The Many Guises of Thermonuclear Supernovae

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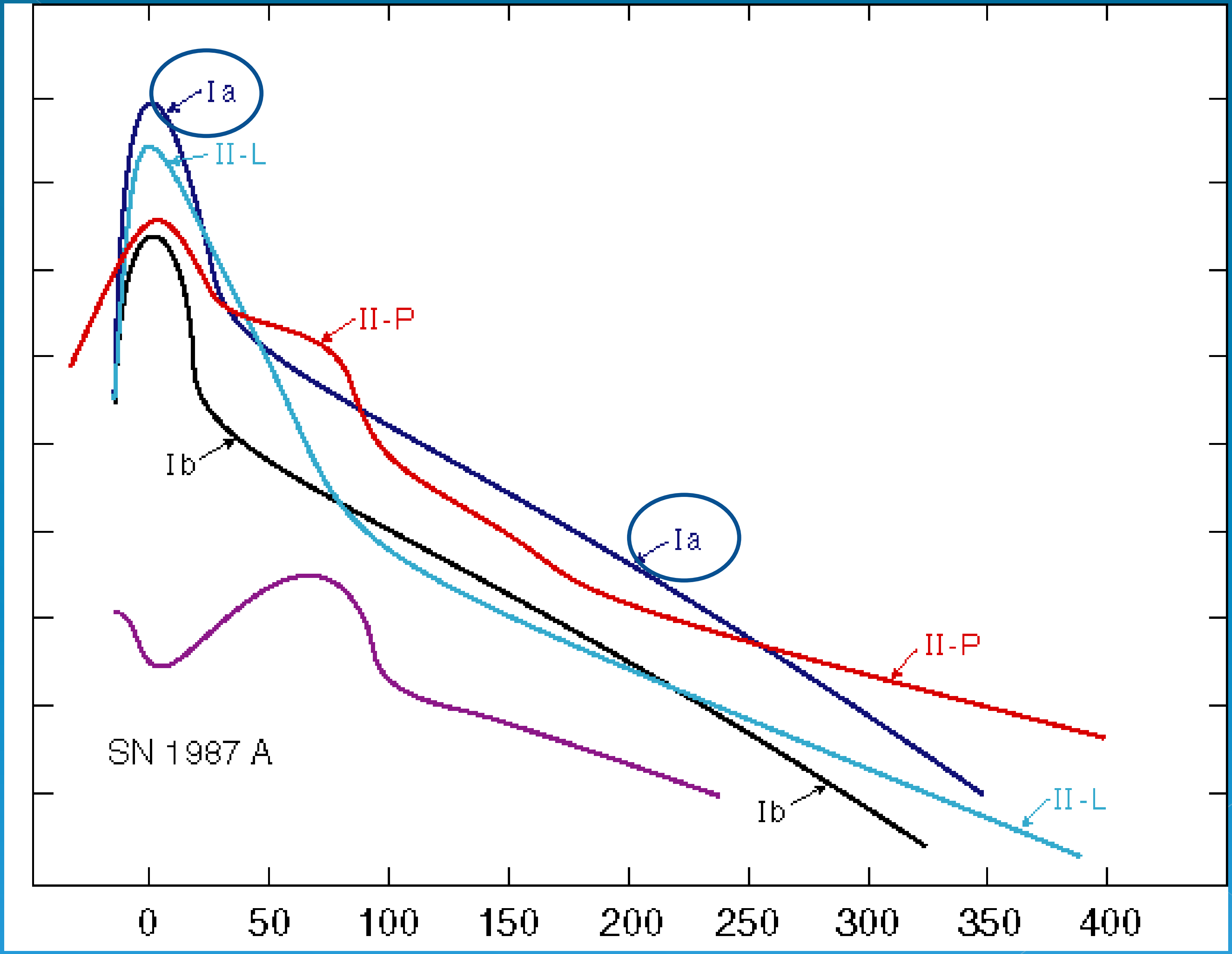
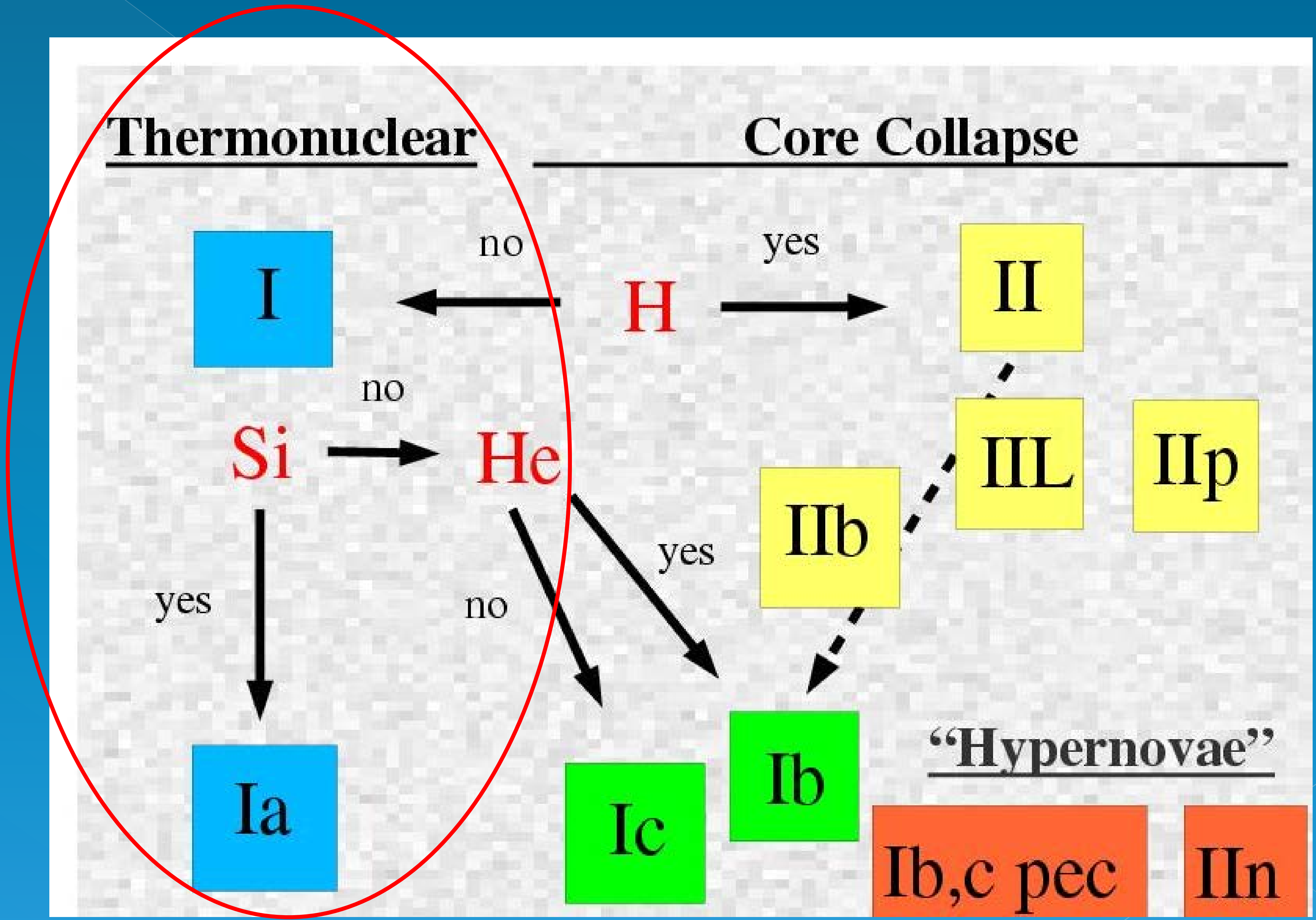
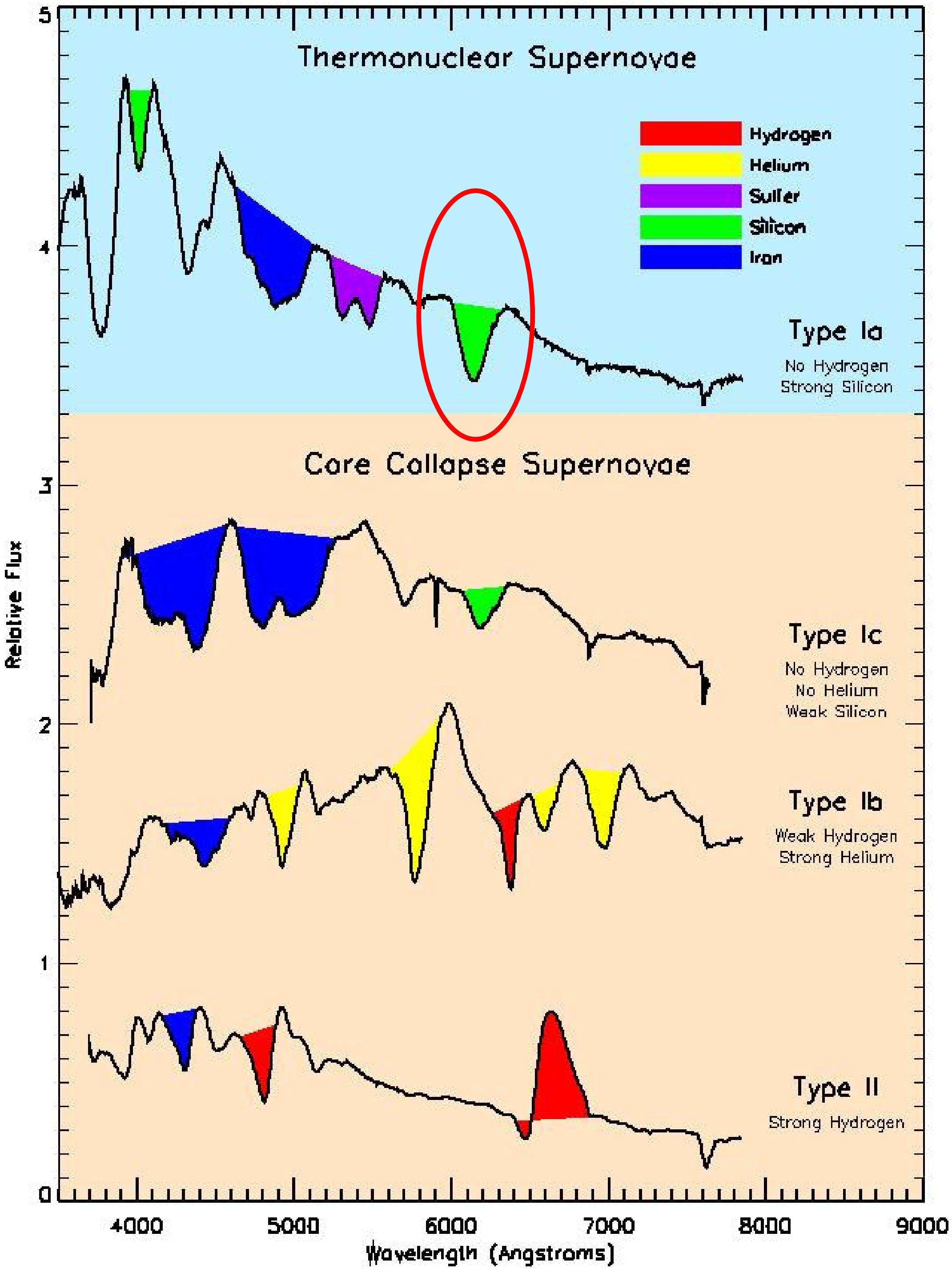
Supernova light curves
(schematically)



Supernova classification





Supernova spectra

(schematically)

SNe Ia from now on!

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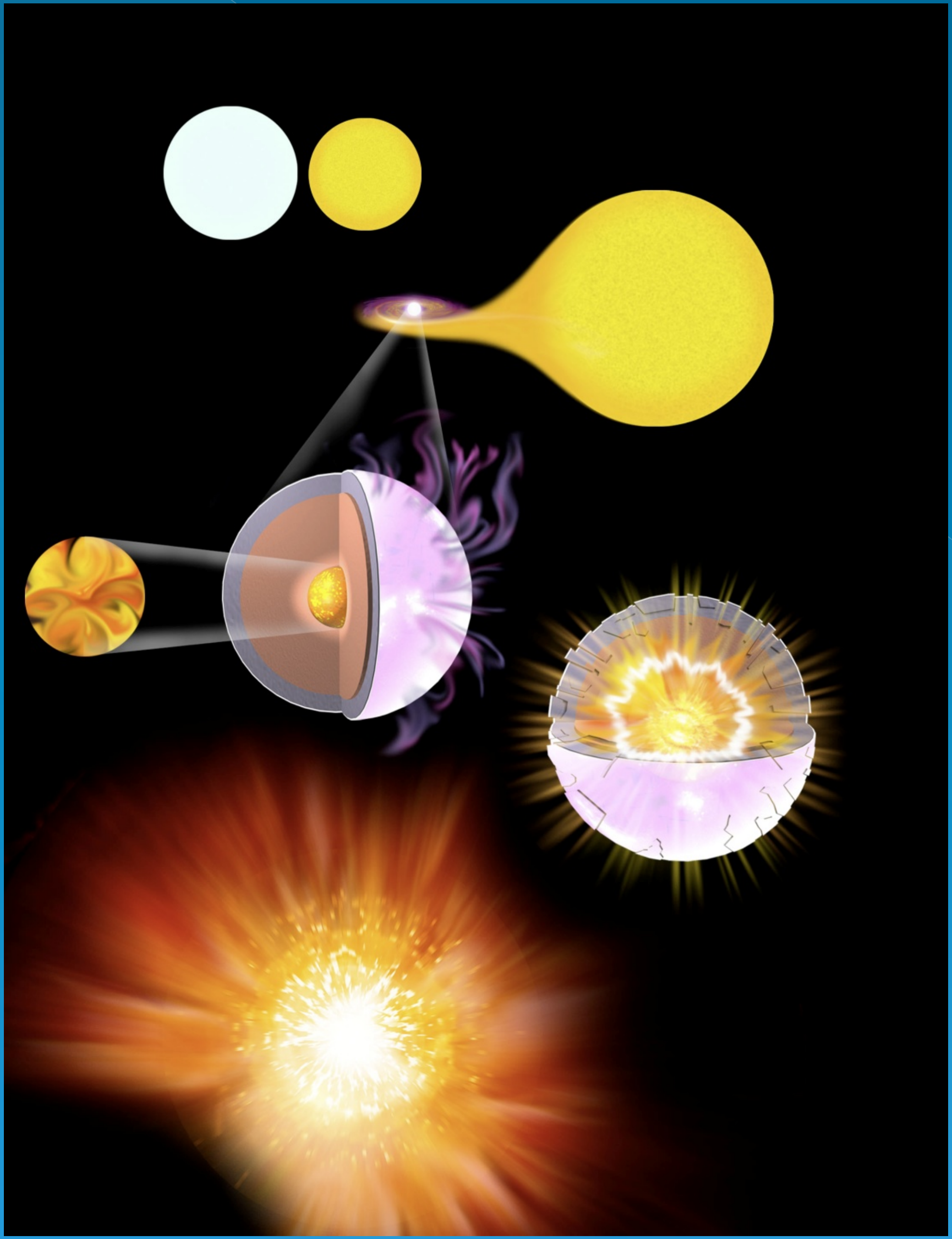
Thermonuclear (Type Ia) supernovae:

- 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

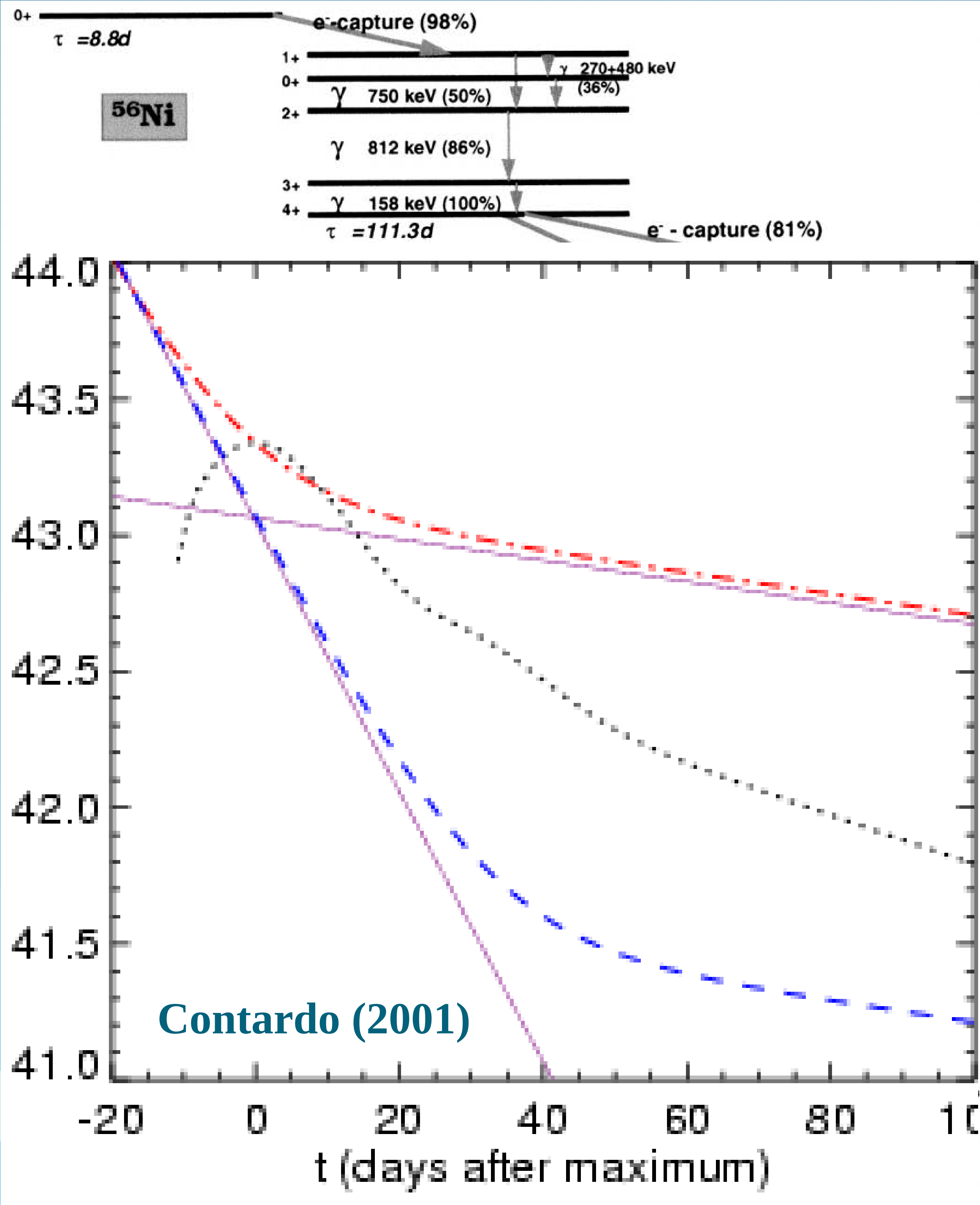


- White dwarf star in a binary system with MS or (R)G star
- Growing to the critical mass ($M_{chan} \approx 1.4\ M_{\odot}$) by mass transfer
- Disrupted by a thermo-nuclear explosion (fusion of C and O to iron-group elements)
- Light comes from radioactive decay : $^{56}Ni \rightarrow {}^{56}Co \rightarrow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

Thermonuclear (Type Ia) supernovae:

Can we be sure about all of this?

Radioactive decay and SN Ia light curves

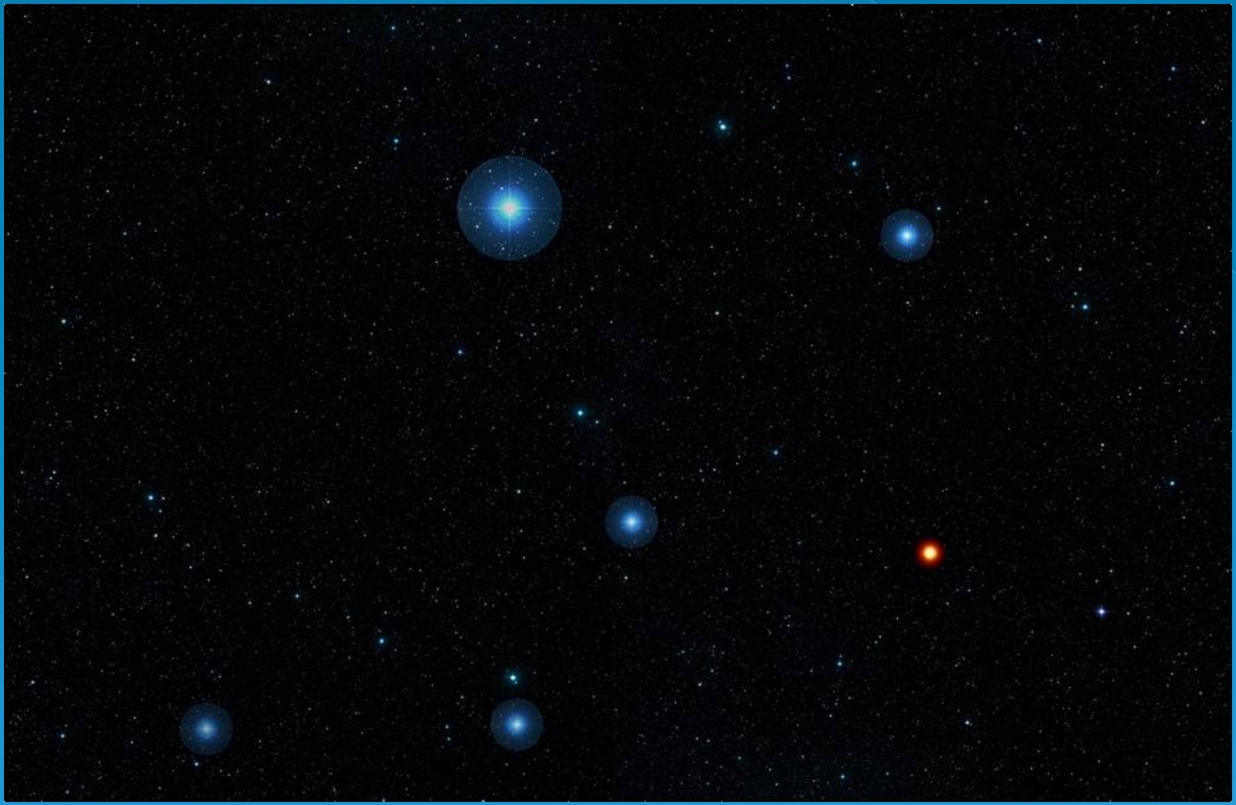


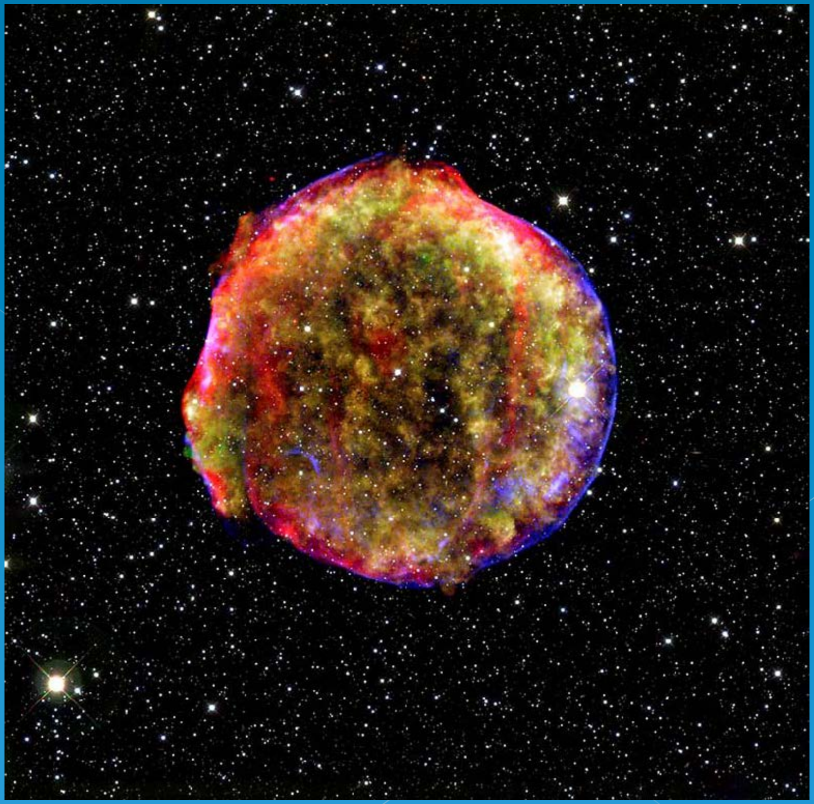
- <u>Isotopes of Ni and other elements:</u>

  conversion of γ-ray photons and positrons into heat and optical photons

Can we be sure about this?

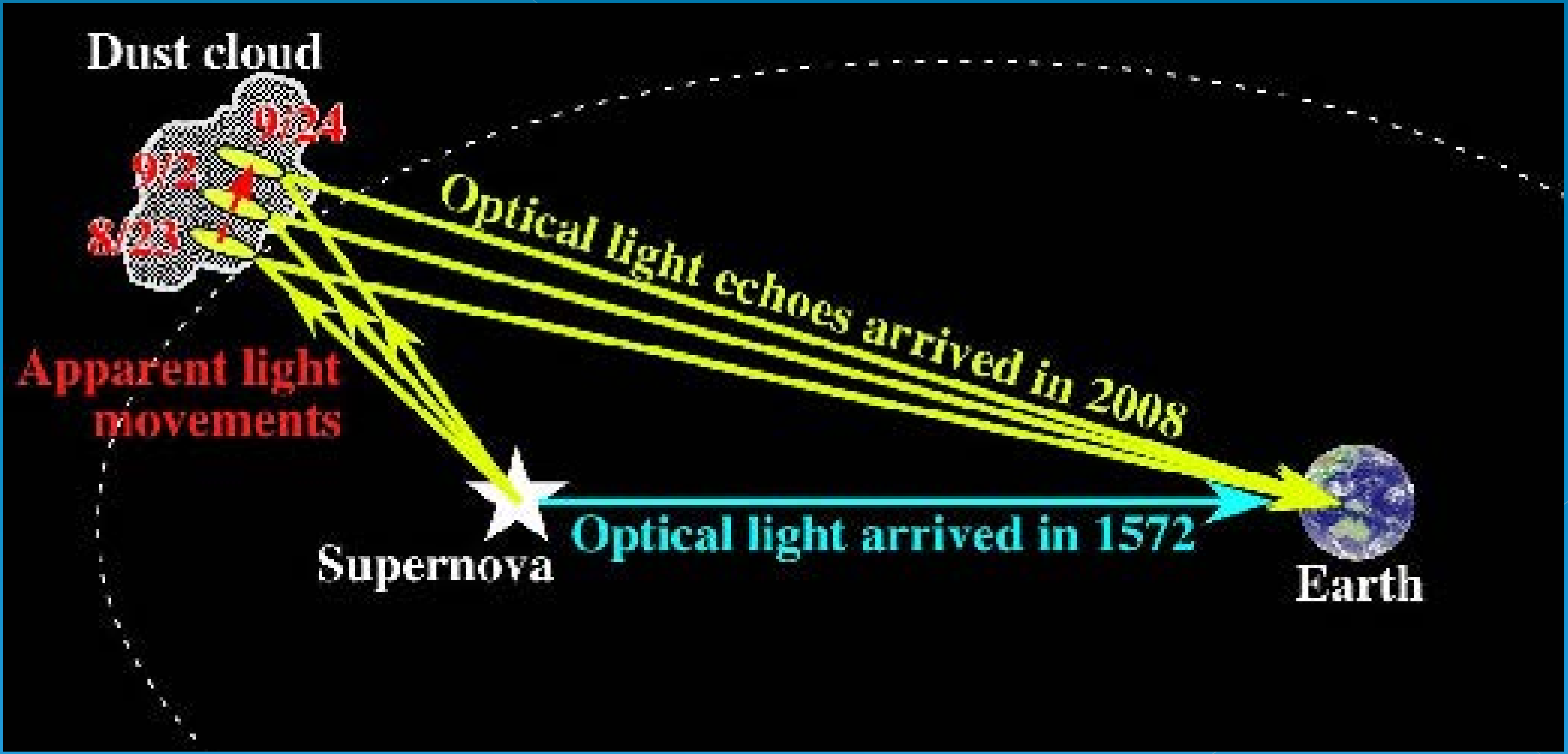
Example: SN 1572 (Tycho's supernova)





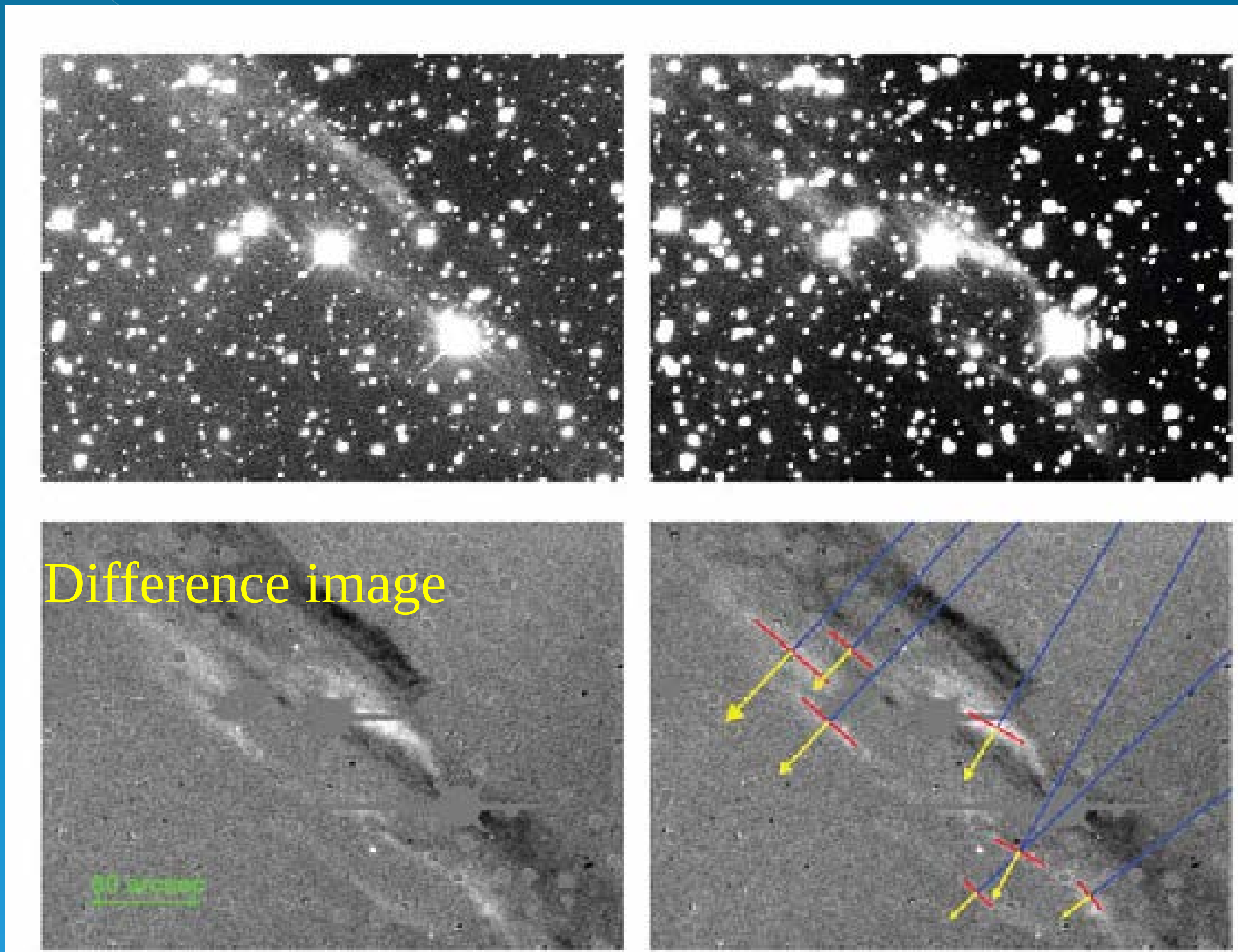
Can we "see" this supernova still today?

Yes, by its light echoes!



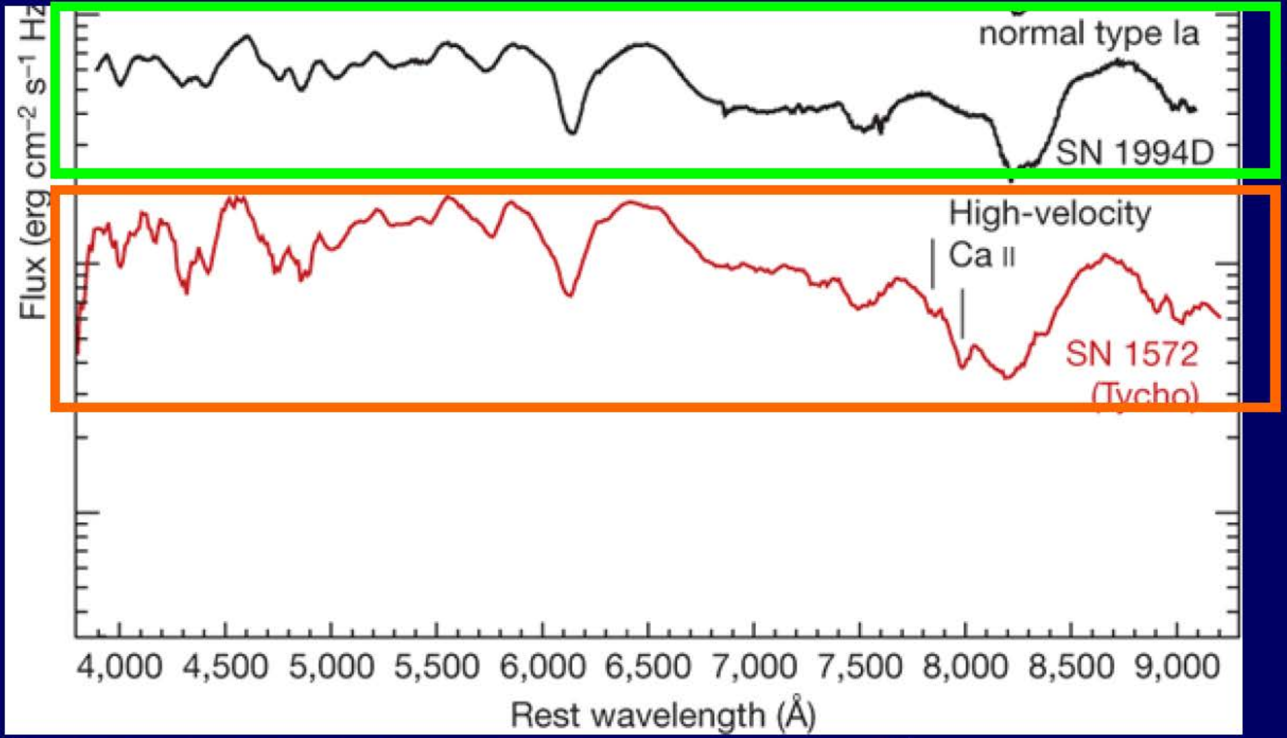
Rest et al. (2008) discovered the light echoes!

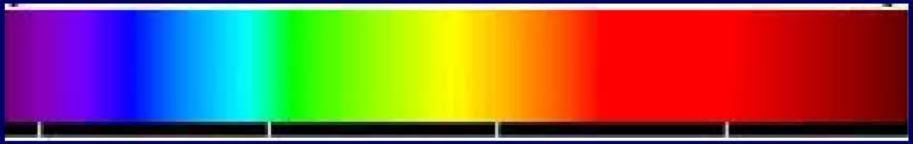
October 2006 December 2007



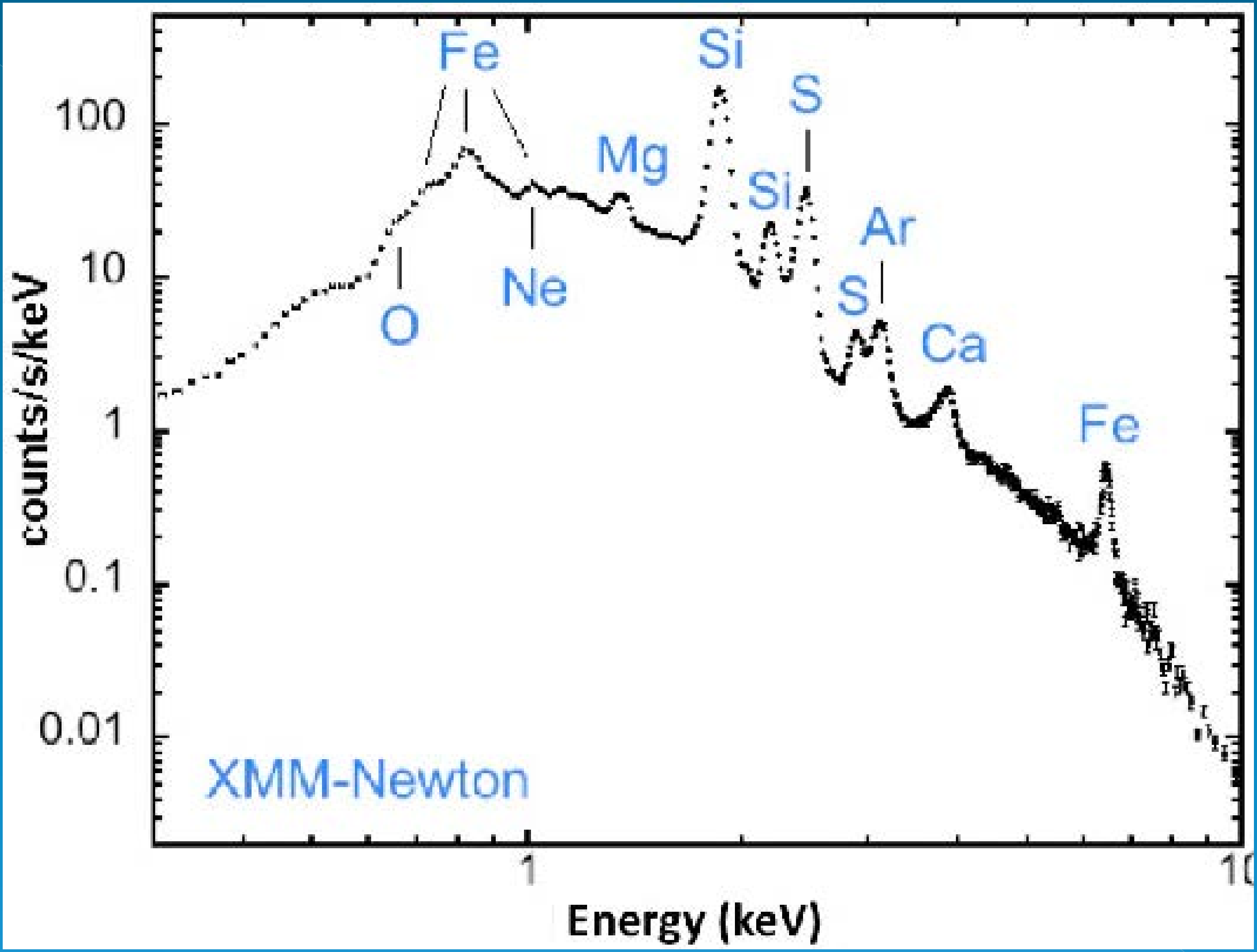
The echo has spectrum of a normal SN Ia (Krause et al. 2008)

Spectrum of SN1994D





spectrum of the echo

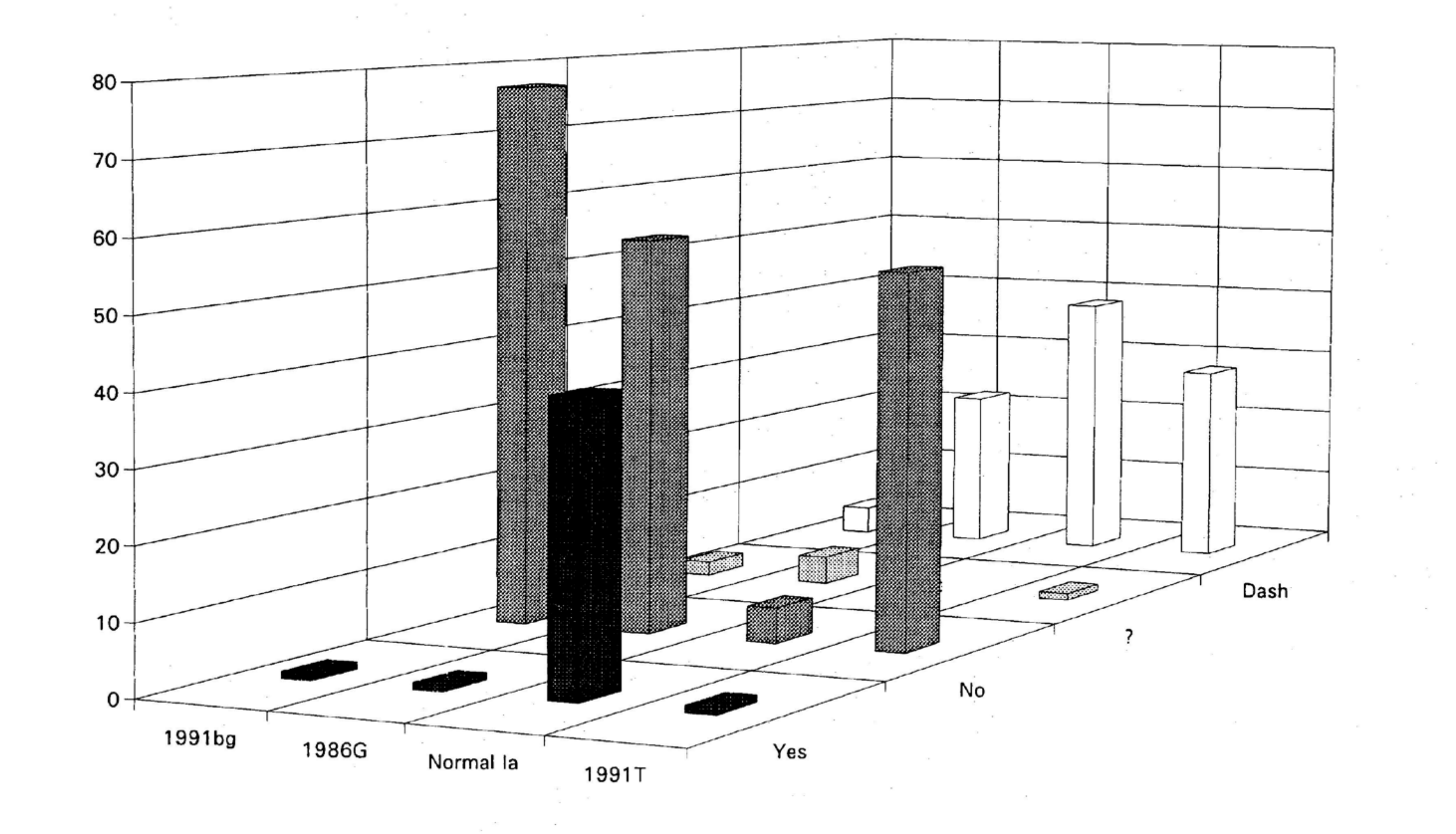


X-ray spectrum (Badenes et al. 2006): M(Fe) ≈ $0.74M_{sun}$

Thermonuclear (Type Ia) supernovae:

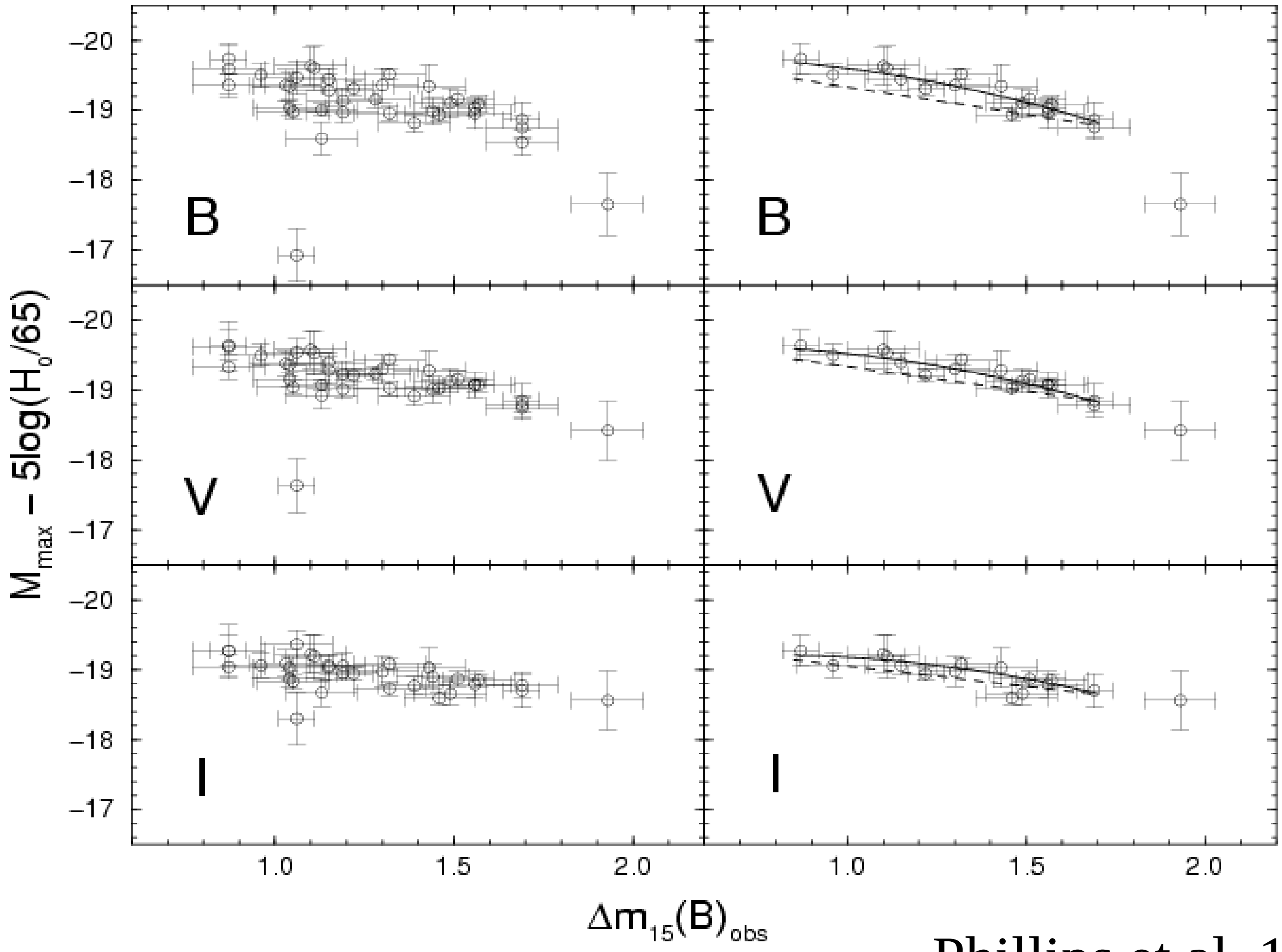
How ‘homogenous’ are they as a ‘class’?

The ‘Branch normals’ and other SNe Ia:



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

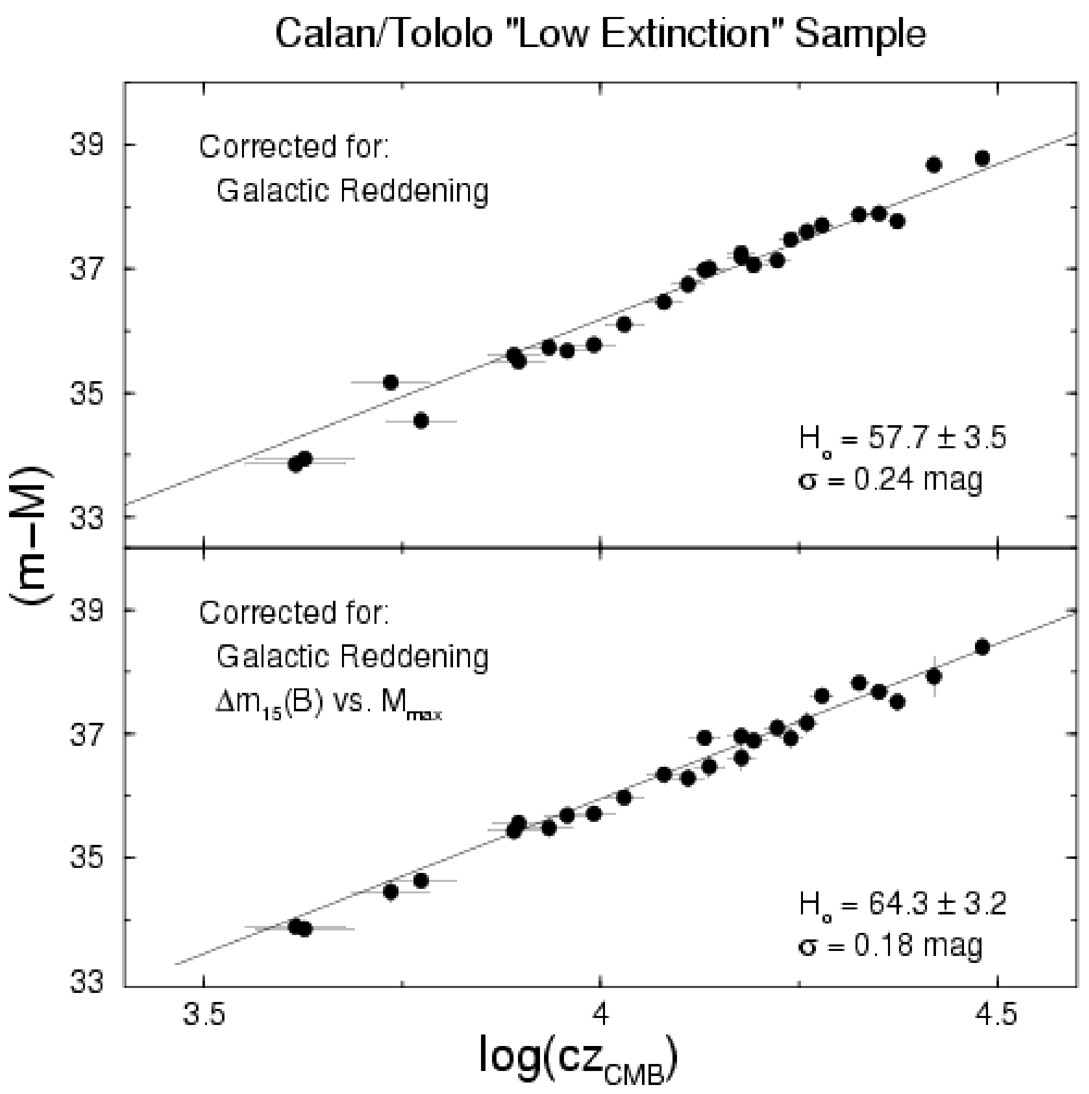
Peak luminosty/light-curve shape correlation:



Phillips et al. 1999

SN Ia Hubble diagram:

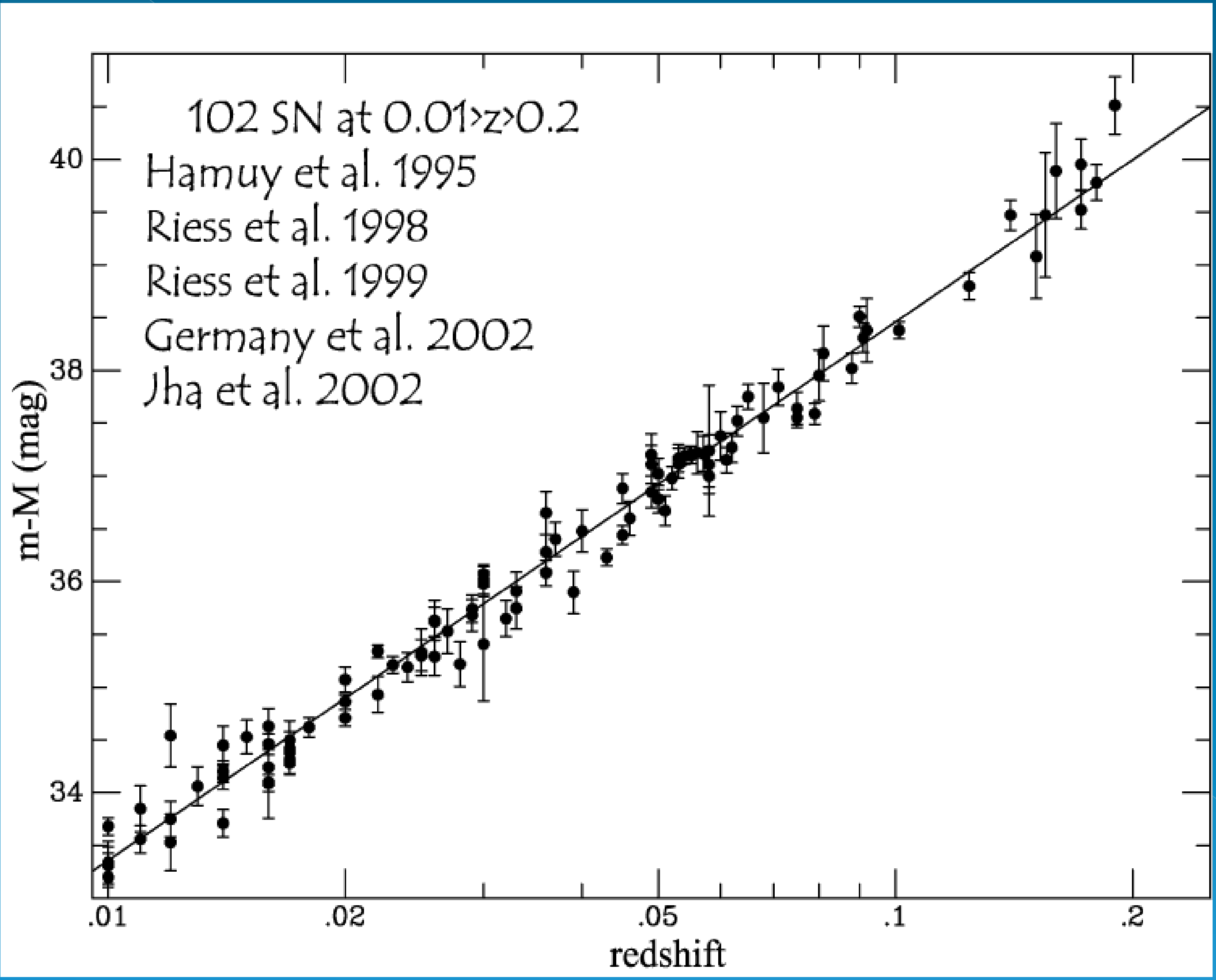
Phillips et al. 1999



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

→

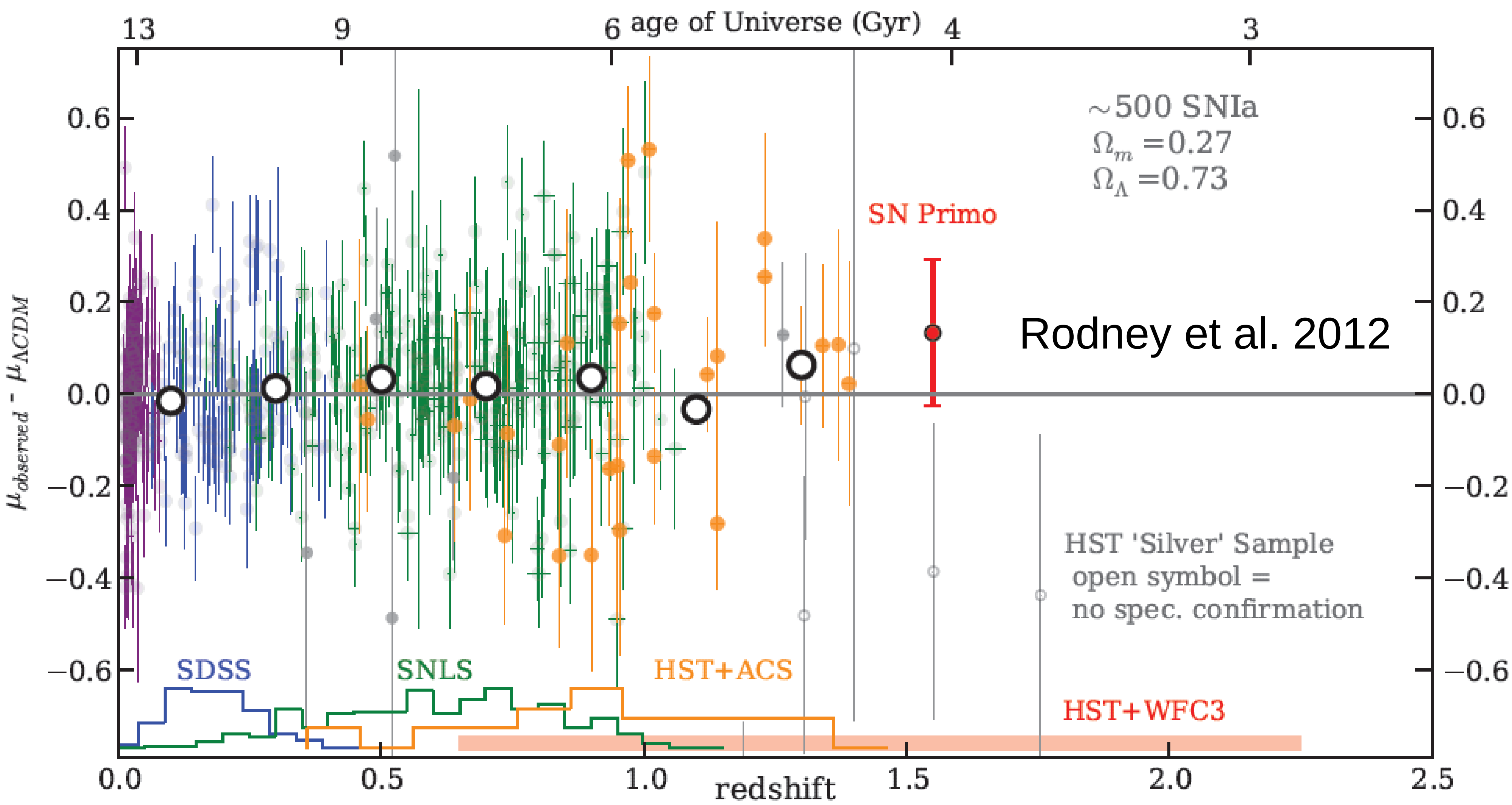
This reduces the scatter in the HD!

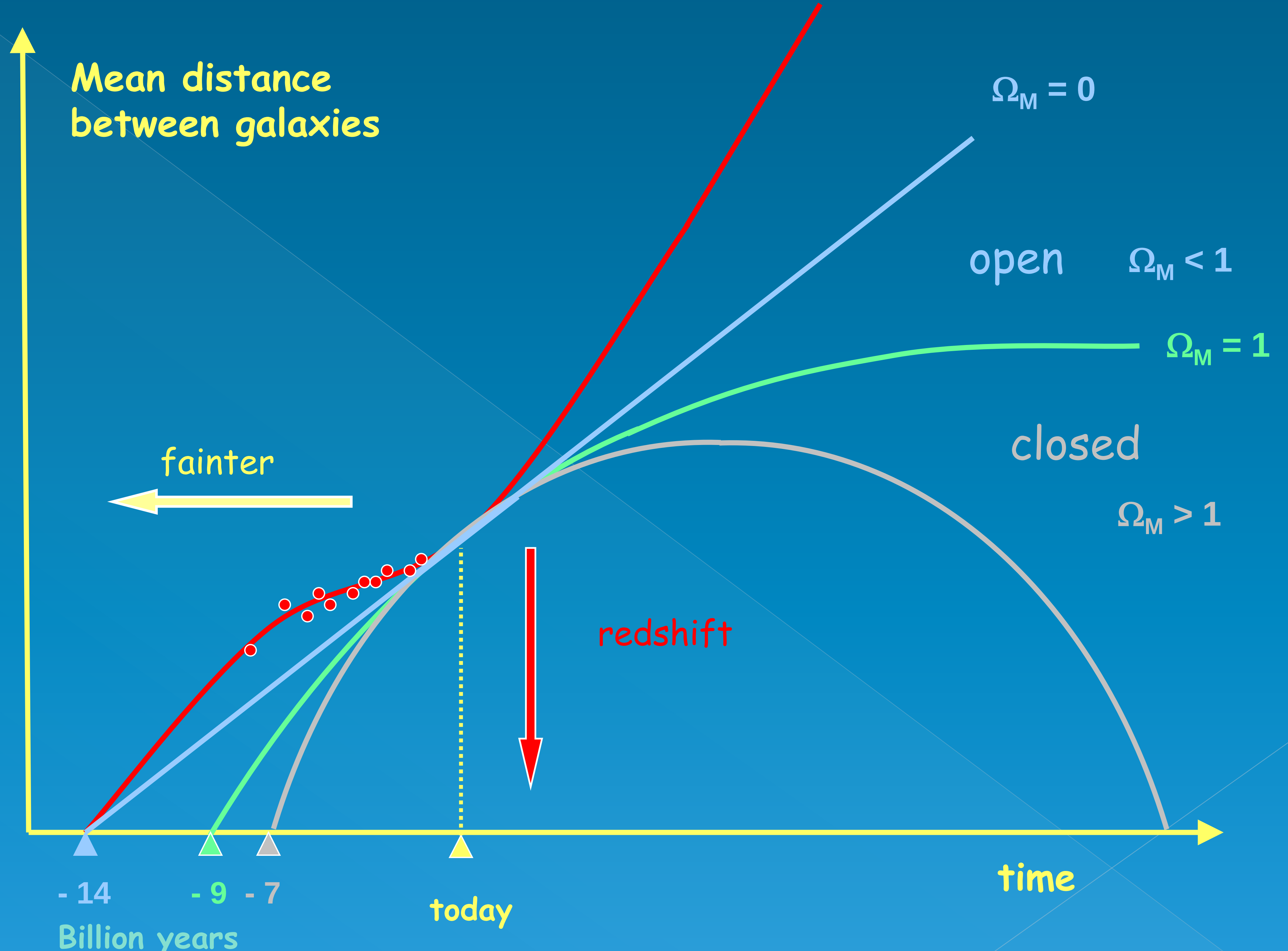


Scatter in (m – M): ≈ ± 0.15 mag (~8%)

(Tonry et al. 2003)

A recent SN Ia Hubble diagram




Mean distance
between galaxies
$\Omega_M = 0$
open
$\Omega_M < 1$
$\Omega_M = 1$
closed
$\Omega_M > 1$
fainter
redshift
- 14
- 9
- 7
Billion years
today
time

Nobel Prize for Physics 2011

Saul Perlmutter

Brian Schmidt

Adam Riess

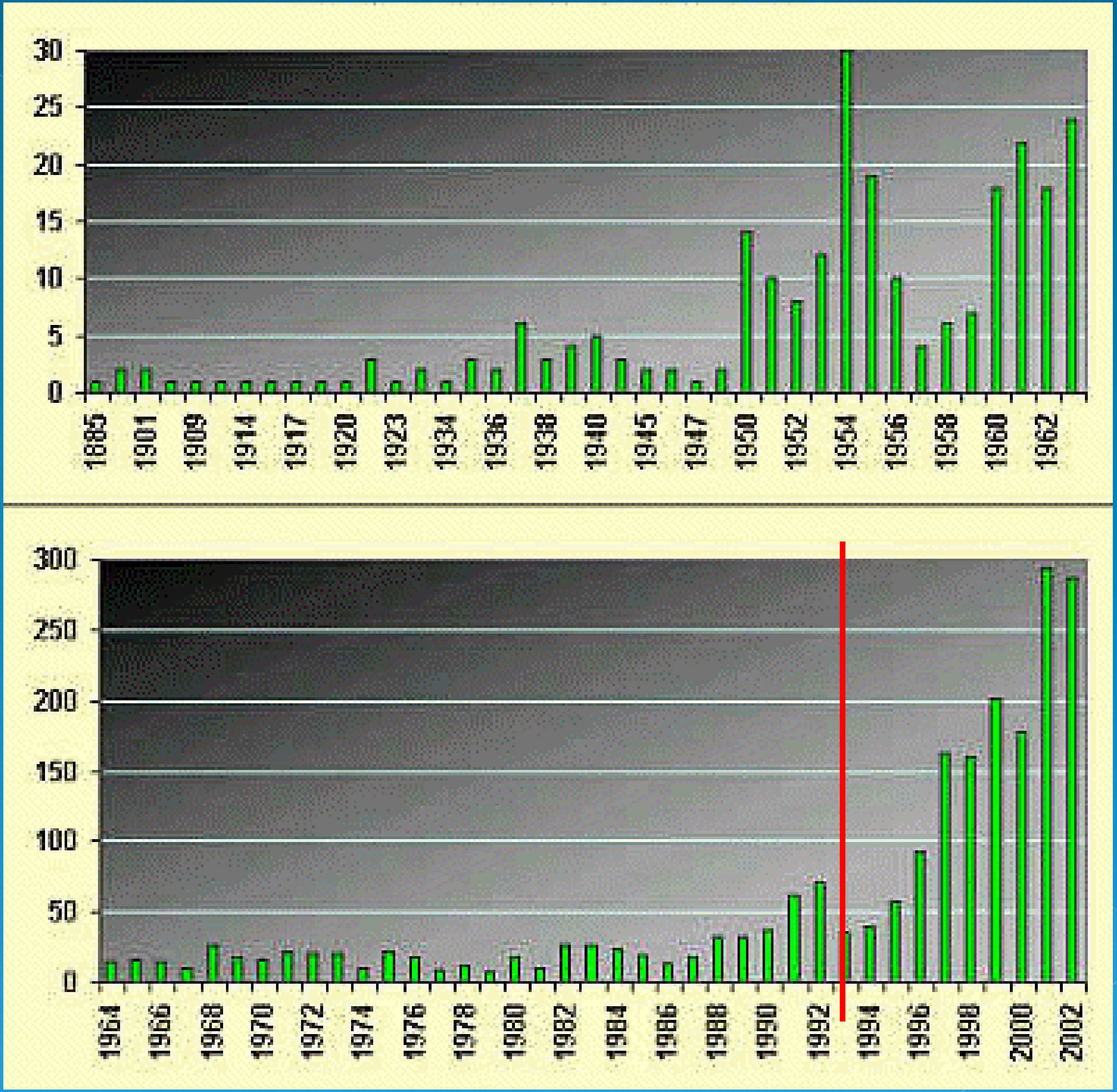
"… for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Thermonuclear (Type Ia) supernovae:

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

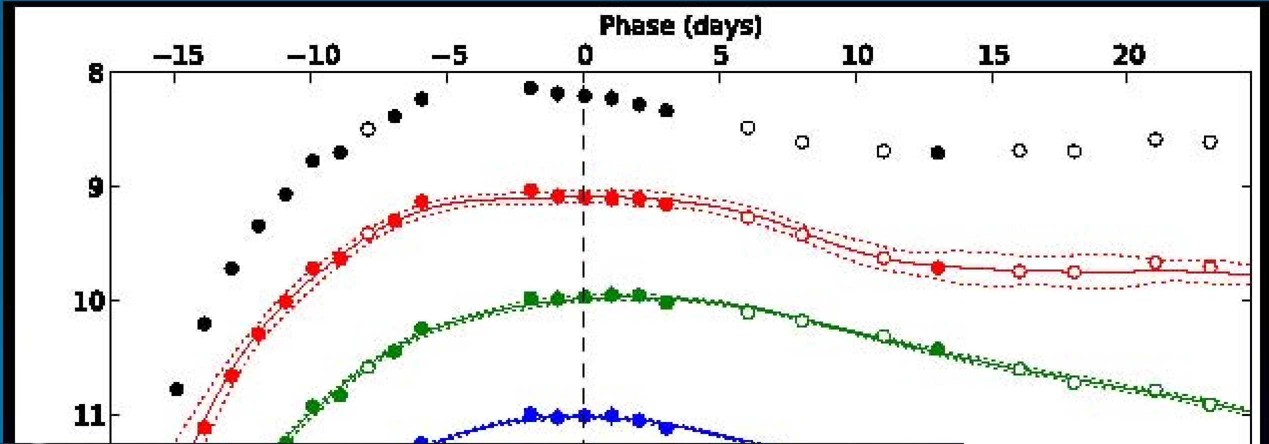
Can we reduce the scatter in their Hubble diagram even further?

Rate of discoveries



Data quality

(SN 2011fe in M101; Supernova Factory data only)



Data quality

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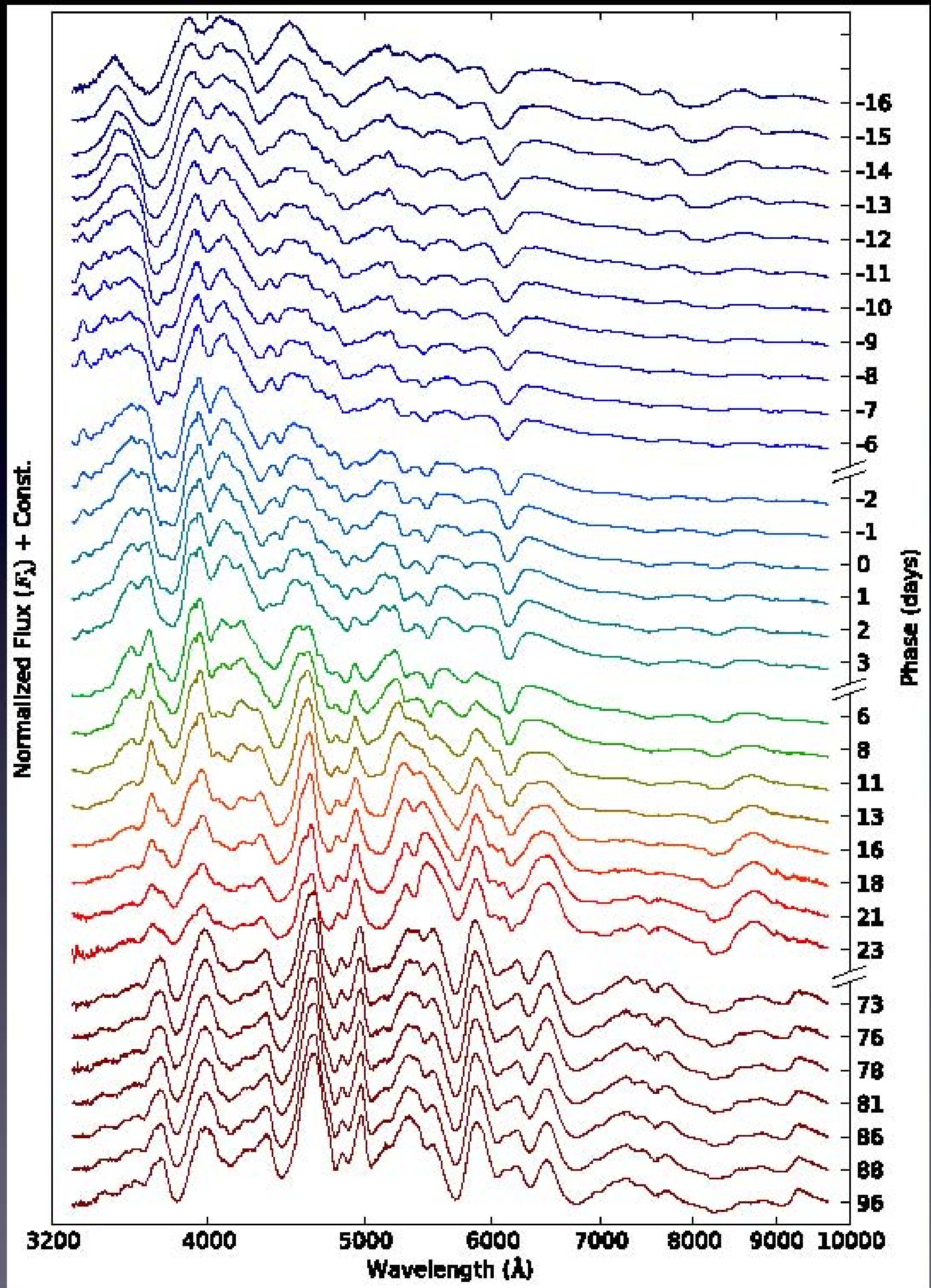
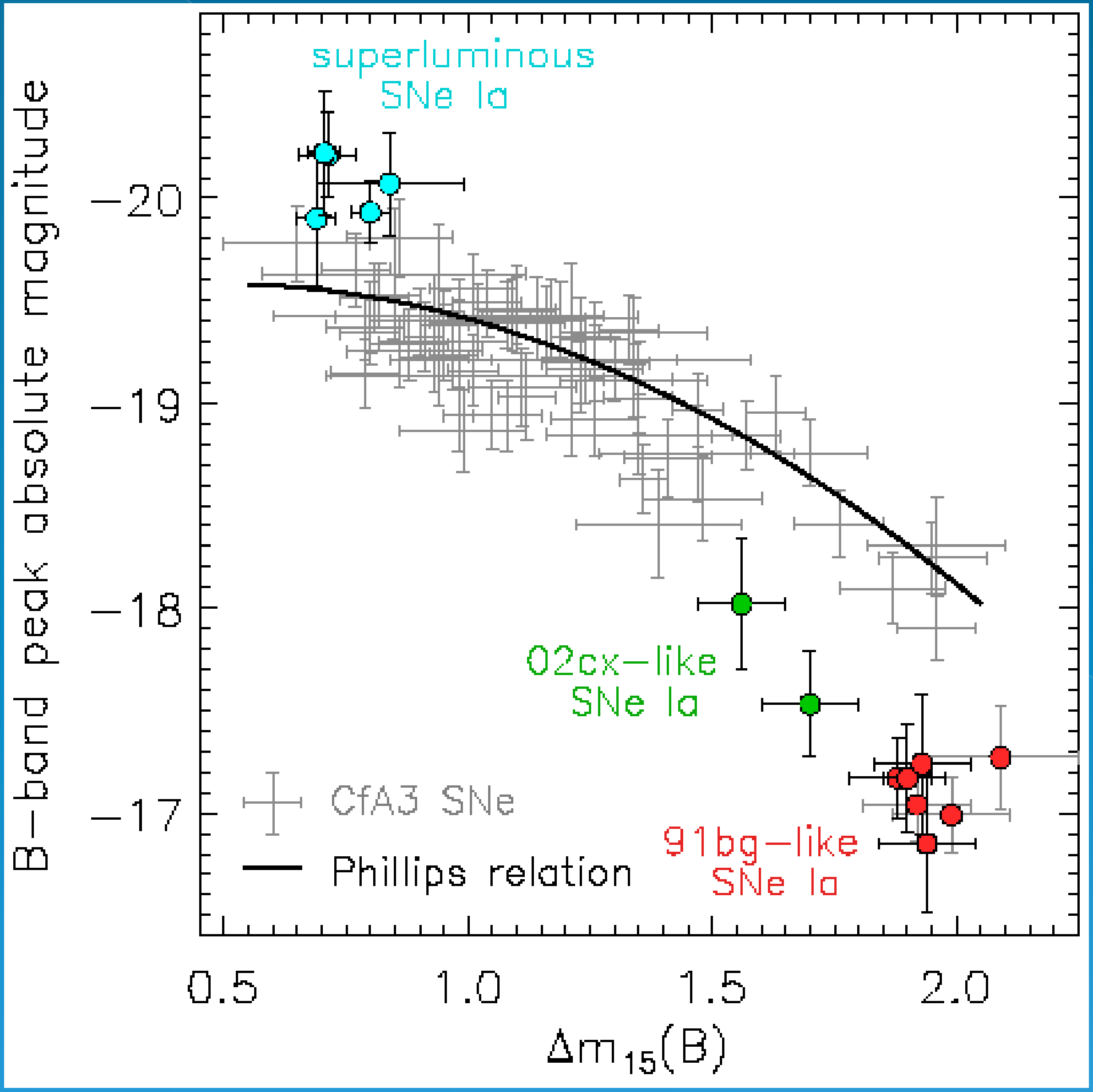


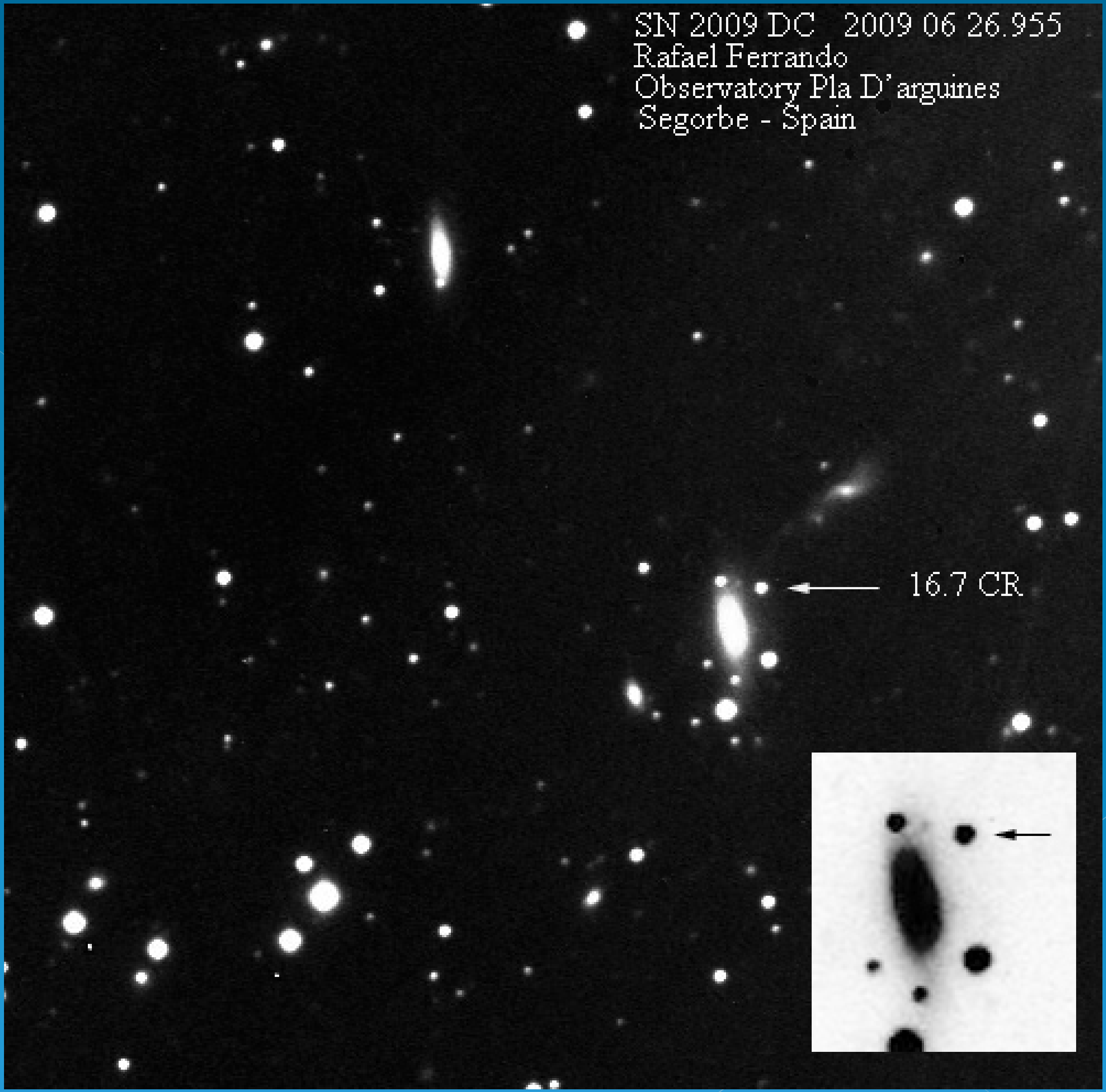
(Pereira et al., 2013)

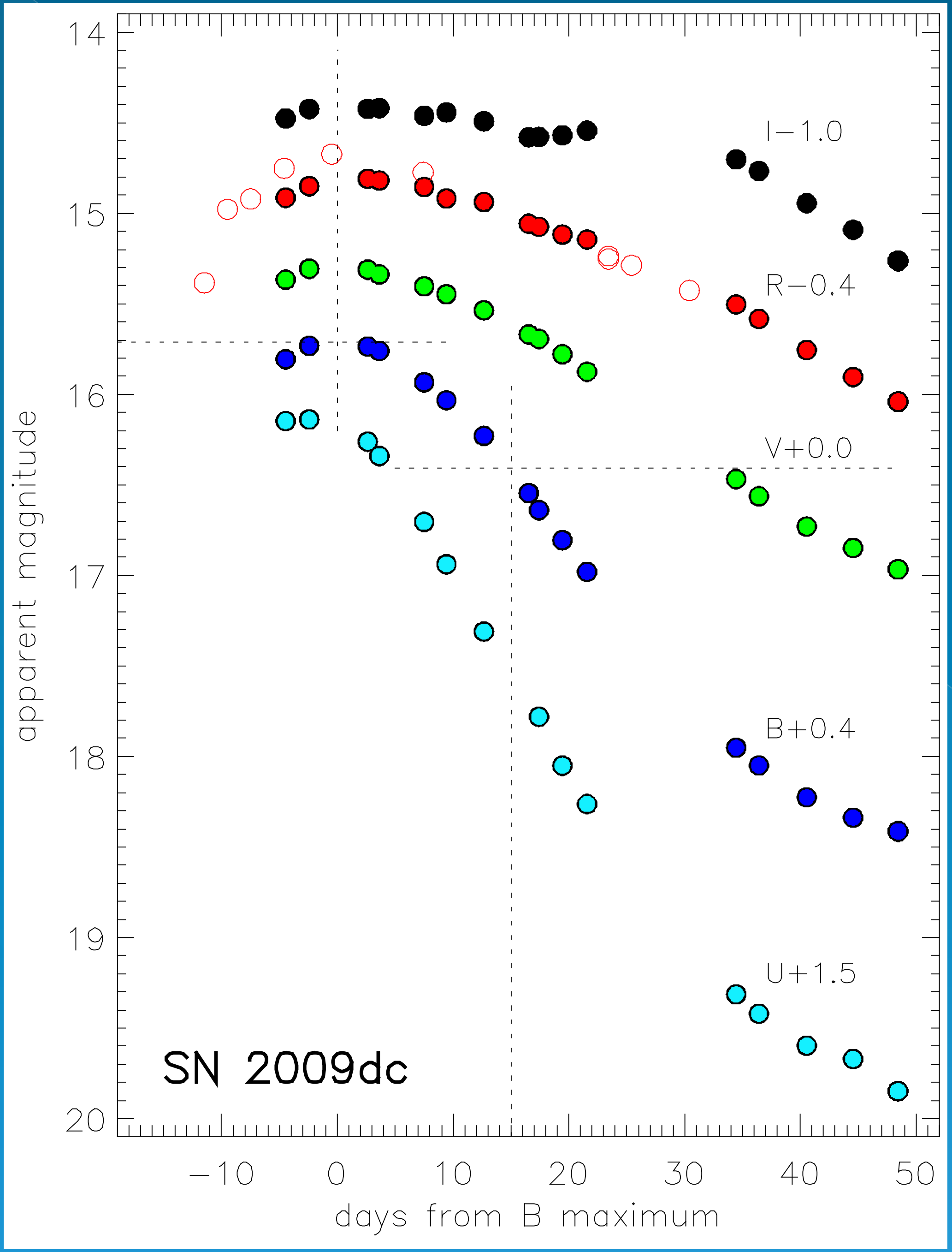
A (more) recent Phillips relation: the "beauties" and the "beasts"



An example of a 'weird' SN Ia: SN 2009dc

- *"very bright"*
- *"unusual color"*
- *"slow"*
- *"C-rich"*

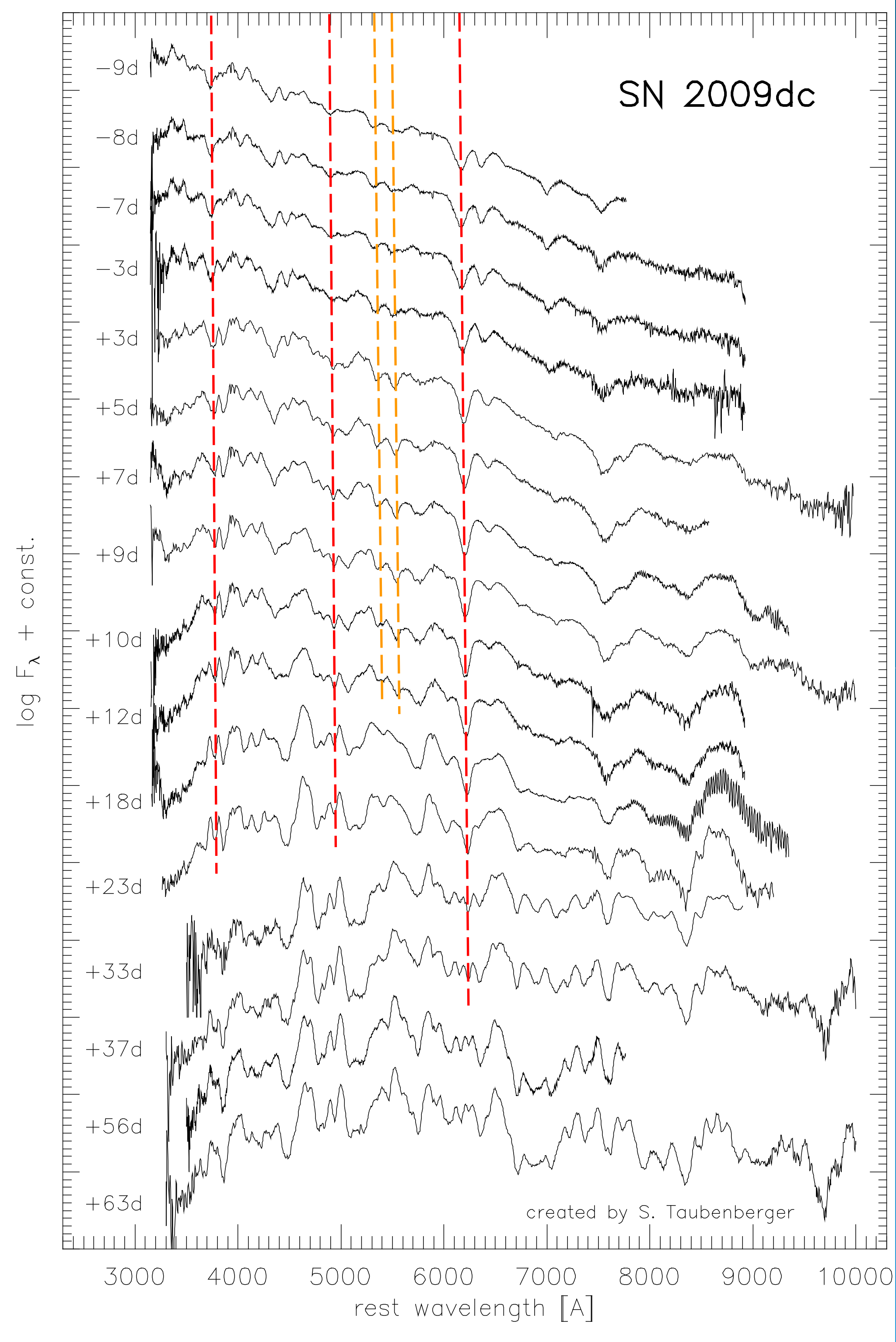




Photometric properties:

- Typical light-curve morphology of SNe Ia
- secondary maximum in I band
- slow decliner: $\Delta m_{15}(B) \sim 0.7$
- but: very bright at maximum, $M_{peak} \sim -20.1$!
- unusually blue U-B colour at early times

Taubenberger et al. (2011)

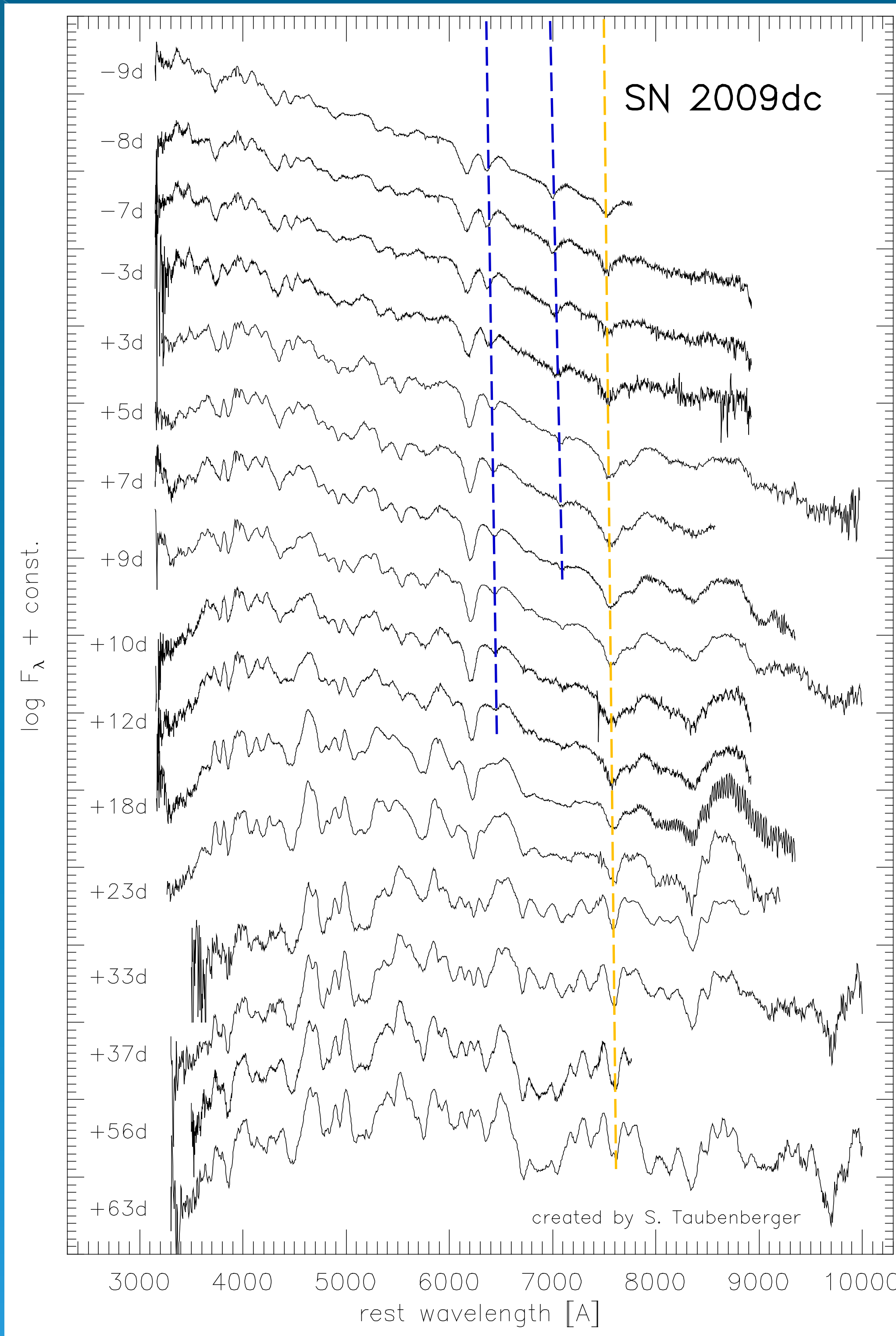


IME:

- Typical sequence of Si II and S II lines of SNe Ia
- Lines form at very low velocity: 7000-8500 km/s for Si II λ6355
- Very slow velocity evolution

Si II
S II

Taubenberger et al. (2011)



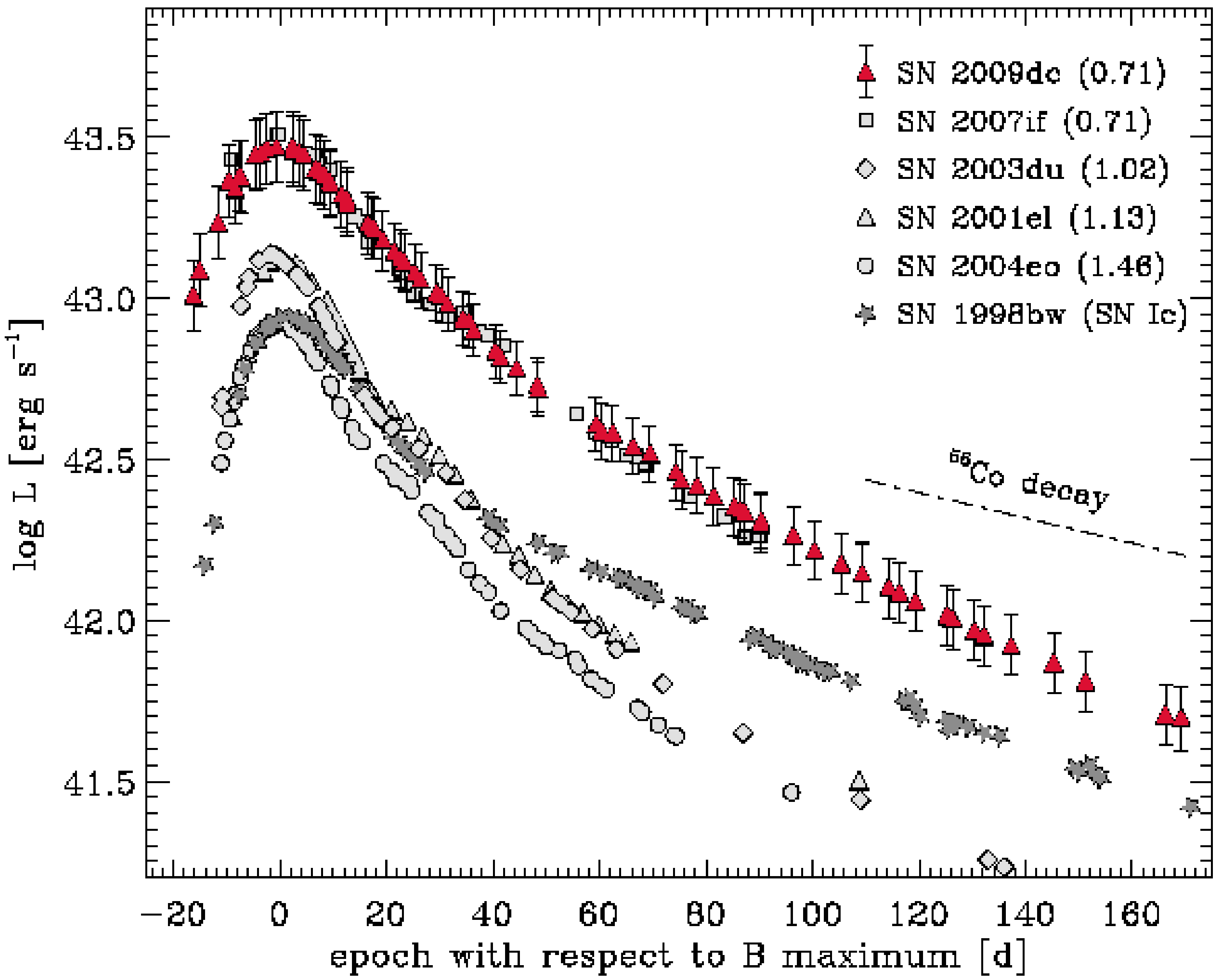
Unburned material:

- Prominent O I
- Unprecedentedly strong and persistent C II lines
- velocities similar to Si II (~8000 km/s) :

C and Si abundant in the same layers?

C II
O I

Taubenberger et al. (2011)


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
log L [erg s^{-1}]
43.5
43.0
42.5
42.0
41.5
−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

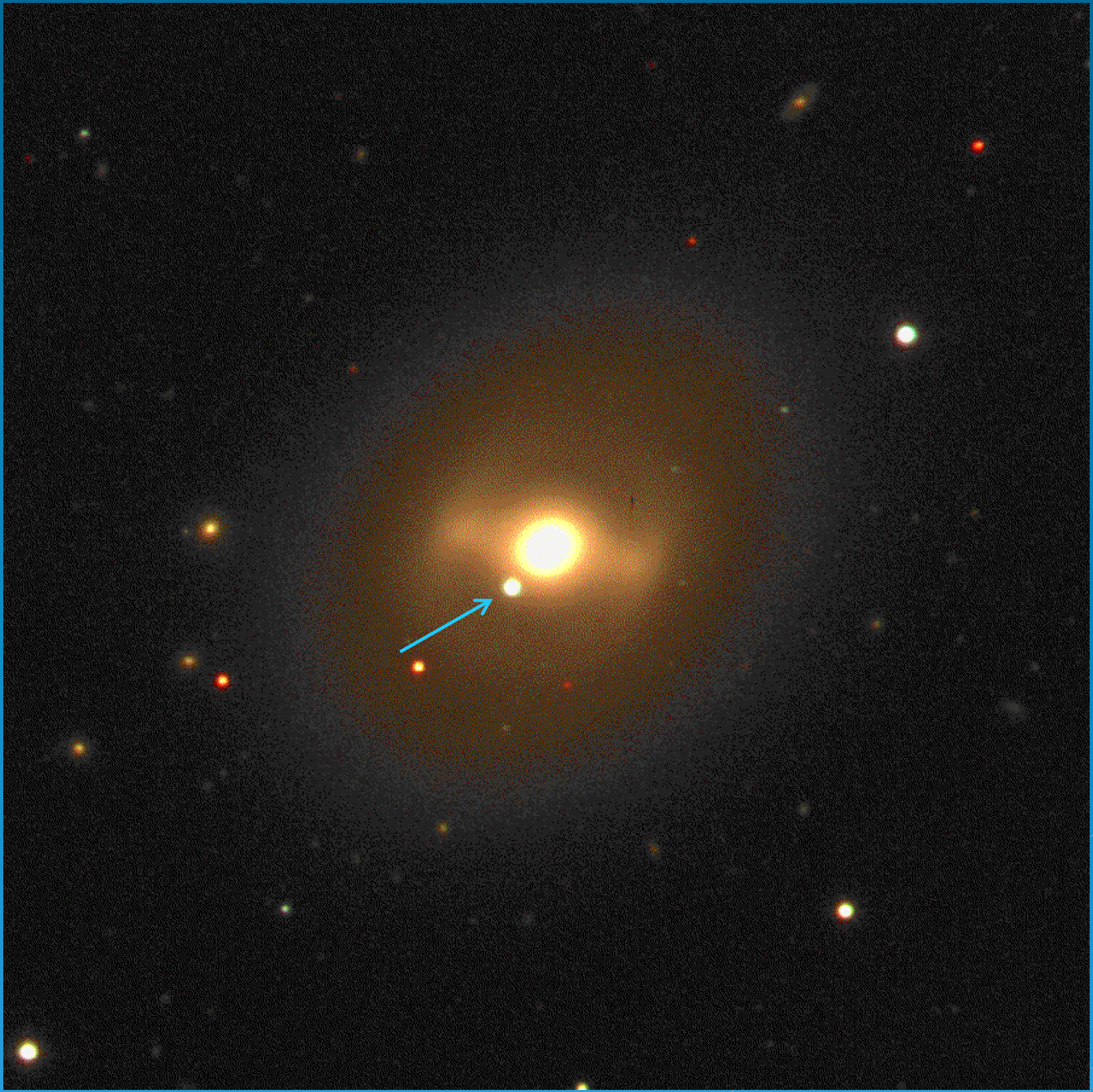
- '05E/05cz like':

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

What are they ????

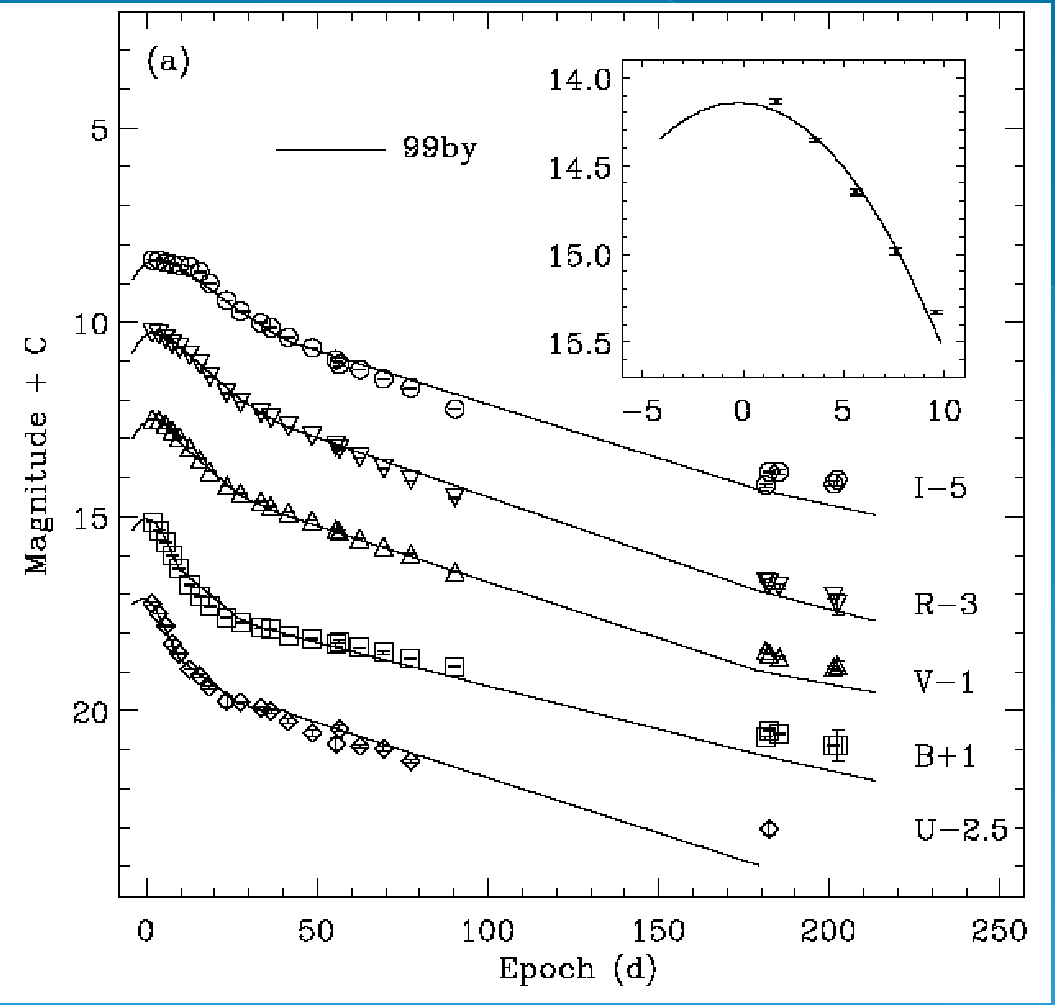
Another example: SN 2003gs

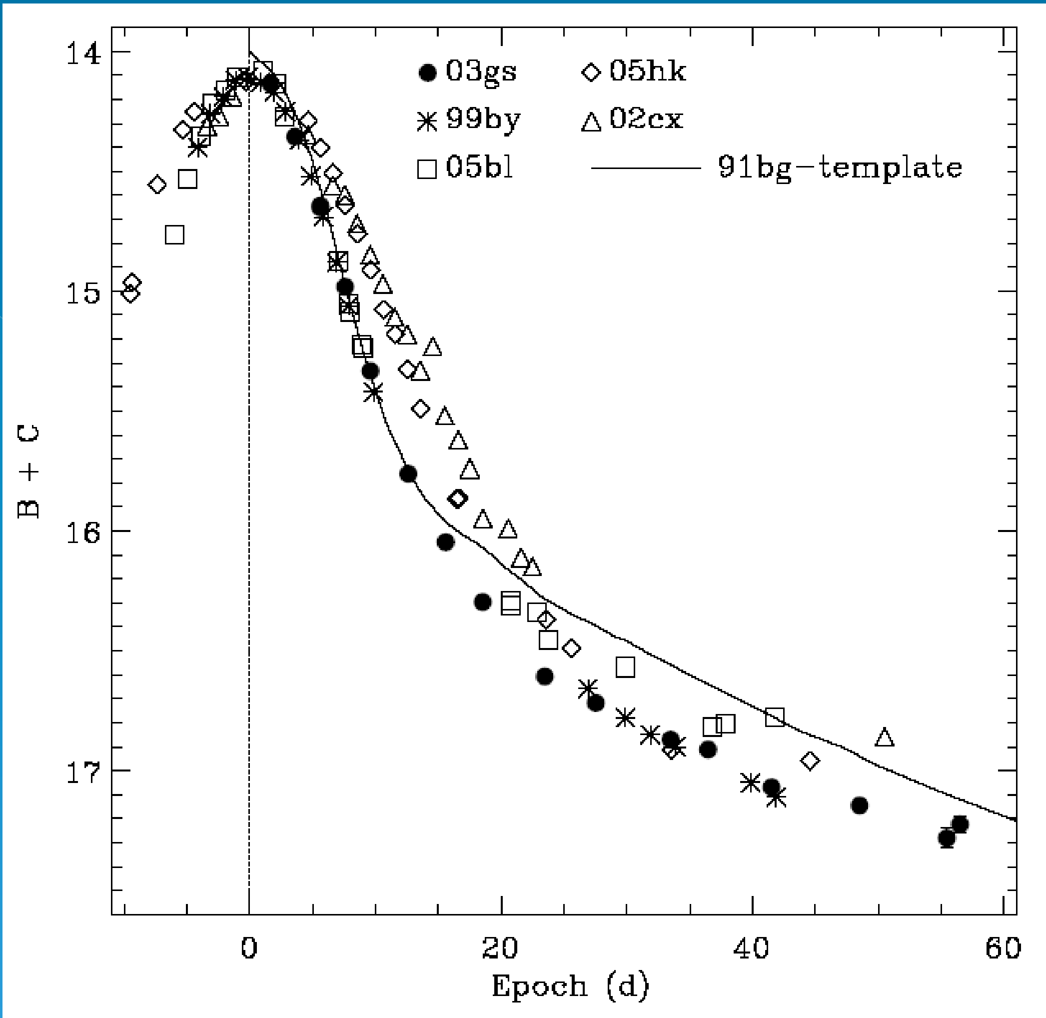
- *“bright”*
- *“red”*
- *“fast”*



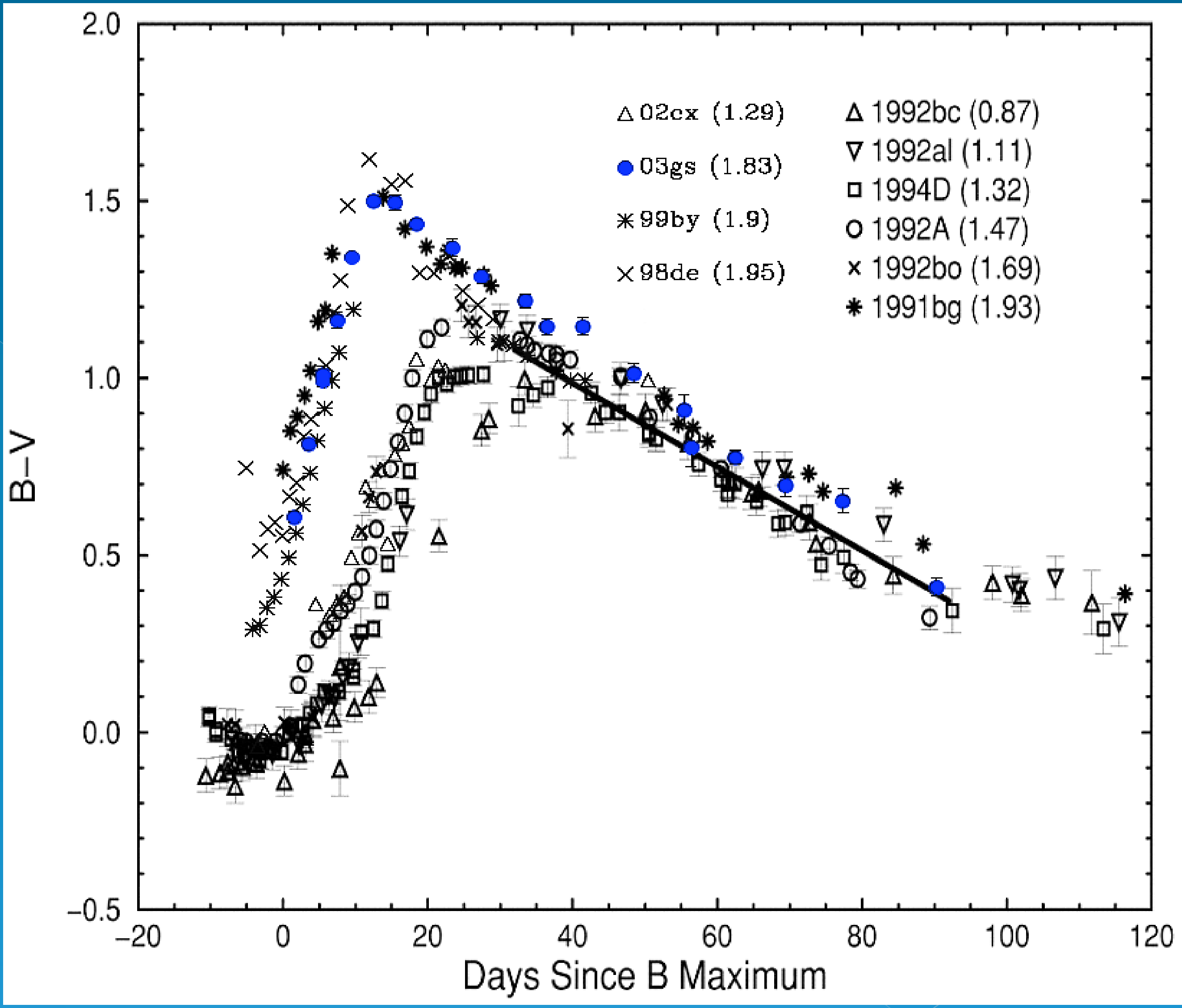
SN 2003gs is similar to subluminous, 91bg-like SNe in (almost) all respects:

- rapidly-declining light curves ($\Delta m_{15}(B) = 1.83$)
- no secondary I-band maximum





- rapid colour evolution
- red early-time colours
- spectroscopically similar to subluminous SN Ia



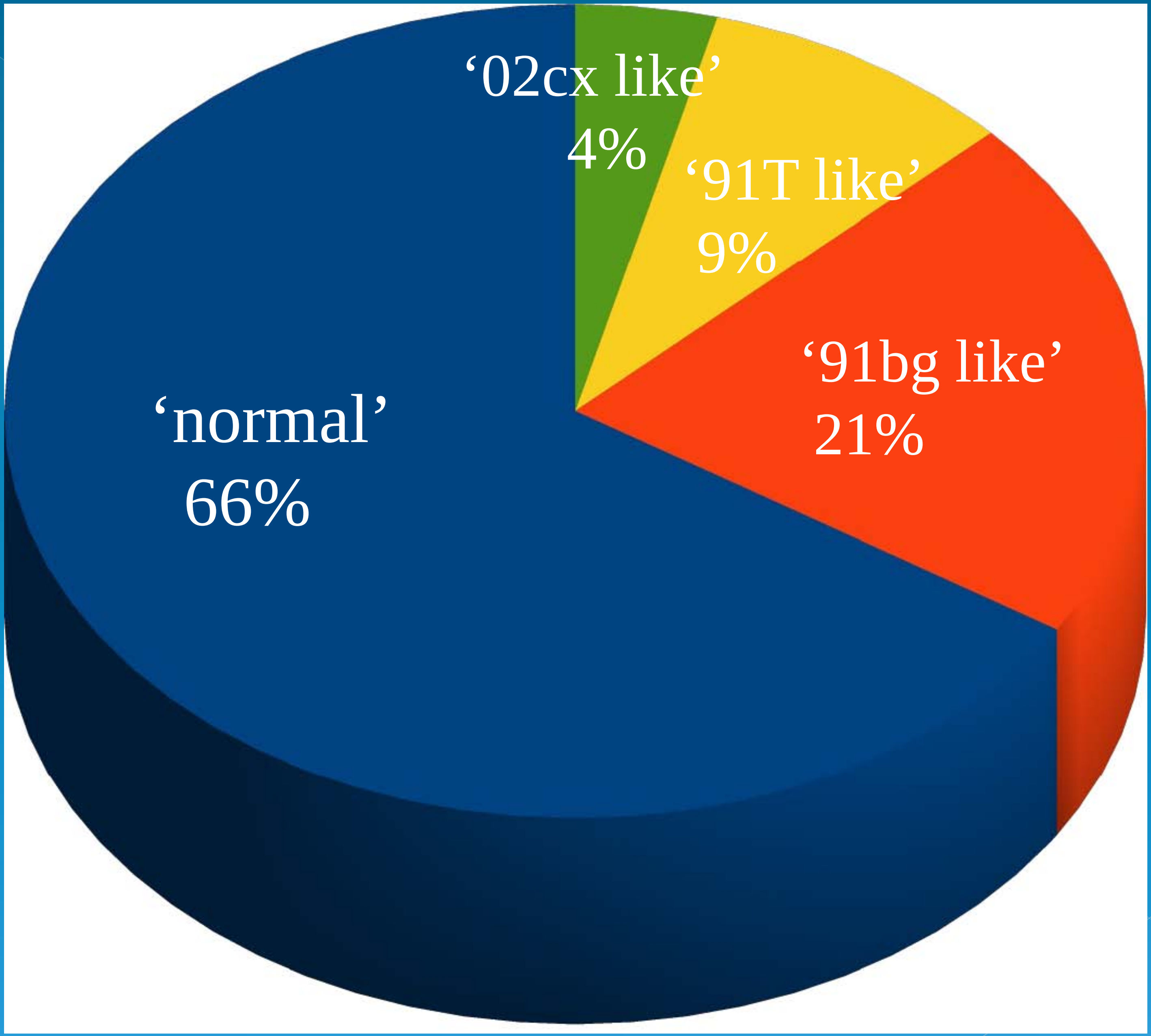
(Krisciunas et al. 2009)

But: 03gs is ~1 mag brighter than 91bg, 98de, … !

- M_{peak} ~ -18.3
- M(^{56}Ni) ~ 0.25 M_{sun} (~ 0.10 M_{sun} for other 91bg-like SNe)
- violates light-curve width – luminosity relationship !

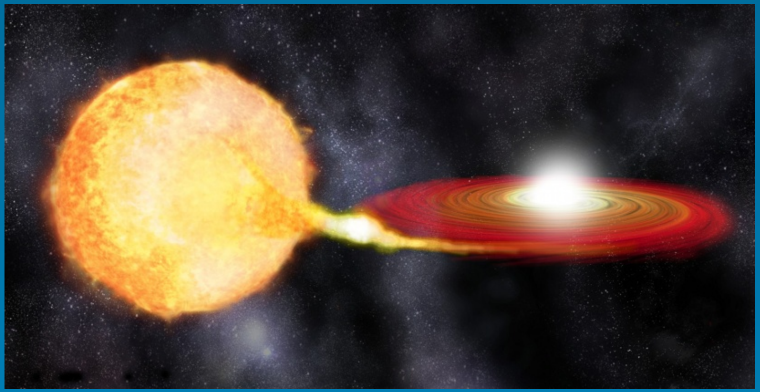
What is it ????

Relative rates (Filippenko, 2009)



The ‘zoo’ of (possible) thermonuclear explosions

- *‘Single degenerates’*
  - Chandrasekhar mass
    - Pure deflagration
    - ‘delayed’ detonation
  - sub-Chandrasekhar mass

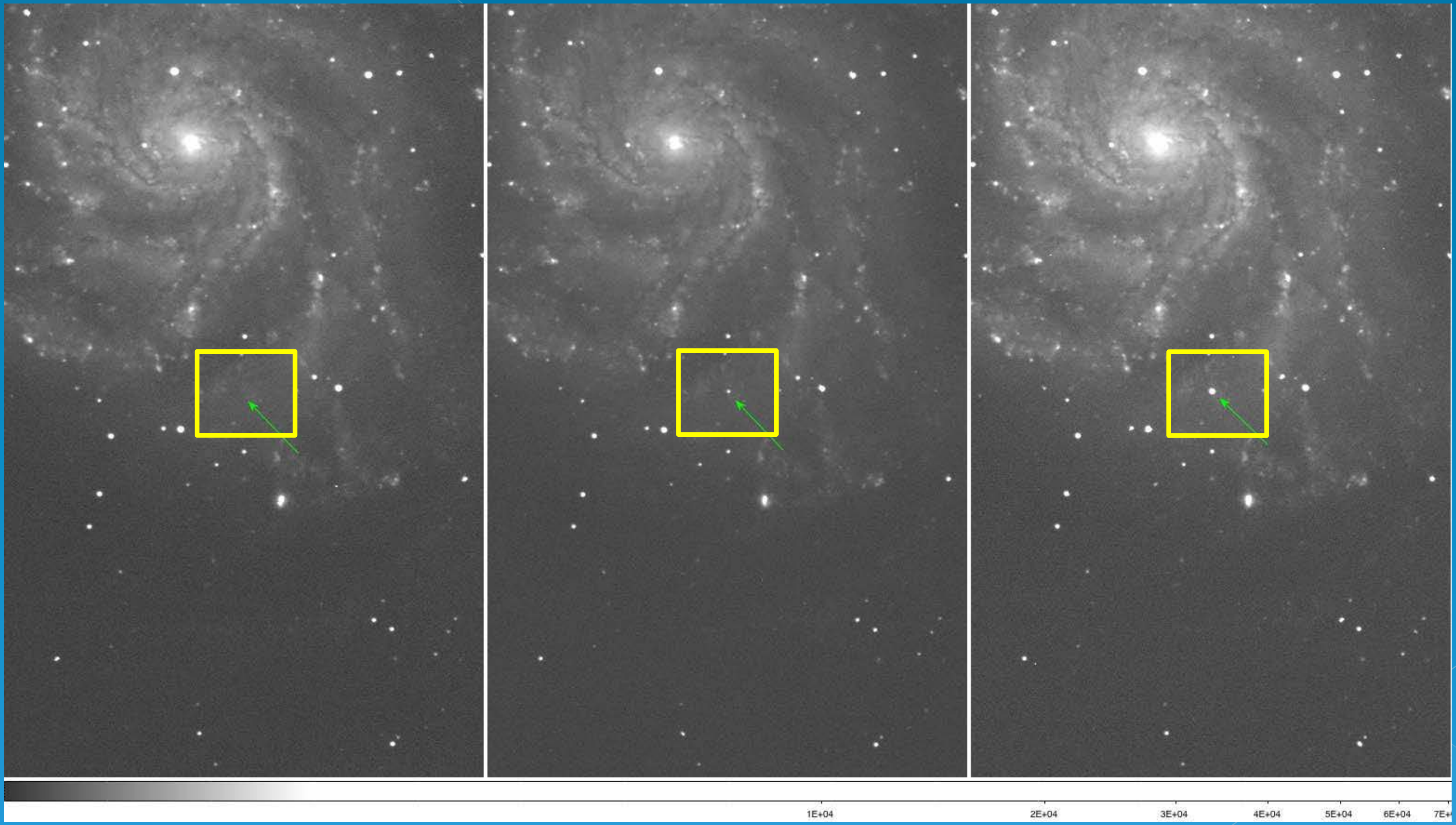


- *‘Double degenerates’*
  - C/O + C/O
  - C/O + He

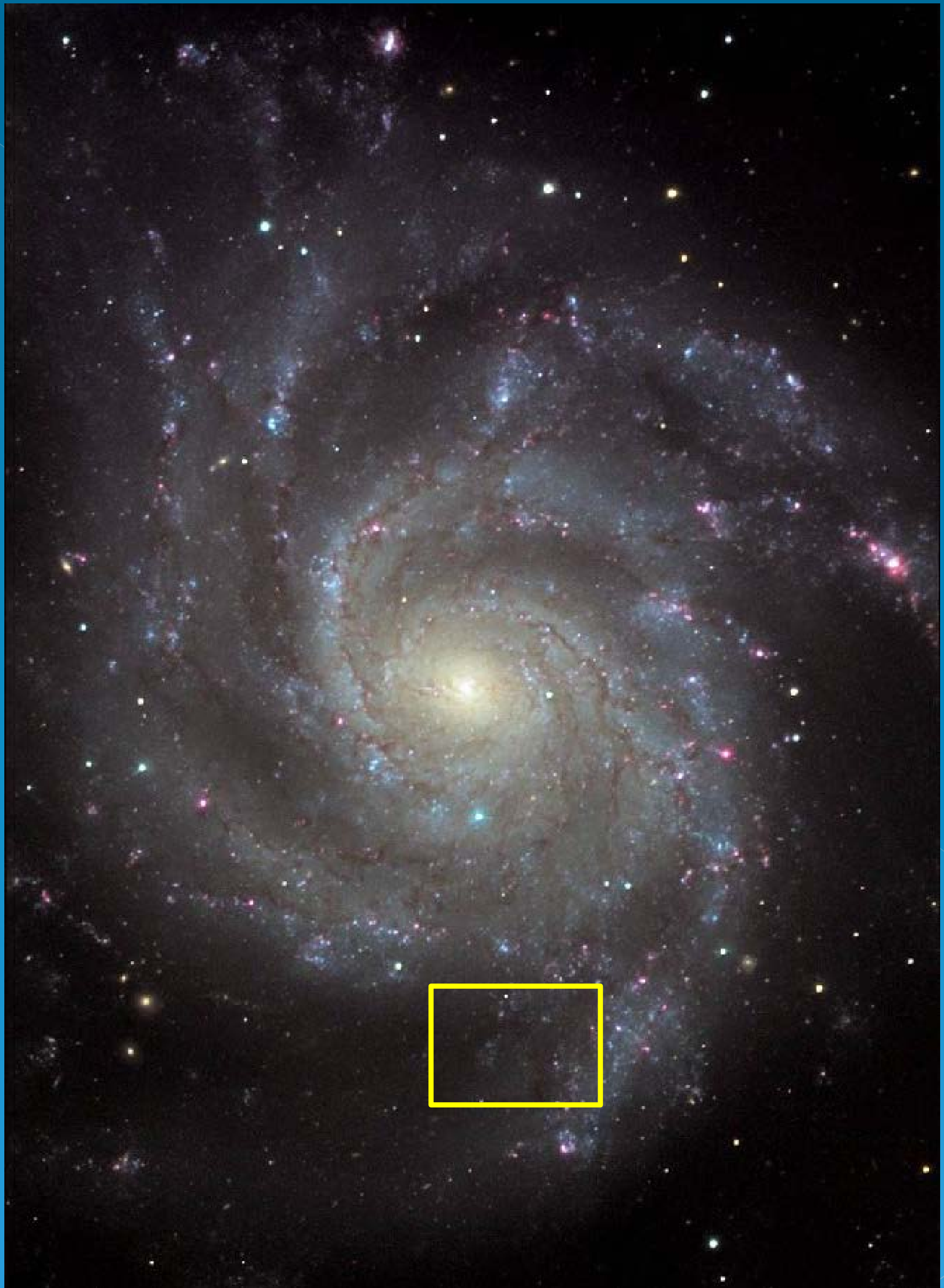
Which of them are realized in Nature? All of them?

Can we get more information on the progenitors?

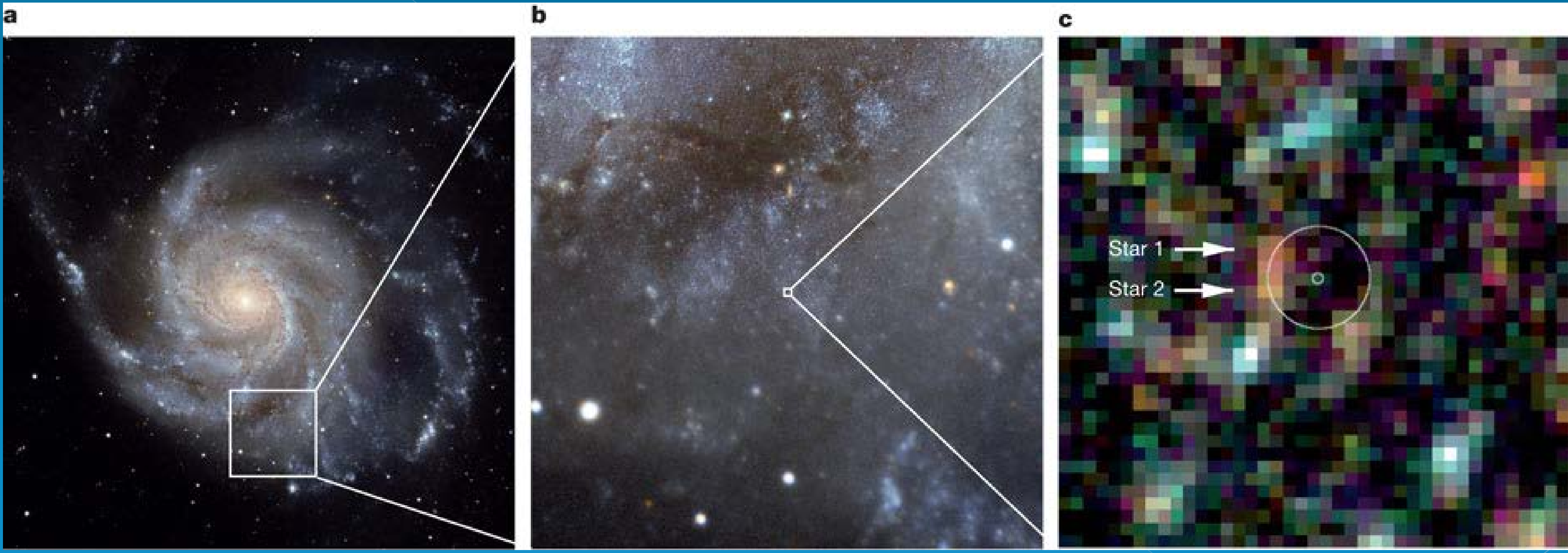
1. Direct observations: SN 2011fe in M101 (d~6 Mpc)



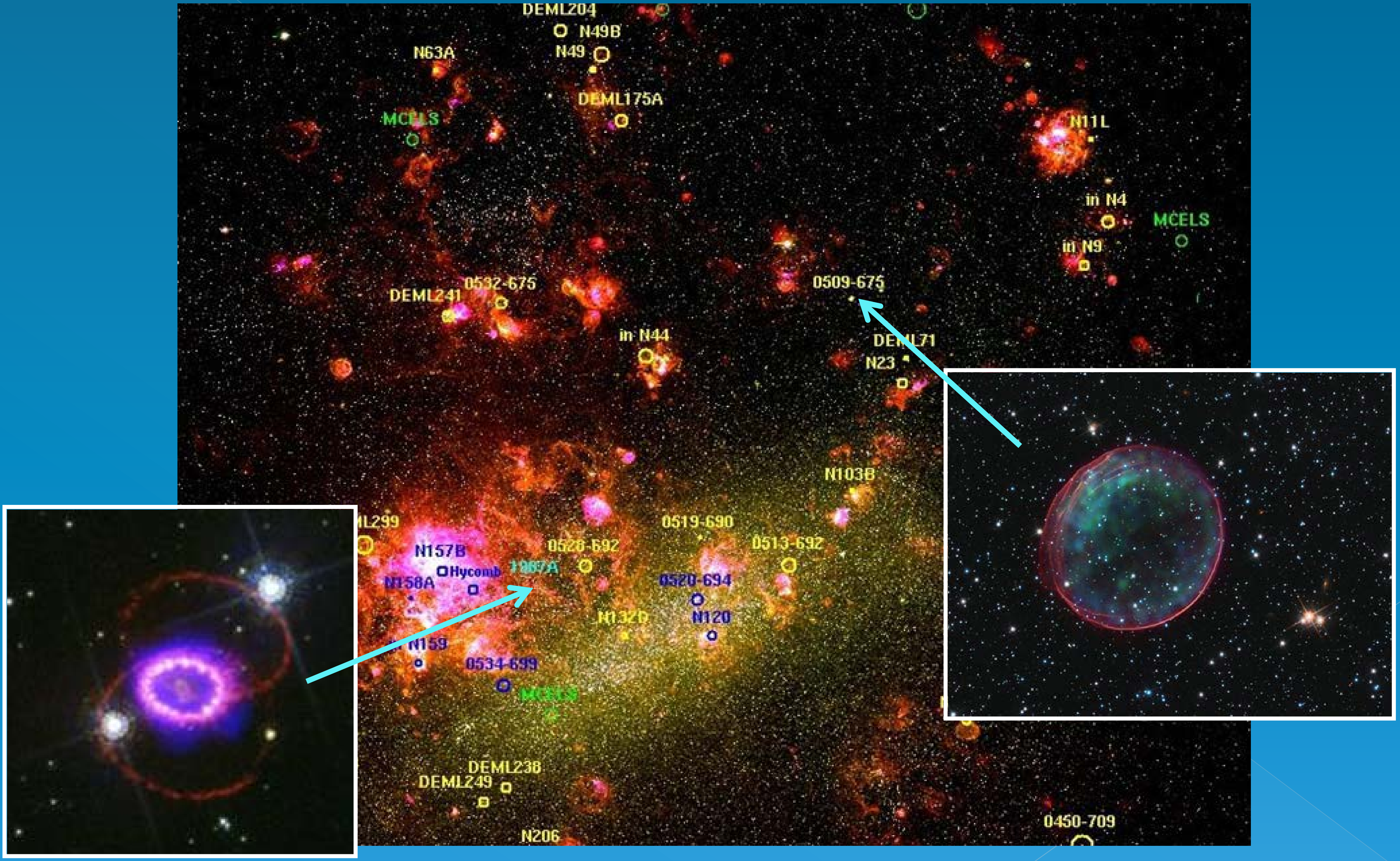
HST pre-explosion image (2002)

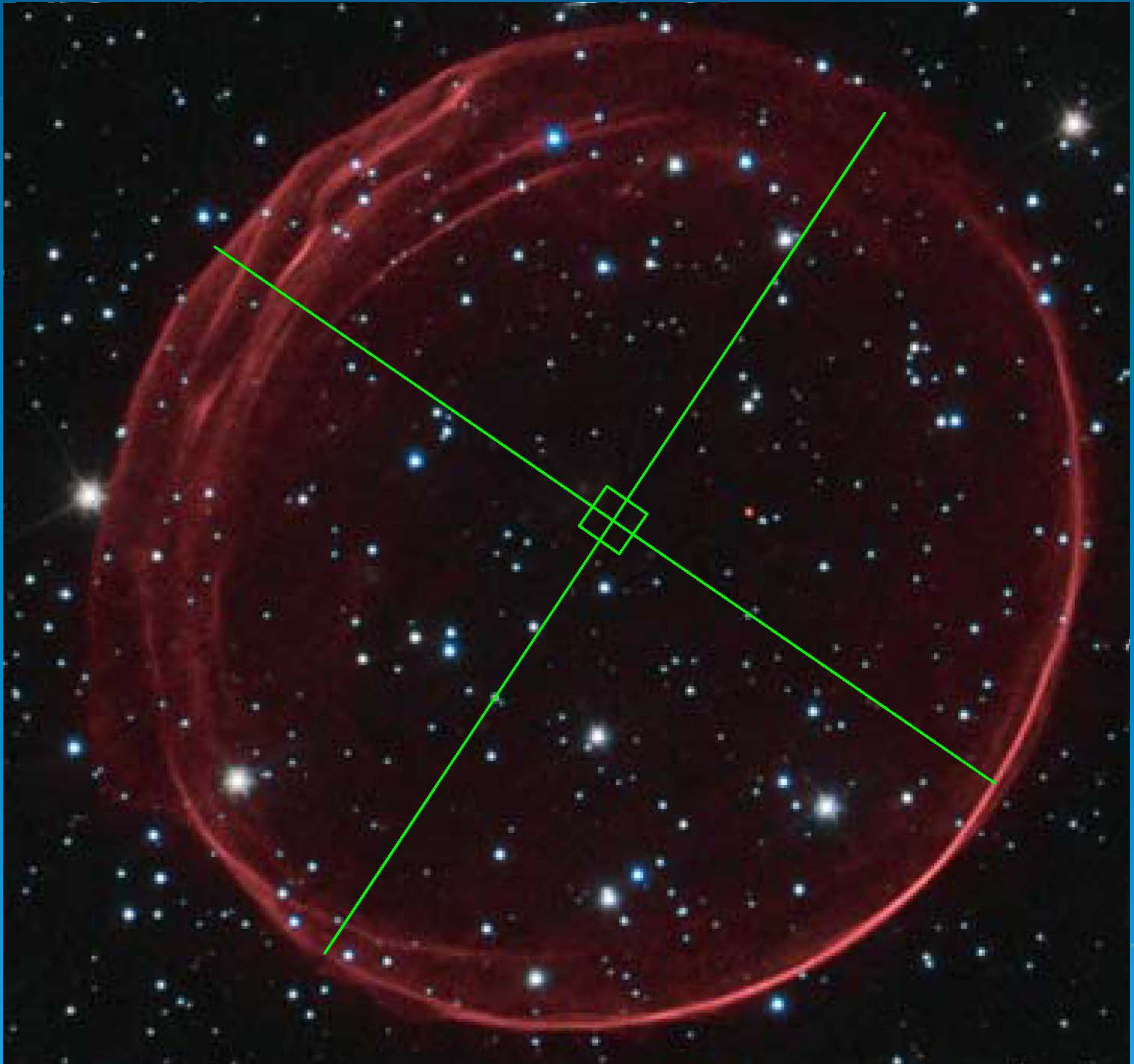


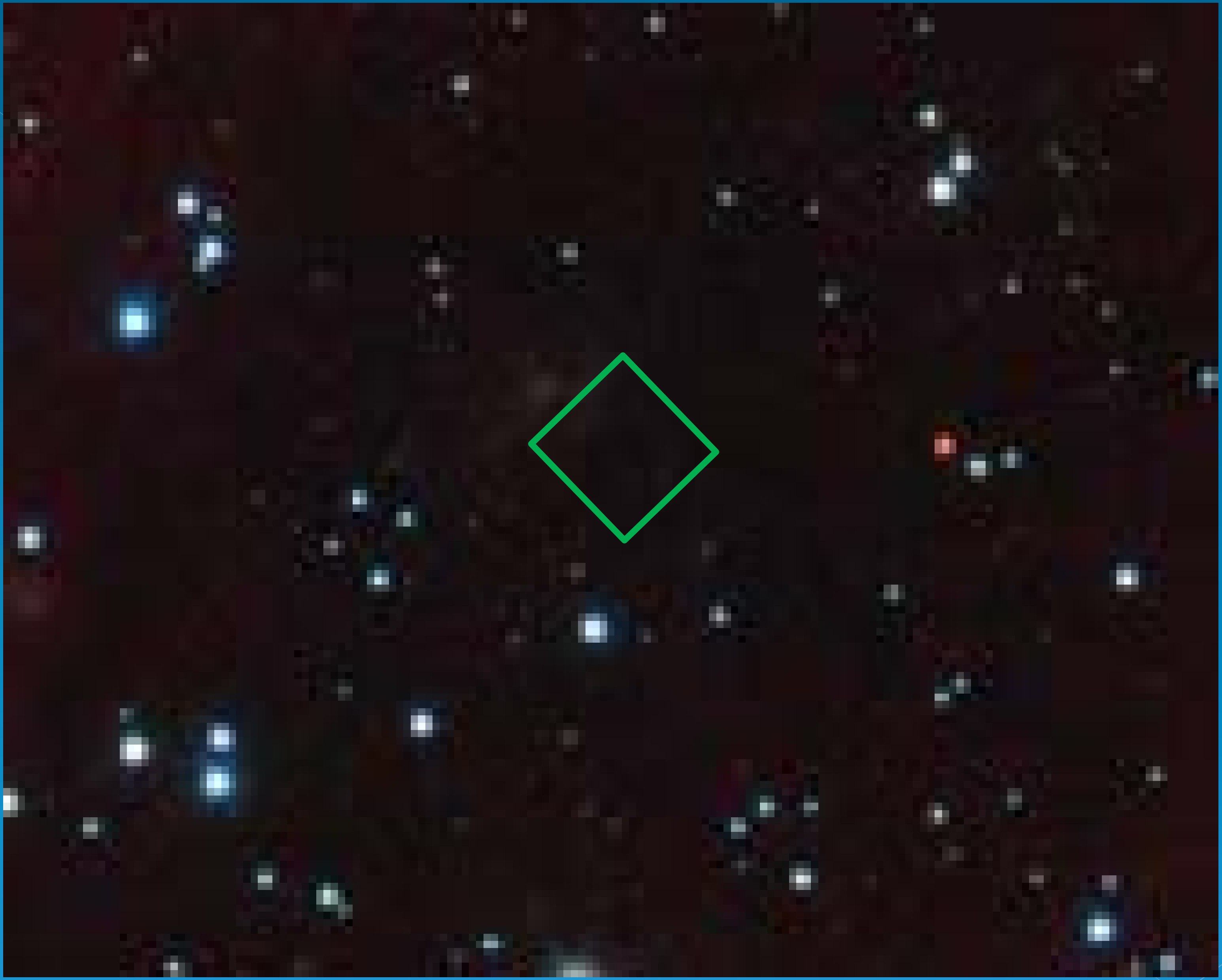
Li et al. (1011): donor was not a red supergiant!



2. Supenova remnants in the LMC





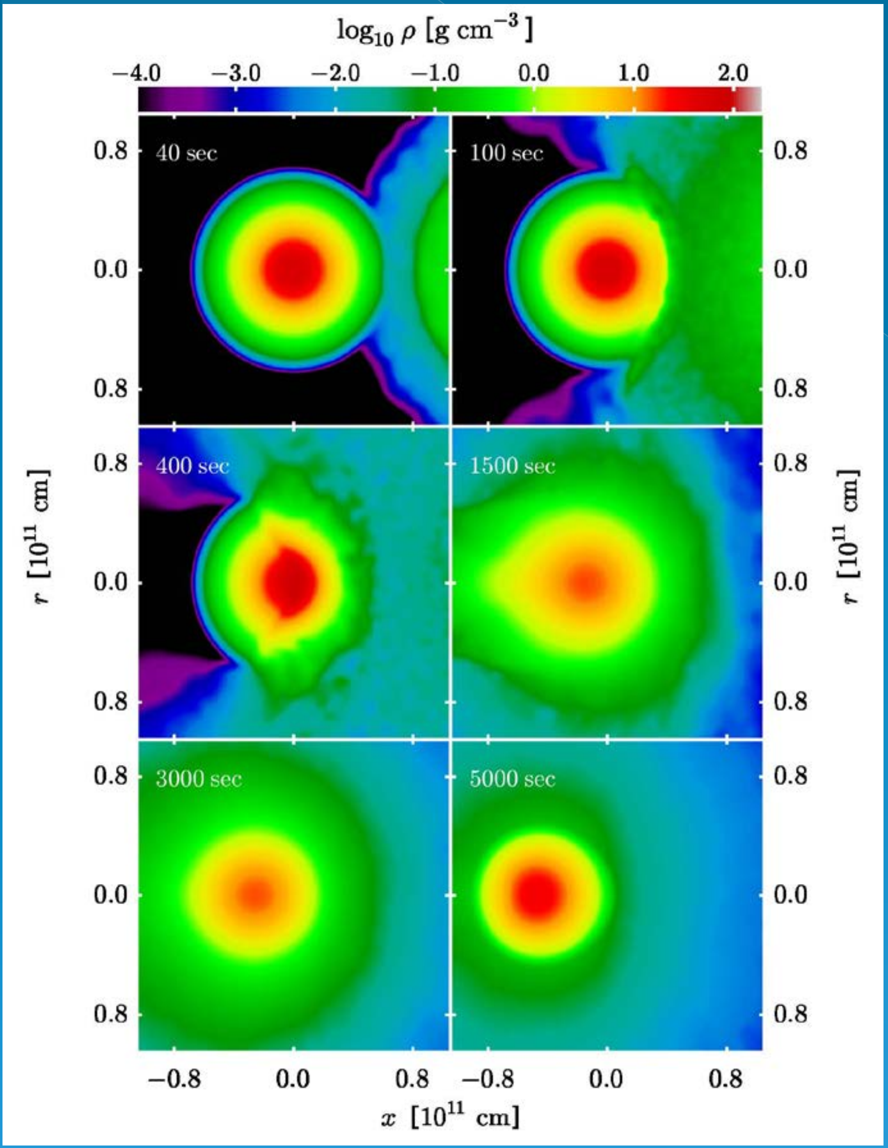


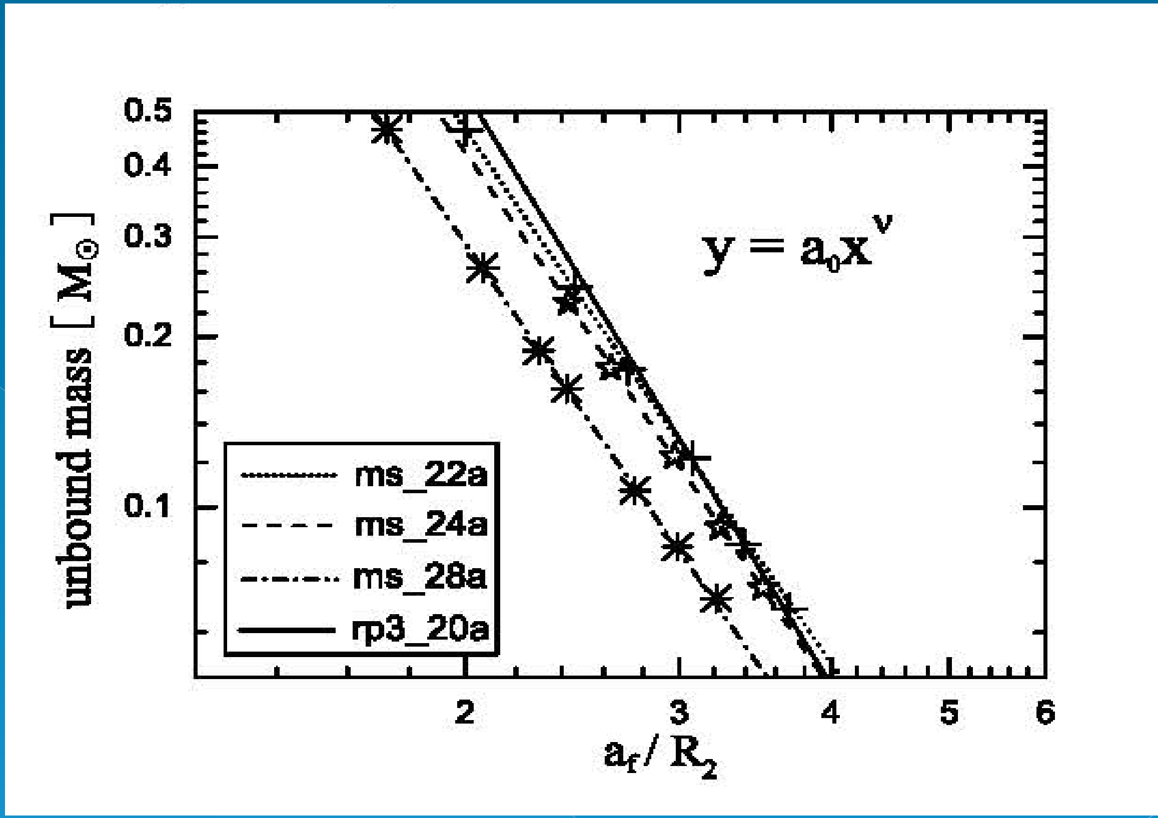
No star down to 0.5 M_{sun} ! (Schaefer & Panotta 2012)

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):

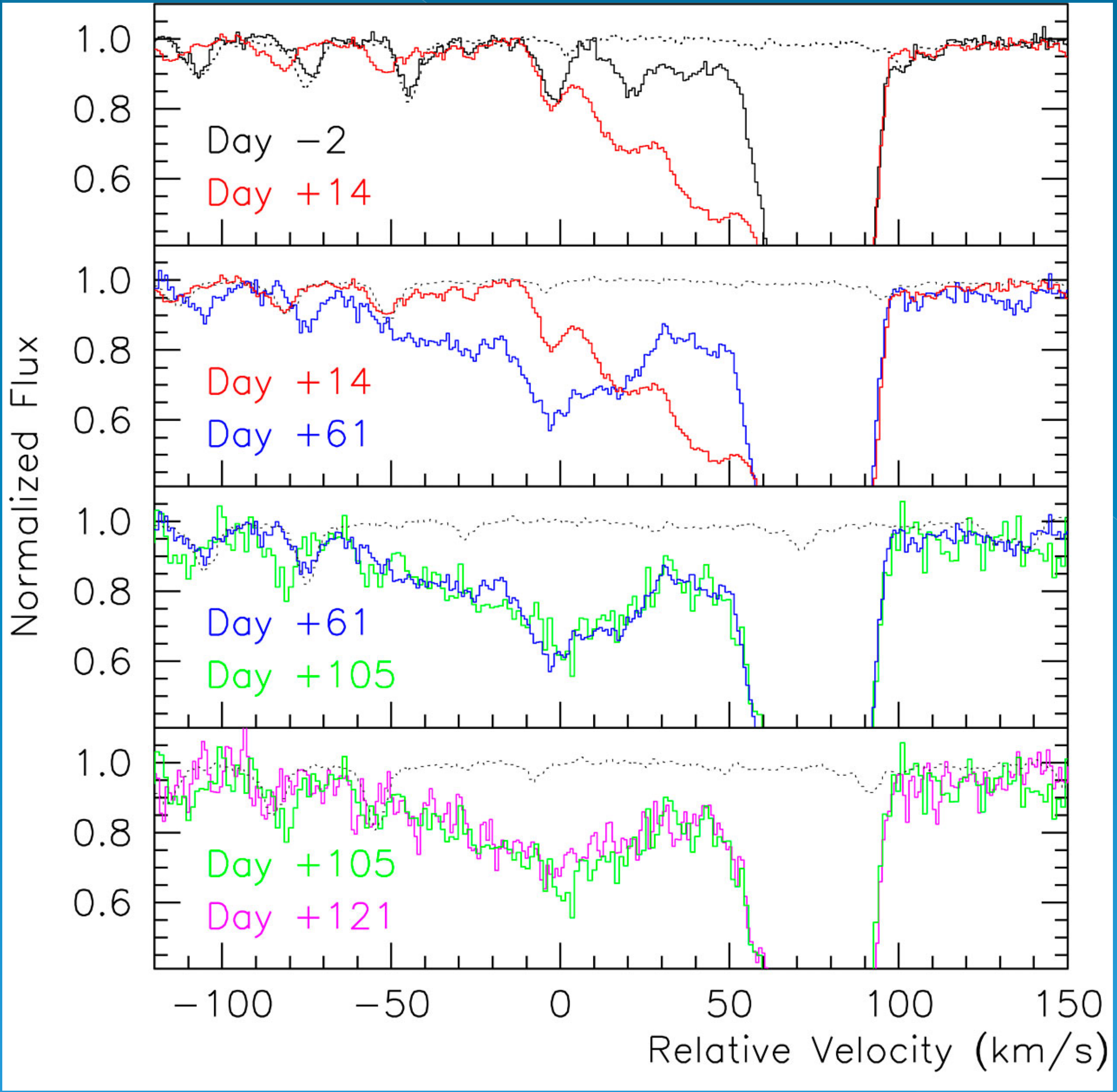




Was never seen!

Circum-stellar gas

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



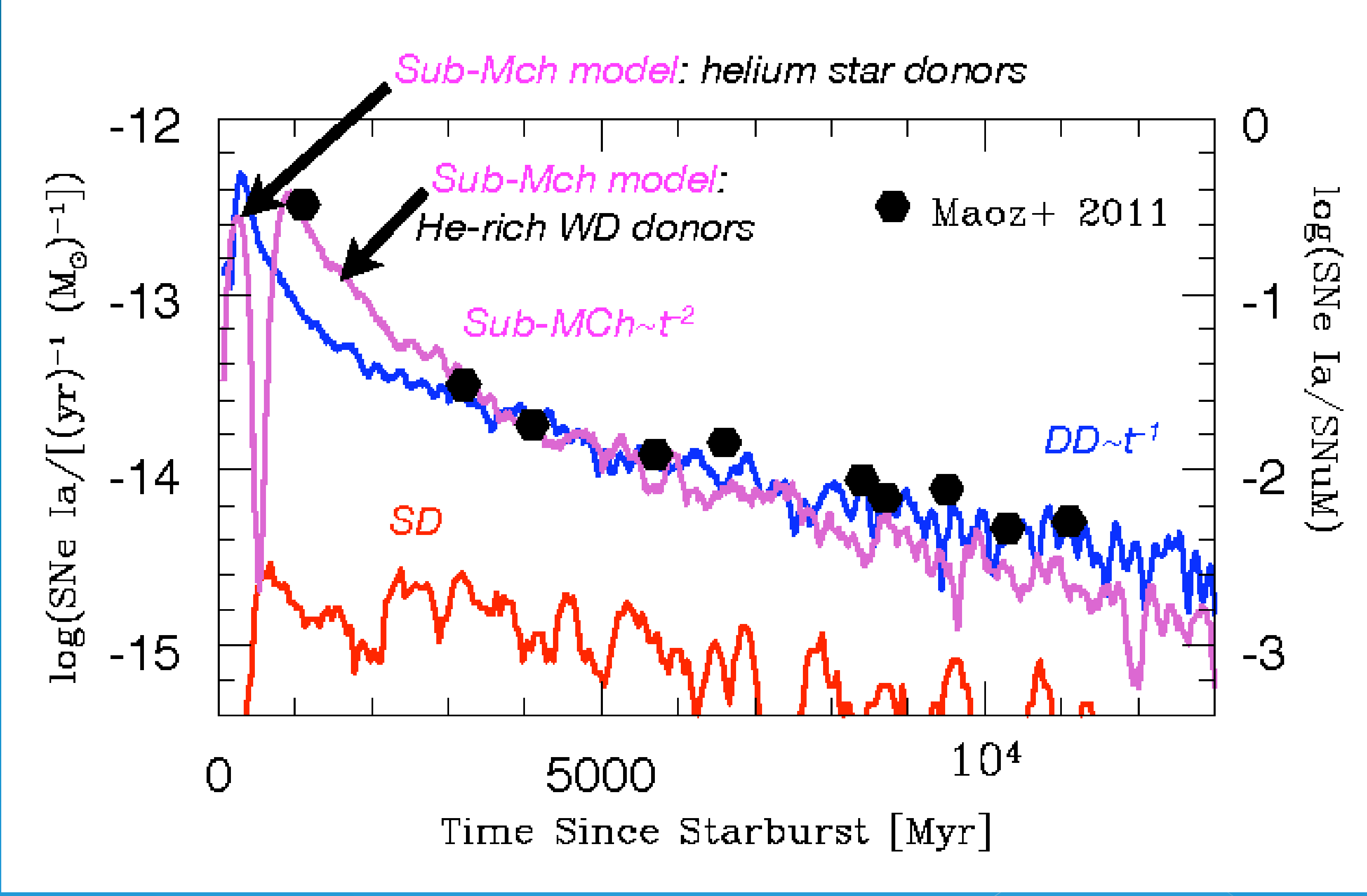
Evidence for circum-stellar gas!
Only seen in SNe in spriral galaxies!

Recurrent nova?
Or also in some DDs?

Rates and delay times (Ruiter et al. 2011)

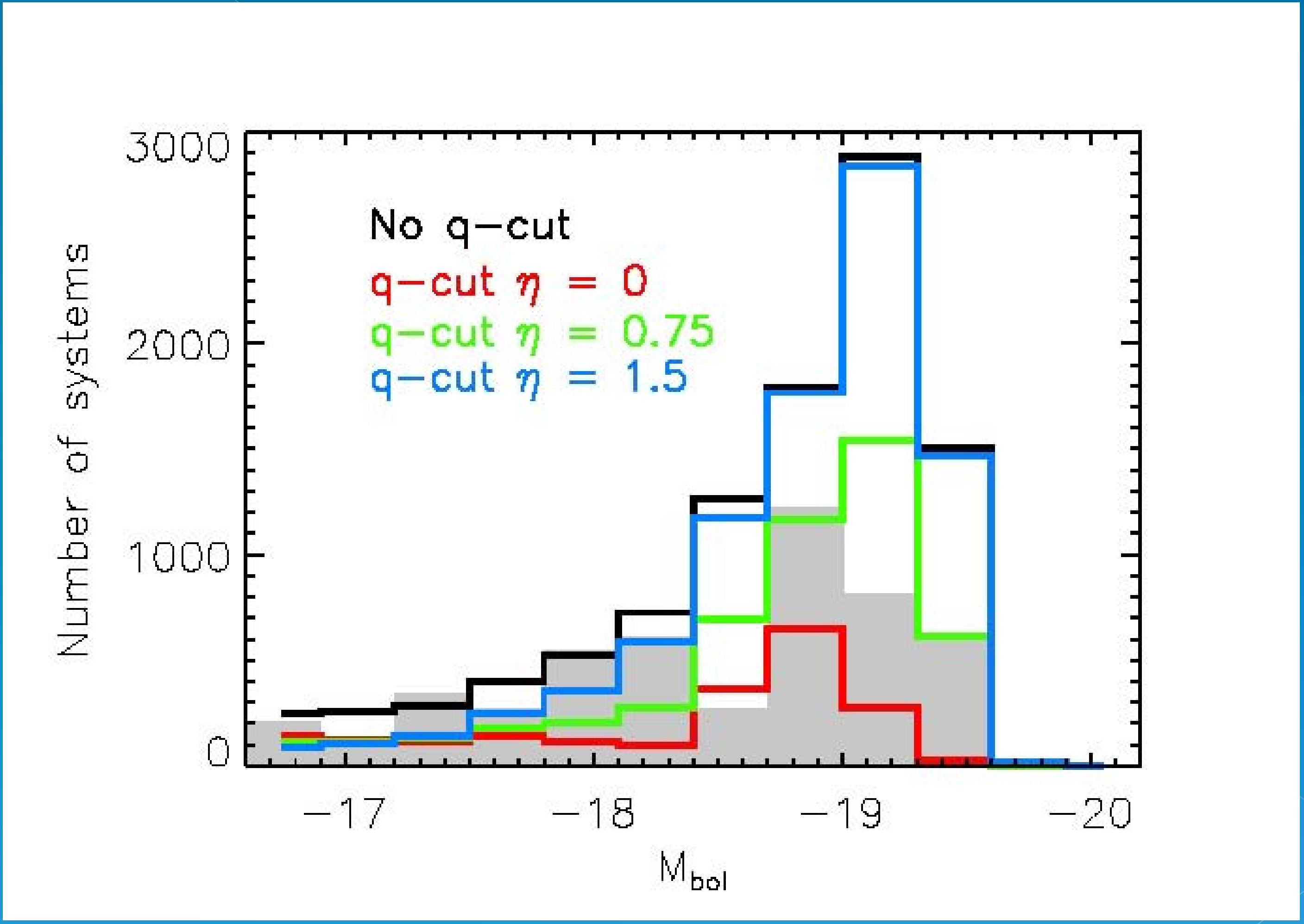
Expected delay times:

~ t^{-1}
(DDs)
~ $t^{-0.5}$
+ cut-off
(SDs)



Peak-luminosity distribution from DD mergers:

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



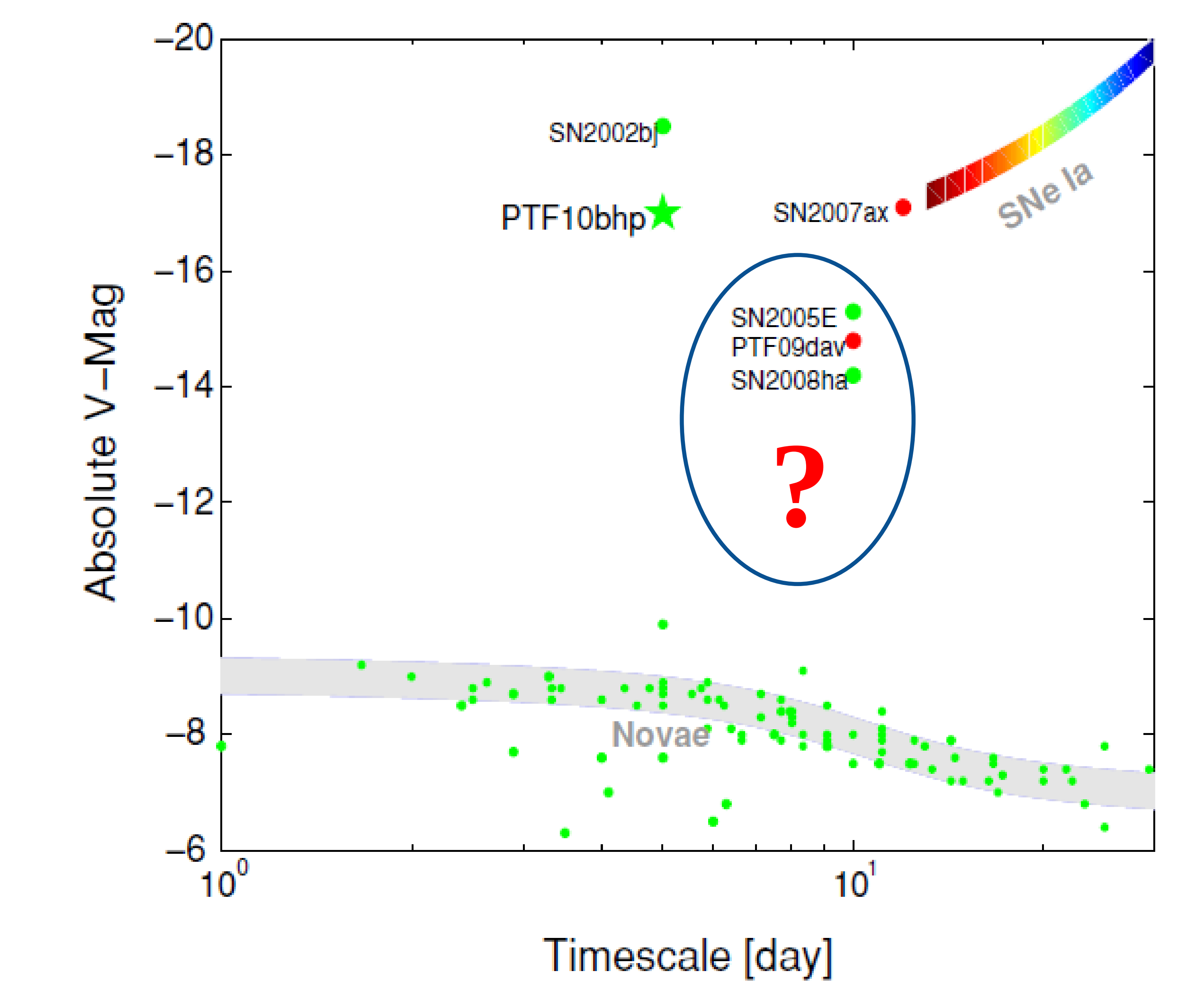
(Ruiter et al. 2013)

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