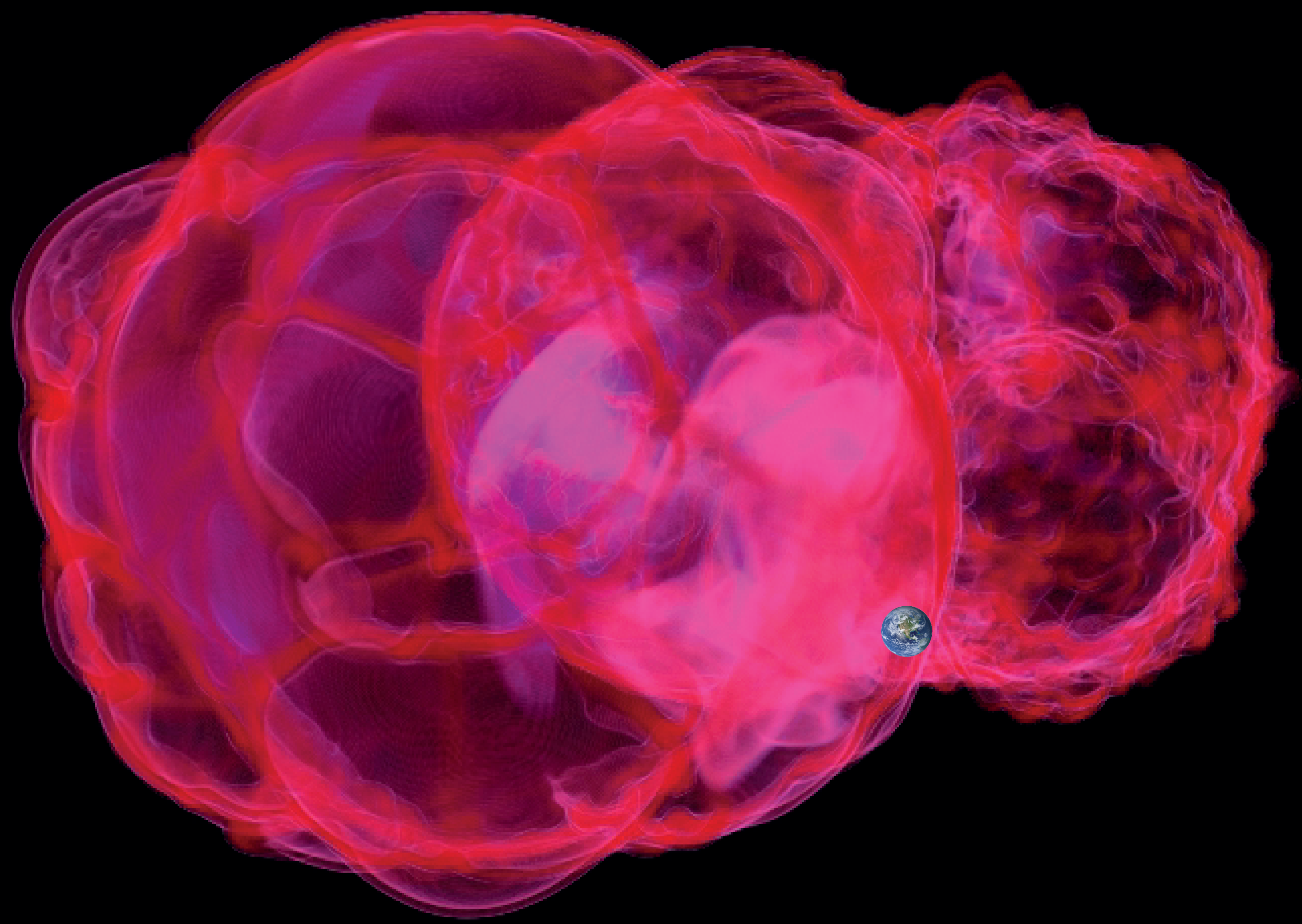
Where and when did recent Near-Earth Supernovae explode?



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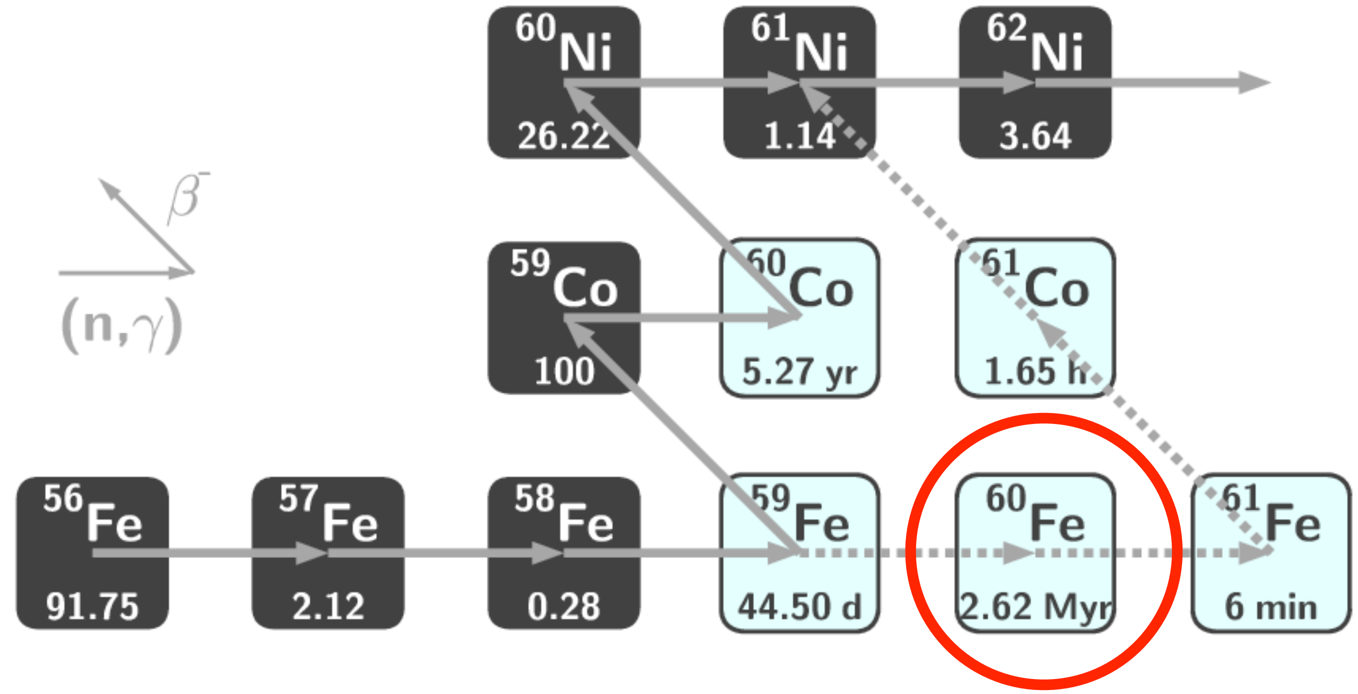
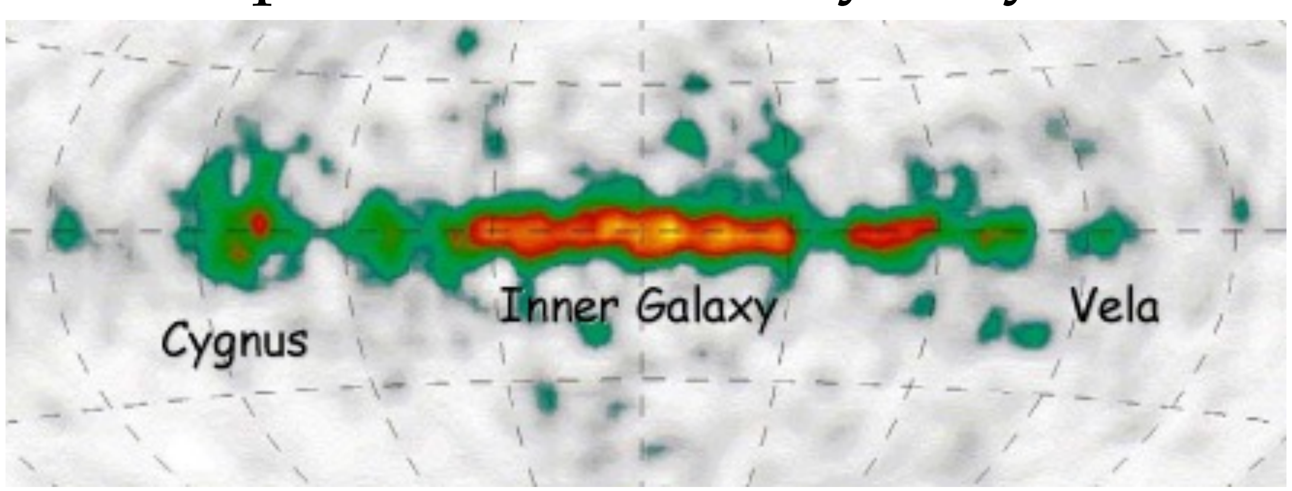
^{60}Fe as SN-Tracer

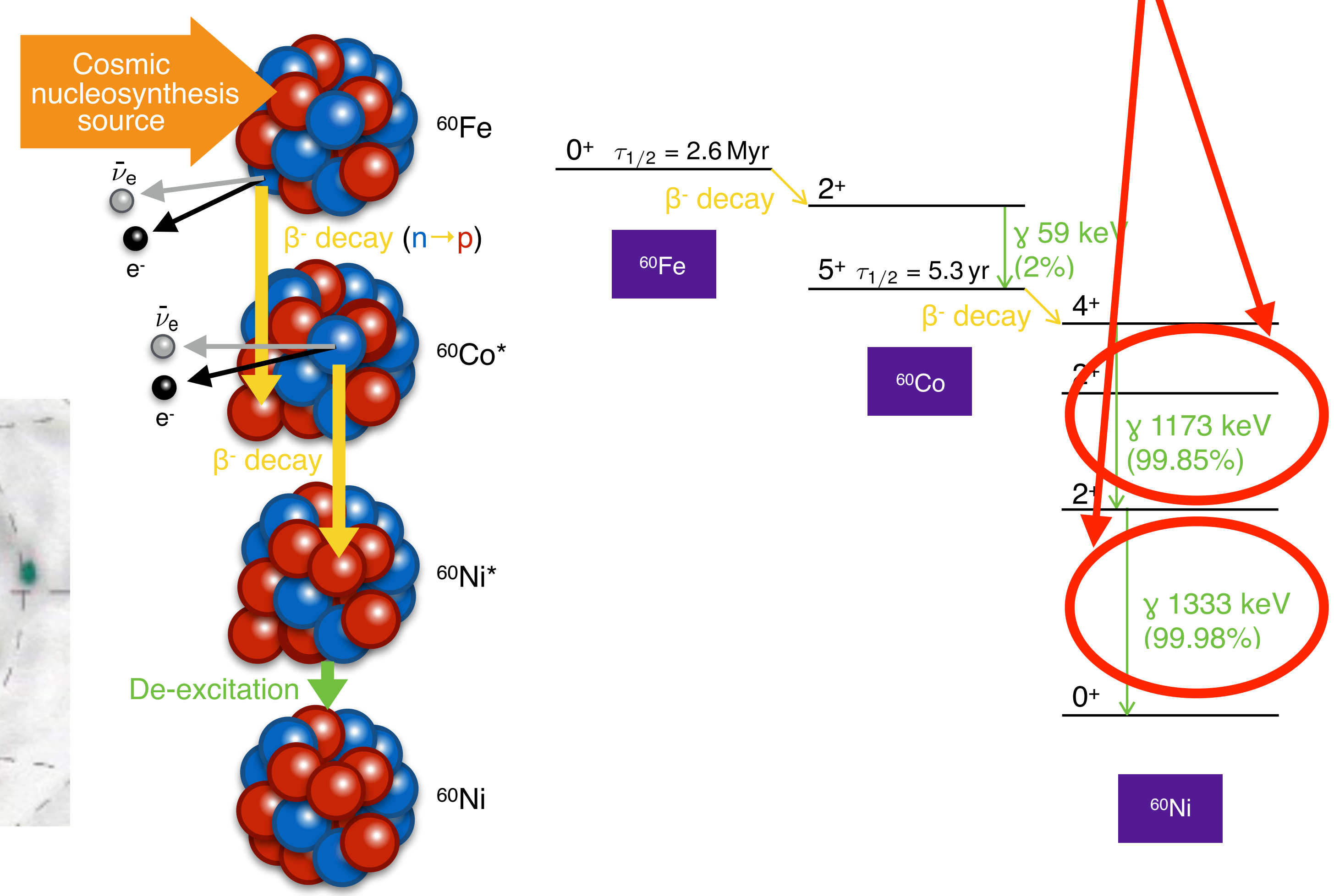


- ^{60}Fe ($t_{1/2} \sim 2.6$ Myr) produced in late AGB stars ($4\ 10^8 < T < 5\ 10^8$ K: C- core + He-shell burning) and explosive Ne-burning: ^{22}Ne(α,n)^{25}Mg ➜ ^{58}Fe(n,γ)^{59}Fe(n,γ)^{60}Fe
- ^{26}Al is SN generated
- INTEGRAL γ-line measurements show that ^{26}Al and ^{60}Fe come from same places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



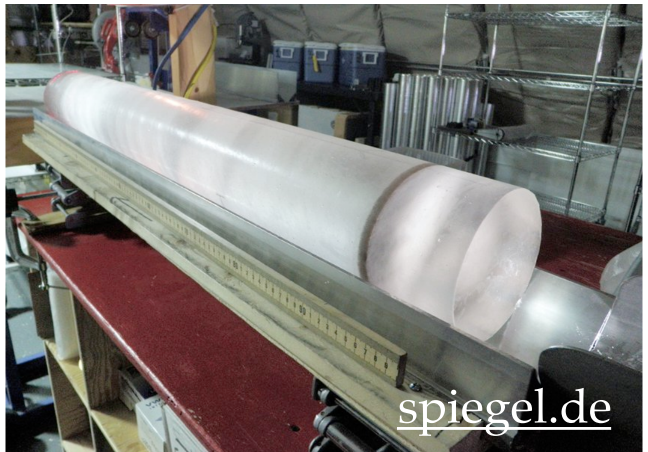
INTEGRAL map of ^{26}Al from the Galaxy
Credit: R. Diehl, MPE

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

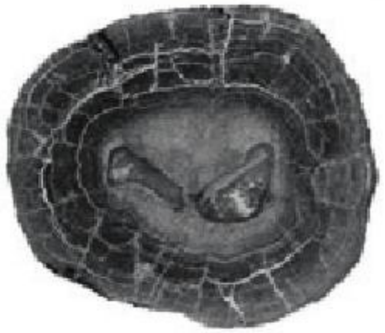


^{60}Fe in the solar system? The Advent of Deep-Sea Astronomy

- 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



ice core drillings



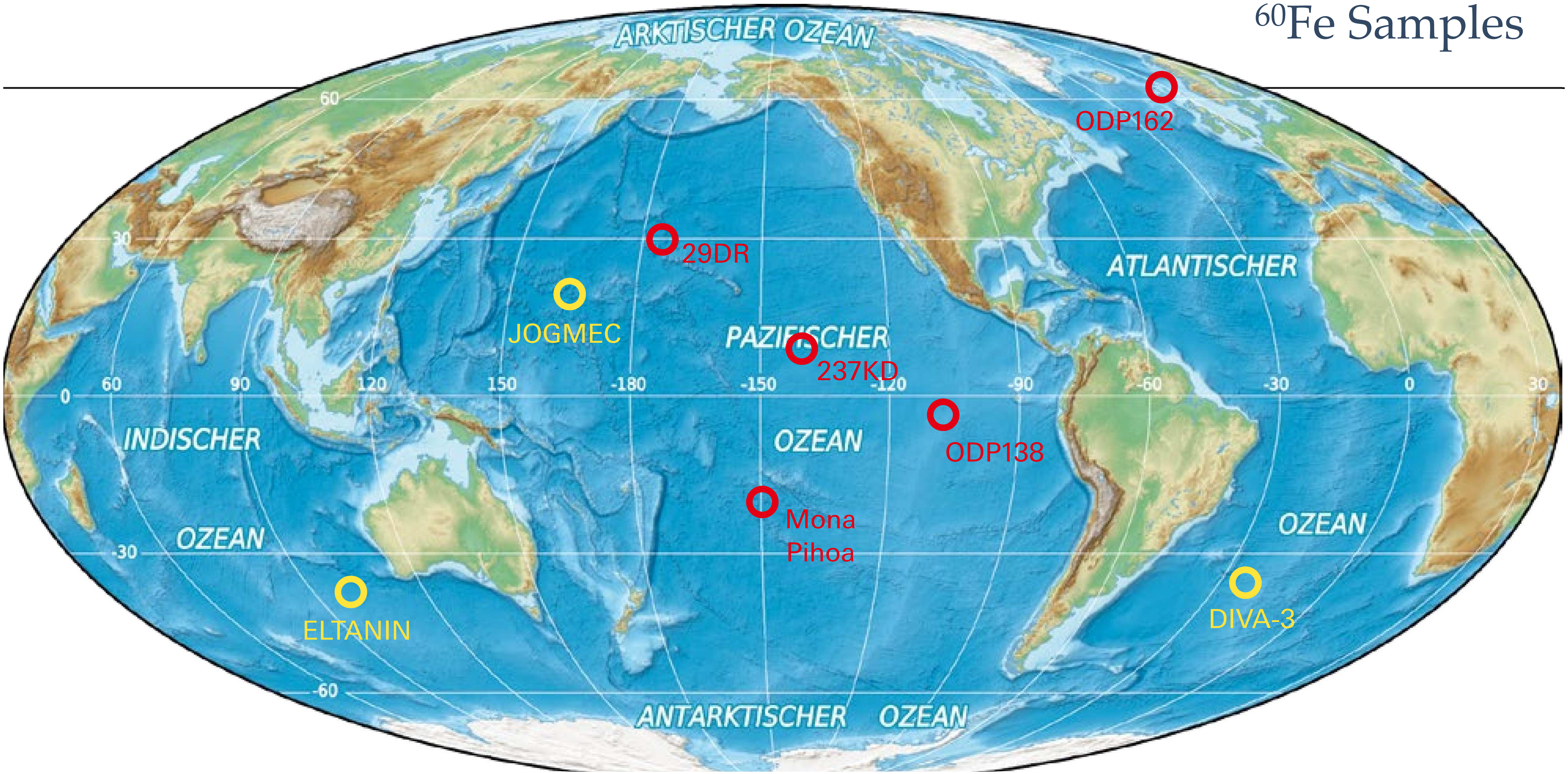
Hein & Koschinsky 2014

nodules

Deep-Sea Astronomy I

Deep-Sea Astronomy II

Locations of ^{60}Fe Samples

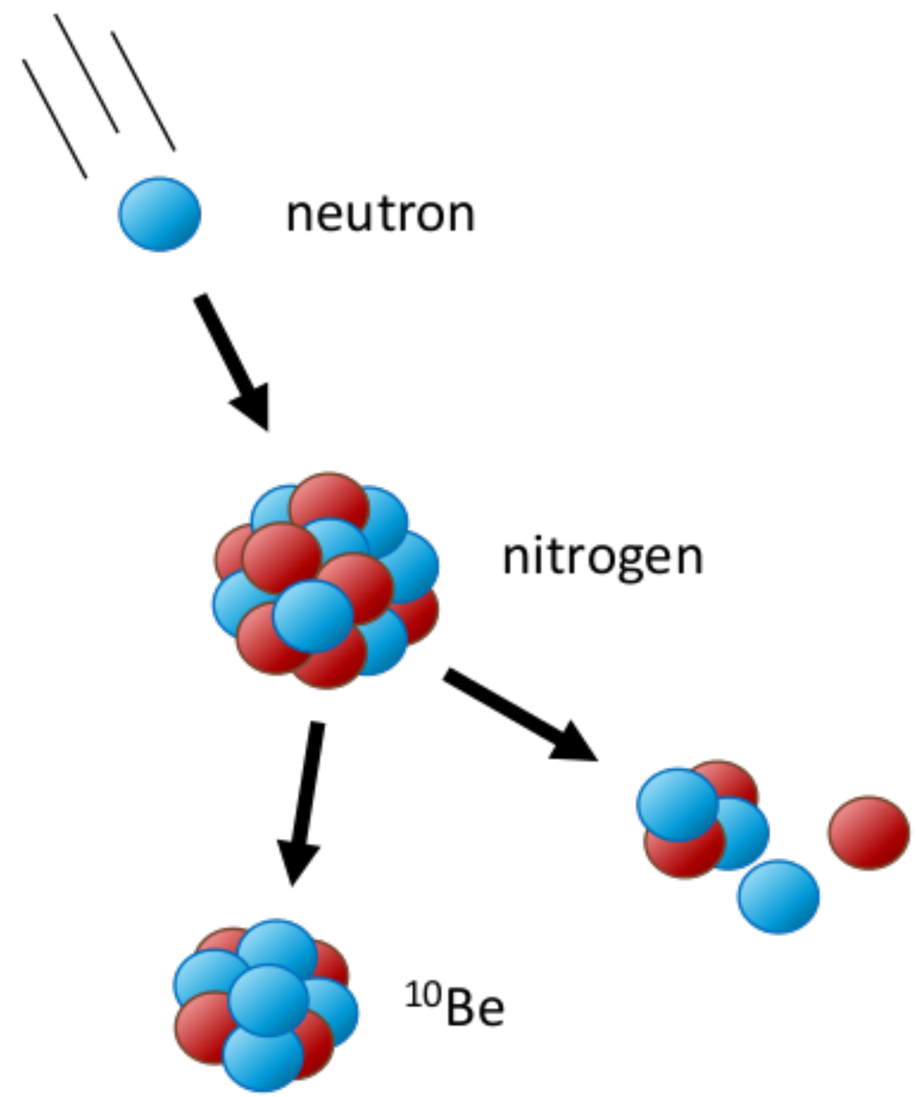


How to determine the age?

- 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

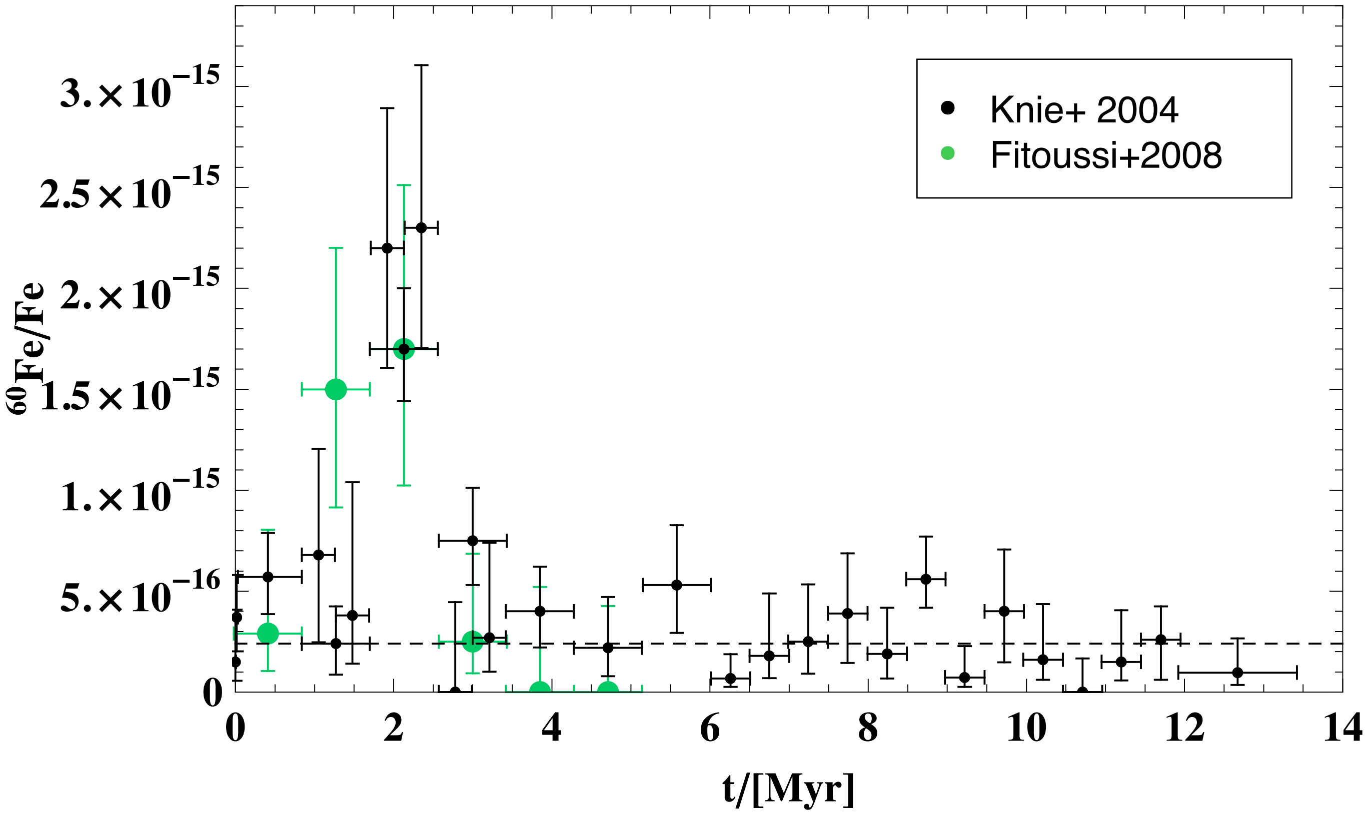
- $N(t) = N_0 \exp[-\lambda t]$ with
- $N(t)$ … measured ^{10}Be/^{9}Be-ratio
- N_0 … initial ^{10}Be/^{9}Be-ratio in atmosphere
- λ … decay constant for ^{10}Be

➜ t … age of sample (sediment/crust)



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

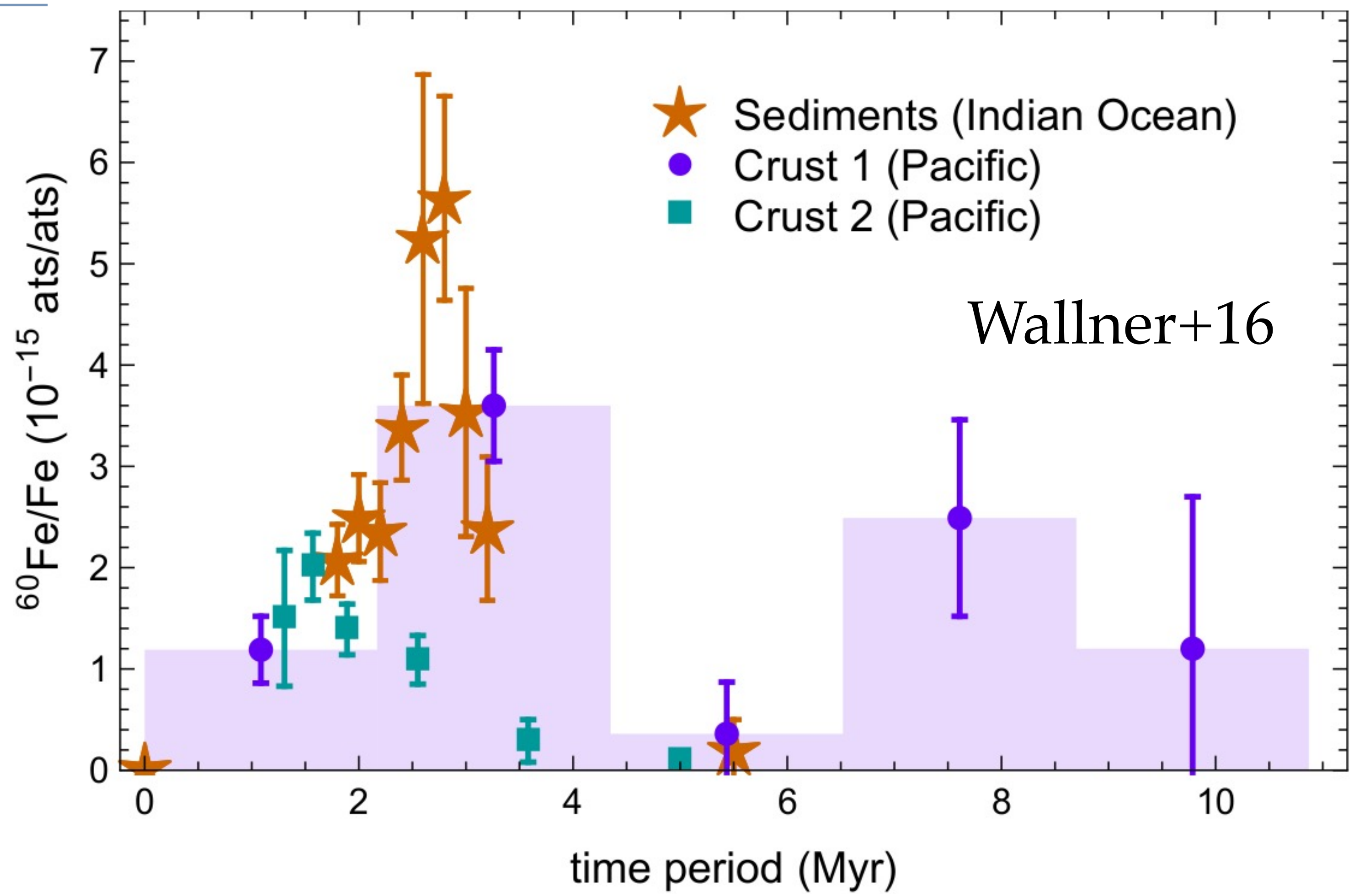
- Small quantities of long-lived isotopes are best measured by Accelerator Mass Spectrometry (AMS), e.g. 14 MV Tandem accelerator at TU München
- Signal in 1.7 - 2.6 Myr old layer detected in crust 237KD
- 2 mm ≙ 8 10^5 yr
- each layer defines range on time axis
- all terrestrial ^{60}Fe decayed long ago ➜ low terrestrial background



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

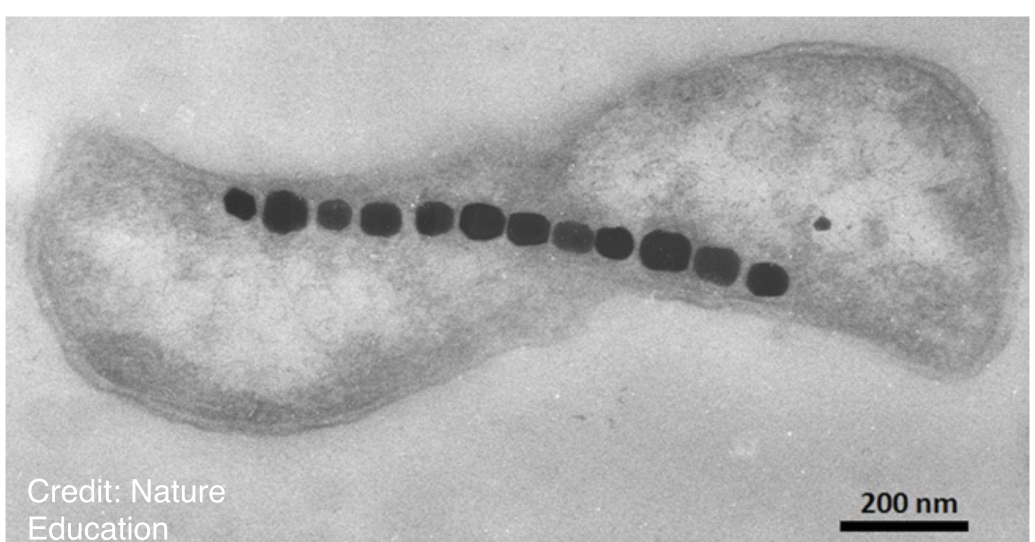
- Signal in crust is **extended** ➜ more than one SN!
- 2nd peak at 6.5 - 8.7 Myr before present (= BP), 4σ above background detected (Wallner+ 2016)
- note higher time resolution of sediments

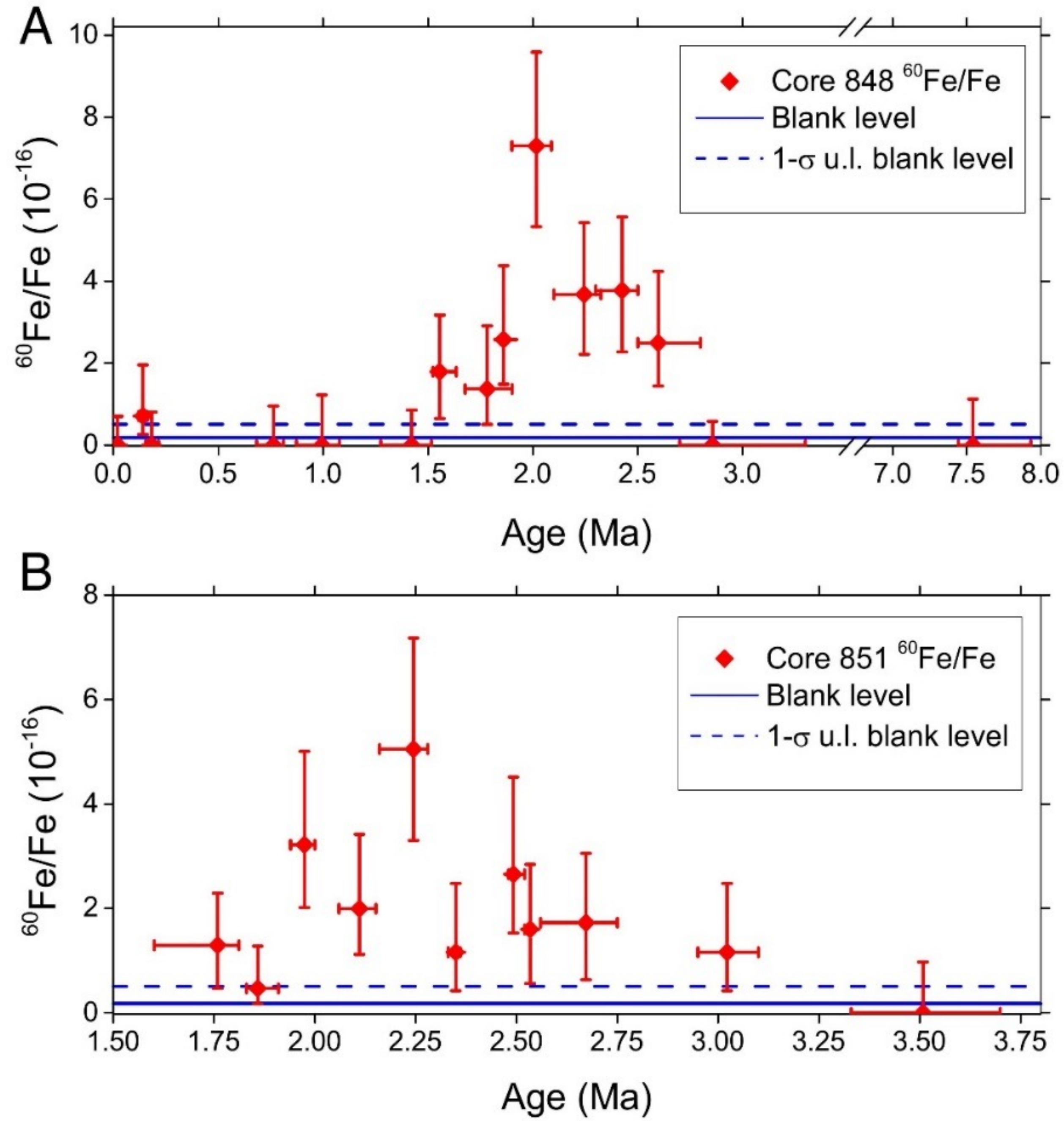
  ➜ signals rule out a constant background of ^{60}Fe
- ^{60}Fe found in all oceans ➜ **global**
- micrometeortic origin excluded ➜ dust influx 400x too low
- meteorite impact like in tertian (65 Myr BP) would have 4500 times too low ^{60}Fe mass



Global Signal III
- ^{60}Fe in magnetotactic bacteria -

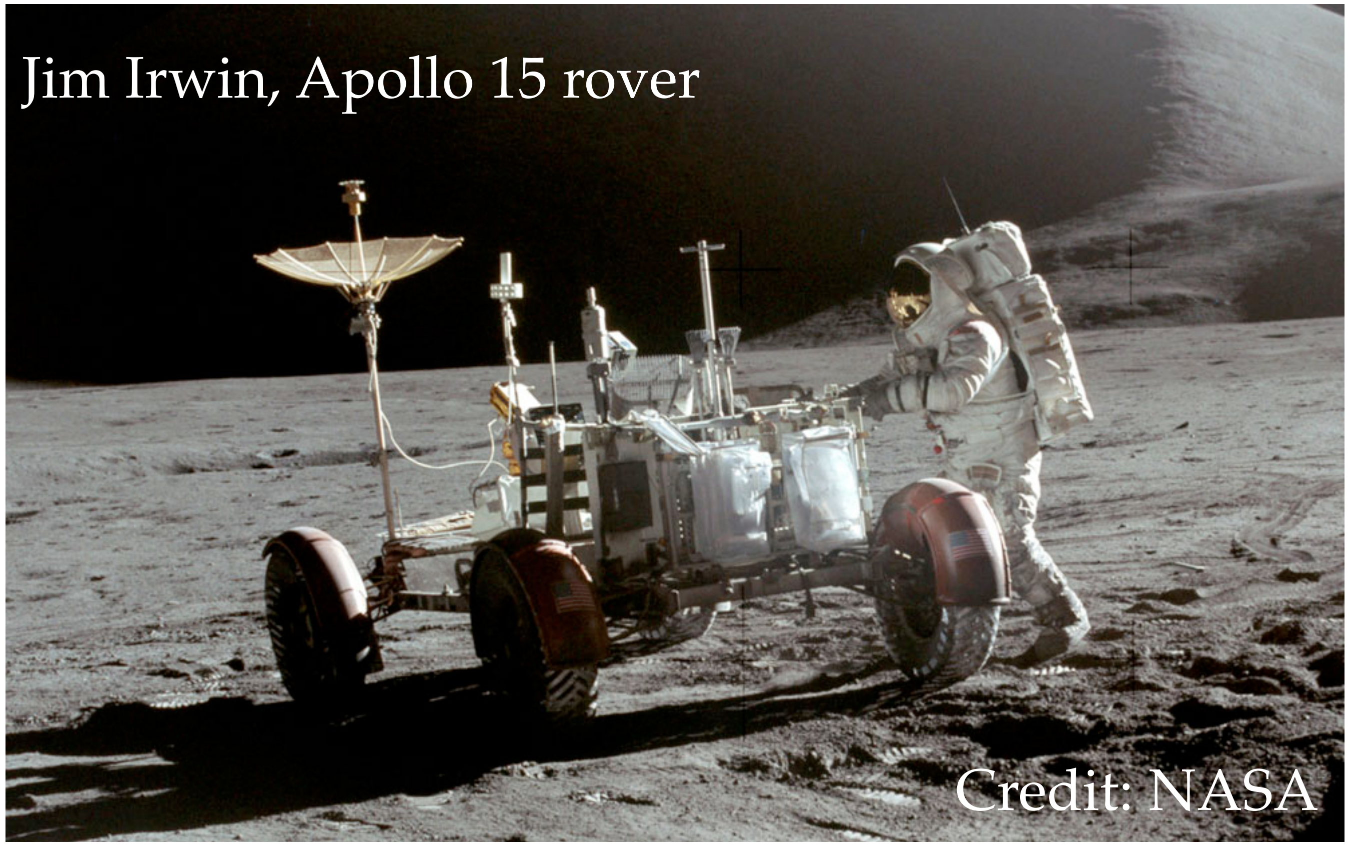
- Signal from 2 marine sediment cores
- ^{60}Fe peak at 1.8 - 2.6 Myr
- ^{60}Fe was incorporated by **magnetotactic bacteria (MTB)**
- MTB produce chains of magnetite (Fe_3O_4) crystal (magnetosomes) for orientation at Earth's magnetic field
- MTB population moves upwards as sediment grows leaving magnetofossils behind



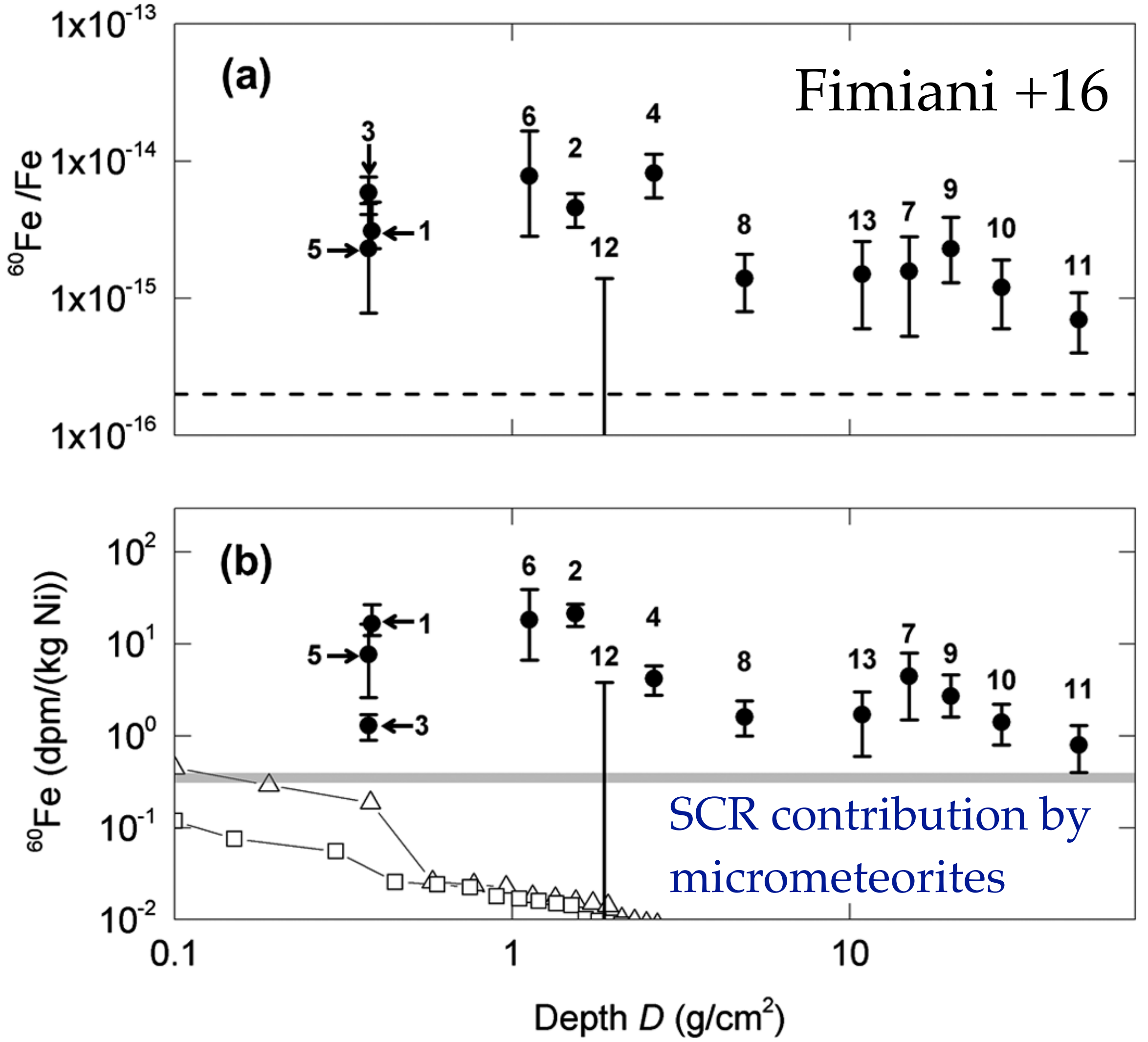


Ludwig+2016, PNAS 113, 9232

Global Signal V: ^{60}Fe on the Moon

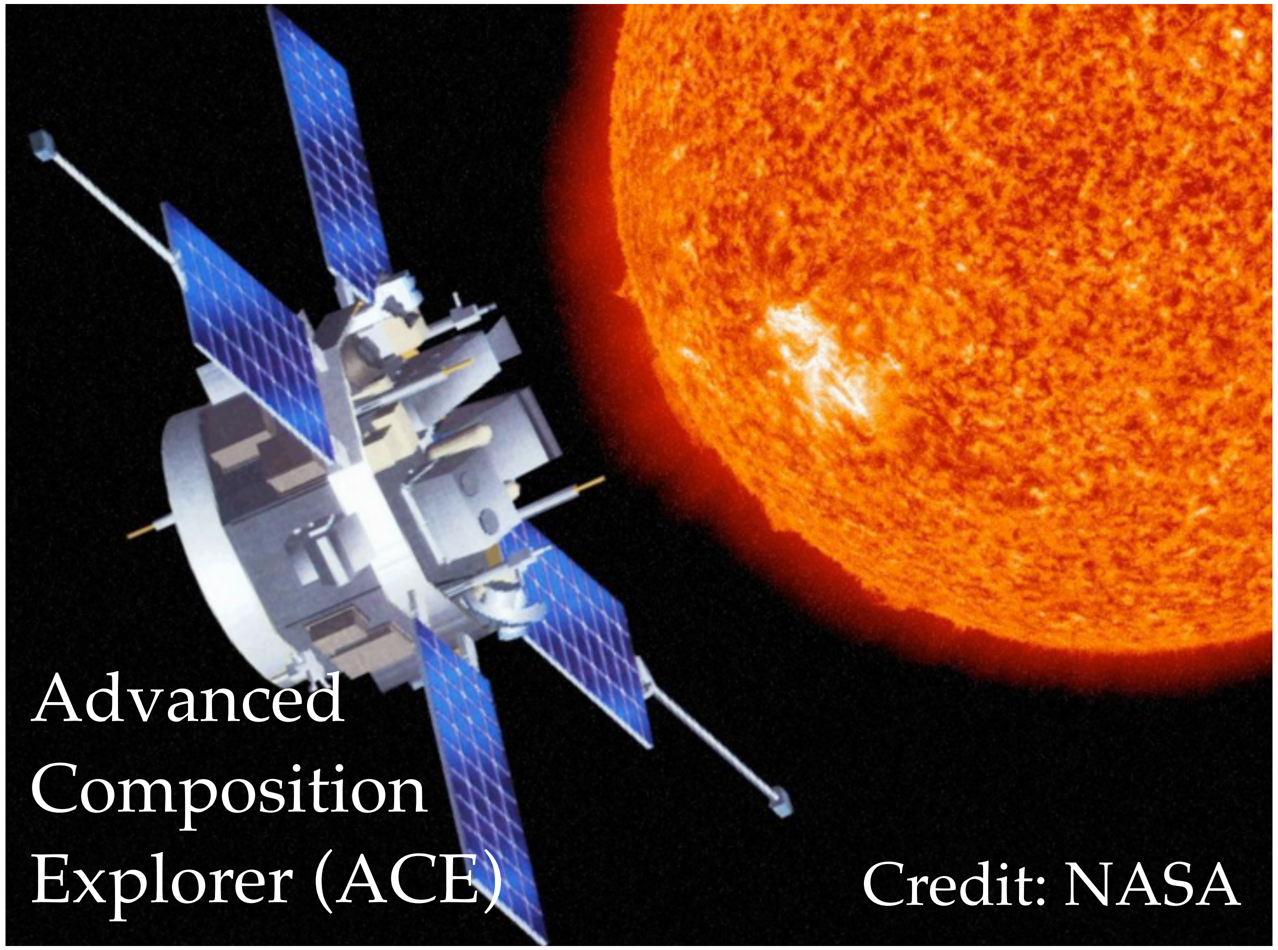


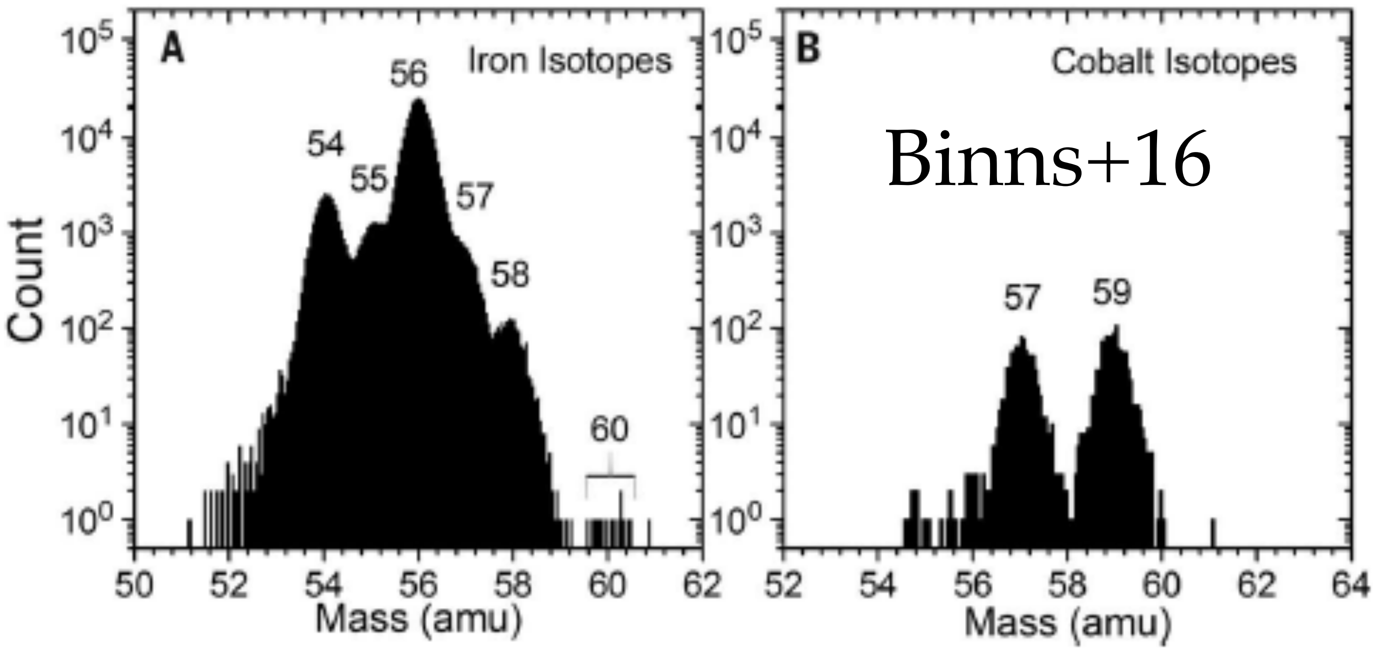
- ^{60}Fe found in lunar samples from Apollo 12, 15, 16 (Fimiani+16)
- Since moon has no atmosphere, ^{60}Fe deposition is less disturbed, sedimentation effects are negligible
- But: gardening effects dilute signal
  ➜ no peak due to mixing
- But: solar and galactic cosmic rays can generate ^{60}Fe (and ^{53}Mn)
  ➜ contribution < 10%
  ➜ bulk of ^{60}Fe is from SNe
- upper limit of interstellar ^{60}Fe fluence:
  ➜ ~ 10^8 at/cm^2 (uptake factor ~ 1) for uniform spread over lunar surface



Global Signal IV: ^{60}Fe in Cosmic Rays

- 15 atoms of ^{60}Fe found by **ACE-CRIS** experiment (1997 - 2014) from a total of 3.55 10^5 cosmic ray particles
- CRIS energy range 50 - 500 MeV/nuc
- acceleration of nuclei by SN blast wave (**1st order Fermi process**)
- ^{60}Fe/^{56}Fe ratio ➜ time elapsed since ejection: ~ a few Myr (Binns+16)
- distance to source due to $t_{1/2}$(^{60}Fe) of 2.6 Myr < 620 pc (diffusion model!)
- **PAMELA** measures excess of positrons and antiprotons ≳ 20 GeV, plus discrepancy in slope of protons and heavier nuclei ➜ consistent with SN source 2 - 4 Myr old (Kachelrieß+15)





Hein & Koschinsky 2014

1st Summary

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

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

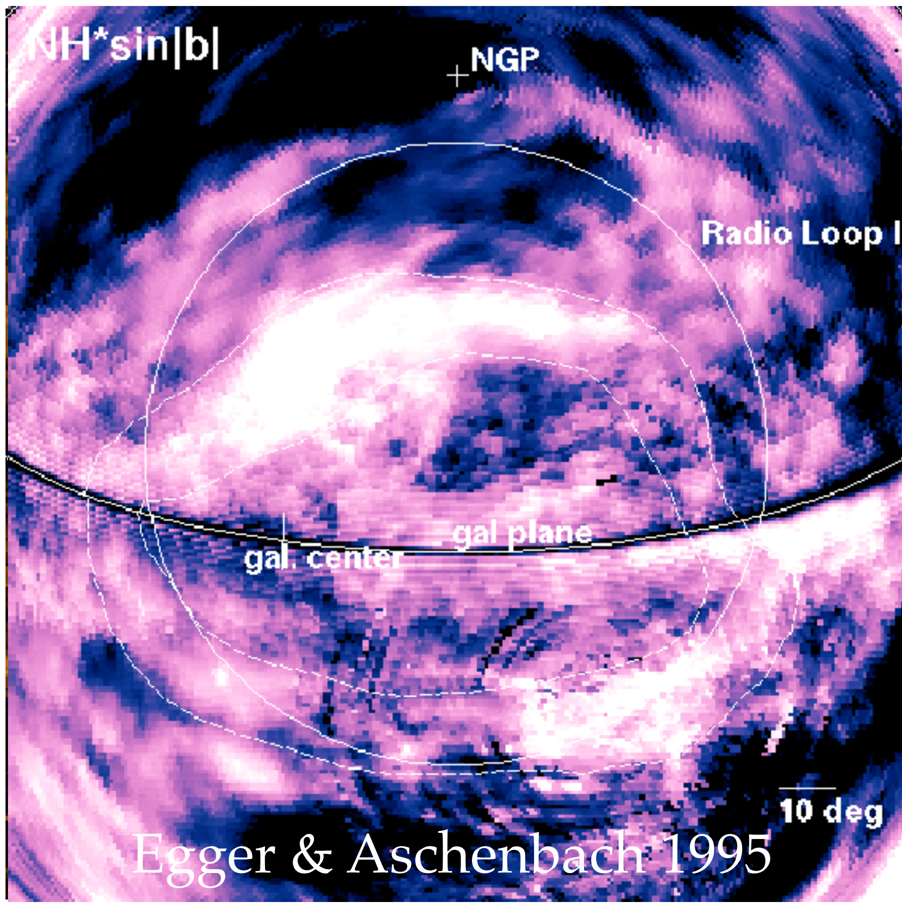
LETTER

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]

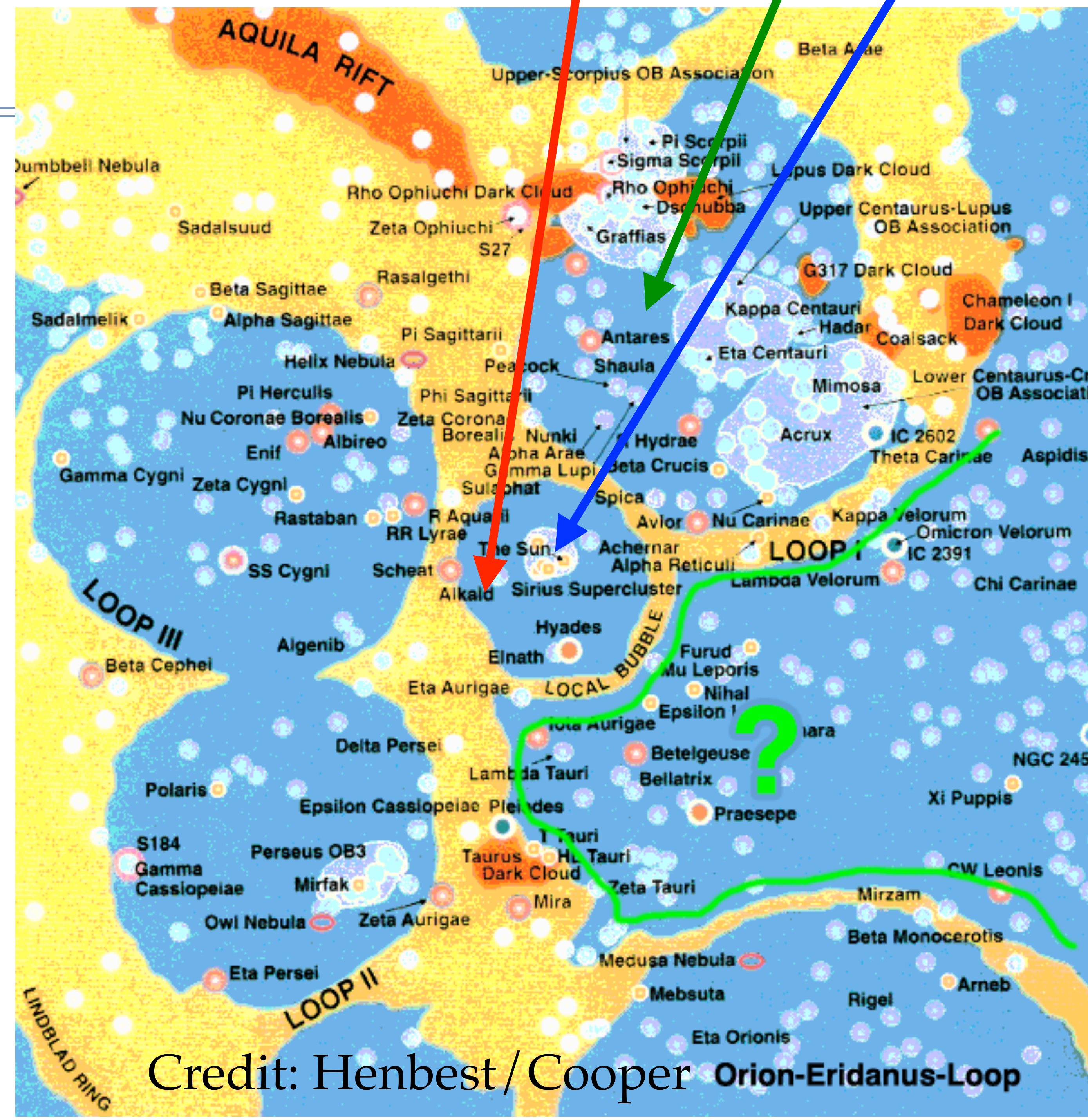
Solar Neighbourhood I



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

- solar system embedded in local superbubble: **Local Bubble (LB)**
- LB in interaction with LB (Egger & Aschenbach 1995)
- **no young star cluster inside LB!**

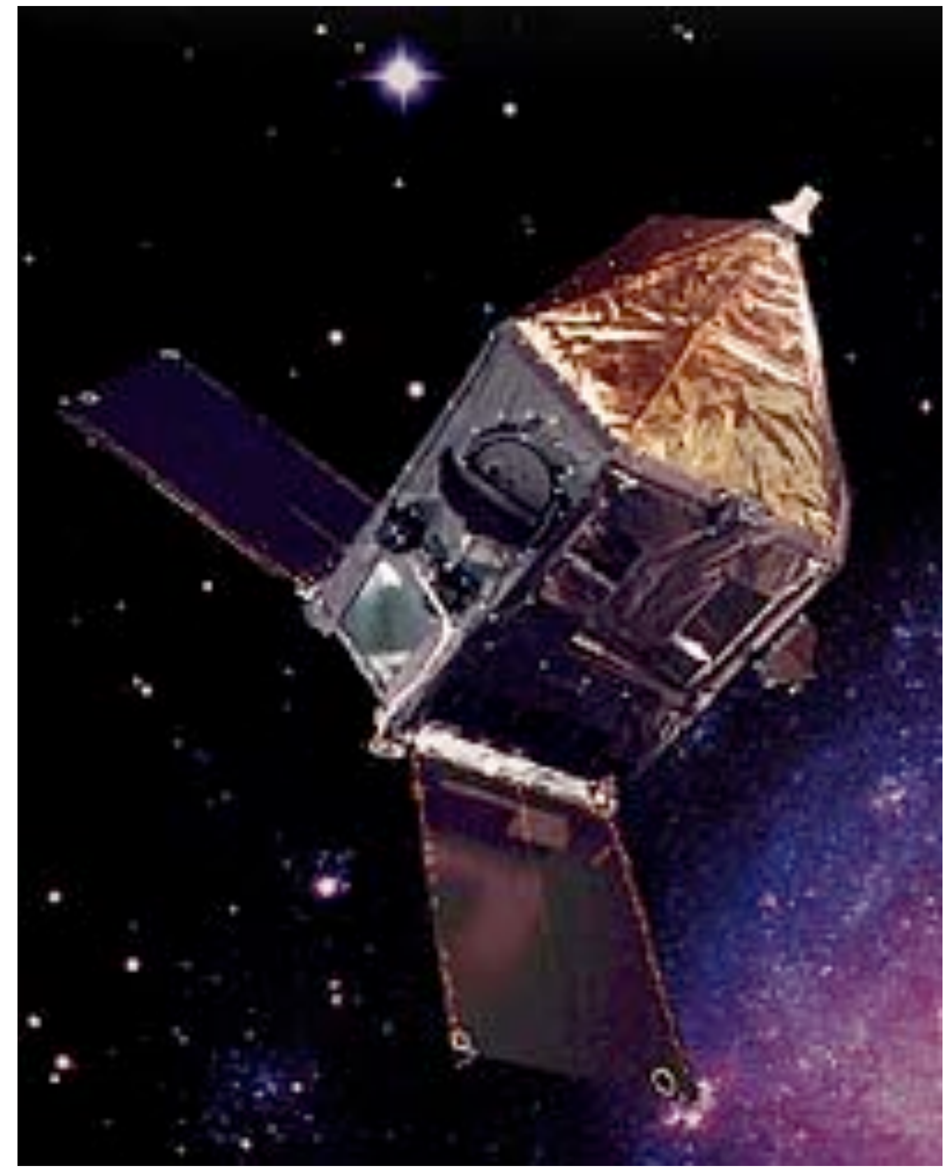
Local Bubble
Loop I
Solar System



Superbubbles in solar neighbourhood

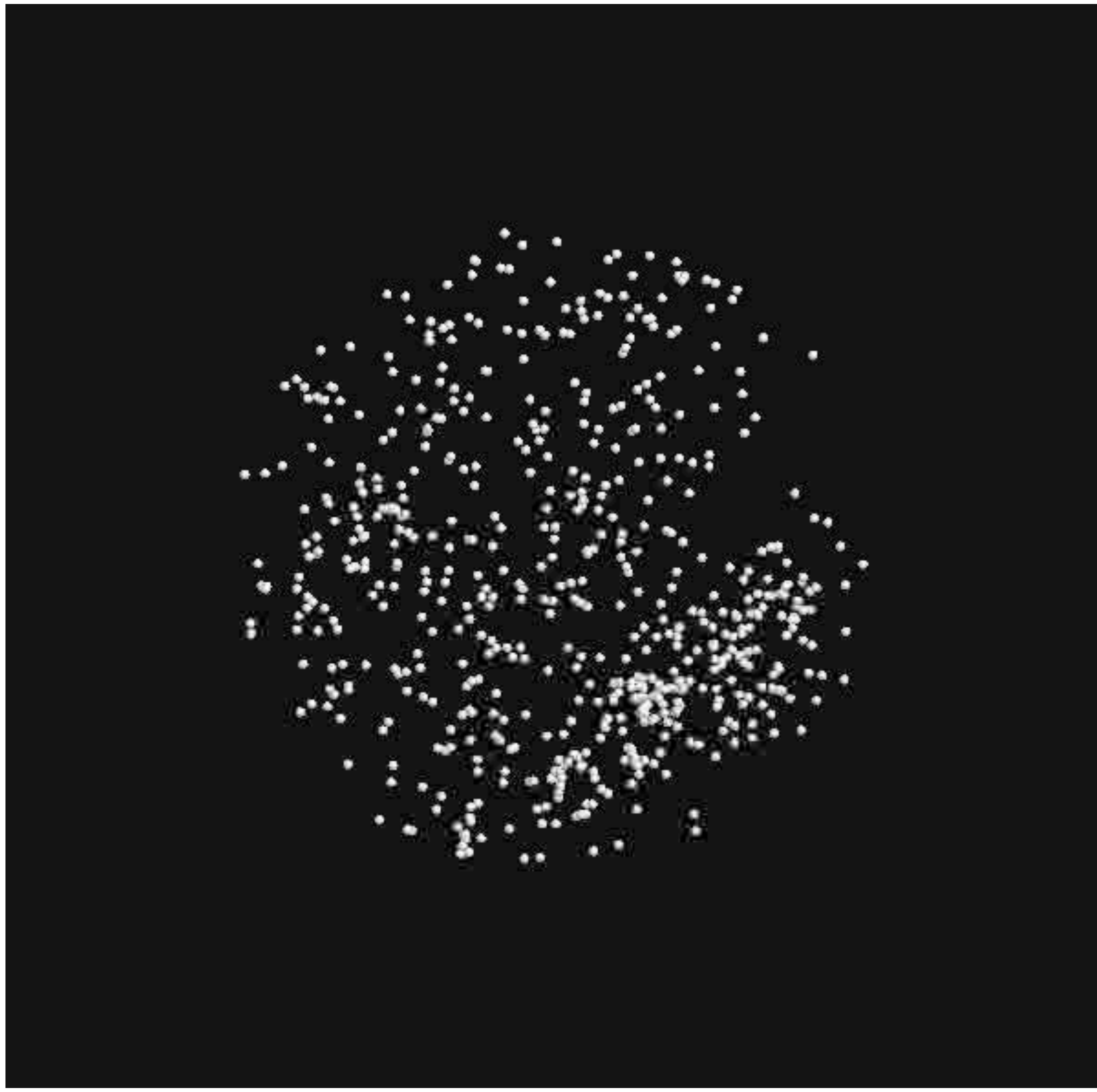
Local Interstellar Medium (LISM)

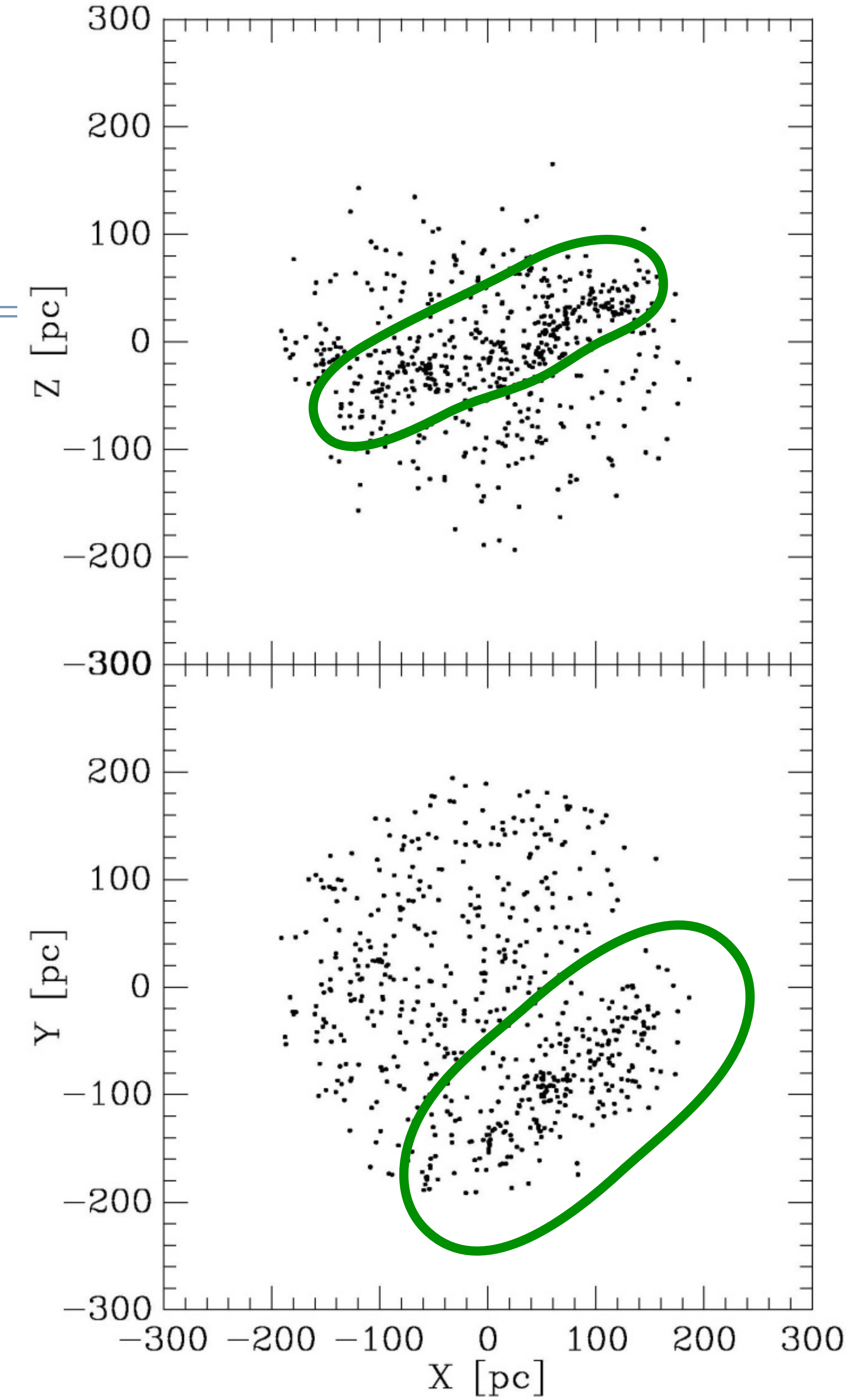
- LB could be the result of SNe (Sanders+77, Hartquist & Innes+84, Breitschwerdt & Schmutzler+94, Cox & Smith+01 etc.)
- But where is the star cluster in which massive members exploded?
- **Idea**: Stars exploded in moving group (Berghöfer & Breitschwerdt+02)
- Pleiades subgroup B1 (age 25 Myr) crossed LB during the last 20 Myr
- Fuchs, Breitschwerdt+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

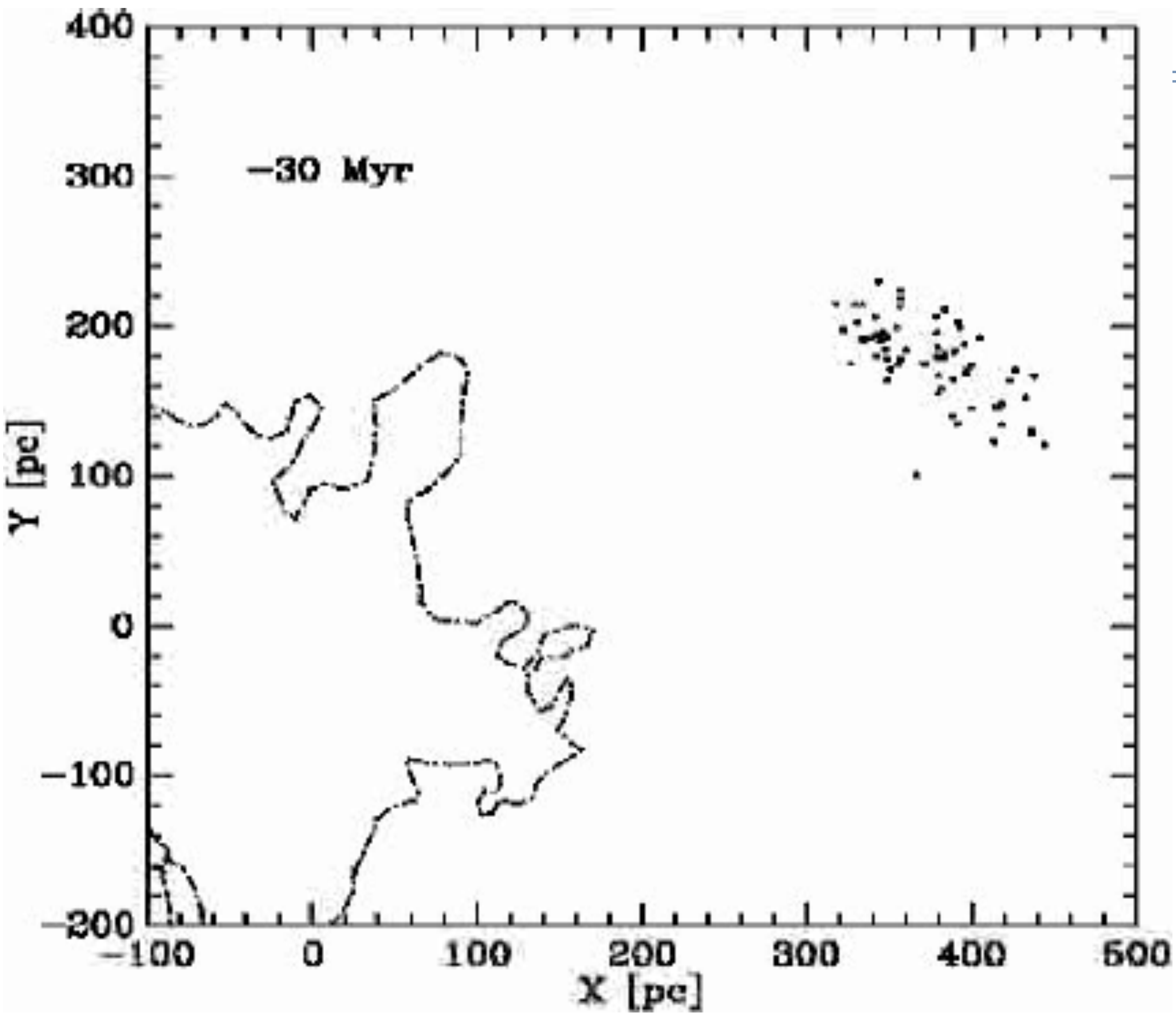


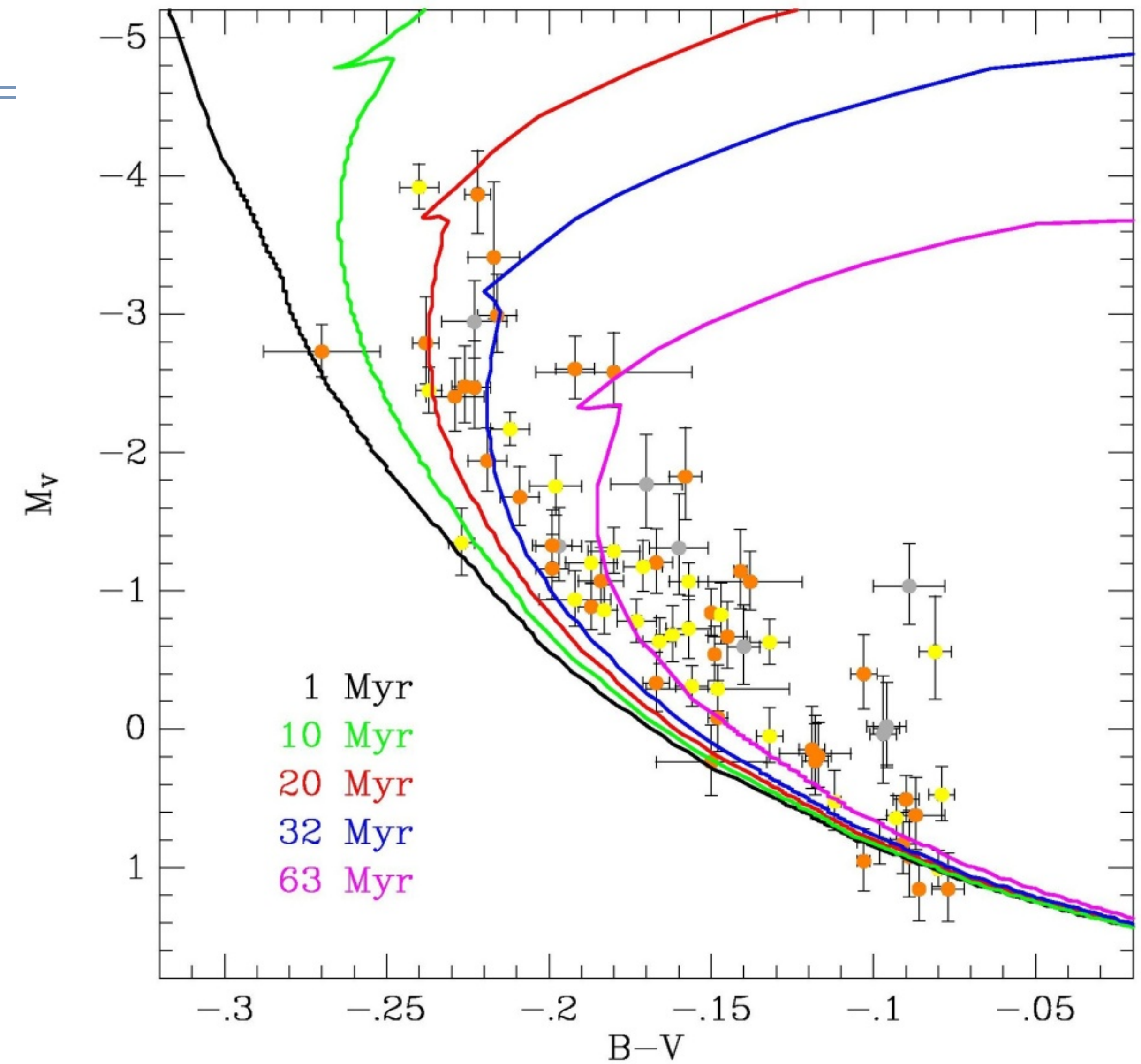


- Clustering of stars ➜ stellar moving group
- complete phase space information {**x,p**}, i.e. all stellar **positions** and **velocities** are known
- surviving members are now part of Sco-Cen association (UCL, LCC) ➜ calculate trajectories back in time (epicyclic eqs.)

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)

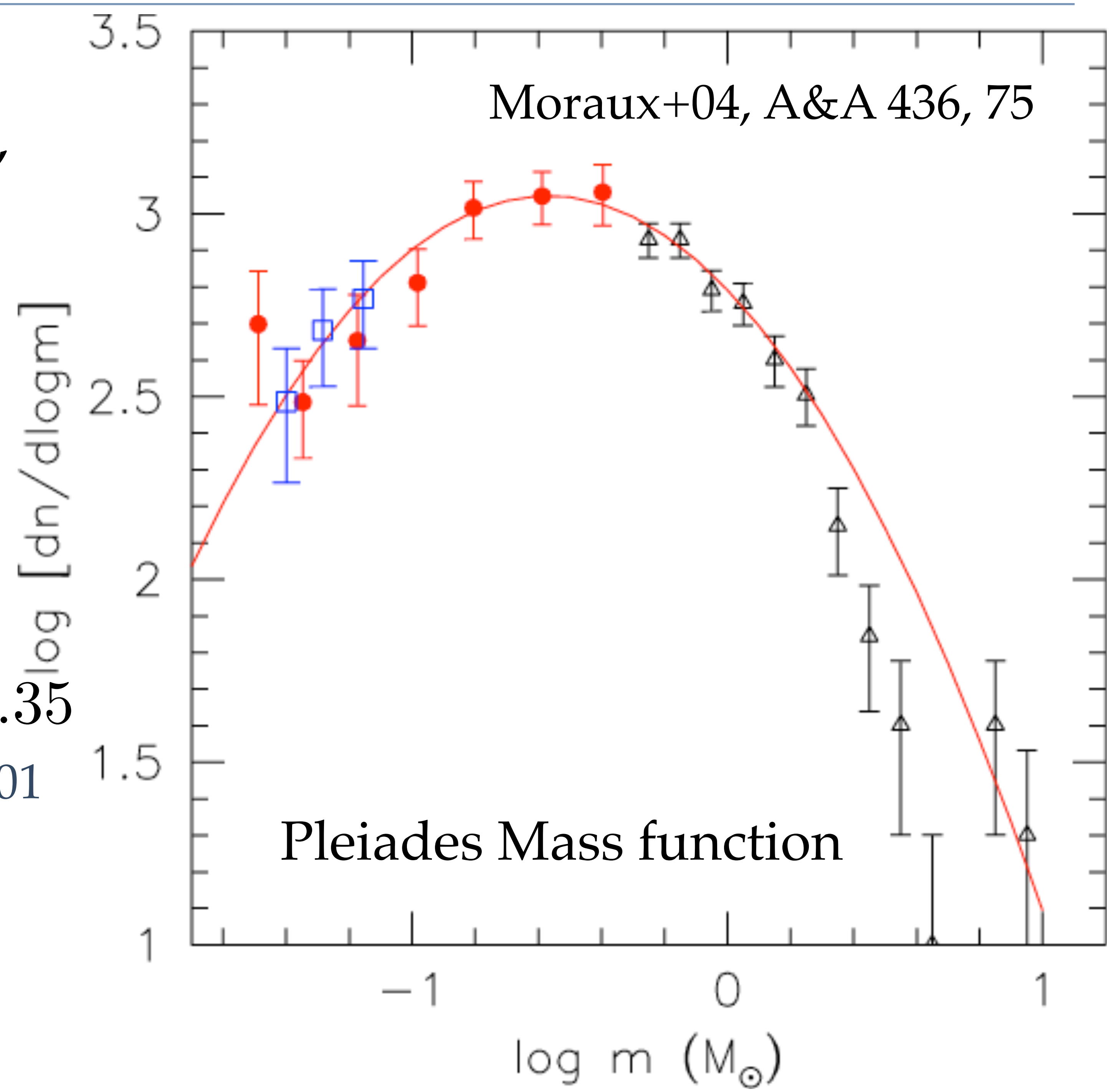
- Stars form in dense **molecular clouds**, M ~ 10^4 - 10^6 $M_\odot$, T ~ 10 K, R ~ 10 - 100 pc, Σ_g ~ 100 $M_\odot$ pc^{-2} (Krumholz+14)
- **Initial Mass Function (IMF)** is empirical relation for mass distribution in clusters, approximated by a broken power law

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

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

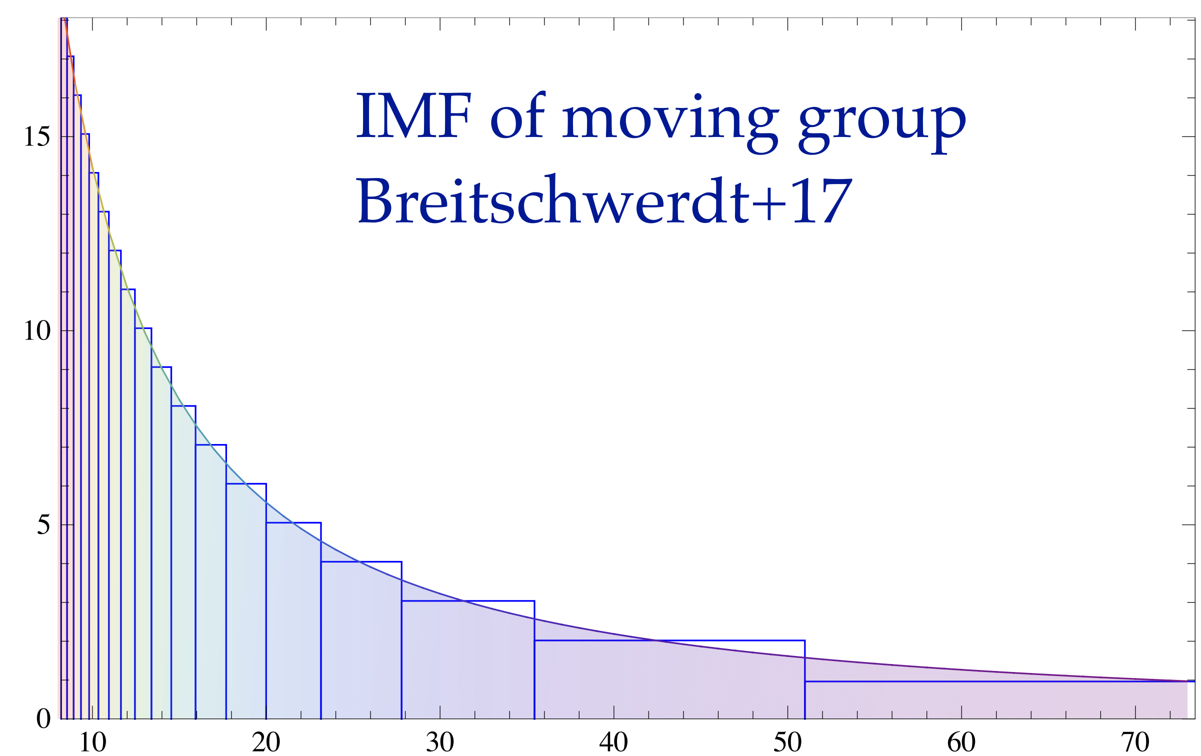
N(m) … number of stars per logarithmic mass bin

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



Number & Masses of deceased stars

- 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 $N(m) \leq 1$
  4. data: 69 stars with $2.6 \leq m \leq 8.2$
  5. $\alpha = 1.1$ (Massey+95), 1.35 (Salpeter)
  6. Result: 16 stars exploded, 2 not yet
  7. we adopt $\tau_{cl} = 20$ Myr (HRD)
  8. apply same procedure to Loop I

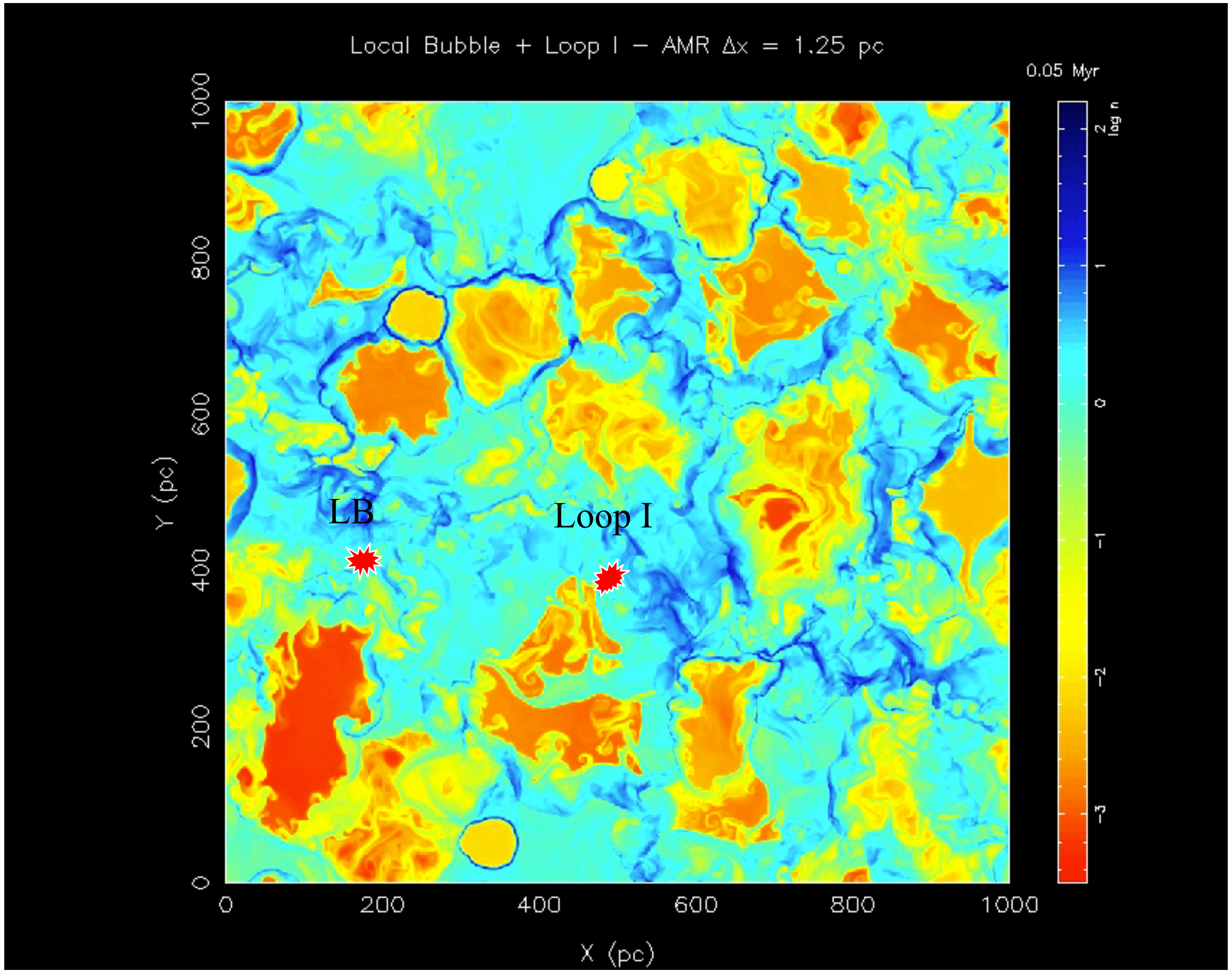


ISM and LB simulations IV

- 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



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, stars as sink 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

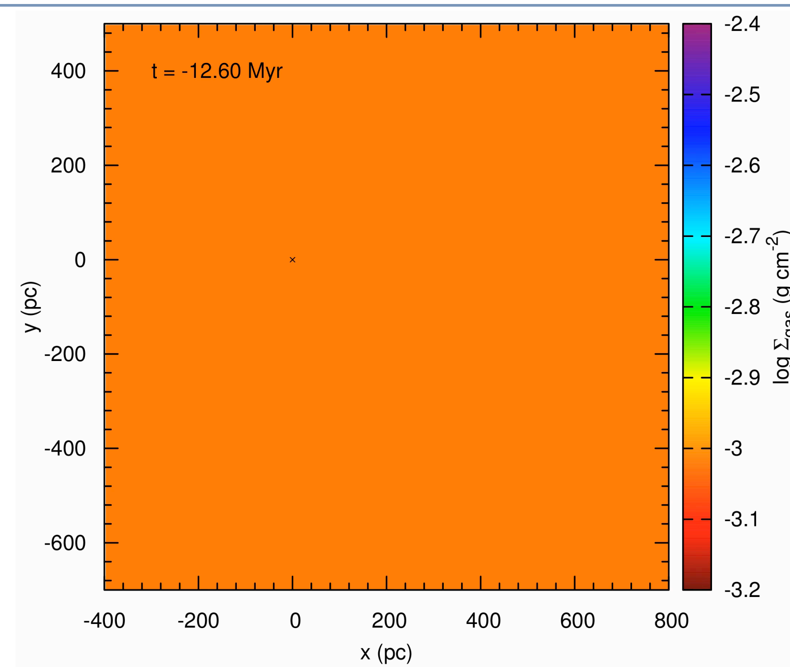
ISM and LB simulations V

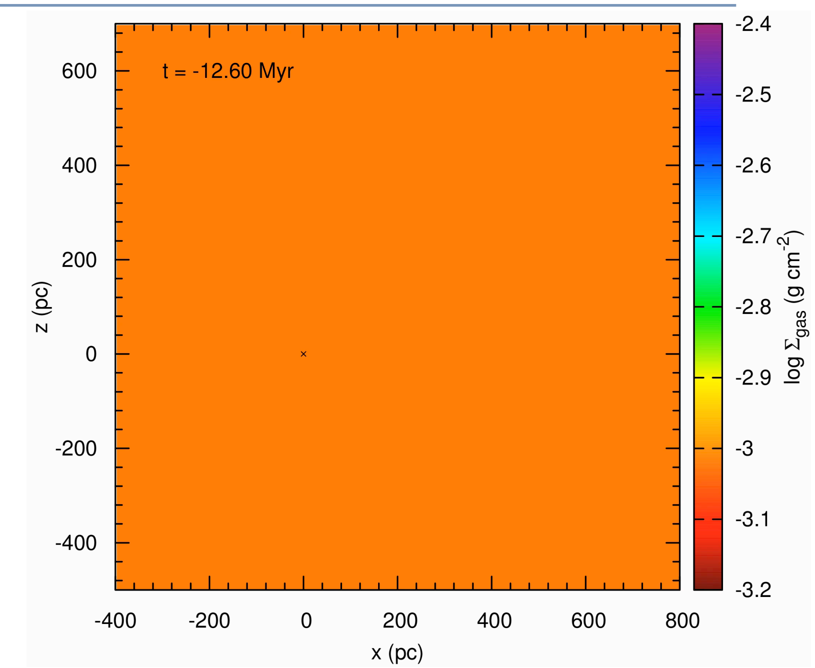
PhD Thesis: M. Schulreich, 2015

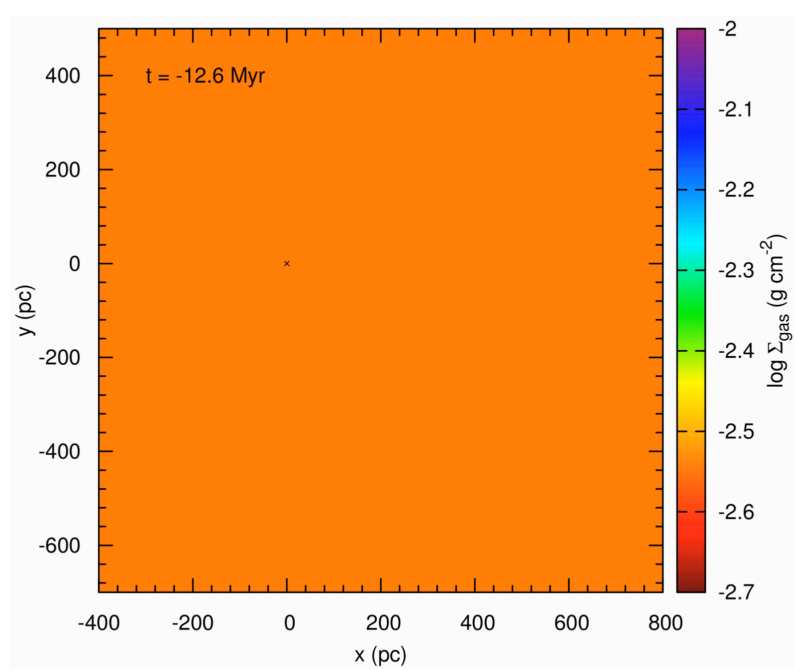
- Gas surface density Σ_g integrated over 3rd co-ordinate; t_{ev} =12.6 Myr

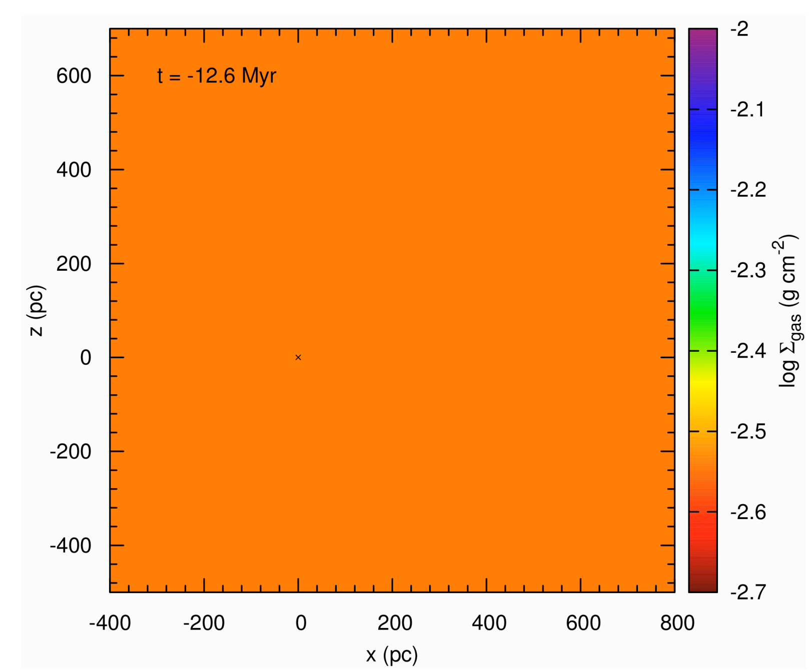
- **Model A** (~ WIM)
- n = 0.1 cm-3
- $T = 10^4$ K
- Z/Z⊙ = 1
- $\Delta x = 0.7$ pc

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







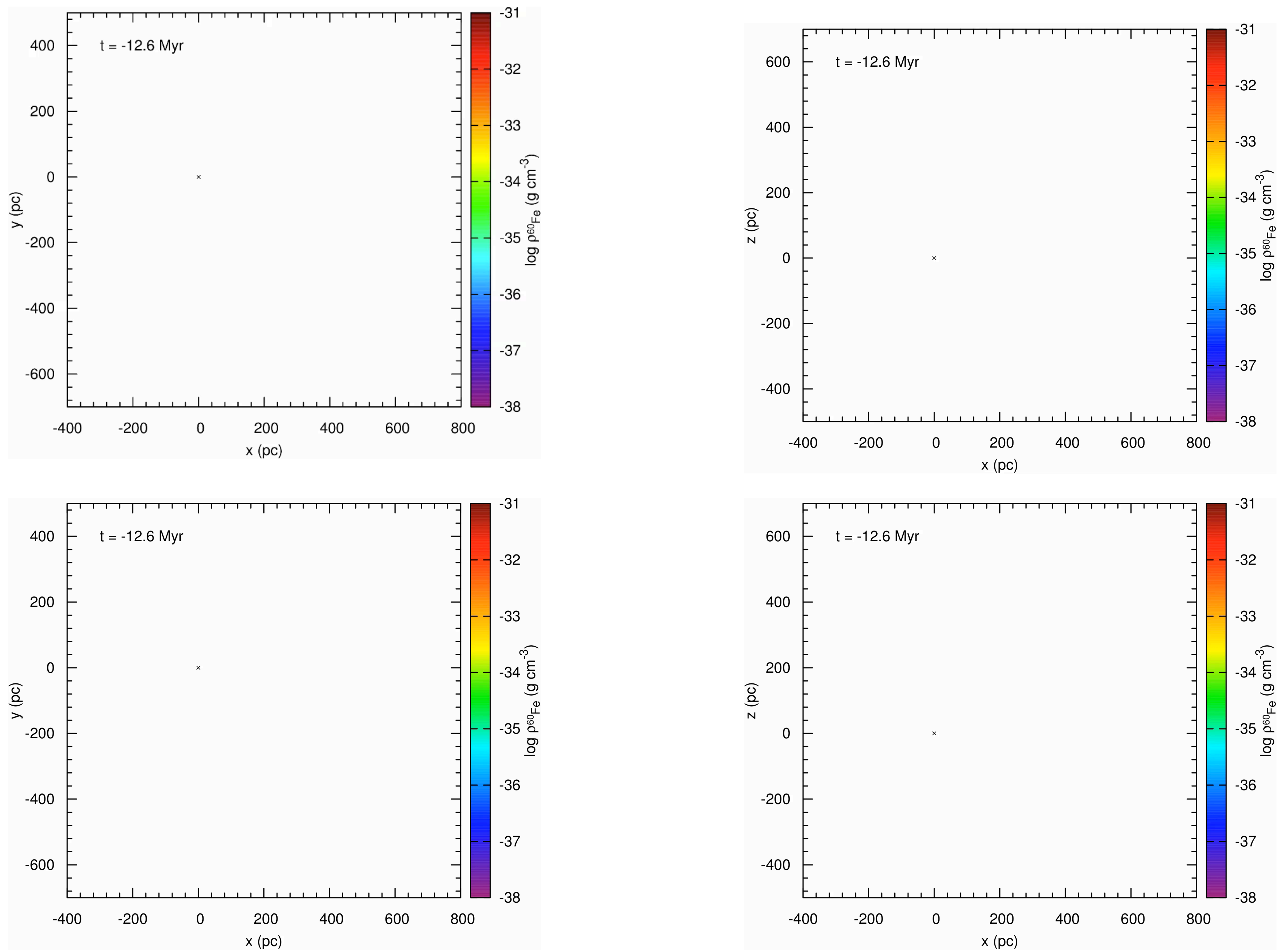


ISM and LB simulations VI

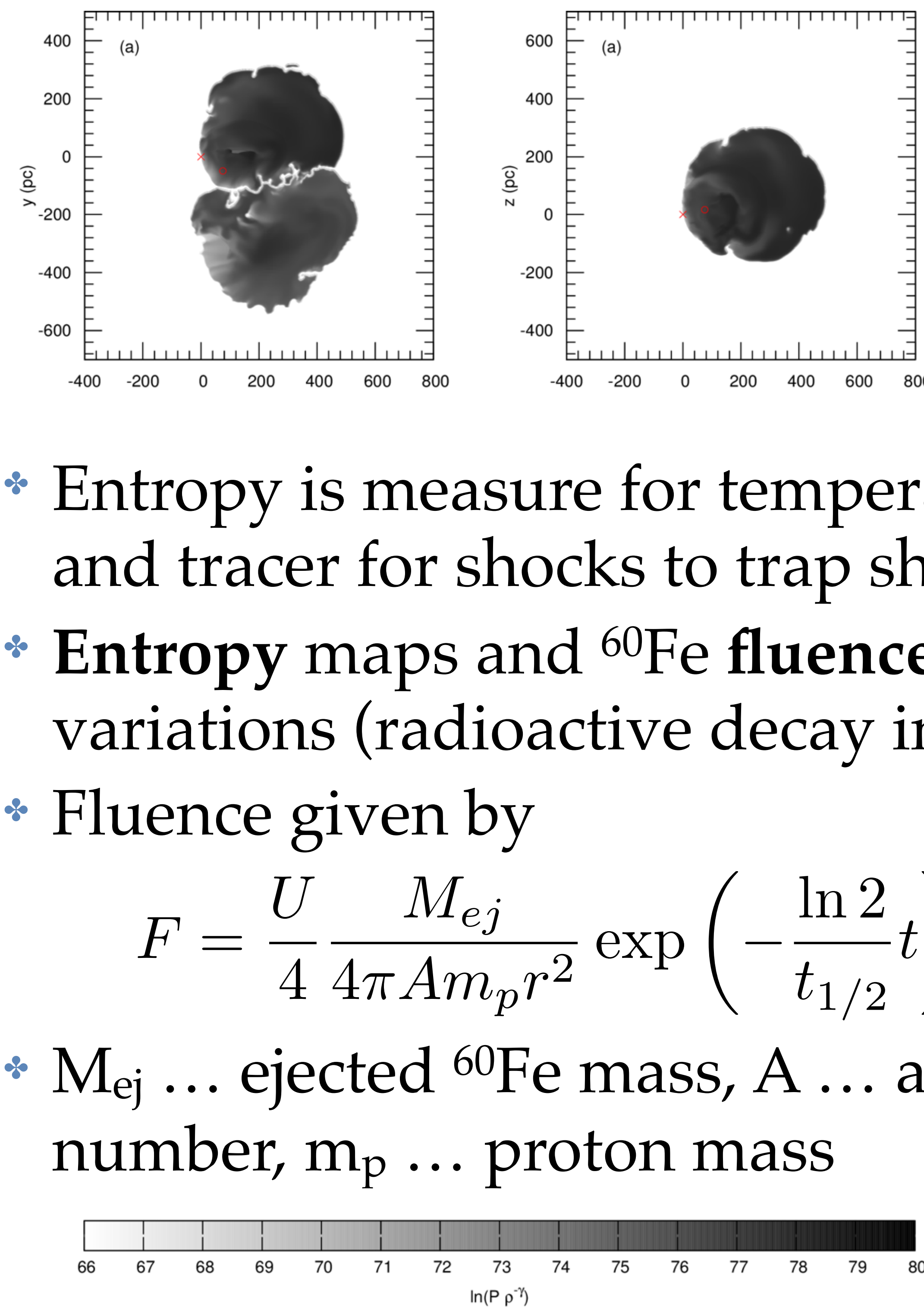
- ^{60}Fe density ϱ_{Fe} integrated over 3rd co-ordinate; t_{ev} =12.6 Myr

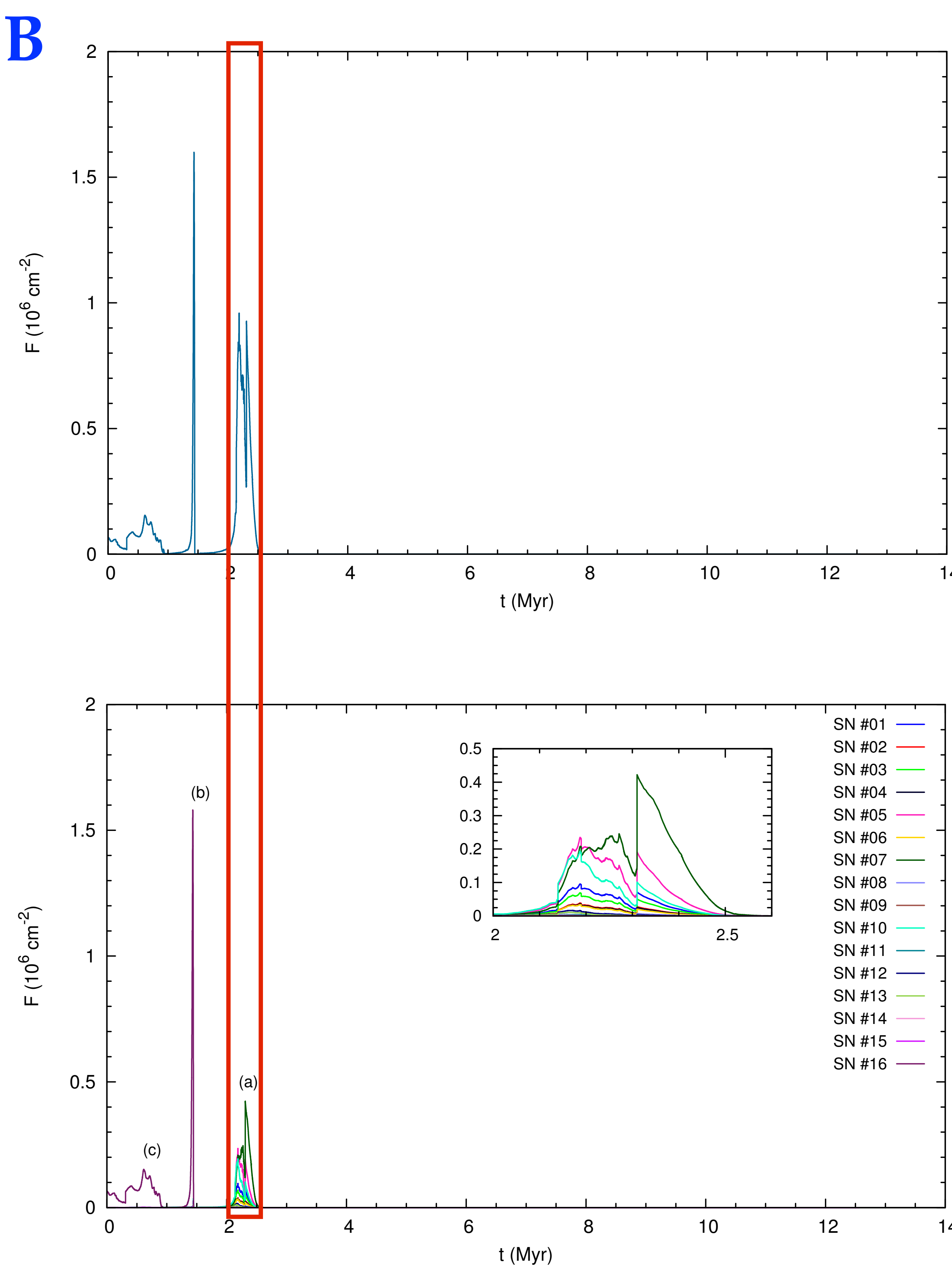
- **Model A** (~ WIM)
- n = 0.1 cm-3
- T = 10^4 K
- Z/Z⊙ = 1
- Δx = 0.7 pc

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



ISM and LB simulations VII



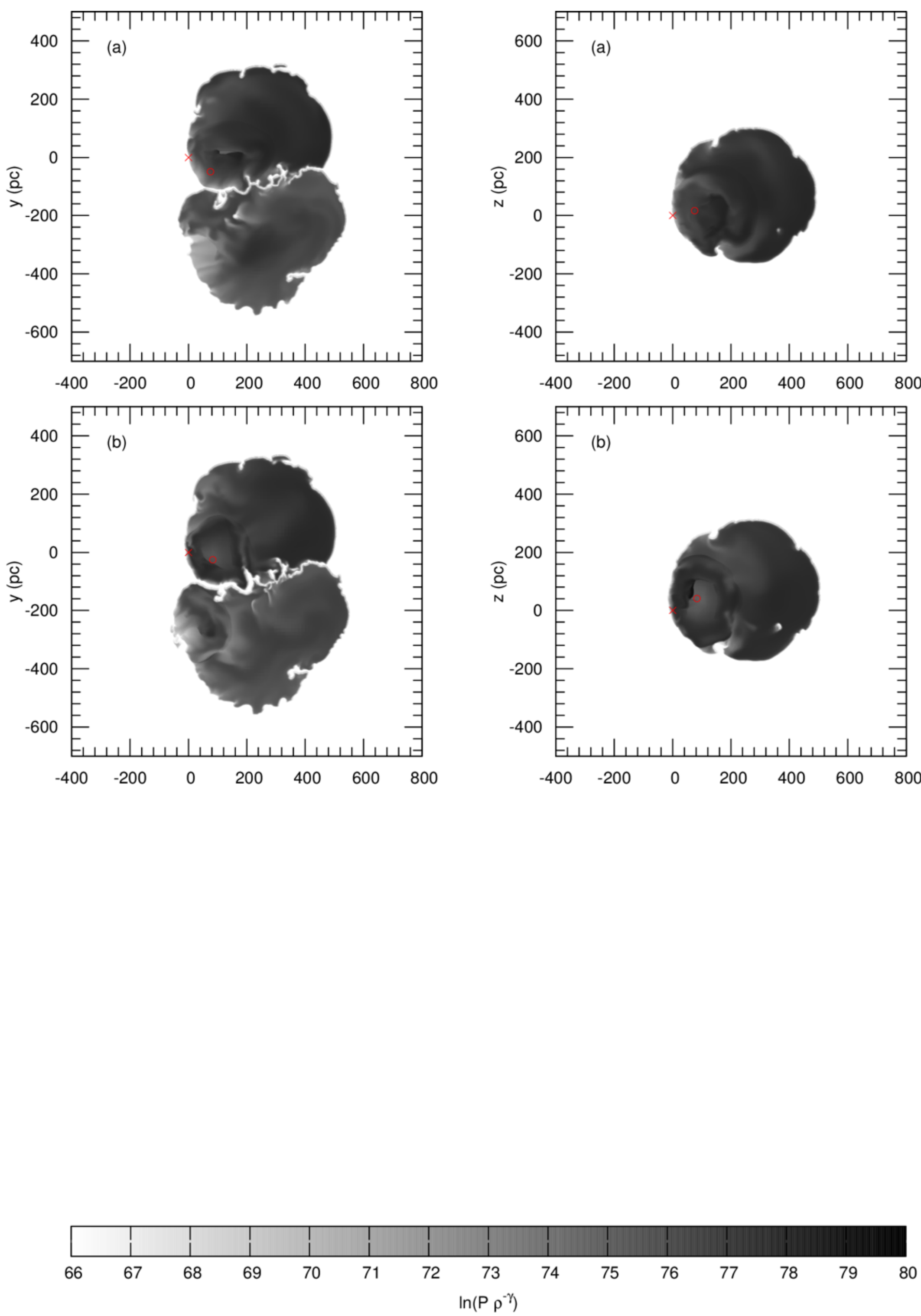


- Entropy is measure for temperature and tracer for shocks to trap shells
- **Entropy** maps and ^{60}Fe **fluence** variations (radioactive decay incl.)
- Fluence given by

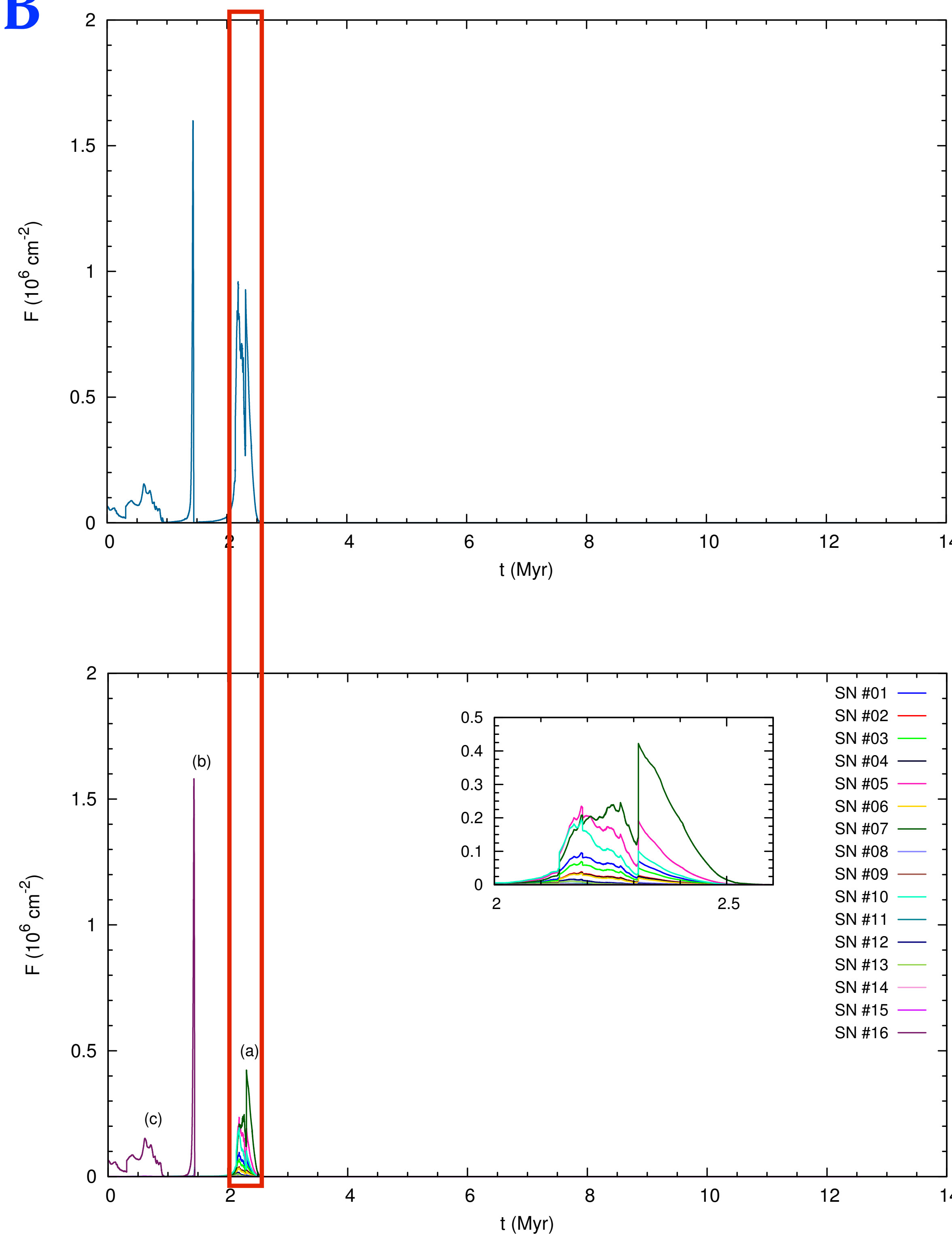
$$F = \frac{U}{4} \frac{M_{ej}}{4\pi A m_p r^2} \exp\left(-\frac{\ln 2}{t_{1/2}} t\right)$$

- M_{ej} … ejected ^{60}Fe mass, A … atomic number, m_p … proton mass

ISM and LB simulations VIII

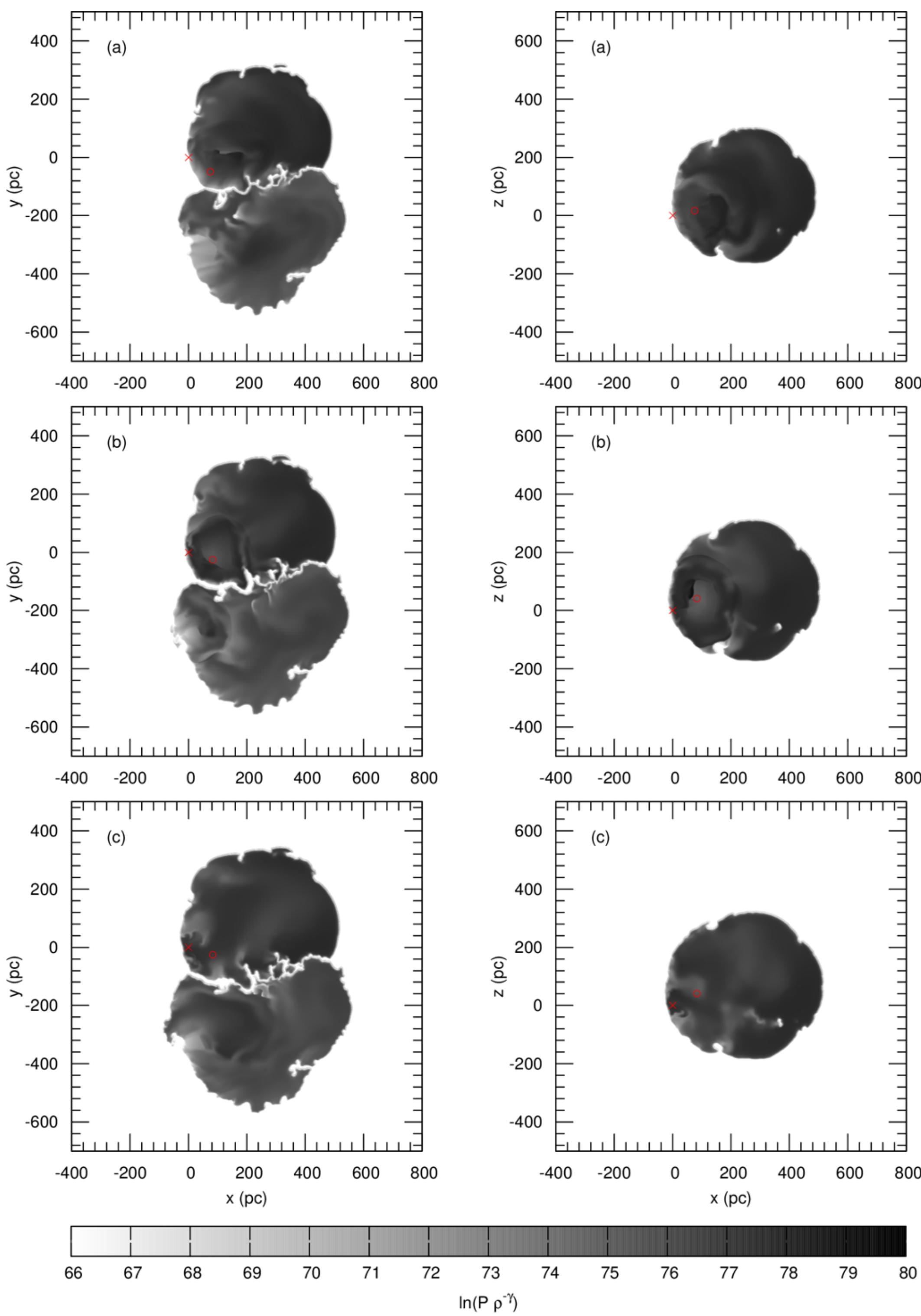


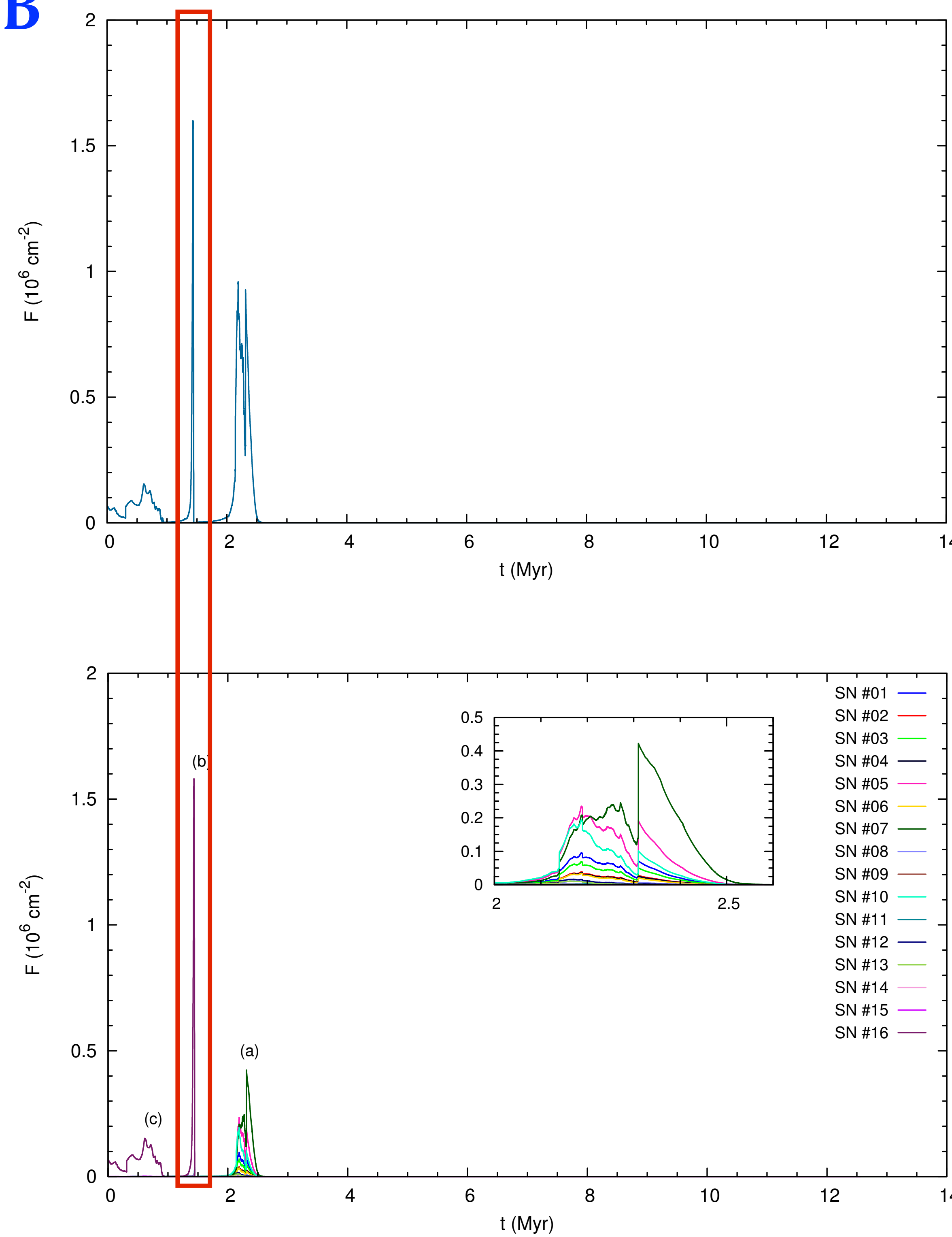
Model B



ISM and LB simulations IX

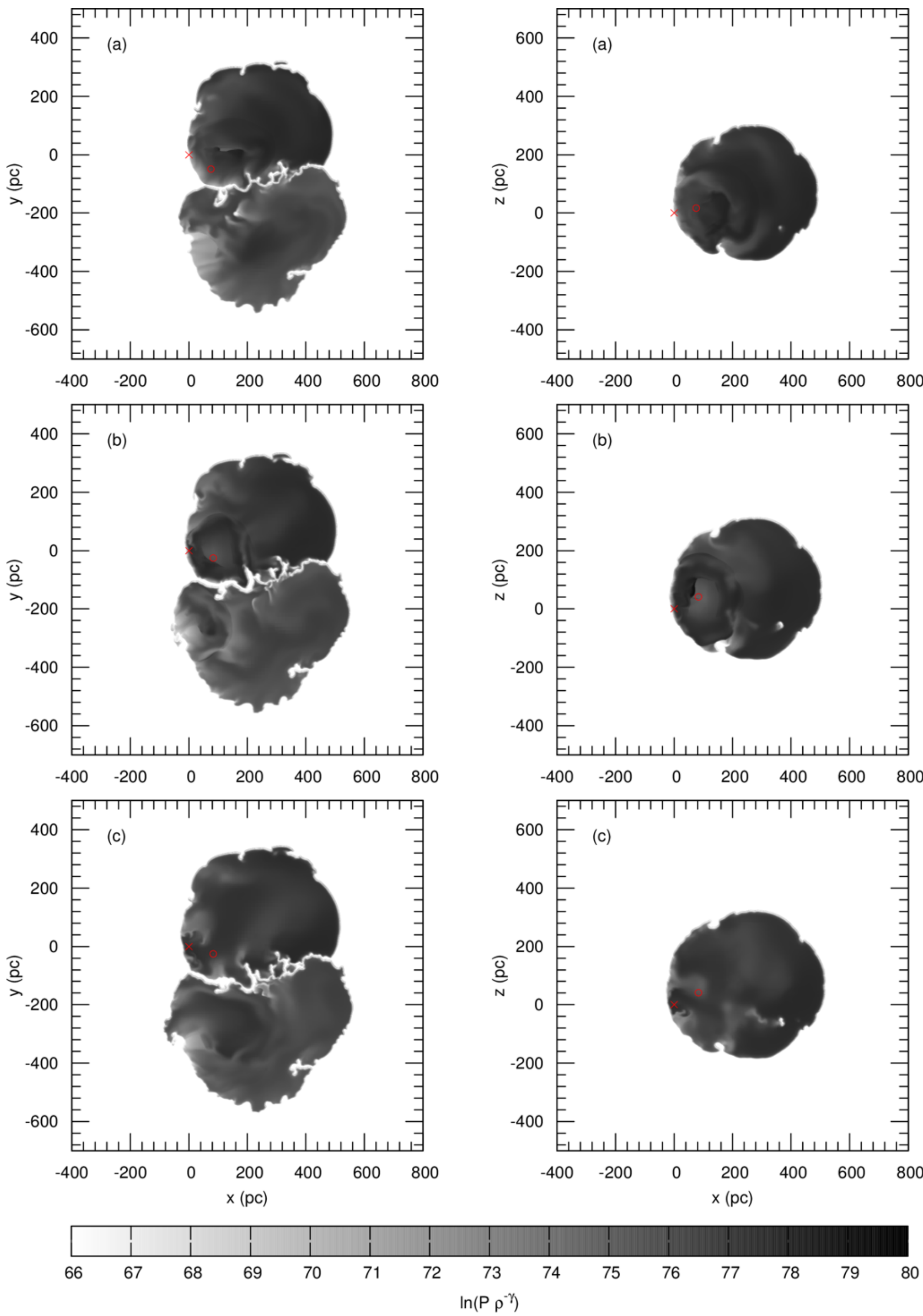
Model B

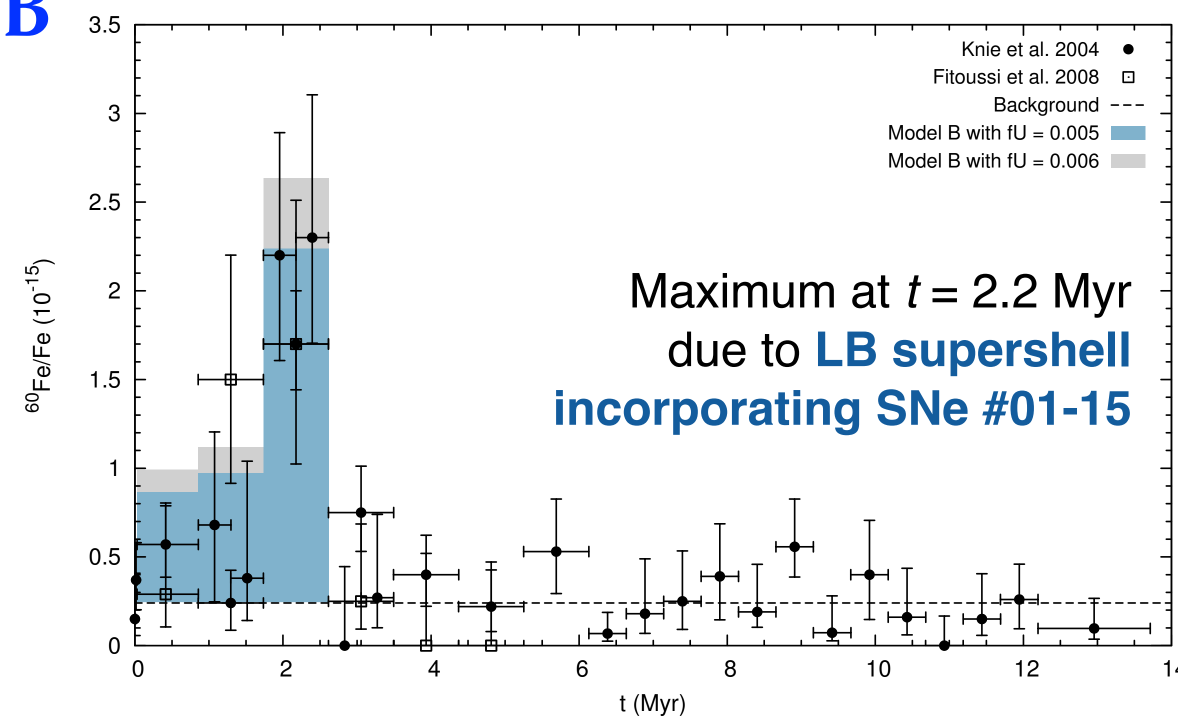


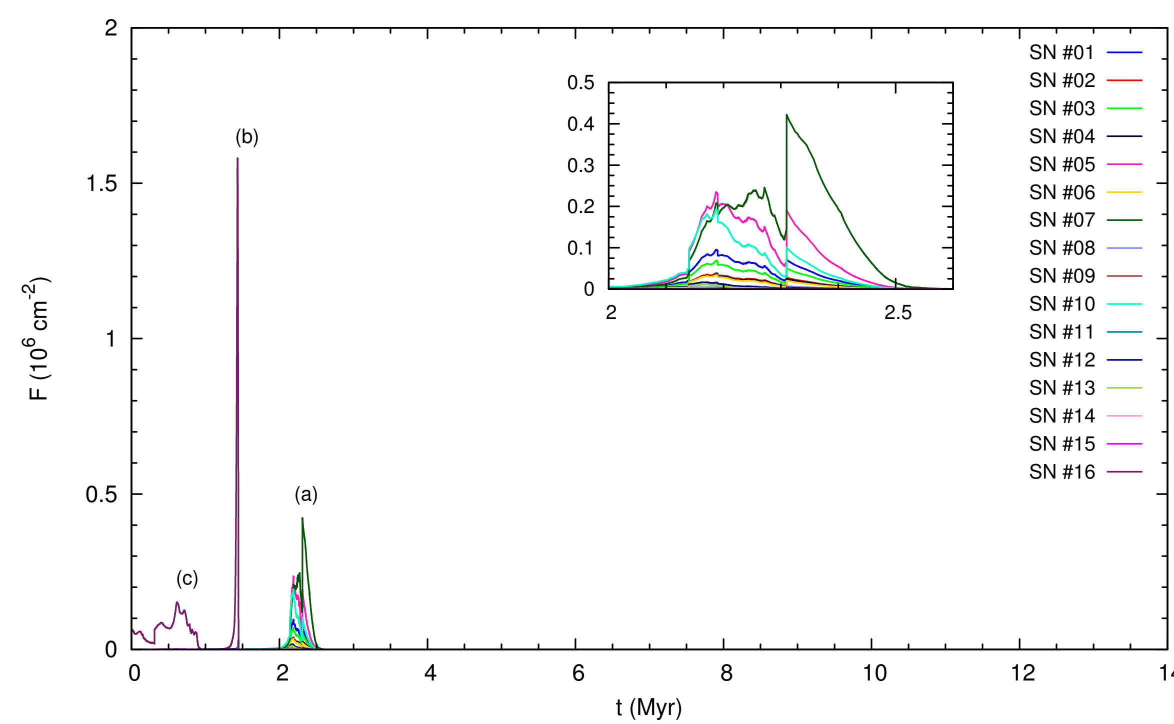


ISM and LB simulations X

Model B

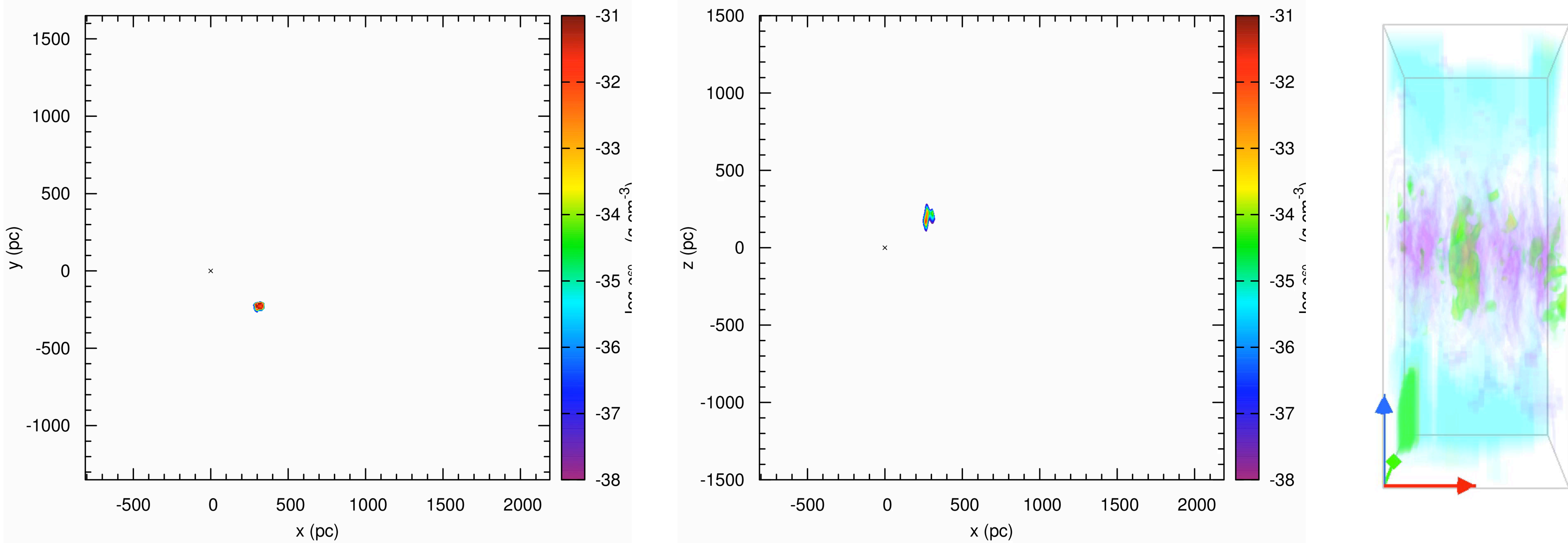






ISM and LB simulations XI

^{60}Fe mass surface density

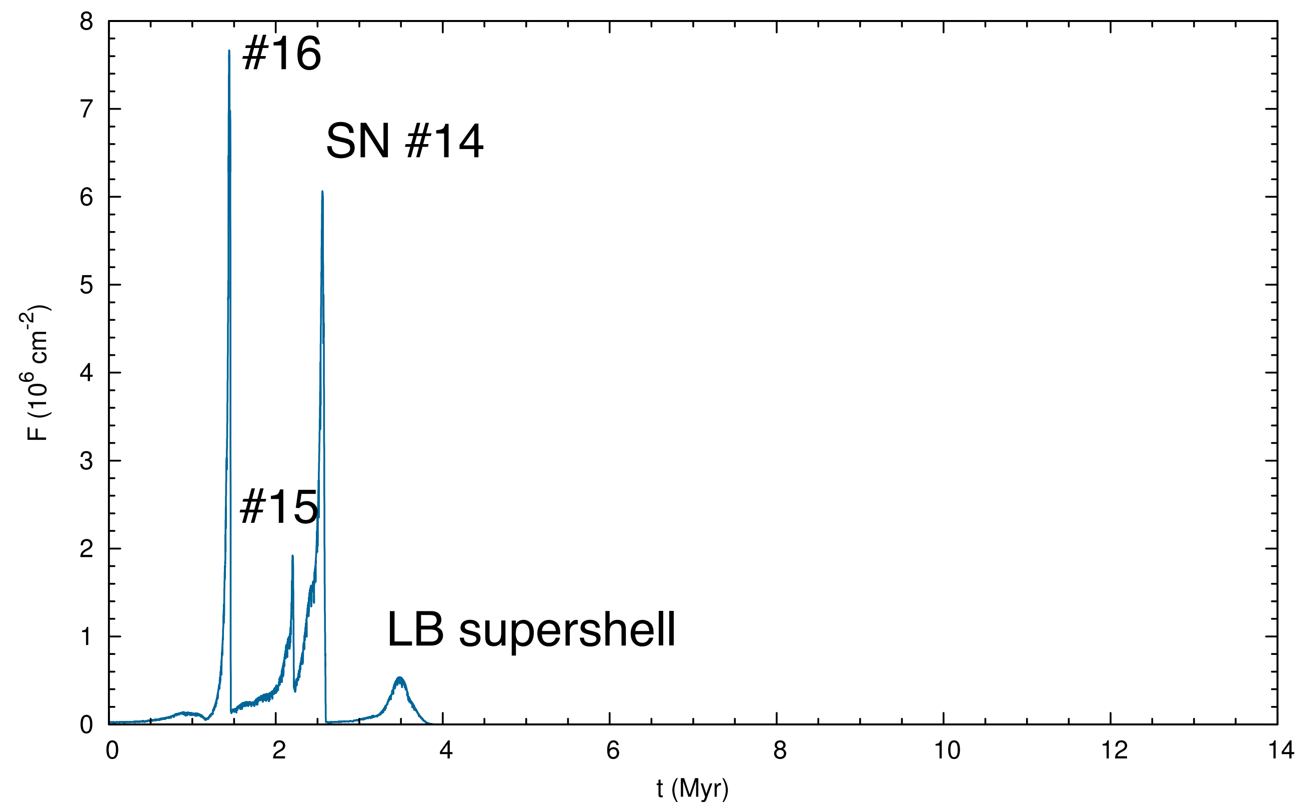


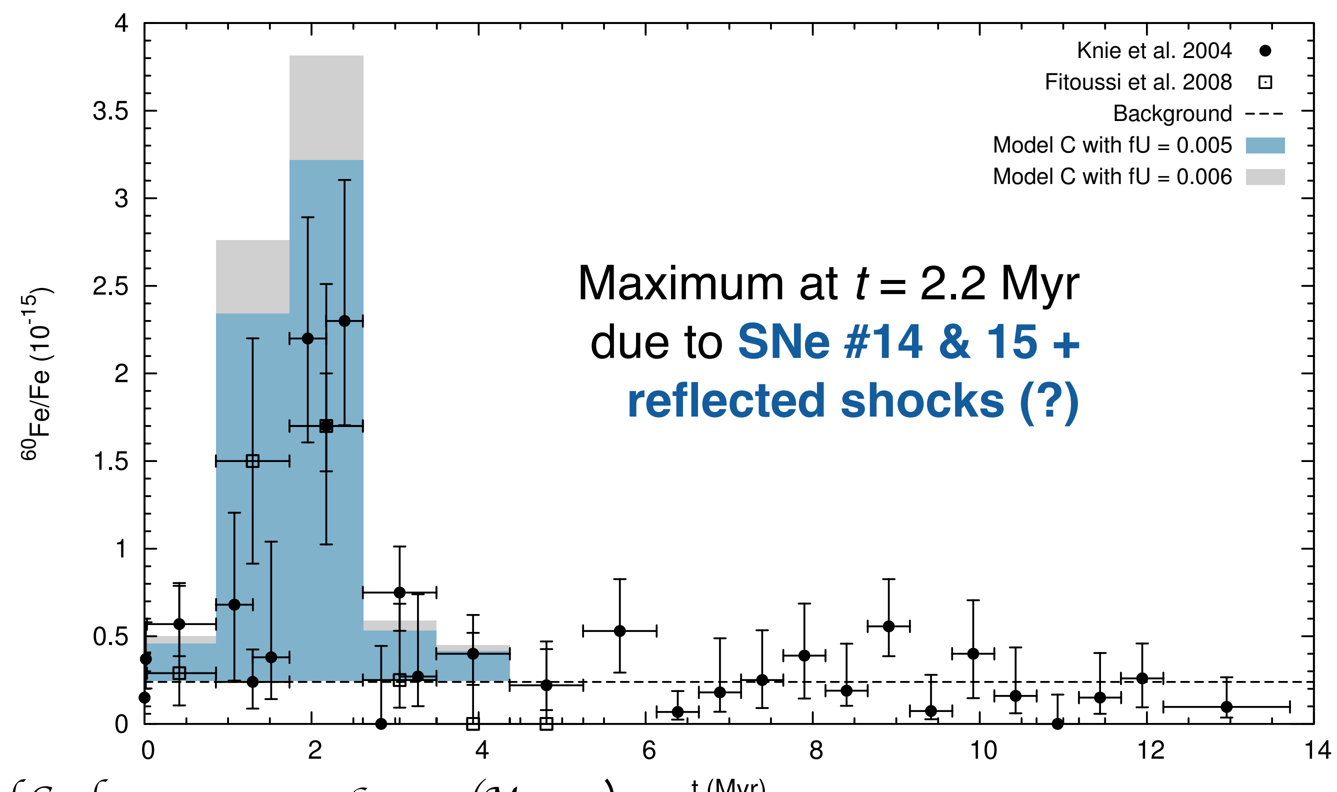
- Model C with **inhomogeneous** background evolved for 150 Myr with SN explosions at Galactic rate
- ^{60}Fe density ϱ_{Fe} integrated over 3rd co-ordinate (z and y); t_{ev} =12.6 Myr

ISM and LB simulations XII

Model C

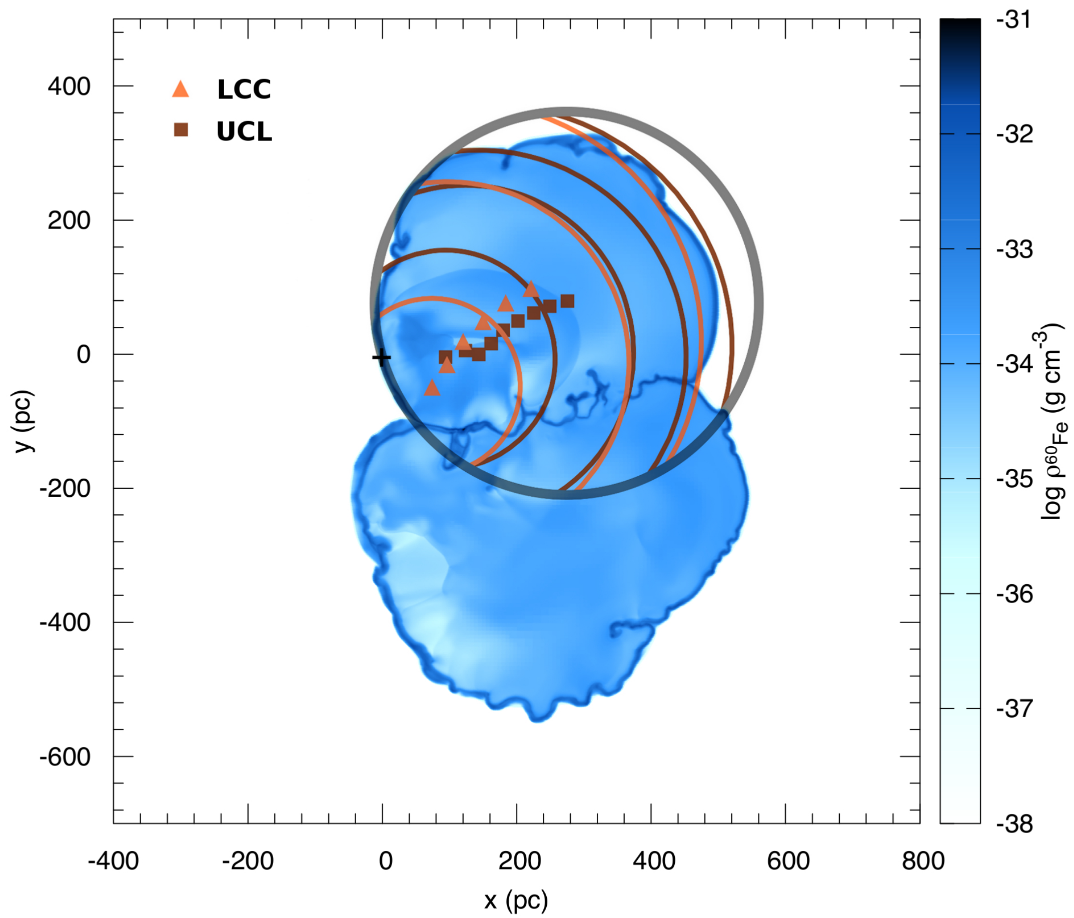
- Model C is a hybrid between A and B
- average number density n = 0.2 cm^{-3}
- Fewer pulses (shells) than A but more than in B
- excellent fit to data (f U = 0.005)

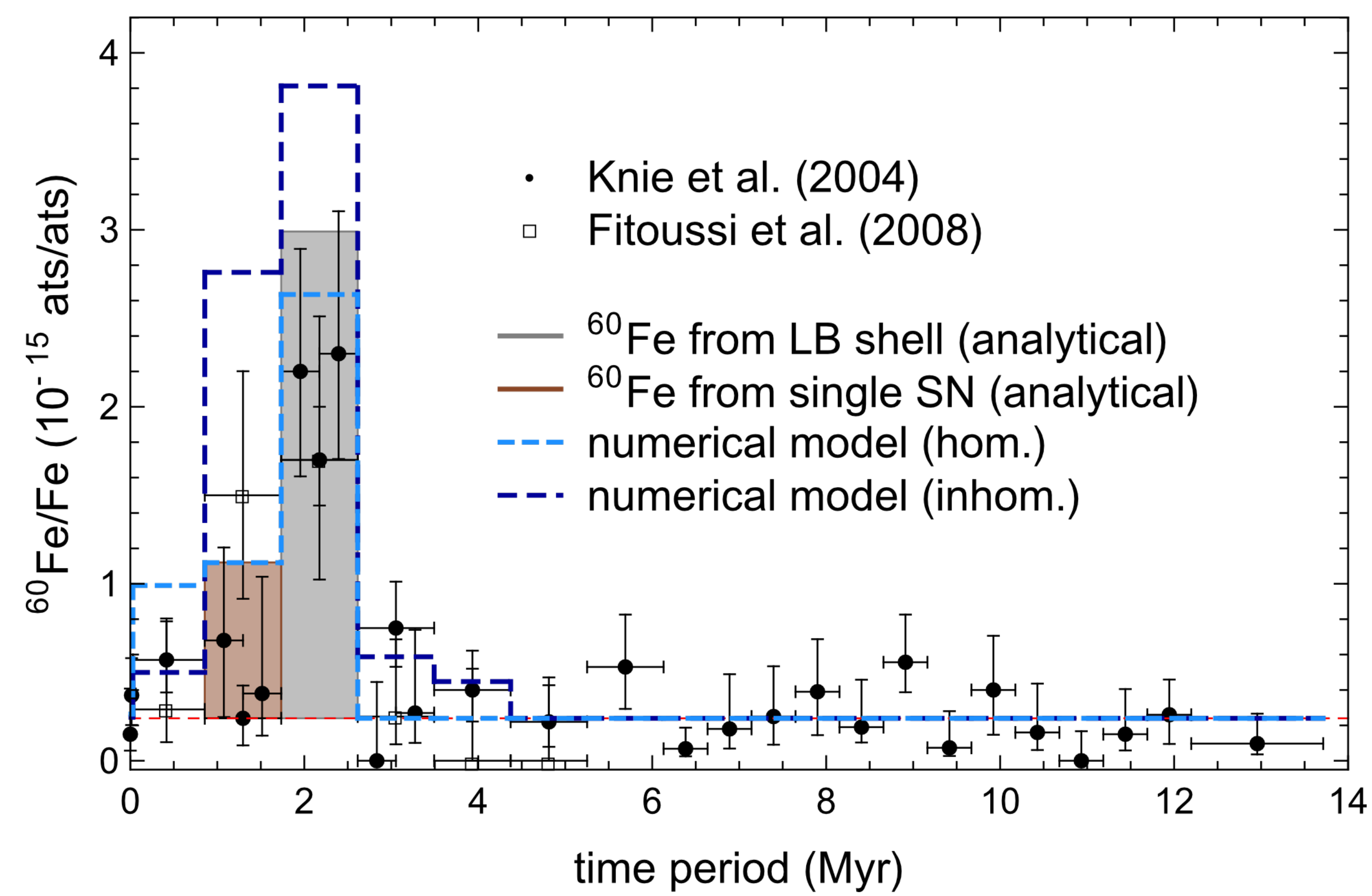




Analytical vs. Numerical Model

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	$-7^\circ09^m$	Oph
-12.0[3]	18.61	5.5	223	99	71	254	23.94	16.22	17^h37^m	$-0^\circ21^m$	Oph
-11.3[2]	17.34	5.0	251	67	87	274	14.95	18.52	17^h12^m	$-6^\circ39^m$	Oph
-10.0[2]	15.41	4.2	227	57	83	248	14.10	19.53	17^h07^m	$-6^\circ48^m$	Oph
-10.0[3]	15.36	4.1	185	77	67	211	22.60	18.49	17^h27^m	$-0^\circ23^m$	Oph
-8.7[2]	13.89	3.6	203	45	79	222	12.50	20.80	17^h00^m	$-7^\circ23^m$	Oph
-8.0[3]	13.12	3.4	151	49	57	169	17.98	19.75	17^h14^m	$-3^\circ34^m$	Oph
-7.5[2]	12.65	3.3	181	31	75	198	9.72	22.22	16^h49^m	$-8^\circ46^m$	Oph
-6.3[2]	11.62	3.0	163	11	73	179	3.86	24.10	16^h30^m	$-12^\circ03^m$	Oph
-6.1[3]	11.48	2.9	121	19	47	131	8.92	20.99	16^h52^m	$-10^\circ04^m$	Oph
-5.0[2]	10.76	2.7	145	-5	69	161	-1.97	25.43	16^h12^m	$-15^\circ19^m$	Sco
-4.2[3]	10.21	2.6	97	-15	33	104	-8.79	18.58	16^h16^m	$-24^\circ35^m$	Sco
-3.8[2]	10.02	2.6	125	1	51	135	0.46	22.19	16^h28^m	$-15^\circ40^m$	Oph
-2.6[2]	9.37	2.4	95	-9	47	106	-5.41	26.22	16^h01^m	$-17^\circ05^m$	Lib
-2.3[3]	9.21	2.4	75	-49	17	91	-33.16	10.74	15^h10^m	$-45^\circ35^m$	Lup
-1.5[2]	8.81	2.3	83	-25	41	96	-16.76	25.31	15^h32^m	$-24^\circ44^m$	Lib

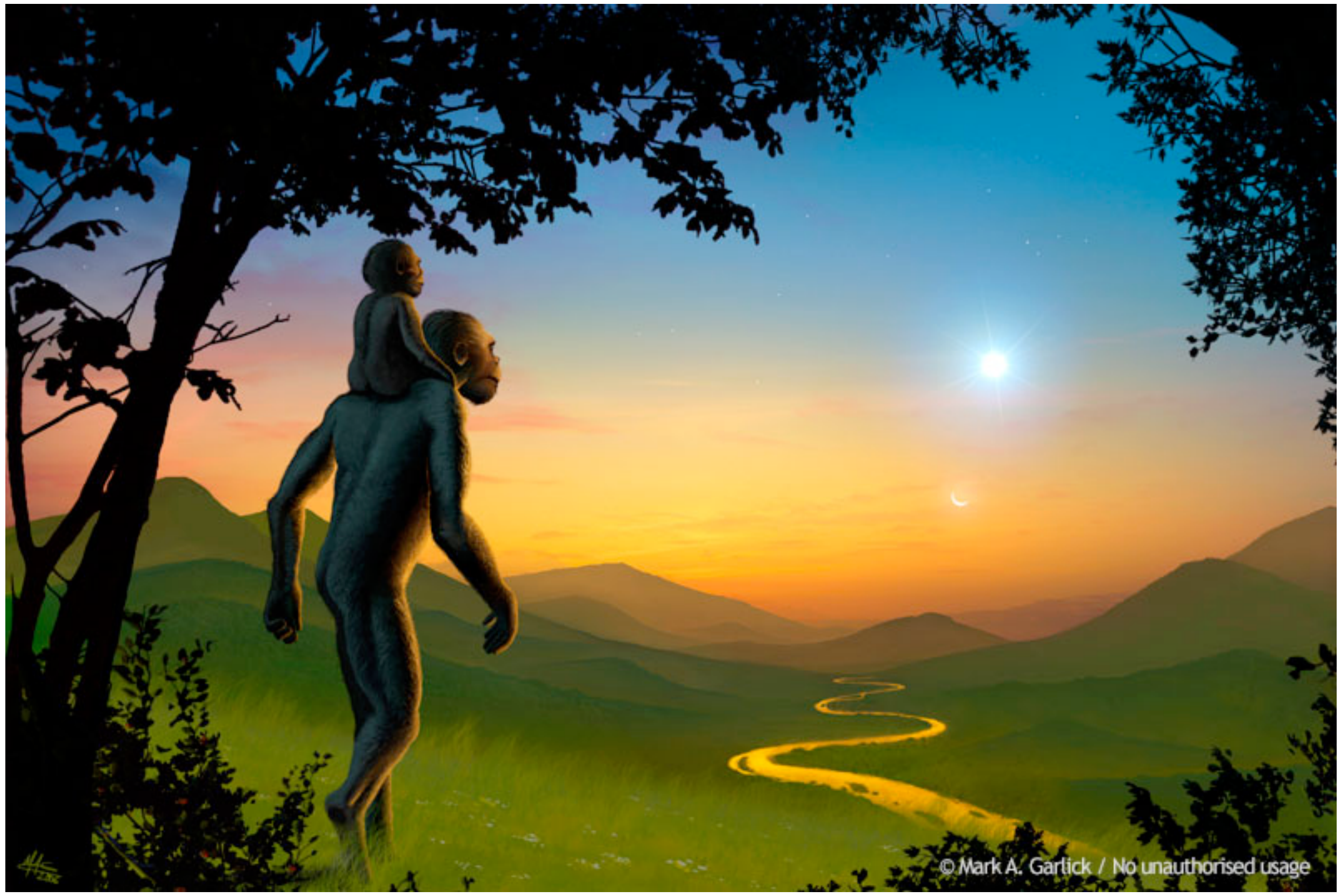
Effects of Near-Earth SNe I - some speculations -

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

  ➜ would lead to ionisation of atmosphere

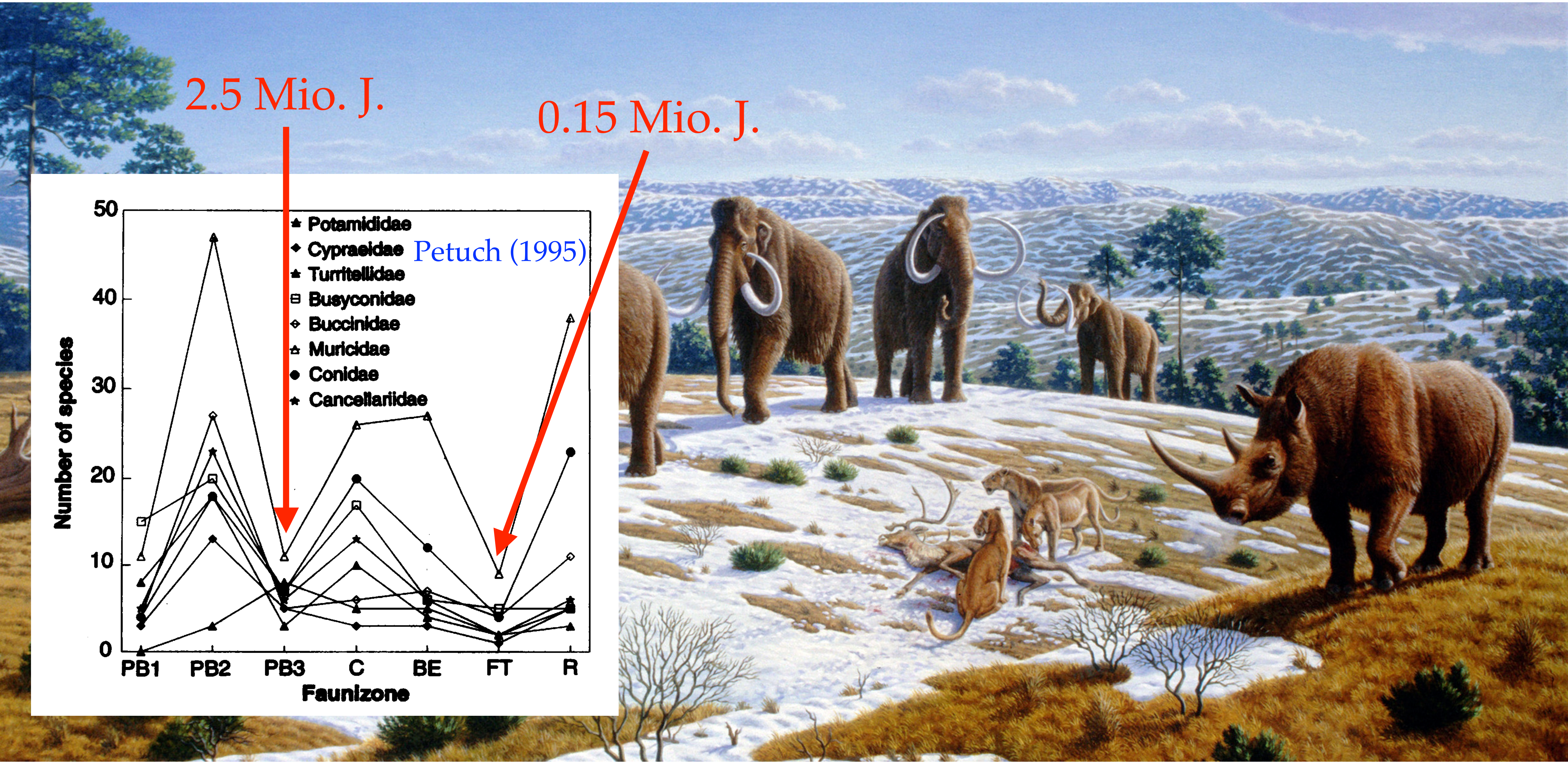
  ➜ NO_x formation ➜ ozone layer destruction ➜ increased solar UV radiation ➜ damage of DNA / cells
- X- and γ-ray flux too low for mass extinction, but long-term mutations?
- Cosmic ray flux significantly higher

  ➜ 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

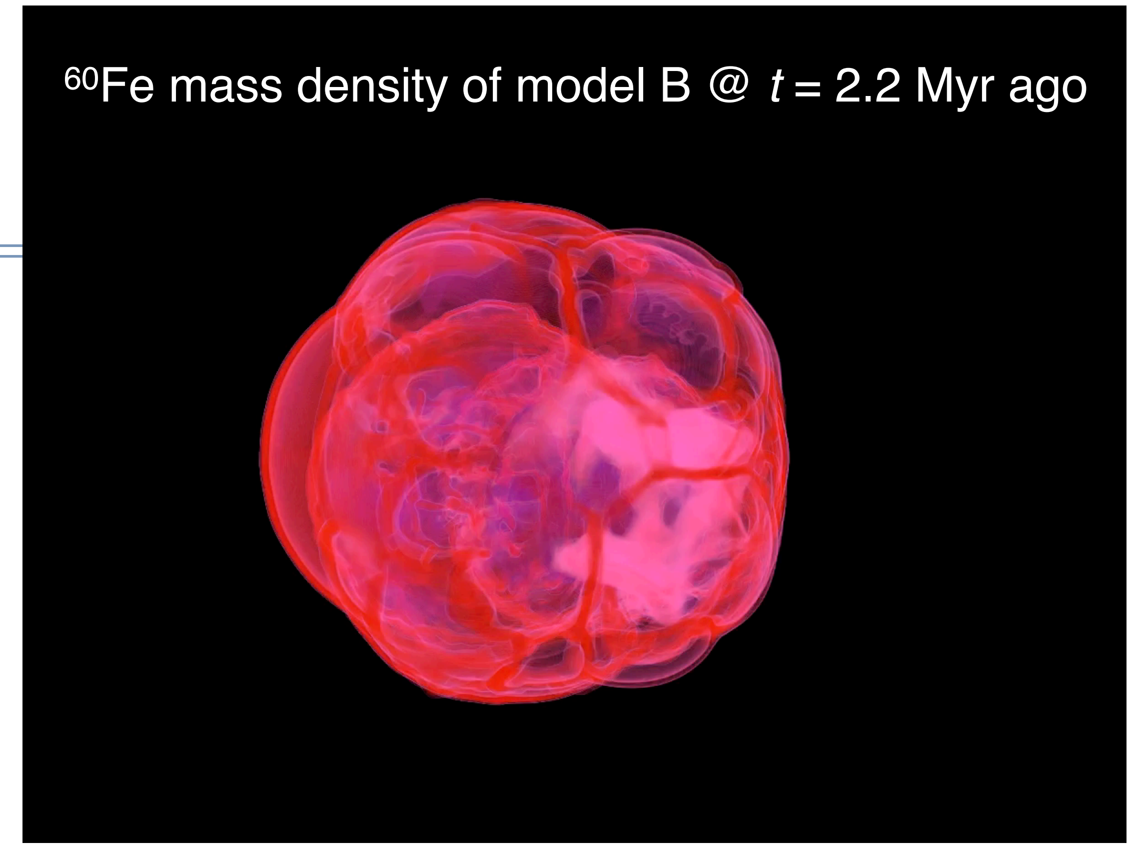
Effects of Near-EarthSNe II

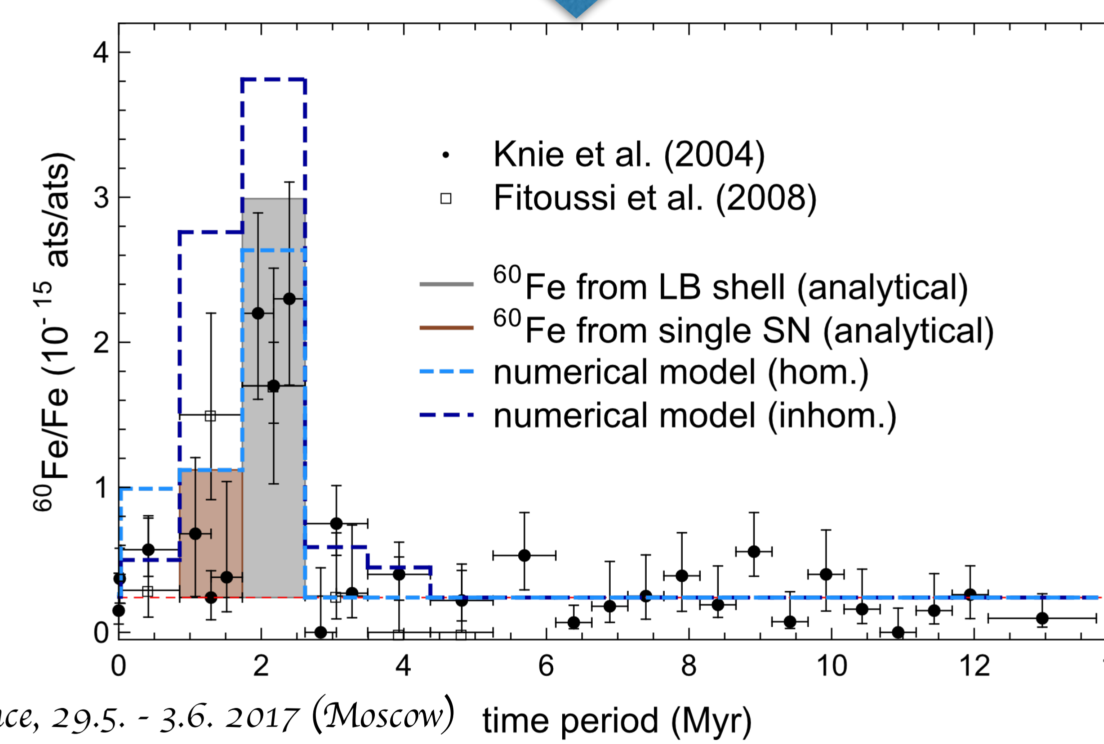


- increase in glaciation down to mid-latitudes
- only dominant species survived ➜ among hominini: homo erectus ➜ direct ancestor of homo sapiens (Africa) and Neanderthals (Europe)

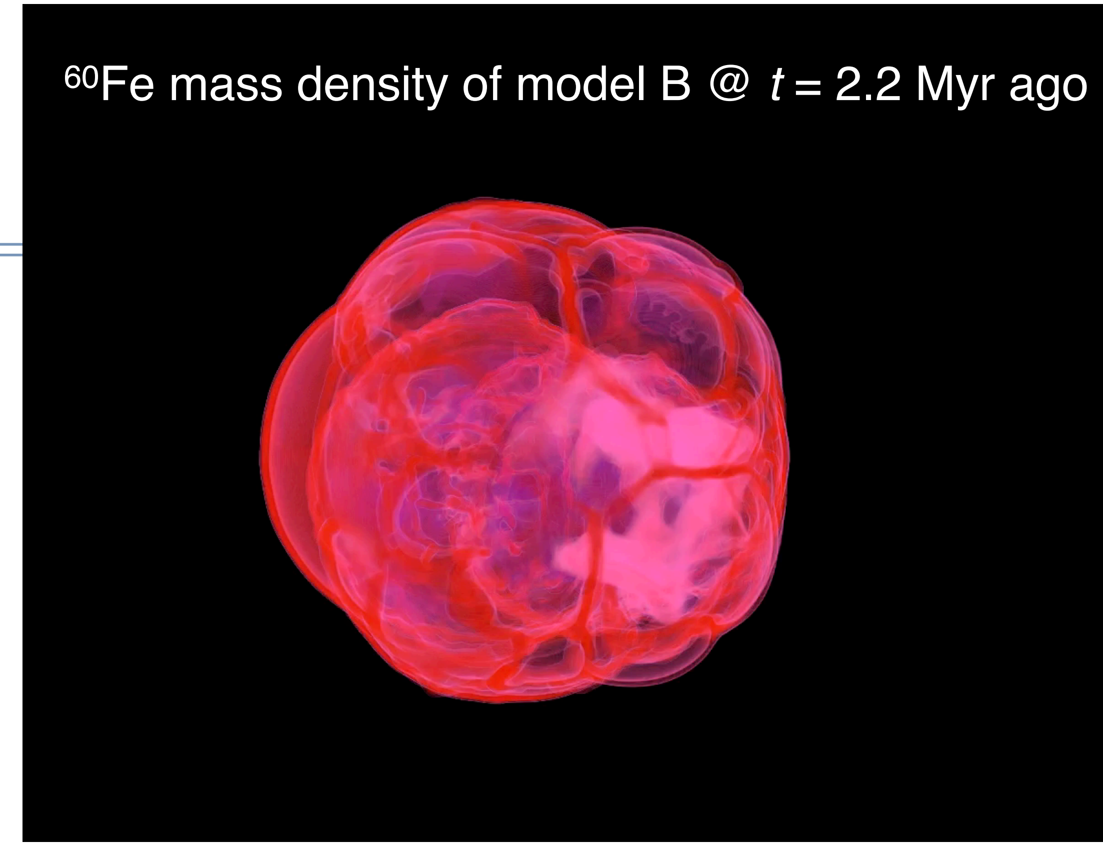
2nd Summary

- We found SNe responsible for **both** the **LB and ^{60}Fe deposition** on Earth
- ^{60}Fe ejected by SN explosions, mixed and transported to Earth by ISM turbulence
- 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

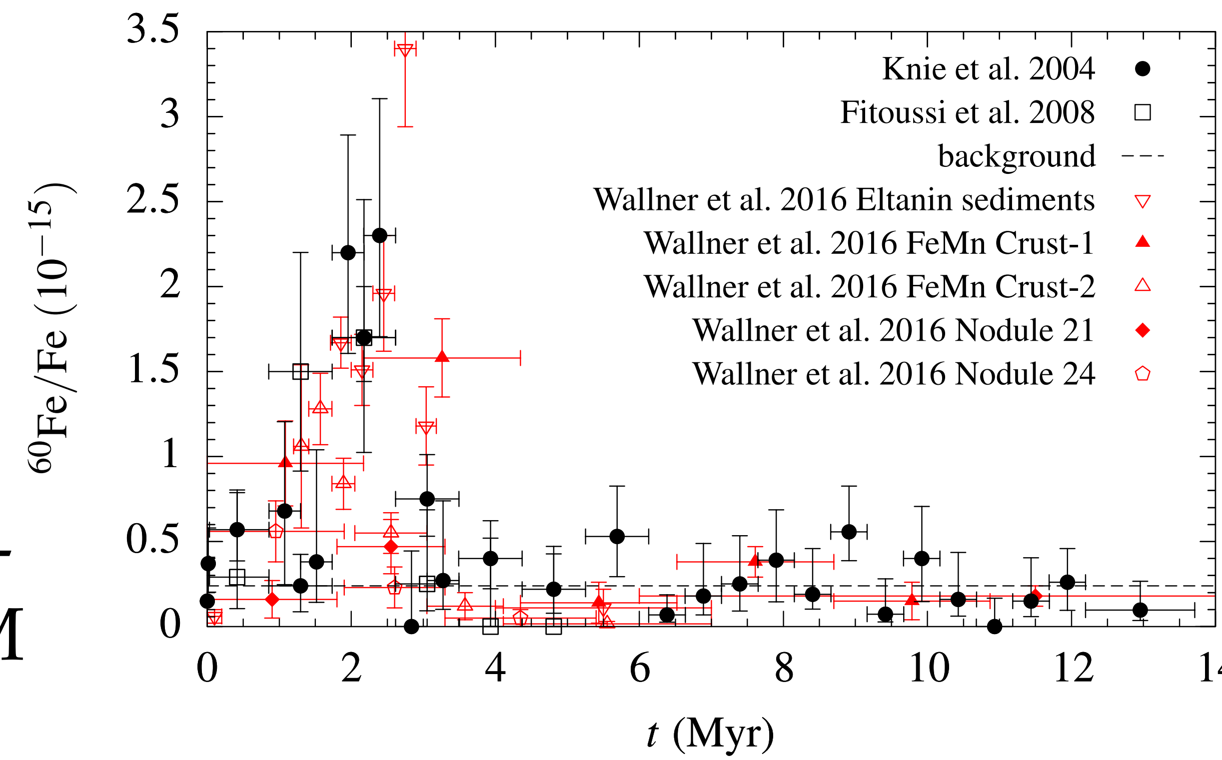




2nd Summary cont.



- 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 (s. Avillez & Breitschwerdt, 2012)
- Use radioactive tracers, deep-sea astronomy and stellar dynamics to uncover LISM history ➜ **local galactic archaeology**



Media Response

- Breitschwerdt, D., Feige, J., Schulreich, M. M., de Avillez, M. A., Dettbarn, C. 2016, Nature, 532, 73
- Schulreich, M. M., Breitschwerdt, D., Feige, J., Dettbarn, C. 2016, A&A, submitted
- Schulreich, M. M. & Breitschwerdt, D. 2016, A&A, in prep.

German quiz show “Wer weiß denn sowas?” (July 2016)

Thank you for your patience and attention!

How could scientists prove that our Earth has recently seen several supernovae?

A) by multiply coloured meteorite craters
B) by pulverised dinosaur bones
C) by star dust on the ocean floor