SUPERNOVAE
PhD Course 2013, SISSA

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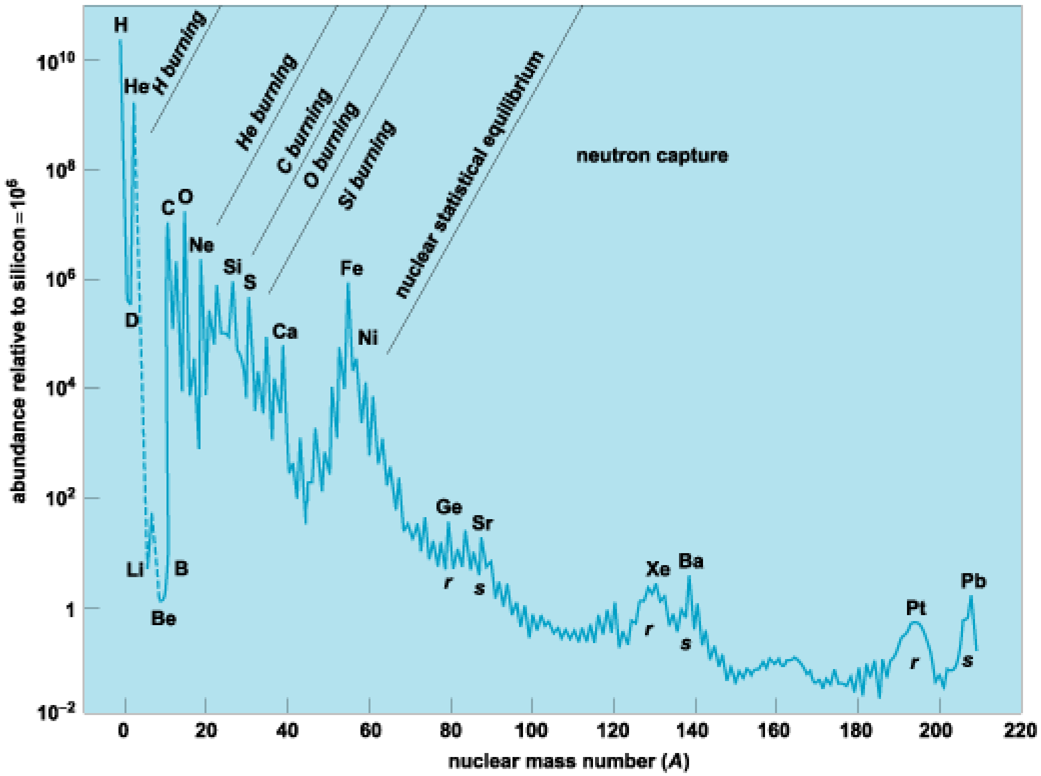
IV. Explosive nucleosynthesis and chemical yields

Solar abundance of the elements

Solar System isotopic abundances



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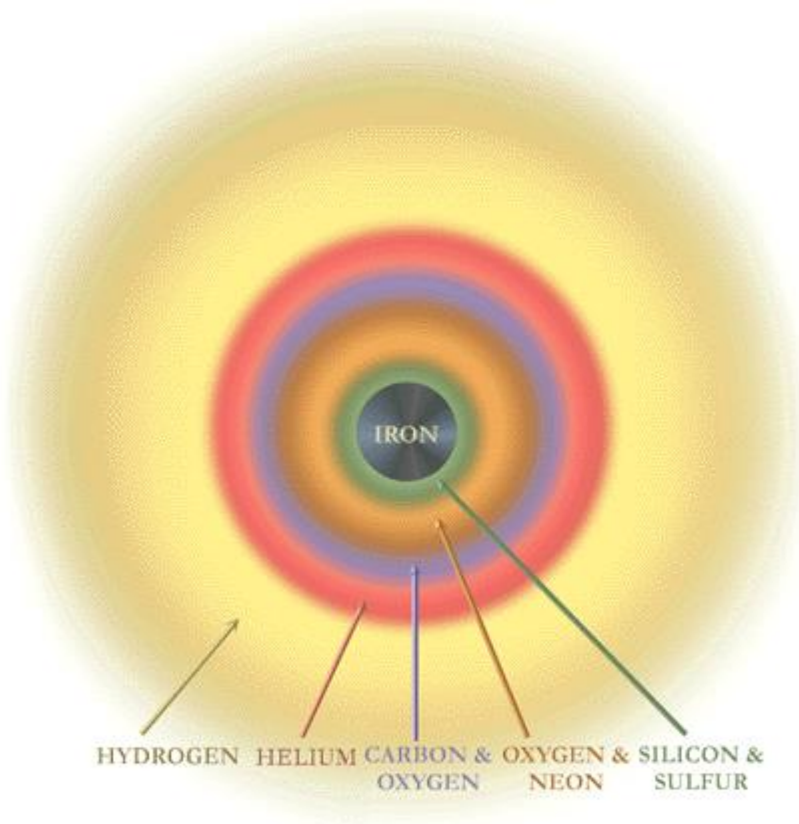
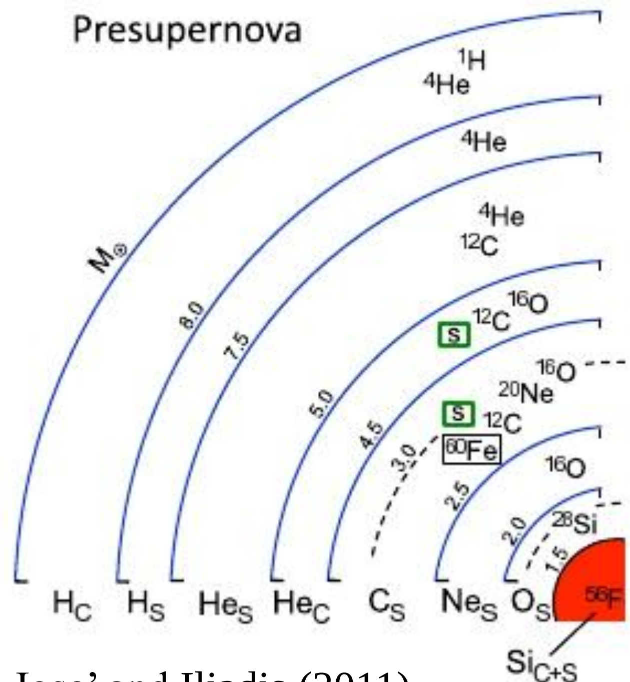
Abundances based on meteoritic samples and on values inferred from solar photosphere

H and He are the most abundant species. Abundances generally decreasing for increasing mass number. Exceptions to this behavior include the light elements Li, Be and B, extremely underabundant. Note a pronounced peak near 56Fe (the so-called iron-peak) and several noticeable maxima in the region of A > 100.

Onion-like progenitor structure before explosion

Typical composition of a massive star at the onset of collapse





Jose' and Iliadis (2011)

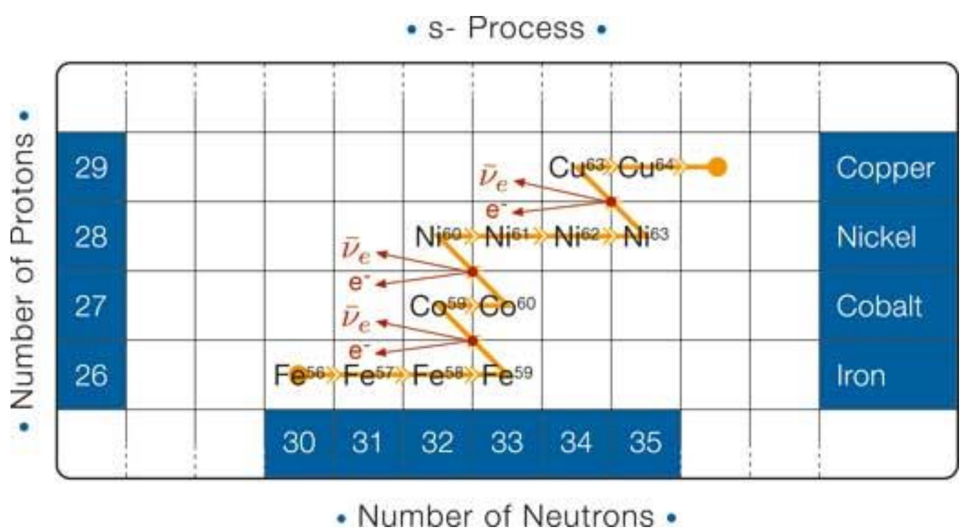
Structure (not to scale) of a 25 Msun star of solar metallicity, as predicted by one-dimensional, spherically symmetric models (Limongi et al. 2000; Limongi and Chieffi 2010), shortly before core-collapse. Main constituents and some minor constituents in boxes (among them important γ-ray emitters) are shown.

s(low neutron capture)-process

Elements heavier than iron cannot be produced easily in stars via charged-particle reactions, since the rapidly decreasing transmission through the Coulomb barrier will inhibit their formation.

They are made instead by exposing lighter seed nuclei to a source of neutrons, such that neutron capture reactions can be initiated. Successive neutron captures by a chain of isotopes occur until a radioactive isotope is reached.

β- decay probability of this species is much larger than the probability for another neutron capture to occur → β- decay back to stability and another chain of neutron captures is initiated.



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s(low neutron capture)-process

Solar system s-process abundance distribution indicates existence of 3 distinct components: weak ($A < 90$) , main ($A \sim 90–205$) and strong ($A \sim 208$) s-process component, characterized by the capture of ~ 3, 10 and 140 neutrons per seed nucleus.

main and strong s-process → low mass ($M < 4$ Msun) AGB stars
weak s-process → core He burning and subsequent C shell burning in massive stars ($M > 11$ Msun), with 22Ne(α,n)25Mg as the most important n source. The gamma-ray emitter 60Fe is produced through this process in the CNeO layer

Explosive nucleosynthesis: Si burning in NSE

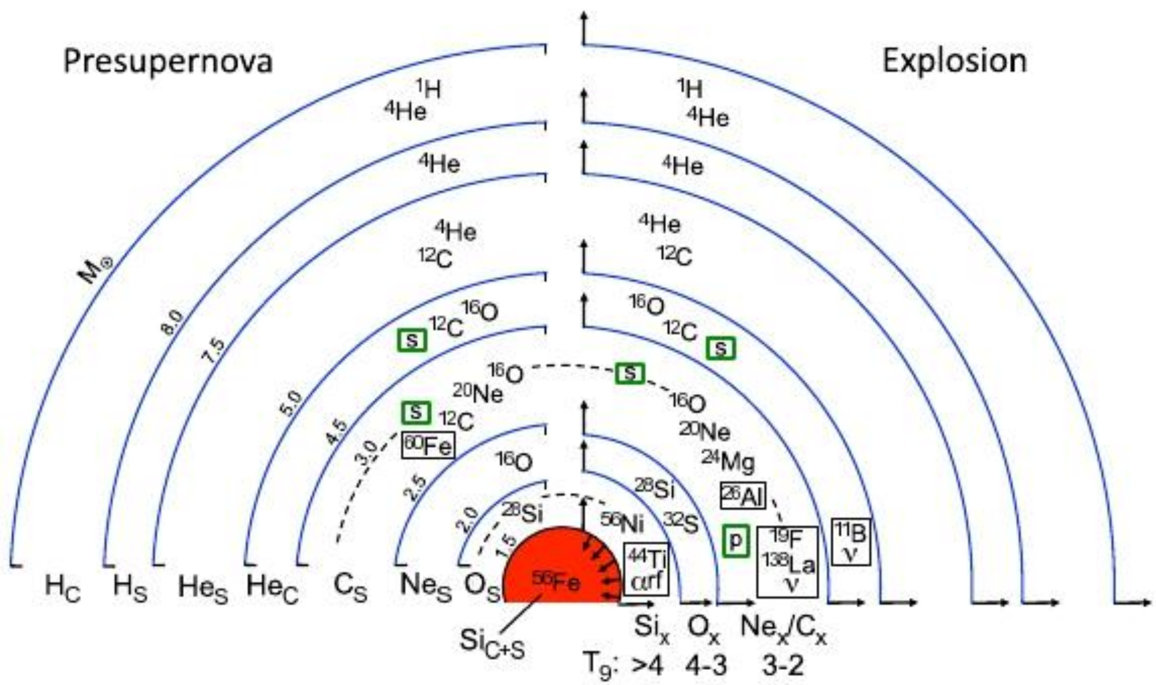
Si burning in NSE

After core collapse and neutrino reheating, the shock propagates through the envelope
$\rightarrow$ energy deposition and nucleosynthesis

First zone encountered: inner 28Si layer
- heated to $T > 5.0e9$ *K*
- *rho* $\sim 1.0e8$ *g/cm*^{3}
- very small neutron excess *eta* ~ 0.003

All 28Si undergoes complete explosive burning in NSE $\rightarrow$ NSE favors 56Ni as the main constituent (Hartmann et al. 1985)

Nuclear reactions will start to fall out of equilibrium at a certain *freeze-out temperature*
- Expansion time scale and *rho* large $\rightarrow$ NSE predicts very small light particle (p, n, alpha) abundances. Their subsequent capture during freeze-out does not alter the NSE composition
- Expansion time scale and *rho* small $\rightarrow$ NSE predicts relatively large light particle abundance (especially of alpha particles). NSE composition altered during this *alpha-rich freeze-out* (Woosley et al. 1972). Main product again 56Ni, but additional species are produced, as 44Ti



Jose’ and Iliadis (2011)

Si burning in QSE

Second zone encountered: outer 28Si layer

- heated to *T = 4-5.0e9 K*

28Si undergoes explosive burning in quasi-equilibrium (QSE)

In QSE no global equilibrium among all species, but only locally in some mass ranges
→ Final abundances determined also by abundance of 28Si (Bodansky et al. 1968)

Two clusters of nuclear reactions occur in the mass regions of Si and the Fe peak

At freeze-out a significant amount of 28Si remains (*incomplete silicon burning*; Hix and Thielemann 1999)

O burning in QSE

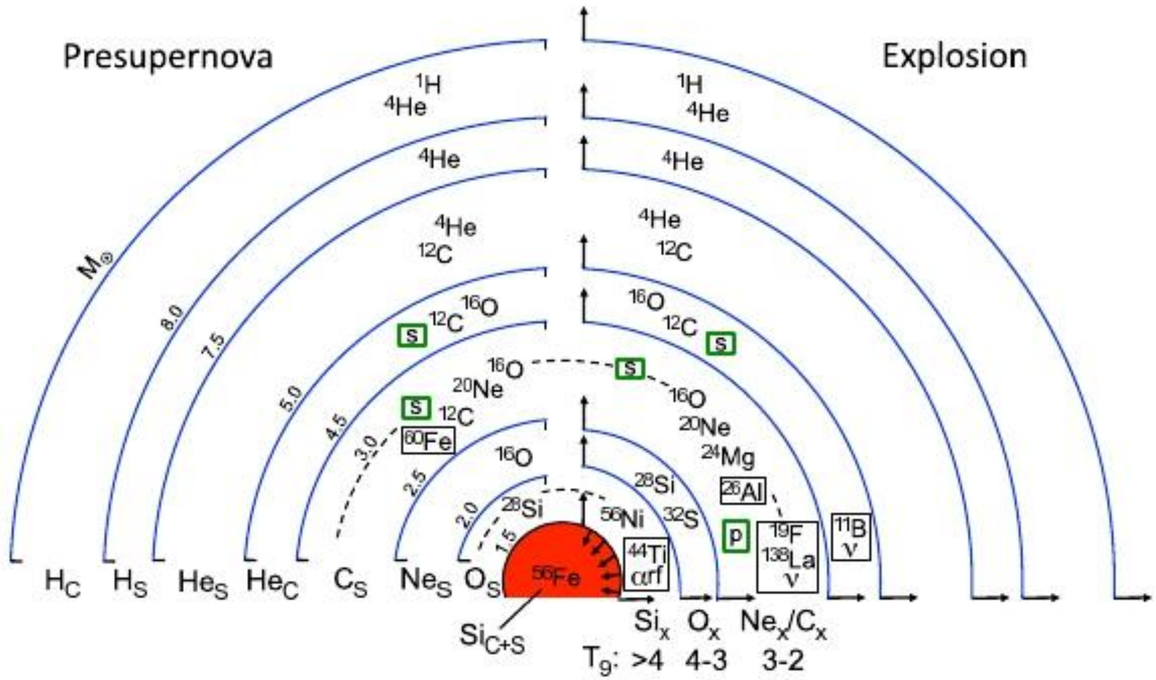
Third zone encountered: 16O layer

- heated to *T = 3-4.0e9 K*

16O undergoes explosive burning in quasi-equilibrium (QSE)

Two clusters of nuclear reactions occur again in the mass regions of Si and the Fe peak

At freeze-out the most abundant nuclides in this zone are 28Si, 32S, 36Ar and 40Ca



Jose' and Iliadis (2011)

Ne/C burning

Forth zone encountered: 16O, 20Ne, 12C layer

- heated to *T = 2-3.0e9 K*

20Ne and 12C undergo explosive burning far from equilibrium

The abundance of a given species does not depend only on a few parameters (sensitively influenced by the initial composition)

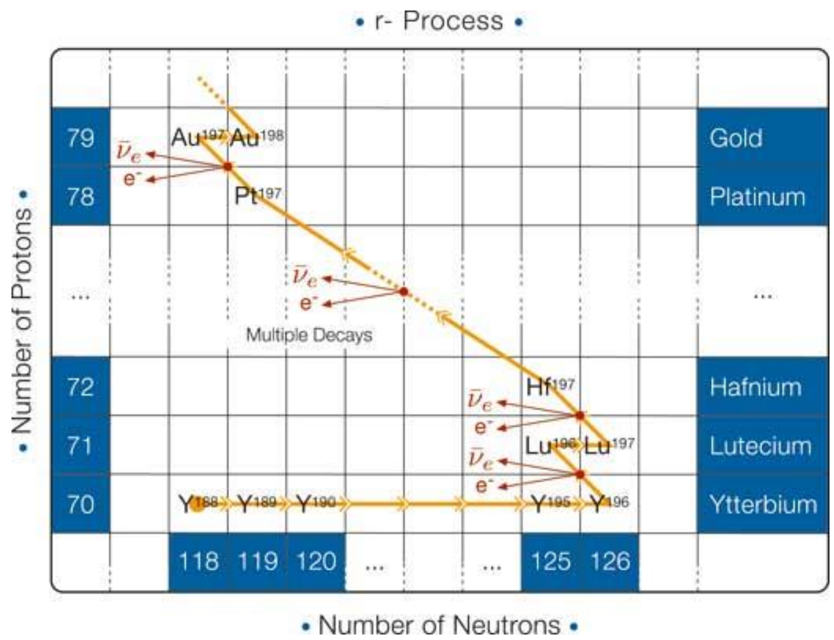
After freezeout the most abundant species in this zone are 16O, 20Ne, 24Mg and 28Si

Also 26Al is produced (unstable, half-life 7.0e5 yrs) → observed in the Galactic interstellar medium (Mahoney et al. 1982, Diehl et al. 1995), *providing unambiguous direct evidence that nucleosynthesis must be occurring currently throughout the Galaxy*

Explosive nucleosynthesis depends sensitively on:

- mass-radius relation (or density profile) of the pre-SN star
- neutron excess (or *Ye*) profile of the pre-SN star (influenced by treatment of convection, time delay between CC and shock revival, and previous hydrostatic evolution of the star)

r-process



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It occurs when nuclei are exposed to very strong neutron fluxes (and high temperatures) for a very short time

Neutron capture more likely than β− decay → isotopic abundances driven away from the stability valley toward the neutron-rich side and accumulates at certain nuclides (Iliadis 2007)

After termination of the neutron flux, nuclei undergo series of β− decays along chains at *A* = *const* until the most neutron-rich stable (or very long-lived) nuclide is reached

About half of the nuclides beyond the iron peak, including gold, silver, platinum and uranium, are believed to be synthesized in this way

The neutrino-driven wind has been proposed as r-process site. However, recent long-term simulations of core-collapse supernovae predict unfavorable conditions (proton-rich environment; Fischer et al. 2009; Hudepohl et al. 2010).

Nucleosynthesis in thermonuclear SNe

Nuclear burning regimes in Type Ia SNe

Abundance pattern depends critically on the peak temperature achieved, as well as on the neutron excess. The latter depends in turn on the metallicity of the WD

Four different burning regimes: NSE in the inner regions (54Fe, 56Fe, 56Ni), incomplete Si-burning, O-burning, and C/Ne burning in the outermost layers

Type Ia SNe produce about half of the Fe content in the Milky Way. Models must reproduce the isotopic abundances of the Fe-peak elements in the Solar System (requiring Galactic chemical evolution models to account for different contributions)

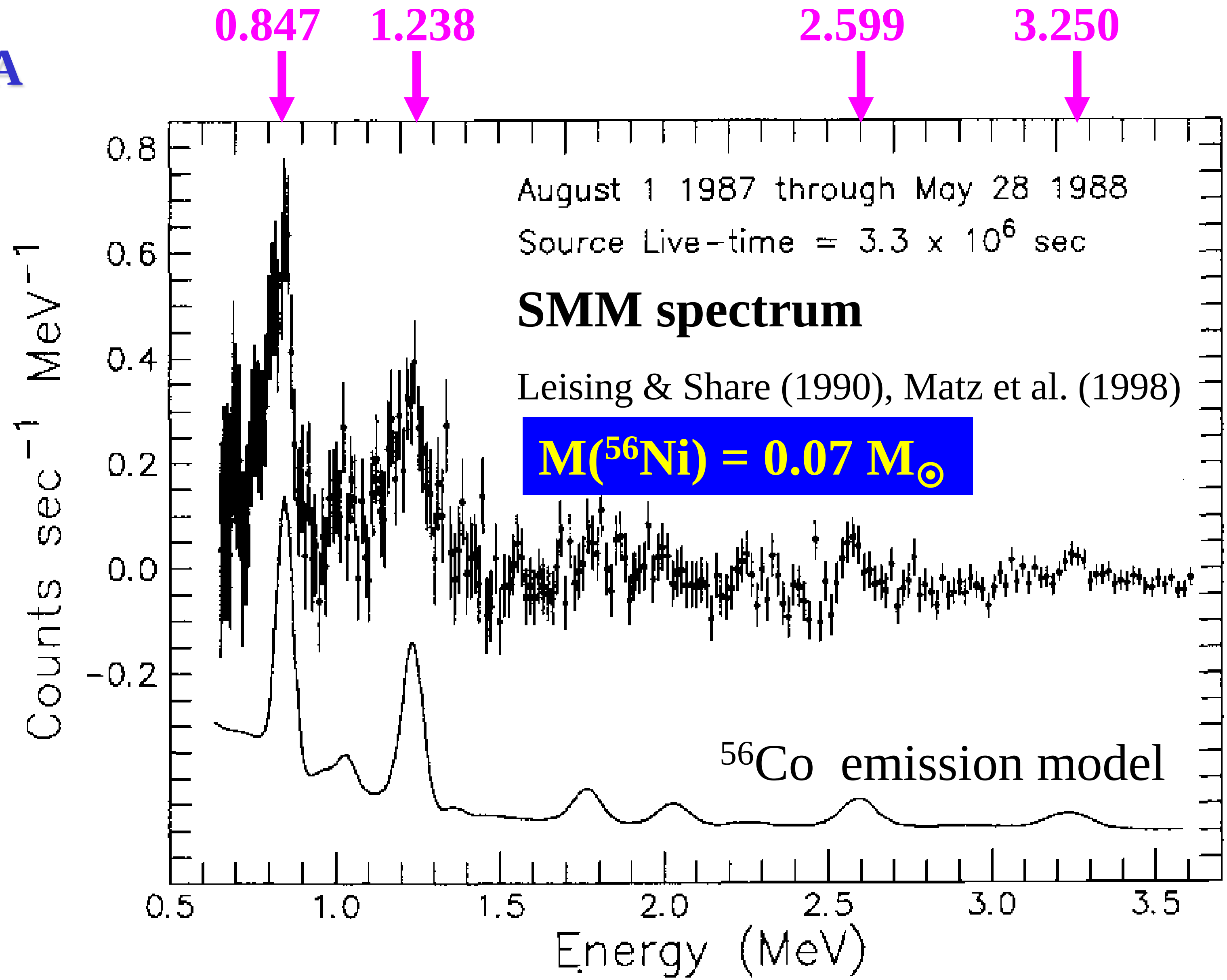
- C deflagration model in spherical symmetry (W7; Nomoto et al. 1984)
- Pure turbulent deflagration model and delayed detonation model in multidimensions (Roepke and Niemeyer 2007, Gamezo et al. 2005, Bravo and Garcıa–Senz 2008, Maeda et al. 2010) reproduce the observed abundaces in Type Ia SN spectra

Since delayed detonation models are initiated by a deflagration, the WD can expand prior to the onset of the detonation. The detonation moves through low density layers producing only intermediate-mass elements → *similar distribution of Fe-peak elements*

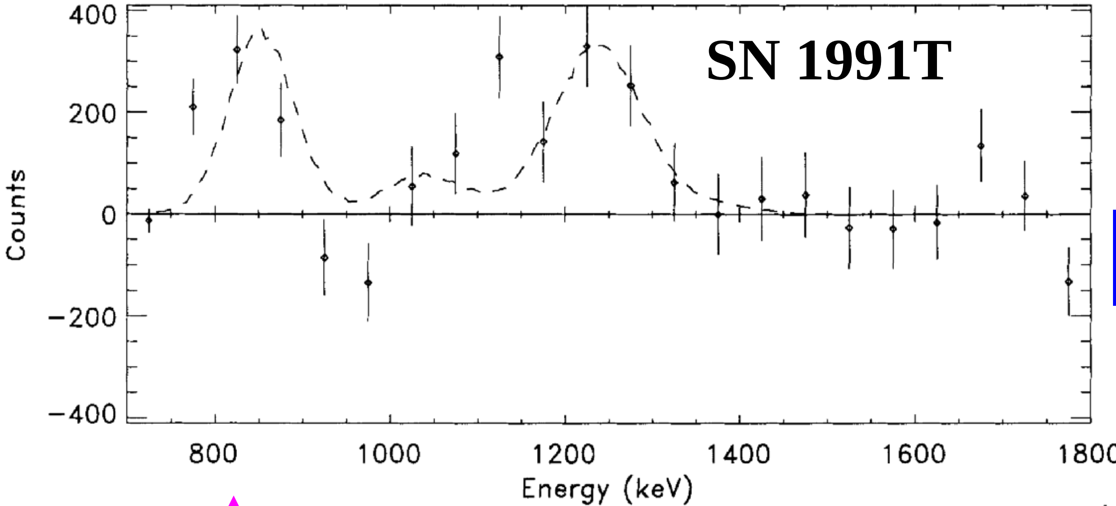
The delayed detonation model reproduces the observed *layered structure*, in contrast to what is found for deflagrations (but not in all models)

Direct detection of gamma-ray emission

56Co in SN 1987A



56Co in SN 1991T and 44Ti in Cas A

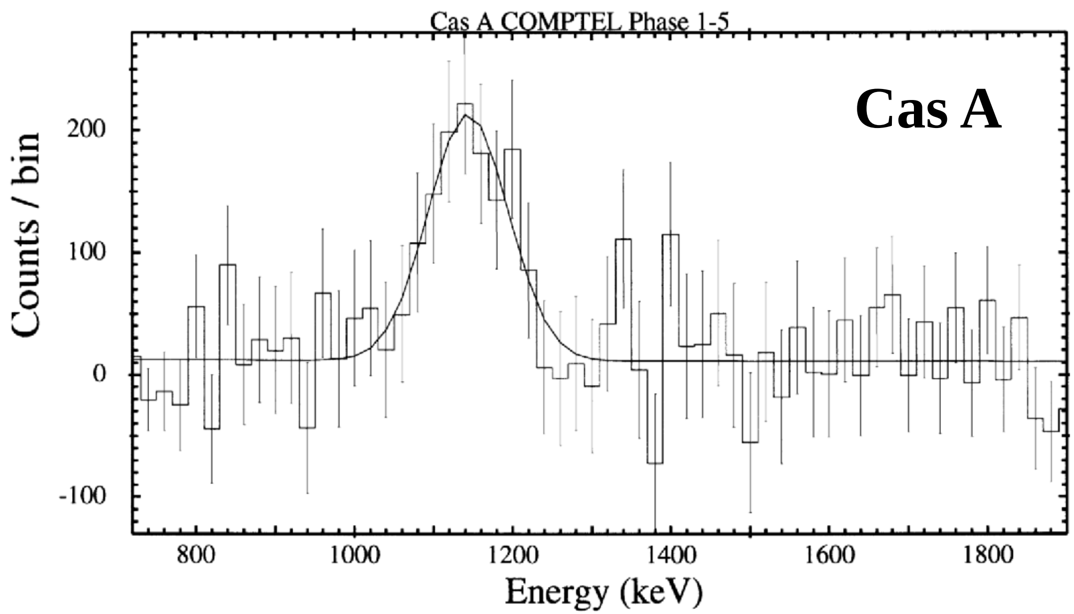


Comptel/CGRO spectrum

(Diehel & Timmes 1998; Morris et al. 1995, 1998)

$1.3 \leq M(^{56}Ni) \leq 2.3\ M_\odot$

0.847 **1.238**



Comptel/CGRO

(Iyudin et al. 1997; Renaud et al. 2006)

$M(^{44}Ti) = 2.4e\text{-}4\ M_\odot$