The origin of ^{60}Fe in the solar system

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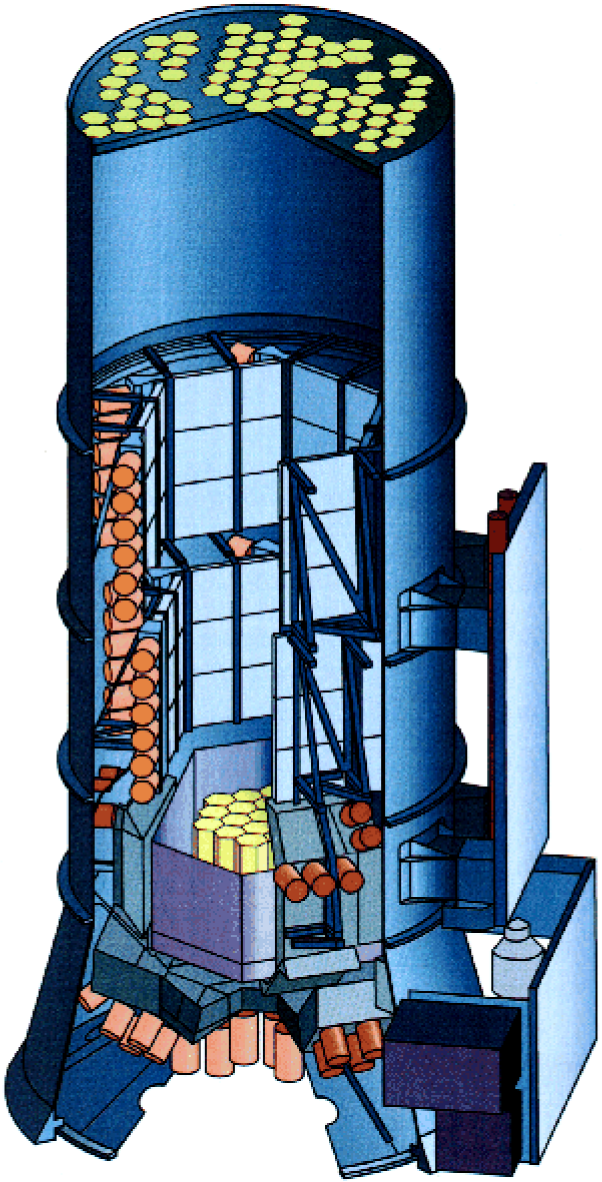
Palavas les flots, 9 septembre 2009

1. Introduction

When microscopes meet telescopes…

nanoSIMS 50 @ MNHN



INTEGRAL γ–ray satellite

Chondrites

	CI	CM	CO	CR	CB	CH	CV	CK	H L LL	EH EL	R	K
Class →	Carbonaceous								Ordinary	Enstatite		
Group →	CI	CM	CO	CR	CB	CH	CV	CK	H L LL	EH EL	R	K
Petr. type →	1	1-2	3-4	1-2	3	3	3-4	3-6	3-6	3-6	3-6	3
Subgroup →					CB_a CB_b		CV_A CV_B CV_{red}					

Nonchondrites

Primitive

Single asteroid?
Acapulcoites
Lodranites

Single asteroid?
Winonaites
IAB silicate inclusions
IIICD silicate inclusions

Differentiated

Achondrites

Angrites
Aubrites
Brachinites
Ureilites
HED
Single asteroid? (Vesta?)
Howardites
Eucrites
Diogenites
Martian (SNC)
Mars
Shergottites
Nakhlites
Chassignites
Orthopyroxenites
Moon
Lunar

Stony irons

Mesosiderites pallasites
Main group
Eagle Station
pyroxene

Irons

IAB*
IC
IIAB
IIC
IID
IIE*
IIIAB
IIICD*
IIIE
IIIF
IVA*
IVB

*irons with silicate-rich irons

Meteorites are complex *rocks*

Primitives meteorites

(chondrites)

Differenciated meteorites

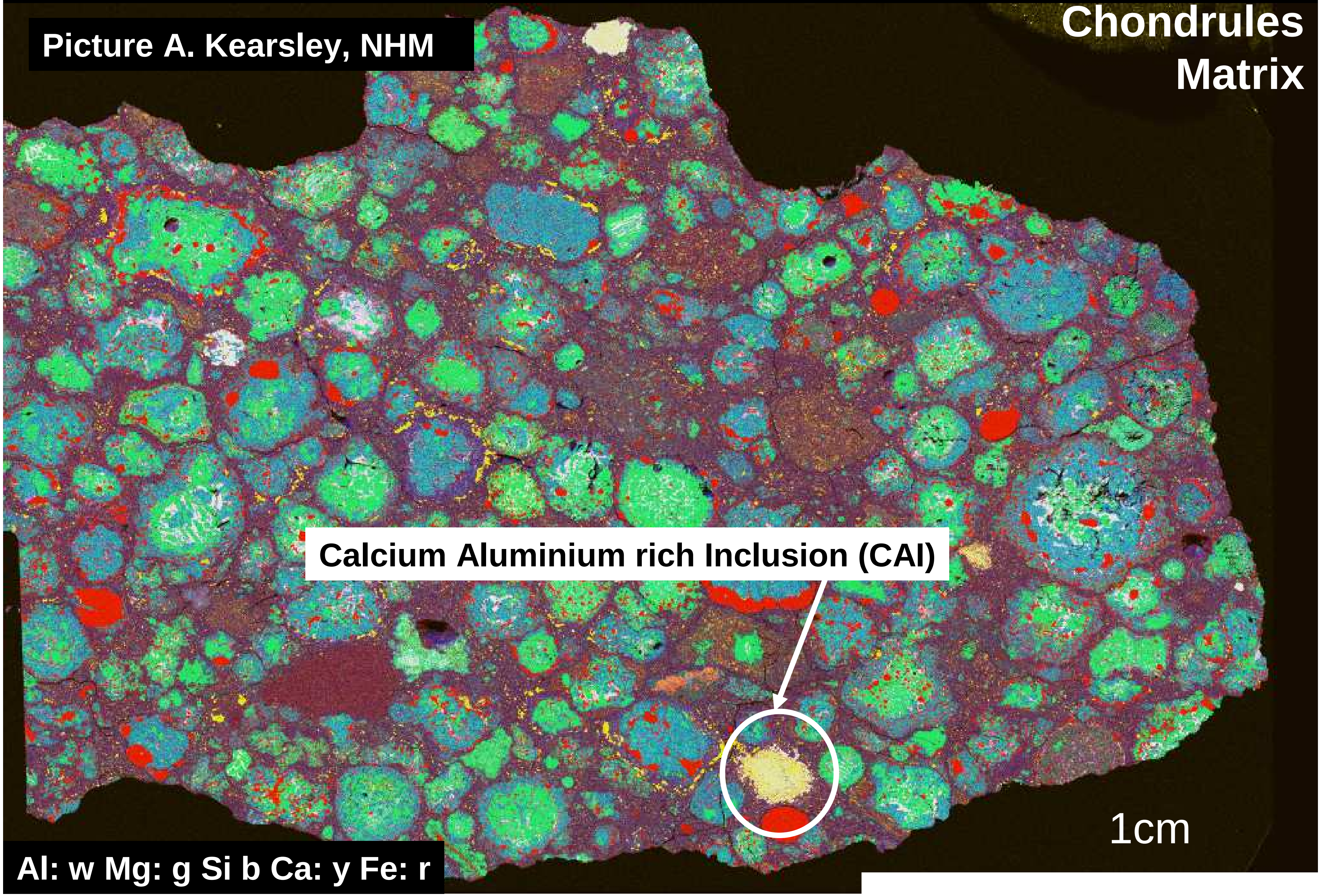
(achondrites, irons, stony-irons)

Chondrites

CAIs [Calcium-Aluminium-rich inclusions]

Chondrules

Matrix



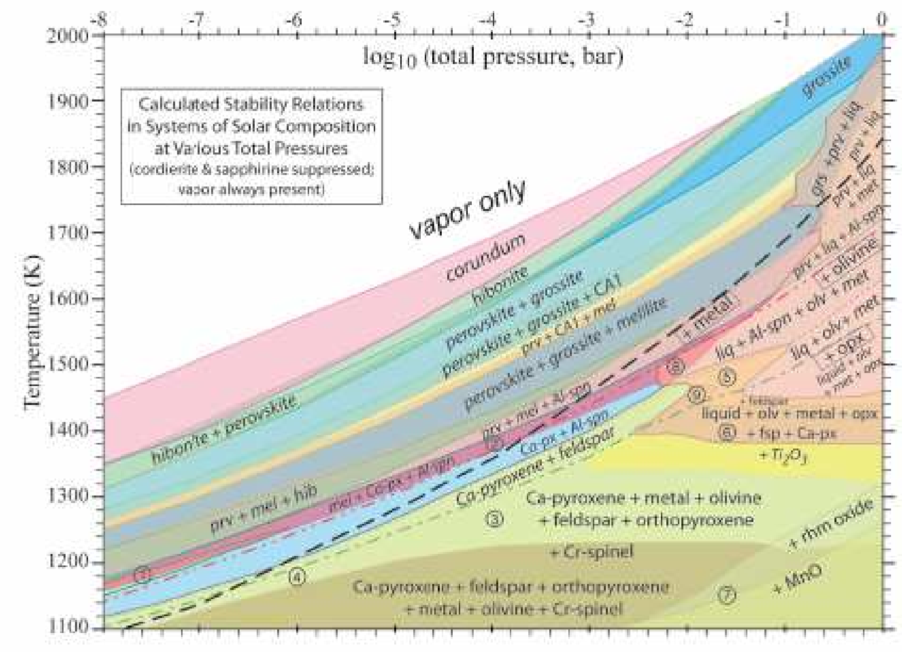
Picture A. Kearsley, NHM

Calcium Aluminium rich Inclusion (CAI)

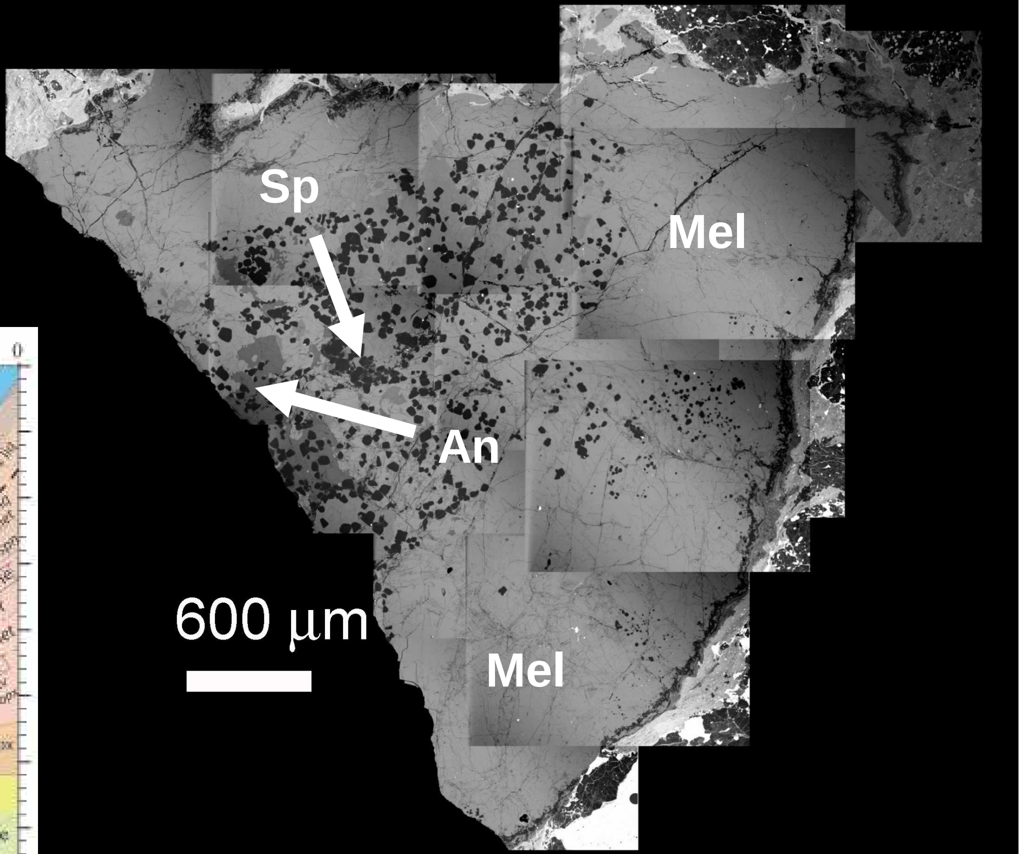
1cm

Al: w Mg: g Si b Ca: y Fe: r

CAI in Leoville (CV3)



Ebel *MESS2* 2006

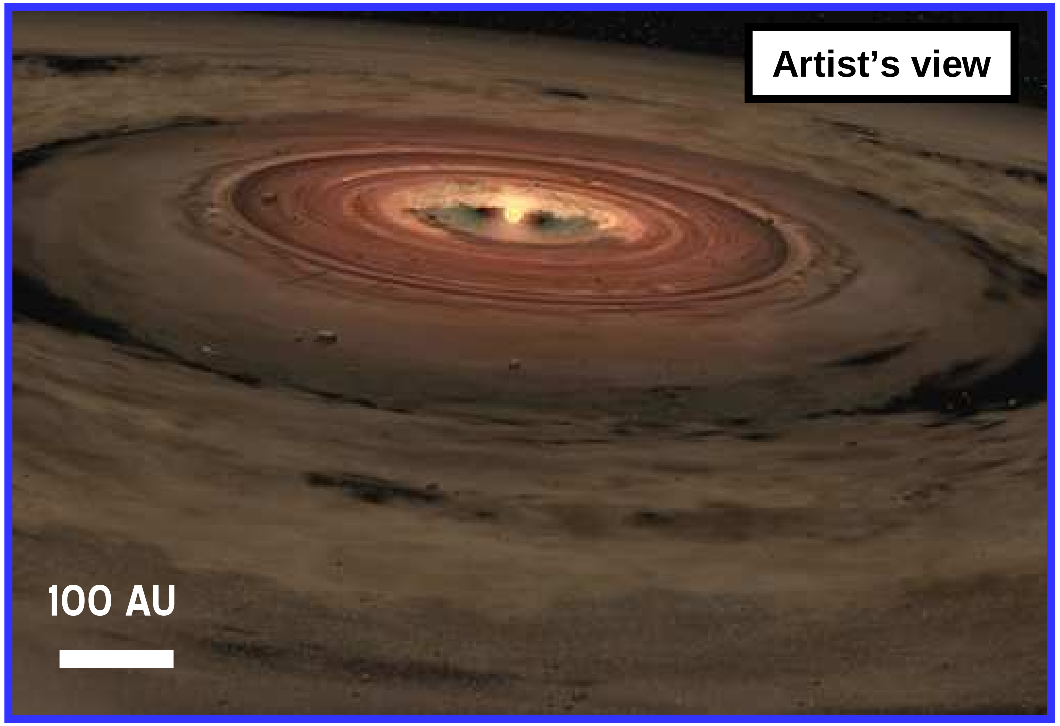


Melilite [$CaAl_{2x}Mg_{1-x}Si_{2-x}O_7$]
Spinel [Mg_2AlO_4]
Anorthite [$CaAl_2Si_2O_8$]

Mineralogy compatible with gas-solid condensation
Formed ~ 4.567 Ga ago [oldest dated solid]

Our premices

☆ **Chondrites' components (CAIs, matrix, chondrules) formed and aggregated in the <u>solar accretion disk</u> 4.6 Ga ago**



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

2. Short-lived radionuclides

Short-lived radionuclides (SRs)

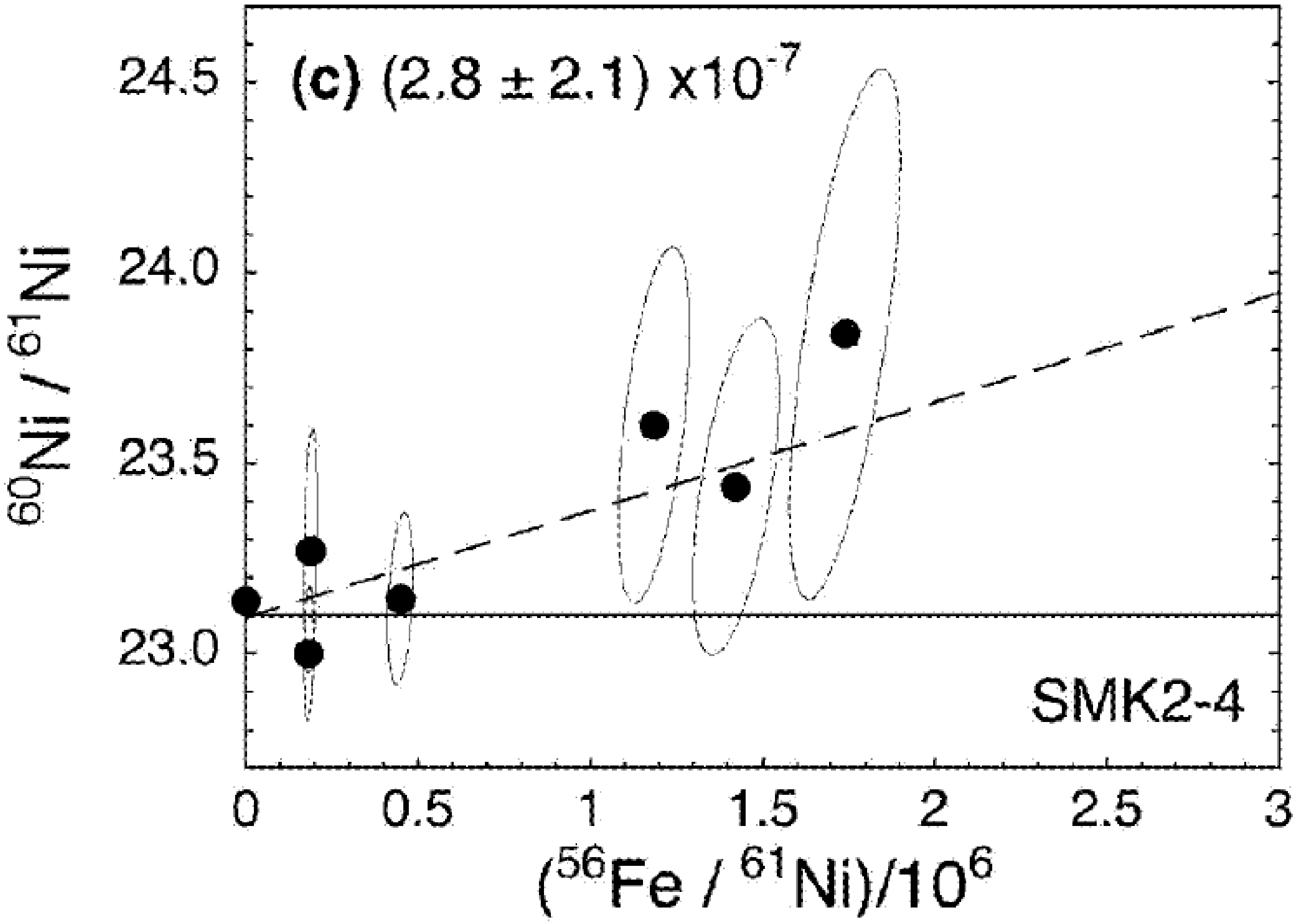
- ☆ Short-lived radionuclides are radioactive elements whose half-life (~Ma) is shorter than the age of the Solar System

- ☆ They have entirely decayed: they are now extinct

e.g. $^{60}\mathrm{Fe} \rightarrow {}^{60}\mathrm{Ni} + e^{-} + \bar{\nu}_e$

(β^{-}, $T_{1/2}$ = 2.6 Myr, Gudel et al. 2009)

Isochron diagram



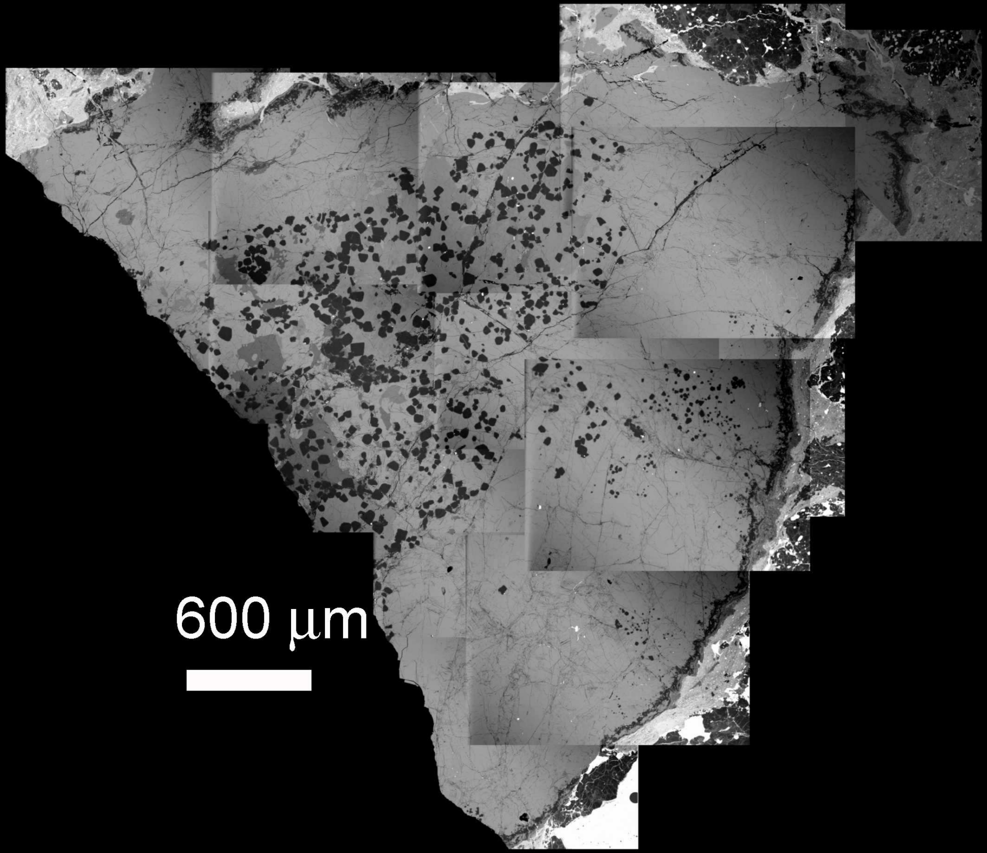
Tachibana et al. ApJ 2006

The detection techniques

Movie

- ☆ Secondary Ion Mass Spectrometer (SIMS) or ionprobe
- ☆ Inductively Coupled Plasma Mass Sepctometer (ICPMS)

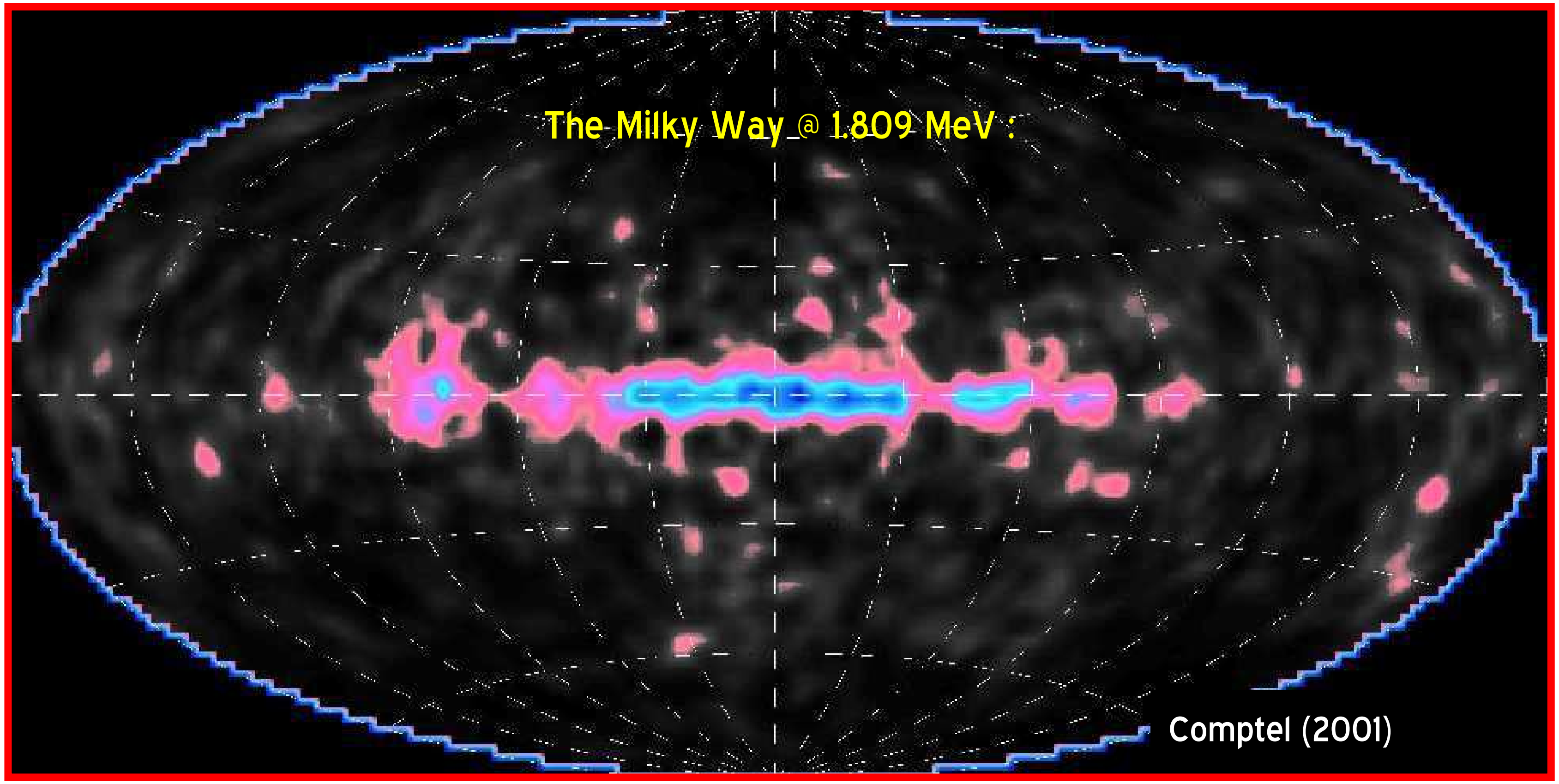
The Solar System initial value of SRs = abundance in CAIs



The initial value of short-lived radionuclides

Radioactive Isotope (R)	T (Ma)	Daughter Isotope	Stable Isotope (S)	Initial Abundance (R/S)
^{7}Be	52 days	^{7}Li	^{9}Be	6 x 10^{-3}
^{41}Ca	0.1	^{41}K	^{40}Ca	> 1.5 x 10^{-8}
^{36}Cl	0.3	^{36}S, ^{36}Ar	^{35}Cl	> 1.6 x 10^{-4}
^{26}Al	0.74	^{26}Mg	^{27}Al	5 - 7 x 10^{-5}
^{10}Be	1.5	^{10}B	^{9}Be	4-14 x 10^{-3}
^{60}Fe	1.5	^{60}Ni	^{56}Fe	0.3 x 10^{-6}
^{53}Mn	3.7	^{53}Cr	^{55}Mn	0.1 - 1.2 x 10^{-4}
^{107}Pd	6.5	^{107}Ag	^{108}Pd	5 - 40 x 10^{-5}
^{182}Hf	9	^{182}W	^{180}Hf	1 x 10^{-4}
^{129}I	16	^{129}Xe	^{127}I	1 x 10^{-4}
^{92}Nb	36	^{92}Zr	^{93}Nb	10^{-5} - 10^{-3}
^{244}Pu	81	Fission products	^{238}U	7 x 10^{-3}
^{146}Sm	103	^{142}Nd	^{144}Sm	4-15 x 10^{-3}

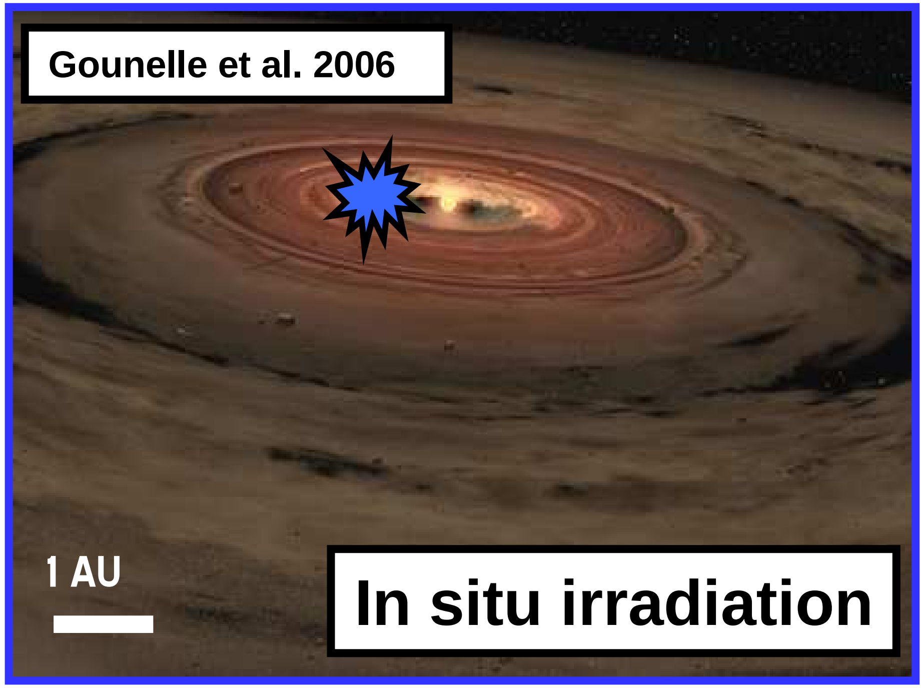
The origin of short-lived radionuclides



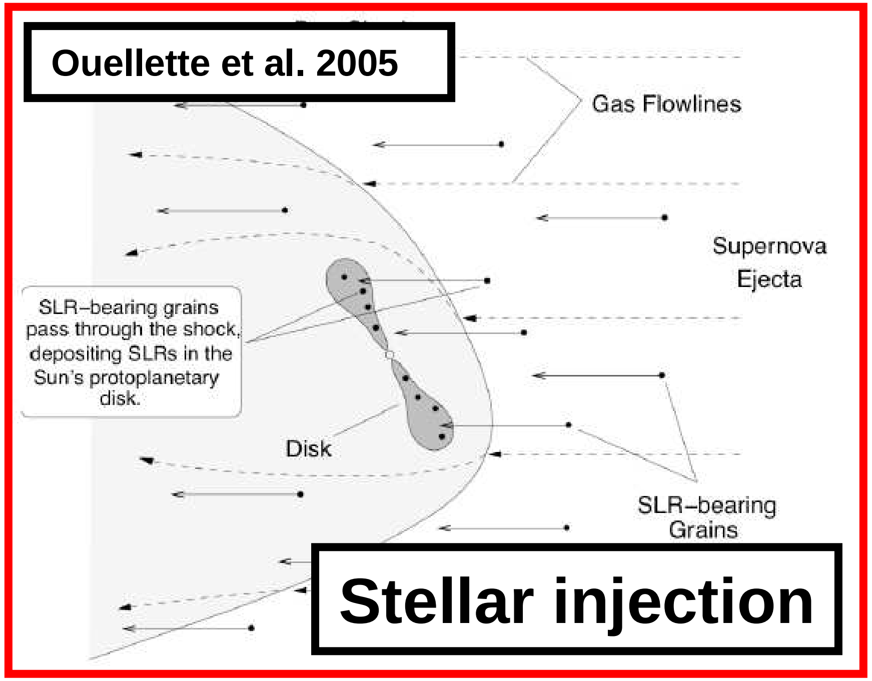
☆ Some short-lived radionuclides have abundances **in excess relative** to abundances calculated by models of **the chemical evolution of the Galaxy**

The last-minute origin of short-lived radionuclides

☆ ^{7}Be, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn (?), ^{60}Fe (?) have a <u>last minute origin</u>


Gounelle et al. 2006

In situ irradiation


Ouellette et al. 2005

Stellar injection

The importance of short-lived radionuclides

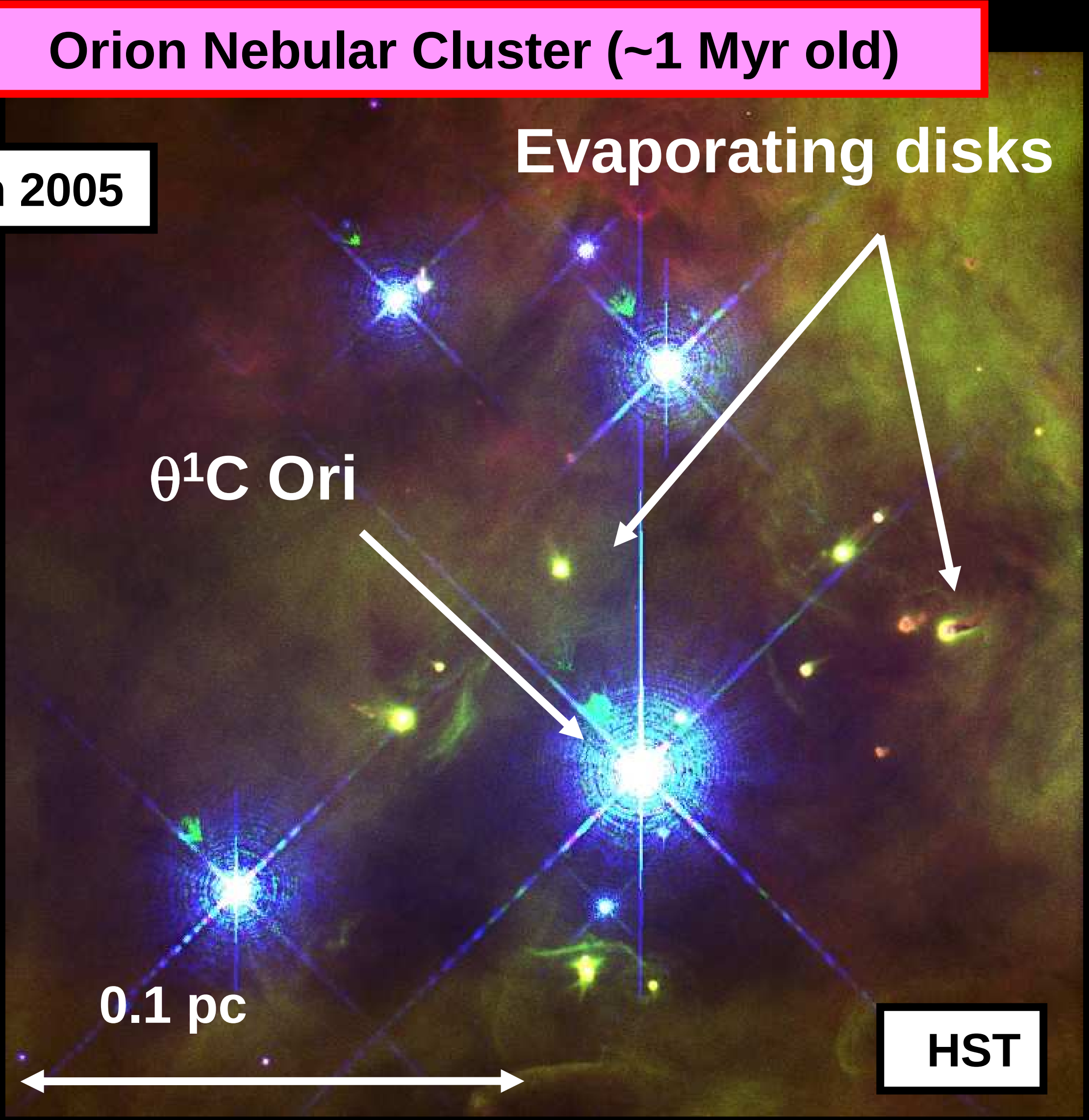
- ☆ Understanding the origin (as well as abundance and spatial distribution) of extinct short-lived radionuclides is a key task for cosmochemists and astrophysicists
  - ☆ It offers the possibility to characterize **Galactic evolution**
  - ☆ It constrains the **astrophysical environment** of the protoSun
  - ☆ It constrains the **irradiation conditions** in the solar accretion disk
  - ☆ SRs offer the possibility to build a **chronology**
  - ☆ γ-ray emitters SRs are a potential **heat source** for planetesimals

3. The origin of iron-60

The origin of iron-60

1. Galactic background NO
2. *In situ* irradiation of solar system dust by solar cosmic rays NO
3. Last minute injection by a nearby star
4. SPACE model

Injection of SRs in a protoplanetary disk



Hester & Desch 2005

θ^1C Ori is the most massive star of the ONC (~40 $M_{\odot}$) which will explode as a supernova 5 Myr after the onset of star formation, ie 4 Myr from now

Requirements for supernova delivery of SRs

SN nearby a *young* disk

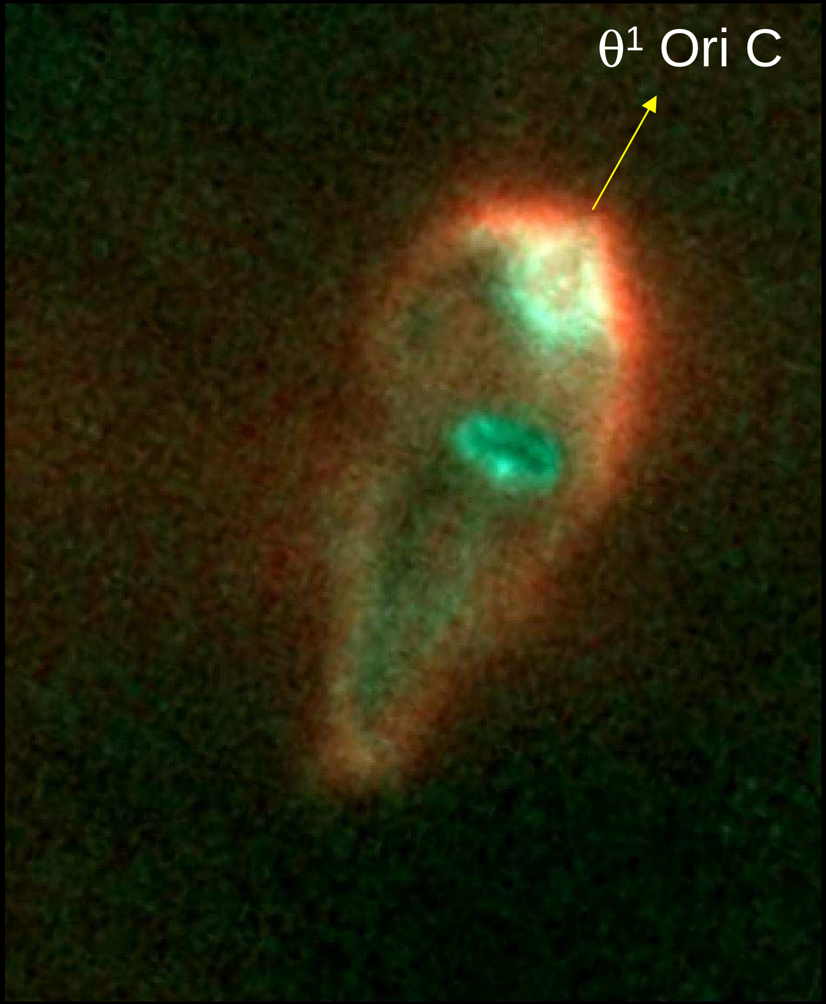
*nearby = 0.3 pc (from the SRs inventory and the SN yields)
*young = 1 Myr (from the cosmochemical data)

Problems for supernova delivery of SRs

1. Disk survival

2. Distance

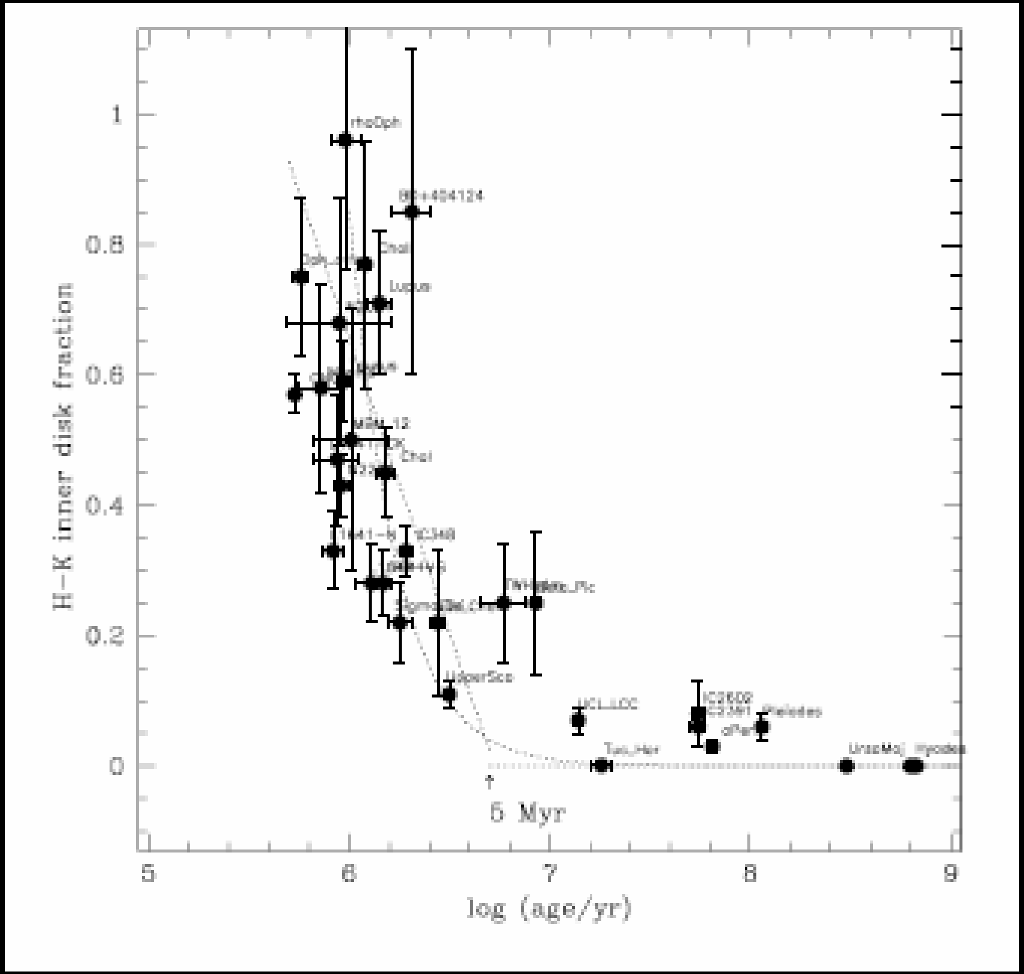
1. Disk survival - Evaporation



Evaporation timescale ~ 0.01-1 Myr

The time needed for θ^1C Ori (~40 $M_\odot$) to go supernova is ~ 5 Myr

1. Disk survival – disk dissipation



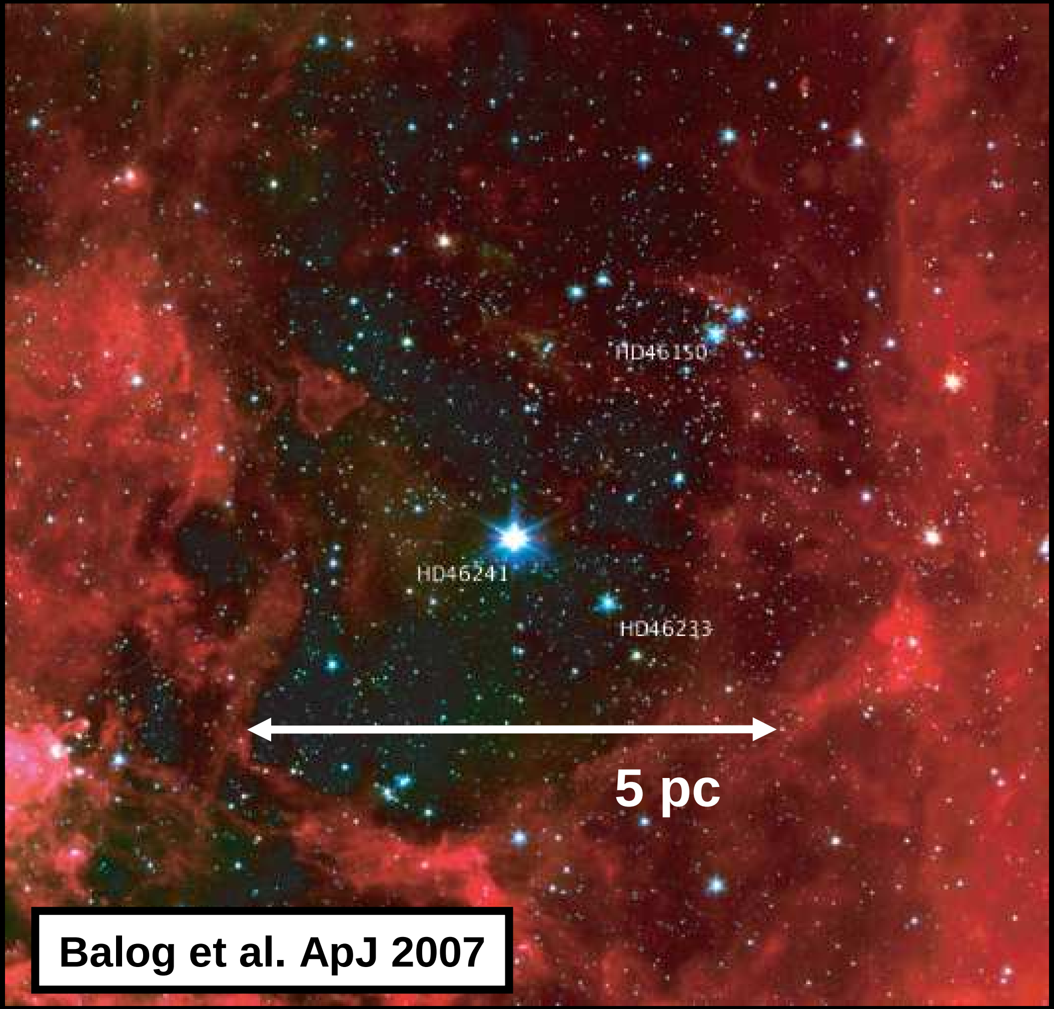
Even if disks do not evaporate, planets form on a few Myr timescale (before massive star death)

2. Distance issue

NGC2244 (~ Orion in 1-2 Myr)

~ 2-3 Myr old cluster

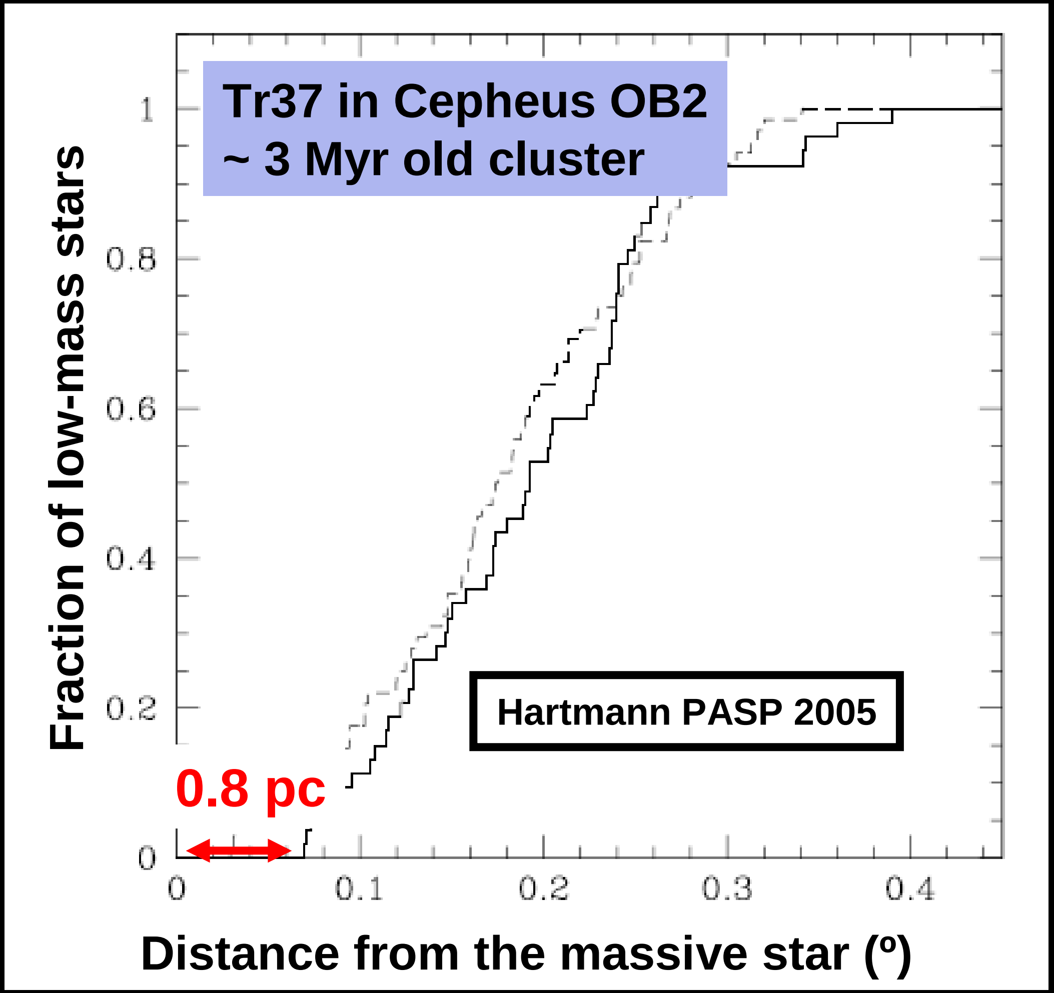
~ 2-3 Myr before the central O star goes SN



Balog et al. ApJ 2007

The rapid growth of an ionized (HII) region around the massive star prevents star formation in the enrichment zone

2. Distance issue



Tr37 in Cepheus OB2
~ 3 Myr old cluster

Hartmann PASP 2005

Most disks are *not* in the enrichment zone (0.2 < r < 0.4 pc)

Probability of SN contamination

$$\mathcal{P} = \int_{10^2}^{5\times 10^5} f_{\mathrm{disk}}(N_*)\ f_{\mathrm{enrichment}}(N_*)\ f_{\mathrm{survivors}}(N_*)\frac{1}{N_*}dN_*$$

Probability for a star to have a young, intact disk close to a SN ~ 10^{-3} (generous upper limit)

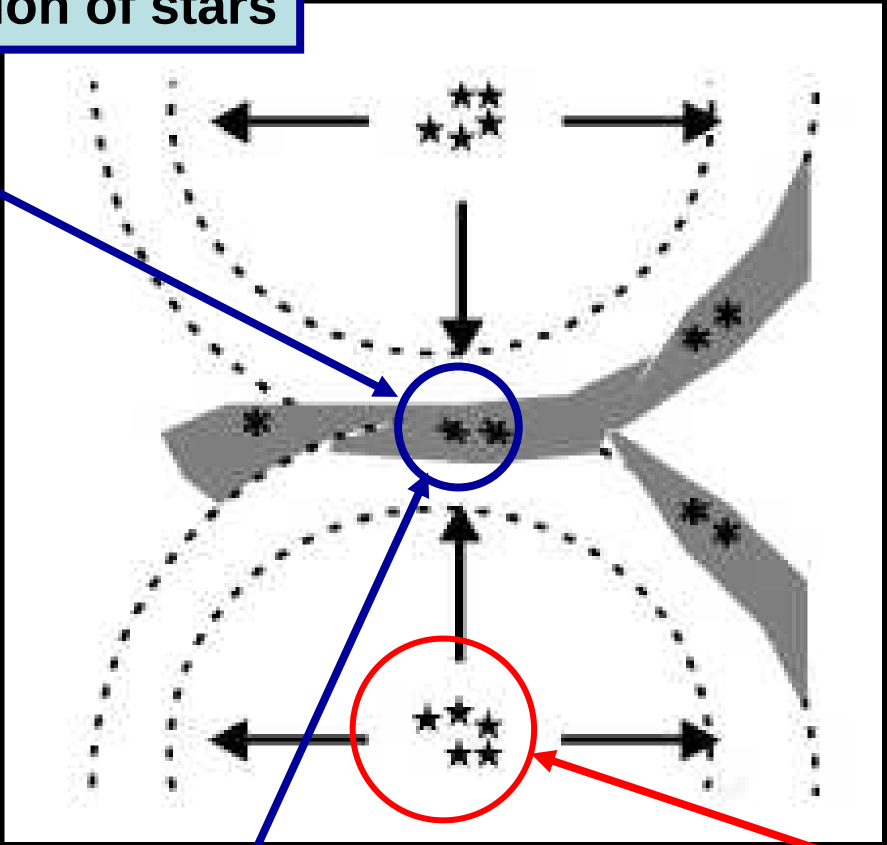
The delivery of SRs into the *disk* by a *nearby SN* is a very unlikely event

Williams & Gaidos ApJL 2007; Gounelle & Meibom ApJ 2008

4. The SPACE model

Formation of molecular clouds by turbulent convergent flows

Second generation of stars



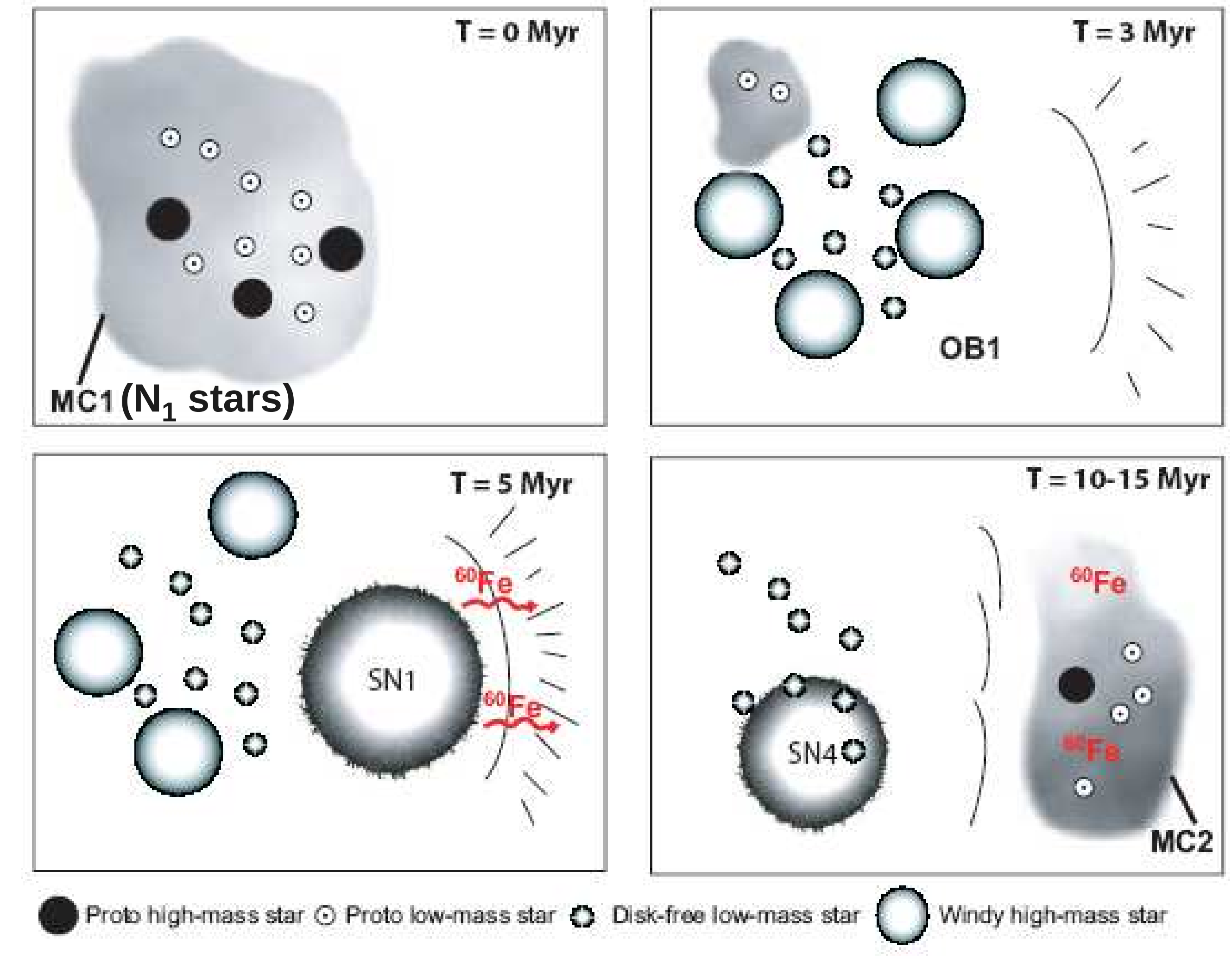
Drawing from Hartmann et al. ApJ 2001

First generation of stars

Vazquez-Semadeni, Elmegreen, Hartmann, Heitsch, MacLow, Ballesteros-Paredes…

Contains ^{60}Fe delivered by the 1st generation of stars

Supernovae Propagation And Cloud Enrichment (SPACE)



Gounelle et al. ApJL 2009

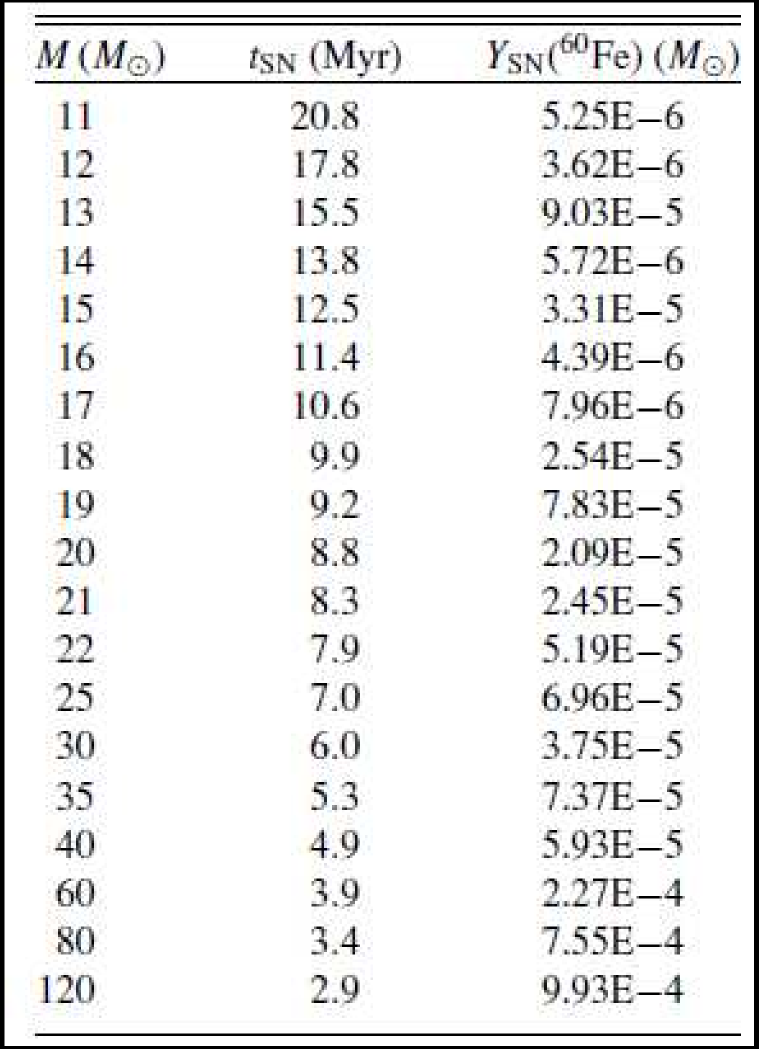
A stochastic quantitative calculation

$$M_{\mathrm{MC2}}(^{60}\mathrm{Fe})[t] = f\eta \sum_{i=1}^{i=N_{\mathrm{SN}}} Y_{\mathrm{SN}_i}(^{60}\mathrm{Fe})e^{-(t-t_i)/\tau}$$

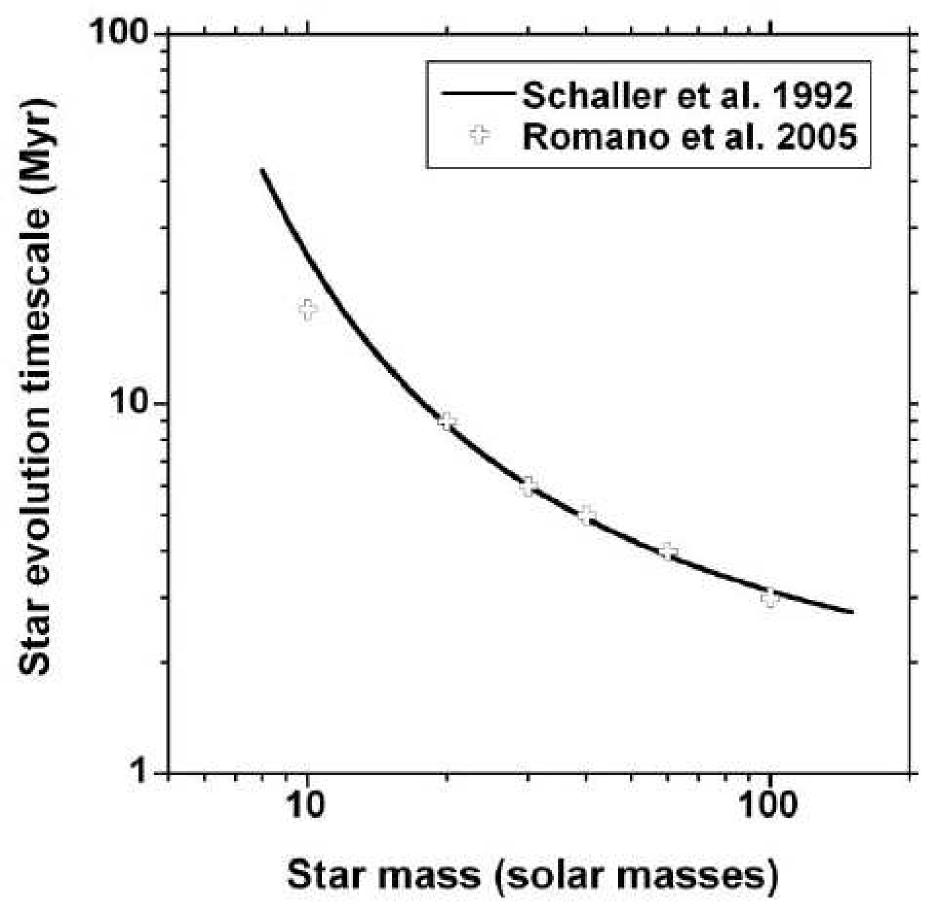
η: mixing efficiency of SRs
f: geometrical dilution factor
N_{SN}: number of supernovae
Y_{SNi}: yields of ^{60}Fe of supernova i
t_i: explosion time of the i^{th} SN
τ: ^{60}Fe mean life

For a given size of the MC1 cloud (a given N_1),
the calculation will be realized 100 times

^{60}Fe yields and supernovae lifetimes



M ($M_\odot$)	t_{SN} (Myr)	$Y_{SN}(^{60}Fe)$ ($M_\odot$)
11	20.8	5.25E−6
12	17.8	3.62E−6
13	15.5	9.03E−5
14	13.8	5.72E−6
15	12.5	3.31E−5
16	11.4	4.39E−6
17	10.6	7.96E−6
18	9.9	2.54E−5
19	9.2	7.83E−5
20	8.8	2.09E−5
21	8.3	2.45E−5
22	7.9	5.19E−5
25	7.0	6.96E−5
30	6.0	3.75E−5
35	5.3	7.37E−5
40	4.9	5.93E−5
60	3.9	2.27E−4
80	3.4	7.55E−4
120	2.9	9.93E−4

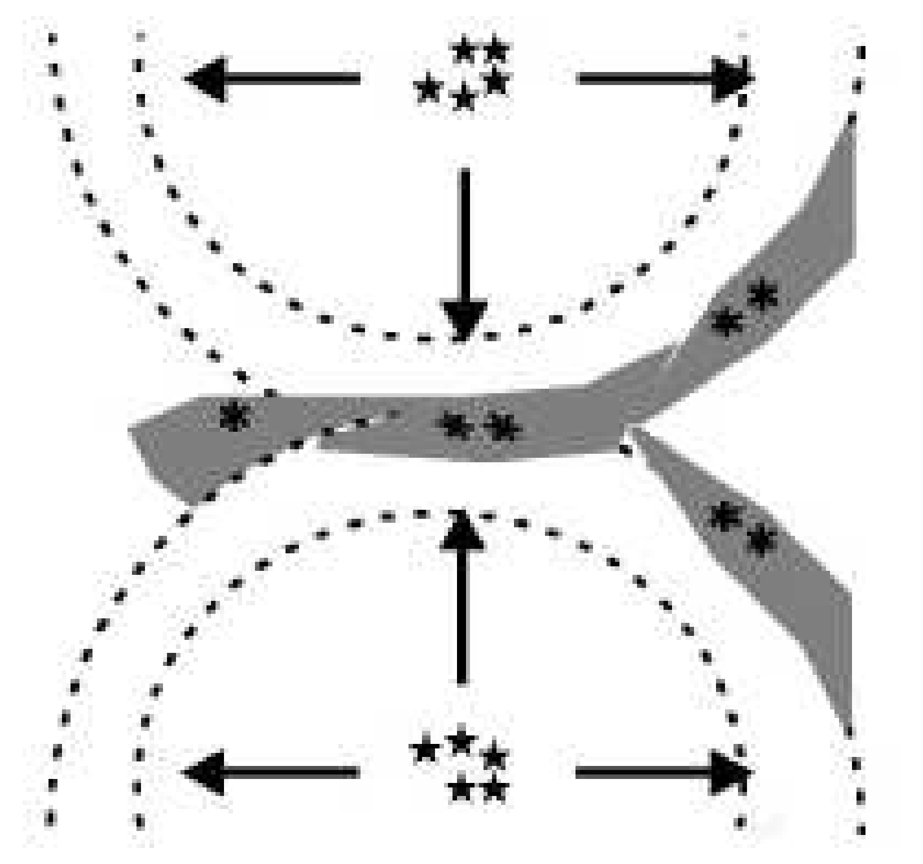


Woosley & Weaver (1995); Rauscher et al. (2002); Limongi & Chiffi (2006)

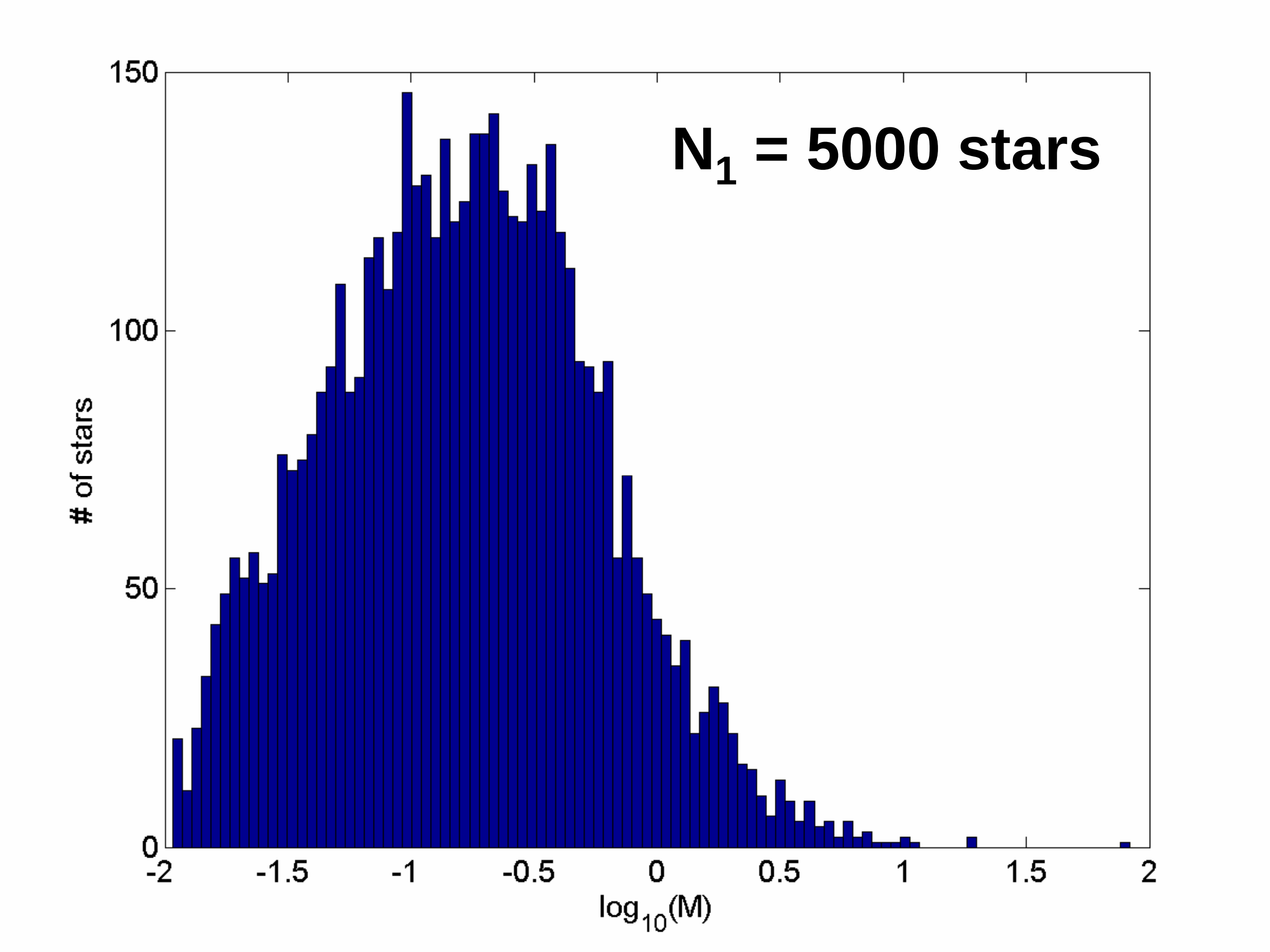
Geometry and dilution

Large scale turbulent flows: f = 0.5. We conservatively assume f = 0.1

Mixing favoured by low densities (Koyama & Inutsuka 2002): η = 1 (cf. Looney et al. 2006; Ouellette et al. 2005)



Generating a set of N_1 stars following the IMF



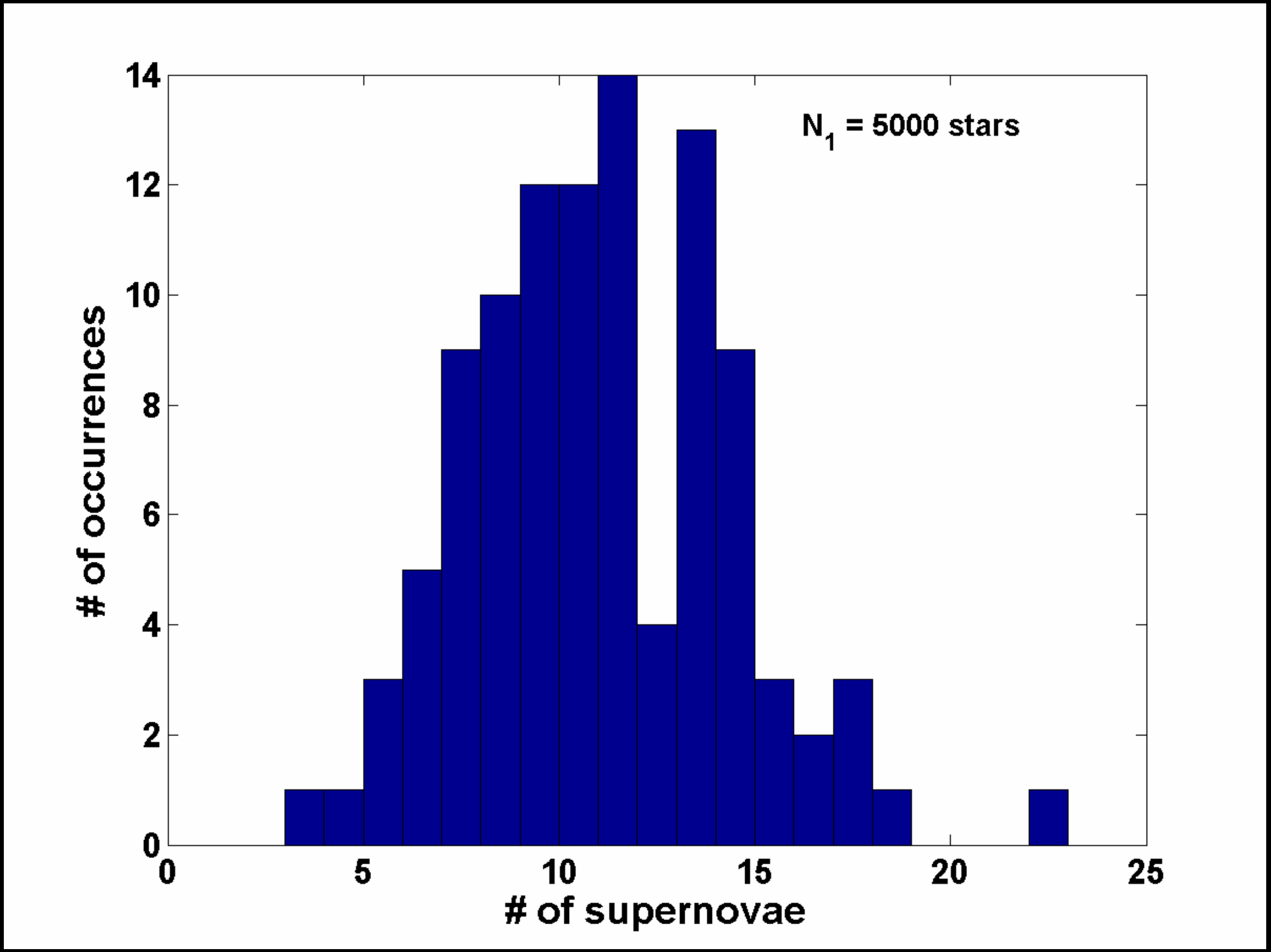
$$dN/dM \propto M^{-(1+\alpha)}$$

α = 2.7 for stars more massive than 1 M_o

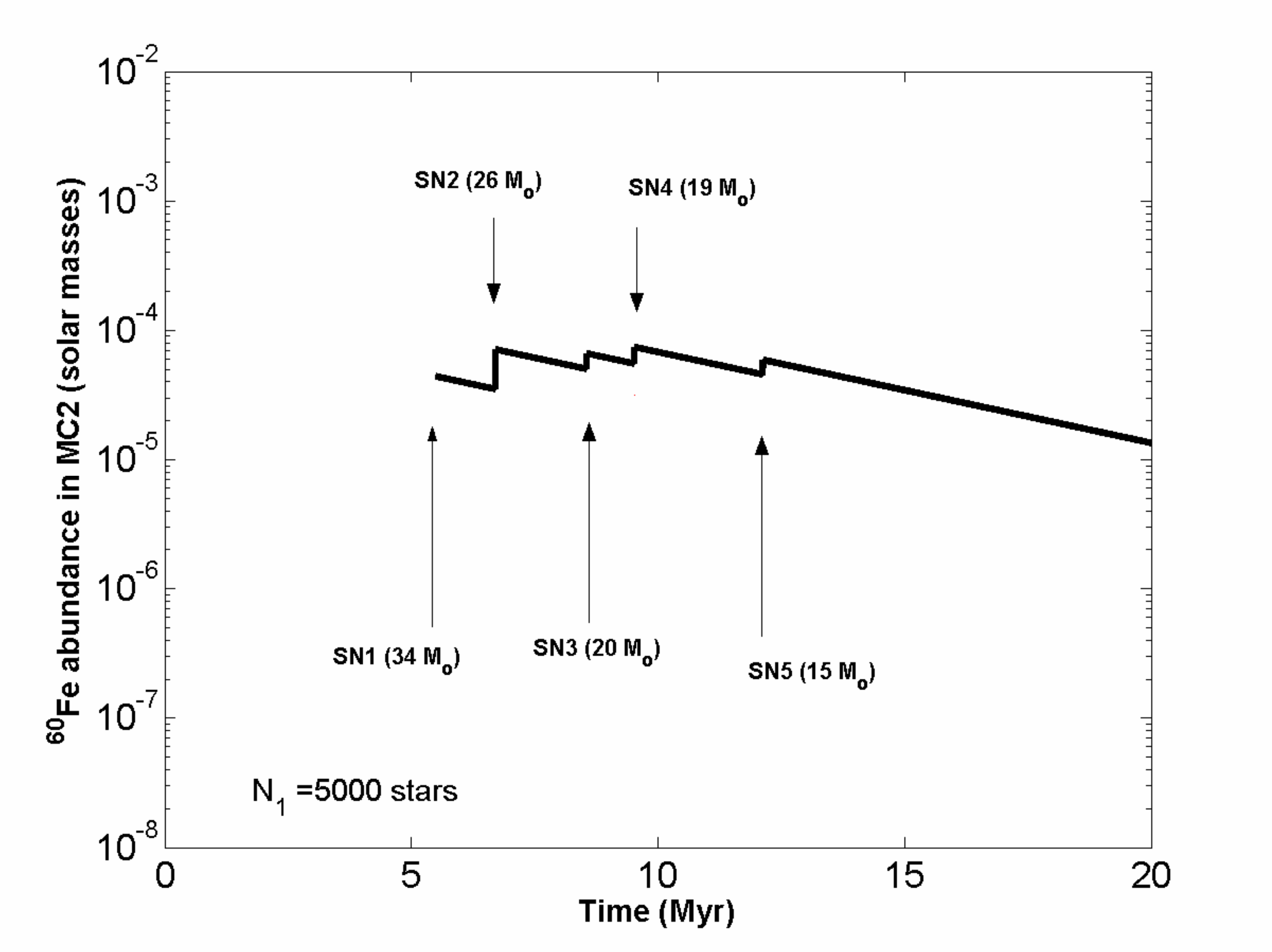
Kroupa et al. 1993

The number of supernovae

100 realizations of the IMF

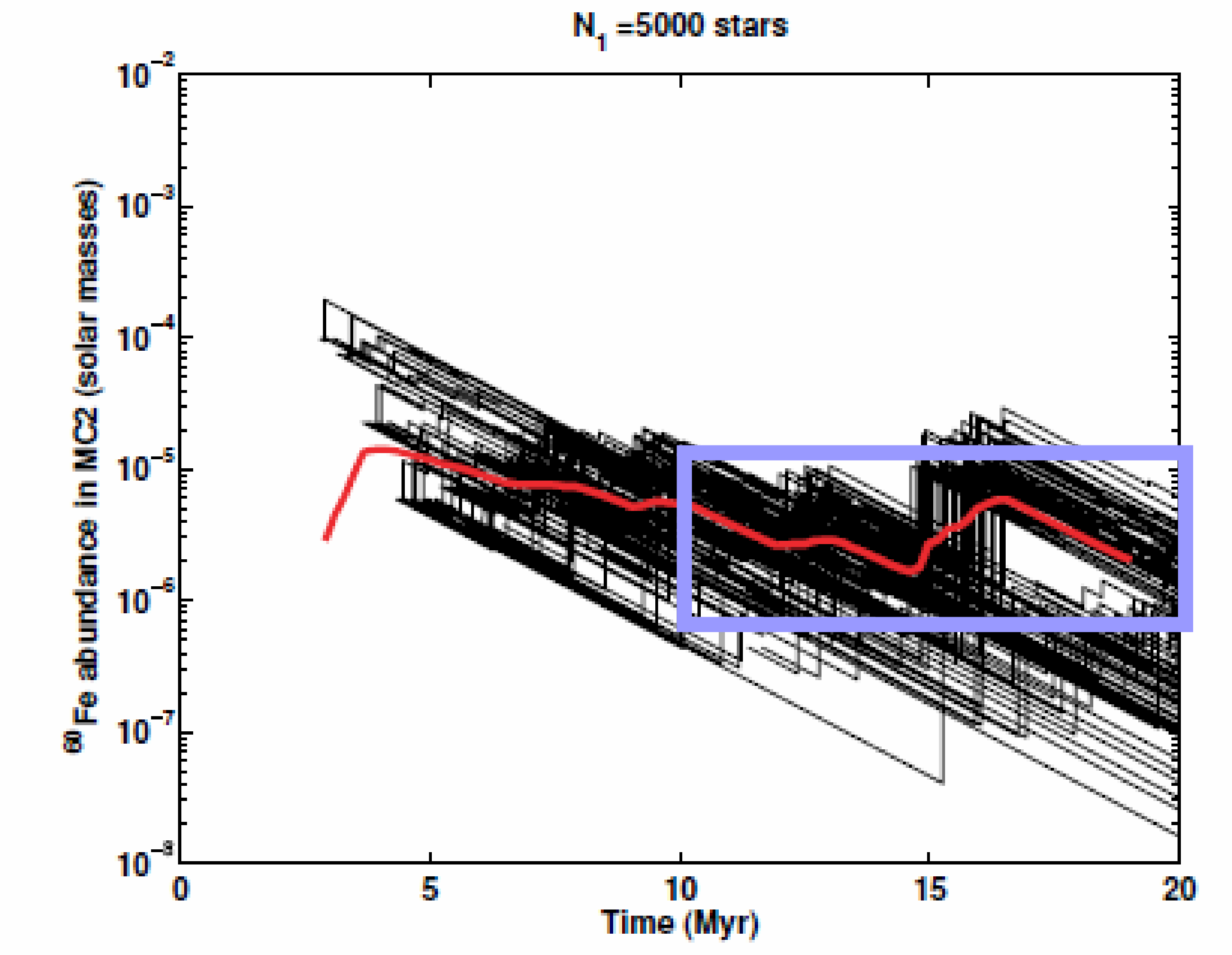


SPACE model - Results



One realization of the IMF with N_1 = 5000 stars

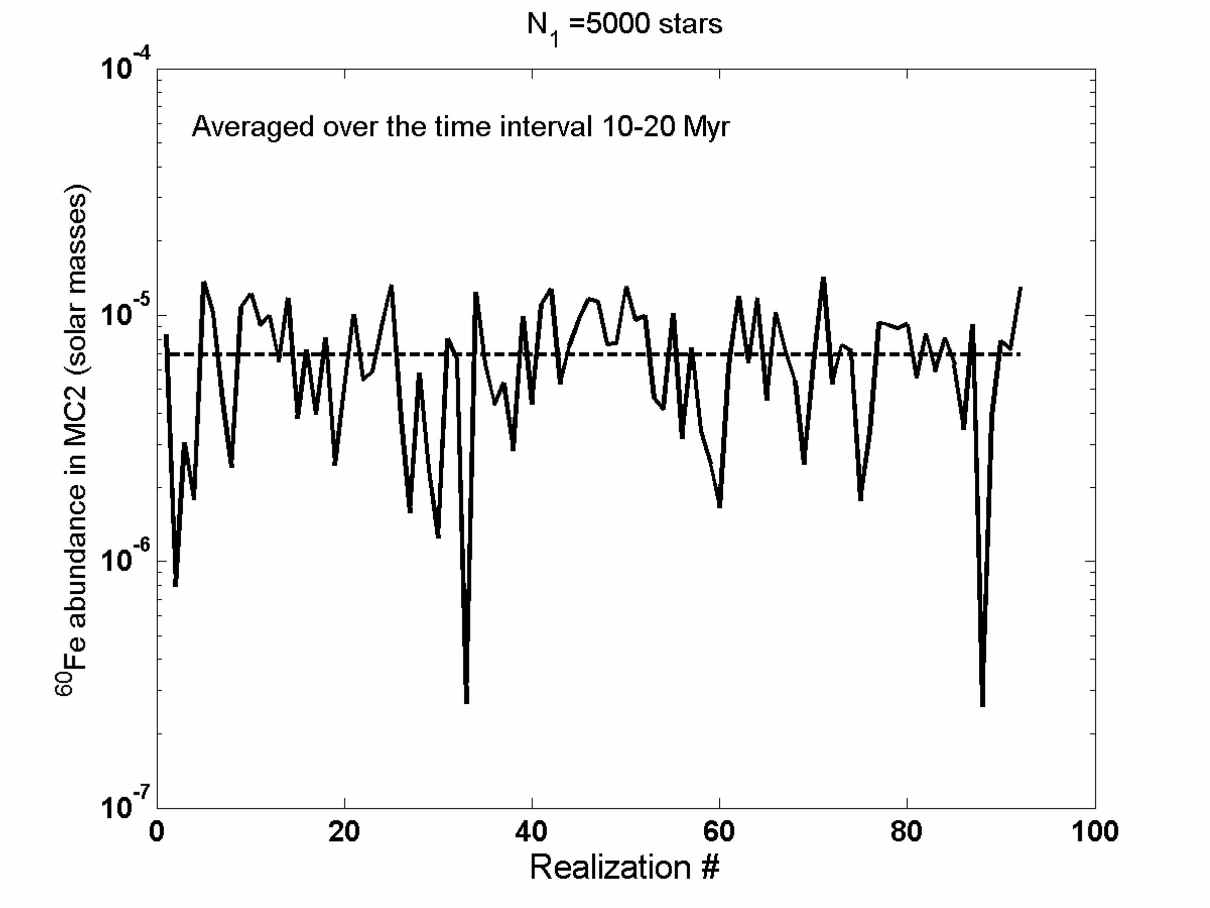
SPACE model - Results



Molecular clouds made by turbulent convergent flows need 10-20 Myr to be assembled (e.g. Vazquez-Semadeni et al. 2007)

SPACE model - Results

$$\overline{M}_{60Fe} = (6.9 \pm 3.5) \times 10^{-6}\ M_{\odot}$$



Comparison with the solar system
Numbers

M_{MC2} [^{60}Fe] = $(6.9 \pm 3.5) \times 10^{-6} M_o$ [N_1 = 5000 stars]

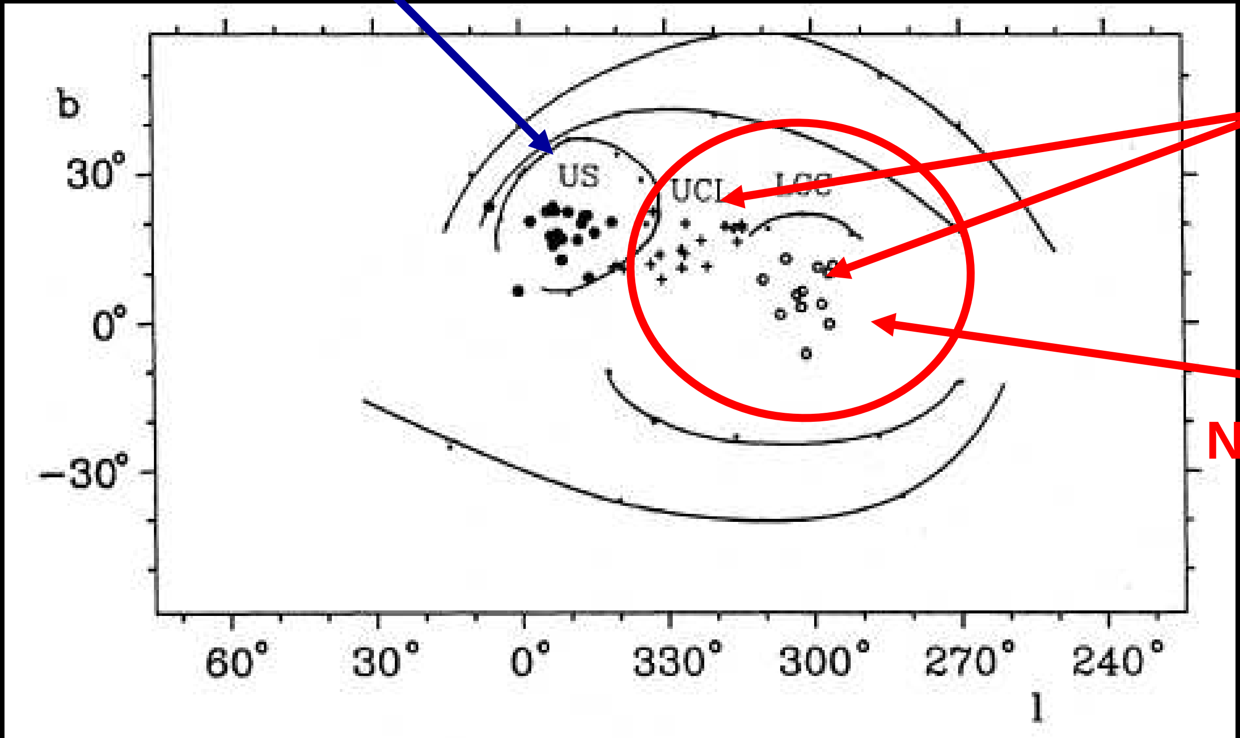
With $[^{60}Fe]_{SS}$ = 0.4 ppb ($^{60}Fe/^{56}Fe = 3 \times 10^{-7}$), a molecular cloud of mass $M_{MC2} = (1.7 \pm 0.9) \times 10^4\ M_o$ would have the same ^{60}Fe abundance than the solar system

How reasonable is it to have a cloud of mass

$M_{MC2} = (1.7 \pm 0.9) \times 10^4\ M_o$ made by turbulent convergent flows created by an OB association of N_1 = 5000 stars?

The astrophysical setting

De Geus et al. 1992
Mamajek et al. 2002



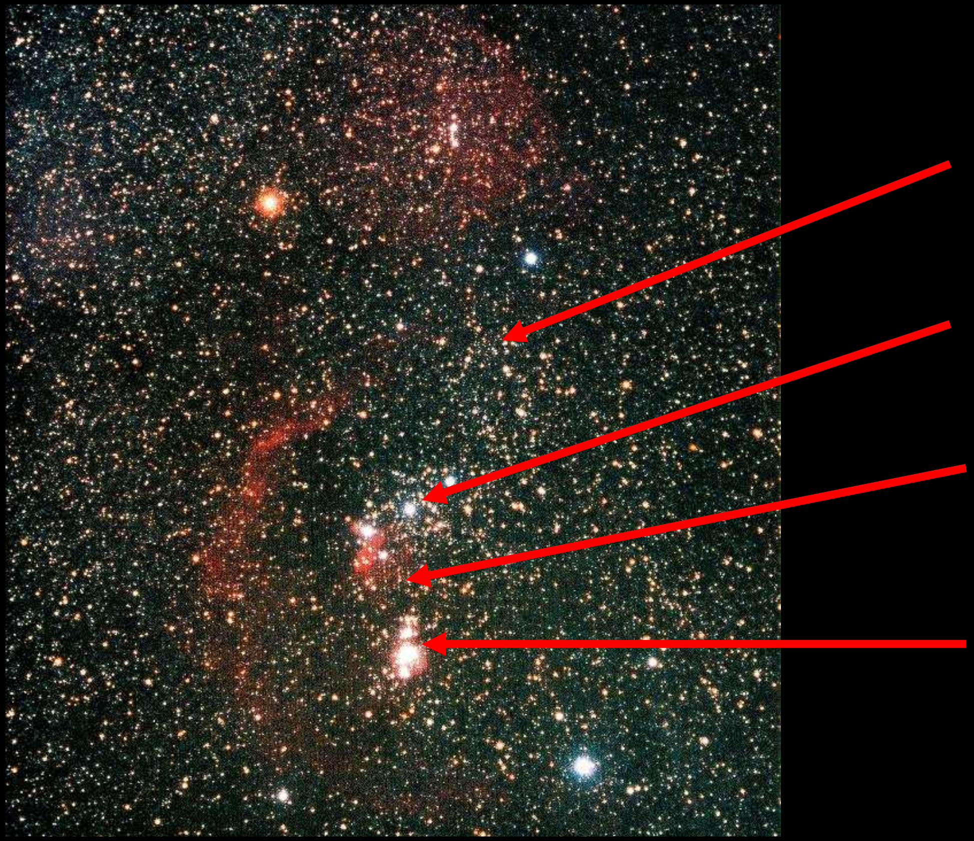
5 Myr

17 Myr

N_1 = 5000 stars

The MC progenitor of the Upper Sco OB association had a mass $M_{MC2} = (0.8 – 4.7) \times 10^4\ M_o$ (de Geus 1992; Lada & Lada 2003)

Metallicity [iron] enrichment in Orion



1a ~8-12Myr

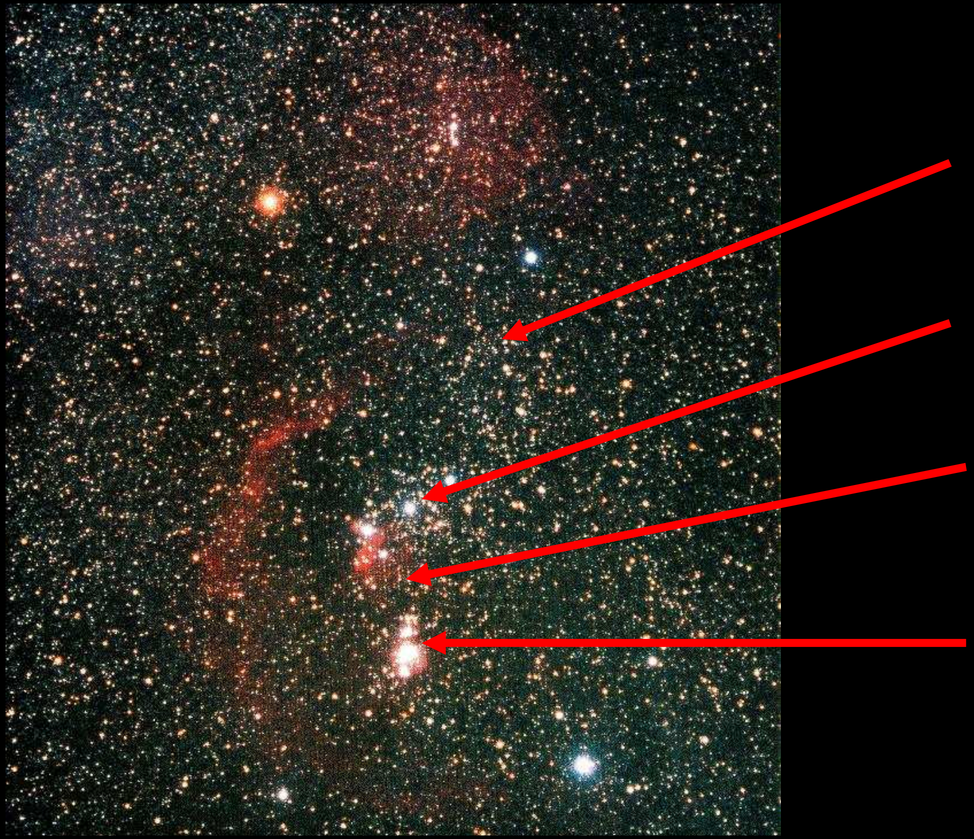
1b ~3-6Myr

1c ~2-6Myr

1d ~1Myr

Blaauw 1991

Metallicity [iron] enrichment in Orion



1a ~8-12Myr

1b ~3-6Myr [Fe/H] = -0.16

1c ~2-6Myr

1d ~1Myr [Fe/H] = 0.01

than the ONC. The ~ 0.1 dex difference in the Fe content of the ONC and the OB1b subgroup is consistent with the self-pollution scenario originally proposed by Cunha and collaborators (1992, 1994, 1998) for the Orion region.

D’Orazi et al. astro-ph

Conclusions

- ★ Unlikely ^{60}Fe injected by a nearby SN
- ★ A significant proportion of MCs built by turbulent convergent flows
- ★ The SPACE model proposes that while MCs are *being built*, they receive ^{60}Fe from SNe belonging to a previous episode of star formation and responsible for the turbulent convergent flows
- ★ Quantitative, stochastic calculations show that the ^{60}Fe content of our solar system can be accounted for by such a generic mechanism

Gounelle et al. (2009) *ApJL* 694 L1-L5