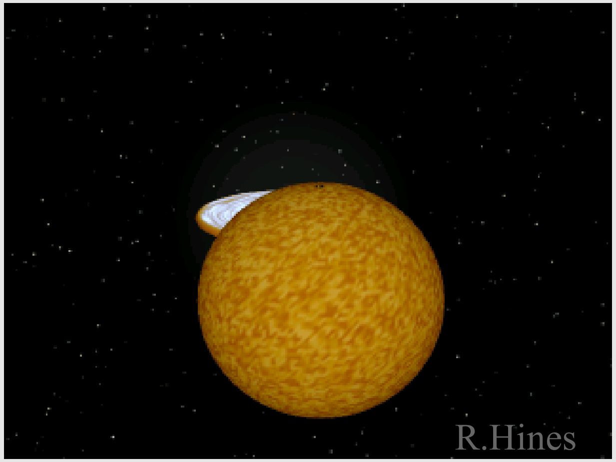
Models for Type Ia Supernovae NIR as Occam's Razor & Progenitors

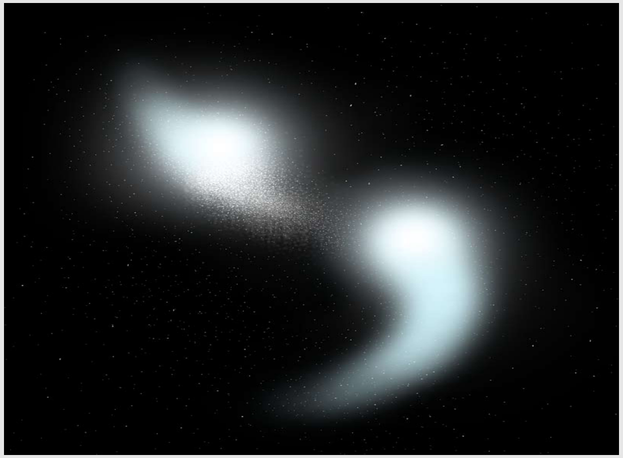
1) Intro: what, why & the diversity ?

2) Probing the Explosion Scenario &3D
- NIR light curves
- Flux and polarization spectra
- Late-time NIR & B-fields

3) Secondary LC parameters
(which reduce residuals to 0.02m)

4) For Gremlin's, see Eddi Baron's talk





Incomplete list of collaborators:

Baade (ESO), Dominguez et al.(Grenada), Fesen & Co(Dartmouth), Khokhlov & Co (Chicago), Baron & Co (Oklahoma), Hamuy & Co(CTIO), Kevin/Suntzeff/Wang(Texas A&M), Quimby, Straniero &Co(Terramo), Patat (ESO), Phillips (Carnegie), Wheeler(UT),
FSU (Gerardy, Hastings, Mandelau, Pelluchi, …, Prosper, Rogashov, Wiedenhover, Green)

& Workers (sometimes called PhD students)

Tiara Diamond (w. C.Gerardy) : Observation and analysis late-time IR spectra
Paul Dragolin: : Interaction of high velocity winds and ISM
Robert Dungan: : rp-Process
Joe Mitchell : Flashes in rapidly rotating WD (U of San Diago)
Brendan Penny : Gamma-ray and positron transport (U Clemson)
Ben Sadler: : Secondary parameters in light curves
Shaojie Yuan (with HEP) : Probing the Dark Matter distribution by gravitational lensing of SNe Ia

Diversity: Maximum Brightness varies by factor of 10
but much smaller in the IR

(CTIO group: e.g. Phillips 1987, Hamuy et al. 1996, Suntzeff et al. 1996)
Their atlas of 29 SNeIa is the basis for all(!) modern empirical methods!

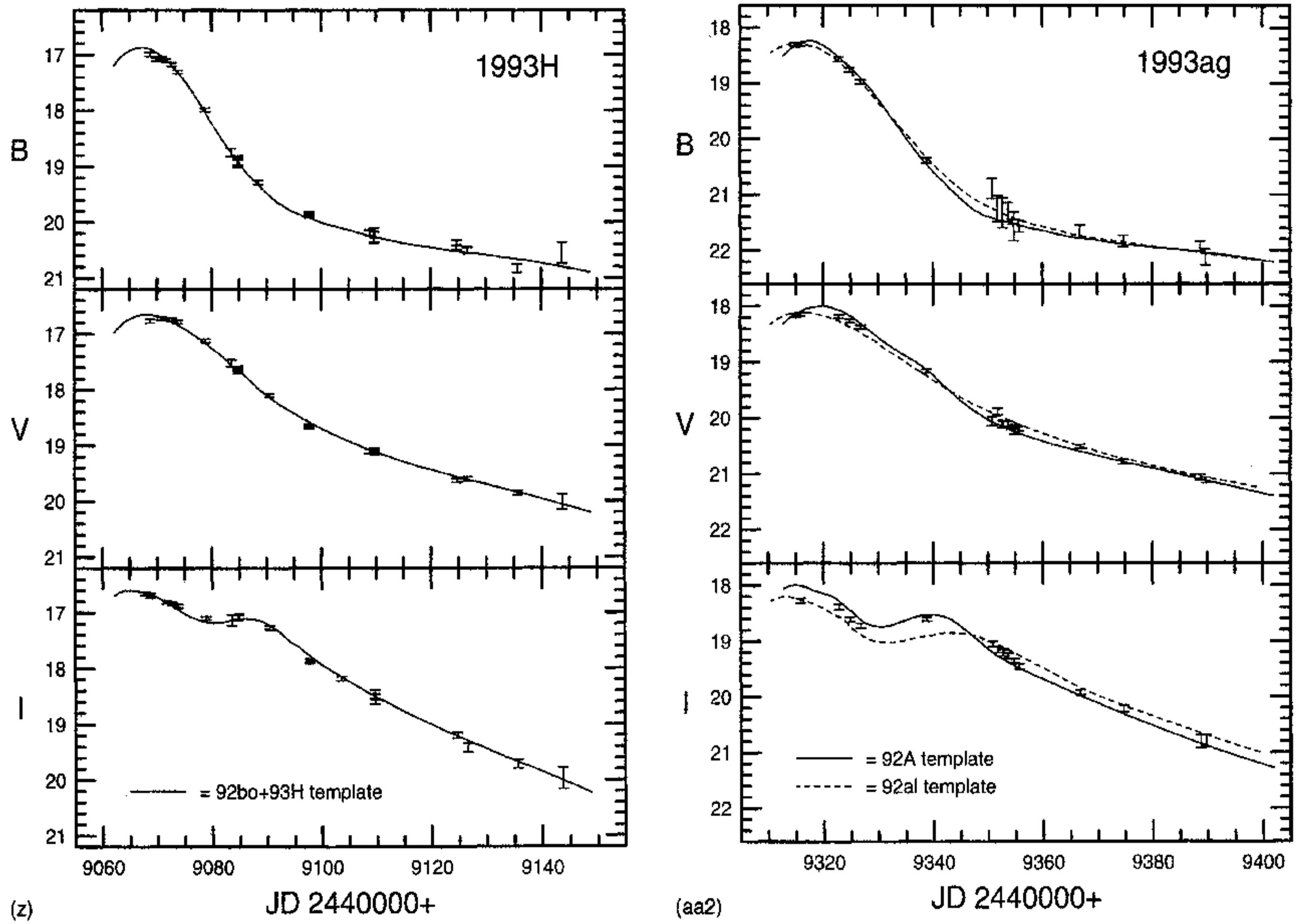
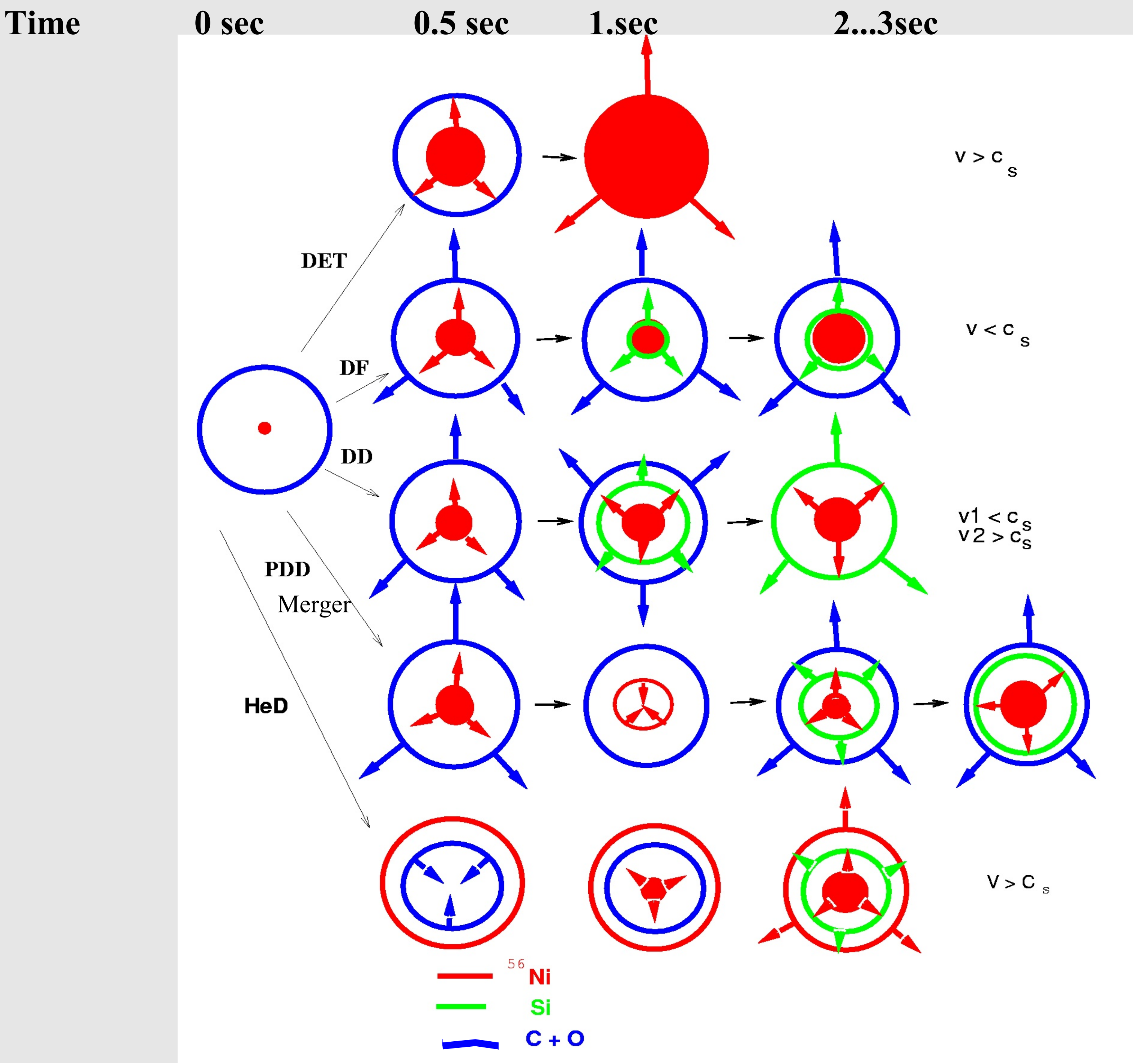


FIG. 3. (continued)

Thumbnail Sketch of Thermonuclear SNe

- 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"***

The Zoo: Explosion Scenarios of White Dwarfs

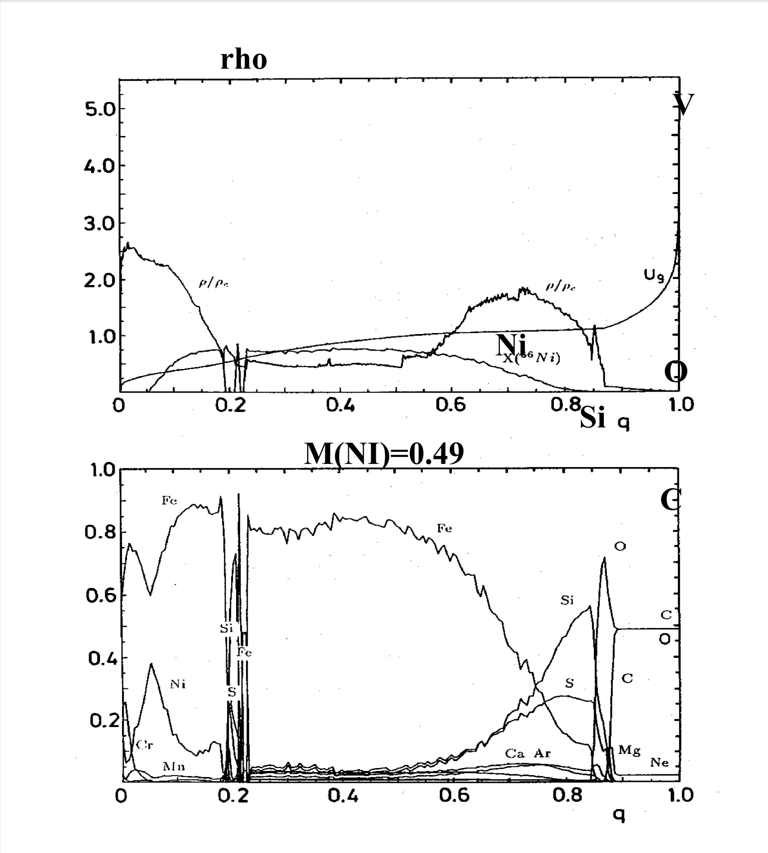


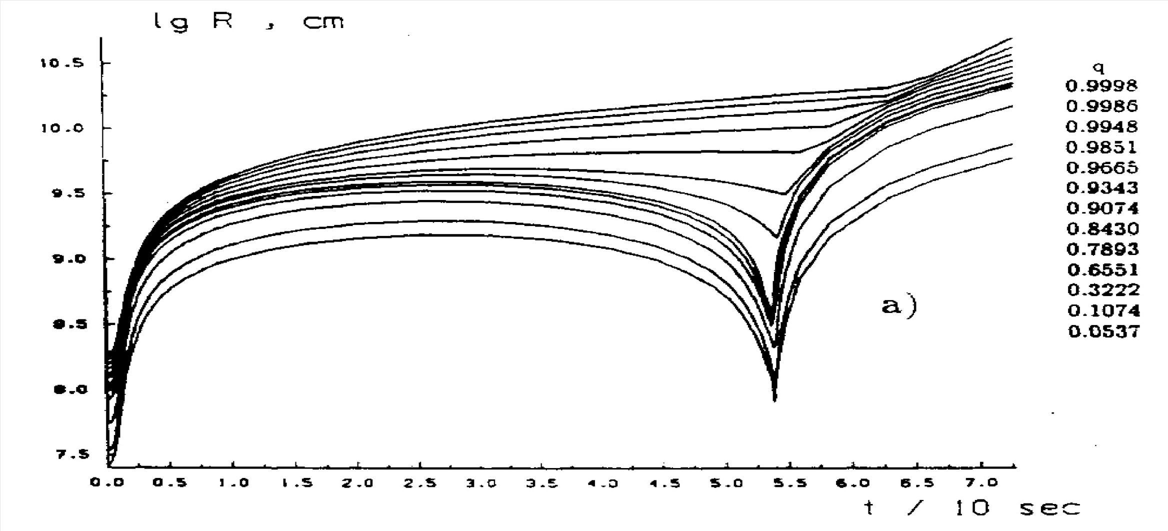
Pulsating Delayed Detonation Models & Mergers

Example: rho(c)=2.E9g/ccm

Evolution of hydro of PDD3 over 7 seconds

PDD3: rho(tr)=2.1E7g/ccm





- same as DDs but no prompt transition
- both normal bright and subluminous
- outer shell unburned with v>10-14000km/sec

from HKM93 KMH93

Merger Models

Example (simplification): WD of 1.2 Mo surrounded by envelope

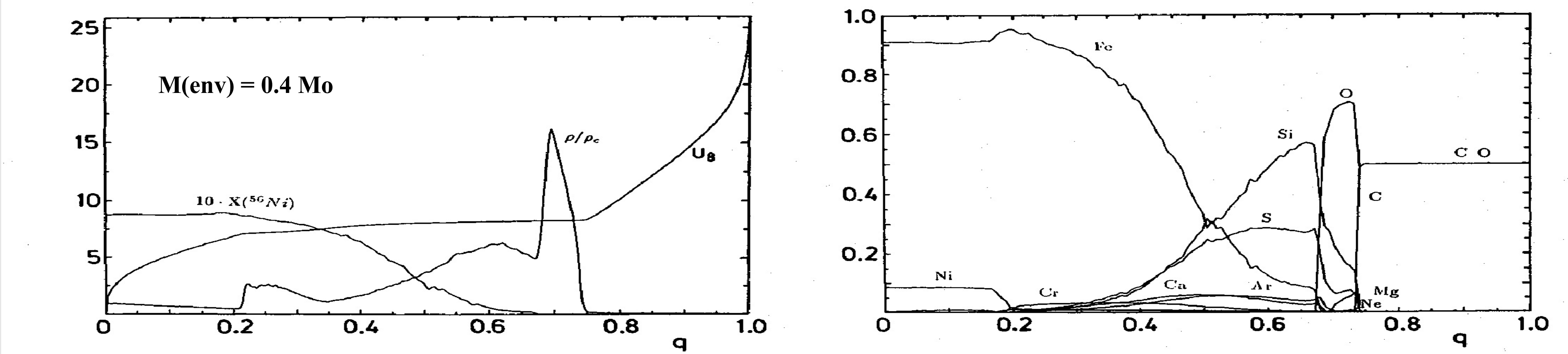
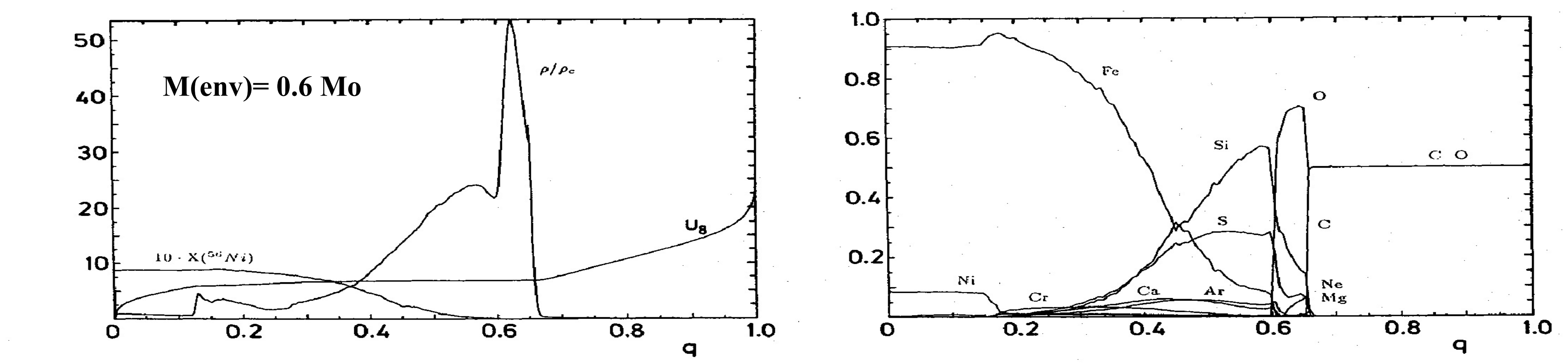


Fig. 9. Same as Fig. 1 but for model DET2ENV4 and the velocity given in units of 10^8 cm/s

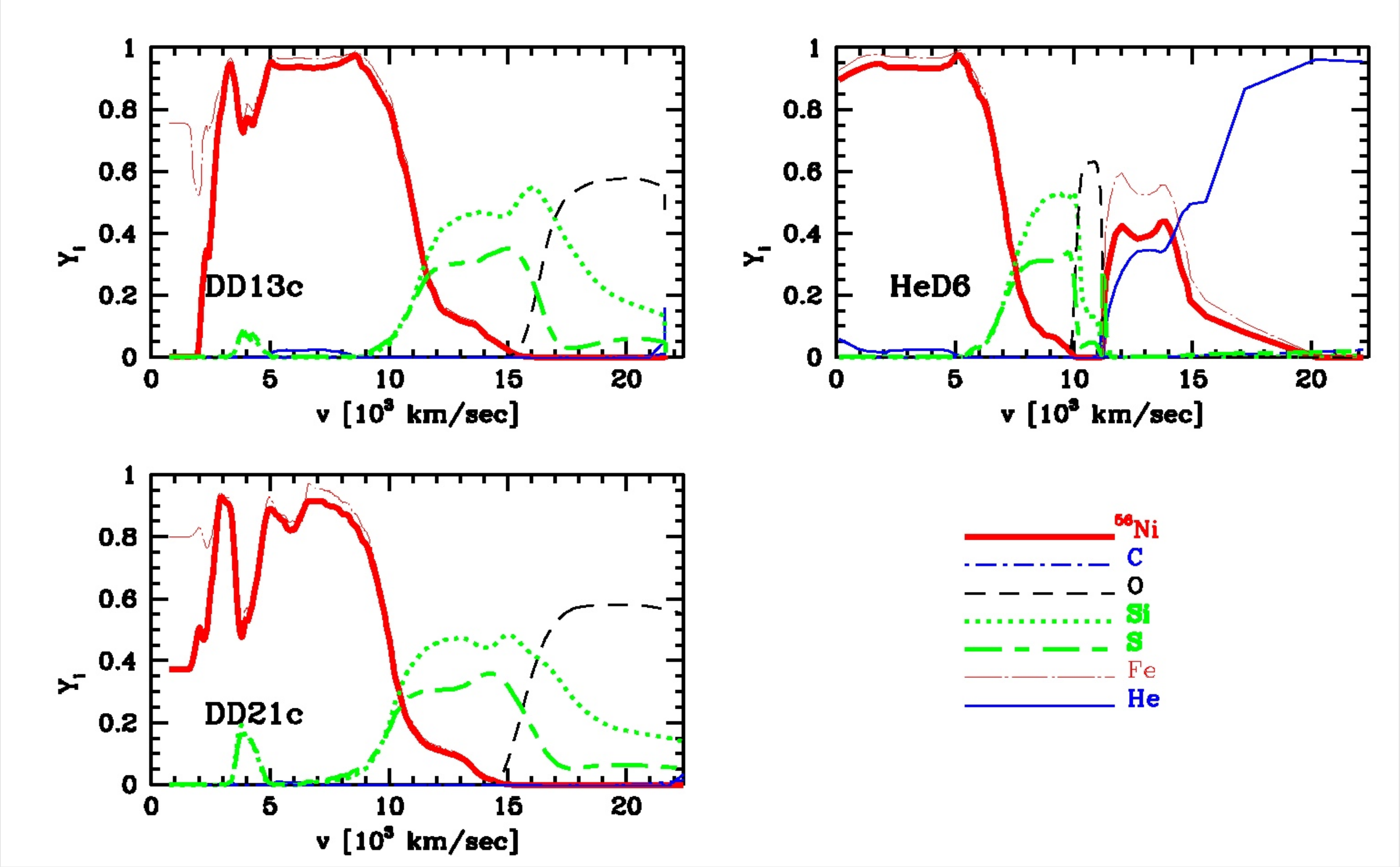


- Shell-like envelope with unburned C/O outside (v> 10,000- 12,000 km/sec)
- either detonation in intermediate Sub-Chandra/DD or D of Mch
- total mass can be larger than Mch
- thin layers of Mg and Ne

From KMH93

Some Examples for Final Chemical Structures

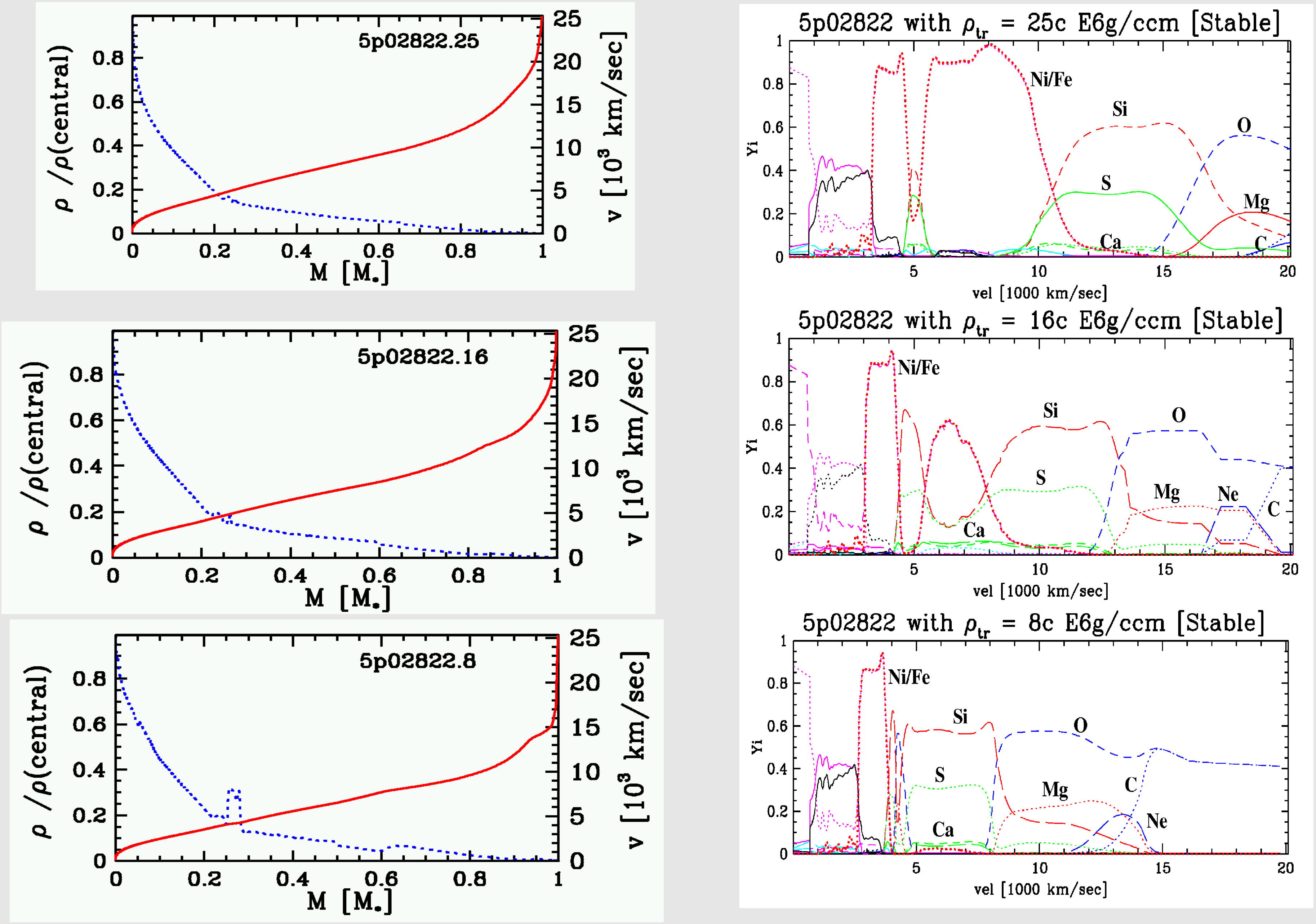
DD13: DD model; M(Ch) with rho(c)=2.4Eg/ccm; rho(tr)=3.0 E7g/ccm
DD26: " rho(tr) =2.4E7g/ccm
HeD6: Helium detonation of a Sub-M(CH) with 0.6 (CO) +0.14M(He)



HK96

I) Delayed detonation models for various transition densities rho(tr)

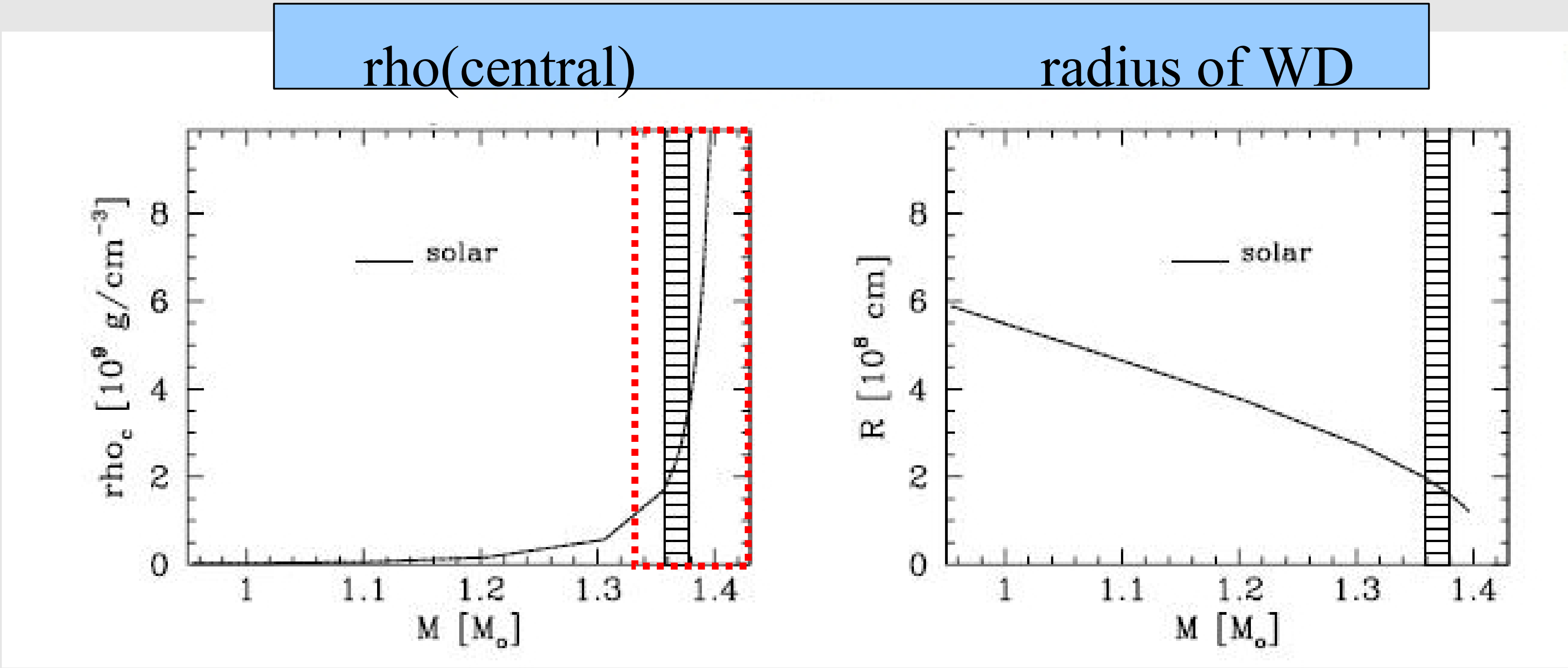
[M(MS)= 3 Mo; Z = 1.E-3 solar; rho(c)= 2E9 g/ccm with rho(tr)=8, 16, 25 g/ccm]



56Ni (deflagration phase) / 56Ni (total) $\simeq$ 10 … 12

M(Chandra) vs. Mergers, Sub-Chandra WD (HWT98)

Central density as a function of Mass of the WD



Remark: We need rho>1E9g/ccm to have electron capture rates < 1 second => No 56Ni

Summary of Generic Chemical Structure (simplified)

Thermonuclear Explosions **(outer layers)**

56Ni at high v

Y → Sub-Chandra (HeD)
(or rising bubble/Flash)

No → Mergers, M(Ch): DD, PDD

Lots of C at surface

Y → Mergers, PDDs
Sublum. DDs

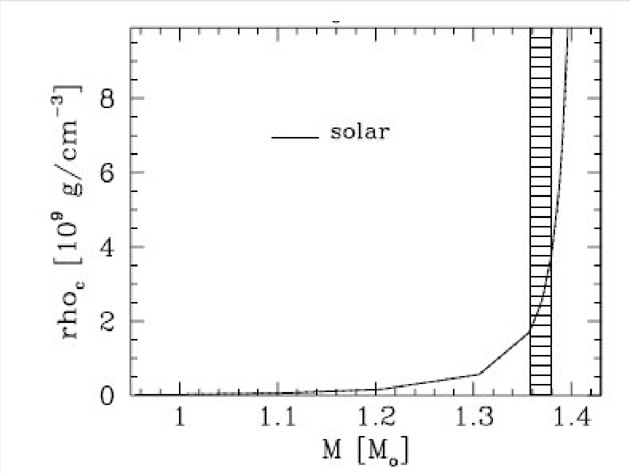
No → Normal bright DD

Thermonuclear Explosion (inner layers)

56Ni to the center
(rho<1e9g/ccm)

Y → Sub-Chandra,
Dynamical mergers

NO → M(Ch) Wds
DD s, slow mergers



COMPLICATION: Mixing (needs to be measured)

Why is the dispersion in brightness smaller in the IR?

Example PDDs (normal and subluminous, HKW95)

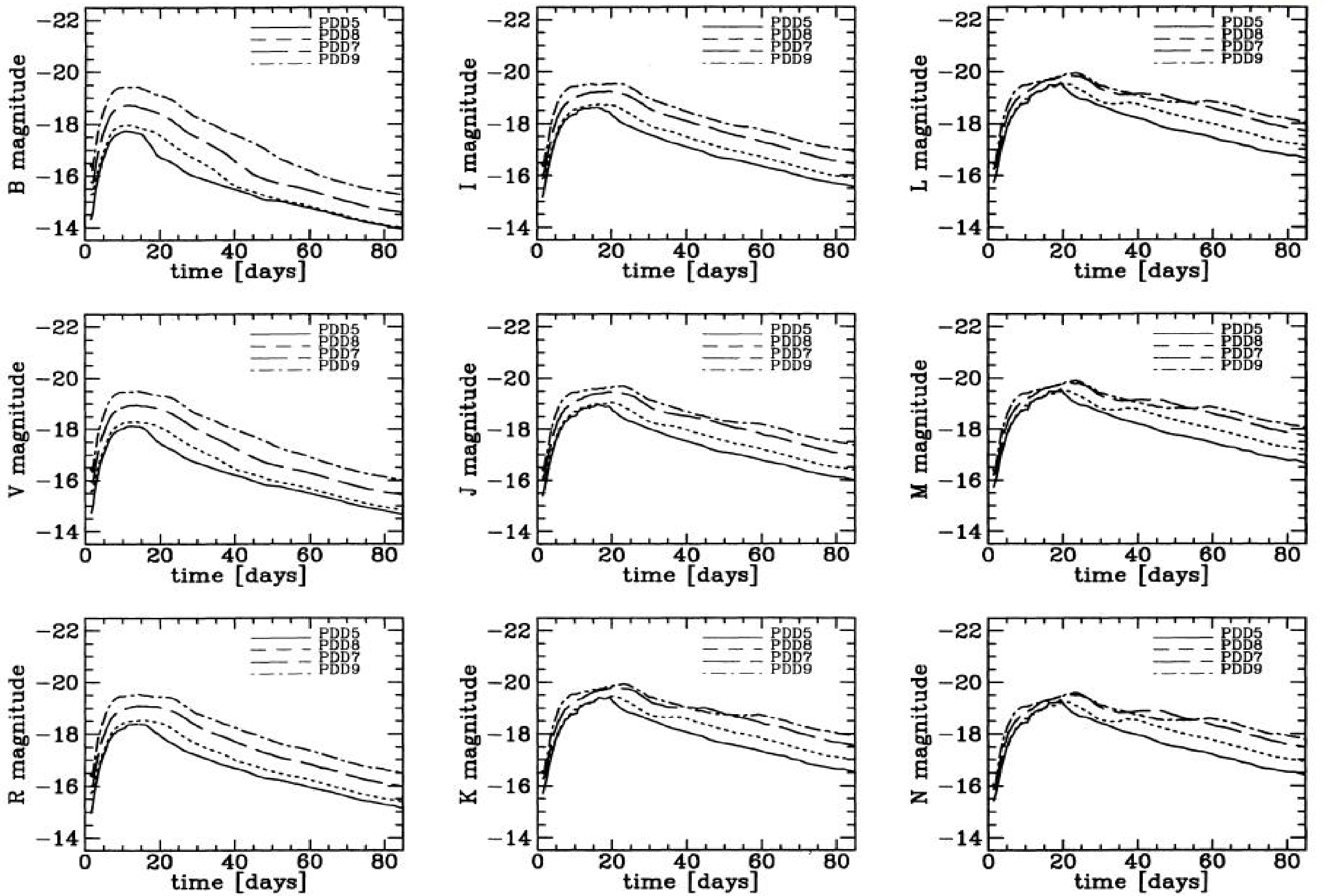
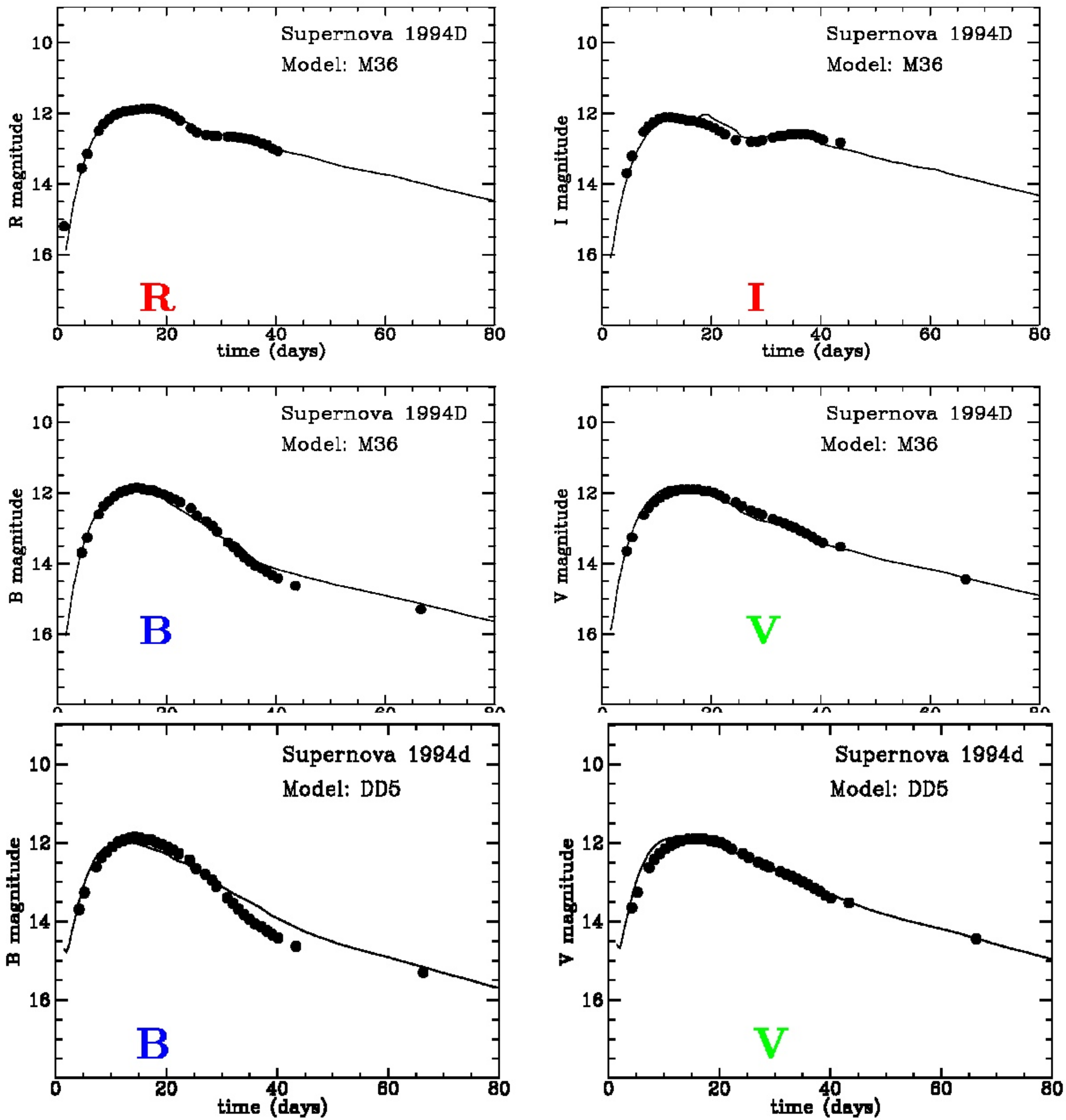


FIG. 8.—Monochromatic colors in Johnson's *UBVRIJKLMN* system as a function of time for models with different transition densities

- atmosphere becomes cooler with time
- in IR $L \sim T * R_{ph}^2$ (Wien's limits)
- Secondary maximum occurs when R opacity drops by recombination (maxima 'merge' for subluminous SneIa and Mch).

Light Curves up to Day 80: SN94D vs. DD-models



C/O WD with

rho(c)=2.E9g/ccm

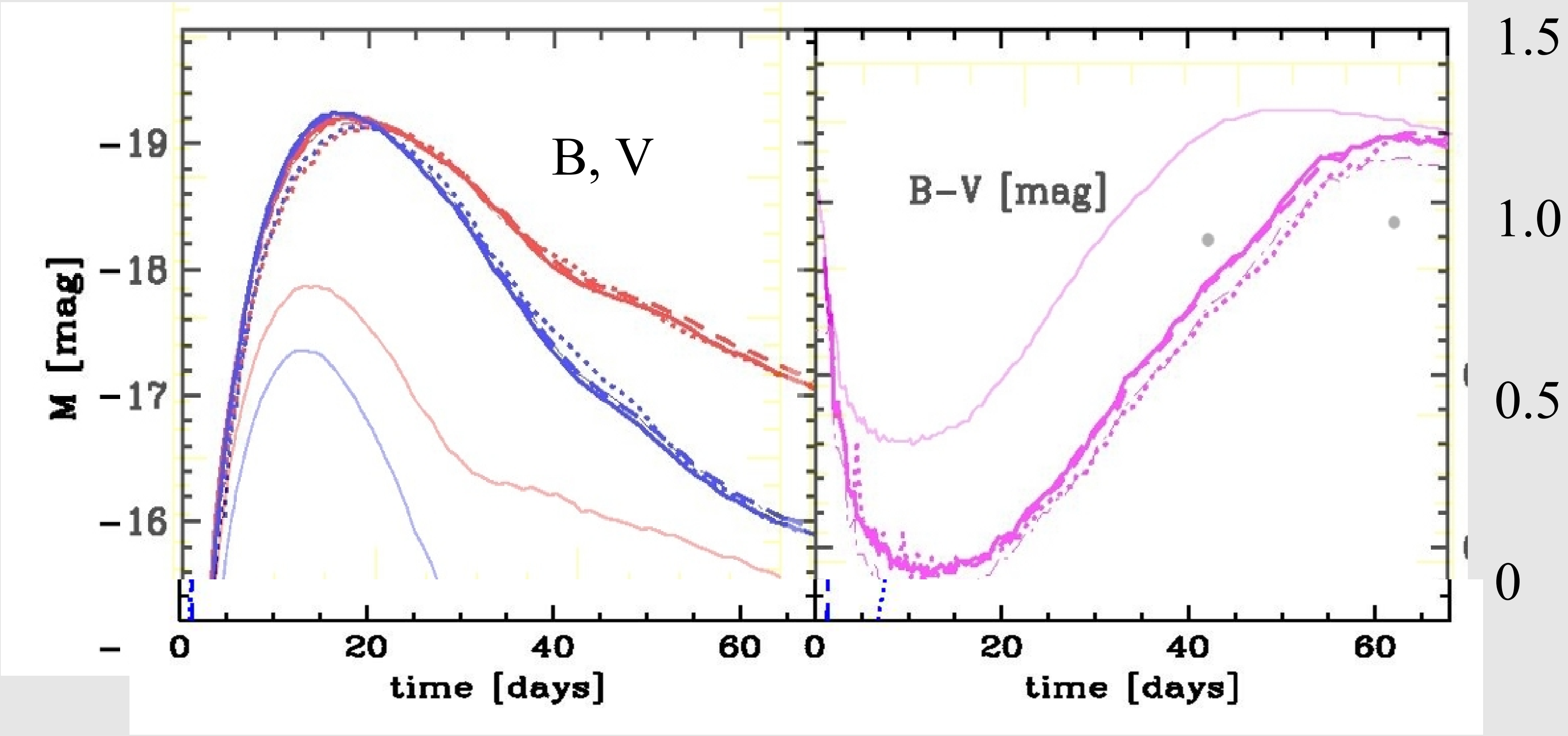
rho(tr)=2.4E7 g/ccm

Same but

rho(tr)=2.7E7g/ccm

H95

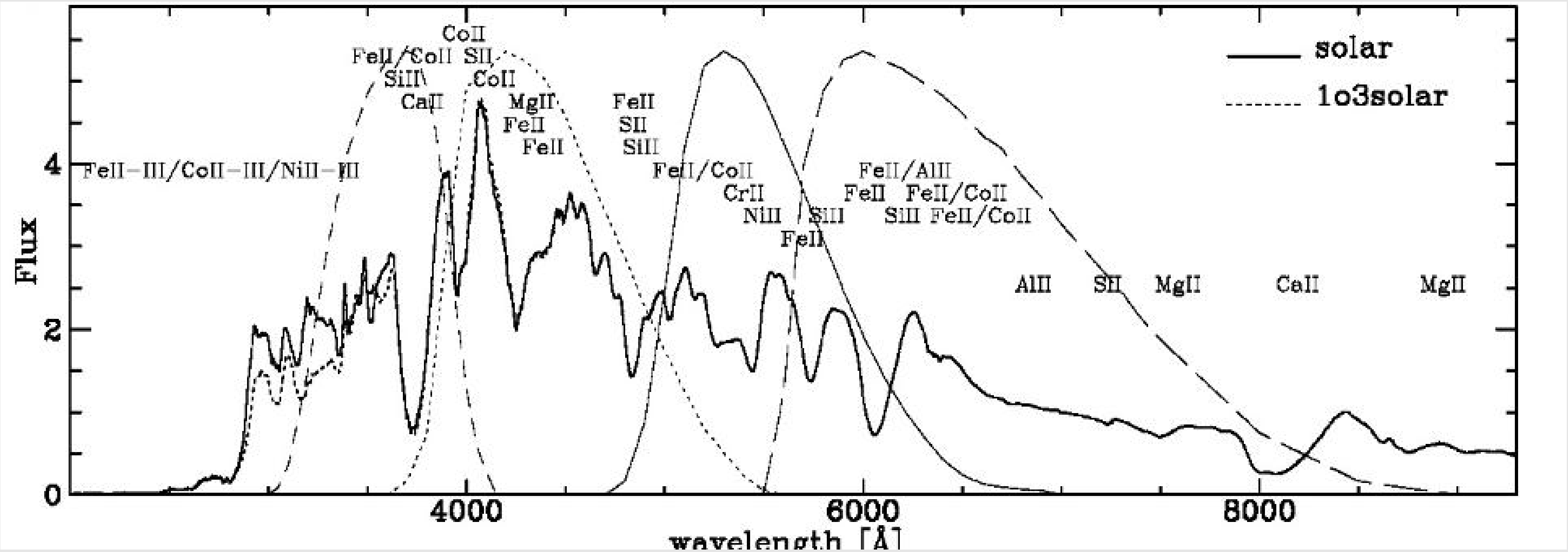
Ingrediences of the Lyra's Relation



At a **common(!)** **time**
conditions of at the photosphere **are similar with respect to**
- temperature, density and ionization
- abundances

Why Does the Optical Suck?

Example: Optical spectrum of SN1994D at maximum light (H95)



- 'famous' CII identification (for mergers) may be Fe/Co II
  (problem mixing can Doppler shift)

- No good Ne, O or Mg lines

=> gives us a hard time to distinguish explosion scenarios

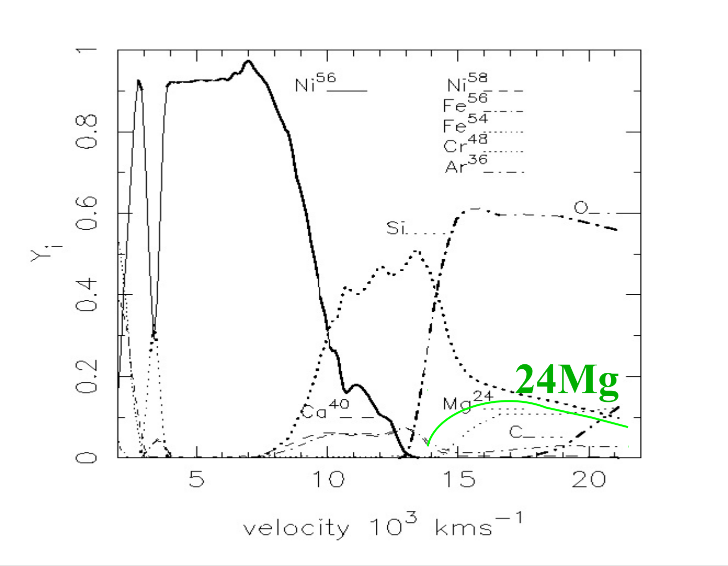
H95, HWT98

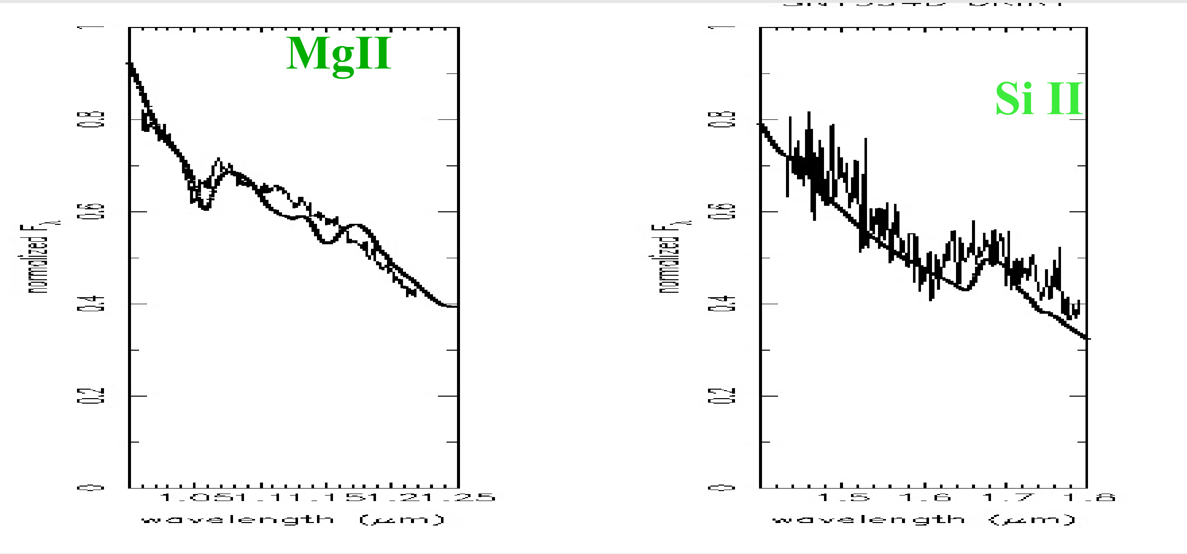
IR-Spectra at Day -3 in Comparison with SN1994D at Day -7

Examples: DD with rho(c)=2.5E9g/ccm & Peter Meikle (Mr. IR)

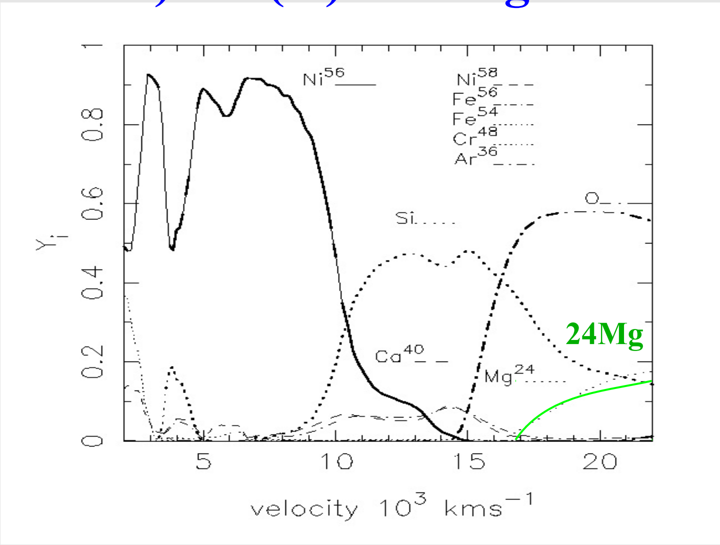
a) rho(tr)=2. 0E7g/ccm

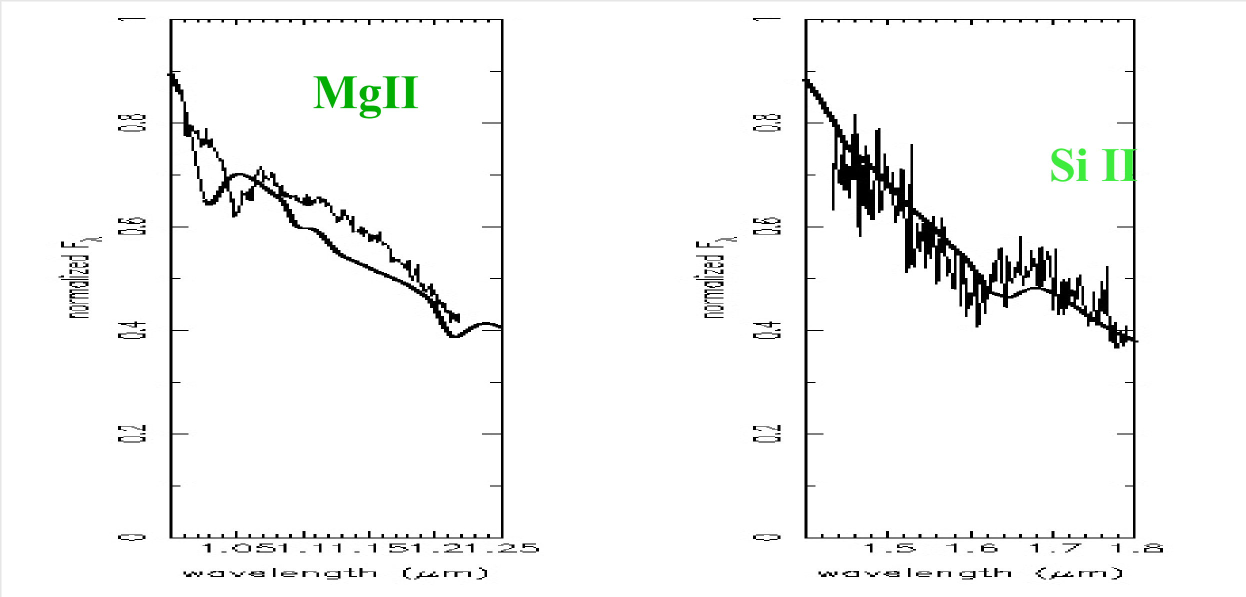
Spectra between 1.05-1.25 & 1.4-1.8 A





b) rho(tr)=2.4E7g/ccm





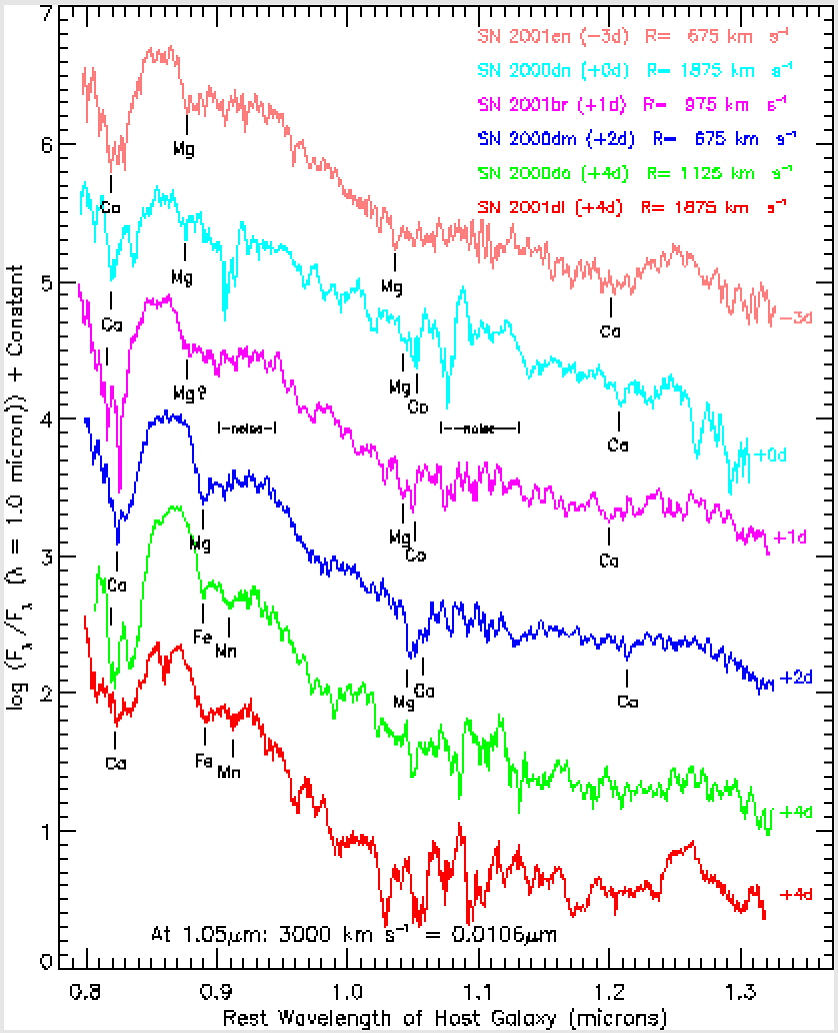
WHHS98

SN94D by P.Meikle

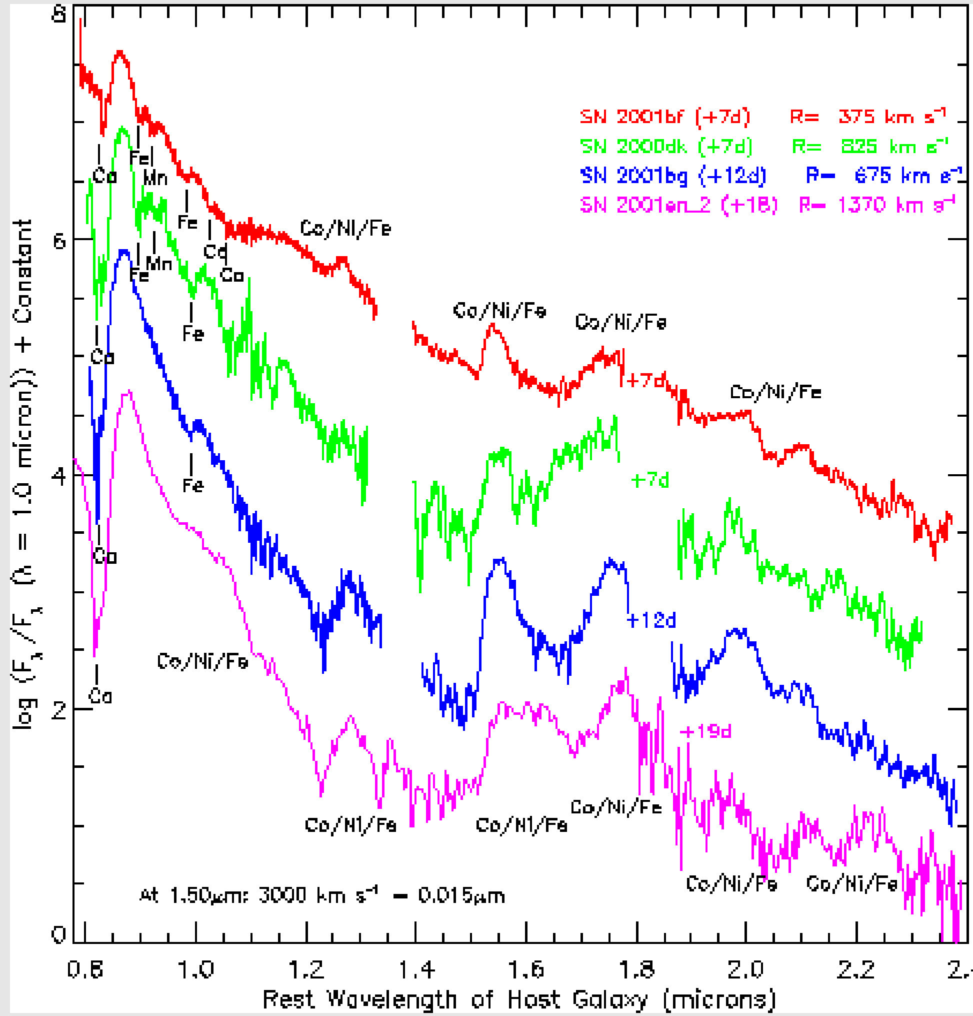
Breakthrough: IR-Spectra of 10 SN.eIa between -4 and +18 days

(Snapshot IRTF observations by Marion et al. 2007, PhD thesis & published)

Early time spectra



Late time spectra

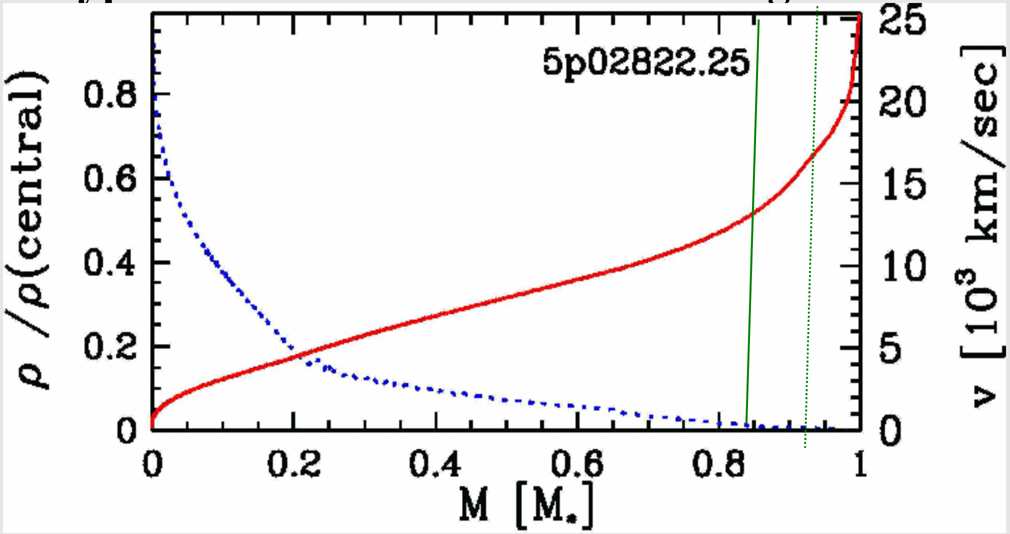


- time series of various SN.eIa look very similar => homogeneous class
- No HeII line at 2.05 mu but multiple Mg II lines
- No CI and CII lines although observable if present

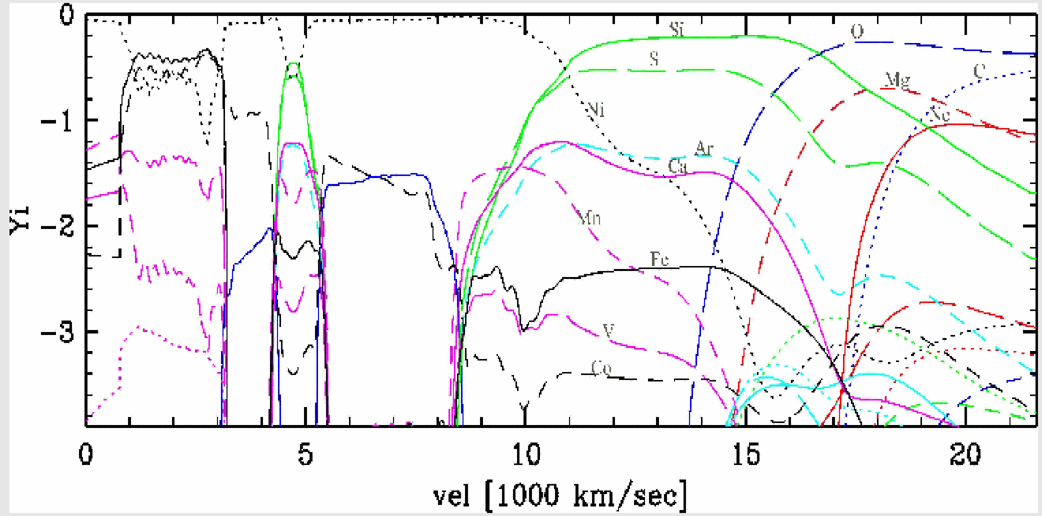
Marion et al. 2007

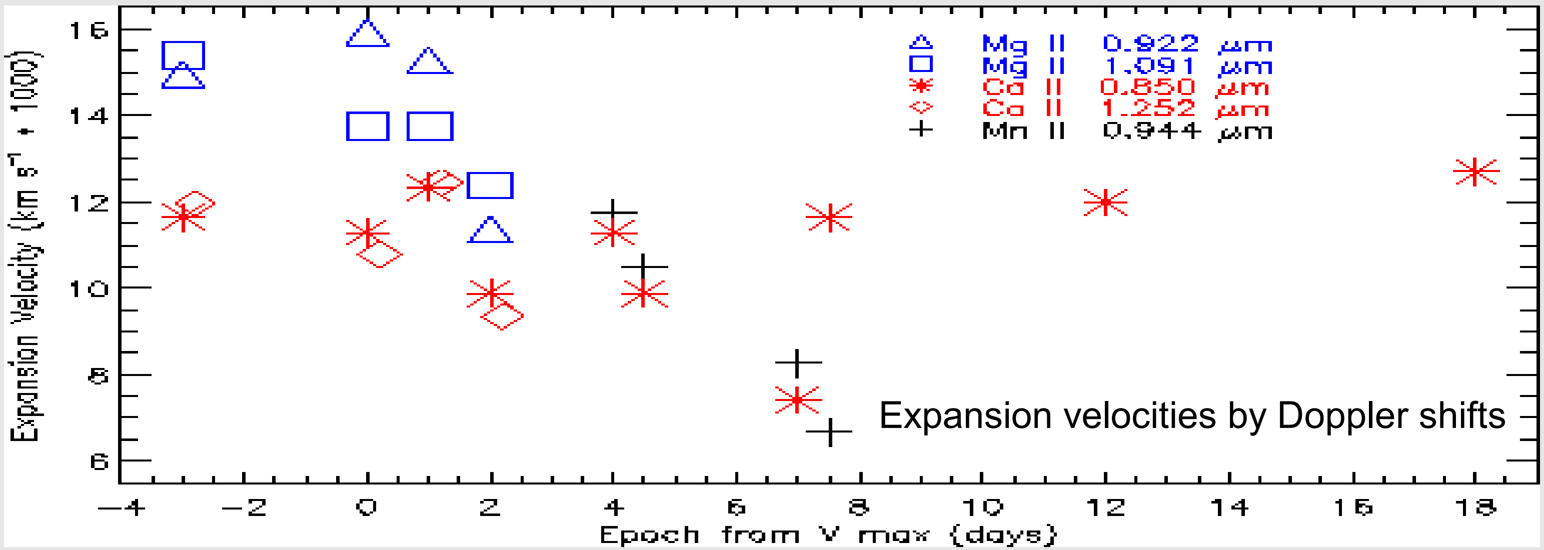
Quantitative Conclusions from the IR-sample

Typical DD model for a normal-bright SN.Ia



Abundances (log/mass fractions)

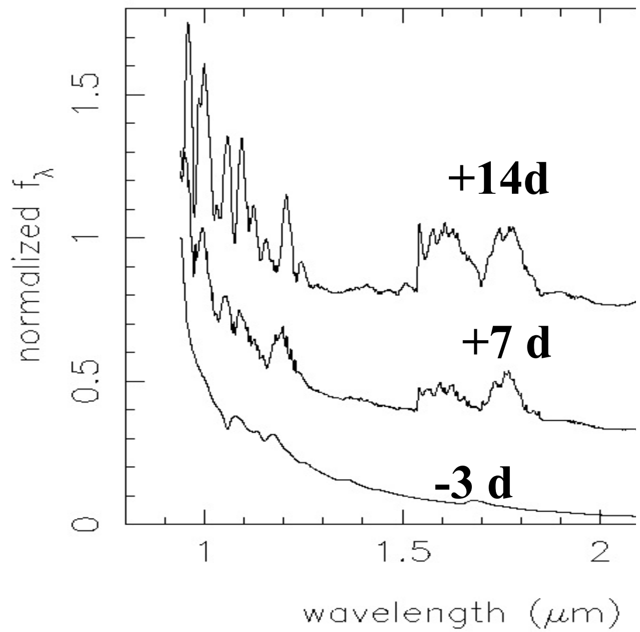


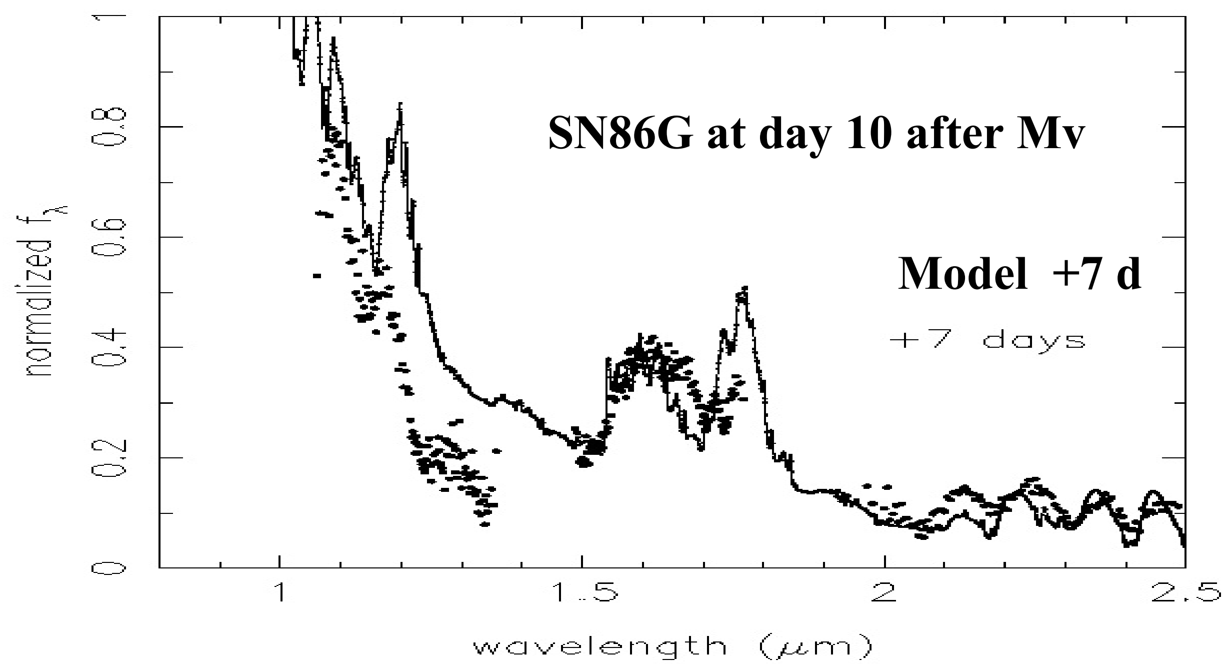


- Mg II is an important probe for the burning temperature in the Si/S region
- Layered, chemical structure (without evidence for non-radial component/mixing)
- Minimum Mg II velocities between 12,000 to 16,000 km/sec in the sample
  => typical of unburned matter << 0.1 to 0.2 to Mo !!! (from line wing < 0.1 Mo in all cases)
- significant individual variations are about 4000 km/sec

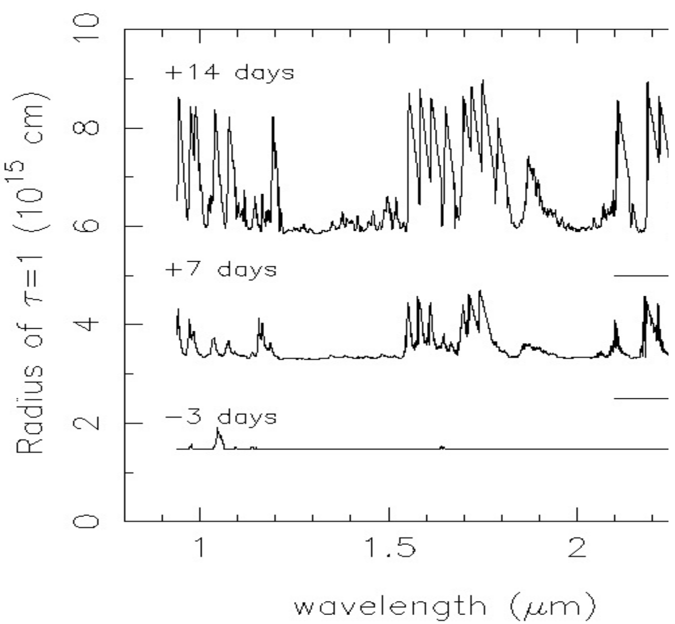
Post-maximum IR-Spectra of DD200 in Comparison with SN86G

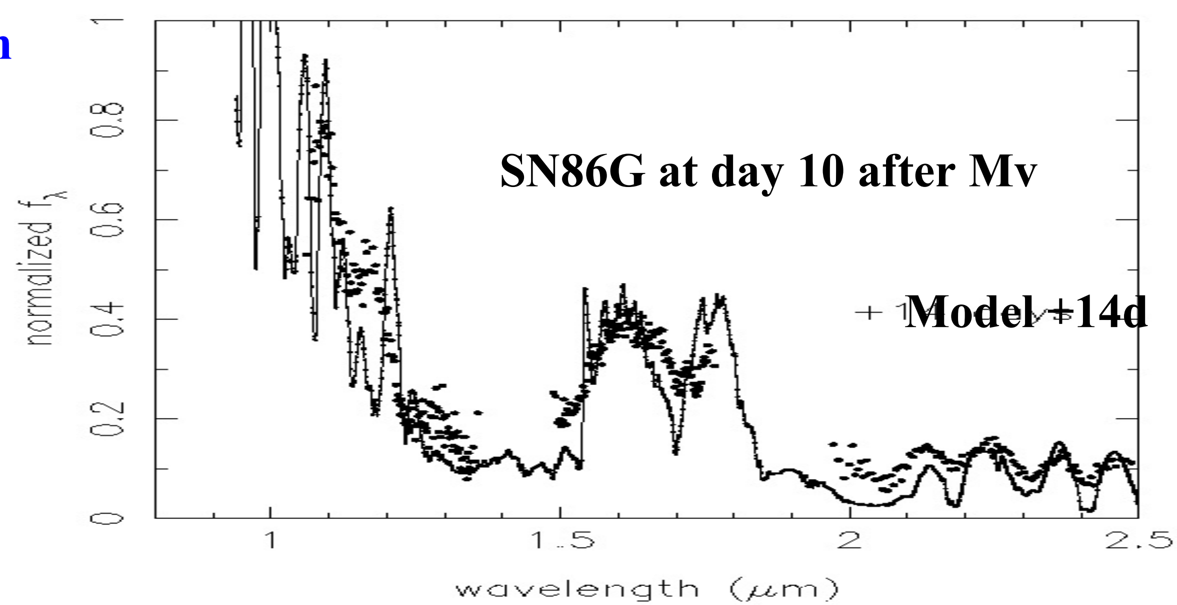
Flux between 1 and 2.5mum





Radius between 1 and 2.5 mum



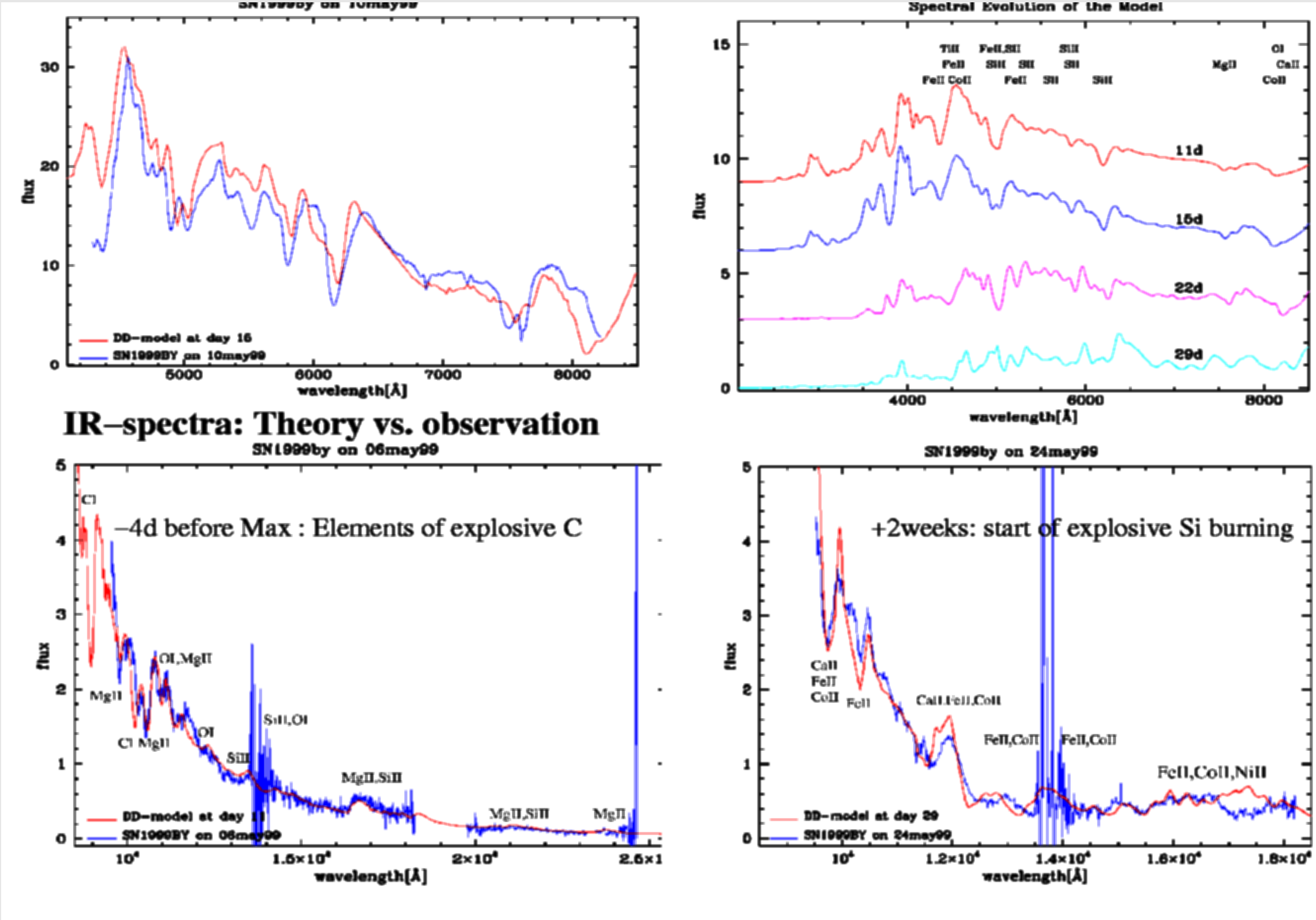


SN86g by P. Meikle et al.

WHHS98

IR-Analysis of SN1999BY (as followed form explosion without tuning)

Optical spectrum at maximum light **Evolution of theoretical spectra**



Ni is located in the center and little or no mixing occured. Is this the reason for the subluminosity?

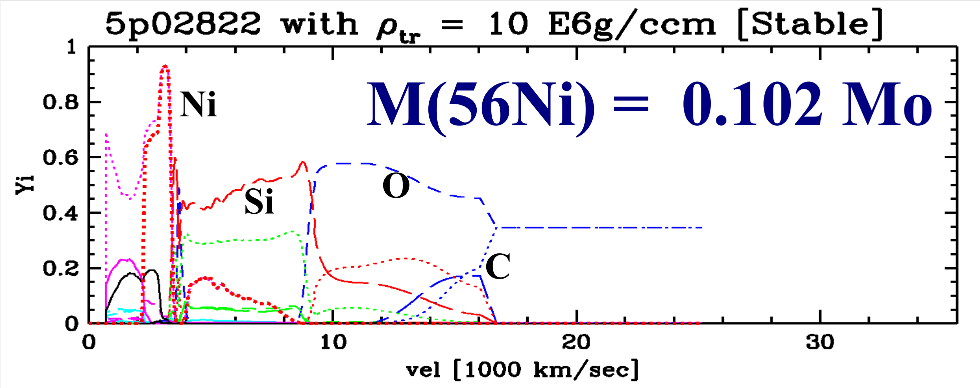
-4d before Max : Elements of explosive C

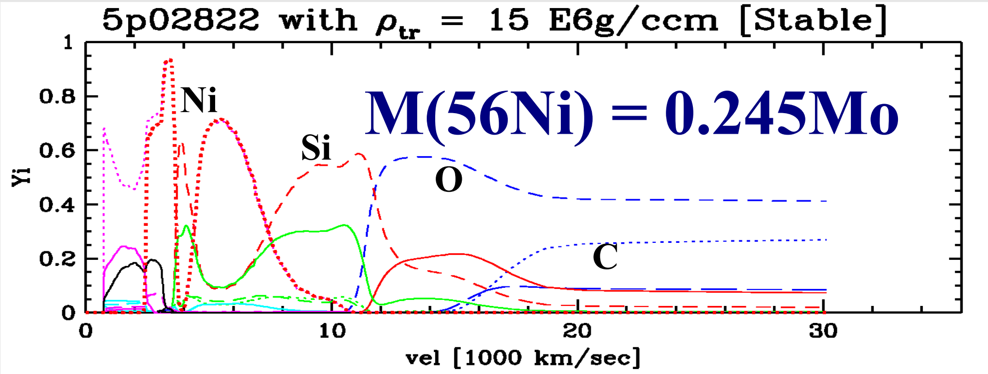
+2weeks: start of explosive Si burning

HGFS02

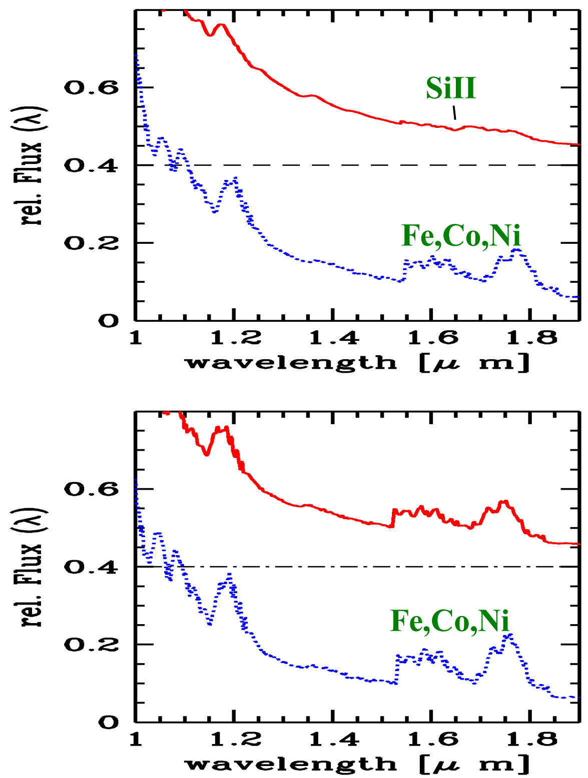
Structures and IR Spectra for Subluminous DD-Models

C/O-WD; rho(c)=2.E9 g/ccm





IR-flux 1 & 2 weeks after M(V)

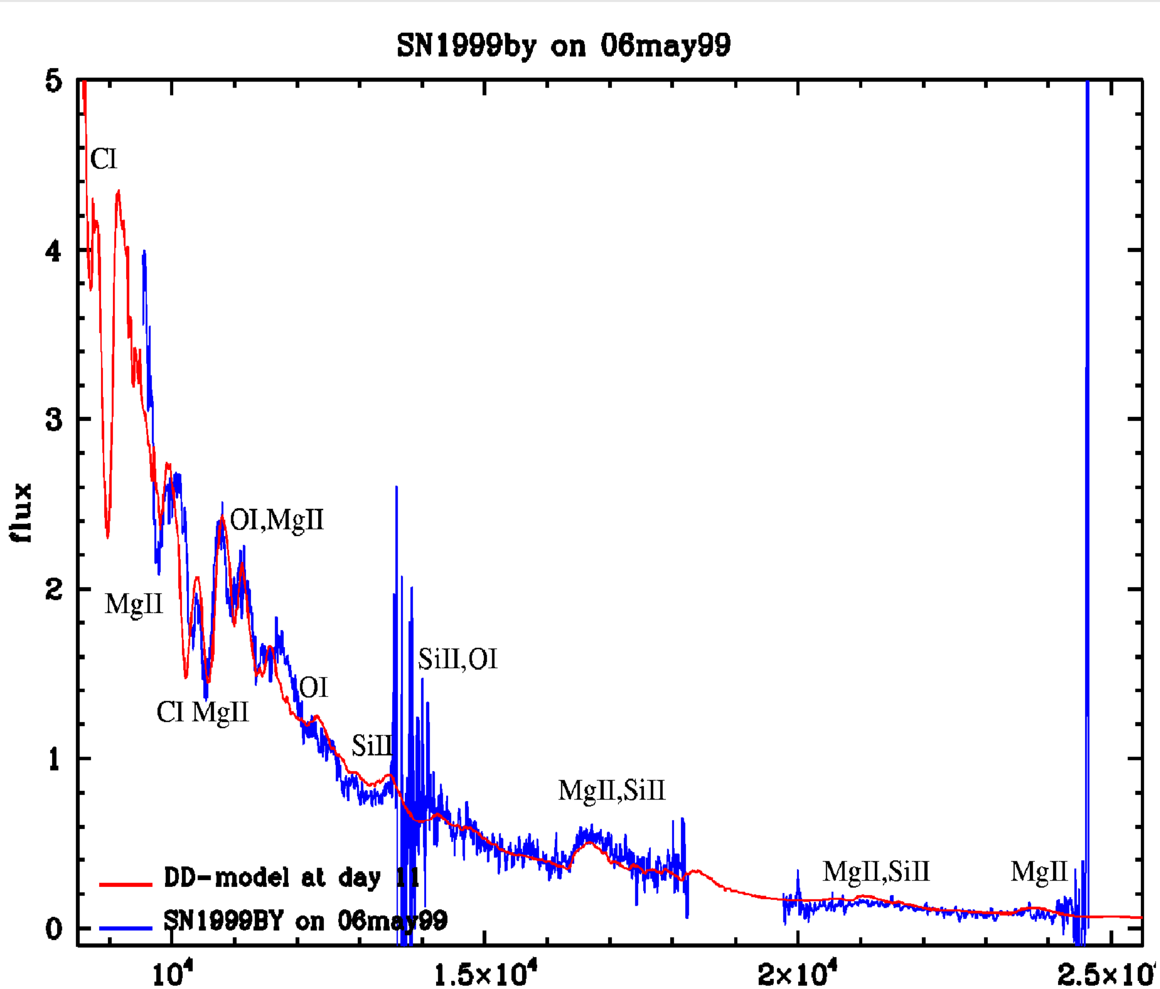


- Only very subluminous models are consistent with SN1998by
- Layers up to 12-15000 km/sec must undergo explosive O-burning
- Strong mixing or extended Ni-tails are not allowed (PDD5 and PDD1c problems)
- Models shall not mix large blobs into the outer layers during deflagration!!!

Is this specific/the reason for subluminous SNeIa ???

HGFS02

The nature of subluminous SNeIa

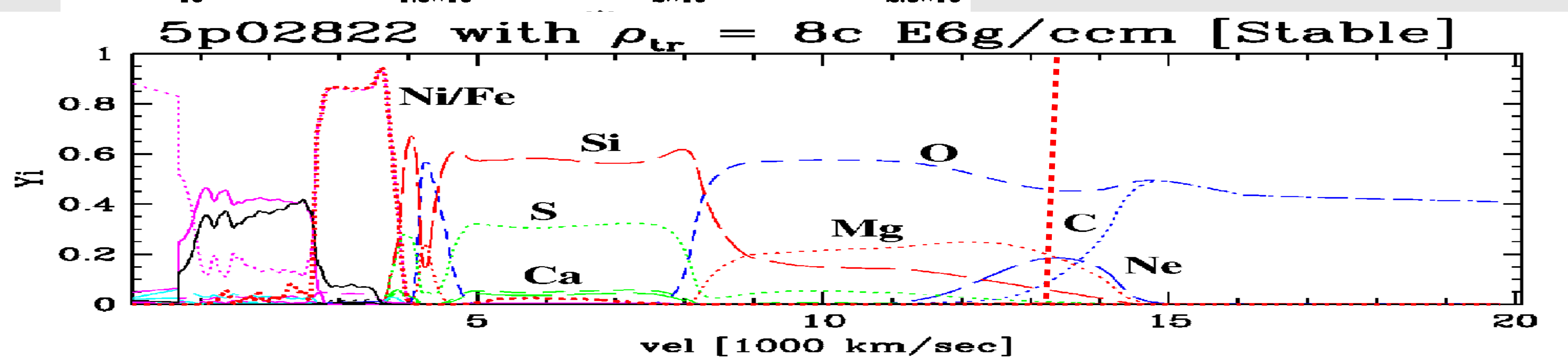


- Spectrum is formed in O-rich layers

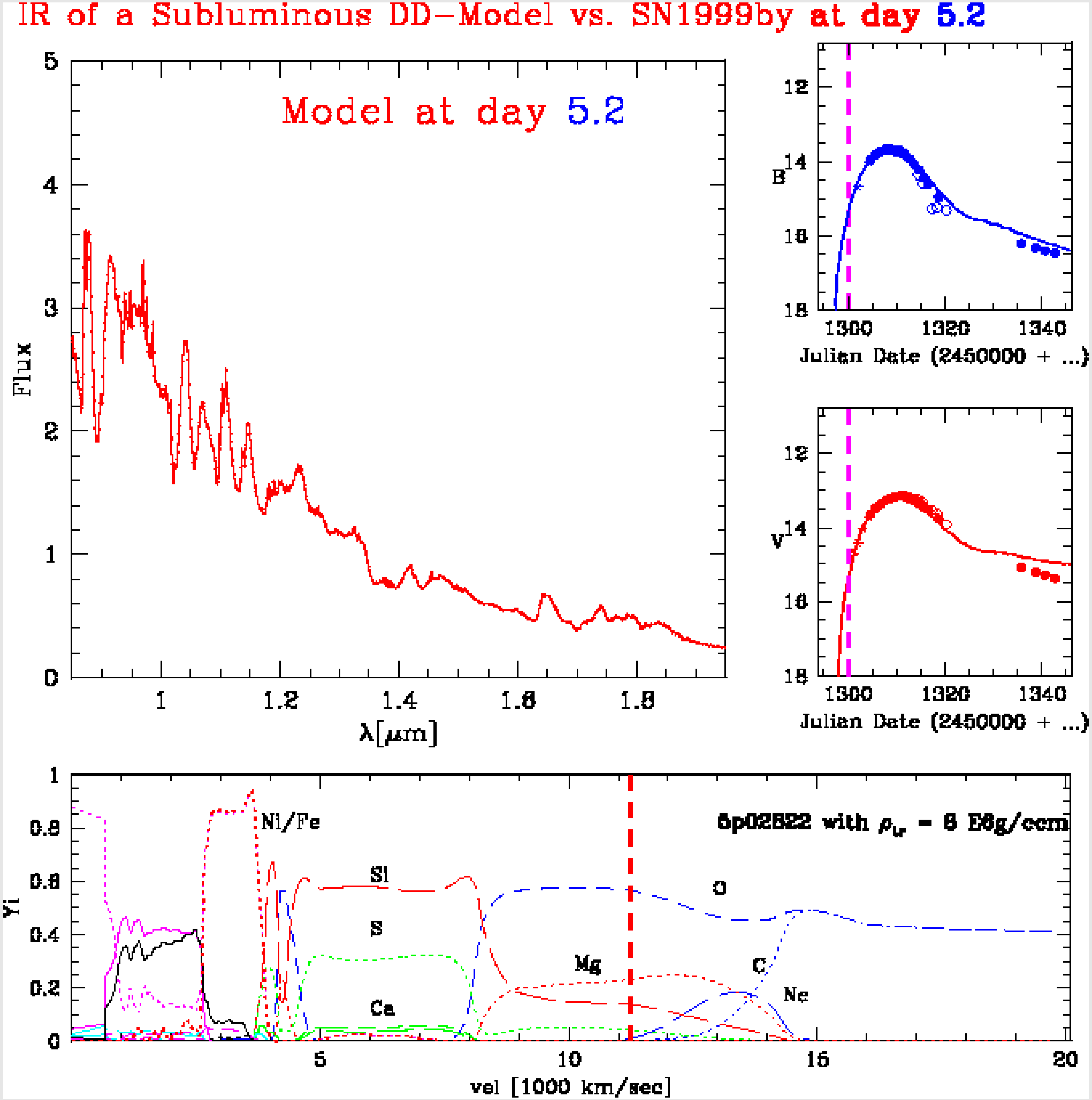
model

observation

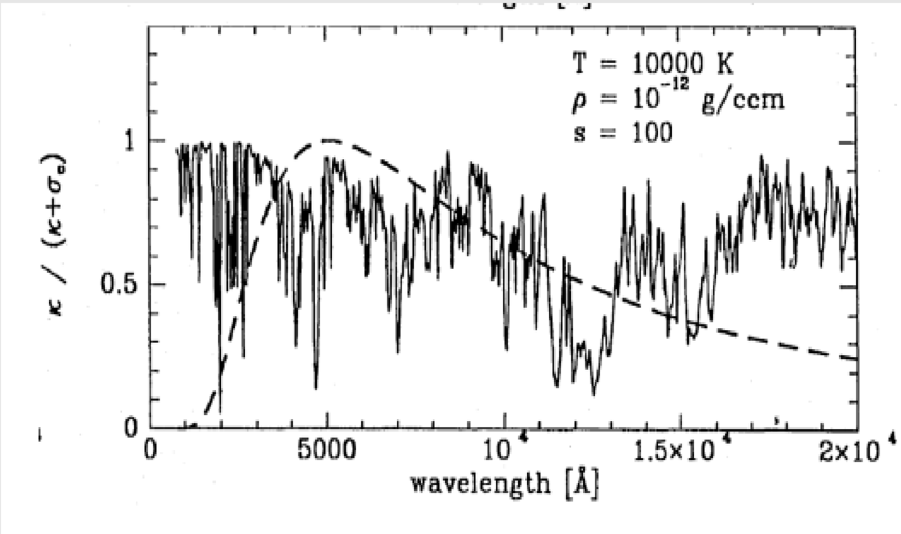
Thompson photosphere

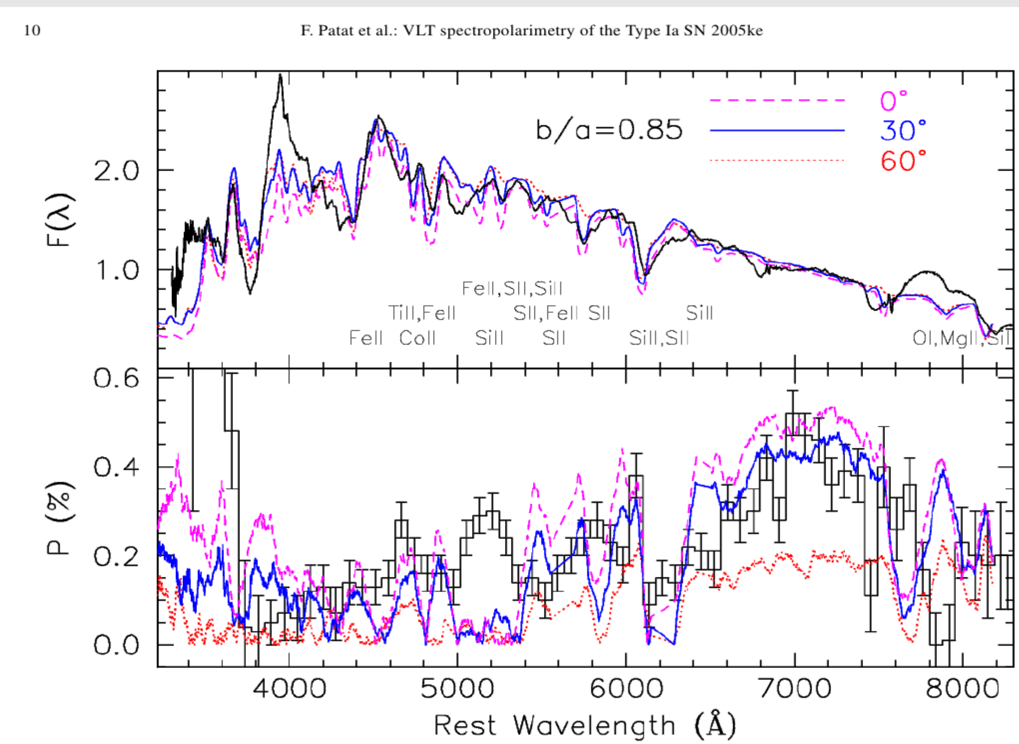


IR-Analysis of SN1999by (as followed from explosion without tuning)



Asymmetry in the Subluminous SN05ke (Patat et al., submitted)



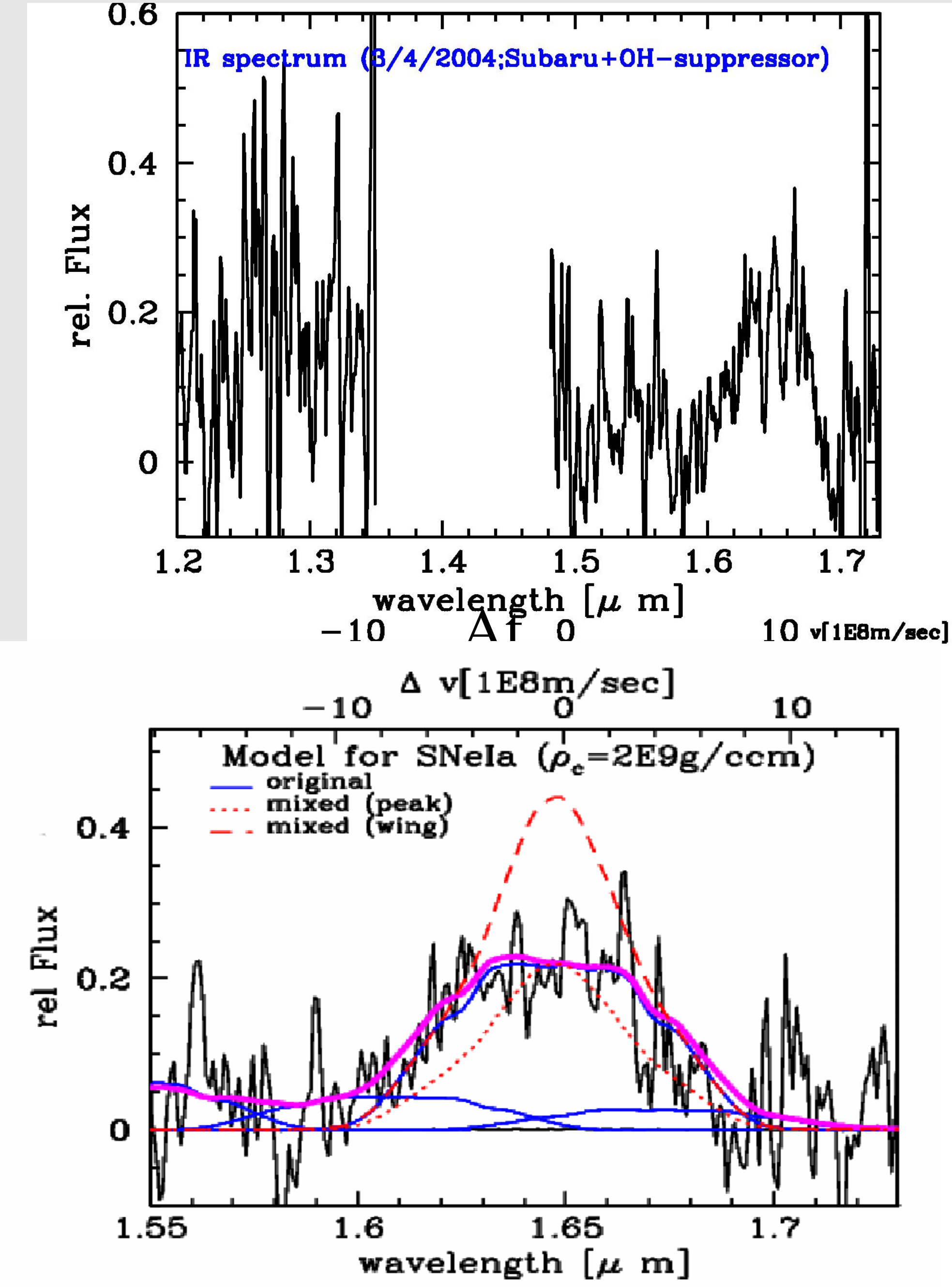


Suggested, inconclusive conclusion

- P is due to opacity vs. Thomson
- Rotational asymmetry of 15 %
- Branch-normal's are more round
- We cannot distingish mergers from rotators because the lack of late time spectra.

See also 99by Howell et al. 2001

II) Search for the Signatures of DDT with Subaru with Motahara
IR at 300 days after maximum



Comparison with DD-model
of rho=2E9g/ccm

- mixing of neutron rich isotopes
  as expected from 3D

- spherical model

Central 56Ni hole = 3000 km/sec
56Ni wind = 9000 km/sec
- pretty symmetric profile
=> not much of rising plumes

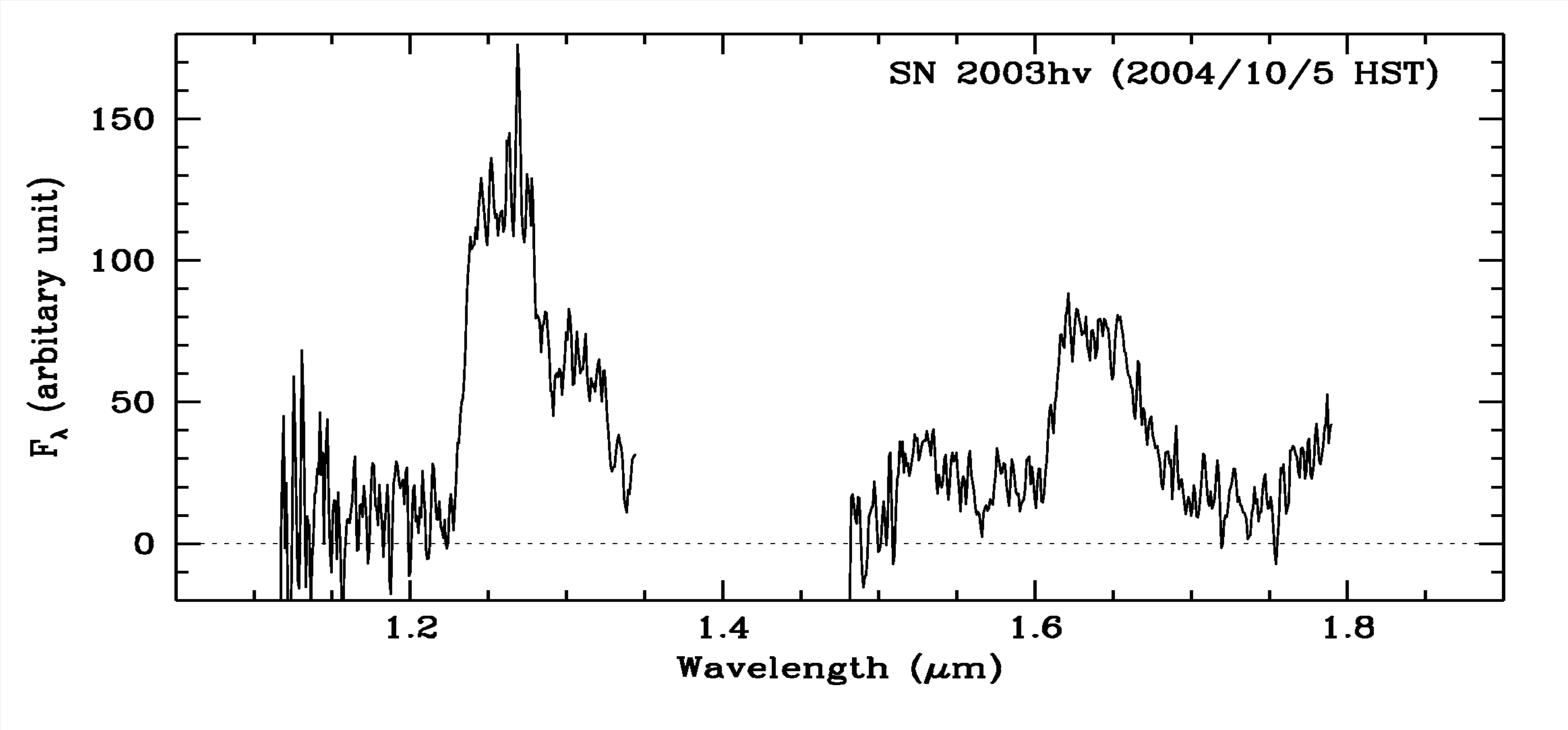
Possible solutions: pre-existing,
small scale velocity fields or
Flash-model/rising plume (Plewa et al. 2004)

Understanding of non-expl. burning

HGMMNW04

Part 2: Search for the Isotopic Composition

SN2003hv at about 390 days after the explosion



Similarities to SN2003du:
 Flat topped profile (v~2500km/sec)-> central hole in 56Ni distribution

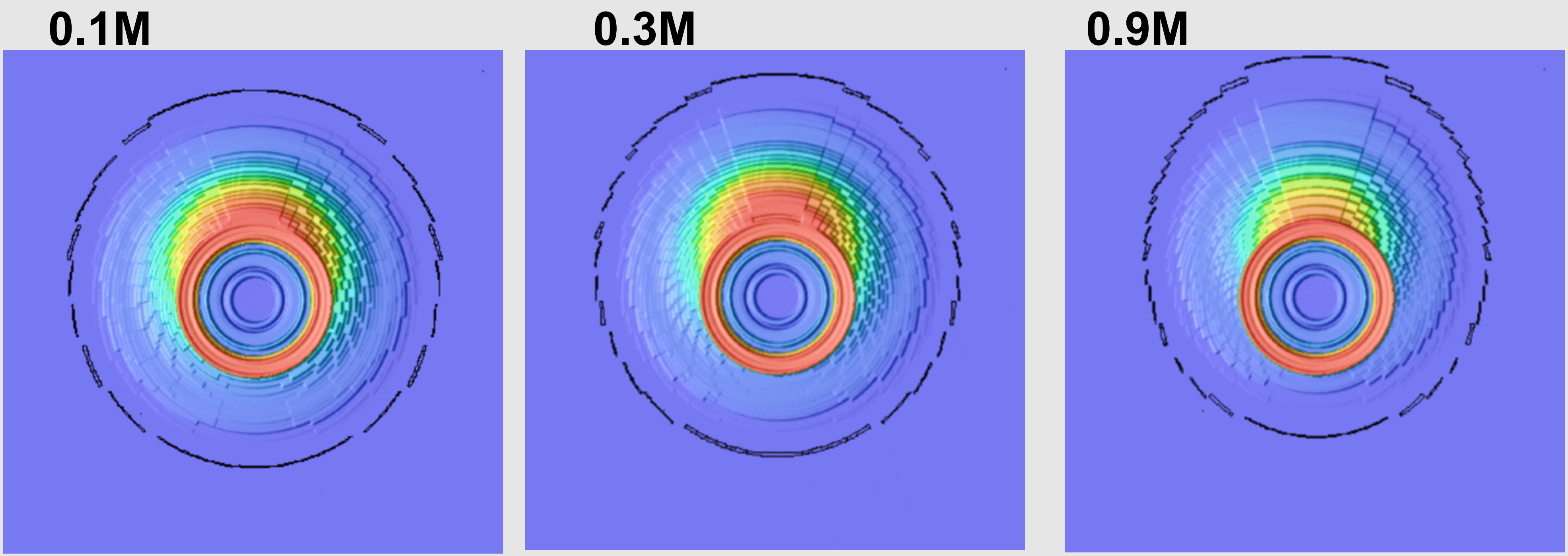
Differences:
- Very asymmetric line wings.
 Blue vs. red edge (v<1000km/sec vs. 3000 km/sec)

Motahara et al. 2006

Forward to the past: Search for the off-center DDT?

Approach: Spherical deflagration to mimic little mixing and DDT at DM

The 56 Ni distribution for various off-center ignitions

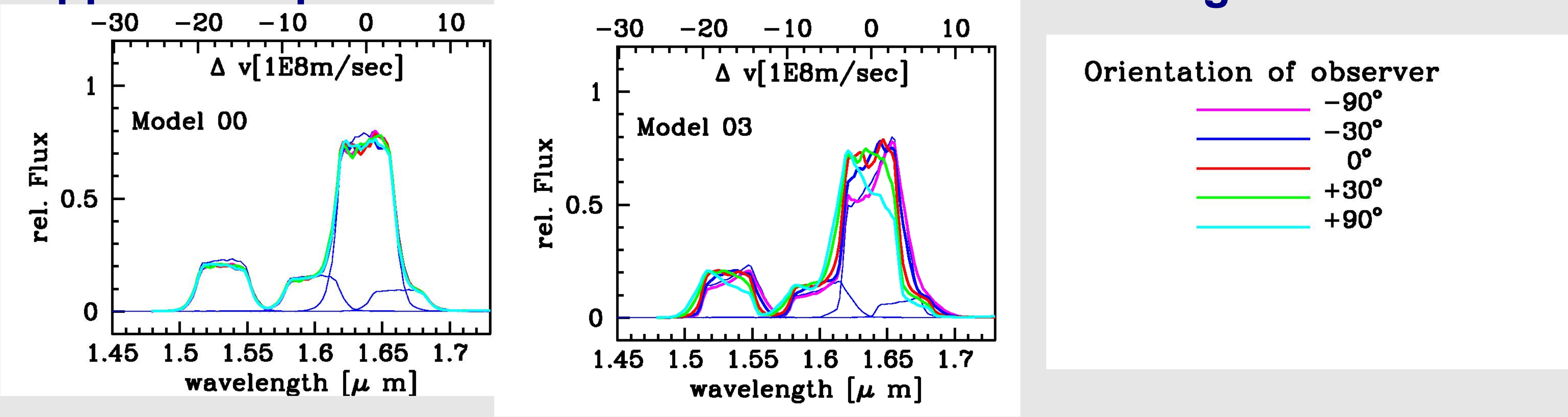


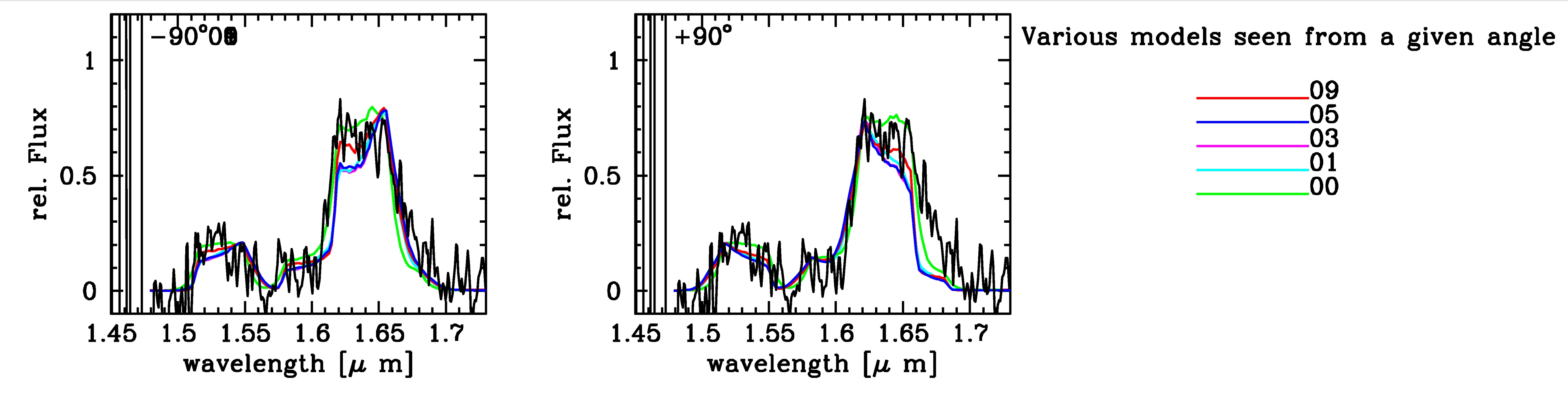
- Ni distribution depends on the ignition point

- Asymmetric distributions are caused by 'runtime' effects

Forward to the past: Search for the off-center DDT?

Approach: spherical deflagration to mimic little mixing and DDT at DM





PROBLEM: non-unique solutions

Asymmetry in profile => seen from -30 to -90 degrees

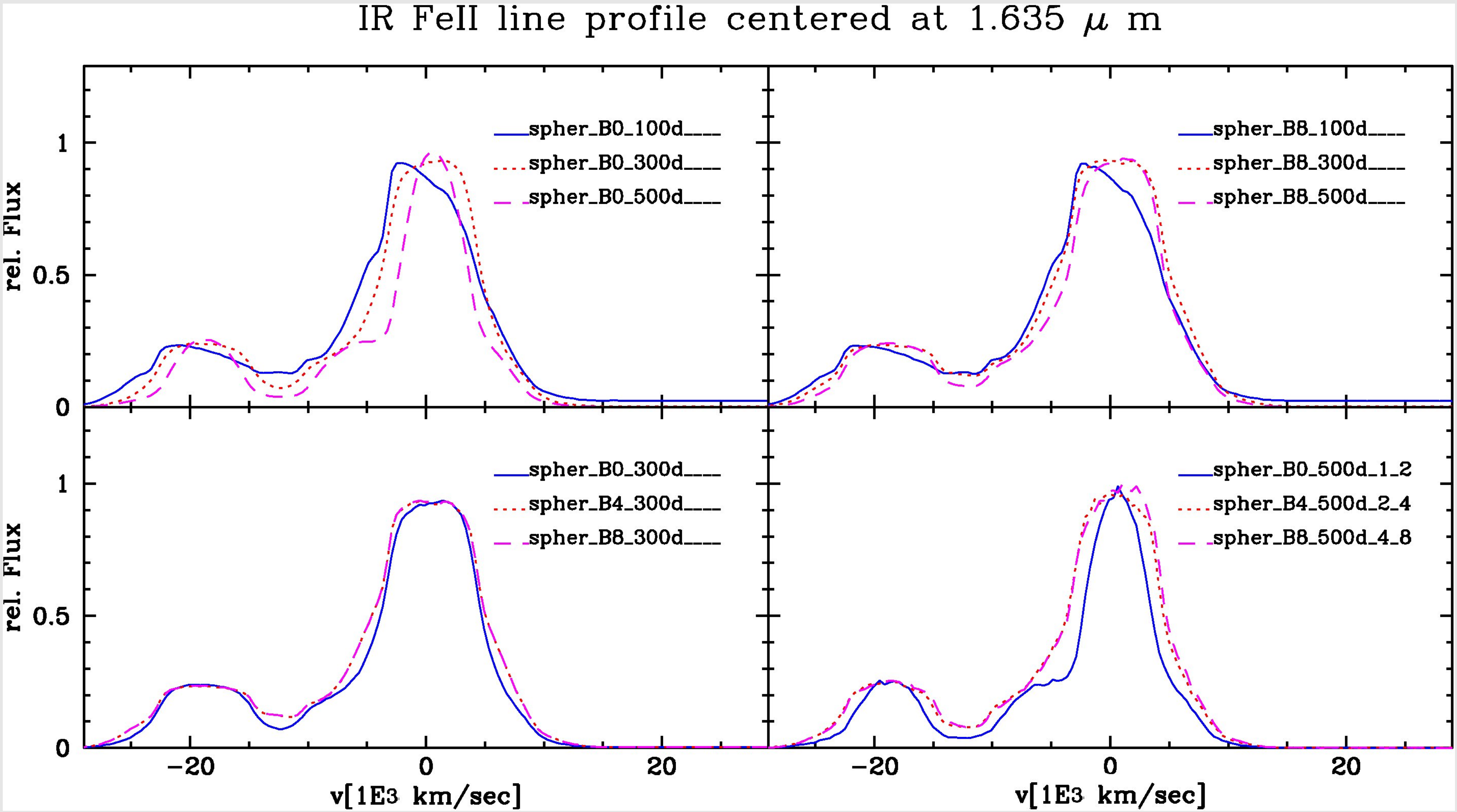
Still flat topped => -30 degrees are favored for 0.3 off-center

or -90 degrees for 0.9 off-center

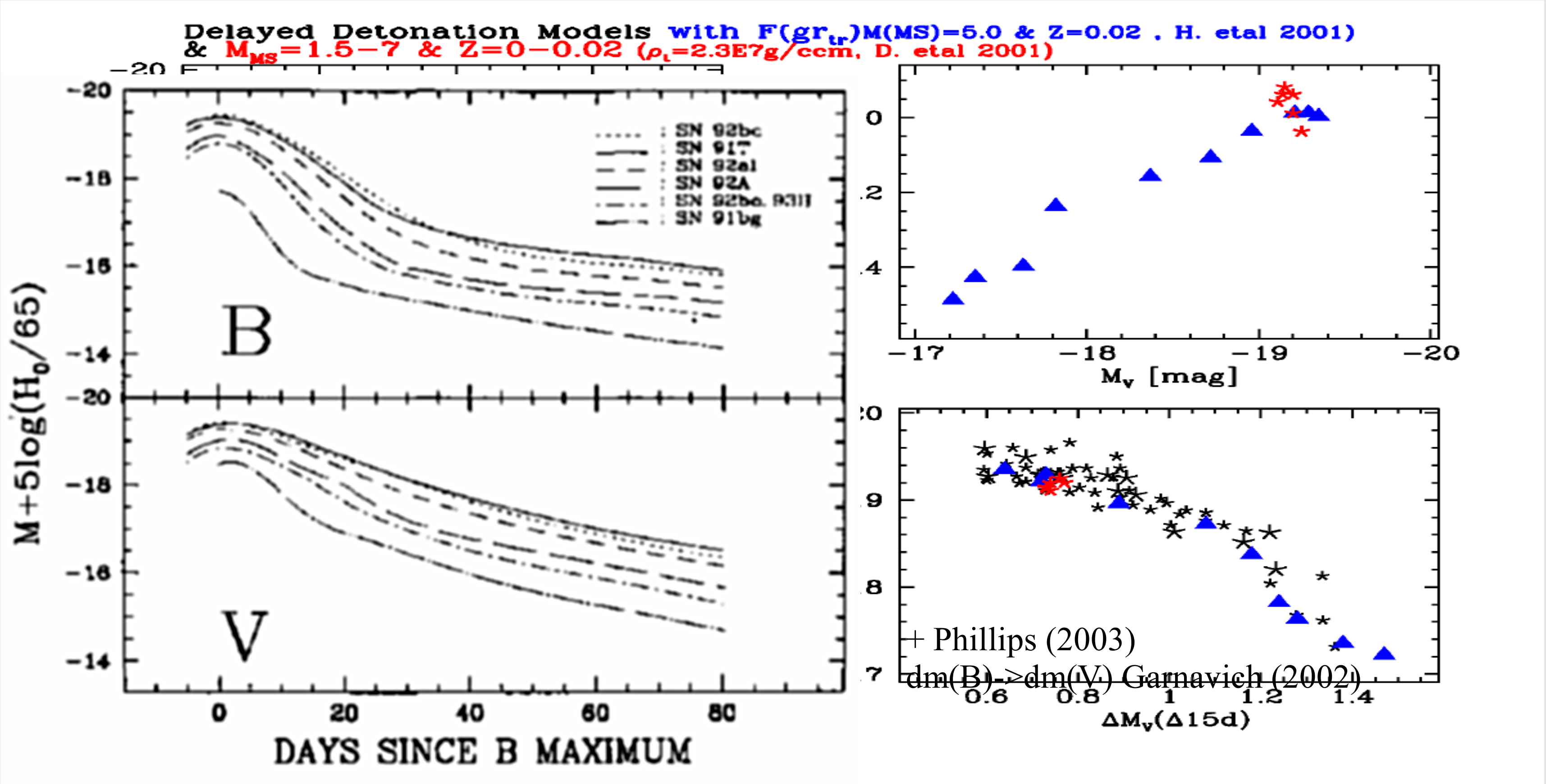
Discrepancies => deflagrations not entirely symmetric

H, Gerardy Quimby 96

Influence of GRT& Positron Transport Effect of Magnetic Fields (Penny PhD 2011, Penny & H, 2012)



Progenitor System of Type Ia Supernovae



ORIGIN of the Brightness Decline Relation:

More 56Ni => brighter and hotter => higher opacity => longer diffusion time scales => slower release of stored energy => slower decline with increasing brightness

(Hoeflich et al 96, Nugent et al. 1997, Mazzali et al. 2001)

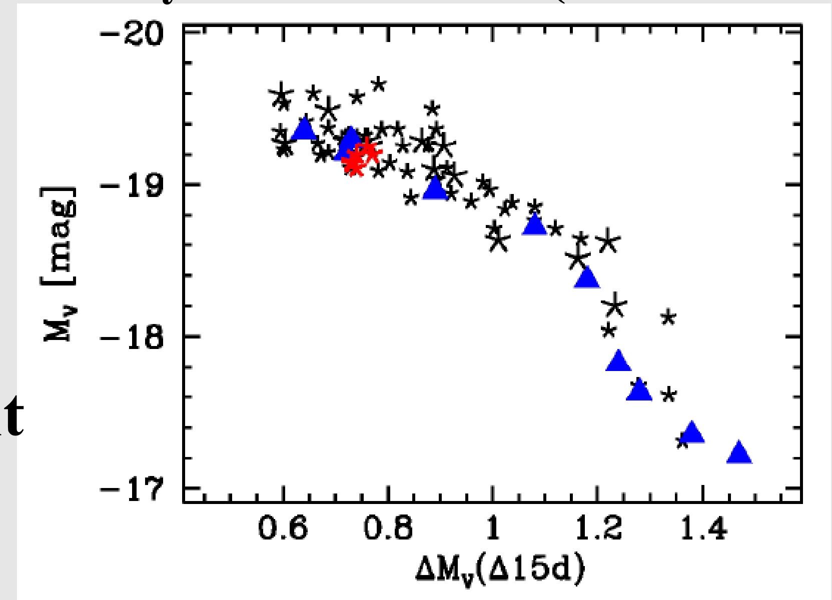
REQUIREMENT:

- **Excess energy at maximum light (L(SN) > L(instant gamma)** (overshoot of L with respect to Arnett's law, 1980)
- Small spread requires similar explosion energies and small directional dependence (H. et al. 91/96)

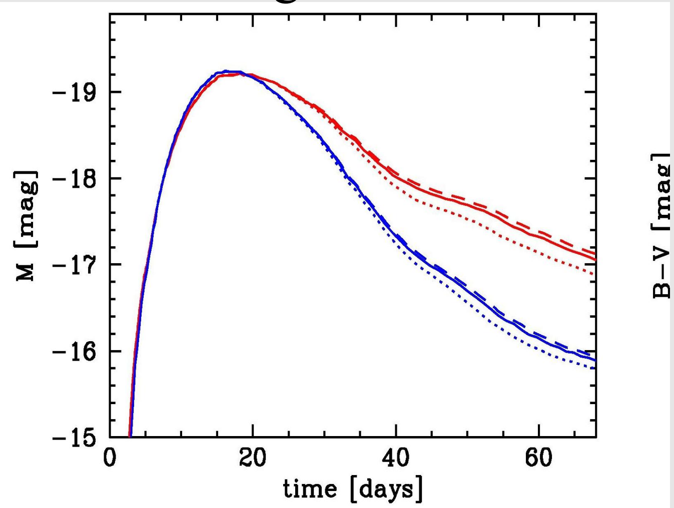
Finding Predicted Signatures of Secondary Effects

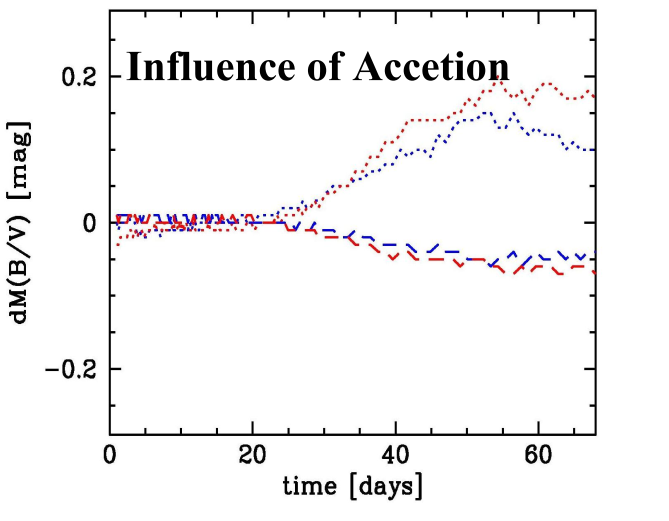
Breakthrough: CSP-Survey with consistent LC (Fogliatelli et al 2010)

Theory vs. Observations (Hoeflich 2006)



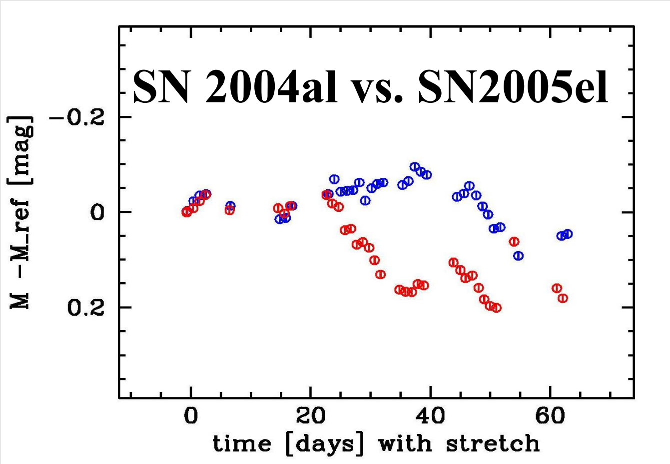
Model Light Curves





Burning Front Physics

Progenitor Physics



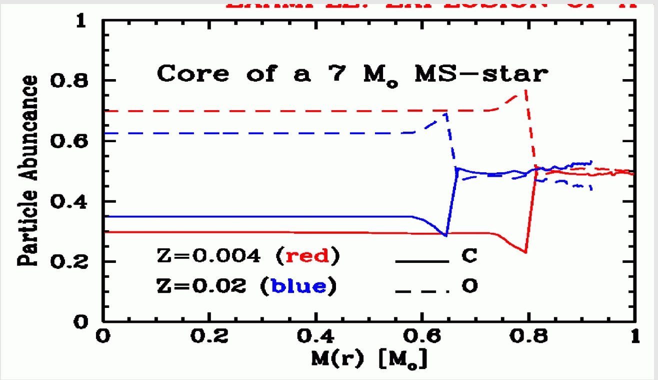
Progenitor Signatures in Differentials of SNIa pairs

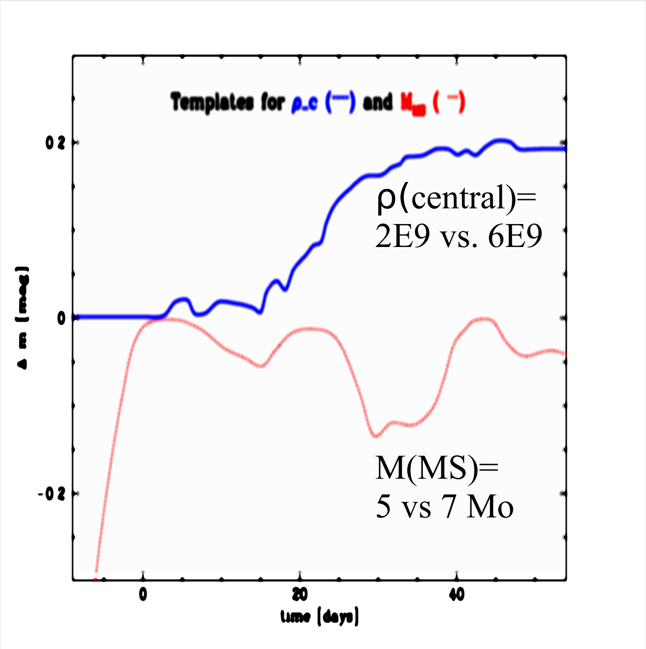
Differential change light-curves after Stretch (Hoeflich et al. 2010)

Observations (Fogliatti et al. 2010)

C/O profile of the WD (explosion energy)
depends on MS mass
and metallicity of progenitor
(from Nomoto, Hetal01)

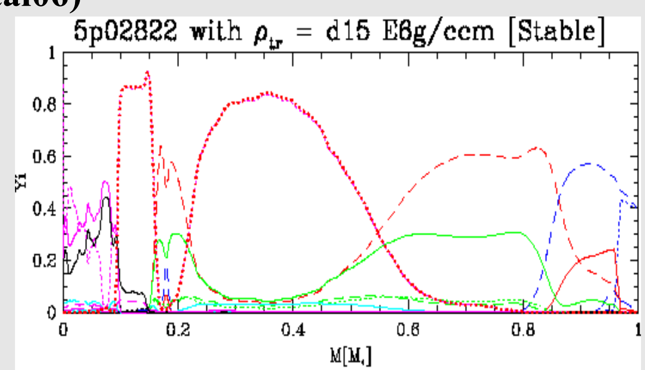
Theory (predicted, H.etal 98)





Accretion Rate =>

Central density at explosion
changes electron capture
(inner 56Ni contribution)
(Htal06)



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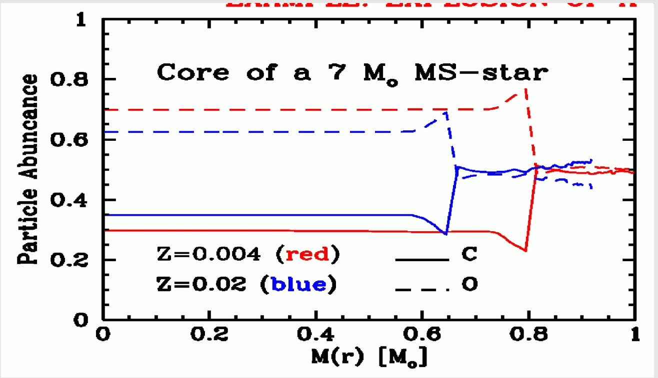

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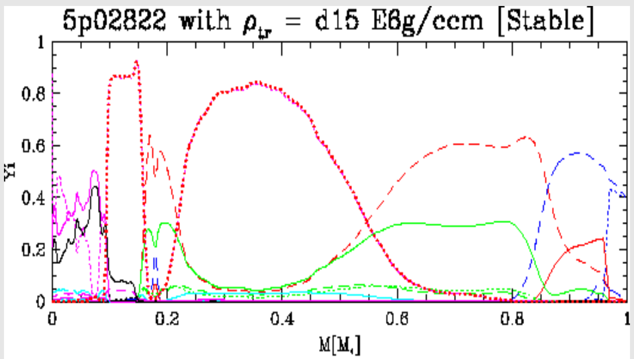

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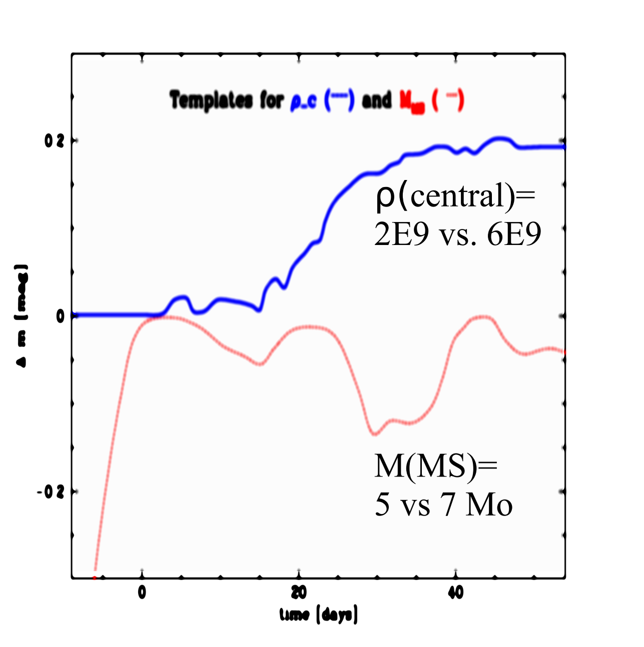

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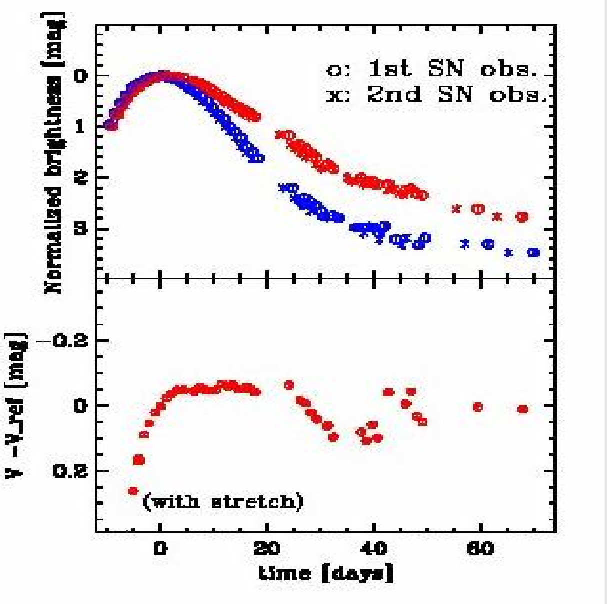
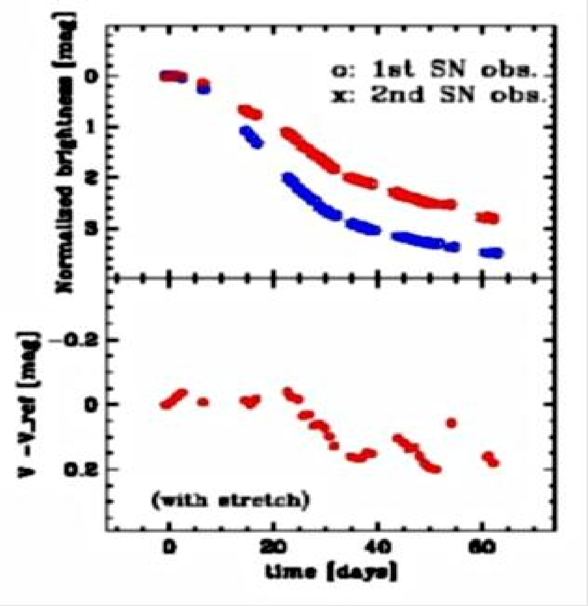


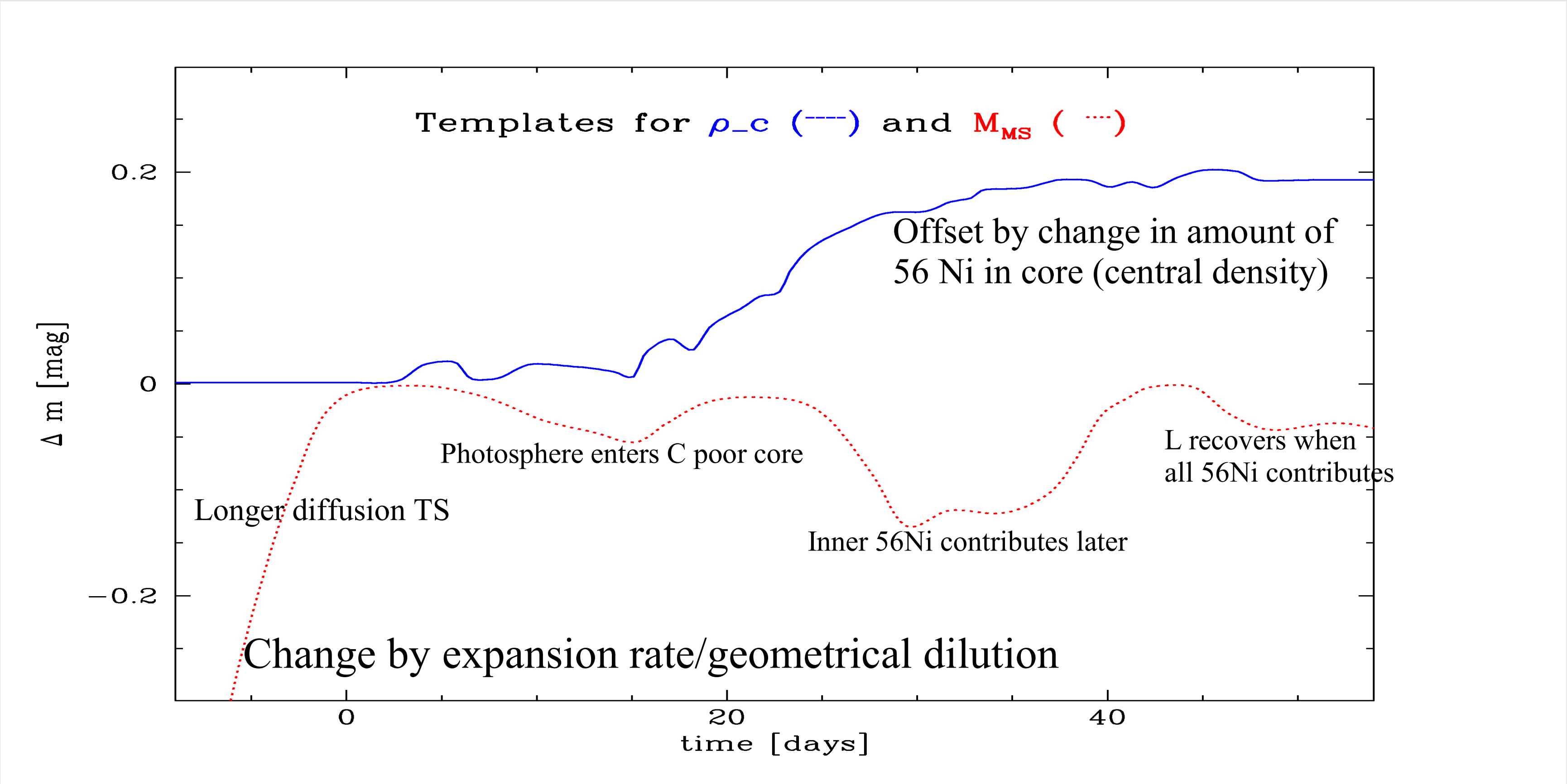


Analyzing the Differences between SN-Pairs

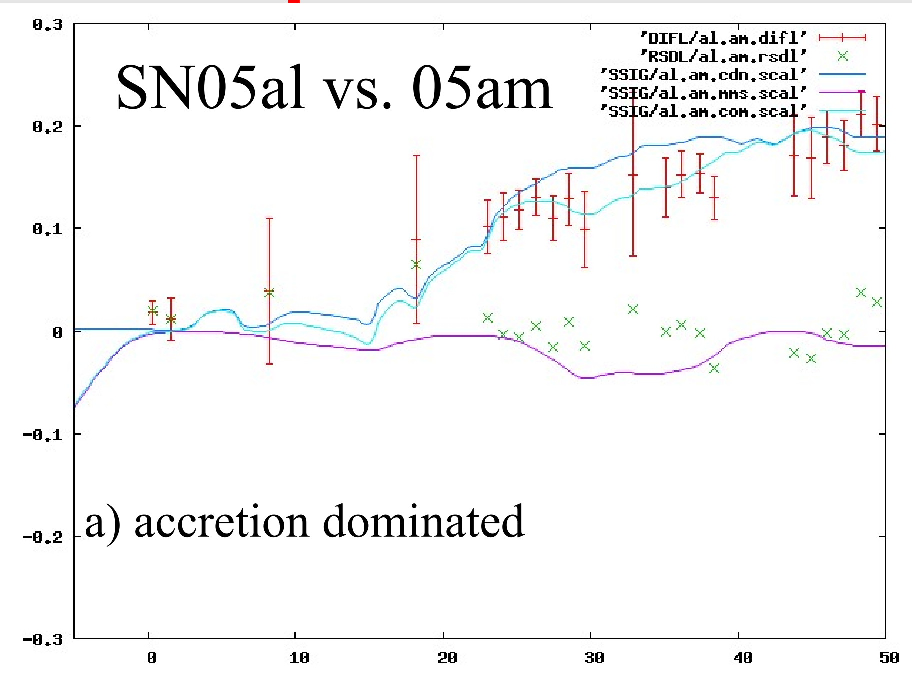
Procedure & Determine the optimal weights (Sadler et al. 2011, 2012)

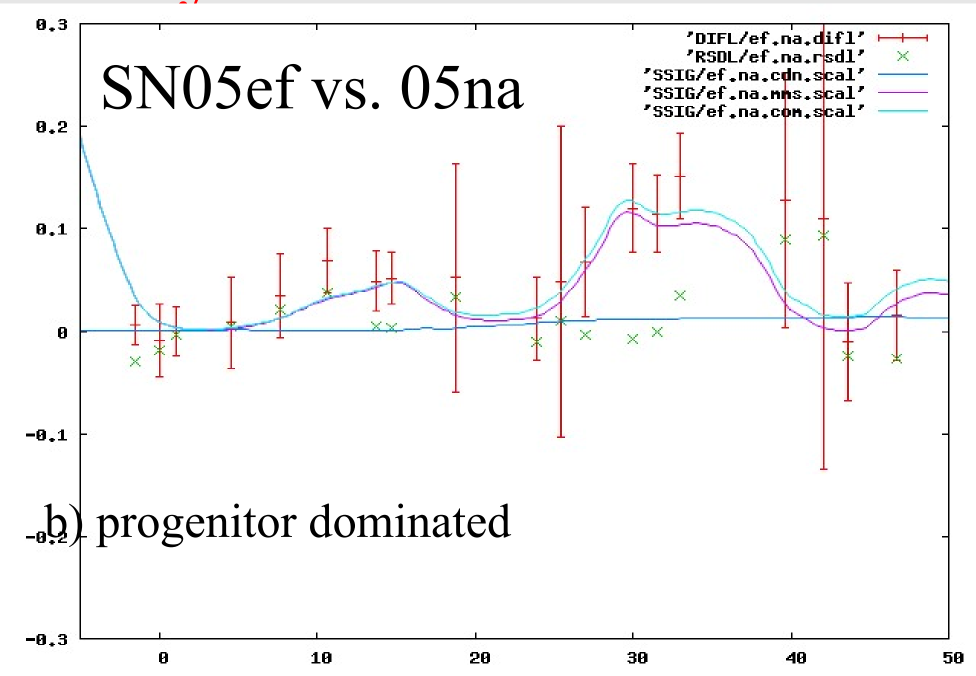
$$F_{obs} = \sum_i g_i f_i(t) + O(t)$$

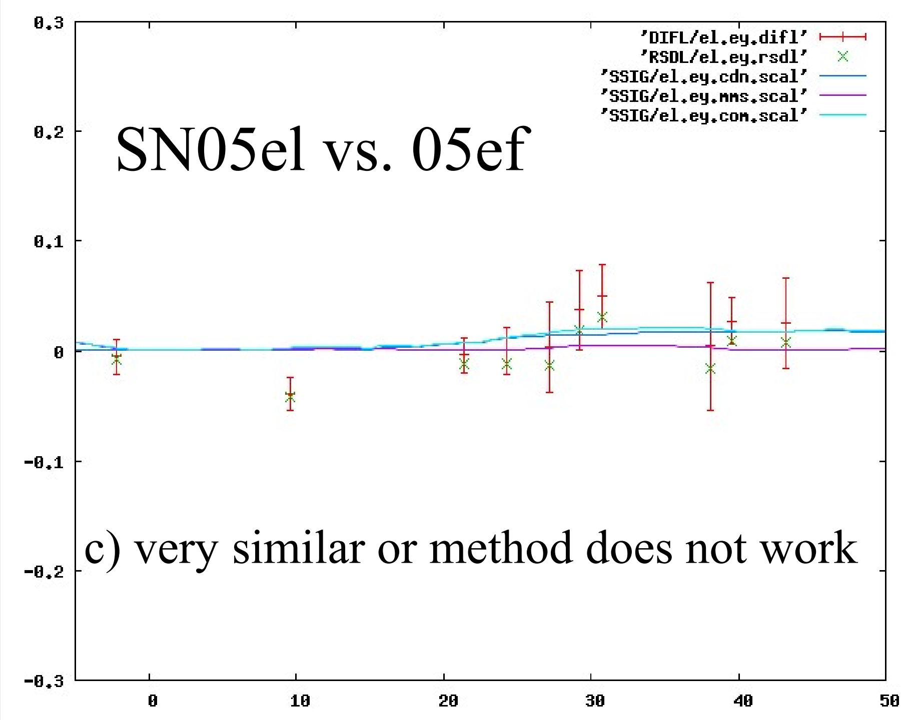
- Use two templates from models
- O(t) minimal (with Gaussian error bars)

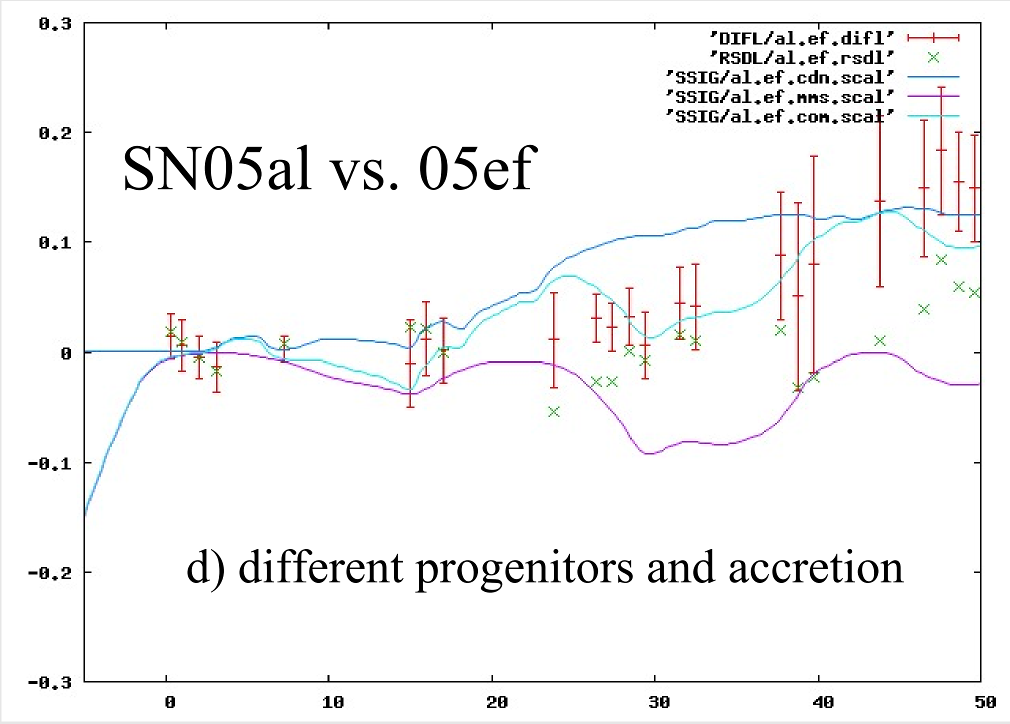


Examples from the CSP survey:





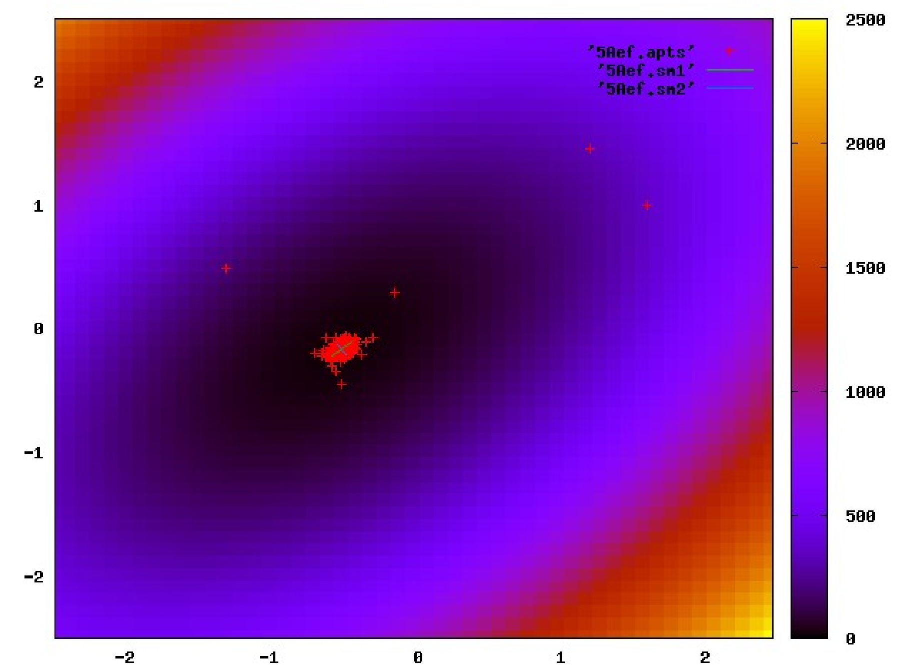


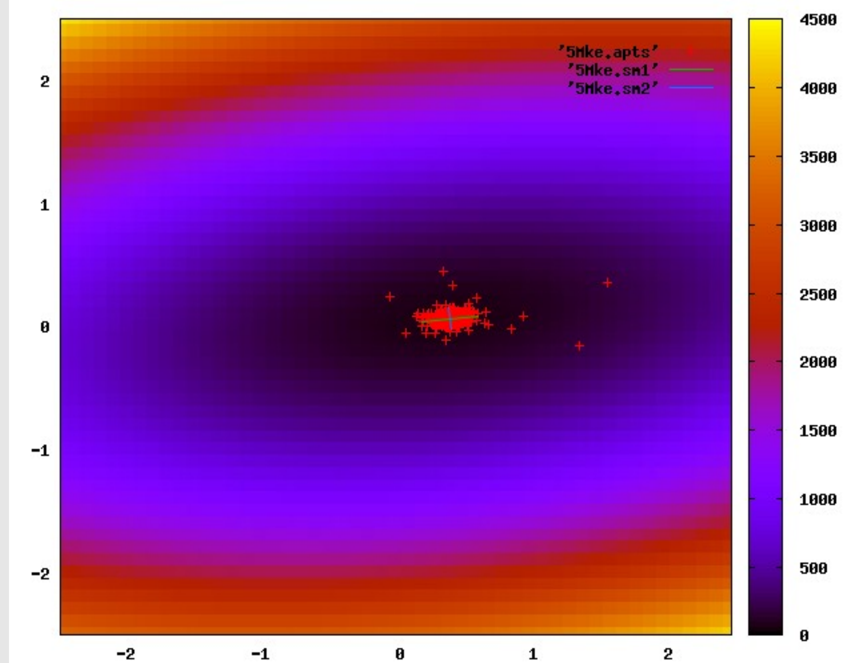


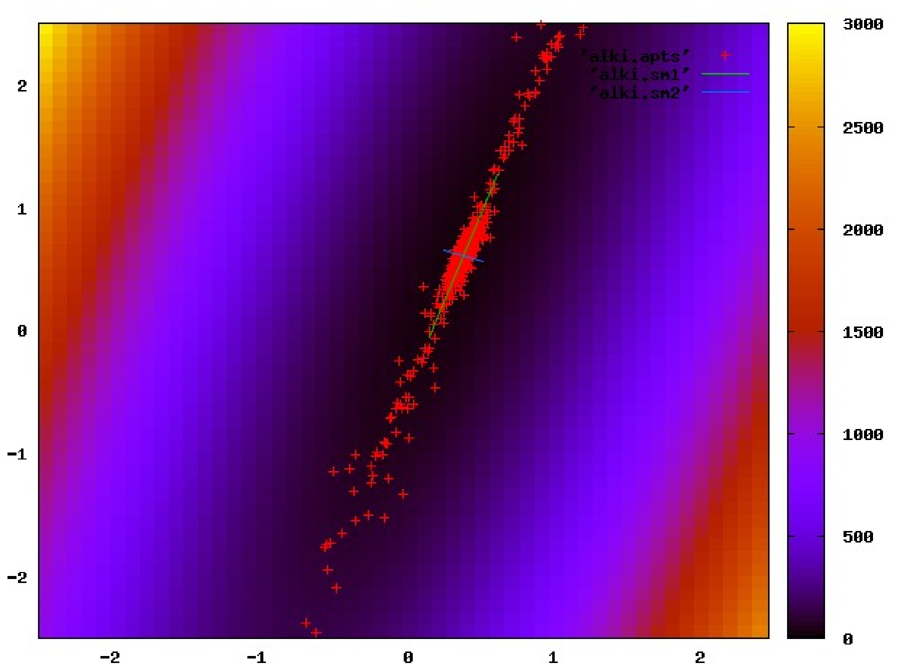
THE UNIQUENESS PROBLEM:

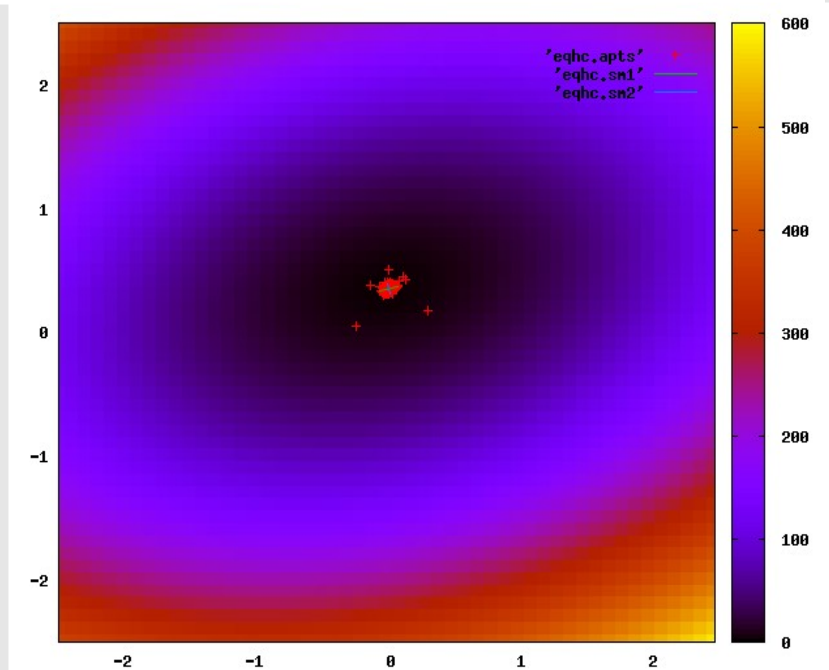
Probability distribution of g1 and g2 by MC starting points

(Nelder & Mead, 1965, CJ 7, 308, A Simplex Method for Function Minimization)









Over-Determination of the System as Test

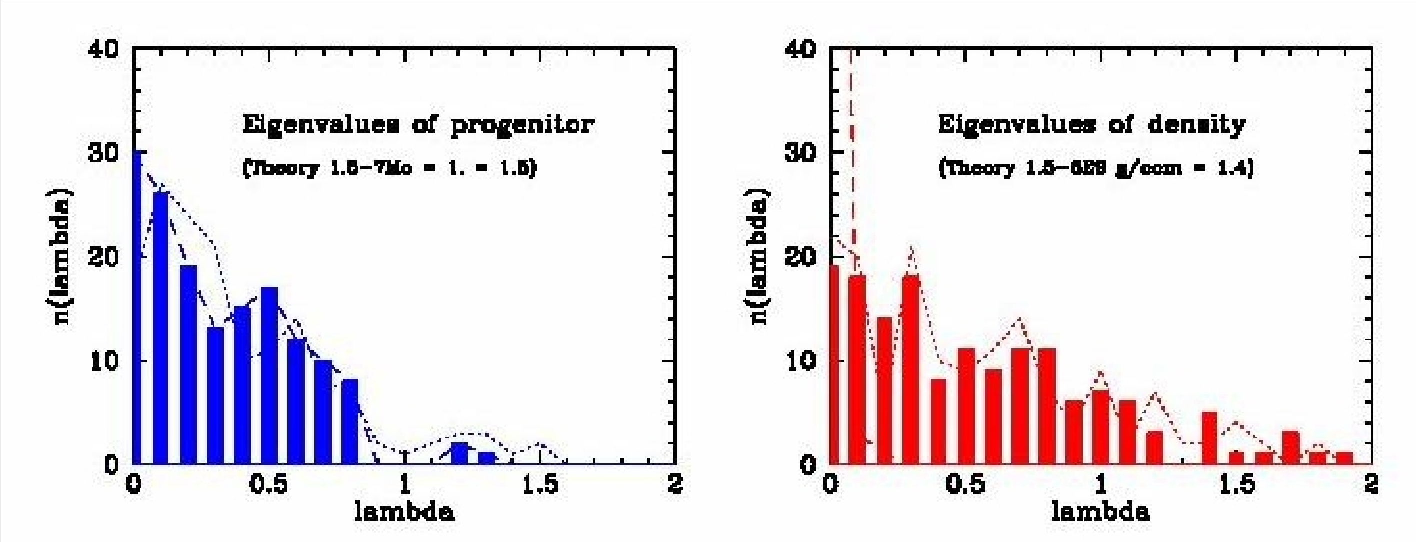
Example: 153 pairs P(i,j) but only 36 free paramters g(i)

Test: Determine best g1(i) and g2(j) including error ellipses
 Assumption: Orthogornal system

- compare (see out)
  a) Individual P(i,j) with the 'fitted' P(g(i),g(j))
  b) Error distribution with error estimates
  c) Test stability of the results by using sub-sets

a) looks ok. Maximum lambda in Rho and M 1.80 and 1.02
b) 37.2 % > sigma errors; 5.2 % > 2 sigma errors

Distribution of Weight Factors/Parameters



Trends in the Distribution of Progenitors and Accretion Rates

- Progenitors come form the higher end of MSM (3+ Mo)
=> SNe Ia should occur during the dark ages

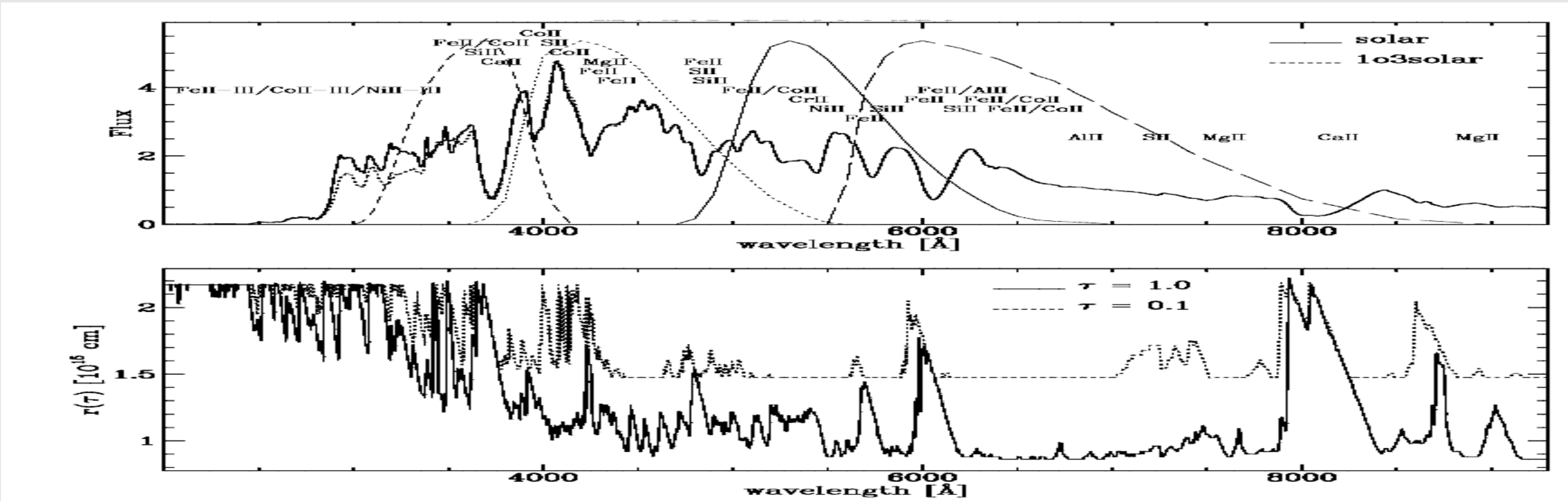
- Accretion rates are in a wide range (Influence on Nucleosynthesis?)
=> AIC should be common

- Subluminous SNe~Ia originate from the low end of the mass spectrum
=> Consistent that we see no subluminous SNe Ia in the high redshift samples, i.e. 4-5 Gyrs after the Big Bang

- **Does not work for SN1991t like objects (Mergers, PDDs ???)**

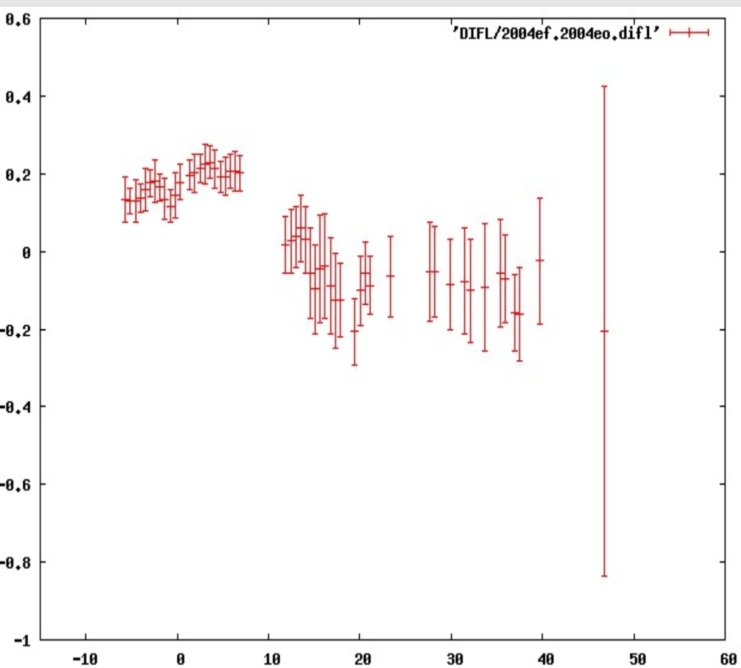
Probing the Metallicty by U (HWT98 & Sadler et al. 2012)

Expectation: Off-set around maximum light in differentials up to 0.8mag

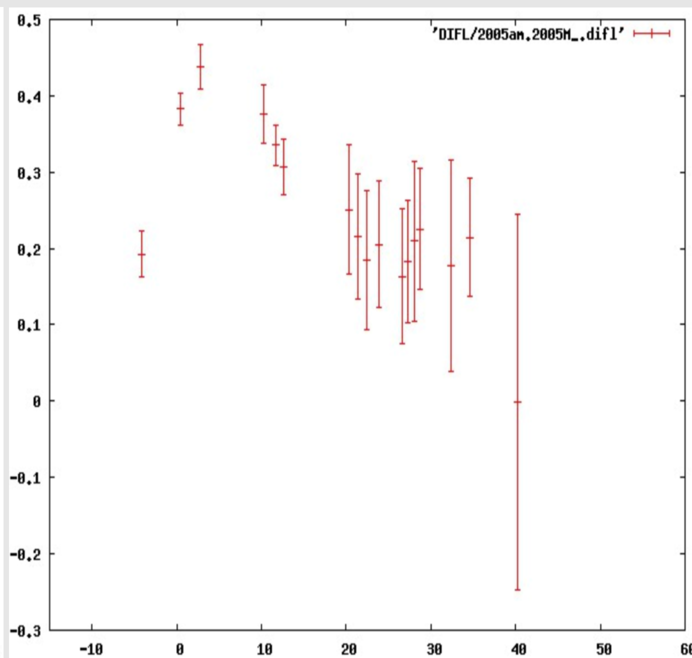


Examples dU(t) : Works often but not always

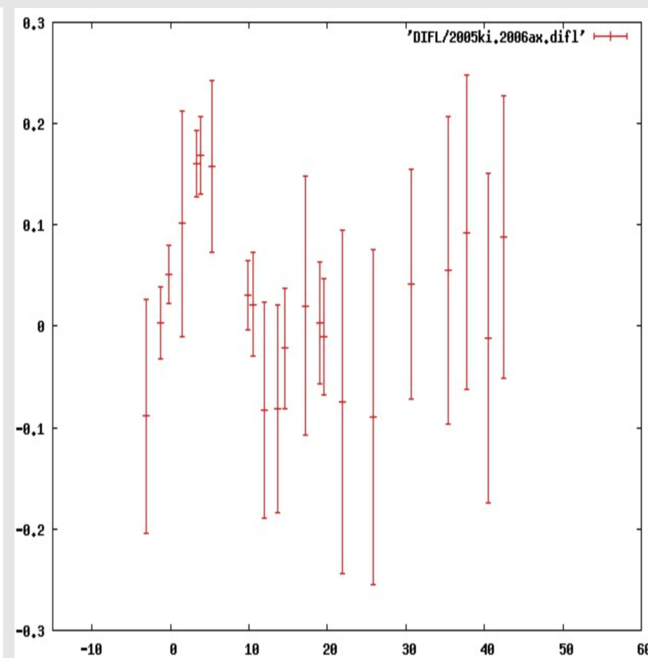
SN05ef vs. 04eo



SN05am vs. 05M



05ki vs 06ax



Non-Final Summary

- Double-degenerate progenitor evolution does not (!) imply M(Ch) vs. dynamical mergers !!!

- IR LC can be understood within DD,PDD (and dynamical Mergers

- Smaller dm15 does not (!) imply no dispersion K-correction in IR depend on dm15

- NIR LC s & Lyra-relation allows to probe diversity [Mergers/PDD vs. MCh]

- Secondary parameters (MS,rhoc) reduce residuals to 0.02 mag.
- SN91bg-likes seem to come from low main sequence masses

- 1991t are alike, and we see no signatures of MS and rho(c)
- WHATEVER IS POSSIBLE, NATURE REALISES