Can merging white dwarfs explain most Type Ia supernovae?

Ashley J. Ruiter

Postdoctoral Fellow
Max Planck Institute for Astrophysics
Garching bei München, Germany

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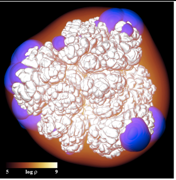
Max-Planck-Institut
für Astrophysik

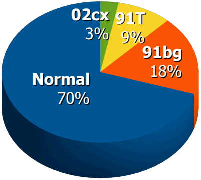
Collaborators (Ruiter, Sim, Pakmor et al. 2013)

- Stuart Sim (ANU/Queen's U Belfast)
- Rüdiger Pakmor (Heidelberg ITS)
- Markus Kromer (MPA)
- Ivo Seitenzahl (Würzburg/MPA)
- Krzysztof Belczynski (Warsaw)
- Fritz Röpke (Würzburg)
- Michael Fink (Würzburg)
- Wolfgang Hillebrandt (MPA)
- Stefan Taubenberger (MPA)
- Matthias Herzog (MPA)



I. Seitenzahl

- Li et al. 2011 SN survey → → →



F. Röpke

- **Old paradigm**: accreting WD approaches the *Chandrasekhar mass limit* ($\sim$ 1.4 $M_\odot$) → heats up and turns to thermonuclear burning → explosion (delayed detonation).
- Companion star donating mass - what is it?
- Light-curve is powered by radioactive decay chain of ^{56}Ni.
- Pie chart: SN Ia spectra idicate that multiple formation channels and/or explosion mechanisms exist.

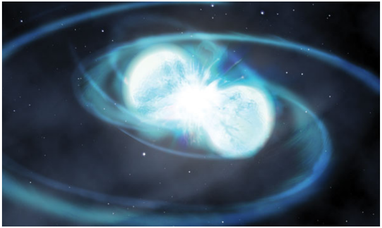
Two most favoured formation scenarios: **SD** and **DD**

- Whelan & Iben (1973)

D. A. Hardy

- Single Degenerate (SD) Scenario; $M_{\rm WD,final} \sim 1.4\ {\rm M}_\odot$
- WD accretes mass from (normal) star filling Roche-lobe (main seq. or evolved star).

- Webbink (1984)



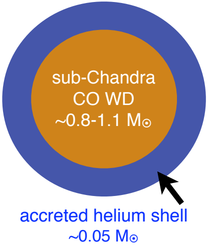
Nature

- Double Degenerate (DD) Scenario; $M_{\rm tot} > 1.4\ {\rm M}_\odot$
- Two carbon-oxygen WDs merge; lighter WD accreted onto more massive WD.

A third formation channel: sub-Chandra mass SD

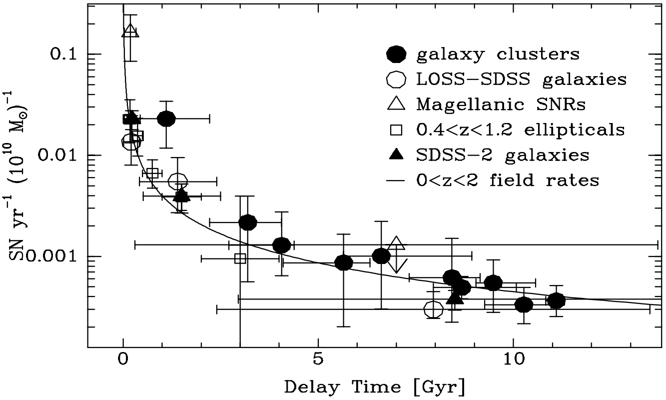
Often called double-detonation scenario *(See K. Shen talk)*

- **Mechanism**: detonation in helium shell around WD accreted from a (He-rich) companion leads to detonation in CO WD ('double-detonation'; Taam+, Livne+, Woosley+).
- Don't require 1.4 $M_\odot$ WDs; Sub-Chandra mass WDs much more common.
- Gives **natural explanation** for variety among light-curves: range of exploding WD masses → **range** in amount of ^{56}Ni → bright and dim SNe Ia. **But**: Uncertainty in He detonation/burning.

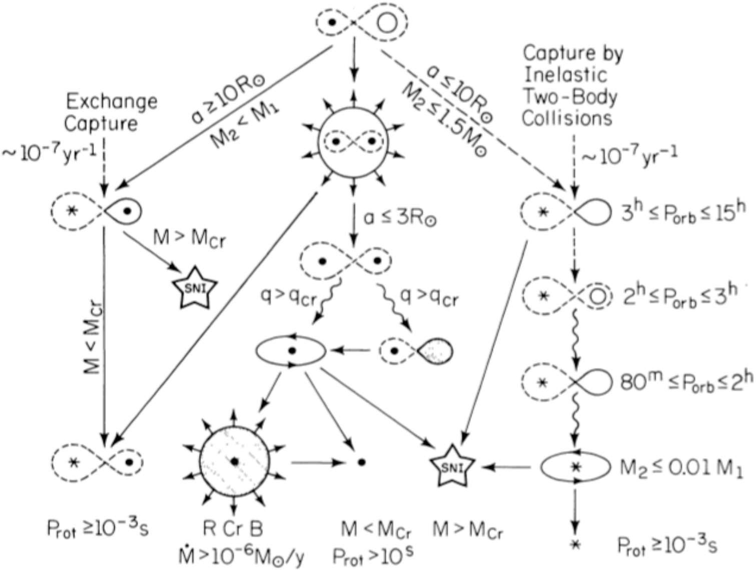


Delay Time Distribution (DTD)

- DTD: distribution in time of SNe Ia explosions following a starburst. Power-law form $\sim t^{-1}$ expected from DD binaries since gravitational radiation timescale $t_{\rm GR} \propto$(orb separation)^4.



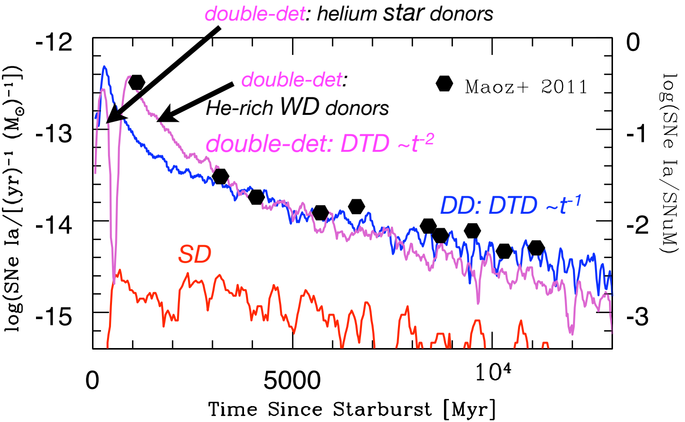
Maoz & Mannucci (2011)



Iben & Tutukov 1984

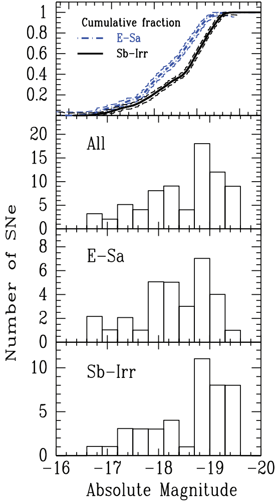
StarTrack Delay Time Distributions (cf. Ruiter et al. 2009,2011)

SN rate as function of time from birth constrains progenitor **age**.



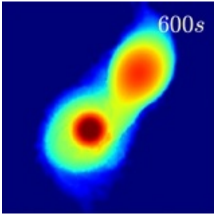
Peak luminosity of SN Ia: exploding WD mass→^{56}Ni

- Promising progenitor must be able to reproduce the observed peak brightness distribution (cf. Li et al.).
- Prompt detonations: absolute brightness of a SN Ia is determined by the mass of the exploding WD.
- Straightforward to compute brightness of DD mergers from the mass of the primary (exploding) WD for **violent WD mergers.**



W. Li et al. 2011

Violent WD merger: subclass of DD

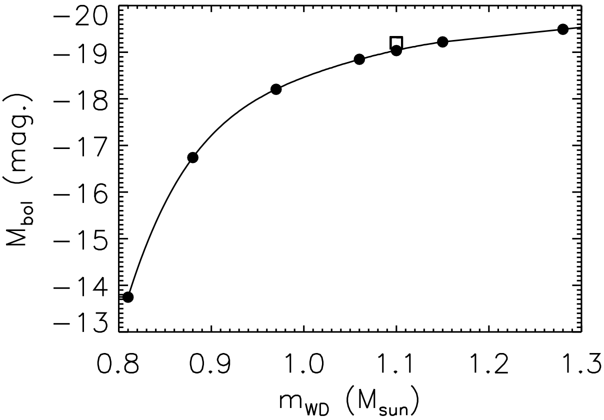


R. Pakmor

- Previous studies (Miyaji, Saio, Nomoto): Merger $\geq$ 1.4 $M_\odot$ $\rightarrow$ non-explosive burning $\rightarrow$ collapse to neutron star ?
- Violent merger $=$ prompt detonation in m_p; both WDs are burned, ^{56}Ni synth. in m_p.
- m_p: determines peak luminosity!
- **What we did**: 1D hydro exploding WDs + radiative transfer modelling $\rightarrow$ Mass-Luminosity relation $\rightarrow$ map merging systems (WD masses) from population synthesis to explosion luminosities $\rightarrow$ compare to observations.

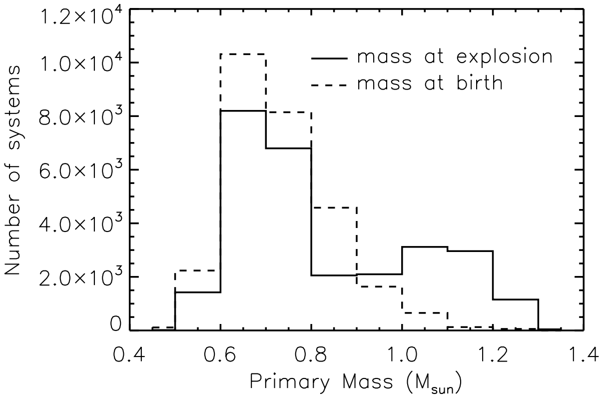
m_{WD} – M_{bol} relation (Sim et al. 2010; Fink et al. 2010)

Detonations in 1-D hydrostatic sub-MCh mass WDs (LEAFS, ARTIS).

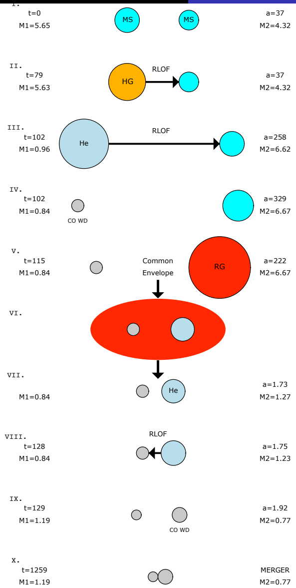


Startrack mass range for all CO-CO WD mergers

StarTrack (Belczynski et al. 2002; 2008).

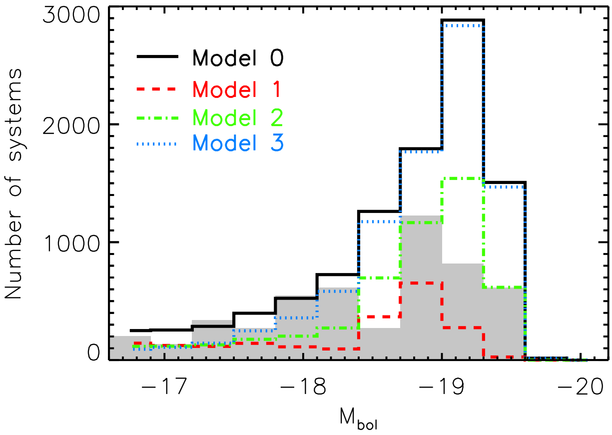


Ruiter, Sim, Pakmor et al., 2013 MNRAS 429, 1425

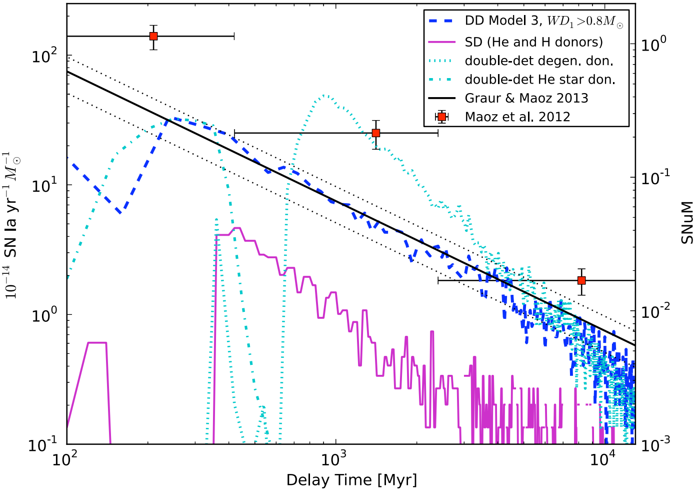

I.
t=0
M1=5.65
MS
MS
a=37
M2=4.32
II.
t=79
M1=5.63
HG
RLOF
a=37
M2=4.32
III.
t=102
M1=0.96
He
RLOF
a=258
M2=6.62
IV.
t=102
M1=0.84
CO WD
a=329
M2=6.67
V.
t=115
M1=0.84
Common
Envelope
RG
a=222
M2=6.67
VI.
VII.
M1=0.84
He
a=1.73
M2=1.27
VIII.
t=128
M1=0.84
RLOF
a=1.75
M2=1.23
IX.
t=129
M1=1.19
CO WD
a=1.92
M2=0.77
X.
t=1259
M1=1.19
MERGER
M2=0.77

Li et al. 2011, 74 *LOSS* SNe Ia within 80 Mpc.

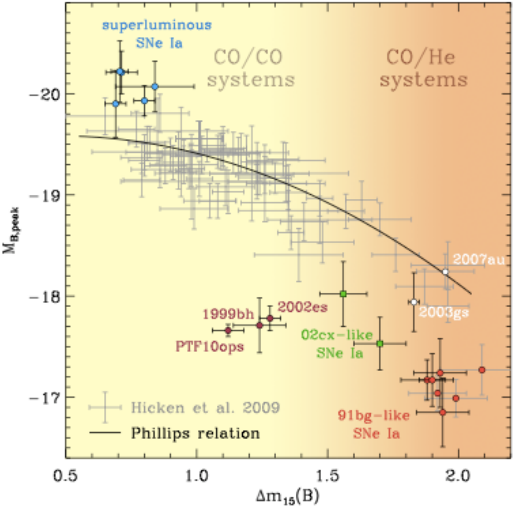
cf. Ruiter et al. 2013 (see dash-dot line/Model 2)



Delay Time Distributions (cf. Hillebrandt et al. 2013)



↑
peak
brightness



Pakmor, Kromer & Taubenberger, submitted.

← Broad light-curves ... Narrow light-curves →

Summary

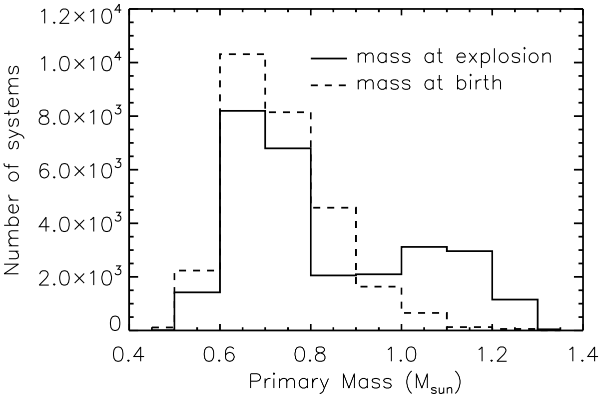
- Need future observations to confirm whether such an accretion phase (He-star $\rightarrow$ WD) is encountered among progenitors of WD mergers.
- Helium stars are important for WD merger progenitors: implementation of additional (helium) accretion physics into *StarTrack*, input from detailed binary evolution modeling with helium donors (e.g., STARS) is needed.
- Bottom line: probably multiple SN Ia evolutionary channels exist, and **either violent mergers contribute substantially, or some other progenitor channel(s) drive(s) the underlying brightness distribution**.

Violent mergers are promising SN Ia progenitors

- Binary population synthesis calculations are needed to assess relative birthrates of SNe Ia and their delay times!
- **Delay Time Distribution**: violent WD mergers ☺
- **Rates**: violent WD mergers ☺
- Using *StarTrack* we have identified a formation channel which is crucial for producing massive primary CO WDs.
- We mapped m_{p} (from BPS) to peak M_{bol}: theoretical and observational M_{bol} distributions compare well.
- BPS + WD merger models + radiative transfer → **peak brightness distribution**: violent WD mergers ☺

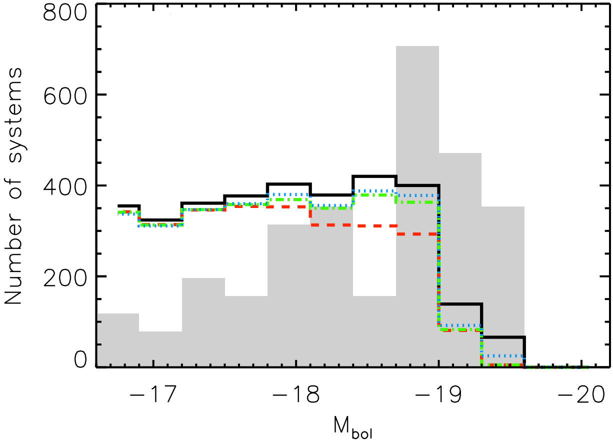
extra slides ...

What about primary WD masses at WD birth (dashed line)?

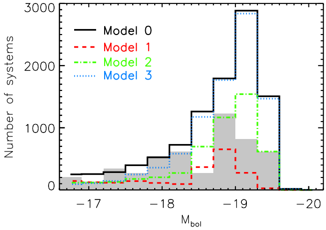


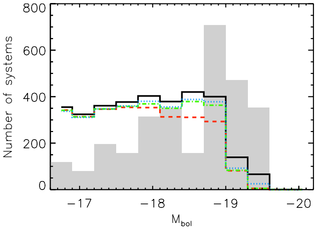
Li et al. 2011, 74 *LOSS* SNe Ia within 80 Mpc.

cf. Ruiter et al. 2013



- The StarTrack mass-distribution of merging CO+CO WD pairs gives rise to a range of explosion brightnesses that match those observed for SNe Ia (Li et al 2011).
- The agreement between the synthetic and observed brightness distributions depends critically on a critical evolutionary phase: the primary WD accretes ($\sim 0.25\ M_{\odot}$) while the companion is a slightly-evolved helium star.



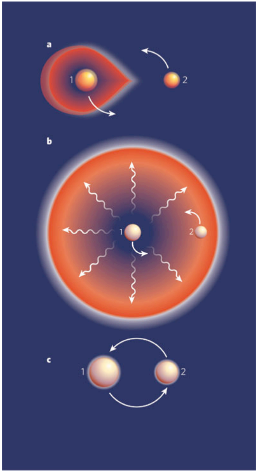


Binaries: treatment of mass transfer and AML

- Angular Momentum Loss through Roche-lobe overflow (RLOF), Common Envelope (CE), magnetic braking, gravitational radiation $\rightarrow \dot{J}_{\rm orb}$
- Is MT stable? $\rightarrow \dot{M}_{\rm nuc}$ or $\dot{M}_{\rm th}$,? Non-degenerate vs. degenerate? RLOF: fraction of mass loss/gain. CE: $\dot{M}_{\rm dyn}$, **two formalisms**: Webbink (α); Nelemans (γ):

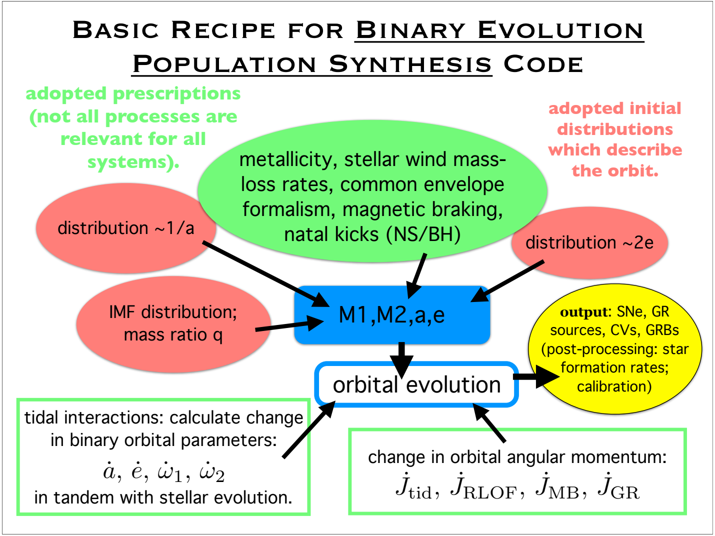
$$\alpha\left(\frac{-G\,M_{\rm rem}\,M_2}{2a_{\rm f}} + \frac{G\,M_{\rm giant}\,M_2}{2a_{\rm i}}\right) = -\frac{G\,M_{\rm giant}\,M_{\rm env}}{\lambda\,R_{\rm giant}}$$

$$\gamma\,\frac{J_{\rm i}}{M_{\rm giant}+M_2} = \frac{J_{\rm i}-J_{\rm f}}{M_{\rm env}}$$

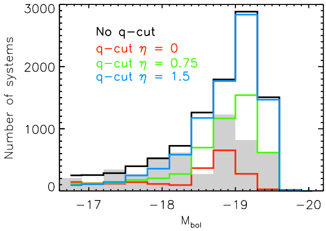


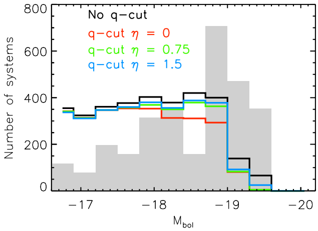
Nature

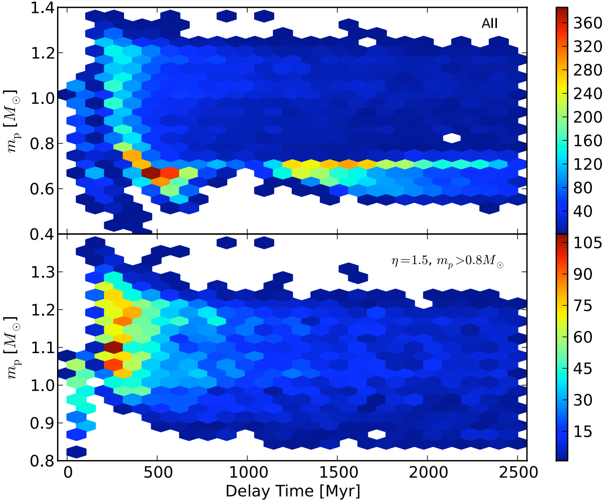
Evolving Ia progenitors: StarTrack (Belczynski et al.)

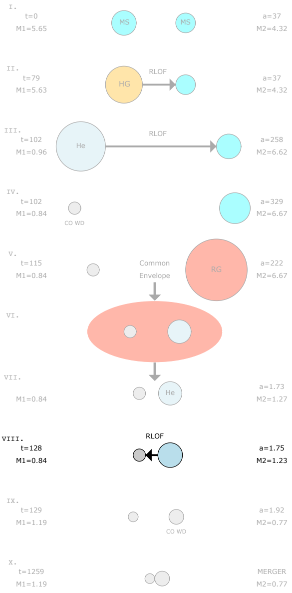


- It remains to be confirmed, by future observations and detailed accretion modeling, whether such a phase is encountered among double WD progenitors.
- If such a mass transfer phase does not readily occur in nature, then likely another explosion scenario drives the underlying shape of the observed SN Ia brightness distribution.

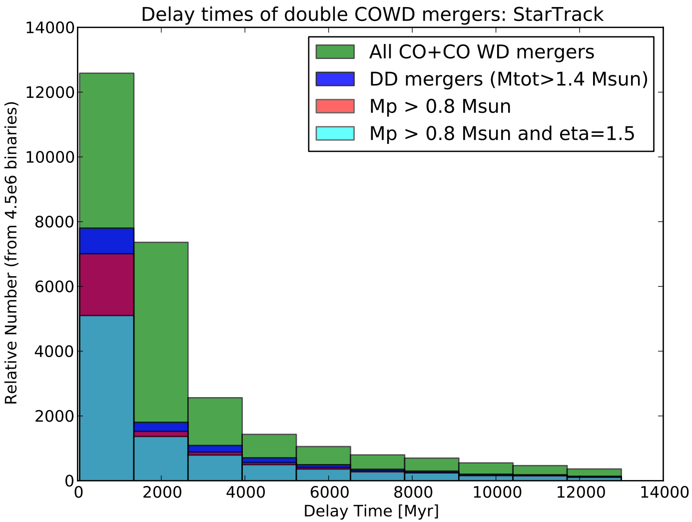


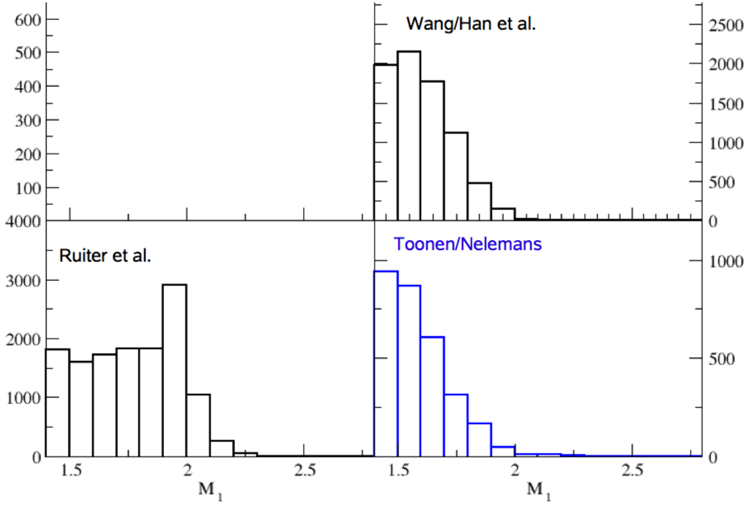



All
$\eta=1.5$, $m_p>0.8M_\odot$
$m_{\rm p}$ $[M_\odot]$
Delay Time [Myr]
1.4
1.2
1.0
0.8
0.6
0.4
1.3
1.2
1.1
1.0
0.9
0.8
0
500
1000
1500
2000
2500
360
320
280
240
200
160
120
80
40
105
90
75
60
45
30
15



Important phase for primary WD growth: primary WD accretes from helium sub-giant.


Delay times of double COWD mergers: StarTrack
Relative Number (from 4.5e6 binaries)
0
2000
4000
6000
8000
10000
12000
14000
Delay Time [Myr]
0
2000
4000
6000
8000
10000
12000
14000
All CO+CO WD mergers
DD mergers (Mtot>1.4 Msun)
Mp > 0.8 Msun
Mp > 0.8 Msun and eta=1.5


Wang/Han et al.
Ruiter et al.
Toonen/Nelemans
600
500
400
300
200
100
4000
3000
2000
1000
0
2500
2000
1500
1000
500
0
1000
500
0
1.5
2
2.5
1.5
2
2.5
M_1
M_1

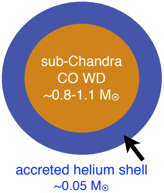
StarTrack binary evolution population synthesis code

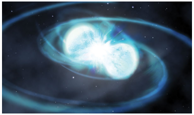
Belczynski et al. 2008

- Uses Monte Carlo methods to rapidly evolve a large number ($\sim 10^6+$) of stars from the Zero-Age Main Sequence to a Hubble time.
- Stars are evolved using modified analytical formulae (evol. tracks) for single stellar evolution (Hurley et al. 2000).
- Physical processes important for binary stars are taken into account (e.g., mass transfer, magnetic braking, tides, gravitational radiation, common envelopes).
- Can study the **formation and evolution** of objects which is impossible to do with detailed stellar evolution codes.

Pros and Cons: three formation scenarios

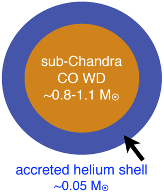
Observations	sub-Chandra	SDS (1.4 $M_\odot$)	DD mergers
Progenitors?	?	☺	☹?
Hydrogen:	☺	☹	☺
Companion?	☺?	☹?	☺
SN 2011fe:	☺?	☹?	☺

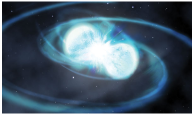


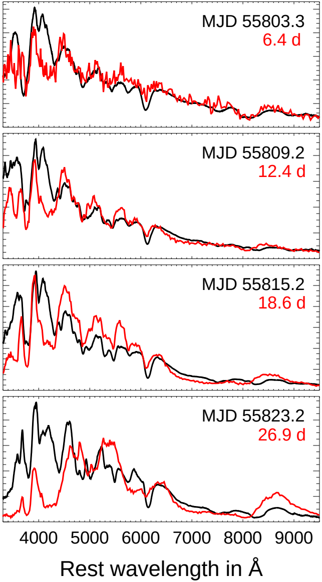


Pros and Cons: three formation scenarios

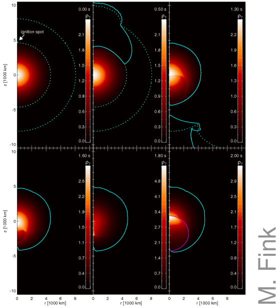
Theory	sub-Chandra	SDS (1.4 $M_\odot$)	DD mergers
expl. mech.:	☺?	☺☺	☺
mod. spectra:	☺?	☺	☺
LC diversity?	too much?	not enough?	☺?
Rates/DTD:	☺	☹	☺

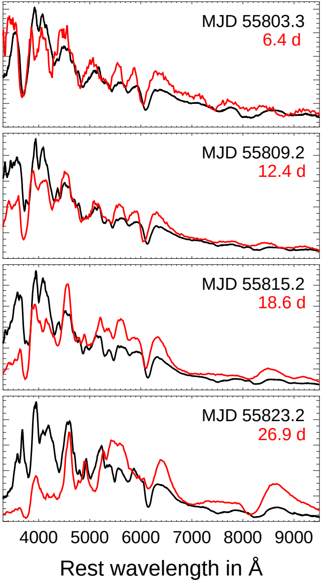




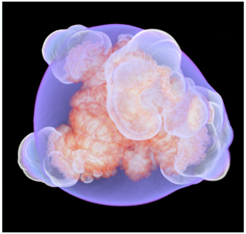


- Kromer et al. double-detonation model: sub-Chandra (1.03 $M_\odot$ CO WD with 0.05 $M_\odot$ helium shell)
- **black line**: 2011fe data
- Explosion model yields 0.6 $M_\odot$ ^{56}Ni → in good agreement with normal SNe Ia

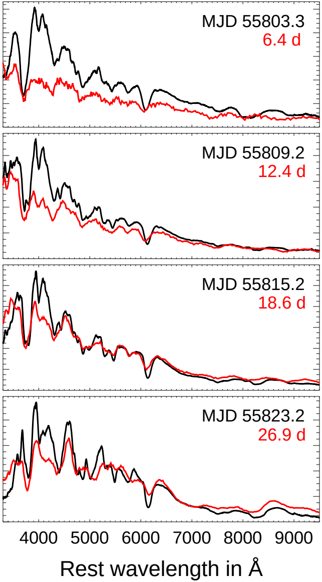




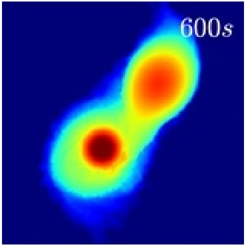
- Röpke et al. 2012 delayed detonation model: Single Degenerate (1.4 $M_\odot$ WD)
- **black line**: 2011fe data
- Explosion model yields 0.6 $M_\odot$ ^{56}Ni → in good agreement with normal SNe Ia



I. Seitenzahl



- Pakmor et al. 2012 merger model: Double Degenerate ($0.9 + 1.1\ M_\odot$)
- **black line**: 2011fe data
- Explosion model yields $0.6\ M_\odot$ ^{56}Ni $\rightarrow$ in good agreement with normal SNe Ia



R. Pakmor