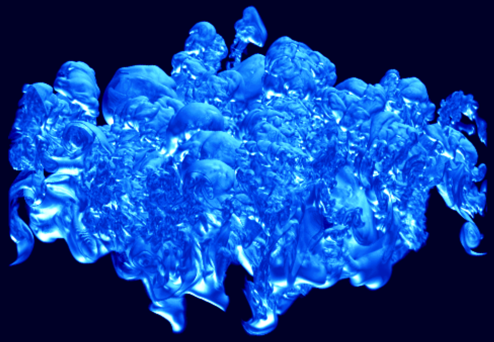
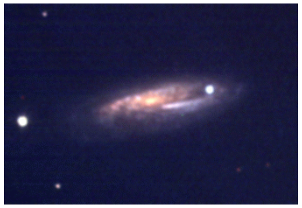
Lecture 17

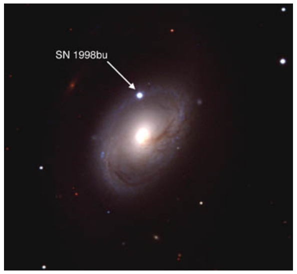


Type Ia Supernovae

SN 1998aq



SN 1998dh



SN 1998bu

SN 1994D

Type Ia supernovae are the biggest thermonuclear explosions in the universe.

Twenty billion, billion, billion megatons (~10^{51} erg).

For several weeks their luminosity rivals that of a large galaxy.

Observational Facts

- Very bright, regular events, peak $L \sim 10^{43}$ erg s^{-1}
- Associated with an old stellar population (found in ellipticals, no clear association with spiral arms)
- No hydrogen in spectra; strong lines of Si, Ca, Fe
- Not strong radio sources
- Total kinetic energy ~10^{51} erg (no compact remnant)
- Higher speed, less frequent than Type II

SN 1994D

Models that have been suggested:

- *All based upon accreting white dwarfs – to explain association with old population, absence of hydrogen, regularity, etc. (Hoyle and Fowler 1960)*

- *Chandrasekar mass model*

  CO white dwarf in a binary accreting at ~ 10^{-7} solar masses per year reaches 1.38 solar masses and ignites a runaway near its center. Initial deflagration later transitions to a detonation. Very bright progenitor.
- *Sub-Chandrasekhar mass models*

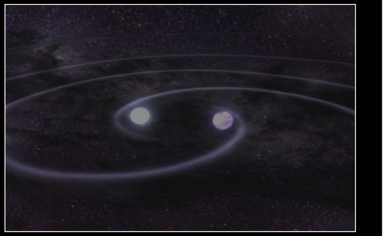
  Accretion at 1 – 10 x 10^{-8} solar masses/yr. Build a thick He layer ~ 0.1 solar masses on top of a CO dwarf of variable mass (0.9 to 1.1). Helium detonation leads to carbon detonation when the CO core is compressed. Moderately bright progenitor.
- *Merging white dwarfs*

  Two white dwarfs, one a CO dwarf with mass ~1 solar mass, merge because of gravitational radiation. The CO dwarf detonates. Faint progenitor.

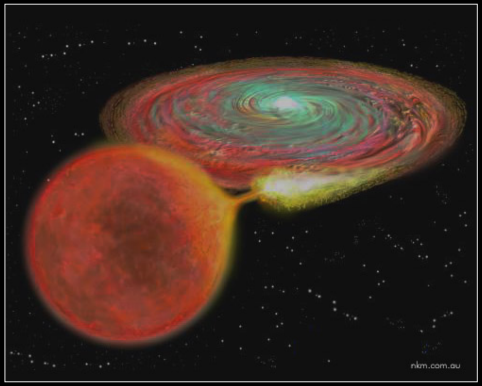
Always a CO white dwarf in a binary.

SN Ia Progenitor Systems

explosions of carbon/oxygen white dwarf stars

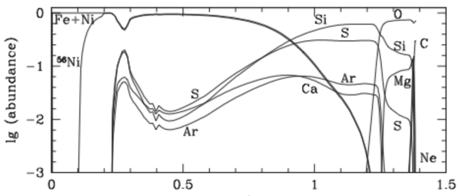


merging double white dwarf binary.

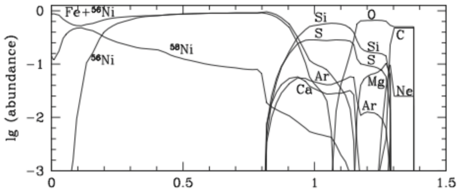


accreting white dwarf near the either near the Chandrasekhar limit (1.4 Msun) or less.

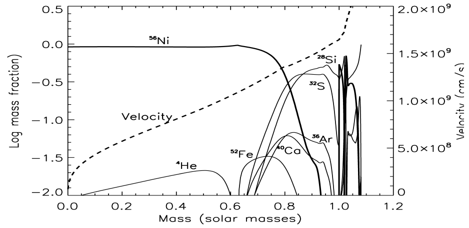
Delayed Detonation – DD4 - (WW90)



Accelerating deflagration – W7 – (NTY84)



sub-Chandrasekhar – 10H – (WK11)



The common theme. ~ 1 solar mass of CO burns to ^{56}Ni and intermdiate mass elements

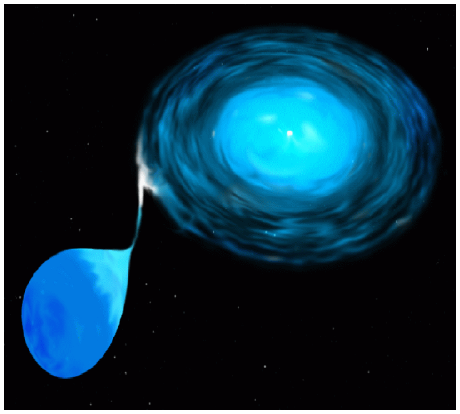
Model	**^{56}Ni**	**Si+S**	**KE/gm**
	Msun	Msun	10^{17}
DD4	0.63	0.42	4.5
W7	0.63	0.23	4.7
10H	0.62	0.29	5.3*

*6.0 if include outer 0.045 solar masses of hi-v helium

A SN Ia is the outcome of detonating 1 solar mass of carbon and oxygen with $\rho_{\max} \approx 0.5 - 2 \times 10^8$ g cm^{-3}

Chandraskhar Mass Model

Accretion and growth to *almost* he Chandrasekhar Mass (1.38 solar masses)
-corrected for Coulomb effects but usually relativity effects are ignored.
-$Y_e \sim 0.50$



In order to avoid the nova instability must accrete at a rate ~10^{-7} solar masses per year.

This must be maintained for millions of years.

Possible observational counterpart – supersoft x-ray sources (controversial)

Ignition

Arnett (1968, 1969)
Nomoto, Sugimoto, & Neo (1976)

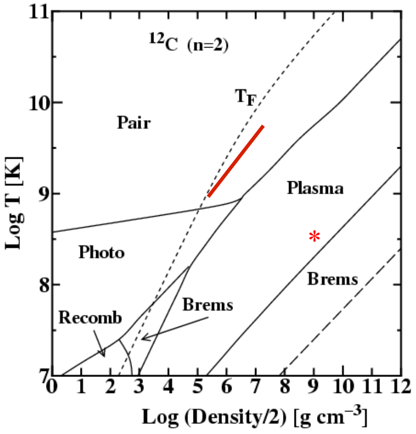
Ignition occurs as the *highly screened* carbon fusion reaction begins to generate energy faster than (plasma) neutrino losses can carry it away.

At a given temperature, the plasma neutrino losses first rise with density and then decline when $\hbar\omega_p > kT$.

$$\text{As } \rho \rightarrow 3\times10^9 \text{ gm cm}^{-3}; \ T \approx 3 \times 10^8 \text{ K}$$

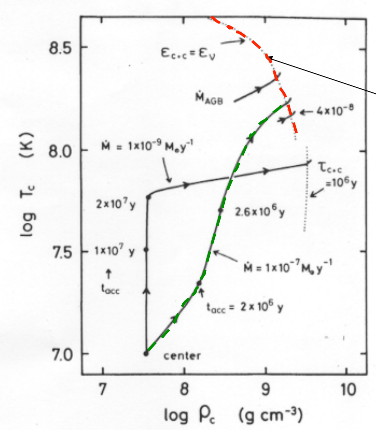
$$S_{\rm nuc}(^{12}\mathrm{C}+^{12}\mathrm{C}) \geq S_\nu(\text{plasma}); \qquad M \approx 1.38\ M_{\rm sun}$$

Neutrino Losses



Itoh et al 1996, *ApJS,* **102**, 411, see also
Beaudet, Petrosian, & Salpeter 1967, *ApJ*, **147**, 122

The ignition conditions depend weakly on the accretion rate. For lower accretion rates the ignition density is higher. Because of the difficulty with neutron-rich nucleosynthesis, lower ignition densities (high accretion rates) are favored.



Ignition when nuclear energy generation by (highly screened) carbon fusion balances cooling by neutrino emission.

Conditions in the Star

- *Supernova preceded by 100 years of convection throughout most of its interior. Energy goes into raising the temperature of the white dwarf (not expansion, not radiation).*

- *Last "good convective model" is when the central temperature has risen to 7 x 10^8 K*

Pressure scale height: 400 km

Nuclear time scale: 10^2 s

Convective time scale: 10^2 s

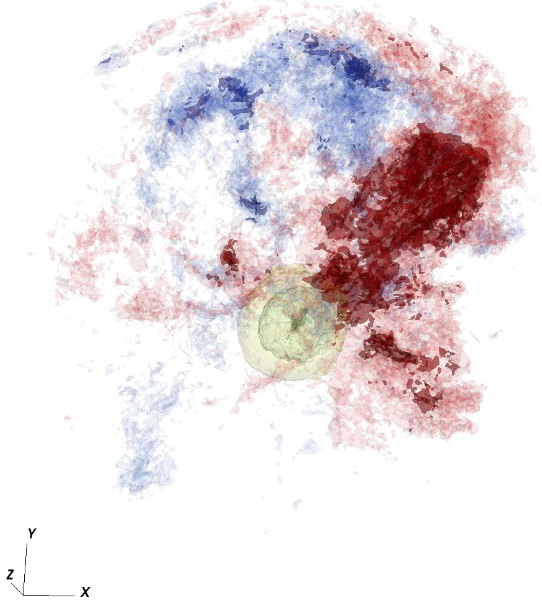
Convective speed: 50 km s^{-1}

Binding energy: 4 x 10^{50} erg

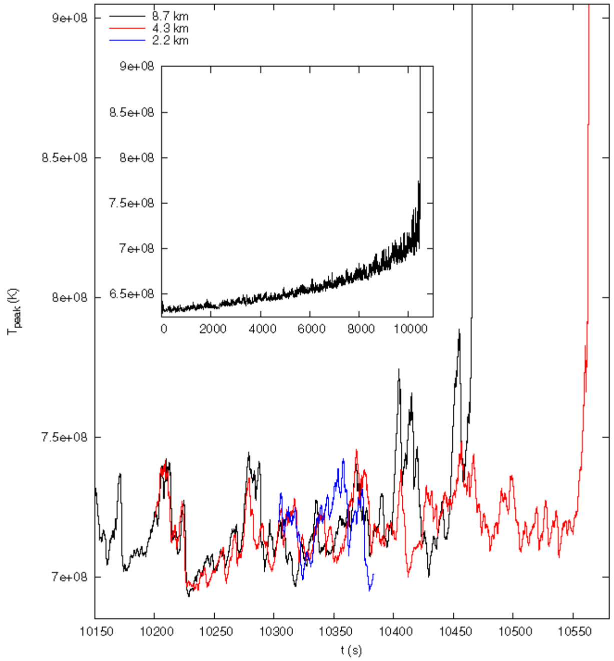
Density: 2.7 x 10^9 g cm^{-3}

Burning 0.05 solar masses can cause expansion by a factor of three

using MAESTRO

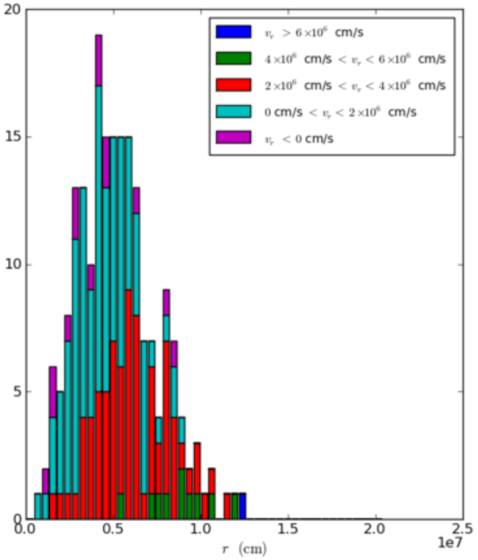


Nonaka et al (2012); *ApJ*, 745, 73



Peak temperature as a function of time for three studies with effective resolution 8.68, 4.35, and 2.17 km

Note that the time between successive hot spots is many seconds. Once ignited, the explosion only takes 1 s. The WD only ignites once.



Zingale et al (2011)

This figure shows the distribution with radius of the hottest spot in the 3D simulation during the last few minutes leading up to ignition.

The Typical SN Ia will ignite a runaway at a single point around 50 km off center, but there will be a distribution of ignition points in various SN Ia ranging all the way from central ignition to 120 km off center.

This chaotic ignition could cause considerable diversity in the outcome starting from virtually identical models.

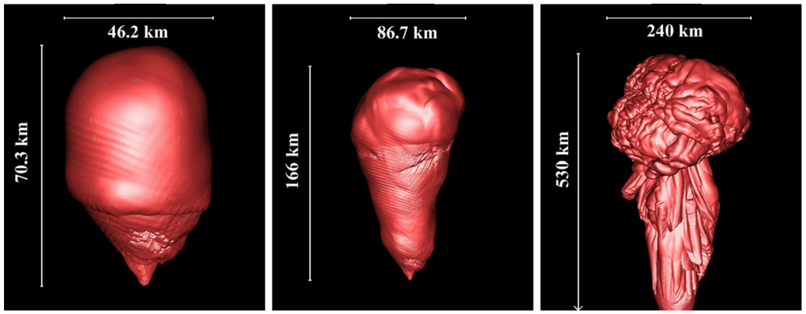
- Off-center ignition overwhelmingly likely
- Typical offset 50 km; range 0 – 110 km
- Typical convection speed ~50 km s^{-1}
- Single point, single time ignition

Initially laminar propagation from a point
Malone et al (2014)

0 5.9 ms 11.9ms

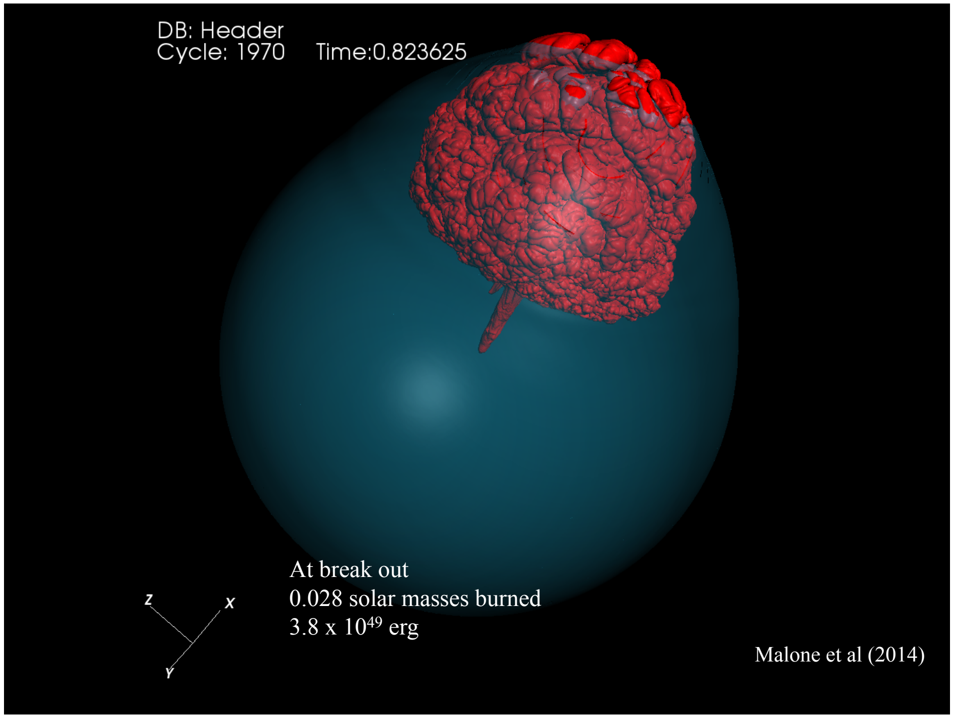
$38{,}640^3$ effective resolution
5 levels of AMR
8.68, 4.34, 1.09, 0.271 and 0.135 km

Malone et al (2014)



150 ms 265 ms 469 ms

WD radius = 1800 km



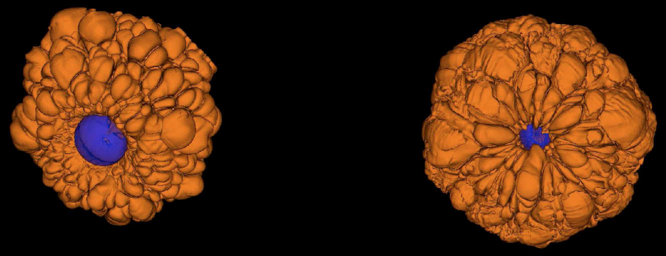
At break out
0.028 solar masses burned
3.8 x 10^{49} erg

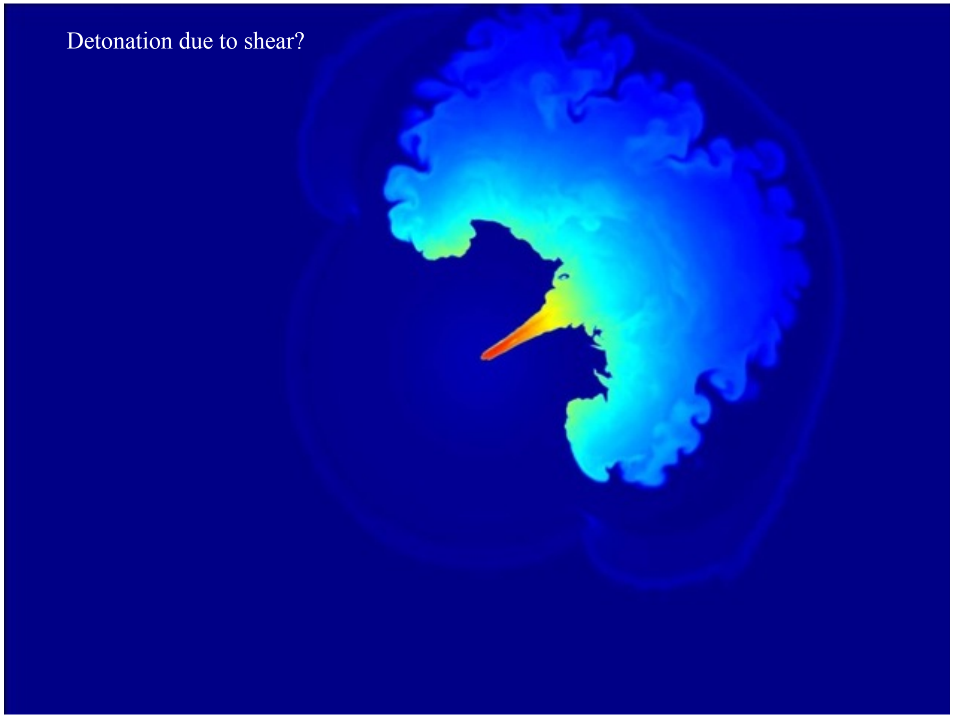
Malone et al (2014)

What happens next?

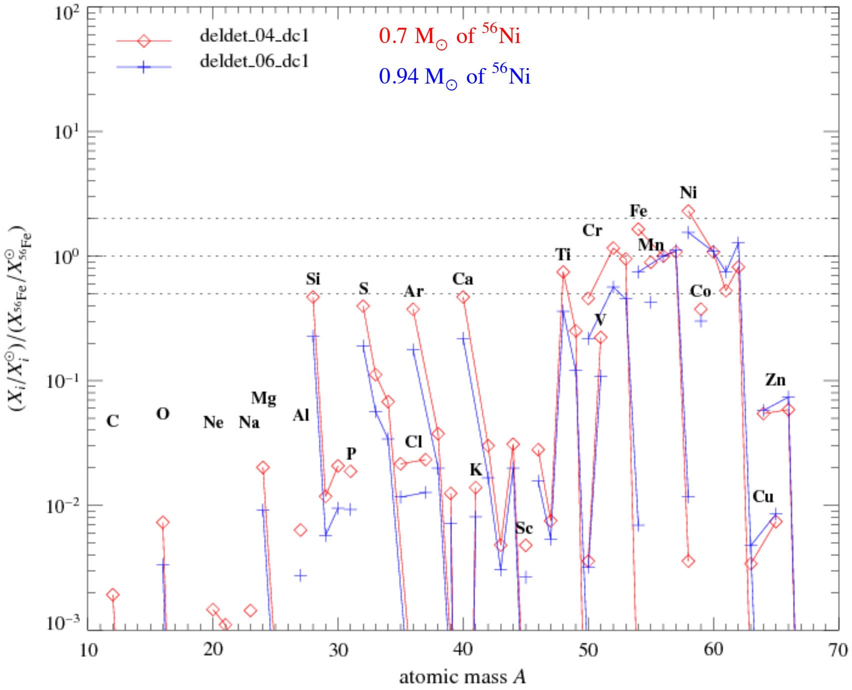
1. Mechanical compression to a state that burns supersonically – compressional detonation (Chicago).
2. Creation of a “warm” mixture of cold fuel and hot ash that eventually heats up and has a supersonic phase velocity for burning. This is difficult, but feasible for certain restrictive conditions (Germany).
3. A pulse followed by additional burning (Arnett and Livne 1994)

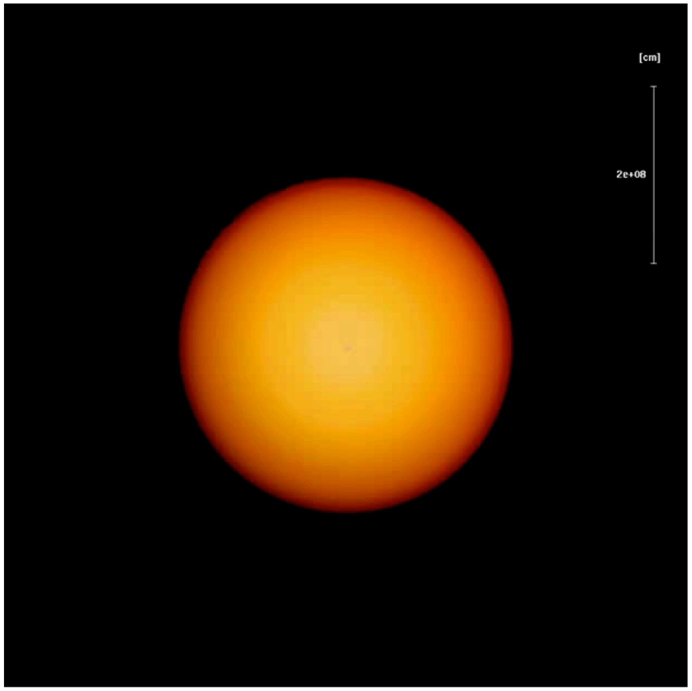
Gravitationally Confined Detonation?



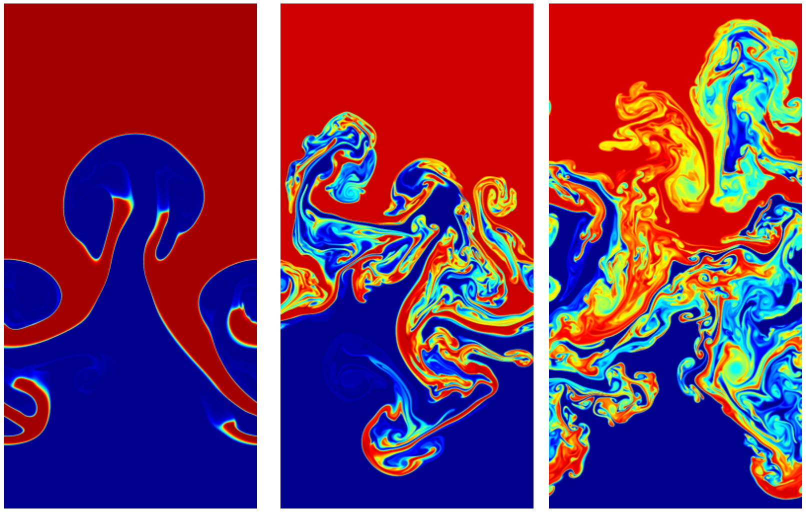


Detonation due to shear?





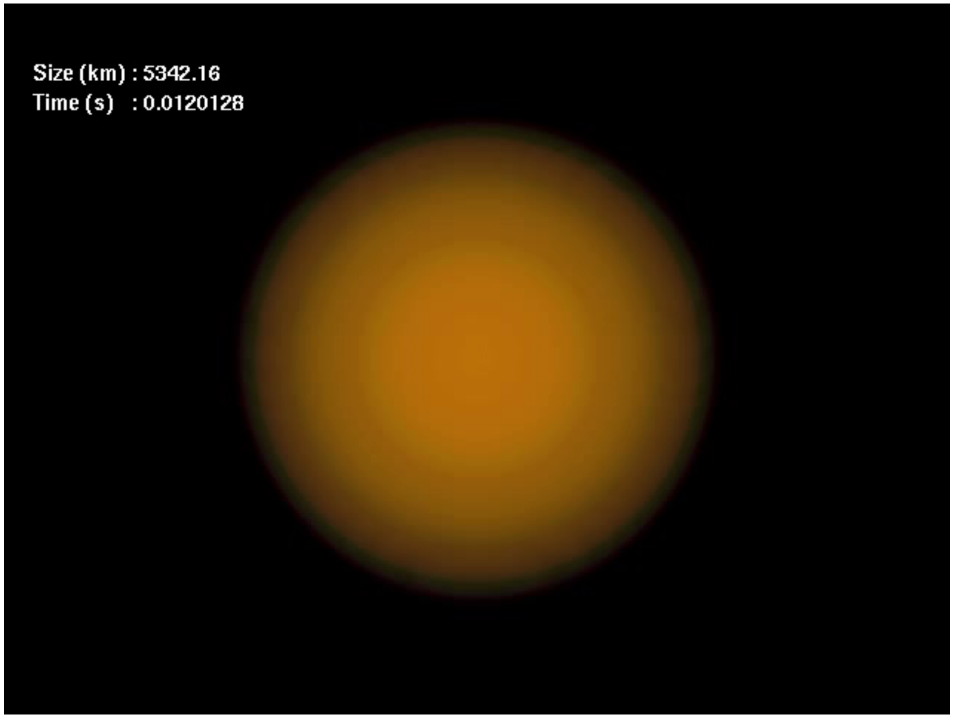
Transition to detonation?



1.5 x 10^7

1.0 x 10^7

0.667 x 10^7

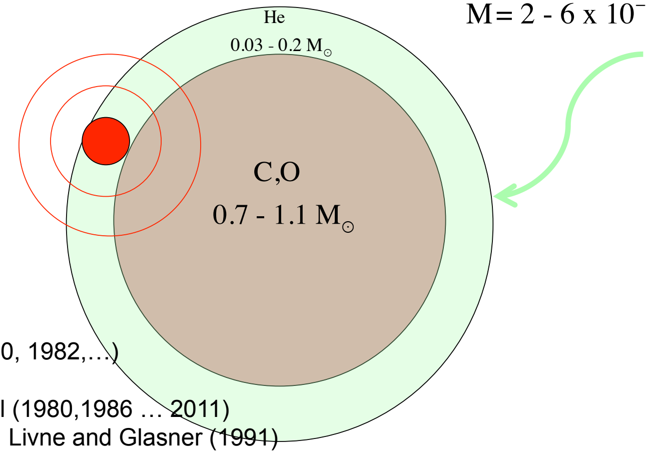


MCh Model Summary

- Asymmetric
- Overall very little burning occurs prior to break out. Expansion is thus minimal. A transition to detonation (DDT) may occur as a result of nearly sonic shear as the hot ashes of the “volcano” slide over the WD surface but the SN will be quite bright.
- Or, later, the Chicago GCD model works, but depending upon how much burning happens after break out, the SN may still be unusually bright.
- If a DDT does not happen at this time, the continued evolution is of interest. The flame never dies. A white dwarf remnant seems doubtful.

SUB-CHANDRASEKHAR MASS MODELS

A critical mass of He accretes from a companion. The helium ignites and detonates. This may set off a secondary detonation of the carbon



$\dot{M} = 2 - 6 \times 10^{-8}\ M_\odot\ y^{-1}$

Nomoto (1980, 1982,…)
Taam (1980)
Woosley et al (1980,1986 … 2011)
Livne (1990); Livne and Glasner (1991)
Fink et al (2007)
Sim et al (2010)

and others

ISSUES

- Initiation of the helium detonation – critical mass, location.

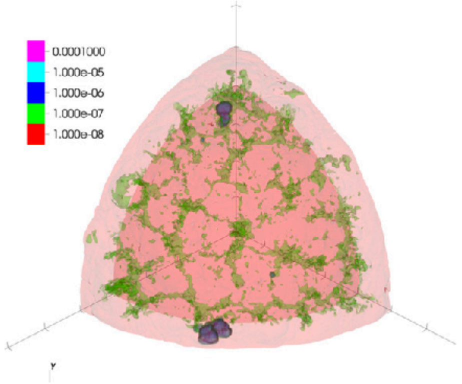
  The critical He-shell mass has come down considerably since the early models because of finer zoning, a better treatment of the nuclear physics (esp $^{12}C(p,\gamma)^{13}N(\alpha,p)^{16}O$ - Ken Shen), and use of a hot white dwarf accretor

- Critical mass for propagation of the detonation

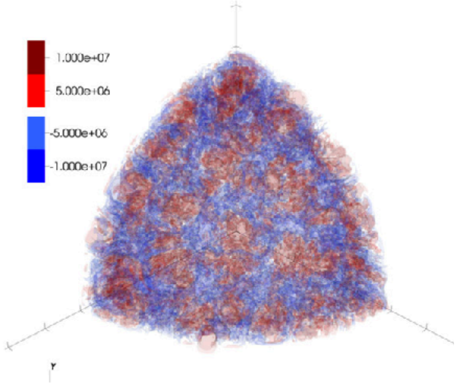
  The critical helium density to sustain a detonation is considerably less than the critical density needed to initate the detonation by the Zel'dovich criterion.

- Diversity of outcomes

Zingale et al (2013) ApJ, and in progress using MAESTRO



Oxygen mass fraction

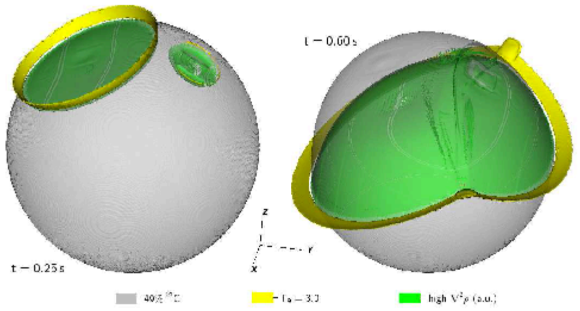


Velocity

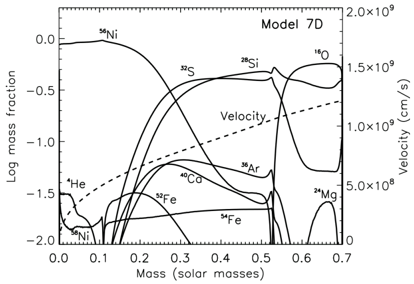
at 100 s

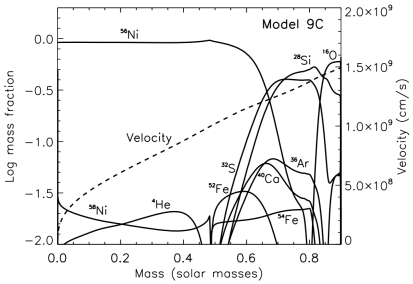
Shows cellular structure of convection. As expected
cell size ~ pressure scale height ~ few hundred km
The ignition region should be much smaller than that

Study of asynchronous multiple ignition points by
Moll and Woosley (2013). All models studied
detonated the CO core provided the helium itself detonated.
Fink et al (2010) found CO core detonation for He shells as low
as 0.0035 solar masses. Moll and Woosley had trouble initiating
the detonation if the shell mass was < 0.03 M_o

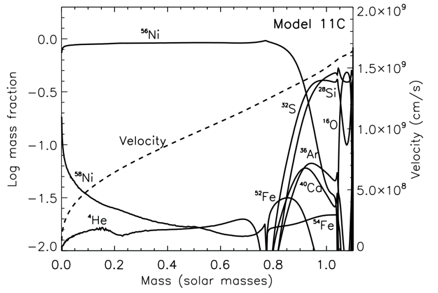


Woosley and Kasen (2011)





neglecting helium shell



Mass WD	^{56}Ni
0.7	0.24
0.8	0.34
0.9	0.57
1.0	0.66
1.1	0.83

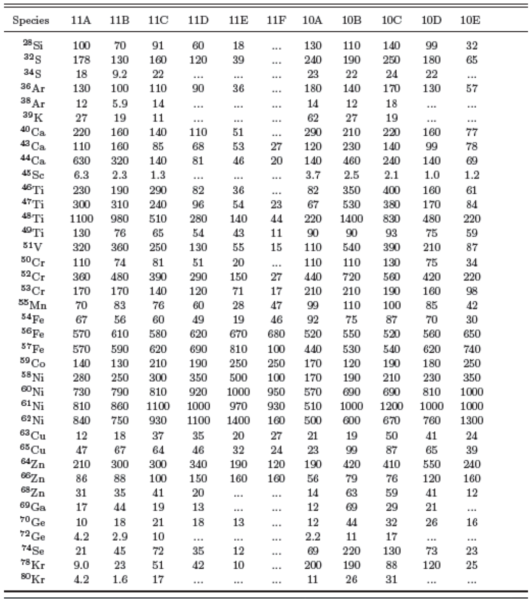
hard to detionate?

↑
Good
↓

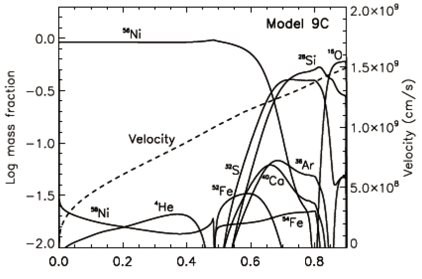
Max CO WD

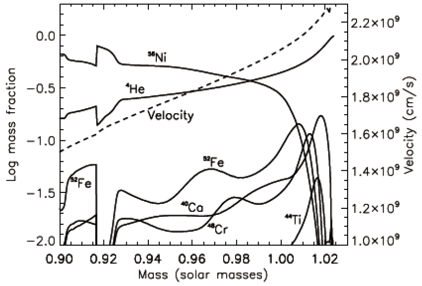
(some variation with accretion rate,
and WD temperature)

Nucleosynthesis

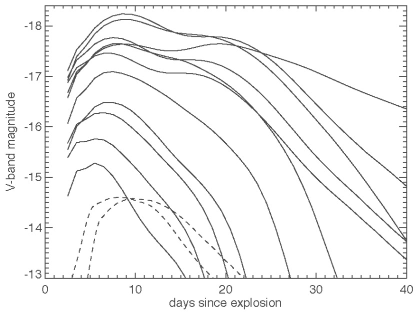


Species	11A	11B	11C	11D	11E	11F	10A	10B	10C	10D	10E
^{28}Si	100	70	91	60	18	...	130	110	140	99	32
^{32}S	178	130	160	120	39	...	240	190	250	180	65
^{34}S	18	9.2	22	...	...	...	23	22	24	22	...
^{36}Ar	130	100	110	90	36	...	180	140	170	130	57
^{38}Ar	12	5.9	14	...	...	...	14	12	18	...	...
^{39}K	27	19	11	...	...	...	62	27	19	...	...
^{40}Ca	220	160	140	110	51	...	290	210	220	160	77
^{43}Ca	110	160	85	68	53	27	120	230	140	99	78
^{44}Ca	630	320	140	81	46	20	140	460	240	140	69
^{45}Sc	6.3	2.3	1.3	...	...	...	3.7	2.5	2.1	1.0	1.2
^{46}Ti	230	190	290	82	36	...	82	350	400	160	61
^{47}Ti	300	310	240	96	54	23	67	530	380	170	84
^{48}Ti	1100	980	510	280	140	44	220	1400	830	480	220
^{49}Ti	130	76	65	54	43	11	90	90	93	75	59
^{51}V	320	360	250	130	55	15	110	540	390	210	87
^{50}Cr	110	74	81	51	20	...	110	110	130	75	34
^{52}Cr	360	480	390	290	150	27	440	720	560	420	220
^{53}Cr	170	170	140	120	71	17	210	210	190	160	98
^{55}Mn	70	83	76	60	28	47	99	110	100	85	42
^{54}Fe	67	56	60	49	19	46	92	75	87	70	30
^{56}Fe	570	610	580	620	670	680	520	550	520	560	650
^{57}Fe	570	590	620	690	810	100	440	530	540	620	740
^{59}Co	140	130	210	190	250	250	170	120	190	180	250
^{58}Ni	280	250	300	350	500	100	170	190	210	230	350
^{60}Ni	730	790	810	920	1000	950	570	690	690	810	1000
^{61}Ni	810	860	1100	1000	970	930	510	1000	1200	1000	1000
^{62}Ni	840	750	930	1100	1400	160	500	600	670	760	1300
^{63}Cu	12	18	37	35	20	27	21	19	50	41	24
^{65}Cu	47	67	64	46	32	24	23	99	87	65	39
^{64}Zn	210	300	300	340	190	120	190	420	410	550	240
^{66}Zn	86	88	100	150	160	160	56	79	76	120	160
^{68}Zn	31	35	41	20	...	...	14	63	59	41	12
^{69}Ga	17	44	19	13	...	...	12	69	29	21	...
^{70}Ge	10	18	21	18	13	...	12	44	32	26	16
^{72}Ge	4.2	2.9	10	...	...	...	2.2	11	17	...	...
^{74}Se	21	45	72	35	12	...	69	220	130	73	23
^{78}Kr	9.0	23	51	42	10	...	200	190	88	120	25
^{80}Kr	4.2	1.6	17	...	...	...	11	26	31	...	...

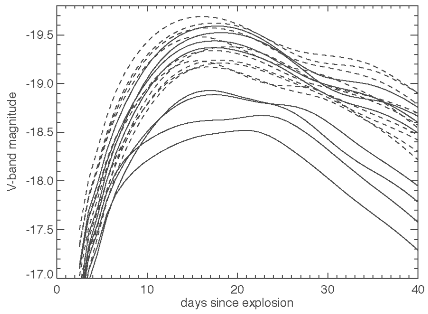




The general class of sub-Chandrasekhar mass models can give a wide variety of transients ranging from very luminous SN Ia to super “novae”.



He shell only explodes

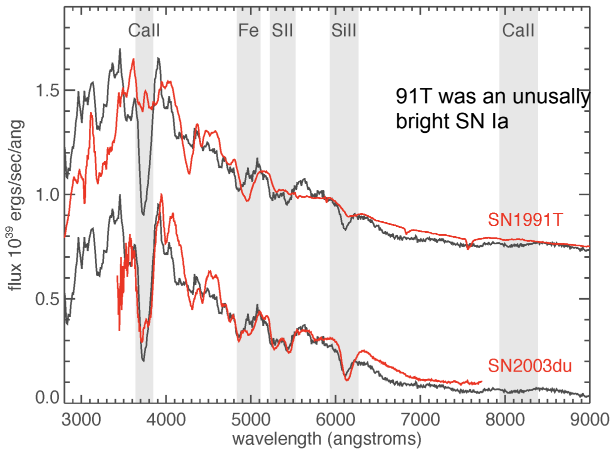


Entire star explodes

Some of these look like SN Ia…

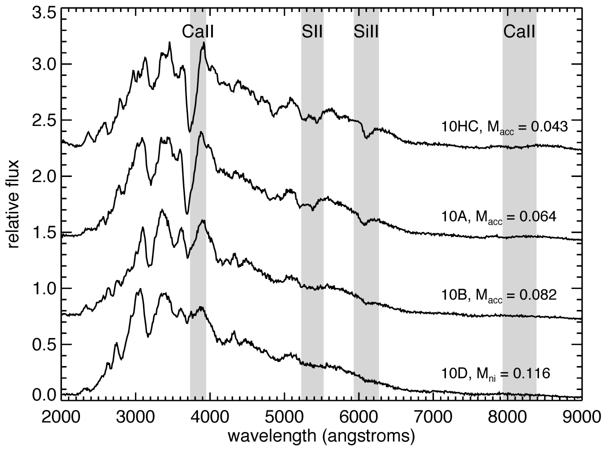
Model 10HC (hot 1.0 solar mass CO WD accreting at 4 x 10^{-8} solar masses per year, 0.045 solar mass He shell) – peak light spectrum vs observations.

Good agreement with typical SN Ia 2003du



“Hot” WD here means a white dwarf with L = 1 Lsun

But others do not



Same WD mass (1.0 M_o) with different helium shell masses.

If the shell mass is too big, the IME absorption features are degraded

D. Kasen in
Woosley and Kasen (2011)

Requirements– sub-MCh

The single degenerate models that resemble common SN Ia have CO white dwarf masses of 1.0 ± 0.1 $M_\odot$ capped by He shells of less than 0.07 $M_\odot$ (spectrum) and greater than 0.03 $M_\odot$ (to detonate).

But, the helium shell mass can be less in a detonation initiated directly by compression (as in a merger), but probably not much less than ~0.01 $M_\odot$. (See Fink et al (2010) who got 0.0035 $M_\odot$)

How To Detonate ~0.01 M_o of He on a 1 M_o WD?

- Accrete on a hot white dwarf. Slowly decrease the accretion rate. Initially get repeated helium novae, but eventually a layer of the necessary minimum mass detonates (Bildsten et al 2007; Woosley and Kasen 2011)

Or

- Merger of a low mass helium WD with a ~ 1 solar mass CO WD. Make a shell of ~ 0.01 solar masses around the CO WD then detonate by compression (Dan et al 2011)

Or

- Merge CO WDs that already have a 0.01 Msun layer of He on top and detonate by impact – Pakmor et al (2013)

Merging White Dwarfs

Wide variety of outcomes possible.

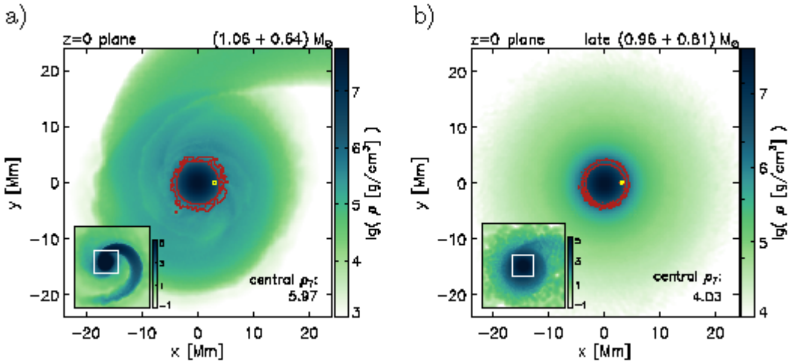
- If the merger results in slow accretion, a common outcome is the production of a neon-oxygen white dwarf. This seems to be the case unless the merger itself results quickly in a detonation.

- Detonation can occur "promptly" in the merger initiated by compression or "delayed" initiated by shear in a single differentially rotating object.

- One WD is CO but the other can be He, CO, or NeO

Late time mergers

e.g. Raskin et al (2014)



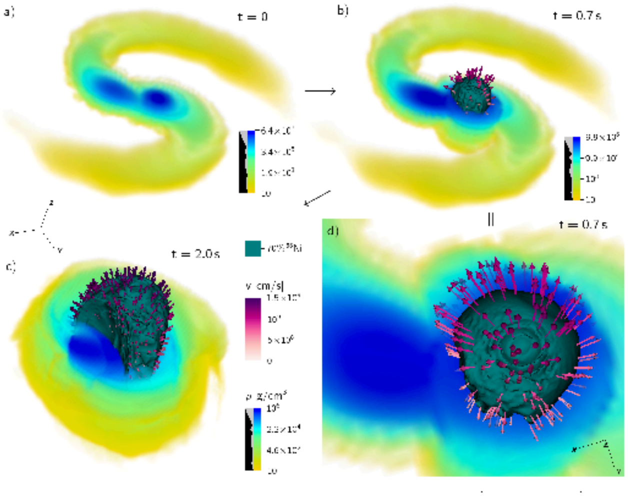
Detonation initiated artificially at highest T point in sheared layer. 1.4 x 10^9 and 7 x 10^8 K, respectively
not realistic in my opinion

Yoon, Podsiadlowski, and Rosswog (2007)
Schwabb et al (2012)
Raskin et al (2012,2014)
Zhu et al (2012)
Dan et al (2012, 2014)

Prompt Detonation

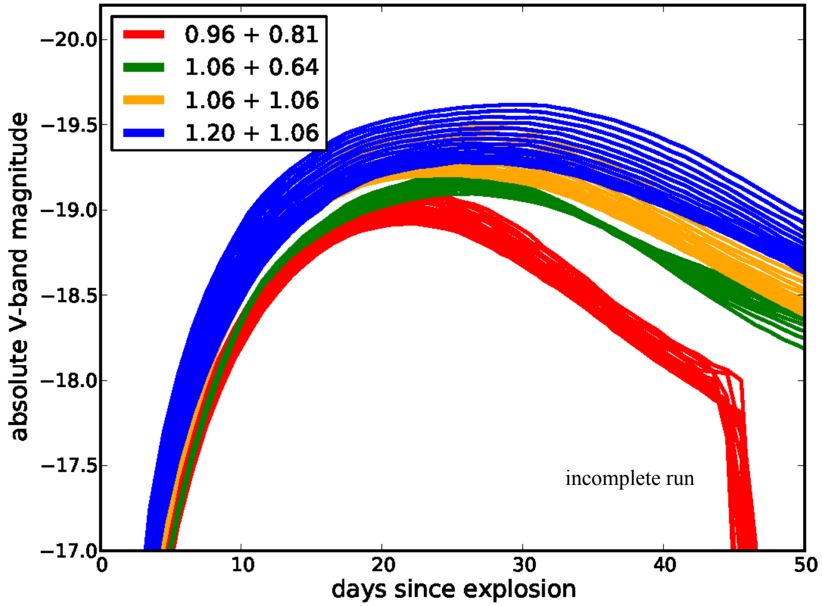
Guillochon et al (2010)
Pakmor et al (2010,2011,2012ab)
Kromer et al (2013)
Moll et al(2014)

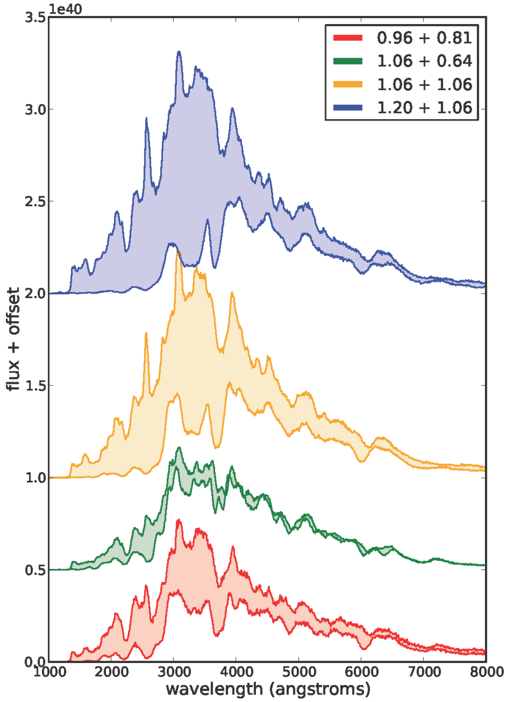
Moll, et al, 2014
1.06 $M_\odot$ + 1.06 $M_\odot$



Density contours
Sphere with arrows
is ^{56}Ni

Moll et al (2014) in preparation; light curves and spectra by Dan Kasen





Angle-dependent
spectra for
merging CO WDs

D. Kasen in
Moll et al (2014)

(low mass He+CO may
be a different story)

Model Summary

- All models probably happen. Their observable consequences and realization frequencies should be explored.
- Chandrasekhar mass (single degenerate) models starting to be better understood, but observational constraints suggest these may not be the most common event.
- A promising explanation today for common SN Ia – 1.0 CO M_o WD capped by 0.01 M_o of He

  Can detonation be initiated in ~0.01 solar masses of helium in a realistic, frequent event – verify

  Can the overproduction of too many alternate outcomes be avoided? E.g. 0.6 – 0.9 solar mass WDs, thicker He shells

  ^{44}Ca production will place interesting limits on occurrence

Light Curves

After the white dwarf has expanded a few times its initial radius its internal energy (and entropy) will be chiefly due to radiation, that is -

$$T^3/\rho \approx \text{constant}$$

$$\rho \propto 1/r^3, \text{ so}$$

$$T \propto 1/r$$

$$\varepsilon = aT^4/\rho \propto 1/r$$

Before the radiation can diffuse out the supernova has expanded from a ~2 times 10^8 to 10^{15} cm. During that time, the internal energy goes down from ~10^{51} erg to ~10^{44} erg. The remaining internal energy is totally inadequate to power the light curve (10^{49} erg).

Energy from explosion:

$E \sim 10^{51}$ erg
$T \sim 10^{10}$ K $R \sim$ few x 10^8 cm

Light can escape when the diffusion time equals the age:

$$\tau_{diff} \sim t$$

$$\frac{R^2\kappa\rho}{c} \sim t \qquad \kappa = \kappa_{es} + \kappa_{line} \sim 0.1\,\mathrm{cm^2\,g^{-1}}$$

$$\rho \sim \frac{3M}{4\pi R^3} \qquad M = 1.4 M_\odot = (1.4)*2\times10^{33}\,\mathrm{gm}$$

$$R = vt \qquad v \sim 7000\,\mathrm{km\,s^{-1}}$$

$$t \approx \frac{3R^2\kappa M}{4\pi R^3 c} \approx \frac{3\kappa M}{4\pi v t c}$$

$$\Rightarrow t_{peak} \approx \sqrt{\frac{3\kappa \mathrm{M}}{4\pi \mathrm{vc}}} = 1.8 \times 10^6\,\mathrm{s} \quad \Rightarrow \quad R \sim 10^{15}\,\mathrm{cm}$$

But then adiabatic expansion implies that the the interior temperature has dropped by 10^6 and the interior energy is negligible.

Radioactivity is essential to keep the supernova hot and shining!

Radioactivity

$$^{56}\mathrm{Ni} + e^- \rightarrow {}^{56}\mathrm{Co} + \nu \qquad \tau_{1/2} = 6.1\,\text{days}$$

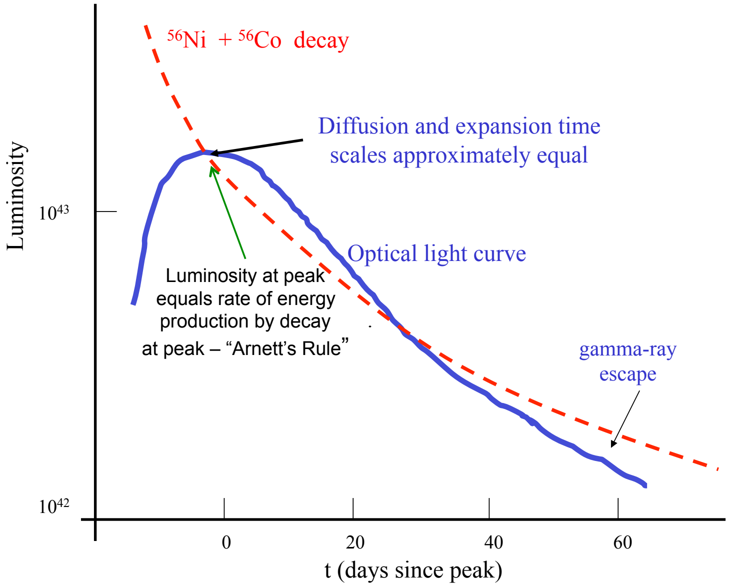
q = 3.0 x 10^{16} erg/gm

$$^{56}\mathrm{Co} + e^- \rightarrow {}^{56}\mathrm{Fe} + \nu \qquad \tau_{1/2} = 77.1\,\text{ days}$$

q = 6.4 x 10^{16} erg/gm

0.6 solar masses of radioactive Ni and Co can thus provide 1.1 x 10^{50} erg at late times after adiabatic expansion is essentially over.

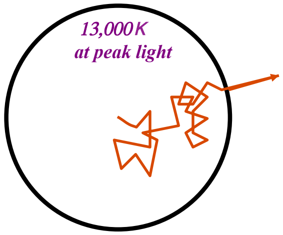
Qualitative Type Ia Supernova Light Curve



Why is there a Philipps Relation?

Pinto & Eastman (2001)
New Astronomy

Broader = Brighter



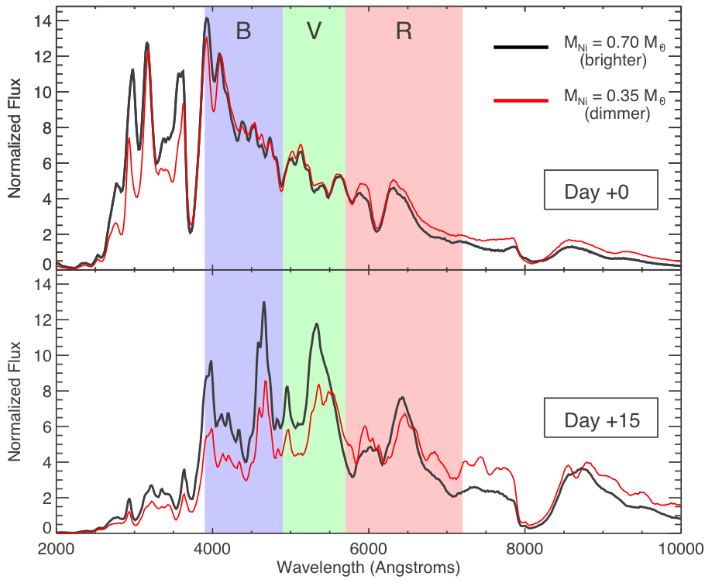
Photons must diffuse through a forest of lines in a differentially expanding medium.

Doppler shift causes a migration from line to line.

The trapped radiation is mostly uv and the uv optical depth is very large.

Photons escape chiefly by fluorescence.

The decline is faster in B than in other bands. Some of the energy that is lost from B appears in R



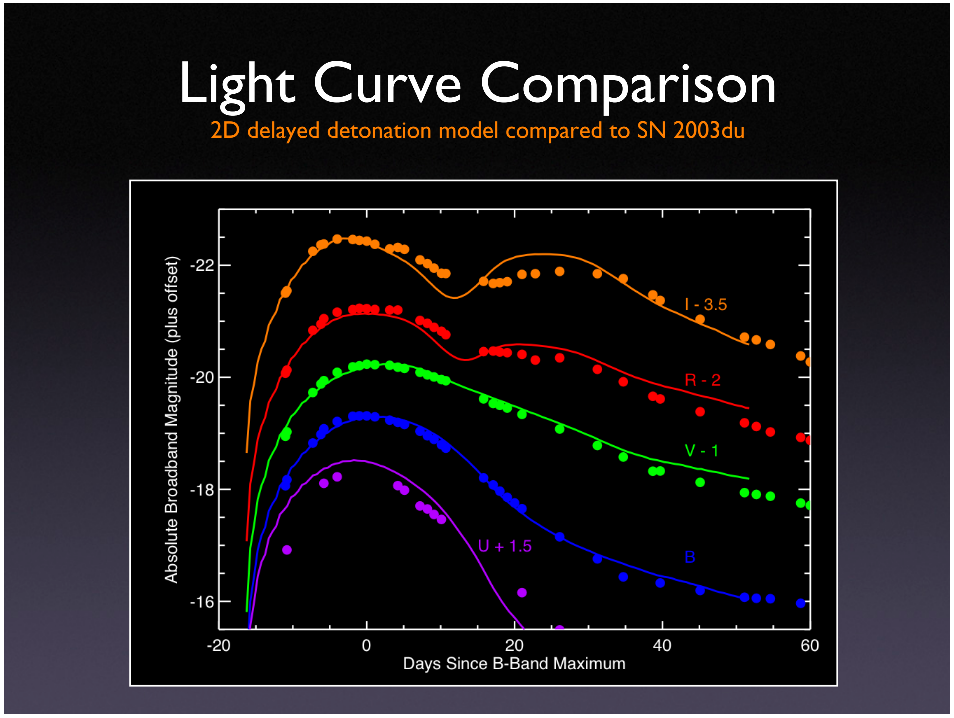
Dan Kasen's explanation of the Phillipp's Relation:

More ^{56}Ni implies a larger luminosity at peak.

But more ^{56}Ni also implies higher temperature in the interior. This in turn implies that Fe, Co, Ni are more highly ionized (III rather than II)

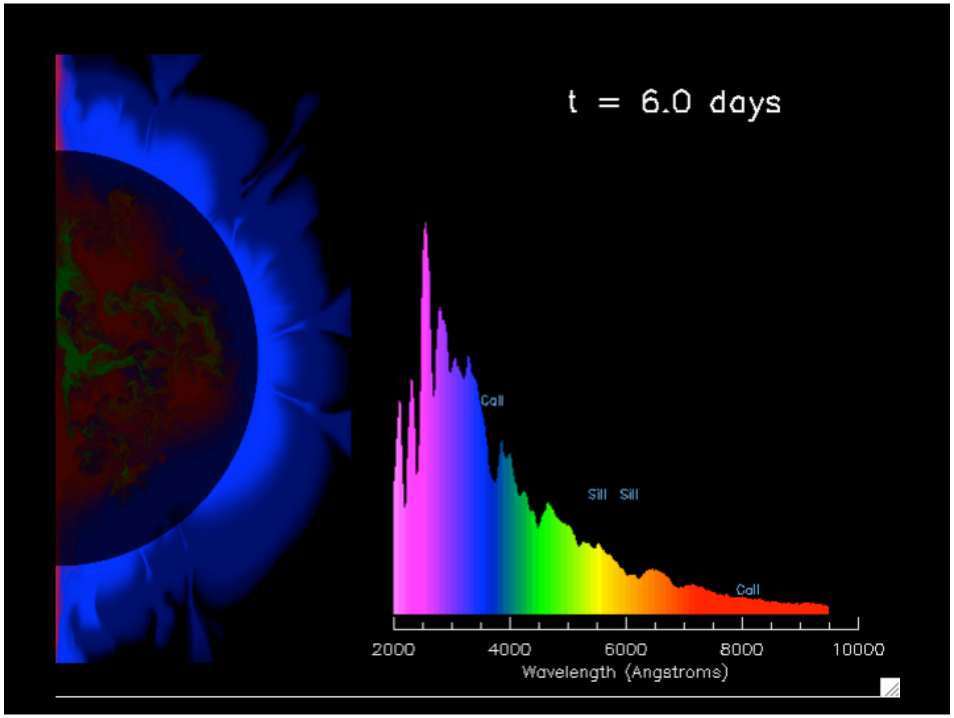
The more highly ionized Fe is less effective at redistributing the blue light into the red because it has fewer lines.

Hence hotter implies more optical opacity (actually less optical efficiency)



Light Curve Comparison

2D delayed detonation model compared to SN 2003du


t = 6.0 days
CaII
SiII
SiII
CaII
2000
4000
6000
8000
10000
Wavelength (Angstroms)