Type Ia supernovae: Observations & Theory

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Energetics

The kinetic energy can be obtained from the expansion velocity (v_{exp} ~ 5000 – 10000 km/s) if the time elapsed from the moment of the explosion to the beginning of the nebular phase is known (assuming the Thomson opacity for instance: 0.2 cm^2/g)

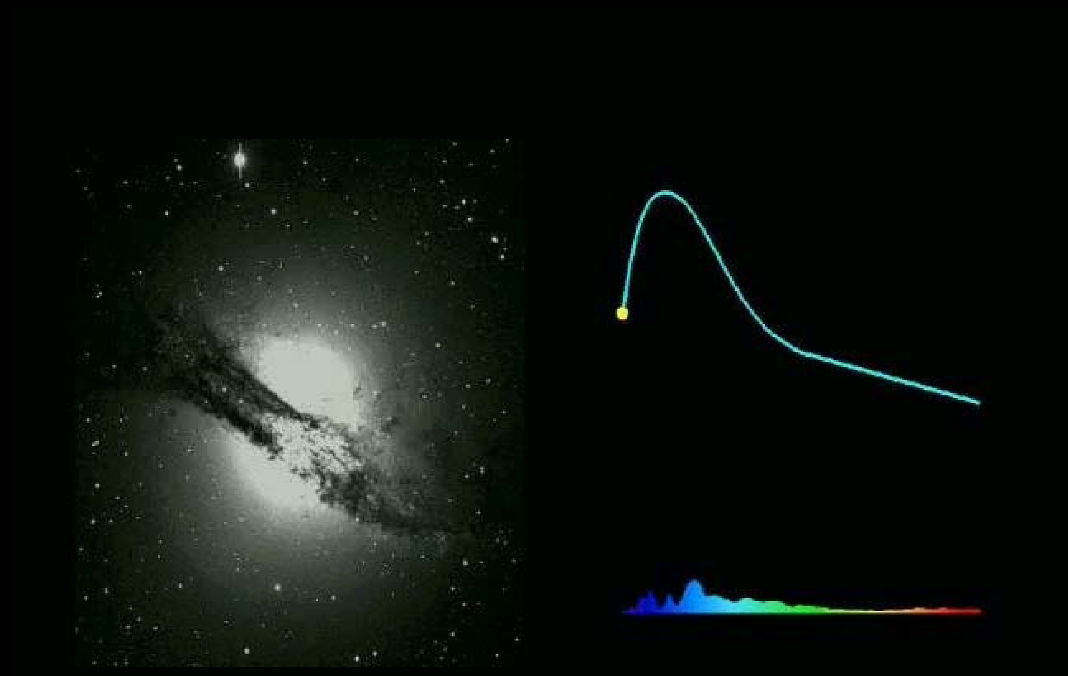
$$R \sim v_{\exp}\tau$$

$$\rho\kappa \mathrm{R} \sim 1$$

$$\rho \sim M_{ej} \Big/ \frac{4}{3}\pi R^3$$

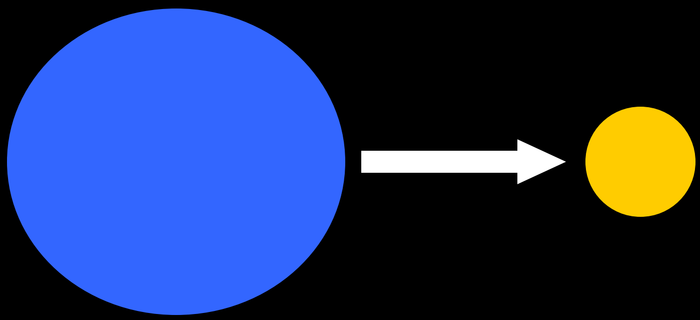
$$M_{ej} \approx 3\left(\frac{v_{\exp}}{5000\,km/s}\right)^2 \left(\frac{\tau}{1yr}\right)^2$$

$$E_{kin} = \frac{1}{2} M_{ej} v_{\exp}^2 \approx 10^{51} \left(\frac{v_{\exp}}{5000\,km/s}\right)^4 \left(\frac{\tau}{1yr}\right)^2 erg$$



Explosive sources of energy

Gravitational collapse



Electron degenerate core

M ~ 1.4 Mo
R ~ 10^8-10^9 cm

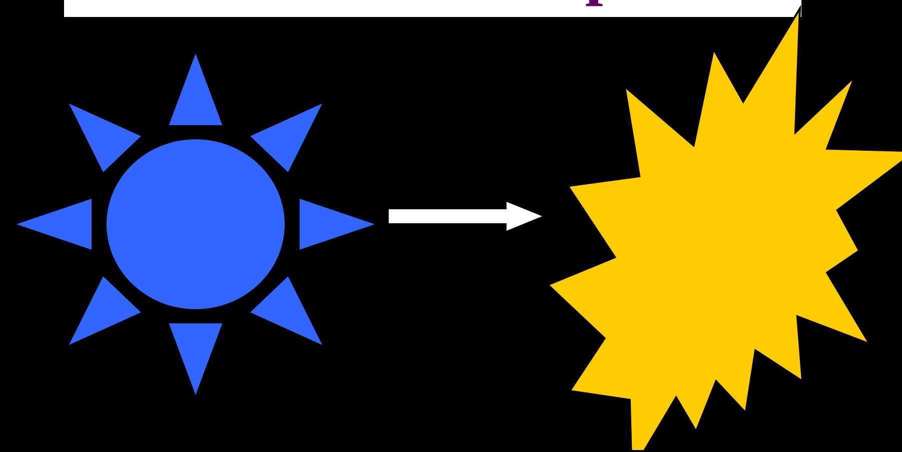
Neutron star

M ~ 1.4 Mo
R ~ 10^6 cm

$\Delta E_G \sim 10^{53}$ erg
$K \sim 10^{51}$ erg
$E_{em} \sim 10^{49}$ erg

Zwicky (1938)

Thermonuclear explosion



$\{^{12}C, ^{16}O\} \rightarrow \{^{56}Ni\}$
$q \sim 7x10^{17}$ erg/g
1 Mo x $q \sim 10^{51}$ erg
$K \sim 10^{51}$ erg
$E_{em} \sim 10^{49}$ erg
$L_{max} \sim 10^{43}$ erg/s

Hoyle & Fowler (1960)

There is not a length scale

If $\delta E < 0$ $\delta R < 0$

Star contracts

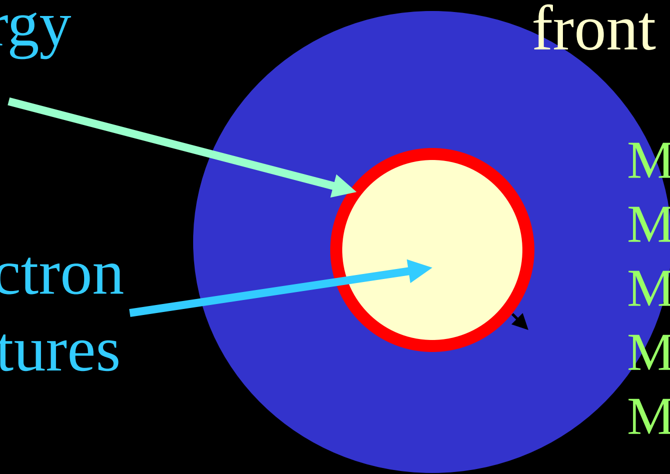
If $\delta E > 0$ $\delta R > 0$

Star explodes

The energy losses by electron captures depend on the ignition density

The injected energy depends on the velocity of the burning front

Nuclear energy release



Electron captures

M<0.08 Mo, H is never ignited

M<0.5 Mo, He is never ignited

M<8-9 Mo, C is never ignited

M<10-12 Mo, Ne is never ignited

M>10-12 Mo, Fe cores are formed

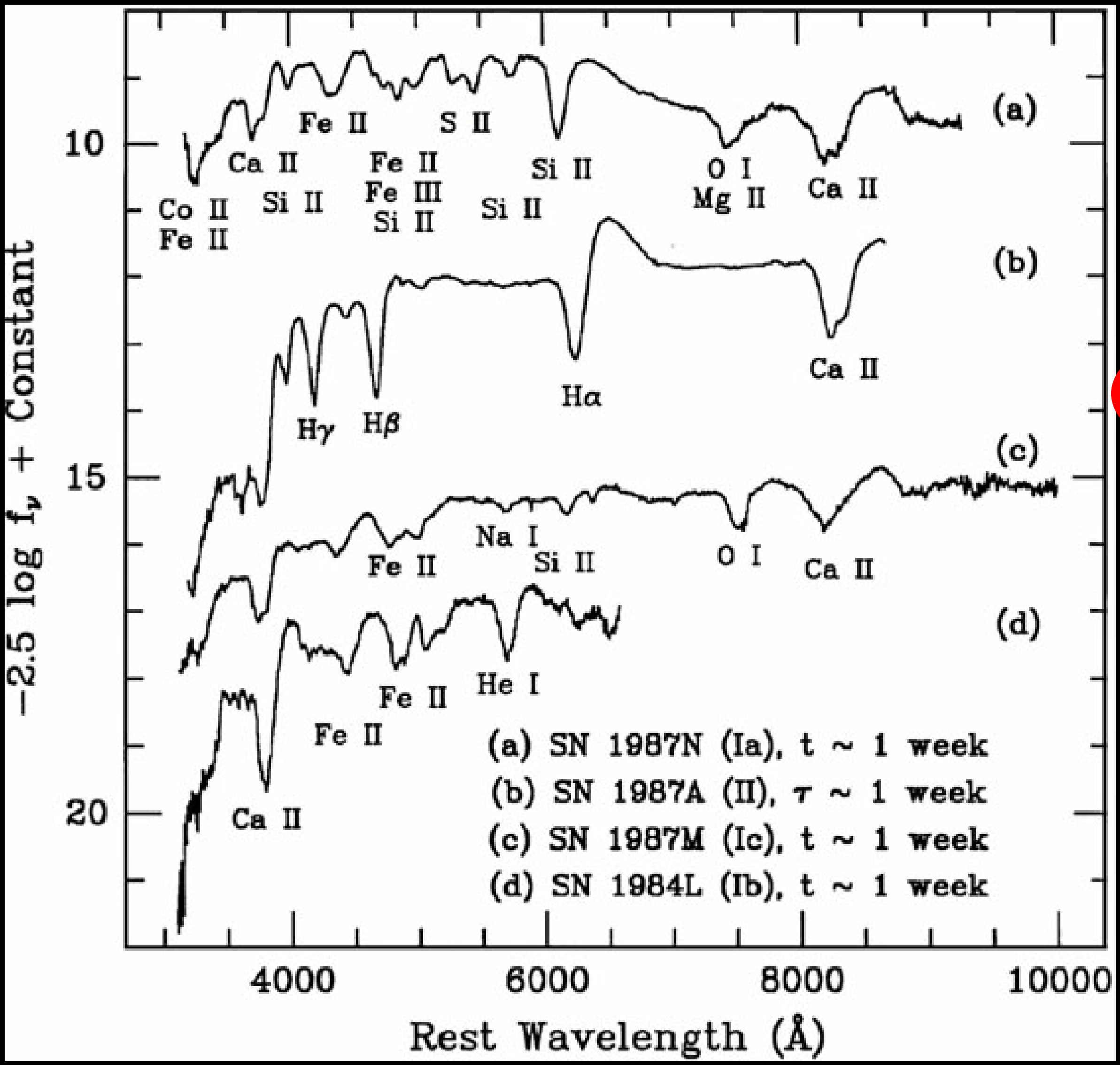
He cores always experiment a thermonuclear explosion

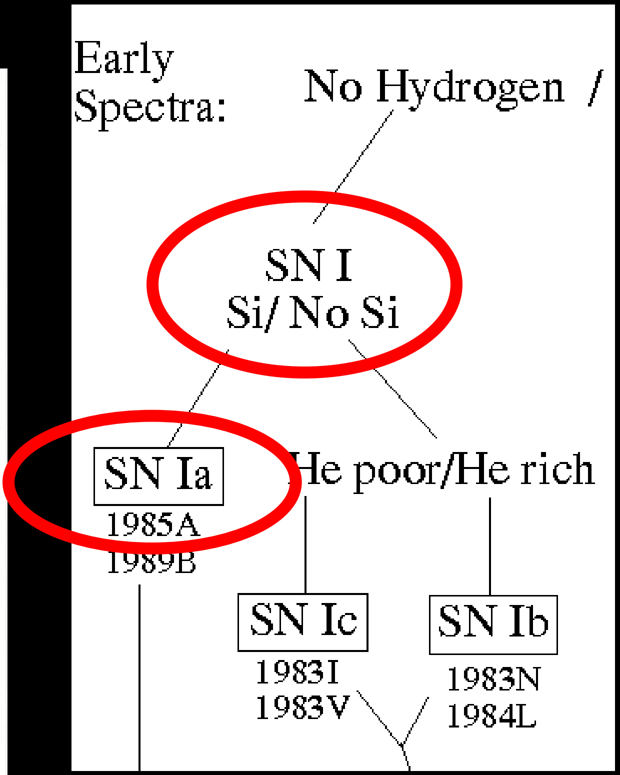
CO cores can explode or collapse to a neutron star

ONe cores always collapse to a neutron star

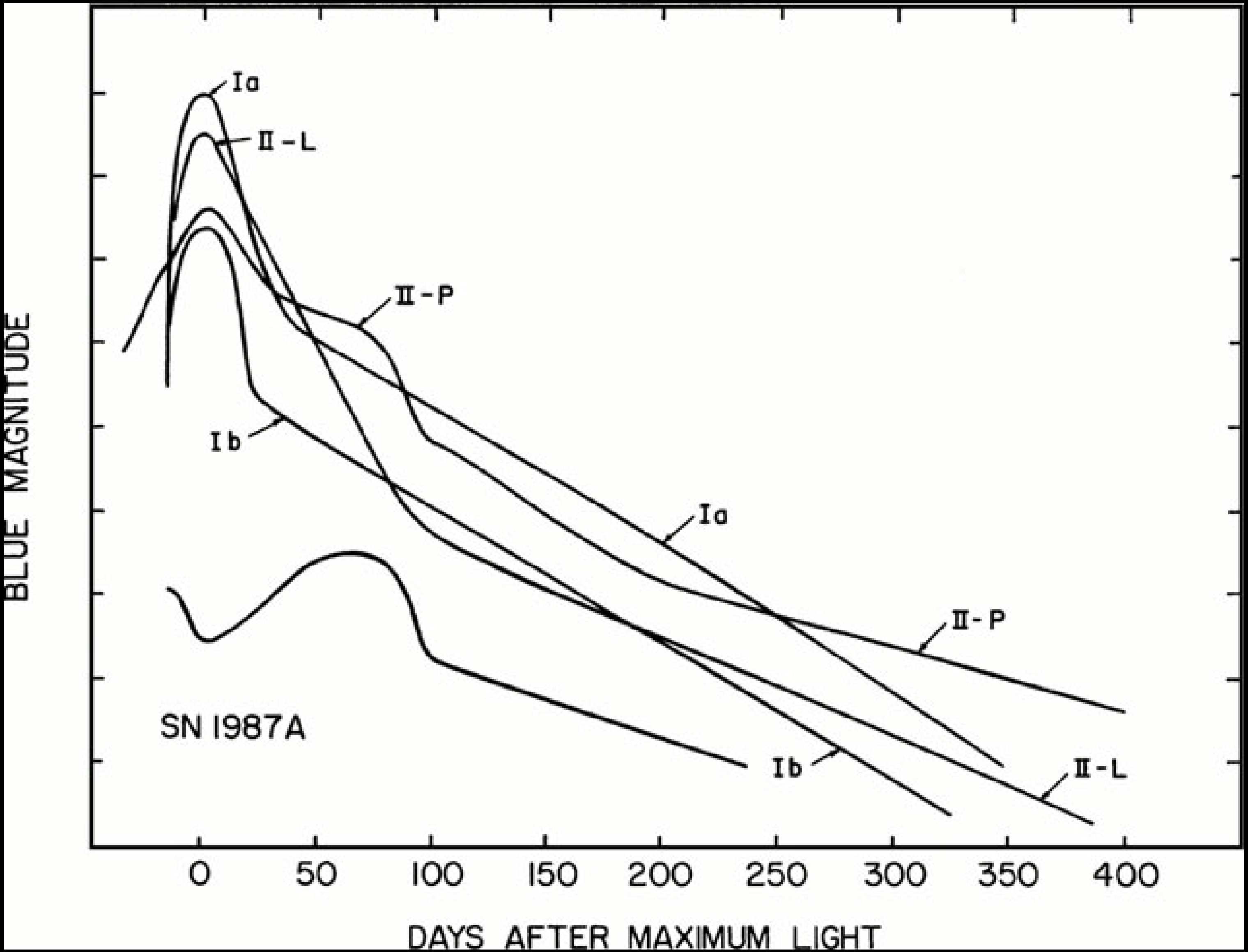
Fe cores always collapse to a neutron star or black hole

A more careful analysis shows:





Light curves



SNe Statistics

SN rate per unit Mass $(10^{-11} M_o\ 10^{-2}\ yr\ (H_o/75)^2$

Galaxy	Ia	Ib/c	II	All
E-S0	0.16±0.03	< 0.01	< 0.01	0.16±0.03
S0a-Sb	0.29±0.07	0.16±0.07	0.69±0.17	1.14±0.20
S0c-Sd	0.46±0.10	0.30±0.11	1.89±0.34	2.65±0.37
All	0.27±0.03	0.11±0.03	0.53±0.07	0.91±0.08

Cappellaro, Barbon, Turatto 2003

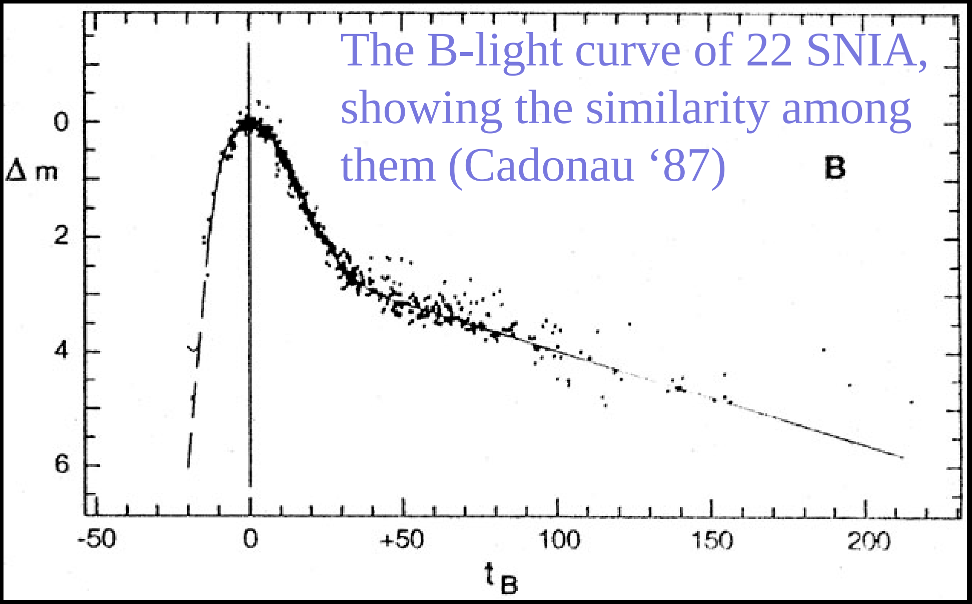
- H must be absent at the moment of the explosion
- Progenitors should be long lived to account for their presence in all galaxies, including ellipticals
- The explosion should produce at least ~ 0.3 M_0 of ^{56}Ni to account for the light curve and late time spectrum
- The short risetime of the light curve indicates that the exploding star is a compact object

⬇

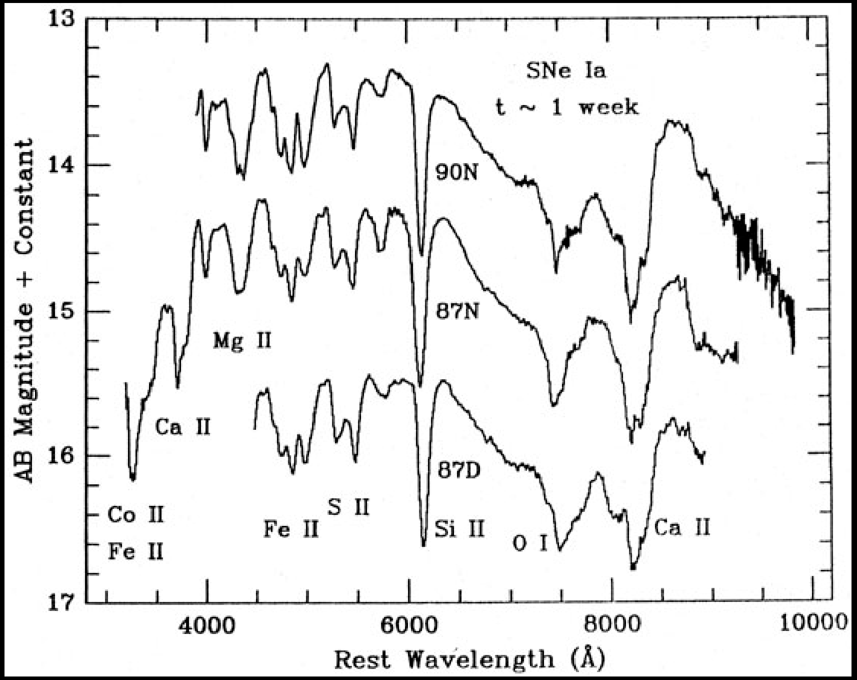
SNIa are caused by the thermonuclear explosion of a C/O white dwarf near the Chandrasekhar's mass in a close binary system

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

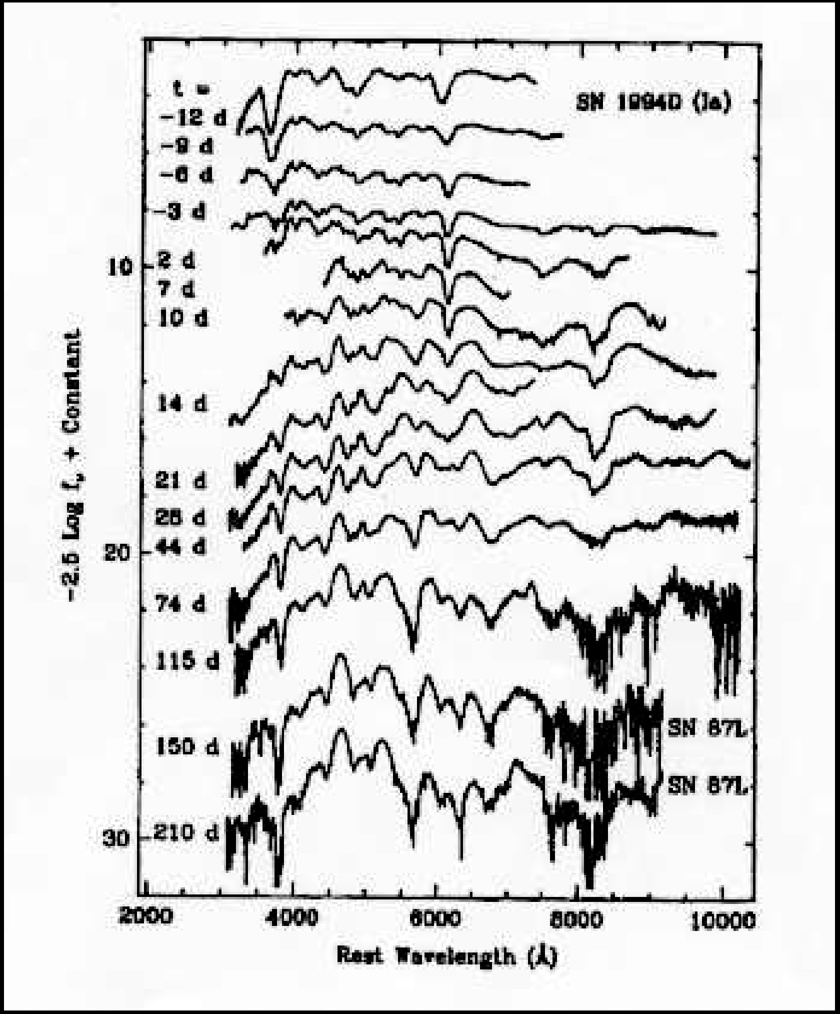
Spectral and photometric homogeneity



The B-light curve of 22 SNIA, showing the similarity among them (Cadonau '87)



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



Observations at differente epochs allow to obtain a tomography of the supernova

No conspicuous lines of H or He at early photospheric phases

Strong SiII absorption lines ($\lambda 6355 \rightarrow \lambda 6100$)

High-velocity SiII, CaII, SII, OI features ($v \sim 8,000 - 30,000\ \mathrm{km\,s^{-1}}$)

Nebular phase dominated by Fe lines

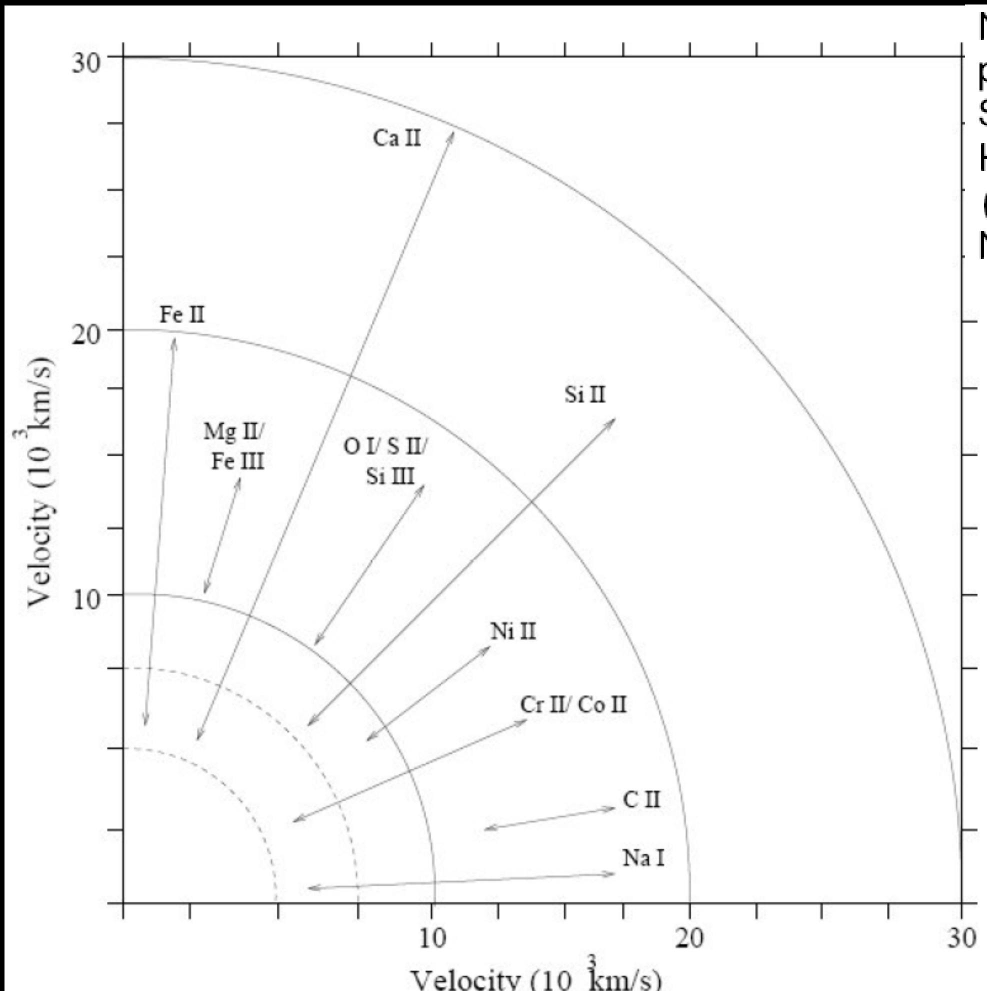


Fig. 11.— The velocity intervals within which the ions were used in the synthetic spectra. The upper bound is the velocity at which the line optical depth fell below 0.1.

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

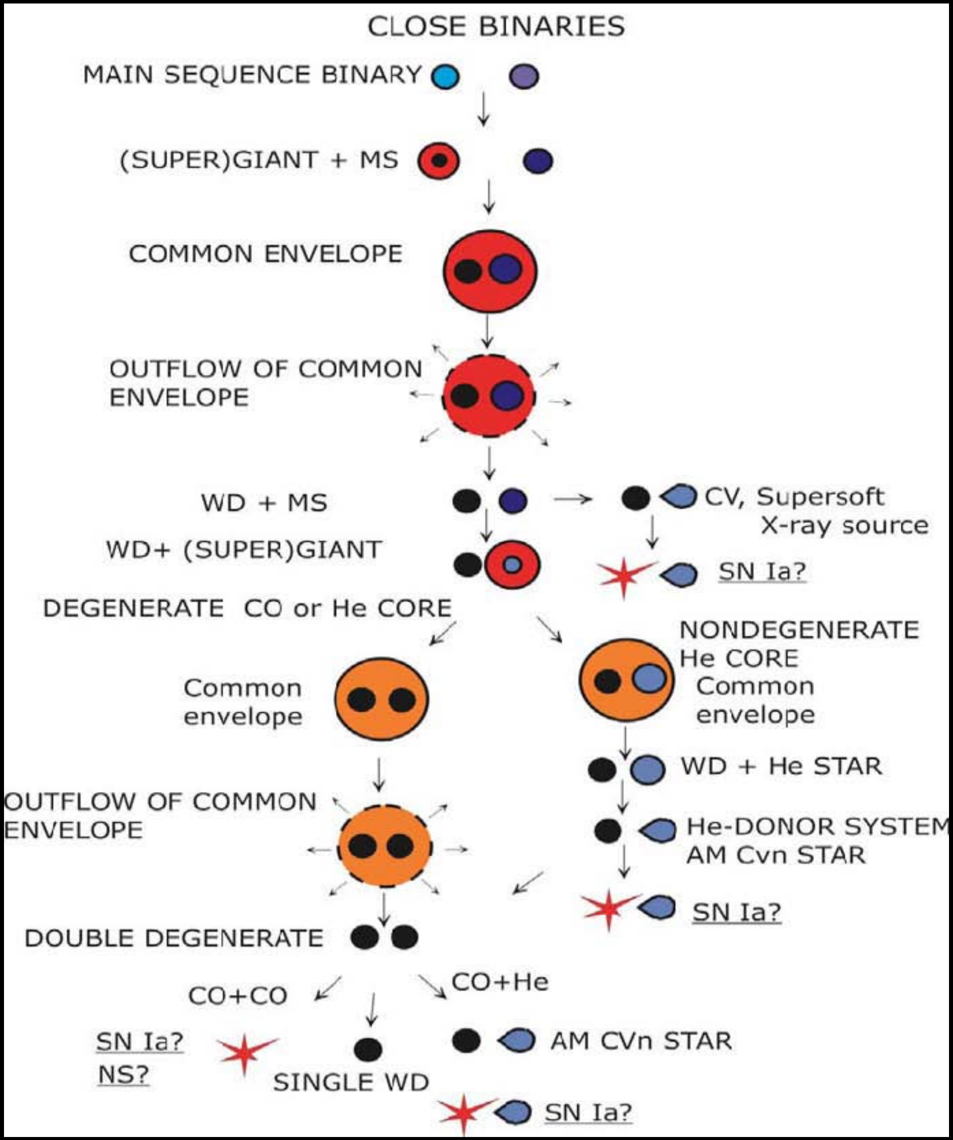
Deflagration

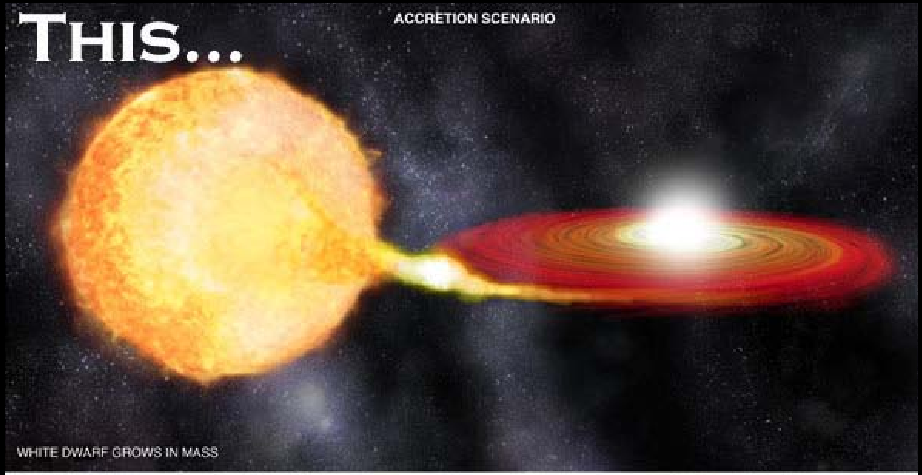
Delayed detonation

Pulsational delayed detonation

The equivalent in 3D also exist

Scenarios leading to a SNIa



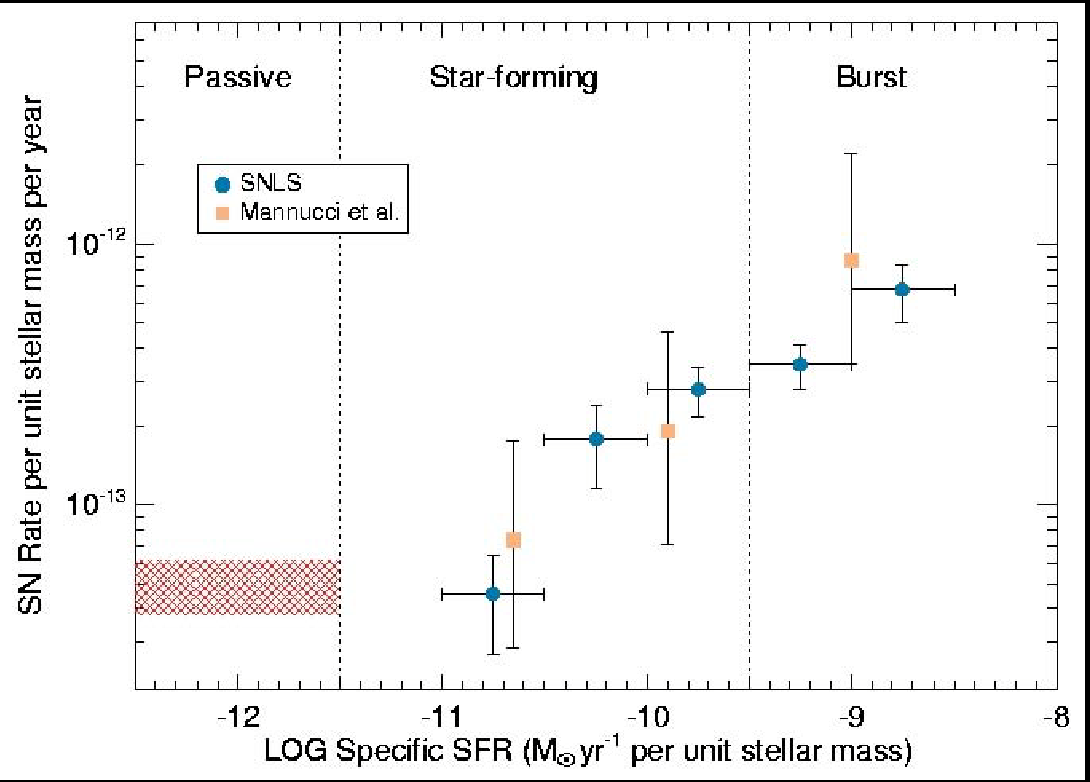


Accreted matter: H or He or C/O

Everything able to explode eventually do it:

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

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



Sullivan et al. 2006

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 $M_{WD} \geq 1.2\ M_{o,}$ but they are made of ONe
- $10^{-6}\ M_o/y > dM_H/dt > 10^{-9}\ M_o/yr$. Hydrogen burns in flashes or syeadily, but for some values 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?

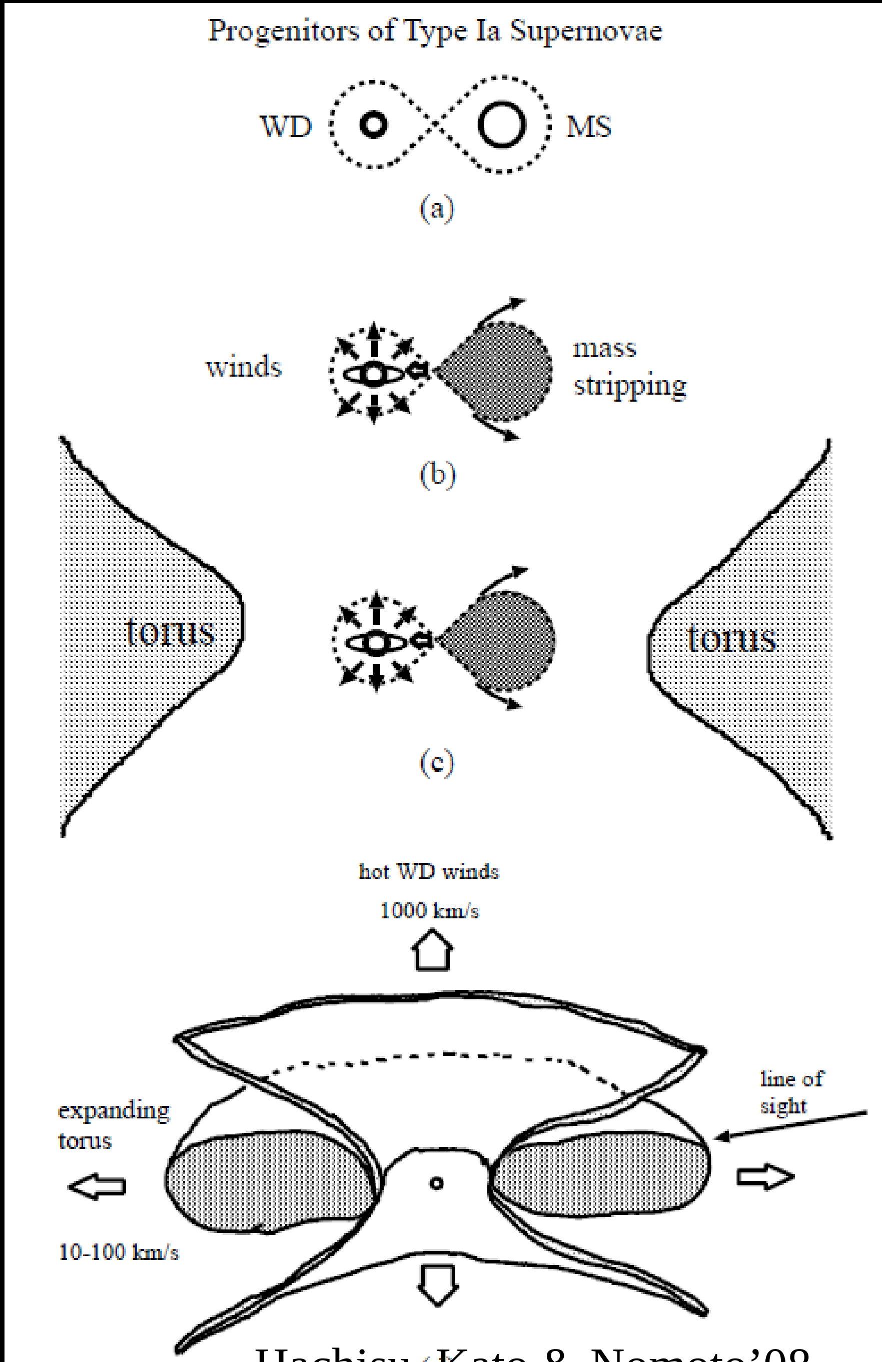
Where is the surviving star?

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

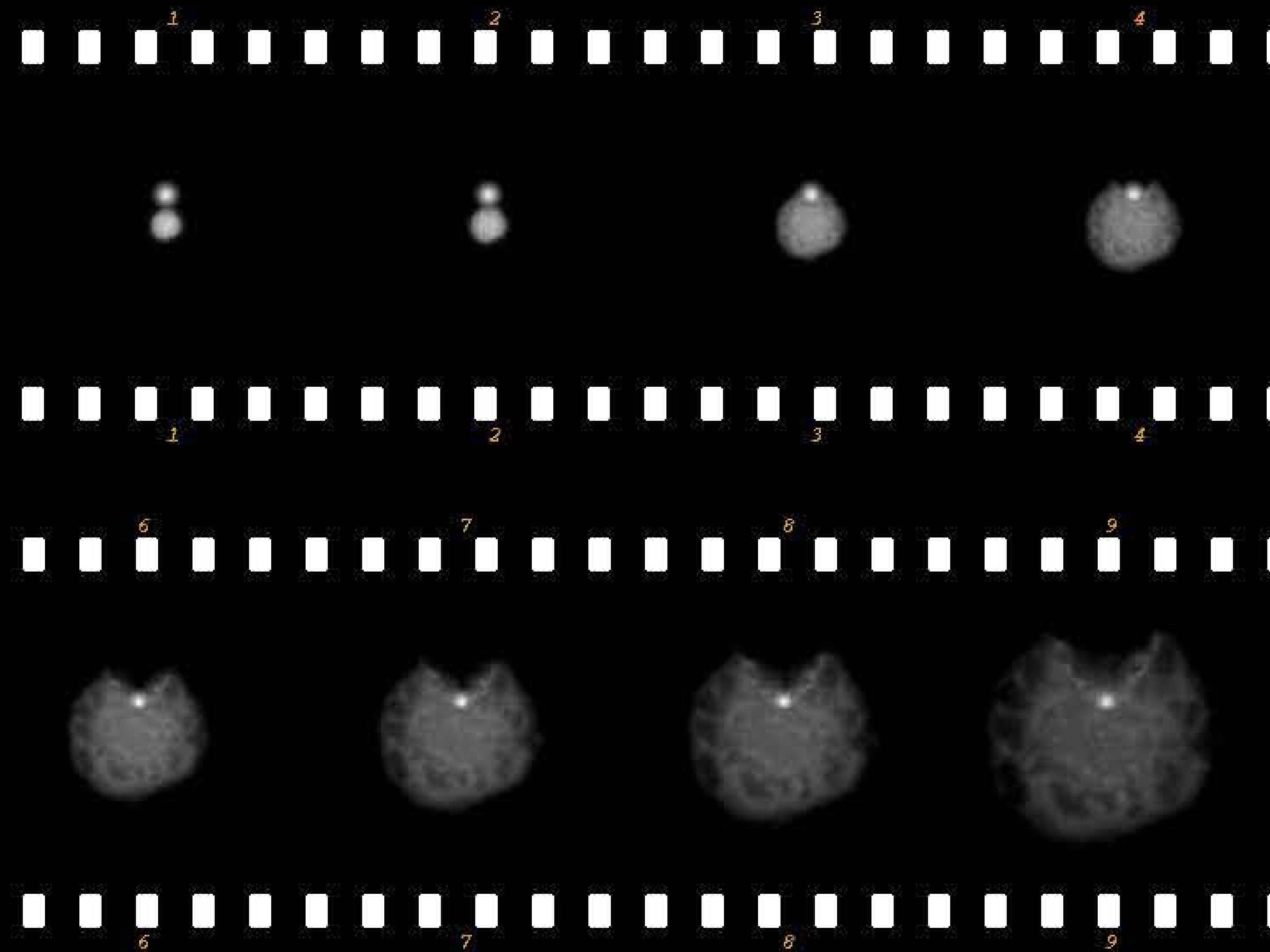
Are they hidden?
 -Heavy winds could do the job
 - If dM/dt decreases with time
 symbiotic/SSS/recurrent novae

Convincing evolutionary paths have been found: Hachisu, Kato & Nomoto'08
Heavy winds appear and forms a massive torus of circumstellar material.

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



Hachisu, Kato & Nomoto'08



1
2
3
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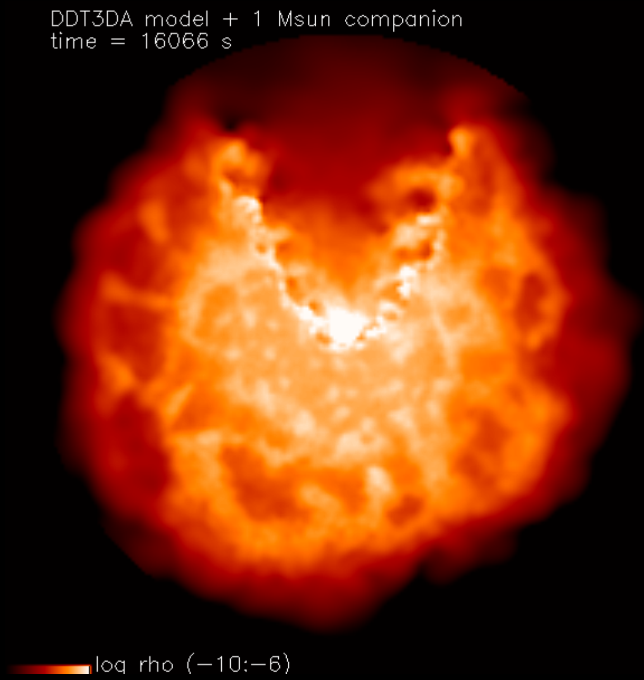
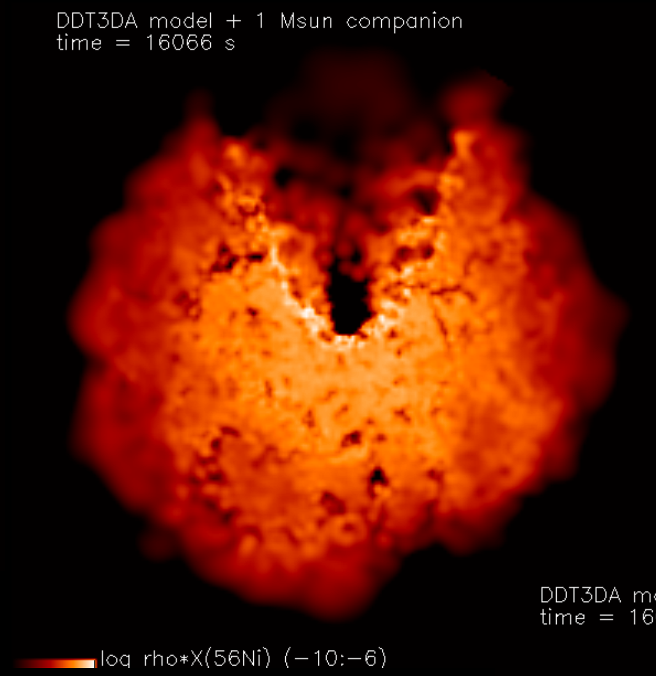
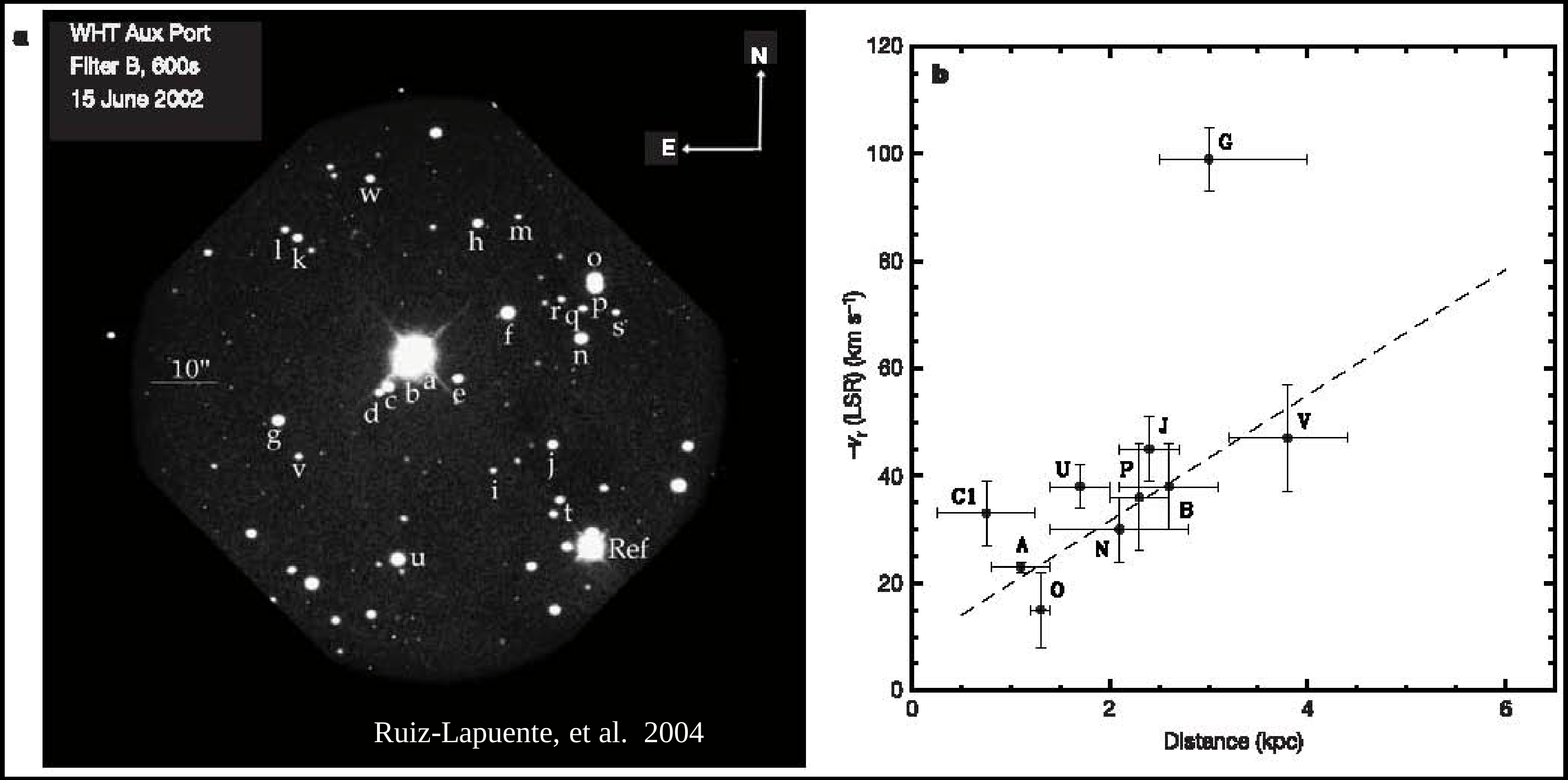




Stripped mass: 0.15-0.53 M_o

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

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

Double Degenerate Scenarios

There are several double degenerate binary systems able to merge in a time shorter than the Hubble time.
They provide the right statistics

The merging process

The less massive star transfers mass to the most massive

As R_2 increases when M_2 decreases, transfer accelerates

$$\frac{da}{a} = -2\left(\frac{1}{M_1} - \frac{1}{M_2}\right) dM_1$$

Conservative transfer

Since $dM_1 > 0$, $da > 0$ and the separation increases

There is a critical value $M_c \sim 0.3 - 0.4\ M_o$

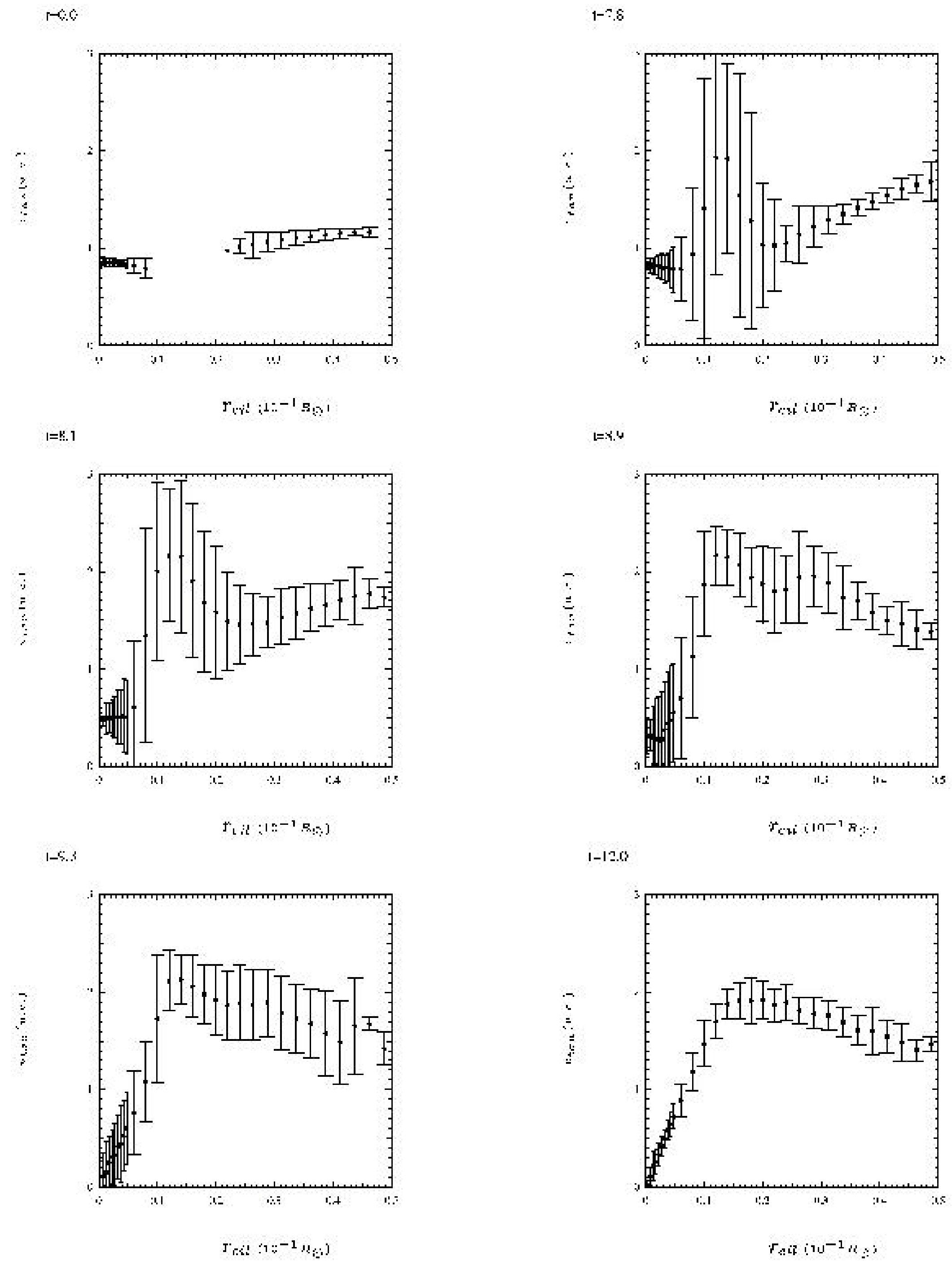
If $M_2 > M_c$ dynamic merging

If $M_2 < M_c$ self regulated merging

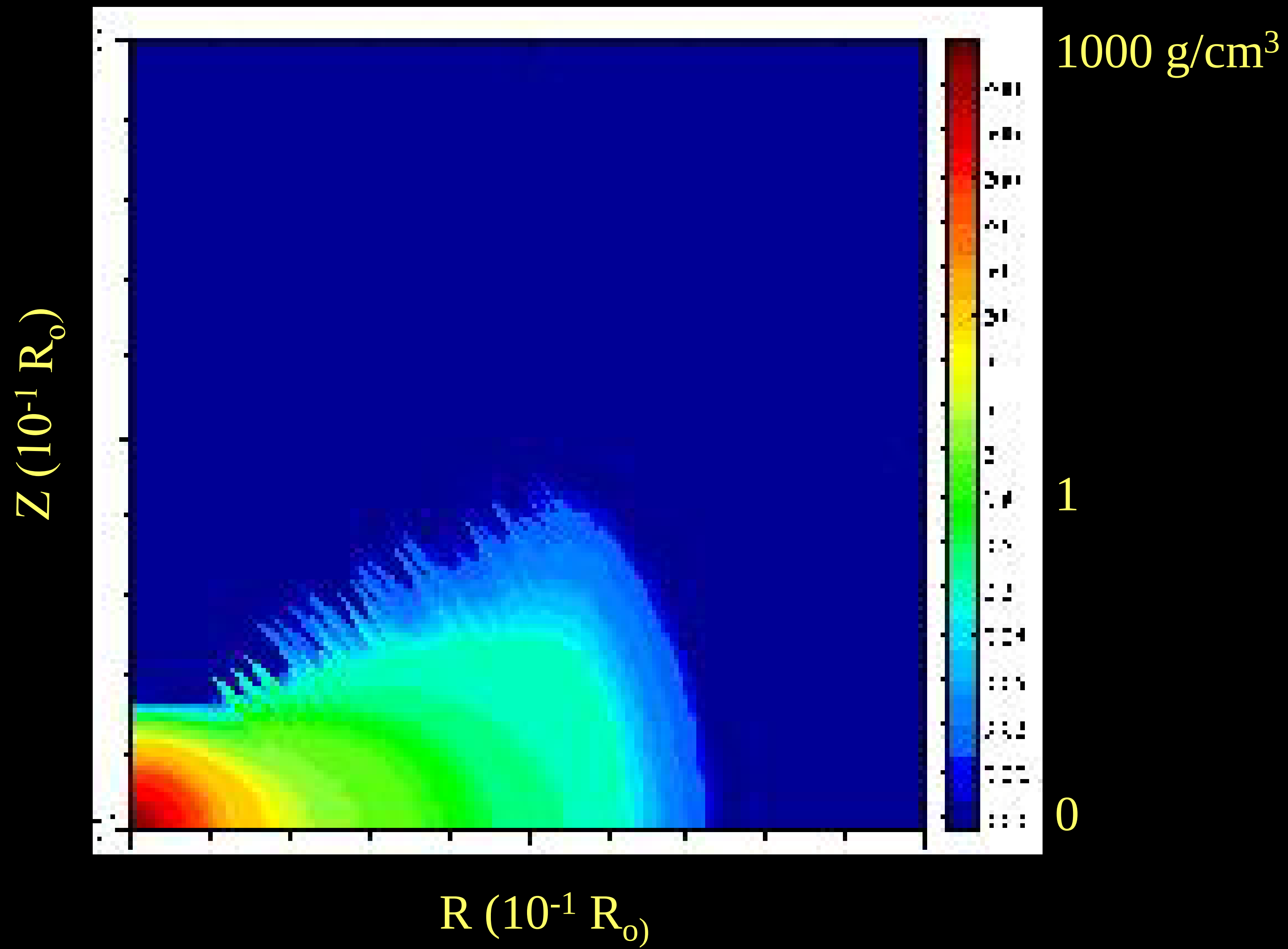
0.6+0.8 case

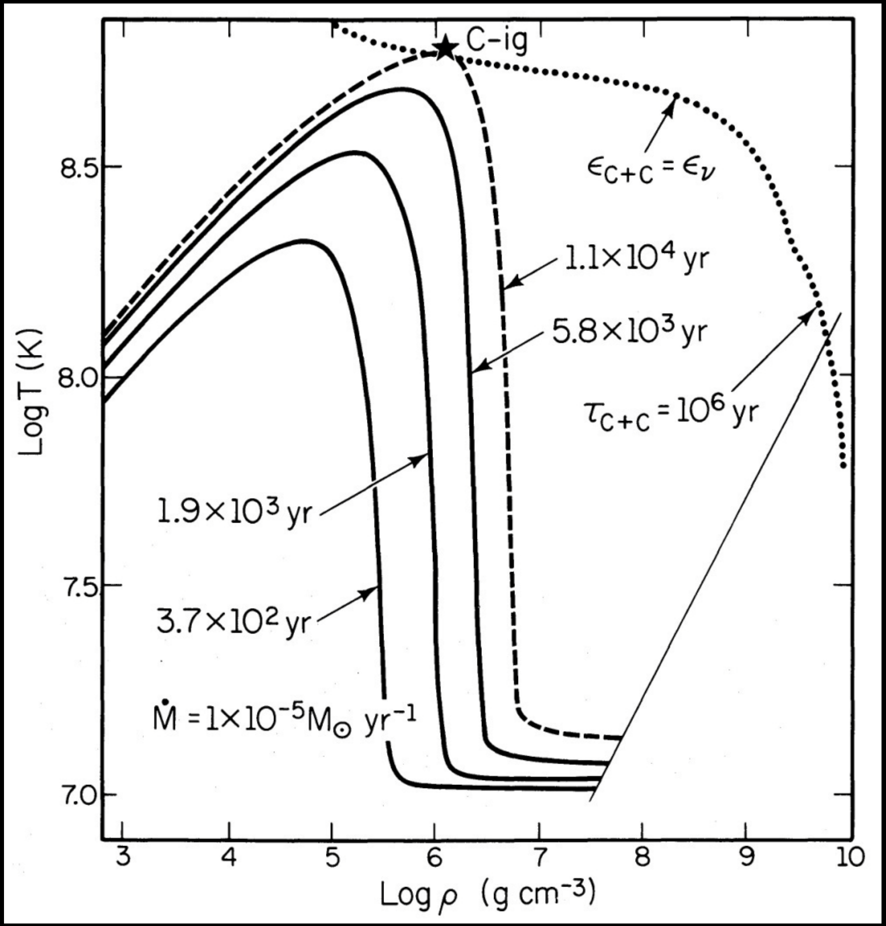
Evolution of the tangential velocity respect to the center of masses

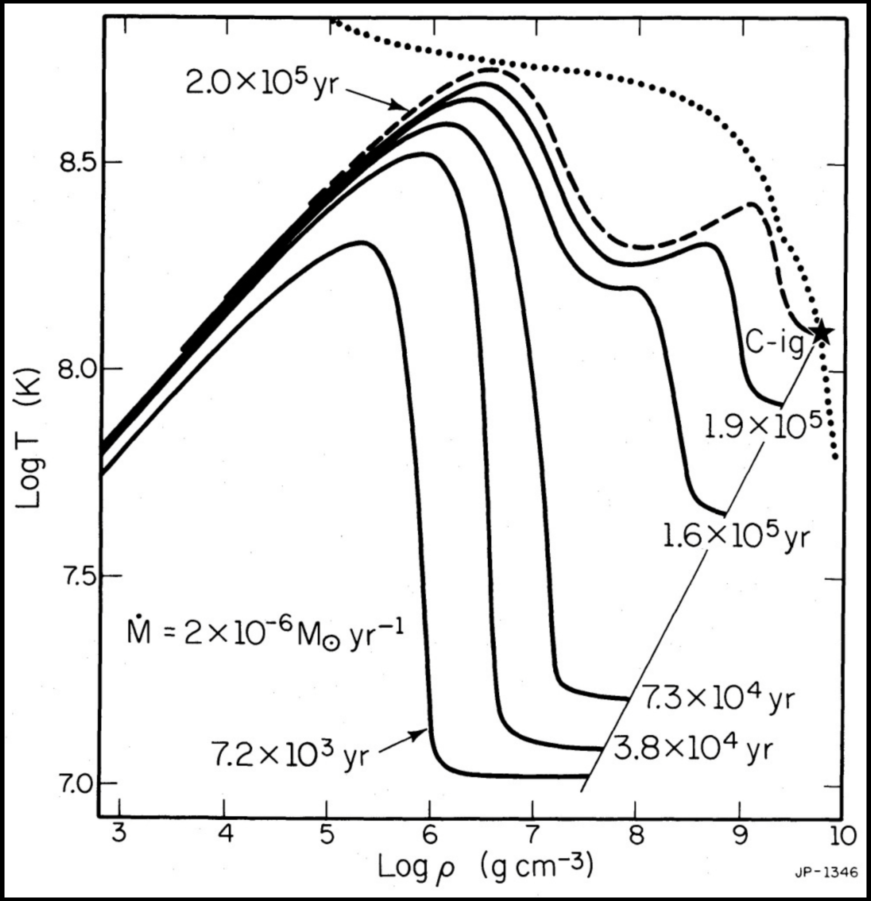
The critical point is the intrinsic viscosity of the SPH methods



0.6+0.8 case Density profiles of the disk



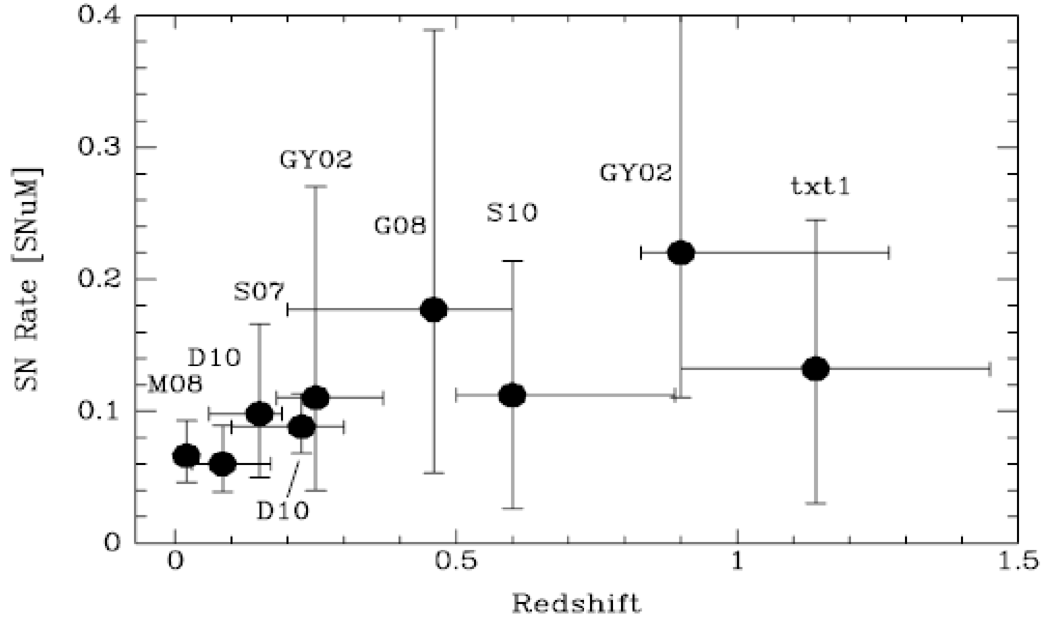




High accretion rates are expected. If they are larger than $2x10^{-6}$ M_o/yr C ignites at the surface, flame propagates inwards and a ONeMg WD forms. The outcome is an AIC (Nomoto & Iben 1985)

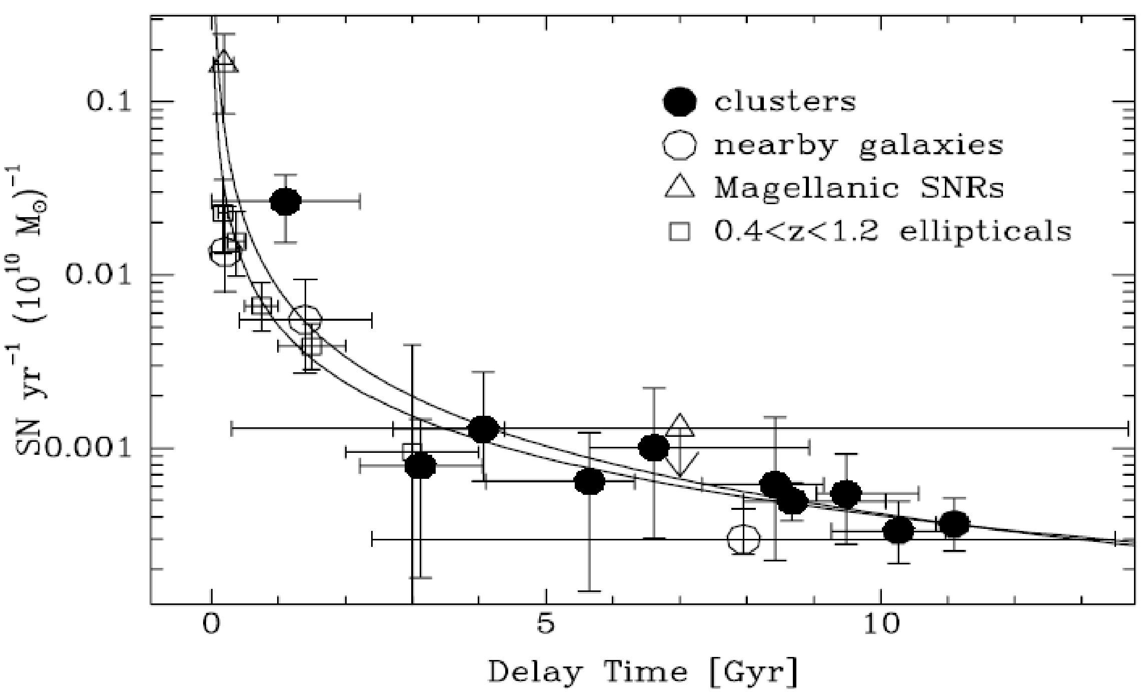
SN rates in galaxy clusters

units: 10^{-12} SN yr^{-1} $Msol^{-1}$



Delay time distribution (DTD)

tails t^{-s} , s = -1.1, -1.3



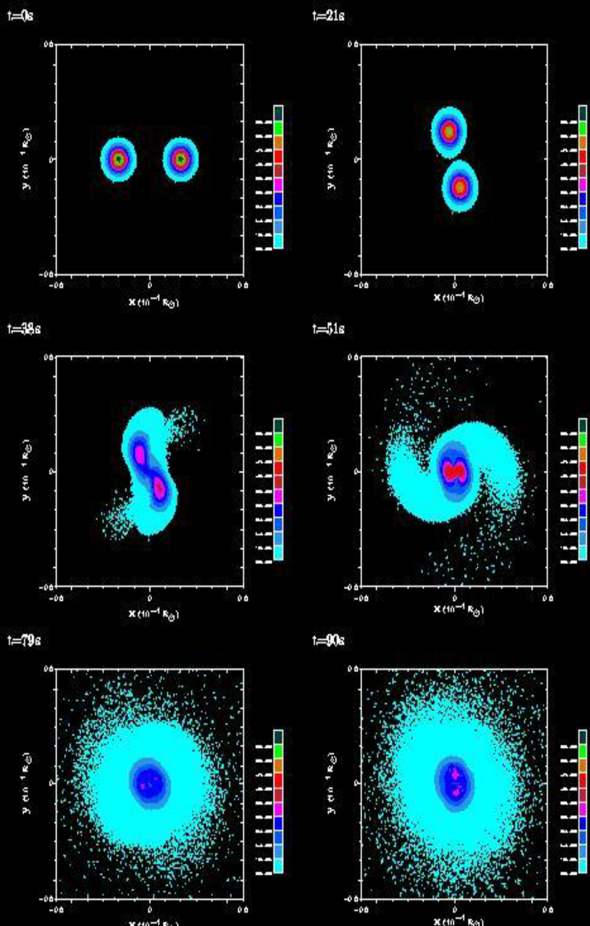
These tails are characteristic of the DD scenario

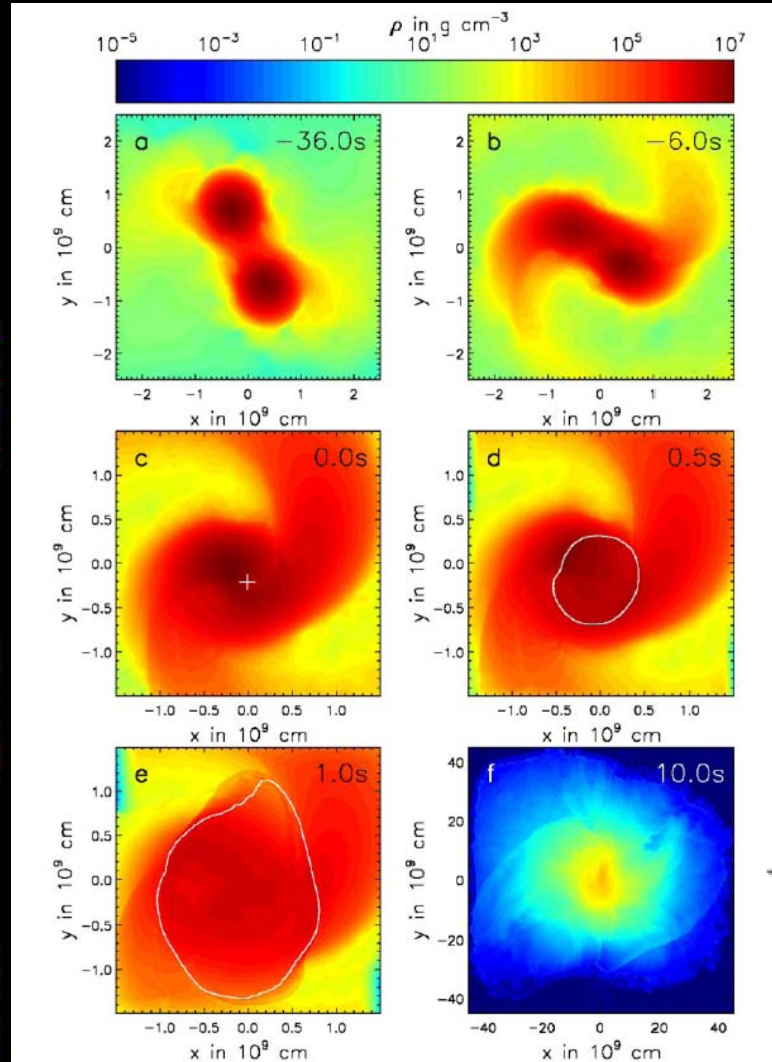
Cannot be reproduced by SD

Maoz et al'10

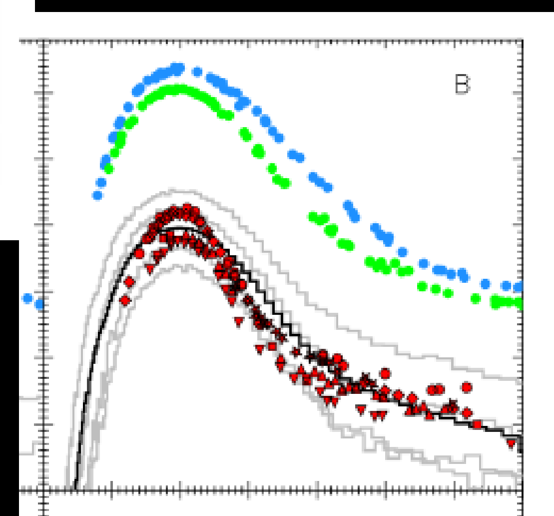
Loren et al'08

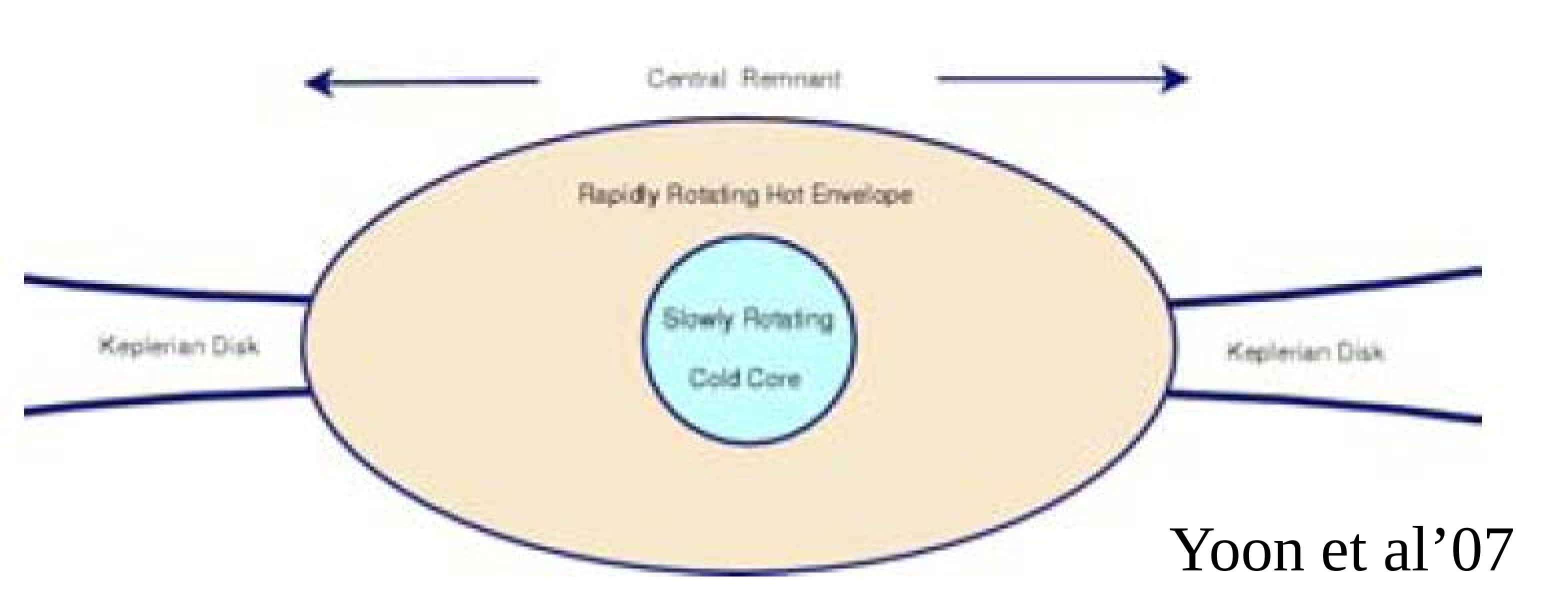
Riemann solver
0.6+0.6 Mo





0.9+0.9 Mo
Pakmor et al'10





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

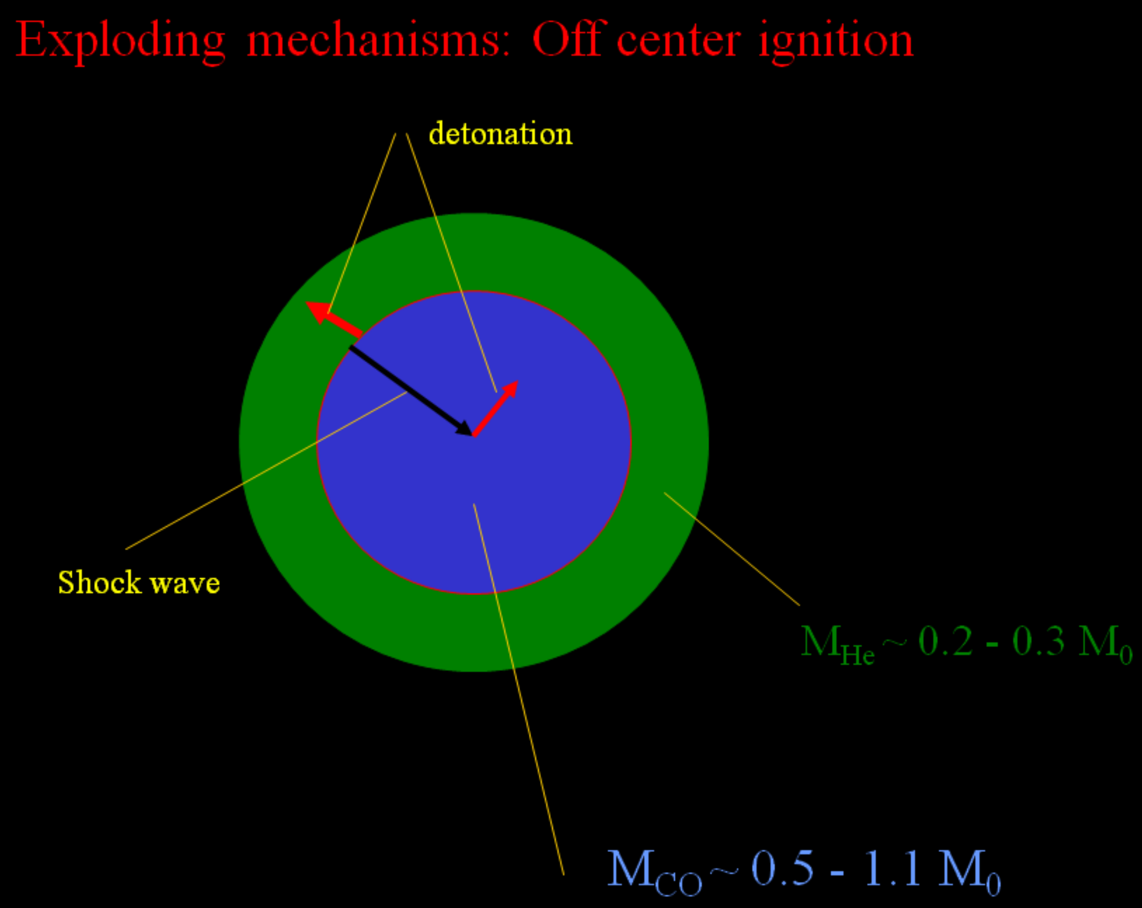
The mass accretion rate dM/dt </~ 5 x 10^{-6} – 10^{-5} M_o/yr

Edge-lit ignition

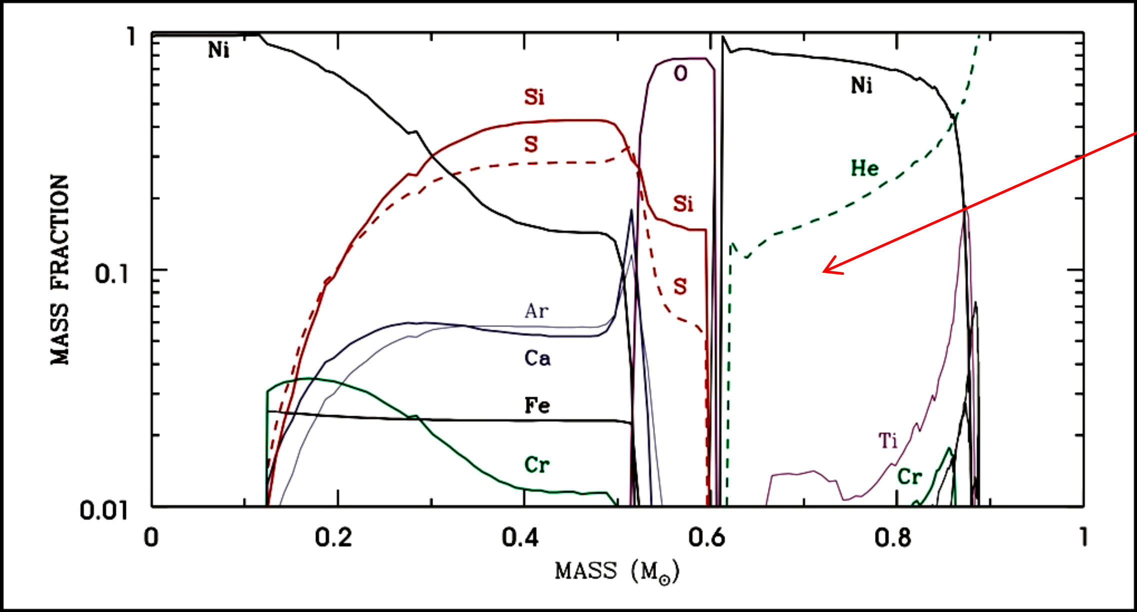
He-accreting white dwarfs

(merging of white dwarfs, CO WD + Helium star)

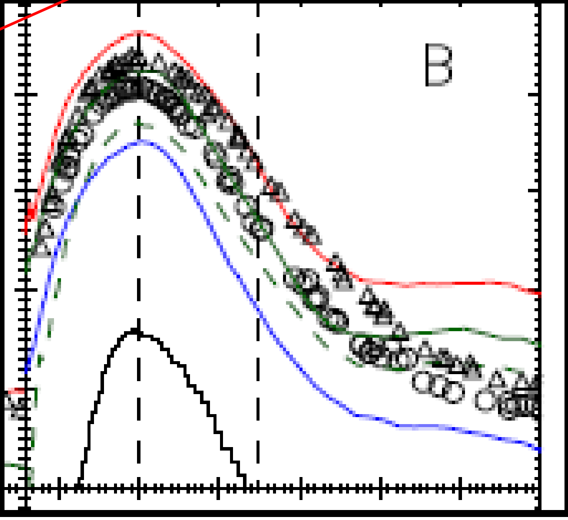
- If $5x10^{-8}\ M_o/y \geq dM_H/dt \geq 10^{-9}\ M_o/yr$. And $M_{WD} < 1.13\ M_o$ an off center detonation forms

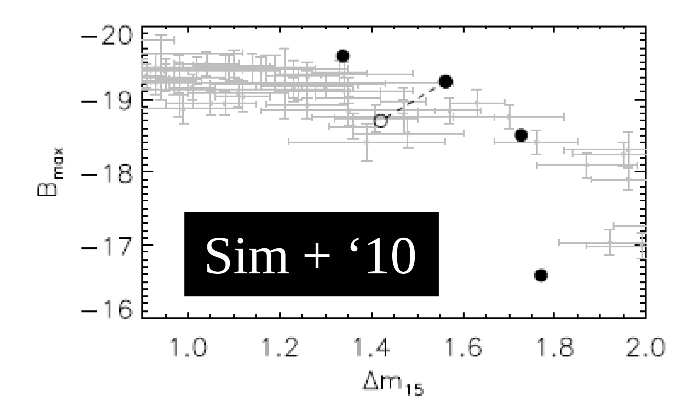


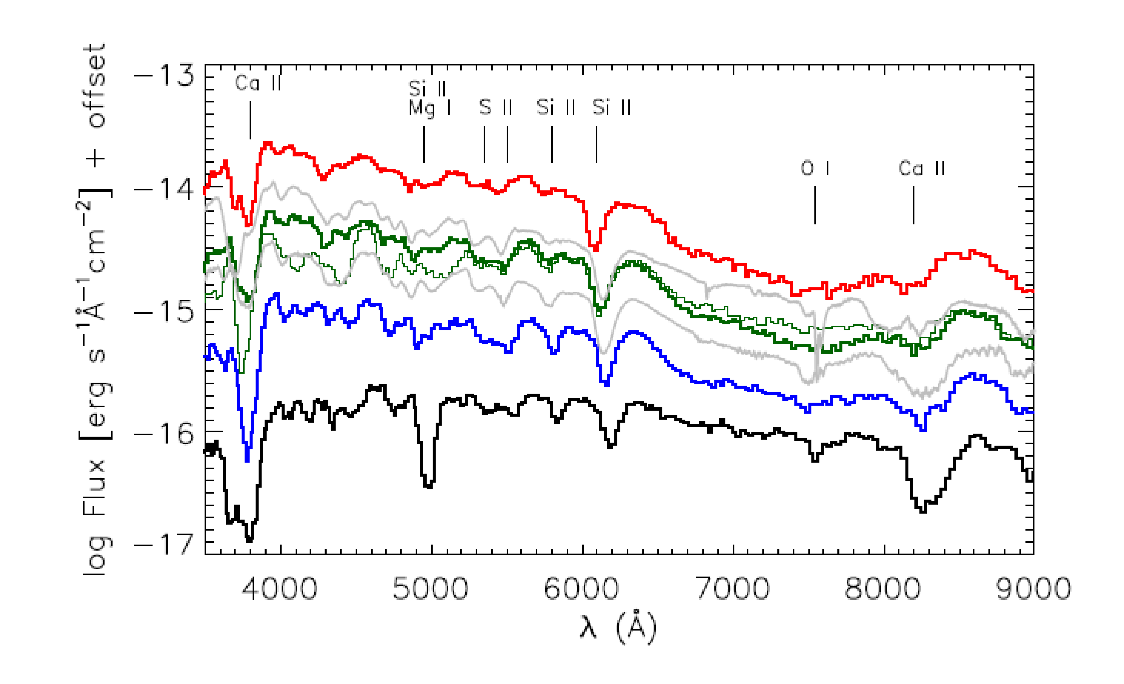
He-detonation



Inconsistent with the observations





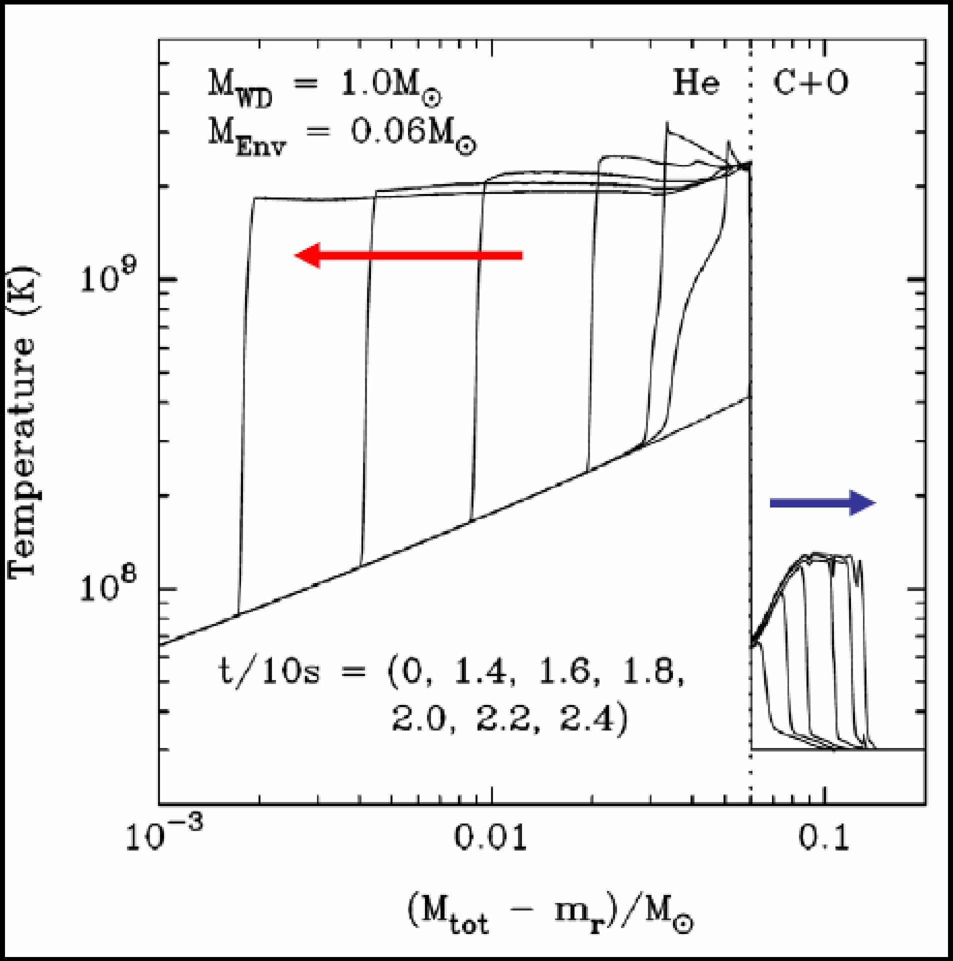


The detailed process of formation of the He envelope is critical
Guillochon et al'2010

Talk by Chamulak

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

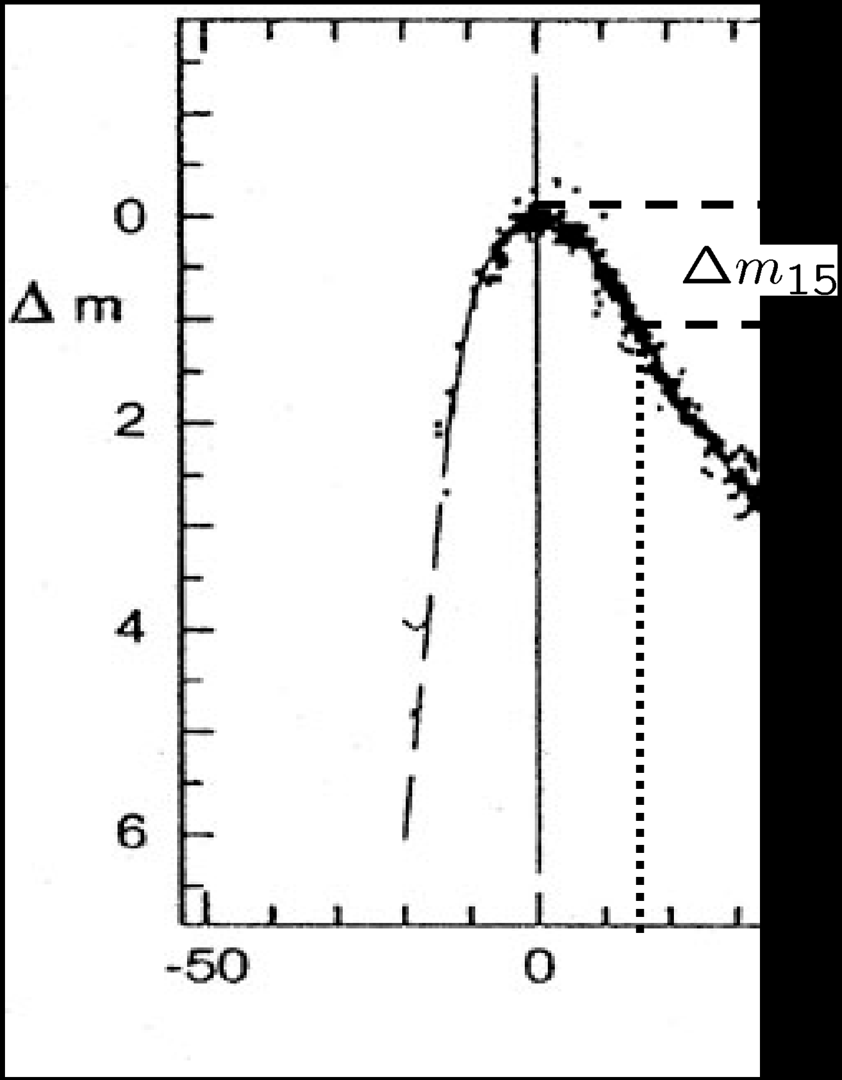


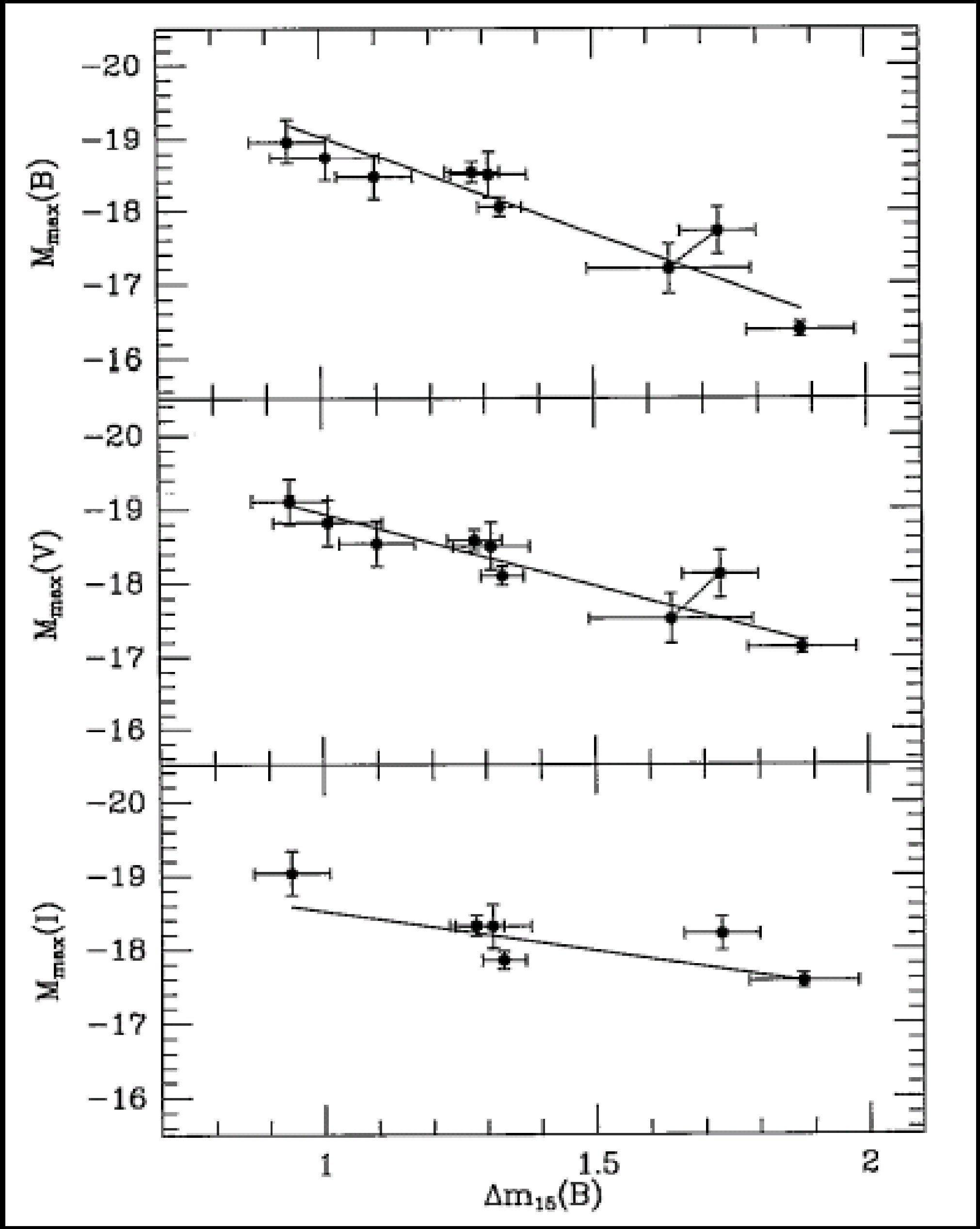
Possible candidates:

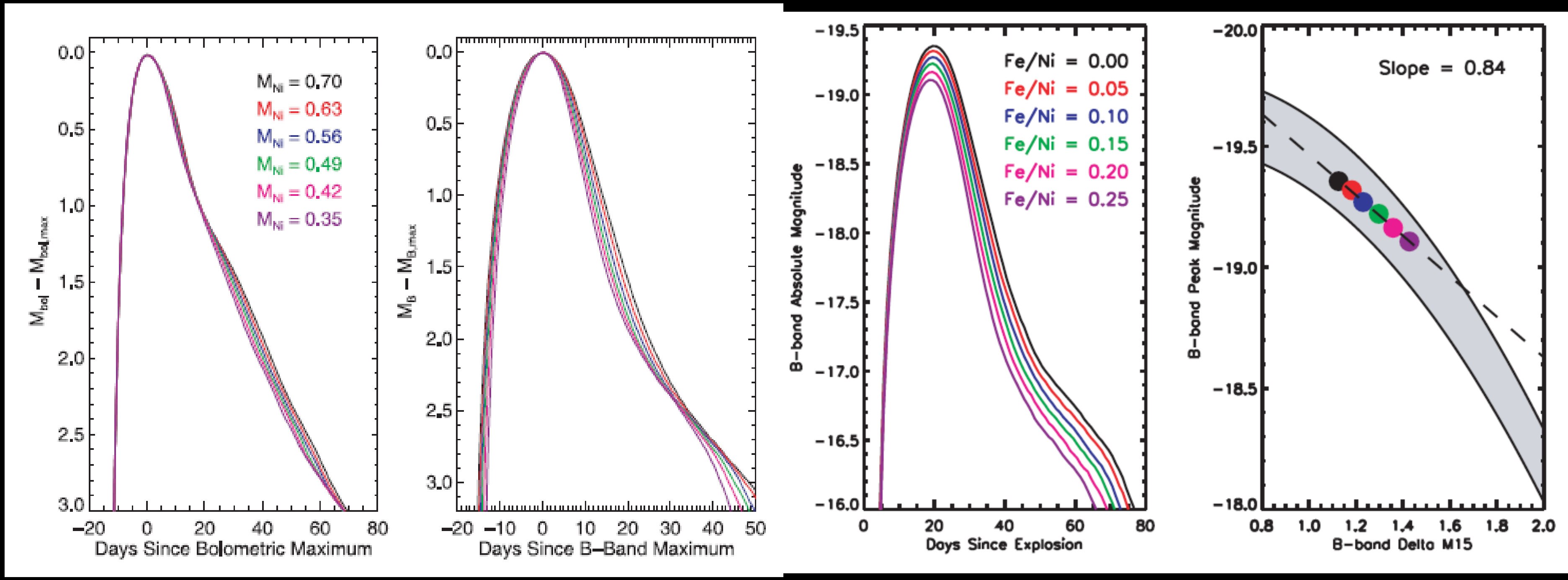
SN2002bj (Poznanski+'10)
SN2005E (Perets +'09)

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

Phillips (1993; ApJ 413, L105)







Origin of the Width-Luminosity relationship

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

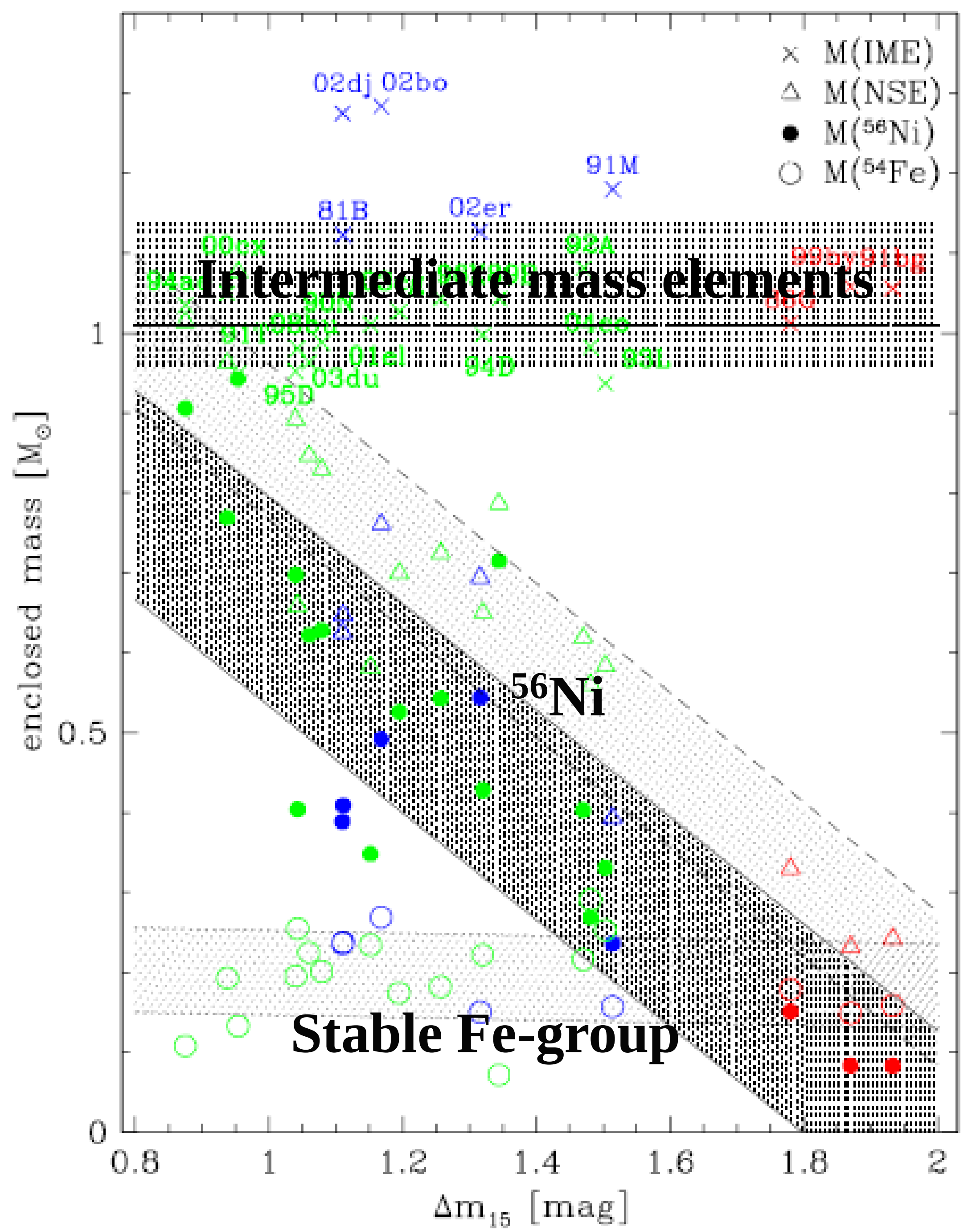
The models have the same kinetic energy, but the Ni mass is substitued by IME

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

ΔM_{15} (B) dpends on M_{ni} mainly but also on additional parameters that can be responsible of internal dispersion in the WLR. The most important are M_{burn} & metal distribution. Figure right: Fe core 0.1 Mo + uniform mixture Ni/Fe + Mb= 1.1 Mo



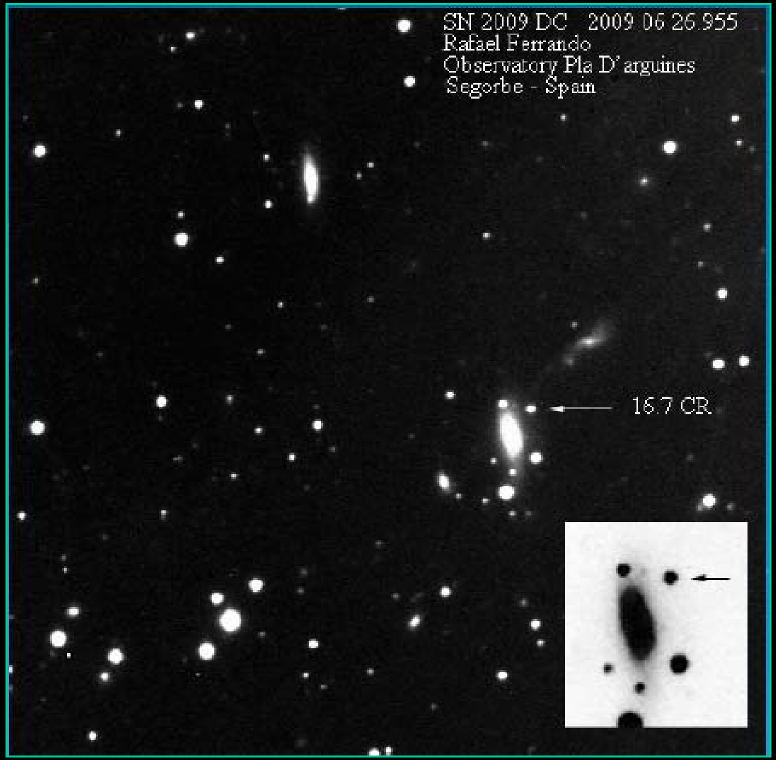
As a first approximation the Δm_{15} relationship can be explained as due to the abundance of 56Ni and the non radiactive products of the carbon incineration.

But why similar stars behave in a different way?

Mazzali et al 2006

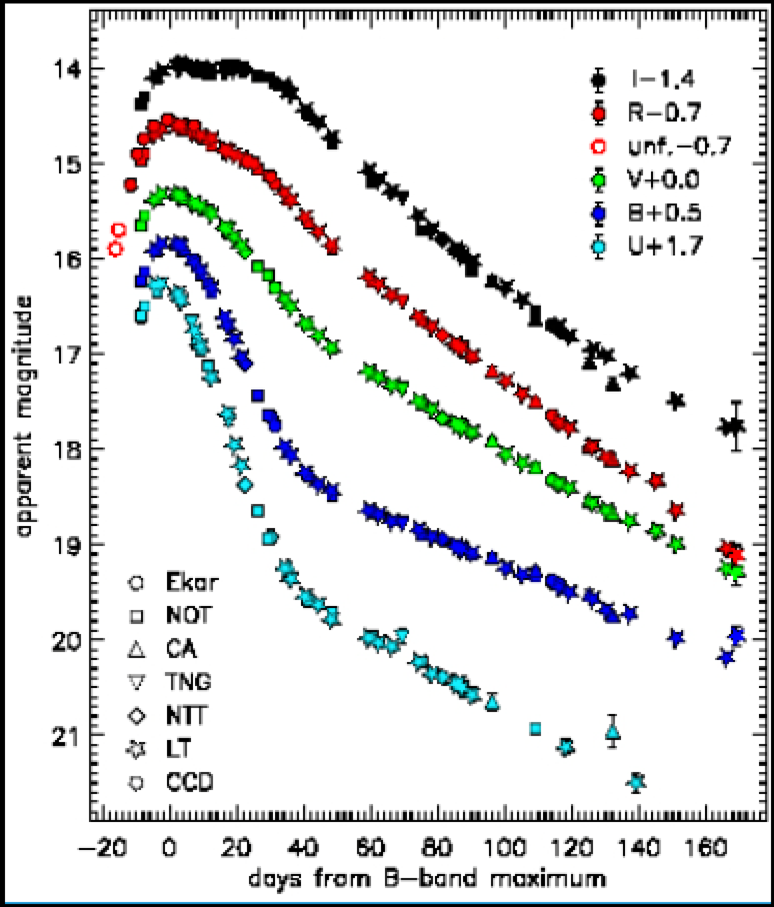
$0.08 < M_{Ni}/M_o < 0.94$

SN2009dc



(from Hilebrandt'10)

- Very bright
- Unusual color
- Slow
- C-rich

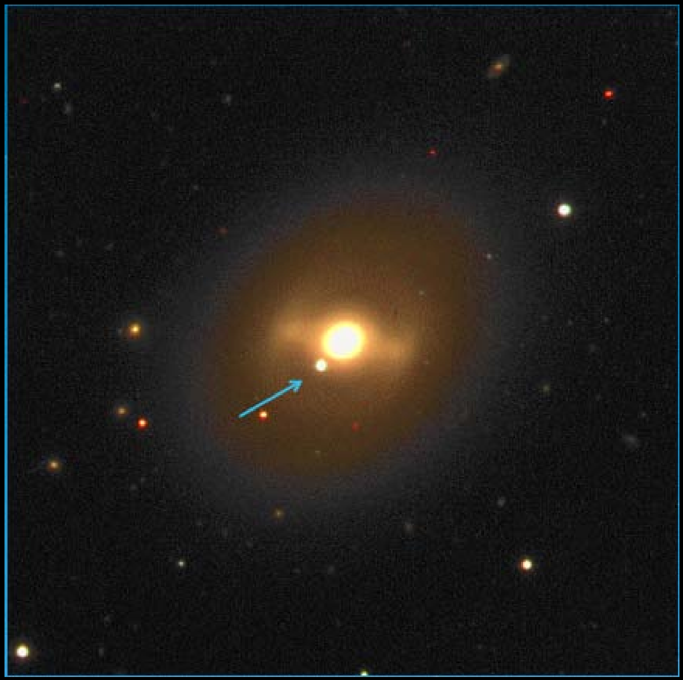


Photometric properties (Taubenberger et al)

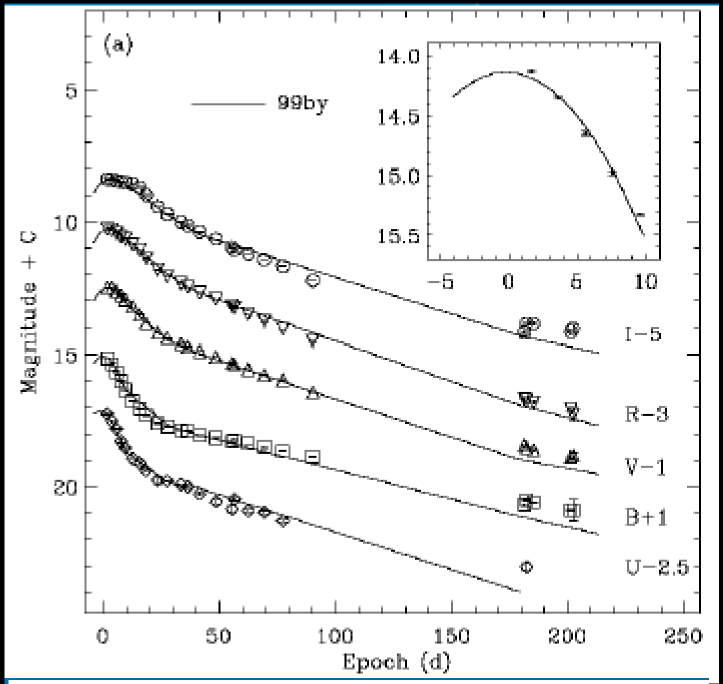
- Typical light curve morphology from SNIa
- Secondary maximum in the I-band
- Slow decline (Δm_{15} (B) = 0.7)
- Very bright at maximum: M_{peak} ~ -20.1
- Unusually blue U-B color at early times

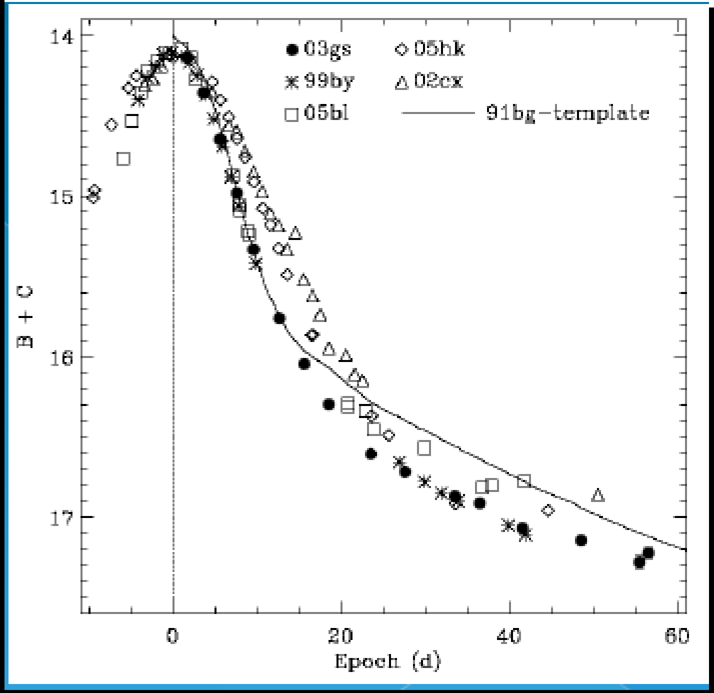
SN 2003gs

(from Hilebrandt'10 & references there in)



- Bright
- Red
- Fast



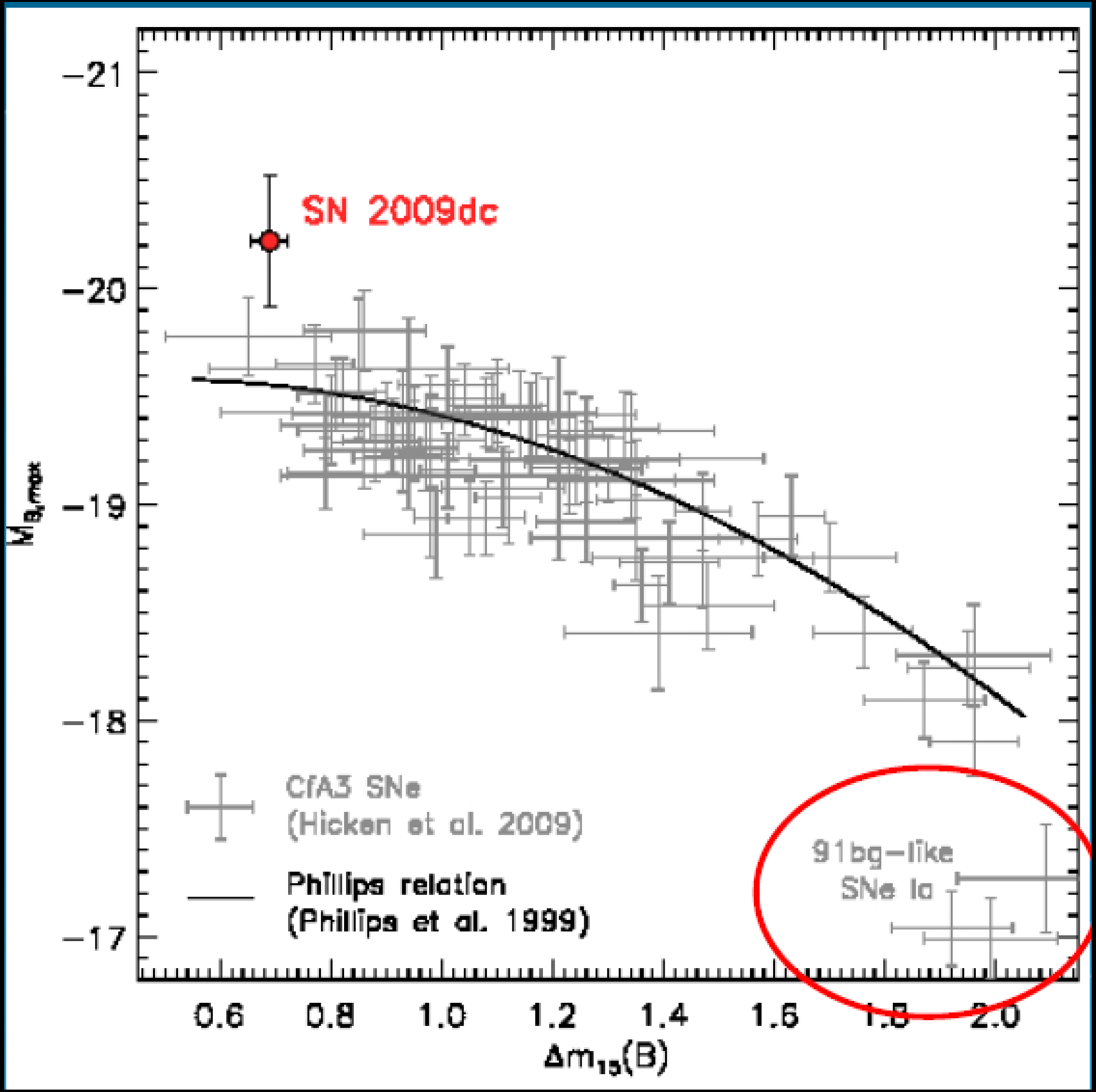


Similar to 91bg like:

* Rapid luminosity decline (Δm_{15} (B)=1.83)
* No secondary I-band maximum

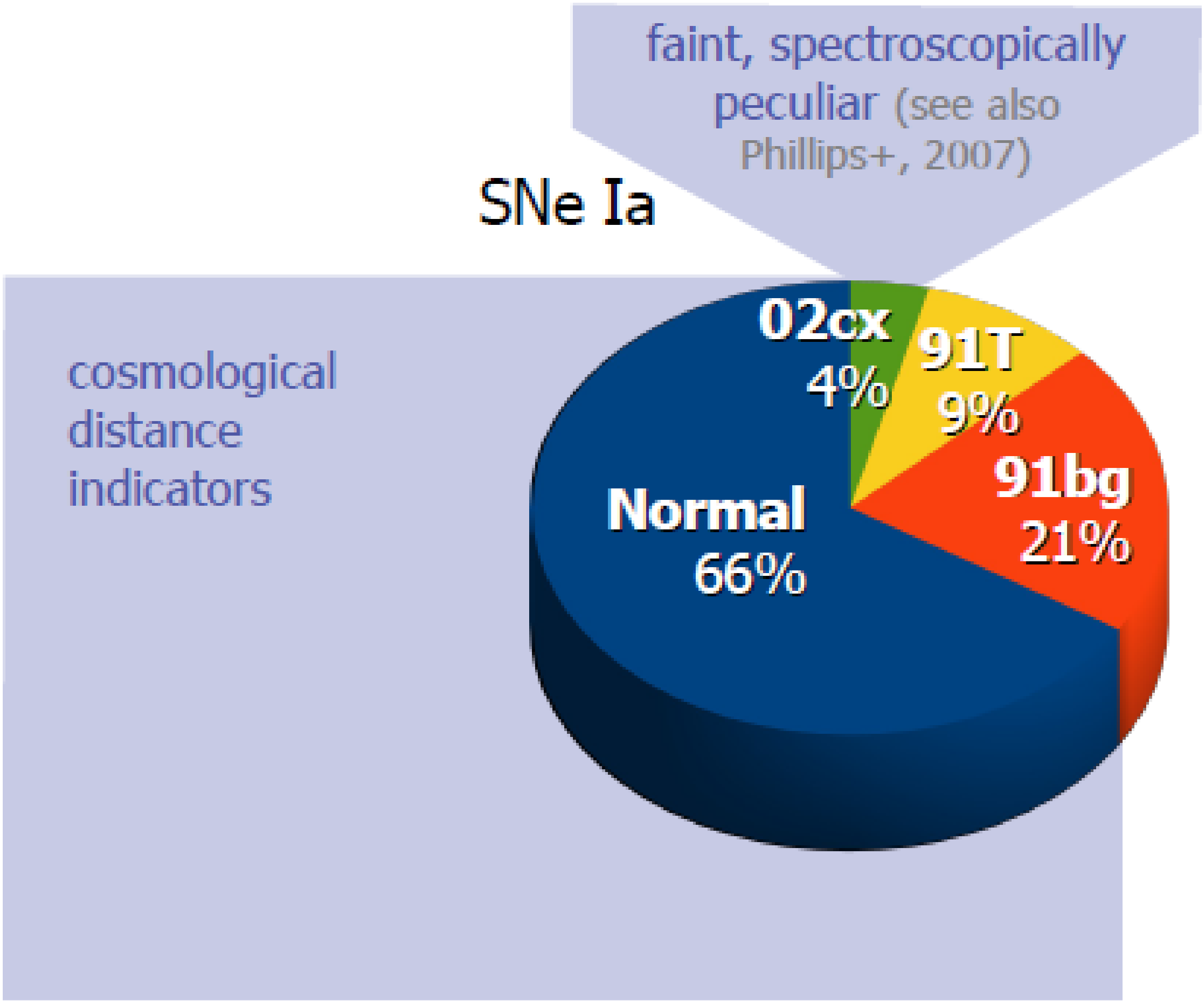
but…

- M_{peak} ~ -18.3, about 1^{mag} brighter then the prototype
- $M(^{56}Ni)$ ~ 0.25 M_o (~ 0.1 M_o for 91bg-like)
- It violates the width-luminosity relationship!



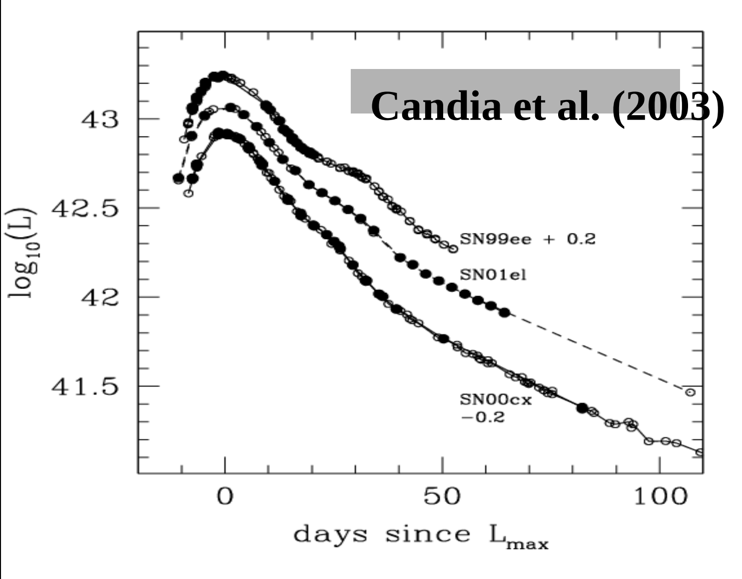
SN 2009dc
CfA3 SNe
(Hicken et al. 2009)
Phillips relation
(Phillips et al. 1999)
91bg-like
SNe Ia
−21
−20
−19
−18
−17
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Δm15(B)
MB,max

- volume-limited (Filippenko, Santa Barbara, Aug 2009)



Bolometric light curves

- provide global parameters
  - size
  - nickel mass
  - ejecta mass
  - explosion energy
  - (distances)
  - indicate the total energy output/conversion from γ-rays



M. Stritzinger et al.: Bolo

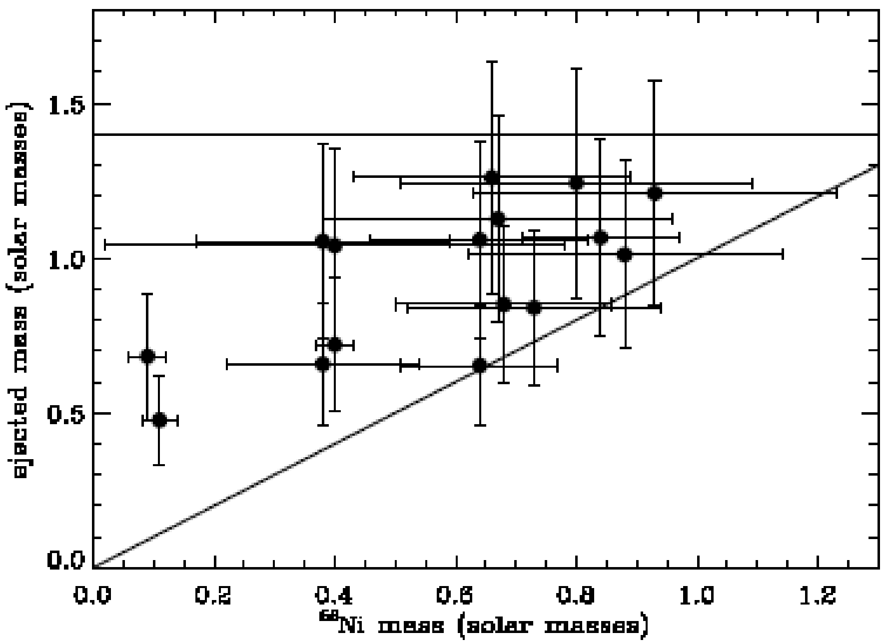
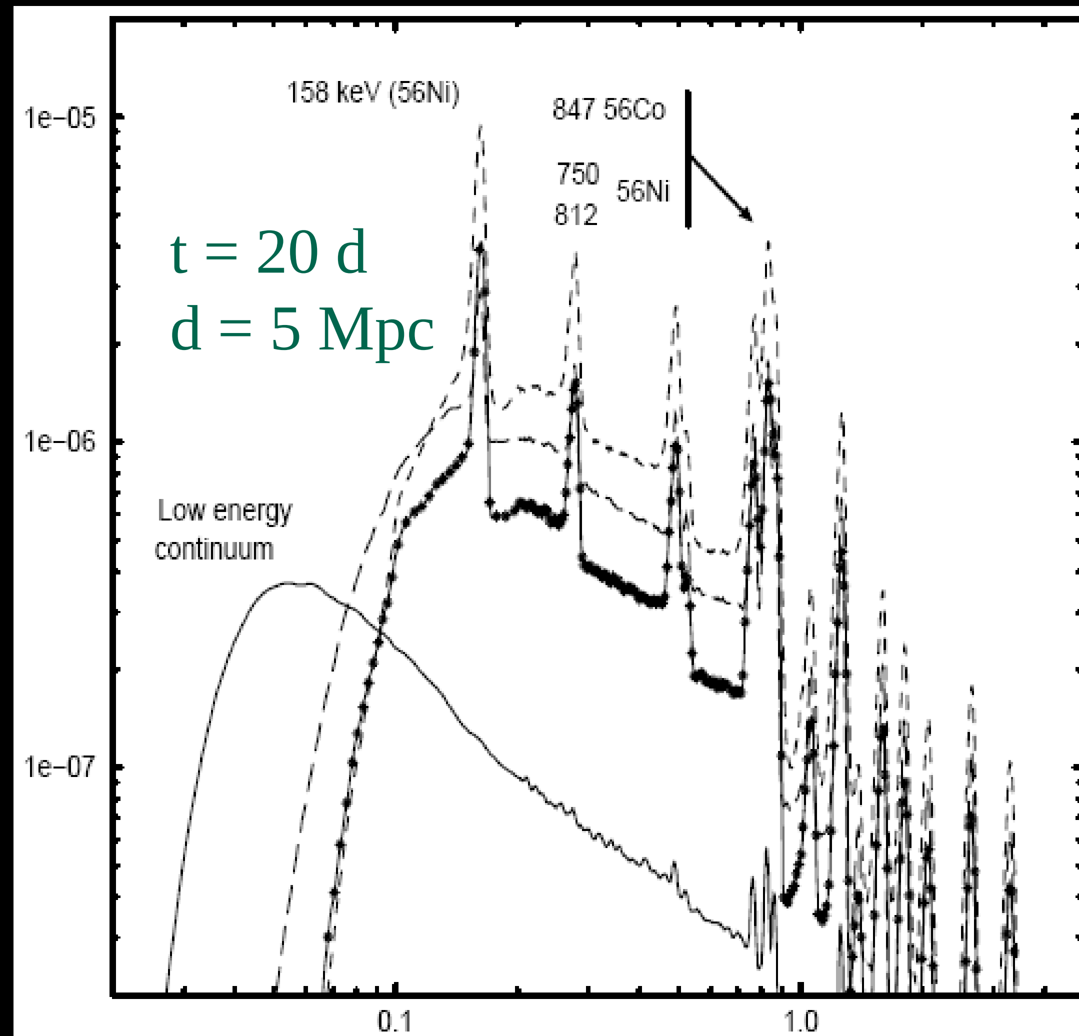


Figure 4 Ejected mass plotted vs. ^{56}Ni mass for 16 SNe Ia. Units are in solar mass. See text for comments concerning the error bars.
Solid horizontal line indicates the Chandrasekhar mass. Slanted line has a slope of 1.

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

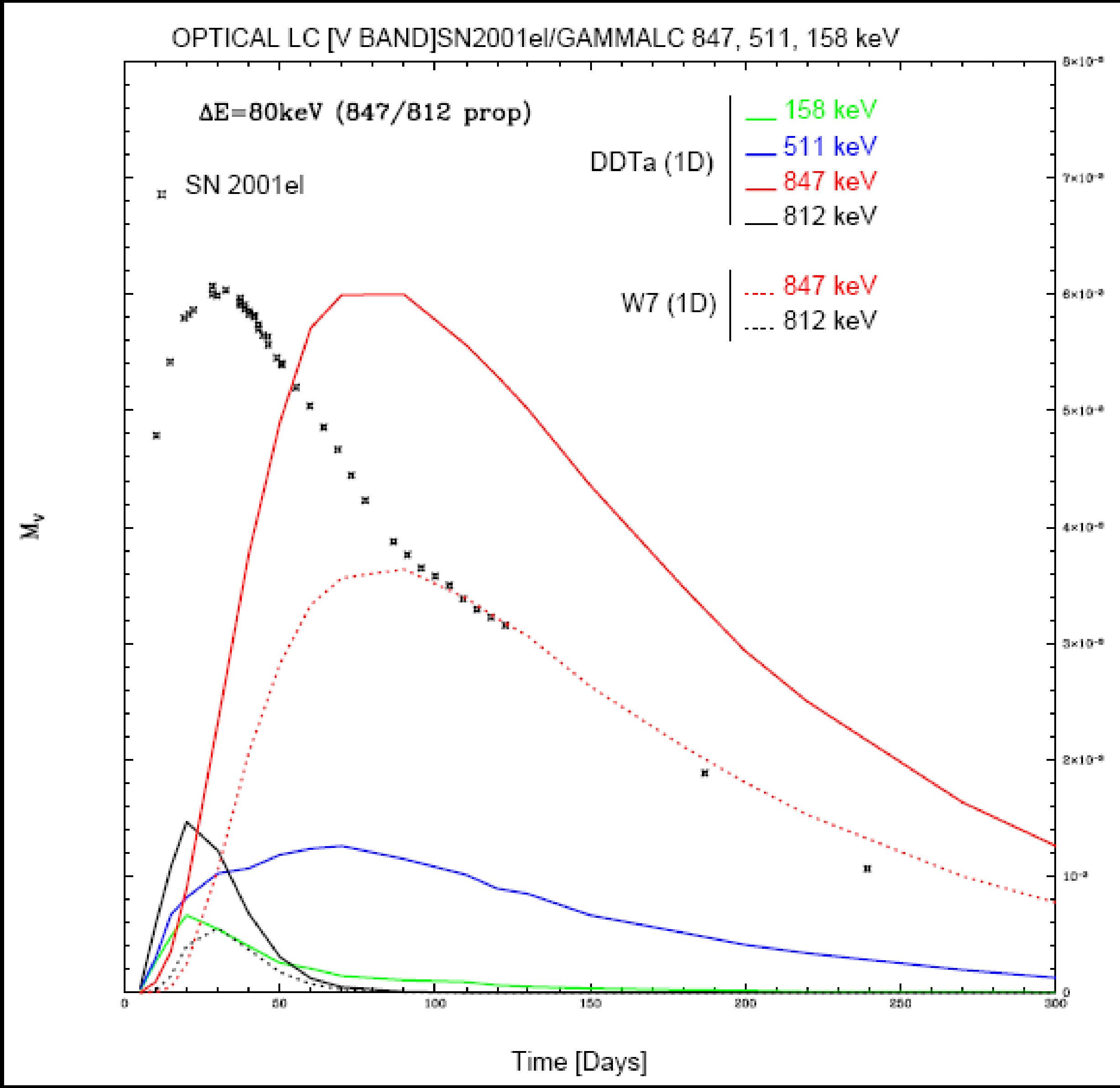
Flux
($cm^{-2}s^{-1}keV^{-1}$)



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

Energy (MeV)

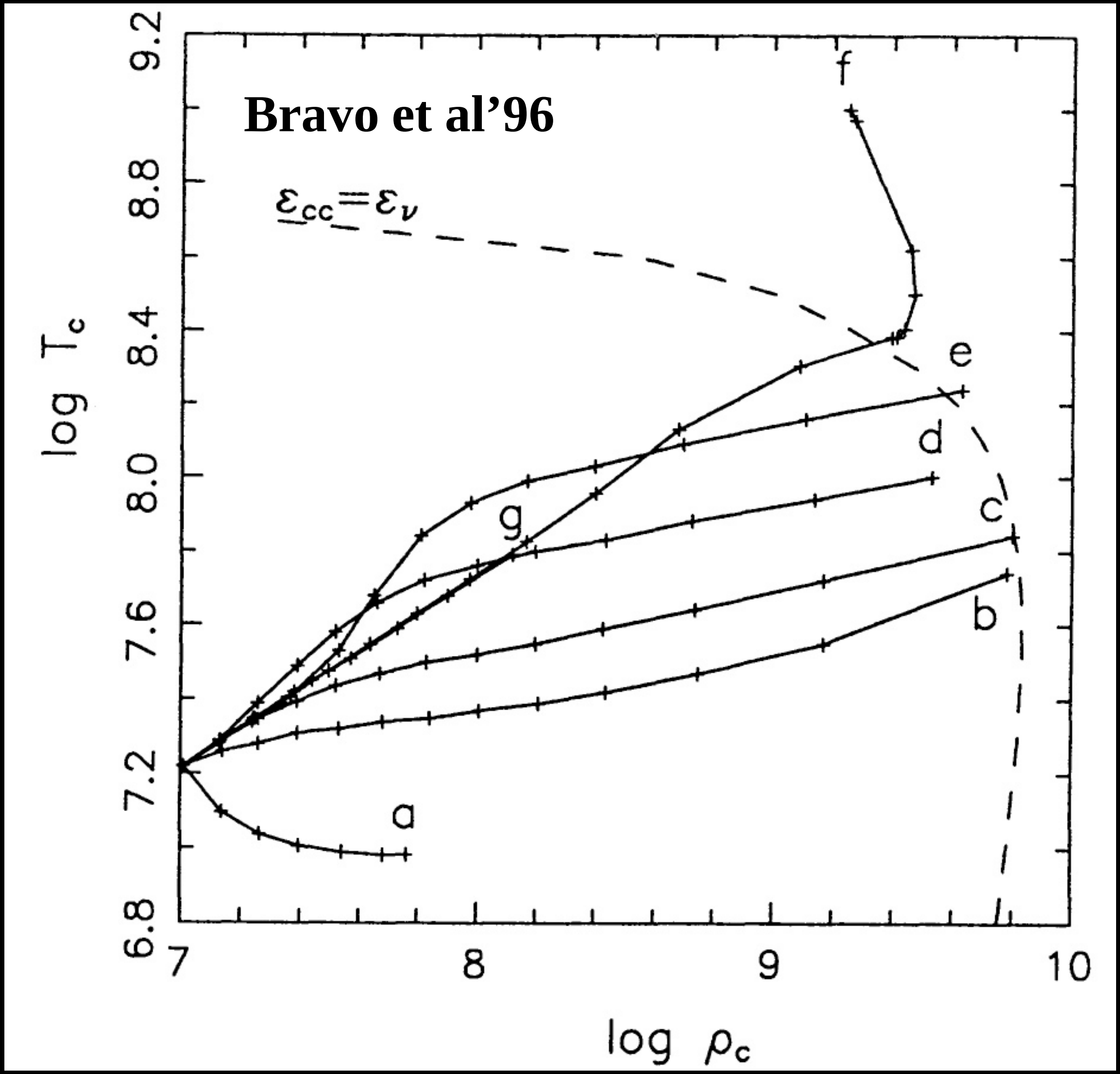
Gómez-Gomar, Isern, Jean 1998, MNRAS 295, 1



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

See Leising's poster

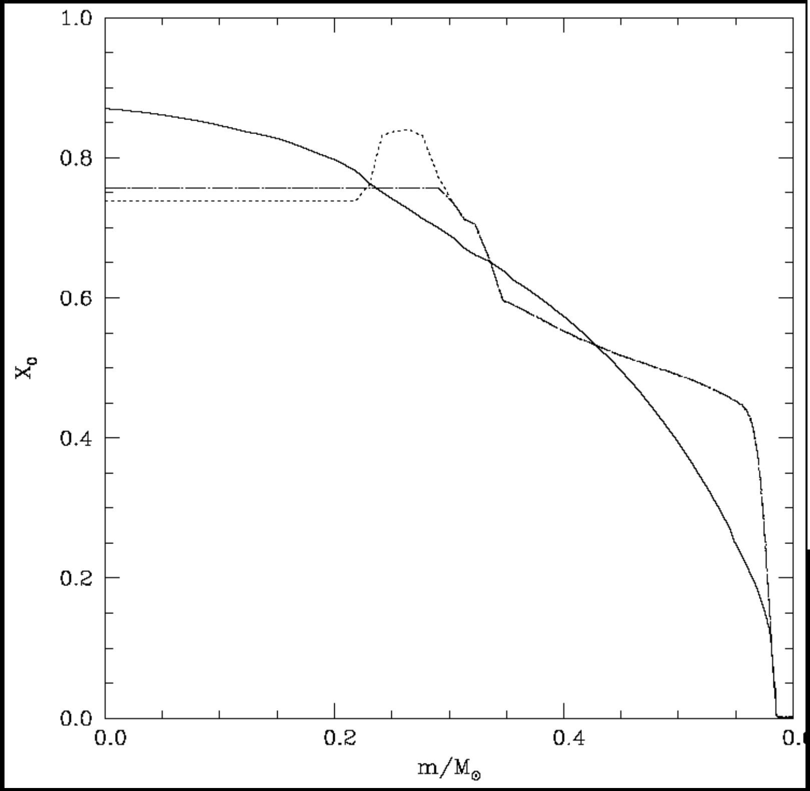


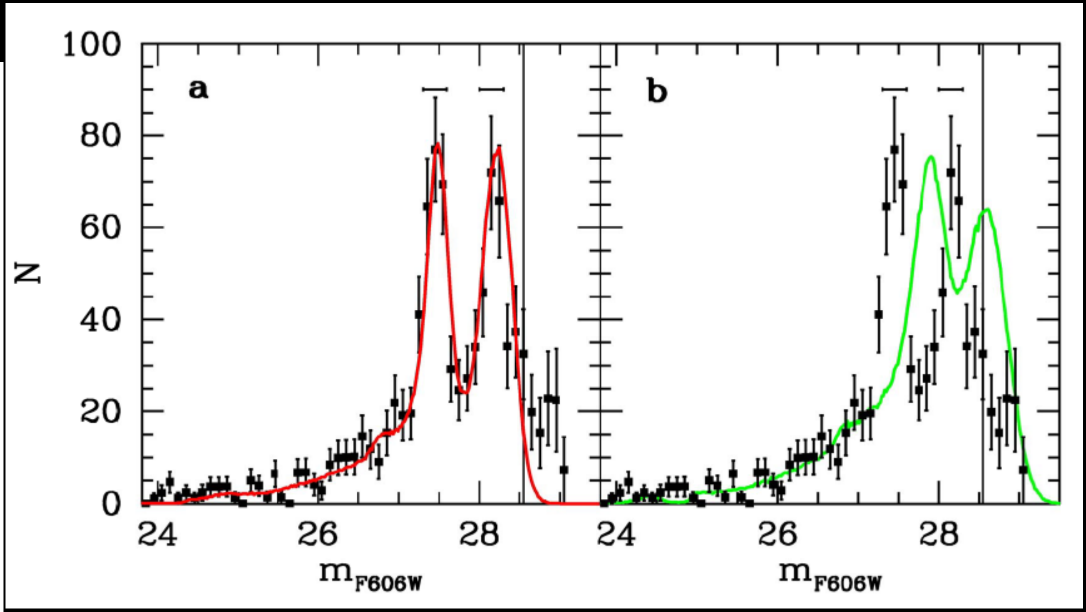
The velocity of the burning front depends on the density and chemical composition

Electron captures behind the front

White dwarfs start to crystallize after ~ 1 Gyr

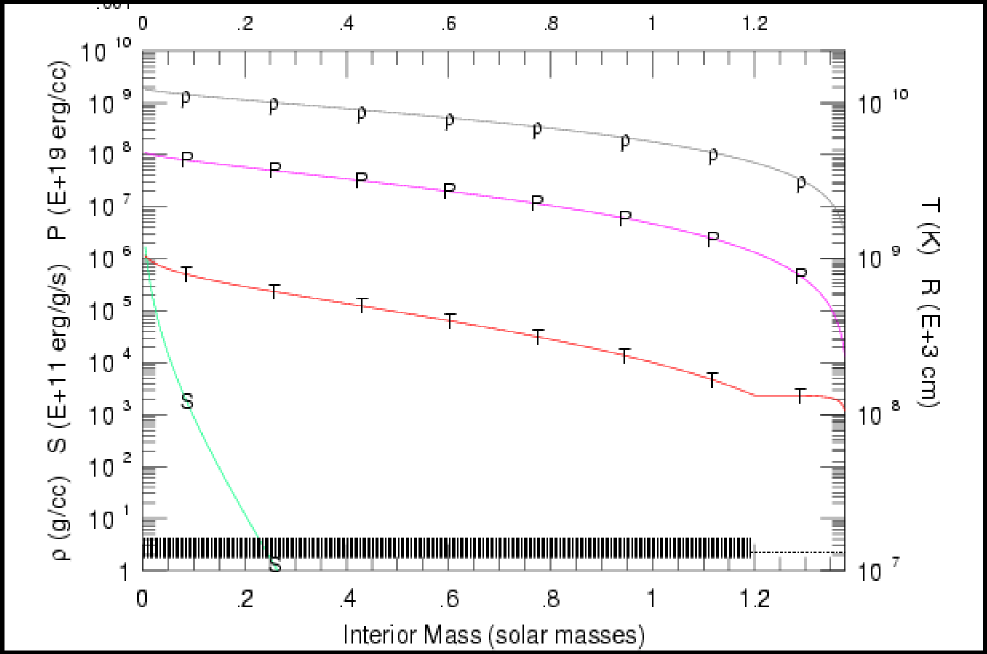
The initial profile depends on the M_{WD} and on the metallicity
^{56}Fe migrates towrds the center with X_{56} ~ 0.2
^{22}Ne follows ^{12}C and ^{16} O but diffuses gravitationally
^{16} O migrates towards the center



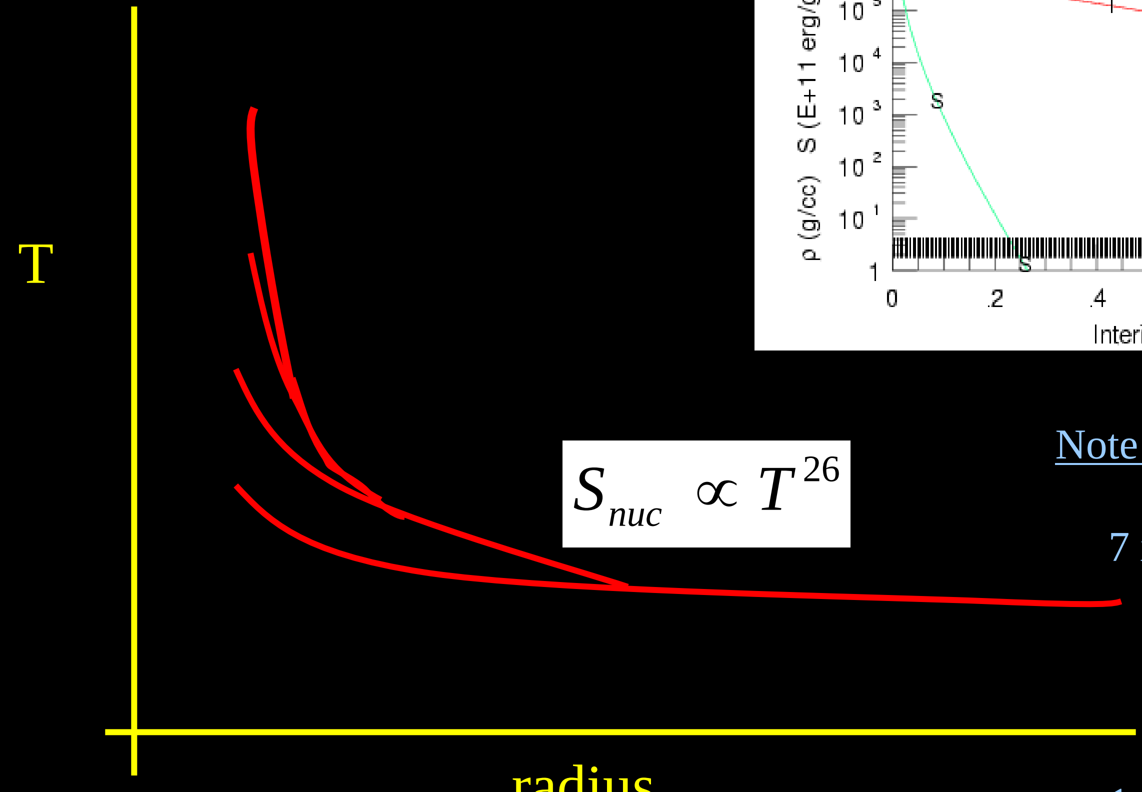


Age of NGC6791 (Garcia-Berro +'10)
Turn off Main Sequence: 8 Gyr
WD age (no sed) : 6 Gyr (green)
WD age (sed): 8 Gyr (red)

The onset of the thermonuclear runaway



Woosley



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

<u>Note that at:</u>

7 x 10^8 K the burning time and convection time become equal. Adiabatic gradient cannot be maintained

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

$H_P \approx 400$ km

$v_{conv} \approx 50$ km/s

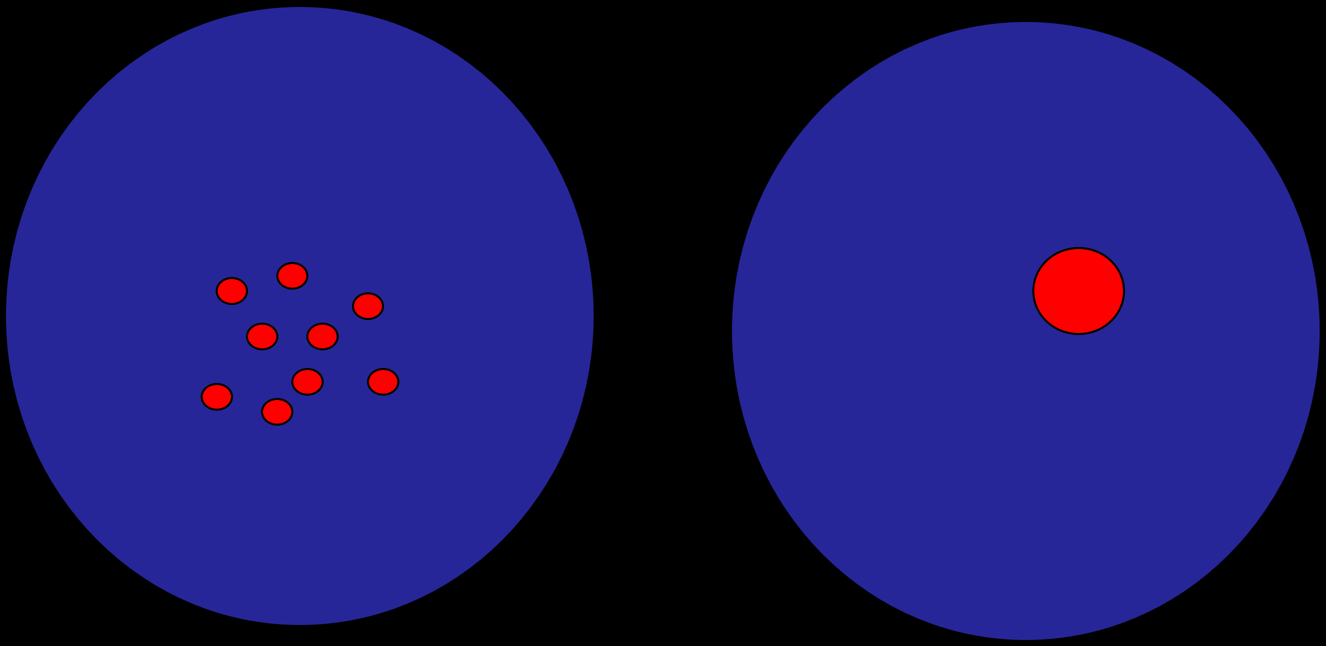
$\tau_{nuc} \approx \tau_{conv} \approx 10^2$ s

$\mathrm{BE} \approx 4 \times 10^{50}$ erg

Burning of 0.05 M_o causes en expansion by a factor 3

Burning becomes localized

How the ignition starts?



Maeda+'10:
Comparison of the early and late expansion velocities suggest an asymmetric explosion i.e. ignition stats of center → 3D models ignition/explosion
Next talks by: Zindale & Ropke

Conclusions:

#The classical problem still remain: 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 ignition phase and the development of the explosion as well as in the obtention of spectrophotometric properties