Modelling the SN Ia Light Curve Diversity

Elena Sorokina

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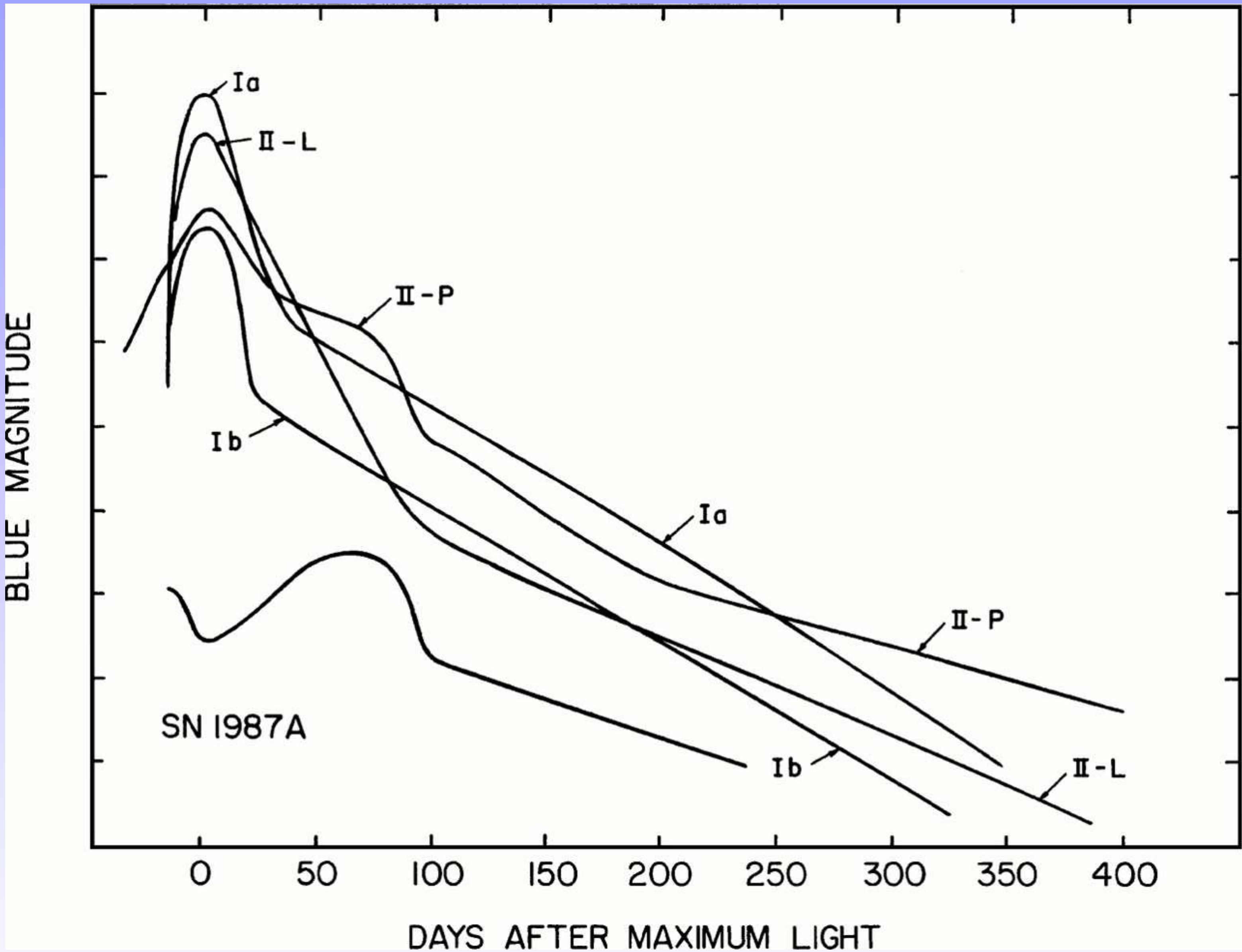
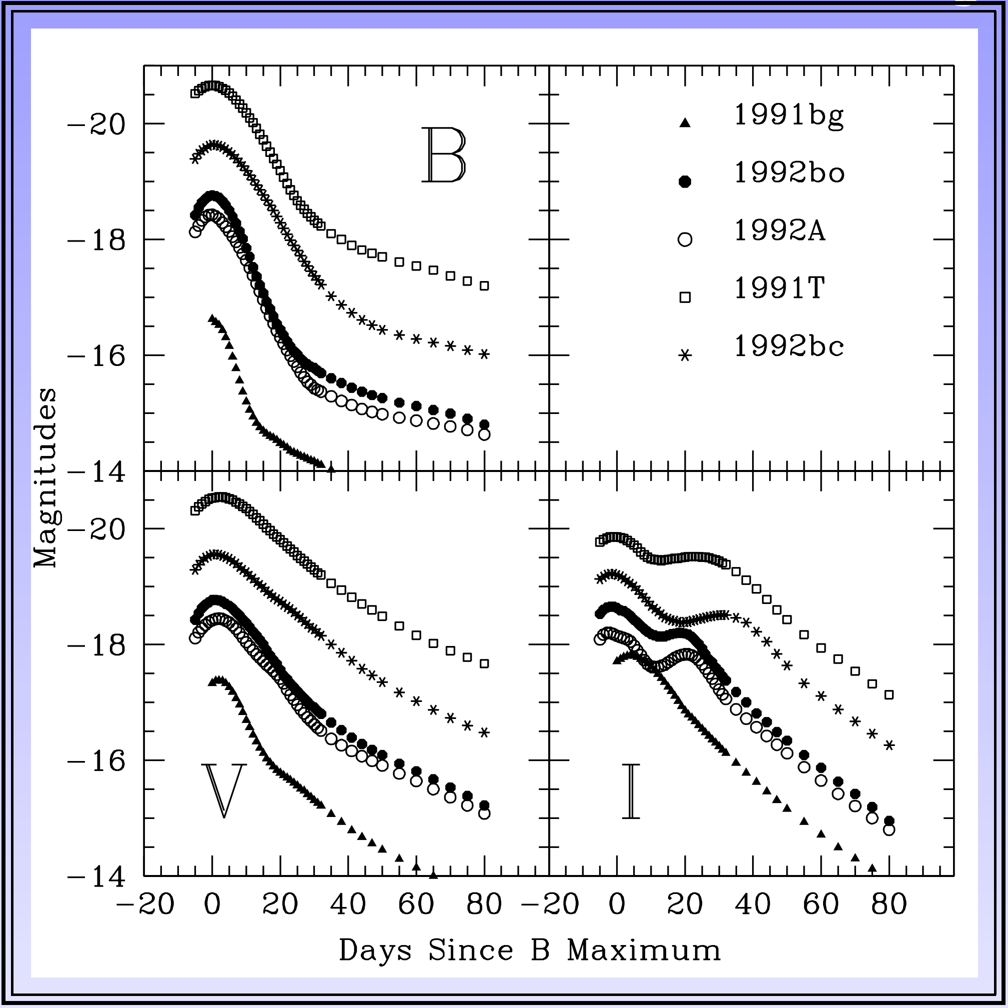
SN Light Curves



SN Ia LC Diversity



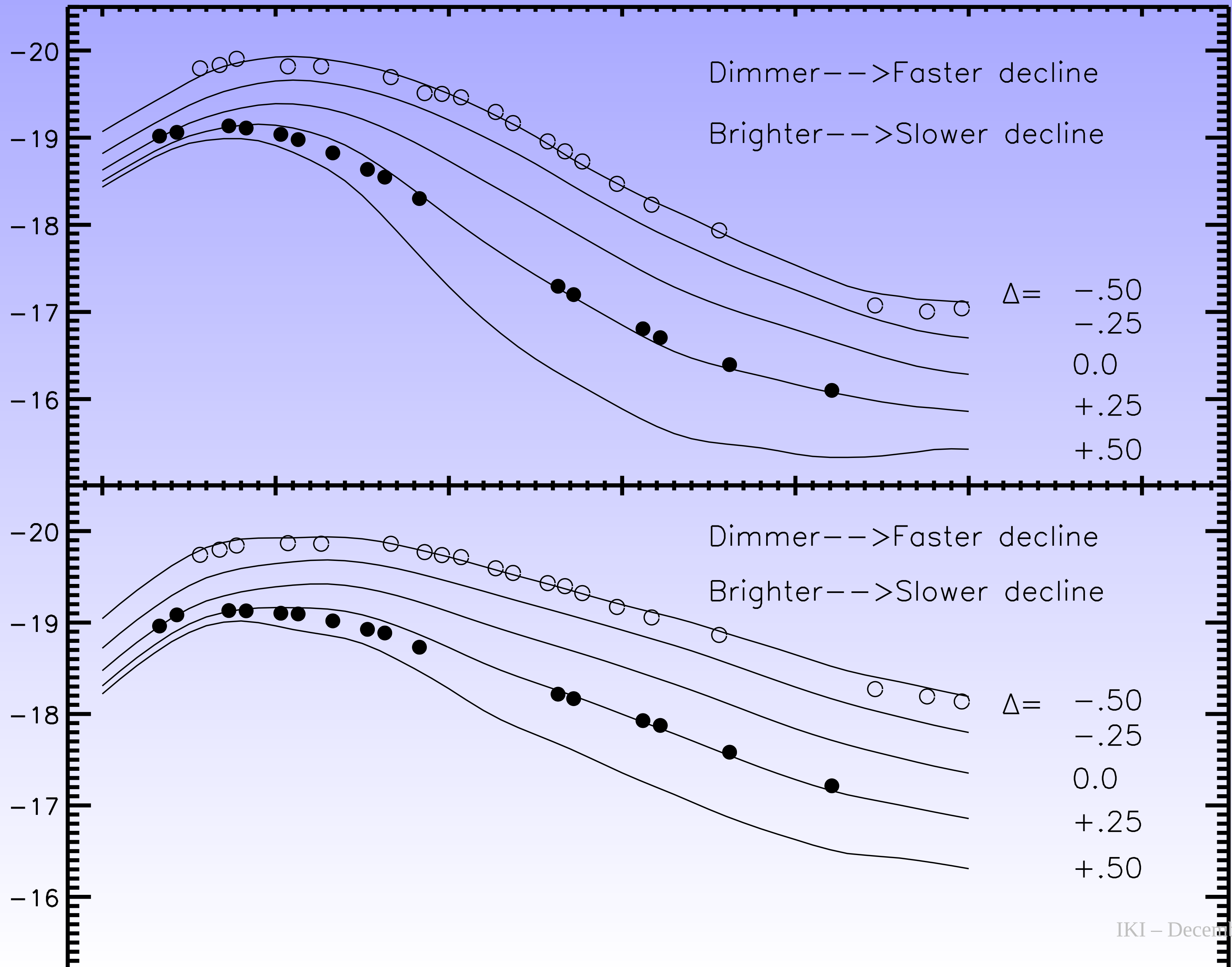
A set of SN Ia in BVI filters, the absolute magnitudes are given

Peak luminosity – decline rate relation

Yu.P. Pskovskii, Astron. Zh. **54**, 1188 (1977)
M.M. Phillips, ApJL **413**, L105 (1993)
See the history in M.Phillips (Padua, 2004)
— PP-relation hereafter
(an example is $B - \Delta m_{15}$ correlation).

More luminous are slower

$B(\Delta m_{15}), V(\Delta m_{15})$



M.Phillips (1993)

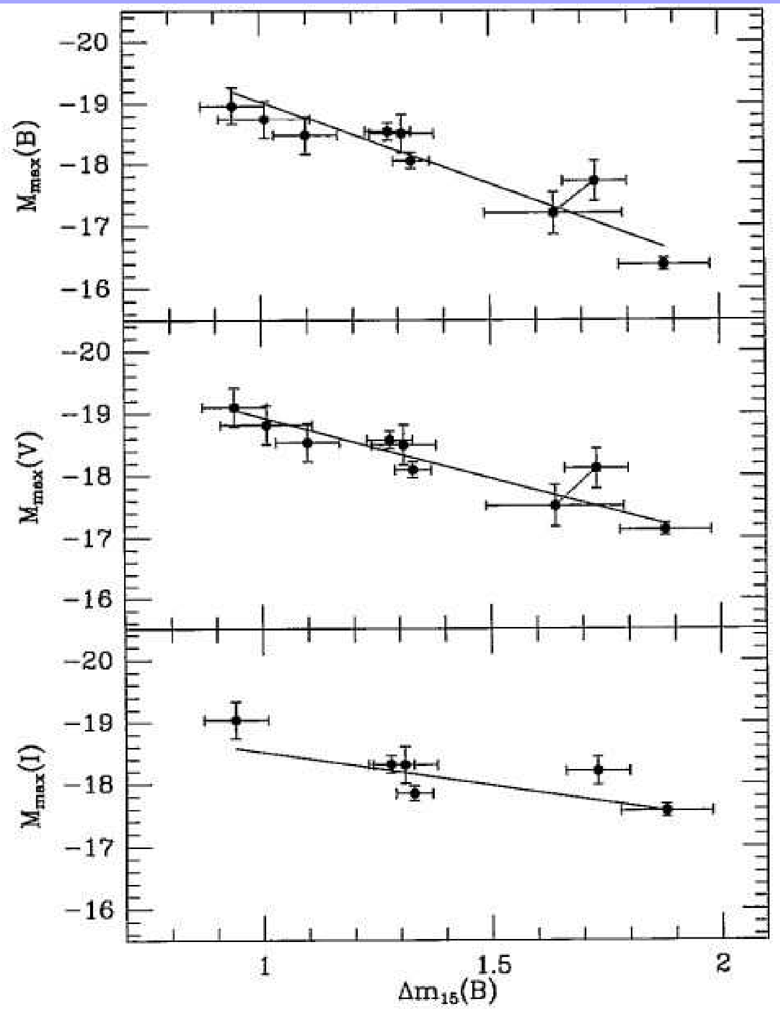
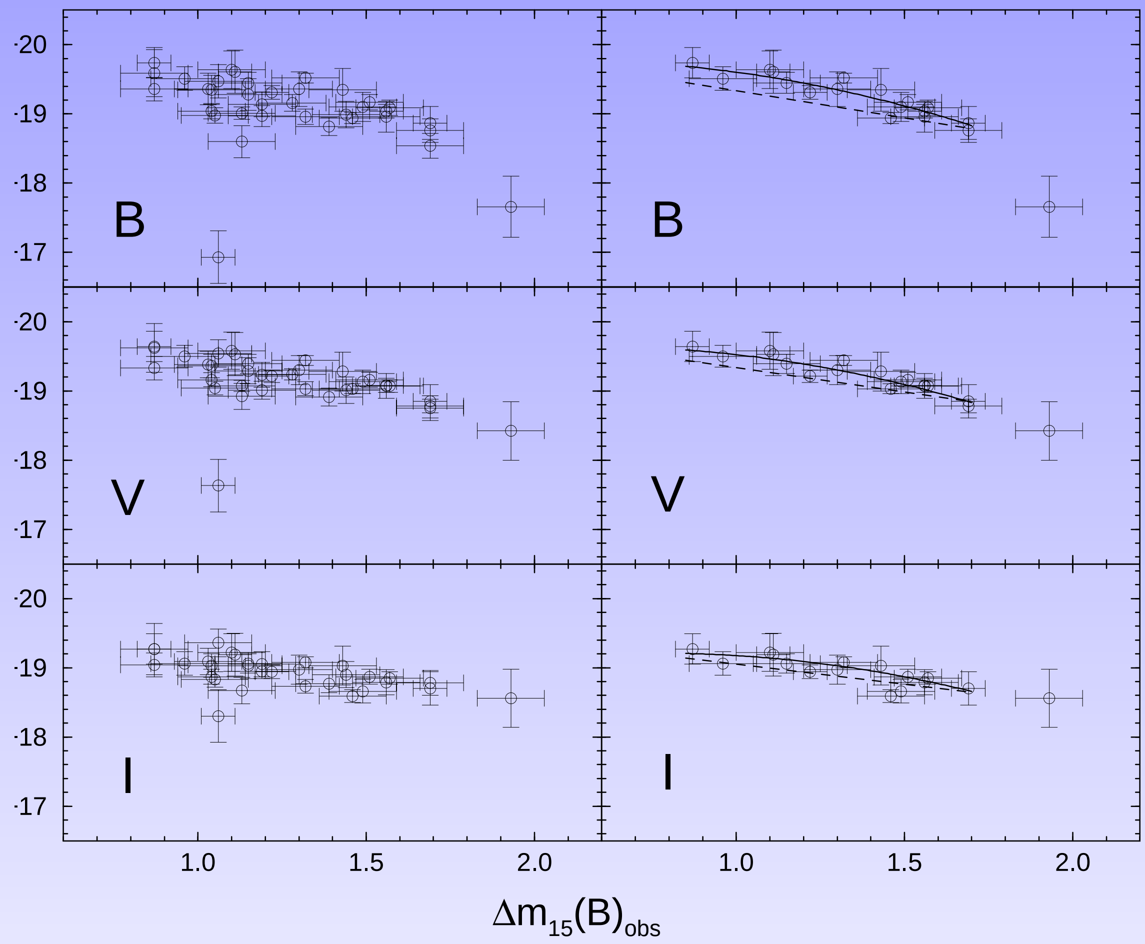
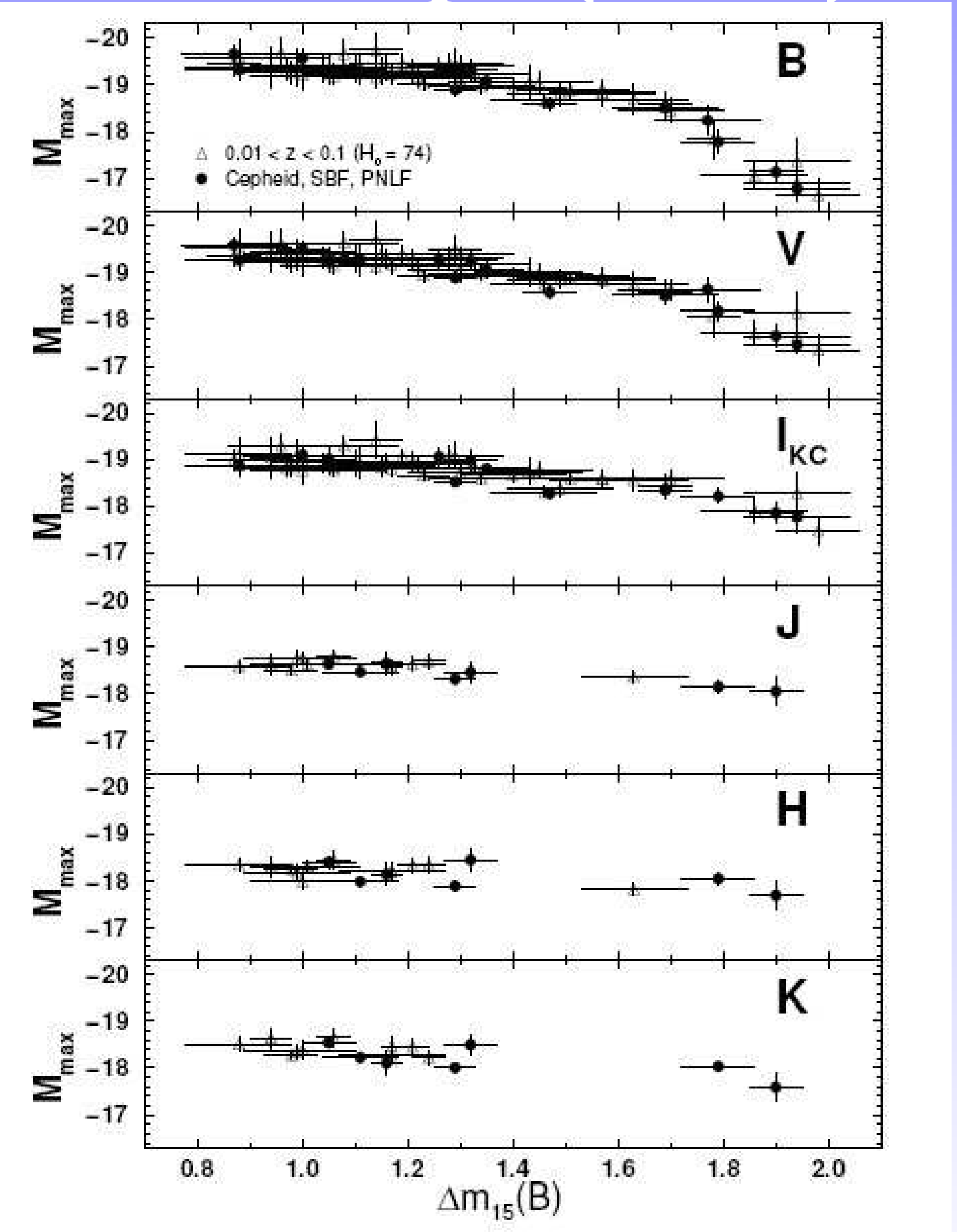


FIG. 1.—Decline rate–peak luminosity relation for the nine best-observed SN Ia's. Absolute magnitudes in *B*, *V*, and *I* are plotted vs. $\Delta m_{15}(B)$, which measures the amount in magnitudes that the *B* light curve drops during the first 15 days following maximum.

Phillips et al. (1999)



Phillips (2005)



Steps to understand PP-relation

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— Radiation transport $\rightarrow$ light curve

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How does light come through the ejecta?
— Radiation transport $\longrightarrow$ light curve

ANOTHER way to check an explosion model:
hydrodynamical interaction with CSM $\longrightarrow$ X-ray spectrum of young SNR, with SN ejecta illuminated by reverse shock wave

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- √ up to ~ 400 zones for the Lagrangean coordinate and up to 200 frequency bins are used

Code STELLA

- √ heating by decays of ^{56}Ni $\longrightarrow$ ^{56}Co $\longrightarrow$ ^{56}Fe with the γ-ray transfer in a one-group approximation following Swartz et al. 1995 (with purely absorptive opacity in the gamma-ray range)

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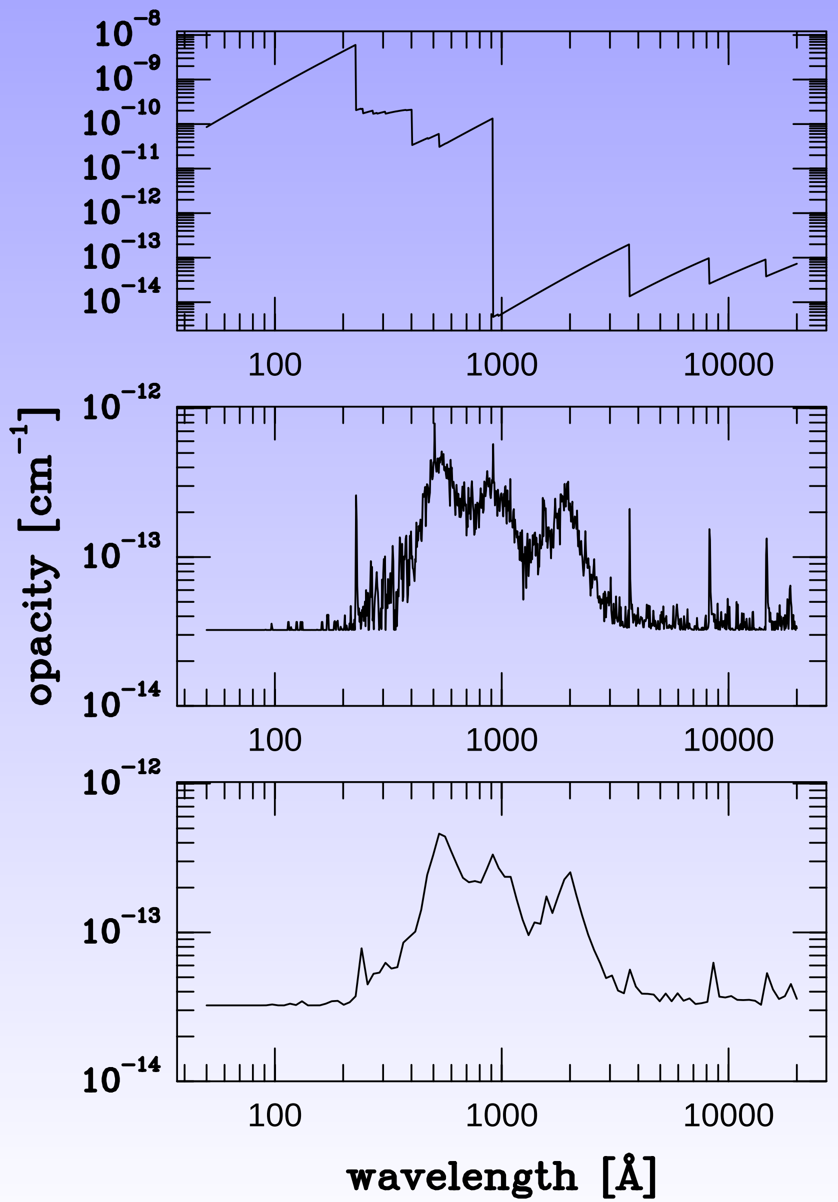
- √ the effect of line opacity is treated as an expansion opacity according to Eastman & Pinto 1993 (and our new recipes).

Opacity

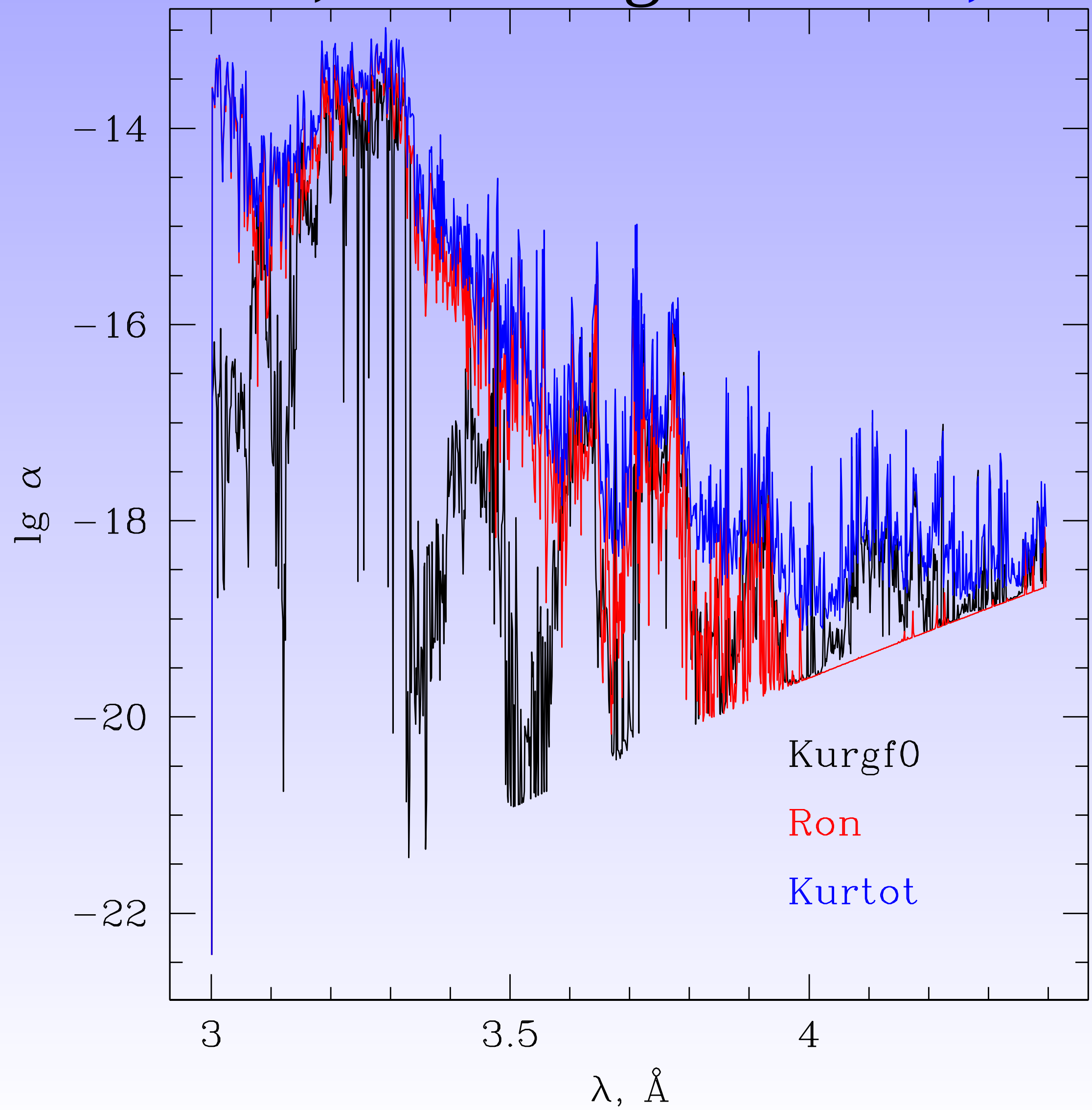


opacity [cm^{-1}]
wavelength [Å]
100
1000
10000
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}

Different Kurucz line lists (1000 frequency bins)

$\rho = 10^{-14}$ g/cm^3, $T = 15 \cdot 10^3$ K

155,000 lines   300,000 strong lines   26,000,000 lines



Different Kurucz line lists (100 frequency bins)

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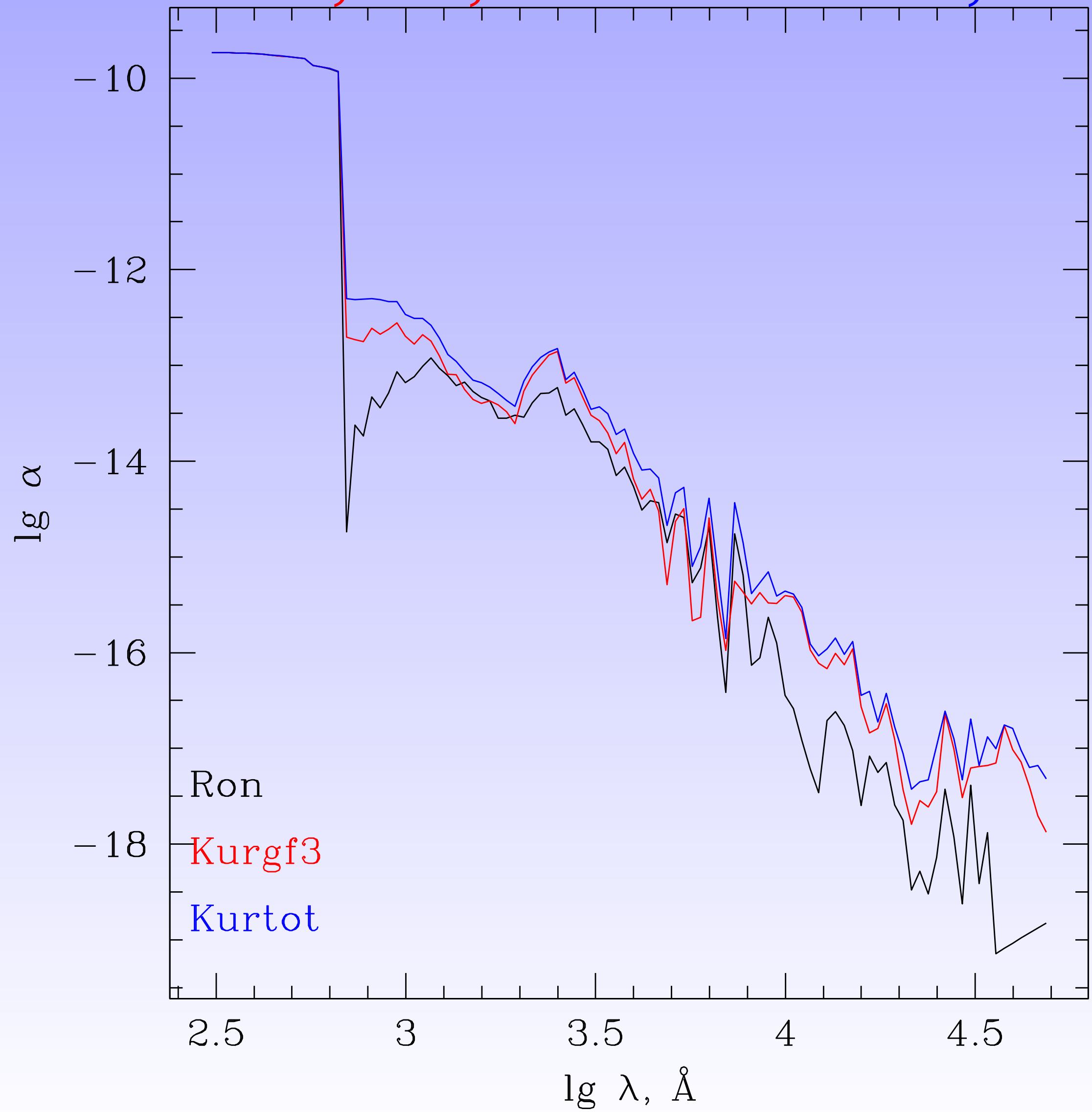
155,000 lines 11,000,000 lines 26,000,000 lines



How to understand nature of SN Ia through their light curves

Light curves for hydrodynamical models:
help us to select probable ways of explosion and decline unrealistic ones;

Light curves for “toy” models:
show the structure of SN ejecta which leads to realistic light curve (The way to obtain this structure may still remain unknown);
allow to choose subsets of models which fit observational dependences, like PP-relation.

Different SNe Ia models

W7 – deflagration, Chandrasekhar mass (Nomoto et al. 1984);
DD4 – delayed detonation, Chandrasekhar mass (Woosley, Weaver 1994);
WD065 – very low-mass sub-Chandrasekhar (Ruis-Lapuente et al. 1993)
LA4 – off-center ignition, sub-Chandrasekhar (Livne, Arnett 1995);

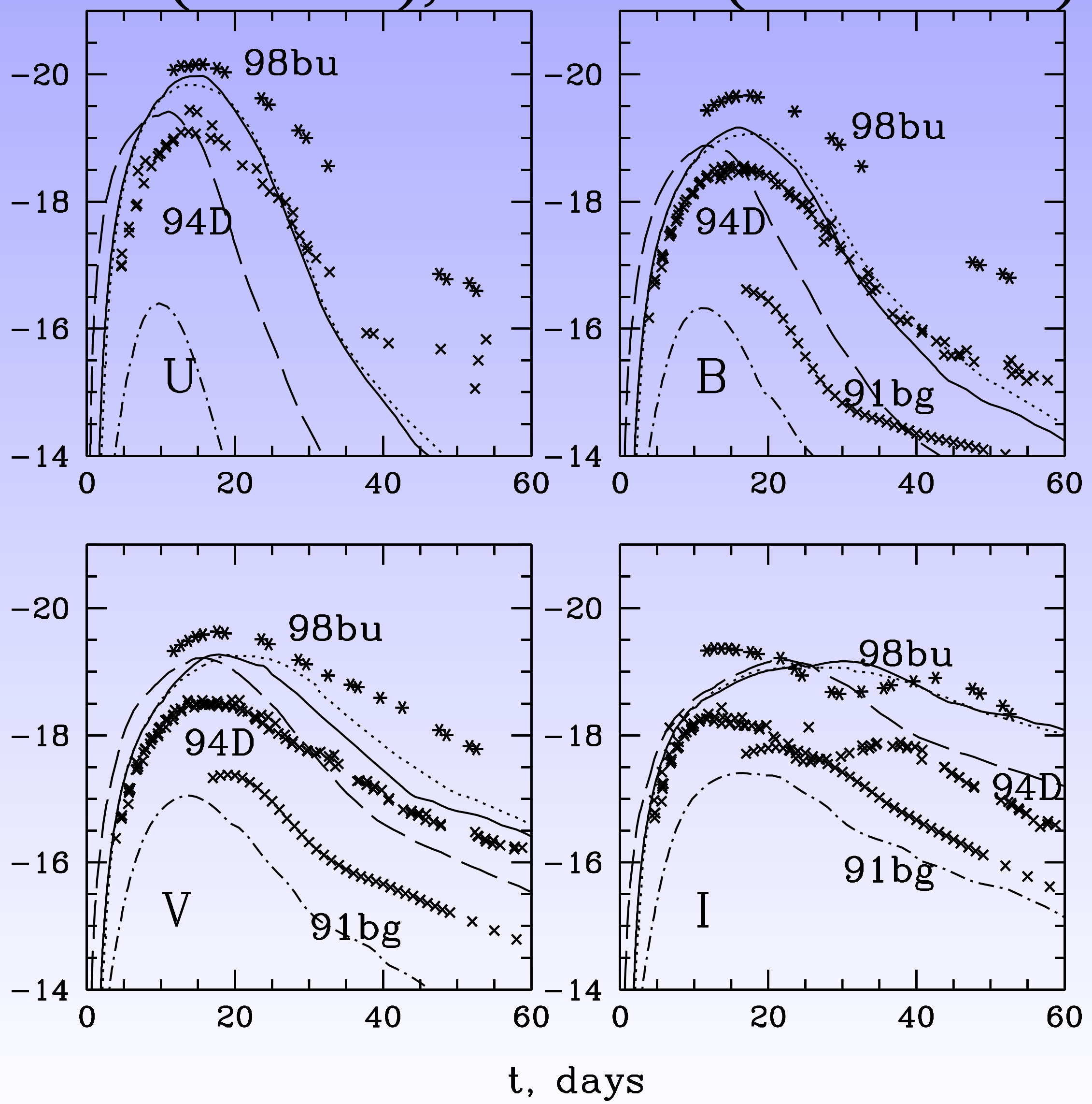
Model	DD4	W7	LA4	WD065	MR0
$M_{\rm WD}$[a]	1.3861	1.3775	0.8678	0.6500	1.4
$M_{^{56}\rm Ni}$[a]	0.63	0.60	0.47	0.05	0.42
E_{51}[b]	1.23	1.20	1.15	0.56	0.46

[a]in $M_\odot$

[b]in 10^{51} erg s^{-1}

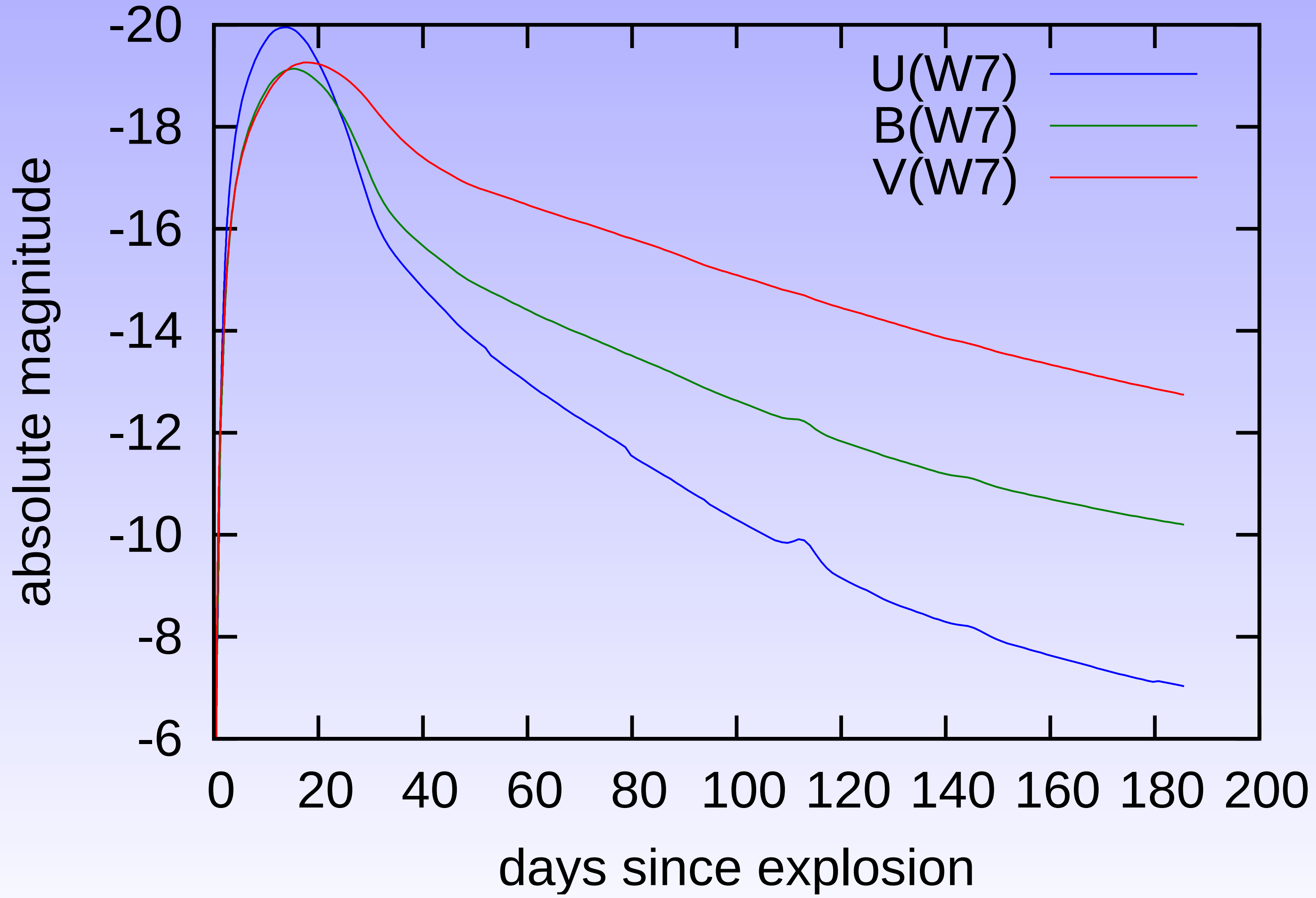
SN Ia light curves for different models

W7 (solid), DD4 (dots),
LA4 (dashes), WD065 (dash–dots)



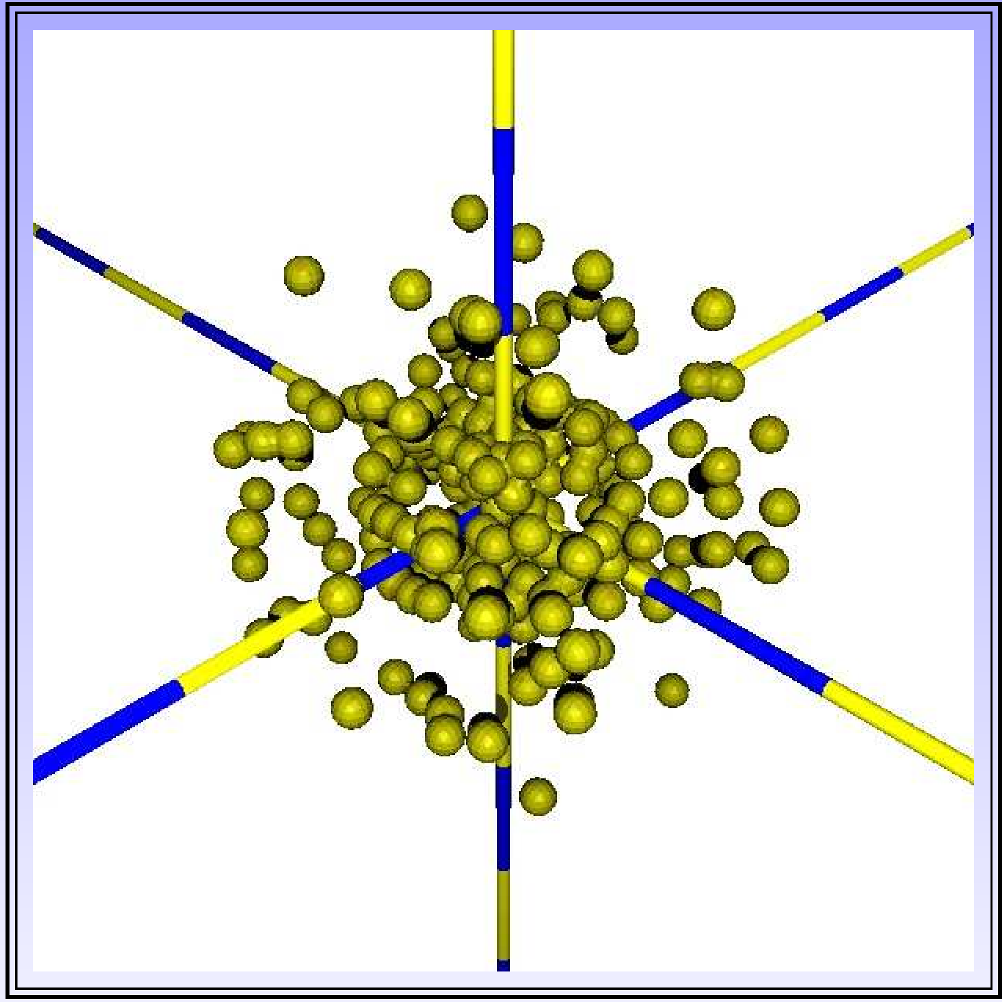
Good ^{56}Ni tail for hundreds days

Kamiya et al. 2008



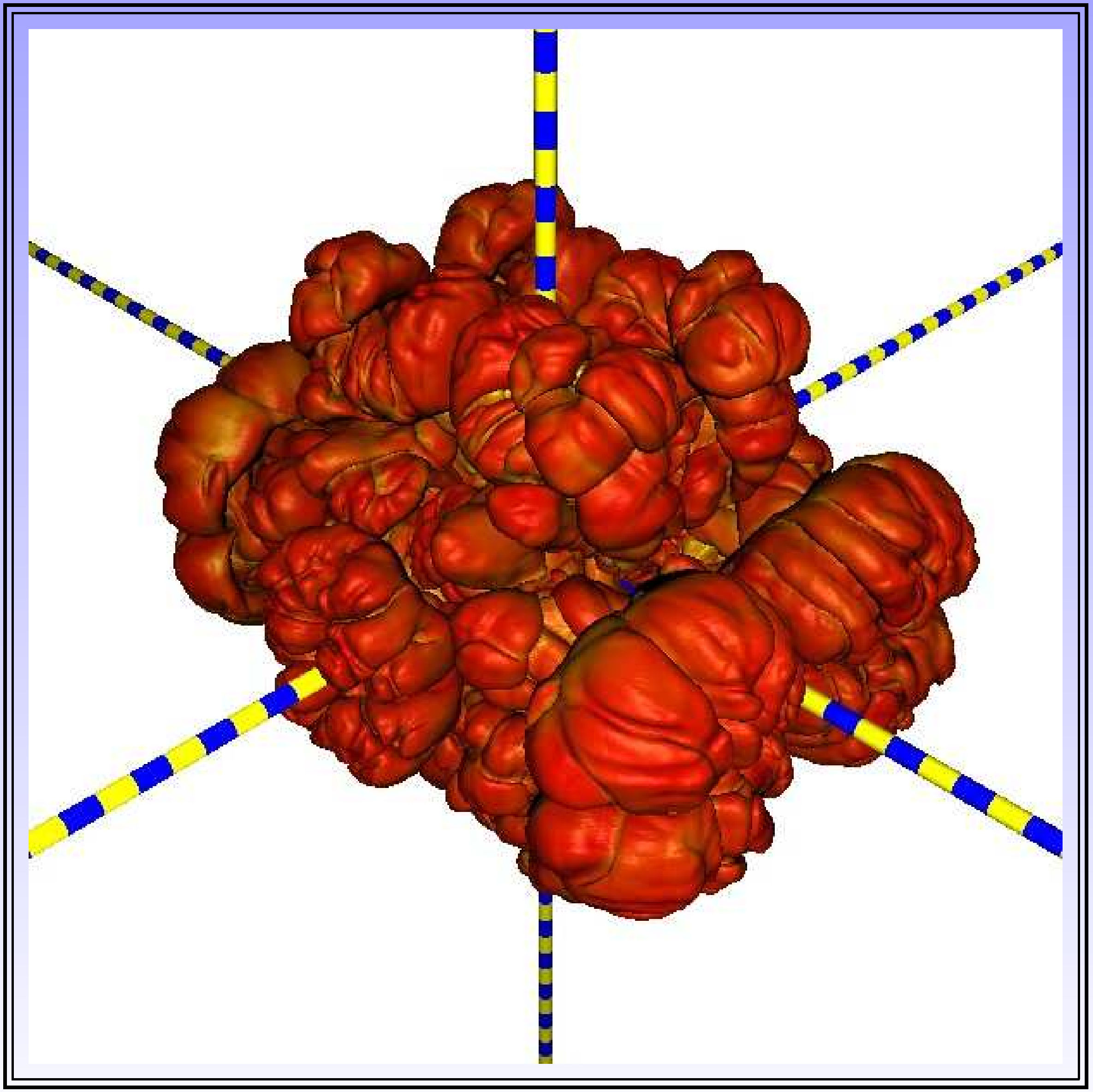
Multi-D SN Ia simulations, MPA

Initial conditions



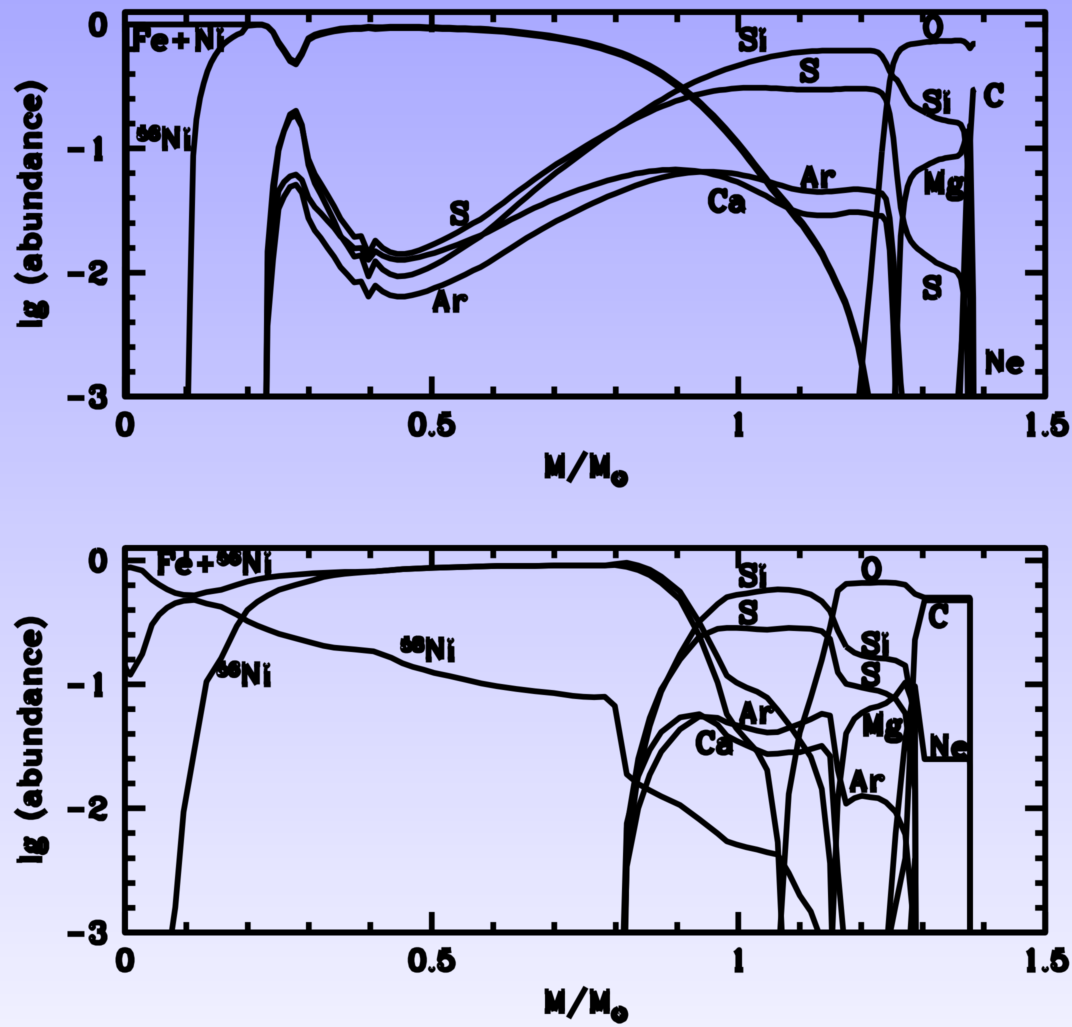
M.Reinecke,
W.Hillebrandt,
J.Niemeyer 2002

t=0.6 s



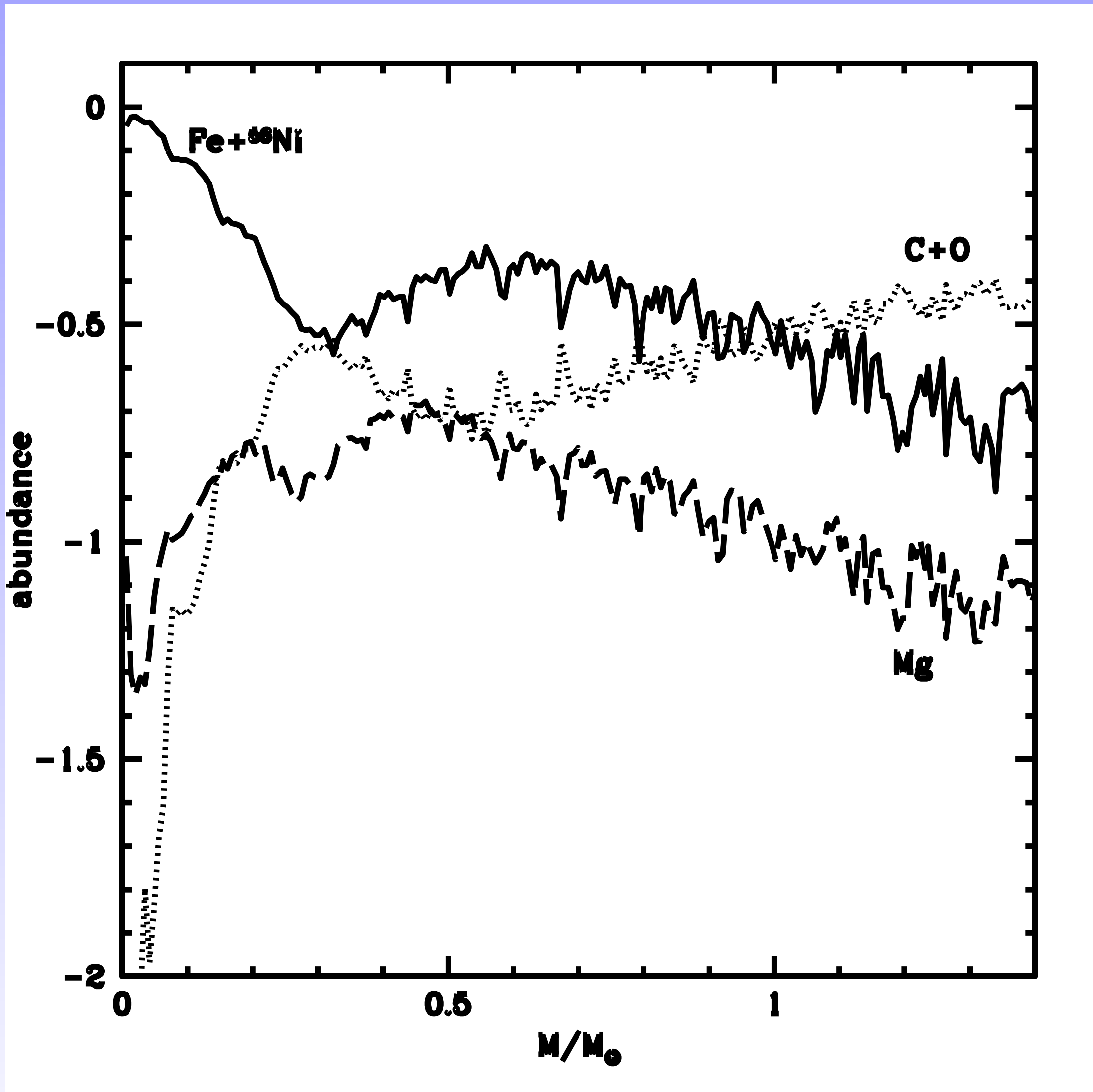
Composition W7 & DD4

While a delayed detonation one DD4 (Woosley, Weaver, 1994; above) and a classical 1D deflagration model W7 (Nomoto, Thielemann, Yokoi, 1984; below) like this:

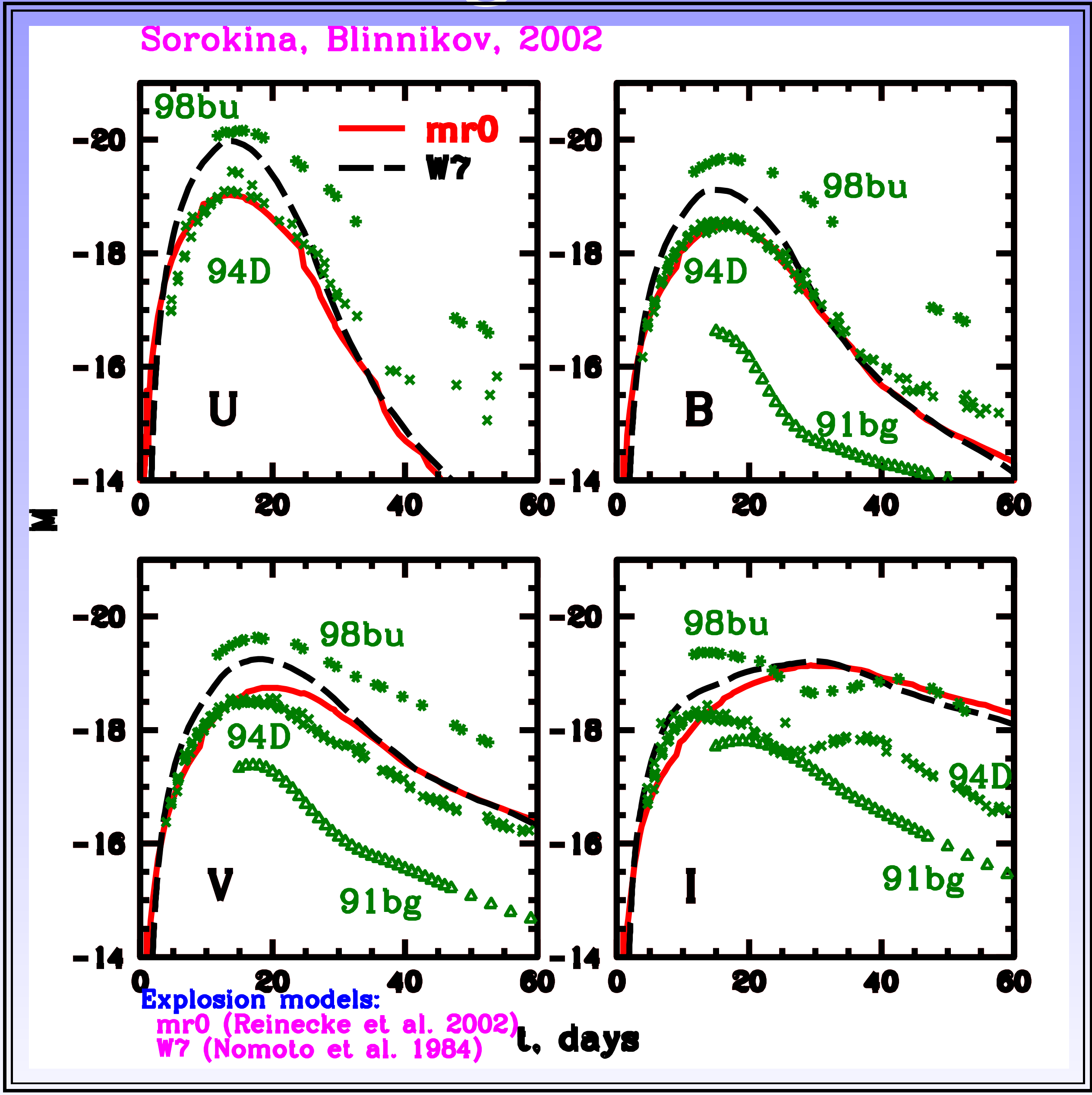


Composition MR0

This explosion produced elements distributed like this (log of abundance is plotted):



LCs for 1st generation model



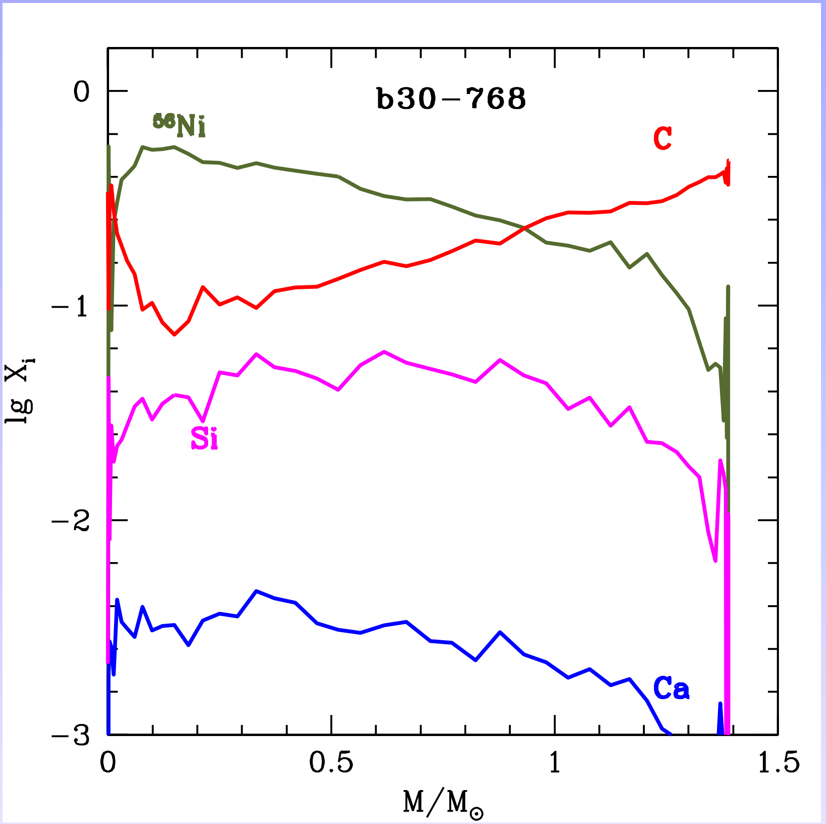
More recent simulations, MPA

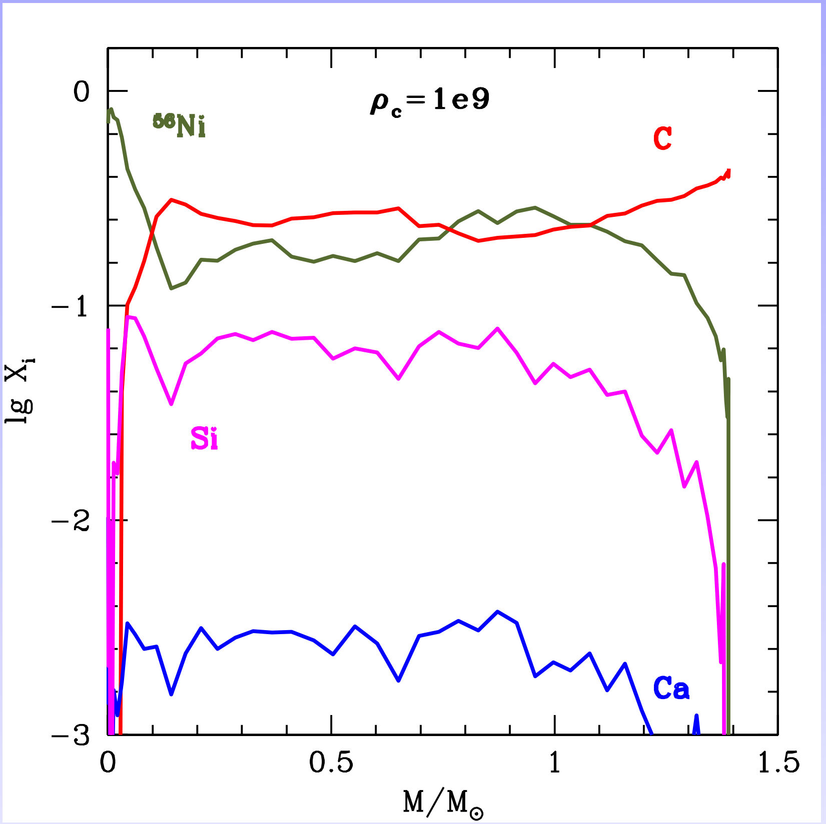
Three-dimensional calculations by F.Röpke, W.Hillebrandt, + nucleosynthesis C.Travaglio

C.Travaglio et al. (2004)
F.Röpke et al. (2005)

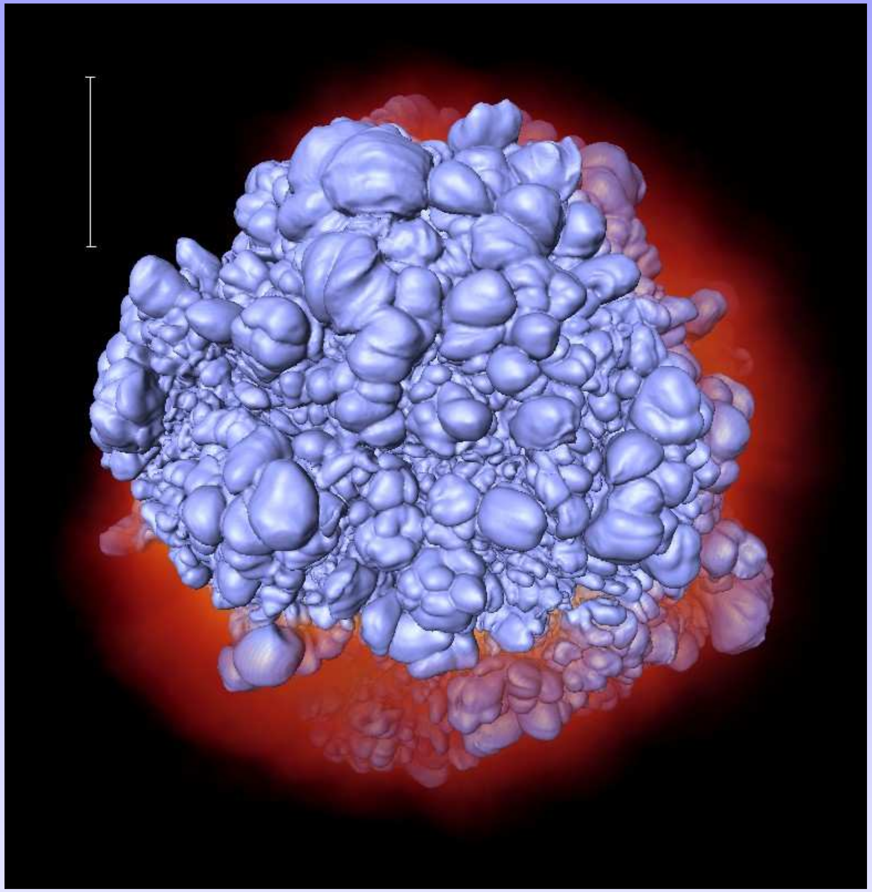
Composition

b30 lc1_2_2





SN Ia 3D-explosion

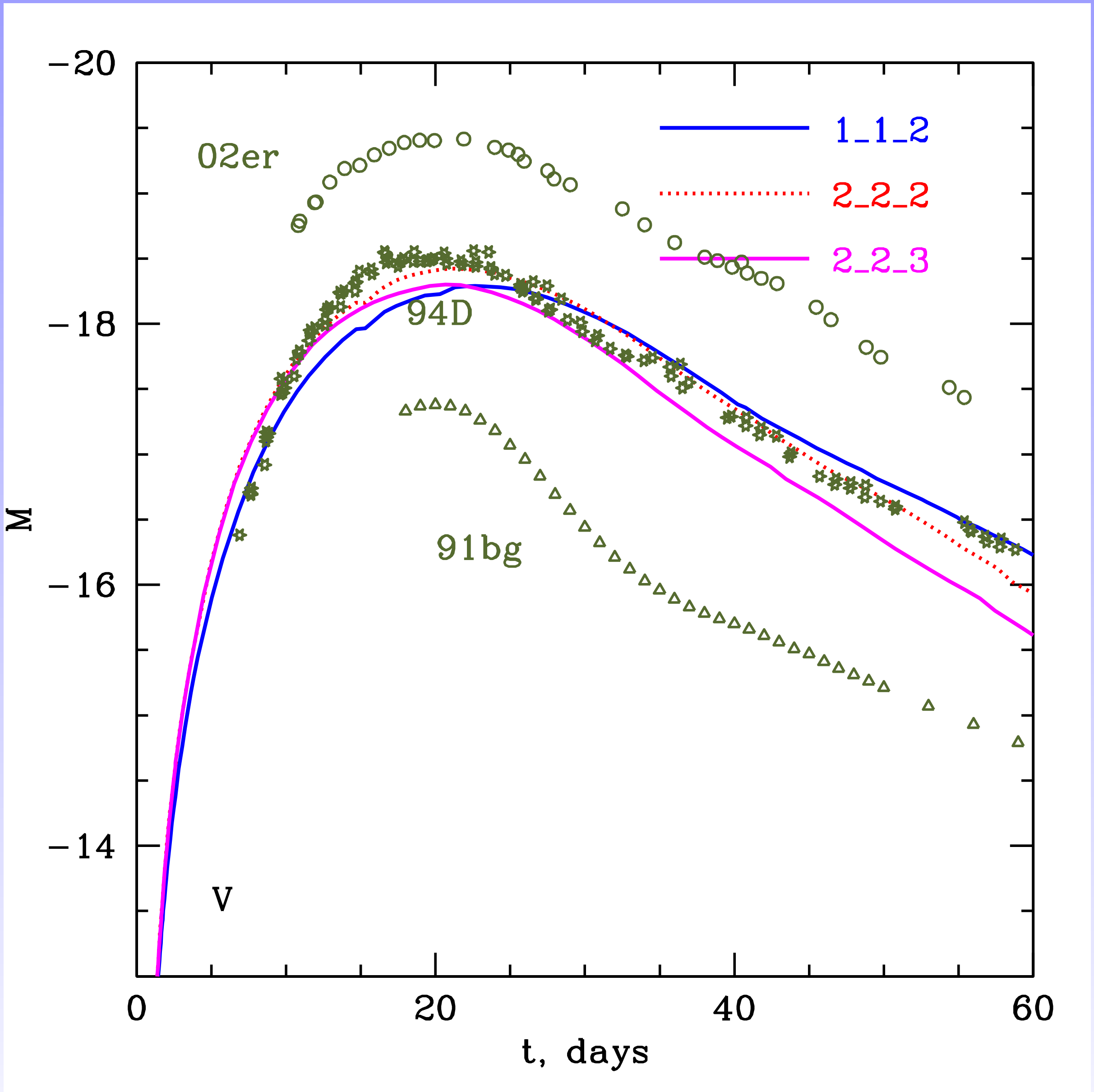


An important way to check those models is to study young SNRs.

$M_{^{56}\mathrm{Ni}}$ and model energetics

model	$M(^{56}\mathrm{Ni})[M_\odot]$	E_{kin}, foe, init	E_{kin}, foe, asympt
1_3_3	0.24	0.357	0.365
2_2_2	0.31	0.441	0.453
c3_3d	0.28	0.431	0.441
b30	0.42	0.663	0.679

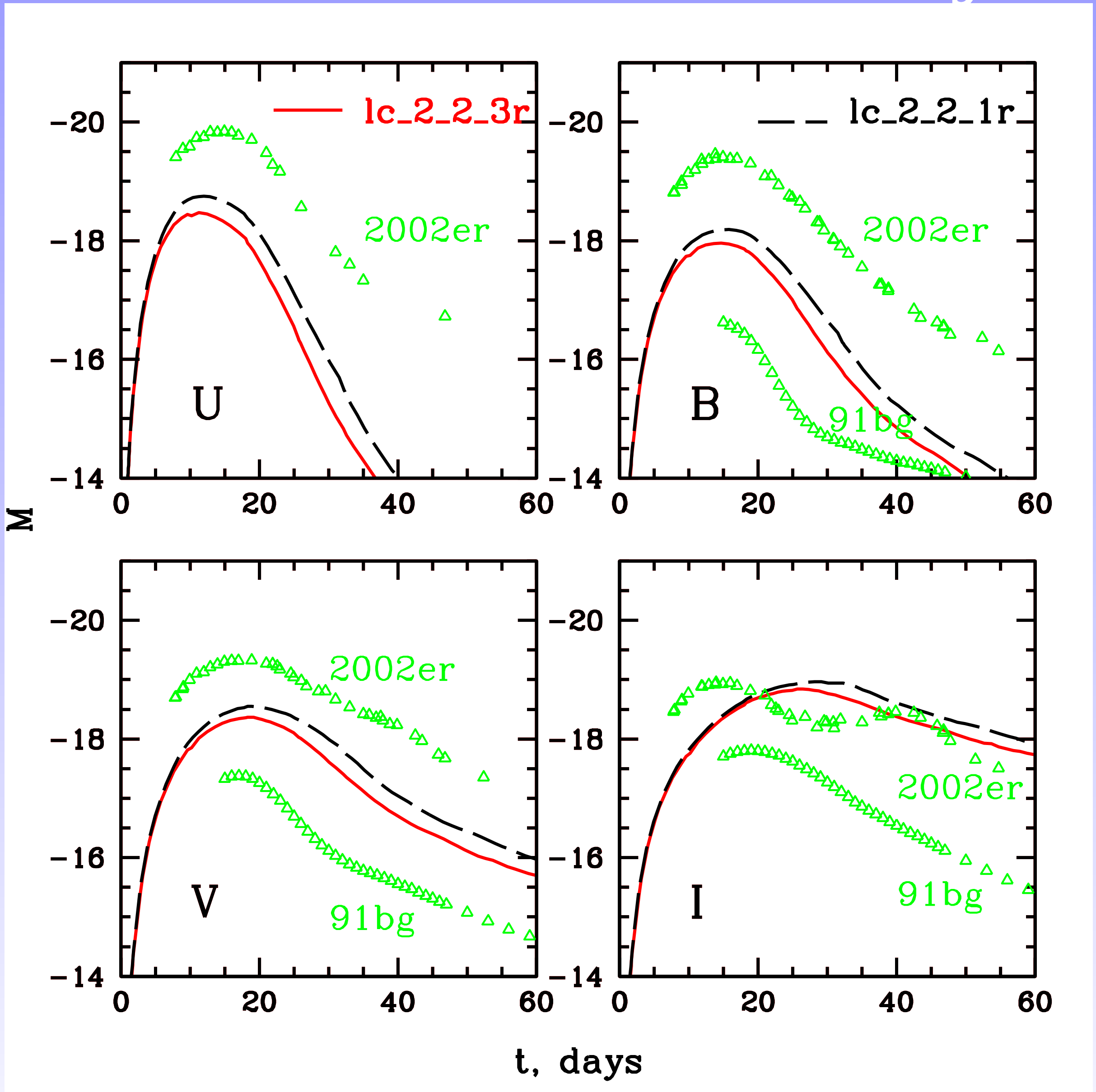
OK in V



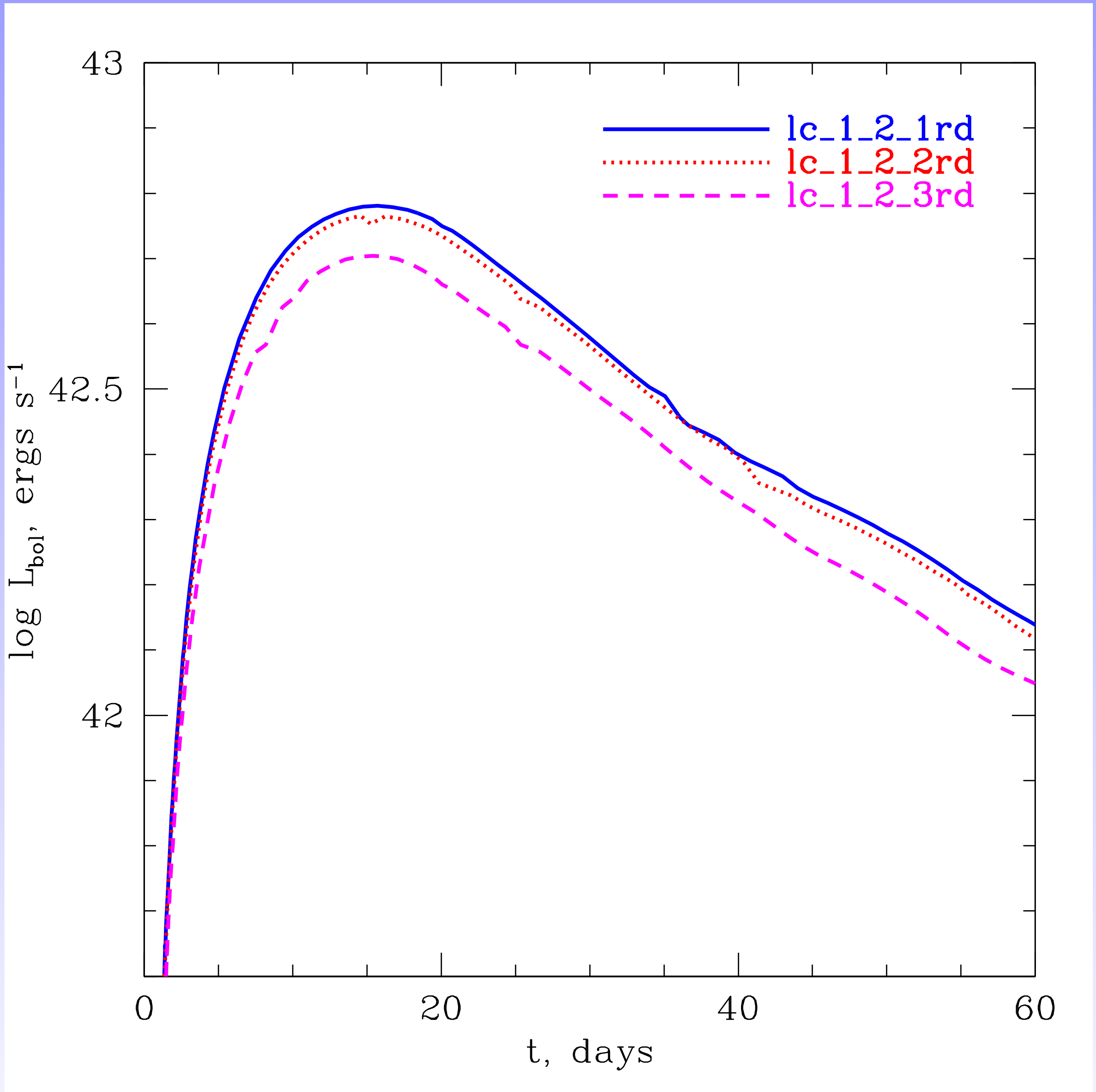
Total Variations of the MPA set

Parameter	range of variation	effect on ^{56}Ni production	effect on total energy
$X(^{12}C)$	[0.30,0.62]	$\leq 2\%$	$\sim$14%
ρ_c [10^9 g/cm^3]	[1.0,2.6]	$\sim$6%	$\sim$17%
Z [$Z_\odot$]	[0.5,3.0]	$\sim$20%	none

Effect of “metalicity”

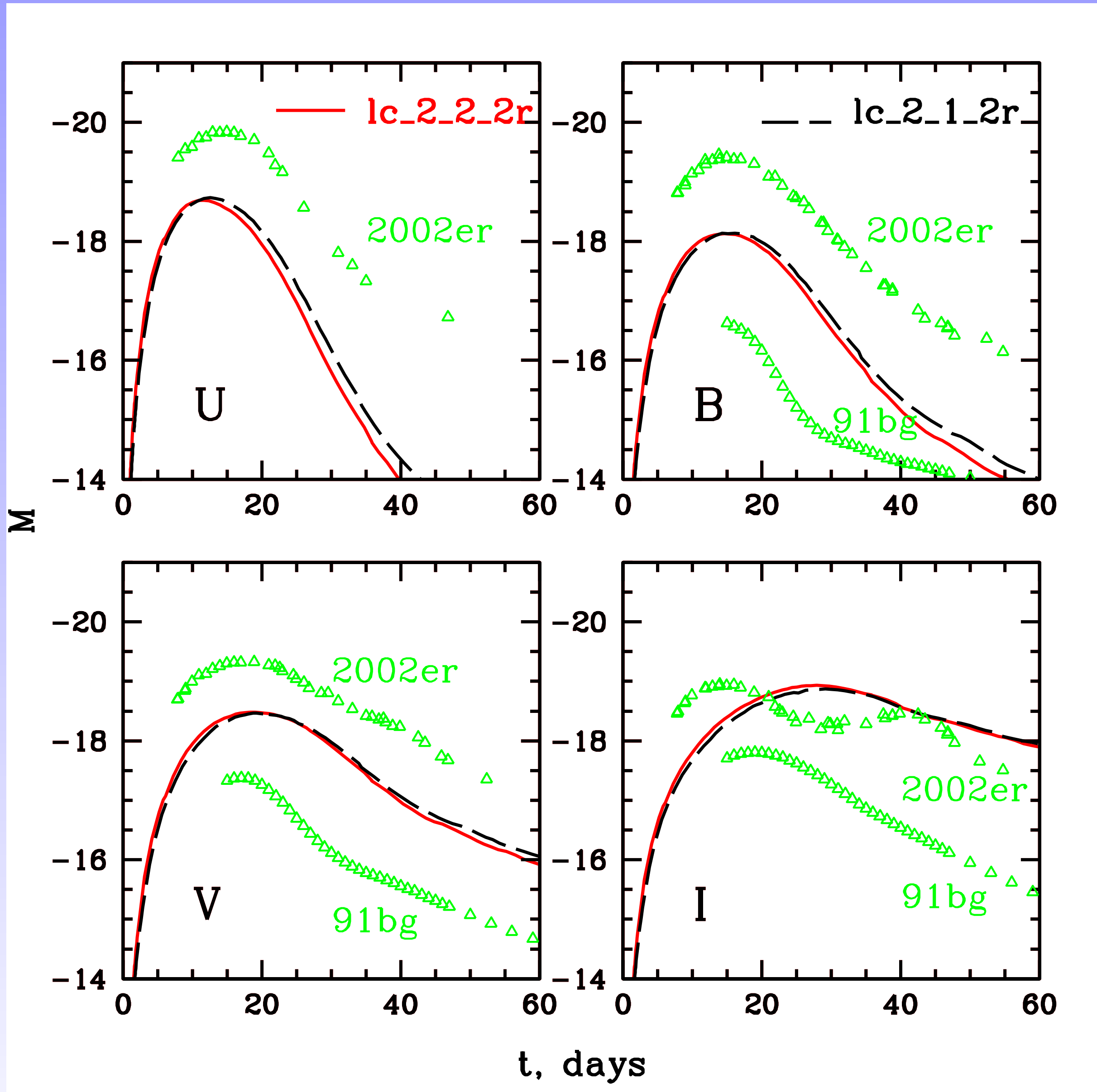


seen also on the bolometric LC:

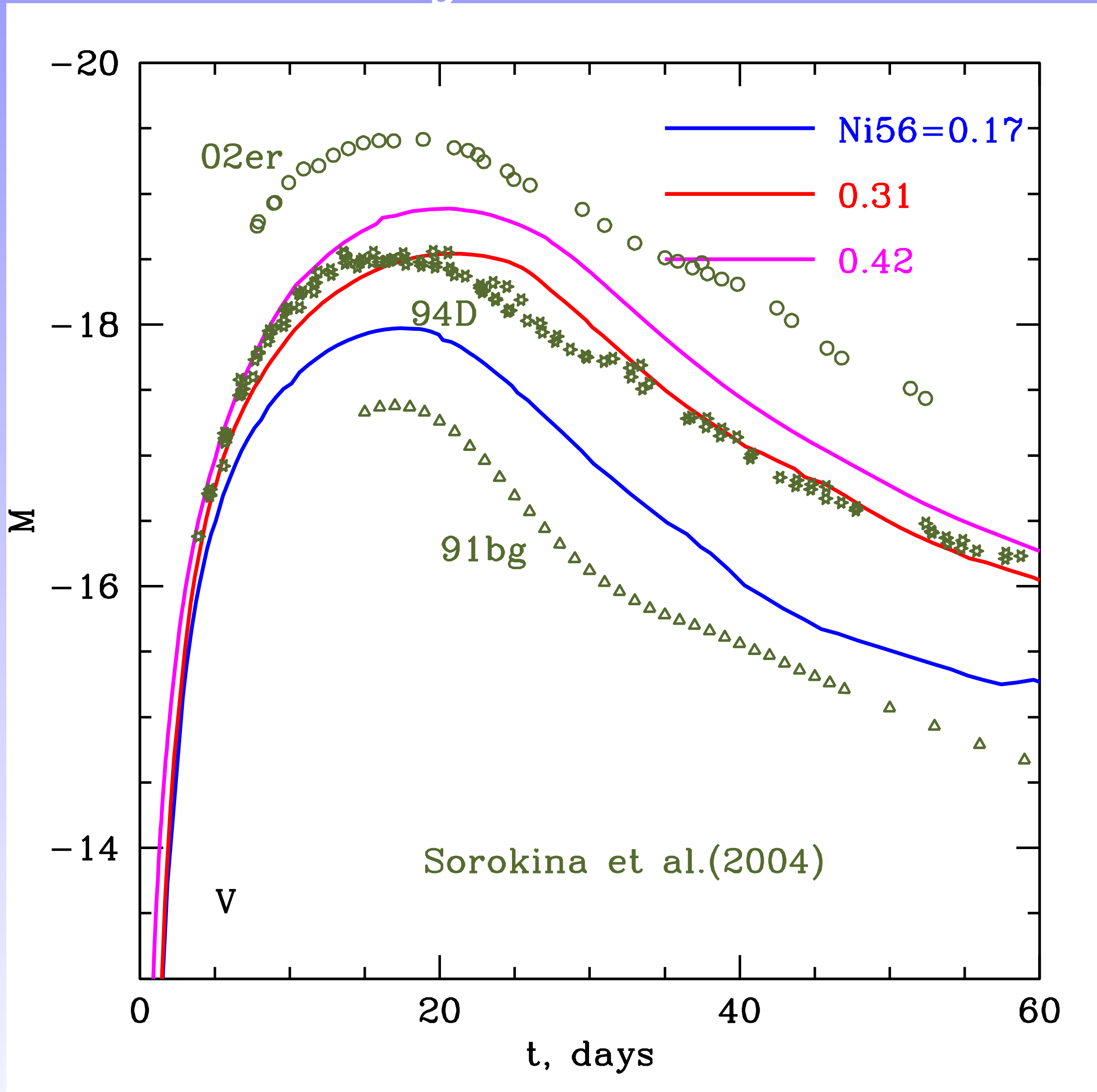


Mostly due to different ^{56}Ni production.

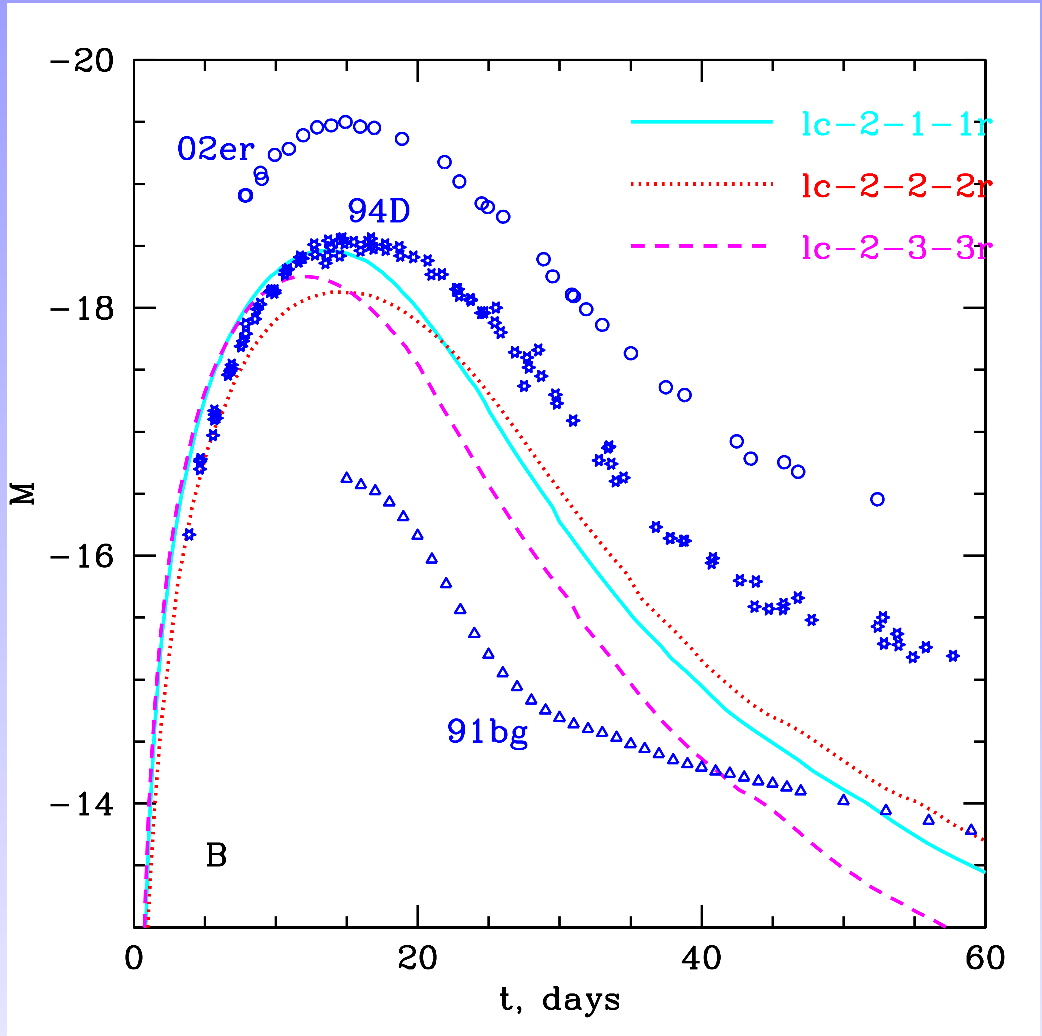
Weak effect of C/O ratio



Diversity set MPA LCs



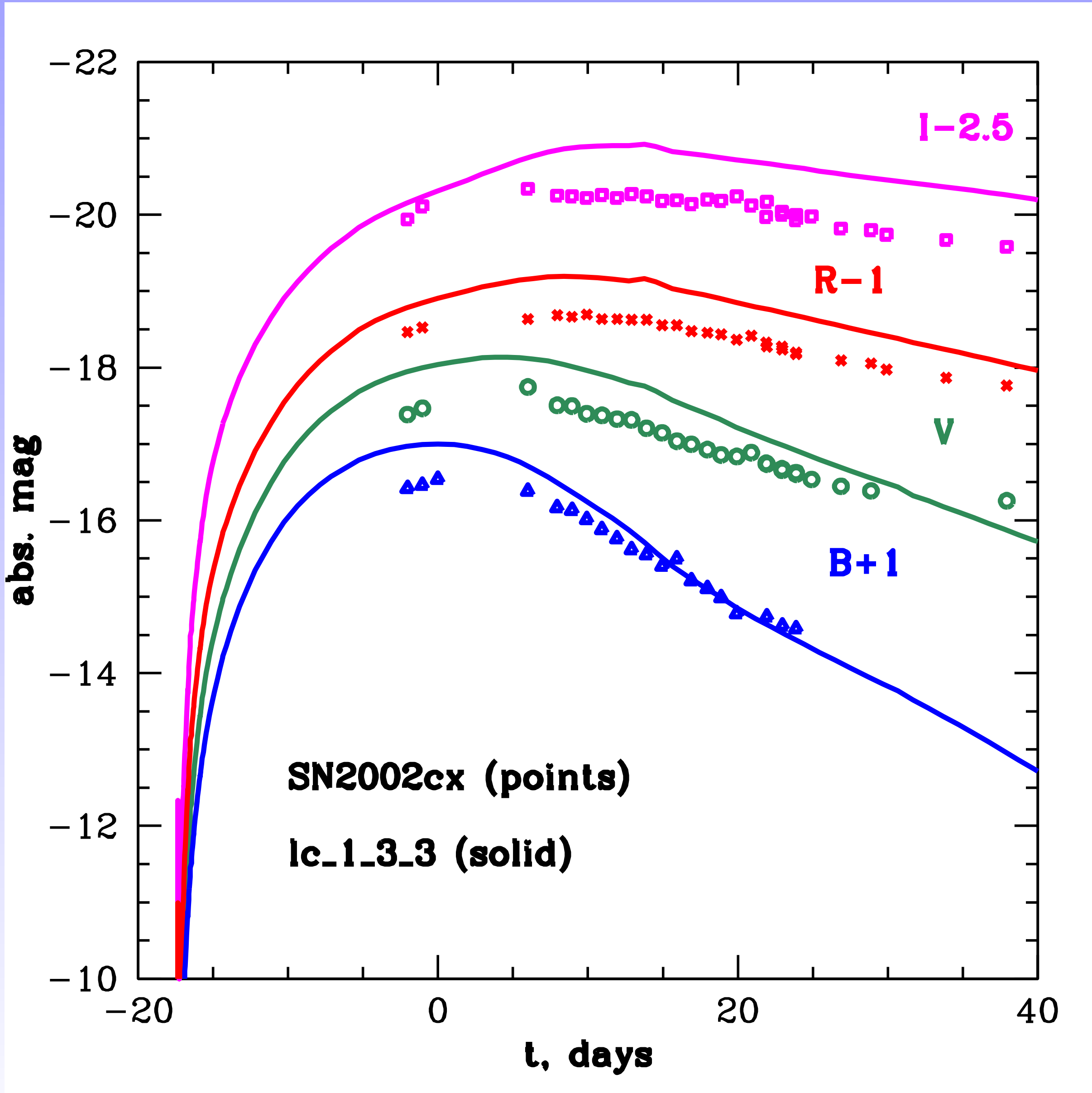
Scatter around PP relation



Weak, but slow models are promising in explanation of several pecular SNe Ia, like SN 2002cx and SN 2005hk

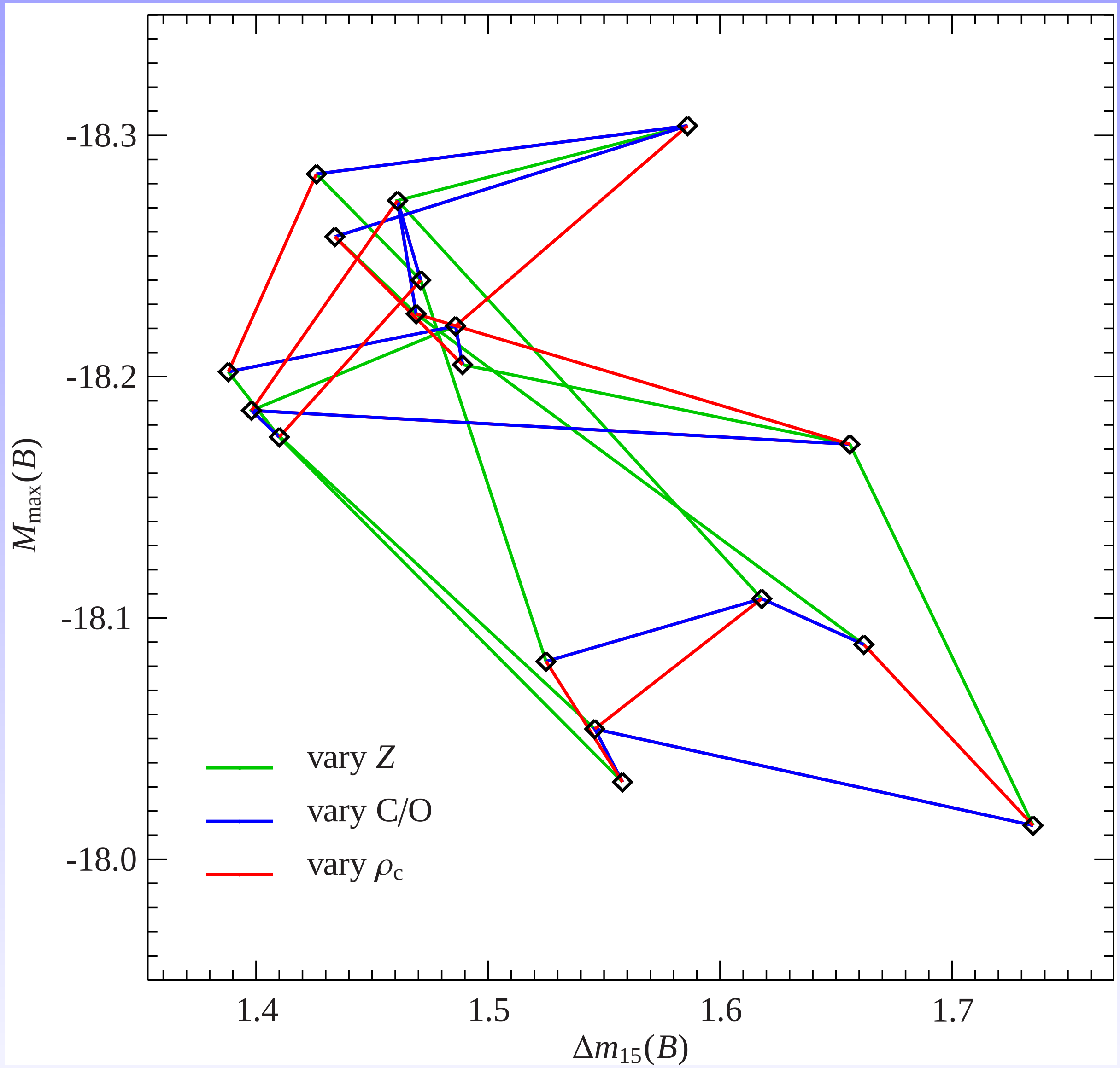
SN 2002cx vs lc1_3_3

with $m - M = 35.09$



Influense of parameters on PP

Roepke, Hillebrandt, Blinnikov:astro-ph/0609631

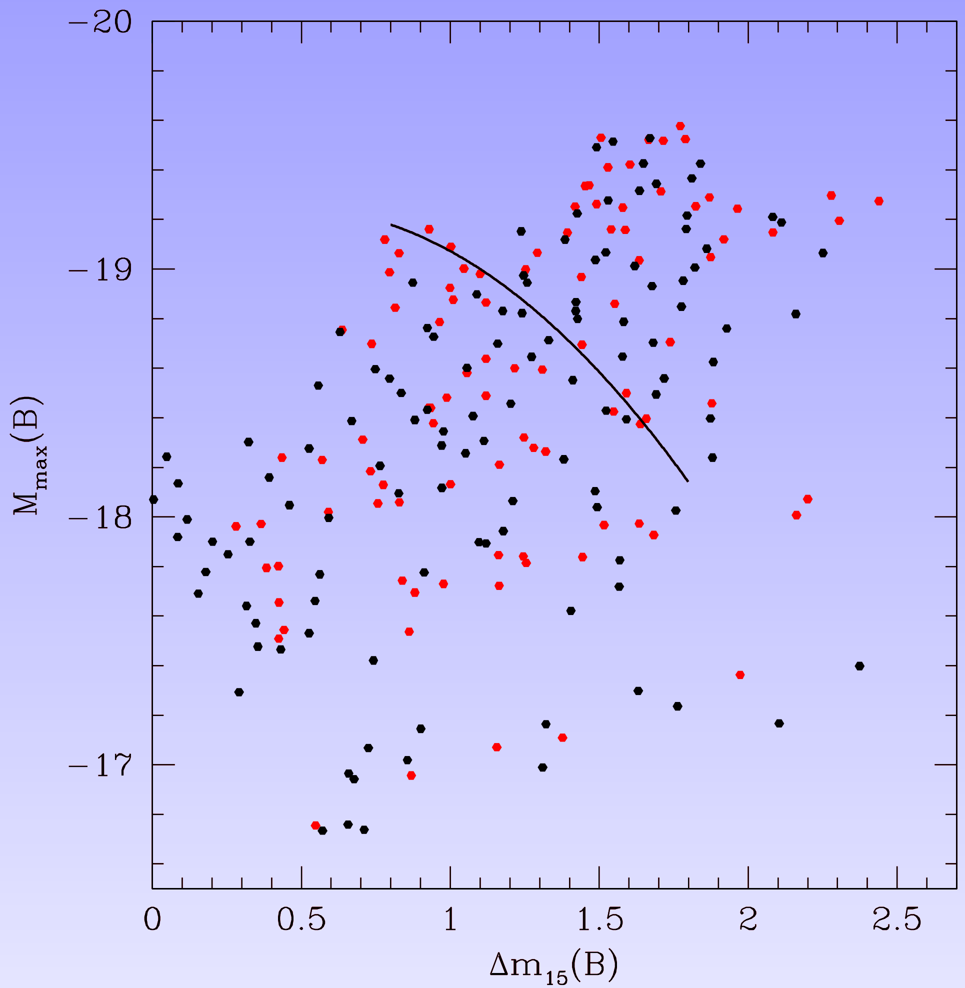


SN Ia toy models

We have more than 200 different Chandrasekhar mass SN Ia models with plausible distribution of initial composition (Woosley, Kasen, Blinnikov, Sorokina 2007) and kinetic energy consistent with this composition.

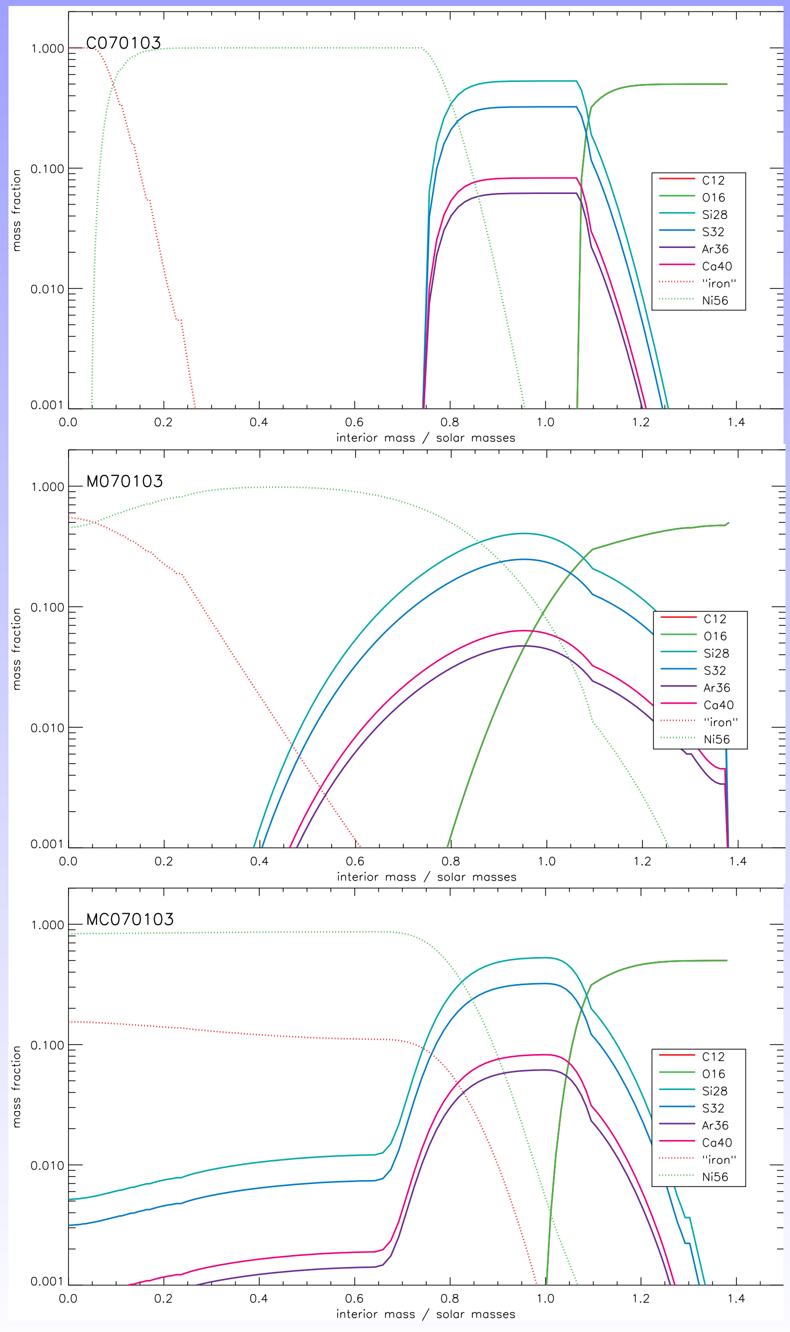
2 light curve codes:
SEDONA – MC, no hydro, huge line list (Kasen);
STELLA – direct radiation transport PLUS hydro, shorter line list (Blinnikov, Sorokina)

All in B

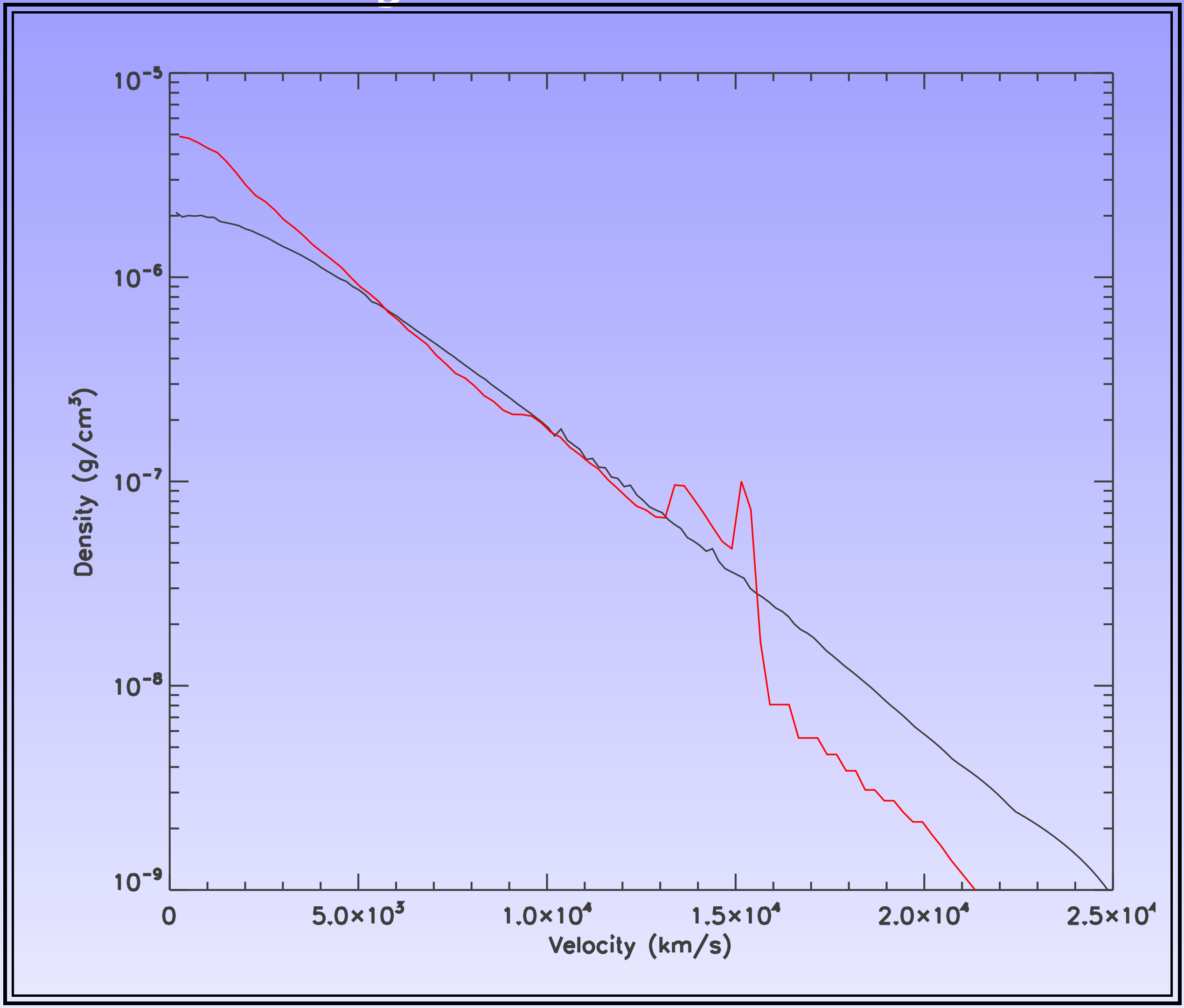


Only a small subset follows the PP-relation.
Theoretical models may go opposite to PP-relation – dangerous for cosmological applications!

Samples of composition

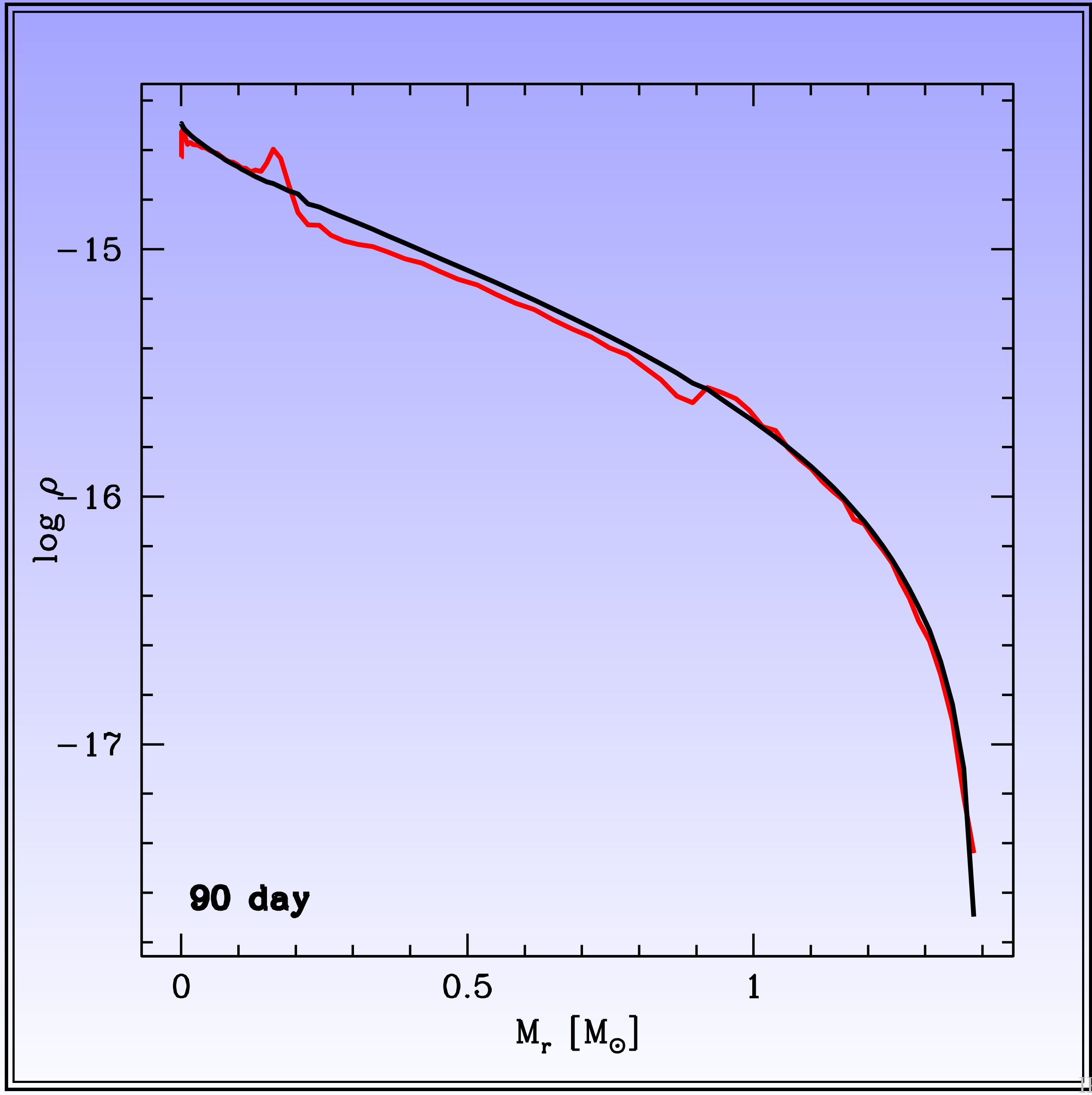


Density m060303 vs W7

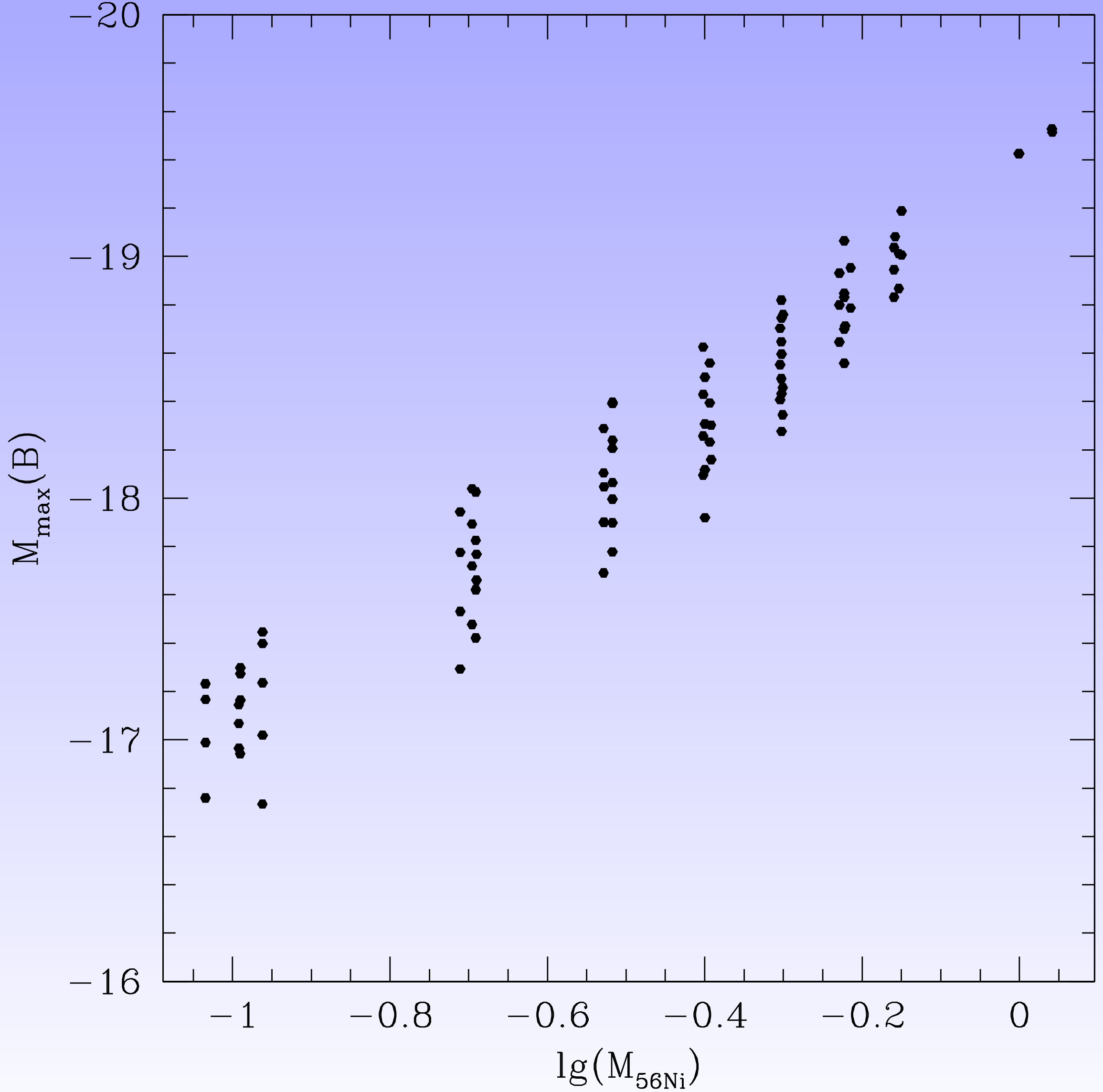


W7 – red

^{56}Ni bubble growth

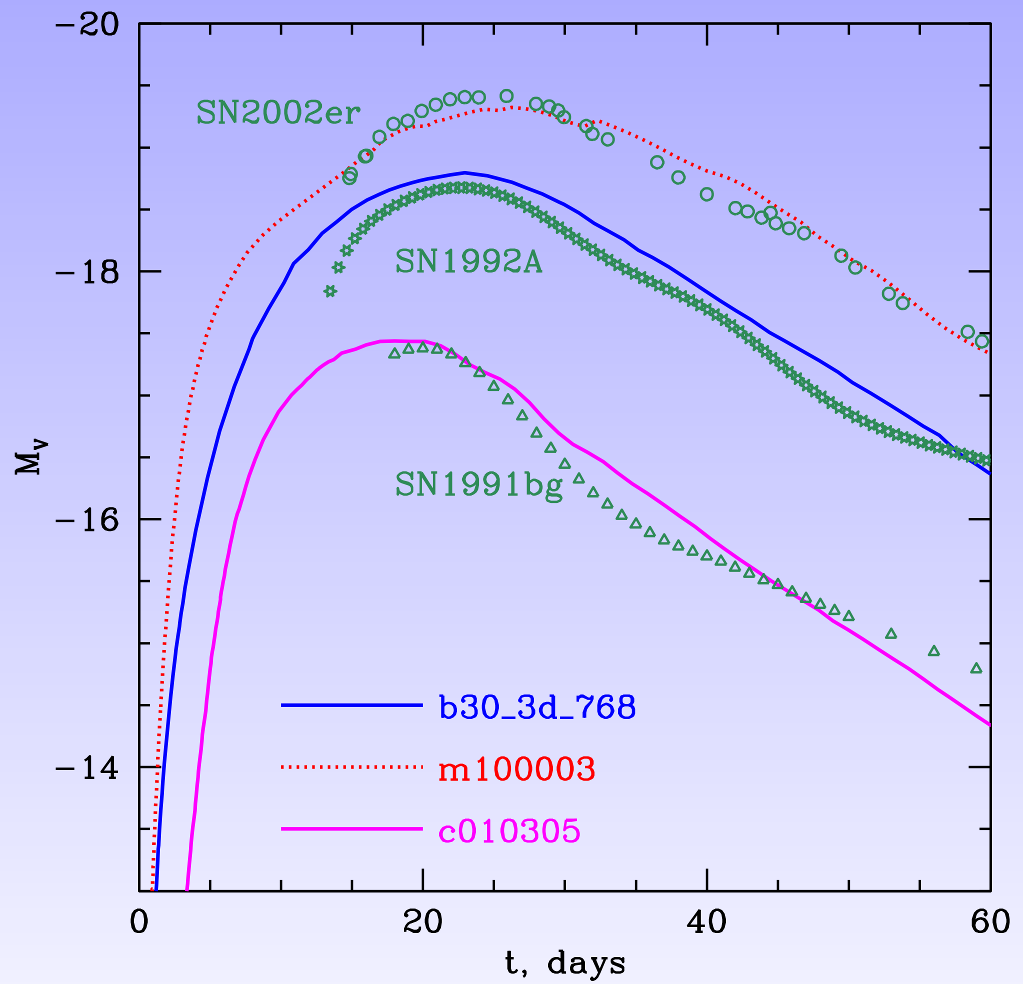


Peak magnitude vs. Ni mass

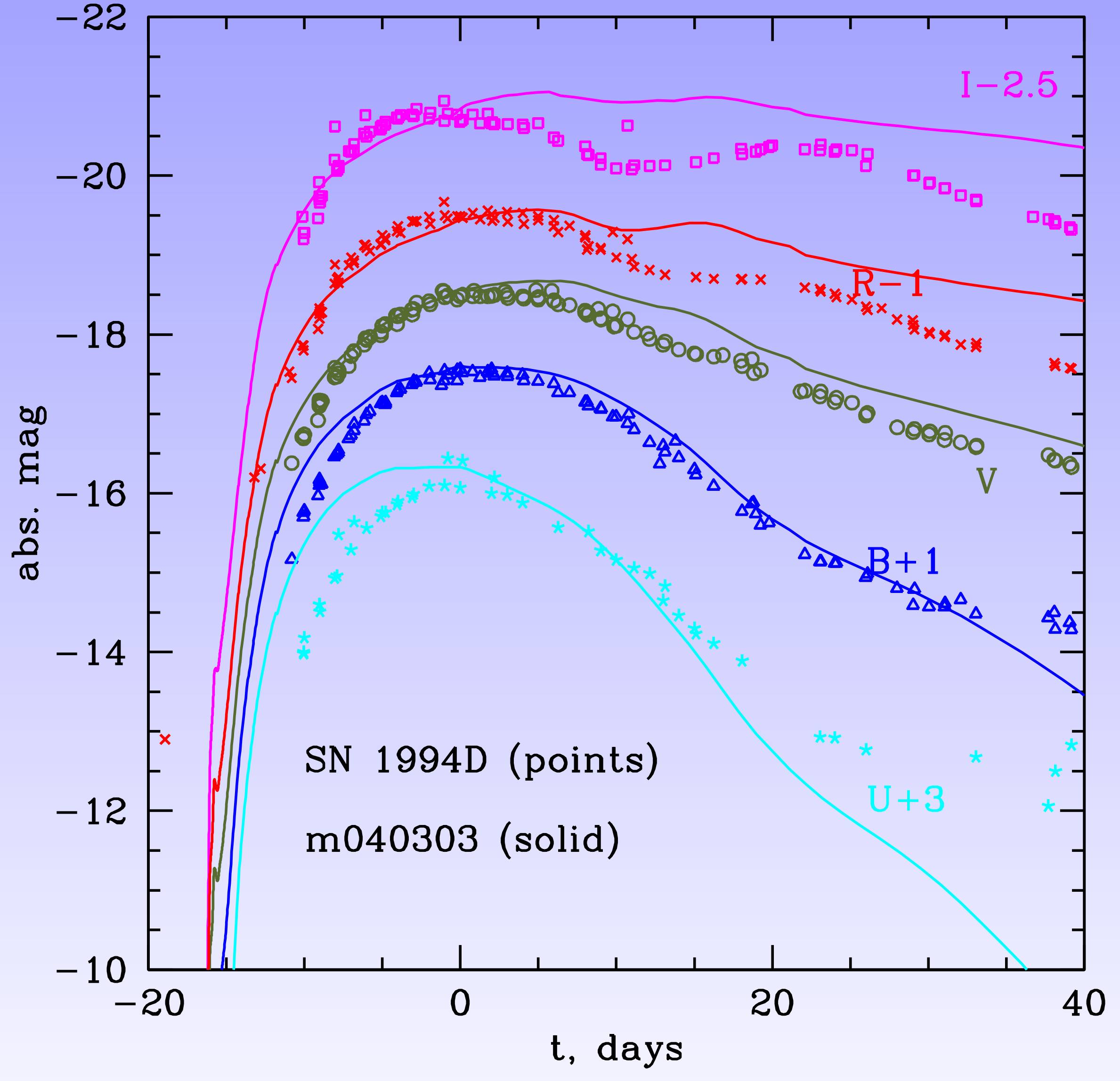


Comparison with observations in V-band

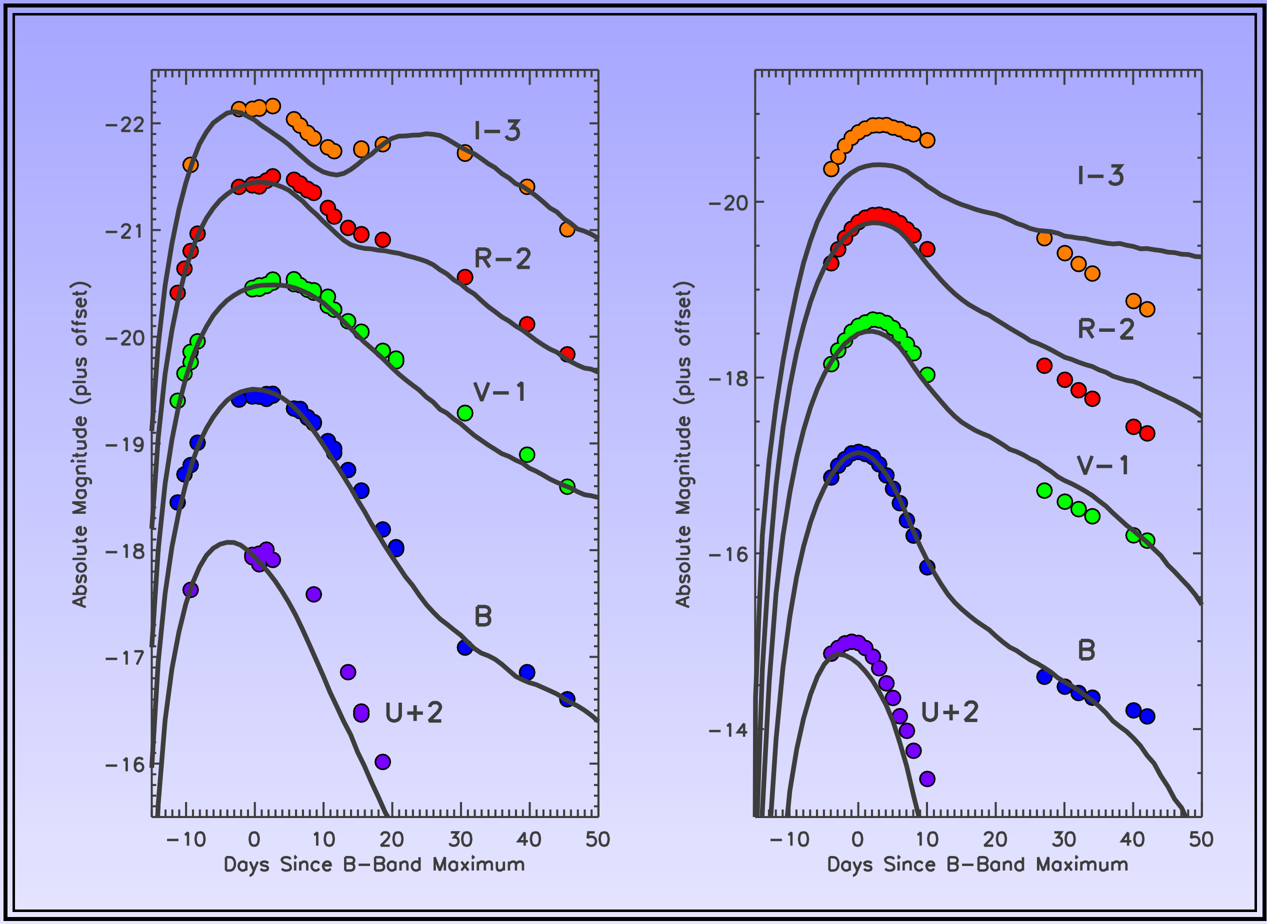
Rather good agreement for some models



Comparison with UBVRI observations:

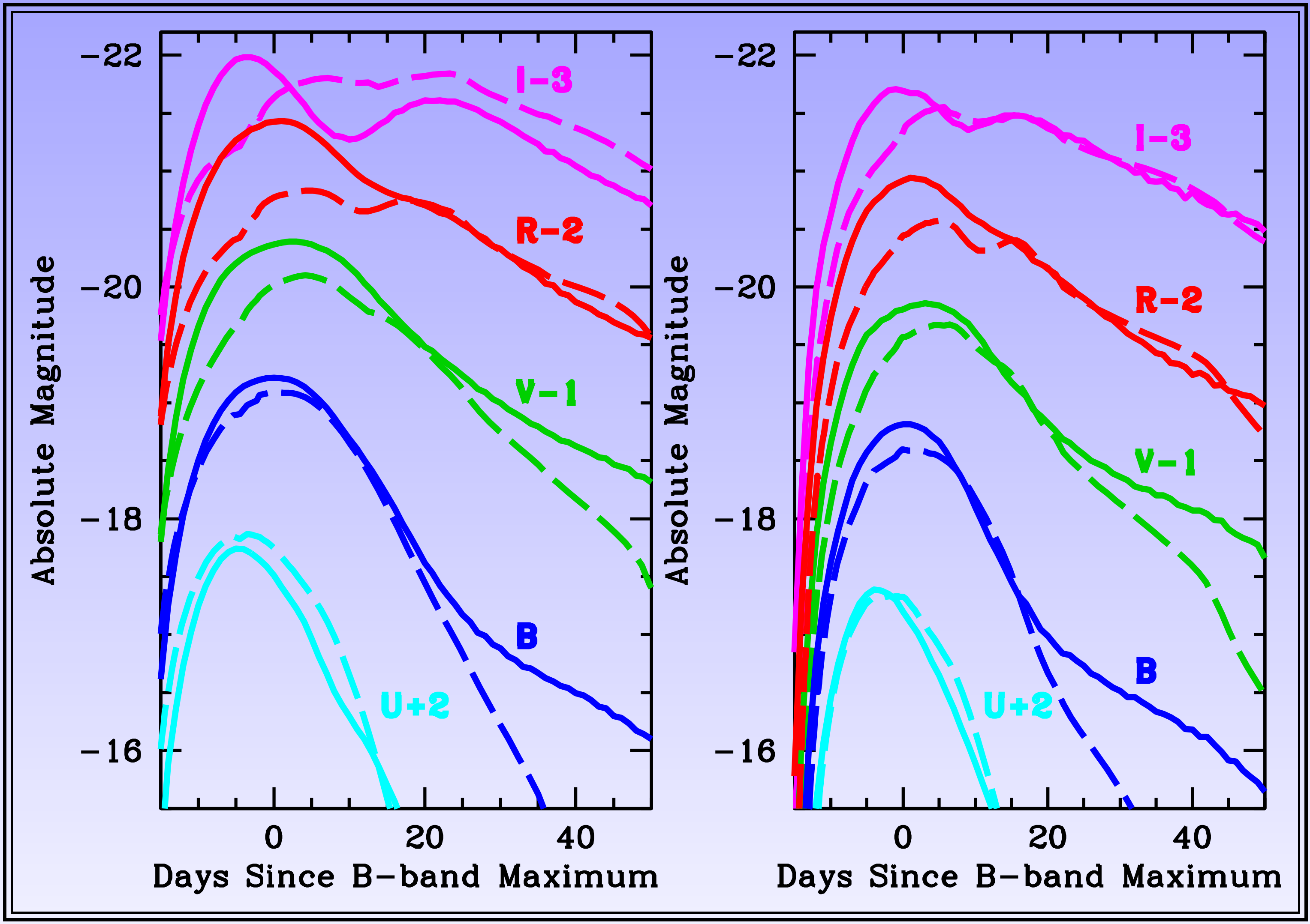


SEDONA vs. UBVRI observations



M080202 and M010309

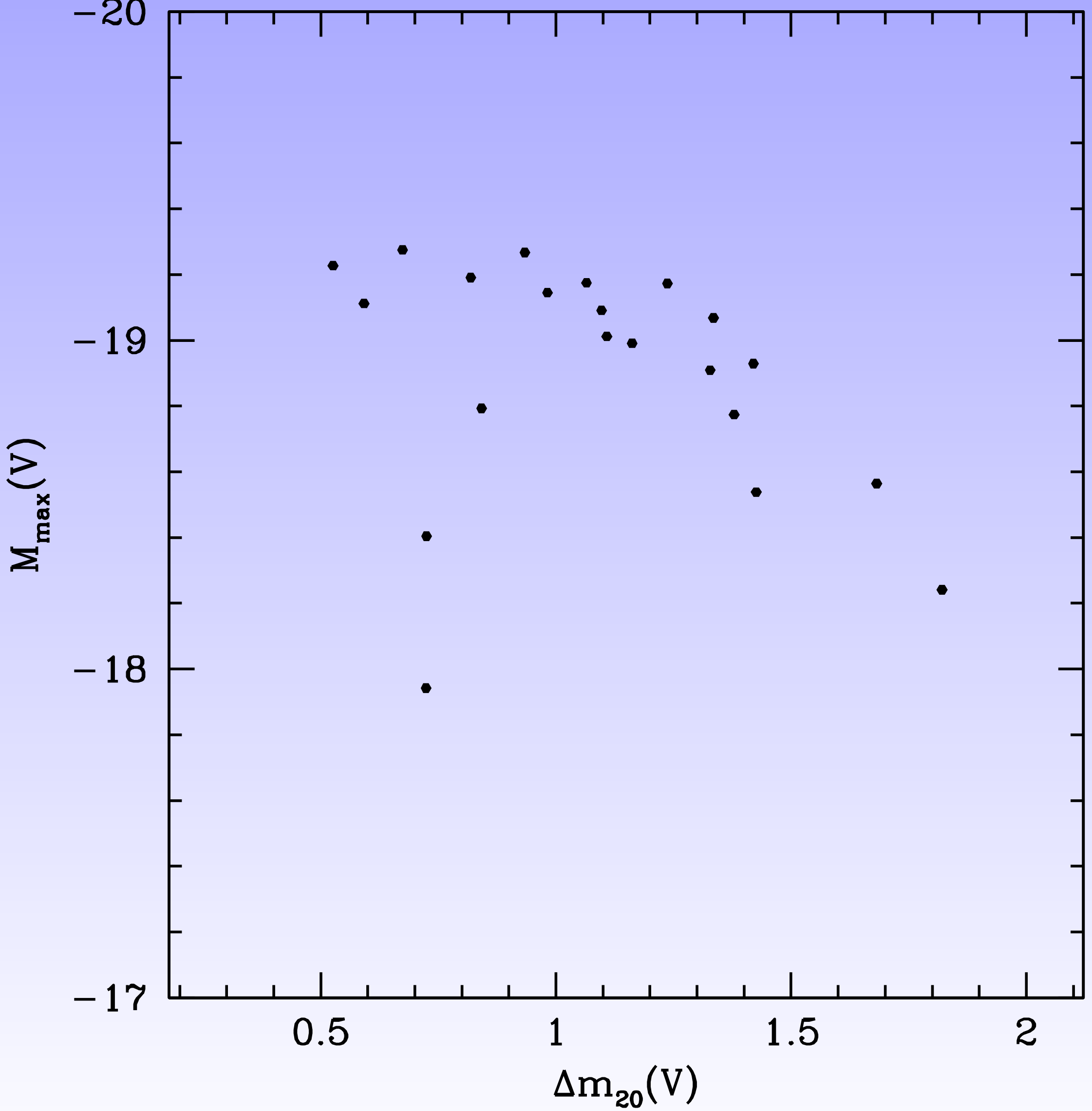
LCs M070103 & M040303



SEDONA – solid, STELLA – dashed

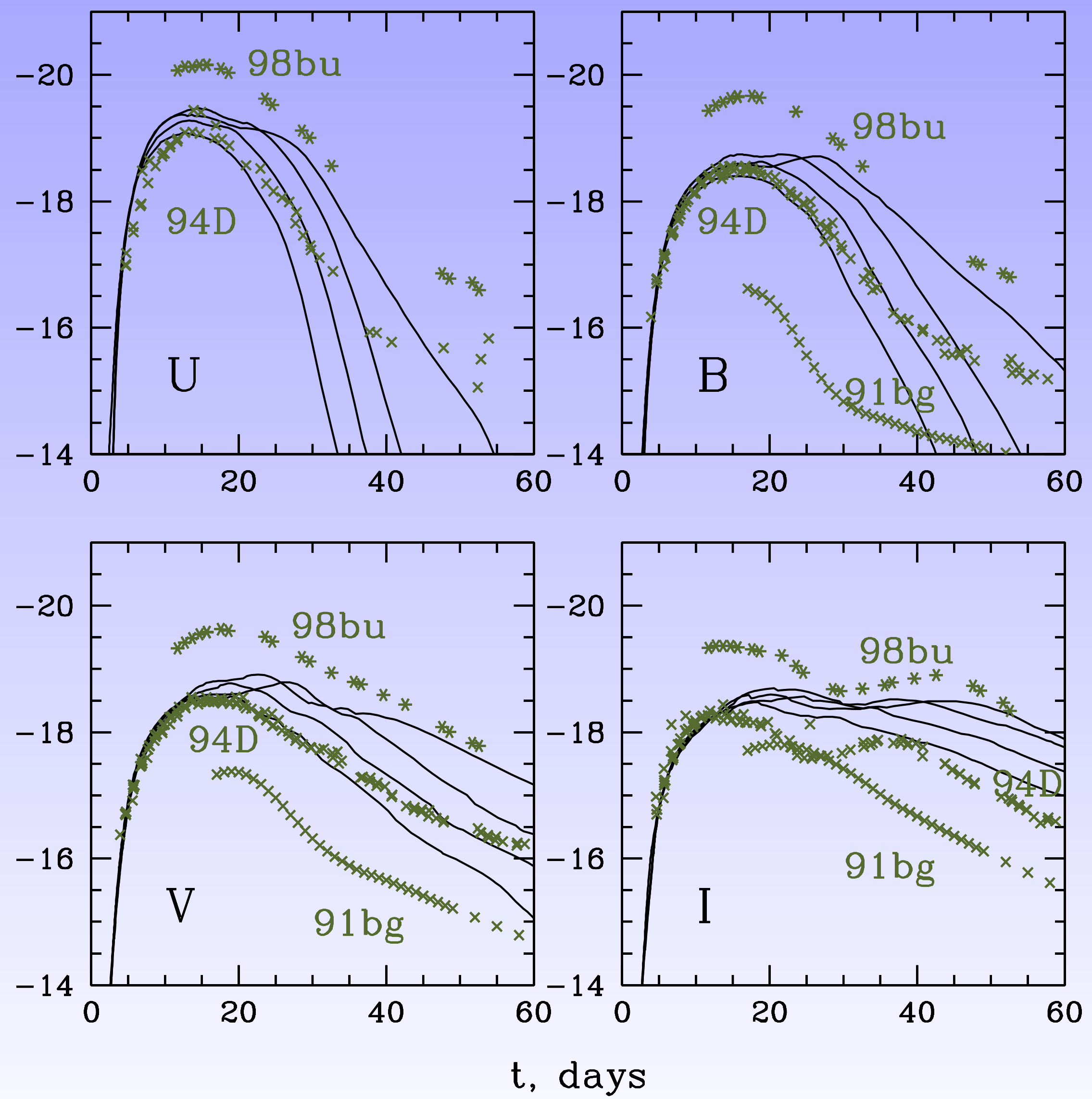
A DD4-like subset

(Ni+Fe) + (Si+S) = 1.3

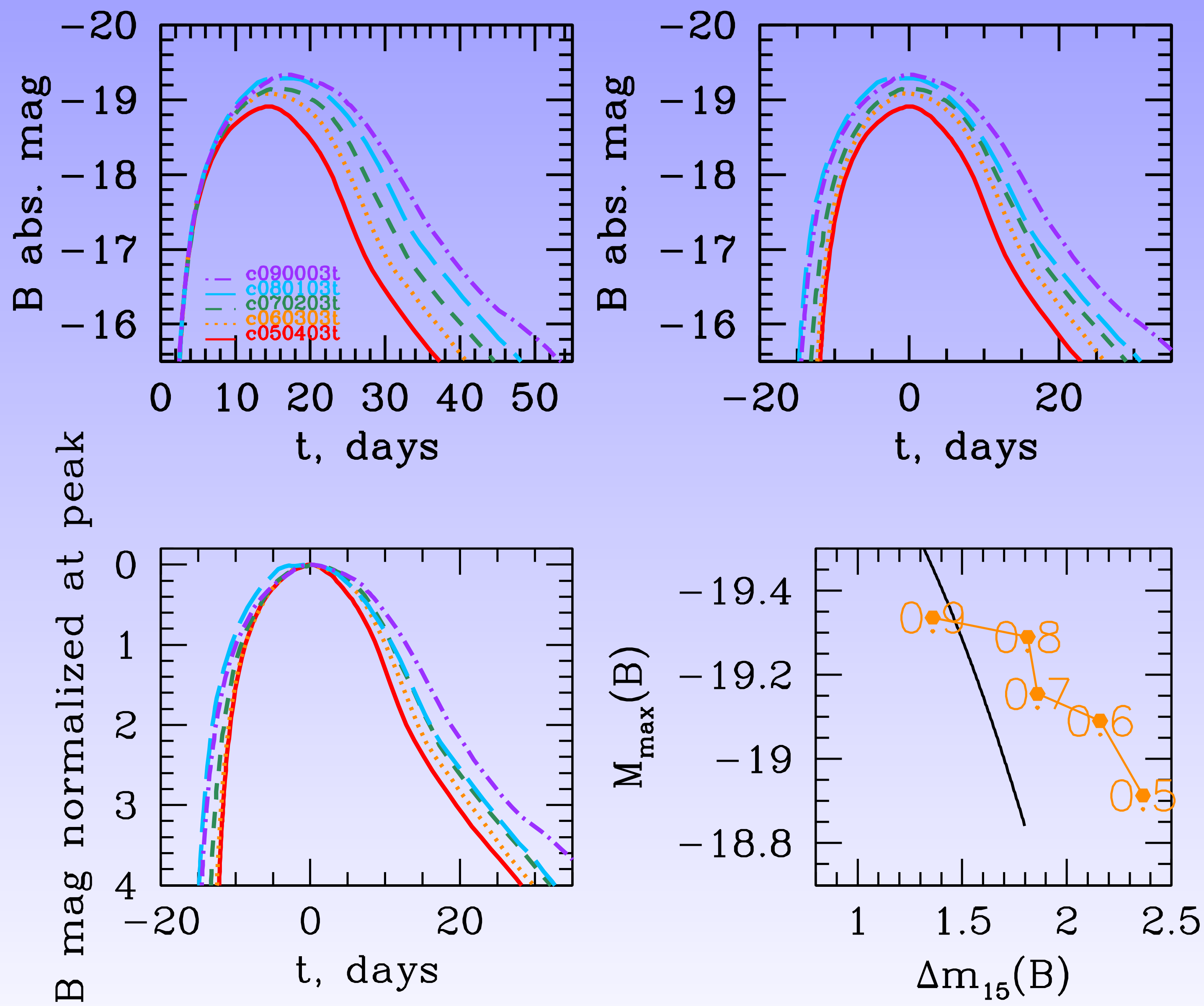


Si+S=0.7, Ni+Fe=0.6

Ni=0.3; 0.4; 0.5; 0.6



Si+S=0.3, Ni+Fe=0.9, unmixed



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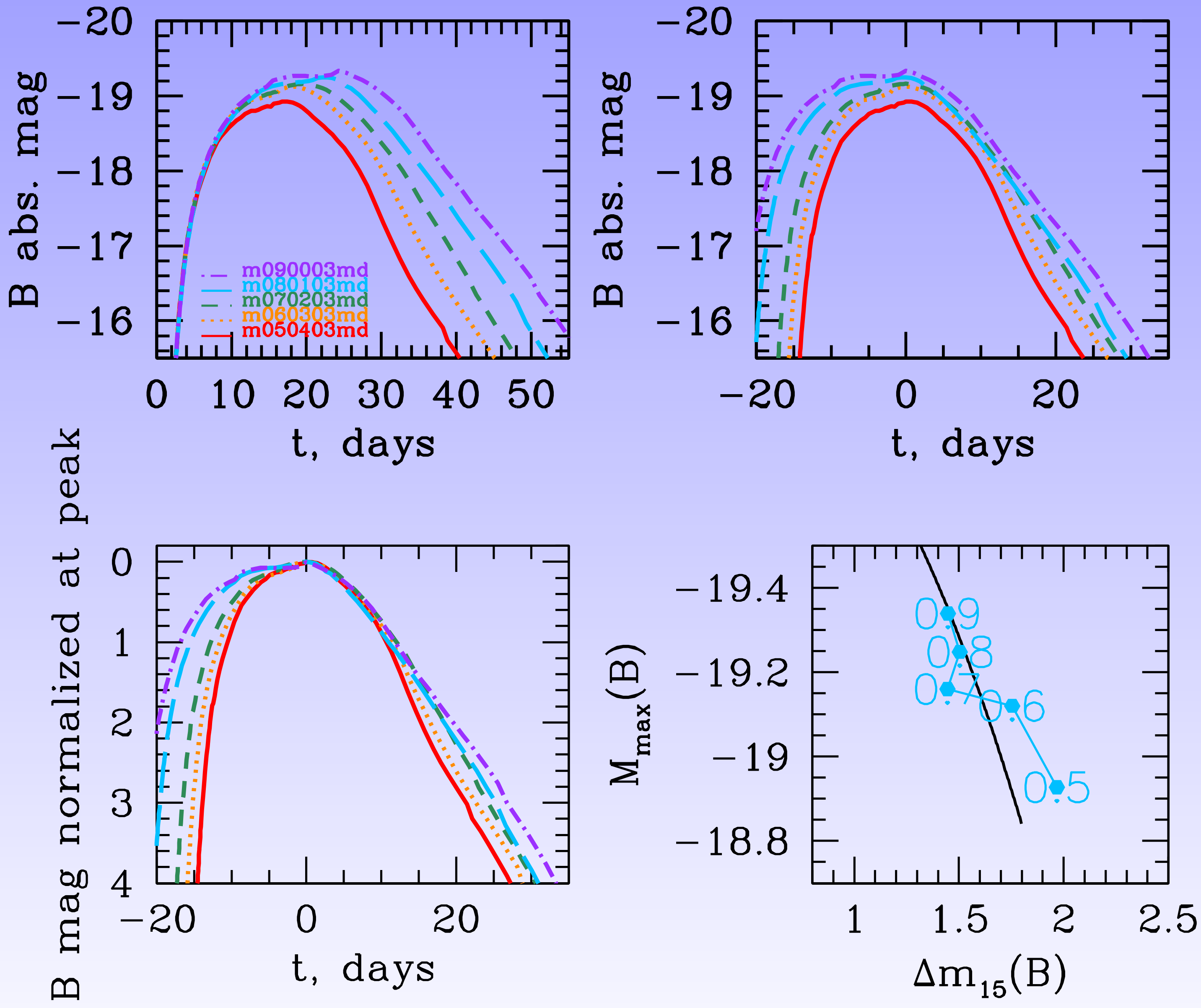
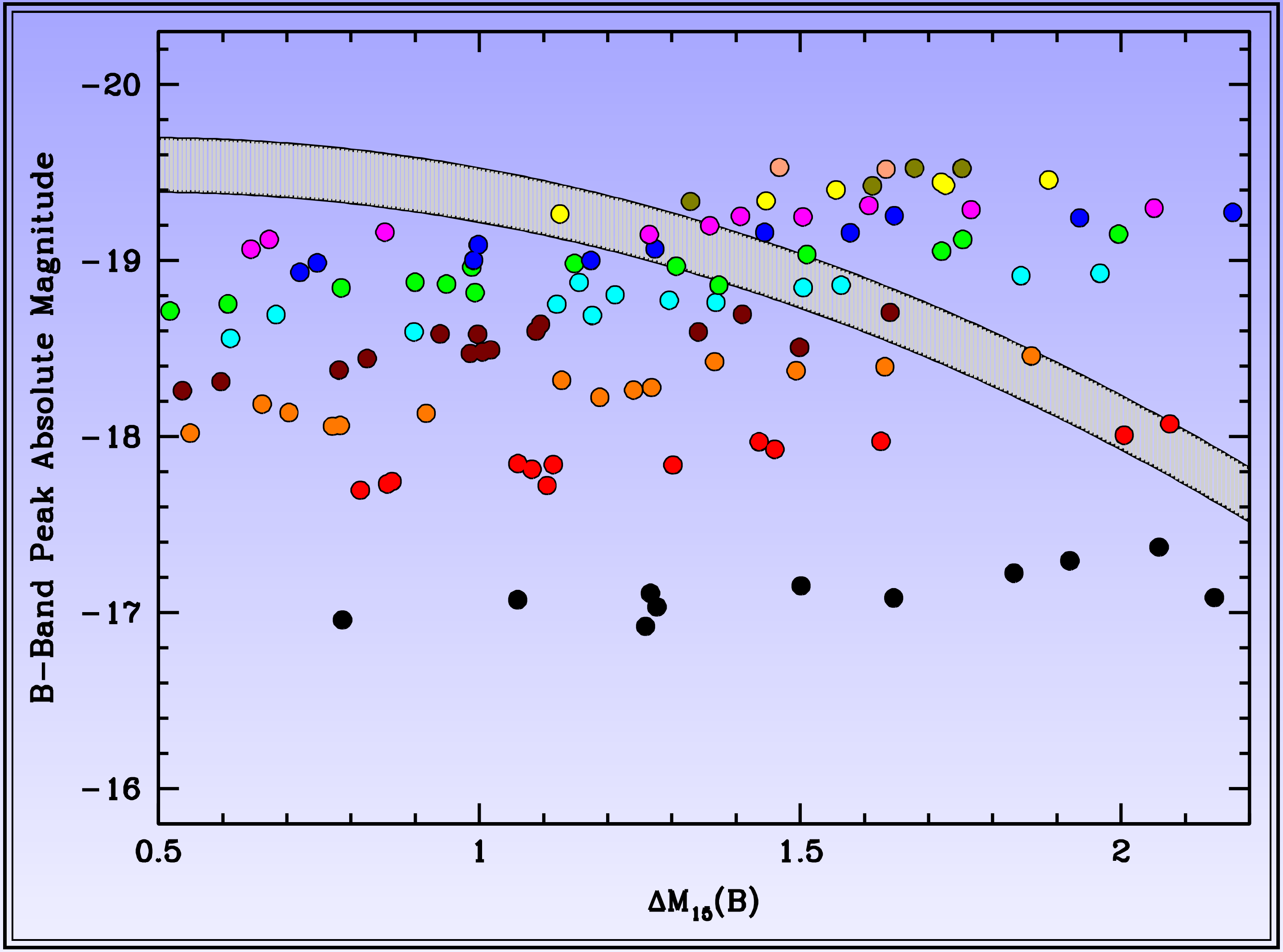
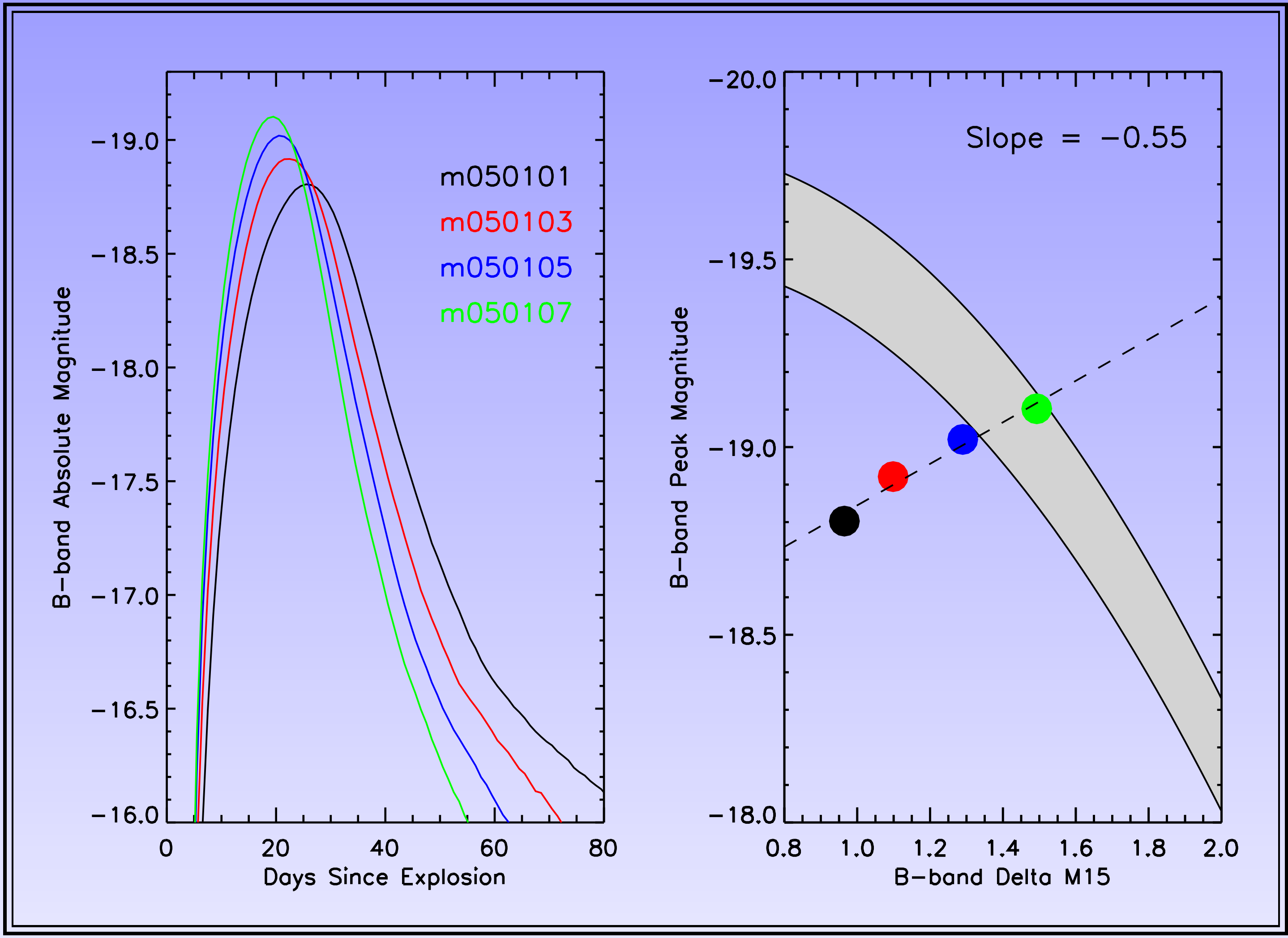


The full set of mixed models calculated by STELLA

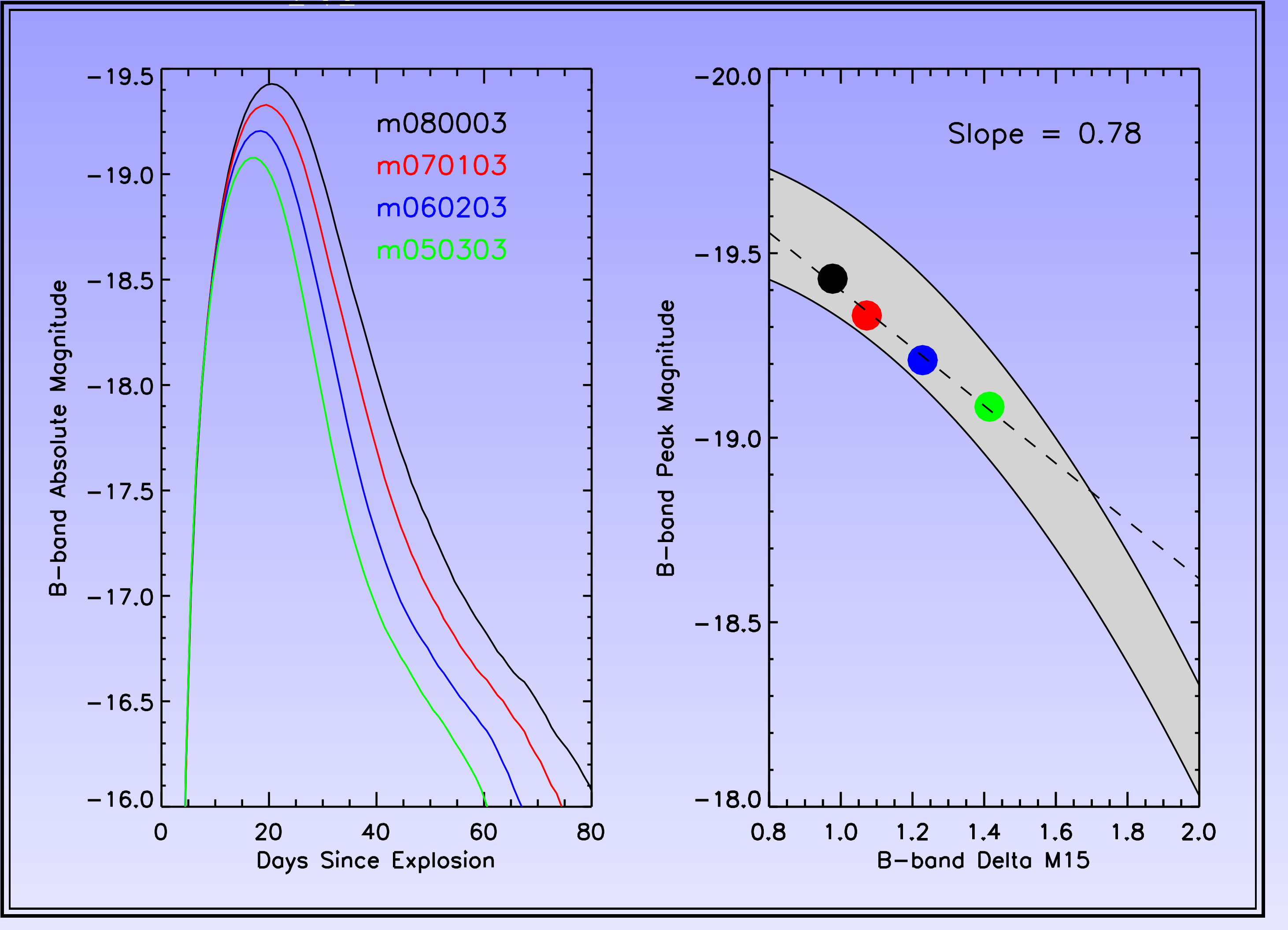


Total burnt mass variation



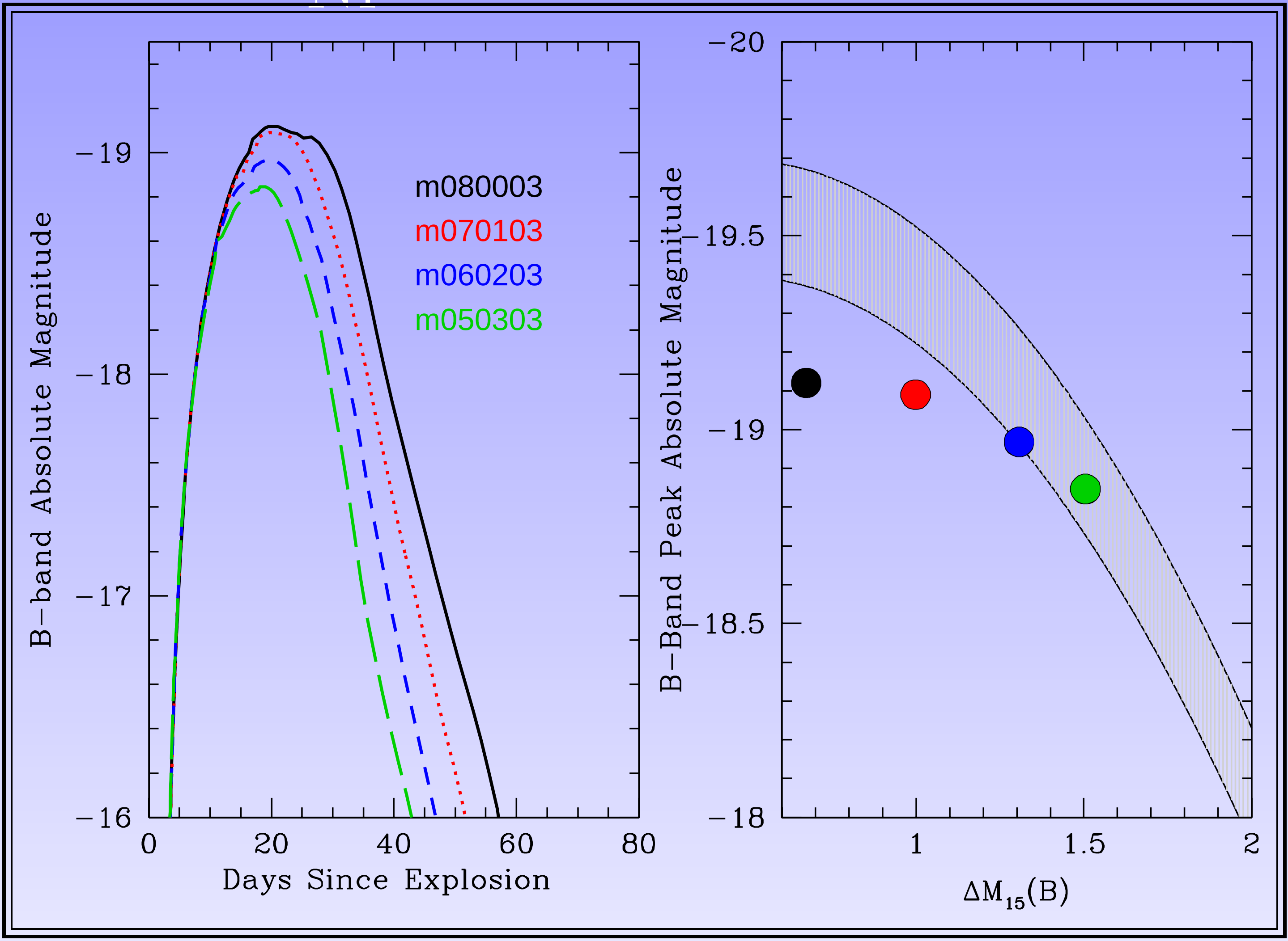
$M_{^{56}\mathrm{Ni}} = 0.5 M_\odot$ is fixed

$M_{^{56}\mathrm{Ni}}$ **variation,** SEDONA



$M_{^{56}\mathrm{Ni}} + M_{\mathrm{Fe}} = 0.8 M_{\odot}$ **is fixed**

$M_{^{56}\mathrm{Ni}}$ **variation,** STELLA

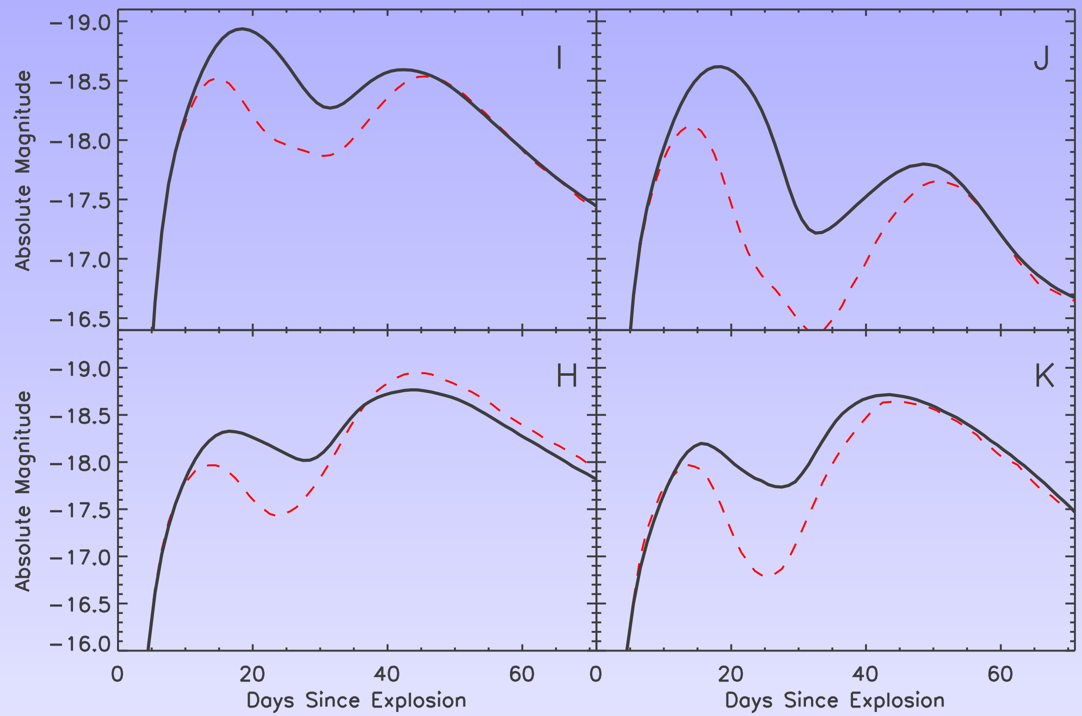


$M_{^{56}\mathrm{Ni}} + M_{\mathrm{Fe}} = 0.8 M_\odot$ is fixed

poorer Ni and Co list

Kasen 2006

IR light curves for different line lists



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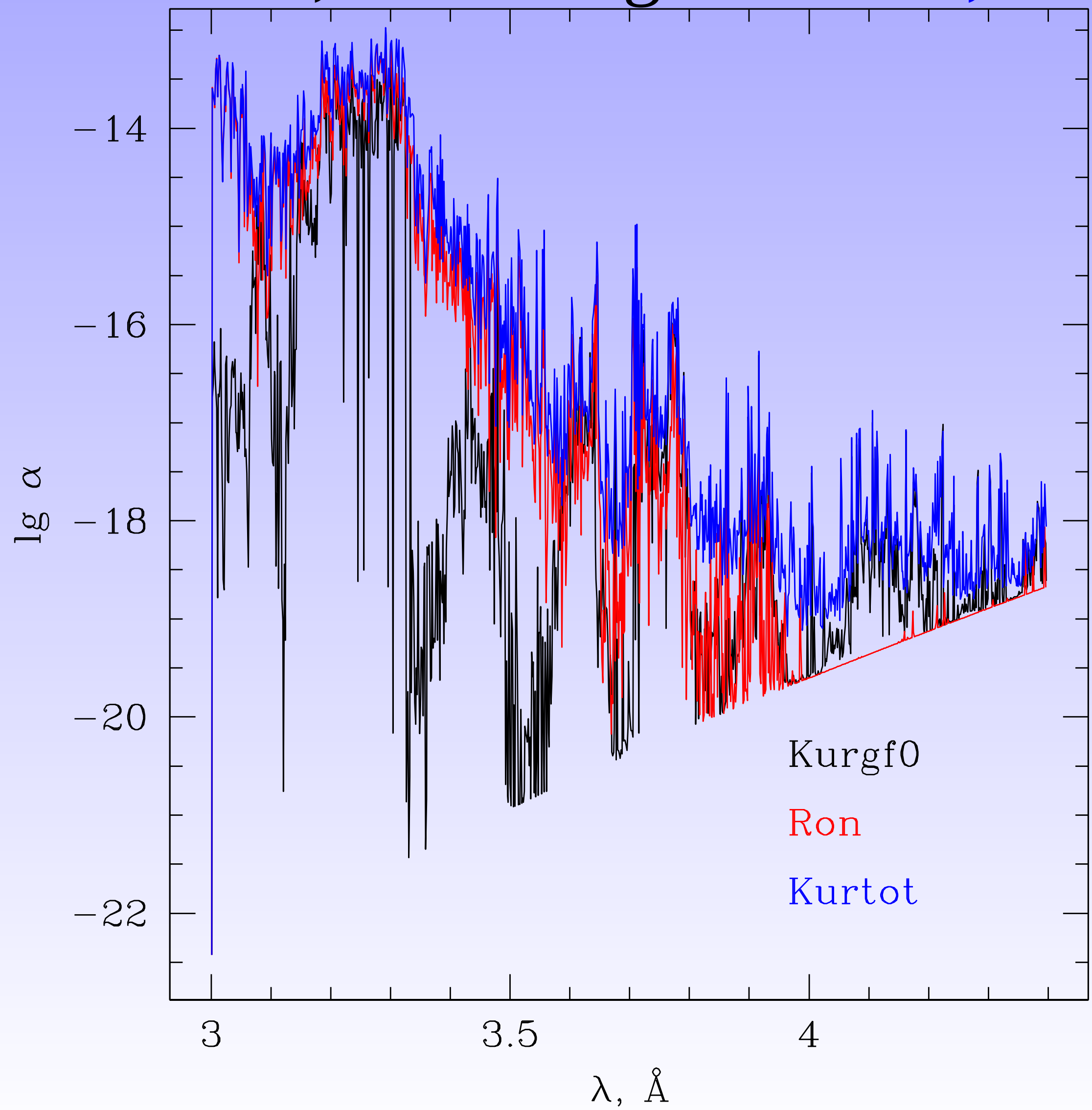

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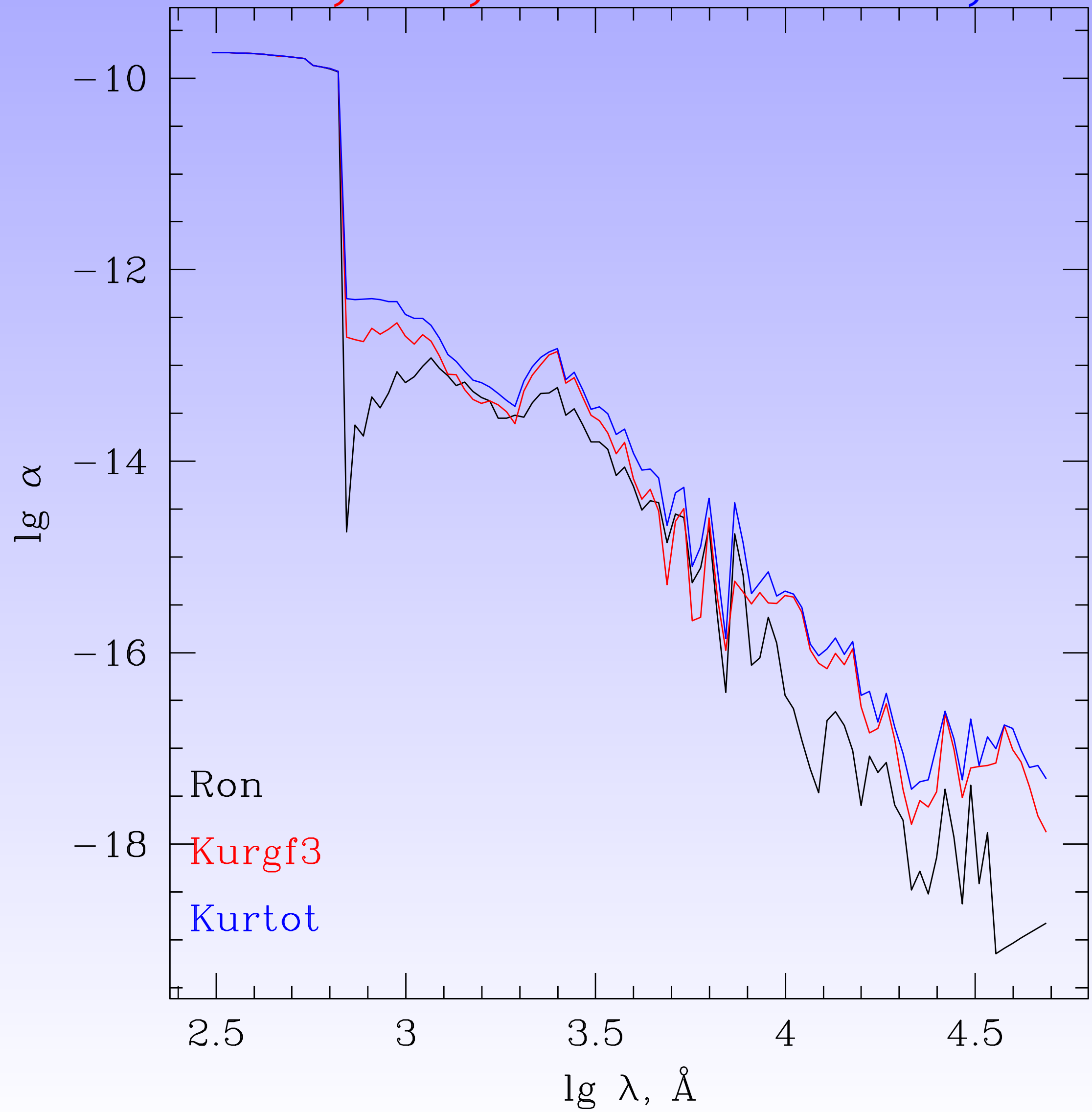
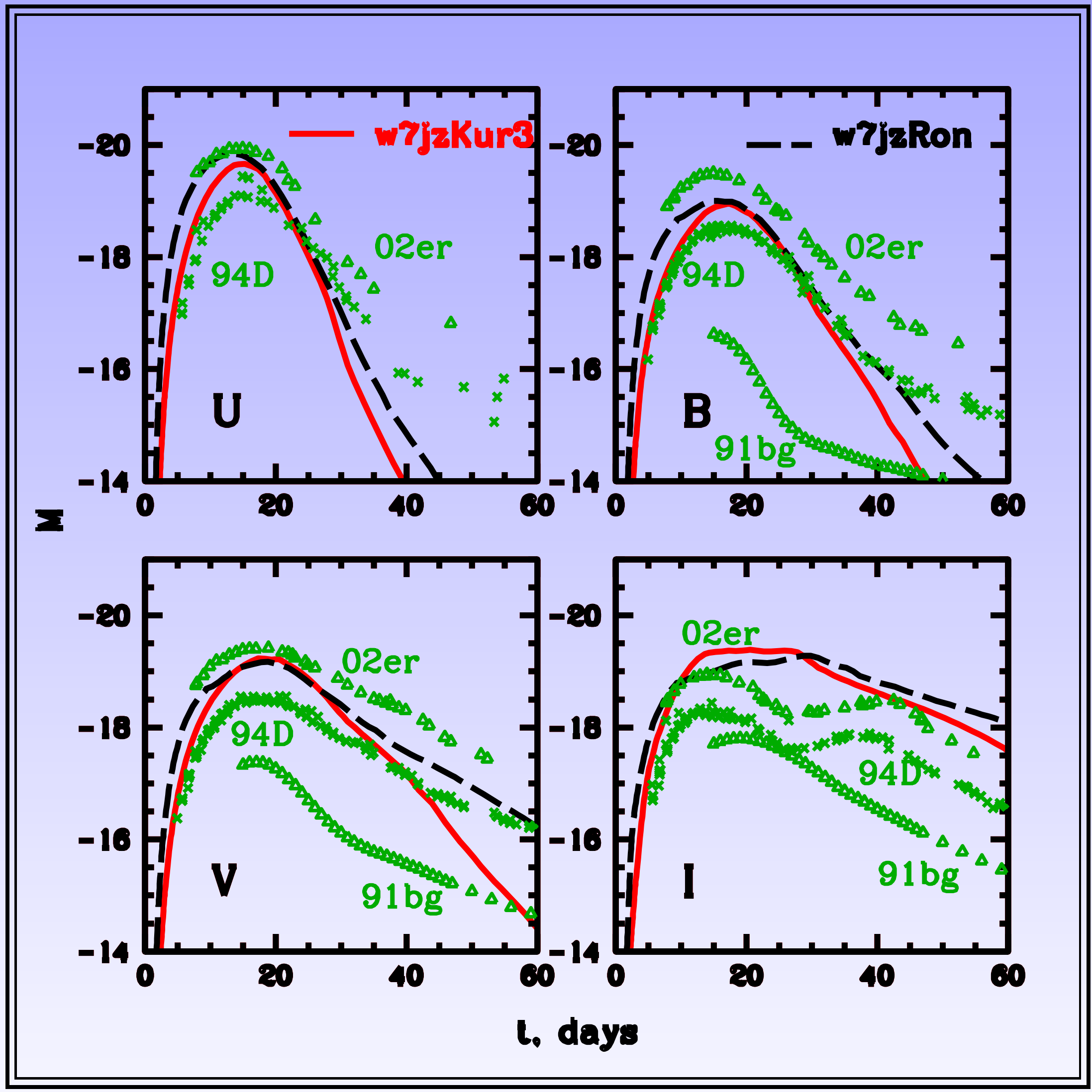


Light curves with different line lists

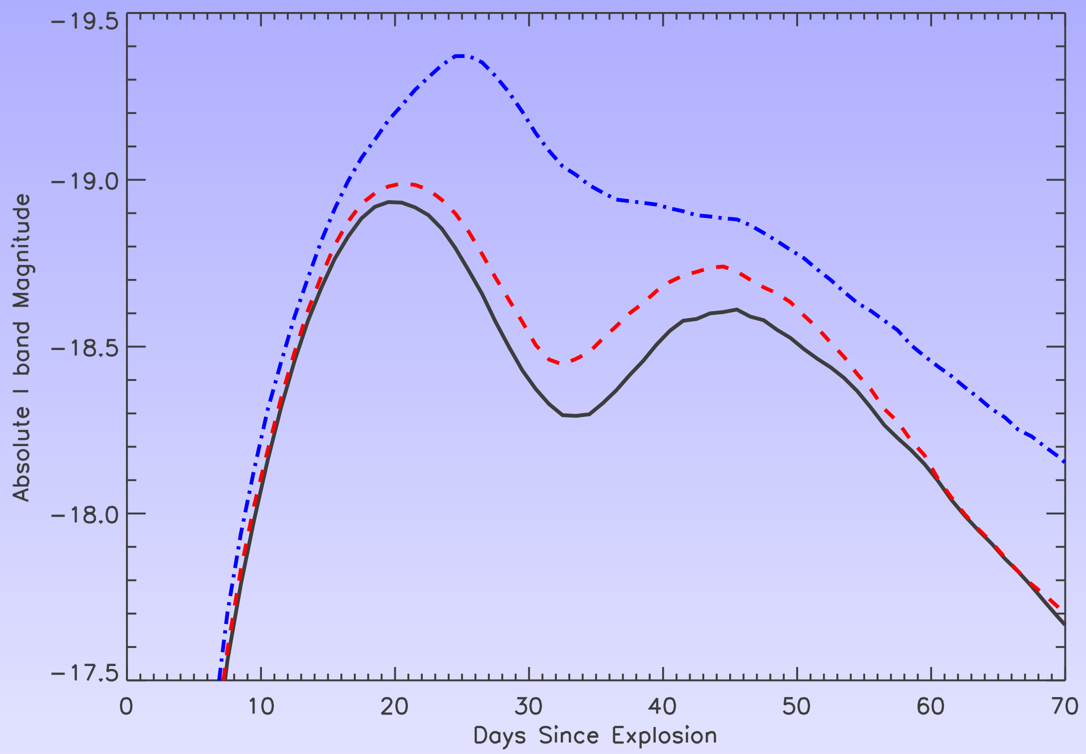
11M lines – red, 155k lines – black

(opacities are not yet limited here)



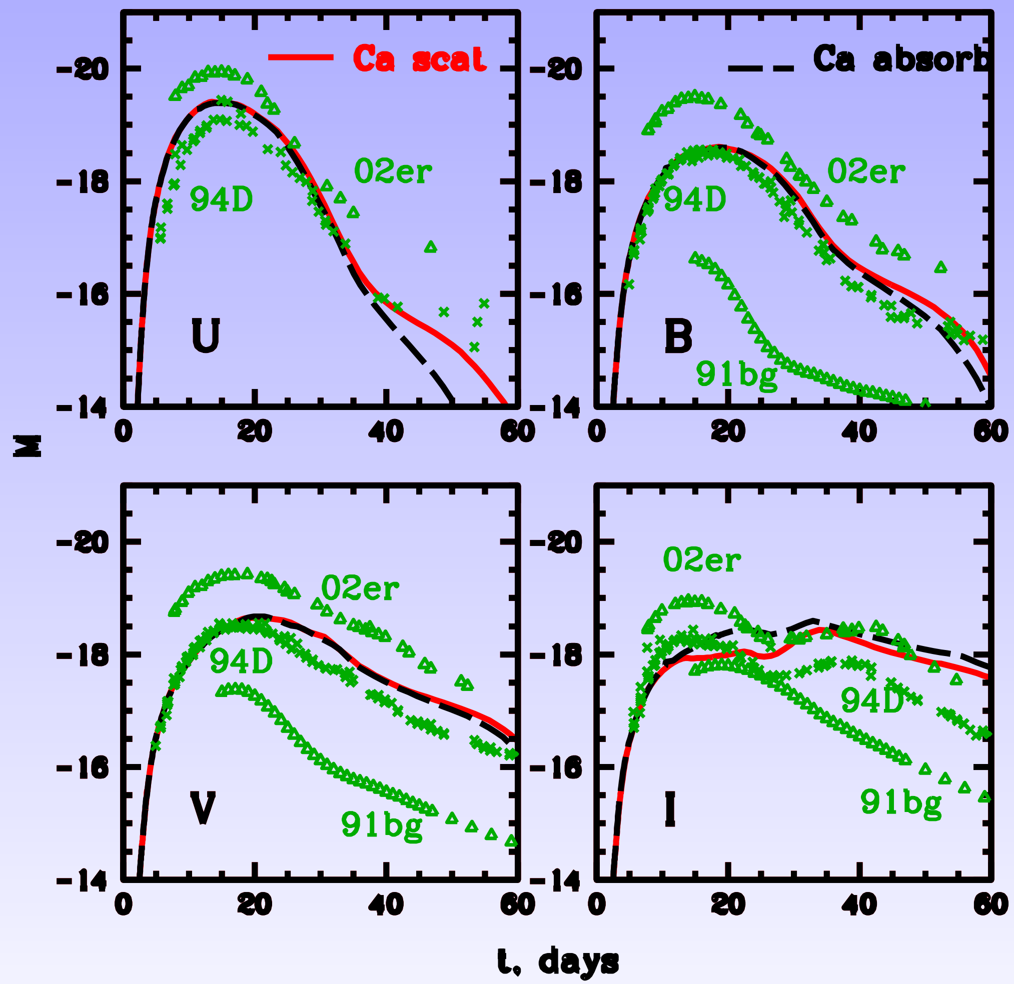
Kasen 2006

CaII trick: let us make it scattering



CaII triplet (absorptive or scattering)

Model m040303, old line list (155k lines)



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- √ 3D transport

Conclusions

- √ SN light curves are a good tool to understand physics of explosion
- √ We analyse a toy model set to constrict the wide range of explosion parameters: many physically plausible models are not realised.
- √ There are many subsets among toy models which can reproduce light curves for real SN Ia and PP relation. For example, a set of models with total burned mass M(Ni+Fe)+M(Si+S)=1.1$M_\odot$
- √ A little diversity is obtained for 3D MPA models, but peak magnitude–decline rate relation looks promising. MPA models can be also used to explain some pecular SN Ia light curves