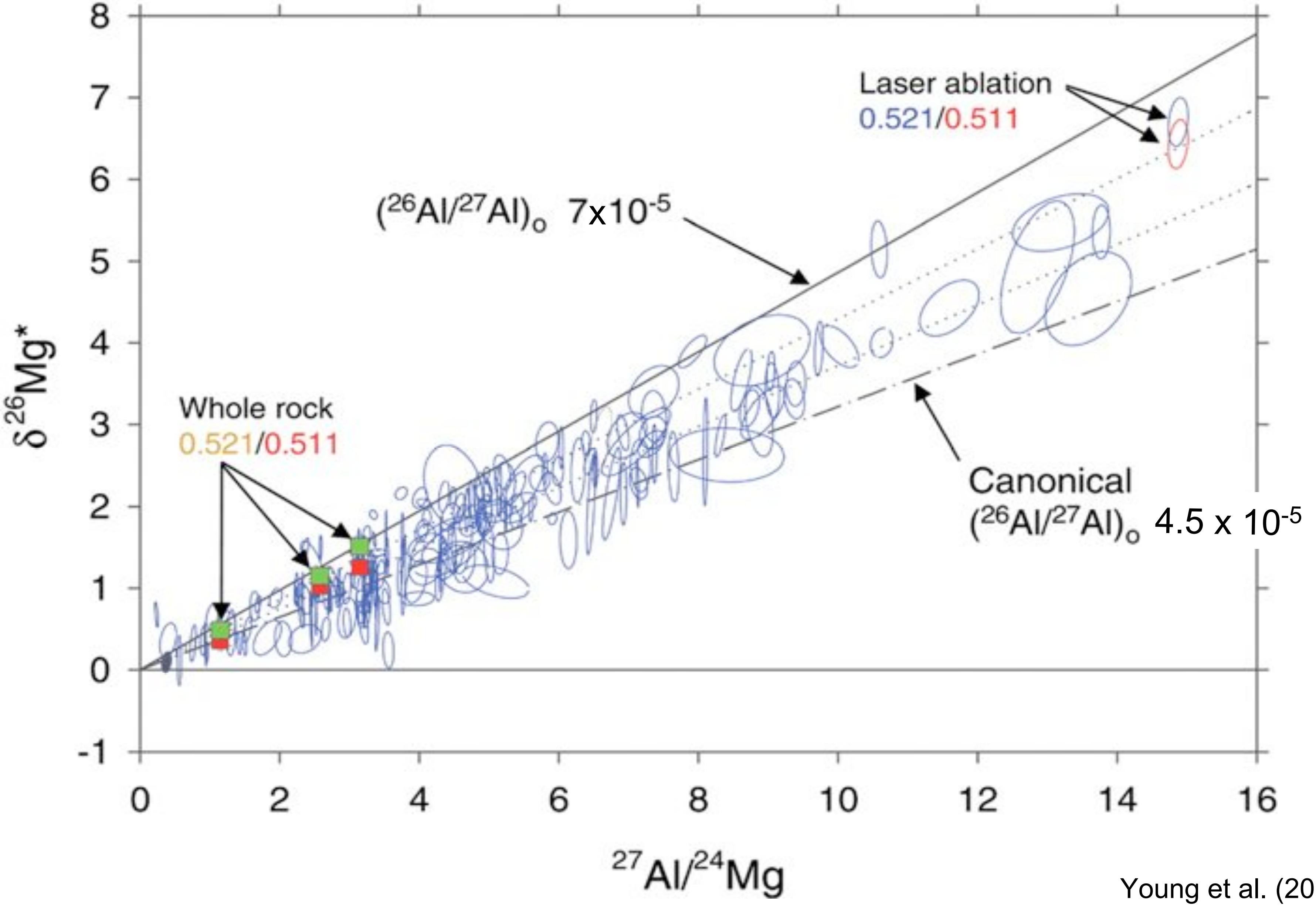
Shu et al. (1997)

^{26}Al-^{26}Mg radiogenic decay scheme



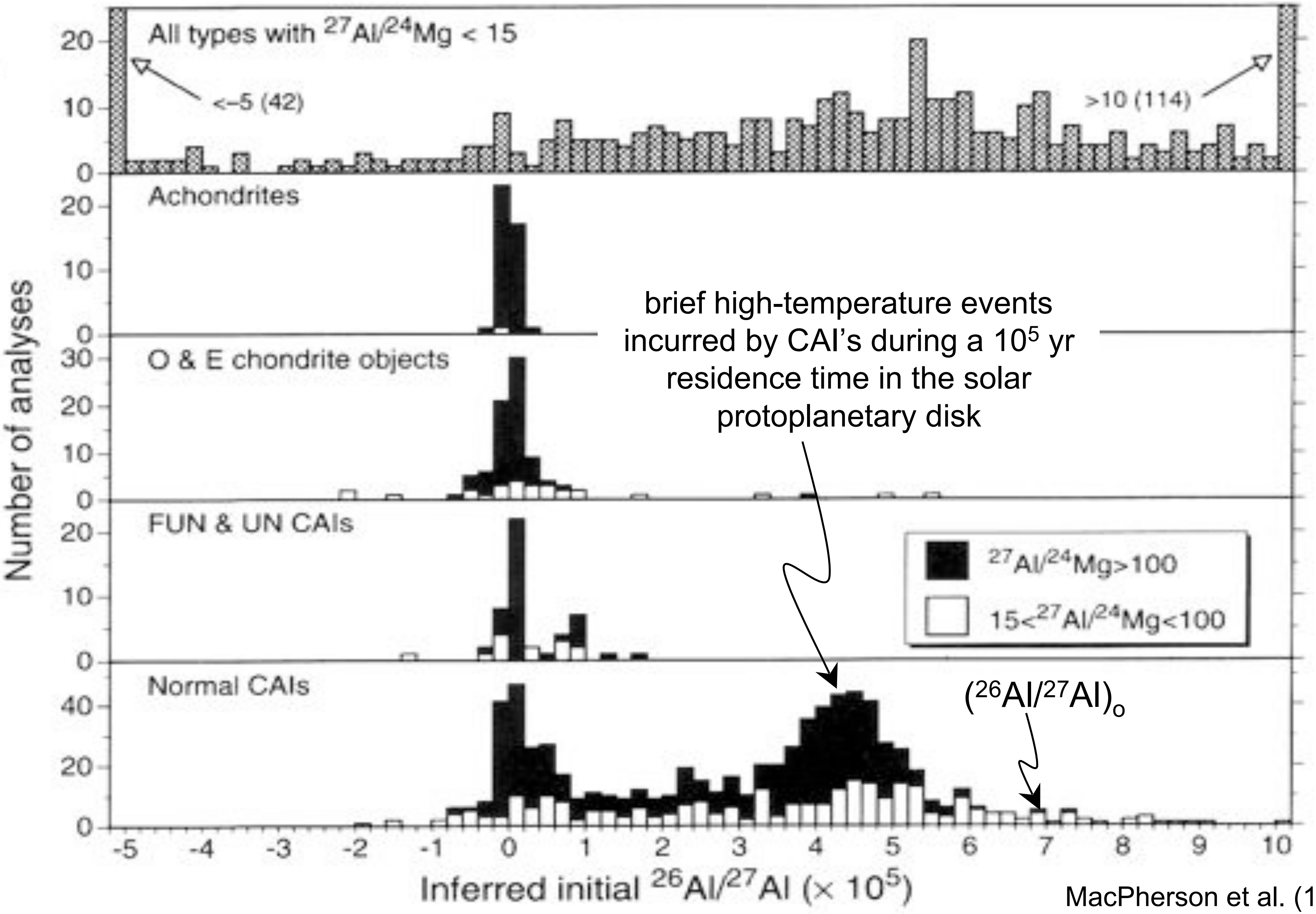
MacPherson et al. (1995)

^{26}Al-^{26}Mg radiogenic decay scheme



Young et al. (2005)

^{26}Al-^{26}Mg radiogenic decay scheme



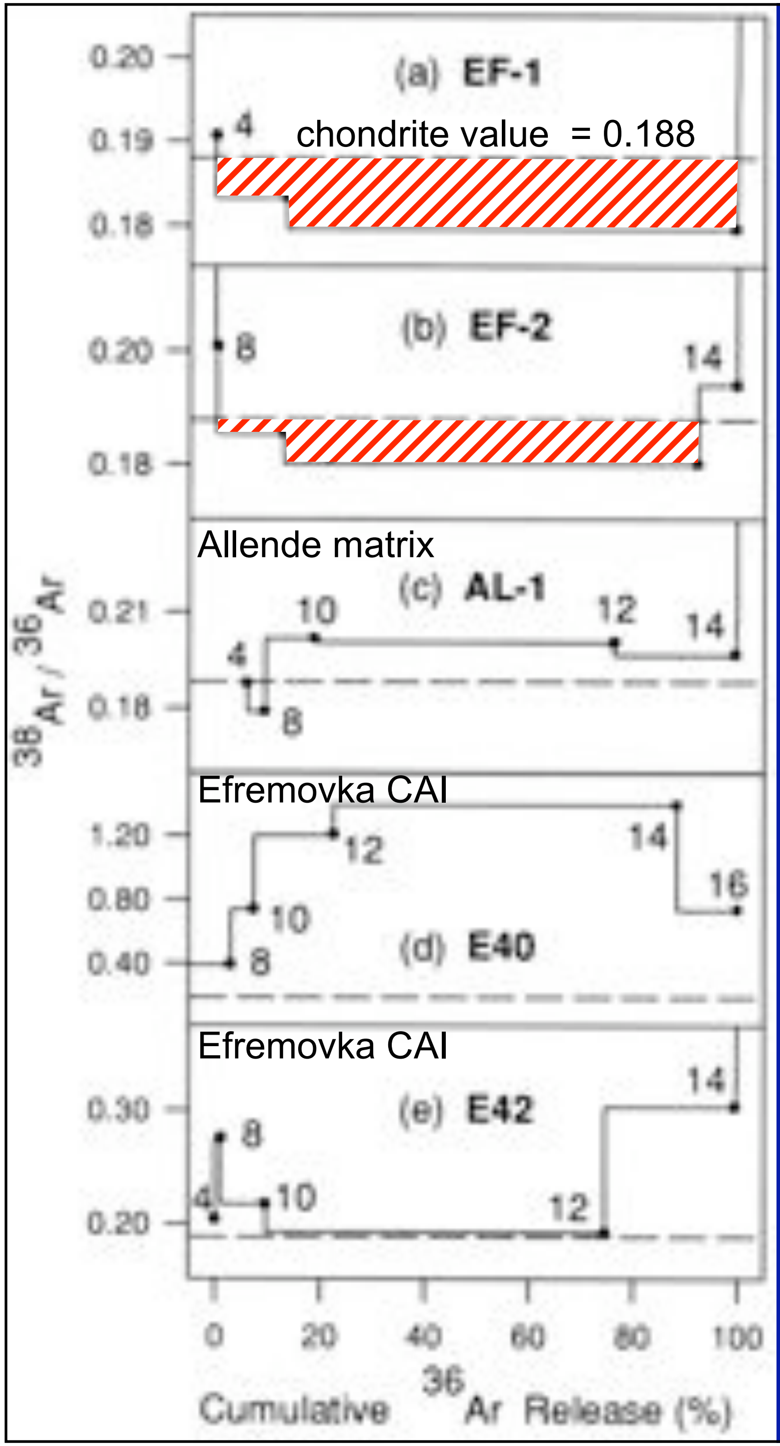
brief high-temperature events incurred by CAI's during a 10^5 yr residence time in the solar protoplanetary disk

$(^{26}Al/^{27}Al)_o$

MacPherson et al. (1995)

^{36}Cl-^{36}Ar radiogenic decay:

a “strong hint” becomes $^{36}Cl/^{35}Cl_i = (1.4 \pm 0.2) \times 10^{-6}$



Efremovka fine-grained silicate matrix

elevated $^{38}Ar/^{36}Ar$:

- spallation: ^{38}Ar production favored over ^{36}Ar

low $^{38}Ar/^{36}Ar$:

- $^{35}Cl(n,\gamma)^{36}Cl \rightarrow {}^{36}Ar$ by cosmic ray induced secondary neutrons
- trapped solar wind, $^{38}Ar/^{36}Ar_{sw} < 0.188$
- *in-situ* decay of stellar-derived ^{36}Cl

neutron-produced ^{36}Ar was estimated from $^{129}I(n,\gamma)^{129}Xe$ and Cl/I ratio and assumed to be insignificant

Murty et al. (1997) *Excess ^{36}Ar in the Efremovka Meteorite: a **strong hint** for the presence of ^{36}Cl in the early solar system. ApJ*

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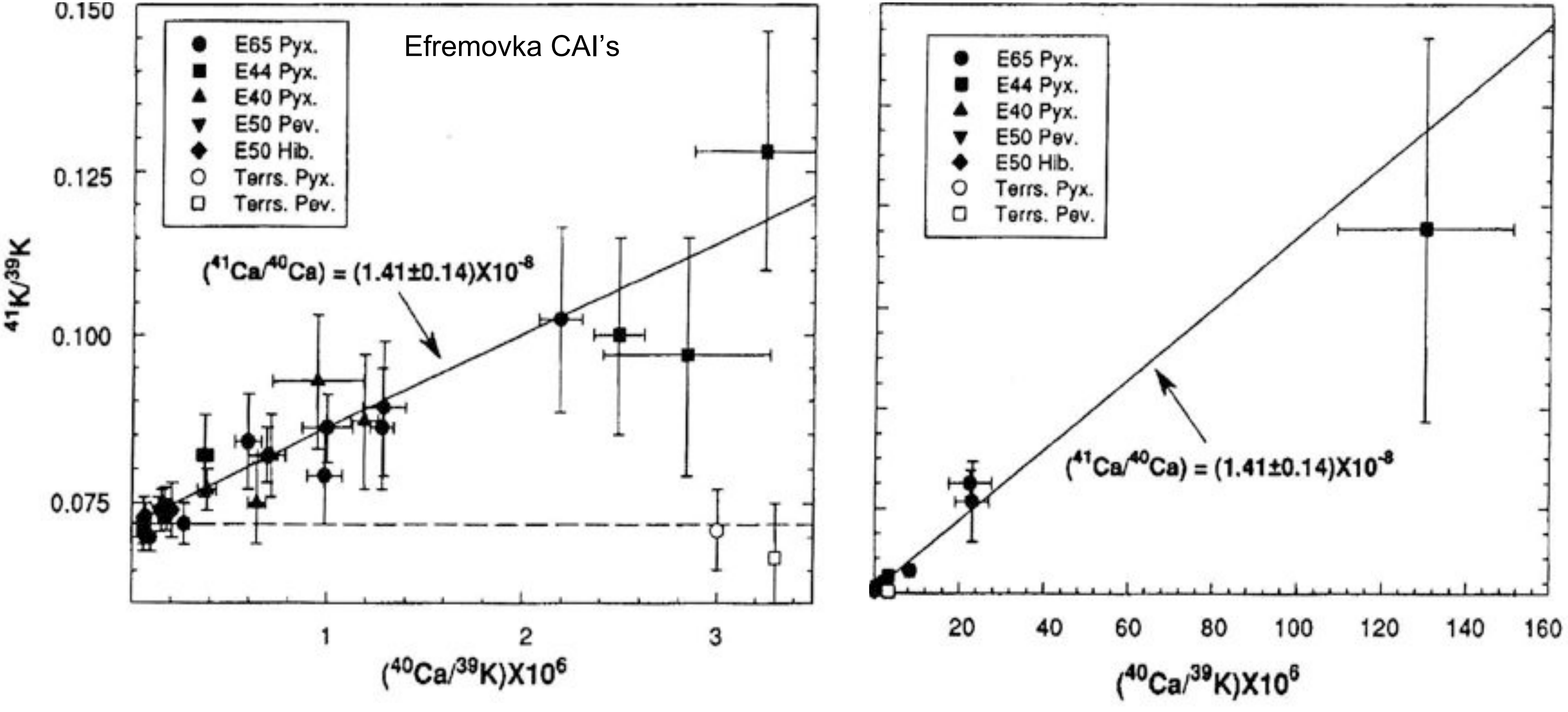
$\Delta <$ few Ma

🟥 $t_{1/2} \leq 5$ Ma

^{41}Ca-^{41}K radiogenic decay scheme

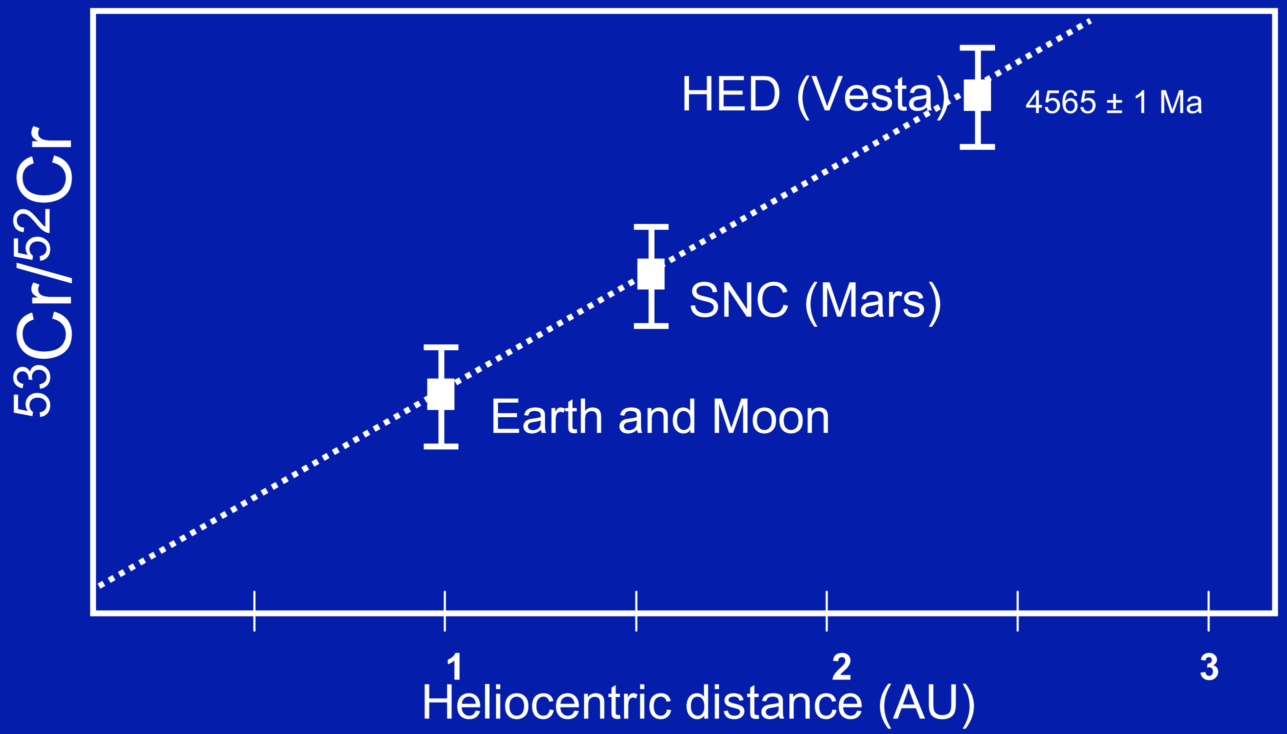


Srinivasan et al. (1996)
2σ uncertainties

Explanations:

- ^{40}Ca(n,γ)^{41}Ca via secondary neutrons during cosmic ray exposure (based on CAI size, composition and exposure age, neutron fluence considered insufficient)
- pre-solar (or "fossil") ^{41}Ca (i.e. mixing: not favored, due to observed parent-daughter correlation)
- *in situ* decay of live ^{41}Ca

^{53}Mn-^{53}Cr radiogenic decay scheme

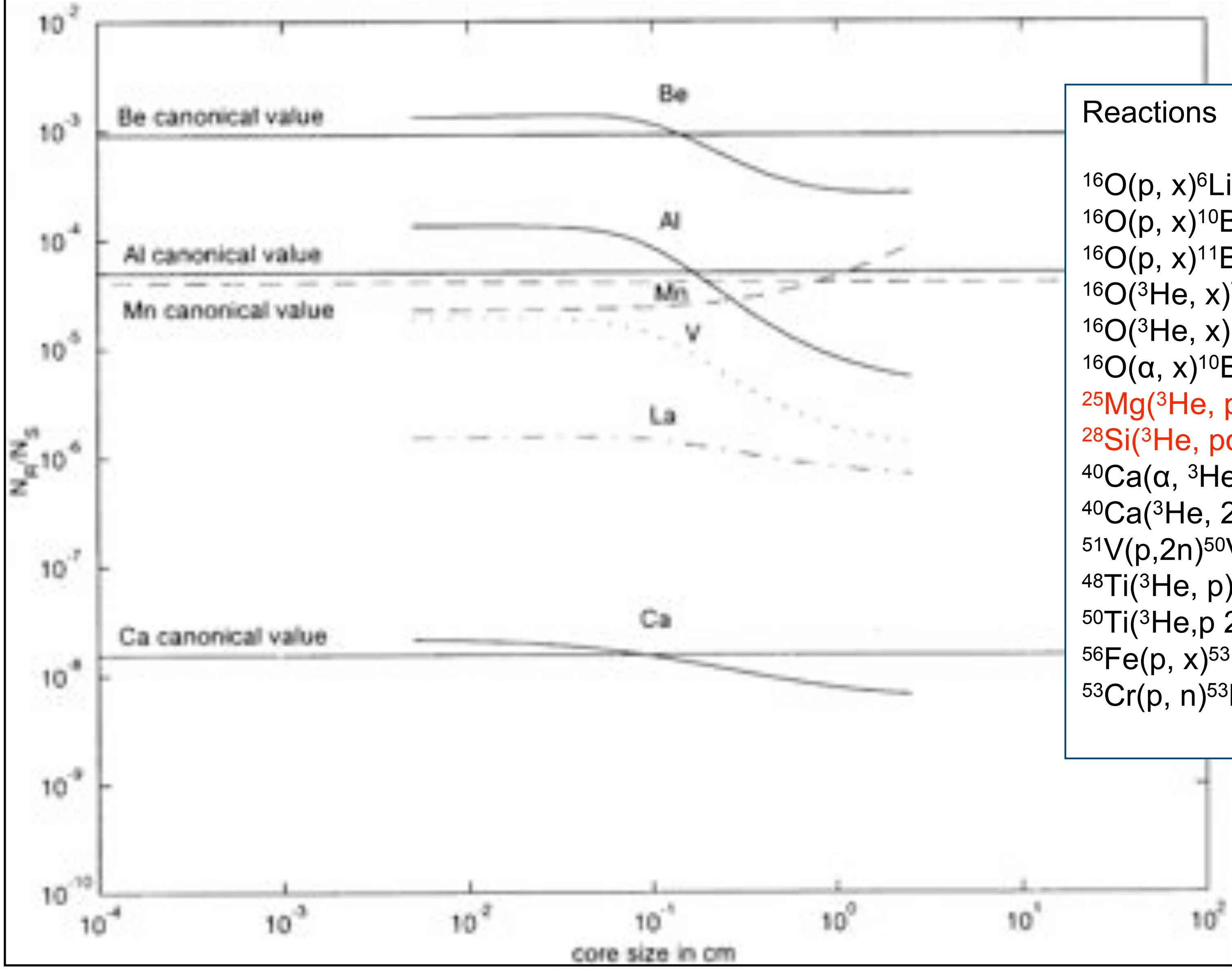


Adapted from
Lugmair and Shukolyukov (1998)

large range in Mn/Cr ratios only in differentiated meteorites

observed ^{53}Cr/^{52}Cr increase with radial distance from Sun due to:
- heterogeneous injection of ^{53}Mn into solar system?
- volatility-controlled Mn/Cr fractionation (redistribution of Mn outwards relative to Cr) during condensation of an initially uniform nebula?

solar system formation: short-lived nuclide synthesis by solar energetic particle (SEP) irradiation



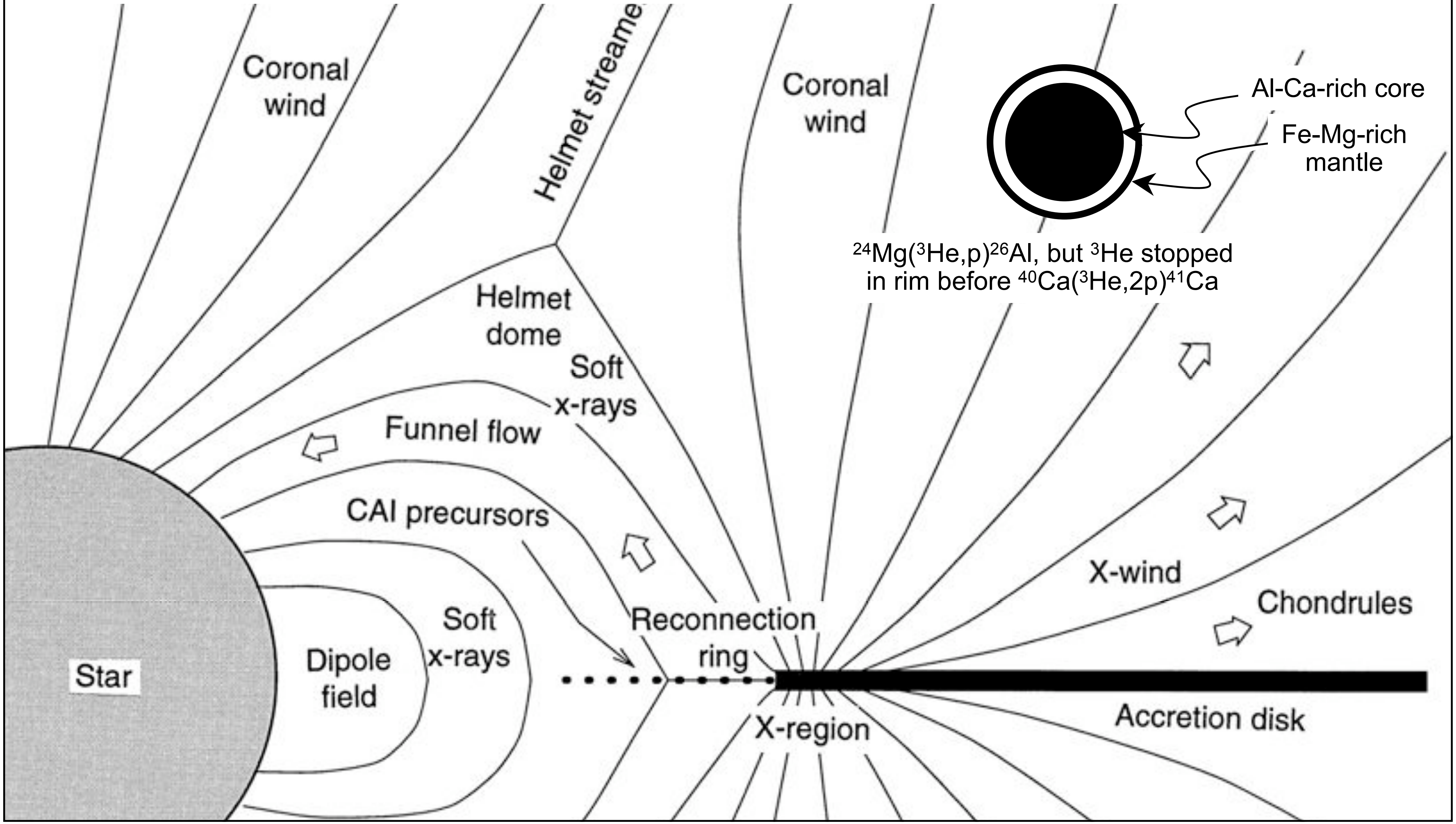
Reactions

^{16}O(p, x)^{6}Li
^{16}O(p, x)^{10}B
^{16}O(p, x)^{11}B
^{16}O(^{3}He, x)^{7}Li or ^{7}Be
^{16}O(^{3}He, x)^{10}Be
^{16}O(α, x)^{10}Be
^{25}Mg(^{3}He, pn)^{26}Al
^{28}Si(^{3}He, pα)^{26}Al
^{40}Ca(α, ^{3}He)^{41}Ca
^{40}Ca(^{3}He, 2p)^{41}Ca
^{51}V(p,2n)^{50}V
^{48}Ti(^{3}He, p)^{50}V
^{50}Ti(^{3}He,p 2n)^{50}V
^{56}Fe(p, x)^{53}Mn or ^{53}Fe
^{53}Cr(p, n)^{53}Mn

^{16}O(p, x)^{7}Li or ^{7}Be
^{16}O(p, x)^{10}Be
^{16}O(^{3}He, x)^{6}Li
^{16}O(^{3}He, x)^{10}B
^{16}O(^{3}He, x)^{11}B
^{24}Mg(^{3}He, p)^{26}Al
^{27}Al(^{3}He,α)^{26}Al
^{42}Ca(p, pn)^{41}Ca
^{40}Ca(α, ^{3}H)^{41}Sc
^{50}Ti(p, n)^{50}V
^{52}Cr(p, 2pn)^{50}V
^{49}Ti(^{3}He, pn)^{50}V
^{48}Ti(α, pn)^{50}V
^{56}Fe(p, α)^{53}Mn
^{138}Ba(p, n)^{138}La

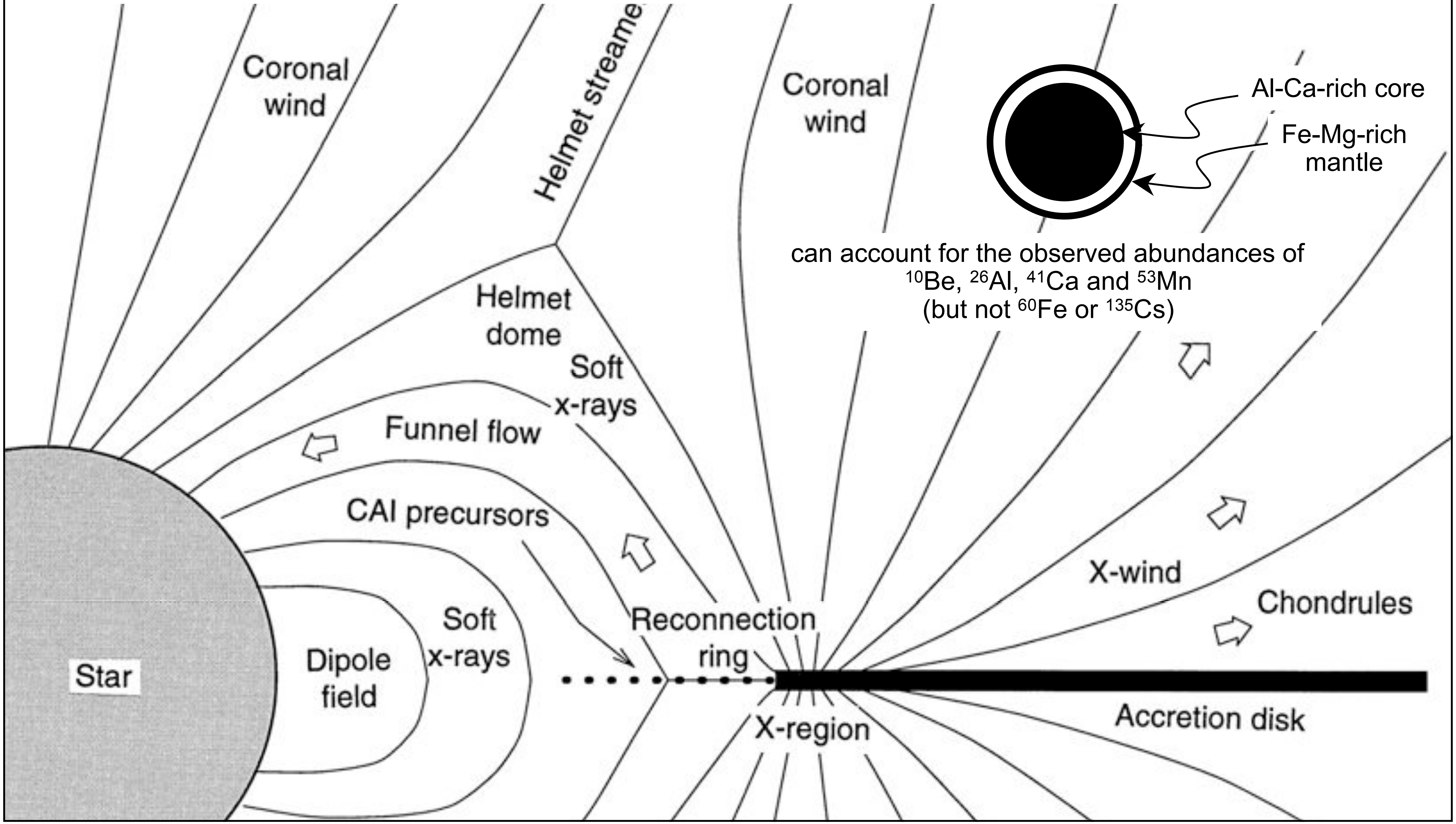
Gounelle et al (2001)

solar system formation: short-lived nuclide synthesis by solar energetic particle (SEP) irradiation



$^{24}Mg(^{3}He,p)^{26}Al$, but ^{3}He stopped in rim before $^{40}Ca(^{3}He,2p)^{41}Ca$

solar system formation: short-lived nuclide synthesis by solar energetic particle (SEP) irradiation



can account for the observed abundances of
^{10}Be, ^{26}Al, ^{41}Ca and ^{53}Mn
(but not ^{60}Fe or ^{135}Cs)

solar system inventory of short-lived nuclides

Spallation:

- ^{10}Be present in Allende CAI and therefore in the early solar-system: (some proportion of) *^{26}Al, ^{41}Ca and ^{53}Mn* may also be spallogenic?

- Sahijpal et al. (1998) "*… spallation cannot explain the observed abundances of ^{26}Al without over-production of ^{41}Ca…*"

  - interpretation dependent on production ratios, exposure history etc.

  - including ^{3}He reactions and mantling of CAIs with Fe–Mg rich covering can enhance ^{26}Al production relative to ^{41}Ca (Lee et al. 1998)

  - supra-canonical ^{26}Al/^{27}Al: CAI's experienced brief high-temperature events during a 10^5 yr residence time in the solar proto-planetary disk. Such events *must* also have disturbed the ^{41}Ca-^{41}K and other systems

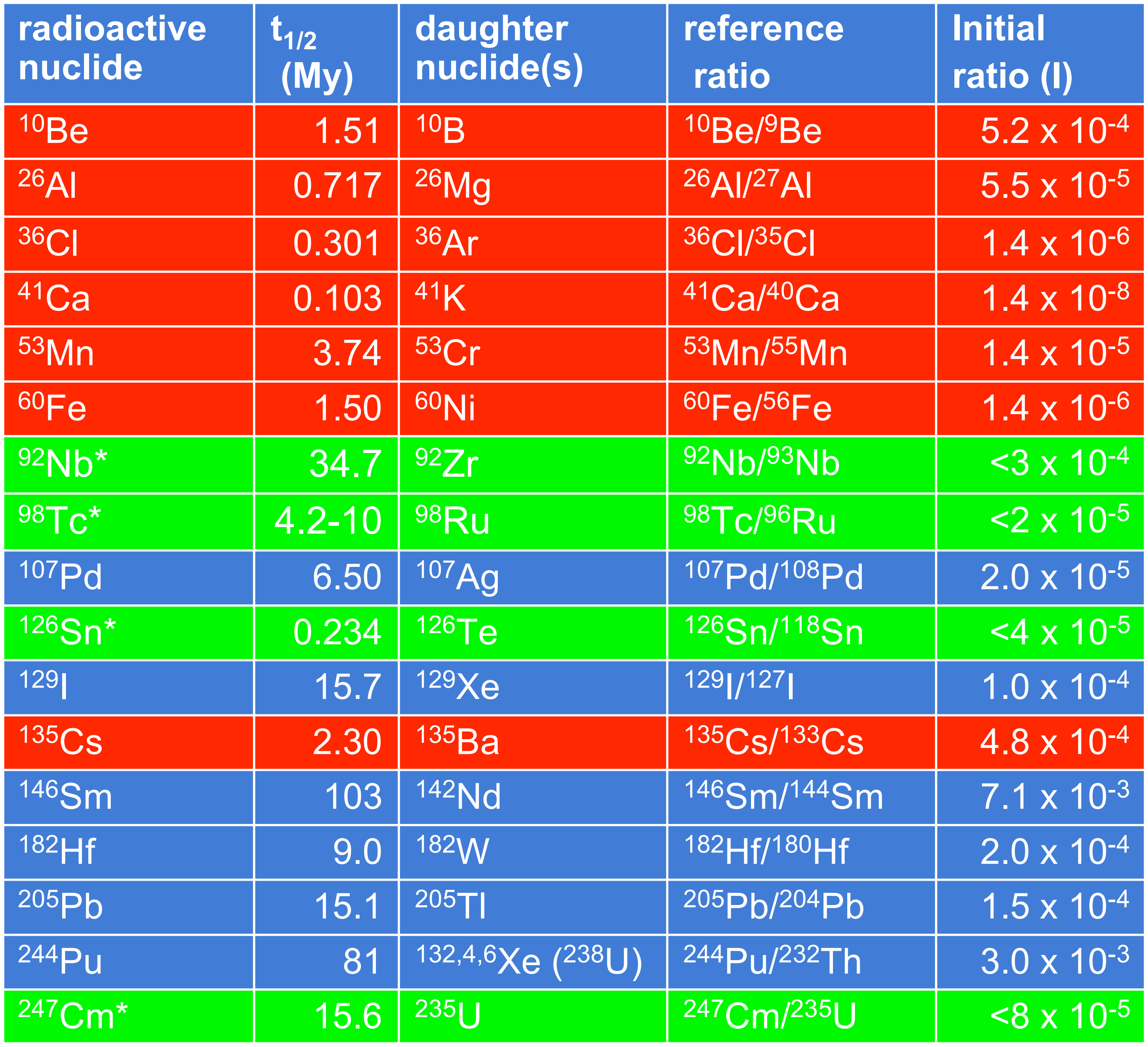
- spallation processes probably contributed to, and might account entirely for, the abundances of all short-lived extinct nuclides with $t_{1/2}$ <5 Ma *except* for ^{60}Fe and ^{135}Cs

solar system inventory of short-lived nuclides

radioactive nuclide	$t_{1/2}$ (My)	daughter nuclide(s)	reference ratio	Initial ratio (I)
^{10}Be	1.51	^{10}B	^{10}Be/^{9}Be	5.2 x 10^{-4}
^{26}Al	0.717	^{26}Mg	^{26}Al/^{27}Al	5.5 x 10^{-5}
^{36}Cl	0.301	^{36}Ar	^{36}Cl/^{35}Cl	1.4 x 10^{-6}
^{41}Ca	0.103	^{41}K	^{41}Ca/^{40}Ca	1.4 x 10^{-8}
^{53}Mn	3.74	^{53}Cr	^{53}Mn/^{55}Mn	1.4 x 10^{-5}
^{60}Fe	1.50	^{60}Ni	^{60}Fe/^{56}Fe	1.4 x 10^{-6}
^{92}Nb*	34.7	^{92}Zr	^{92}Nb/^{93}Nb	<3 x 10^{-4}
^{98}Tc*	4.2-10	^{98}Ru	^{98}Tc/^{96}Ru	<2 x 10^{-5}
^{107}Pd	6.50	^{107}Ag	^{107}Pd/^{108}Pd	2.0 x 10^{-5}
^{126}Sn*	0.234	^{126}Te	^{126}Sn/^{118}Sn	<4 x 10^{-5}
^{129}I	15.7	^{129}Xe	^{129}I/^{127}I	1.0 x 10^{-4}
^{135}Cs	2.30	^{135}Ba	^{135}Cs/^{133}Cs	4.8 x 10^{-4}
^{146}Sm	103	^{142}Nd	^{146}Sm/^{144}Sm	7.1 x 10^{-3}
^{182}Hf	9.0	^{182}W	^{182}Hf/^{180}Hf	2.0 x 10^{-4}
^{205}Pb	15.1	^{205}Tl	^{205}Pb/^{204}Pb	1.5 x 10^{-4}
^{244}Pu	81	^{132,4,6}Xe (^{238}U)	^{244}Pu/^{232}Th	3.0 x 10^{-3}
^{247}Cm*	15.6	^{235}U	^{247}Cm/^{235}U	<8 x 10^{-5}

🟥 $t_{1/2} \leq 5$ Ma

solar system inventory of short-lived nuclides



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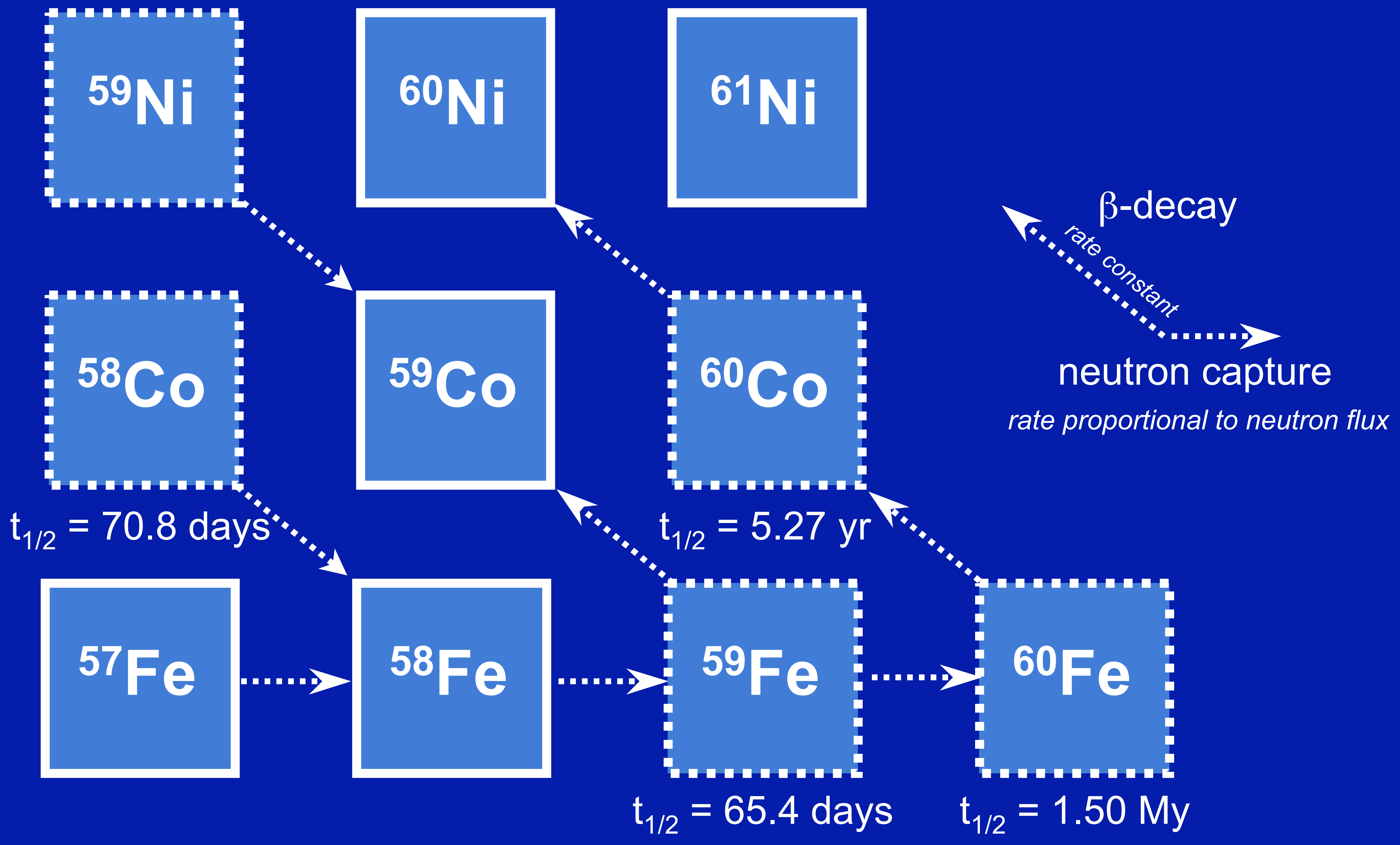
🟥 $t_{1/2} \leq 5$ Ma

🟩 not detected

not
synthesized
~10 Ma prior
to SSF?

^{60}Fe synthesis



^{59}Ni

^{60}Ni

^{61}Ni

^{58}Co

^{59}Co

^{60}Co

^{57}Fe

^{58}Fe

^{59}Fe

^{60}Fe

$t_{1/2}$ = 70.8 days

$t_{1/2}$ = 5.27 yr

$t_{1/2}$ = 65.4 days

$t_{1/2}$ = 1.50 My

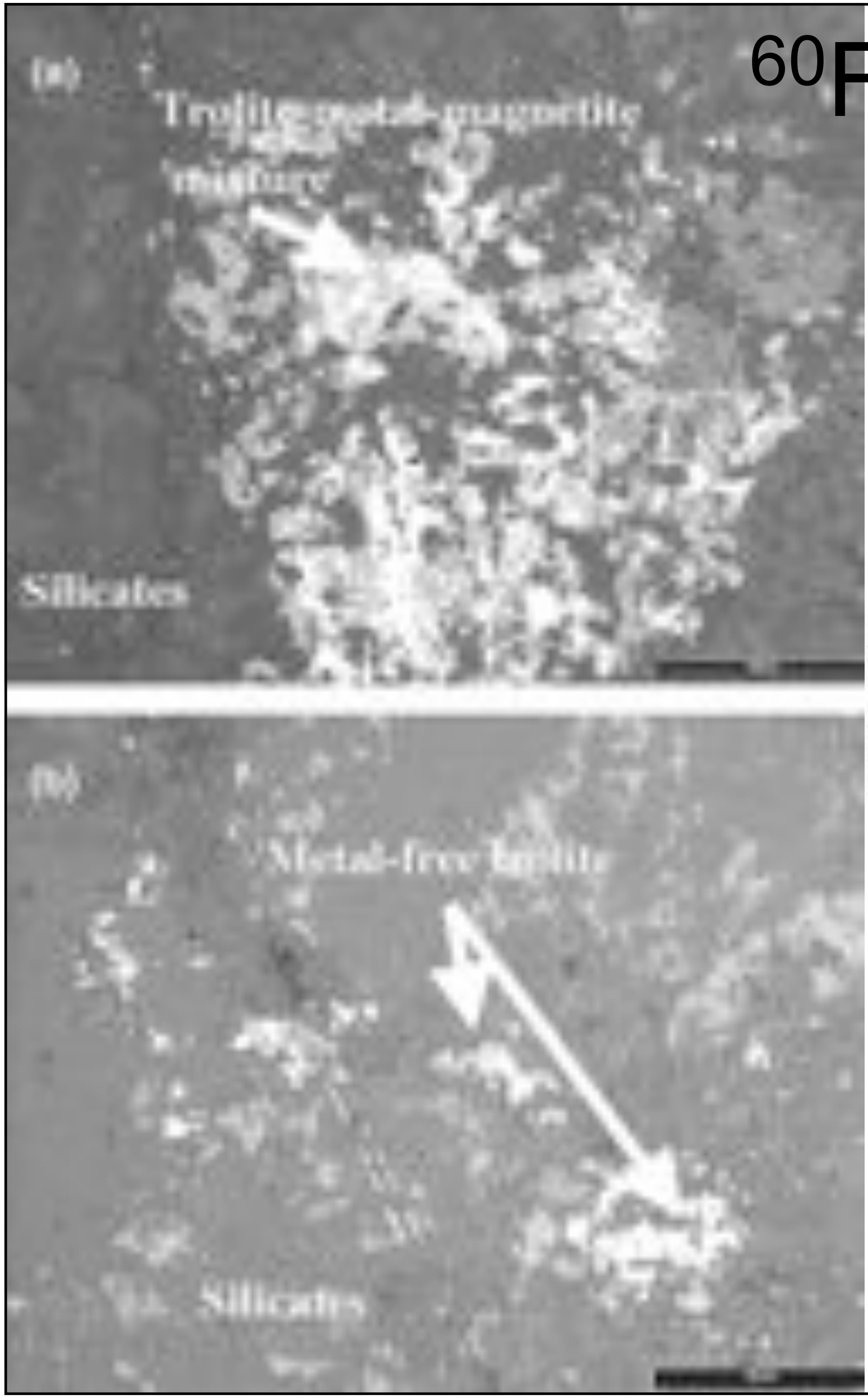
β-decay

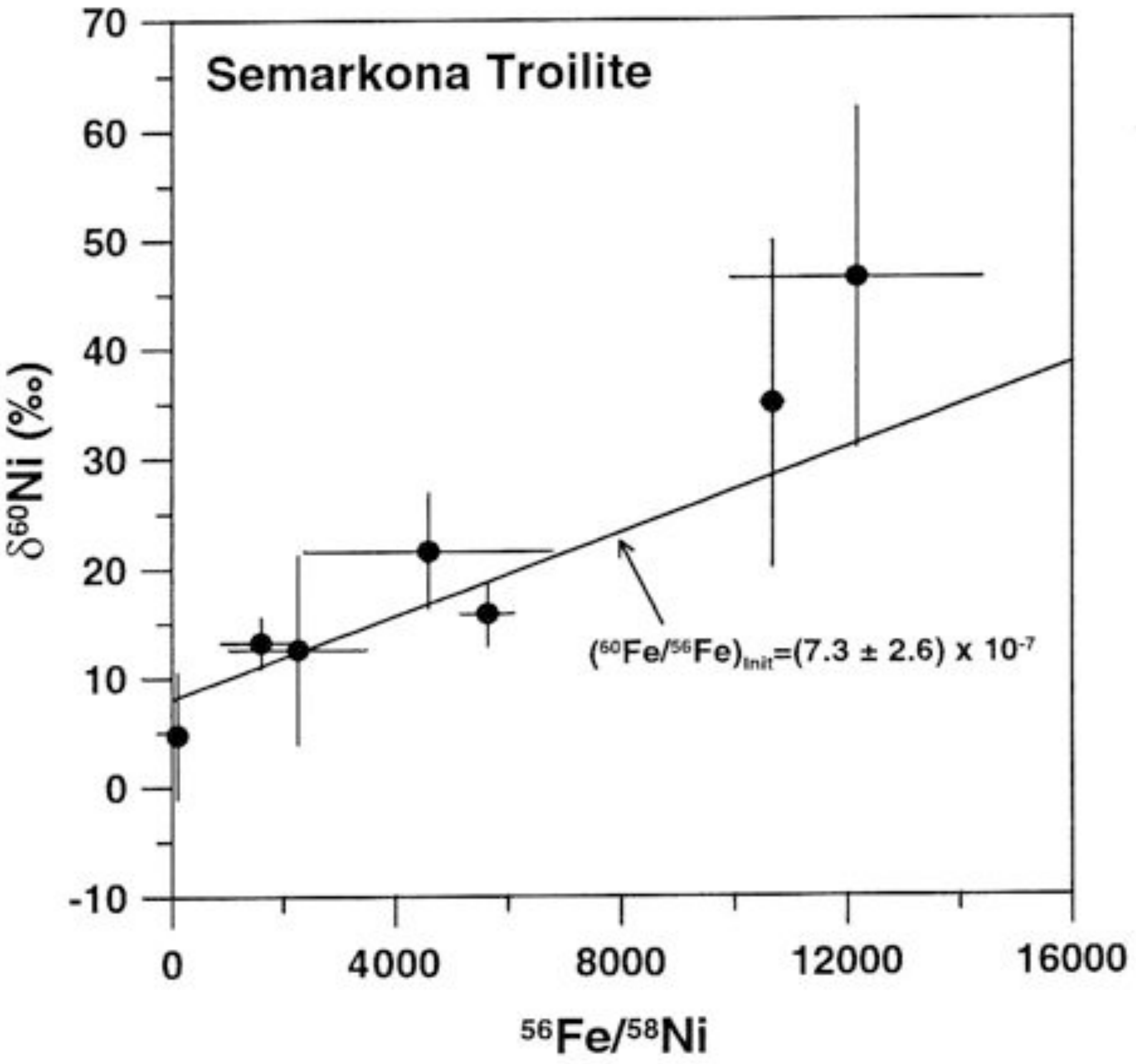
rate constant

neutron capture

rate proportional to neutron flux

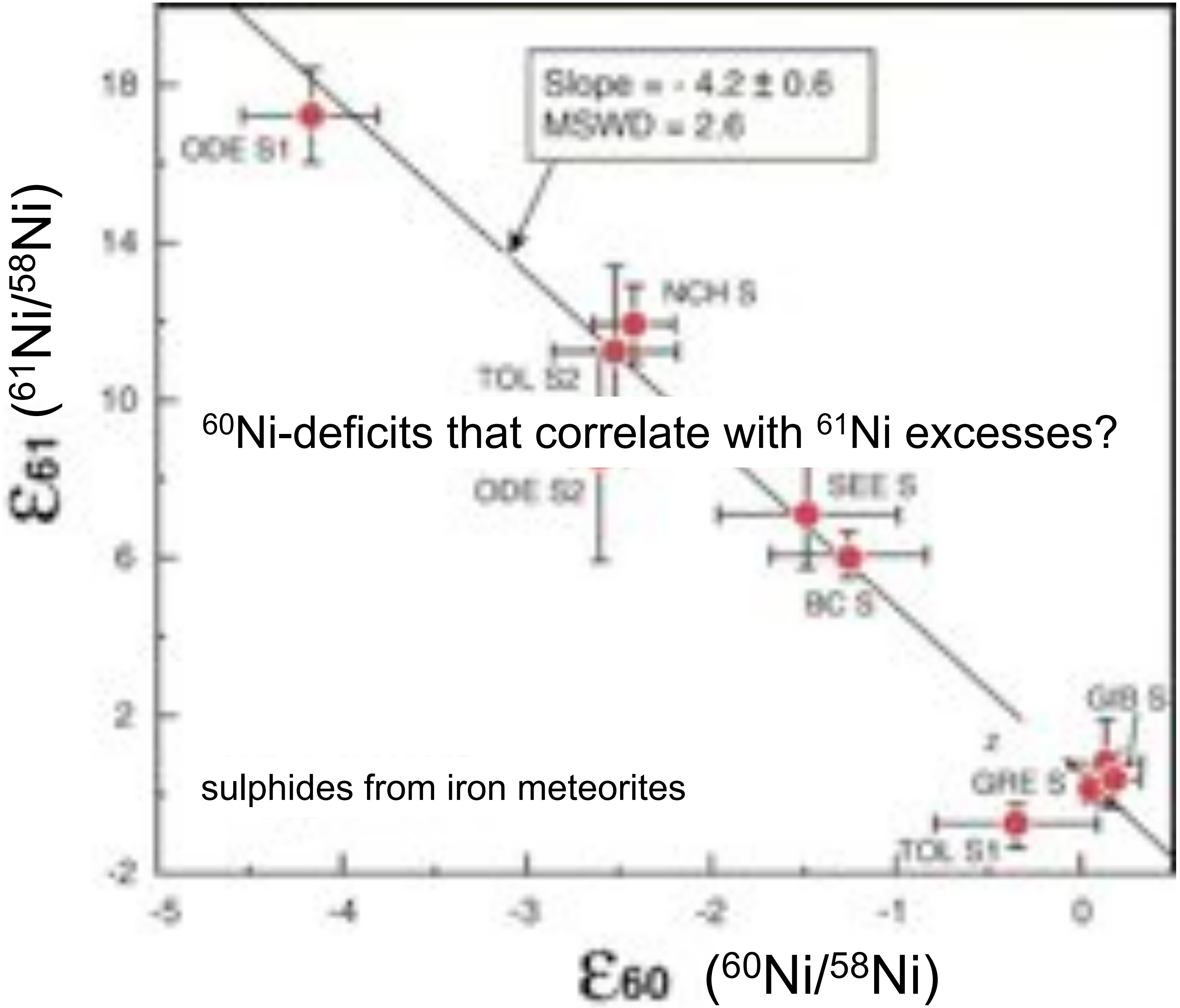
^{60}Fe-^{60}Ni radiogenic decay scheme





S. Mostefaoui, G. W. Lugmair, P. Hoppe and A. El Goresy (2004)

^{60}Fe-^{60}Ni radiogenic decay scheme

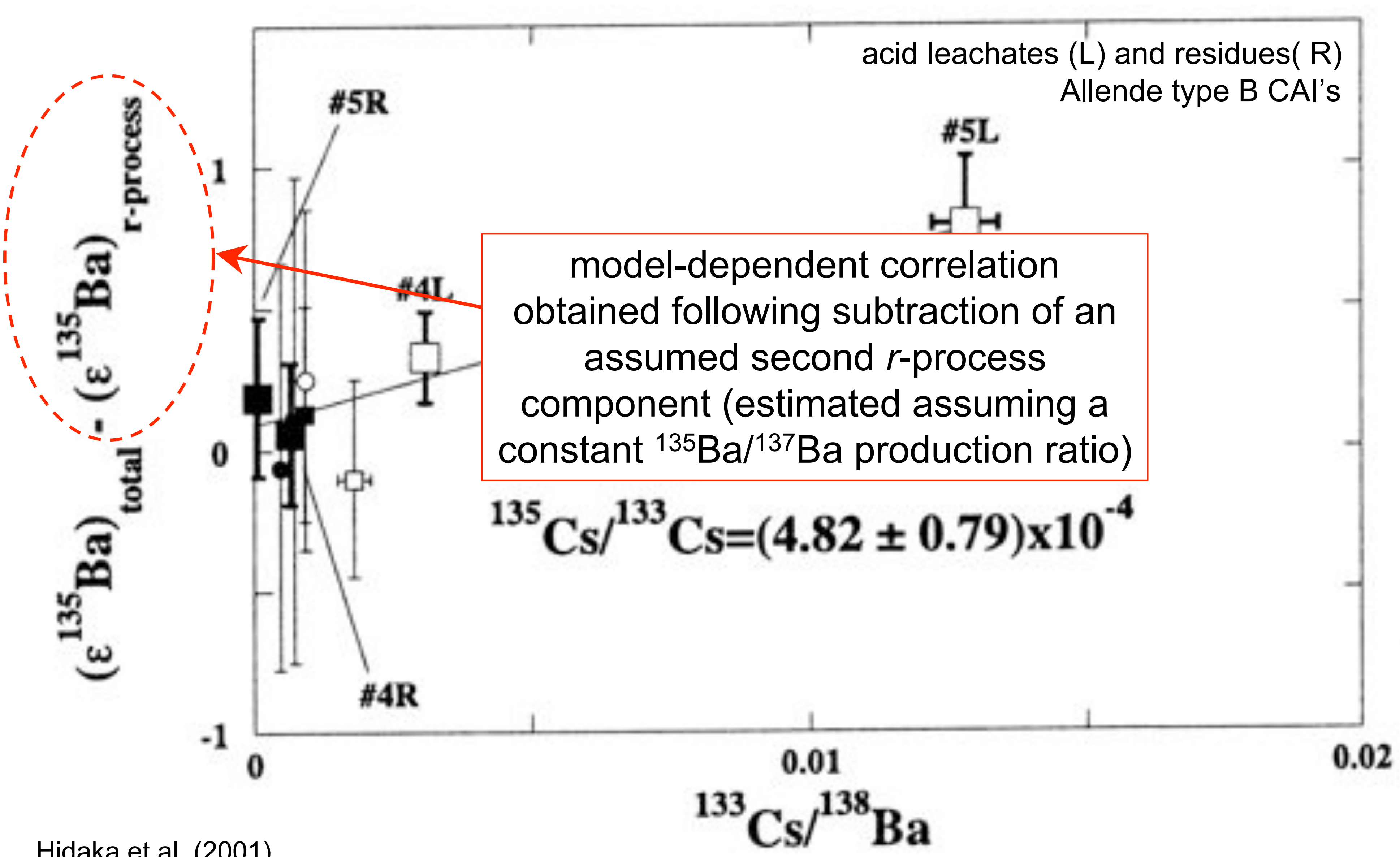


^{60}Ni-deficits that correlate with ^{61}Ni excesses?

sulphides from iron meteorites

Quitté et al. (2006)

^{135}Cs-^{135}Ba radiogenic decay scheme



acid leachates (L) and residues(R)
Allende type B CAI's

model-dependent correlation obtained following subtraction of an assumed second *r*-process component (estimated assuming a constant ^{135}Ba/^{137}Ba production ratio)

Hidaka et al. (2001)

summary

solar system initial abundances of short-lived radioactive nuclides:

with $t_{1/2} < 5$ Ma

- ➡ well constrained for ^{26}Al and ^{10}Be
- ➡ to a lesser extent for ^{41}Ca and ^{53}Mn (heterogeneity?, sample formation times, metamorphic disturbance)
- ➡ poorly constrained for ^{36}Cl and ^{135}Cs (metamorphic disturbance, requires model-dependent assumptions)
- ➡ ?poorly constrained for ^{60}Fe (ambiguous analytical results from differentiated meteorite phases such as troilite, Ni isotopic anomalies require model-dependent assumptions)

with $t_{1/2} > 5$ Ma

- ➡ reasonably well constrained for ^{107}Pd, ^{129}I, ^{182}Hf and ^{244}Pu
- ➡ poorly constrained (?zero*) for ^{92}Nb*, ^{98}Tc*, ^{126}Sn*, ^{146}Sm, ^{205}Pb, ^{247}Cm*

summary

synthesis of our solar system's short-lived radioactive nuclide inventory:

with $t_{1/2} < 5$ Ma

➡ spallation for (a proportion of) ^{10}Be, ^{26}Al, ?^{36}Cl, ^{41}Ca and ^{53}Mn, ?plus GUP for ^{60}Fe (and ^{135}Cs?), i.e. no trigger

or

➡ spallation ?plus (unconstrained) stellar source for ^{60}Fe (and ^{135}Cs?)

with $t_{1/2} > 5$ Ma

➡ multiple stellar sources (i.e. GUP) required for ^{107}Pd, ^{129}I, ^{182}Hf and ^{244}Pu

summary:
short-lived nuclides: synthesis mechanisms

1. intra- (i.e. post-) solar system
   - ✓ spallation induced by early solar (T Tauri phase) x-winds (solar energetic particle irradiation: SEP)

2. extra- (i.e. pre-) solar system
   - ✓ multiple stellar sources (continuous galactic production)
   - ? stellar winds from a TP-AGB or Wolf-Rayet star
   - ? contamination by core-collapse (type II) supernova ejecta