SNIa: wonders & mysteries

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The Origin of Cosmic Elements
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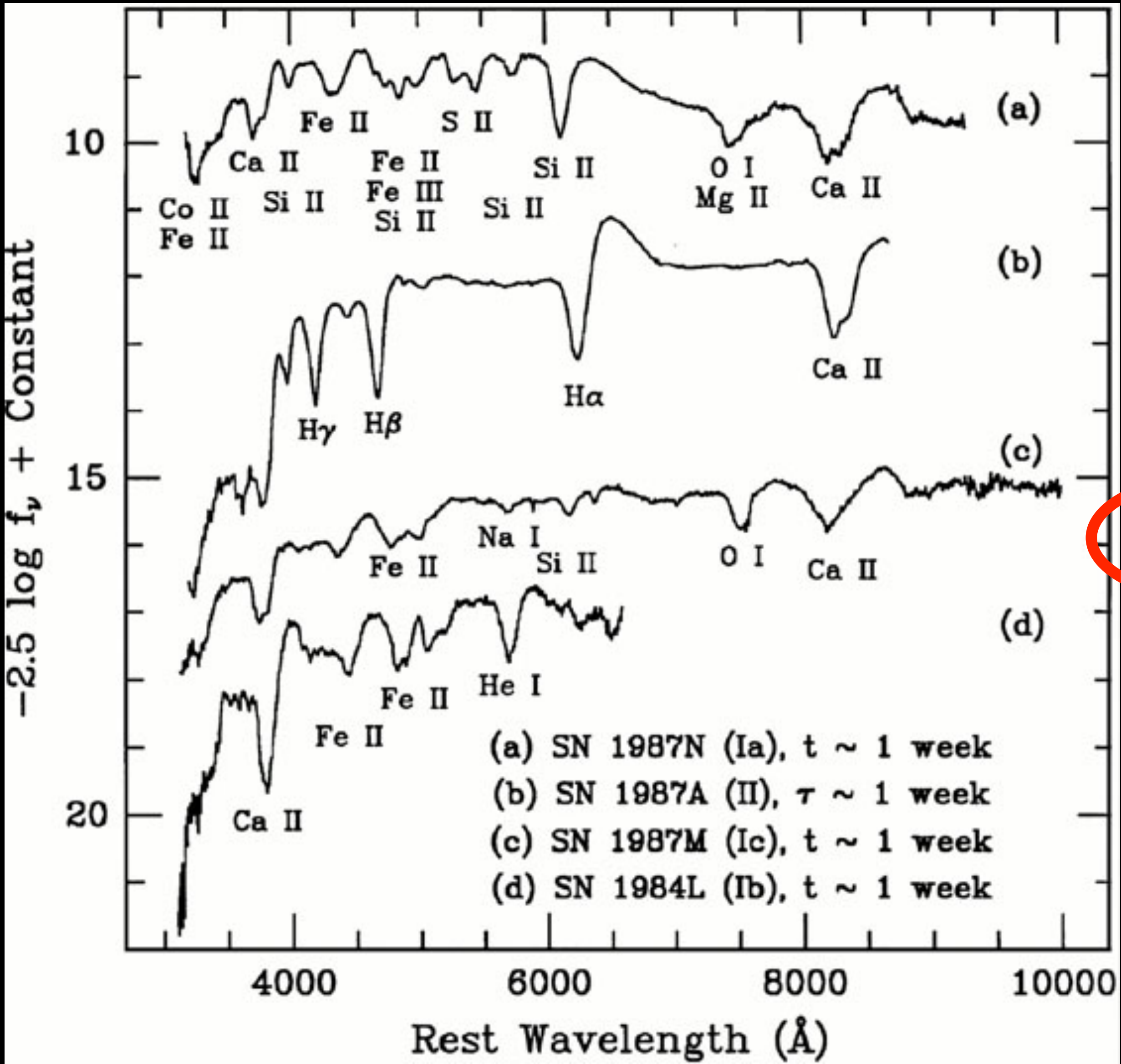
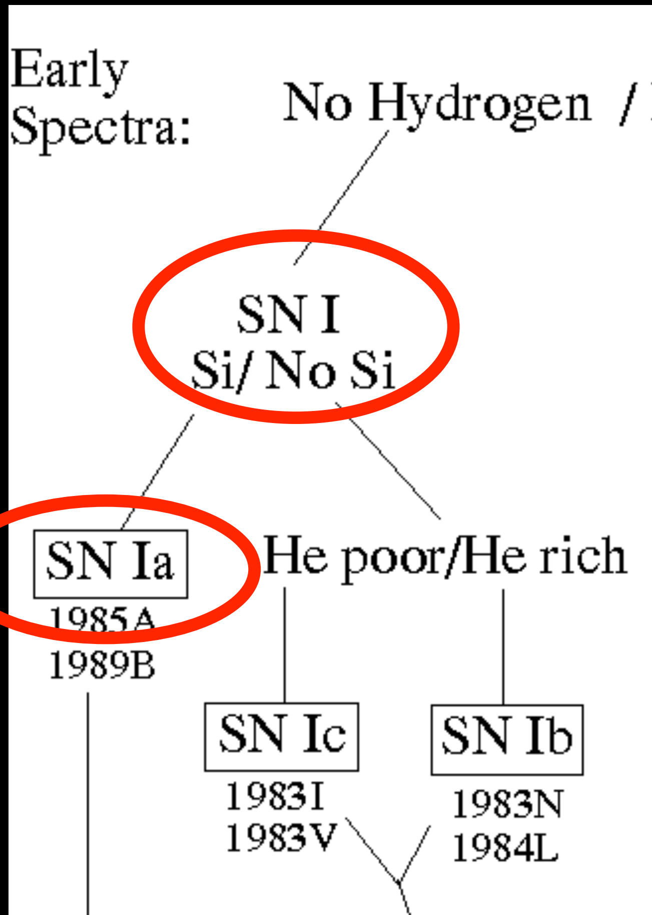
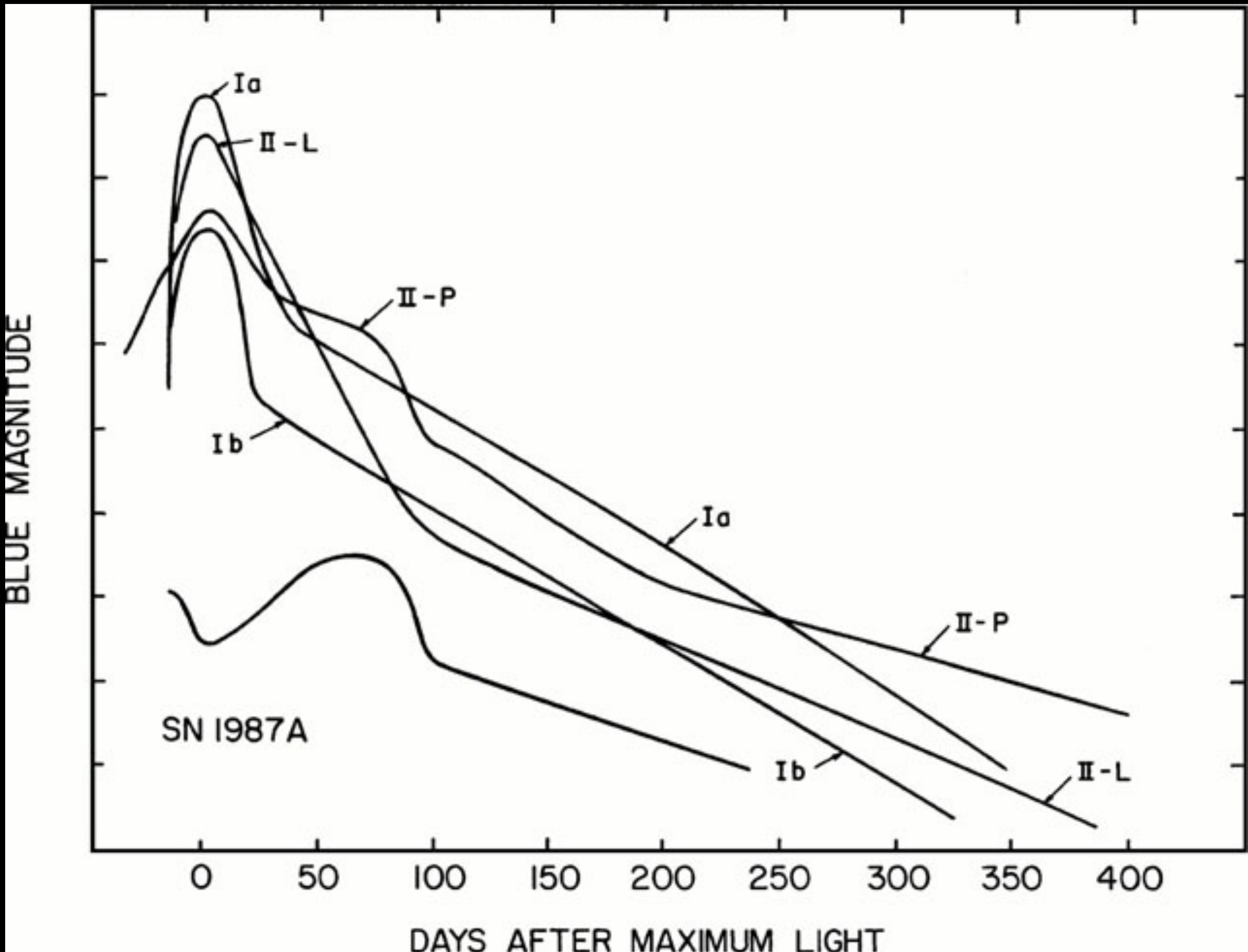
Overview on Supernovae

Taxonomy:





Light curves



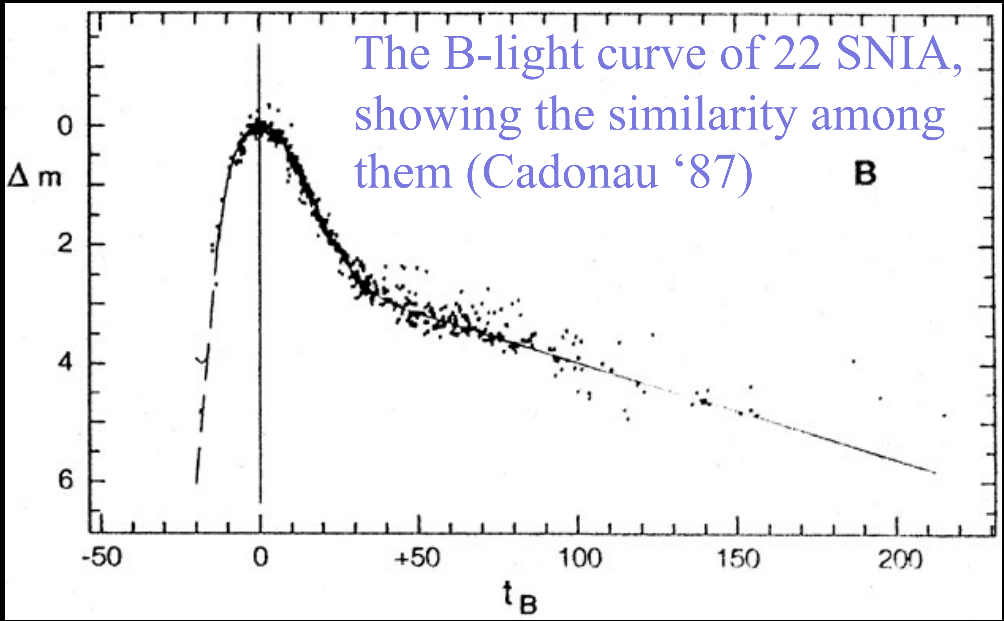
- H must be absent at the moment of the explosion
- Progenitors should be long lived to account for their presence in all galaxies, including ellipticals
- The explosion should produce at least ~ 0.3 M_0 of ^{56}Ni to account for the light curve and late time spectrum
- The explosion should not incinerate the outer layers of the parent
- The short risetime of the light curve indicates that the exploding star is a compact object

⬇

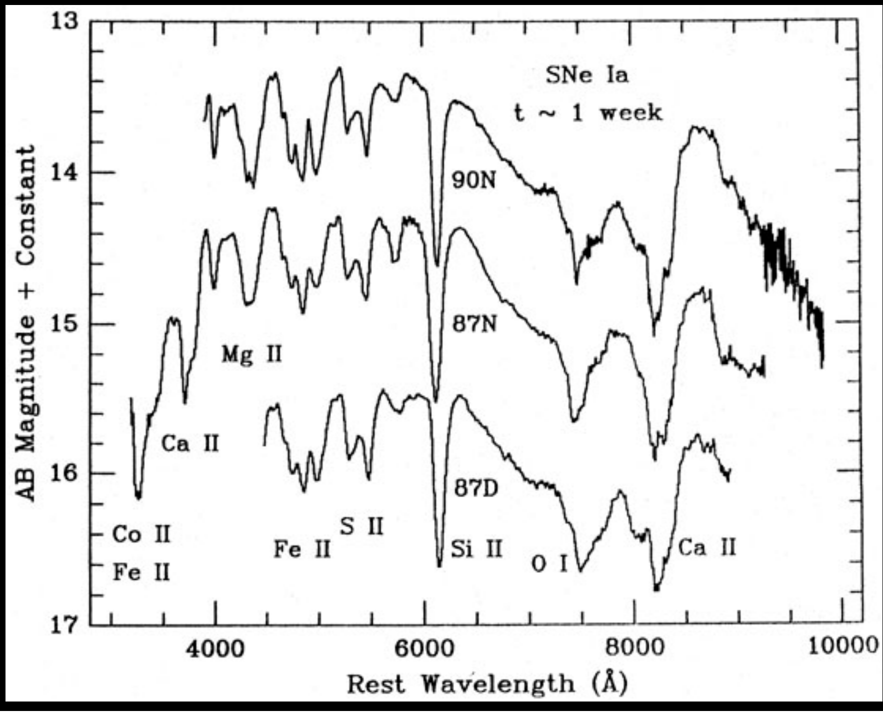
SNIa are caused by the thermonuclear explosion
of a C/O white dwarf near the Chandrasekhar's mass
in a close binary system

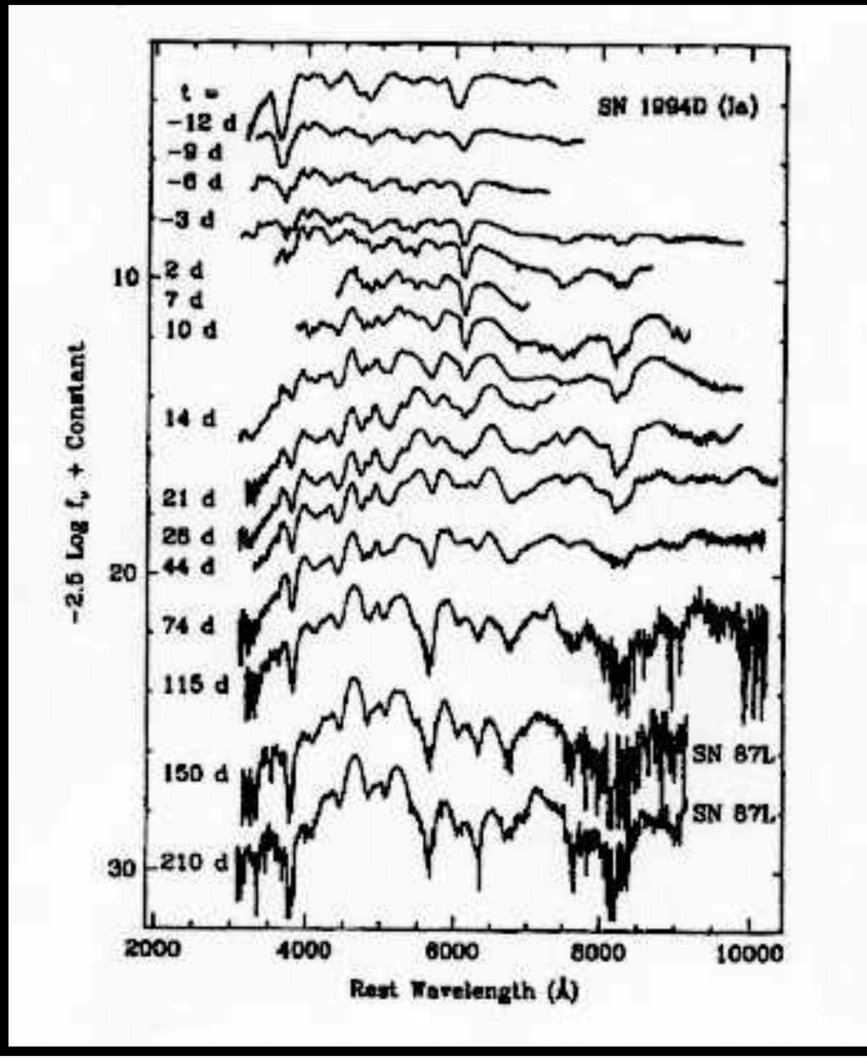
(He white dwarfs detonate and are converted in Fe and ONe collapse to a neutron star)

Spectral and photometric homogeneity supported this paradigm!

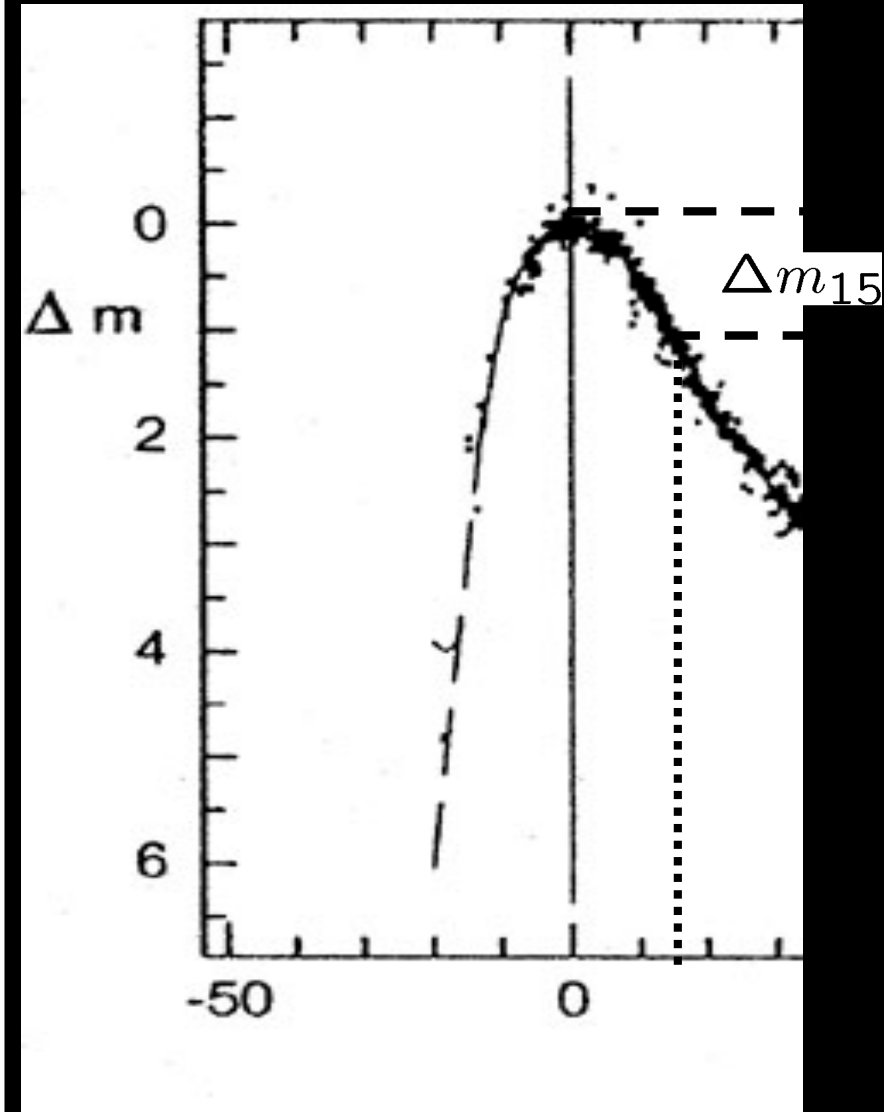


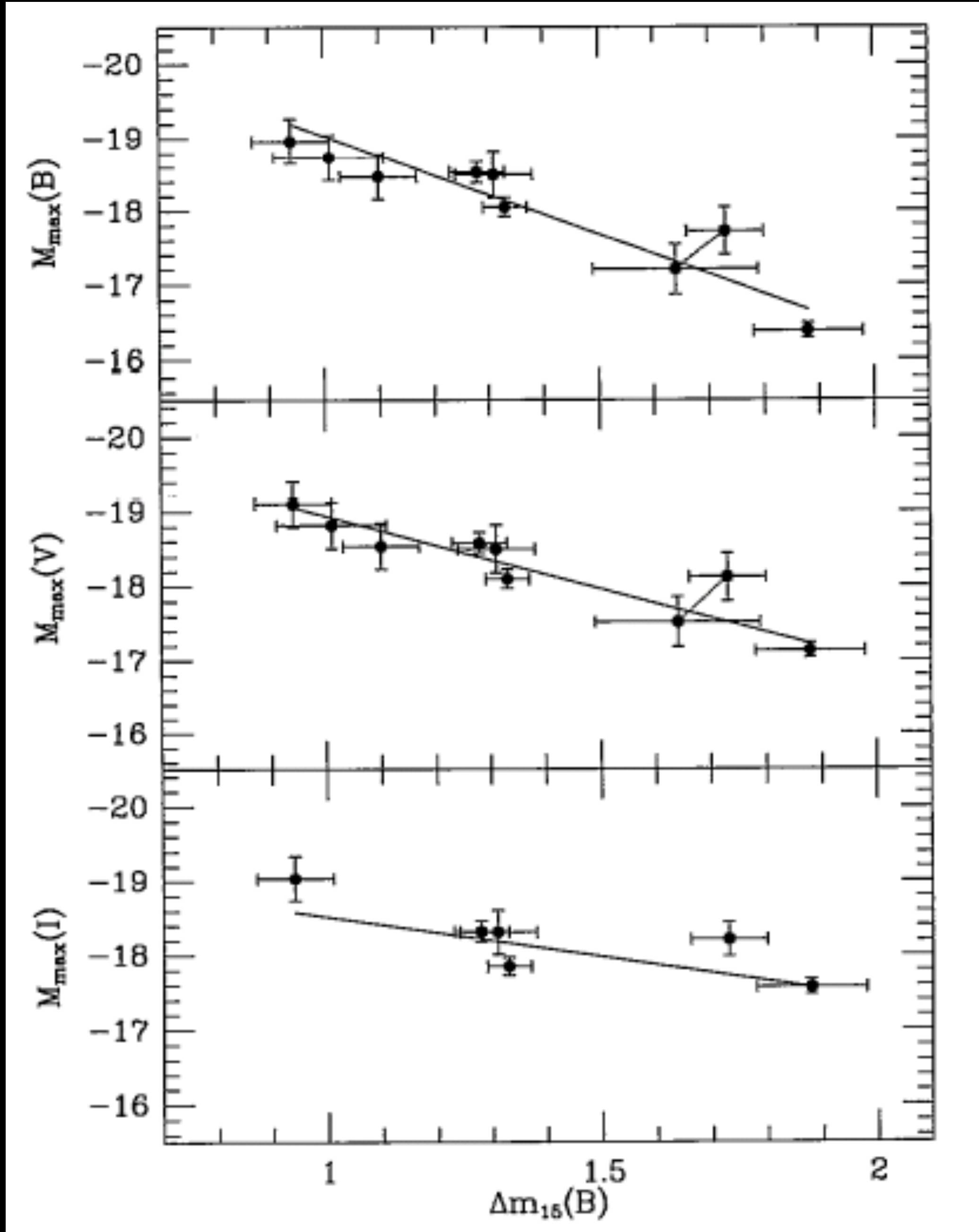
Spectral homogeneity near the maximum light &over the time (Fillipenko)



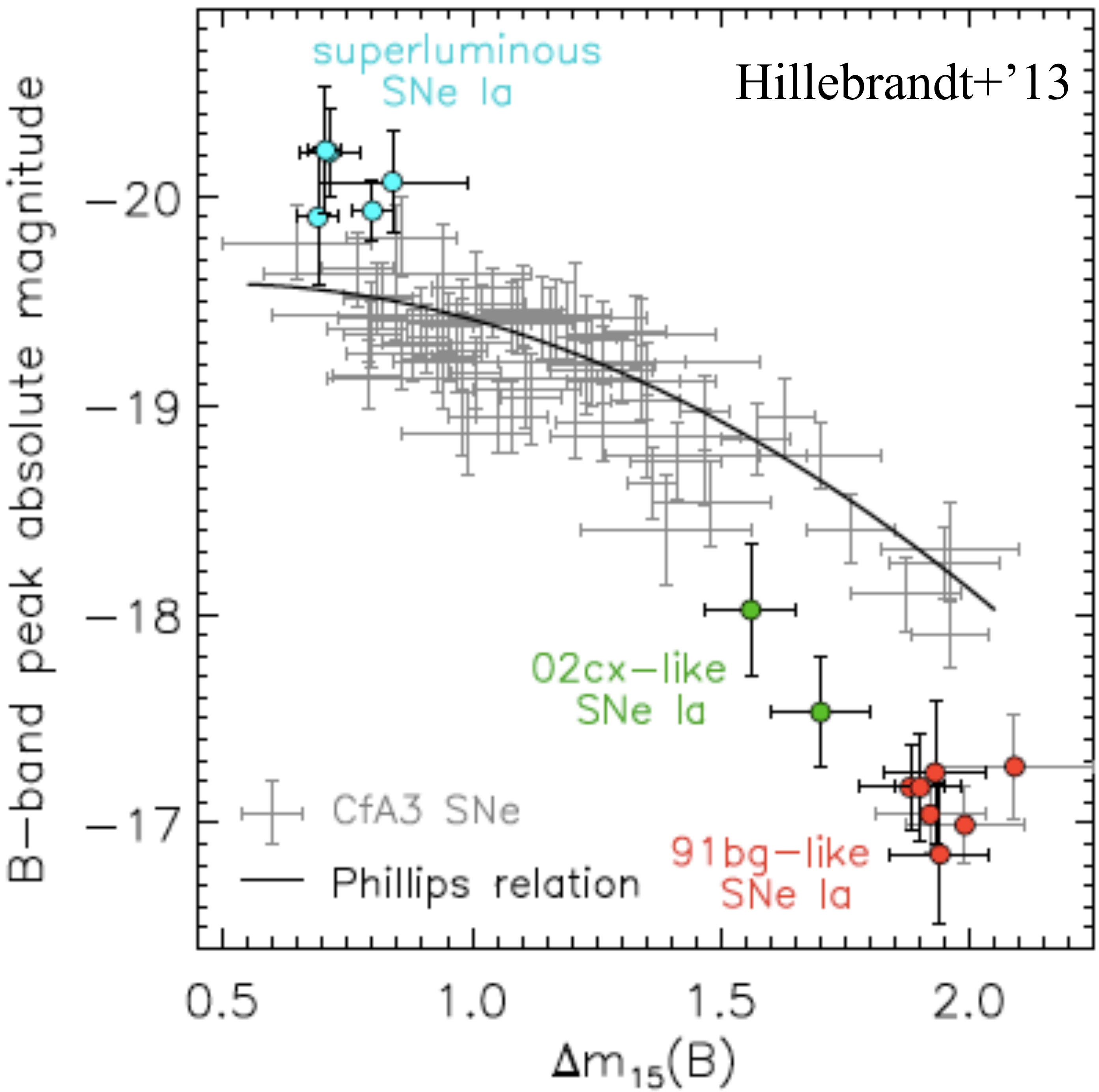


Furthermore, normal display some differences…





Phillips (1993; ApJ 413, L105)



superluminous
SNe Ia
Hillebrandt+'13
02cx-like
SNe Ia
91bg-like
SNe Ia
CfA3 SNe
Phillips relation
B-band peak absolute magnitude
−20
−19
−18
−17
0.5
1.0
1.5
2.0
$\Delta m_{15}(B)$

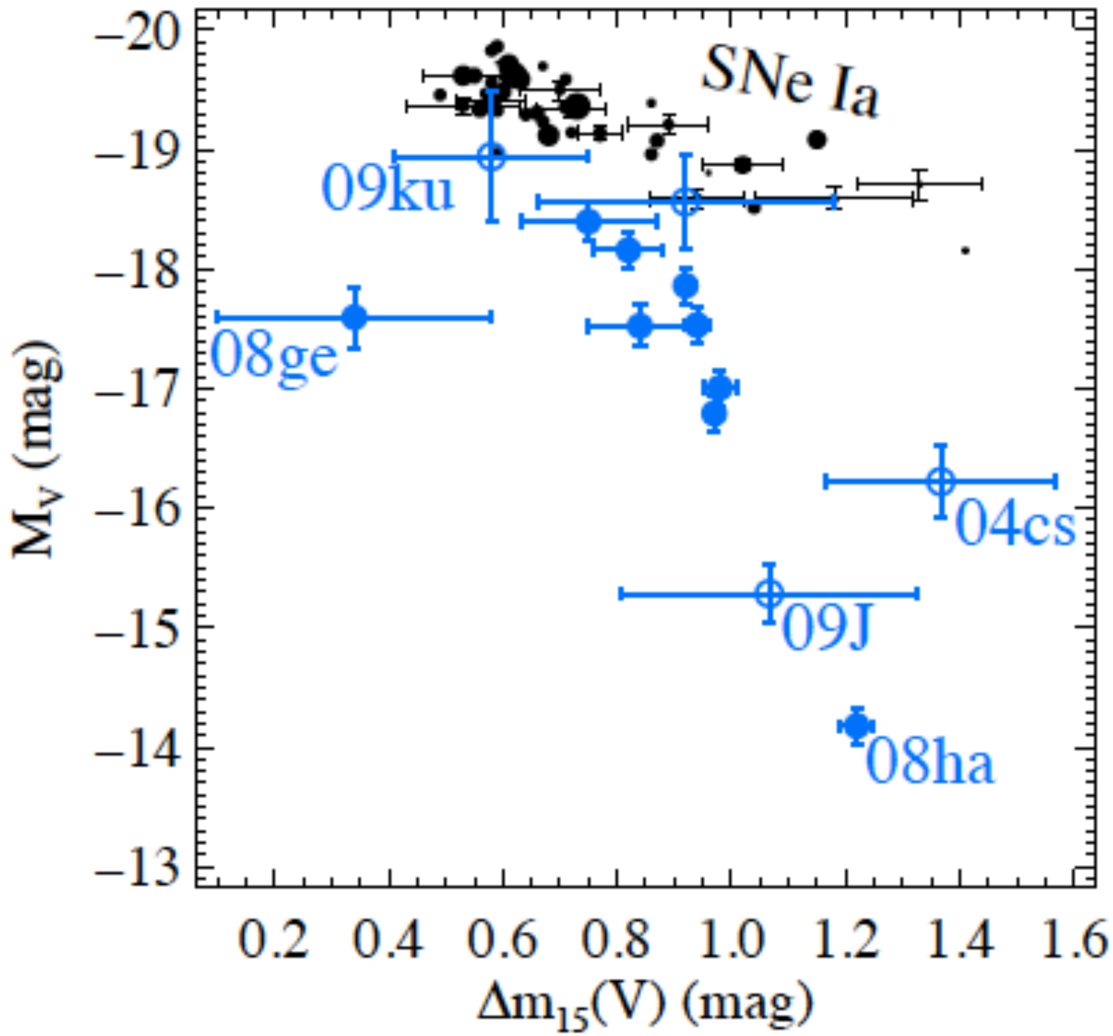


FIG. 26.— WLR ($\Delta m_{15}(V)$ vs. M_V) for SNe Ia (black points) and SNe Iax (blue points). Filled points are direct measurements in V, while the open points (SNe 2004cs, 2009J, and 2009ku) are an estimate by converting parameters measured from unfiltered (assumed to be R) or r and i to V. The sizes of the SN Ia points are inversely proportional to their uncertainty, with some points having representative errors bars to show the scaling.

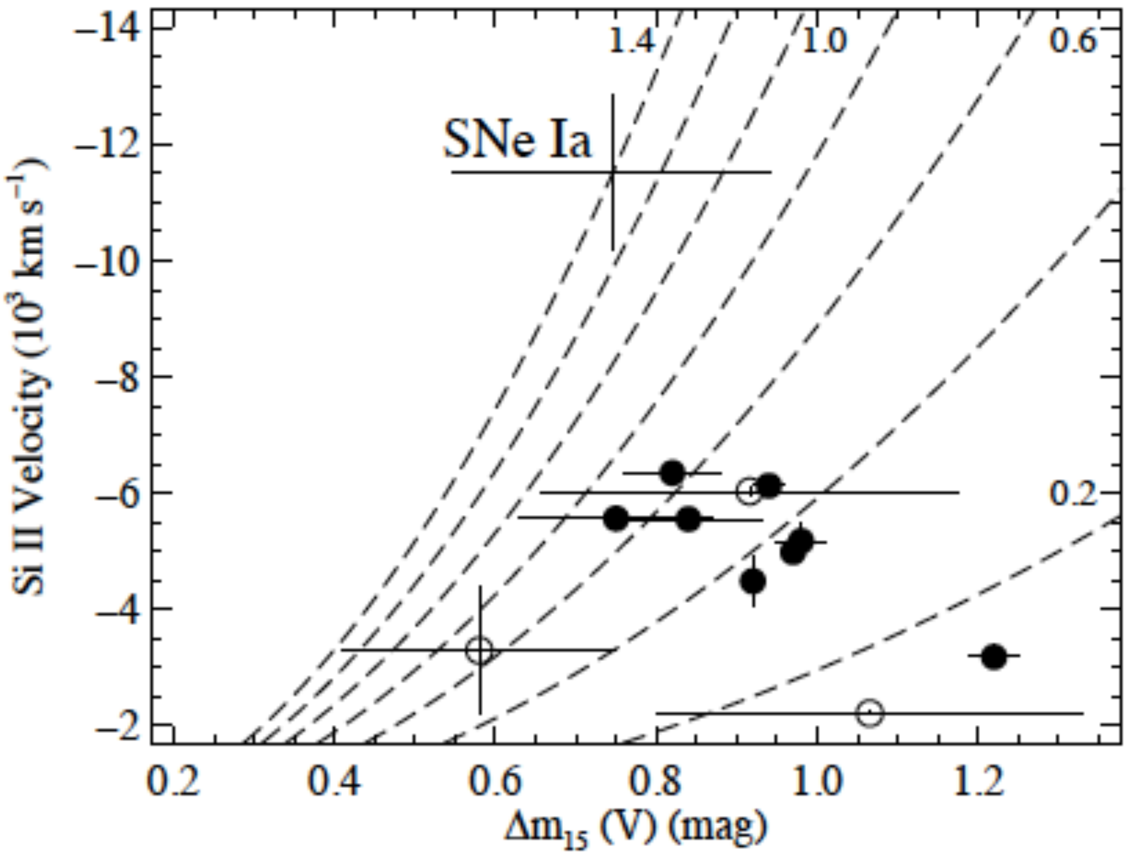
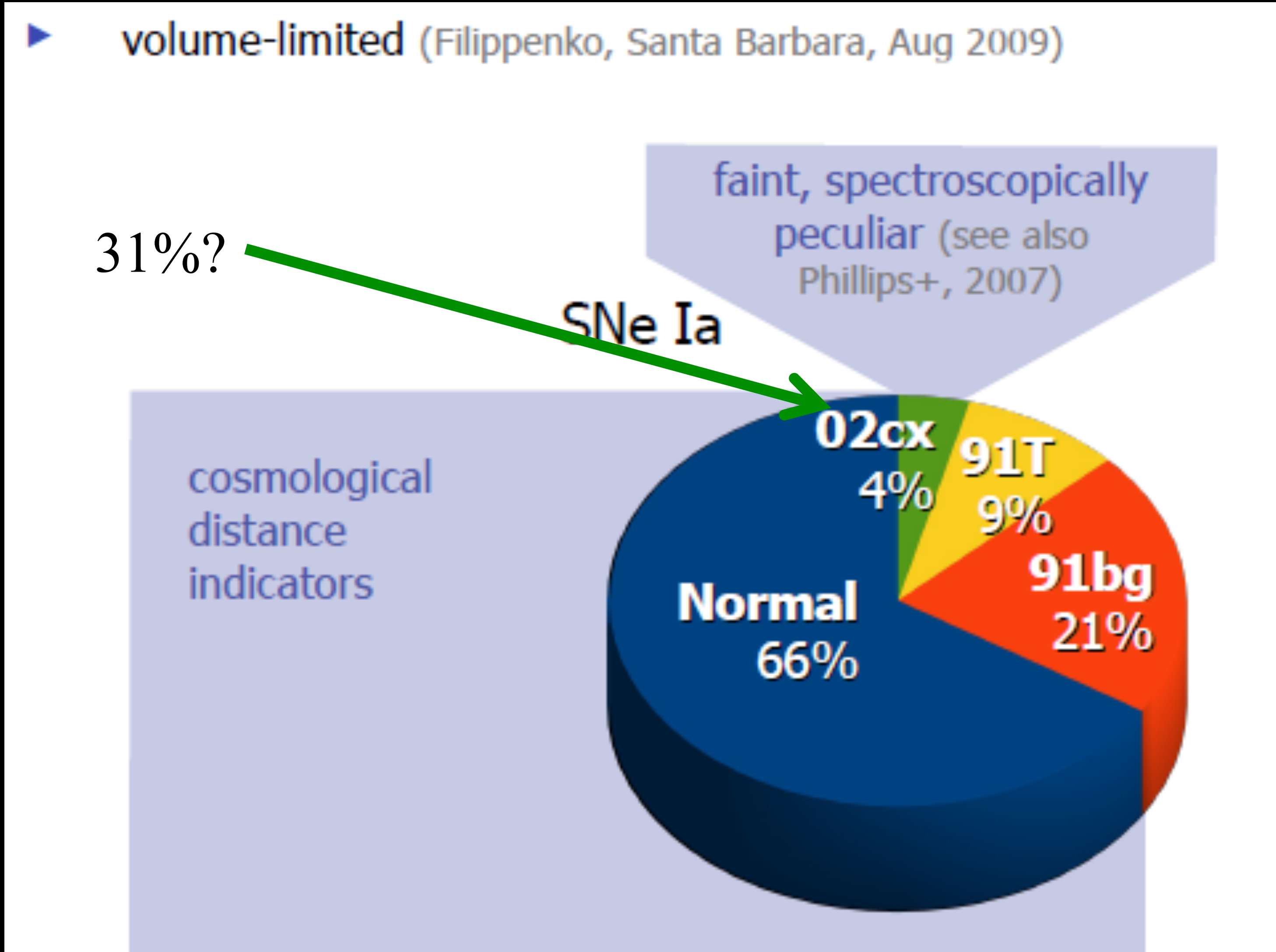


FIG. 31.— Light-curve shape vs. Si II λ6355 velocity for SNe Iax. SNe 2009J, 2009ku, and 2012Z, for which $\Delta m_{15}(V)$ is estimated using the relations derived in Section 4.1, are represented by the empty circles, indicating their approximate values. The average and standard deviation for normal SNe Ia are plotted as a single cross and labeled. The dashed lines represent lines of equal ejecta mass, ranging from 1.4 $M_\odot$ in the upper left to 0.2 $M_\odot$ in the lower right in steps of 0.2 $M_\odot$. The majority of SNe Iax cluster at ~0.5 $M_\odot$.

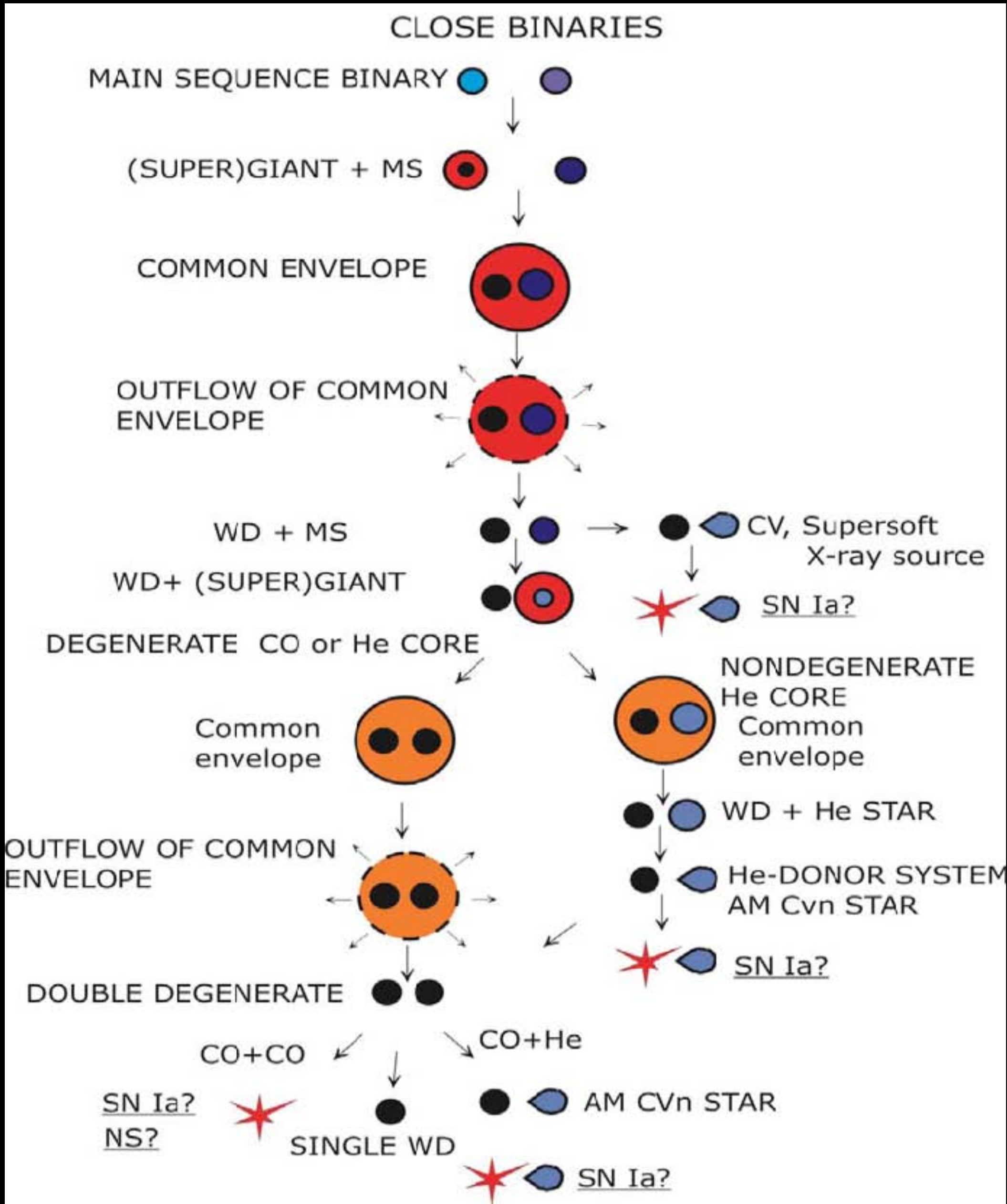
Ejected mass cluster ~ 0.5 M_o

The majority are dim M_{Ni} ~ 0.05 M_o

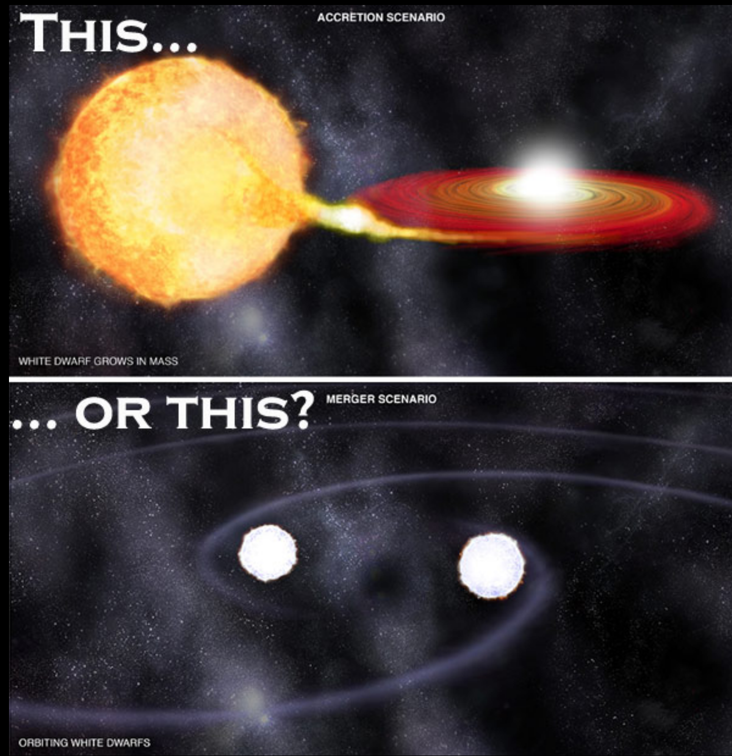
A peculiar object is just a well observed object!



It makes sense to look for different coexisting scenarios & explosion mechanisms



Scenarios leading to a SNIa



Accreted matter:
H, He or C+O

Everything able to explode eventually do it!
At a first glance both scenarios SD & DD can coexist!

Direct evidences from stellar remnants

- Tycho SN, hint of a possible survivor candidate (controversial) (Ruiz-Lapuente'04)
- SNR 0509-675, no stellar remnant, DD-candidate (Schaefer & Pagnotta'12)
- SNR 0519-690, no stellar remnant, DD-candidate (Edwards+'12)
- SN1006, no stellar remnant, DD-candidate (Gonzalez+'12)

SN 2011fe

(Nugent et al, ATel 3581, 2011)

Host galaxy: M101
Coordinates (J2000):
RA: 14:03:05.81
Dec: +54:16:25.4
Discovery: August 24th, 2011
(Palomar Transient Factory:
PTFkly)
Distance: 6.4 ±0.7 Mpc

Early observations rule out:
Symbiotic stars, Supersoft X sources, novae
Only valid for SN2011fe!

Howell & Fulton

Nearby SNIa

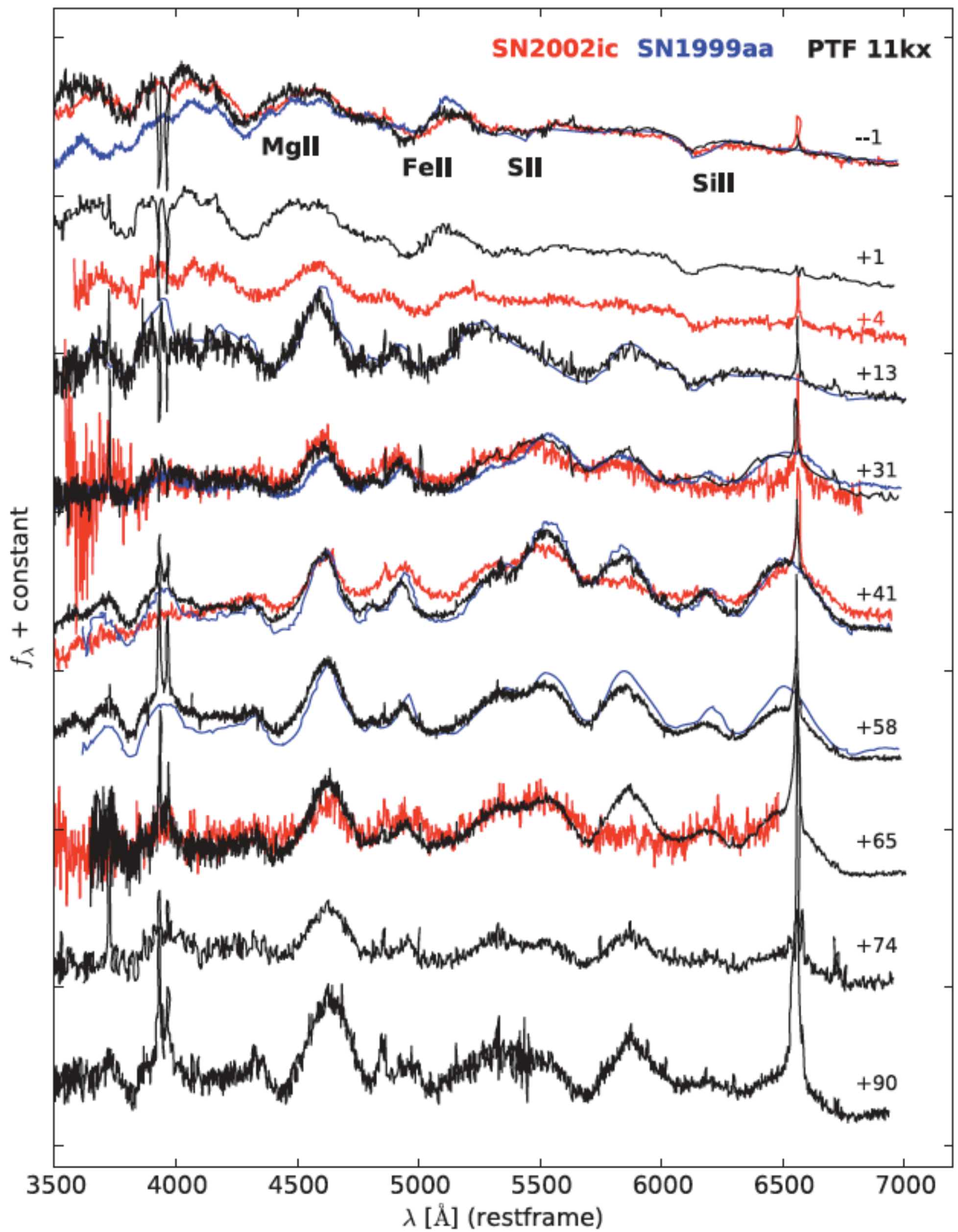
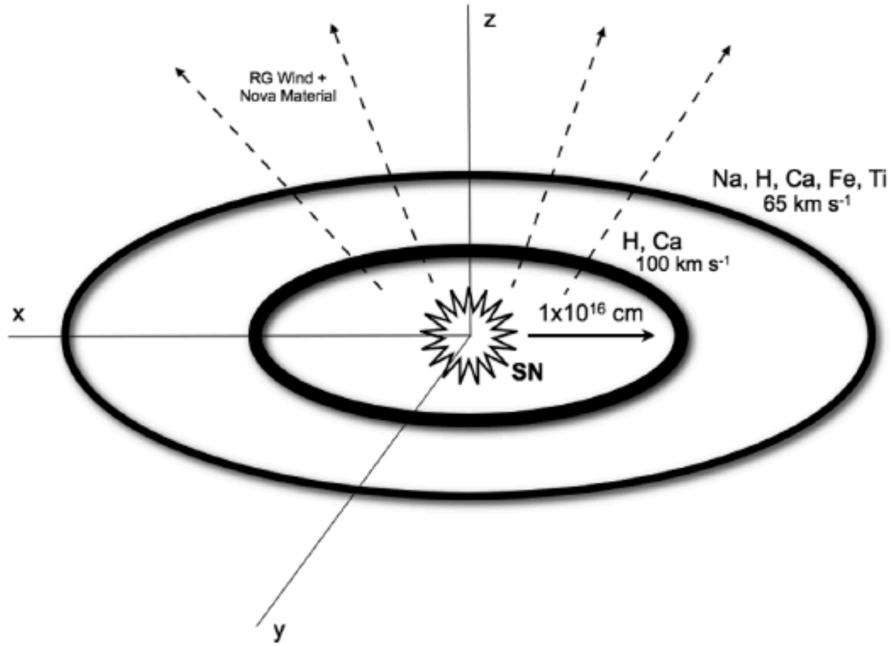


Fig. 1. Comparison of spectra. A temporal series of spectra of PTF 11kx is compared with that of the broad/bright SN 1999aa (*7*) and the CSM interaction SN Ia, SN 2002ic (*16*), all at a similar phase. The location of Mg II, Fe II, S II, and Si II present in the SN ejecta are labeled. The presence of both Si II and S II is a feature seen uniquely in SNe of type Ia.



PTF 11kx

Single Degenerate scenarios

H-accreting white dwarfs

(cataclysmic variables, symbiotic stars, supersoft X-ray sources)

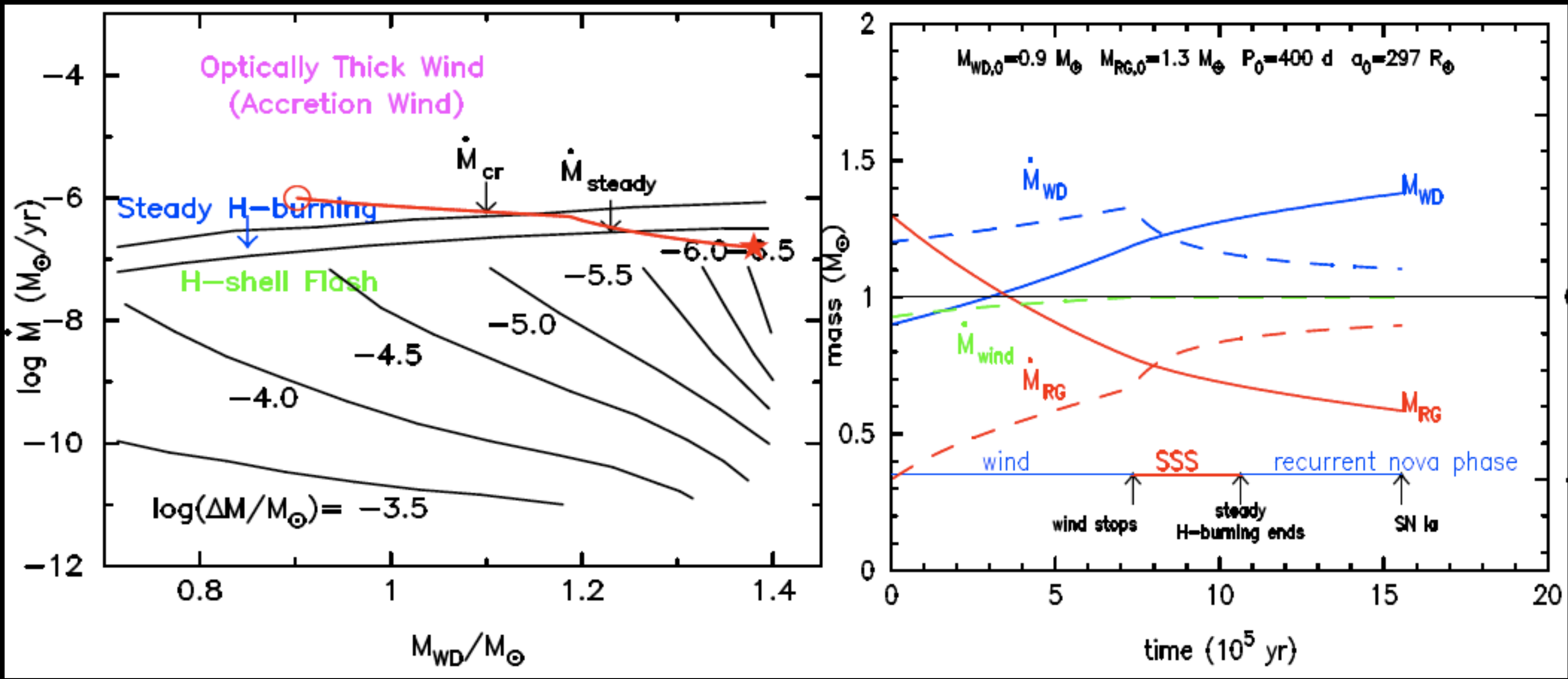
- $dM_H/dt < 10^{-9}$ M_o/yr. Nova explosions. Novae reduce the mass or produce a very inefficient increase of the total mass, except if $M_{WD} >$ 1.2 $M_{o,}$ but they are made of ONe
- 10^{-6} M_o/y $> dM_H/dt > 10^{-9}$ M_o/yr. Hydrogen burns in X-ray flasshes, but produces He at a rate that can ignite under degenerate conditions.
- $M_{Edd} > dM_H/dt > 10^{-6}$ M_o/yr. Formation of a red giant

Unobserved excess of Super Soft X-ray sources?
Contamination by H?
Where is the surviving star?

If all SNIa come from SSS:
MW or M31 need ~ 10^3 sources
Surveys only detected 10 – 50

Possible candidates:
SN2002ic,2005gj: H-emission lines
SN2005ke: thermal X-rays
SN2006X: Na I D lines

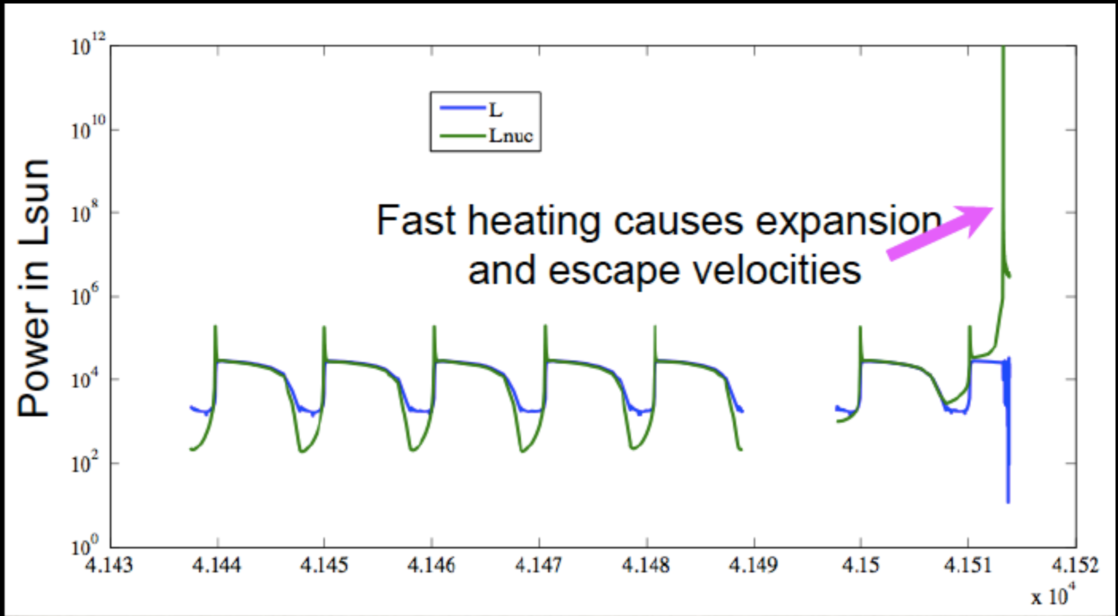
Are they hidden?
Heavy winds appear and form a massive torus of circumstellar material.
If dM/dt changes with time
Eevolutionary paths involving symbiotic/SSS/recurrent novae have been found: Hachisu, Kato & Nomoto'08



But, can recurrent novae reach the Chandrasekhar's mass?

Idan et al'11 claim that recurrent novae eventually eject all the accreted mass

- 1 M_o, $dM/dt \approx 10^{-6}$ M_o/yr ejection after 4000 cycles
- Very fine zoning, treatment of accreted layers are critical



Cycle number

The fast rise is due to helium burning runaway. The H burning is not degenerate. The He is very degenerate

Merger of 0.6+0.8 CO-WD

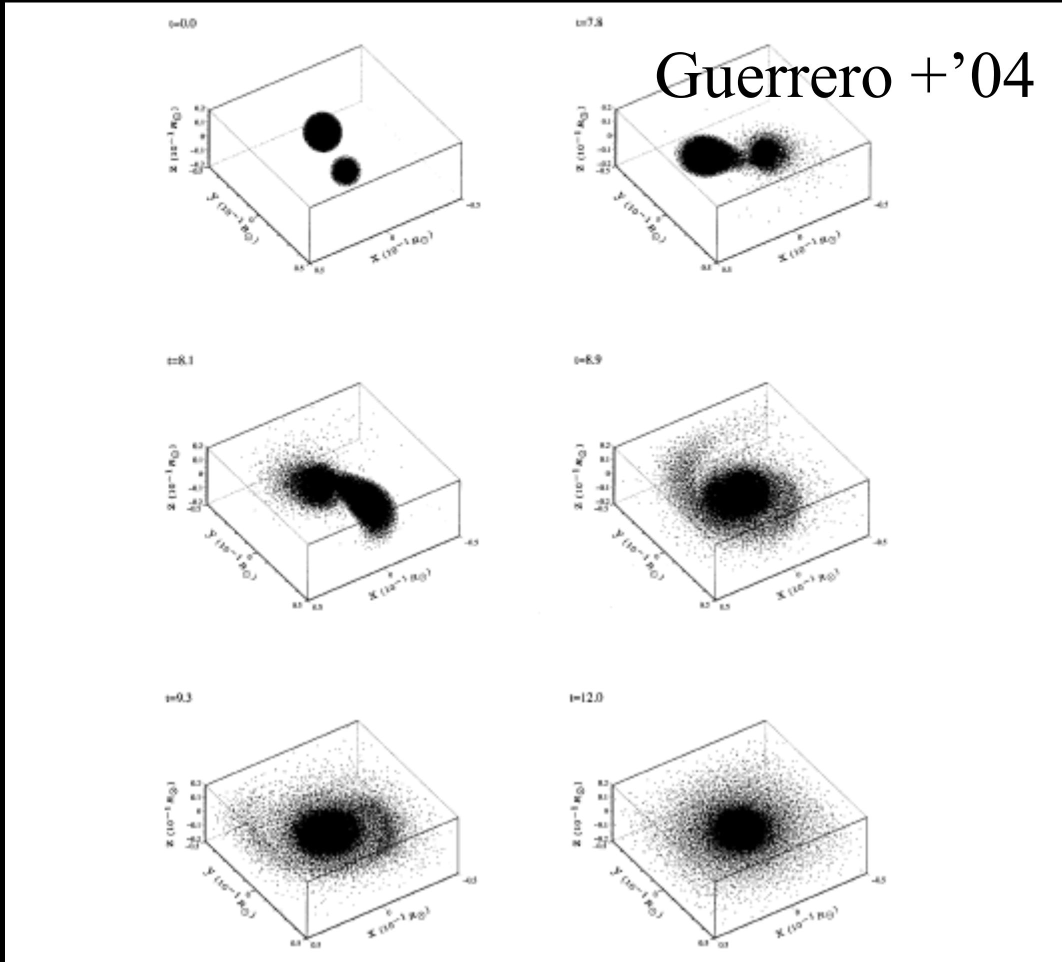


Fig. 1. Temporal evolution of the positions of the SPH particles for the 0.6 + 0.8 $M_{\odot}$ system. Time is shown – in code units – in the upper left corner of each panel.

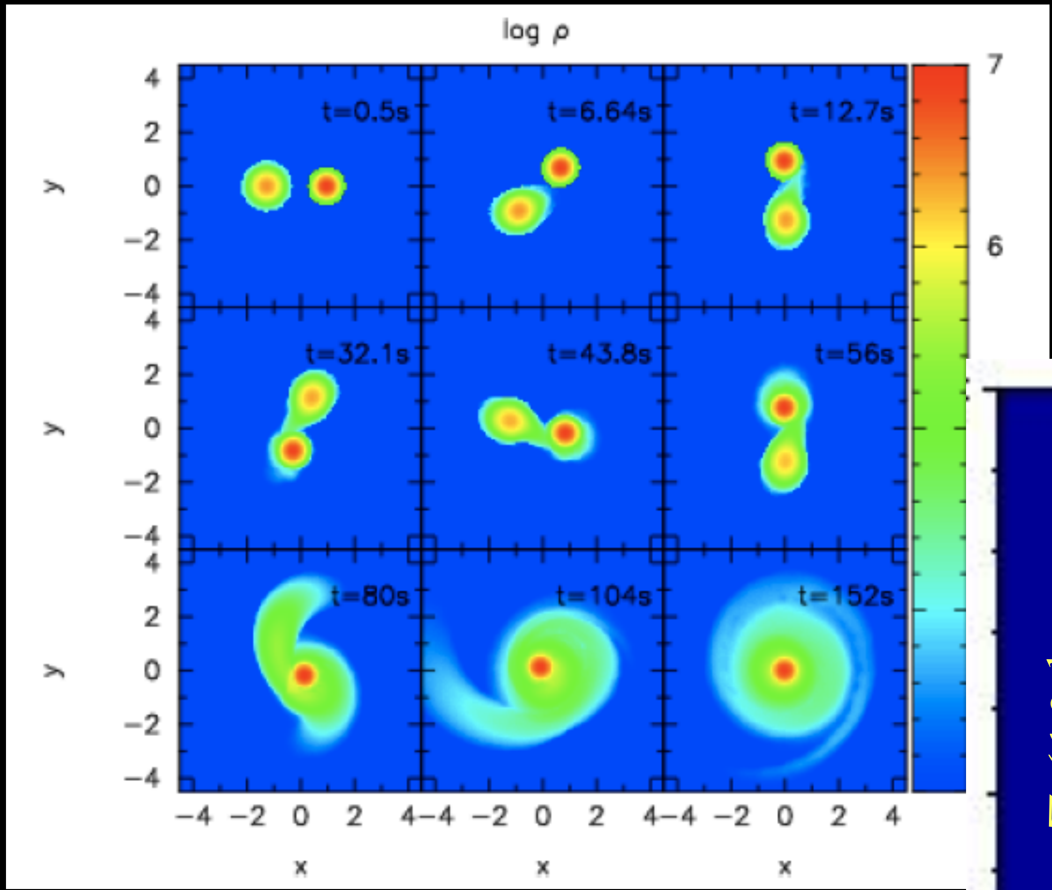
Benz'90
Rasio&Shapiro'94
Segretain +'97
Rosswog +'07

If a < $3R_o$ both WD merge in less than a Hubble time due to the emission of gravitational waves

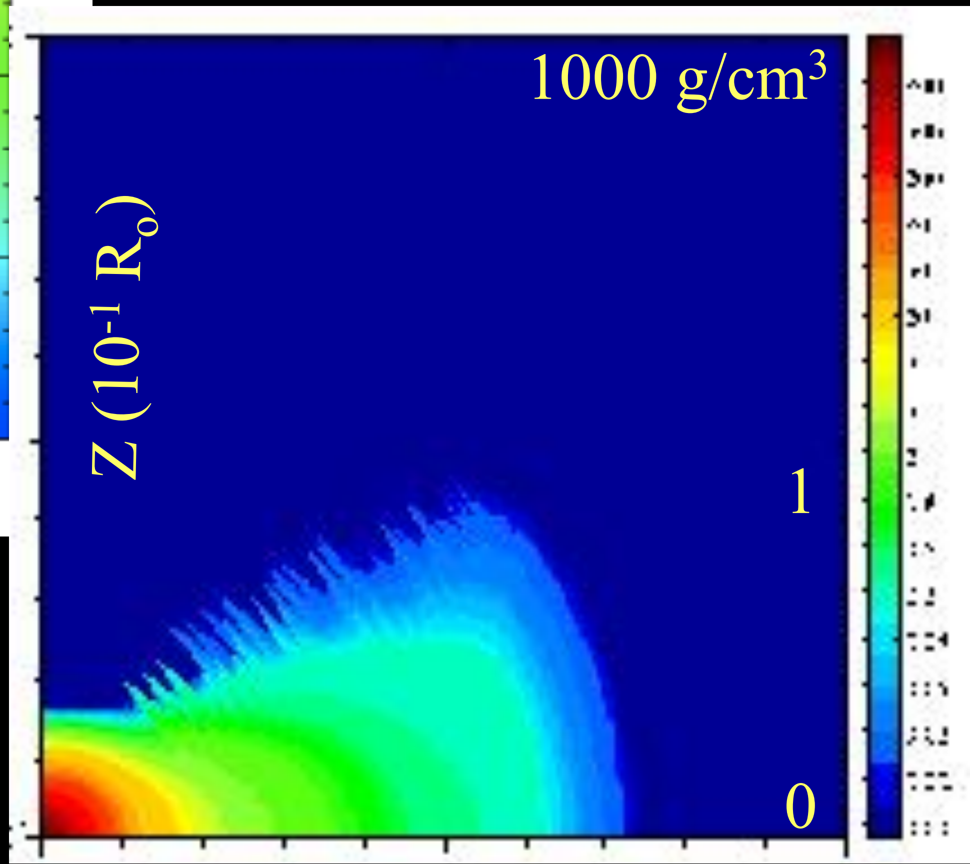
Because of $R \propto M^{-1/3}$ the less massive starts to transfer mass to the most massive

Depending on the mass ratio the merger can be dynamical or self regulated

Merging of 0.6+0.8 Mo WD (Loren-Aguilar+09)



Density profiles of the disk



R (10^{-1} R_o)

Double Degenerate Scenarios

Several DDs able to merge in less than a Hubble time (Napiwotzki et al'04, Badenes et al'11)

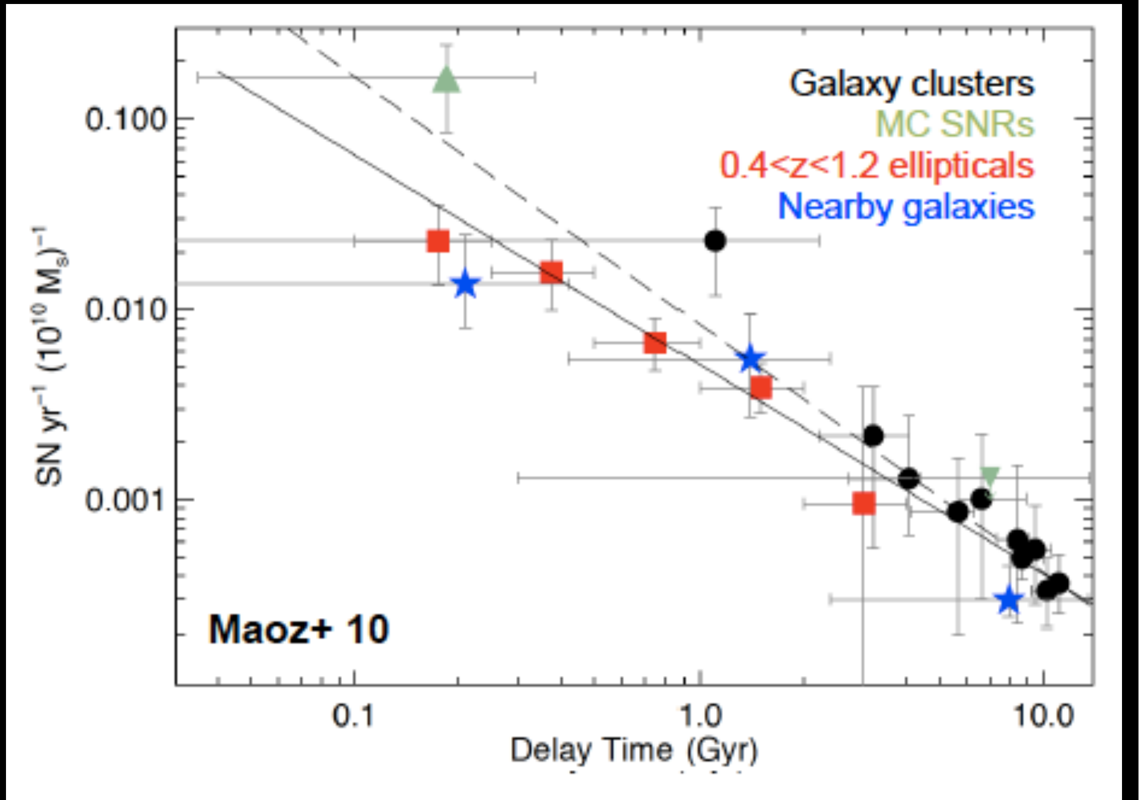
The expected merger rate consistent with the expected SNIa rate (Isern et al'97, Neelemans & Tout'05)

Delay time Distribution (DTD): SNIa rate versus time after a short SF burst

* For t < 1 dispersion of data. Several origins?
* For t > 1 Gyr data consistent with a distribution

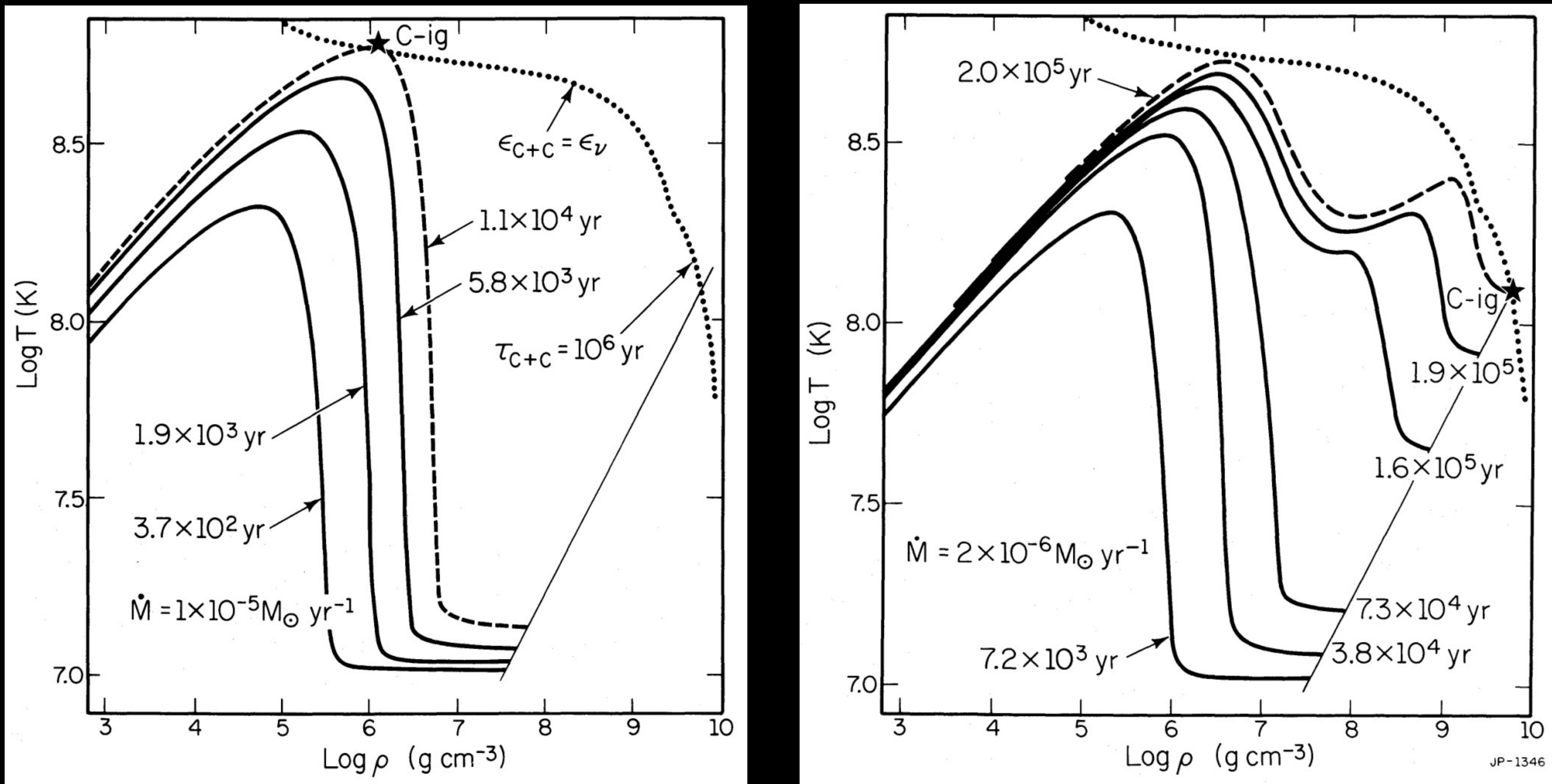
$$\Xi \propto {}^{1}\!/_{t}$$

characteristic of WD merging rate driven by gravitational radiation

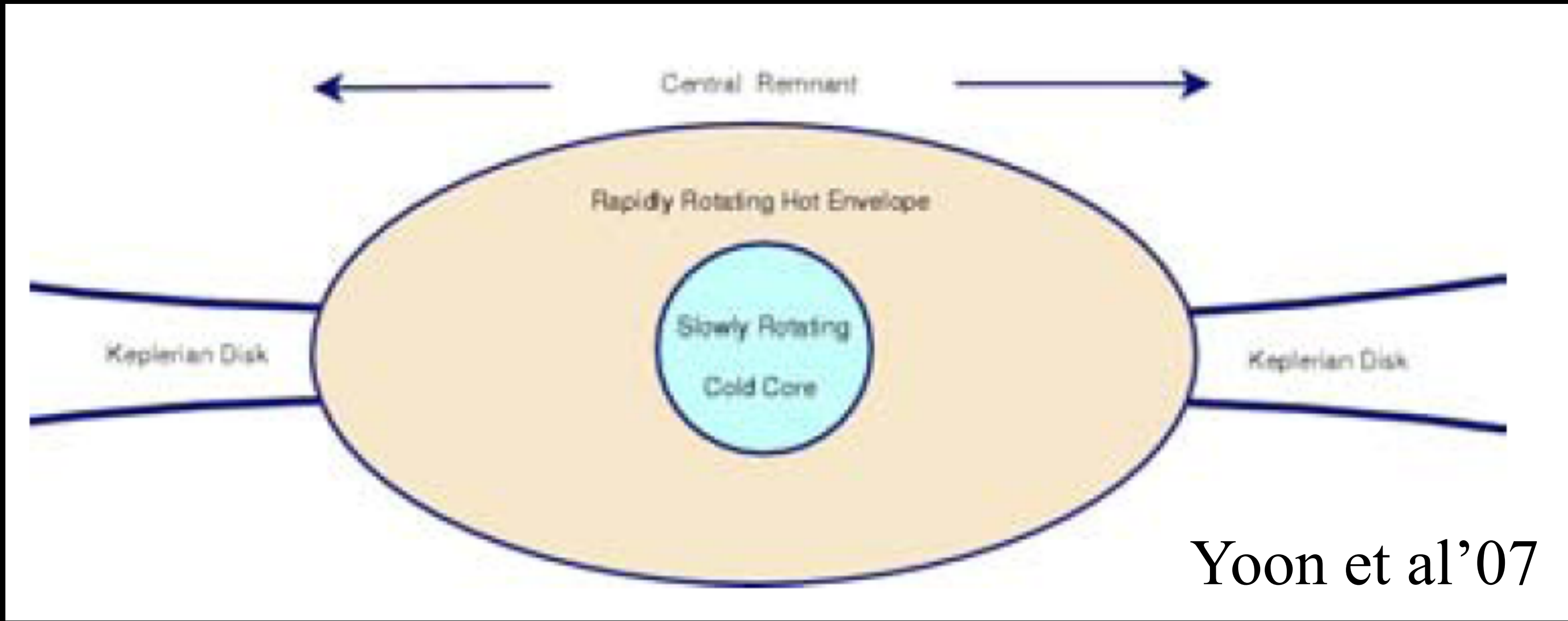


But…

Merging of CO + CO WD



High accretion rates are expected. If they are larger than 2×10^{-6} M_o/yr
C ignites at the surface, flame propagates inwards and a ONeMg WD forms.
The outcome is an AIC (Nomoto & Iben'85, Saio & Nomoto'85, Mochkovitch & Livio'90)



Yoon et al'07

The off-center ignition can be avoided if:

The T_{max} at the interface < T_{ign} when the quasi-static equilibrium is reached

Time scale for angular momentum losses > Time escale for ν-cooling

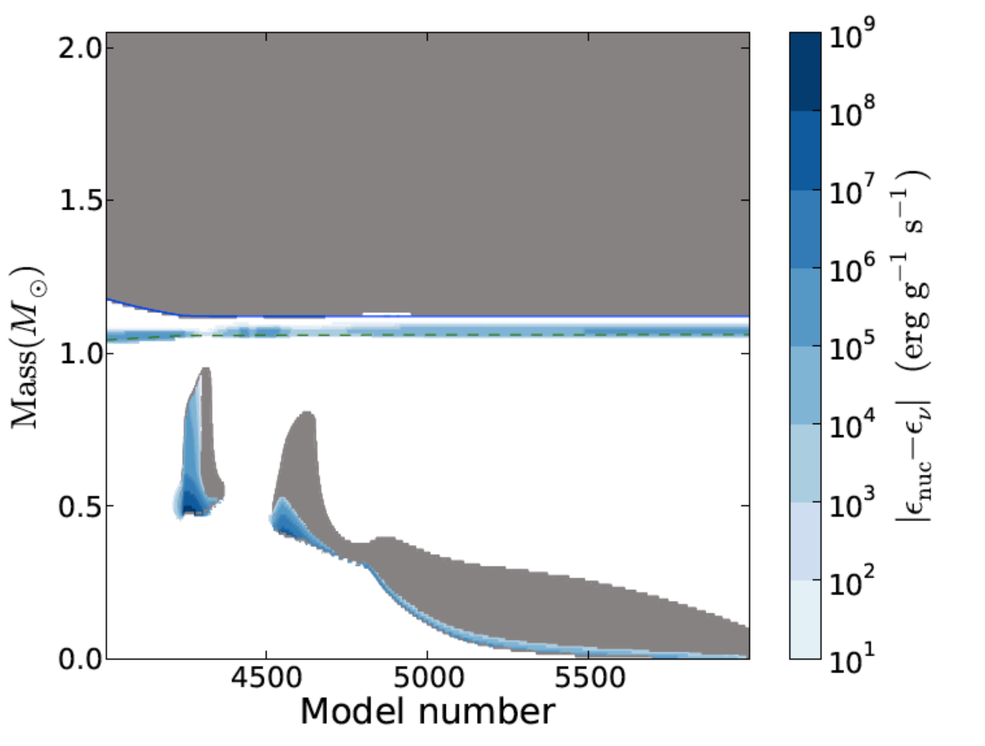
The mass accretion rate dM/dt </~ 5 x 10^{-6} – 10^{-5} M_o/yr

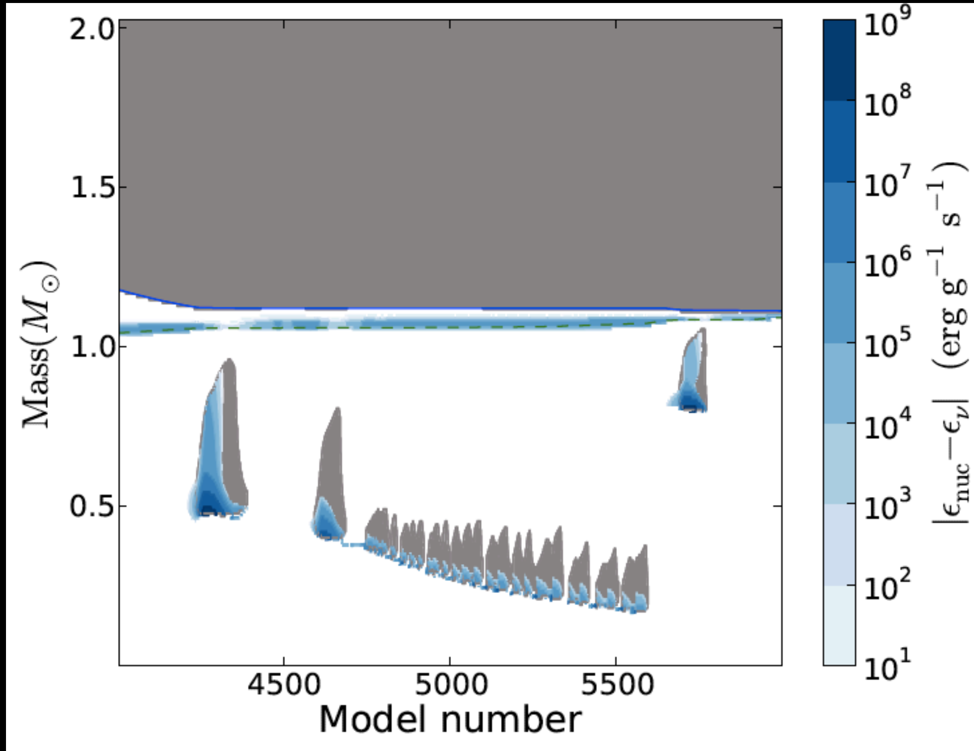
The rapidly rotating envelope and the thick disk produces powerful magnetic fields (Garcia-Berro+'12)

Angular momentum rapidly redistributed and a hot envelop forms. Cools down in a Kelvin Helmholz scale. High accretion rate. Off center C ignition. (Shen +'11)

#Classical Iben & Nomoto problem reproduced!

Evolution of super-AGB stars



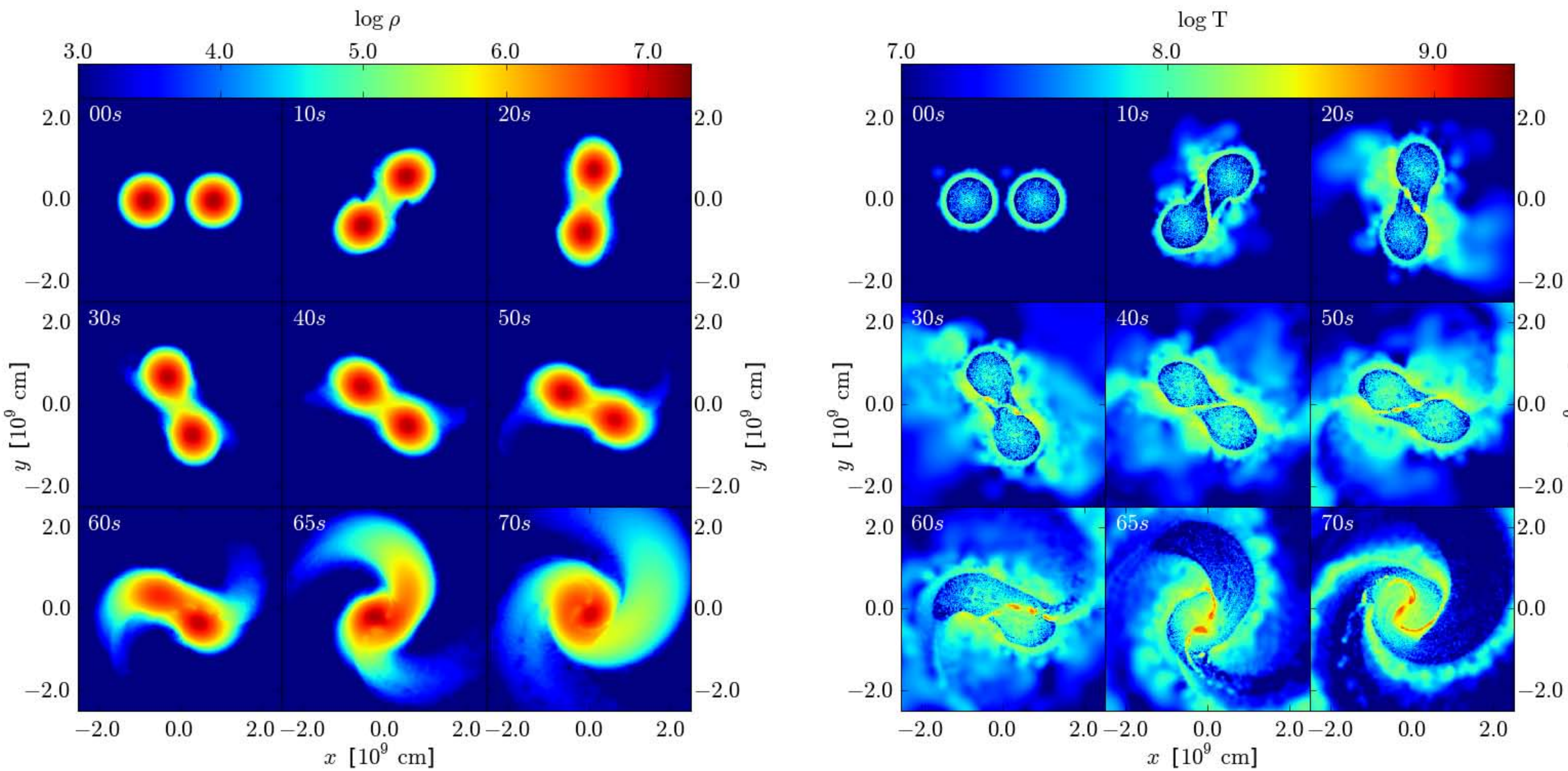


Miyaji & Nomoto ‘80, 84,87
Domínguez+’93
Garcia-Berro,Iben, Rotossa’96-97
Siess’07
Denissenkov+’13

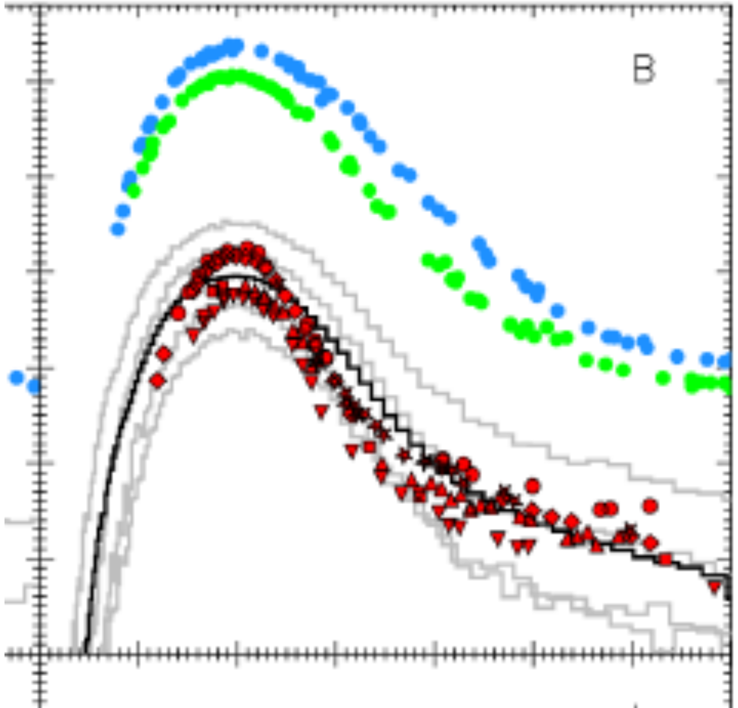
When convective boundary mixing (Glassner+’97,Herwig+’06, Casanova+’11 is included the flame is quenched hybrid CO+ONe +CO structure forms!

What happens in the merging case?

Merger of two WDs of ~ equal mass

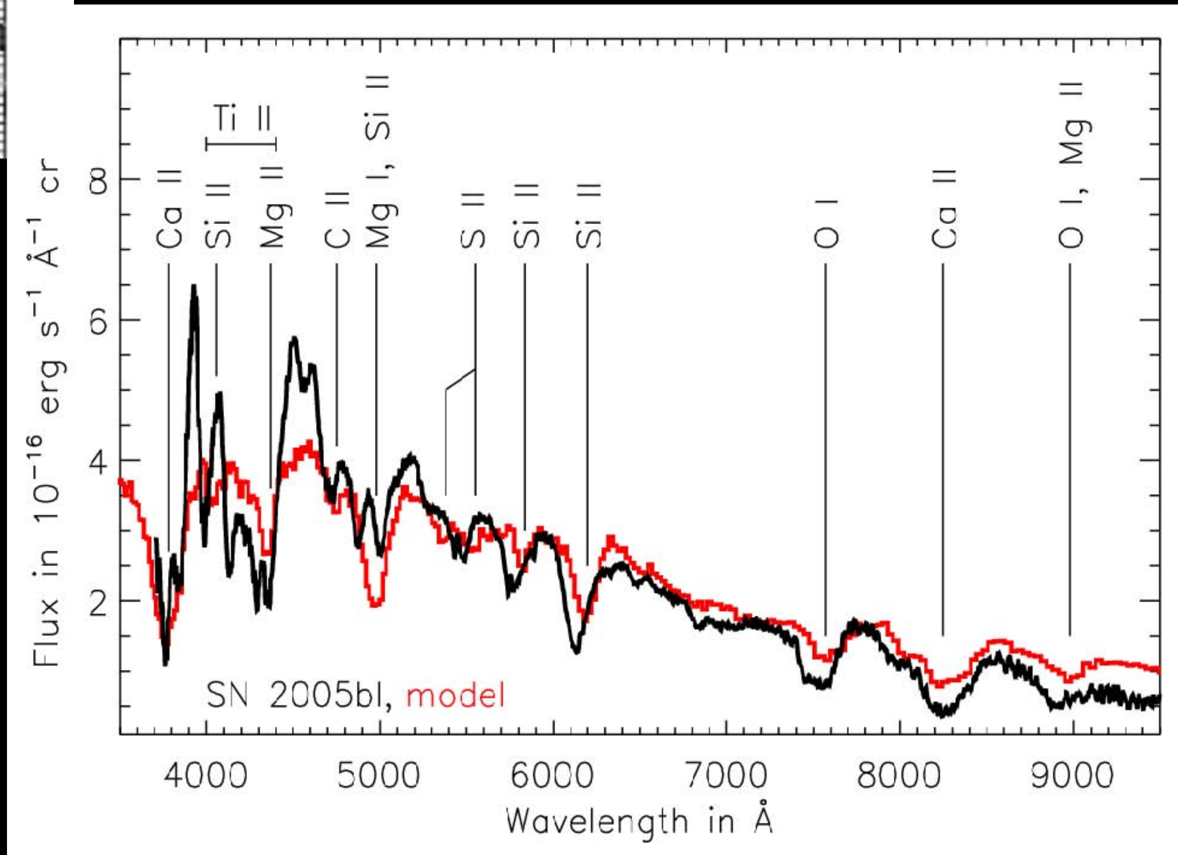


Pakmor et al'10



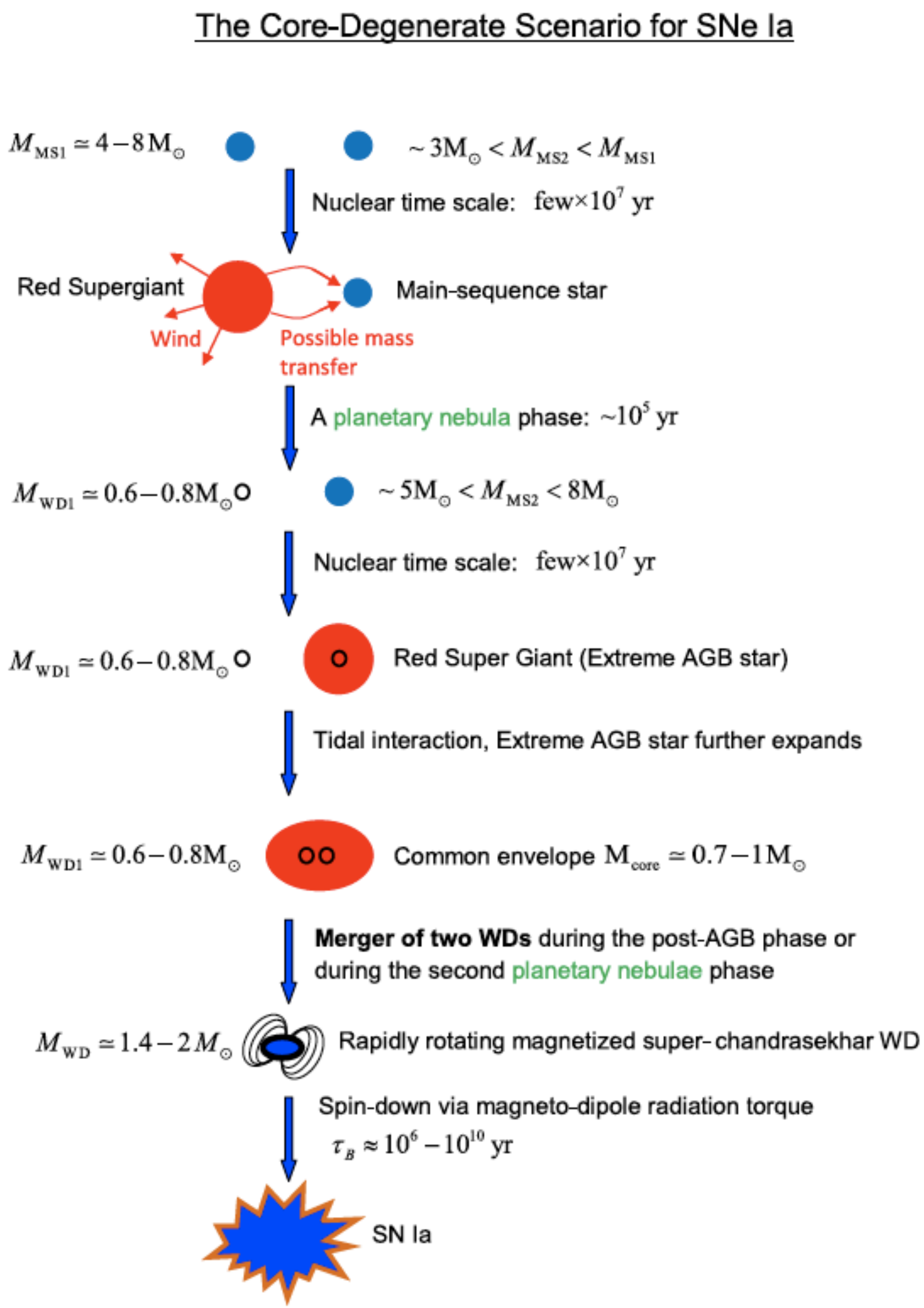
Faint supernovae

Pakmor et al'10



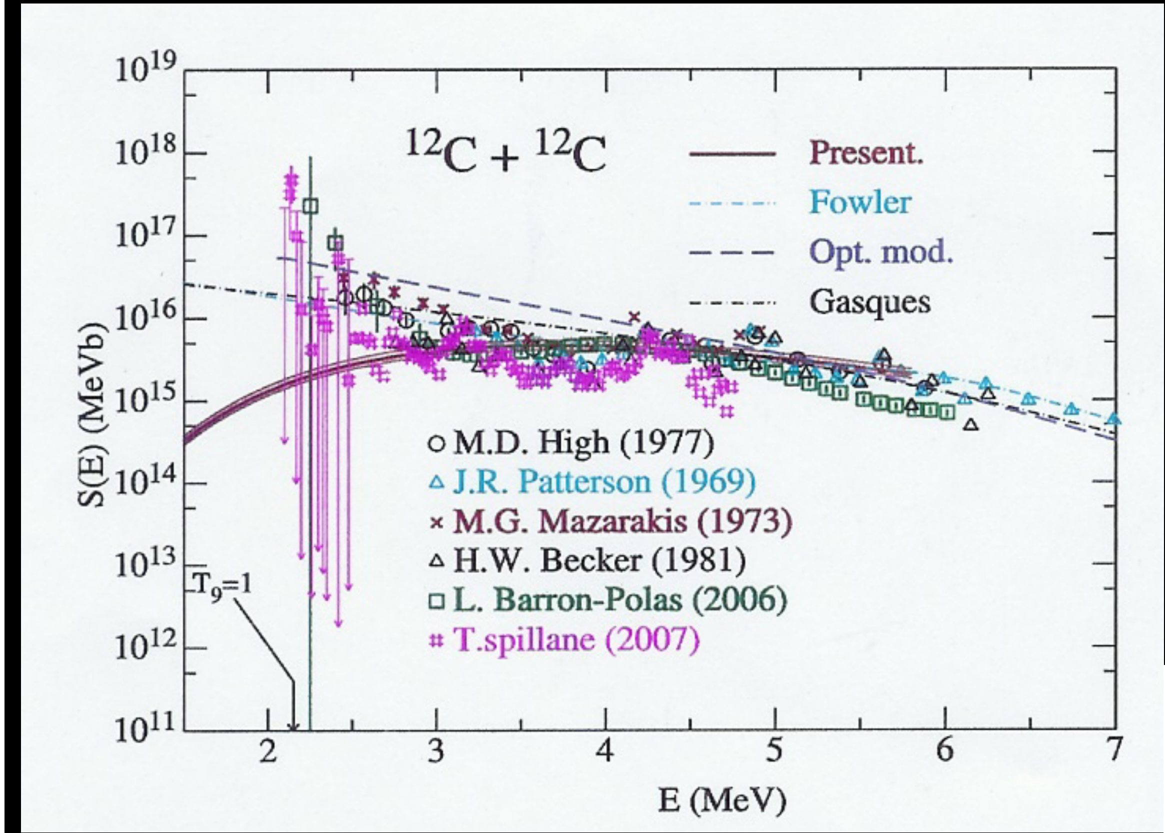
This picture has been challenged by Motl+'02,D'Souza+'06, Motl'07. They claim that the prompt capture was an artifact due to initial conditions.

Effectively, if both stars are allowed to relax to the quasiequilibrium conditions before the beginning of mass transfer, they can survive for many orbits before merging (Rosswog+,09, Dan+'11, Loren-Aguilar+'11)

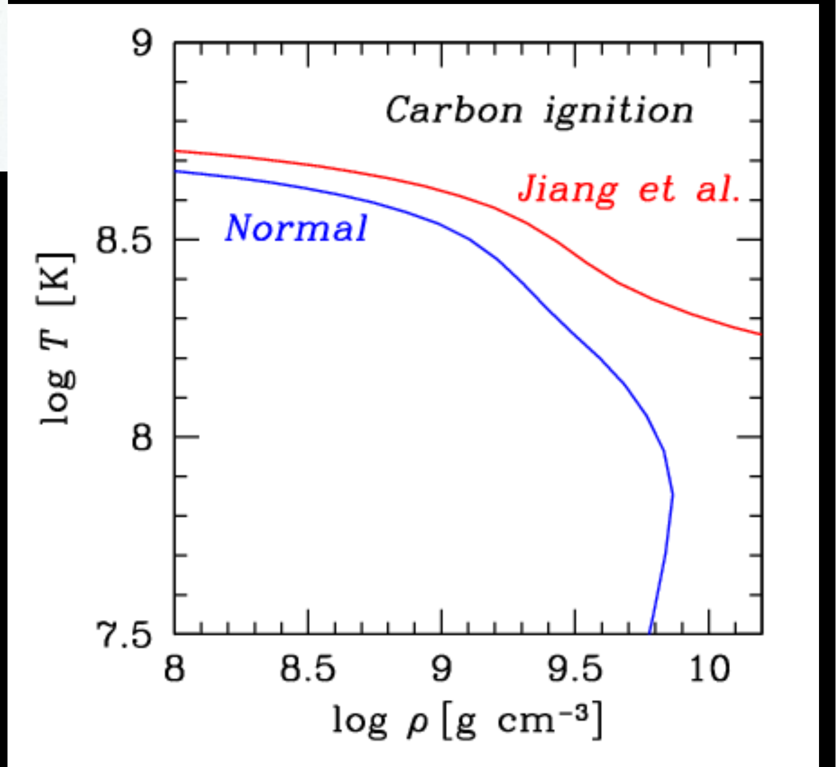


Ilkov & Soker'11)

$^{12}C + {}^{12}C$ fusion



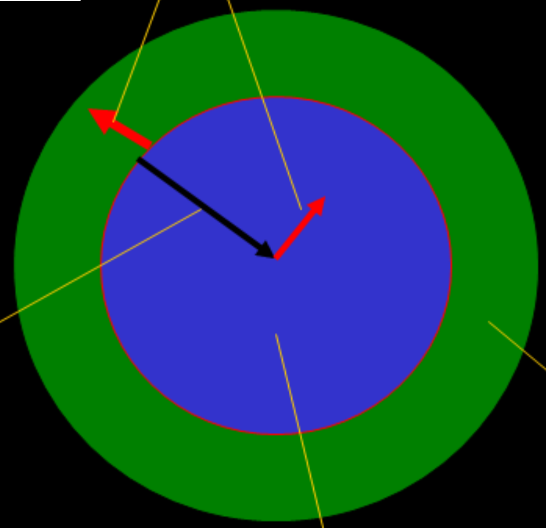
From
Gasques et al'07
Jiang'10, NPA5



See Bravo+'12 for a discussion on resonances

Exploding mechanisms: Off center ignition

Merging of CO + He WD

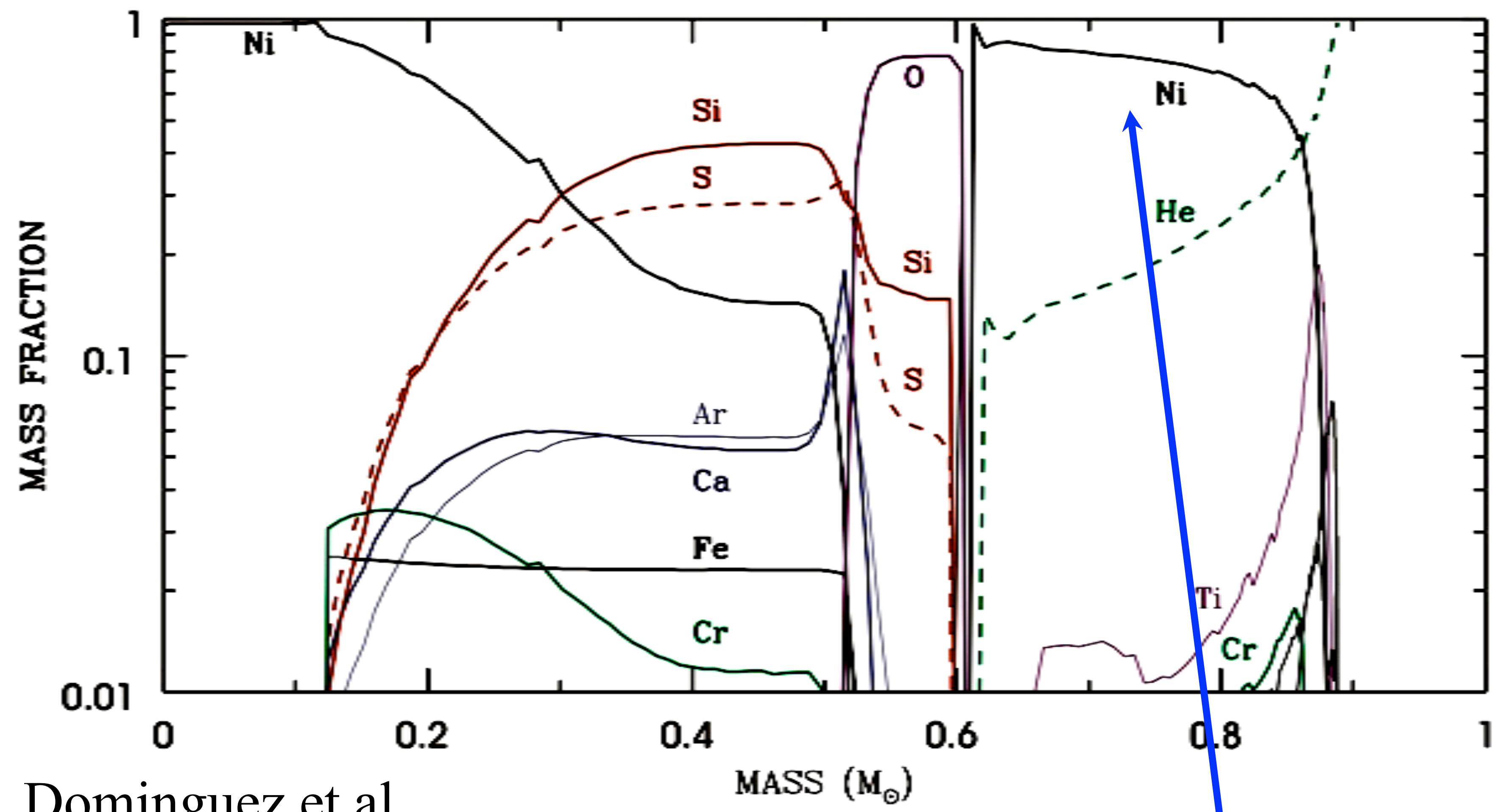


CO + He WD/He star
For dM/dt = 1 to 5 10^{-8} Mo/yr, He ignites off-center before reaching the Chandrasekhar's mass
$\Delta M_{He} = 0.05 - 0.1\ M_o$

He detonation occurs if $\rho > 2 \cdot 10^6$ g/cm^3 and the T profile is flat enough.

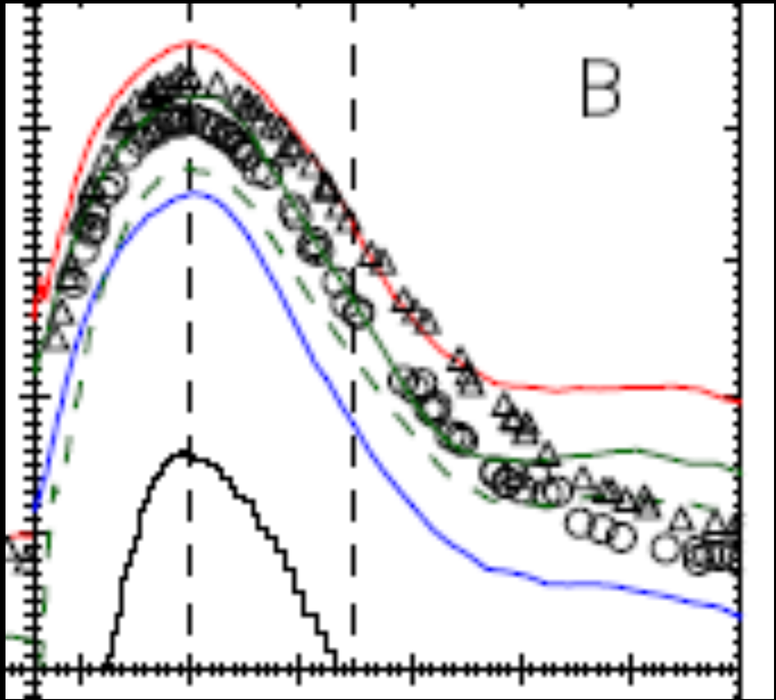
- He deflagration: Faint transients
- Single He detonation
- Double detonation

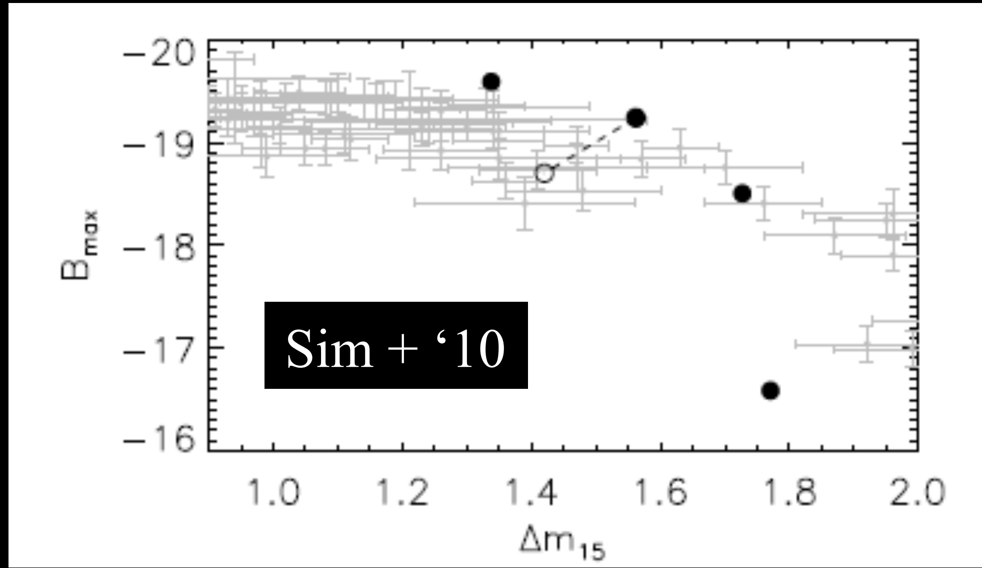
Merging of CO + He WD

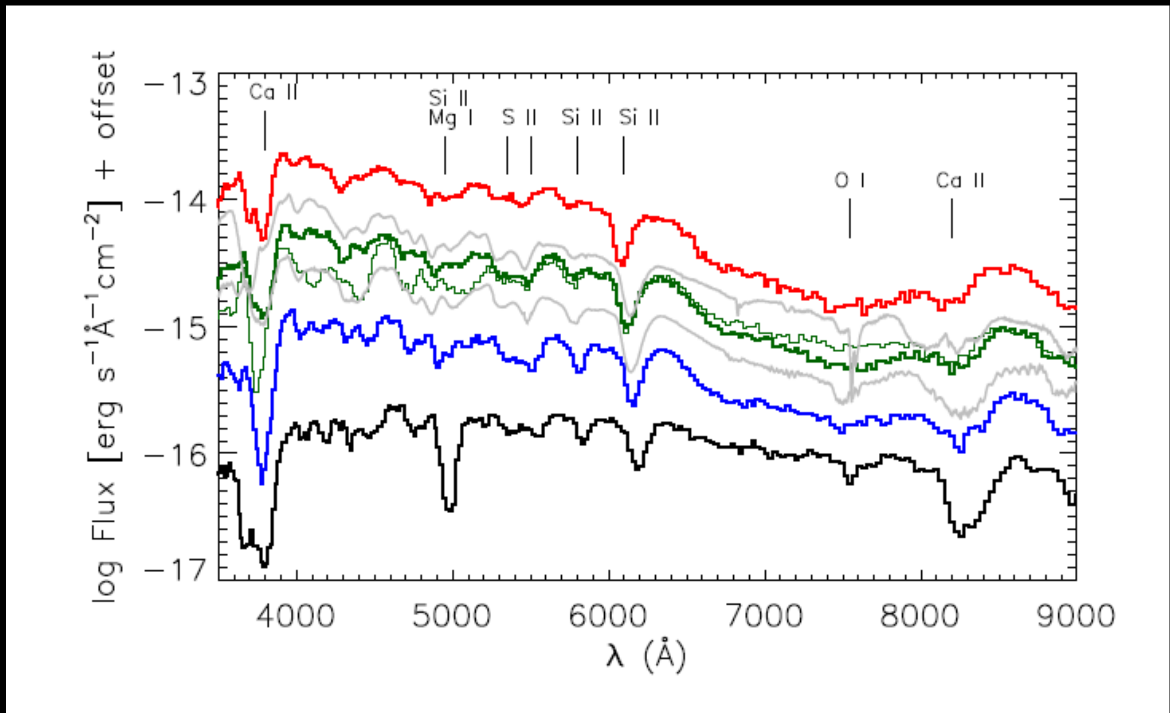


Dominguez et al

Inconsistent with observations



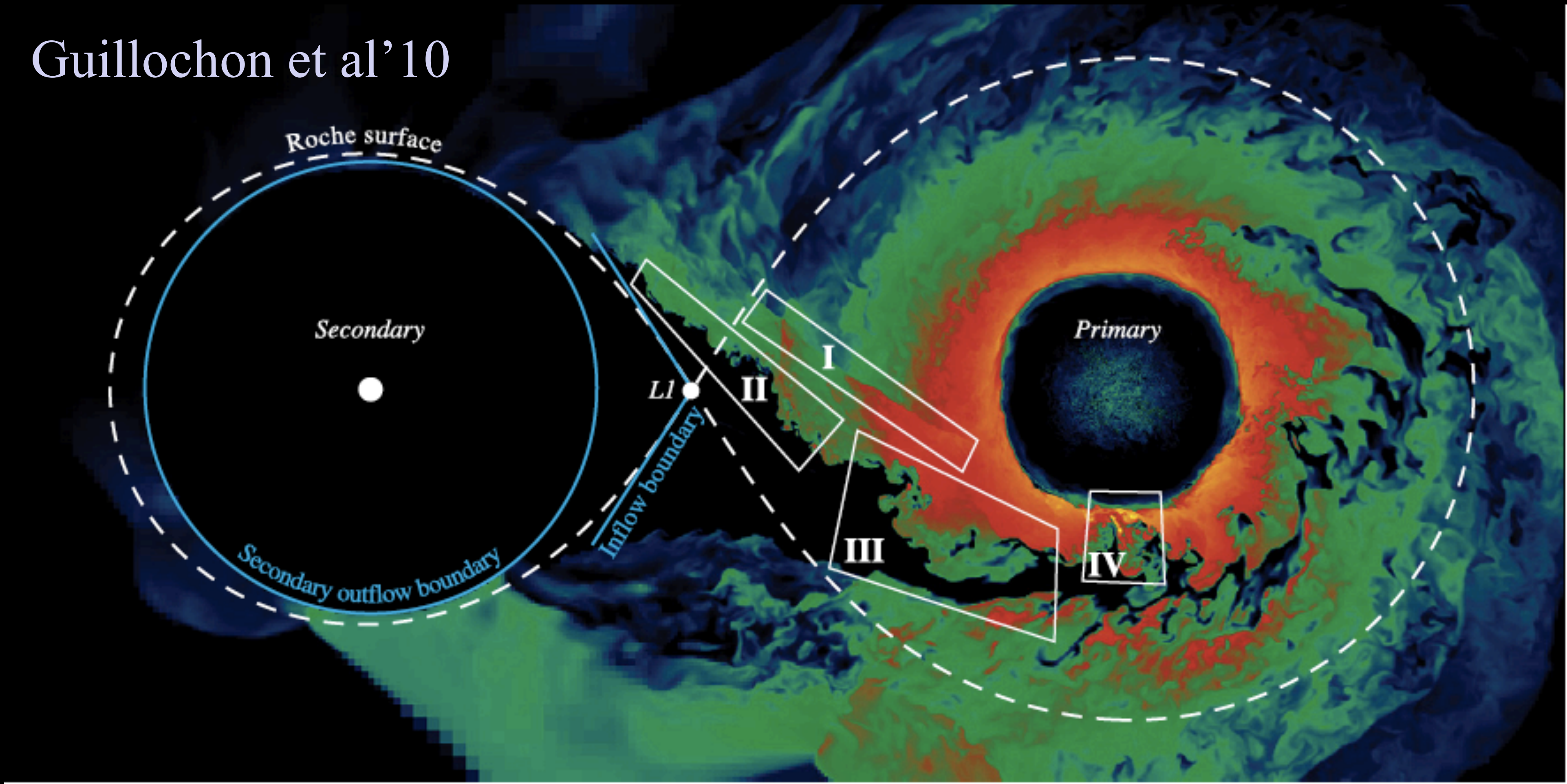




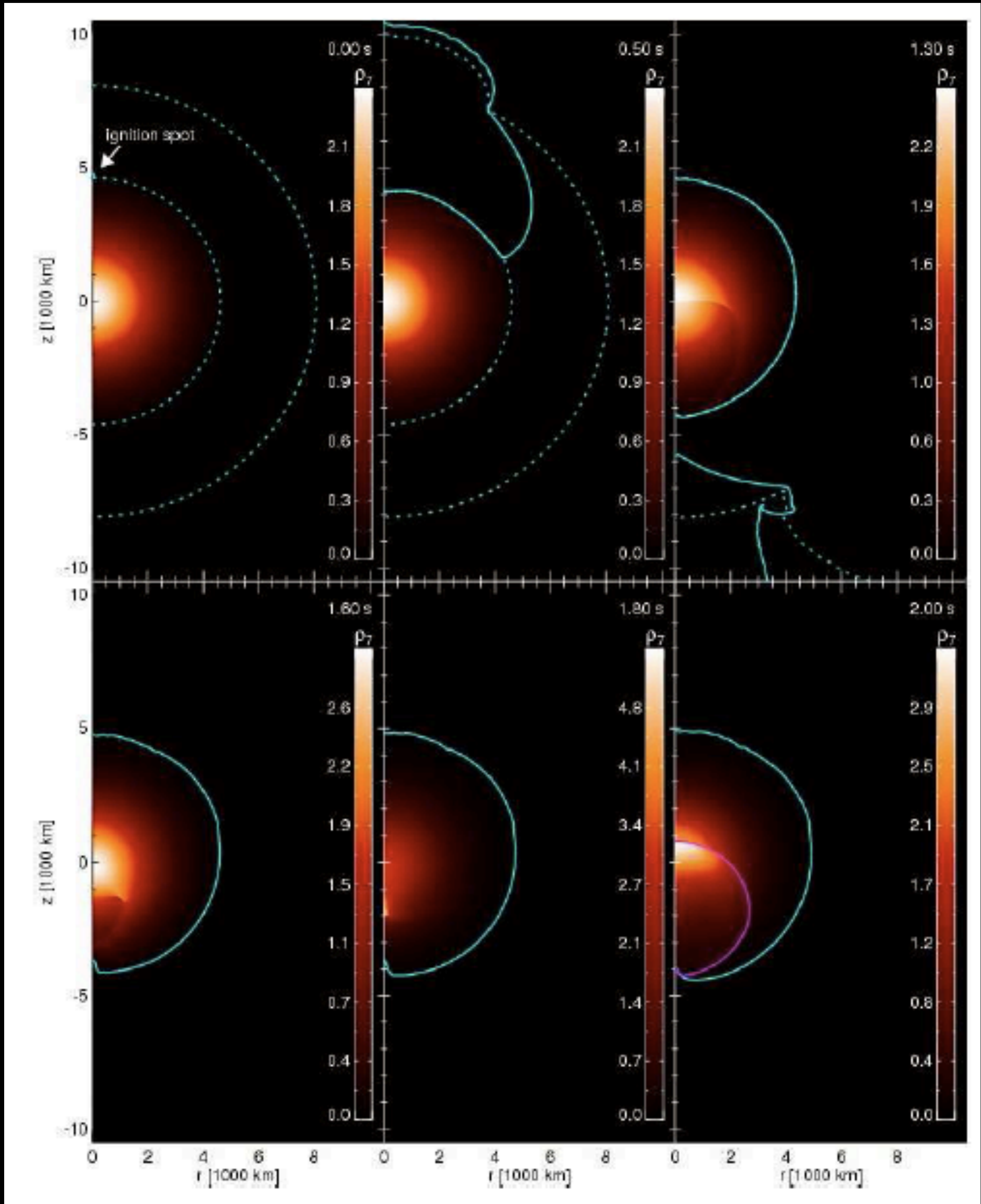
He-detonation

Artificially suppressing the effects of the outer layers

Guillochon et al'10



The detailed process of formation of the He envelope is critical Guillochon et al'2010
Hot spots can trigger the detonation of He

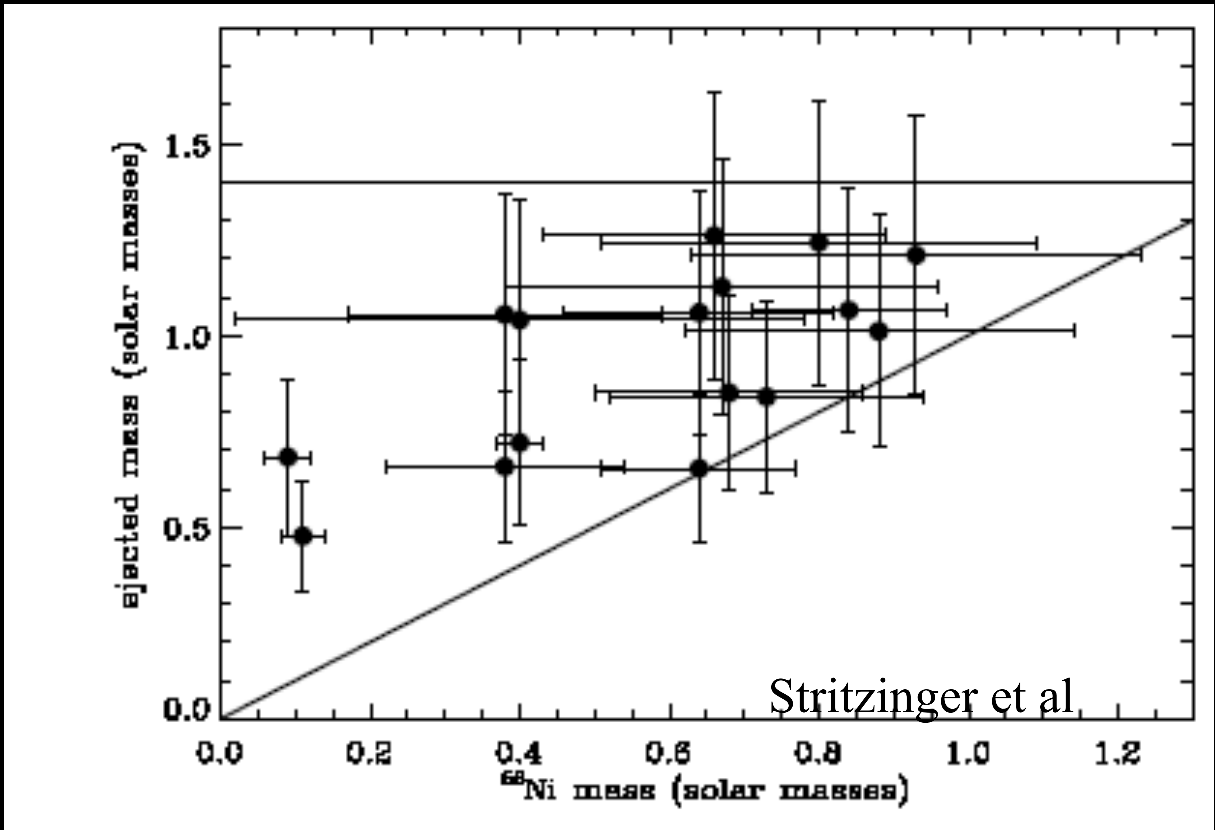


0.00 s
0.50 s
1.30 s
1.60 s
1.80 s
2.00 s
ignition spot
z [1000 km]
r [1000 km]

Fink et al'11

Properties of the light curve:

The mass & distribution of Ni is poorly known

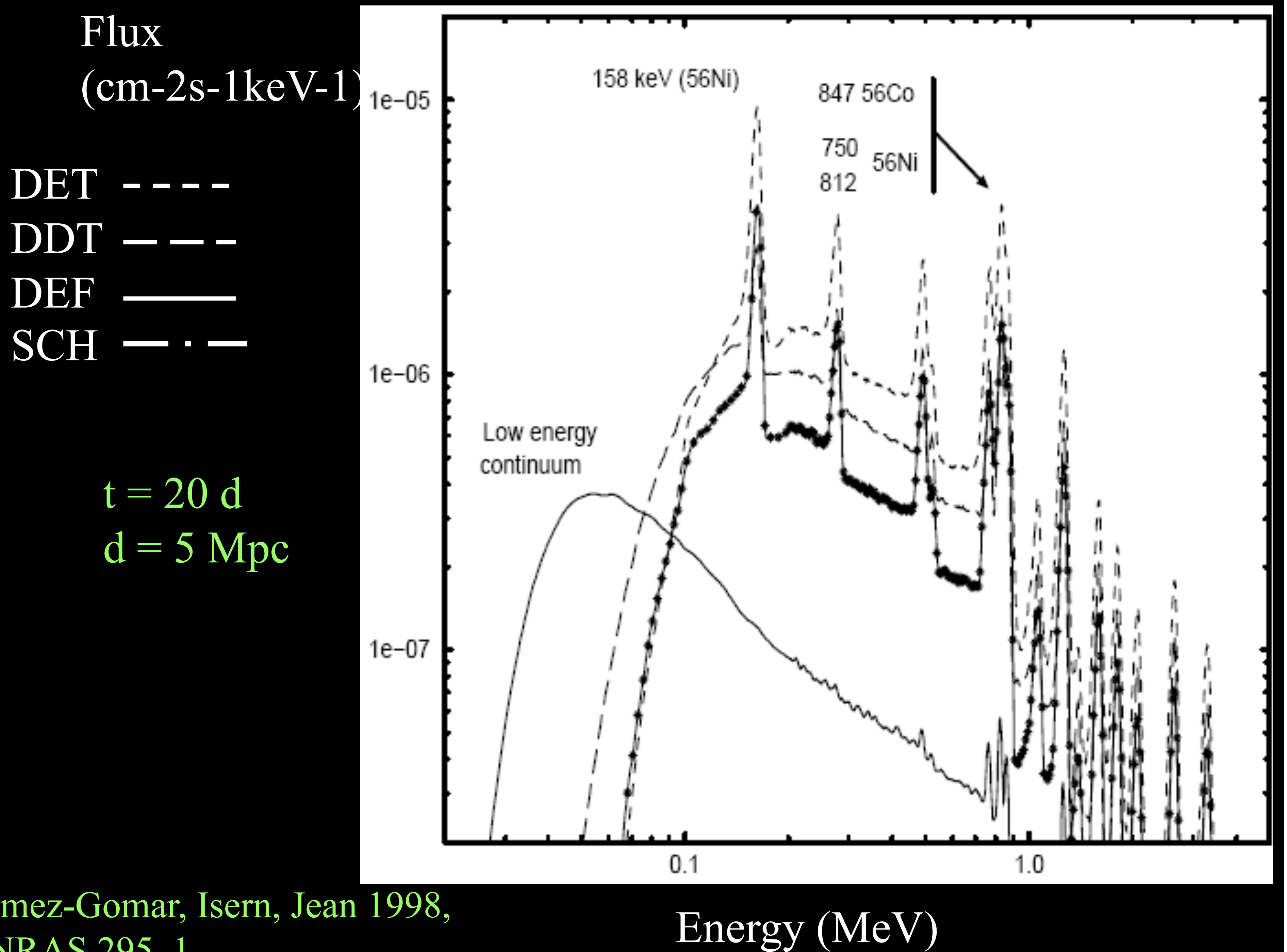


The luminosity at maximum:

$L \sim f\, M_{Ni} \exp(-t_p/t_{Ni})$

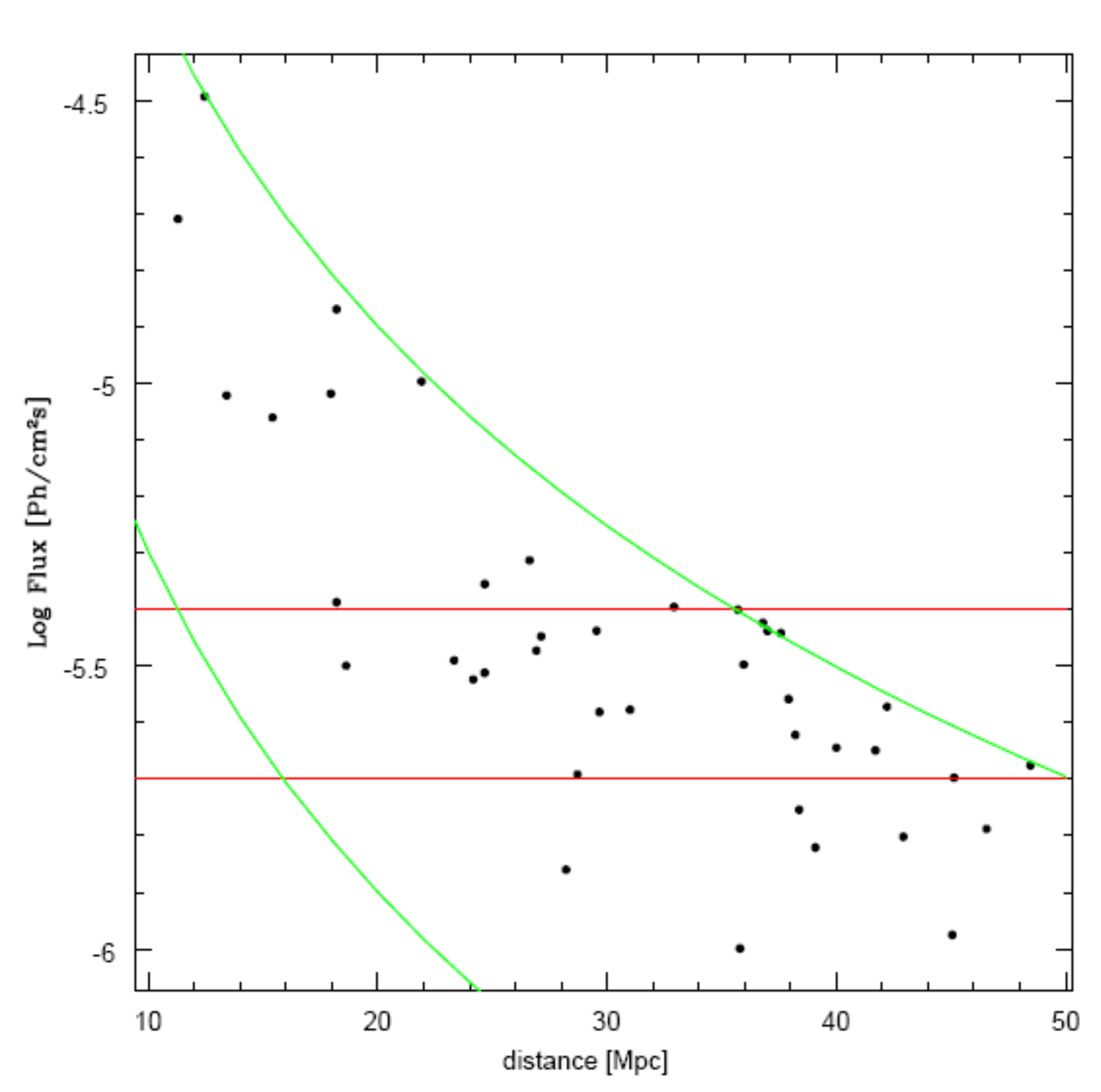
The width depends on the diffusion time:

$t_d \sim \Phi_{Ni}\, \kappa^{1/2}\, M^{3/4}\, E_K^{\;-1/4}$



Gómez-Gomar, Isern, Jean 1998,
MNRAS 295, 1

Broad lines ~ 35 keV



Conclusions:

#New perspectives to the classical problem:

- which systems explode?
- why they explode?
- how they explode?

Nevertheless, substantial advances in the observational properties:

- New indications about the properties of the parent population
- Surveys have identified events that shake the old paradigm
- New evidences about the geometry of the flame

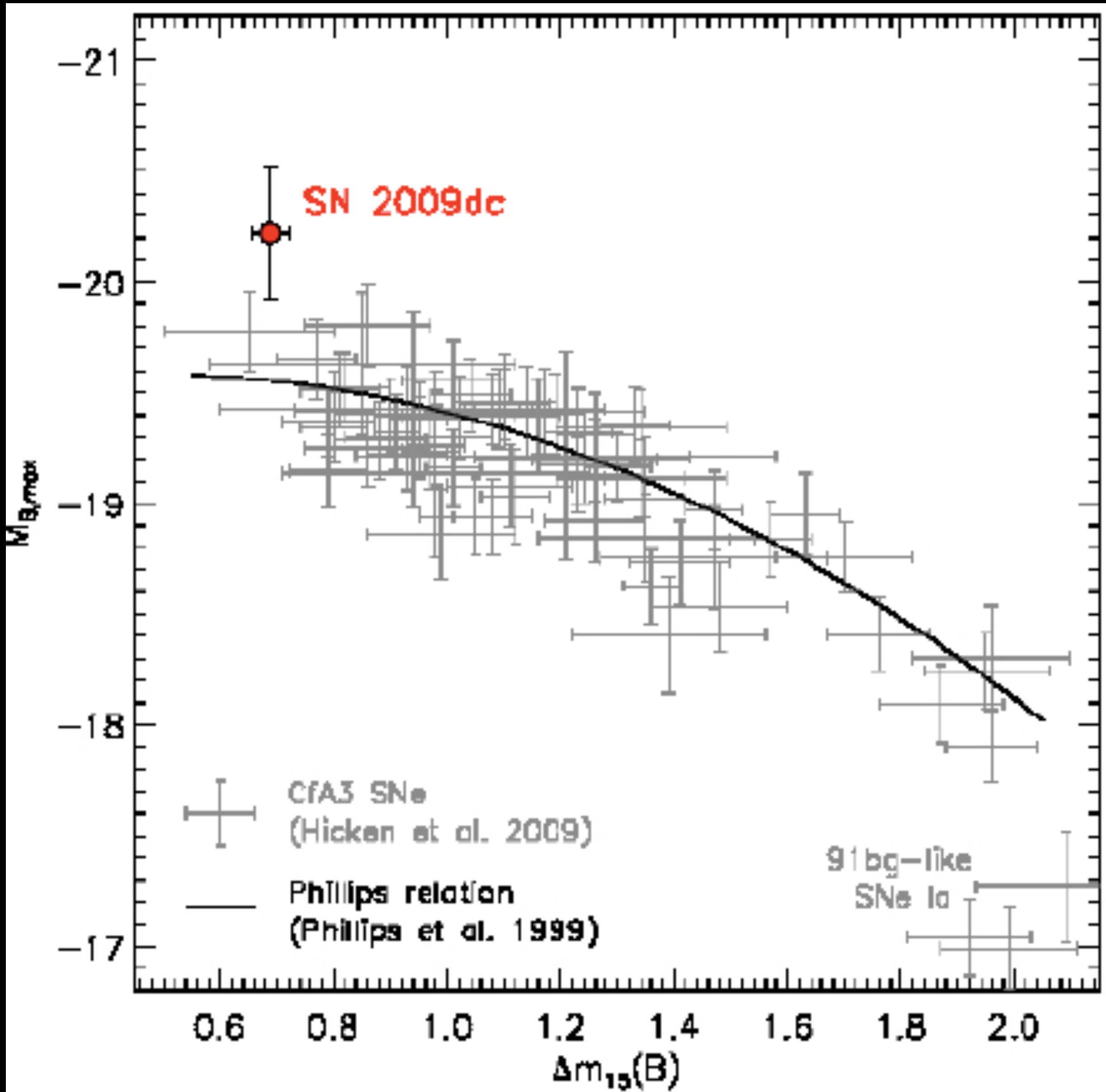
Substantial advances in modelling the phase prior to ignition are necessary

#Gamma-rays allow to determine the total amount of 56Ni and provide constraints to its distribution.

A statitsically representative sample of SNIa must be observed

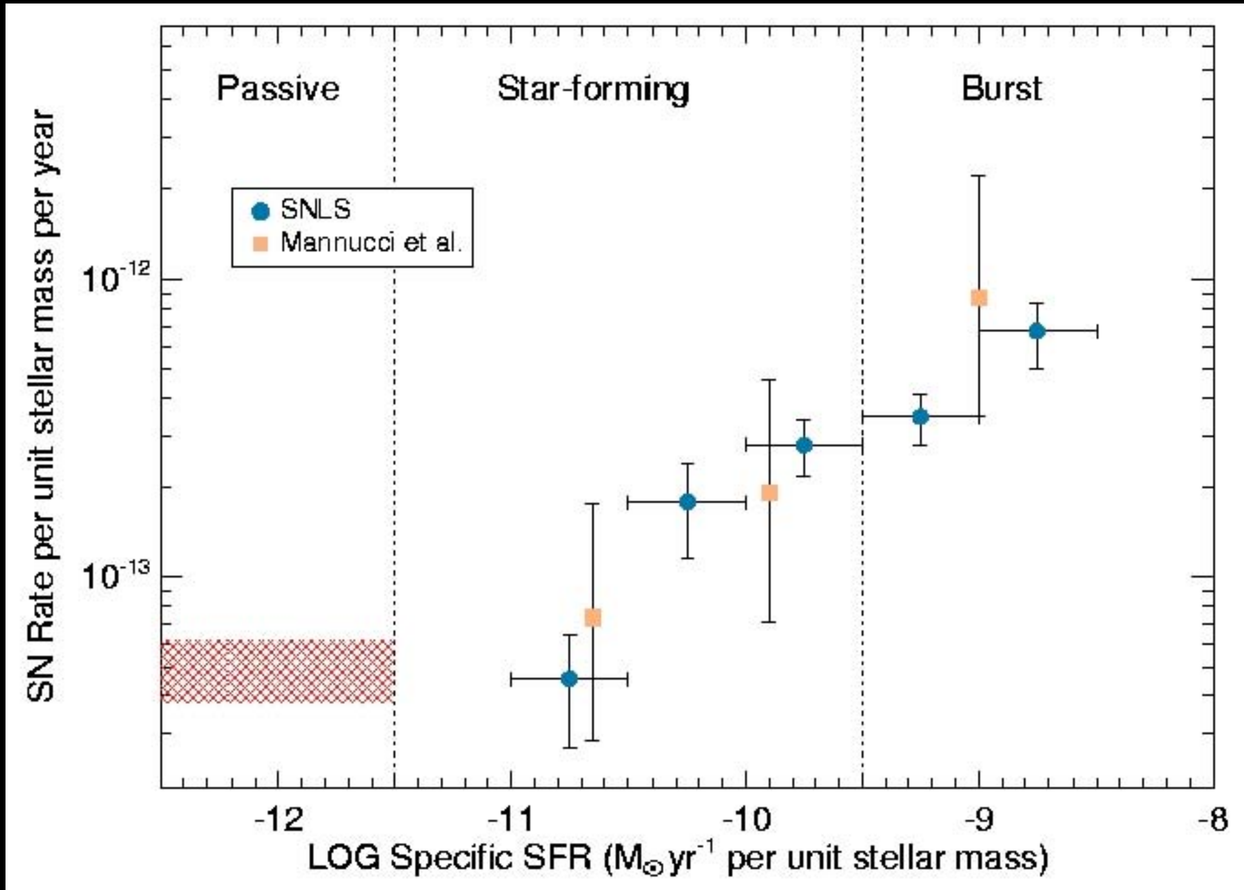
The necessay sensitivity is challenging:

$(\sim 10^{-5.5}\ cm^{-2}\ s^{-1} / 35\ keV \sim 10^{-7}\ cm^{-2}\ s^{-1}\ keV^{-1})$



SN 2009dc
CfA3 SNe
(Hicken et al. 2009)
Phillips relation
(Phillips et al. 1999)
91bg-like
SNe Ia
$M_{B,max}$
$\Delta m_{15}(B)$
−21
−20
−19
−18
−17
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

- Rate in spirals correlates with star formation rate (prompt component)
- Persistent rate among passive (elliptical) galaxies (delayed component)

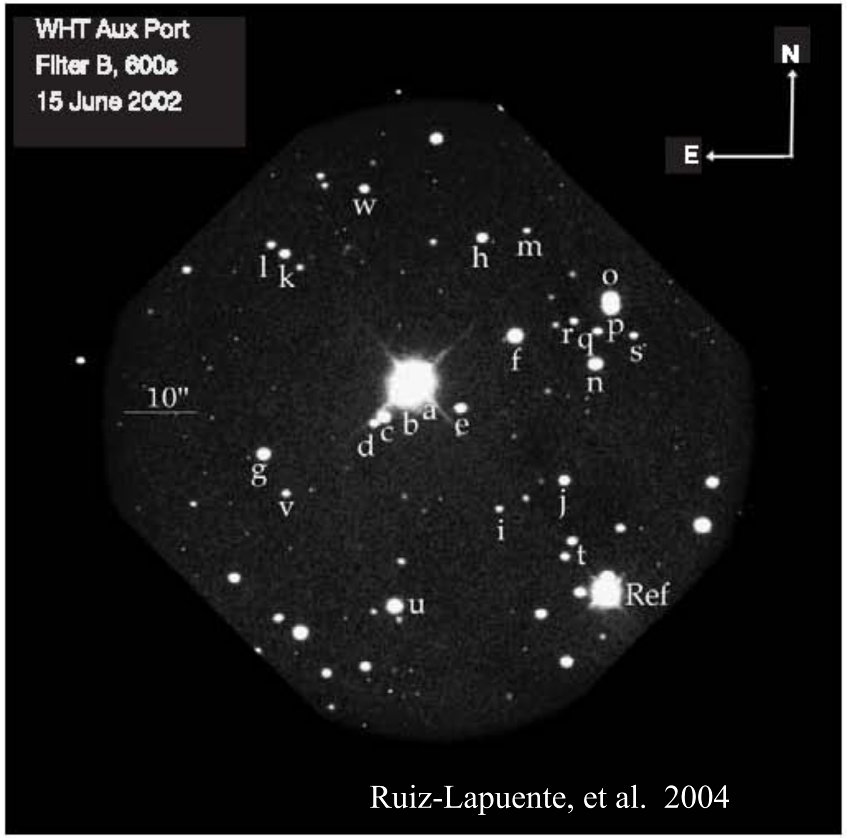


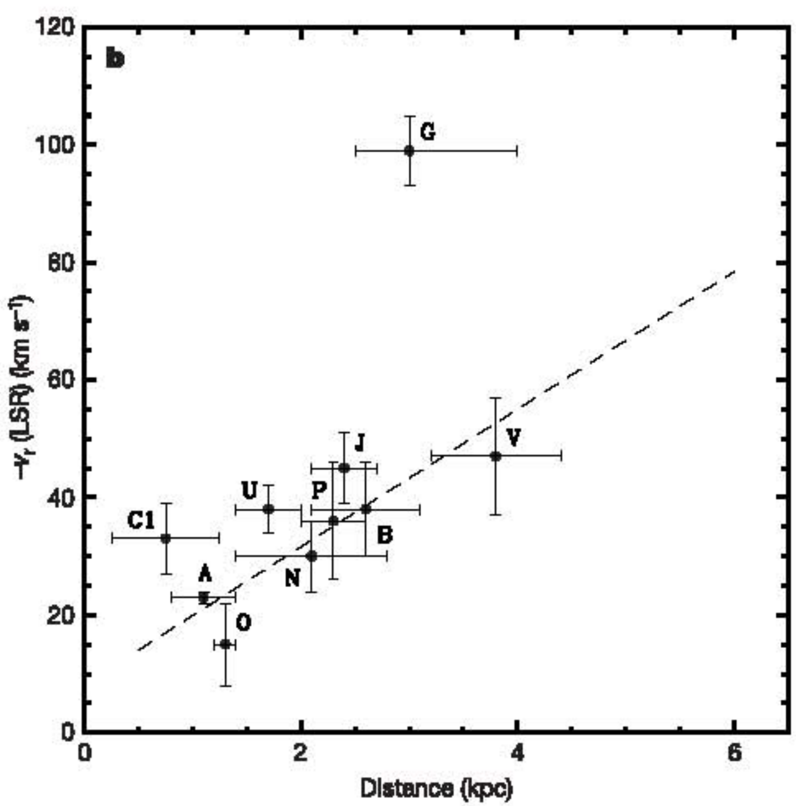
Sullivan et al. 2006

At a first glance both scenarios SD & DD can coexist!
Everything able to explode eventually do it

What prevents the explosion? or Why we do not see it?

Tycho (SN1572) Companion?





The G star is a G2 subgiant with a velocity 3X the velocity at that distance (Ruiz.Lapuente+'04)
Chemical abundances consistent with being contaminated by the explosion (Gonzalez-Hernandez+'09
Slow rotator (GH09, Kerzendorf'09). Not consistent with a Roche-lobe filling donor
Fuhmann'05 suggest a thic disk star passing a 3 kpc

Where is the missing star?

SNR 0509-65.5
Credit: J. Hugues/NASA
Hubble telescope
Chandra X-ray (green)
400 yr old

The companion, if any,
must be very faint

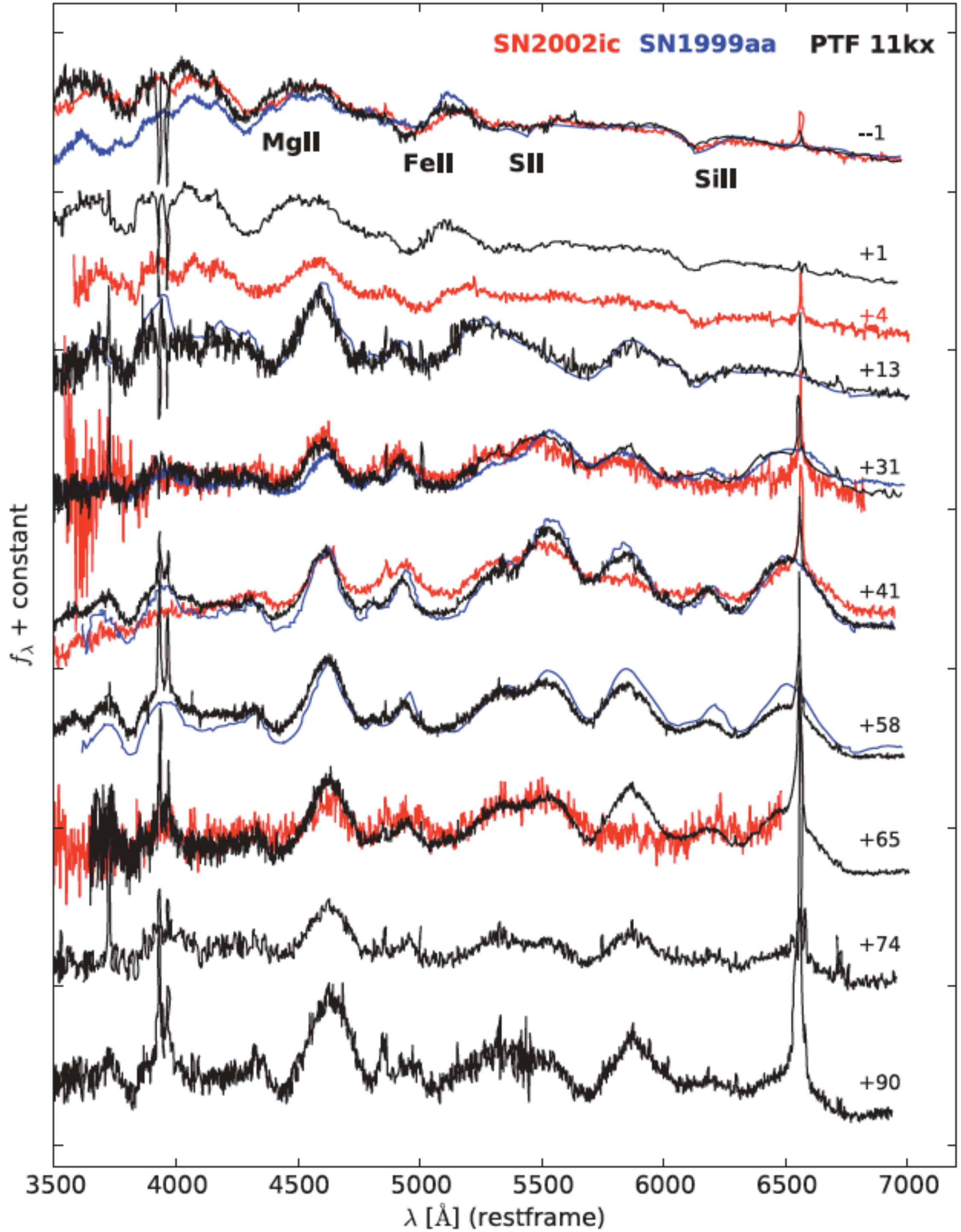
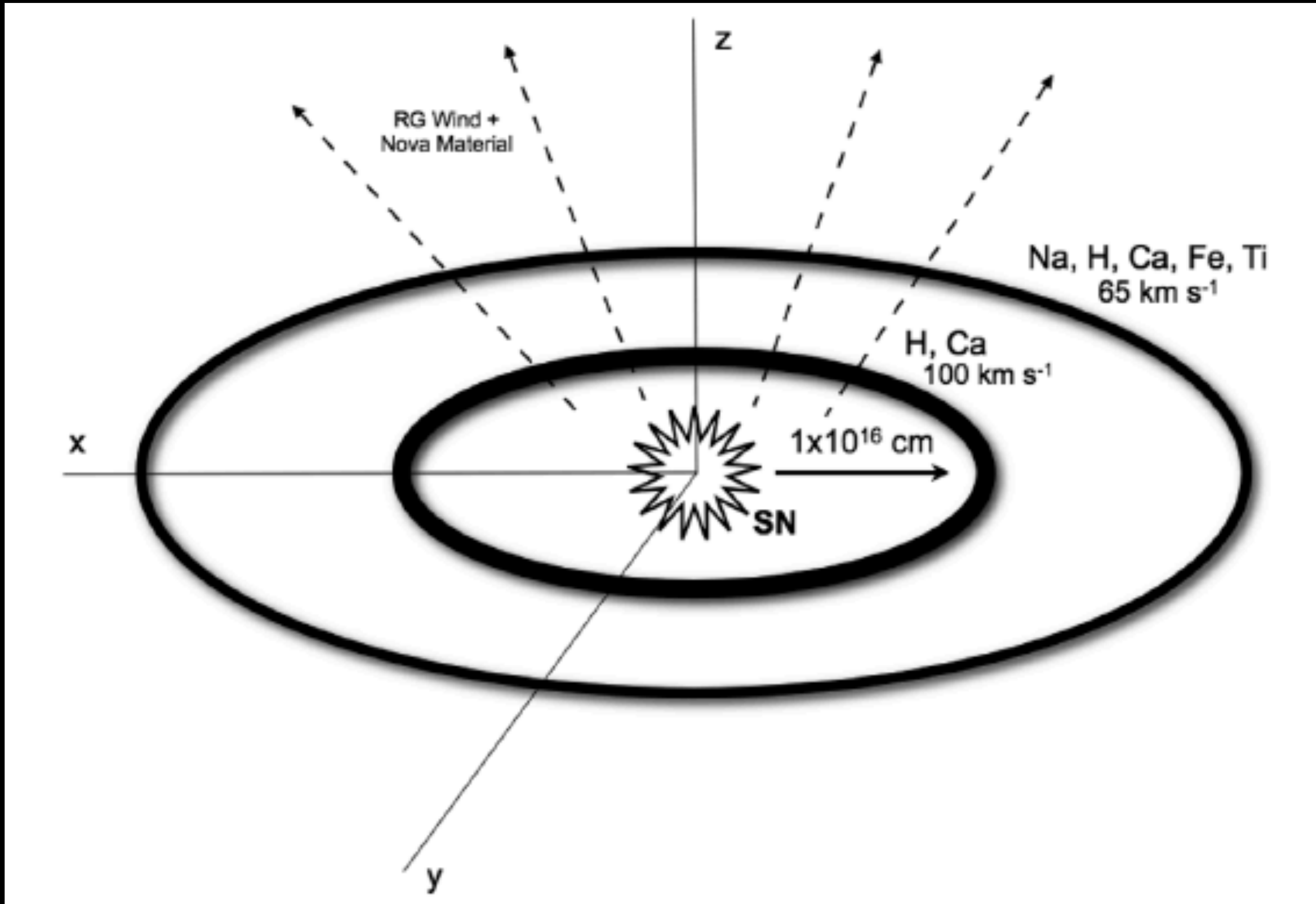
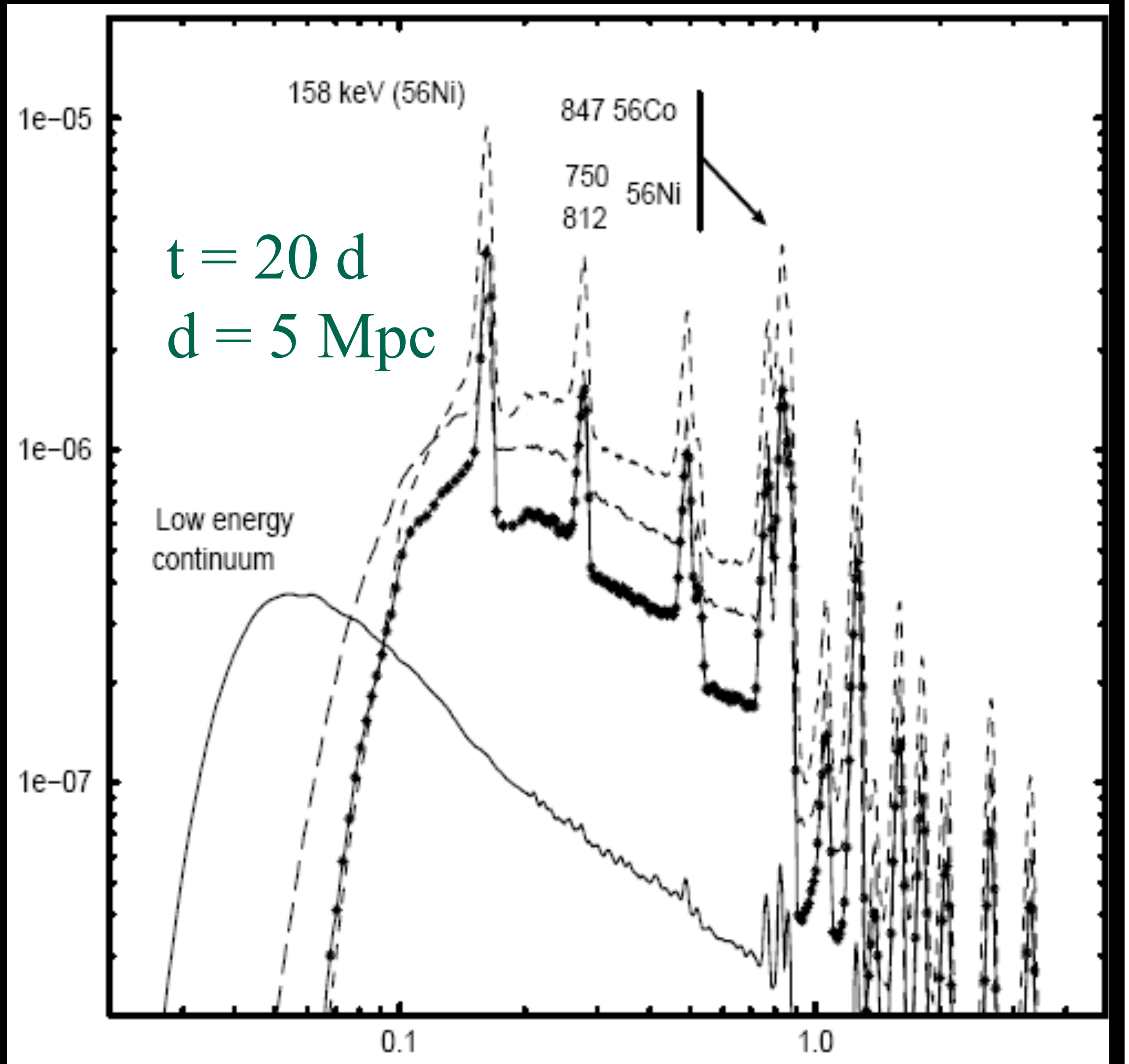


Fig. 1. Comparison of spectra. A temporal series of spectra of PTF 11kx is compared with that of the broad/bright SN 1999aa (*7*) and the CSM interaction SN Ia, SN 2002ic (*16*), all at a similar phase. The


z
RG Wind +
Nova Material
Na, H, Ca, Fe, Ti
65 km s-1
H, Ca
100 km s-1
x
1x1016 cm
SN
y

Gamma-ray opacities are simpler
They offer the most simple method
to obtain the mass of Ni
(Clayton et al'69)

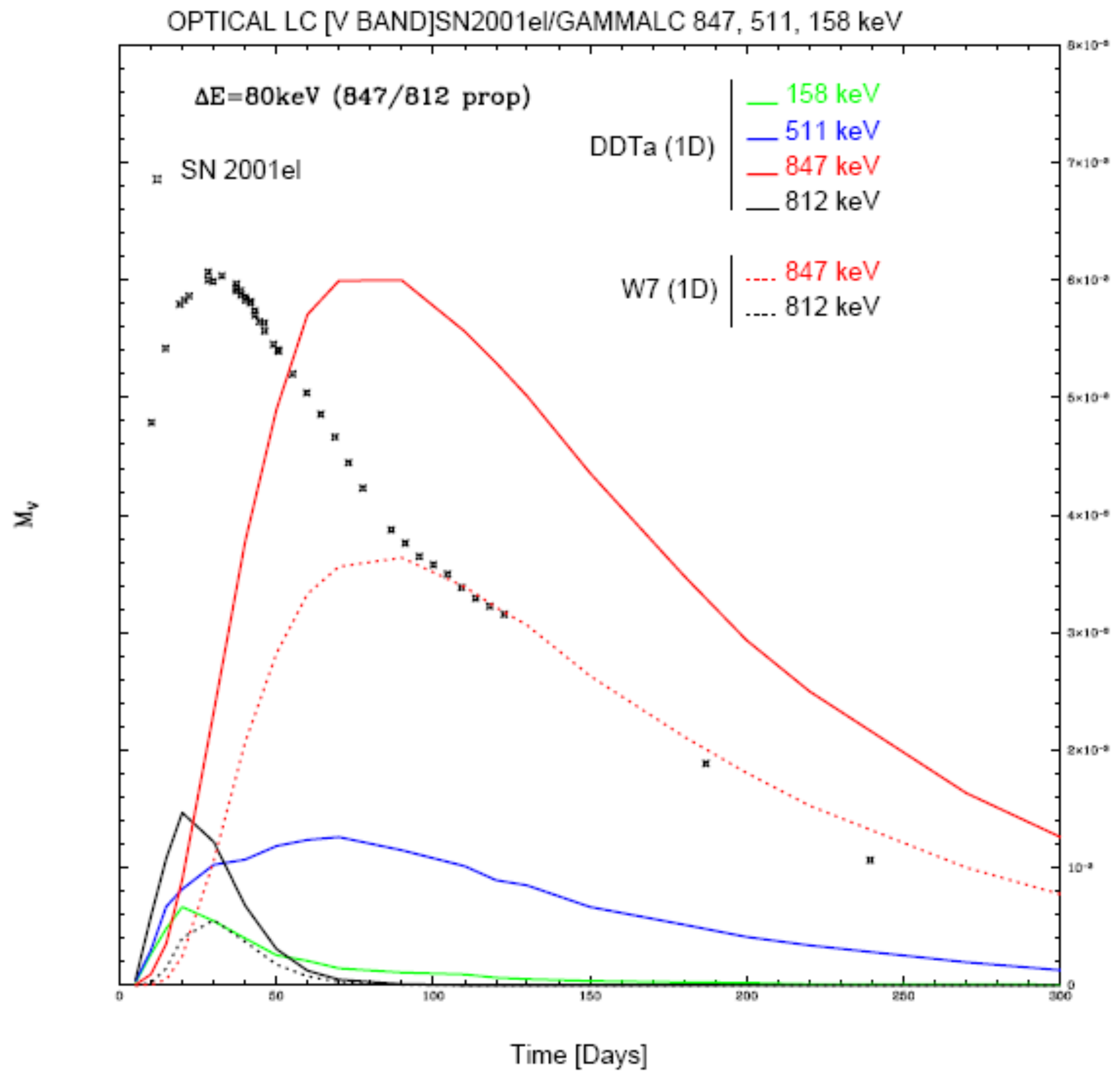
Flux
($cm^{-2}s^{-1}keV^{-1}$)



DET - - - -
DDT — — -
DEF ———
SCH — · —

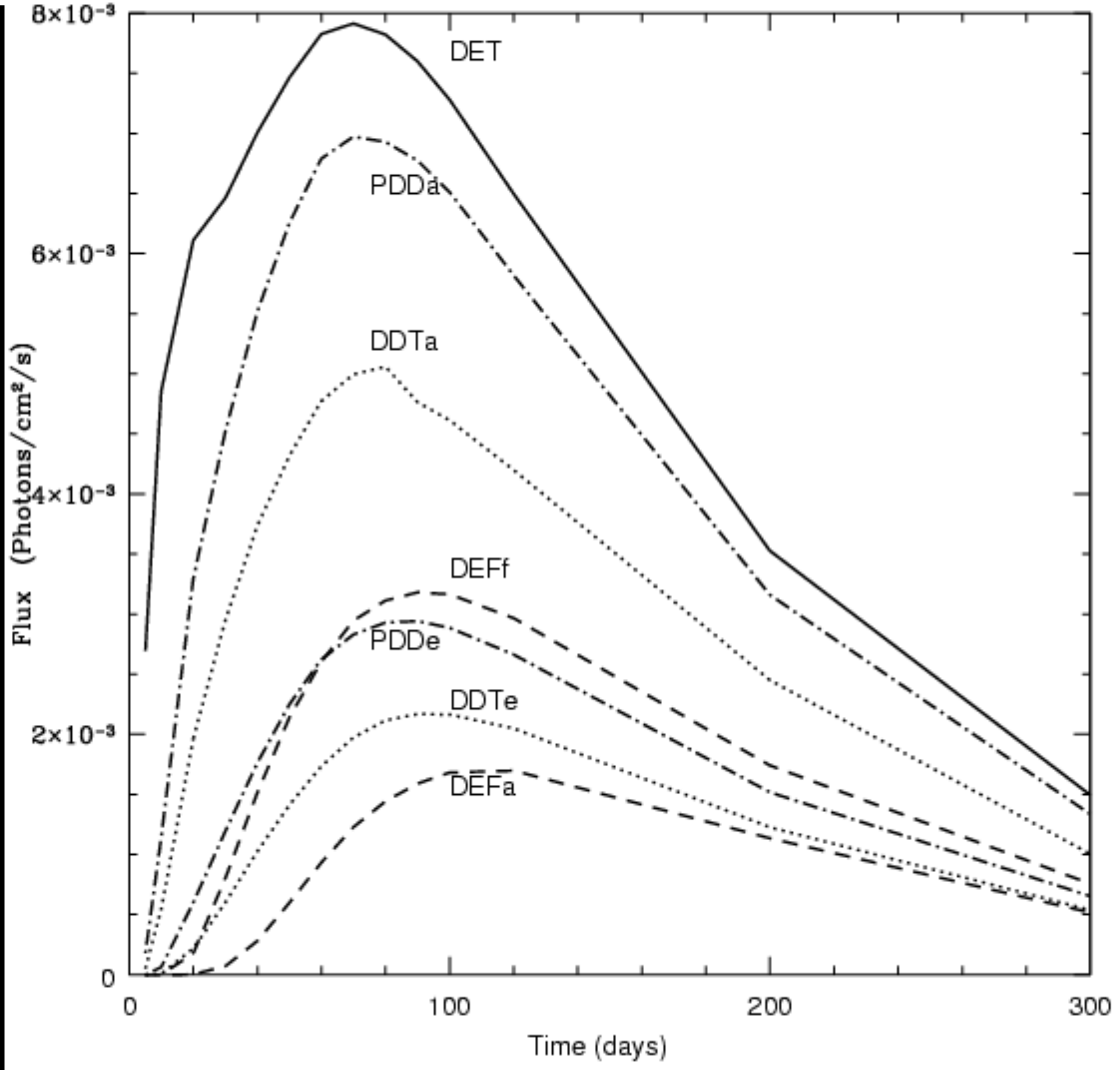
Energy (MeV)

Gómez-Gomar, Isern, Jean 1998,
MNRAS 295, 1



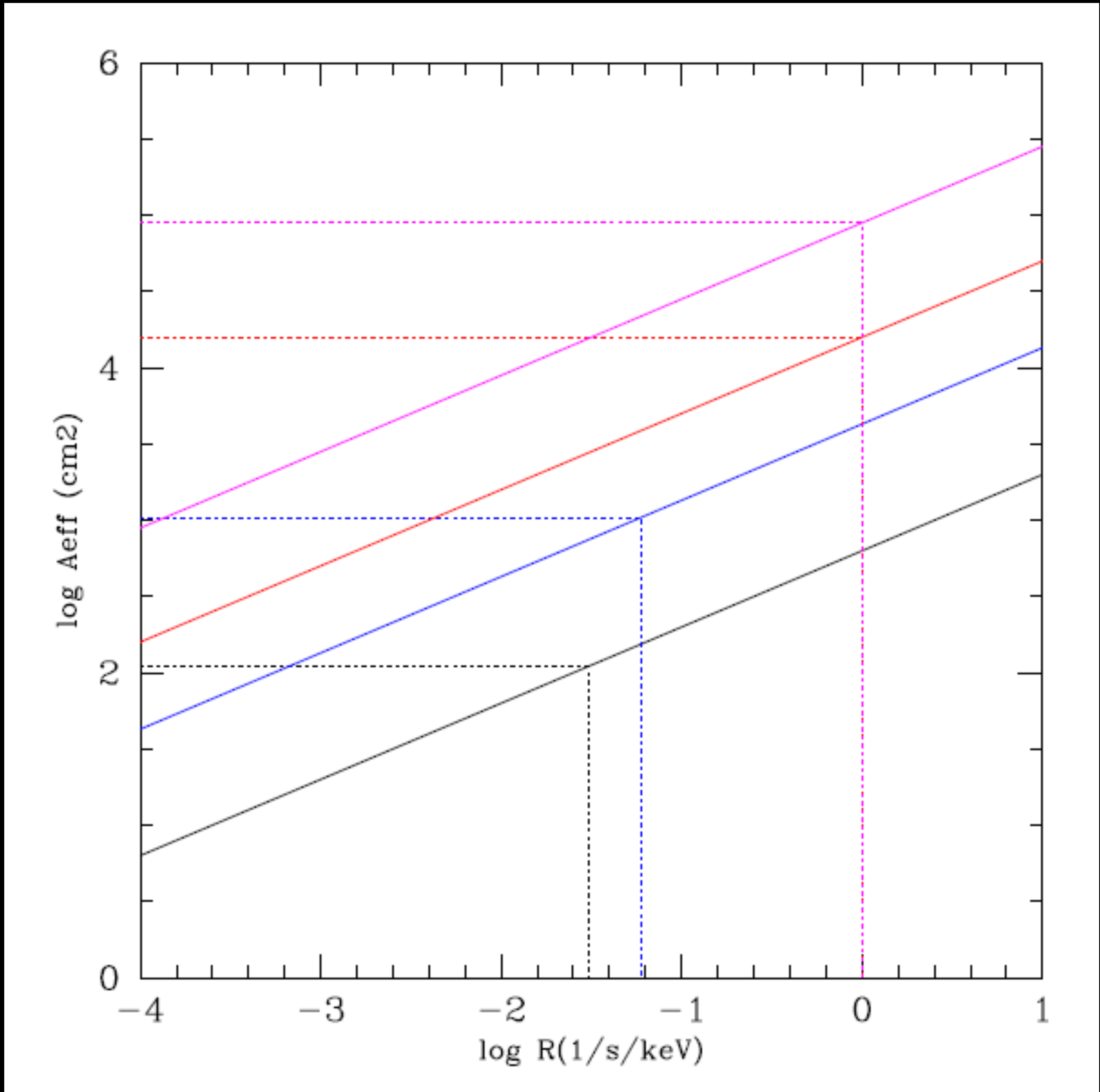
The measurement of the 847keV- ^{56}Co line directly provides the mass of ^{56}Ni

The comparison of the intensity of the ^{56}Ni (158 keV for instance) and the Co lines gives information about the distribution of radioactive material



Light curves obtained from the different families of solutions overlap

Because of the degeneracy among parameters and burning modes & SNIa subtypes, it is necessary a statistycally significative sample!



$t_{obs} = 10^6$ s

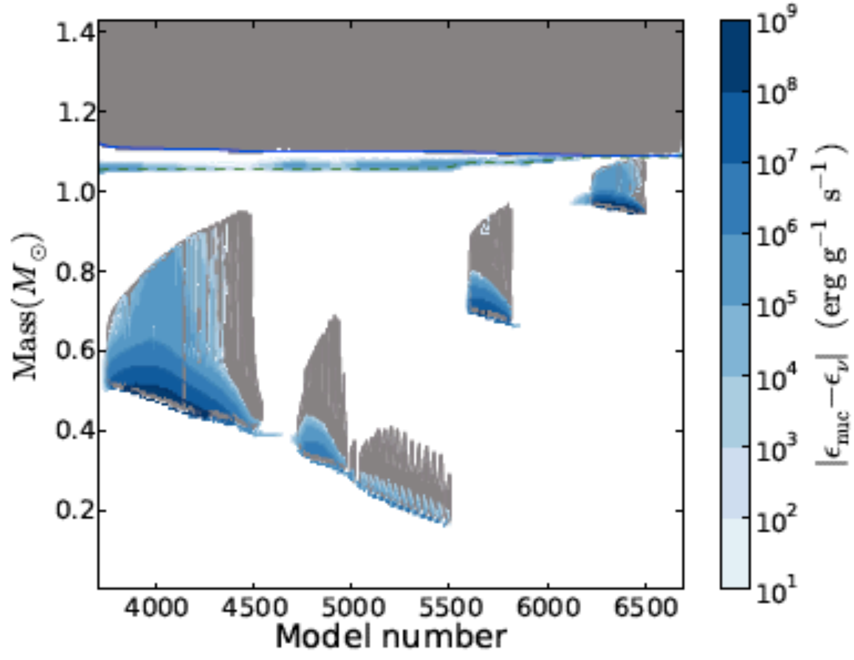
Total effective area (effective area x efficiency) necessary to detect the W7 model versus the detector noise up to a distance of 50 Mpc.

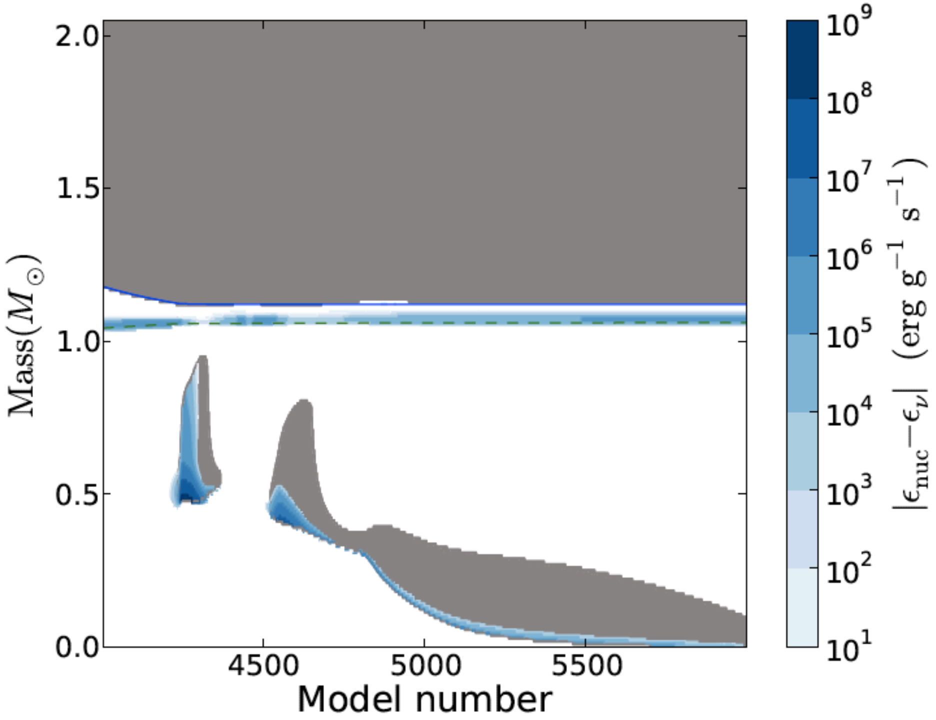
Dashed lines correspond to the TGRS detector (Weidenspointner et al, ApJS 156, 69, fig 5)

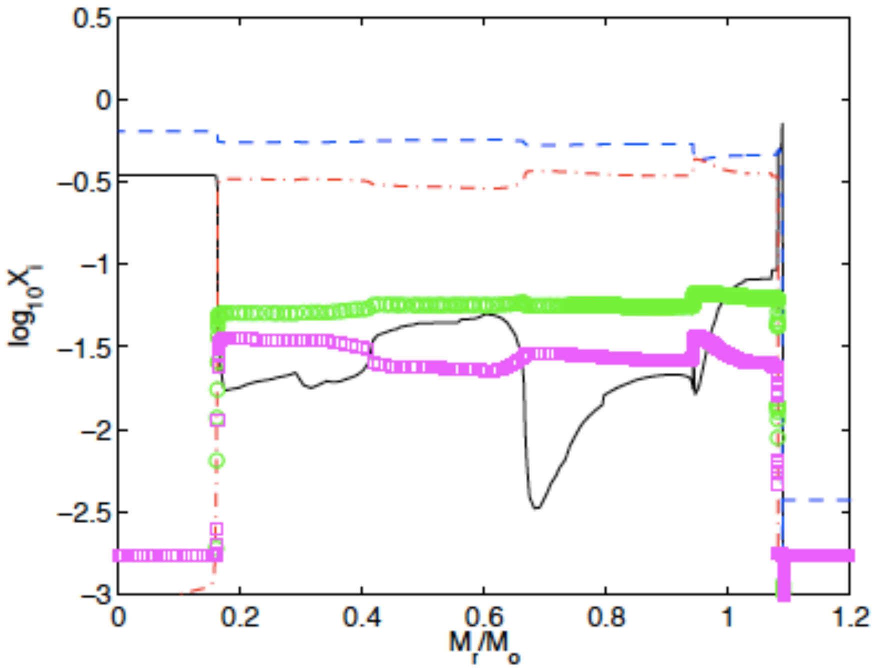
122 keV
158 keV
511 keV
847 keV

The 847keV line is the best suited for detection

Evolution of super-AGB stars







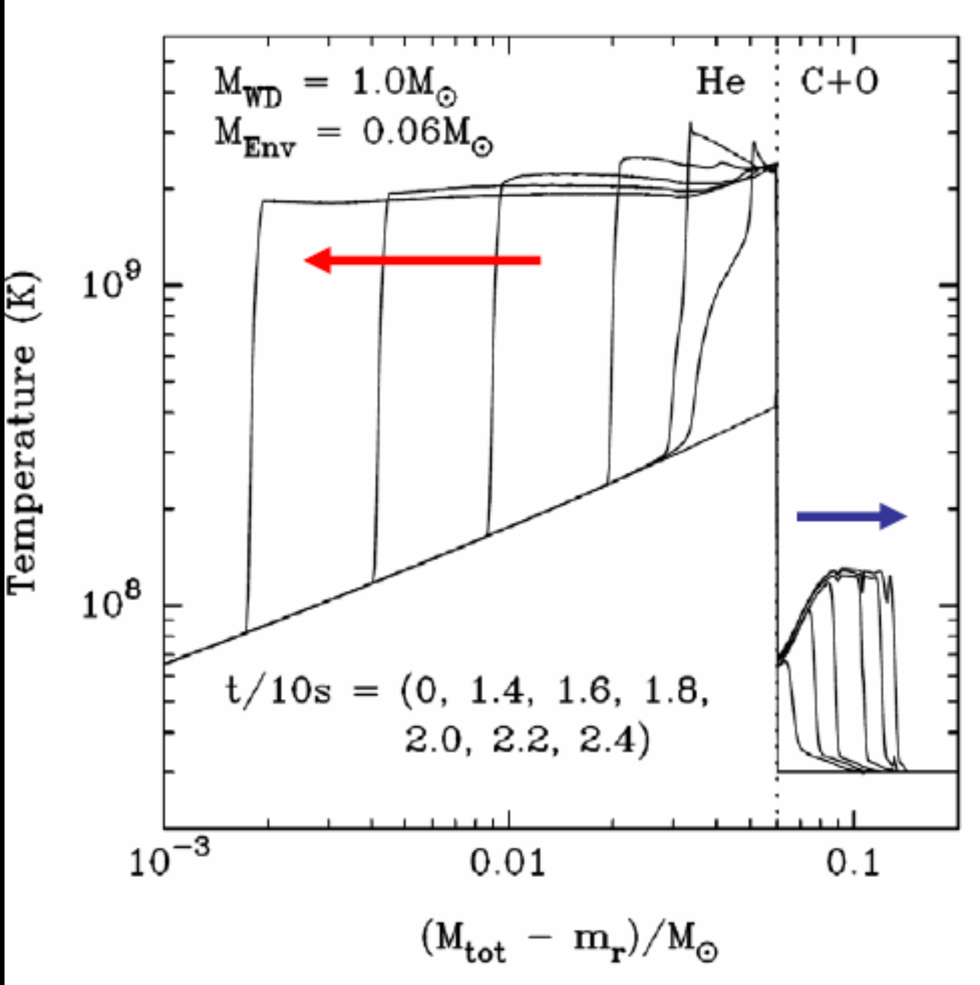
Thermonuclear .Ia supernovae

CO/ONe WD + He WD

Initial ly dM/dt ~ 10^{-6} Mo/yr (stable He burning)

dM/dt decreases with time : unstable He burning

Detonation: 0.02-0.1 Mo of ^{56}Ni, … M_V ~ -16, -18



Possible candidates:

SN2002bj (Poznanski+'10)
SN2005E (Perets +'09)

But other possibilities:
SN 2005cz (Kawabata+'10)
CC SN (8-12 Mo)

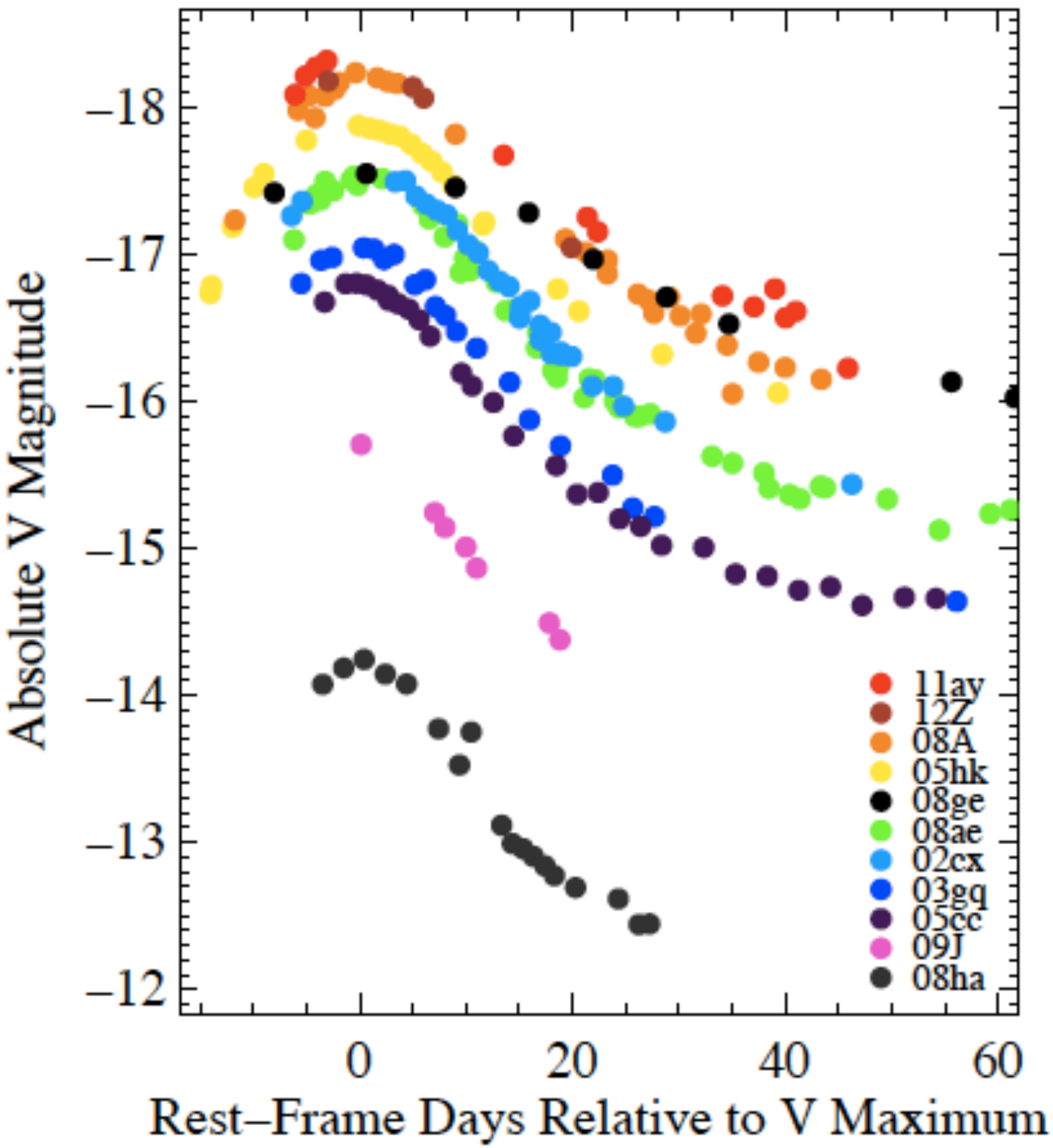
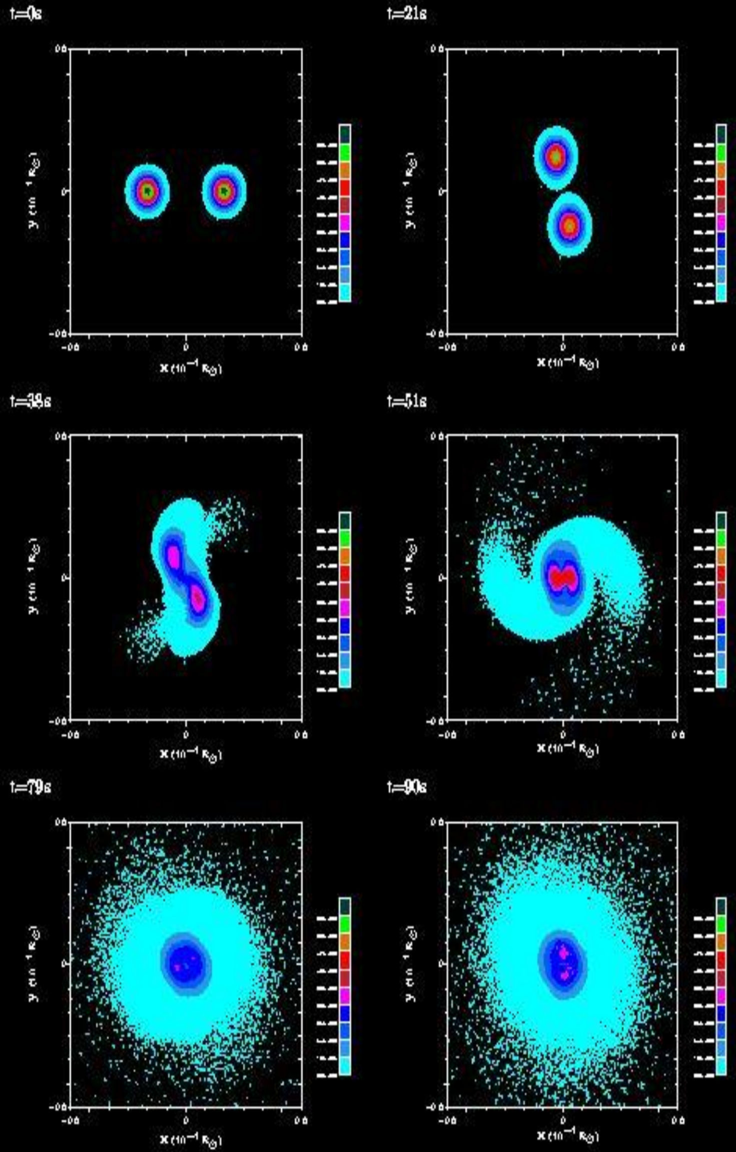


FIG. 25.— Absolute V-band light curves for a subset of SNe Iax. Each SN is plotted with a different color.

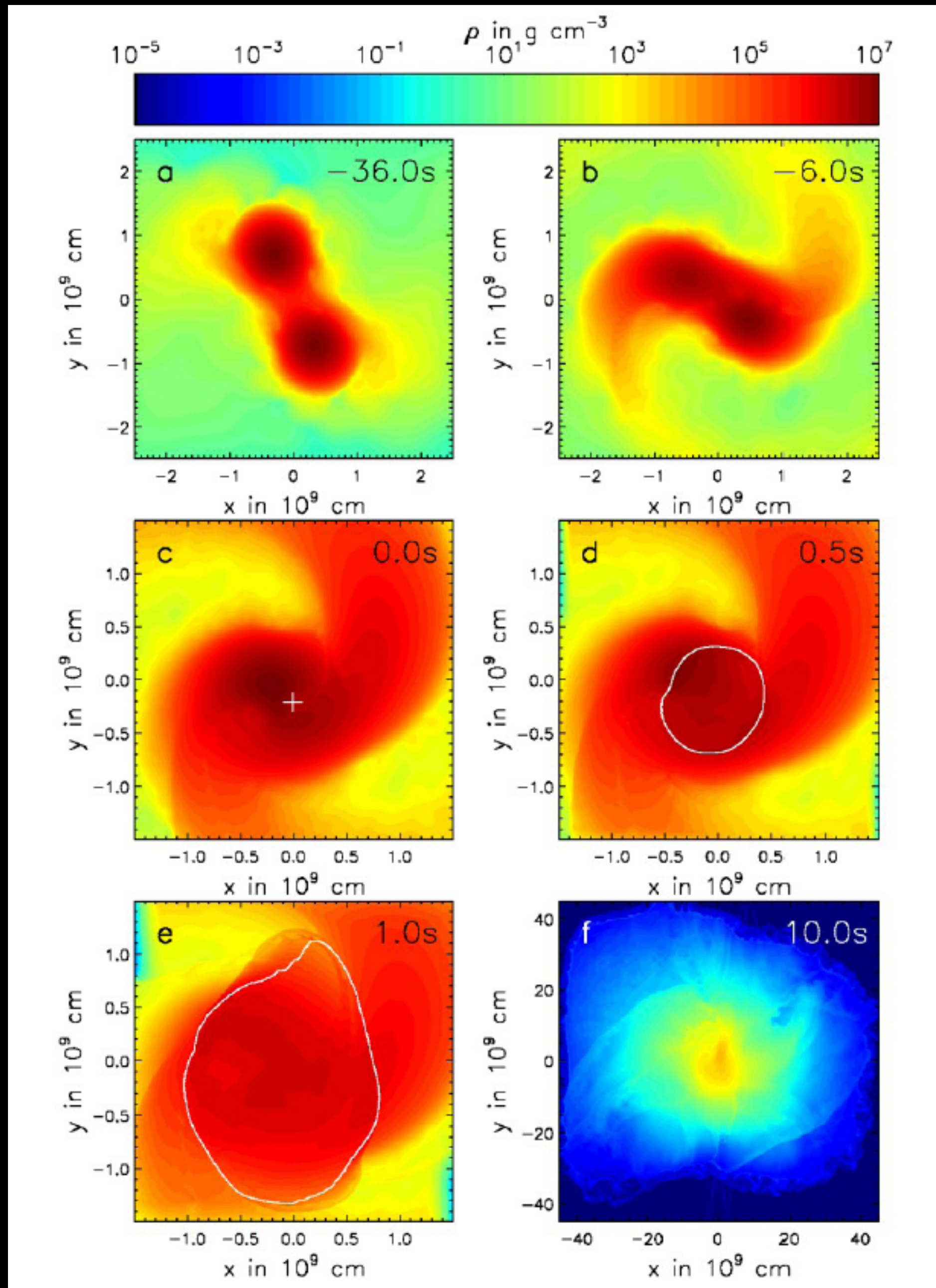
Type Iax
Prototype 2002cx

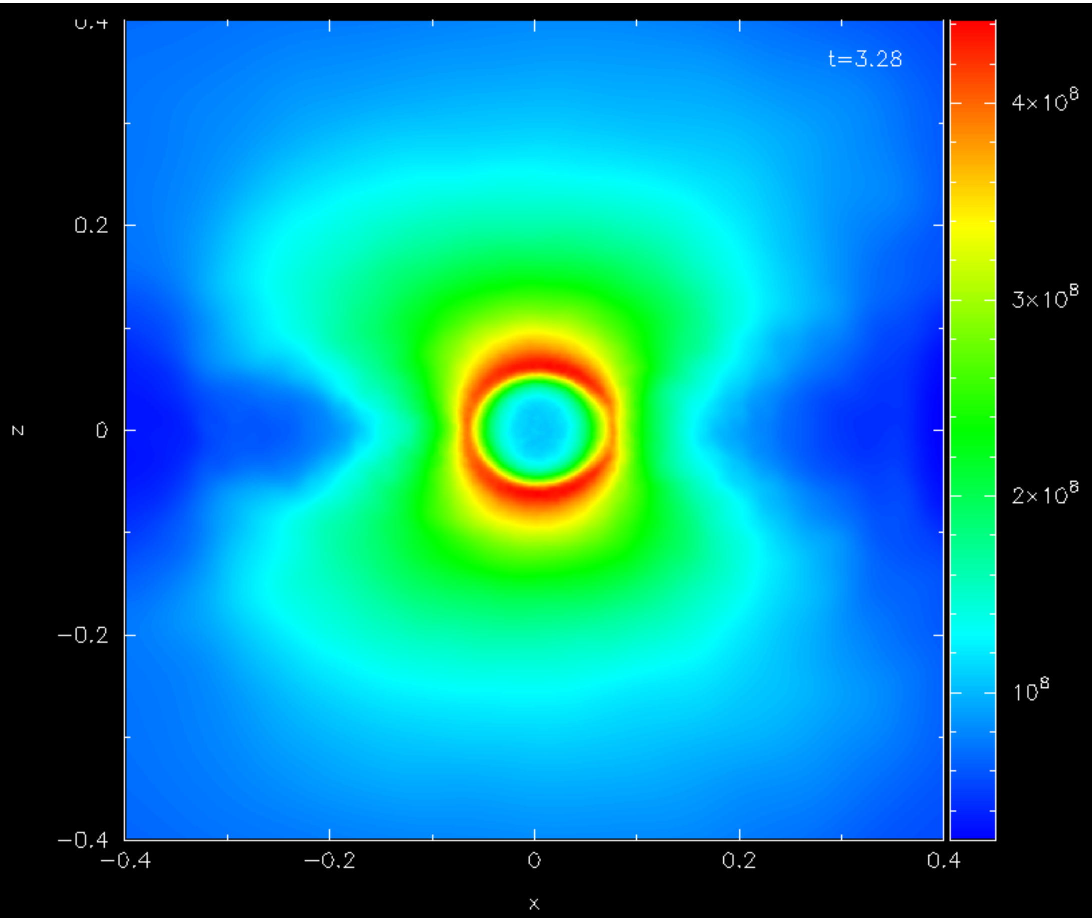
Loren et al’08

Riemann solver
0.6+0.6 Mo

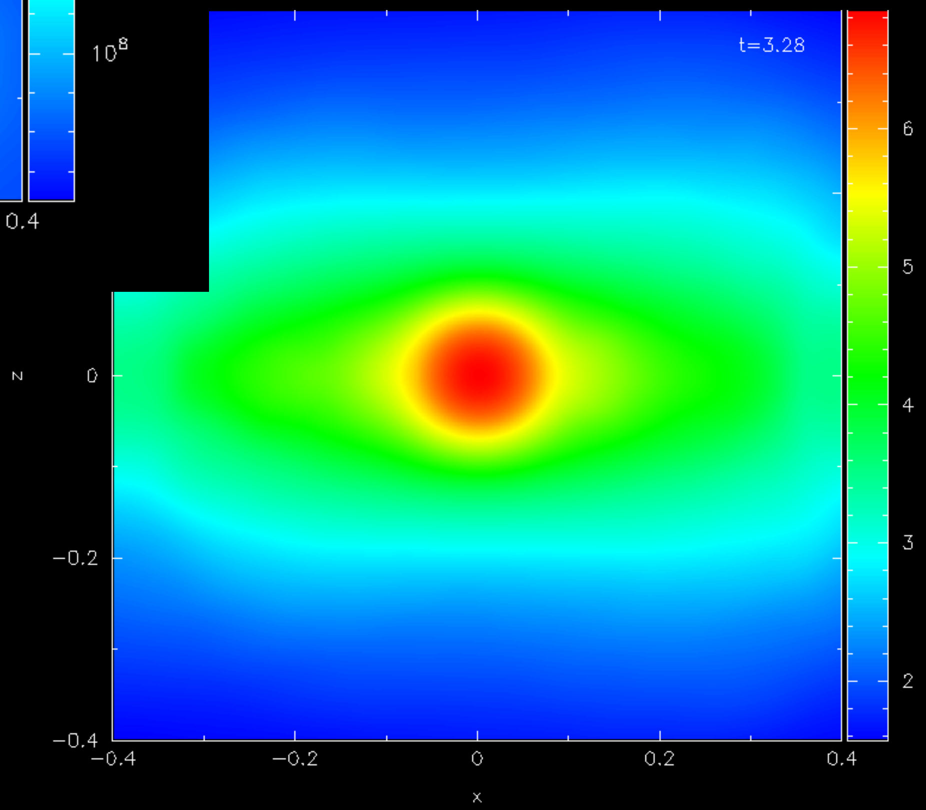


0.9+0.9 Mo
Pakmor et al’10

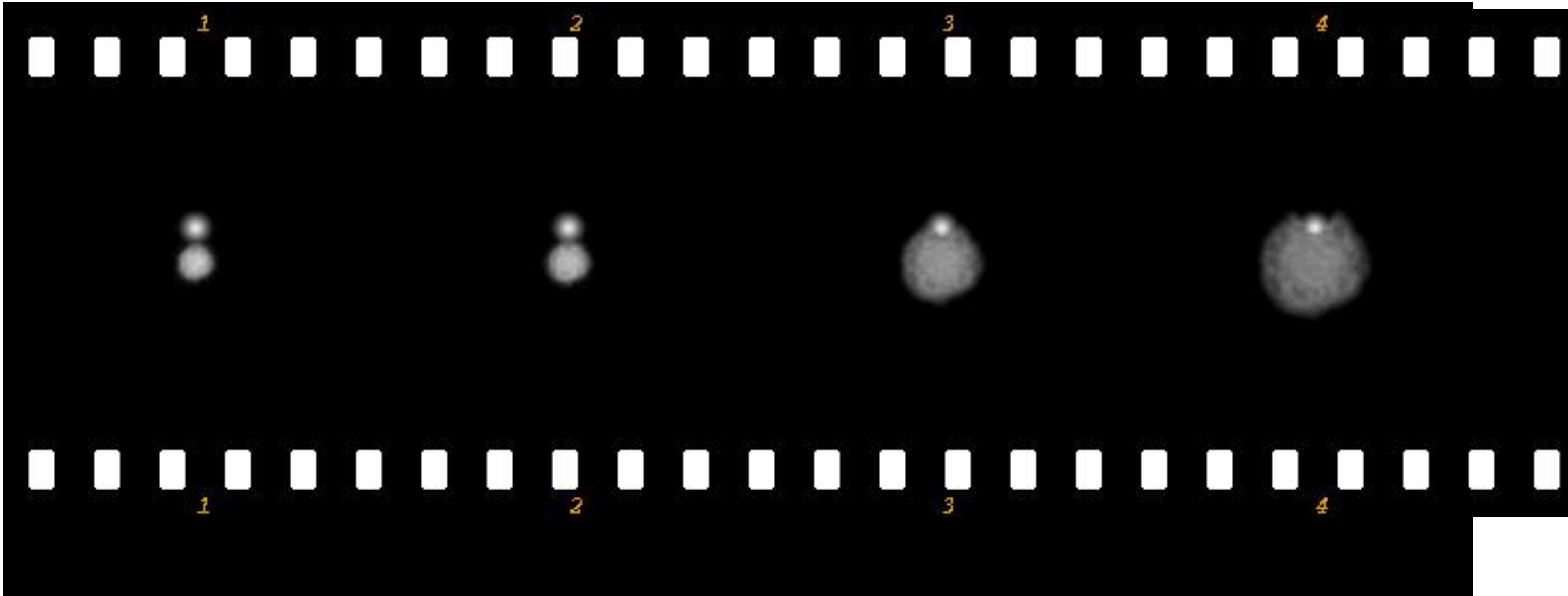
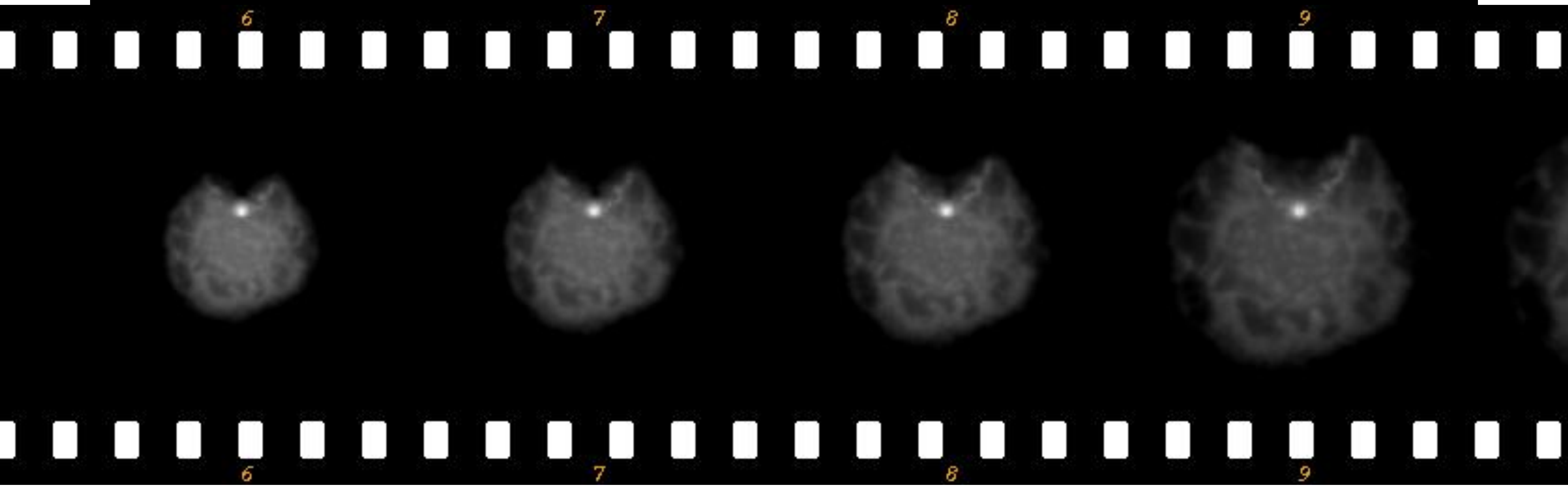




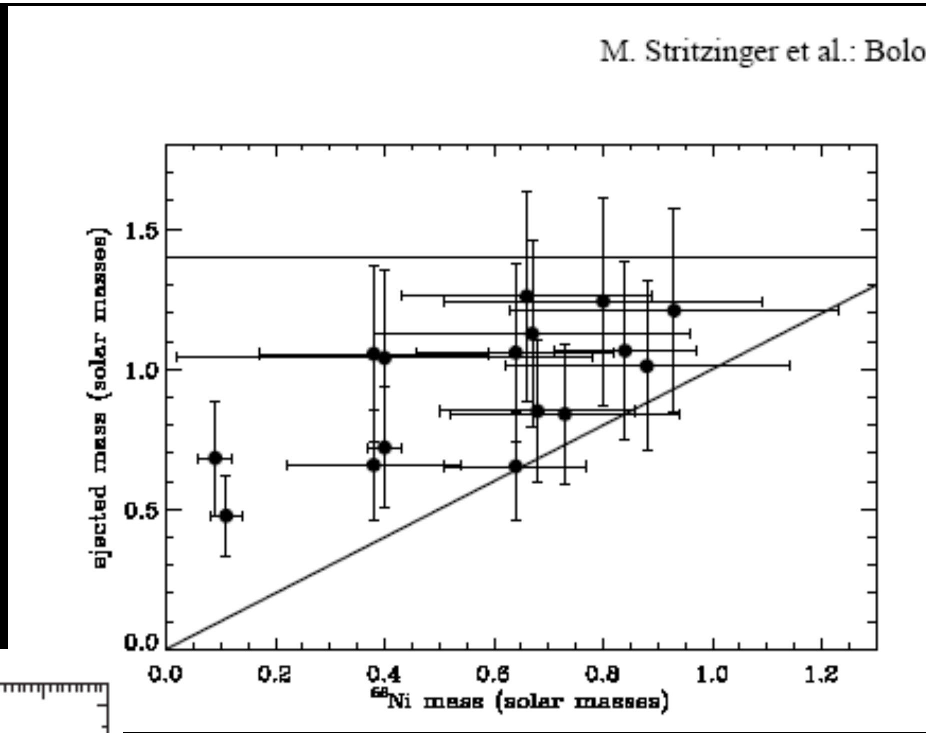
Temperature



Density


1
2
3
4
1
2
3
4

6
7
8
9
6
7
8
9

Light curve properties



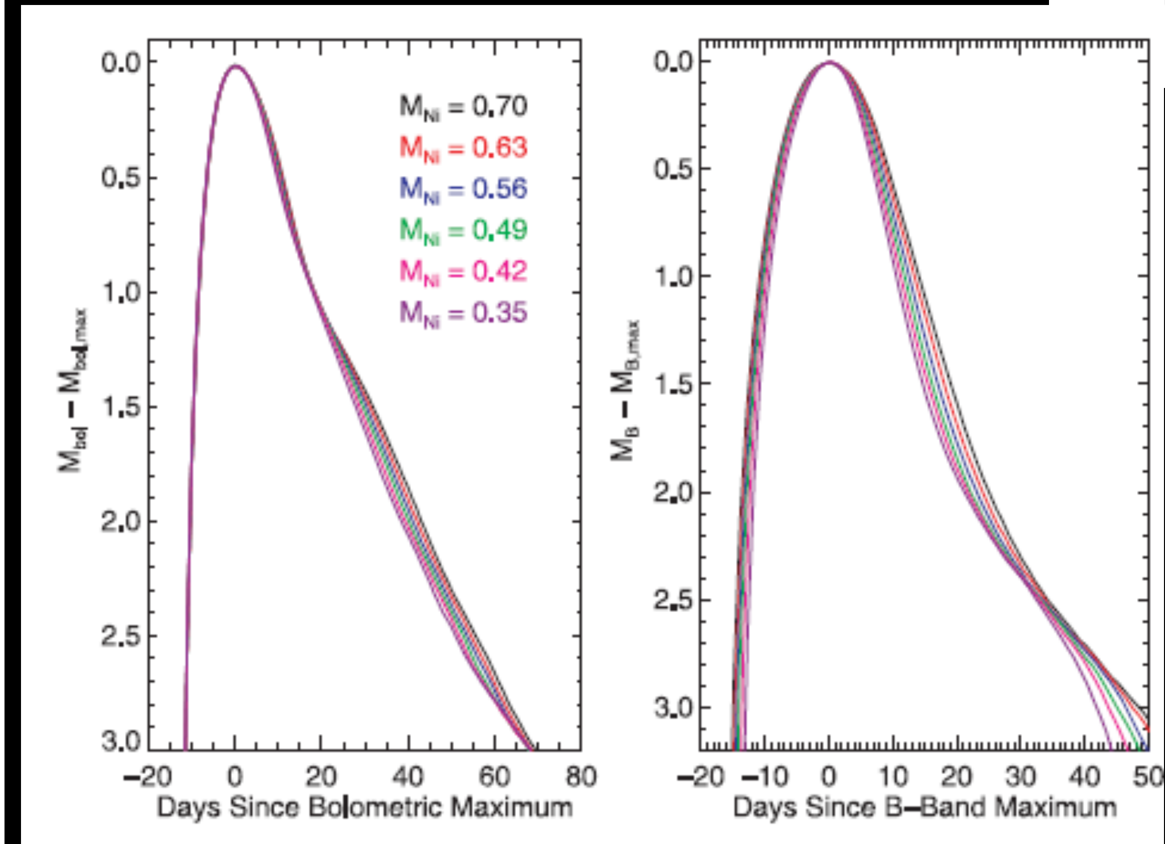
Origin of the Width-Luminosity relationship

(Kasen & Woosley'07; Woosley et al'07)

The models have the same kinetic energy, but the Ni mass is substitued by IME

It is a broad band effect.

The bolometric luminosity is not afected



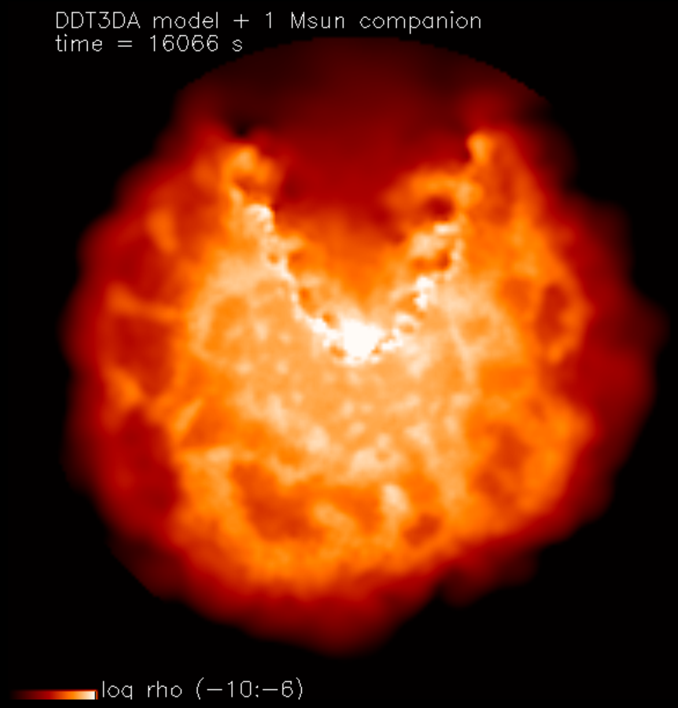
The luminosity at maximum:

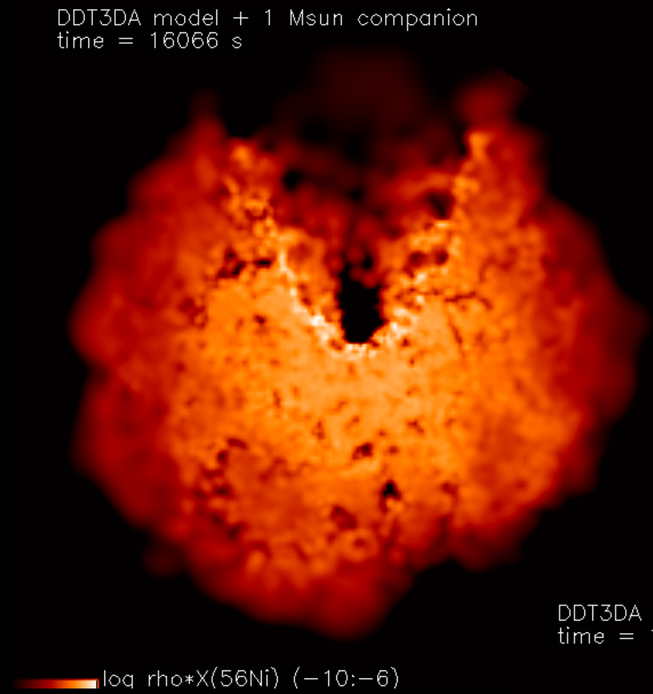
$L \sim f\, M_{Ni} \exp(-t_p/t_{Ni})$

The width depends on the diffusion time:

$t_d \sim \Phi_{Ni}\, \kappa^{1/2}\, M^{3/4}\, E_K^{\ -1/4}$

The mass & distribution of Ni is poorly known



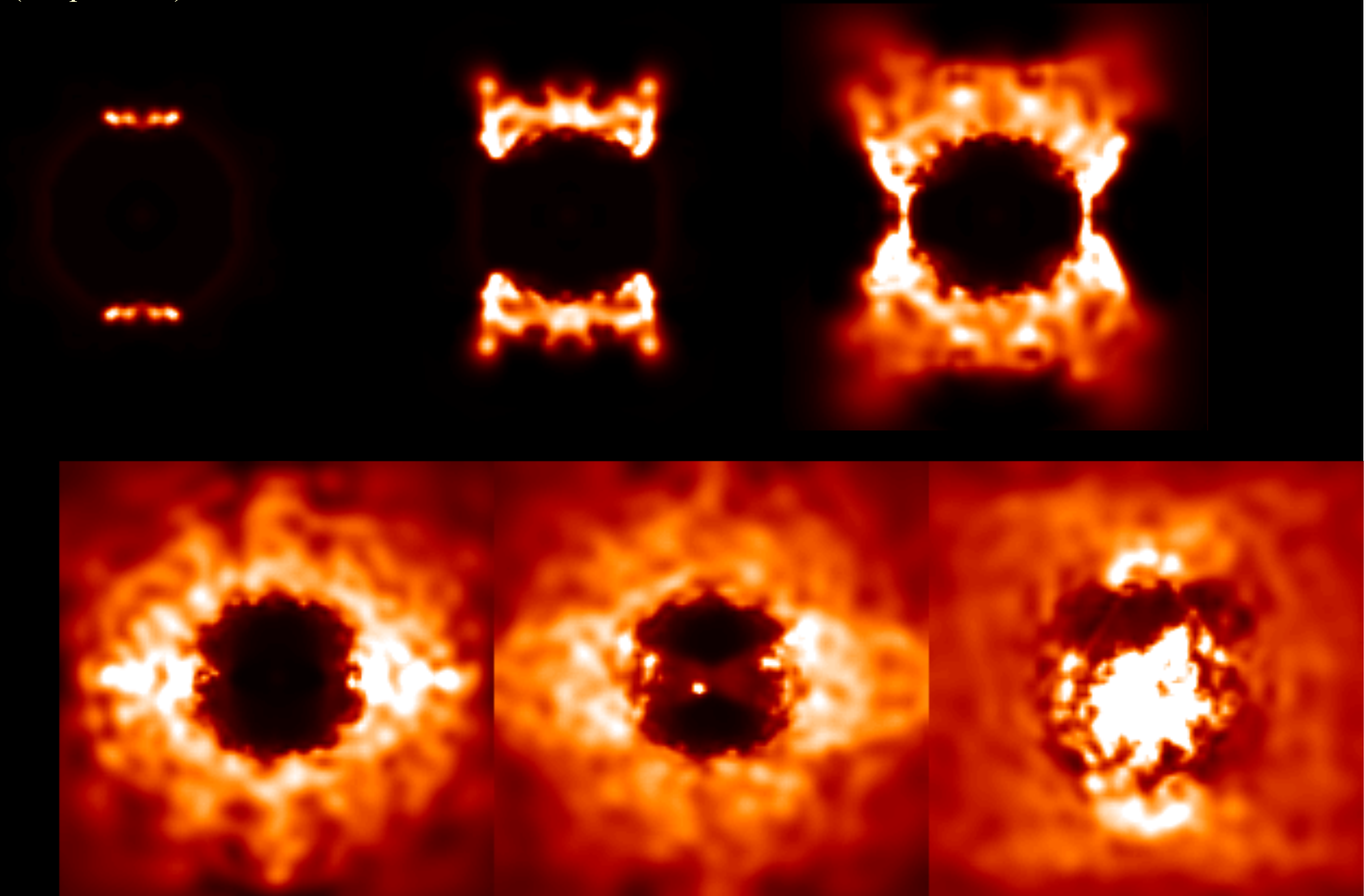


Stripped mass: 0.15-0.53 M_o

Depends on tha mass, separation and evolutionary status of the secondary

Off center detonations (E. Bravo et al '07)

(temperature)



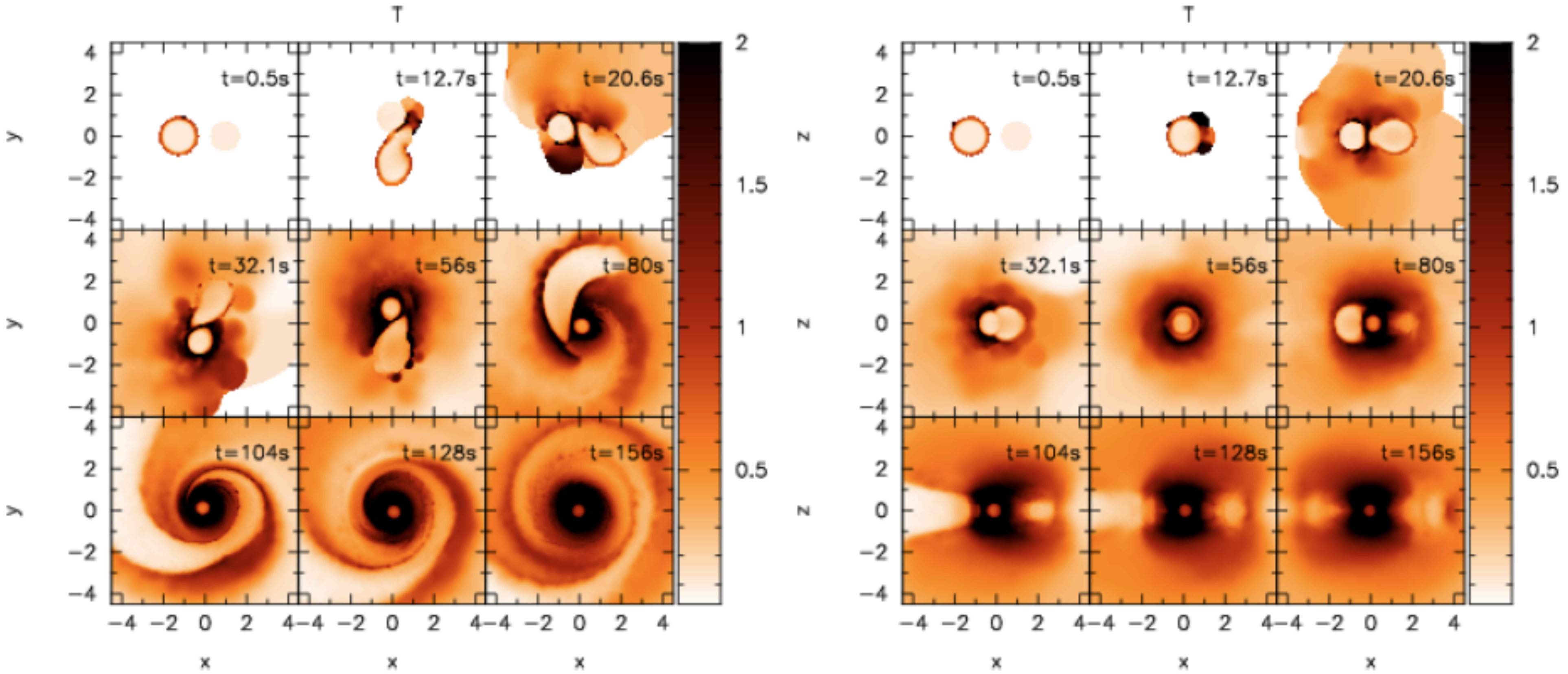
The presence of intermediate elements, the absence of important amounts Fe-peak elements at maximum

The burning has to be subsonic (deflagration)
Detonations confined to regions with $\rho \leq 10^7$ g/cm^3

Deflagration and detonation can be combined:
In 1D
Deflagration
Delayed detonation
Pulsational delayed detonation

The equivalent in 3D also exist

Sub-Chandrasekhar models



Very high temperatures can be achieved due to shocks
but they are quenched by expansion (Loren-Aguilar+'09)