Type Ia Supernova Explosions: Nucleosynthesis and Chemical Evolution…

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Paths to Exploding Stars: Accretion and Eruption
KITP, University of California, Santa Barbara
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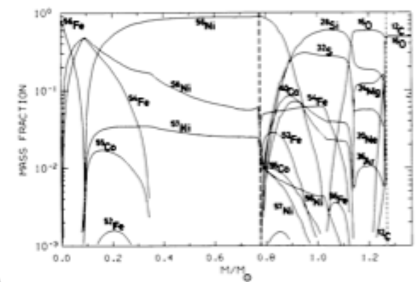
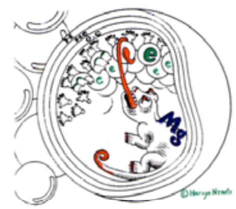
Ken Nomoto and SNe Ia

- **SNe Ia Modeling and Nucleosynthesis**

  (Thielemann, Nomoto, Yokoi 1986)

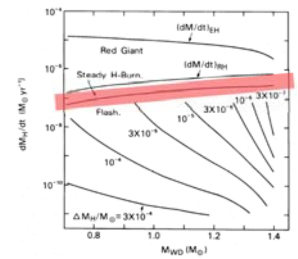


- **Implications of Neutronization**



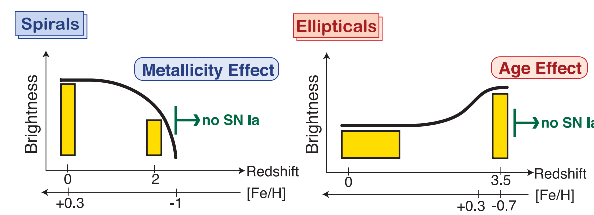
- **Progenitor Identification and Evolution**

  (Nomoto 1982)



- **Population Dependences**

  (Hachisu, Kato, Nomoto 1997)

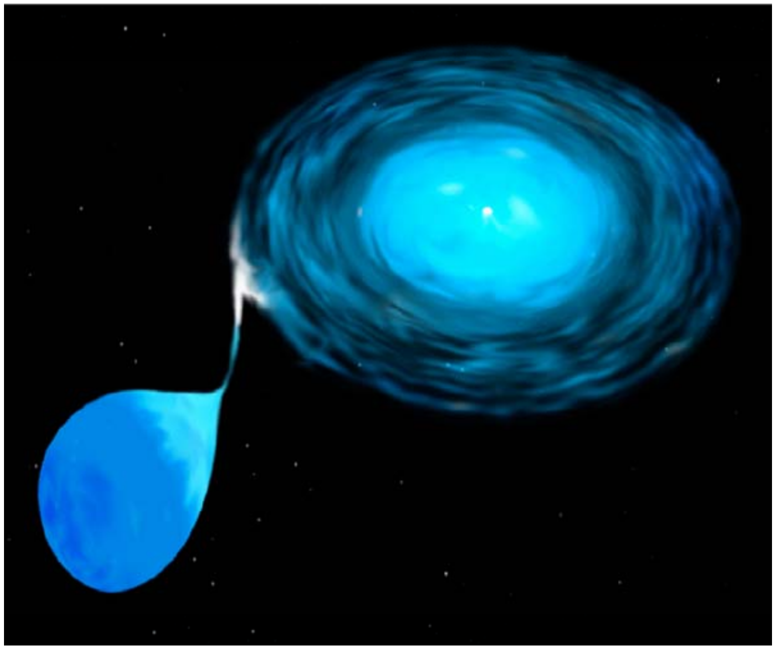


- **Chemical Evolution Considerations**

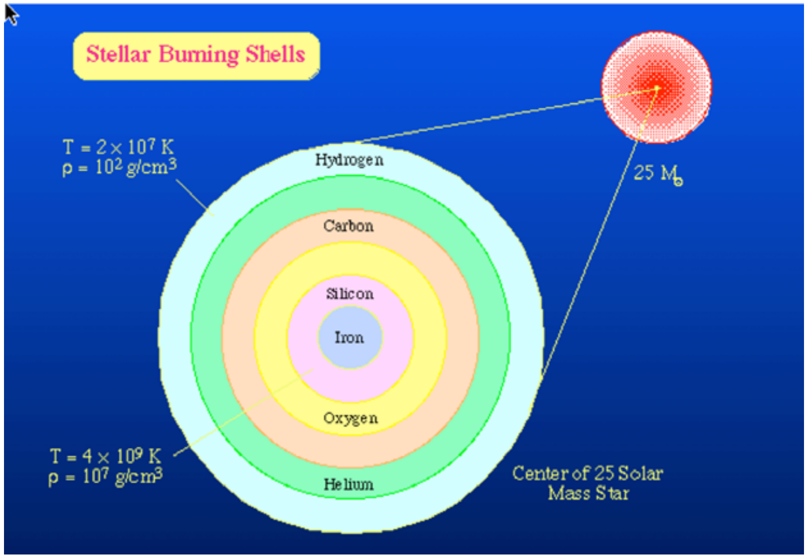
  (Yoshii, Tsijumoto, and Nomoto 1996) $\Longrightarrow$ $\tau_{SNeIa} \approx 1.5$ **Gyr**

Type Ia and Type II Supernovae: Theory

- "Standard model" (Hoyle & Fowler 1960):
  - SNe Ia are thermonuclear explosions of C+O white dwarf stars.
- Nucleosynthesis contributions: 1/2-2/3 of the iron-peak nuclei in nature. Production of $\approx 0.6\ M_{\odot}$ of ^{56}Fe as ^{56}Ni.

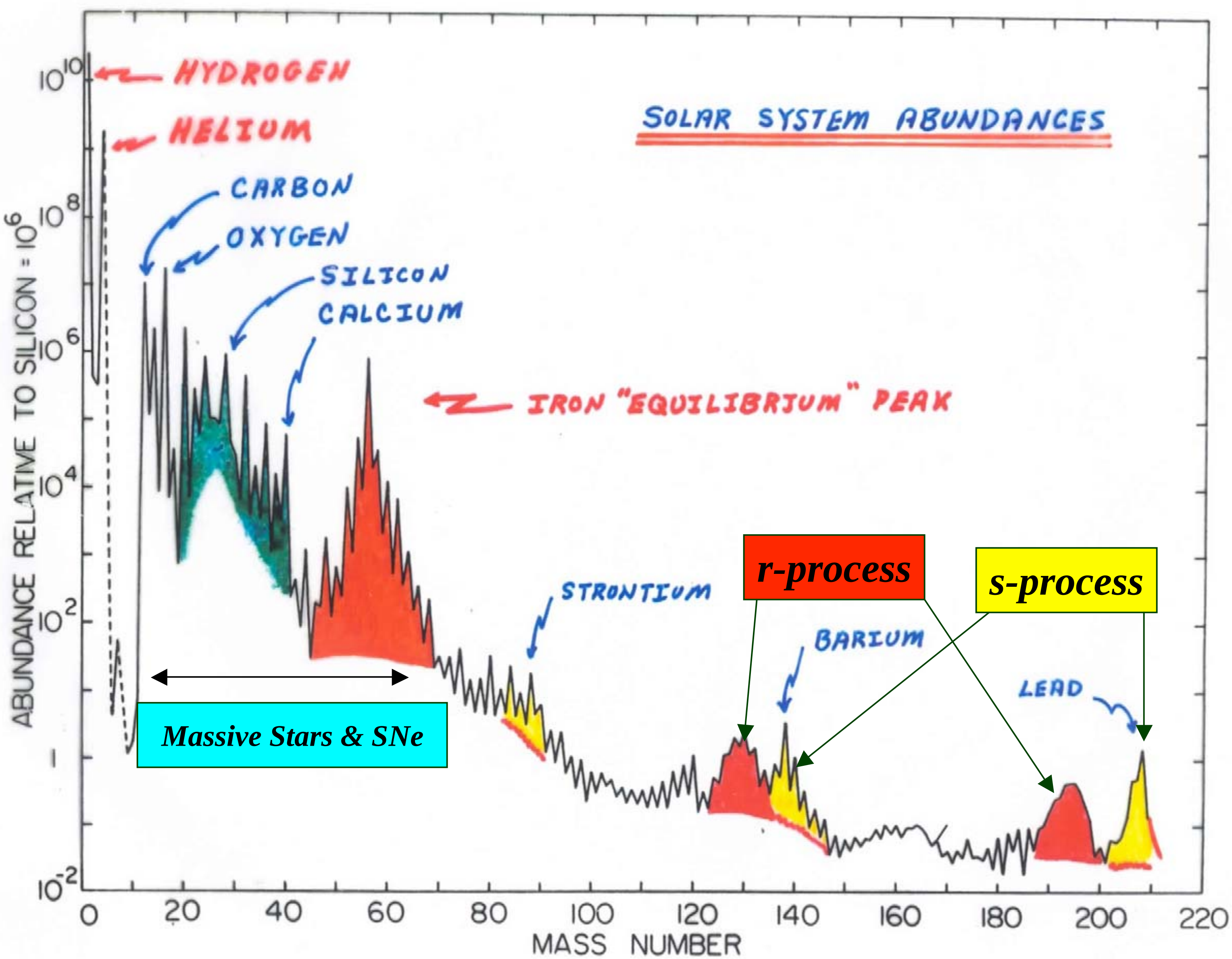


- "Standard model" (Hoyle & Fowler 1960):
  - SNe II are the product of the evolution of massive stars $10 < M < 100\ M_{\odot}$.
- Nucleosynthesis contributions: elements from oxygen to iron (formed as ^{56}Ni) and neutron capture products from krypton through uranium and thorium. Production of $\approx 0.1\ M_{\odot}$ of ^{56}Fe as ^{56}Ni.



Courtesy Mike Guidry: guidry@utk.edu

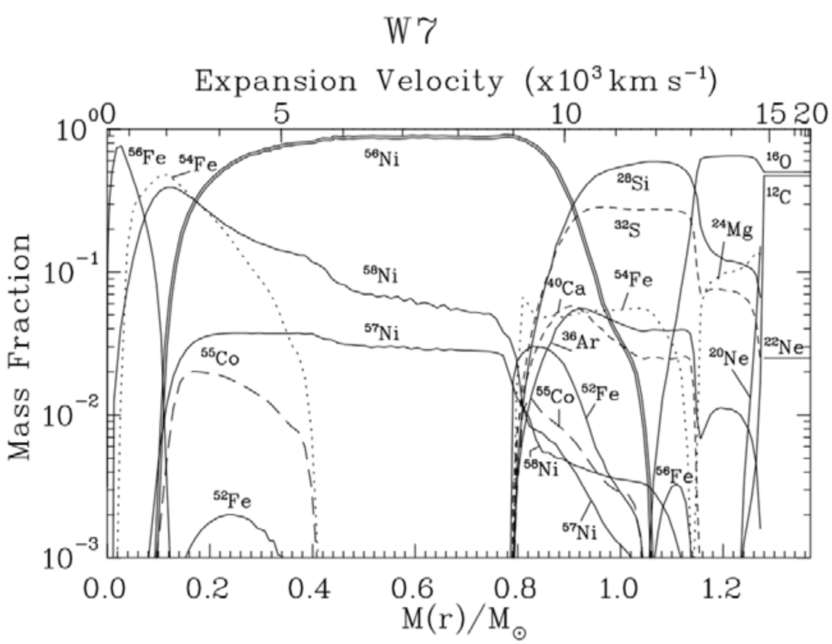
"Cosmic" Abundances of the Elements



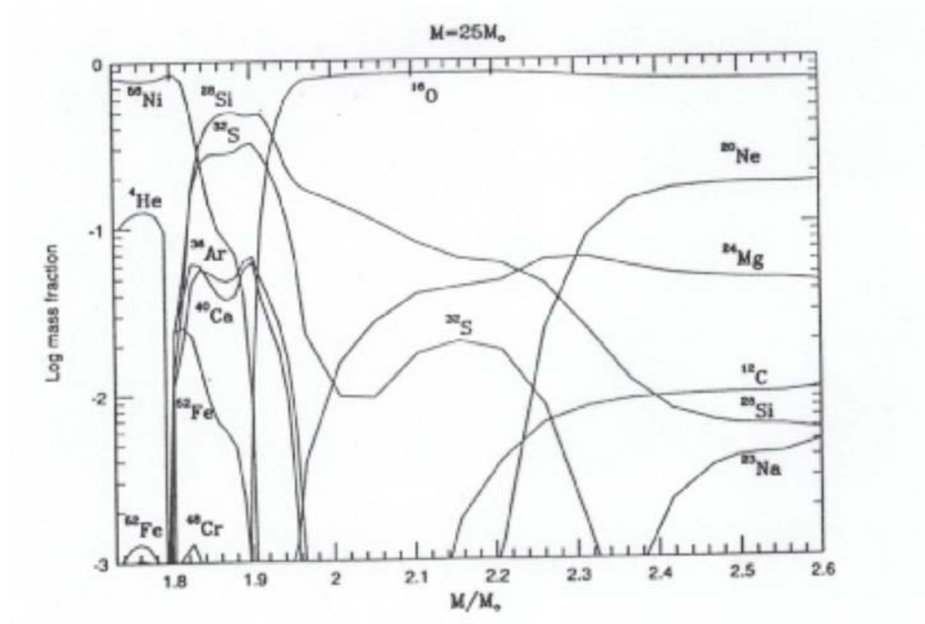
Supernova Nucleosynthesis Contributions

- **Type Ia Supernovae**
  - **SNe Ia are thermonuclear explosions of C+O white dwarf stars.**
  - **Accretion from a binary companion yields growth of the white dwarf to 1.4 $M_{\odot}$.**
  - **Nucleosynthesis Products: 1/2 to 2/3 of the iron peak nuclei in nature.**
  - **Production timescale: ($\tau_{nucleosynthesis} \approx 10^9$ yrs)**

- **Type II Supernovae**
  - **SNe II are the product of the evolution of stars 10 < M < 100 $M_{\odot}$.**
  - **Nuclear burning stages yield a layered compositional structure and ^{56}Fe core.**
  - **Nucleosynthesis Products: oxygen to iron nuclei with [O/Fe]~0.3-0.5 and heavy r-process nuclei.**
  - **Production timescale: ($\tau_{nucleosynthesis} < 10^8$ yrs)**



(Iwamoto et al. 1999)

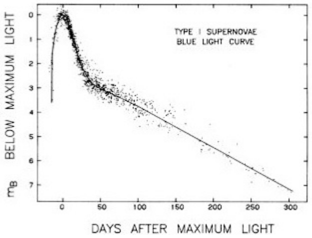


(Thielemann et al. 1992)

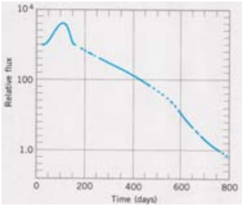
Supernova Nucleosynthesis Contributions

- ❑ **Type Ia Supernovae: Thermonuclear explosions of CO white dwarfs.**
- ❑ **Type II Supernovae: Core collapse driven events in massive stars.**

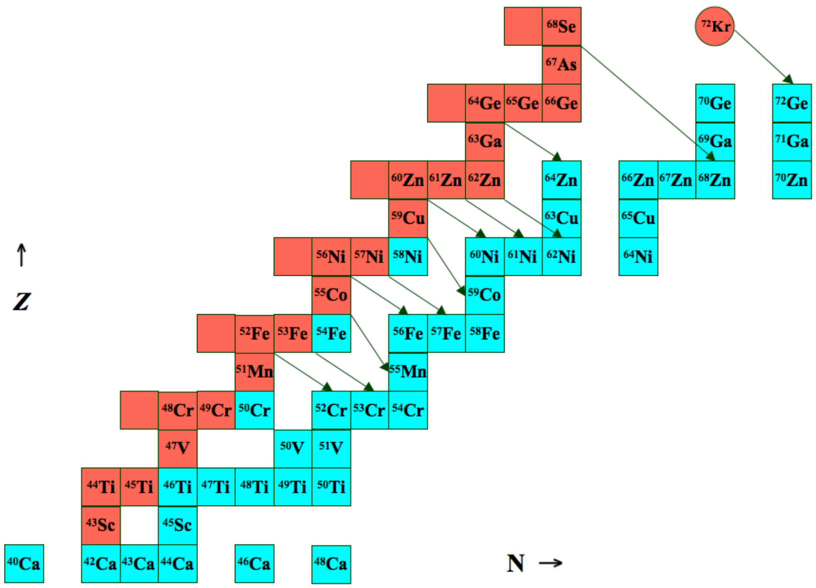
- ❑ ***In both instances,the formation of iron peak elements in explosive nucleosynthesis occurs under neutron-poor conditions. This is reflected in the $^{56}Ni \Rightarrow ^{56}Co \Rightarrow ^{56}Fe$ signatures in both Type Ia and Type II supernova light curves***



SNe



SNe 1987A



… and in the isotopic compositions of iron-peak elements in solar matter:

- ❑ **Consider e.g. isotopic production of even-Z elements.**
  - ❑ **^{48}Ti and ^{49}Ti formed in situ as ^{48}Cr and ^{49}Cr**
  - ❑ **^{50}Cr as ^{50}Cr: ^{52}Cr and ^{53}Cr formed as ^{52}Fe and ^{53}Fe**
  - ❑ **^{54}Fe as ^{54}Fe; ^{56}Fe and ^{57}Fe formed as ^{56}Ni and ^{57}Ni**
  - ❑ **^{58}Ni as ^{58}Ni; ^{60}Ni,^{61}Ni,^{62}Ni formed as ^{60}Zn,^{61}Zn, and ^{62}Zn**
  - ❑ **^{64}Zn contributions from ^{64}Ge ?**
  - ❑ **^{72}Ge contributions from ^{72}Kr ?**

Cannot fit Solar iron peak abundances with an NSE dominated by ^{56}Fe.

Abundance Constraints on SNe Ia Evolution

- ***The heavy element content of the Galaxy at any point in its history reflects the integrated nucleosynthesis contributions from earlier stellar generations.***

- ***Since distinctive abundance patterns are identified with the nucleosynthesis products of stars of different masses (and lifetimes), constraints on the early nucleosynthesis and star formation histories of the Galaxy will be contained in the spectra of halo stars as a function of [Fe/H].***

- ***The production of iron peak nuclei by both Type II and Type Ia supernovae provides a particularly important example:***

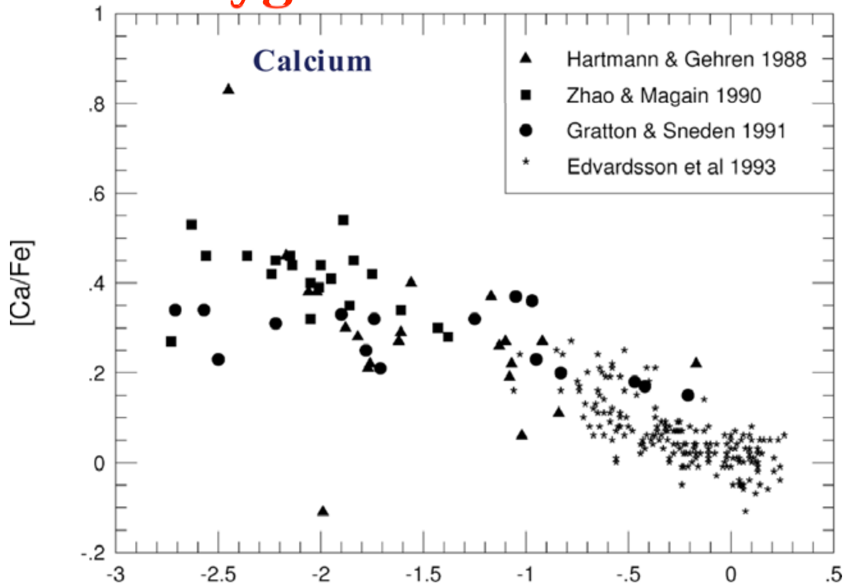
  - ***Massive stars ($M > 10\ M_{\odot}$) and SNe II synthesize most of the nuclear species from oxygen through zinc (and the r-process neutron capture heavy elements from barium through the actinides). A characteristic of such nucleosynthesis is the overproduction of the 'α-particle nuclei' from oxygen to calcium relative to iron by a factor $\approx$ 2-3.***

  - ***SNe Ia synthesize the 1/2-2/3 of the iron peak nuclei not produced by SNe II.***

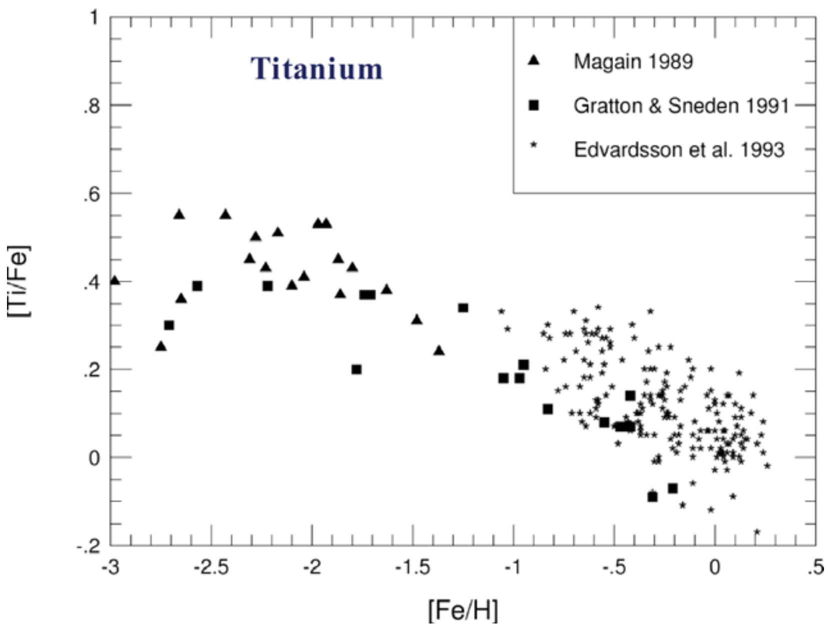
  - ***The time histories of the (α-element/Fe) ratio identify the early entry of the contributions from SNe II and the ensuing "delayed" entry of SNe Ia ejecta . Yoshi et al. (1996)estimated a time 'delay' $\approx$ 1.5 Gyr from chemical evolution considerations.***

Halo Abundance Trends for -3 < [Fe/H] < -1

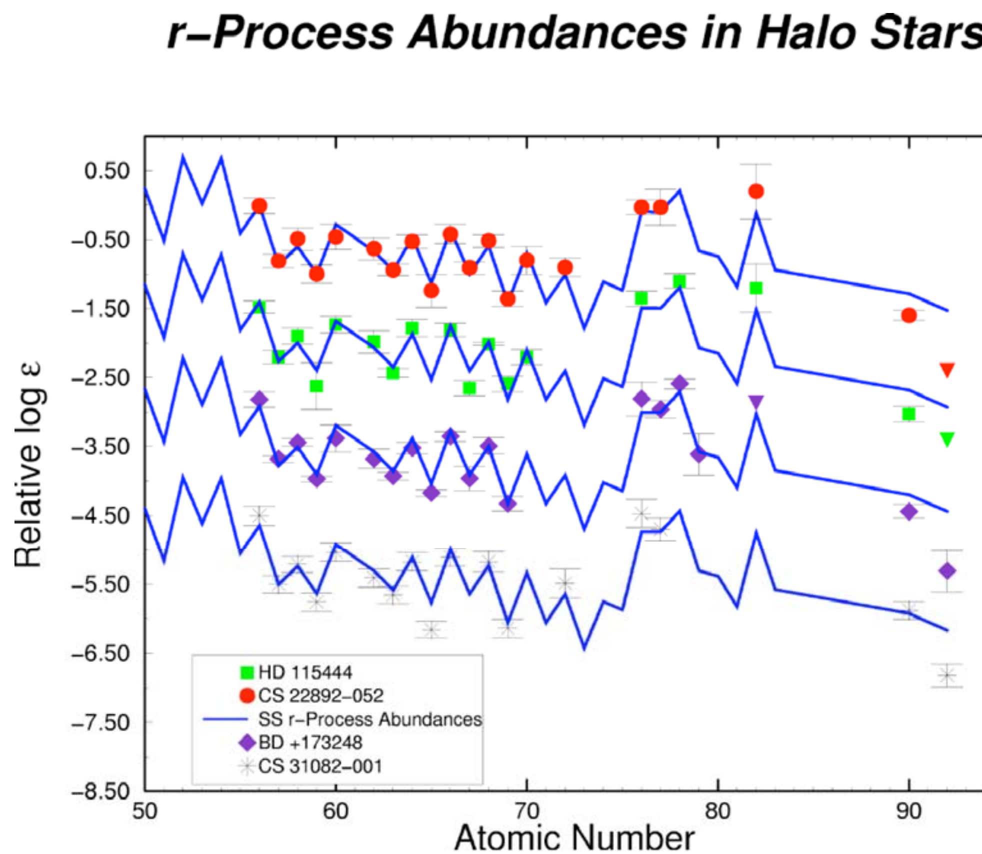
Oxygen and α-Elements



Figures courtesy F. X. Timmes



r-Process Elements



(Truran et al. 2002)

- ❑ **These behaviors are compatible with nucleosynthesis predictions for SNe II.**

Supernova Ia: Progenitors and Sites

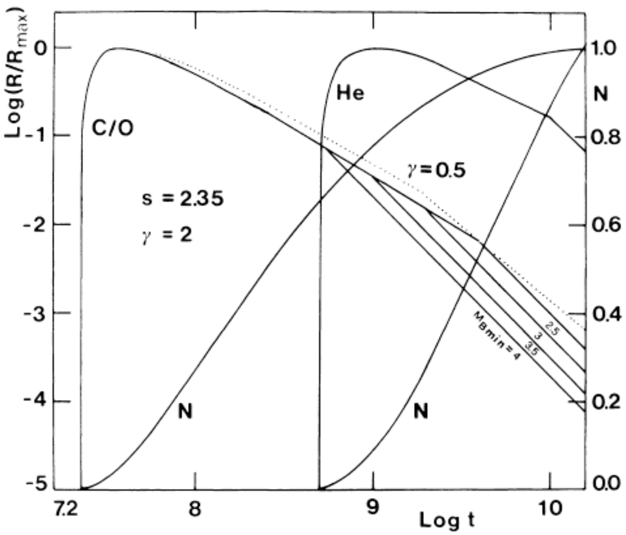
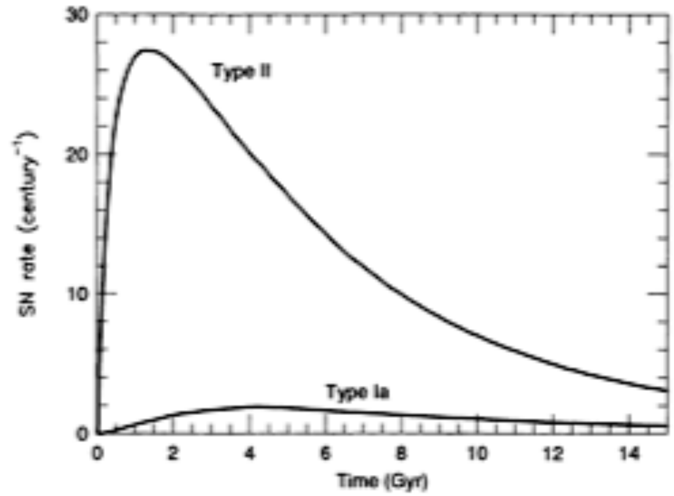
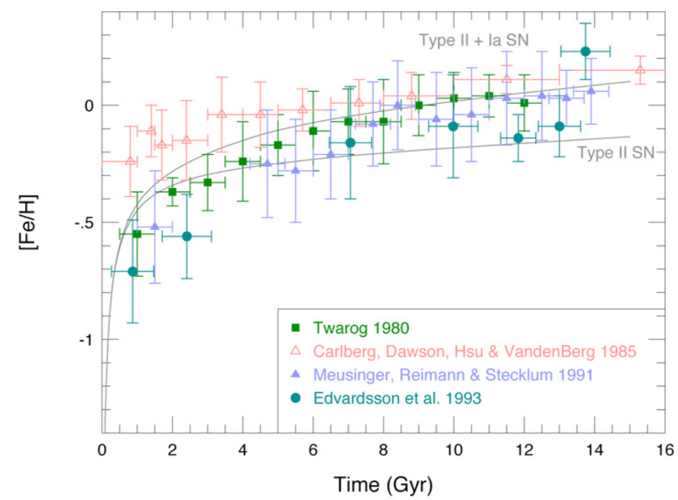


Fig. 1. The SNI rate following a burst of star formation *vs* the time (in yr) elapsed since the burst. The rates refer to both C/O and He white dwarf precursors, and are normalized to their respective maximum values. The values of the parameters s, γ, and $M_{B,\min}$ are reported. The dotted line refers to $\gamma=0.5$ and $M_{B,\min}=3$. The number of SNe exploded until the time t is also drawn for both kinds of precursors



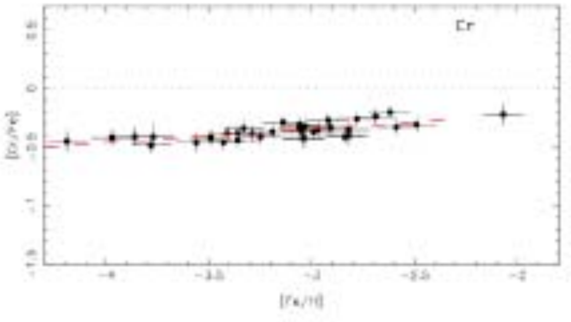


(Greggio and Renzini 1983)

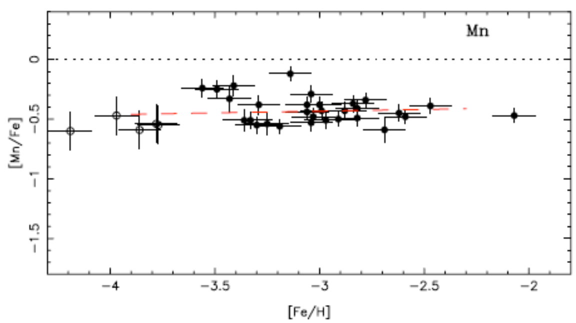
(Timmes et al. 1995)

[a/Fe] in Halo Stars to Lowest Metallicities

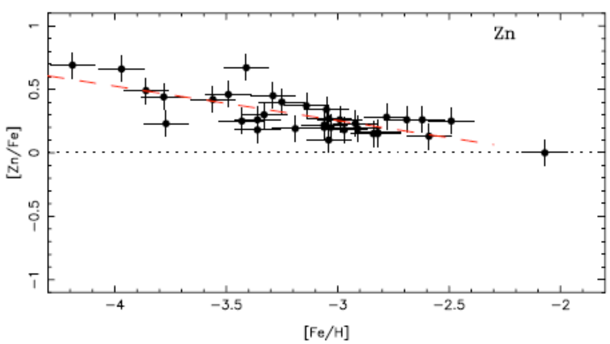
(Cayrel et al. 2004)



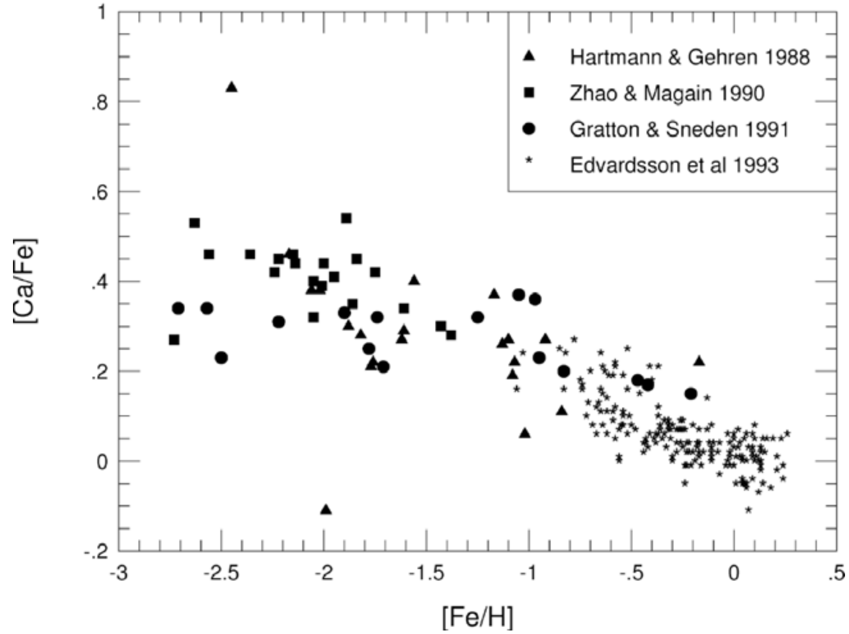
[Cr/Fe]

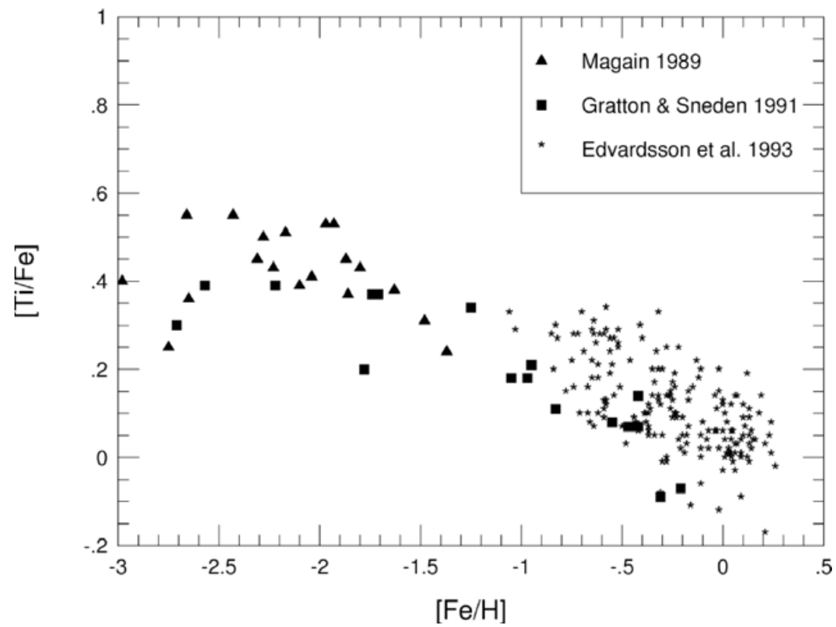


[Mn/Fe]



[Zn/Fe]

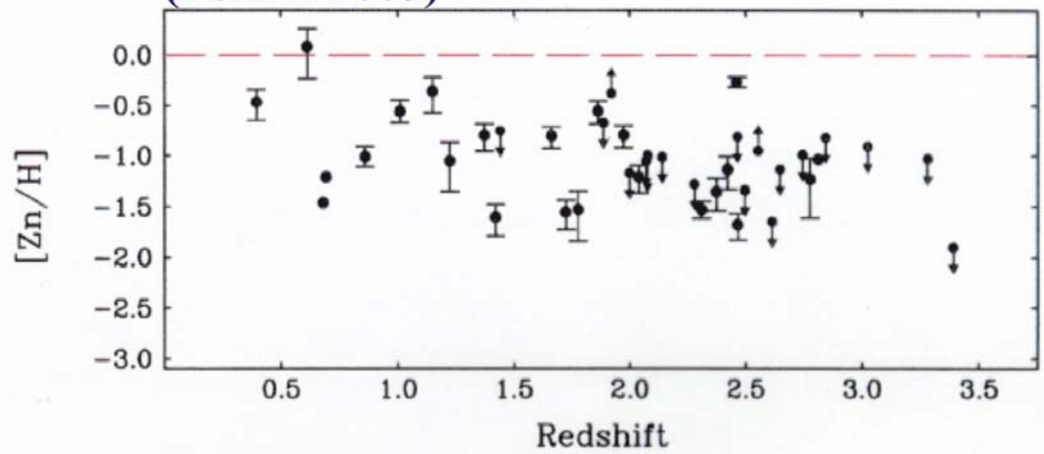




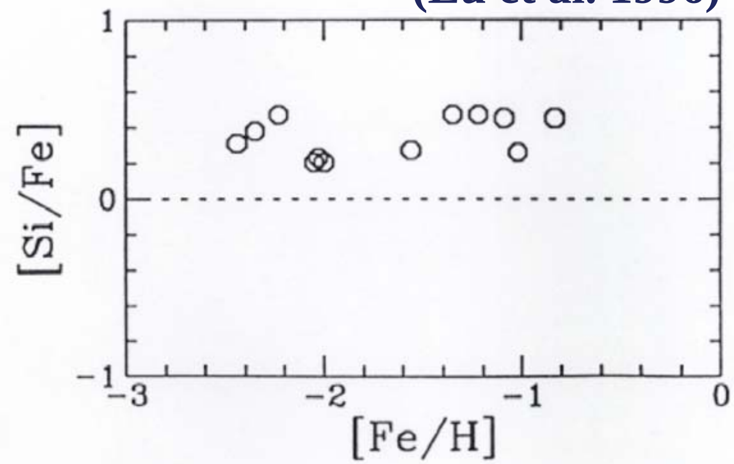
[Si/Fe] Trends in Diverse Environments

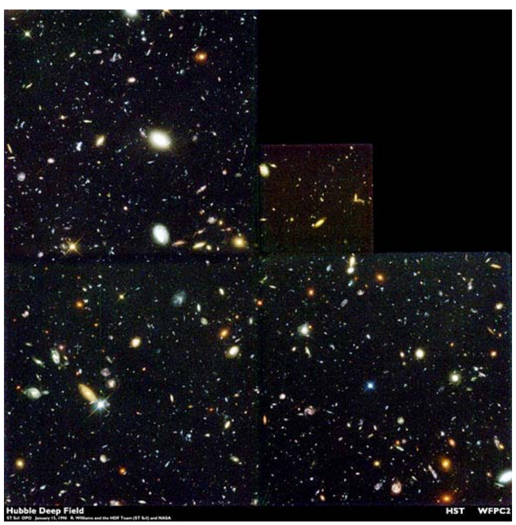
Abundances in DLAs

(Pettini 2003)

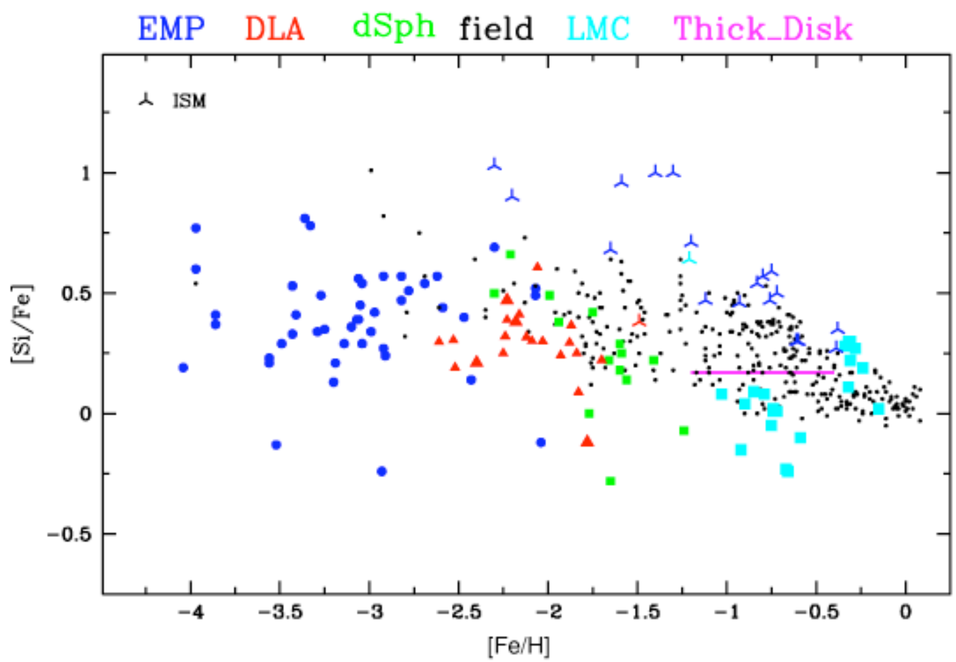


(Lu et al. 1996)





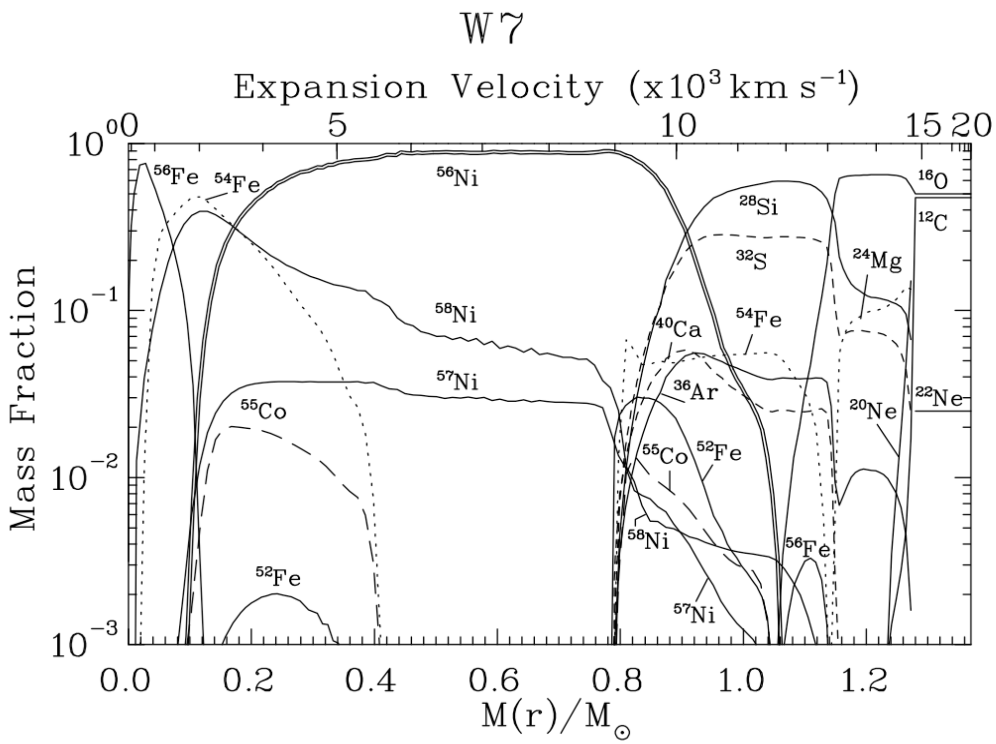
Hubble Deep Field



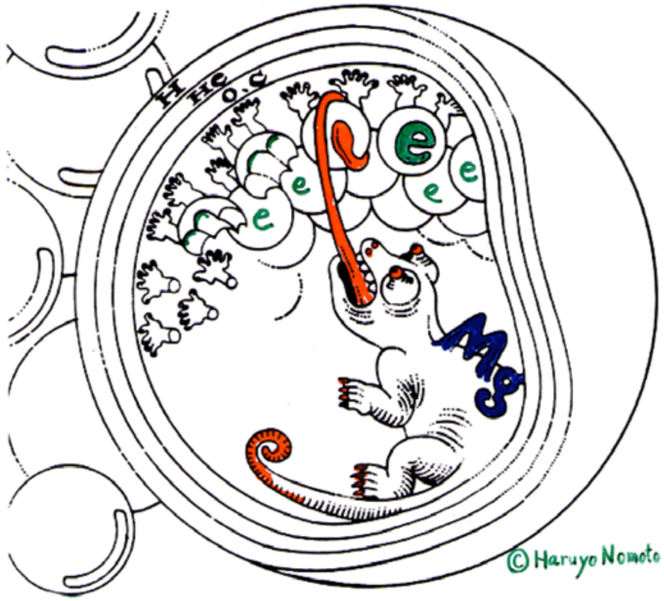
Francesca Primas (2003)

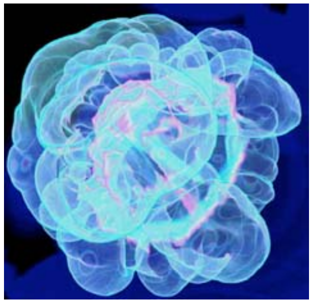
Neutronization and ^{56}Ni Production

- Nearly all one-dimensional Chandrasekhar mass models of Type Ia supernovae produce most of their ^{56}Ni in a nuclear statistical equilibrium environment between mass shells 0.2 $M_{\odot}$ and 0.8 $M_{\odot}$.
- In this region weak reactions occur on timescales longer than the timescale for disruption of the white dwarf by a burning front.



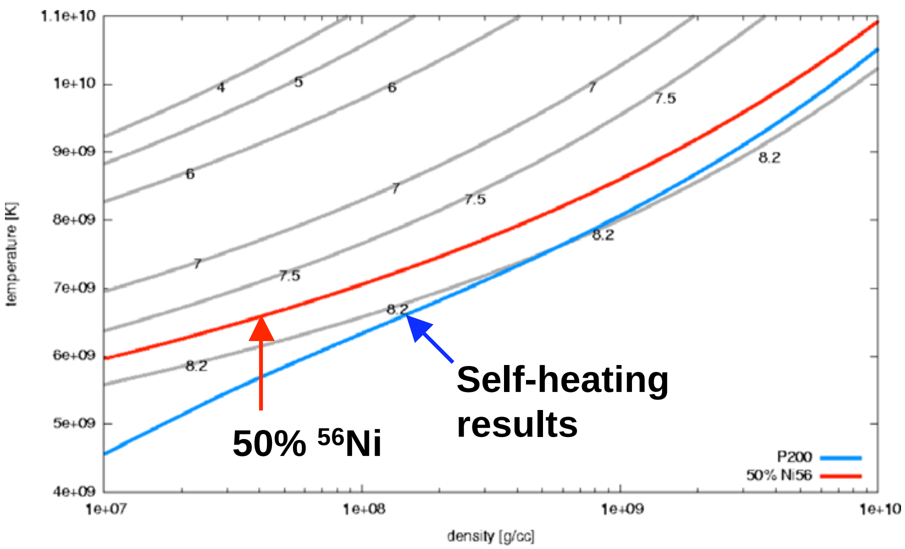
(Iwamoto et al. 1999)





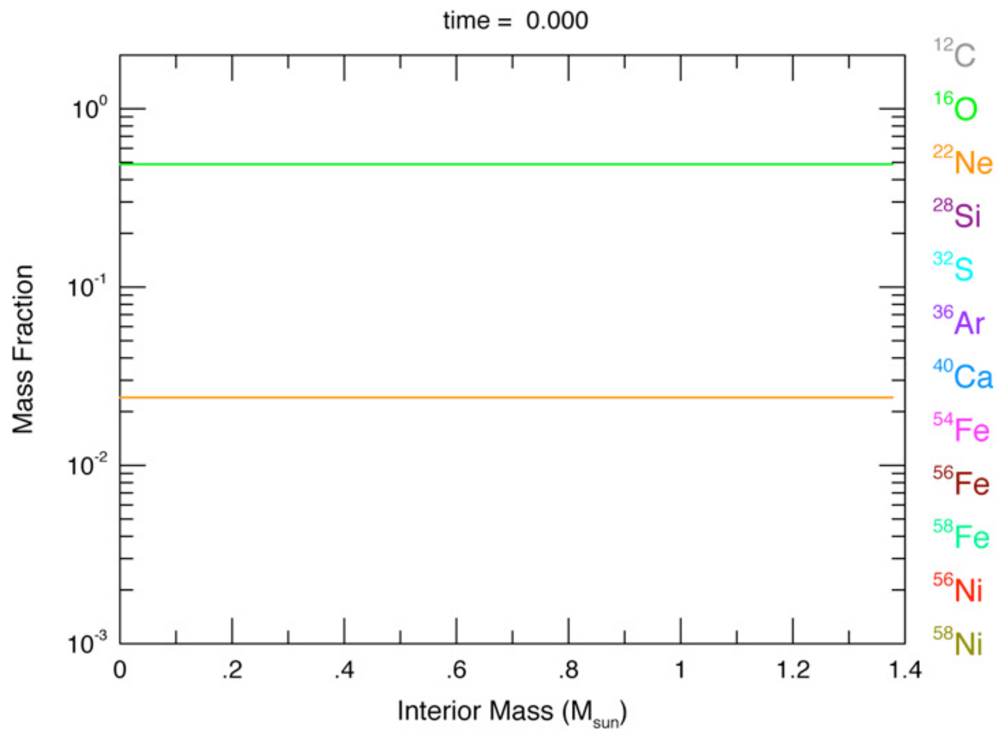
Supernova Ia: Nucleosynthesis

Average Binding Energy per Nucleon



Deflagration Simulations
(Calder et al. 2007; Townsley et al. 2007)

Y_e < 0.5 ***^{56}Ni Production*** ***Intermediate Mass Nuclei***



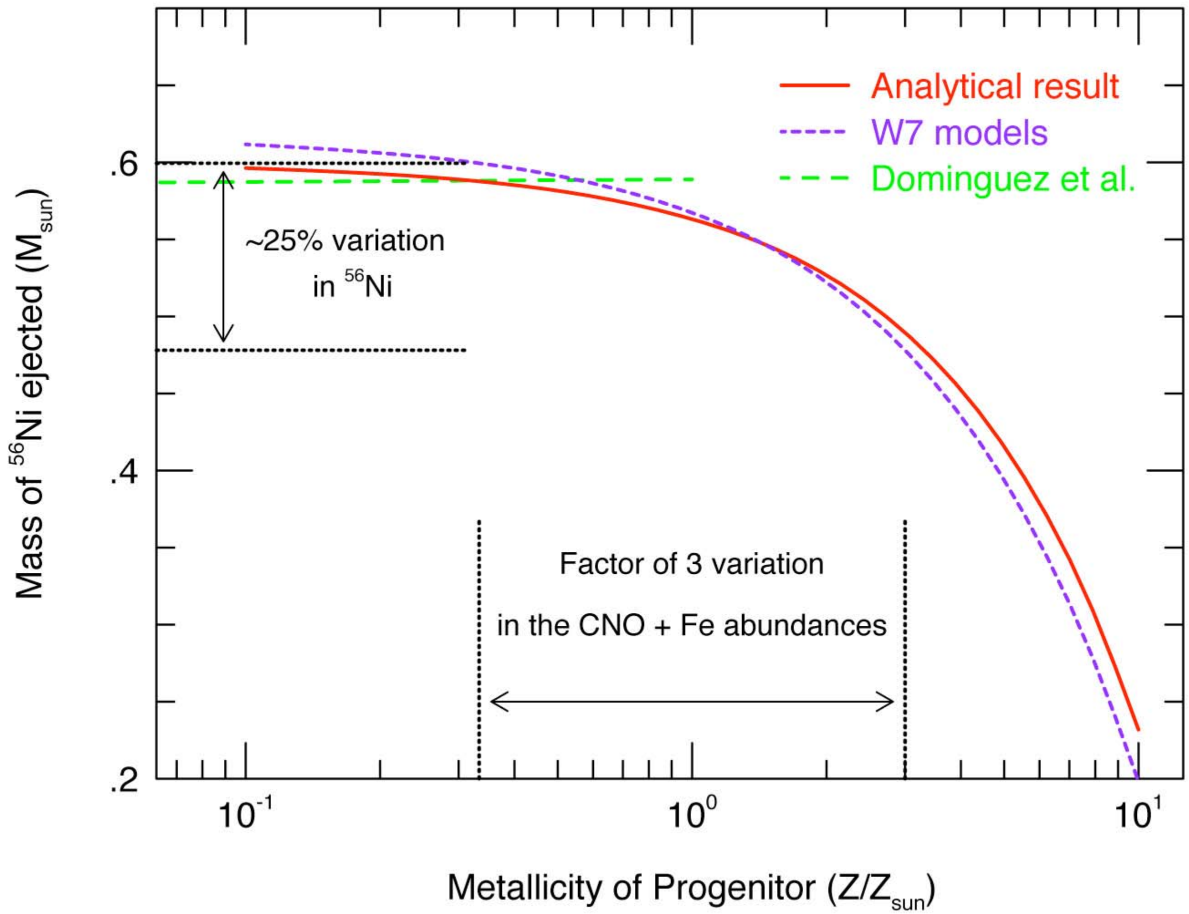
Evolution (W7) of Core Composition *(Timmes et al. 2003)*

The sensitivity of the emerging elemental and isotopic patterns to neutronization (e.g. Y_e) underscores the importance of accurate weak interaction (e.g. electron capture) rates for both Type Ia (thermonuclear) and Type II (collapse) supernovae.

Abundance Scatter

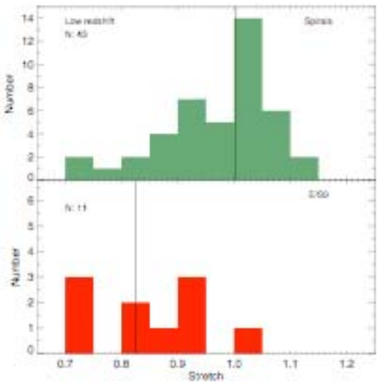
- A scatter of a factor of 3 about the mean in the initial metallicity of the progenitor star (or its stellar population) leads to a variation of about 25% (0.13 $M_{\odot}$) in the mass of ^{56}Ni ejected.

Timmes, Brown, & Truran 2003

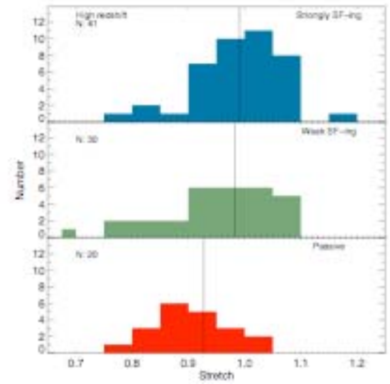


- The peak brightness variation caused by this variation in the mass of ^{56}Ni ejected is DMV ~ 0.3 mag. which doesn't account for all the observed variation.

Population Dependences of Outburst Properties

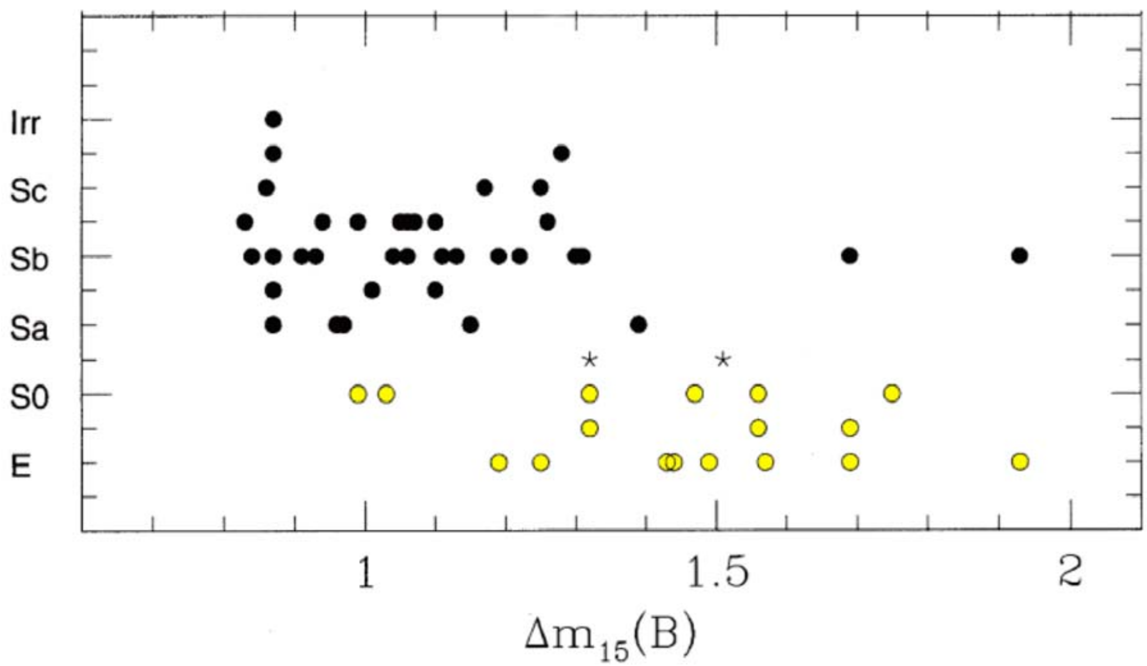


The top panel shows galaxies morphologically specified as spirals, while the lower panel shows SNe in ellipticals or S0s.



The top panel shows galaxies with a specific star formation rate (sSFR) of log(sSFR)>-9.5, the middle panel those with -12< log(sSFR)<-9.5, and the lower panel log(sSFR)<-12.

(Sullivan et al. 2006)



(Hamuy et al. 2002)

SN Ia Luminosity Evolution

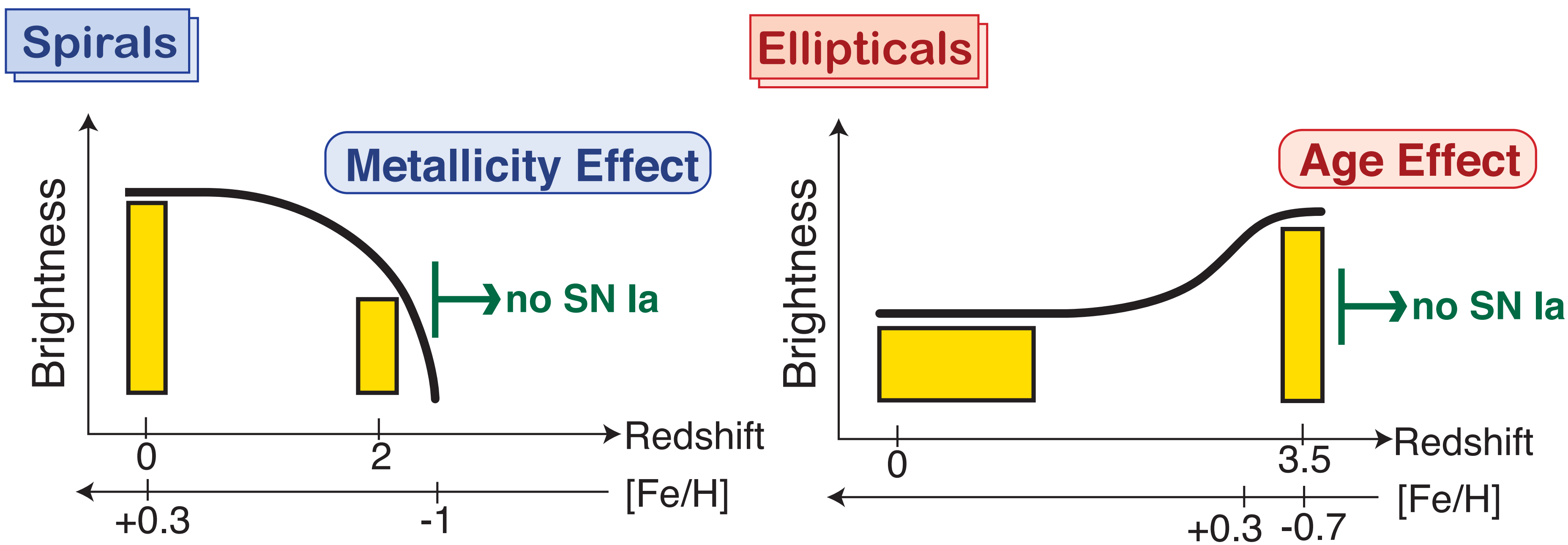


Figure Courtesy Ken Nomoto

Supernova Ia: Progenitors and Sites

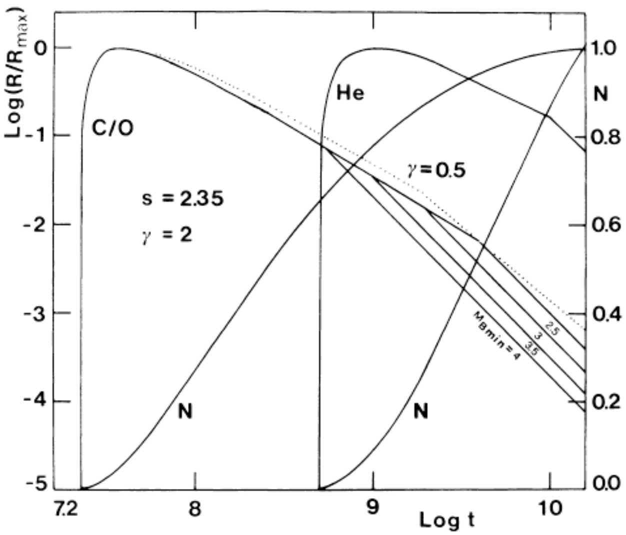
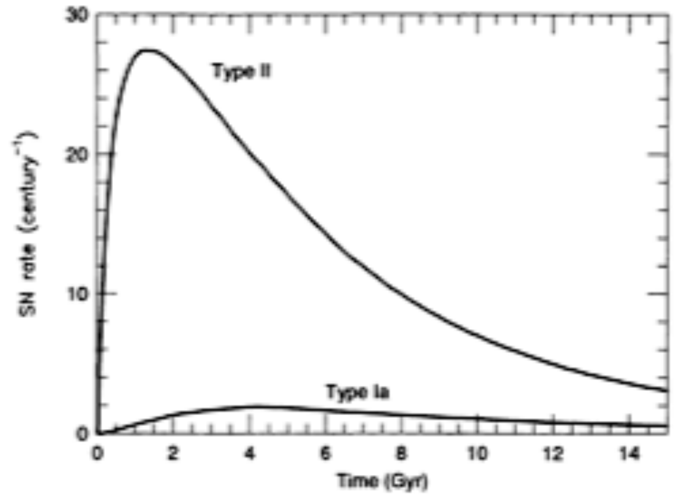
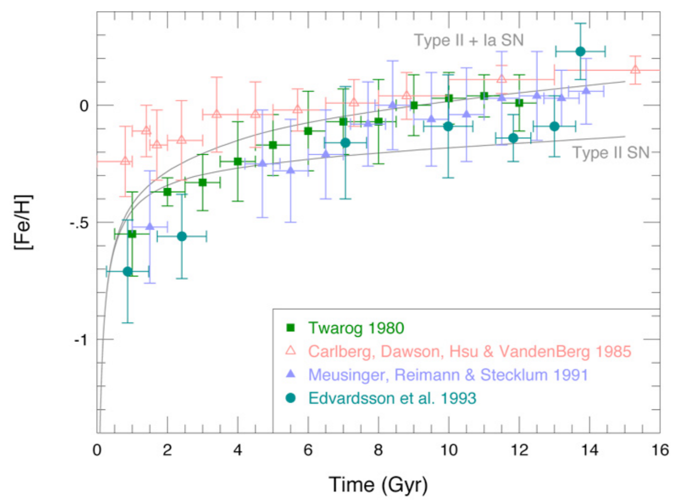


Fig. 1. The SNI rate following a burst of star formation *vs* the time (in yr) elapsed since the burst. The rates refer to both C/O and He white dwarf precursors, and are normalized to their respective maximum values. The values of the parameters *s*, γ, and $M_{B,\min}$ are reported. The dotted line refers to $\gamma=0.5$ and $M_{B,\min}=3$. The number of SNe exploded until the time *t* is also drawn for both kinds of precursors





(Greggio and Renzini 1983)

(Timmes et al. 1995)

Sne Ia and Galactic Chemical Evolution

❑ **Abundance determinations for metal deficient field halo stars and globular cluster stars have quantified the overproduction of α-particle nuclei (^{16}O to ^{40}Ca) in Type II supernovae: [α-nuclei/Fe] ≈ +0.3 to +0.5**

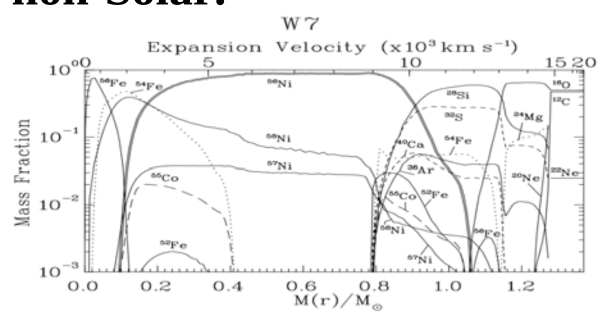
❑ **Following recent nucleosynthesis studies for SNe Ia and SNe II, we can assume here that SNe Ia produce ≈ 0.6 $M_{\odot}$ per event, while the SNe II iron yield is ≈ 0.1 $M_{\odot}$ per event. We can conclude that over Galactic history of the ratio of Type II to Type Ia events lies in the range $N_{SNe\ II}/N_{SNe\ Ia}$ ≈ 3-6.**

❑ **The history of the α-nuclei/Fe ratio over the history of our Galaxy reveals the emergence of SNe Ia products at a stage for which the iron enrichment [Fe/H] ≈ -1.5 to -2, while the observed rate of SNe Ia events traces the star formation rate. Yoshi, Tsijumoto, and Nomoto (1996) estimated a delay time ~ 1.5 Gyr from chemical evolution consideations.**

Contraints on SNe Ia Models and Nucleosynthesis

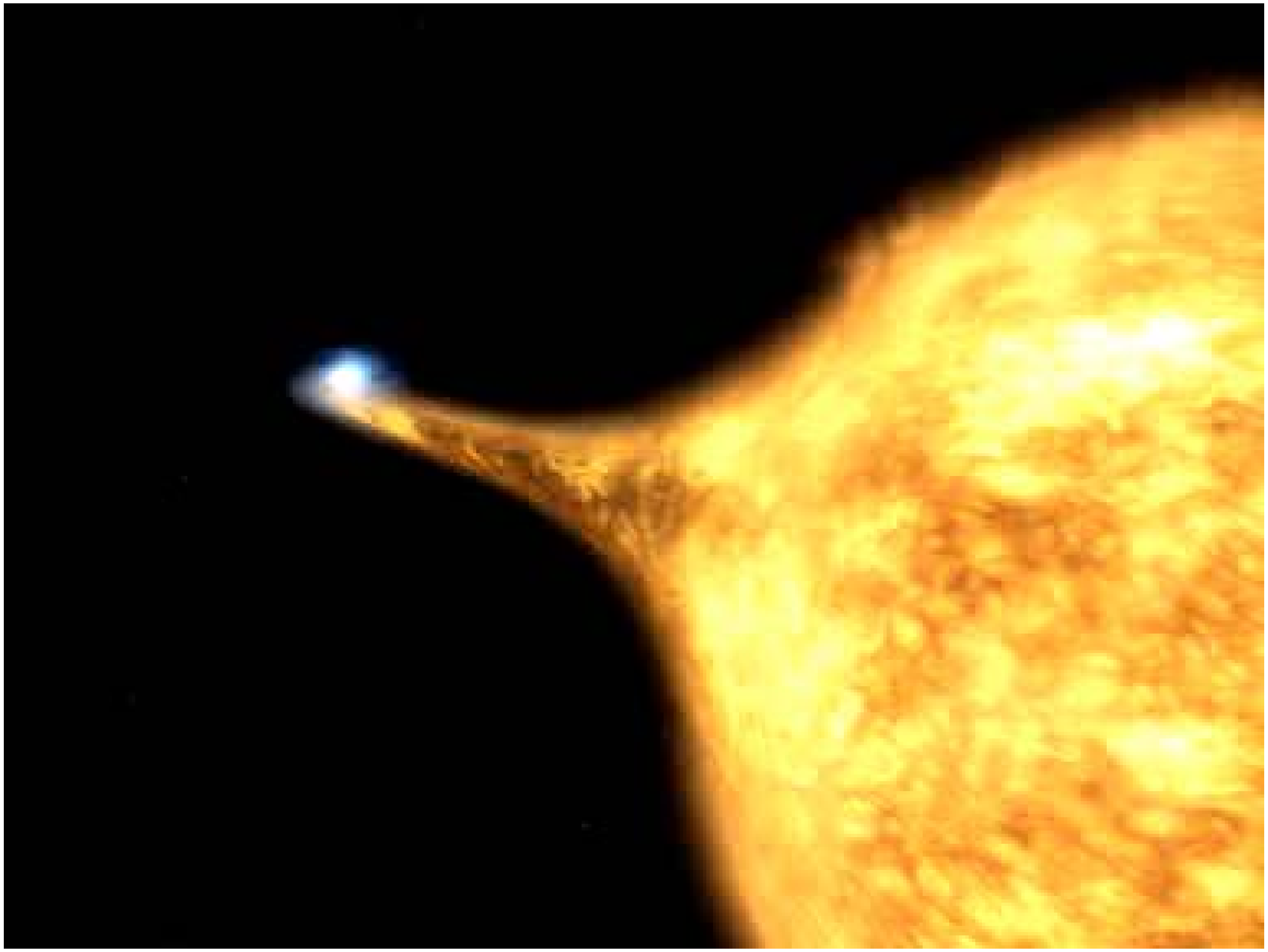
- **Given our recognition of the fact that the brightness of a Type Ia supernova is proportional to the mass ejected in the form of ^{56}Ni, it seems natural to seek an explanation for the observed spread in SNe Ia peak luminosities that involves varying degrees of neutronization of the core matter: neutronization $\Rightarrow$ lower Y_e $\Rightarrow$ presence of more neutron-rich iron- peak nuclei $\Rightarrow$ lower ^{56}Ni concentration. A concern here is whether the levels of neutronization required to effect these changes will alter the iron peak abundance pattern.**

- **Note that neutronization alone cannot easily explain the entire spread in peak SNe Ia luminosities. If a significant fraction of the ~ 0.6 $M_\odot$ of ^{56}Ni in e.g. the W7 model were neutronized to form ^{54}Fe or ^{58}Ni at the expense of ^{56}Ni, the isotopic composition of the resulting iron peak would be extremely non-Solar.**



- **As best we know from observations, the characteristics of the iron-peak abundance patterns emerging from SNe Ia and SNe II are similar. Cosmic ray (ACE) studies (the only source of such information available) reveal no significant evolution of the isotopic composition of Fe-peak isotopes.**

The Standard Model for SNe Ia



- **Progenitor: White dwarf in a binary system**
- **Growth to the Chandrasekhar limit by mass transfer**

Thank you Ken for all of your wonderful contributions.