Type Ia Supernovae

where are they coming from and where will they lead us?

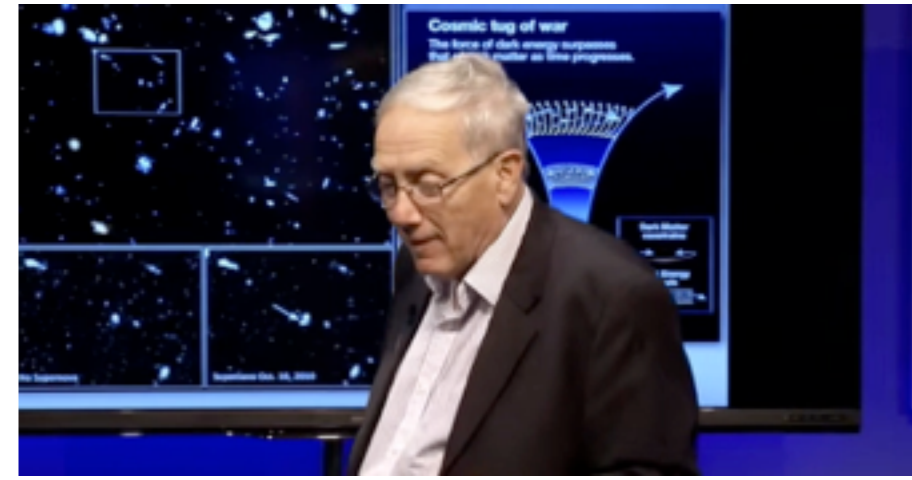
N@&O P@@

European Southern Observatory

Maoz, Mannucci & Nelemans (MMN), 2014, ARAA 52:107-70



Why?



"The fact that we do not know yet what are the progenitor systems of some of the most dramatic explosions in the universe has become a major embarrassment and one of the key unresolved problems in stellar evolution".

M. Livio (2000)

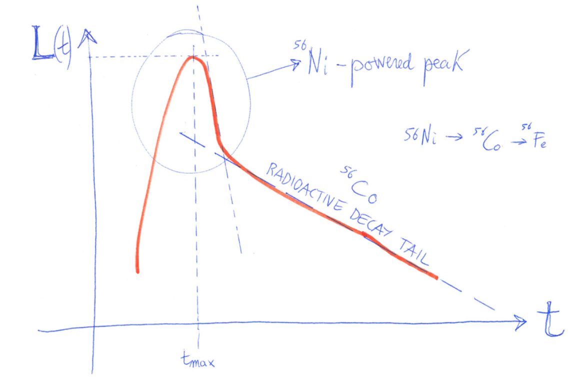
Nobody in the audience should take this as a personal offence

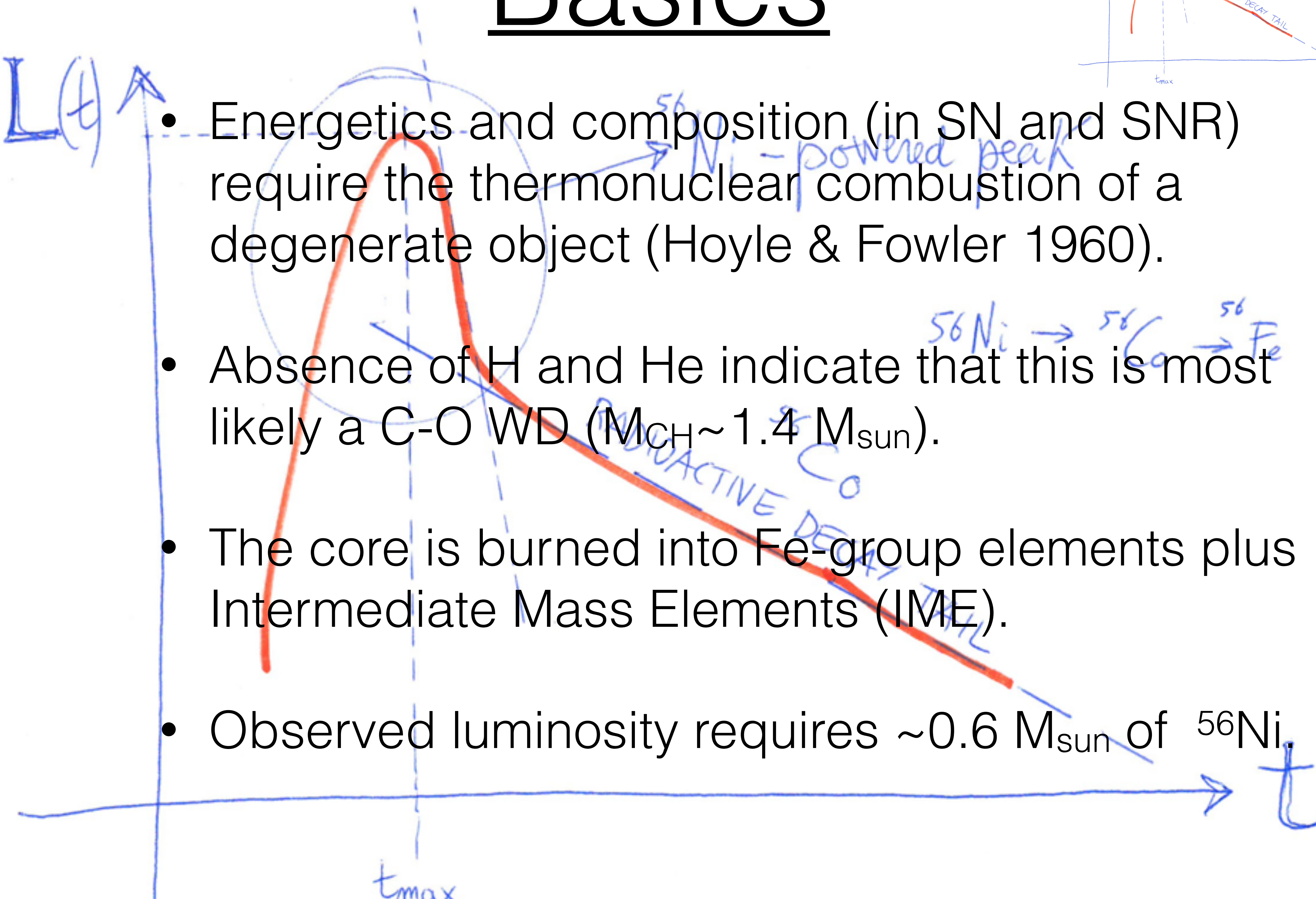
Key Facts

- Type Ia SNe do not show H lines;
- They are homogene-ous[izable] in terms of peak luminosity, spectra and light curve shape;
- They appear in elliptical galaxies (CCs do not).

This rules out the core-collapse of massive ($M>8\ M_{sun}$), young stars.

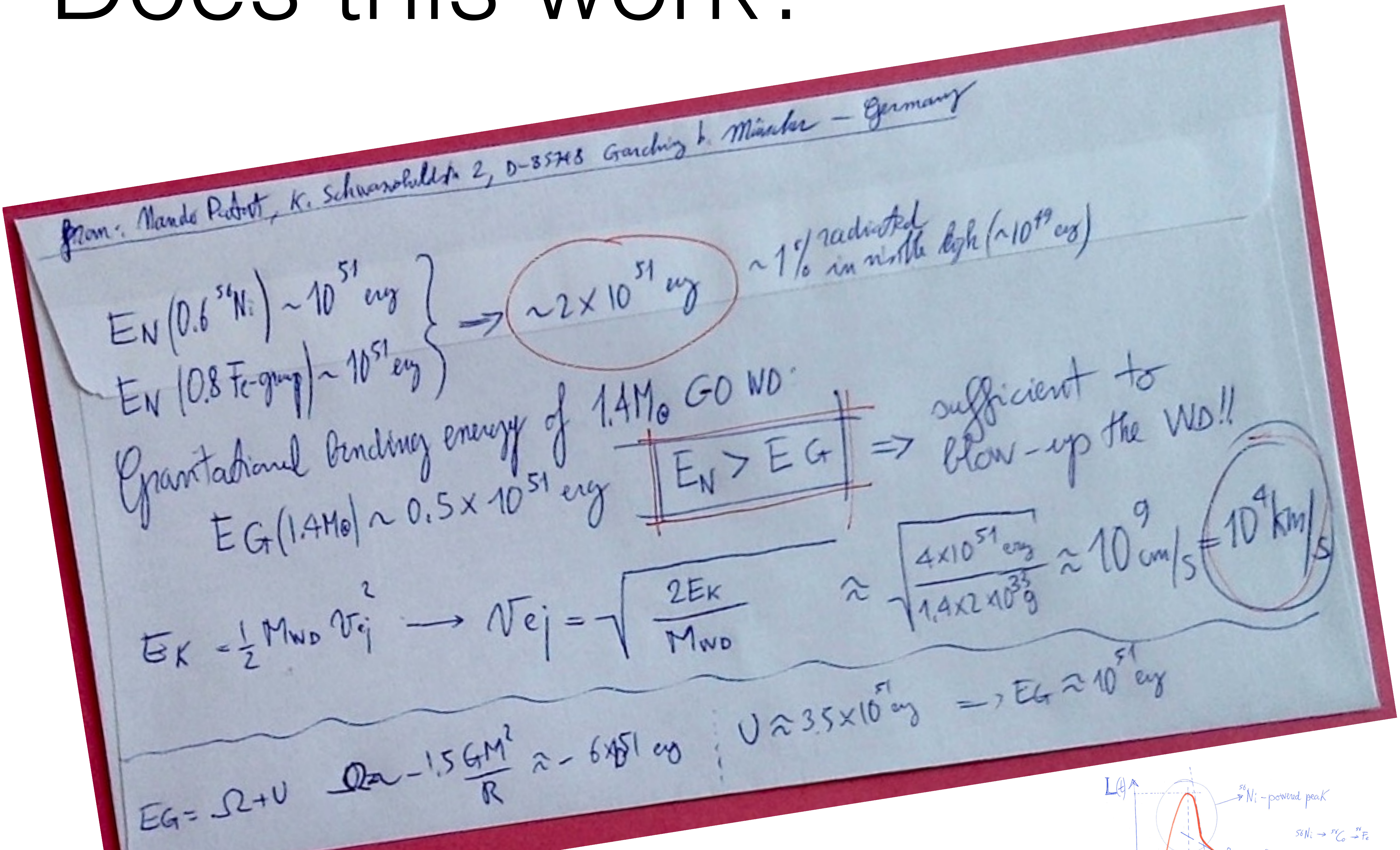
Basics

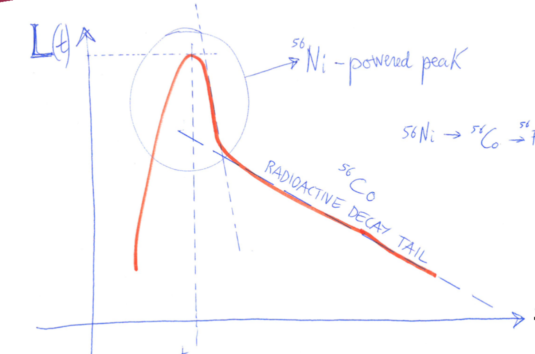




- Energetics and composition (in SN and SNR) require the thermonuclear combustion of a degenerate object (Hoyle & Fowler 1960).
- Absence of H and He indicate that this is most likely a C-O WD (M_{CH}~1.4 M_{sun}).
- The core is burned into Fe-group elements plus Intermediate Mass Elements (IME).
- Observed luminosity requires ~0.6 M_{sun} of ^{56}Ni.

Does this work?





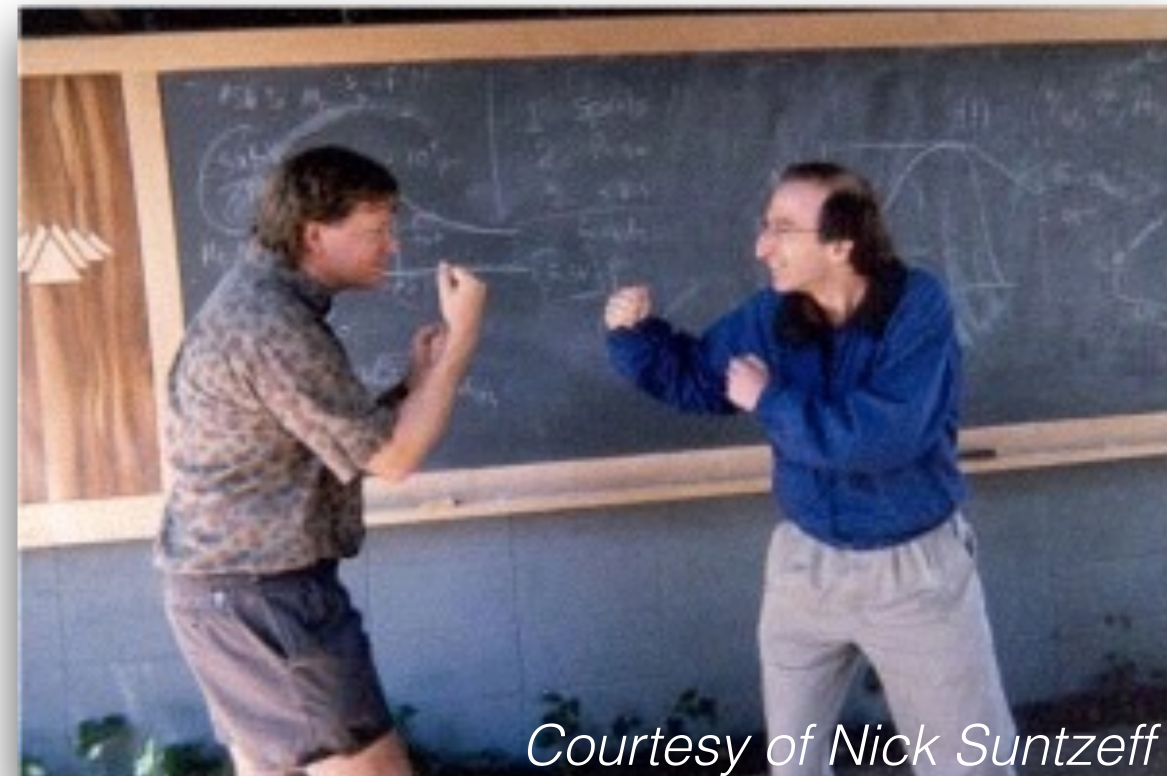
The consensus statement

SNe Ia represent thermonuclear disruptions of mass accreting C-O WDs, when these approach the Chandrasekhar limit and ignite carbon.

Somehow, Sometime, Somewhere

Growing a WD to the critical limit is not that easy, though…

40^{+} years, and counting…



Despite SNe Ia are used for "precision cosmology", the nature of the progenitor system[s] is still unknown.

This sentence is very frequently found in Ia papers and proposals…

The Ia progenitor problem

An observational approach

- Populations of potential progenitors
- Pre-explosion imaging of [nearby] explosion sites
- Explosion properties carrying progenitor's imprints
- CS environment
- SN remnants (diffuse [and compact])
- Explosion rates as f(t) and f(x) and BinPopSyn (BPS)

Candidate Populations

- Recurrent novae (SD)
- Supersoft X-Ray sources (SD)
- Rapidly accreting WDs (SD)
  See work by Gilfanov+Woods
- He-rich donors (SD)
- Binary WDs (see Na'ama Hallakoun's talk)

One thing is speculating about the existence of binary systems with a $M \sim M_{CH}$ accreting WD. Another is looking around for real examples. And see what they tell us…

RNe

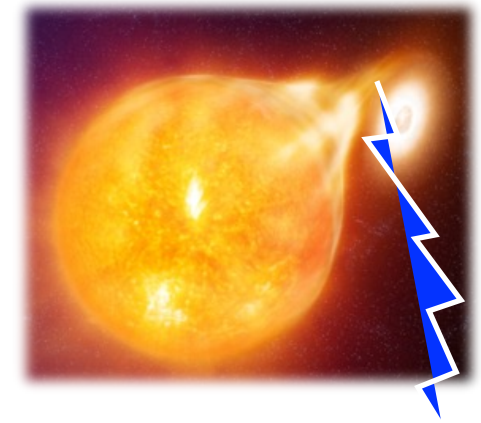
MS companion	RG companion	RG companion
		

All contain WDs claimed to be close to M_{CH}

BUT:

- Is the WD really a C-O WD? If O-Ne-Mg, then …
- Is it increasing in mass? In outburst it may loose…
- And, briefly, there are not enough in the MW…

Super Soft X-Ray Sources



- SD systems are supposed to spend some Myr in a phase of steady nuclear burning while accreting material from the donor. In virtue of this fact they should be detectable as **s**uper-**s**oft X-ray **s**ources (SSS; Di Stefano 10).
- Under certain conditions, also DD systems may undergo a SSS phase, with much lower luminosities (Yoon+07, Di Stefano 10).
- The detection of a SSS in coincidence with a SN site would allow a direct study of [some of] the progenitor's properties.
- First applied to SN2007on (Voss&Neelemans 08). Detection in pre-explosion imaging claimed, but not fully convincing (Roelofs+08).
- If the bulk of Ia is to be explained by SSS, only 1% of the WD mass accretion takes place in this phase to match the observed Ia rate in the MW…

Binary WDs

Courtesy of F. Röpke

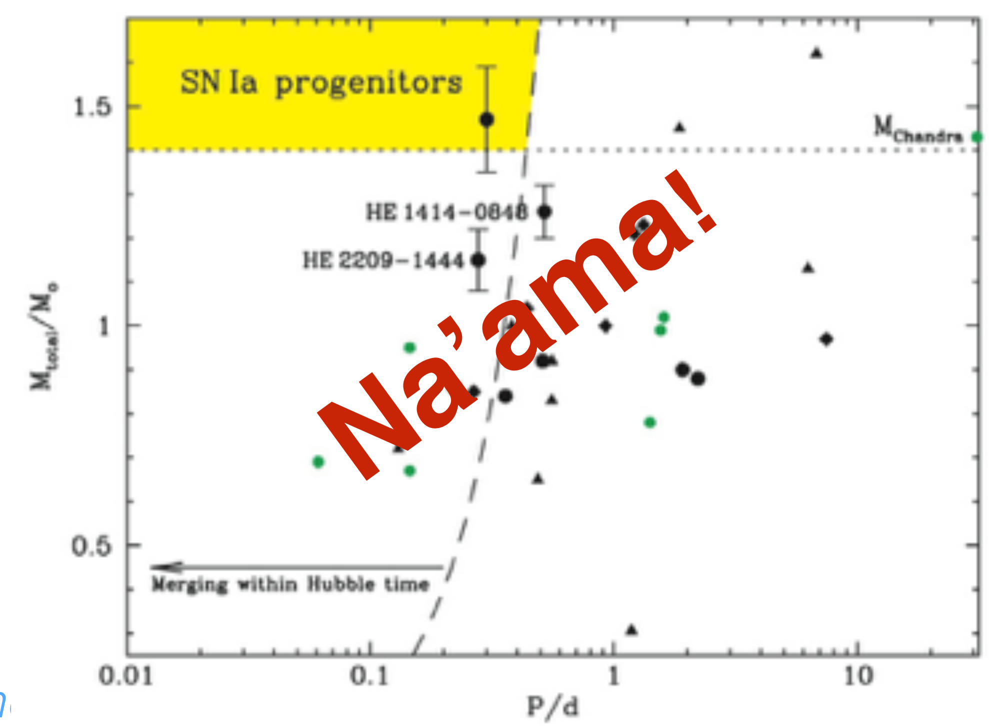
This was a disfavoured scenario until a few years ago, because:

- Not clear whether there were enough suitable systems in nature;
- Because of the ranges of WD masses, this was seen as something against the observed homogeneity of SNe Ia;
- The merger was suspected to result into an Accretion Induced Core Collapse (AICC), leading to a neutron star.

First large-scale attempt **ESO-SPY** (Napiwotzki+04).

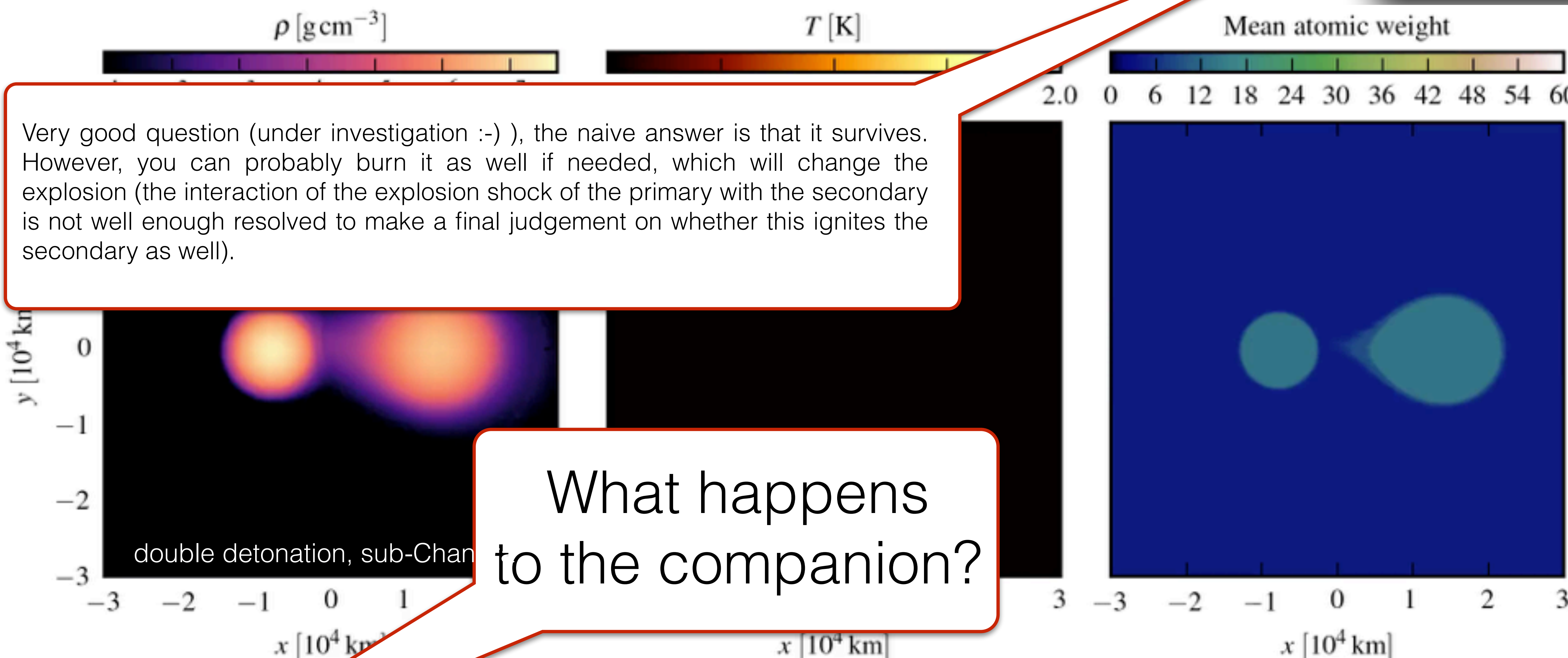
~1000 WDs and 1 candidate found.

See also Badenes+09, Maoz & Hallakoun 17.



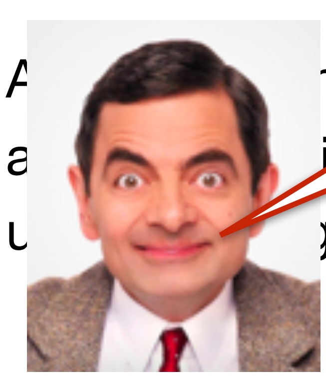
Final evolution of two C-O WDs (0.7+1.0 M_{sun}) with a thin He envelope (10^{-2} M_{sun} each)

Courtesy of Rüdiger Pakmor



Very good question (under investigation :-)), the naive answer is that it survives. However, you can probably burn it as well if needed, which will change the explosion (the interaction of the explosion shock of the primary with the secondary is not well enough resolved to make a final judgement on whether this ignites the secondary as well).

What happens to the companion?

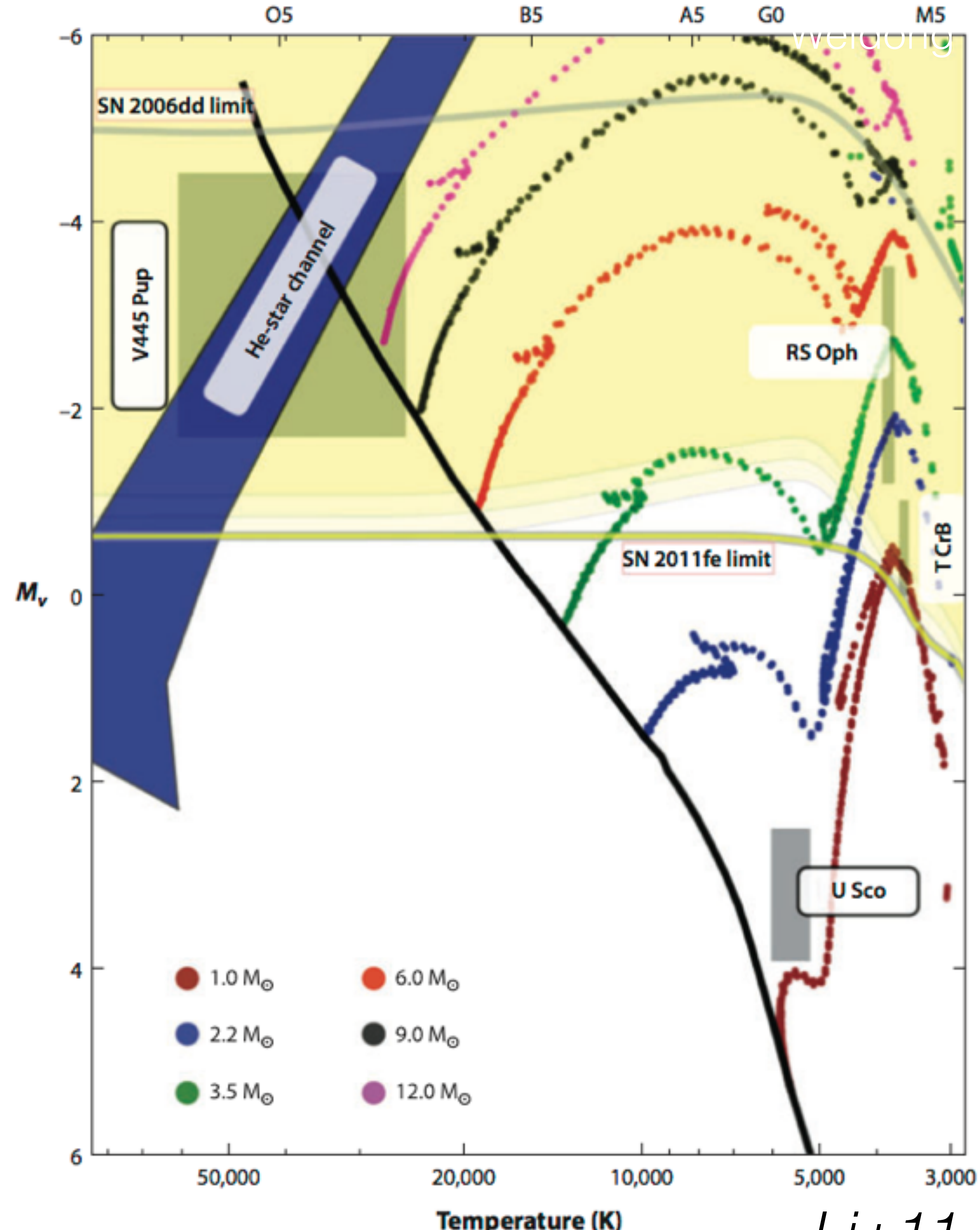


A m the s ndary on the primary leads to dynamical effects on the surface of the primary that ignite a i . The He-detonation wraps around the primary WD and sends a shock into its C-O core that u ging into a single point ignites a carbon detonation in the CO core and the primary WD explodes.

Pre-explos

The case of 2011fe in M

- Very close-by (6 Mpc), very (few hours), standard Ia
- Unique opportunity to probe earliest phases in great det a wide wavelength range.
- Rich pre-explosion, HST da
- Red giants at the locat the decade before the
- Stars with M>3.5Msun a
- MS or sub-giant donor
- A RG is also excluded



Li+11

Interlude on WD spin-up/down

- WD rotation has been invoked in the spin-up/spin-down scenario (Di Stefano10, Voss&Claeys11, Justham11, Yoon&Langer04,05, and Hachisu+12) in the context of SD progenitors.
- A WD that has grown in mass, even beyond M_{CH}, could be rotation-supported against collapse and ignition during the accretion.
- The traces of the process (including the donor) could disappear. DD mergers explosions delayed by rotational support have also been proposed (Piersanti +03, Tornambè&Piersanti13).
- Differential rotation seems to be required by models.
- There may be a population of rapidly spinning WD, waiting to spin-down and eventually explode. But…

Quoting MMN14: *Observationally, a spin-up/spin-down scenario could potentially "erase" many of the clues we discuss in this review.*

Explosion properties

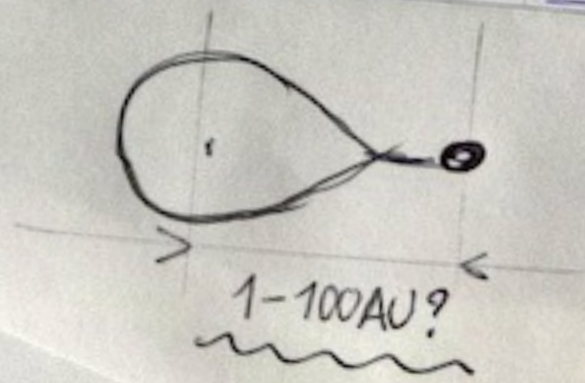
A number of aspects seen during the explosion relate, often ambiguously (*&^!@#*), to the progenitor properties:

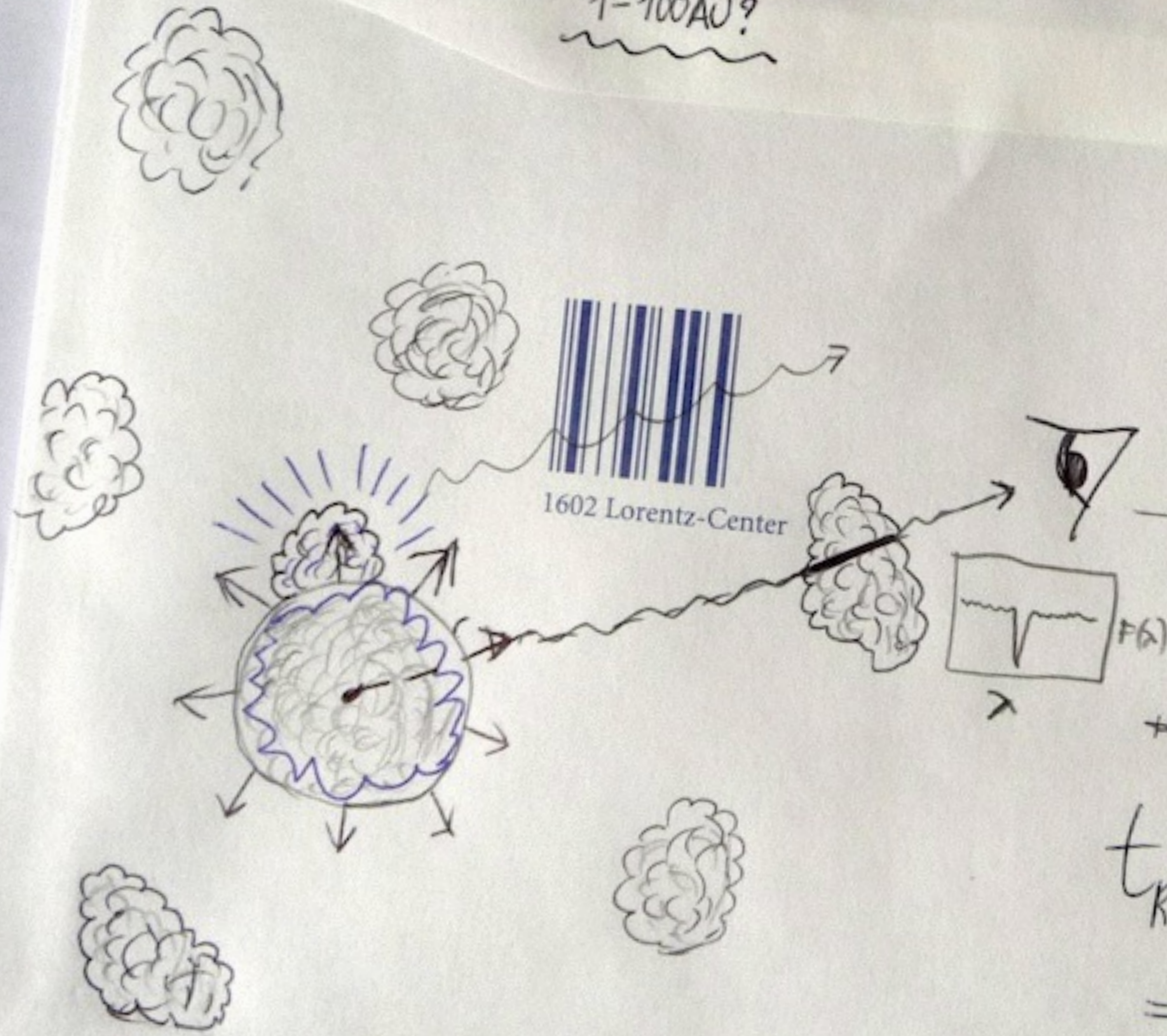
- Early light curve and spectral evolution
- Shocks on [possible] companion star
- Ejecta asymmetries (polarimetry)
- Emission from hydrogen
- Radio, X-Ray CSM emission
- Narrow time-variable absorptions
- CS Dust and light echoes (specphot and polarimetry)

never detected

2011fe

- Using optical and UV observations, Nugent+11 excluded the presence of shock effects from SN ejecta hitting an alleged companion. A RG is definitely excluded.
- Bloom+12 ruled out even a MS, concluding that the DD scenario is the most probable <u>for this one object</u>. Unless spin-up/down is there…
- For the first time provide a direct upper limit to the size of the exploding object, $R<0.02R_{sun}$ (either a WD or a NS).





$v_{ej} \sim 10^4$ km/s

$\approx 10^5$ s/day

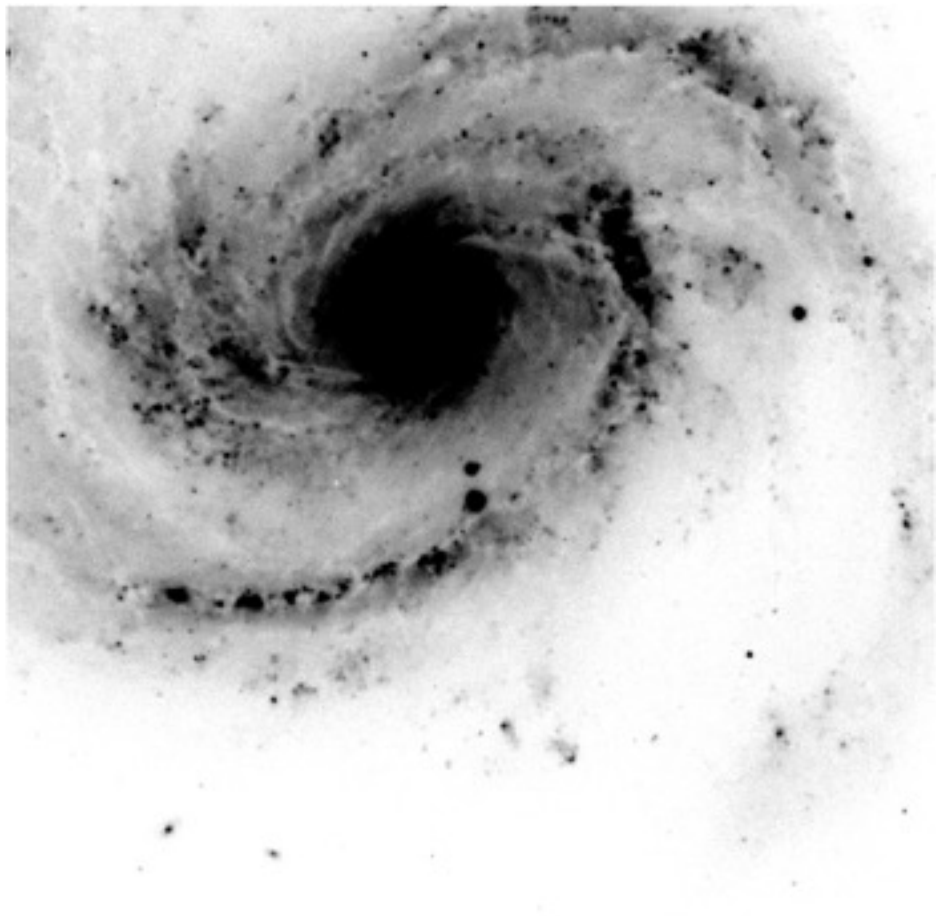
$\Rightarrow \sim 10^9$ km/day

1.5×10^8 km/AU

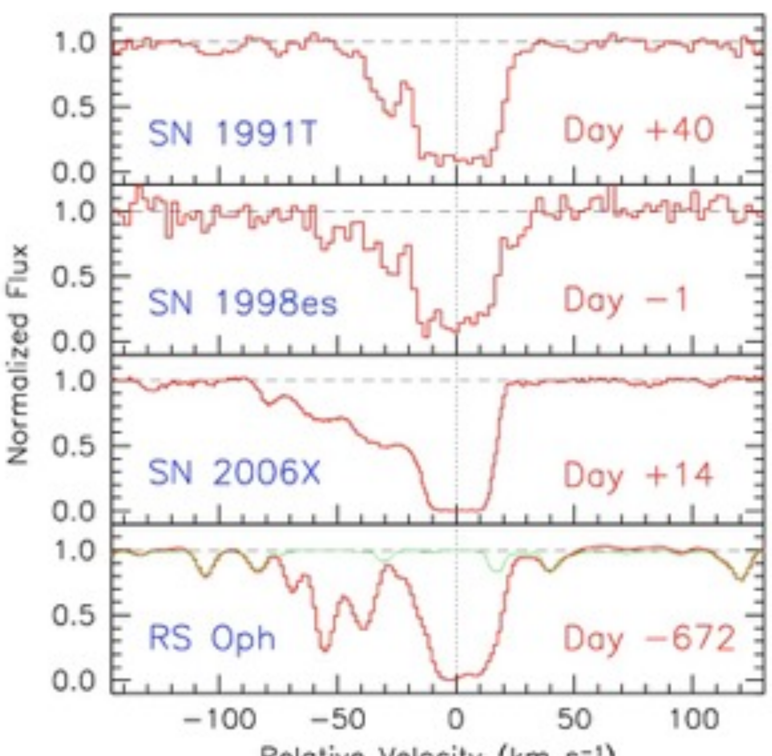
$\Rightarrow \sim 7$ AU/day

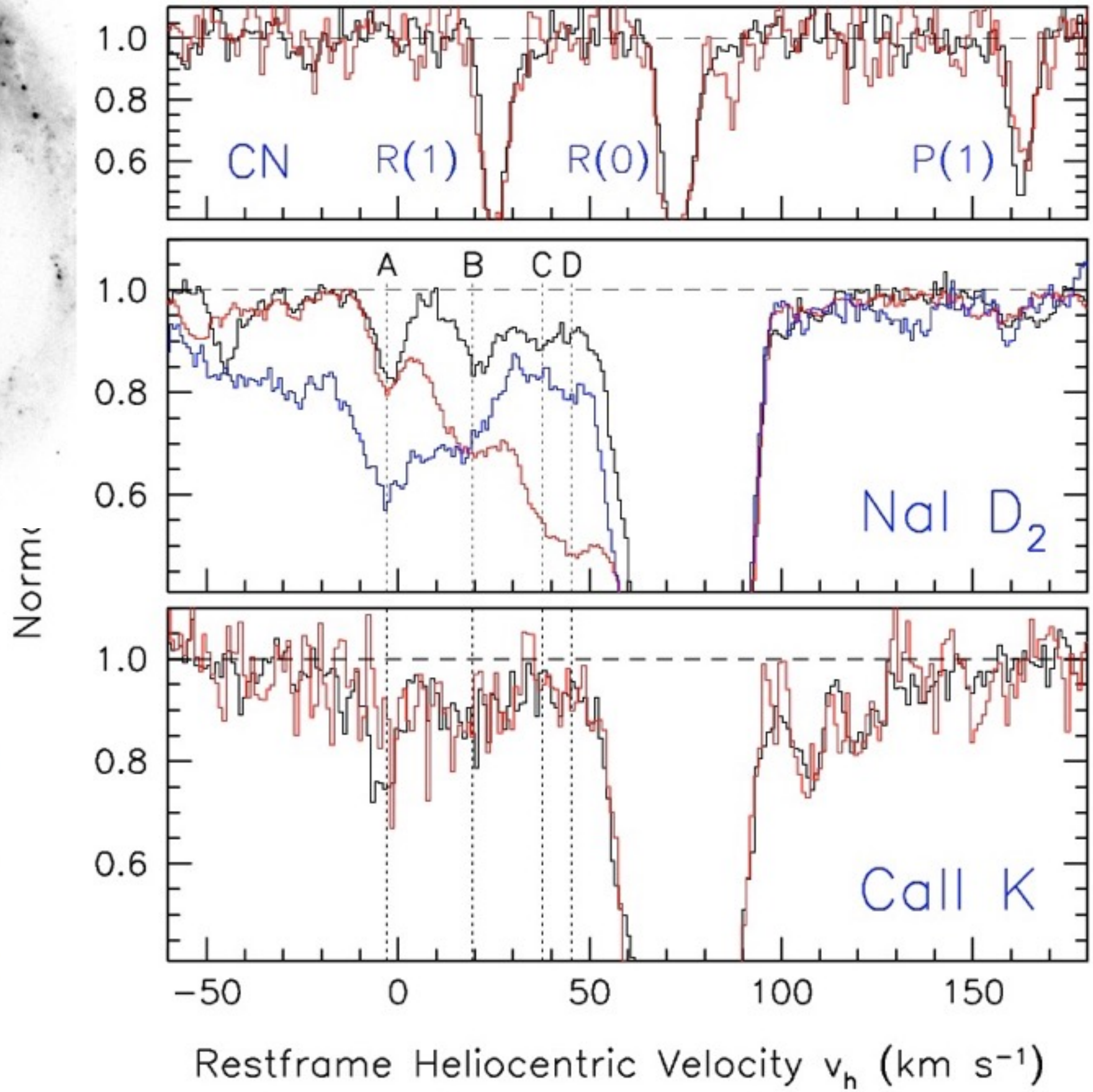
$t_{RISE} \sim 20^d$

$\Rightarrow R_{ej}(max) \sim 140$ AU



SN2006X

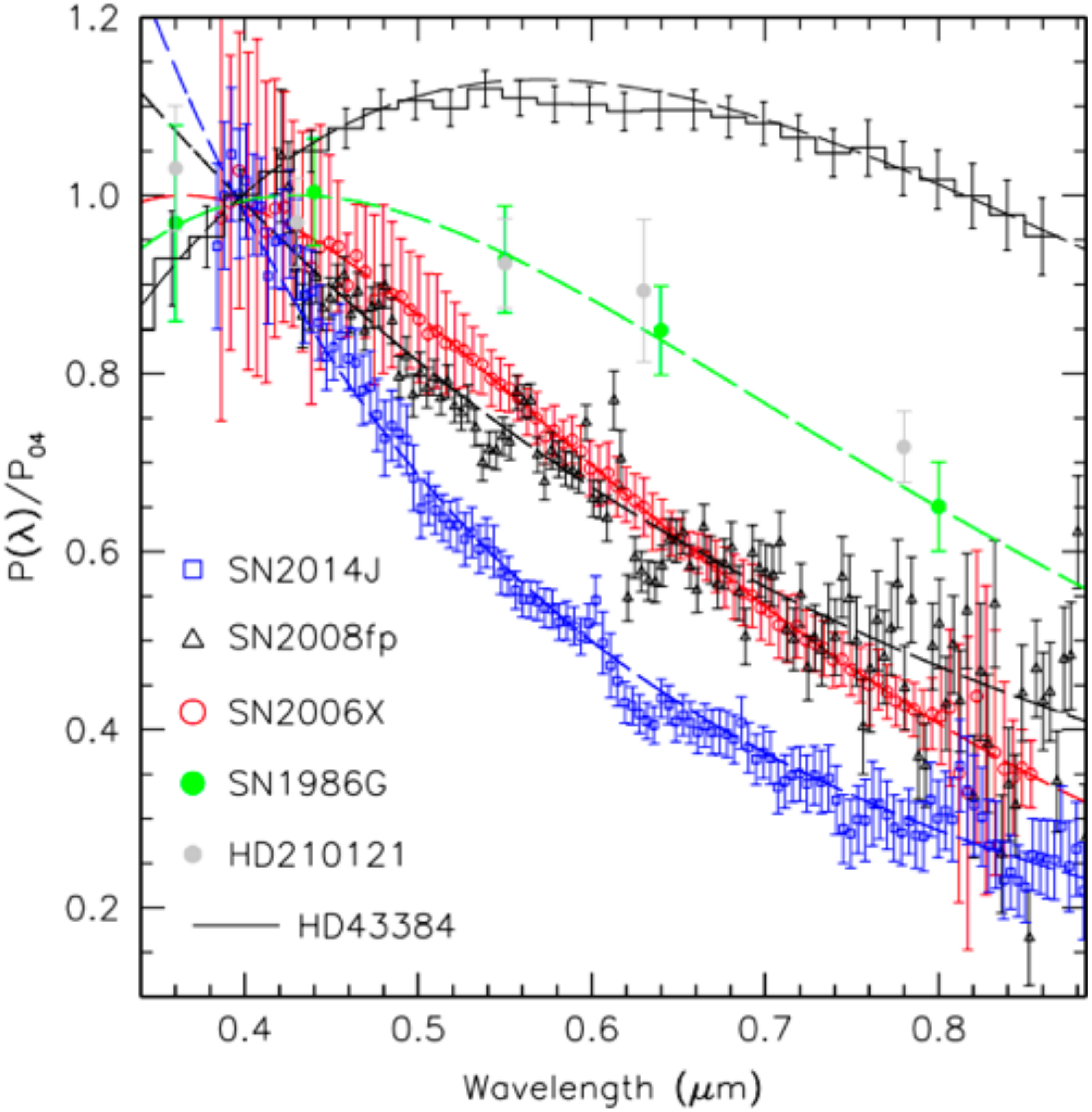




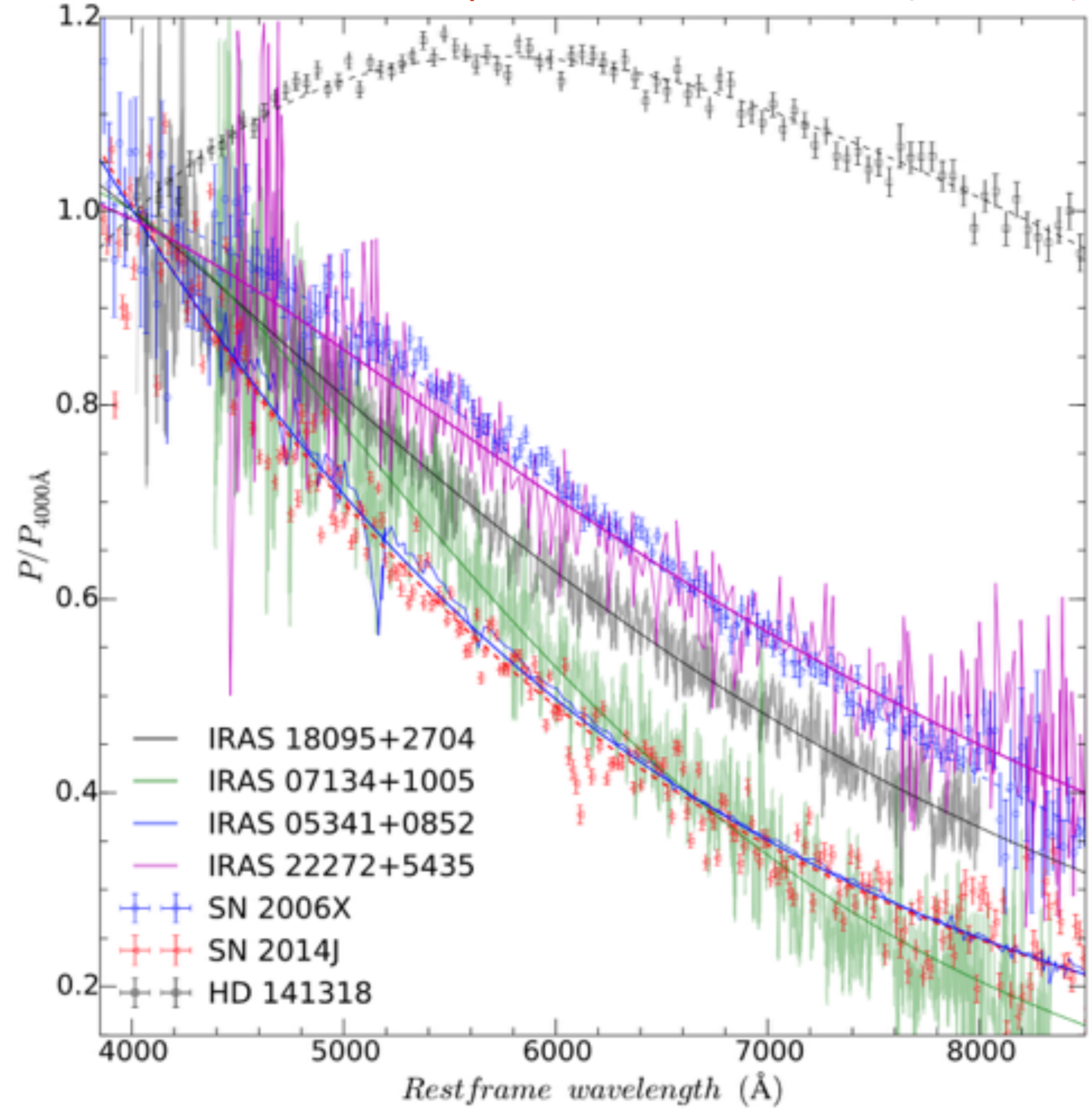
Patat+07

CS Dust Properties

post-AGB stars (PPNe)



Patat+15



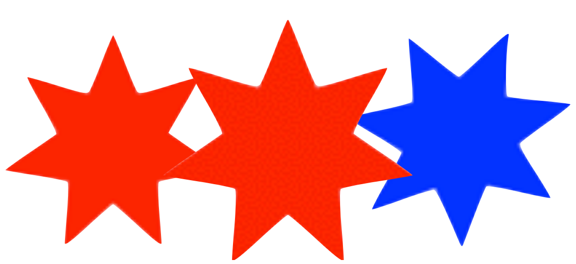
Cikota+17

Surviving companions

One difference between DDs and SDs is, of course, the presence of a companion that becomes unbound after the explosion. And it runs away…

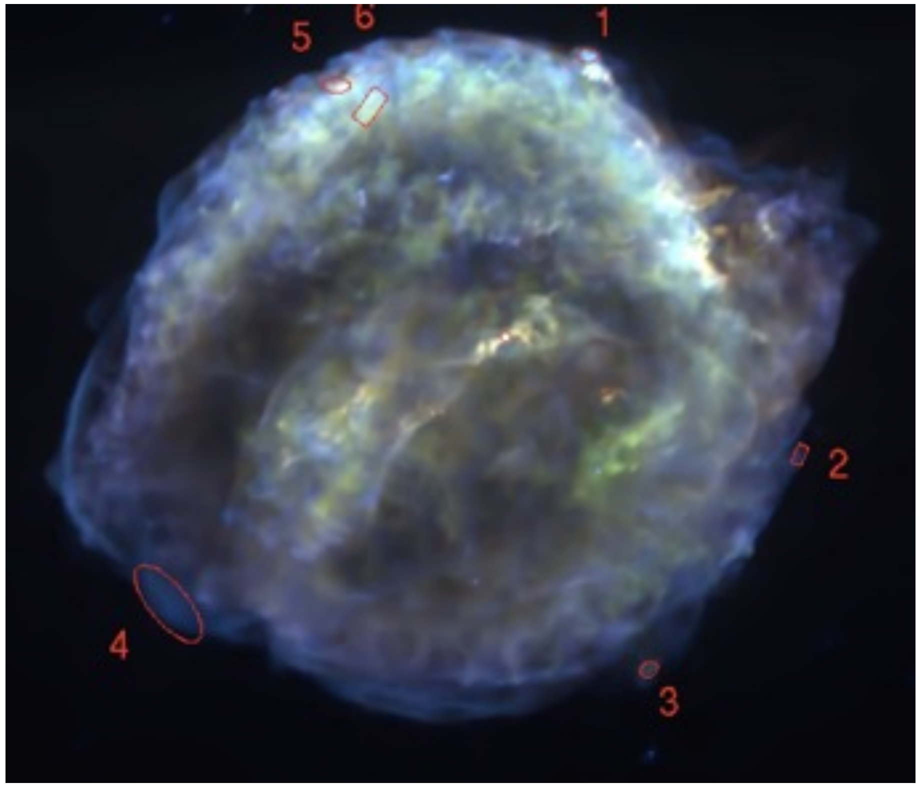
Kerzendorf+
La Puente+

- The companion star survives the explosion
- It gains an anomalous transversal speed
- It acquires an anomalous rotational speed
- It probably gains a weird chemical composition in the atmospheric layers (ejecta pollution)

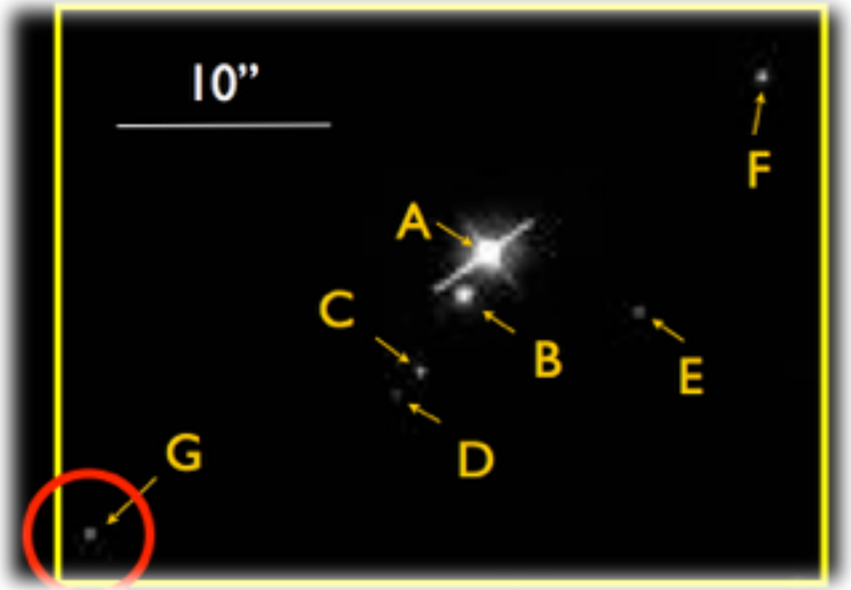


Search historical SNRs for weird composition, fast moving, rapidly rotating stars not far from the explosion center.

no star <=> no SD



- First claimed detection Tycho's star G (La Puente+97)
- Not confirmed by Kerzendorf+09,12
- Re-stated (Bedin+14)

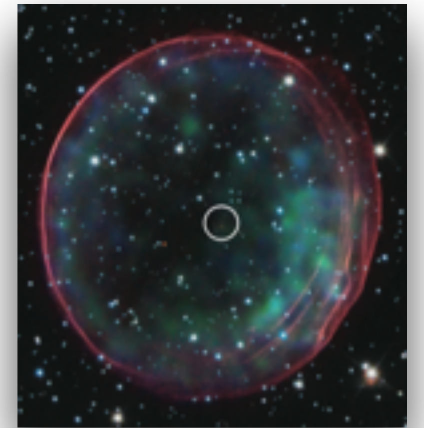


- No detections in SN1006 (Kerz+13), SNR0509-67.5 (Schaefer&Pagnotta12), Kepler (Kerzendorf+14)
- **No convincing evidence so far**

SN Remnants

The idea is to look for possible interactions between the remnant and pre-explosion material, and to compare to hydro-predictions

- In the SD scenario one expect a cavity to be blown in the ISM (3-30 pc) during the fast-wind phase.
- Such cavity was not detected in 7 type Ia SNR (Badenes+07).
- X-ray observations consistent with a uniform ISM density. So, either no fast-wind or accretion stopped well before explosion.

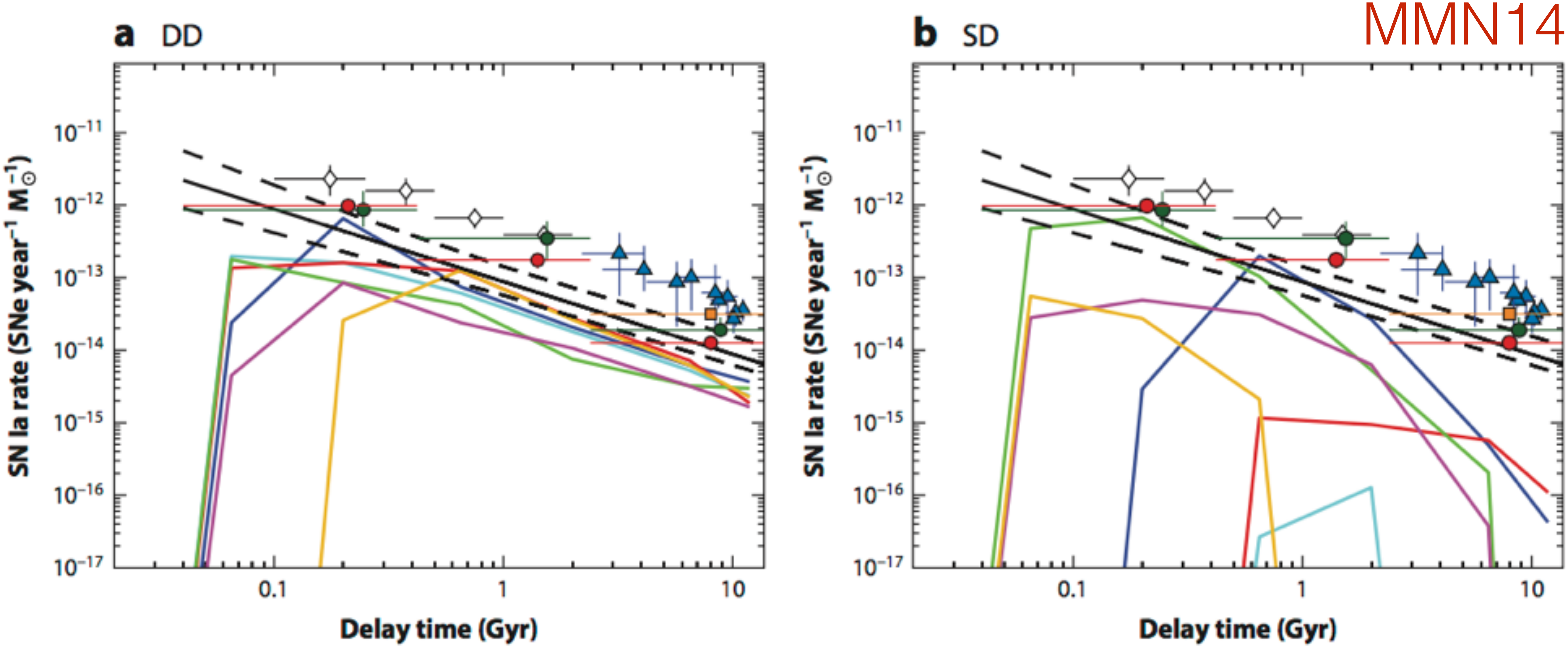


SN rates and BPS

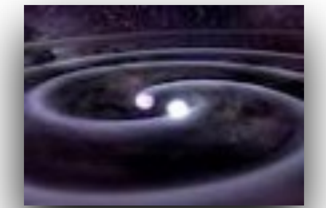
See Chris Pritchet's talk

- The Galactic Ia rate is known (~5x10^{-3} yr^{-1}). This can be used to constrain the progenitor scenarios using Binary Population Synthesis (BPS).

MMN14



so that different DTDs produced by BPS (or parameterised models) can be compared to the observed rates.

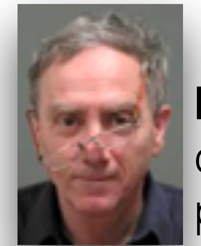


From underdog to favorite

- The paradigm has changed, both from the observational (surveys) and the theoretical (3D simulations) point of view.
- The DD scenario has become much more physically viable and popular.
- BPS calculations and surveys indicate that the merger rate is compatible with the observed Ia rate in the MW.
- C-O + C-O mergers are likely too rare. This requires sub-Chandra or C-O + He WD mergers.
- It remains to be seen whether this explains the bulk of normal Type Ia in terms of observed properties.

Is this it?

A few expert opinions

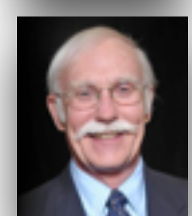


Mario Livio :A review of all the proposed models reveals that each one of them still encounters a few significant difficulties. Consequently, the inescapable conclusion may be that Type Ia supernovae can be produced by a number of progenitor systems.

Kenichi Nomo … basic observed
features of Type … models have been
examined. How … ignition, i.e.,
whether the wh … O white dwarfs
merge [DD].

Wolfgang Hild … I attach another a
picture of anoth

Stan Woosley … $\times 10^8$ g cm^{-3} .

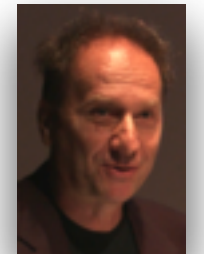


Craig Wheeler … ategory of "Type Ia"
and the limitati … odels (low central
densities). I stil … roducing the
spectral evoluti … e Ia, but there are
variations that r

Alex Filippenk … creasingly clear
that Type Ia sup … ystems and white
dwarf masses.

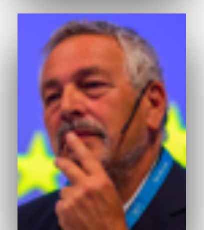
Robert Kirshn … nteraction is sparse
and strong evid … unded, but not
dead. Perhaps

Brian Schmidt: Probably more than one way to make a SN Ia, but seems the primary track involves a White dwarf + another compact star.



Massimo Della Valle: At least two types of progenitor systems can produce SNe-Ia: SD and/or DD. When the WDs reach the Chandra mass, they can explode in different ways: detonation, deflagration, delayed detonation... There are some occurrences in which WDs explode as sub-Chandra or super Chandra. Therefore, from a phenomenological point of view, we potentially have a large variety of outcomes. To some extent, this fact seems supported by observation. In conclusion there are different progenitors, different lifetimes, different sizes, different ages, different chemical compositions, and probably different spins. Nevertheless this variety is characterised by a common ending: after the explosion nothing is left: "Much ado about nothing" or shall we think again?

Bruno Leibundgut: Binaries in all cases, white dwarf in any case, leftover companion in no case (seen so far). Case to be made for binary evolution to produce the massive white dwarfs.



Alvio Renzini: As we are hesitant to choose between SD and DD, so may have been Nature, perhaps making prompt and late Ia's, respectively. Few, but not so few, intermediate mass binaries end up with a spectacular Type Ia display, as few of the more massive ones make BH mergers and solar masses in gravitational waves. For us, understanding these paths is understanding how binaries evolve through two common envelope phases, which makes our job quite difficult, as uncertainties multiply uncertainties. But don't forget, haemoglobin comes from Ia's as chlorophyll from CCs. We have a special link to Ia's, hence an obligation to understand how they come about.

Rosanne Di Stefano: In one sentence: Beware assumptions! Adding another: Pre-and post explosion signatures of DD and SD models can be very much alike.

David Branch: For typical SN Ia that eject about a Chandra mass, I like the canonical SD model (perhaps a DD model in which the merger product spins down long enough to become rather like the SD model, although with a total mass at least a bit above Chandra rather than a bit beneath it, might be OK), but if some SN Ia eject substantially less than a Chandra mass yet are basically symmetric, then the DD model with a Shen-Moore very low-mass helium shell may be best for them.

Dani Maoz: This matter can be addressed by looking at what is the major challenge for each of the two scenarios, SD and DD, based solely on the MW SN Ia rate and on what we know about the putative progenitor populations.

Take home

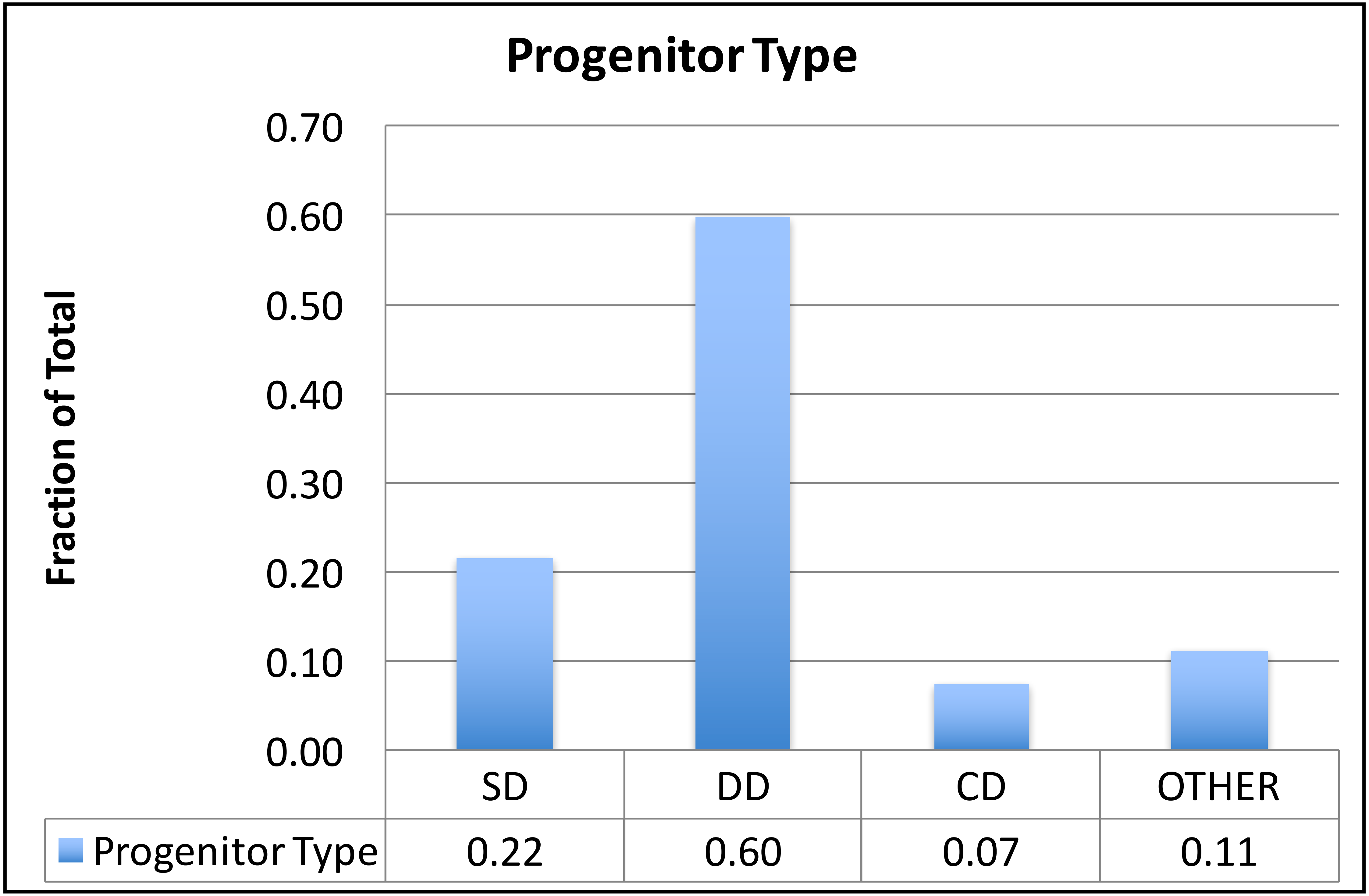
- Lots of work went into this problem
- The problem is not solved, yet
- Binary evolution still needs work
- Common-envelope phase, which concerns both SD and DD, still has to be fully understood
- We gained quite some insights, though, and we managed to change our minds quite a bit

Sociological Appendix

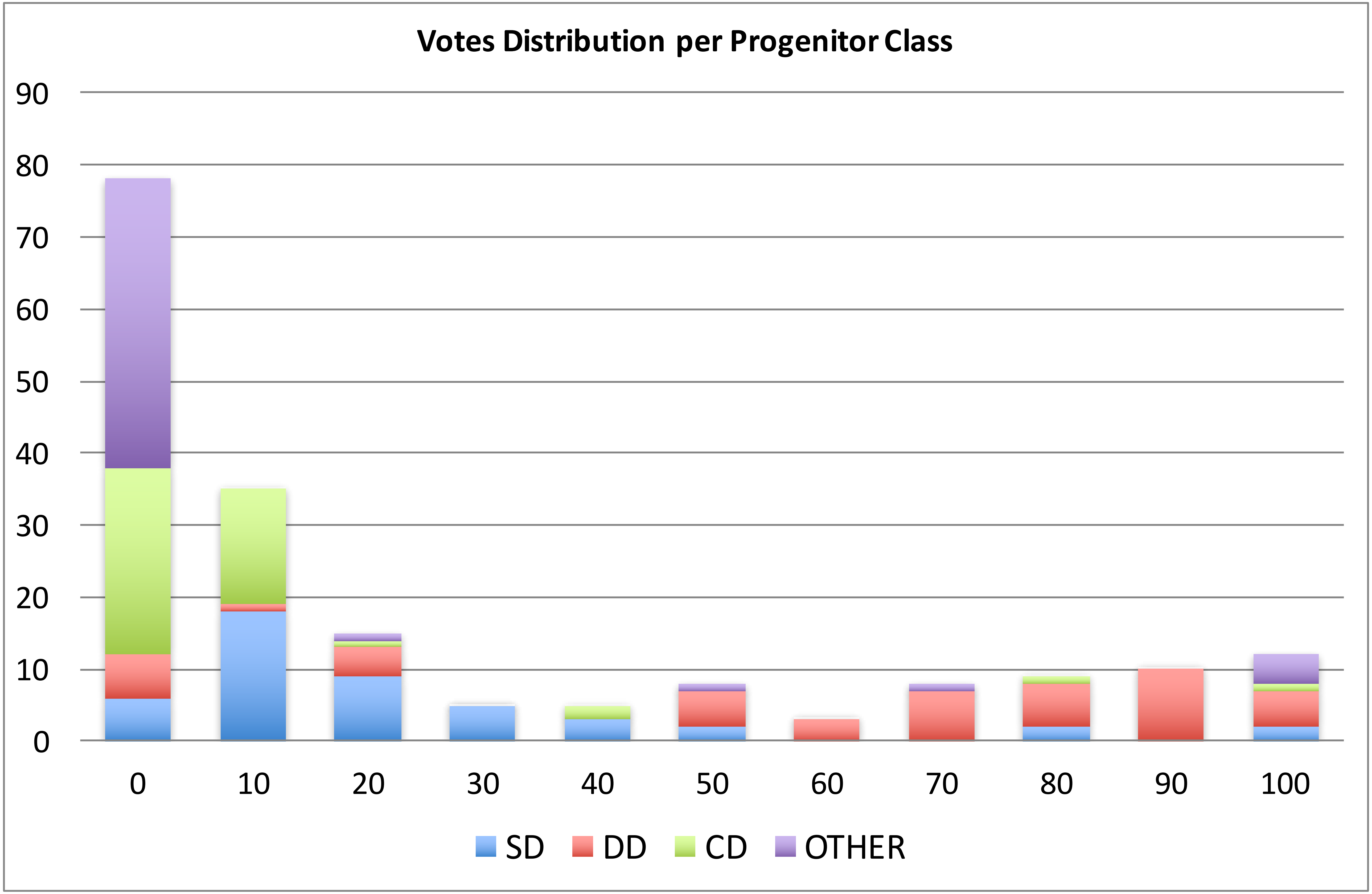
The next two slides report the results of a poll run in Leiden (2013) at the Fireworks workshop, where about 50 SN experts were asked to attribute percentages (adding up to 100%) to the four SN Ia progenitor types:

1. Single Degenerate
2. Double Degenerate
3. Core Degenerate
4. Other

The Leiden Fireworks 2013 poll



Patat 20XX, in perennial preparation


Votes Distribution per Progenitor Class
90
80
70
60
50
40
30
20
10
0
0
10
20
30
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50
60
70
80
90
100
SD
DD
CD
OTHER