The Many Guises of Thermonuclear Supernovae

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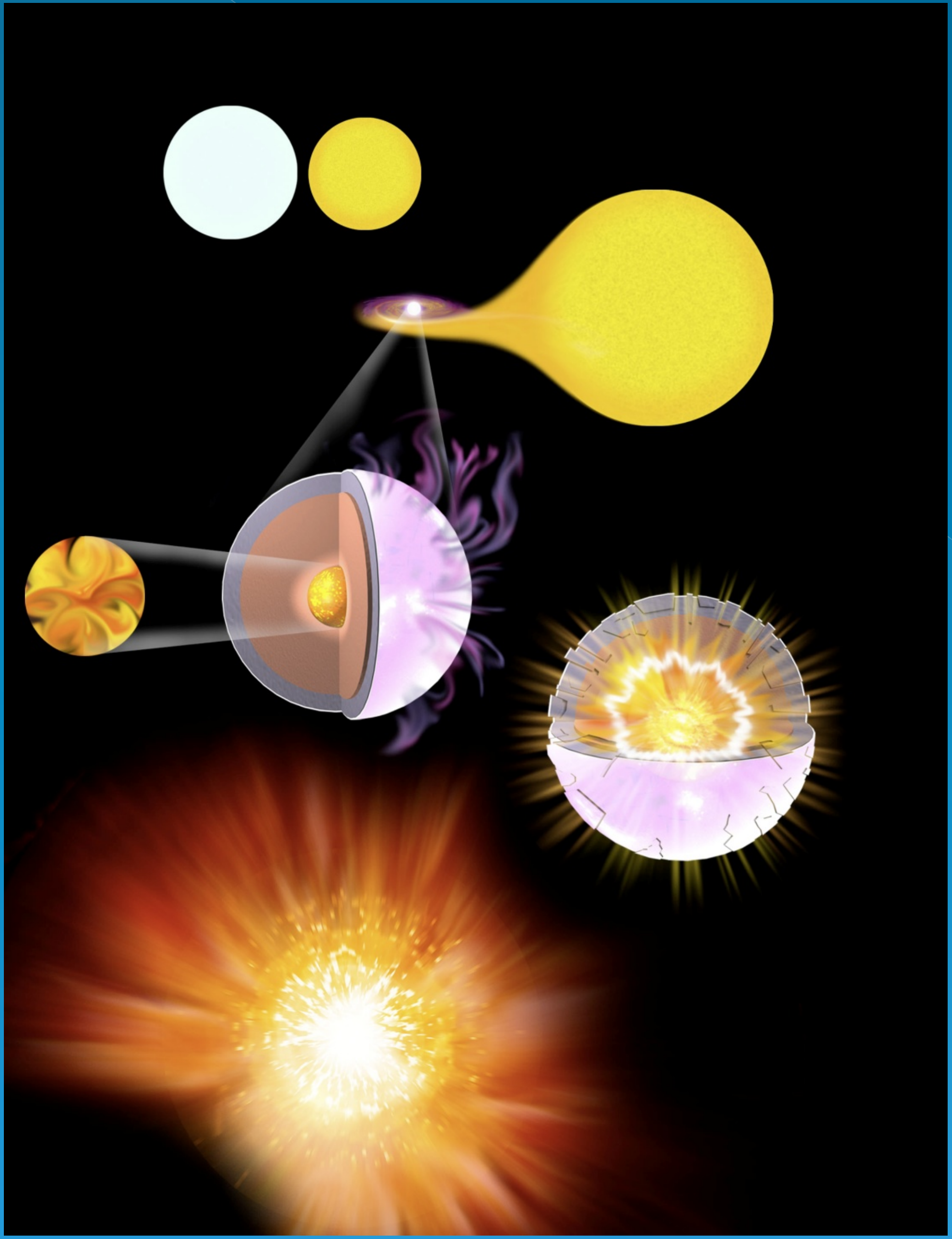
Thermonuclear (Type Ia) supernovae:

- They are a homogenous ‘class’
- They make most of the iron in the Universe
- They make some p-process elements
- Some of them make n-rich isotopes such as ^{48}Ca, ^{50}Ti and ^{54}Cr
- They can be used as distance indicators

…………….

This is based on the assumption that they are all Chandrasekhar-mass C+O white dwarfs

The standard 'single-degenerate' model



- Growing to the critical mass ($M_{chan} \approx 1.4\ M_{\odot}$) by mass transfer

- Disrupted by a thermo-nuclear explosion (fusion of C and O to iron-group elements)

- Light comes from radioactive decay : $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

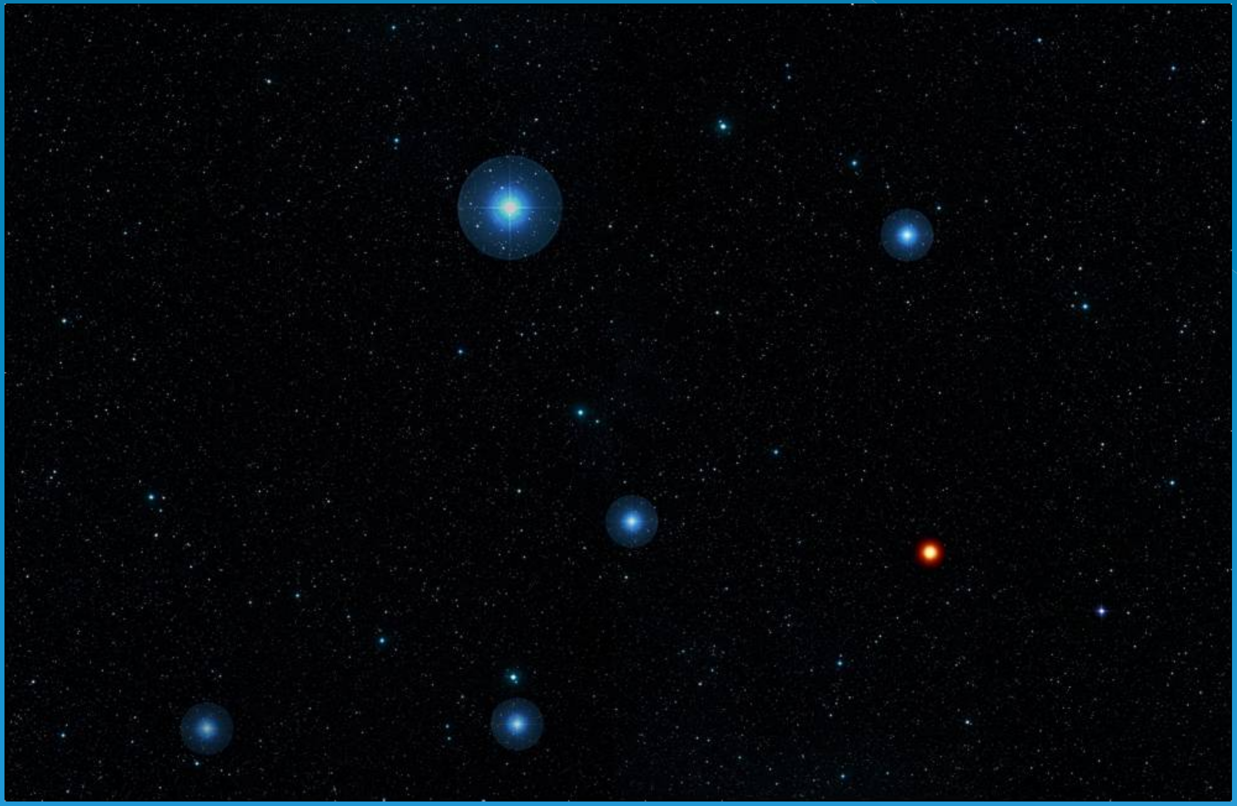
- White dwarf star in a binary system with MS or (R)G star

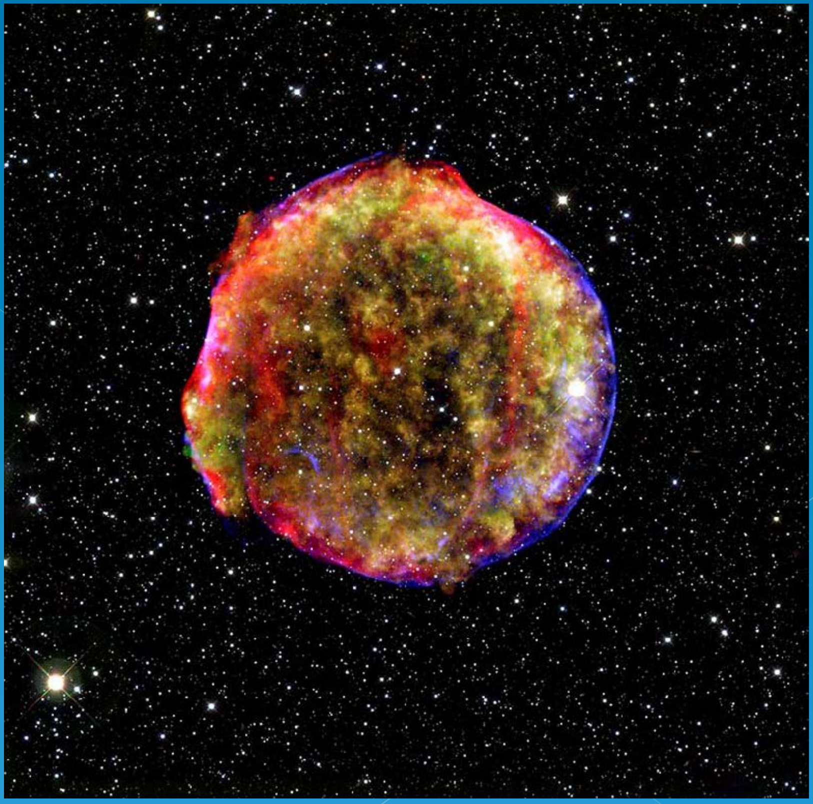
Thermonuclear (Type Ia) supernovae:

Can we be sure about all of this?

Can we be sure about this?

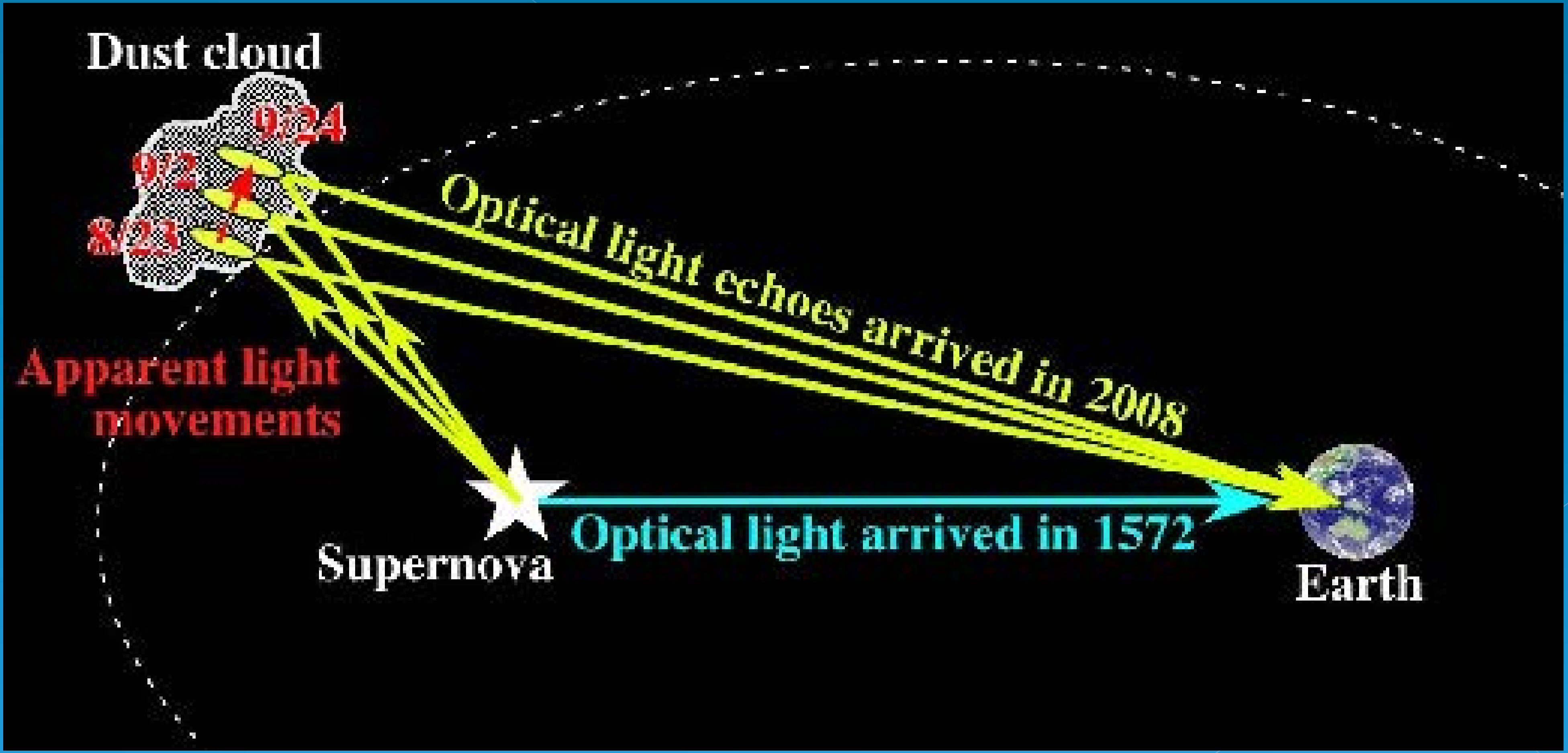
Example: SN 1572 (Tycho's supernova)





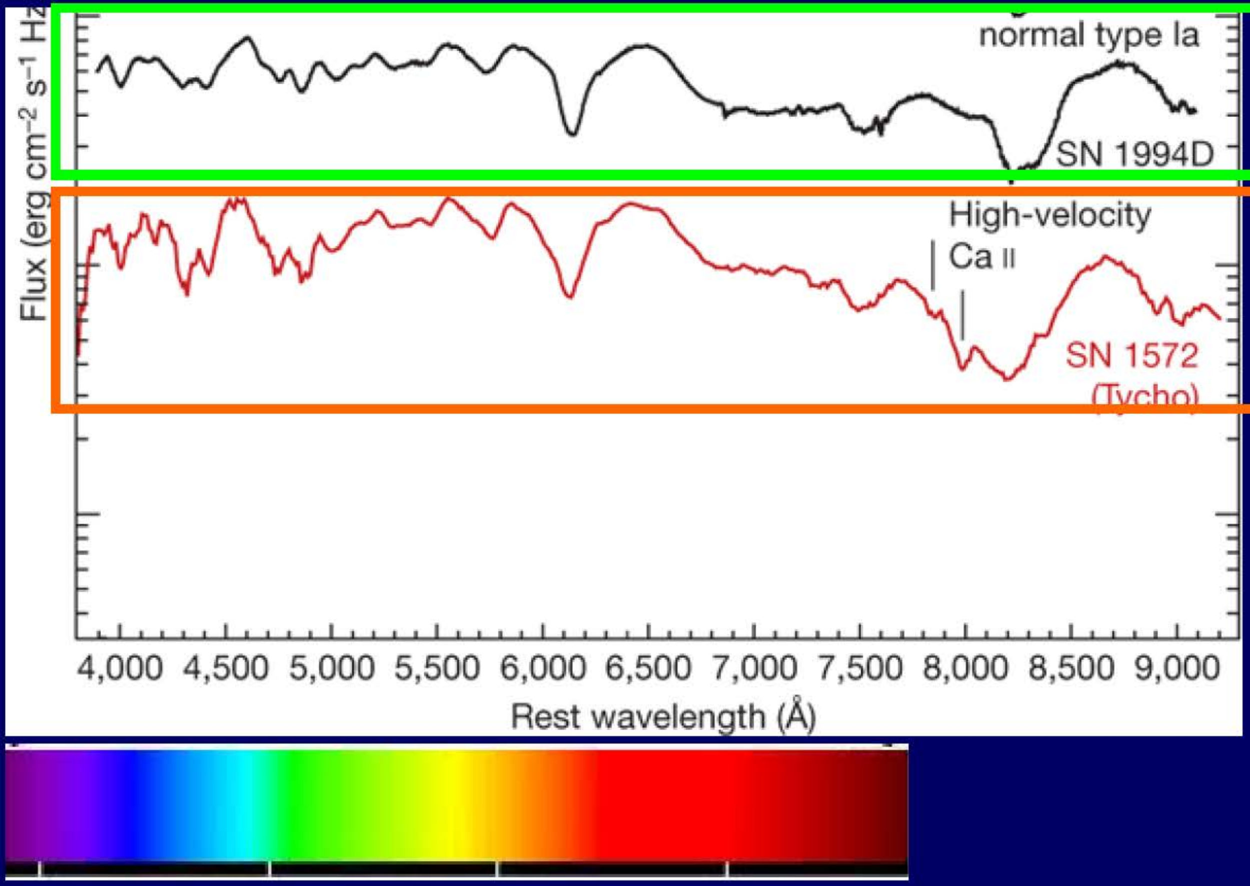
Can we "see" this supernova still today?

Yes, by its light echoes!

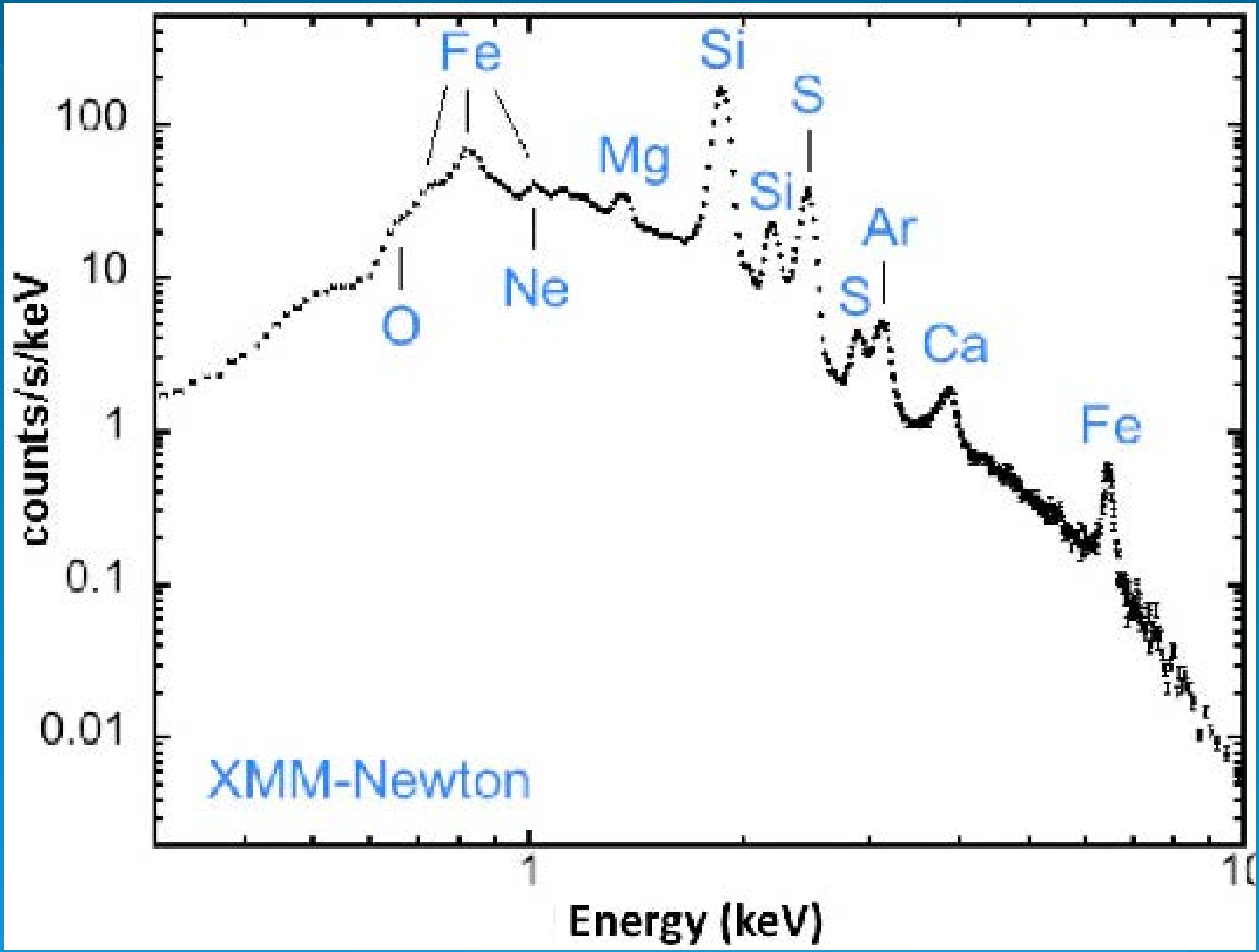


The echo has spectrum of a normal SN Ia (Krause et al. 2008)

Spectrum of SN1994D



spectrum of the echo

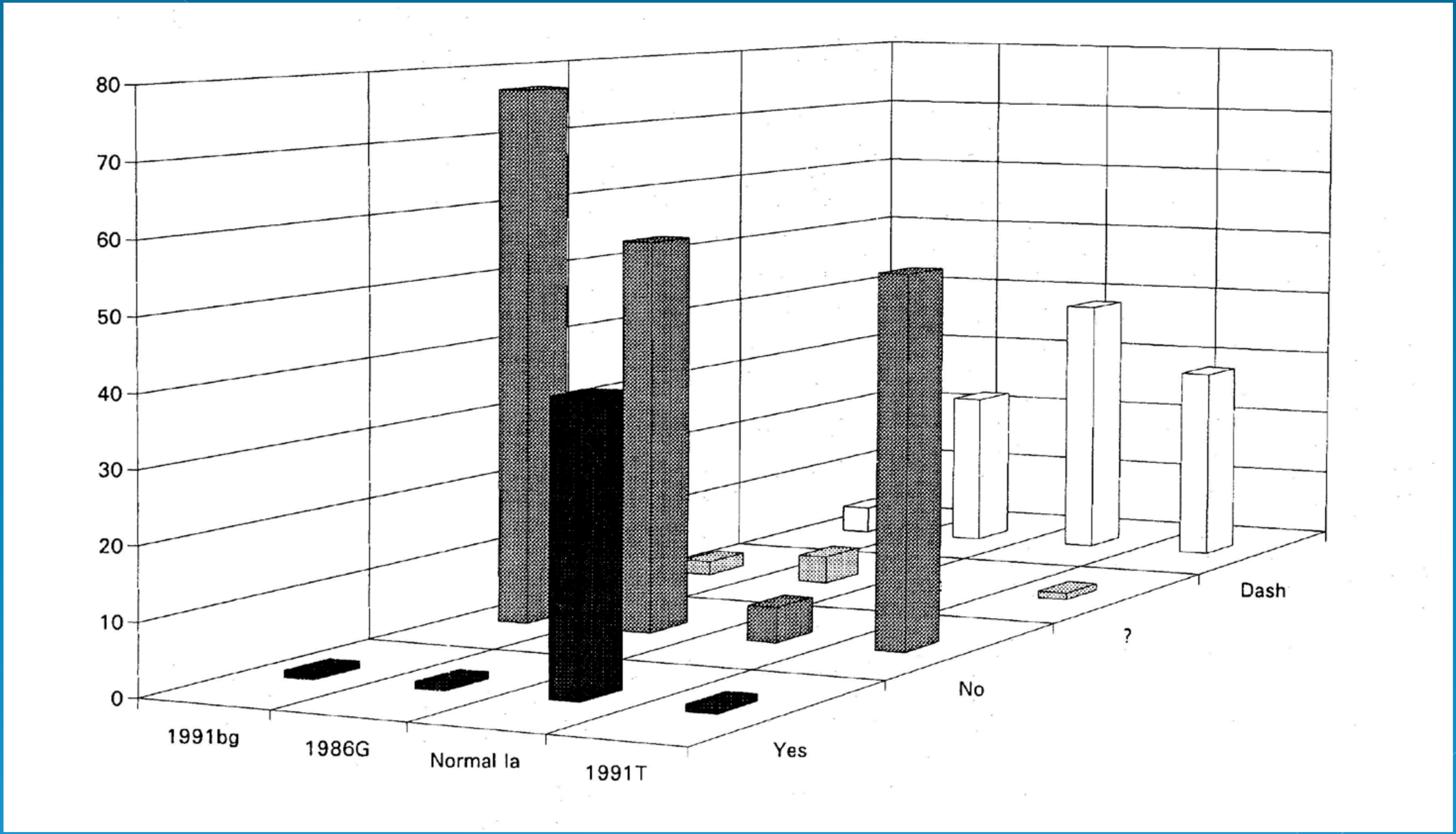


X-ray spectrum (Badenes et al. 2006): M(Fe) ≈ 0.74M_{sun}

Thermonuclear (Type Ia) supernovae:

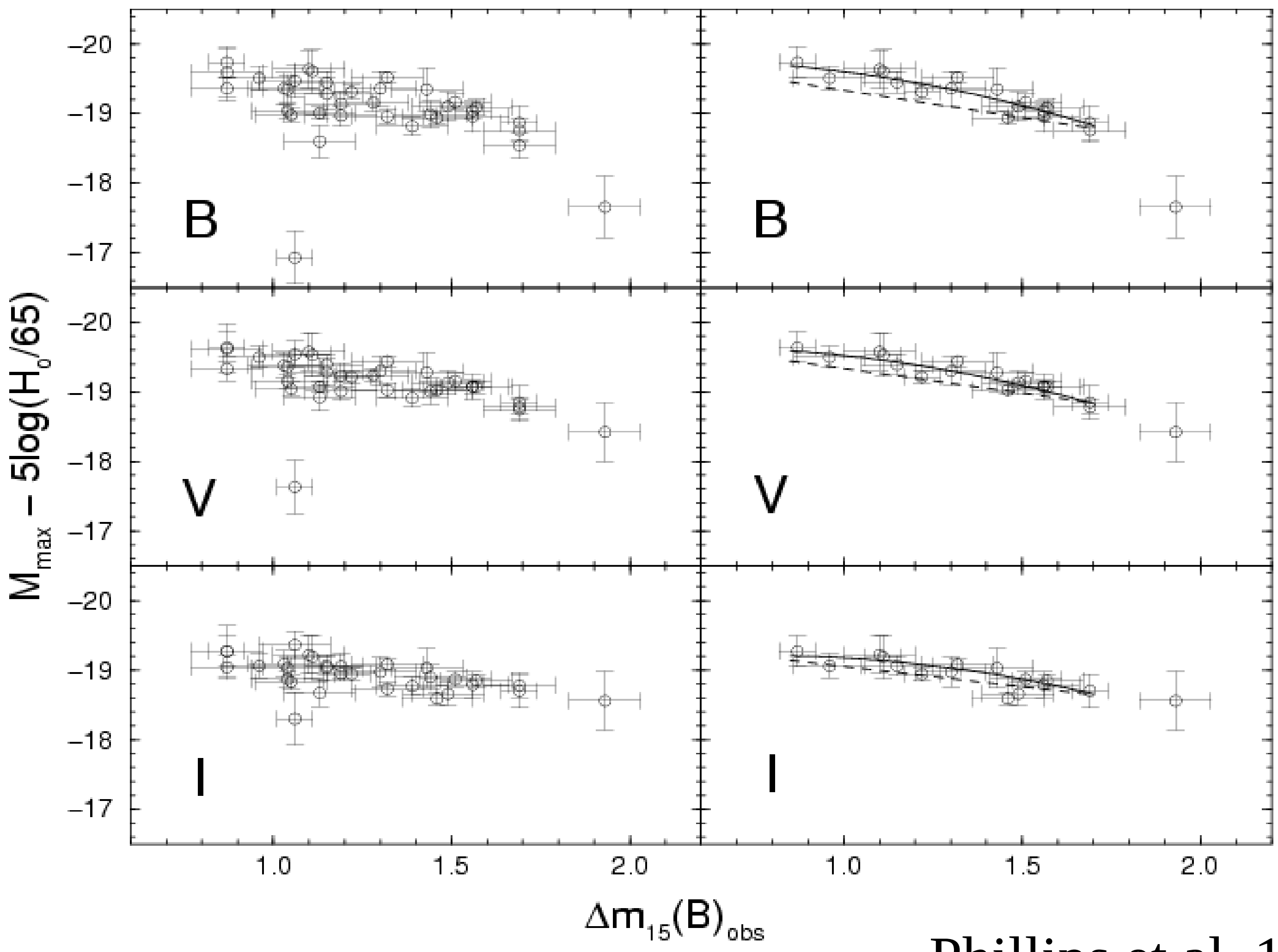
How 'homogenous' are they as a 'class'?

The 'Branch normals' and other SNe Ia:



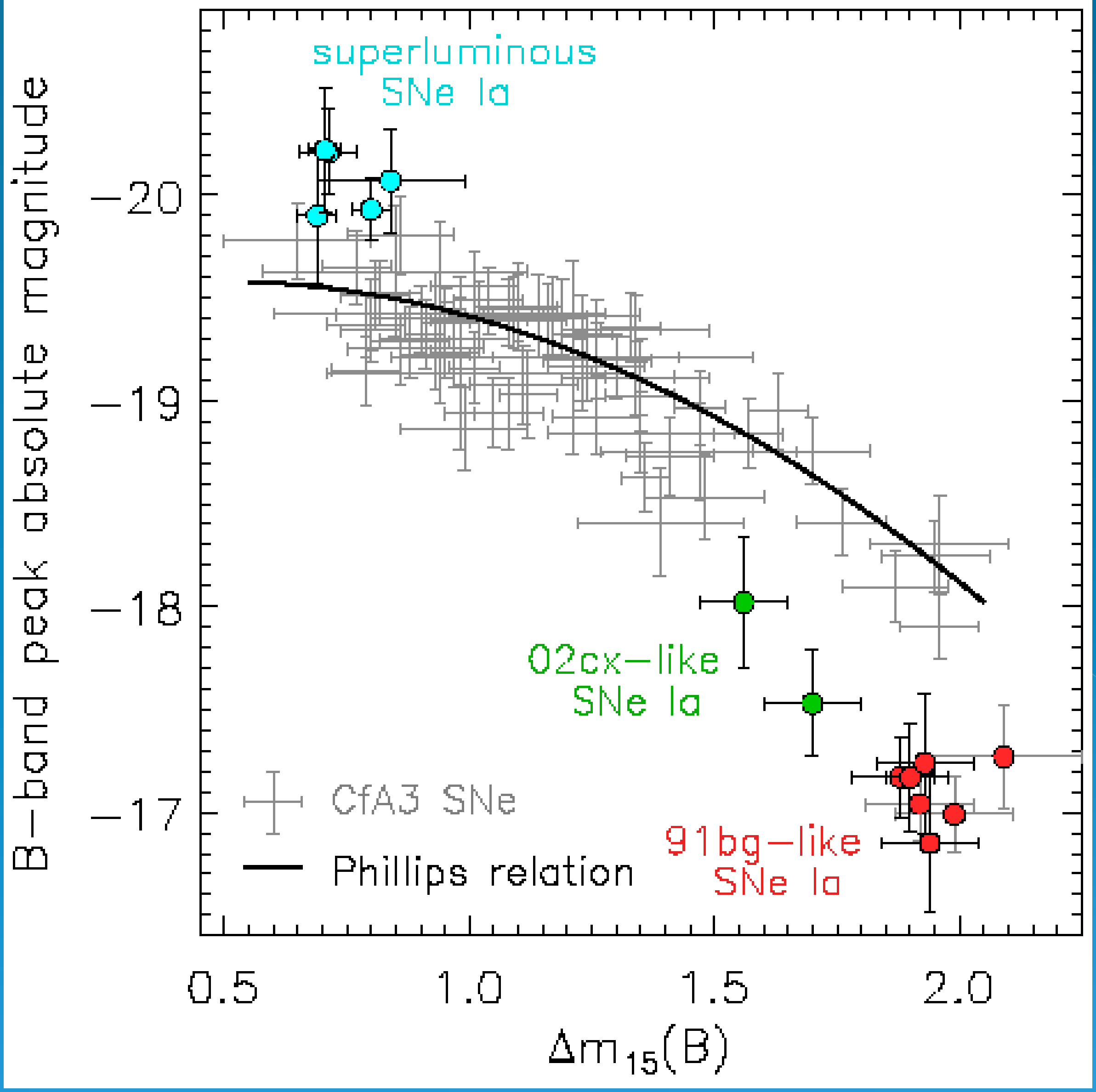
Branch et al. (1993), based on a sample of 84 SNe

Peak luminosty/light-curve shape correlation:



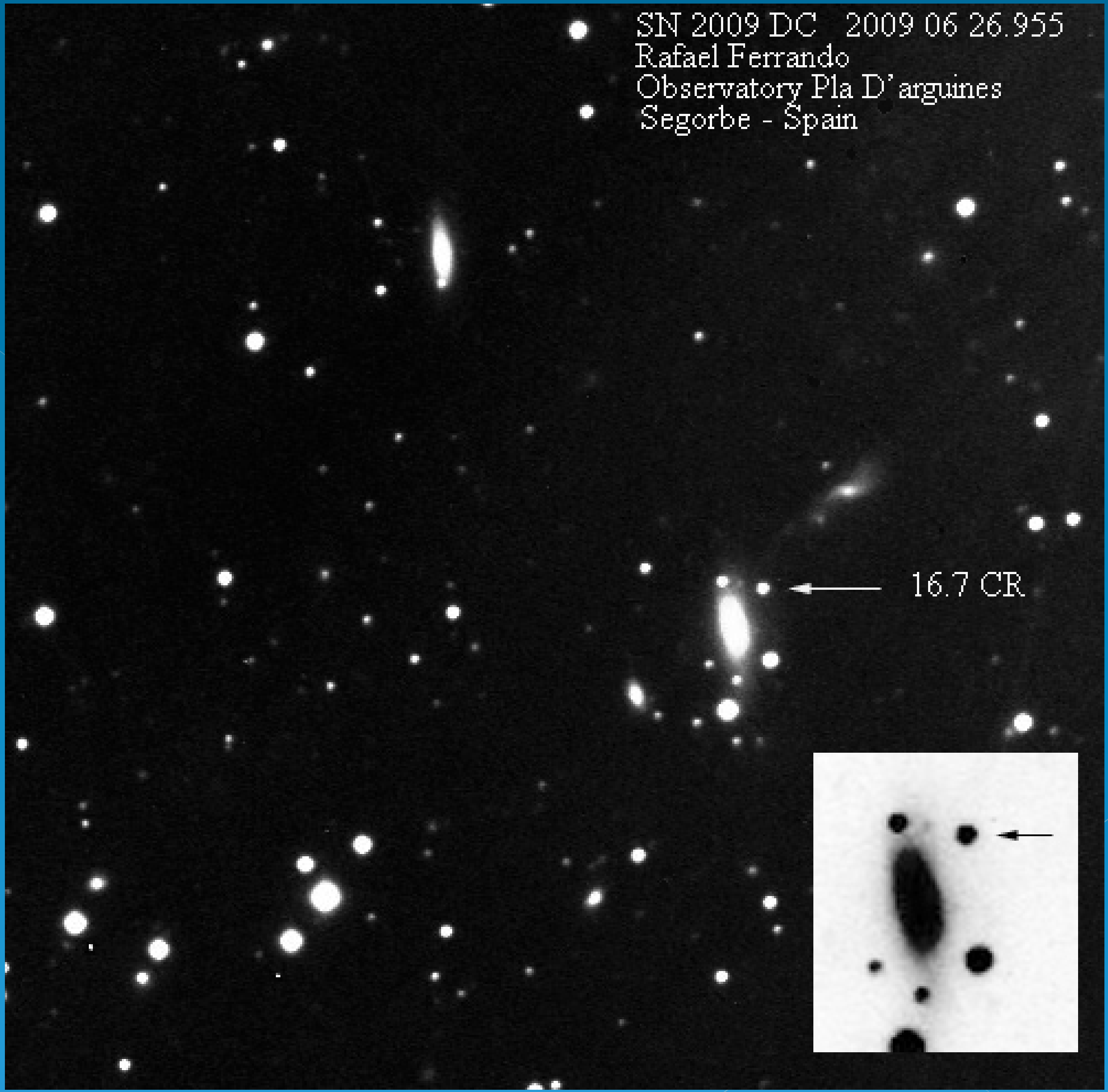
Phillips et al. 1999

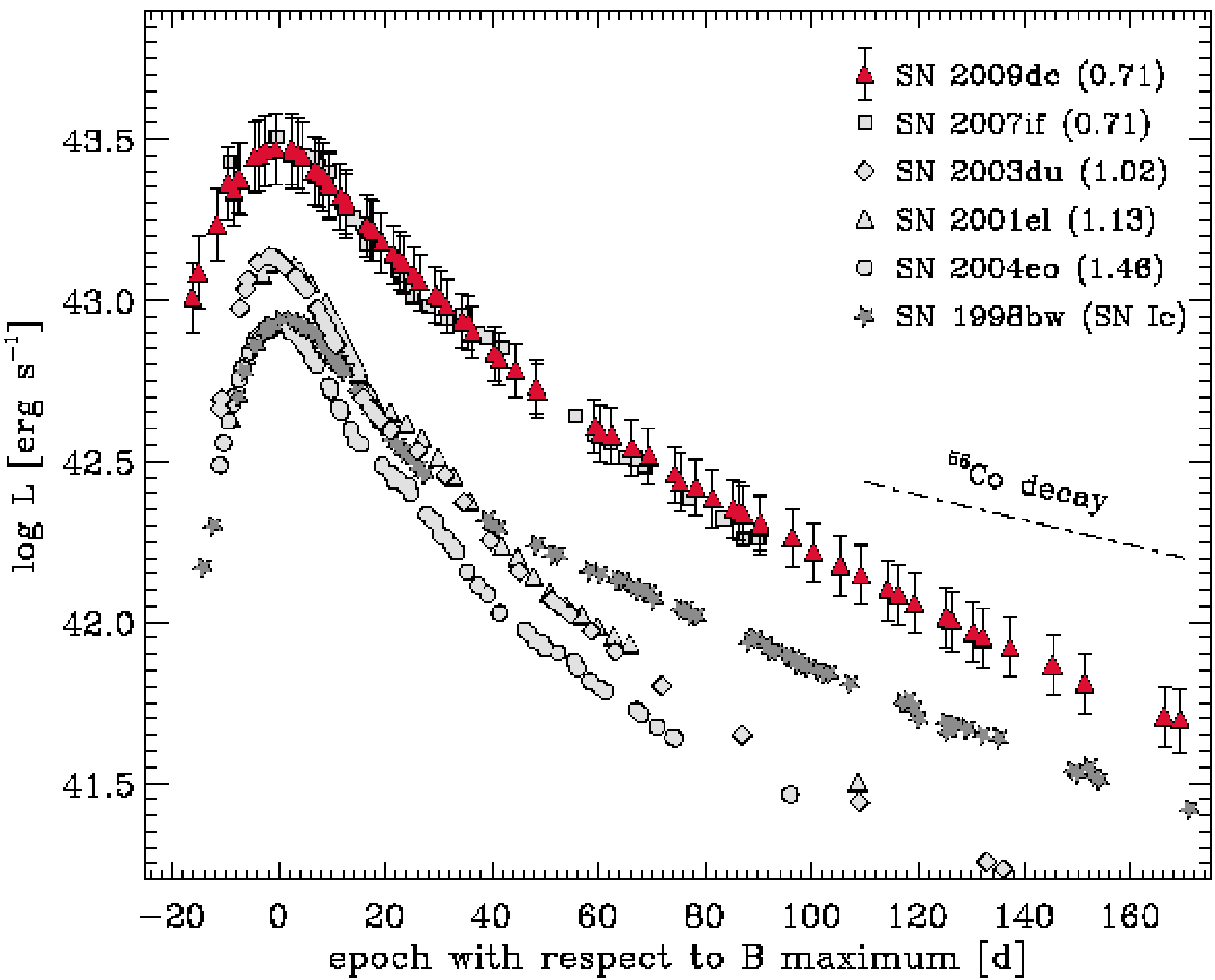
A recent Phillips relation:
the “beauties” and the “beasts”



An example of a ‘weird’ SN Ia: SN 2009dc

- ❖ *“very bright”*
- ❖ *“unusual color”*
- ❖ *“slow”*
- ❖ *“C-rich”*





SN 2009dc (0.71)
SN 2007if (0.71)
SN 2003du (1.02)
SN 2001el (1.13)
SN 2004eo (1.46)
SN 1998bw (SN Ic)
^{56}Co decay
43.5
43.0
42.5
42.0
41.5
log L [erg s^{-1}]
−20
0
20
40
60
80
100
120
140
160
epoch with respect to B maximum [d]

The properties of 09dc (and other very bright SNe Ia)

- High peak luminosity, broad light curves & low ejecta velocity
- large Ni mass (?) (~ 1.2 M_{sun} of ^{56}Ni)
- large ejecta mass (?) (> 1.4 M_{sun})
- At the same time unburned material at rather low velocities

What are they ????

Other 'weirdos':

- '91bg like':

 low luminosity (~0.1 M_{sun} ^{56}Ni), evidence for unburned C & O; strong Ti absorption

- '02cx/05hk like':

sub-luminous (~0.2 M_{sun} ^{56}Ni), narrow lines

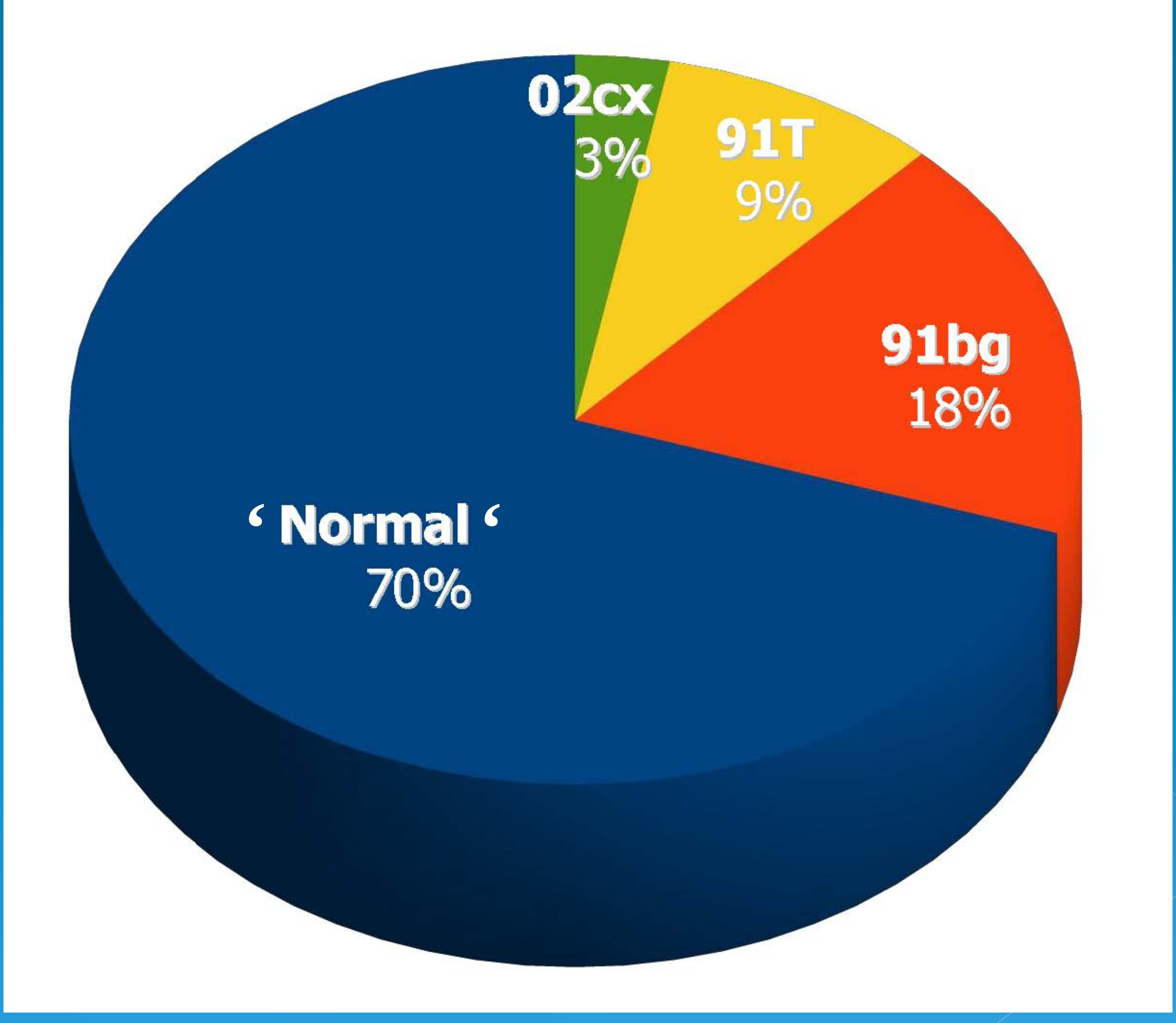
- '05E/05cz like':

very low Ni masses (0.01 - 0.05 M_{sun}), Ca rich, He lines, low ejecta mass(?)

What are they ????

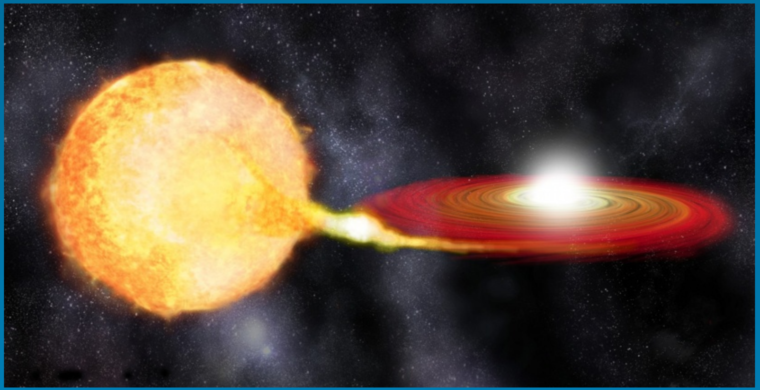
'Weirdos' are not rare! Relative rates:

(Li et al., 2011)



The 'zoo' of (possible) thermonuclear explosions

- *'Single degenerates'*
  - Chandrasekhar mass
    - Pure deflagration
    - 'delayed' detonation
  - sub-Chandrasekhar mass

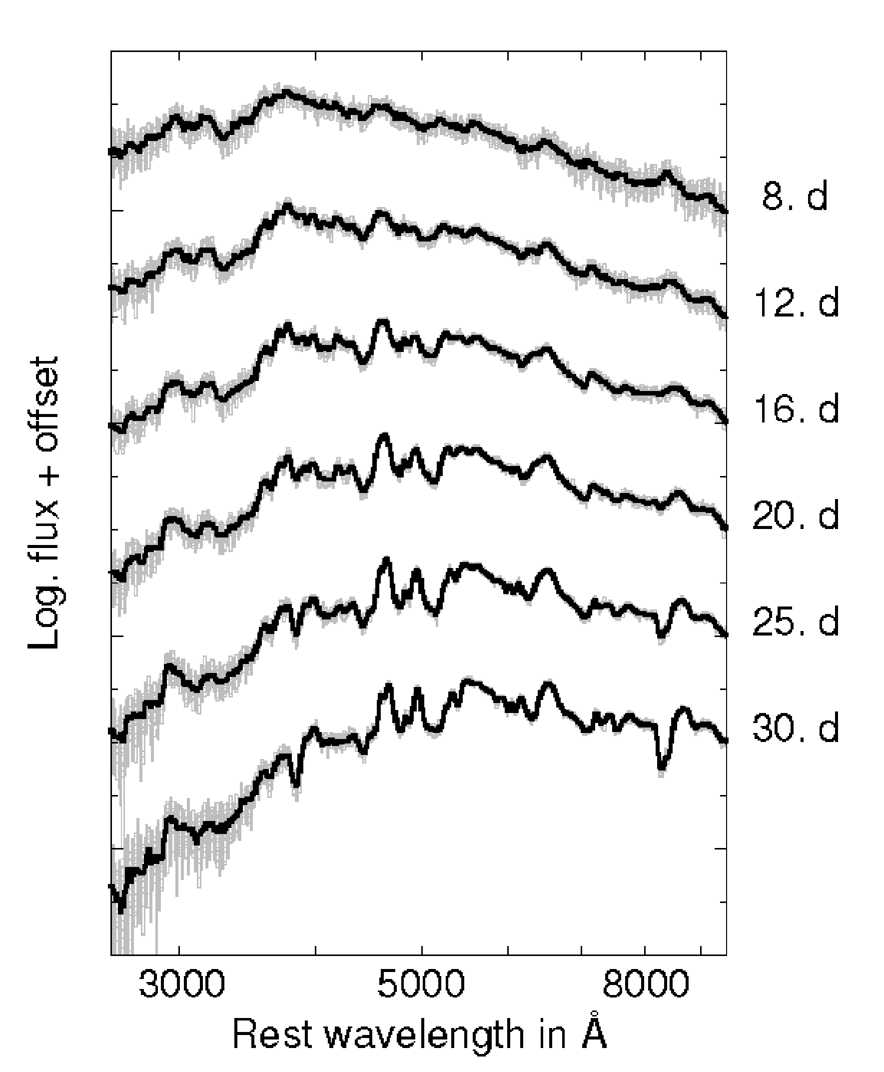


- *'Double degenerates'*
  - C/O + C/O
  - C/O + He

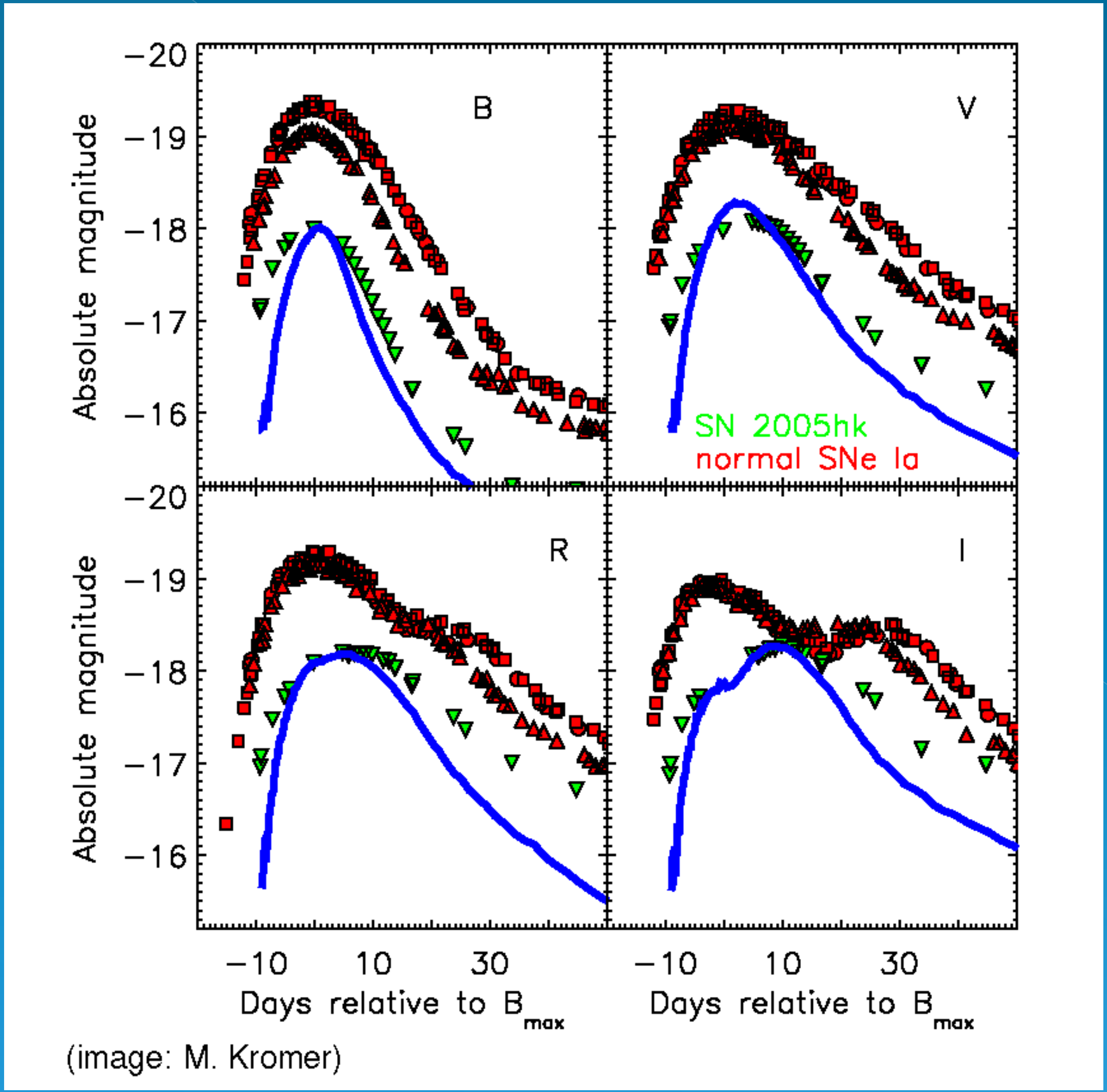
Which of them are realized in Nature? All of them?

A few examples:

1. ‘Pure deflagration’ SD ($M_{Ni} \approx 0.2M_{sun}$)

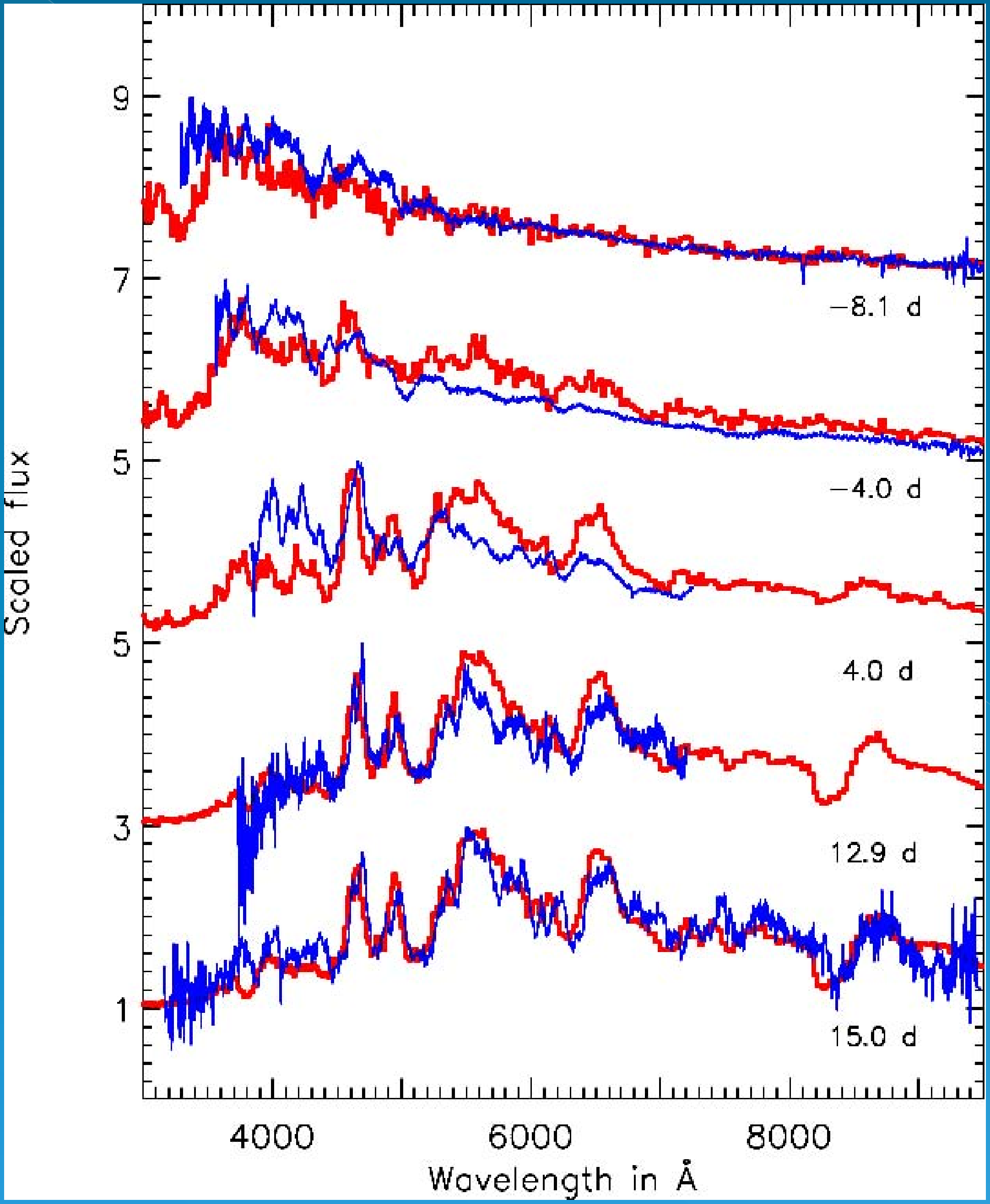


Synthetic lightcurves:



Typical 'pure deflagation' model (blue) compared with various 'normal' SNe Ia (red) and SN 2005hk (green)

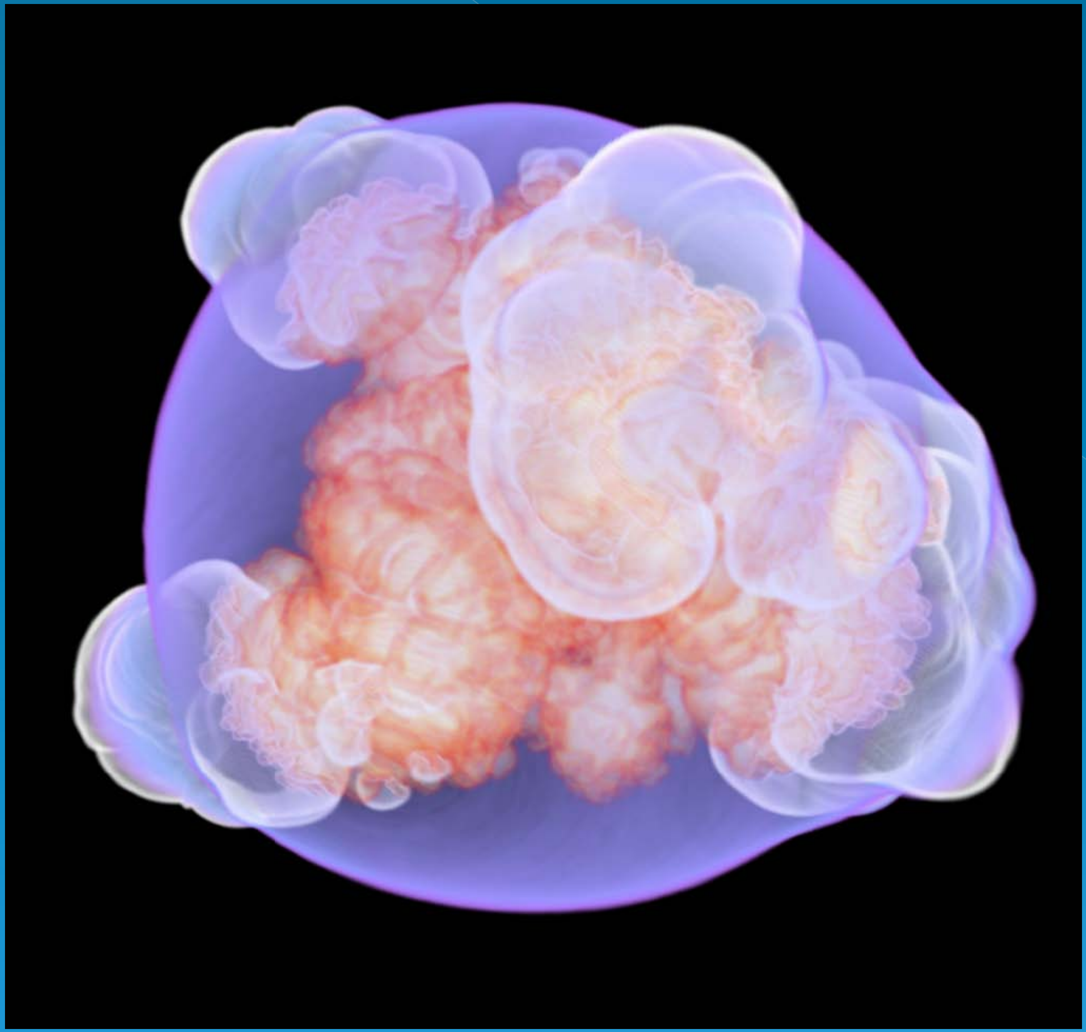
Synthetic spectra:

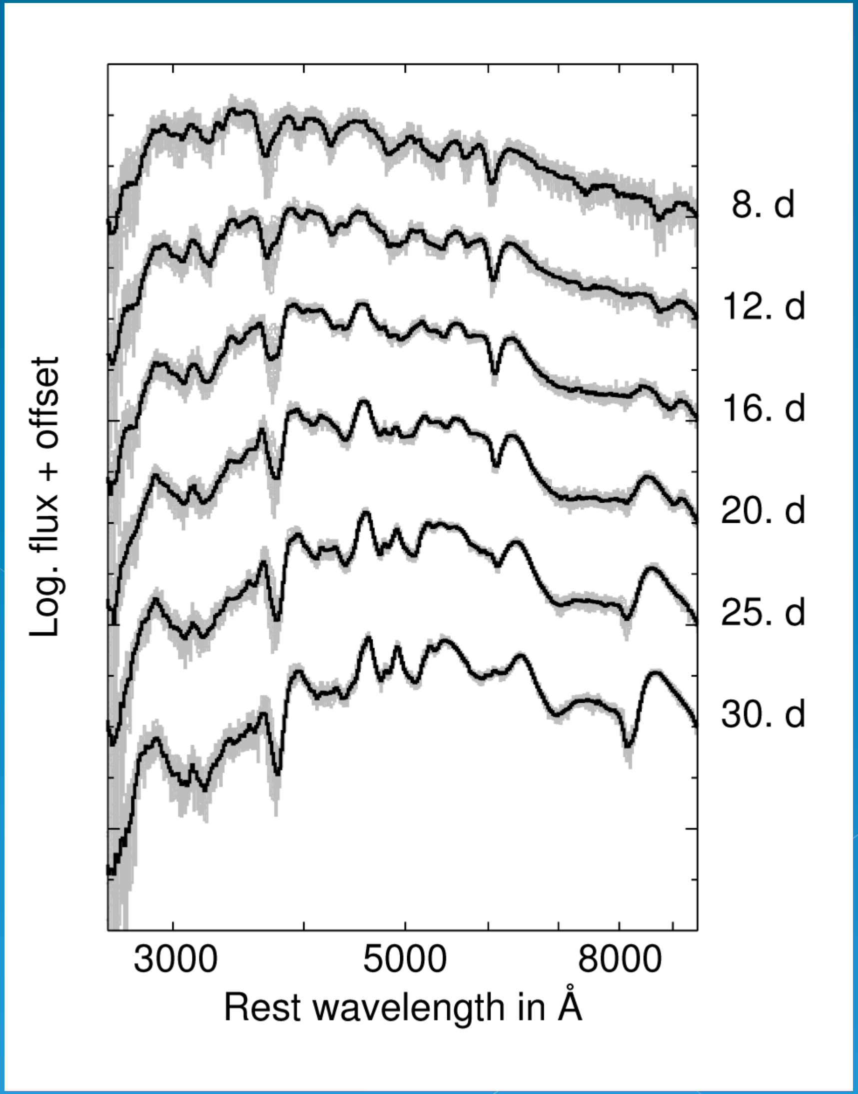


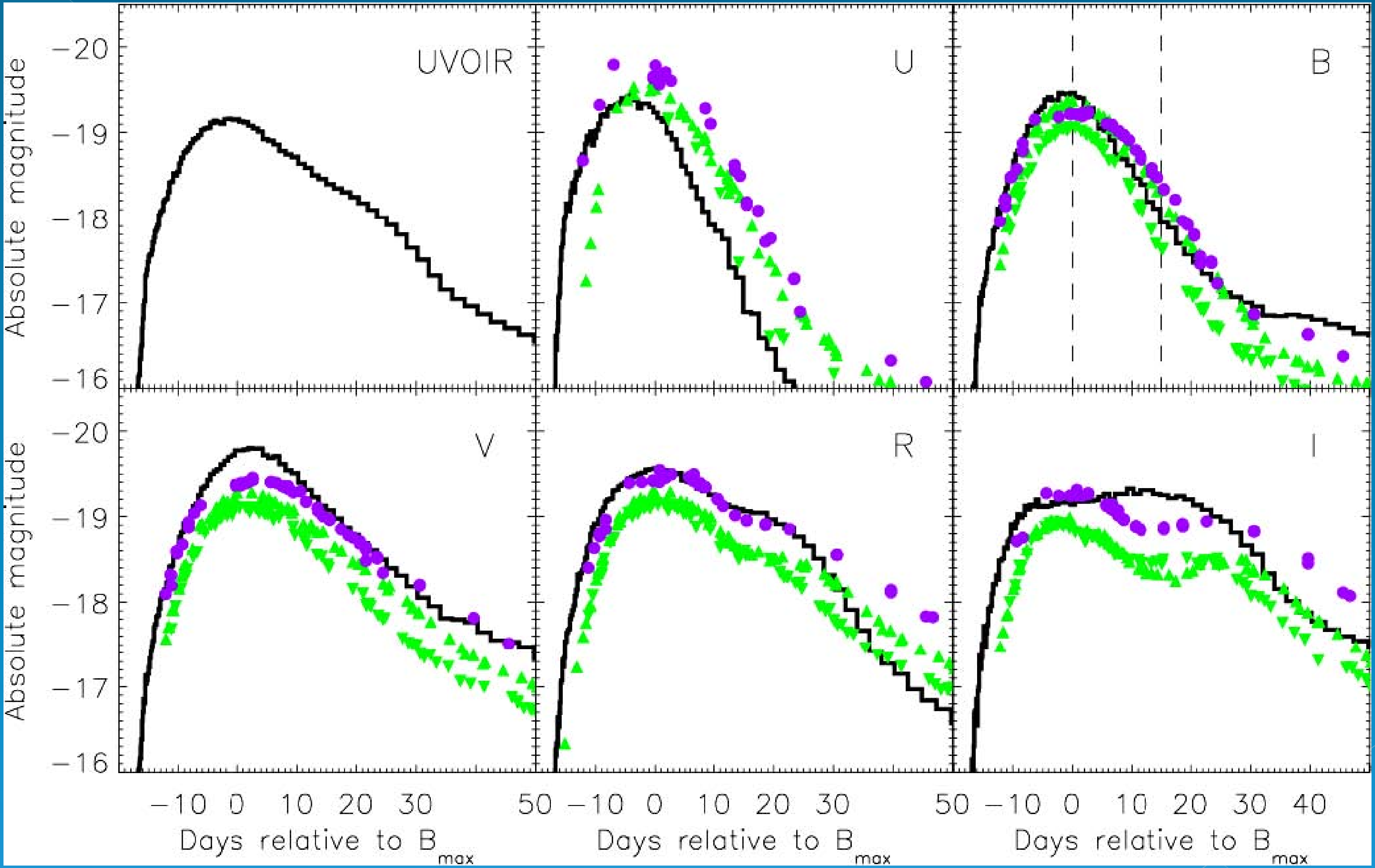
'Pure deflagation' models (red) fit some ***peculiar faint*** SNe Ia (SN 2005hk, blue), but neither 'normal' nor subluminous ones

Are the SN 2005hk-likes the 'pure-deflagration' Chandrasekhar-mass explosions???

2. ‘Delayed detonation’ SD ($M_{Ni} \approx 0.6M_{sun}$)



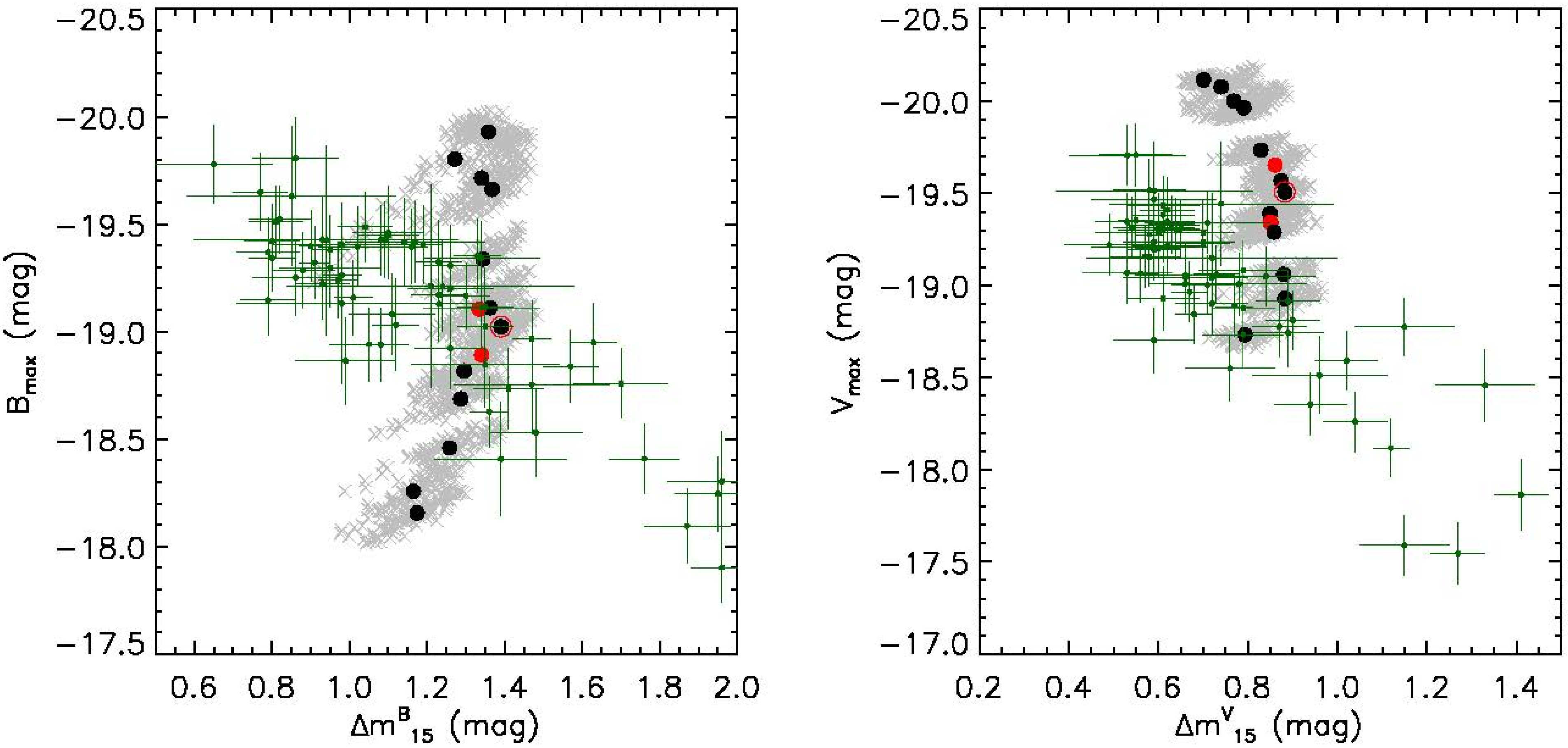




DDT model, angle averaged (black solid lines)

‘Delayed detonation’ Chandrasekhar-mass explosions fit lightcurves (and spectra) of ‘normal’ SN Ia well.
Do we need anything more???

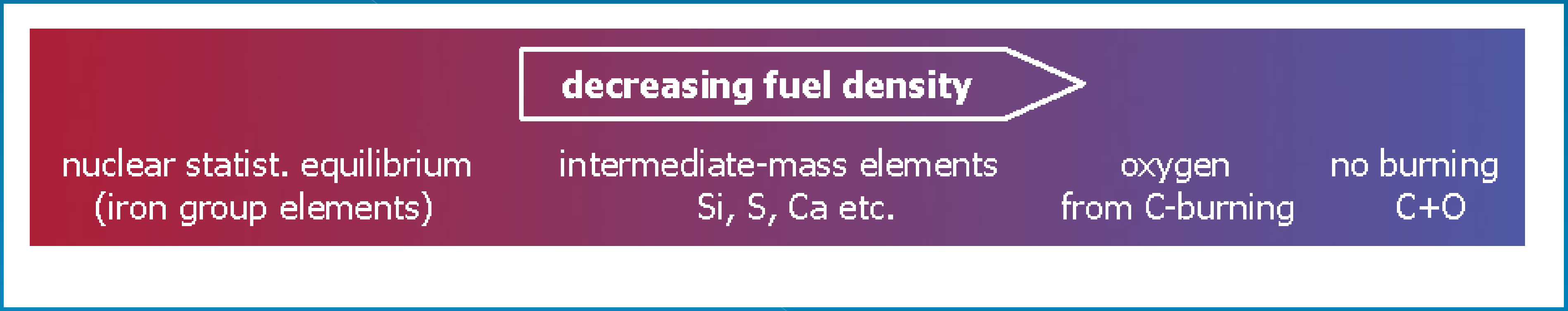
Canonical M_{chan} DD models do not follow the Phillips relation and they are too 'red' !



Sim et al. (2013)

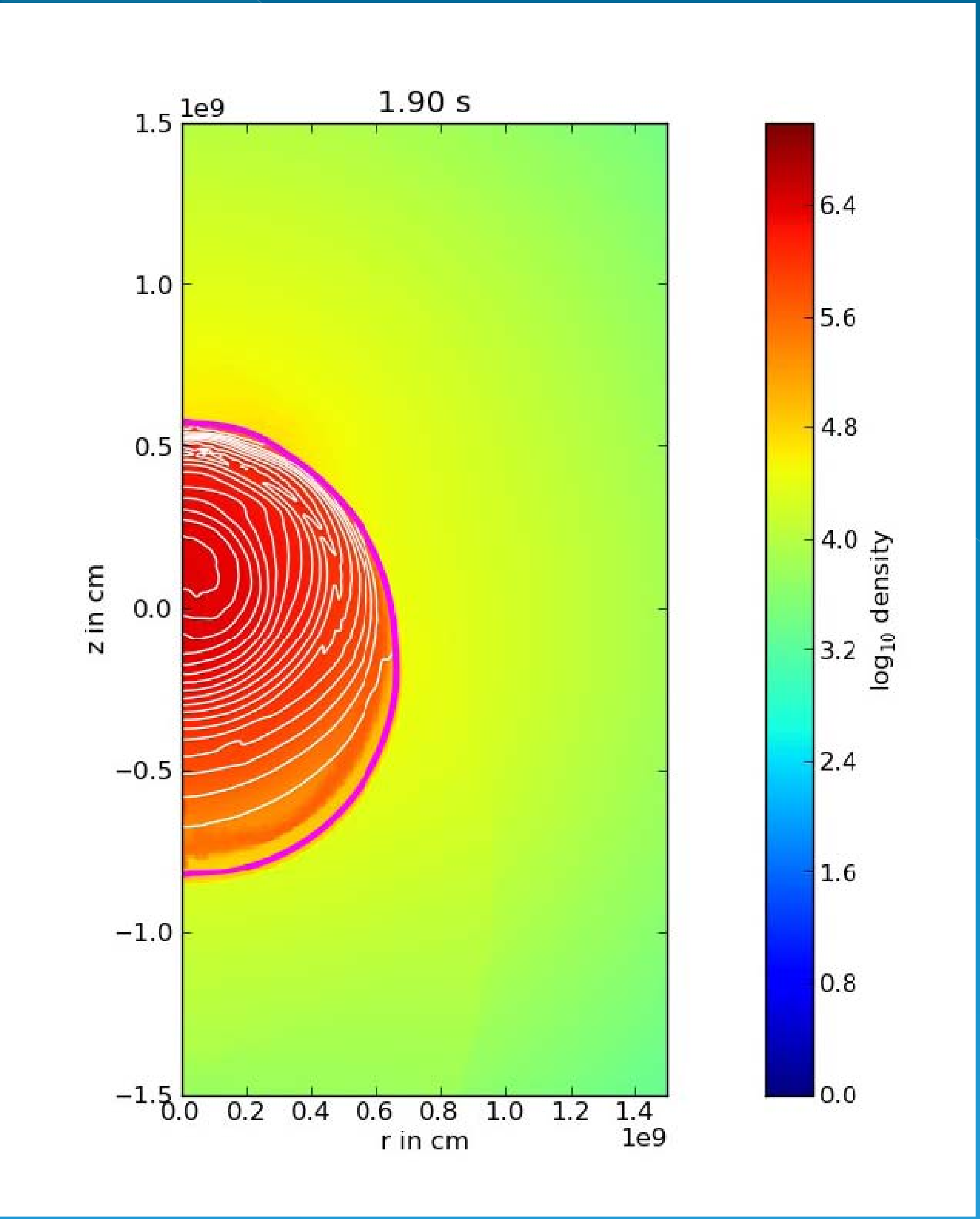
Are some SNe Ia (or all?) 'super-Chandra' mergers and/or 'sub-Chandra' detonations???

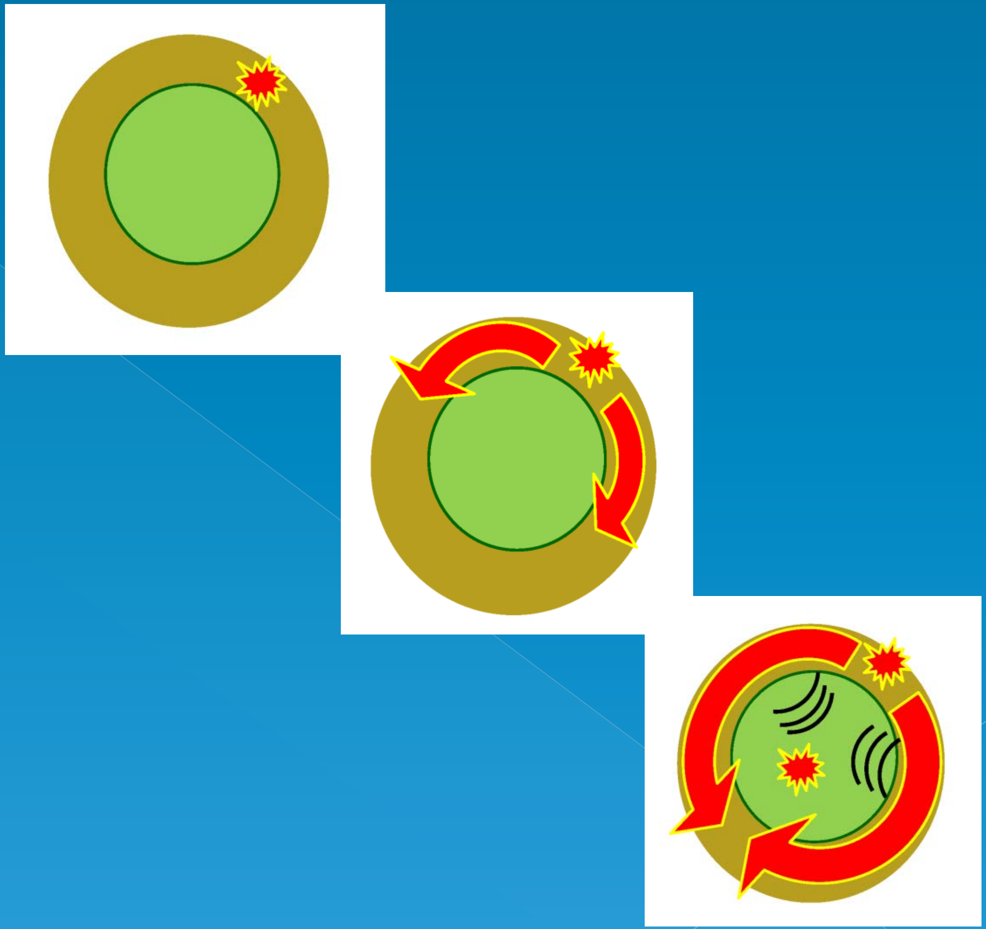
The basic idea:
Let there be detonatins only!



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

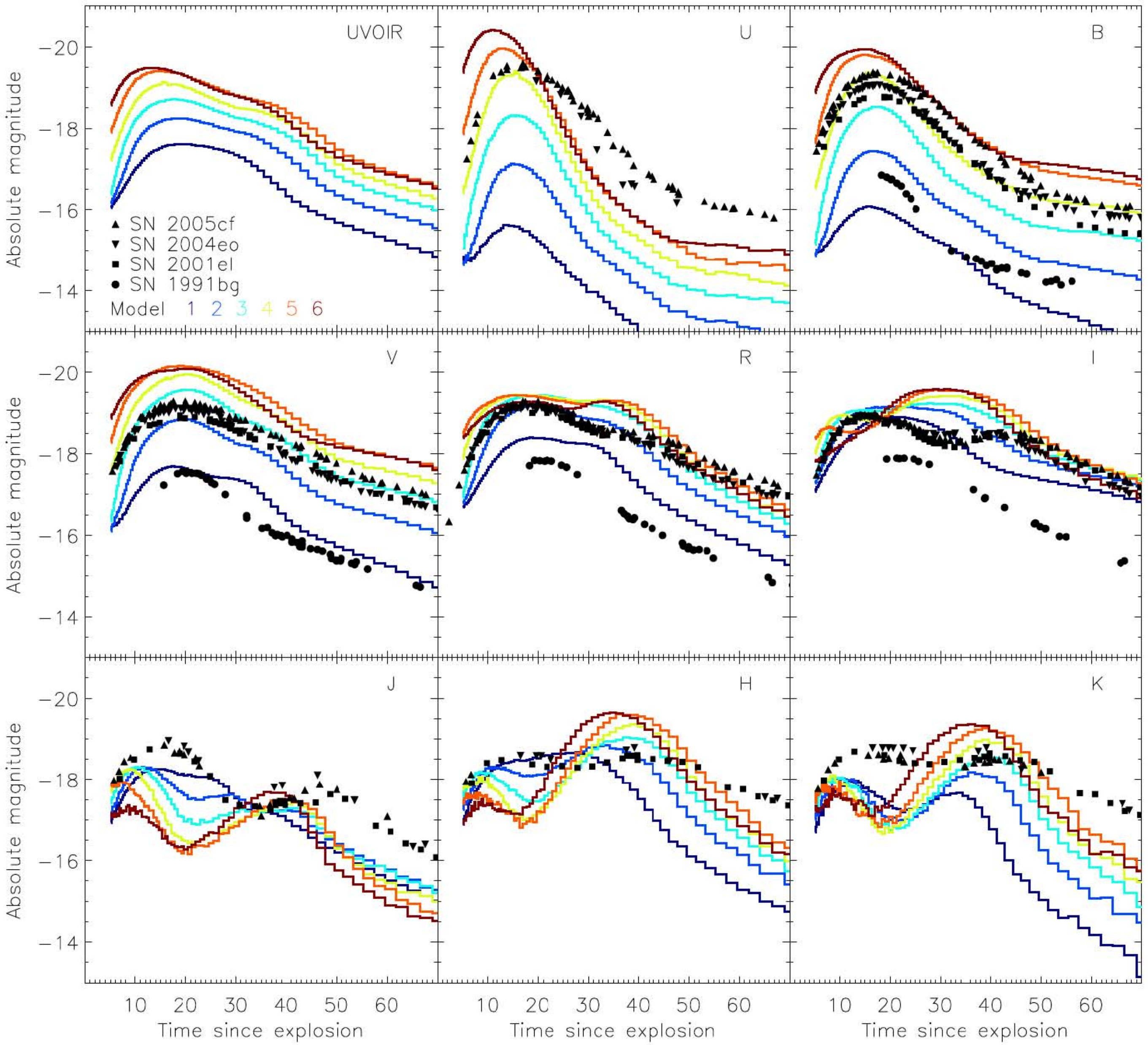
An example: *'sub-Chandra double-detonation' model*





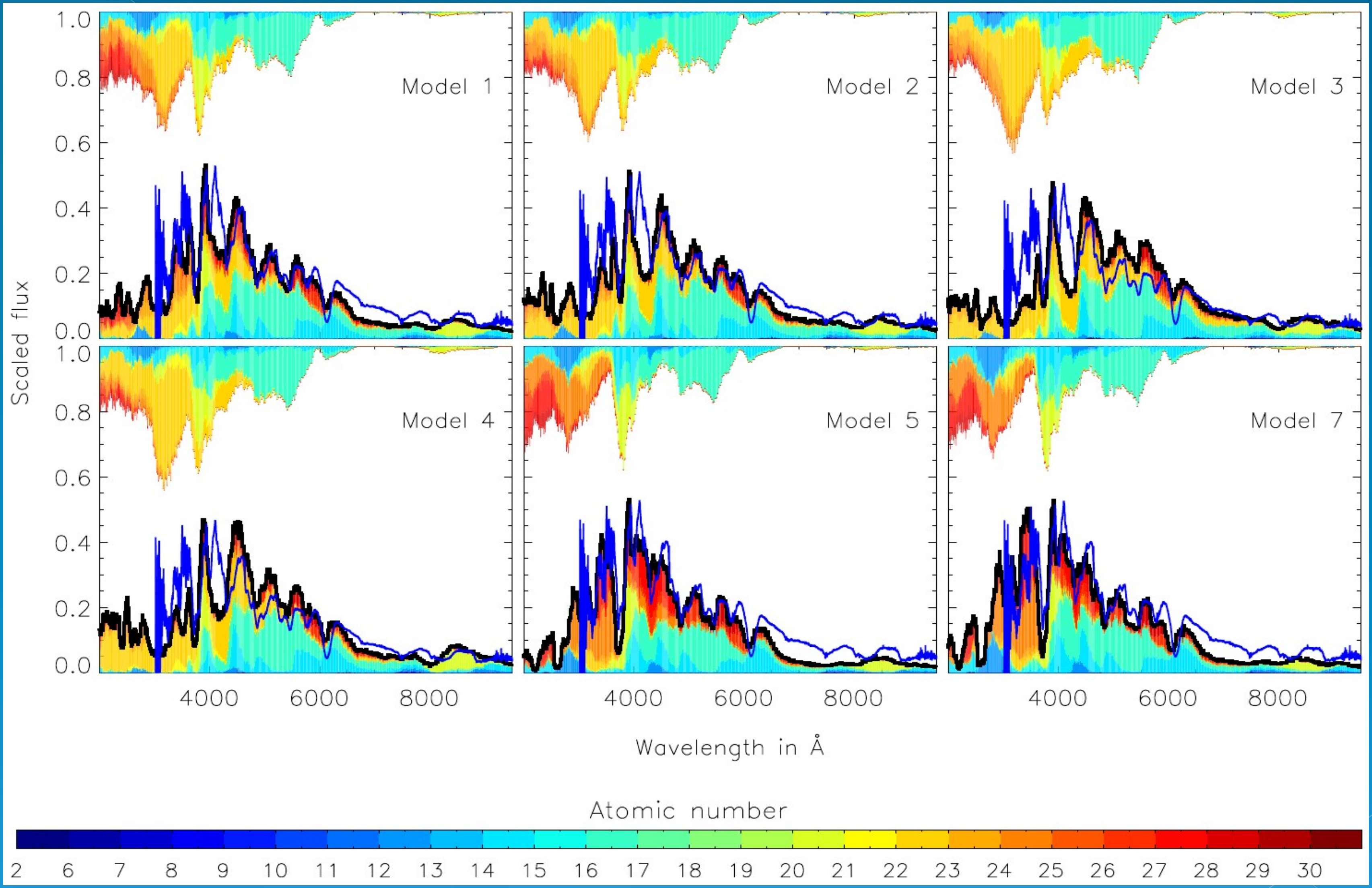
Fink et al. (2010)

Synthetic LCs ….



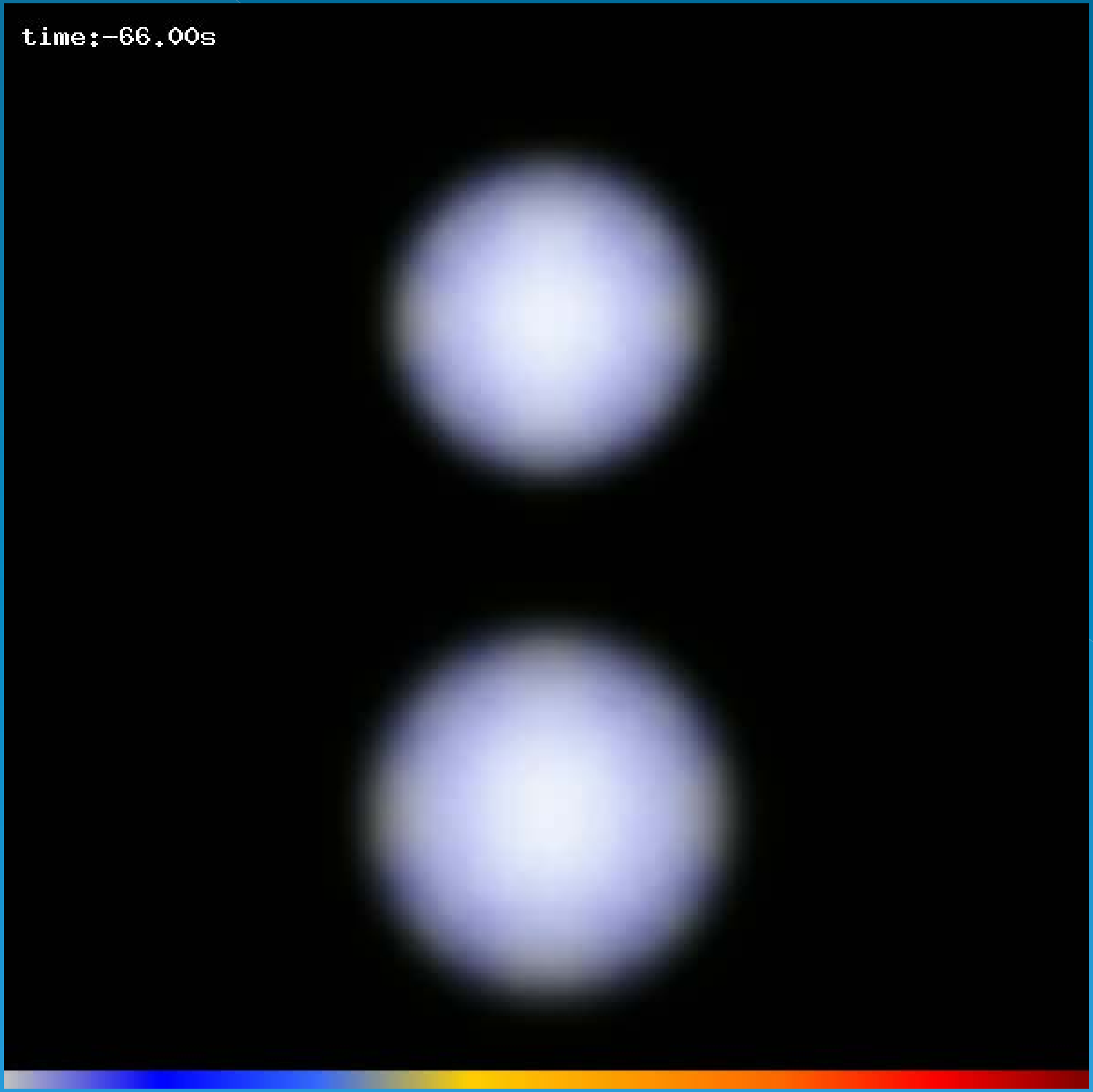
Kromer et al. (2010)

…. and spectra

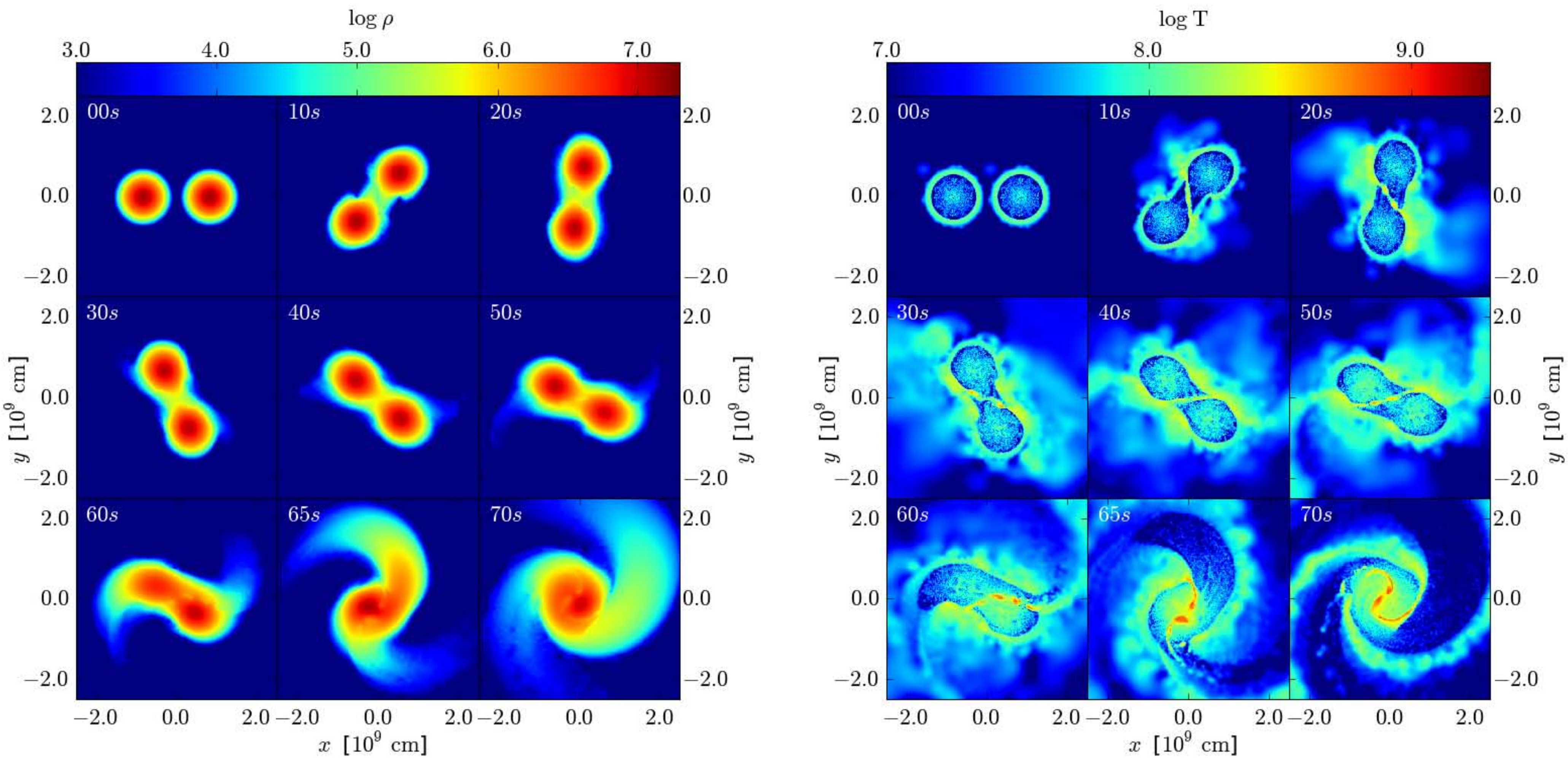


Blue lines: SN 2004eo 3d before B_{max} (Kromer et al. 2010)

A second example: *'double-degenerate' merger*



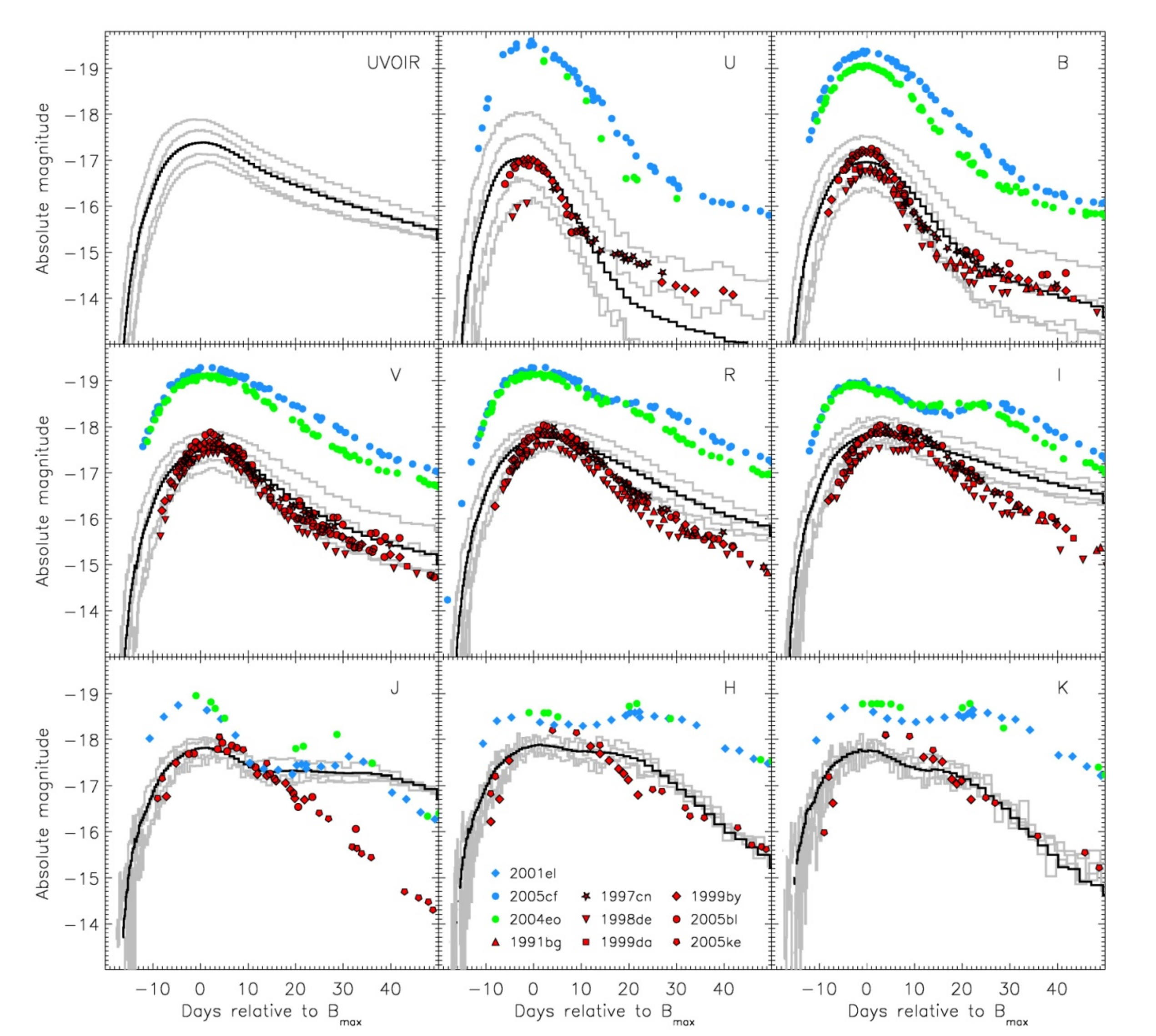
Pakmor et al. (2011)



Violent merger of two WDs of ~ equal mass:

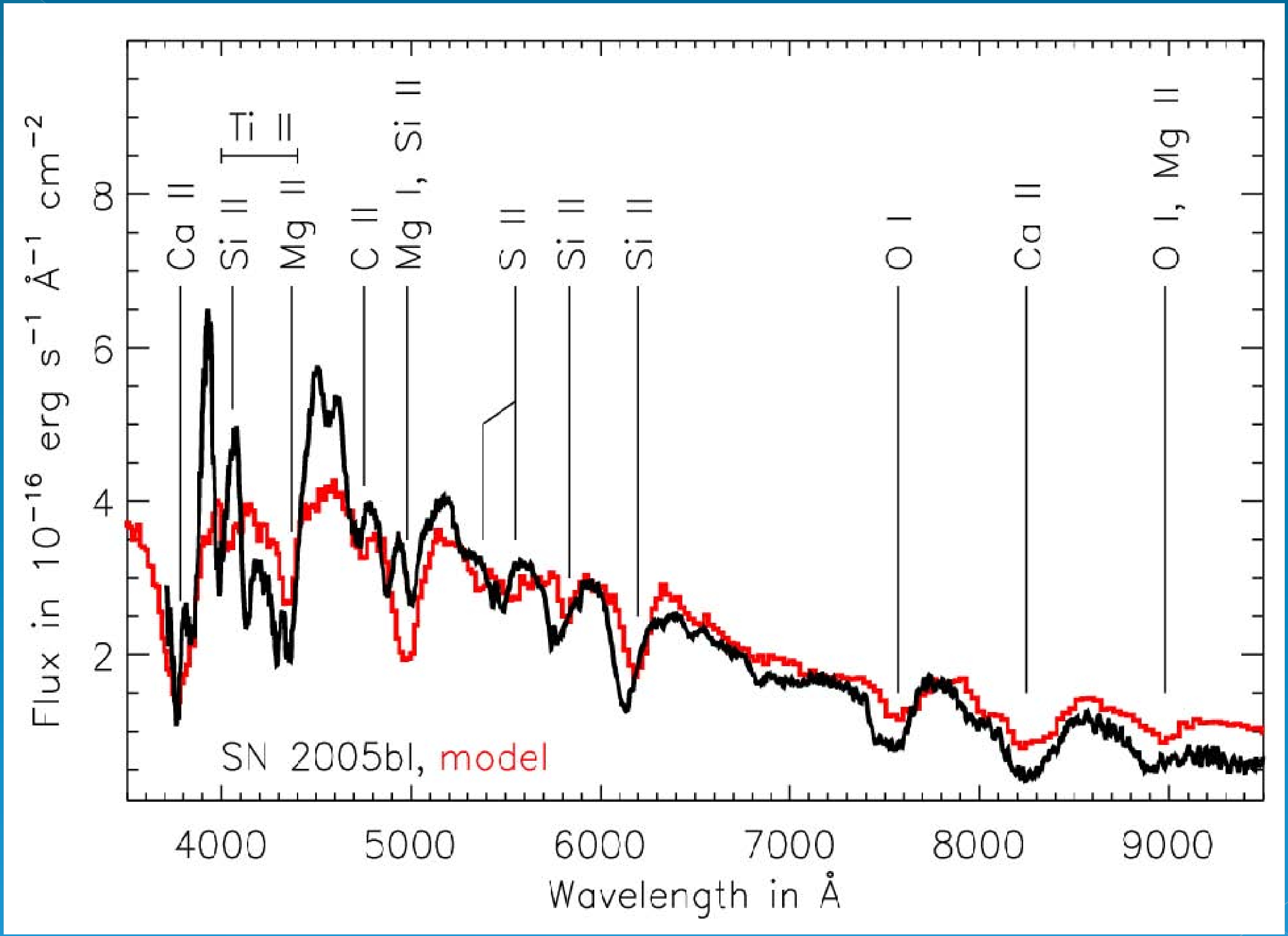
- *Detonation likely*
- *Will be faint (in general, if $M \approx 0.9\ M_{\odot}$)*

Synthetic LCs ….

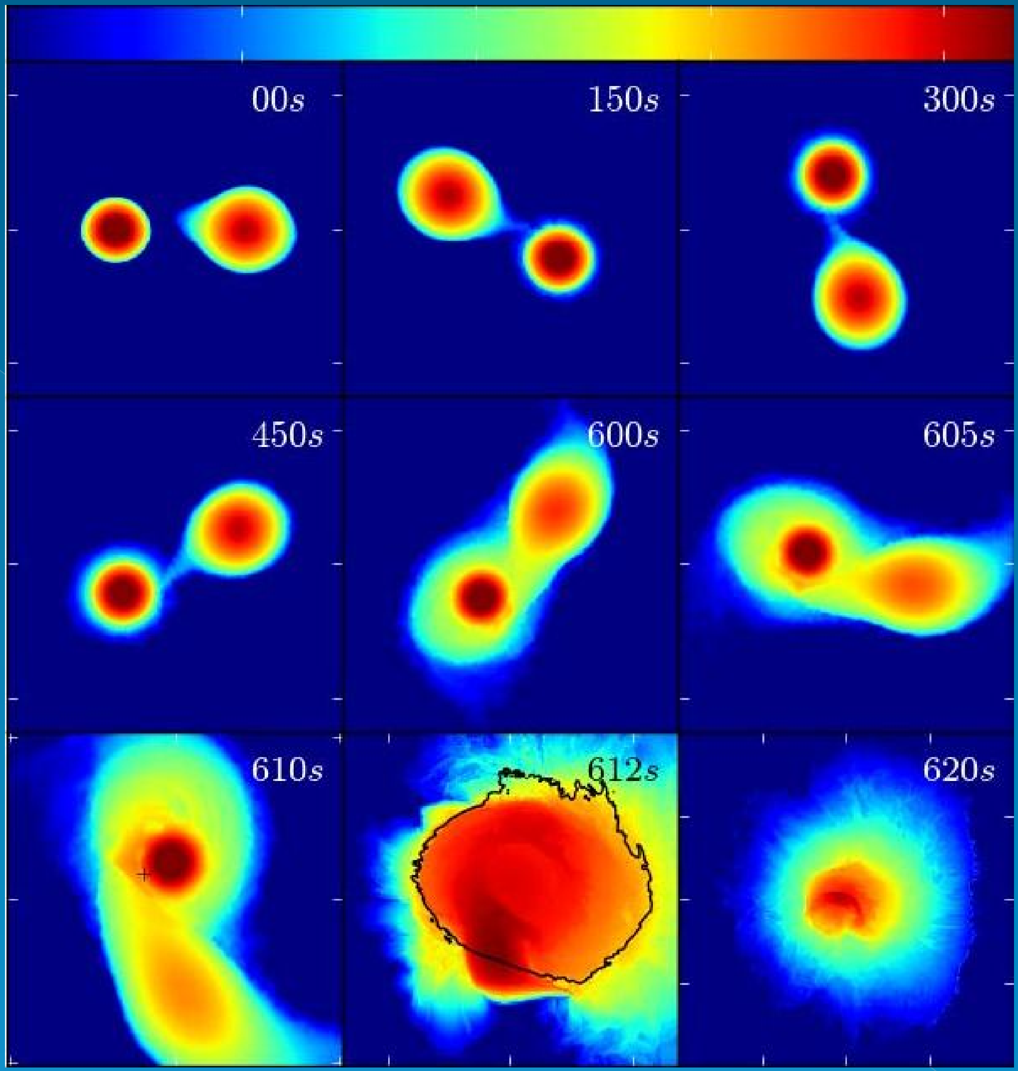


Pakmor et al. (2010)

…. and spectra



Pakmor et al. (2010)



(density color coded)

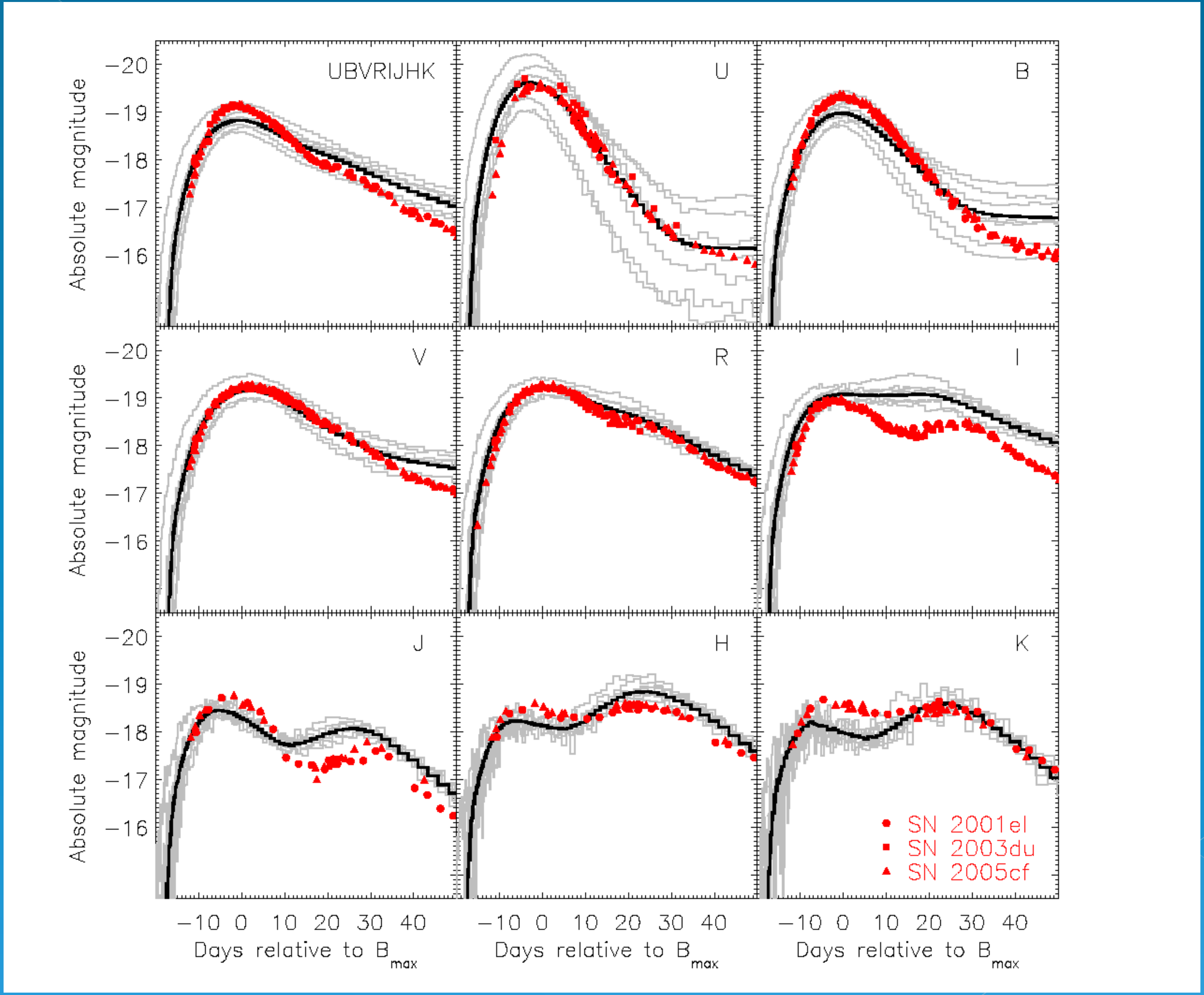
Pakmor et al. (2012)

Dynamical merger of two WDs of similar masses:

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

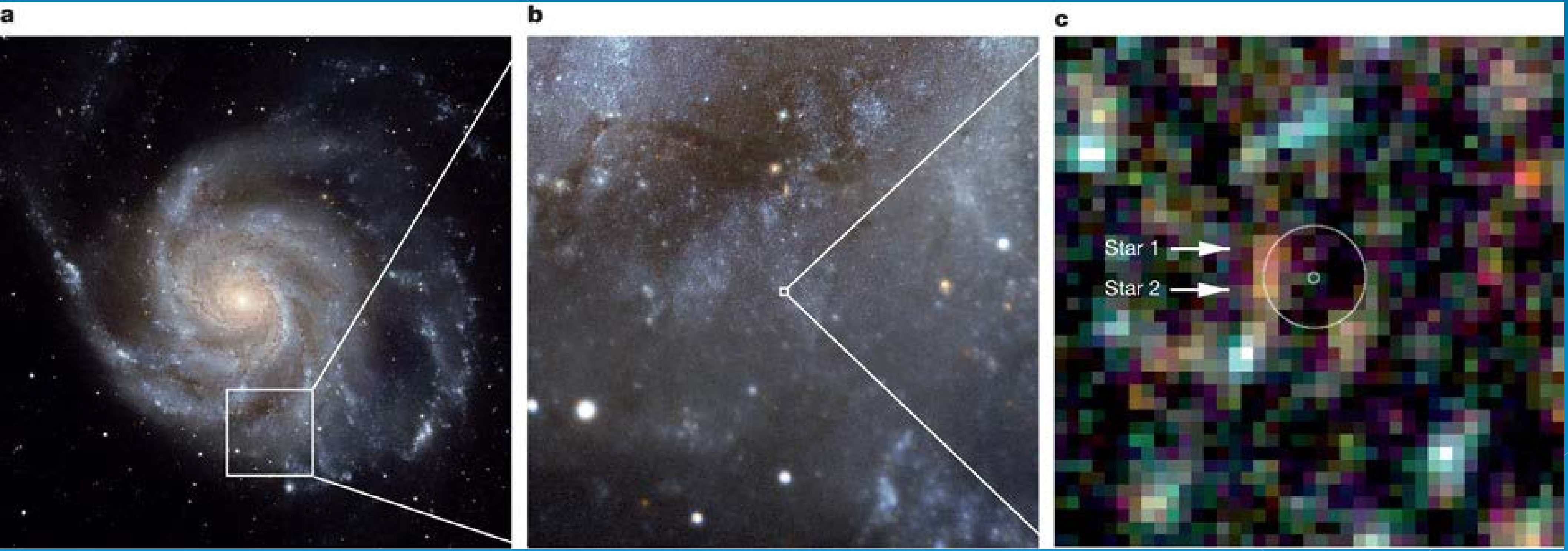
Dynamical merger of two WDs of similar masses:

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



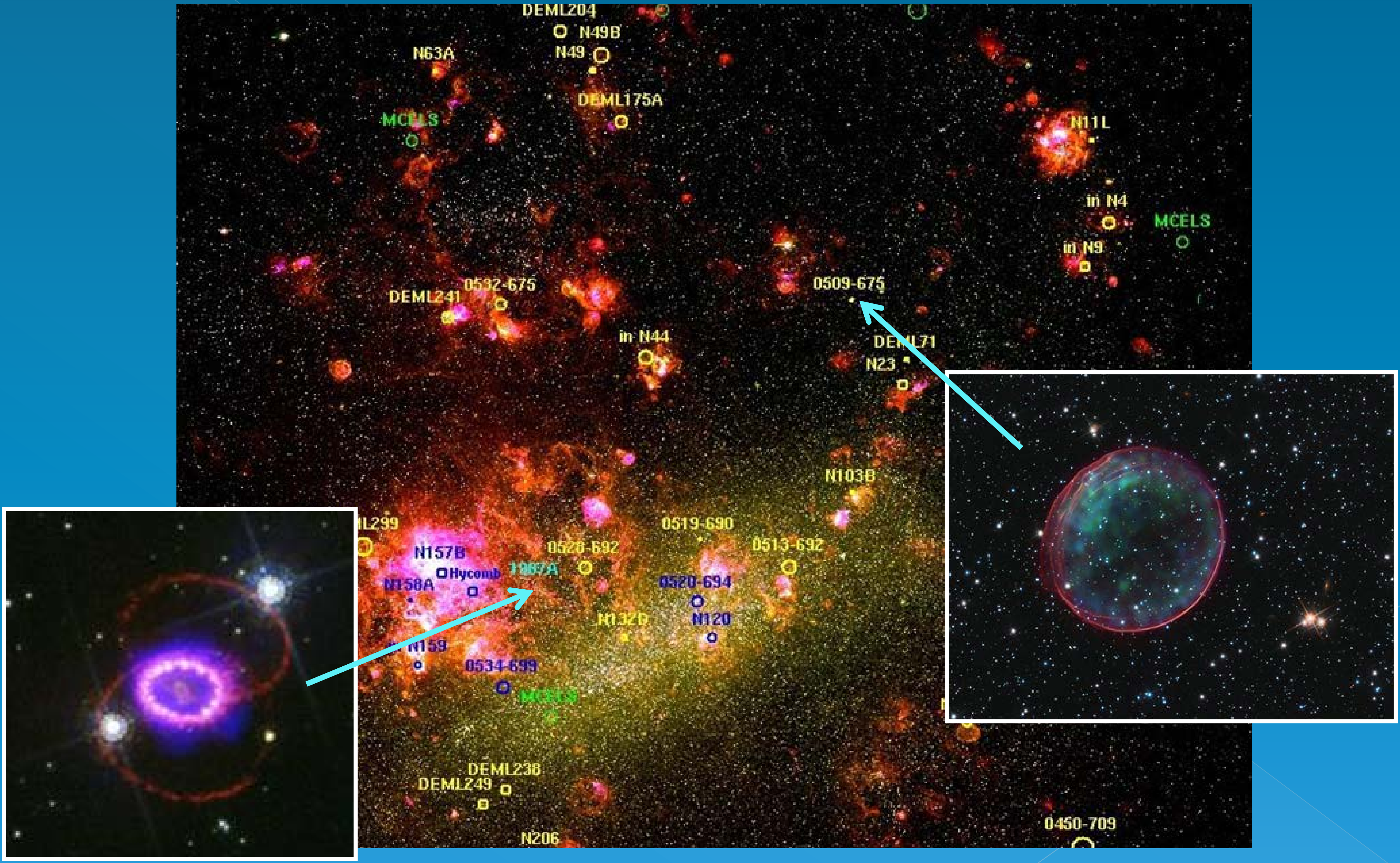
Can we get more information on the progenitors?

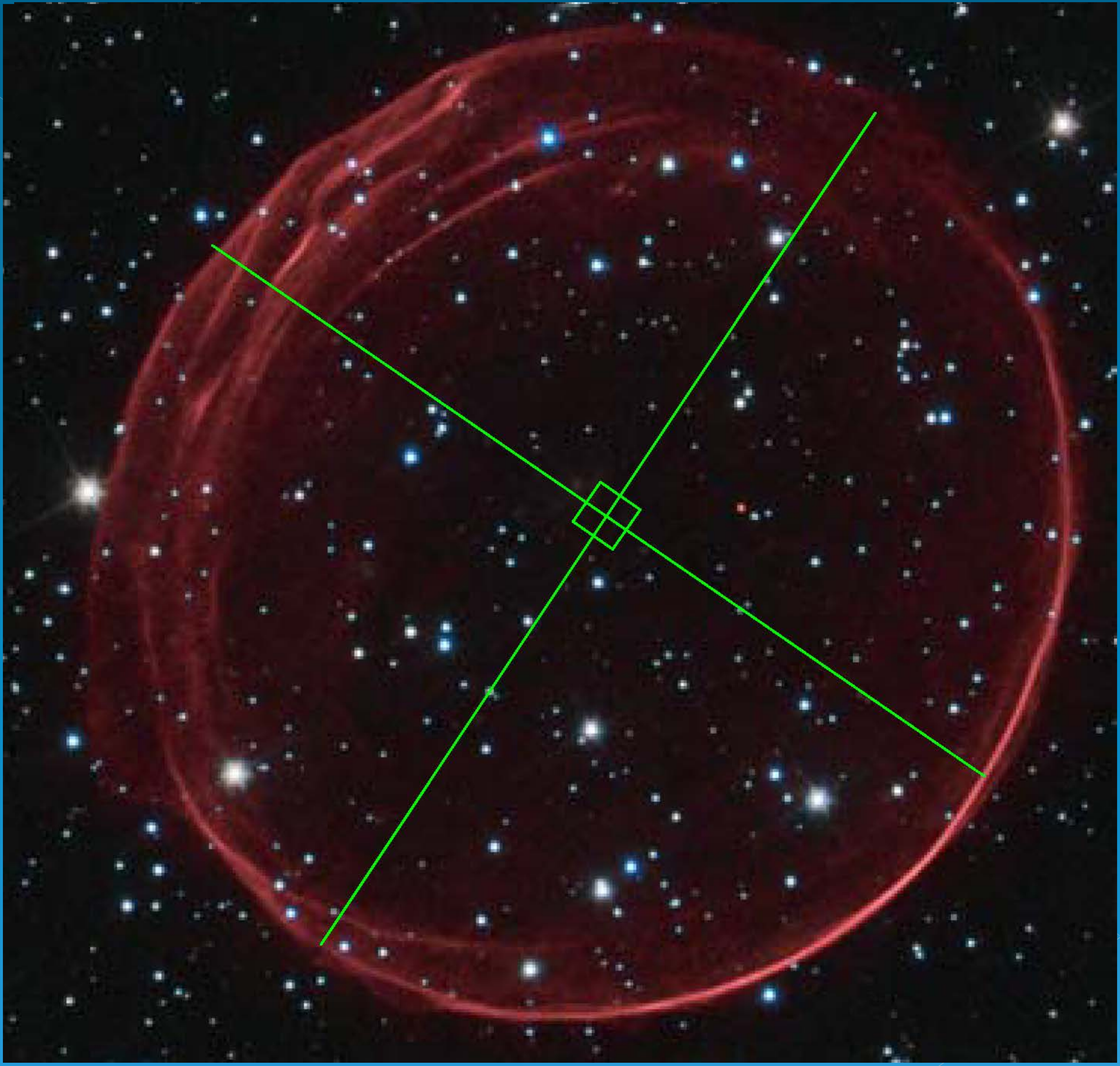
1. Direct observations: SN 2011fe in M101 (d~6 Mpc)

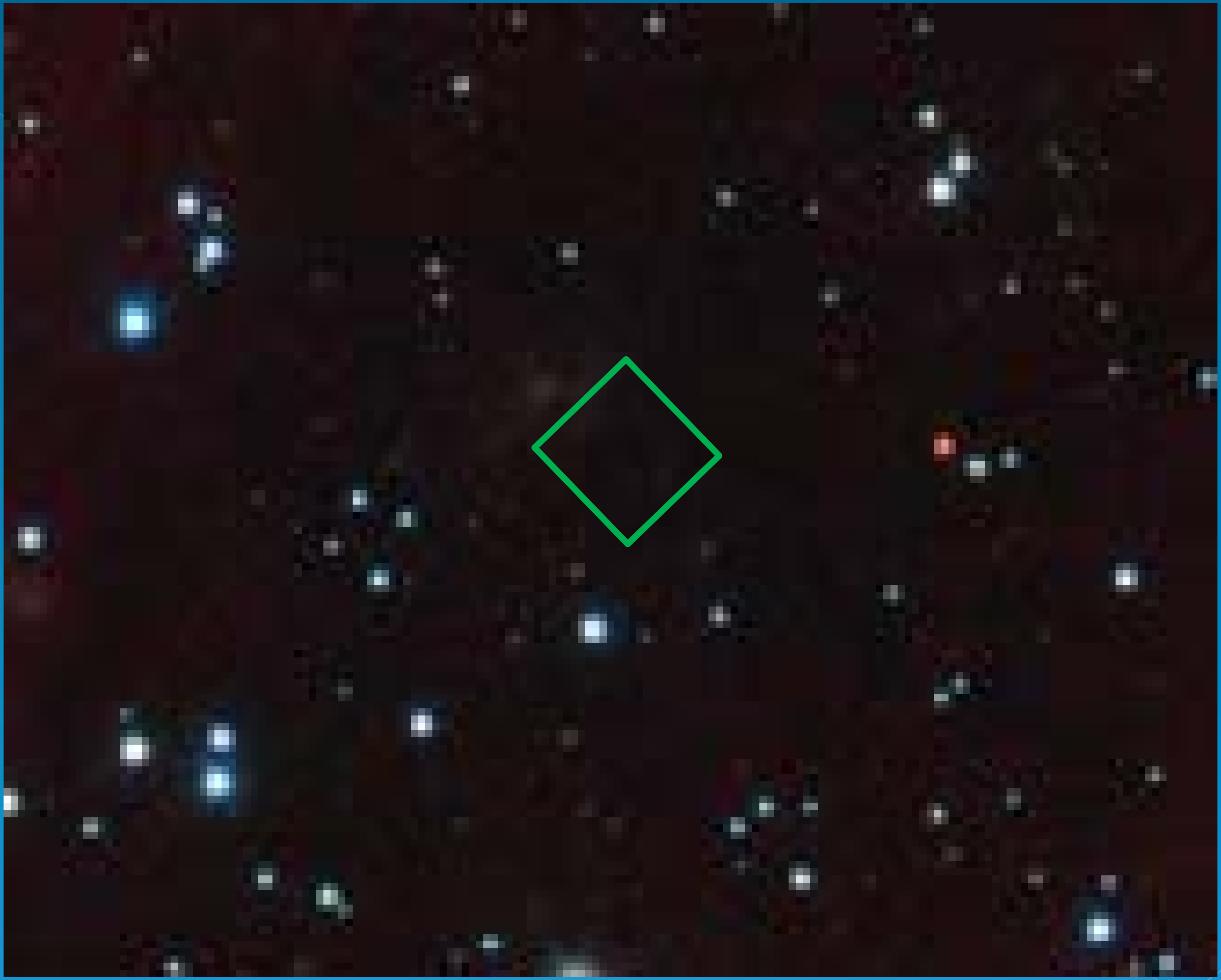


Li et al. (1011): donor was not a red supergiant!

2. Supenova remnants in the LMC





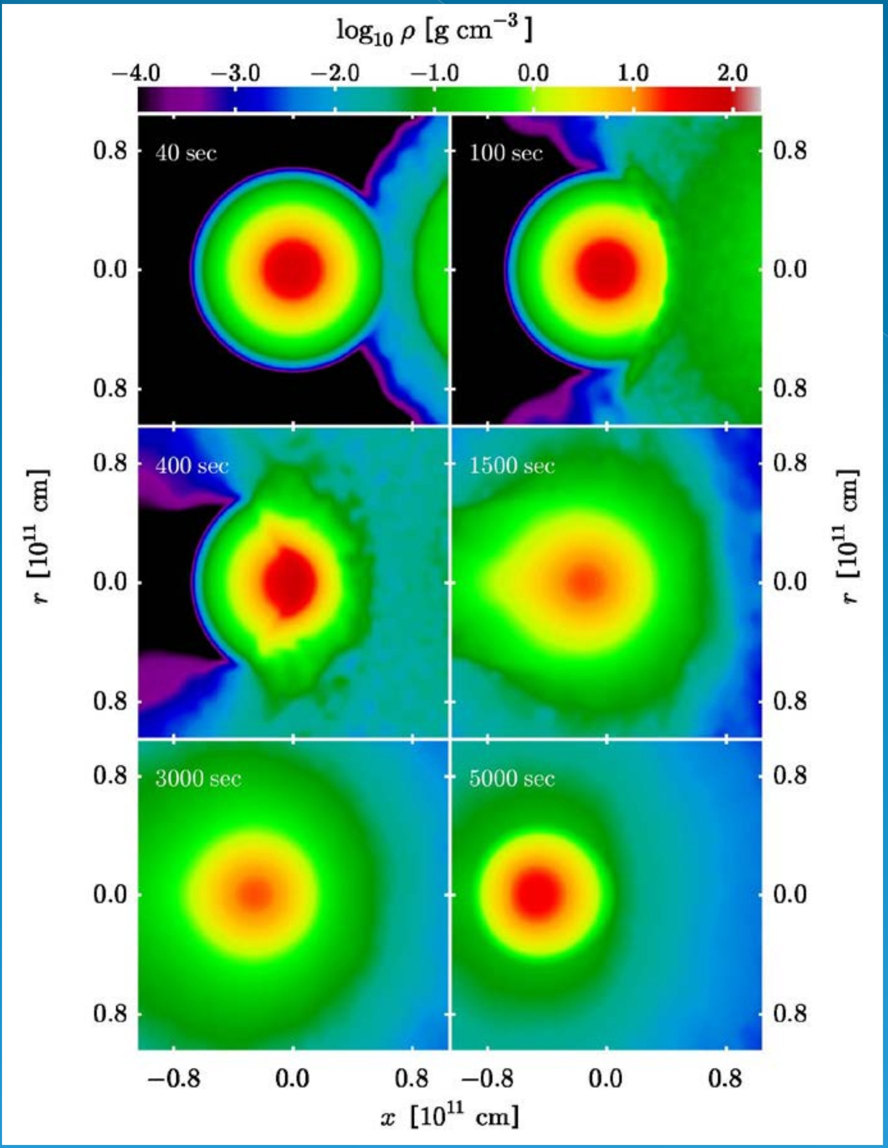


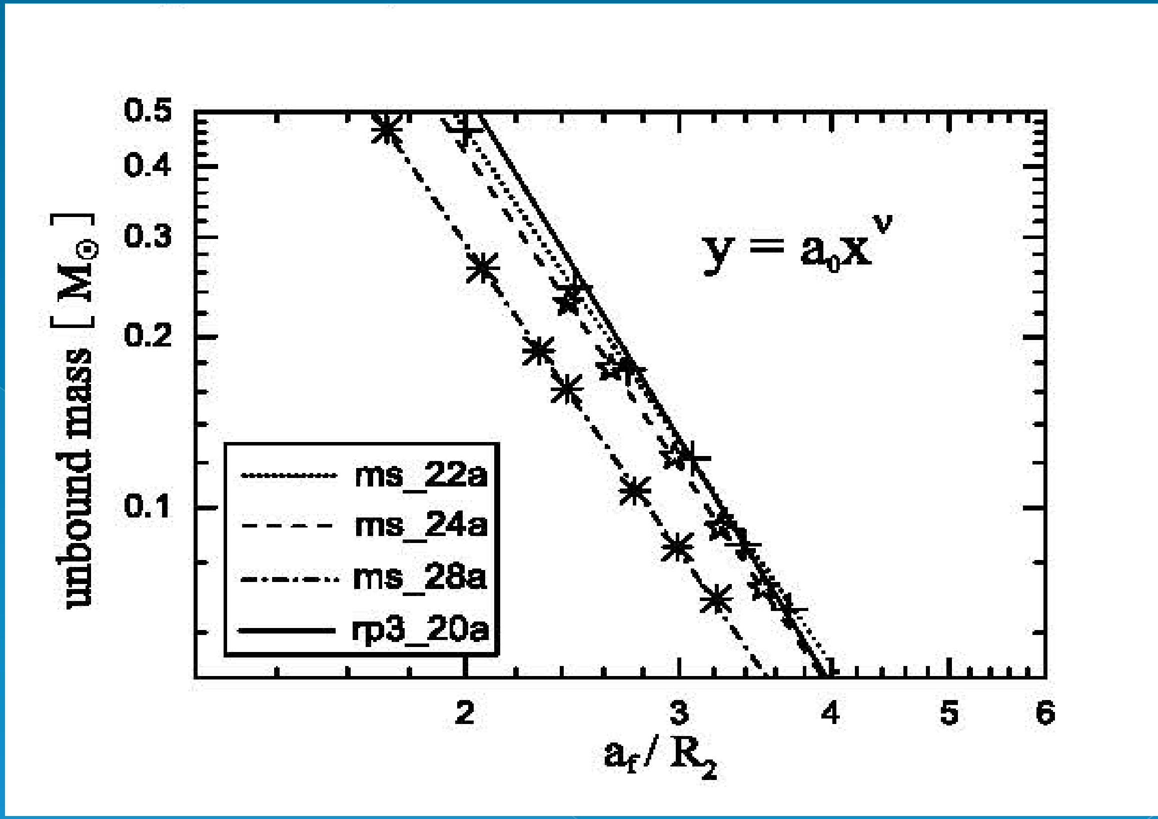
No star down to 0.5 M_{sun} ! (Schaefer & Panotta 2012)

3. *What else can we do to get information on the progenitors?*

Circum-stellar gas

Stripped gas from a (MS) companion:



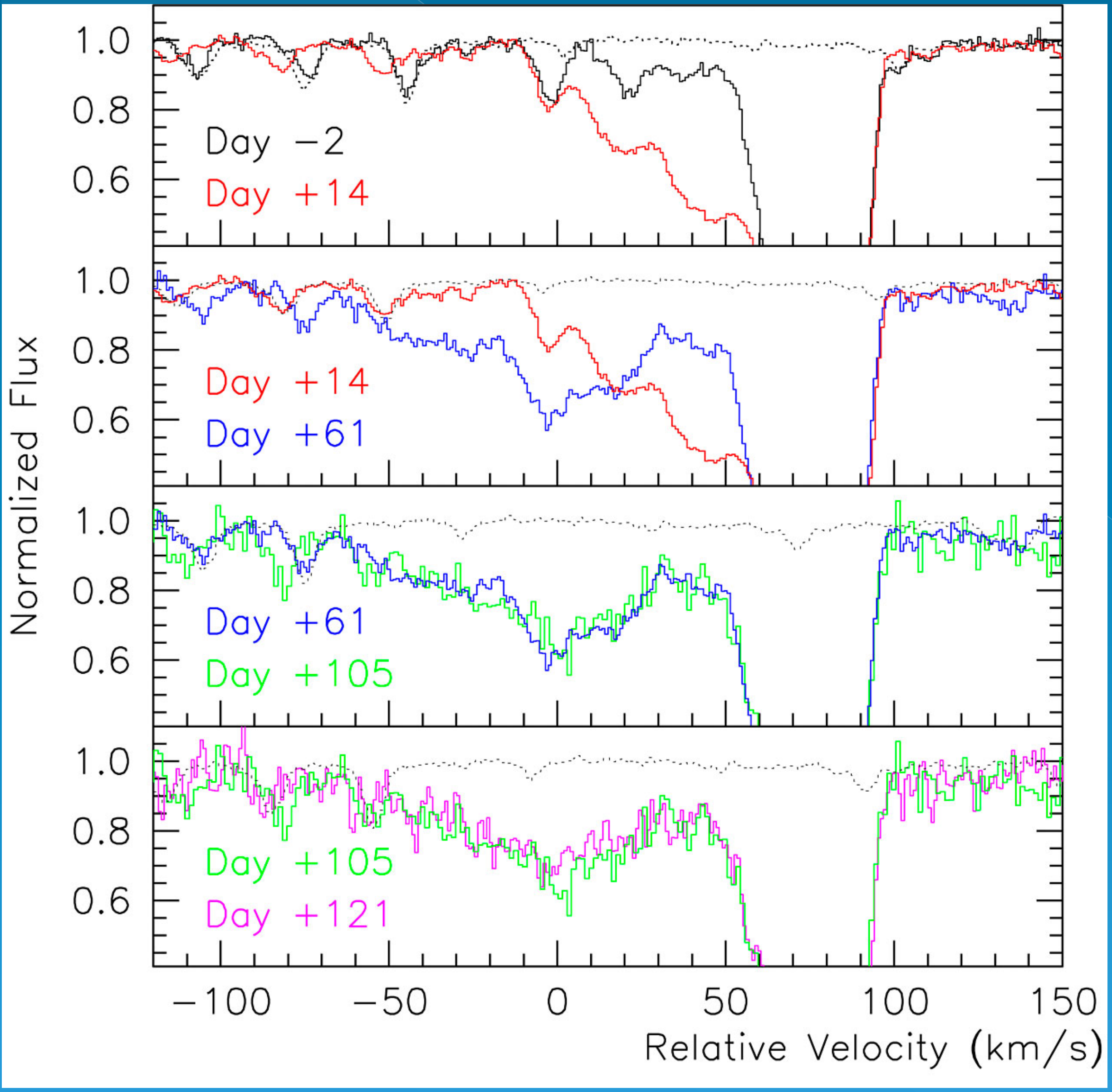


(Liu et al. 2012)

Was never seen!

Circum-stellar gas

Variable Na ID absorption (e.g. SN 2006X, Patat et al. 2007)



Evidence for circum-stellar gas! Only seen in SNe in spriral galaxies!

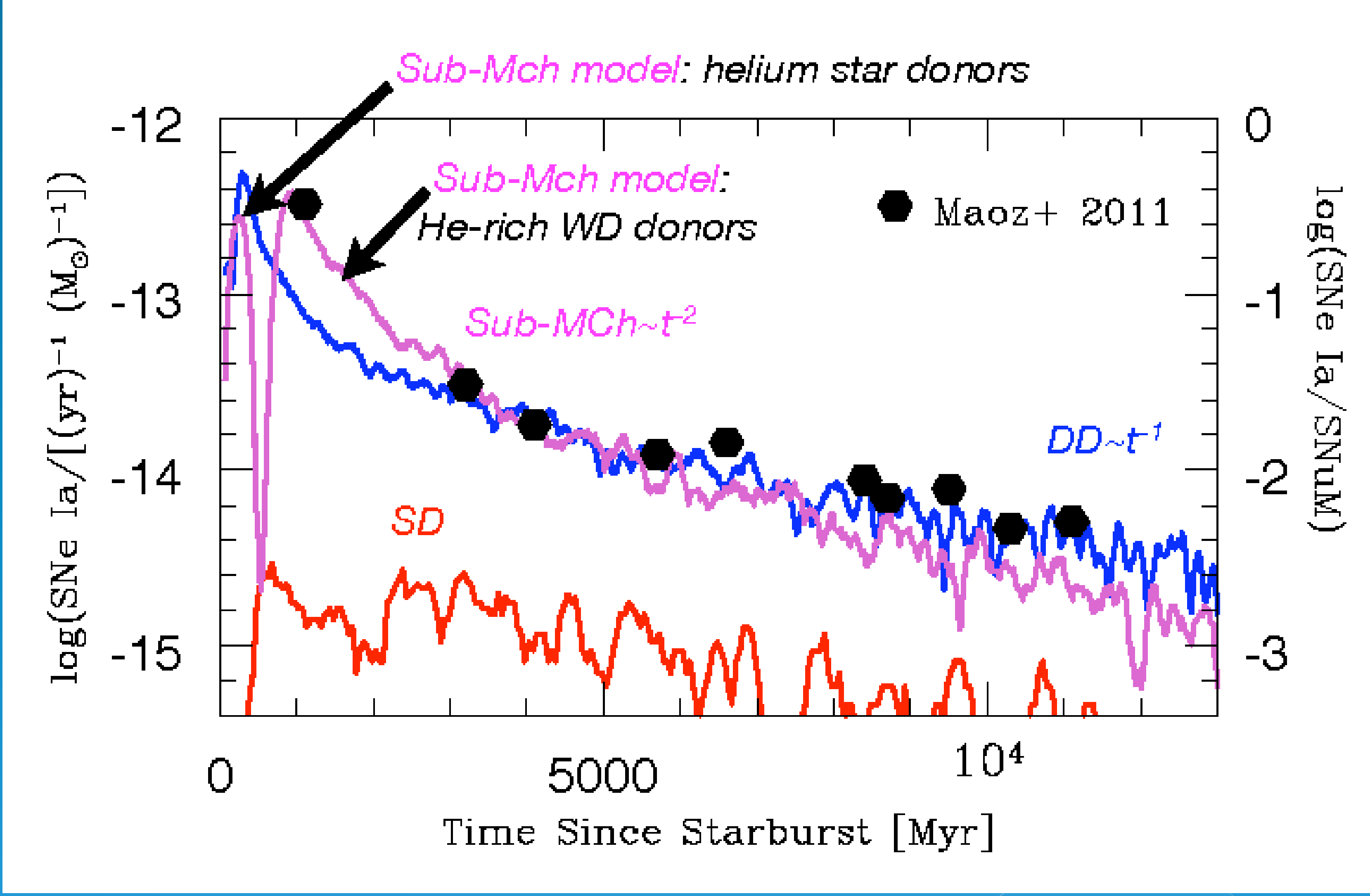
Recurrent nova? Or also in some DDs?

Rates and delay times

Expected delay times:

~ t^{-1} (DDs)

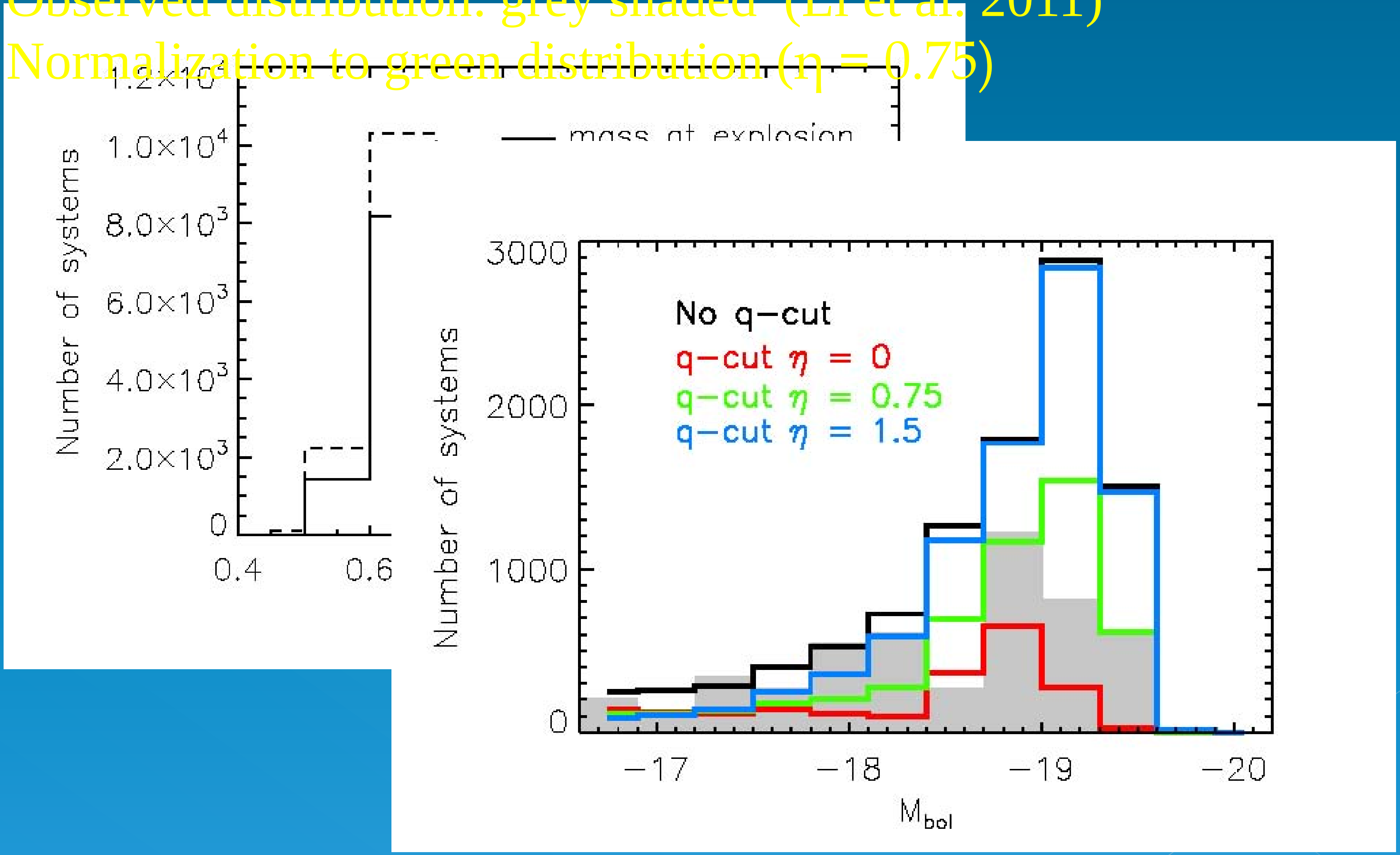
~ $t^{-0.5}$ + cut-off (SDs)



(Ruiter et al. 2011)

Peak-luminosity distribution from DD mergers:

Observed distribution: grey shaded (Li et al. 2011)
Normalization to green distribution ($\eta = 0.75$)



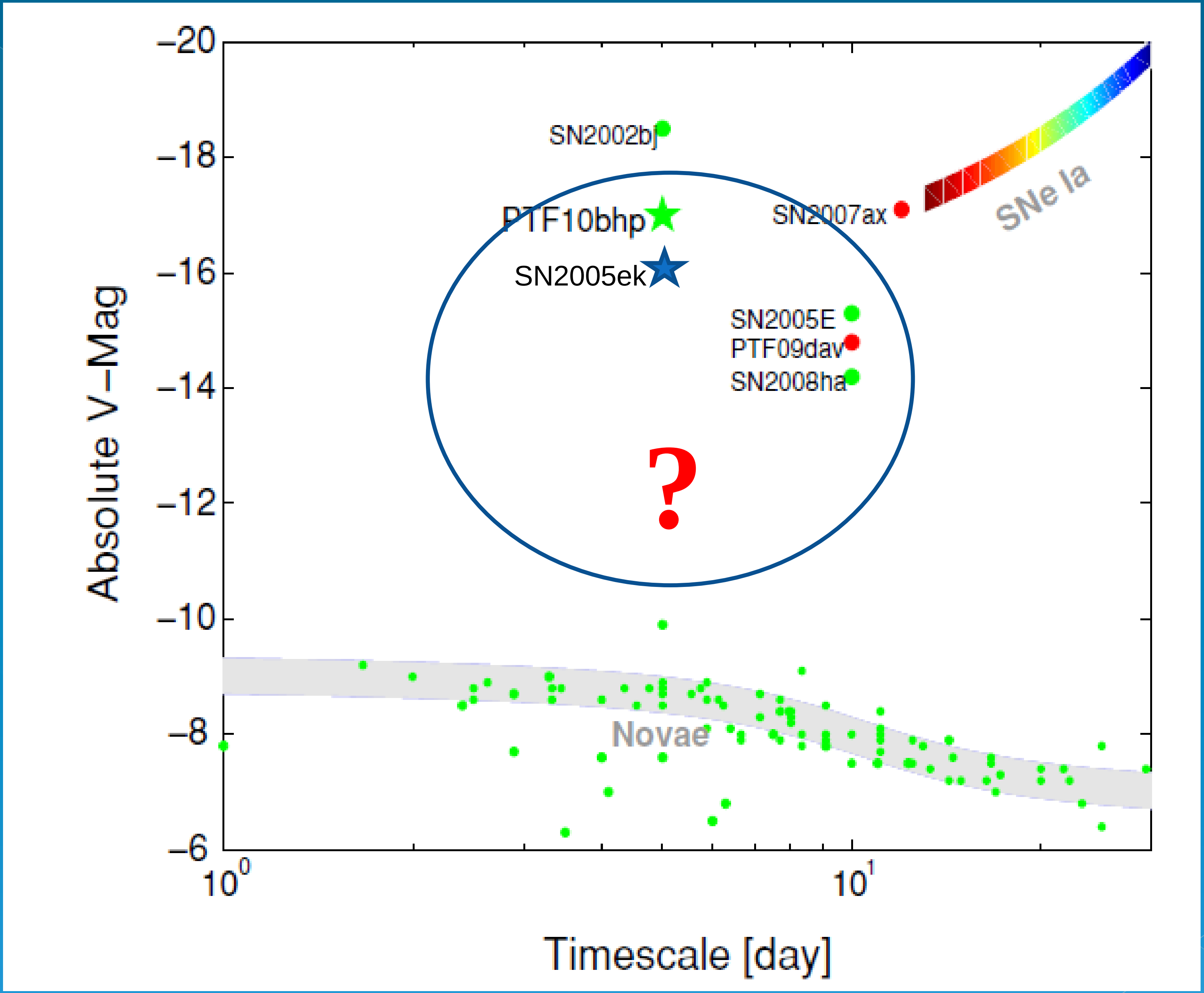
(Ruiter et al. 2012)

Summary and conclusions
SNe Ia: where do we stand?

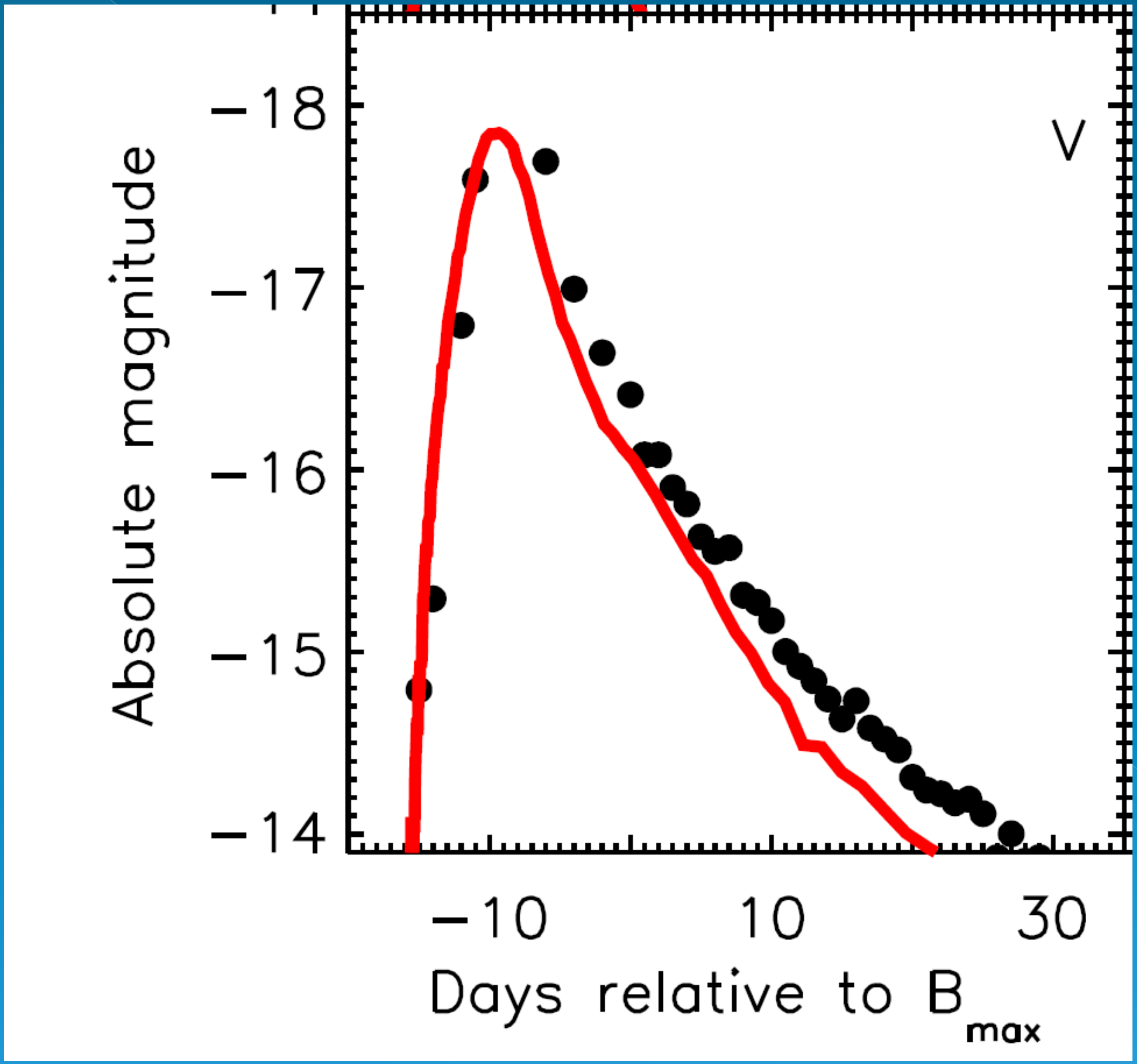
- Type Ia Supernovae are well explained by thermonuclear explosion models of white dwarfs, *but they form a rather inhomogenous class!*
- The normal ones (~70%): *What are they? Mostly DDs?*
- The ‘abnormal’ ones make up for 30% (or more). *Why are they ‘different’? Different progenitors?*
- How can we *separate them from the ‘normal’ ones* if we have broad-band photometry and one (or at most) two colors only (as in future cosmology surveys)? *Evolution???*

- If all (or most) of this is correct there should be many ‘fast and faint’ transients which have escaped discovery (low-mass mergers, low-mass core detonations, low-mass edge-lit detonations ...).

Where are they? Or have we seen them already?



Kasliwal et al. 2010



red curve:
edge-lit detonation,
0.57 M_{sun} C+O
0.21 M_{sun} He

black dots:
SN 1885A
(S Andromeda, de Vaucouleurs & Corwin 1985)

Sim et al., in preparation