Shock Waves Inside the Local Bubble

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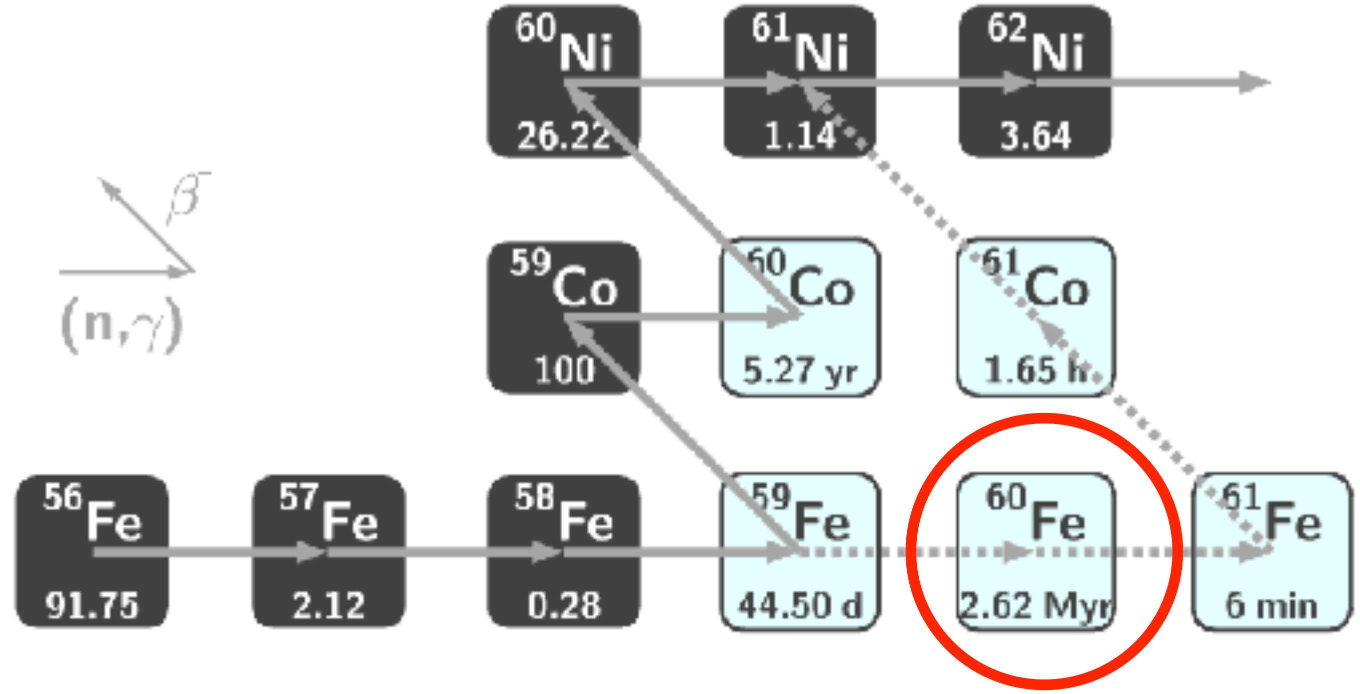
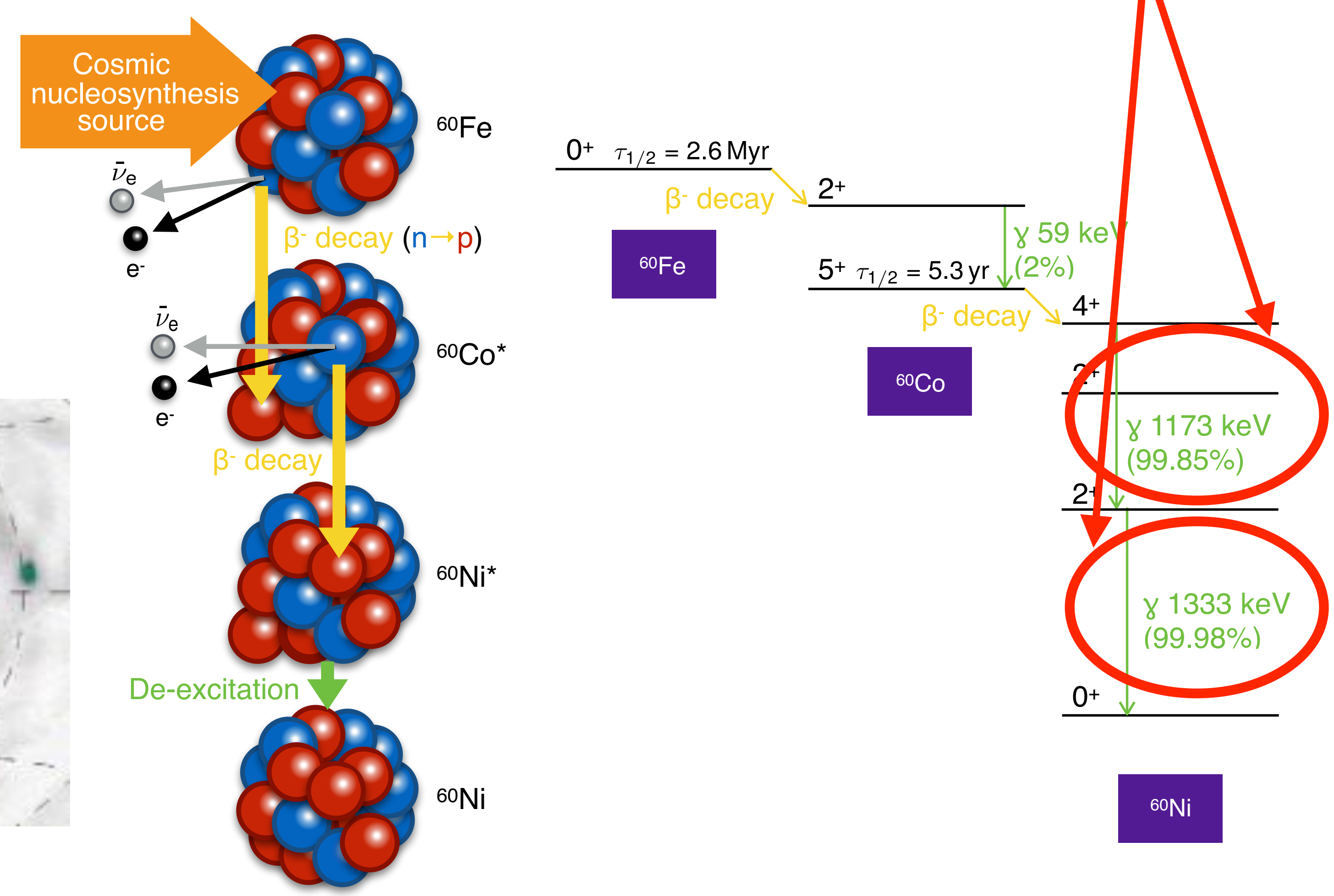
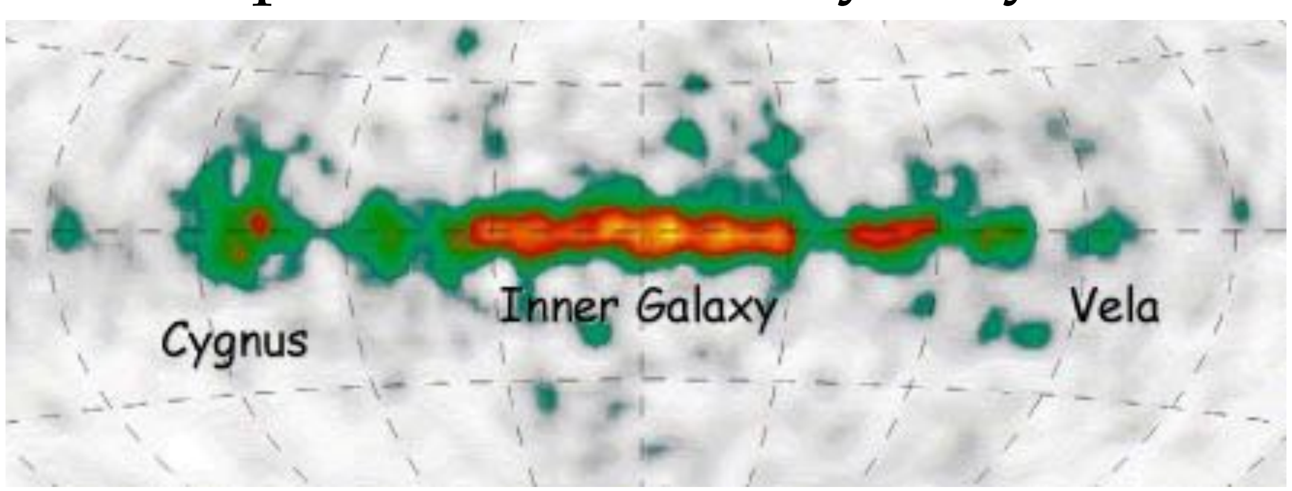
^{60}Fe as SN-Tracer



- ^{60}Fe ($t_{1/2} \sim 2.6$ Myr) produced in late AGB stars ($4\ 10^8 < T < 5\ 10^8$ K: C- core + He-shell burning) and explosive Ne-burning: ^{22}Ne$(\alpha,n)^{25}$Mg ➜ ^{58}Fe$(n,\gamma)^{59}$Fe$(n,\gamma)^{60}$Fe
- ^{26}Al is SN generated
- INTEGRAL γ-line measurements show that ^{26}Al and ^{60}Fe come from same places in the Milky Way

^{60}Fe production and measurement via decay to Co and Ni by β^--decay and emission of 2 γ's





INTEGRAL map of ^{26}Al from the Galaxy
Credit: R. Diehl, MPE

^{60}Fe in the solar system?
The Advent of Deep-Sea Astronomy

- Long-lived isotopes are best found and preserved in the ocean ➜ archives with long memory
- ^{146}Sm, ^{182}Hf, ^{244}Pu also long-lived but ejected at much smaller quantities
- Deep-sea ferromanganese crust and nodules: low growth rate (mm/Myr)

➜ ideal to incorporate ^{60}Fe over long time: $t_{1/2} \sim 2.6$ Myr

- Deep-sea sediments: growth rate mm/kyr ➜ higher time resolution

nodules

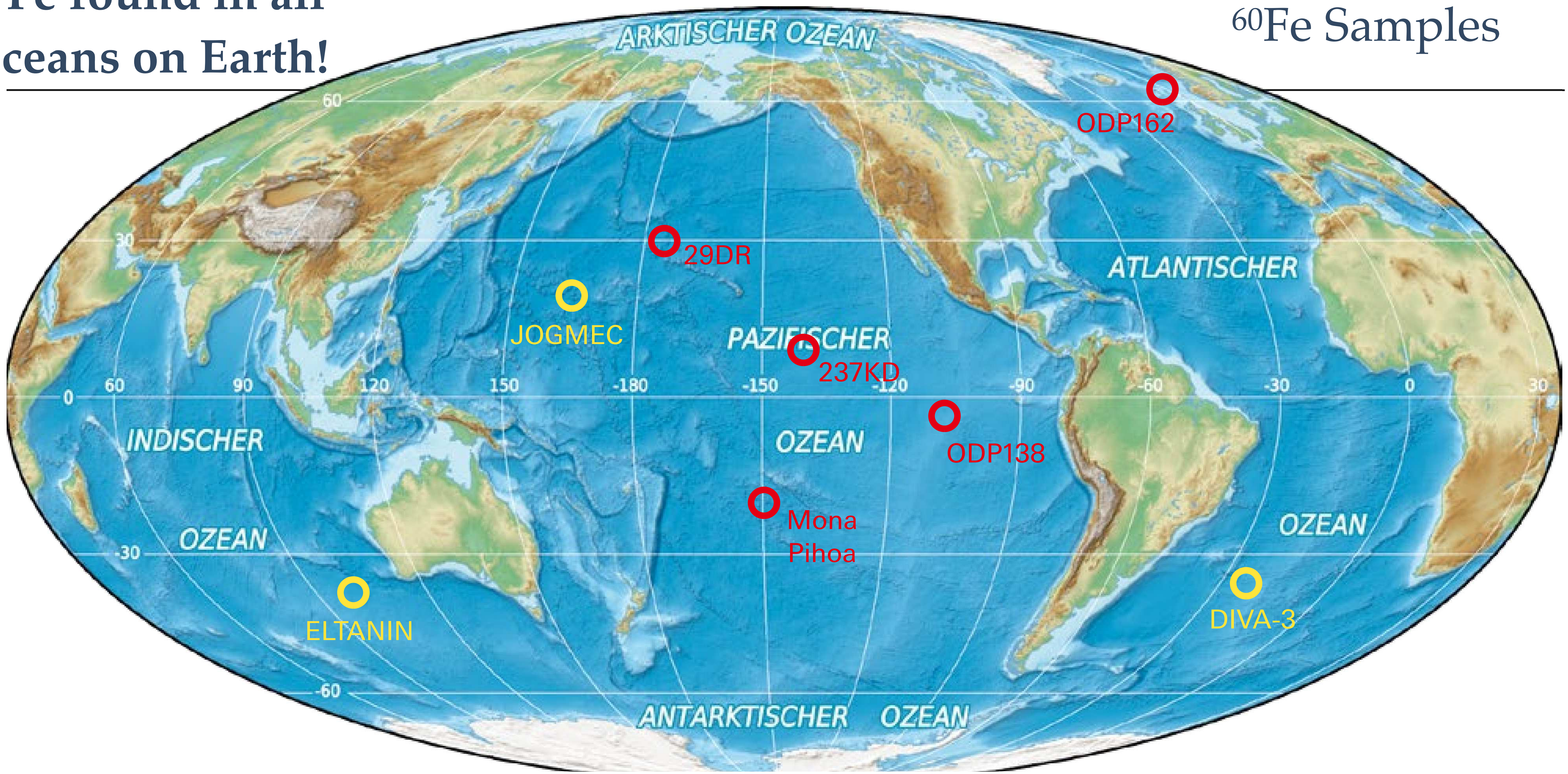
Hein & Koschinsky 2014

Deep-Sea Astronomy I

Deep-Sea Astronomy II

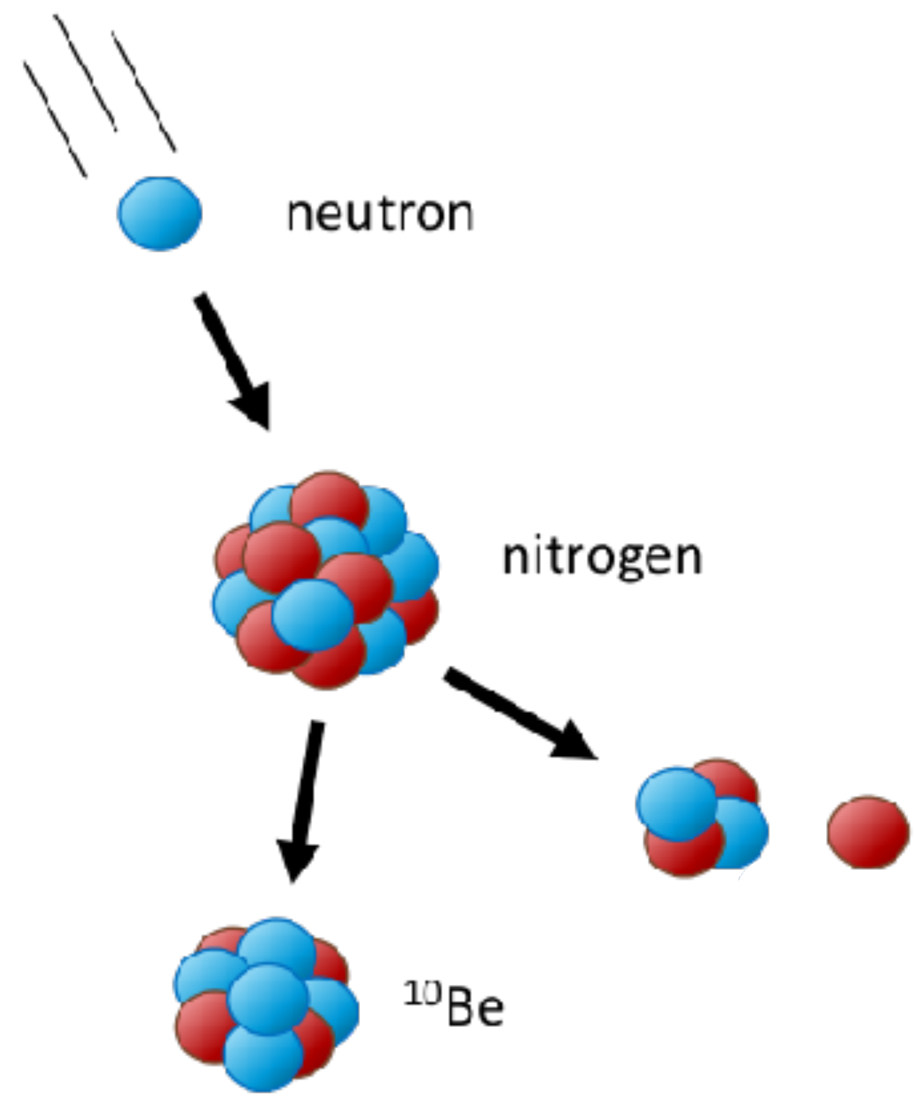
^{60}Fe found in all oceans on Earth!

Locations of ^{60}Fe Samples



How to determine the age?

- Setting the clock by **^{10}Be isotopic dating**
- ^{10}Be ($t_{1/2}$ ~ 1.4 Myr) constantly produced by cosmic ray spallation in the upper atmosphere (e.g. ^{14}N)
  ➜ relatively constant ^{10}Be flux over time
- ^{10}Be also present in crust/sediments

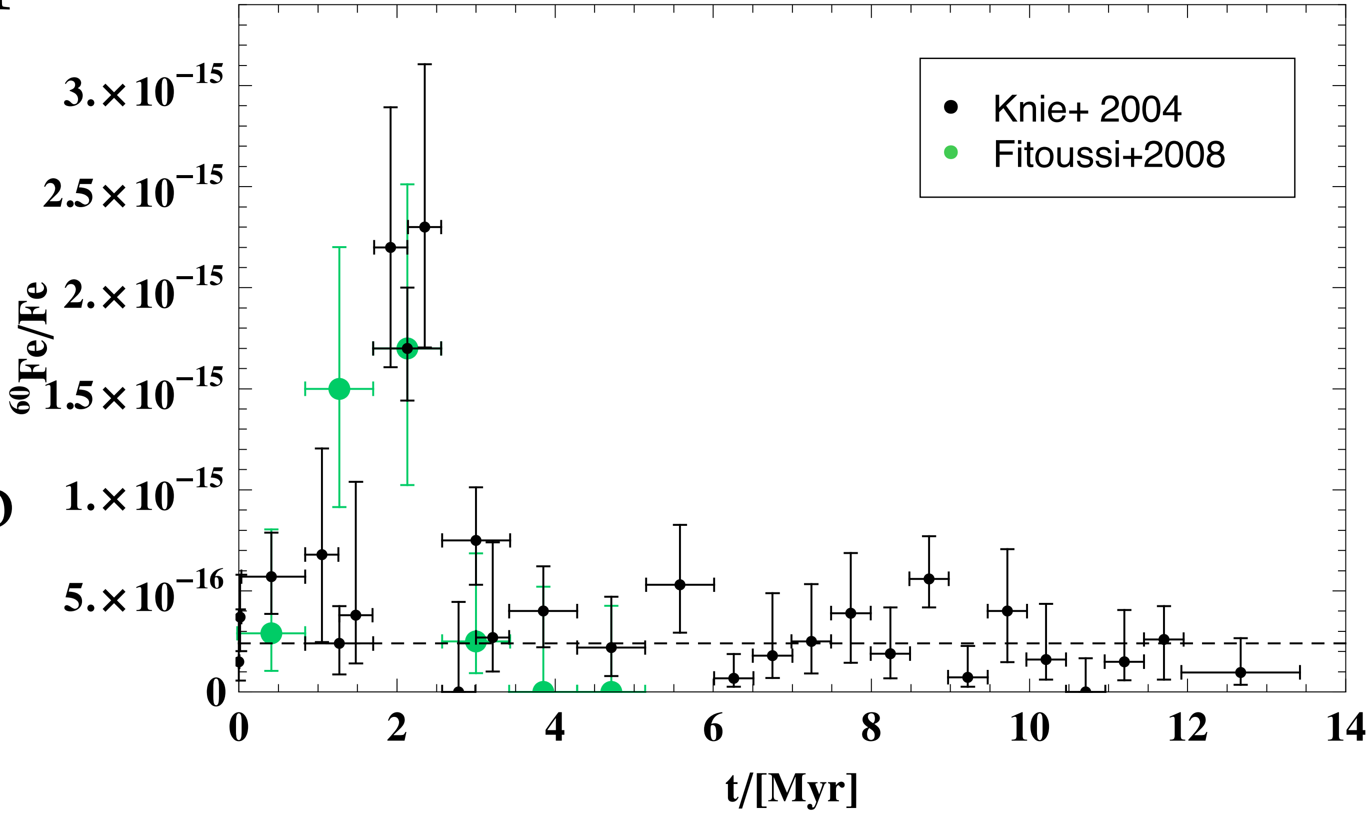


- $N(t) = N_0 \exp[-\lambda\, t]$ with
- $N(t)$ … ^{10}Be/^{9}Be-ratio at a certain depth
- N_0 … ^{10}Be/^{9}Be-ratio at the sediment's surface
- λ … decay constant for ^{10}Be

➜ t … age of sample (sediment/crust)

Global Signal I
- ^{60}Fe in the oceans -

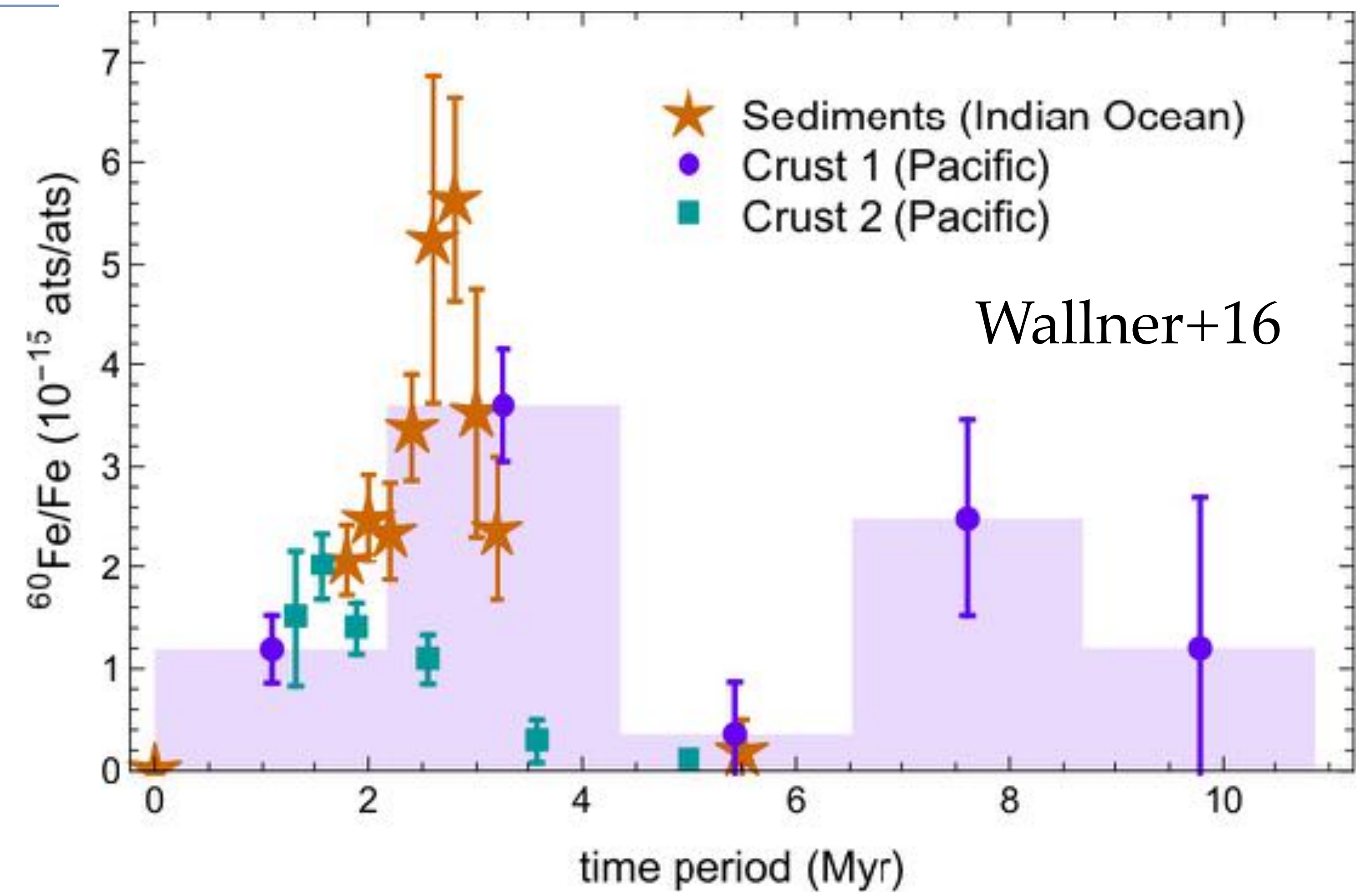
- Small quantities of long-lived isotopes are best measured by Accelerator Mass Spectrometry (AMS), e.g. 14 MV Tandem accelerator at TU München
- ^{60}Fe signal in 1.7 - 2.6 Myr old layer detected in crust 237KD
- 2 mm ≙ 800 kyr
- each layer defines range on time axis
- all terrestrial ^{60}Fe decayed long ago ➜ low terrestrial background



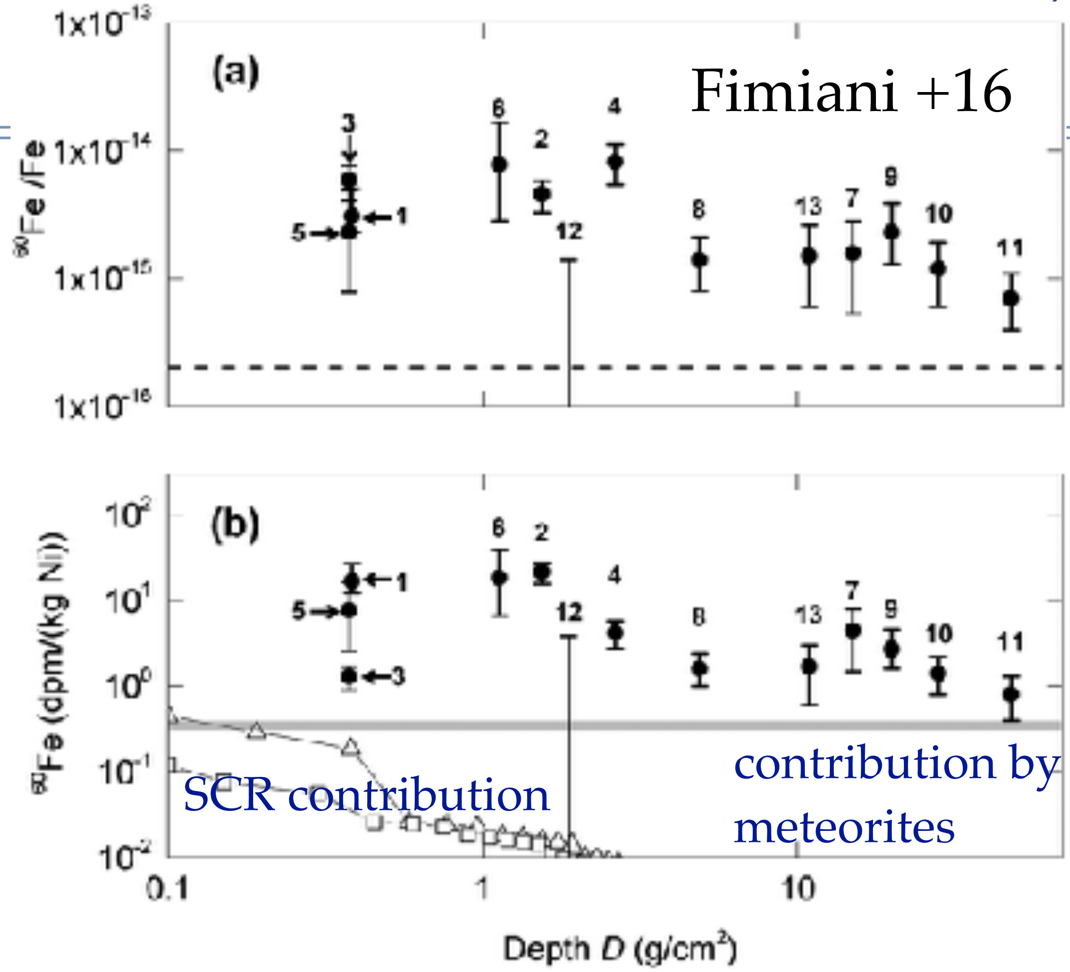
Global Signal II
- ^{60}Fe in the oceans -

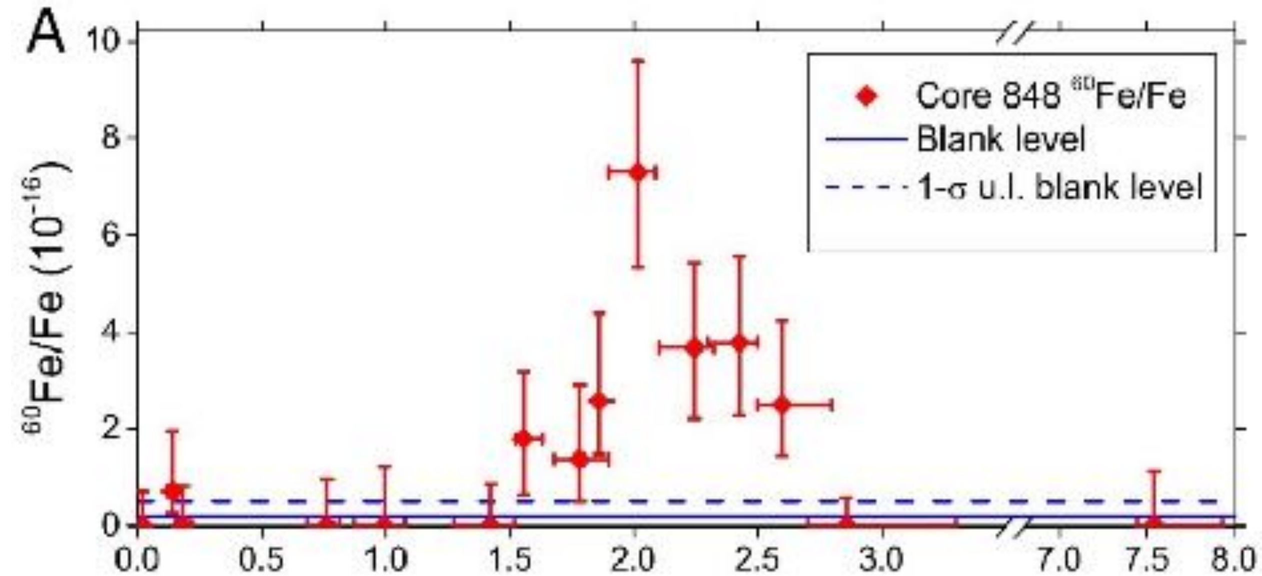
- Signal is **extended** ➜ probably more than one SN!
- 2nd peak at 6.5 - 8.7 Myr before present (= BP), 4σ above background detected (Wallner+ 2016)
- note higher time resolution in sediments

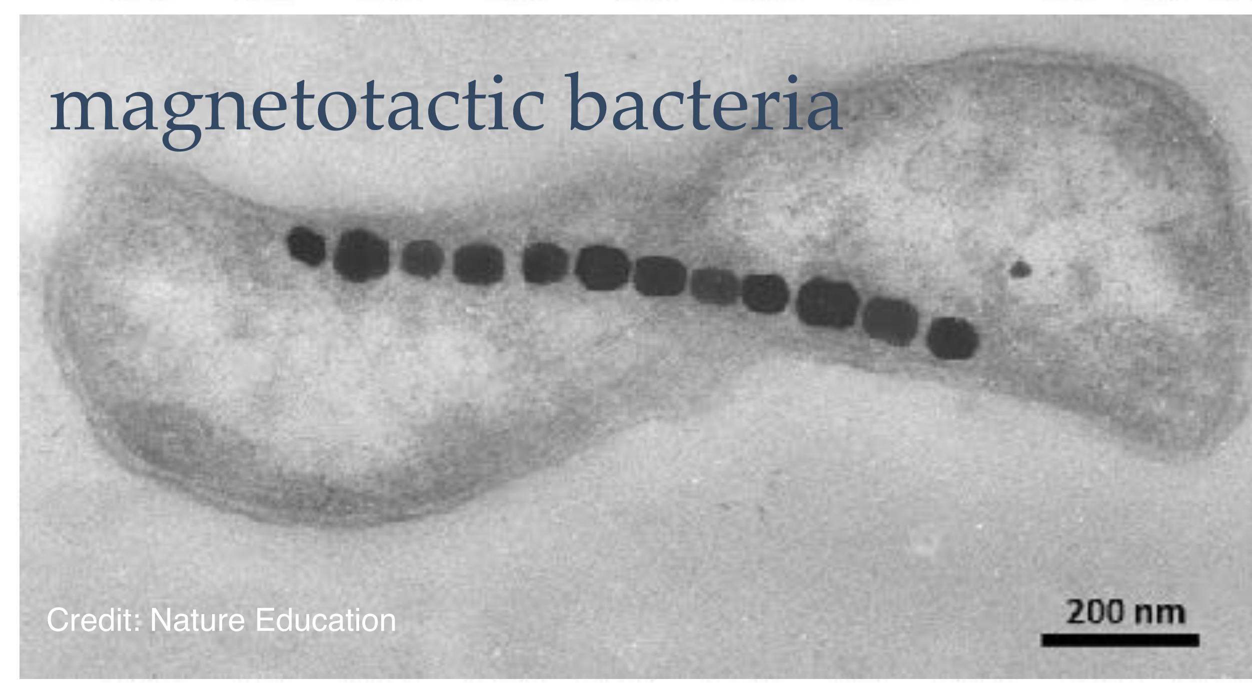
  ➜ signals rule out a constant background of ^{60}Fe
- ^{60}Fe found in all oceans ➜ **global**
- micrometeoritic origin excluded ➜ dust influx 400x too low
- meteorite impact like in tertian (65 Myr BP) would have a 4500 times too low ^{60}Fe mass



Global Signal III
^{60}Fe in bacteria, lunar samples, CRs

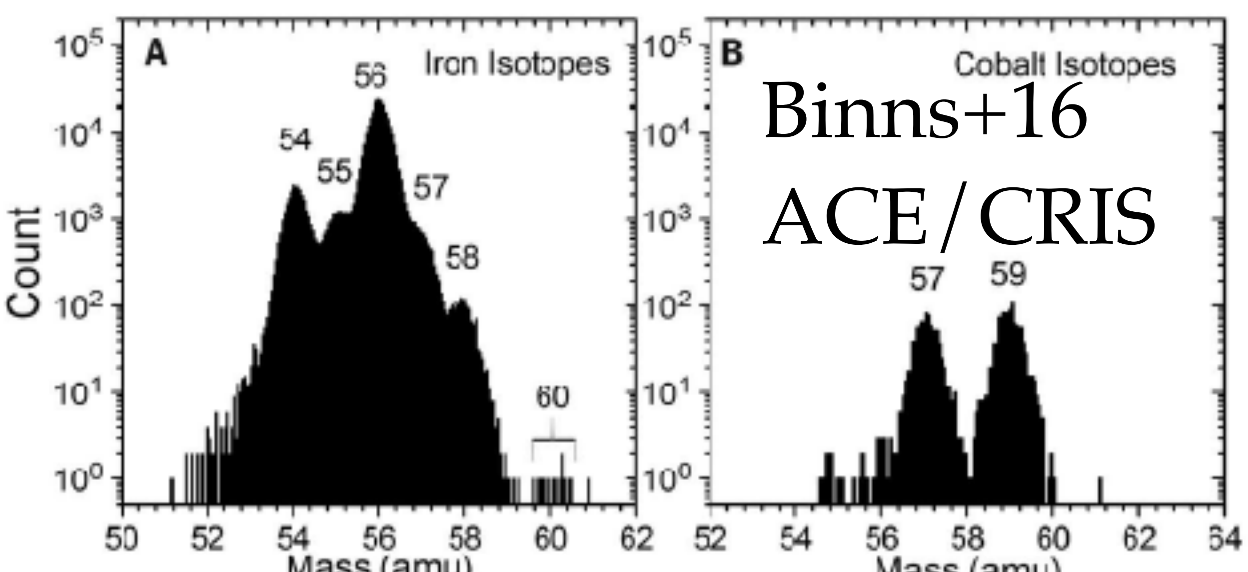






Age (Ma)

Ludwig+2016, PNAS 113, 9232



1st Summary

- Enhancement of extraterrestrial ^{60}Fe found in all oceans, in crusts, nodules and sediments, but also in bacteria, lunar rocks and in SN accelerated cosmic rays
- ➜ signal peak at 2.2 Myr BP
- all ^{60}Fe from the formation of solar system decayed
- cosmogenic ^{60}Fe contribution from asteroids or micrometorites is small
- all evidence points to SN as source
- time resolved measurements in sediments show wider peak (Wallner+16)
- ➜ more than one SN responsible!

Can we find out **when** and **where** these SNe exploded?

LETTER

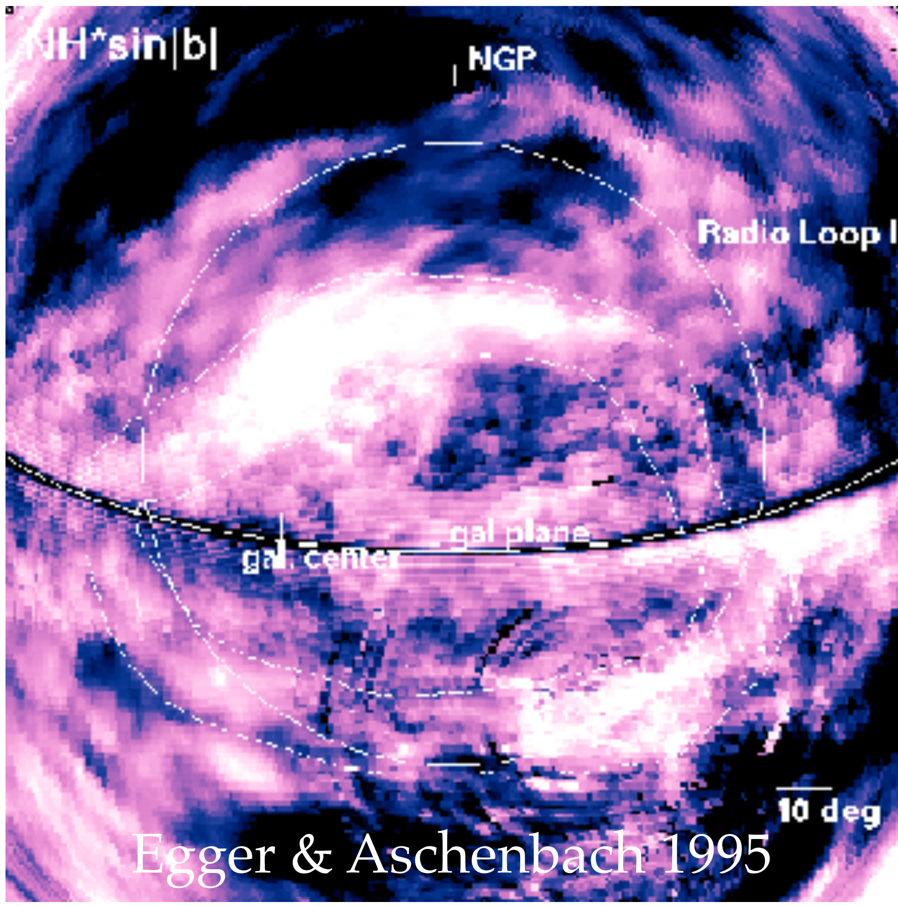
doi:10.1038/nature17424

The locations of recent supernovae near the Sun from modelling ^{60}Fe transport

D. Breitschwerdt[1], J. Feige[1], M. M. Schulreich[1], M. A. de. Avillez[1,2], C. Dettbarn[3] & B. Fuchs[3]

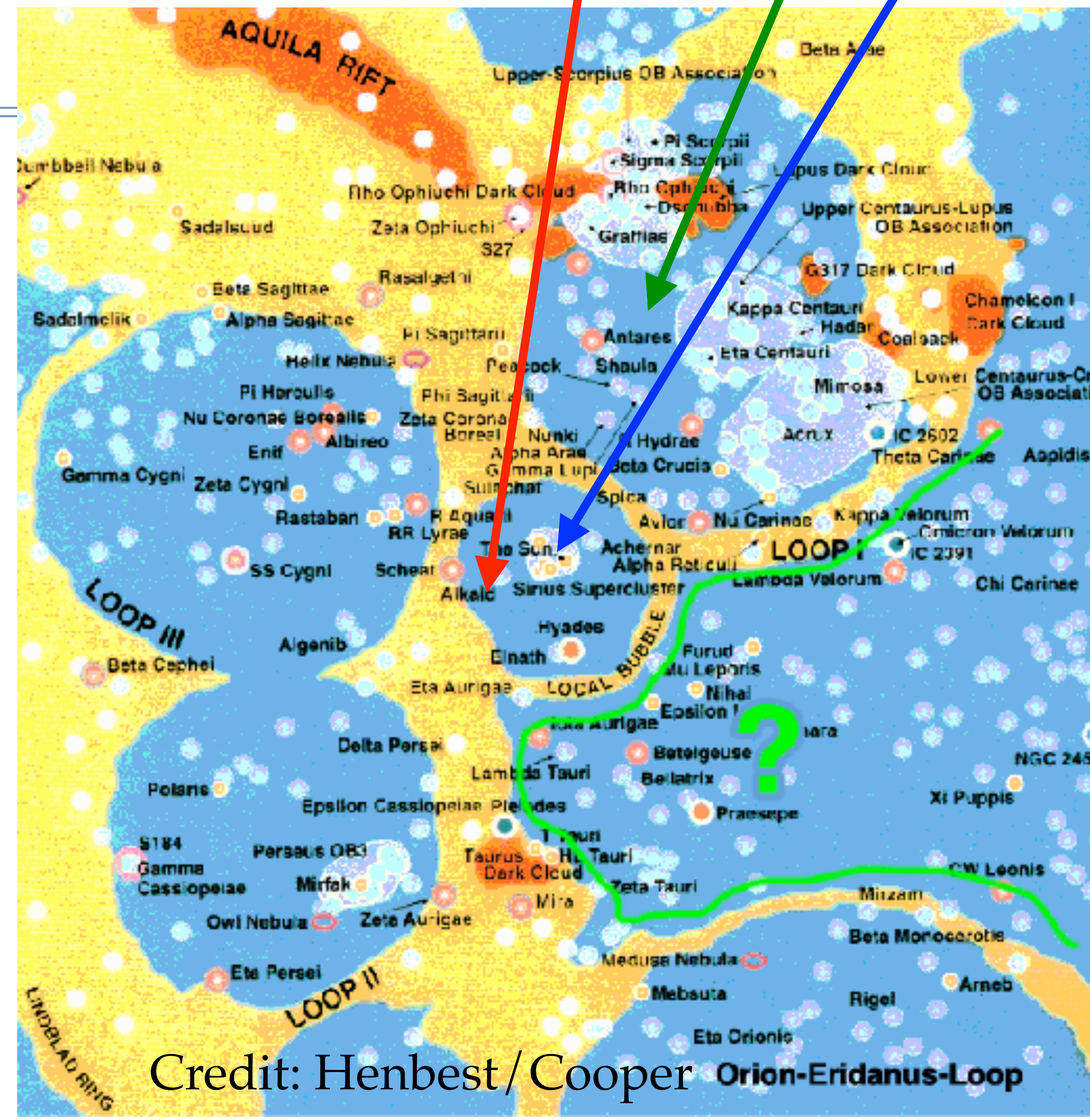
Solar Neighbourhood I

Local Bubble Loop I
Solar System



X-rays from Local Bubble and Loop I - anticorrelated with neutral hydrogen emission

- Solar system embedded in local superbubble: **Local Bubble (LB)**
- low density, high T ~ 10^6 K
- LB in interaction with Loop I (Egger & Aschenbach 1995)
- **no young star cluster inside LB!**



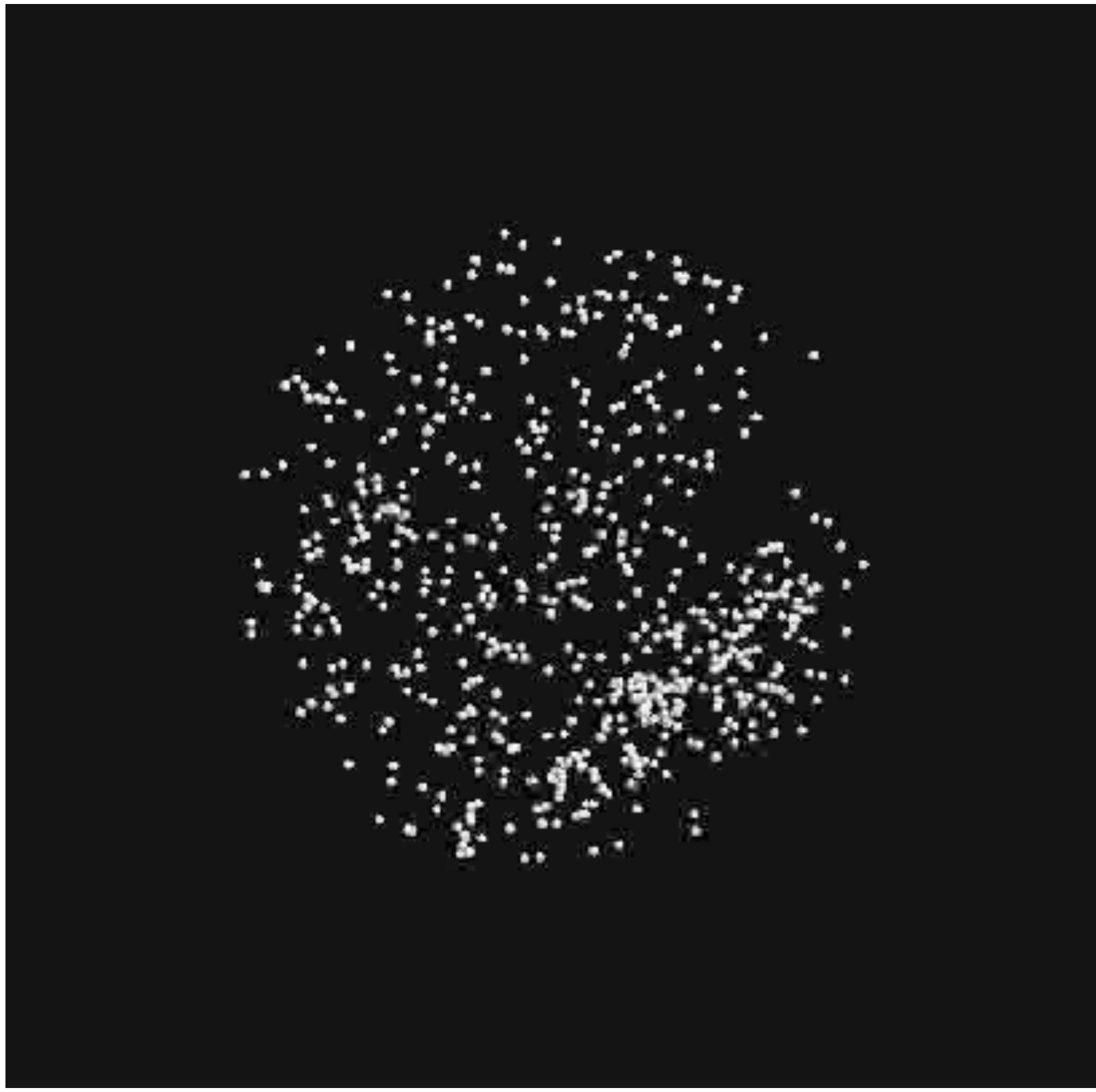
Superbubbles in solar neighbourhood

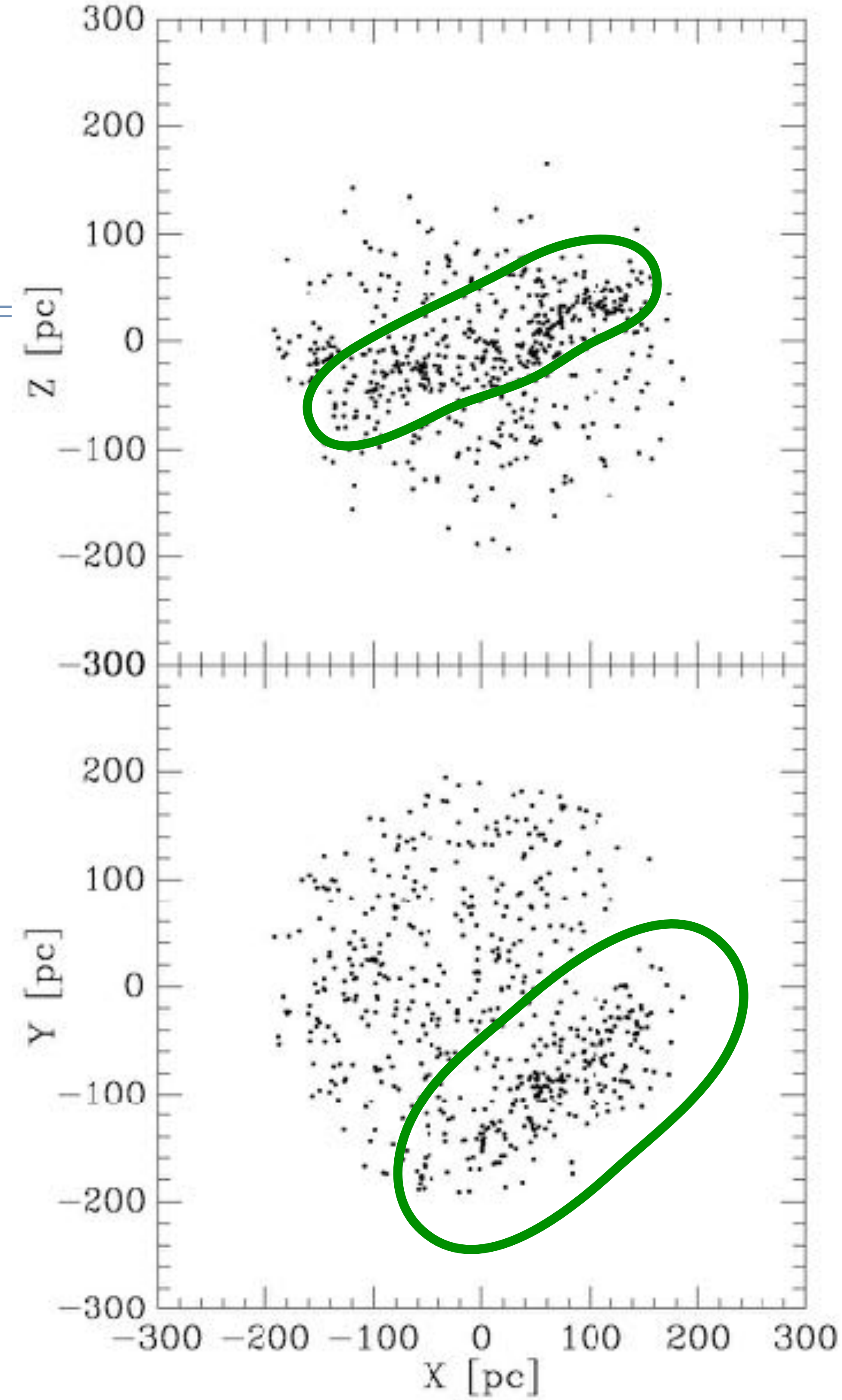
Local Interstellar Medium (LISM) I

- LB could be the result of SNe (Sanders+77, Hartquist & Innes+84, Breitschwerdt & Schmutzler+94, Cox & Smith+01 etc.)
- But where is the star cluster in which massive members exploded?
- **Idea**: Stars exploded in moving group (Berghöfer & Breitschwerdt+02)
- Pleiades subgroup B1 (age 25 Myr) crossed LB during the last 20 Myr
- Fuchs+06 searched volume of 400 pc diameter centred at Sun using **Hipparcos** and **ARIVEL** data ➜ 762 stars ➜ concentration in real and velocity space: 79 stars

Hipparcos Astrometry Satellite, Credit: ESA

LISM II

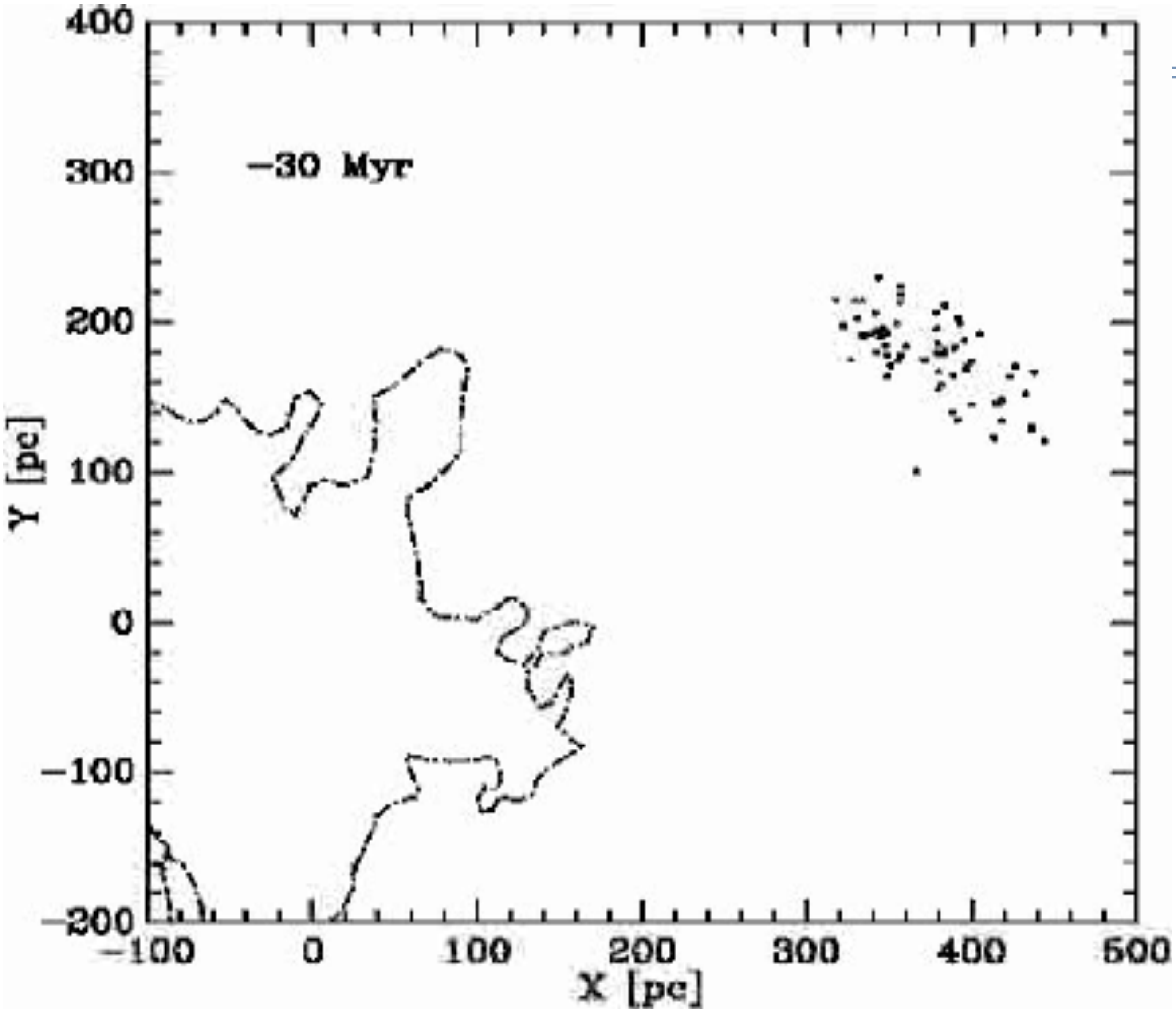


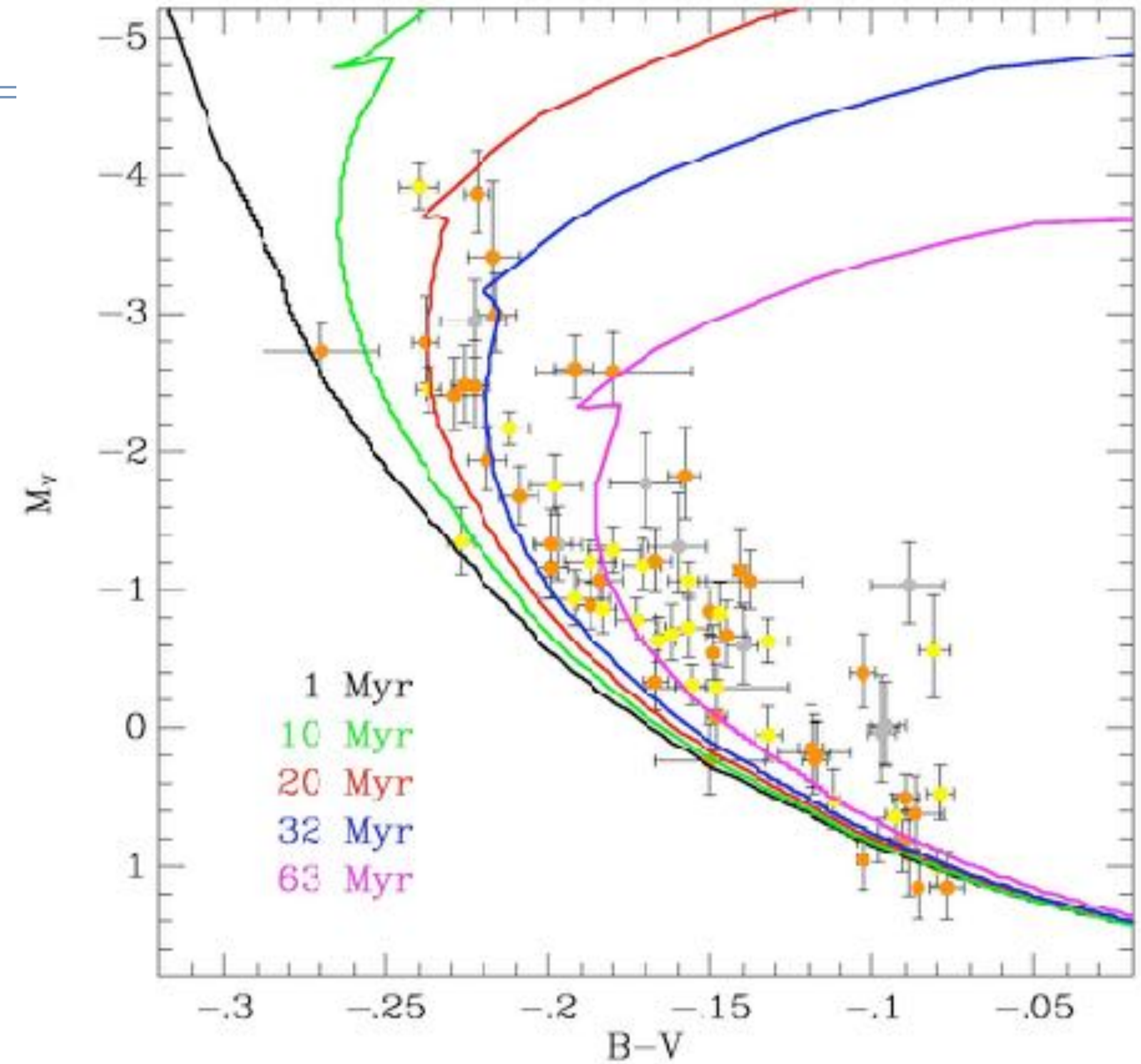


- Clustering of stars ➜ stellar moving group
- complete phase space information {**x,p**}, i.e. all stellar **positions** and **velocities** are known
- surviving members belong to Sco-Cen association (UCL, LCC) ➜ calculate trajectories back in time (epicyclic eqs.)

Hipparcos Astrometry Satellite, Credit: ESA

LISM III





- Cluster age determined by comparison with stellar **isochrones** in HRD
- subsample of 79 de-reddened B-stars
  ➜ turn-off point from mains sequence gives age: 20 - 30 Myr

Initial Mass Function (IMF)

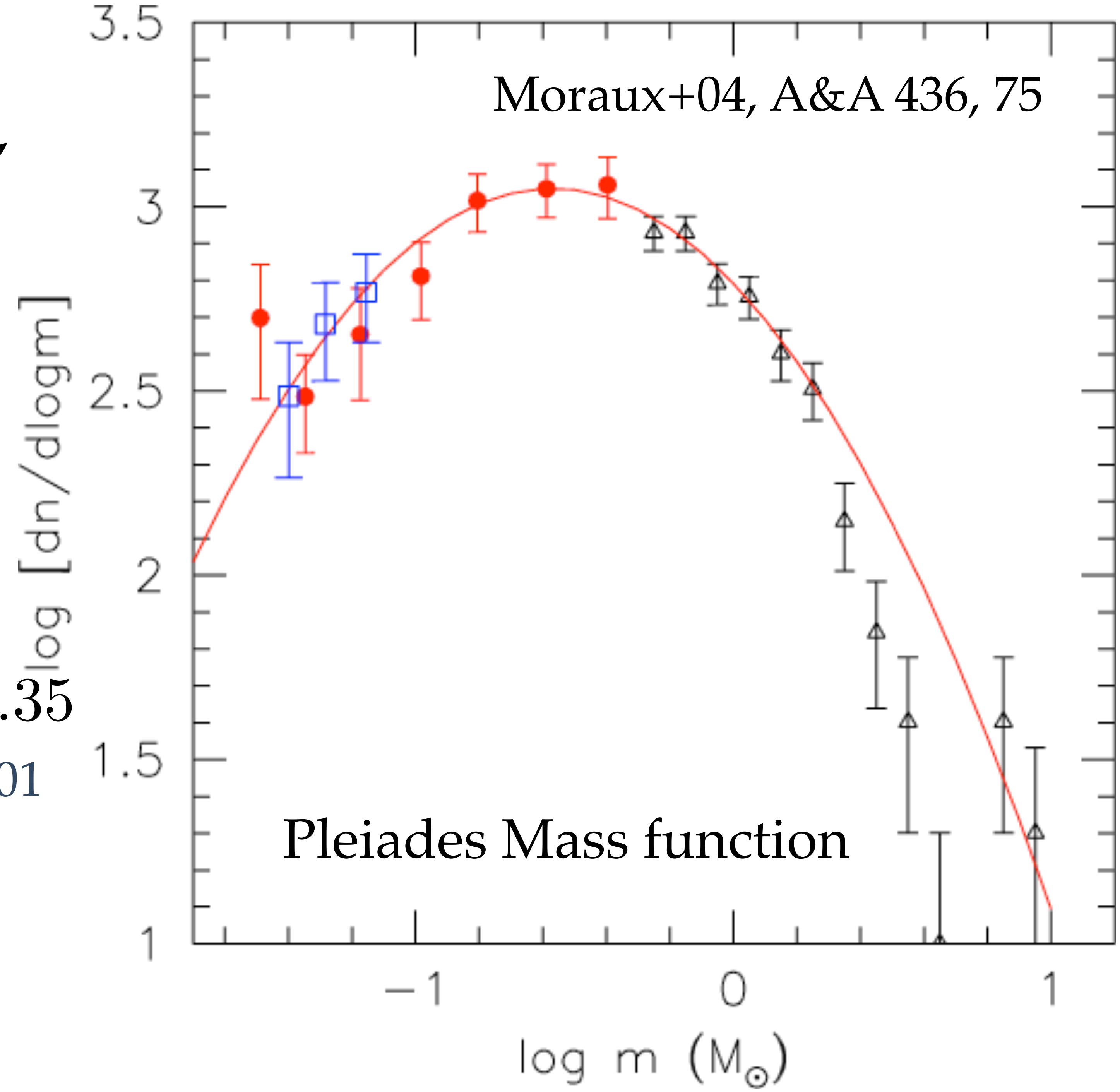
- Stars form in dense **molecular clouds**, M ~ 10^4 - 10^6 $M_\odot$, T ~ 10 K, R ~ 10 - 100 pc, Σ_g ~ 100 $M_\odot$ pc^{-2} (Krumholz+14)
- **Initial Mass Function (IMF)** is empirical relation for mass distribution in clusters, approximated by a broken power law

$$\frac{dN(m)}{d\log m} = Cm^{-\alpha}, \quad \alpha = 1.1 - 1.35$$

M > 0.5 $M_\odot$, Kroupa+01

$N(m)$ … number of stars per logarithmic mass bin

$m = M/M_\odot$ … stellar mass normalised on solar mass

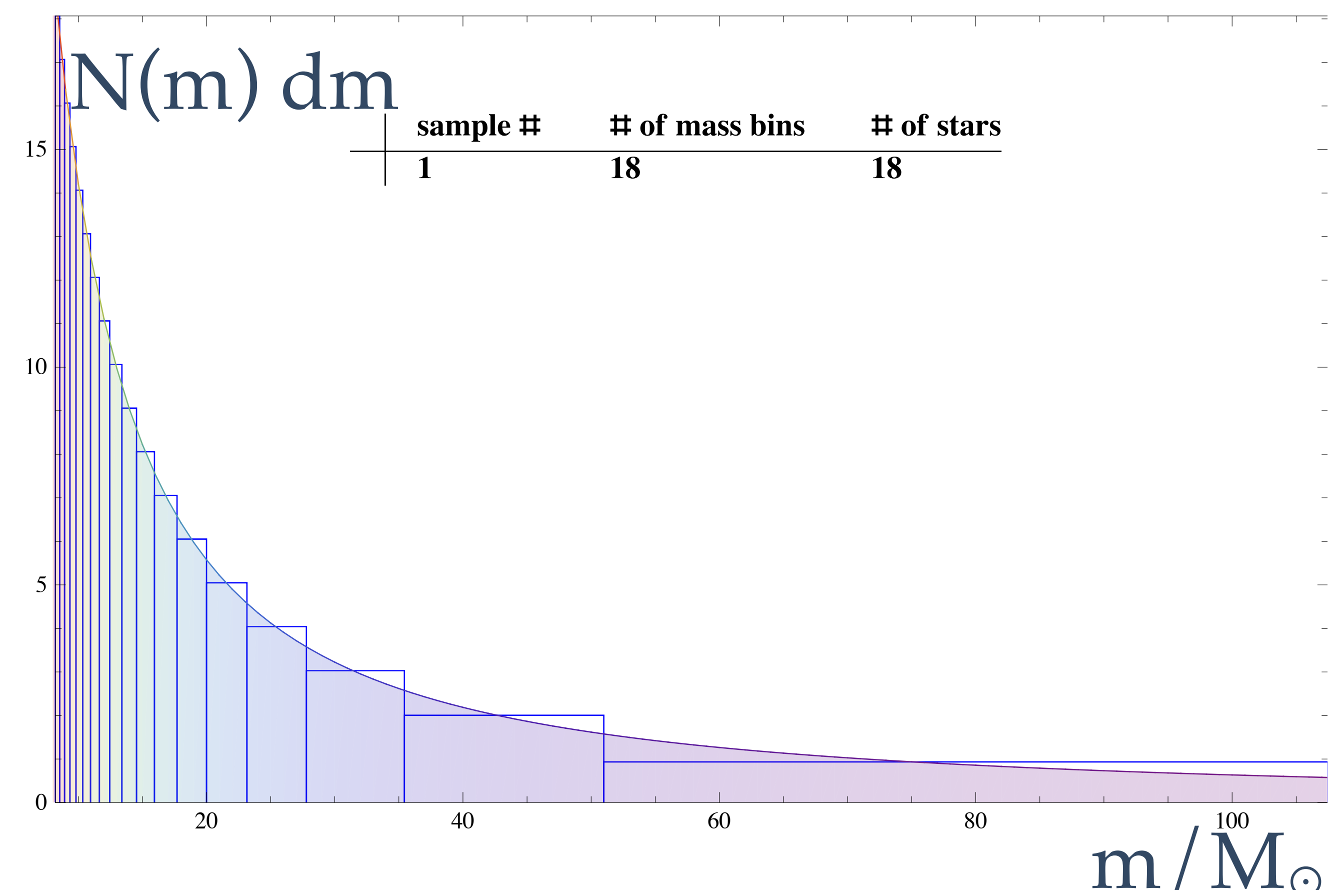


Number & Masses of deceased stars

IMF of moving group
Breitschwerdt+18

- Main-sequence lifetime τ_{ms} of stars depends only on mass (metallicity Z)
  $\tau_{\rm ms} = 1.8 \times 10^8 m^{-\beta}\,{\rm yr}\,, \quad \beta = 0.932$
- SN explosion time $\tau_{ex} = \tau_{ms} - \tau_{cl}$
- Z is the same for all cluster members
- **Method to calculate number of SNe**:

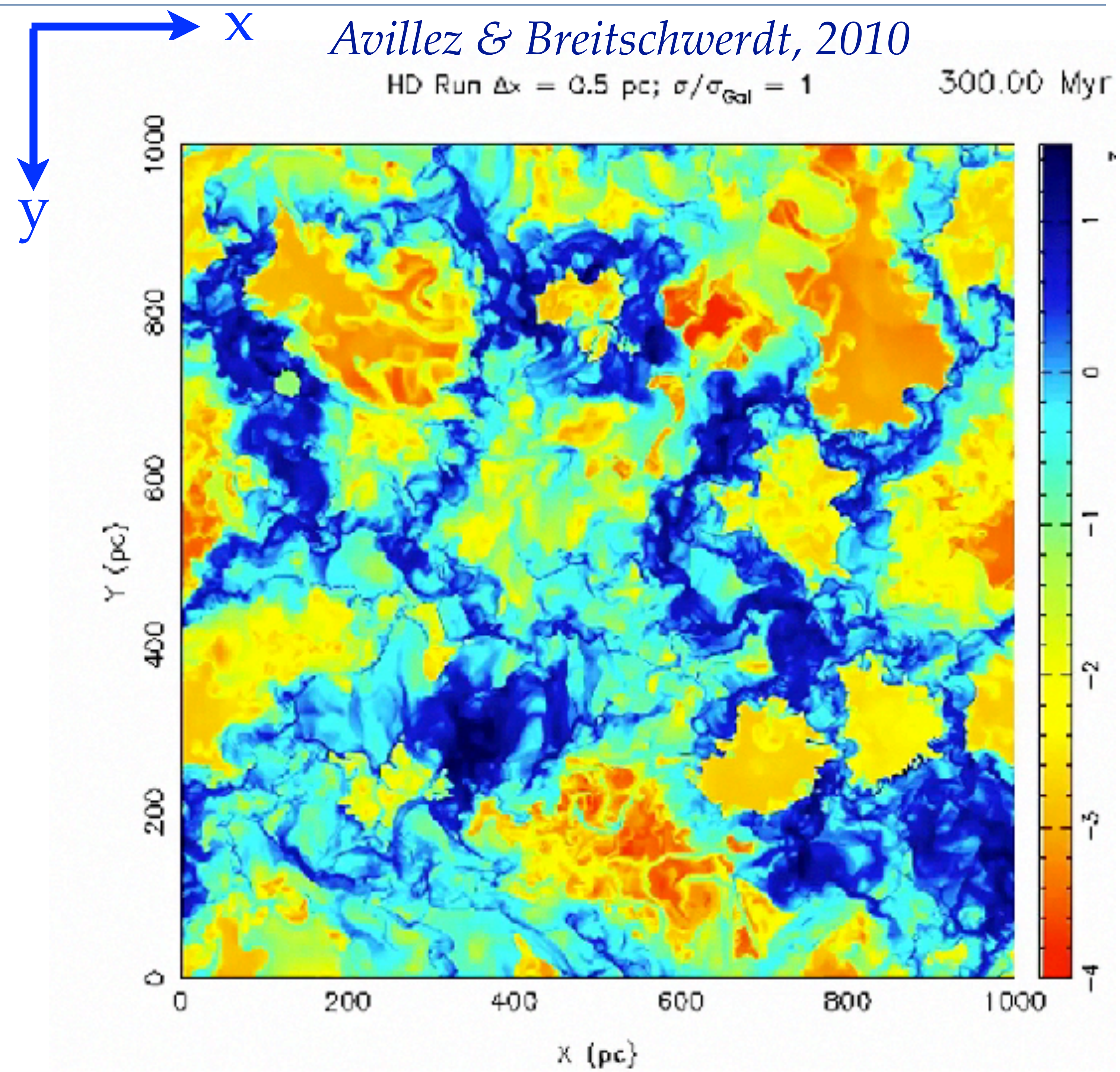
1. calculate constant C of IMF (calibration) by matching it to number of surviving stars
2. variable mass binning ➜ choose bin size such that there is exactly one star per bin (Maiz-Appelaniz & Ubeda (2007))
3. highest mass SN progenitor has N(m) ≤ 1
4. data: 69 stars with 2.6 ≤ m ≤ 8.2
5. α = 1.1 (**Massey+95**), 1.35 (Salpeter)
6. Result: 16 stars exploded, 2 not yet
7. we adopt τ_{cl} = 20 Myr (HRD)
8. apply same procedure to Loop I



ISM and LB simulations III

Gas Density Distribution
Cut through Galactic Midplane

- Density and temperature distribution shows **structures on all scales** (cf. observation of filaments)
- **Shear flow** due to expanding SNRs generates high level of **turbulence ➔ coupling of scales**
- Cloud formation by **shock compressed layers ➔** clouds are **transient** features ➔ generation of new stars
- **Collective** effect of SNe induces **break-out** of ISM disk gas ➔ "**galactic fountain**" (cf. intermediate velocity clouds) ➔ reduce disk pressure
- large amount of gas in **thermally unstable** phases
- **volume filling factor** of HIM ~ 20%
- **no (spatial) pressure equilibrium!**



Avillez & Breitschwerdt, 2010

ISM and LB simulations IV

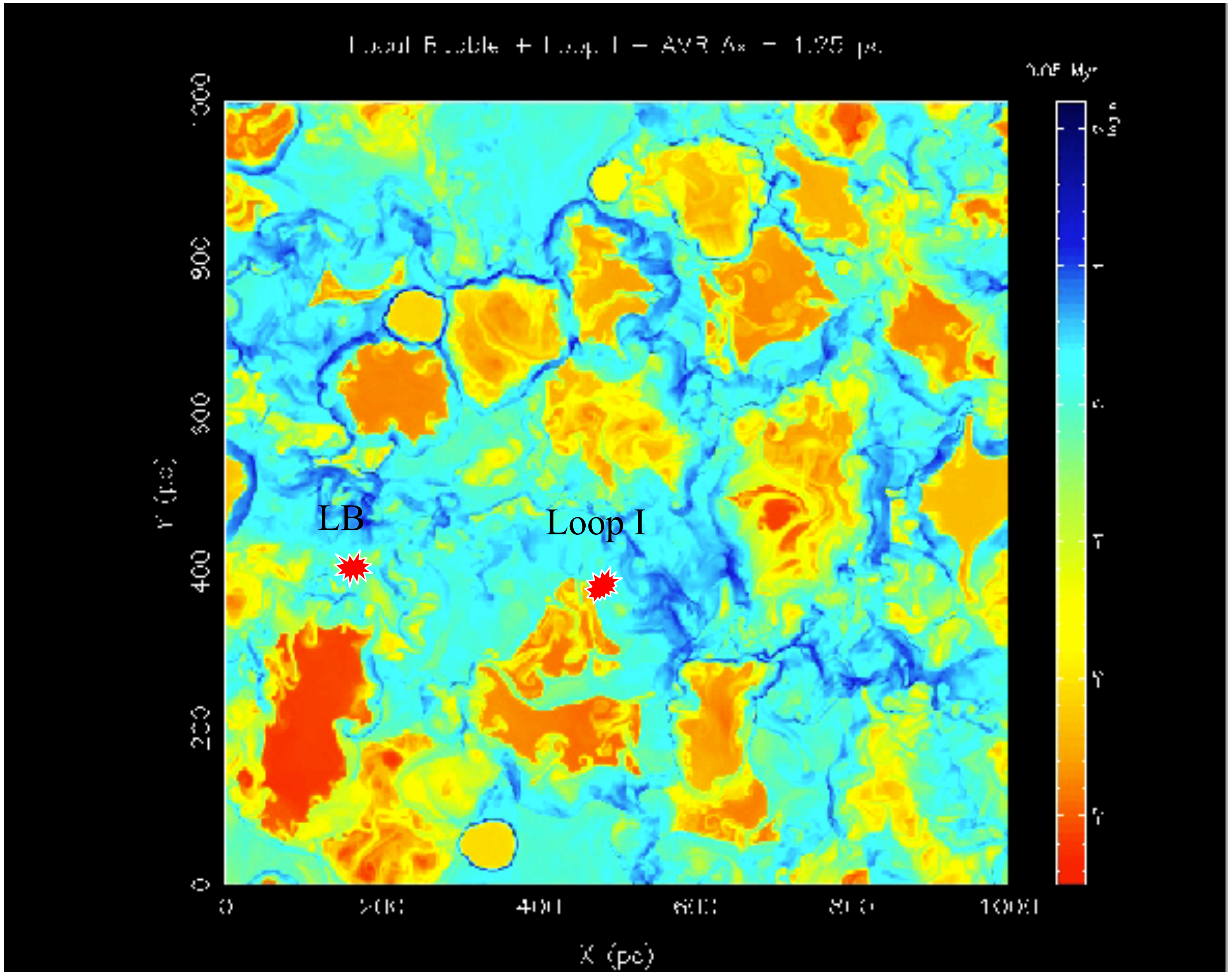
- All information for simulations are now available

1. number of SN progenitors
2. explosion times
3. explosion sites

- but we do not know the **ISM environment**
- Test different scenarios:

(i) **homogeneous** background with constant densities:
$n = 0.1\ cm^{-3}$ (model A),
$n = 0.3\ cm^{-3}$ (model B)

(ii) **inhomogeneous** realistic medium shaped by previous generations of stars (model C)



Simulations by Avillez & Breitschwerdt

ISM and LB simulations IV

PhD Thesis: M. Schulreich, 2015

- Use RAMSES Code: HD/MHD + N-body, Teyssier+02
- Include **self-gravitation** of gas, treated stars as particles, **feedback** from stellar winds and SNe, heliosphere
- ^{60}Fe is marked by "ink" (**passive scalar** field)
- ^{60}Fe incorporated in dust ➜ survival factor f ~ 0.01 (Fry+15), uptake factor: U ~ 0.5 - 1 ➜ fU = 0.006 (Feige+12)

	Homogeneous background models	Inhomogeneous background model
Box size	3 x 3 x 3 kpc^3	3 x 3 x 3 kpc^3
Highest grid resolution	0.7 pc (ℓ_{max} = 12)	2.9 pc (ℓ_{max} = 10)
Boundary conditions (vertical faces / top and bottom)	periodic / periodic	periodic / outflow
Total evolution time	12.6 Myr	192.6 Myr (180 + 12.6 Myr)
Initial gas distribution	homogeneous	analytical fit to observational data of the Galaxy (Ferrière 1998)
External gravitational field	no	yes
Self-gravity	yes	no

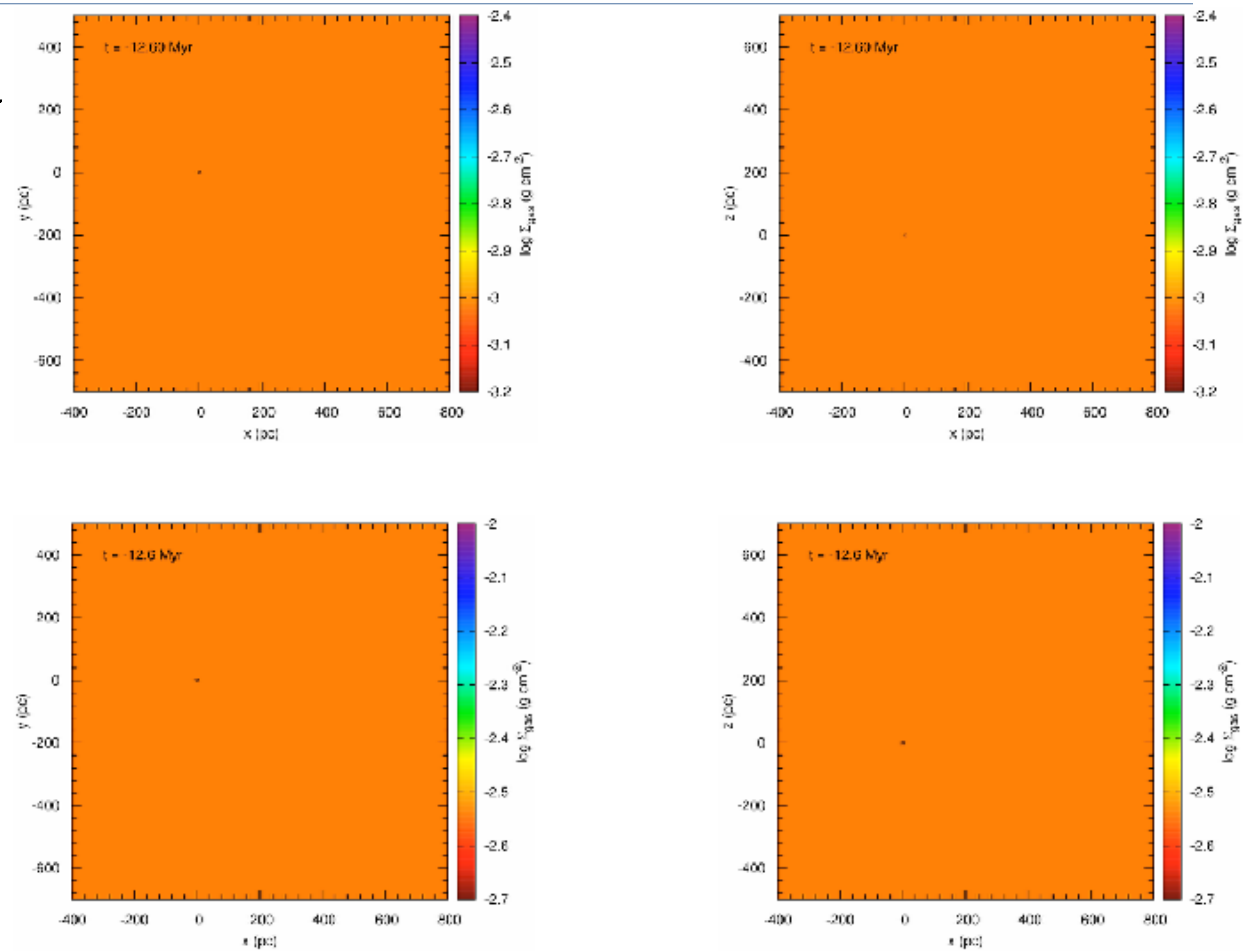
ISM and LB simulations V

PhD Thesis: M. Schulreich, 2015

- Gas column density Σ_g (integrated over 3rd co-ordinate); t_{ev} =12.6 Myr

- **Model A** (~ WIM)
- n = 0.1 cm-3
- $T = 10^4$ K
- Z/Z⊙ = 1
- $\Delta x = 0.7$ pc

- **Model B** (~ WNM)
- $n = 0.3$ cm^{-3}
- T = 6800 K
- Z/Z⊙ = 1
- $\Delta x = 0.7$ pc

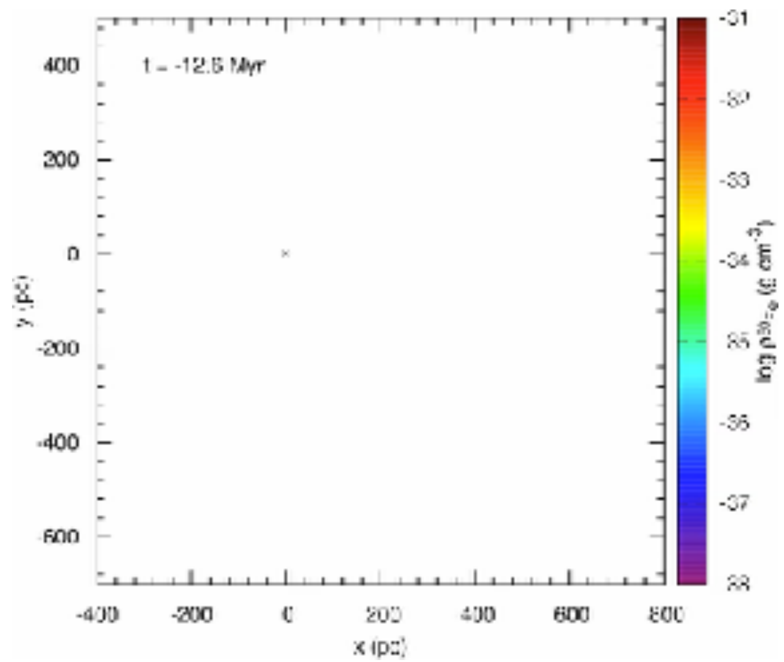


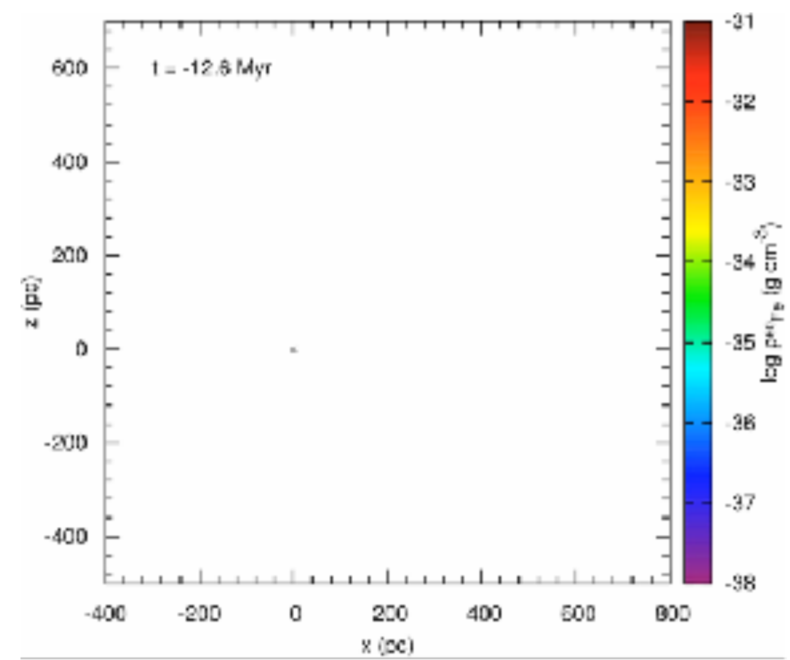
ISM and LB simulations VI

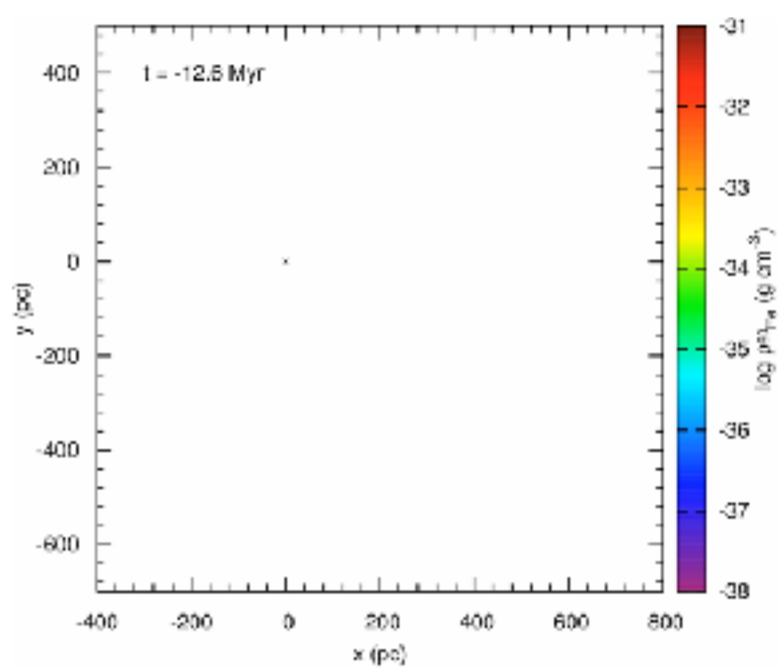
- ^{60}Fe density ϱ_{Fe}
- horizontal cuts at z=0 and y=0, respectively; t_{ev} =12.6 Myr

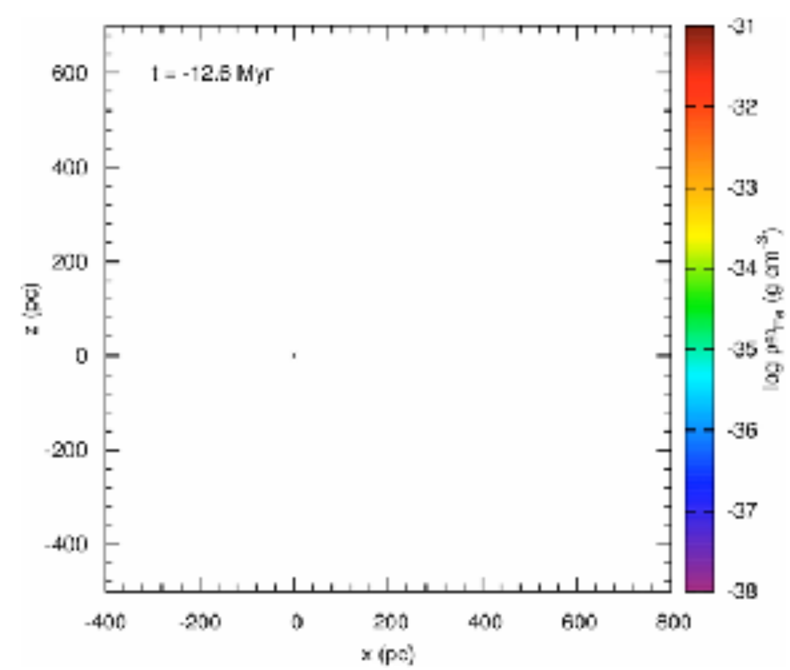
- **Model A** (~ WIM)
- n = 0.1 cm-3
- T = 10^4 K
- Z/Z⊙ = 1
- Δx = 0.7 pc

- **Model B** (~ WNM)
- n = 0.3 cm^{-3}
- T = 6800 K
- Z/Z⊙ = 1



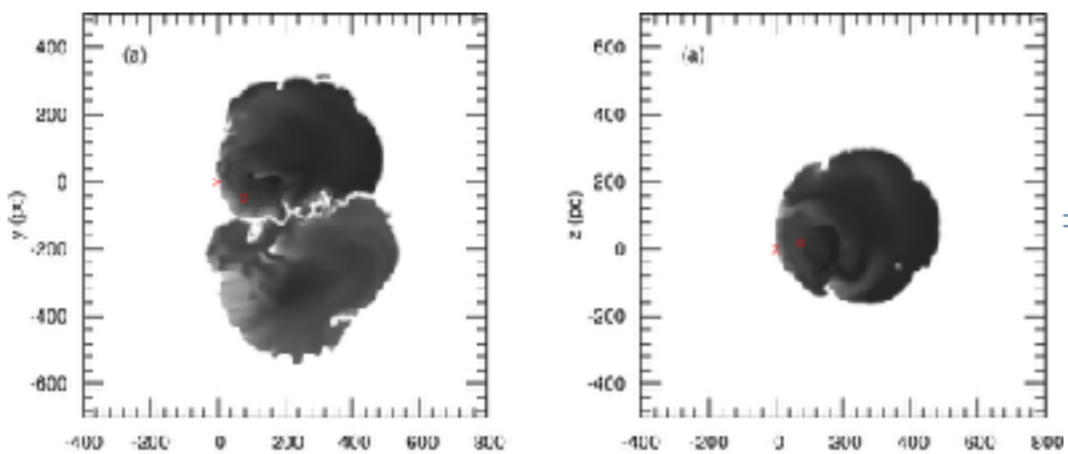






ISM and LB simulations VII

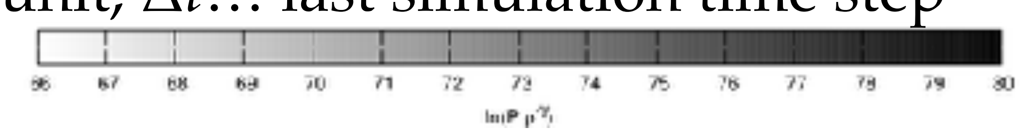
Model B

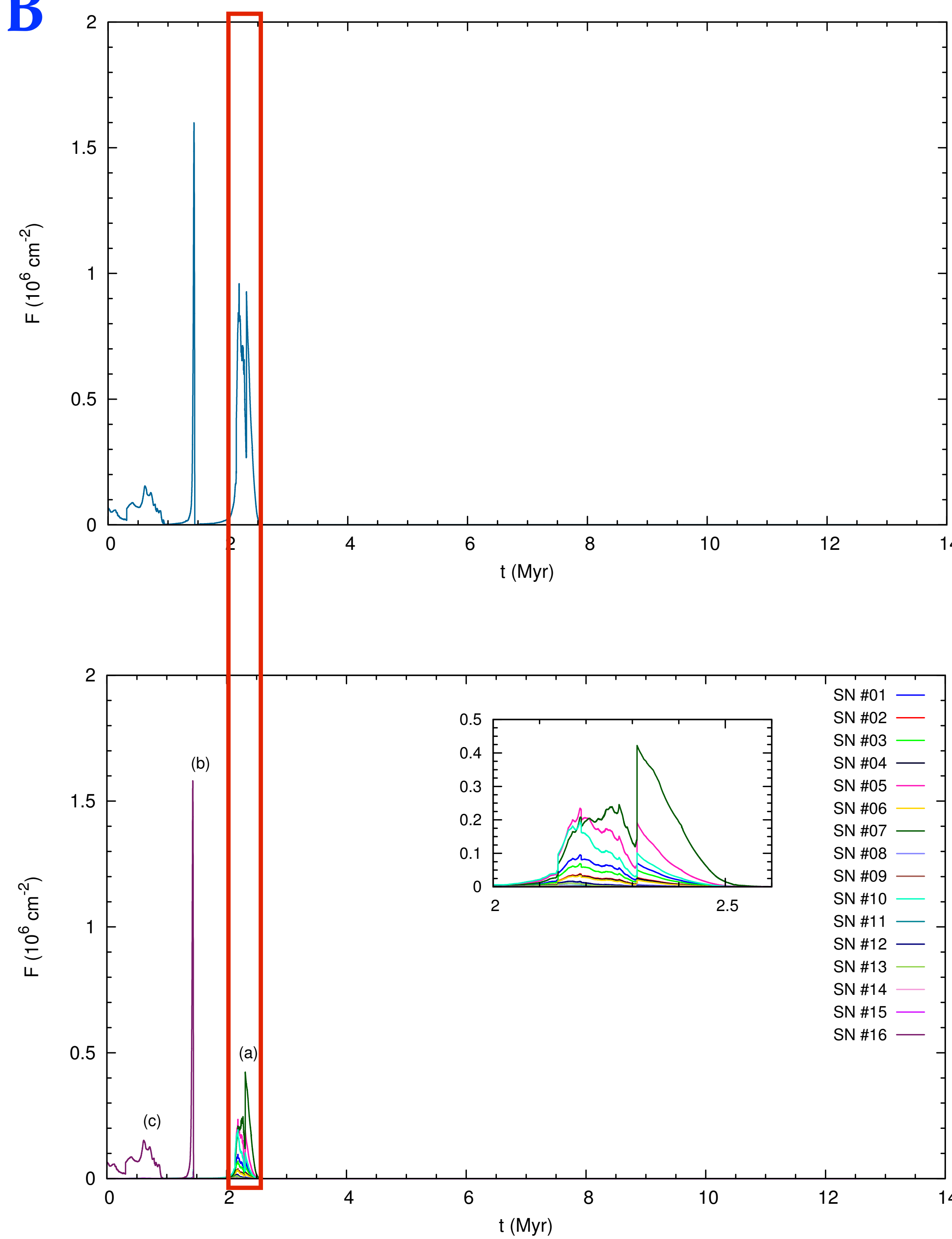


- **Entropy** is measure for temperature and **tracer** for **shocks** to trap shells
- **Entropy** maps and ^{60}Fe **fluence** variations (radioactive decay incl.)
- Local interstellar fluence given by

$$F = \frac{(\rho|\mathbf{u}|Z)_{\mathrm{VA}}}{A m_{\mathrm{u}}} \Delta t$$

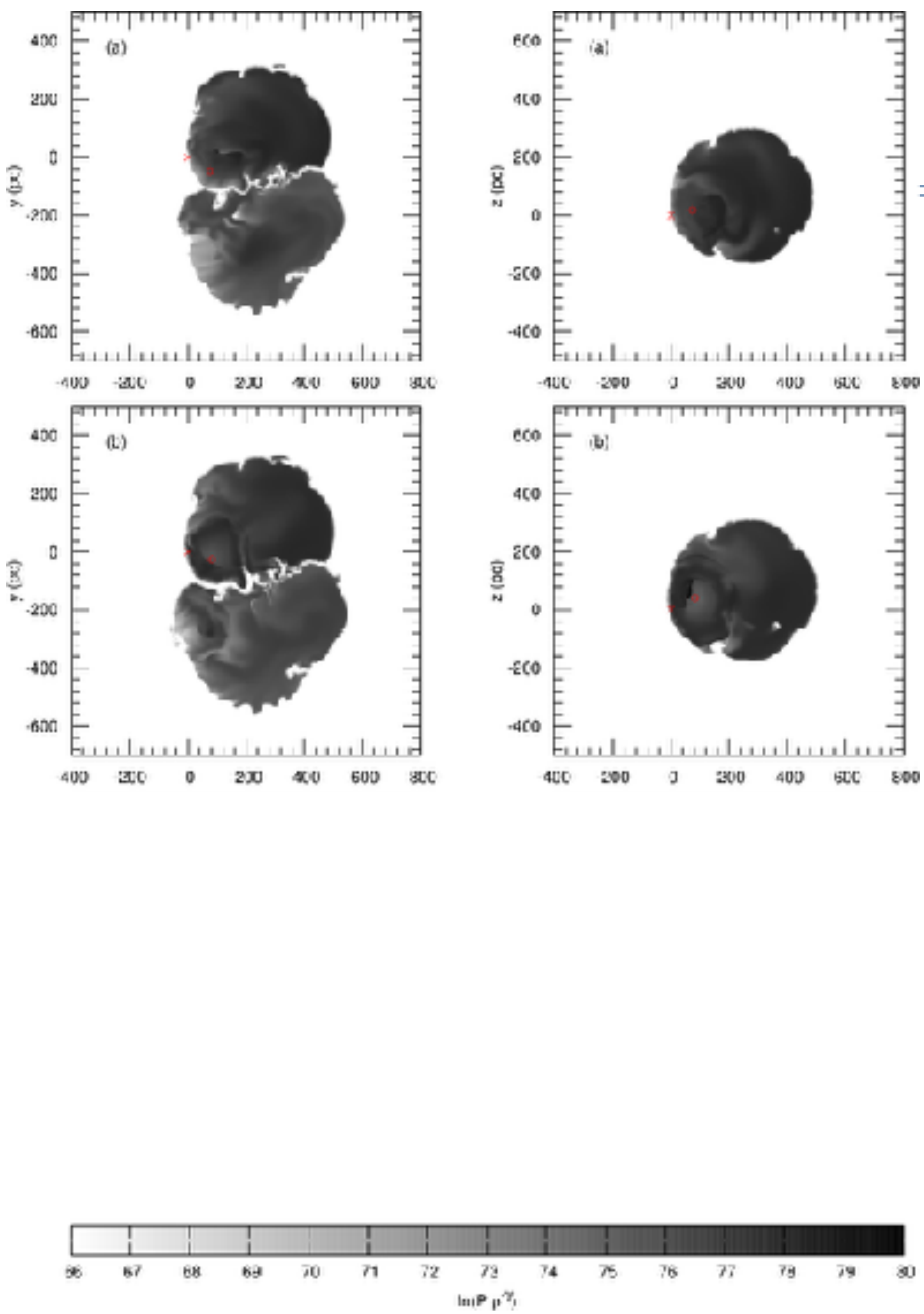
- $(\rho\,|\,\mathbf{u}\,|\,Z)_{\mathrm{VA}}$ … volume-averaged ^{60}Fe mass flux, A … ^{60}Fe mass number, m_{u} … atomic mass unit, Δt… last simulation time step

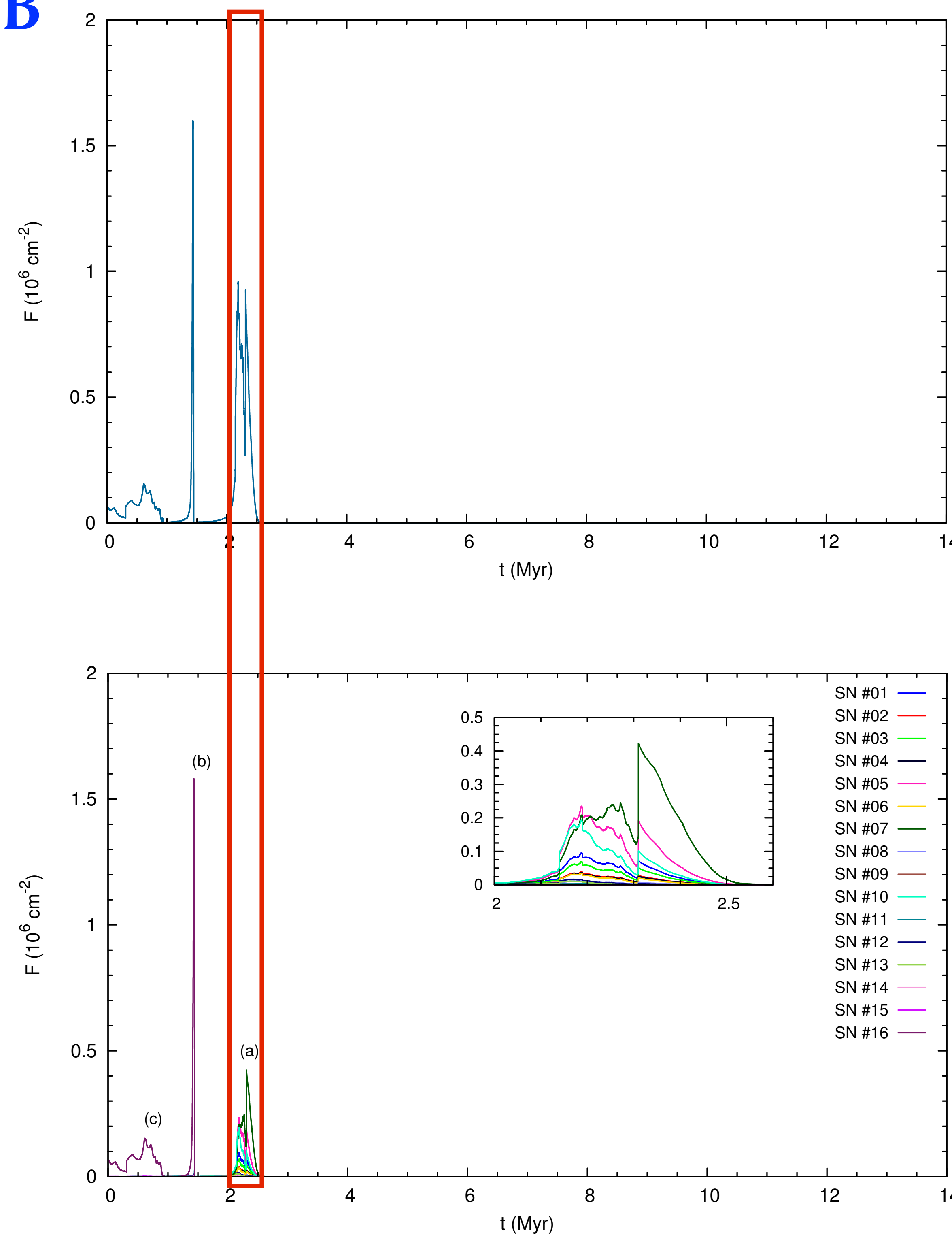




ISM and LB simulations VIII

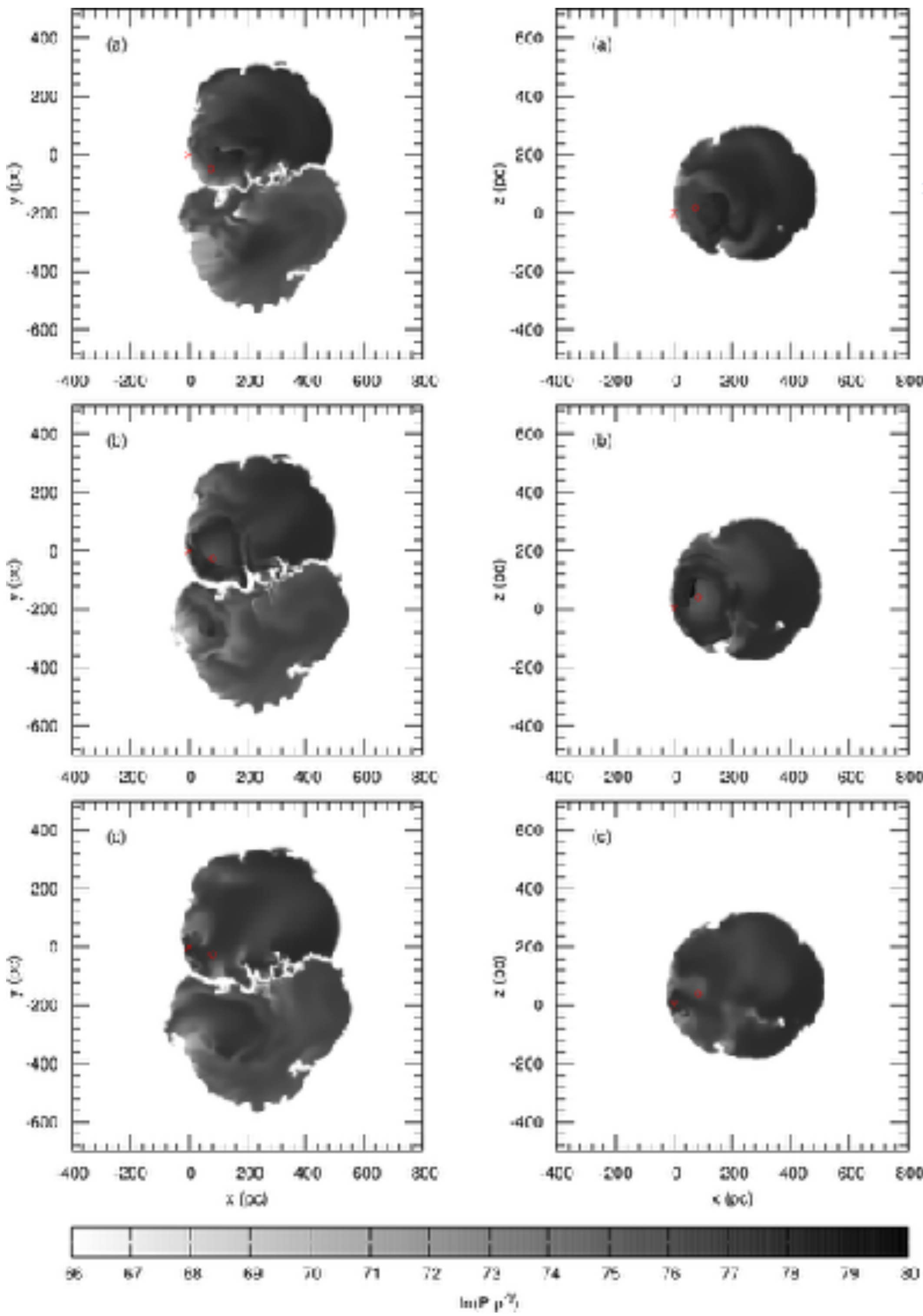
Model B

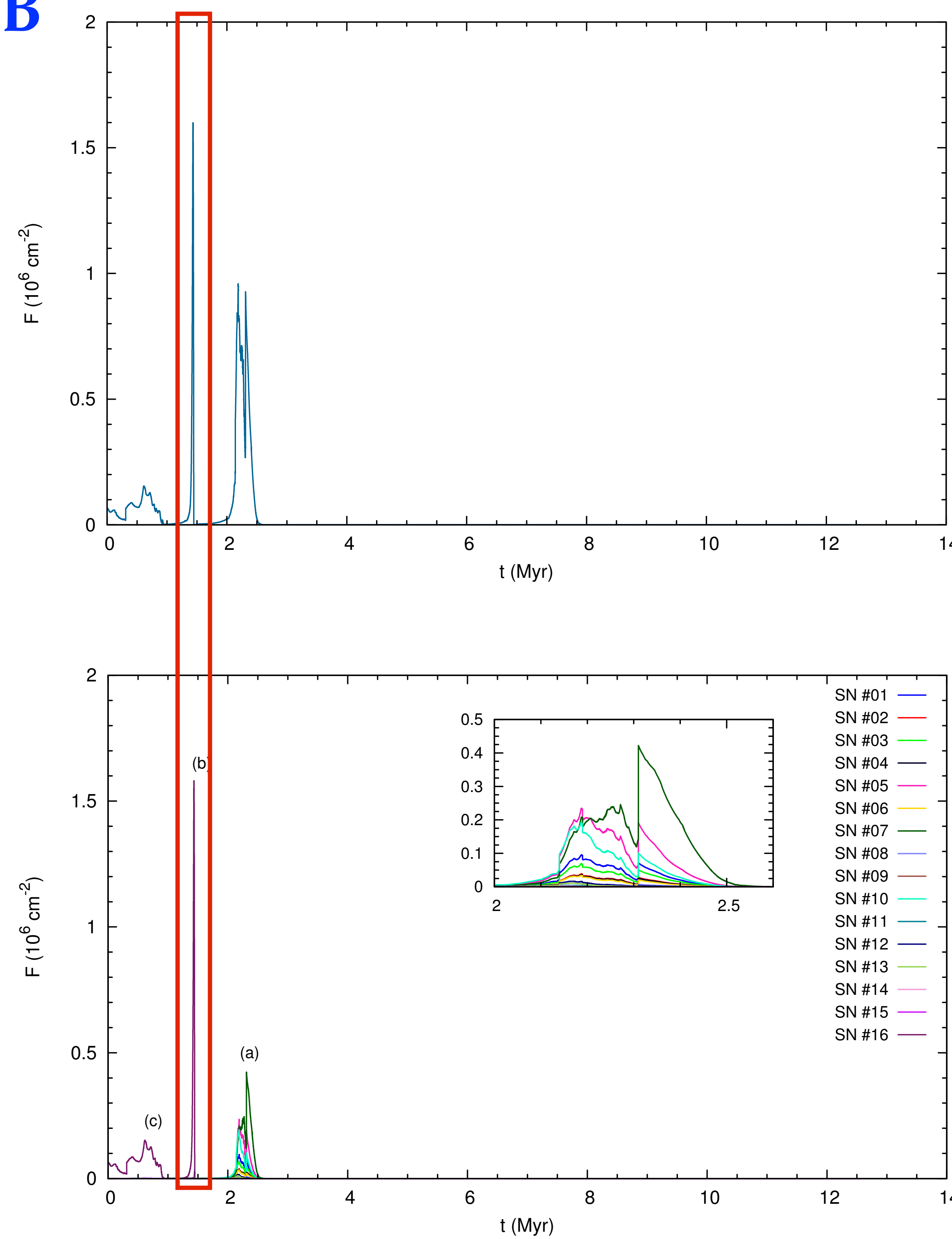




ISM and LB simulations IX

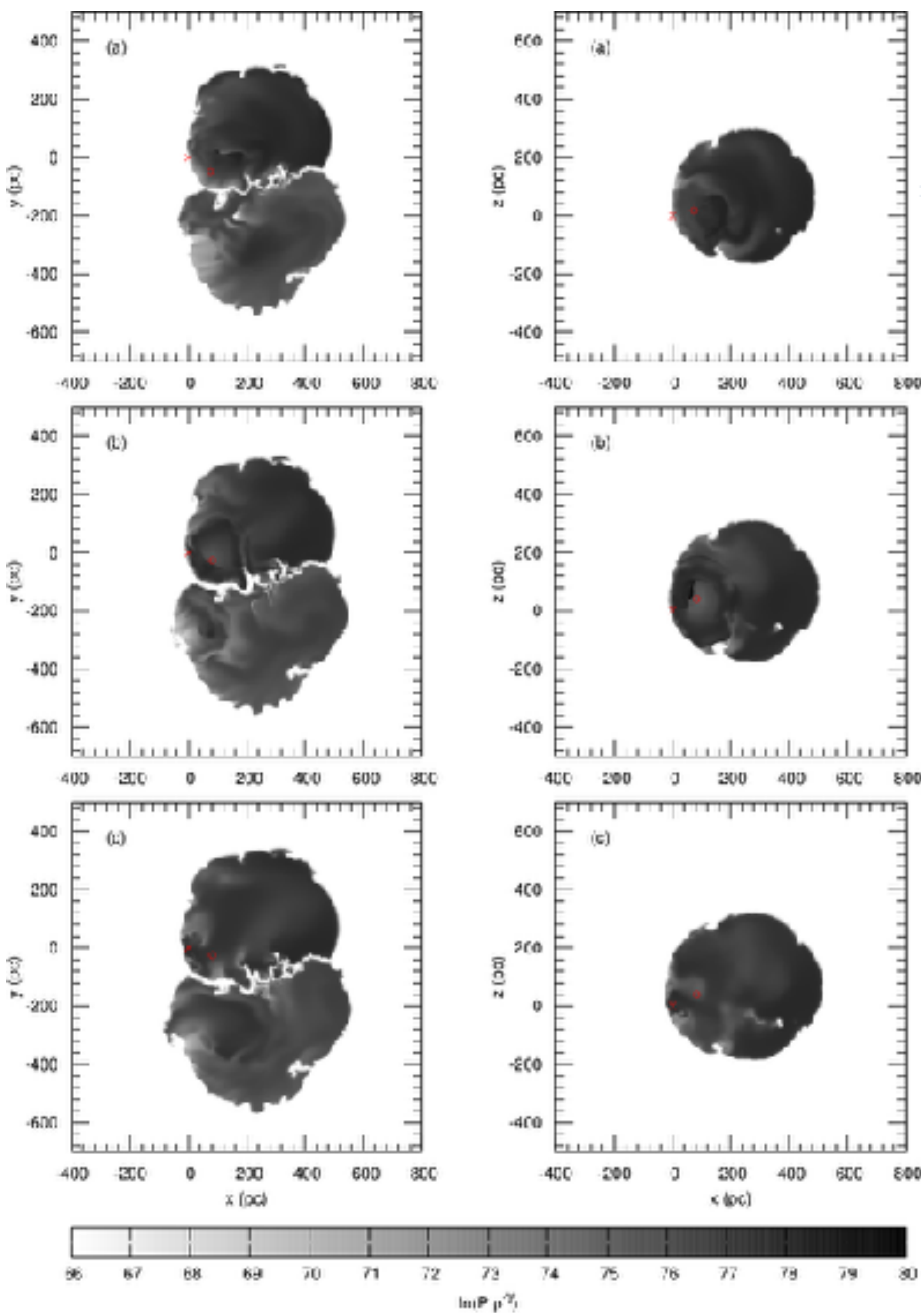
Model B

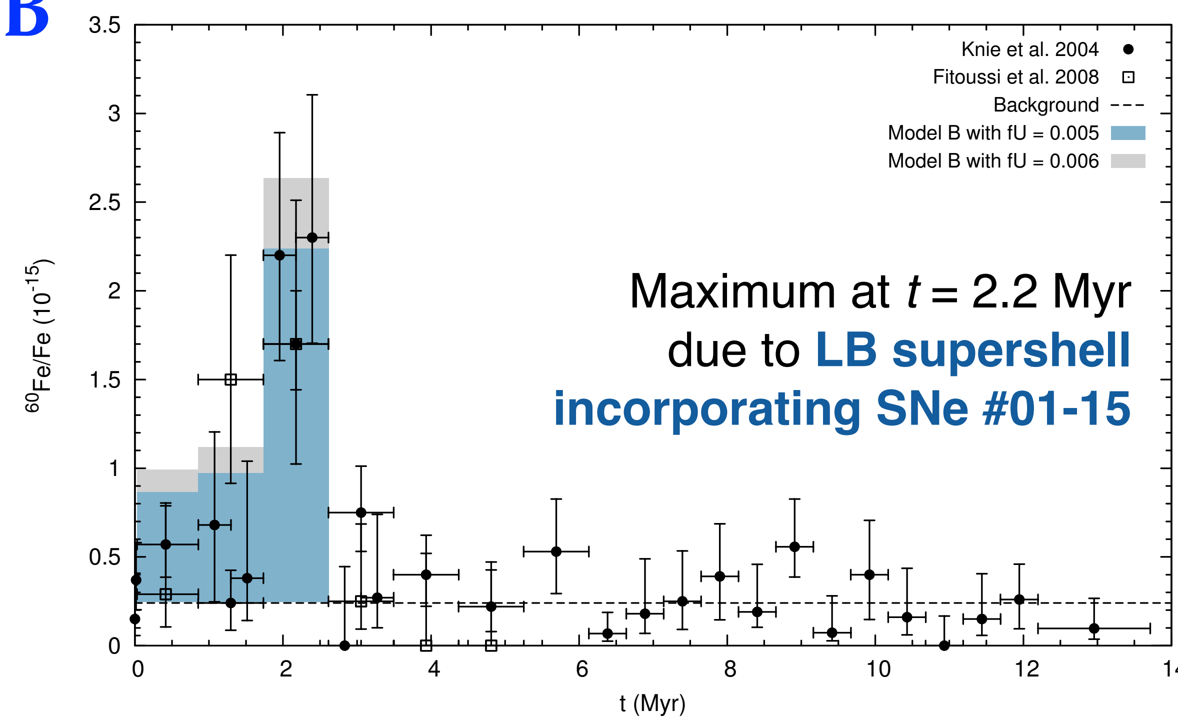


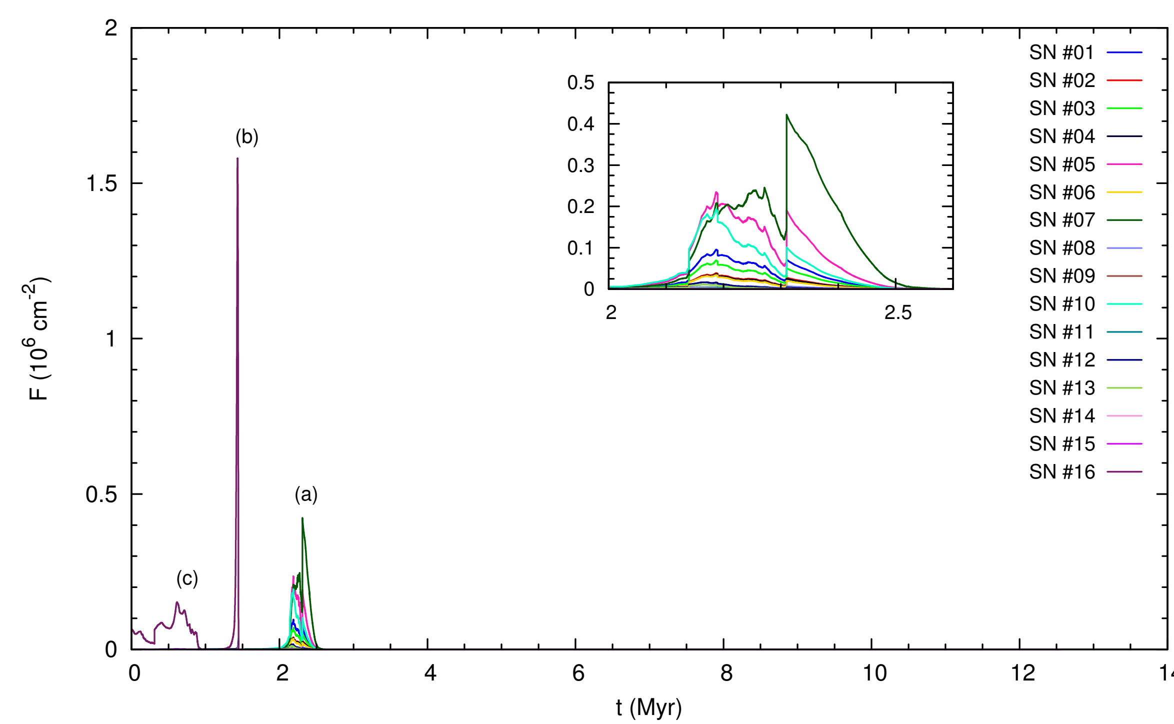


ISM and LB simulations X

Model B

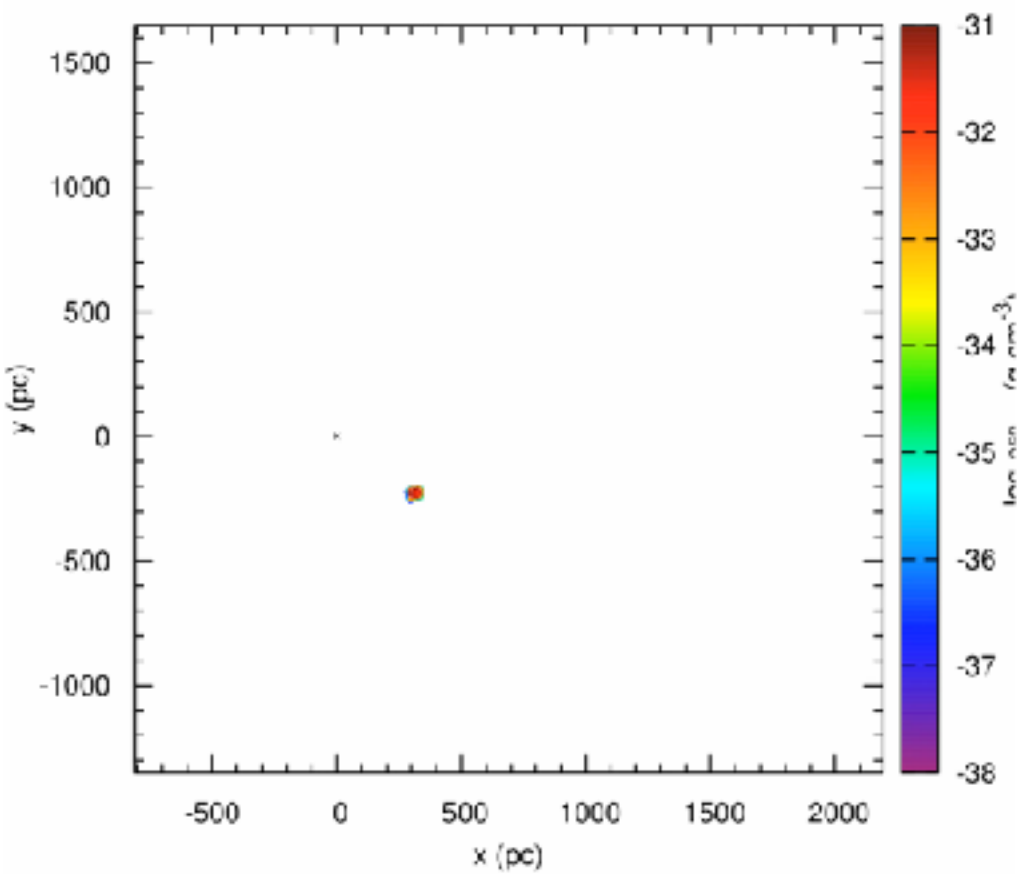


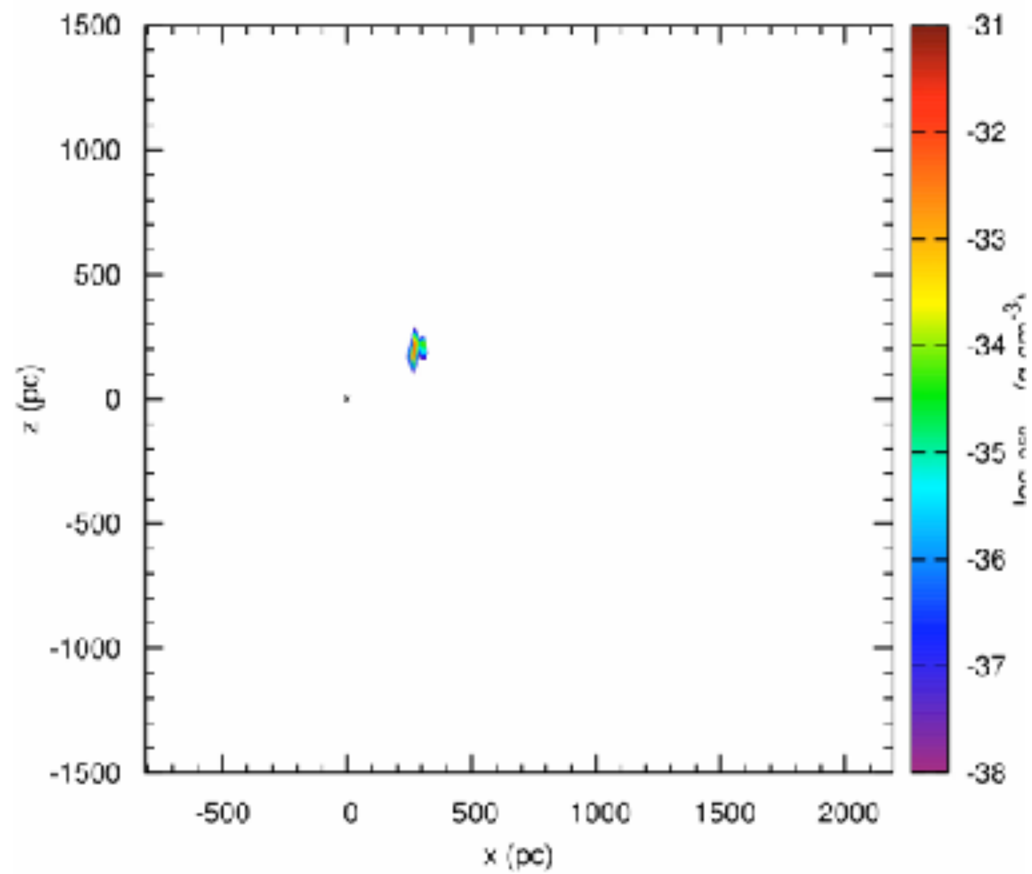




ISM and LB simulations XI

^{60}Fe (horizontal cuts in z=0 and y=0 planes)



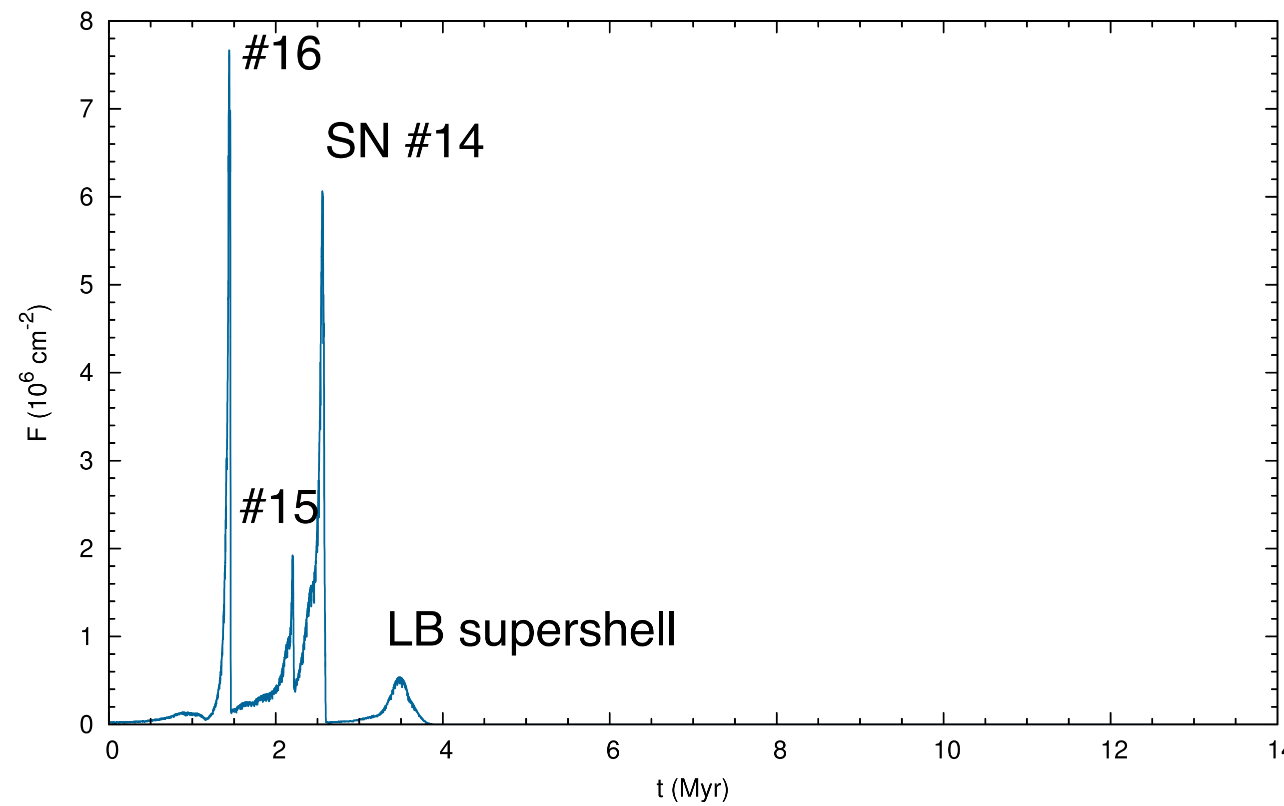


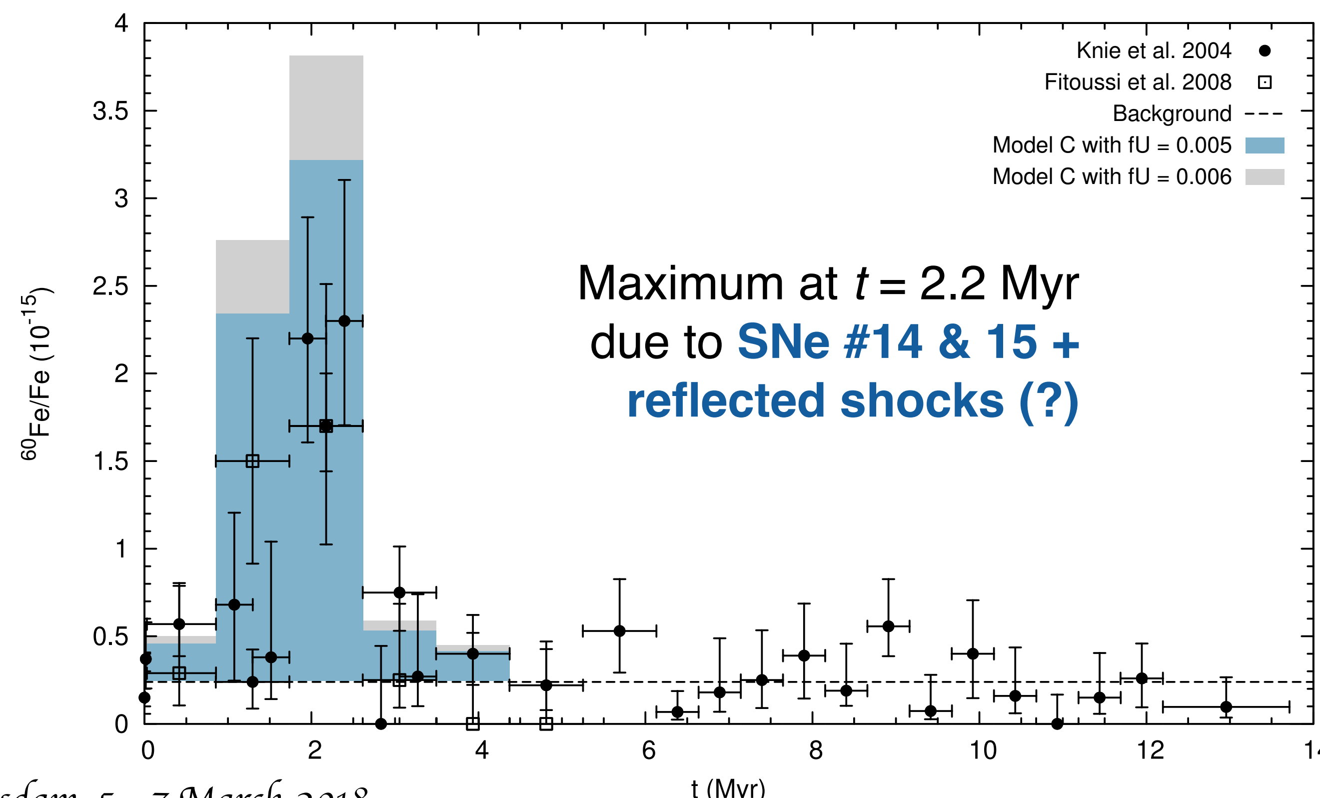
- Model C with **inhomogeneous** background evolved for 150 Myr with SN explosions at Galactic rate
- ^{60}Fe density ρ_{Fe} ; horizontal cuts at z=0 and y=0, respectively; t_{ev} =12.6 Myr

ISM and LB simulations XII

Model C

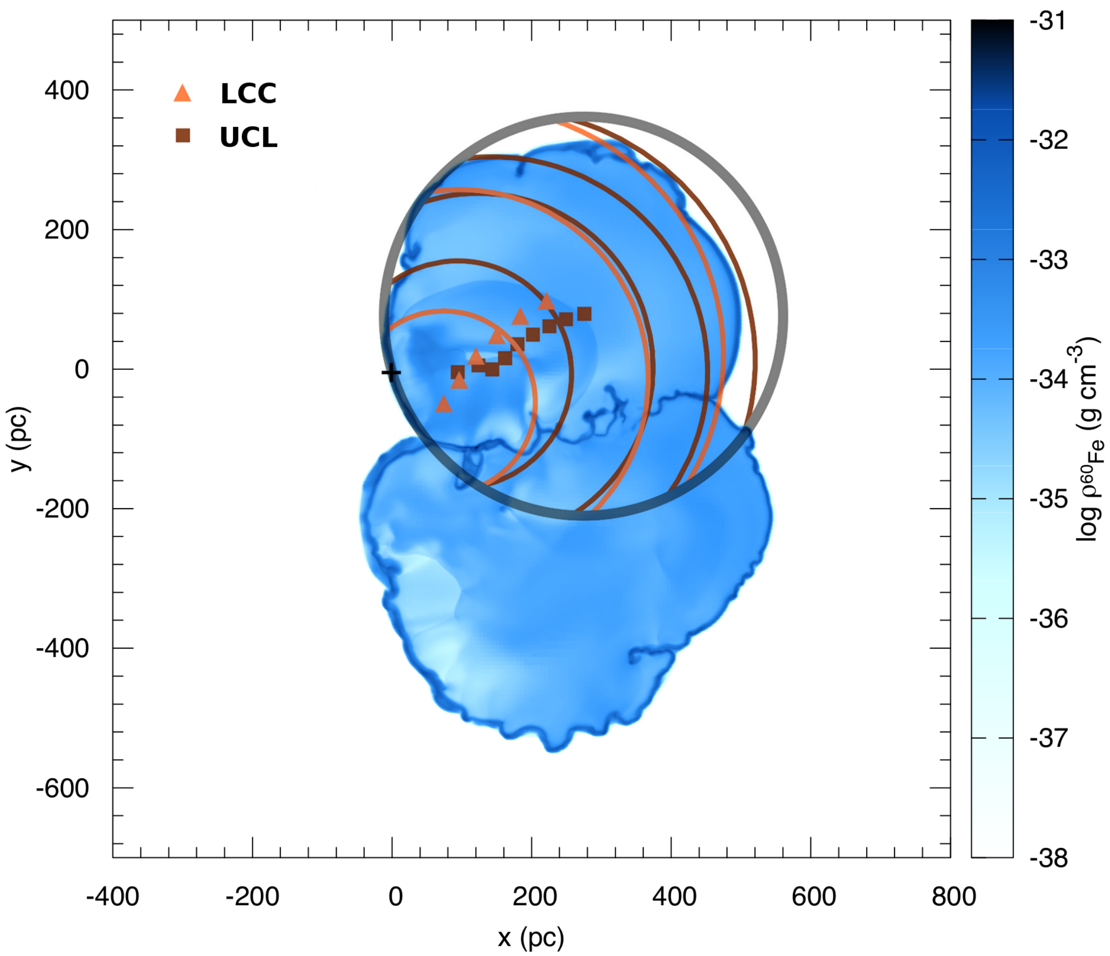
- Model C is a hybrid between A and B
- average number density n = 0.2 cm^{-3}
- Fewer pulses (shells) than A but more than in B
- excellent fit to data (f U = 0.005)

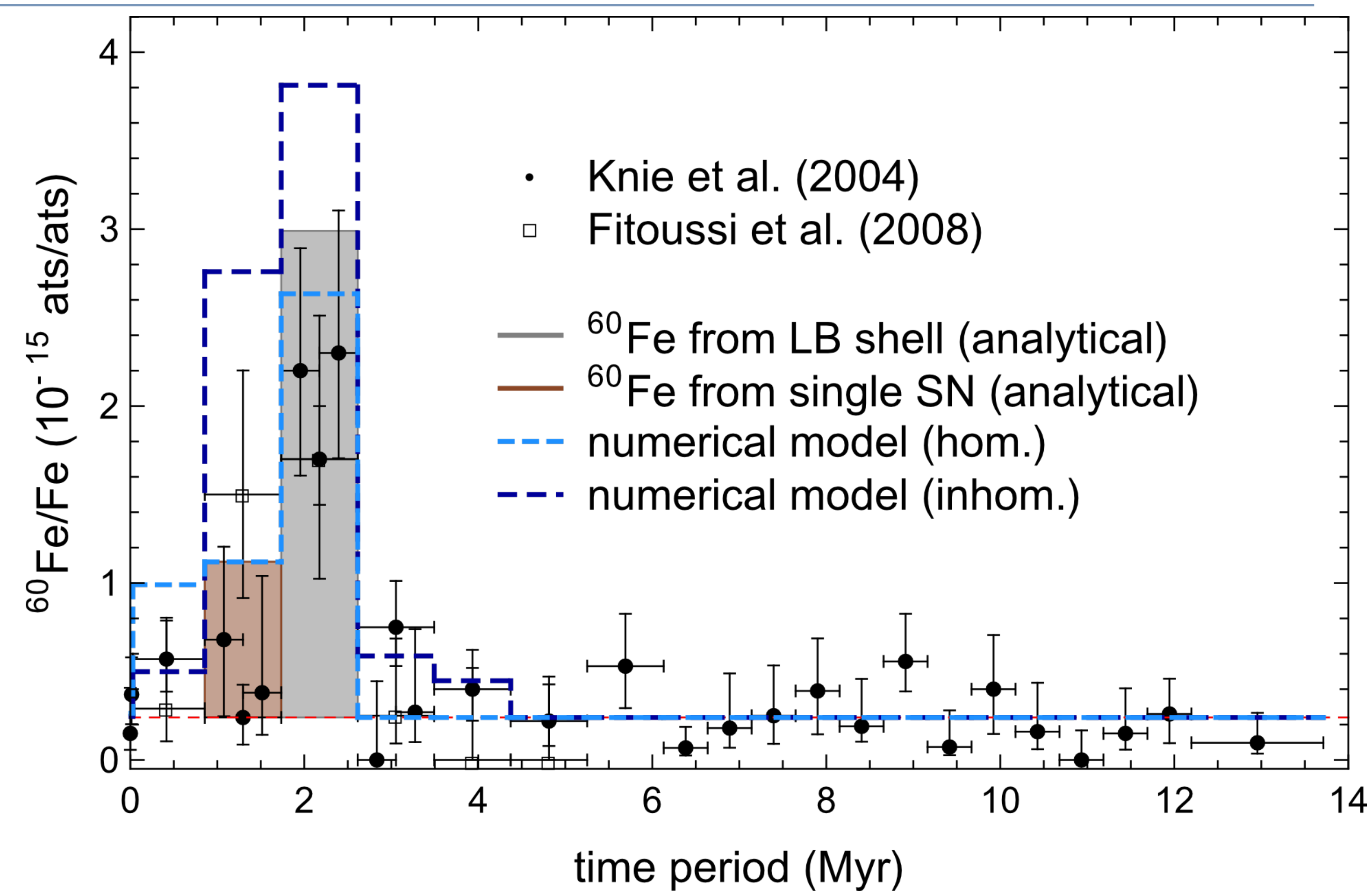




Analytical vs. Numerical Model

MSc Thesis: J. Feige, 2010





- Analytical Model: SN-Remnant expansion into previous remnant (Kahn 98)

$$R_{sh} = \left[\frac{(n+5)(2n+7)E_{SN}}{6\pi\Omega}\right]^{1/(n+5)} t^{2/(n+5)}$$

$$\rho = \Omega r^n, \quad n = \frac{9}{2}$$

$$R_{LB} = 132\left[\frac{N_* E_{SN}}{n_0}\right]^{1/5} t_7^{3/5}$$

- good agreement between analytical and numerical calculations and data!

SNe generating LB and ^{60}Fe

t_{SN}	m ($M_\odot$)	M_{ej} (10^{-5} $M_\odot$)	x (pc)	y (pc)	z (pc)	D (pc)	l (°)	b (°)	α	δ	sc
-12.6[2]	19.86	6.3	277	75	89	300	15.15	17.23	17^h17^m	$-7°09^m$	Oph
-12.0[3]	18.61	5.5	223	99	71	254	23.94	16.22	17^h37^m	$-0°21^m$	Oph
-11.3[2]	17.34	5.0	251	67	87	274	14.95	18.52	17^h12^m	$-6°39^m$	Oph
-10.0[2]	15.41	4.2	227	57	83	248	14.10	19.53	17^h07^m	$-6°48^m$	Oph
-10.0[3]	15.36	4.1	185	77	67	211	22.60	18.49	17^h27^m	$-0°23^m$	Oph
-8.7[2]	13.89	3.6	203	45	79	222	12.50	20.80	17^h00^m	$-7°23^m$	Oph
-8.0[3]	13.12	3.4	151	49	57	169	17.98	19.75	17^h14^m	$-3°34^m$	Oph
-7.5[2]	12.65	3.3	181	31	75	198	9.72	22.22	16^h49^m	$-8°46^m$	Oph
-6.3[2]	11.62	3.0	163	11	73	179	3.86	24.10	16^h30^m	$-12°03^m$	Oph
-6.1[3]	11.48	2.9	121	19	47	131	8.92	20.99	16^h52^m	$-10°04^m$	Oph
-5.0[2]	10.76	2.7	145	-5	69	161	-1.97	25.43	16^h12^m	$-15°19^m$	Sco
-4.2[3]	10.21	2.6	97	-15	33	104	-8.79	18.58	16^h16^m	$-24°35^m$	Sco
-3.8[2]	10.02	2.6	125	1	51	135	0.46	22.19	16^h28^m	$-15°40^m$	Oph
-2.6[2]	9.37	2.4	95	-9	47	106	-5.41	26.22	16^h01^m	$-17°05^m$	Lib
-2.3[3]	9.21	2.4	75	-49	17	91	-33.16	10.74	15^h10^m	$-45°35^m$	Lup
-1.5[2]	8.81	2.3	83	-25	41	96	-16.76	25.31	15^h32^m	$-24°44^m$	Lib

Effects of Near-Earth SNe I - some speculations -

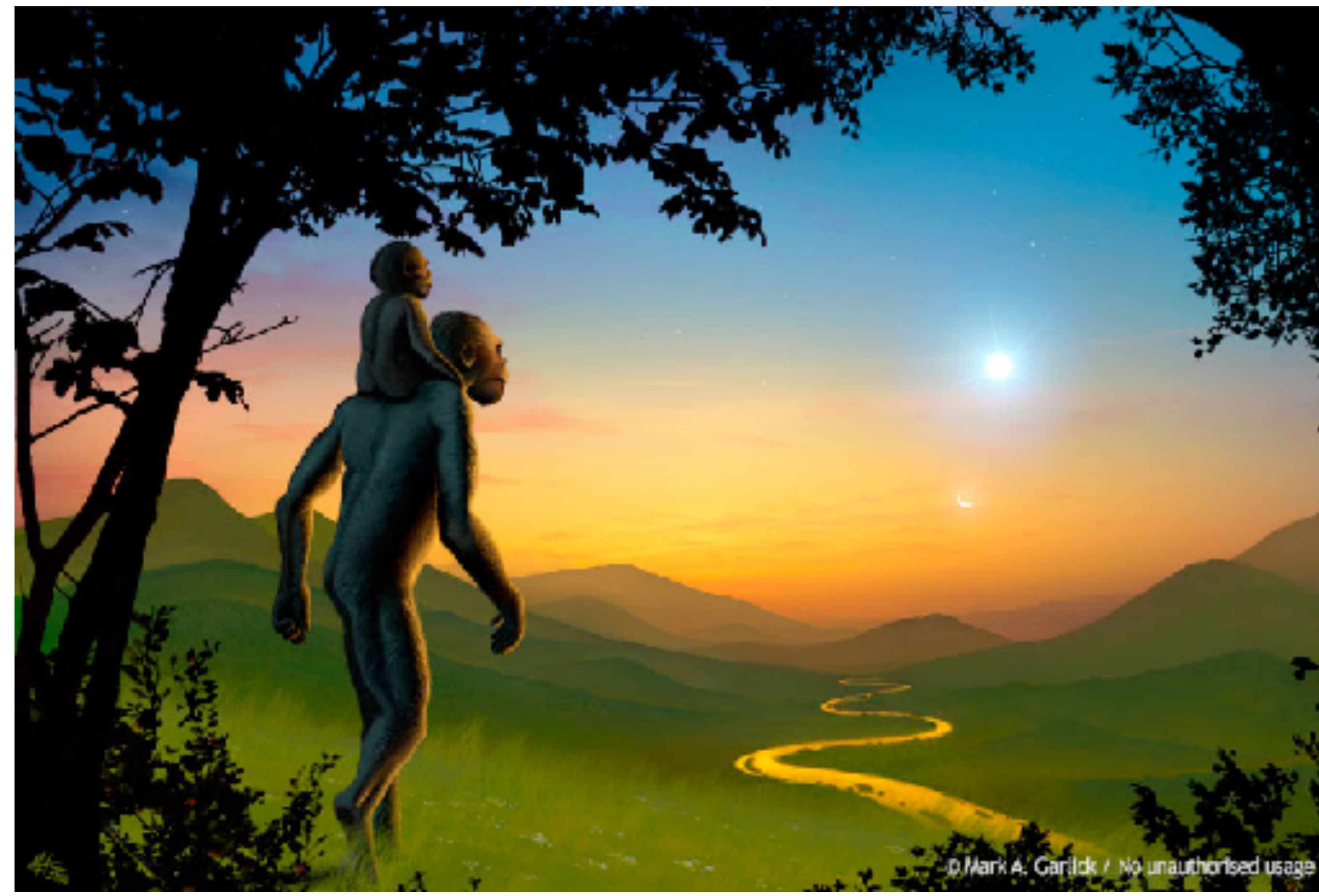
- Australopithecus should have seen SN 2.2 Myr ago during daylight
- SNe beyond “kill radius” (≲ 10 pc)

➜ would lead to ionisation of atmosphere

➜ NO_x formation ➜ ozone layer destruction ➜ increased solar UV radiation ➜ damage of DNA / cells

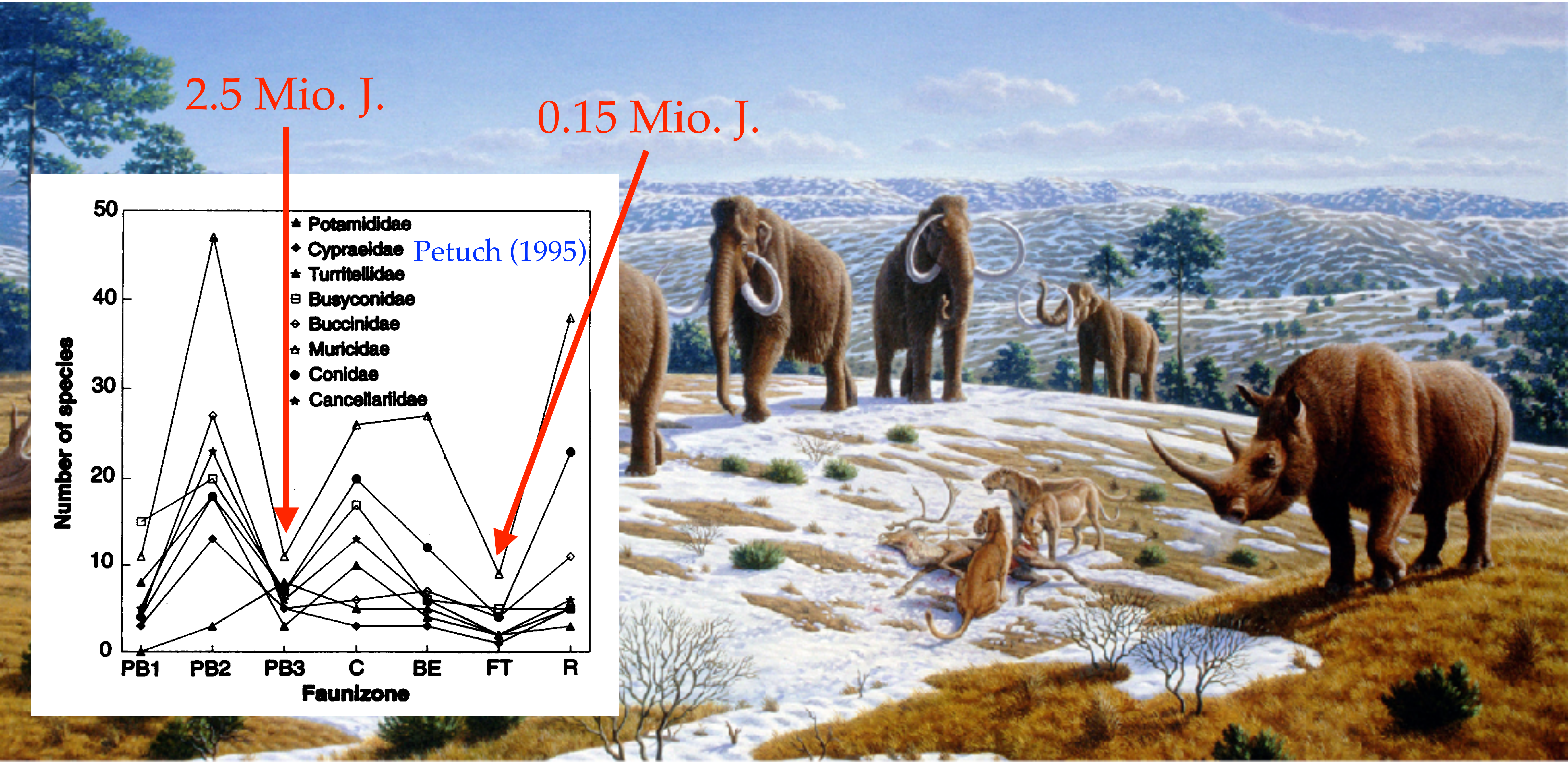
- X- and γ-ray flux too low for mass extinction, but long-term mutations?
- Cosmic ray flux significantly higher

➜ increased nucleation / cloud coverage ➜ climatic changes ➜ global cooling?



- mass extinction near pliocene-pleistocene transition 2.5 Myr ago
- Reason: abrupt cooling ➜ reduction of species, some in warmer regions survived

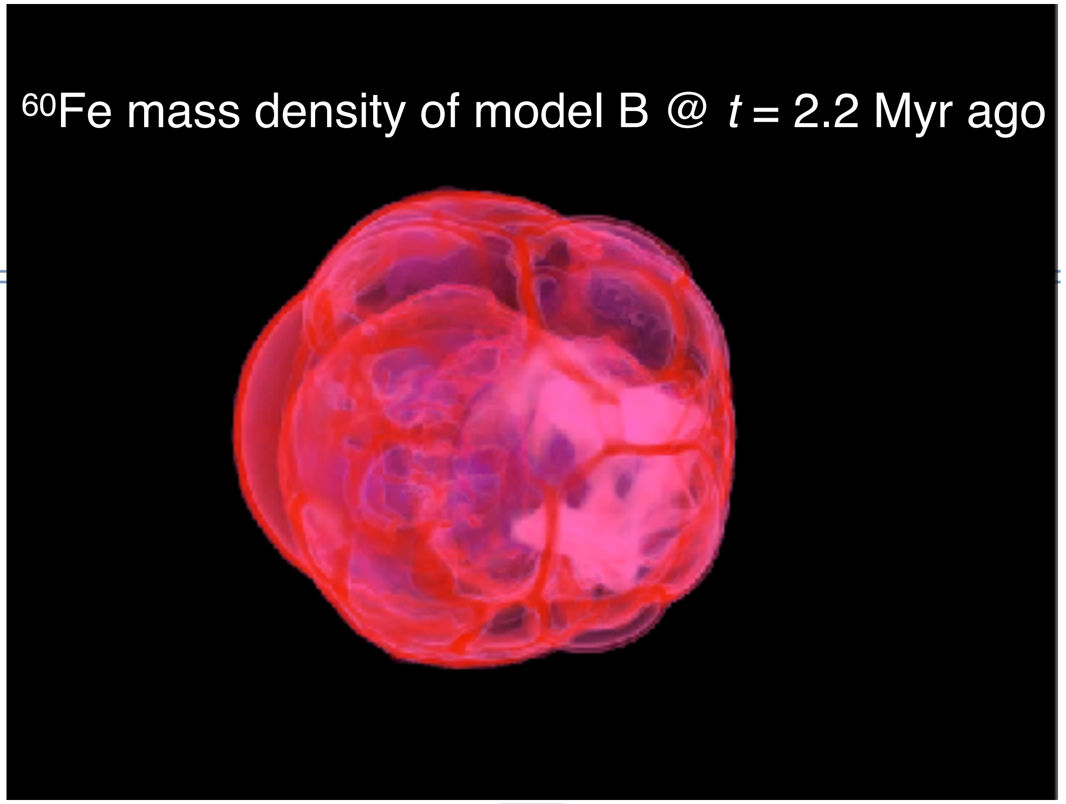
Effects of Near-EarthSNe II

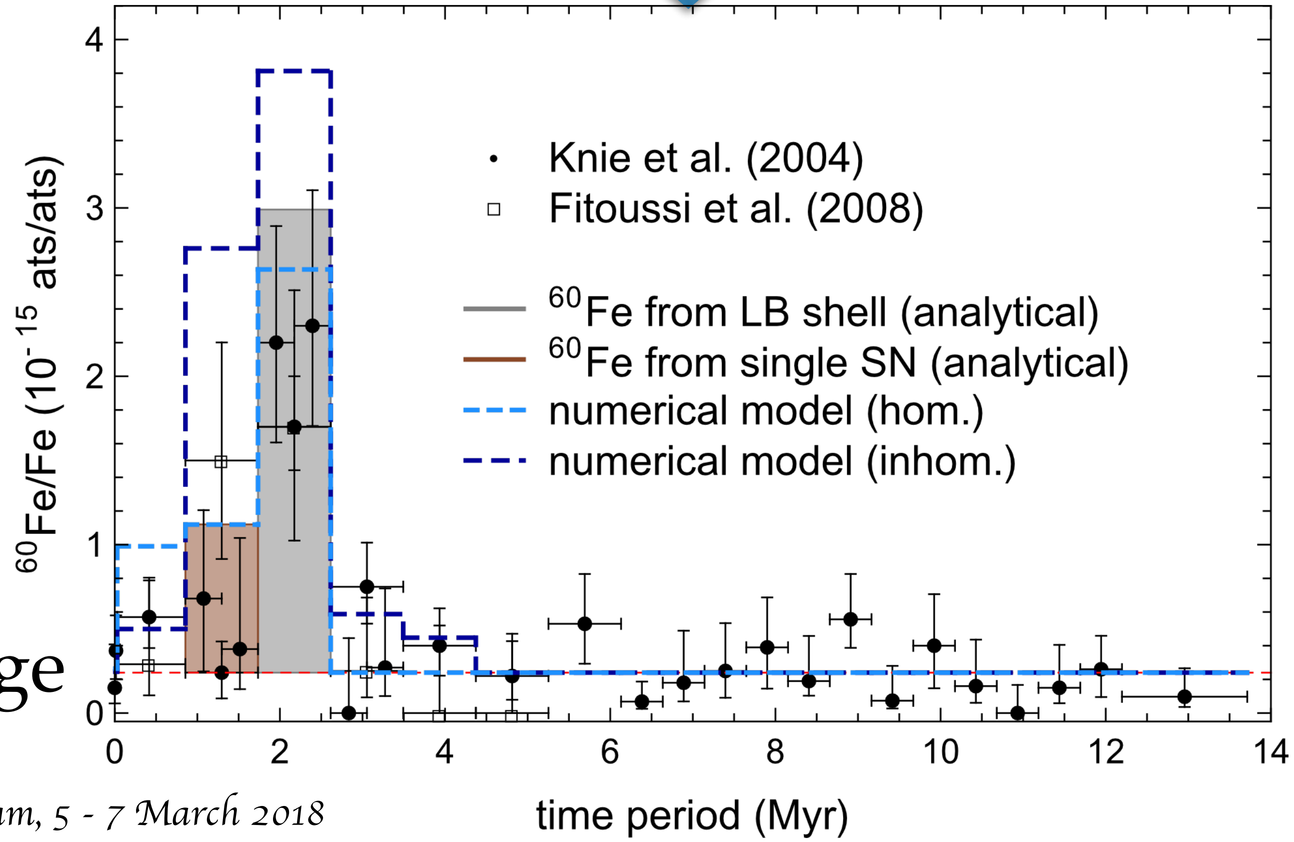


- increase in glaciation down to mid-latitudes
- only dominant species survived ➜ among hominini: homo erectus ➜ direct ancestor of homo sapiens (Africa) and Neanderthals (Europe)

2nd Summary

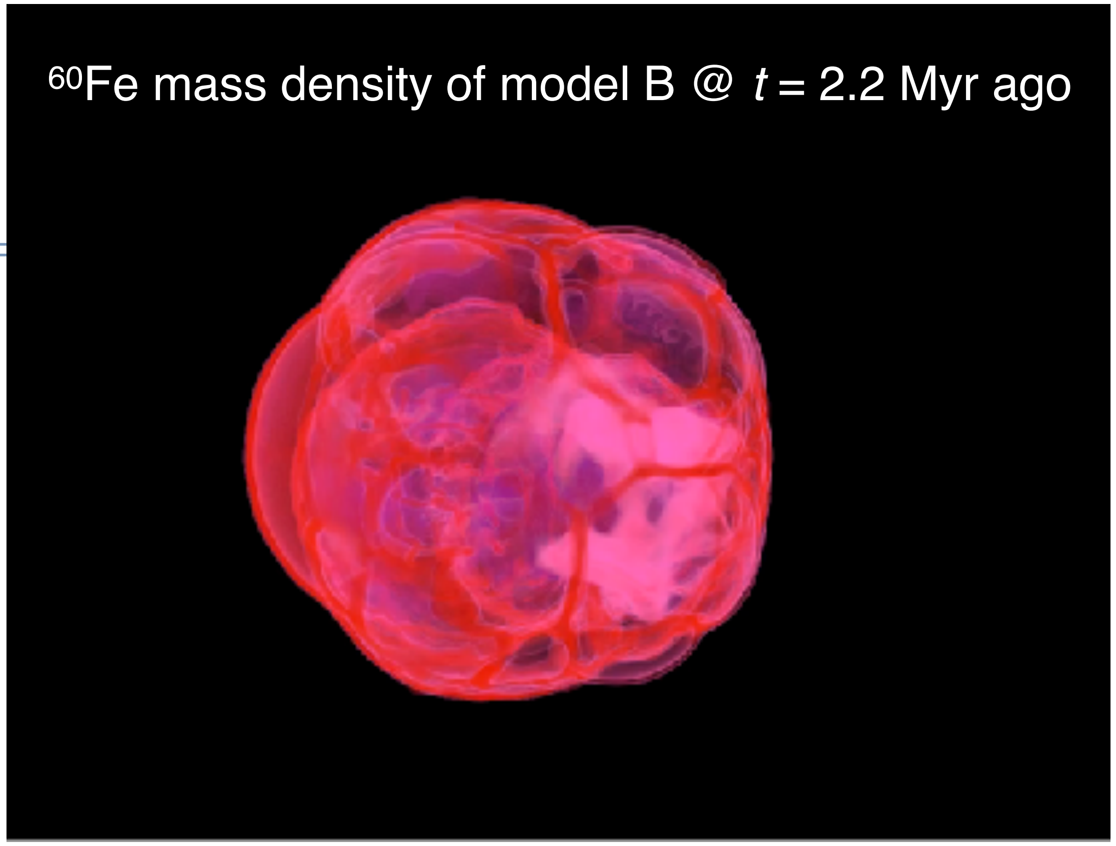
- We found SNe responsible for **both** the **LB and ^{60}Fe deposition** on Earth
- SN ejected ^{60}Fe is mixed and transported to Earth by ISM turbulence and **shocks**
- Cluster age from **isochrones**
- SN progenitor mass calculated from **IMF** ➜ explosion times!
- Stellar trajectories from **HIPP+ARIVEL** ➜ positions of stars as function of time!
- Dust produced in SNe ➜ ^{60}Fe incorporated in dust particles ➜ less affected by solar wind ram pressure ➜ move ballistically
- Dust sputtered during ISM travel ➜ large particles survive

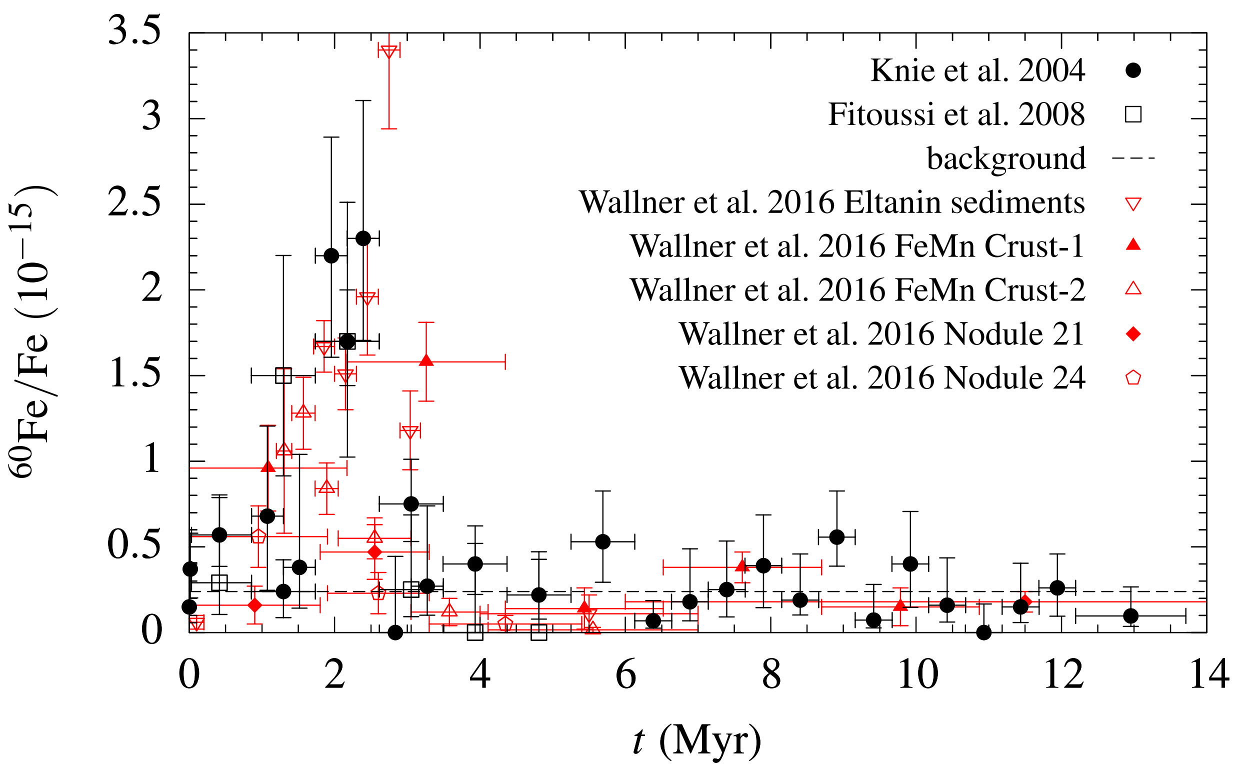




2nd Summary cont.

- Uncertainties in ^{60}Fe yields from SNe and ^{60}Fe uptake and survival factor change absolute but not relative distribution
  ➜ peak and slopes remain!
- Average ambient den. ≤ 0.3 cm^{-3} (mod. B) Two **deposition scenarios**:
  (i) individual SN shells sweep over Earth
  (ii) LB shell crosses Earth ➜ broad peak
- higher time resolution measurements (Wallner+16) favour (ii)
- LB properties best reproduced by inhom. model (AB 2012, Schulreich+17)
- Use radioactive tracers, deep-sea astronomy and stellar dynamics (new GAIA data) to uncover LISM history
- ➜ **Local Galactic Archaeology**





Media Response

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