Type Ia Supernovae - Chasing Dark Energy

Wolfgang Hillebrandt
MPI für Astrophysik
Garching

Facets on Strong-Interaction Physics
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In collaboration with ....

Friedrich Röpke (MPA/U. Würzburg),

Rüdiger Pakmor (MPA/HITS)

Michael Fink (MPA/U. Würzburg)

Stefan Taubenberger (MPA),

Ashley Ruiter (MPA)

Stuart Sim (MPA/ANU),

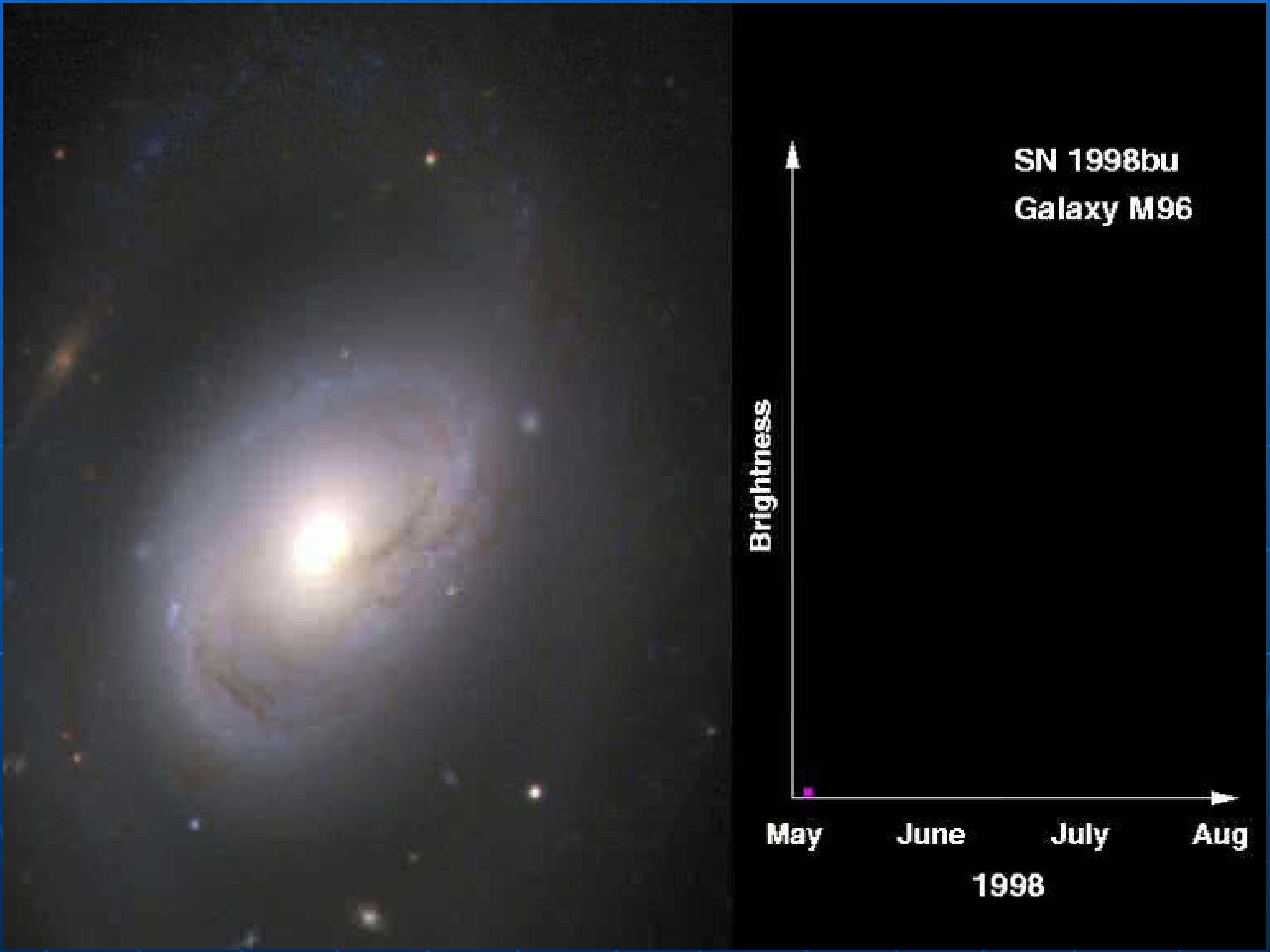
Markus Kromer (MPA)

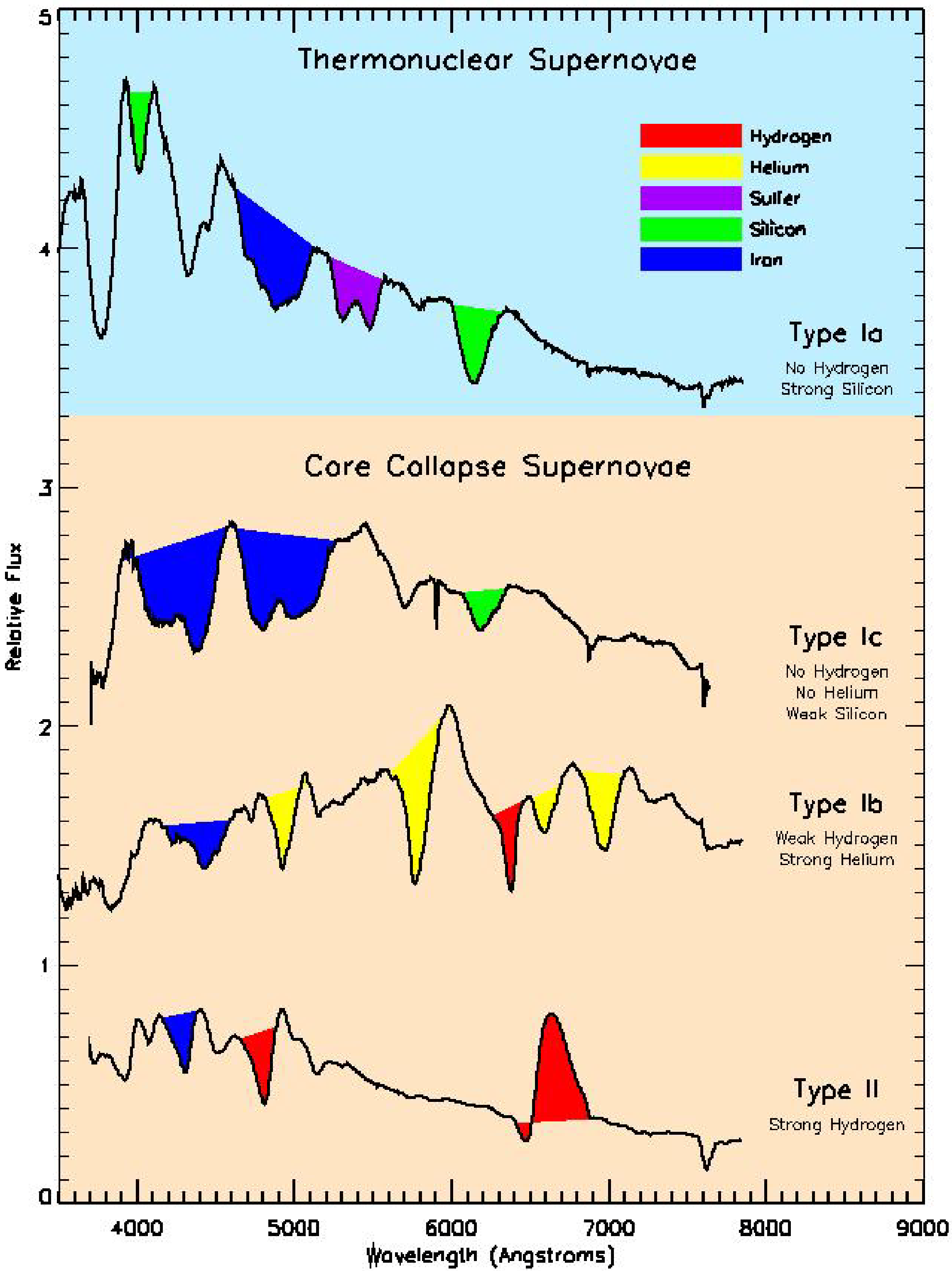
Stephan Hachinger (MPA/INAF Padua)

Sandra Benitez (MPA)

Paolo Mazzali (MPA /SNS Pisa/INAF Padua),

....


SN 1998bu
Galaxy M96
Brightness
May
June
July
Aug
1998



Supernova spectra

(schematically)

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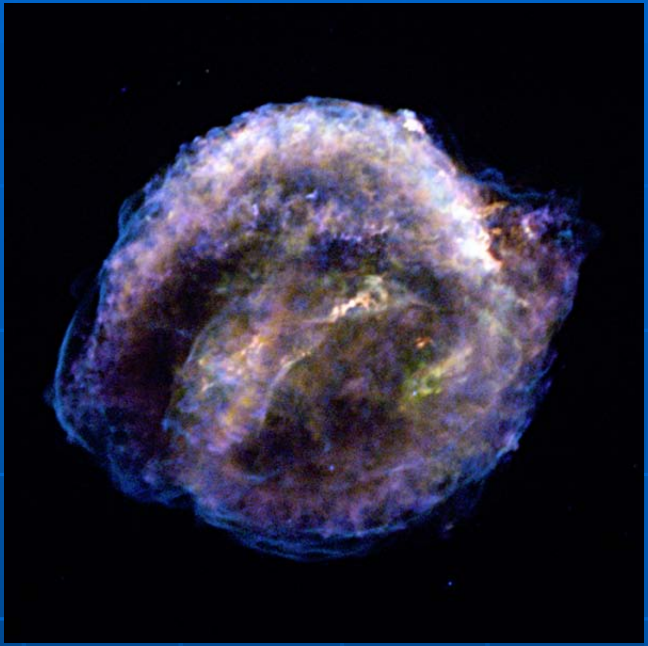
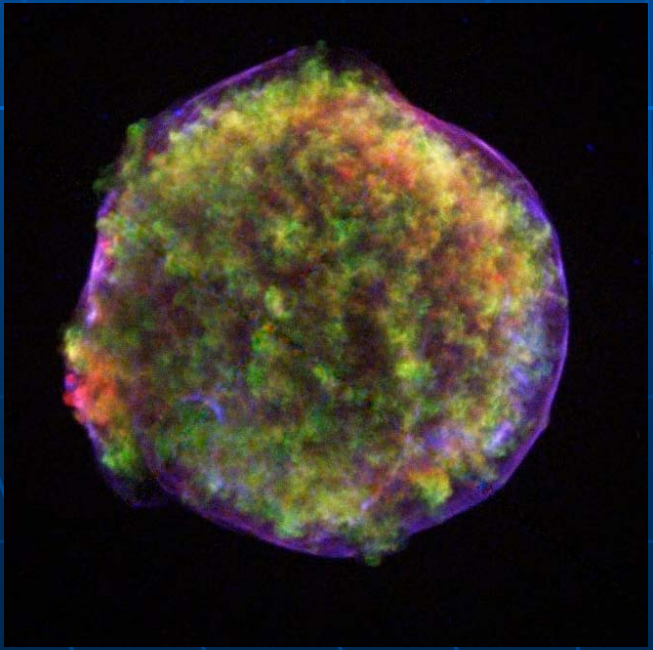
Thermonuclear (Type Ia) Supernovae





Examples:

Kepler's supernova (1604)

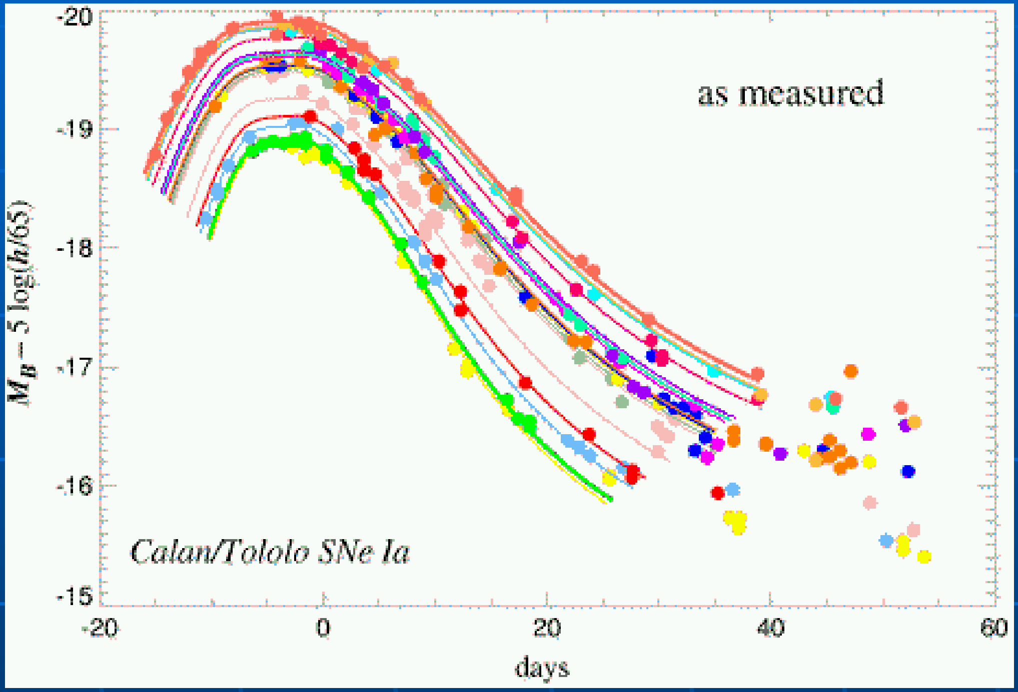
Tycho Brahe's supernova (1572)

“Stella Nova”:

Nobel Prize for Physics 2011….

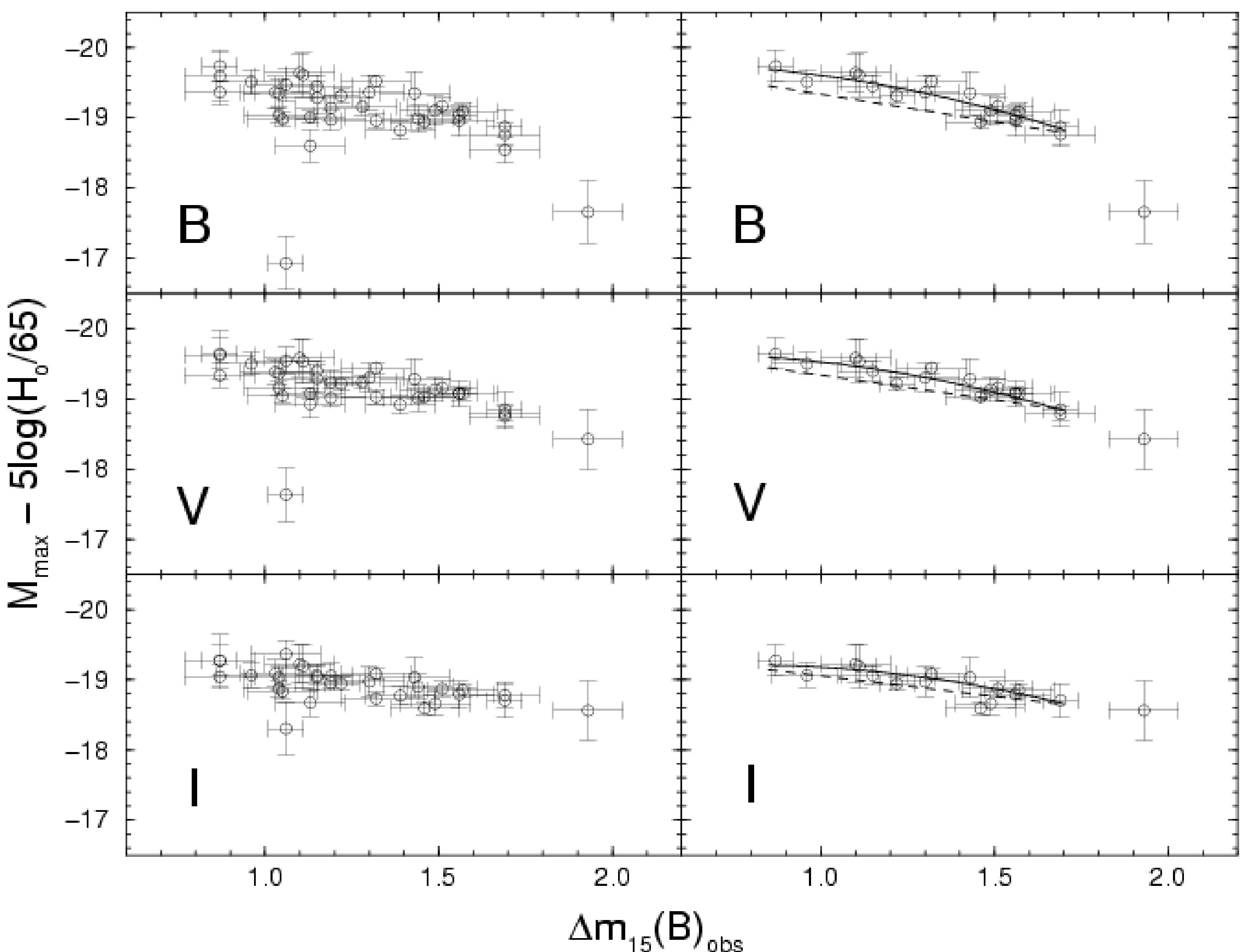
"… for the discovery of the accelerating expansion of the Universe through

Supernova cosmology:
The quest for precise luminosity distances!



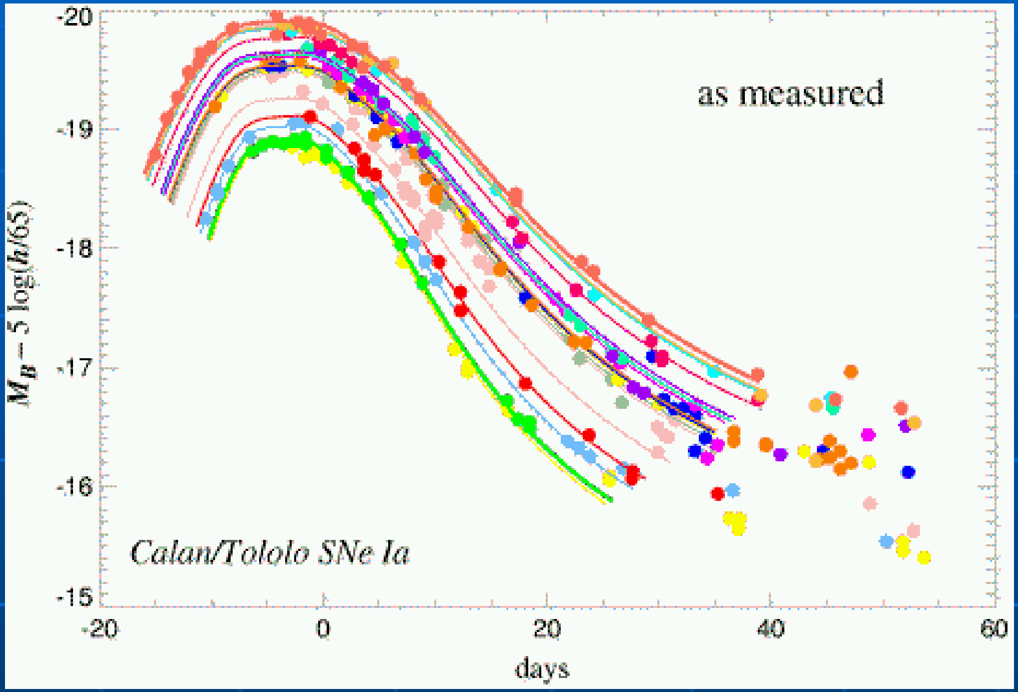
(B-band light curves; Calan/Tololo sample, Kim et al. 1997)

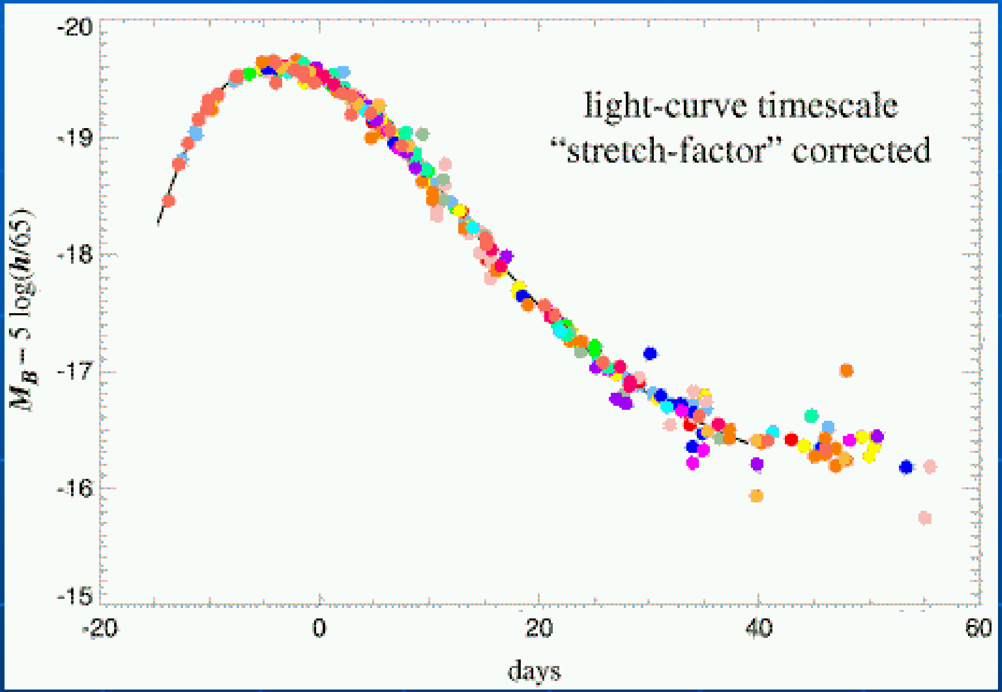
Correlations between peak luminosity and LC shape



Phillips et al. 1999

Supernova cosmology: The quest for precise luminosity distances!

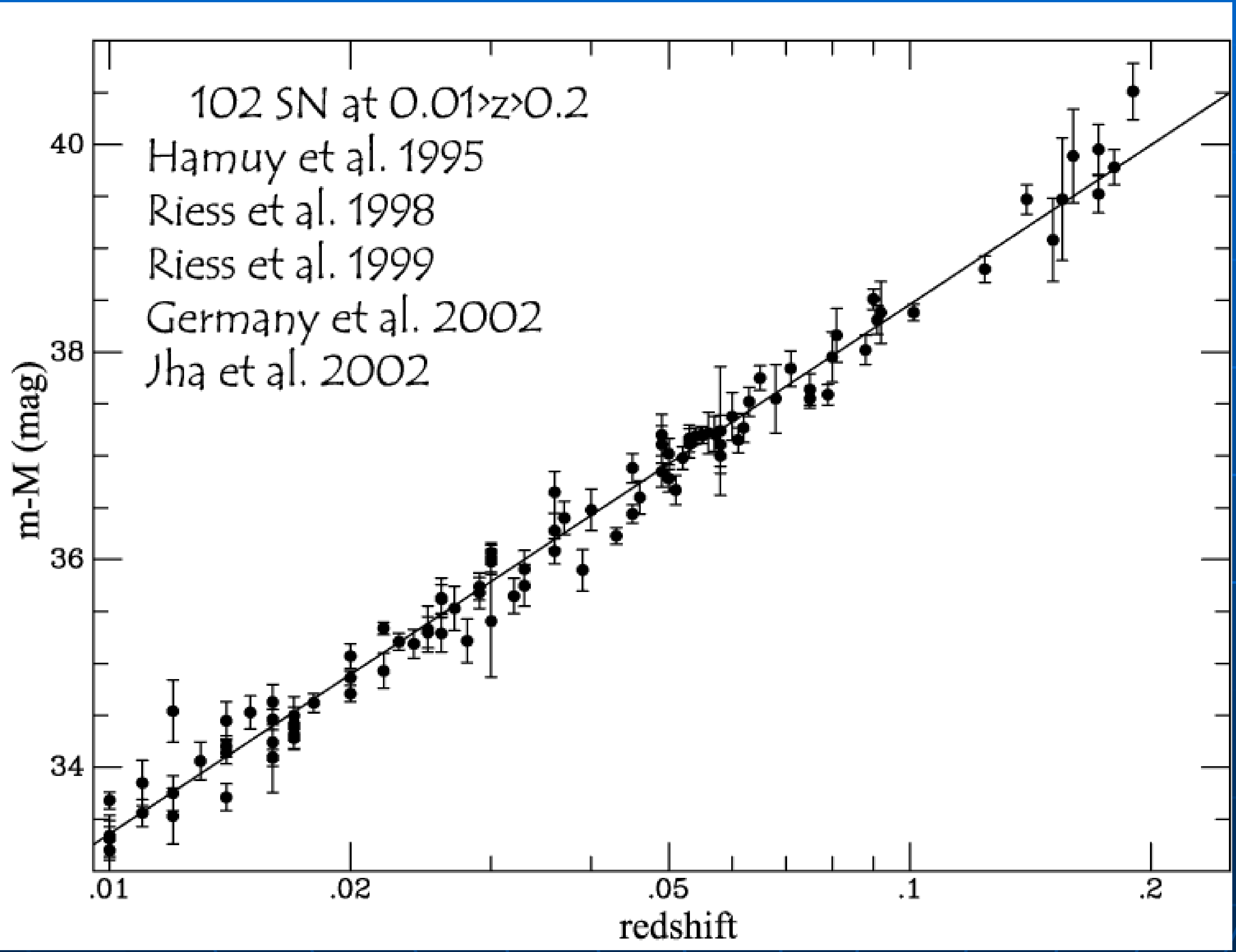




(B-band light curves; Calan/Tololo sample, Kim et al. 1997)

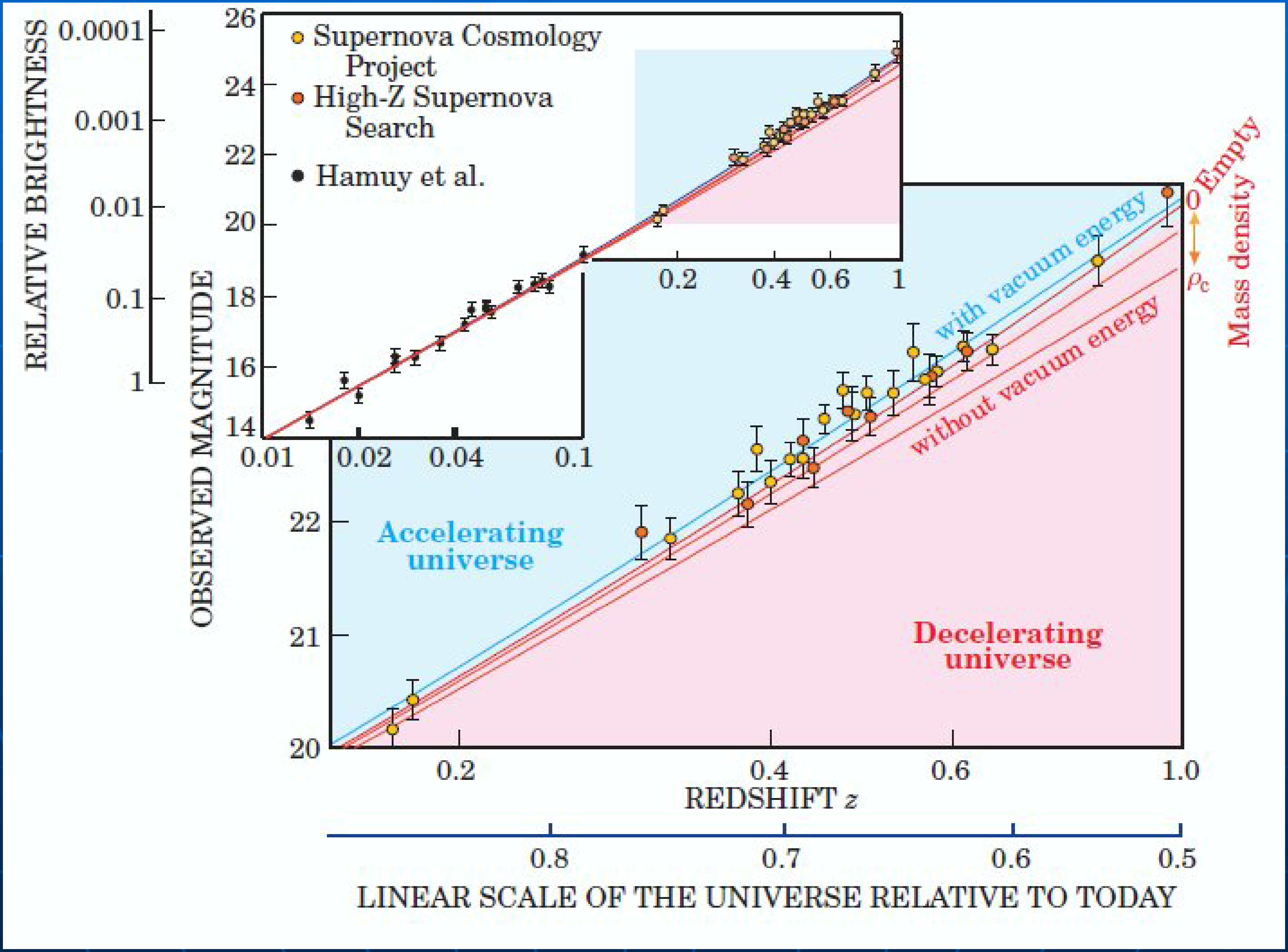
After calibration: *SNe Ia look like good "standard candles"!*

The nearby SN Ia sample

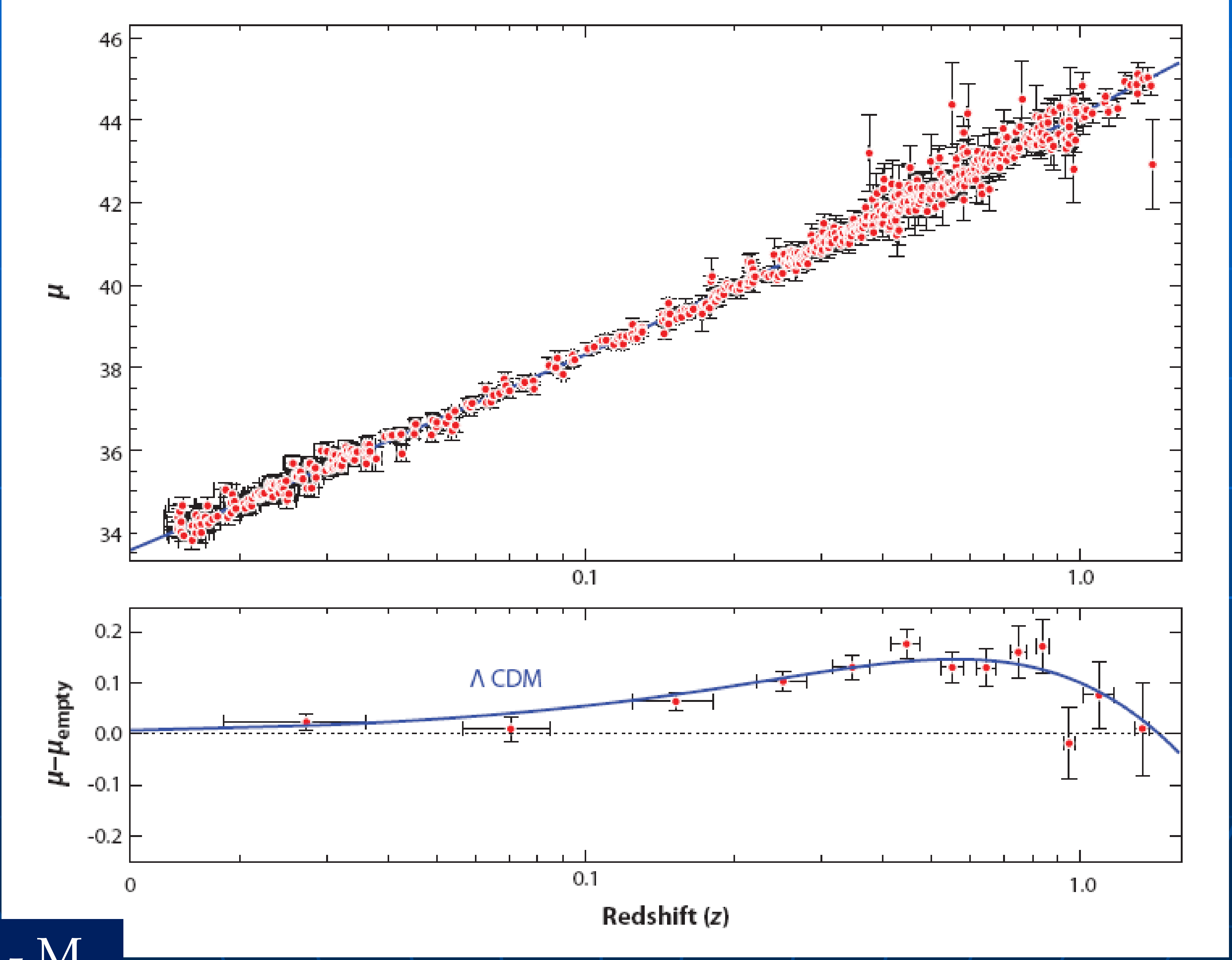


Evidence for good distances; scatter about 8% (0.16 mag)

The "early" data ….

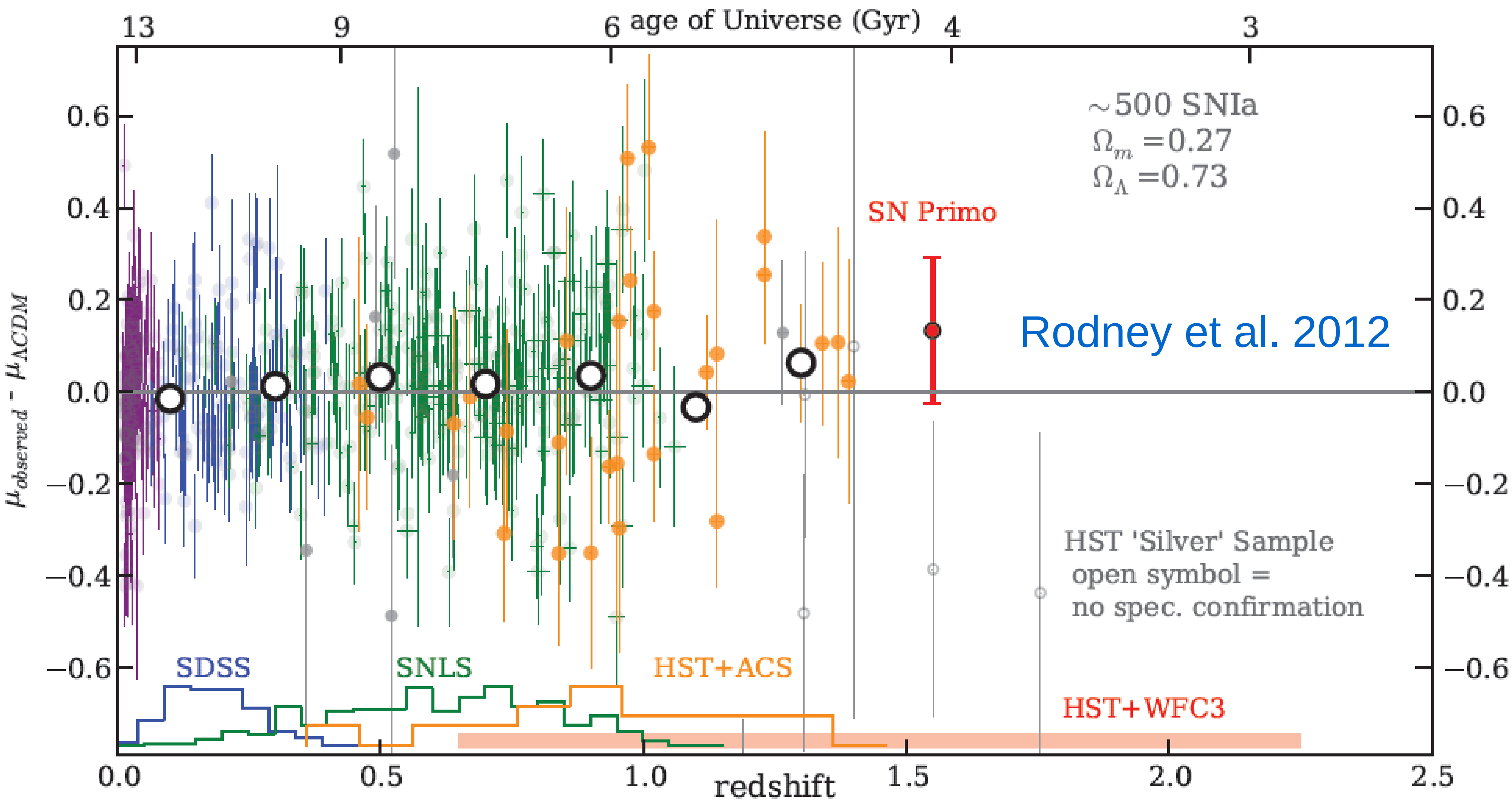


... and the most recent data



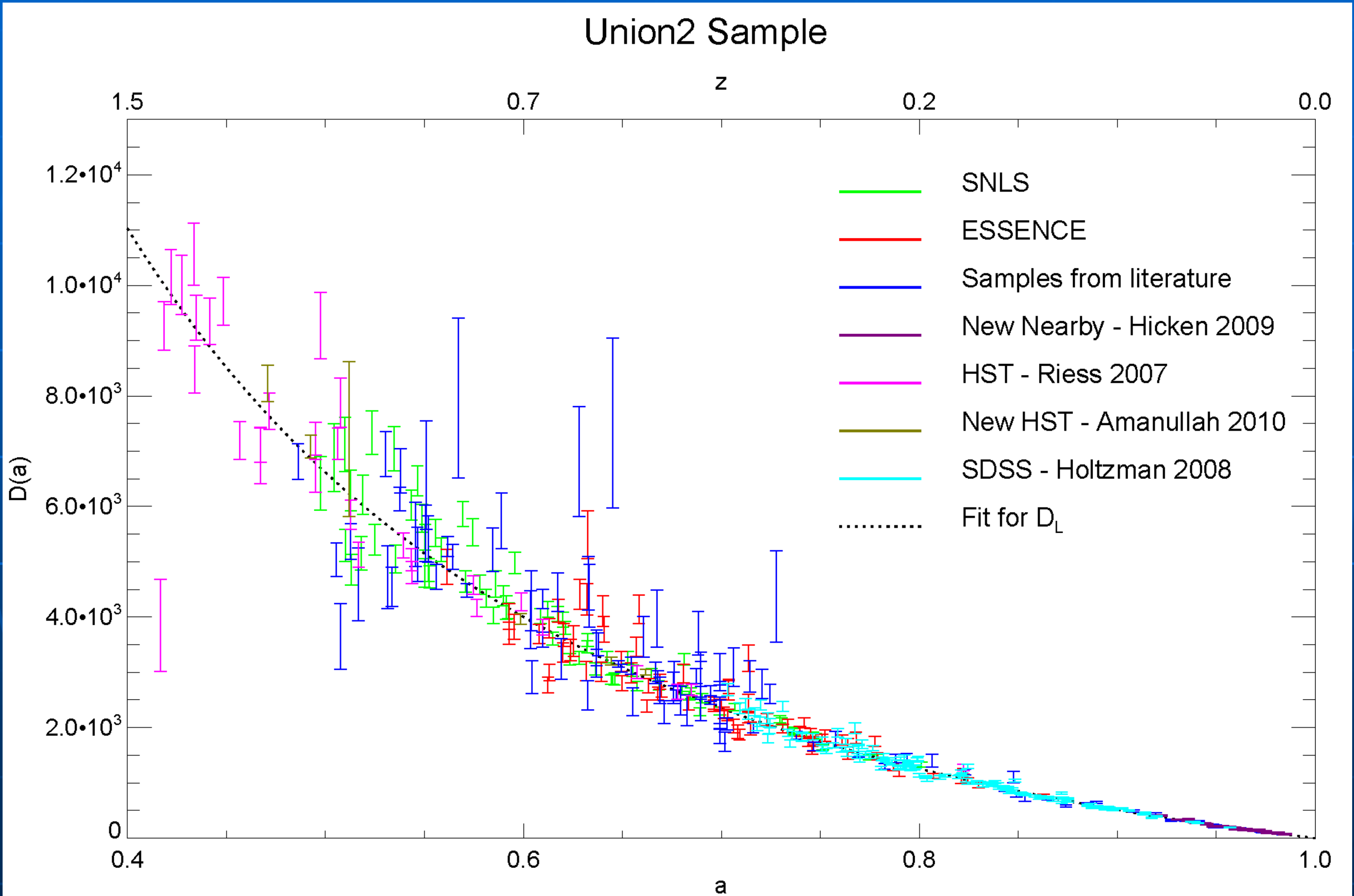
$\mu = m - M$

The most recent Hubble diagram ...



Rodney et al. 2012

... and a different way to plot the data



Benitez-Herrera et al. (2012)

Luminosity distances (FRW cosmologies)

$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}} S\left\{ \sqrt{|\Omega_\kappa|} \int_0^z \left[\Omega_\kappa (1+z')^2 + \sum_i \Omega_i (1+z')^{3(1+w_i)} \right]^{-\frac{1}{2}} dz' \right\}$$

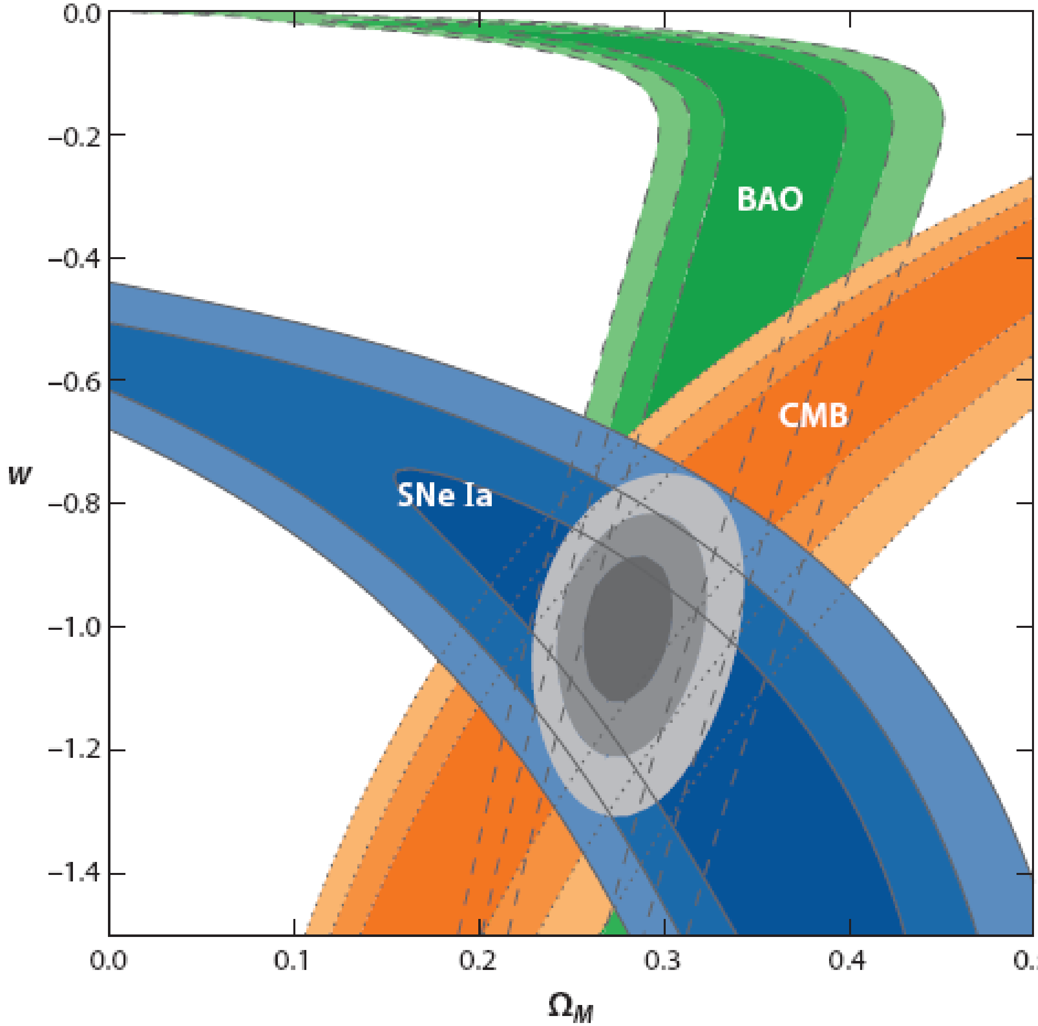
- Where $\Omega_k = 1 - \sum_i \Omega_i$ and $w_i = \frac{p_i}{\rho_i c^2}$

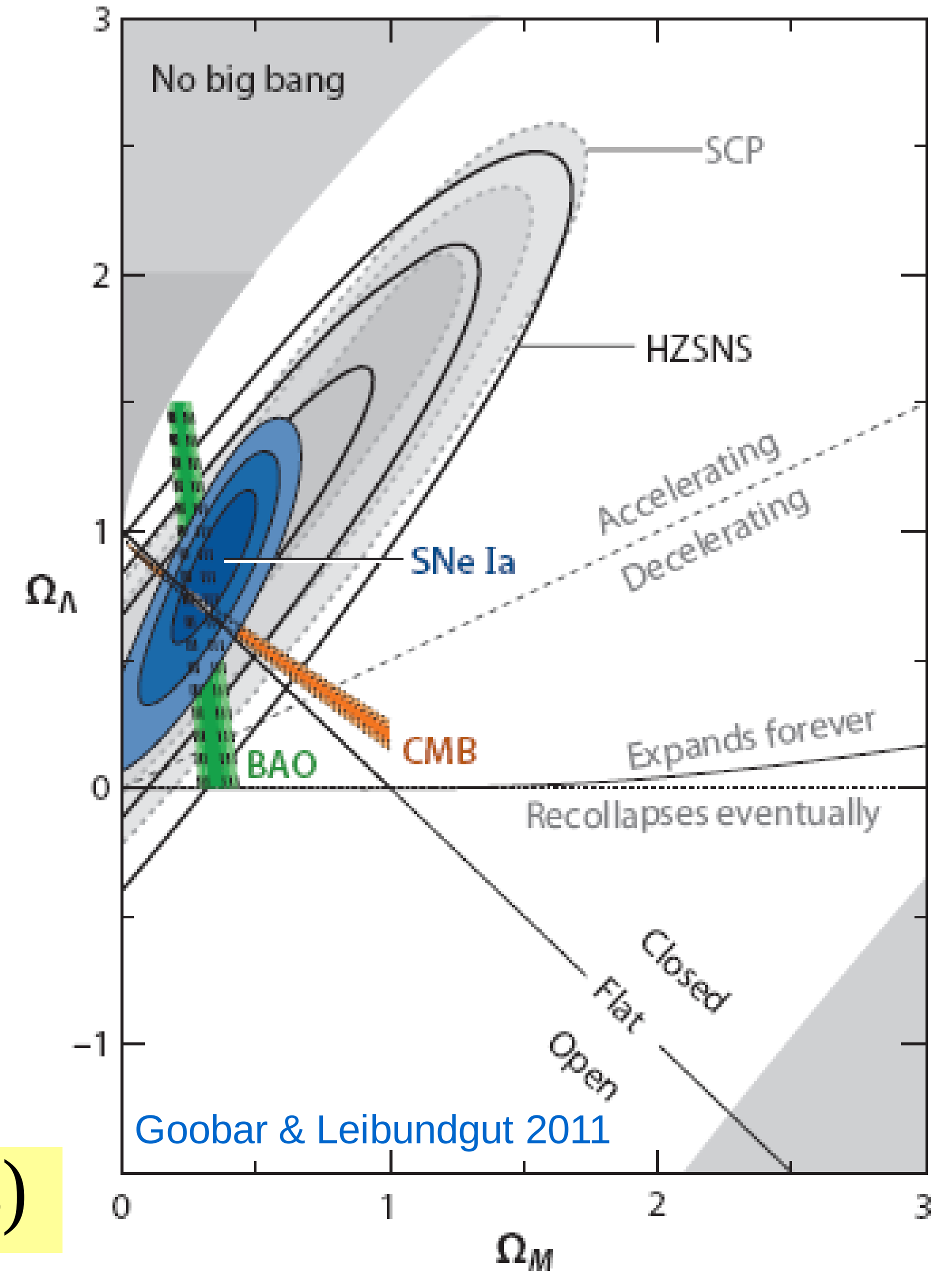
w_M = 0 (matter)

w_R = ⅓ (radiation)

w_Λ = -1 (cosmological constant/vacuum)

Cosmological parameters from different probes





$$w = -1.001 \pm 0.071(\text{stat}) \pm 0.081(\text{sys})$$

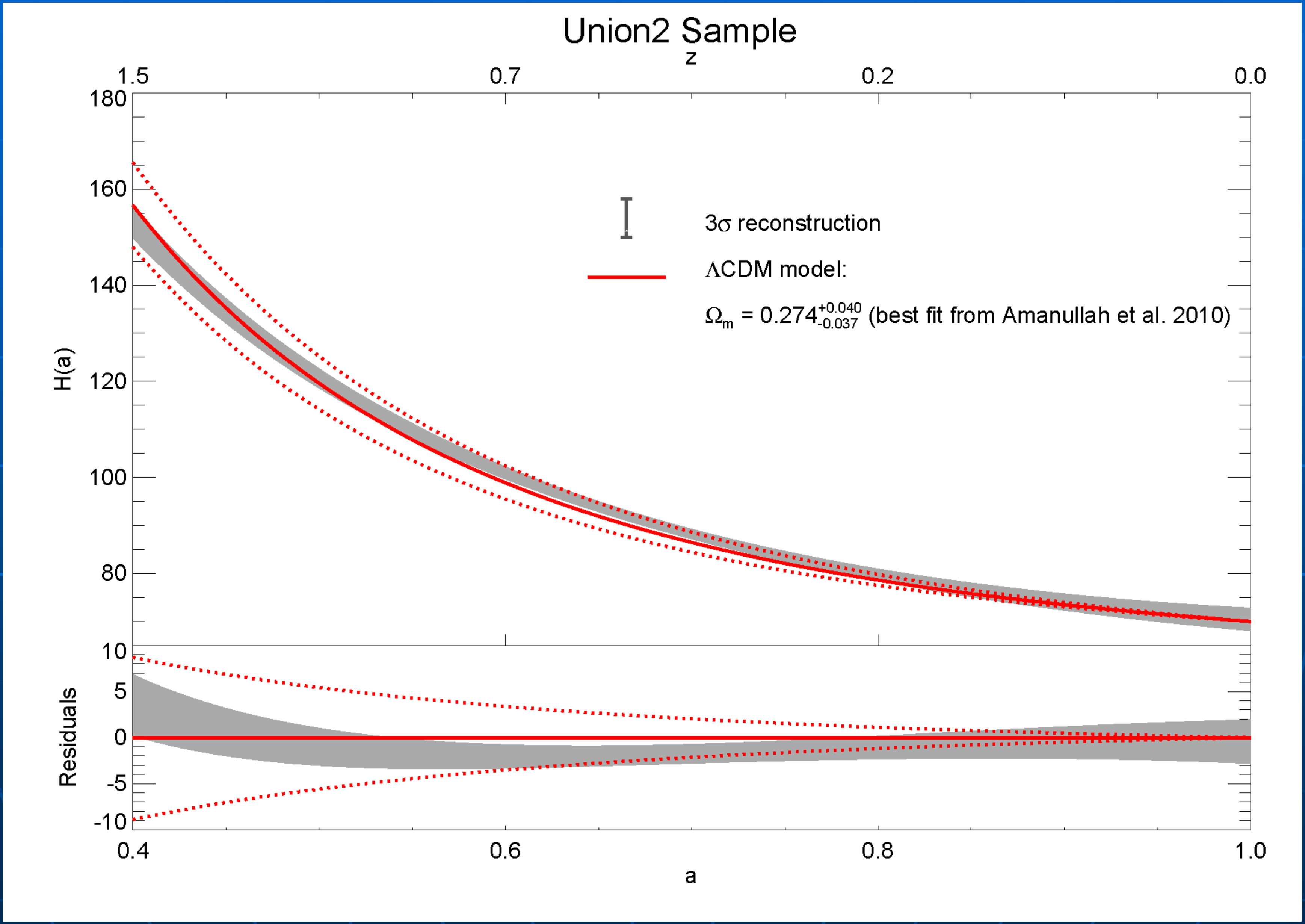
A more general way to use D_L

$$H^2(a) = H_0^2 E^2(a)$$
$$= H_0^2 \left[\frac{\Omega_{\mathrm{r}0}}{a^4} + \frac{\Omega_{\mathrm{m}0}}{a^3} - \frac{\Omega_{k0}}{a^2} + \Omega_{de0} F(a) \right]$$

$$D_{\mathrm{L}}(a) = \frac{c}{H_0} \frac{1}{a} \int_a^1 \frac{dx}{x^2 E(x)} \equiv \frac{c}{H_0} \frac{1}{a} \int_a^1 \frac{dx}{x^2} e(x)$$

→ Reconstruct ("model independently") *H(a)* or *H(z)*

H(z) reconstruction from D_L: ΛCDM



Benitez-Herrera et al. (2012)

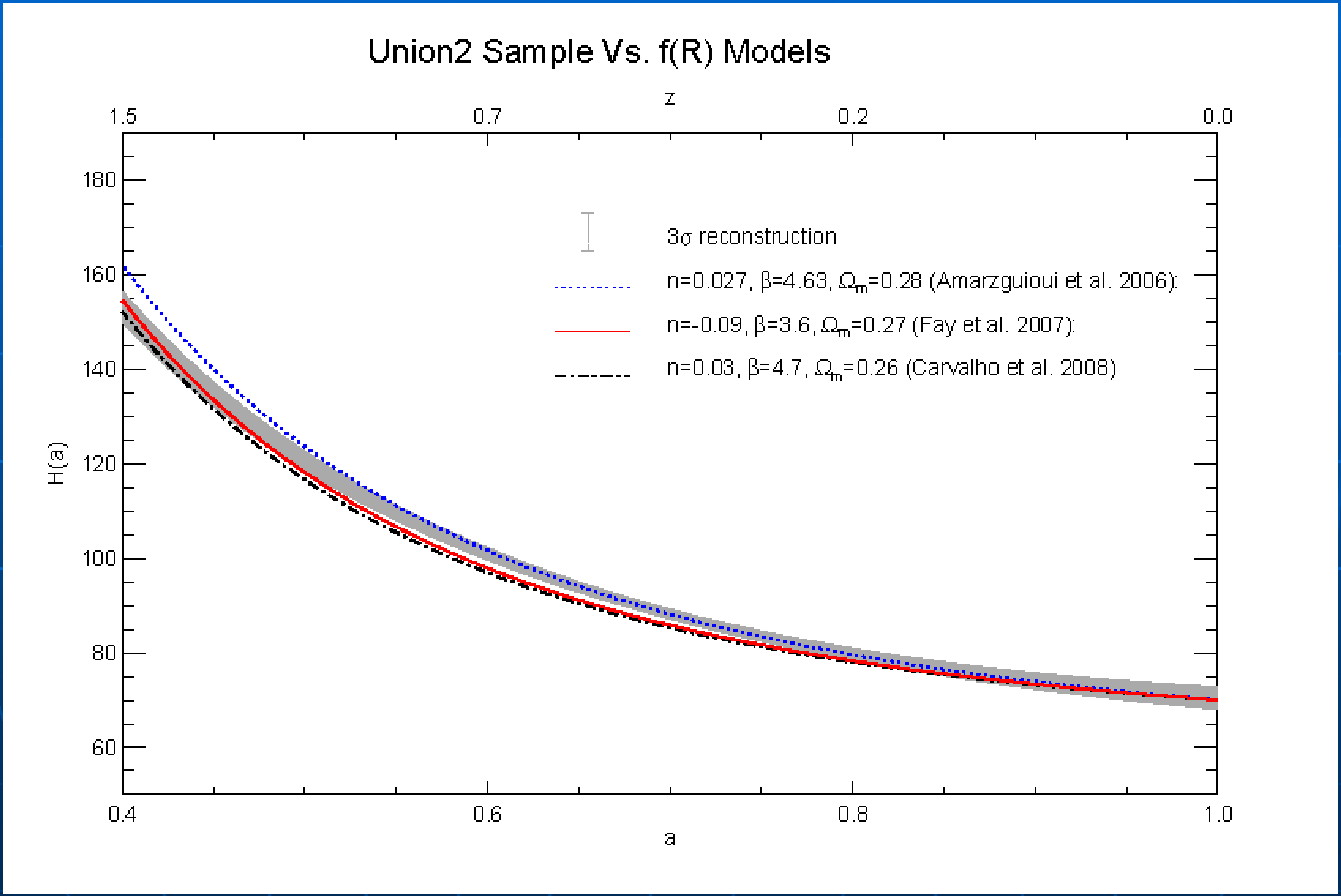
H(z) reconstruction from D_L: f(R) cosmologies

$$H^2(z) = H_0^2 \left[\frac{3\Omega_{\rm m0}(1+z)^3 + f/H_0^2}{6f'\xi^2} \right]$$

$$f(R) = R - \frac{\beta}{R^n}$$

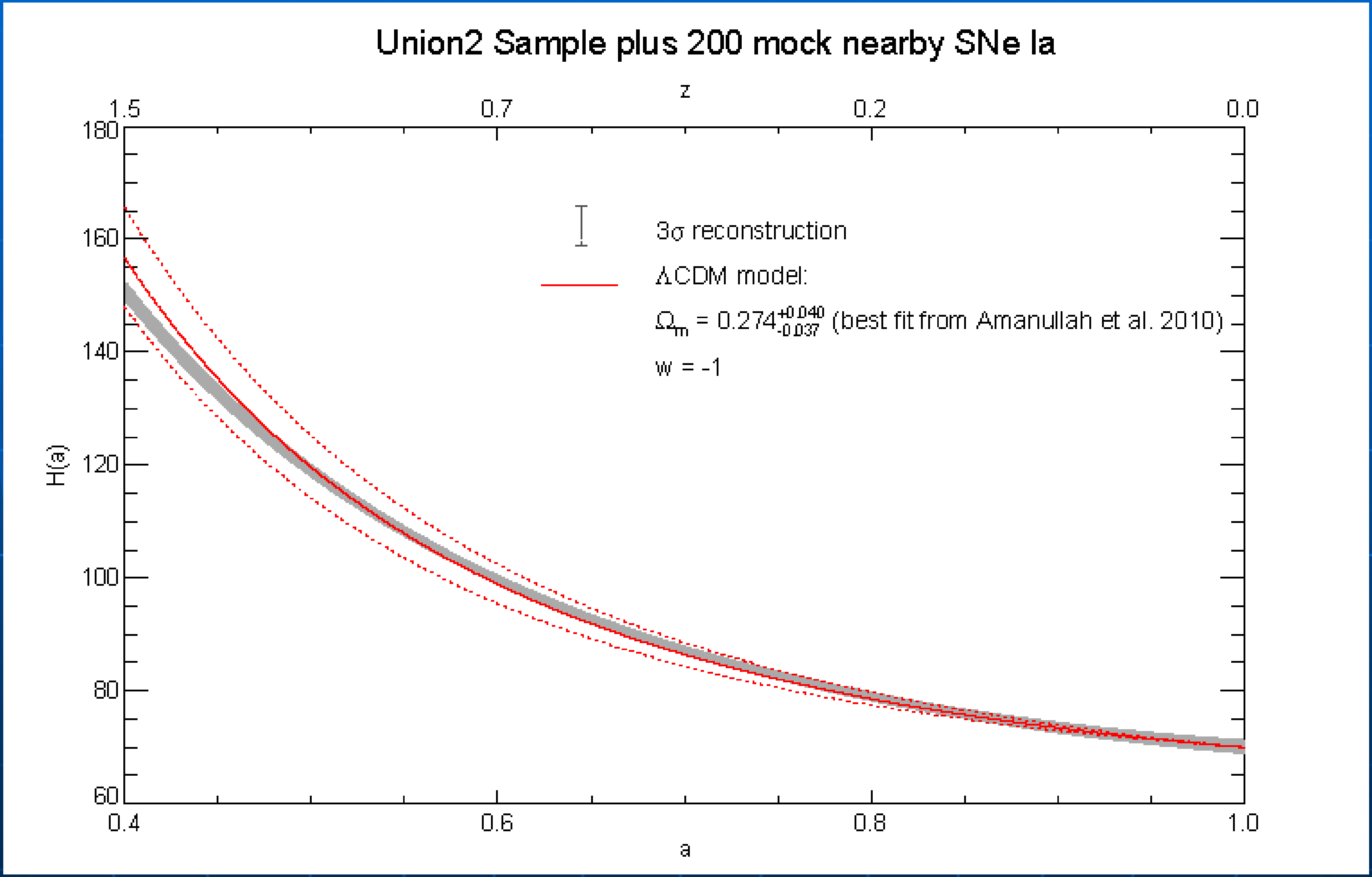
$$\xi = 1 + \frac{9}{2}\frac{f''}{f'}\frac{H_0^2\Omega_{\rm m0}(1+z)^3}{Rf'' - f'}$$

H(z) reconstruction from D_L: f(R) cosmologies



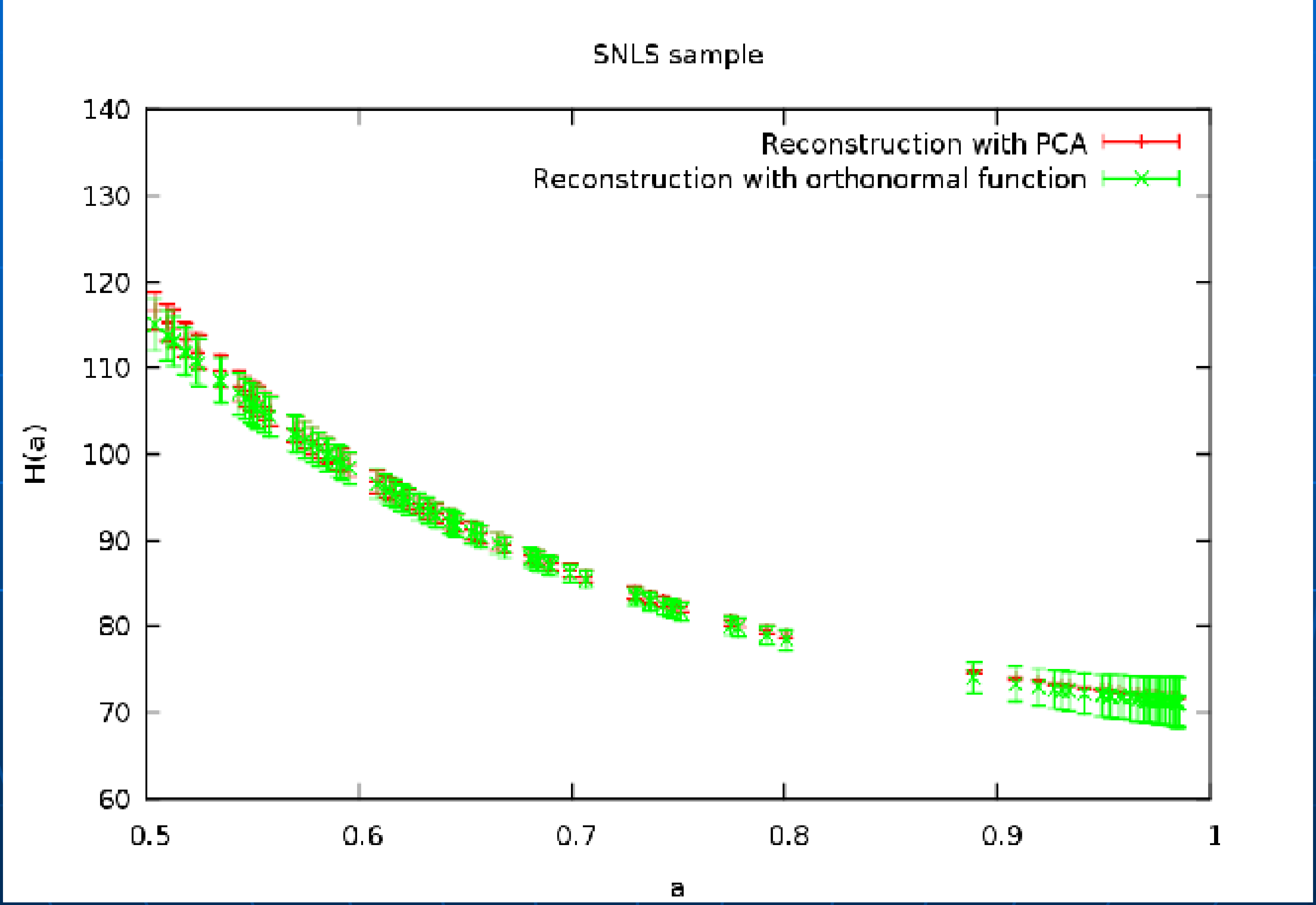
Benitez-Herrera et al. (2012)

H(z) reconstruction from D_L: better data



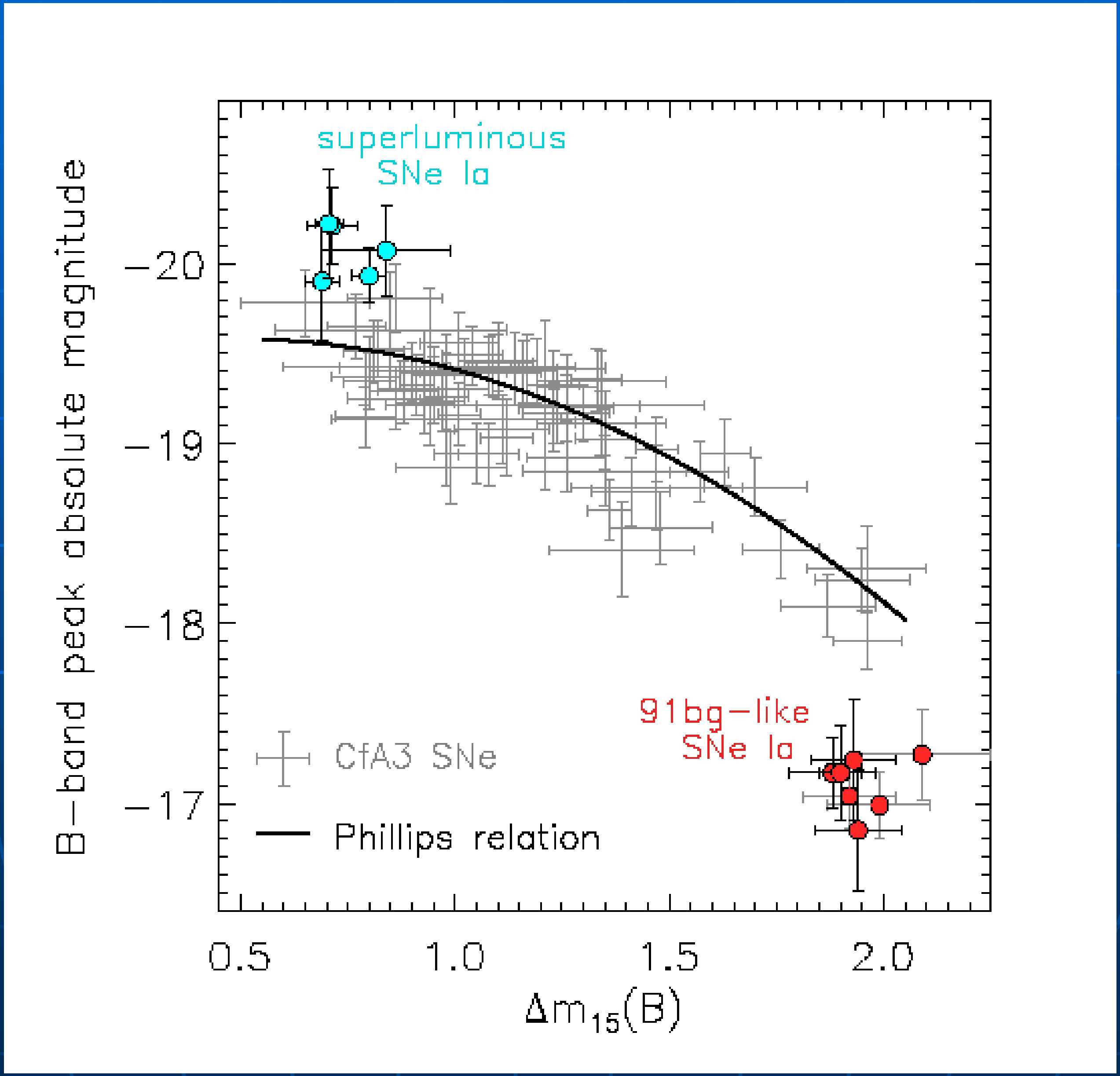
Benitez-Herrera et al. (2012)

H(z) reconstruction from D_L: PCA analysis

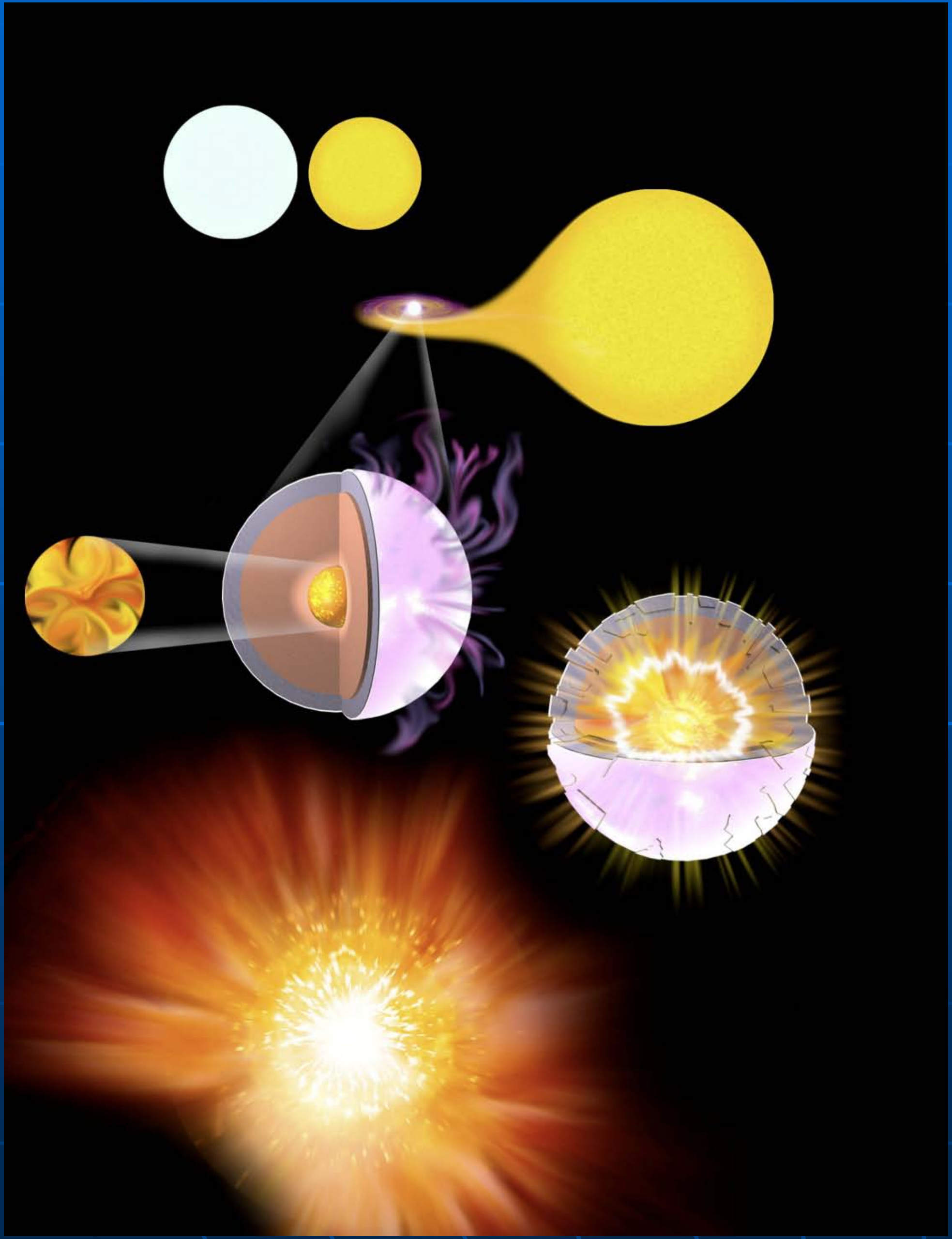


Benitez-Herrera et al. (2012)

BUT: Are there systematic errors???



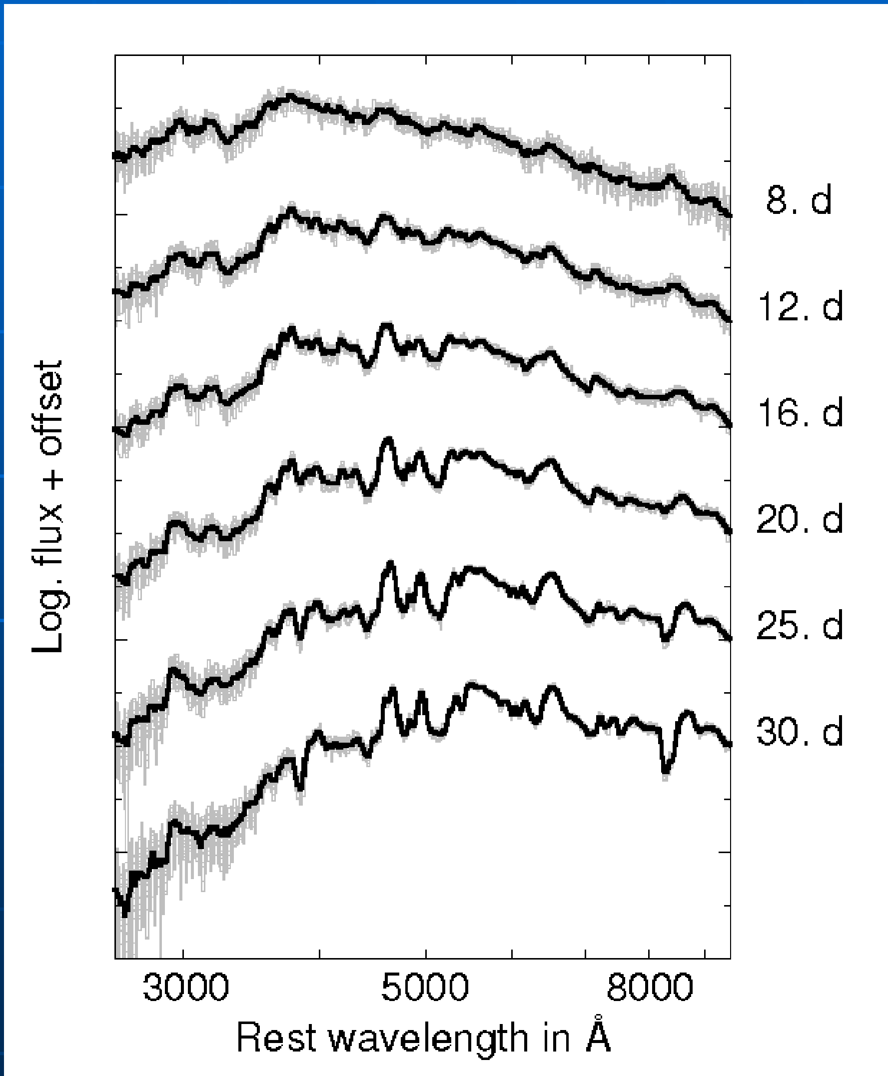
The ‘standard’ (single-degenerate) M_{chan} model



- White dwarf star in a binary system with MS or giant star
- Growing to the critical mass ($\approx 1.4\ M_{\odot}$) by mass transfer
- Disrupted by a thermo-nuclear explosion (fusion of C and O to iron-group elements)
- Light comes from radioactive decay : $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

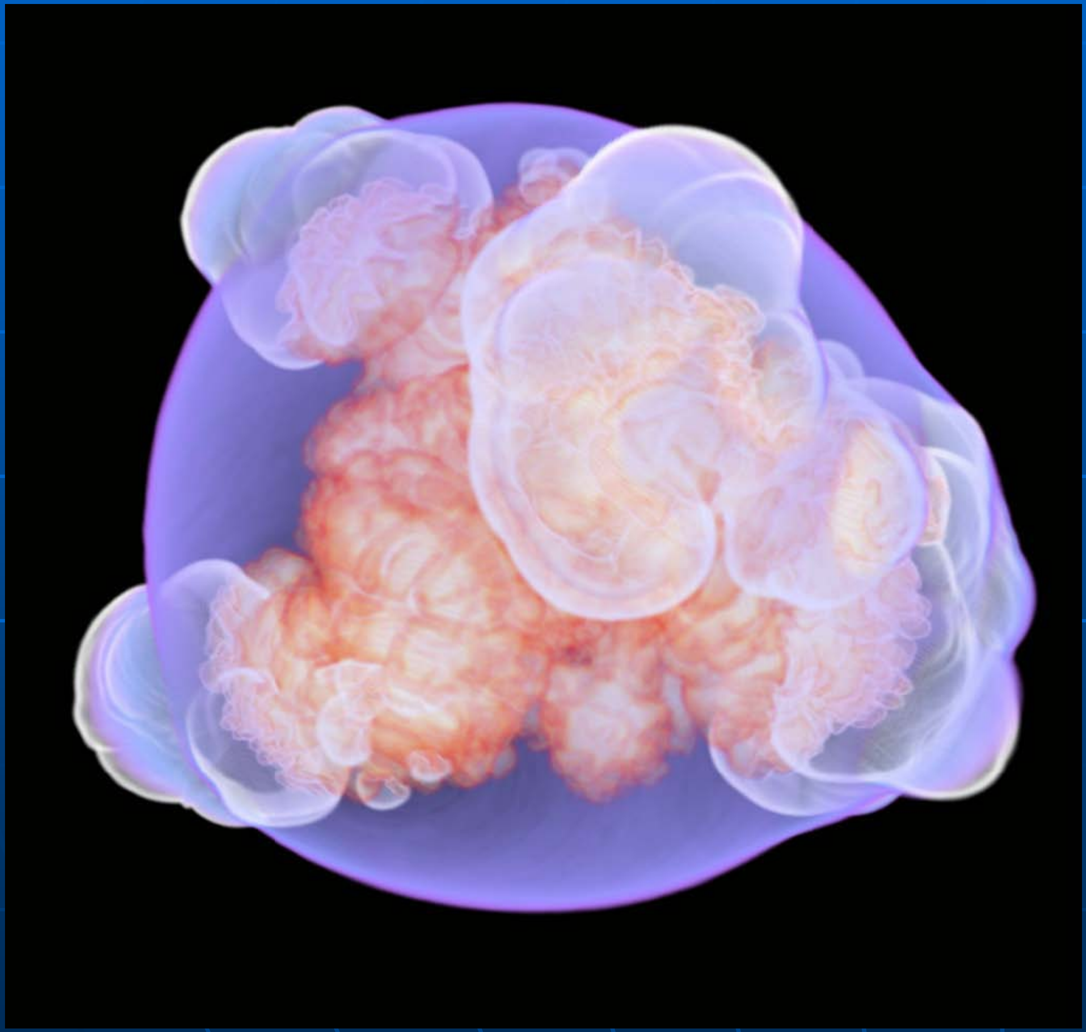
Numerical realisation: 'Pure deflagrations'

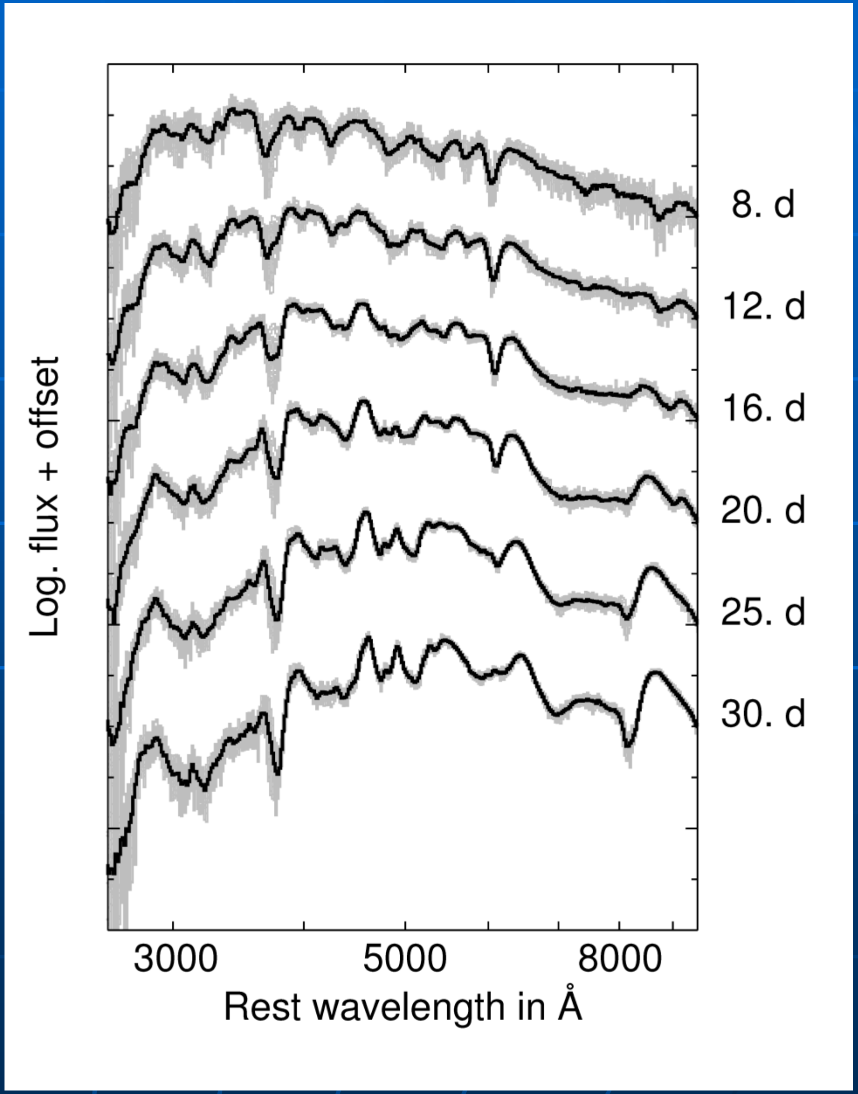
(Reinecke et al. 2002, Garcia-Saenz & Bravo 2005, Röpke et al. 2007, Röpke & Schmidt 2009)



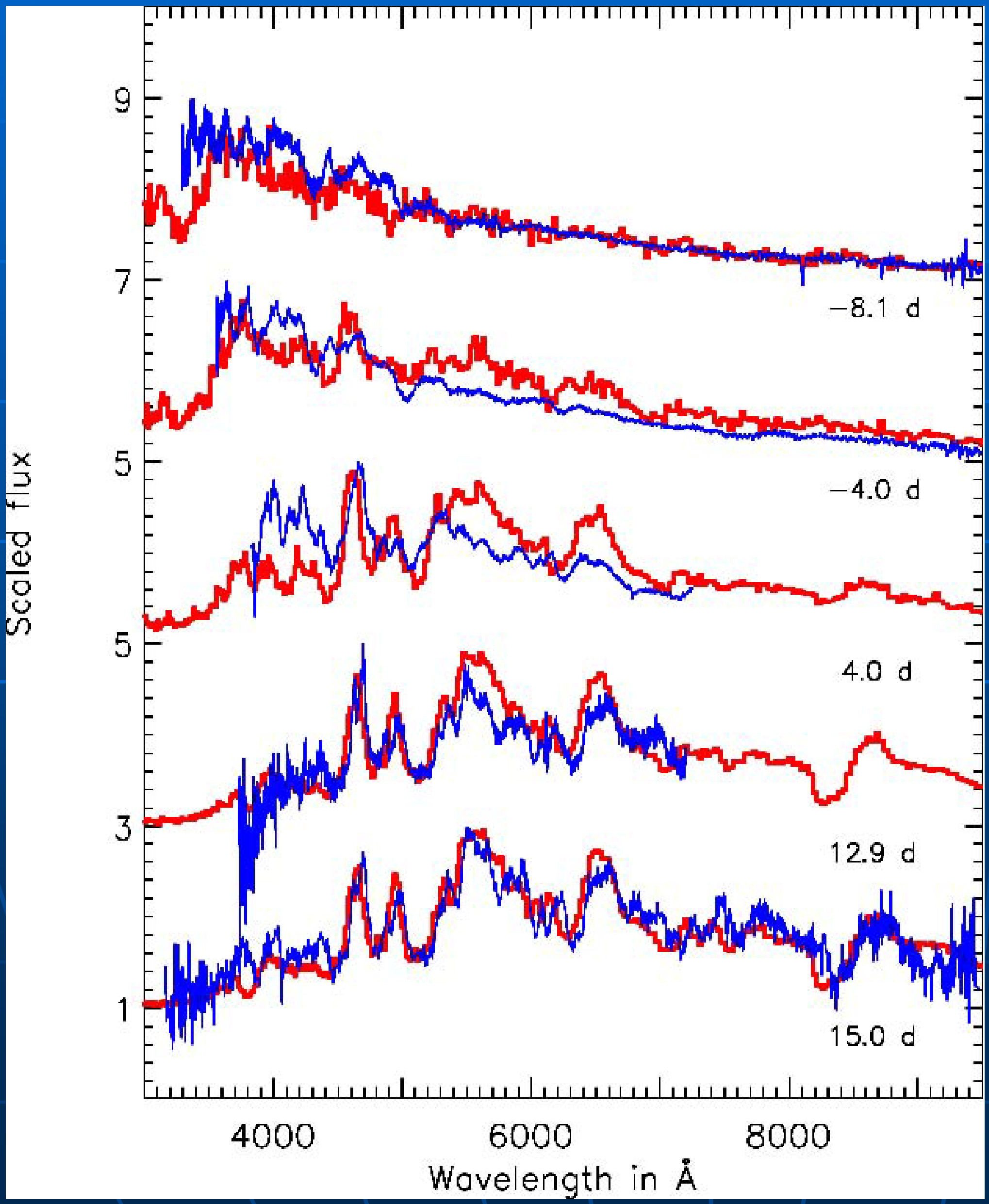
Numerical realisation: or the ‘DDT’ version

(Gamezo et al. 2005, Röpke et al. 2007, Bravo & Garcia-Senz 2008, Kasen et al. 2009, ...)



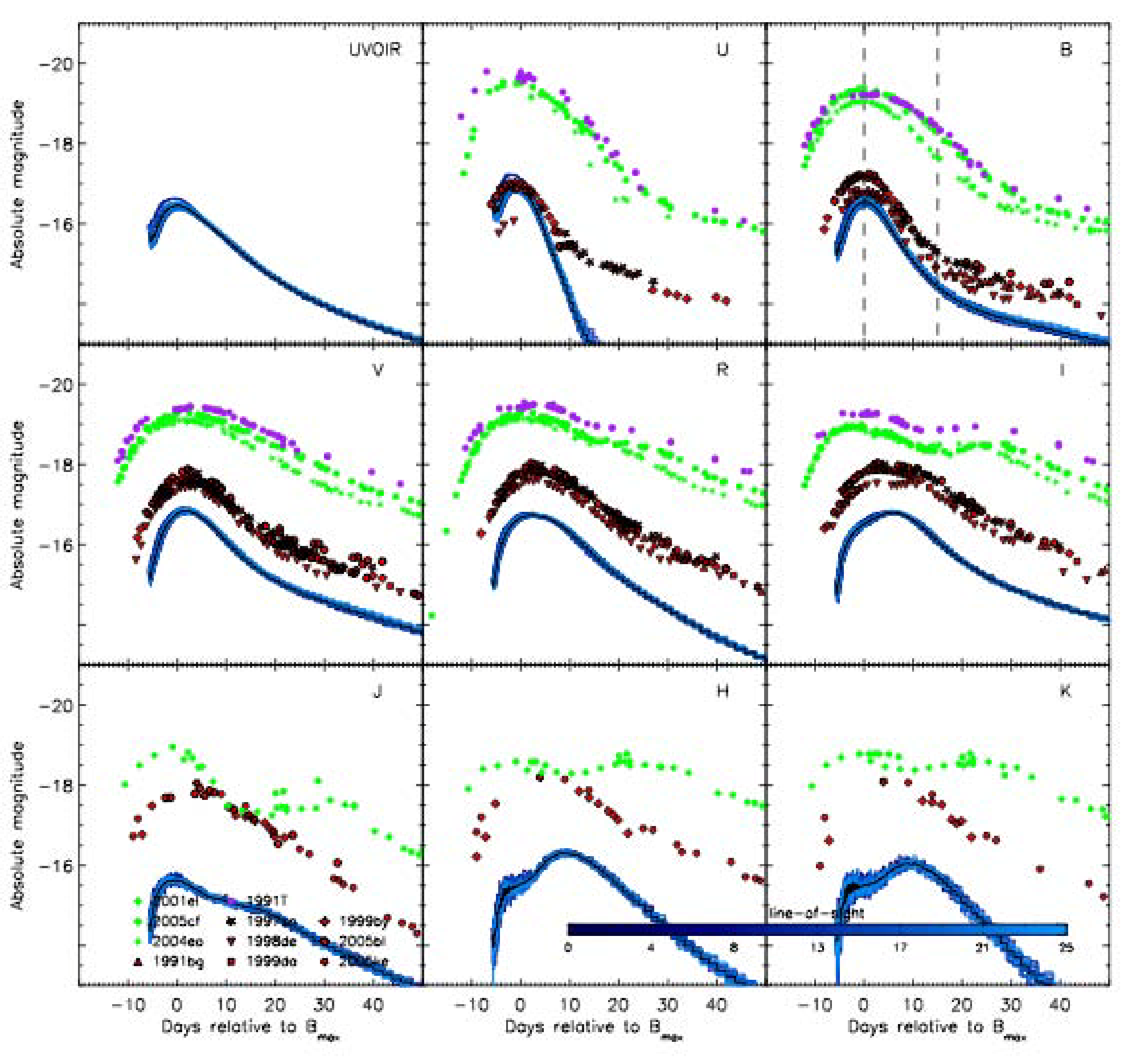


Synthetic observables from ‘single degenerates’: Spectra (Sim et al., in prep.)



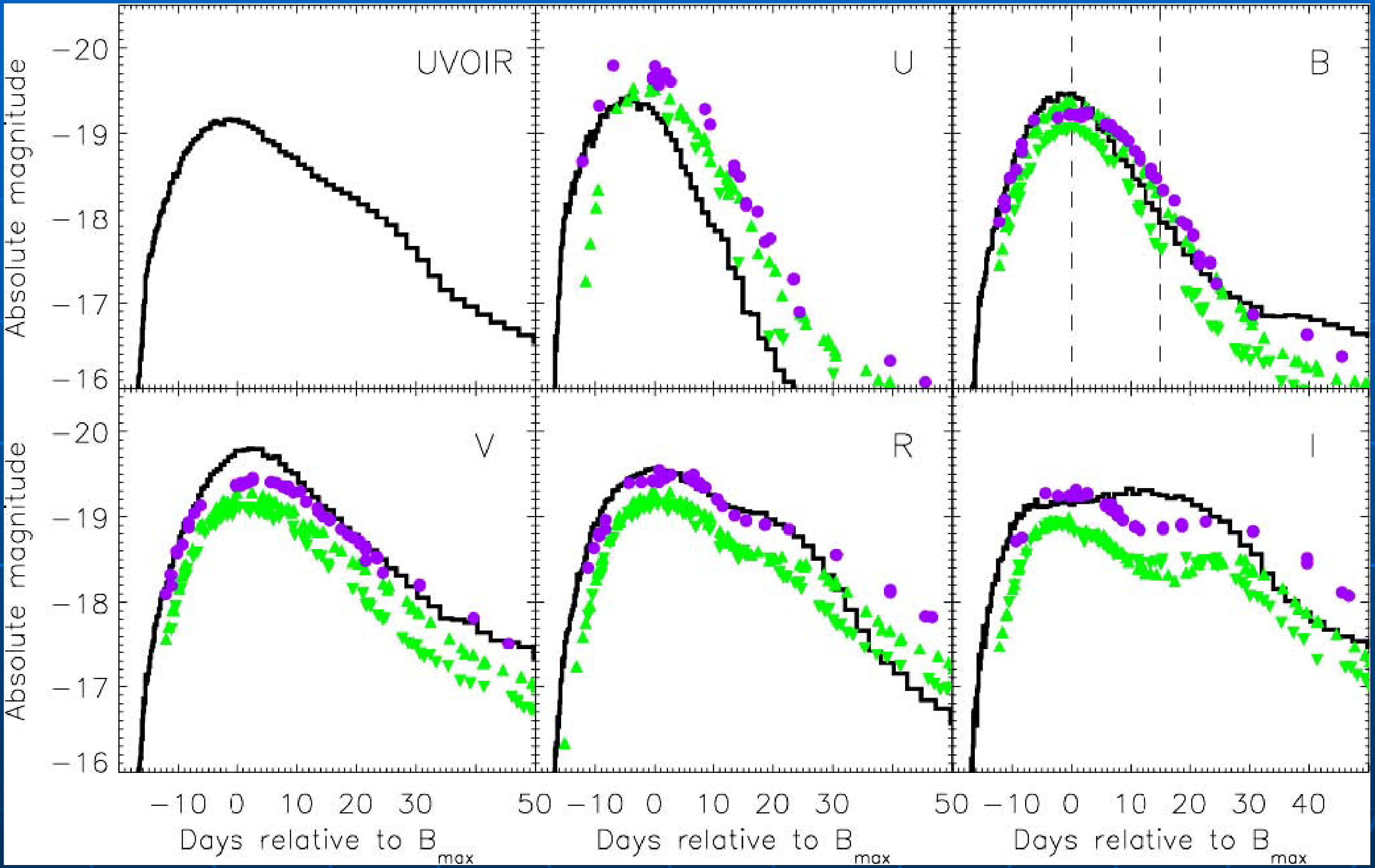
‘Pure deflagation’ model (red) compared with the peculiar SN 2005hk (blue)

Synthetic observables from 'single degenerates': Lightcurves (Kromer et al., in prep.)



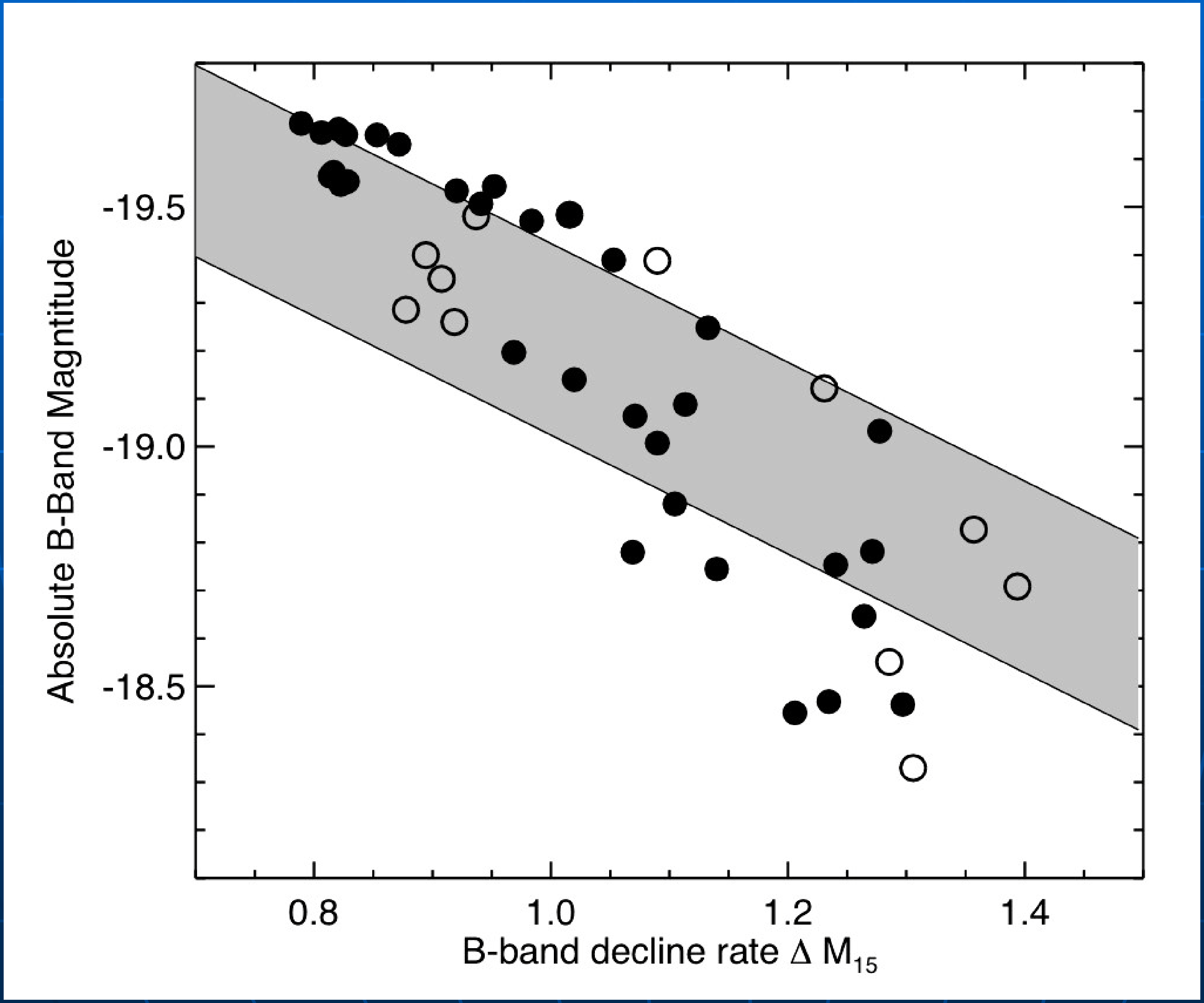
Typical 'pure deflagation' model (blue) compared with various 'normal' SNe Ia

Synthetic observables from 'single degenerates': Lightcurves (Sim et al., 2011)



DDT model, angle averaged (black solid lines, Sim et al. 2011)

Synthetic observables from ‘single degenerates’: the ‘Phillips relation’ (Kasen et al. 2009)

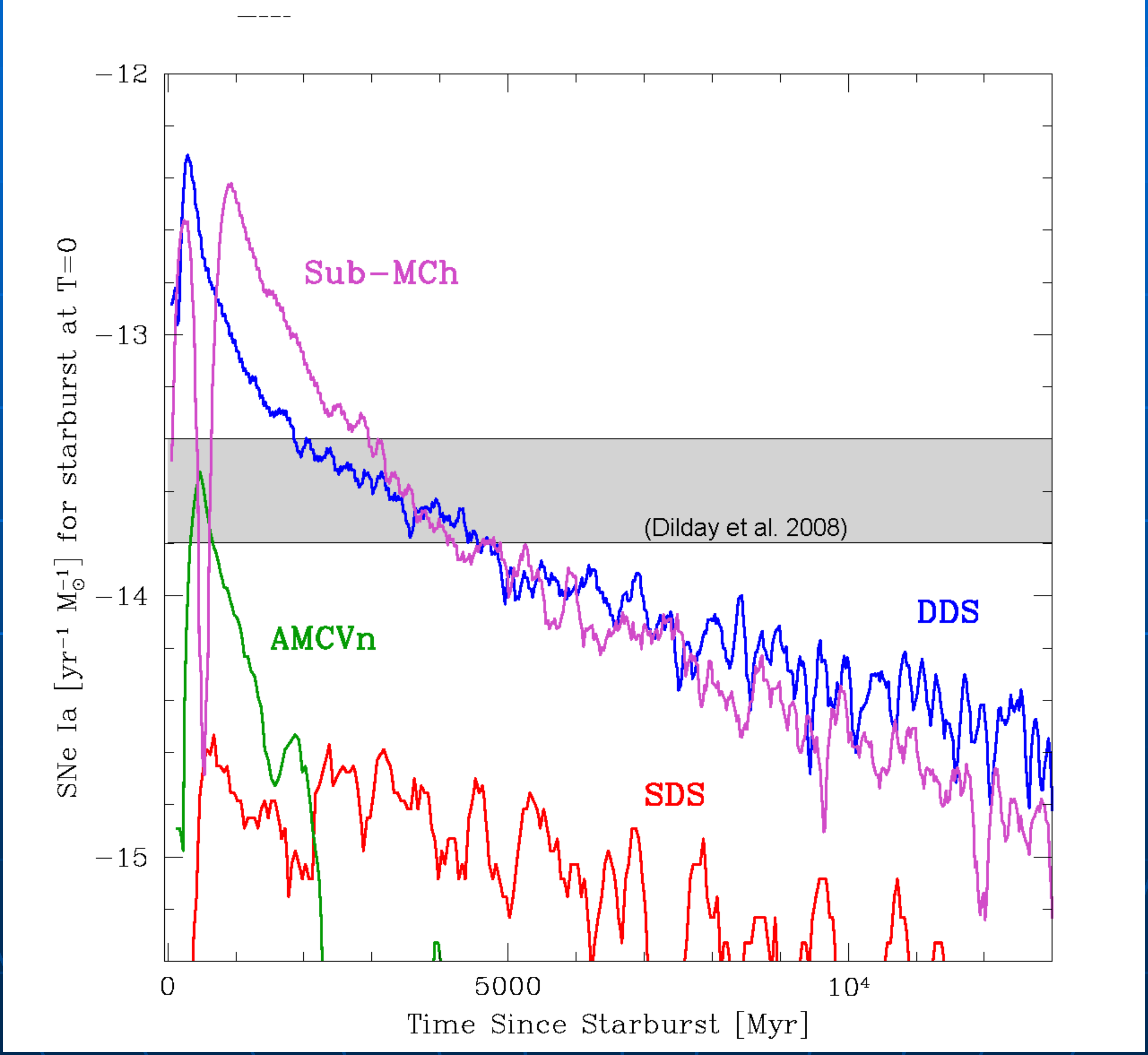


2-dim DDT models only (open: $3Z_\odot$ filled: $0.3Z_\odot$)

So, why do we worry?

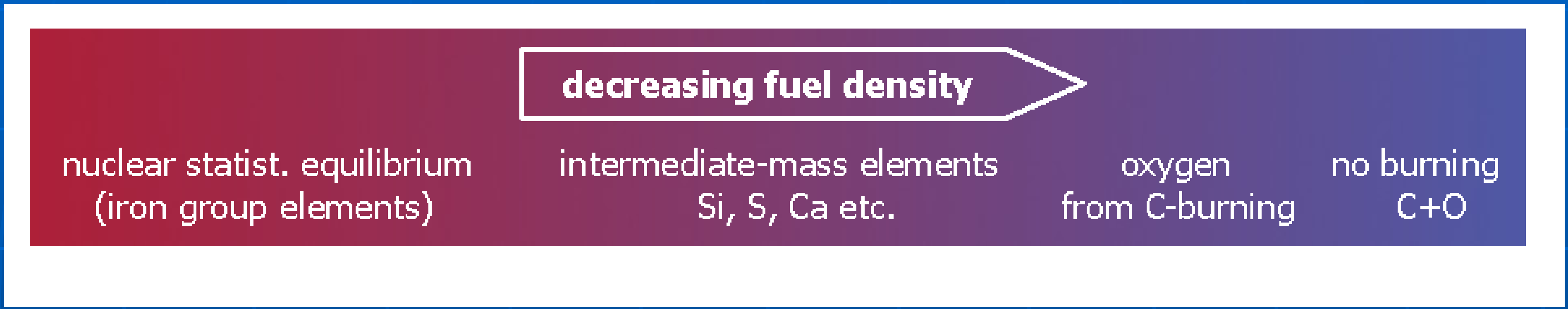
- What causes the deflagration-to-detonation transition?
- Why was hydrogen never detected in a normal SN Ia?
- Models can neither explain the faint (SN 1991bg-like) nor the (very) bright (SN 1991T, SN 2007if, …) SNe Ia
- The predicted rate is too low by about a factor of 10

Rates and delay times (Ruiter et al. 2011)



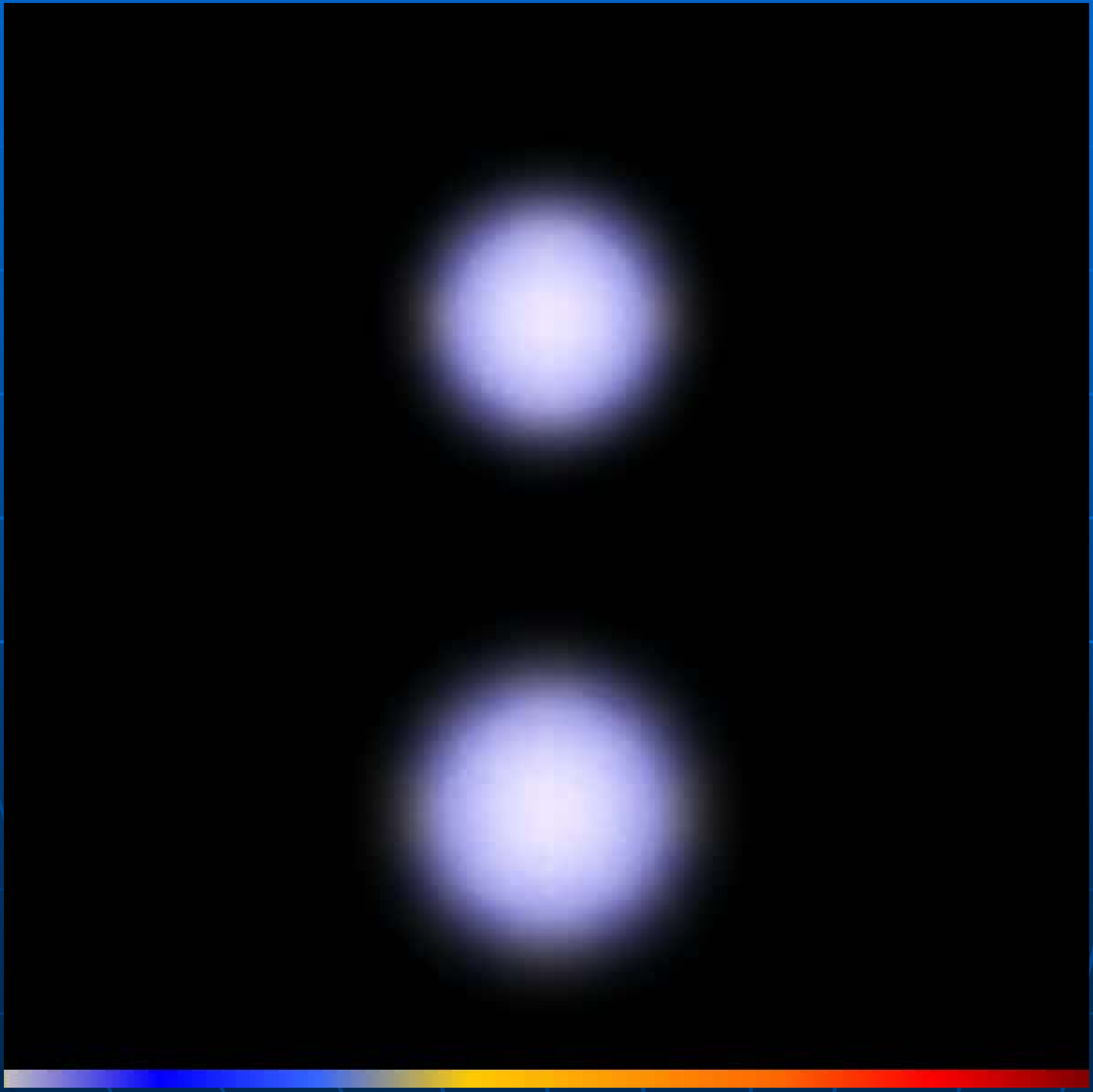
Are some of them (or all?) ‘super-Chandra’ mergers and/or ‘sub-Chandra’ detonations???

The basic idea:

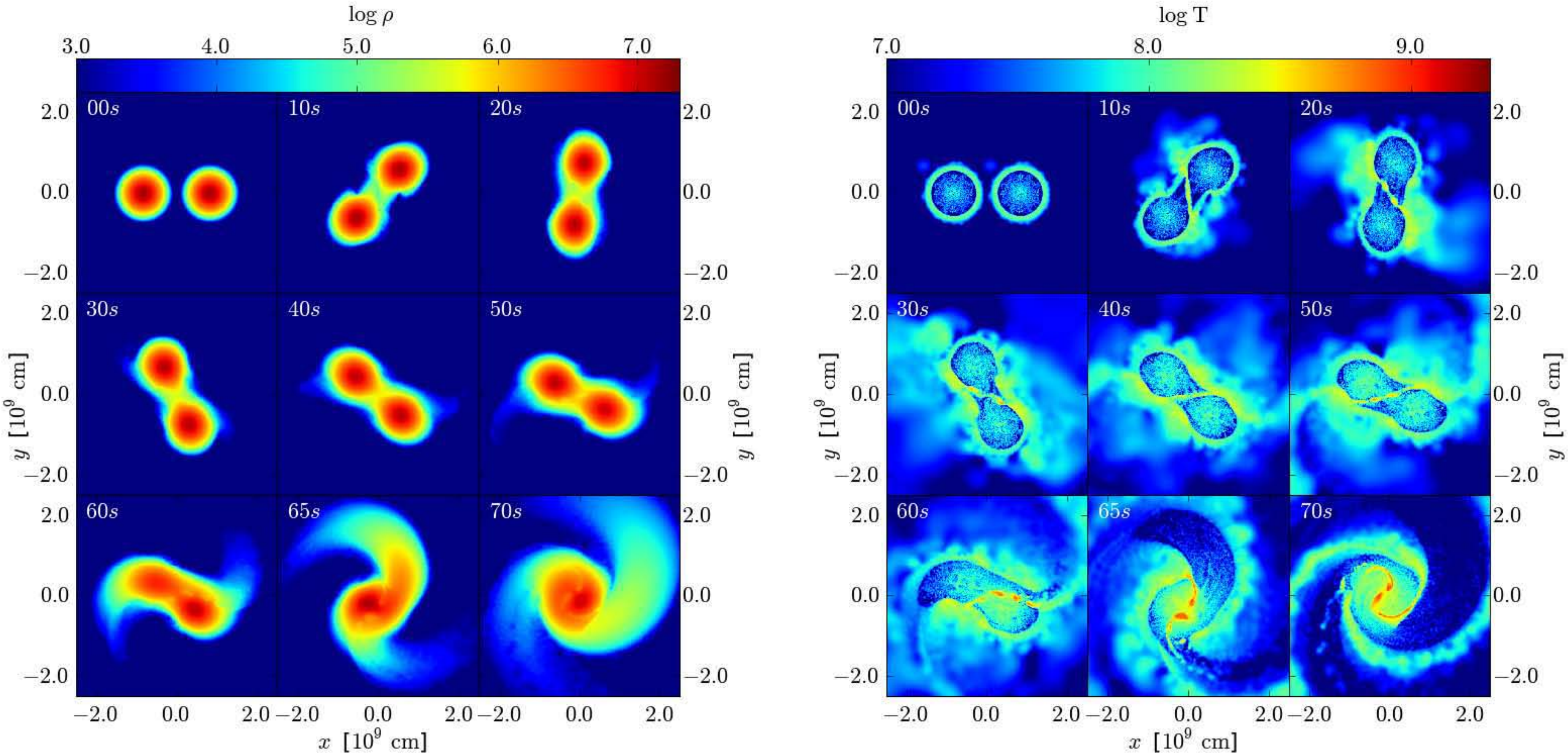


The *brightness* of a SN Ia (the mass of radioactive ^{56}Ni) may be a result of *different white dwarf masses* !

So, let's have a look at "mergers" first …



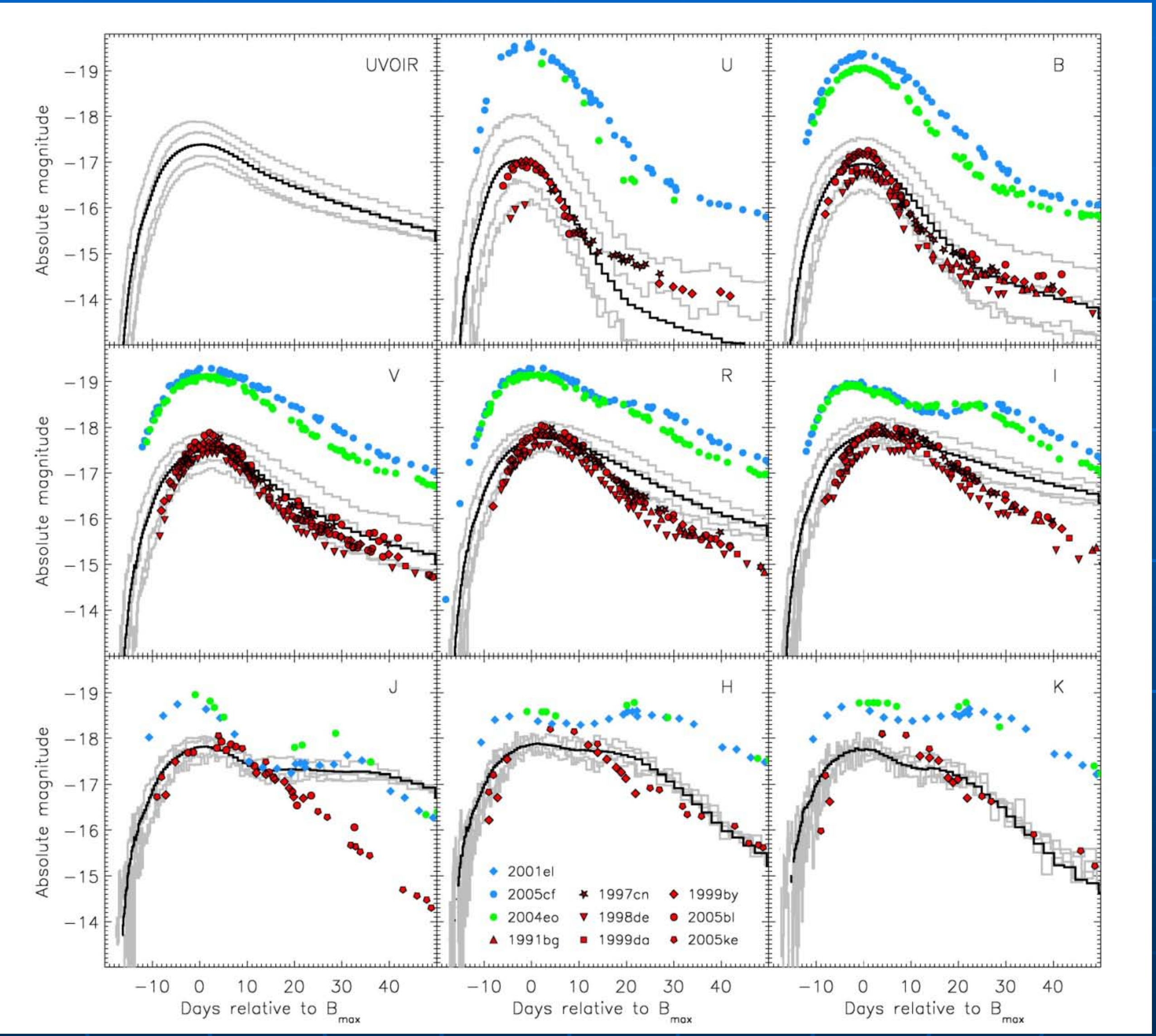
(Pakmor et al. 2010)



<u>Dynamical merger of two WDs of ~ equal mass:</u>

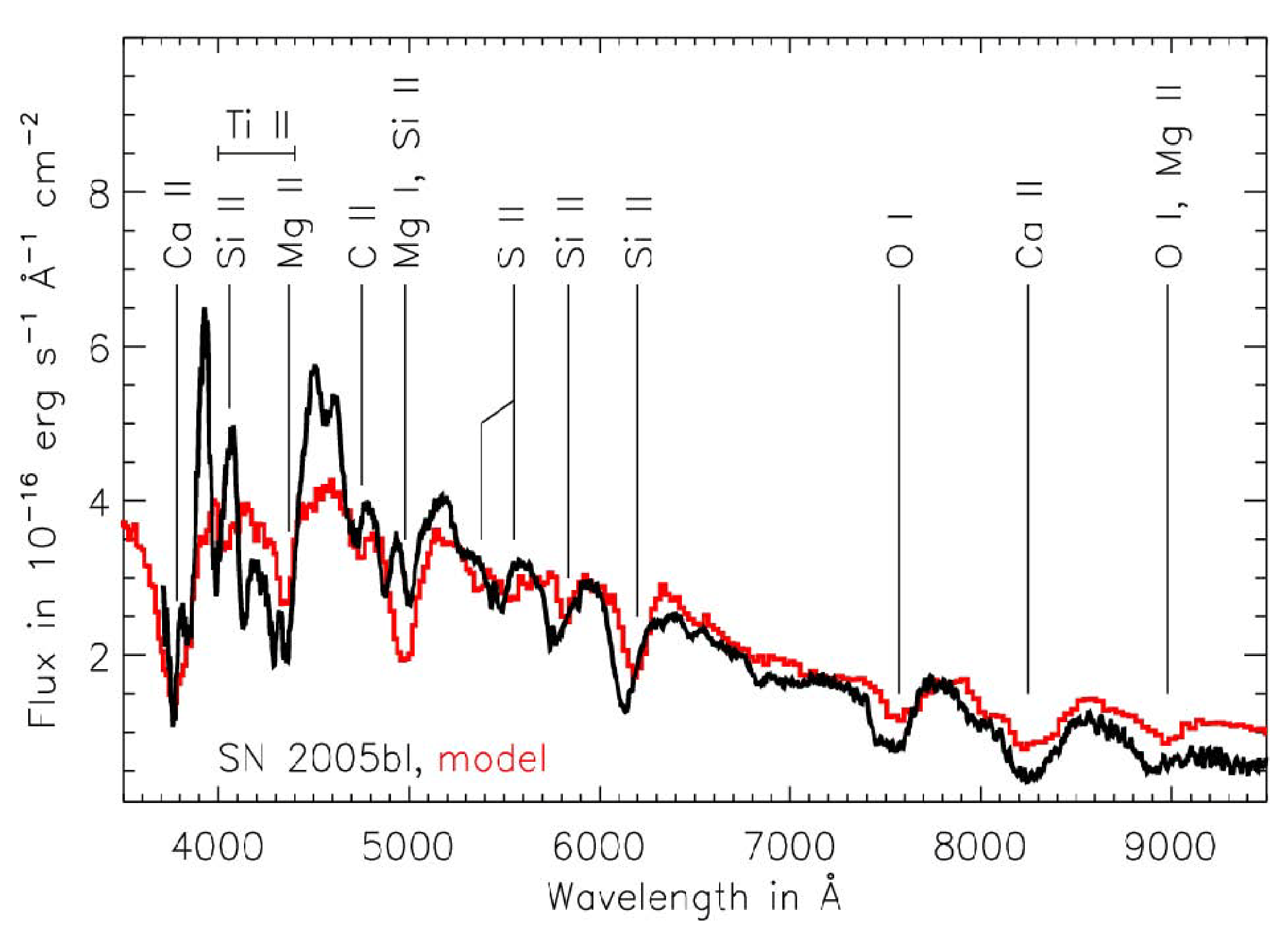
- *Detonation likely*
- *But will be faint (in general, $M \approx 0.9\ M_{\odot}$)*

Synthetic light curves ....

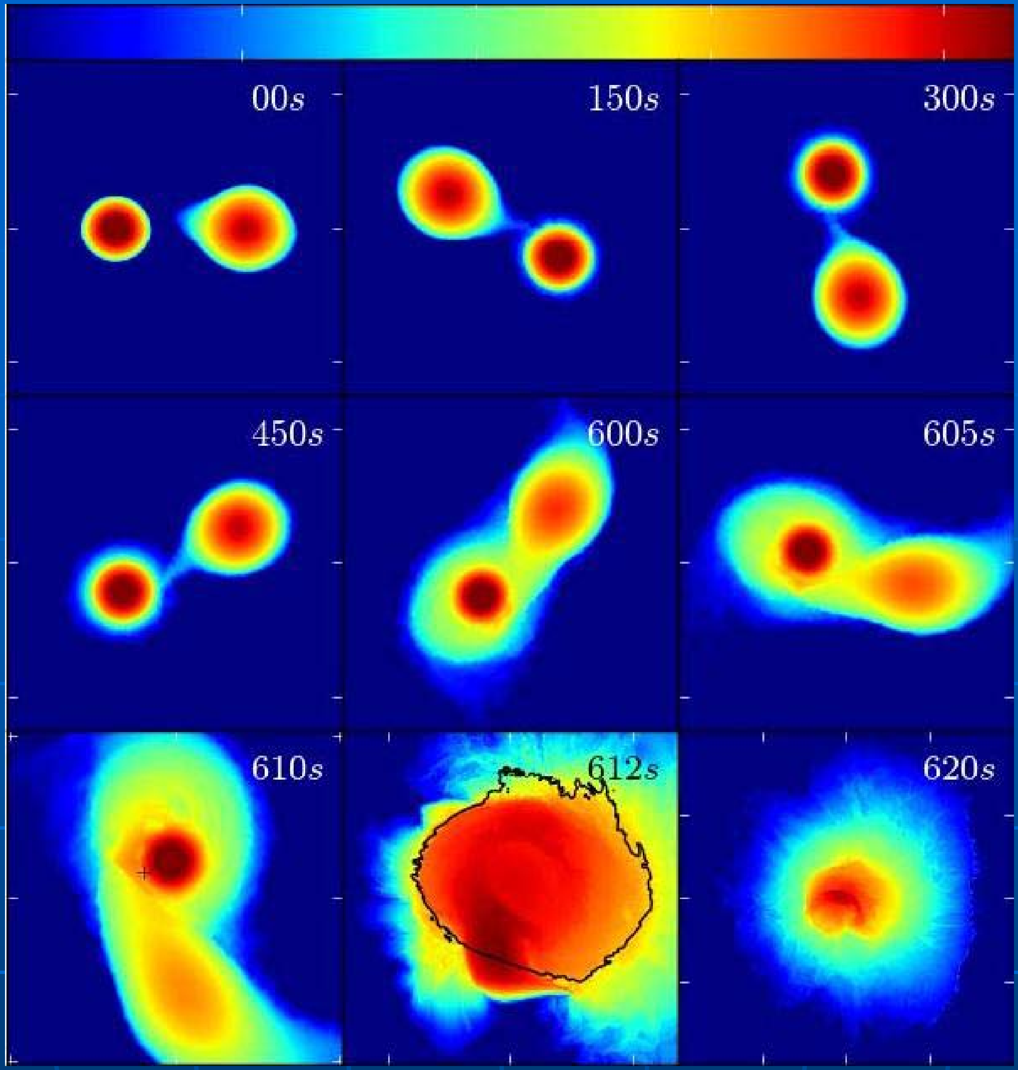


Pakmor et al. (2010)

... and spectra



Pakmor et al. (2010)



(density color coded)

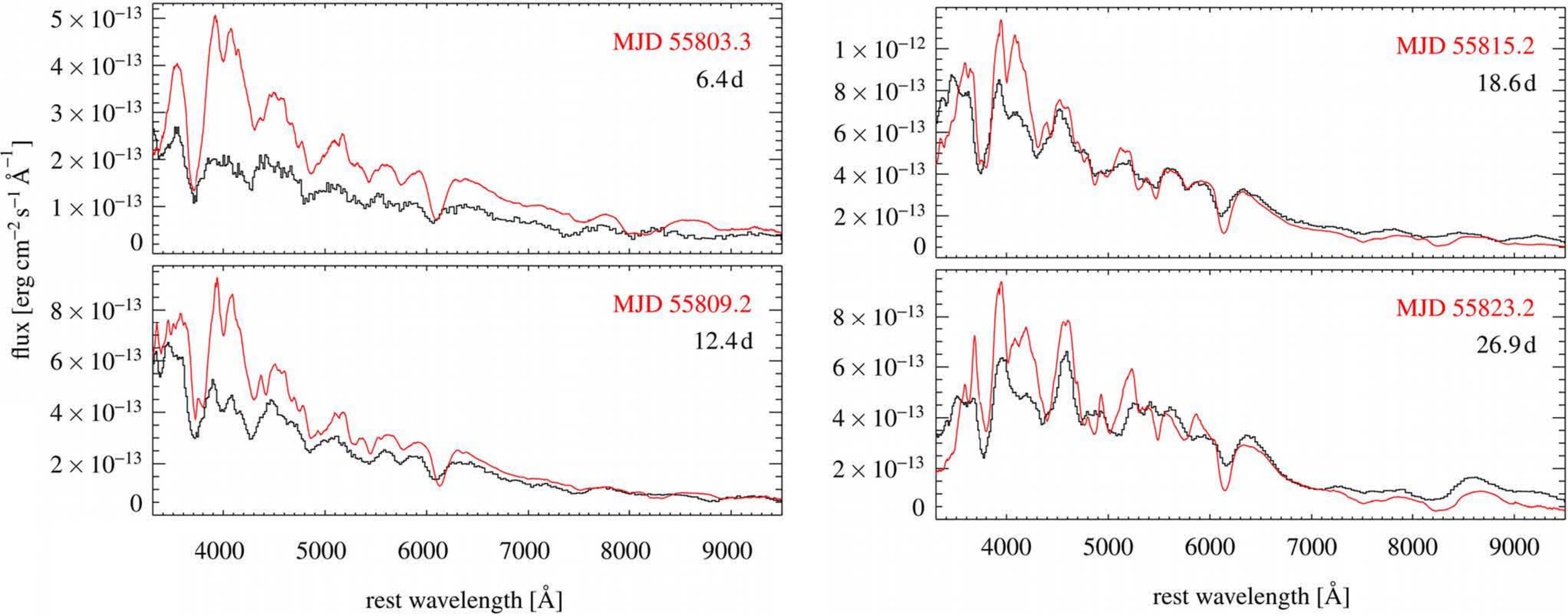
Pakmor et al. (2012)

Dynamical merger of two WDs of similar masses:

- *Detonation still likely*
- *Could be bright if more massive one has $M \geq 1.0\ M_{\odot}$)*

Dynamical merger of two WDs of similar masses:

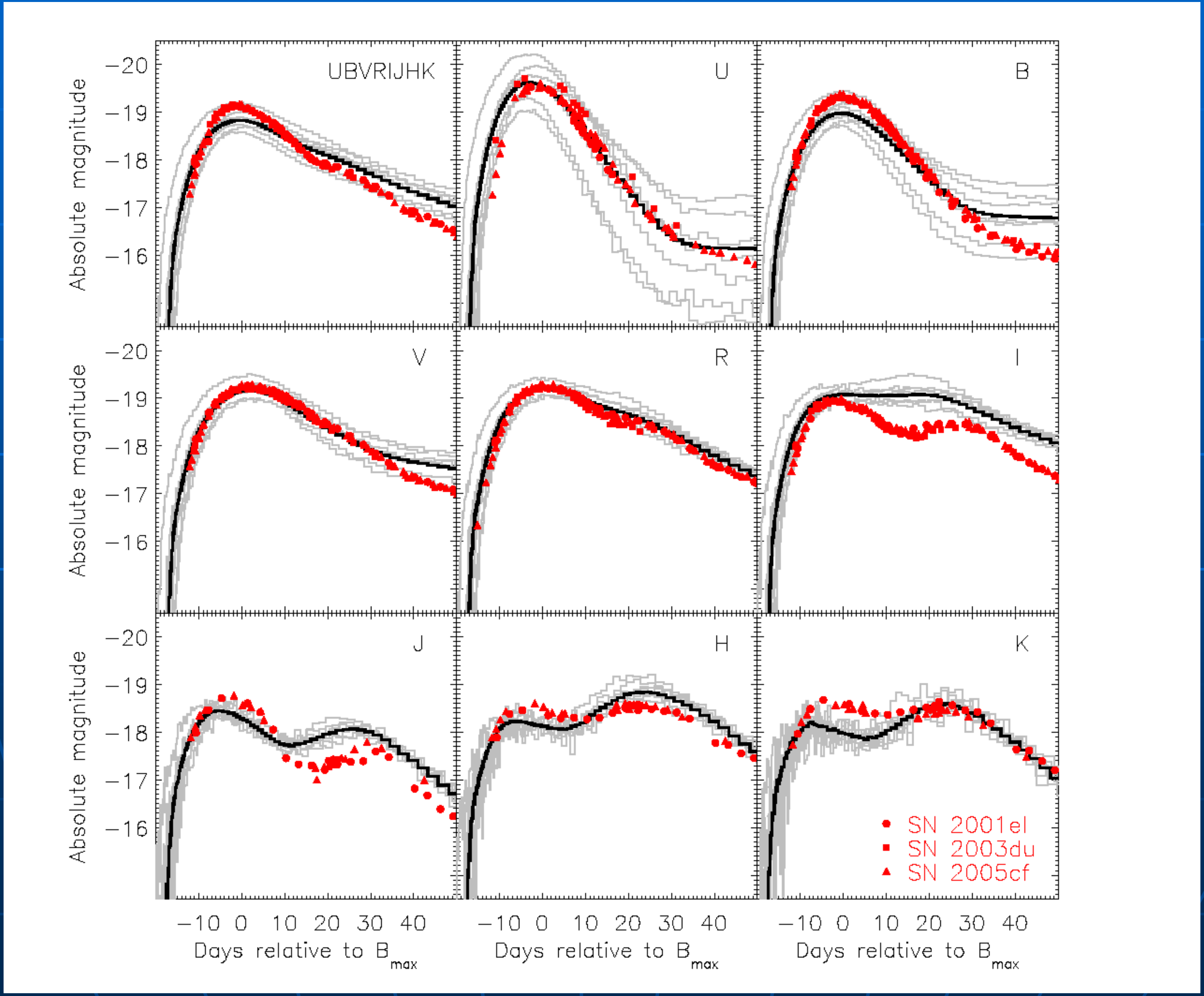
1.1 + 0.9 $M_\odot$



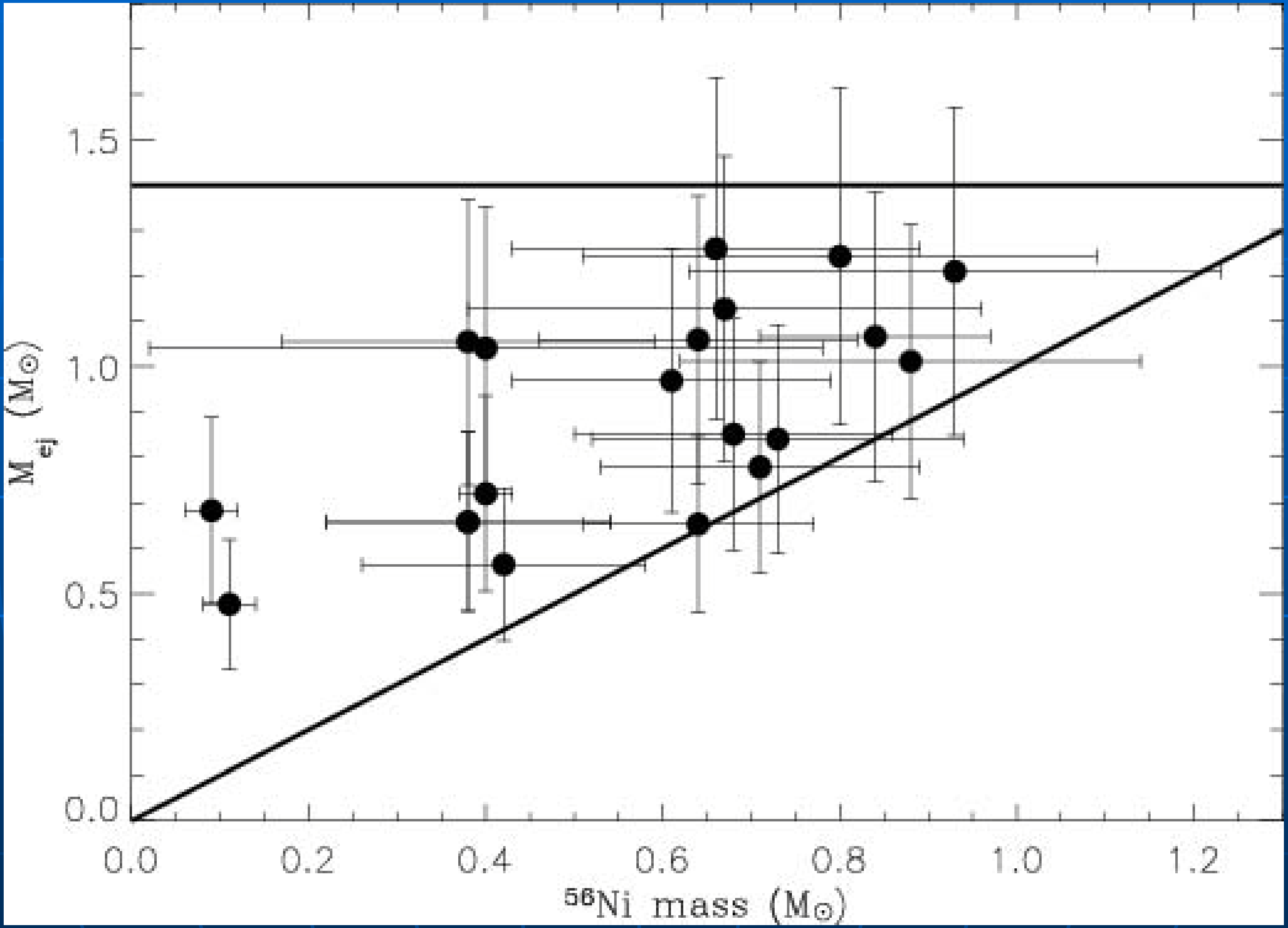
Comparison with SN 2011fe in M 101 (Röpke et al. 2011)

Dynamical merger of two WDs of similar masses:

1.1 + 0.9 $M_\odot$, light curve predictions

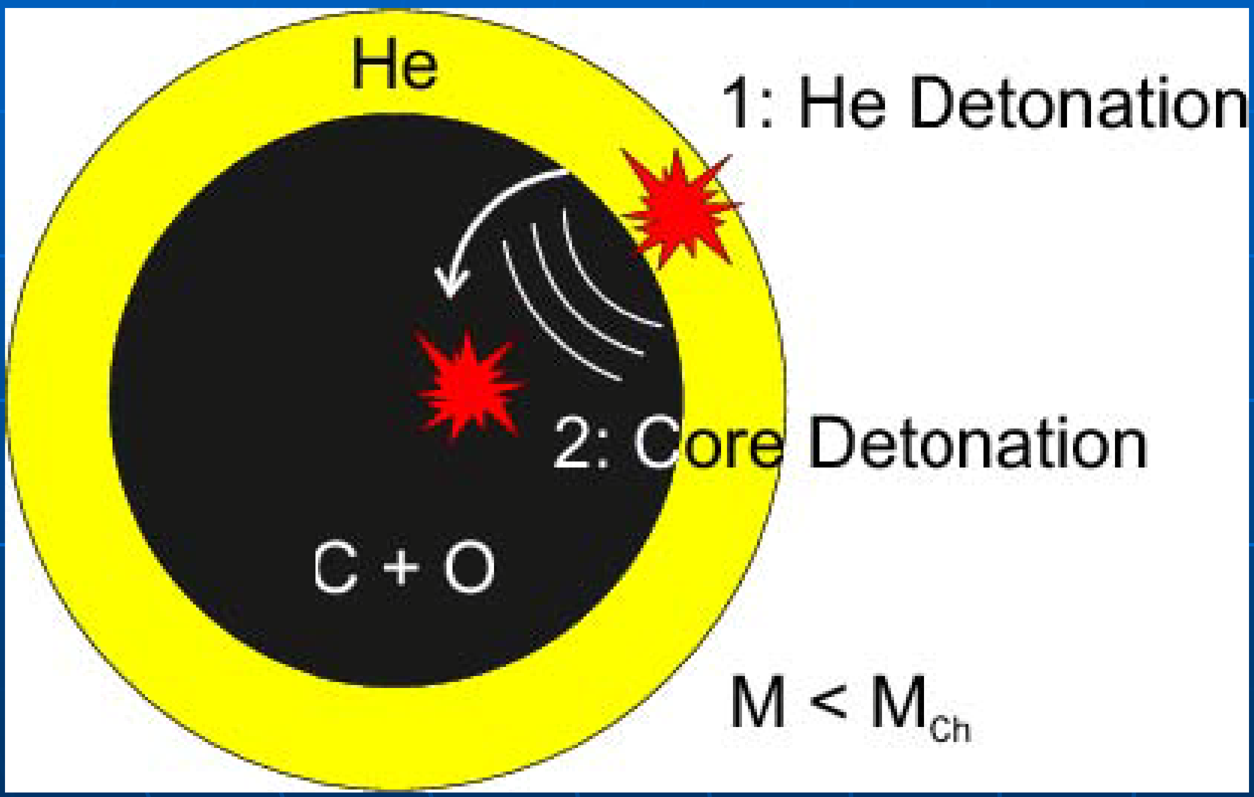


Or, let’s look at ‘sub-Chandras’ …

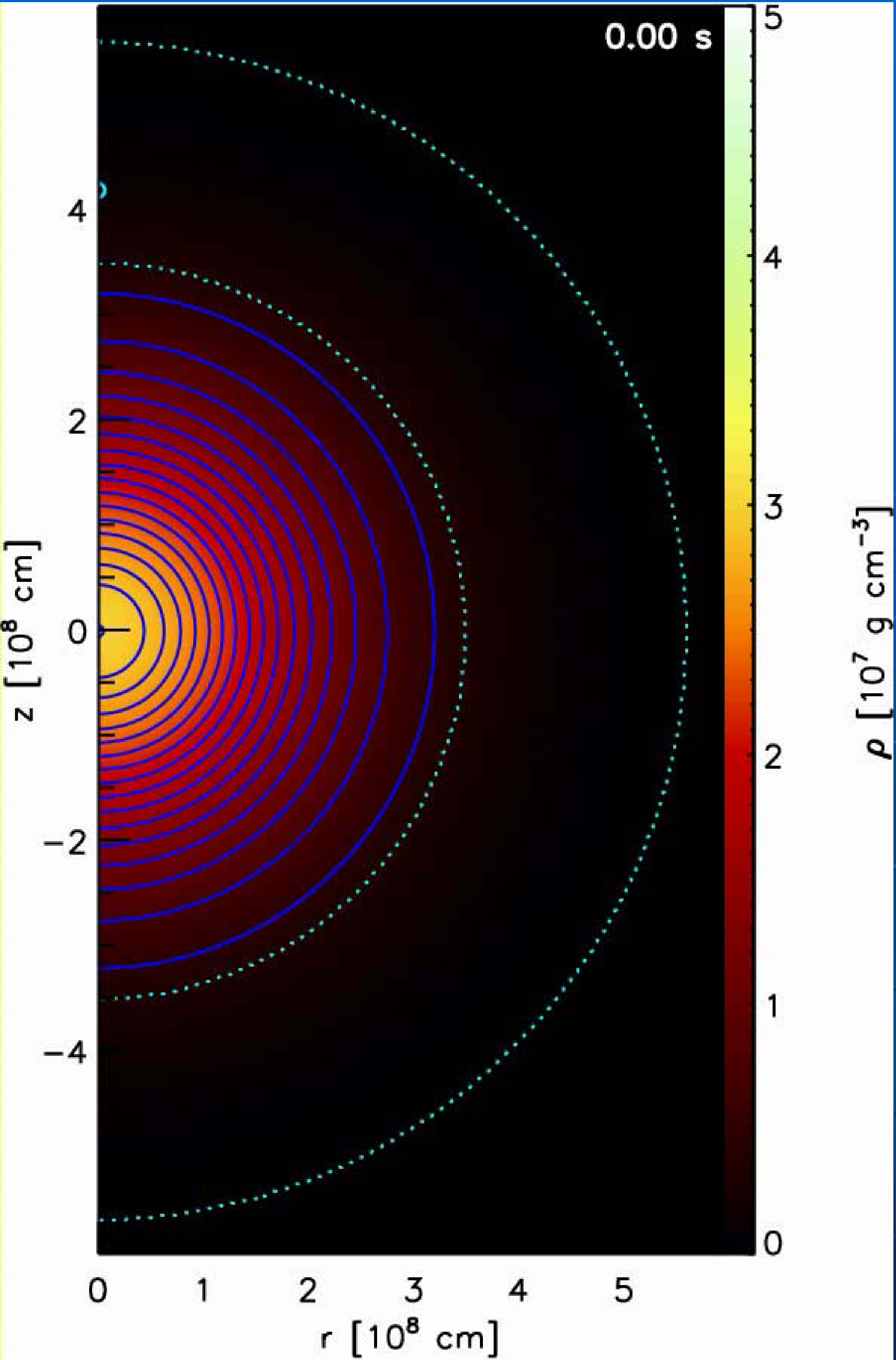


Stritzinger et al. (2006)

How can such a model work?



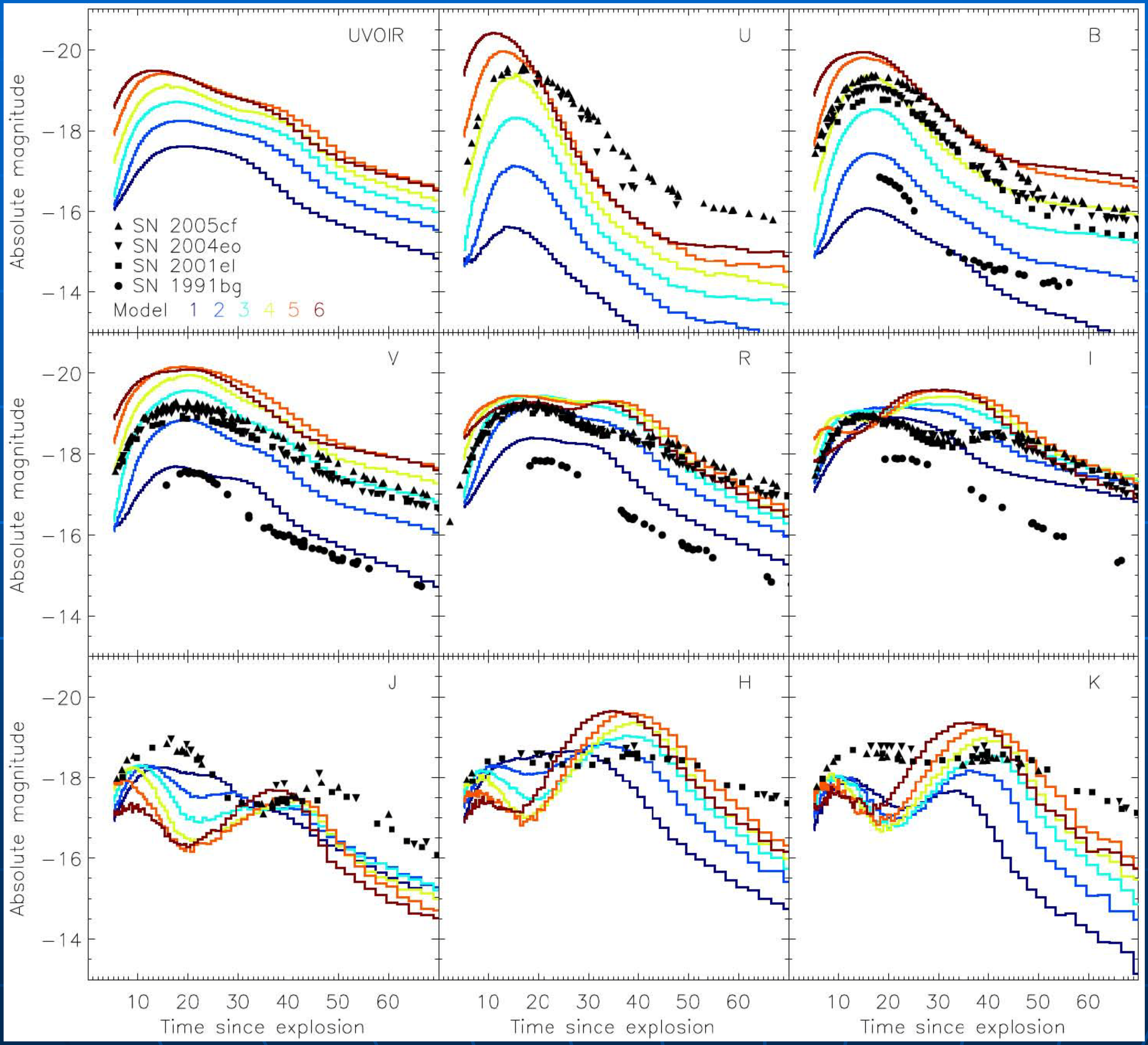
- *He-triggered double detonation is a robust explosion mechanism, provided one can accumulate (and detonate) >0.03 $M_\odot$ of He on a C+O WD (M > 0.8 $M_\odot$).*



- *These explosions can provide the luminosity of faint and 'normal' SN Ia (0.1 – 0.8 $M_\odot$ of Ni). But: "red" at B_{max} ?*

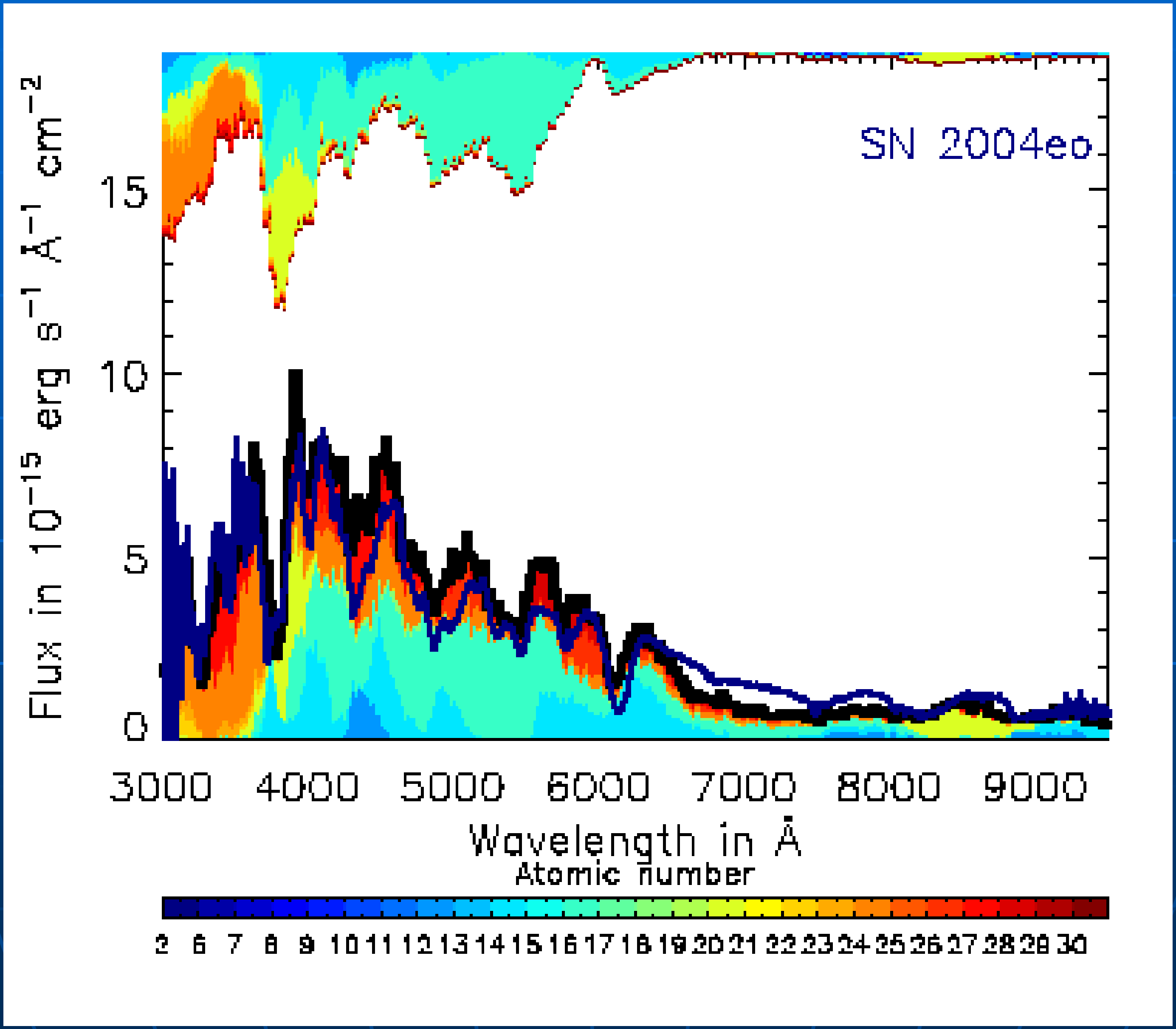
(Fink et al., 2007, 2010)

Synthetic light curves ....



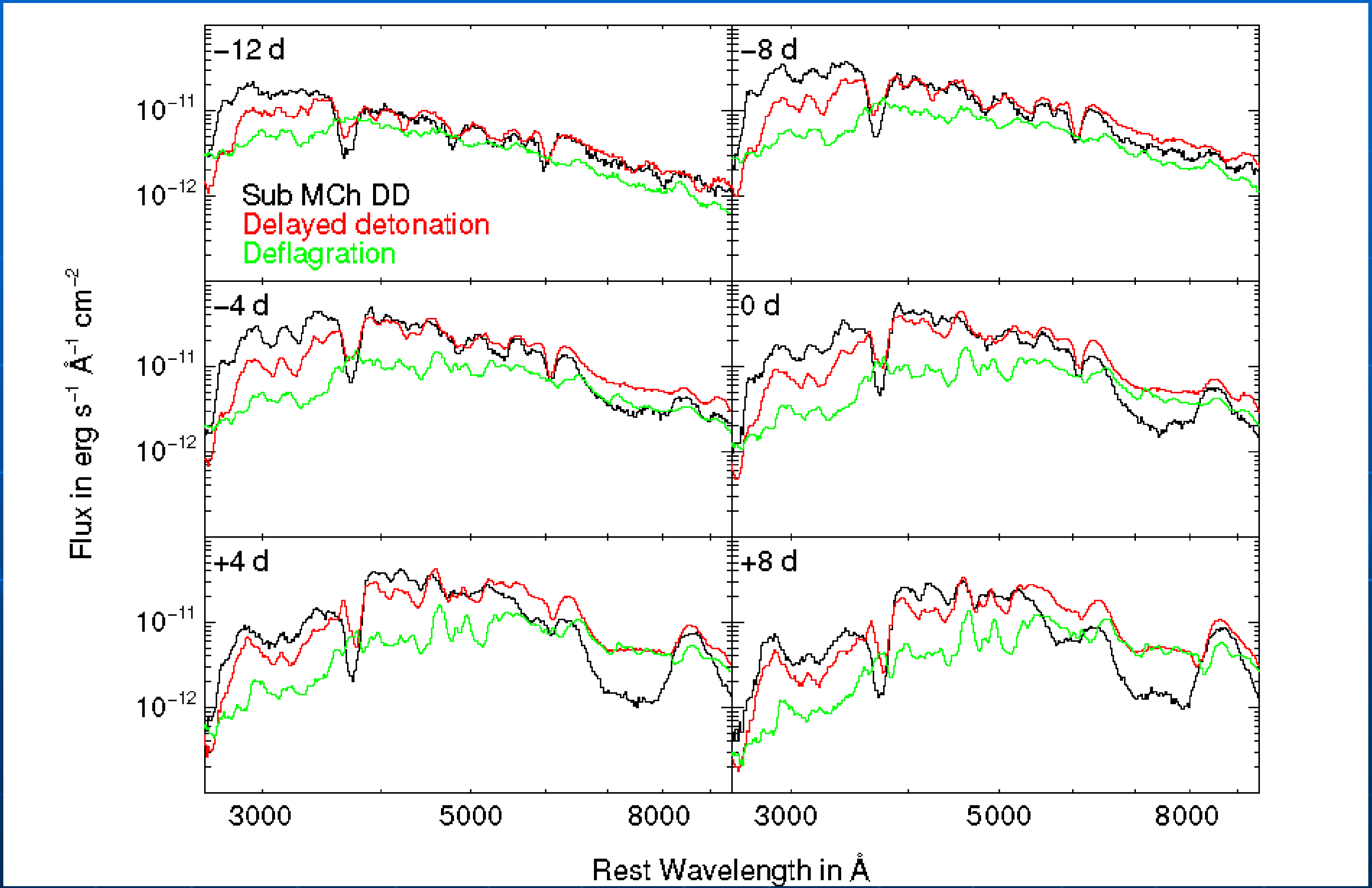
Kromer et al. (2010)

... and spectra



Kromer et al. (2010)

What can we learn from spectra? – A comparison



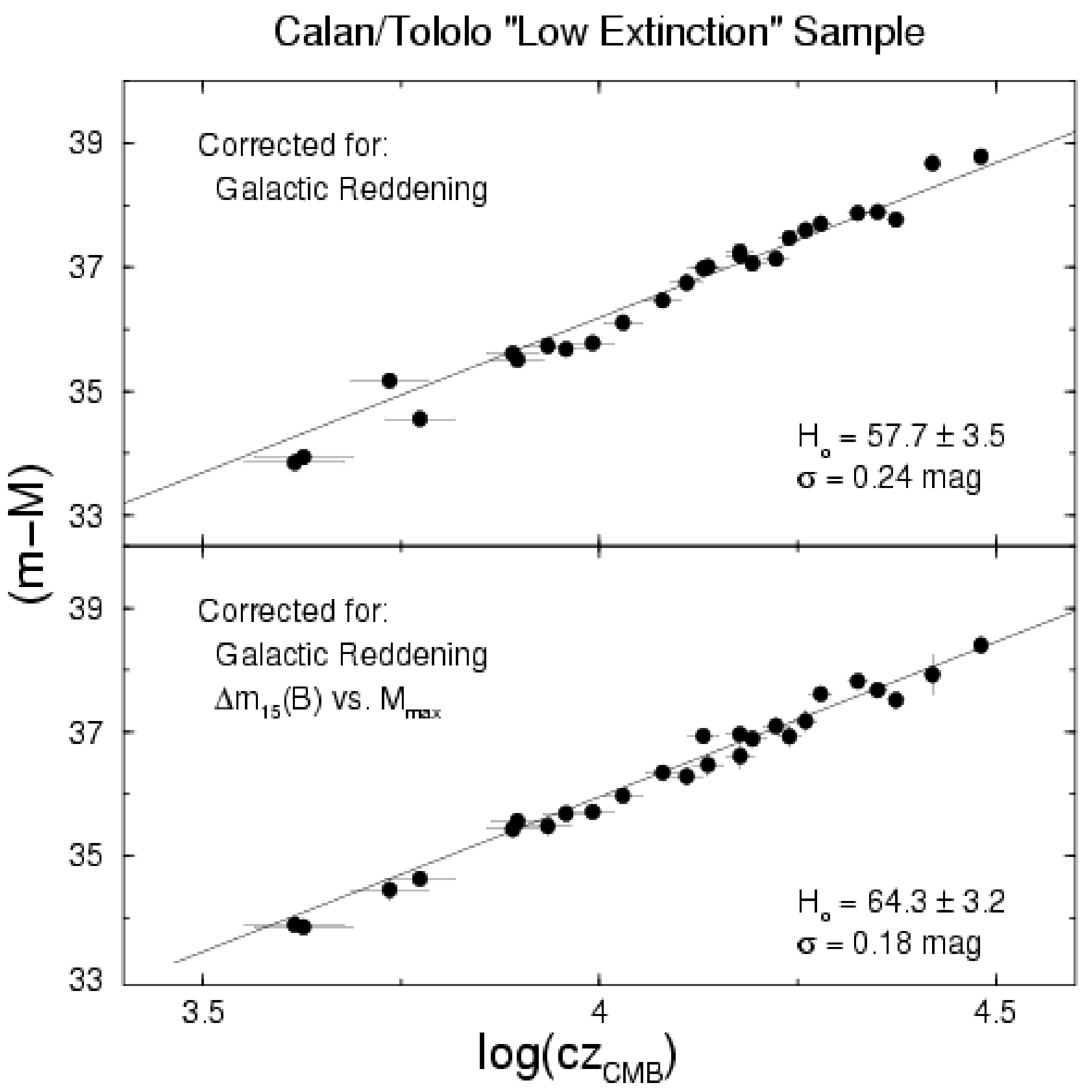
Kromer et al. (2011)

Summary

- Type Ia Supernovae are well explained by thermonuclear-explosion models of white-dwarf stars
- However, the reason *why* they explode is still *very uncertain*
- In principle, several *distinctly different explosion scenarios* reproduce subsets of data (light curves, spectra, ...) *equally well*
- *This may cause problems for future goals of 'supernova cosmology' .*
- *How severe are they???*

Normalisation of the peak luminosity

Phillips et al. 1999



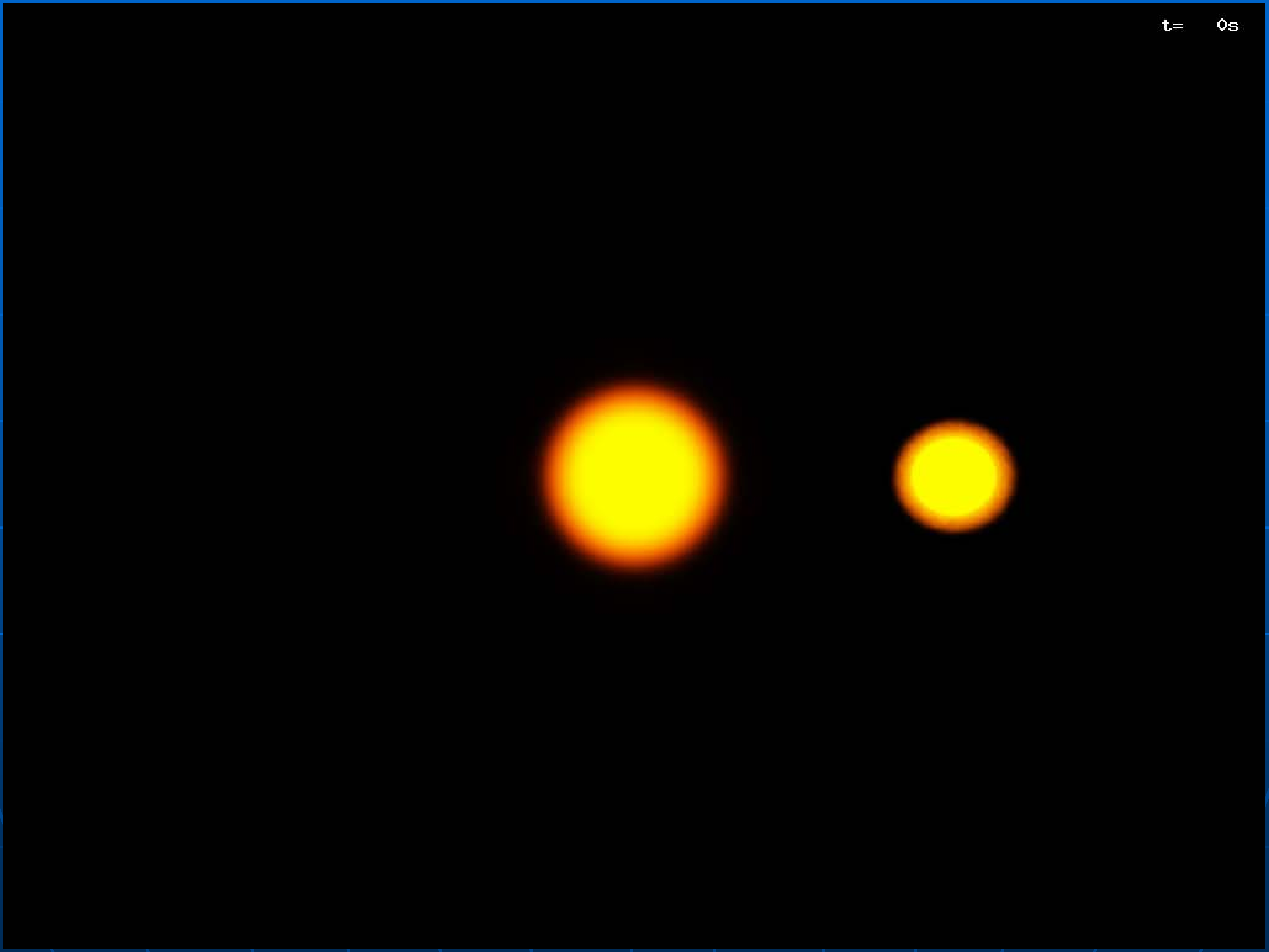
Using the luminosity-decline rate relation one can normalise the peak luminosity of SNe Ia

→

Reduces the scatter!

So, why do we worry?

- What causes the deflagration-to-detonation transition?
- Why was hydrogen never detected in a normal SN Ia?



(Pakmor et al., 2008)