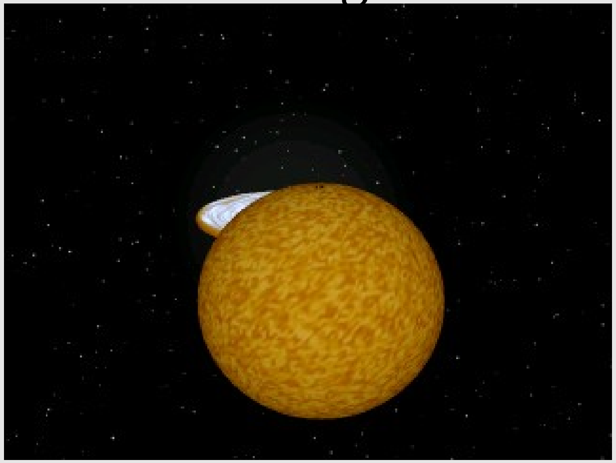
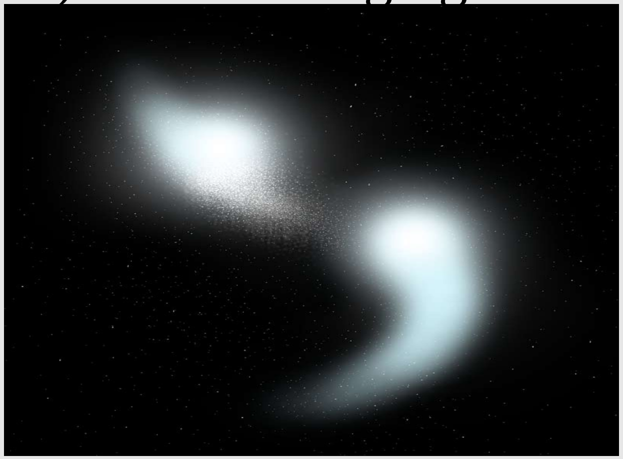
Thermonuclear Explosions & Cosmology

(What, why and how? Problems, fixes and limitations)

1) Thermonuclear Supernovae in a 'Nutshell'
2) Concepts (and Misconcepts)
3) M(Ch) vs. Sub-M(Ch) models
4) Problems with deflagration fronts,
   and why we don't its properties
5) Do we see signs of a deflagration front
6) Secondary Parameters of SNeIa

Subjects: Accreting White Dwarf (WD) Merging WD



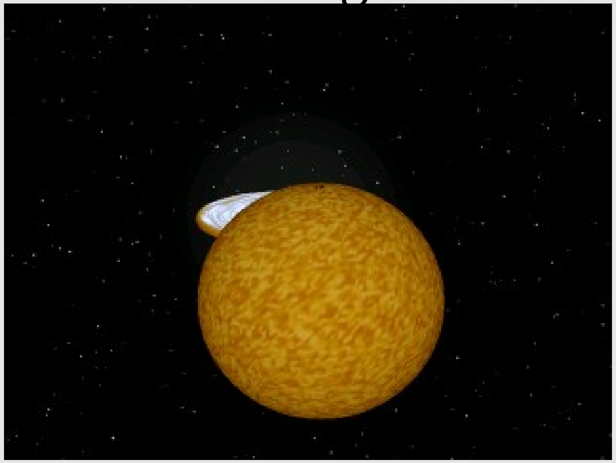


Thermonuclear Explosions & Cosmology

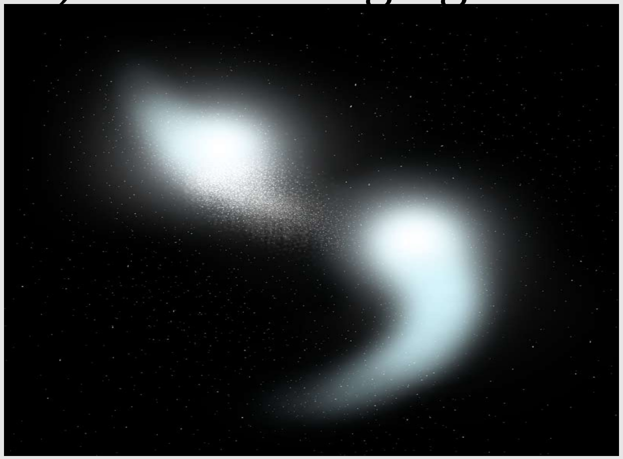
(What, why and how? Problems, fixes and limitations)

1) Thermonuclear Supernovae in a 'Nutshell'
2) Concepts (and Misconcepts)
3) M(Ch) vs. Sub-M(Ch) models
4) Problems with deflagration fronts,
   and why we don't its properties
5) Do we see signs of a deflagration front
6) Secondary Parameters of SNeIa

Subjects: Accreting White Dwarf (WD)



Merging WD



Thumbnail Sketch of Thermonuclear Supernovae

.

- SNe Ia are **thermonuclear** explosions of White Dwarfs (C/O core of a star with less than 8Mo)
-
- SNe Ia are homogeneous because **nuclear physics** determines the W D 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**
-

Classes of Progenitor Systems:)

- Two merging WDs (DD-systems)
- Accreting WD (MS, RG, He-star, C-star) (SD-systems)

•Classes for Explosions

- M(Ch) mass WDs: Ignition by compressional heat

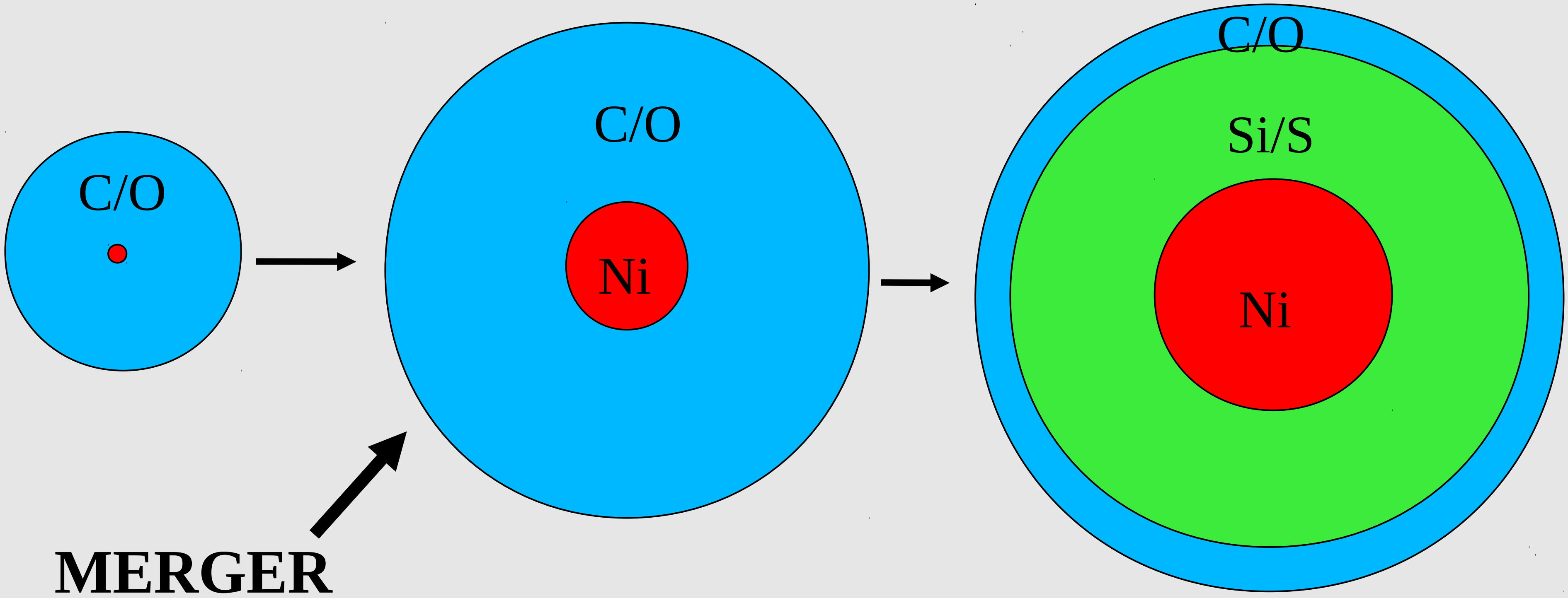
•Hear release during dynamic process (mergers, violent mergers, He-deton).

Explosion Scenarios for Type Ia Supernovae

Initial WD

Deflagration phase(2...3sec)
preexpansion of the WD

Detonation phase (0.2.
hardly any time for further expa

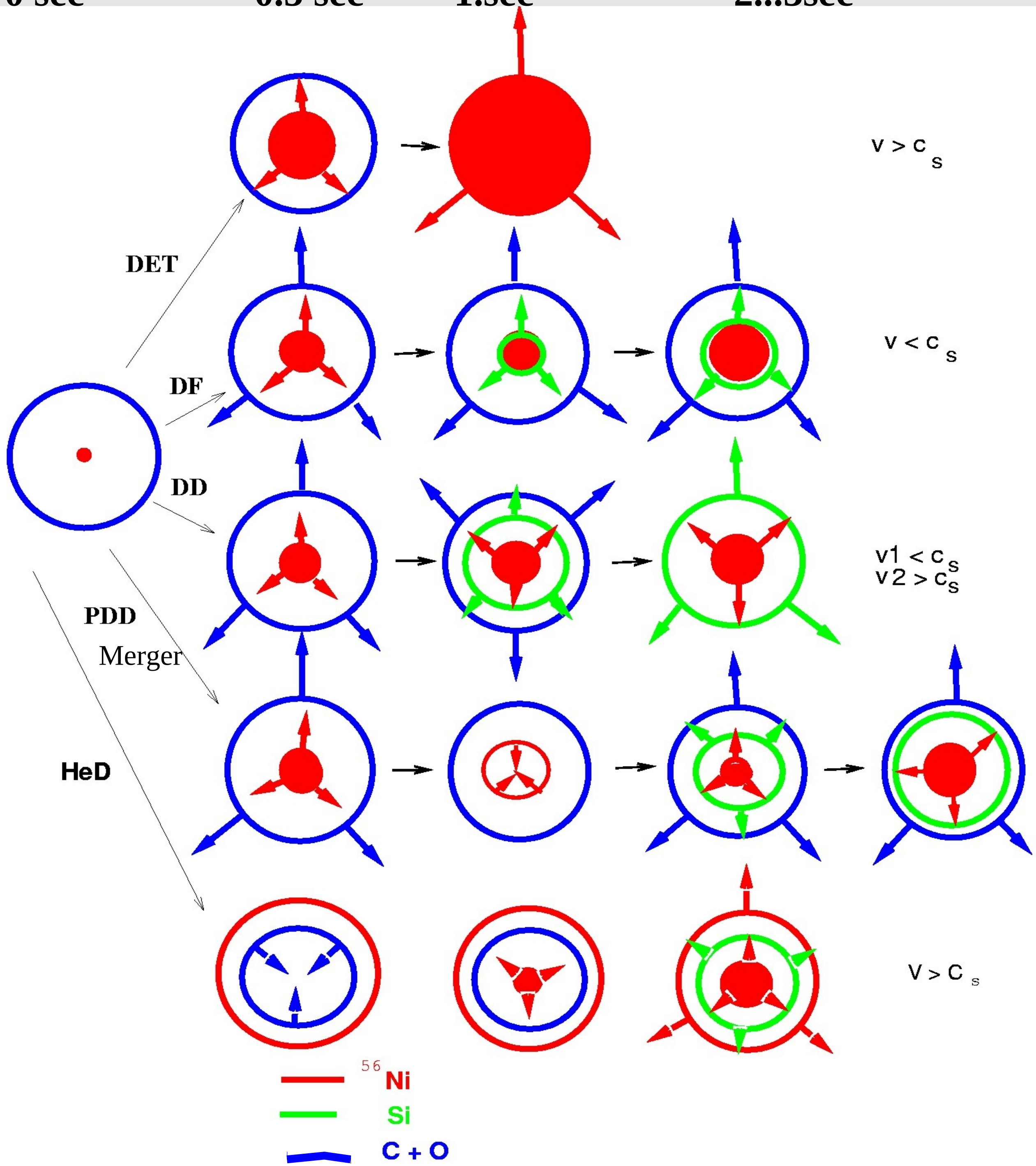


Deflagration: Energy transport by heat conduction over the front, v <<v(sound)
=> ignition of unburned fuel (C/O)

Detonation: ignition of unburned fuel by compression, v = v(sound)

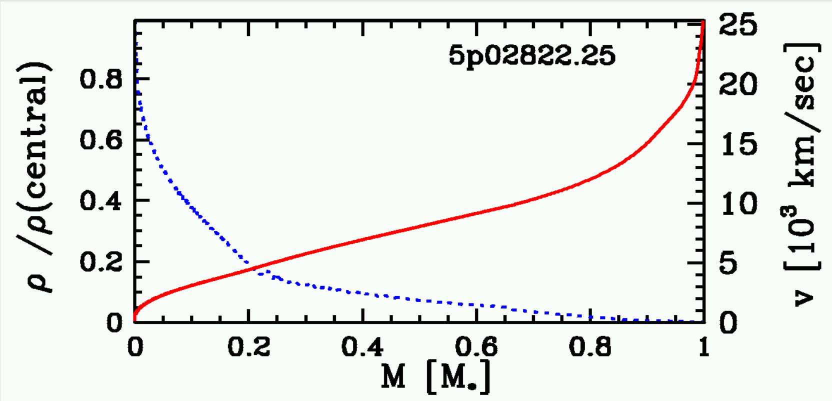
The Zoo: Explosion Scenarios of White Dwarfs

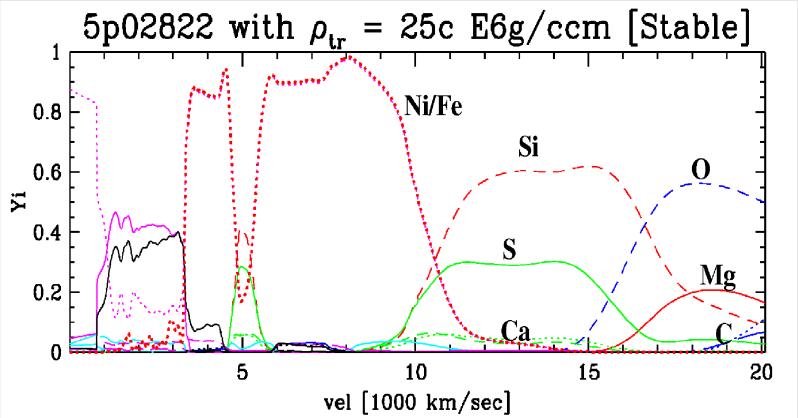
Time **0 sec** **0.5 sec** **1.sec** **2...3sec**

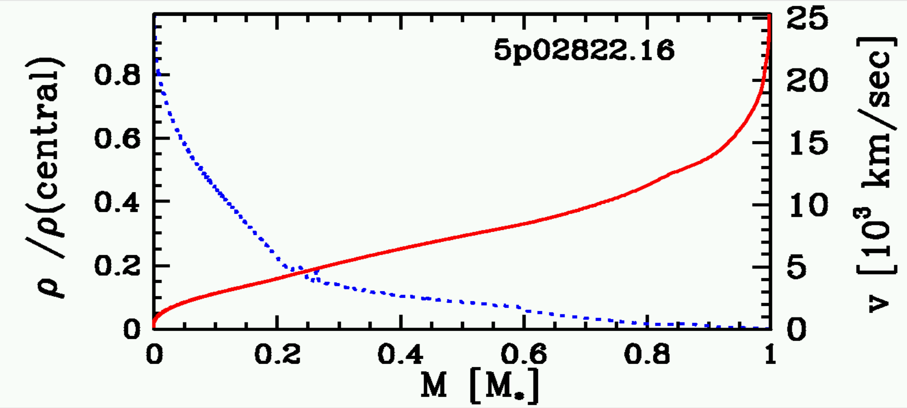


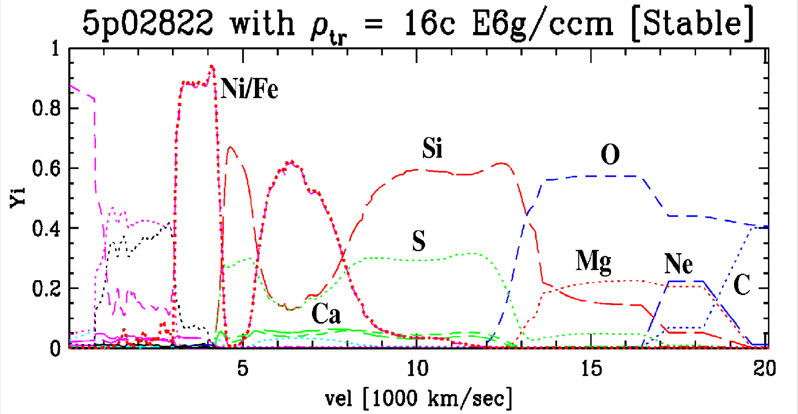
Delayed detonation models for various transition densities rho(tr)

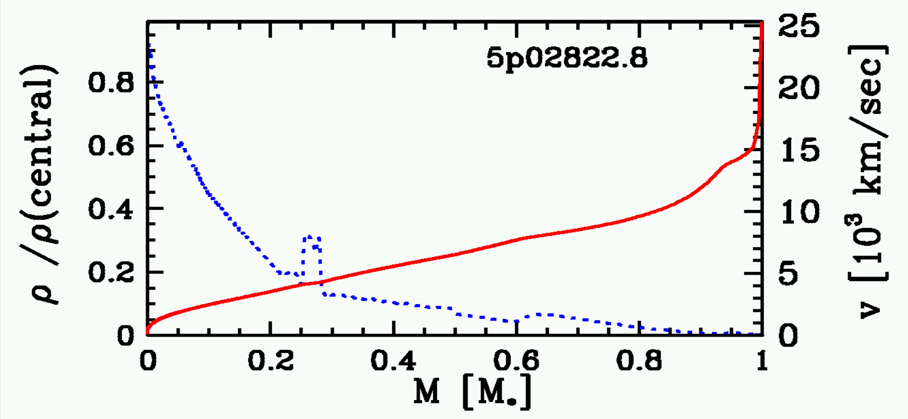
[M(MS)= 3 Mo; Z = 1.E-3 solar; rho(c)= 2E9 g/ccm with rho(tr)=8, 16, 25 g/ccm]

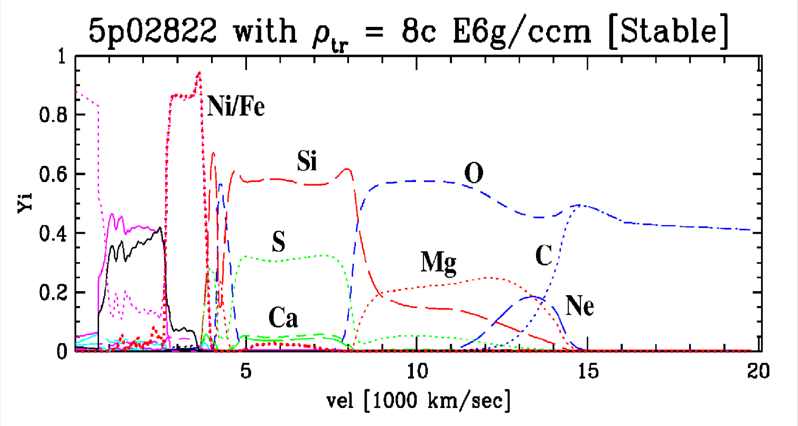










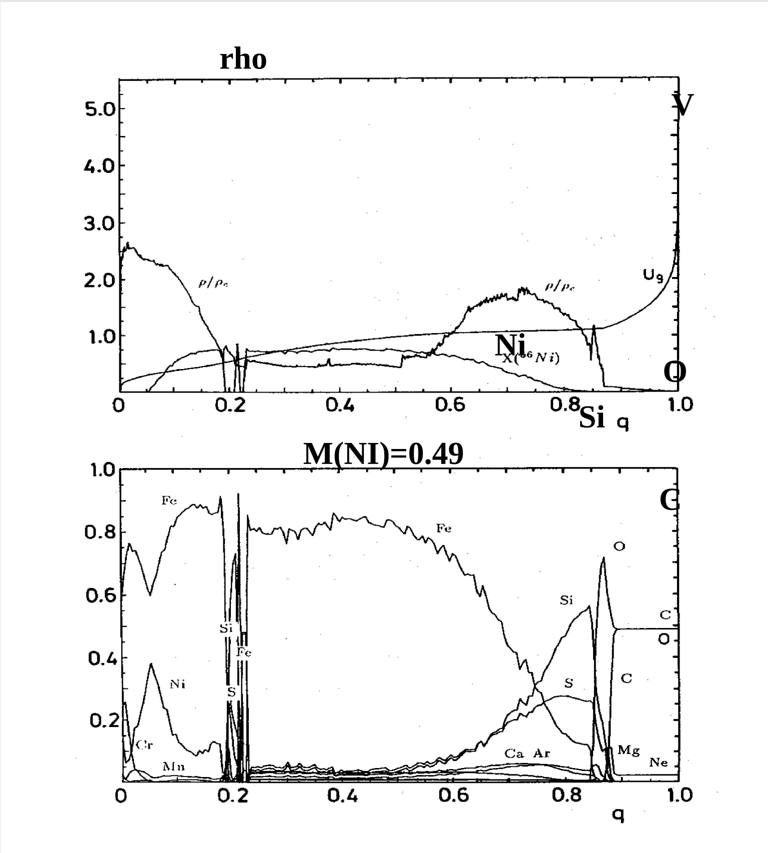


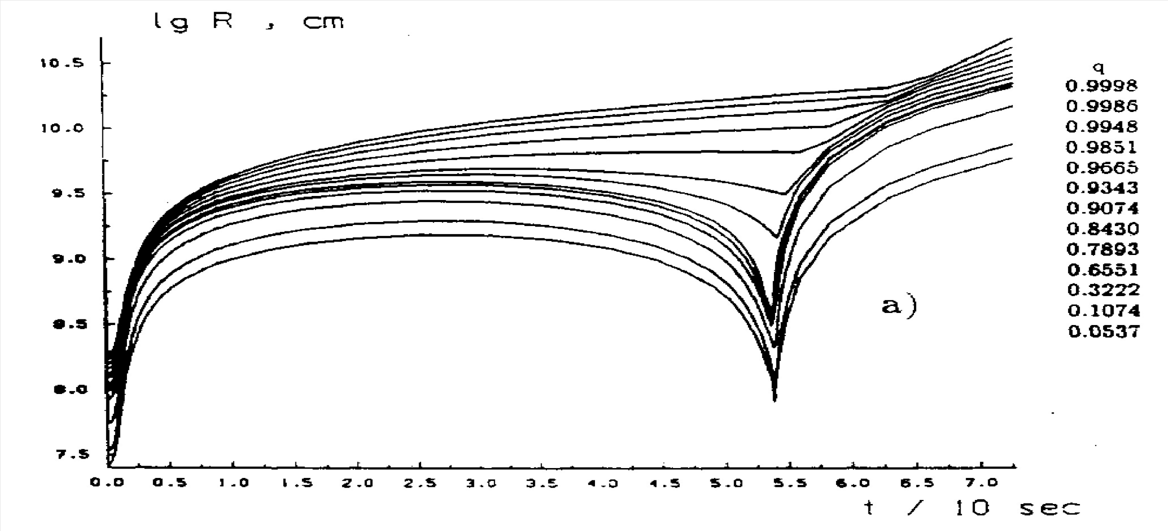
Pulsating Delayed Detonation Models & Mergers

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

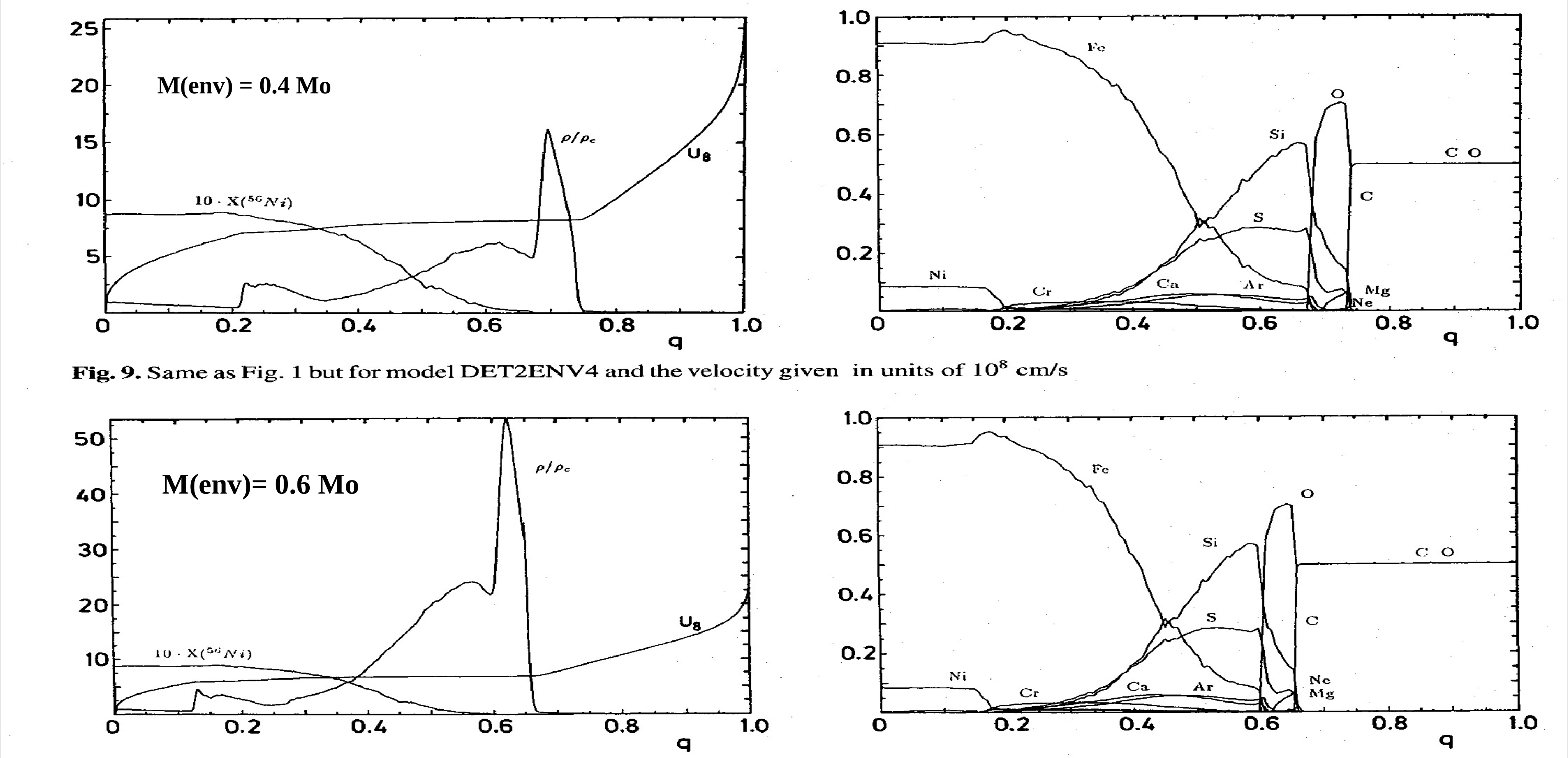


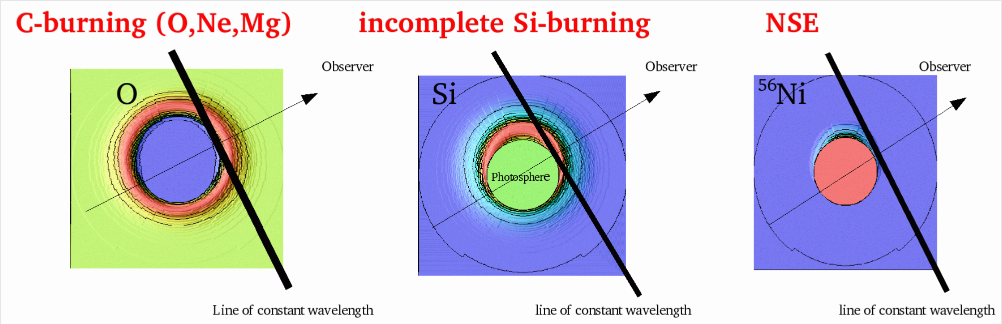
Fig. 9. Same as Fig. 1 but for model DET2ENV4 and the velocity given in units of 10^8 cm/s

- 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

Polarization as Tool to Decipher the 3D Structure of Type Ia SNe

SN2004dt 12 days after the explosion with VLT
VLT vs. Model



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

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

Stokes Parameter (equivalent)

$Q = I_0 - I_{90}$

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

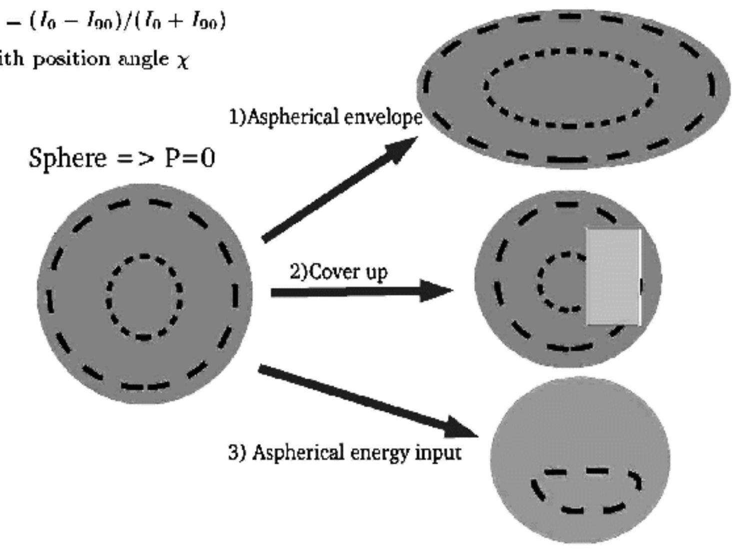
$V = 0$ for linear polarization

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

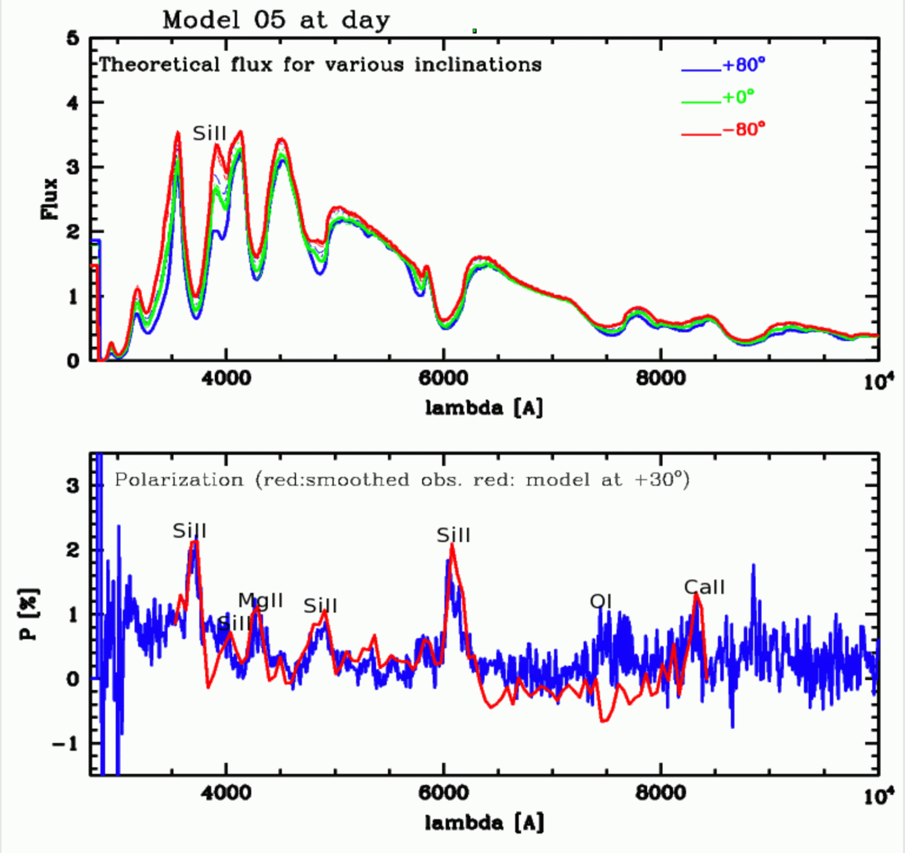
Degree of polarization P

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

with position angle χ



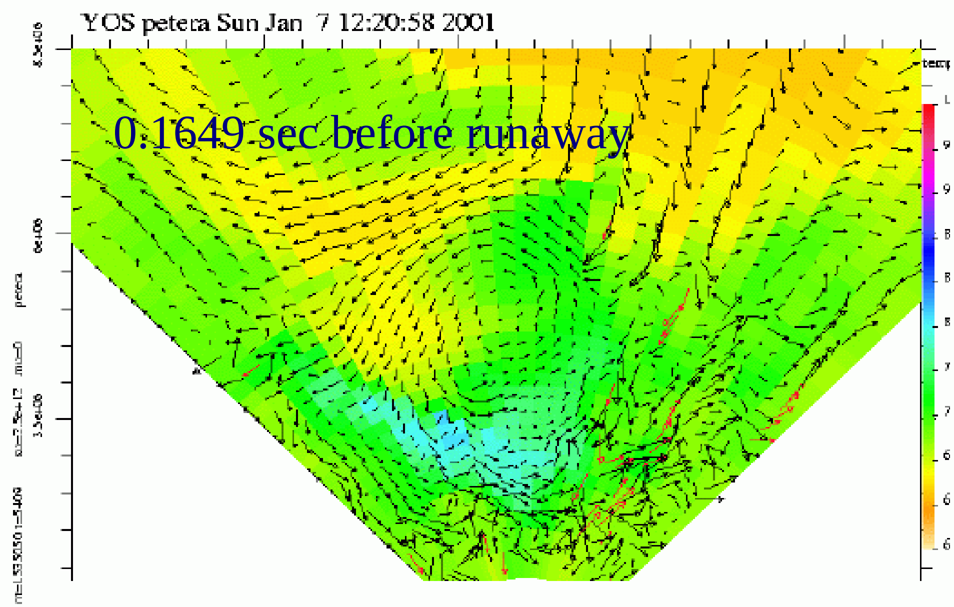
(Hoeflich, 1995)

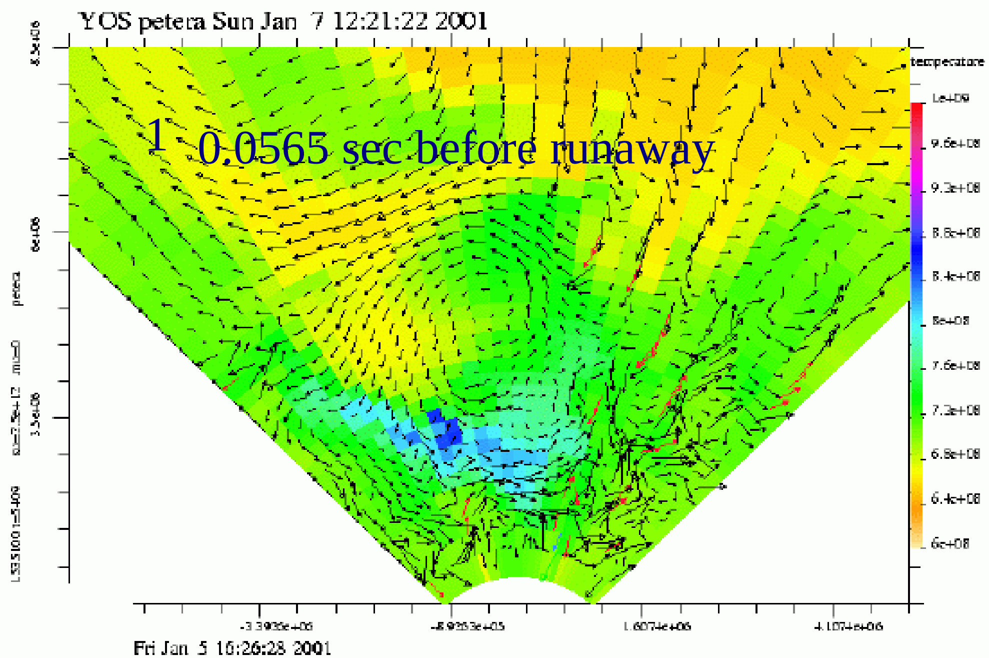


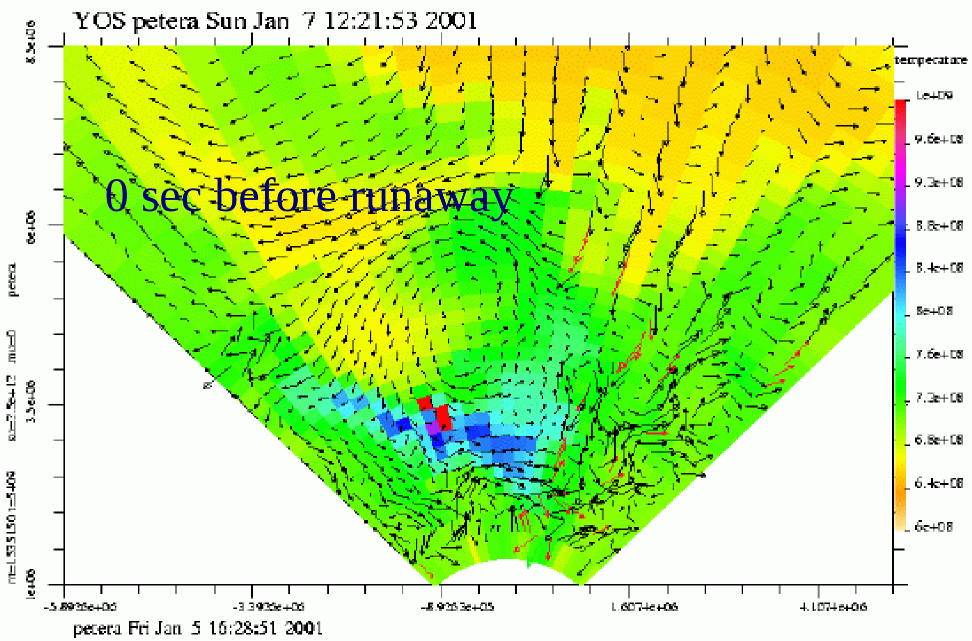
Temperature and velocity evolution at the runaway

(Hoeflich & Stein 2002, ApJ 568, 791) see also Zingale et al. (2005-11)

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







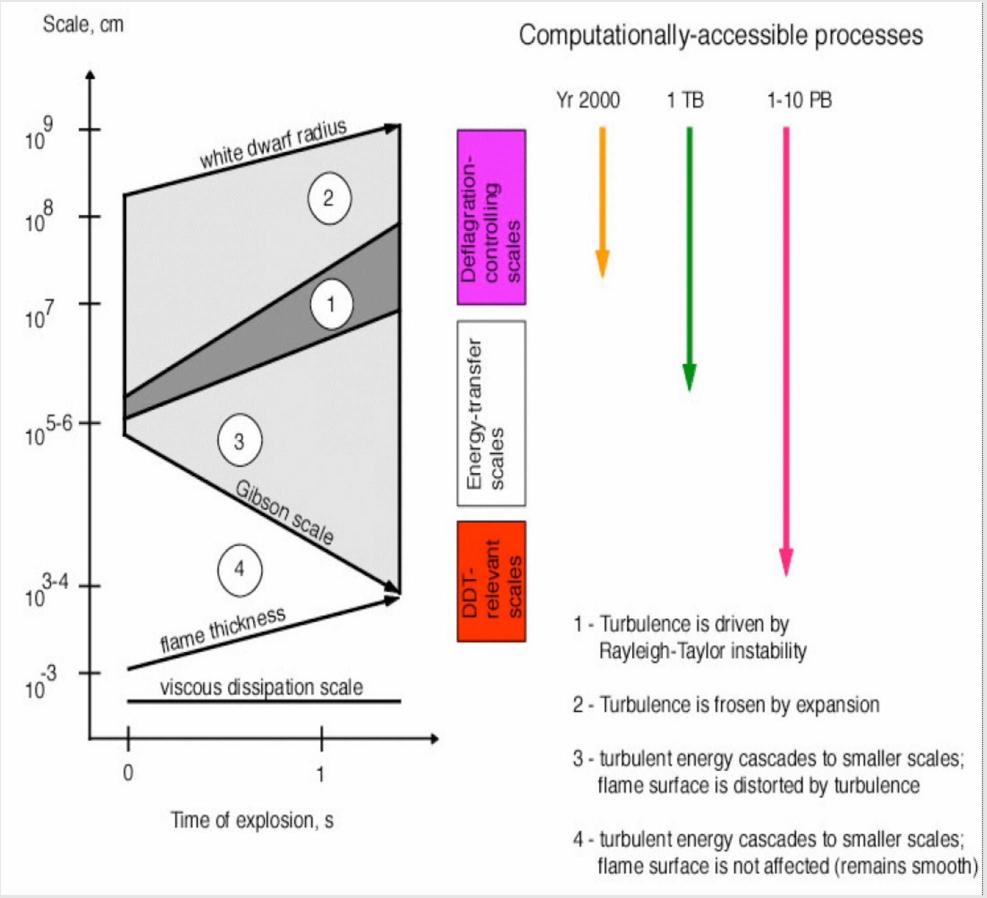
- **size of shown domain: 100 km**
- **size of inner boundary: 13.7 km**

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

Hydrodynamics of Nuclear Burning Fronts (Gamezo et al. 2003)



Khokhlov et al. (2003)

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

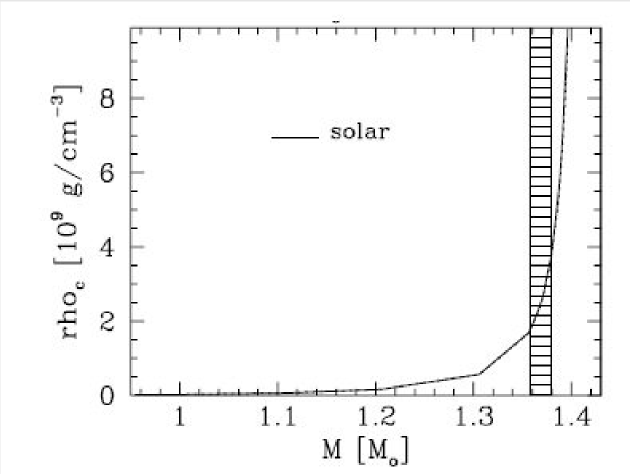
Lots of C at surface

- Y → Mergers, PDDs Sublum. DDs
- No → Normal bright DD

Thermonuclear Explosion (inner layers)

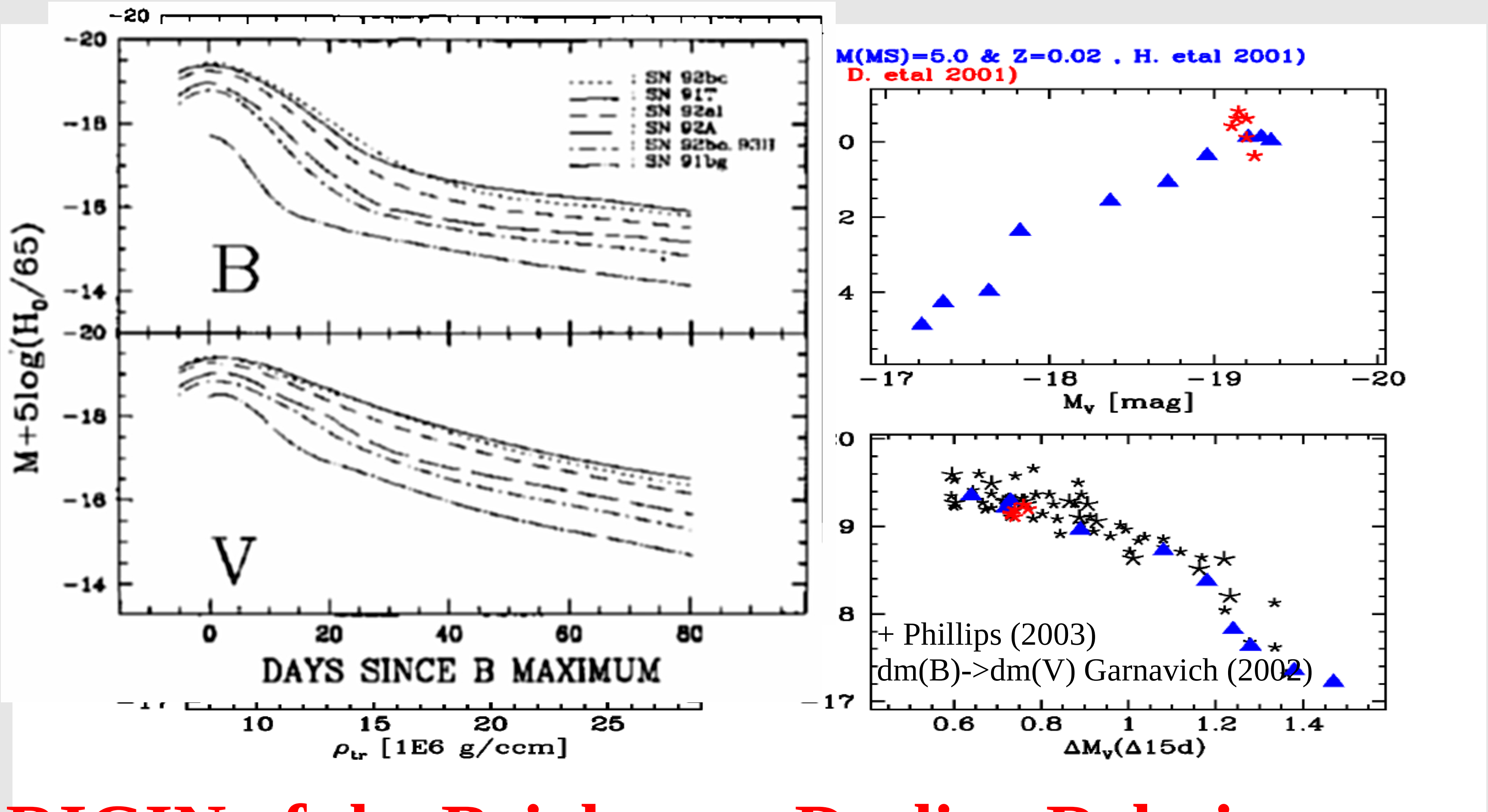
56Ni to the center (rho<1e9g/ccm)

- Y → Sub-Chandra, Dynamical mergers
- NO → M(Ch) Wds DD s, slow mergers



COMPLICATION: Mixing (needs to be measured)

Comparison between Observation and Theory



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)

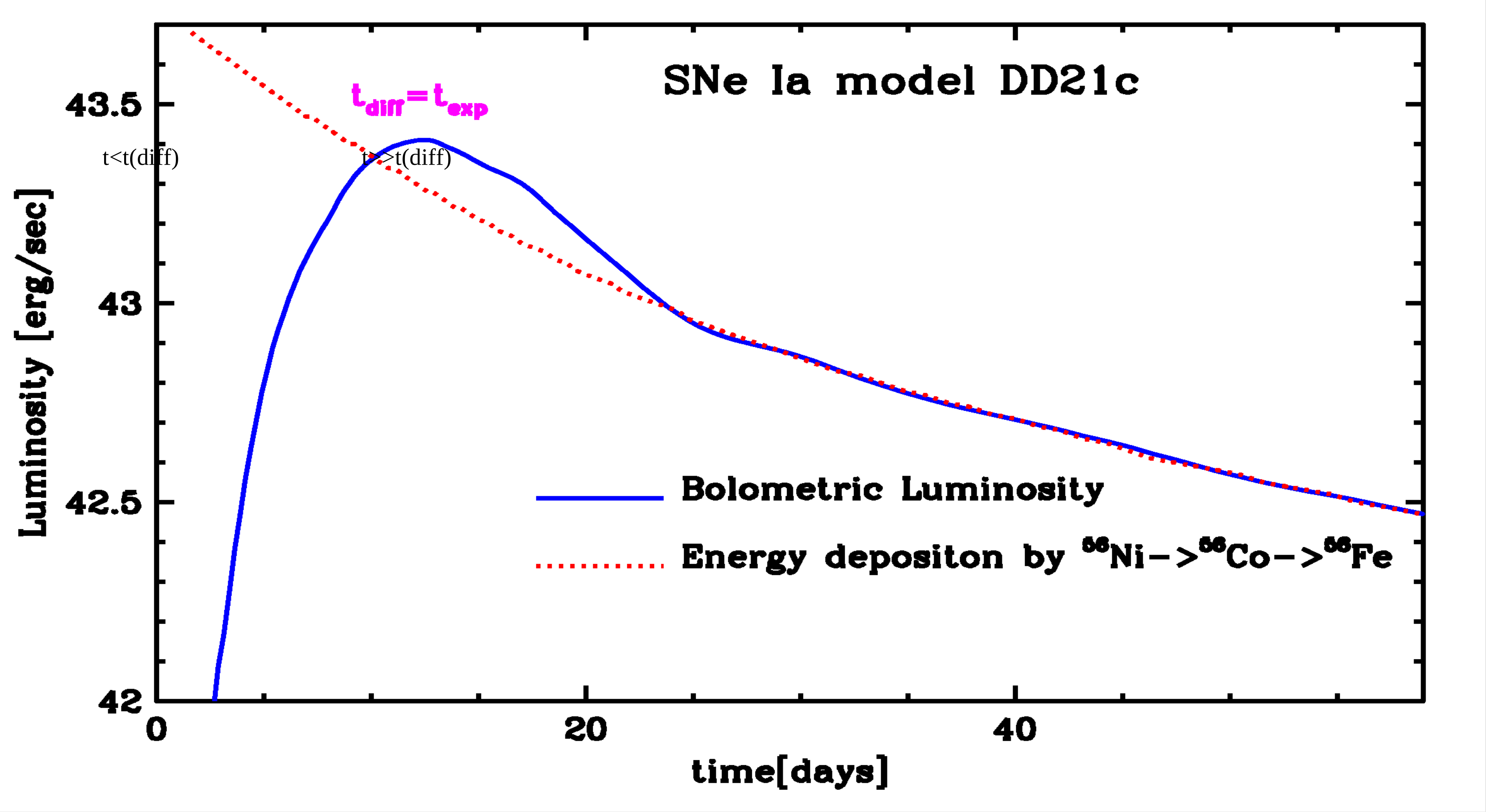
I) The Brightness Decline Relation:Light Curves in a Nutshell

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

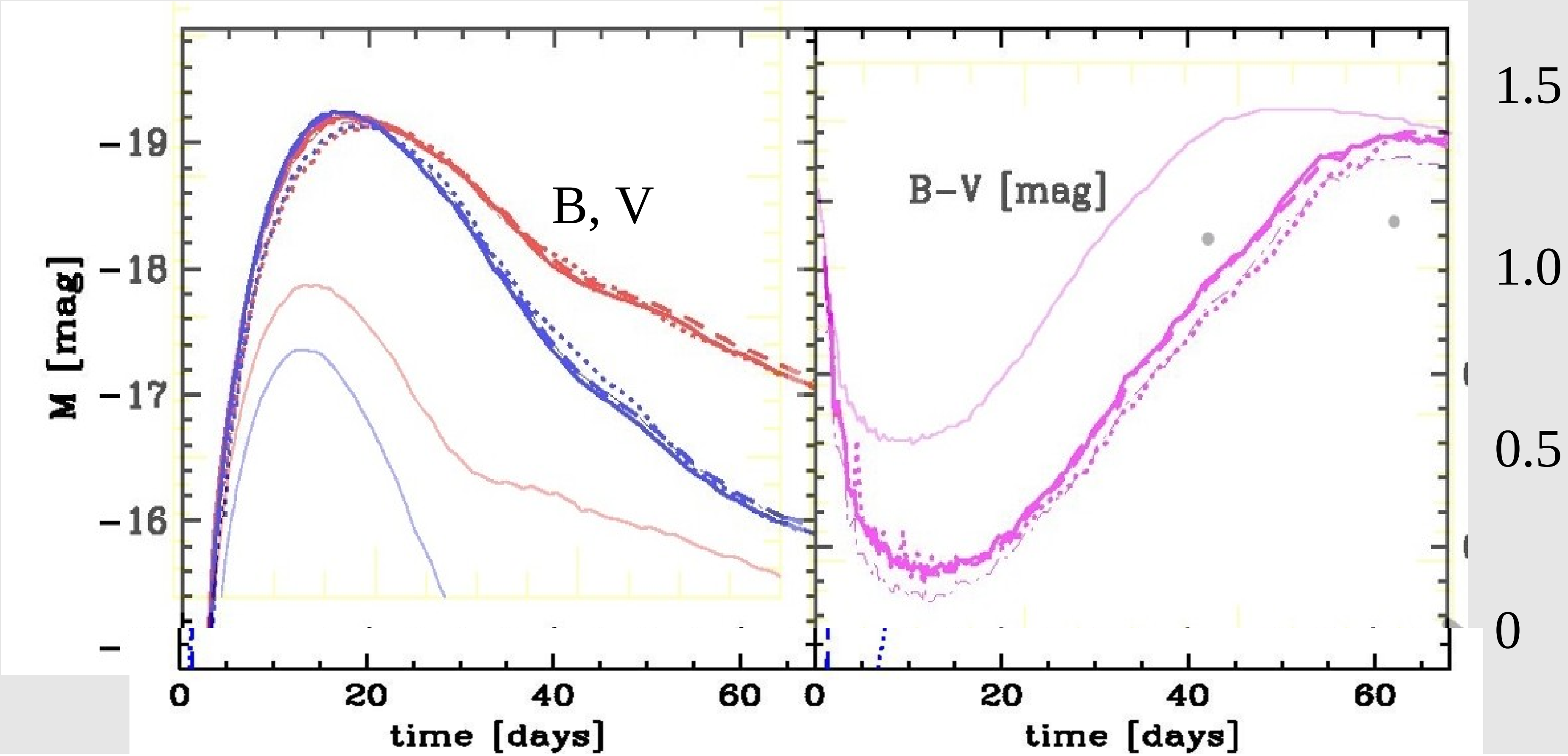
Products: X- and Gamma-ray photos + positrons

Optical Luminosity:

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



Ingrediences of the Lyra's Relation



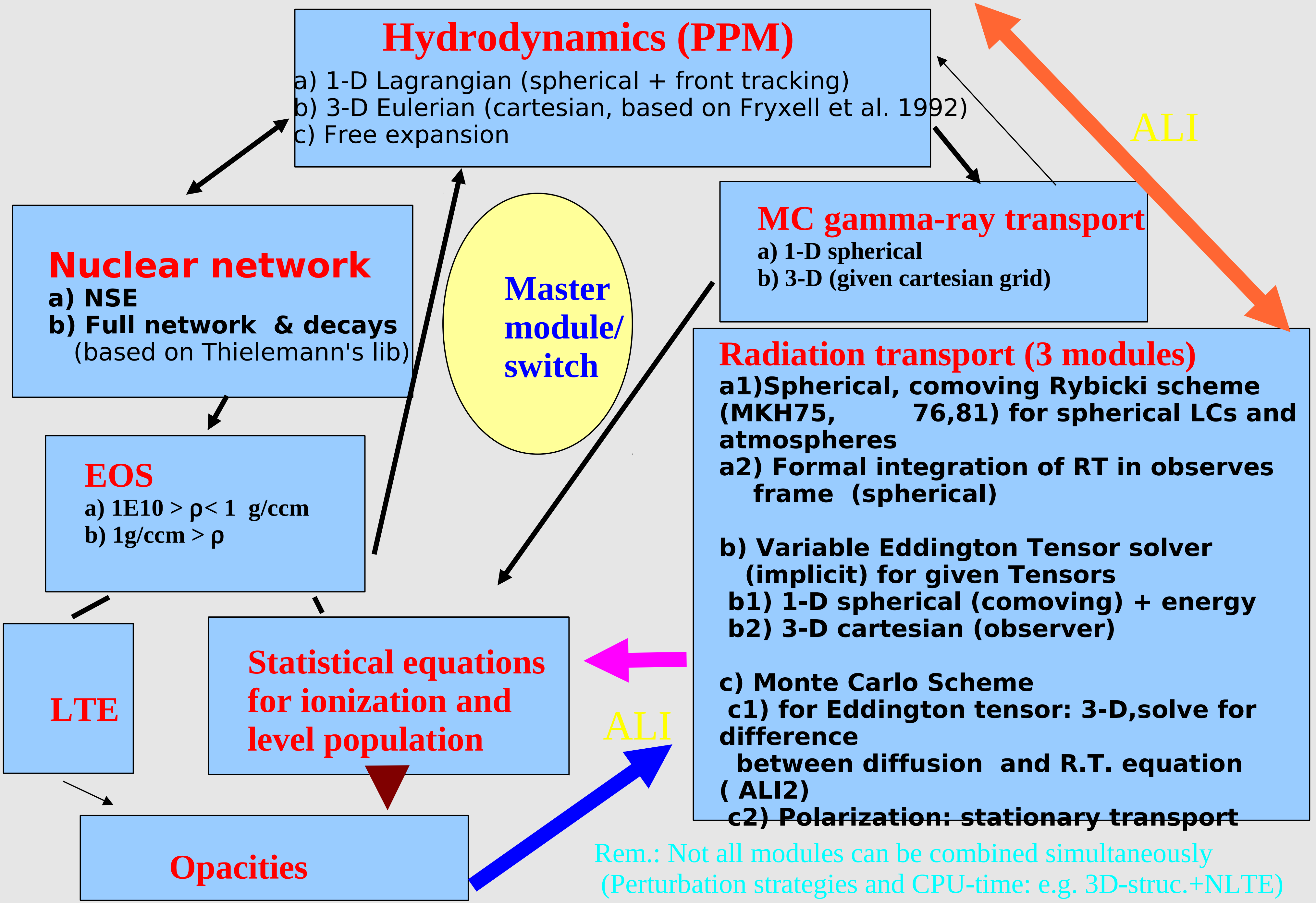
At a **common(!)** **time**

conditions of at the photosphere are similar with respect to

- temperature, density and ionization
- abundances

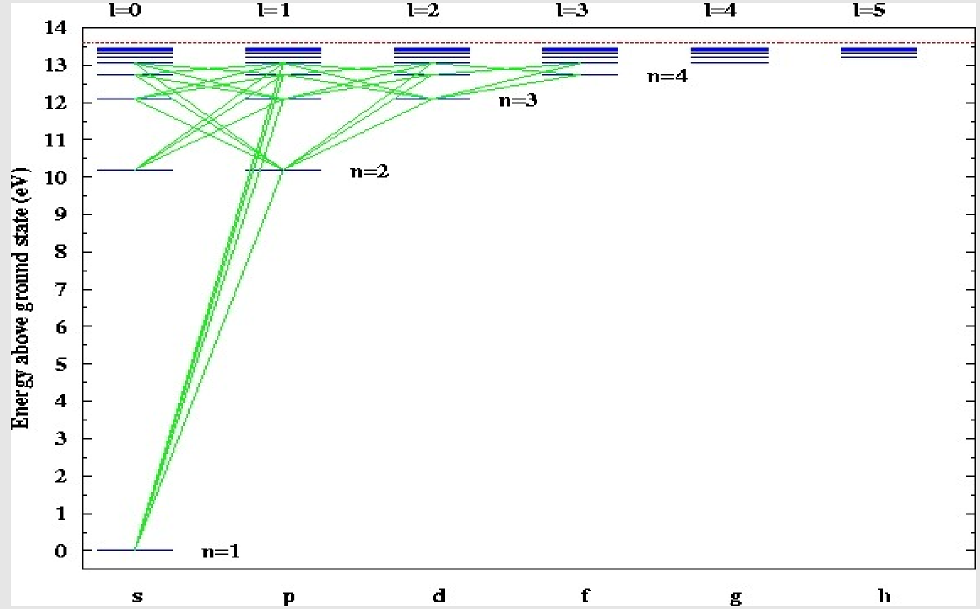
Krisciunas et al. 2003

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

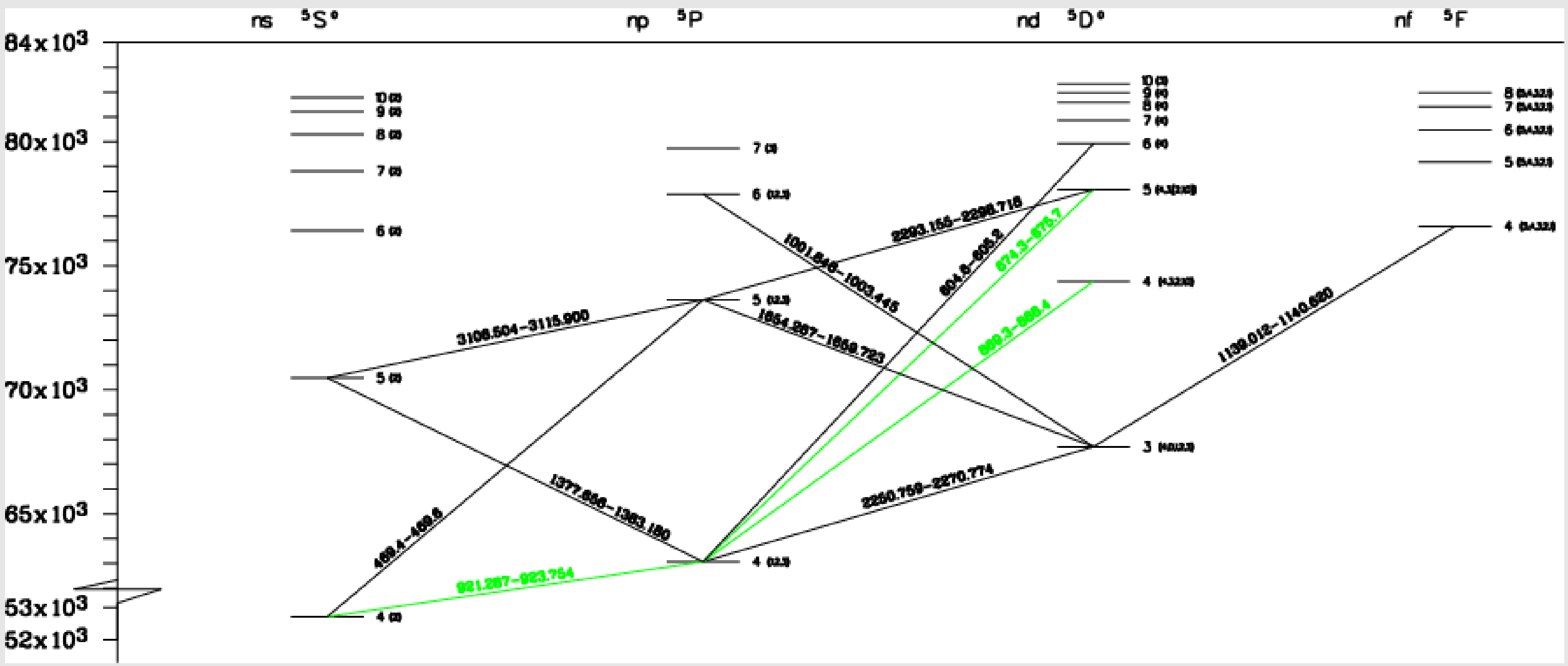


Representation of Atomic Models: Grotrian Diagrams

Hydrogen Atom (not in SNeIa):

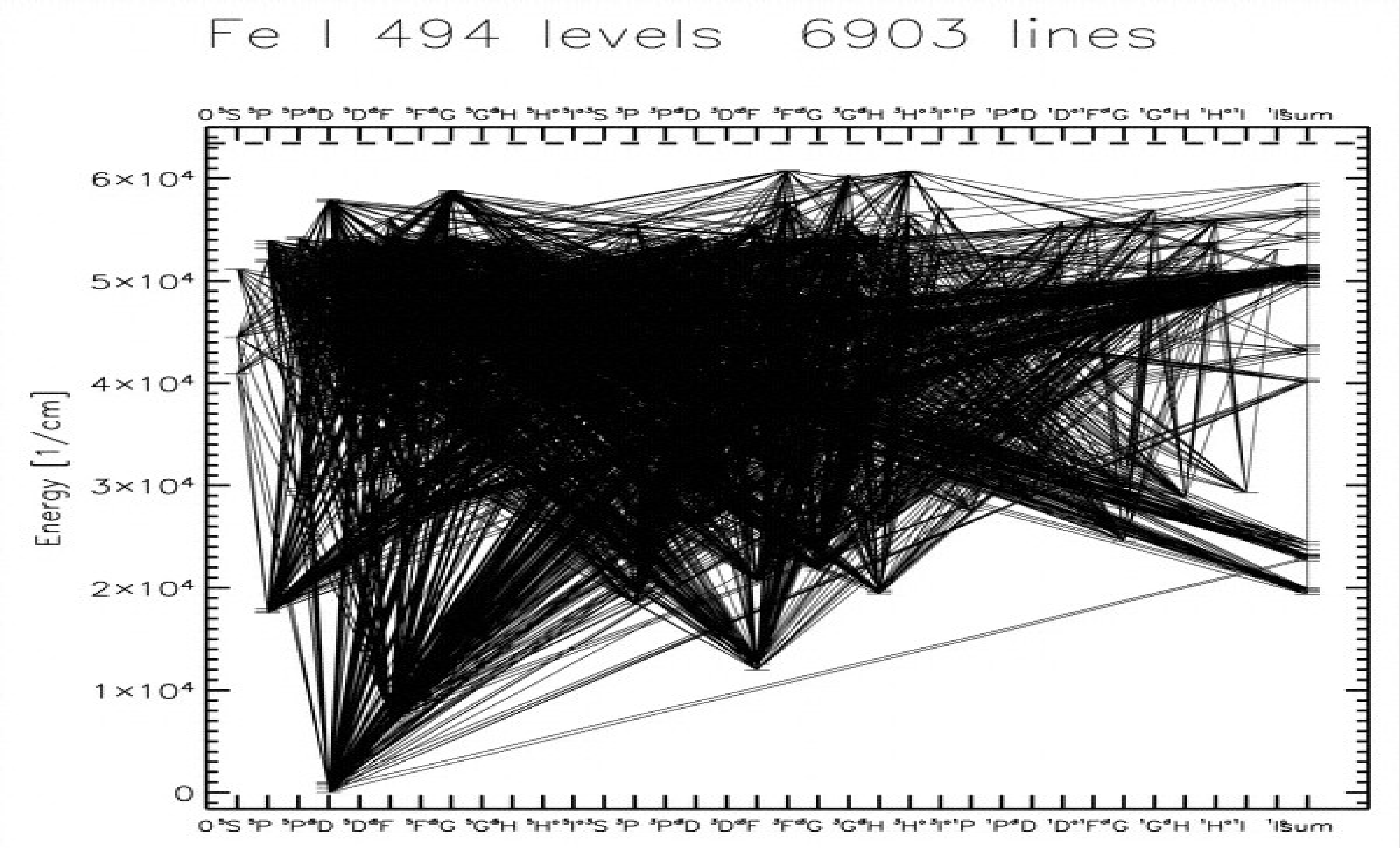


Mn I



Representation of Atomic Models: Grotrian Diagrams

Simpified Fe-atom: (Full line list 1E7 lines and 1E4 levels)

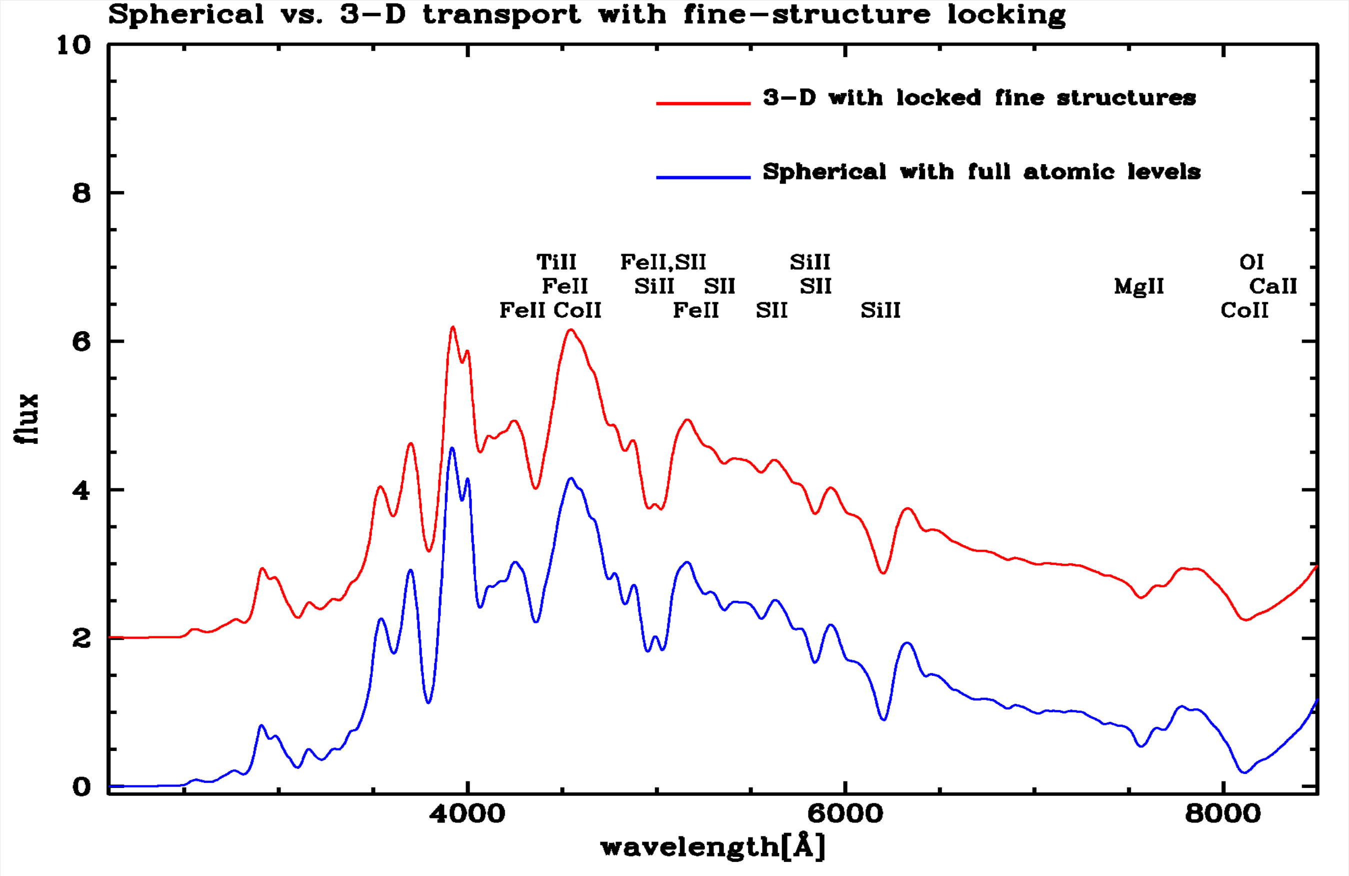


=

=> Level Merging or Superlevels

Verification & Tests & Damage Control

Influence of Level-Locking and 3D-Envelopes



- qualitatively ok but ...
  some discrepancies in particular below 5000 A due to
  a) locking of levels
  b) frequency resolution
  c) for net-rates below 1E-3, deviations from diffusion is set to zero

Opacities and Radiation Transport in Rapidly Expanding Envelopes

Individual opacity:

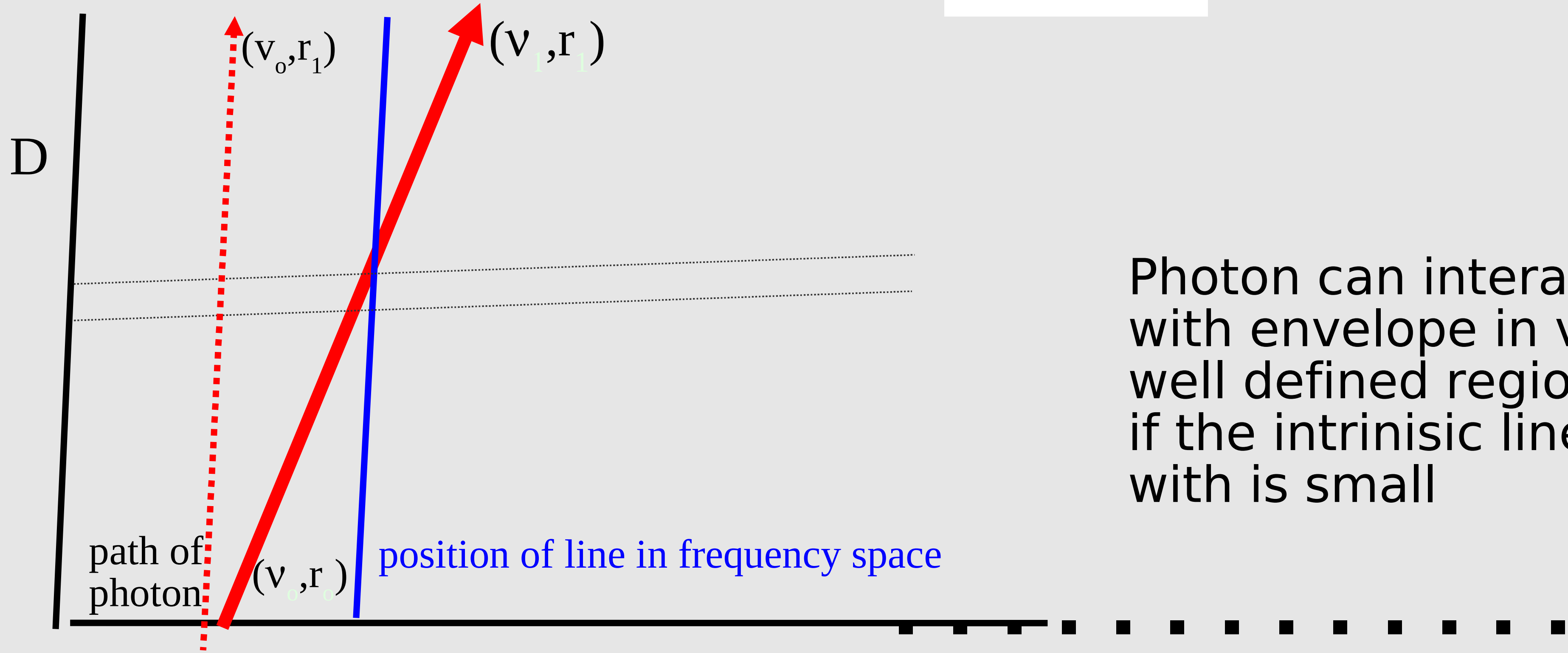
$$\chi_l = \frac{\pi e^2}{m_e c}\frac{f_{ij} n_i}{\nu_{ij}\rho}\left(1 - \frac{g_i n_j}{g_j n_i}\right).$$

$$\tau_i = \chi_i c \varrho \frac{dr}{dv(r)}$$

Photons travel in both the spatial and frequency space !!!

Assumption (valid for small distances):

$$v \propto r$$



Photon can interact with envelope in very well defined region if the intrinisic line with is small

$$J_\nu^{(m)} \approx J_\nu^{(m-1)} + \Lambda_\nu^*\left(S_\nu^{(m)} - S_\nu^{(m-1)}\right) \Rightarrow R_{ij} = 4\pi\int \frac{\alpha_{ij}(\nu)}{h\nu} J_\nu d_\nu + R(\gamma),\quad R_{ji} = 4\pi \int \frac{\alpha_{ij}(\nu)}{h\nu}\left(\frac{2h\nu^3}{c^2}+J_\nu\right) e^{-\frac{h\nu}{kT}} d\nu \text{ and } \frac{dE(rad)/\rho}{dt} = \int \chi(S-J)d\nu$$

for rate equations

energy eq.

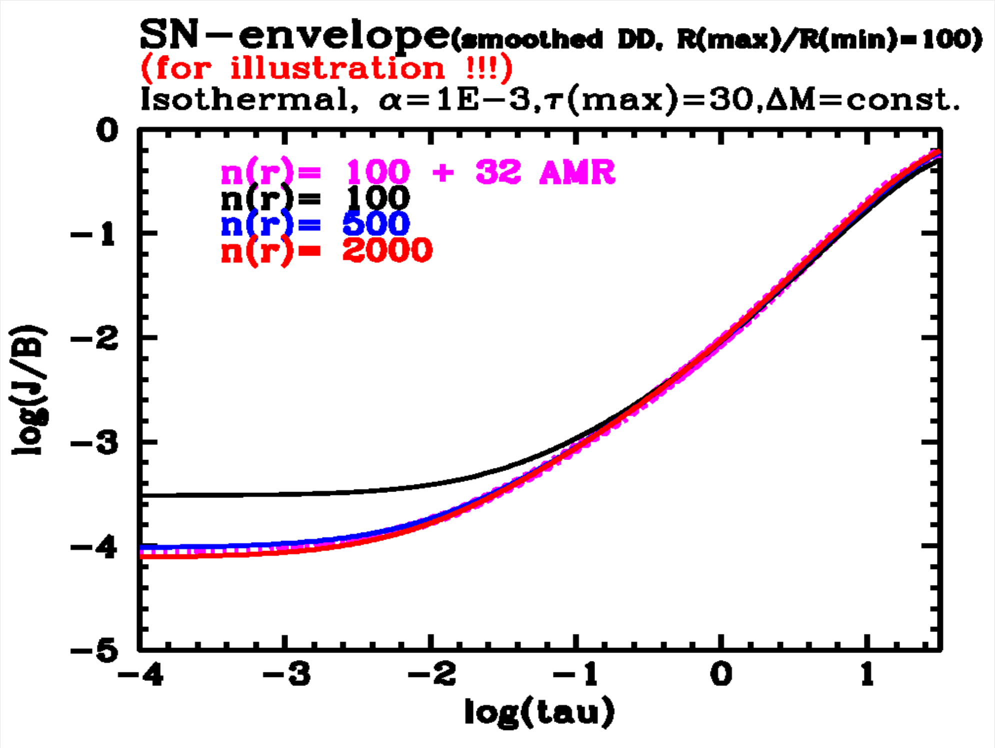
Resolution & Adaptive Mesh Refinement

Why?

- discretization error in explosion because grid is optimized for hydro (e.g.^ M=const.)

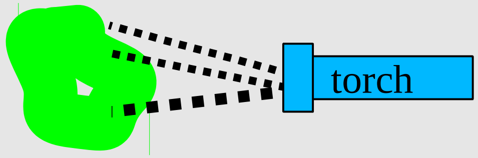
- errors are small for large optical depths (diffusion) but large at small tau.
  Example: 500 ... 1000 depths needed

- reason: radiation field changes from isotropic to un-isotropic at decoupling region. **=> AMR**



Issue: Photon freeze-out

Problem: 'Photosphere' is not related to a local physical property (rho, v, T etc.)



AMR by a Monte Carlo Torch:

Solution: Shoot photons from outside and see where it interacts

Recipes: - number of test photons 1E6 ... 1E7

Spherical case: n(AMR)=1E3 & n(v (repr.)), 3D case: n(AMR)=5E5 & n(⌐ (repr.))

- divide a cell + neighbors by 2 if actual count exceeds average by about 10.
- dezone only after 10 to 20 steps

(Rem.: cavities H2002)

Why is the dispersion in brightness smaller in the IR?

Example PDDs (normal and subluminous, HKW95)

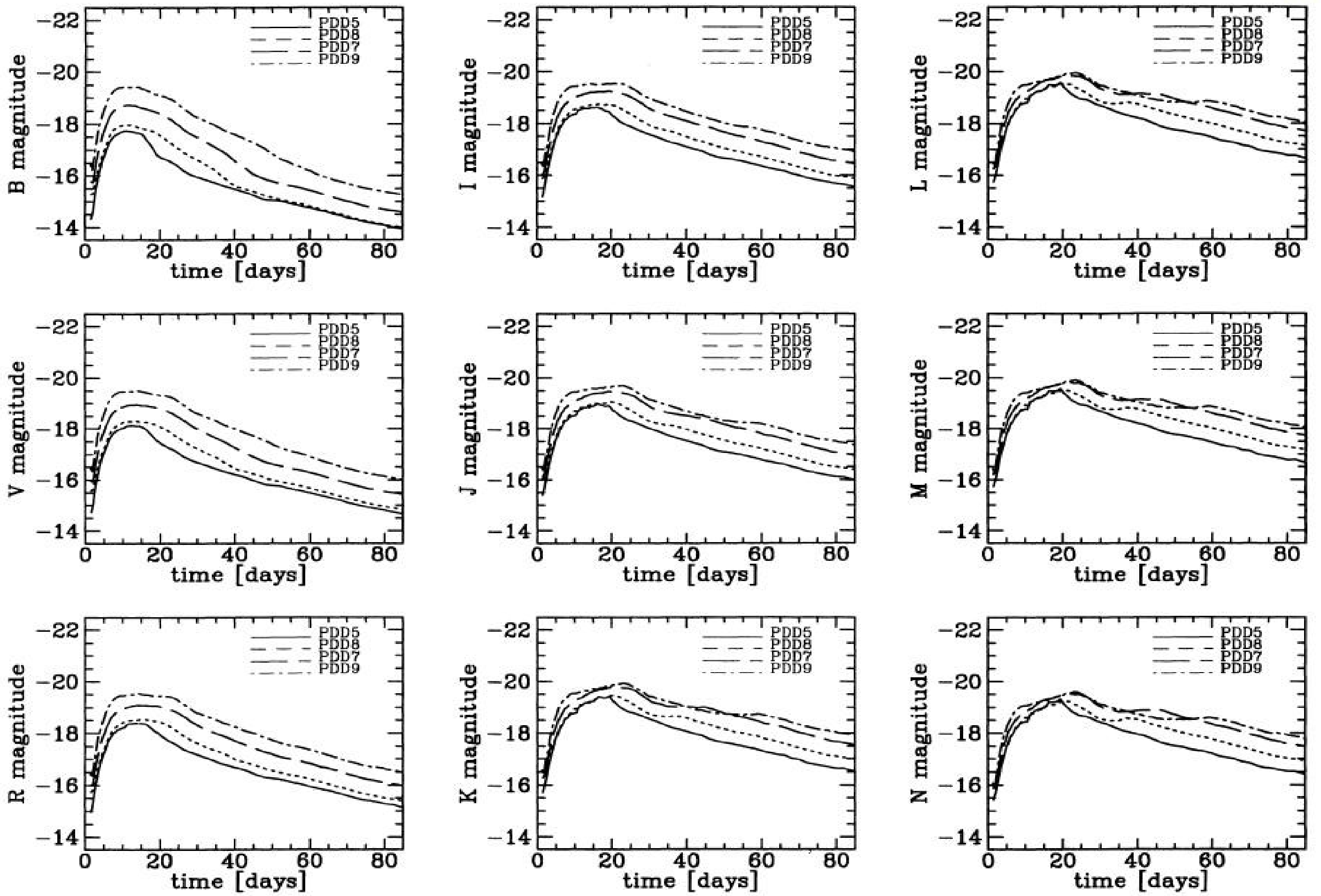
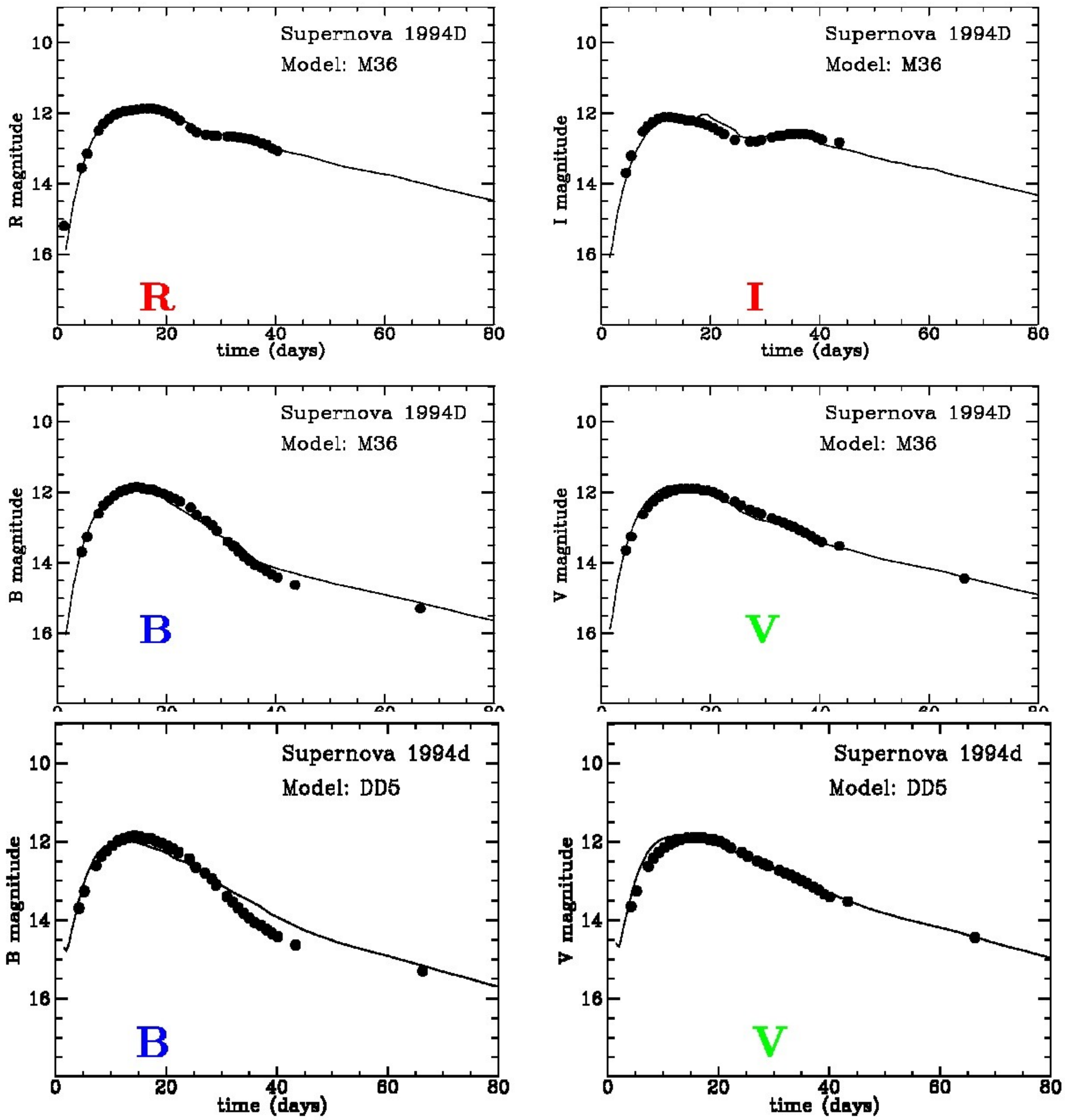


FIG. 8.—Monochromatic colors in Johnson's *UBVRIJKLMN* system as a function of time for models with different transition densities

- 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

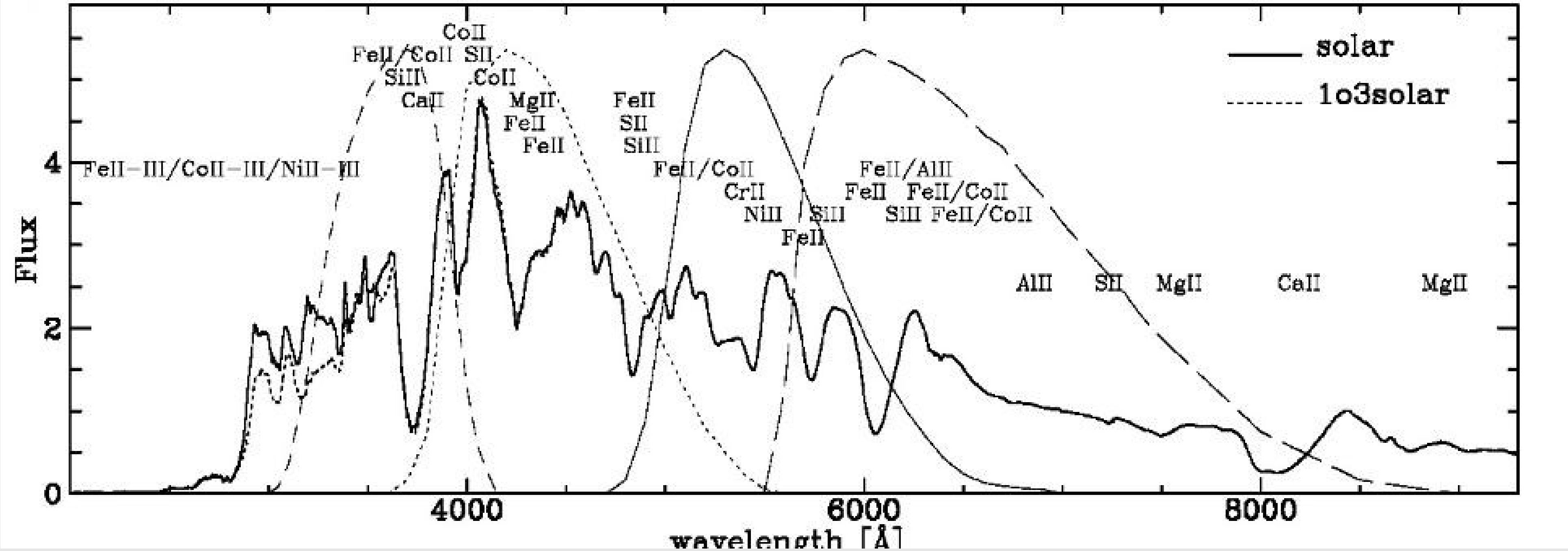
Same but

rho(tr)=2.7E7g/ccm

H95

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)

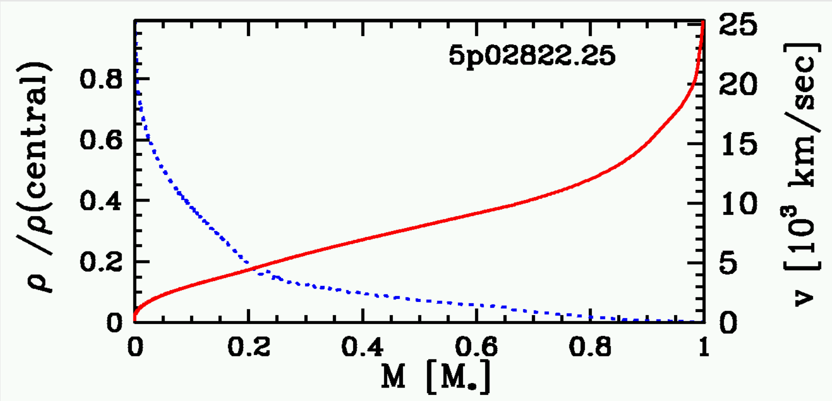
- No good Ne, O or Mg lines

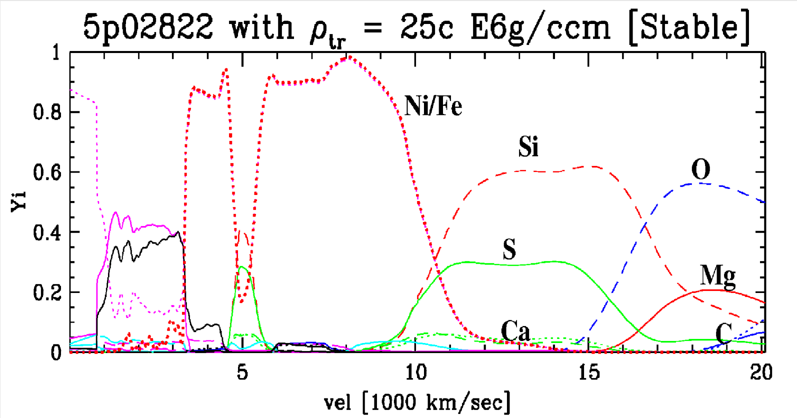
=> gives us a hard time to distinguish explosion scenarios

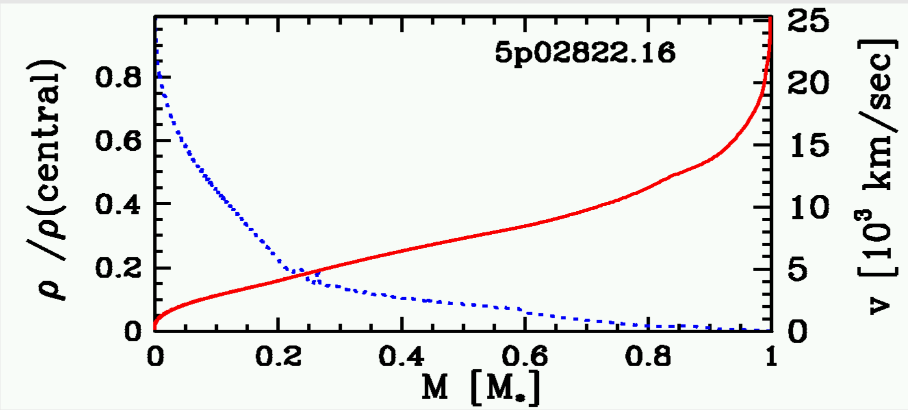
H95, HWT98

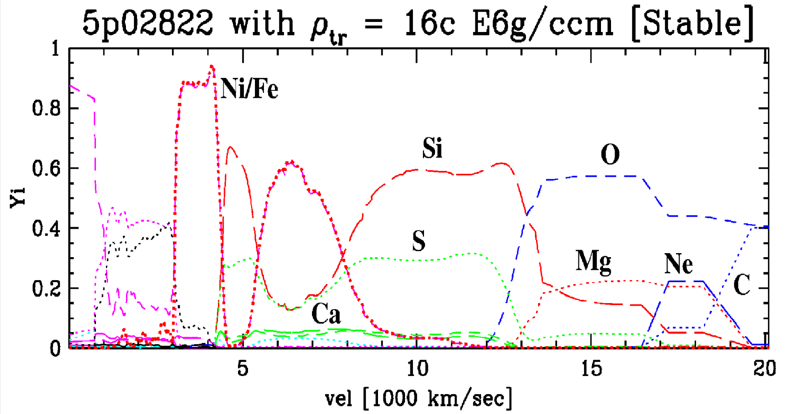
Delayed detonation models for various transition densities rho(tr)

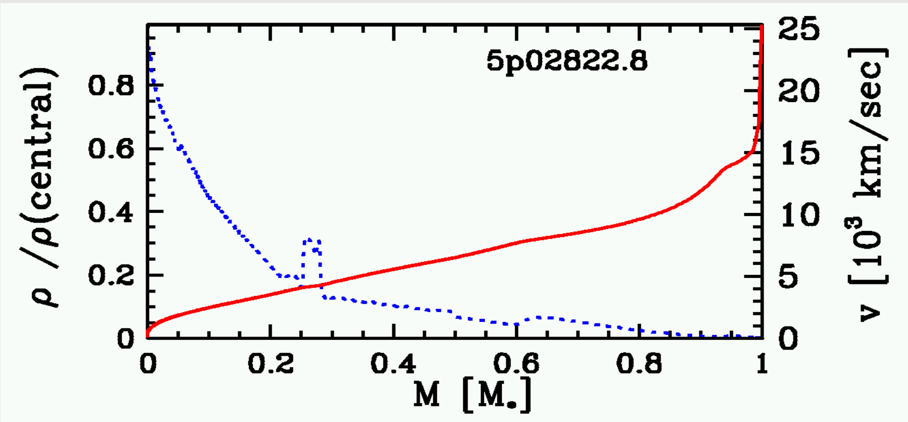
[M(MS)= 3 Mo; Z = 1.E-3 solar; rho(c)= 2E9 g/ccm with rho(tr)=8, 16, 25 g/ccm]

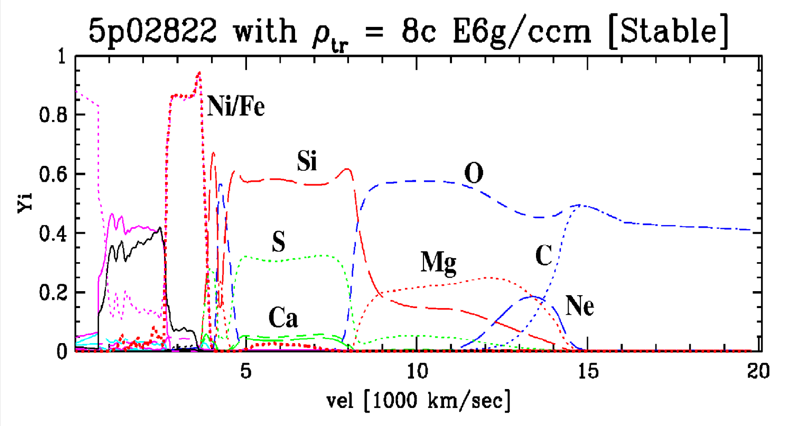




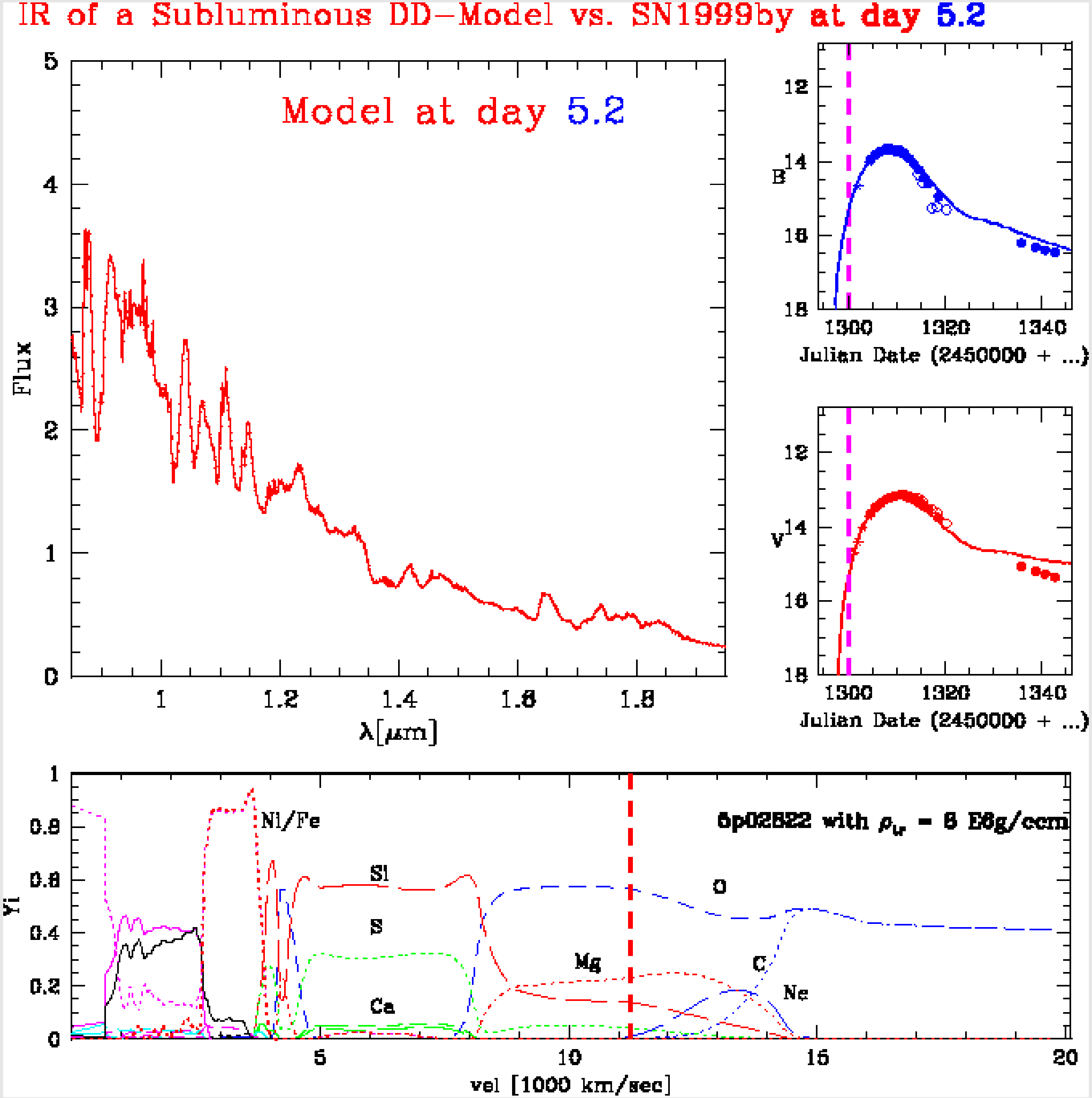






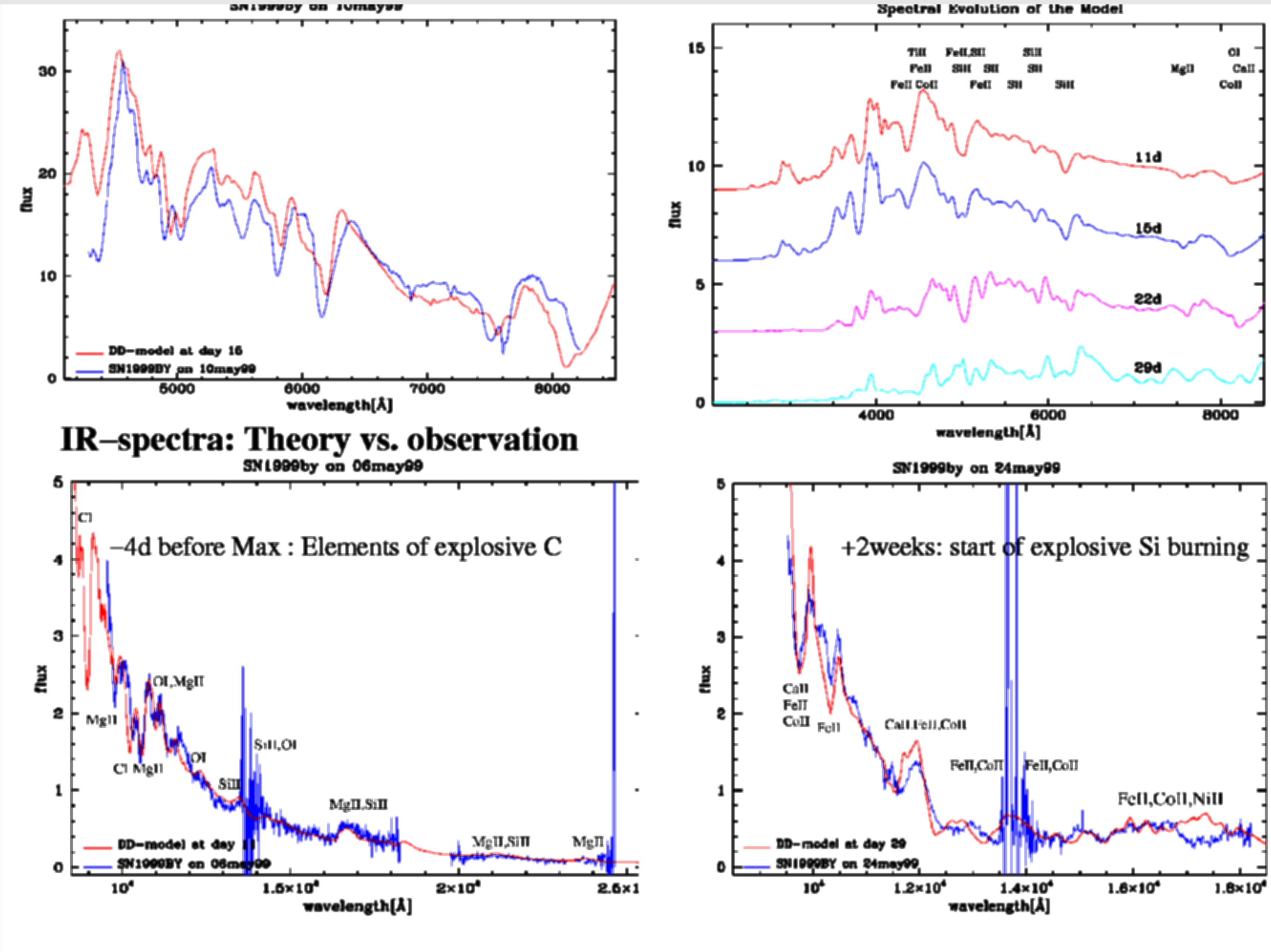


IR-Analysis of SN1999by (as followed from explosion without tuning)



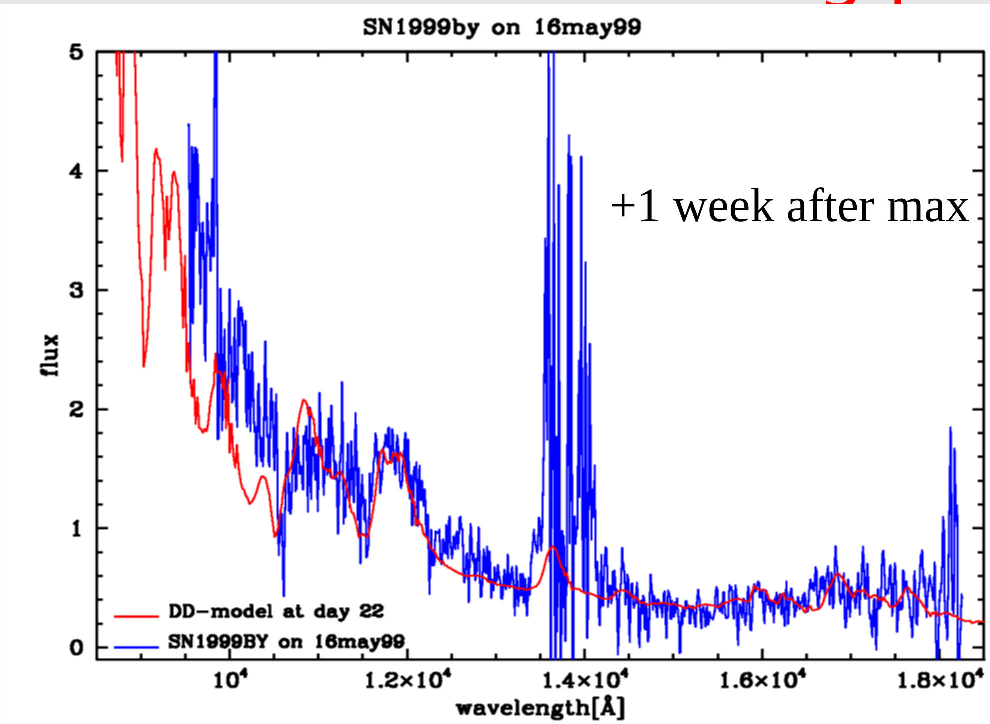
IR-Analysis of SN1999BY (as followed form explosion without tuning

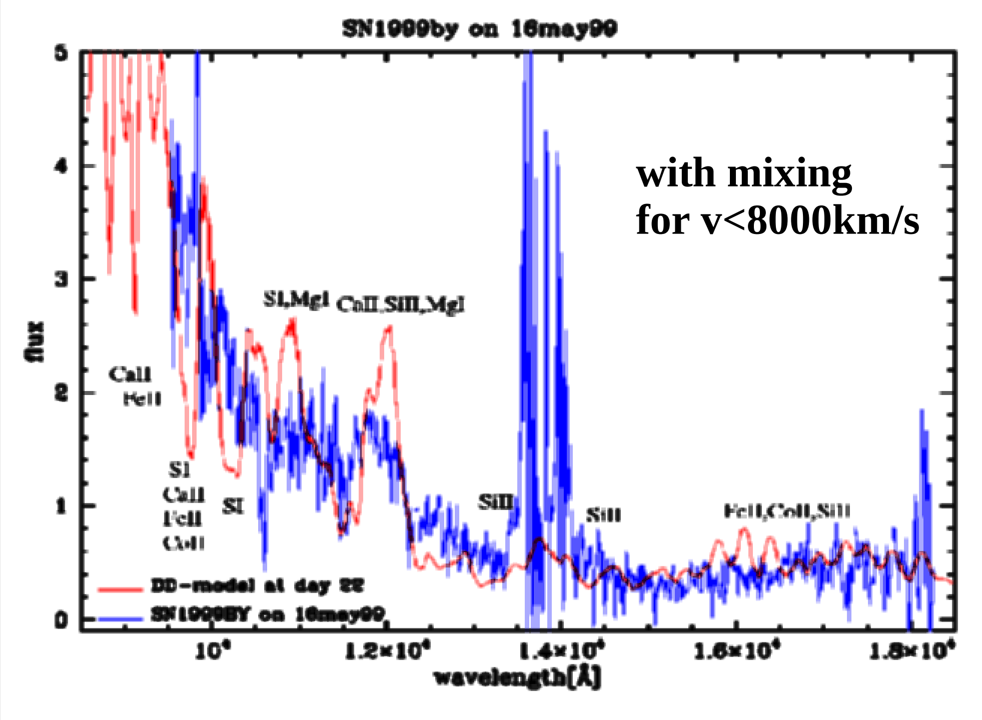
Optical spectrum at maximum light **Evolution of theoretical spectra**



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

Do we have a smoldering phase or a deflagration phase?





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

- No deflagration phase ?

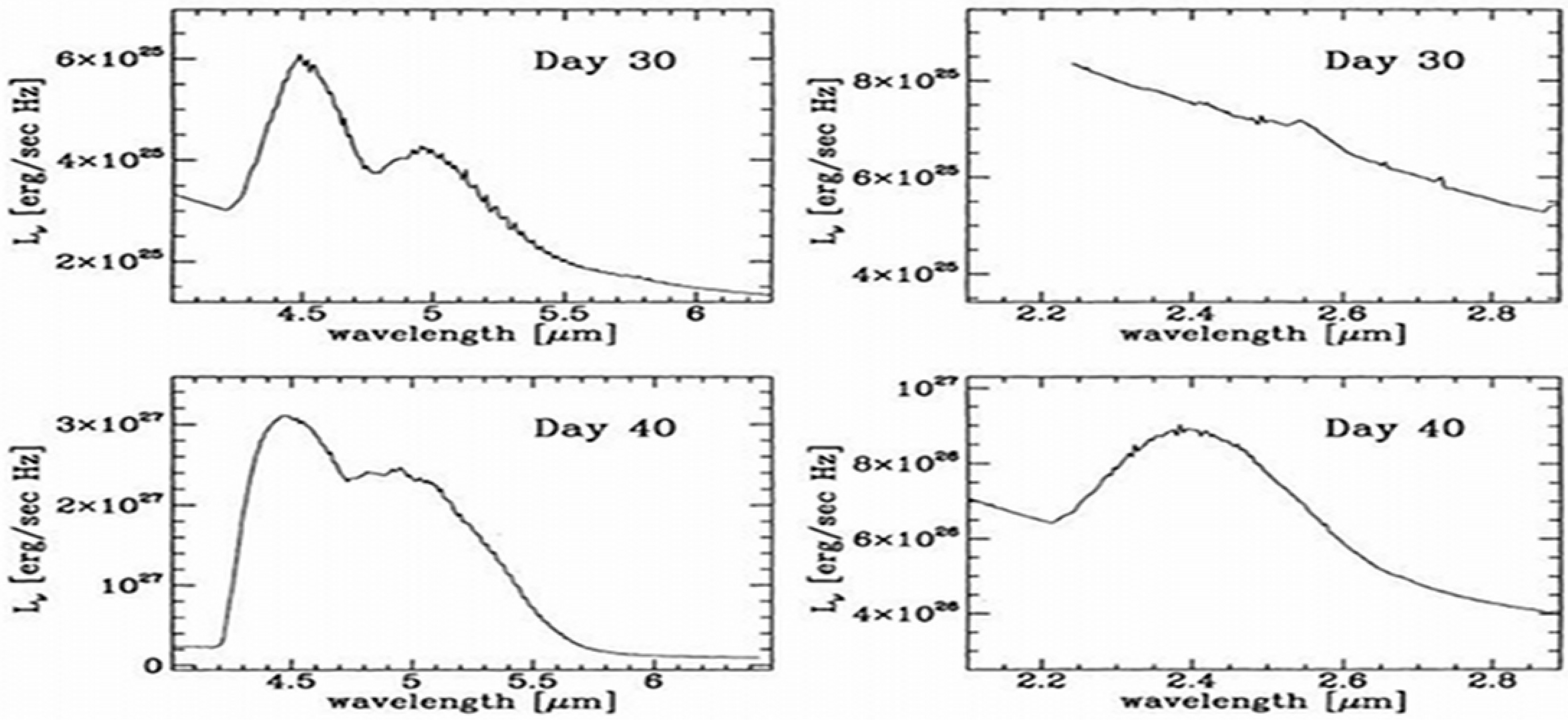
- Smoldering phase ?

- Influence of rotation ?

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

Molecule and Dust Formation in Subluminous SNe

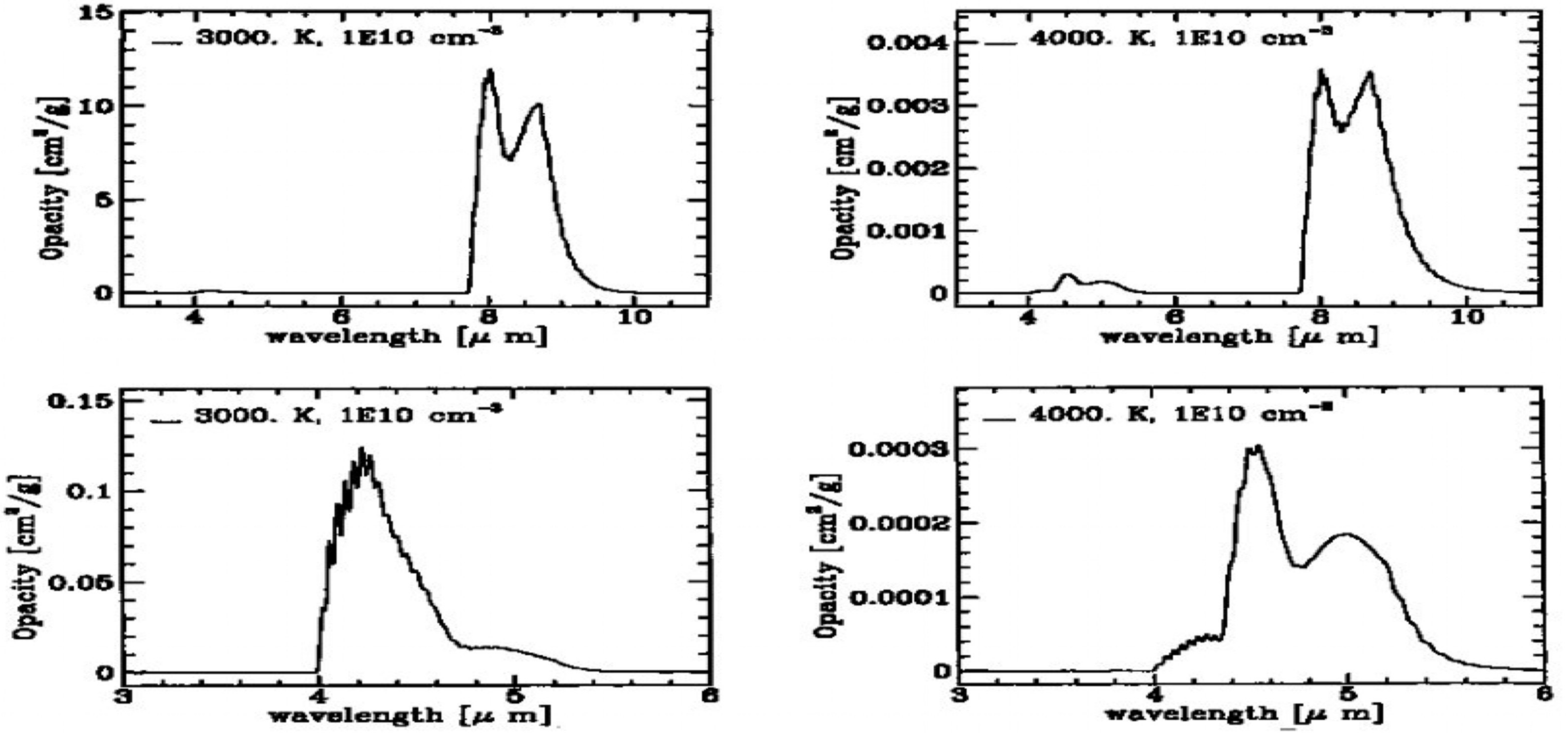
(Hetal 1995ff)



Rem: CO may trigger dust formation

CO and SiO Opacities at late times (200-300 days)

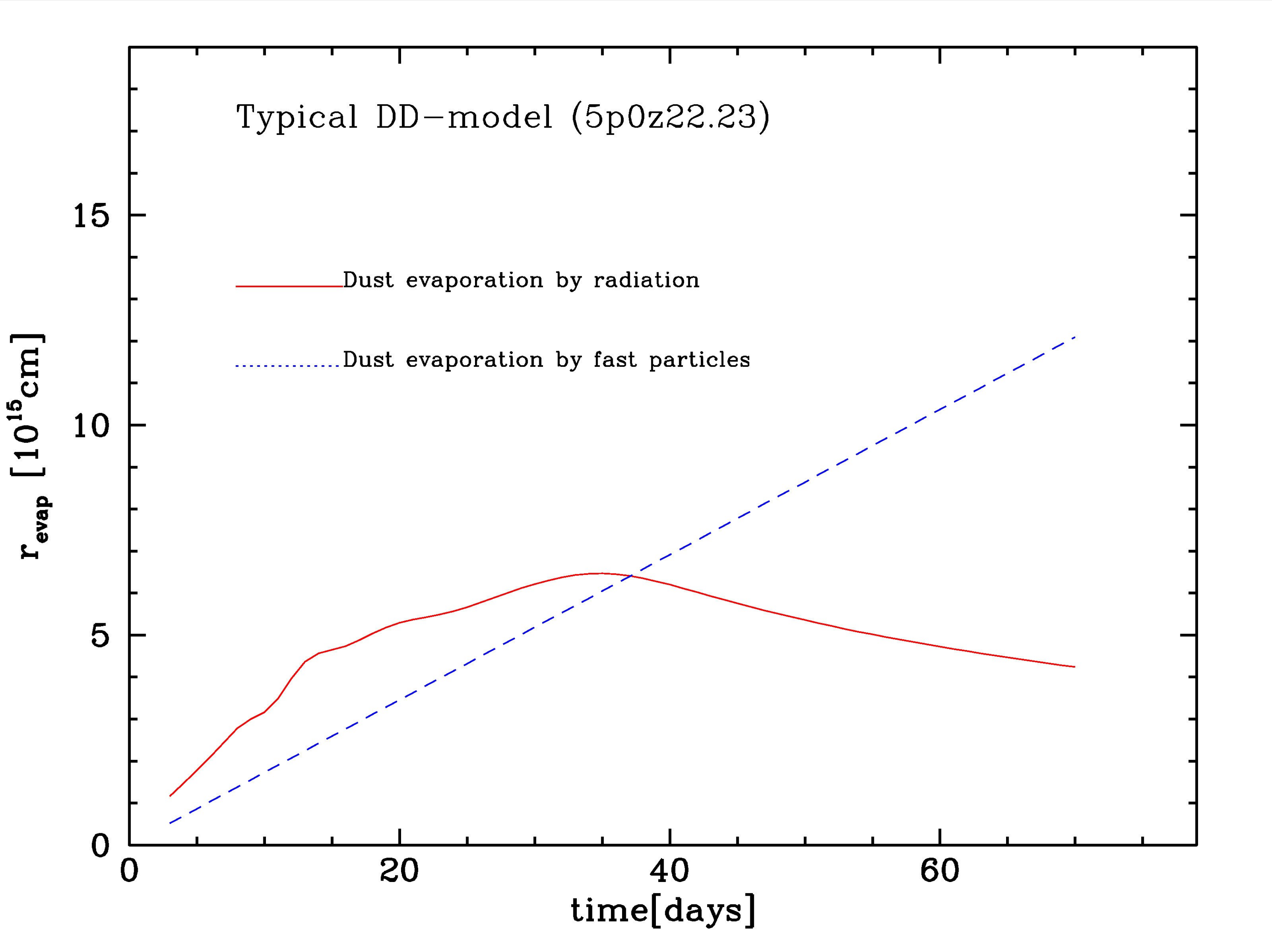
(Hetal 1995ff)



Rem: Formation depends on ionization level via charged ions

Dust Survival, Evaporation and Destruction by a Classical DD-Model for Silicates

(DD 5p0z22.23, Hetal 2002)



Destruction by

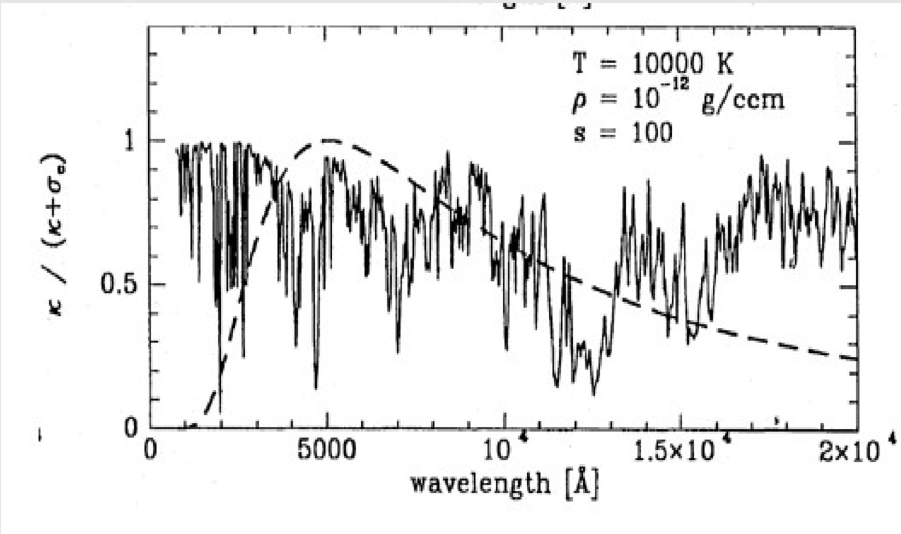
- radiation field of a SNIa

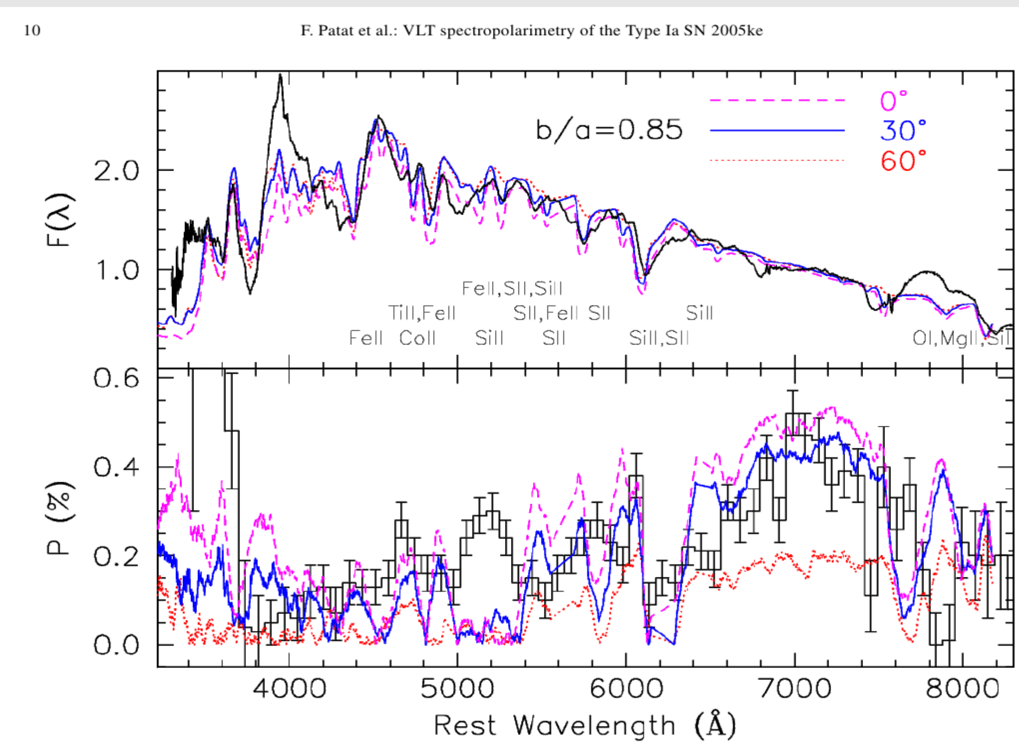
- fast particles

- gamma-rays induce spallation

Assumption:
Binding energy per nucleon for silicates

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





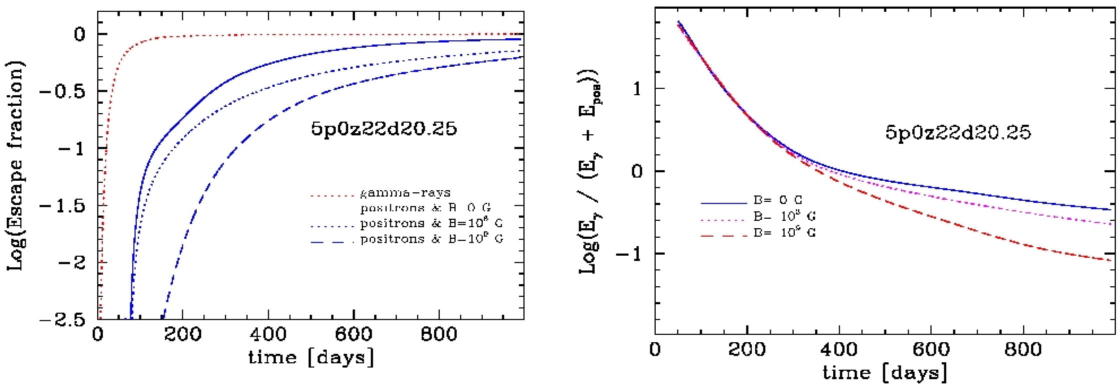
Suggested, inconclusive conclusion

- 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.

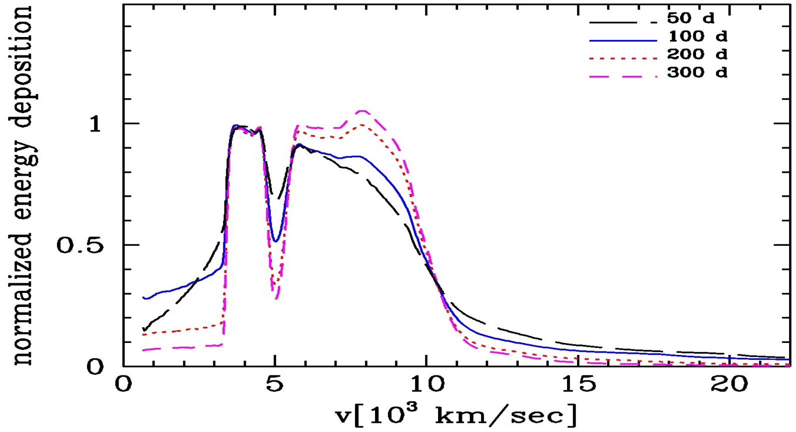
See also 99by Howell et al. 2001

MIR-Evidence for M(Ch): Narrow Ni

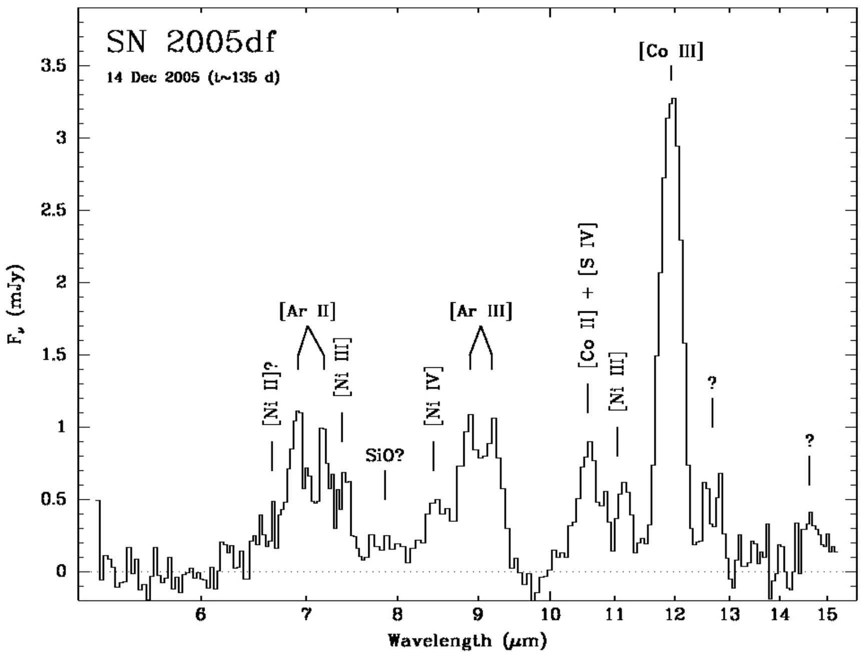
scape fracton of gamma's and positrons



Energy deposition functi

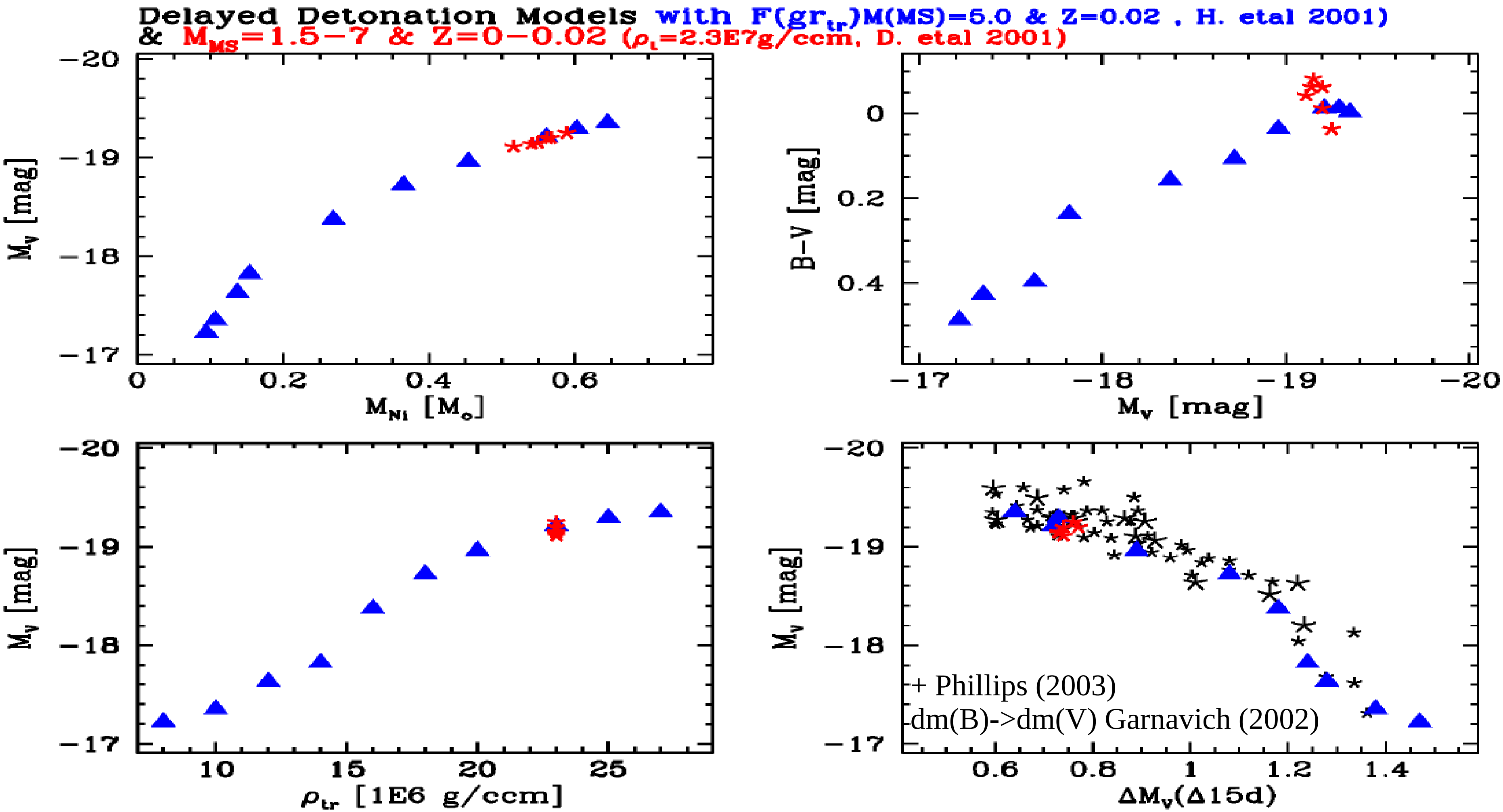


SST (Gerardy et al. 2007): SN05hv



Comparison with Observations

e brightness decline relation and colors (Hoeflich et al. 1996, 2001)



- **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 !!!

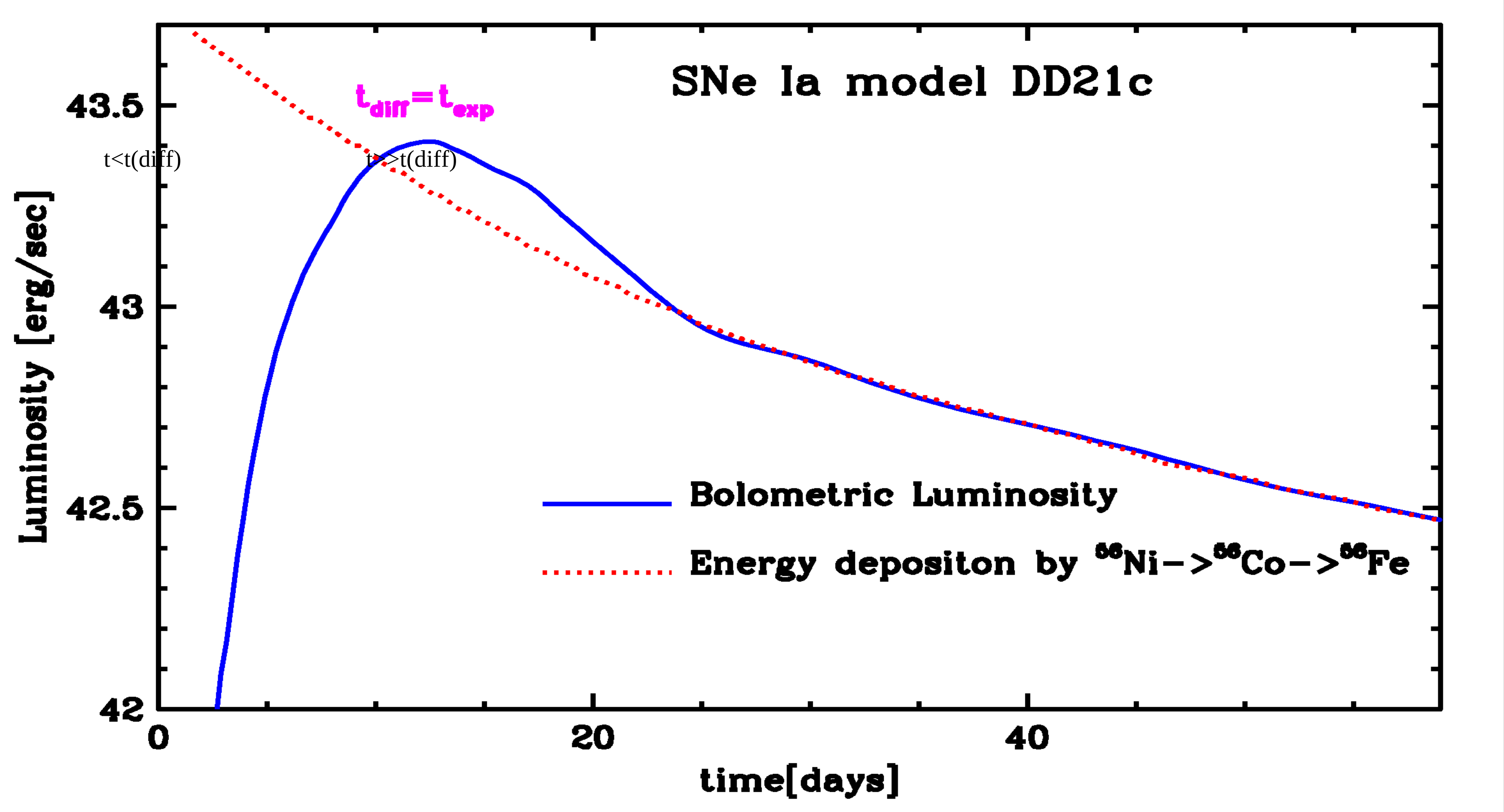
I) The Brightness Decline Relation:Light Curves in a Nutshell

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 low energy photons + geometrical dilution by expansio



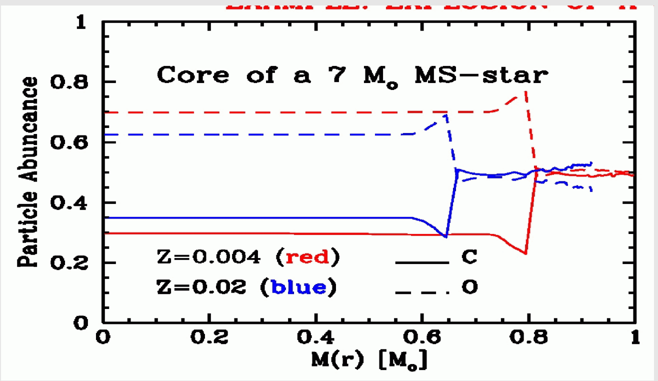
Progenitor Signatures in Differentials of SNIa pairs

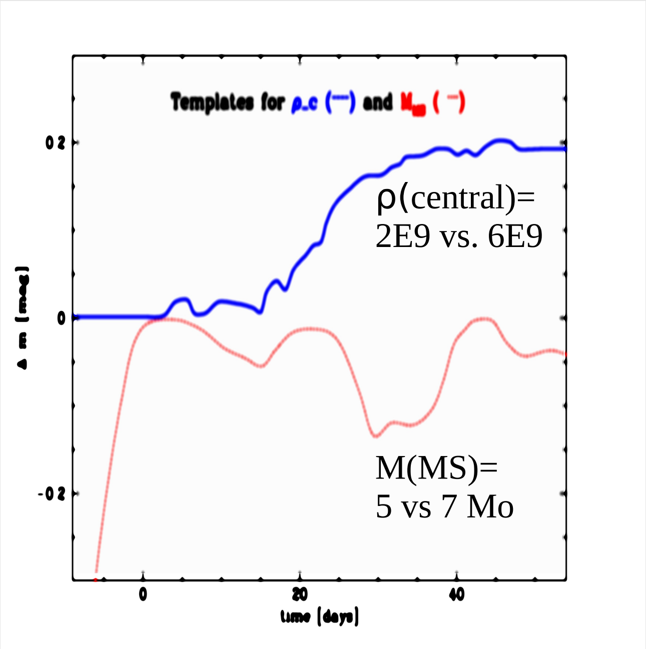
Differential change light-curves after Stretch (Hoeflich et al. 2010)

Observations (Fogliatti et al. 2010)

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

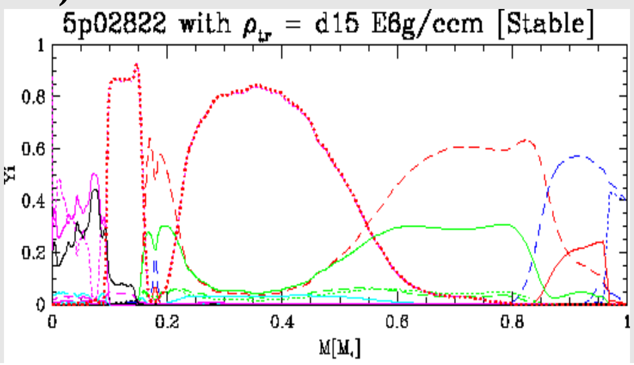
Theory (predicted, H.etal 98)





Accretion Rate =>

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

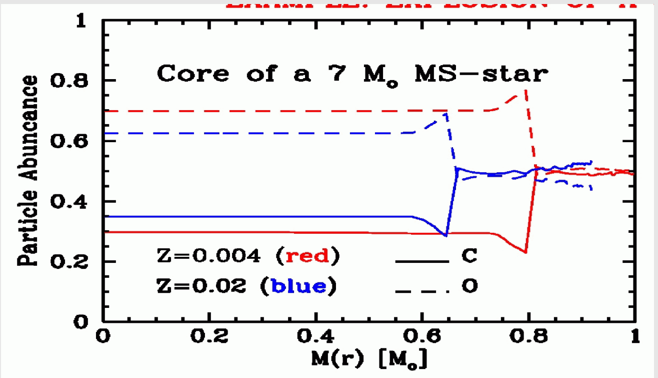


Progenitor Signatures in Differentials of SNIa pairs

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

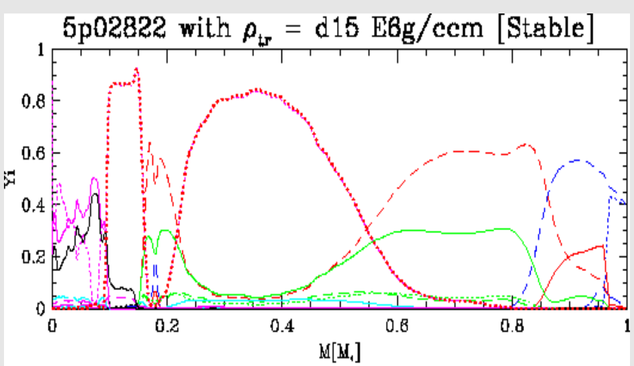
C/O profile of the WD

depends on MS mass and metallicity of WD (from Nomoto, Hetal01)

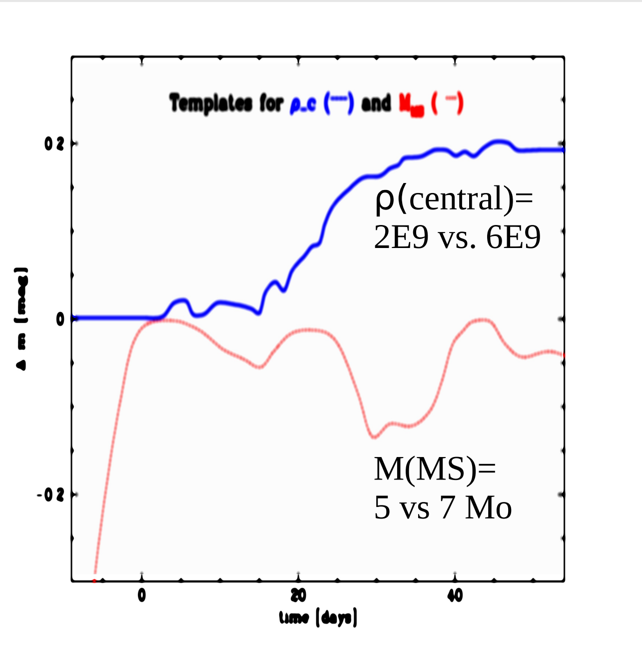


Accretion Rate =>

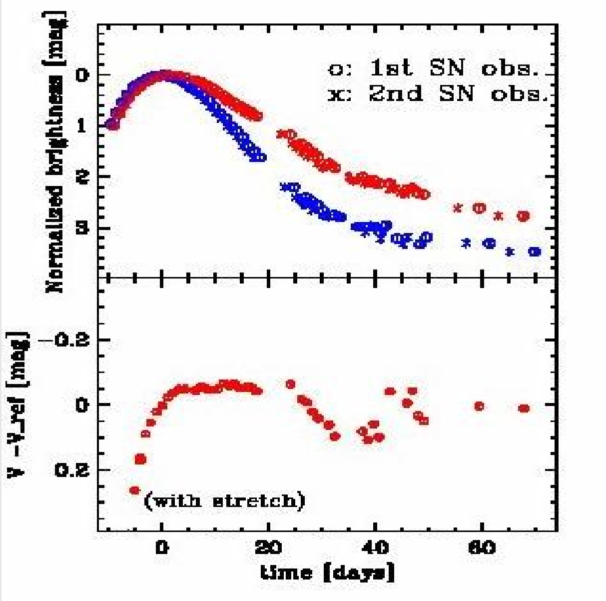
Central density at explosion changes electron capture (Hetal06)

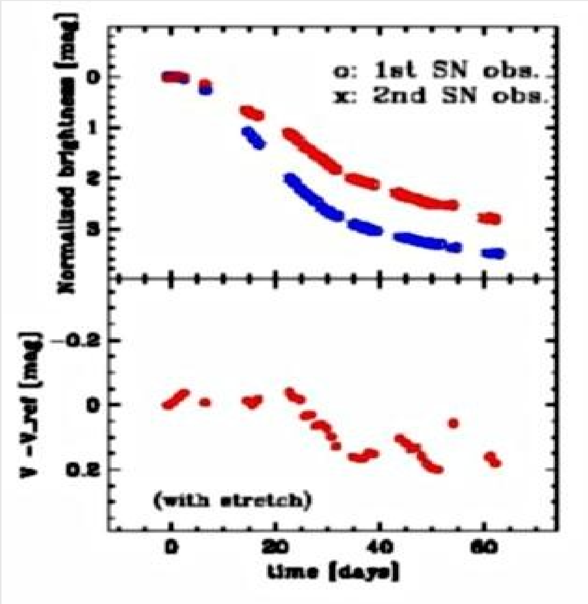


Theory (predicted, H.etal 98)



Observations (Fogliatti et al. 2010)





Analyzing the Differences between SN-Pairs

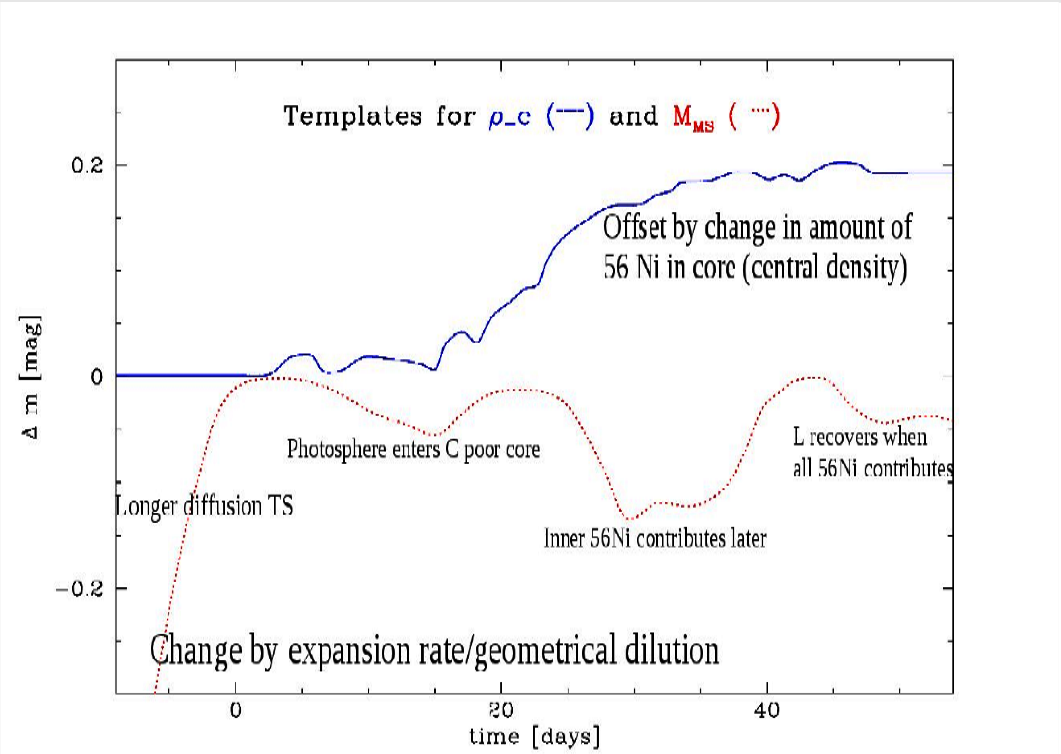
Procedure & Determine the optimal weights (Sadler et al. 2011, 2012)

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

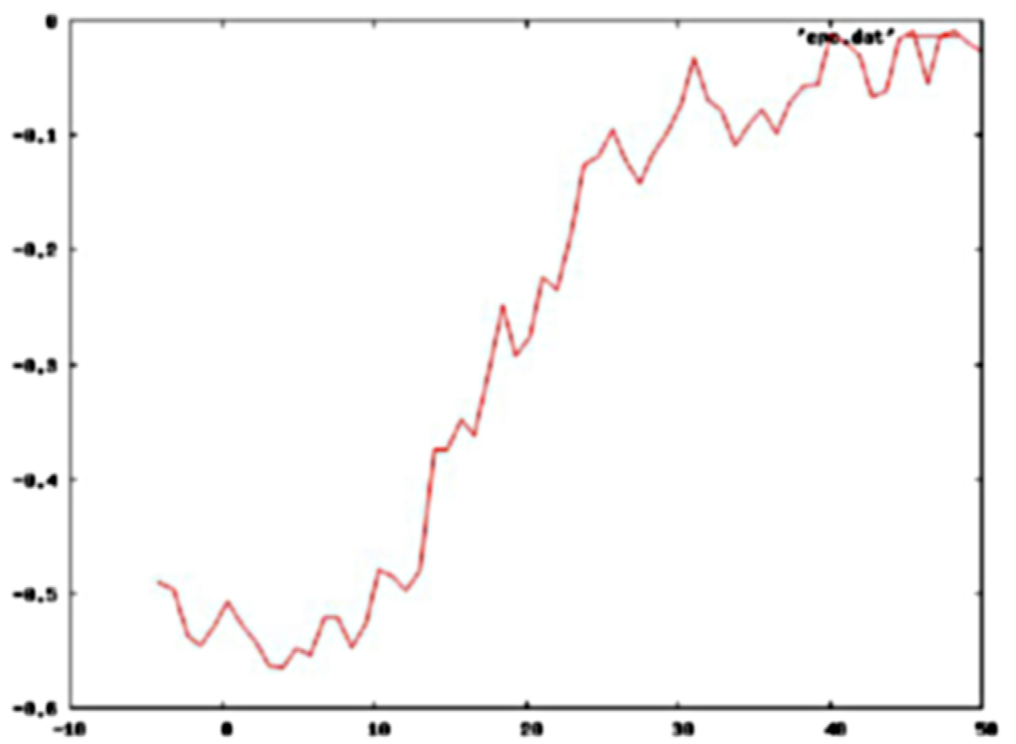
- Use some templates from models
- O(t) minimal (with Gaussian error bars)

Remark:
rho_c is similar
to asphericity
tn Mergers

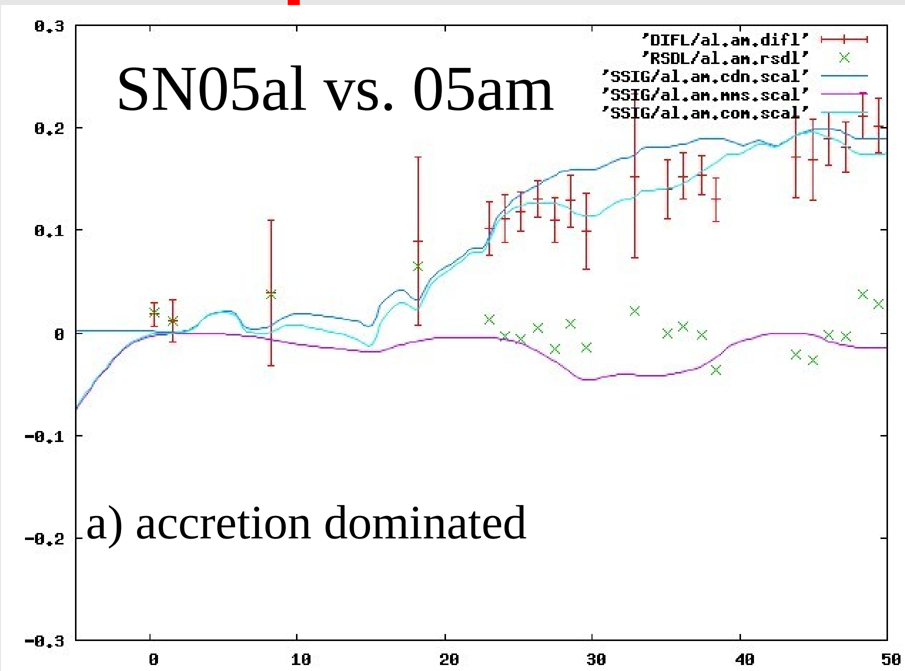
V-templates (rho_c & MS mass)

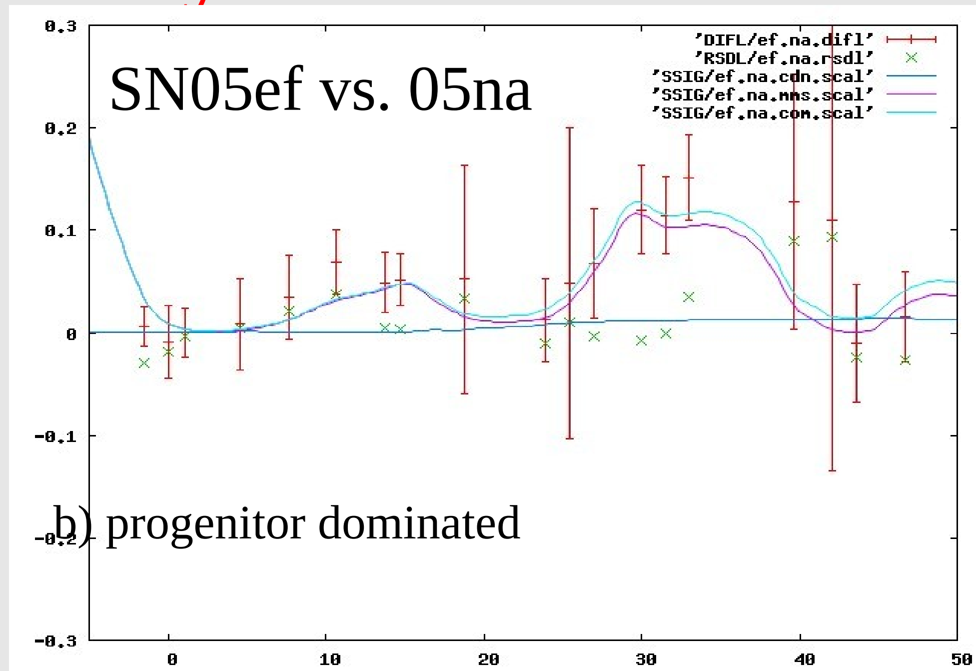


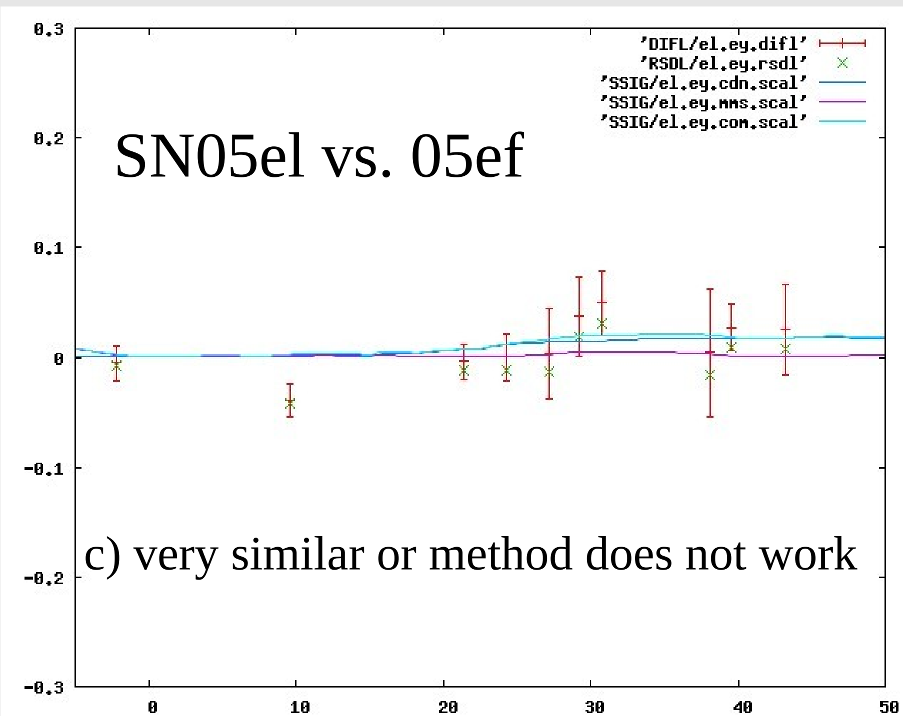
U-templates

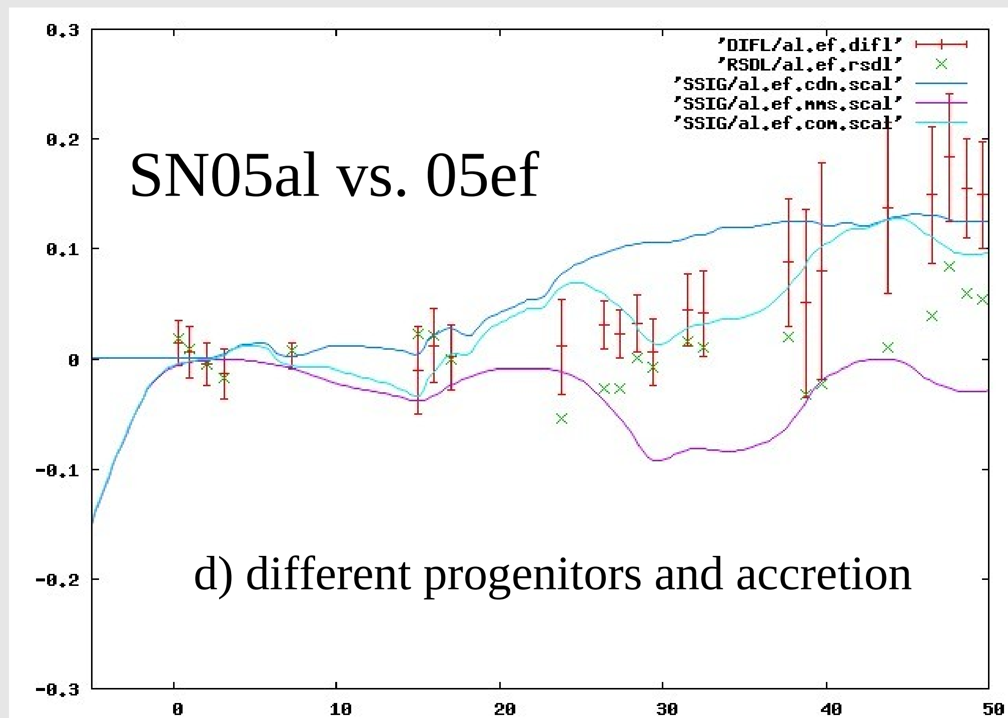


Examples from the CSP survey:





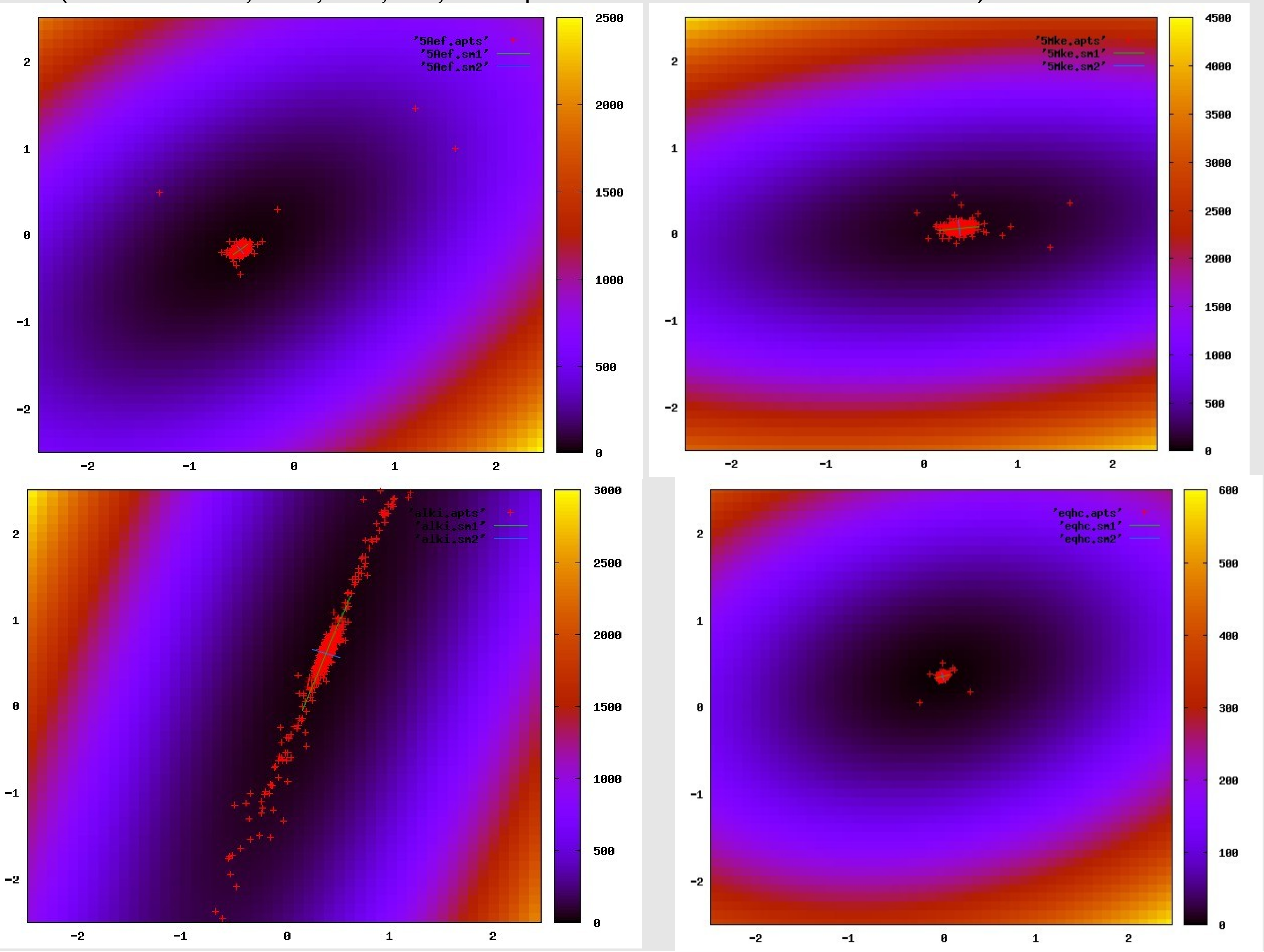




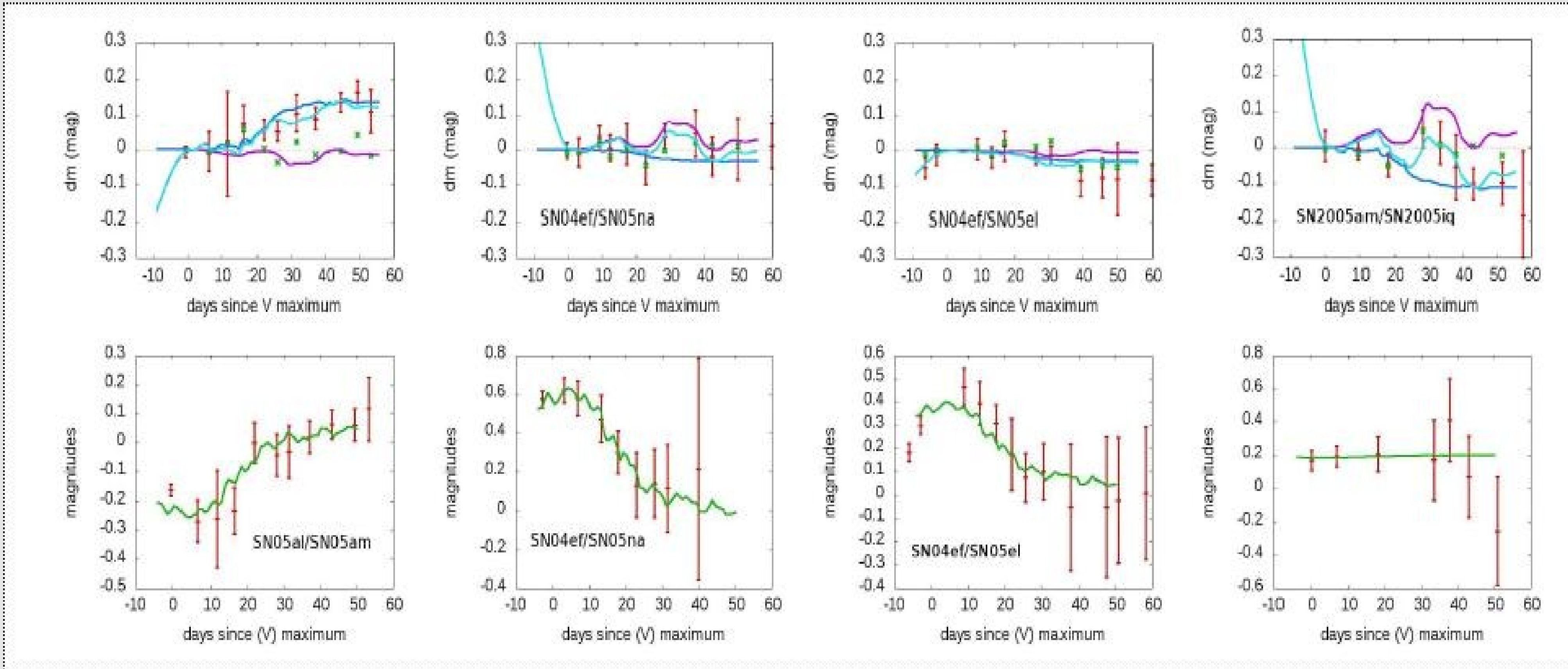
THE UNIQUENESS PROBLEM:

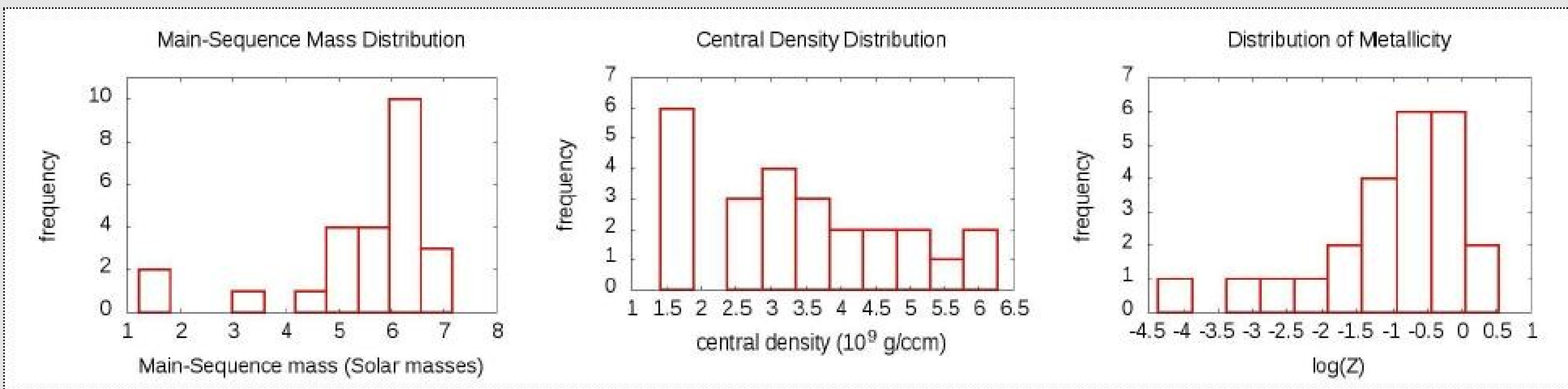
Probability distribution of g1 and g2 by MC starting points

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



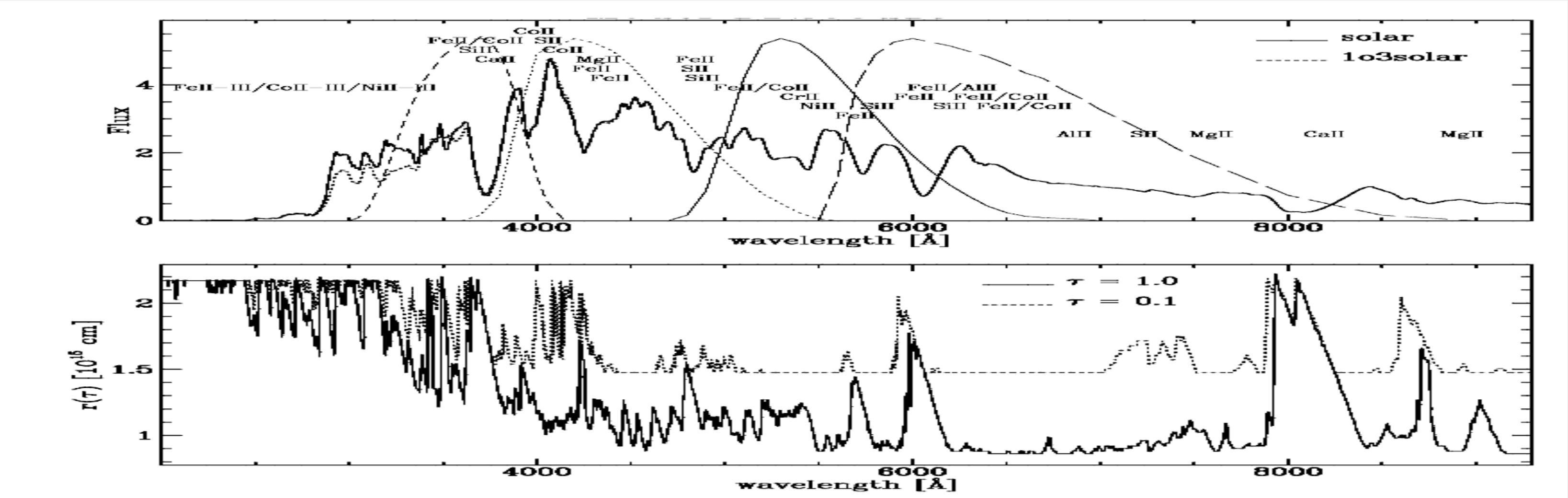
Fits of Actual SN-Pairs & Distribution for CSP





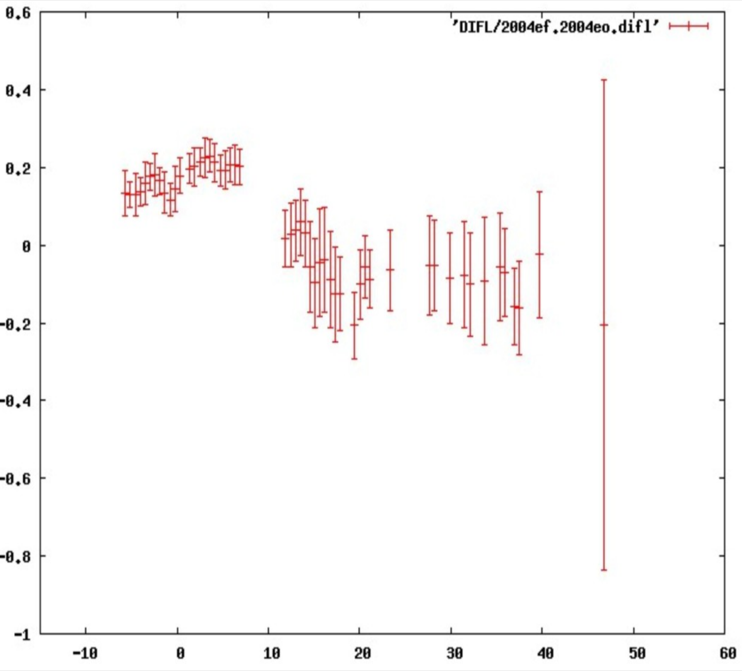
Probing the Metallicty by U (HWT98 & Sadler et al. 2012)

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

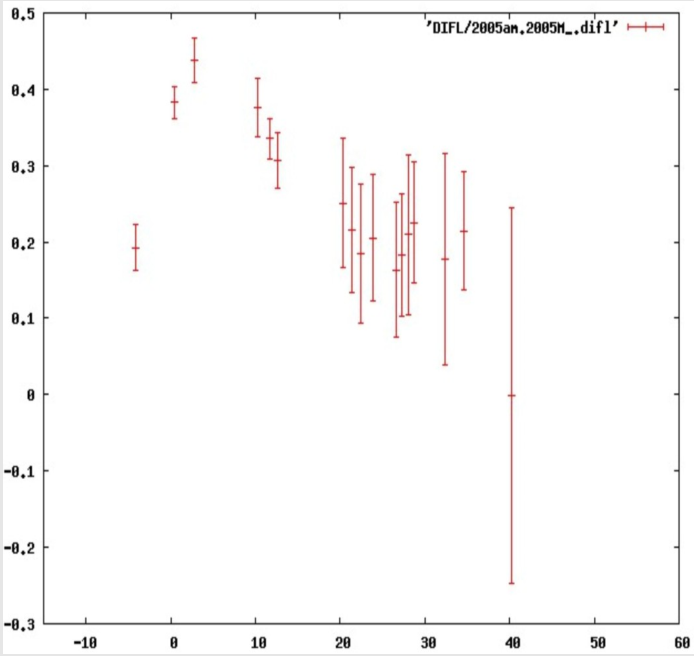


Examples dU(t) : Works often but not always

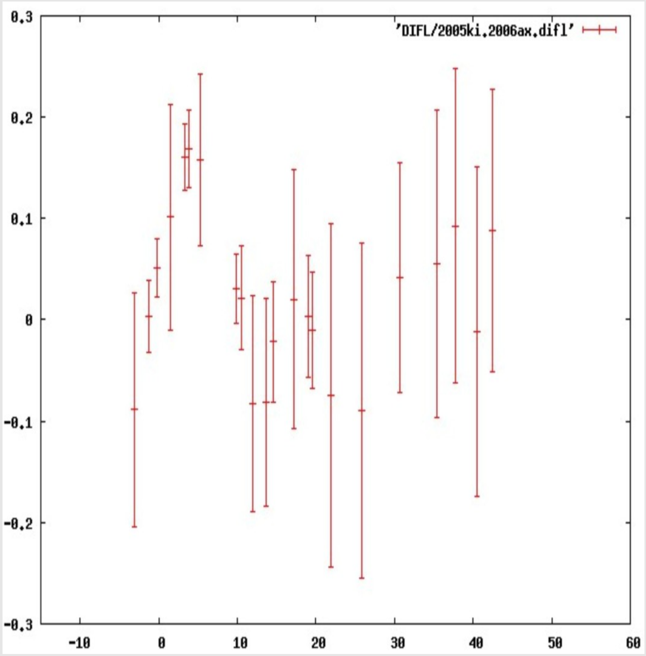
SN05ef vs. 04eo



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