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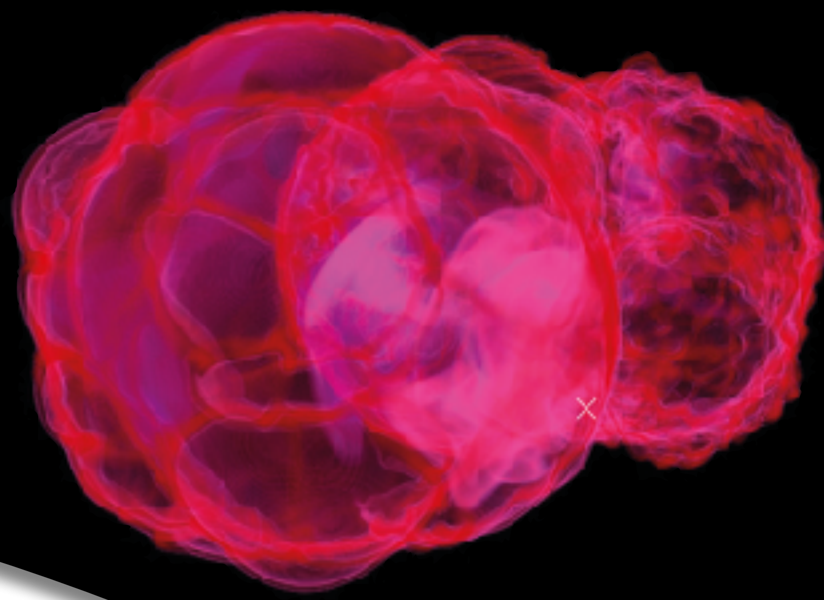

Supernovae and the Local Bubble

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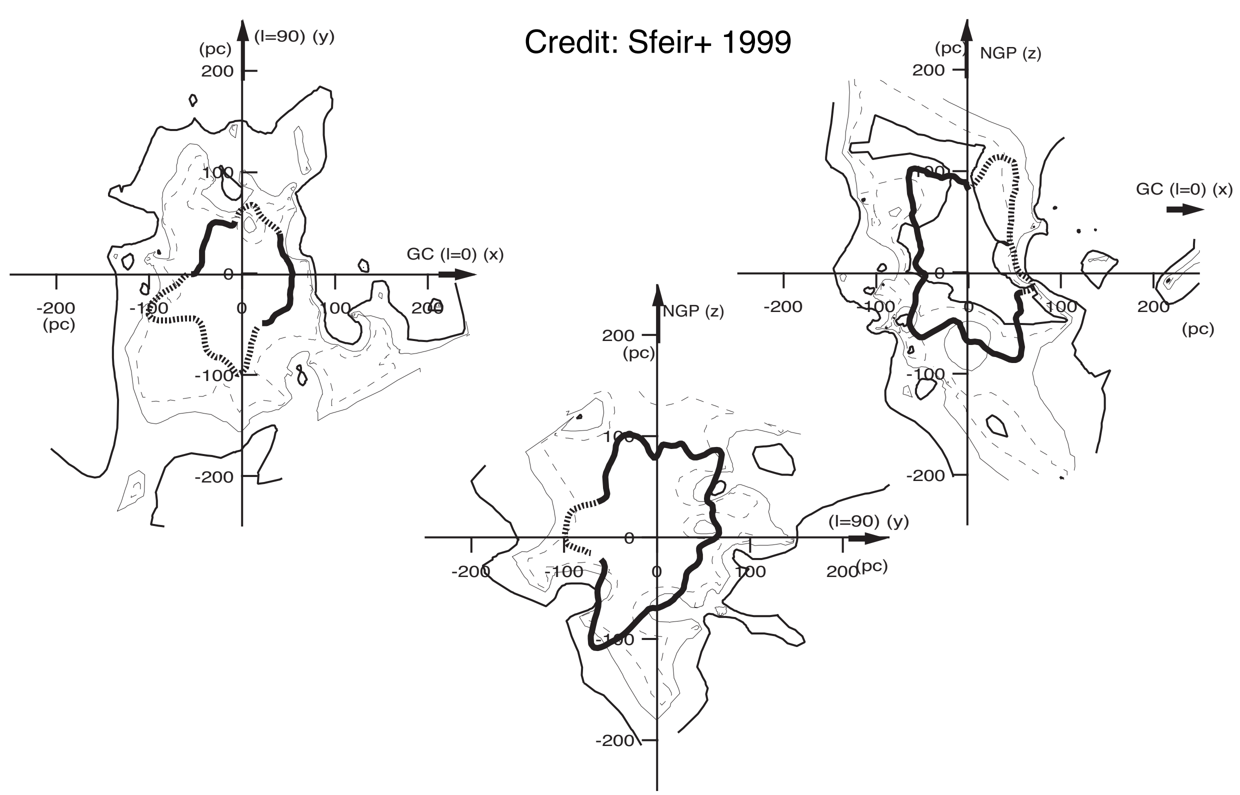
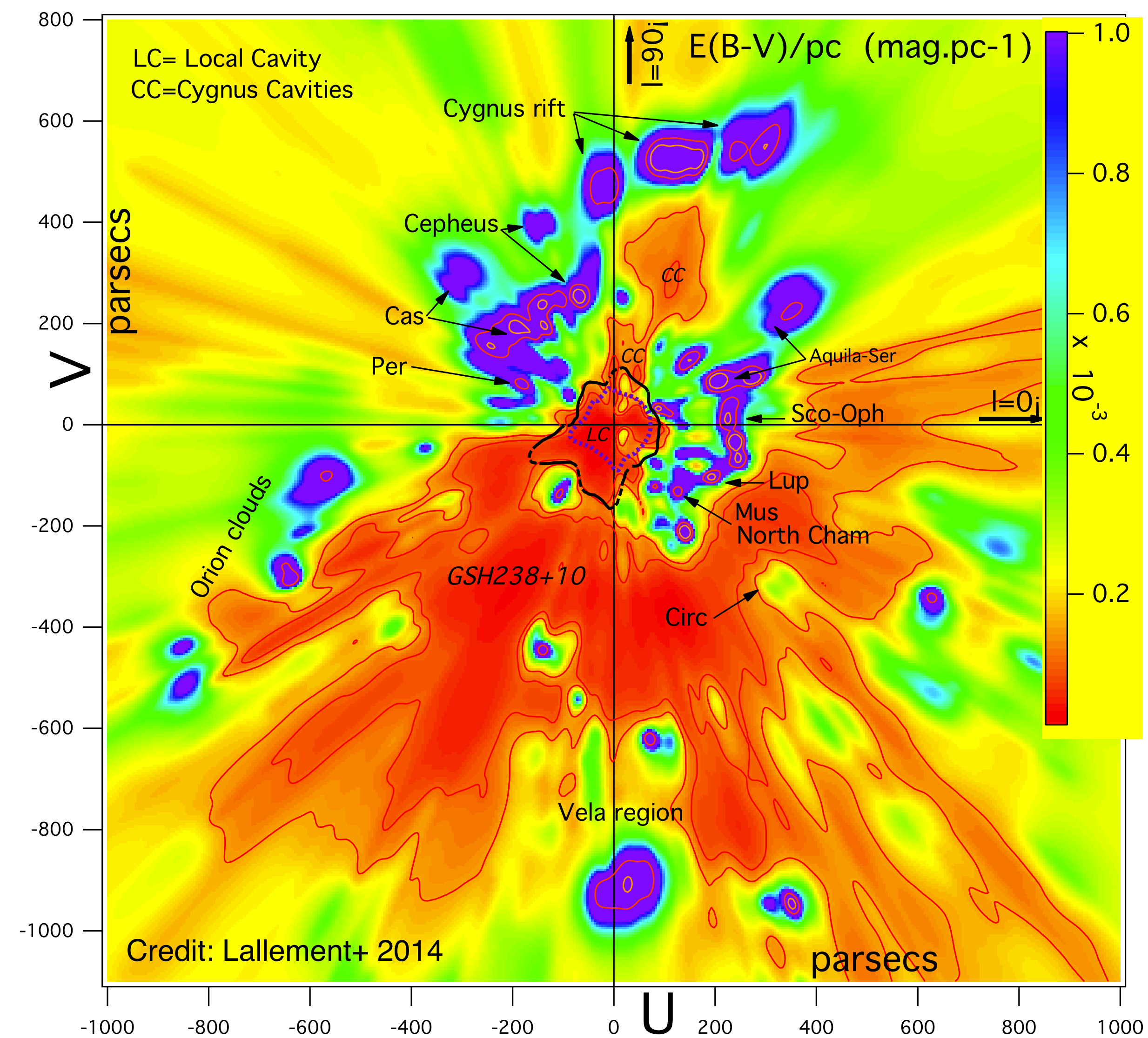
The discovery of the Local Bubble (LB)

- Color excess measurements (Fitzgerald 1968)
  - Sun situated in interstellar dust hole (~ 50 × 100 pc)
- Sounding rocket flights (Mc Cammon & Sanders 1990): Mappings of diffuse **soft** X-ray background
  - due to energy dependent absorption: plasma must be **local**
- Lyman α absorption from nearby hot star spectra
  - HI deficient hole (anti-correlation!)
  - **Displacement model** (Sanders+ 1977; Snowden+ 1991): hot plasma (~ 10^6 K) **pushes HI gas away**

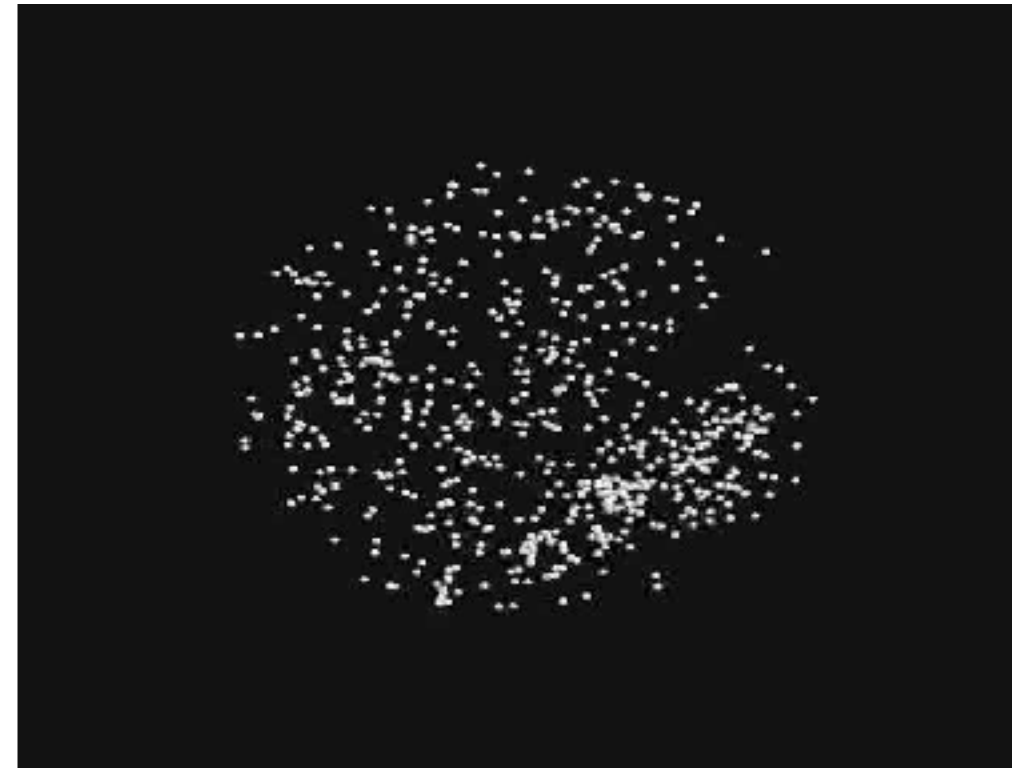


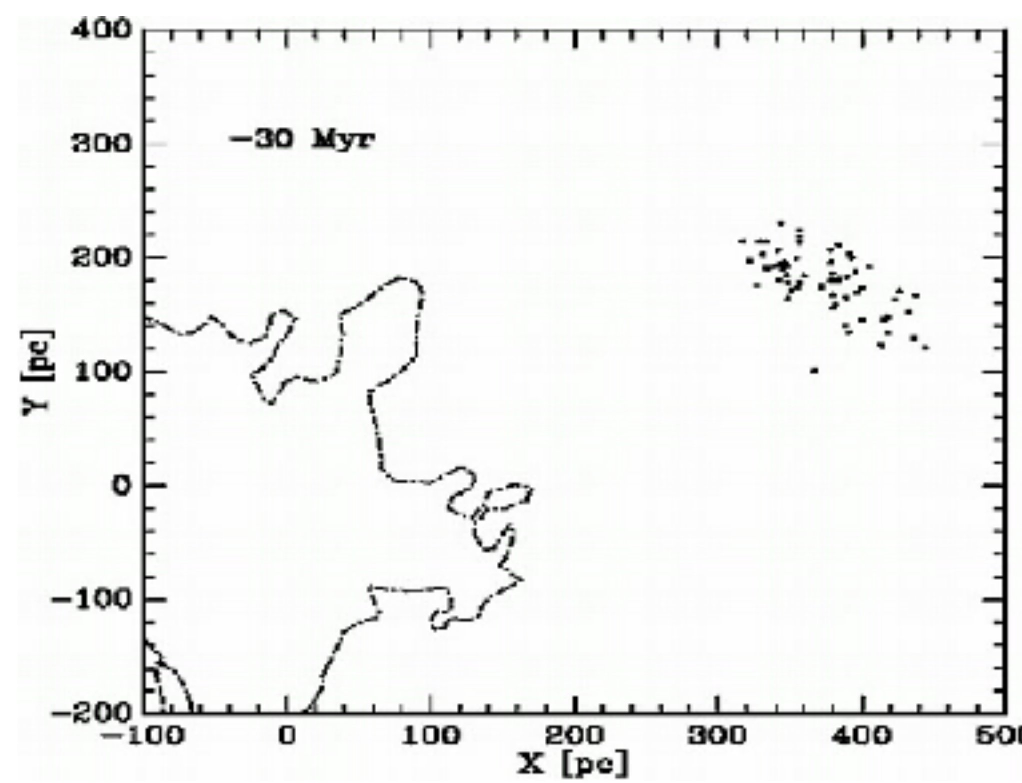
- Further constraints for the LB dimensions from …
  - ROSAT "shadowing experiments" (Snowden+ 1998)
  - NaI absorption lines towards hundreds of stars with known parallaxes (Sfeir+ 1999, Lallement+ 2003) ➔ R ~ 60–250 pc (in Gal. plane); open towards poles? ➔ local chimney?; Welsh+ 1999)



The origin of the Local Bubble

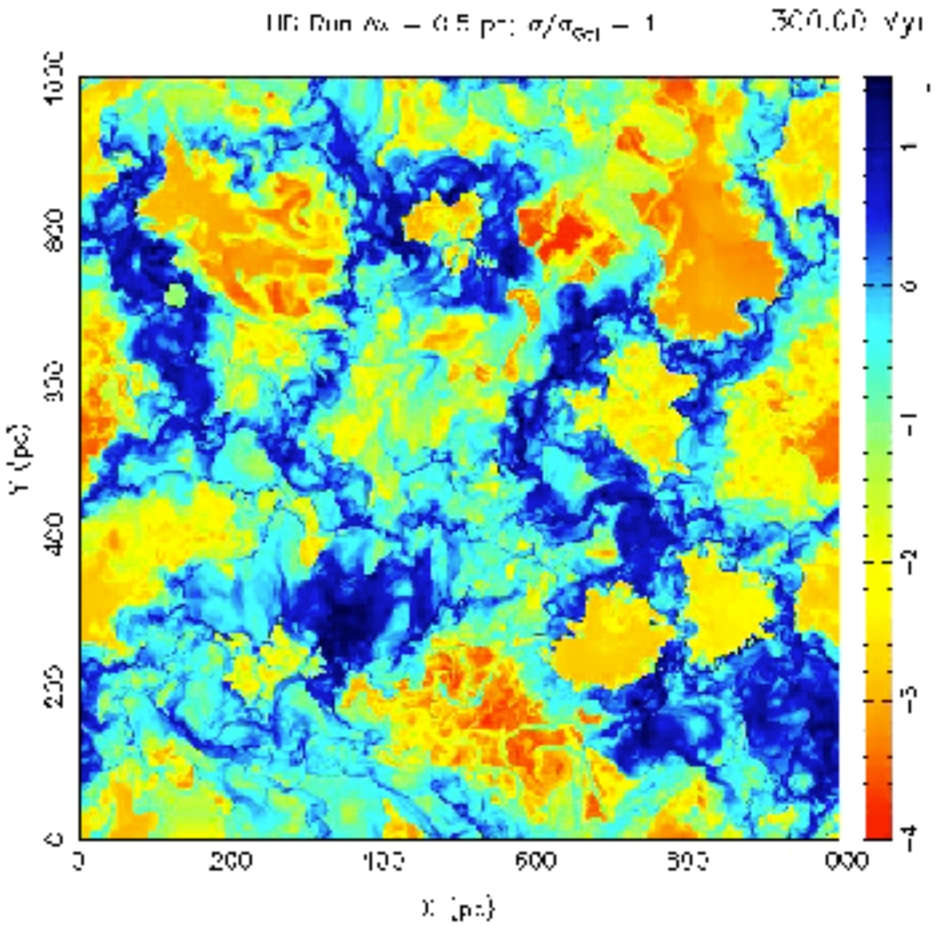
- LB is result of local SN explosions (e.g., Cox & Smith 2001)
- **"Smoking gun" problem:** no young cluster near solar system
- Search for moving group (Berghöfer & Breitschwerdt 2002) ➔ Pleiades subgroup B1
- Fuchs+ (2004) analysed volume complete sample ($D \sim 400$ pc) using HIPPARCOS and ARIVEL (x-p) phase space data
- Selection criterion: compact in real & vel. space ➔ 79 B stars
- **Cluster age:** compare to isochrones in CMD ➔ $\tau_c \sim 20$–30 Myr
- **COM-trajectory** derived from epicyclic eqs.
- Stars entered LB at $\Delta\tau \sim 10$–15 Myr ago
- **Most probable trajectories:** using Gaussian error distr.
- **MS lifetime** of SN progenitors: $\tau = 1.6 \times 10^8 \, (M/M_\odot)^{-0.932}$ yr (for $2 \leq M/M_\odot \leq 67$)
- **Number of past SNe:** IMF (1 star per bin!) for young massive stars (Massey+ 1995) ➔ 14–20 SNe exploding inside LB
- **Explosion times:** $t_{exp} = \tau - \tau_c$ (Assume: coeval star formation)
- Combining most probable trajectories & explosion times ➔ **most probable explosion sites**





Credit: Fuchs+ (2006)

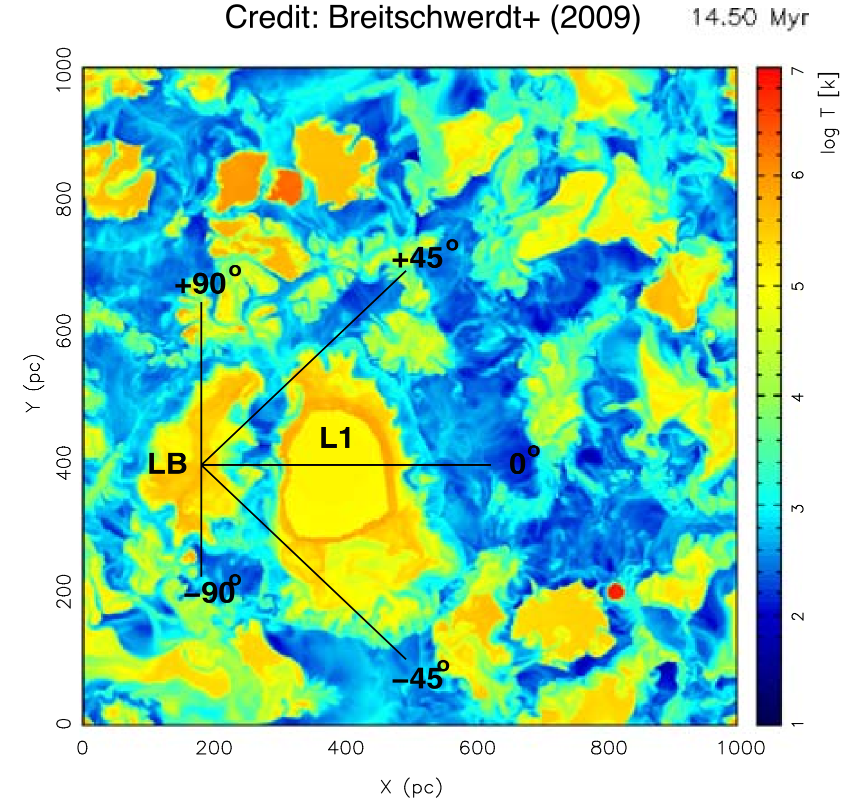
The origin of the Local Bubble



Credit: de Avillez & Breitschwerdt (2010)

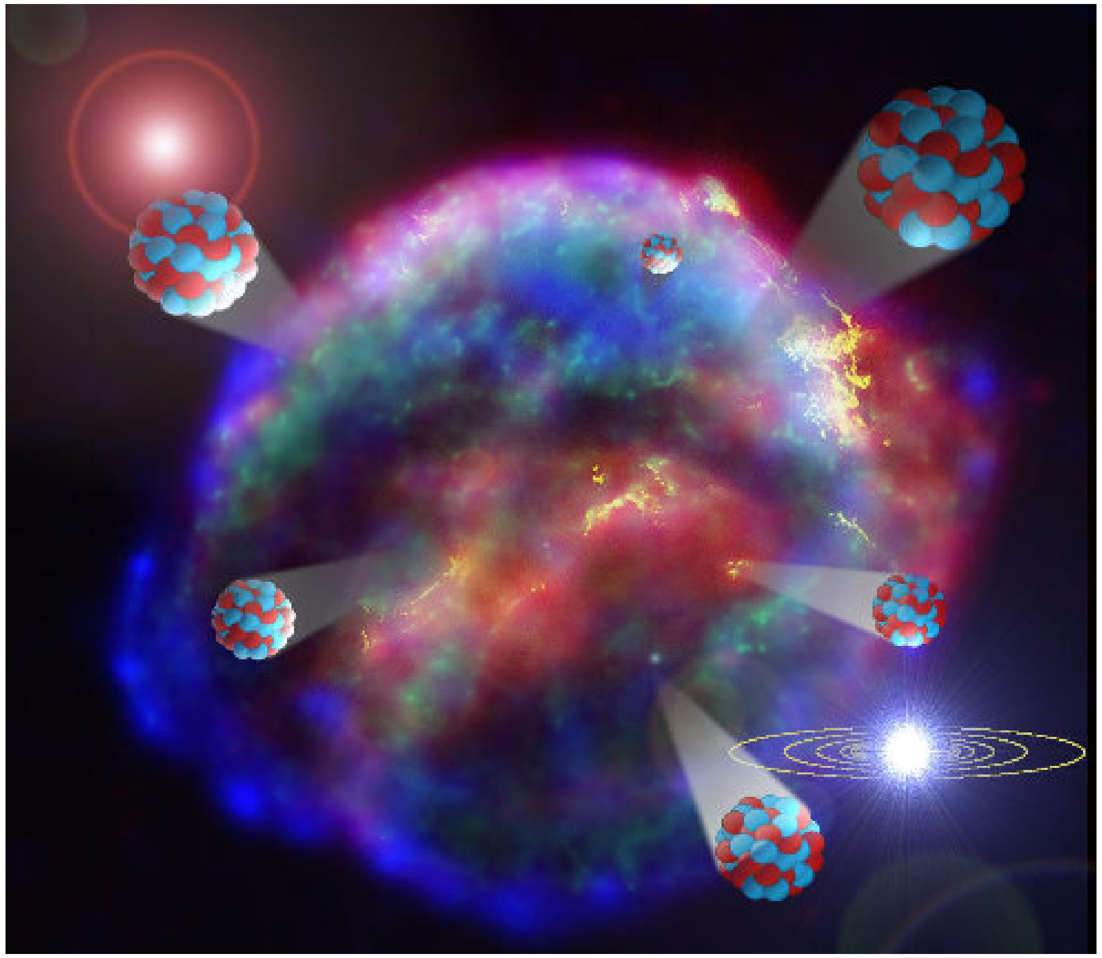
- Scenario further tested by means of mesoscale 3D hydrodynamical simulations
- Follow LB evolution within **self-consistently evolved ISM** that features …
  - Galactic fountain flow
  - structures on all scales in density and temperature distribution
  - shear flow generates high level of turbulence ➔ coupling of scales
  - cloud formation by shock compressed layers ➔ transient features ➔ generation of new stars
- Initial conditions taken from observations
- Dynamical equilibrium after ~200 Myr

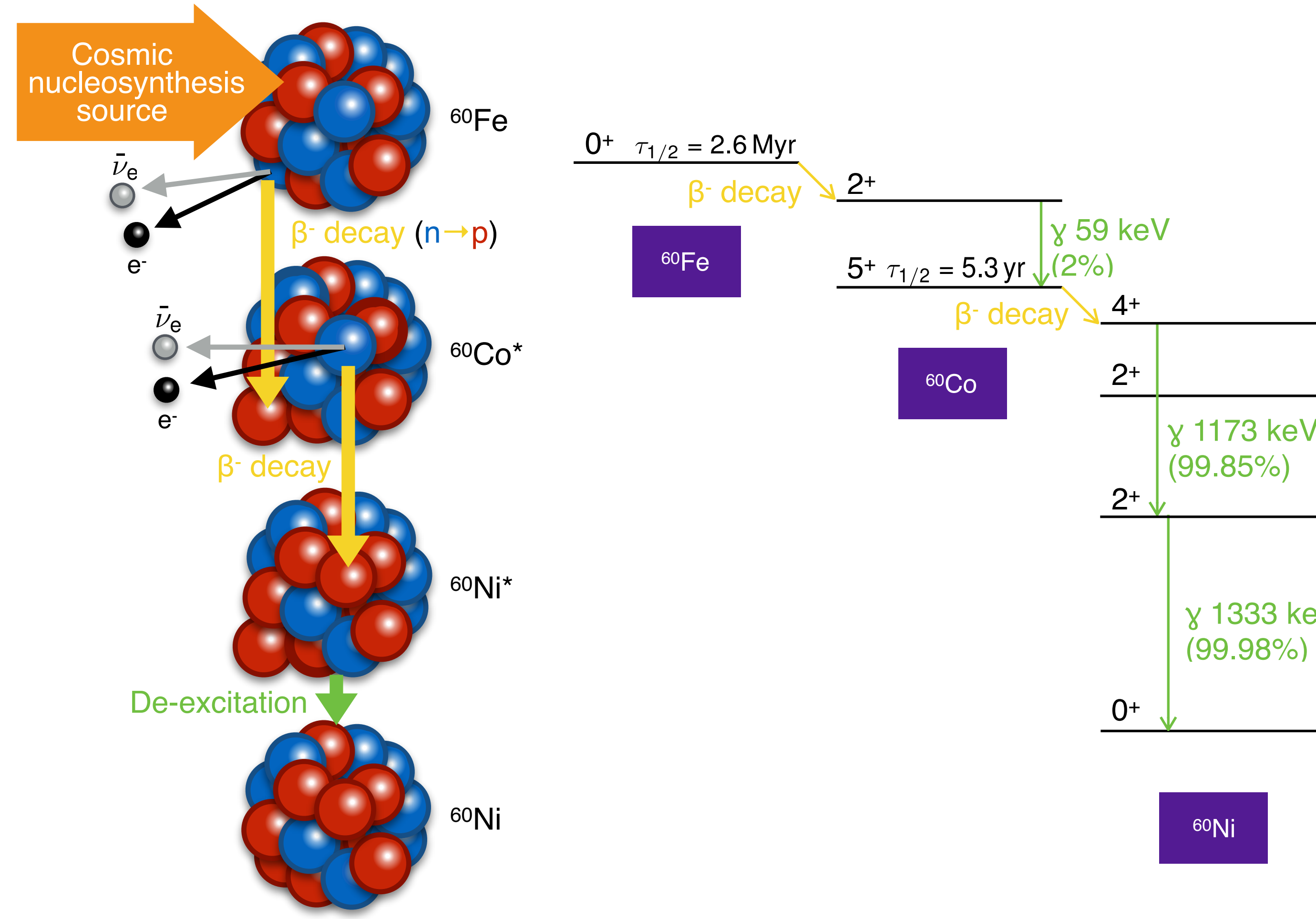
Credit: Breitschwerdt+ (2009)



- Early LB evolution: smooth and spherical; developing internal structure
- After 14.5 Myr: LB size and ion column density ratios nicely reproduced (Breitschwerdt & Avillez 2006 [BA06]; Avillez & Breitschwerdt 2009, 2012)
- **Additional constraints from searches of the traces of the involved SN on Earth!**

Relics of the 'blast from the past'





Promising tracer: radionuclide ^{60}Fe (e.g., Ellis+ 1996)

- Produced during late shell-burning phase in massive stars; predominantly released by core-collapse (incl. electron-capture) SNe (Timmes+ 1995; Wanajo+ 2013)
- Half-life ($t_{1/2}$ = 2.6 Myr) **long enough** to allow for ISM travelling from nearby sources and **short enough** that ^{60}Fe from early solar system epoch has decayed away

- **Indirect detection:** β^- decay via ^{60}Co and γ-ray emission at 1173 and 1333 keV (Wang+ 2007)
- **Direct detection:** Galactic cosmic rays ➔ ^{60}Fe sources must have been within the distance high-energy particles can travel for the duration of $t_{1/2}$ ($\lesssim$ 1 kpc; Binns+ 2016)

Relics of the 'blast from the past'

Ferromanganese (FeMn) crusts

- ~20% Mn and ~15% Fe
- Found on sea-mountains and -plateaus, deep-sea volcanoes and the mid-ocean ridges
- Get elemental composition from ambient water
- Low growth rate (< 10 mm/Myr)

Specific crust 237KD

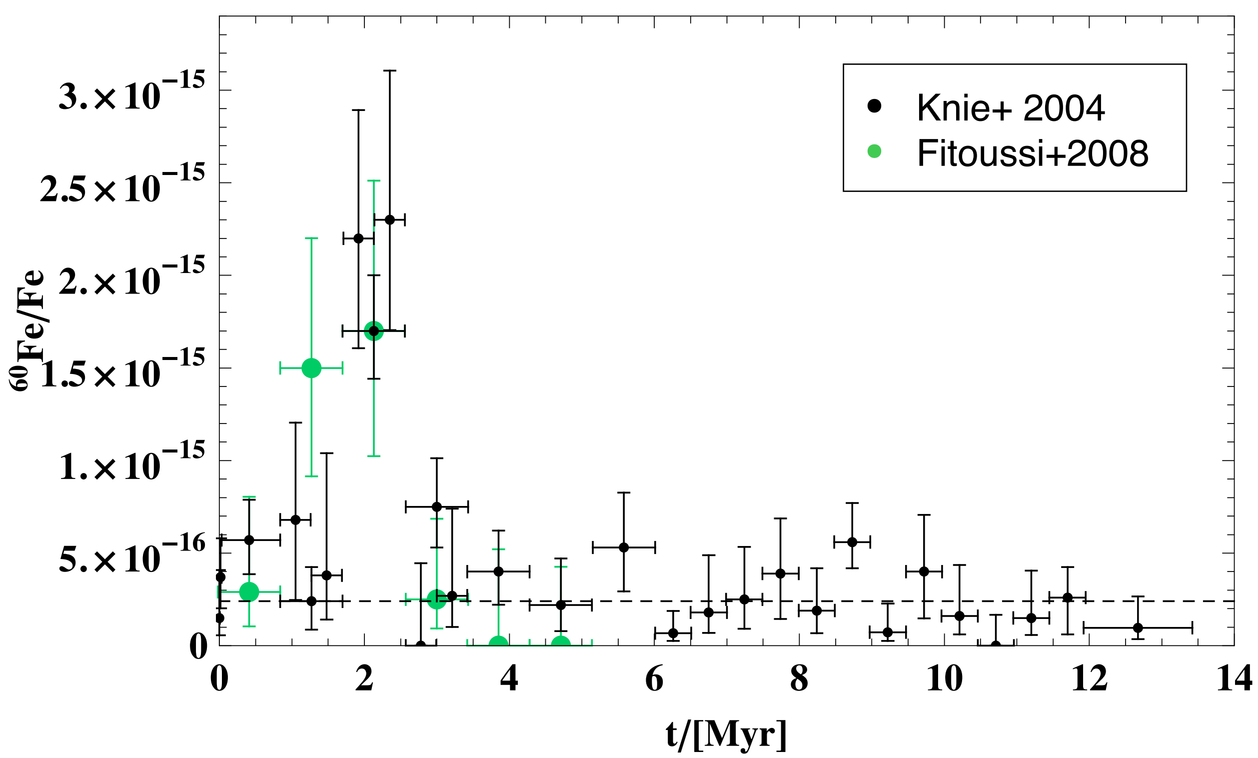
- Among the biggest FeMn crusts ever recovered in North Equatorial Pacific
- Time axes corresponding to thickness of layer
- Time information: 400,000 yr in 1 mm
- Measurement with Accelerator Mass Spectrometry

Image credits: http://www.oceanexplorer.noaa.gov (top right photo), Google Maps (bottom map), D. Quadfasel (all other photos)

Relics of the 'blast from the past'

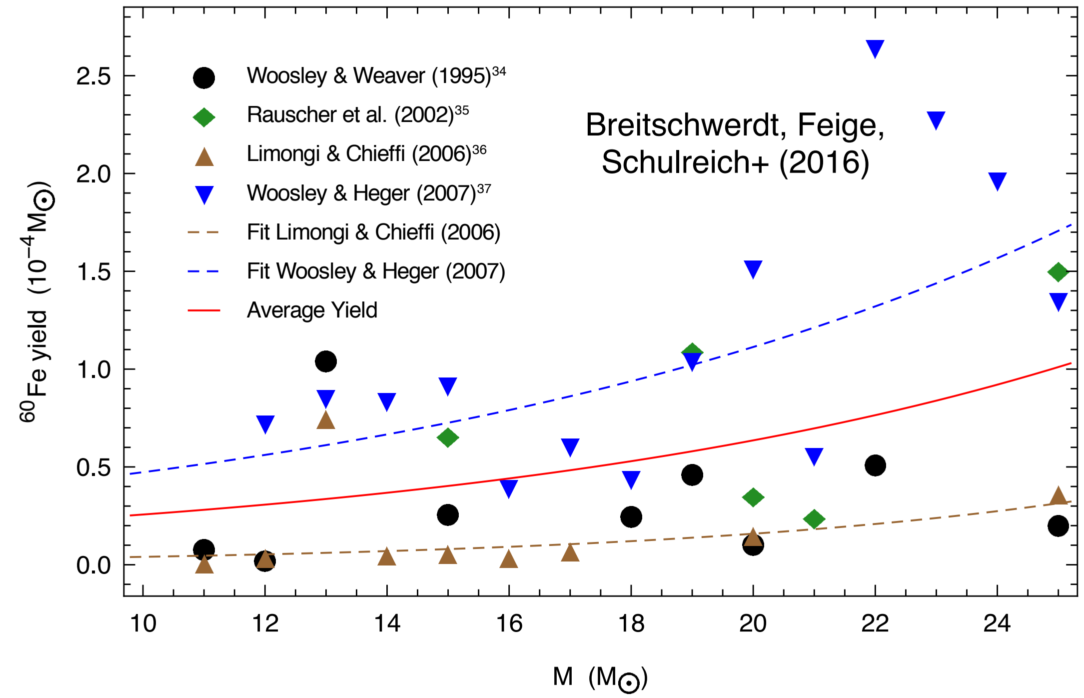
237KD shows **enhanced concentration of ^{60}Fe** at a depth corresponding to 2–3 Myr ago (Knie+2004; Fitoussi+ 2008)

Can ^{60}Fe anomaly be explained as a consequence of the formation of the LB?



Analytical study (Feige 2010; Breitschwerdt+ 2016)**:**

- SNR expansion into previous remnant ($\rho \sim R^{9/2}$) ➔ low Mach-number shocks due to hot interior
- Outer SB shell expansion due to Weaver+ (1977)
- ^{60}Fe content (yield taken from stellar evolution) entrained and deposited by SN blast waves



- Good agreement with crust measurements
- Results show that LB SNe can be responsible for ^{60}Fe deposition

Detailed transport modelling in turbulent medium requires

- performing 3D high-res. numerical simulations
- **treating ^{60}Fe as passive scalars**
- using self-consistently evolved turbulent ISM as a typical background medium (like [BA06])

Numerical simulations

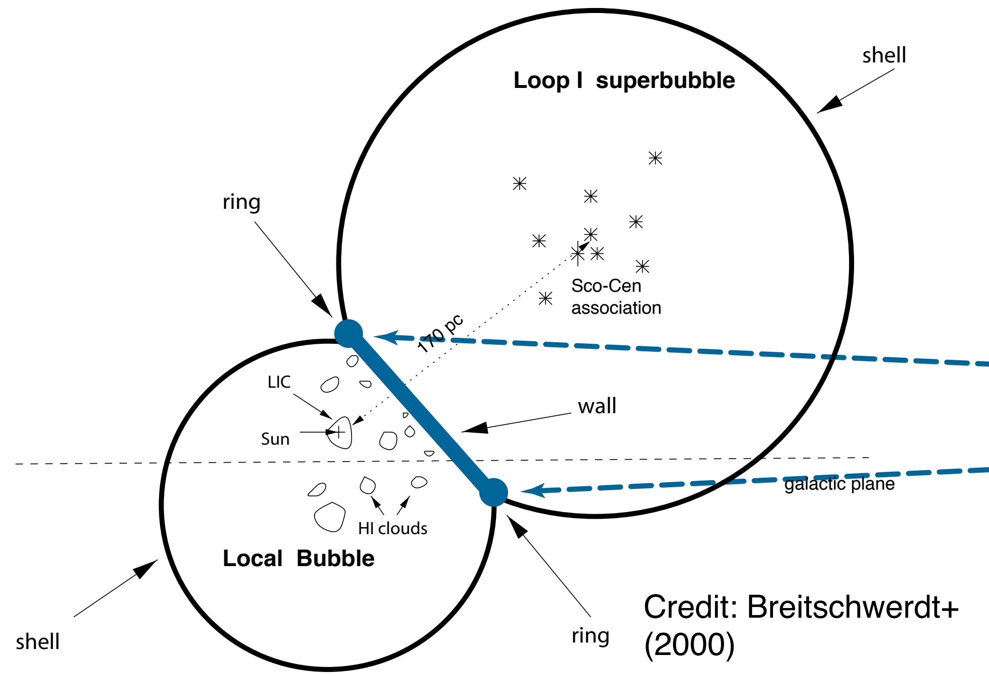
Mesoscale ISM simulations using publicly available AMR (magneto-)hydrodynamics and N-body code RAMSES (Teyssier 2002)

- Star formation (IMF; collisionless particles represent massive stars) at Gal. rate
- Feedback from stellar winds and SNe
- Solar wind bubble (heliosphere)
- Self-gravity of the gas & Galactic gravitational potential
- Heating & CIE cooling for gas with solar metallicity (using CLOUDY code)

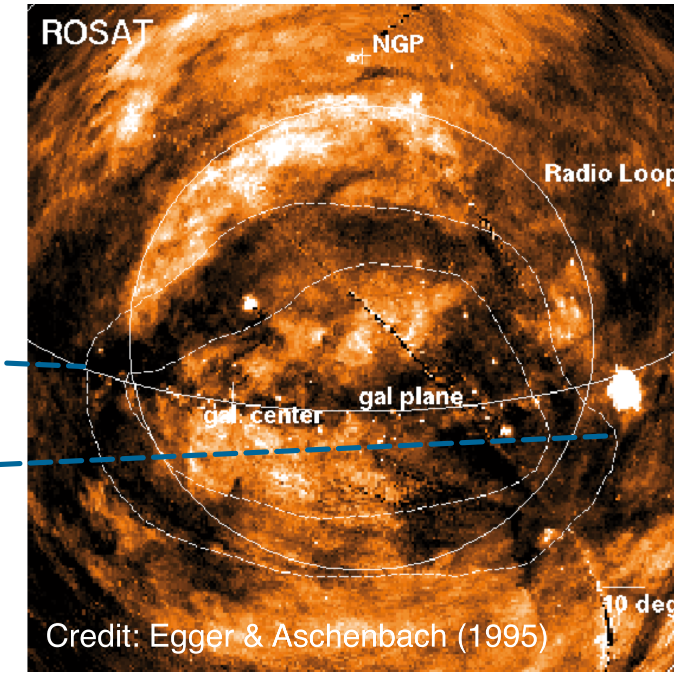
	Homogeneous background models (A & B)	Inhomogeneous background model (C)
Box size	3 x 3 x 3 kpc^3	3 x 3 x 3 kpc^3
Highest grid resolution	0.7 pc (ℓ_{max} = 12)	2.9 pc (ℓ_{max} = 10)
Boundary conditions (vertical faces / top and bottom)	periodic / periodic	periodic / outflow
Total evolution time	12.6 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

Modeling the Loop I superbubble

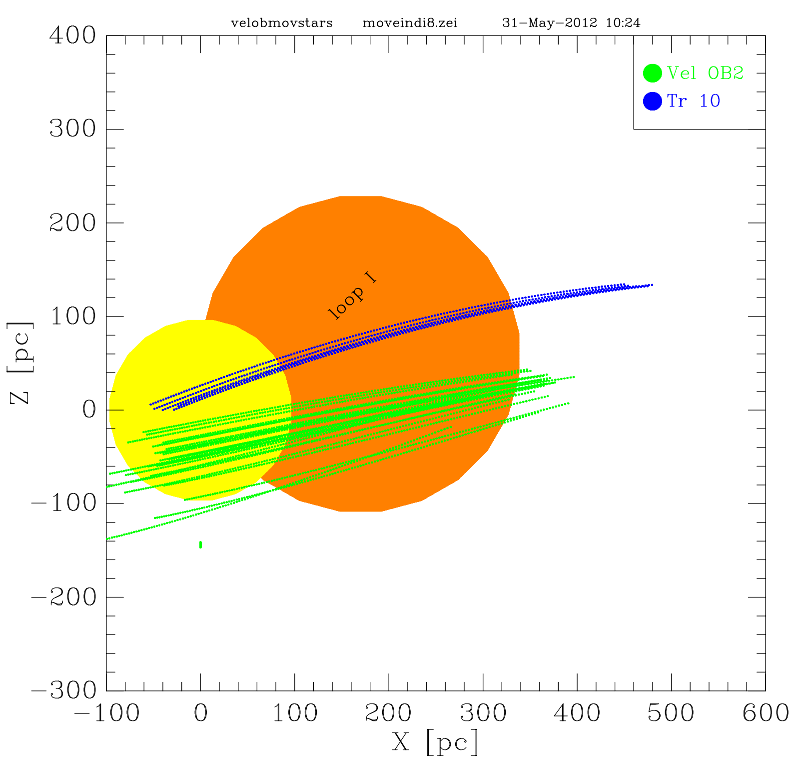
- Further "boundary condition" …
- ROSAT PSPC observations (Egger & Aschenbach 1995): soft X-rays are absorbed by nearby neutral shell
- Possibly result of interaction between LB and its neighbouring SB Loop I (Breitschwerdt+ 2000)
- Applied previous methodology on Loop I clusters Tr 10 and the Vel OB2 association to pin down generating SNe (19)

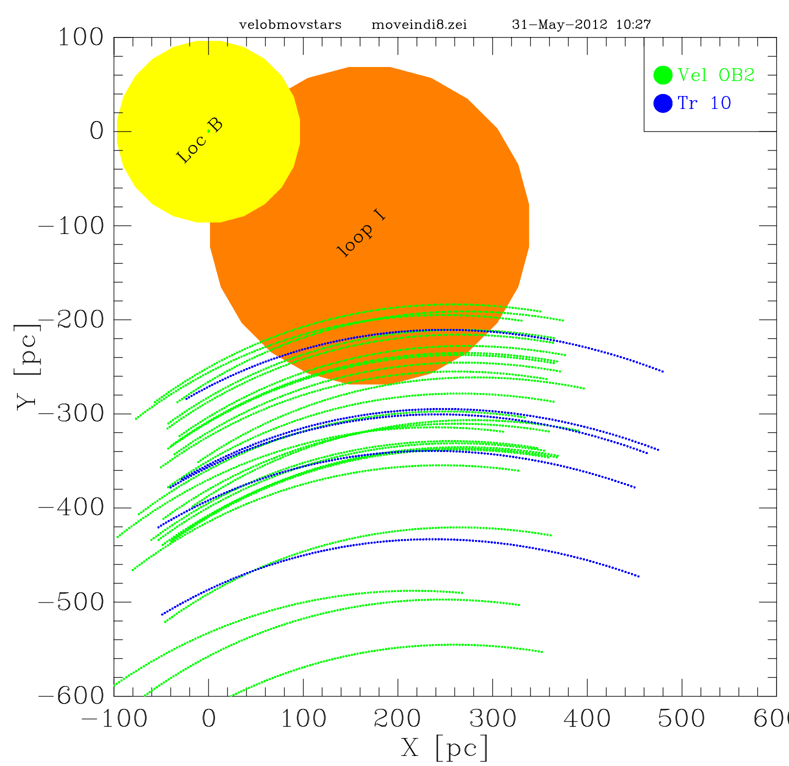


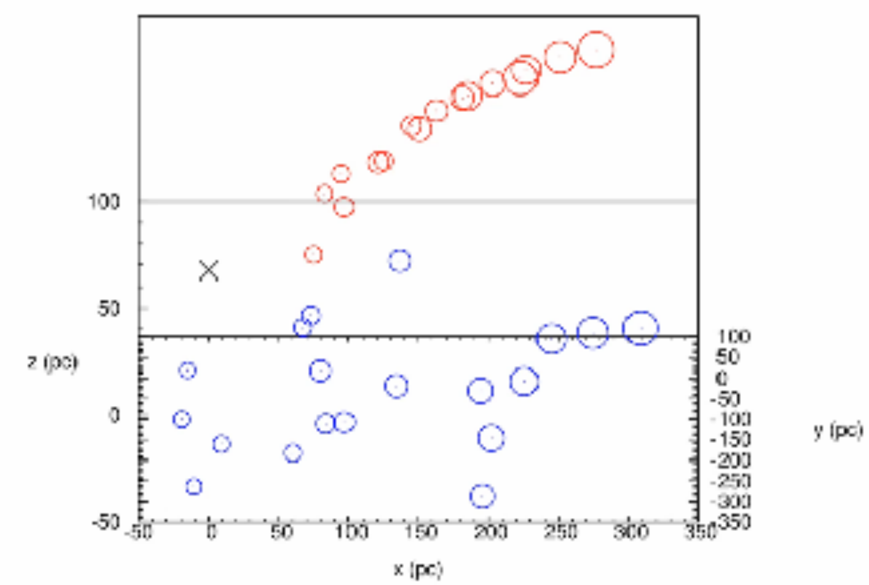
Credit: Breitschwerdt+ (2000)



Credit: Egger & Aschenbach (1995)







Calculating the amount of SN-released ^{60}Fe that arrives on Earth

1. Max. grid refinement around Sun ➔ accurate ^{60}Fe flux in every time step
2. Fluxes are given at cell centres ➔ average over eight innermost grid cells
3. Compute time-integrated flux ('fluence'):

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

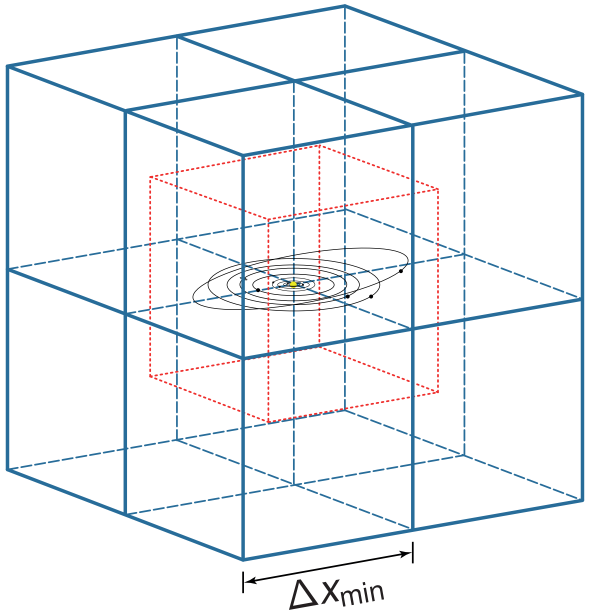
4. Surface density of atoms deposited on Earth at time t before present:

$$\Sigma(t) = \frac{fU}{4} F \exp\left(-t/t_{1/2}\right)$$

- Assume isotropic fall-out (cf. Fry+ 2016)
- **^{60}Fe survival fraction**, fU, only poorly known; dust factor $f \simeq 0.01$ (Fry+ 2015); uptake factor $U \simeq 0.5$–1 (Bishop & Egil 2011; Feige + 2012) ➔ take either $fU = 0.06$ (cf. Knie+ 2004) or 0.05 (lower limit)

5. Obtain ^{60}Fe number density for each crust layer by summing Σ(t) over time intervals divided by thickness of layer
6. Relate $n_{60\mathrm{Fe}}$ to the density of stable iron (i.e. ^{60}Fe/Fe), given by

$$n_{\mathrm{Fe}} = \frac{x_{\mathrm{Fe}} \rho_{\mathrm{crust}} N_{\mathrm{A}}}{\mathcal{A}_{\mathrm{Fe}}} = 2.47 \times 10^{21}\ \mathrm{cm}^{-3}$$



Chemical mixing simulations with homogeneous background medium

Evolution of the gas column density distribution (cuts through $z = 0$ and $y = 0$)

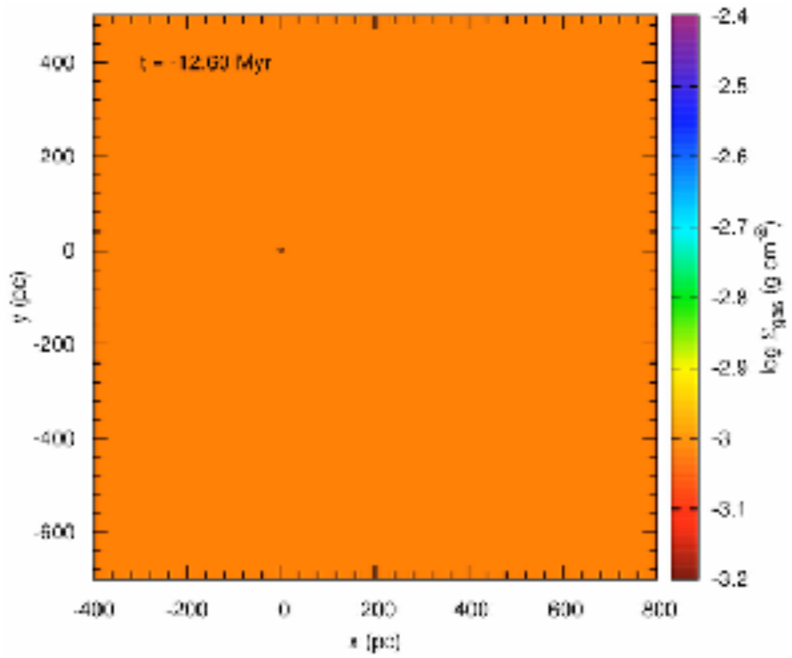
Model A (~ WIM)

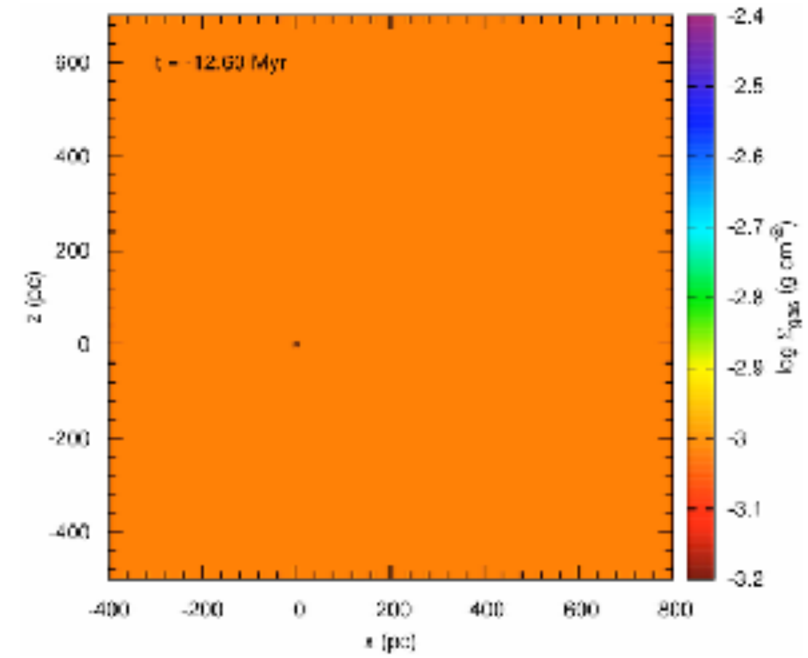
$n = 0.1\ cm^{-3}$

$T = 10^4$ K

$Z/Z_\odot = 1$

$\Delta x = 0.7$ pc





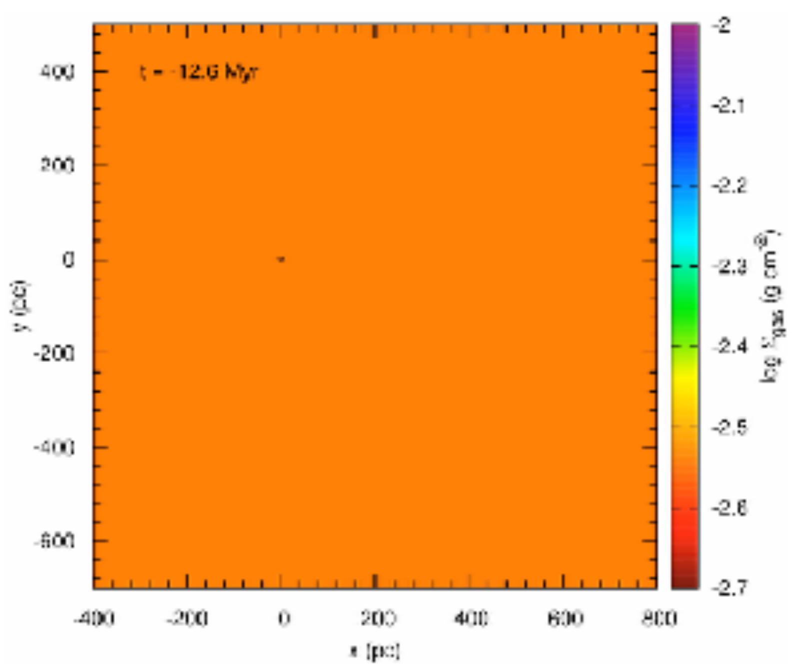
Model B (~ WNM)

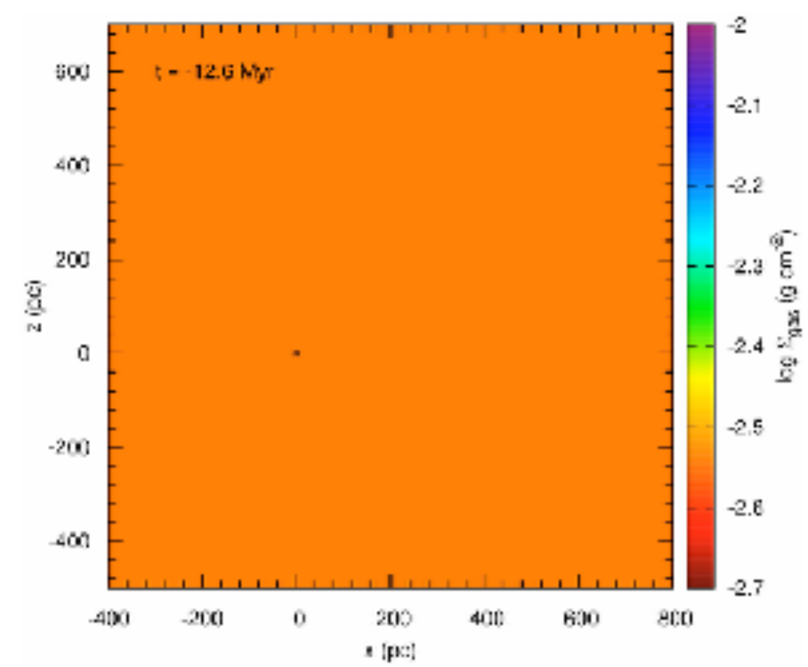
$n = 0.3\ cm^{-3}$

$T = 6800$ K

$Z/Z_\odot = 1$

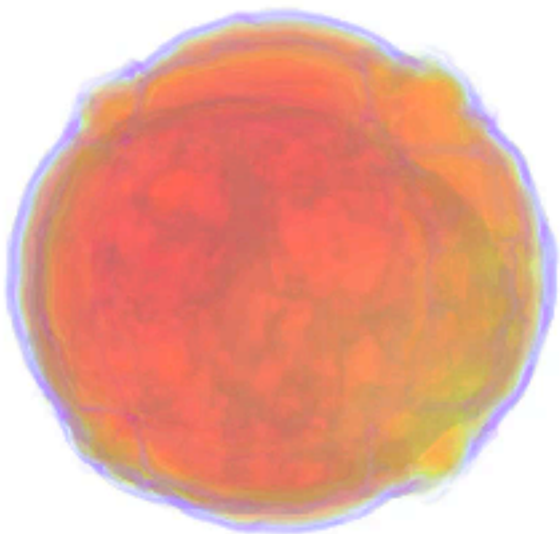
$\Delta x = 0.7$ pc



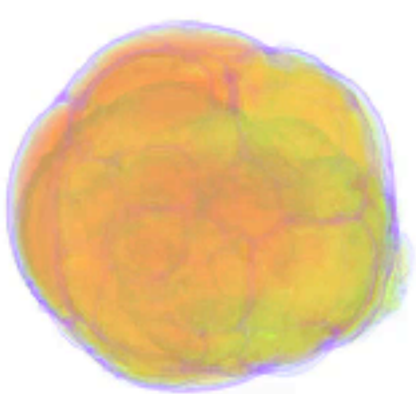


Chemical mixing simulations with homogeneous background medium

Volume rendering of the present-day density distribution



Model A



Model B

- LB and Loop I form almost coevally
- **At first:** independent evolution, formation of cold, dense clumps due to instabilities
- **Later on:** shells collide after 3.0 (model A) and 4.6 Myr (model B) ➔ RT unstable interaction layer
- Shells break-up after 6.5 Myr (model A) or never (model B)
- 'Present' LB extension: (x,y,z) = (800,600,760) pc in model A; (580,480,540) pc in model B
- Hydrogen density and temperature in 'present' LB cavity: $10^{-4.2}$–$10^{-3.9}$ cm^{-3}, $10^{6.9}$–$10^{7.1}$ K in model A; $10^{-4.2}$–10^{-3} cm^{-3}, $10^{5.8}$–10^{7} K in model B
- Agreement between computed and observed extension of bubbles poor ➔ ambient medium not known
- Exact extensions not crucial for ^{60}Fe transport modelling as long as the solar system resides within the LB; exception: supershell arrival

Chemical mixing simulations with homogeneous background medium

Evolution of the ^{60}Fe mass density distribution (cuts through $z = 0$ and $y = 0$)

Model A (~ WIM)

n = 0.1 cm^{-3}

T = 10^4 K

$Z/Z_{\odot} = 1$

$\Delta x = 0.7$ pc

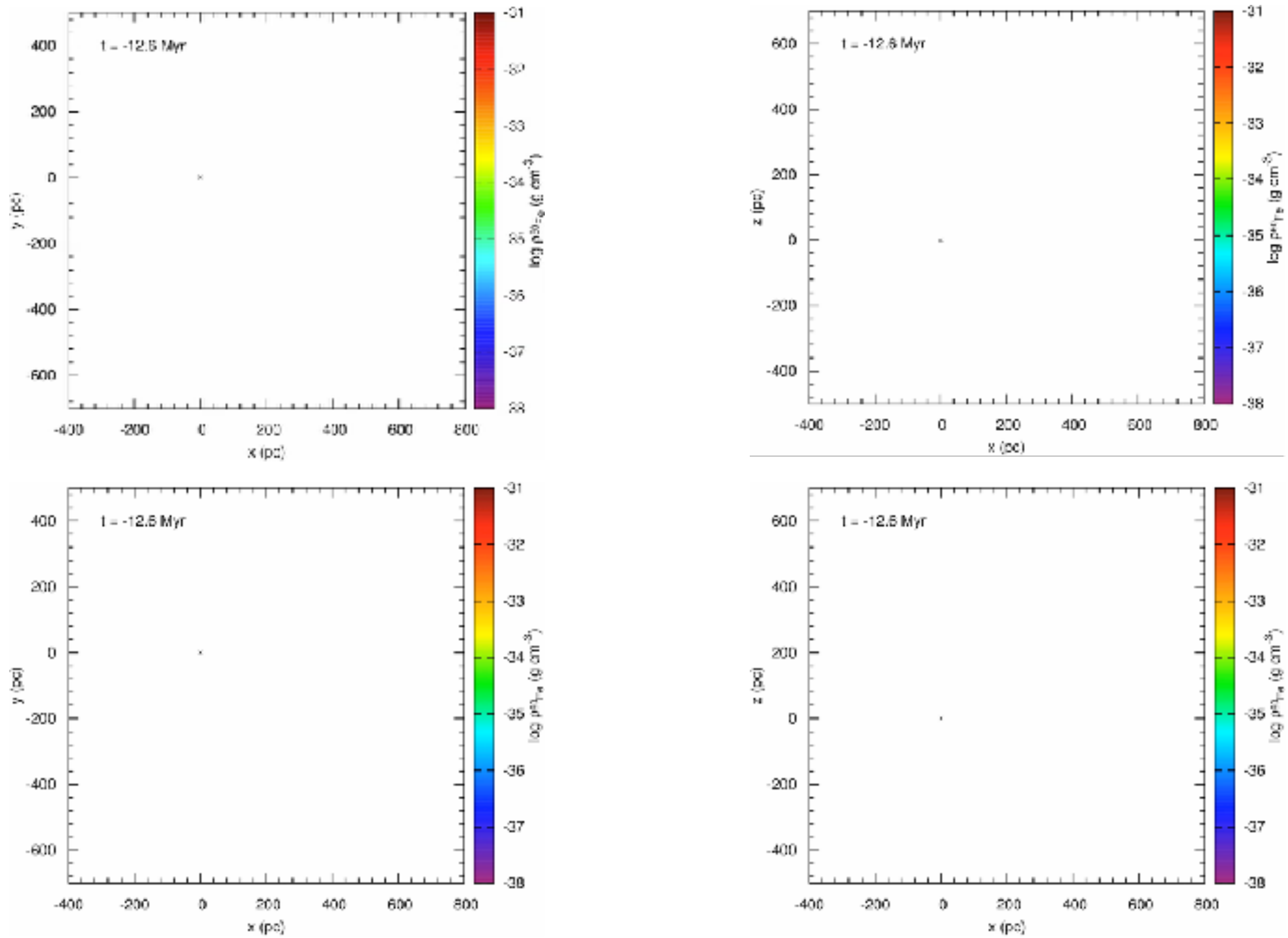
Model B (~ WNM)

n = 0.3 cm^{-3}

T = 6800 K

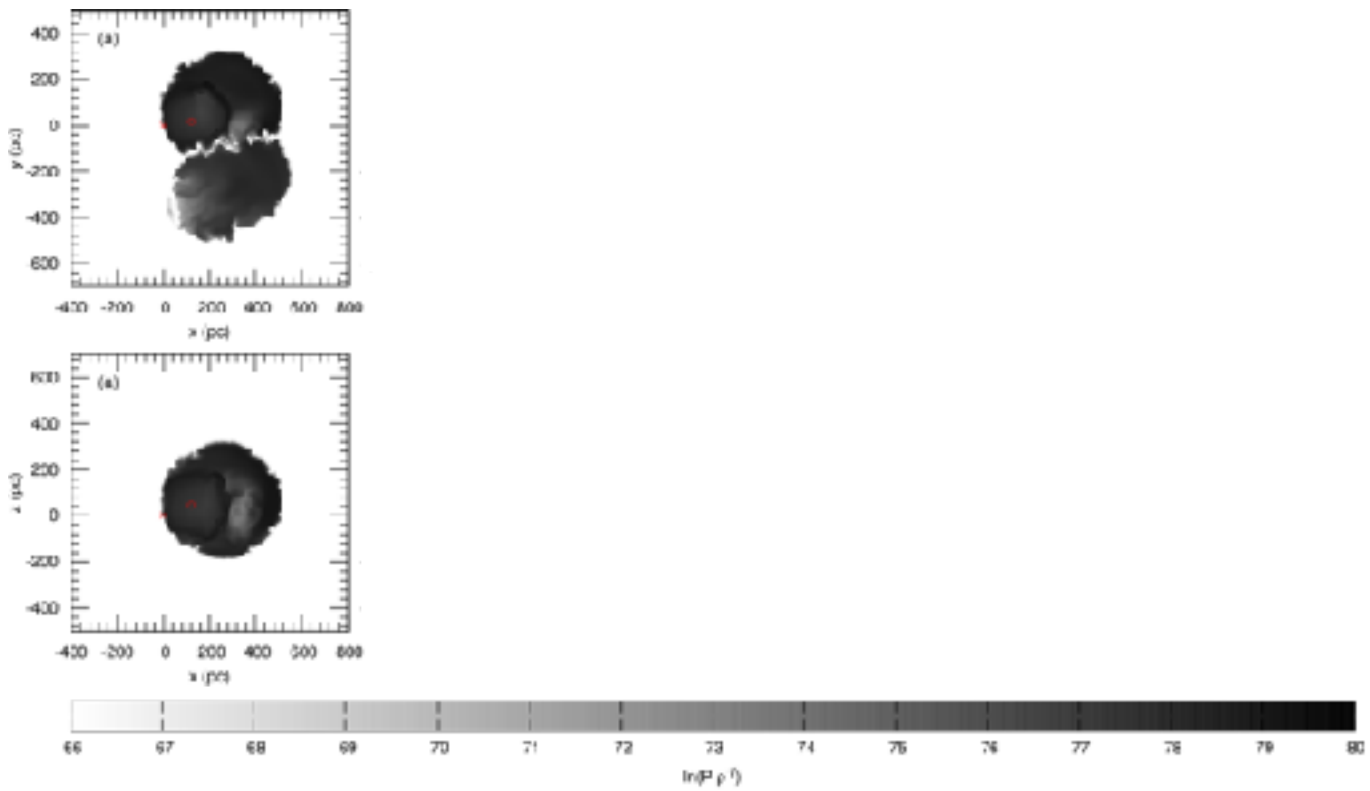
$Z/Z_{\odot} = 1$

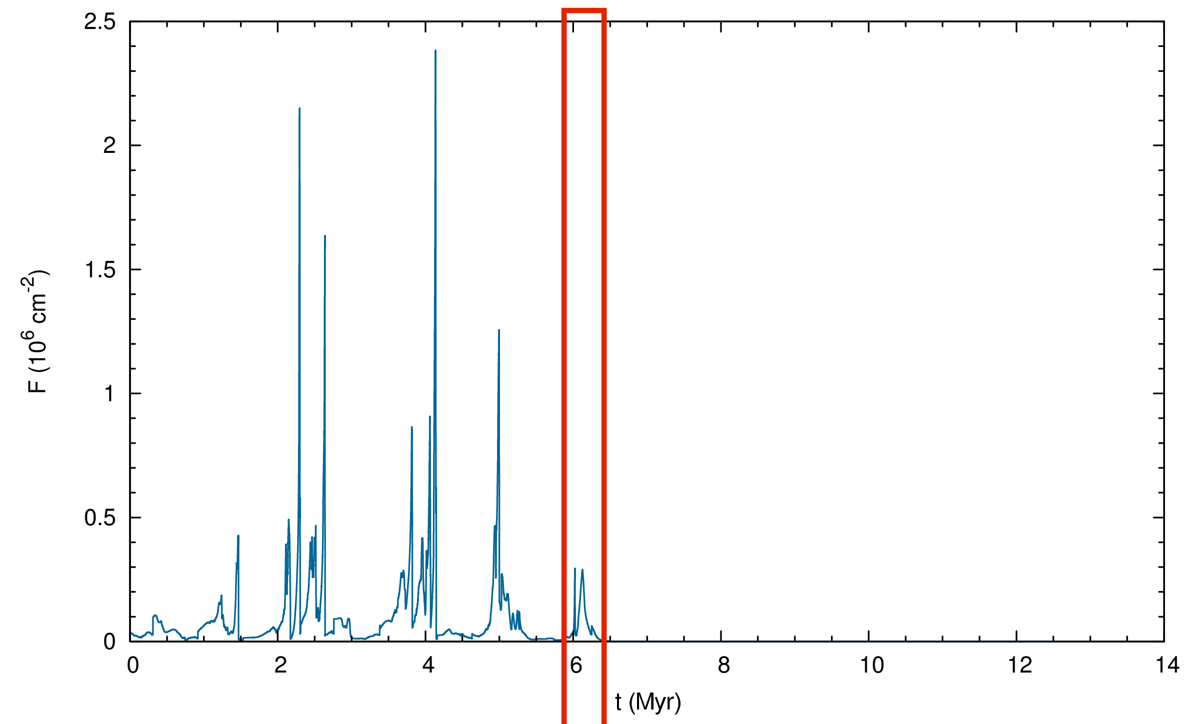
$\Delta x = 0.7$ pc



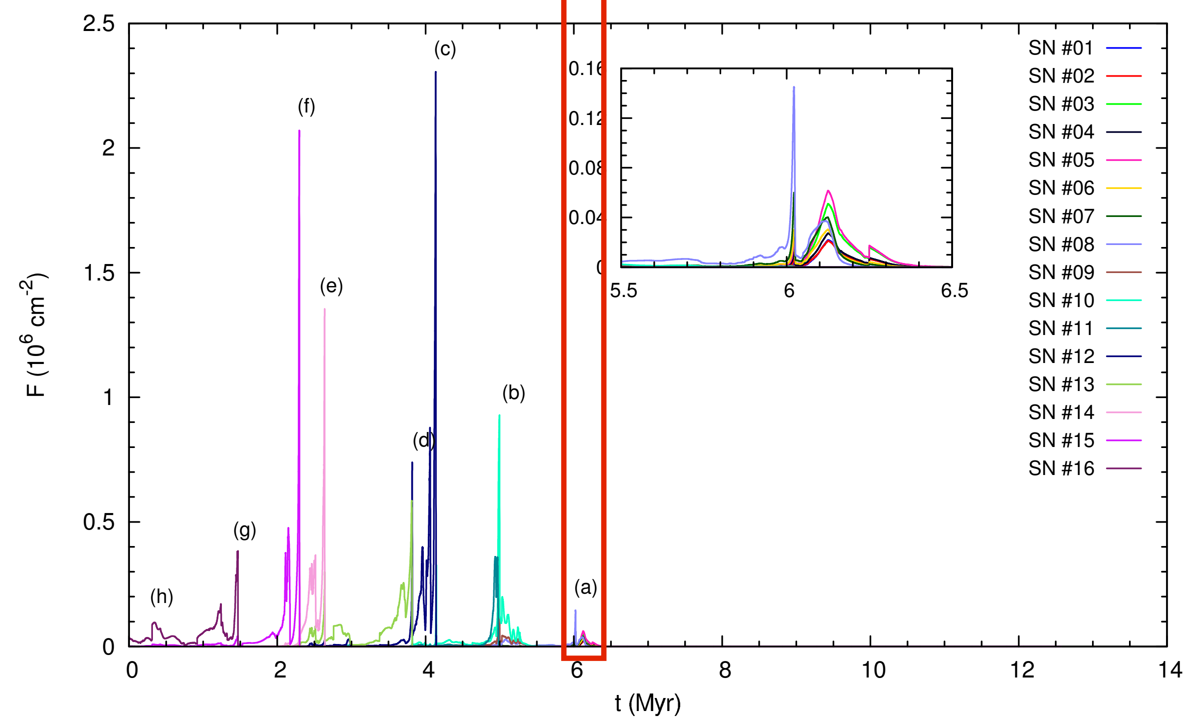
- Inhomogeneities arising from recent SNe are smoothed out over time
- Injection of turbulence by SNRs running into supershell ➔ generating asymmetric reflected shocks

- Time scale of mixing: $\tau_m \lesssim \ell / a$ = (100 pc)/(100 km s^{-1}) = 1 Myr
- ^{60}Fe fairly homogenised since last LB SN occurred about 1.5 Myr ago





F (10^6 cm^{-2})
t (Myr)



F (10^6 cm^{-2})
t (Myr)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
SN #01
SN #02
SN #03
SN #04
SN #05
SN #06
SN #07
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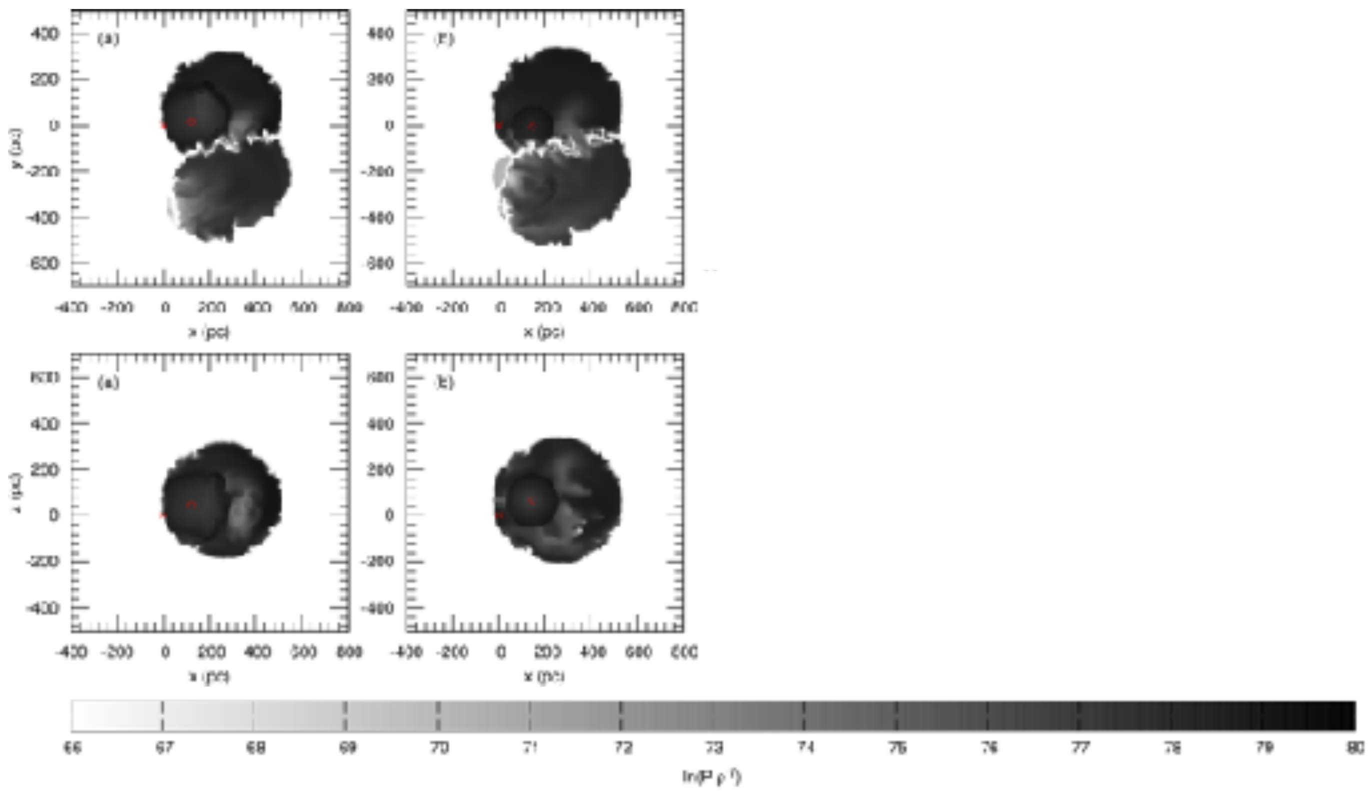
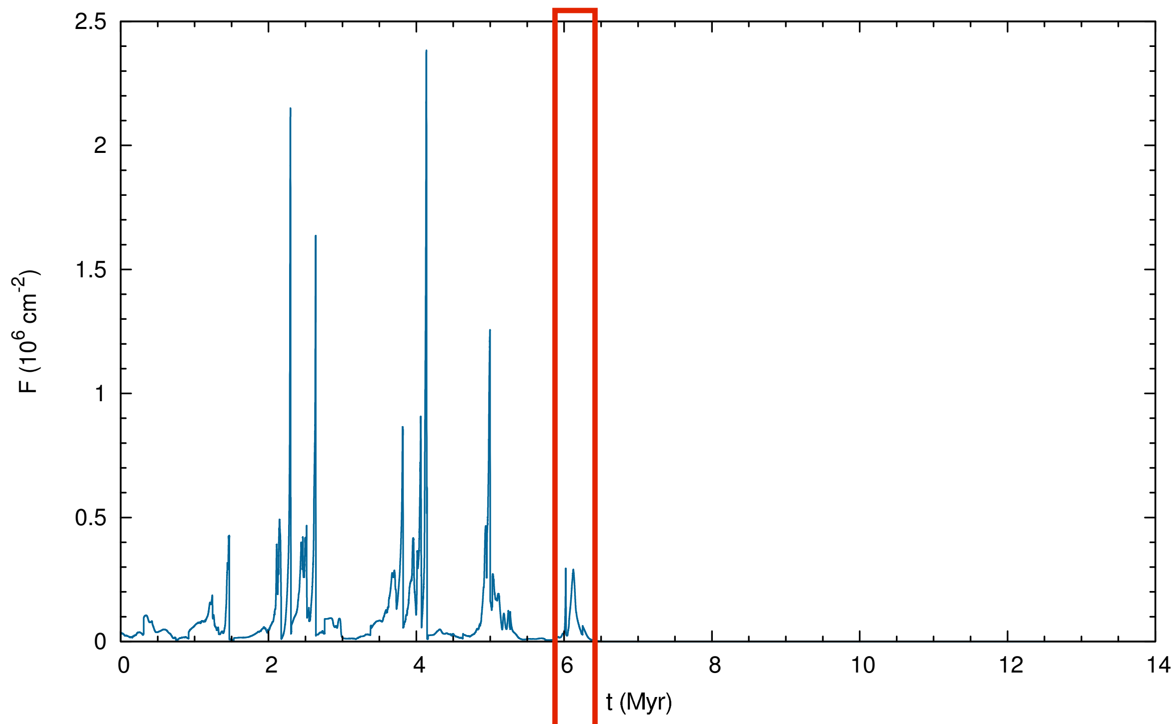
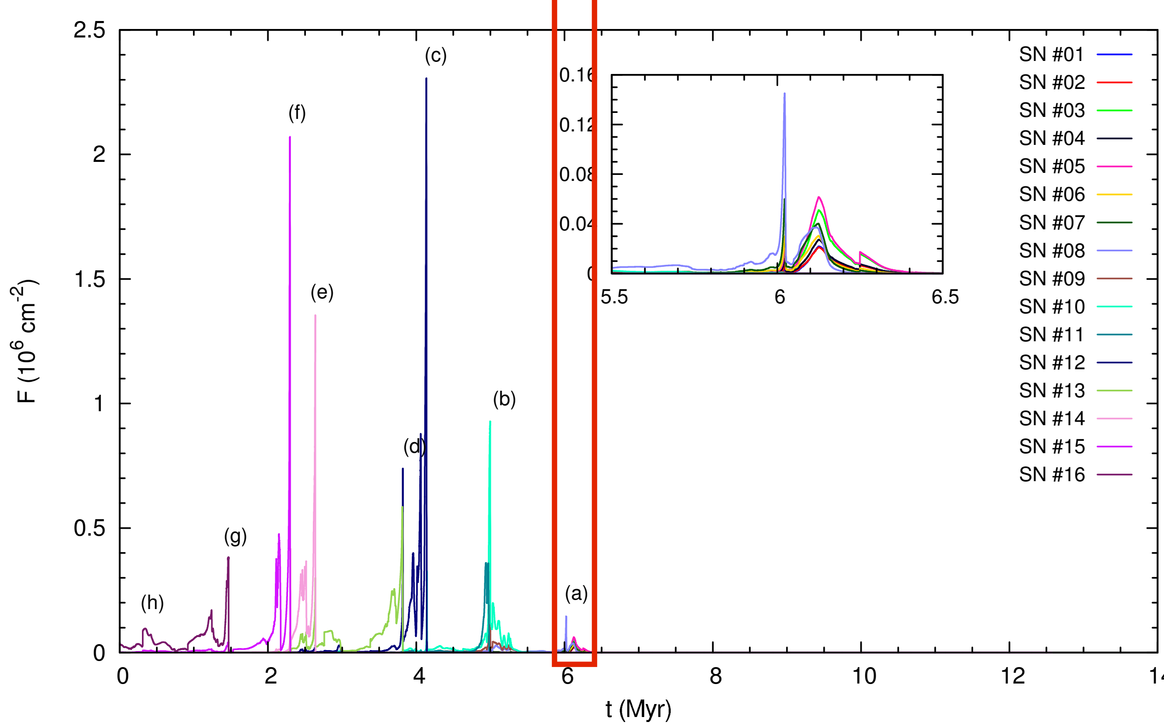
SN #16

Model A: Entropy maps and 60Fe fluence variation

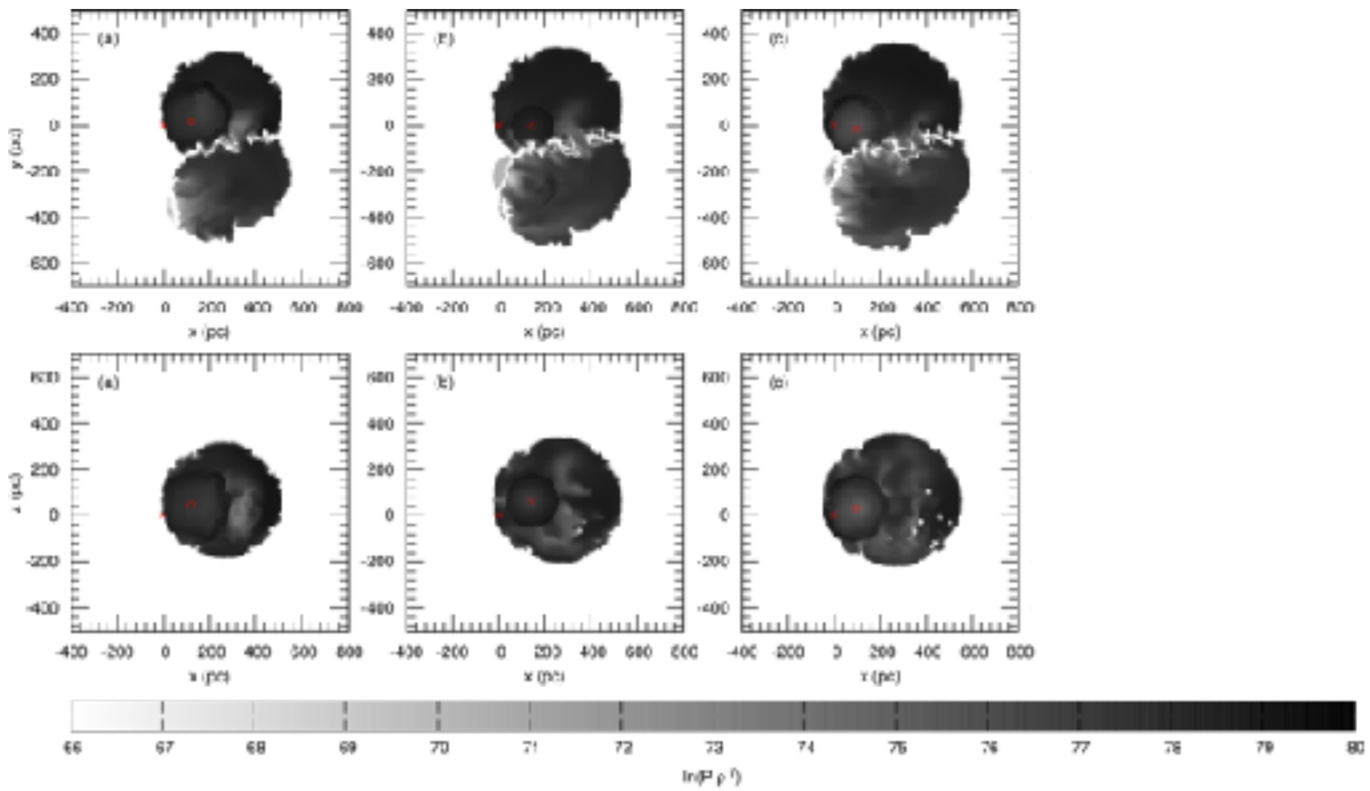


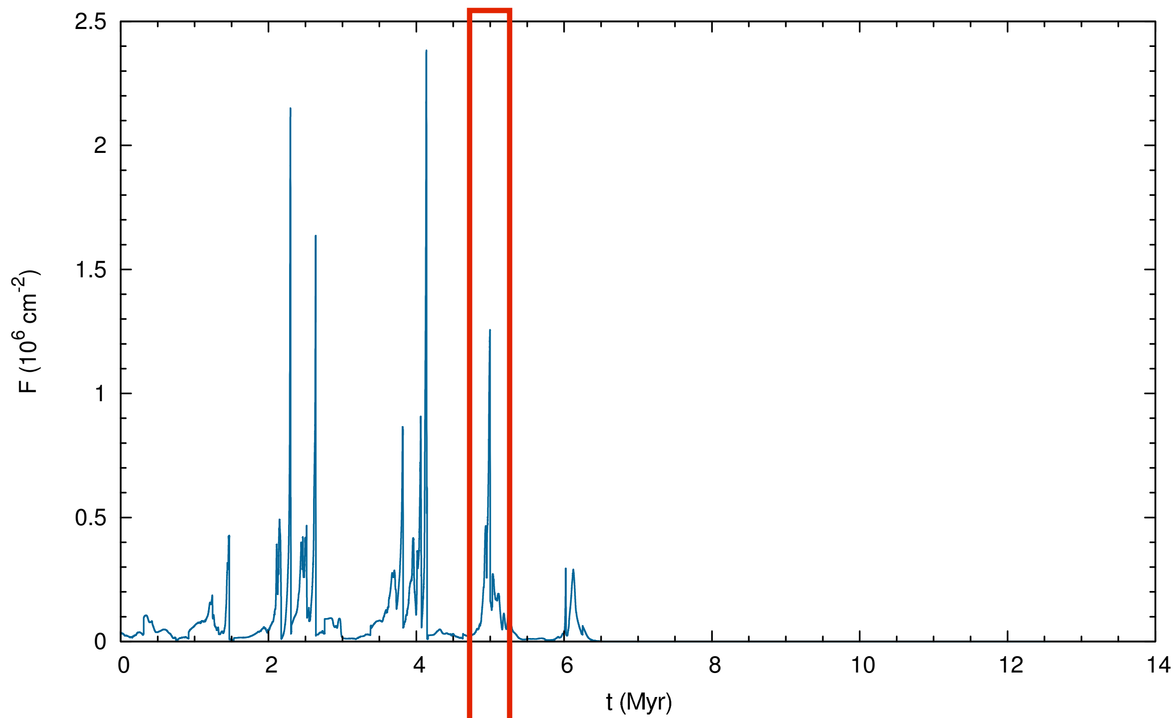


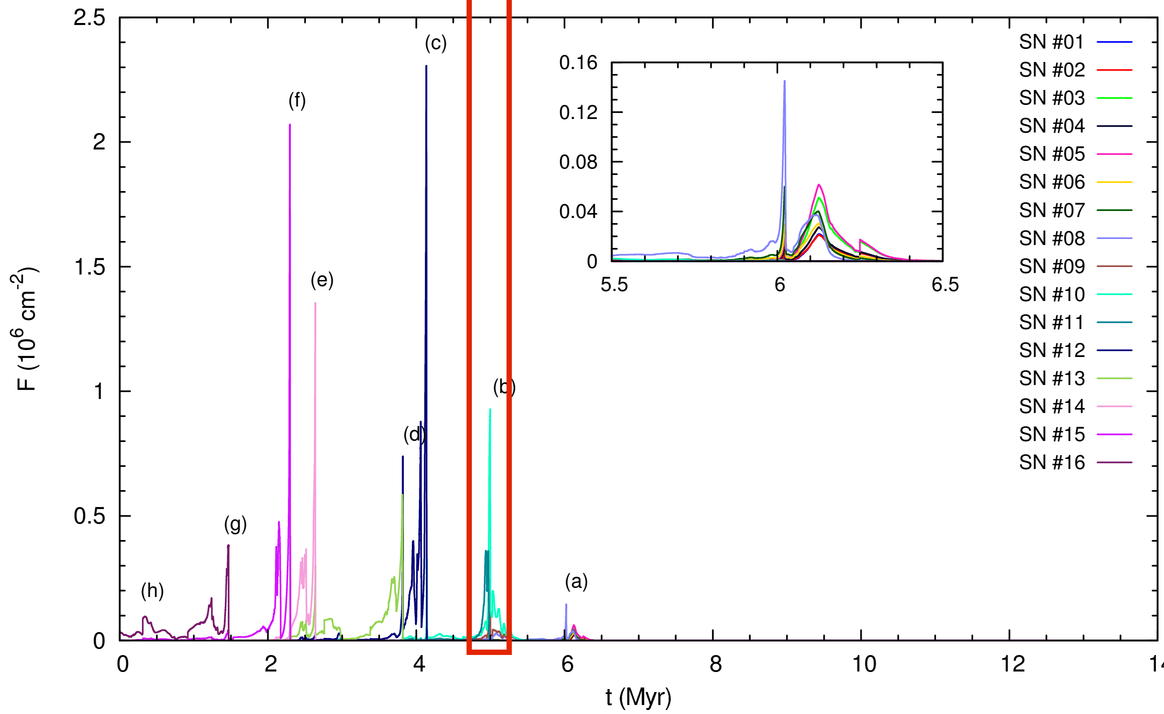


Results — Chemical mixing simulations with homogeneous background medium

Model A: Entropy maps and 60Fe fluence variation

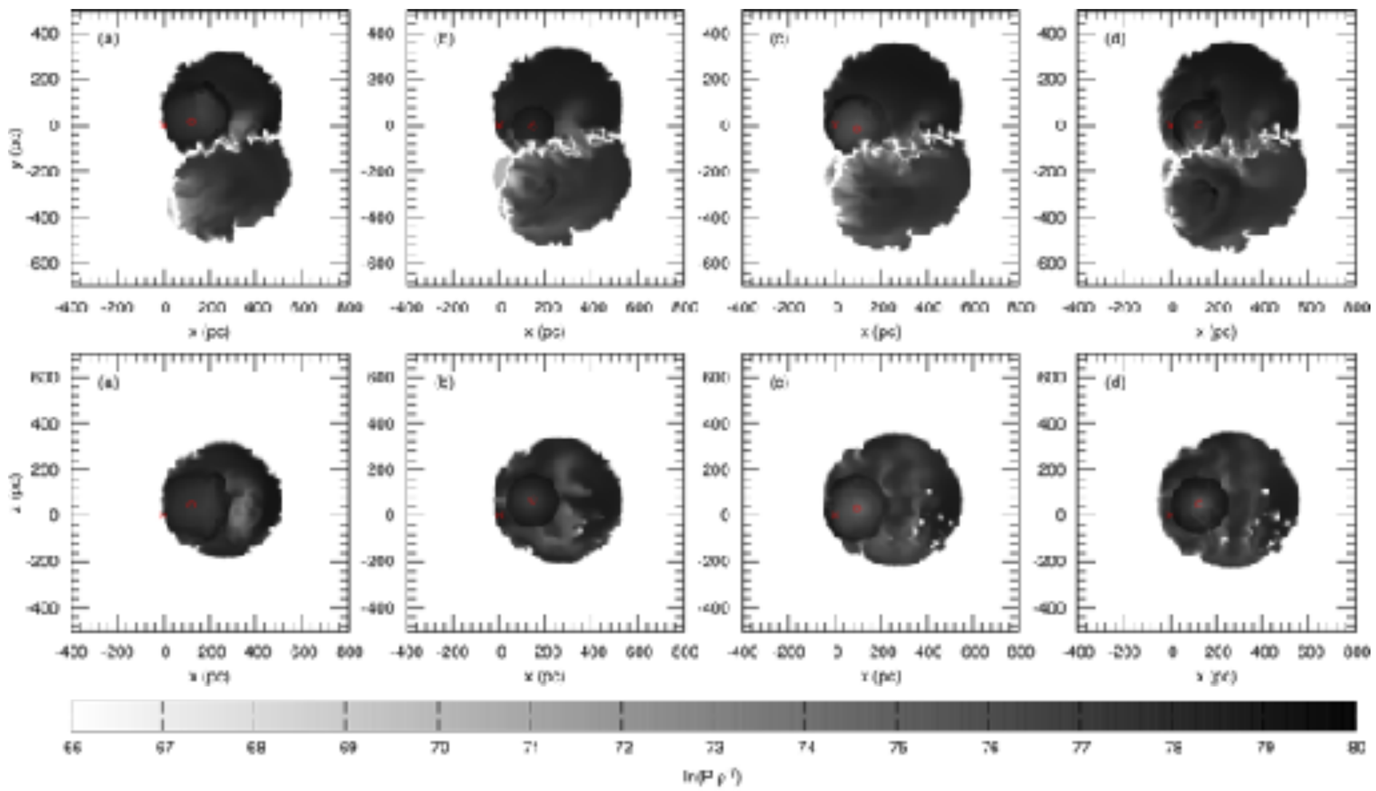


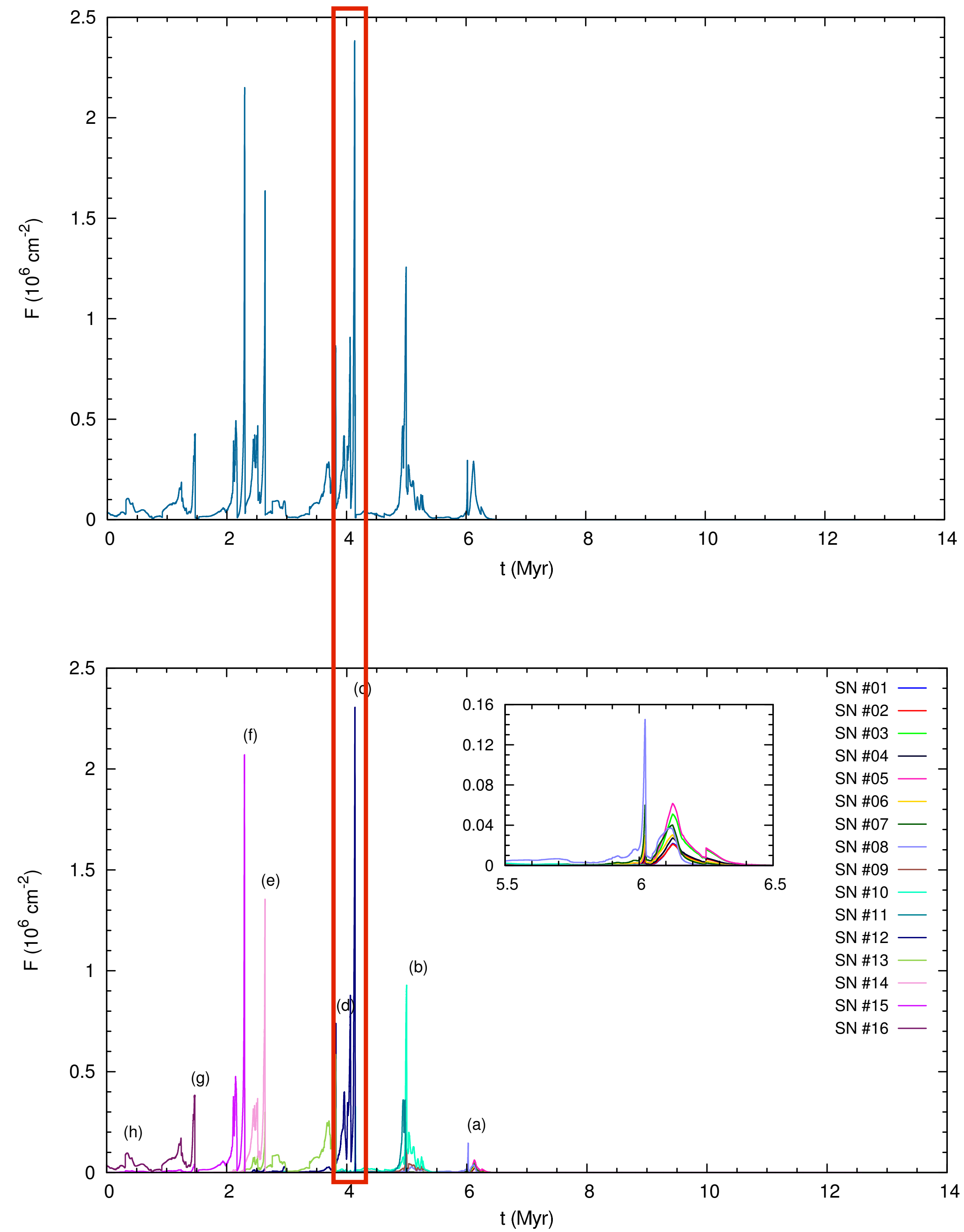




Results — Chemical mixing simulations with homogeneous background medium

Model A: Entropy maps and 60Fe fluence variation





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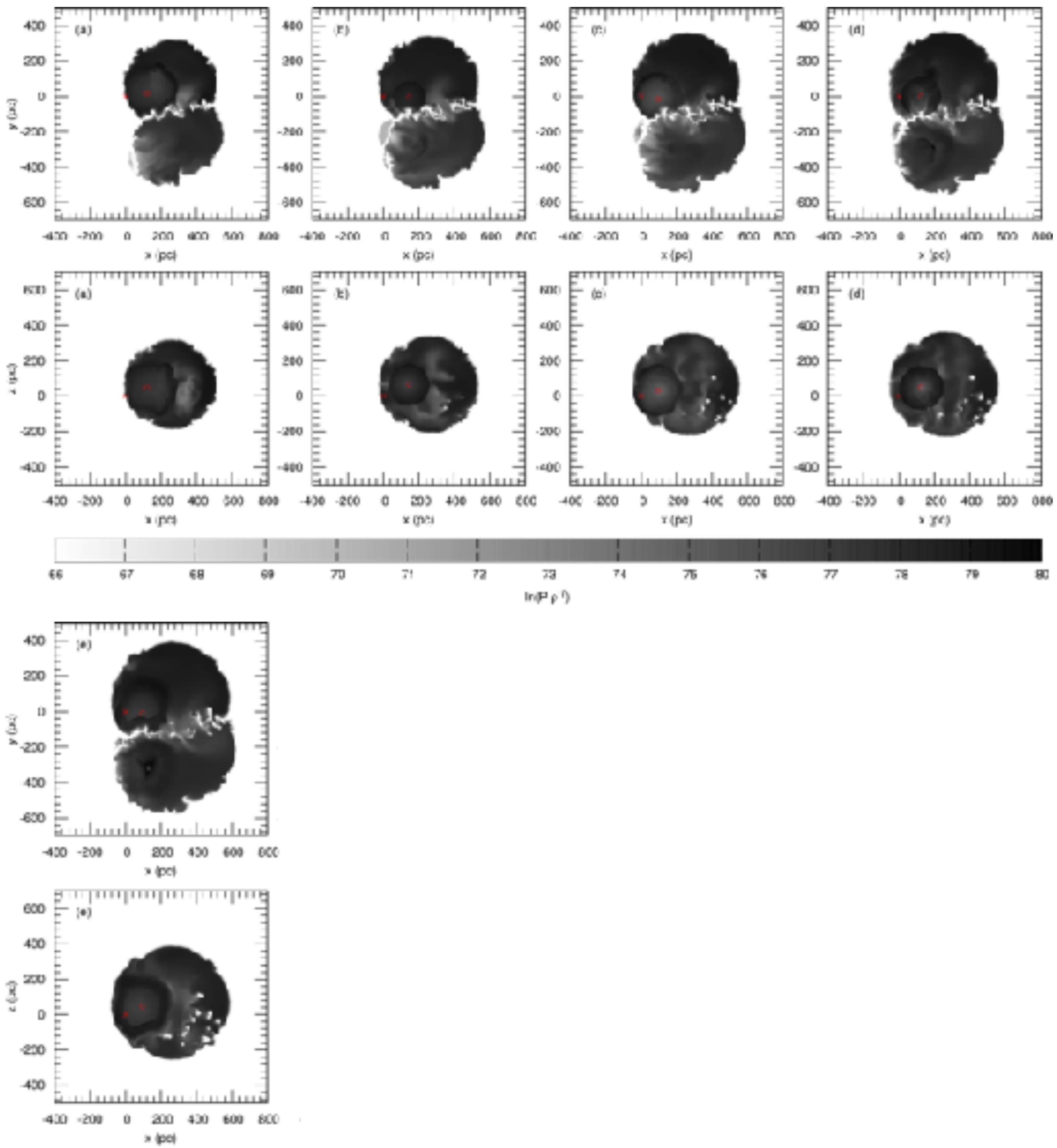

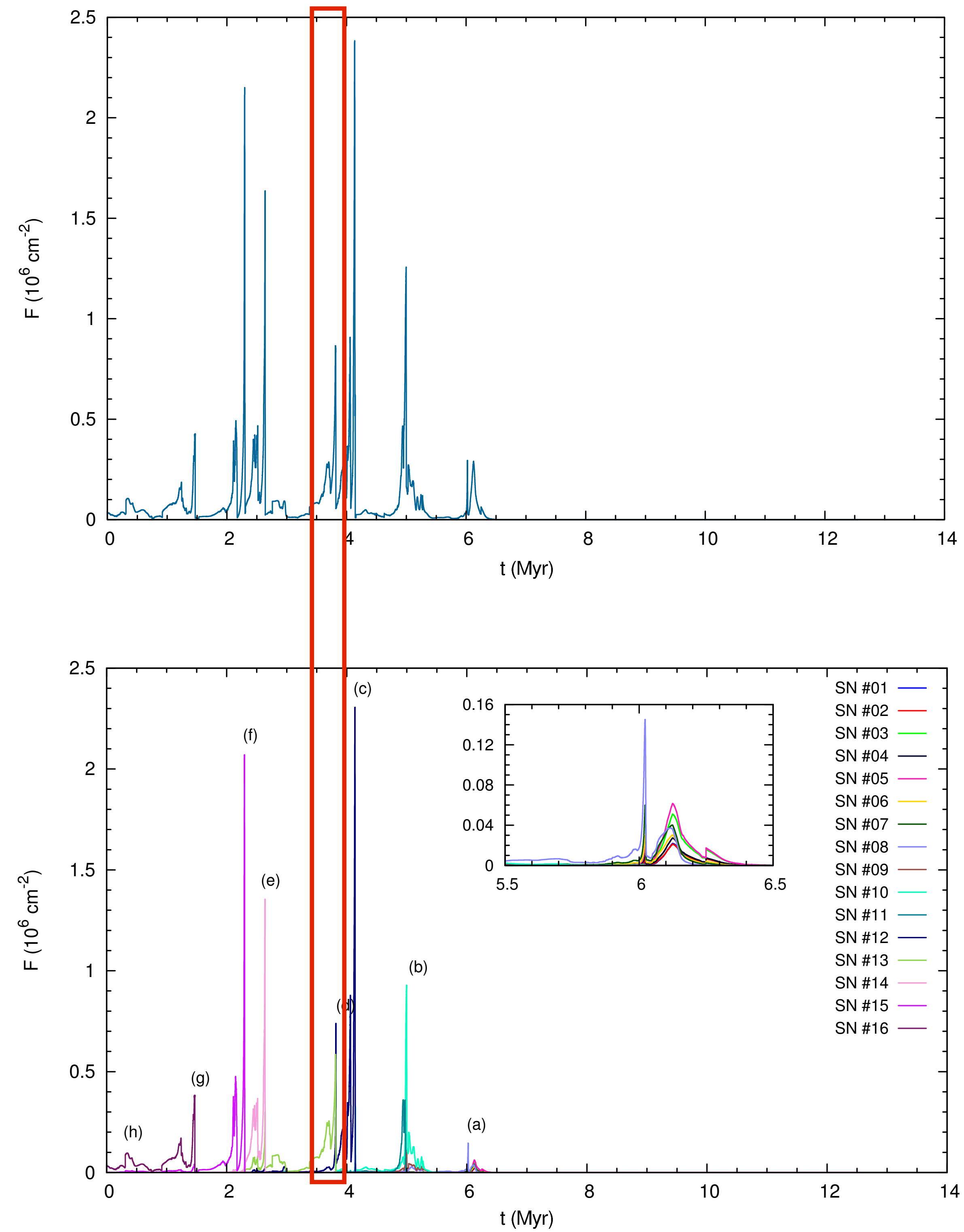

Results — Chemical mixing simulations with homogeneous background medium

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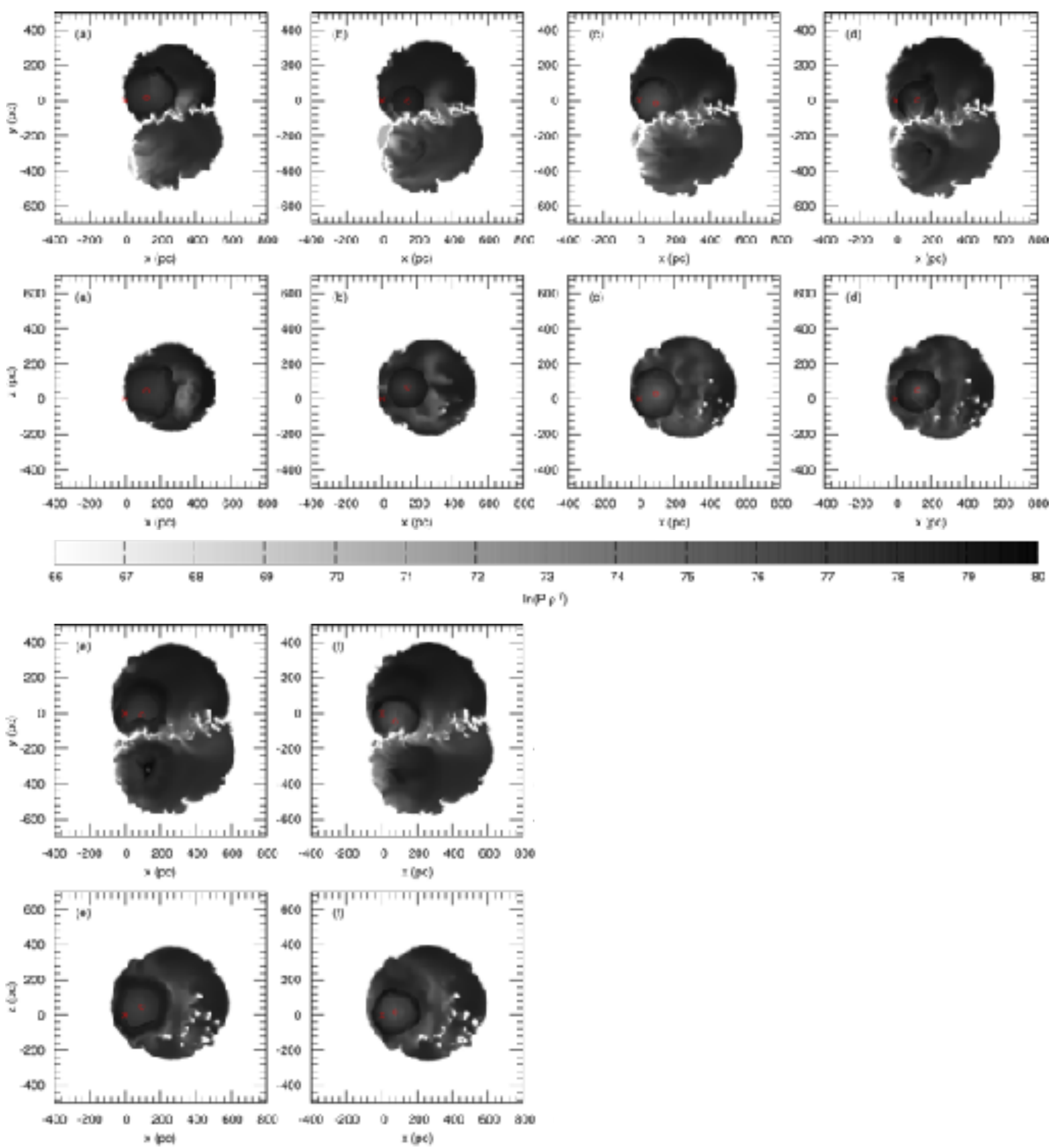

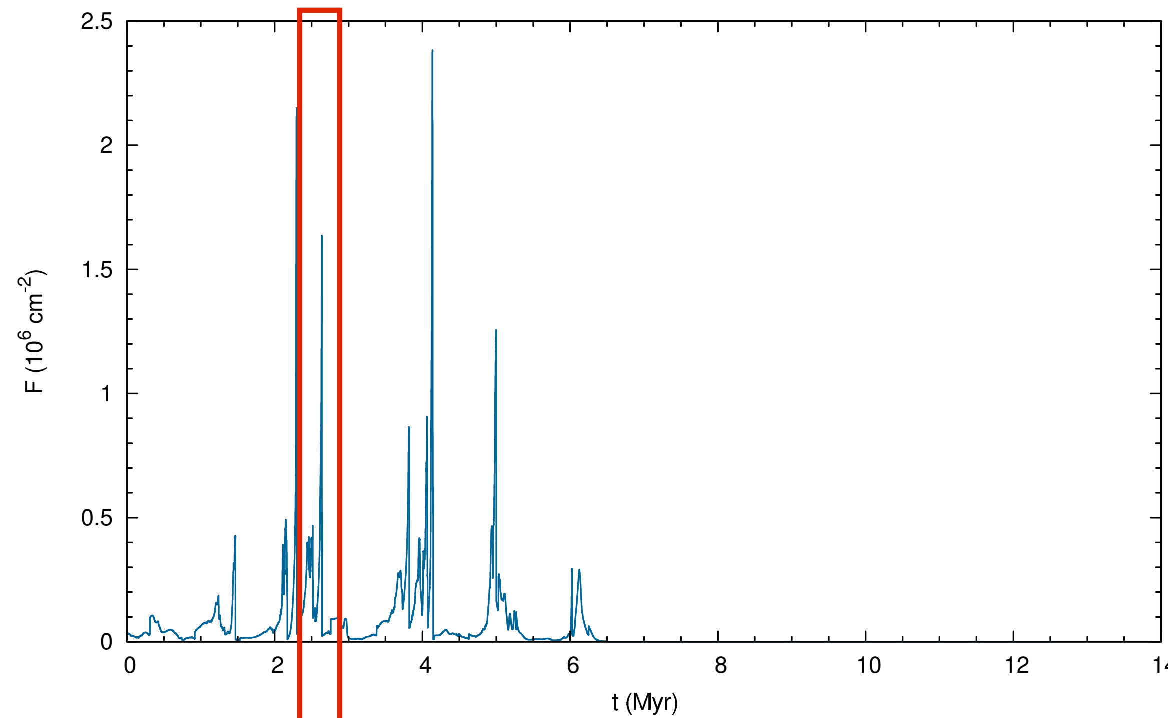

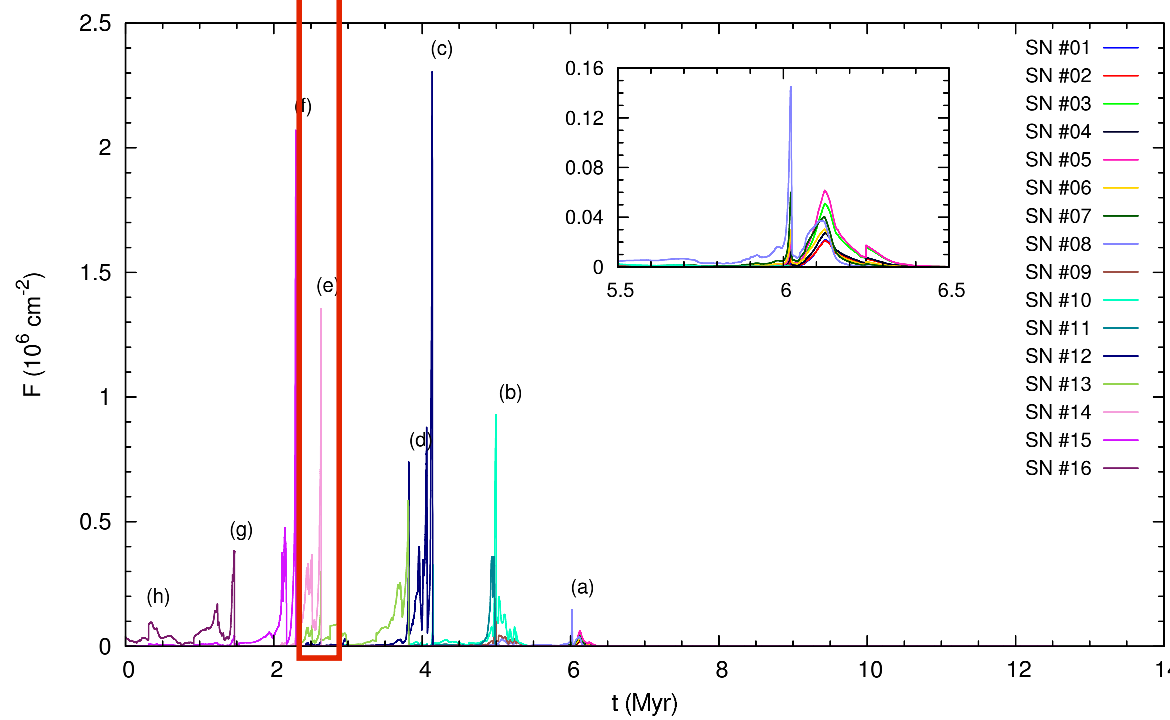

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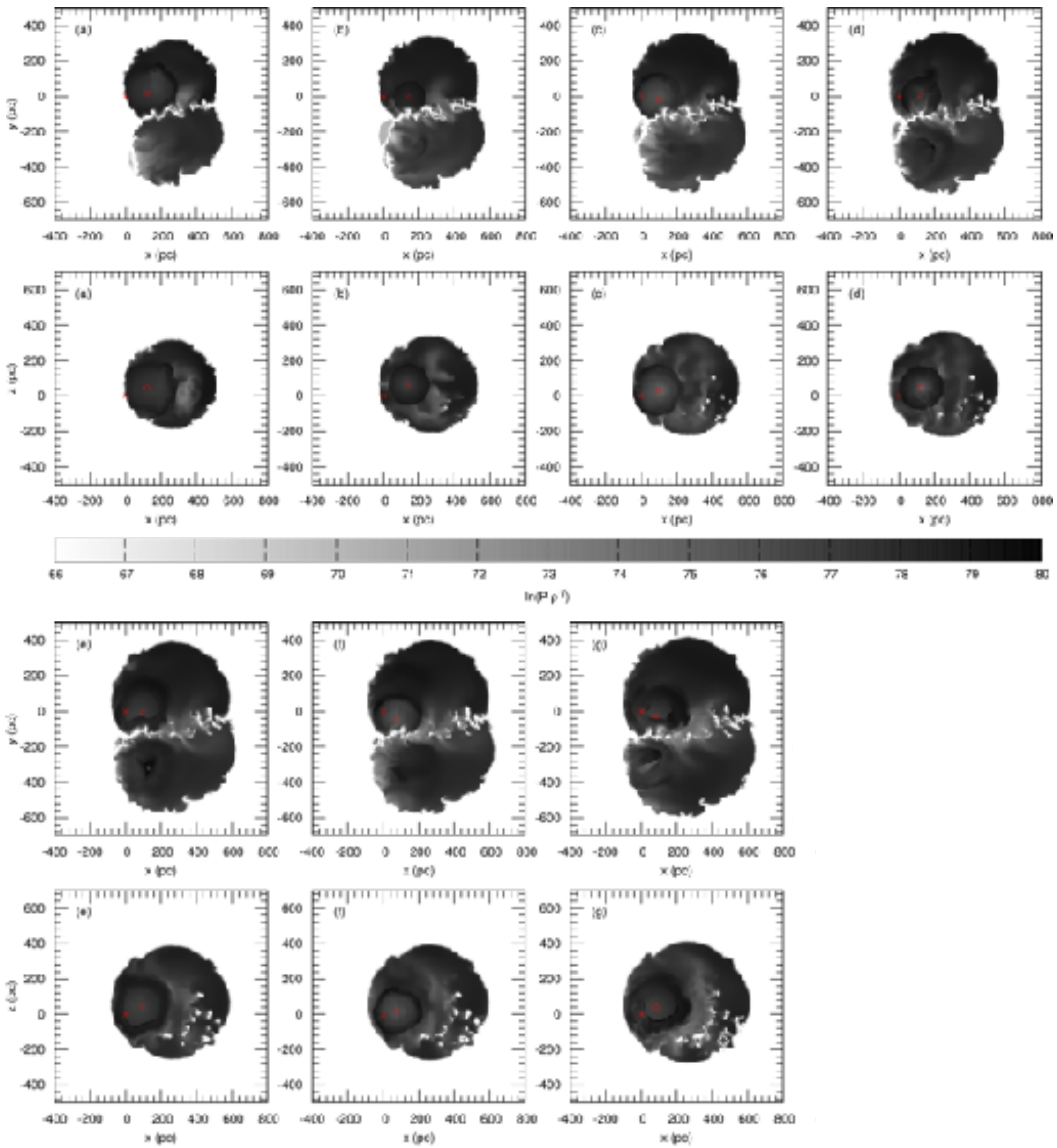

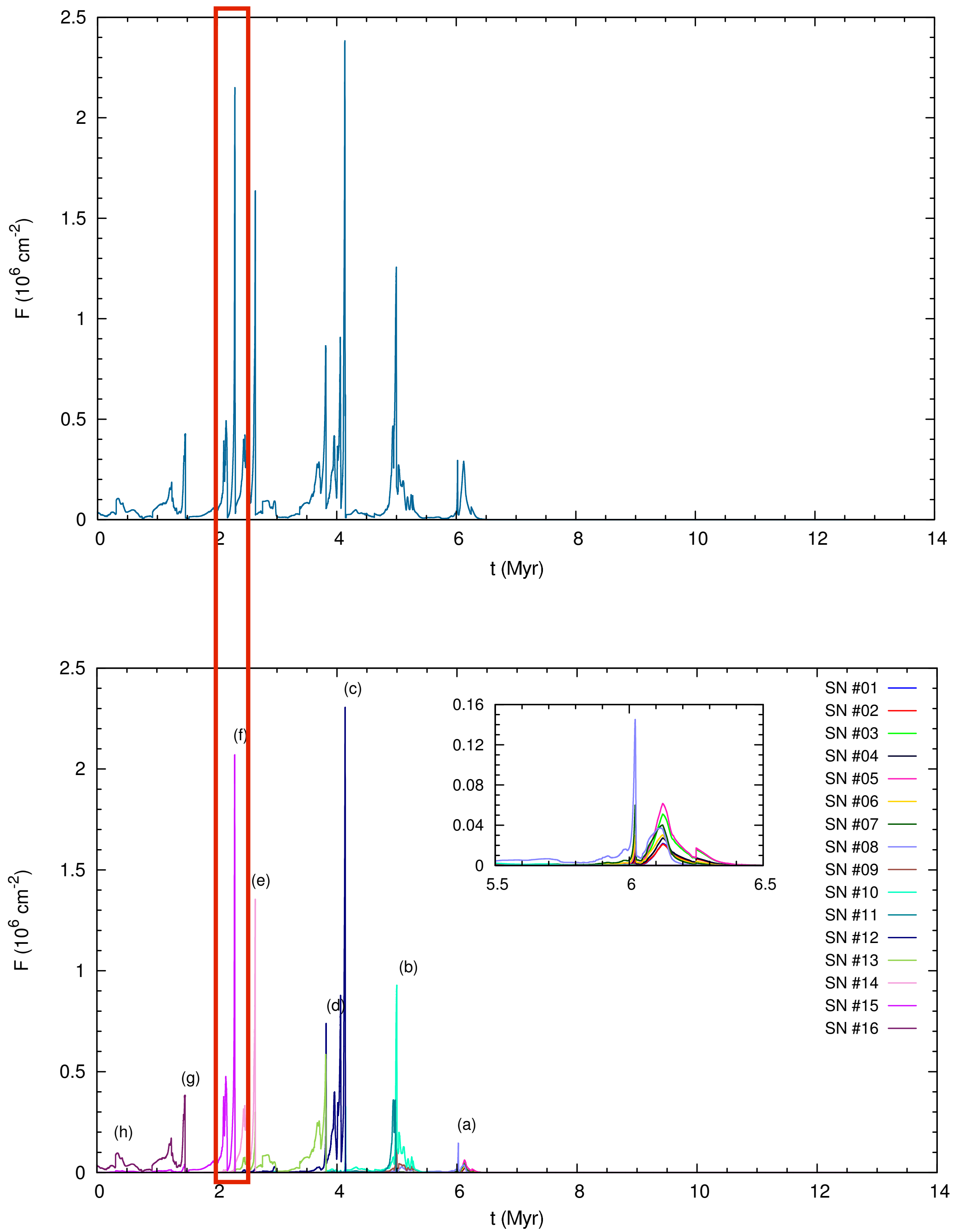

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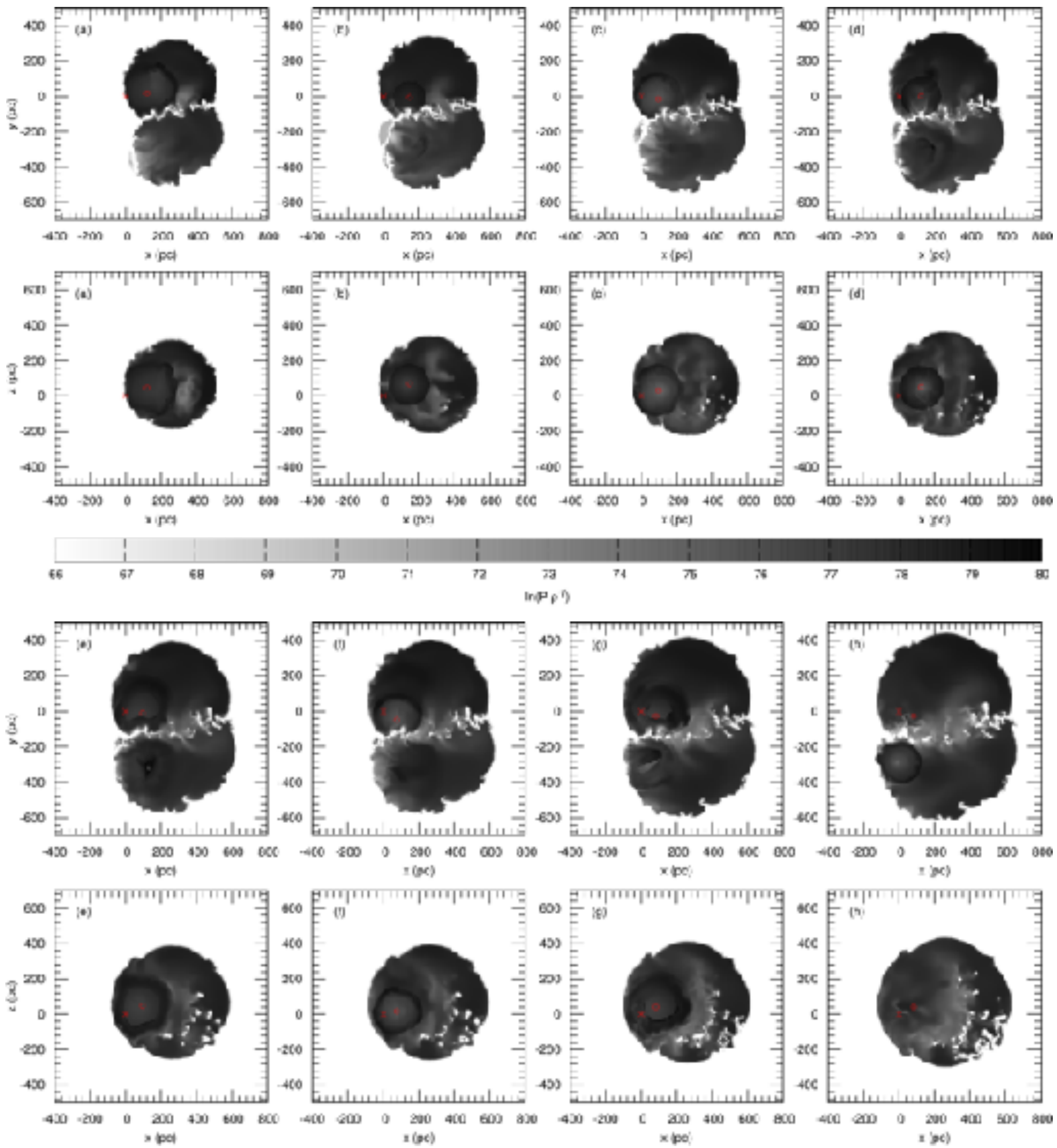
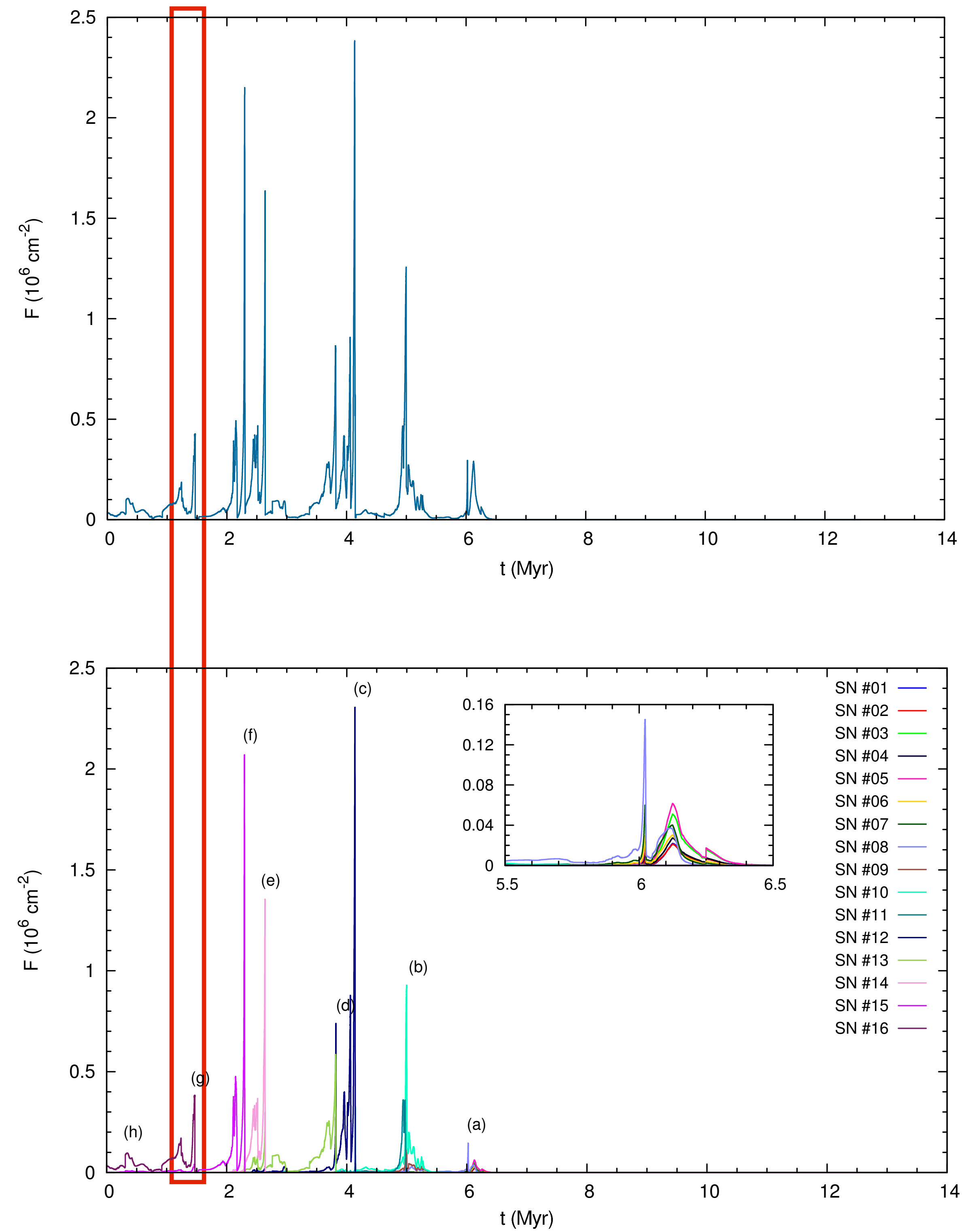
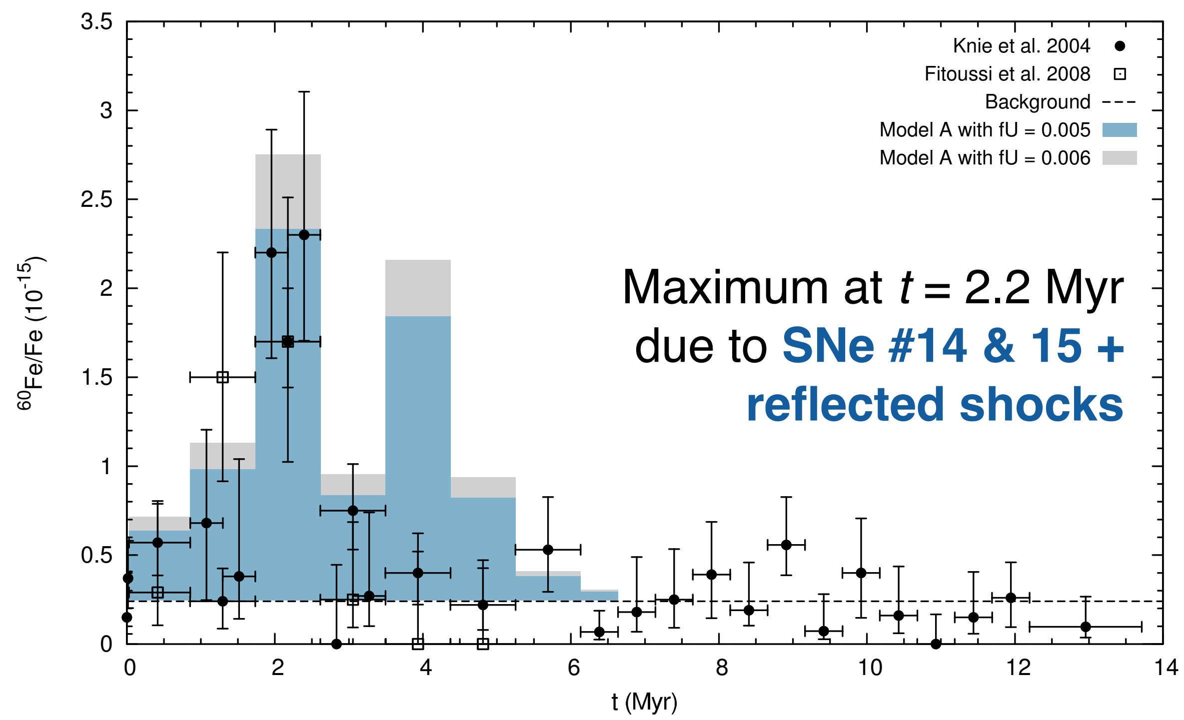
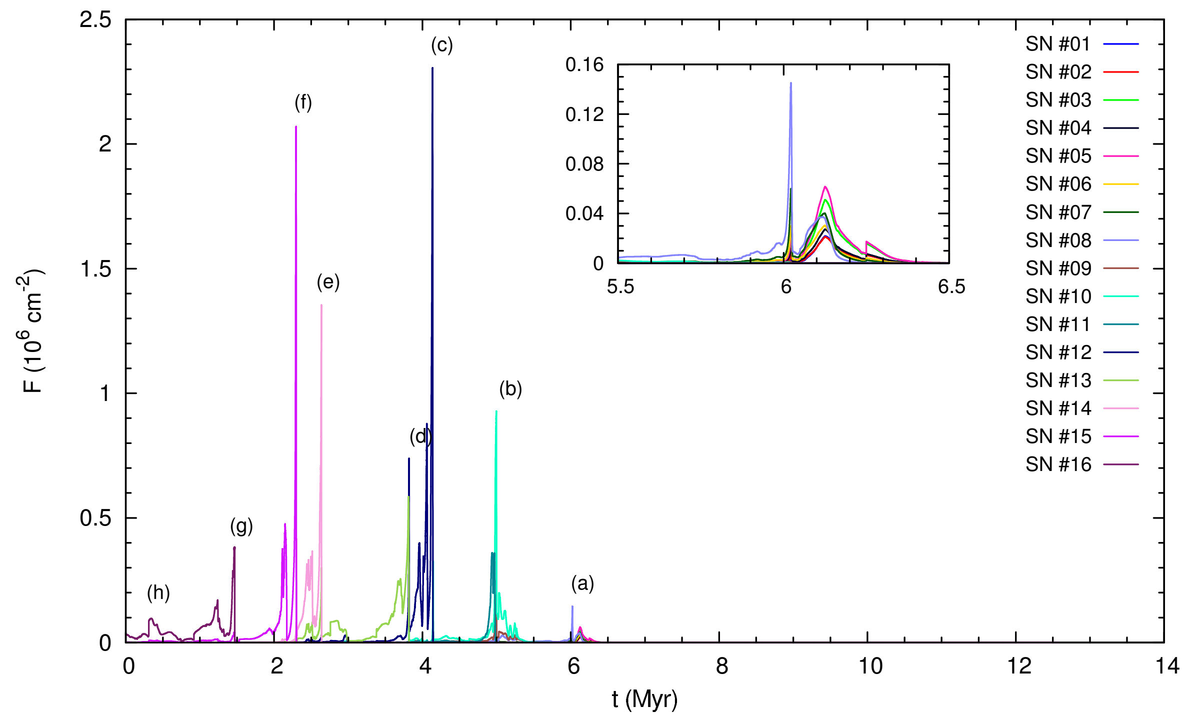




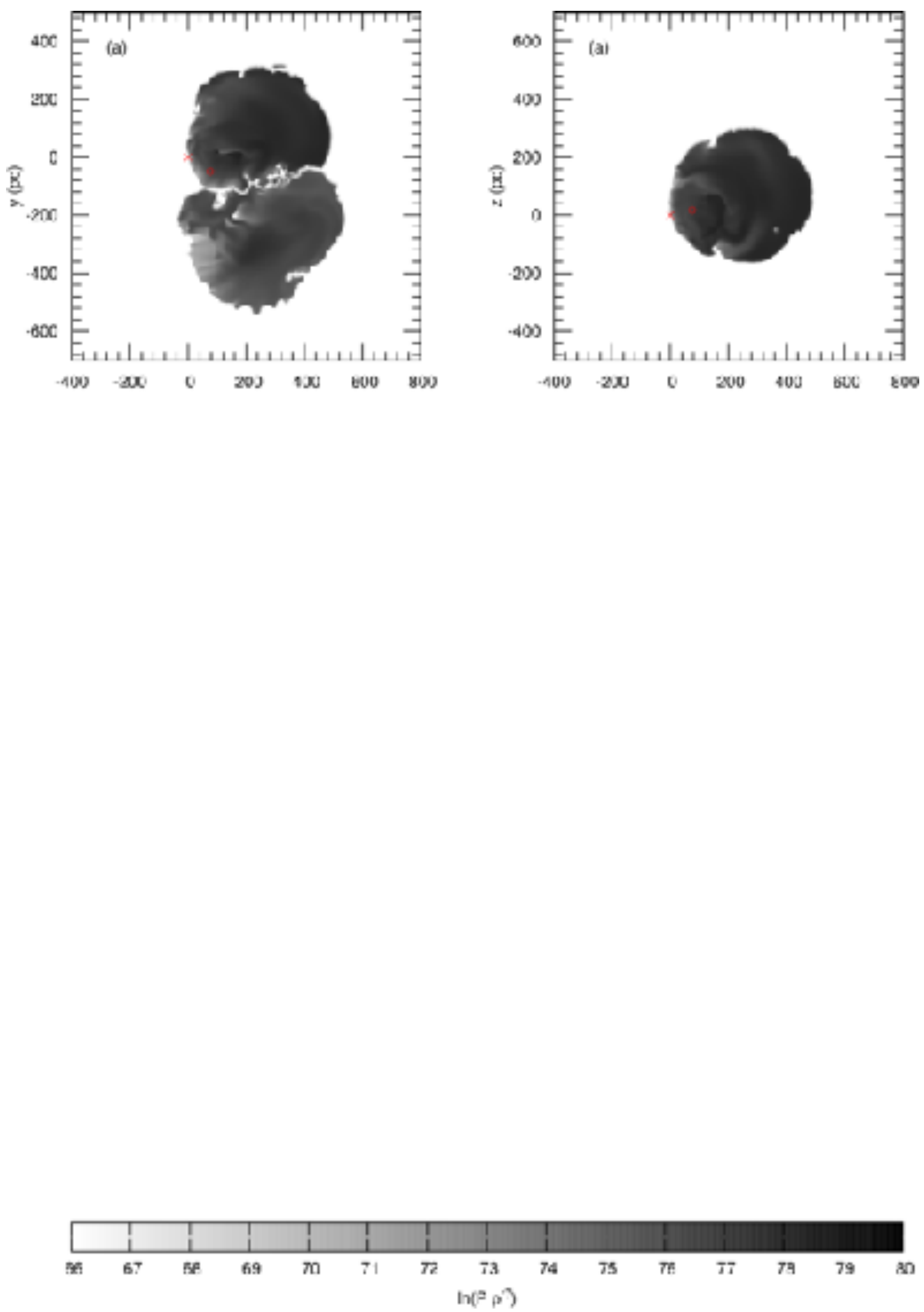
Model A: Entropy maps and modeled $^{60}Fe/Fe$ content in the FeMn crust

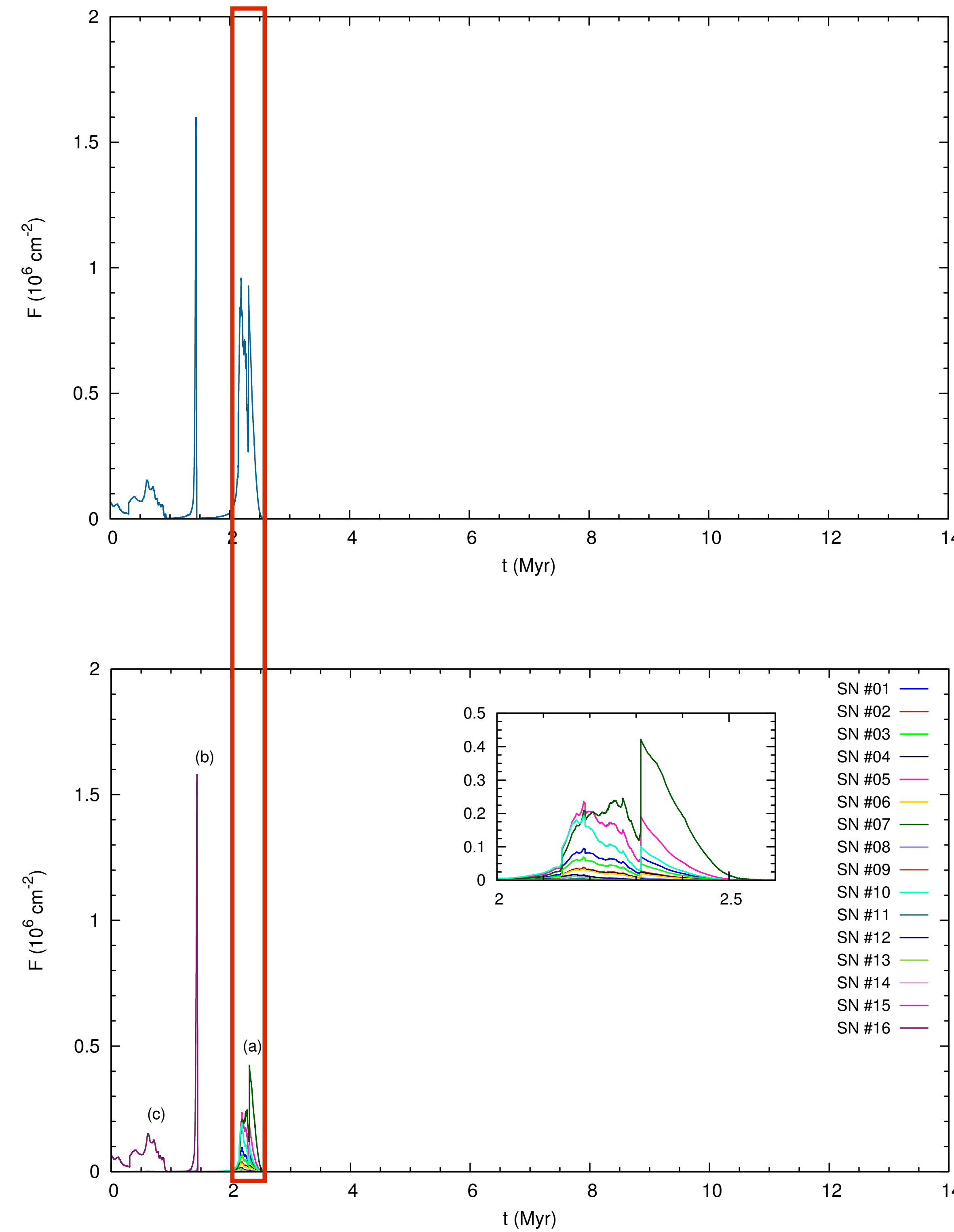
- Three different types of signals:
  1. High and sharp sawtooth waves ➔ Sedov-Taylor-phase SNRs (exposure time: $\Delta t \simeq$ 70–130 kyr ~ shell thickness)
  2. Weaker, more extended signals trailing sawtooth waves ➔ blast wave reflected from supershell (*SN 'echoes'*)
  3. Broad signal at the beginning of the profile ($\Delta t \gtrsim$ 300 kyr) ➔ LB supershell arrival
- All pulses entrain fractions of previously released ^{60}Fe
- ^{60}Fe should arrive on Earth as **dust**:
  - 'Filtering' due to partial condensation, loss during SNR expansion, collision between SNR and solar wind bubble
  - Remaining $f \simeq 1\%$ with grain sizes $\lesssim 0.2\,\mu m$ (Fry+ 2015) travel almost ballistically through solar system
  - Combined with recent uptake factor, $U = 0.5$–1 (Bishop & Egli 2011; Feige+ 2012) ➔ lower limit of survival fraction: $fU \simeq 0.005$





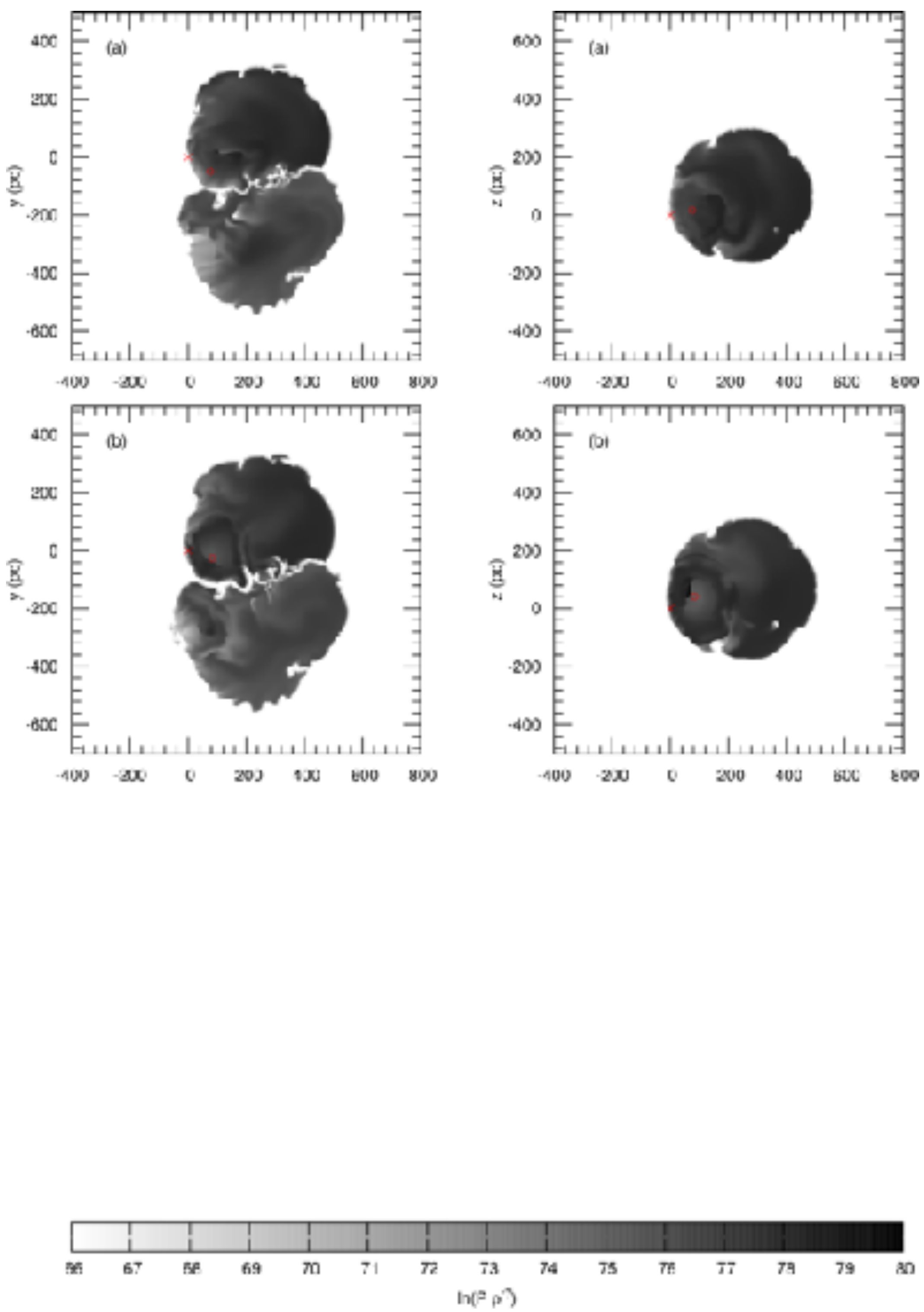
Model B: Entropy maps and 60Fe fluence variation

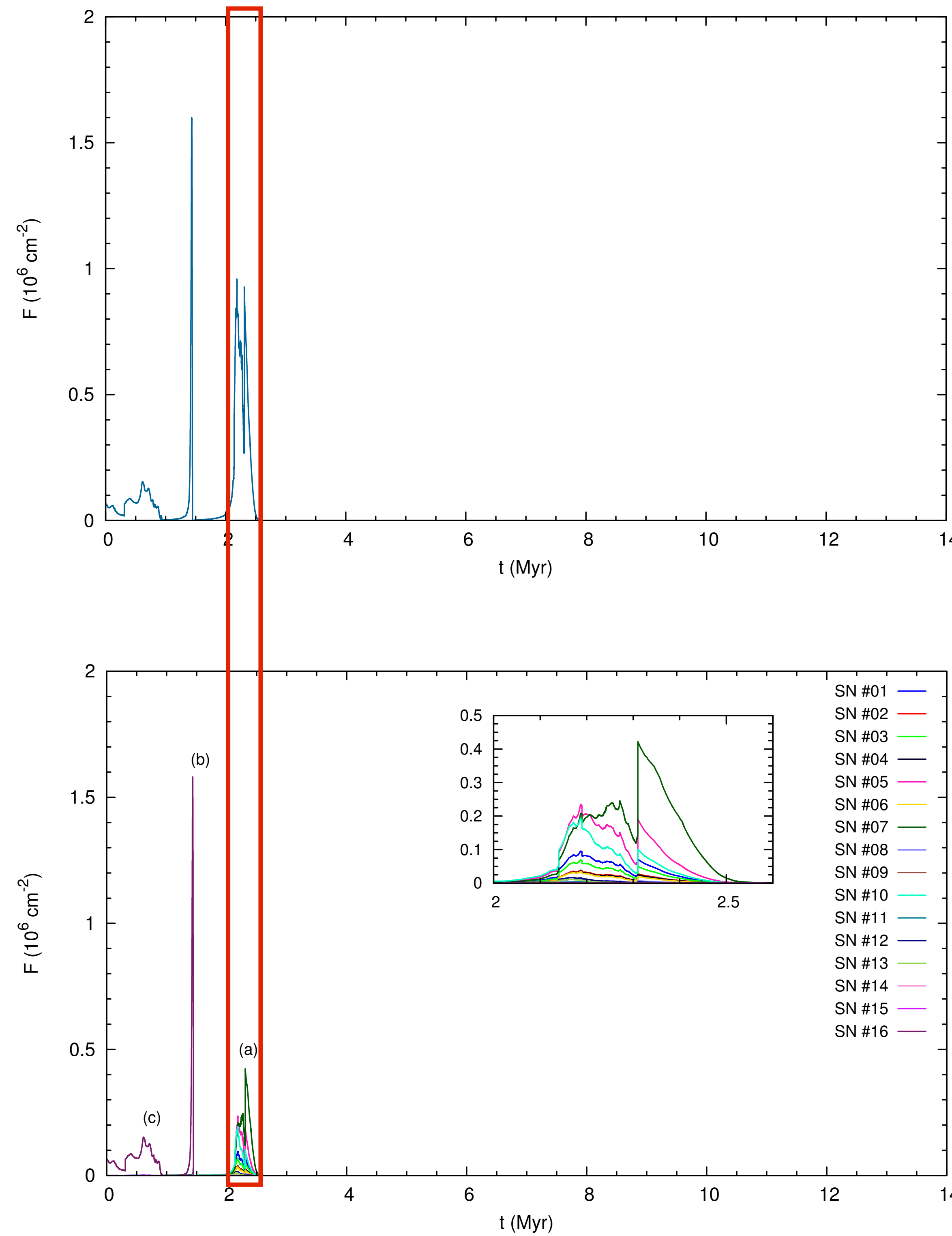




Results — Chemical mixing simulations with homogeneous background medium

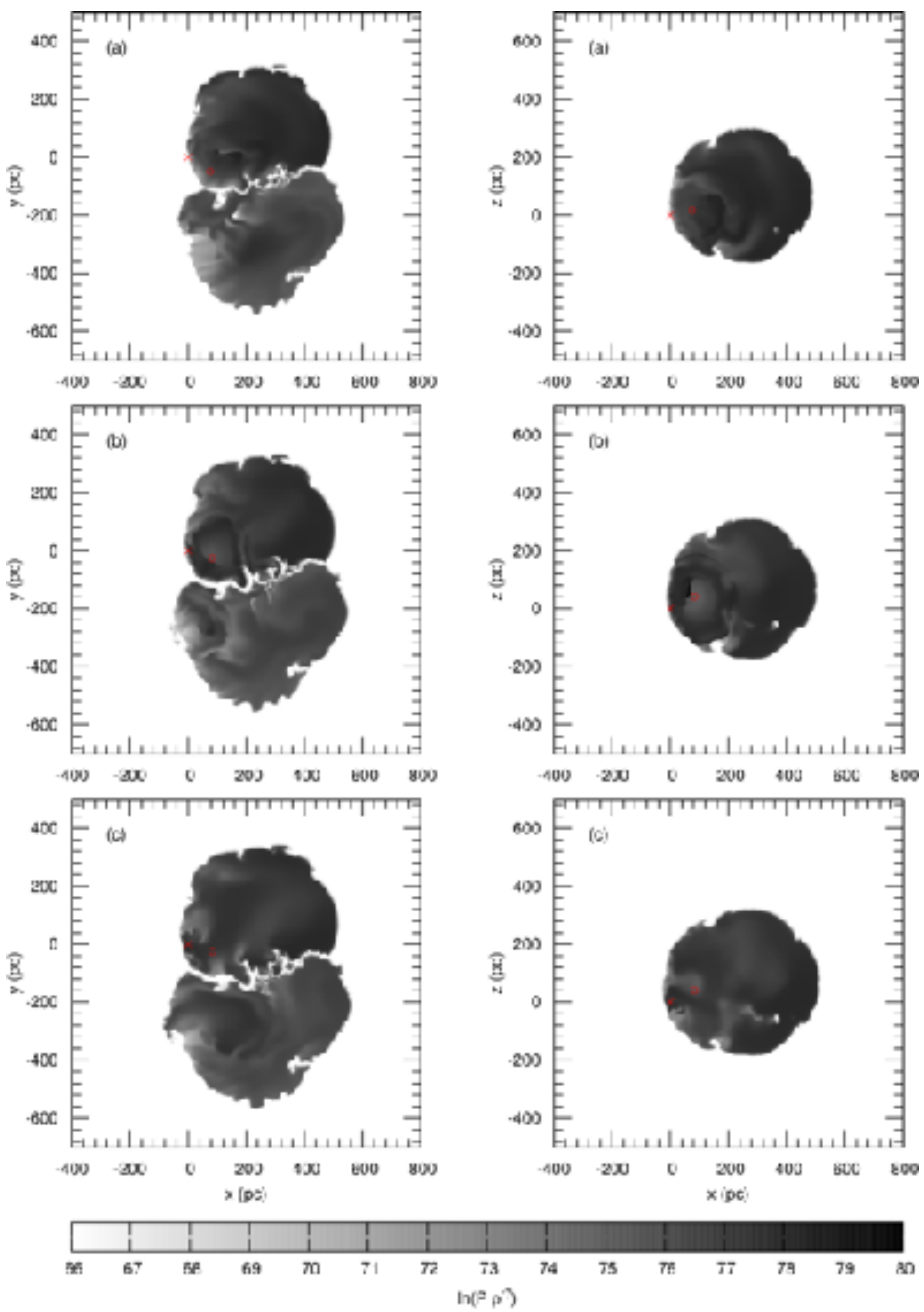
Model B: Entropy maps and 60Fe fluence variation

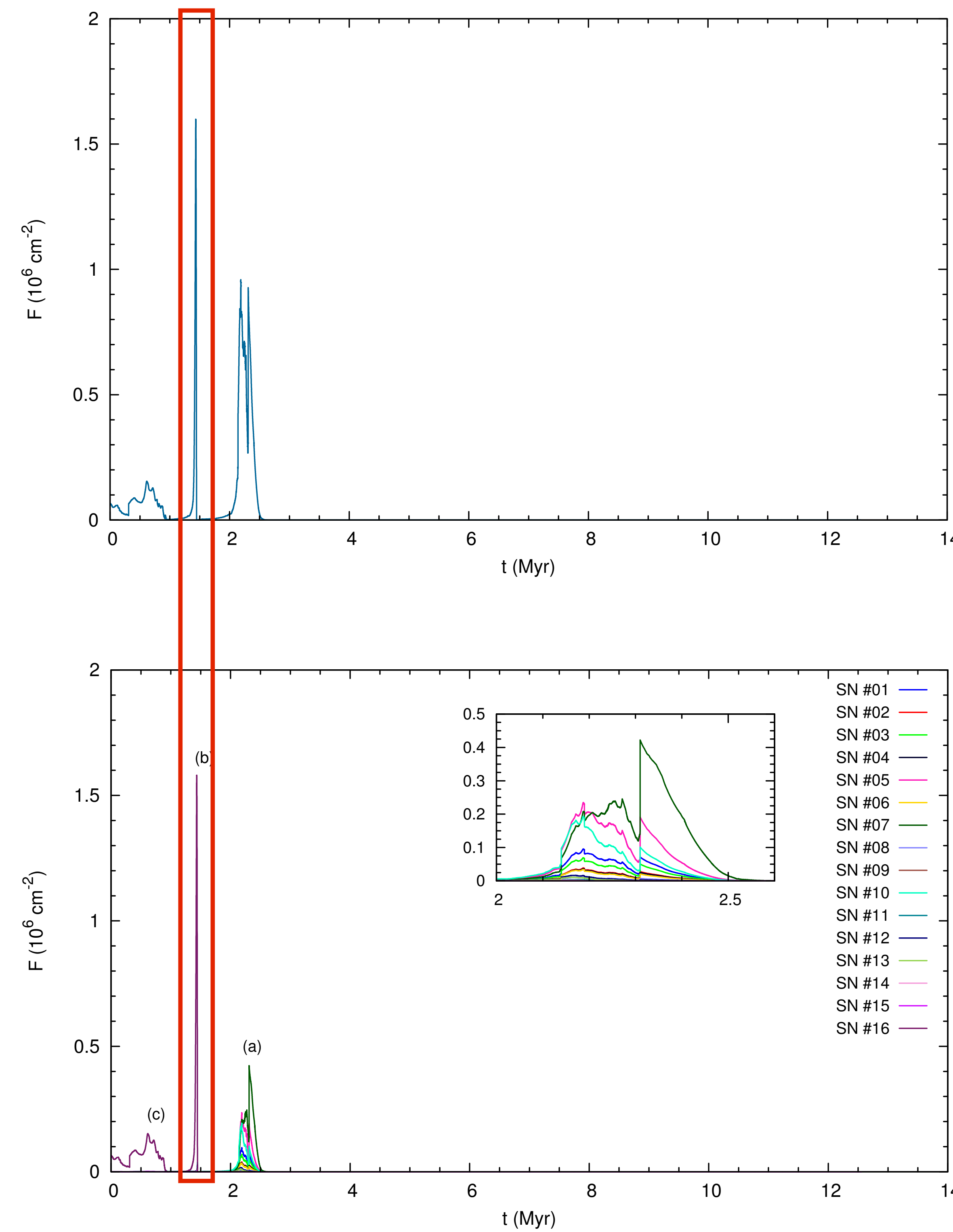




Results — Chemical mixing simulations with homogeneous background medium

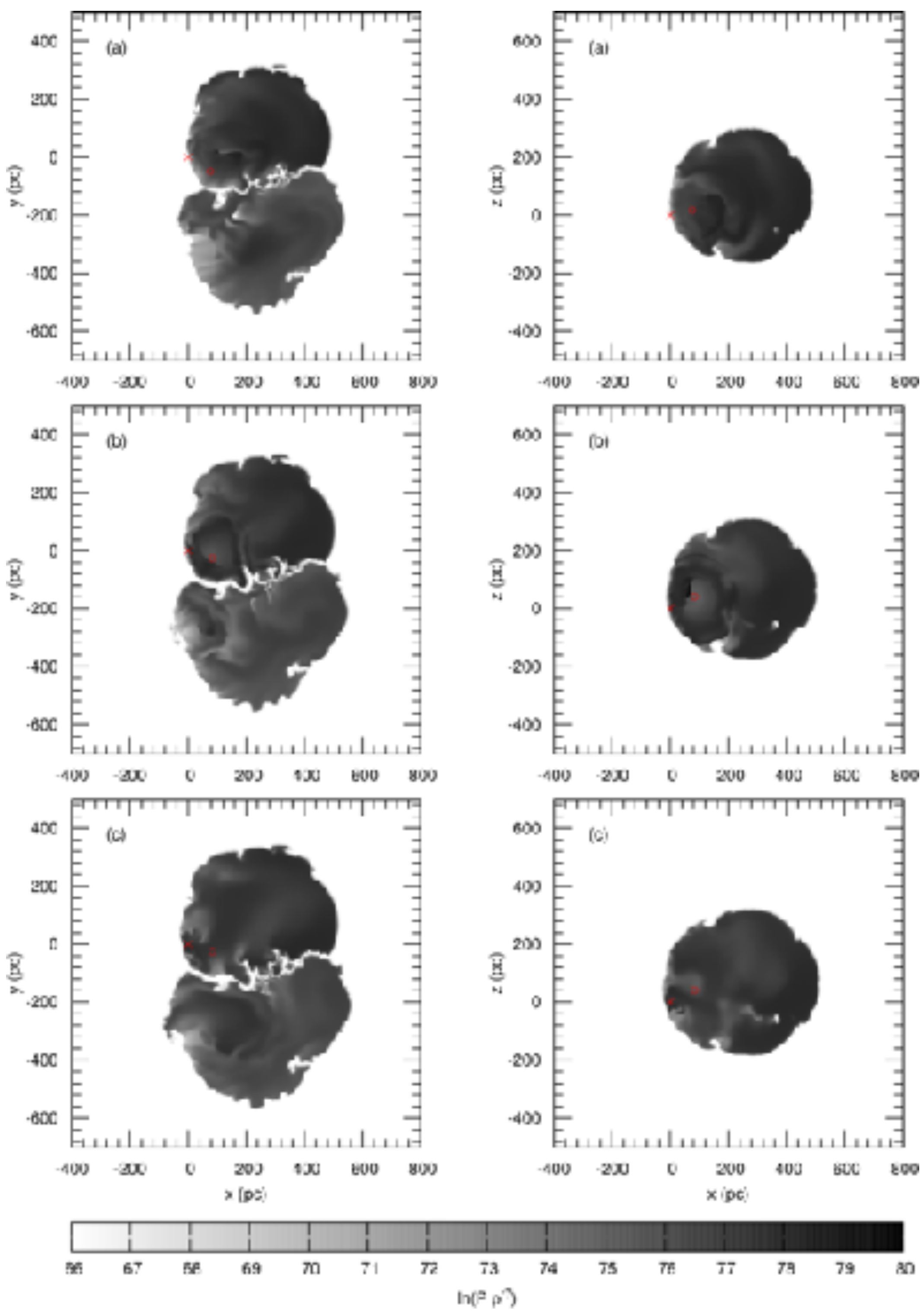
Model B: Entropy maps and 60Fe fluence variation

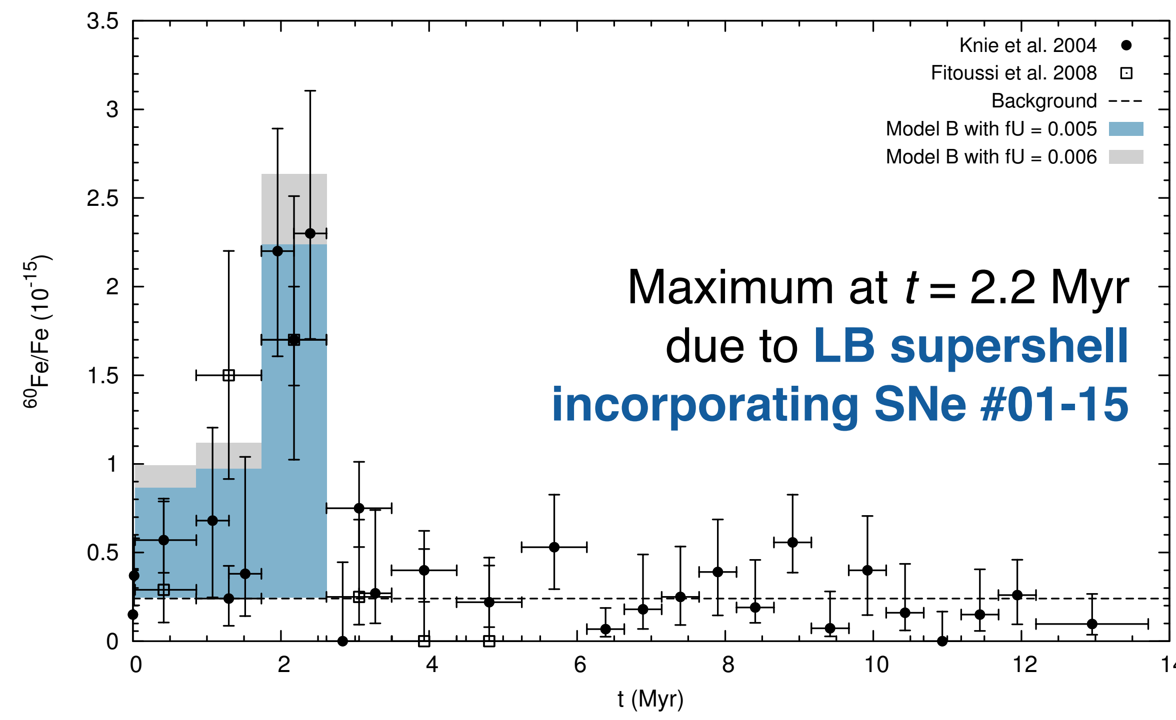


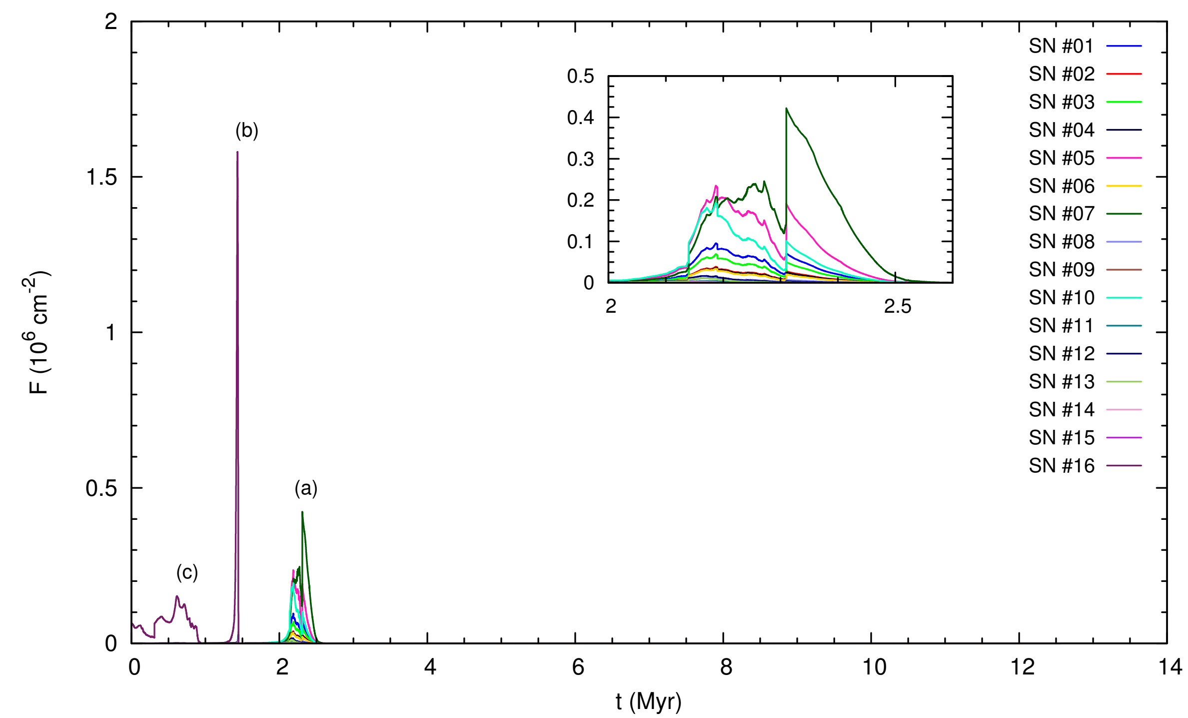


Results — Chemical mixing simulations with homogeneous background medium

Model B: Entropy maps and modeled $^{60}Fe/Fe$ content in the FeMn crust

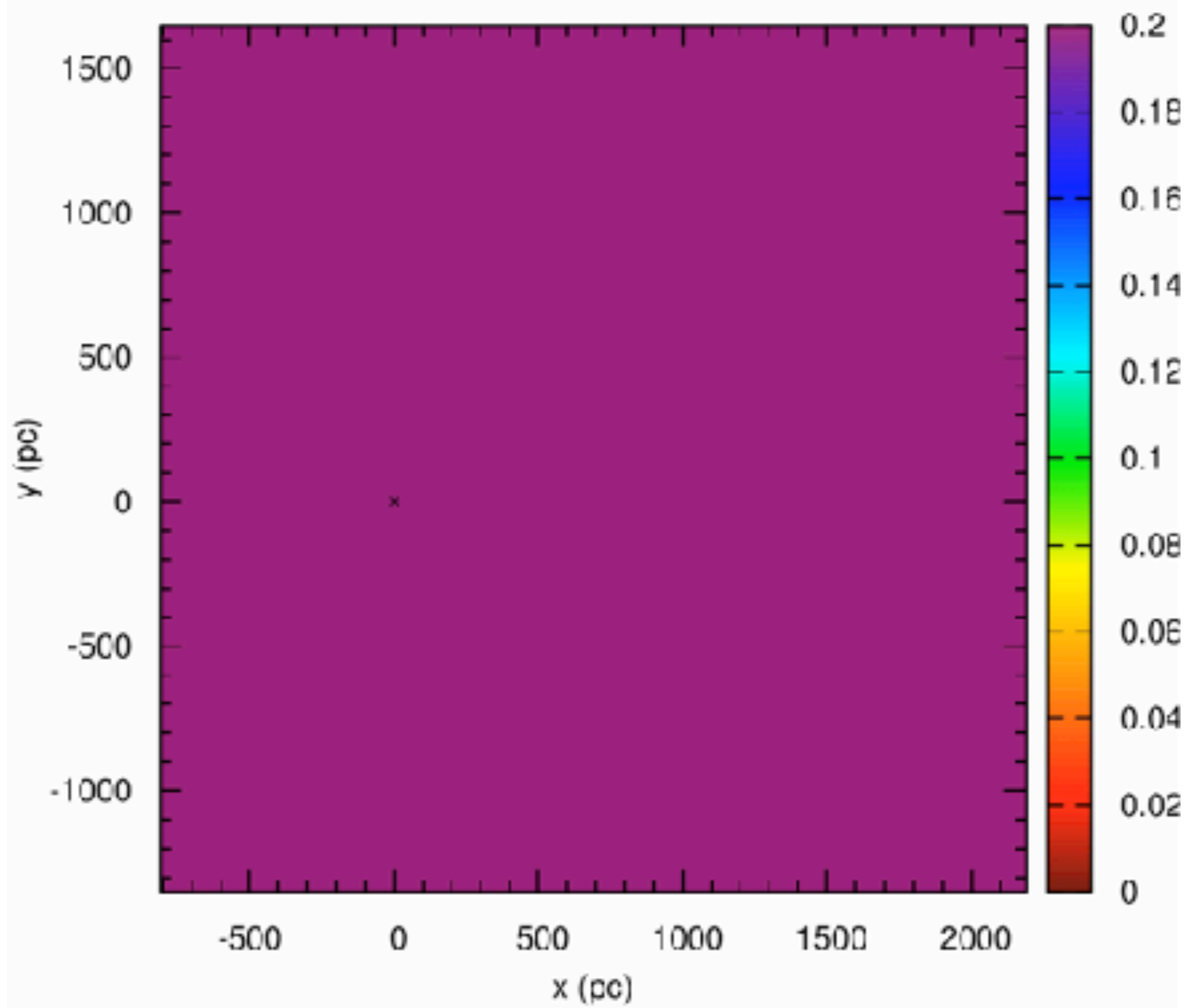


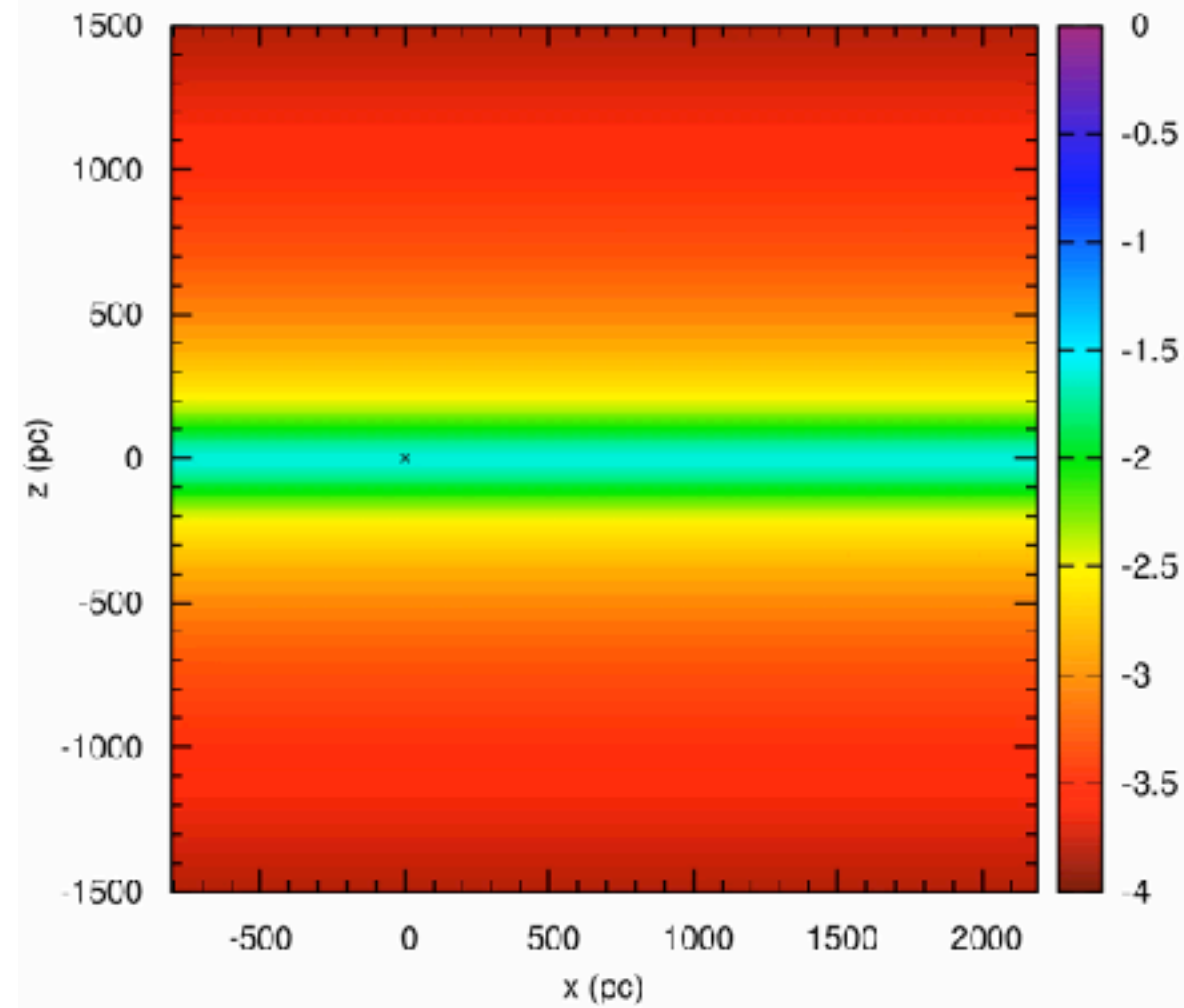




Results — Evolution of the Local Interstellar Medium

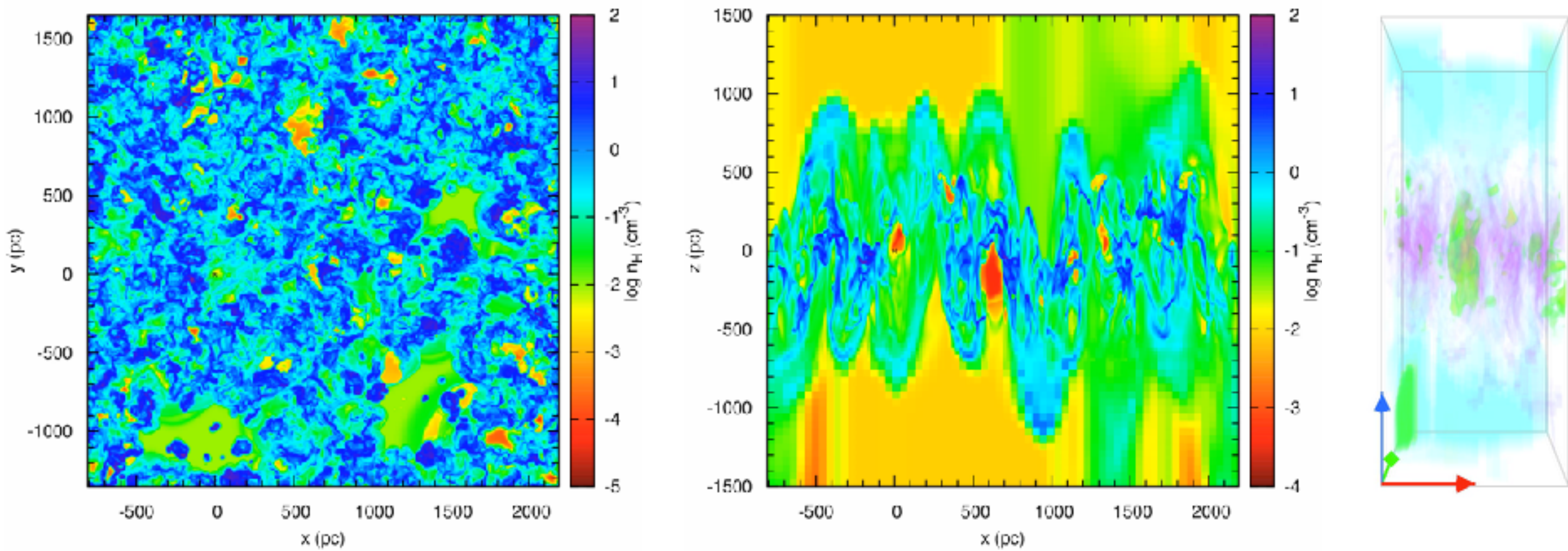
Atomic hydrogen number density and gas column density distribution (cuts through z = 0 and y = 0; 180 Myr evol. time)





Results — Chemical mixing simulations with inhomogeneous background medium

Model C: Evolution of the atomic hydrogen number density distribution (cuts through $z = 0$ and $y = 0$)

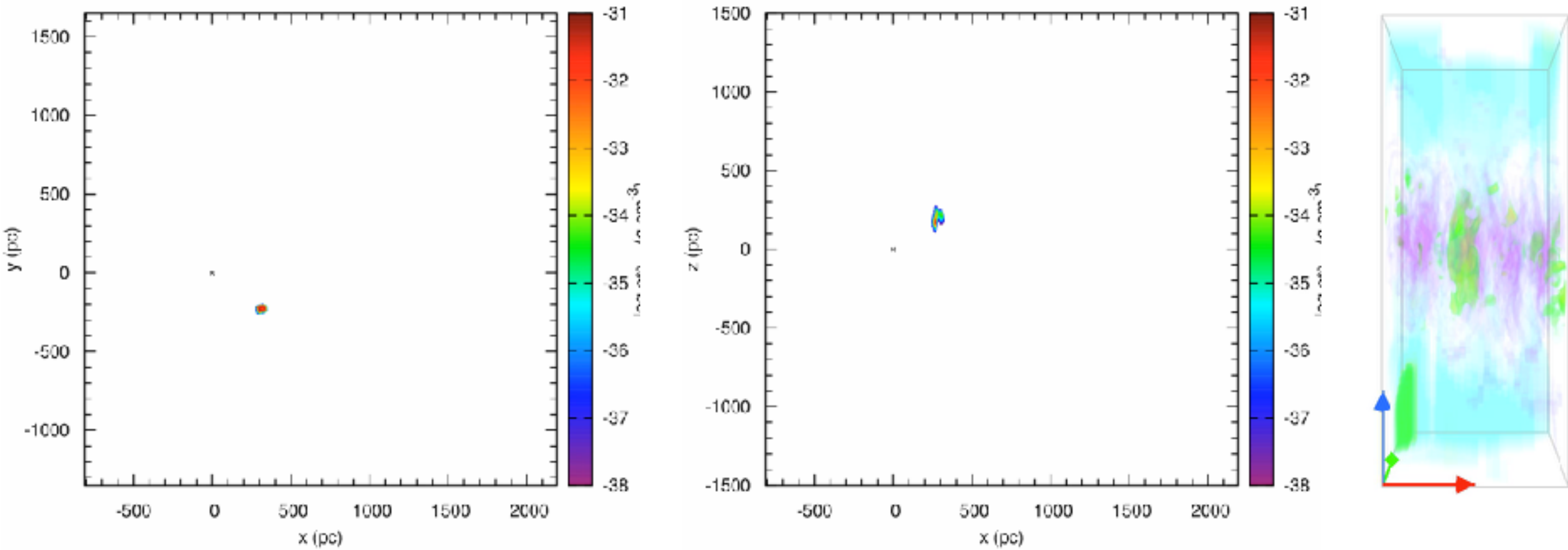


- Launch LB SNe in **"suitable"** environment
- search for extended region that remains sufficiently thin (n ≳ 0.3 cm^{-3}) at least for a few Myr
- dense gas with enough mass and small flow gradients for cluster star formation

- Internal structures after ~8 Myr due to influence of ambient density/pressure gradients
- 'Present' LB extension: $(x,y) = (280,260)$ pc, $|z| \gtrsim 500$ pc (northern half resembles chimney)
- Hydrogen density and temperature in 'present' LB cavity: $10^{-4.1}$-$10^{-2.2}$ cm^{-3}, $10^{4.5}$-$10^{6.5}$ K

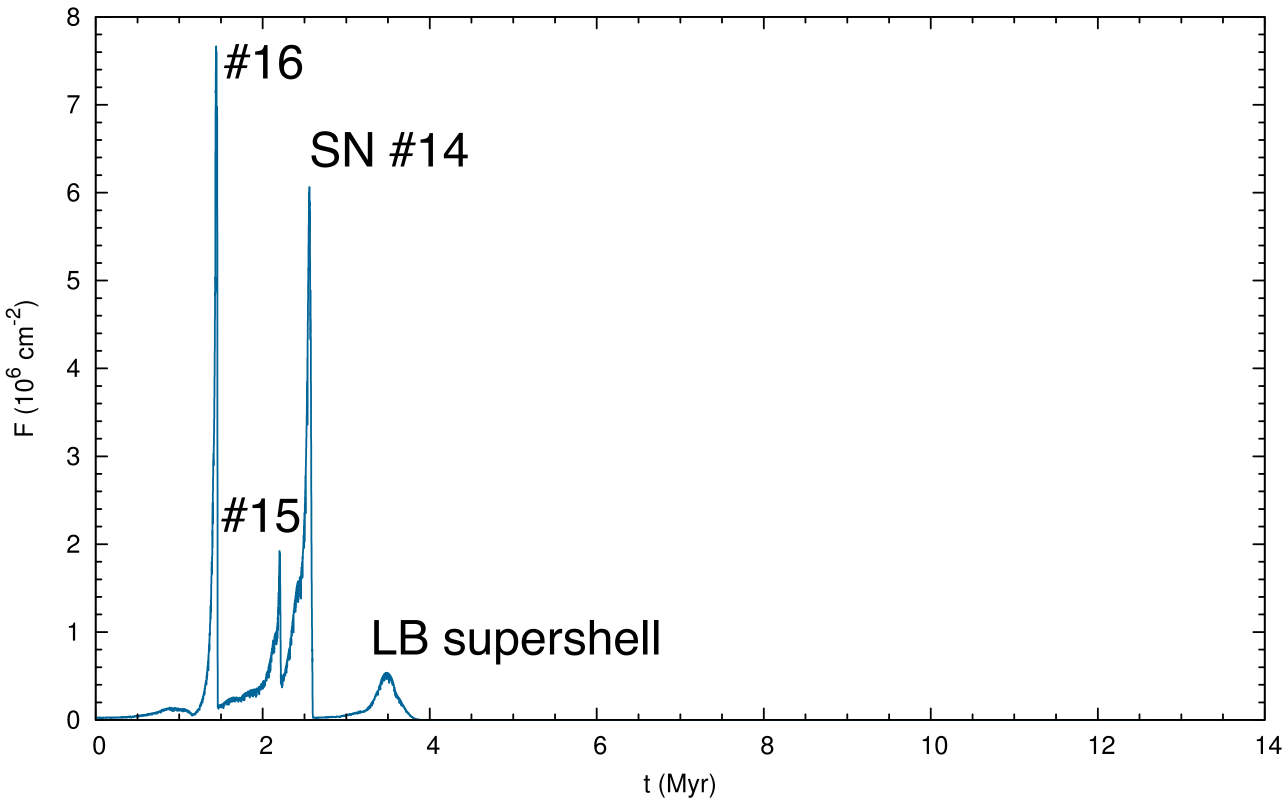
Results — Chemical mixing simulations with inhomogeneous background medium

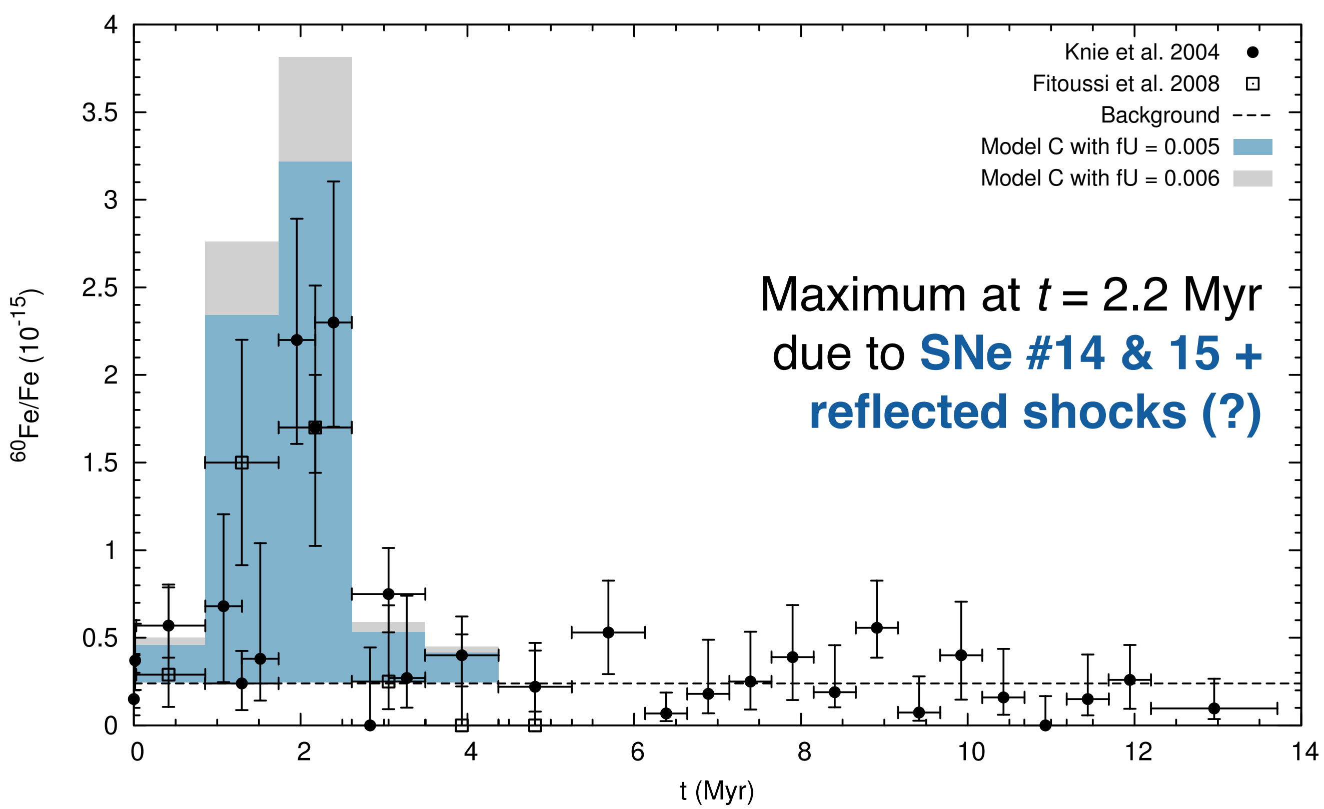
Model C: Evolution of the ^{60}Fe mass density distribution (cuts through $z = 0$ and $y = 0$)



No interstellar ^{60}Fe background ➔ model gives lower limit of ^{60}Fe content in the local ISM!

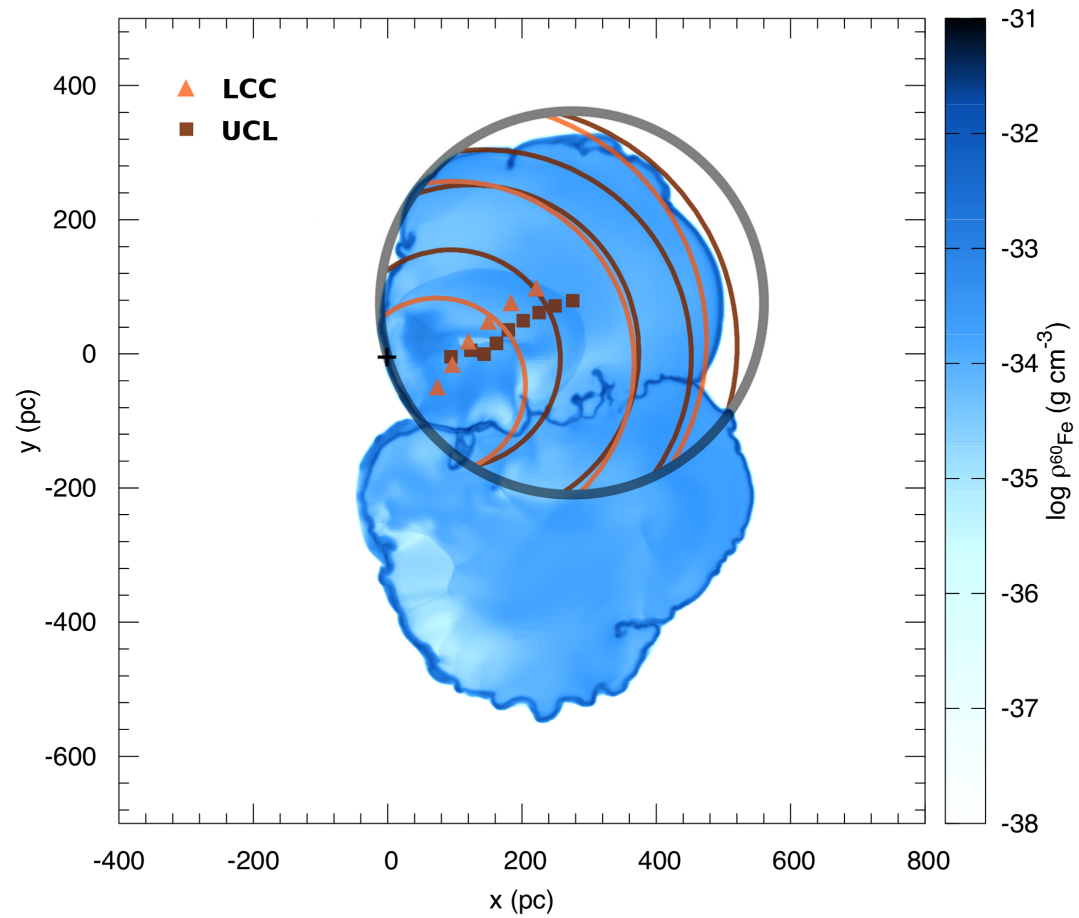
Model C: Comparison between models and crust measurements

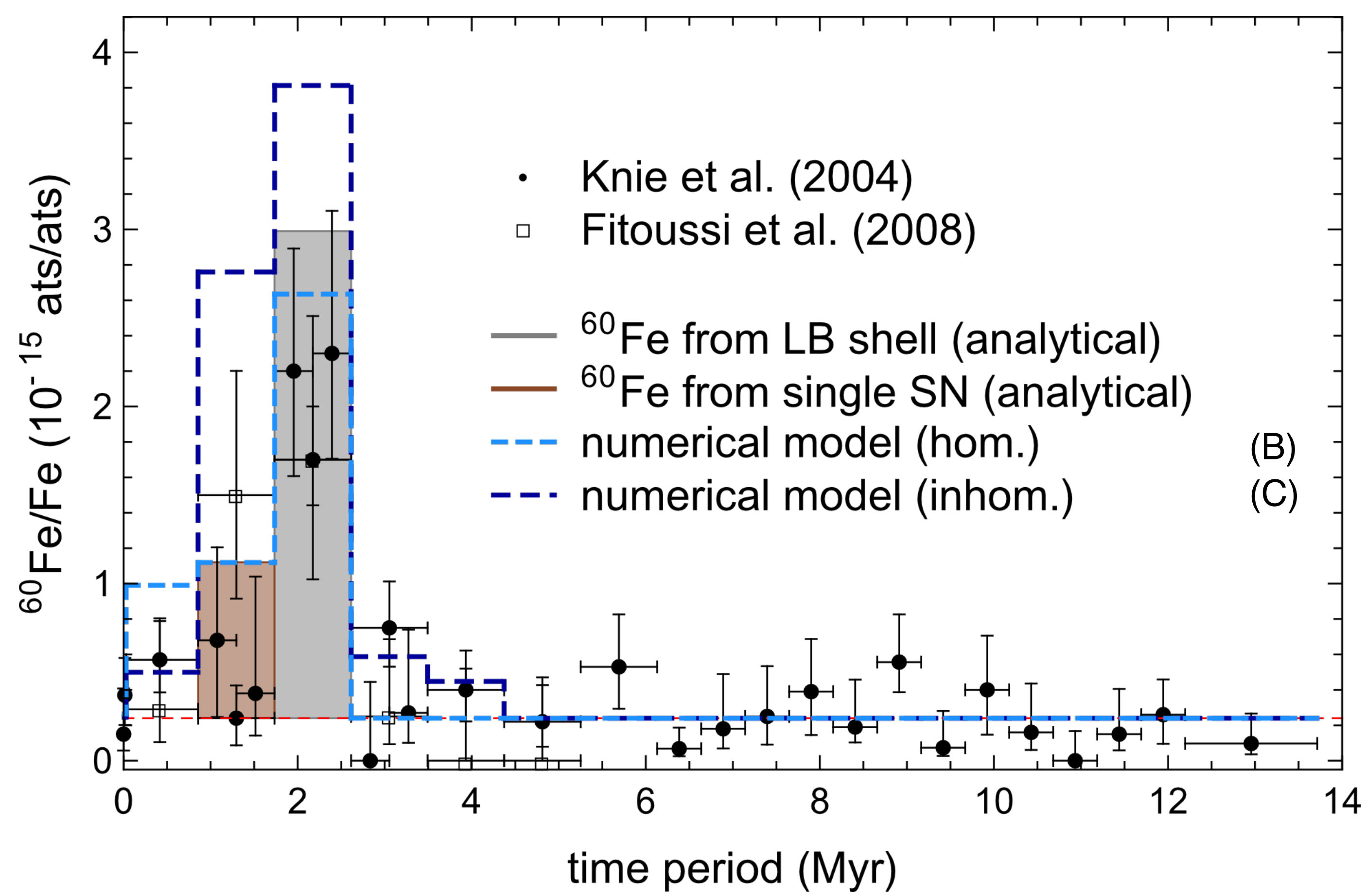




- Artificial signal broadening due to 4x lower resolution
- Model C is a hybrid of model A and B:
  - Fewer pulses due to individual SNe than in model A, but more than in model B
  - Mean density ambient LB medium in between model A and B [i.e., $(n)_{VA} \simeq 0.2$ cm^{-3}]
  - Supershell arrives later in A than in B ➔ self-gravity unimportant in LB evolution

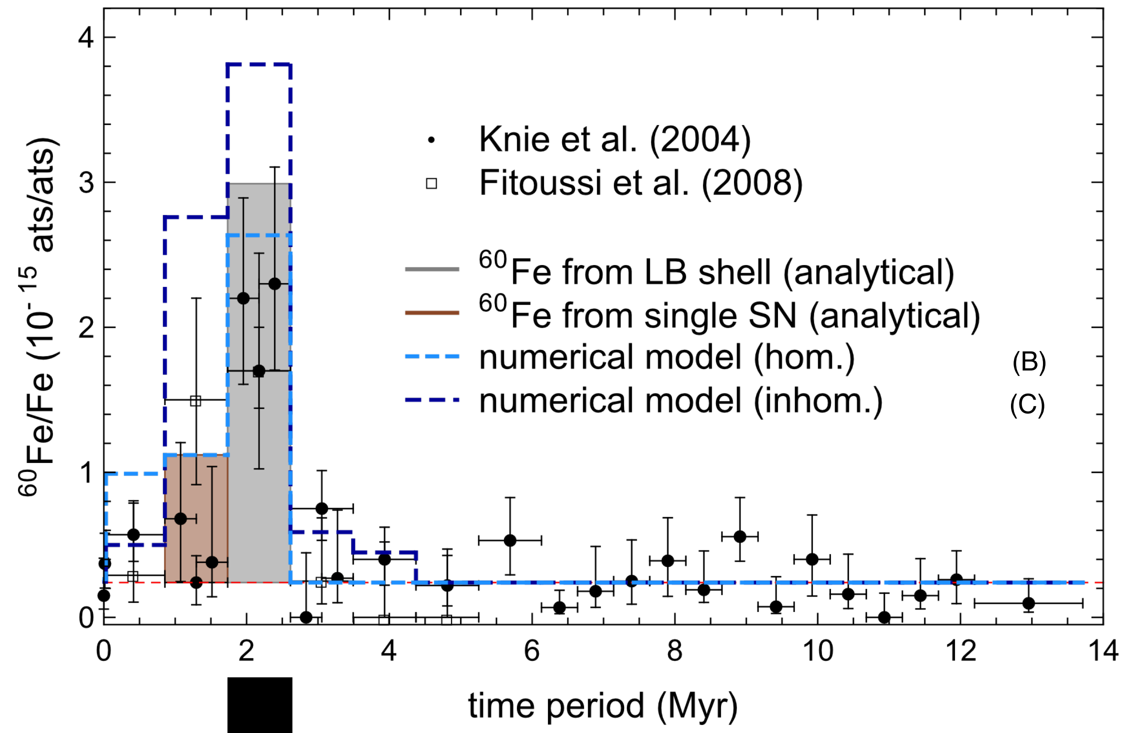
Comparison of numerical and analytical solutions

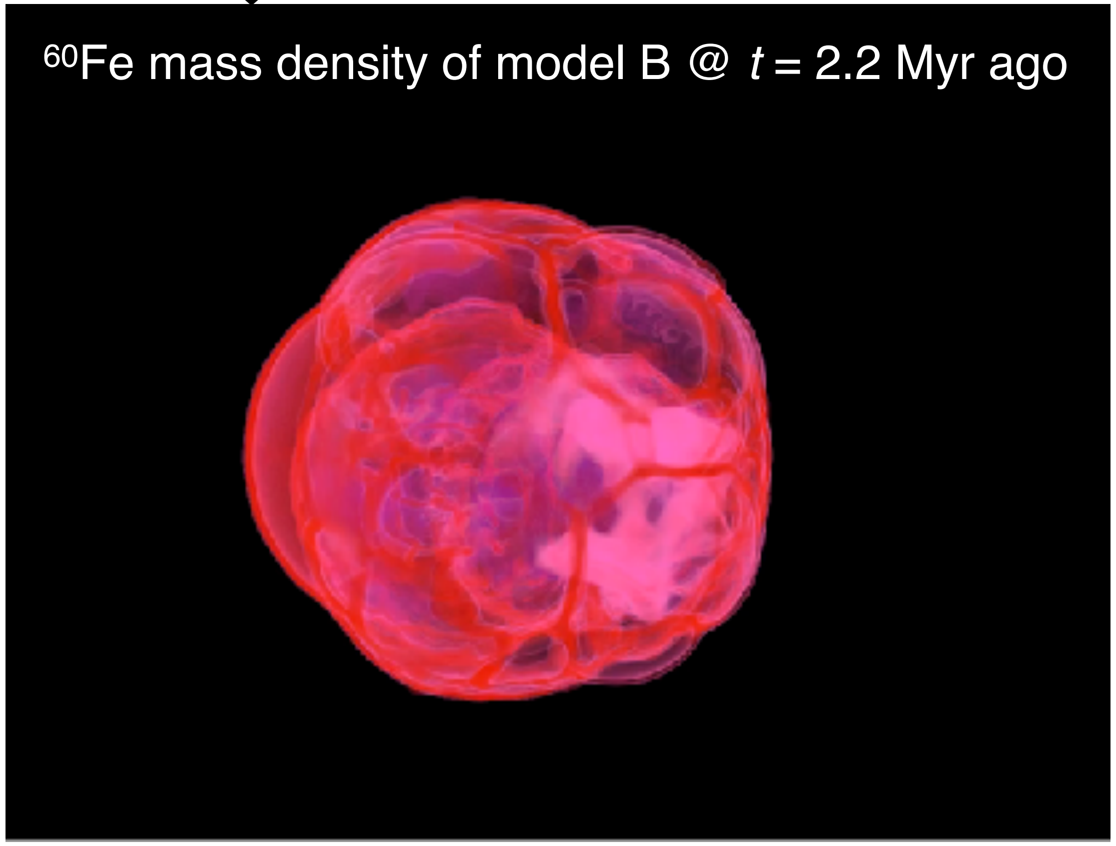




Summary

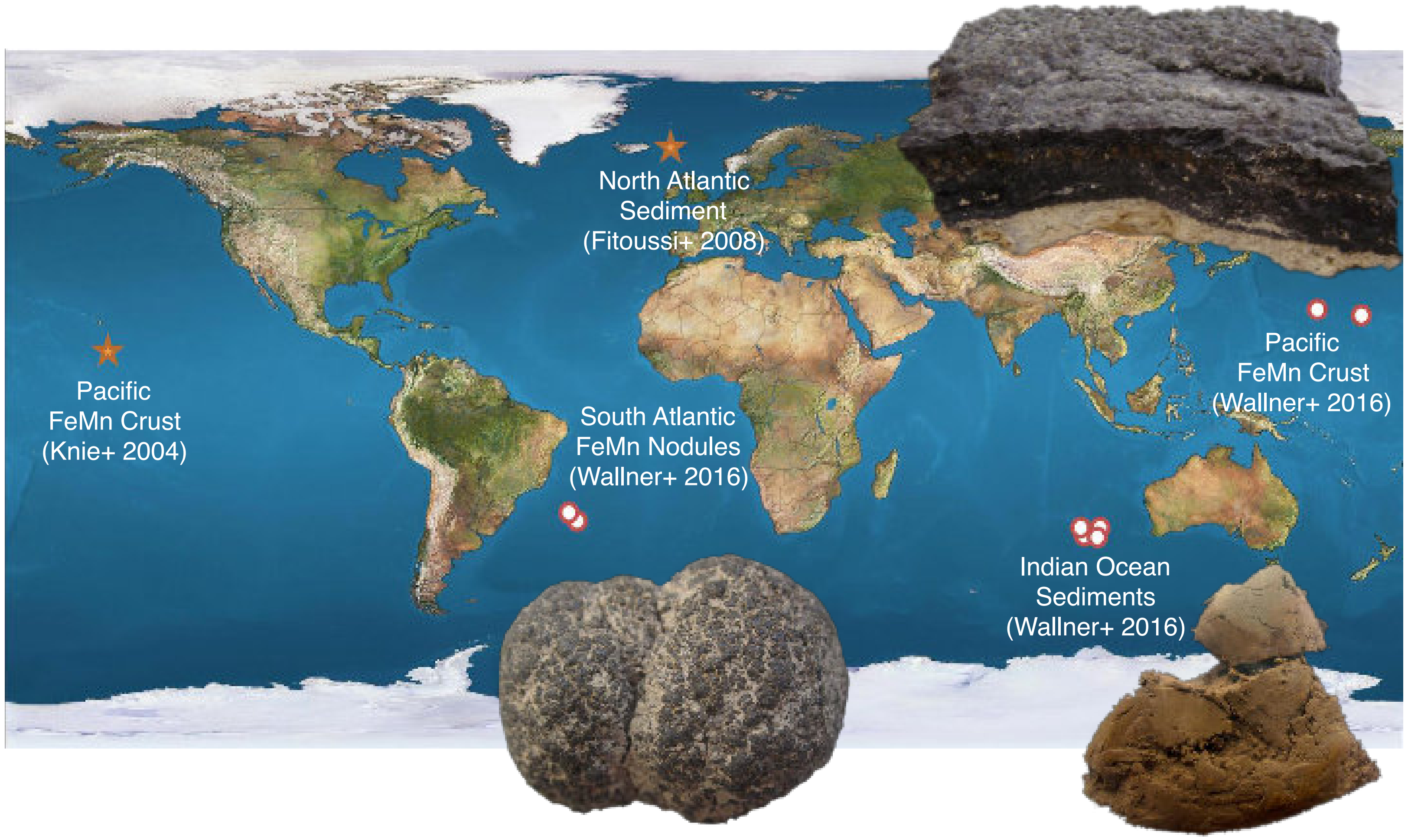
- **Analytical** and **numerical** computations show that SNe creating the LB can also reproduce ^{60}Fe in the crust
- **Cluster age** derived from stellar isochrones
- **Explosion times** derived from stellar masses
- **Masses** derived from **IMF** using most probable binning
- **Cluster trajectory** derived from epicyclic eqs. using phase space (**x**-**p**)-coordinates from Hipparcos & ARIVEL data
- **Explosion sites** derived from most probable paths of the perished moving group members
- **^{60}Fe yields** from stellar evolution calculations
- **Mixing** with ISM followed via passive scalars
- **Joint evolution** of the Local & Loop I SB studied numerically for 3 models: two homogeneous and one inhomogeneous
- Models **reproduce both the timing and the intensity of the ^{60}Fe excess observed** with rather high precision
- **Two deposition scenarios**:
  - individual fast-paced SNRs, whose blast waves can become reflected from the LB's outer shell,
  - the LB supershell itself injecting ^{60}Fe of all previous SNe over a longer time range
- LB properties observed are best matched by the model with inhomogeneous background medium

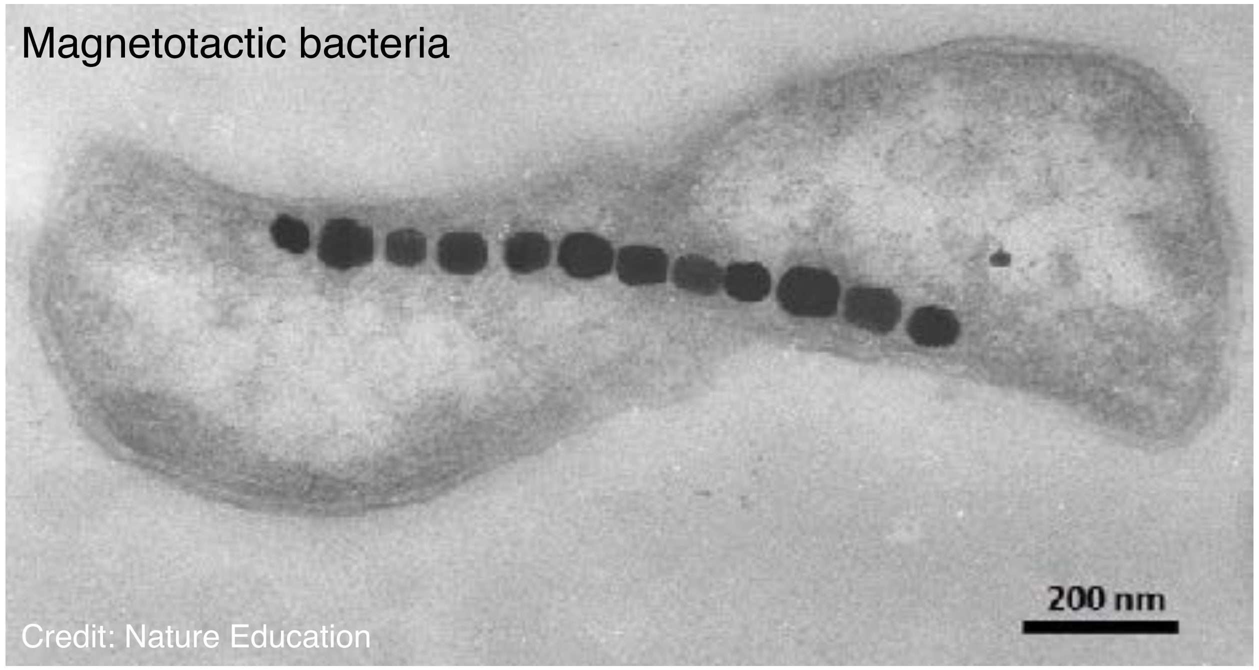


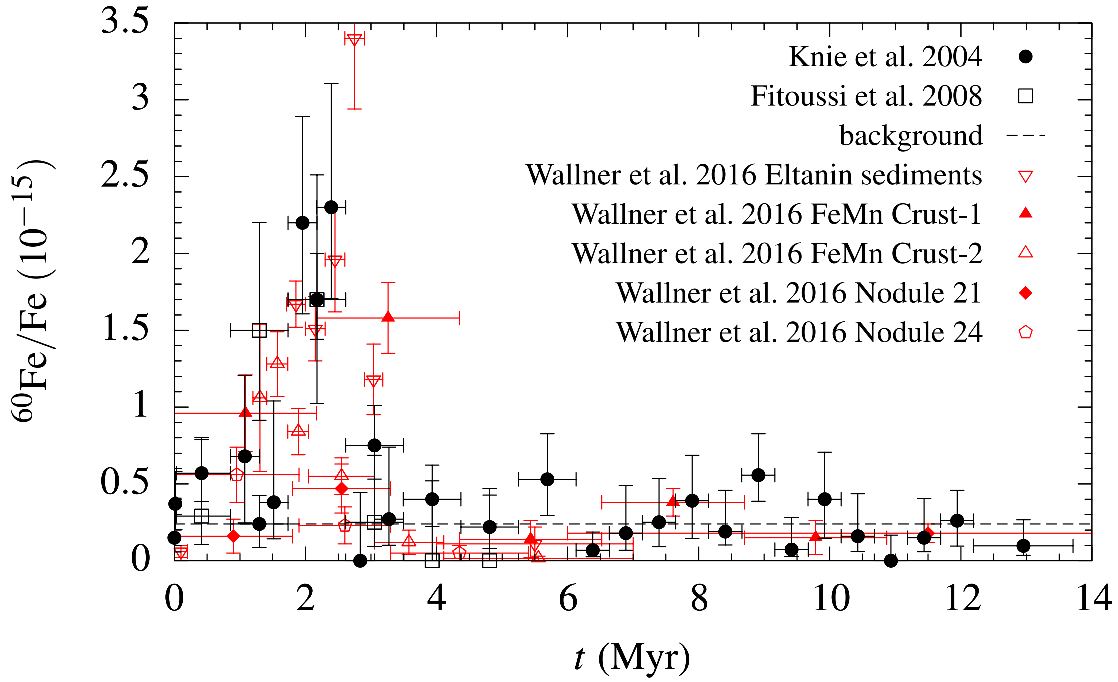


Latest developments

^{60}Fe anomaly is global, extended in time (Wallner+2016; Ludwig+ 2016), and even exists on the Moon (Fimiani+ 2016).







Further reading and other media

- 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
- Feige, J., Breitschwerdt, D., Wallner, A., Schulreich, M. M., et al. 2016, JPS Cong. Proc., accepted

How Our Oceans Helped Reveal The Closest And Most Recent Exploding Stars To Earth

Buzzfeed

Attack of the stars: Radioactive debris from ancient supernova battered Earth millions of years ago

International Business Times (UK)

Finding the Earth-bound evidence for supernovae in the galactic neighbourhood

physicsworld.com

Proof that ancient supernovae zapped Earth sparks hunt for after effects

phys.org

Exploding Stars Spat Radioactive Debris All Over Earth

National Geographic

Supernova Fallout Hit Earth When Human Ancestors Were Alive

Air & Space

Exploding stars left recent, radioactive mark on Earth

BBC News

Radioactive material in ocean crusts likely came from nearby star explosions

The Verge

Ancient exploding stars hurled radioactive debris at Earth — and it's still here

Washington Post

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- 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
- Feige, J., Breitschwerdt, D., Wallner, A., Schulreich, M. M., et al. 2016, JPS Cong. Proc., accepted

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