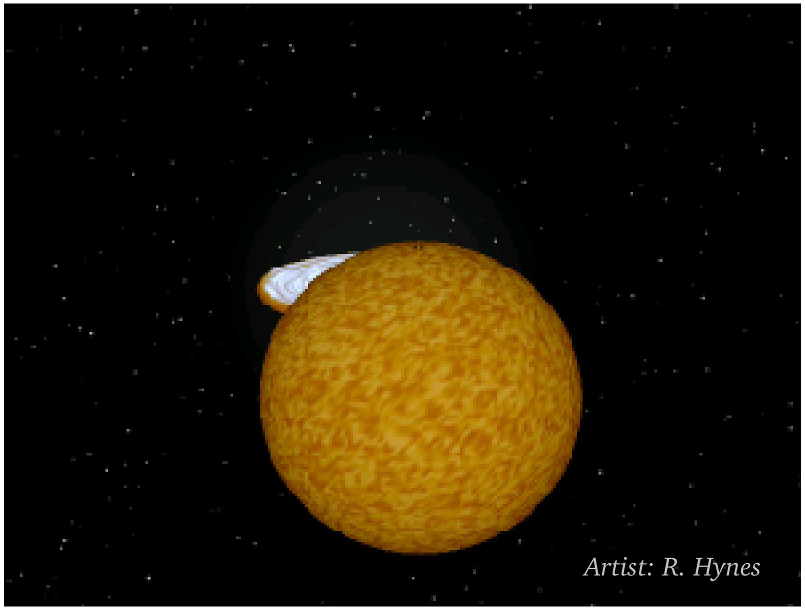
Signatures of SN Ia and Cosmology I

(Understanding the Homogeneity and Probing the Diversity)

(P. Hoeflich/U. Texas at Austin)

Progenitor system of a SNIa



I) Introduction

II) Physics of light curves and spectra

- homogeneity
- signatures of the explosion mechanism(s)
- basic properties of LC s and spectra

III) Diversity & Evolutionary Effects

- progenitors
- progenitor systems
- nuclear burning fronts

IV) Conclusions

Incomplete list of collaborators:

Baade (ESO/Garching); Fesen et al. (Dartmouth); Gamezo (NRL), Garnavich et al. (ND), Khokhlov et al.(Chicago); Krisciunas, Phillips, Suntzeff et al. (CTIO); Langer/Yoon(Amsterdam/NL), Limongi, Chieffi & Straniero (Italy); Meikle et al. (London,UK), Nomoto et al (JP); Rudy (Lick); Stein/Livne(Jerusalem/Israel); Straniero et al.(Rome/Italy); Thielemann et al.(Basel/Ch); Howell, Wang(LBL/Berkely), UT Austin (Gerardy,Marion,Quimby,Wheeler ...)

Why?

I) Distance determination, cosmology & dark energy

II) Origin of the elements

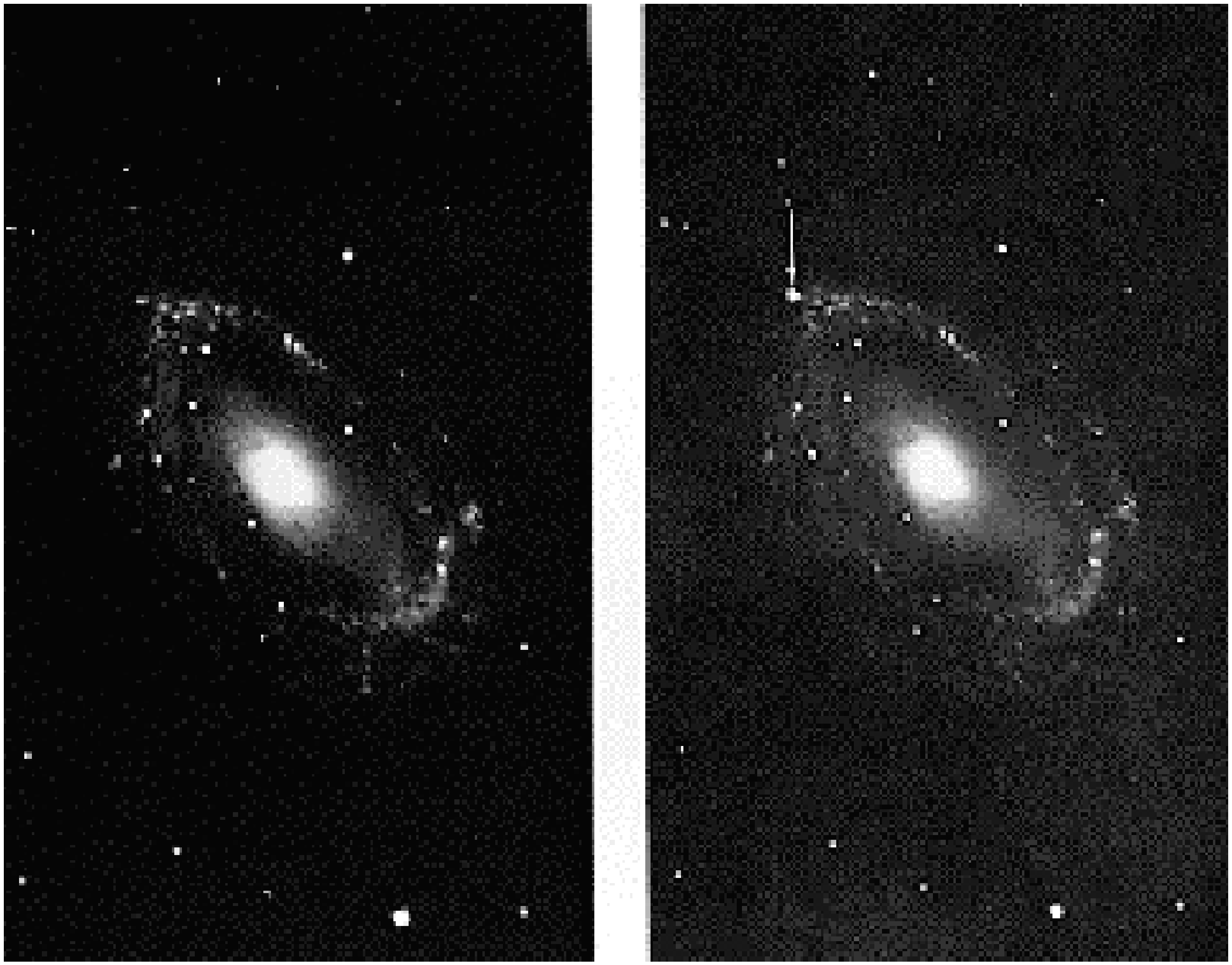
III) Giant laboratory

Why now ?

Ongoing revolution in

- observations
- theoretical physics and mathematics
- computational methods

Then: e.g. SN1940B in NGC 4725 (discovered by Johnson)



Type: SN II

M(ph): 12.8 mag

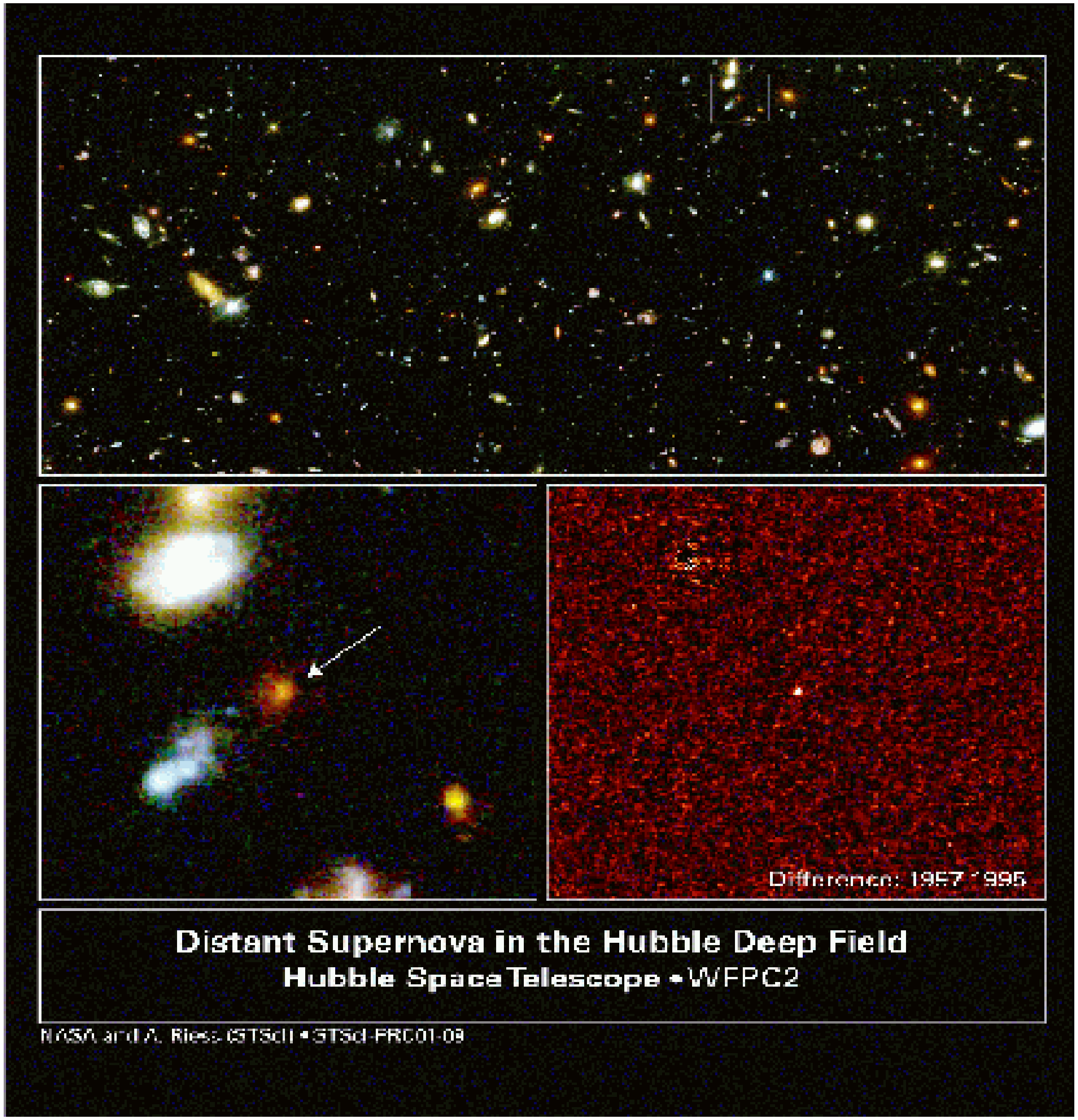
Distance: 5 Mpc

Nomenclature: SNyearalphabetic

e.g SN1940B is the second SN discovered in 1940

SN1997ff, the current record for distance

STScI-press release 01-09 on April 2, 2001 by A.Riess and Co.



SN 1997ff

Distance = 3 Gpc

Red-shift z = 1.7
(based on light curves)

Look-back time:
10,000,000,000 years

Observations: An Ongoing Revolution

	< 1995	now
Discovery:	random, photographic	systematic CCD search
Rate:	5 to 15 /yr	>100/yr
Method:	eye-balling	computer based
Typical reach in z:	z = 0.05 to 0.1	z= 1 to 1.6
Look-back time:	< 100 Myrs	10 Gyrs
Discovered at	maximum light	-3 to -4 mag below
Colors:	UBV,unfiltered	UBVRIJHK
Accuracy of LCs:	0.1 to 0.2 m	0.01m
Spectra:	casual, optical	(UV), 0.3 to 2.4 μm time series
Polarization:	-	0.01 %

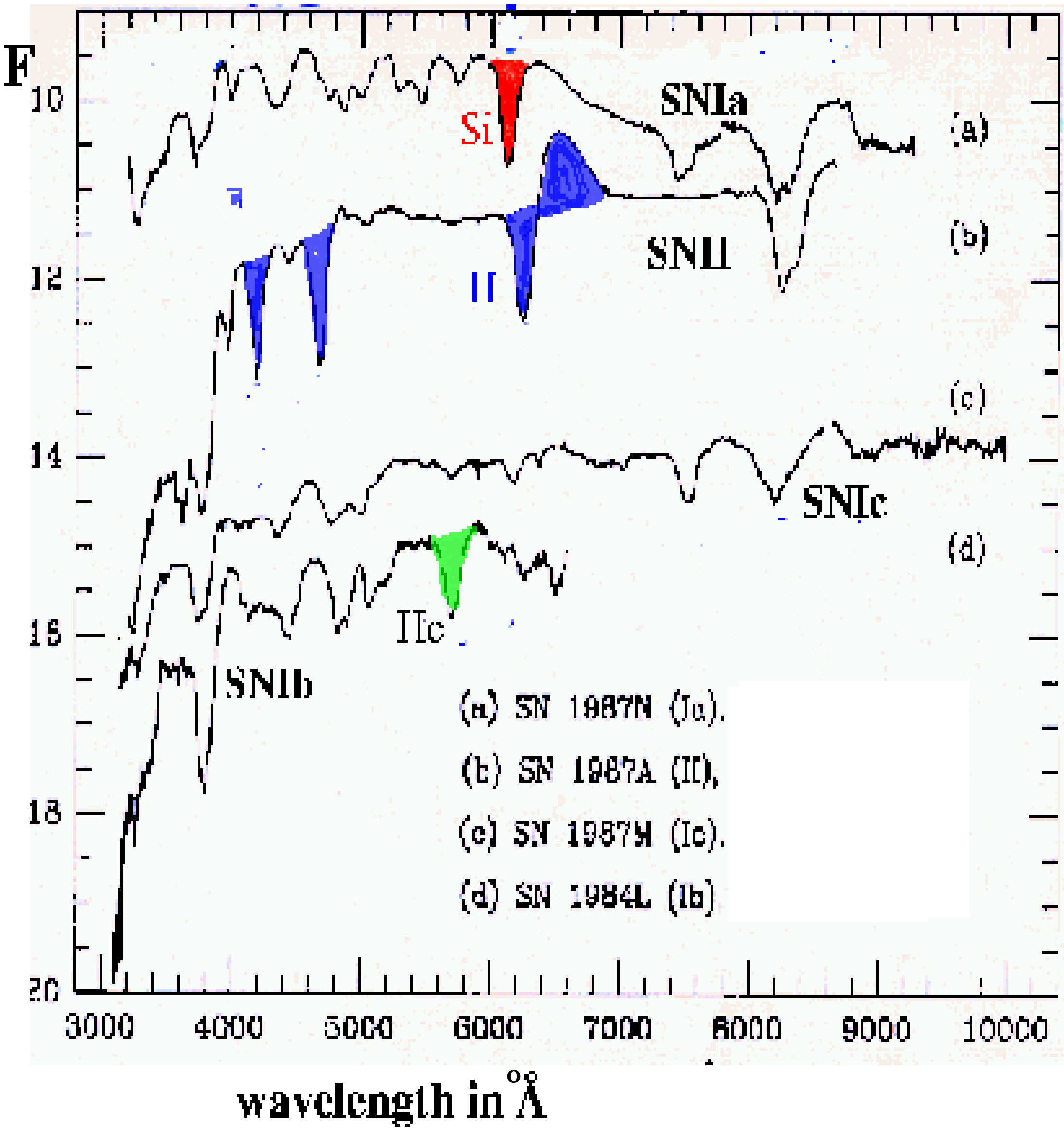
Basic equation for the distance determination

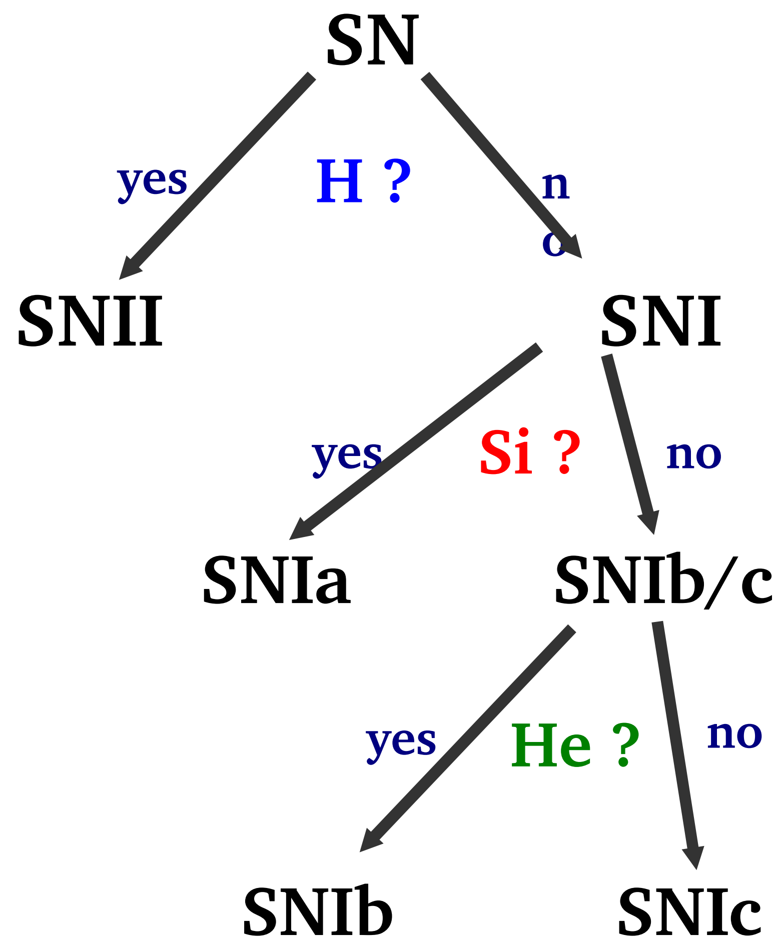
$$m - M = -2.5 \log(r/10pc) + A + \text{cosmology}$$

M = log(L/L(A0-star) normalized to 10pc
m = log(L/L(A0-star)
A = extinction by interstellar material
cosmology = term of interest or correction term

Problems:
- intrinsic brightness
- measurement related (accuracy & systematics)
- different classes of supernovae
- inhomogeneities within a class
- evolution of supernovae with distance/time

Classification of Supernovae by Spectra at Maximum

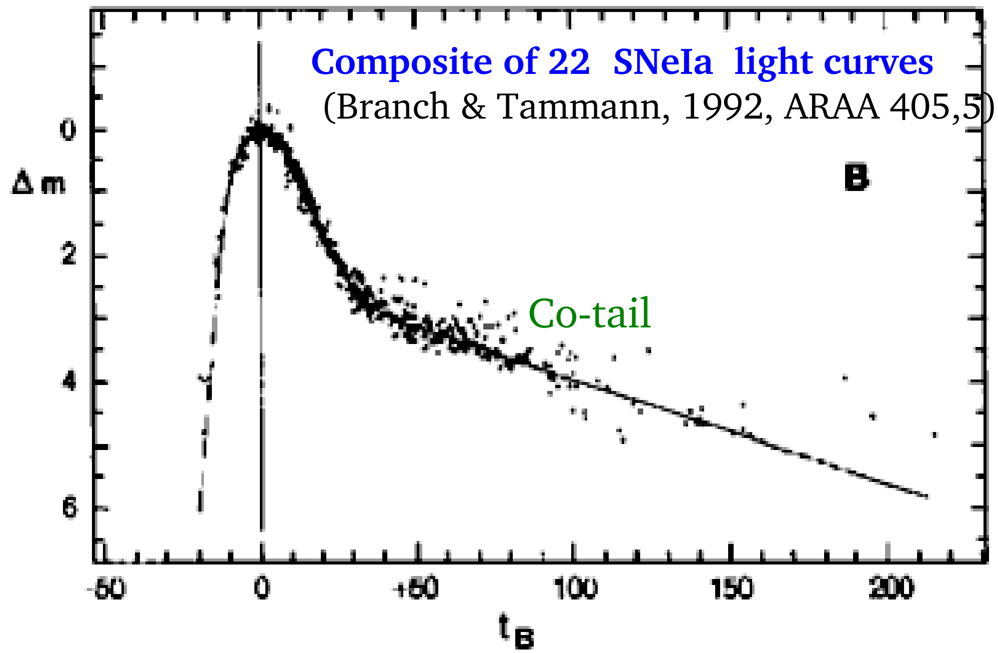


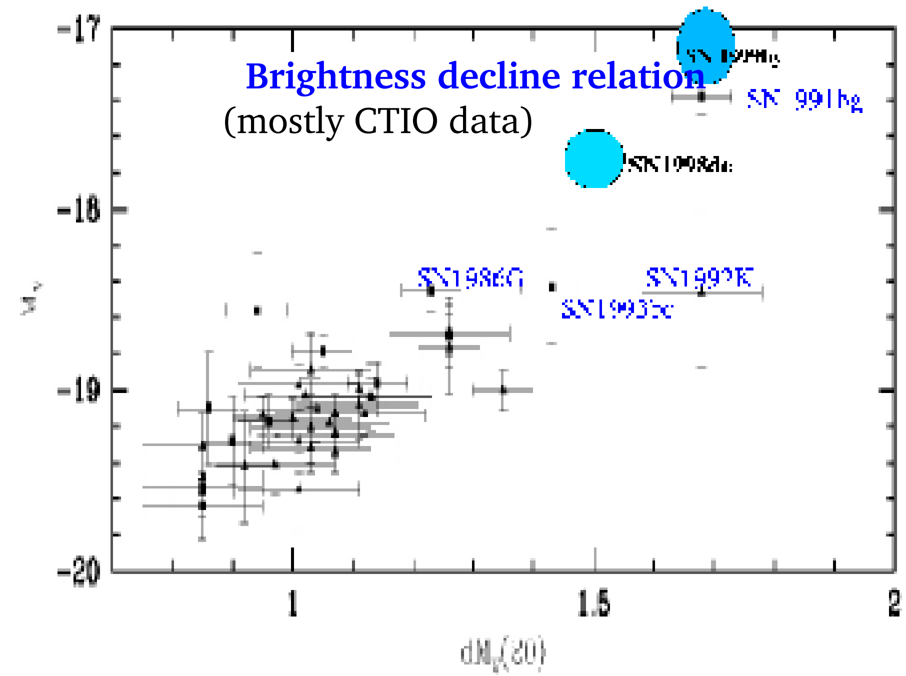


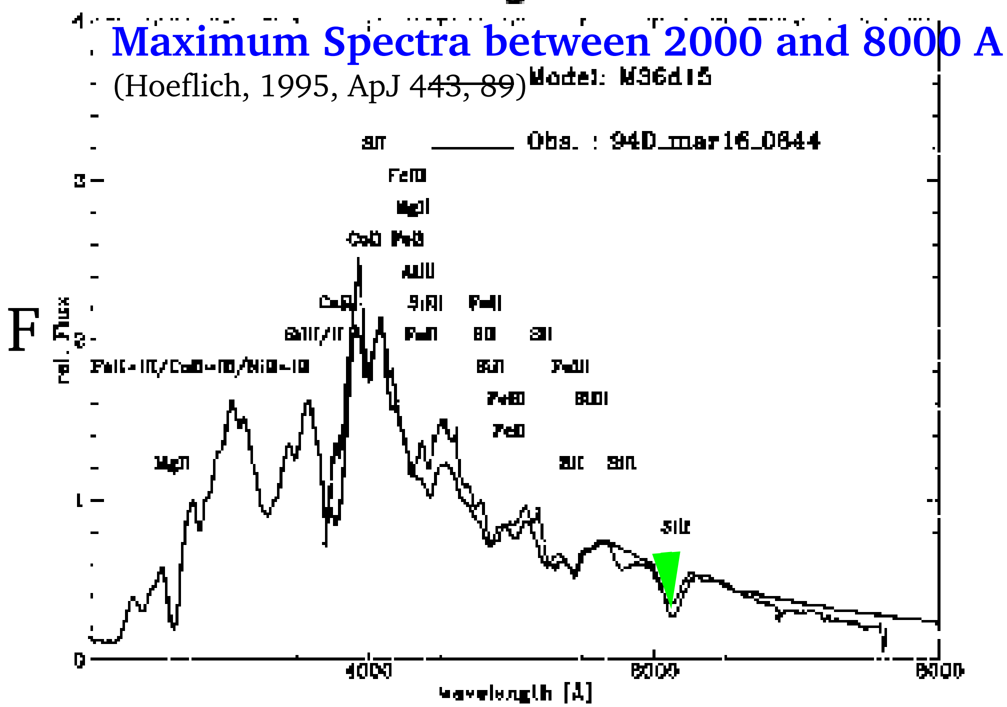
Rem: SNe Ia and Ic are very similar below 5500 A

Rem2: SN Ia are bluer than SN Ib/c (B-V=0 vs 0.25m) =>1st guess by color

Observables: Light Curves, Flux and Pol. Spectra







- LCs are rather similar

- maximum spectra are governed by elements of explosive C/O burning (Mg, Si, S, Fe, Co, Ni)

- Doppler shifts of about 10,000 km/s

=> thermonuclear explosions of WD

Cornerstone: The brightness decline relation

(CTIO group: e.g. Phillips 1987, Hamuy et al. 1996)

Their atlas of 29 SNeIa is the basis for all(!) modern empirical methods!

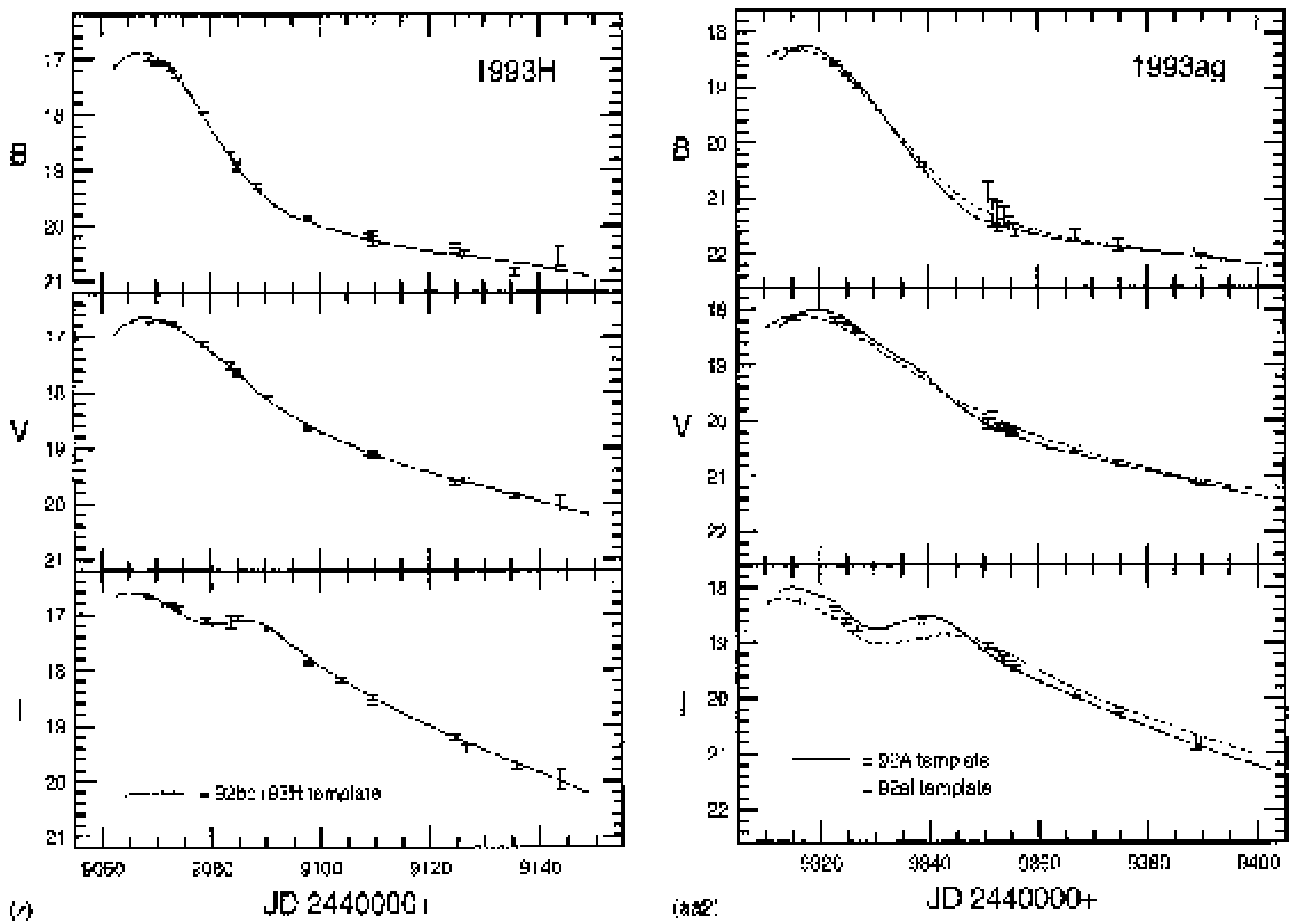


Fig. 3. (continued)

In practice: templates

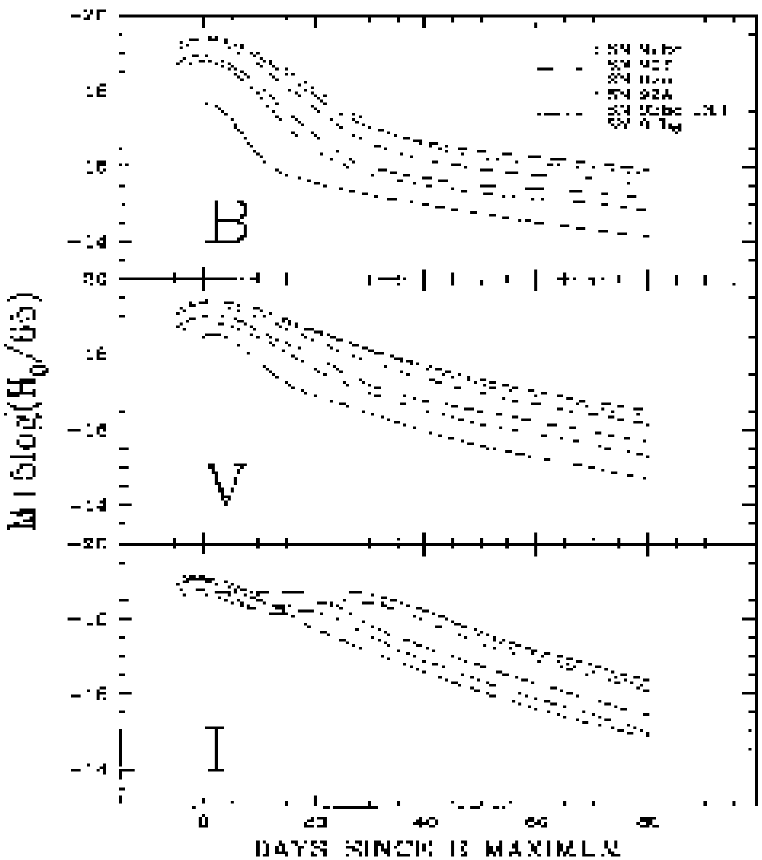


Fig. 9. The six templates B (top), V (middle), and I (bottom) light curves of SNe Ia on the absolute magnitude scale as set by the peak luminosity-$\Delta m_{15}(B)$ relationship of Paper V. The peak absolute magnitudes for the five templates with $0.87 \le \Delta m_{15}(B) \le 1.69$ were calculated using the "low-extinction" fits given in Table 3 of Paper V. The SN 1991bg template is plotted at the peak absolute magnitudes given in Table . of Paper V for the fast-declining event SN 1992K.

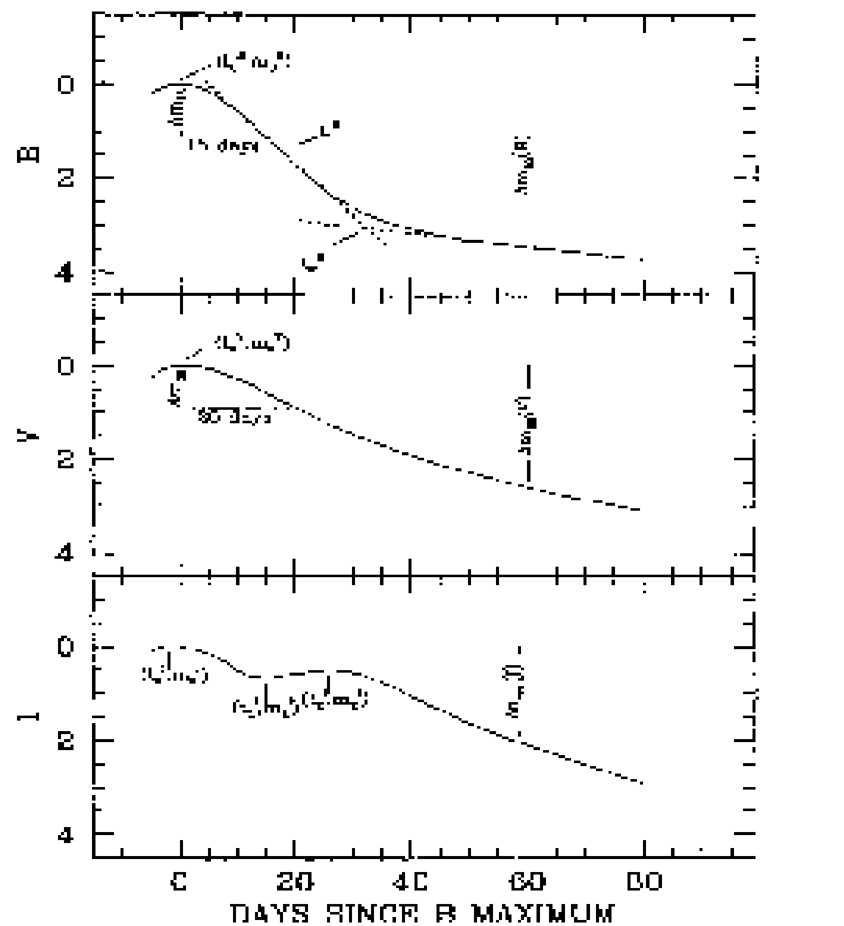


Fig. 8. The template B (top), V (middle), and I (bottom) light curves of SN 1992al. Also shown are the graphical representations of the key parameters defined here in order to characterize the shape of the individual templates.

Recipe: 0) Calibrate the template SN to primary distance indicators

1) Measure the key parameter of a LC
2) Interpolate the key parameters
3) Difference in B-V allows to determine the reddening

Determination of the Hubble Constant (Hamuy et al. 1996)

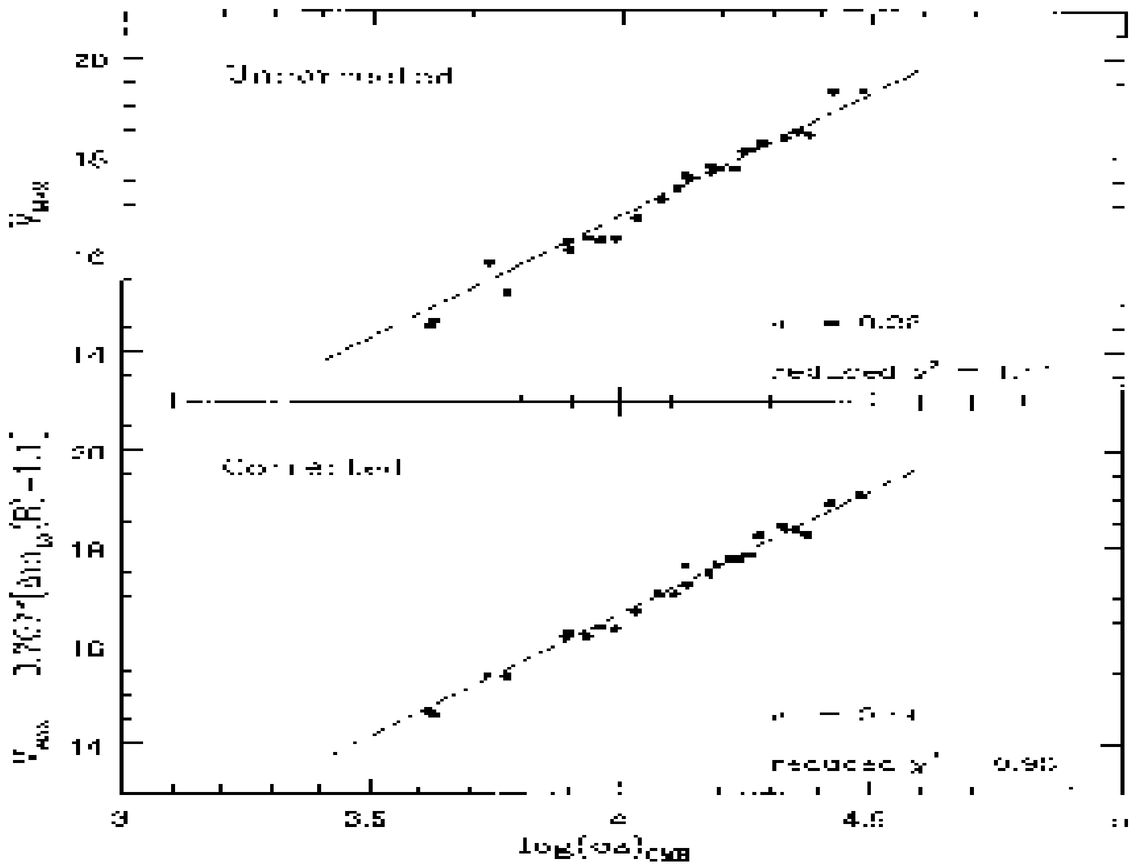


FIG. 5. (top panel) The Hubble diagram in V for the SNe Ia in the Calán/Tololo sample with $B_{MAX}-V_{MAX}\le 0.20$. (Bottom panel) The Hubble diagram for the same 26 events after correction for the peak luminosity-decline rate dependence.

Ho=63.1 +-3.4(internal)+2.9(external)

Errors(internal): ΔM(Δt=15), measurement errors, filter calibrations, reddening, ...
Errors(external): Ceph. Distances
Rem.: Models   67 +- 7 (2 sigma) Mueller & Hoeflich(1994), Hoeflich & Khokhlov 1996

Recent improvements (based on 66 local SN)

(Suntzeff et al. 1999, AJ 117, 1175, Phillips et al. 2000, AJ, 118, 1766)

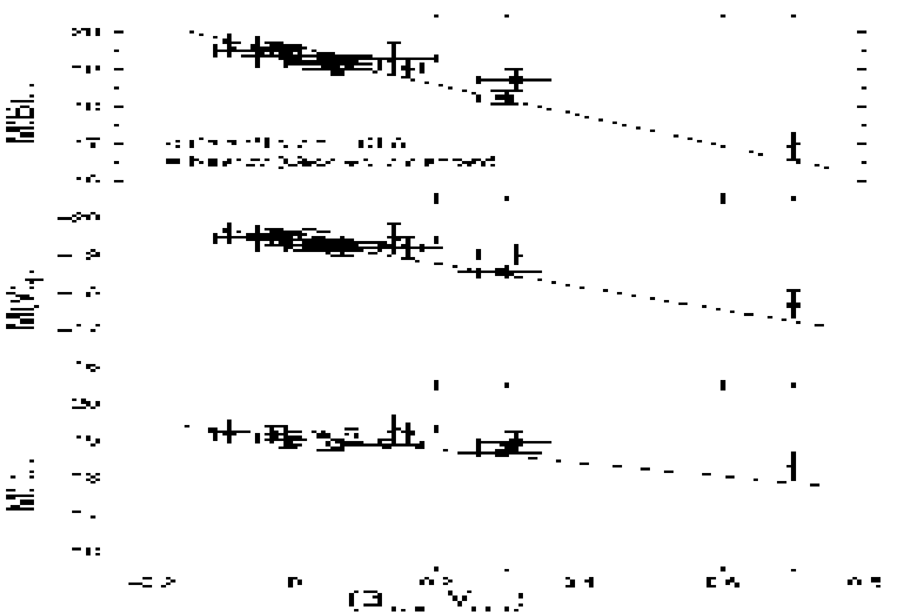
$$M(B)_{1.1} = M(B)_{\max} - 0.786[\Delta m_{15}(B) - 1.1] + 0.633[\Delta m_{15}(B) - 1.1]^2 \,, \quad (20$$

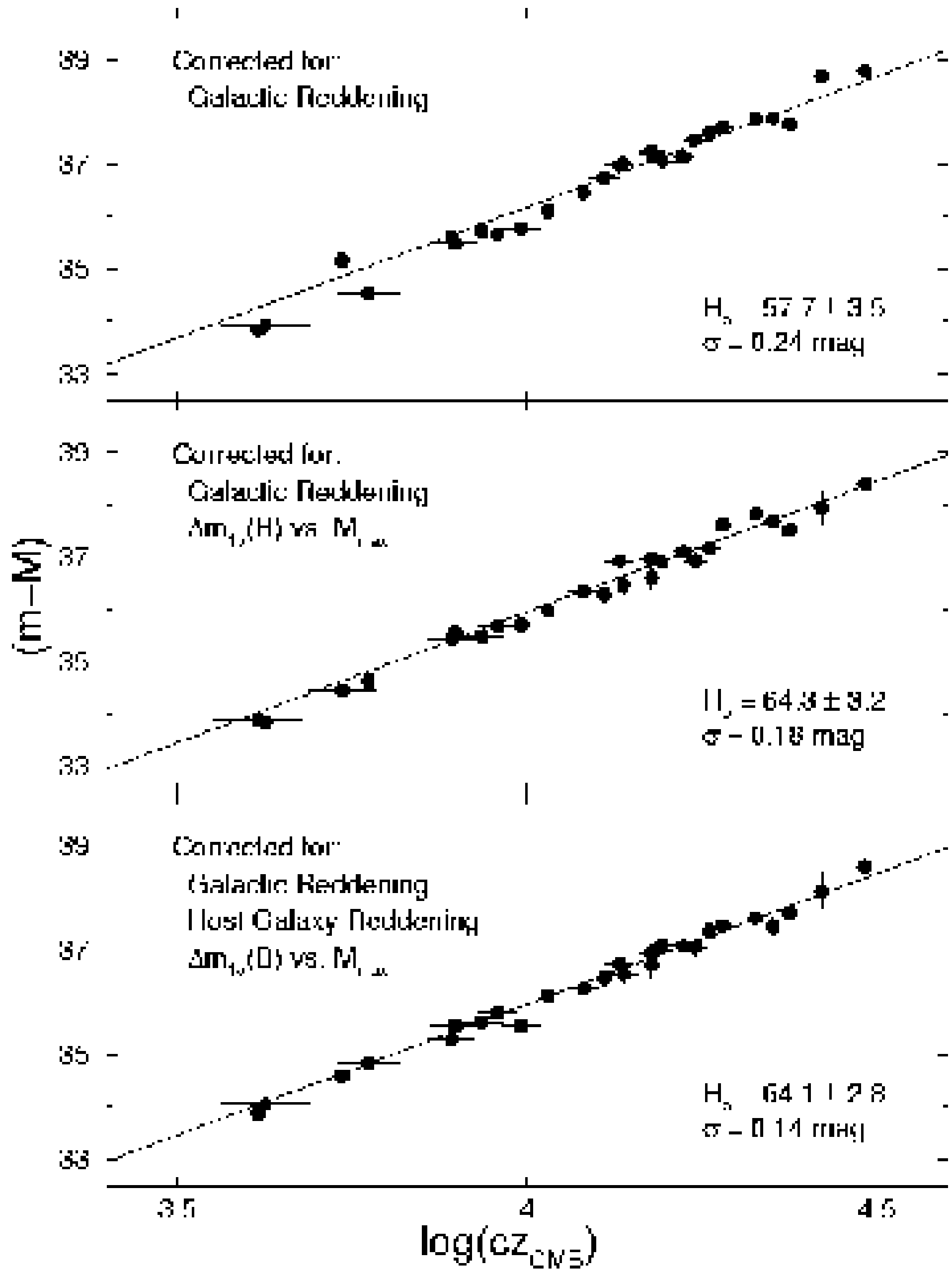
$$M(V)_{1.1} = M(V)_{\max} - 0.672[\Delta m_{15}(B) - 1.1] + 0.633[\Delta m_{15}(B) - 1.1]^2 \,, \quad (21$$

$$M(I)_{1.1} = M(I)_{\max} - 0.422[\Delta m_{15}(B) - 1.1] + 0.633[\Delta m_{15}(B) - 1.1]^2 \,, \quad (22$$

and

$$(B_{\max} - V_{\max})_{1.1} = (B_{\max} - V_{\max}) - 0.114[\Delta m_{15}(B) - 1.1] \,. \quad (23$$





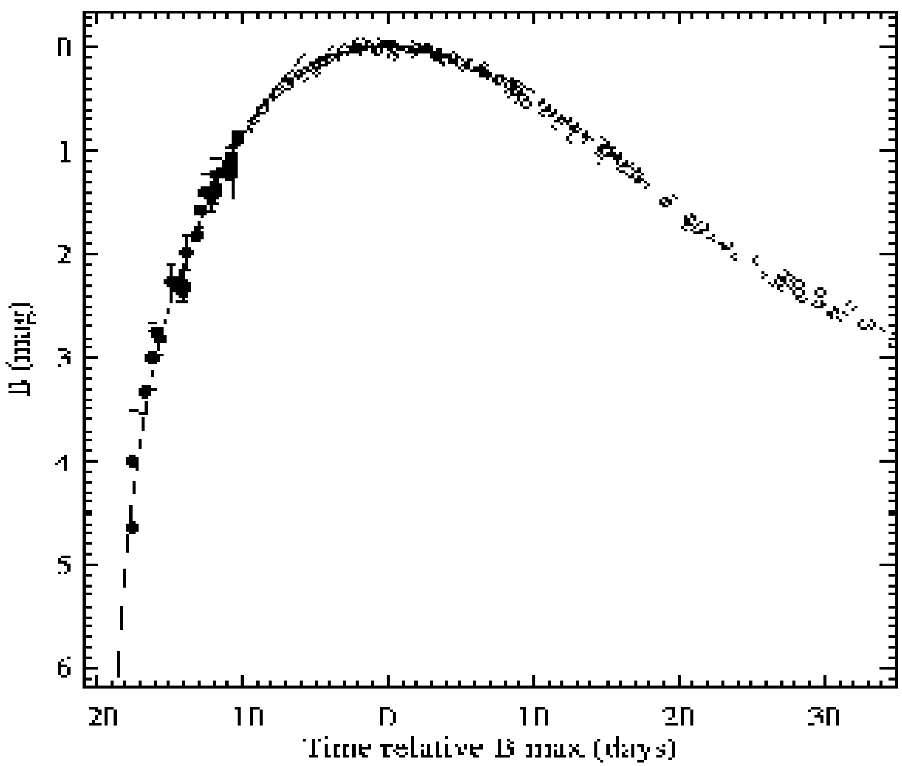
The Stretching Method (Perlmutter et al. 1998, APJ 517, 565)

Rem.: Based on the CTIO-SN and calibrated by the Δm(15) method

M(B),corr = (0.86 +- 0.21) (Δ m(15)-1.1) - (3.32+-0.05)
with
Δm(15)=(1.96 +- 0.17) (1/s -1) +1.07 s: stretching factor of time-axis

Method: Stretching of a standard LC constructed by Leibundgut (1989, PhD thesis)

Test by reversal: use observed LCs and stretch them to s=1



SN Ia Parameters

SN Ia	$\Delta\ (\sigma)^a$	$\Delta m_{15}(B)(\sigma)$	$s(\sigma)$
SN 1996by	0.25 (0.05)	1.37 (0.06)	0.85 (0.02)
SN 1996bo	0.21 (0.05)	1.22 (0.06)	0.93 (0.02)
SN 1996bv	−0.32 (0.07)	0.94 (0.08)	1.14 (0.03)
SN 1997bq	0.14 (0.05)	1.23 (0.05)	0.89 (0.02)
SN 1998dh	0.14 (0.05)	1.23 (0.05)	0.94 (0.02)
SN 1998ef	0.06 (0.05)	1.29 (0.05)	0.92 (0.01)
SN 1998bu	0.02 (0.05)	1.15 (0.05)	0.96 (0.01)
SN 1998aq	0.10 (0.05)	1.12 (0.05)	0.94 (0.01)
SN 1990N	−0.33 (0.05)	1.03 (0.06)	1.02 (0.02)
SN 1994D	0.39 (0.05)	1.40 (0.05)	0.82 (0.01)

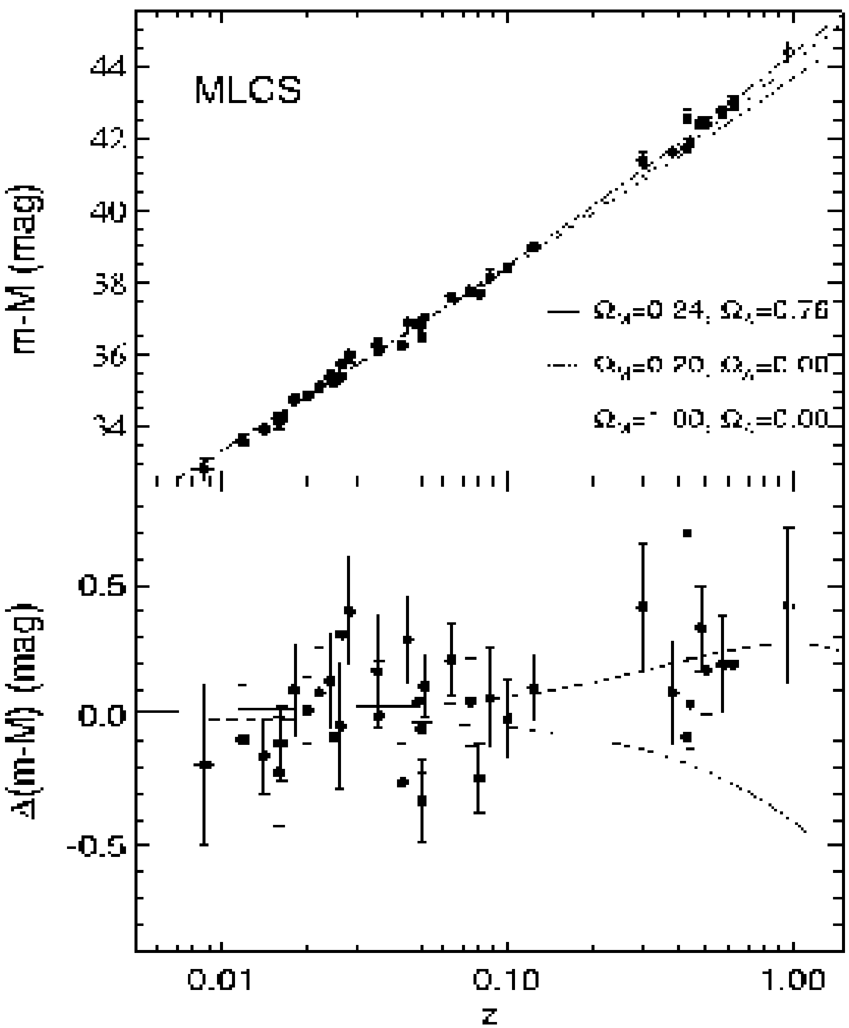


FIG. 4.—MLCS SNe Ia Hubble diagram. The upper panel shows the Hubble diagram for the low-redshift and high-redshift SNe Ia samples with distances measured from the MLCS method (Riess et al. 1995, 1996a; Appendix of this paper). Overplotted are three cosmologies: "low" and "high" Ω_M with $\Omega_\Lambda = 0$ and the best fit for a flat cosmology, $\Omega_M = 0.24$, $\Omega_\Lambda = 0.76$. The bottom panel shows the difference between data and models with $\Omega_M = 0.20$, $\Omega_\Lambda = 0$. The open symbol is SN 1997ck ($z = 0.97$), which lacks spectroscopic classification and a color measurement. The average difference between the data and the $\Omega_M = 0.20$, $\Omega_\Lambda = 0$ prediction is 0.25 mag.

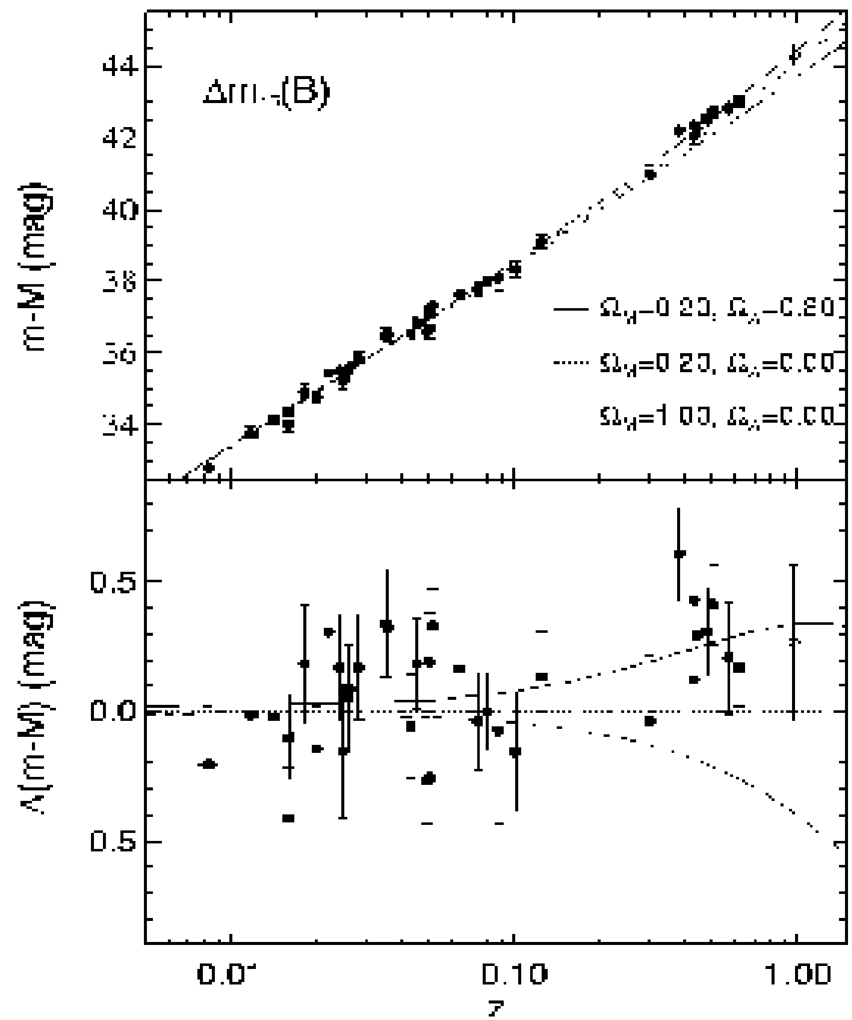
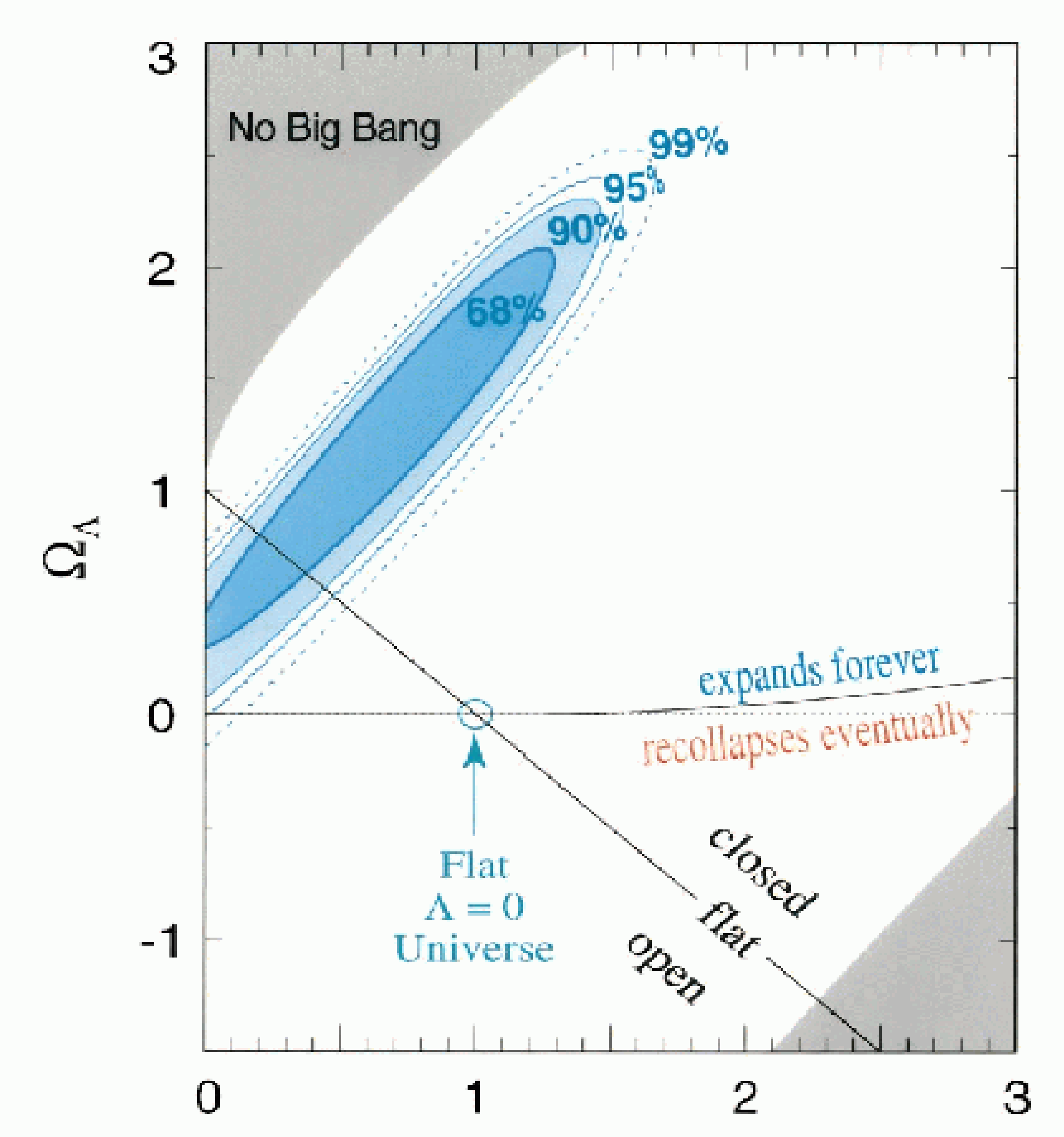


FIG. 5.—$\Delta m_{15}(B)$ SN Ia Hubble diagram. The upper panel shows the Hubble diagram for the low-redshift and high-redshift SNe Ia samples with distances measured from the template-fitting method parameterized by $\Delta m_{15}(B)$ (Hamuy et al. 1995, 1996d). Overplotted are three cosmologies: "low" and "high" Ω_M with $\Omega_\Lambda = 0$ and the best fit for a flat cosmology, $\Omega_M = 0.20$, $\Omega_\Lambda = 0.80$. The bottom panel shows the difference between data and models from the $\Omega_M = 0.20$, $\Omega_\Lambda = 0$ prediction. The open symbol is SN 1997ck ($z = 0.97$), which lacks spectroscopic classification and a color measurement. The average difference between the data and the $\Omega_M = 0.20$, $\Omega_\Lambda = 0$ prediction is 0.28 mag.

Rem.: Error apparently not Gaussian !!!

Application to Cosmology



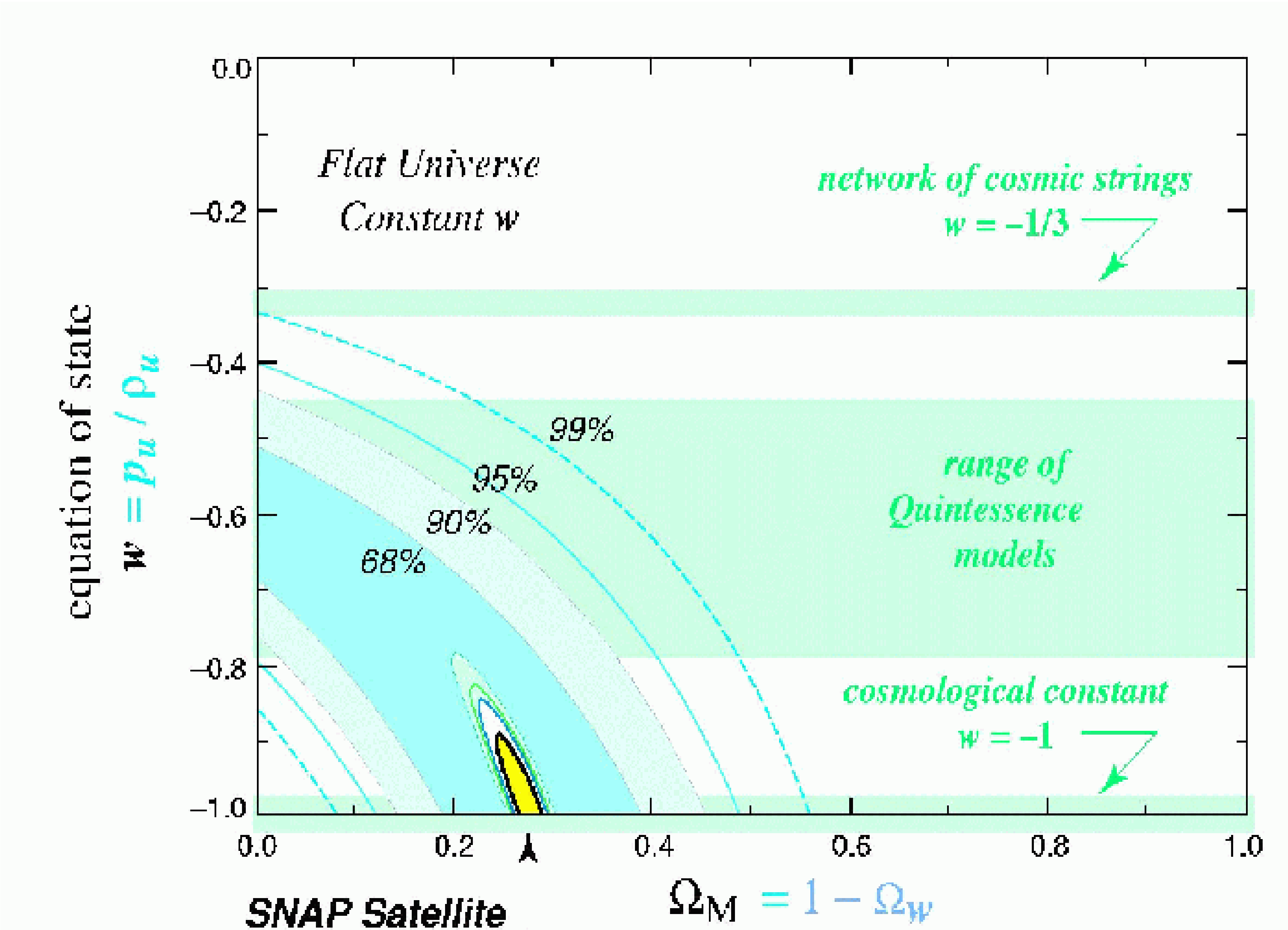
Result:
Evidence for a positive cosmological constant

Rem.: with IMB -> or flat universe

omega(matter) = 0.28+-0.09+-0.0

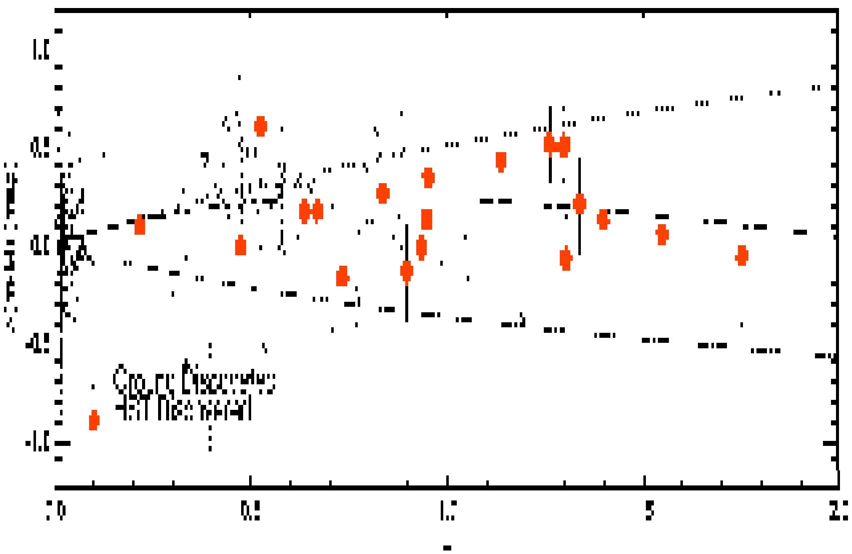
omega(lambda) = 0.72 !!!

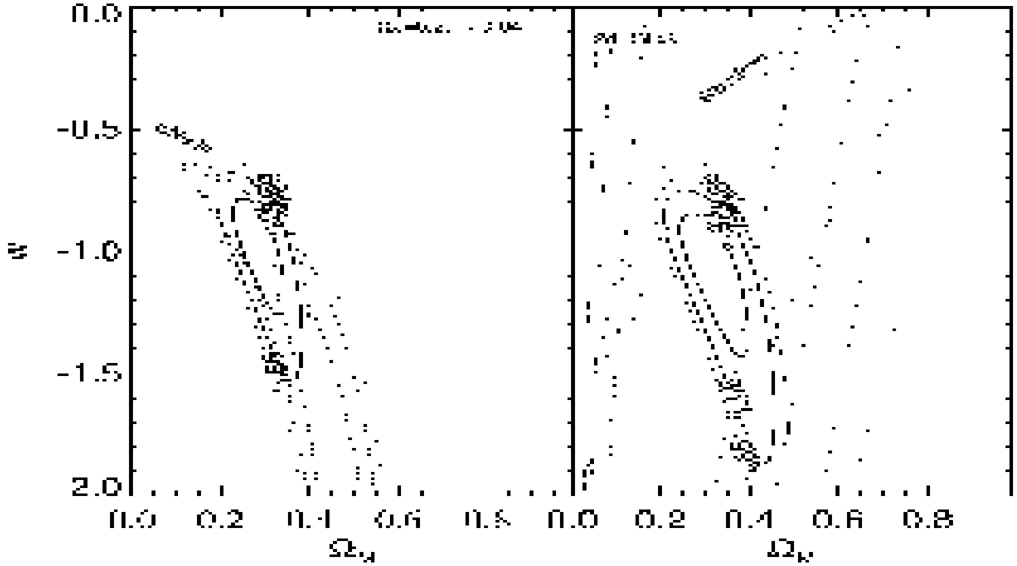
The Quest for the Nature of the “Dark” Energy

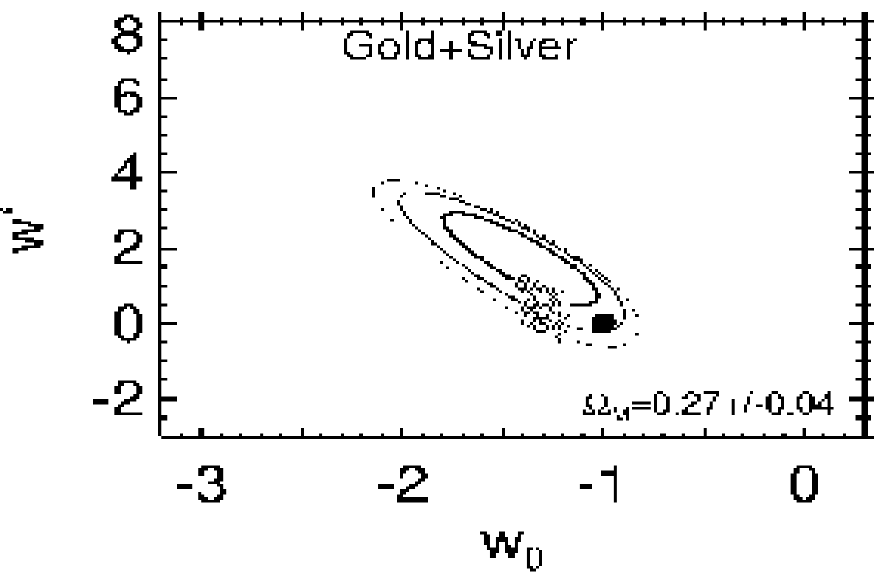


SN at higher Z: The Goods Project (HST)

(Riess et al. 2004, ApJ in press & astro-ph 0402515)







- **Current limit is due to the intrinsic dispersion**

- **We need 2- 3 % accuracy !!!**

Systematic sources of errors for Ho, Ω(m) & Λ

1) Absolute calibration of the zero point of distance scale

a) zero-point of SNe Ia by δ Ceph.
b) δ are secondary distance standards (stellar parallaxes (Hyades) -> Plejades -> LMC)
c) Filter functions and recalibration to standard stars

2) Errors for cosmological parameters

a) Technical problems
- Redshift correction (k-correction)
- Calibration of red-shifted filter

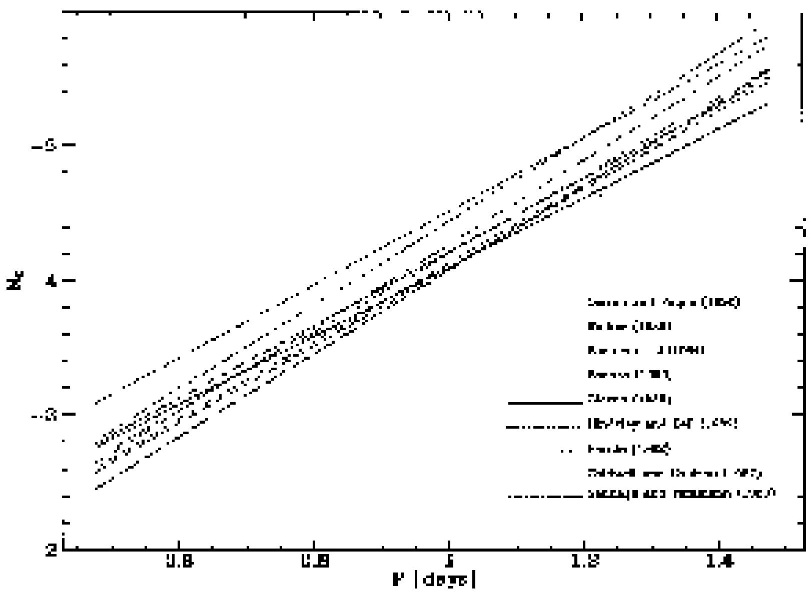
b) Changes of the environment with time
- properties of dust may change
- extinction correction depends on redshift of the absorber

c) Statistical properties of SNe Ia
- change of the 'typical progenitor
- life times of a given progenitor system may change
- change of the progenitor system

d) Physical changes in the progenitors
- chemistry and evolution of the progenitor
- Influence of the initial metallicity Z (Z decreases with time/redshift)

Example:Period-luminosity relation of δ Ceph.

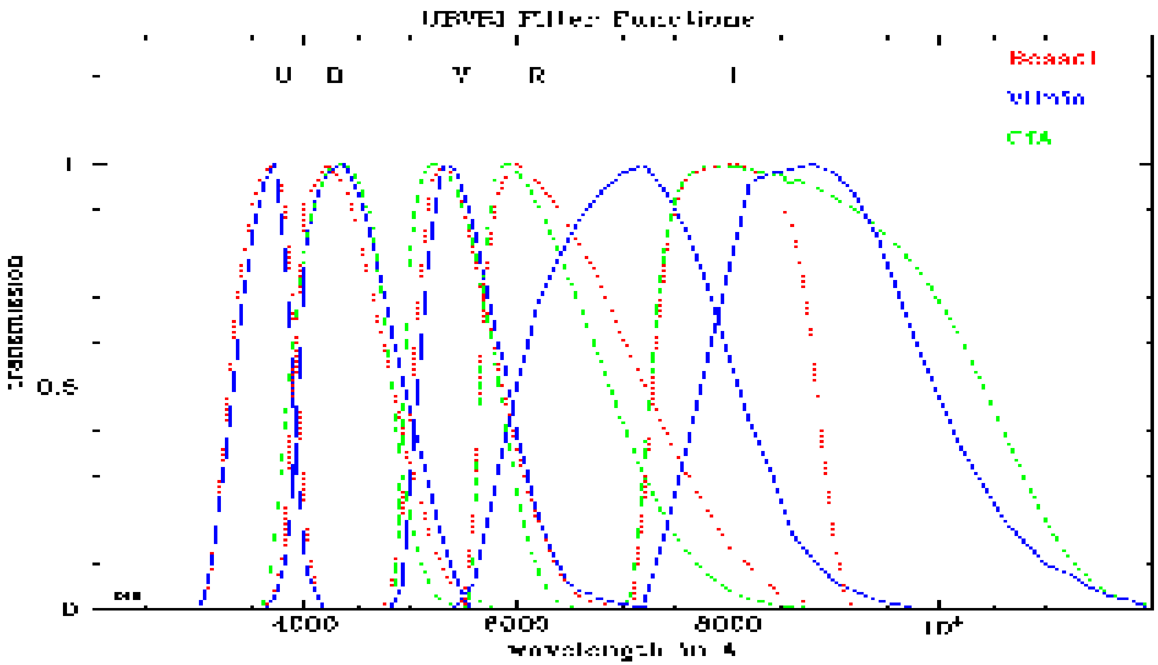
HÖFLICH & KHOKHLOV (1996, ApJ 457, 500)



- spread of about 25 % in relation
  some stars pulsate in the 1st-overtone
  metallicity dependence of P(L) relation

- **today:** uncertainty about 5 % in distance
  Favored P(L) relation:
  Sandage & Tammann (1969)

Filter functions need to be recalibrated



- measurement depends on transmission of filter
- sensitivity of the detector
- condition of atmosphere

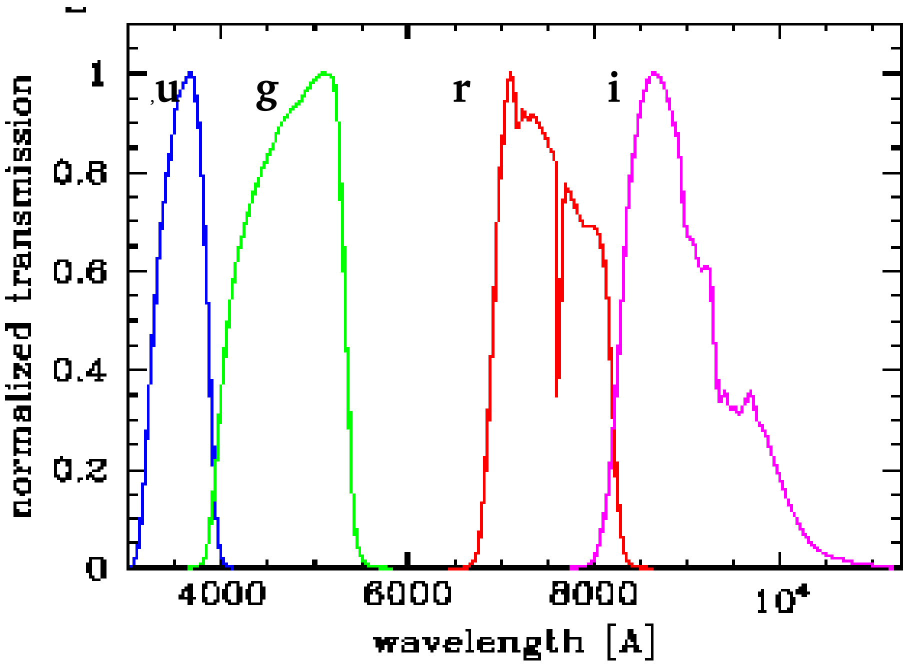
Rem: SN spectrum is no stellar spectrum

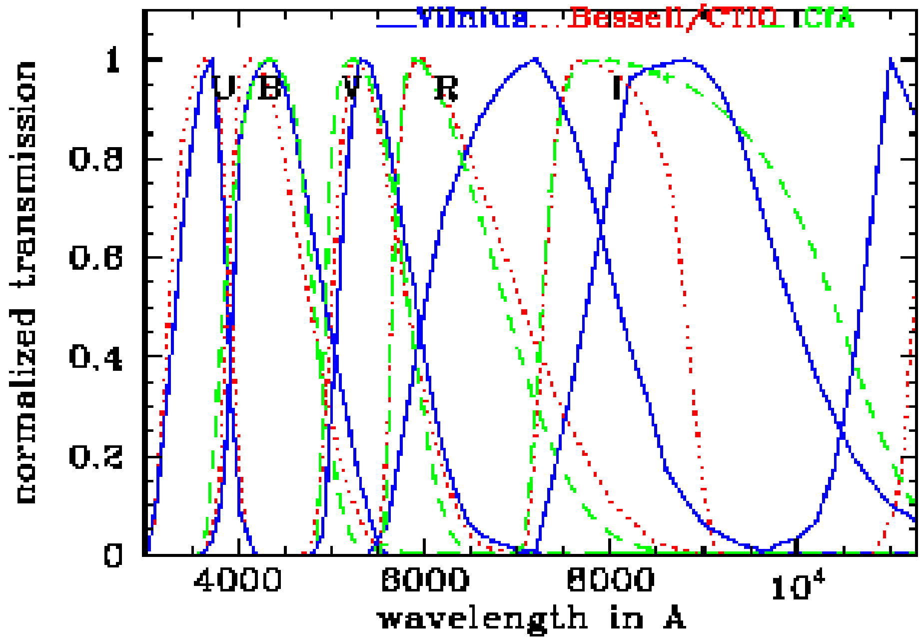
Typical errors:

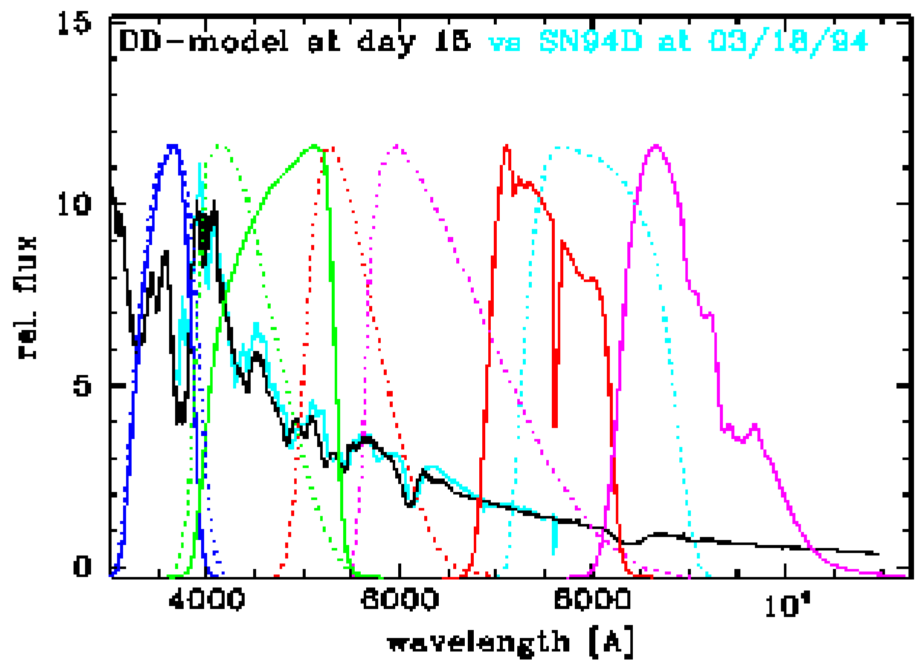
a) internal: 0.02 to 0.03 mag

b) absolute: 0.05 (in B, V, R), somewhat larger in I (up to 0.3mag, see CTIO vs. CfA for SN1994D)

Filter Functions or, what do we measure as a LC?







- SN has no stellar spectrum

-> for 'same systems'
s-correction (Kruczianic et al., 2004)

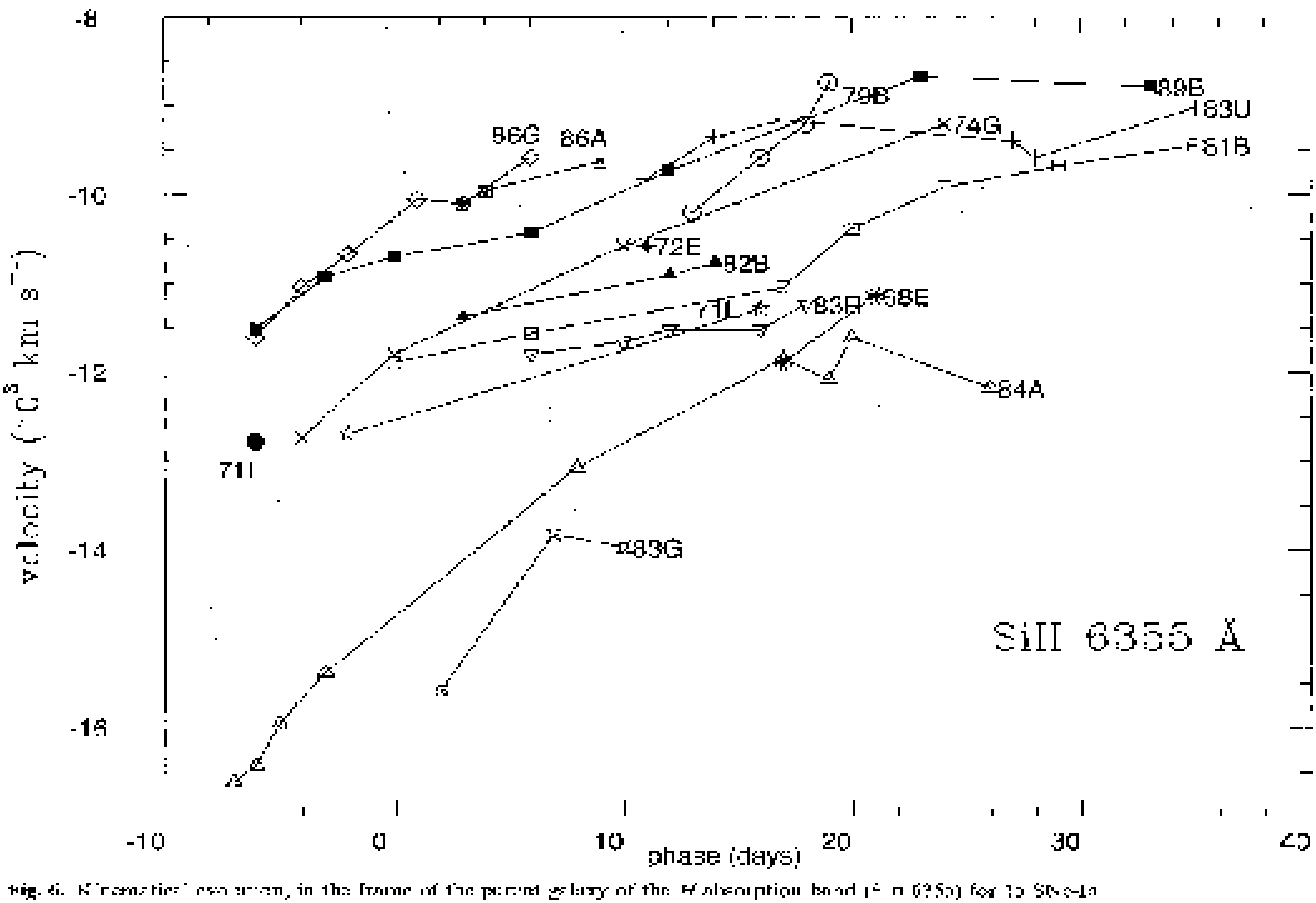
-> SDSS filters will have different
characteristics than B-V

Rem.1: likely, more stable for k-corrections
(but not u) and break degeneracies
Rem.2: in g, may show discontinuities on
the 2...3 % level.
Rem.3: not so well studied for SN

Evidence for the Diversity of SNe Ia

(Barbon et al. 1990, A&A 237, 79)

Doppler-shift as a function of time for 'Branch-normal' SN Ia



Some evidence for evolution

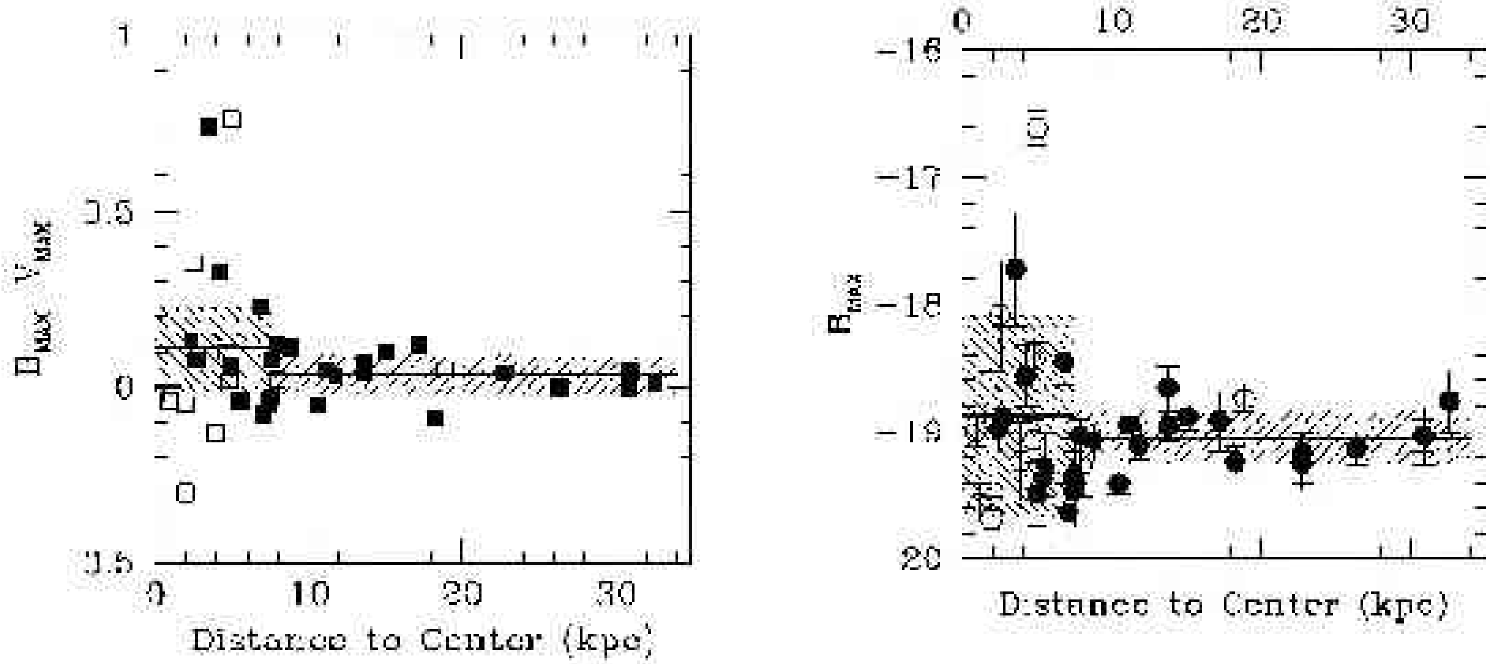
1) SN1991T like SNe Ia are rather common (5-10 %) in local samples but have not been observed at large redshifts

2) SNe Ia are about 0.2 mag dimmer in ellipticals compared to those in spirals (Branch et al. 1998)

3) Properties of SNe Ia depend on the location and type of the host galaxy (Wang et al. 1998)

Statistical properties: (Wang, Hoeflich & Wheeler, 1998, ApJ 483, L29)

Brightness and color as a function of distance in the hostgalaxy



- Larger dispersion in B central regions
- Bluer SNe Ia in central regions

$\Rightarrow$ Intrinsic variation and not reddening

This may/can be corrected by the $M_V(dM15)$ relation (Schmidt et al. 1998, ApJ 507, 46)

WHY MODELS FOR SUPERNOVA EXPLOSIONS

- What is the nature of the supernovae ?

- progenitors
- explosion scenarios
- thermonuclear runaway
- propagation of nuclear burning fronts
- 3D signatures

- Do we understand the observed correlation?

(e.g. brightness decline relation for SNIa)

- Is there one scenario for a SN Ia?

- variation within SN eIa
- normal-bright and subluminous SNeIa

- Distance determination and cosmology

- probe of evolutionary effects with redshift
  (accretion rate, metallicity, rotation, etc.)
- find new correlations which may help to correct for evolution

Main goal of detailed models

- Constrain possible scenarios

(non-unique interpretation)

- Identify the relevant physical problems

(rotation, metalicity, turbulent burning, nuclear flames, nucleosynthesis, ...)

- Test and verify physical processes under extreme condition

(flame properties, preconditioning, ...)

- Understand observations

(spectral and LC properties, brightness decline relation, ranges of brightness, etc.)

- Improve quality of supernovae for cosmology

- size and signatures of evolutionary effects with redshift
- find correlation between observables

How do experiments work in astrophysics ?

Physics: design an experiment to isolate and measure a physical effect

Astrophysics: enter the lab of someone, turn to the wall when the experimental setup fails, and start guessing ...

Sources of Information:

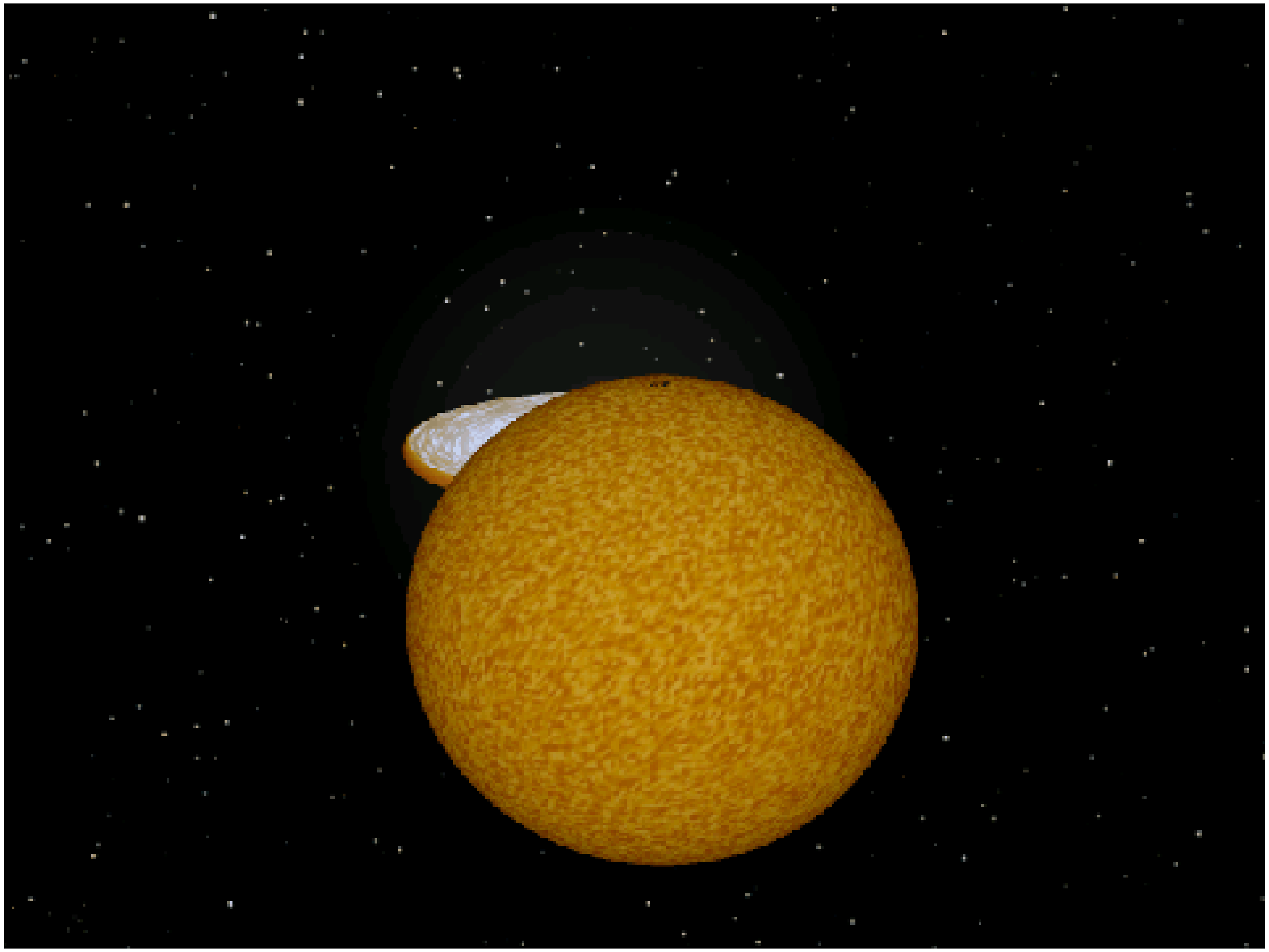
a) Observables (in general):

- Photon fluxes and polarization spectra and their evolution with time
- Statistical properties within the same class of objects
- Integrated quantities (e.g chemical composition of our galaxy)

b) Physical laws and relations used into a model to mimic the observables

I) Scenarios

1) Progenitors: Accreting White Dwarfs



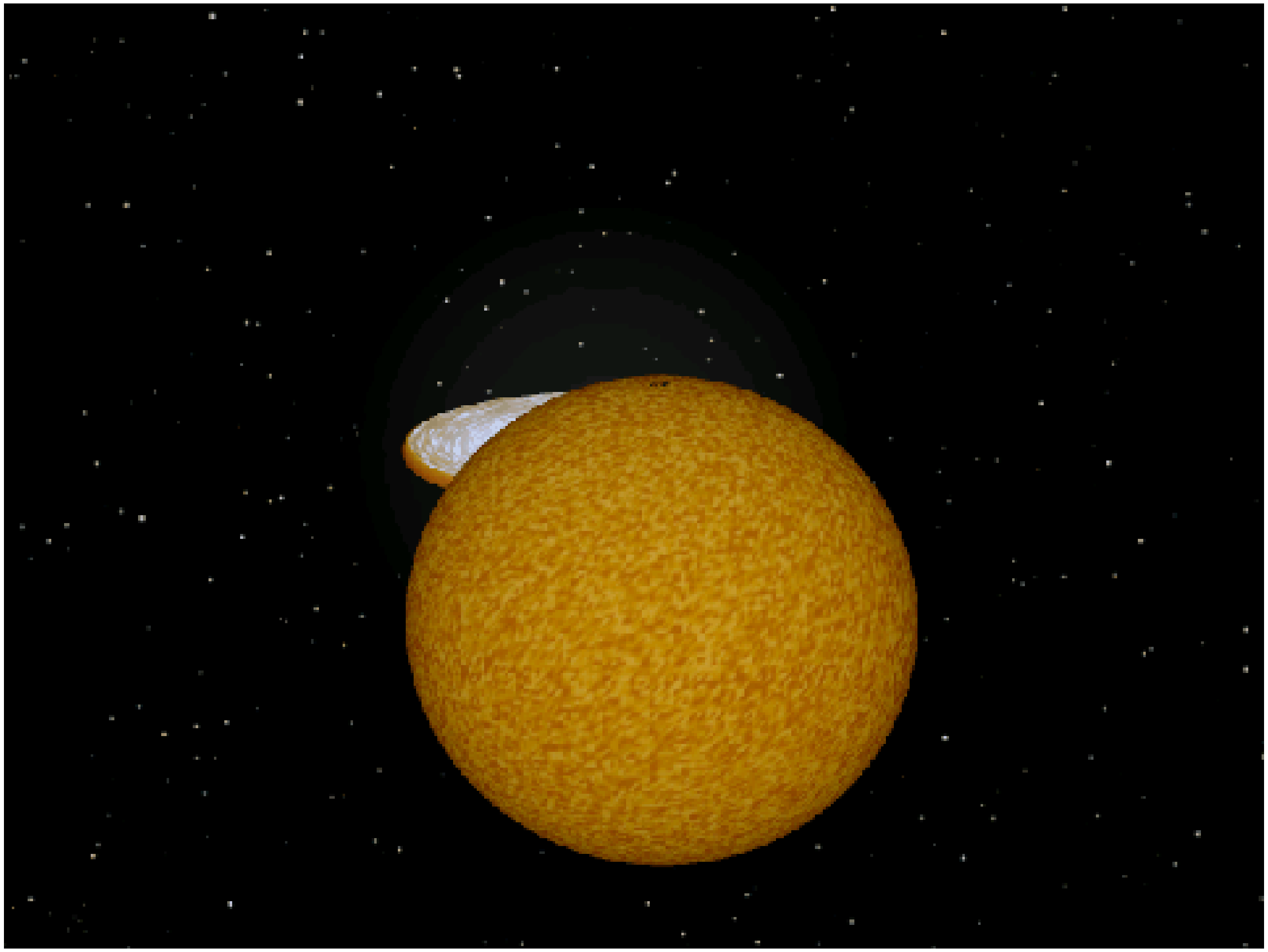
Artist: R. Hynes

Start: WD of 0.6 to 1.2 Mo
Evolution: Accretion of H, He or C/O rich material
Explosion: Ignition when t(nuc) < t(hydro)

2) Progenitors: Merging White Dwarfs

I) Scenarios

1) Progenitors: Accreting White Dwarfs



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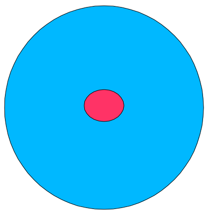
2) Progenitors: Merging White Dwarfs

What do we observe as a supernovae?

SN are the final stages of stellar evolution at with the release of a large amount of energy causes an explosion



1) Exploding progenitor star (hydrodynamical phase)

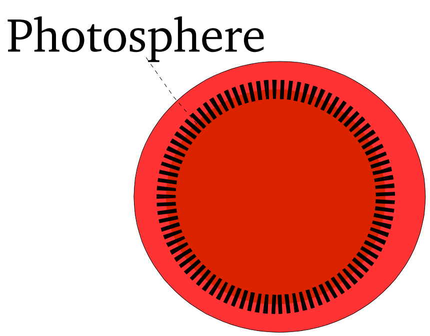
- Nuclear burning releases of about 1 to 2E51 erg into the envelope
- gravitational binding binding energy is about 5E50 erg

=> object becomes unbound

Duration of hydrodynamical phase: several sound crossing times

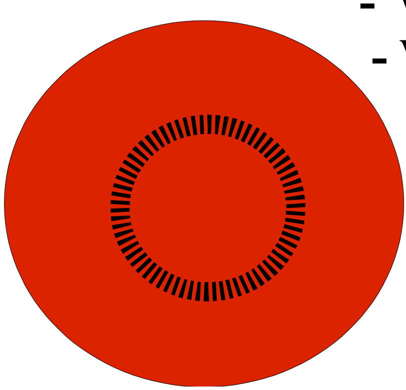
- **sound velocity is about 5,000 to 10,000km/sec**
- **radius of objects 1500km(WD)**

=> hydrodynamical time scale lasts seconds to days



2) Subsequently: Phase of free expansion (homologous phase)

- **We observe a rapidly expanding envelope as a the results of the explosion !!!**
- **expansion velocities are 1000 to 20,000 km/sec**
- **we observe the light emitted from the photosphere**
- **With increasing time, the envelope becomes more an more transparent (due to geometrical dilution)**



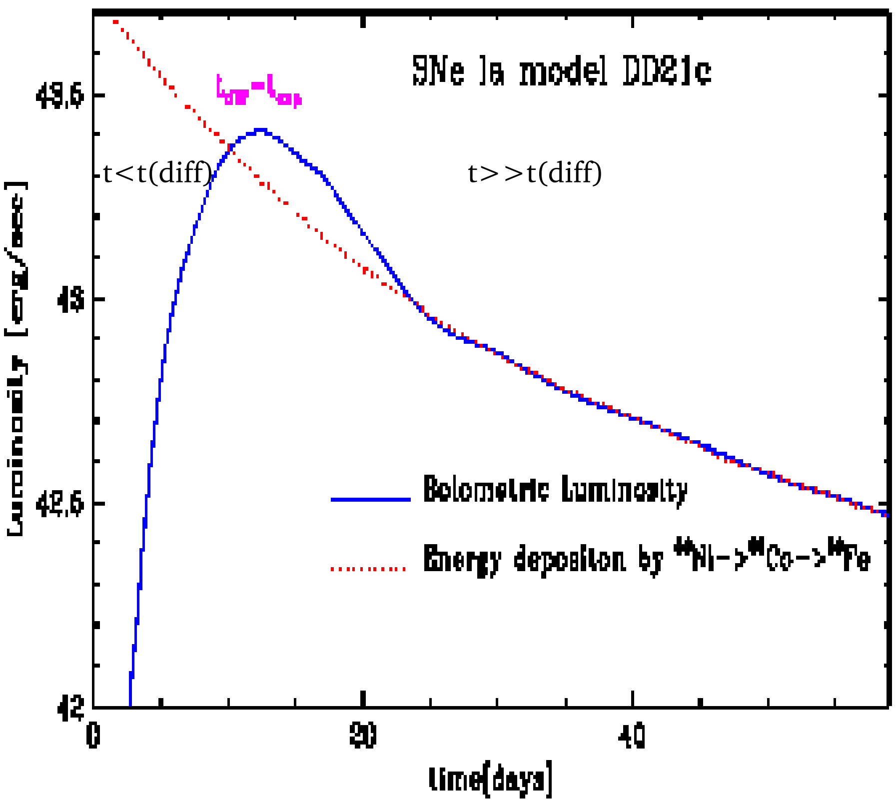
=> The time evolution of the emitted light allows to trace the radial density and chemical structure of the envelope !!!

Light Curves in a Nutshell

Luminosity is given by

emission of energy from regions which become optical thin by the expansion
diffusion of energy deposited by at earlier time by radioactive decay

Luminosity originates from radioactive decay at all phase (in general)



$r_0 \approx r_{WD} = 1600km$ and $v \approx 10,000km/sec$
$\Rightarrow$ pdV cools envelope on time scales of a few minutes.
$\Rightarrow$ Luminosity given by radioactive decay $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$

$r_t(m) = v(m) \times t + r_0 \propto v(m) \times t$
$\rho(m) \propto r(m) **-3 \propto t^{-3}$

Optical depth $\tau = \int \kappa \rho dr \propto (v \times t)^{-2} \times M \approx (E_{nuc} - E_{bind}) \times t^{-2}$

$t_{diff} \propto \tau^2 \propto t^{-4}$ and $t_{max} \approx t_{diff}$

Remark: Details depend on lots of factors including
- distribution of energy source, abundances, etc.

For analytic approximations see e.g. Arnett (1982) (Good to a factor of 1.5 to 2)

Thumbnail Sketch of Thermonuclear SN

- SNe Ia are **thermonuclear** explosions of White Dwarfs
- SNe Ia are homogeneous because **nuclear physics** determines the WD structure, and the 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**
- The progenitor evolution and explosion go through several phases of ***"stellar amnesia"***

=> Homogeneity does not imply a unique explosion scenario !!!
=> Revolution in observations allows to probe physics of SN !!!

Cooking of a Supernovae

A) **Stellar evolution of a low mass star (M< 7Mo, 1E9 years) + mass-loss**
=> initial structure of the WD

B) **Quasi-static evolution of the progenitor (1E6...8 yrs) + accretion**
=> initial structure of the WD at the time of the explosion (SS-X-ray sources)

C) **The thermonuclear runaway (few hours)**
=> preconditioning of the explosive phase

D) **Hydrodynamical phase of explosion (1 to 60 sec)**
=> nucleosynthesis + release of explosion energy

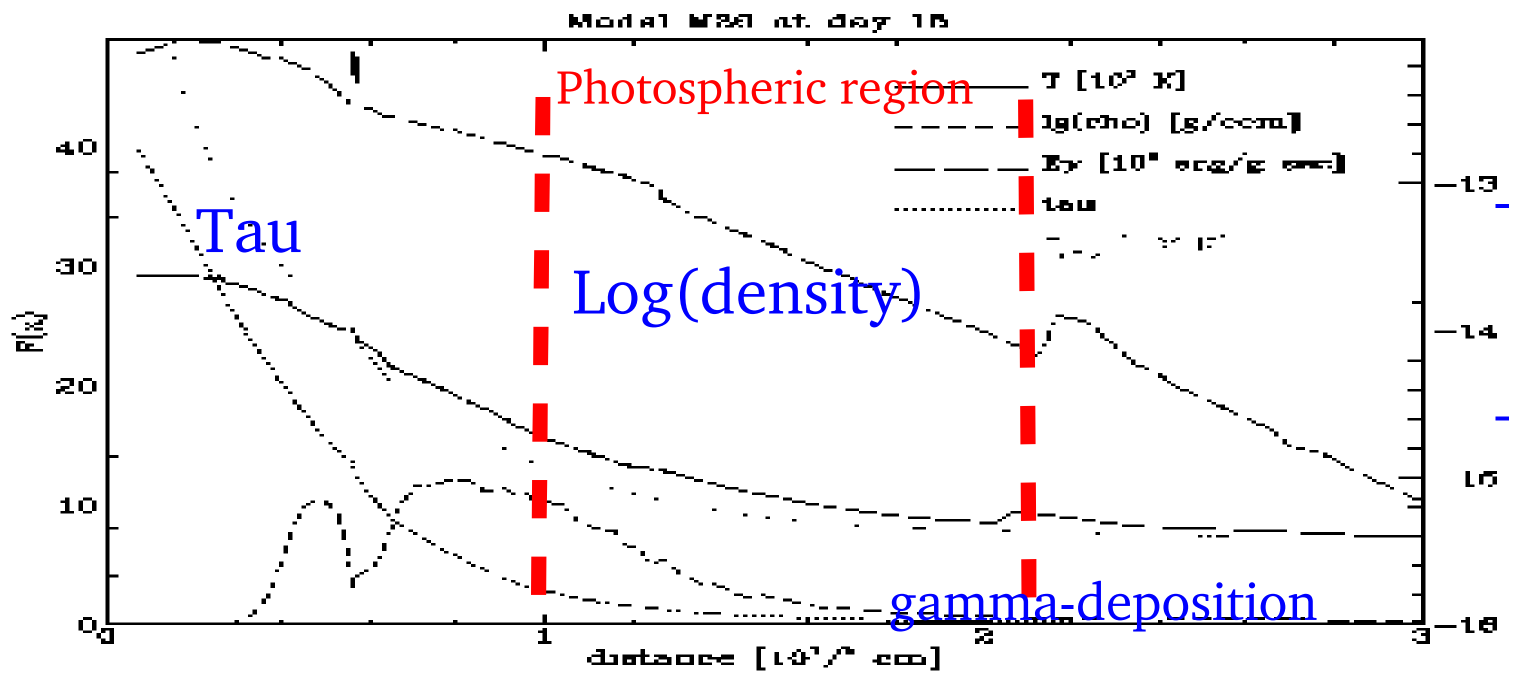
E) Light curve (month to years)
=> time evolution of the expanding envelope

F) Detailed Spectra (Snapshots in time)

Problem: Consistency

Typical Structure of a Type Ia SN at Maximum Light

Example: DD-Model for SN1994D

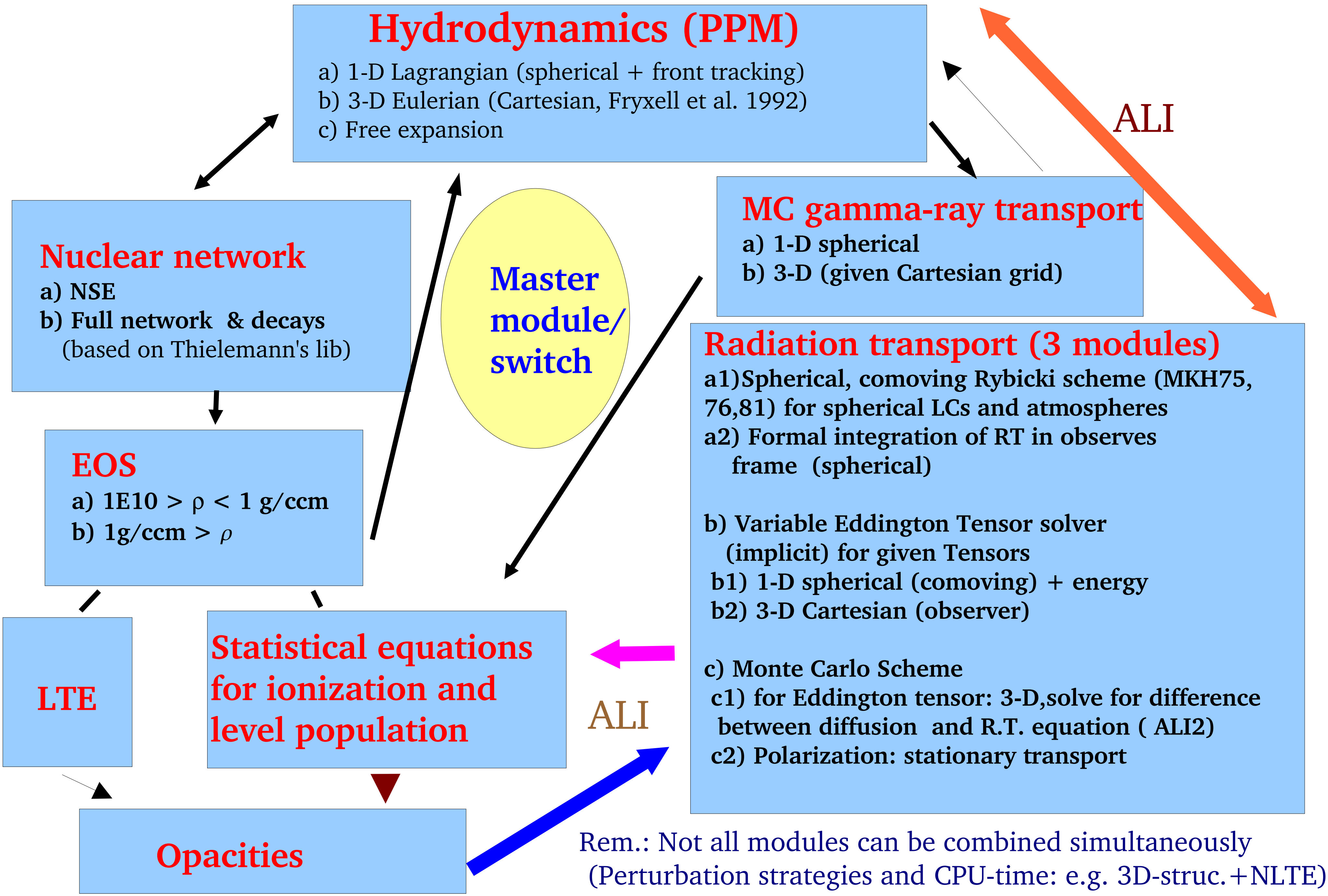


- NLTE up to center

- gamma-deposition at the photosphere => L=L(r)

- gamma-ray deposition has to include multi-scattering
- low density and 'no full' thermalization within the photosphere =>NLTE
- diffusion and expansion time scales are about equal => time dependent

How? Numerical Environment of *HYD*rodynamical *RA*diation transport



HYDrodynamical RAdiation transport for LC.s & Spectra

(1998, 2001, 2003ab)

1) Spherical or full 3D geometry (entire envelope)

2) Explicit hydro (PPM,1D comoving, 3D observer) and implicit radiation transport
(3D-hydro is based on/derived from Prometheus, Fryxell et al.)

3) Detailed nuclear networks (based on Thielemann's reaction lib.)

4) Multi-frequency transport (1E3 ...1E5 for 1D/1-5 for 3D/1...1E4 for P)

5) Time dependent rate equations and RT (for polarization, snapshot)
(For polarization, see Hoeflich 1991,95, H etal.96,Wang etal.96, Howell2001)

6) Full NLTE with superlevels (500 -1000 super-levels,10000 bf-t, 1,000,000 lines,e.g. H02)

7) Coupling of rate, RT and hydro by Accelerated Lambda Iteration

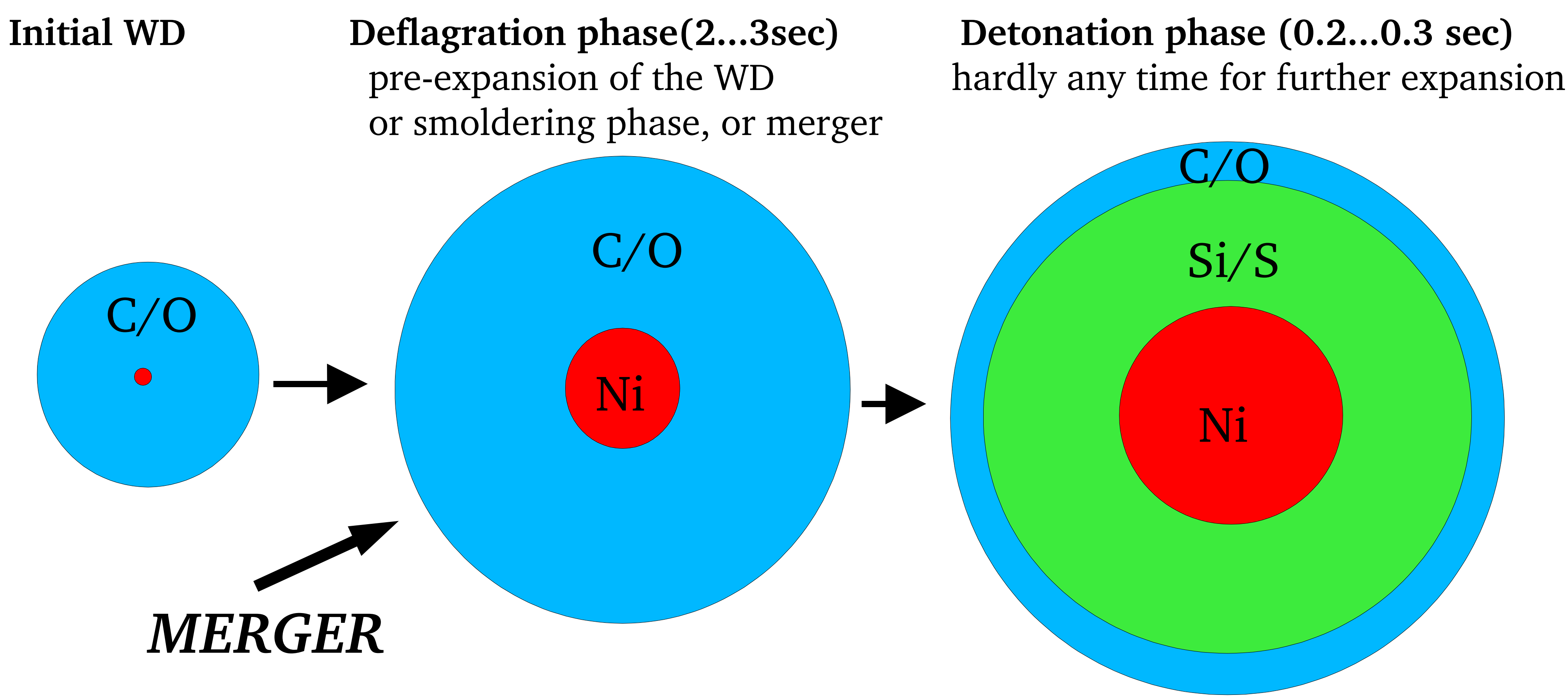
8) AMR for radiation transport (only)

9) Parallel code (PVM -> MPI2)

Rem.: HydRa has been merged by previously independent codes
Interfaces and iterative methods are still in the process of 'streamlining'

Limitations: Currently, implemented methods and approaches are tuned for rapidly expanding atmospheres.

Explosion of a White Dwarfs (Defl., Delayed Det. & Merger)



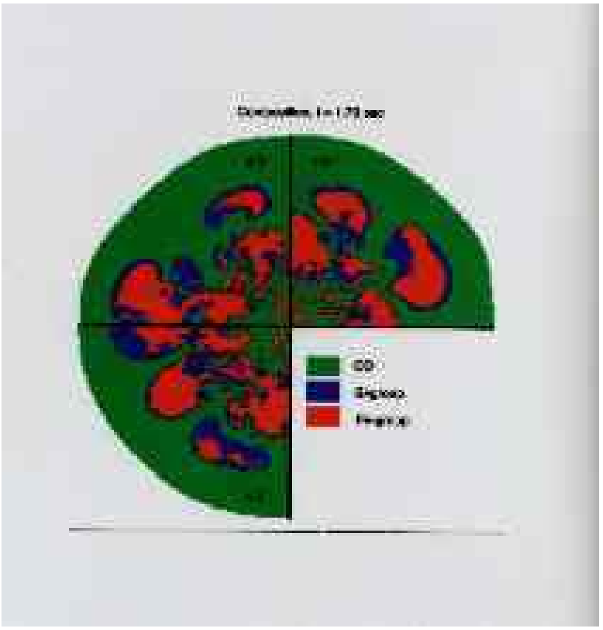
Deflagration: Energy transport by heat conduction over the front, v <<v(sound)=> ignition of unburned fuel (C/O)
Detonation: Ignition of unburned fuel by compression, v = v(sound)

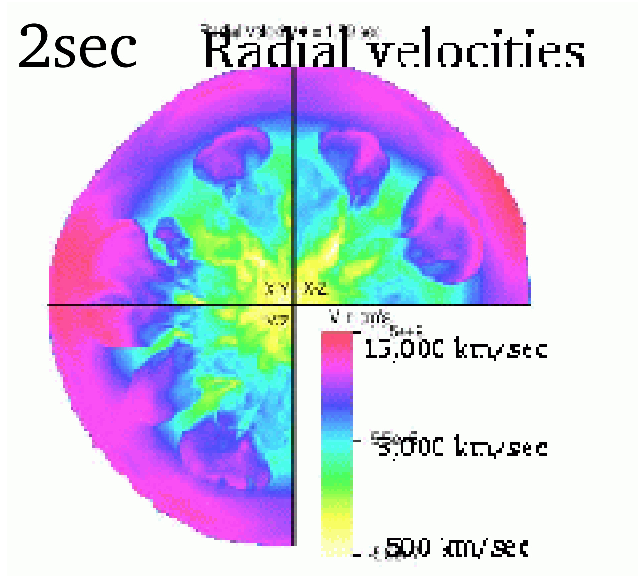
Rem1: Pre-expansion depends on the amount of burning (or change of potential).
The rate of burning hardly changes the final structure for DD-models

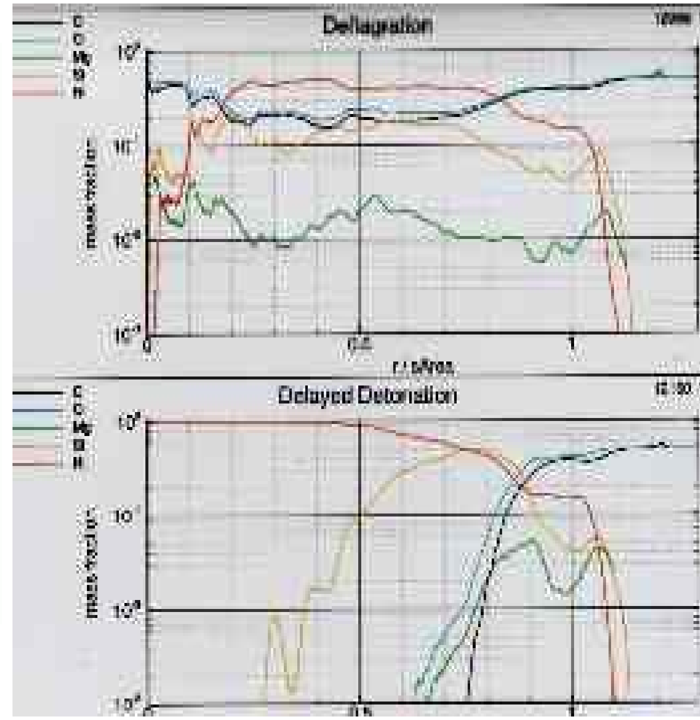
Rem.2: Result hardly depends on the point where DDT occurs

Radial/v-Structures of 3-D Deflagration and DD Models

(from Gamezo et al. 2002/2003, Science)







Deflagration:

- no radially stratified chemistry
- about 1/3 of WD remains unburned => E(kin) = 4-7E50 erg
- importance of RT instabilities for burning front
- 3D effects are important (Livne & Arnett 93, Khokhlov 1995, 2001, Reinecke et al. 2002, Gamezo e
- current 3D deflagration models show consistent results (Roepke et al. 2003)

DDT:

- radially stratified and detonation signatures are almost wiped out (Livne 99, Gamezo et al. 2004)
- almost entire WD is burned and outcome F(amount of burning before DDT) (H95,L99)

Rem.: Spectral analyzes strongly suggest radially stratified chemistry as and Ekin as in DD
(for DD: e.g. Hoeflich 1995,98,02, Fisher et al. 1995, HK96, Wheeler et al. 98, Lentz01, Branch 03)
W7: e.g. Harkness 1986, ...)

Transition from Deflagration to Detonation

Wanted: mechanism to increase rate of burning

(or, even better, avoid the problem all together by changing potential see previous speakers)

Possible mechanism:

1) Crossing shock waves during deflagration phase (e.g. Livne 1997)

2) Zeldovich mechanism: Mixing from burned and unburned material

a) Mixing induced by RT instabilities (Khokhlov et al. 1997, Niemeyer et al. 1997)

- Problem: works only for low fluctuations in the background

b) Shear flows and instabilities induced by differential rotating WDs on rising plumes (Hoeflich et al. 2001, Langer & Yoon 2003).

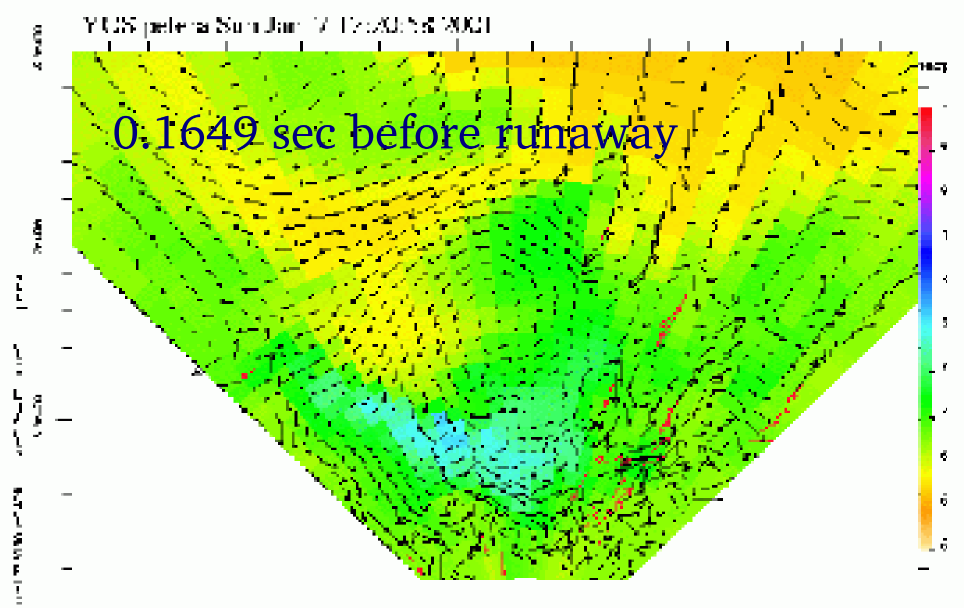
3) Drastically change in the deflagration phase (Chicago/Flash-model)

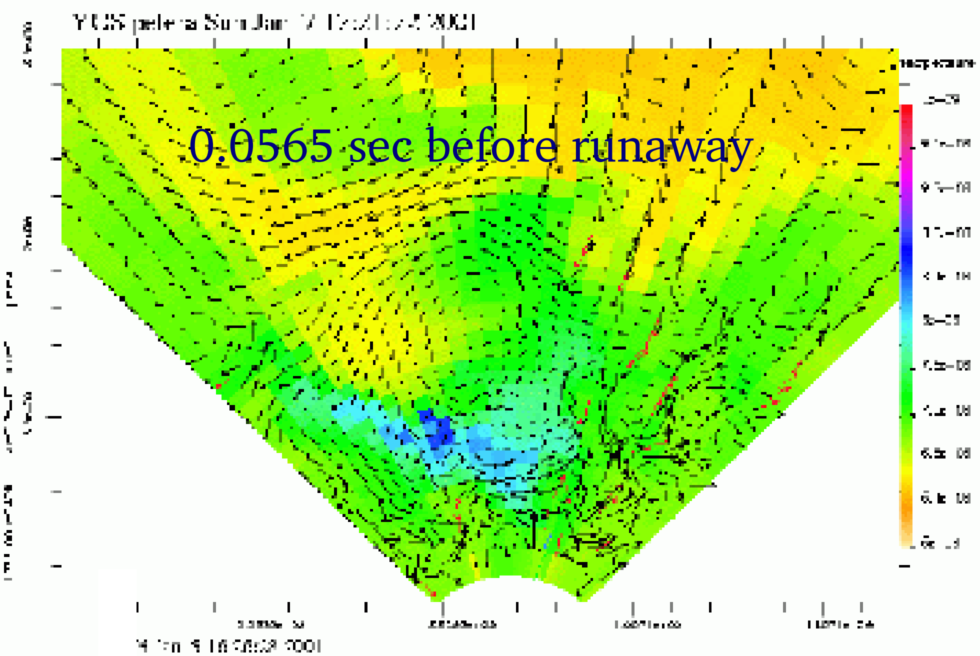
- single rising plume penetrating the WD, wrapping around and trigger a detonation from outside

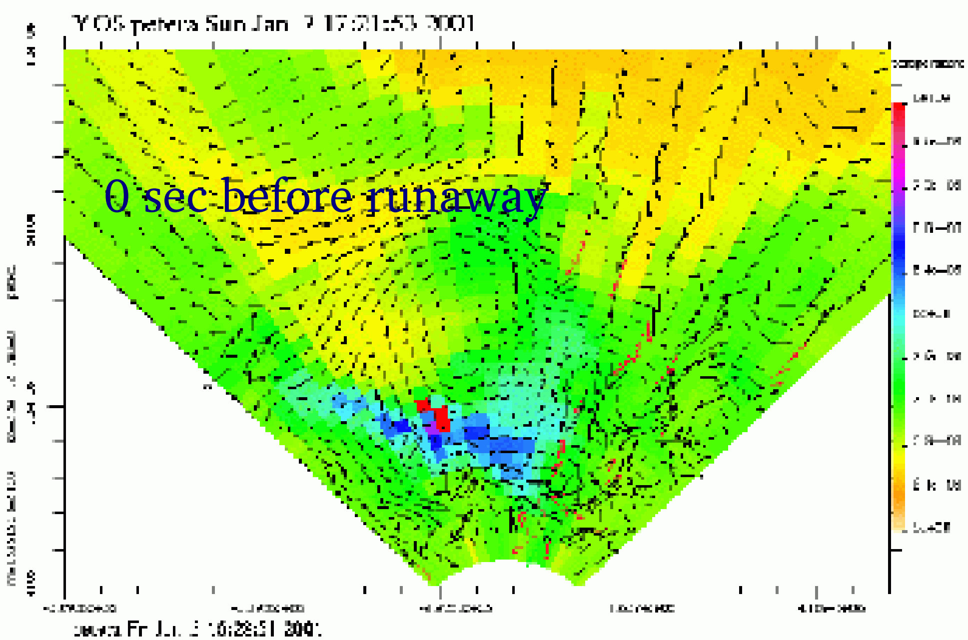
PROBELM: Reconditioning & Run away (see also Stan et al.)

Temperature and velocity before the explosion (Hoeflich & Stein 2002, ApJ 568, 791)

Longest velocity vector in black = 50 km/sec : 600E8 K< T < 1E9 K







- size of shown domain: 1600km/100 km
- size of inner boundary: 13.7 km
 evolution followed over 5 hours
- ignition close to the center at within one cell (about 35 km)
- ignition occurs due to compression of an element due to circulation.
- v(turb) >> v (RT close to center)
 -> early phase of nuclear burning is governed by preconditioning of WD

Physics Problems: Turbulence spectrum in reactive fluids & neutrino cooling

General Characteristics of Scenarios

I) M(Ch) mass models

a) Classical detonation models: pure Ni ☹

b) Deflagration models ☺

- unburned C/O at the outer layers
- large variations of the explosion energy
- no or little chemical layering

c) Delayed detonation models ☺

- very little unburned C/O left
- small variation of the explosion energy
- layered chemical structure

II) Merger models ☺

- layered chemical structure
- unburned C/O at the outer layers

III) He triggered, sub-Chandrasekhar models ☹

- high velocity 56Ni

Quantitative Models for the Explosions, LCs and Spectra

"Free" Parameters

I) Explosion of M(Ch)-WD

- **Central density of the WD** (dependents on accretion rate)
- **Chemical profile of the WD** (from stellar evolution)
- **Description of the burning front** (e.g. Deflagration, DD-transition)

II) Merging WDs

- **Mass of extended envelope for mergers**

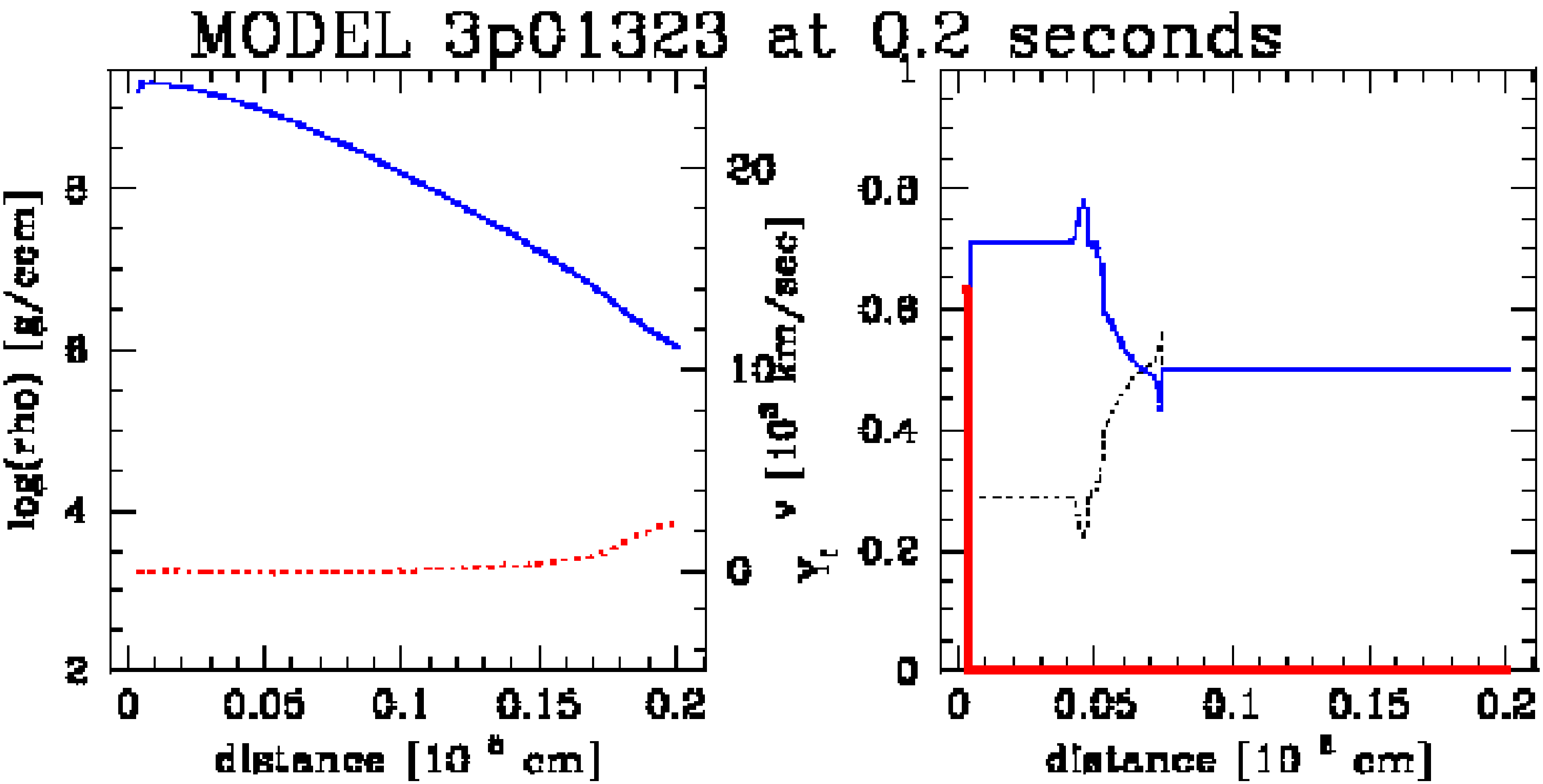
=> Observables

a) Monochromatic light curves
b) Spectra including their evolution with time
c) Polarization and directional dependence of luminosity

Explosion of a delayed detonation model

- progenitor : 3Mo on MS with 1/30 of solar metallicity
- Properties of WD: a) Chandrasekhar mass b) central density 2E9 g/ccm

- Properties of deflagration front: a) v(defl.) with C1=0.15 b) rho(tr) = 2E7 g/ccm



red: complete b. (Fe, Co, Ni) ; **green:** incomplete b. (Si, S, ...) ; **blue:** C and O

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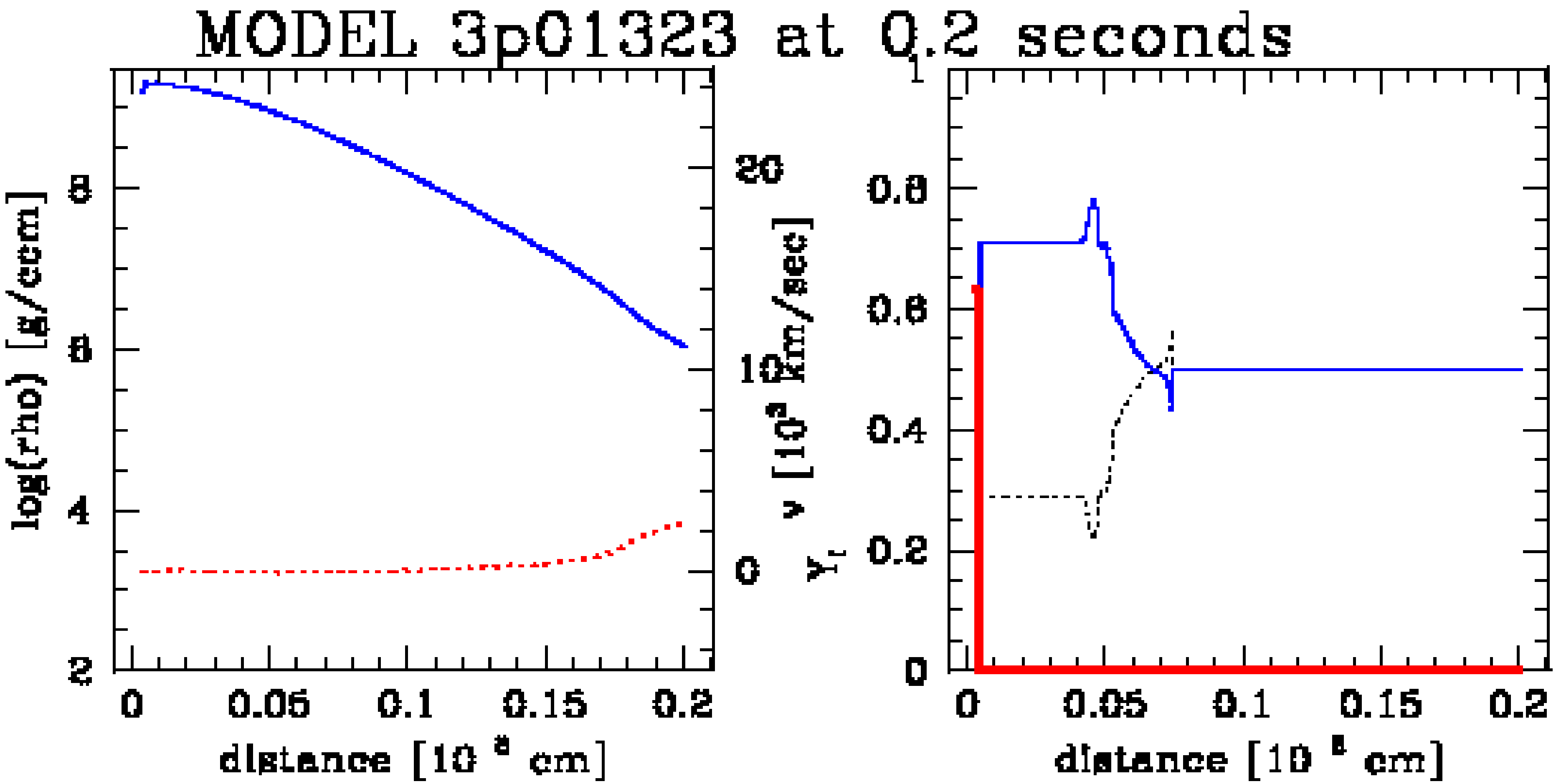
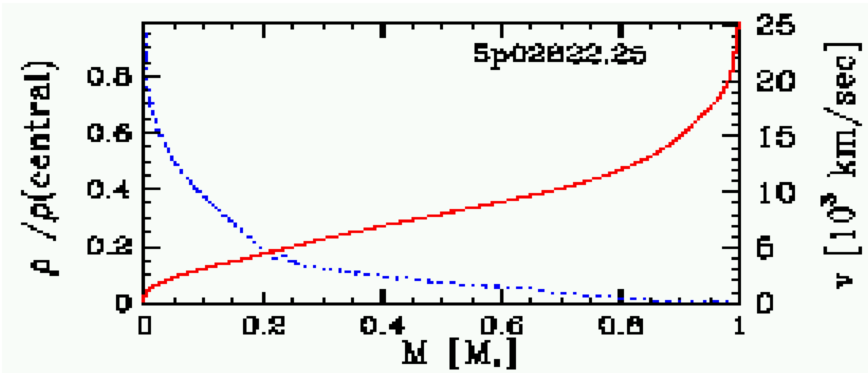
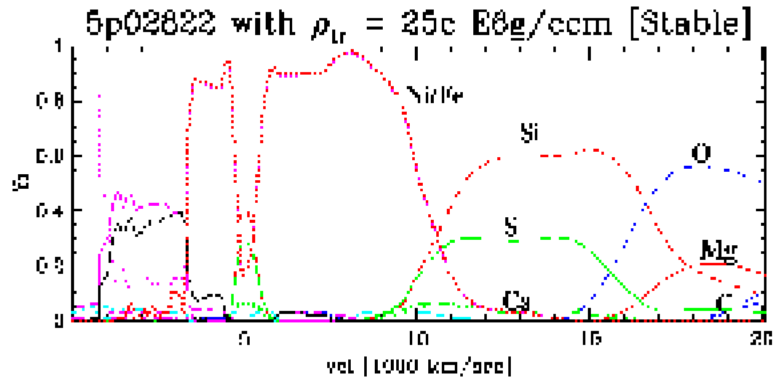


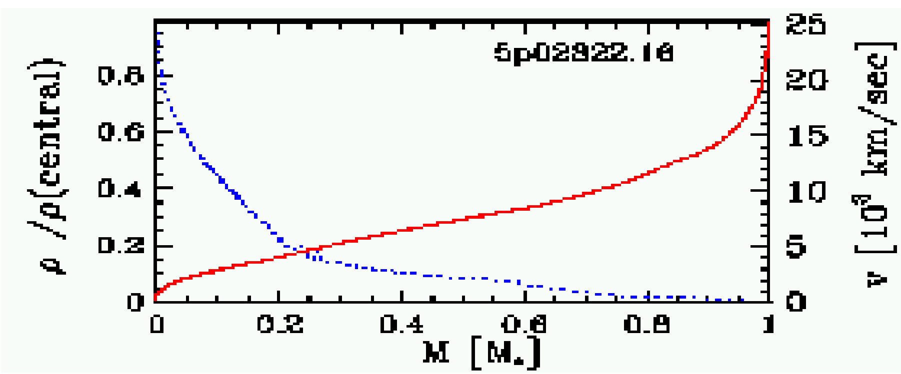
red: complete b. (Fe, Co, Ni) ; **green:** incomplete b. (Si, S, ...) ; **blue:** C and O

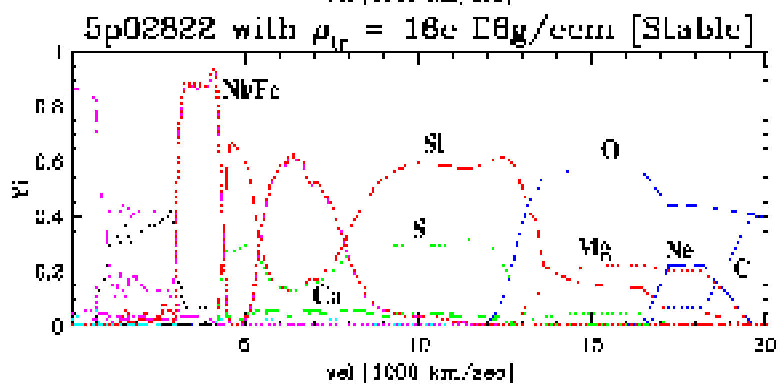
Delayed detonation models for various transition densities rho(tr)

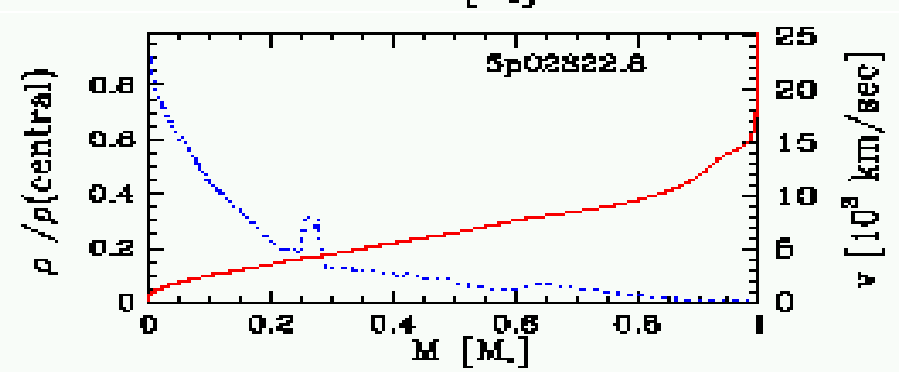
[M(MS)= 3 Mo; Z = 1.E-3 solar; rho(c)= 2E9 g/ccm with rho(tr)=8, 16, 25 g/ccm]

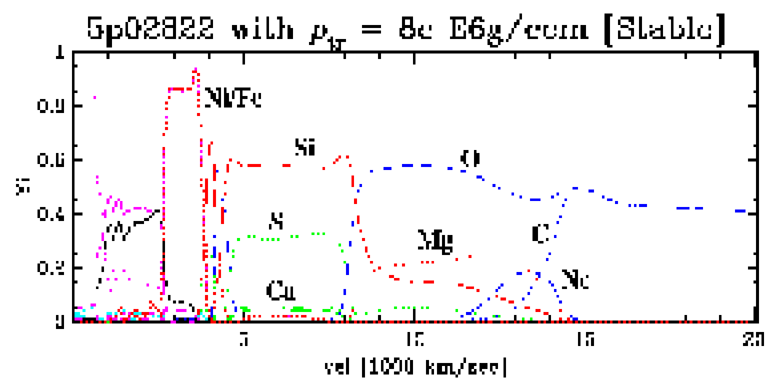












Rem.: similar explosion energies but very different chemical structures (Fact. 6 in M(Ni)) !!!
Rem2.: Defl. and mergers have significant layers of unburned C/O material (0.1 to 0.7 Mo)
Rem3: C in DD down to between 13,000 (91bg) to 26 (92bo) (see also Branch)
Rem4: Mg between 17,000 to 27,000 in Ricky Rudy's SN (see also Meikle)

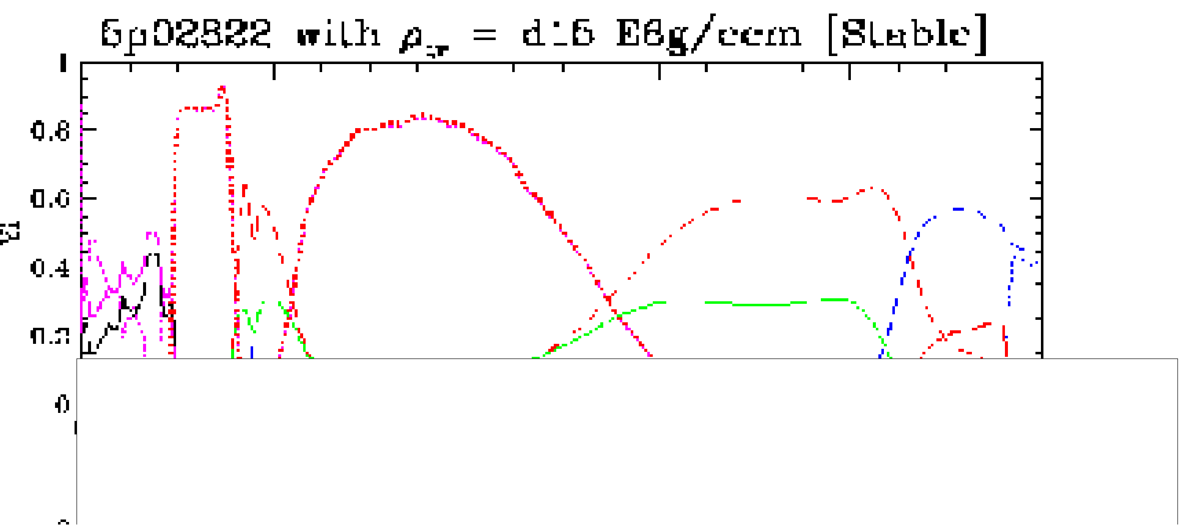
Delayed detonation models for various central densities

[M(MS)= 3 Mo; Z = 1.E-3 solar; rho(tr)=2.3E7g/ccm]

Remark: The central density depends on the accretion rate on the WD

- rho(c) determines the size of region with production of neutron-rich isot

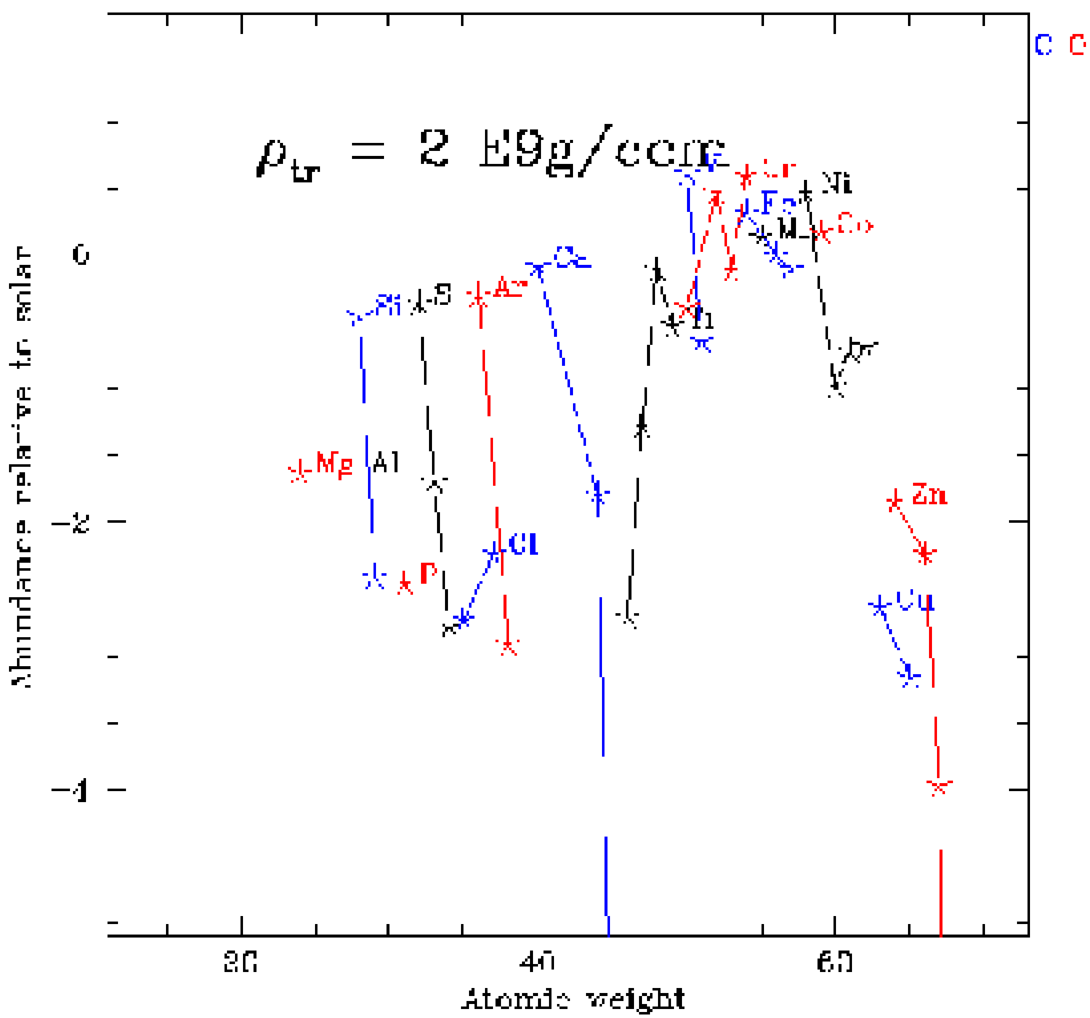
- M(Ni) production changes by 20 %   between rho(c) 1E9 to 6E9 g/ccm



Effect of central WD density on nucleosynthesis

Production of neutron rich Isotopes

Example: Delayed detonation model (Hoeflich et al. 1998)



- Rho(c) changes all isotopes
  WD structure & explosion

Ye	' typical' products
0.5	^{56}Ni, ...
0.470..0.485	^{54}Fe, ^{58}Ni
0.46 ...0.47	^{56} Fe
0.425 ... 0.452	^{50}Ti,^{54}Cr,^{58}Fe
0.425	^{48}Ca

Rem.: Old electron capture rates would have prohibited high central densities

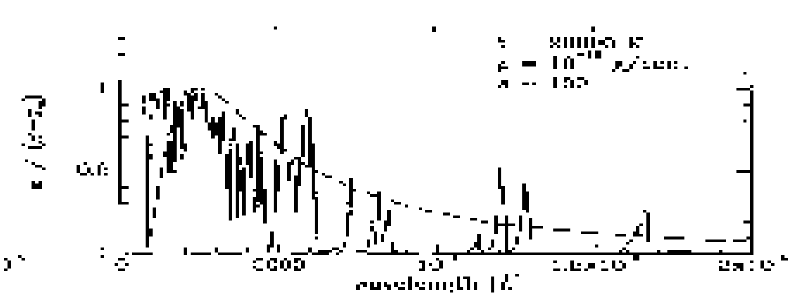
Now: Explosions close to AICs (r-process ???)

III) Statistical Correlations: The Brightness Decline Relation

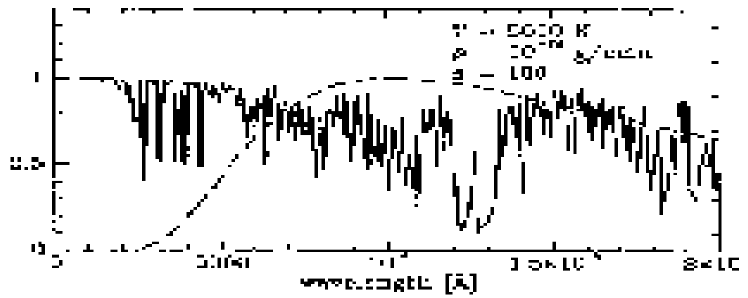
Remarks on Opacities & Emissivities (Hoeflich et al. 1992, AA 268, 510)

Frequency dependence of $\chi(\nu, T, \rho, dv/dr)$ between 1000 -20000 Å

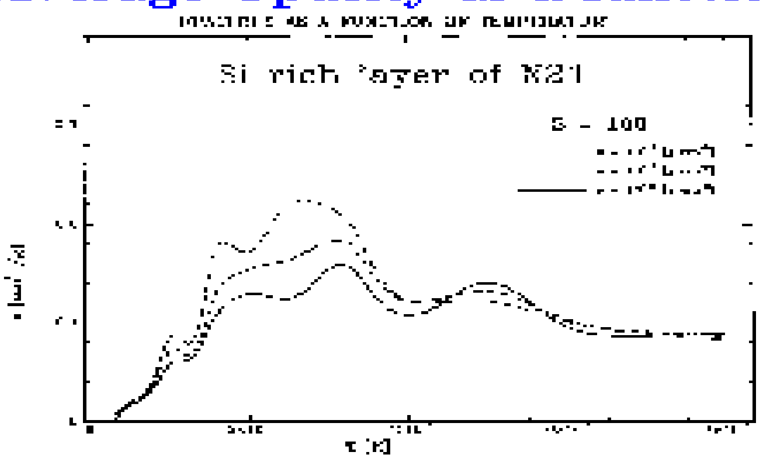
T = 20000 K



T=5000 K



Average Opacity as a function of Temperature

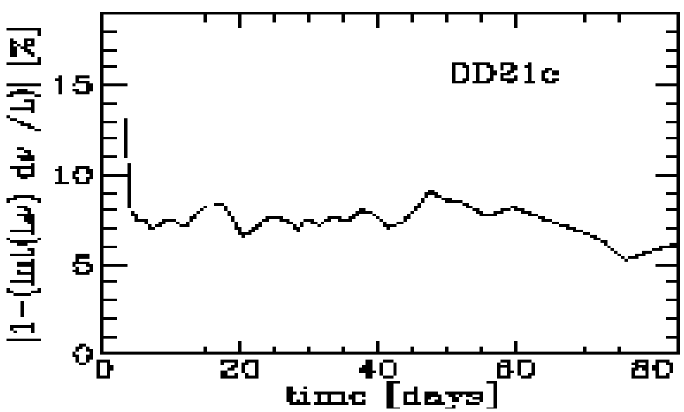


- **Opacity drops fast for T < 10000 K**

Reasons:

- Emissivity shifts into the optical
- line blanketing is less in optical vs. UV
- thermalization is higher

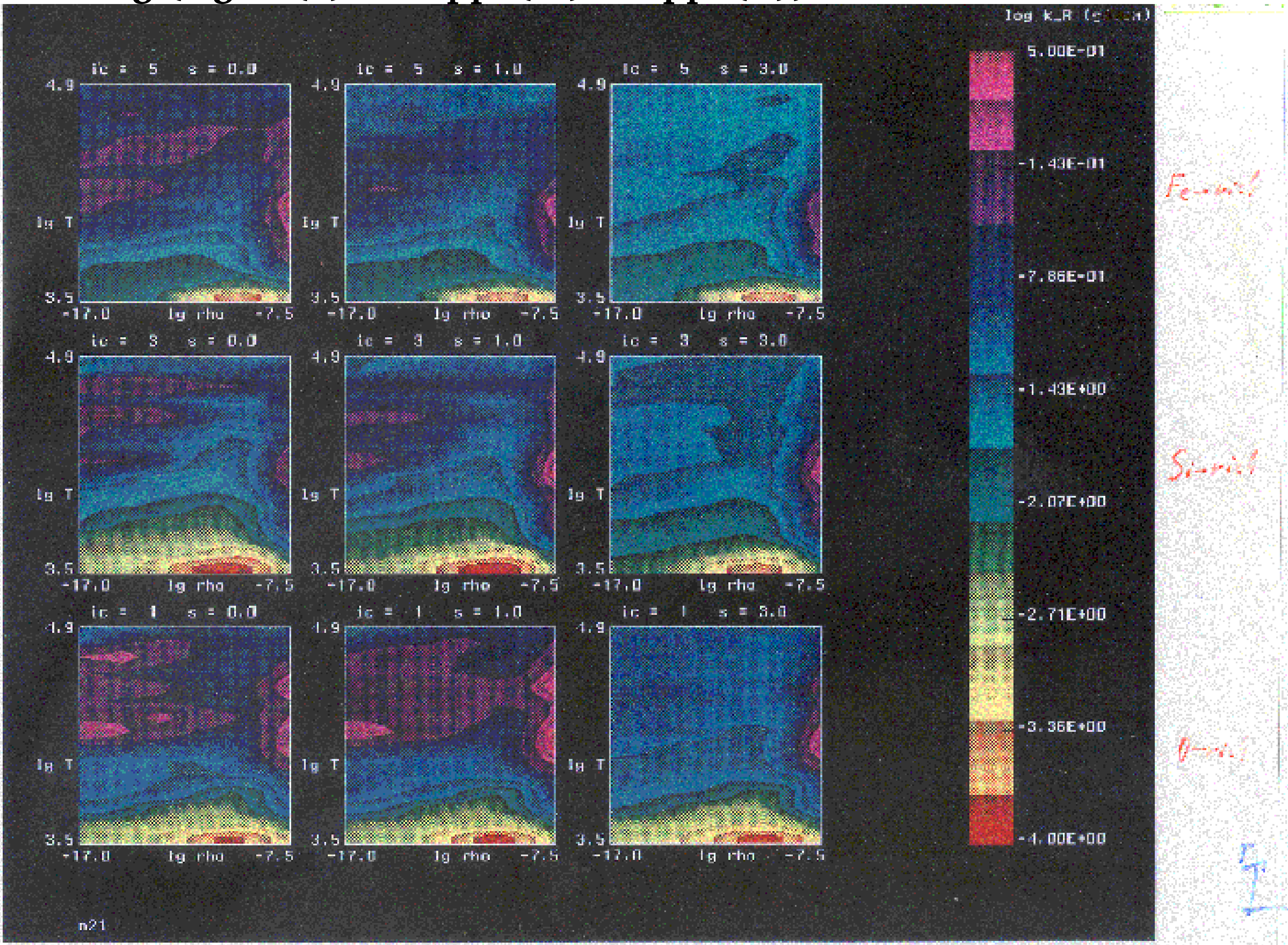
Consistency check: $L(\kappa) vs. L(\kappa_\nu)$



See brightness decline relation

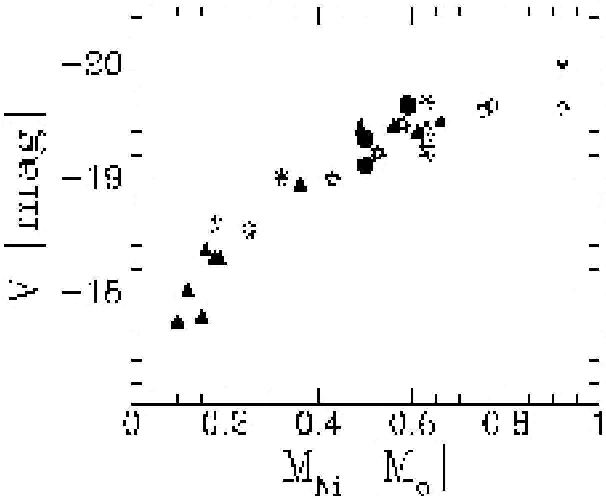
Dependence of the mean opacity on T, rho and s and compos

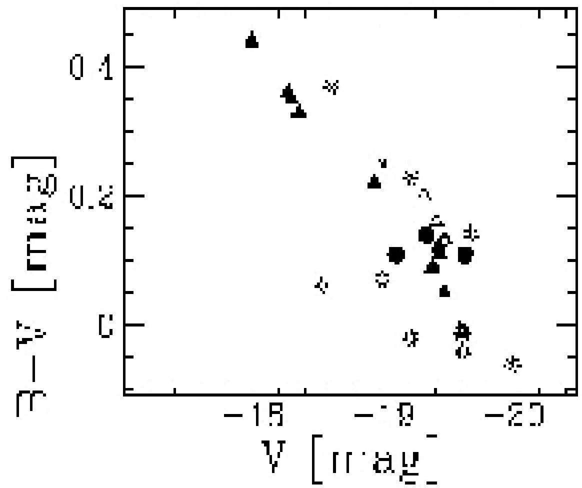
s= log (sigma(e) + kappa(bf)+kappa(ff)) c rho dr/dv



The Brightness Decline and Color Relations

a) M(V) and B-V as a function of M(56Ni)

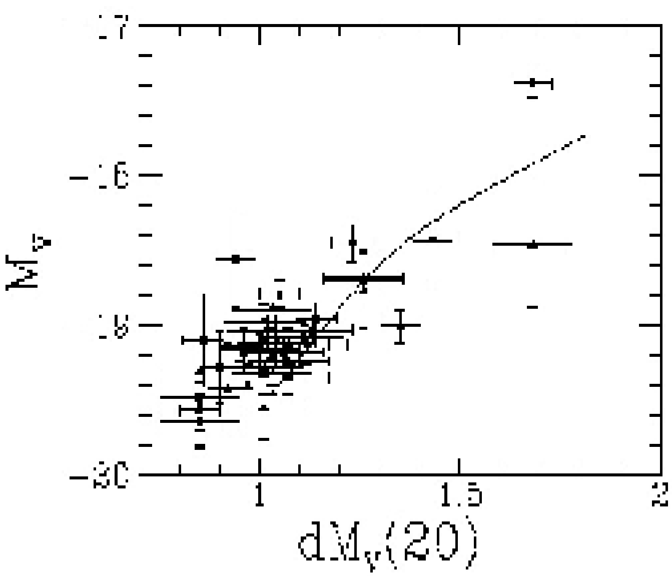


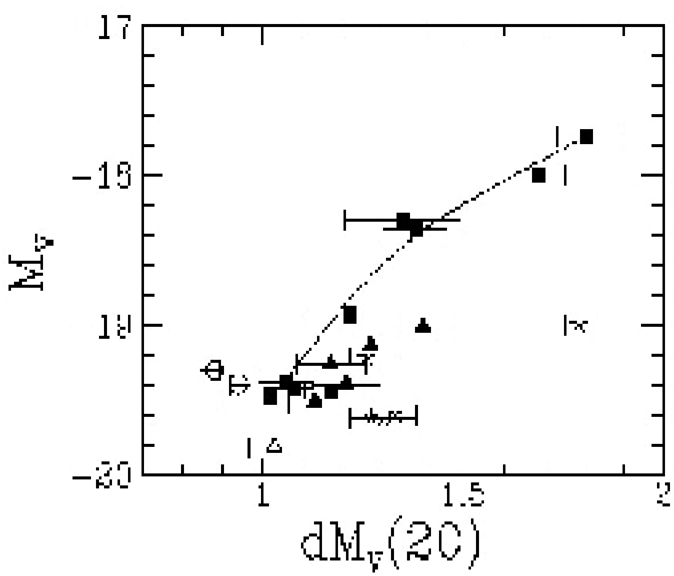


- SNeIa become dimmer & redder with decreasing M(56Ni)

b) Maximum brightness decline relation M(V)=f(dM20)

(Hoeflich et al. 1996, ApJ 472, 81, see also Mazzali et al. 2000 and Pinto et al. 2001)



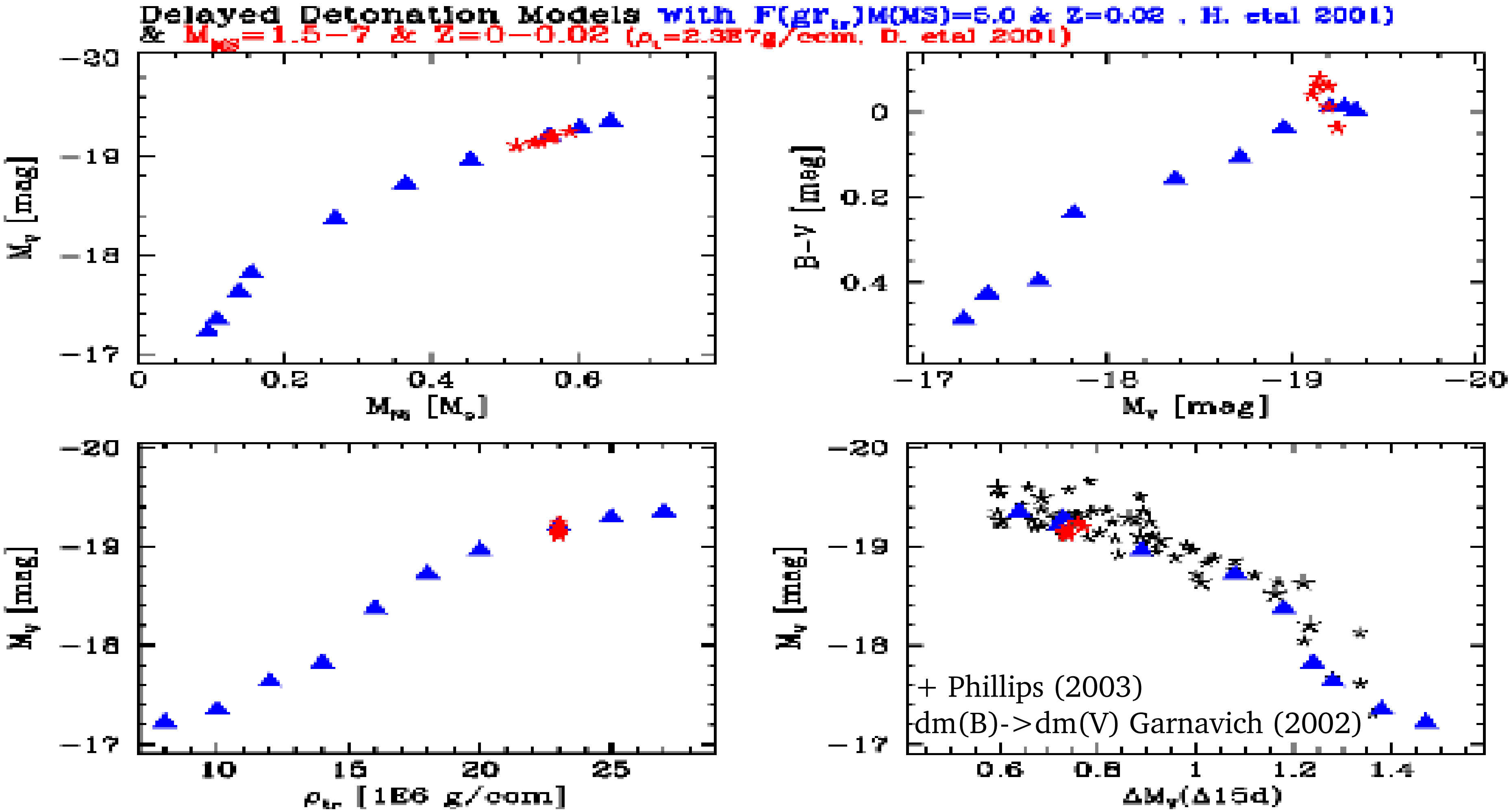


- qualitative agreement but large spread

-- large spread in deflagrations because different explosion energies!

II) Diversity of Type Ia Supernovae:

The brightness decline relation and colors



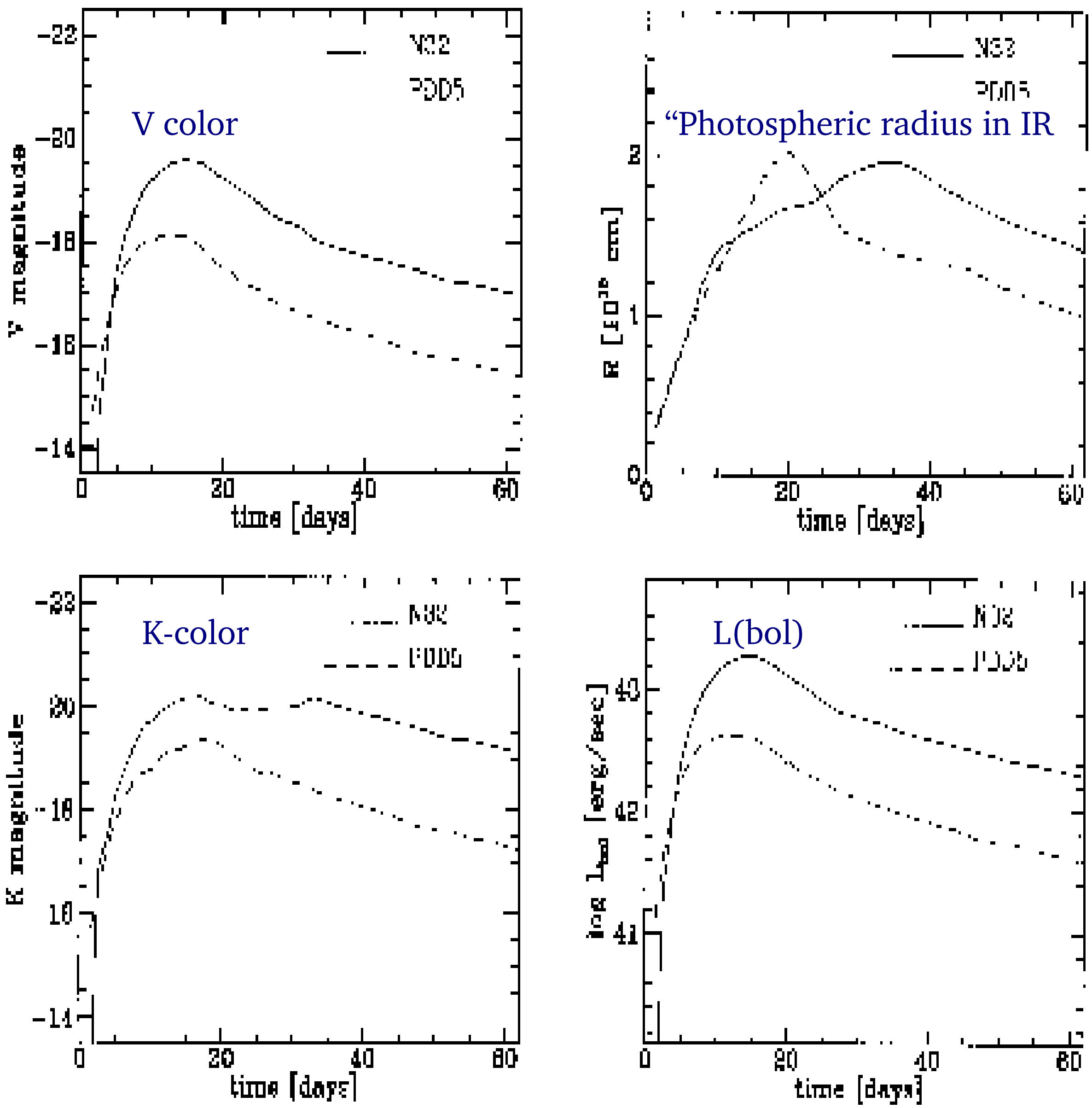
- **Generic: Brightness decline relation is an opacity effect** (Hoeflich etal 96,Mazzali et al. 2001)
- **Small spread requires similar explosion energies** *(±0.5mag for all scenarios H. et al. 96)*
- **Within DD models, relation can be understood as change of burning before DDT**
- **Progenitors (Z=0 ... solar) can produce systematics of about 0.3 mag.**

Attention: Color change of about 0.2 mag -> reddening !!!

Monochromatic Light Curves/The secondary IR maximum

(from Hoeflich et al. 1992, Hoeflich et al. 1995)

Explosions for Chandrasekhar mass WD



0. order approach

Most of the luminosity is emitted in the optical

=> V follows L(bol)

IR light curves:

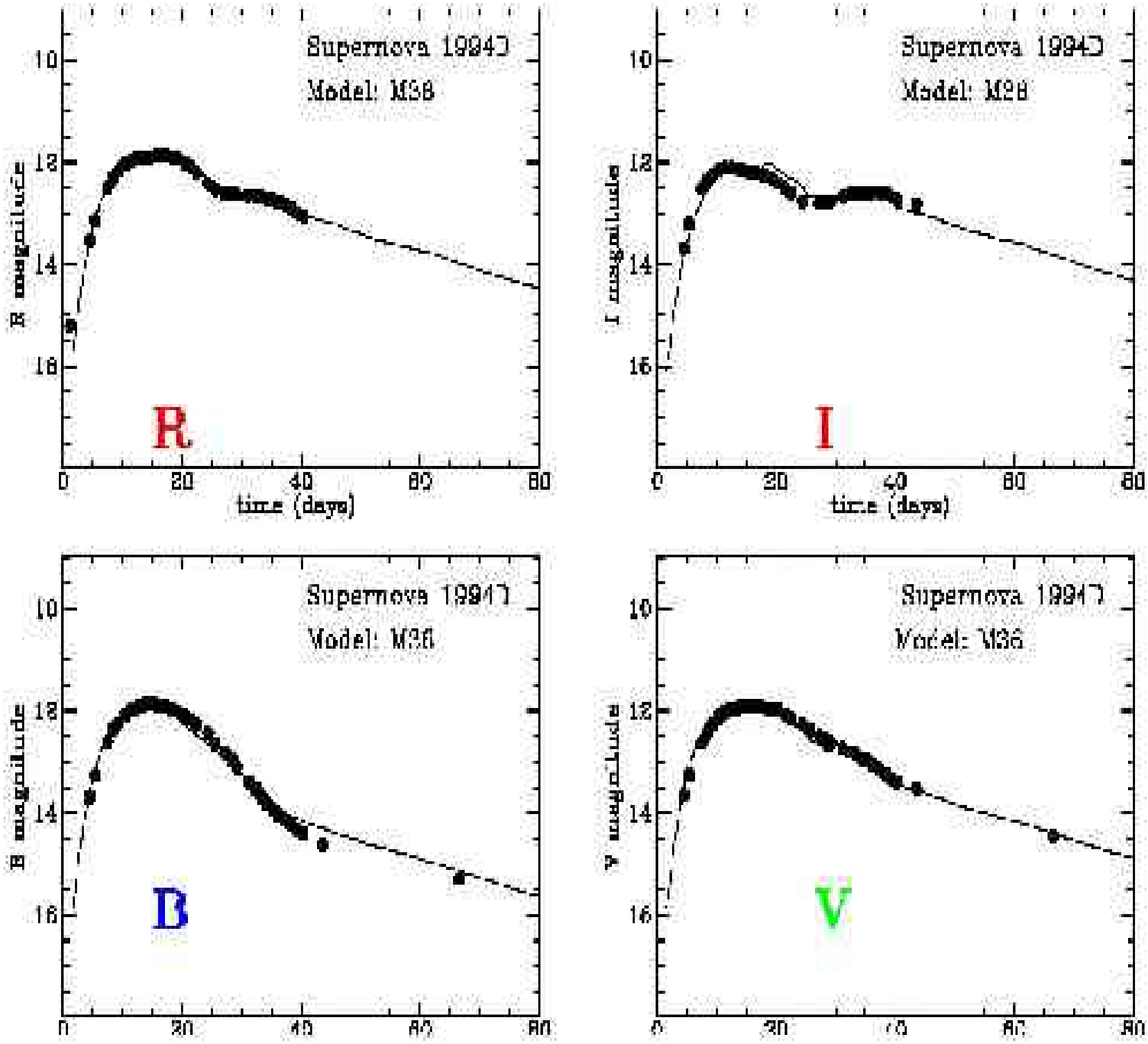
L(IR)~ S(IR) R^2(IR)
with source function
S(IR) ≅ BB ~ T
L(IR) ~ T R^2(IR)
early LC: T changes fast
L(IR) follows L
post-maximum: T ≅ const.
L(IR) ~ R^2

Corrolar: Time of secondary maximum increases with L(bol)

In very subluminous SNIa , first and second IR maxima merge

Individual Objects: SN94D vs. DD-models

(Hoeflich 1995, ApJ 443, 89) **Data obtained by CfA group**



LCs up to day 80

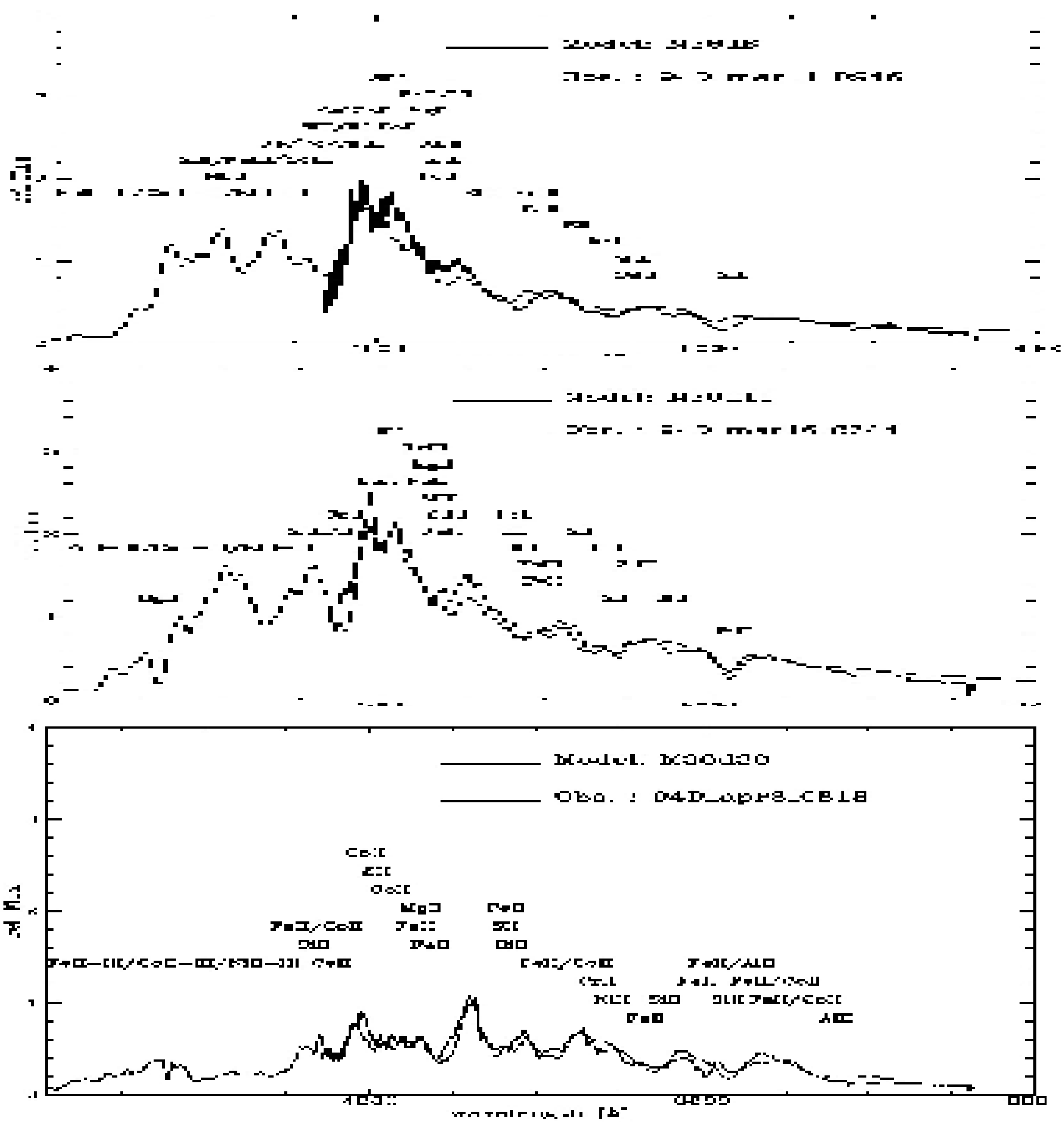
C/O WD with

rho(c)=2.E9g/ccm

rho(tr)=2.4E7 g/ccm

Spectra between 3000 and 8000 A: SN94D vs. M36

C/O WD; rho(c)=2.E9g/ccm; rho(tr)=2.4E7 g/ccm (H95)



- 8 days after explosion
  = -8 days before maximum
  - spectrum is dominated by intermediate mass elements (S,Si) + iron group elements

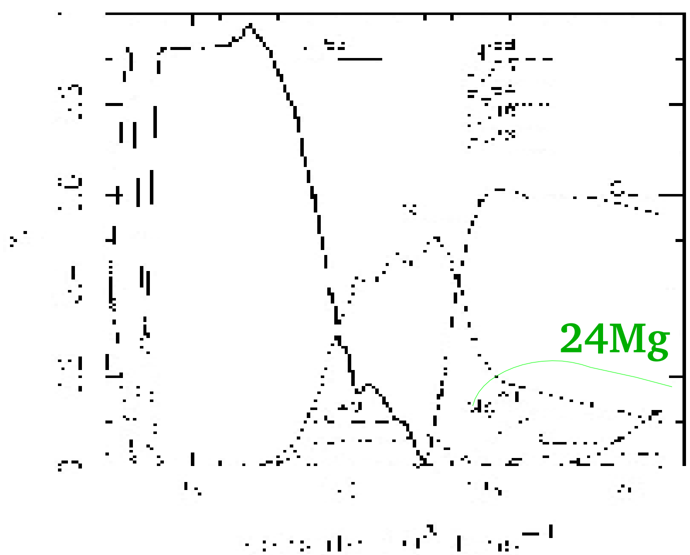
- 16 days after the explosion
  = -2 d before maximum light
  - spectrum is dominated by Si, S, Ca + iron group elements (formed in transition layer between Si and Ni/Co/Fe

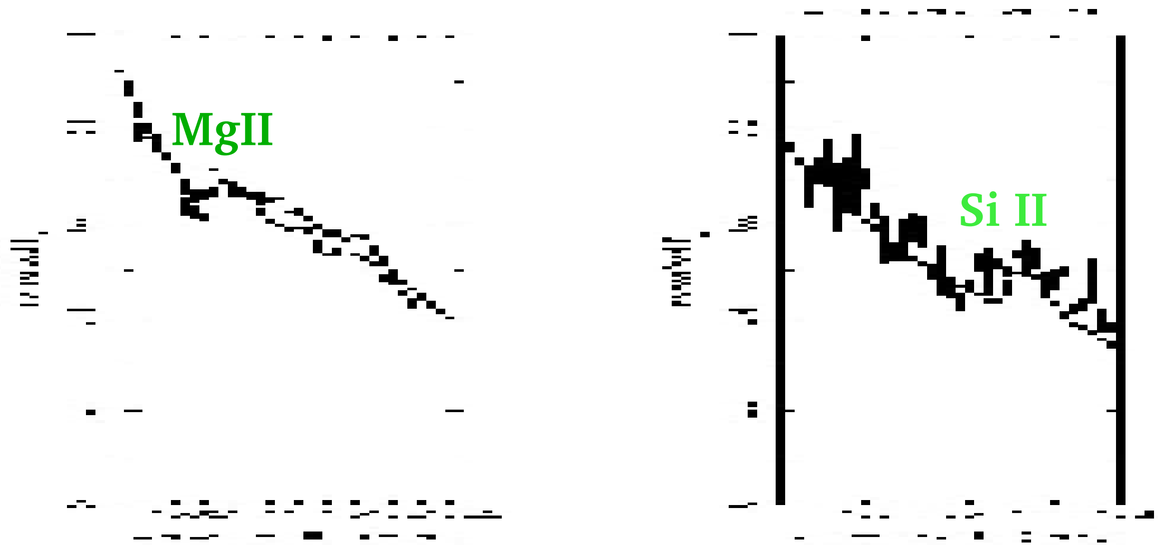
- 31 days after explosion
  = 2 weeks after maximum
  - spectrum is formed in inner Ni/Co/Fe core

IR-Spectra: A test for the amount of burning at the outer laye

Example SN1994D: Comparison with SN1994D at Day -7

Spectra between 1.05-1.25 & 1.4-1.8 A





Observation of SN1994D by P.Meikle

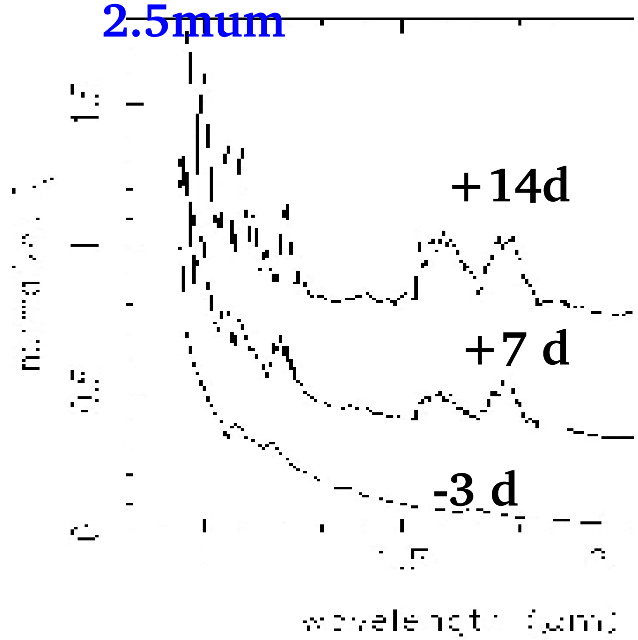
- Explosive carbon burning up to the outer 1E-2 Mo

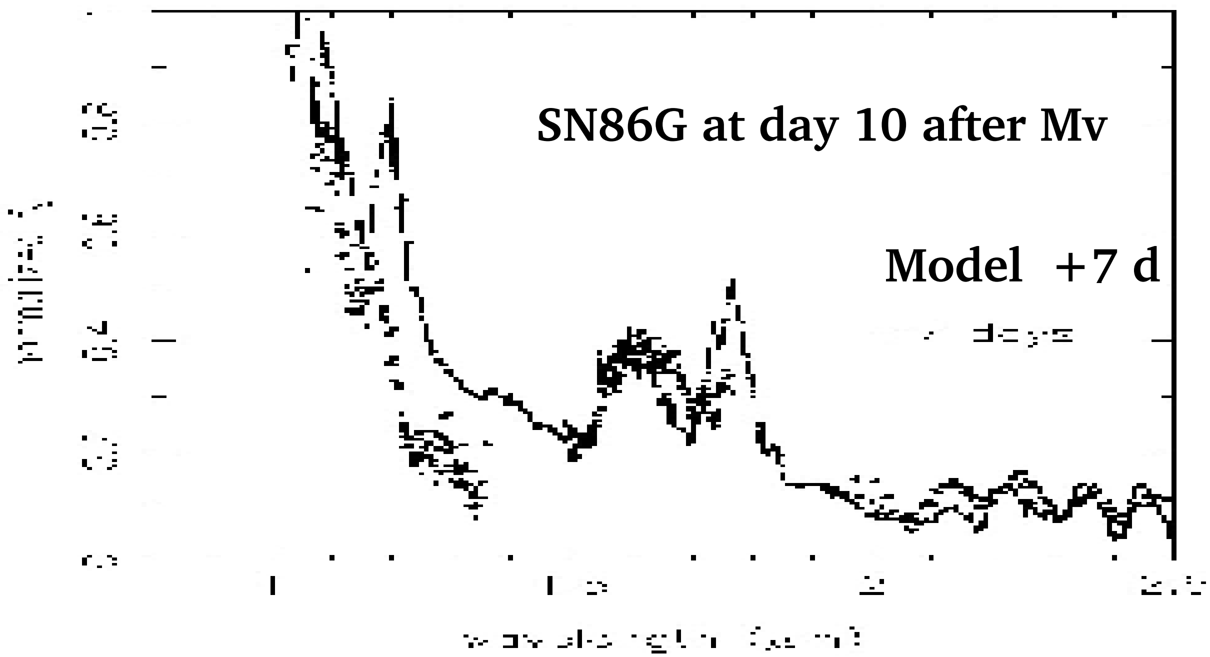
  (similar results for about 7 other SNIa, Marion et al. 2002)

- Si lines at high velocities are not due to mixing !!!

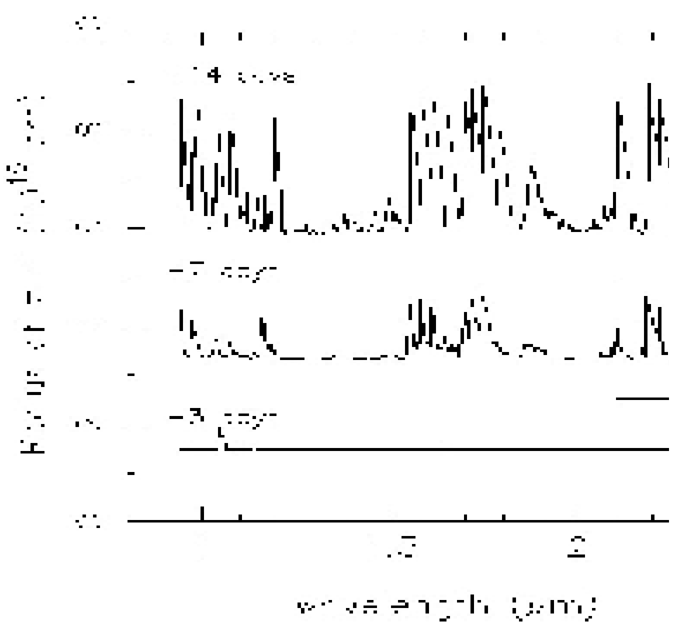
Post-maximum IR-Spectra of DD200 in Comparison with SN86G

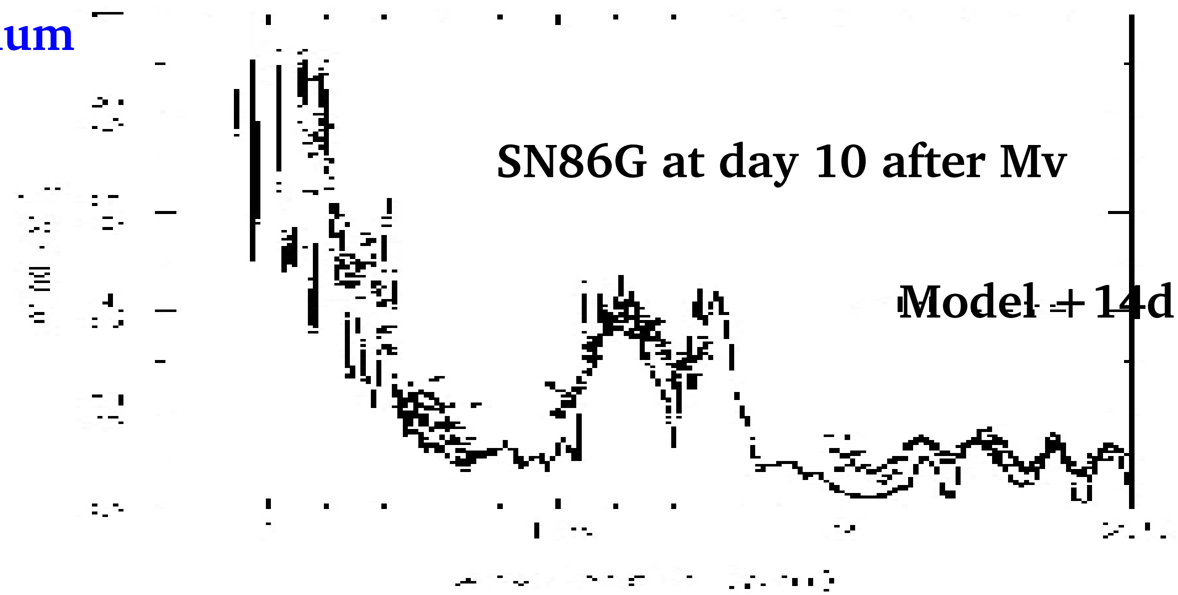
Flux between 1 and 2.5mum





Radius between 1 and 2.5 mum



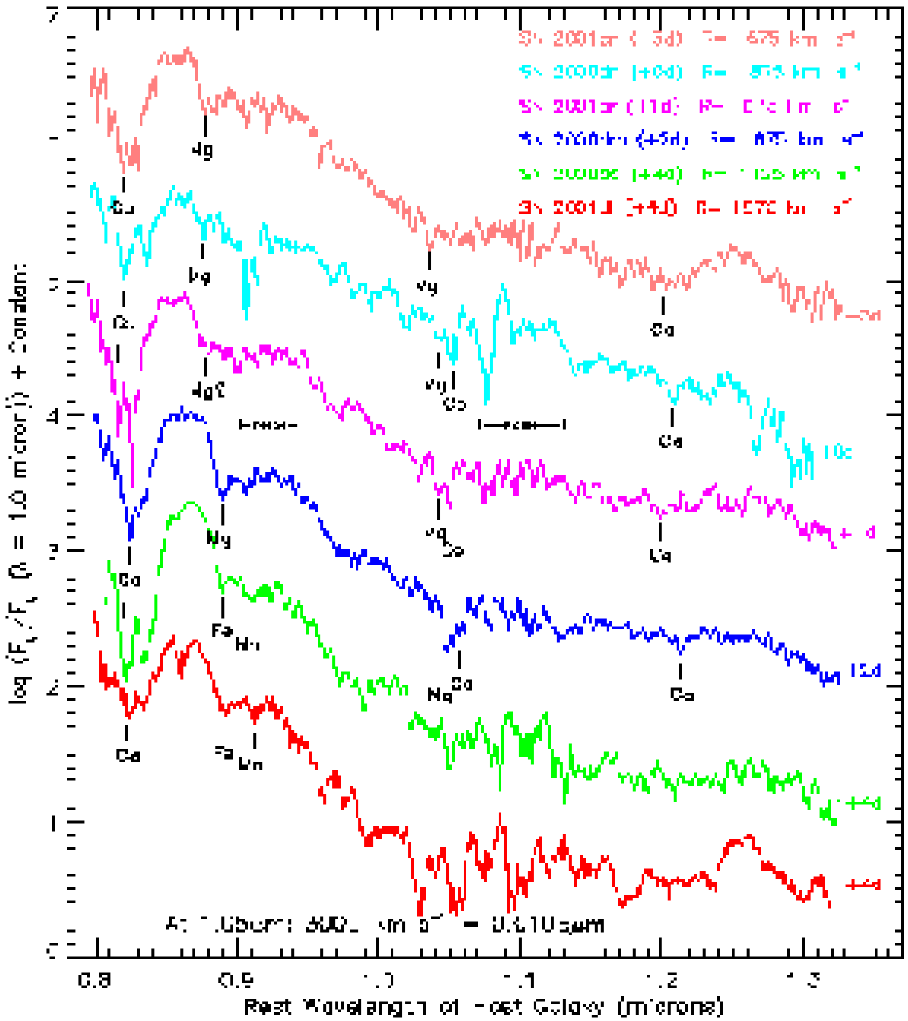


SN86g by P. Meikle et al. (1998)

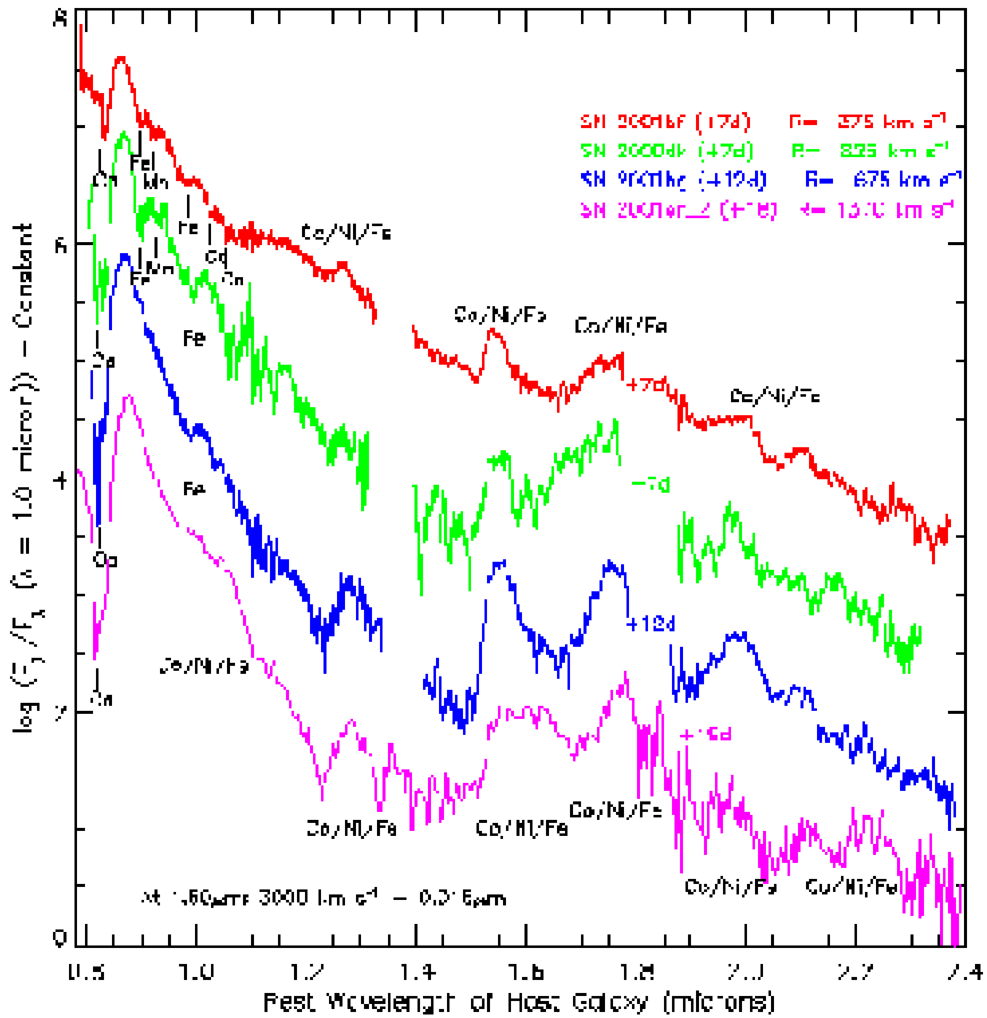
IR-Spectra of 10 SN.eIa between -4 and +18 days between 15...17 mag

(Snapshot IRTF observations by Marion et al. 2002, submitted & future PhD thesis)

Early time spectra



Late time spectra

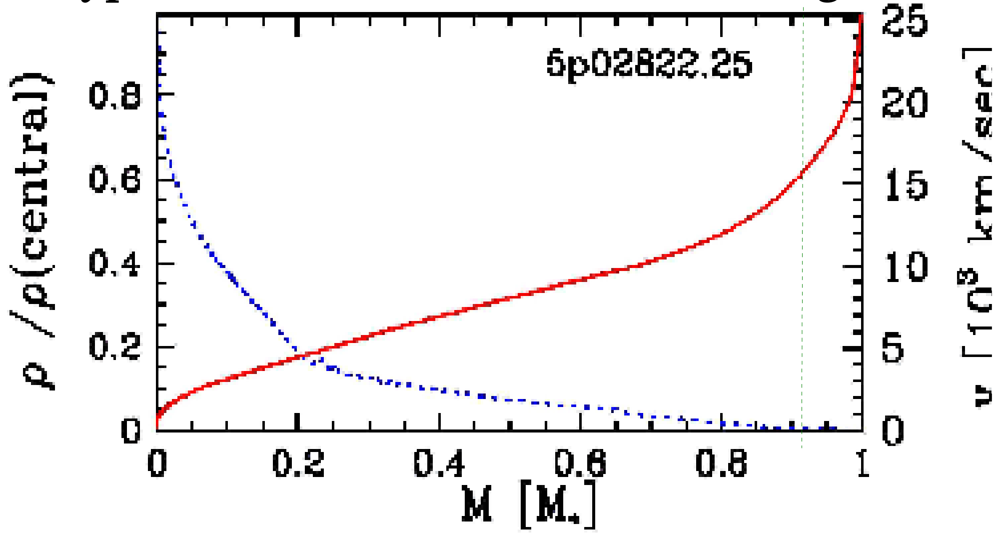


- time series of various SN.eIa look very similar => homogeneous class
- No HeII line at 2.05 mu but multiple Mg II lines
- No CI and CII lines although observable if present
- Possible, first detection of Mn II

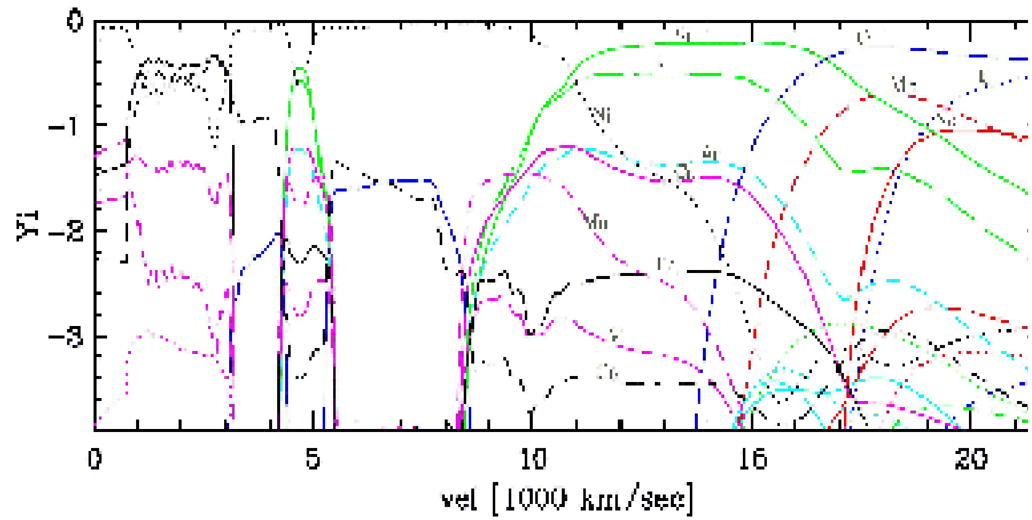
Quantitative conclusions from the IR-sample of SNeIa

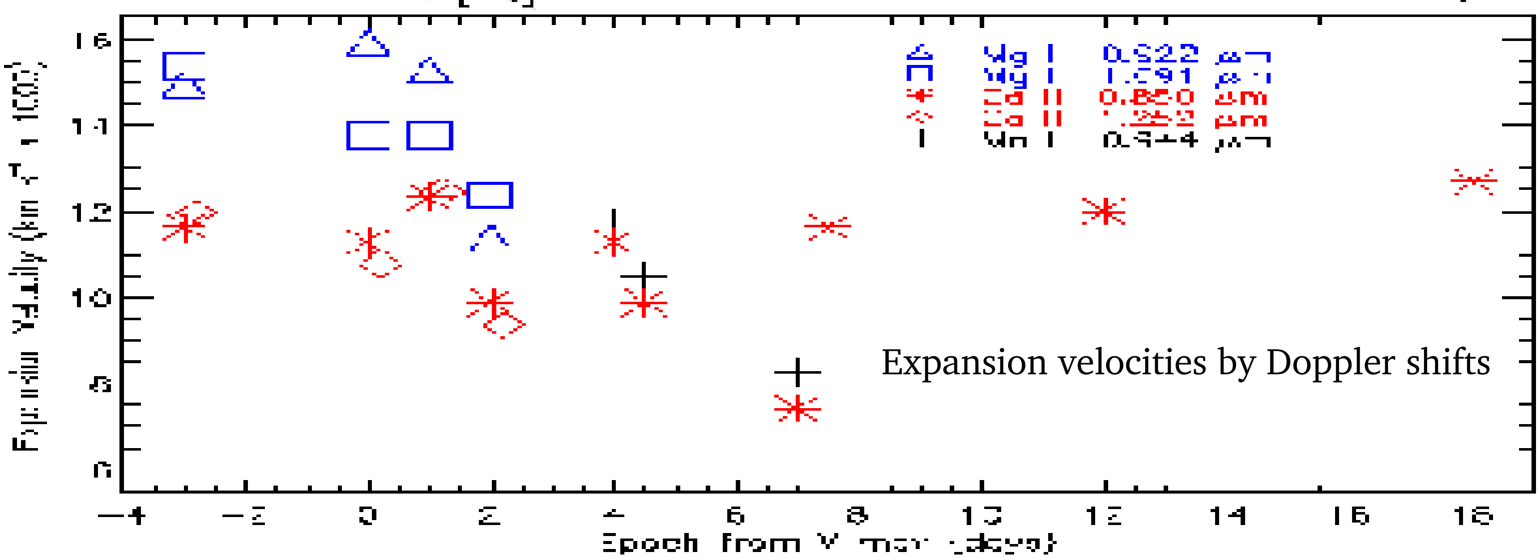
(PhD thesis of H. Marion & Marion, Hoeflich, Vacca & Wheeler 2003, ApJ, in press)

Typical DD model for a normal-bright SN.Ia



Abundances (log/mass fractions)

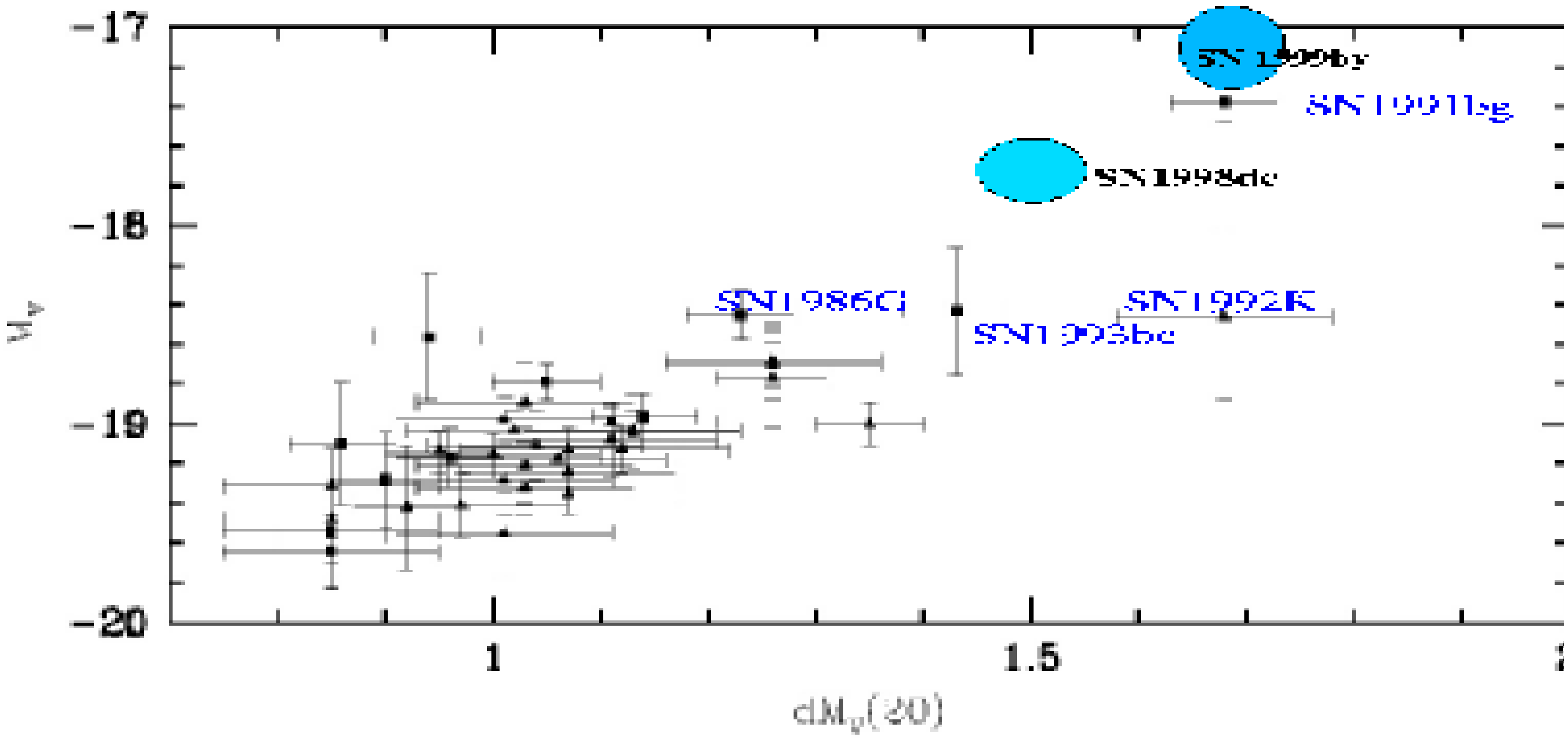




- Layered, chemical structure (without evidence for non-radial component/mixing)
- Minimum Mg II velocities between 12,000 to 16,000 km/sec in the sample
  => typical of unburned matter << 0.1 Mo !!! (from shift of line centers < 0.1 Mo in all cases)
- significant individual variations are about 4000 km/sec

II.1) Are 'normal' and sub luminous SN the same beasts?

The brightness decline relation

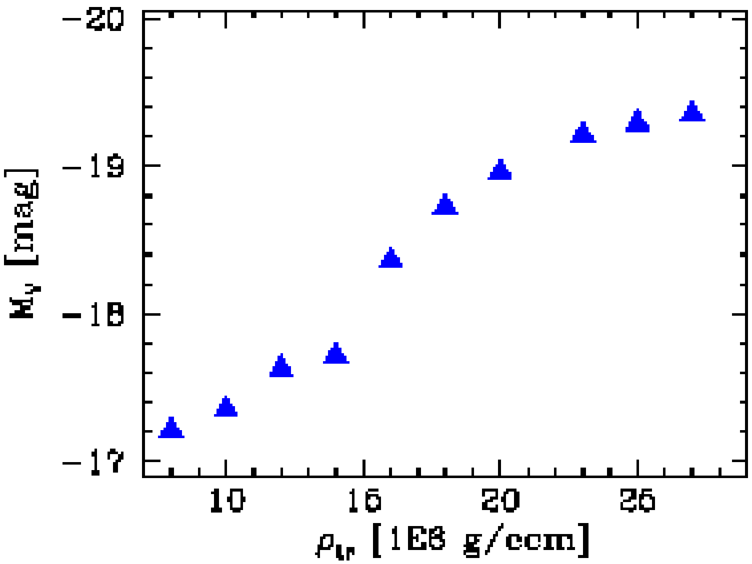


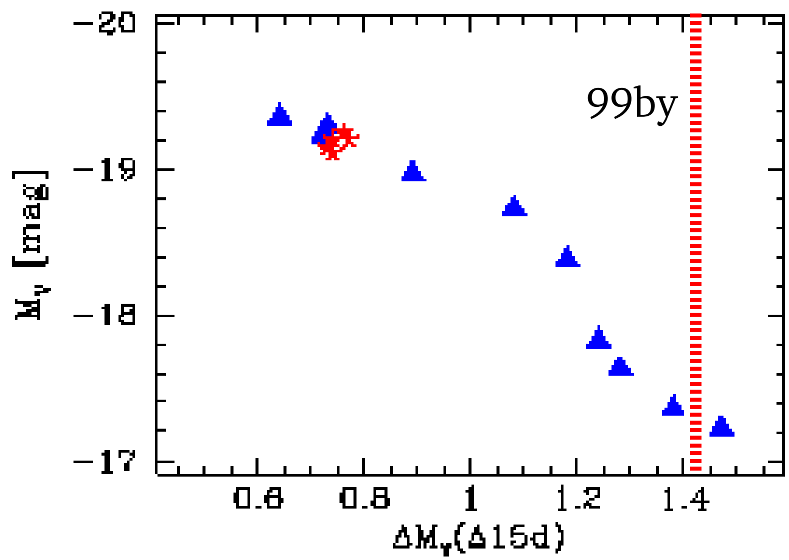
Prototype: SN1991bg
- low velocities of Ni (<4000 km/sec)
- Si rich spectra at maximum light

Problem: Optical spectra give no information about C/O, ie the outer layers
=> All models are possible including:
a) Sub-Chandrasekhar mass models
b) Mergers (merging of two WDs)
c) M(Ch): DD, PDD and pure deflagration models

III.2) The nature of the subluminous SN1999BY

Select model based on optical LC and spectra: here, the brightness decline ratio



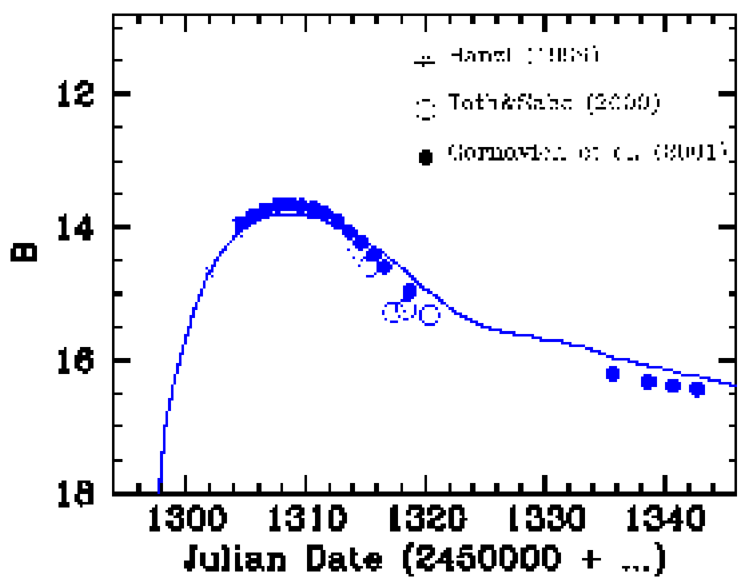


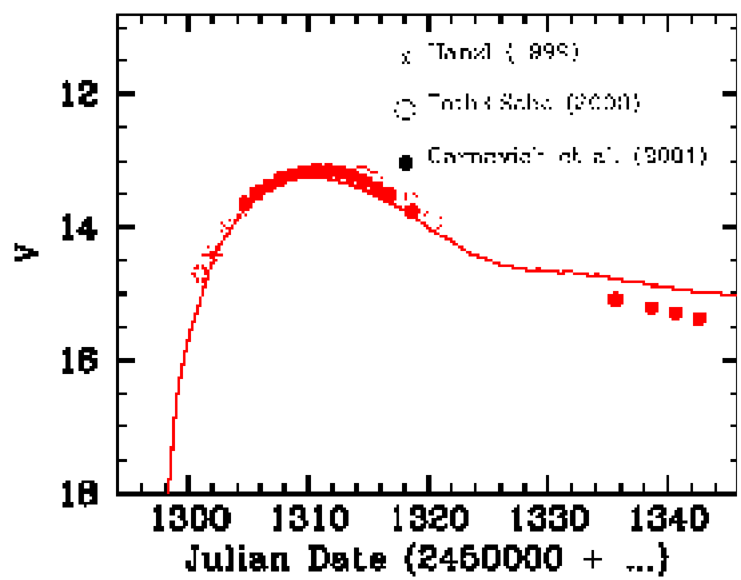
- M(V) = F(❒(tr))
- SN1999BY is at the lower end

Discrepancy in B and V

- 0.05 mag (tmax)
- 0.4 mag (tmax+30d)

Comparison between observed and theoretical LC

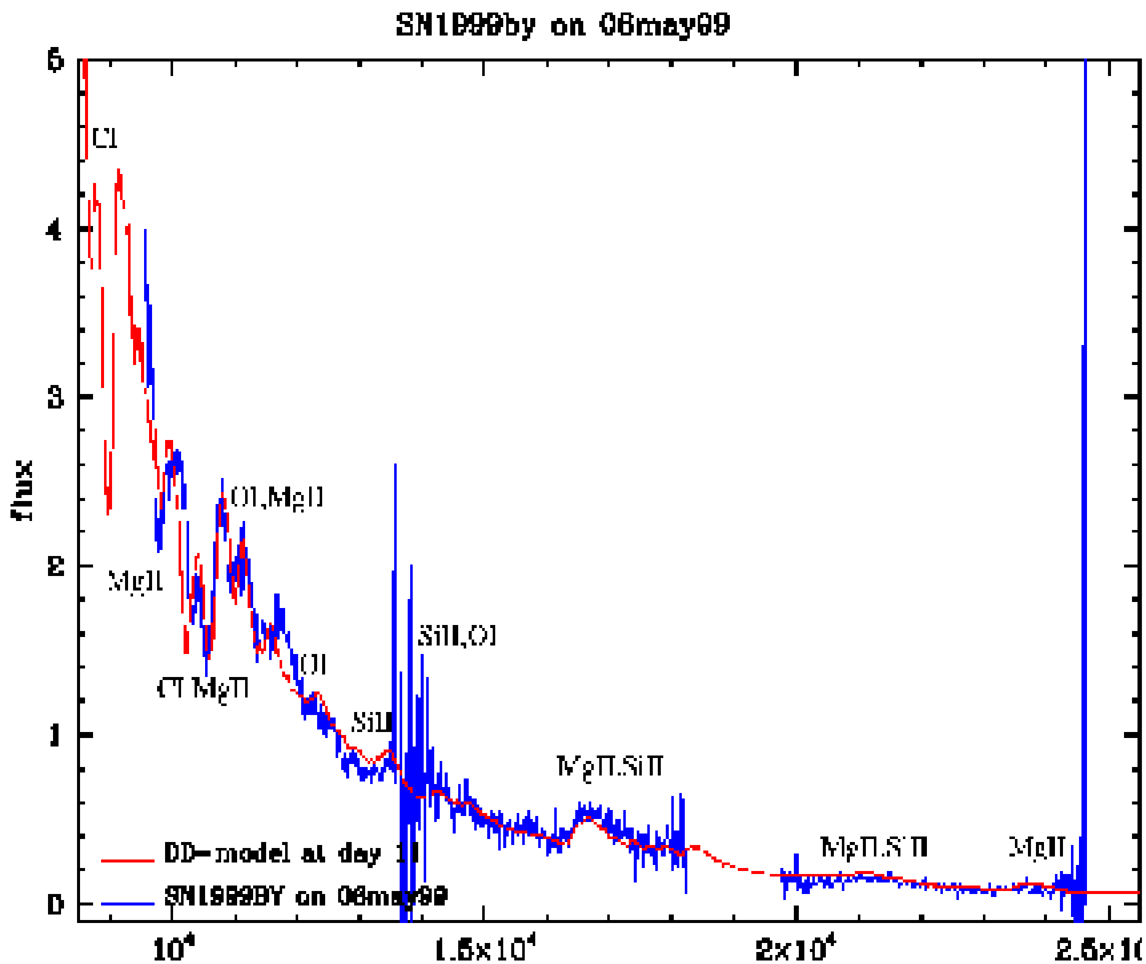




consistency error
between NLTE and LC calculation
- 0.07 mag (tmax)
- 0.2 mag (tmax+30d)

Remark: Compare old LTE + calibration (HKW95) for subluminous SN error(tmax) in (B-V)=0.2 m

IR-Spectrum of SN1999by at -4 days before Maximum Light

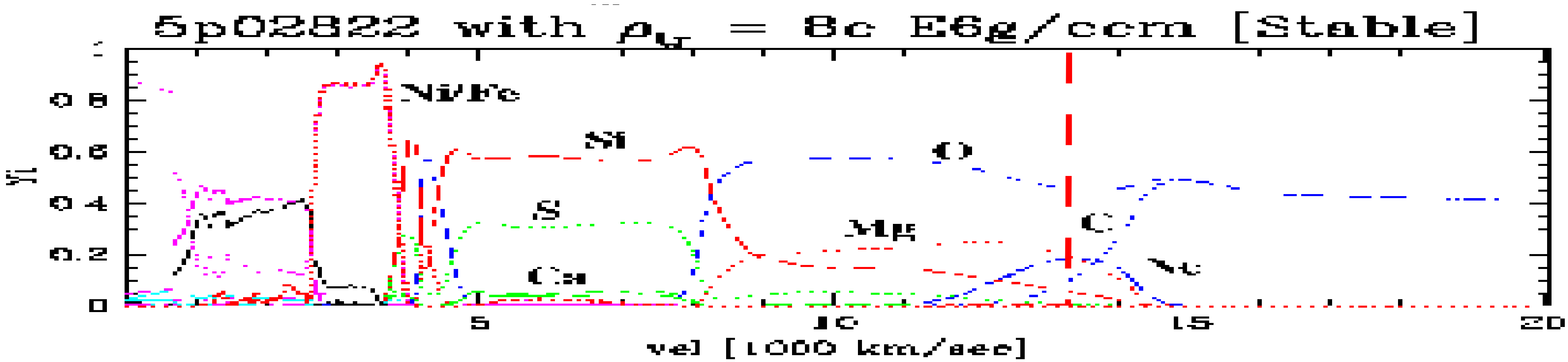


- Spectrum is formed in O-rich layers

model

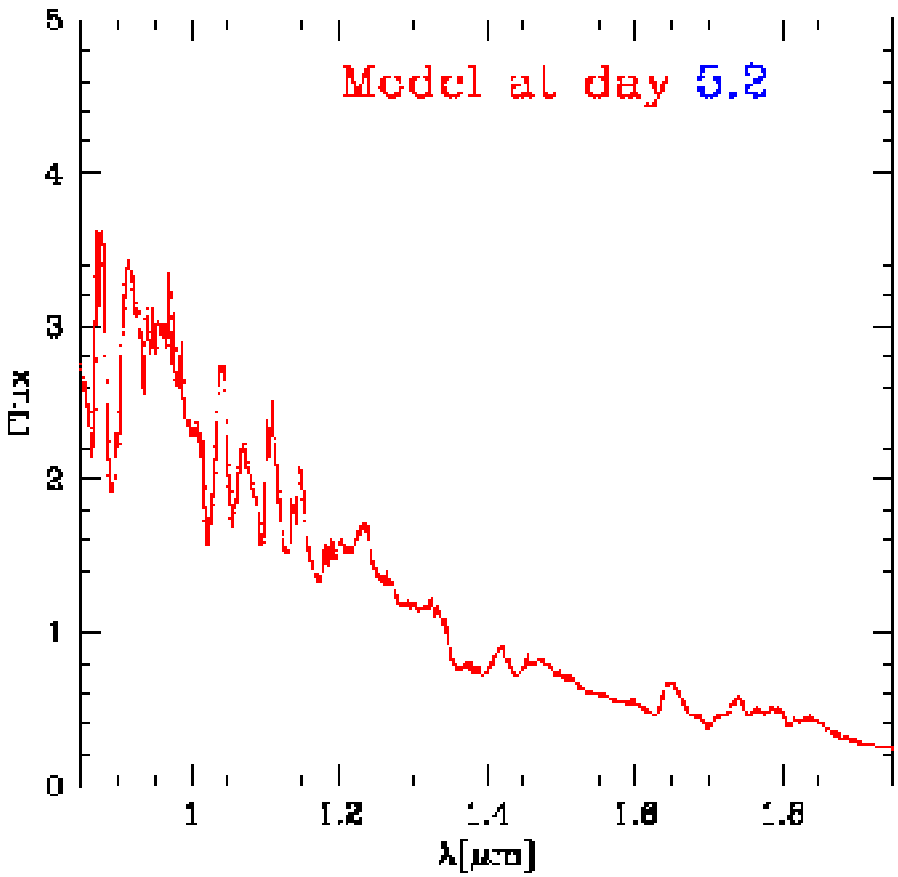
observation
by C. Gerardy

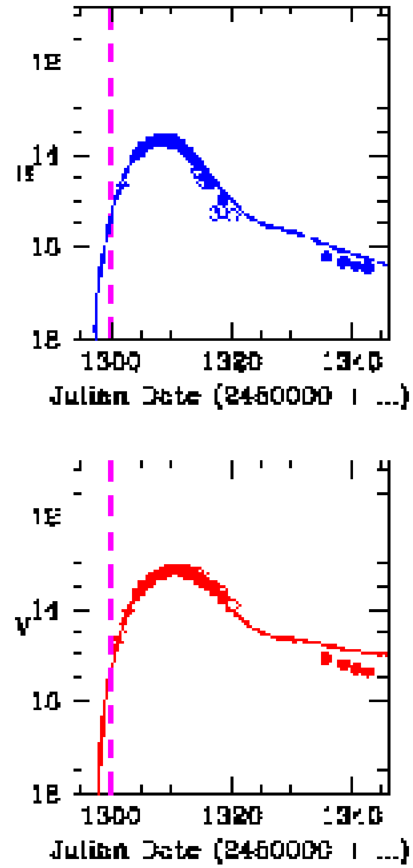
Thompson photosphere



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

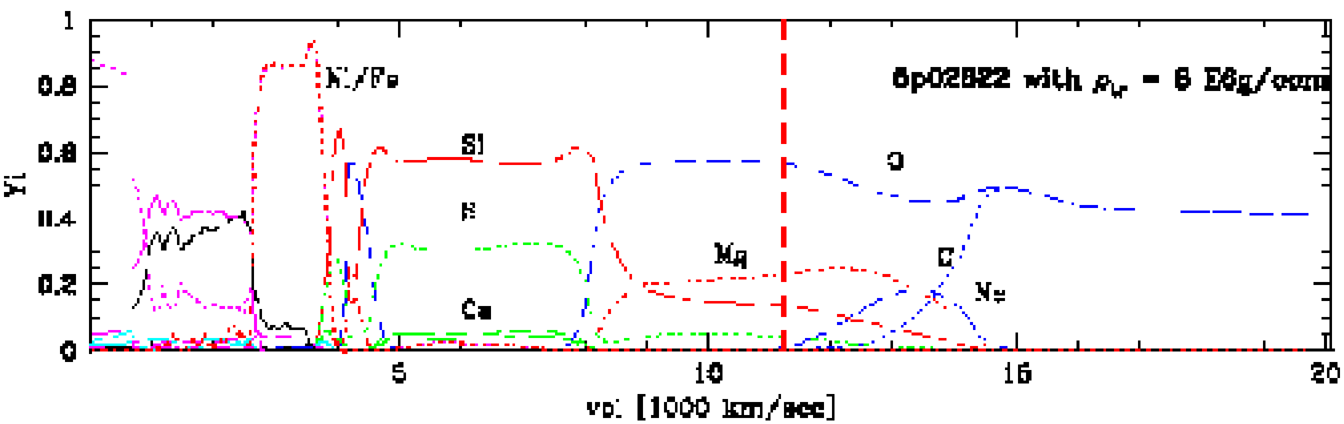
IR of a Subluminous DD Model vs. SN1999by at day 5.2



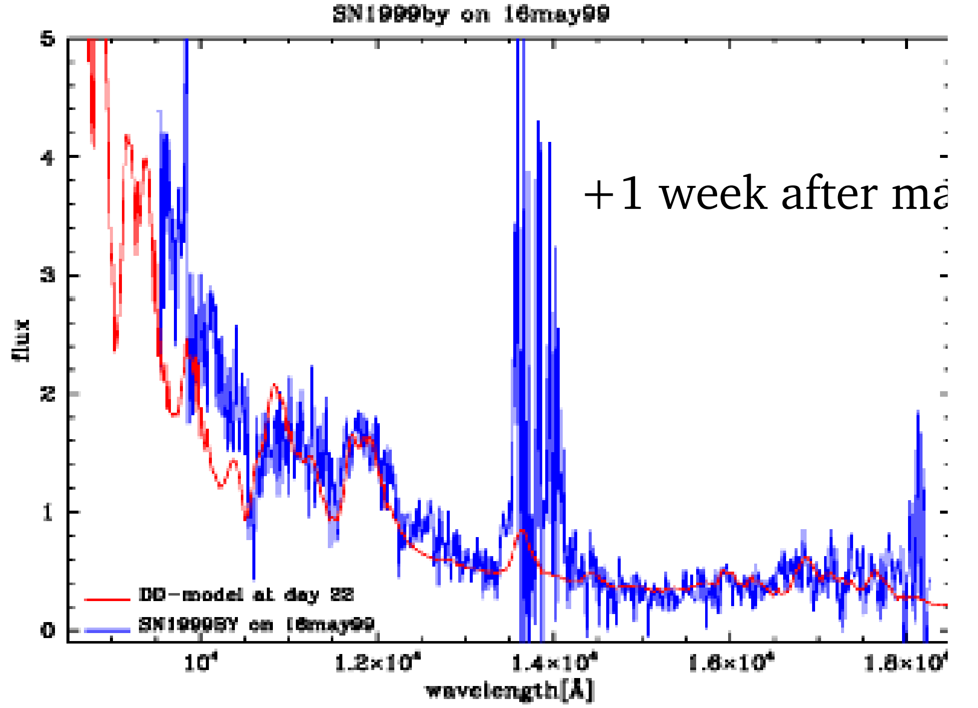


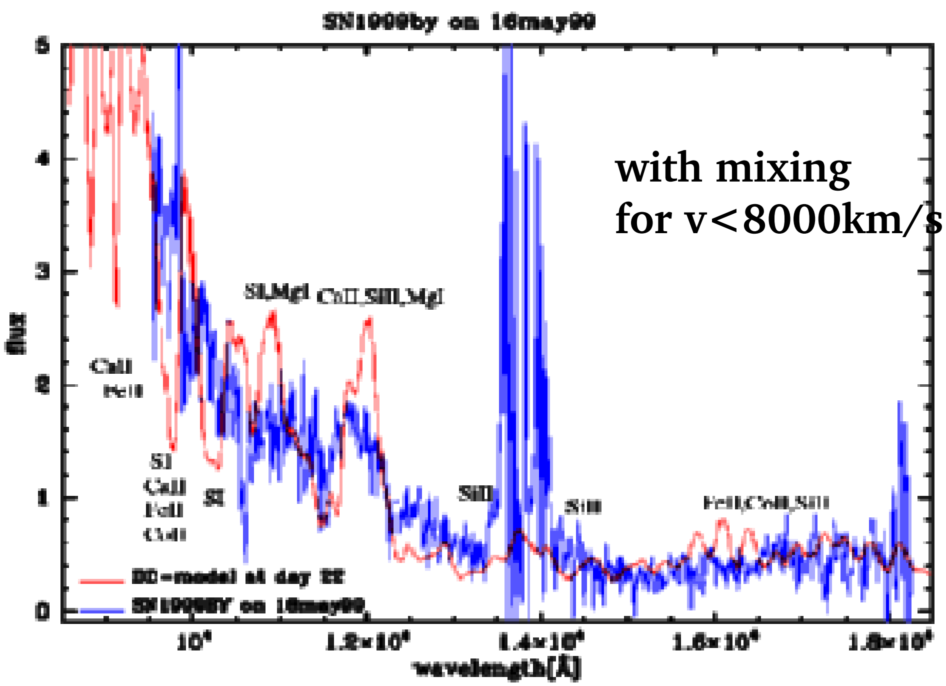
- M(WD) is both M(Ch)
- The entire WD is burned
- for subluminous SN Si/S & O/Mg is increased on expense of Ni
- Ni is very concentrated

=> Density effect
(e.g not direct metallicity)



Imprint of the RT instabilities/rising plumes?





Mixing, predicted from 3-D deflagration model does not occur

- No or different deflagration phase ?

- Smoldering phase ?

Polarization with axial symmetry (Howell et al. 2001) see also next talk by Lifan Wang

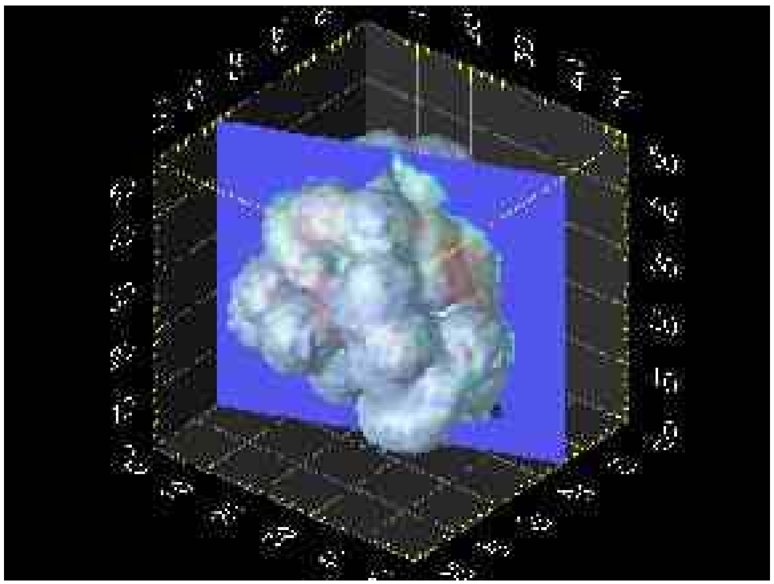
- Influence of rotation ?

In any case, importance of preconditioning of the WD is obvious.

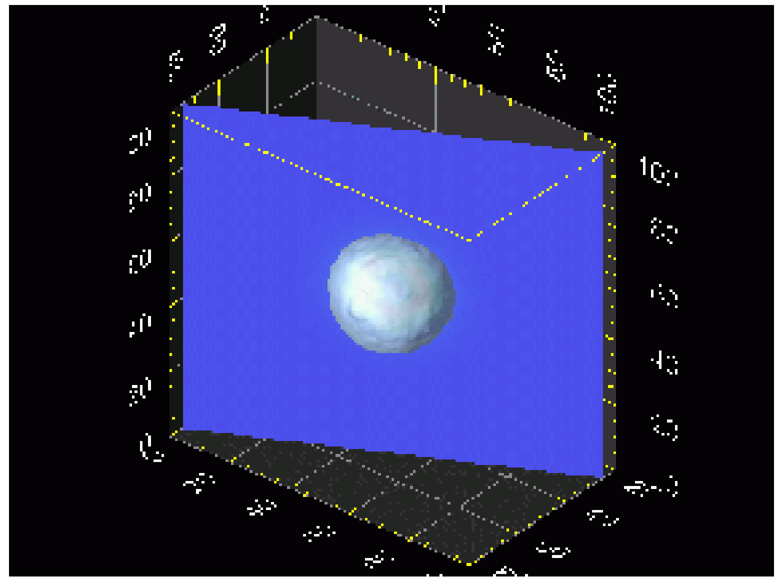
3-D Structure for a deflagration model (H2002)

WD: Mch, rho(c)=2E9 g/ccm

Day 01



Day 21



Contour: 2% of maximum Ni deposition

- Energy deposition is highly aspherical early on but spherical later on

Asphericity: Polarization by Electron Scattering

Electromagnetic wave : $\psi(z,t) = E e^{i(kz-\omega t)}$

$\underline{E} = (E_x, E_y)$

Intensity is defined as the time average over many waves

$I = I_0 + I_{90} = \overline{E_x\ E_x^* + E_y\ E_y^*} = \overline{E_x^2 + E_y^2}$

Degree of polarization P

$P = (I_0 - I_{90})/(I_0 + I_{90})$

with position angle χ

Stokes Parameter (equivalent)

$Q = I_0 - I_{90}$

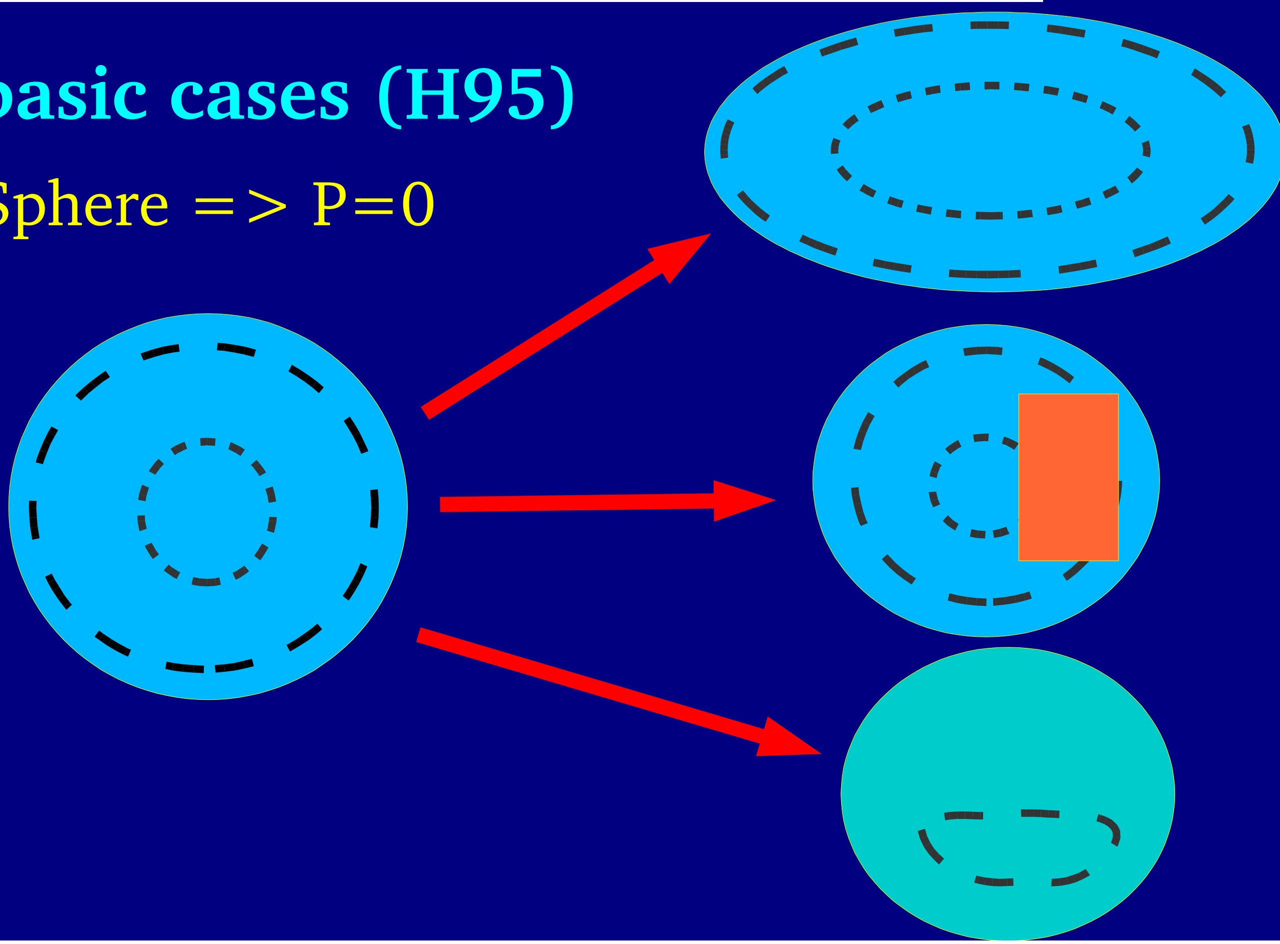
$U = I_{45} - I_{-45}$

$V = 0$ for linear polarization

Rem.: $\tan 2\chi = U/Q$ and $P = \sqrt{Q^2 + U^2}$

3 basic cases (H95)

Sphere => P=0



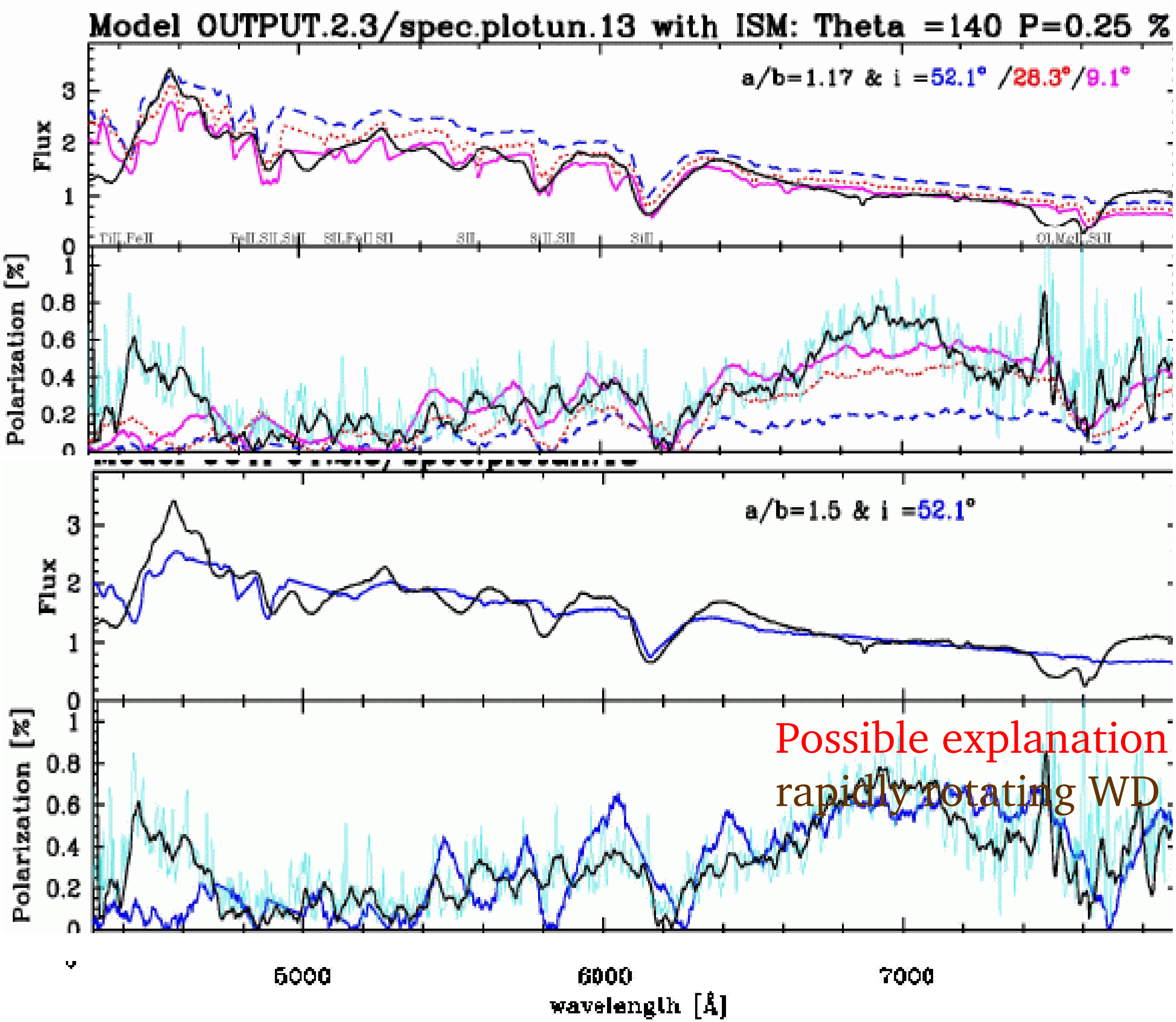
1)Aspherical envelope

2)Cover up
e.g. by opacity/line)

3) Aspherical energy
input

Polarization of the subluminous SN1999by vs. prolate model

(from McDonald program: Howell, Hoeflich, Wang,Wheeler 200,1 ApJ 550, 1030, error 0.25%,
since 2000, systematic VLT program, PI: D.Baade, Hoeflich, Wang, Wheeler, error 0.02%)



- global asymmetry
- asphericity 17 %
- seen equator on

- larger axis + higher inclination does not work

Possible explanation
rapidly rotating WD

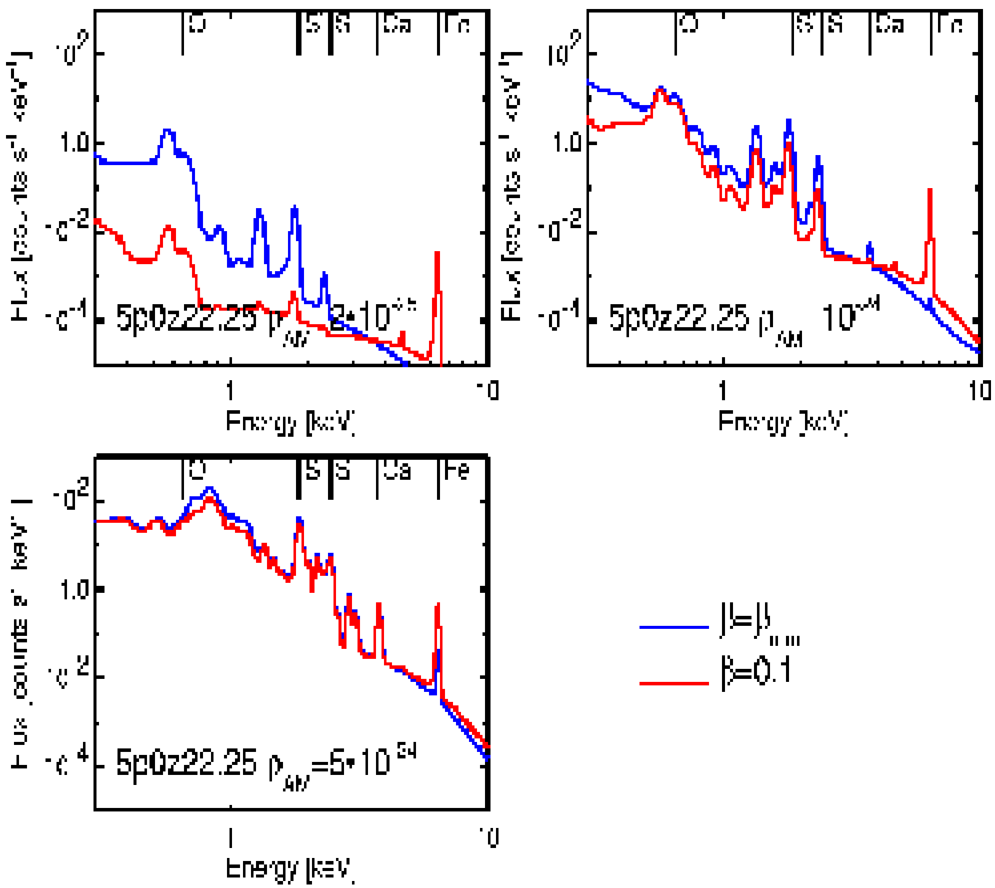
X-rays: Signatures of Thermonuclear Explosions

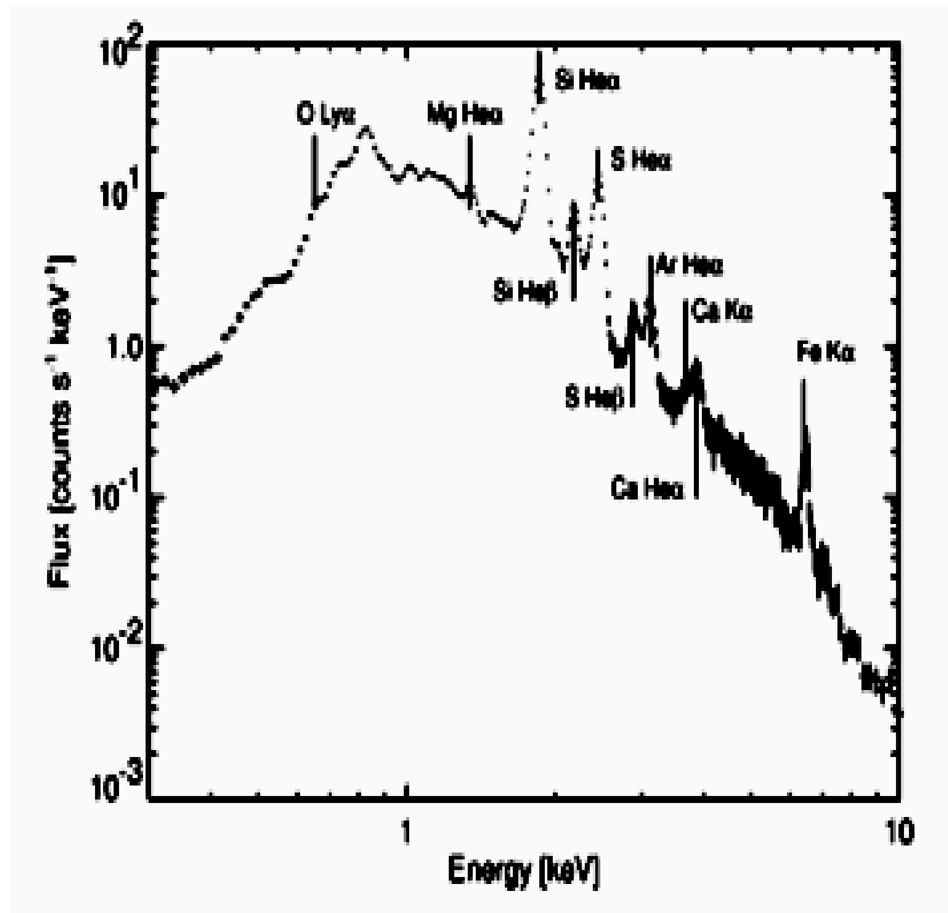
(Carlos Brenda, PhD Thesis, & Brenda et al. 2004, ApJ, submitted)

DD model model 5p0Z02 (Hoeflich et al. 2002) **Tycho observed with XMM**

400 years after the explosion

Parameters: Density of environment





- No C lines -> complete burning

Rem: No fit but generic model and no ISM correction

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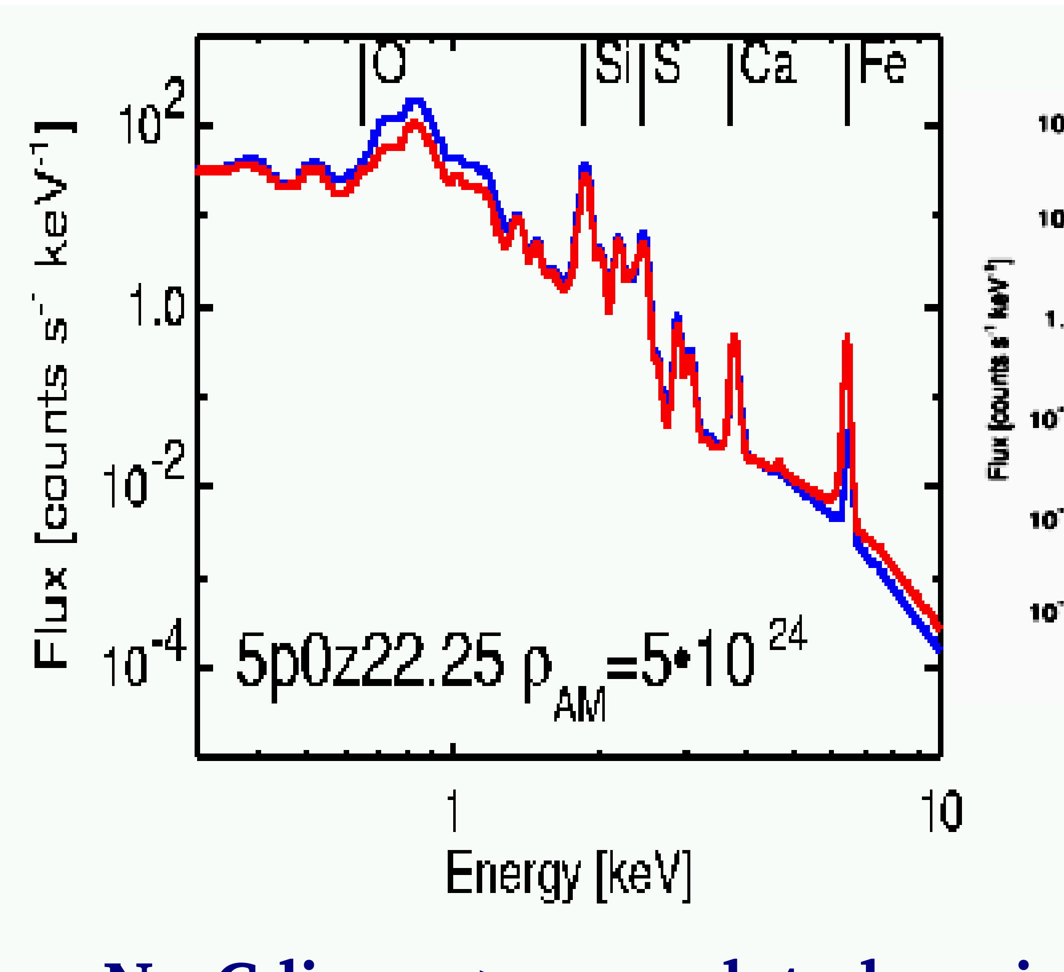

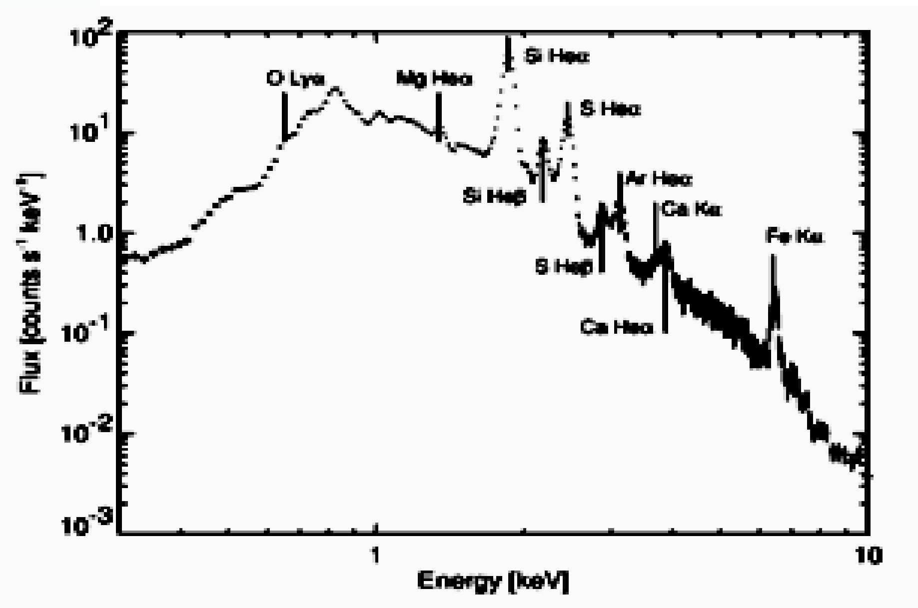

- **No C lines -> complete burning**
- **Correct slope -> energetics ok**

Main Conclusions: All Scenarios have Problems

1) SN.eIa are thermonuclear explosions of a C/O WD (outcome is rather insensitive to details)
2) LC.s and flux and polarization spectra allow for a detailed analysis of SN.
New IR observations + polarization are a key to probe the physics and cosmology

3) Chemical layered structure of the envelope => signature for a detonation phase

4) No detection of H or He at high Z (no HeDs)

5) Almost the entire WD is burned (unburned C/O layers < 0.1 ...0.2 Mo)

6) From the rise times of LC.s and spectra, M=(>) M(Ch) are strongly favored

7) M(V)=dM(15d) can be understood as an opacity effect.

8) Small P (<0.2 %) with the exception of the subluminous SN1999by (0.7% + axial sym.)

9) Preconditioning of WD prior to the explosion is a key to understand SNIa

DD-models: Most optical and IR observations can be understood quantitatively (1-7).
- small spread around M(V)=dM(15) because of similar explosion energies
- rho(tr) /amount of burning is the quanty with determines
- normal and subluminous SN can be understood, including the range of brightnesses

Problems: deflagration phase, i.e. no Ni-plumes in subluminous SN1999by (rotation/smoldering)

Merger: promising contributors but likely not the main mechanism because 5.

Deflagrations: big problems due to 2, 3, 5, (7), ... or we do not understand deflagrations

Final Discussion and Conclusions

- Supernovae are thermonuclear explosions of C/O WDs

- SN are homogeneous because nuclear physics determines the structure of the WD, and the explosion. CONSISTENTENCY between evolution,explosion+LC/Spectra

- Light curve are determined by the radioactive decay of Ni -> Co -> Fe.
=> homogeneity does not imply a unique scenario (partial stellar amnesia) !!!

- Light curves, and flux and polarization spectra allow for a detailed analysis of SN. New IR observations + polarization are a key to probe the physics.
- All chemical layers are radially structures + almost complete burning
-> signature of detonation (but inconsistent with pure deflagration models)

- Most observations can be understood by "delayed detonation" models.
- Density effect/pre-expansion is responsible for luminosity/decline relation
- Metallicity and rho(c) produces spread around the M/DM relation
- No evidence for rising plumes in subluminous (SN99by) or normal bright SN(03du)
- For SN2002bk, V(ph) increase with time => early reheating by gamma's =>above
- Preconditioning of the WD prior to the explosion is a key to understand the differences.
- Models allow to probe evolutionary effects with redshift.
- We start to probe the progenitor system