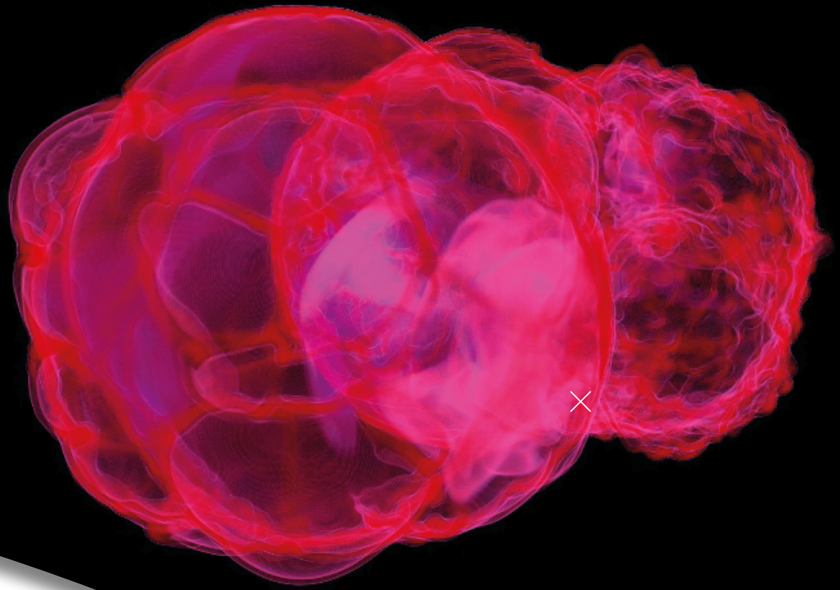


Reconstructing the origin of the Local Bubble and Loop I via radioisotopic signatures on Earth

Michael M. Schulreich

In collaboration with:
Dieter Breitschwerdt (TU Berlin)
Jenny Feige (TU Berlin)
Christian Dettbarn (ARI Heidelberg)
Miguel de Avillez (U Évora)

Workshop on “Three elephants in the gamma-ray sky: Loop I, the Fermi bubbles, and the Galactic center excess”
23 October 2017, Garmisch-Partenkirchen

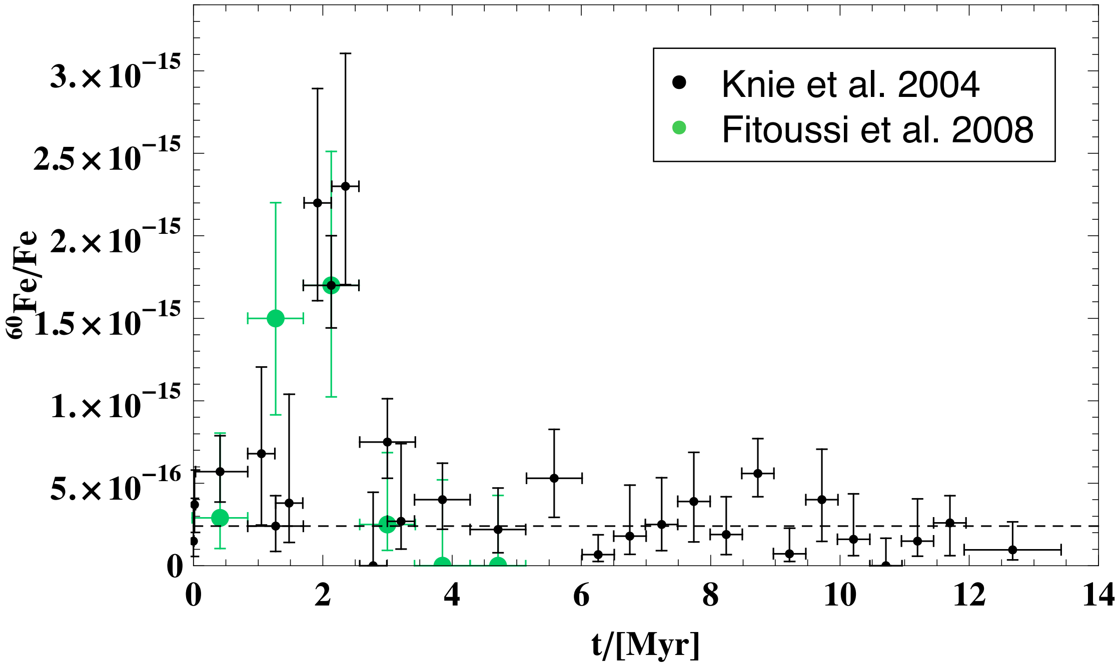
Recovery of the ferromanganese (FeMn) crust sample 237KD from the equatorial Pacific floor in 1976

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

Relics of a 'Blast from the Past'?

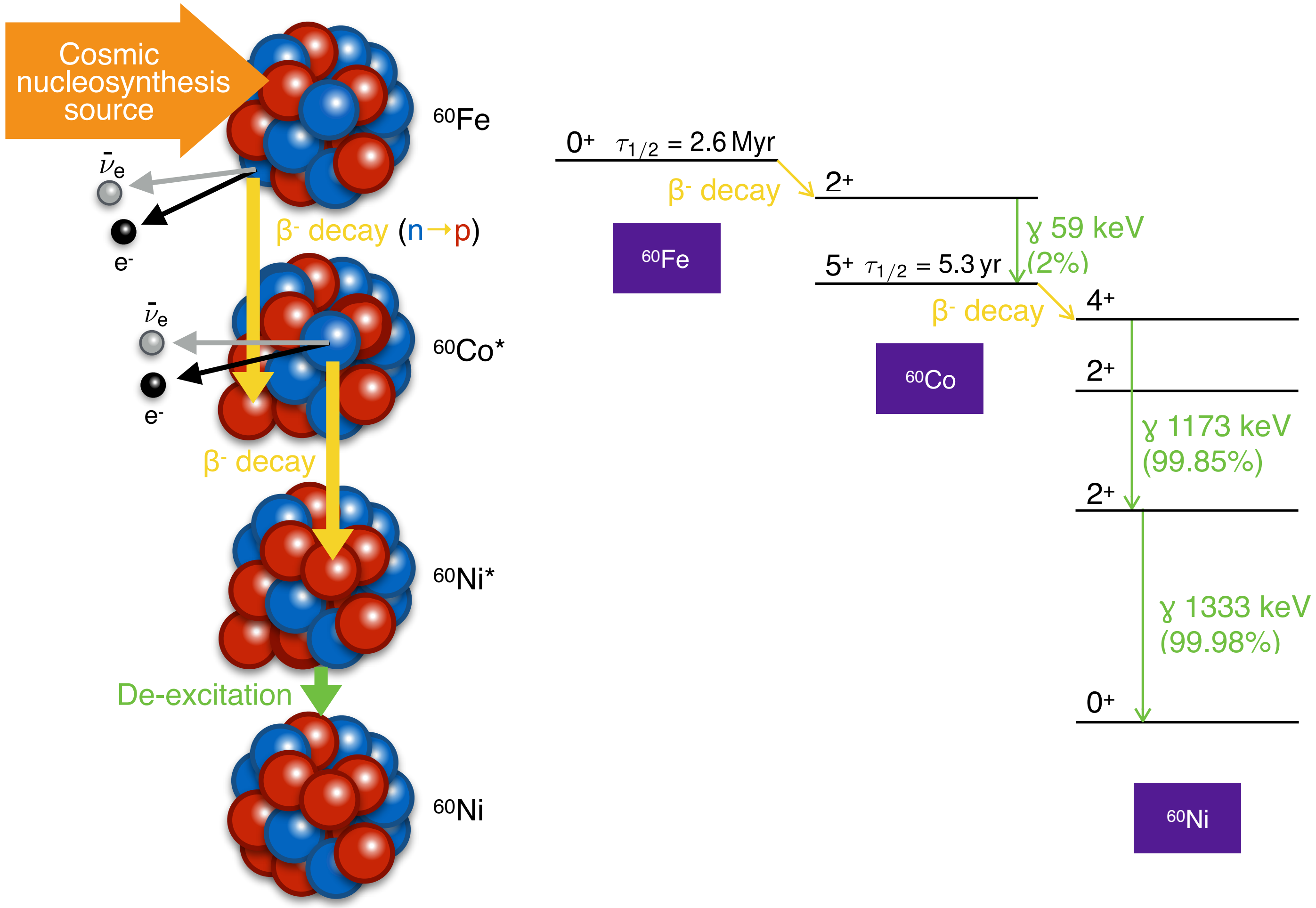
Credit TU Munich

- Each crust layer corresponds to certain age range
- Knie et al. (2004) detected significant abundance increase of radioisotope ^{60}Fe in ~2.2 Myr-old layer; signal confirmed by Fitoussi et al. (2008)



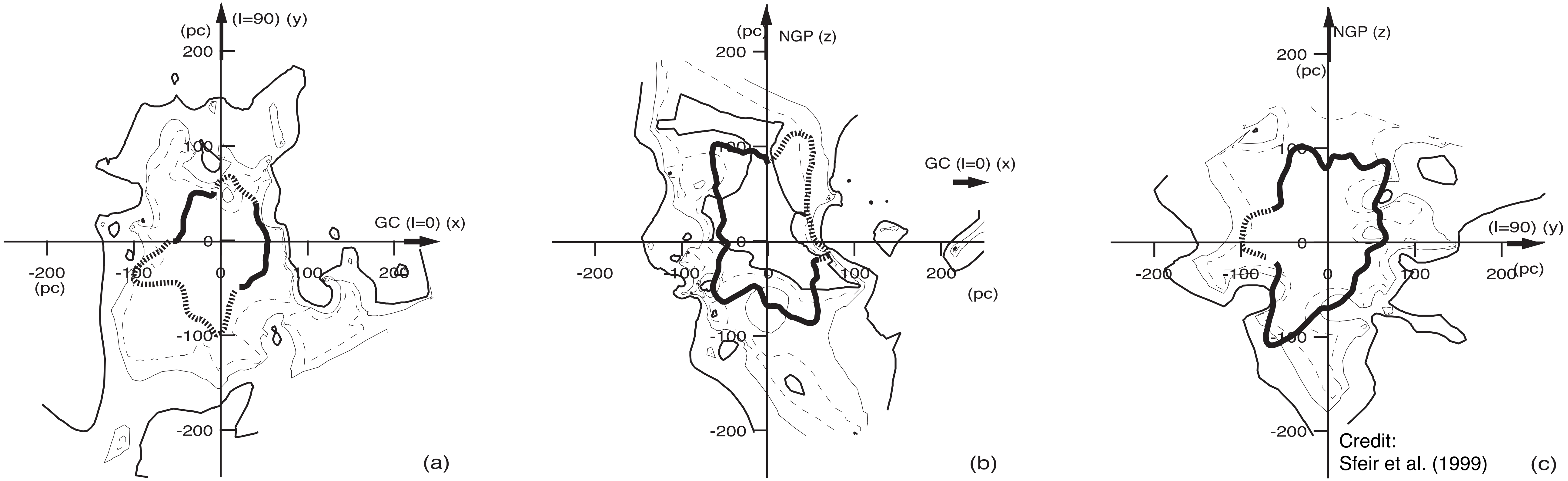
What's so special about ^{60}Fe?

- Produced during late shell-burning phase in massive stars; predominantly released by core-collapse/electron-capture SNe (cf. Knödlseder et al. 2004)
- Low terrestrial background
- Comparatively long half-life ($\tau_{1/2}$ ~ 2.62 Myr) allows for extensive ISM traveling ➔ detectable by β^- decay via ^{60}Co and ɣ-ray emission at 1173 and 1333 keV (Wang et al. 2007)



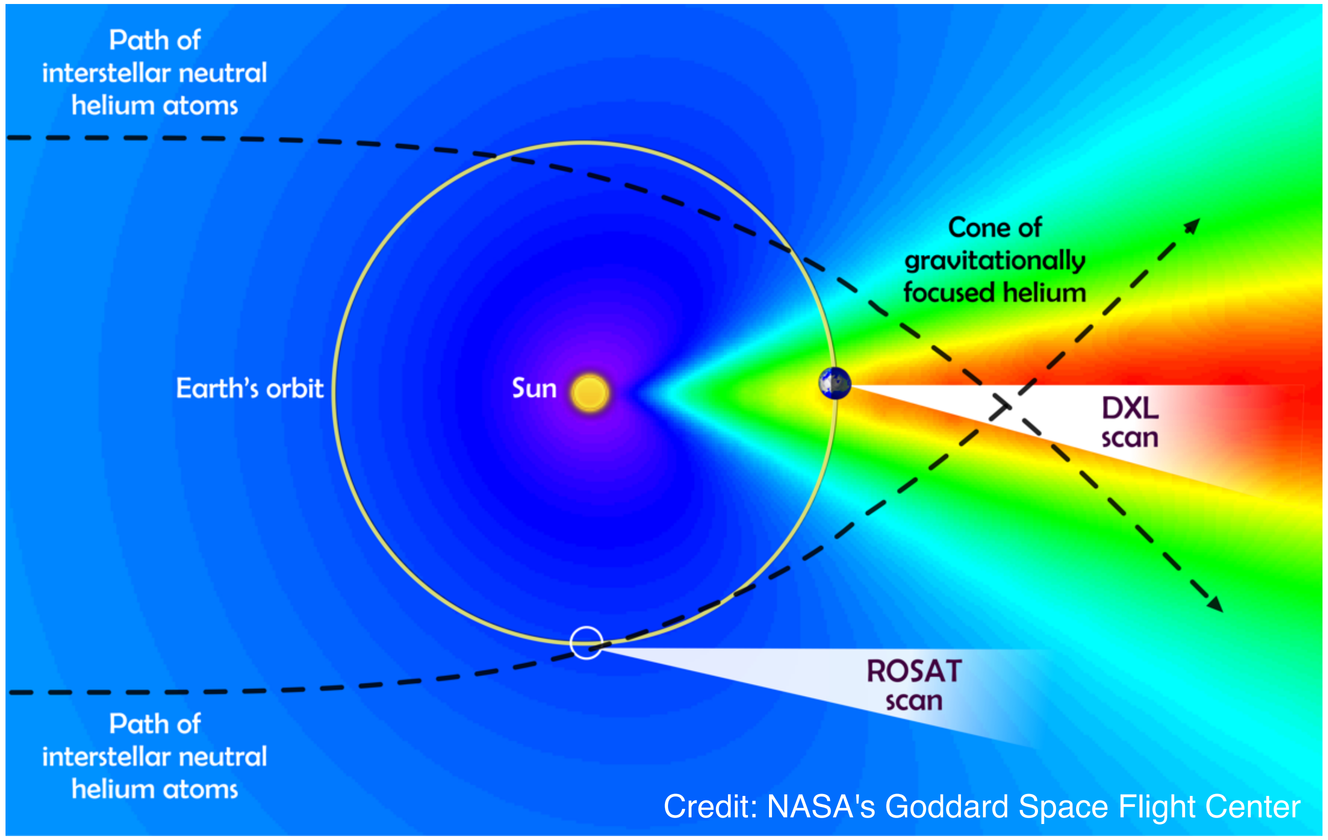
- Link between the ^{60}Fe anomaly and recent SNe near Earth that also contributed to the formation of the **Local Bubble** (LB)

The Local Bubble



Credit: Sfeir et al. (1999)

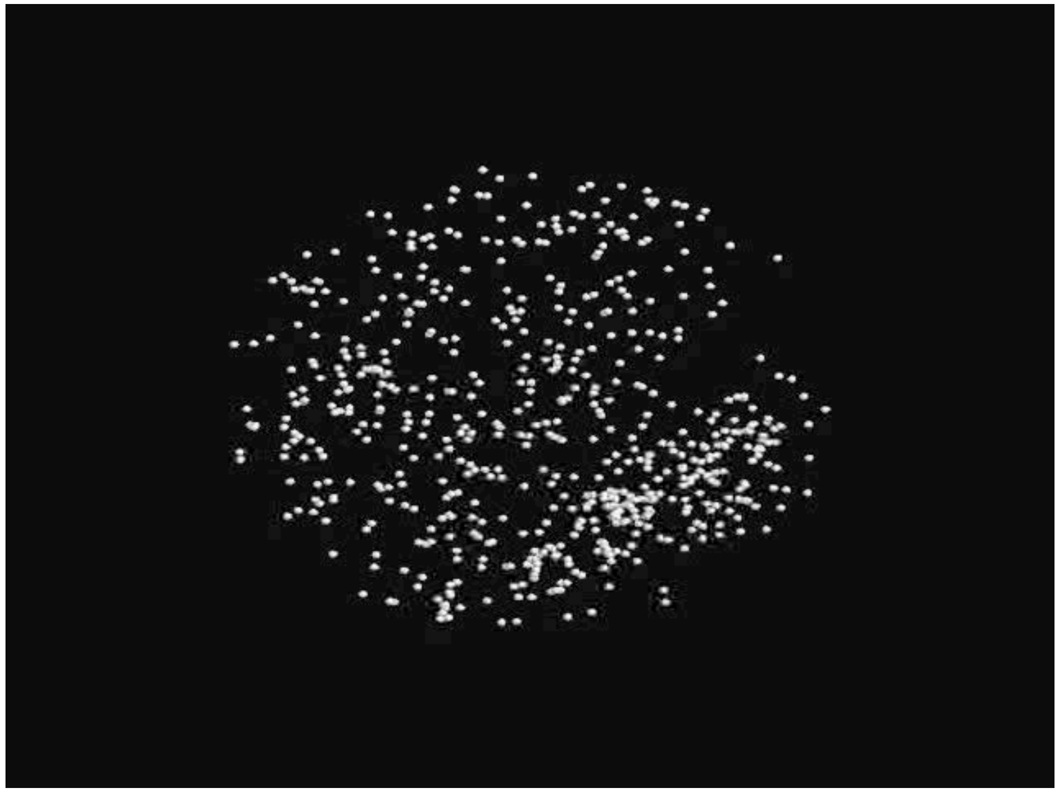
- Our Galactic habitat
- Low-density region of the ISM
- Partially filled with hot, soft X-ray emitting gas
  - Responsible for ~60% of the 0.25-keV flux in the Galactic plane (Galeazzi et al. 2014) ➔ **bold confirmation of its existence**
- **Size:** ~200 pc in the Galactic plane; ~600 pc perpendicular to it (chimney?)
- **Widely accepted origin:** several nearby SN explosions in the last ~10 Myr (e.g., Smith & Cox 2001)
  - But, **no young stellar cluster** could be found inside its boundaries

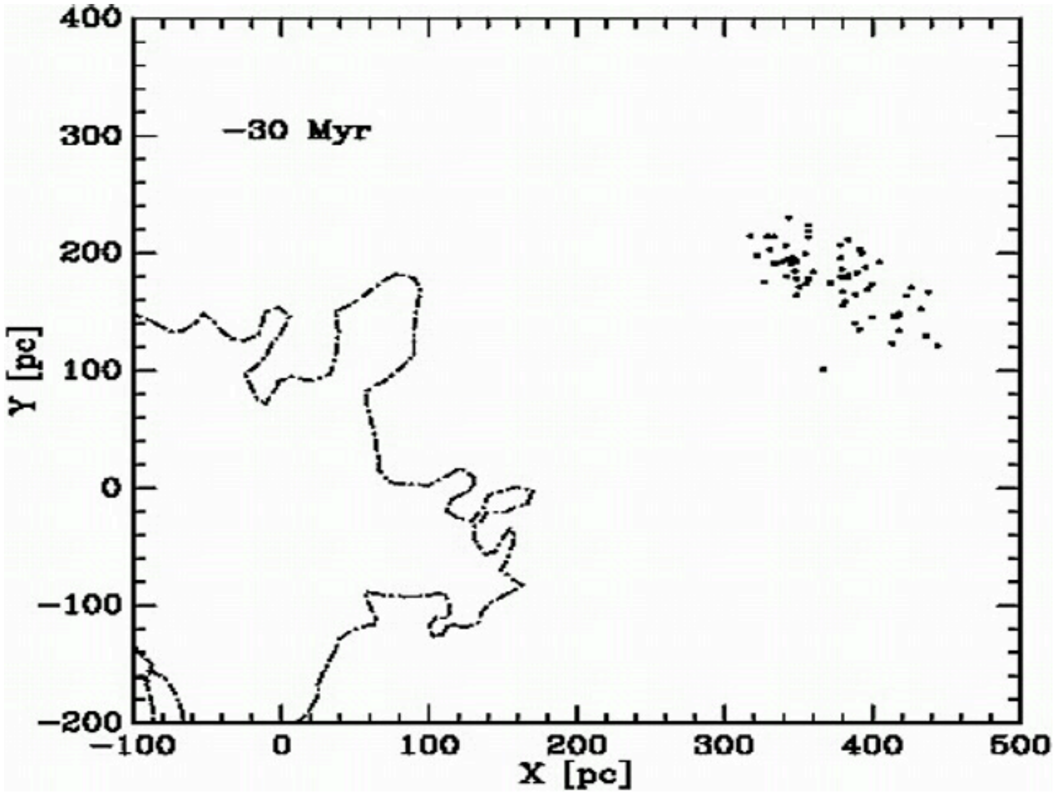


Credit: NASA's Goddard Space Flight Center

The origin of the Local Bubble

- Berghöfer & Breitschwerdt (2002) searched for moving group ➔ Pleiades subgroup B1
- Fuchs+ (2004) analyzed 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 cluster turn-off point with isochrones (Schaller+ 1992) ➔ $\tau_c \sim 20$–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. in positions and proper motions
- **Number of past SNe:** IMF (1 star per bin!) for young massive stars (Massey+ 1995) ➔ 14–20 SNe exploding inside LB
- **MS lifetime** of SN progenitors: $\tau = 1.6 \times 10^8\,(M/\mathrm{M}_\odot)^{-0.932}$ yr (for $2 \leq M/\mathrm{M}_\odot \leq 67$); results from fitting isochrone data
- **Explosion times:** $t_{\mathrm{exp}} = \tau - \tau_c$ (assume: coeval star formation)
- Combining most probable trajectories & explosion times ➔ **most probable explosion sites**





Credit: Fuchs+ (2006)

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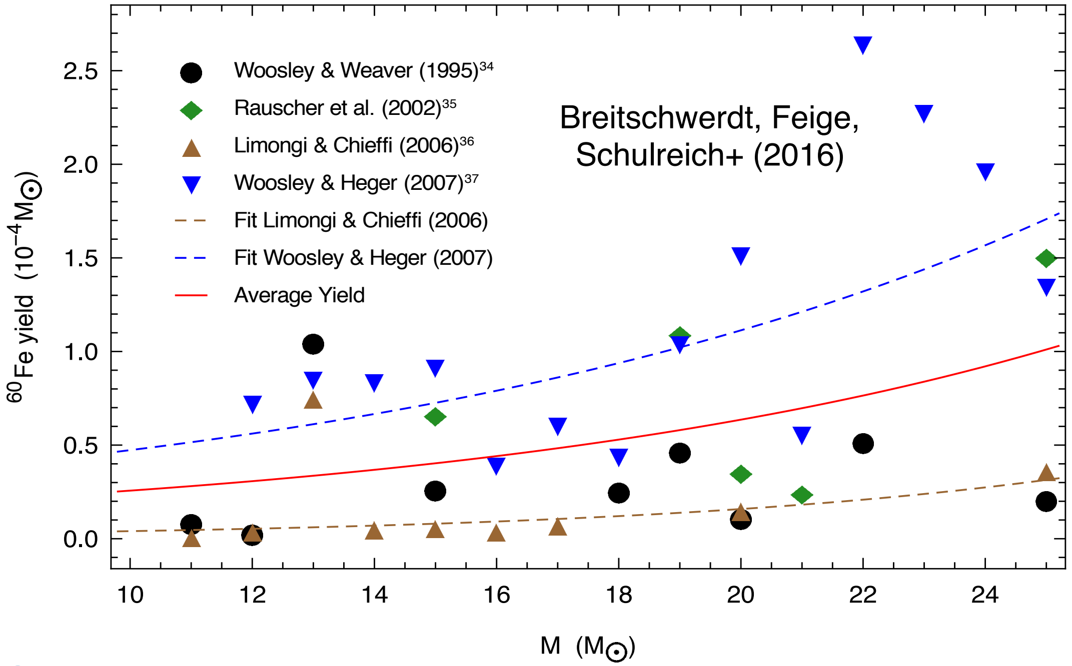
- Combining most probable trajectories & explosion times ➔ **most probable explosion sites**

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 LB shell expansion due to Weaver+ (1977)
- ^{60}Fe content (yield taken from stellar evolution) entrained and deposited by SN blast waves



Breitschwerdt, Feige, Schulreich+ (2016)

- 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 Breitschwerdt & Avillez 2006)

Numerical simulations

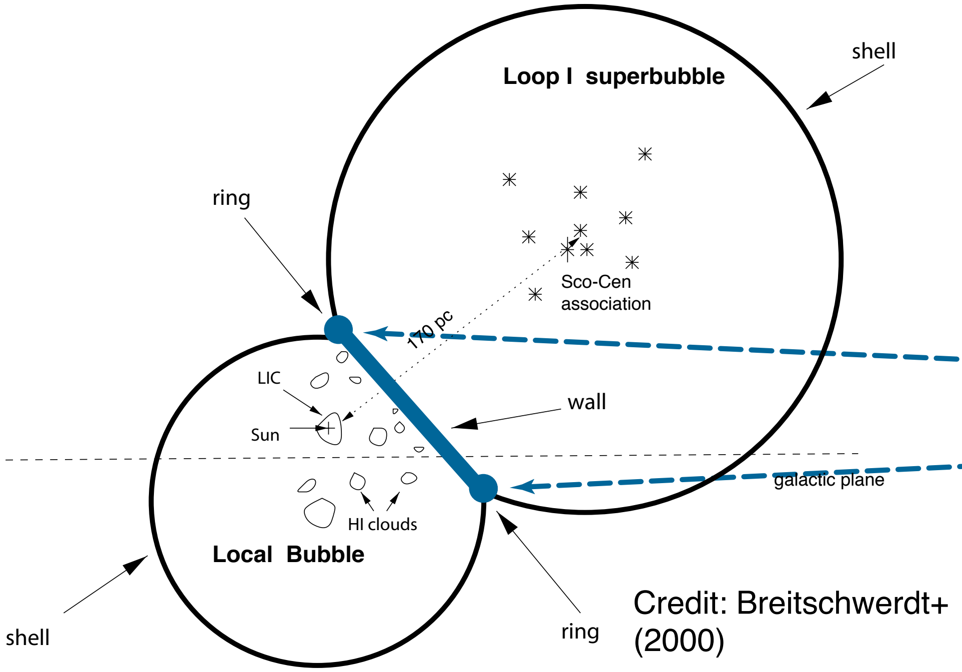
Mesoscale ISM simulations using publicly available AMR (magneto-)hydrodynamics and N-body code RAMSES (Teyssier 2002)

- 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)

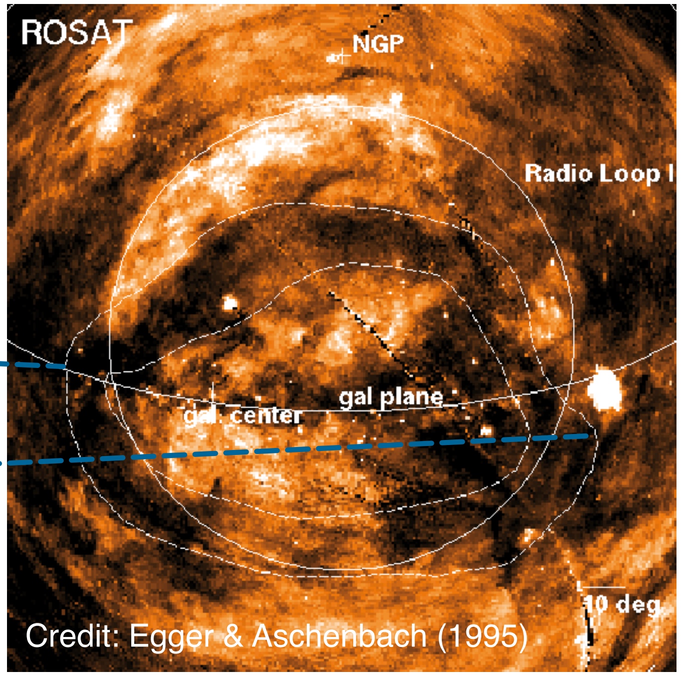
	Homogeneous background models (A & B)	Inhomogeneous background model (C)
Box size	3 x 3 x 3 kpc^3	3 x 3 x 3 kpc^3
Highest grid resolution	0.7 pc (ℓ_{max} = 12)	2.9 pc (ℓ_{max} = 10)
Boundary conditions (vertical faces / top and bottom)	periodic / periodic	periodic / outflow
Total evolution time	12.6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

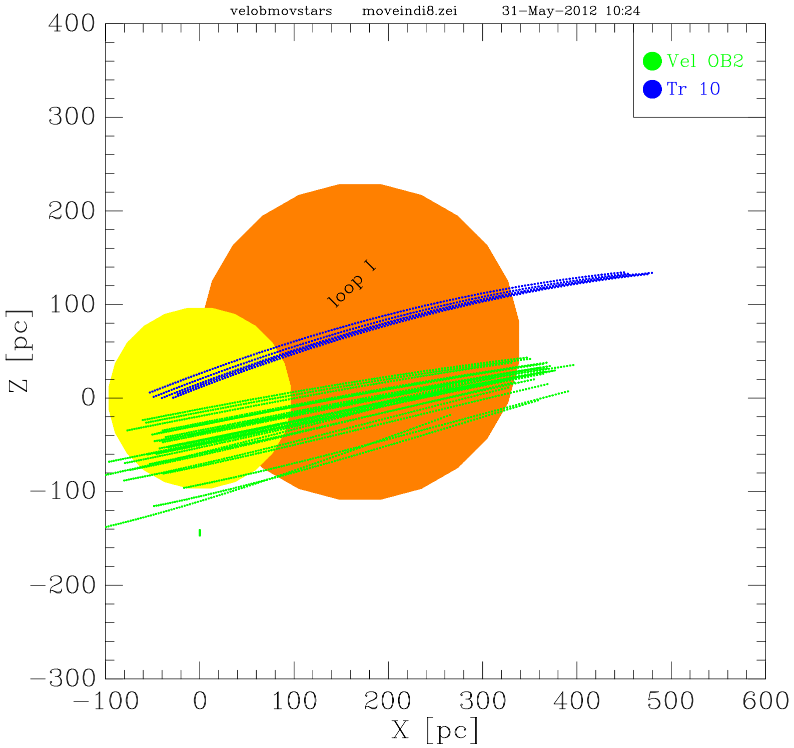
- Further “boundary condition” …
- ROSAT PSPC observations (Egger & Aschenbach 1995): soft X-rays are absorbed by nearby neutral shell
- Possibly result of interaction between LB and its neighbouring SB Loop I (Breitschwerdt+ 2000)
- Applied previous methodology on Loop I clusters Tr 10 and the Vel OB2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

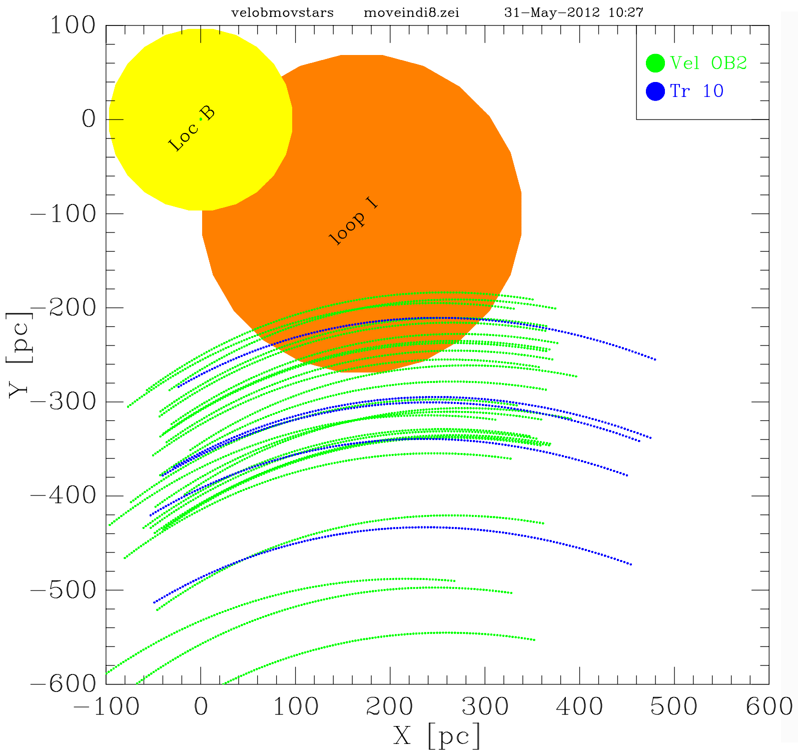


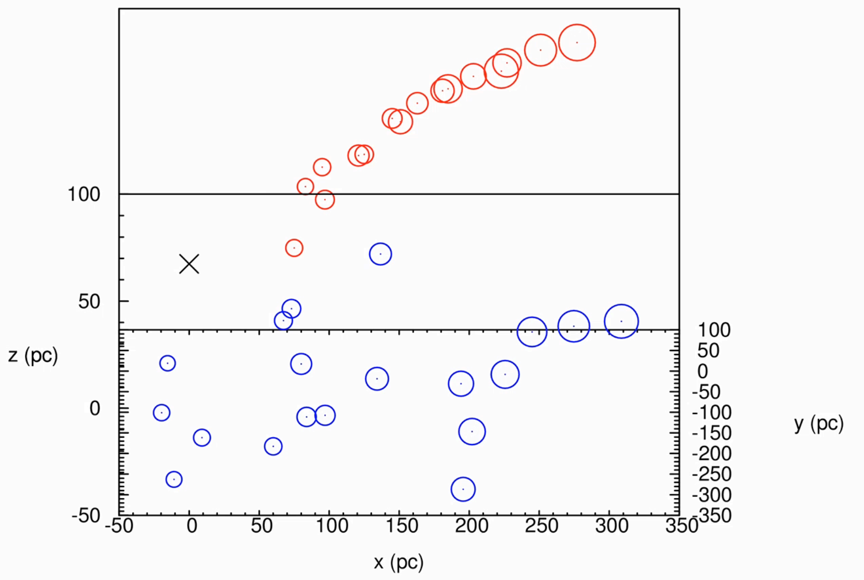
Credit: Breitschwerdt+ (2000)



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'):

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

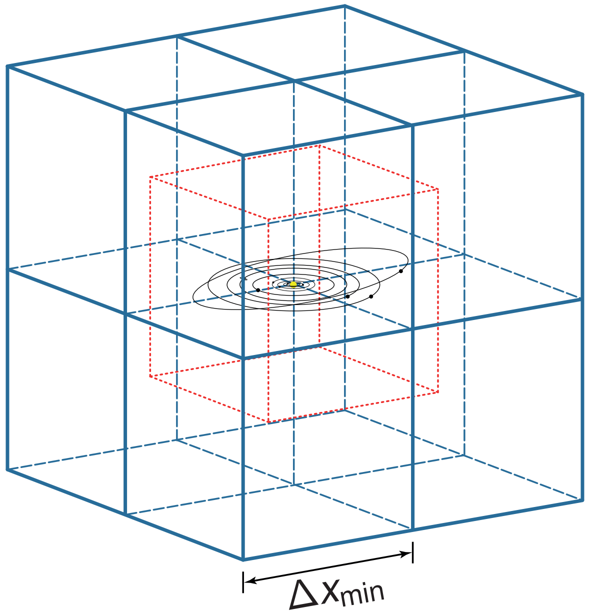
4. Surface density of atoms deposited on Earth at time *t* before present:

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

- 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 $fU = 0.006$ (cf. Knie+ 2004) or 0.005 (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 $y = 0$)

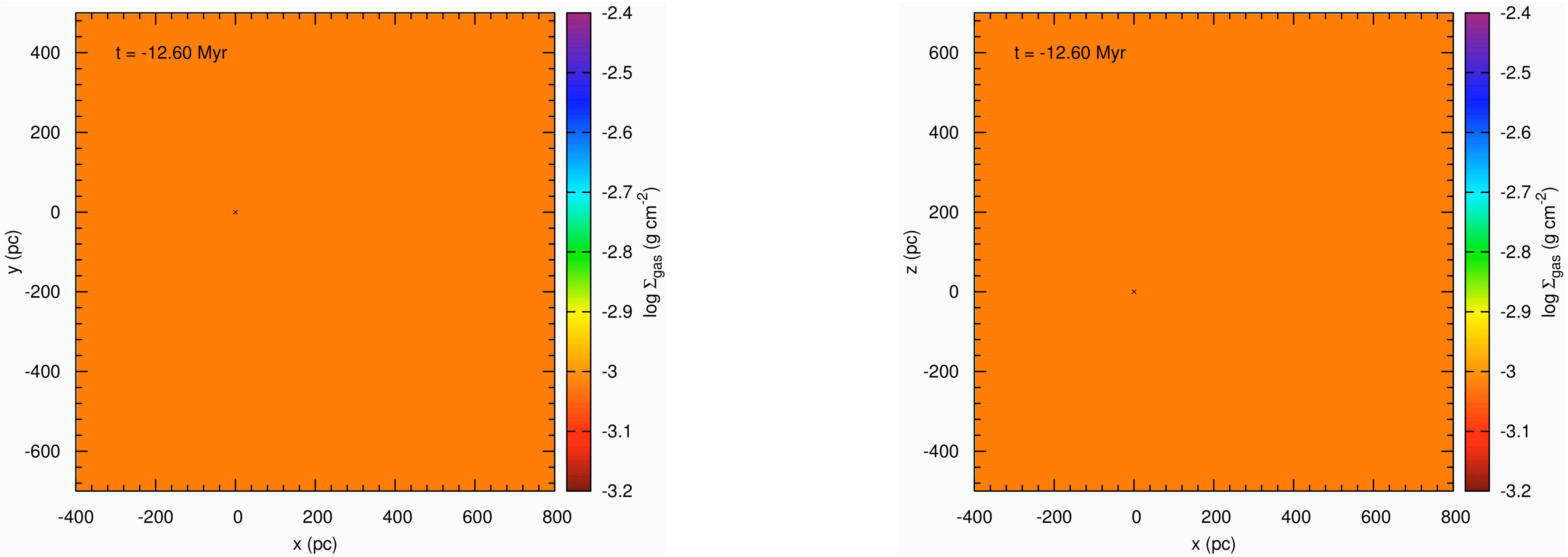
Model A (~ WIM)

$n = 0.1$ cm^{-3}

$T = 10^4$ K

$Z/Z_\odot = 1$

$\Delta x = 0.7$ pc



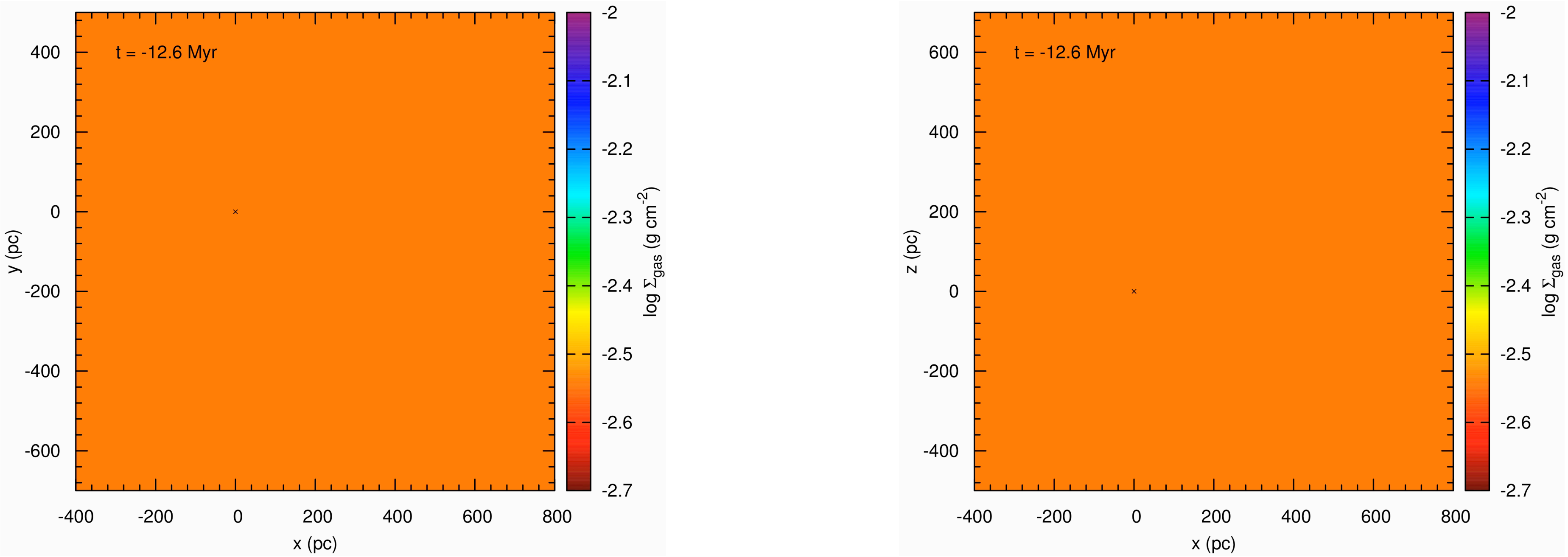
Model B (~ WNM)

$n = 0.3$ cm^{-3}

$T = 6800$ K

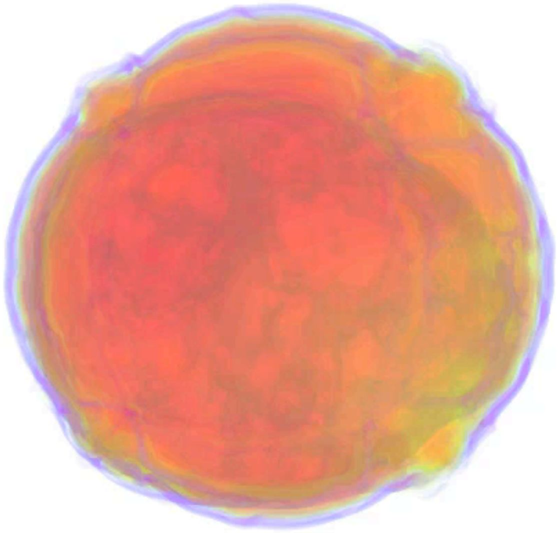
$Z/Z_\odot = 1$

$\Delta x = 0.7$ pc

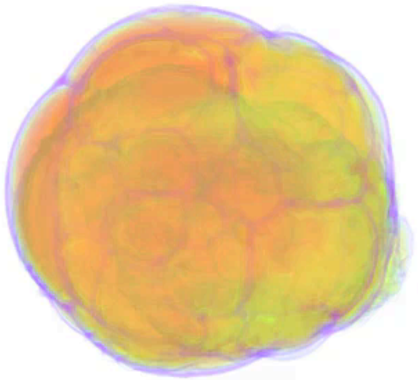


Chemical mixing simulations with homogeneous background medium

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

Δx = 0.7 pc

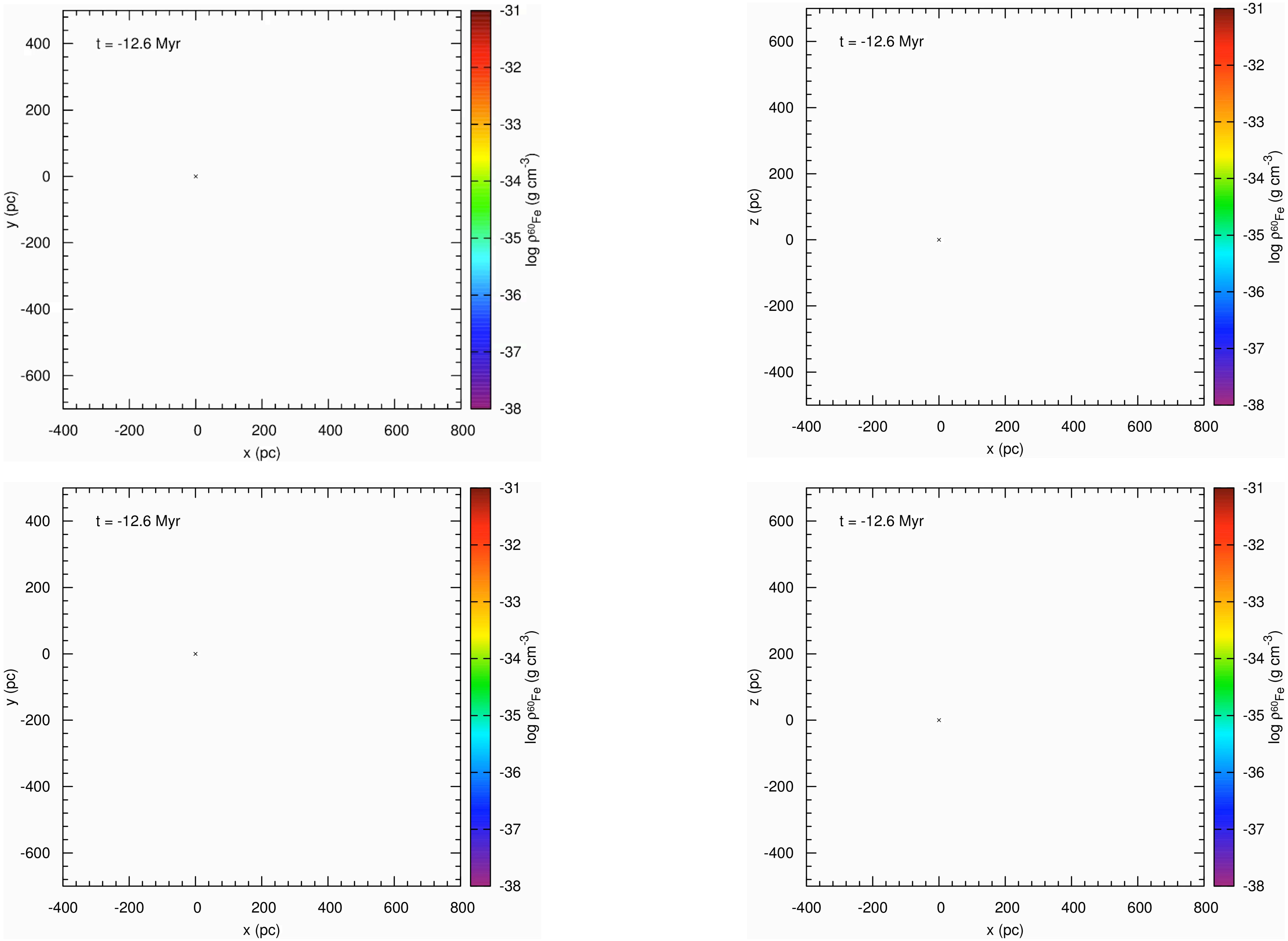
Model B (~ WNM)

n = 0.3 cm^{-3}

T = 6800 K

Z/Z$_\odot$ = 1

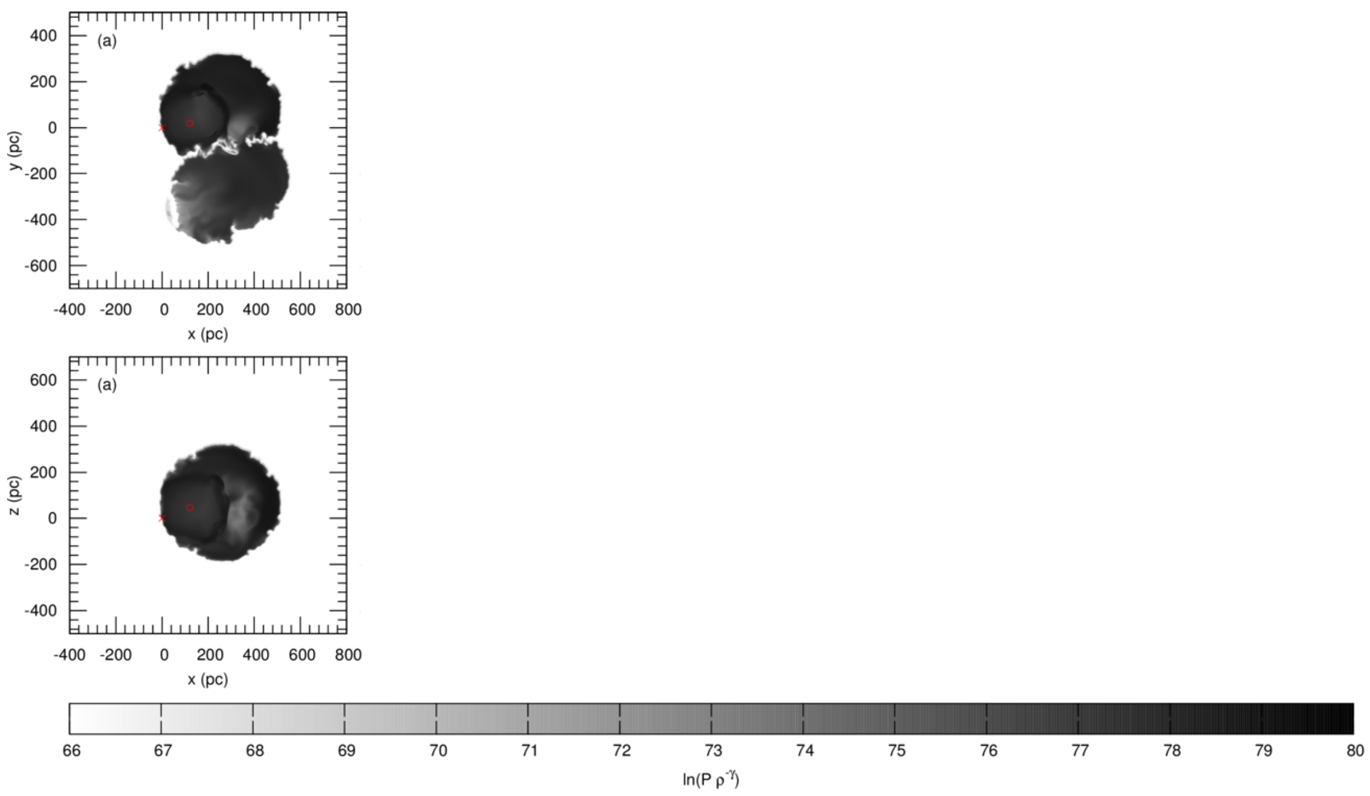
Δx = 0.7 pc

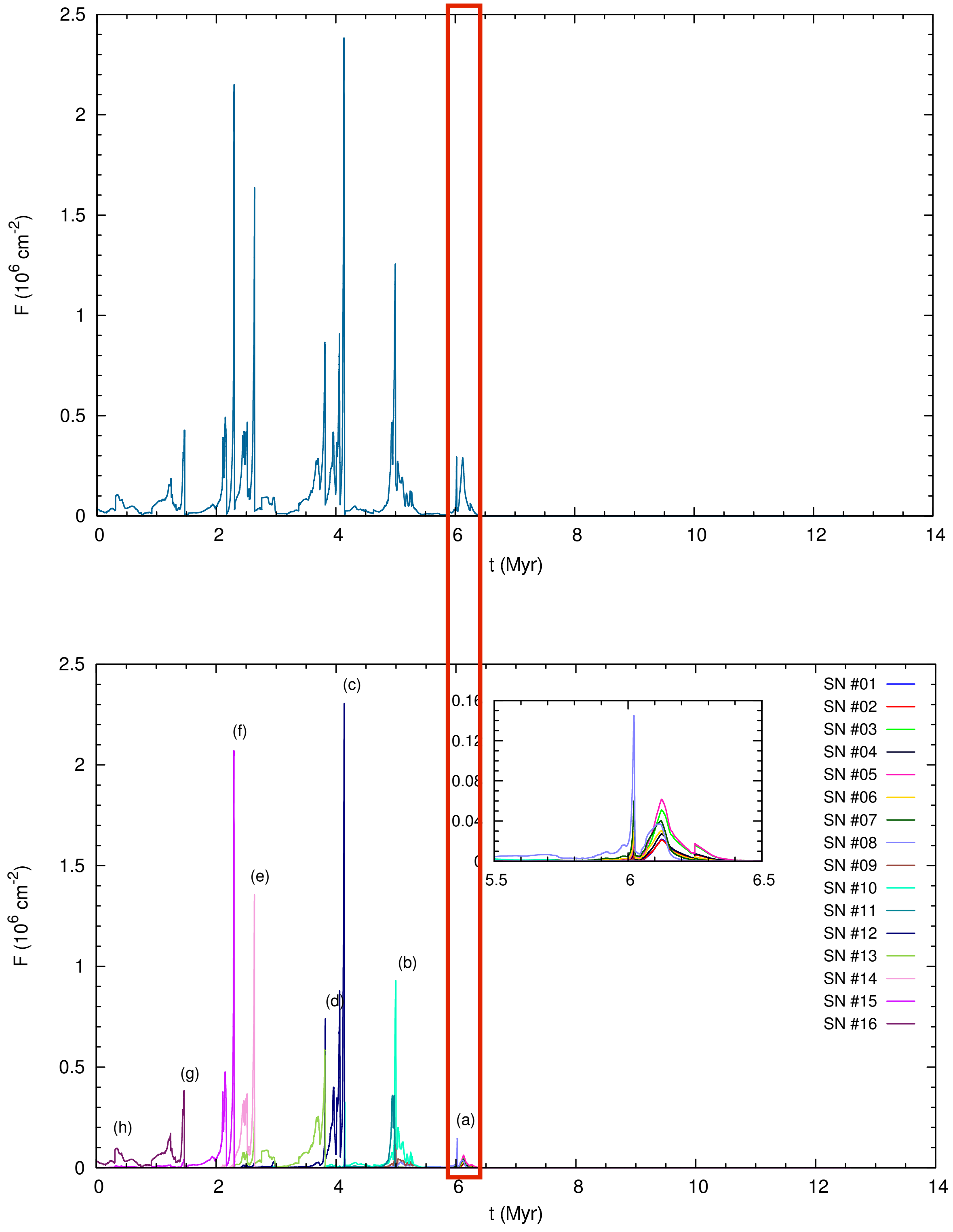


- Inhomogeneities arising from recent SNe are smoothed out over time
- Injection of turbulence by SNRs running into supershell ➔ generating asymmetric reflected shocks
- Time scale of mixing: $\tau_m \lesssim \ell/a$ = (100 pc)/(100 km s^{-1}) = 1 Myr
- ^{60}Fe fairly homogenized since last LB SN occurred about 1.5 Myr ago

Chemical mixing simulations with homogeneous background medium

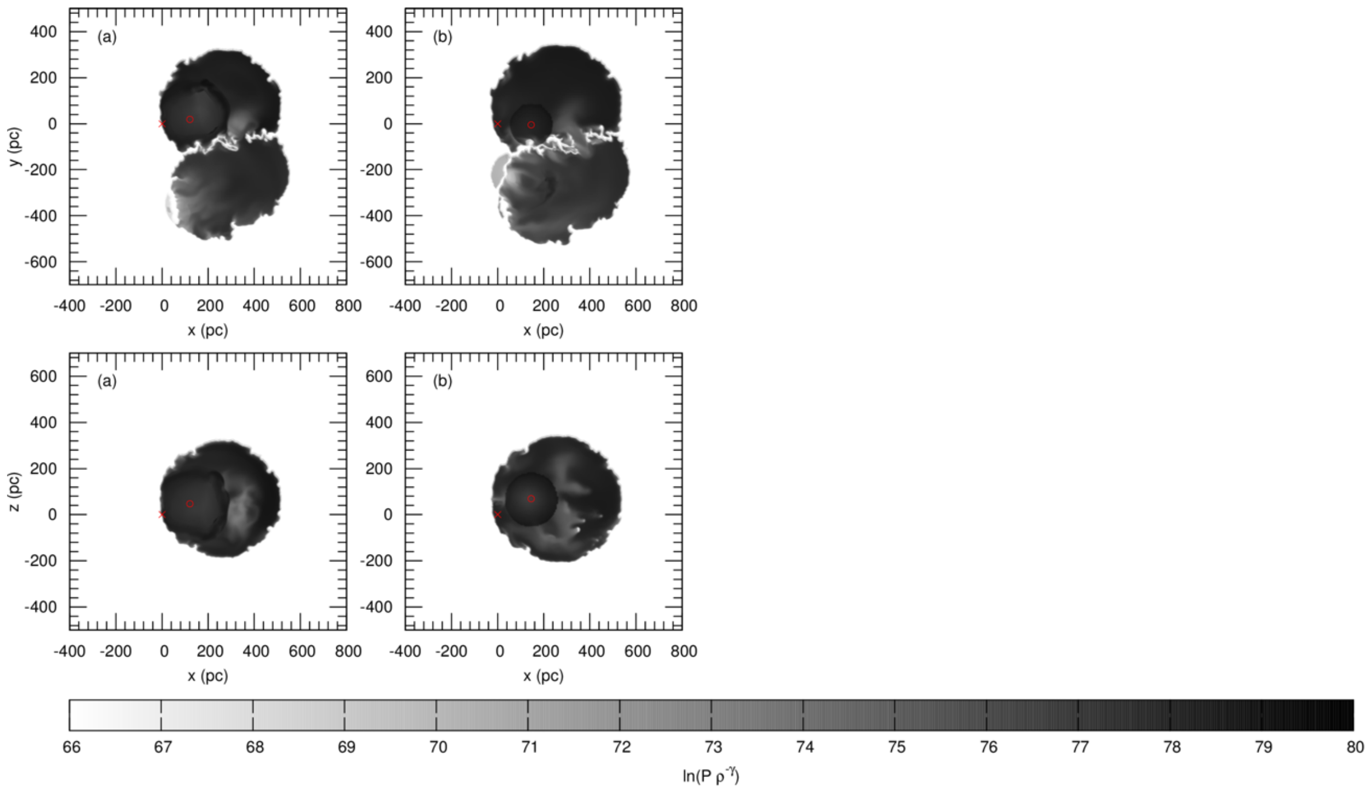
Model A: Entropy maps and ^{60}Fe fluence variation

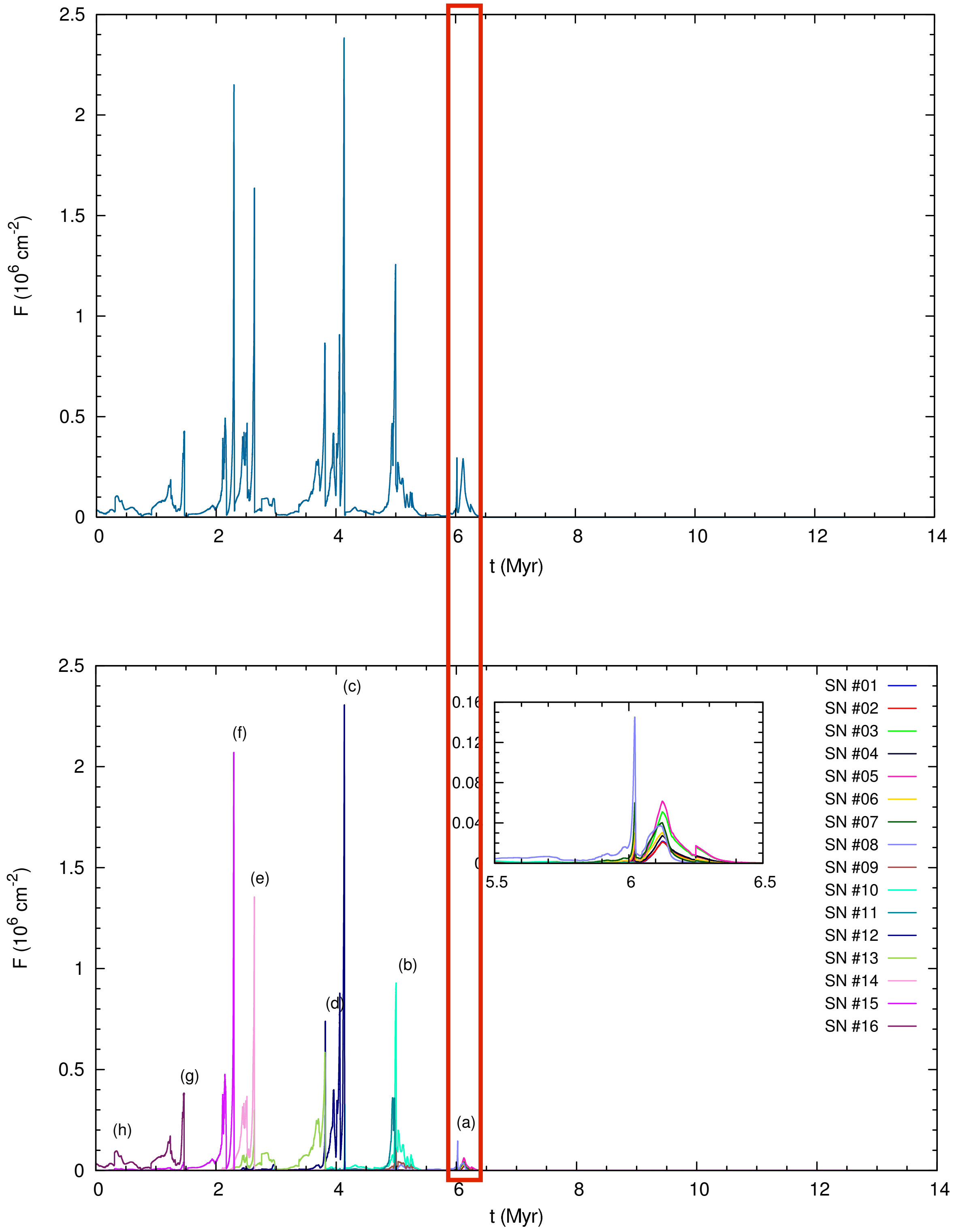




Results — Chemical mixing simulations with homogeneous background medium

Model A: Entropy maps and 60Fe fluence variation





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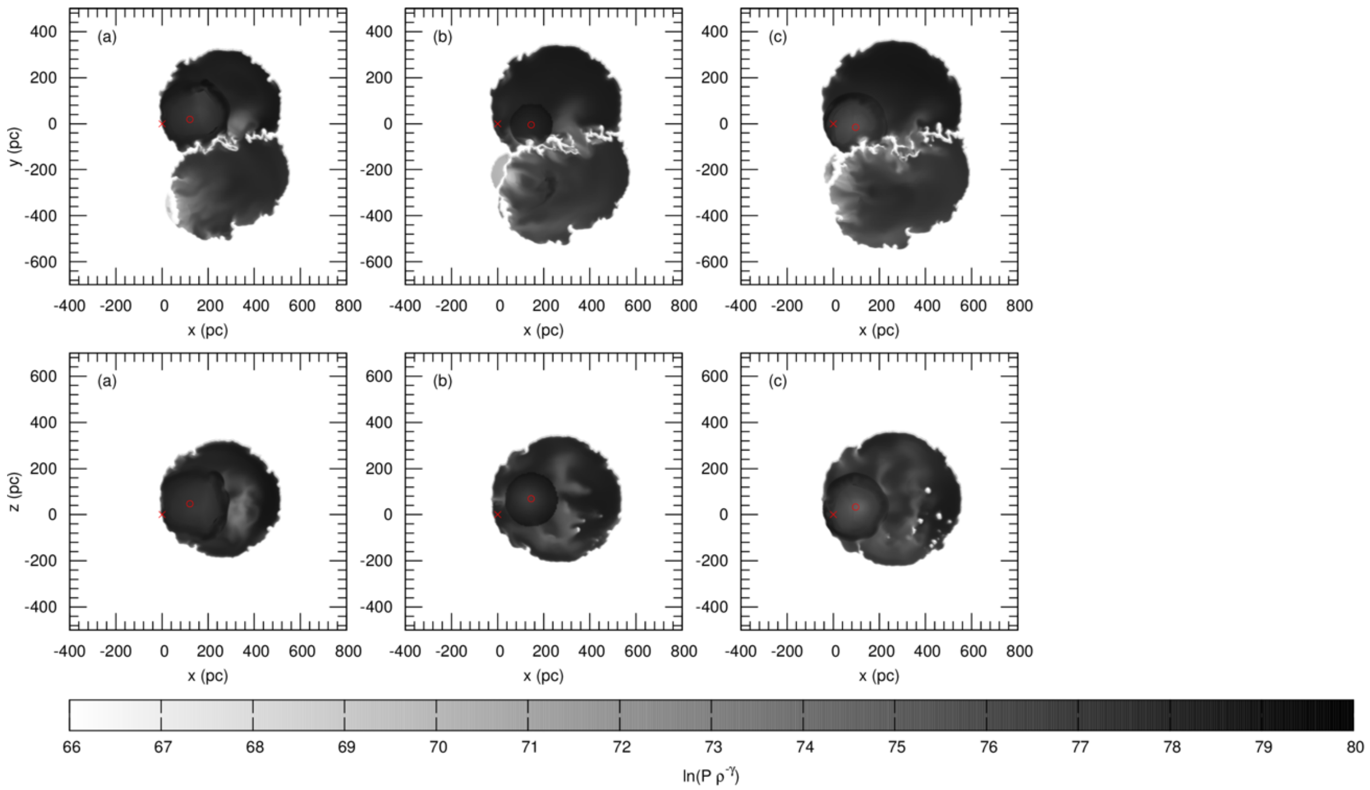

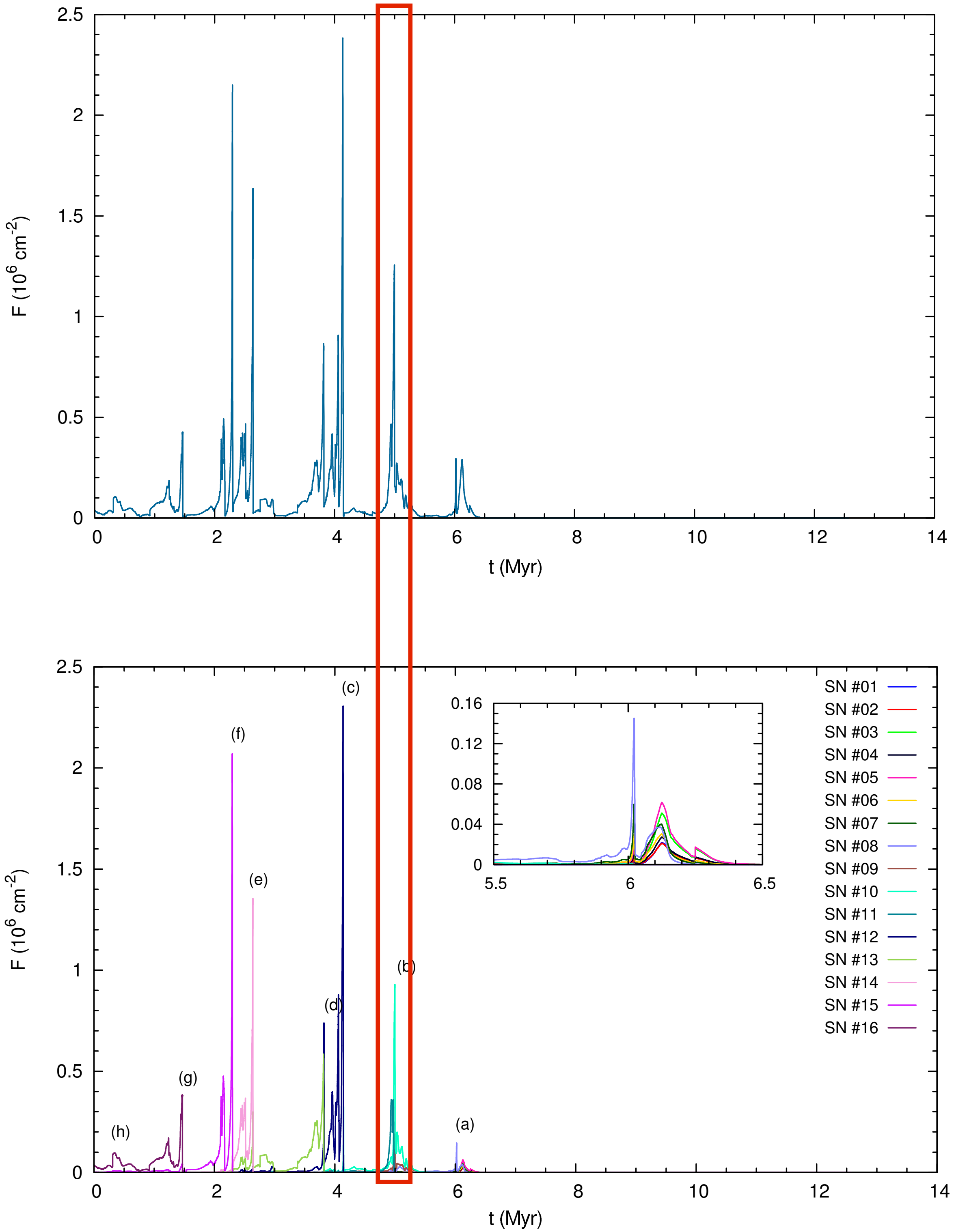

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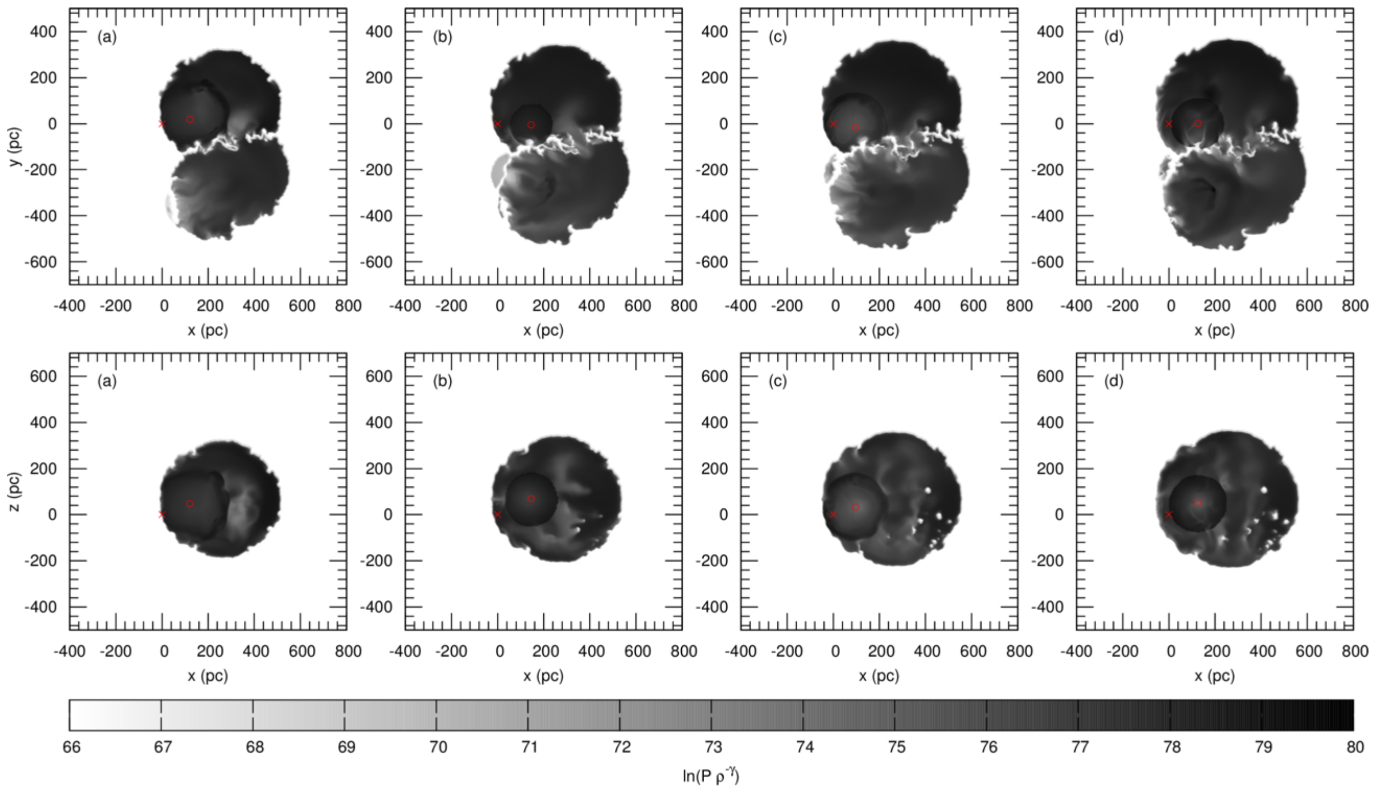

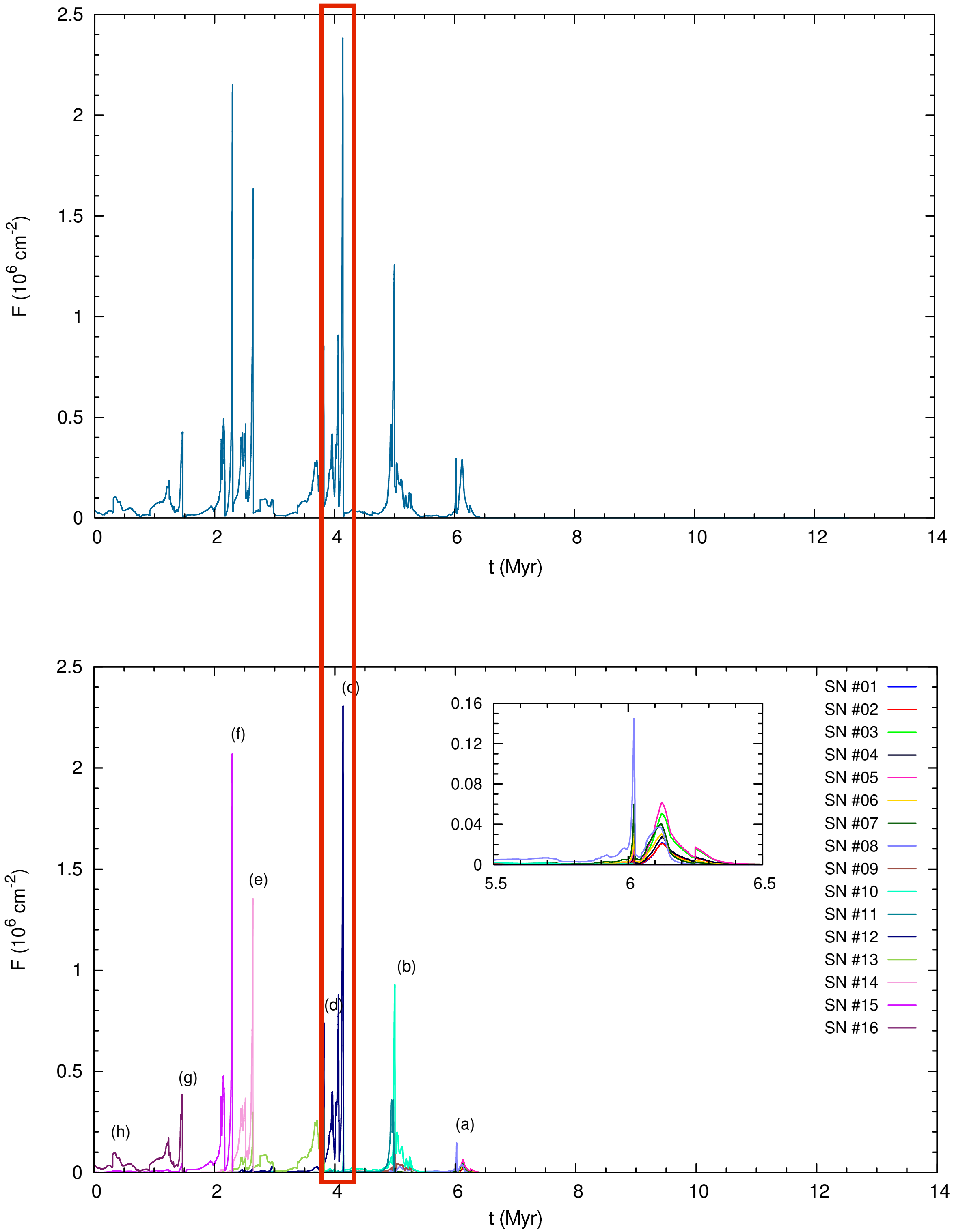

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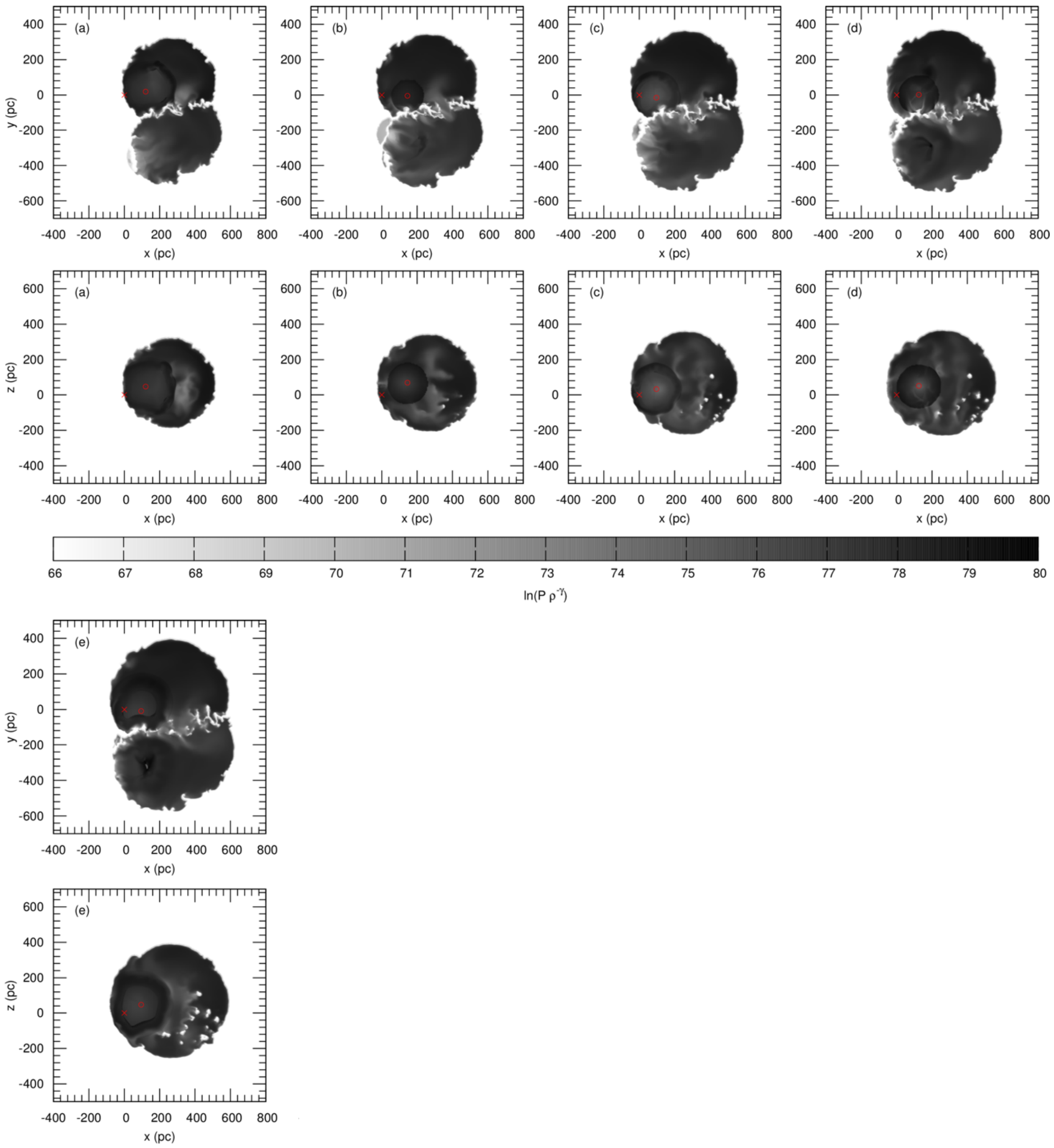

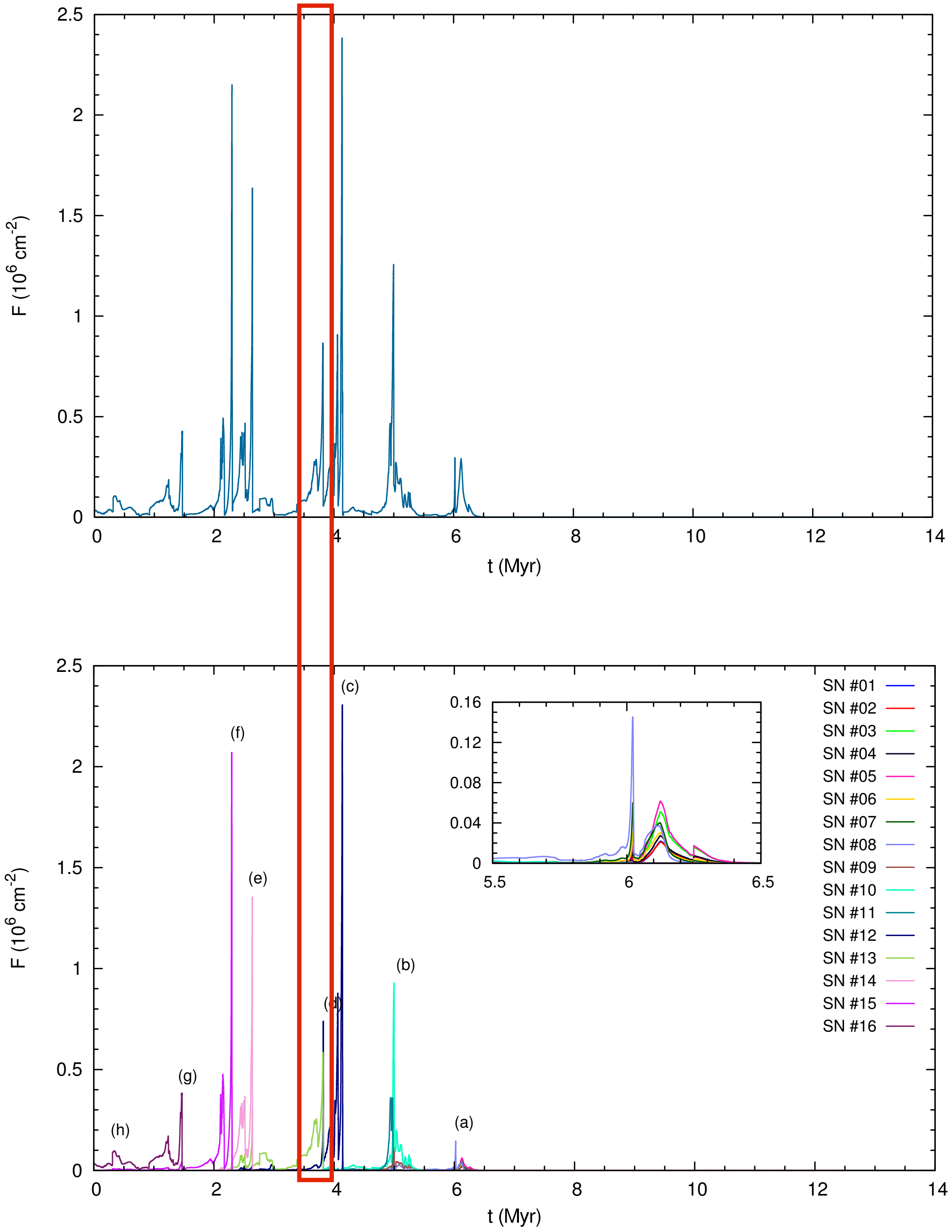

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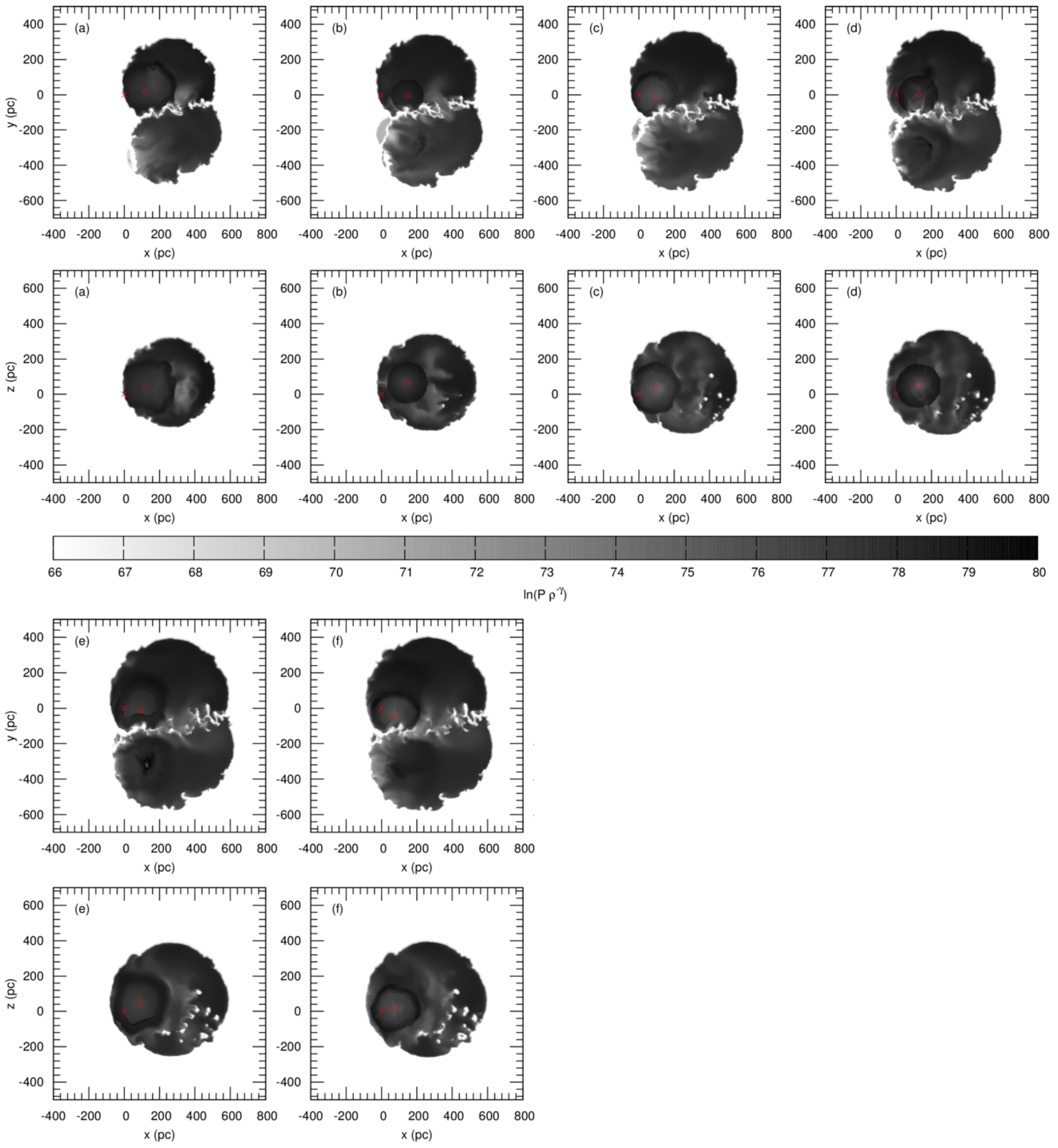

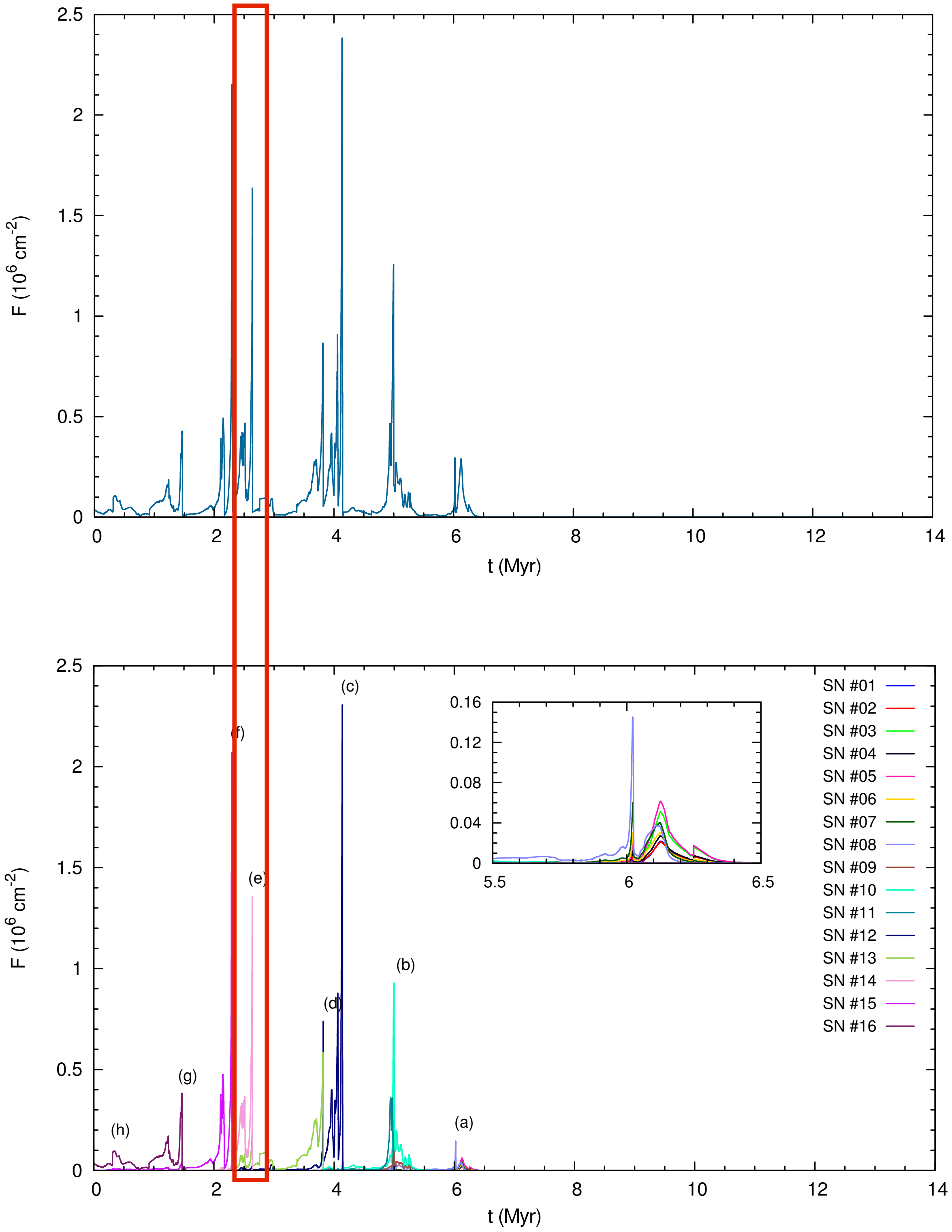

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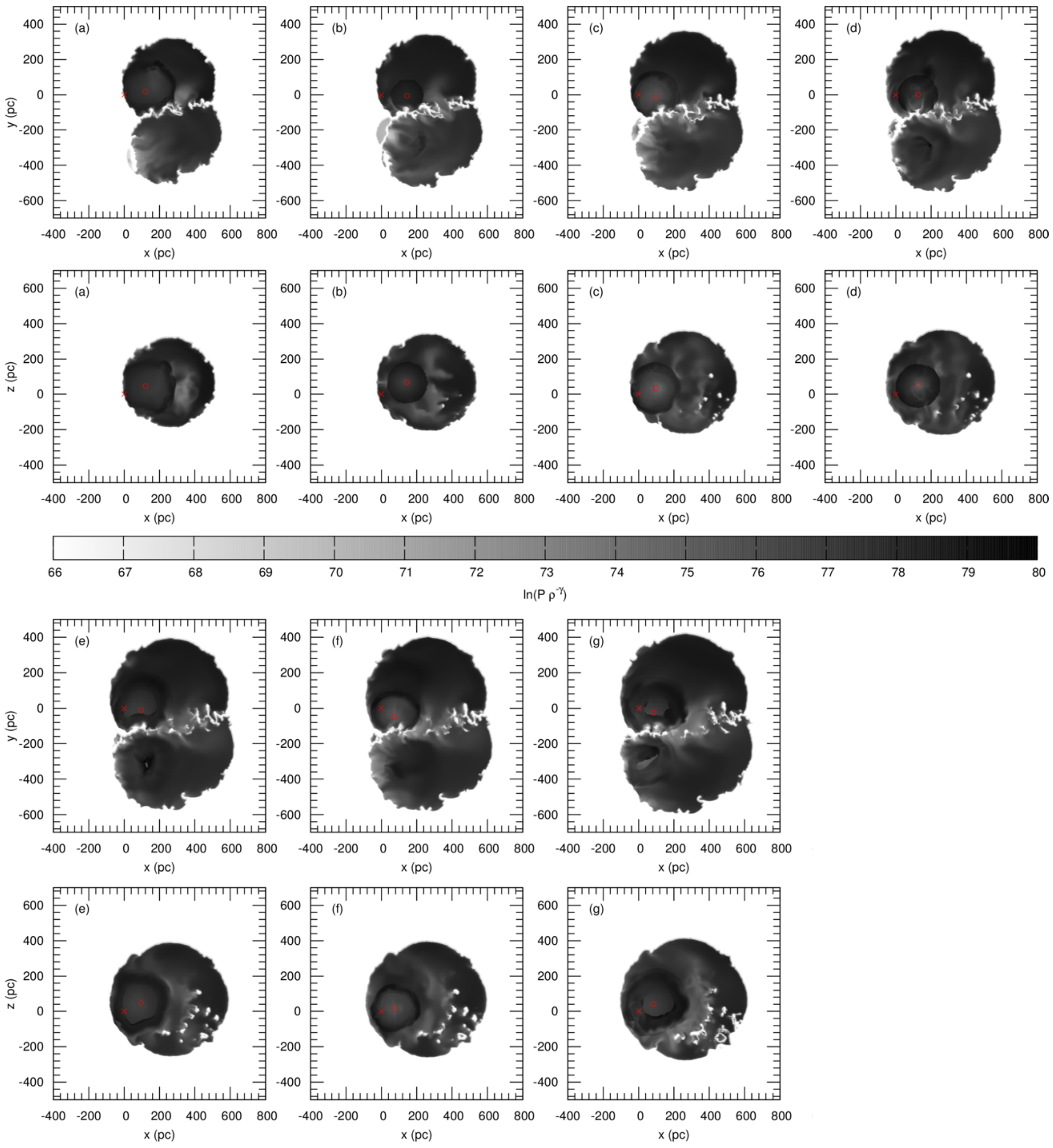

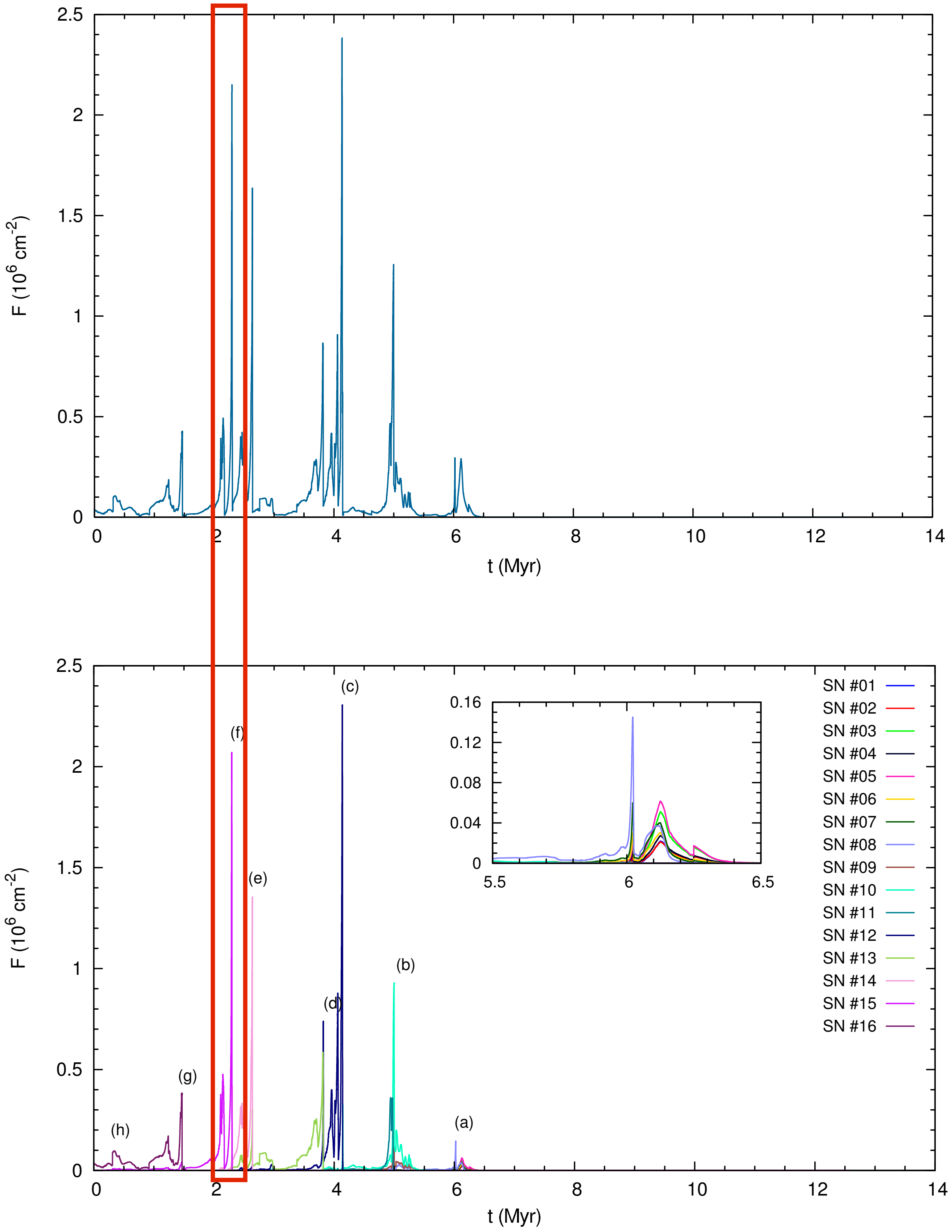

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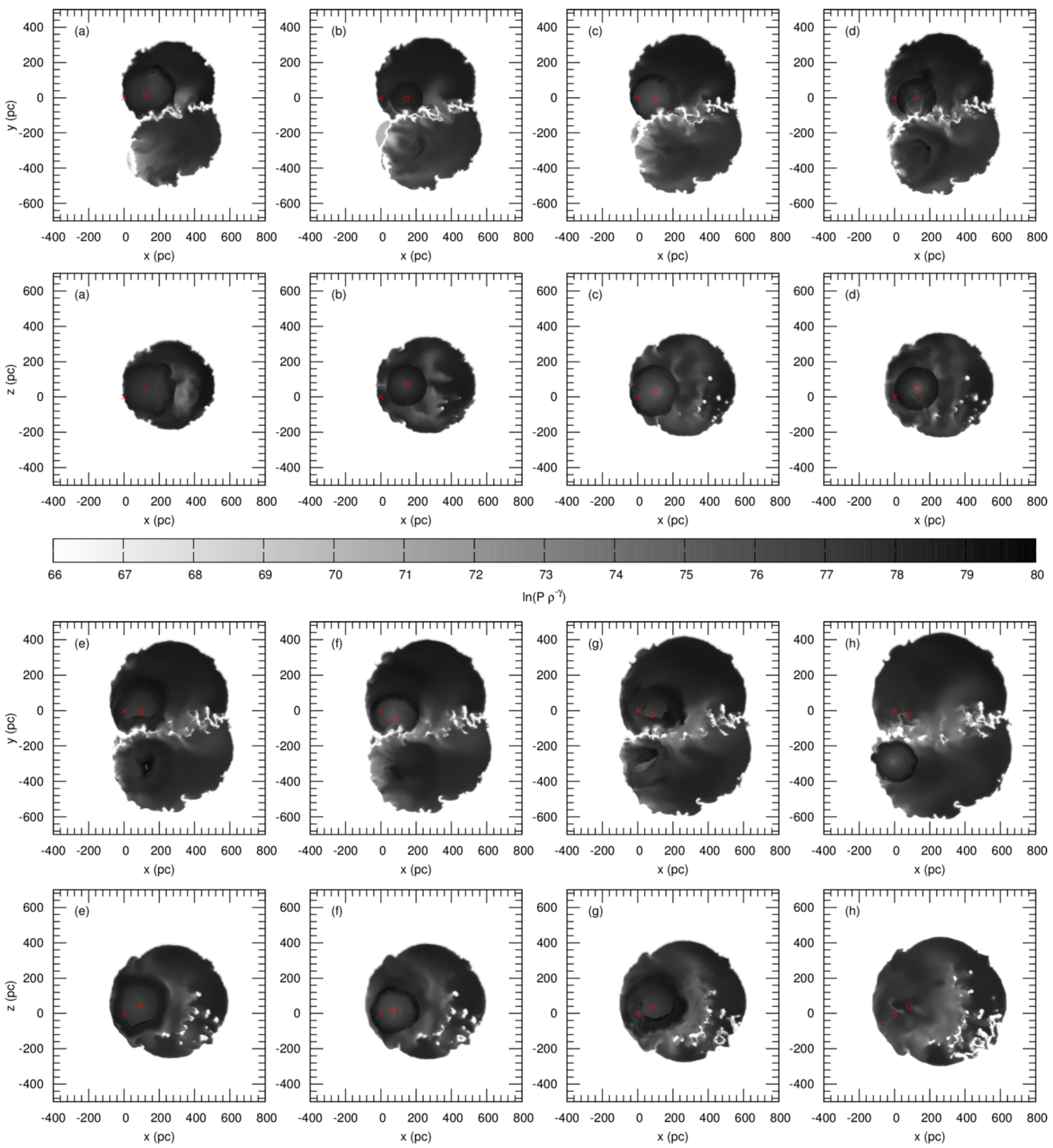
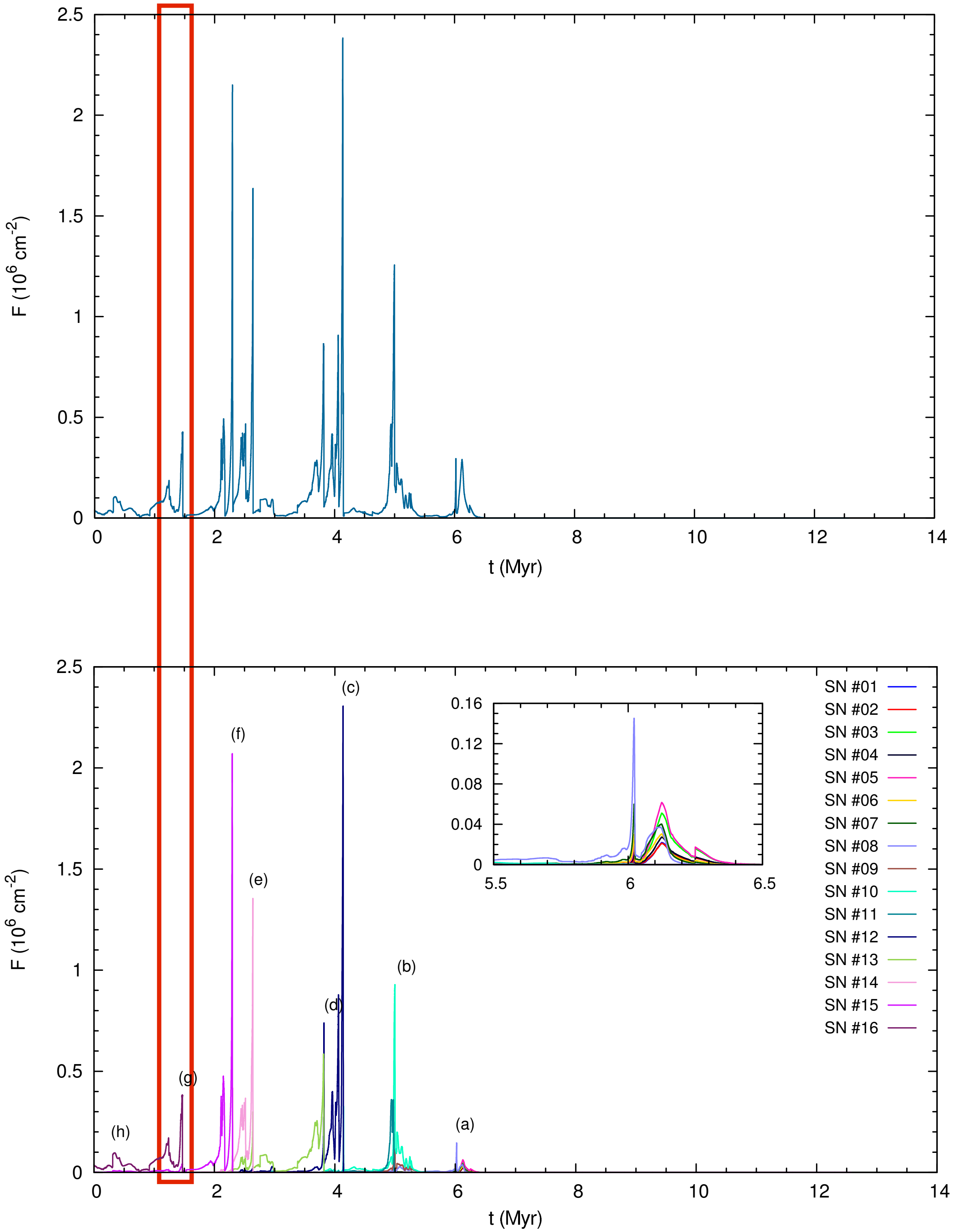
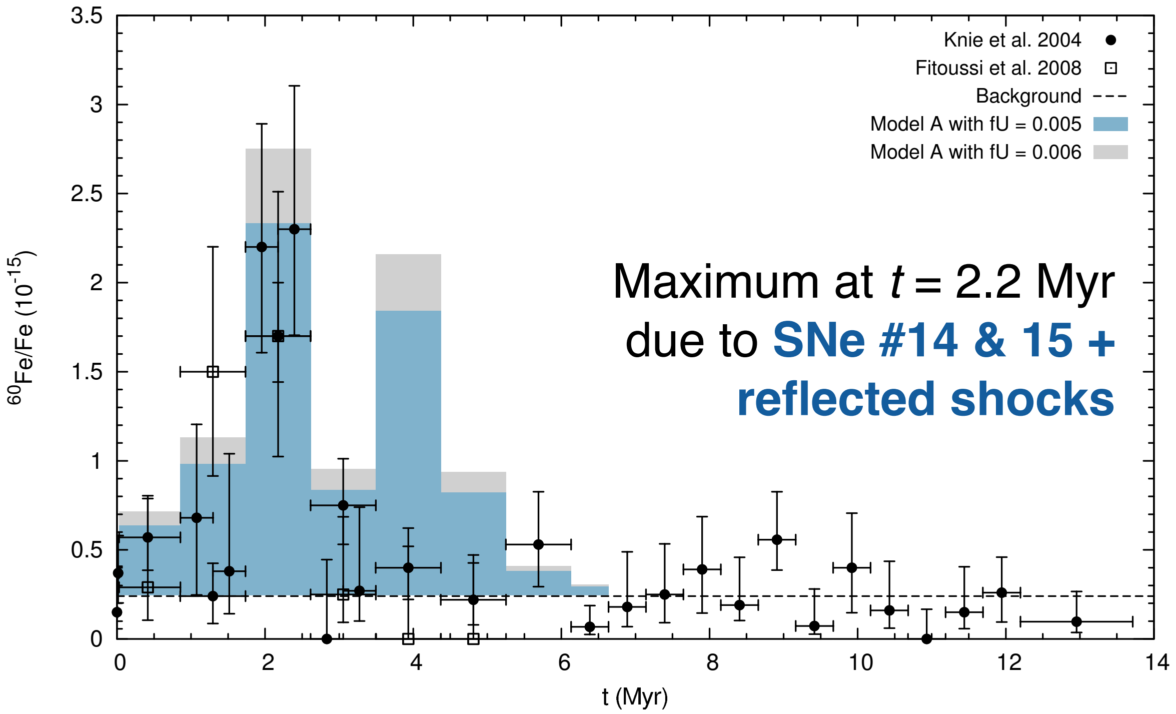




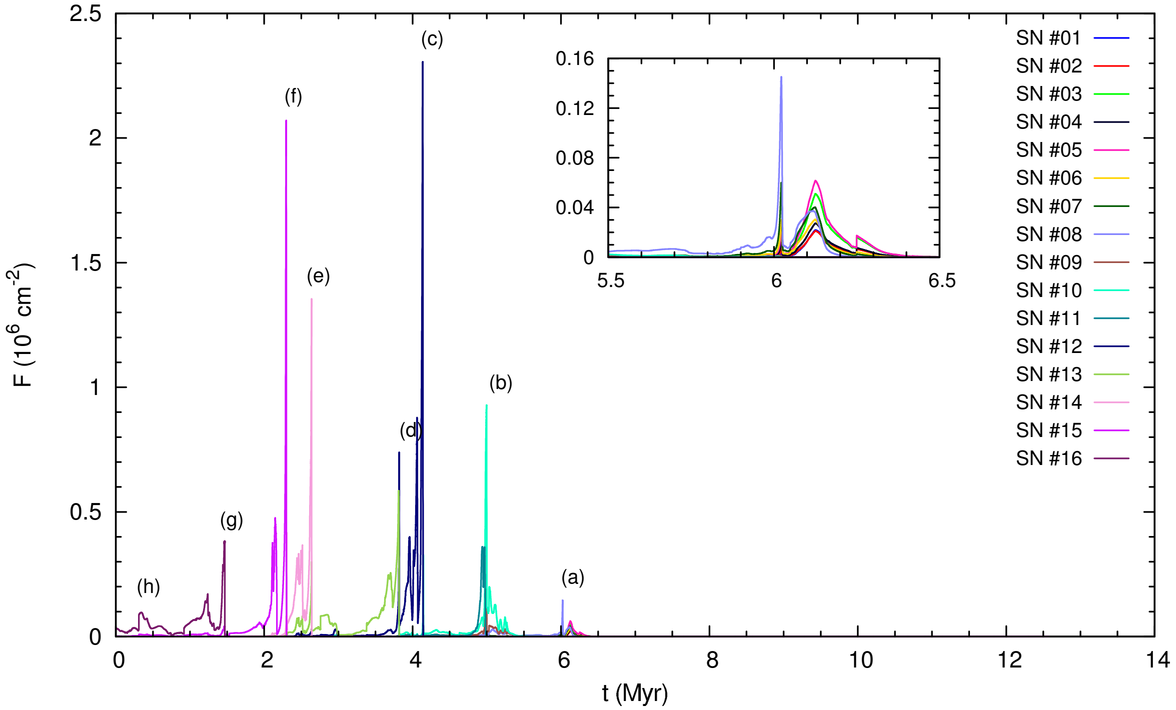
Results — Chemical mixing simulations with homogeneous background medium

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: $fU \simeq 0.005$

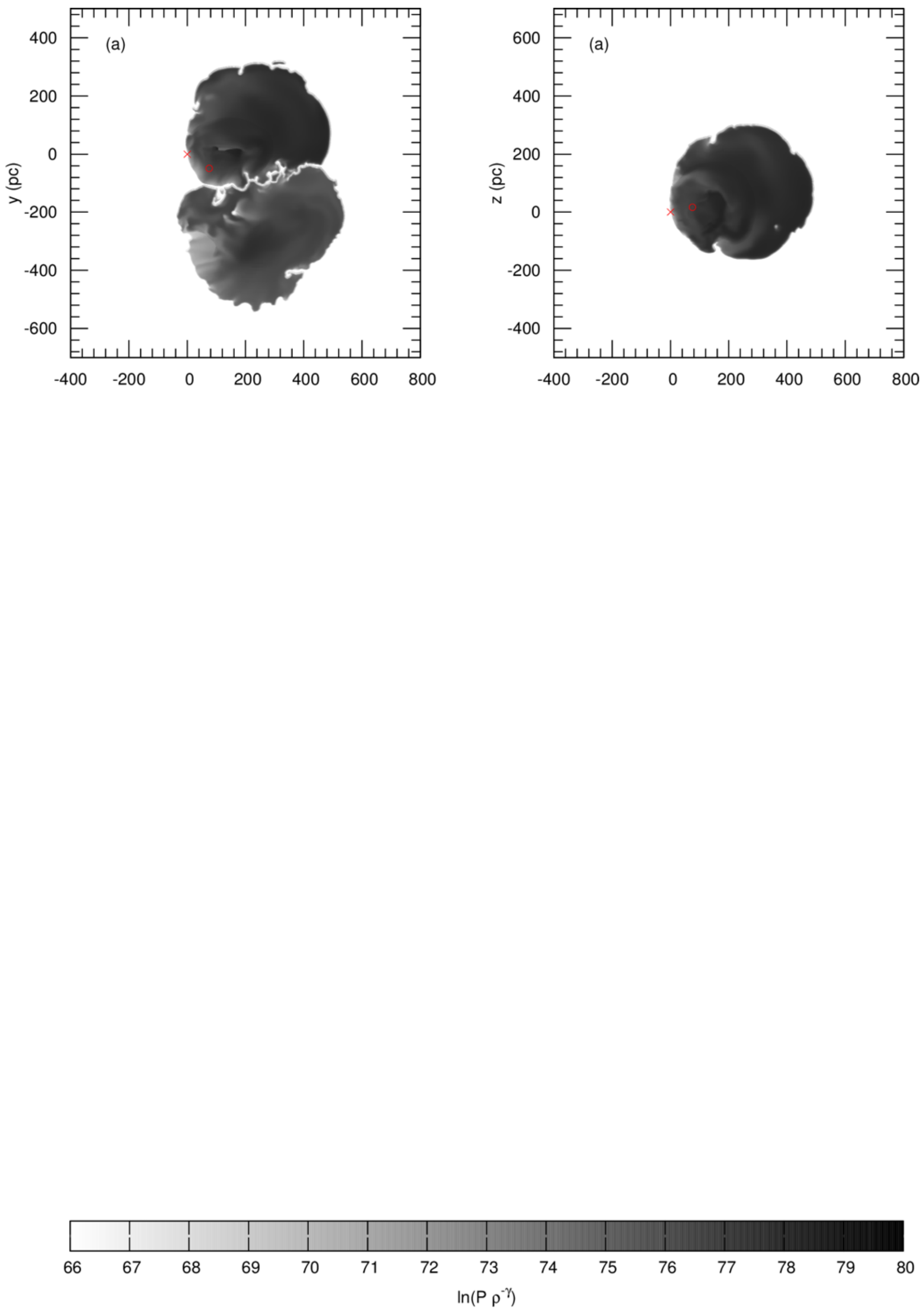


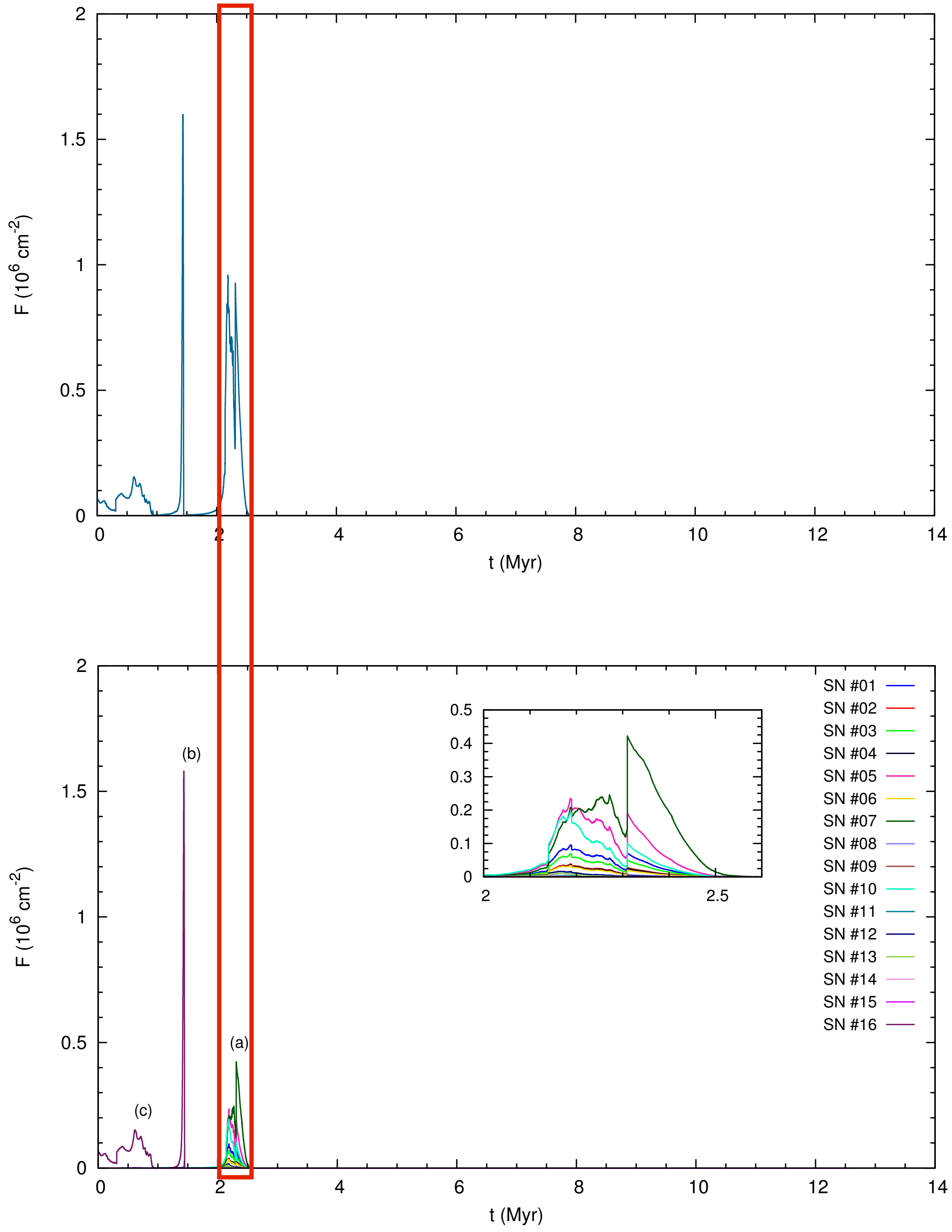
Maximum at $t = 2.2$ Myr due to **SNe #14 & 15 + reflected shocks**



Results — Chemical mixing simulations with homogeneous background medium

Model B: Entropy maps and 60Fe fluence variation





Results — Chemical mixing simulations with homogeneous background medium

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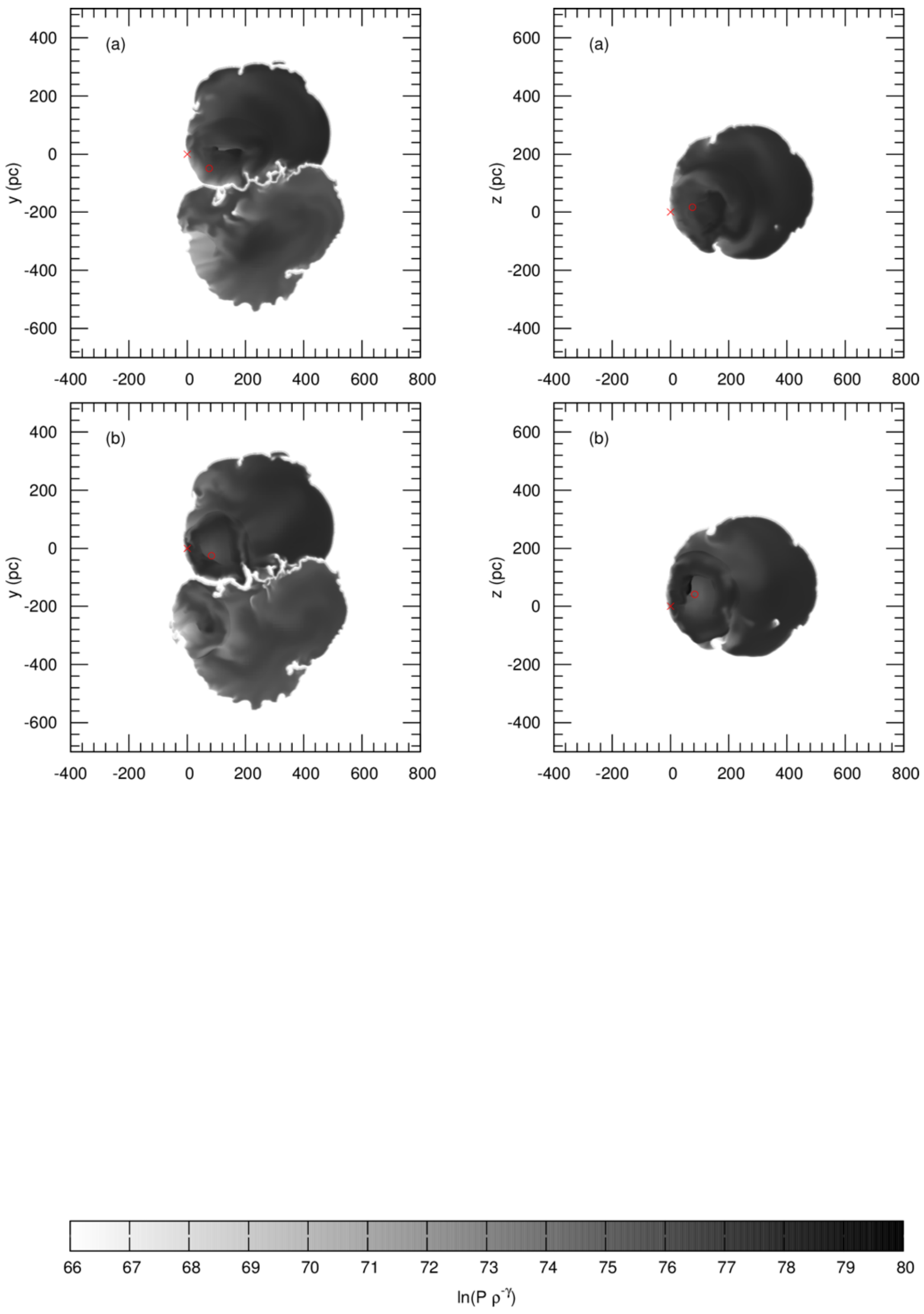

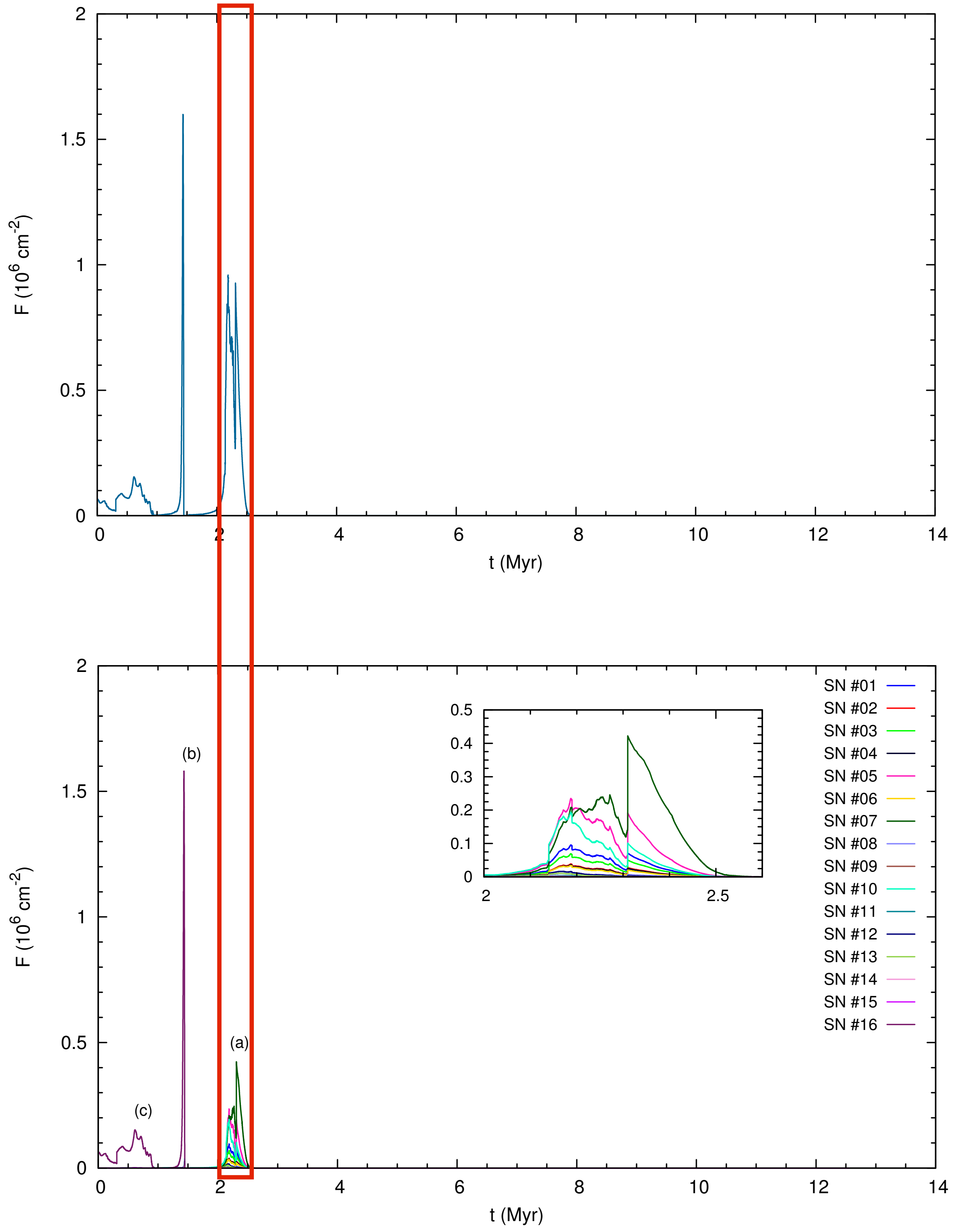

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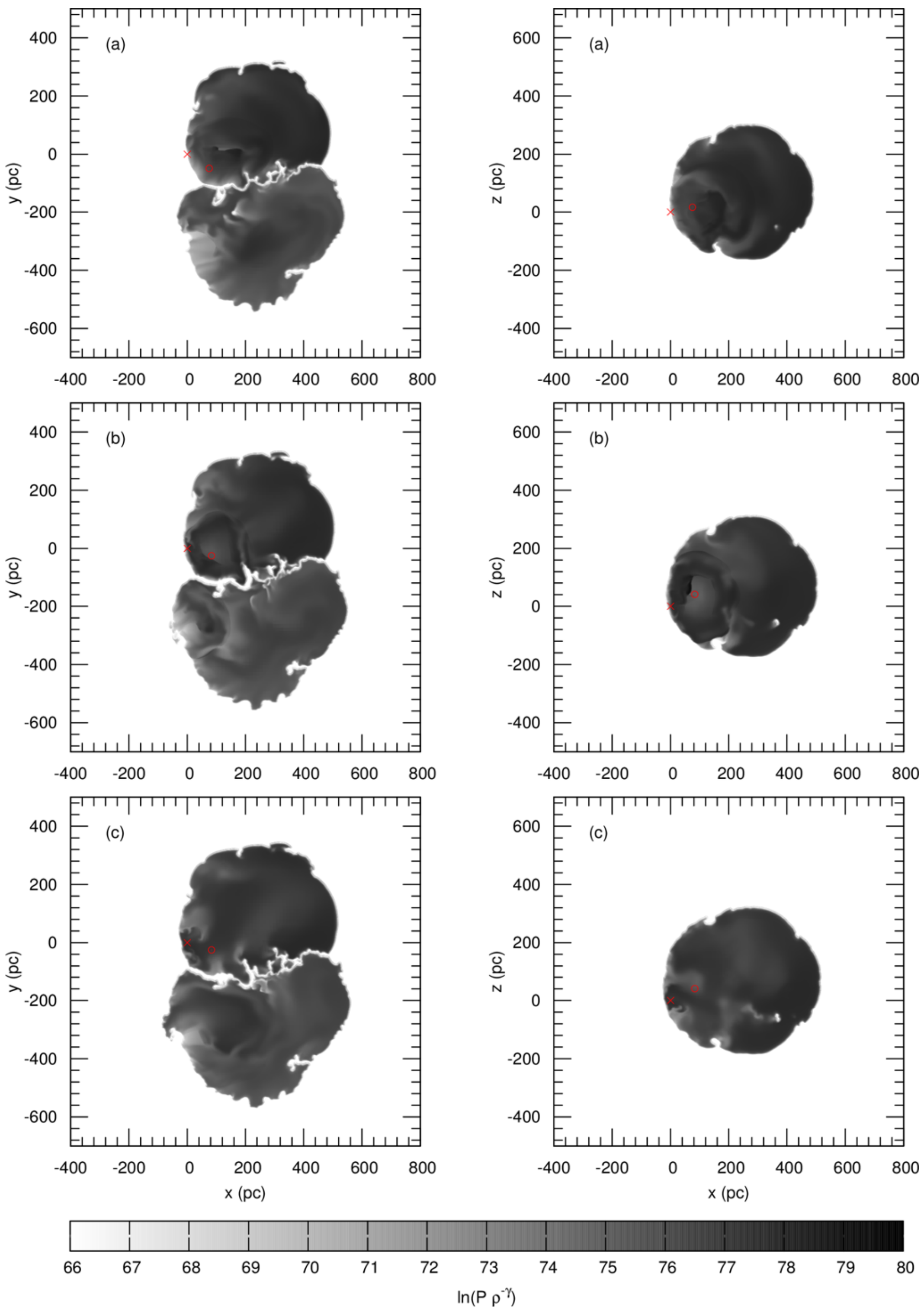
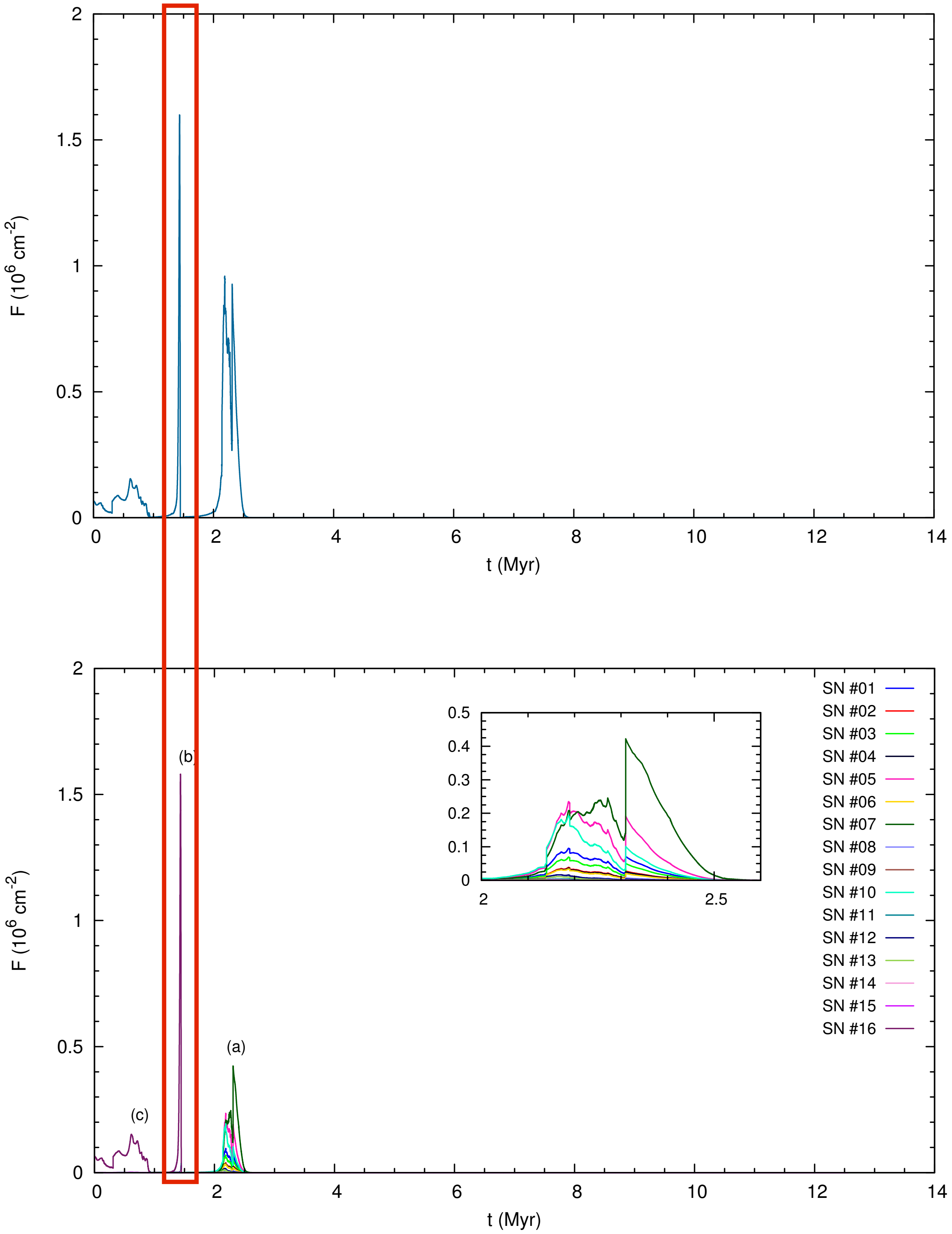
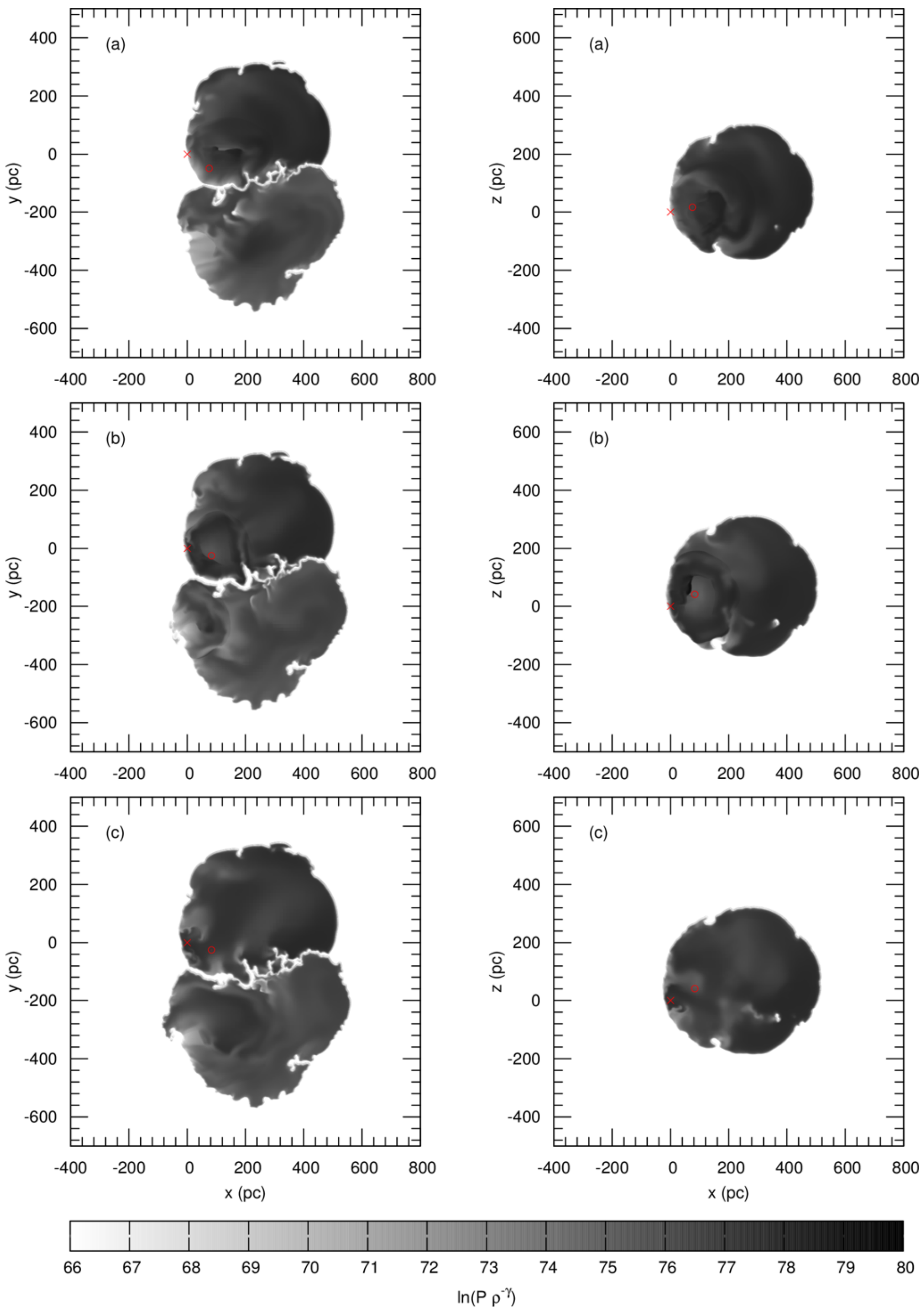
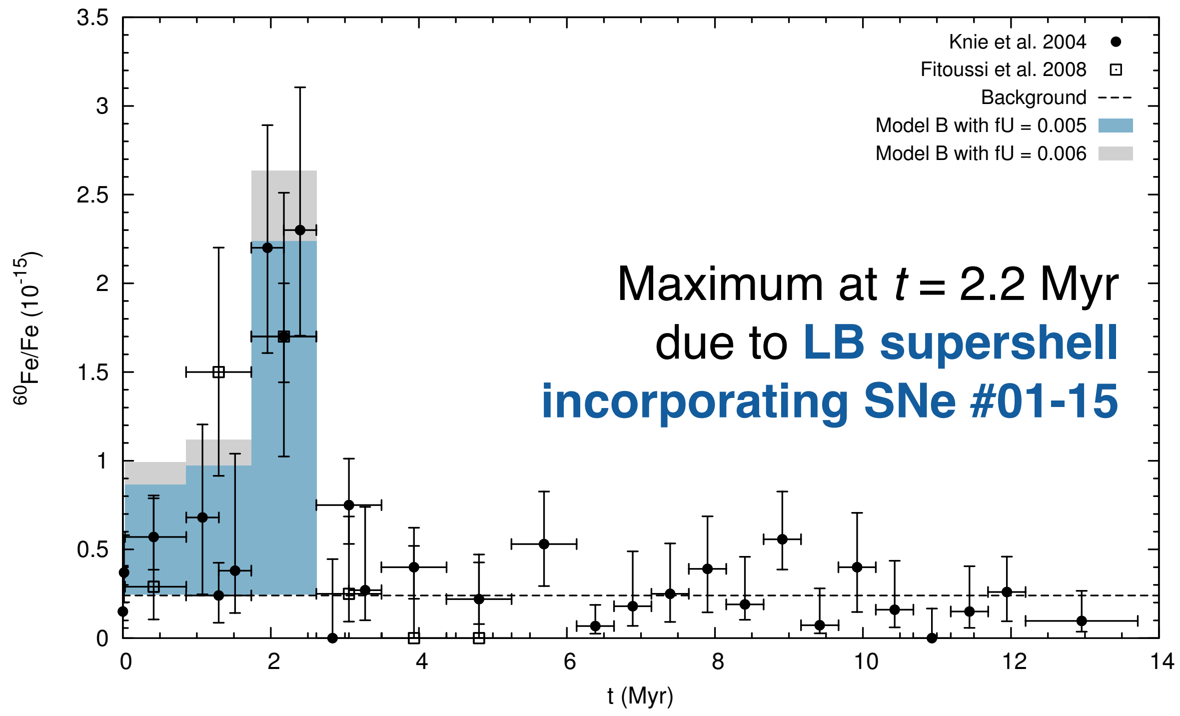




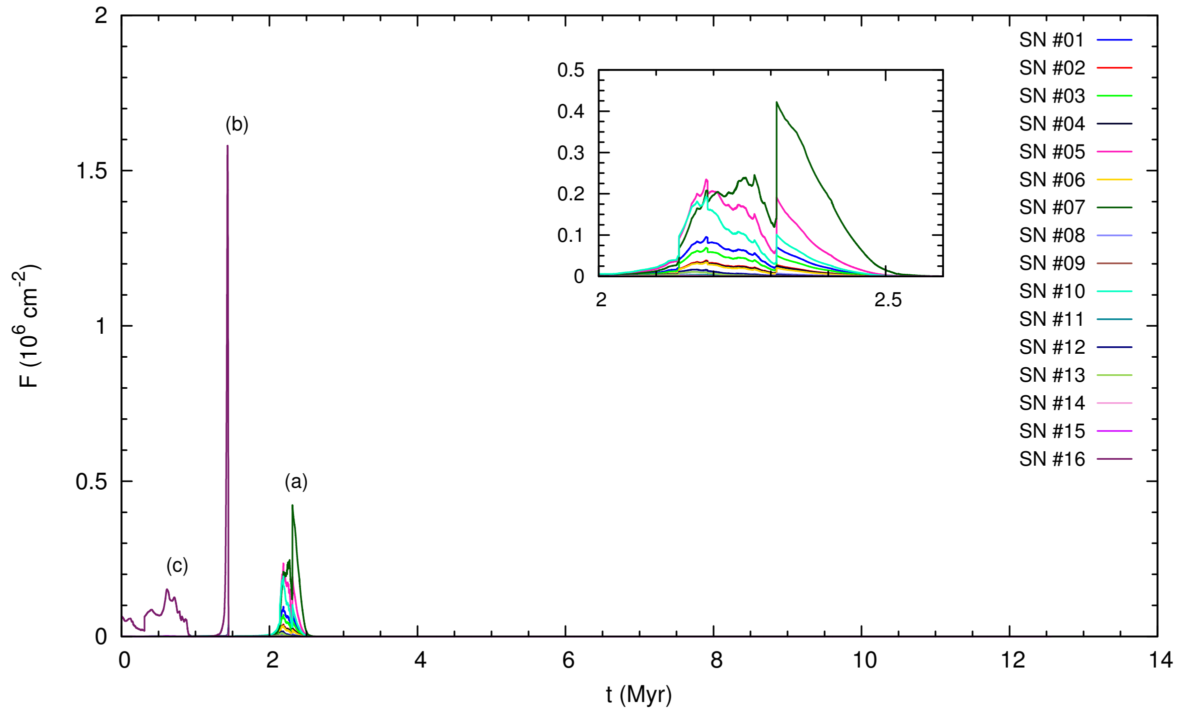
Results — Chemical mixing simulations with homogeneous background medium

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



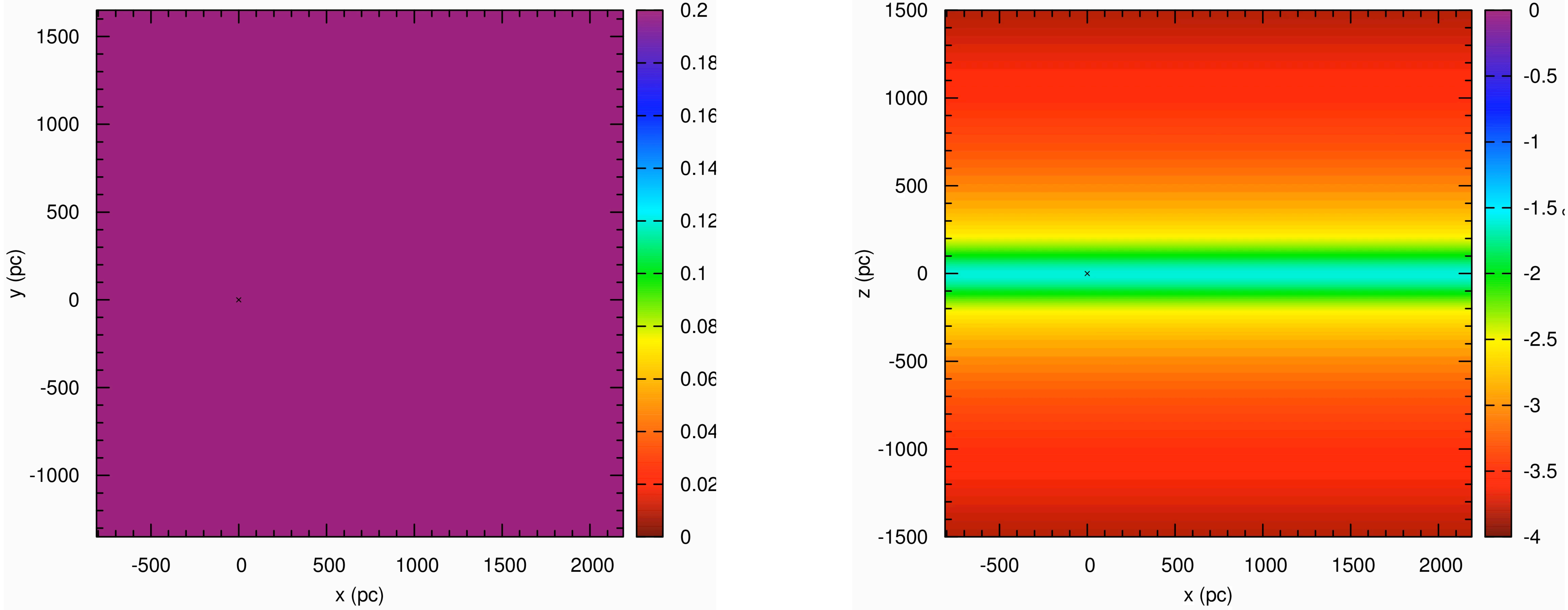


Maximum at *t* = 2.2 Myr due to **LB supershell incorporating SNe #01-15**



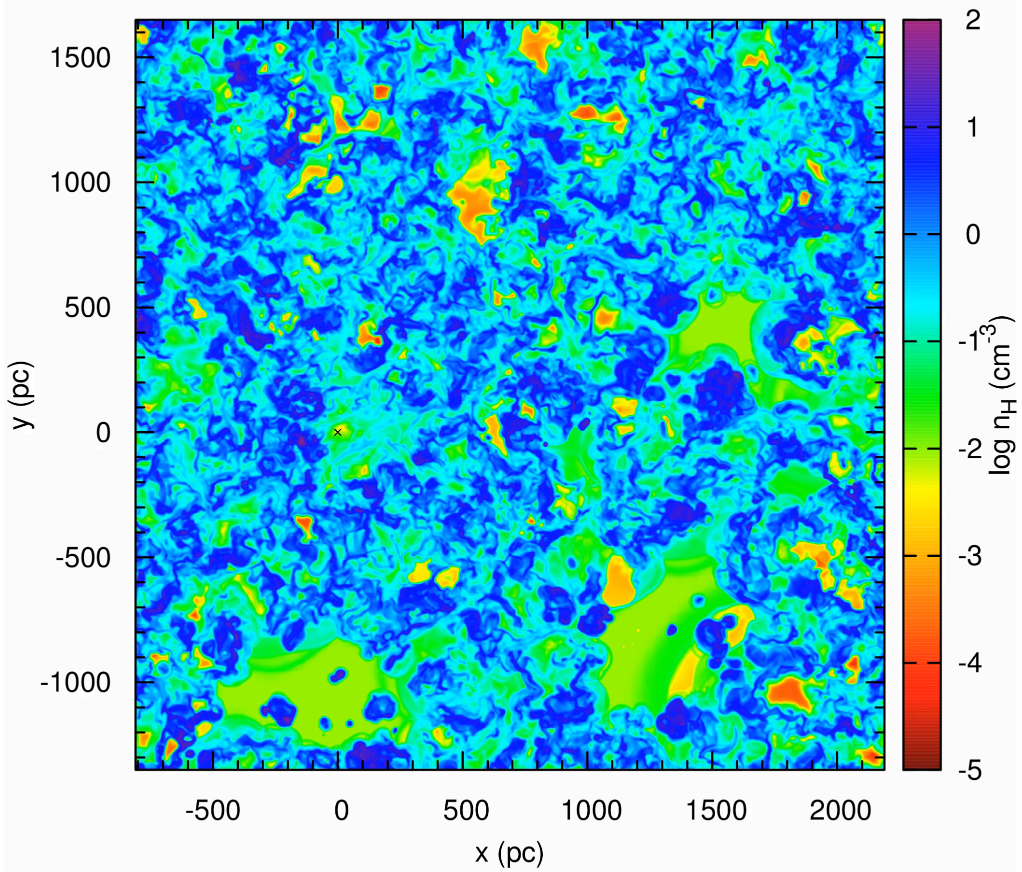
Results — Evolution of the Local Interstellar Medium

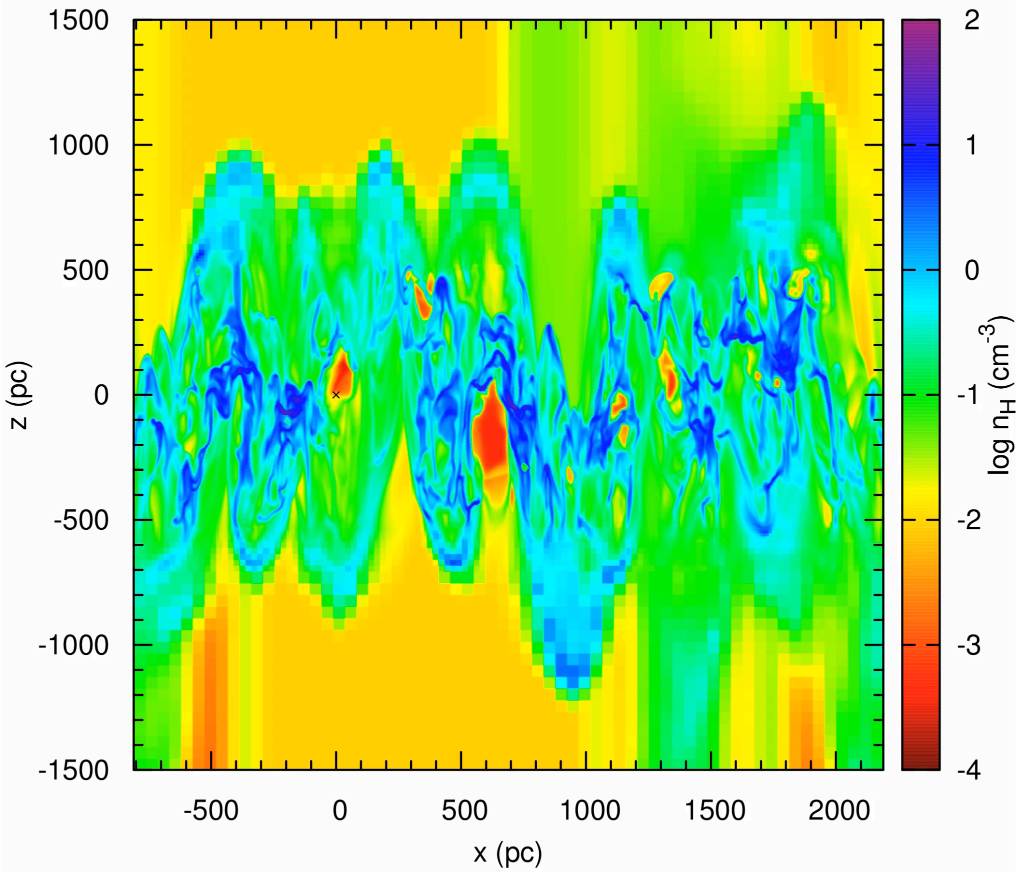
Atomic hydrogen number density and gas column density distribution (cuts through z = 0 and y = 0; 180 Myr evol. time)



Results — Chemical mixing simulations with inhomogeneous background medium

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



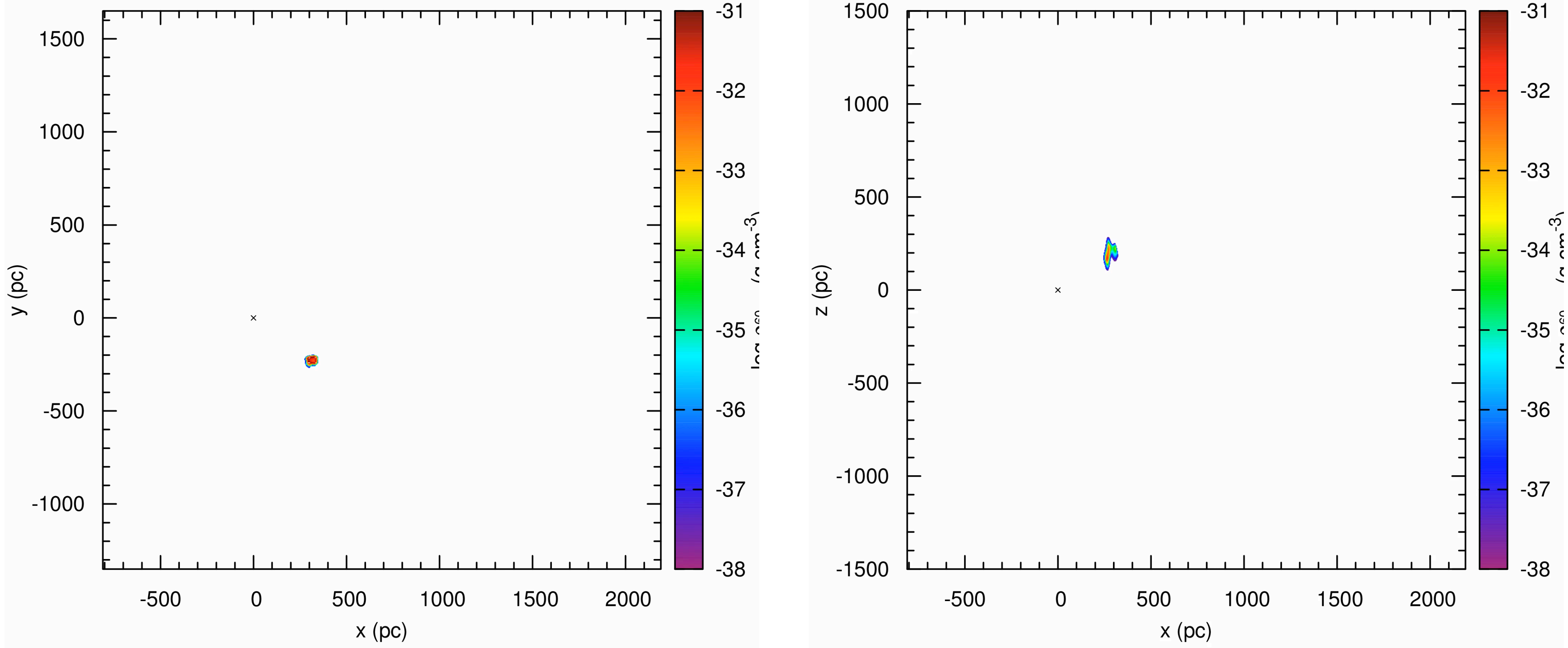


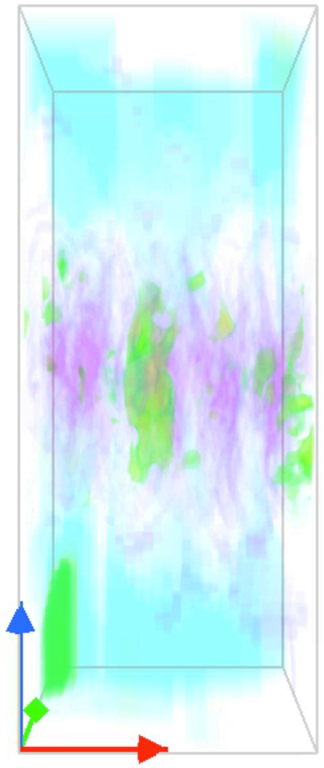
- Launch LB SNe in **“suitable”** environment
- search for extended region that remains sufficiently thin ($n \gtrsim 0.3$ cm^{-3}) at least for a few Myr
- dense gas with enough mass and small flow gradients for cluster star formation

- 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 $y = 0$)

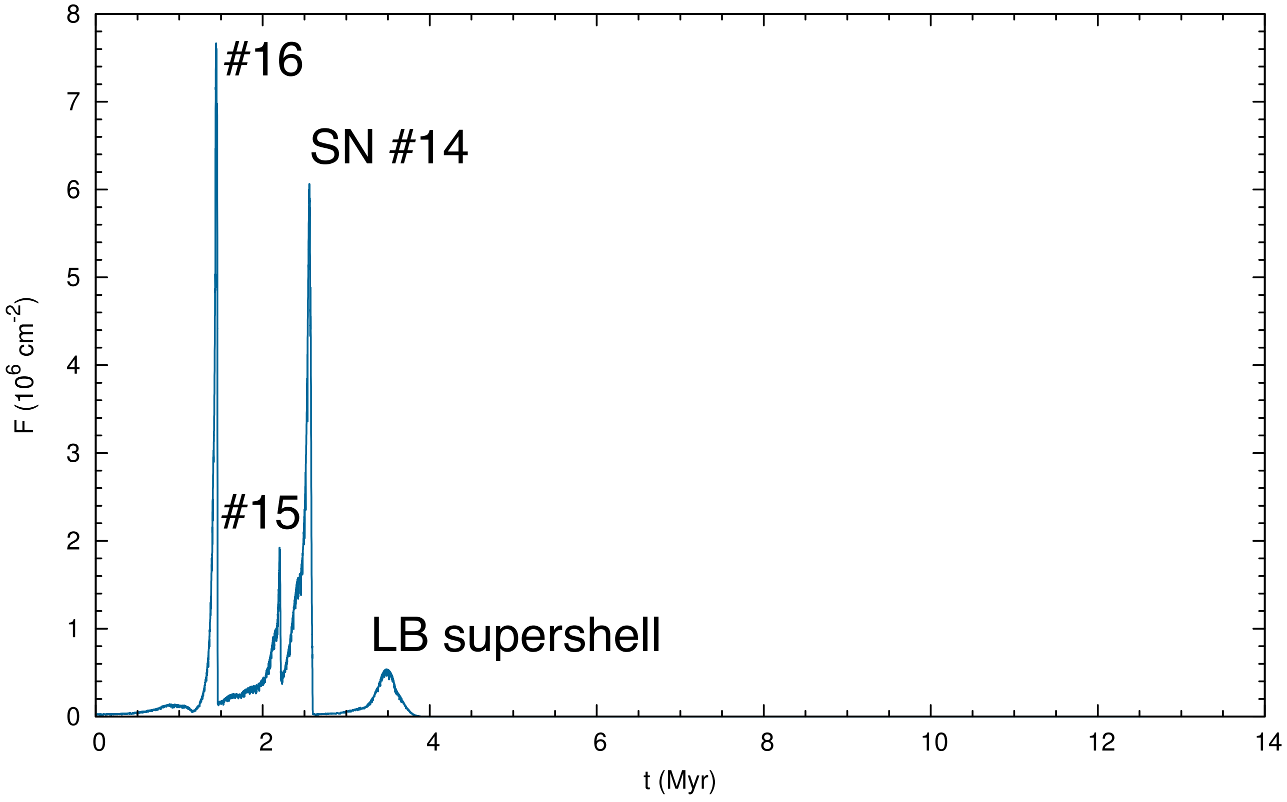


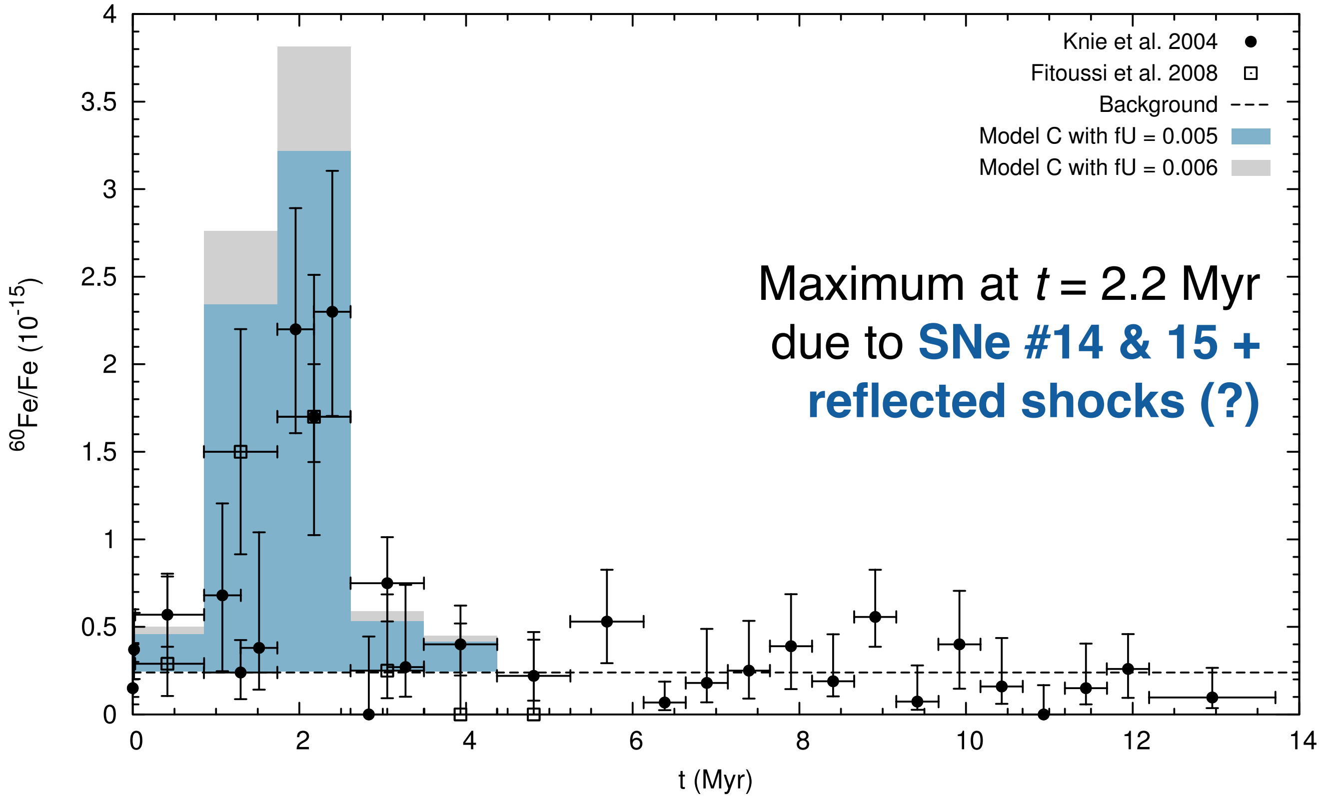


No interstellar ^{60}Fe background ➔ model gives lower limit of ^{60}Fe content in the local ISM!

Chemical mixing simulations with inhomogeneous background medium

Model C: Comparison between models and crust measurements

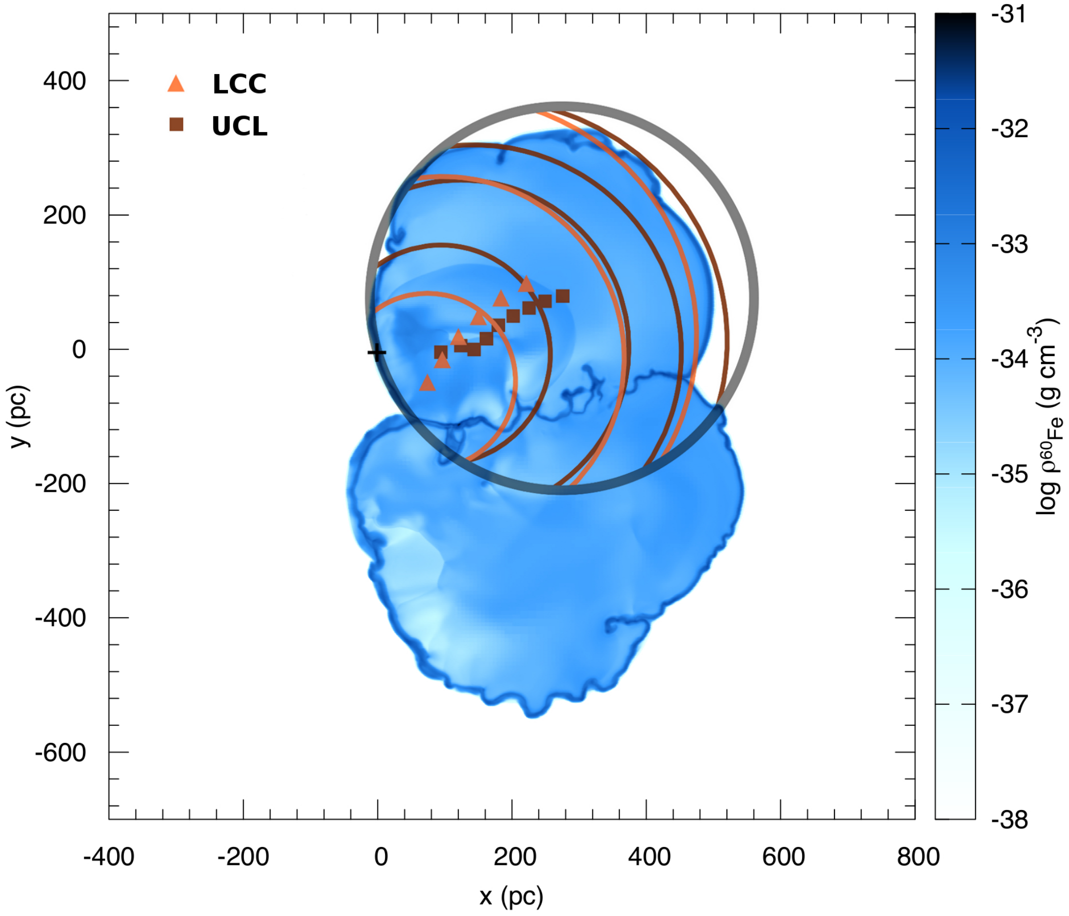


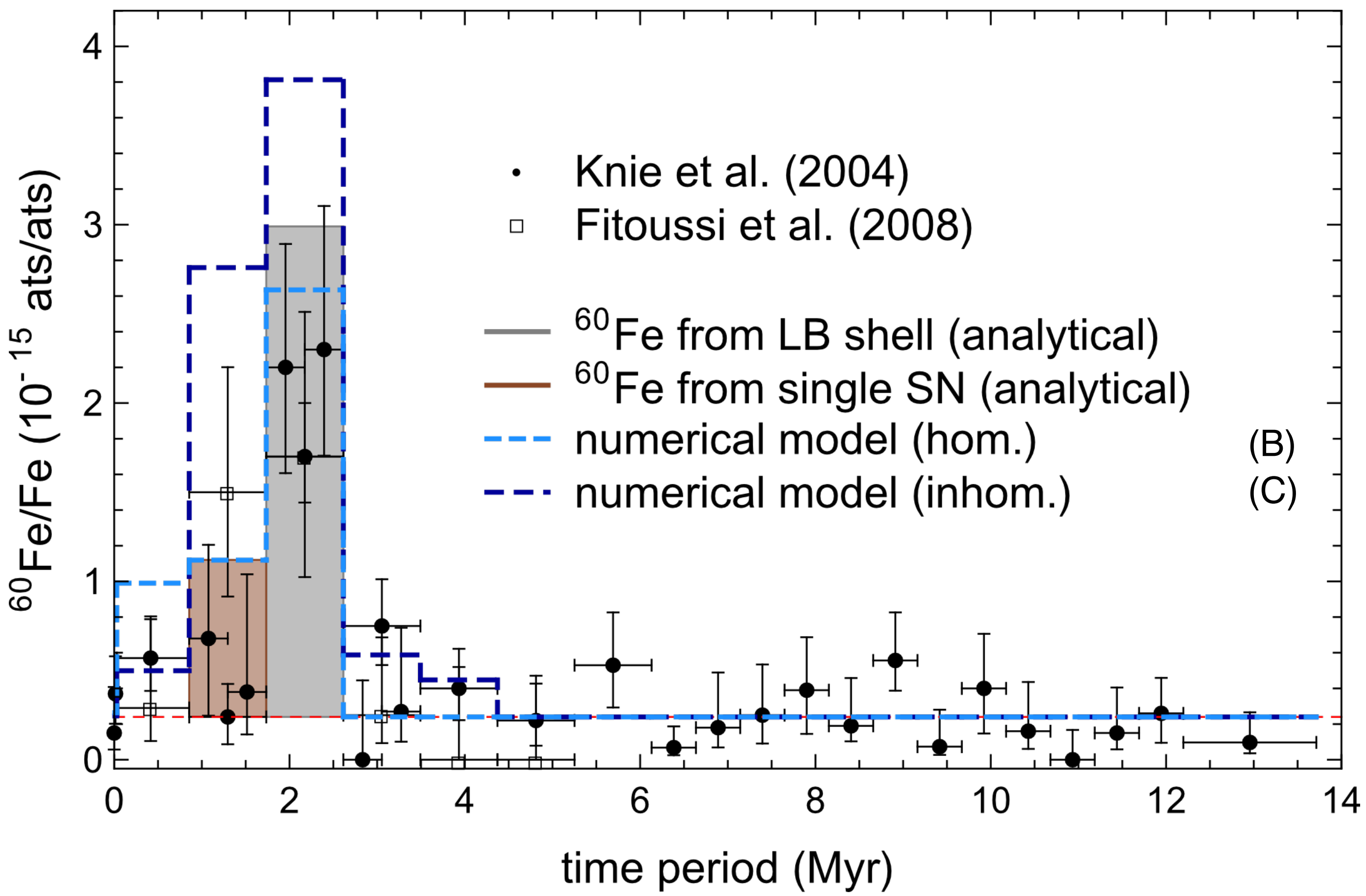


Maximum at $t = 2.2$ Myr due to **SNe #14 & 15 + reflected shocks (?)**

- 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., $(n)_{\mathrm{VA}} \simeq 0.2$ cm^{-3}]
  - Supershell arrives later in A than in B ➔ self-gravity unimportant in LB evolution

Comparison of numerical and analytical solutions

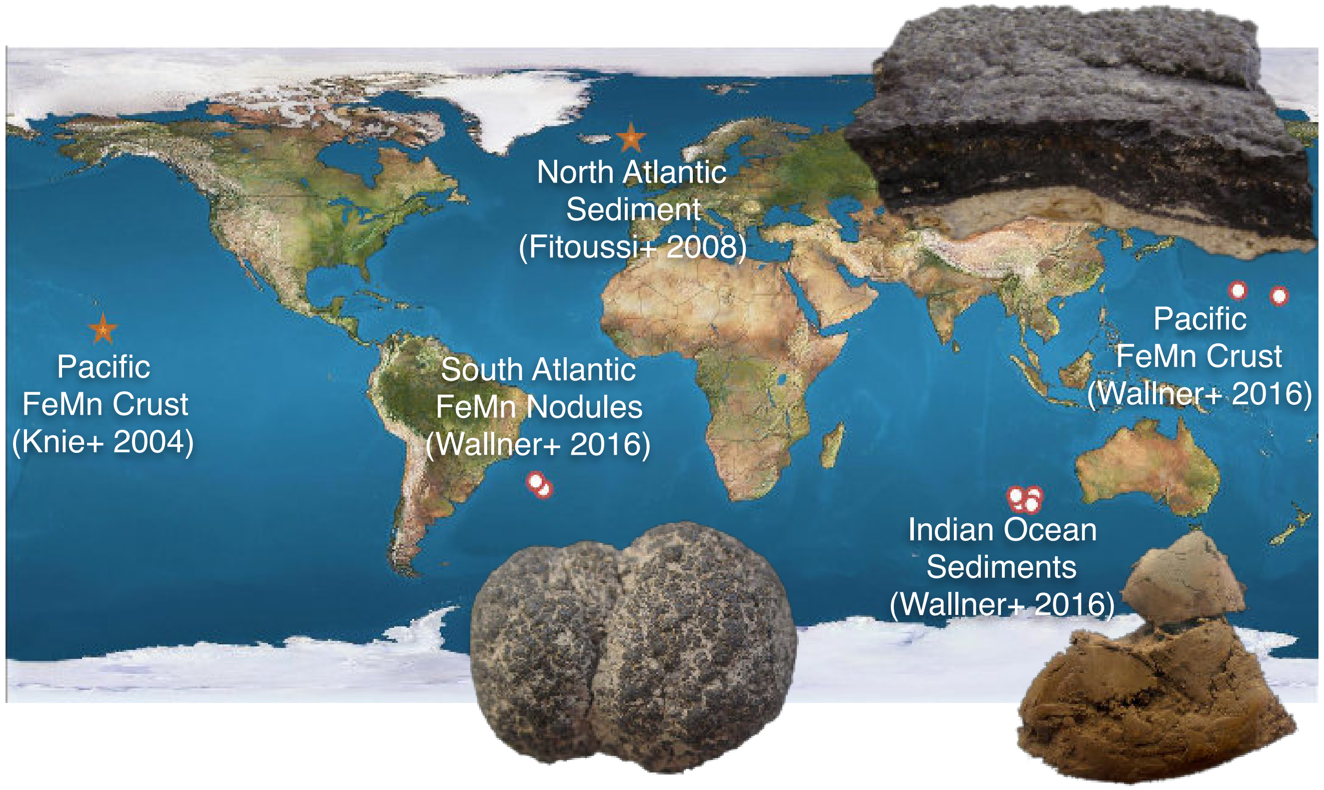


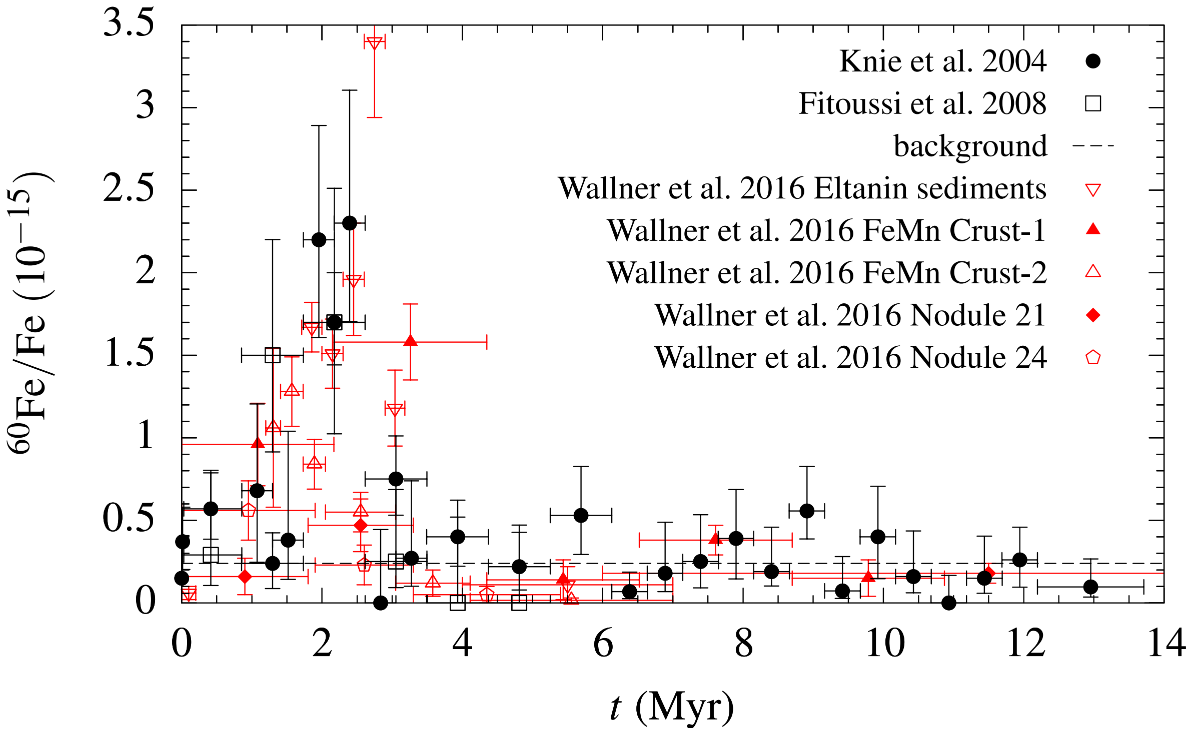


Supporting findings

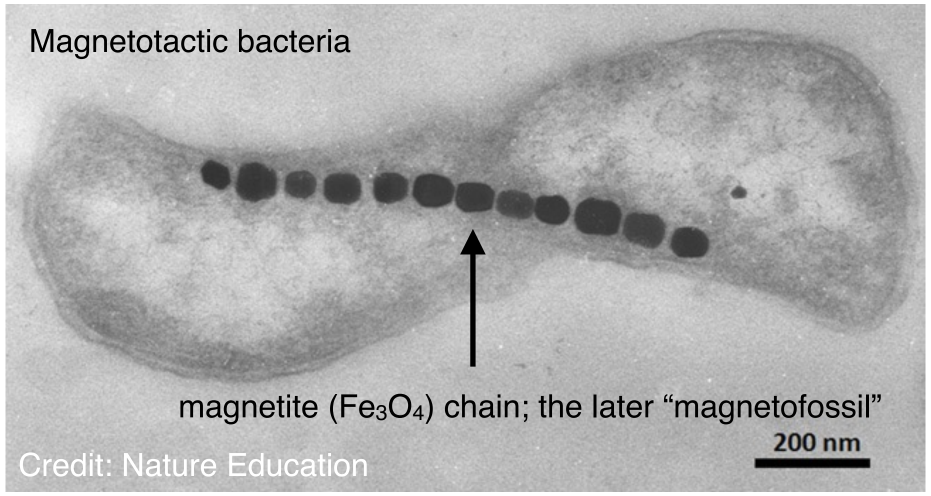
1) Extended ^{60}Fe peak (1.5-3.2 Myr ago) in deep-sea archives from all major oceans (Wallner+ 2016)

- global phenomenon
- width hints at more than one SN



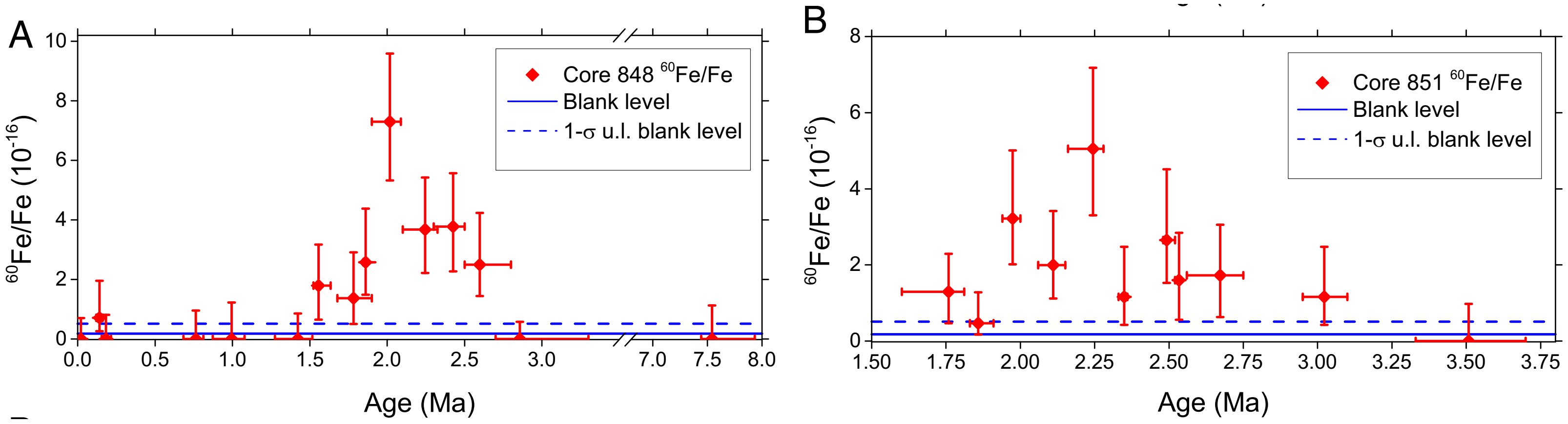


2) Increased ^{60}Fe levels in microfossils dated at 1.8-2.6 Myr (Ludwig+ 2016)



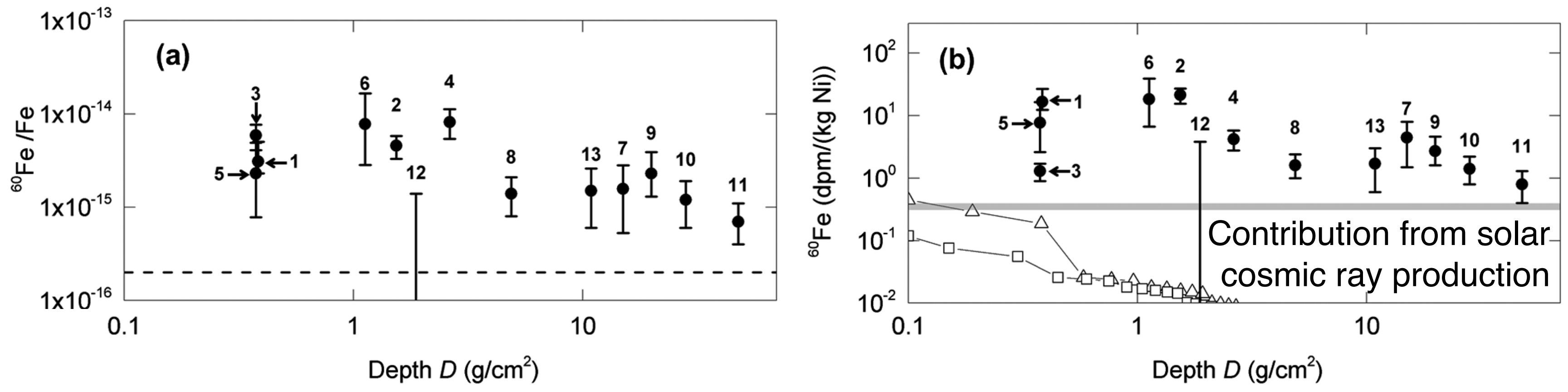
Credit: Nature Education

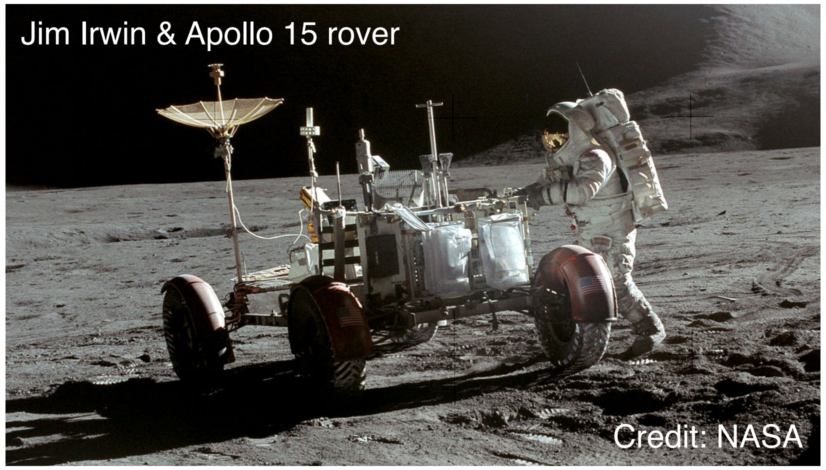
Measurements in two independent Pacific Ocean sediment cores: 42/47 ^{60}Fe events in core A/B



Supporting findings

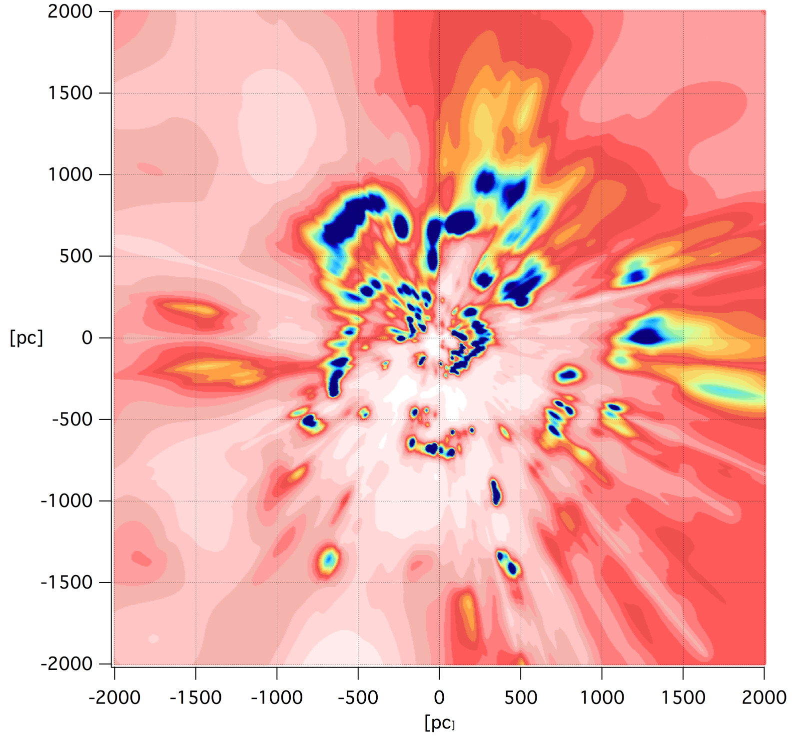
3) **Enhanced ^{60}Fe signatures in lunar soil samples from Apollo 12, 15, and 16** (Fimiani+ 2016)
   - No time-resolved measurements due to ‘gardening’ and absence of sedimentation
   - Detected integrated fluence (F ~ 10^7–6×10^7 cm^{-2}) compatible with LB model if, e.g., $U = 1$, $f = 0.016$



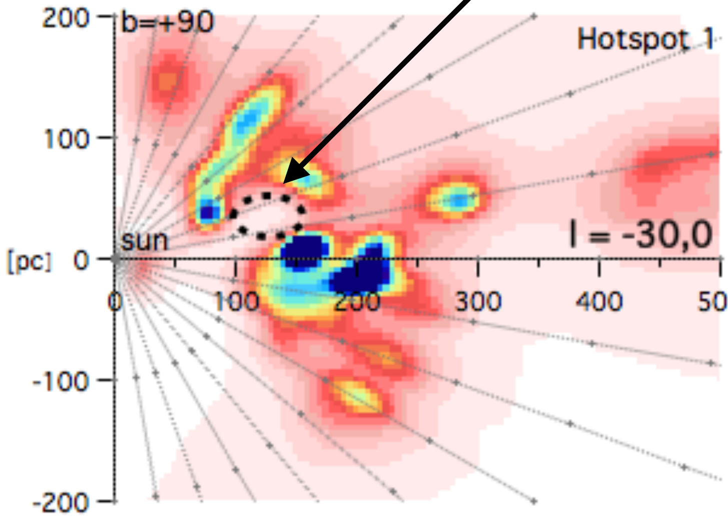

Jim Irwin & Apollo 15 rover

Credit: NASA

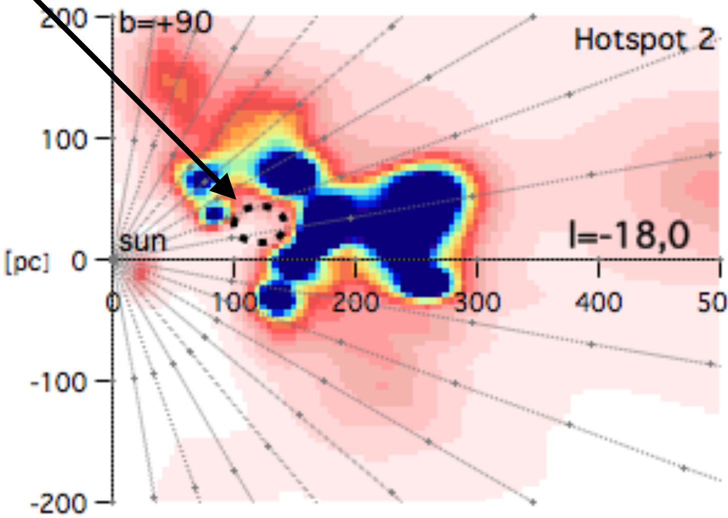
4) **Soft X-ray emitting cavities in 3D local interstellar dust maps match estimated sites of the two most recent SNe** (Capitanio+ 17)
   - Directions within 3° and 7°, respectively
   - Similar distances



Regions lying in directions of ROSAT 3/4 keV X-ray brightness enhancements (cf. Puspitarini+ 2014)



SN #15

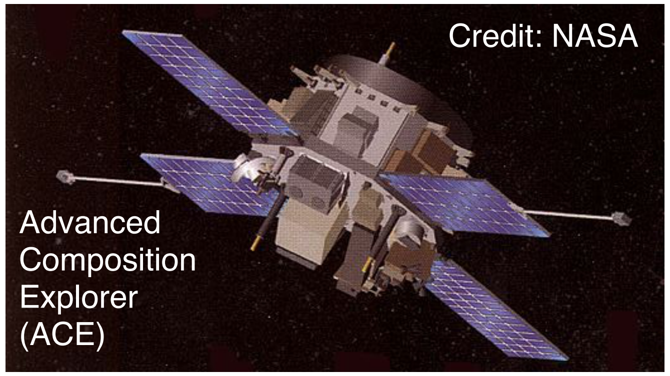


SN #16

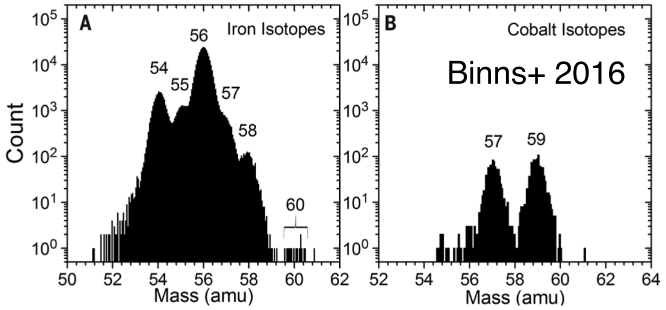
Supporting findings

5) ^{60}Fe in cosmic rays

- During 17 years, ACE-CRIS experiment collected 3.55×10^5 iron nuclei (energy range: ~195–500 MeV/nuc); among them are 15 ^{60}Fe nuclei
- Acceleration of nuclei by SN blast wave (1st order Fermi process)
- ^{60}Fe/^{56}Fe ratio ➔ time elapsed since ejection: ~ a few Myr
- Distance to source from ^{60}Fe half-life: < 620pc (diffusion model!) (Binns+ 16)
- 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 ago (Kachelrieß+ 15)


Credit: NASA

Advanced Composition Explorer (ACE)



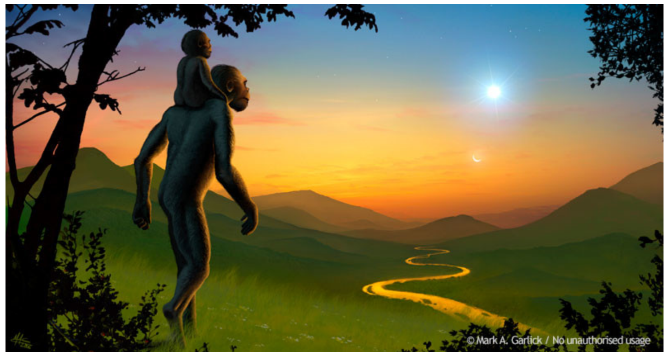
Binns+ 2016

6) We *Homines sapientes* exist

- Australopithecus should have seen SN 2.2 Myr ago during daylight
- Thomas+ (2016) modeled impact of nearby (d ~ 100 pc) SN event in already-excavated region on terrestrial atmosphere and biota

  ➔ Weak chemical changes, like ozone depletion; small physiological effects from weeks-long blue-light enhancement

  ➔ But, tropospheric ionization down to the ground increases by ~order of magnitude for ≳ 1 kyr **and** irradiation by muons on ground / in atmosphere increases by factor of ~20 ➔ **tripled** overall radiation load on terrestrial organisms ➔ climate changes; increased cancer & **mutation rates** (?)
- Relationship with minor mass extinction near Pliocene-Pleistocene transition **2.5 Myr ago**?
- Widely accepted reason: abrupt cooling ➔ increase in glaciation down to mid-latitudes ➔ only dominant species survived ➔ among hominins: *Homo erectus* ➔ direct ancestor of *Homo sapiens* (Africa) and *Neanderthals* (Europe)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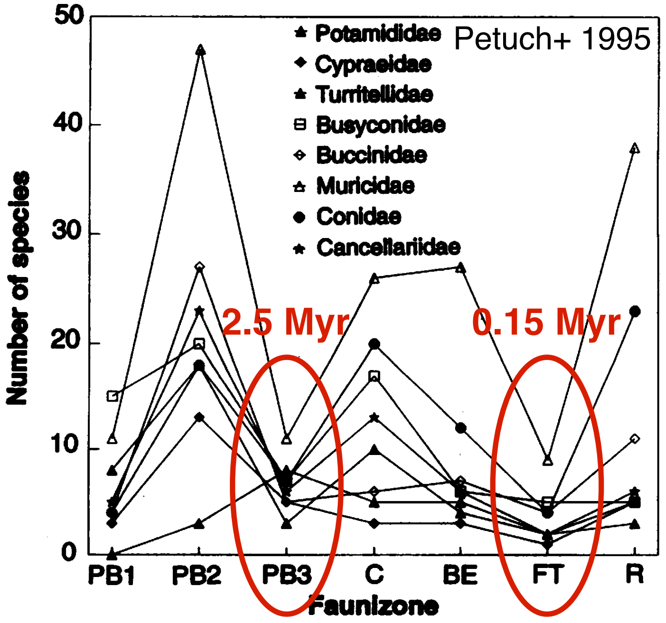
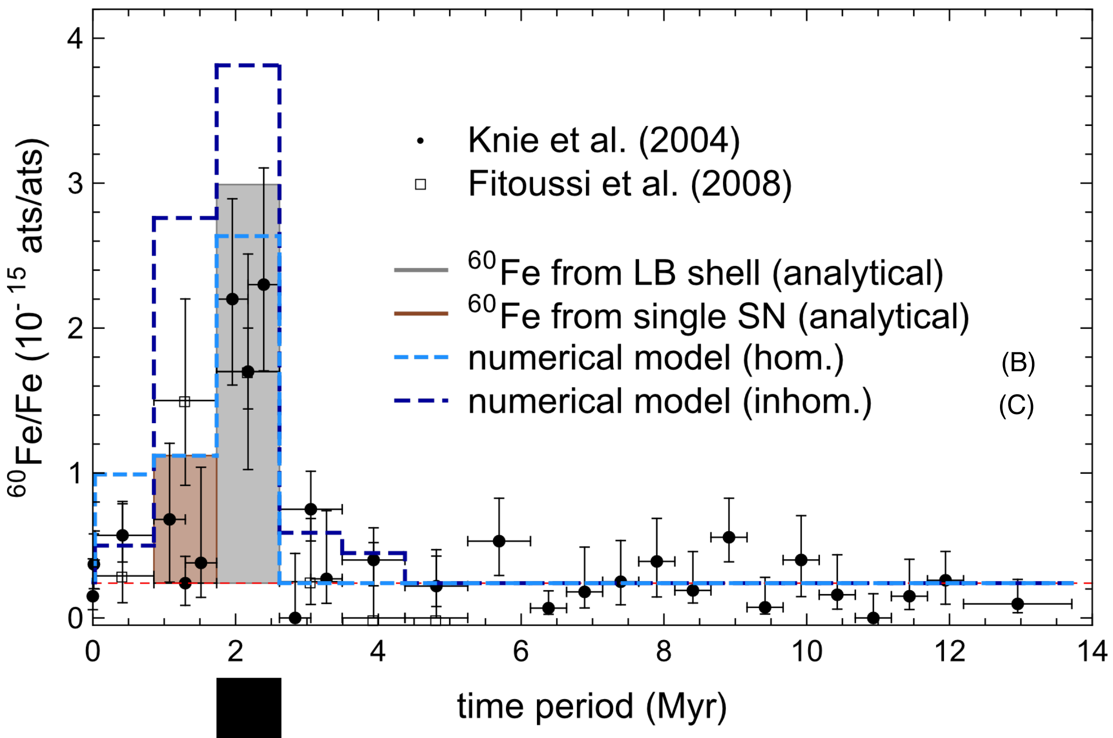


Petuch+ 1995

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



^{60}Fe mass density of model B @ t = 2.2 Myr ago