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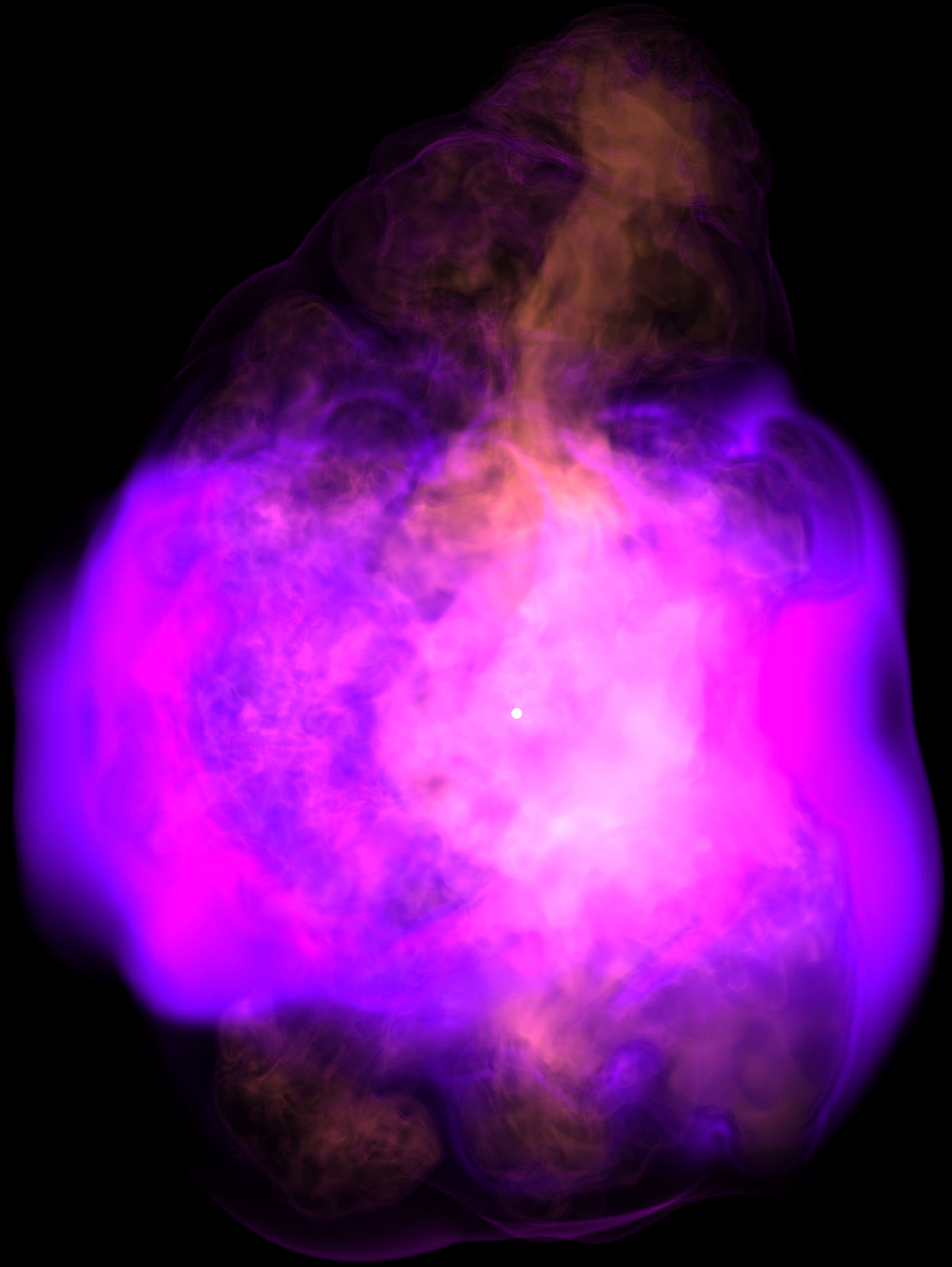
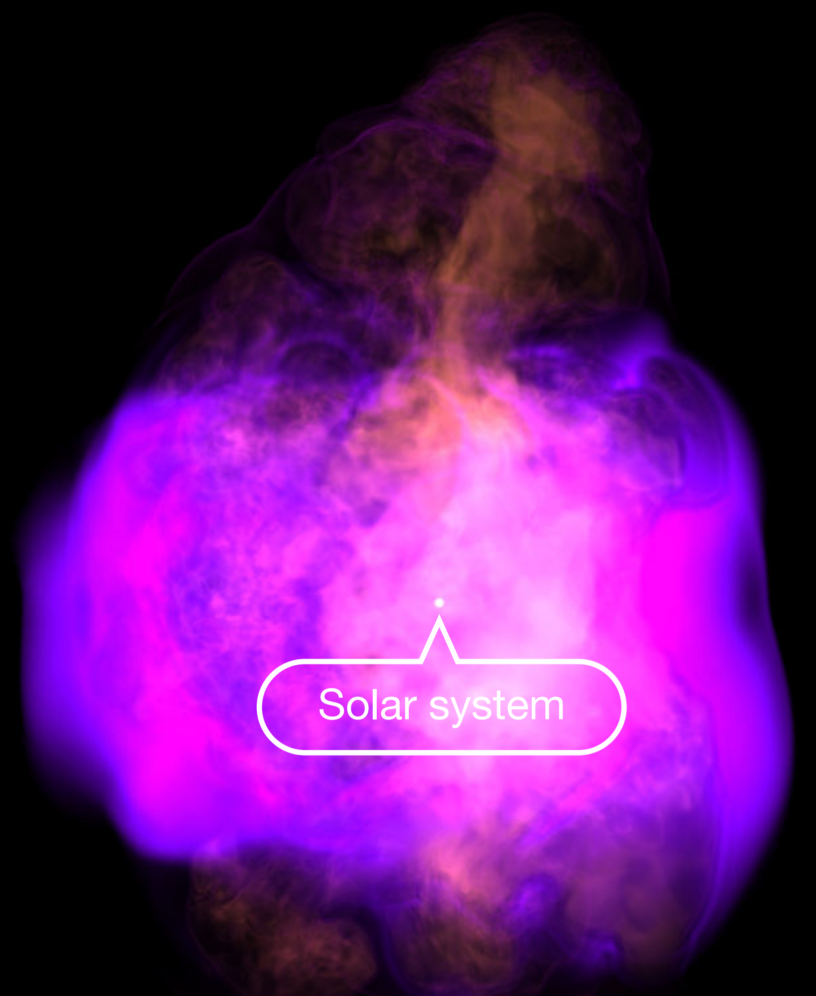
The supernova link between the Local Bubble and deep-sea radioisotopes

Michael M. Schulreich



The Local Bubble



Schulreich+ (2023)

Principle of dust extinction mapping

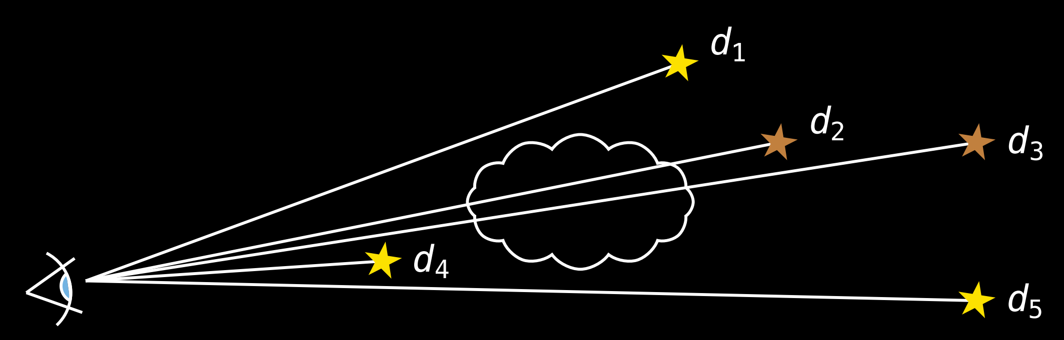


Image modified from Leike+ (2021)

ROSAT all-sky survey 1/4 keV intensity

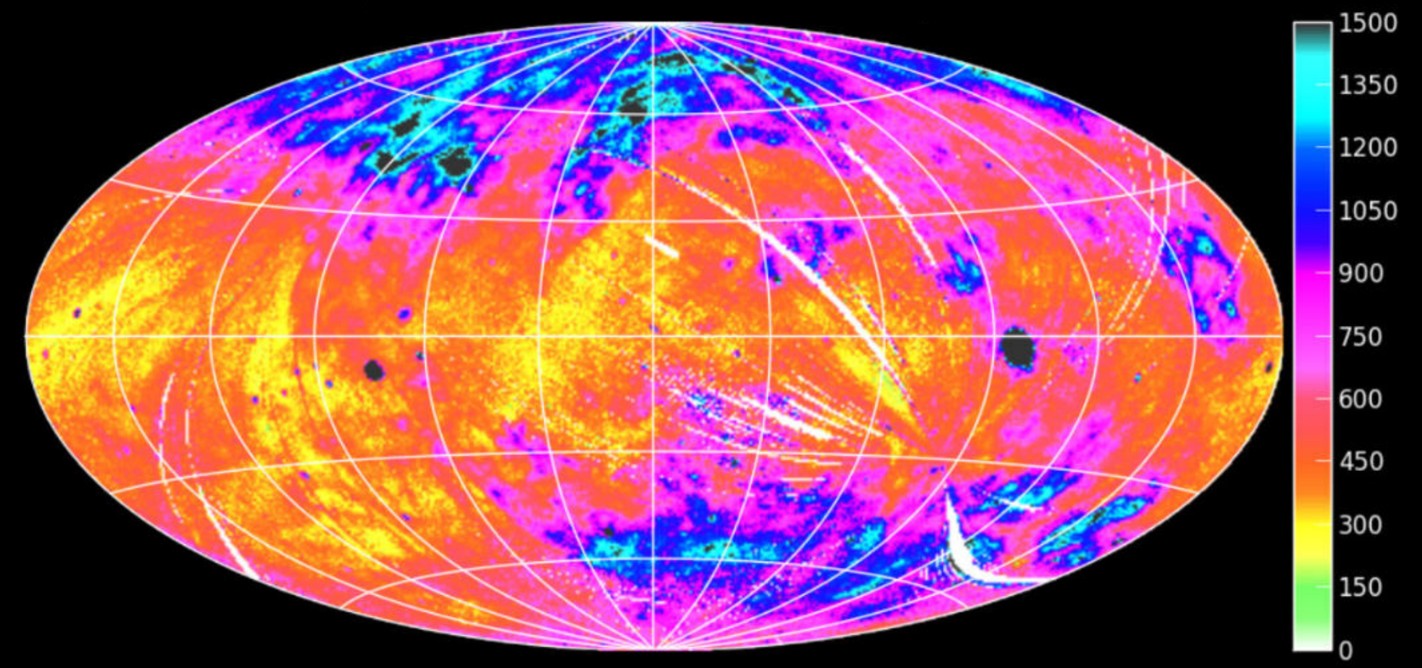
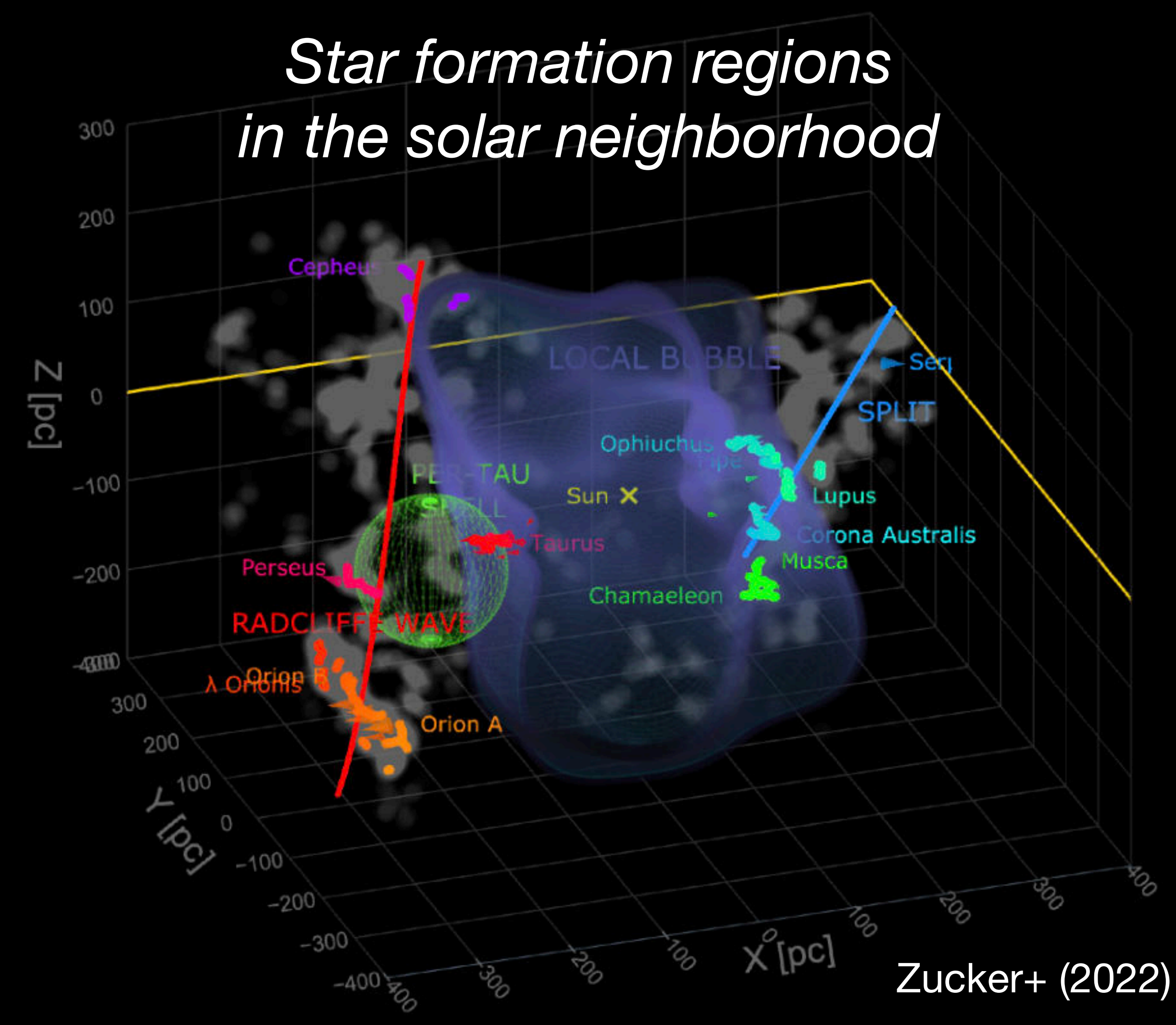


Image modified from Slavin+ (2016)

Star formation regions in the solar neighborhood



Zucker+ (2022)

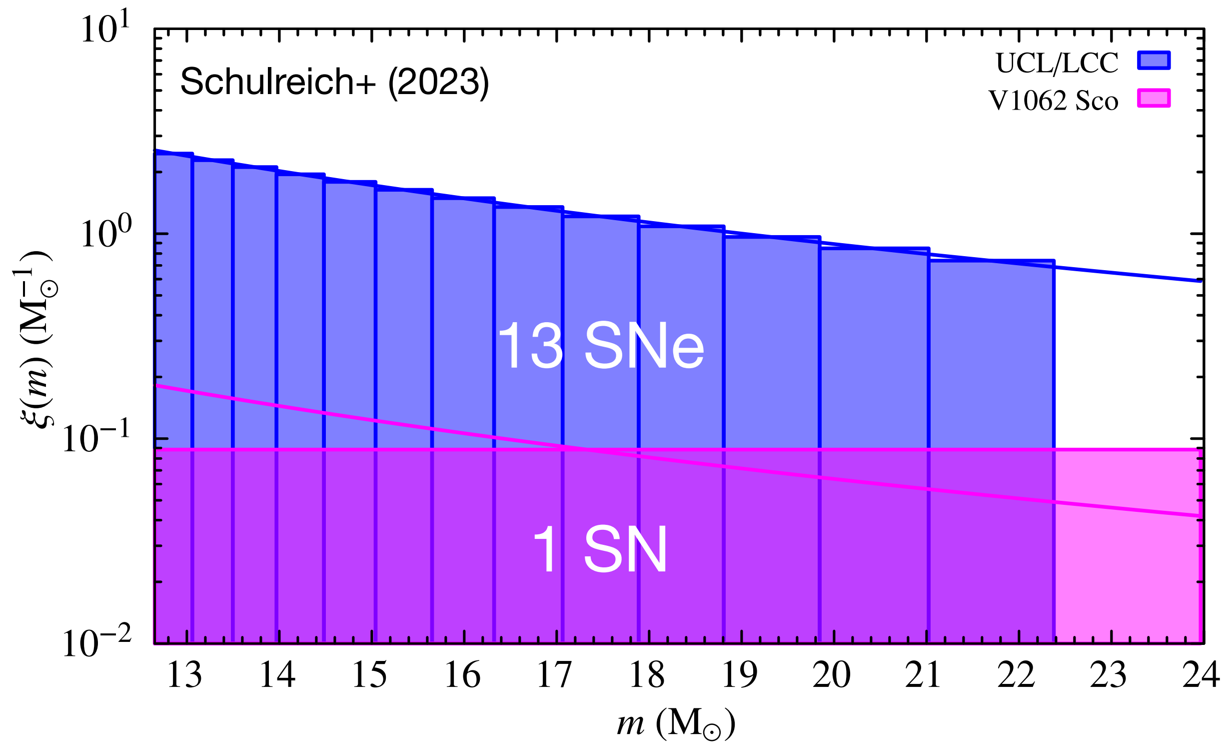
- **Cavity** of **low-density** (n < 0.005 cm^{-3}), **high-temperature** (T ≳10^6 K) **plasma** surrounded by **cold, dusty gas shell**
- Harbors the **solar system**
- Discovered, e.g., via NaI and CaII absorption lines and dust extinction mapping
- **Extension:** ~50–200 pc into Galactic plane; ≫100 pc perpendicular to it
- Hot LB plasma responsible for **majority of diffuse soft X-ray background**, first observed by sounding rockets and later by ROSAT and eROSITA
- Expanding LB shell probably **triggered almost all nearby star formation**
- **Widely accepted origin: stellar winds** and **supernovae** from nearby massive stars
- **But:** no OB association ***inside*** present LB!

➡ Young star cluster must have passed through today's LB region **in the past**, providing enough SNe to inflate LB in the process

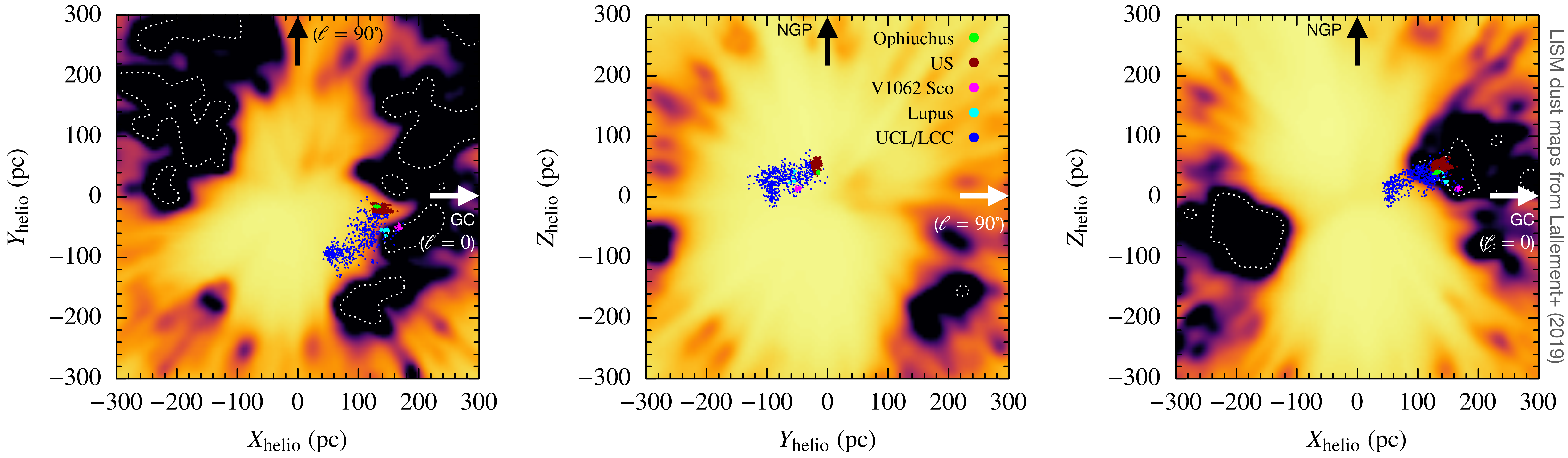
Recent near-Earth SNe:

- How many? ⟵ IMF fitting (Kroupa 2001)
- When? ⟵ rotating stellar evolution models (Ekström+ 2012)
- Where? ⟵ stellar tracebacks in a Monte Carlo fashion

Suitable sample of stars provided

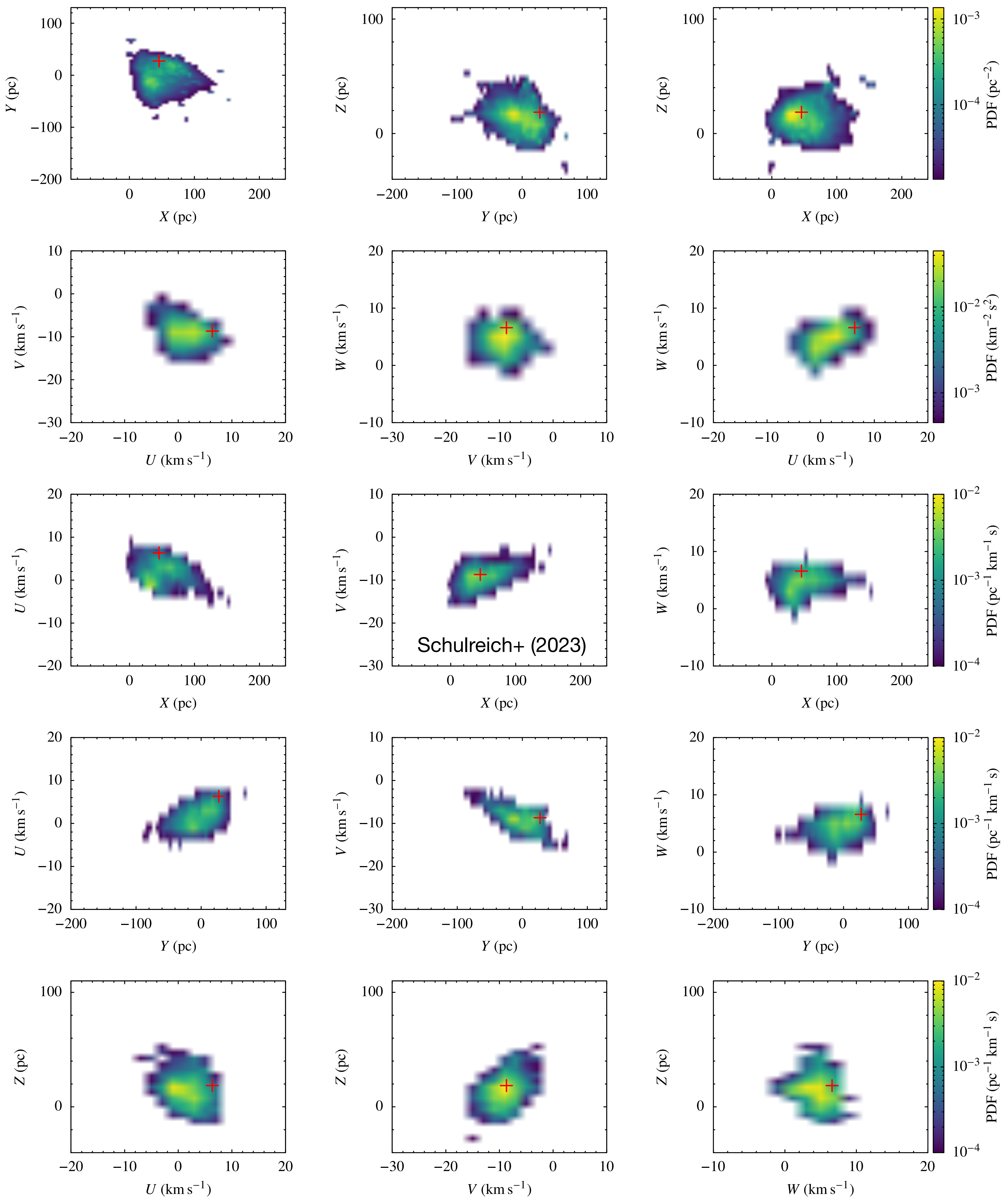


Sco-Cen complex populations extracted from *Gaia* EDR3 (Luhman 2022)

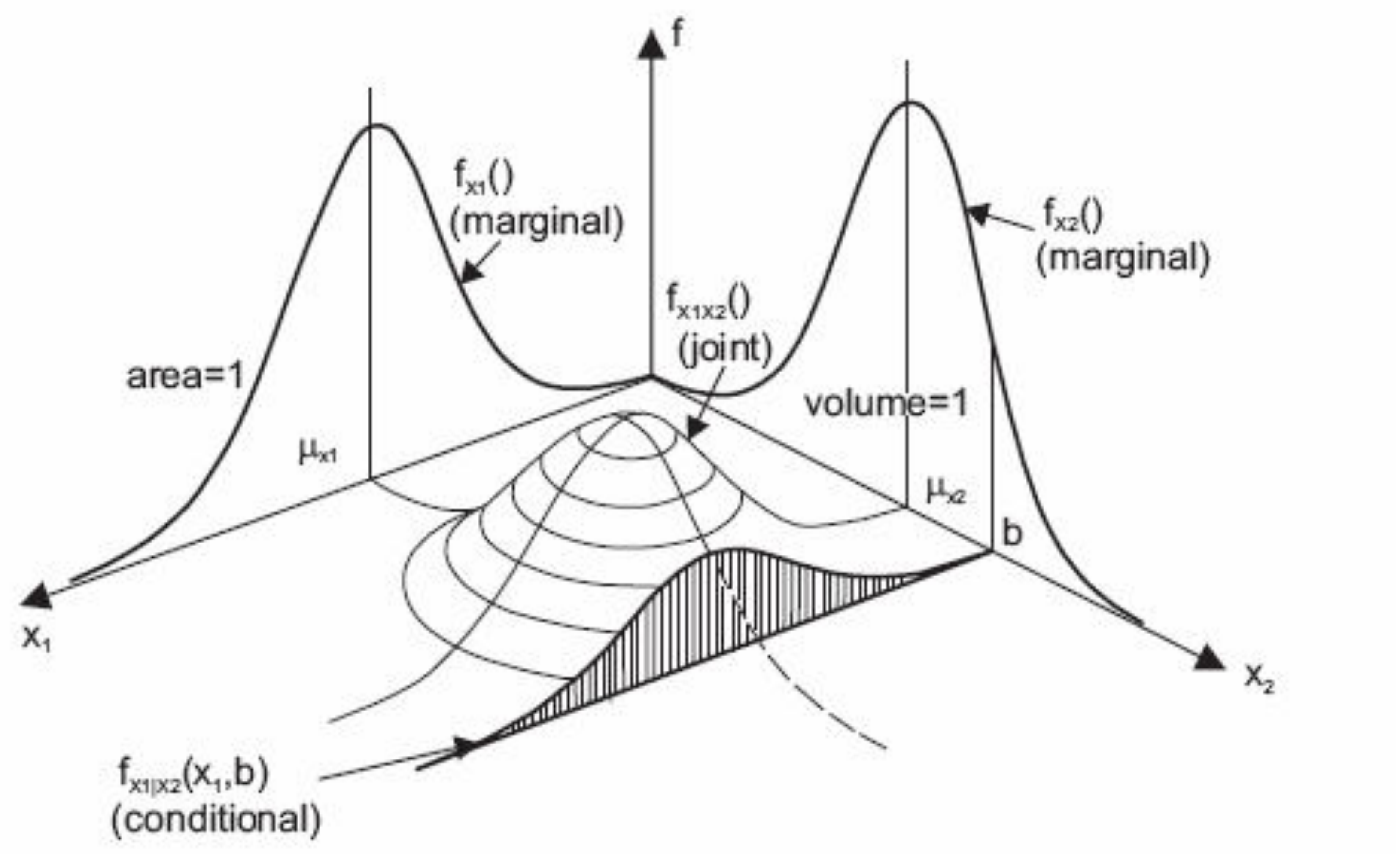


Marginal phase-space PDFs for Sco-Cen populations

UCL/LCC @ *t* = -10.16 Myr | # realizations = 10,000



Joint and marginal probability density functions (PDFs)

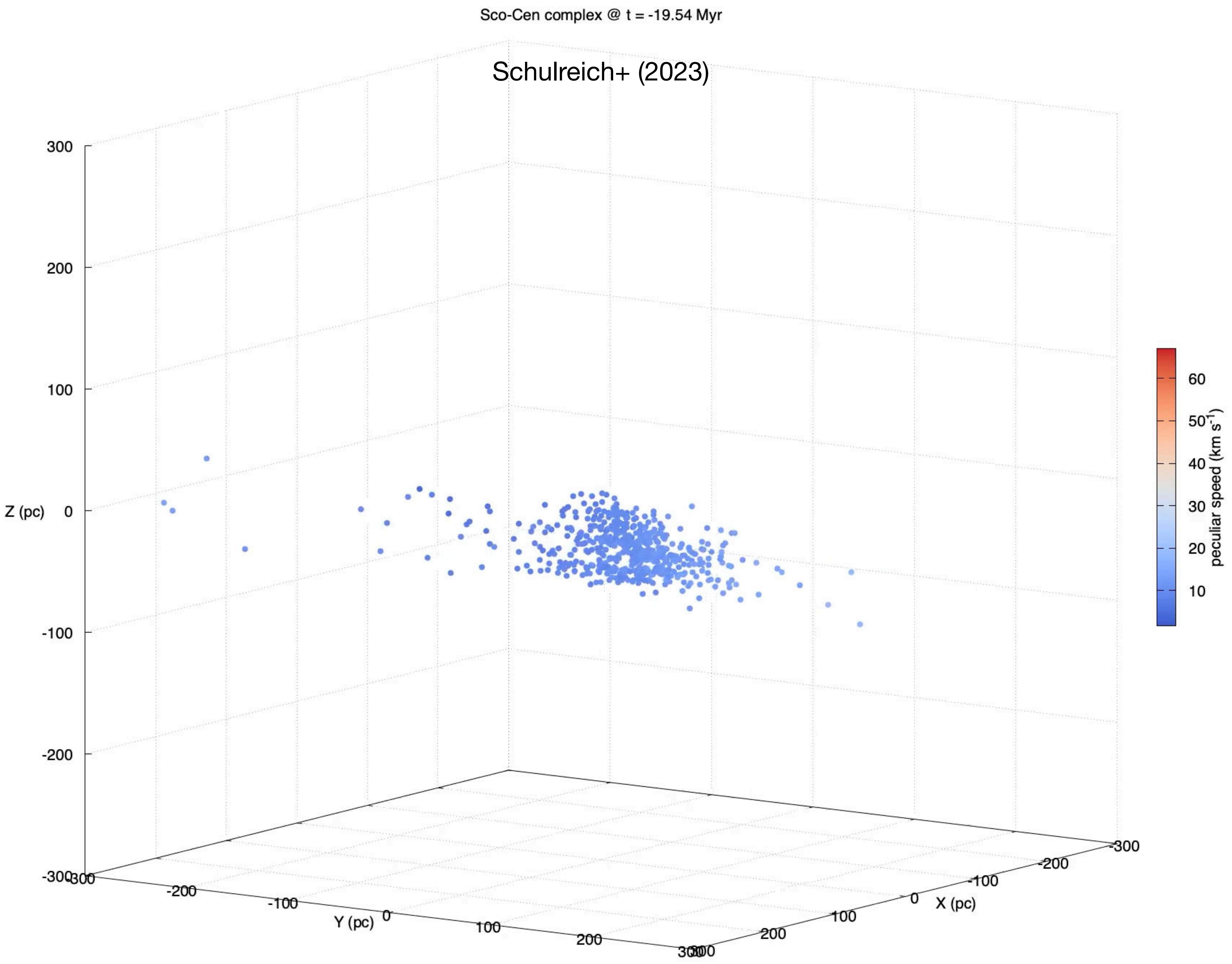


Melchers (1999)

Red crosses = phase-space coordinates of massive star just before its explosion (maximum of 6D PDF)

➡ sets entire trajectory of (wind-blowing) SN progenitor

Test particle simulations



- Gray sphere = LB approximated as a very large Weaver+ (1977) wind-blown bubble, neglecting its wind-driven phase

- Mechanical luminosity of SNe:

$$L_{\mathrm{SN}} = \frac{E_{\mathrm{SN}}}{\Delta t_{\mathrm{exp}}} \approx (4.44 \times 10^{37}\,\mathrm{erg\,s^{-1}}) \left(\frac{E_{\mathrm{SN}}}{10^{51}\,\mathrm{erg}}\right) \times \left(\frac{\Delta t_{\mathrm{exp}}}{0.71\,\mathrm{Myr}}\right)^{-1}$$

- LB radius evolution law:

$$R = \left(\frac{125}{154\,\pi}\right)^{1/5} \left(\frac{L_{\mathrm{SN}}}{\rho_0}\right)^{1/5} t_{\mathrm{SN}}^{3/5} \approx (241\,\mathrm{pc}) \left(\frac{L_{\mathrm{SN}}}{4.44 \times 10^{37}\,\mathrm{erg\,s^{-1}}}\right)^{1/5} \left(\frac{n_{\mathrm{H},0}}{0.7\,\mathrm{cm^{-3}}}\right)^{-1/5} \times \left(\frac{t_{\mathrm{SN}}}{10.16\,\mathrm{Myr}}\right)^{3/5}$$

Radioisotopic tracers

Isotope	Half-life (Myr)	Decay mode	Nucleosynthesis process	Background	Measurement efforts
^{60}Fe	2.61 ± 0.04[1,2]	β^-	s- and r-process	✘	Detection in FeMn crusts[3,4,5,6,7] and nodules[6], deep-ocean sediments[8,9], Antarctic snow[10], lunar regolith[11], diffuse Galactic γ-ray emission[12], and Galactic cosmic rays[13]

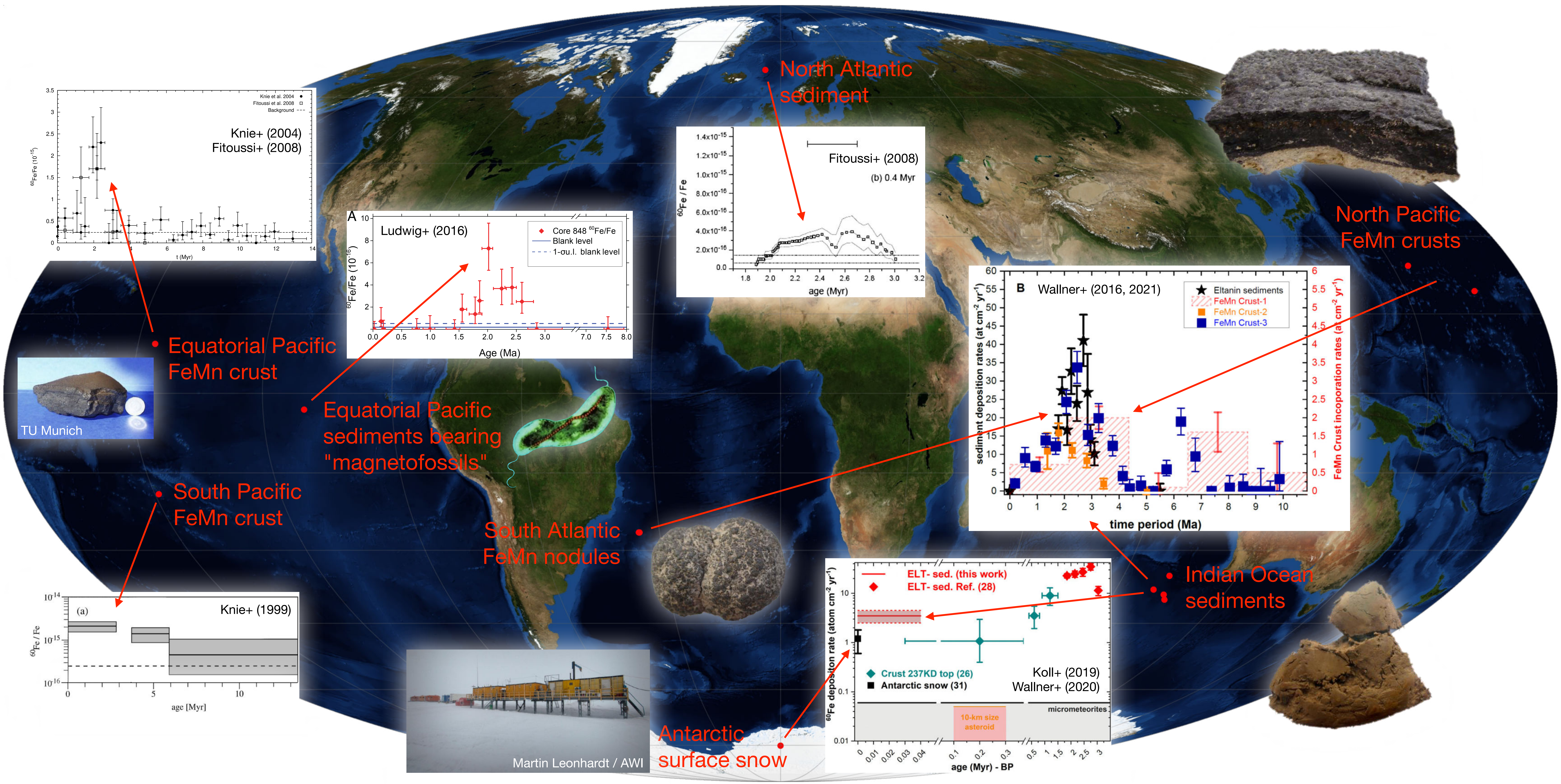
(S)AGB stars, EC & CC SNe

Negligible influx from sources other than SNe

Courtesy of kurzgesagt.org

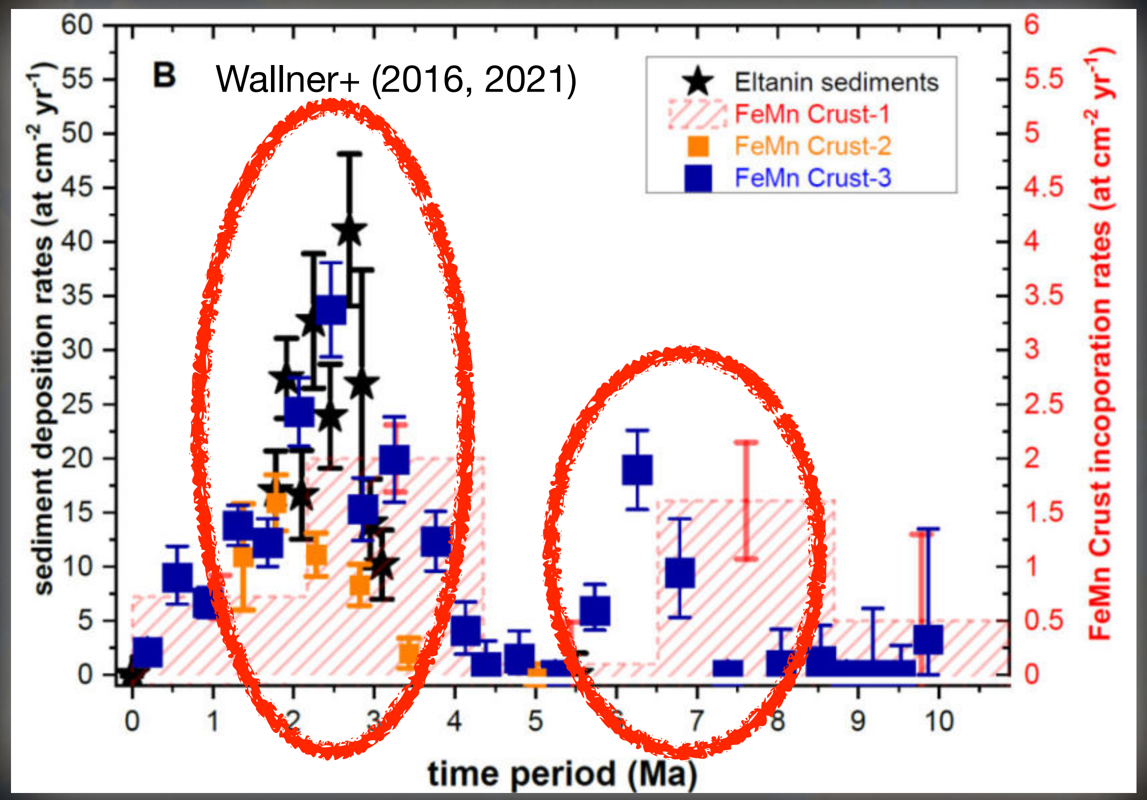
[1] Rugel+ (2009); [2] Wallner+ (2015); [3] Knie+ (1999); [4] Knie+ (2004); [5] Fitoussi+ (2008); [6] Wallner+ (2016); [7] Wallner+ (2021); [8] Ludwig+ (2016); [9] Wallner+ (2020); [10] Koll+ (2019); [11] Fimiani+ (2016); [12] Wang+ (2007); [13] Binns+ (2016); [14] Basunia & Hurst (2016); [15] Feige+ (2018); [16] Plüschke+ (2001); [17] Honda & Imamura (1971); [18] Korschinek+ (2020); [19] Nesaraja (2017)

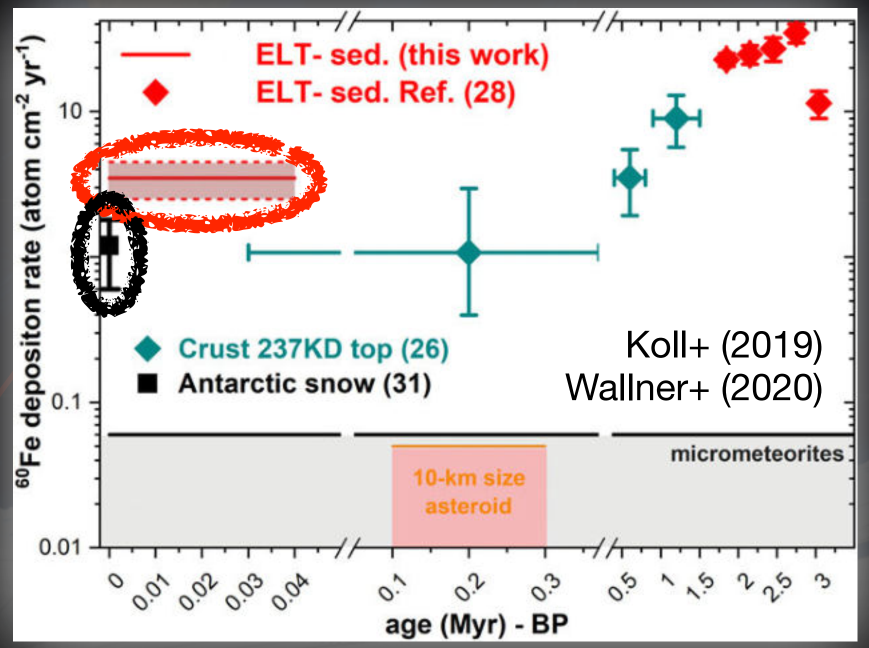
^{60}Fe signatures on Earth ...



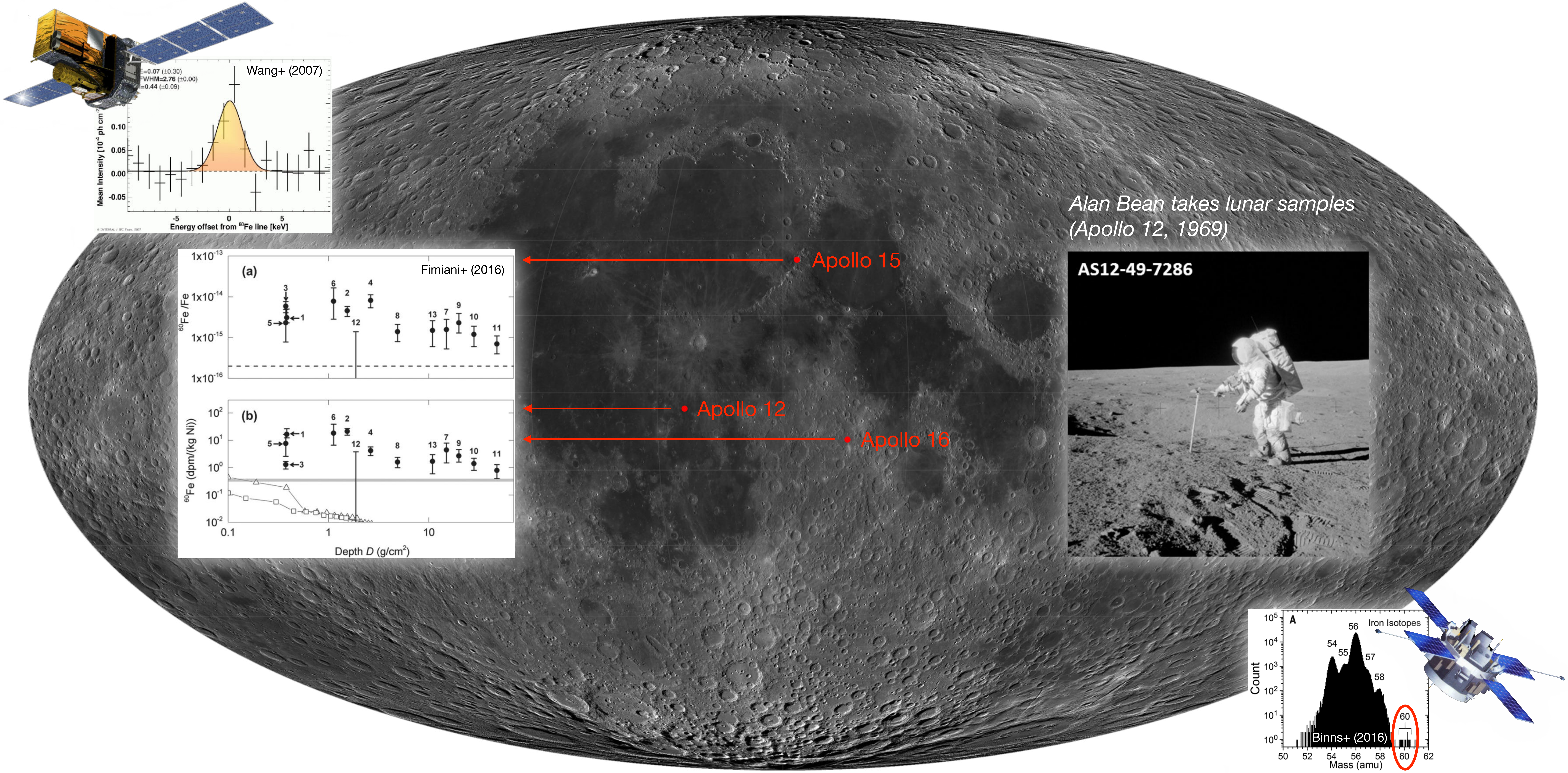
^{60}Fe signatures on Earth ...

- **Two temporally separated signals** around 2–3 and 6–7 Myr ago that are **wider** than could be explained by a **single SN blast each**
- **Low recent influx** over last 33 kyr





... and beyond



Wang+ (2007)
Mean Intensity [10^-4 ph cm^-2 ...]
Energy offset from 60Fe line [keV]
Fimiani+ (2016)
(a)
(b)
60Fe /Fe
60Fe (dpm/(kg Ni))
Depth D (g/cm²)
Apollo 15
Apollo 12
Apollo 16
Alan Bean takes lunar samples (Apollo 12, 1969)
AS12-49-7286
A
Iron Isotopes
Count
Binns+ (2016)
Mass (amu)

Radioisotopic tracers

Isotope	Half-life (Myr)	Decay mode	Nucleosynthesis process	Background	Measurement efforts
^{60}Fe	2.61 ± 0.04[1,2]	β^-	s- and r-process	✘	Detection in FeMn crusts[3,4,5,6,7] and nodules[6], deep-ocean sediments[8,9], Antarctic snow[10], lunar regolith[11], diffuse Galactic γ-ray emission[12], and Galactic cosmic rays[13]
^{26}Al	0.717 ± 0.024[14]	β^+, electron capture	^{25}Mg(p,γ) reaction	✔	Searches in FeMn crusts[15] Detection in diffuse Galactic γ-ray emission[16]
^{53}Mn	3.7 ± 0.4[17]	Electron capture	Explosive Si & O burning	✔	Evidence in FeMn crusts[18]

(S)AGB stars, EC & CC SNe

Negligible influx from sources other than SNe

(S)AGB & WR stars, CC SNe

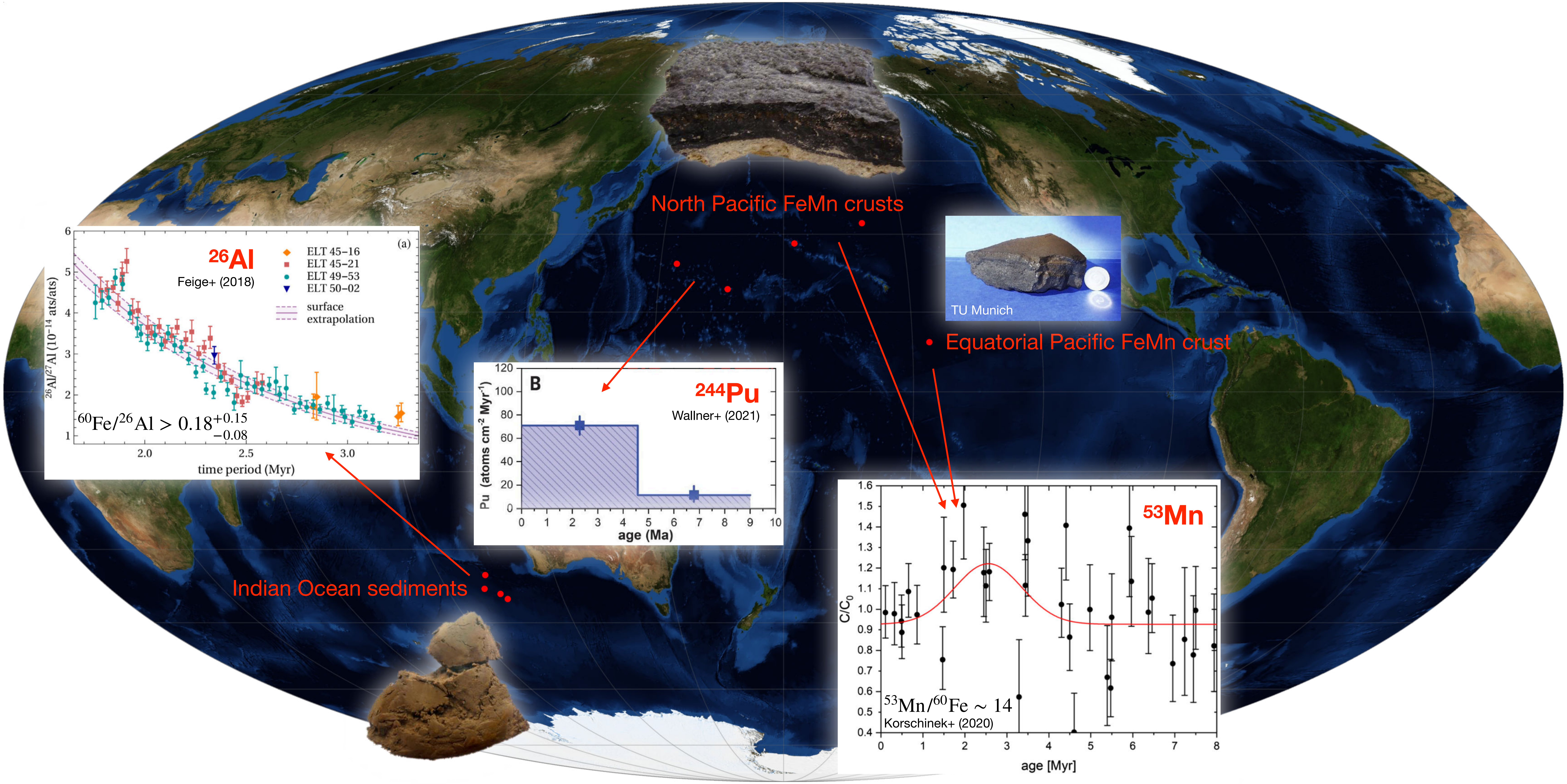
Continuous influx from production in the Earth's atmosphere

CC SNe

Continuous influx from production in IDPs

[1] Rugel+ (2009); [2] Wallner+ (2015); [3] Knie+ (1999); [4] Knie+ (2004); [5] Fitoussi+ (2008); [6] Wallner+ (2016); [7] Wallner+ (2021); [8] Ludwig+ (2016); [9] Wallner+ (2020); [10] Koll+ (2019); [11] Fimiani+ (2016); [12] Wang+ (2007); [13] Binns+ (2016); [14] Basunia & Hurst (2016); [15] Feige+ (2018); [16] Plüschke+ (2001); [17] Honda & Imamura (1971); [18] Korschinek+ (2020); [19] Nesaraja (2017)

Signatures of other radioisotopes on Earth



Radioisotopic tracers

Isotope	Half-life (Myr)	Decay mode	Nucleosynthesis process	Background	Measurement efforts
^{60}Fe	2.61 ± 0.04[1,2]	β^-	s- and r-process (S)AGB stars, EC & CC SNe	✘ Negligible influx from sources other than SNe	Detection in FeMn crusts[3,4,5,6,7] and nodules[6], deep-ocean sediments[8,9], Antarctic snow[10], lunar regolith[11], diffuse Galactic γ-ray emission[12], and Galactic cosmic rays[13]
^{26}Al	0.717 ± 0.024[14]	β^+, electron capture	$^{25}Mg(p,\gamma)$ reaction (S)AGB & WR stars, CC SNe	✔ Continuous influx from production in the Earth's atmosphere	Searches in FeMn crusts[15] Detection in diffuse Galactic γ-ray emission[16]
^{53}Mn	3.7 ± 0.4[17]	Electron capture	Explosive Si & O burning CC SNe	✔ Continuous influx from production in IDPs	Evidence in FeMn crusts[18]
^{244}Pu	81.3 ± 0.3[19]	α-decay: 99.88% Spontaneous fission: 0.12%	r-process CC SNe? KNe? MR SNe?	✔ Recent influx from anthropogenic production	Detection in FeMn crusts[7]

Measurements of these radioisotopes pose **additional constraints on the LB formation scenario**, which we further investigated by means of **3D hydrodynamic simulations**

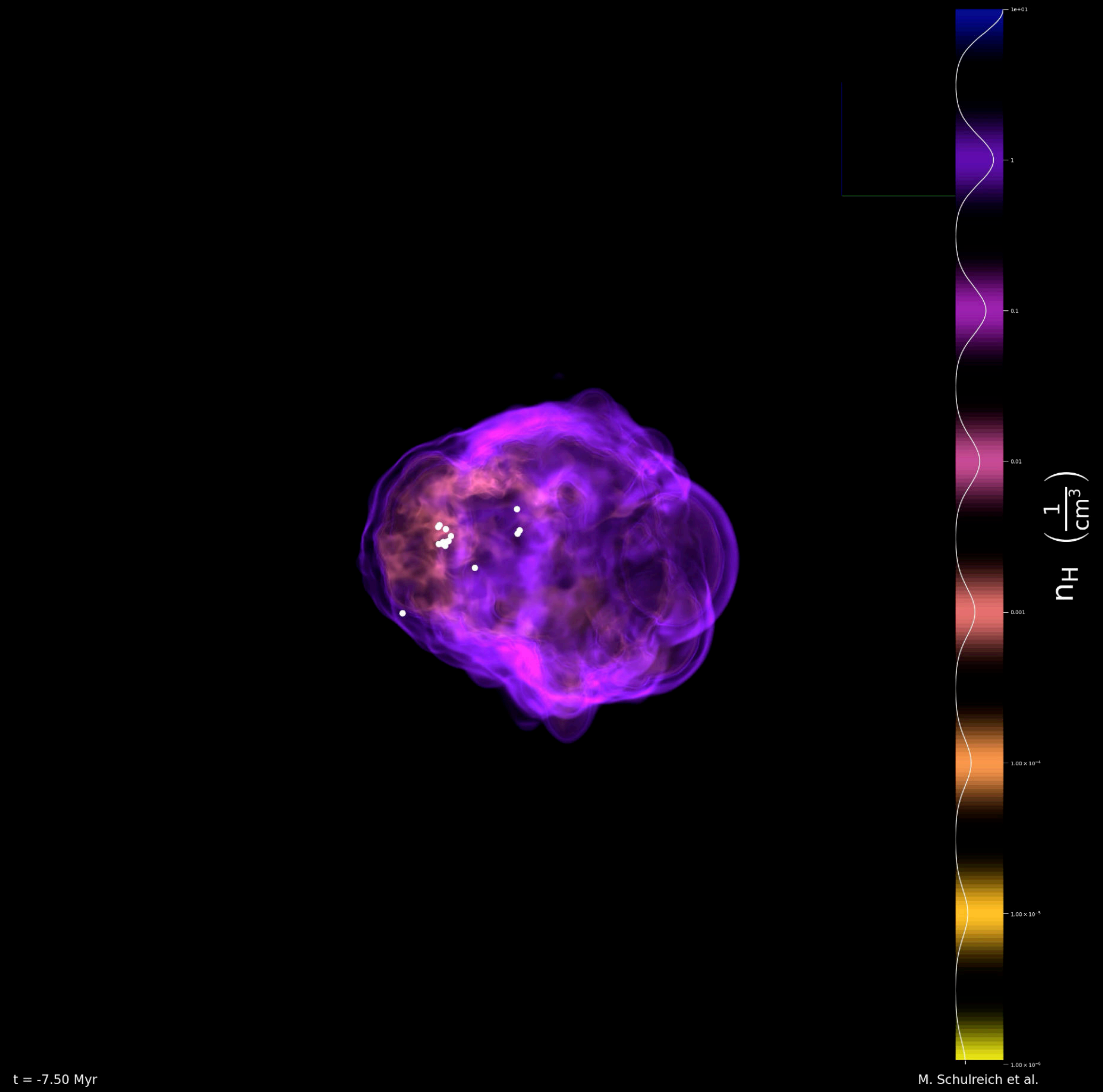
[1] Rugel+ (2009); [2] Wallner+ (2015); [3] Knie+ (1999); [4] Knie+ (2004); [5] Fitoussi+ (2008); [6] Wallner+ (2016); [7] Wallner+ (2021); [8] Ludwig+ (2016); [9] Wallner+ (2020); [10] Koll+ (2019); [11] Fimiani+ (2016); [12] Wang+ (2007); [13] Binns+ (2016); [14] Basunia & Hurst (2016); [15] Feige+ (2018); [16] Plüschke+ (2001); [17] Honda & Imamura (1971); [18] Korschinek+ (2020); [19] Nesaraja (2017)

Hydrodynamic simulations

- performed with second-order Godunov-type tree-based AMR code RAMSES (Teyssier 2002)
- solve full 3D HD equations on cubic cutout of Galactic disk (800^3 pc^3) that co-rotates with LSR
- sub-parsec theoretical resolutions: ≤0.78 pc
- stratified background medium in hydrostatic and thermal equilibrium
- external gravitational field from Barros+ (2016)
- CIE cooling for gas with solar metallicity using GRACKLE cooling library (Smith+ 2017)

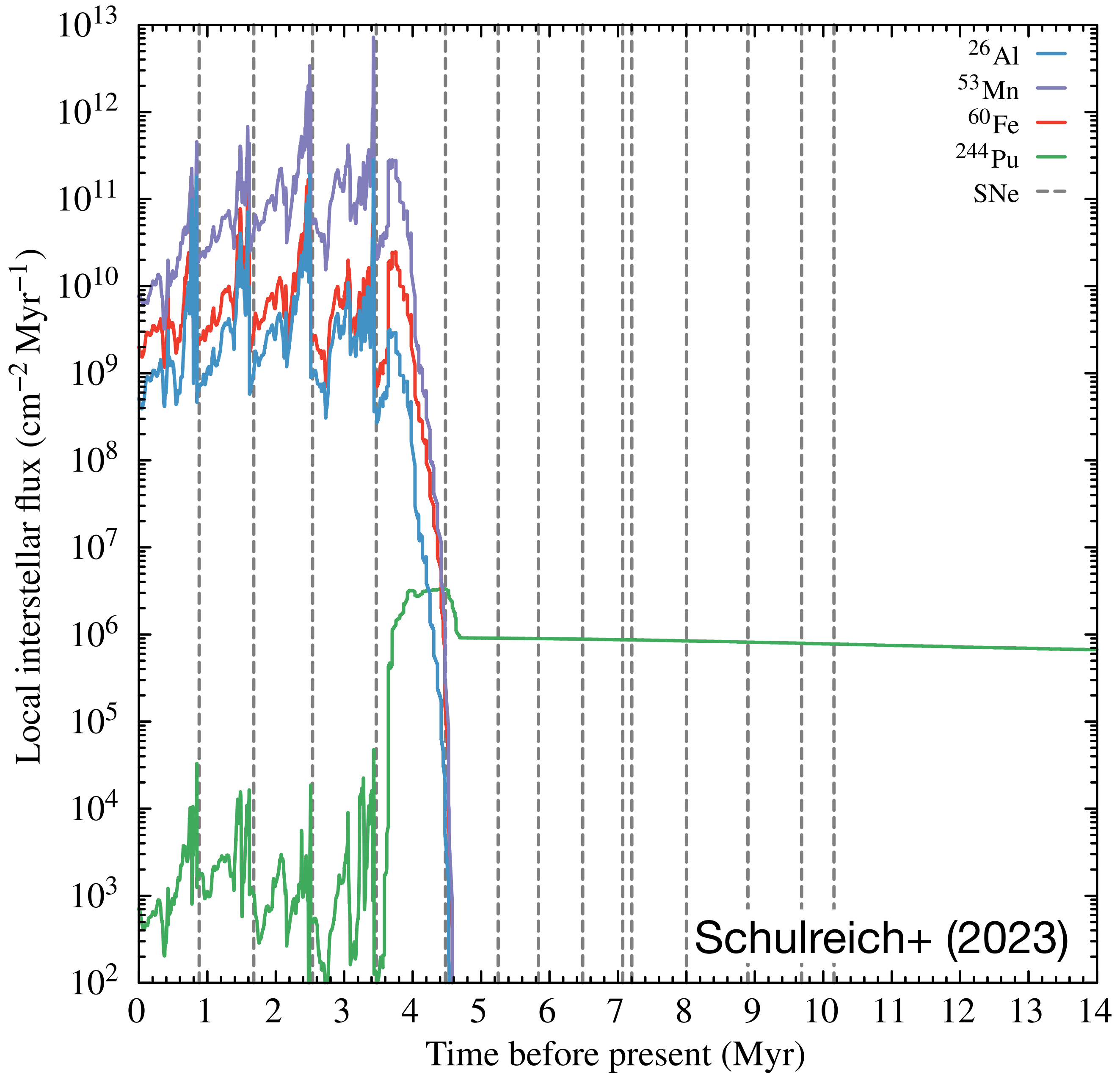
- collisionless particles:
  - massive stars: move along pre-calculated trajectories, blow (MS-/RSG-[/WR-]) winds, and explode as SNe when their lifetime has run out
  - Sun/Earth: represents "moving detector" for radioisotopic fluxes
- radioisotopes (^{26}Al, ^{53}Mn, ^{60}Fe, ^{244}Pu) treated as decaying passive scalars:
  - stellar-wind yields from Ekström+ (2012)
  - SN yields from Limongi & Chieffi (2018)

Hydrodynamic simulations

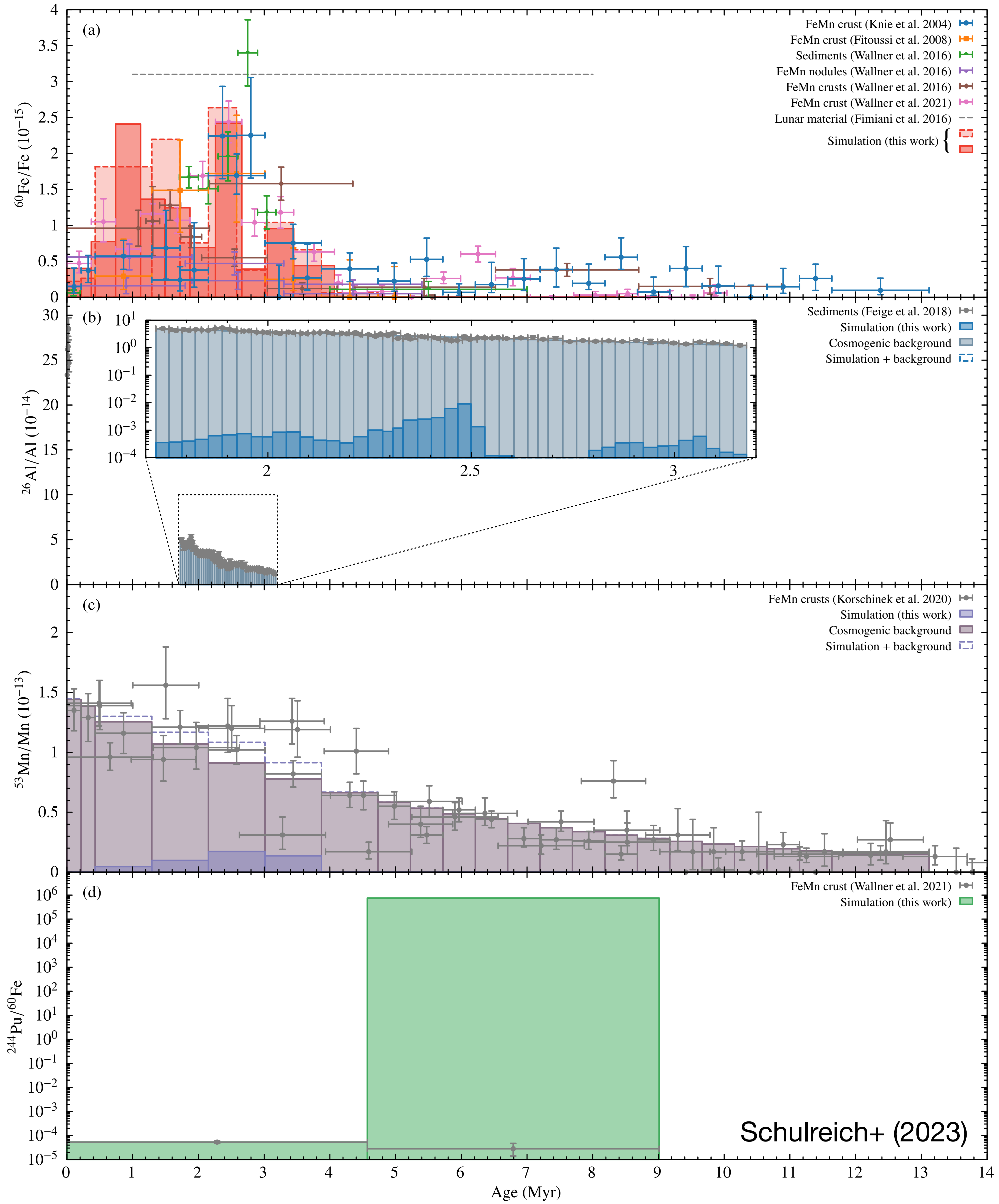


Comparison with radioisotopic measurements

$$F_i = \frac{\rho\, \tilde{u}\, C_i}{A_i\, m_\mathrm{u}}$$



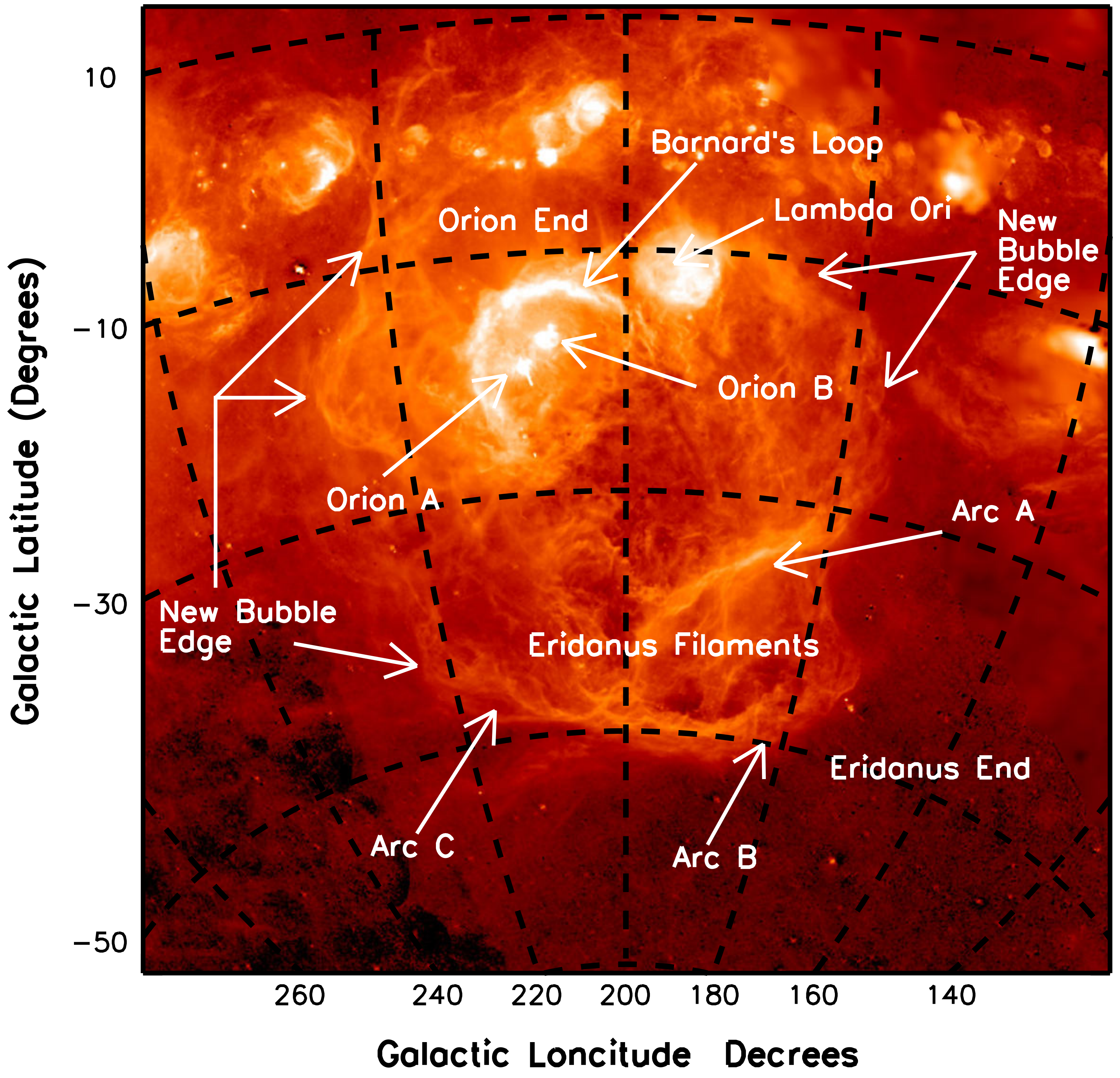
$$\frac{n_i(\Delta a_\ell)}{n_j} = \frac{1}{n_j}\, \frac{\frac{f_i}{4} \int_{a_{\ell,1}}^{a_{\ell,\mathrm{u}}} F_i(a)\, \exp(-\lambda_i\, a)\, \mathrm{d}a}{\Delta d_\ell}$$



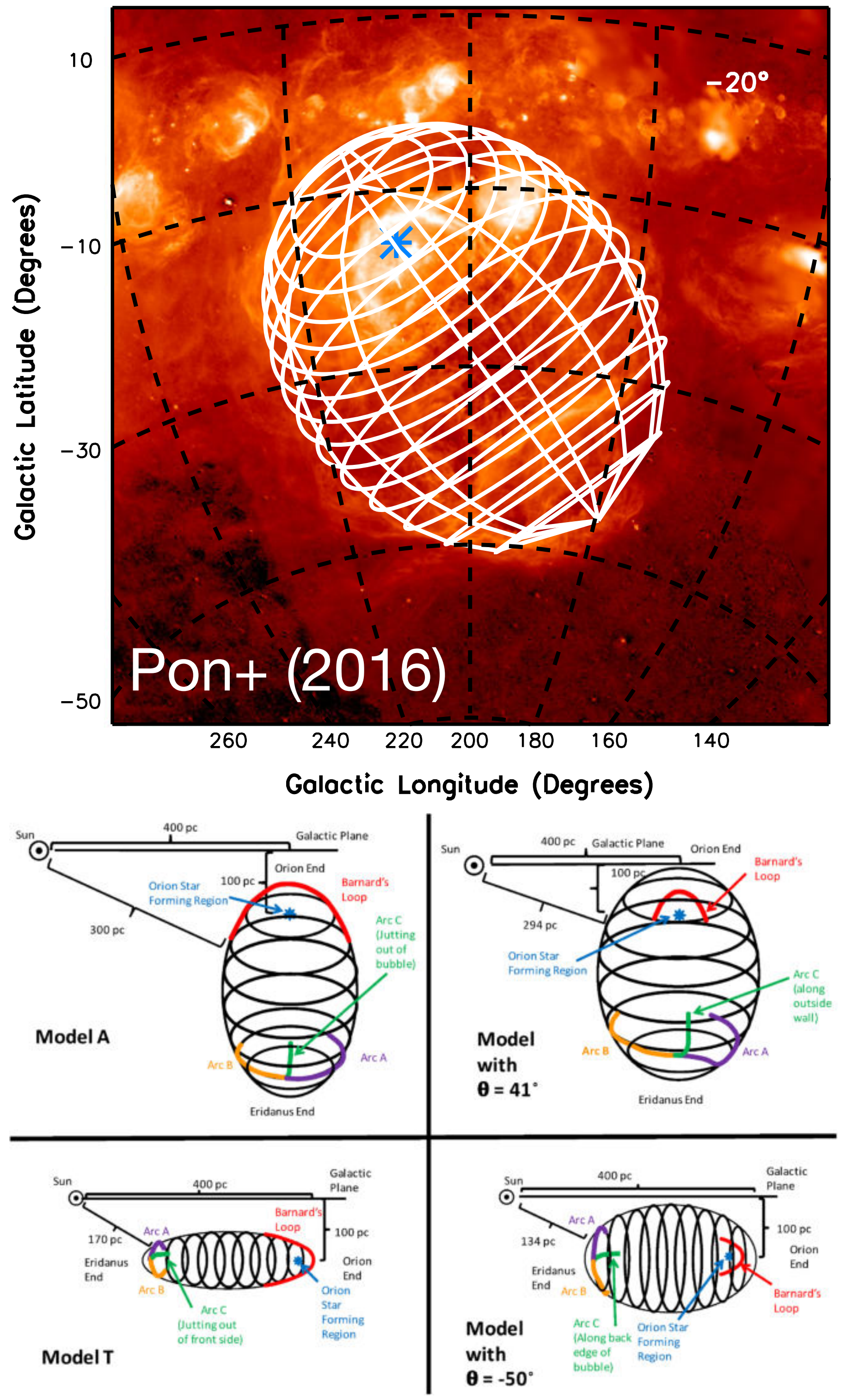
- **Current model nicely fits measurements before older peak** (younger peak generated by **SN blast waves & reflected shocks**), incl. **recent influxes** (generated by yet undecayed **turbulence in LB cavity**)
- **Older peak** requires inclusion of **neighboring superbubble** to be crossed by the solar system before entering the LB about 4.6 Myr ago

The Orion-Eridanus superbubble

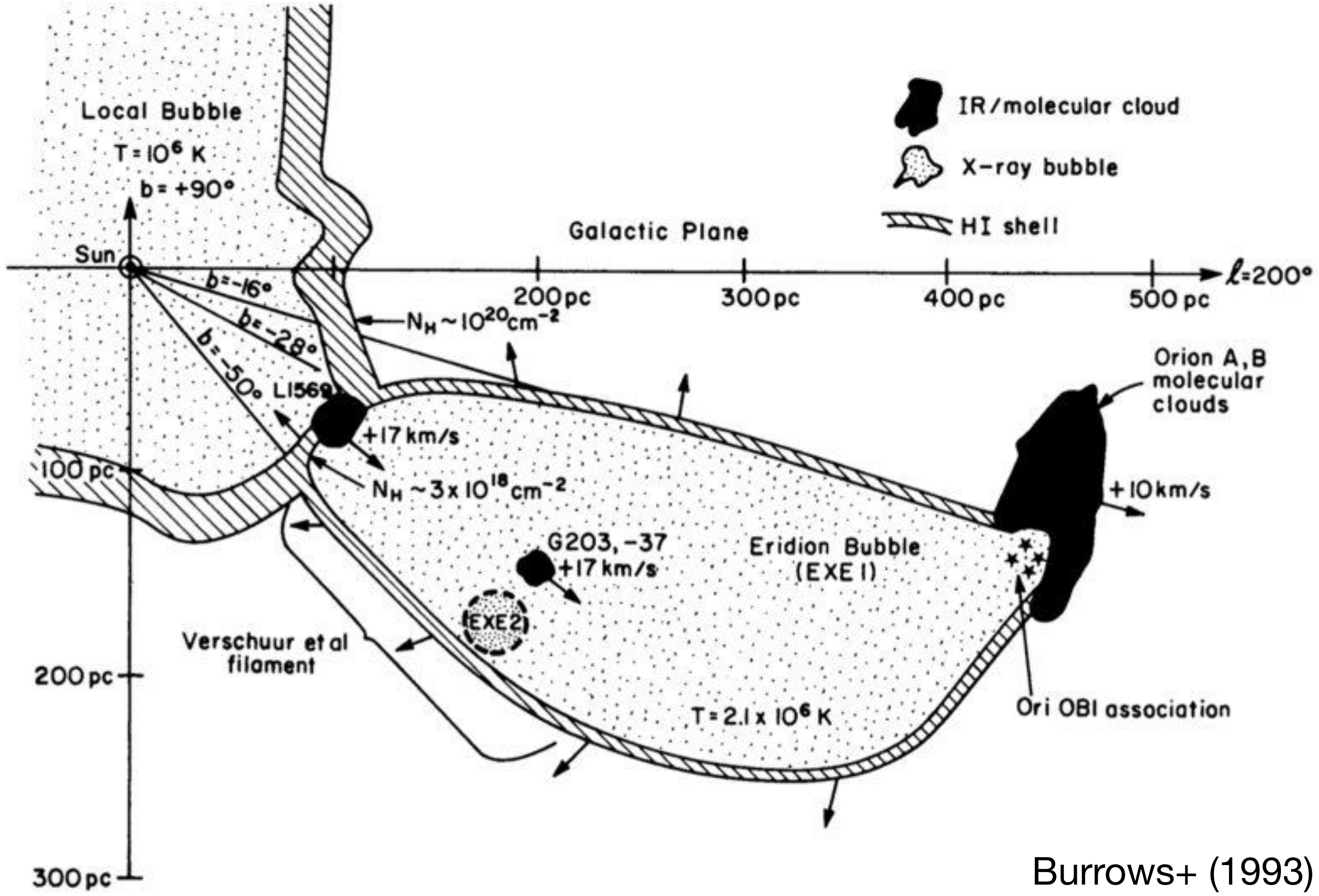
Ha emission map



Kompaneets fitting



Possible geometry of the superbubble



Burrows+ (1993)

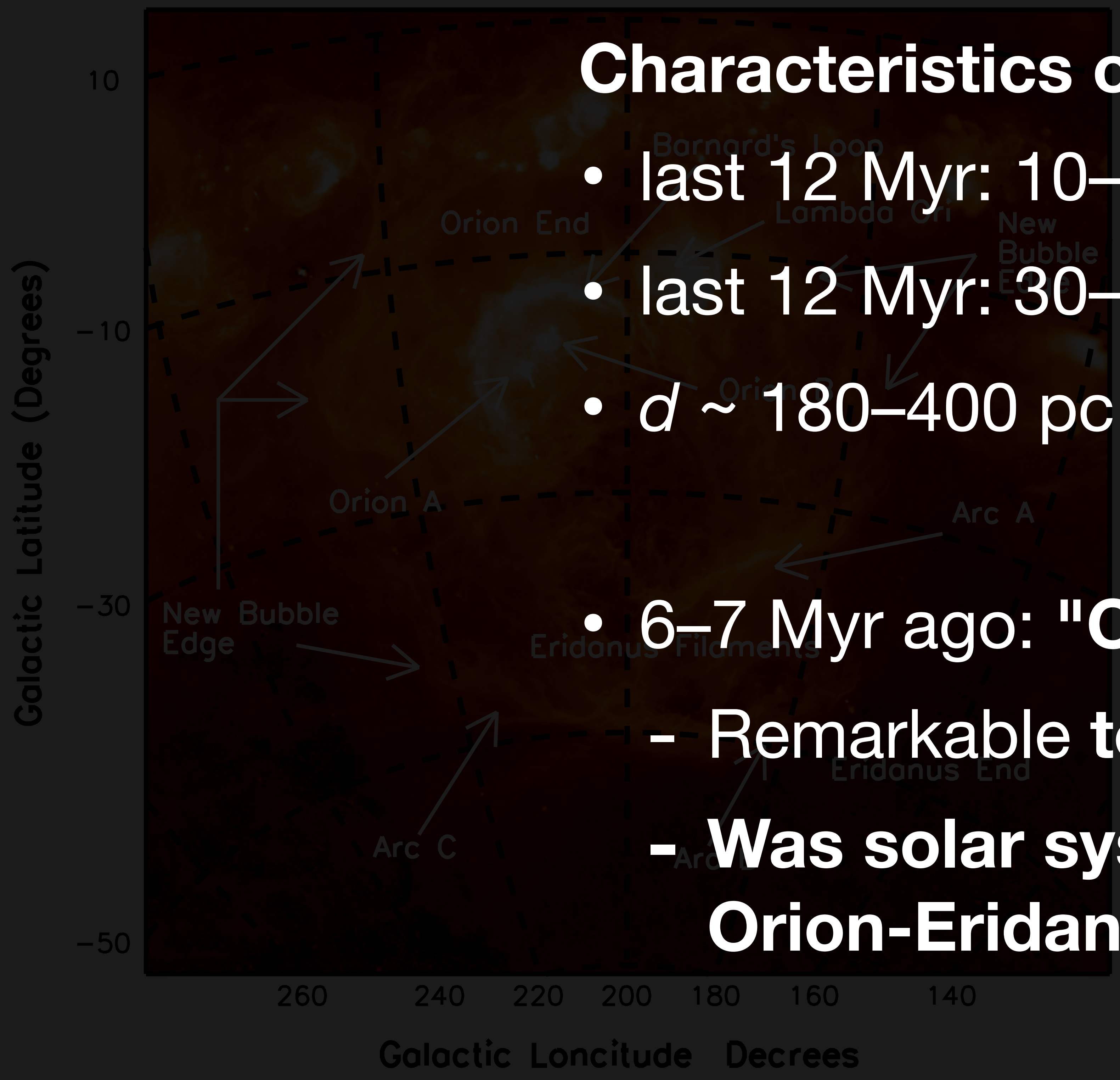
The Orion-Eridanus superbubble

Characteristics of the superbubble (Bally 2008)**:**

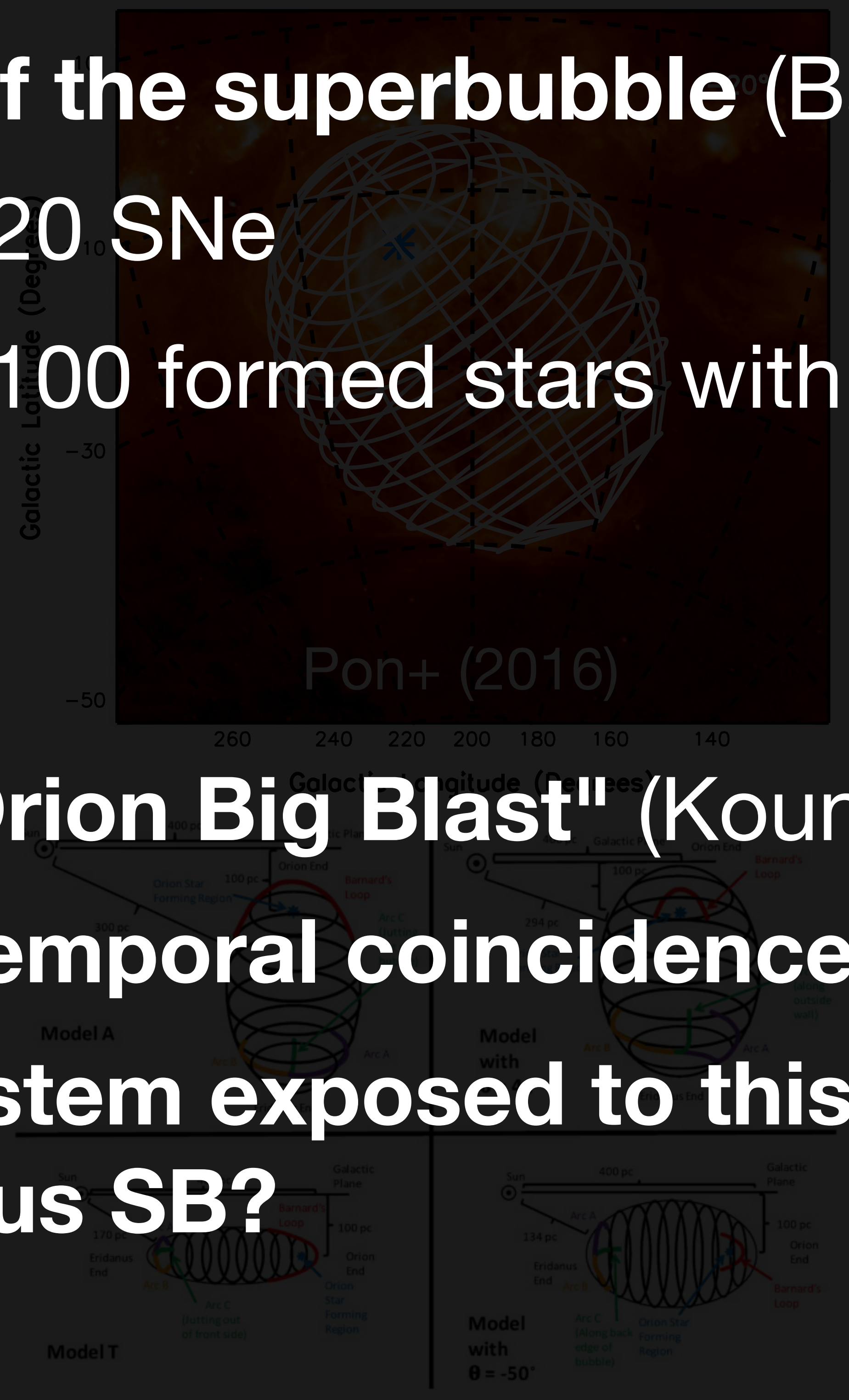
- last 12 Myr: 10–20 SNe
- last 12 Myr: 30–100 formed stars with $M \geq 8\ M_\odot$
- d ~ 180–400 pc

- 6–7 Myr ago: **"Orion Big Blast"** (Kounkel 2020; Großschedl+ 2021)
  - Remarkable **temporal coincidence with older ^{60}Fe peak**
  - **Was solar system exposed to this and/or other SN events in the Orion-Eridanus SB?**

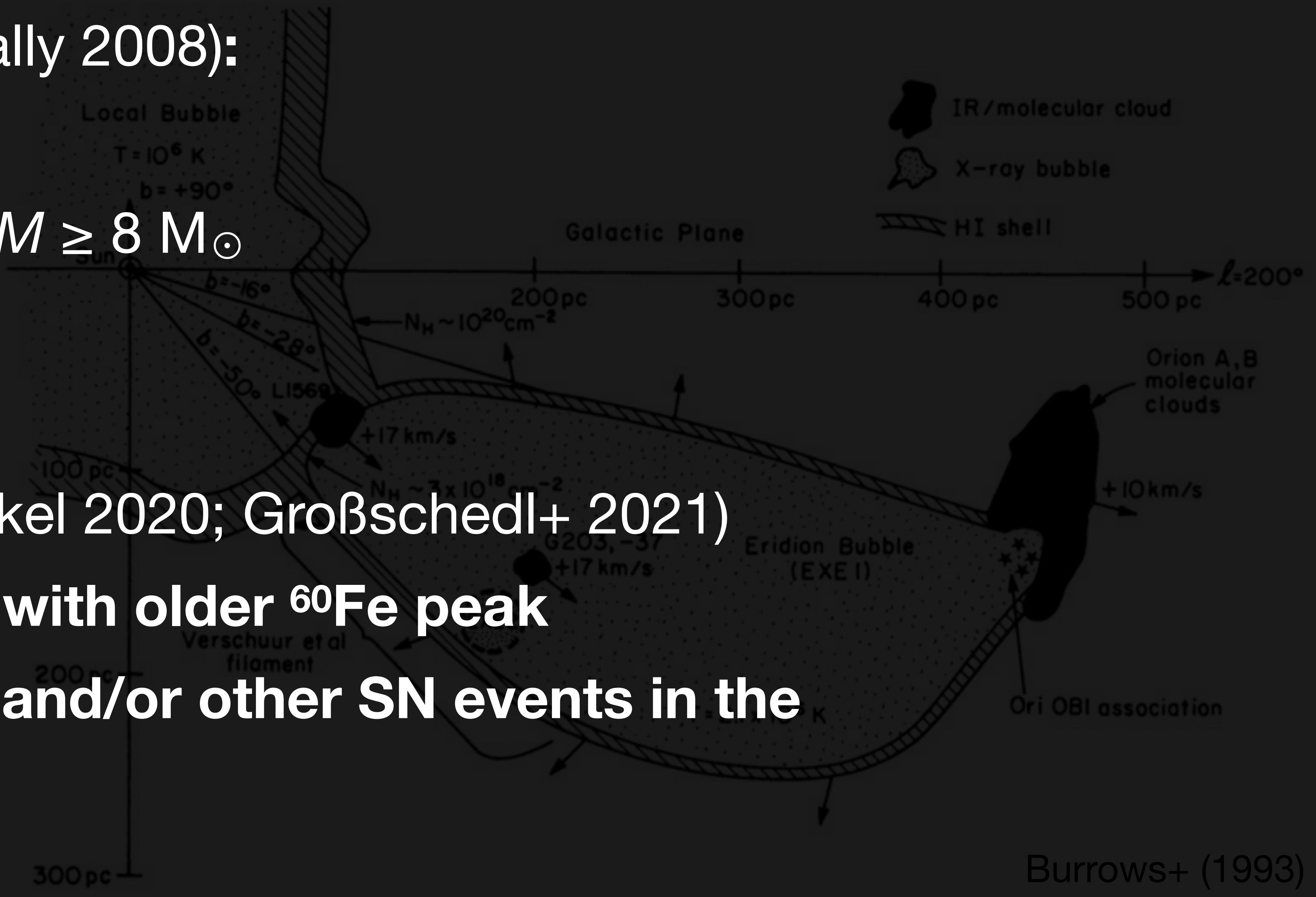
Hα emission map

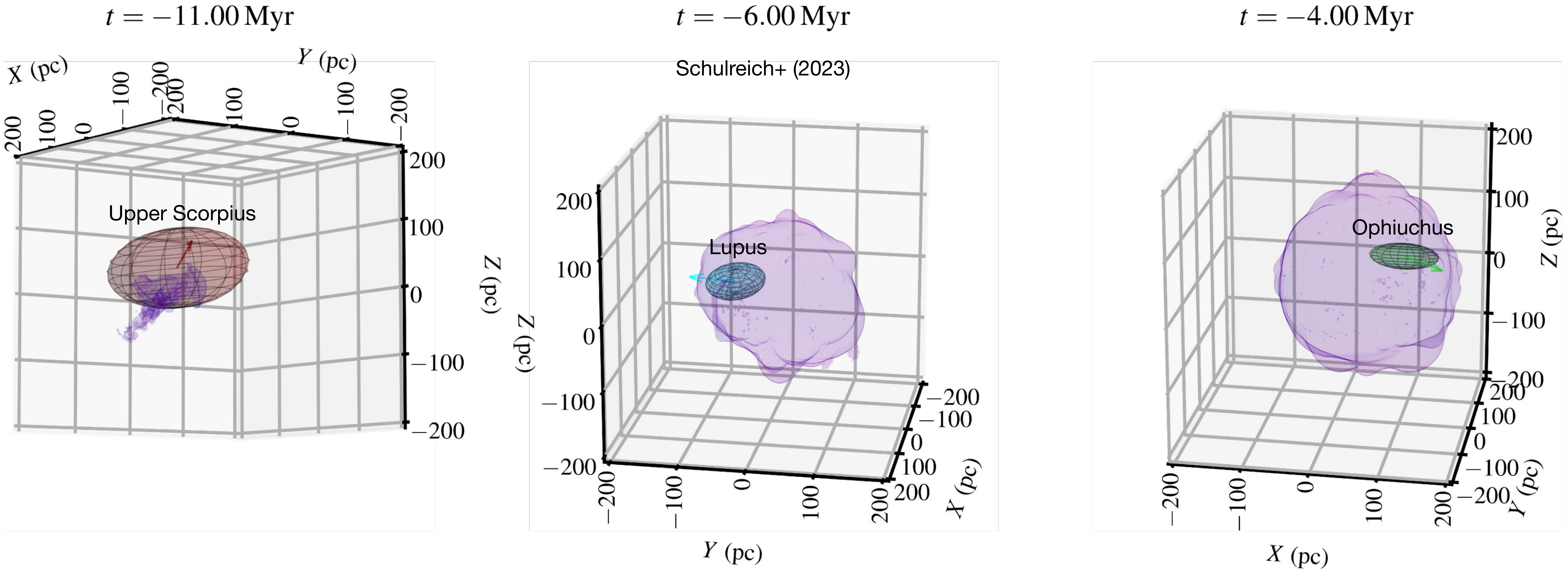


Kompaneets fitting



Possible geometry of the superbubble





LB could indeed have **triggered star formation near the Sun** through its expansion!

Takeaways

- **Measurements of ^{26}Al, ^{53}Mn, ^{60}Fe, and ^{244}Pu in terrestrial archives** – particularly a 2–4 Myr old ^{60}Fe peak – are **consistent with the formation of the LB through a series of near-Earth SNe over the last ~10 Myr**
- Stellar winds impact radioisotope distribution and LB dynamics
- The **solar system entered the LB about 4.6 Myr ago**
- **Recent influx of ^{60}Fe in Antarctic snow and deep-sea sediments explained by turbulent radioisotopic transport**, primarily from SN explosions and LB shell reflections
- Support for the hypothesis that the **LB triggered star formation in the solar vicinity** through its expansion
- **Second, separate ^{60}Fe peak** measured at 6–9 Myr ago presumably resulted from the **solar system passing through a neighboring cavity (the Orion-Eridanus superbubble?)**, before settling in the LB

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https://doi.org/10.1051/0004-6361/202347532

Astronomy & Astrophysics

Numerical studies on the link between radioisotopic signatures on Earth and the formation of the Local Bubble

II. Advanced modelling of interstellar ^{26}Al, ^{53}Mn, ^{60}Fe, and ^{244}Pu influxes as traces of past supernova activity in the solar neighbourhood

M. M. Schulreich[1], J. Feige[1,2], and D. Breitschwerdt[1]