From Accreting White Dwarfs to Explosions: The Story of W7 ... and beyond,

or spherically symmetric approaches to SNe Ia

Wickenburg, AZ

HP

Sony DSC-W7 Digital Camera
CCD 7.2Mpixels

Eutelsat W7 Communication Satellite (Launch 2009)

W7 Traffic Sign Series

Deflagration

Detonation

Pre-History

Pioneering Ideas: el-degenerate cores (Hoyle & Fowler 1960), C-detonations (Arnett 1969, but inconsistant abundances)

Observational Constraints: H-deficient stars (Oke & Searke 1974), only SNe in elliptical galaxies (Tammann 1974), not concentrated in spiral arms (Maza & van den Bergh1976), exponential tail of light curves (Barbon et al. 1973), detailed (light curve) observations of 1972e (Kirshner & Oke 1975), Ni-Co-Fe in spectra (Meyerott 1980), Branch (1982,1984) saw Ca,Si,S,Mg,O and Co at v_{exp}=10 000km in 1981b...., the differences between the SNe I subclasses became just clear or recognized.

Theoretical Conclusions and Models:

Exploding white dwarfs (Finzi & Wolf 1967, Whelan & Iben 1973),

energy source ^{56}Ni (Arnett 1979, Colgate et al. 1980, Axelrod 1980, Weaver, Axelrod, Woosley 1980, Chevalier 1981, Trimble 1982, Wheeler 1982),

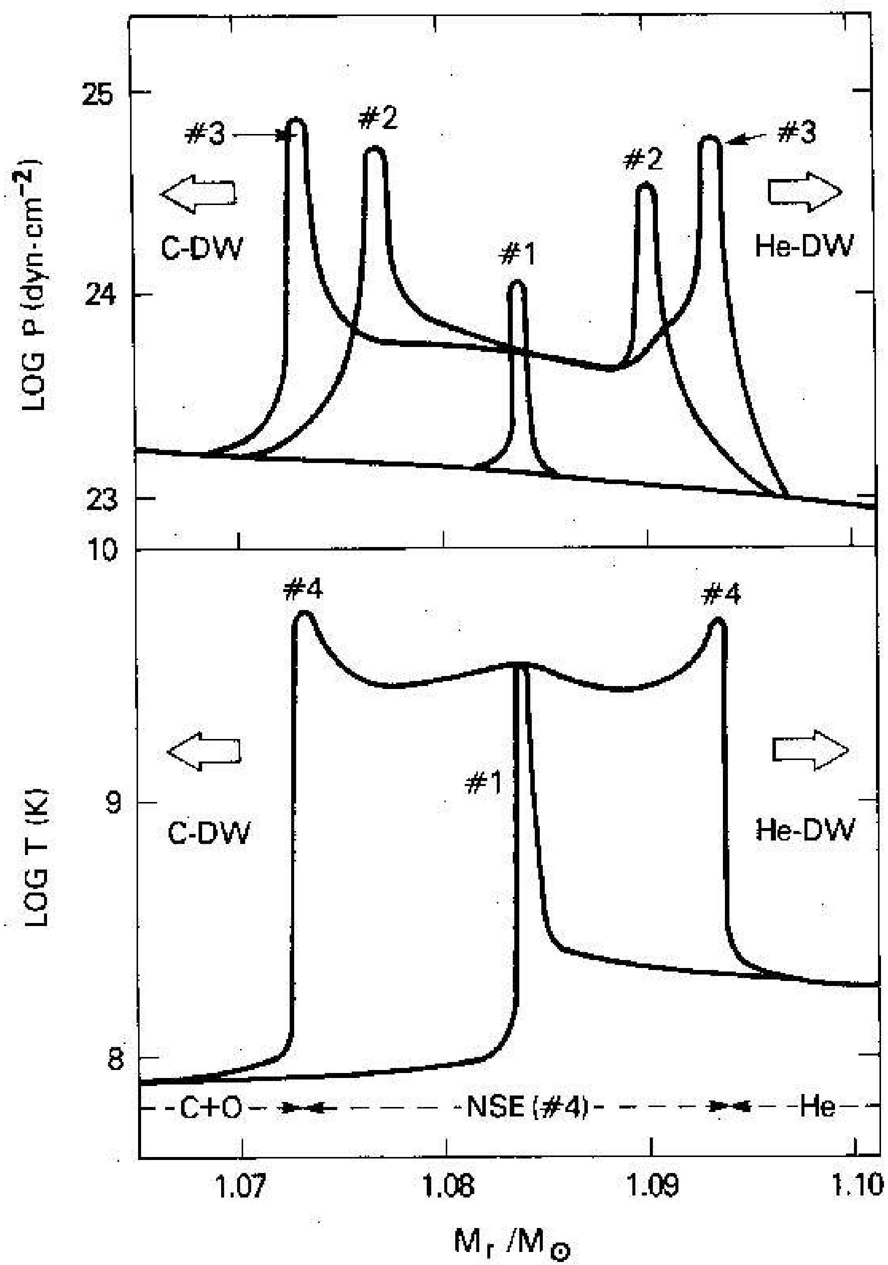
He white dwarfs (Arnett 1971, Mazurek 1973, Nomoto & Sugimoto 1977, Wheeler 1978, Arnett 1979),

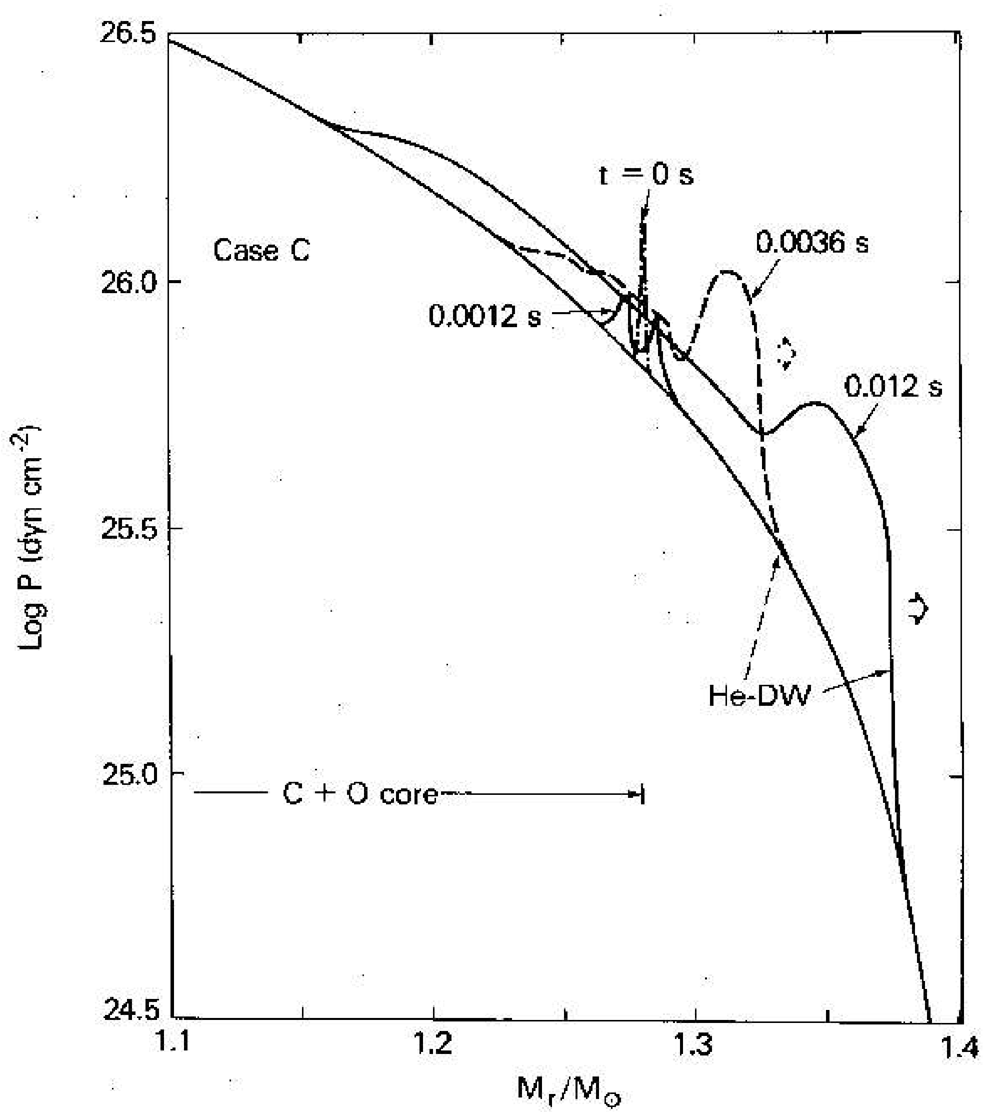
He-accreting white dwarfs (Nomoto & Sugimoto 1977, Fujimoto & Sugimoto 1979, 1981 Taam 1980, Nomoto 1980, 1981, Woosley, Weaver & Taam 1980, Sugimoto & Miyajy 1981, Fujimoto & Sugimoto 1982)

Options: Single detonations, double detonations, central carbon deflagrations (Ivanova, Imshennik & Chechetkin 1974, instabilities and convective propagation: Buchler & Mazurek 1975, Nomoto, Sugimoto & Neo 1976, Müller & Arnett 1982, 1984, Sutherland & Wheeler 1984)

Single and Double Detonations and other Options

Nomoto 1982



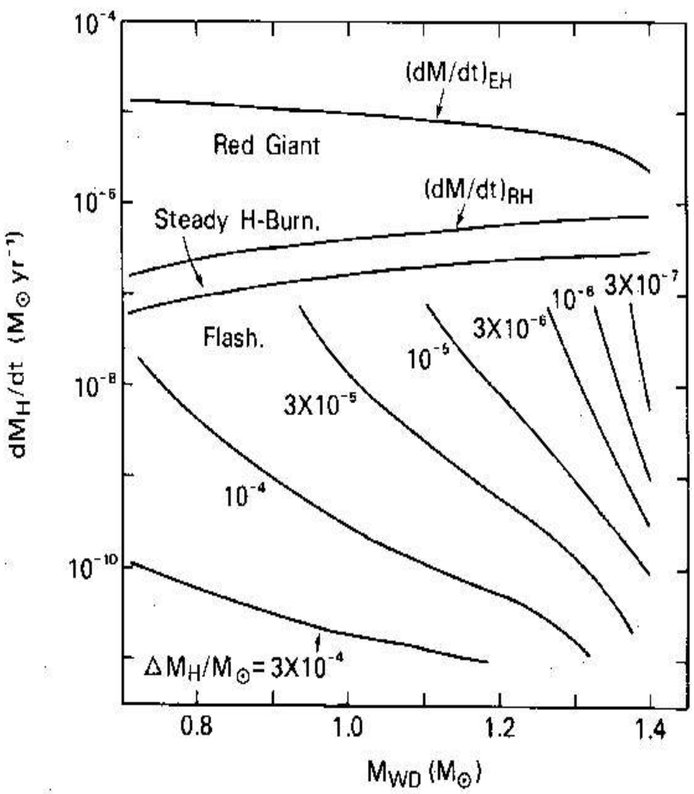


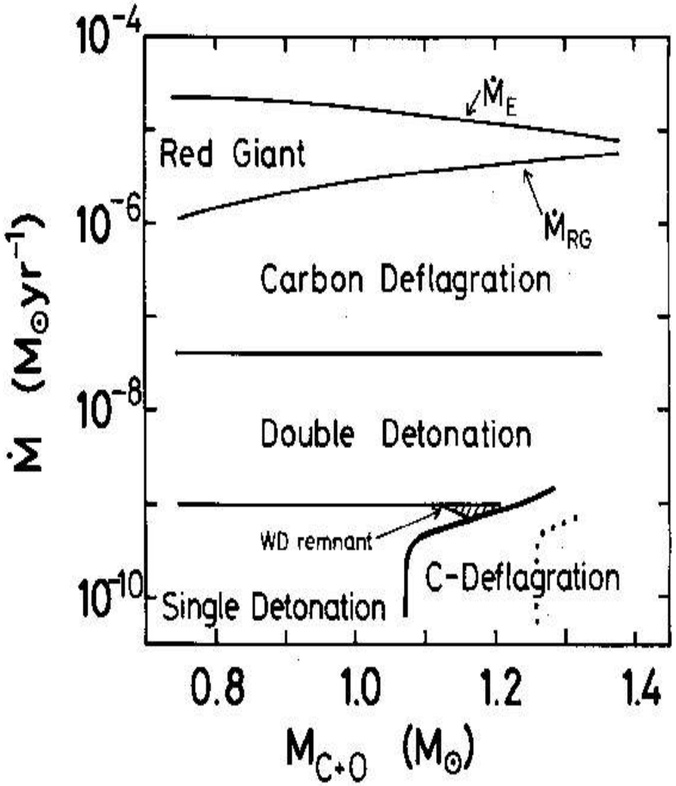
Accretion History and Outcome:

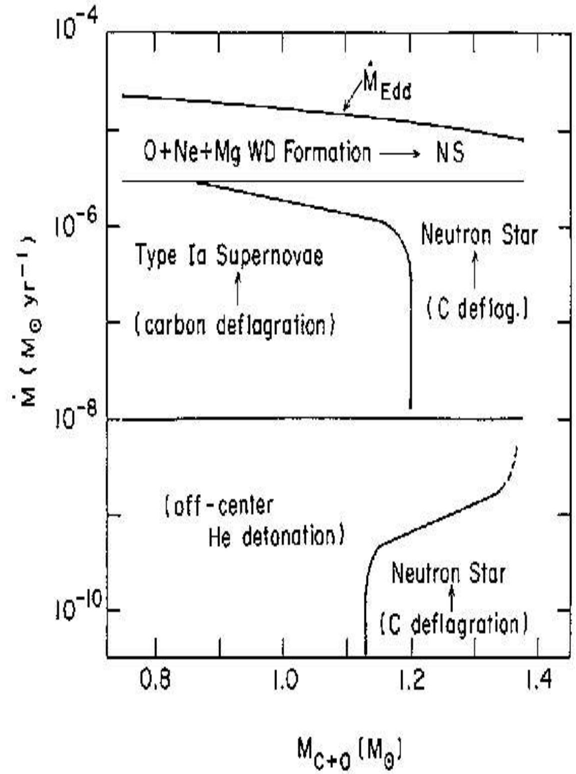
Nomoto 1982a,b, Nomoto & Kondo 1991

H-accretion

He-accretion



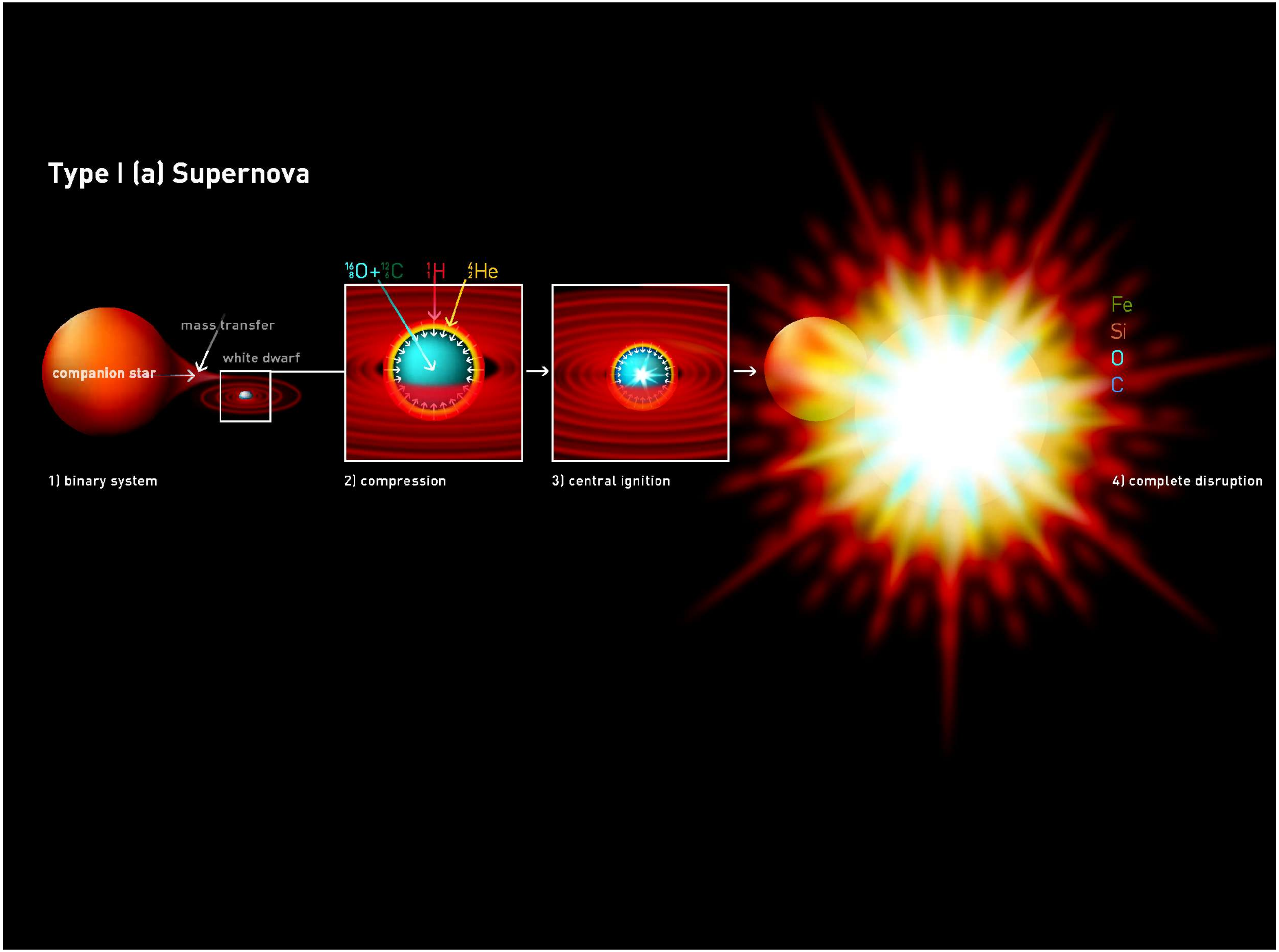




Preparation for W7

In 1982 and 1983 Ken and Yoyo came to the MPA in Garching.
The large nuclear network was just ready to go with the new WFHZ rates and after some tests with Dave Arnett in Chicago.

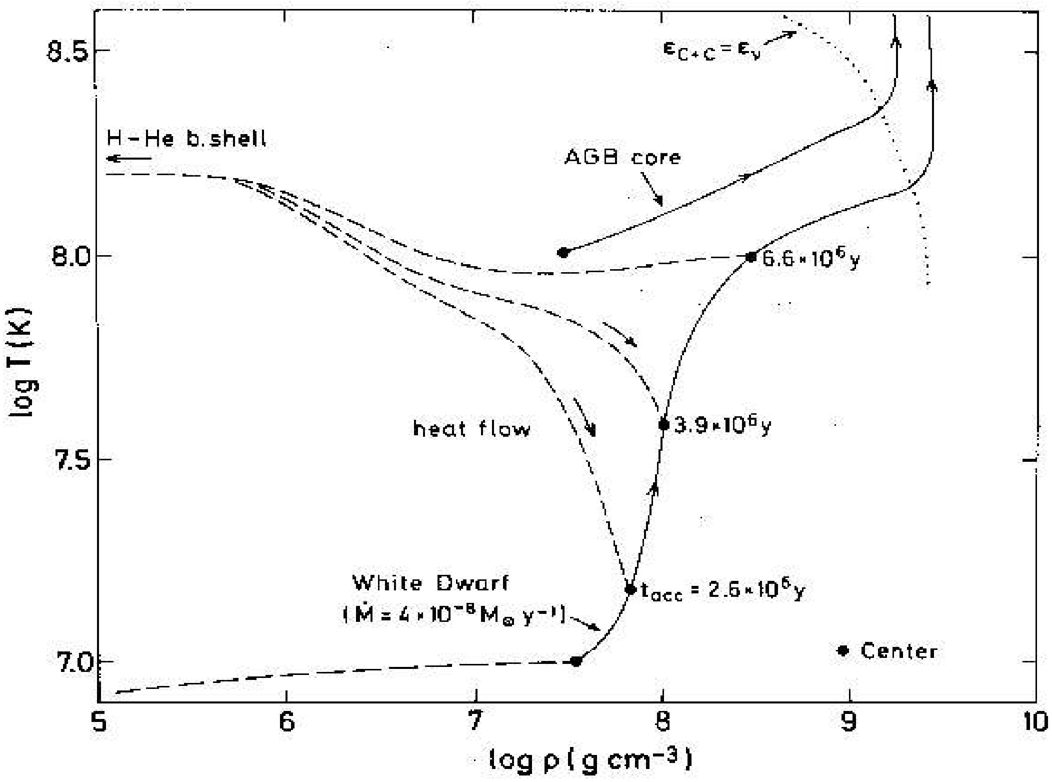
Type Ia Supernovae from Accretion in Binary Stellar Systems

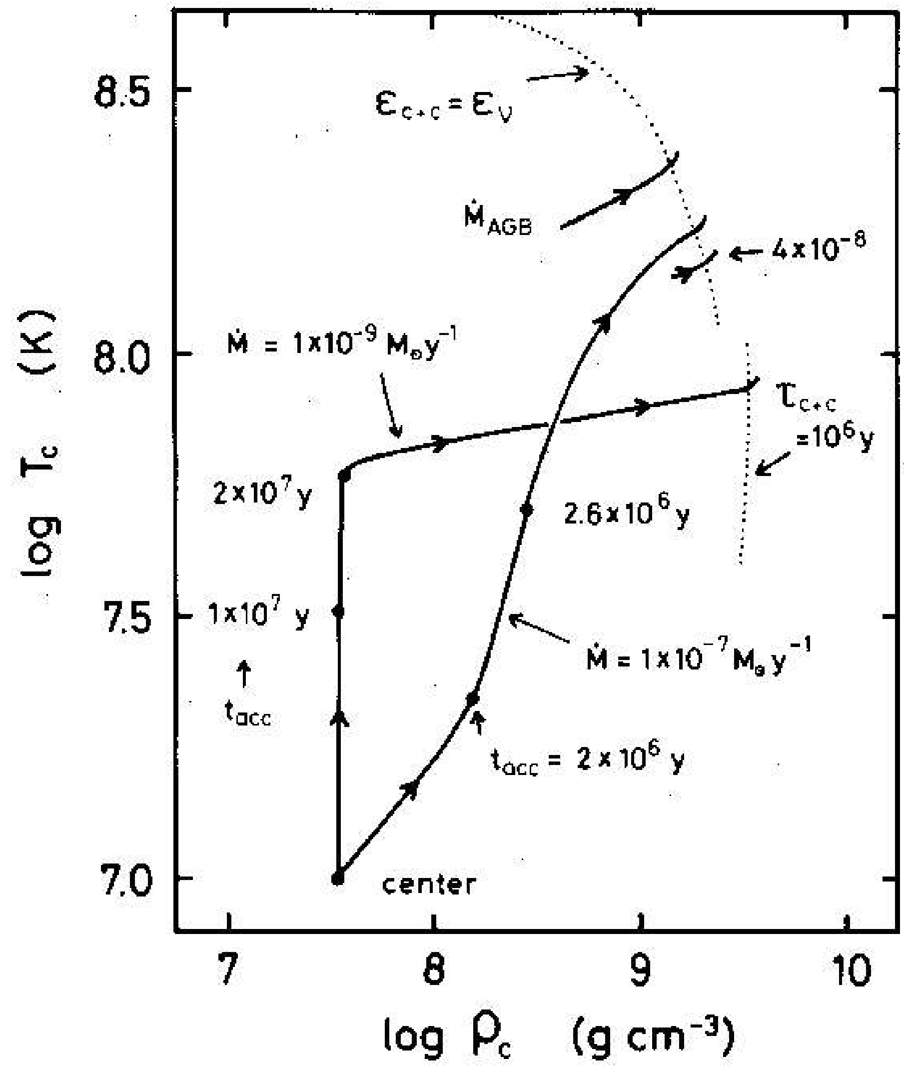


Central Ignition

for three different accretion rates

Nomoto, Thielemann, Yokoi 1984





W7: A C-Deflagration Supernova

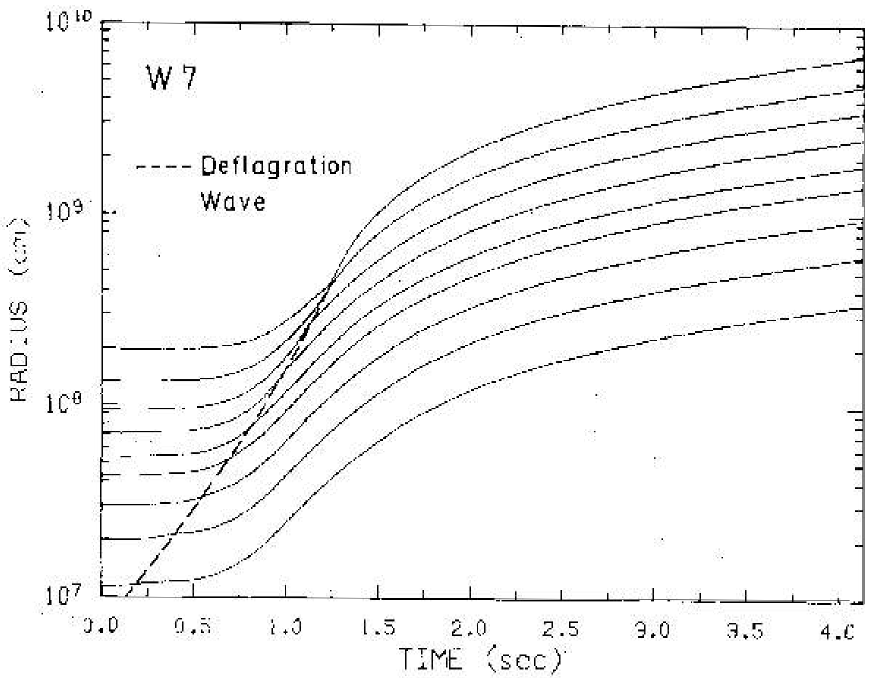
Ignition of adjacent layers due to subsonic heat transport via turbulence/convection (or conduction in very early phase). Approximation of 1D (spherically symmetric) burning front velocity from time-dependent mixing length theory of Unno (1967) with

$$l = \alpha H_p \quad \alpha = 0.7$$

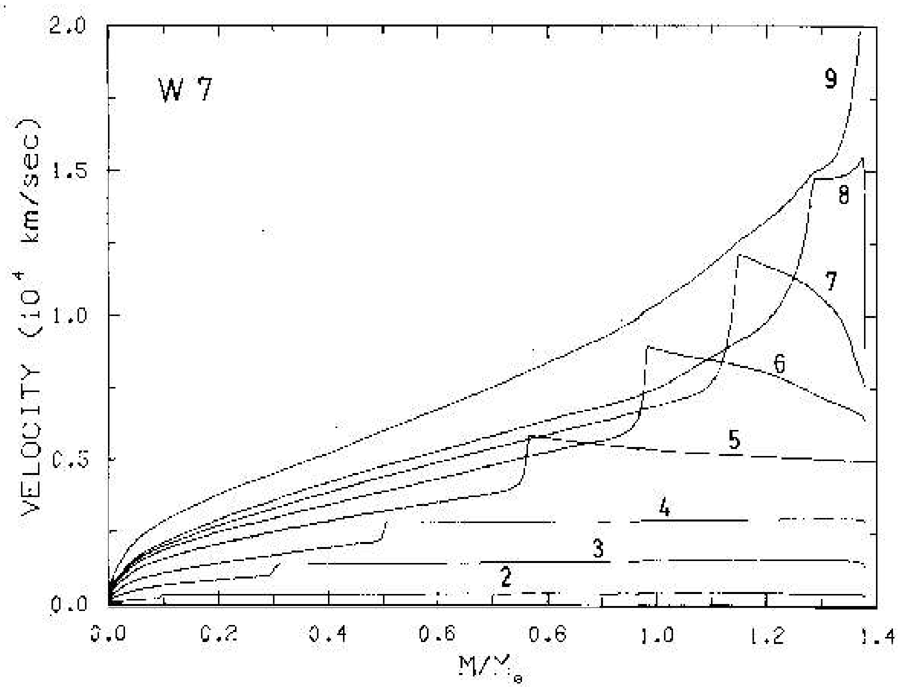
controling heat transport. The parameter choice 0.7 is responsible for the name W7 (W for white dwarf model). This parameter choice, used together with Lagrangian, implicit hydro code (Sugimoto, Nomoto & Eriguchi 1982), an alpha-network and parametrized QSE-network for energy generation in hydro code (full network for postprocessing) gives a good fit to the lightcurve of 1972e (Graham 1986), about 0.6 M_{sol} of ^{56}Ni and agreement with spectra of intermediate mass elements of 1981b by Branch (1985).

Deflagration Phase of W7

Nomoto, Thielemann, Yokoi 1984



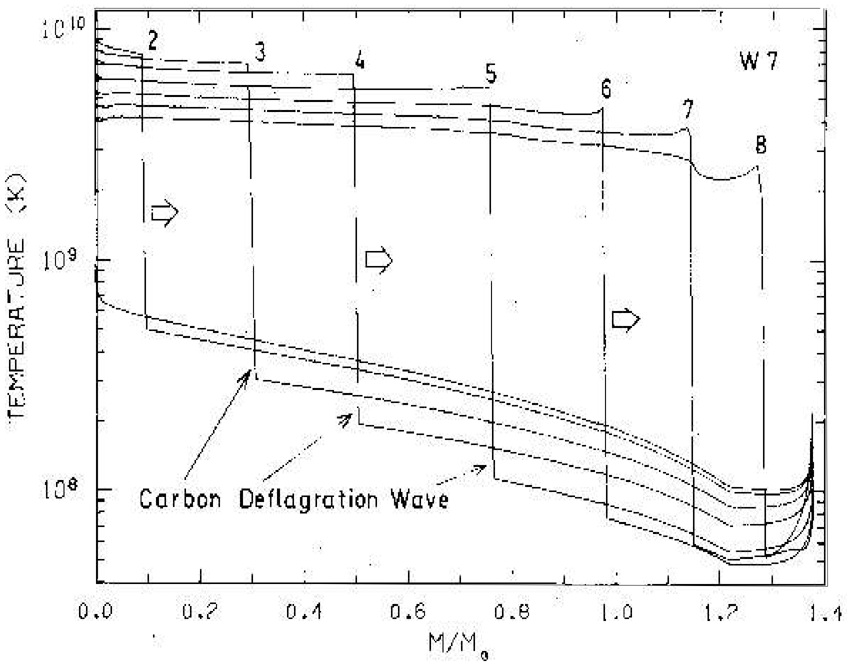
mass zones

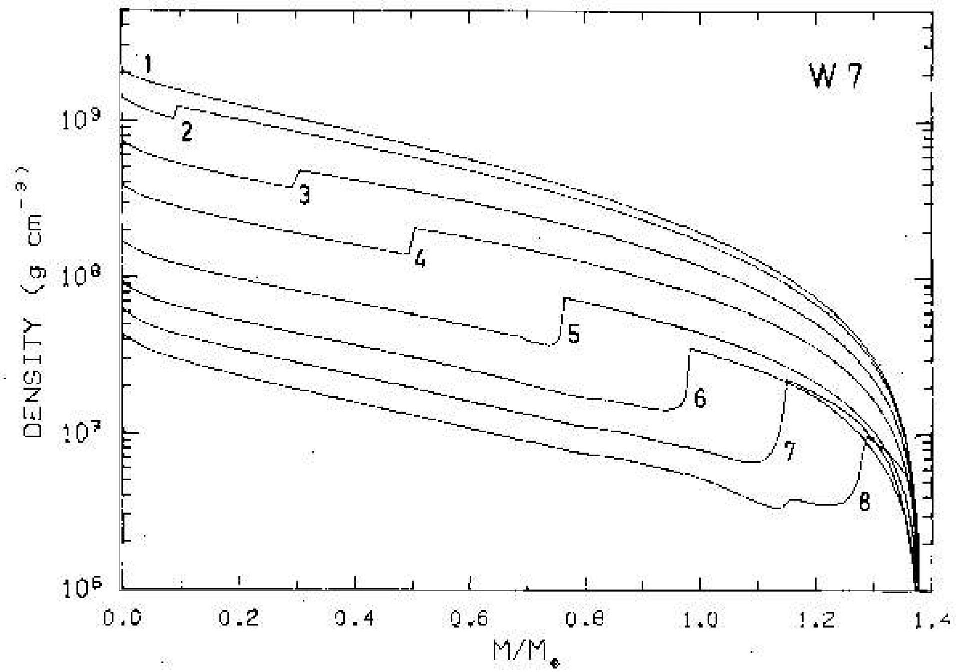


snapshots in time

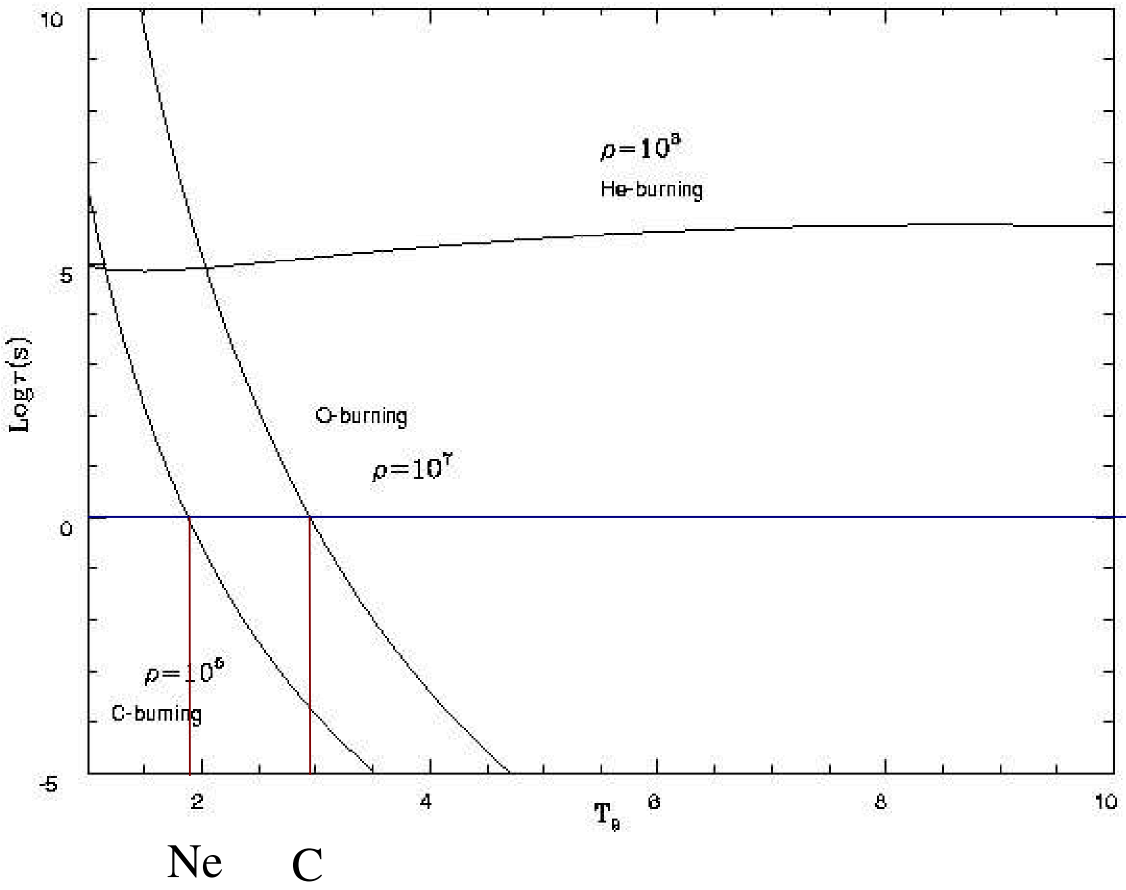
Temperature and Density

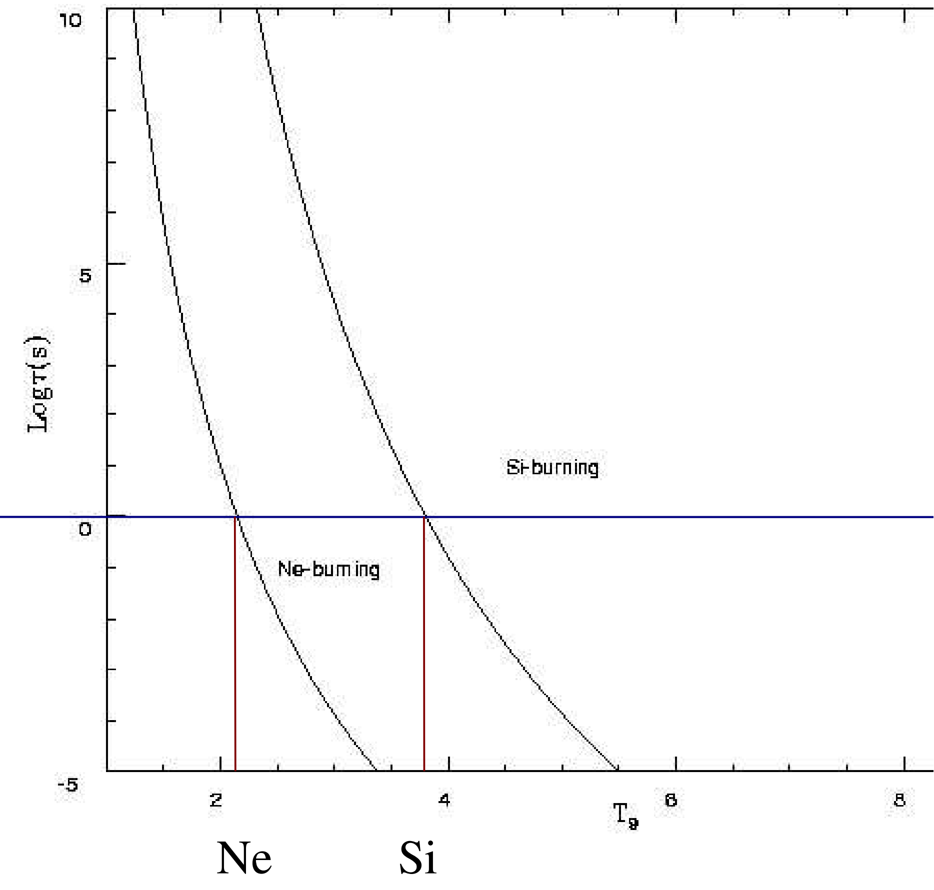
snapshots in time





Explosive Burning



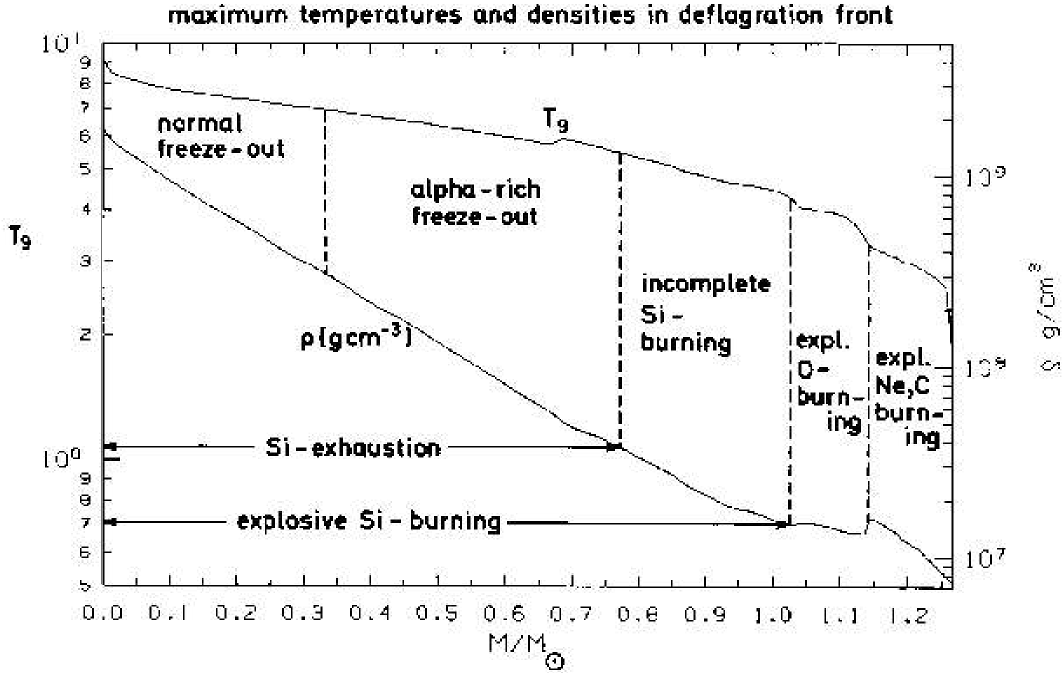


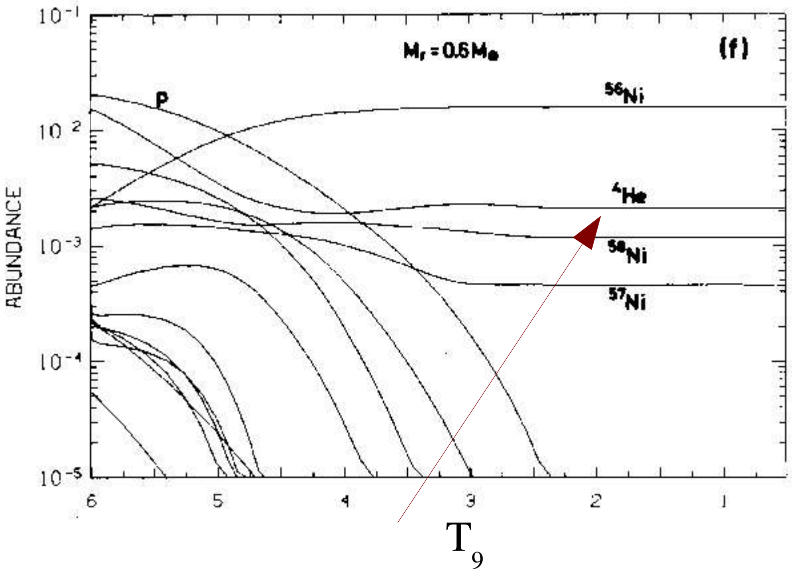
typical explosive burning process timescale order of seconds: fusion reactions (He, C, O) density dependent (He quadratic, C,O linear) photodisintegrations (Ne, Si) not density dependent

Explosive Burning

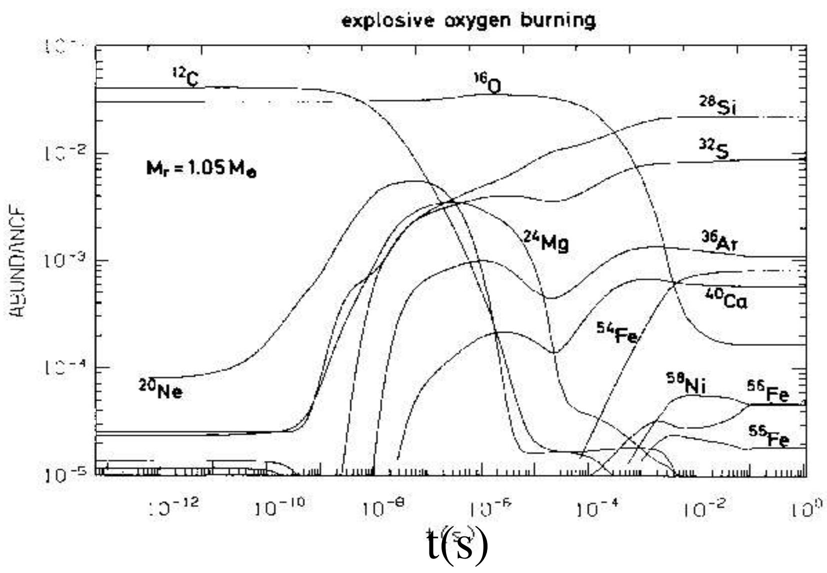
detailed analysis

Thielemann, Nomoto & Yokoi 1986 with reaction rate updates of Thielemann, Arnould & Truran 1986

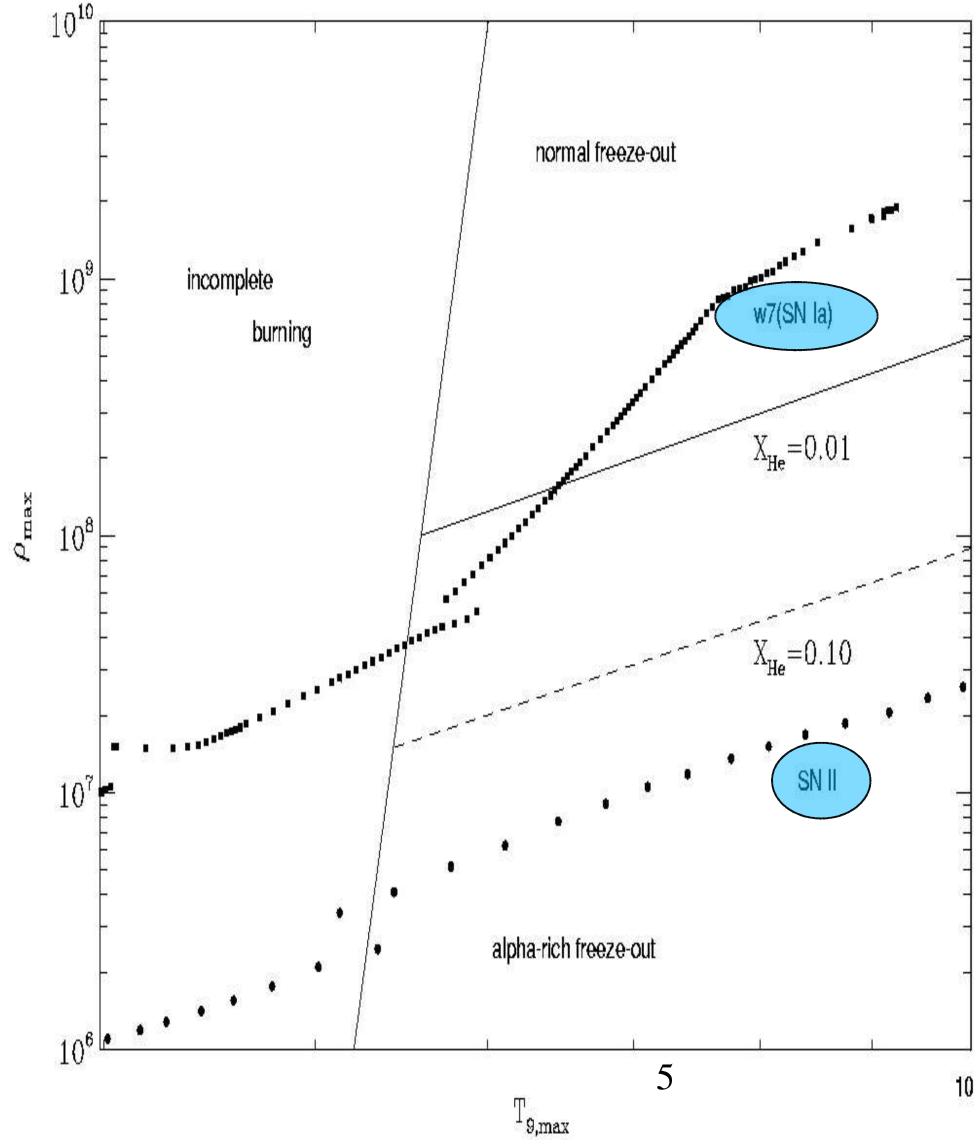


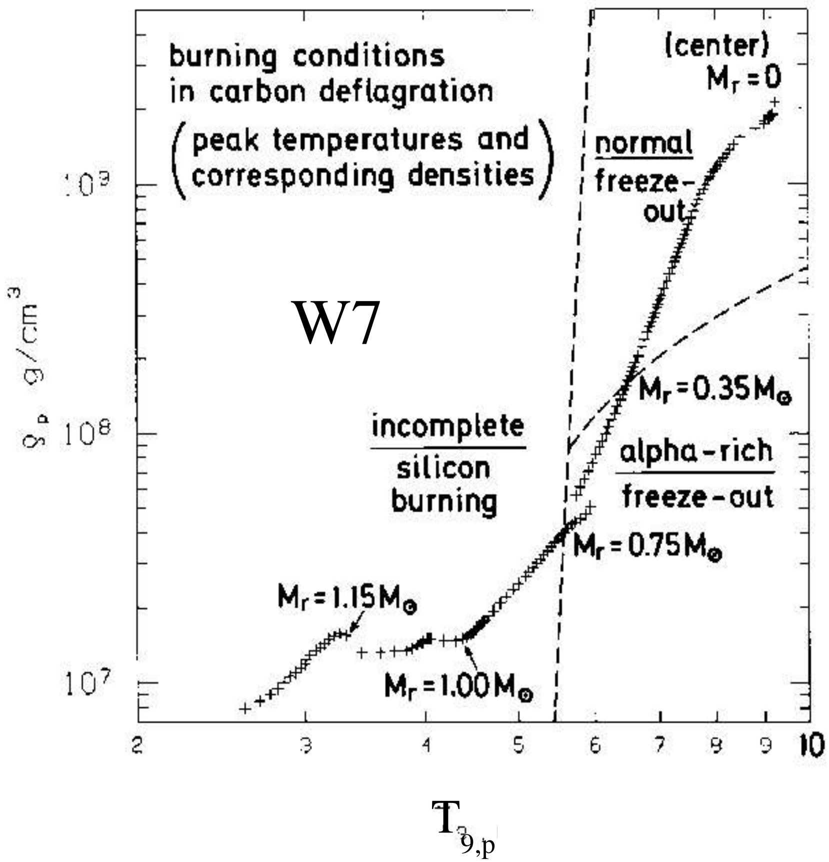


complete expl. Si-burning with alpha-rich freeze-out



Explosive Si-Burning



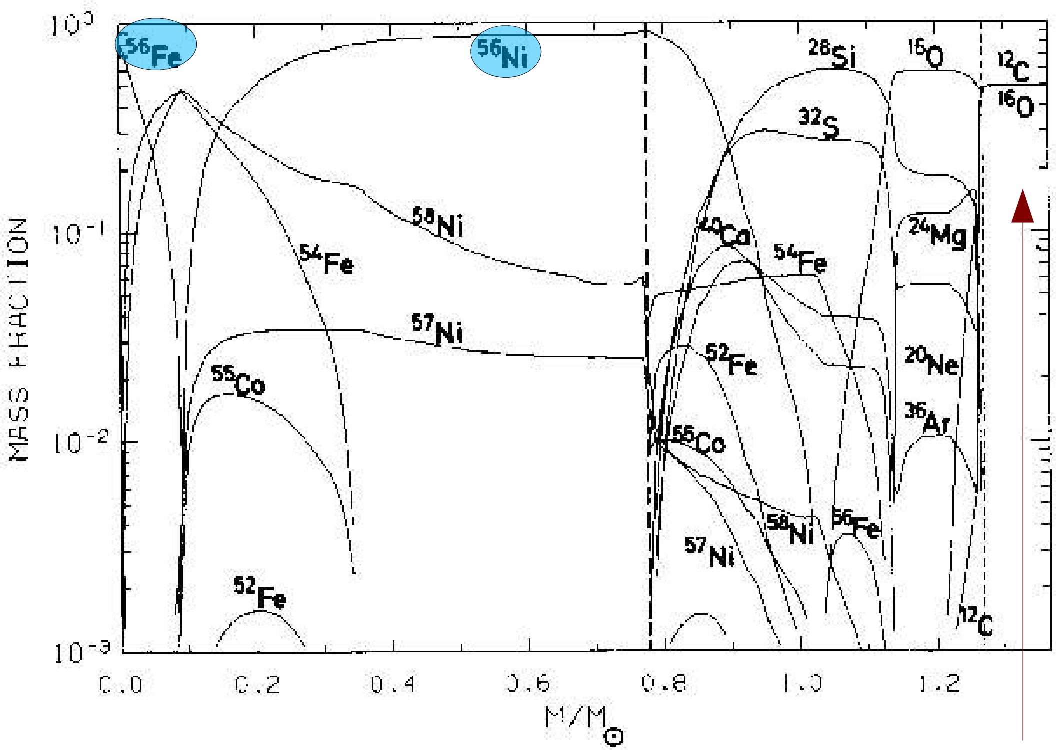


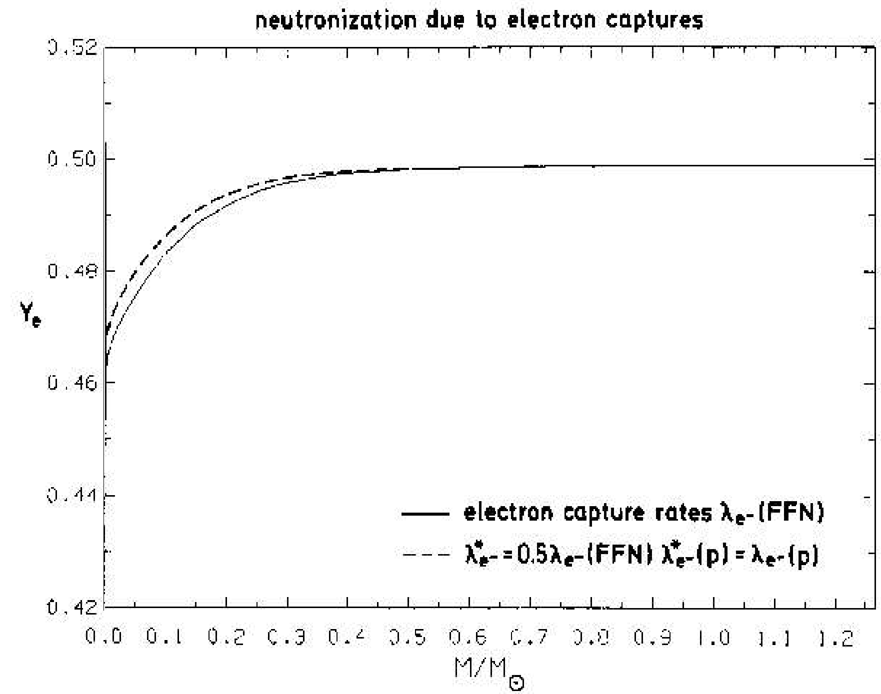
Explosive Burning above a critical temperature destroys (photodisintegrates) all nuclei and (re-)builds them up during the expansion. Dependent on density, the full NSE is maintained and leads to only Fe-group nuclei (normal freeze-out) or the reactions linking ^{4}He to C and beyond freeze out earlier (alpha-rich freeze-out).

Nucleosynthesis in W7

electron capture in central high density/temperature regions

electron capture on protons well known, for nuclei from
Fuller, Fowler & Newman 1982-1984



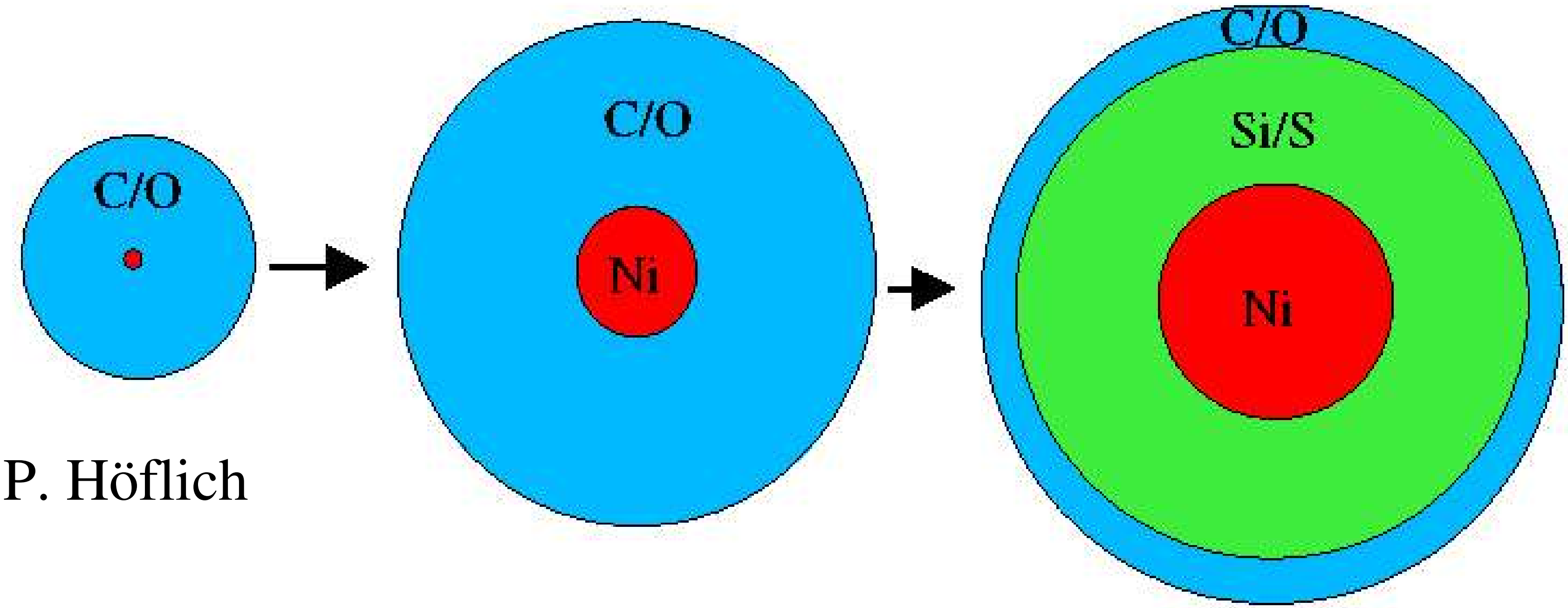


unburned

Back of the Envelope SN Ia

Initial WD

Observational Constraints: 0.2-1M_{sol} "Ni" from lightcurves (dependent on H_0, Wheeler 1982), and intermediate mass elements (from spectra, Branch 1982, 1984)

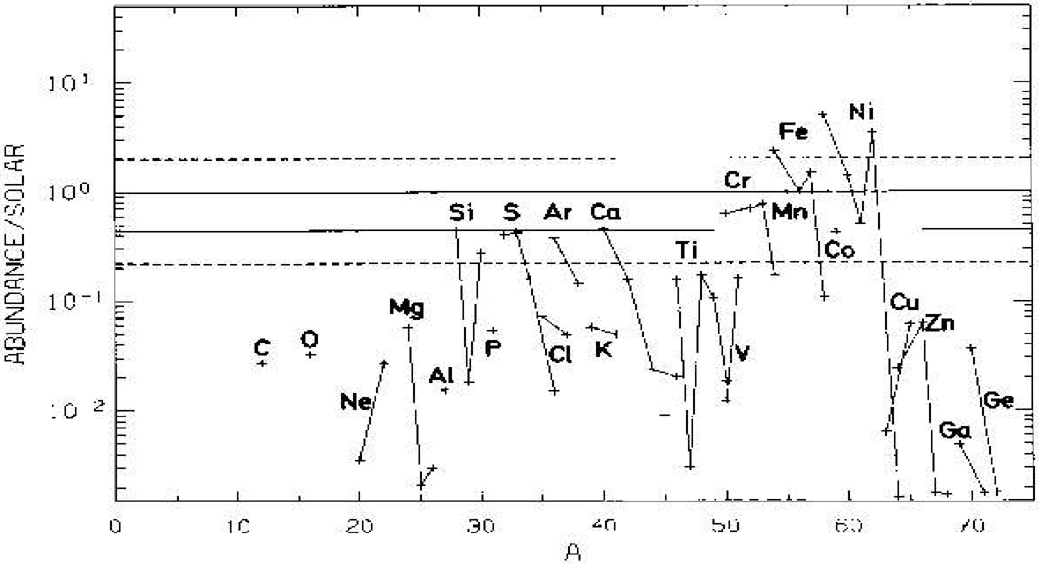


P. Höflich

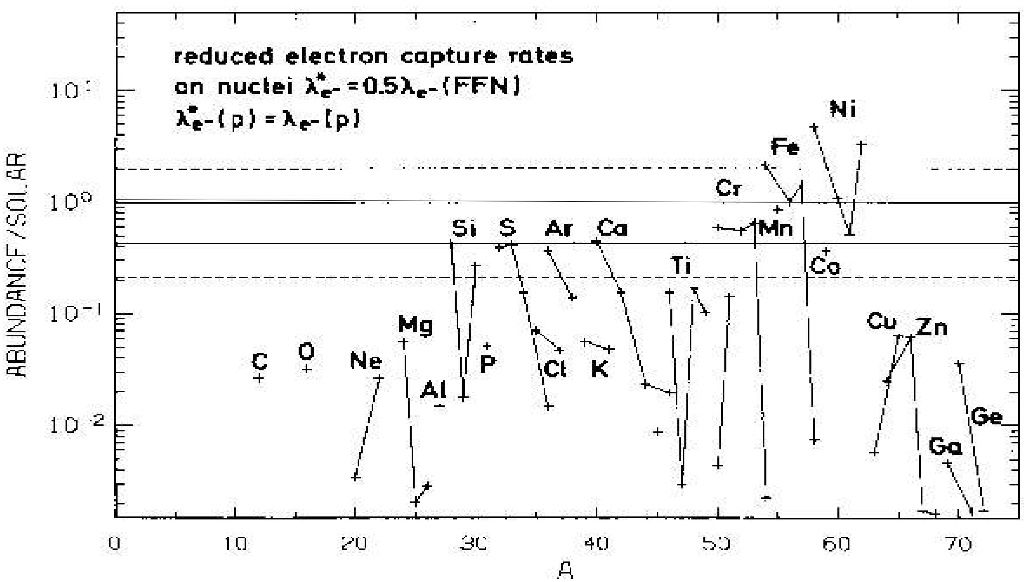
$M_{ch} \approx 1.4 M_\odot$ of $^{12}C/^{16}O$=1 WD $\rightarrow$ 1.398776 $M_\odot$ ^{56}Ni
$\rightarrow$ 2.19$\times10^{51}$ erg - $E_{grav} \approx (5-6)\times 10^{50}$ erg
reduction due to intermediate elements like Mg, Si, S, Ca

$\rightarrow$ 1.3$\times10^{51}$ erg

Comparison with solar abundances



Fe-group to intermediate mass elements factor 2-3, still some problems with Fe-group composition

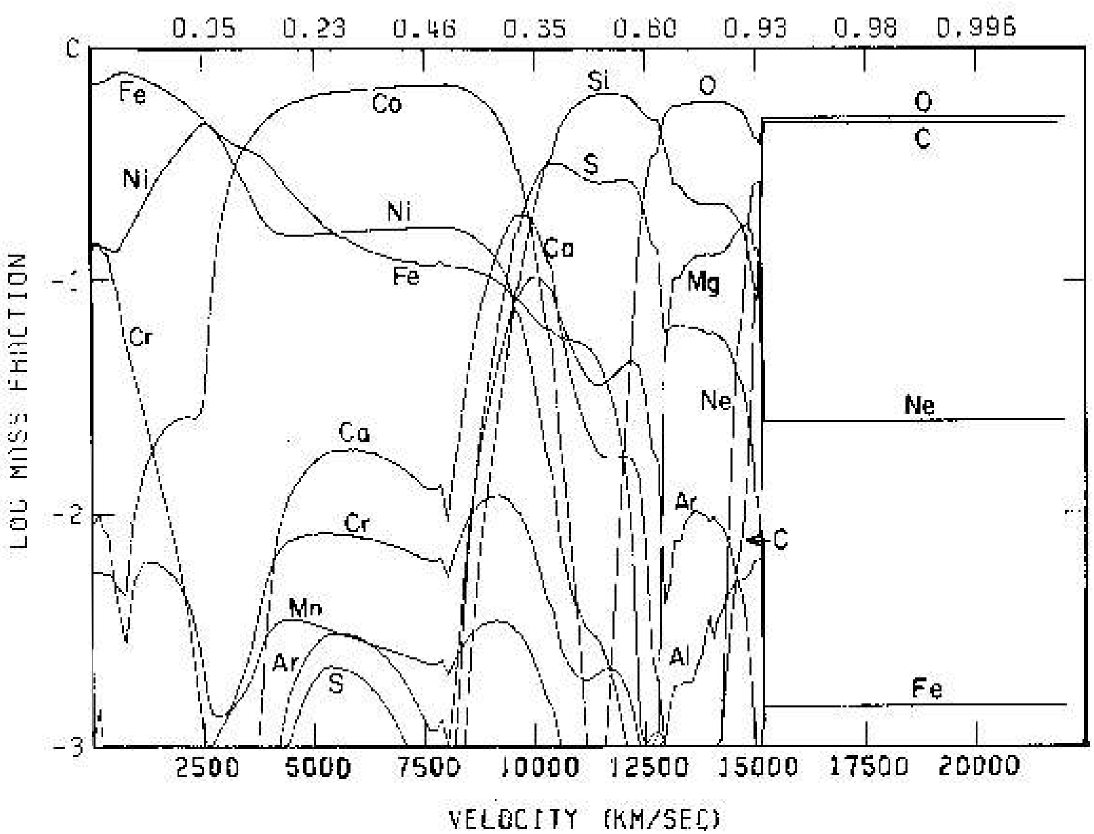


first presentation of results in Erice 1983

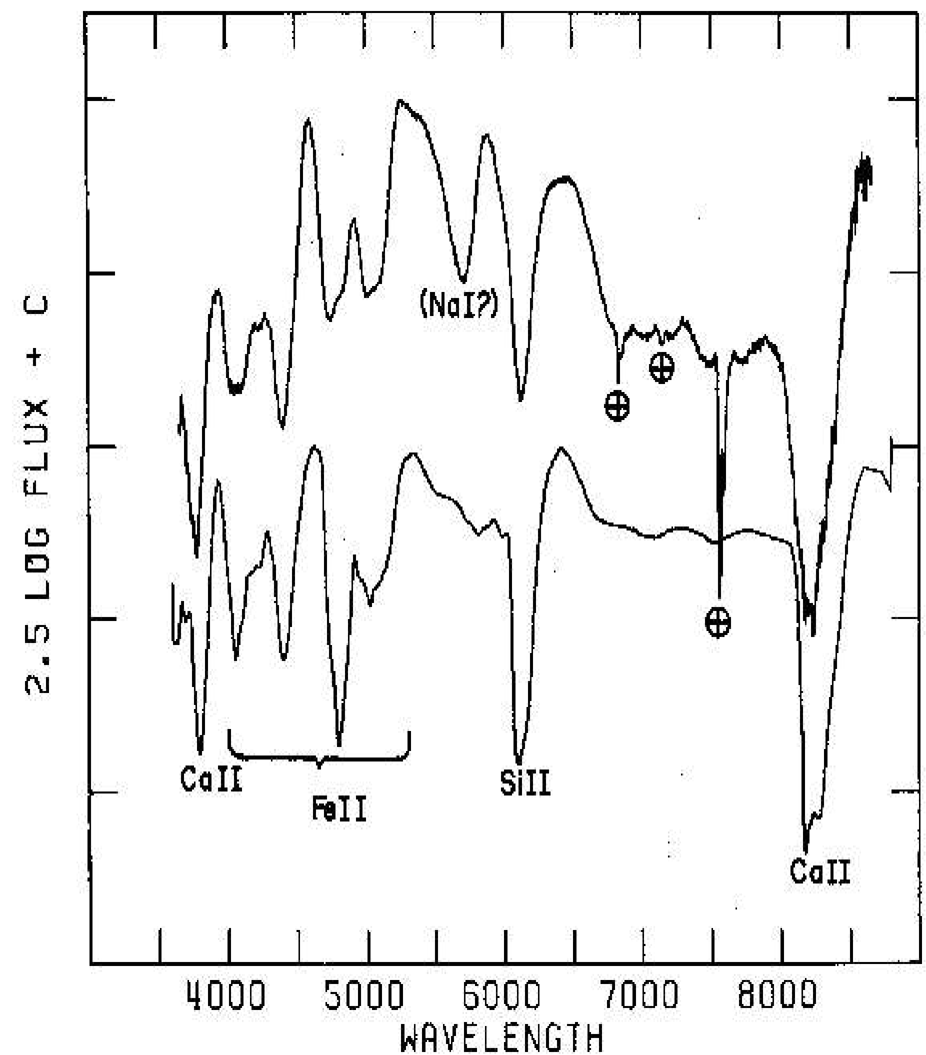
Comparison with spectra of 1981b

Branch, Doggett, Nomoto, Thielemann 1985

composition and velocities 15 days after explosion

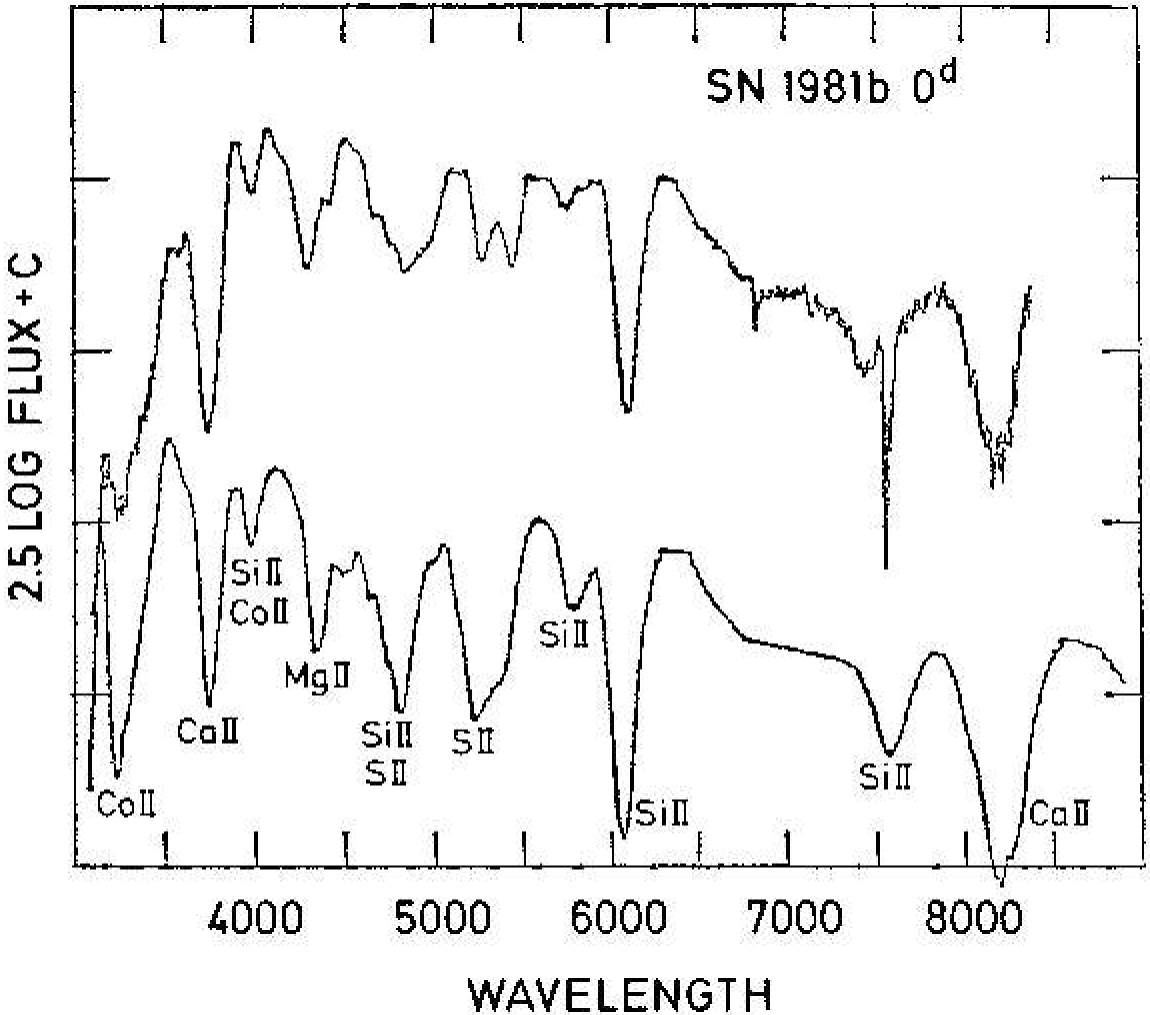


spectra 17 days after maximum light



Comparison with Spectra of 1981b

Nomoto, Thielemann, Yokoi & Branch 1986



science and fun in Oklahoma

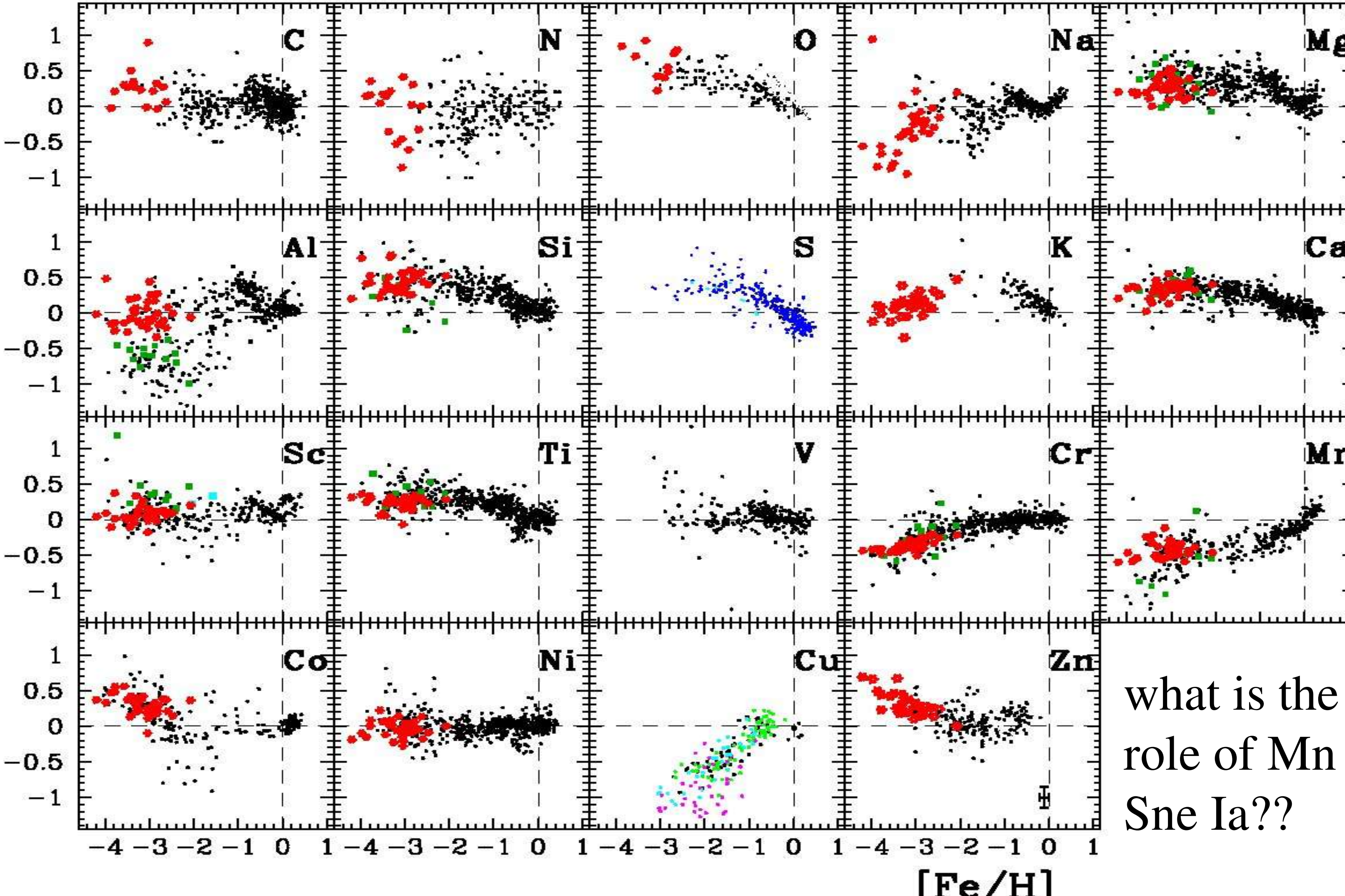
“Historical” Burning Processes (B^2FH)

- H-Burning
- He-Burning
- alpha-Process
- e-Process
- s-Process
- r-Process
- p-Process
- x-Process

Present Understanding

- H-Burning
- He-Burning
- expl. C, Ne, O-Burning, incomplete Si-Burning
- explosive Si-Burning
- about 70% normal freeze-out with Y_e=0.42-47, about 30% alpha-rich freeze-out with Y_e=0.5
- s-Process (core and shell He-burning, neutrons from alpha-induced reactions on ^{22}Ne and ^{13}C)
- r-Process (see below)
- p-Process (see below)
- x-Process (light elements D, Li, Be, B [big bang, cosmic ray spallation and neutrino nucleosynthesis])

Galactic Chemical Evolution and the Role of SNe Ia



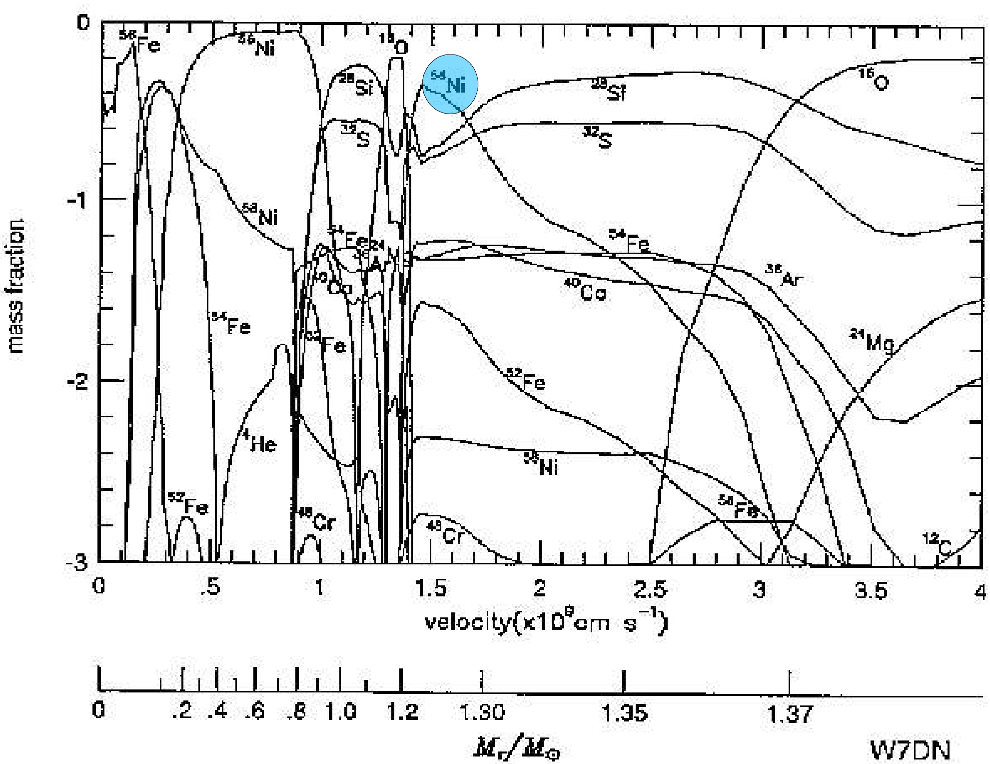
what is the role of Mn in Sne Ia??

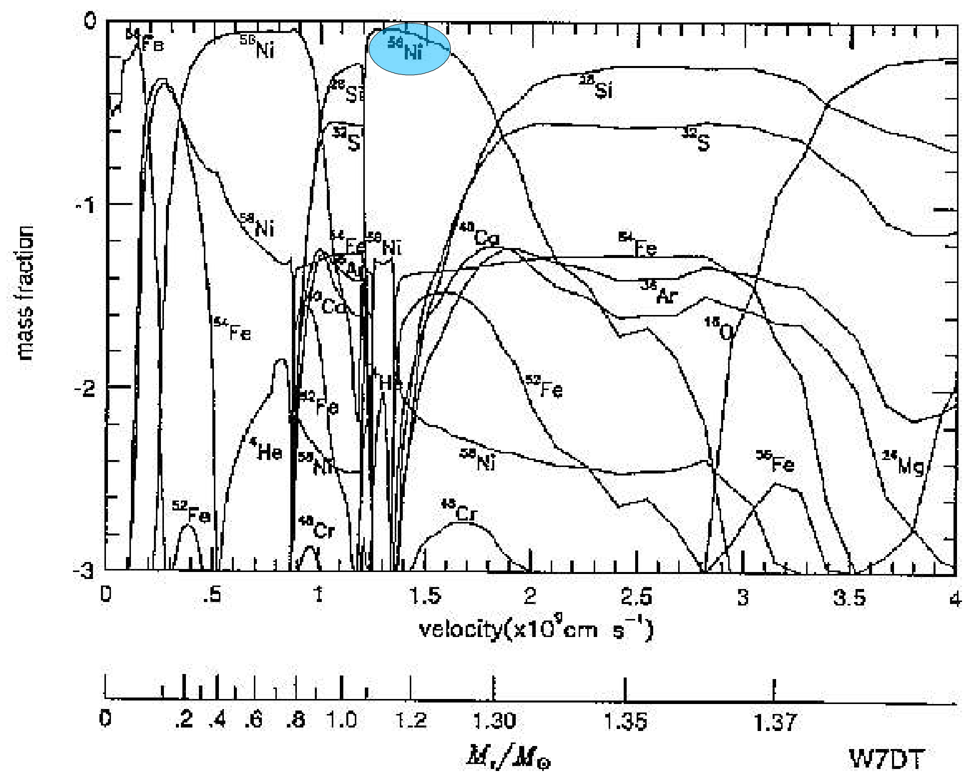
Further Progress and Delayed/Late Detonations

- variations in Ia observations: Phillips et al. 1990
- binary evolution approaches: Iben & Tutukov 1984, Webbink 1984; Nomoto & Iben 1985, Saio & Nomoto 1985, Nomoto & Kondo 1991, supersoft sources van den Heuvel et al. 1992
- He-detonation: Woosley & Weaver 1986
- Laminar burning front speed in 1D: Timmes & Woosley 1992
- URCA process during ignition: Iben 1982, Barkat & Wheeler 1990
- Delayed Detonations (detonations at low density do leave intermediate mass elements!): Khokhlov 1991ab, Höflich, Khokhlov & Müller 1991, Woosley & Weaver 1991, Khokhlov, Müller, Höflich 1992, Shigeyama, Nomoto, Yamaoka, Thielemann 1992 (detonations in low mass WDs), late detonations Yamaoka, Nomoto, Shigeyama, Thielemann 1992 (W7DN, W7DT, W8DT)

Late Detonations

to explain 1991T and 1990N (Yamaoka, Nomoto, Shigeyama & Thielemann 1992)





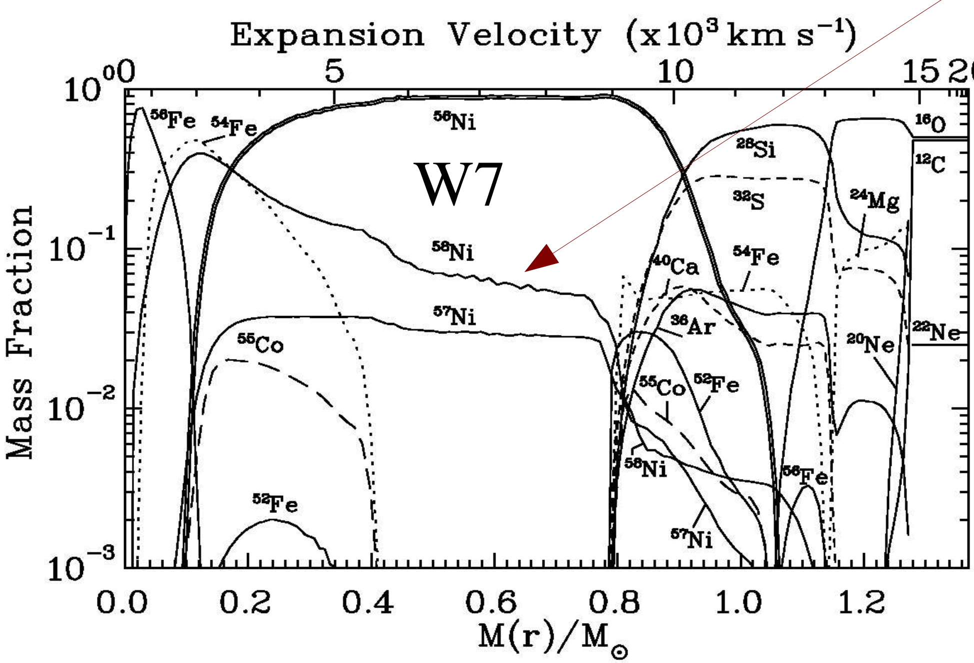
Rapid Progress/Activity on all Fronts

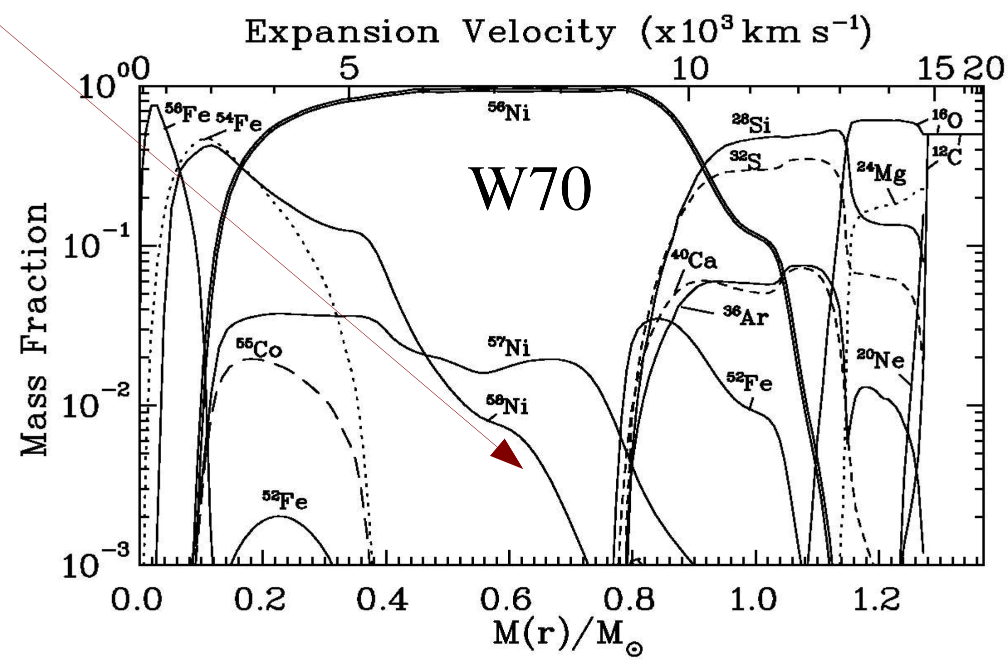
observational: basic understanding Fillipenko 1997 and many others, polarisation ..., cosmology: CFA, STScI, Berkeley, ESO...
progenitor models: Yungelson, SSSs, Hachisu, Starrfield...
burning front progress:
Santa Cruz: flame propagation, instabilities, fractal dimension, ignition points...
Garching: multi-D hydro and burning, spectra and lightcurves
Chicago: large scale modeling
Texas: Modeling, synthetic spectra
Barcelona: 3D Modeling with SPH

continue 1D spherically symmetric studies for nucleosynthesis and comparison with observations

Metallicity Effects

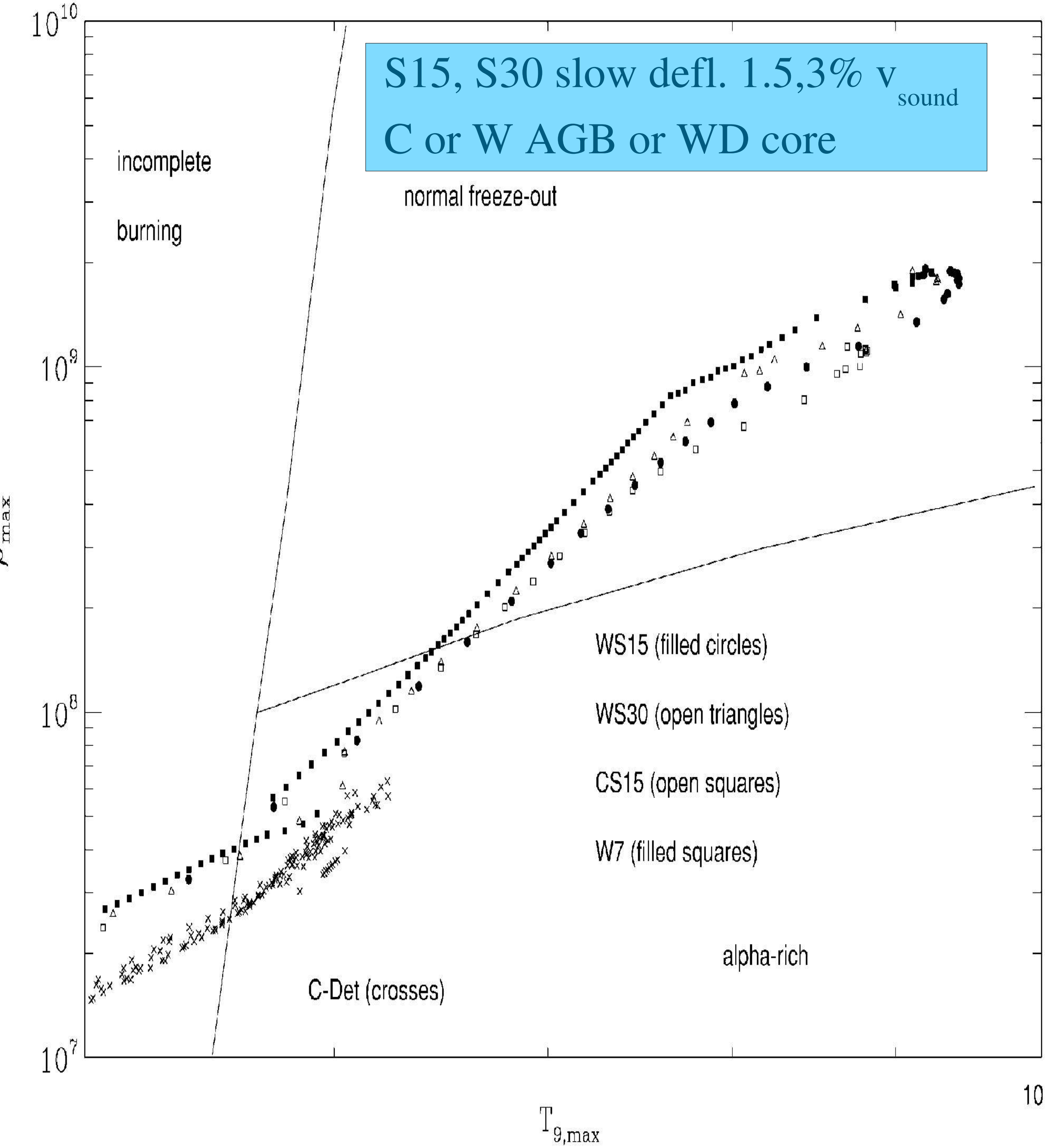
Iwamoto, Brachwitz et al. (1999); Y_e in outer zones made by initial ^{22}Ne

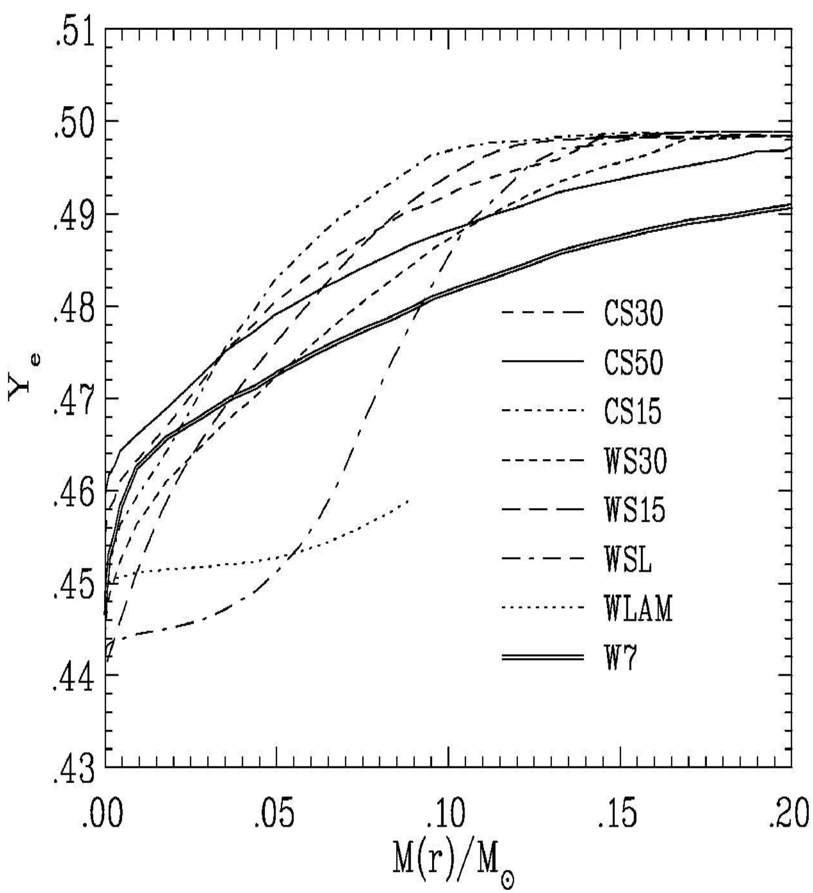




Deflagration Speeds, Ignition Densities

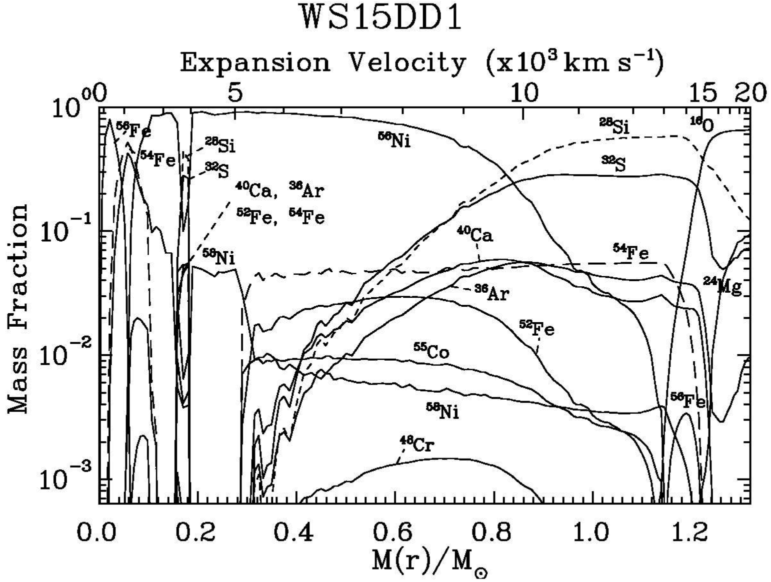
Iwamoto, Brachwitz et al. 1999

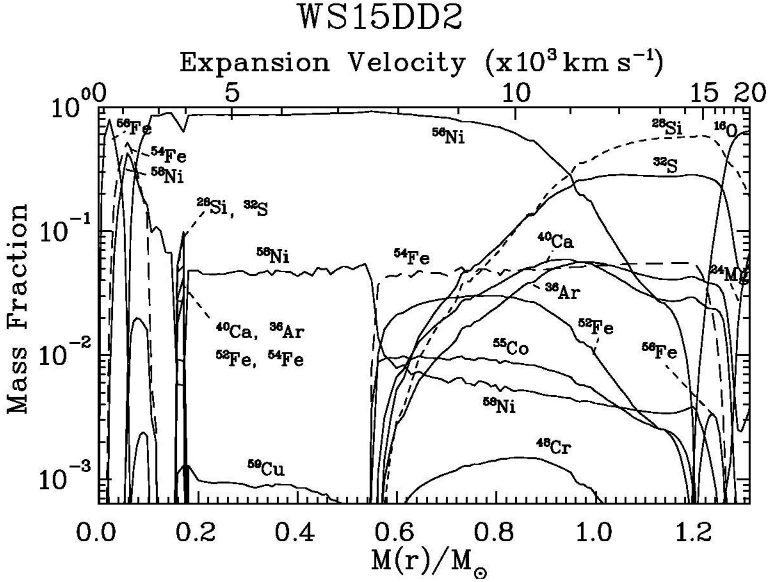




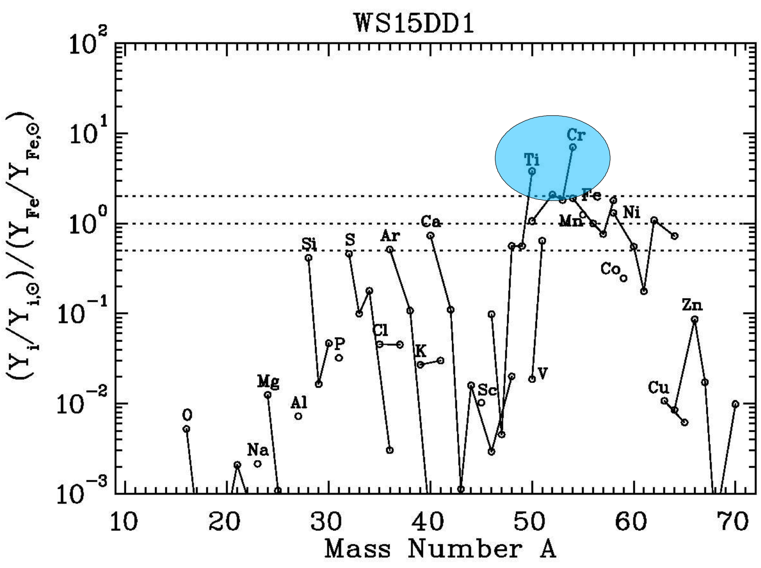
Delayed Detonations

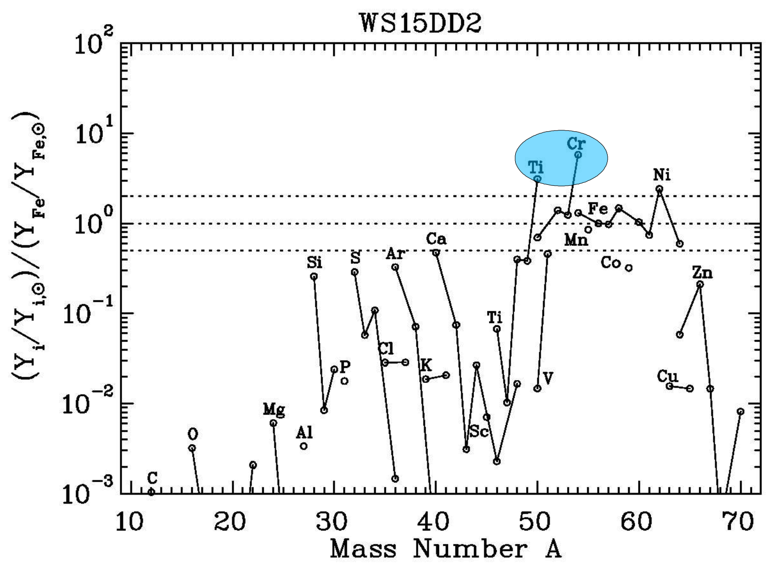
Iwamoto, Brachwitz et al. 1999; delayed detonations change Fe-group to intermediate mass ratio, but not central neutron-rich composition!!





Conclusion: We need ignition densities below $2x10^9 gcm^{-3}$?



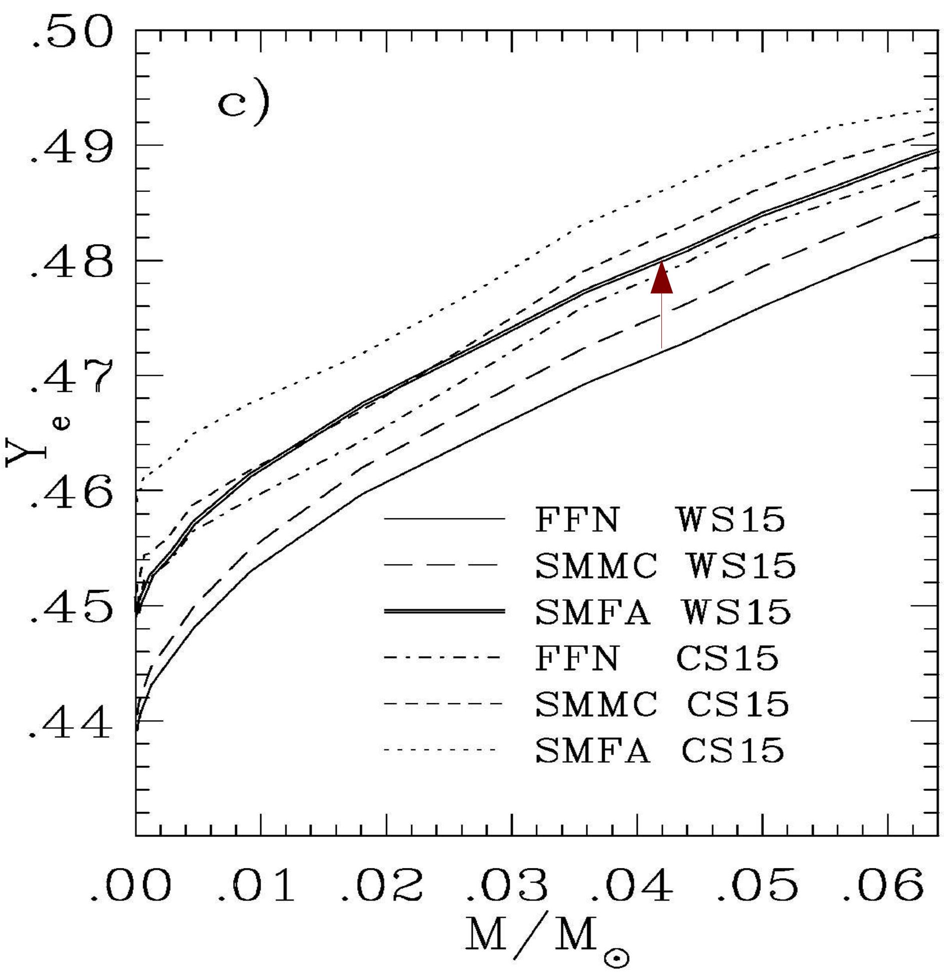


^{50}Ti and ^{54}Cr

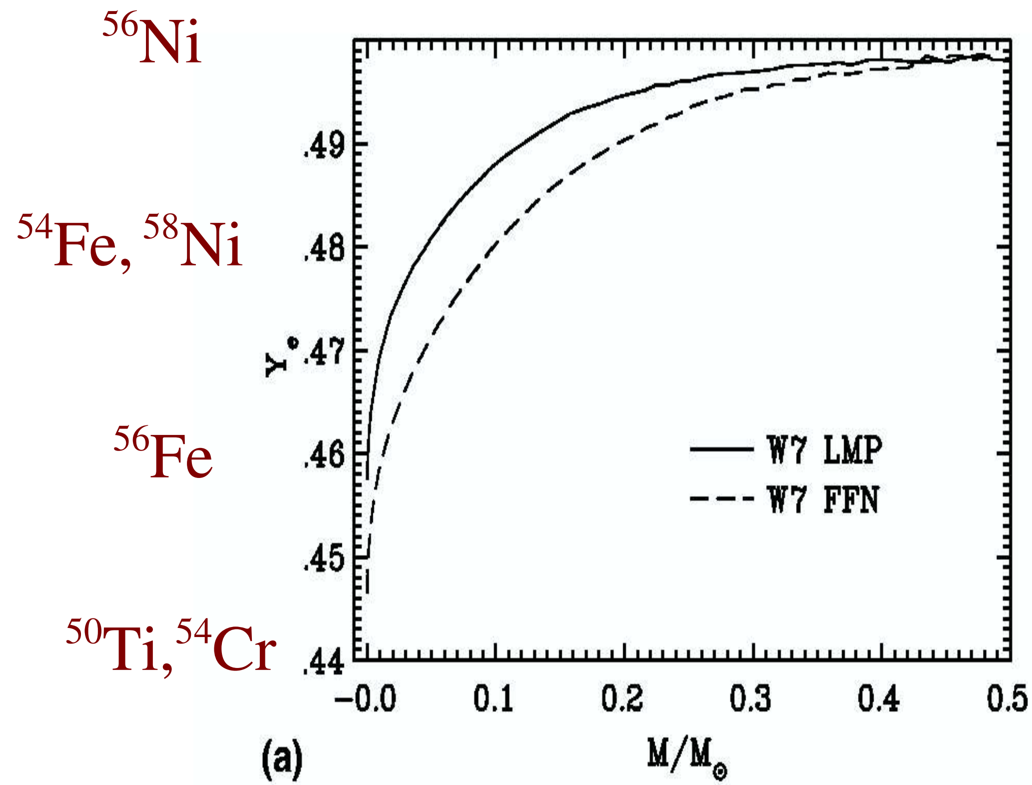
Role of large shell model calculations for e-capture on Fe-group nuclei

Neutronization via electron capture (high Fermi energies at central densities)

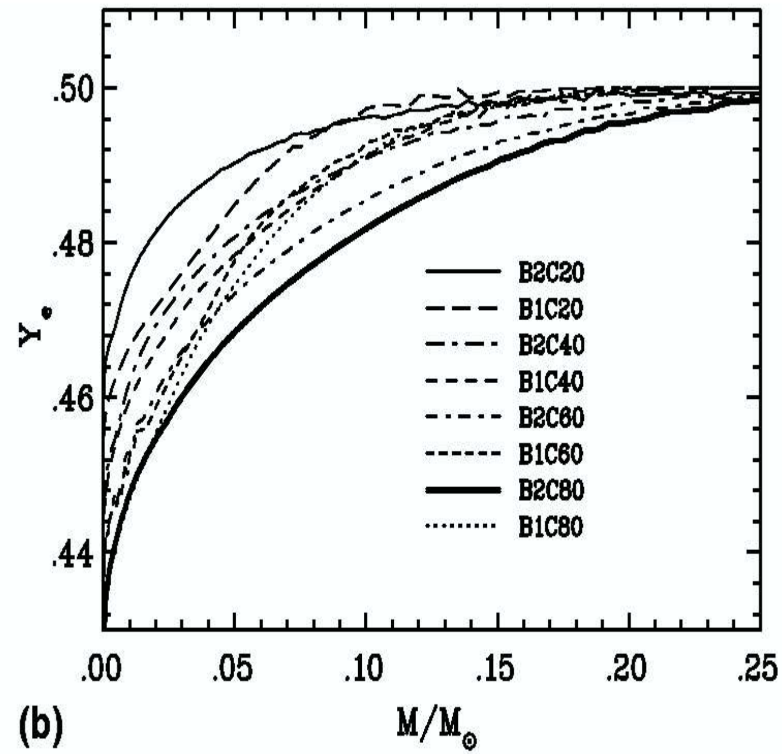
Langanke & Martinez-Pinedo 2000
-> SNe Ia calculations



Brachwitz, Dean, Hix, Iwamoto, Langanke, Martinez-Pinedo et al. 2000

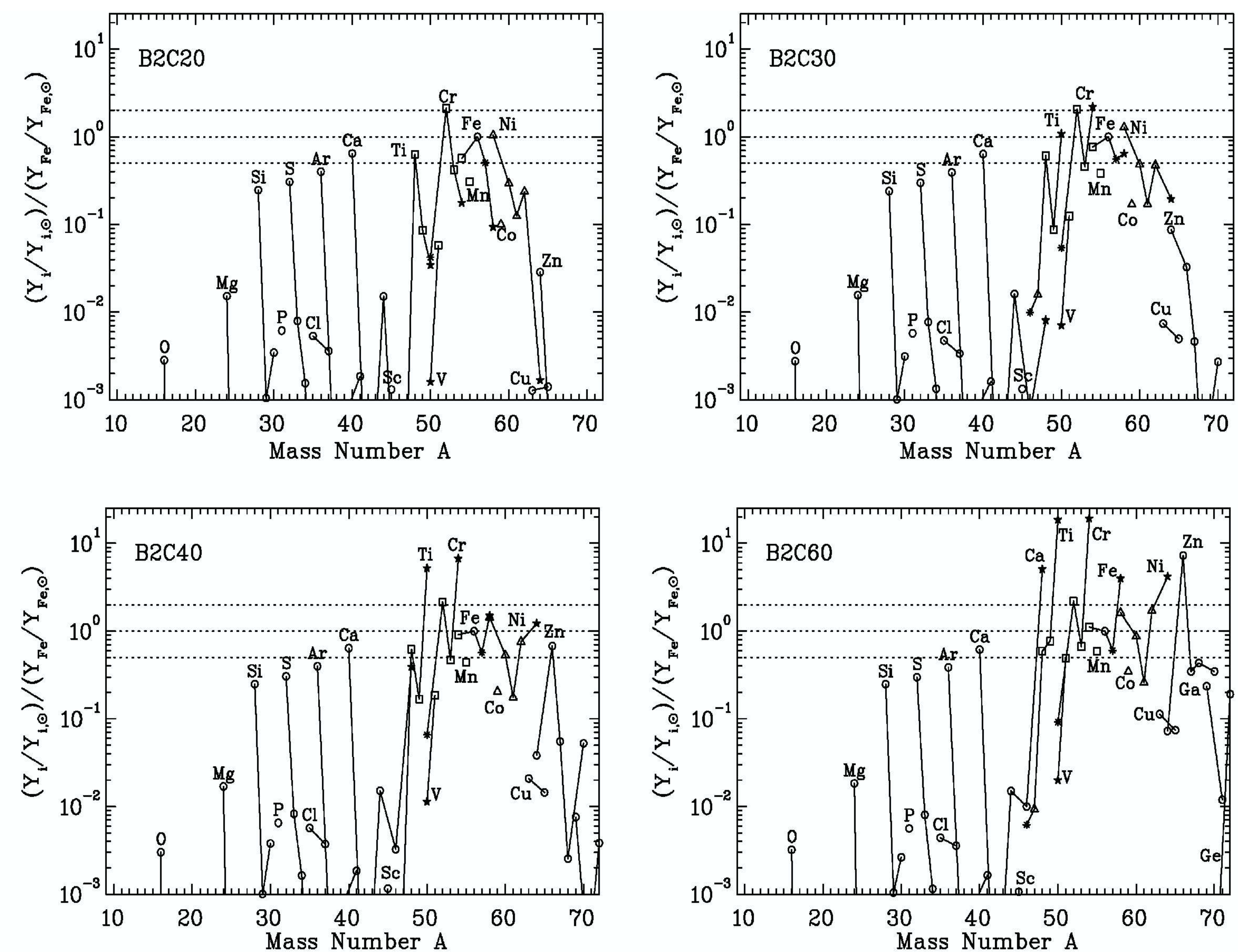


Test KHM-like delayed detonation models with LMP weak rates and detailed nucleosynthesis



Thielemann, Brachwitz, Höflich, Martinez-Pinedo, Nomoto 2004

Ignition density determines Y_e and neutron-richness of (60-70% of) Fe-group



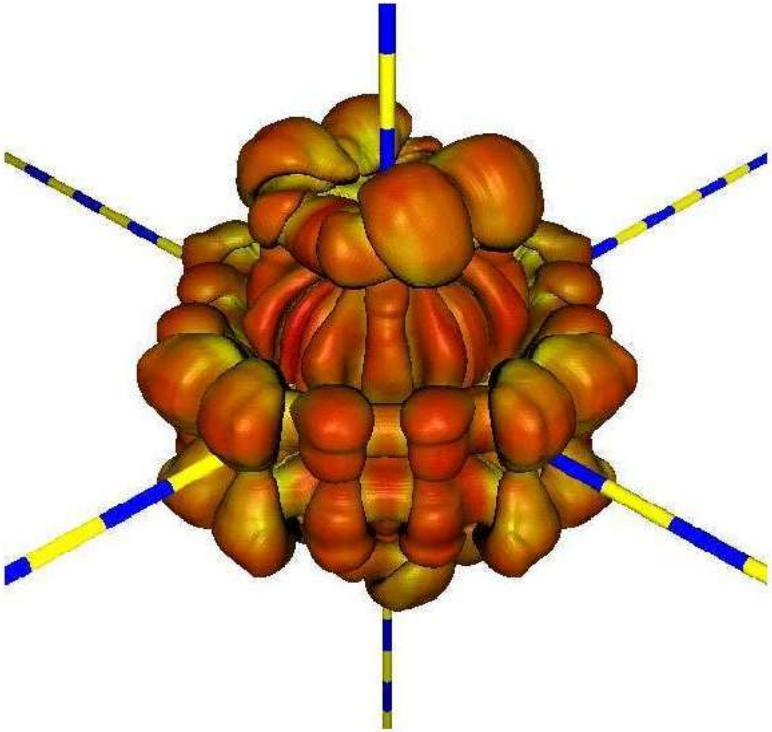
results of explosive C, Ne, O and Si-burning:
Fe-group to alpha-elements 2/1-3/1

SNe Ia dominate Fe-group, over-abundances by more than factor 2 not permitted

→

central density $<4\ 10^9\ gcm^{-3}$

Where is the Future?



A Waggi is a costume in the Basel Fasnacht (Carneval).

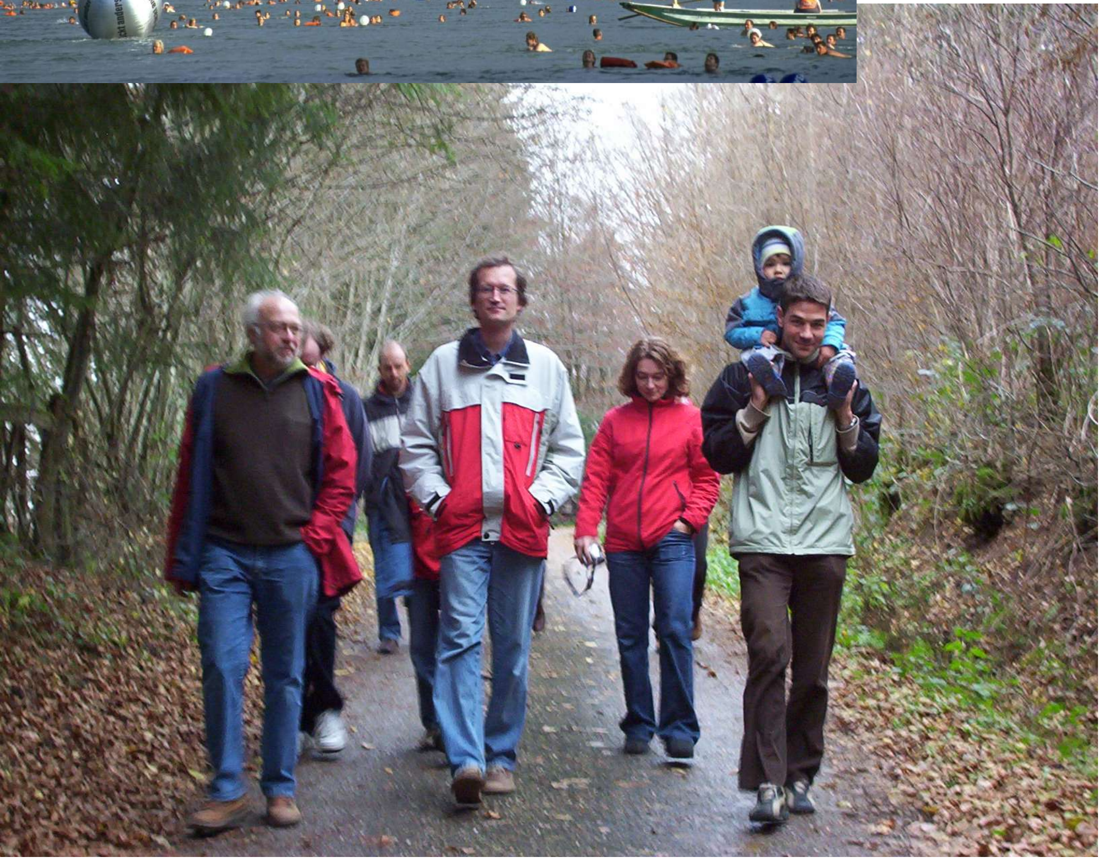
•At first glance (zeroth order) and from the back it looks spherically symmetric (our past approaches, lacking self-consistent burning front propagation).

•Second order: multi-D variations around spherical picture? (randomly chosen ignition points in MPA Garching model)

•Or do we have the effect of a one point ignition (Chicago model)?

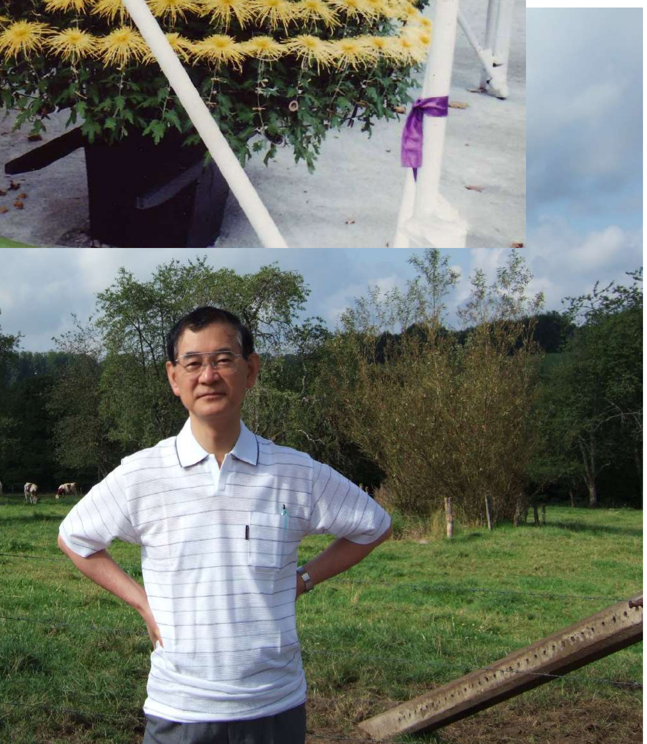
•What will be the differences in nucleosynthesis and their manifestation in observations?

Happy Birthday



Ken !

From your friends in Basel: The Nuclear and Computational Astrophysics Group



What I learned from Ken:

Besides learning a lot about SNe Ia and II!!

1. Work hard!!!! A plot of 3:30am can make an impression at the next day's conference (so happened with W7 results in Erice 1983).

2. Work through the night before an international flight: a. you get work done, b. you can sleep everywhere without jetlag.

3. If it is too hard to solve a problem from first principles, make a simple parametrized model and compare with constraints from observations. You might learn a lot.

4. Have many friends and students around the world