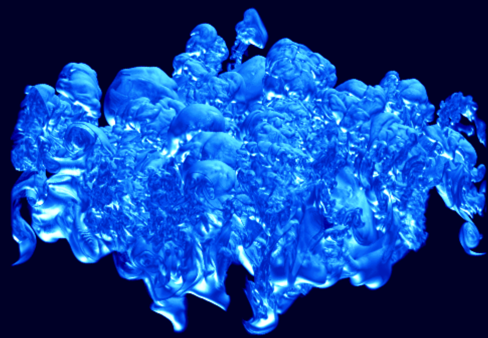
Lecture 18



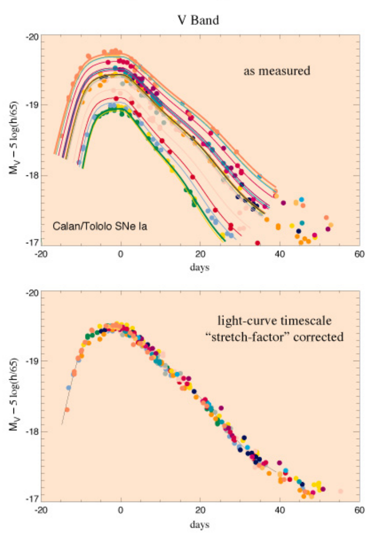
Type Ia Supernovae

SN Ia - Observational Facts

SN 1994D

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

Low Redshift Type Ia Template Lightcurves



<u>The Phillips Relation</u>
(post 1993)

Broader = Brighter

Can be used to compensate for the variation in observed SN Ia light curves to give a "calibrated standard candle".

Note that this makes the supernova luminosity at peak a function of a single parameter – e.g., the width.

<u>Leading Models:</u>

- *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.

Number of White Dwarfs

Number of white dwarfs in the Galaxy ~ 1 x 10^{10} (only stars > 0.8 M_{O} will have finished their evolution) Napiwotzki 2009 J. Phys.: Conf. Ser. 172 012004

population	SPY	corr.	vol. limited	ρ [pc^{-3}]	Galaxy	$N/10^9$
thin disc	92%	86%	59%	2.9×10^{-3}	17%	2.0
thick disc	6%	12%	35%	1.7×10^{-3}	34%	3.9
halo	2%	2%	6%	2.7×10^{-4}	49%	5.6

Nearby measurements extrapolated using Monte Carlo.

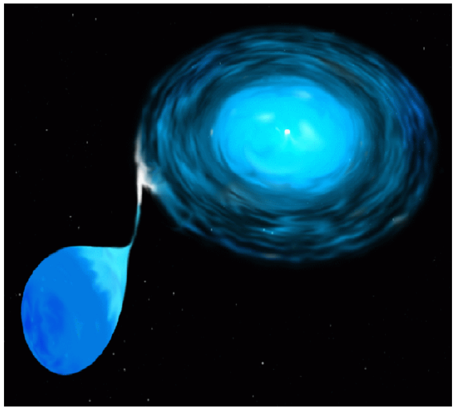
Fraction of all WDs that are in binaries that will merge in a Hubble time ~10% (Maoz, Hallakoun, and Badenes (MNRAS 2018). Same authors say WD merger rate in the Galaxy 10^{-11} per year per WD, about 6 times the SN Ia rate

Number of SN Ia in Galaxy in a Hubble time ~10^8 so 1% of all WDs must become SN Ia.

This implies about 10% of mergers would need to involve a WD over 1 solar mass (threshold for making something that looks like a SN Ia)

The Classical* Chandraskhar Mass Model

Accretion and growth to *almost* the cold Chandrasekhar Mass (1.38 solar masses)
-corrected for Coulomb effects, but usually relativity effects are ignored.
-Y_e ~ 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)

*It is possible to create a Chandrasekhar or even super-Chandrasekhar mass model in a merger.

Ignition

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

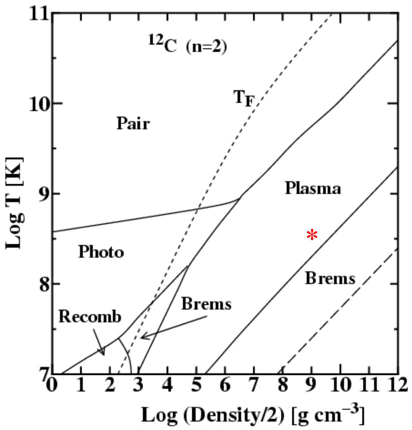
Ignition occurs as the *highly screened* carbon fusion reaction begins to generate energy faster than (plasma) neutrino losses can carry it away.

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

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

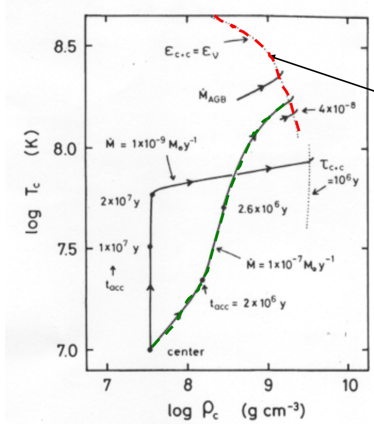
$$S_{nuc}\,(^{12}C + ^{12}C) \geq S_\nu\,(\text{plasma}); \qquad M \approx 1.38\ M_{sun}$$

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 for common SN Ia.



Ignition when nuclear energy generation by (highly screened) carbon fusion balances cooling by neutrino emission.
$T \sim 3 \times 10^8$ K, $r \sim 3 \times 10^9$ g cm^{-3}

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

The Astrophysical Journal, 745:73 (22pp), 2012 January 20 — Nonaka et al.

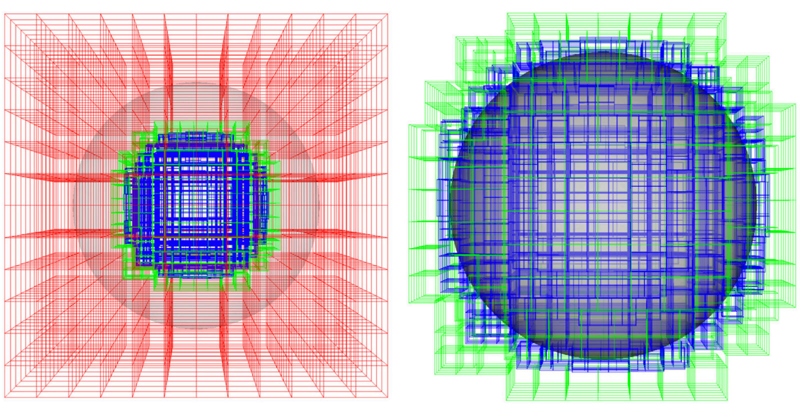


Figure 2. Grid structure for our three-level simulations. The base grid has 576^3 grid cells (8.68 km resolution), and the refined grids have effective 1152^3 (4.34 km) and 2304^3 (2.17 km) grid cells. The red, green, and blue outlines indicate boxes which can contain up to 64^3 grid cells. Left: the shaded region indicates the edge of the star, defined by the location where $\rho = 10^5$ g cm^{-3} at $r \approx 1890$ km. Right: in this zoom-in, the shaded region indicates the edge of the convective region, defined by the location where $\rho \approx 1.26 \times 10^8$ g cm^{-3} at $r \approx 1030$ km. The finest grids contain the entire convective region.

(A color version of this figure is available in the online journal.)

using MAESTRO

The Astrophysical Journal, 745:73 (22pp), 2012 January 20 — Nonaka et al.

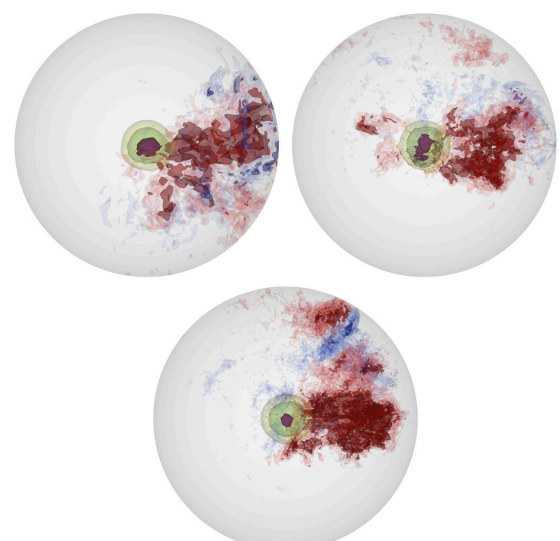
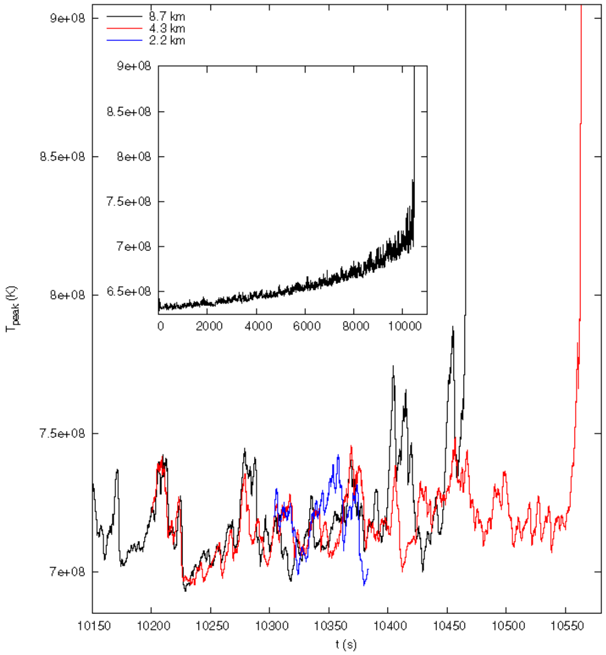


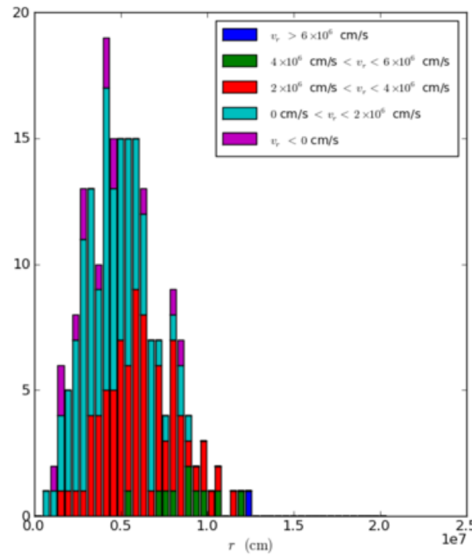
Figure 16. Contours of nuclear energy generation rate (yellow to green to purple, corresponding to 4×10^{12}, 1.27×10^{13}, and 4×10^{13} erg g^{-1} s^{-1}) and radial velocity (red is outflow, corresponding to 3×10^6 and 6×10^6 cm s^{-1}; blue is inflow, corresponding to -3×10^6 and -6×10^6 cm s^{-1}) for the (clockwise, from top left) 8.68 km, 4.34 km, and 2.17 km simulations at $t = 10{,}380$ s. Only the inner $r = 1000$ km are shown.

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
  Initial explosion will be grossly asymmetric

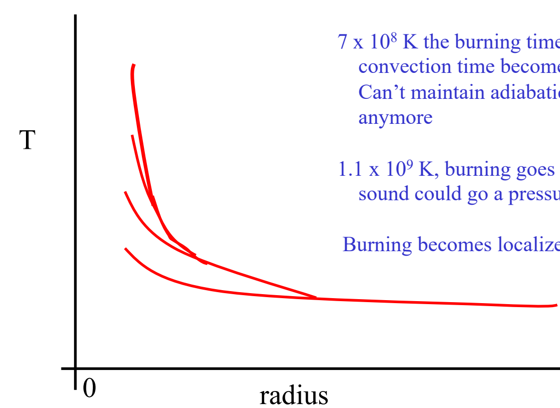
Convection for 100 years, then formation of a thin flame sheet.
First bubbles

Note that at:

7×10^8 K the burning time and convection time become equal. Can't maintain adiabatic gradient anymore

1.1×10^9 K, burning goes faster than sound could go a pressure scale height

Burning becomes localized

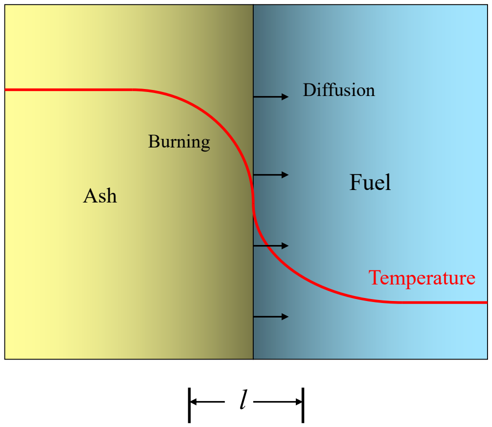


$$S_{nuc} \propto T^{26}$$

$$\tau_{diffusion} \approx \tau_{nuc}$$

$$\left(\frac{l^2 \kappa \rho}{c}\right) \approx \left(\frac{\varepsilon}{S_{nuc}}\right)$$

ε = internal energy (erg/g)
κ = opacity (cm^2 / g)
S_{nuc} = energy generation (erg/g/s)
ρ = density (g/cm^3)



A *laminar* flame

$$l = \left(\frac{\varepsilon c}{\kappa \rho S_{nuc}}\right)^{1/2}$$

$$v_{cond} = l / \tau$$

This is the conductive
- or sometimes "laminar"
- flame speed.

Laminar Flame Speed

nb The critical mass is ~ flame width. Very small.

$$v_{cond} \approx \left(\frac{c S_{nuc}}{\varepsilon \kappa \rho}\right)^{1/2} \qquad c_{sound} \approx 10{,}000 \text{ km/s}$$

Carbon-Oxygen Conductive Wave Properties[a]

ρ_9	v_{cond}	Width	$\Delta\rho/\rho$
10.0	187 km/s	1.27 (−5)	0.085
8.0	152	1.65 (−5)	0.090
6.0	115	2.50 (−5)	0.098
4.0	76.3	4.96 (−5)	0.111
2.0	35.3	1.85 (−4)	0.139
1.0	15.1	7.28 (−4)	0.205
0.5	5.46	2.79 (−3)	0.222
0.2	1.09	2.03 (−2)	0.398
0.1	0.415	8.11 (−1)	0.415
0.05	0.113	2.31	0.483
0.01	9.82 (−3)	8.68 cm	0.503

Timmes and Woosley, (1992), *ApJ*, **396**, 649

nb. these speeds are comparable to the convective speeds prior to runaway

Heat Capacity

$$C_P = \left(\frac{\partial \varepsilon}{\partial T}\right)_{ions} + \left(\frac{\partial \varepsilon}{\partial T}\right)_{electrons} + \left(\frac{\partial \varepsilon}{\partial T}\right)_{radiation}$$

$$\approx 9.1 x 10^{15} + \left(\frac{8.7 x 10^{15}\, T_9}{\rho_9^{1/3}}\right) + \left(\frac{3.0 x 10^{13}\, T_9^3}{\rho_9}\right) \text{erg/(gm } 10^9 \text{ K)}$$

Nuclear burning to the iron group gives q_{nuc} = 7 x 10^{17} erg/gm
" " " silicon group " " 5 x 10^{17} erg/gm

Solving $C_P T = q_{nuc}$ for temperature:

At $\rho_9 = 1$ $\quad T_9 \approx 10$ $\quad$ (electrons)
$\rho_9 = 0.02$ $\quad T_9 \approx 4$ $\quad$ (radiation)

Above about 10^7 gm cm^{-3} burning will go to nuclear statistical equilibrium and make only iron group elements

At 10 billion K burning always goes to completion and makes iron. Only below four billion K (few x 10^7 gm cm^{-3}) does one begin to make Si, S, Ar, Ca, Mg, etc. Almost all the initial white dwarf is more dense than that.

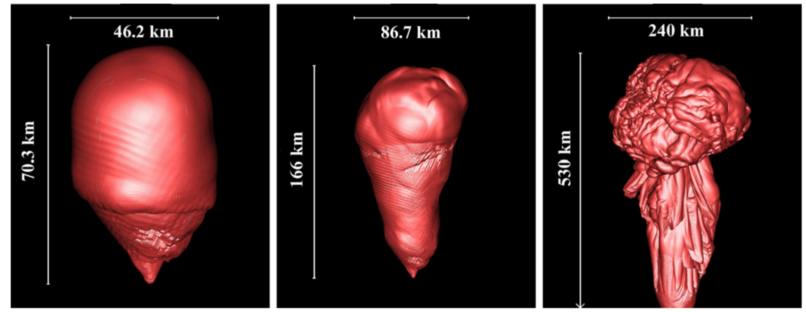
So, naive physics gives us a flame that burns the star slowly to iron, experiences a lot of electron capture, and barely unbinds the star – maybe after several pulses

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

0 5.9 ms 11.9ms

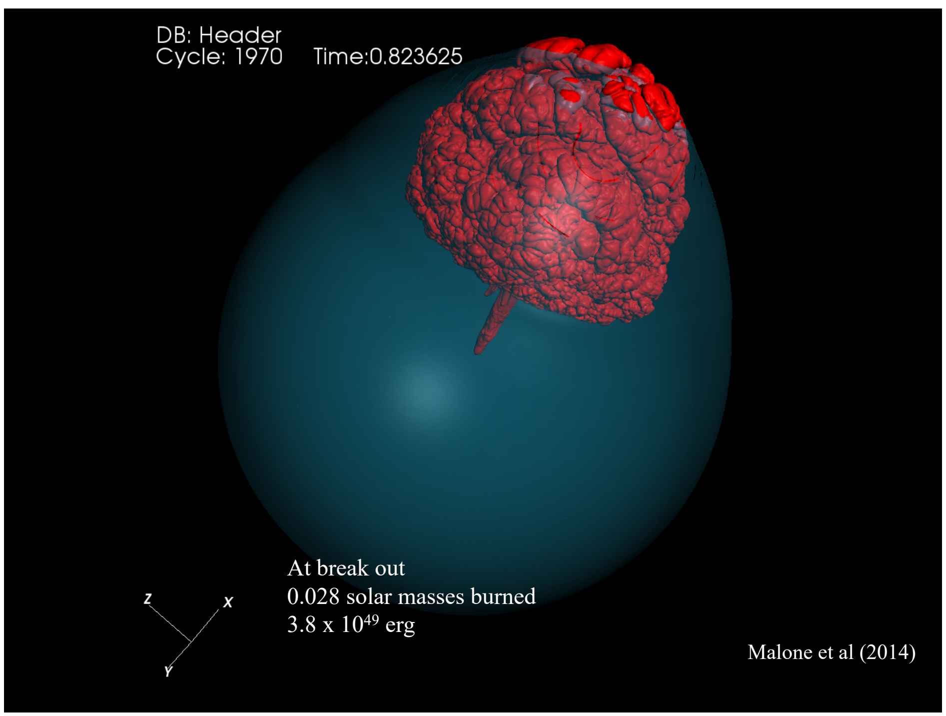
38,640^3 effective resolution using CASTRO
5 levels of AMR
8.68, 4.34, 1.09, 0.271 and 0.135 km

Malone et al (2014)



150 ms 265 ms 469 ms

WD radius = 1800 km



What happens next?

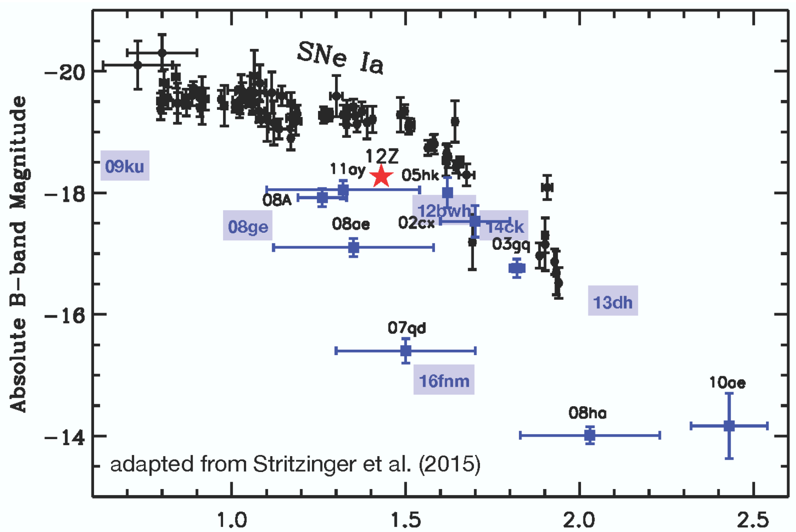
1. Mechanical compression to a state that burns supersonically – compressional detonation (Chicago).

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)

4. Nothing – Type Iax SN?

6 Saurabh W. Jha (2017)



Colored points are SN Iax

Foley et al (2013)

The Astrophysical Journal, 767:57 (28pp), 2013 April 10

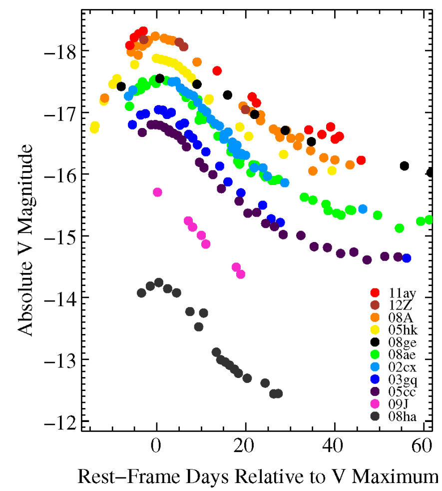


Figure 15. Absolute *V*-band light curves for a subset of SNe Iax. Each SN i plotted with a different color.

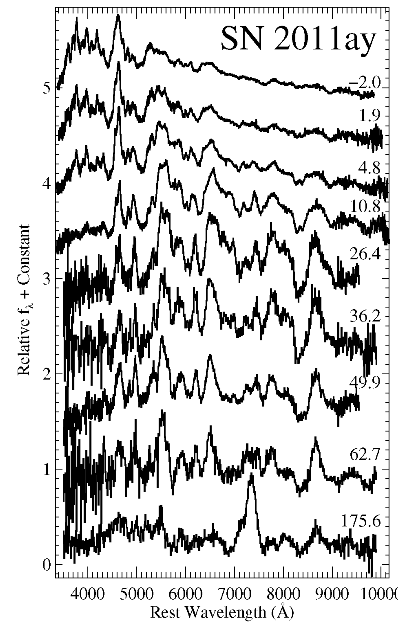
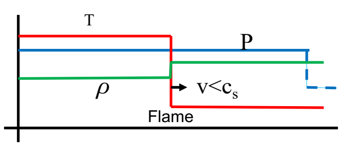


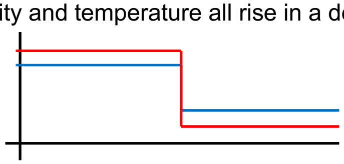
Figure 13. Optical spectra of SN 2011ay. Rest-frame phases relative to *V* maximum are listed to the right of each spectrum.

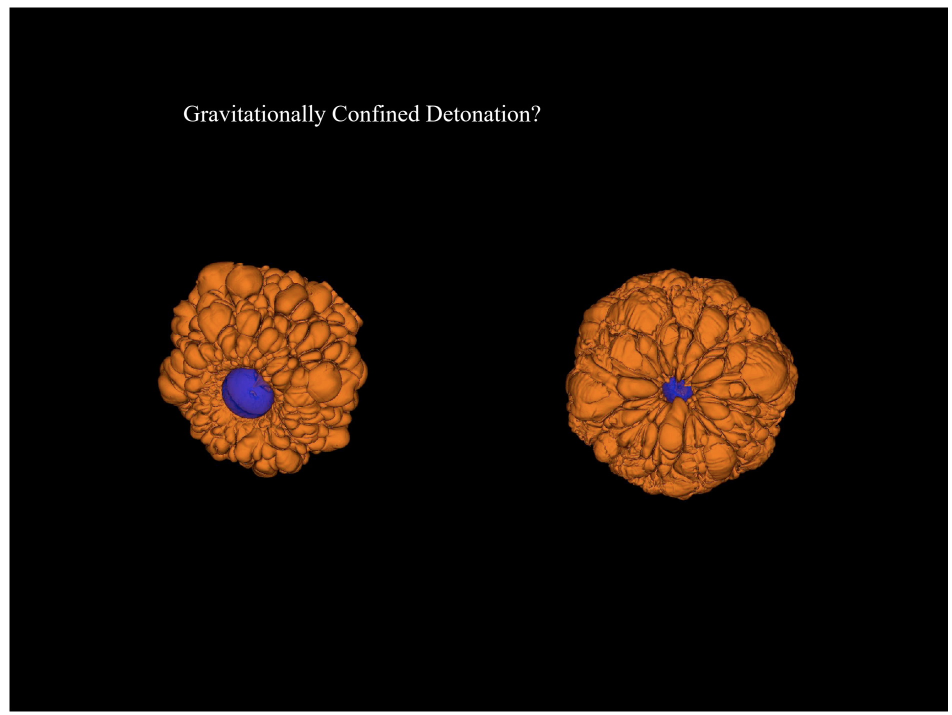
Detonation and Deflagration

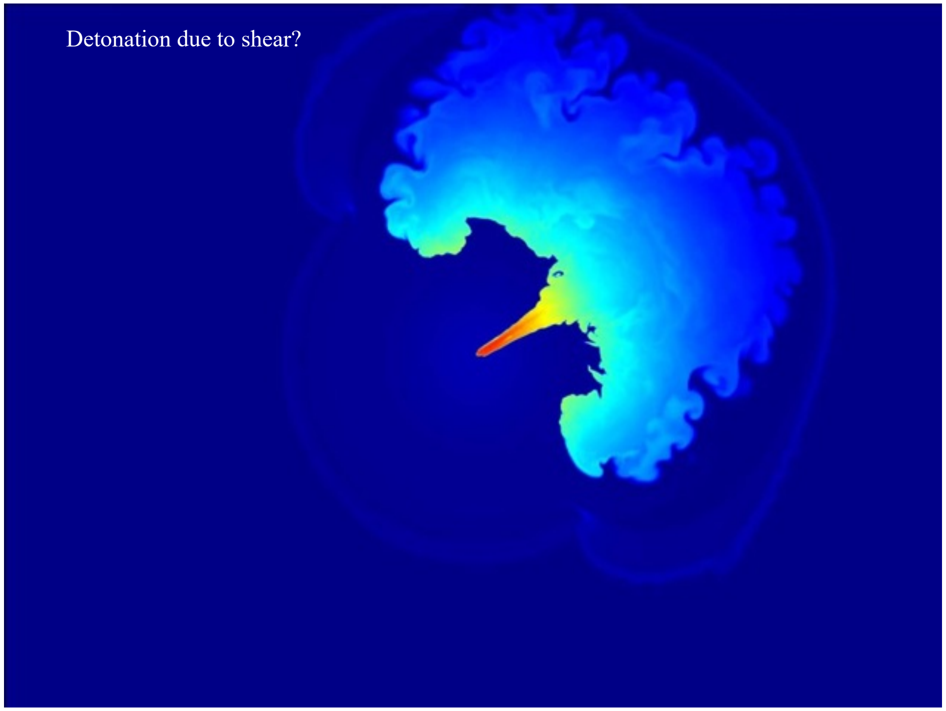
A deflagration is a subsonic burning front propagated by conduction and possibly turbulent mixing. Across a deflagration pressure is constant, temperature goes up and density goes down



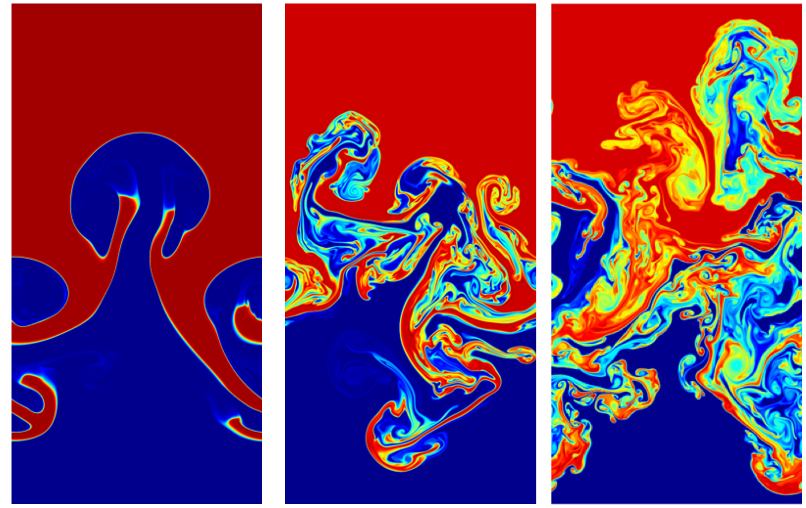
A detonation is a supersonic burning front in which a shock wave heats and compresses matter causing it to burn. If the rise in pressure from burning is large and rapid enough it drives the shock wave and keeps it from decaying. Pressure, density and temperature all rise in a detonation



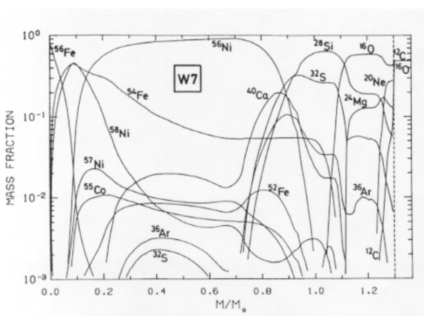


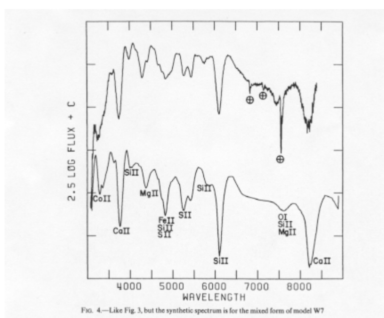


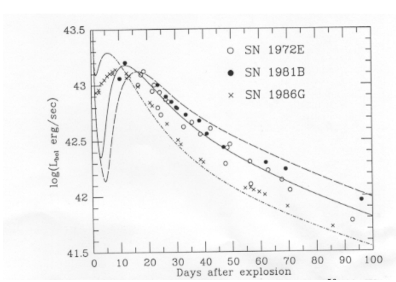
Transition to detonation?



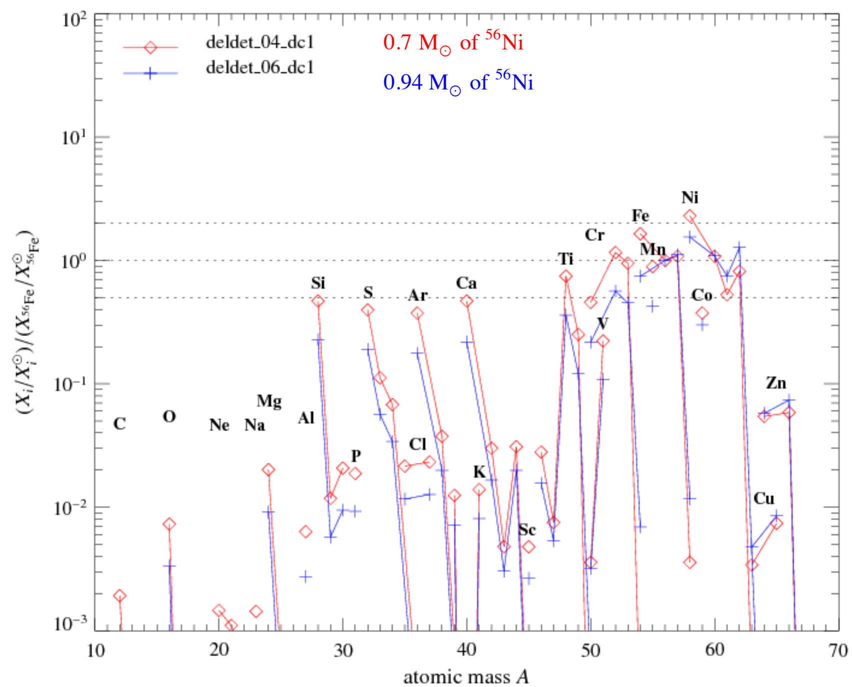
1.5×10^7 1.0×10^7 0.667×10^7







The fact that W7, an empirical parameterized model agrees so well with observations suggests that the correct SN Ia model should have similar properties.

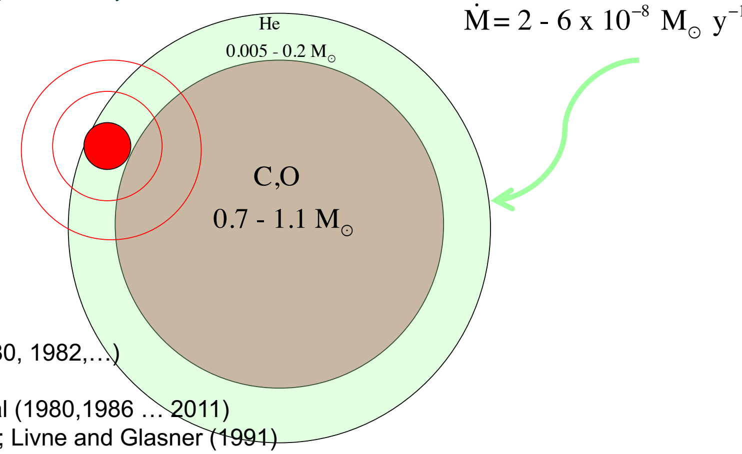


MCh Model Summary

- 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.

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



Nomoto (1980, 1982,…)
Taam (1980)
Woosley et al (1980,1986 … 2011)
Livne (1990); Livne and Glasner (1991)
Fink et al (2007) and others
Sim et al (2010) Shen and Moore (2014ab) Shen et al (2017)

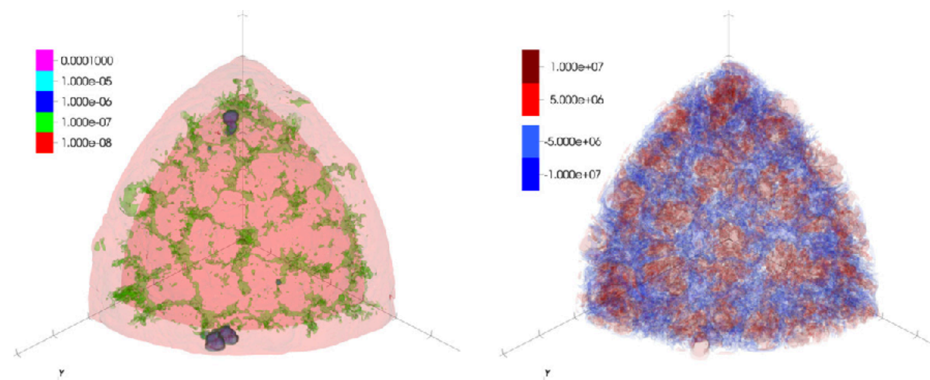
ISSUES

- 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

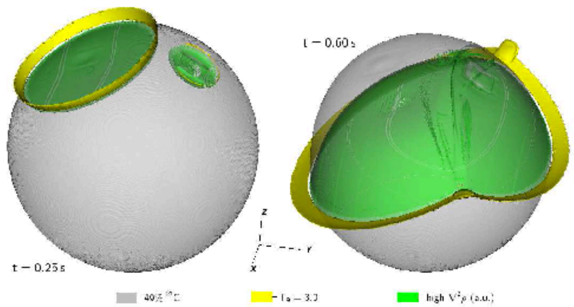


Oxygen mass fraction Velocity

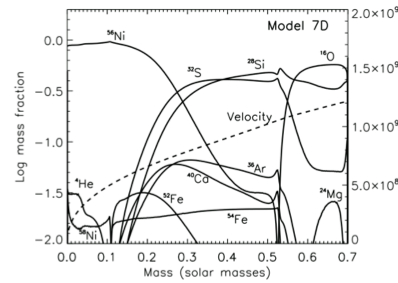
at 100 s

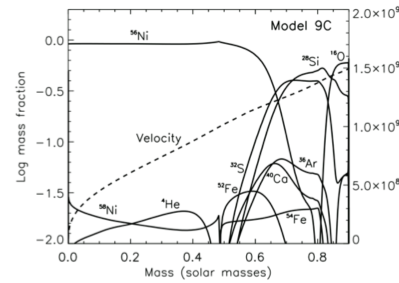
Shows cellular structure of convection. As expected
cell size ~ pressure scale height ~ few hundred km
The ignition region should be much smaller than that

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

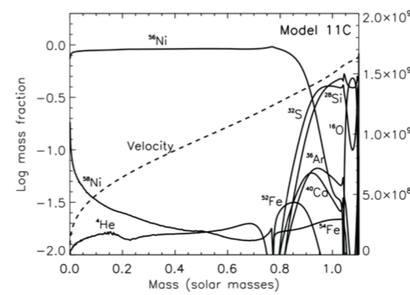


Woosley and Kasen (2011)





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 detonate?

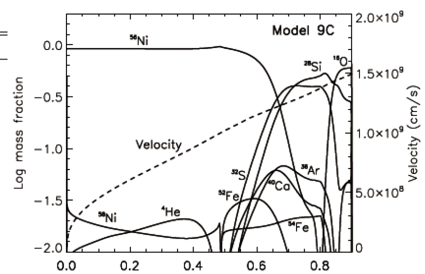
Good

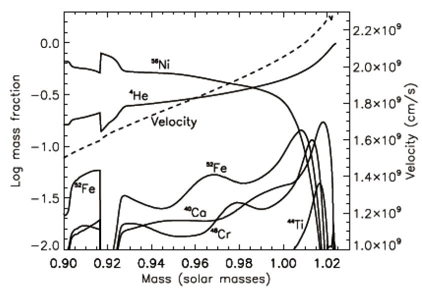
Max CO WD

(some variation with accretion rate, and WD temperature)

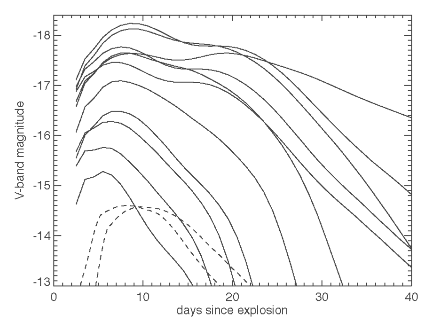
Nucleosynthesis

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	...	...

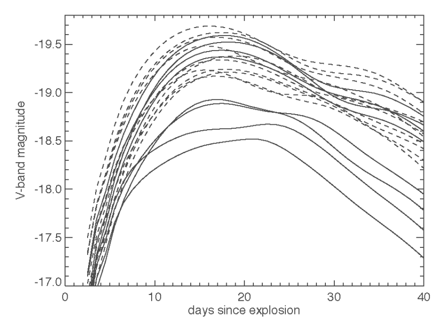




The general class of sub-Chandrasekhar mass models can give a wide variety of transients ranging from very luminous SN Ia to super "novae".



He shell only explodes

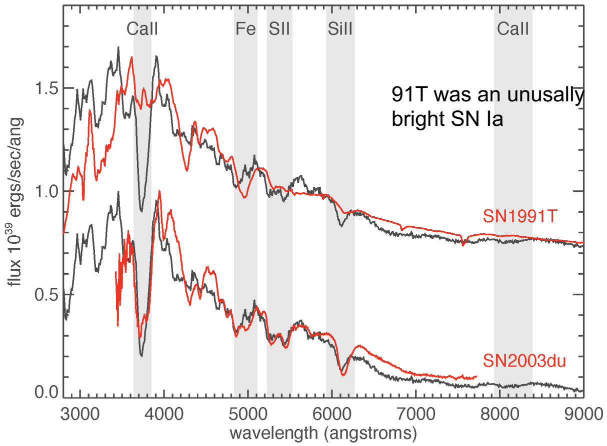


Entire star explodes

Some of these look like SN Ia…

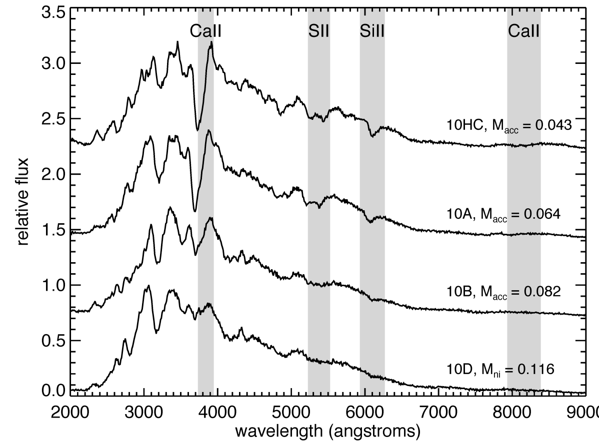
Model 10HC (hot 1.0 solar mass CO WD accreting at 4 x 10^{-8} solar masses per year, 0.045 solar mass He shell) – peak light spectrum vs observations.

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)

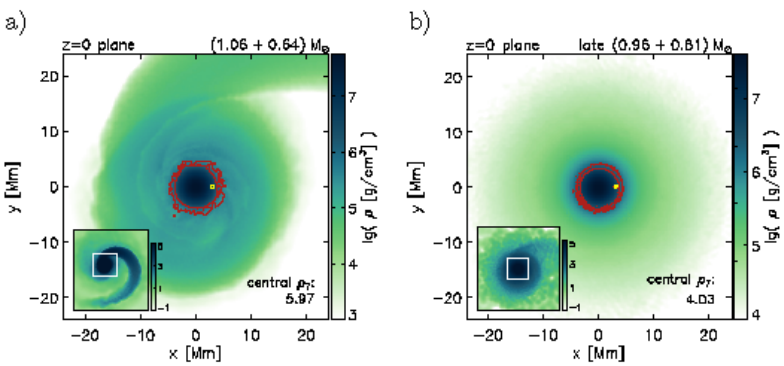
Merging White Dwarfs

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

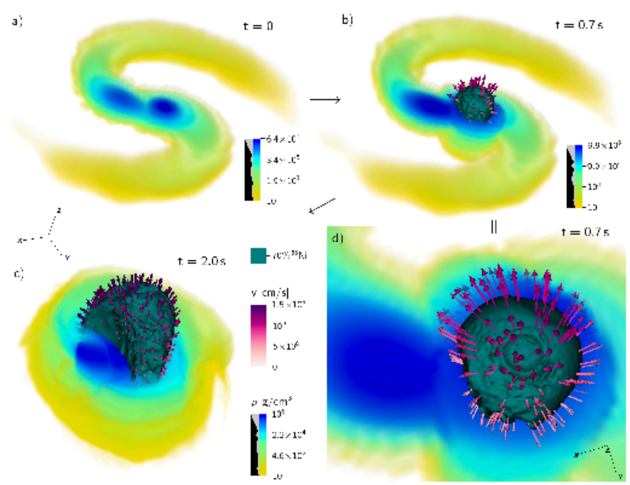
not realistic in my opinion

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

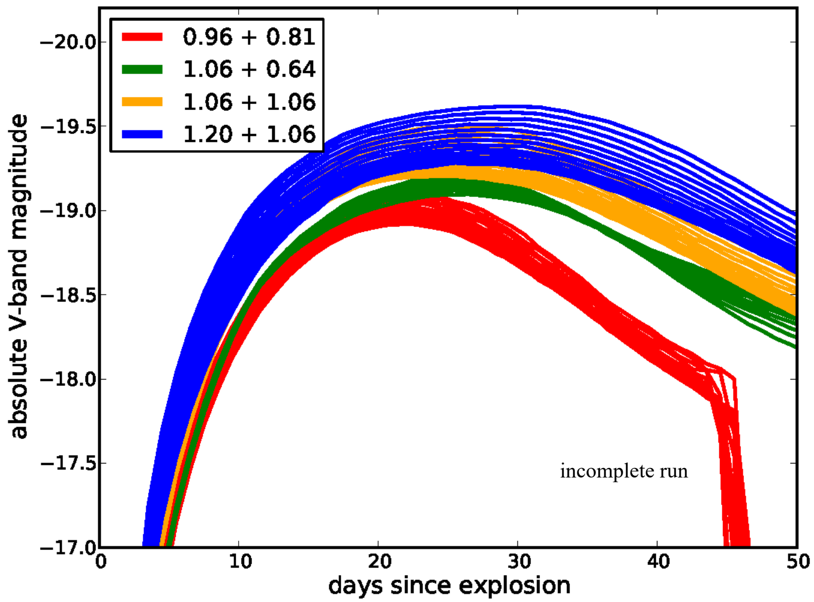
Guillochon et al (2010)
Pakmor et al (2010,2011,2012ab)
Kromer et al (2013)
Moll et al(2014)

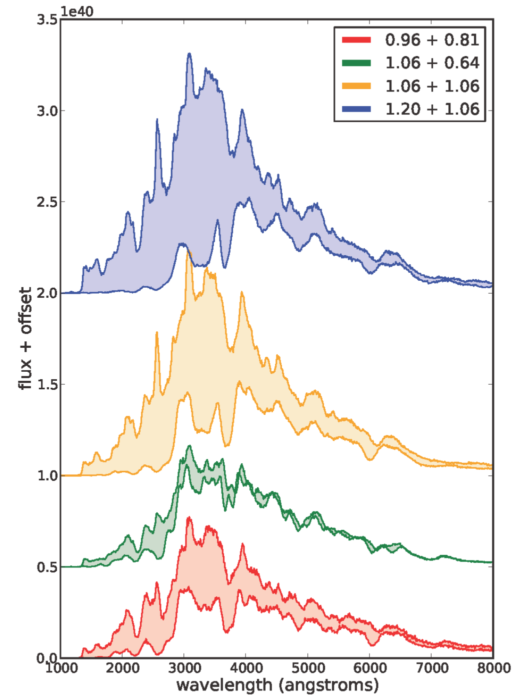
Moll, et al, 2014
$1.06\ M_\odot + 1.06\ M_\odot$



Density contours
Sphere with arrows is ^{56}Ni

Moll et al (2014)





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

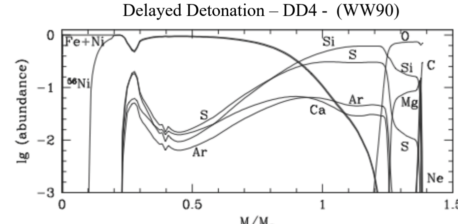
- All models probably happen. Their observable consequences and realization frequencies should be explored.
- Chandrasekhar mass (single degenerate) models starting to be better understood, but observational constraints suggest these might not be the most common event, or at least not the only event
- 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?

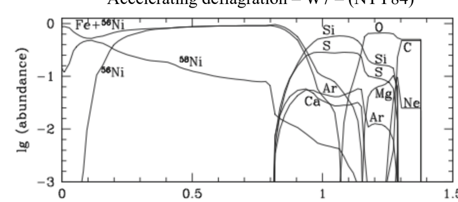
  Can the overproduction of too many alternate outcomes be avoided? E.g. 0.6 – 0.9 solar mass WDs, thicker He shells

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

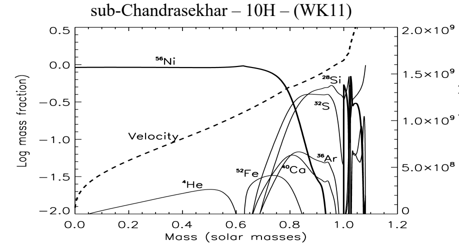
Delayed Detonation – DD4 - (WW90)



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 $\rho_{max} \approx 0.5 - 2\times10^{8}$ g cm^{-3}

Clues

- Limits on x-ray luminosity of preSN

Kirkpatrik et al (2018) SN 2017ejb Mdot < 3 x 10^{-7}
Bloom et al (2012) SN 2011fe R_{prog} < 0.02 R_O $R_{companion}$ < 0.2 R_O
Stefano (2010) - the majority of SN Ia progenitors are not supersoft x-ray sources (or nuclear burning accreting WDs)
Margutti et al (2016) no x-rays from SN 2014J – limits mass loss from the system to < 10^{-9} M_O y^{-1}
Nielson et al (2014) – SN 2014J progenitor not an accreting 1.38 M_O WD with the usual accretion rate needed to make an SN Ia. x-rays absent.

But Darnley et al (2016) M31N2008-12a a recurrent nova with repetitions roughly every year seems on the way to approaching M_{Ch}
Sahman et al (2013) nova CI Aquilae – massive WD on way to becoming a SN Ia

Clues

- Need to make 55Mn

Seitenzahl (2013) – don't make enough Mn in core-collapse Sne need the high density of M_{CH} supernovae to have enough electron capture to make it

- Need to make ^{44}Ca.

Timmes and Woosley – can only make solar abundance of ^{44}Ca and several other species in helium detonation. This only occurs in sub-M_{Ch} models

- High velocity WDs. Runaways?

Shen et al (2018) – three "hyper-velocity" WDs (1000 – 3000 km s^{-1}) observed by Gaia. Such high velocities would only originate from the ejection of the less massive component in a binary merger

- Diversity of light curves

Deflagrations in general are too faint to be common SN Ia. Delayed detonations are usually too bright

6 SHEN

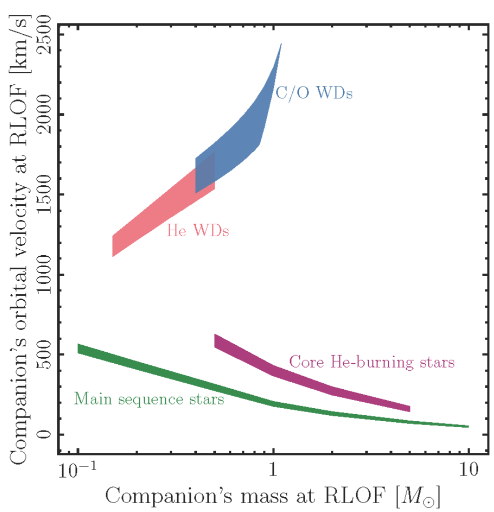


Figure 1. The companion's orbital velocity vs. mass at RLOF. The upper boundary of each region corresponds to a 1.1 $M_\odot$ primary WD; the lower corresponds to a 0.85 $M_\odot$ primary.

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 -

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

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

$$\text{T} \propto 1/r$$

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

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^{50} erg to ~10^{43} erg. The remaining internal energy is totally inadequate to power the light curve (10^{49} erg).

In greater detail:

Energy from explosion:

E ~ 10^{51} erg

This is what you get from fusing C+O to iron with an energy yield of 7.5 x 10^{17} erg/s in 0.6 solar masses of white dwarf. In matter at ~10^9 g cm^{-3} this raises the temperature to

T ~ 9 x 10^9 K

(Less farther out where the density is lower)
For a white dwarf radius of ~ 2 x 10^8 cm and an average temperature ~5 x 10^9 K, this gives a radiation content

$$\frac{4}{3}\pi R^3 a T^4 \sim 10^{50} \text{ erg}$$

Most of the initial internal energy is in relativistic electrons

Recall from previous lecture, Light can escape when the diffusion time equals the age implies

$$t_{peak} = 0.41\left(\frac{\kappa}{c}\right)^{1/2}\left(\frac{M^3}{E}\right)^{1/4}$$
$$= 15 \text{ days}\left(\frac{\kappa}{0.1}\right)^{1/2}\left(\frac{M}{M_\odot}\right)^{3/4}\left(\frac{10^{51}\text{ erg}}{E}\right)^{1/4}$$

and

$$L(t_{peak}) \approx E_0 R_0\left(\frac{4\pi c}{3\kappa M}\right)$$
$$= 6\times 10^{42}\text{ erg s}^{-1}\left(\frac{E_0}{10^{51}}\right)\left(\frac{R_0}{10^{13}}\right)\left(\frac{0.1}{\kappa}\right)\left(\frac{M_\odot}{M}\right)$$

But if the starting radius is ~10^8 cm (WD) , the interior temperature has dropped by 10^6 before light can escape and the interior energy is negligible.

Radioactivity is essential to keep the supernova hot and shining!

Aside:

Branch and Wheeler express this a bit differently (eq. 5.10)

$$t_{peak} \approx \sqrt{\frac{\kappa M}{4\pi v c}} = \sqrt{\frac{\kappa M\, M^{1/2}}{4\pi c (2E)^{1/2}}} = \left(\frac{1}{4\pi\sqrt{2}}\right)^{1/2}\left(\frac{\kappa}{c}\right)^{1/2}\left(\frac{M^3}{E}\right)^{1/4}$$
$$= 0.24\left(\frac{\kappa}{c}\right)^{1/2}\left(\frac{M^3}{E}\right)^{1/4}$$

which they say is

$$\simeq 1/4\left(\frac{\kappa}{c}\right)^{1/2}\left(\frac{M^3}{E}\right)^{1/4}$$

The difference is whether the radiative diffusion coefficient is taken to be $\sim\ell_{mfp}\, c = c/\kappa\rho$ or $\sim\ell_{mfp}\, c/3 = c/3\kappa\rho$

The radius is just the speed times this,

$$R(t_{peak}) = v\, t_{peak} \approx v\sqrt{\frac{\kappa M}{4\pi v c}} = t_{peak} \approx \sqrt{\frac{\kappa v M}{4\pi c}}$$

and the optical depth at peak is

$$\tau_{peak} = \kappa\rho R_{peak} = \frac{3\kappa M}{4\pi R_{peak}^2} = \frac{\kappa M}{4\pi v^2 t_{peak}^2}$$
$$= \frac{\kappa M^2}{4\pi(2E)t_{peak}^2} = \frac{3\kappa M^2}{4\pi(2E)}\frac{4\pi\sqrt{2}}{1}\frac{c}{\kappa}\frac{E^{1/2}}{M^{3/2}}$$
$$= \frac{3M^{1/2}c}{(2E)^{1/2}} = \frac{3c}{v}$$

So at peak the optical depth of the supernova is ~100 and (very crudely) independent of the opacity.

Radioactivity

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

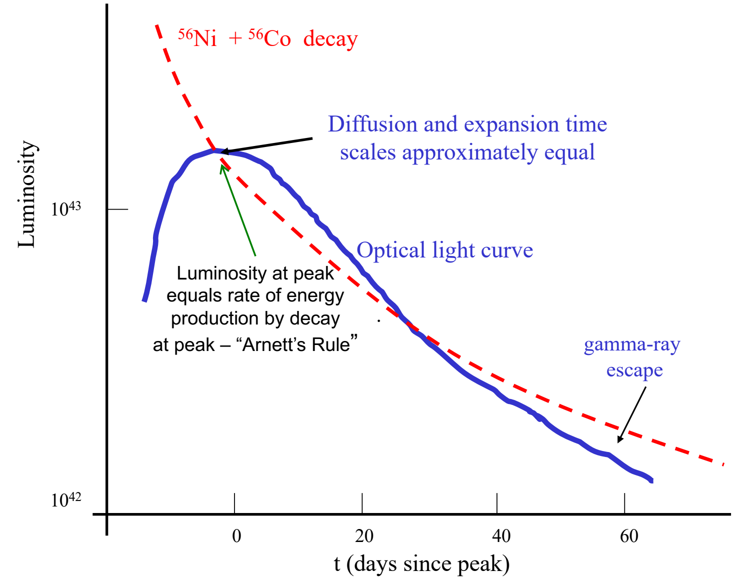
q = 3.0 x 10^{16} erg/gm

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

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



More accurate treatment of diffusion in supernovae

Weaver, Woosley, Axelrod (1980; obscure conference)

Arnett (1982), Inserra et al (2013) for magnetars

$$L_{SN}(t) = e^{-(t/\tau_m)^2} \int_0^{t/\tau_m} P(t')\, 2\left(t'/\tau_m\right) e^{(t'/\tau_m)^2} \frac{dt'}{\tau_m} \quad \mathrm{erg\ s^{-1}}$$

Arnett82, eq. 31

where

$$\tau_m = \frac{1.05}{(\beta c)^{1/2}} \kappa^{1/2} M^{3/4} E^{-1/4} \quad \text{and } \beta \approx 13.7$$

and P(t') is the power from all radioactivities (or the magnetar) evaluated at time t' *e.g.* $P(t) = \sum L_i(t)\, D_i(t)$ where L_i is the energy generated by the decay of the i^{th} isotope and D_i is the deposition function

$$L_{56Ni} = 7.8 \times 10^{43} \left(\frac{M_{56Ni}}{M_\odot}\right) e^{-t/\tau_{56Ni}} \quad \mathrm{erg\ s^{-1}}$$

$$L_{56Co} = 1.4 \times 10^{43} \left(\frac{M_{56Ni}}{M_\odot}\right) \frac{e^{-t/\tau_{56Co}} - e^{-t/\tau_{56Ni}}}{1 - \dfrac{\tau_{56Ni}}{\tau_{56Co}}} \quad \mathrm{erg\ s^{-1}}$$

$$\tau_{56Ni} = 8.7\ d \qquad \tau_{56Co} = 111\ d$$

Also $L_{magnatar} = 4.9 \times 10^{46} B_{14}^2\, P_{ms}^{-4} \dfrac{1}{1 + (t/t_p)^2}$ erg s^{-1}

$$t_p = 4.7\, B_{14}^{-2} P_{ms}^2 \ \mathrm{days}$$

Assumptions:

- Homologous expansion. No acceleration
- Total power in light << original expansion KE
- Usually assume complete absorption
- Constant opacity
- Radiation pressure dominated gas
- Radioactivity centrally concentrated

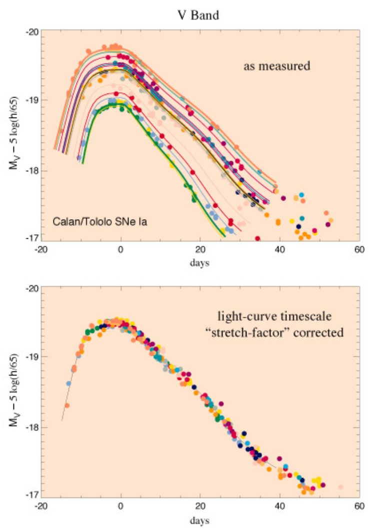
Differentiation of Arnett 82 eq. 31 gives the condition that at maximum light the luminosity is equal to the instantaneous deposition of energy by radioactive decay.

Thus evaluating the luminosity and supernova age at bolometric luminosity maximum allows the determination of the mass of ^{56}Ni synthesized in the explosion.

This is known as "Arnett's Rule" and is generally applicable to supernovae where radioactivity provides the luminosity and diffusion dominates the energy transport

$$L(t_{peak}) \approx L(^{56}Ni) + L(^{56}Co)$$

Low Redshift Type Ia Template Lightcurves



<u>The Phillips Relation</u>
(post 1993)

Broader = Brighter

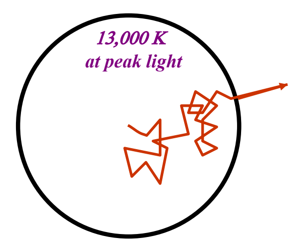
Can be used to compensate for the variation in observed SN Ia light curves to give a "calibrated standard candle".

Note that this makes the supernova luminosity at peak a function of a single parameter – e.g., the width.

<u>*Why is there a Philipps Relation?*</u>

Broader = Brighter

Pinto & Eastman (2001) New Astronomy



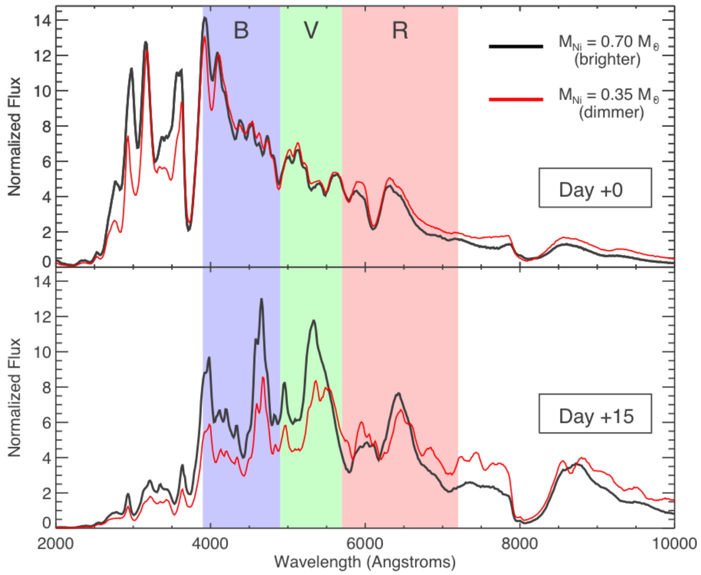
Photons must diffuse through a forest of lines in a differentially expanding medium.

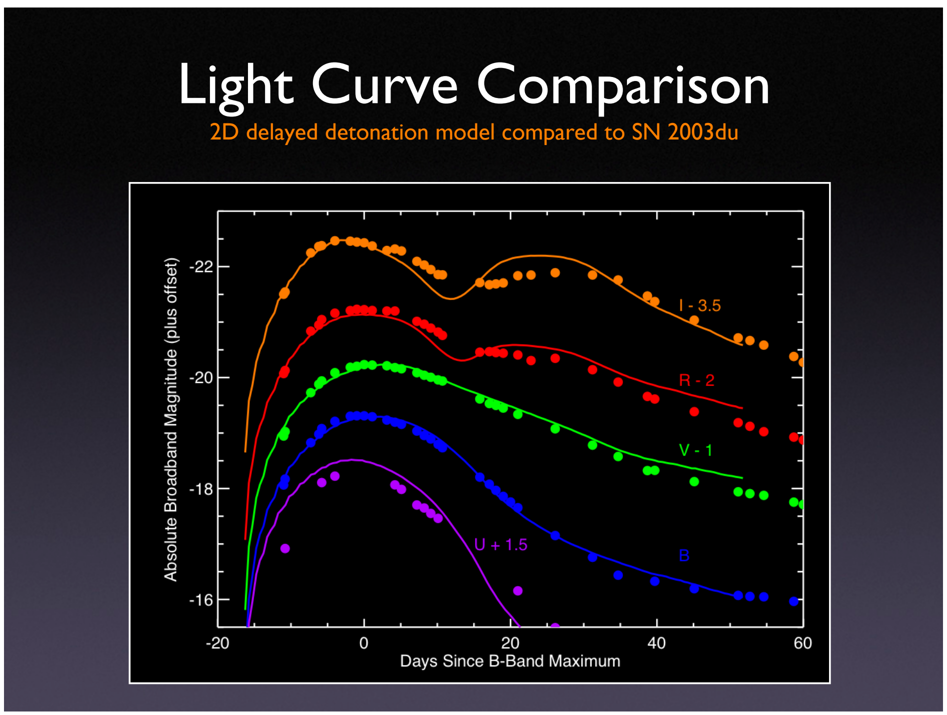
Doppler shift causes a migration from line to line.

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:

(Kasen and Woosley 2007)

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 less redistribution out of the blue band. Faint supernovae evolve more rapidly to the red. The bolometric luminosity is not so sensitive to the Ni mass but the decline rate in the blue band is.