Type Ia Supernova Progenitors

An Observer's Perspective

Nando Patat
N&O P@@

European Southern Observatory - Germany

Why?

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



Why?

Why?

Once upon a time (early 1990s) things, were simpler…

Roberto Barbon

- Type II: explosion of a RG
- Type I: a WD accreting from a RG

The Puzzle

W.Kerzendorf (C)

"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

“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

4 reasons 4

1. Using SNe Ia in Cosmology requires an understanding of the evolution of the luminosity, and the SN rate with cosmic epoch. Both depend on the nature of the progenitors;

2. Galaxy evolution depends on the radiative, kinetic energy, and nucleosynthetic output of SNe Ia;

3. A knowledge of the initial conditions and of the distribution of matter in the environment of the exploding star is essential for the understanding of the explosion itself;

5. An unambiguos identification of the progenitors, coupled with observationally determined SN rates will help placing constraints on the theory of binary star evolution.

3. A knowledge of the initial conditions and of the distribution of matter in the environment of the exploding star is essential for the understanding of the explosion itself;

5. An unambiguos identification of the progenitors, coupled with observationally determined SN rates will help placing constraints on the theory of binary star evolution.

I concede this is a bit of a circular argument

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.

The Conundrum

- you need to make a low-mass, “old” star explode
- you need to produce ~always the ~same luminosity (i.e. amount of ^{56}Ni)
- you ought to hide the most abundant element in the universe

THE ASTROPHYSICAL JOURNAL, 186:1007–1014, 1973 December 15

BINARIES AND SUPERNOVAE OF TYPE I*

JOHN WHELAN† AND ICKO IBEN, JR.
University of Illinois
Received 1973 April 9

ABSTRACT

It is suggested that the immediate progenitors of Type I supernovae in elliptical galaxies are binary systems of long period (1–6 years) that have evolved from an initial configuration consisting of a light secondary of mass less than or equal to 0.8 $M_{\odot}$ and a primary of intermediate mass (1.8–3 $M_{\odot}$), with orbital period between 5 and 9 years. Beginning on the main sequence, the primary evolves rapidly and, following mass loss and/or mass transfer, becomes a carbon-oxygen white dwarf of mass close to 1.4 $M_{\odot}$. The secondary, now of mass 0.8 $M_{\odot}$, evolves for 10^{10} years before reaching the asymptotic giant branch. On swelling beyond its Roche surface, the secondary transfers mass onto the primary which then (we presume) develops rapidly into a supernova. An examination of the frequency of binary systems with appropriate orbital characteristics shows that our conjecture is not inconsistent with the available data concerning the frequency of Type I supernovae.

Subject headings: binaries — mass loss — supernovae

I. THE CONUNDRUM AND A POSSIBLE SOLUTION

The Astrophysical Journal, 186:1007–1014, 1973 December 15

BINARIES AND SUPERNOVAE OF TYPE I*

John Whelan† and Icko Iben, Jr.
University of Illinois
Received 1973 April 9

ABSTRACT

It is suggested that the immediate progenitors of Type I supernovae in elliptical galaxies are binary systems of long period (1–6 years) that have evolved from an initial configuration consisting of a light secondary of mass less than or equal to 0.8 $M_\odot$ and a primary of intermediate mass (1.8–3 $M_\odot$), with orbital period between 5 and 9 years. Beginning on the main sequence, the primary evolves rapidly and, following mass loss and/or mass transfer, becomes a carbon-oxygen white dwarf of mass close to 1.4 $M_\odot$. The secondary, now of mass 0.8 $M_\odot$, evolves for 10^{10} years before reaching the asymptotic giant branch. On swelling beyond its Roche surface, the secondary transfers mass onto the primary which then (we presume) develops rapidly into a supernova. An examination of the frequency of binary systems with appropriate orbital characteristics shows that our conjecture is not inconsistent with the available data concerning the frequency of Type I supernovae.
Subject headings: binaries — mass loss — supernovae

I. THE CONUNDRUM AND A POSSIBLE SOLUTION

THE ASTROPHYSICAL JOURNAL, 186:1007–1014, 1973 December 15

BINARIES AND SUPERNOVAE OF TYPE I*

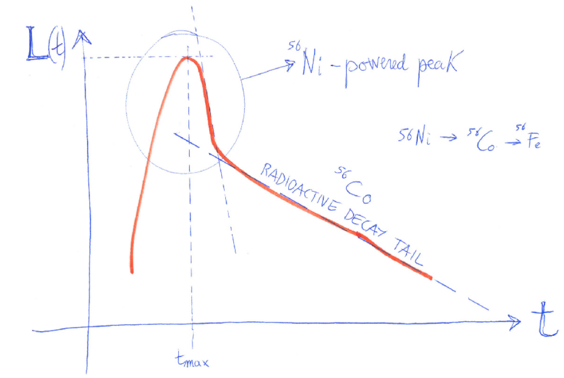
JOHN WHELAN† AND ICKO IBEN, JR.
University of Illinois
Received 1973 April 9

Putting two and two together, we might conclude that supernovae could not occur in elliptical galaxies. Yet we know that supernovae of Type I occur in such galaxies at a frequency of 1 per 100 years per 10^{11} stars.

A possible solution may involve mass transfer between members of a binary system (see, e.g., Wheeler and Hansen 1971; Truran and Cameron 1971; Hartwick 1972; Mazurek 1973).

We propose an initial binary system that consists of (1) a massive component (primary), that passes through its active nuclear burning life in a time short compared with a galactic lifetime, leaving an inactive white dwarf composed primarily of carbon and oxygen, and (2) a light component (secondary) whose nuclear burning lifetime is comparable to the galactic age.

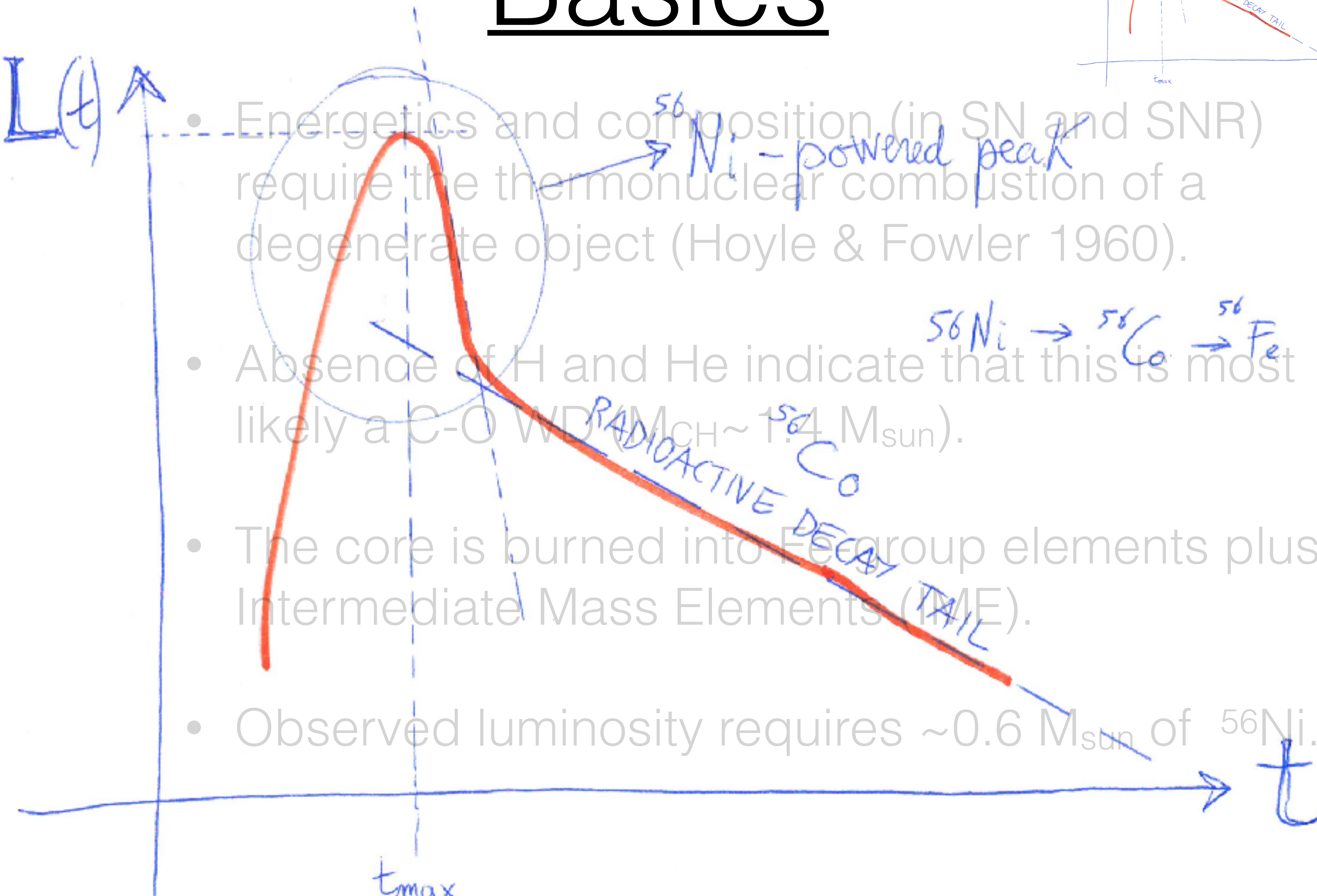
I. THE CONUNDRUM AND A POSSIBLE SOLUTION



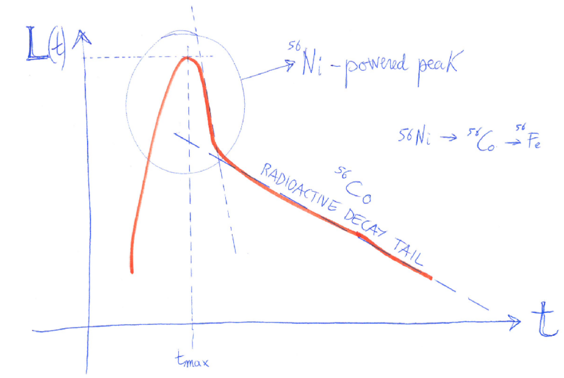
Basics

- 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.

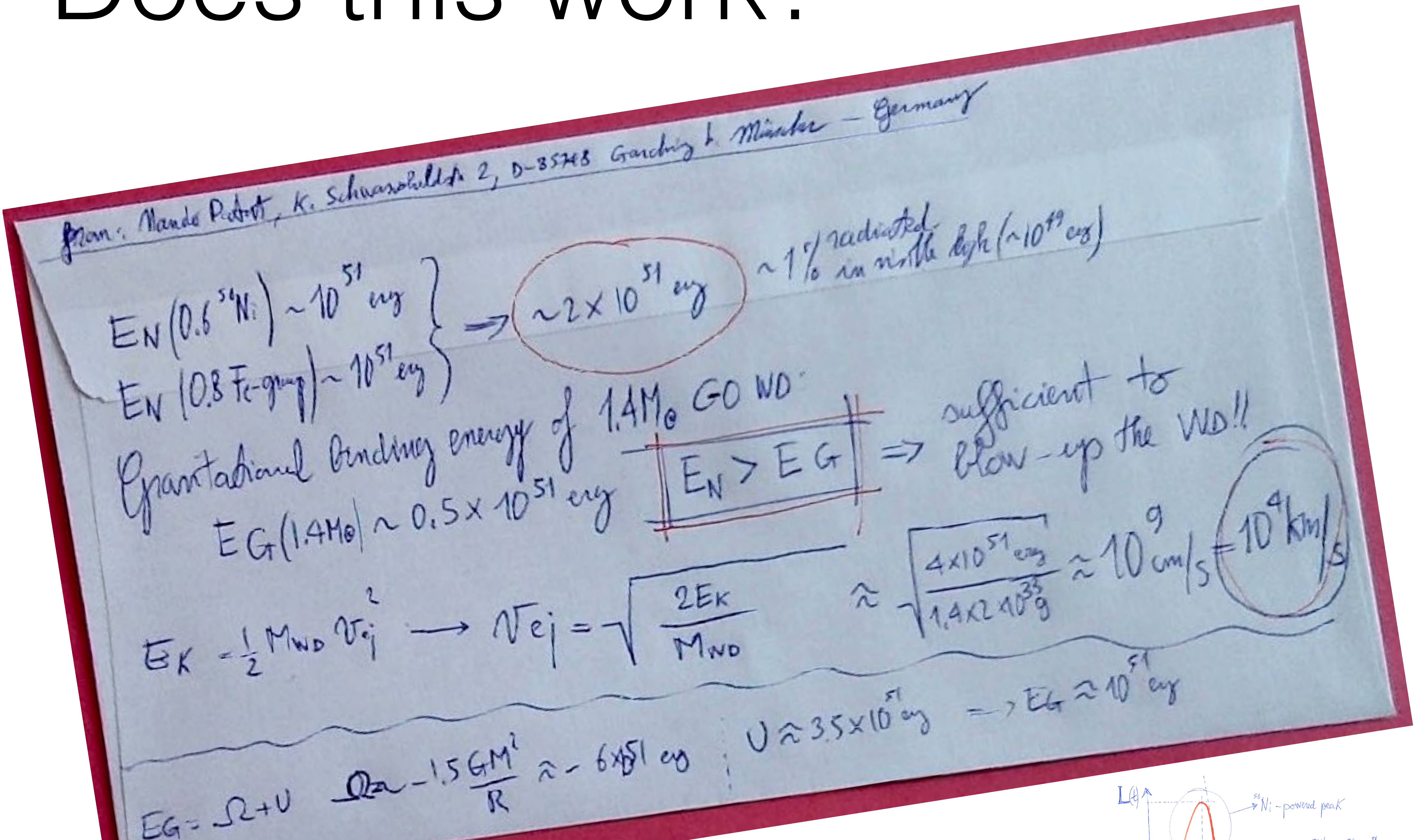
Basics

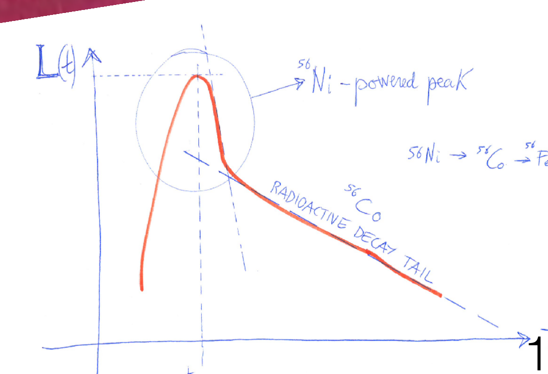


- Energetics and composition (in SN and SNR) require the thermonuclear combustion of a degenerate object (Hoyle & Fowler 1960).
- Absence of H and He indicate that this is most likely a C-O WD (M_{CH}~ 1.4 M_{sun}).
- The core is burned into Fe-group elements plus Intermediate Mass Elements (IME).
-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

The consensus statement

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

Somehow, Sometime, Somewhere

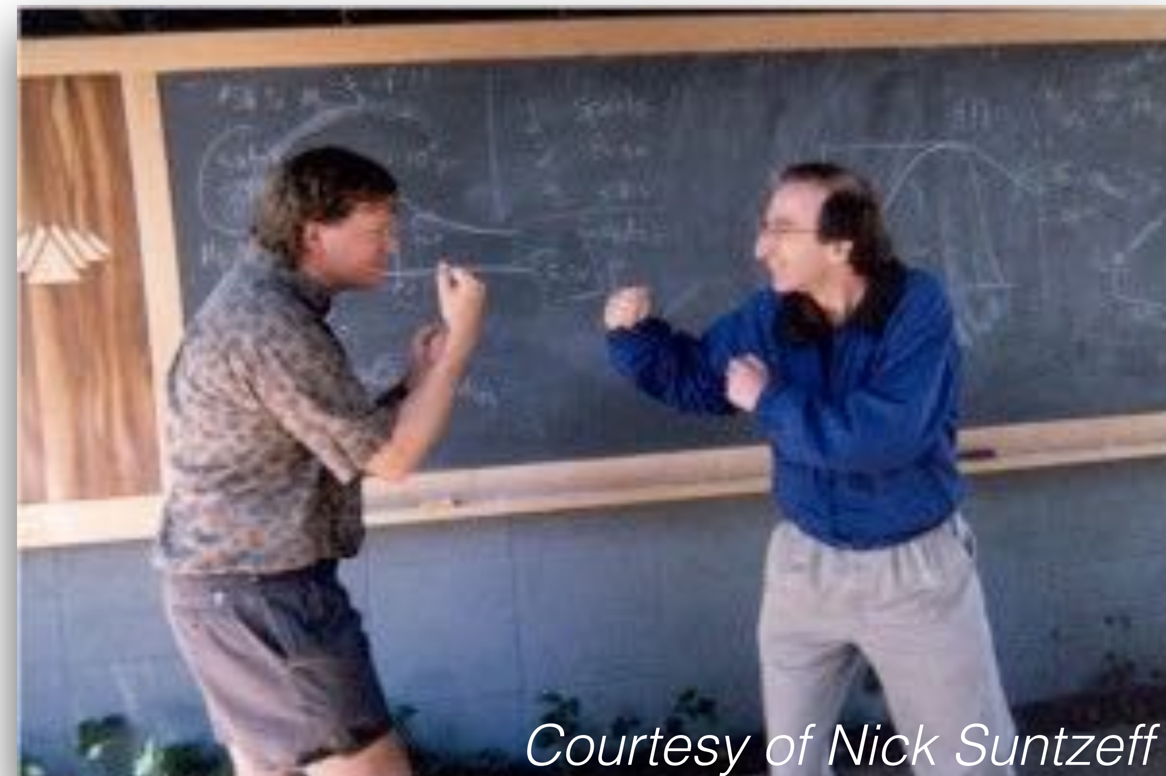
The consensus statement

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

Somehow, Sometime, Somewhere

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

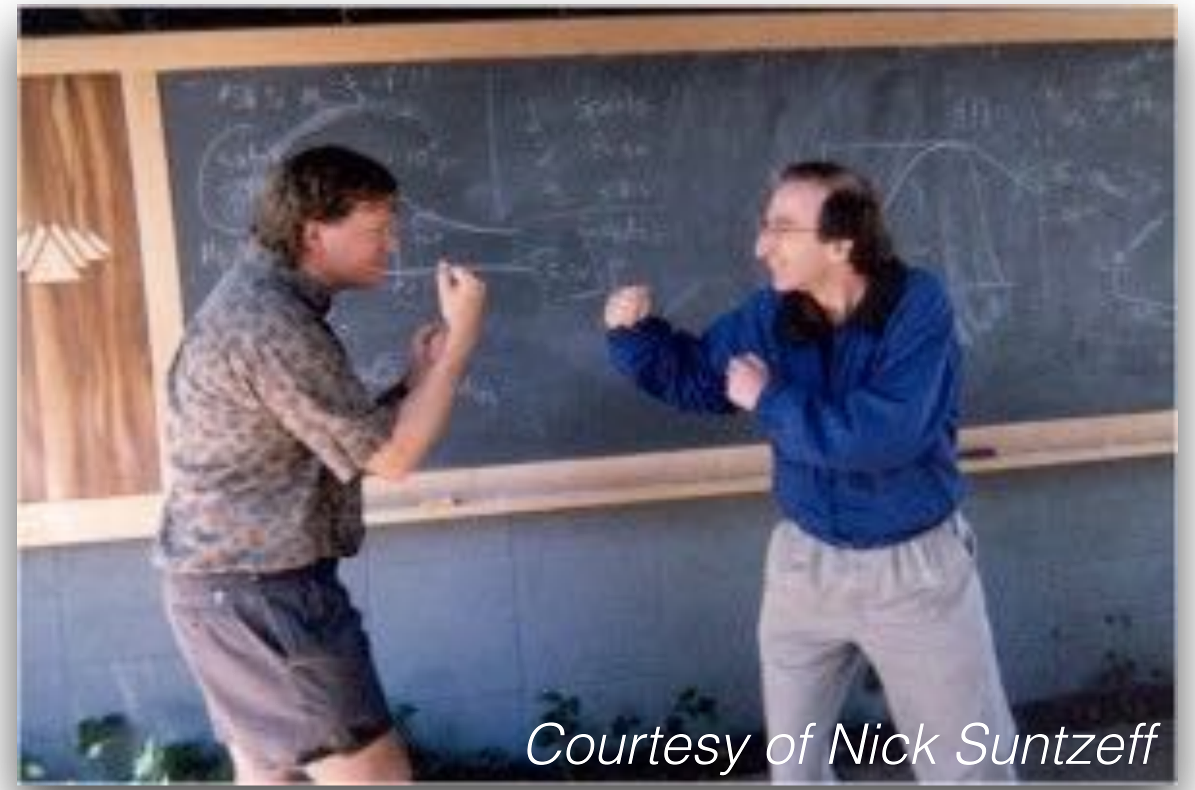
40^{+} years, and counting…



Despite SNe Ia are used for "precision cosmology",

the nature of the progenitor system[s] is still unknown.

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
- Supersoft X-Ray sources
- Rapidly accreting WDs
  See work by Gilfanov+Woods
- He-rich donors
- Binary WDs

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}

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

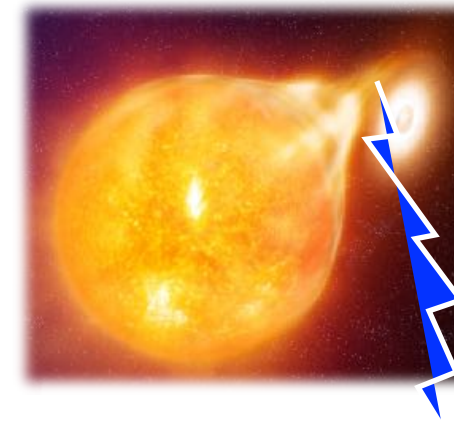
MS companion	RG companion	RG companion
		

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…

Tutukov & Yungelson 1981

Binary WDs

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

Courtesy of F. Röpke

- 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.

Tutukov & Yungelson 1981

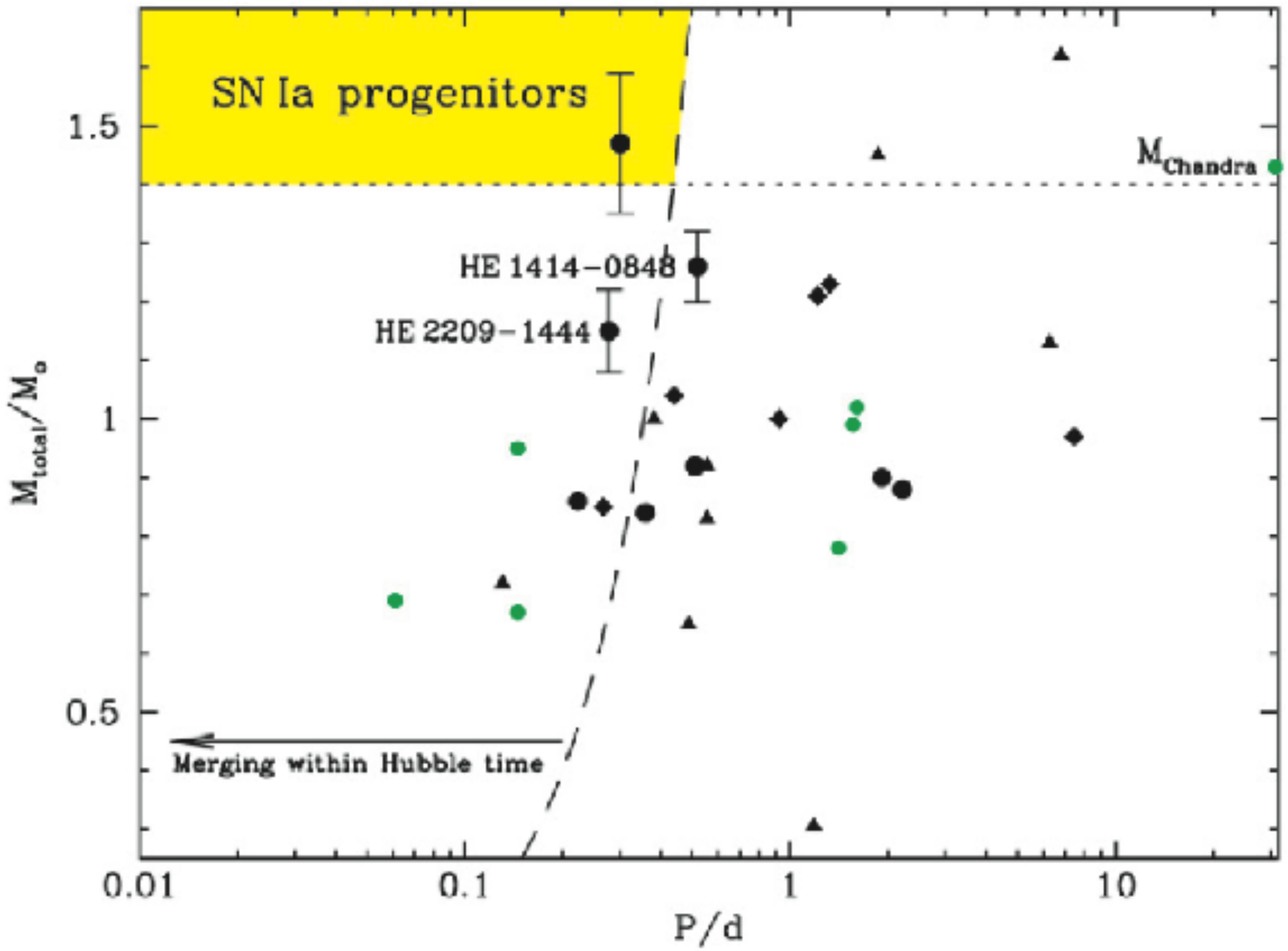
Binary WDs

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

Courtesy of F. Röpke

- 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;

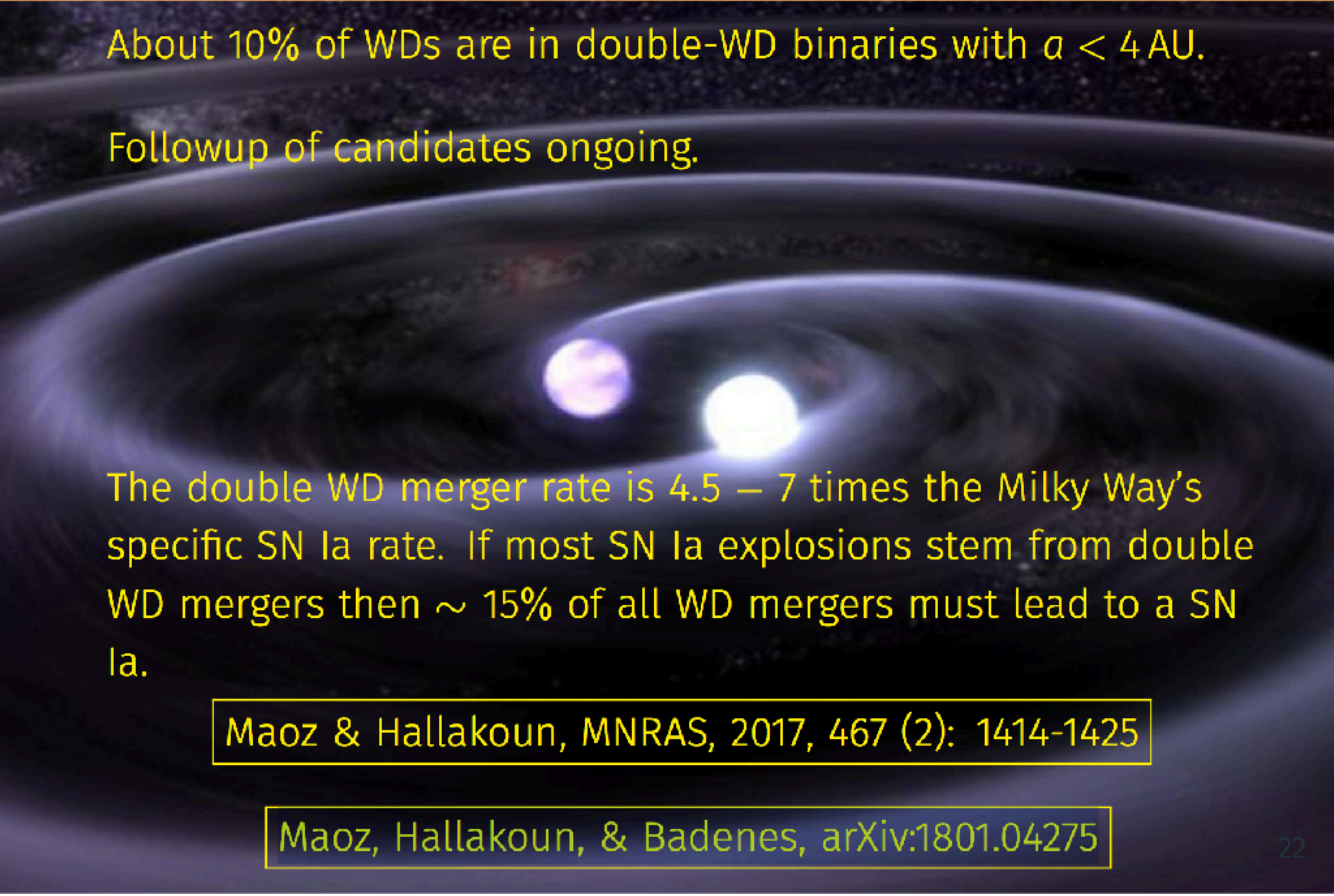
- The merger was suspected to result into an Accretion Induced Core Collapse (AICC), leading to a neutron star.



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

~1000 WDs and 1 candidate found.

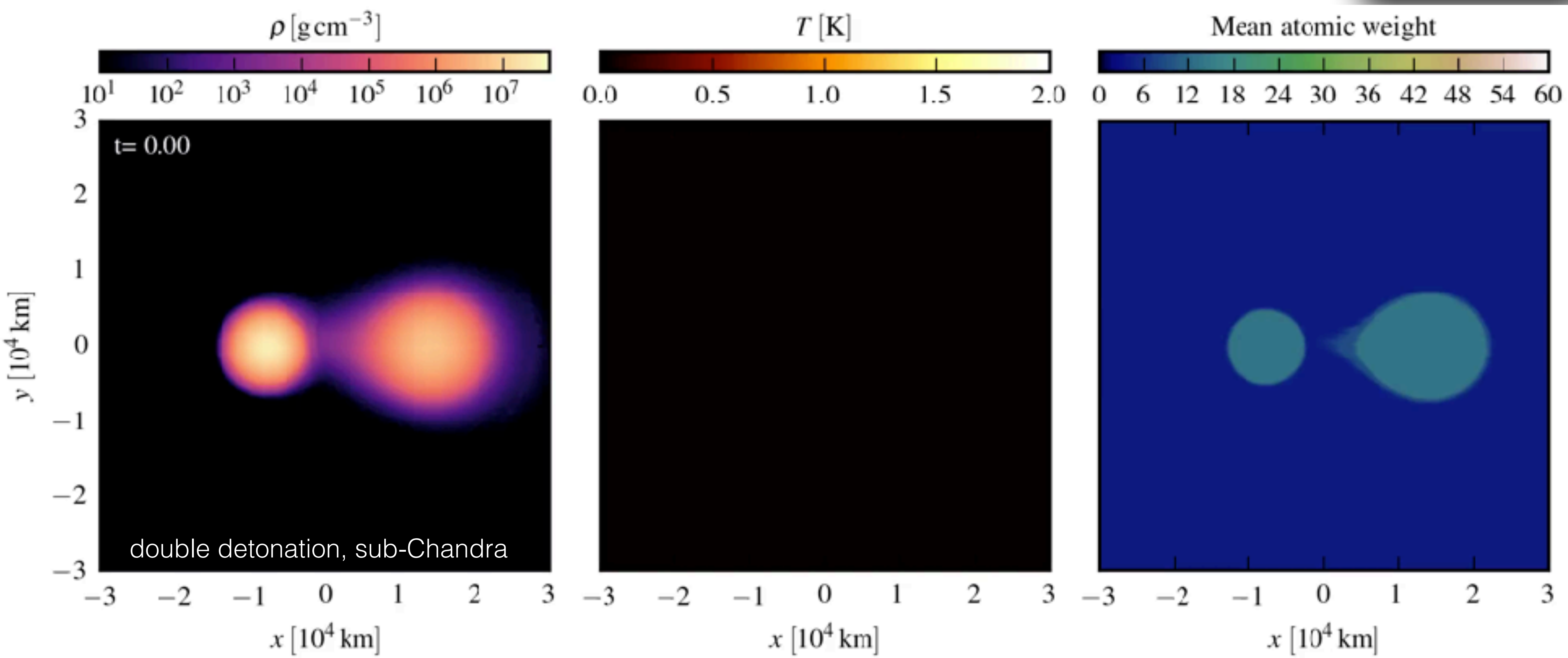
See also Badenes+09, Maoz & Hallakoun 17, Maoz, Hallakoun, Badenes 18


About 10% of WDs are in double-WD binaries with $a < 4$ AU.
Followup of candidates ongoing.
The double WD merger rate is 4.5 – 7 times the Milky Way's specific SN Ia rate. If most SN Ia explosions stem from double WD mergers then ∼ 15% of all WD mergers must lead to a SN Ia.
Maoz & Hallakoun, MNRAS, 2017, 467 (2): 1414-1425
Maoz, Hallakoun, & Badenes, arXiv:1801.04275

2018, MNRAS

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

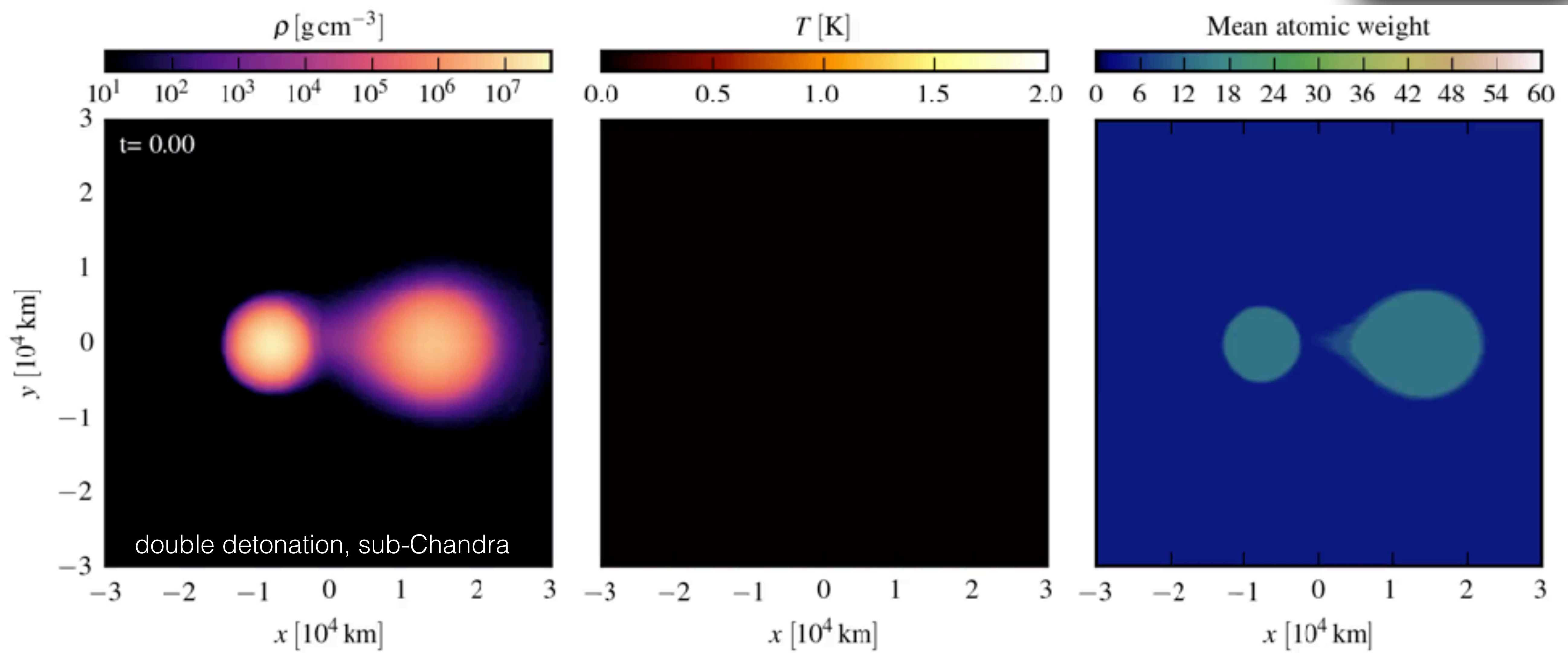
Courtesy of Rüdiger Pakmor



Accretion from the secondary on the primary leads to dynamical effects on the surface of the primary that ignite a He-detonation. The He-detonation wraps around the primary WD and sends a shock into its C-O core that upon converging into a single point ignites a carbon detonation in the CO core and the primary WD explodes.

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

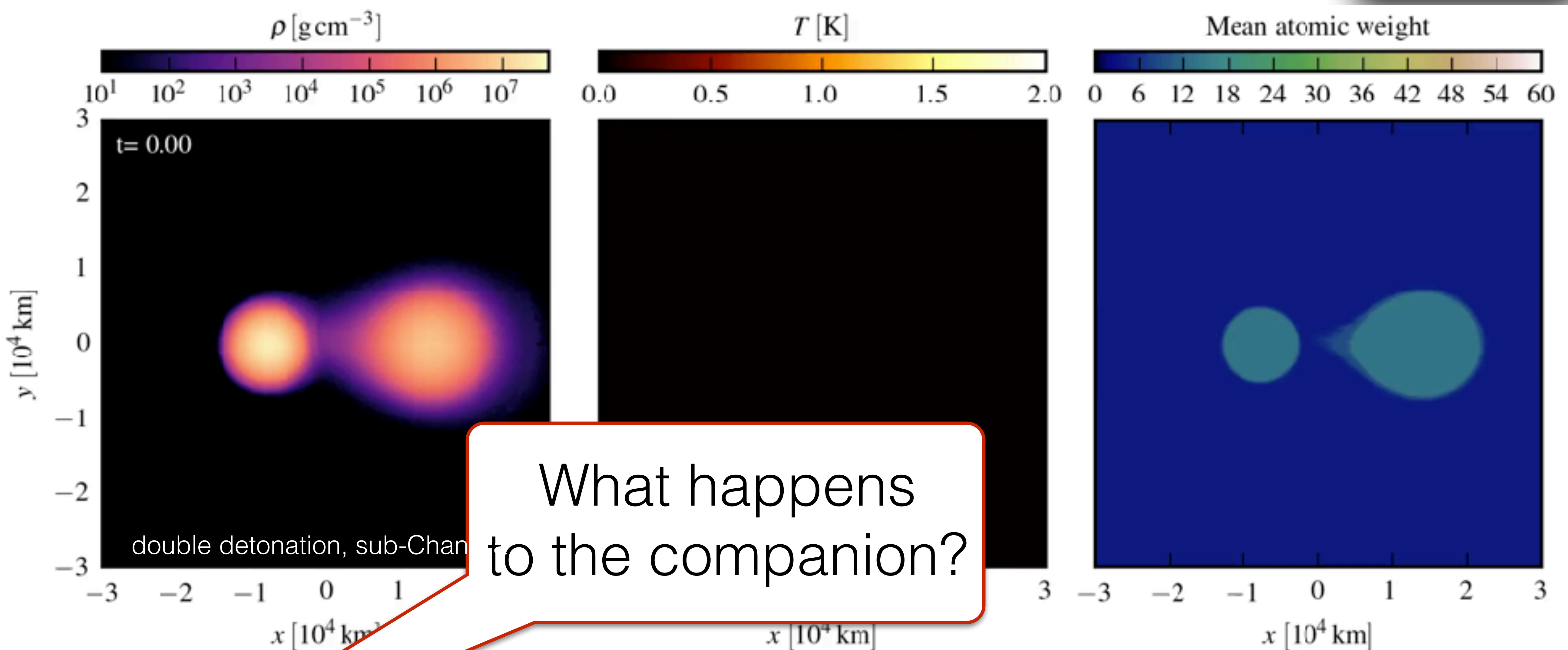
Courtesy of Rüdiger Pakmor



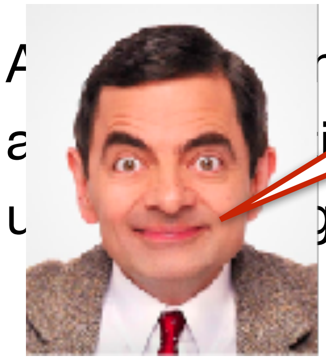
Accretion from the secondary on the primary leads to dynamical effects on the surface of the primary that ignite a He-detonation. The He-detonation wraps around the primary WD and sends a shock into its C-O core that upon converging into a single point ignites a carbon detonation in the CO core and the primary WD explodes.

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



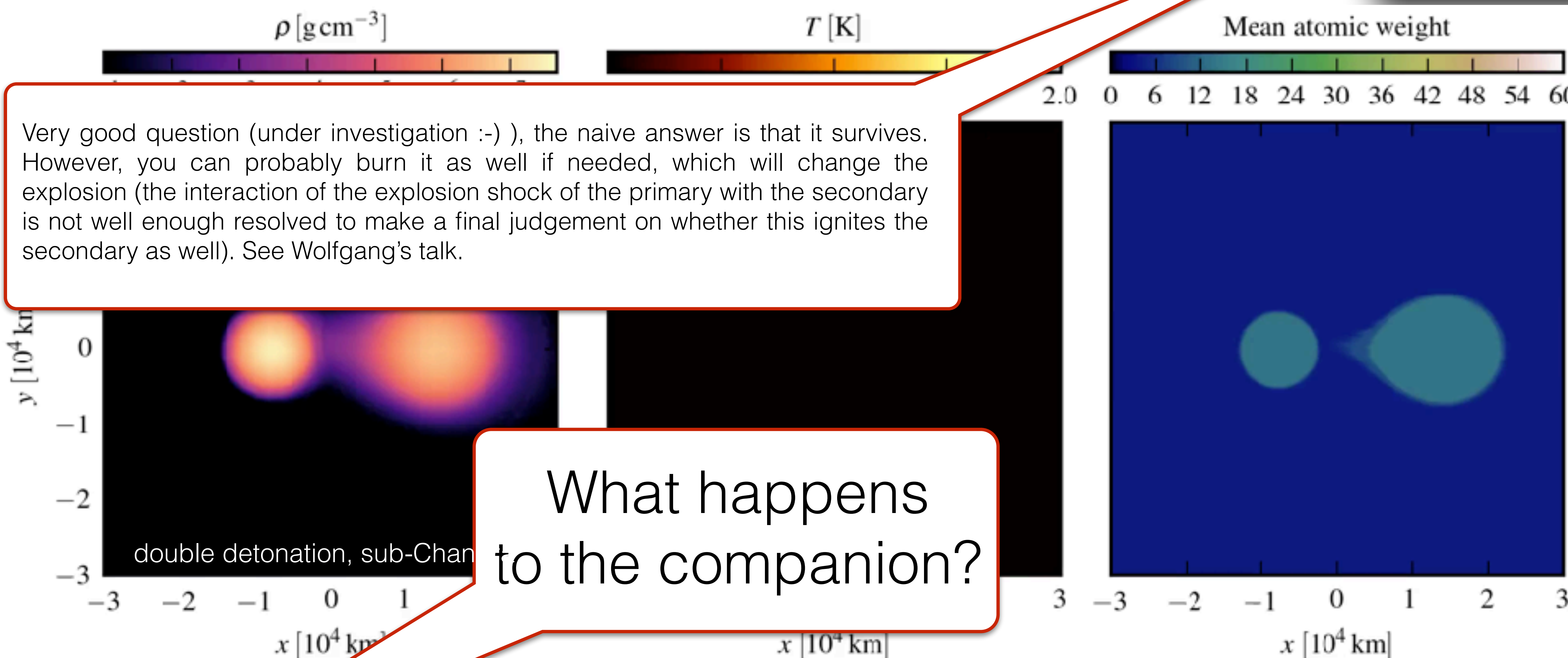
What happens to the companion?



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.

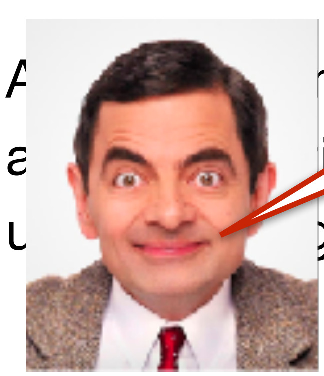
Final evolution of two C-O WDs (0.7+1.0 M_{sun}) with a thin He envelope (10^{-2} M_{sun} each)

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). See Wolfgang's talk.

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 ... ic... 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-explosion sites

The case of 2011fe in M101

- Very close-by (6 Mpc), very early (few hours), standard Ia
- Unique opportunity to probe the earliest phases in great detail, across a wide wavelength range.
- Rich pre-explosion, HST data.

Pre-explosion sites

The case of 2011fe in M101

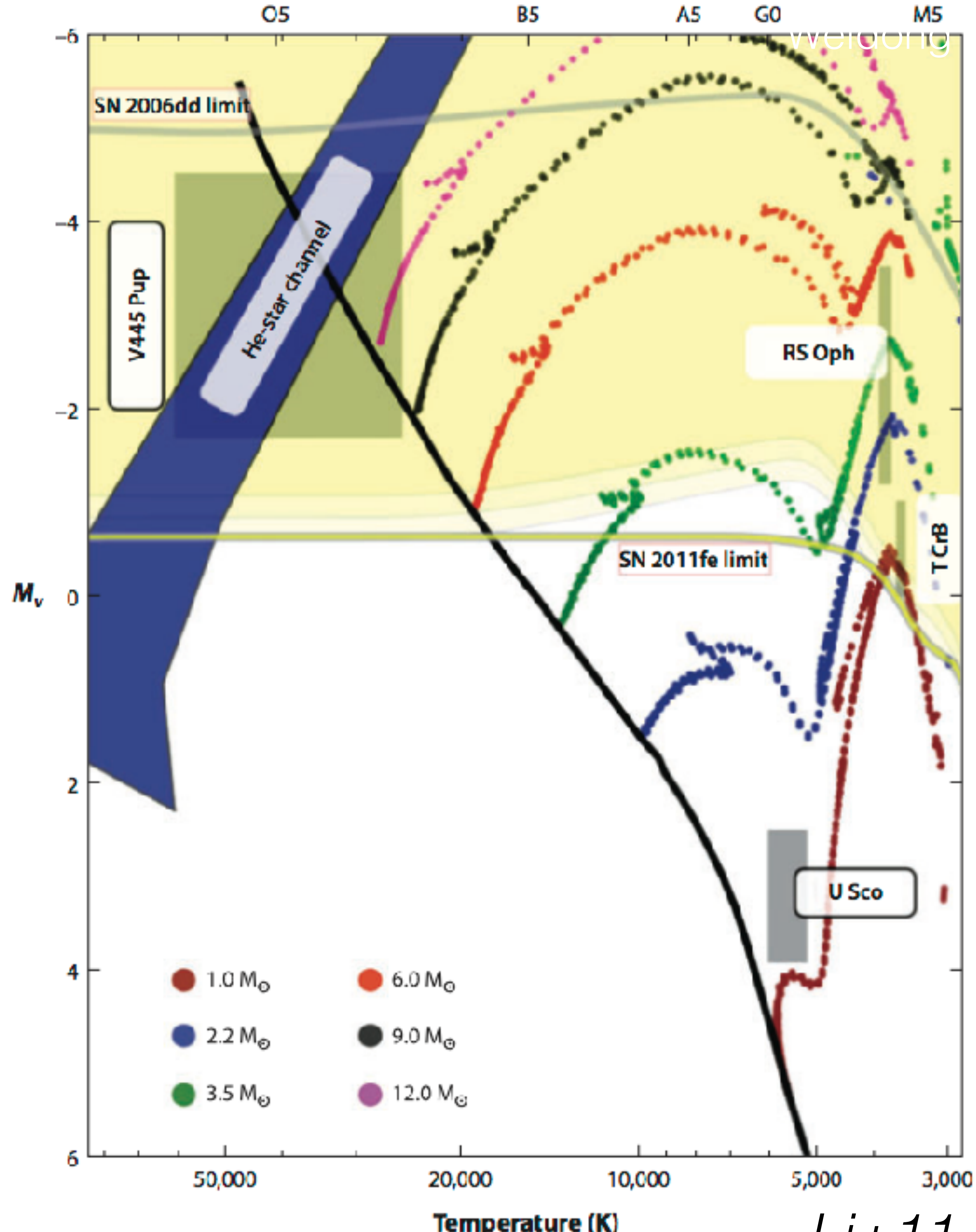
- Very close-by (6 Mpc), very early (few hours), standard Ia
- Unique opportunity to probe the earliest phases in great detail, across a wide wavelength range.
- Rich pre-explosion, HST data.

- Red giants at the location of the SN is ruled out (Li+11) in the decade before the explosion (no RS-Oph, T CrB)
- Stars with $M>3.5M_{sun}$ are also excluded
- MS or sub-giant donors are allowed (U Sco in quiescence).
- A RG is also excluded for SN2014J (3.5Mpc; Kelly+14).

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

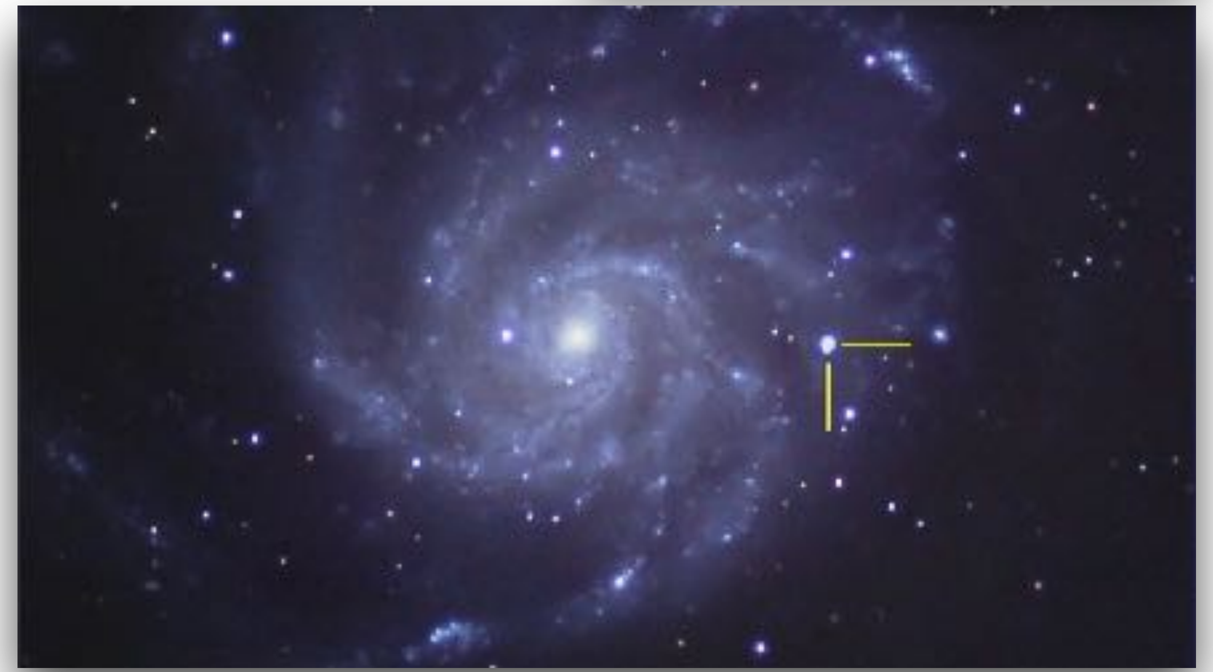


Li+11

Pre-explosion sites

The case of 2011fe in M101

- Very close-by (6 Mpc), very early (few hours), standard Ia
- Unique opportunity to probe the earliest phases in great detail, across a wide wavelength range.
- Rich pre-explosion, HST data.



- Red giants at the location of the SN is ruled out (Li+11) in the decade before the explosion (no RS-Oph, T CrB)
- Stars with $M>3.5M_{sun}$ are also excluded
- MS or sub-giant donors are allowed (U Sco in quiescence).
- A RG is also excluded for SN2014J (3.5Mpc; Kelly+14).

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 see Kerzendorf+ 2017

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 see Kerzendorf+ 2017

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:

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)

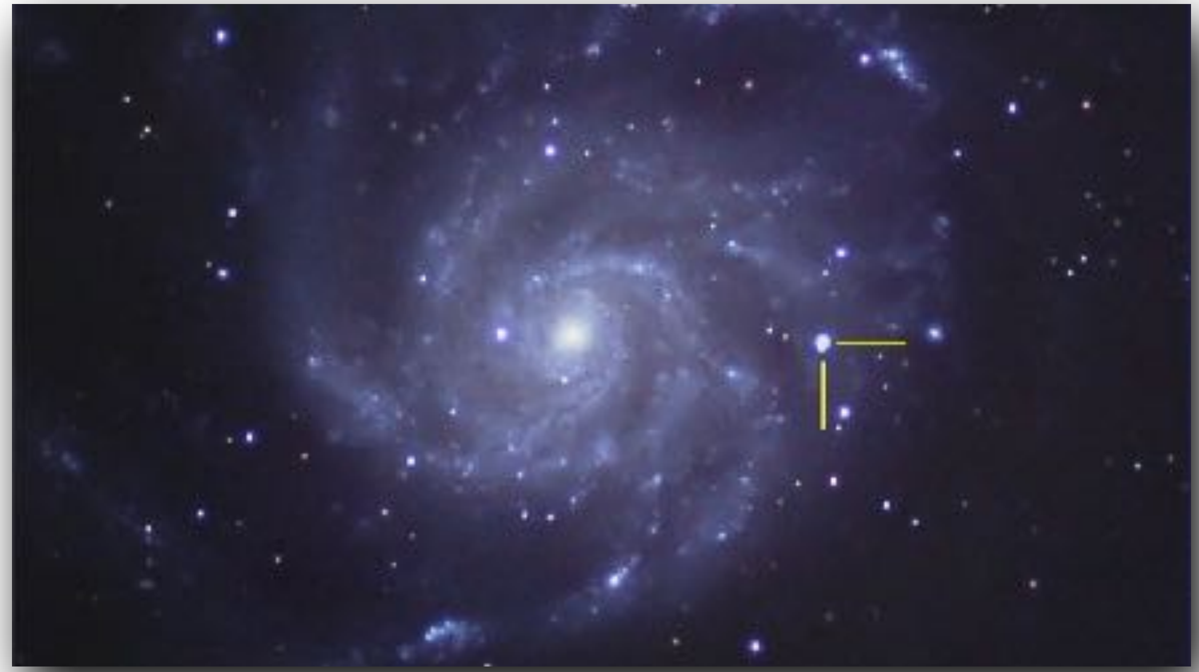
Explosion properties

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

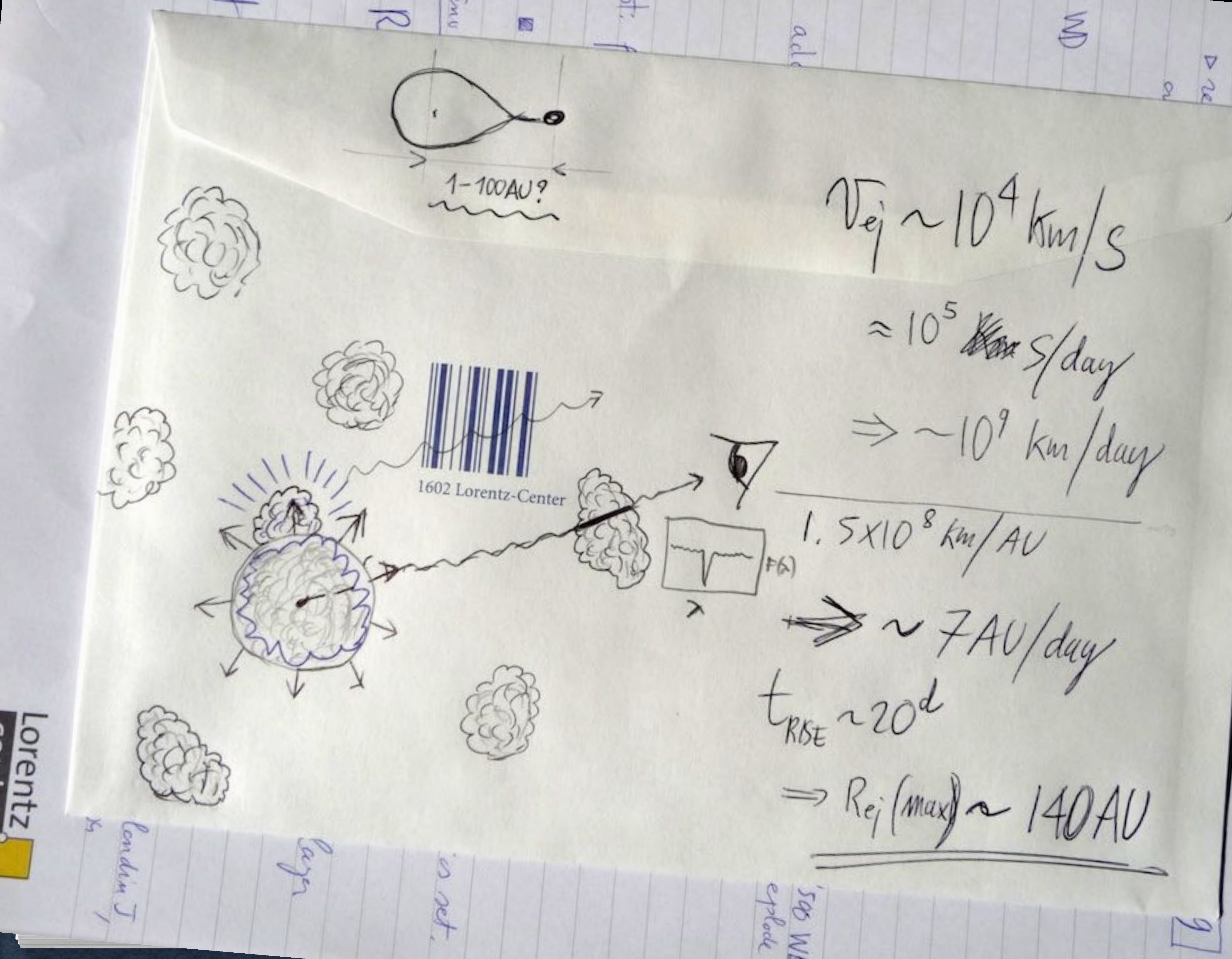
- Early light curve and spectral evolution
- Shocks on [possible] companion star
- Ejecta asymmetries (polarimetry)
- Emission from hydrogen
- Radio, X-Ray CSM emission
- Narrow time-variable absorptions
- CS Dust and light echoes (specphot and polarimetry)

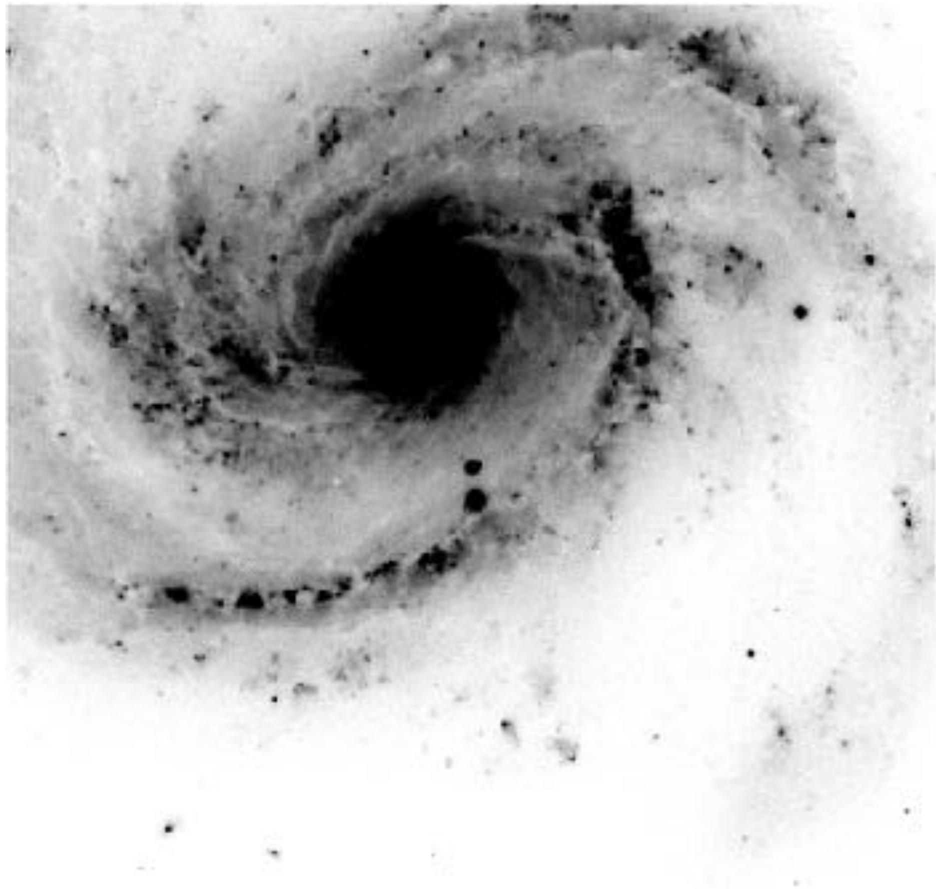
never detected

2011fe

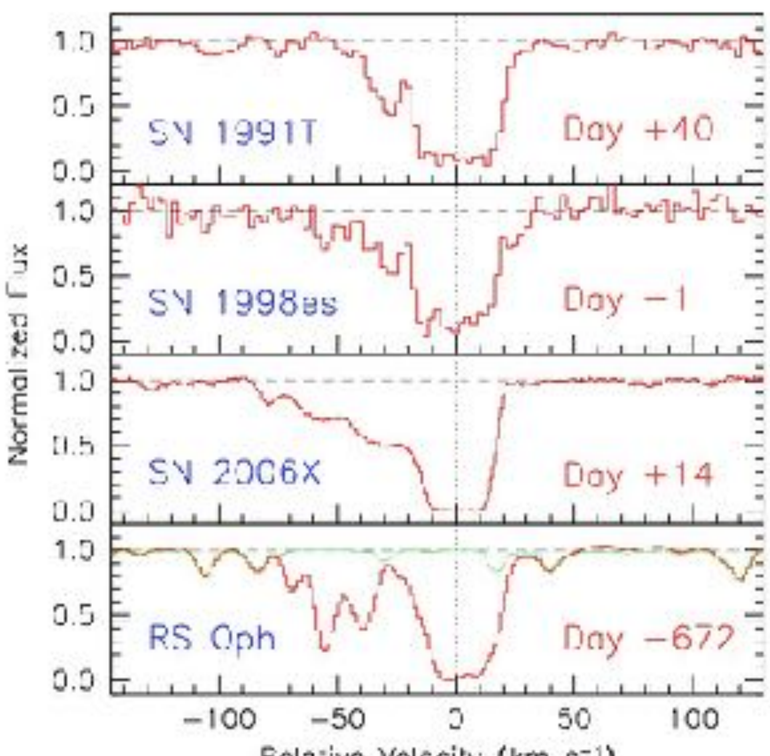


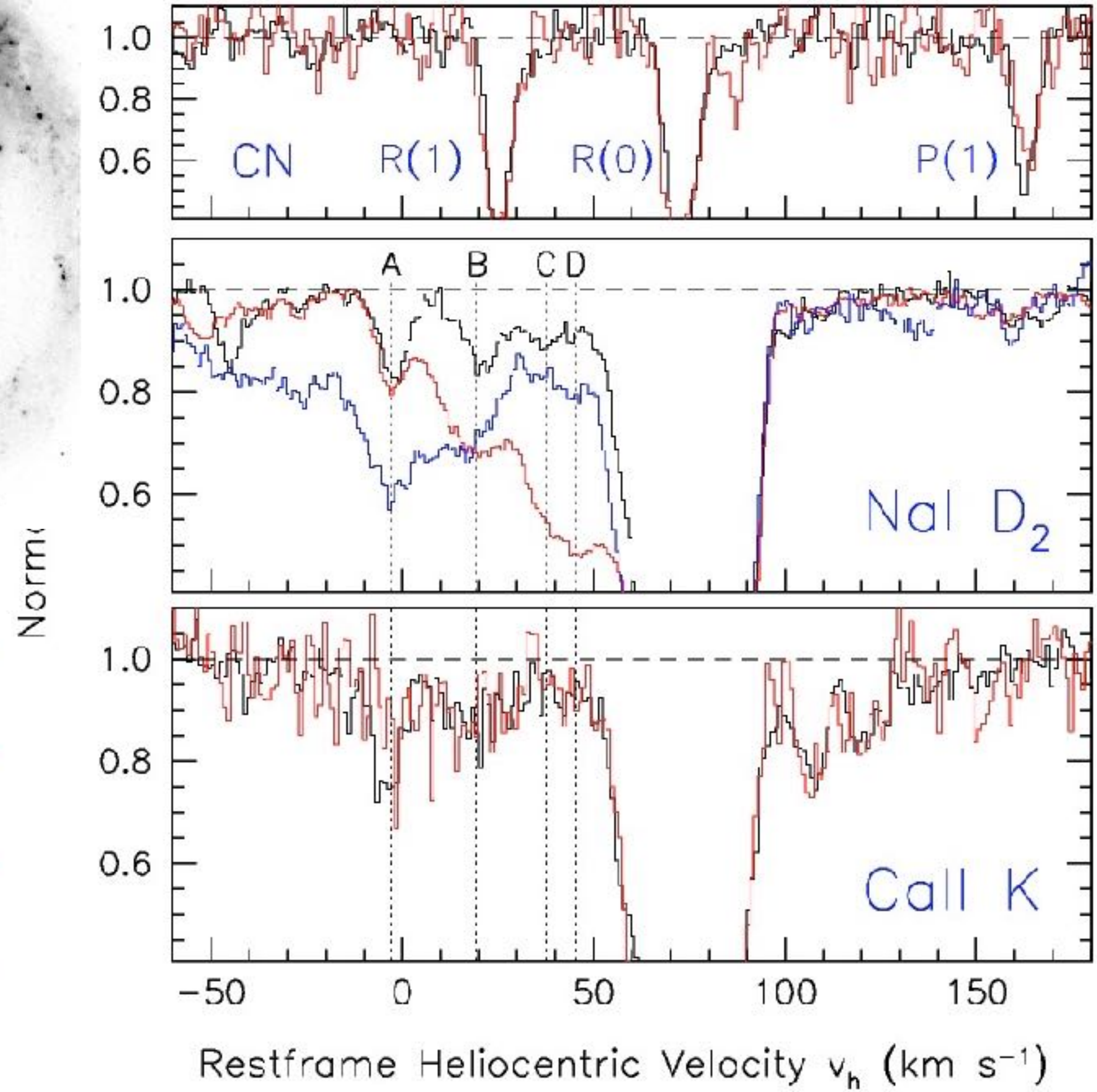
- Using optical and UV observations, Nugent+11 excluded the presence of shock effects from SN ejecta hitting an alleged companion. A RG is definitely excluded.
- Bloom+12 ruled out even a MS, concluding that the DD scenario is the most probable for this one object. Unless spin-up/down is there (but see Kerzendorf+ 2017)
- 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).


1-100AU?
1602 Lorentz-Center
$v_{ej} \sim 10^4$ 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

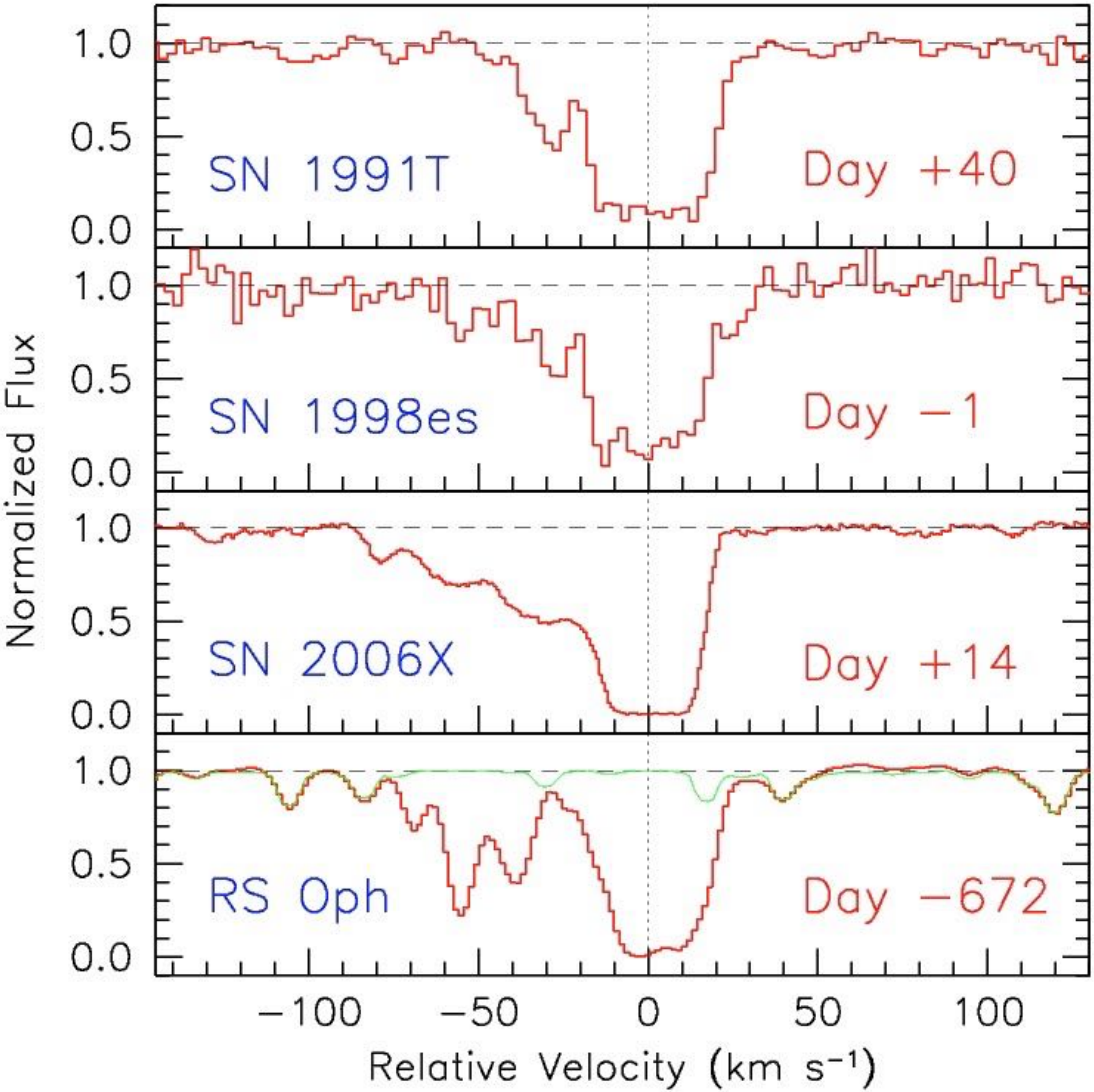


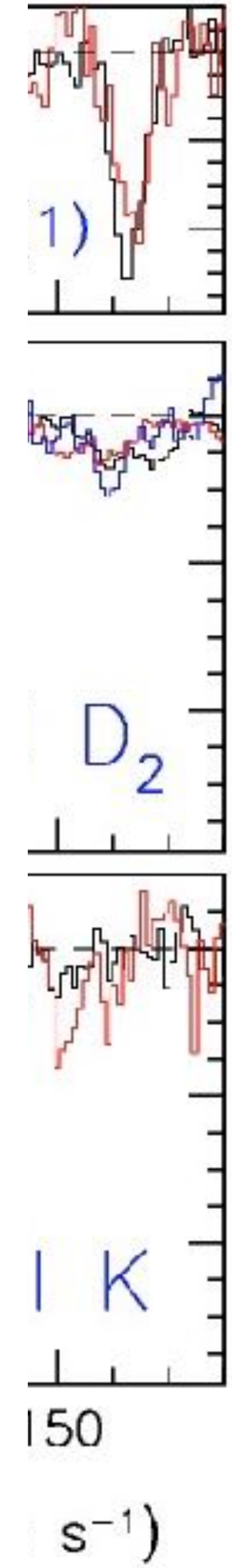
SN2006X



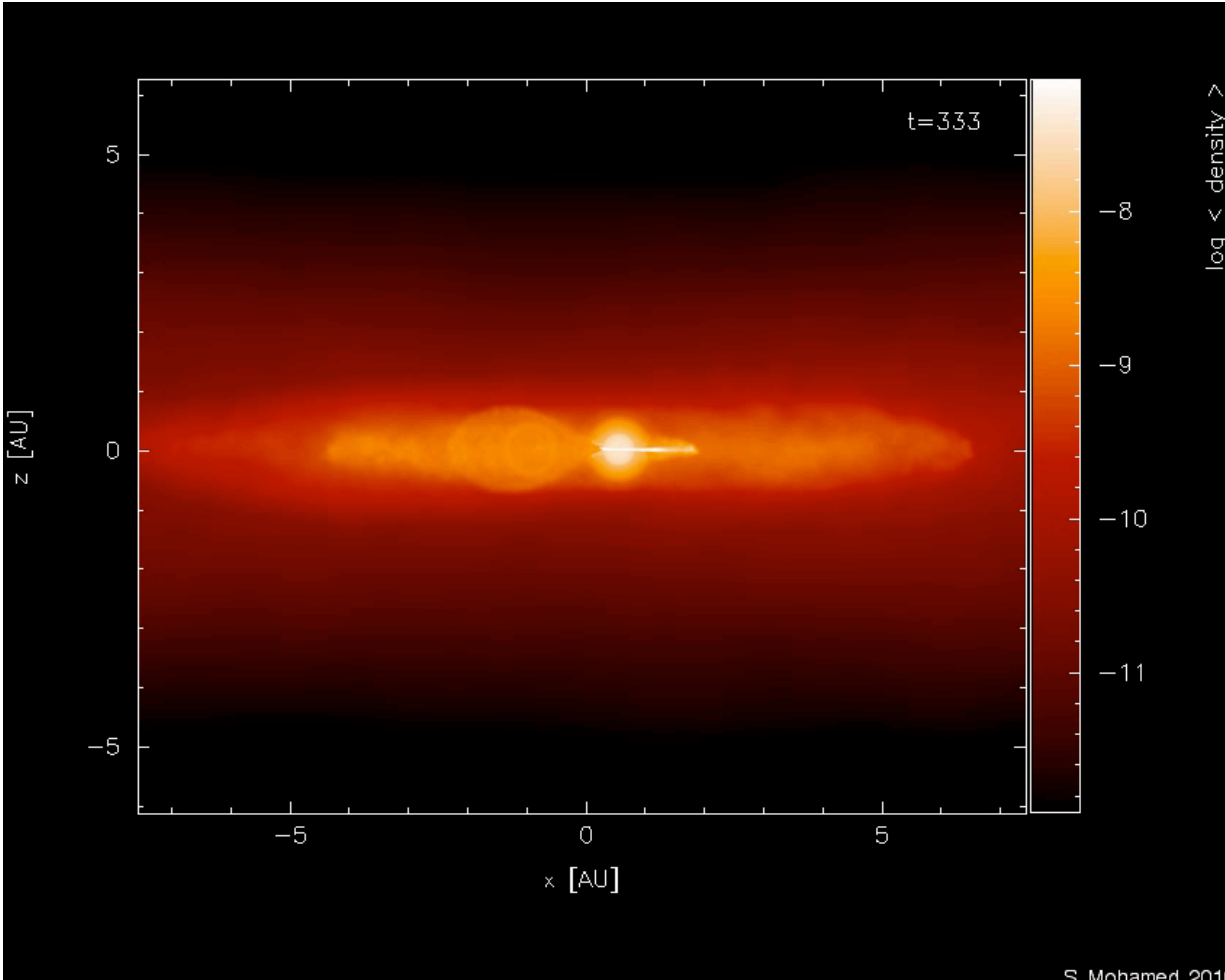


Patat+07

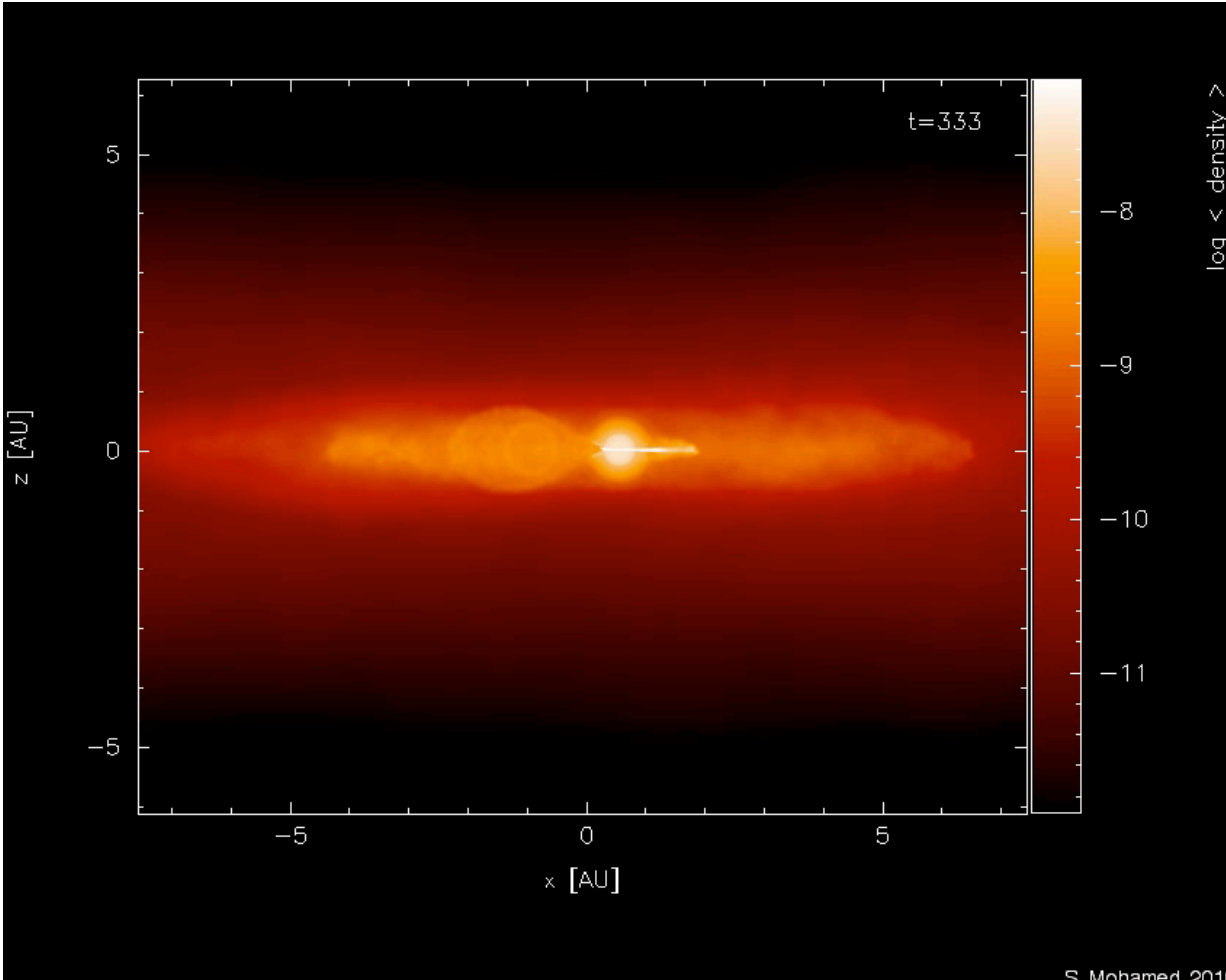

1.0
0.5
0.0
SN 1991T
Day +40
SN 1998es
Day −1
SN 2006X
Day +14
RS Oph
Day −672
Normalized Flux
−100
−50
0
50
100
Relative Velocity (km s⁻¹)



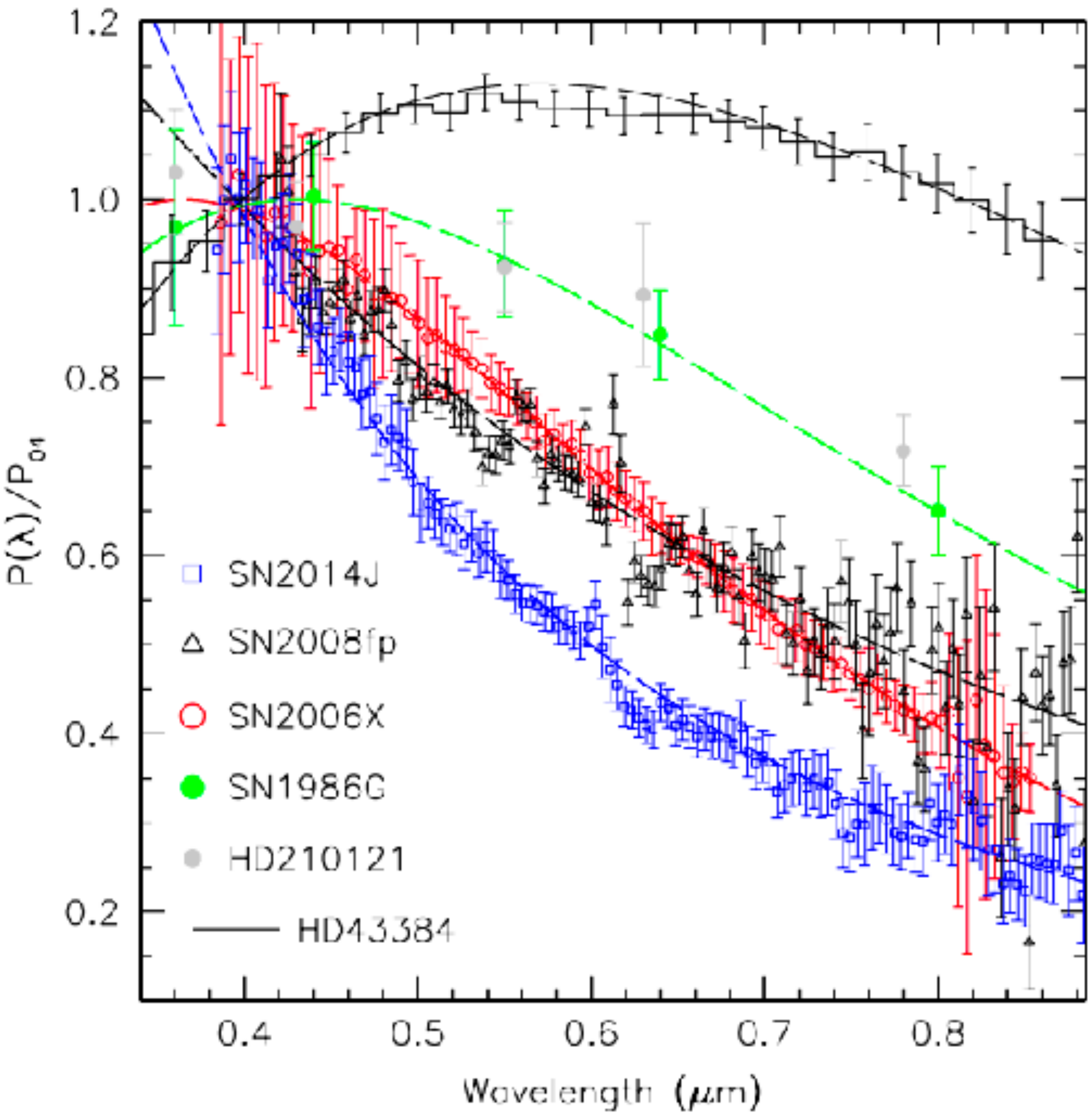
Patat+07



t=333
z [AU]
x [AU]
log < density >
5
0
−5
−8
−9
−10
−11
S. Mohamed, 2010


t=333
5
0
−5
z [AU]
x [AU]
−8
−9
−10
−11
log < density >
S. Mohamed, 2010

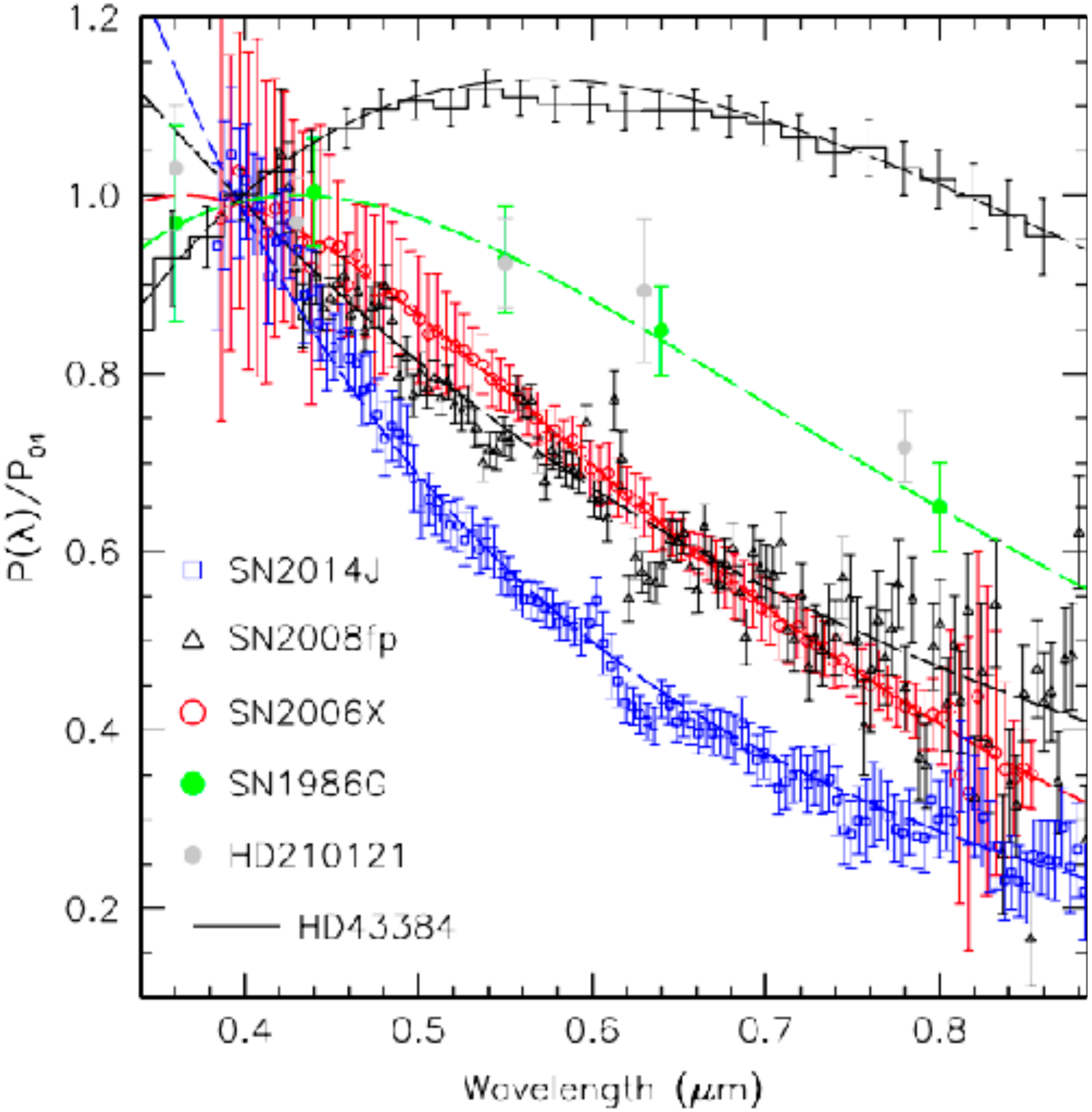
CS Dust Properties



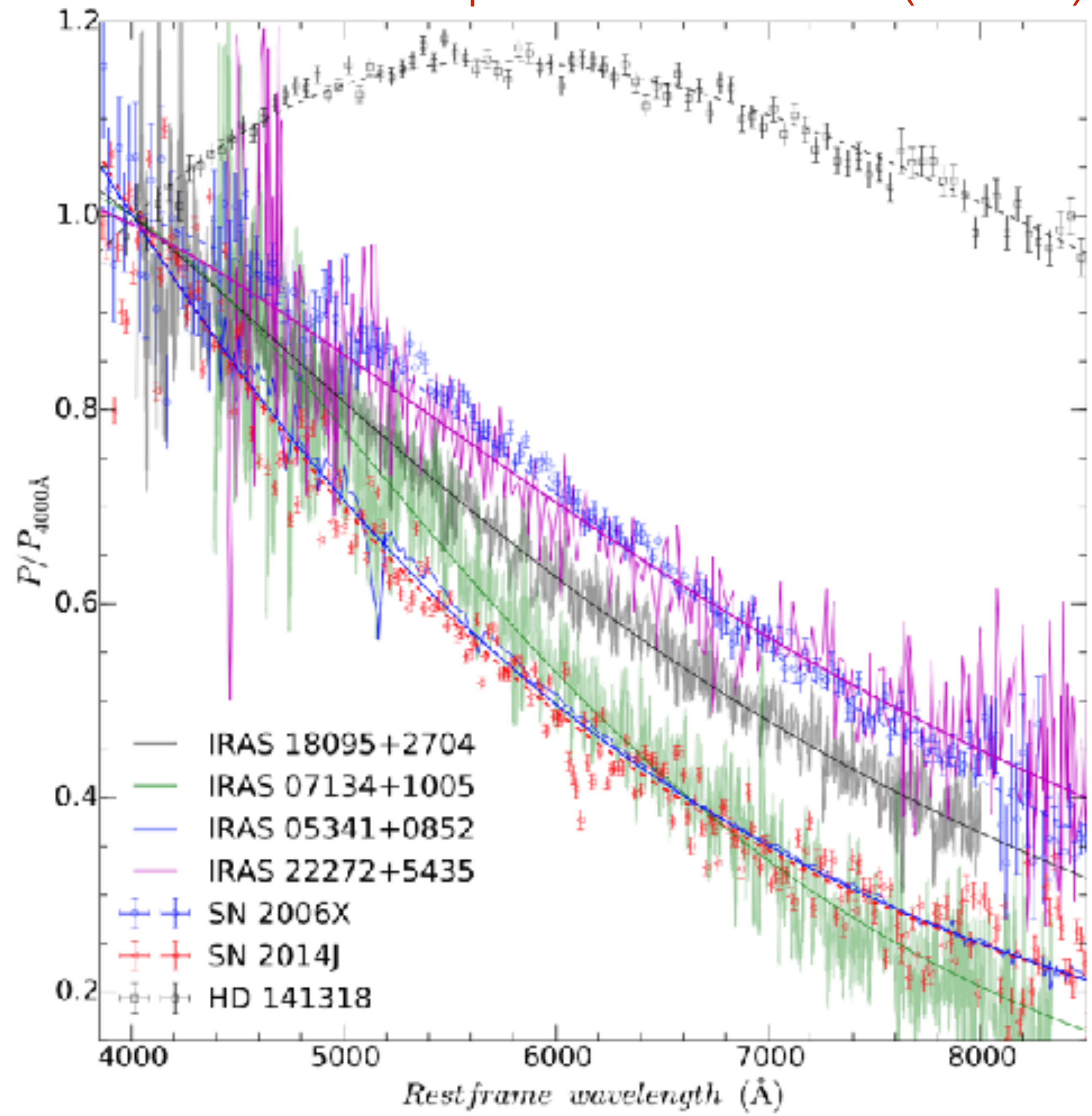
Patat+15

CS Dust Properties

post-AGB stars (PPNe)



Patat+15



Cikota+17

An alternative scenario

- Kashi & Soker11 proposed the **core-degenerate scenario**: the WD merges with an AGB star during the CE phase. The envelope is ejected, the explosion of the merged core is delayed by rotation, spins down (magnetic dipole radiation) and explodes.

- It has the advantage of “clearing” the immediate surroundings, and still leave material to be seen in absorption.

An alternative scenario

- Kashi & Soker11 proposed the **core-degenerate scenario**: the WD merges with an AGB star during the CE phase. The envelope is ejected, the explosion of the merged core is delayed by rotation, spins down (magnetic dipole radiation) and explodes.

- It has the advantage of "clearing" the immediate surroundings, and still leave material to be seen in absorption.

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+

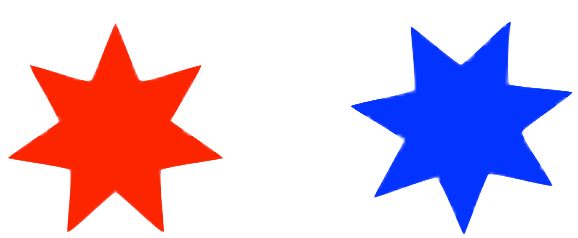
- The companion star survives the explosion
- It gains an anomalous transversal speed
- It acquires an anomalous rotational speed
- There is the possibility of a weird chemical composition in the atmospheric layers. But…

Surviving companions

Kerzendorf+
La Puente+

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

- The companion star survives the explosion
- It gains an anomalous transversal speed
- It acquires an anomalous rotational speed
- There is the possibility of a weird chemical composition in the atmospheric layers. But…



Surviving companions

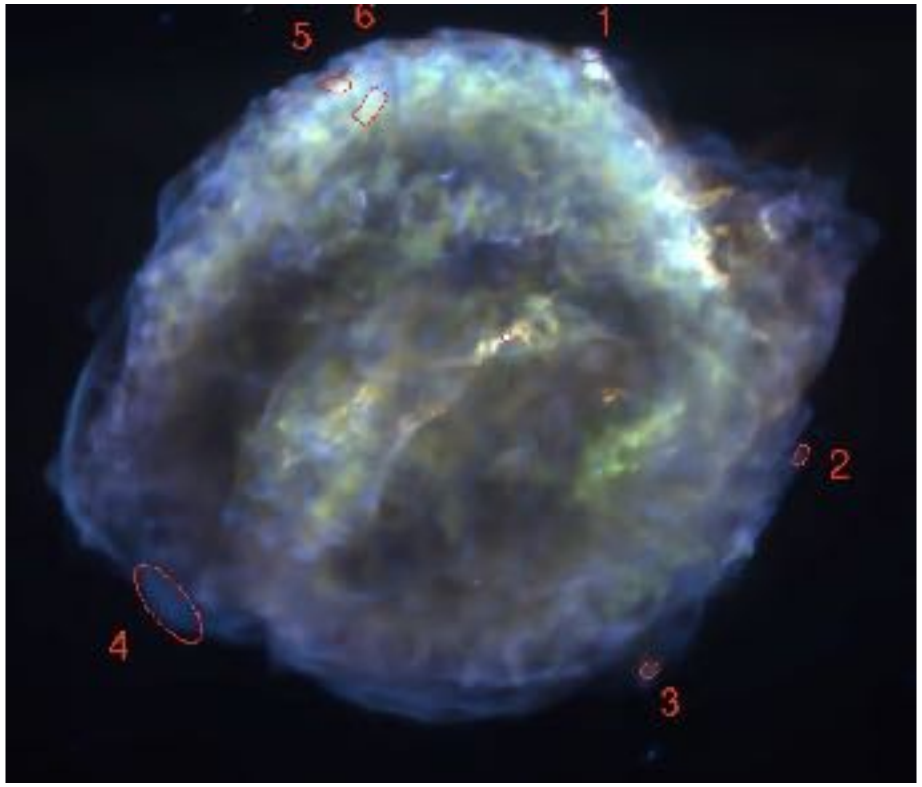
One difference between DDs and SDs is, of course, the presence of a companion that becomes unbound after the explosion. And it runs away…

Kerzendorf+
La Puente+

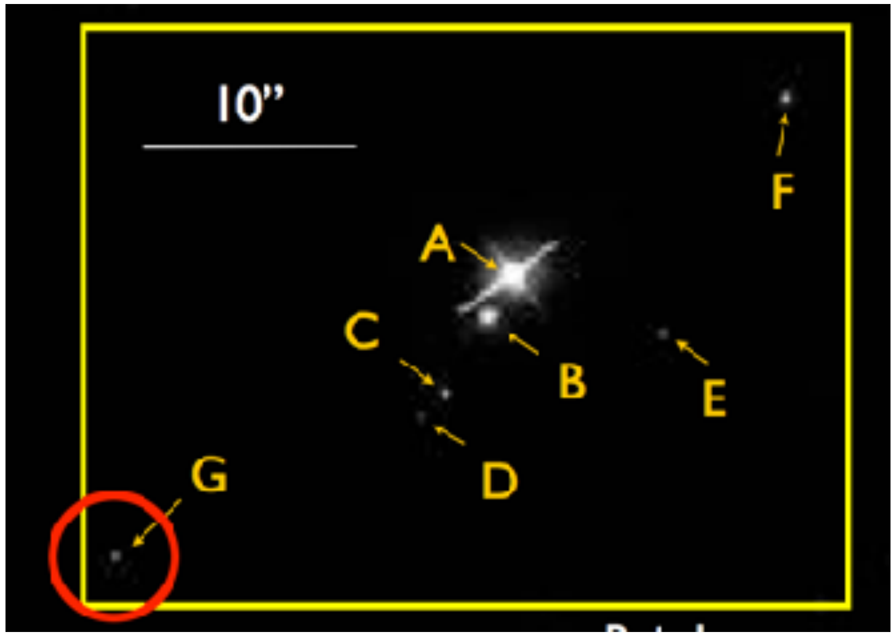
- The companion star survives the explosion
- It gains an anomalous transversal speed
- It acquires an anomalous rotational speed
- There is the possibility of a weird chemical composition in the atmospheric layers. But…

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

no star <=> no SD

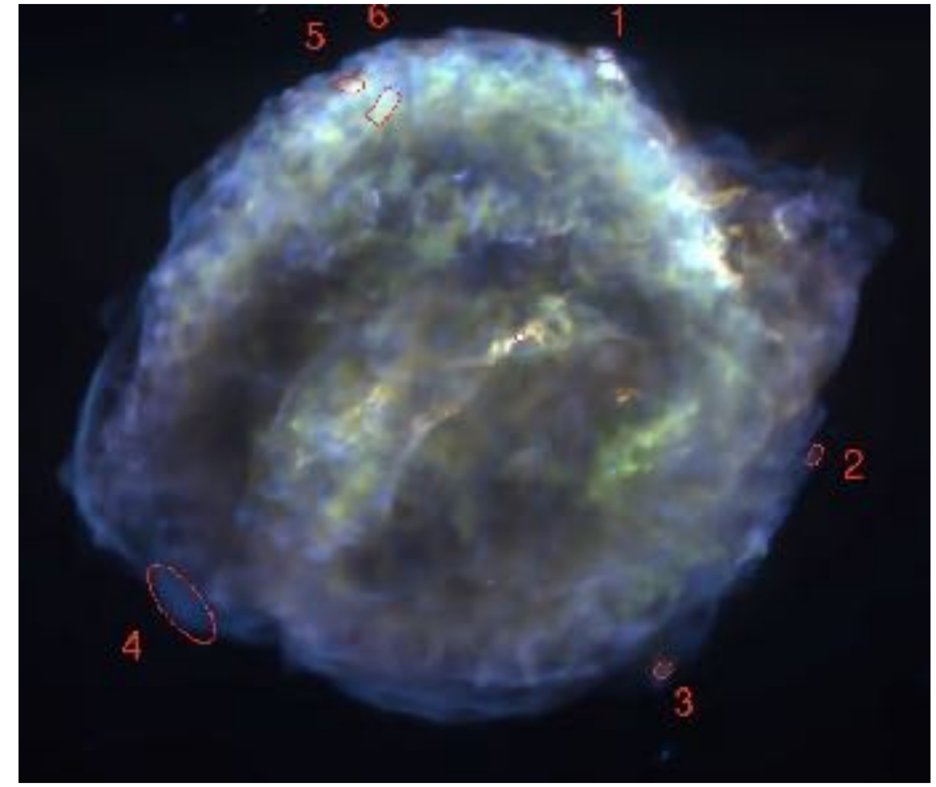


- First claimed detection Tycho's star G (La Puente+04)
- Not confirmed by Kerzendorf+09,12
- Re-stated (Bedin+14)

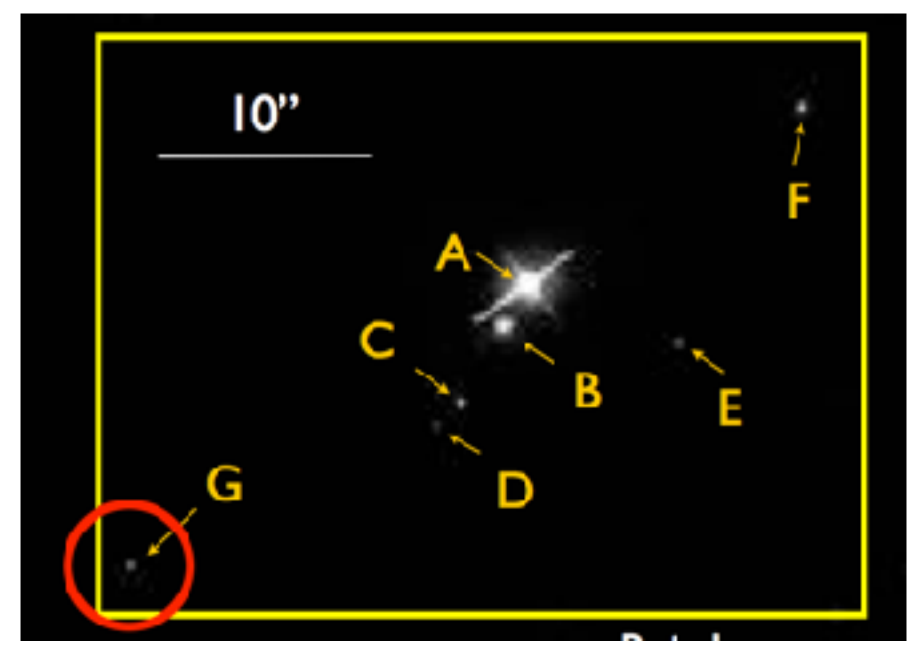


Search historical SNRs for weird composition, fast moving, rapidly rotating stars not far from the explosion center.

no star <=> no SD



- First claimed detection Tycho's star G (La Puente+04)
- 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**

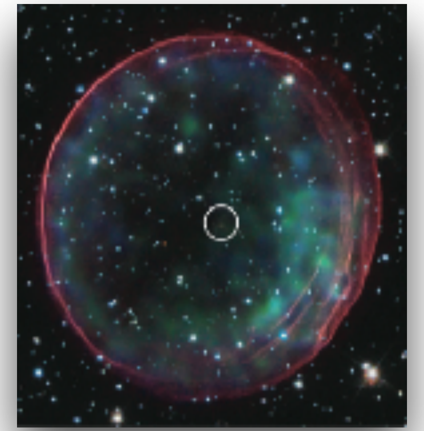
[…] The second hypothesis is that these surviving WD companions do not exist. This hypothesis could be extended (due to the various non detections of companions in literature) to the claim that generally SNe Ia do not leave any survivors. This would firmly point to the merger and complete disruption of WDs. However, the merger hypothesis has for now no easily falsifiable predictions except for the detection of a companion.

Kerzendorf+ 2017

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

- The Galactic Ia rate is known (~5×10^{-3} yr^{-1}). This can be used to constrain the progenitor scenarios using Binary Population Synthesis (BPS).
- In principle, DDs can account for this
- SDs can only account for some fraction of the observed rate (with WD+MS being the most "productive", and WD+RG the less "productive").
- The star formation rate AND the delay time distribution contribute to the SN rate r(t):

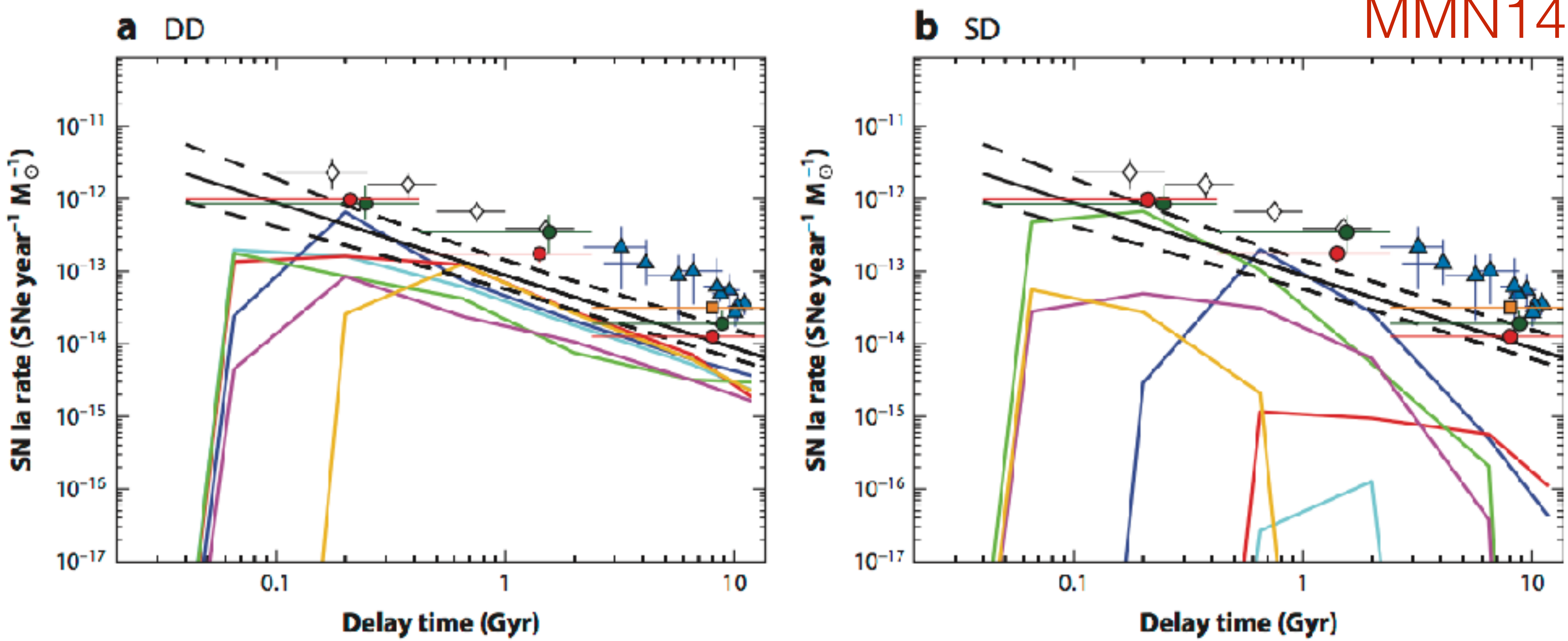
$$r(t) = \int_0^t SFR(t-t')DTD(t')\,dt'$$

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

SN rates and BPS

- 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



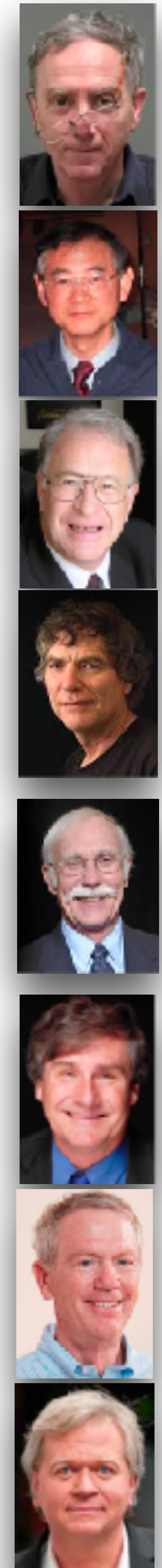
so that different DTDs produced by BPS (or parameterised models) can be compared to the observed rates.

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 Nomoto: The thermonuclear explosion of a C+O white dwarf has successfully explained the basic observed features of Type Ia supernovae (SNe Ia). Both the Chandrasekhar and the sub-Chandrasekhar mass models have been examined. However, no clear observational indication rejects how the white dwarf mass grows until C ignition, i.e., whether the white dwarf accretes H/He-rich matter from its binary companion [SD] or whether two C+O white dwarfs merge [DD].

Wolfgang Hildebrandt: All men are created equal - but not type Ia supernovae. Nature does it right! I attach another a picture of another supernova. It is just barley, yeast, and water.

Stan Woosley :A SN Ia is the outcome of detonating 1 solar mass of C and O with $\rho_{max} \approx 0.5 - 2 \times 10^8 \text{ g cm}^{-3}$.

Craig Wheeler: I recognise the need to consider a variety of models that might apply to the broad category of "Type Ia" and the limitations of the SD model, but still have reservations about DD models and sub-Chandra models (low central densities). I still think a delayed-detonation model, for its flaws, is the standard to beat in terms of reproducing the spectral evolution. Igniting carbon near the Chandrasekhar mass seems to work best for typical Type Ia, but there are variations that might work for both SD and DD. I'm intrigued by spinup/spindown models.

Alex Filippenko: Just as all roads lead to Rome, and one size does not fit all, I think it's becoming increasingly clear that Type Ia supernovae are produced by several evolutionary paths leading to different progenitor systems and white dwarf masses.

Robert Kirshner: Do not be a slave to fashion! Scientific ideas ebb and flow. Though evidence for interaction is sparse and strong evidence for partners is missing, keep an open mind. The single degenerate model is wounded, but not dead. Perhaps nature finds more than one way to explode a white dwarf.

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

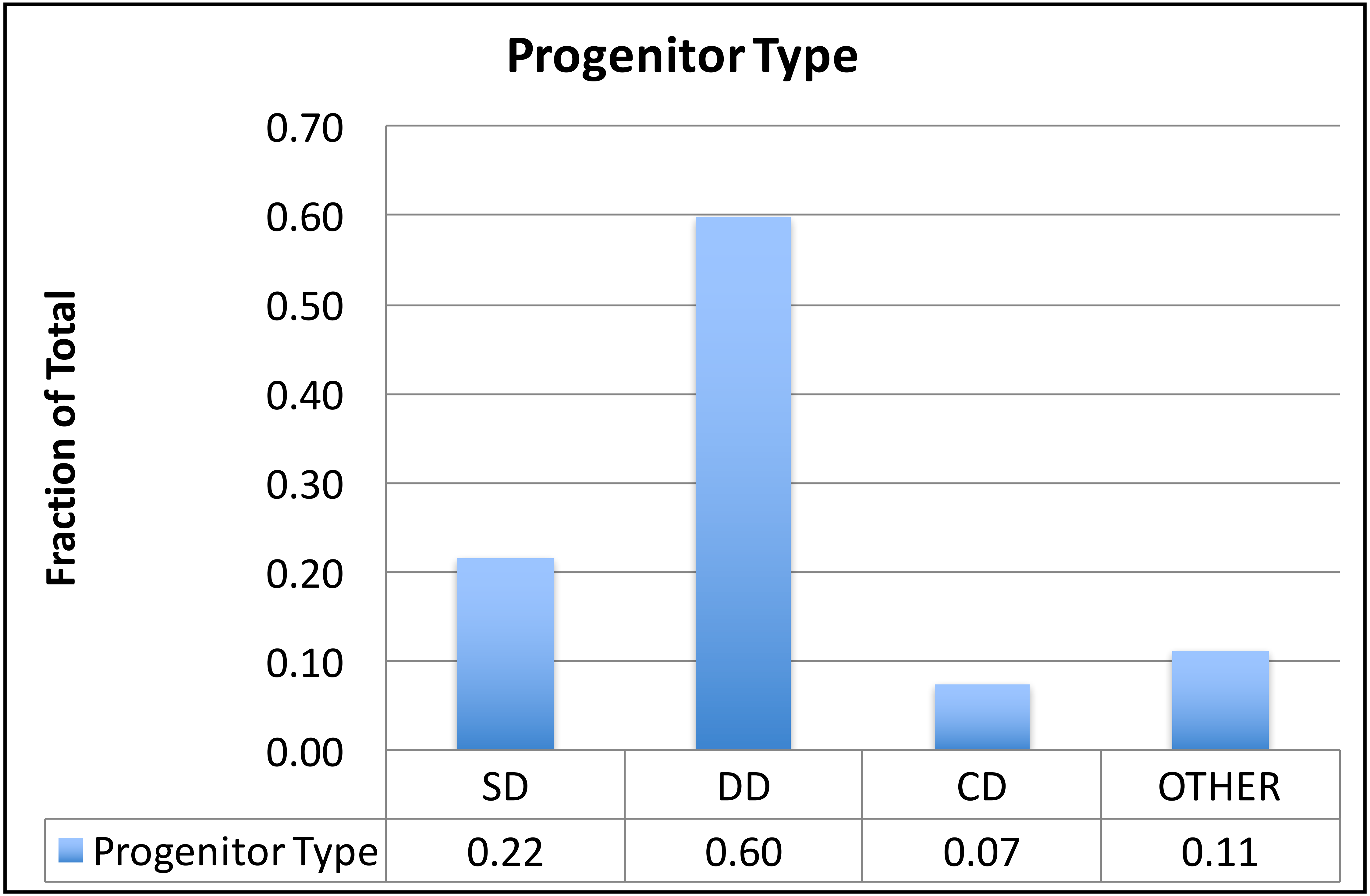
Sociological Appendix

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