Modelling thermonuclear supernovae

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CAASTRO ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

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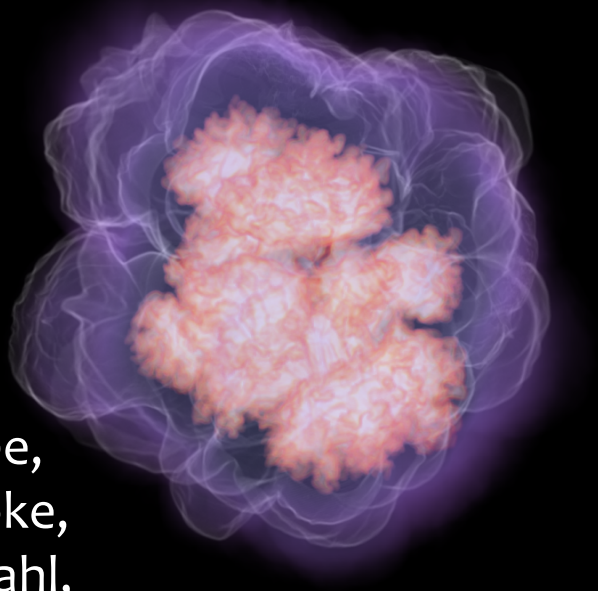


Supernovae in astrophysics

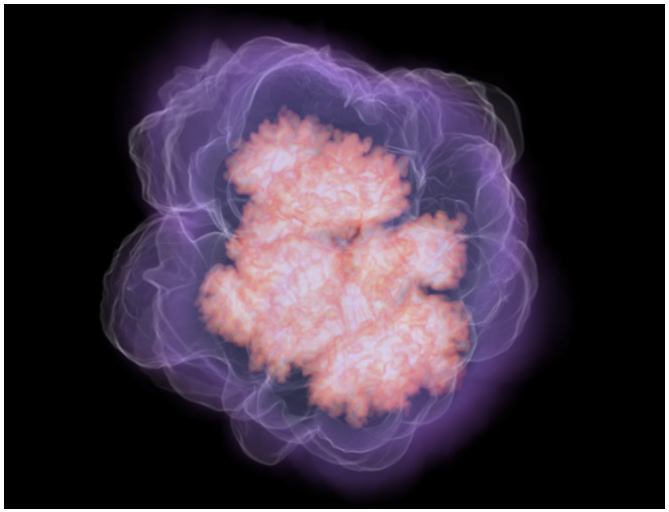
- Explosive death of star – dramatic end point of **stellar evolution**
- Nuclear burning in SNe **makes the heavy elements**
- Inject energy, momentum and metals; can **affect galaxy evolution**
- Type Ia "***Standardizable candles***", probes of **expansion history of the Universe**
- Challenge our understanding of **physics**
  - Turbulence and hydrodynamics
  - Combustion and flame physics
  - Nuclear physics
  - Radiative transfer

SN1994D in NGC 4526
NASA/HST

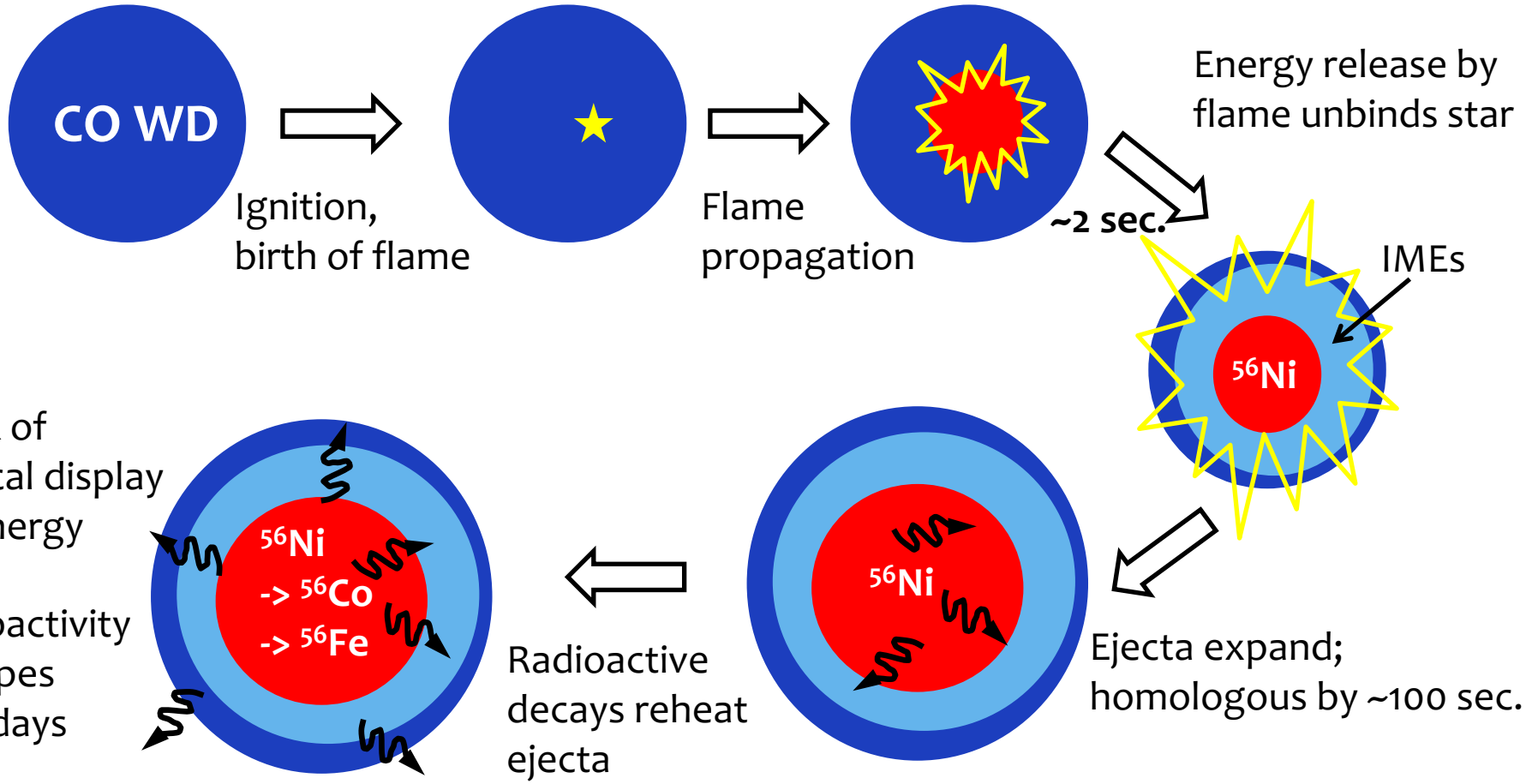
Overview

- **Thermonuclear supernovae**
  - Reminder of basic picture for Type Ia supernovae

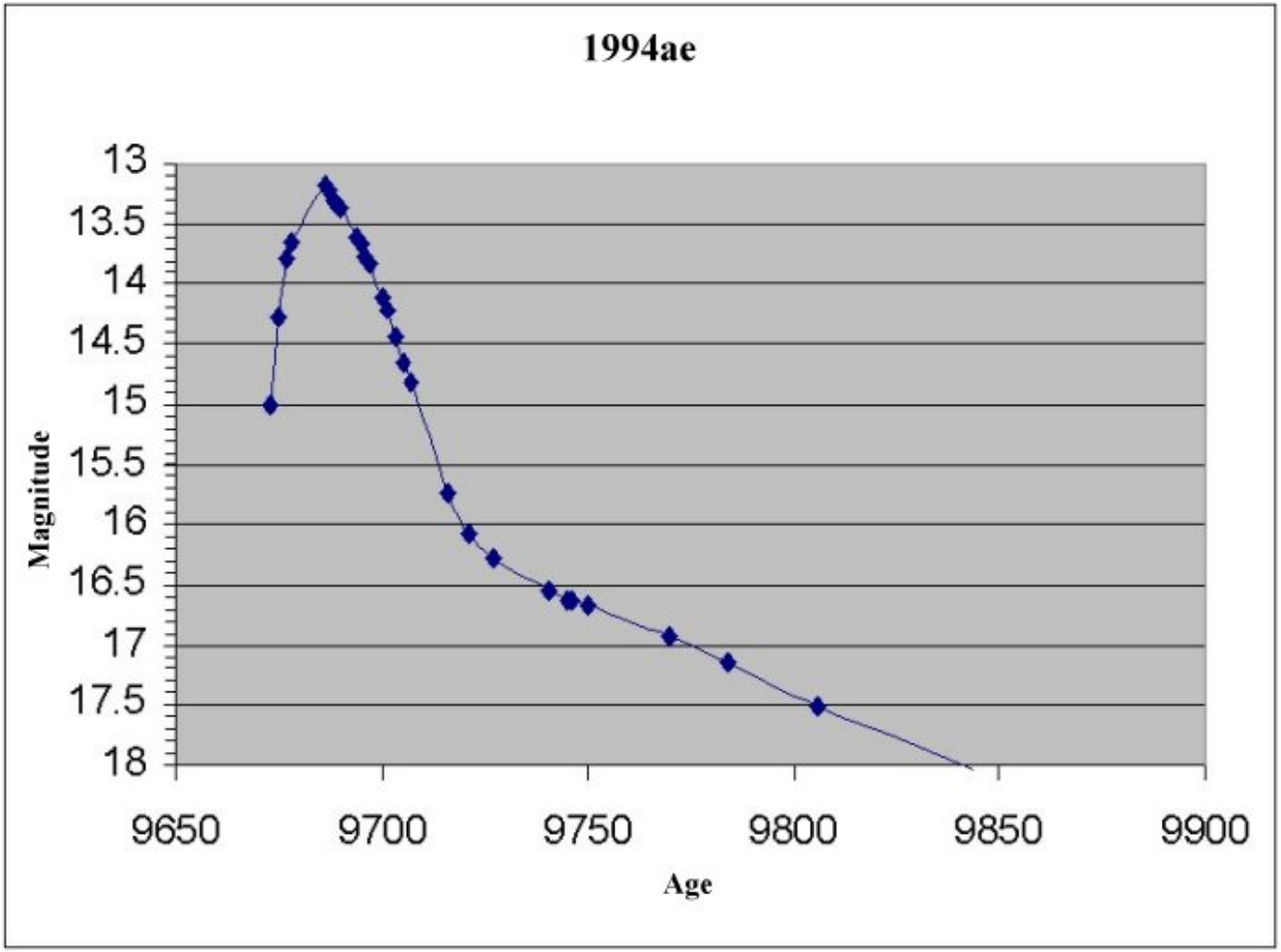
- **Explosion models**
  - Chandrasekhar mass explosions
    - Pure deflagrations and SNe Iax (Magee)
  - Sub-Chandrasekhar mass models



Established picture for a thermonuclear supernova explosion

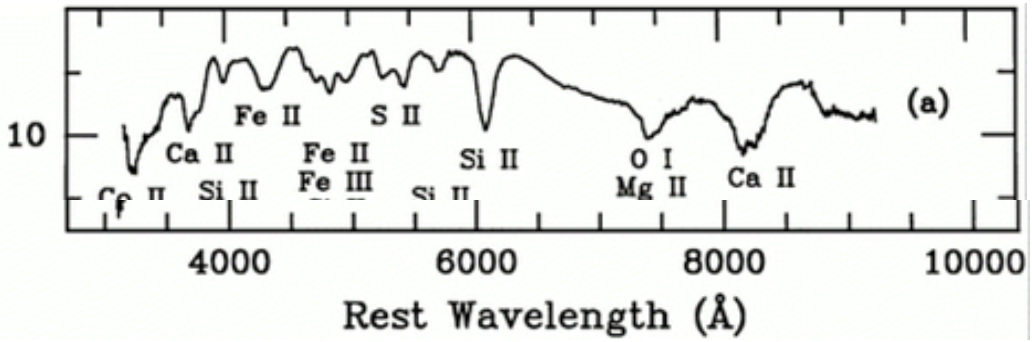


Supernovae Ia

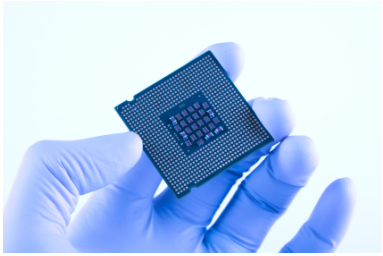


~0.7 $M_\odot$ of ^{56}Ni is typical

Supernovae Ia



Made of Si, S and Fe



H and He not detected

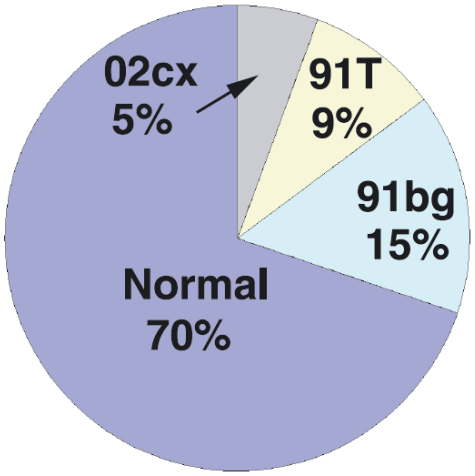
Velocities measured from lines

$$v \sim 15{,}000\ \mathrm{km/s}$$

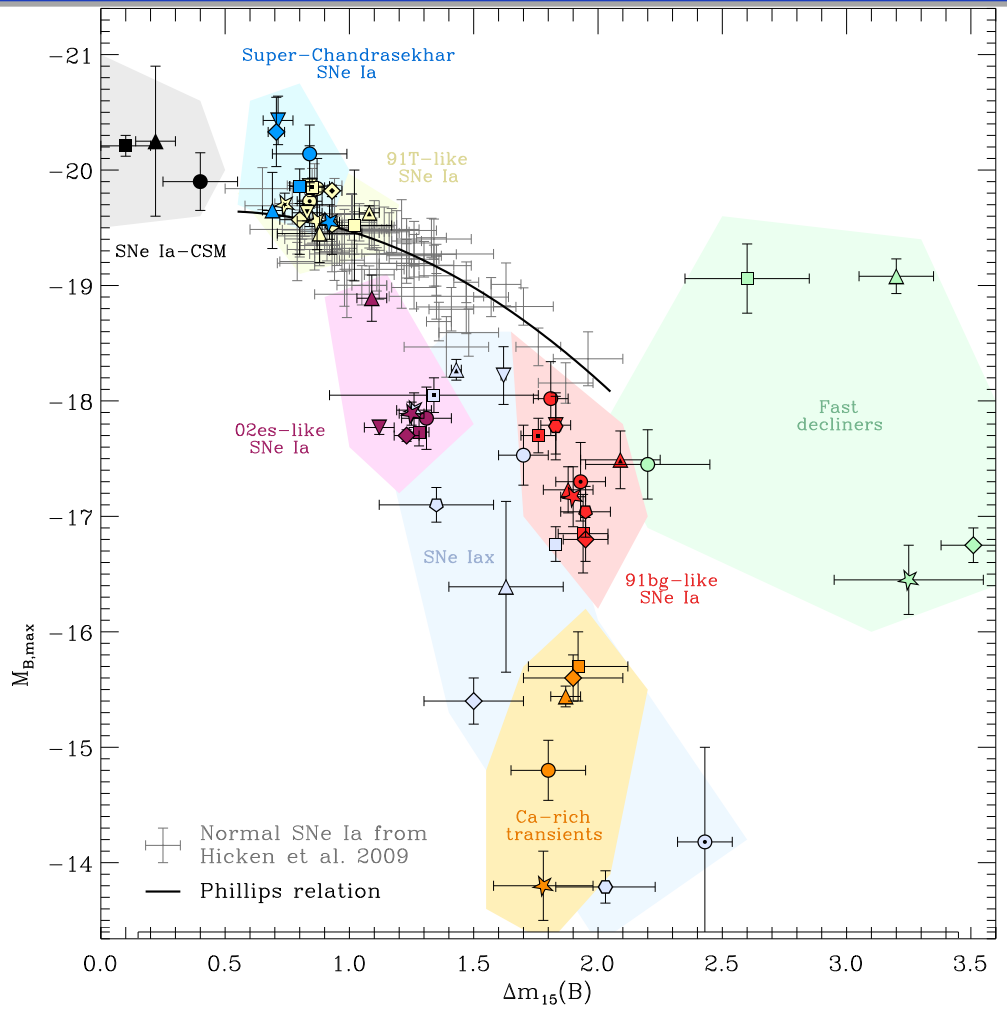
Supernovae Ia: diversity

Diversity in SNe Ia and related transients

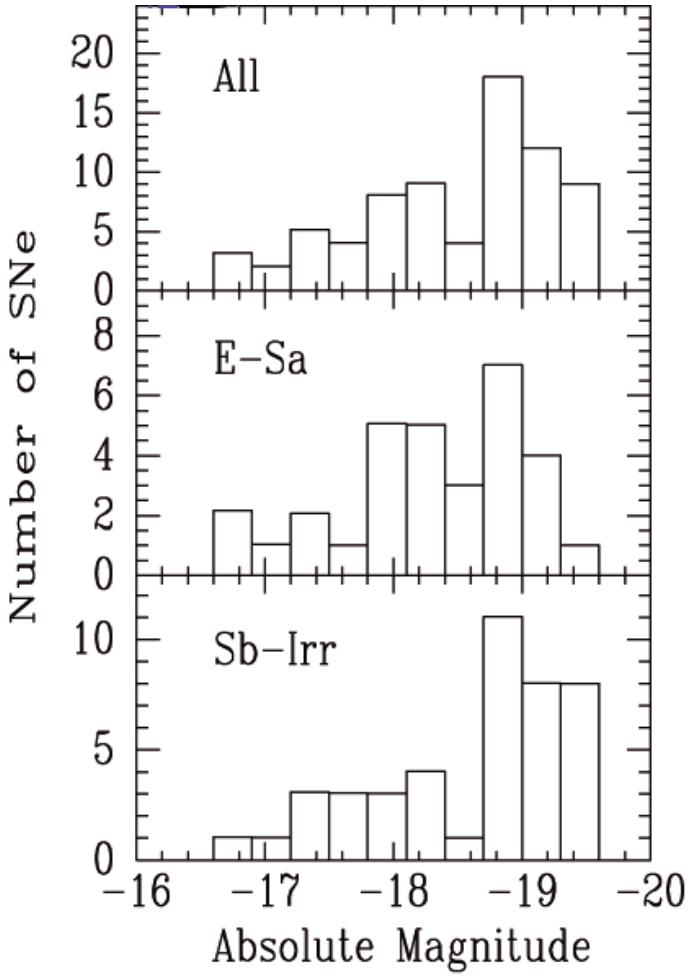
(figure from Taubenberger 2017)



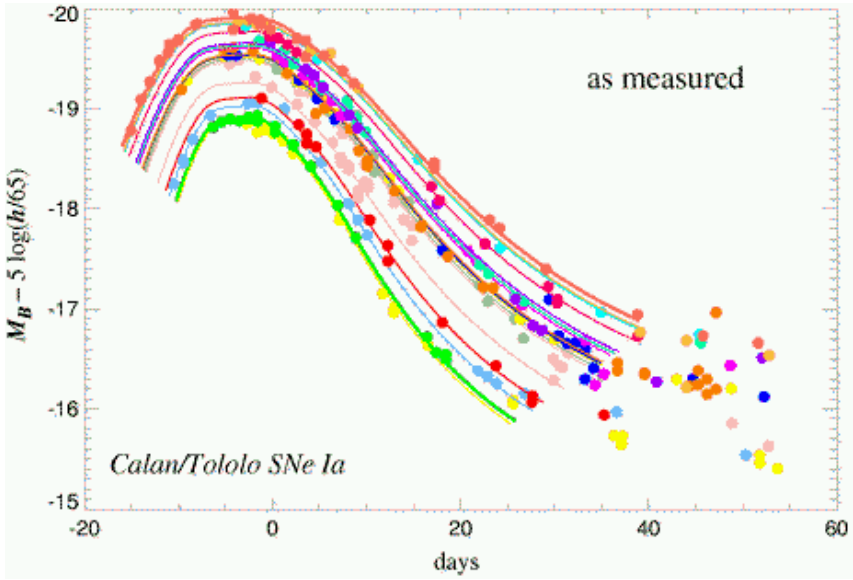
(rates from Li et al. 2011)



Supernovae Ia



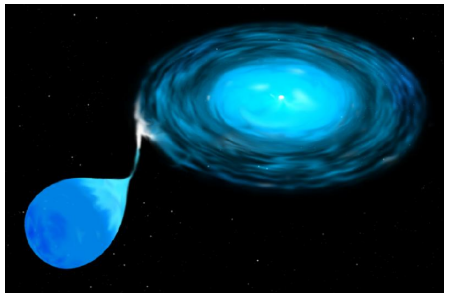
Li et al. 2011
(Lick Obs. SN. Search)

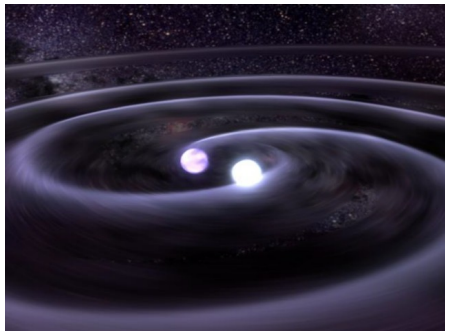


Thermonuclear Supernovae

Many unanswered questions remain:

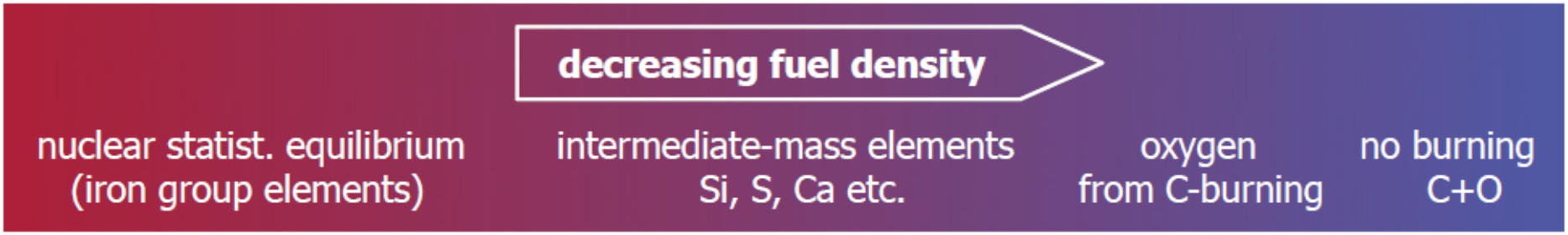
- **How did the system evolve to ignition?**
  - **Progenitor channel debate ("single vs double degenerate")**
- **What are the properties of the exploding star and how do these affect what we see?**
  - **Mass of WD, composition, immediate environment?**
- **Where does the flame ignite and how does it propagate (deflagration, detonation)?**





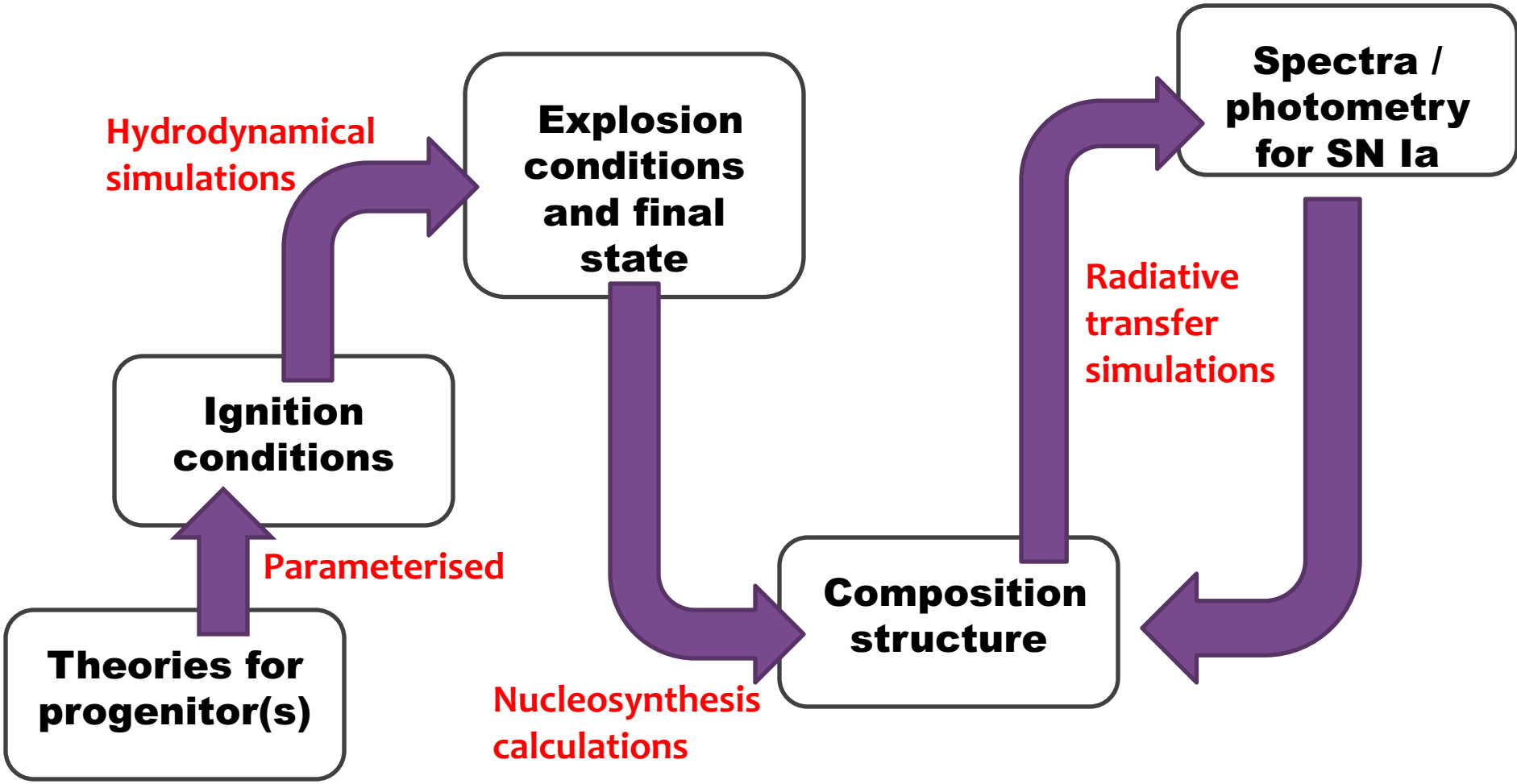
SN Ia Flame Basics

- Instantaneously **narrow region** in which nuclear reactions are taking place
- Thermonuclear flame propagation modes
  - **Deflagration (*sub-sonic*)**
  - **Detonation (*supersonic*)**
- Flame **generates energy** (nuclear burning)
  - Eventually unbinds star



Synthetic explosions:

testing models by comparing to data



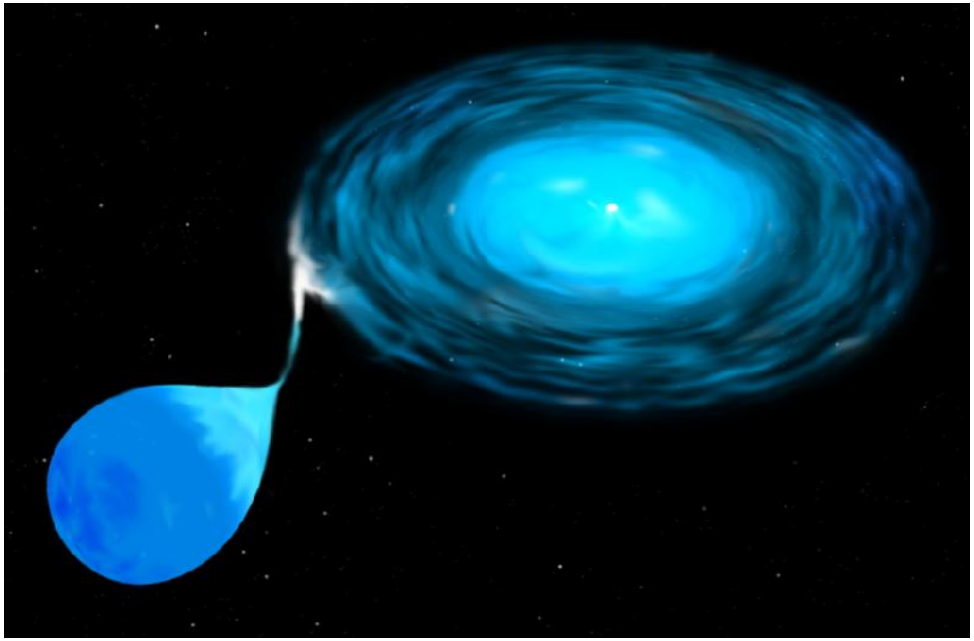
Testing explosion scenarios

Explosion scenarios

Best known paradigm:

(Near-)Chandrasekhar-mass single-degenerate scenario

- WD in binary with **H-rich star** (main-sequence or giant)
- Mass-transfer
- **Mass is retained** (avoid net mass-loss in nova explosions)
- H burned to He then C/O
- WD grows in mass: central density and temperature rise



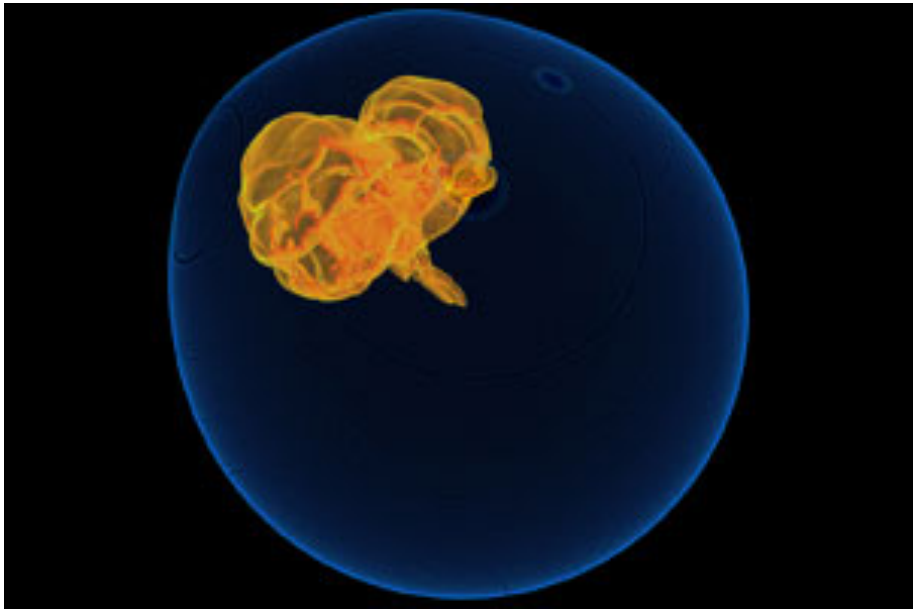
Explosion scenarios

Best known paradigm:

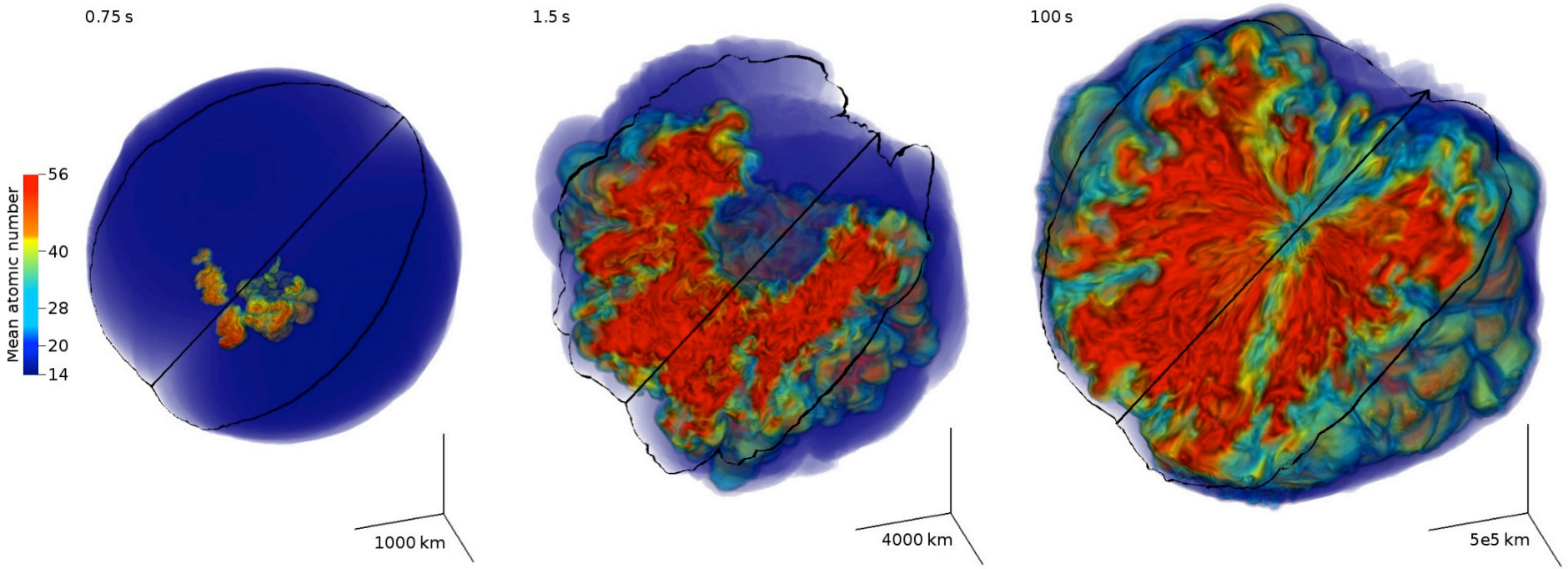
(Near-)Chandrasekhar-mass single-degenerate scenario

Explosion mechanism:

- WD heated by C burning during ~1000 yr "simmering" phase (Kuhlen et al. 06, Zingale et al. 06, 11)
- Thermonuclear runaway occurs
- Deflagration born (prompt detonation is no good for Ch mass)
- Proceeds as pure deflagration?

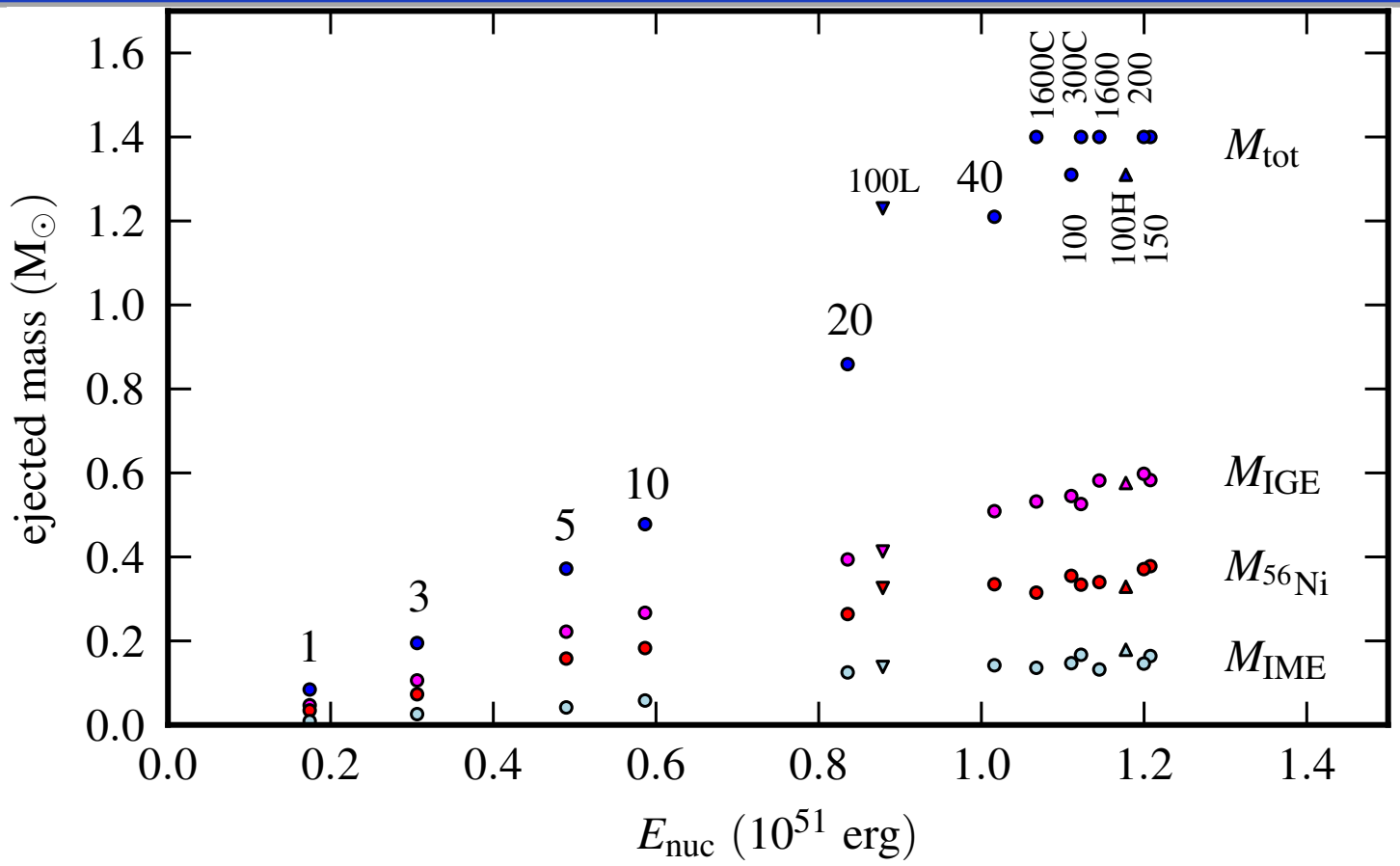


Deflagration models



3D simulation: Kromer+ 13

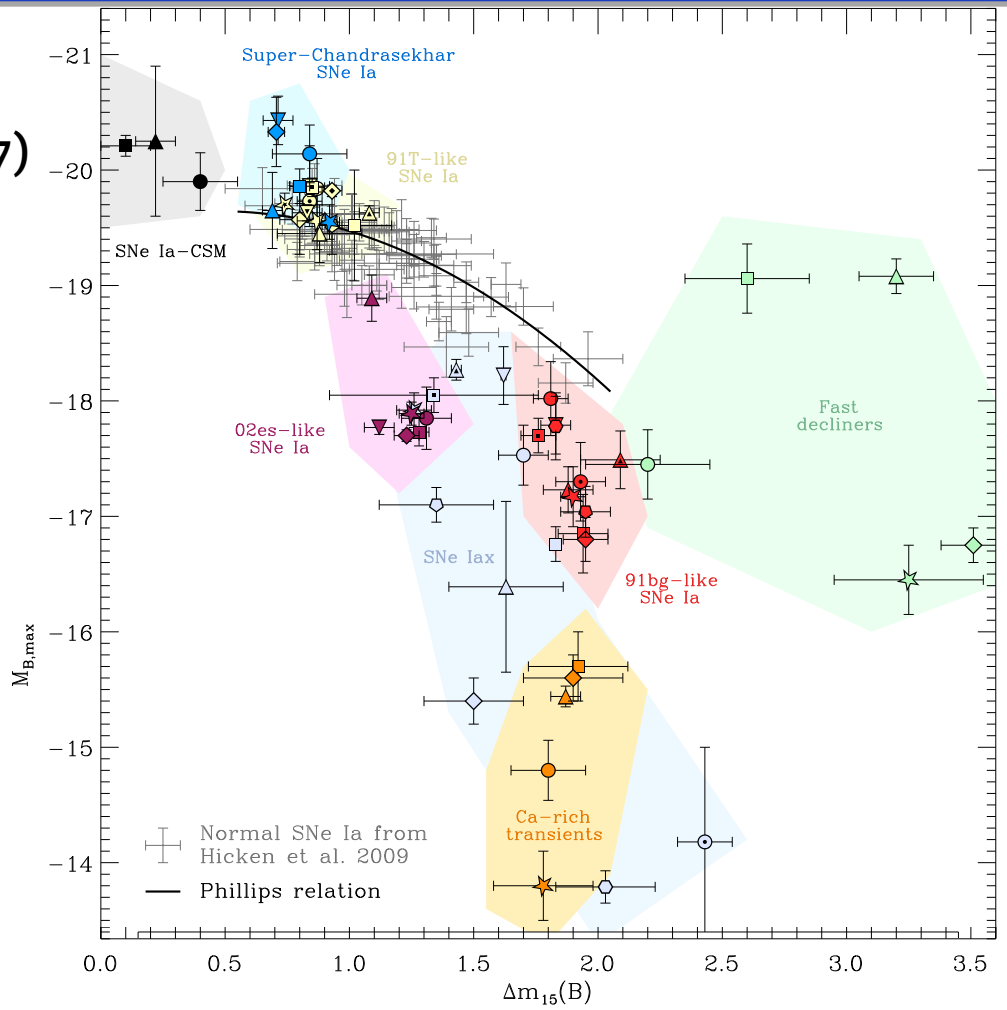
Deflagration models



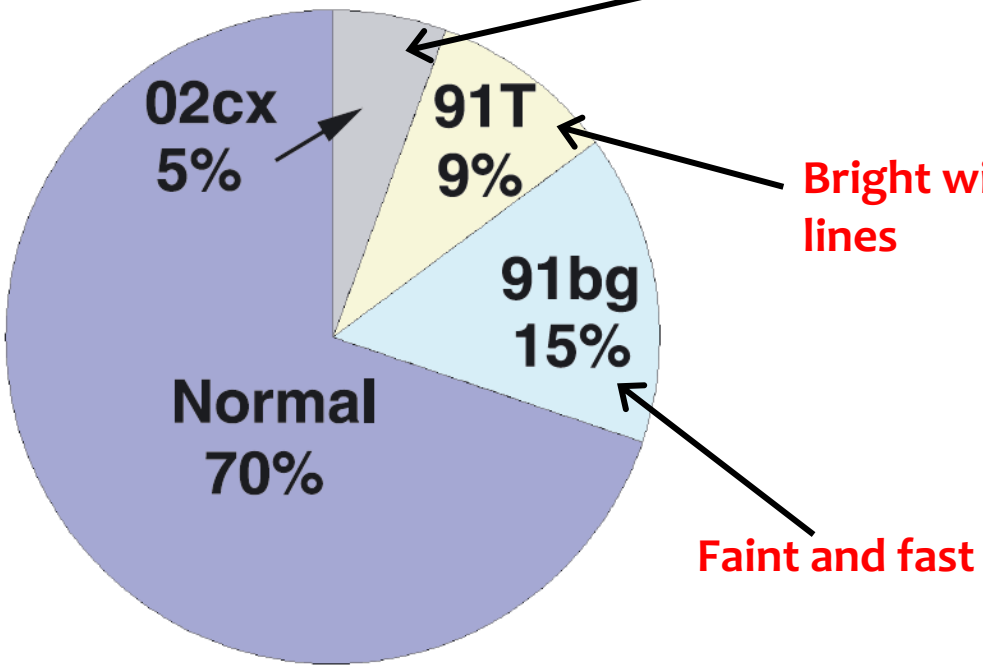
Sequence of models: Fink+14. – roughly 1 order of magnitude in 56Ni mass.
Bound remnant found in some cases, in agreement with Jordan+12.

Supernovae Ia: diversity

Multiple sub-classes of SNe Ia / related transients **(figure from Taubenberger 2017)**



Supernovae Ia: diversity



Faint with weak IMEs

Bright with early IGE lines

Faint and fast

There are now multiple sub-classes of SNe Ia

(from Li et al. 2011)

Also a sample of **very bright cases e.g.**

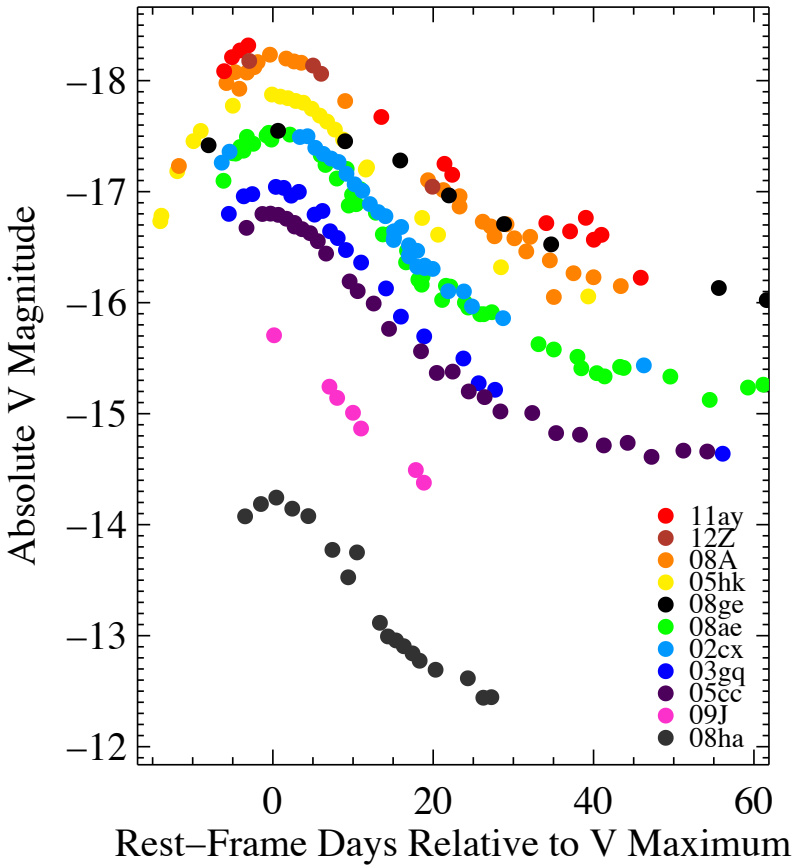
2003fg (Howell+);
2007if (Scalzo+, Yuan+);
2009dc (Yamanaka+)...

And a handful of faint, slowly evolving cases

PTF10ops (Maguire+);
2010lp (Pignata+)

Pure deflagration: 02cx-like SNe?

Foley+ 13



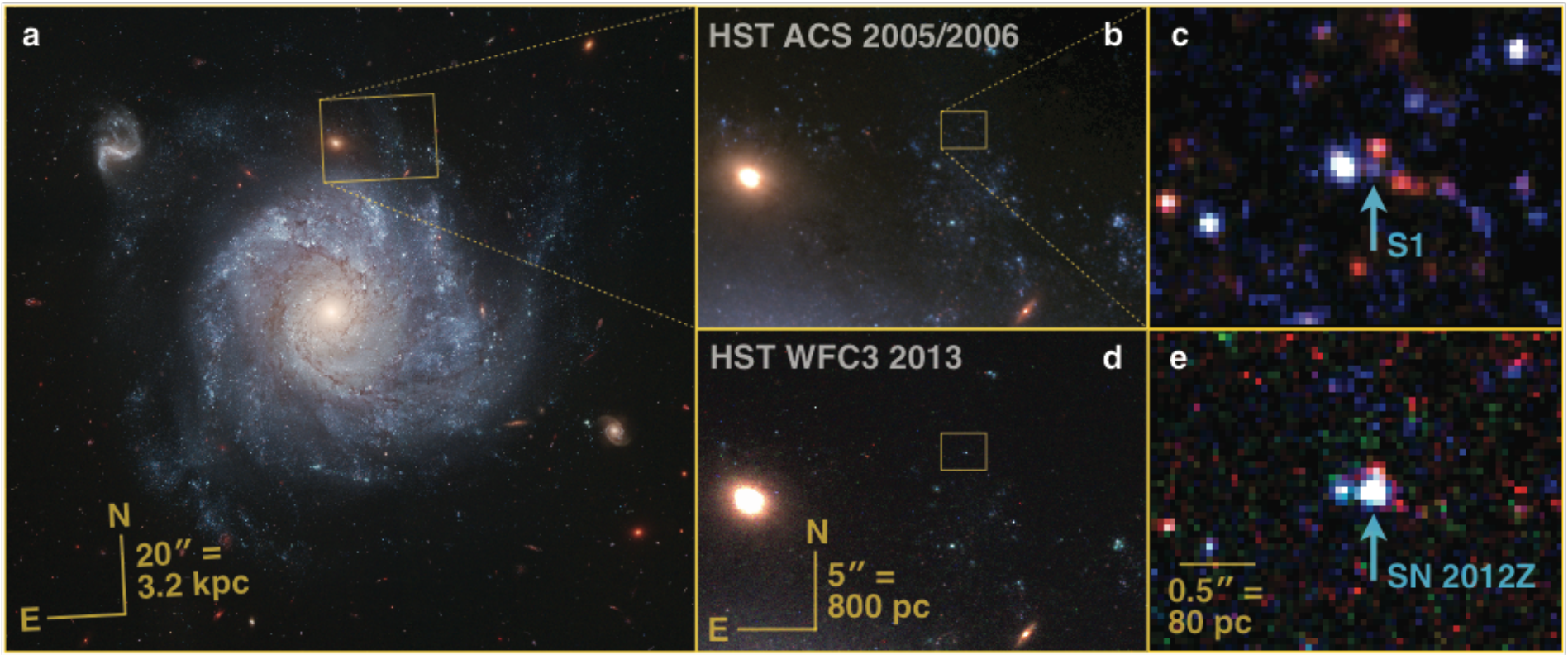
Pure deflagration models:

Suggested connection to peculiar (faint) Ia's:
Branch+04, Jha+06, Phillips+07

Now evidence that 02cx-like class ("SNe Iax"; Foley+09,13)

- is large and diverse
- range of ejecta mass ("failed" deflagrations)

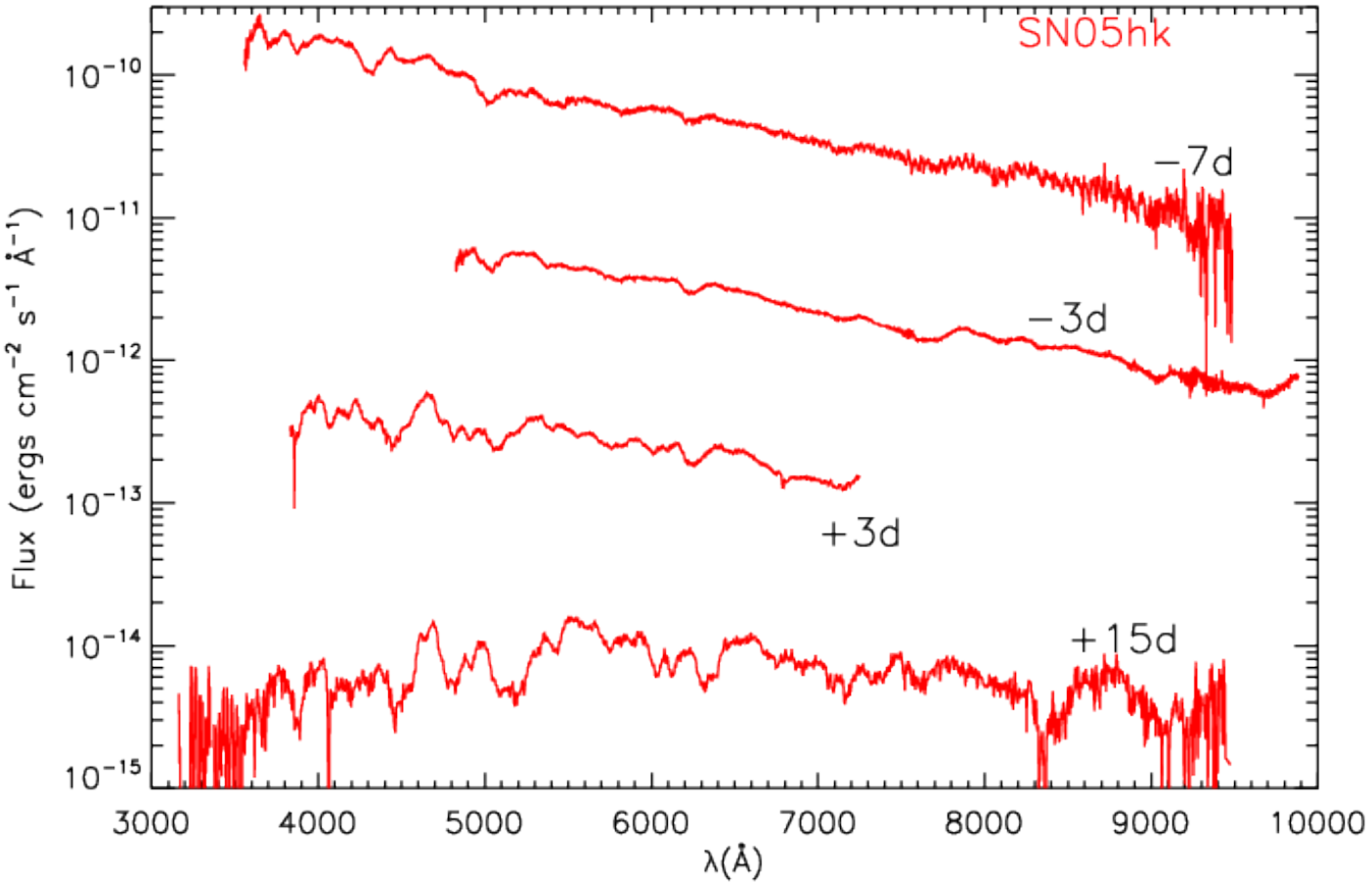
Supernovae Ia: a progenitor?



First plausible detection of a Ia progenitor:

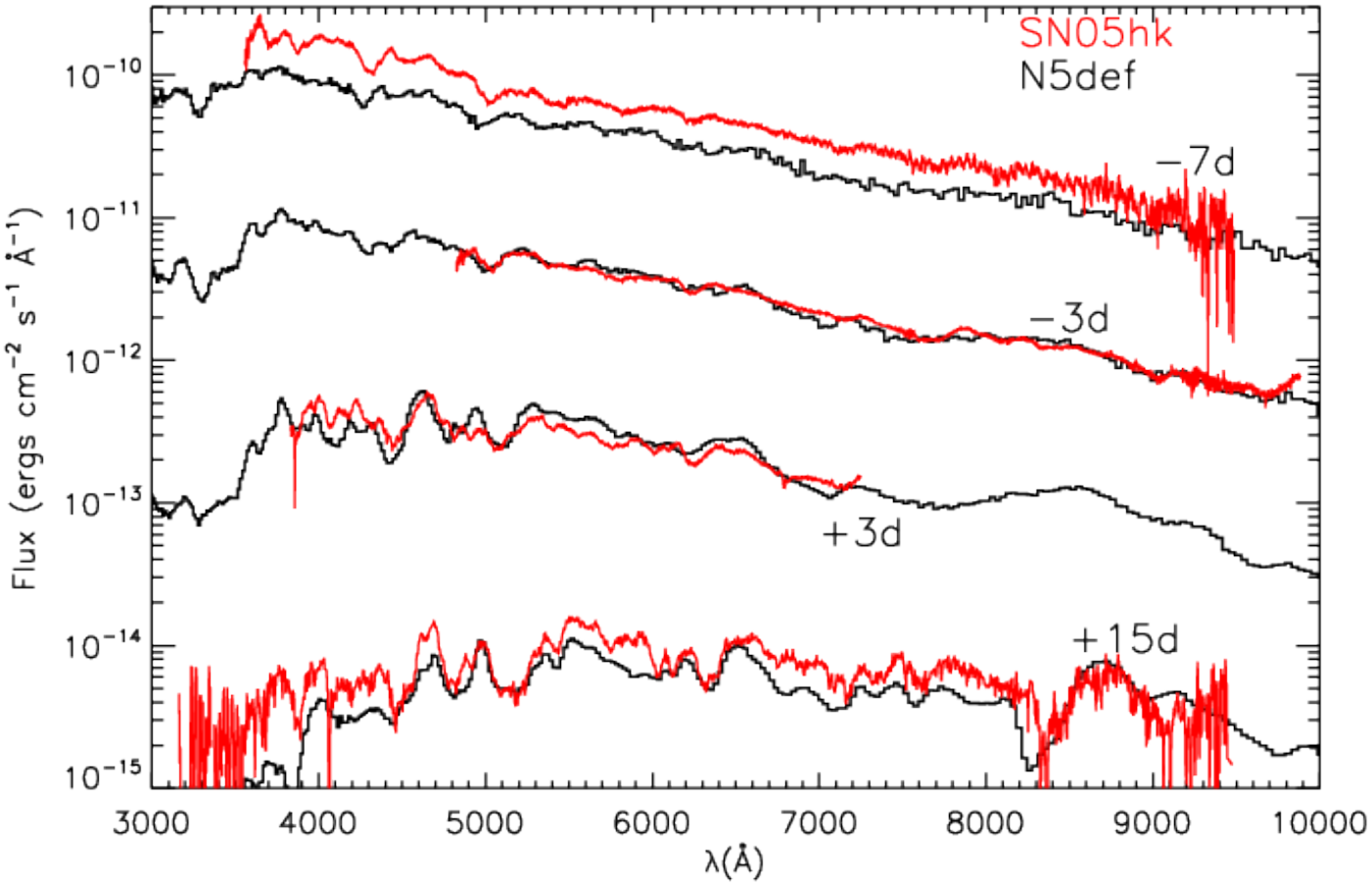
(from McCully et al. 2014)

Deflagration models



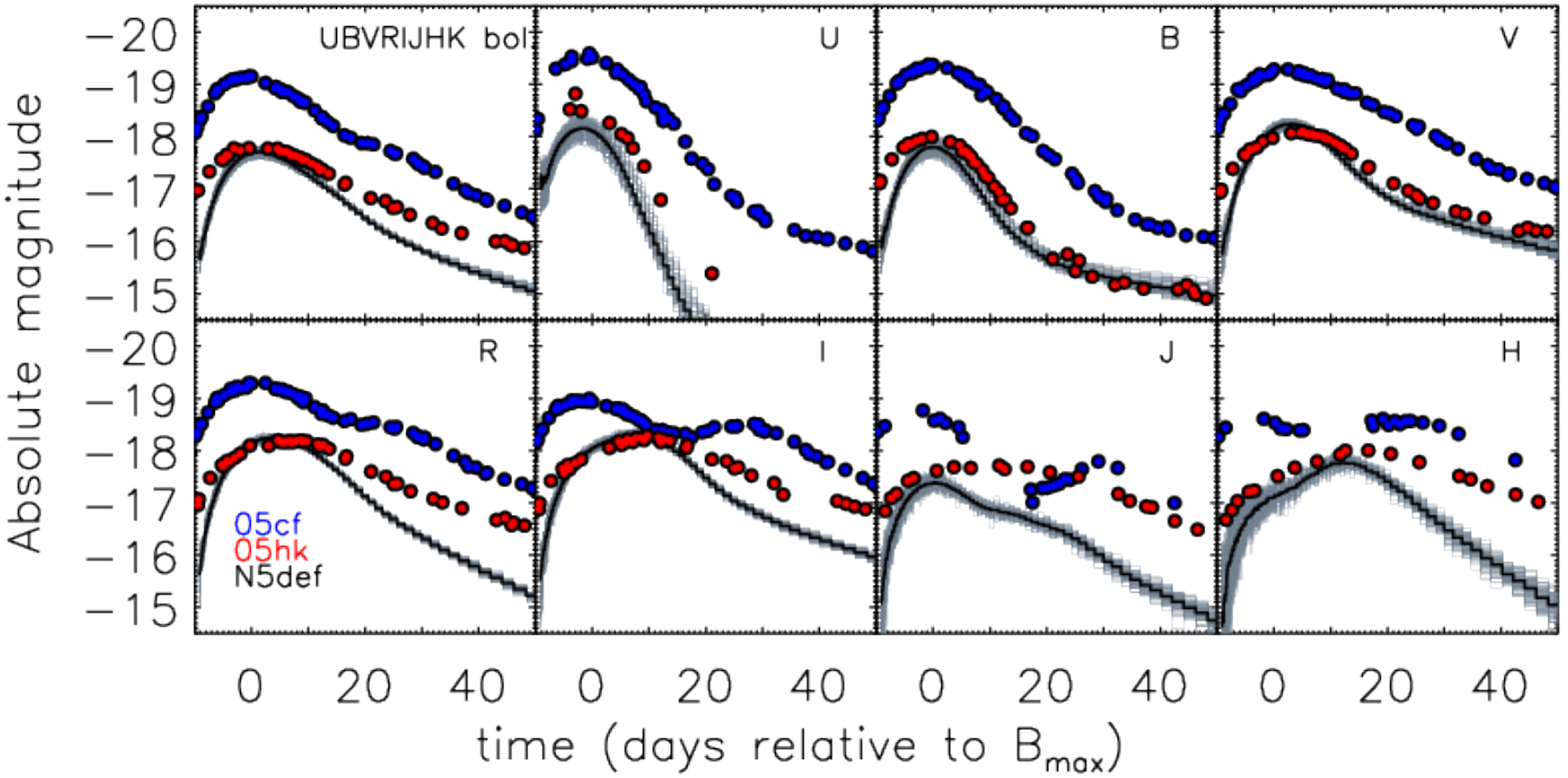
Spectra of 05hk from Phillips+07

Deflagration models



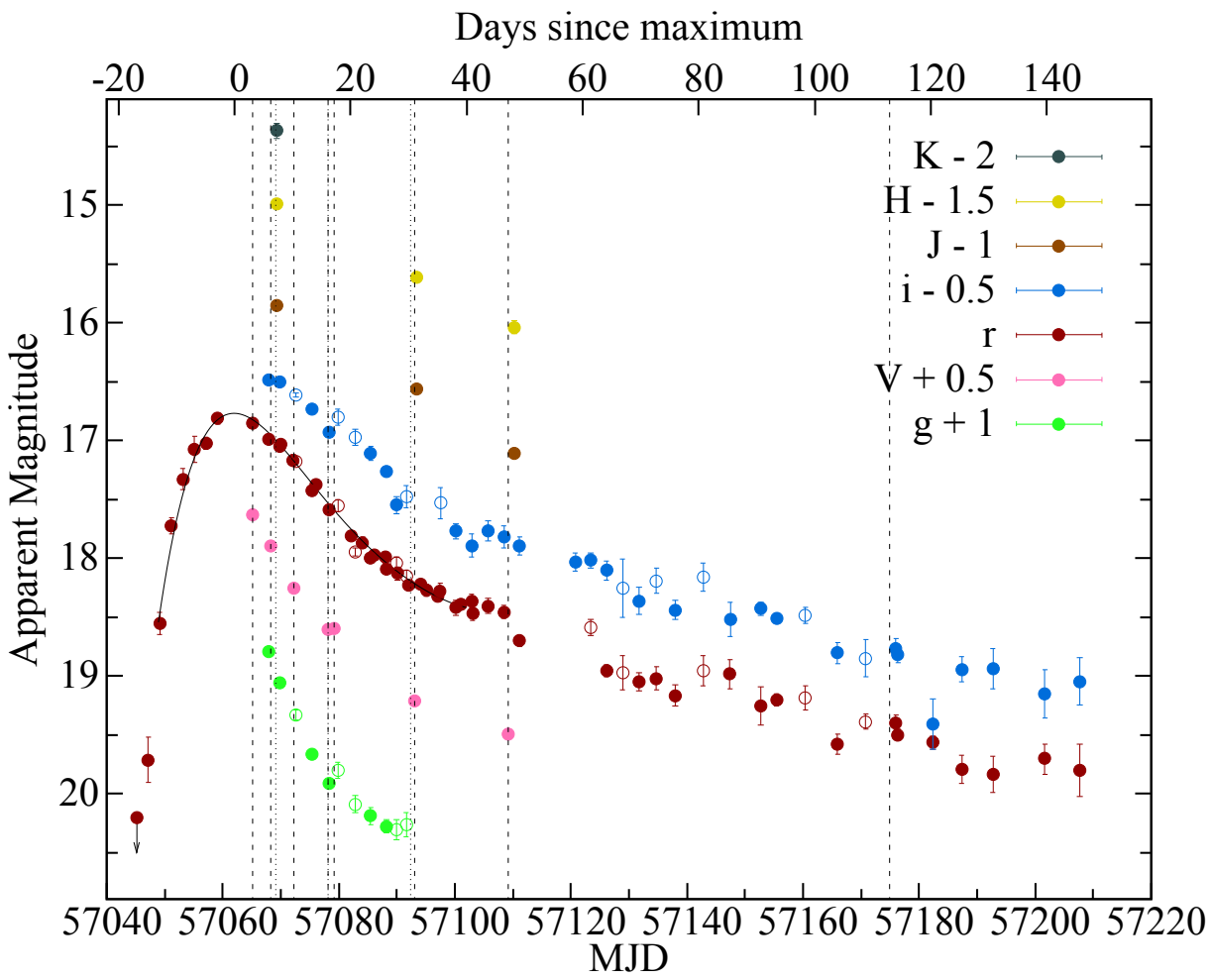
Spectra of 05hk from Phillips+07 - pretty good match to model (Kromer+ 13)

Deflagration models



N5 compared to 05hk – **late times**?

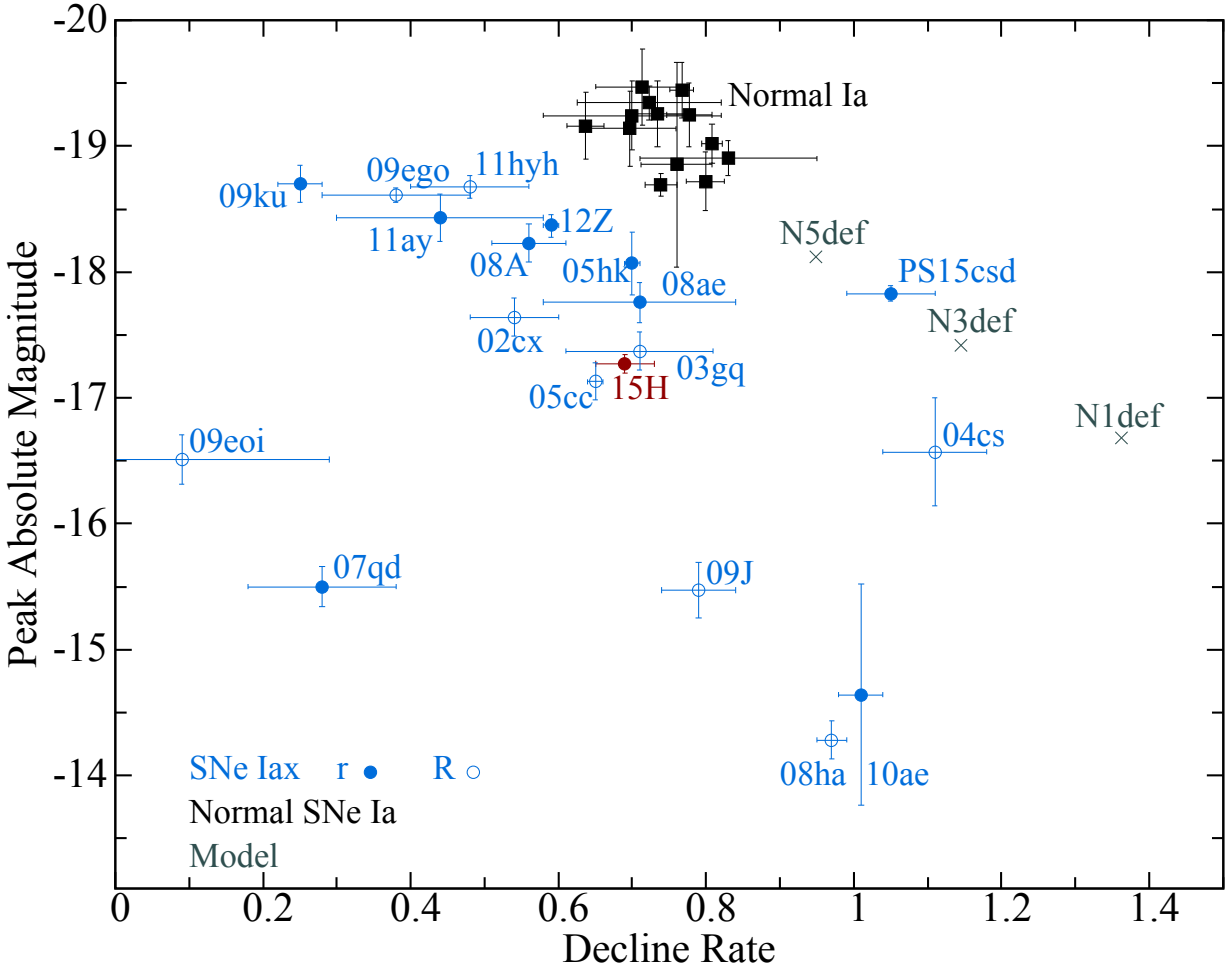
Deflagration models



Comparison extended to fainter example:

SN2015H
Magee+2016

Deflagration models



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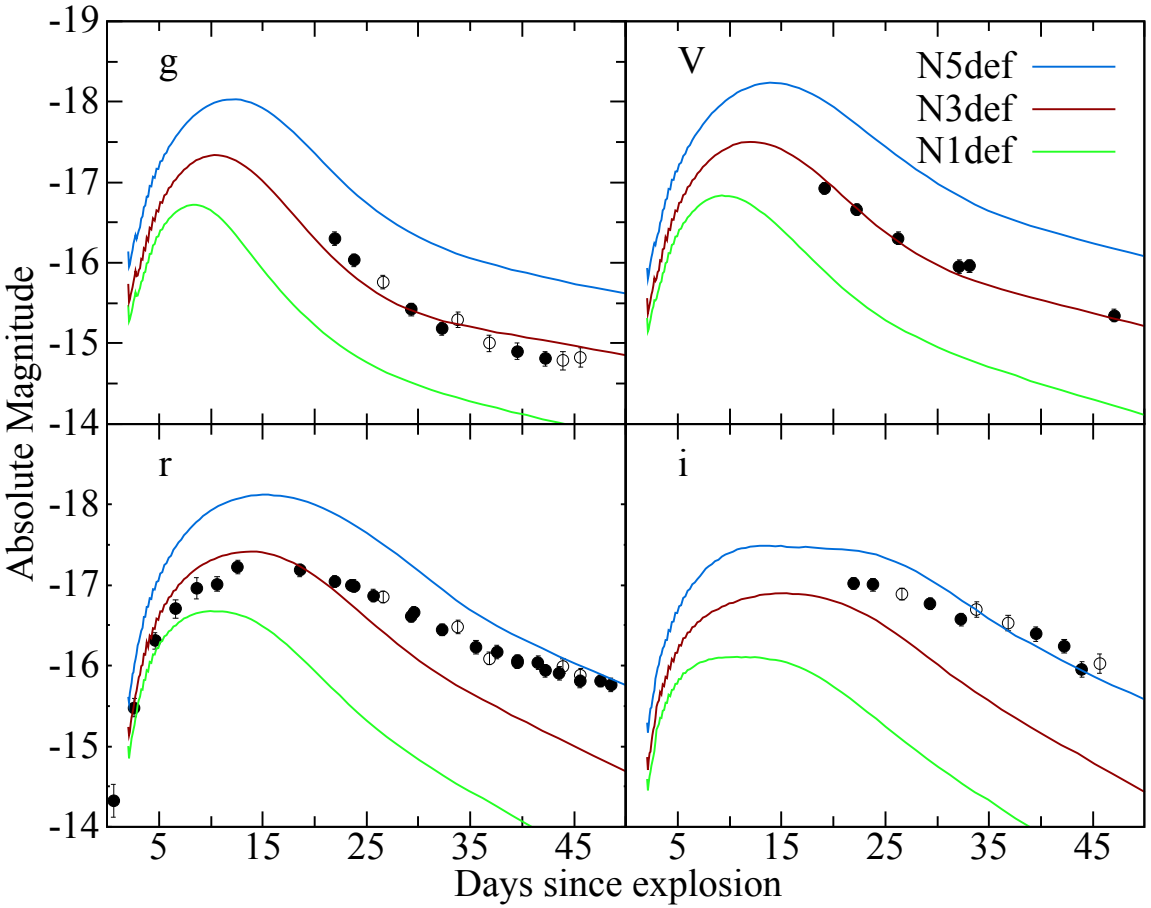
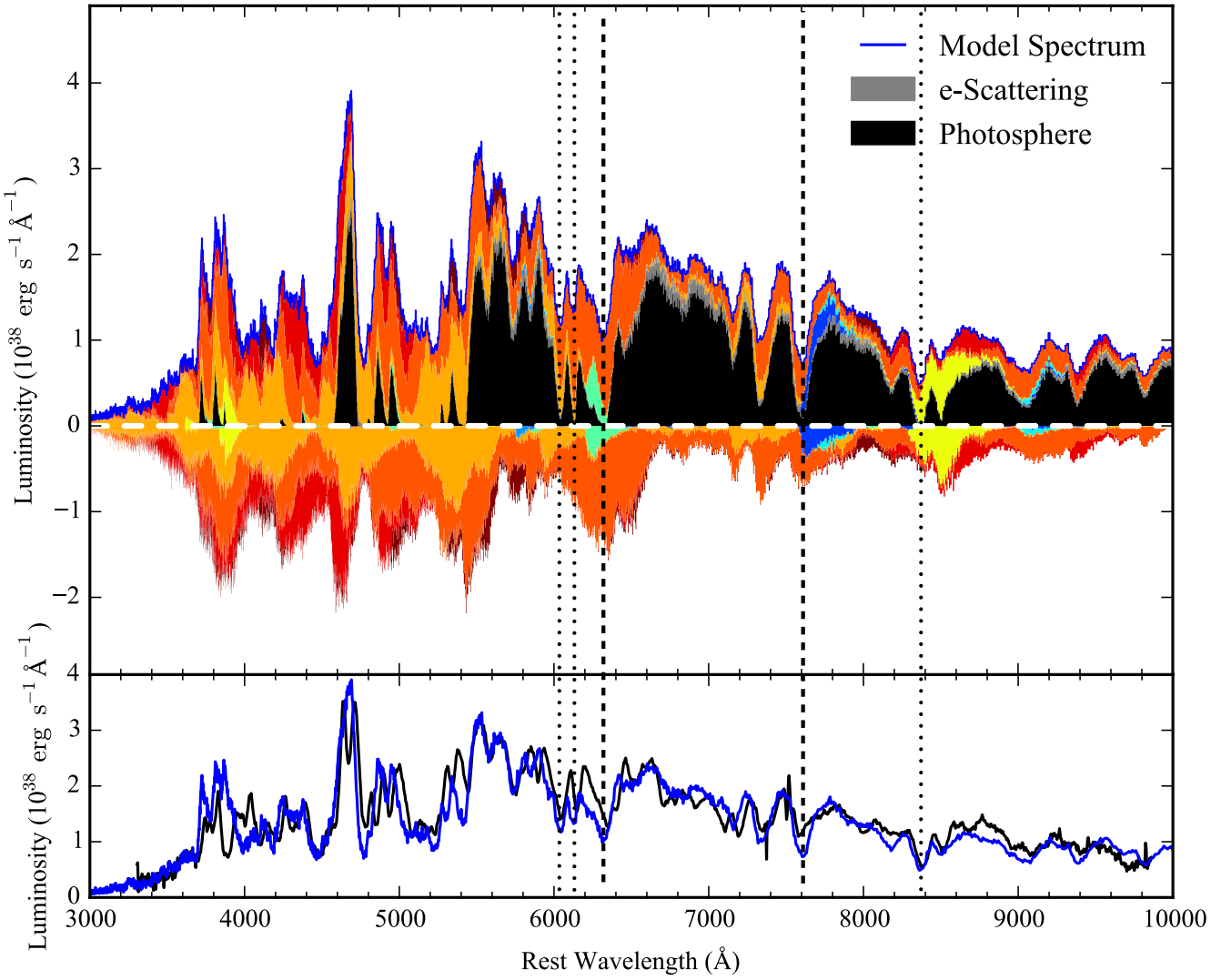
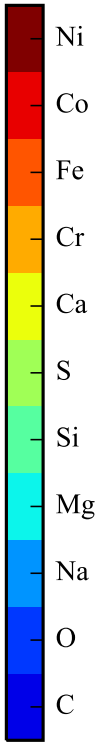


SN2015H
Magee+2016

Deflagration models





SN2015H
Magee+2016
(22 days)

Deflagration models: summary

Strengths:

- Full star, multi-D deflagration simulations – explosions occur
- Star not (always) full disrupted
- Synthetic spectra are fair matches to observed SN Iax class
- Peak luminosities (and colours) match fairly well

Deflagration models: summary

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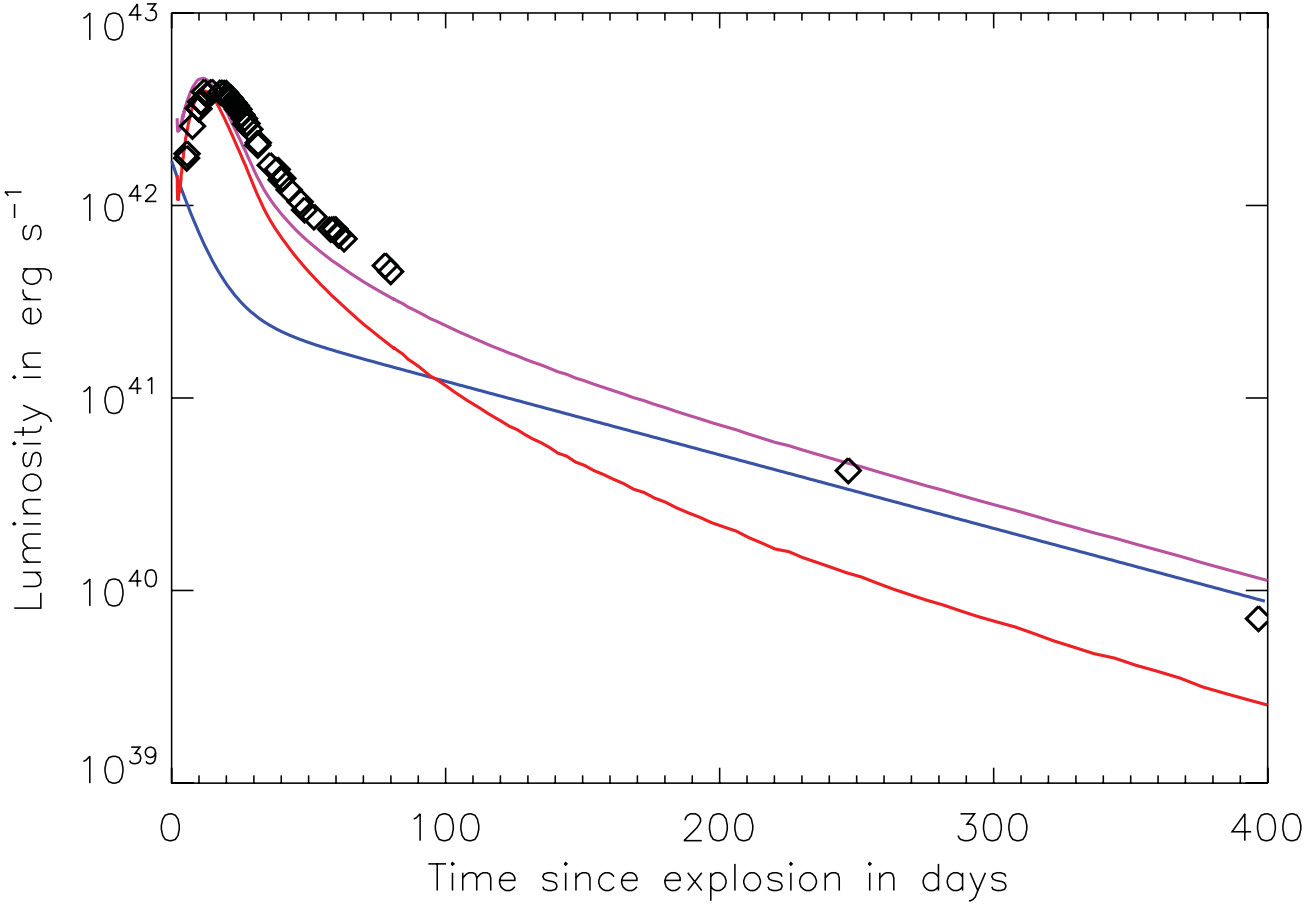
Open issues:

- Light curve timescales too fast in models: need more ejecta mass?
- Support for alternative models (e.g. PDD models; Stritzinger et al. 2015)
- Major challenge: late times
- Major challenge: very faint objects (08ha needs only ~3×10^{-3} M_{sun} of ^{56}Ni)

Deflagration model: late evolution

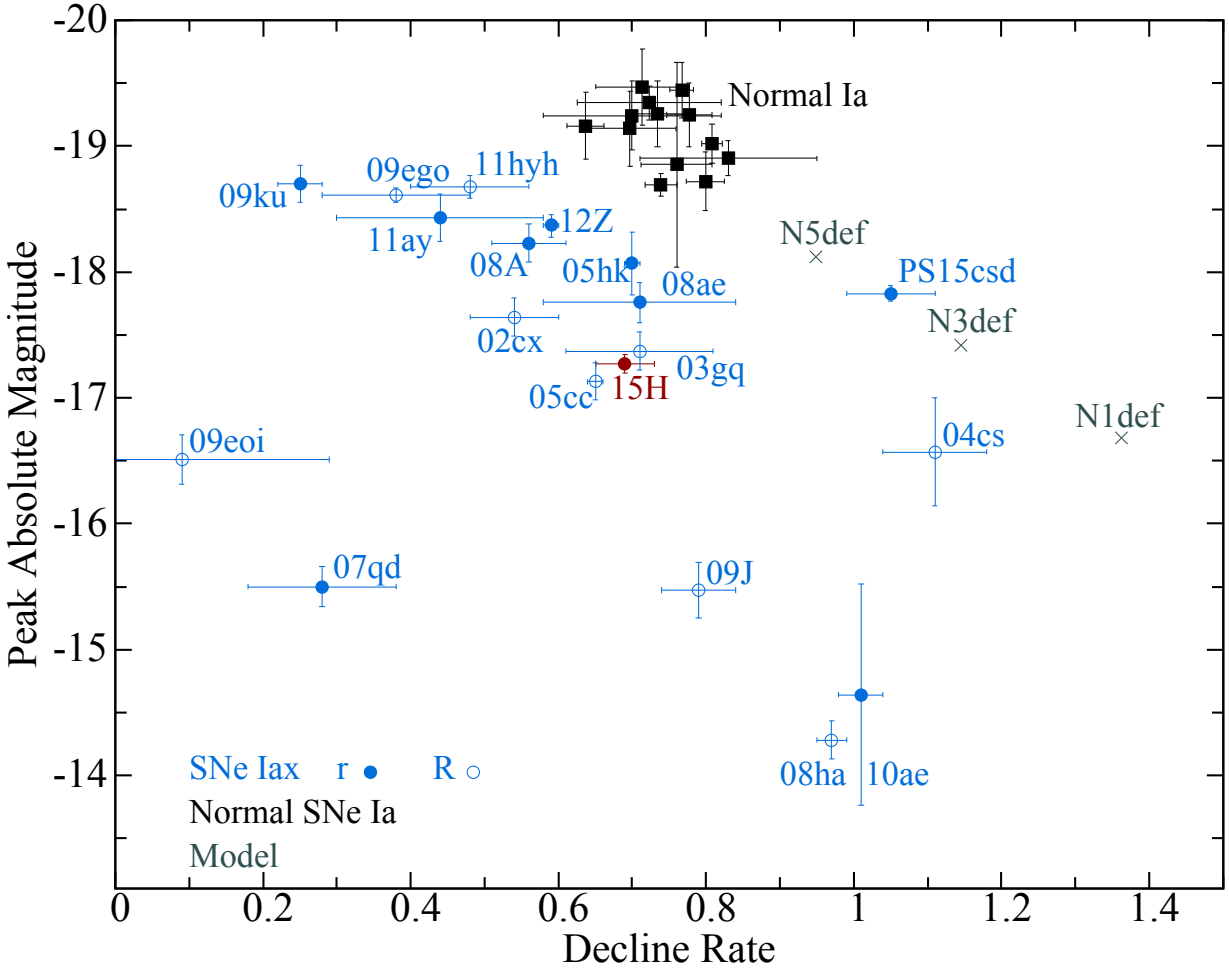


Comparison of bolometric light curve out to late times (Kromer+13)

Energy deposited in the "bound" remnant?

Jha+06, Sahu+08, Foley+16, Shen+17

Deflagration models



Comparison extended to fainter example:

Deflagration models

Conclusion:

(Jordan et al. 2012; Kromer et al. 2013, Fink et al. 2014, Kromer et al. 2015, Magee et al. 2016)

Near-Chandrasekhar mass WD deflagrations may work well for the 2002cx-like SNe Ia

… still multiple loose ends

… what are the "normal" ones?!