Type Ia Supernovae
What Are They?

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Northern Cal + SUNYSB

TYPE Ia SUPERNOVAE:

Observationally (typically):

- Bright (~10^{43} erg s^{-1}) explosive transients lasting several weeks. More luminous at peak than (common) SN II or SN Ibc

- Spectroscopically, at peak, no H, ionized Si and other intermediate mass (Mg, S, Ca) and Fe-peak elements

- Not strongly associated with star formation. Happen in all kinds of galaxies

- Regular light curves and spectra (compared with SN II)

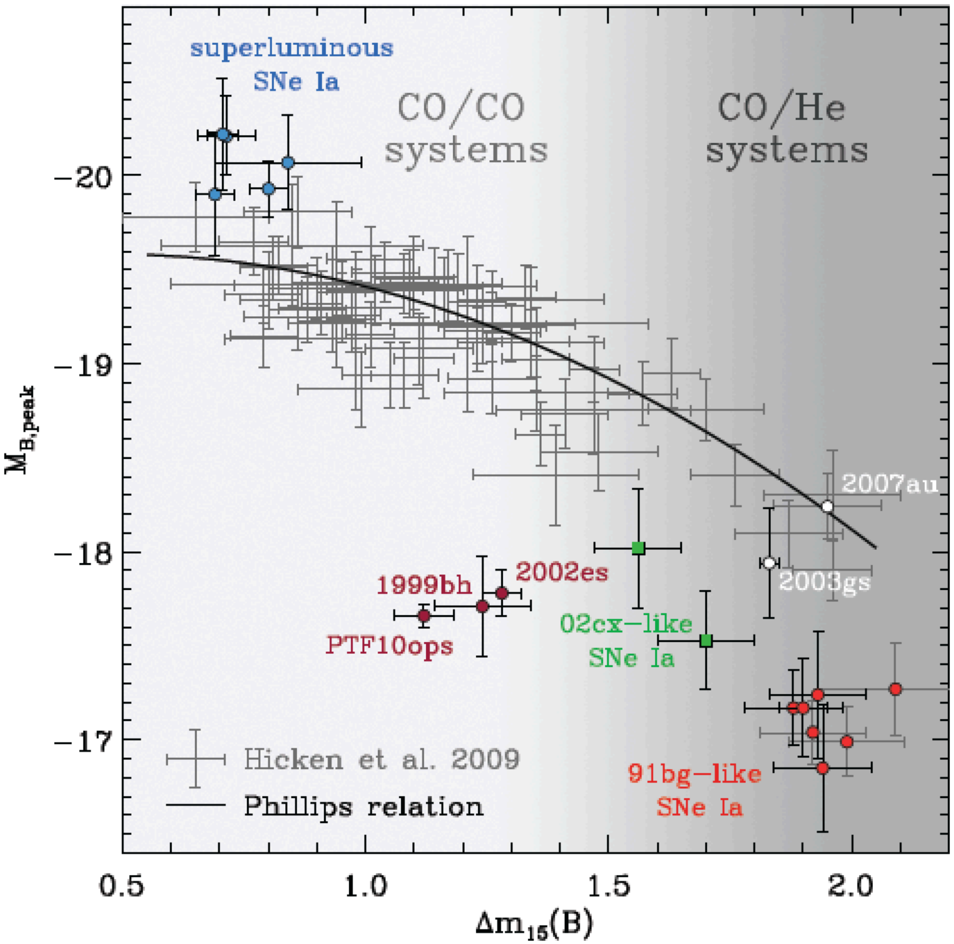
- Make ~0.6 solar masses of ^{56}Ni (gamma-lines seen in SN 2014J; also needed to explain light curve)

- At least some events lack a bright progenitor

- Can show wide diversity in less common events

- In most cases have a useful correlation between peak luminosity and rate of decline (or light curve width (Mark Phillips talk)

Pakmor et al 2013)



TYPE Ia SUPERNOVAE:

Models:

- It is agreed that most Type Ia supernovae are the thermonuclear explosions of carbon-oxygen white dwarfs in binary systems.

- In order to produce 0.6 M_o of ^{56}Ni and at least 0.2- 0.3M_o of Si – Ca, the white dwarf must exceed 0.9 M_o and a large part must burn at nearly sonic speeds, but the prompt detonation of a nearly Chandrasekhar mass white dwarf (over 1.2 M_o) is forbidden.

- The challenges for the model builder therefore lie in determining the mass of the white dwarf that burns, how it ignites, and how the burning progresses.

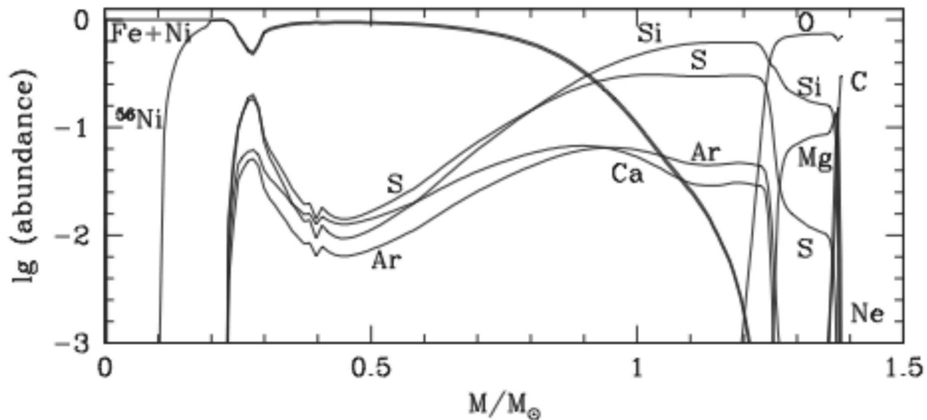
Today, there are three leading classes of models

- The Chandrasekhar Mass WD model (MCh model) in a binary with a non-degenerate companion (for a long time the “standard” model)

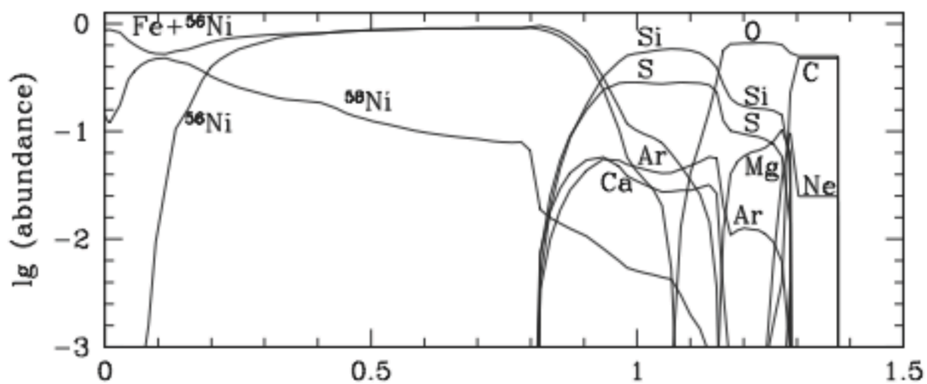
- The Sub-Chandrasekhar Mass WD Model (sub-MCh) in a binary with a non-degenerate companion

- Merging or Colliding White Dwarfs – which can also produce the two classes above)

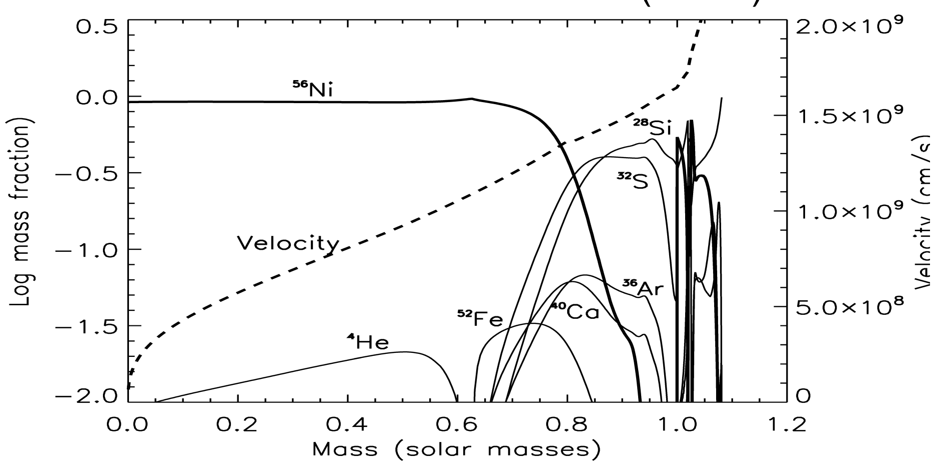
Delayed Detonation – DD4 - (WW90)



Accelerating deflagration – W7 – (NTY84)



sub-Chandrasekhar – 10H – (WK11)



Each of these model classes can produce an acceptable SN Ia

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}

The MCh Model

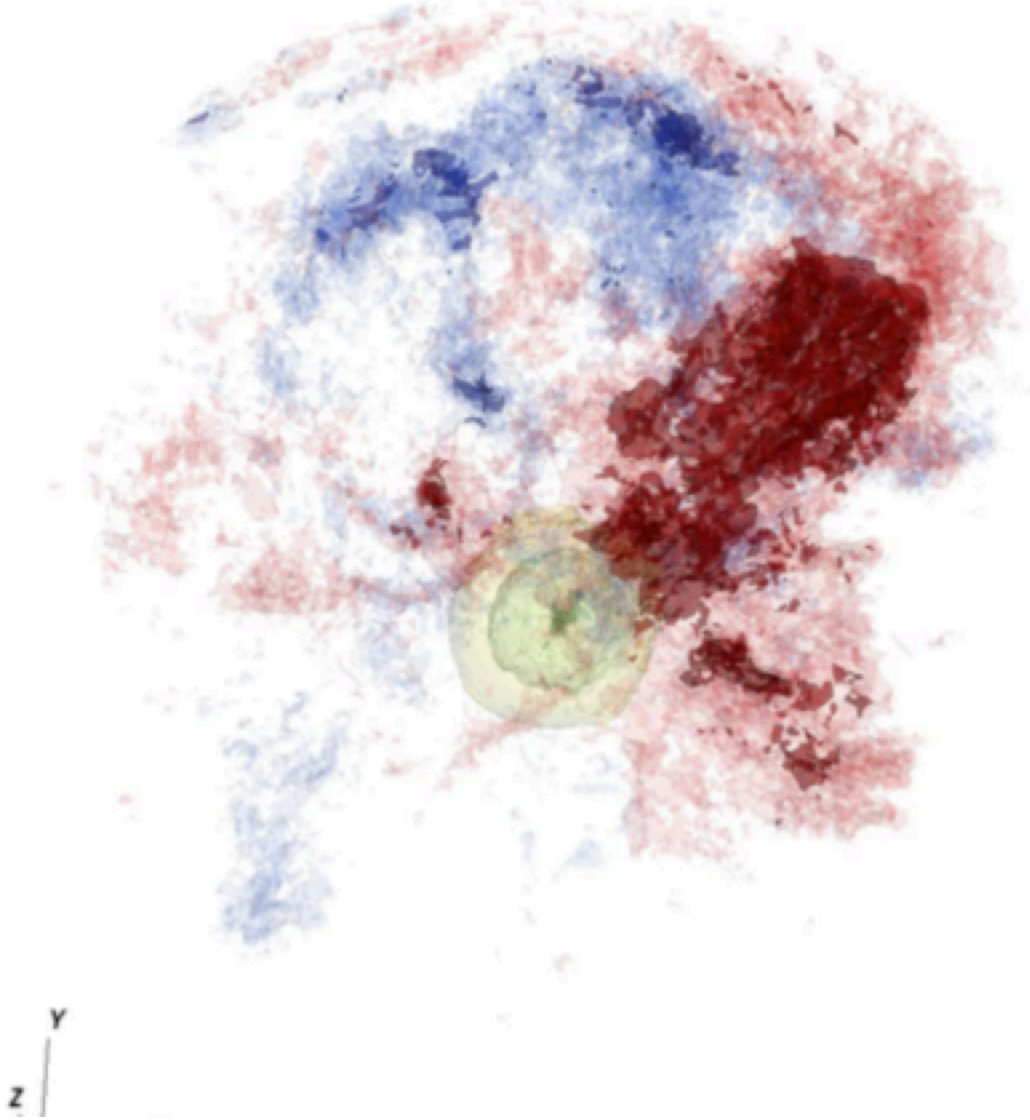
$1.38\ M_{\odot}$ of CO, $\rho_{ign} = 2.5 - 3.5 \times 10^{9}$ g cm^{-3}

Issues

- Ignition (following roughly a century of convection)
- Initial propagation (aka the “deflagration”)
- Transition to detonation

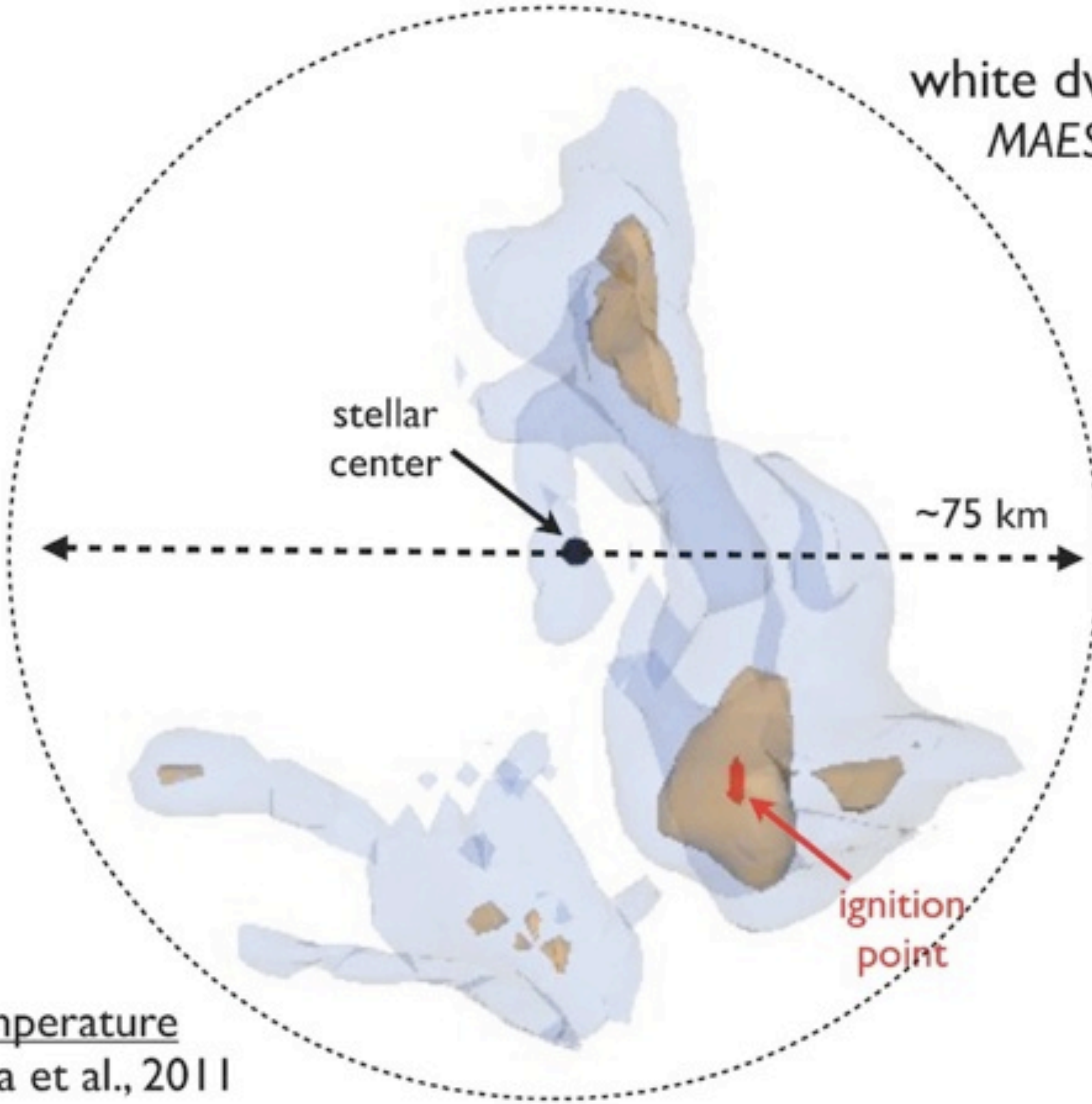
using MAESTRO

using MAESTRO



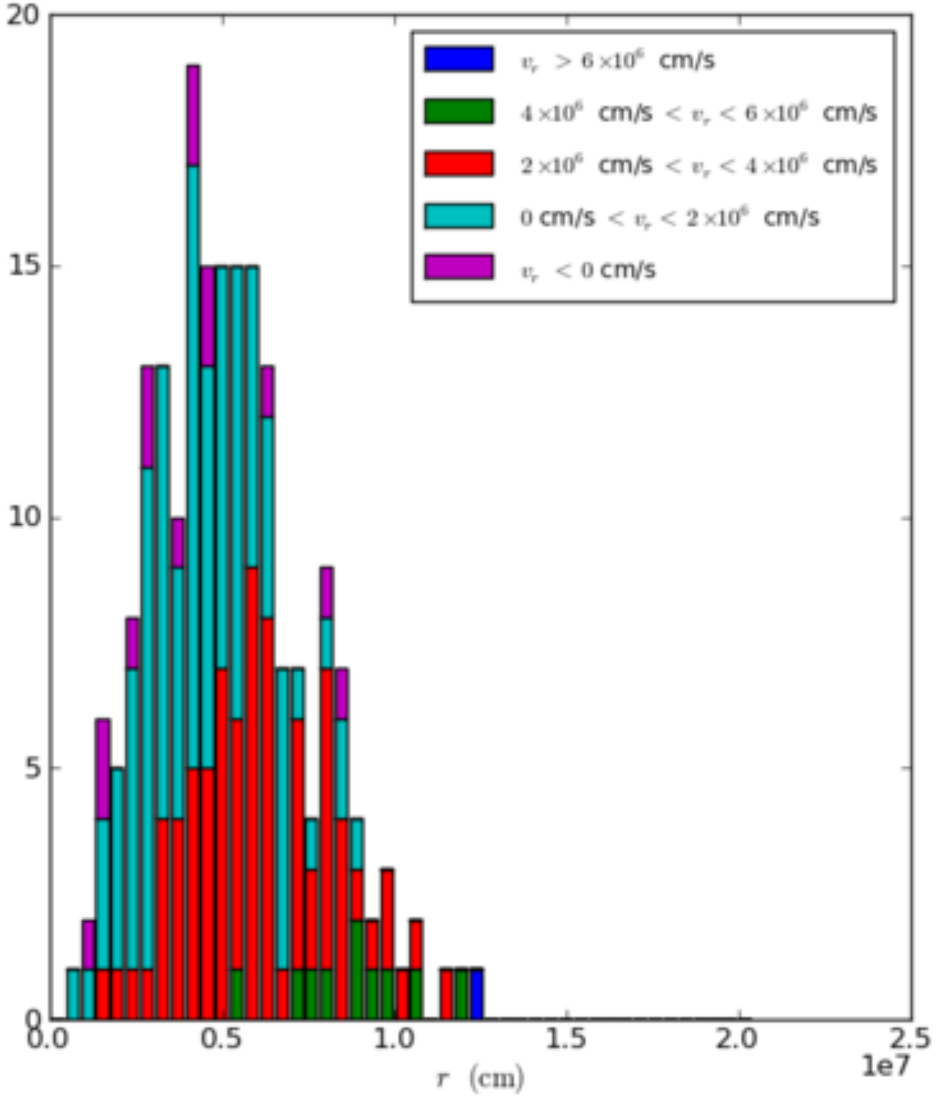
white dwarf ignition

MAESTRO code



temperature

nonaka et al., 2011



Zingale et al (2011)

The Typical SN Ia will ignite a runaway at a single point around 50 km off center, but the exact location will vary.

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

- Off-center ignition overwhelmingly likely (even 5 km displacement results in a different outcome from central ignition)

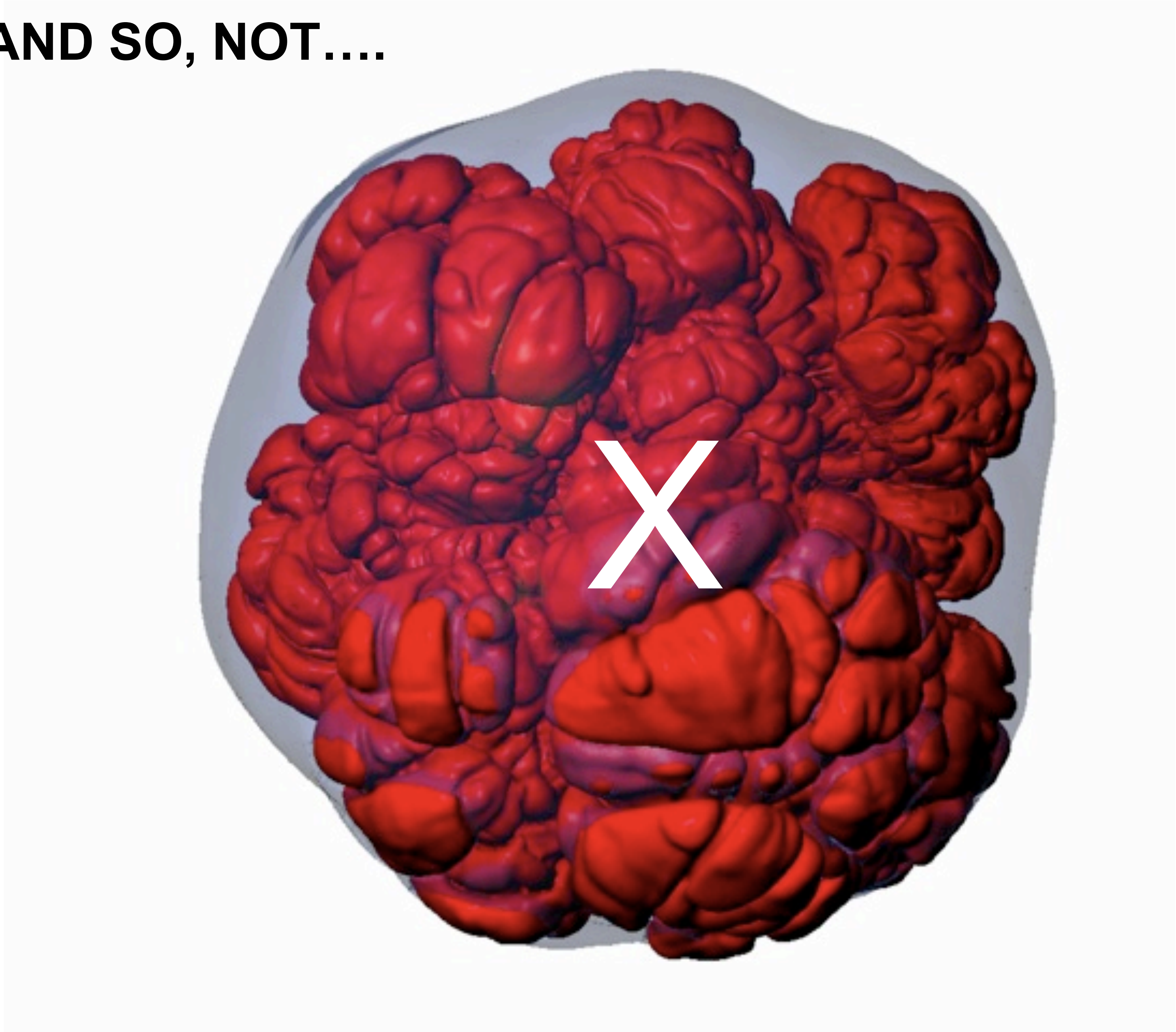
- Single point, single time ignition

Possible concerns – work needed:

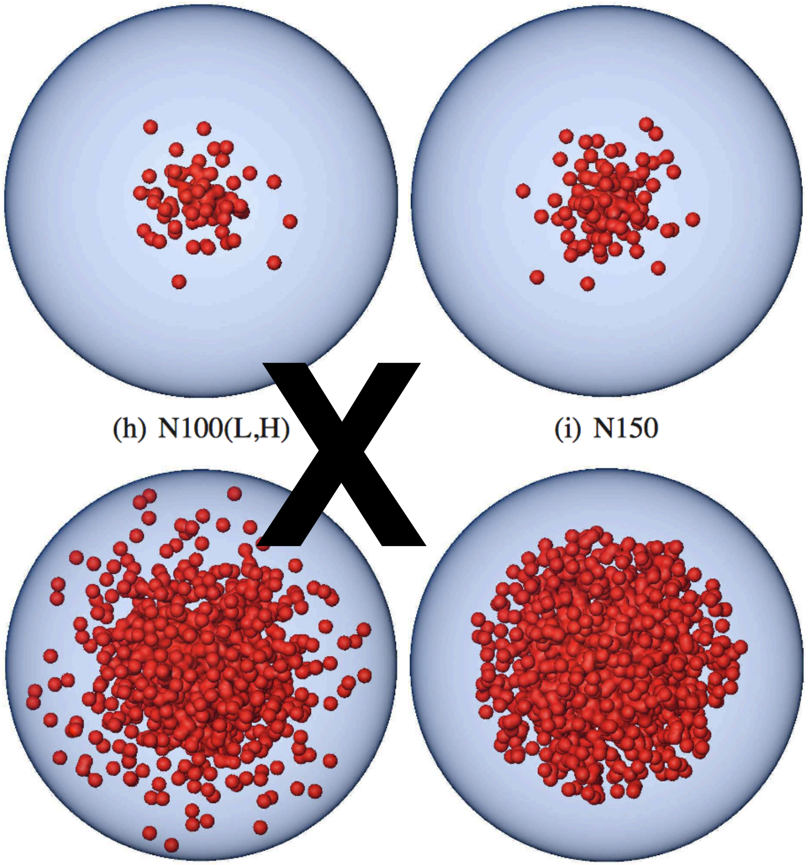
- Rotation – will have an effect but will not qualitatively change the outcome

- URCA Process (^{23}Na, ^{25}Mg) – important during "simmering phase"; not so important at 7×10^8 K

AND SO, NOT….



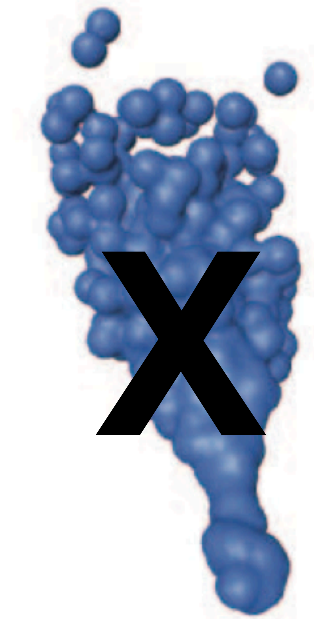
AND NOT…



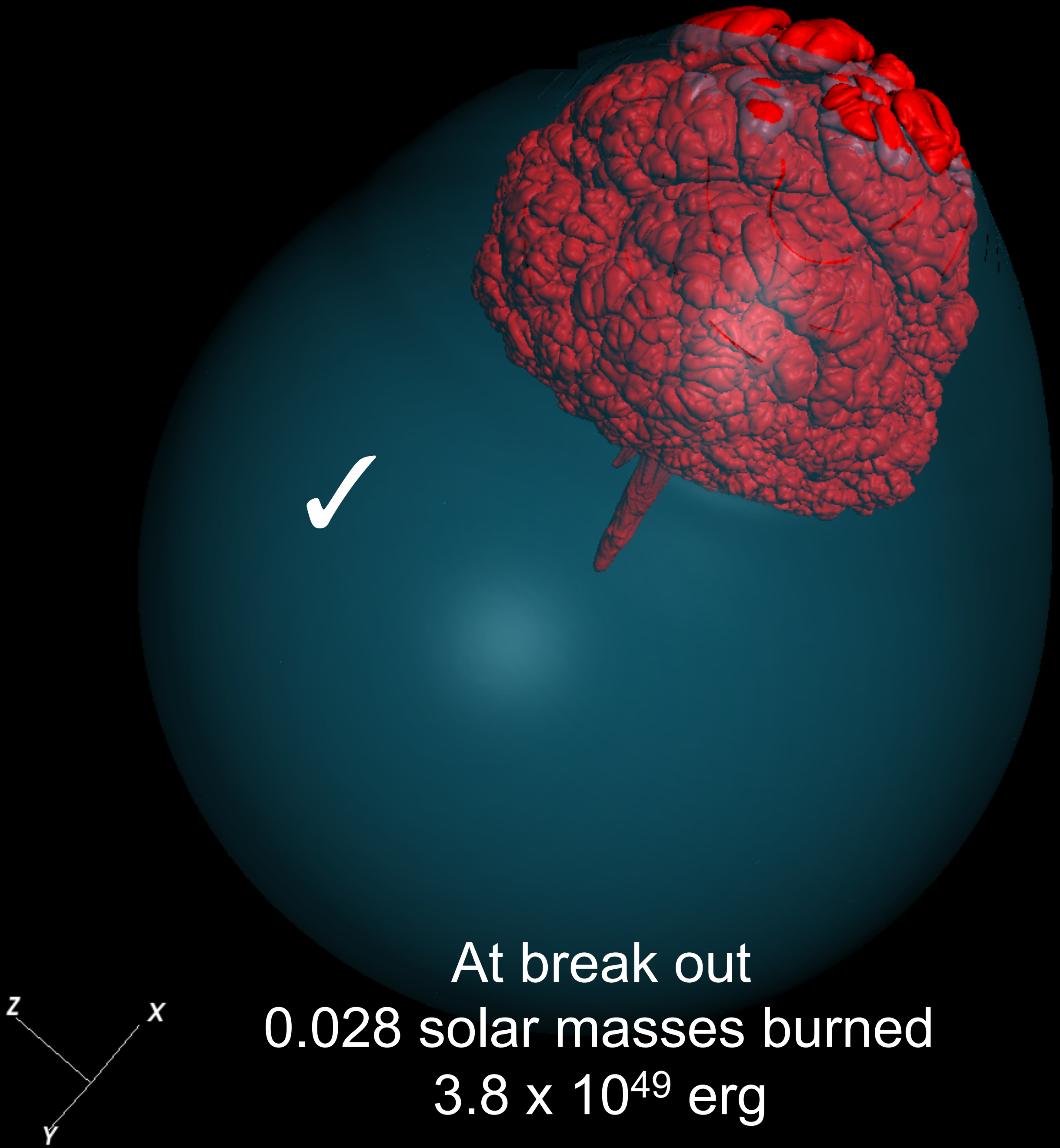
(h) N100(L,H) (i) N150

(l) N1600 (m) N1600C

or



BUT



At break out

0.028 solar masses burned

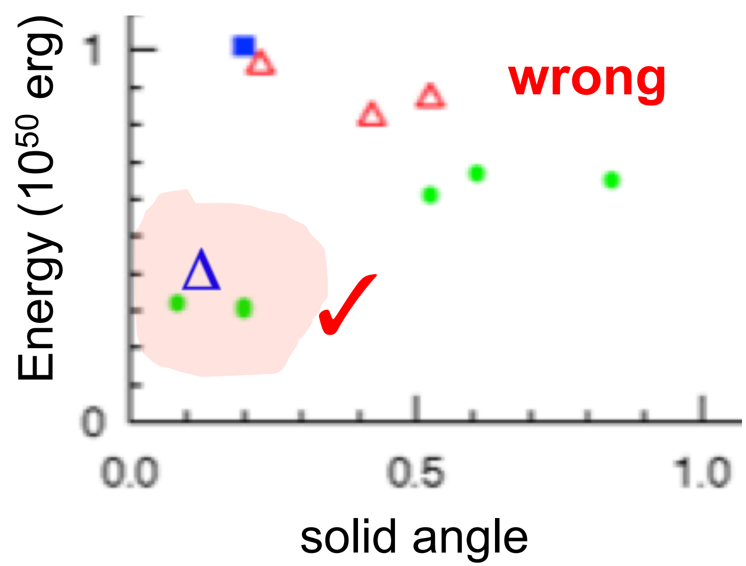
3.8×10^{49} erg

Malone et al (2014)

At a similar time (0.95 s) Model N1 from Seitenzahl et al (2013) had burned 0.052 solar masses (compared with 0.028 here). The difference might be the solid angle of the initial bubble or the flame model

Also very similar to the results obtained for the deflagration stage by Jordan et al (2008) for models 16b100o8r, 25b100o6r, and 25b100o8r which had similar initial solid angles. The white dwarf remains bound.

Other calculations starting with single point off-center ignition find the sane thing



What happens next?

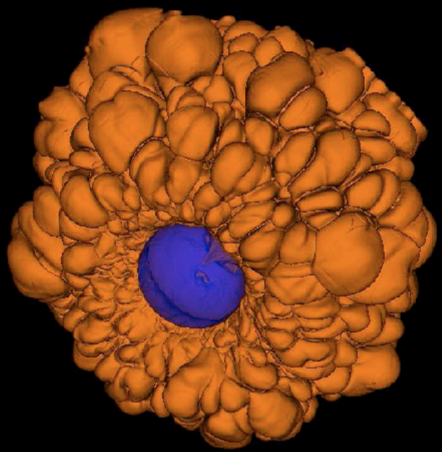
1. Mechanical compression to a state that burns supersonically – compressional detonation (Chicago).

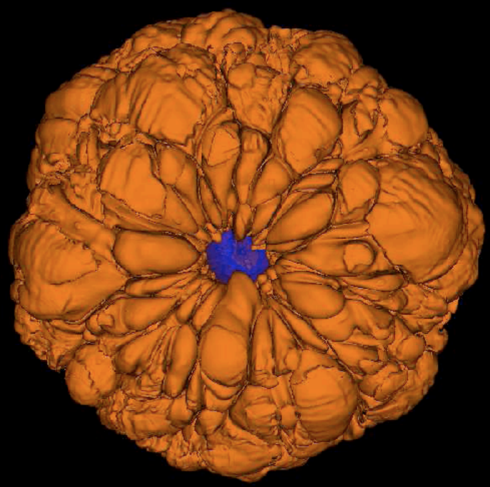
2. Creation of a “warm” mixture of cold fuel and hot ash that eventually heats up and has a supersonic phase velocity for burning. This is difficult, but feasible for certain restrictive conditions (Germany).

3. A pulse followed by additional burning (Arnett and Livne 1994)

Detonation due to shear?

Gravitationally Confined Detonation?





Effect of rotation?
Garcia-Senz et al (2015)

MCh Model Summary

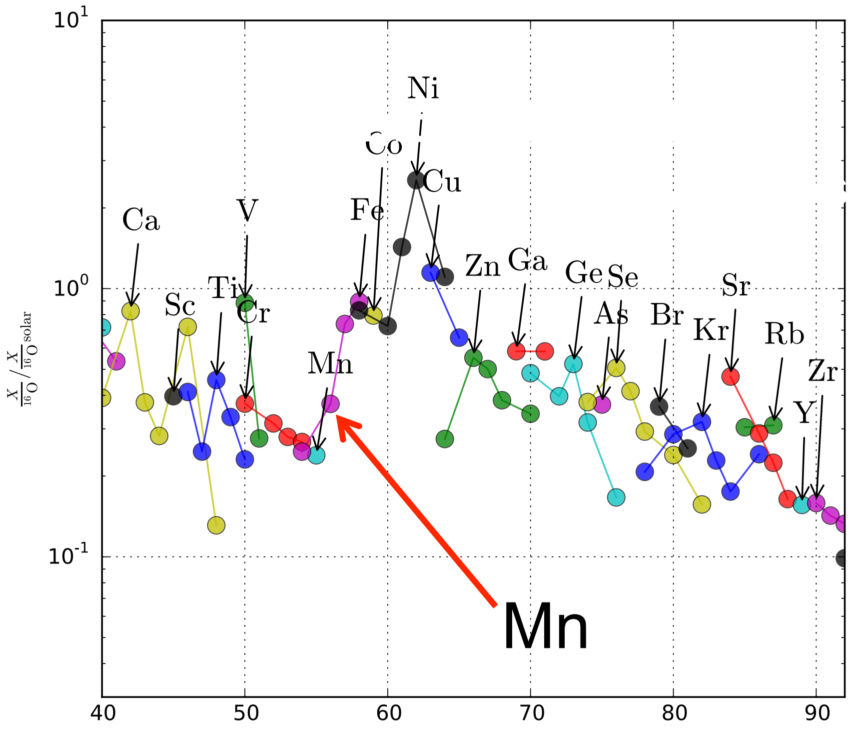
- Asymmetry expected. [Does DDT fail sometimes? (SN 2008ha; Kromer et al 2015)]

- May tend to produce more luminous SN Ia when successful (Meakin et al 2009; Malone et al 2014)

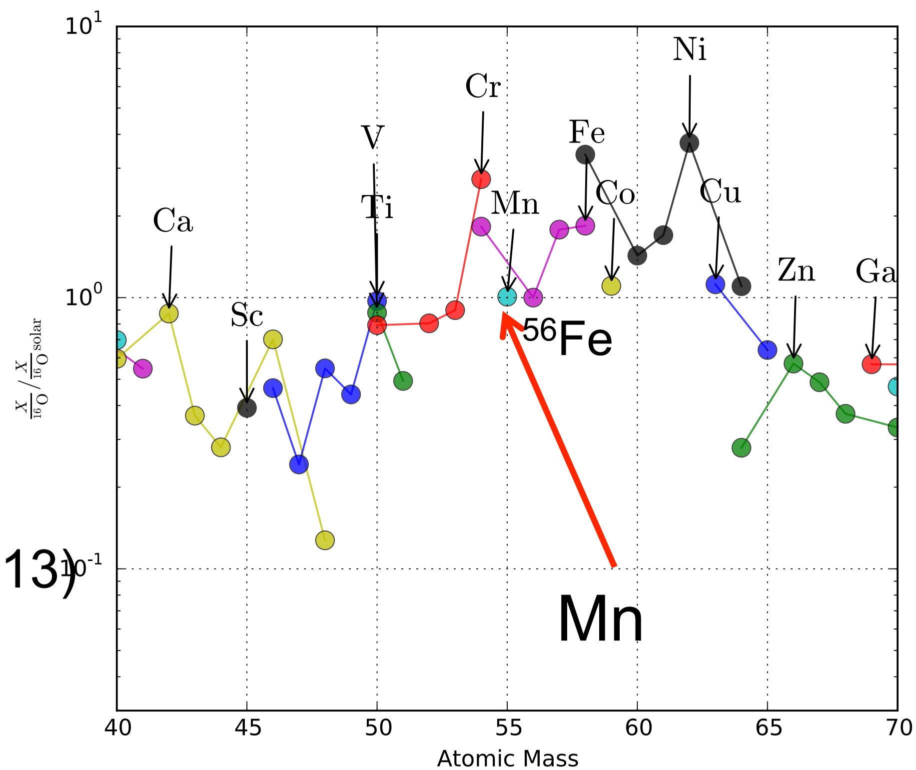
- Bright progenitors corresponding to the accretion of 10^{-7} M_o yr^{-1} pose a problem in some cases

- Still a viable model, but current work suggests reproducing the observed WLR may be difficult (worked in 2D - Kasen et al (2009); but not 3D - Sim et al (2013))

- May be needed to explain origin of manganese (e.g. Seitenzahl et al 2013)



Massive star nucleosynthesis
9 – 120 solar masses
Sukhbold et al (2015, in prep)

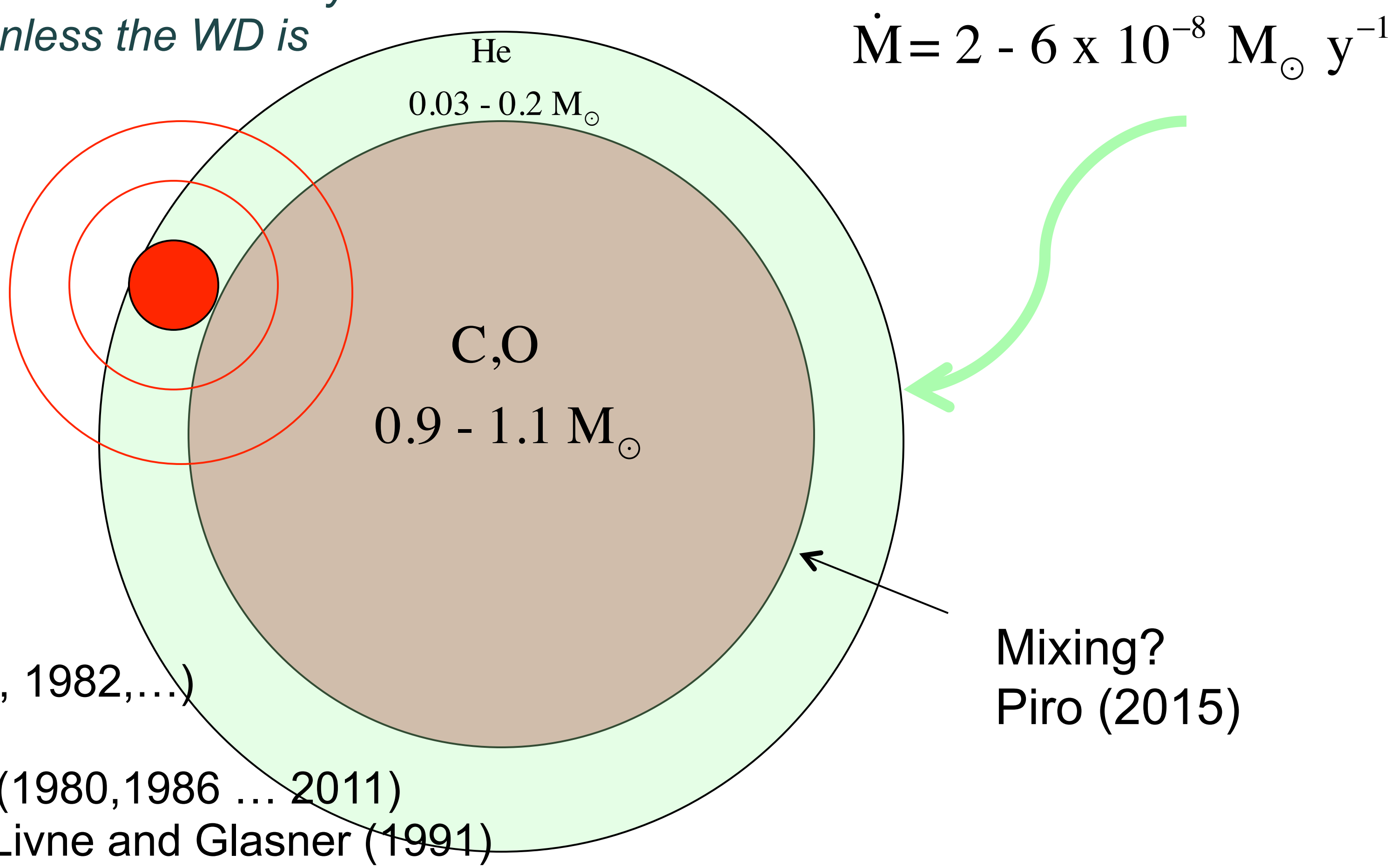


Add W7

see also Seitenzahl et al (2013)

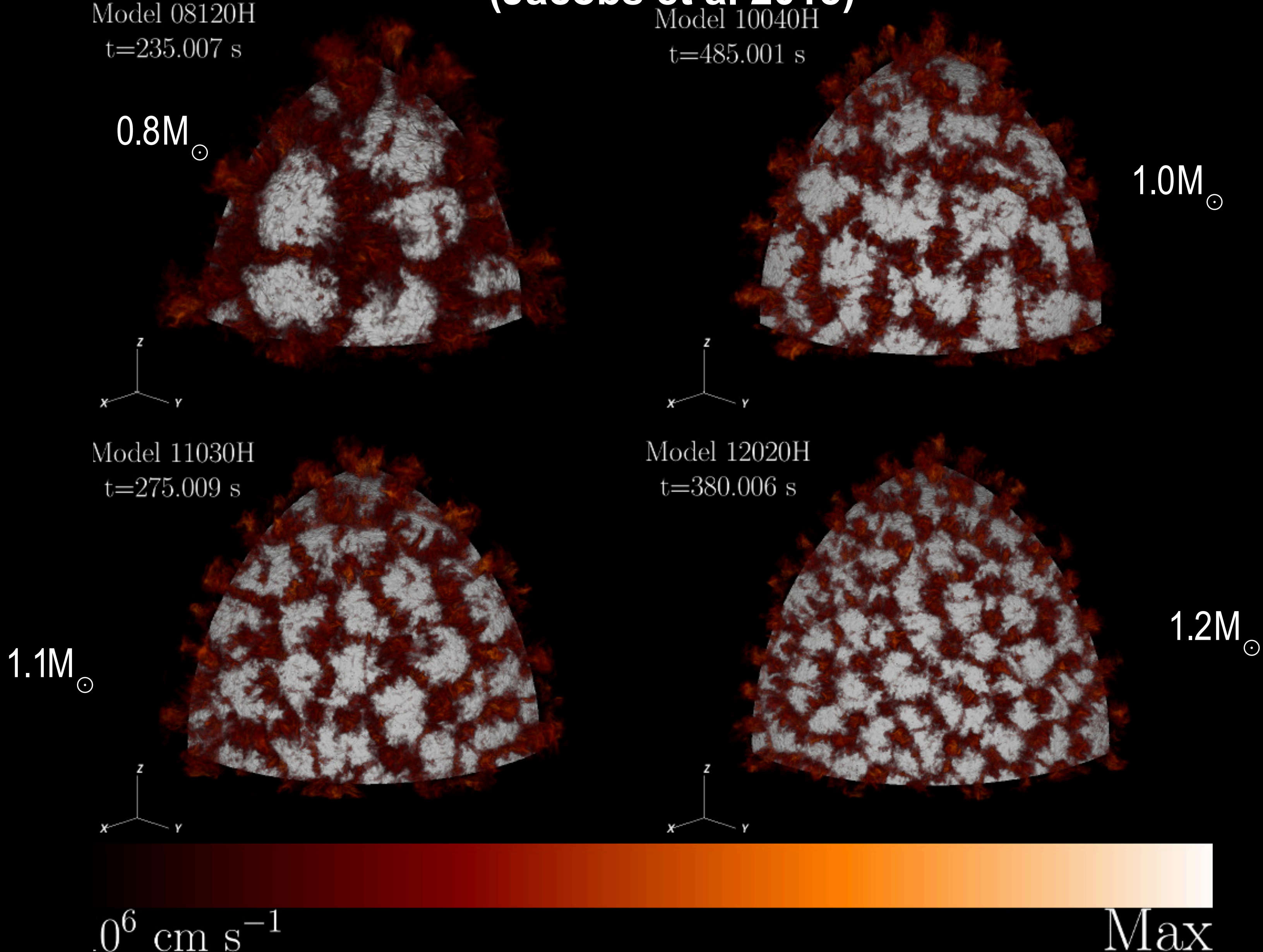
SUB-CHANDRASEKHAR MASS MODELS (traditional version)

A critical mass of He accretes from a companion. The helium ignites and detonates. This usually sets off a secondary detonation of the carbon unless the WD is very light

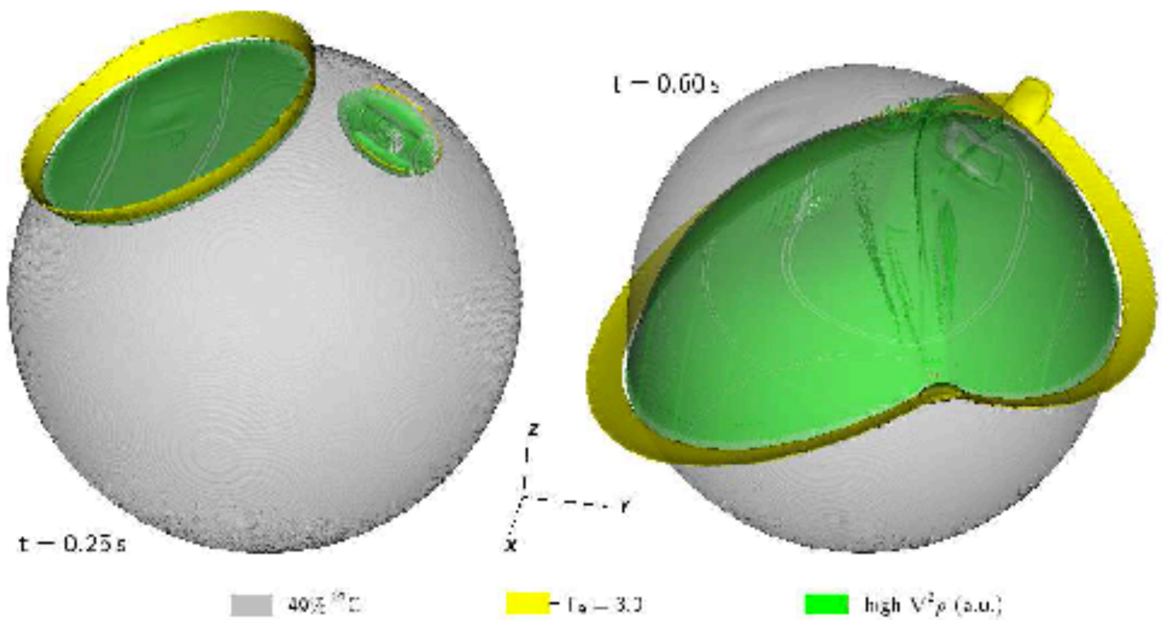


Nomoto (1980, 1982,…)
Taam (1980)
Woosley et al (1980,1986 … 2011)
Livne (1990); Livne and Glasner (1991)
Fink et al (2007)
Sim et al (2010) and others

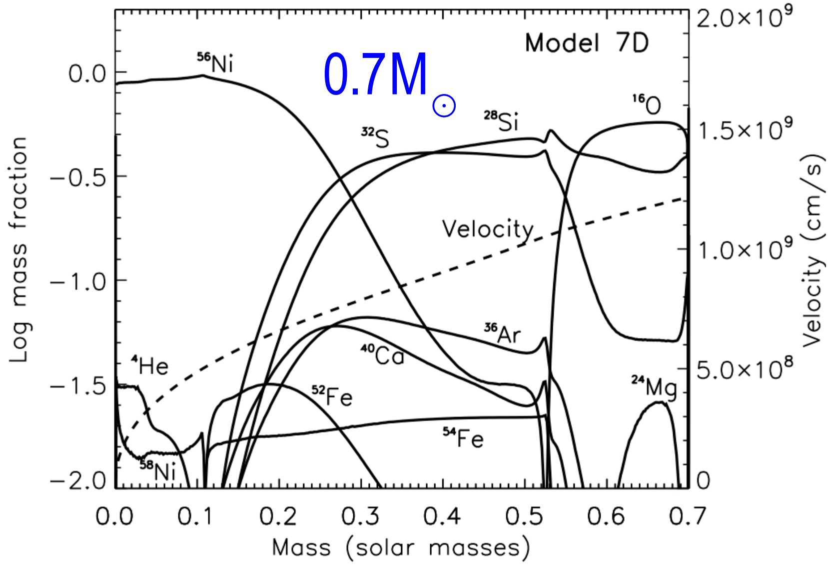
Ignition for sub-MCh models of varying mass (Jacobs et al 2015)

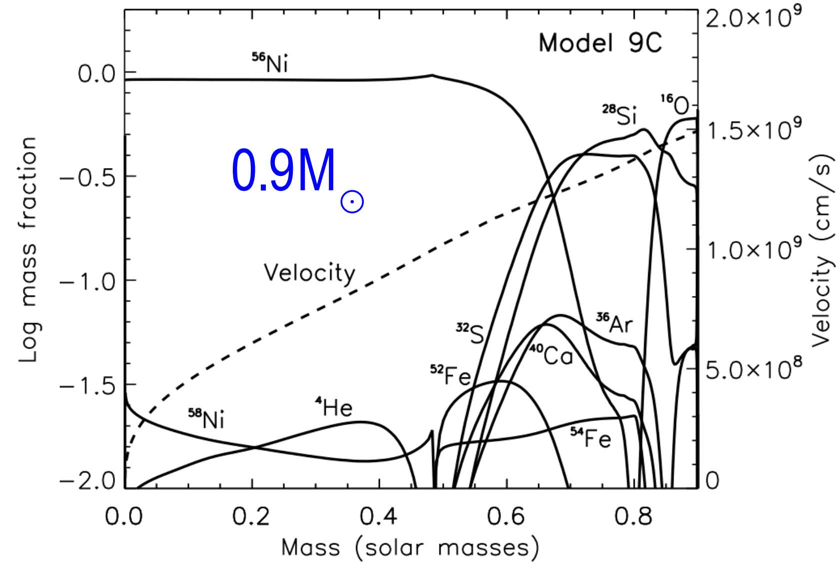


Study of asynchronous multiple ignition points by Moll and Woosley (2013). All models studied detonated the CO core provided the helium itself detonated. Fink et al (2010) found CO core detonation for He shells as low as 0.0035 solar masses (though for high mass WDs). Moll and Woosley had trouble initiating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

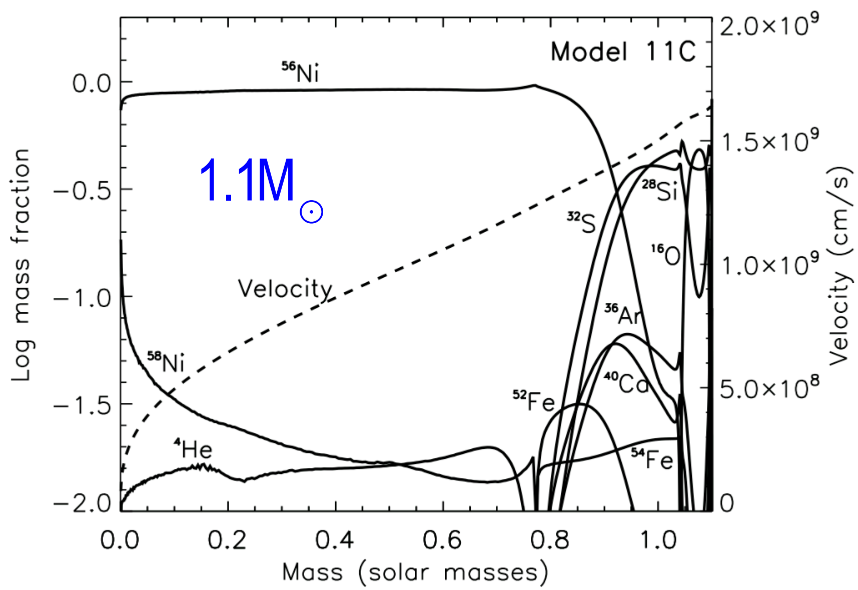


Woosley and Kasen (2011)





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

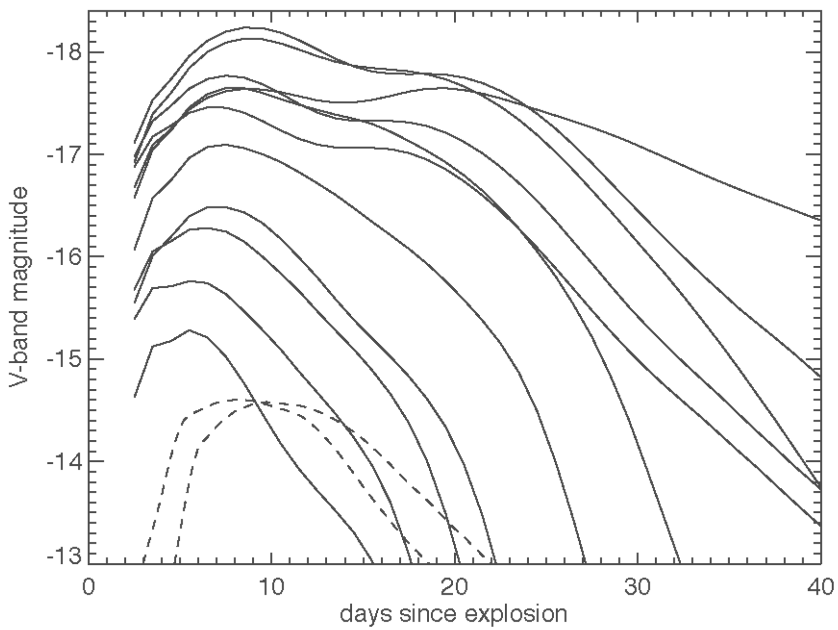
faint; hard to detionate?

Good

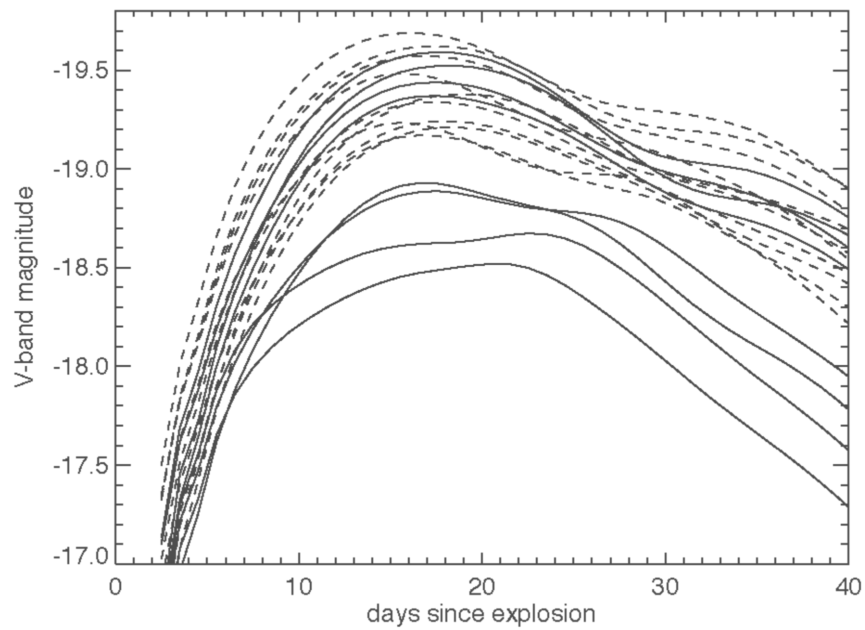
Max CO WD

(some variation with accretion rate, and WD temperature)

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

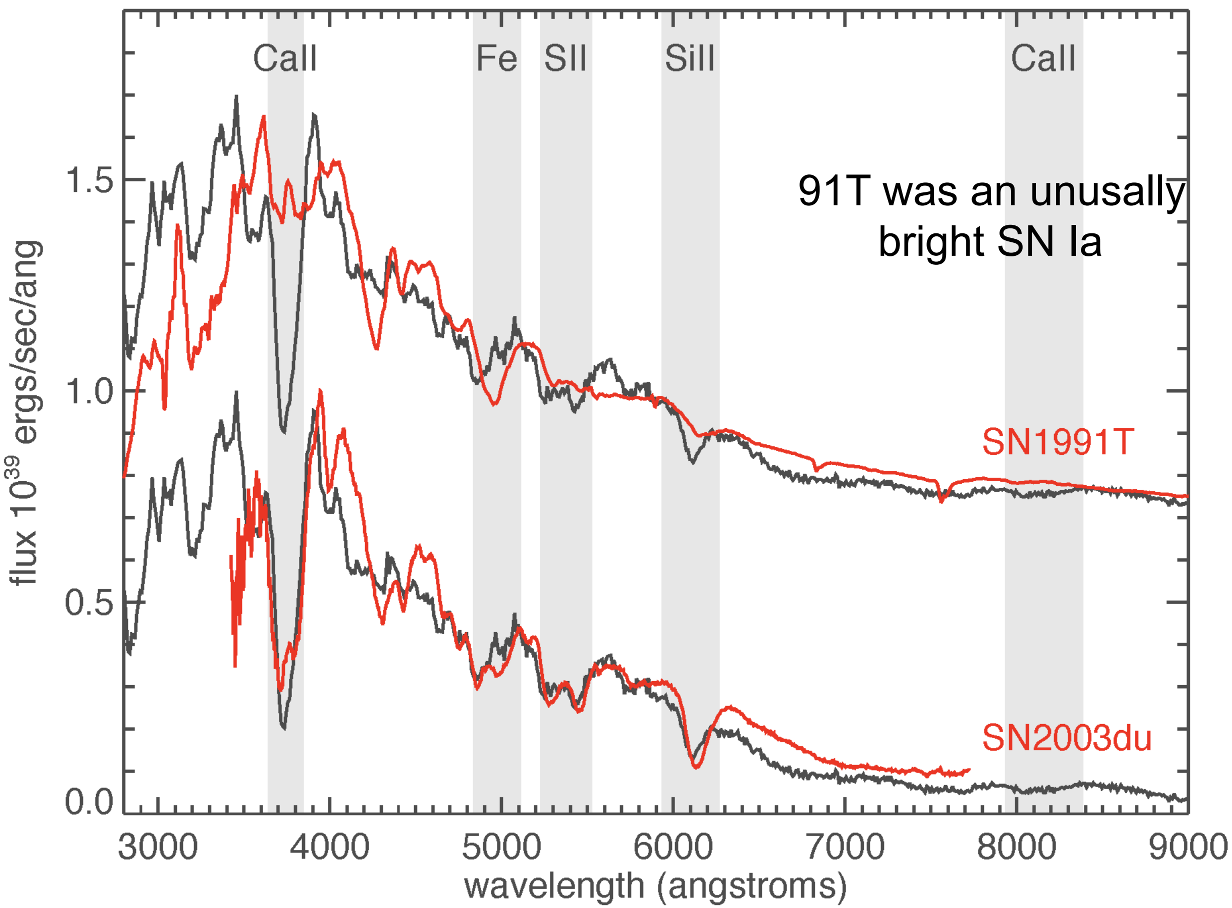


Entire star explodes

Some of these look like SN Ia…

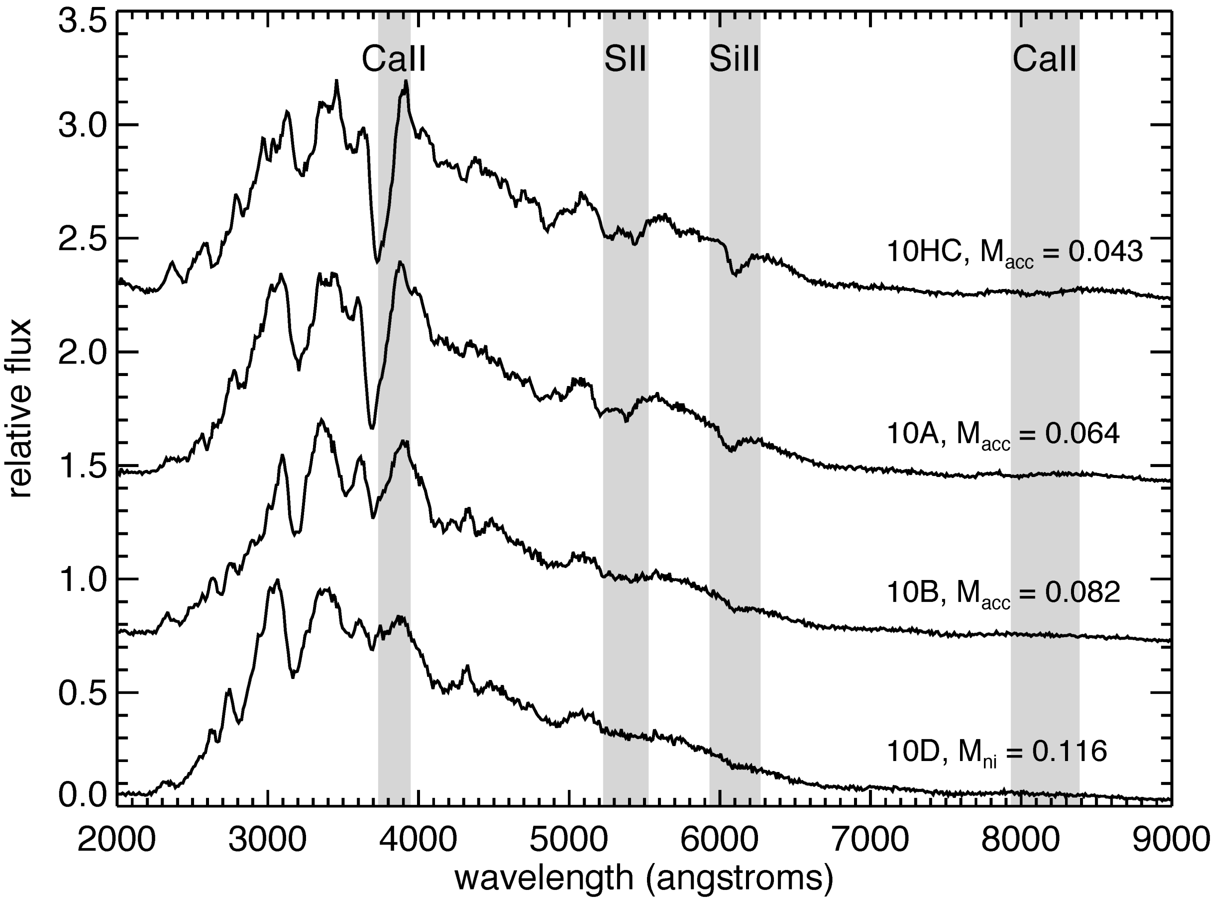
Model 10HC (hot 1.0 solar mass CO WD accreting at 4 x 10^{-8} solar masses per year, 0.045 solar mass He shell) – peak light spectrum vs observations.

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

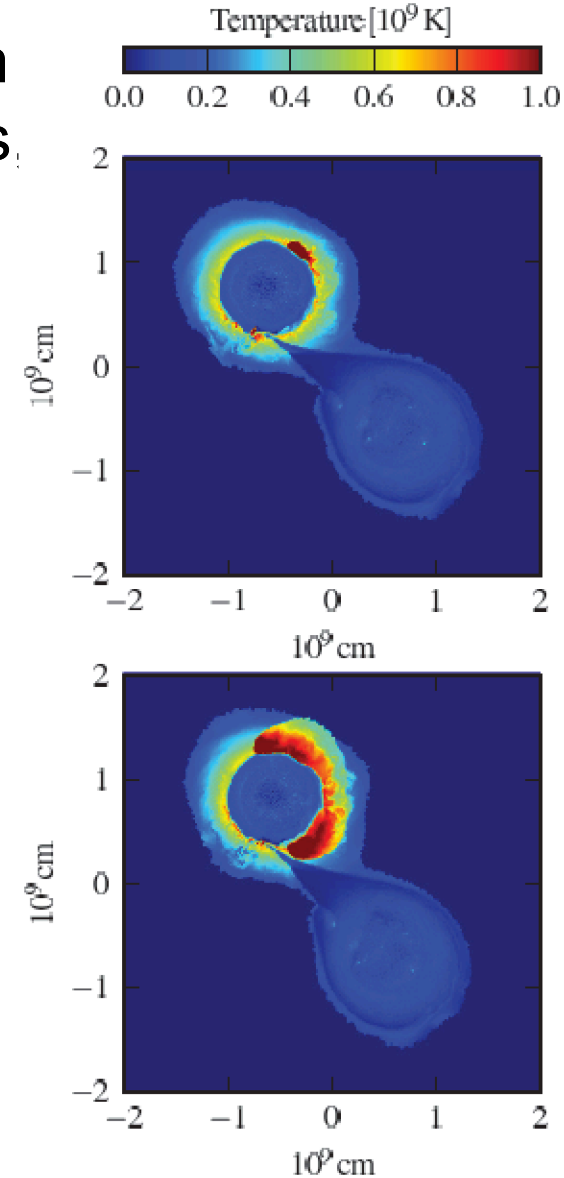
D. Kasen in
Woosley and Kasen (2011)

Getting the Helium Shell Mass Down

Recently attention has shifted to systems where the helium may already be in place in outer layers of one of two merging CO WD's, or where one of the WDs is helium.

The advantage is a potentially robust detonation with a low mass of helium.

Pakmor et al (2013)



Guillochon et al (2010)
Dan et al (2012)
Raskin et al (2012)
Pakmor et al (2013)
Shen and Moore (2014)

Summary– 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 much less than 0.07 $M_\odot$ (spectrum) and greater than ~0.03 $M_\odot$ (to detonate without mechanical compression).

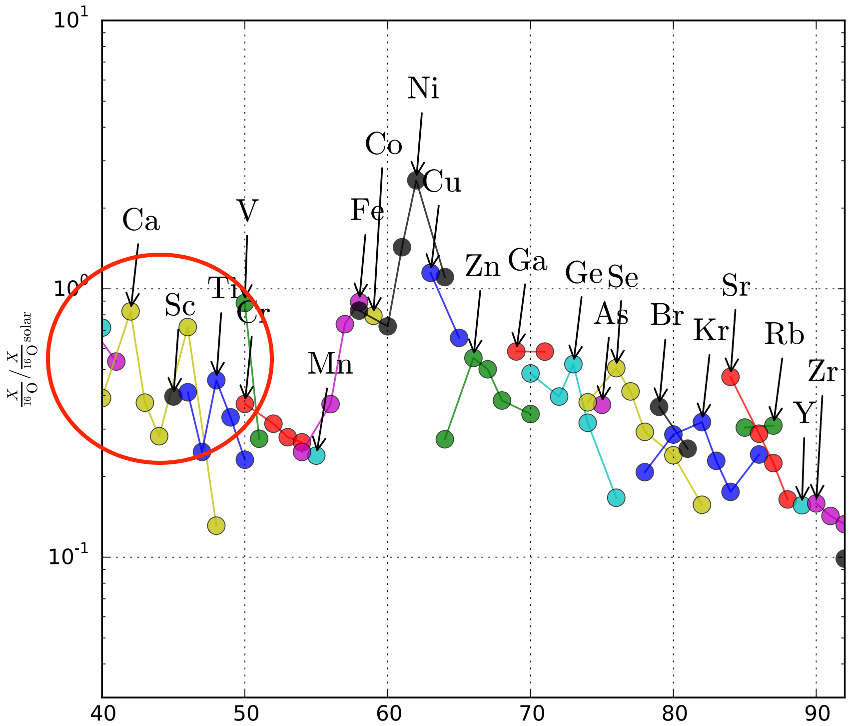
The helium shell mass can be less in a detonation initiated directly by compression (as in a merger), but probably not much less than ~0.01 $M_\odot$ on a 1 $M_\odot$ WD.

(Shen and Moore (2014) got 0.005 $M_\odot$ by using a large network).

Why are just 1.0 $M_\odot$ WDs with thin helium shells selected?

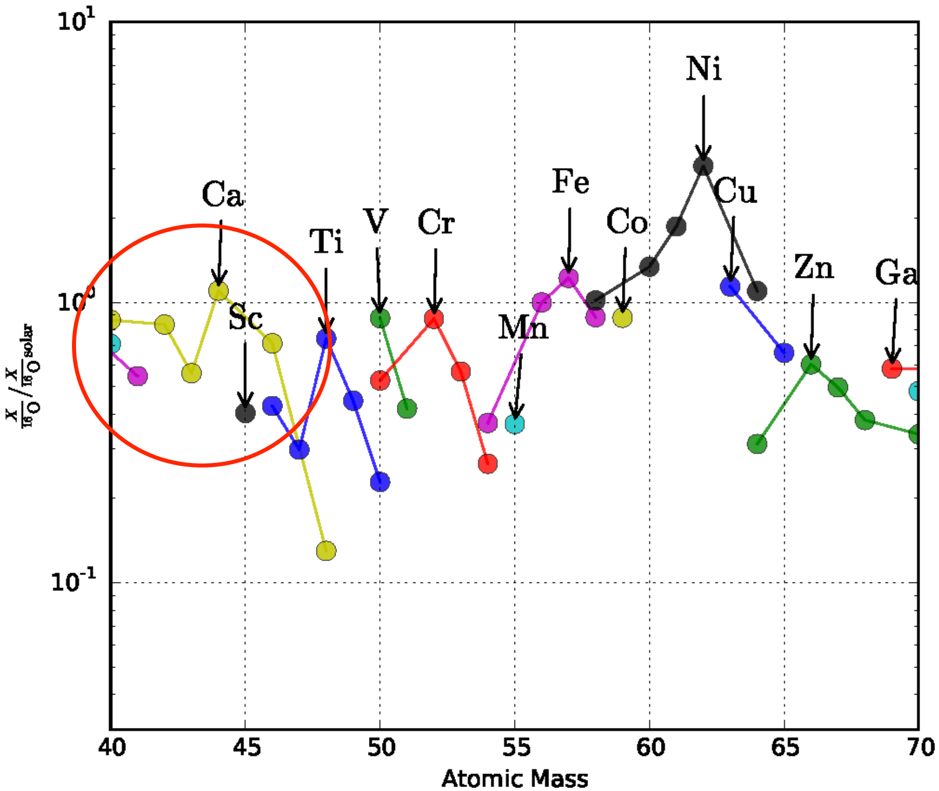
Possible He detonation event w/o C detonation – SN Iax - Perets et al (2010) SN 2005E, but 0.3 M_o of ejecta? See also Foley et al (2013)

Sub-MCh SN Ia needed to make ^{44}Ca (and ^{40}Ca?)



Massive star nucleosynthesis
8 – 120 solar masses
Sukhbold et al (2015)

Add sub-MCh SN Ia
Model 10HC of
Woosley and Kasen
(2011)



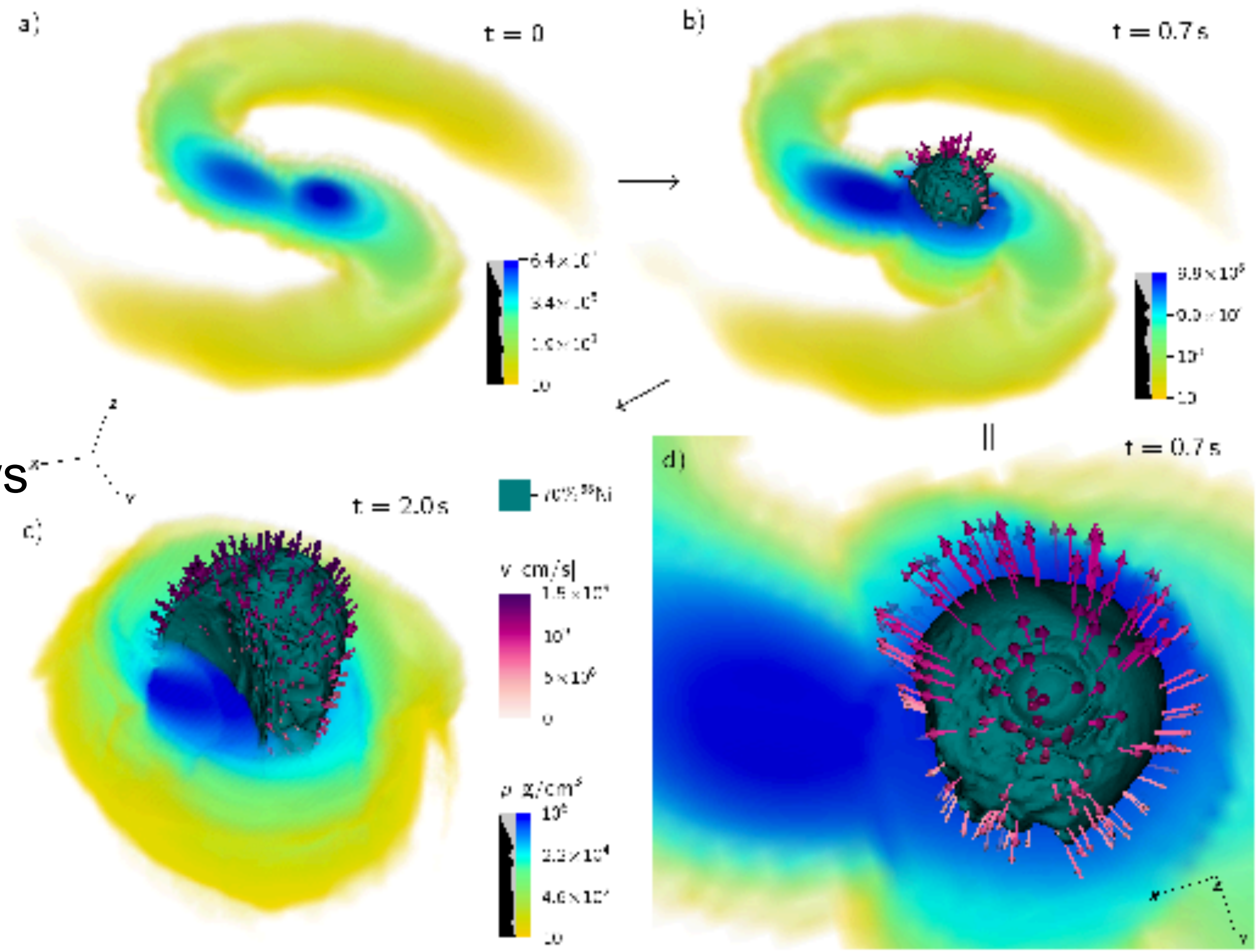
Merging
White Dwarfs

Prompt Detonation

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

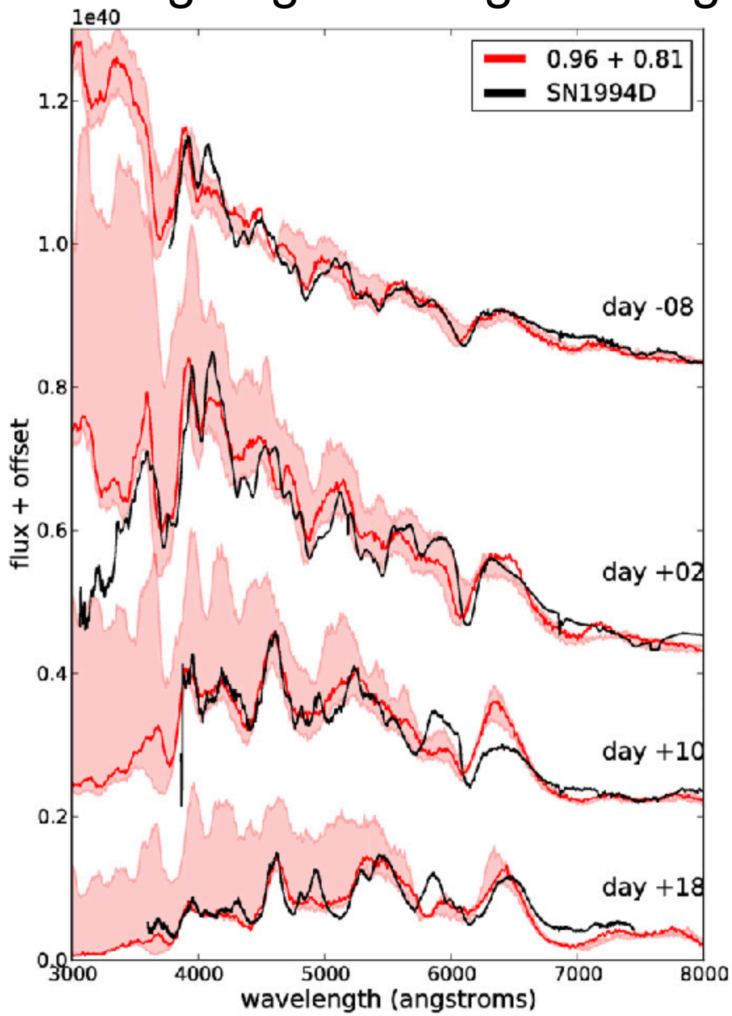
Moll, et al, 2014

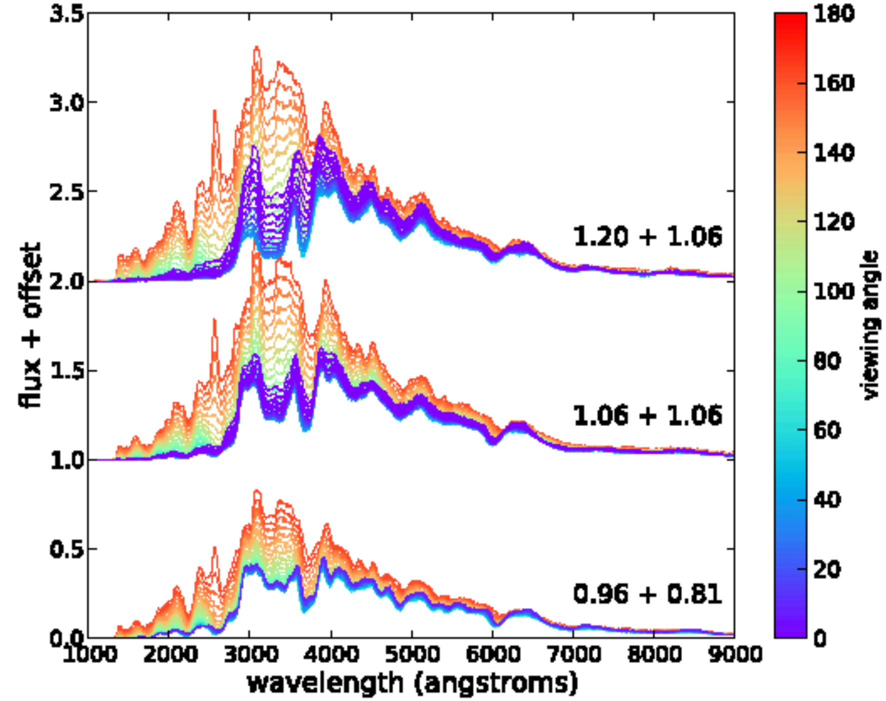
$1.06\ M_{\odot} + 1.06\ M_{\odot}$

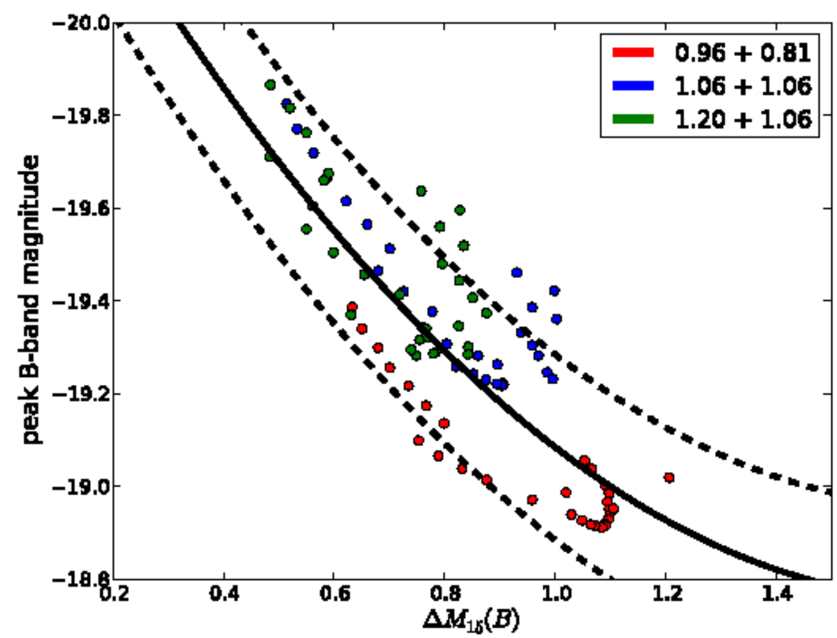


Density contours
Sphere with arrows is ^{56}Ni. Length of arrow denotes velocity.

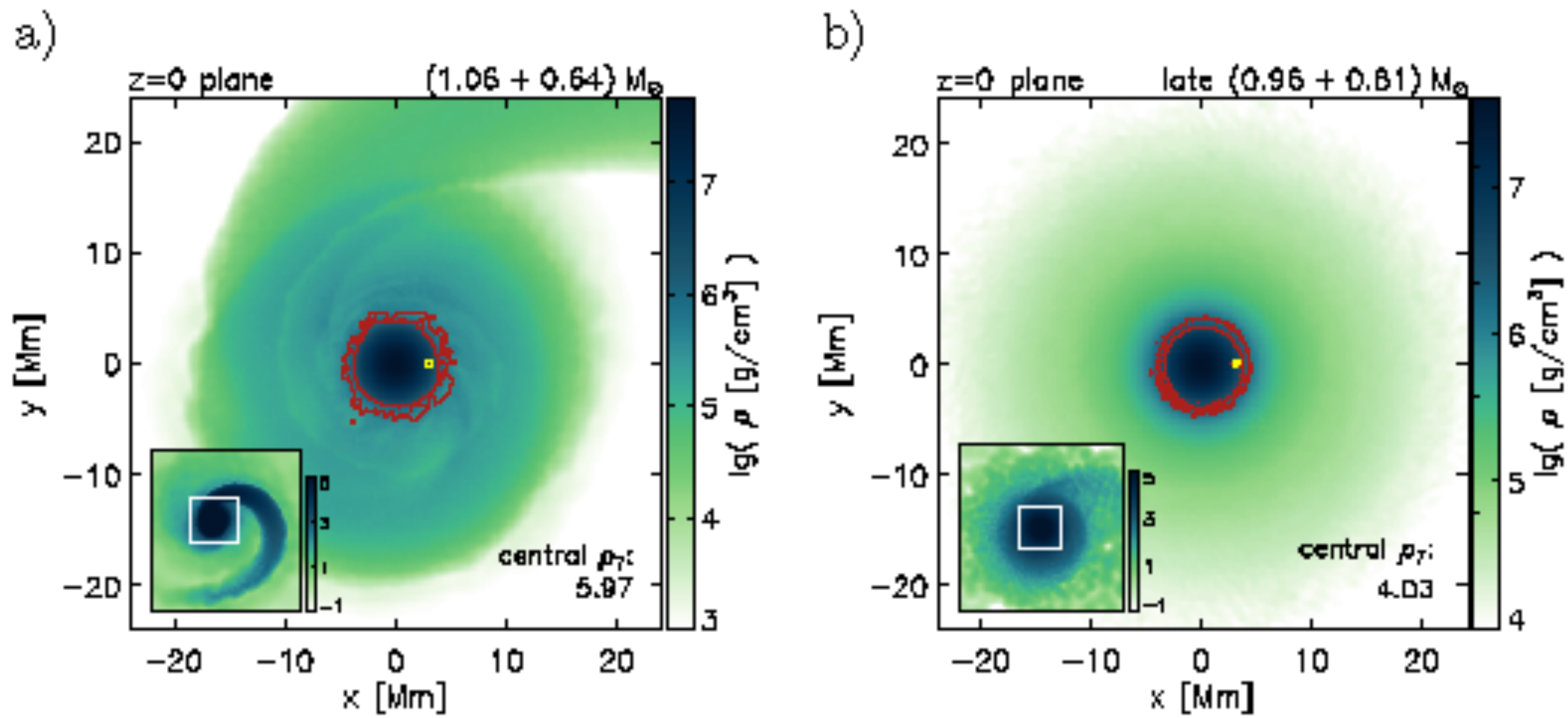
At many angles (especially closer to the equator) some of the models agree with typical SN Ia. At other angles they do not. The WLR is in qualitative agreement with viewing angle having a strong effect







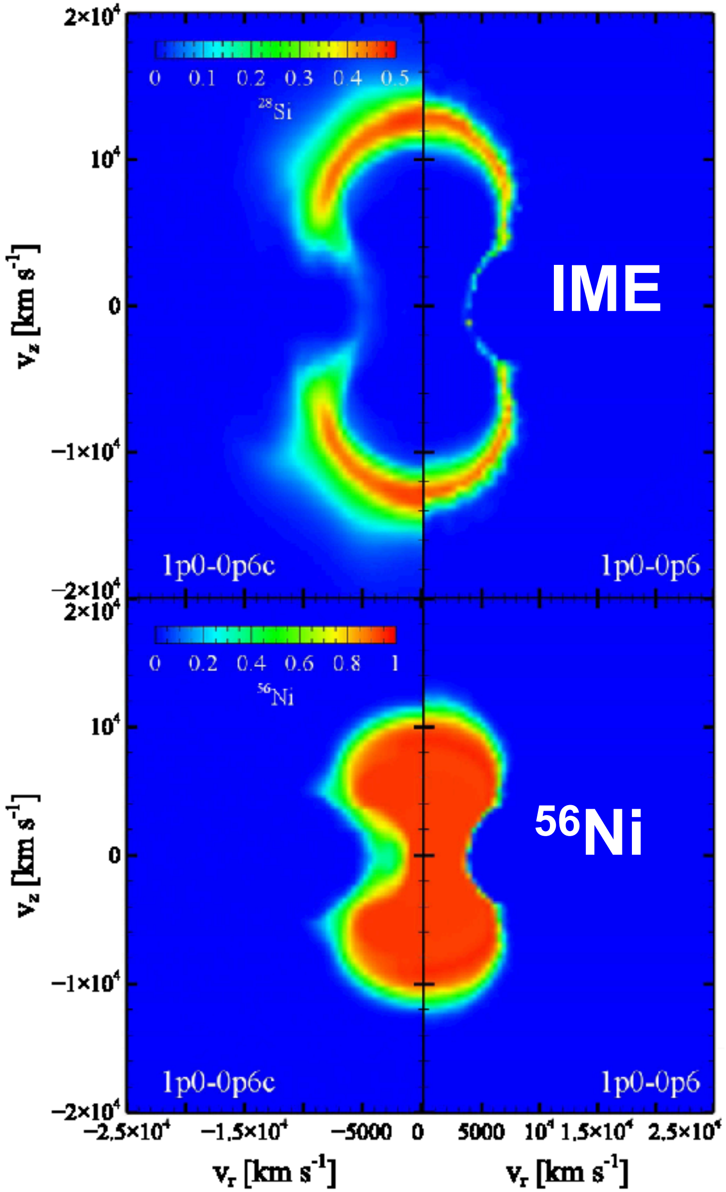
Late time explosion from mergers e.g. Raskin et al (2014)



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)

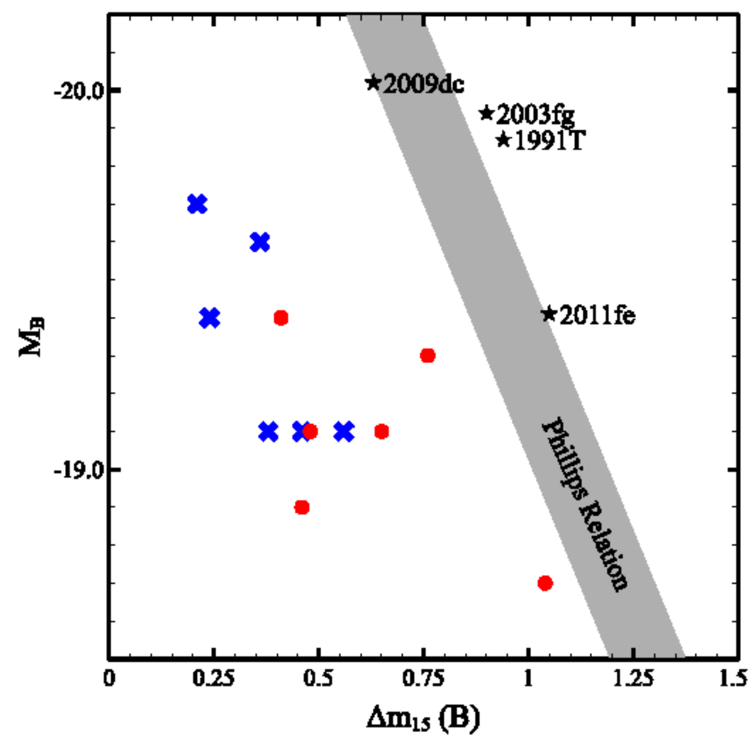
Reaches higher density;
Makes more ^{56}Ni



Raskin et al (2014)

Ejecta have strong angle dependence due to interaction with disk

Tend as a group to be brighter than prompt detonation during merger and to decline slower than typical SN Ia



Summary and Questions

- All 3 classes of models probably happen, but in general they predict a wide diversity of outcomes. How diverse is the observed set and why does nature frequently choose just the subset that makes common SN Ia?

- Chandrasekhar mass ignition is starting to be better understood. Does detonation ever happen without mechanical compression and confinement?

- How asymmetric are Type Ia supernovae?

- A promising explanation today for common SN Ia –
  1.0 CO M_o WD capped by 0.01 M_o of He
  Can this event be selected against all other possibilities and is the event rate sufficiently high?
  What is the preferred channel?