Classical Novae and Thermonuclear Supernovae

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Outline

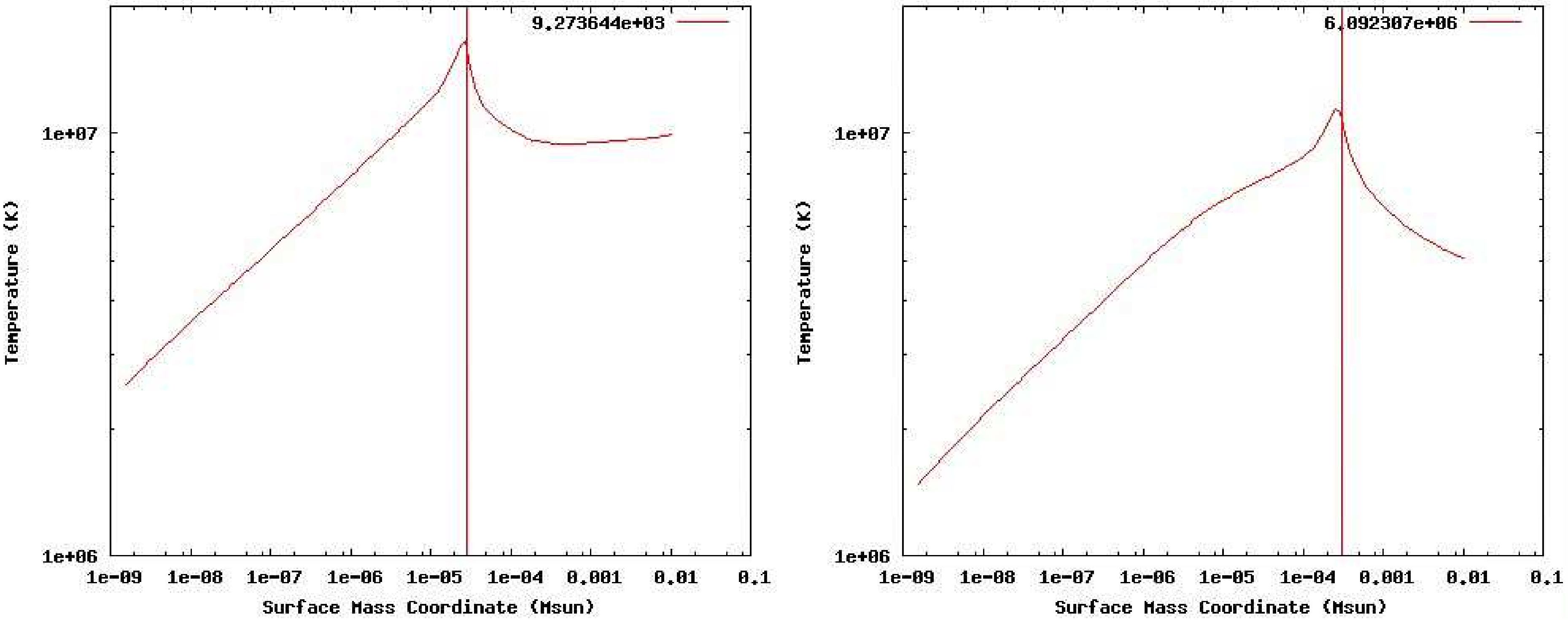
Classical Novae

- Buildup and runaway
- Importance of core composition
- Observables
- Reaction sensitivity

Type Ia Supernovae

- Critical observables - brightness and spectrum
- importance of electron captures for ^{56}Ni yield
- importance of C+C

Example Buildup and Runaway



m

$$\langle \dot{M} \rangle = 3 \times 10^{-9} M_\odot \ \mathrm{yr}^{-1}$$

$$T_c = 10^7$$

Direct to $p + \mathrm{C}$ or $^3\mathrm{He} + ^3\mathrm{He}$

Most novae by number

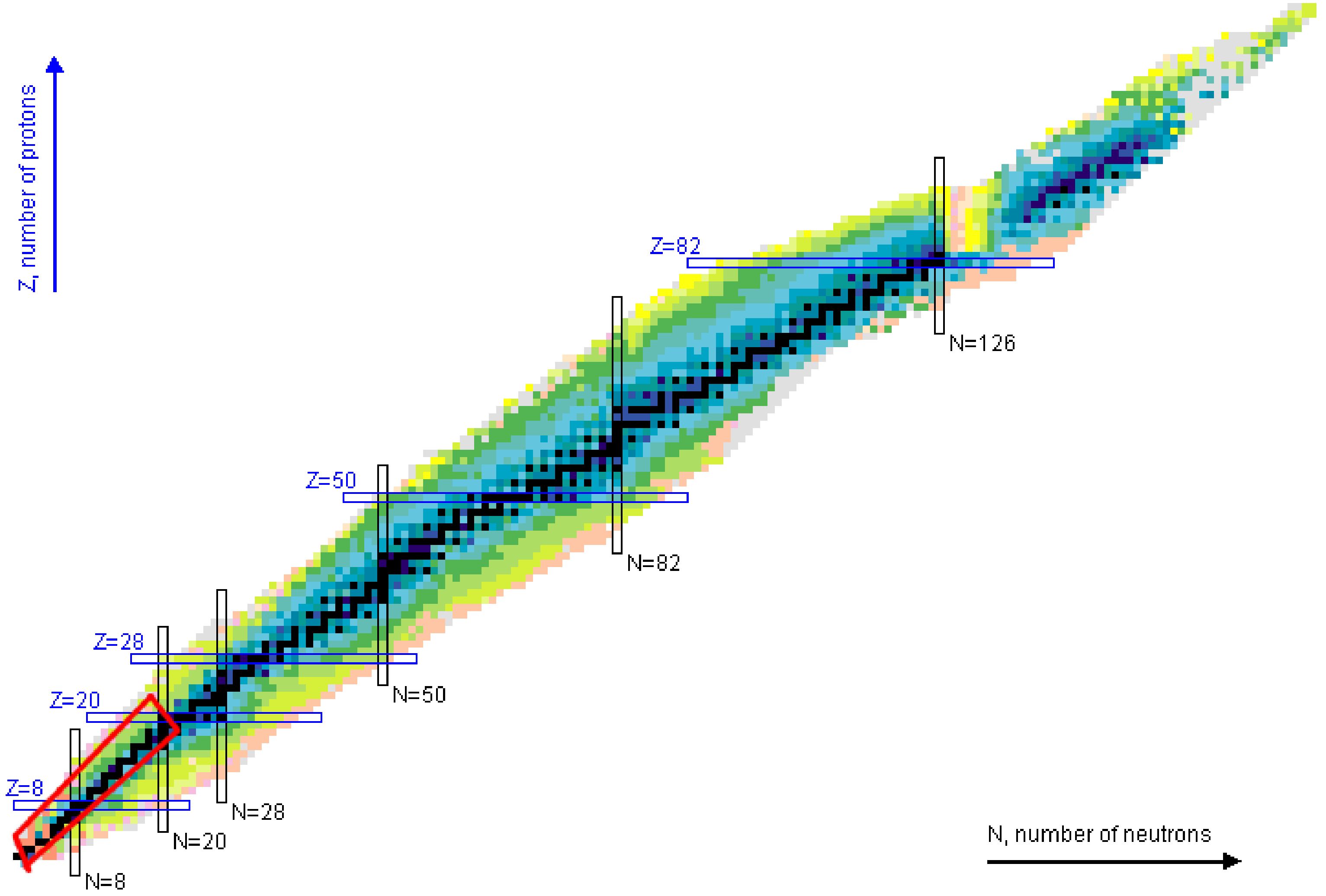
$$\langle \dot{M} \rangle = 5 \times 10^{-11} M_\odot \ \mathrm{yr}^{-1}$$

$$T_c = 5 \times 10^7$$

$p + p$ (partial chain) envelope heating eventually leads to $p + \mathrm{C}$

Large accumulated mass

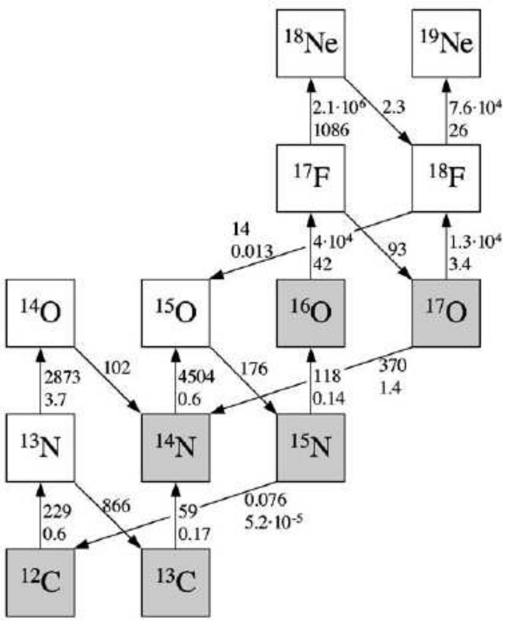
The Important Nuclides

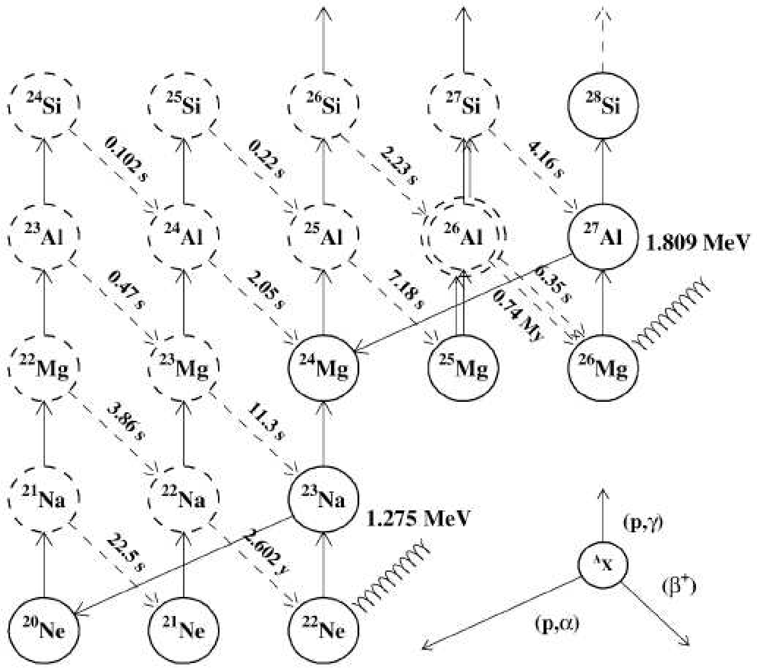


- Novae undergo explosive hydrogen burning
- (p,γ) and (p,α) on stable and slightly-proton-rich nuclides and β decays
- Potentially all measurable in the lab at astrophysical energy (few 100 keV)

Nuclides and reactions

J. José et al. / Nuclear Physics A 777 (2006) 550–578

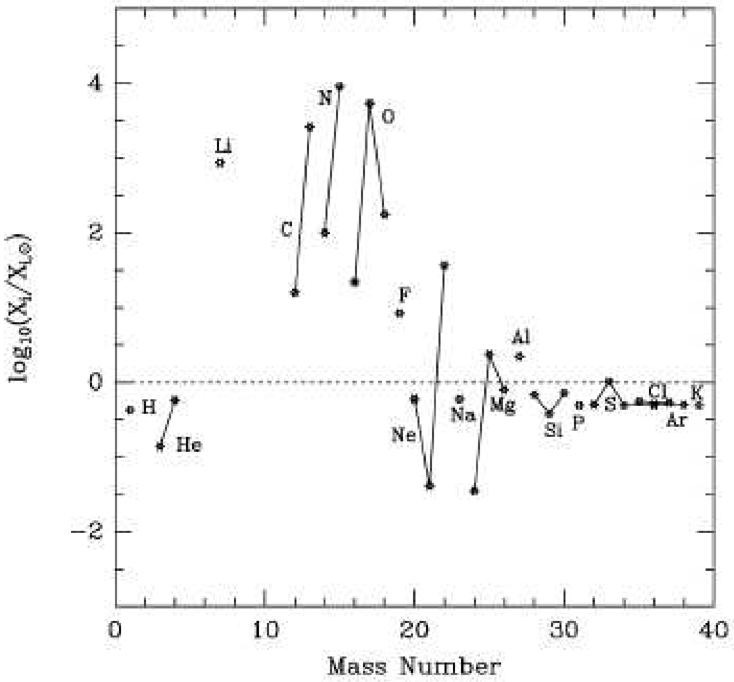




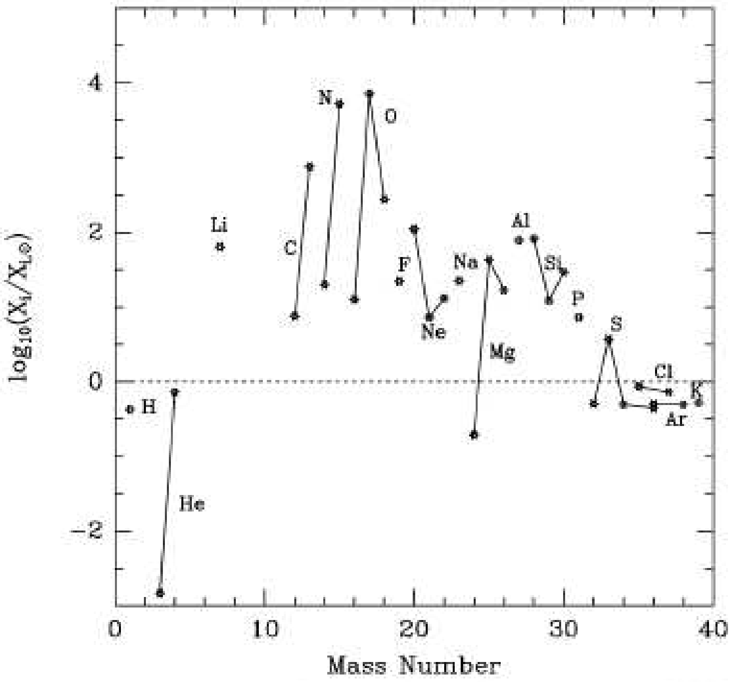
- Stable and slightly proton rich
- Explosive burning – creation and destruction reactions are important
- Seeds available are critical C&O or O-Ne-Mg give distinctive products (Mg$\rightarrow^{26}$Al) (Breakout is an exception)
- Lots of recent progress on critical rates

Nuclides and reactions

carbon-oxygen core



oxygen-neon(+Mg) core



J. José et al. / Nuclear Physics A 777 (2006) 550–578

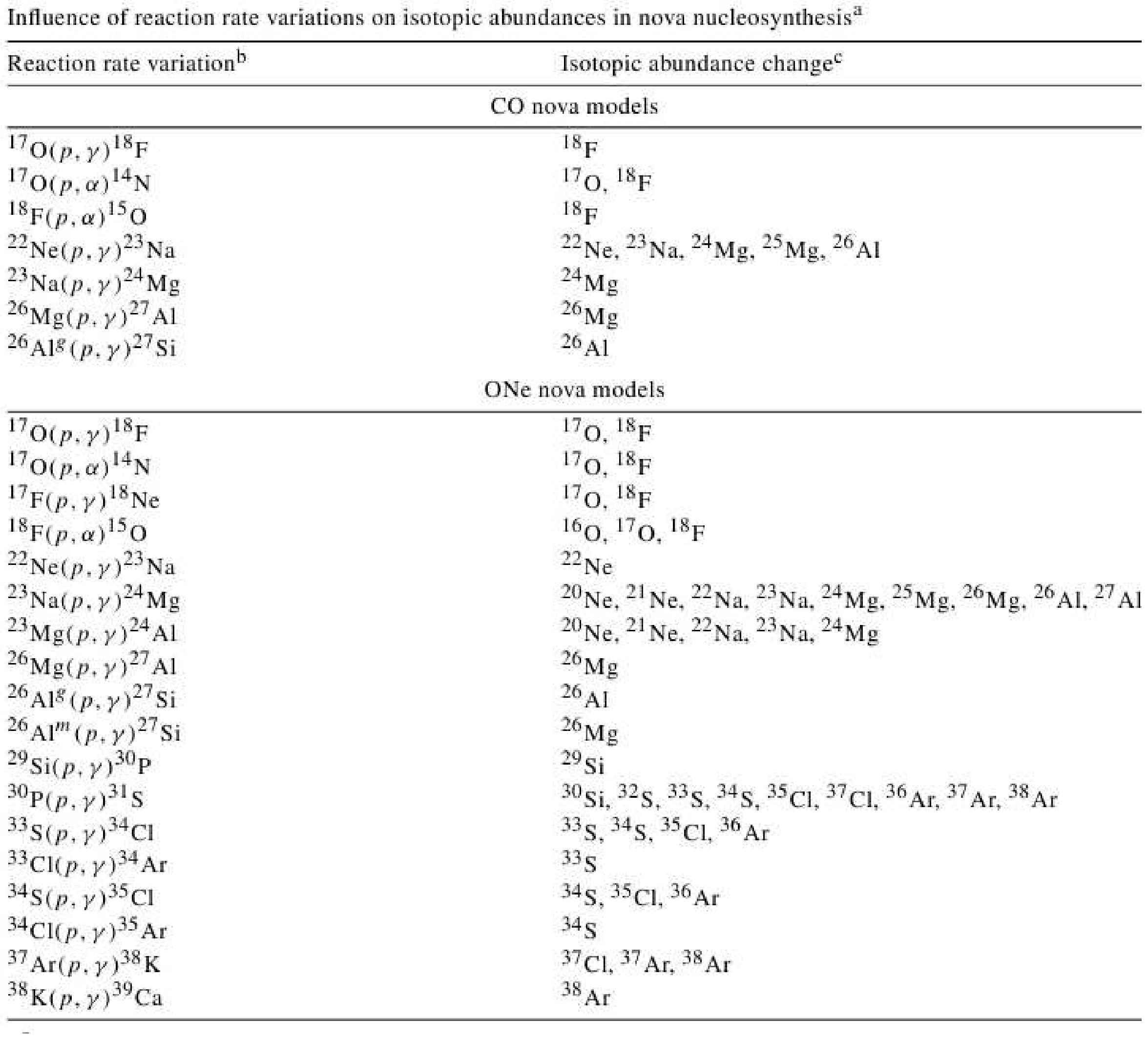
- ONe WDs generally show enhancements for heavier nuclides

Observable of Nuclear Processes

- Ejecta abundance measurements - spectral modeling, elemental only
- γ-ray emission
  - ^{13}N and ^{18}F (prompt)
  - ^{22}Na
  - ^{26}Al (diffuse, not dominant contribution)
- Meteoritic dust grains - isotopic abundances

Reaction rate sensitivities

- Table: Uncertainties that change abundances by factor of 2
- Many of these have been improved since 2002



Influence of reaction rate variations on isotopic abundances in nova nucleosynthesis[a]

Reaction rate variation[b]	Isotopic abundance change[c]
CO nova models	
$^{17}O(p,\gamma)^{18}F$	^{18}F
$^{17}O(p,\alpha)^{14}N$	^{17}O, ^{18}F
$^{18}F(p,\alpha)^{15}O$	^{18}F
$^{22}Ne(p,\gamma)^{23}Na$	^{22}Ne, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Al
$^{23}Na(p,\gamma)^{24}Mg$	^{24}Mg
$^{26}Mg(p,\gamma)^{27}Al$	^{26}Mg
$^{26}Al^{g}(p,\gamma)^{27}Si$	^{26}Al
ONe nova models	
$^{17}O(p,\gamma)^{18}F$	^{17}O, ^{18}F
$^{17}O(p,\alpha)^{14}N$	^{17}O, ^{18}F
$^{17}F(p,\gamma)^{18}Ne$	^{17}O, ^{18}F
$^{18}F(p,\alpha)^{15}O$	^{16}O, ^{17}O, ^{18}F
$^{22}Ne(p,\gamma)^{23}Na$	^{22}Ne
$^{23}Na(p,\gamma)^{24}Mg$	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{26}Al, ^{27}Al
$^{23}Mg(p,\gamma)^{24}Al$	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg
$^{26}Mg(p,\gamma)^{27}Al$	^{26}Mg
$^{26}Al^{g}(p,\gamma)^{27}Si$	^{26}Al
$^{26}Al^{m}(p,\gamma)^{27}Si$	^{26}Mg
$^{29}Si(p,\gamma)^{30}P$	^{29}Si
$^{30}P(p,\gamma)^{31}S$	^{30}Si, ^{32}S, ^{33}S, ^{34}S, ^{35}Cl, ^{37}Cl, ^{36}Ar, ^{37}Ar, ^{38}Ar
$^{33}S(p,\gamma)^{34}Cl$	^{33}S, ^{34}S, ^{35}Cl, ^{36}Ar
$^{33}Cl(p,\gamma)^{34}Ar$	^{33}S
$^{34}S(p,\gamma)^{35}Cl$	^{34}S, ^{35}Cl, ^{36}Ar
$^{34}Cl(p,\gamma)^{35}Ar$	^{34}S
$^{37}Ar(p,\gamma)^{38}K$	^{37}Cl, ^{37}Ar, ^{38}Ar
$^{38}K(p,\gamma)^{39}Ca$	^{38}Ar

Evaluation by Iliadis et al. ApJS 2002, 142, 105

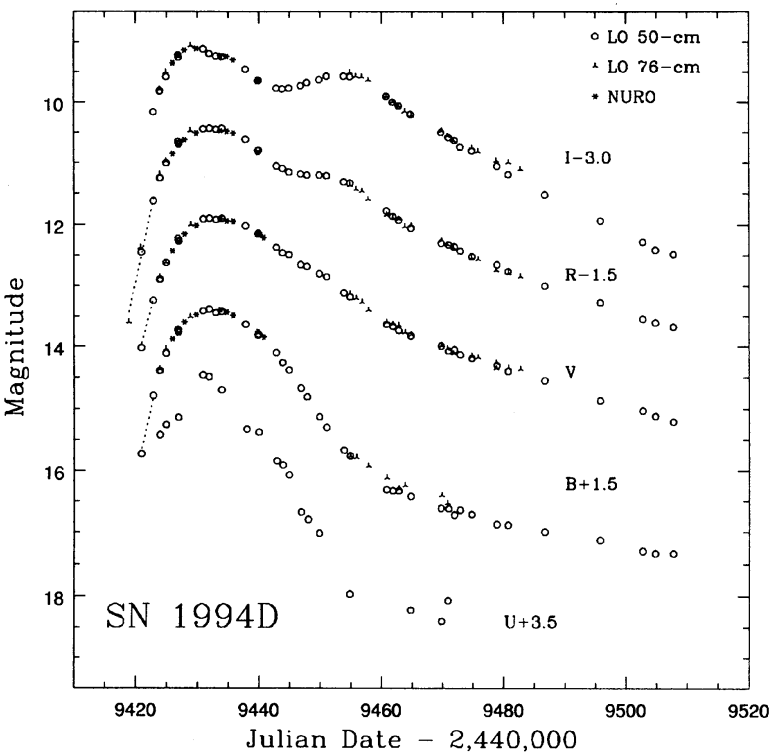
Some Current Frontiers

- Continuing improvement in reaction rates
- Mixing is Critical - Simulations are improving
- Low accretion rate, low T_c interesting cases for breakout

Still a lot to do in terms of ejection processes and transition to supersoft phase.

Thermonuclear Supernovae

NASA, ESA, The Hubble Key Project Team, and The High-Z Supernova Search Team



"lightcurve" – brightess vs. time

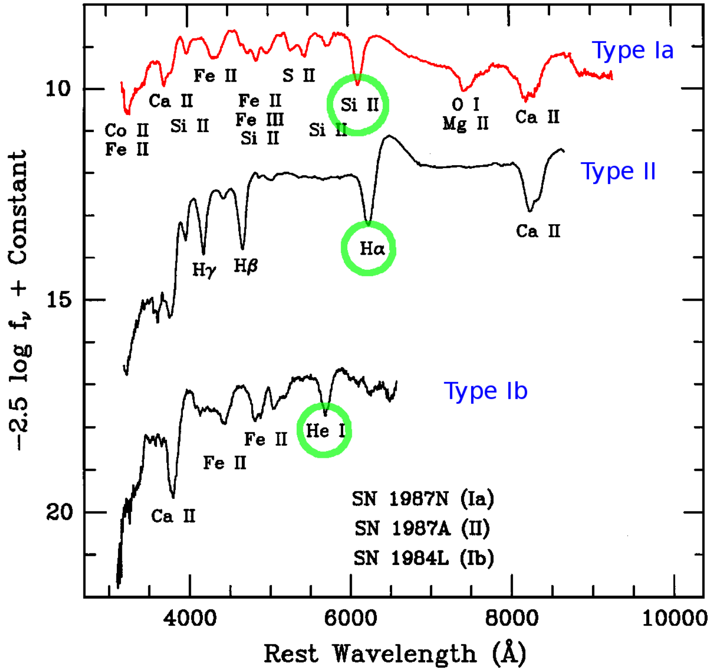
Richmond et al. 1995, AJ, 109, 2121

Type Ia supernova 1994D in the galaxy NGC 4526 – a prototypical "normal" SN Ia

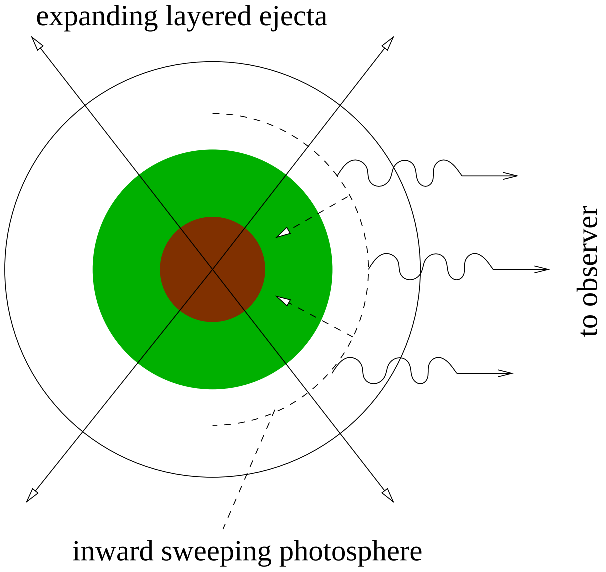
- Brightness comparable to entire galaxy
- Bright for a few weeks with a long, slow decay
- Powered by decay of ^{56}Ni

Supernova Types

Observational



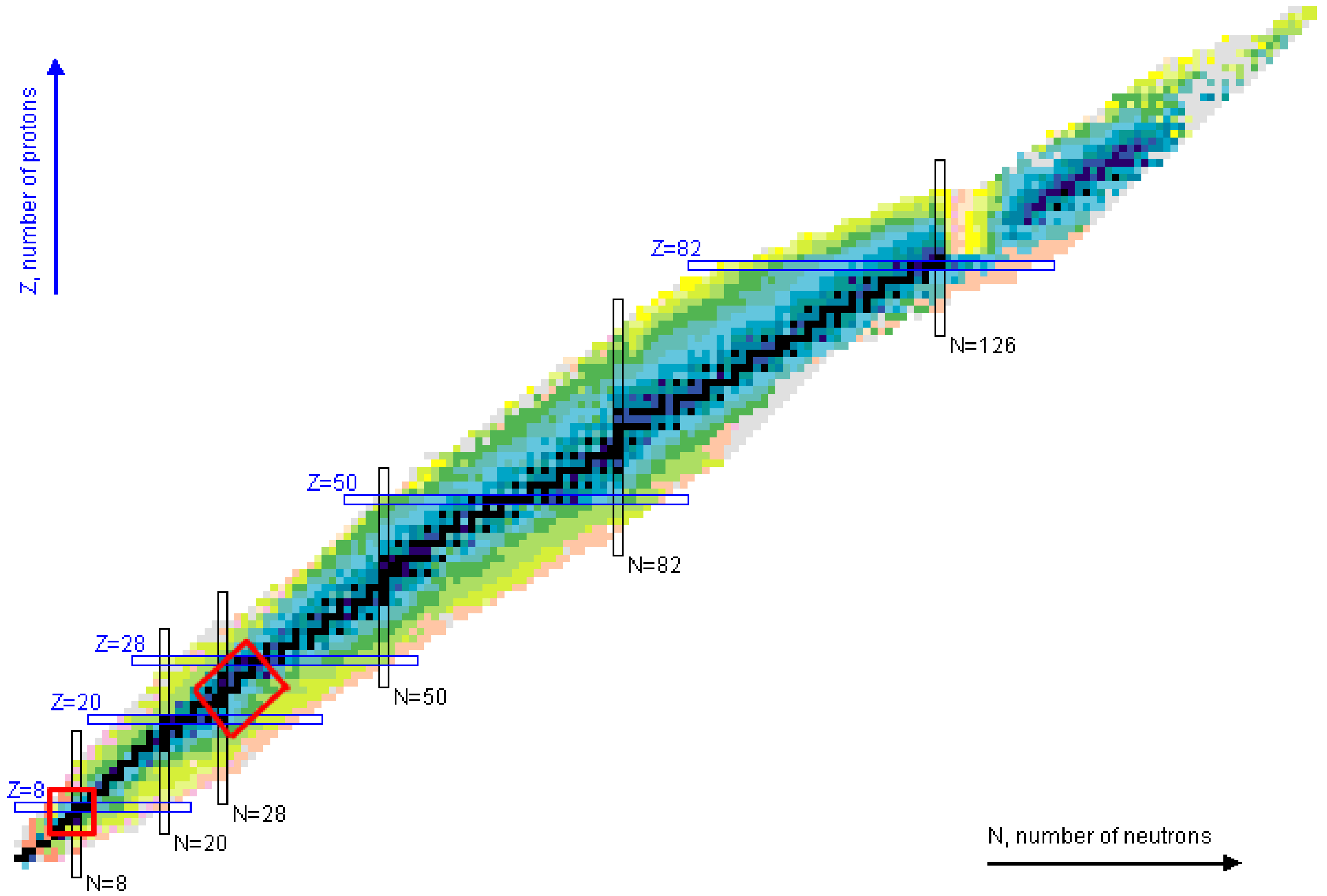
Filippenko 1997, ARA&A, 35, 309



Physical

- Thermonuclear
  - Type Ia (No Hydrogen, Helium; clear Silicon)
  - Arise from remnants of binary stars
  - Elements seen from explosive nuclear burning
  - No remnant
- Core collapse
  - Type II, Ib, Ic
  - Arise from death of massive stars
  - Collapse of stellar core to neutron star or black hole

Some important Nuclides for SNIa



- Electron capture on Fe-group nuclides - depletes the radioactive ^{56}Ni ejected - converting it to more neutron rich species
- carbon-oxygen fusion rates - important for both ignition conditions and low density burning that yields intermediate mass elements

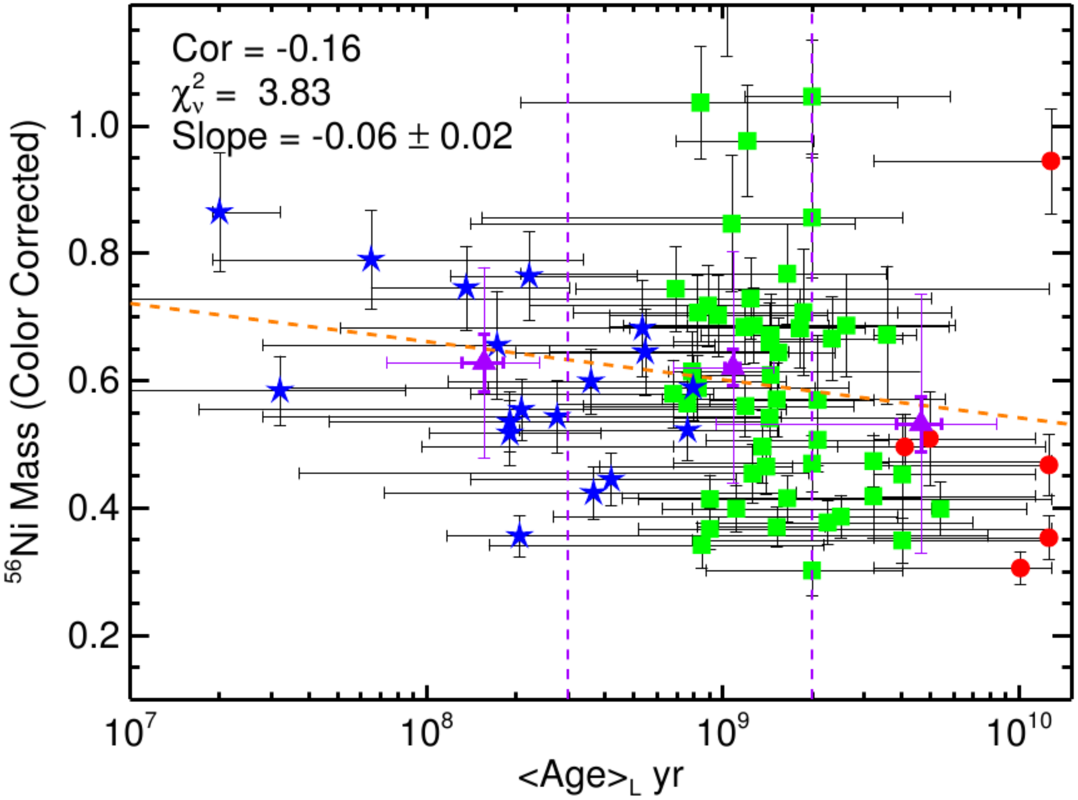
A Possible Supernova

Deflagration Detonation Transition Scenario

There are other promising scenarios including WD+WD mergers and sub-Chandrasekhar mass surface ignition. Things I say here today will play out differently in other scenarios.

Mean Stellar Age

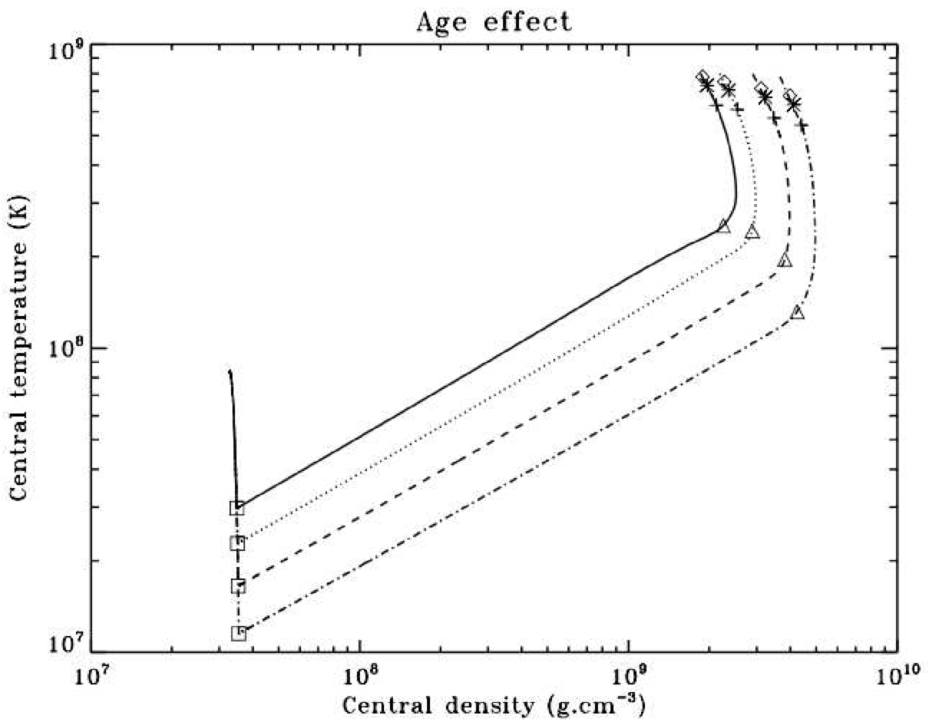
The motivating observations



(from Neill et al 2009, ApJ, 707, 1449)

SNIa in older populations are on average dimmer - may be due to electron capture

Age and Central Density



Orbital separation after common envelope phase sets time to onset of accretion.

WD will cool – longer cooling times lead to ignition at higher central densities

Average mass will also vary, not accounted for here, but has the same sign.

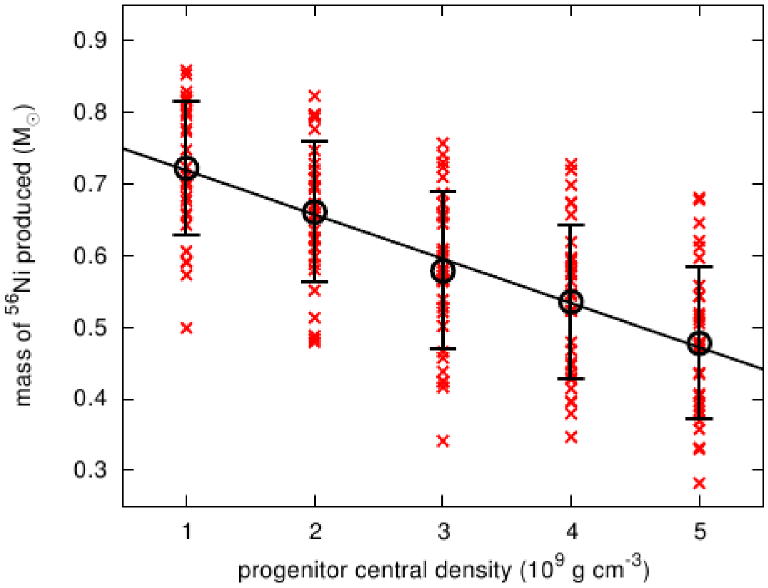
For accretion onset at 0.1, 0.2, 0.4 and 0.8 Gyr for 1.0$M_\odot$.

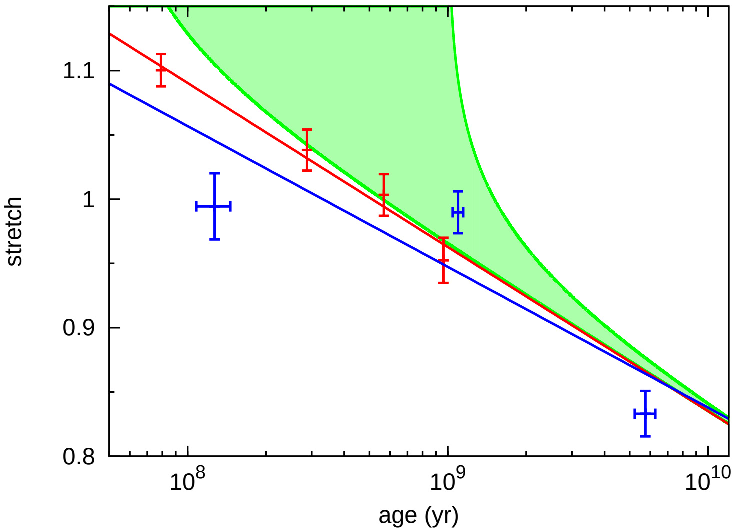
Lesaffre et al. 2006, MNRAS, 368, 187L

Higher central densities leads to more electron capture

Forms more neutron-rich stable Fe-group material and less ^{56}Ni

Reduction of Nickel





See Krueger et al. 2012, ApJ, 757, 175 for more details

Higher central densities yield less ^{56}Ni *on average*

Associate each central density with a delay time $\rightarrow$ delayed supernovae eject less ^{56}Ni

Nontrivial dynamics here – deflagration phase is 50% shorter at high densities (star expands much faster)

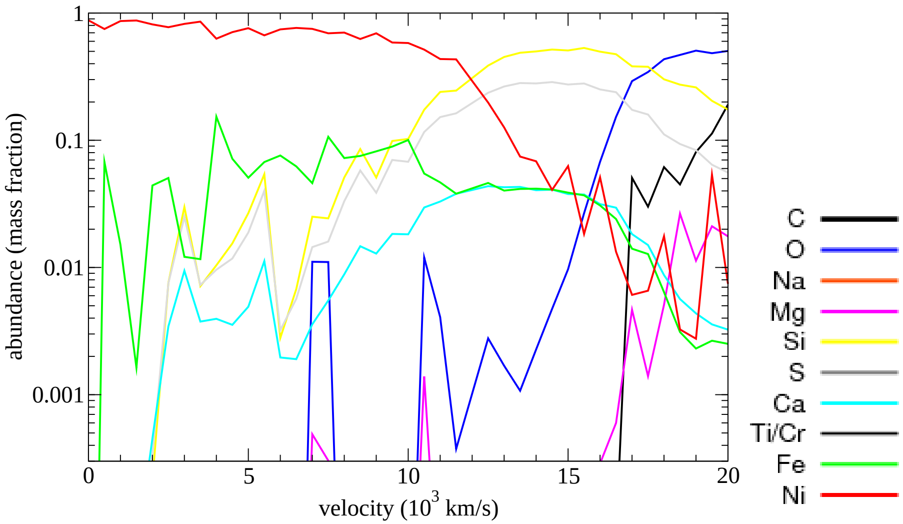
A more complete treatment for observational comparison would require averages over progenitor mass and age distributions.

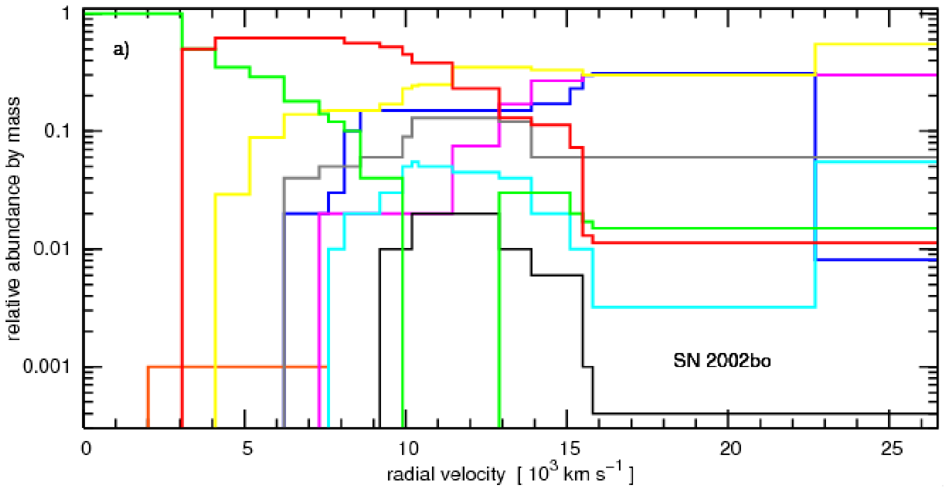
May be different in 3D - or with different DDT conditions (Seitenzahl et al. 2011, MNRAS, 414, 2709)

Burning at Low Densities

Outer ejecta abundance profile

2D DDT:



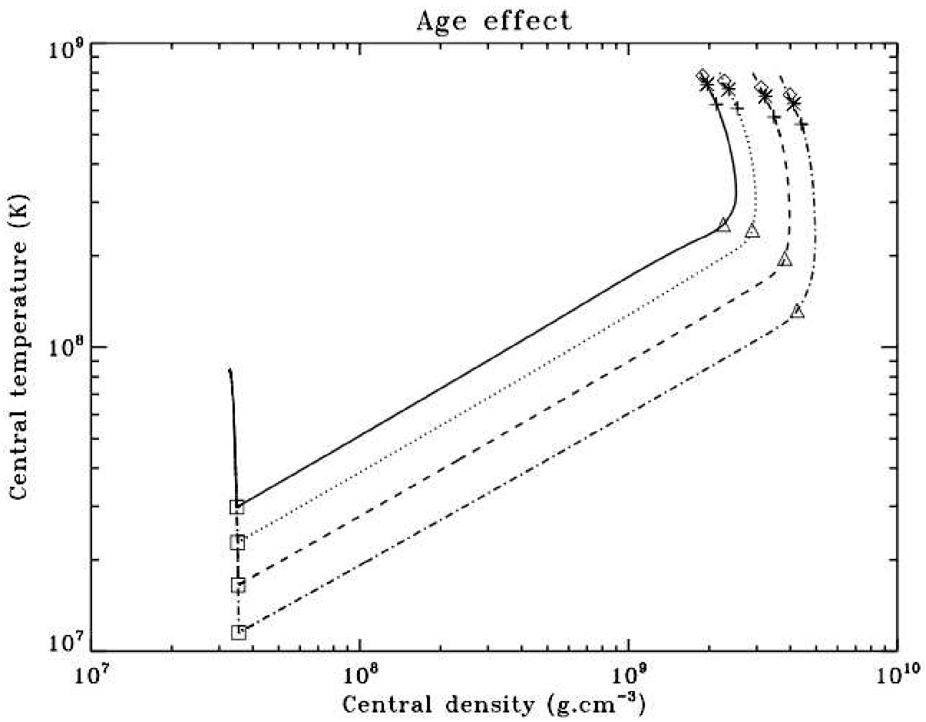


SN2002bo from Stehle et al. 2005, MNRAS, 360, 1231

Results from central ignition (imposed symmetry) in 2 dimensions with transition to detonation at density of 10^7 g/cc

- Distribution of species in expansion velocity can be used as diagnostic when compared to observed spectral evolution
  much like comparing spectra at various epochs
- C+C rate will change strength of detonation in outer regions and shift transitions between abundance layers.

Change in Ignition



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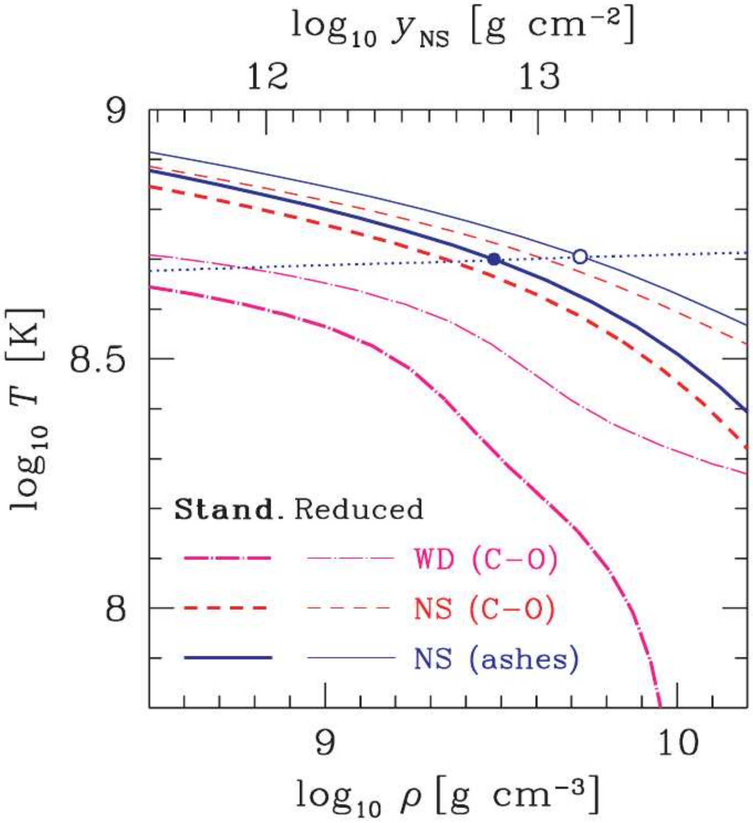

Gasques et al. 2007, Phys. Rev C, 035802

Change in C+C rate or central C abundance will have important impact on density for central ignition.

Ignition at higher densities would lead to more electron capture

Some Nuclear challenges in SNIa

- Improving electron capture rates for Fe-group nuclei
  - not just a handful of measurable rates
  - incorporating measurements into rate theory non-trivial step
- Carbon fusion rate
  - determines ignition density
  - important for intermediate mass element production
- Plenty of astrophysical uncertainties
  - Other scenarios; double degenerate, sub-Chandrasekhar
  - DDT conditions
  - flame propagation
  - main sequence evolution (progenitor composition)
  - ...