

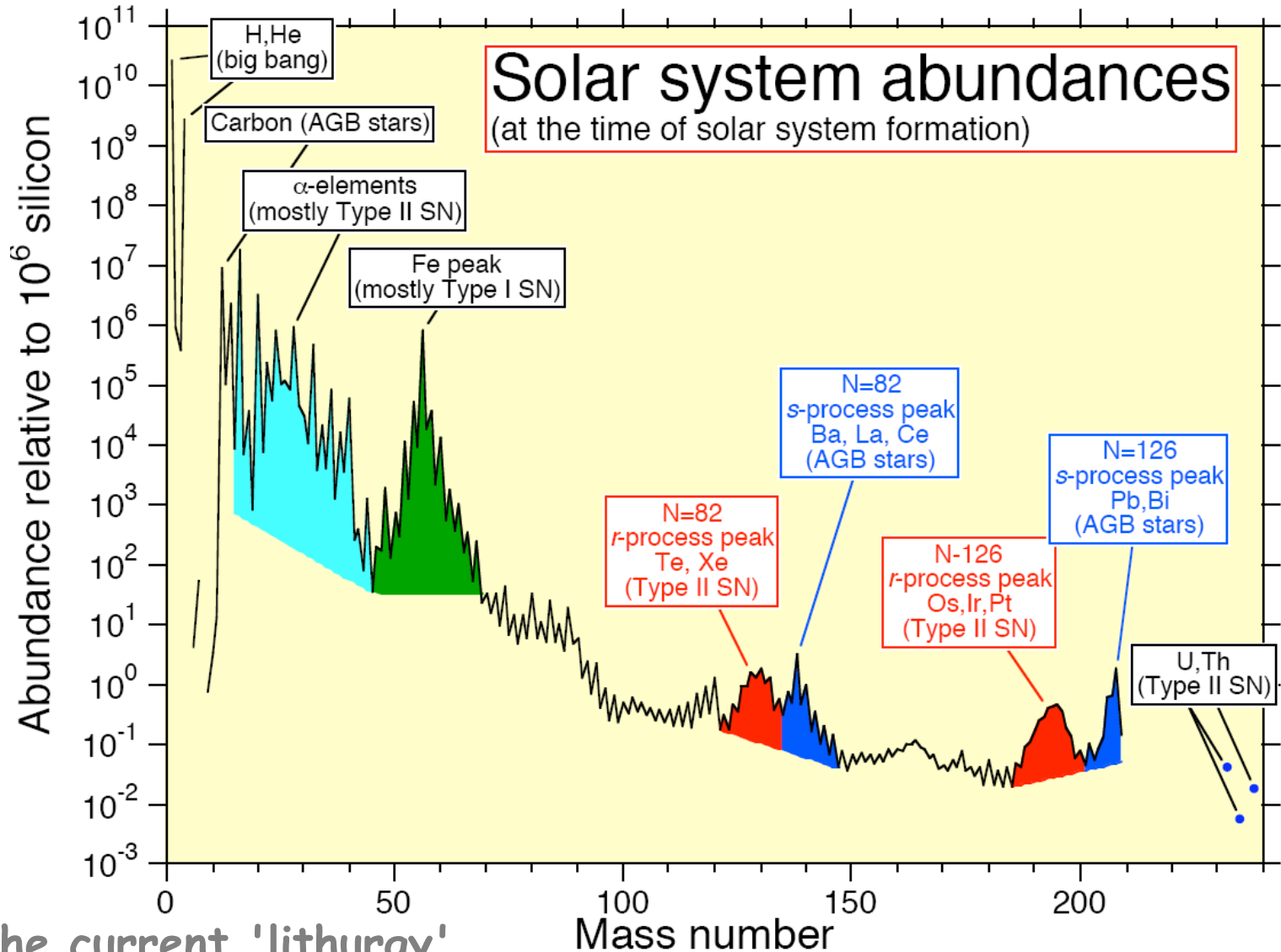
Why ^{60}Fe Is Interesting for Nuclear-Astrophysics Studies

*by Roland Diehl
MPE Garching*

Outline:

- ★ The ^{60}Fe Radio-Isotope
- ★ ^{60}Fe on Earth
- ★ ^{60}Fe in the Solar System
- ★ ^{60}Fe in the Interstellar Medium
- ★ ^{60}Fe Science Applications and Issues

Where do we come from?



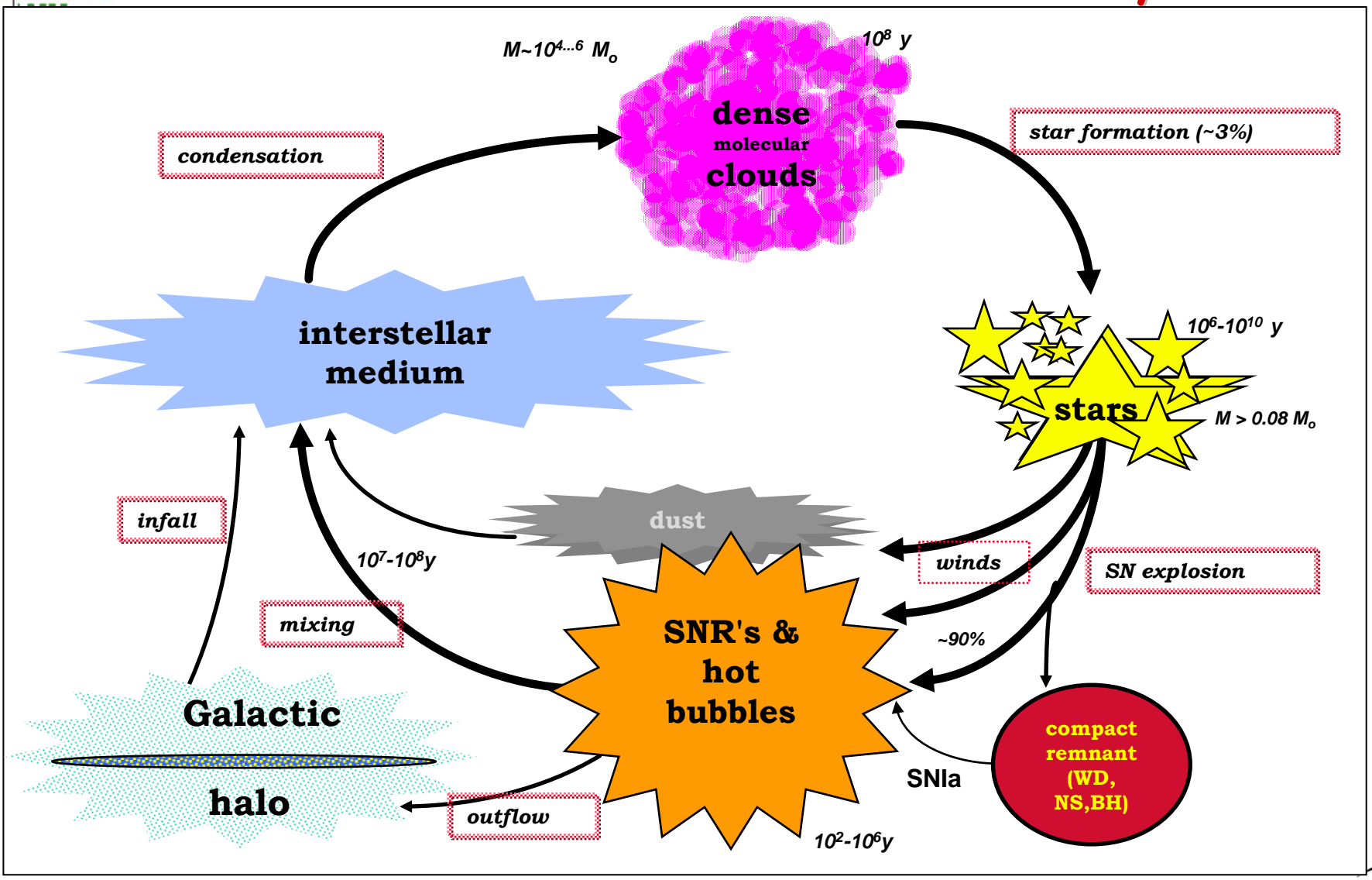
☆ ... the current 'lithurgy'
-> how much do we understand?

Courtesy: Andy Davis





How was the Universe Enriched with Heavy Elements?



- ☆ Nuclear Reactions in Stars and Supernovae Rearrange Baryons -> New Atoms
- ☆ New Atoms are Mixed into ISM which Forms New Stars & Planets



^{60}Fe : Why is it Interesting?

$2.0 \cdot 10^6 \text{y}$ $^{60}\text{Fe} \rightarrow ^{60}\text{Co}^* \rightarrow ^{60}\text{Ni}^+$ 59, 1173, 1332

Co55 17.53 h 7/2- EC	Co56 77.27 d 4+ EC	Co57 271.79 d 7/2- EC	Co58 70.82 d 2+ EC *	Co59 7/2- 100	Co60 5.2714 y 5+ *	Co61 1.650 h 7/2- *	Co62 1.50 m 2+ *	Co63 27.4 s (7/2)- *
Fe54 0+ 5.8	Fe55 2.73 y 3/2- EC	Fe56 0+ 91.72	Fe57 2 2.2	Fe58 0 0.28	Fe59 44.503 c 3/2- *	Fe60 1.5E+6 y 5+ *	Fe61 5.98 m 3/2- *	Fe62 68 s 0+ *
Mn53 3.74E+6 y 7/2- EC	Mn54 312.3 d 3+ EC, β^-	Mn55 5/2- 100	Mn56 2.5785 h 3+ β^-	Mn57 85.4 s 5/2- β^-	Mn58 3.0 s 0+ *	Mn59 4.6 s 3/2-, 5/2- β^-	Mn60 51 s 0+ *	Mn61 0.71 s (5/2)- β^-

★ ^{60}Fe is Produced through Successive Neutron Captures

☞ n Capture Astrophysics...(->s-Process...)

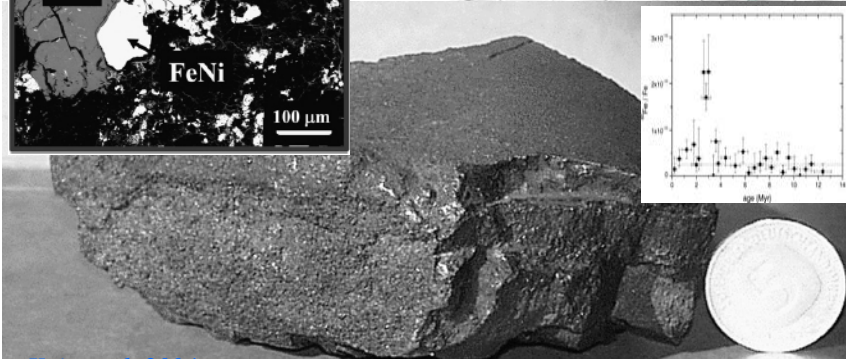
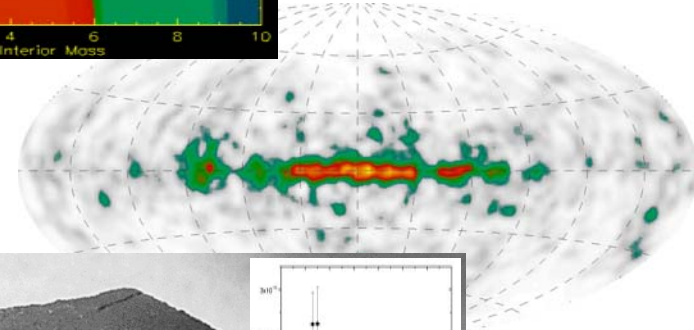
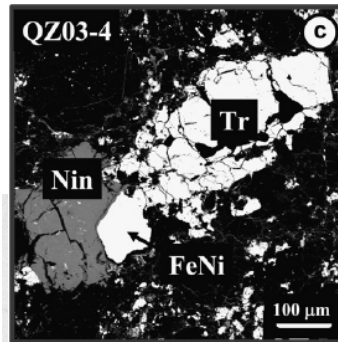
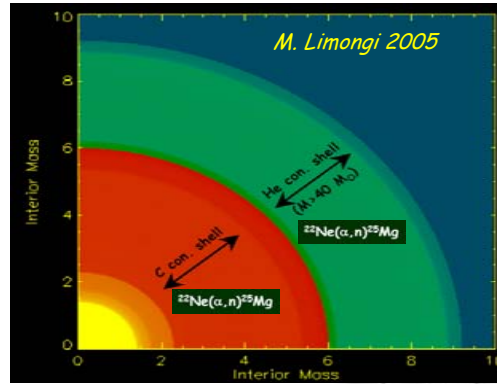
★ Massive Stars are Likely Sources of ^{60}Fe

☞ ... the MAIN Agents of Cosmic Evolution

★ ^{60}Fe has been Detected in

- ☞ a Pacific-Ocean Crust
- ☞ Solar-System Meteorites
- ☞ the Interstellar Medium

☞ Radioactive Dating of Different Astrophysical Events!



Knie et al., 2004

Nuclear Reactions & Stellar Structure

★ n Capture Rates of ^{58}Fe , ^{59}Fe , ^{60}Fe

★ β Decay Lifetimes of $^{59,60}\text{Fe}$ $\tau_{\beta}(T)$

☞ decrease of $\tau_{\beta,59}$ at $T \sim 5 \cdot 10^8 \text{K}$

☞ decrease of $\tau_{\beta,60}$ at $T \sim 4 \cdot 10^8 \text{K}$

★ n Density in Stellar Regions of Interest: $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$

☞ n densities must exceed $3 \cdot 10^{10} \text{cm}^{-3}$ (to exceed ^{59}Fe β decay) (more for $T > 5 \cdot 10^8 \text{K}$)

☞ T must remain in range $4 \cdot 10^8 \text{K} < T < 5 \cdot 10^8 \text{K}$ (n source activation, ^{59}Fe β decay)

★ This Excludes Core He Burning:

☞ He Core Burning is Convective $\rightarrow T < 3 \cdot 10^8 \text{K}$

★ He (and C) Shell Burning Zones as ^{60}Fe Sources

☞ He (and C) Shell Burnings Very Localized

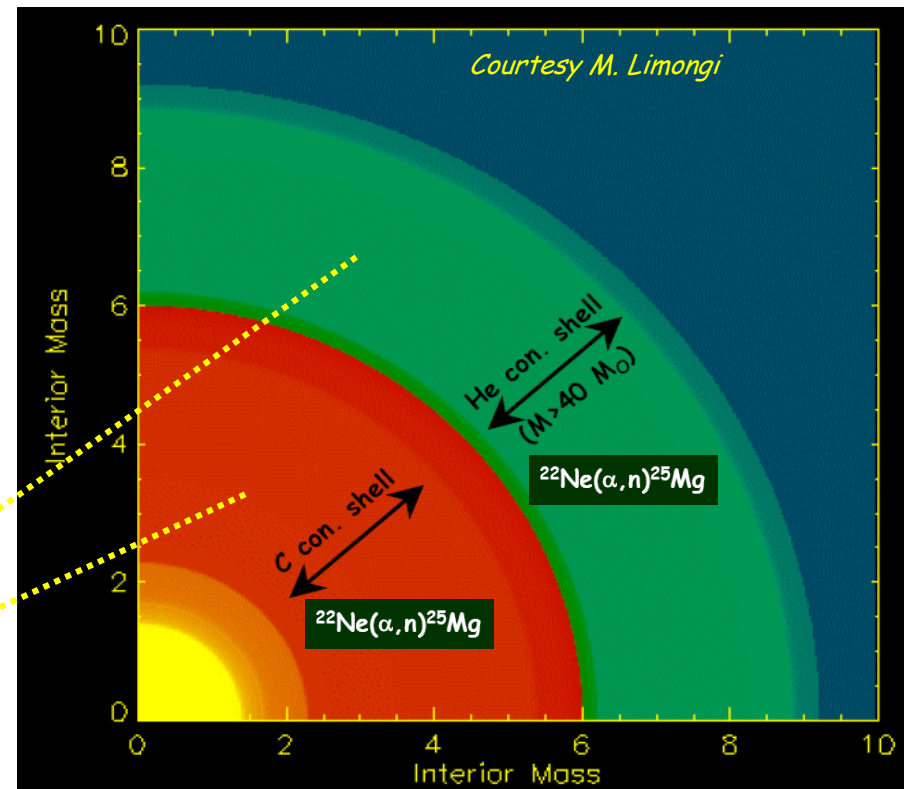
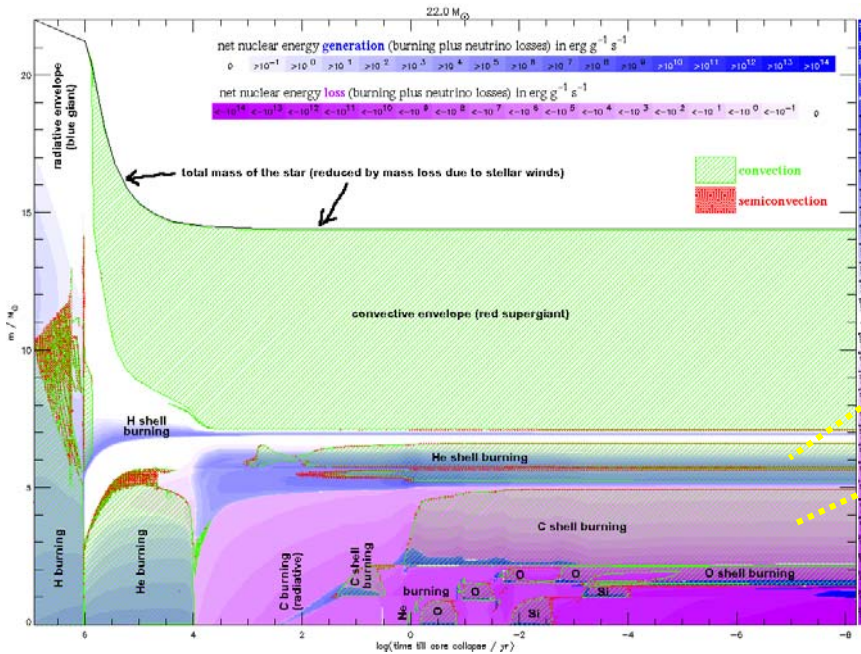
(burning core was well-mixed \rightarrow sharp inner edge of unburnt He)

Co55 17.53 h 7/2- EC	Co56 77.27 d 4+ EC	Co57 271.79 d 7/2- EC	Co58 70.82 d 2+ EC *	Co59 7/2- 100	Co60 5.2714 y 5+ *	Co61 1.650 h 7/2- *	Co62 1.50 m 2+ *	Co63 27.4 s (7/2)- *
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^{60}Fe Production in Stars

$2.0 \cdot 10^6 \text{y}$	$^{60}\text{Fe} \rightarrow ^{60}\text{Co}^* \rightarrow ^{60}\text{Ni}^*$	59, 1173, 1332
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- ★ No Production during ANY Central-Burning Phase
- ★ Need Convection plus n Source

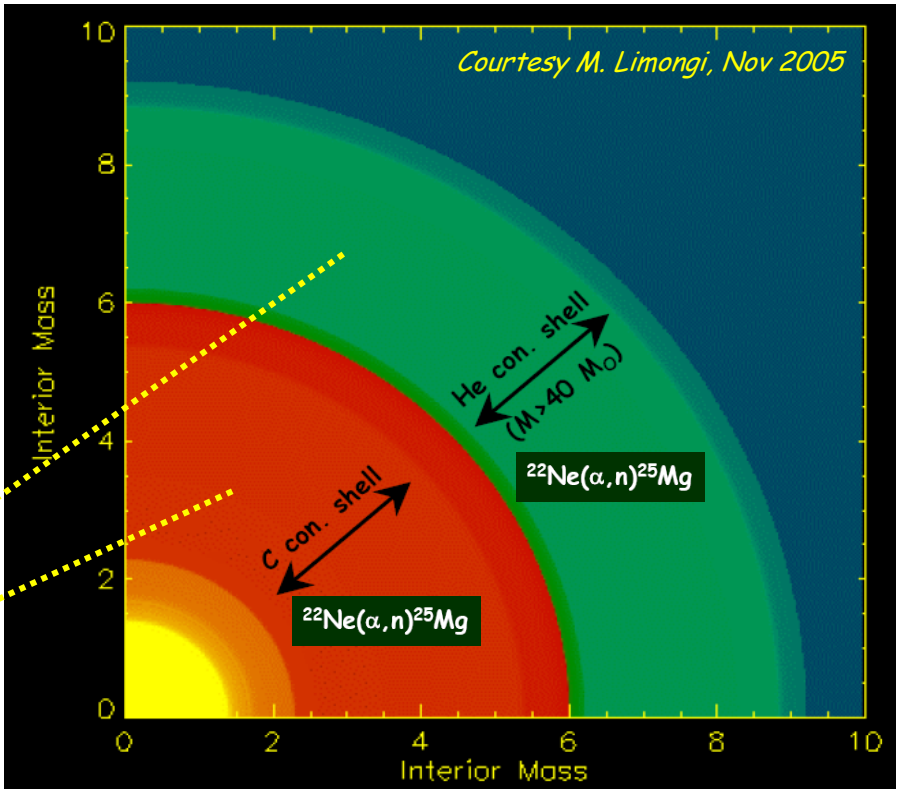
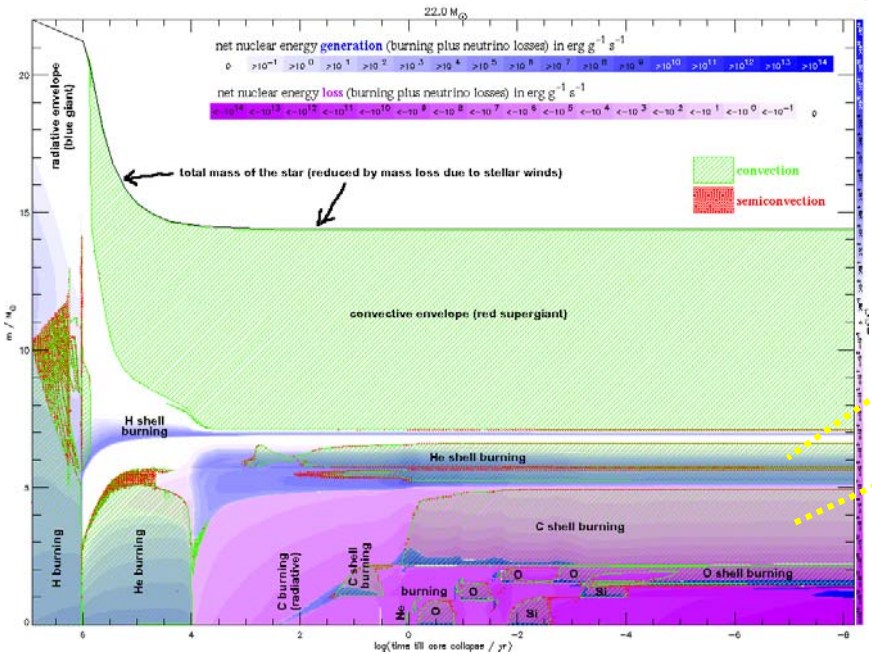


- ★ Explosive-Burning Contributions Negligible
- ★ Ejection by Supernova Explosion

^{60}Fe Production in Stars: Issues

- ☆ What are the n Densities from $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$?
- ☆ What are the Temperatures (and gradients) in the Shell? (τ_β)

$2.0 \cdot 10^6 \text{y}$	$^{60}\text{Fe} \rightarrow ^{60}\text{Co}^* \rightarrow ^{60}\text{Ni}^*$	59, 1173, 1332
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- ☆ ...and: n Capture Cross Sections
- 👉 Yields Can Be HUGE if T is "just right"

Production of ^{60}Fe and ^{26}Al in Massive-Stars

★ Ratio Differences with Progenitor Mass

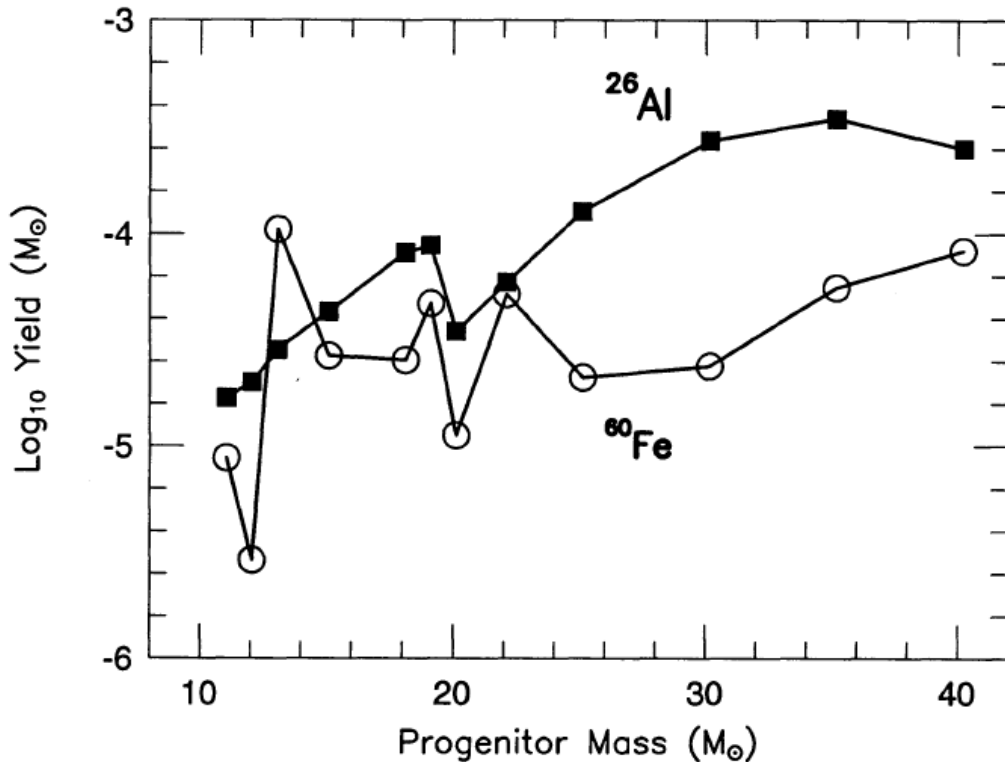
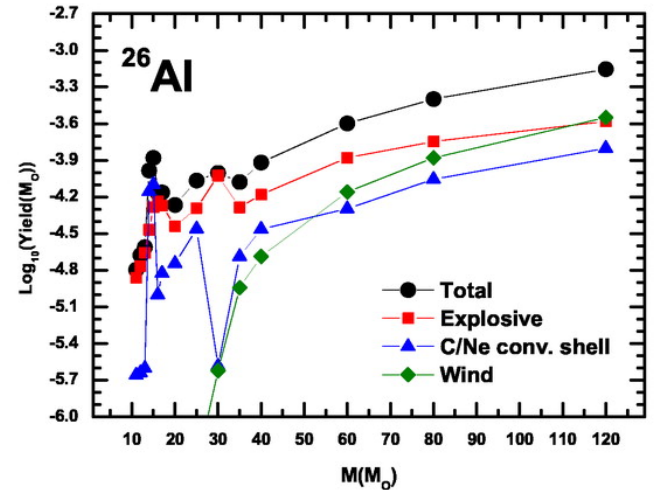
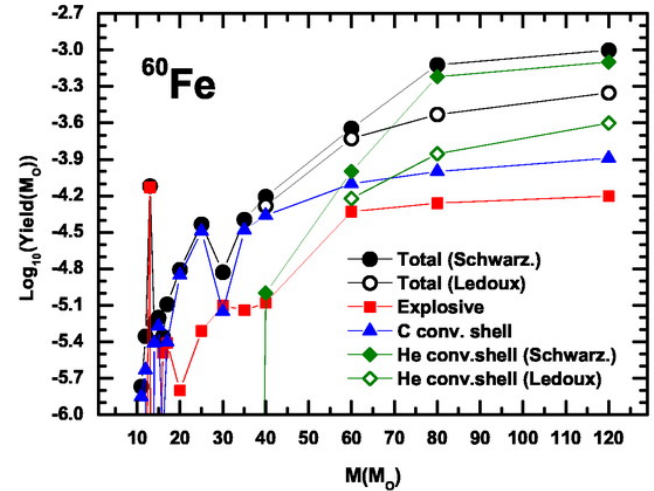


FIG. 3.—Mass of ^{26}Al (filled squares) and ^{60}Fe (open circles) ejected as a function of the main-sequence progenitor mass.

Timmes et al. (1995)



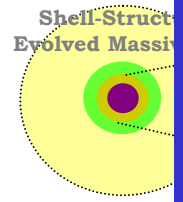
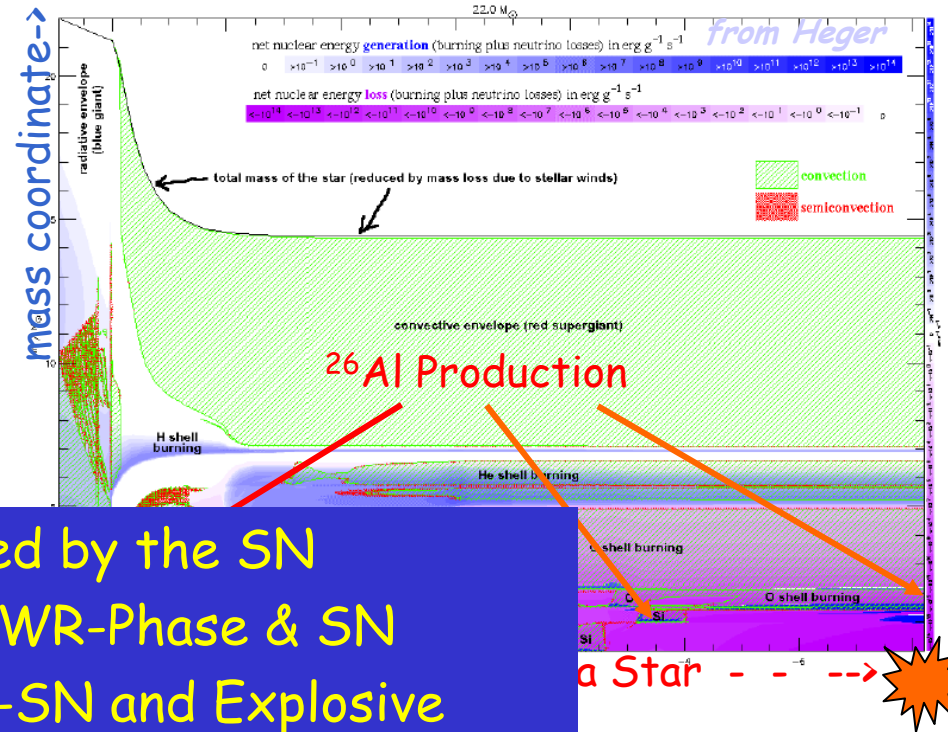
Limongi & Chieffi (2006)



Cosmic Nucleosynthesis: A Complex Astrophysics Issue

★ Massive Stars

- ☞ Stellar Structure
- ☞ Evolutionary Phases
- ☞ Mass Loss
- ☞ Convection & Mixing



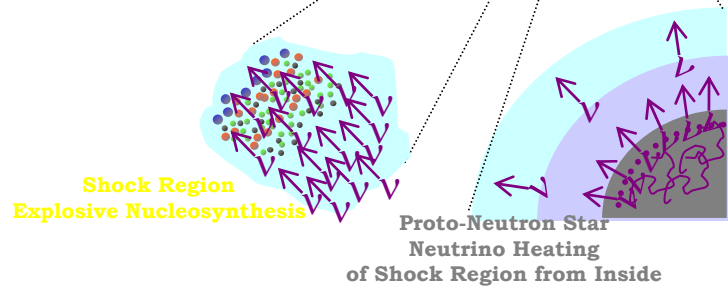
★ ⁶⁰Fe is only Ejected by the SN

★ ²⁶Al is Ejected in WR-Phase & SN

★ Both Combine Pre-SN and Explosive Nucleosynthesis

★ Supernova Physics

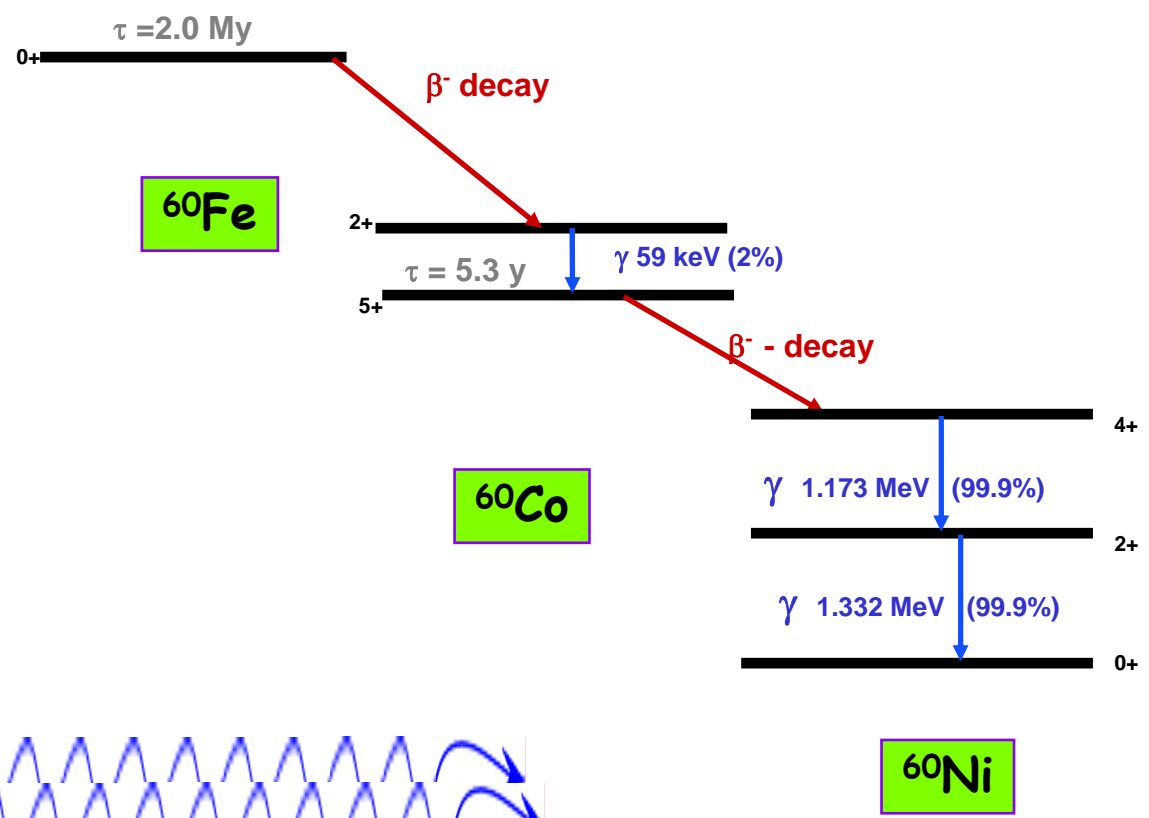
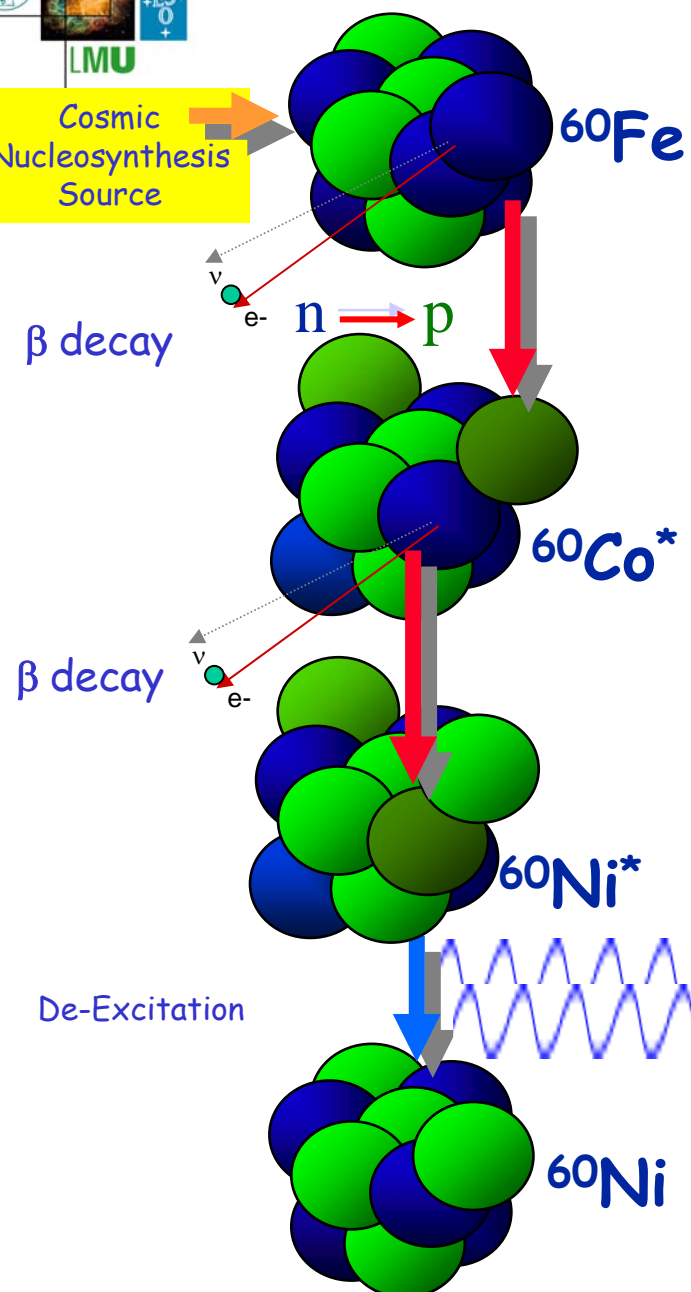
- ☞ Explosion Trigger
- ☞ Shock Structure and Mixing



^{60}Fe : a Radioactive Nucleosynthesis By-Product

γ

Cosmic Nucleosynthesis Source



Radioactive Dating

★ Compare Daughter Nuclide Abundance to Abundance of a Stable Nuclide which is Co-Produced with the Parent

☞ ^{60}Fe co-produced with ^{56}Fe

☞ ^{60}Ni as ^{60}Fe Decay Product

★ other Radioactive Dating Examples

☞ ^{14}C : $\tau=8270 \text{ y}$ from Cosmic-Ray Spallation of N

» Dating of Historic Events, Material Origins, ...

☞ $^{232}\text{Th}/^{238}\text{U}$: $\tau=1.4 \cdot 10^{10}\text{y}, 4.5 \cdot 10^9\text{y}$ both from r-process

» Dating of the Age of the Galaxy, Universe, ...

★ Issues

☞ Contaminations from Secondary Producers of the Key Isotopes

☞ Chemical Fractionations & Alterations of Isotope Ratios

★ ^{60}Fe is Favorable

☞ Not Significantly Produced by Cosmic-Ray Spallation

☞ Fe, Ni are Abundant Minerals

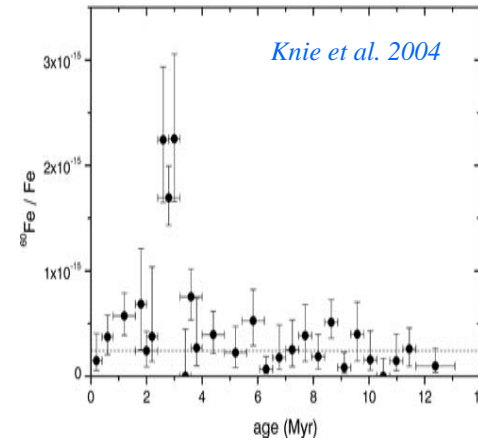
★ ^{60}Fe Addresses a Unique Time Scale

☞ Massive Star Lifetime, ISM Mixing, Planetary-System Evolution



^{60}Fe on Earth

★ Detected in Pacific Ocean Crust



★ Cannot Come from Atmospheric Production

★ Probably Originated from a Nearby Supernova

☞ recent massive-star activity in solar vicinity

the Sco-Cen Association
($d \sim 140\text{pc}$)

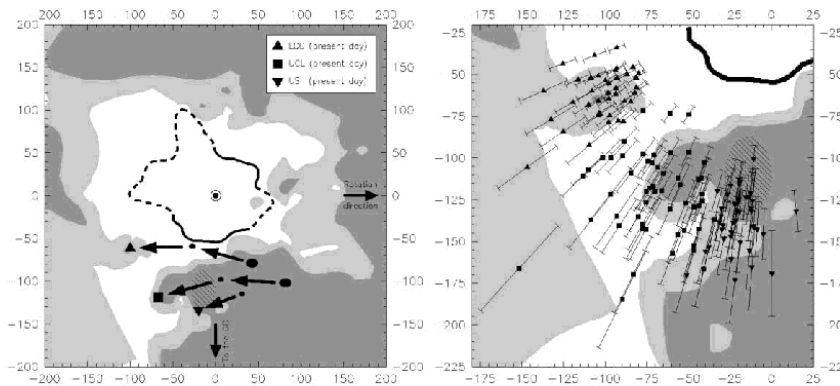


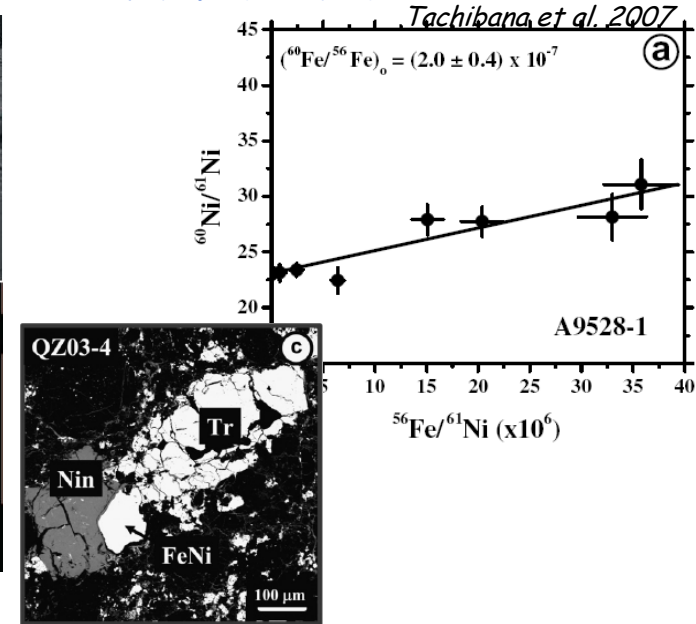
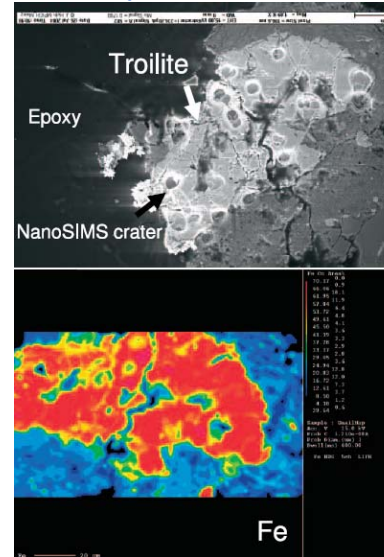
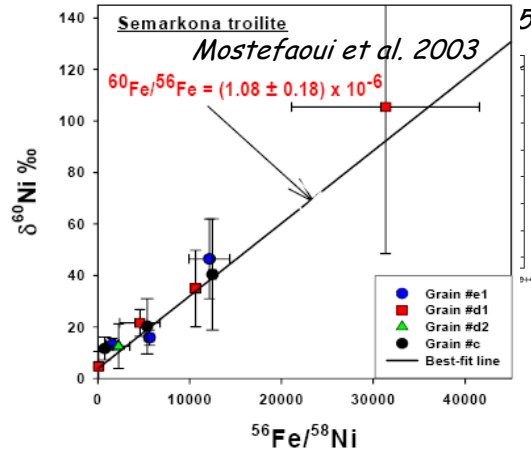
FIG. 1.—*Left*: Local cavity and LB in the plane of the Galactic equator. The filled contours show the Na I distribution (Sfeir et al. 1999), with white used for low-density regions and dark gray for high-density ones. The black contour shows the present size of the LB as determined from X-ray data (Snowden et al. 1998), with the dashed lines indicating contaminated areas where the limits of the LB cannot be accurately determined. The hatched ellipse shows the approximate position of the Ophiuchus molecular cloud (de Geus et al. 1989; Loren 1989a, 1989b). The present and past x - and y -coordinates of the center of the three subgroups of the Sco-Cen association are shown. For LCC and UCL, the past positions shown are those of 5 and 10 Myr ago, while for US only the position of 5 Myr ago is shown. The dimensions of the filled ellipses indicate the uncertainties in the past positions. Coordinates are expressed in units of parsecs. *Right*: Blowup of the left panel with the present positions of the OB stars in each of the three subgroups. Only those stars with accurately determined positions are shown. The symbol used in each case indicates the subgroup membership using the code established in the left panel.

^{60}Fe in Solar-System Meteorites

☆ ^{60}Ni Excesses wrt. Ni Isotopes Detected in Meteorites

☞ $^{60}\text{Fe}/^{56}\text{Fe}$

$\sim 3 \cdot 10^{-7} \dots 1 \cdot 10^{-6}$



☆ ISM Abundance Ratio?

☞ ^{26}Al & ^{60}Fe from ISM γ 's & SAD ^{27}Al , ^{56}Fe $\rightarrow \sim 1.4 \cdot 10^{-7}$

☆ The "Disk Area" of a Newly-Formed Stellar System is ~ 10 My

☆ Chondrules are Formed \sim Myrs after Decoupling of SolarSys from ISM

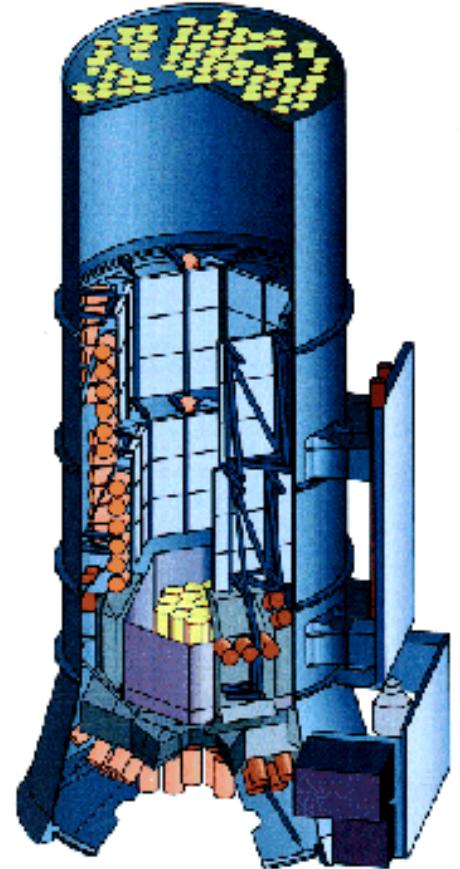
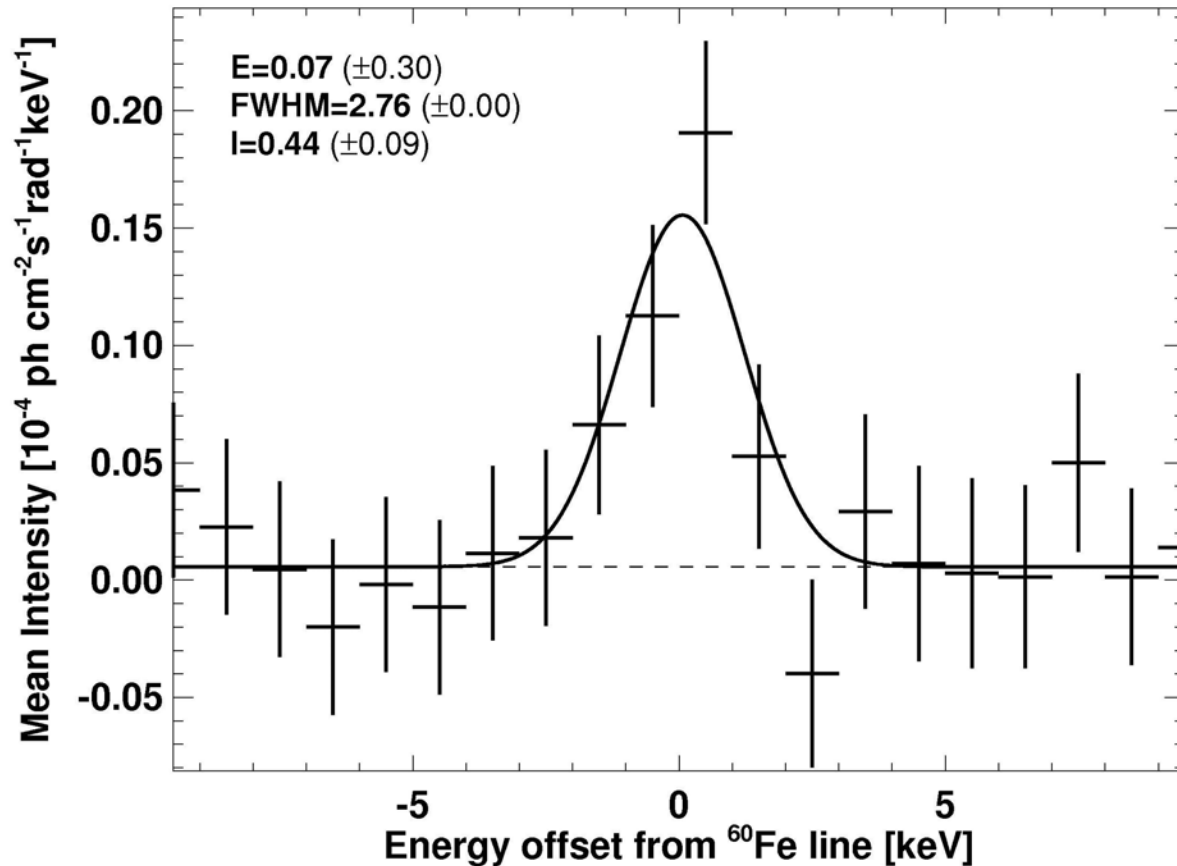
☞ When, Exactly, Does Chondrule Formation Occur?

☞ Was ^{60}Fe a Significant Heat Source of Chondrules?

☞ Has there been 'late' SN Enrichment?



^{60}Fe Emission is Seen from the Galaxy γ

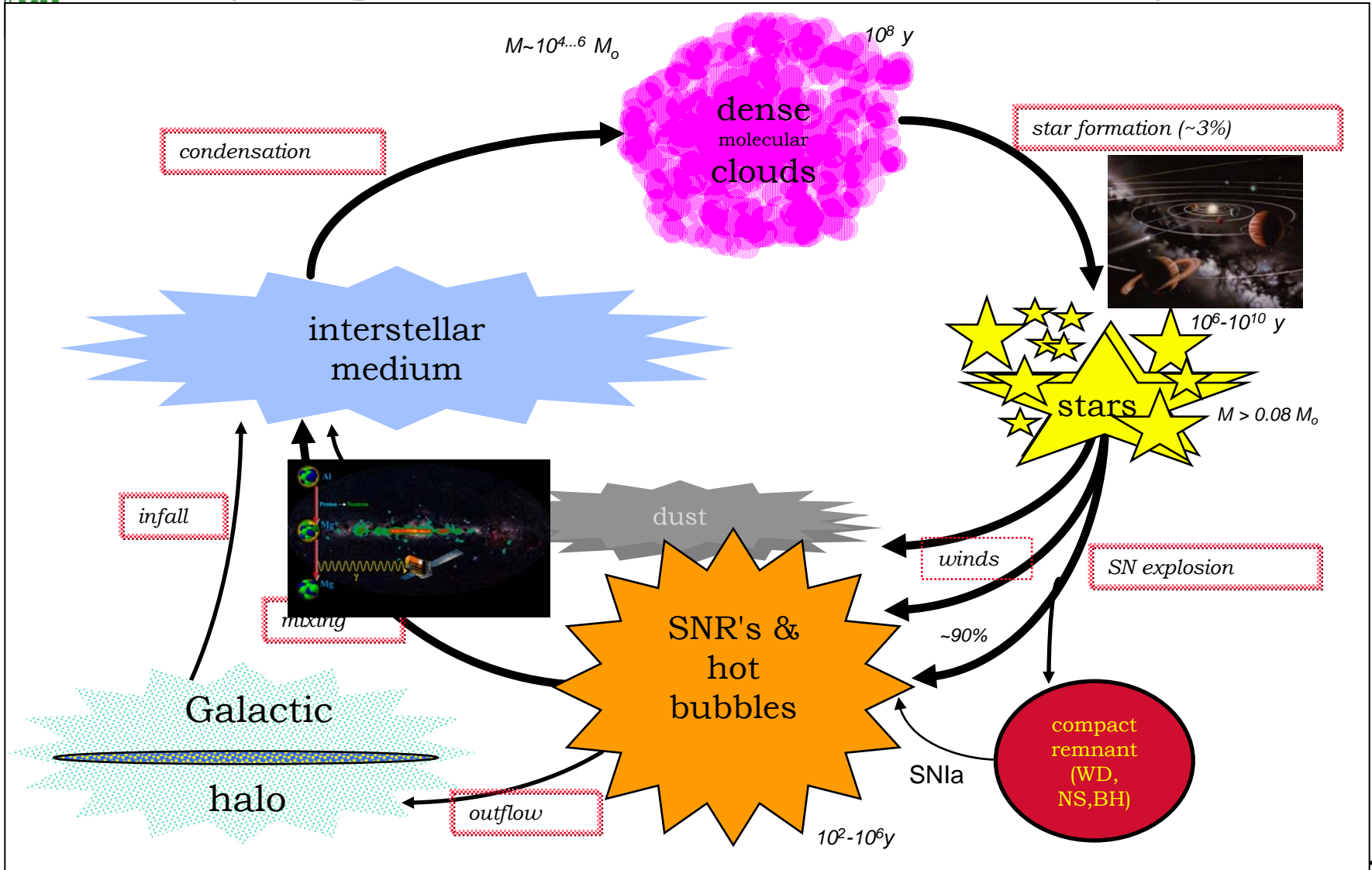


★ Gamma-ray Signal from ^{60}Fe in Diffuse/Extended ISM

👉 $^{60}\text{Fe}/^{26}\text{Al}$ Emission Ratio $\sim 15\%$

👉 *W. Wang, A&A (2007)*

...Cycling of Matter and ^{60}Fe ($\tau \sim 2 \cdot 10^6 \text{y}$)



👉 Provide Event Dating Near/In Solar-System

👉 Trace Nucleosynthesis Ejecta into ISM