Super-Bright Thermonuclear SNe

Peter Hoeflich (FSU)

Subclass of SNe Ia, often called "Super-Chandra":

- 1st object discovered: SNLS-03D3bb/SN2007if (Howell 2007, Nature 443, 308)
- Since then, a handful more: Rotse J011051+152740, SN2009dc, SN2011aa, SN2012dn, SN2013dy, SN2017cbv → very rare

Characteristics (or Character Flaws) compared to SNe Ia:

- Nuclear signature: alpha elements → thermonuclear
- 1 to 1.5^m brighter corresponding to 1.5 Mo M(56Ni) (Arnett's law)
- slow decline rates
- Strong carbon lines
- slow expansion rates (3-5,000 km/sec)
- Layered structure with lot's of Carbon, little Si/S and lot's of Ni
- late time spectra are not dominated by f orbidden lines
- very low continuum polarization for two (Maeda, Patat, …) -> round ?

Common Models:

- Merging of massive WDs to form a "super-M(Ch)"
- alternative models ?

Some Questions

- Do we really need 1.5 Mo of 56Ni ?
- Are superbright SNe Ia a different class ?
- Are all ‘superbright’ SNe Ia really superbright ?
- Are all ‘superbright’ SNe Ia super-M(Ch) ?
- Have all ‘superbright’ SNe Ia more than 1.4 Mo ?
- Do we suggest a different scenario, and where does it differ?
- Why are 'superbright' SNe Ia superbright ?

Some Questions (with short answers):

- Do we really need 1.5 Mo of 56Ni ? **No**
- Are superbright SNe Ia a different class ? **Yes**
- Are all ‘superbright’ SNe Ia really superbright ? **No**
- Are all ‘superbright’ SNe Ia super-M(Ch) ? **No but ...**
- Have all ‘superbright’ SNe Ia more than 1.4 Mo ? **Yein**
- Do we suggest a different scenario, and where does it differ ? **Yein**
- Why are 'superbright' SNe Ia superbright ? **Let's see ...**

Some Questions

- Do we really need 1.5 Mo of 56Ni ?
- Are superbright SNe Ia a different class ?
- Are all 'superbright' SNe Ia really superbright ?
- Are all 'superbright' SNe Ia super-M(Ch) ?
- Have all 'superbright' SNe Ia more than 1.4 Mo ?
- Do we suggest a different scenario, and where does it differ ?

Outline

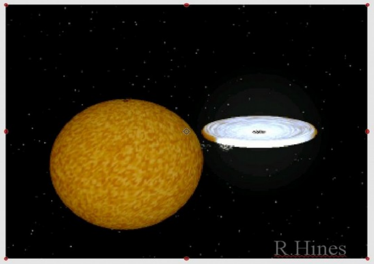
- Common ground: Basic Physics of Thermonuclear SNe
- Alternative Explosion Scenario
  (by inverting the problem & mixing all crazy ideas and shake well)
- Light curve simulations
- Spectral properties and tests
- Open questions

Thumbnail Sketch of Thermonuclear Supernovae

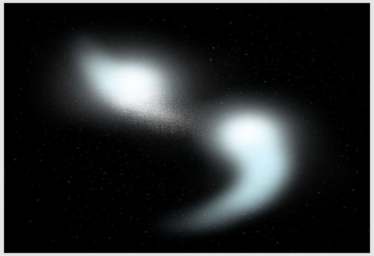
SNe Ia are **thermonuclear** explosions of White Dwarfs (C/O core of a star with less than 8 M_o)

SNe Ia are homogeneous because **nuclear physics** determines the WD structure & explosion
The total energy production is given by the total amount of burning
The light curves are determined by the amount of radioactive ^{56}**Ni**

Classes of Progenitor Systems



Accreting WD (MS, RG, He-star, C-star) (SD-systems)
(e.g.Nomoto et al. 1984, Wang &Han, 2013), see presentation of Han & Toonen)
Two merging WDs (DD-systems)



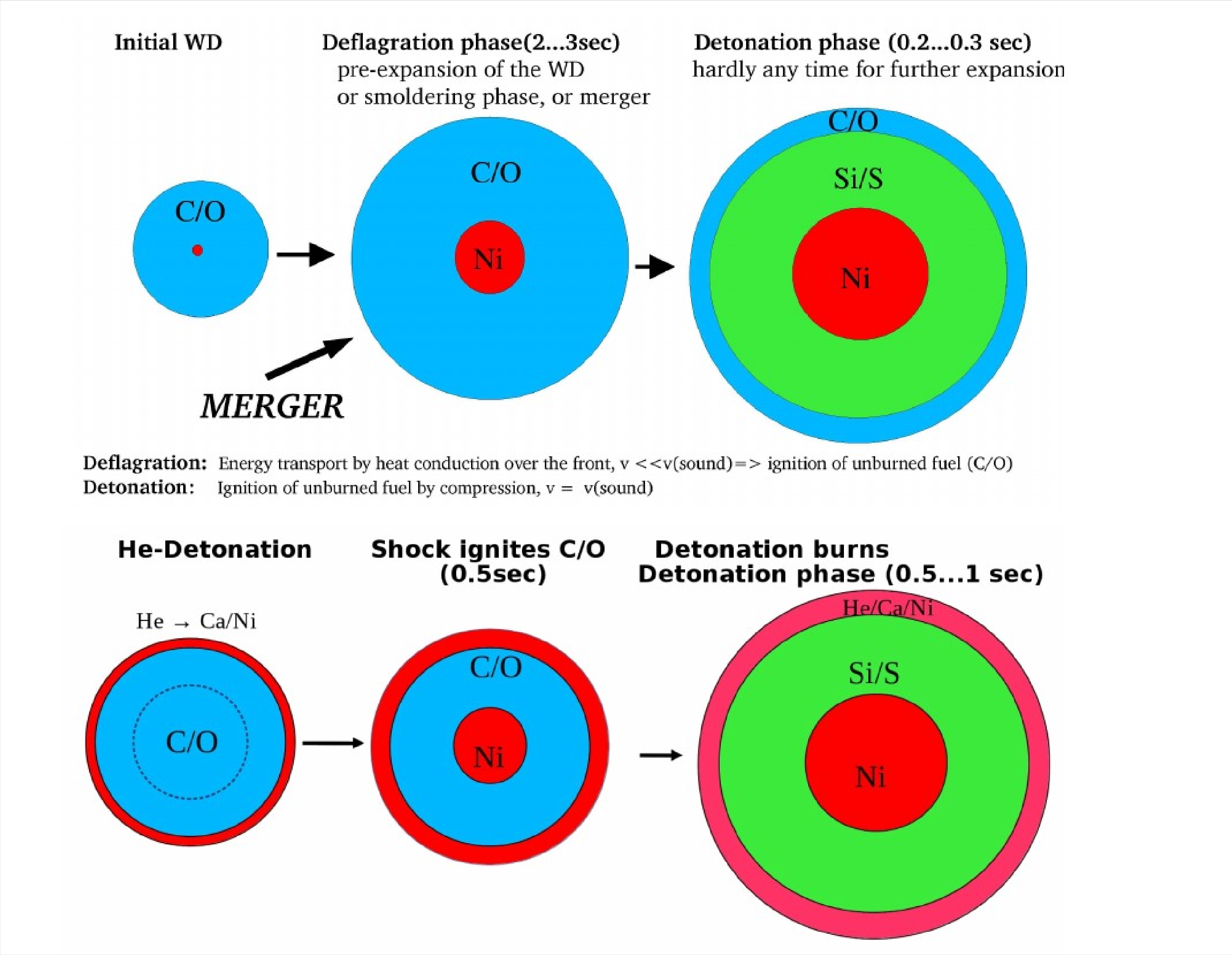
Common Causes Diversity:

- Main Sequence mass M(MS) → Explosion energy E(nuc)
- Mass of progenitor → central density
- Metallicity Z → E(nuc) and 56Ni
- Magnetic fields → Hydro & Spectra
- Environment → Interaction, 'ISM'

Classes for Explosions

M(Ch) mass WDs: Ignition by compressional heat (originates from either SD or DD, CD)
Heat release during dynamic process (dynamical mergers, violent mergers, He-detonations)

The Zoo of Explosion Scenarios



Delayed Detonation: Khokhlov et al. 1989, Niemeyer et al.1995,Hoeflich & Khokhlov 1996, Gamezo et al. 2003, Roepke et al. 2006, … ; PDD & shell models, HK 95, 96, …

Mergers: Benz et al. 1990, … Garcia-Sanzec et al. 2015 ,…

Double-Detonations: Nomoto et al. 1984, Woosley et al, 86, HK96, Livne et al. 1998 …, Kromer 2014, ff.CDs Yoon 2006,

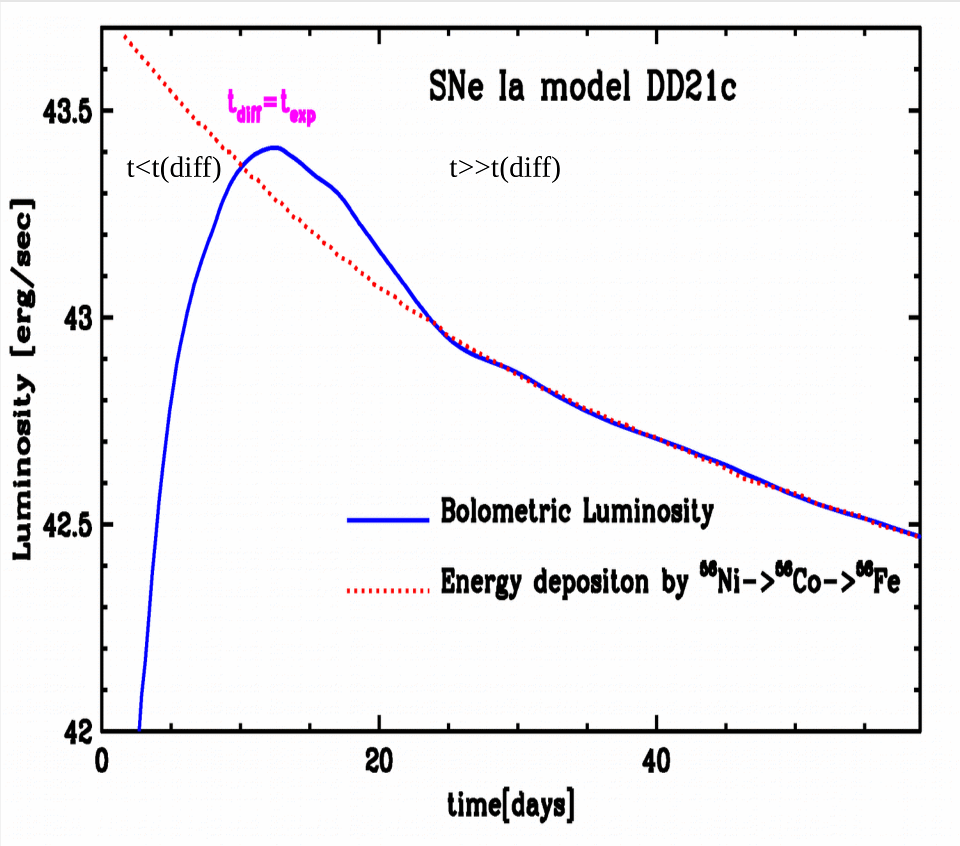
II) Light Curves in a Nutshell

Energy Input: Radioactive Decay ^{56}Ni → ^{56}Co → ^{56} Fe

Products: X- and Gamma-ray photos + positrons

Optical Luminosity:

Deposition of hard photos/positrons + diffusion of low energy photons+geometrical dilution by expansion



The Role of the Opacity by Lines

Dependencies:

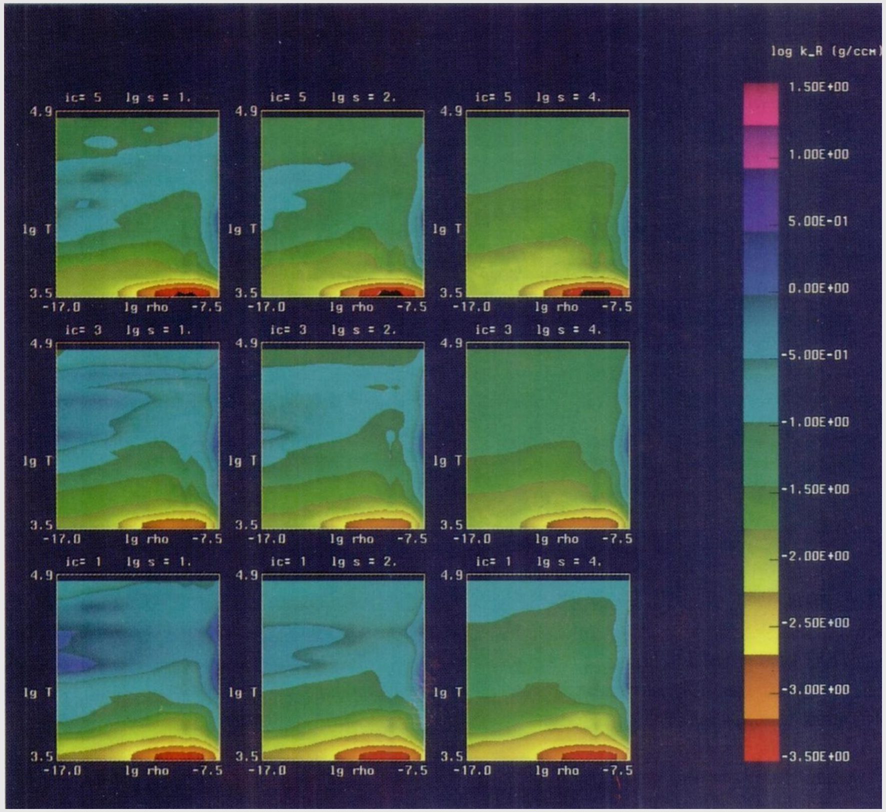
T, ρ, abundances and dv/dr = 1/s

(Flux → Rosseland opacities)

Fe

Si/C

C/O



(Hoeflich, Khokhlov, Mueller 1993)

Light Curves In a Nutshell **(Luminosity from X- to FIR)**

Energy Input: Radioactive Decay $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

Products: X- and Gamma-ray photos + positrons

Optical Luminosity:

Deposition of hard photos/positrons + diffusion of

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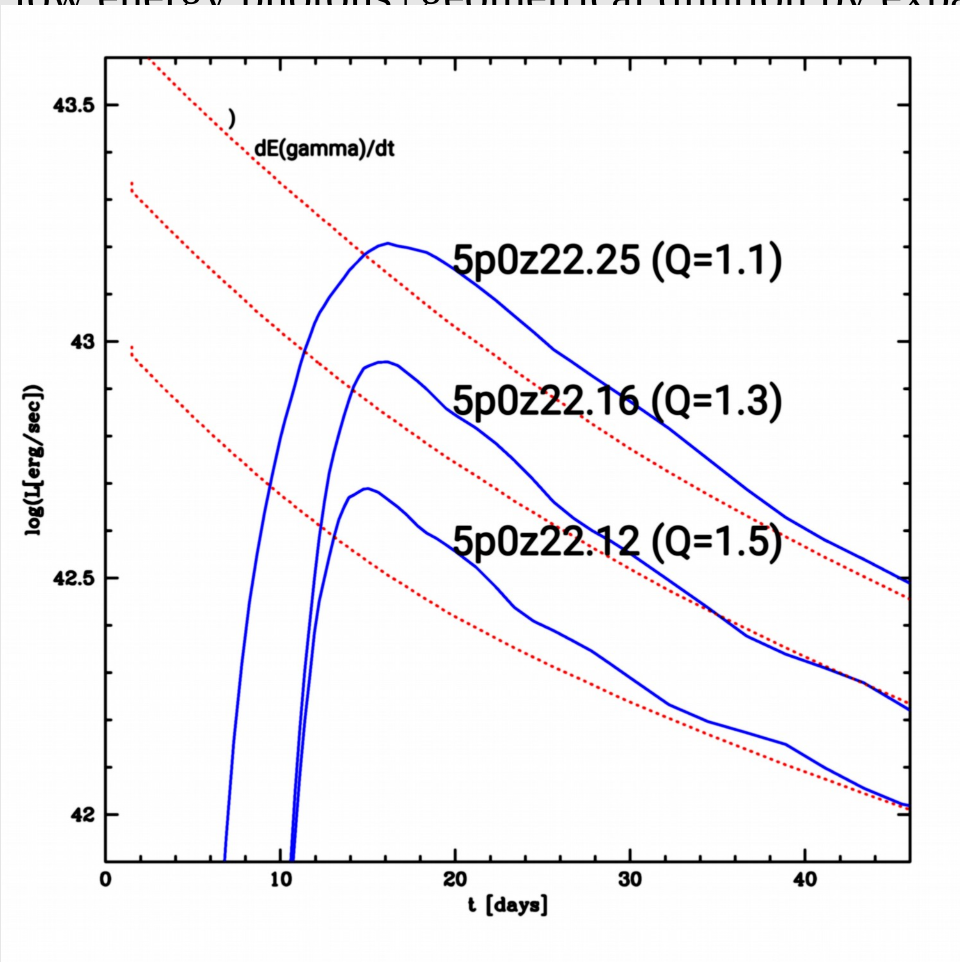

The Role of the Opacity by Lines

Dependencies:

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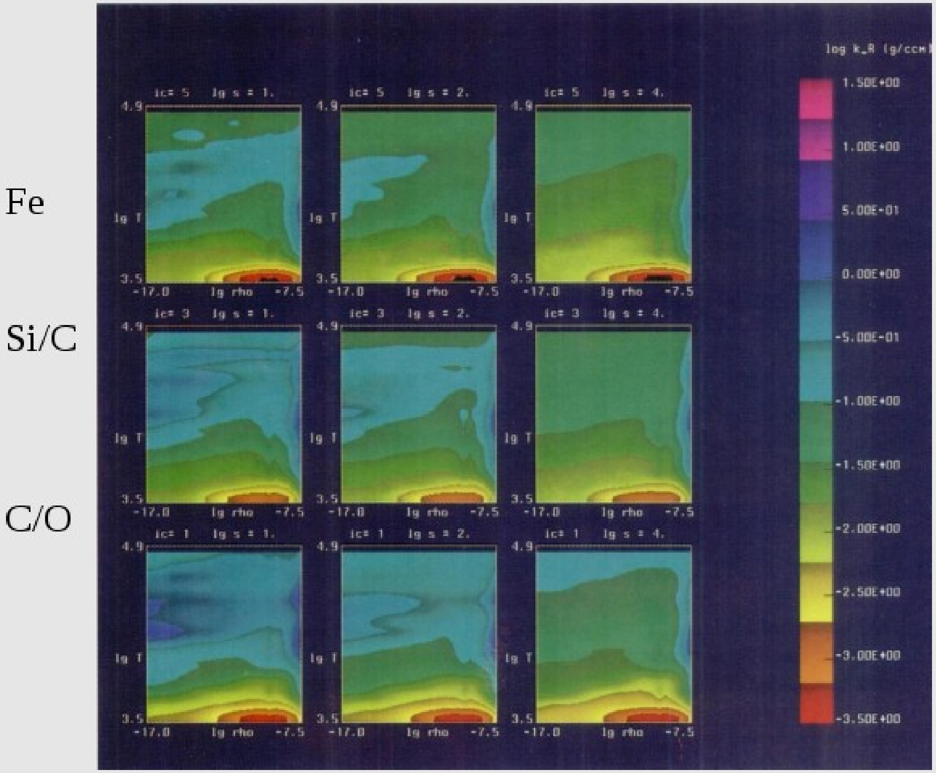


(Hoeflich, Khokhlov, Mueller 1993)

Numerical Environment of ***HYD***rodynamical ***RA***.diation transport

Hydrodynamics (PPM)

a) 1-D Lagrangian (spherical + front tracking)
b) 3-D Eulerian (cartesian, based on Fryxell et al. 1992)
c) Free expansion

MC-TP gamma & positrons

a) 1-D spherical
b) 3-D (given cartesian grid)

ALI

Nuclear network

a) NSE
b) Full network & decays
(based on Thielemann's lib)

Master module/ switch

EOS

a) 1E10 > ρ< 1 g/ccm
b) 1g/ccm > ρ

Radiation transport (3 modules)

a1)Spherical, comoving Rybicki scheme (MKH75, 76,81) for spherical LCs and atmospheres with partial redistribution
a2) Formal integration of RT in observes frame (spherical)

b) Variable Eddington Tensor solver (implicit) for given Tensors
b1) 1-D spherical (comoving) + energy
b2) 3-D cartesian (observer)

c) Monte Carlo Scheme
c1) for Eddington tensor: 3-D,solve for difference between diffusion and R.T. equation (ALI2)
c2) Polarization: stationary transport

Statistical equations f(t) for ionization and levels
&
molecular formation

LTE

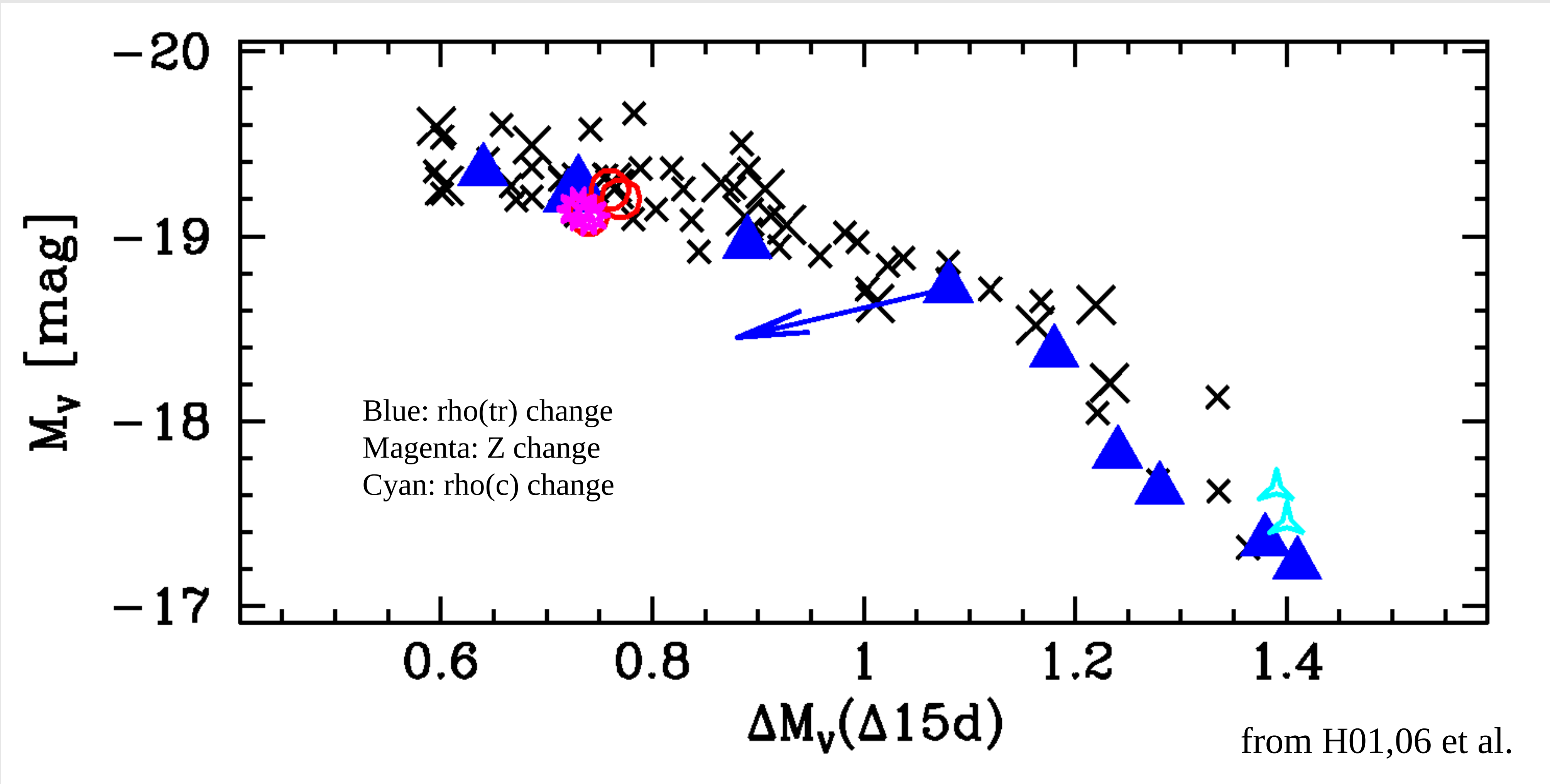
ALI

Opacities

Rem.: Not all modules can be combined simultaneously
(Perturbation strategies and CPU-time: e.g. 3D-struc.+NLTE)

Comparison with Observations (CSP I, Burns et al. 2014)

The brightness decline relation and colors (Hoeflich et al. 1996, Maeda et al. 2001, Kasen et al. 2009)
Ref. M(WD)=M(Ch), rho(c)=2E9g/ccm Z=solar, M(MS)=5Mo (WD structures from Dominguez et al. 2002)

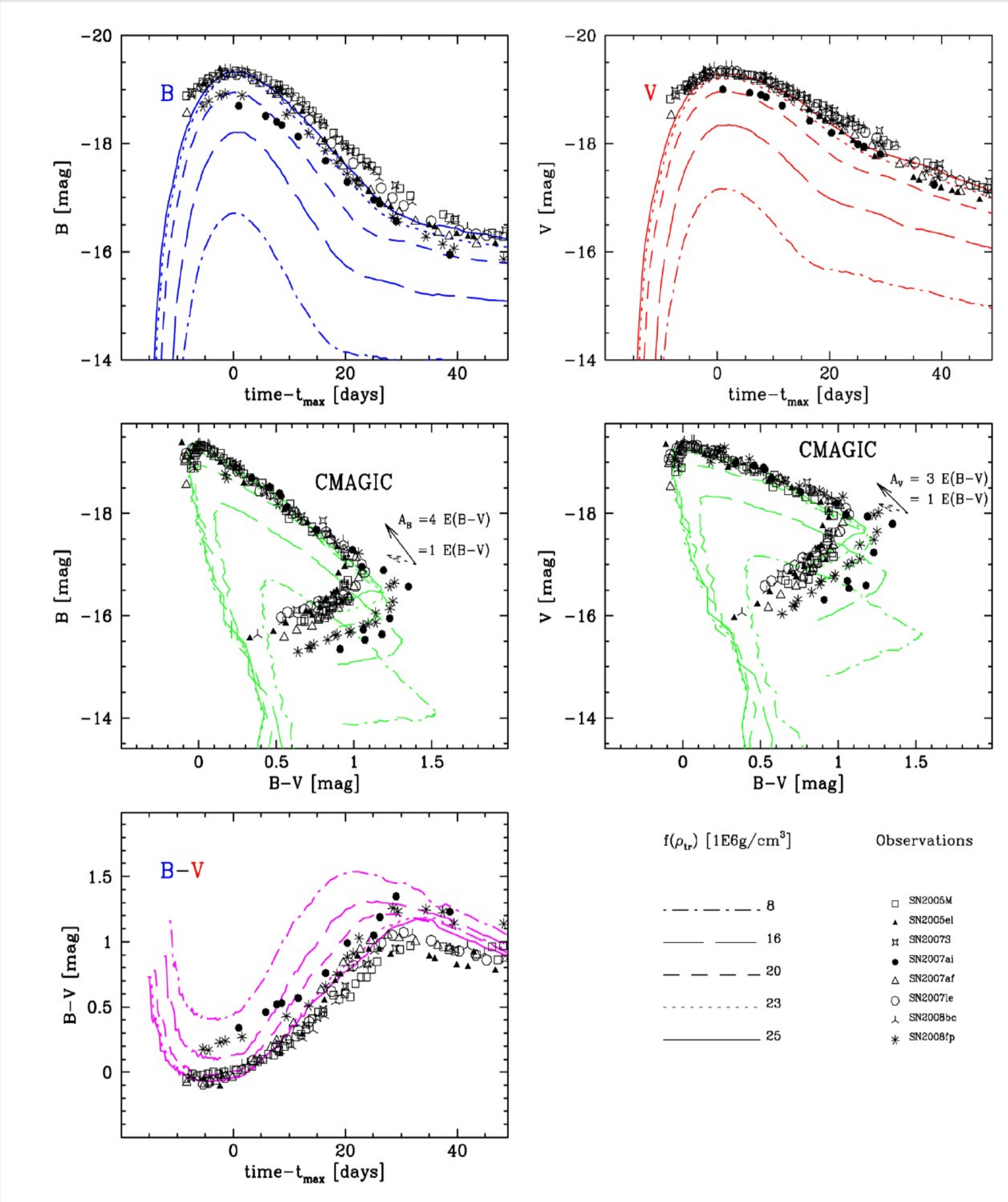


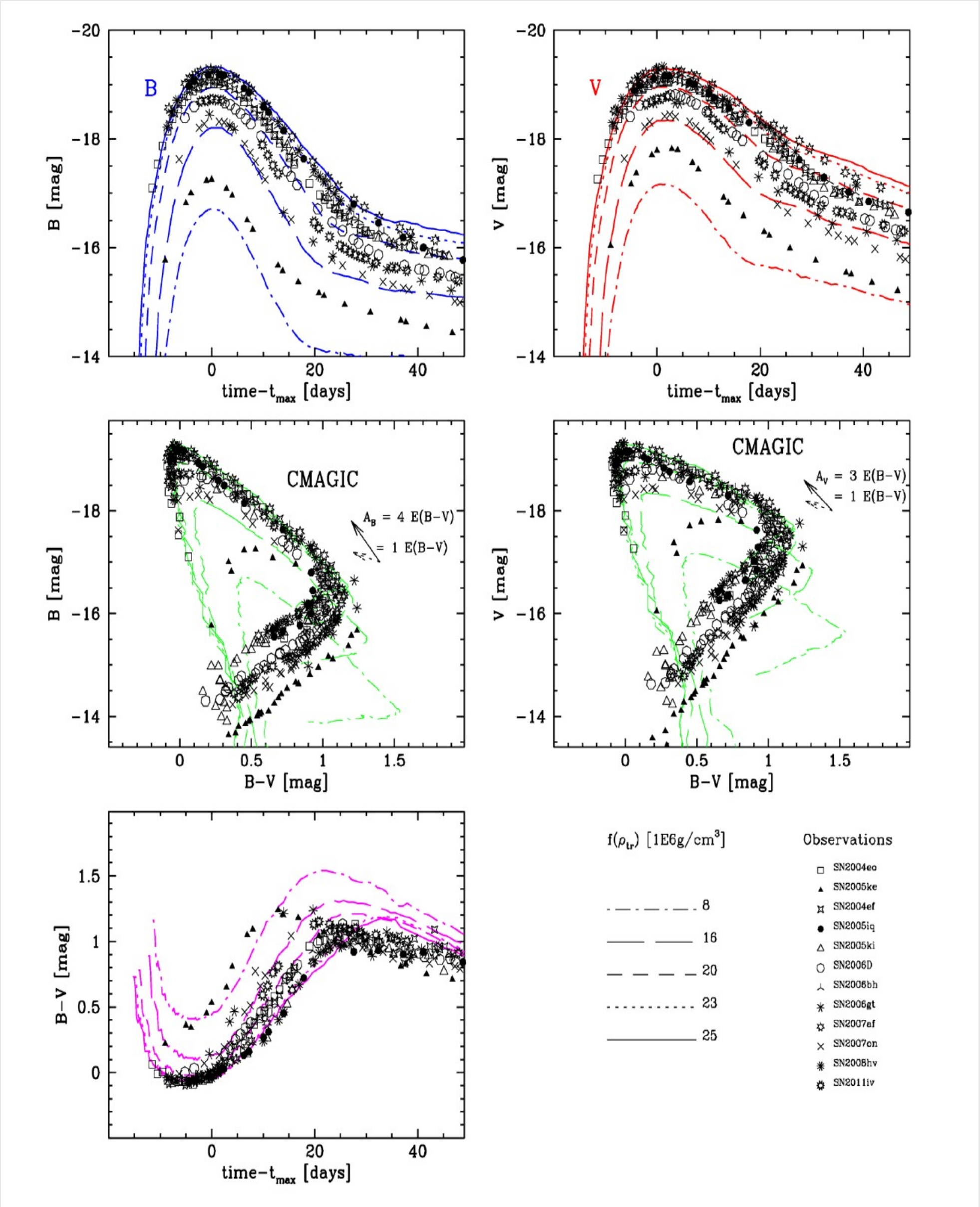
Superbright SNe may follow dm15 but, then, Q should be small !

Mixing suppressed: **B-field** (H.et al. 04, Penney & H., 12, Fesen etal. 07/15, Remming et al. 2014, Hiskov et a

Diversity of SNe Ia: Burn's CDR and Wang's CMagic

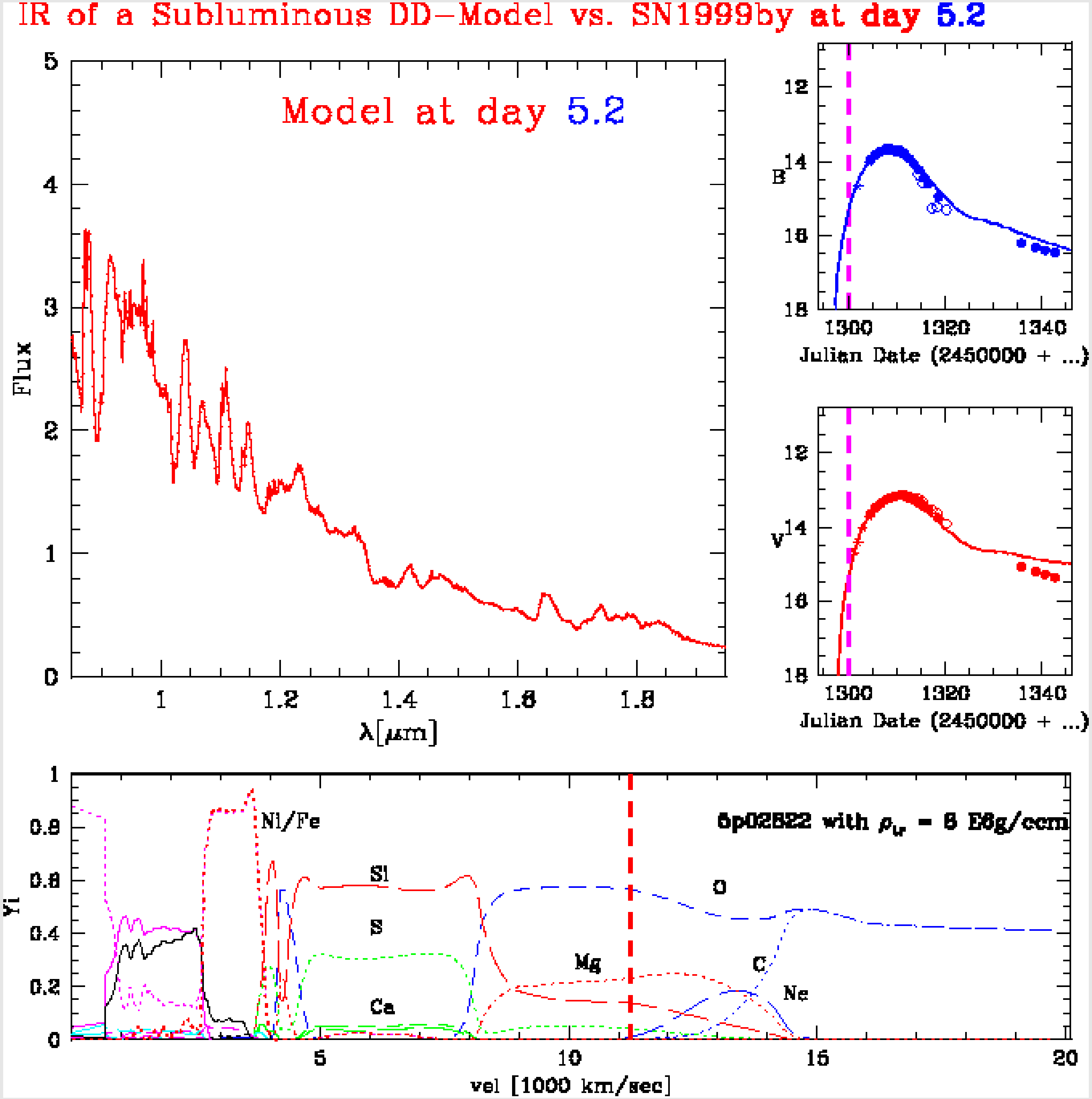
CSP - SN with ‘same’ dm15 different dm15





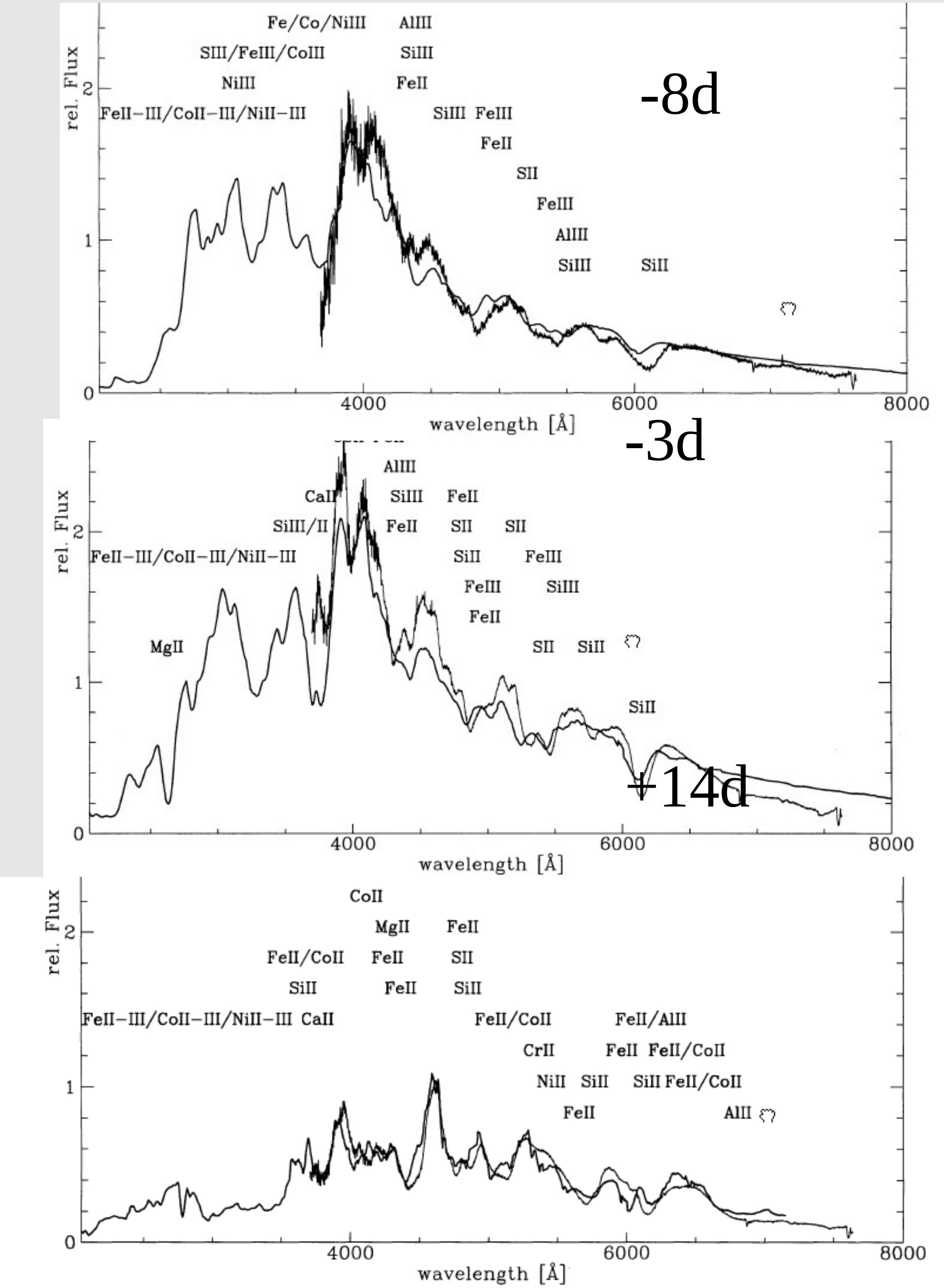
Super-M(Ch) are not following → separate class

IR-Analysis of SN1999by (as followed from explosion without tuning)



The Transition form Fe III to Fe II in a normal bright SNe Ia

A NLTE model vs . SN1994D (H95)



Fe/Co/Ni III & Si/SII dominate

Fe/CoII & Si/SII dominate

Fe/Co II dominate
(some emission components
Starts to get stronger)

The Trouble with Thermonuclear Models with respect to Super_M(Ch)

Scenario	Initial mass	Defl.	Det.	M_{56Ni}	$A\rho$	$A(X_i)$	C & O	stable Ni
Det.	≈ 1.37	-	x	0.83-0.9	$<<$	no	no	x
Defl.	≈ 1.37	x		0.05: ... 0.6	$<<$	small scale	< 0.1	x
DDT	≈ 1.37	x	x	0.05-0.8	$<<$ (axial)	some	$\approx 10^{-4...-2}$ *	x
PDDT	≈ 1.37	x	x	0.1-0.8	$<<$	some	typical ≈ 0.3 $^{*}*$ (s)	x
HeD	0.6-1.2	-	x	0.-1.07	$<$	some	no	no
Mergers	$0.6 - 2.7$	no	x	0.-1.7:	large(:)	x	x (s)	no

* for normal bright SNe Ia but increasing to $0.3M_\odot$ for subluminous SNe Ia models. $^{*}*$ small amplitude pulsations can produce C & O down to DDT models

Problems with ‘bright’ M(Ch) and below

- too little 56Ni ?
- no layered structure for Defl.
- too little C/O for all but PDD
- too fast expansion velocities

Problems with ‘Mergers’

- Polarization ?
- Directional dependence of L ?
- too fast

Energetics: How to bring the velocity down?

Envelope models: Sub-M(Ch) WD of 1.2 Mo surrounded by envelope

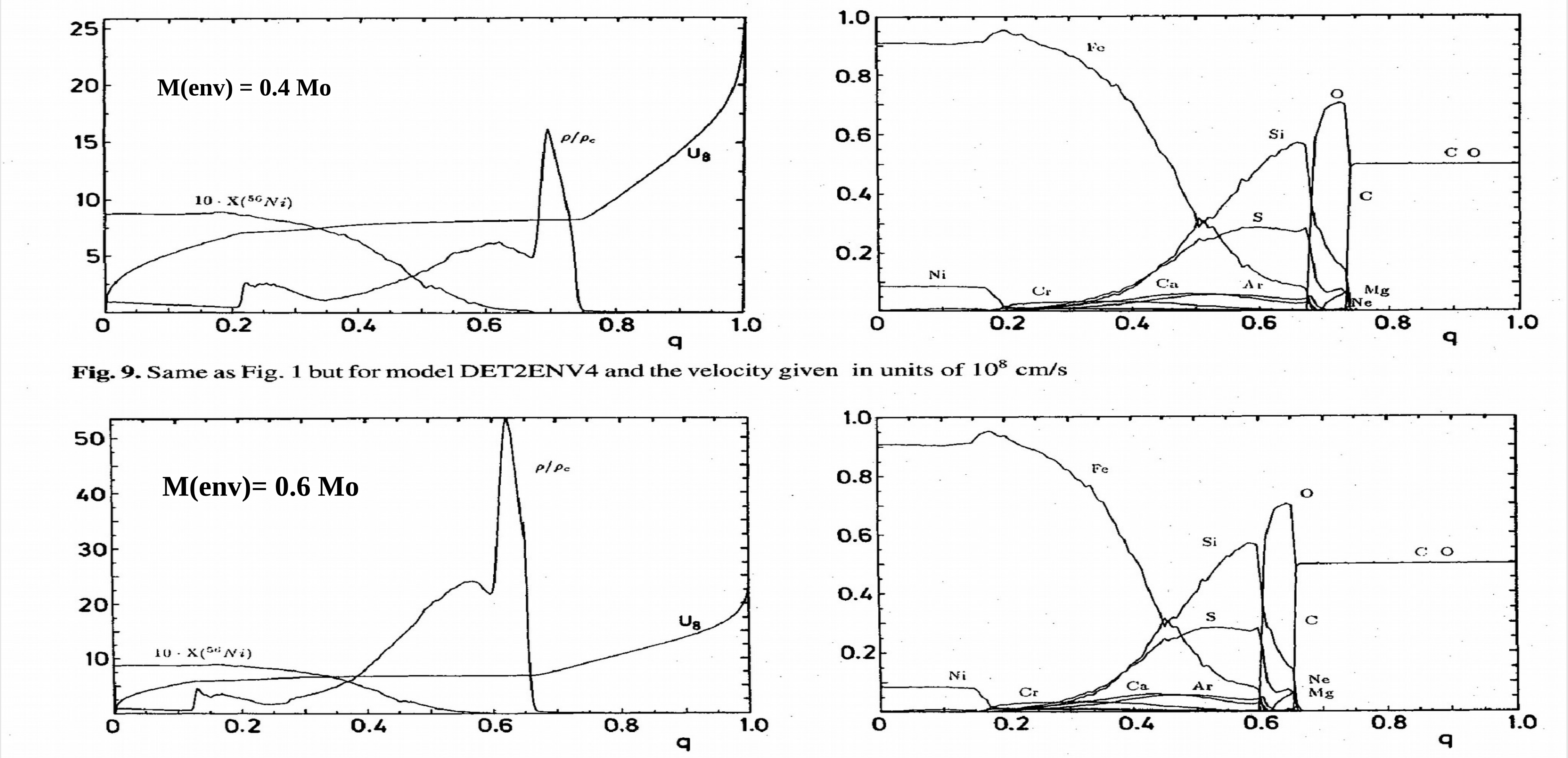


Fig. 9. Same as Fig. 1 but for model DET2ENV4 and the velocity given in units of 10^8 cm/s

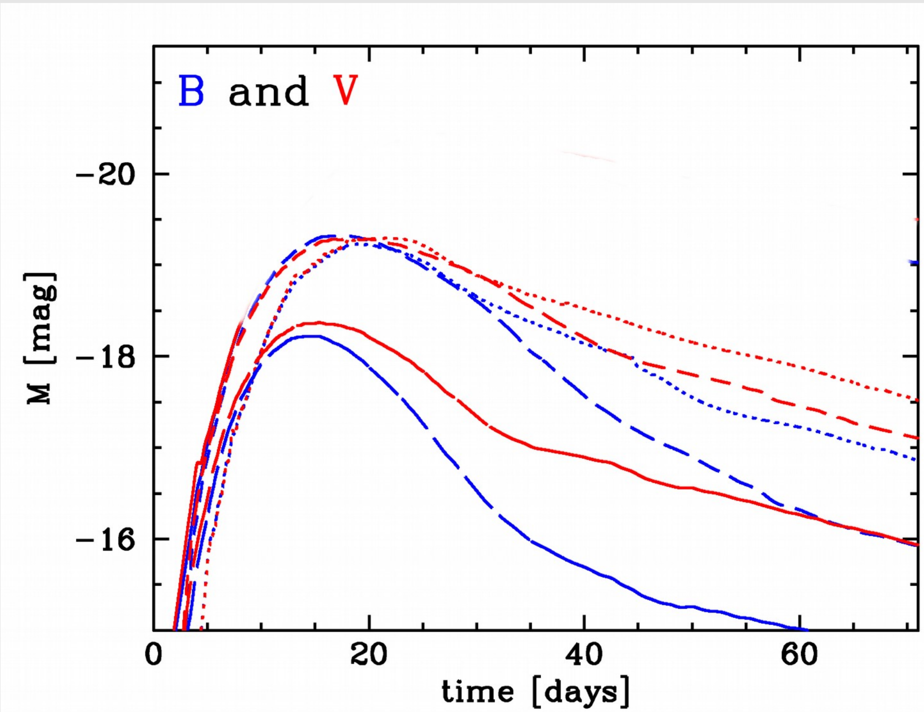
- Shell-like envelope with unburned C/O outside (v> 10,000- 12,000 km/sec)
- thin layers of S/Si, Mg and Ne
- about 0.5 to 0.6 Mo of 56Ni

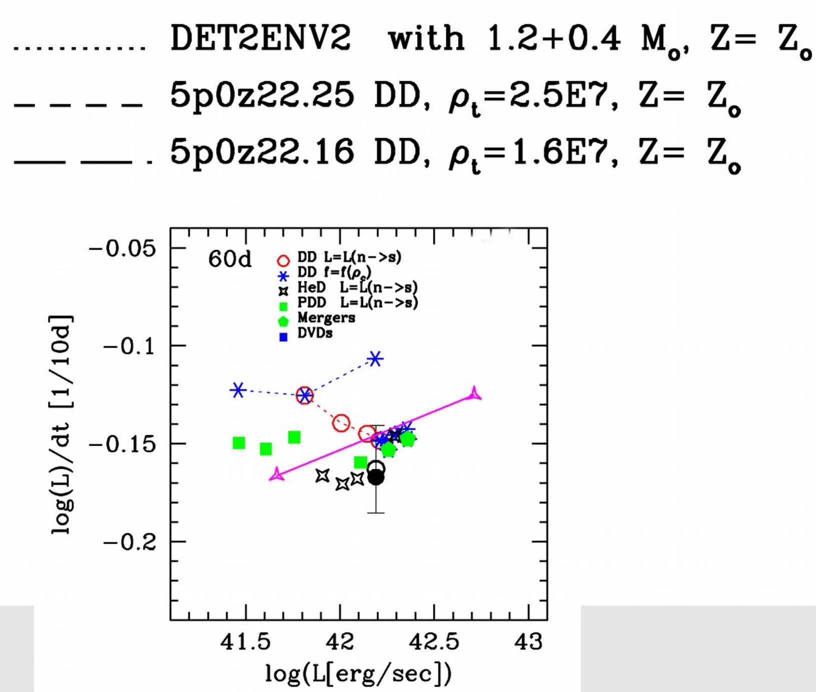
Numerical corrolar: Challenges are gradients

Delta v (0.3-0.6M(r))= 500 km/sec, delta rho(0.6) > 10 → 1000+ depth point in RT

From HK96

How do LC s look like?



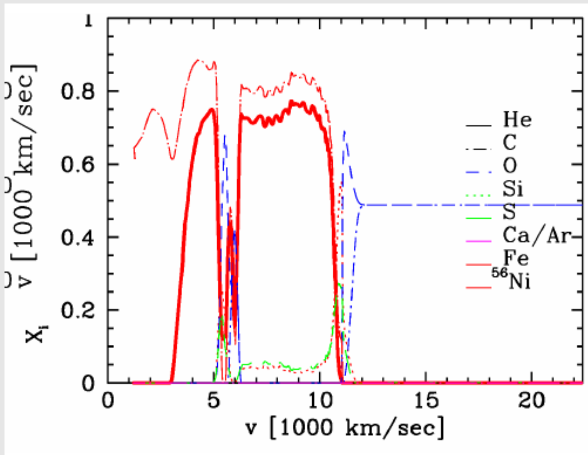


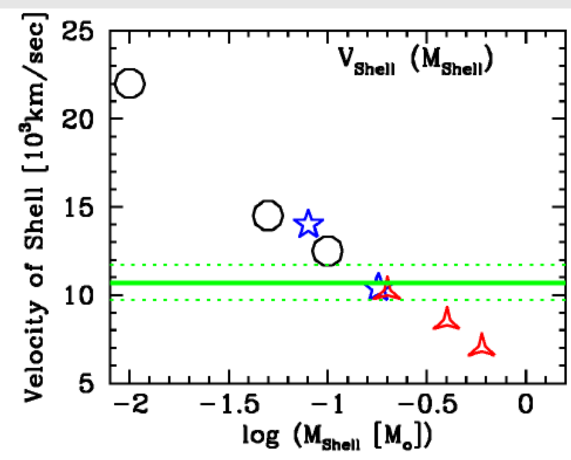
Spectral & LC properties:

- up to about -19.7 mag
- as brighter as redder
- B-V up to 0.2 mag
- as brighter as redder
- as brighter as more C
- as brigther as lower v

Problem (celing):

All Superbrights are reddened





Quimby et al. 2006

Similar model based on Core-Degenerate Explosions

1) Suggested by Yoon (2008) based on stellar evolution:

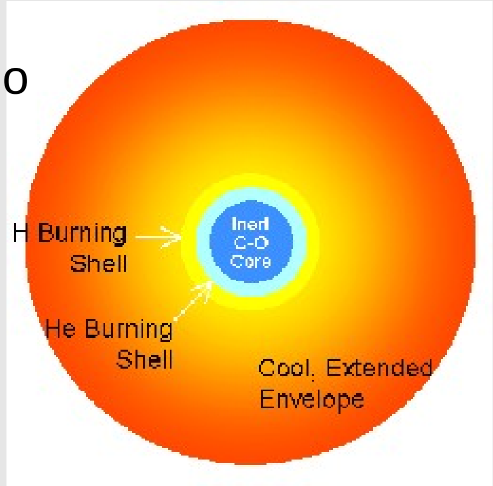
AGB star: with an accreting, degenerate core WD:

core-degenerate scenario in Common Envelope Scenario

Problem: evolutionary time longer than Age of the Universe

for low core masses and longer than stellar evolution

of He-shell burning by for more massive stars.



2) Kashi & Soker (2009), Rashkin et al. (2010)

High magnetic fields may increase the accretion rate significantly

(hand-waving): Rotation will stabilize the WD and angular losses will, eventually,

produce the deflagration of the degenerate core.

Soker et al. (2014) suggested to have shown from a statistical analysis that this will work

for all normal and subluminous supernovae (80 % CDs, 20% dynamical mergers).

Problems: Low accretion → Deflagration

High accretion will either go like a Double Degenerate Scenario,

- no high velocity Si/S, …

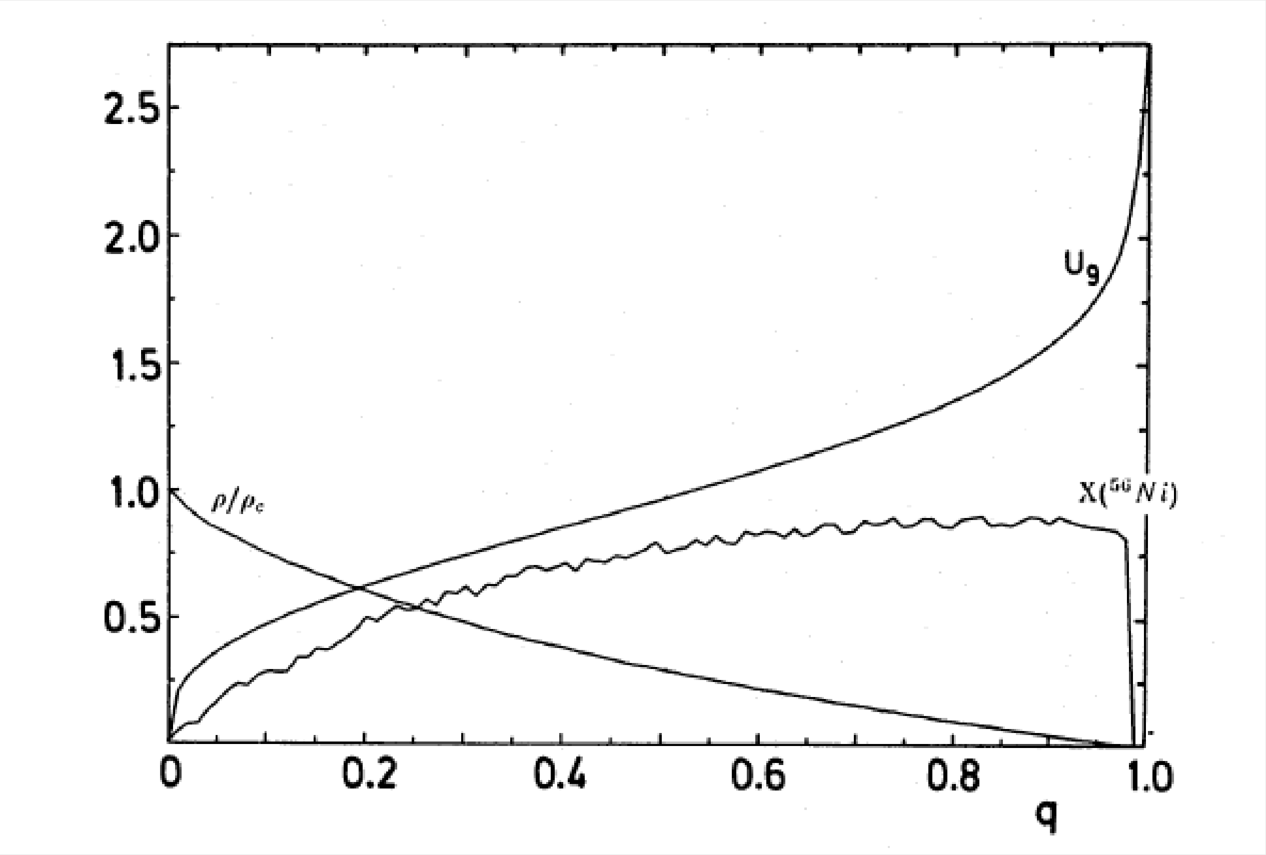
3) May result in super-bright SNeIa (Hoeflich 2016, in HB of Supernovae, Springer)

Problem for super-bright SNe Ia: Deflagration is too dim because of Ni production

Suggestion: Core-degenerate Scenario (CD) → Detonating Core Degenerates (DCD)

Bright: Increase mass of 56Ni

Classical Detonation Model



Strong points:

Up to 0.85 Mo of 56Ni

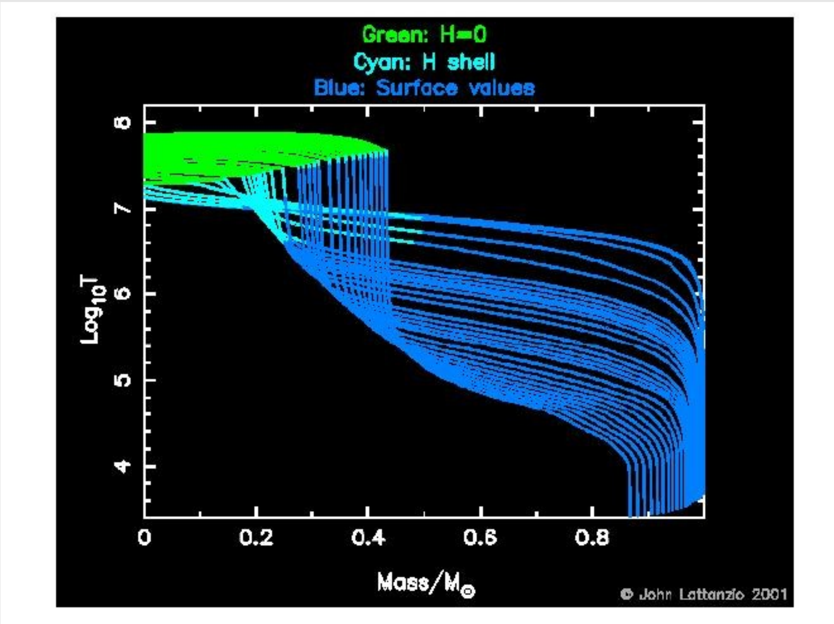
M(V) = -19.8 mag

B-V = -0.10 mag

Problems: Electron capture limits 56Ni production

Velocity gradients by compression produces deflagration (Zeldovic et 1976, Shigimoto & Nomoto 1978, Blinnikov & Khokhlov 1979, ...)

Back to Stellar evolution (Kippenhahn 1978, Yoon



(Chandrasekhar Limit for core)

- Maximum central T can be reached for a

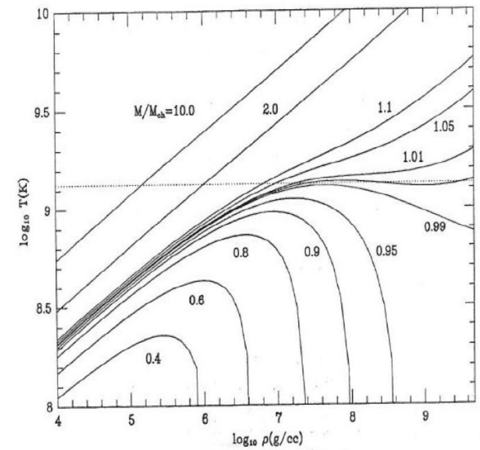
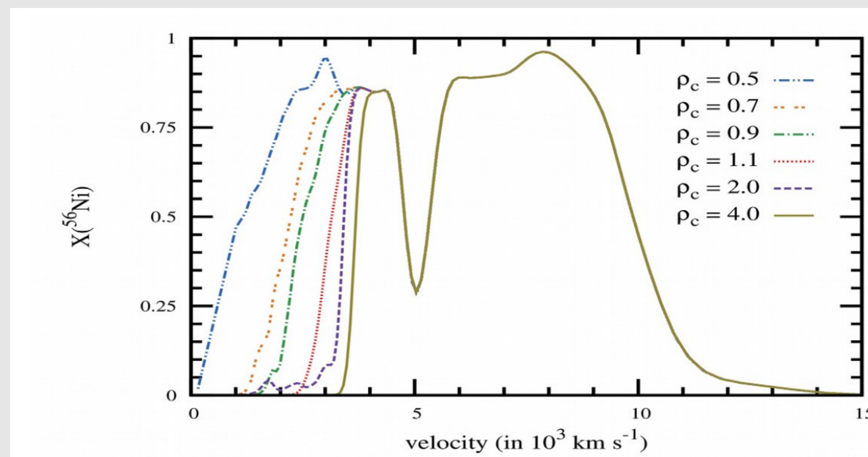


Fig. 6.3. ρ − T for Ignition Masses

mass $[M_{Ch}]$	T_{max} $[10^9 K]$	$Y_e\rho$ [g cm^{-3}]
0.100	0.0392	1.79×10^4
0.316	0.195	2.88×10^5
0.501	0.399	1.12×10^6
0.631	0.586	2.77×10^6
0.794	0.929	1.07×10^7
0.891	1.250	3.65×10^7
0.931	1.530	9.66×10^7
0.966	2.170	2.84×10^8
0.983	3.060	8.08×10^8
0.986	3.430	1.13×10^9

Super-M(Ch) should be rare
Balance between energy loss,
progenitor mass etc.



Needed: Much slower accretion (but faster than Yoon 2009)

=> Isothermal core

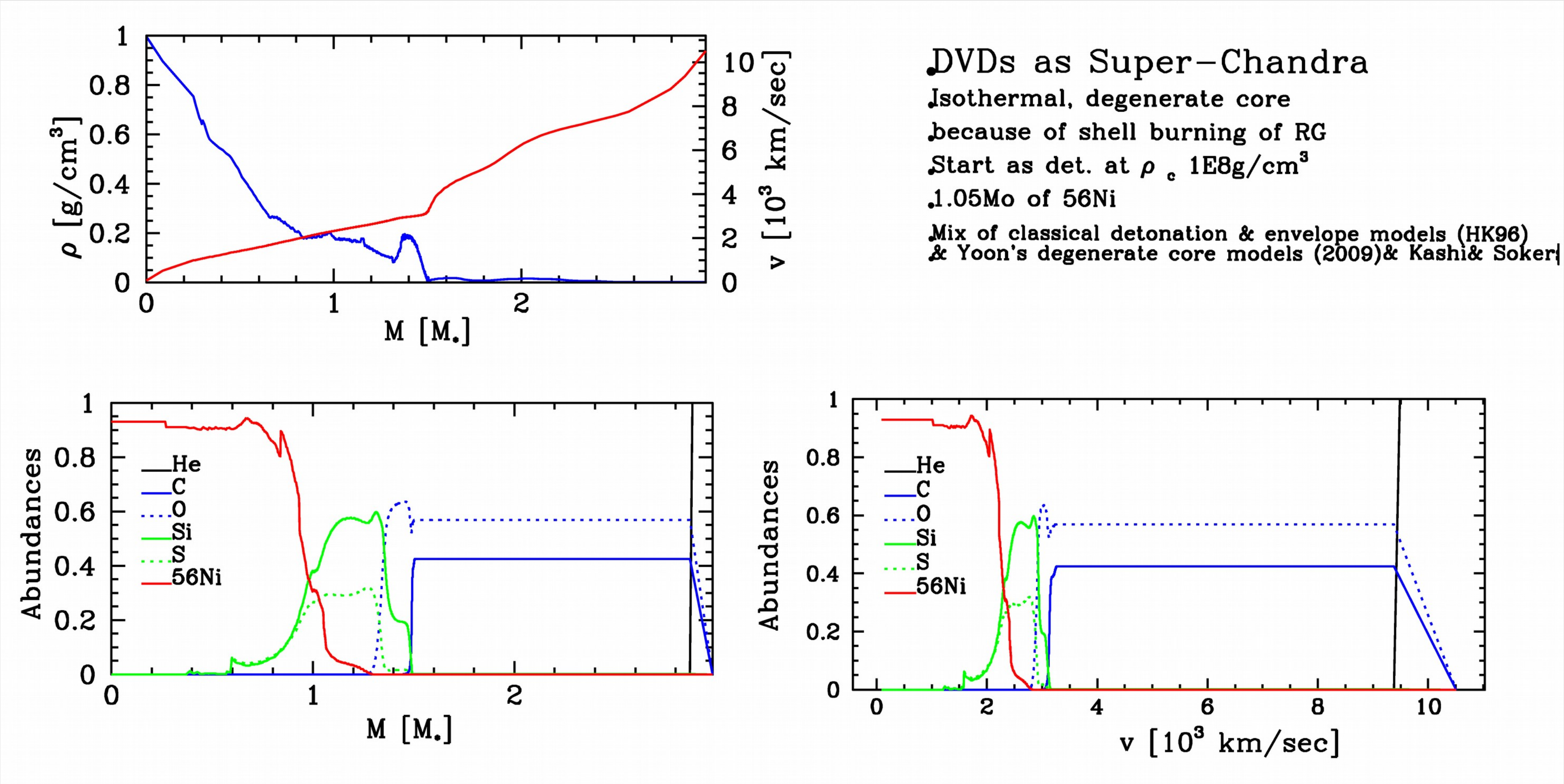
=> Detonation but at lower density

Tests with MESA: 6-7Mo which gains 0.4 Mo CO mass during AGB on time-scales of 100-1000yrs

'Sufficient' small T-gradients/close to isothermal to detonate (Niemeyer et al. 1995)

Suggested Scenario for Super-M(Ch):

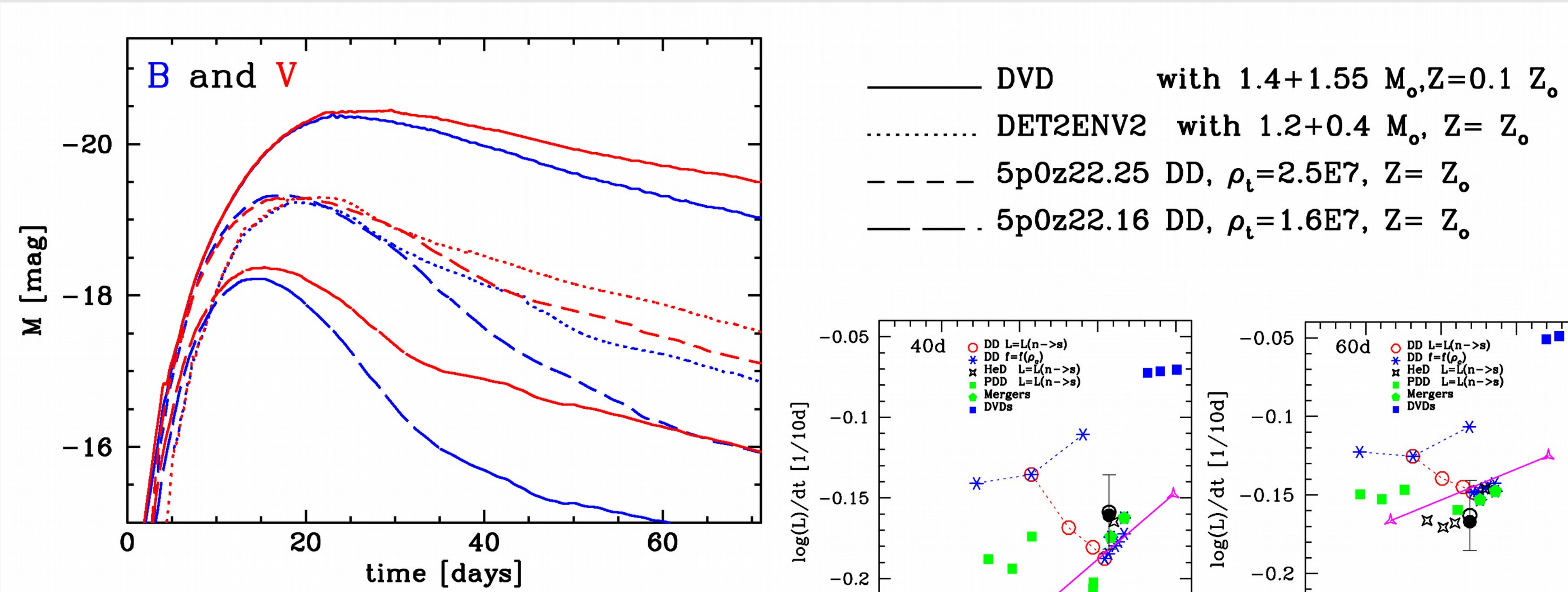
Hybrid of classical detonations, envelope model, and CDs
Detonations in an AGB star which gained high mass CO-core

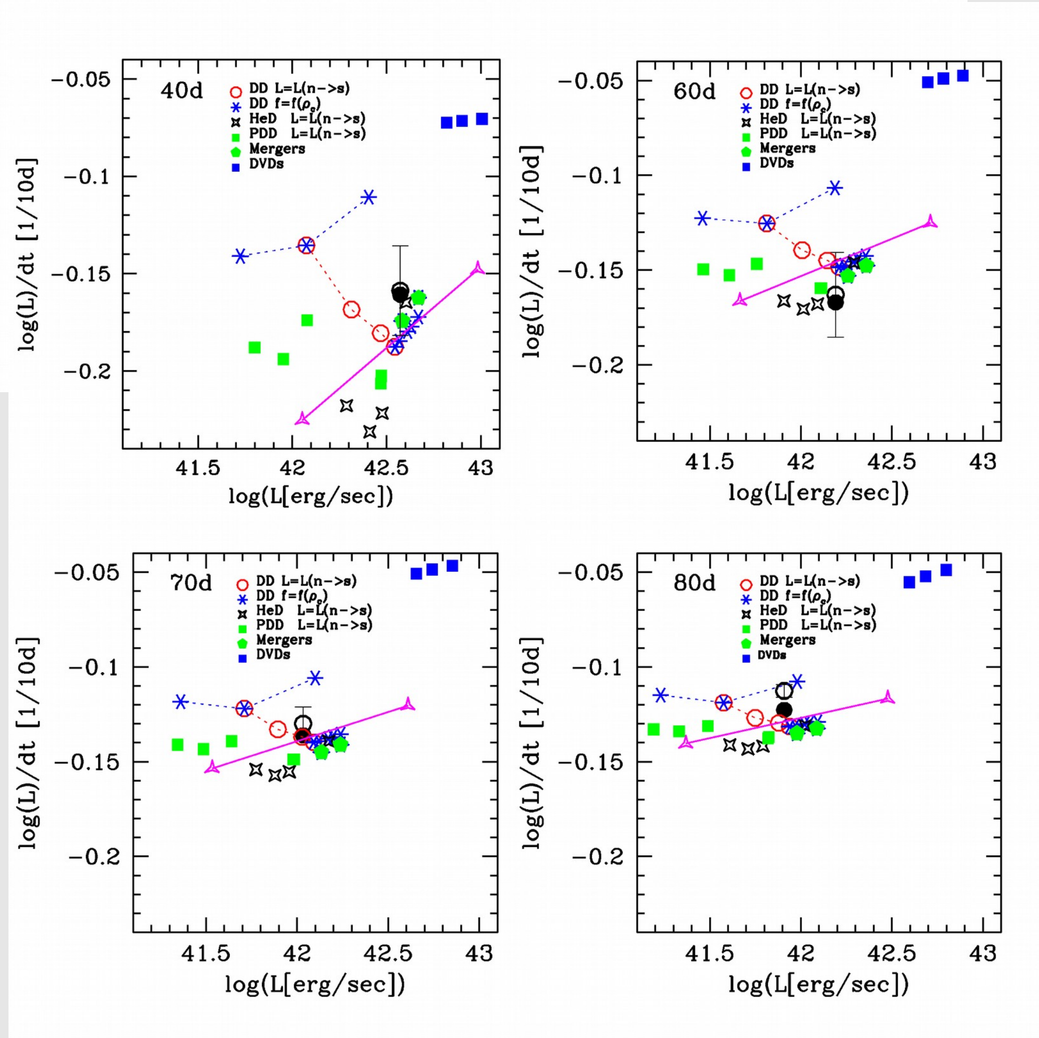


- Shell-like envelope with unburned C/O outside (v> 3000...6000 km/sec)
- up to about 1.1 Mo of 56Ni
- thin layers of S/Si, Mg and Ne

(Extreme case: 2x1.25 rotating CO-core with 0.5 He-mantel)

How do LC s look like in V,B and





Spectral & LC properties:

- up to about -20.5 mag
- B-V up to 0.01 to 0.2 mag
- correlation between v & M(env)
- Higher accretion means dimmer

  (down to normal SNeIa, ENV-models, HK96)

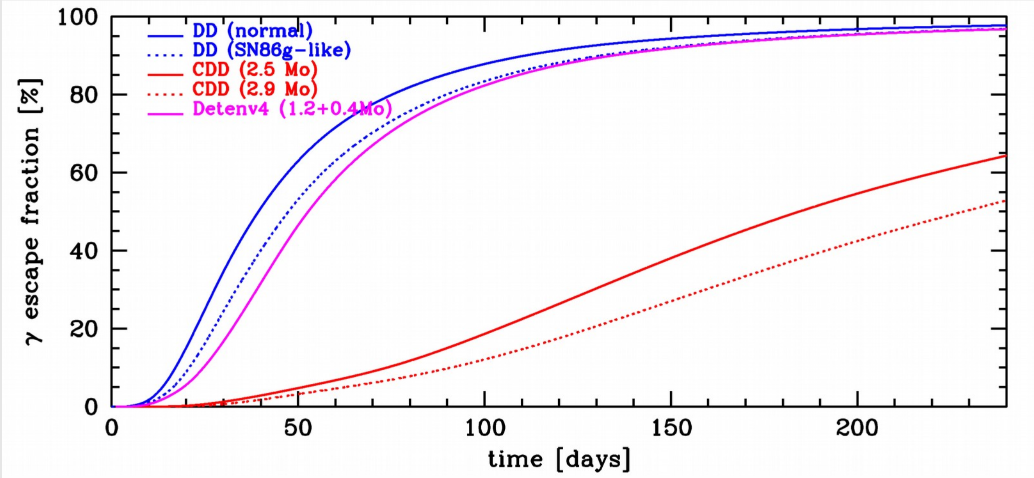
Problem (free parameters):

How low can we go in AGB mass & brightness

Favorable properties to produce a bright thermonuclear Supernovae or what makes the bright ?

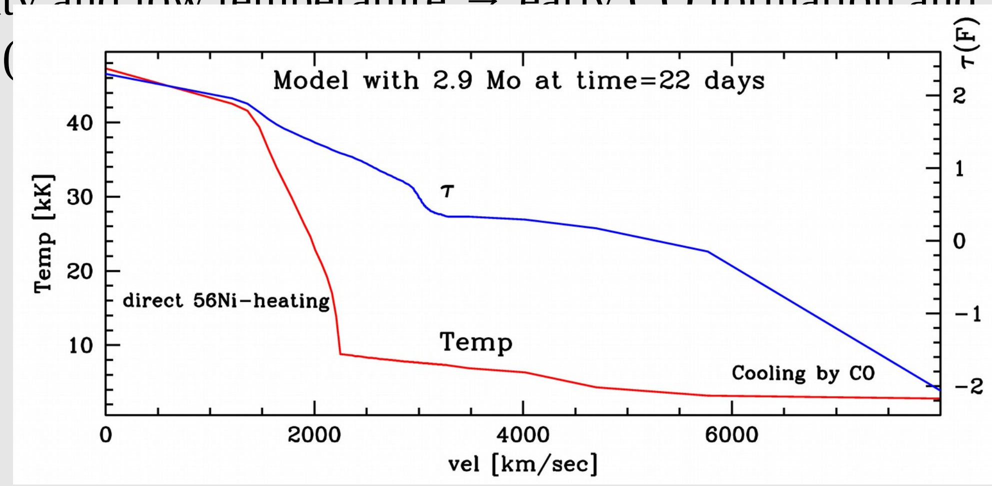
- Low expansion velocity of radioactive 56Ni from more 56Ni (currently 0.6 … 1.1 Mo)

a) Small escape probability for regular SNe Ia → gain of 1+ mag for same 56Ni mass



b) What let the large CO mass disappear ?

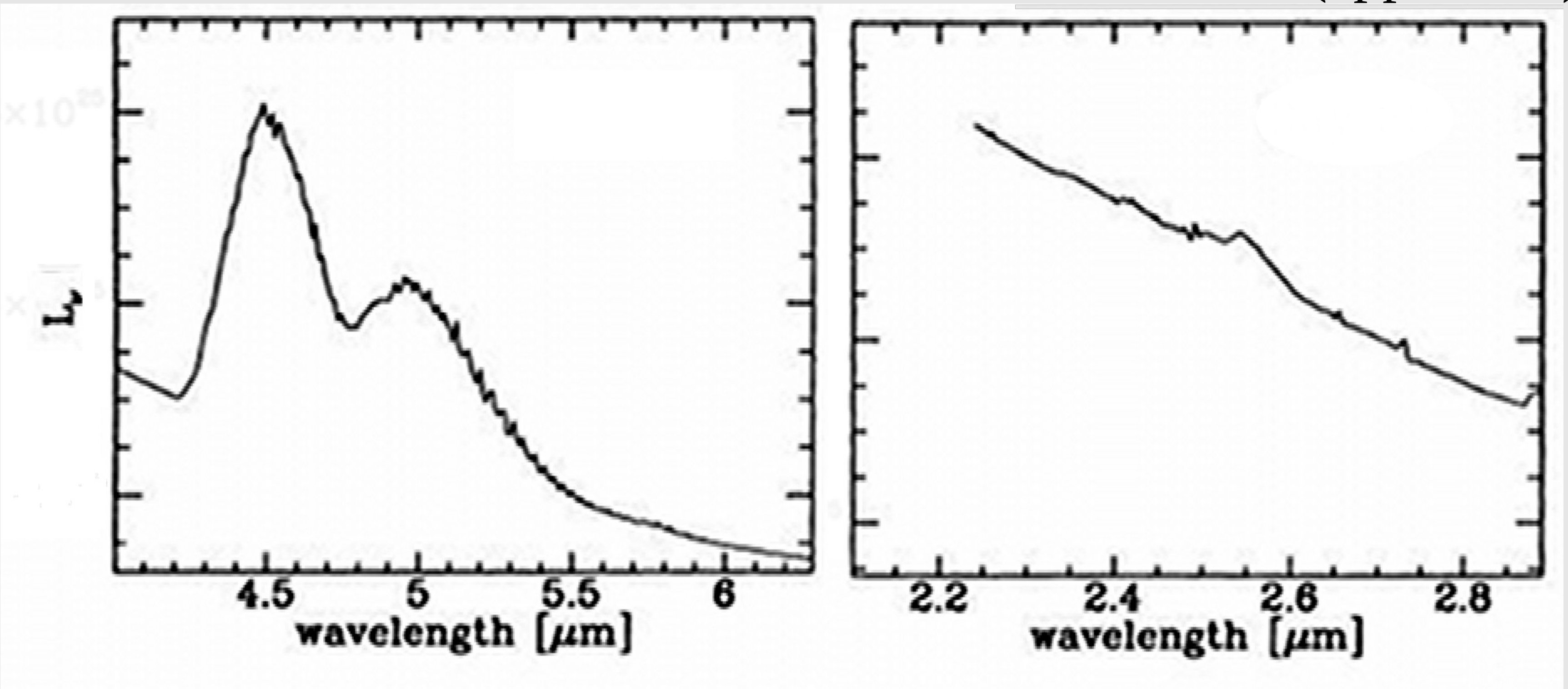
High density and low temperature → early CO formation and low-opacity (C+O->CO) envelope. (… ore maximum).



Molecule prevent re-heating

$$\mathrm{C} + \mathrm{O} \rightarrow \mathrm{CO}$$
$$\mathrm{C} + \mathrm{O}^+ \rightarrow \mathrm{CO}^+ + \mathrm{Me} \rightarrow \mathrm{CO} + \mathrm{Me}^+$$
$$\mathrm{C}^+ + \mathrm{O} \rightarrow \mathrm{CO}^+ + \mathrm{Me} \rightarrow \mathrm{CO} + \mathrm{Me}^+$$

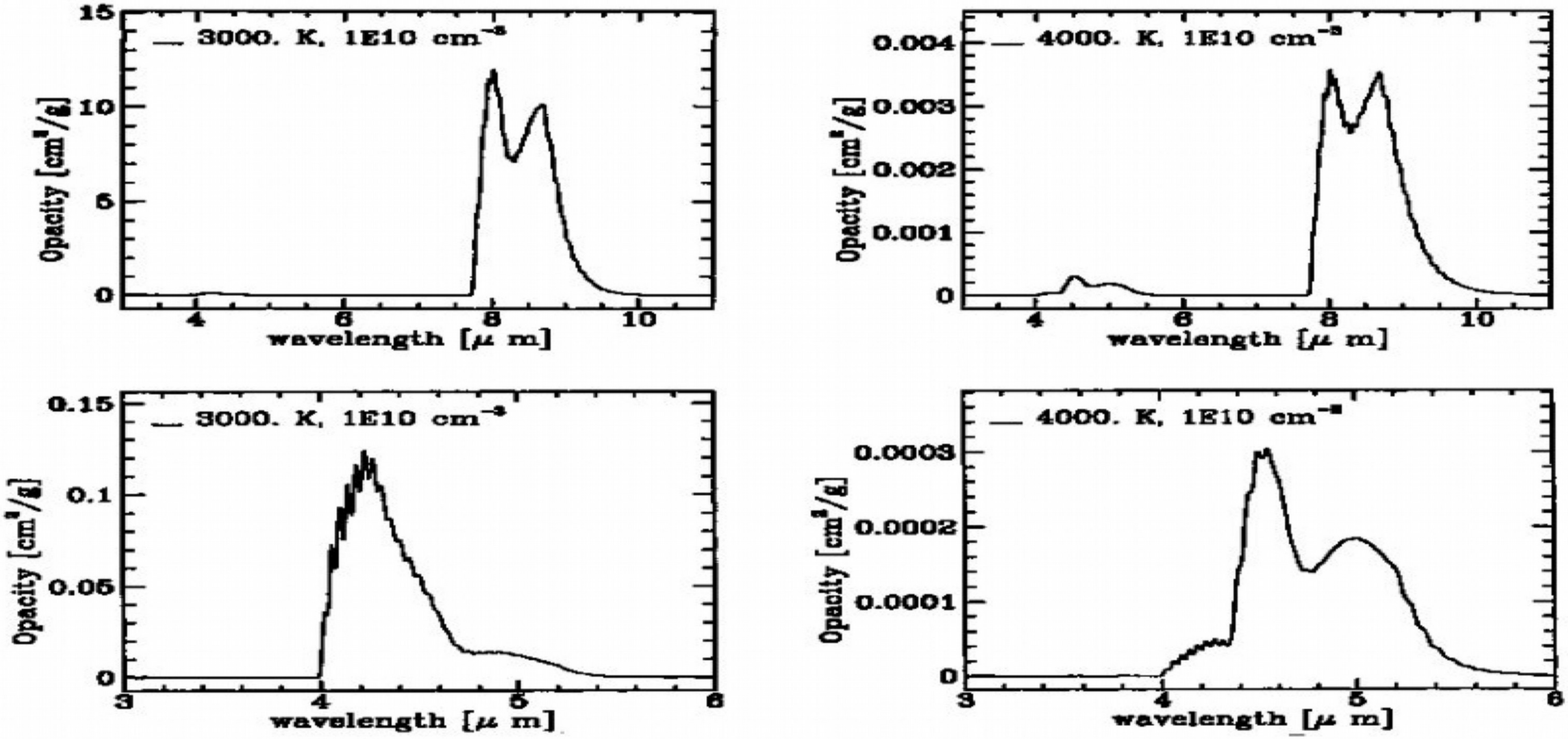
Fundamental   1st Overtone   (approx 4d)



Rem: CO may trigger dust formation (eventually)

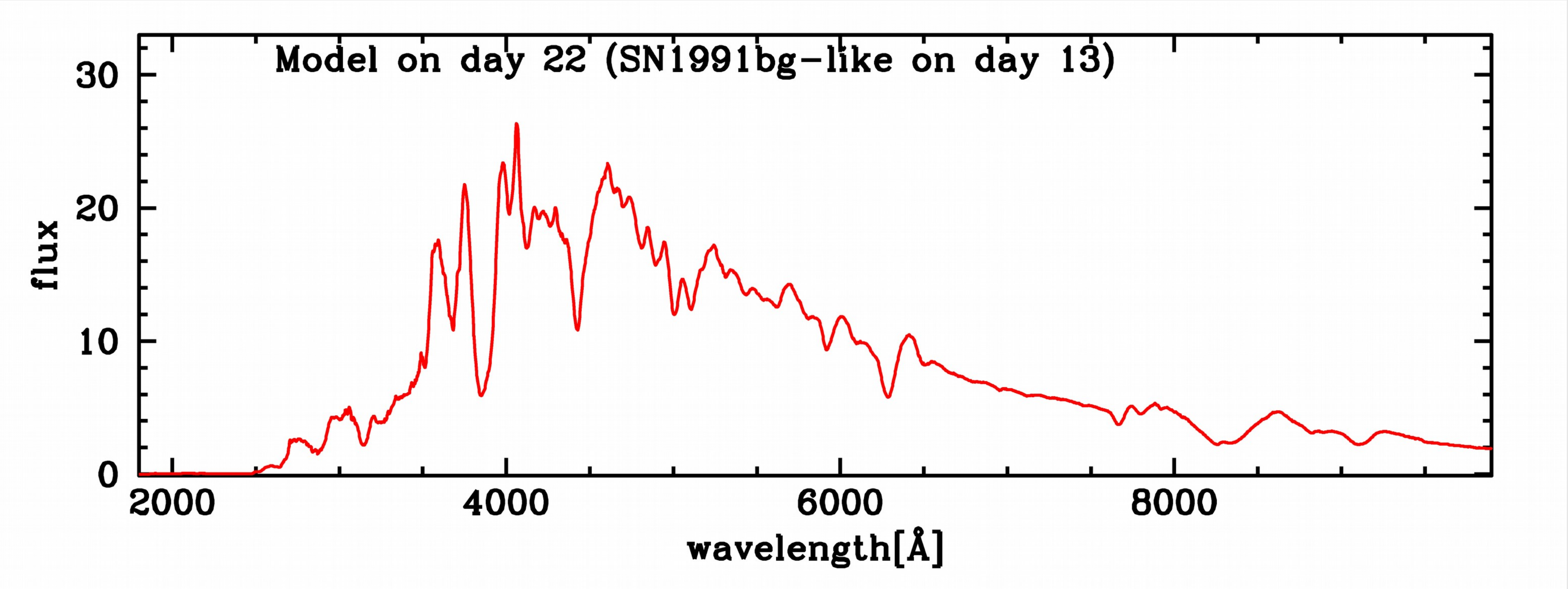
CO as diagnostical tools (and SiO Emission at late times)

(Hetal 1995ff)



Rem: Formation depends on ionization level via charged ions

Remarks on Spectra:



- SN1991bg-like spectra at an earlier time → spectra measure energy density at photosphere

Not surprising because spectra are insensitive to radii.

- UV brightness depends on either low Z or flat density structure.

- MIR: CO-fundamental band already early on

- As brighter as lower the velocity of IME

- NIR Fe-island starts to appear only approx 1.5-2 months after maximum

(SN 1991by at about 2-3 weeks after max, normal SNeIa some 1 week after max, H. et al. 2002).

Not surprising either because the low velocity of Fe-groups.

- **Low expansion → high density and hardly any forbidden lines for months**

Was SN1991T a ‘dimm’ DCD ?

(H.et al. 1993, AA)

- **Si/S in narrow range → shell**
- **Si/S at high velocity 11,000km/sec → 0.2 Mo**
- **Distance 12.5 vs. 13.5 (Saha et al. 1989)**
- **Narrow late-time spectra (Bowers et al. 1994)**

-> 56 Ni to the center

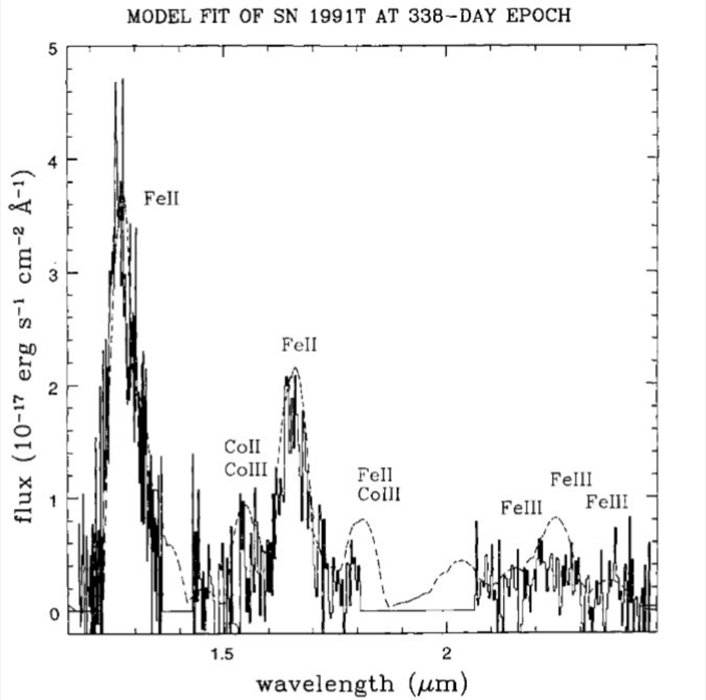


Figure 12. NIR spectrum (solid line) of SN 1991T at +338 d, obtained at the United Kingdom Infrared Telescope with the cooled grating spectrometer CGS4 (see Table 2 for details). Other details as described in Fig. 5 caption.

Finite & Future

- UV & colors will depend sensitively on the initial metallicity
- Si/S velocity will depend sensitively on the envelope masses
- Spectra measure the physical condition in the decoupling region

  (not wavelength independent)
- LC measure the transport time scales → need CO cooling
- Do we see broad He in some cases and at late times ?
- Do we see evidence for shells of an AGB-superwind ?
- What do we see ? (or models are models)
- Was SN1991t a 'dimm' DCD without CO formation ?

…

- WHAT DOES NATURE REALIZE ?

ADDED: He-trigger for sub-M(Ch)

Note: the minimum density in a He-detonation is larger than 5E5 g/cm3 (Livne 1995, ApJ 452, 84). For example, this corresponds to a minimum of 0.035 Mo of He needed for a self-driven detonation.
For triggering a CO-detonation and due to instabilities, the actual mass must be expected to be significanty la rger.
(Answer to a suggestion by W.Hillebrandt during this talk that 1E-2 Mo of He are sufficient for an 0.9 Mo and this amount and this amount does not dependent on M(WD)).

Core + He-shell	56Ni	56Ni(shell)	Iron-group elements(shell)
Hoeflich & Khokhlov 1996 (ApJ, accretion 2E-8Mo/yr)			
0.6 + 0.22	0.43	0.12	
0.6 + 0.14	nova		
0.8 + 0.16	0.526	0.05	
1.0 + 0.15	1.07	0.02	
Woosley & Weaver 1994 (ApJ 423, 371, accretion 1E-8)			
0.6 + 0.20	0.23	0.12	
0.6 + 0.16	nova		
0.8 + 0.17	0.56	0.07	
0.9 + 0.18	0.79	~0.06	
0.9 + 0.24	0.98	0.09	
Nomoto 1982 (ApJ 253, 798out o)			
1.08 + 0.078	na		
Livne & Arnett 1995 (ApJ 452, 62L, 2D, 8 models, schematic models)			
0.60 + 0.10	"nova" (no front under 5E5 g/cm^3)		
0.60 + 0.20	0.14	~0.10	
0.80 + 0.20	0.648	~0.08	
1.1 + 0.20	0.71	na	
Kromer et al. 2010 (dynamical accretion, non-merging mergers)			
0.810 + 0.126	0.17	0.008	0.011(Cr)/~0.04 (iron-group)
1.025 + 0.084	0.24	0.0011	~0.05 (iron-group)
1.280 + 0.013	1.05	0.0015	~0.06 "