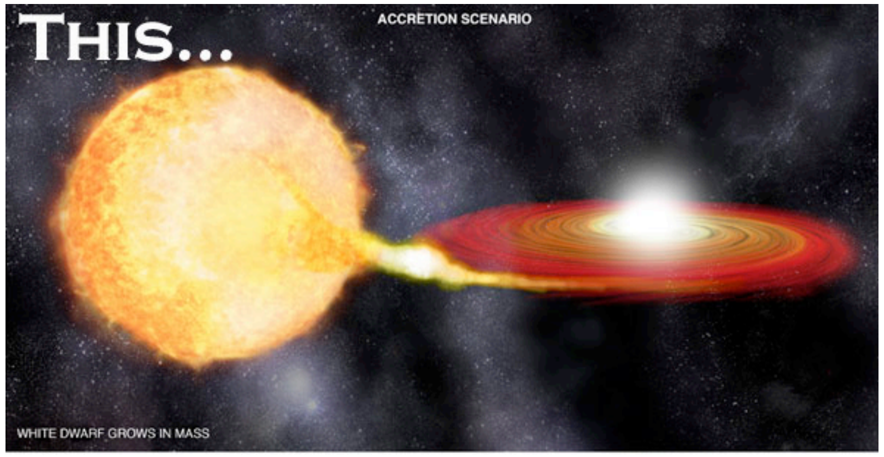
Review: Population synthesis & rates of supernovae



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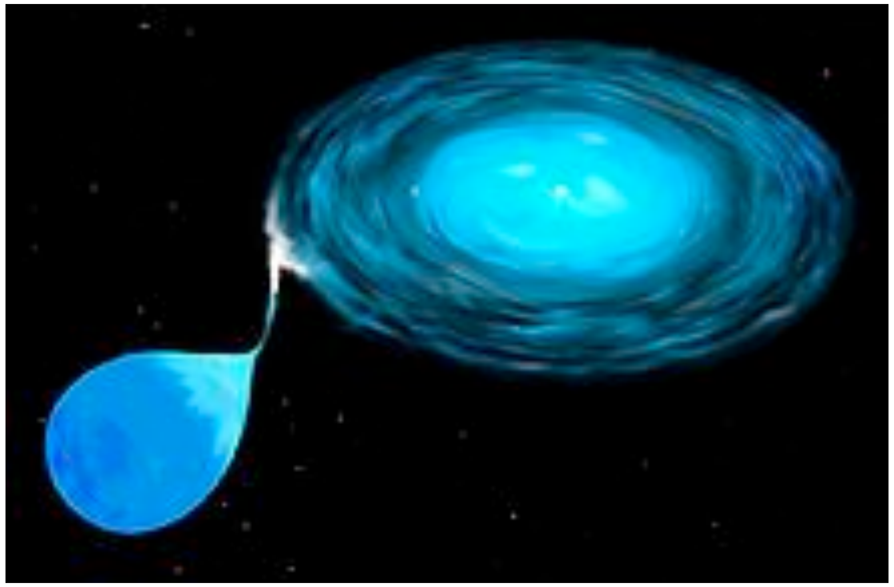
Hagai Perets, Rasmus Voss, Christian Knigge
Joke Claeys, Nicki Mennekens, Ashley Ruiter

This talk



1. Review of binary population synthesis (BPS)
   - Comparison of BPS codes (PopCORN)

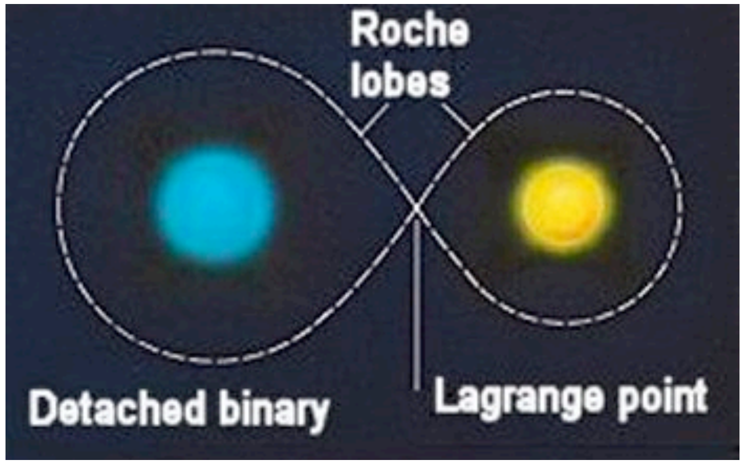
2. Review of SNIa rates and delay times
   - For different channels

Binary population synthesis

Binary population synthesis

- Simulate the evolution of a large number of binaries
- From ZAMS to remnant formation (or any desired evolutionary phase)
- At each timestep for each binary take into account relevant physics e.g. processes as stellar winds, mass transfer (stability), mass accretion, angular momentum loss, tidal evolution

Binary population synthesis

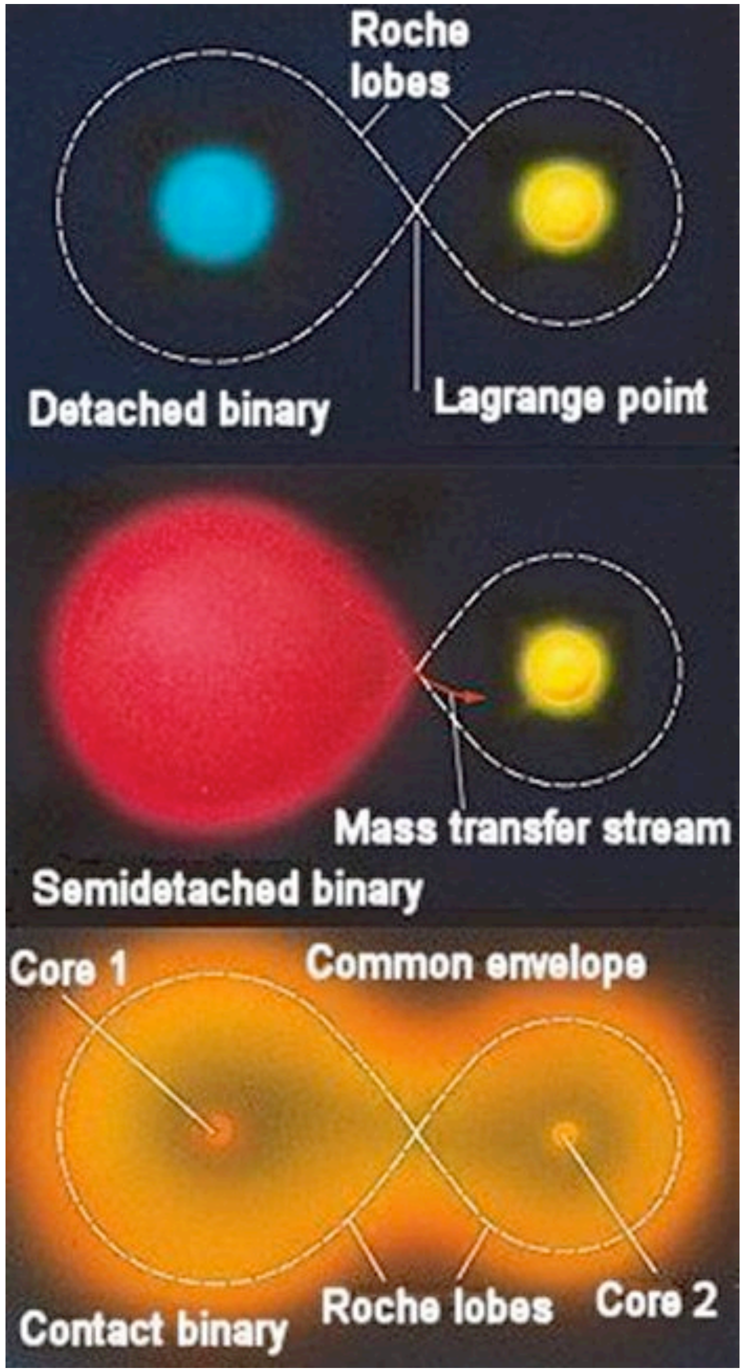


Stellar evolution

- Stellar winds

Stellar dynamics

Binary population synthesis



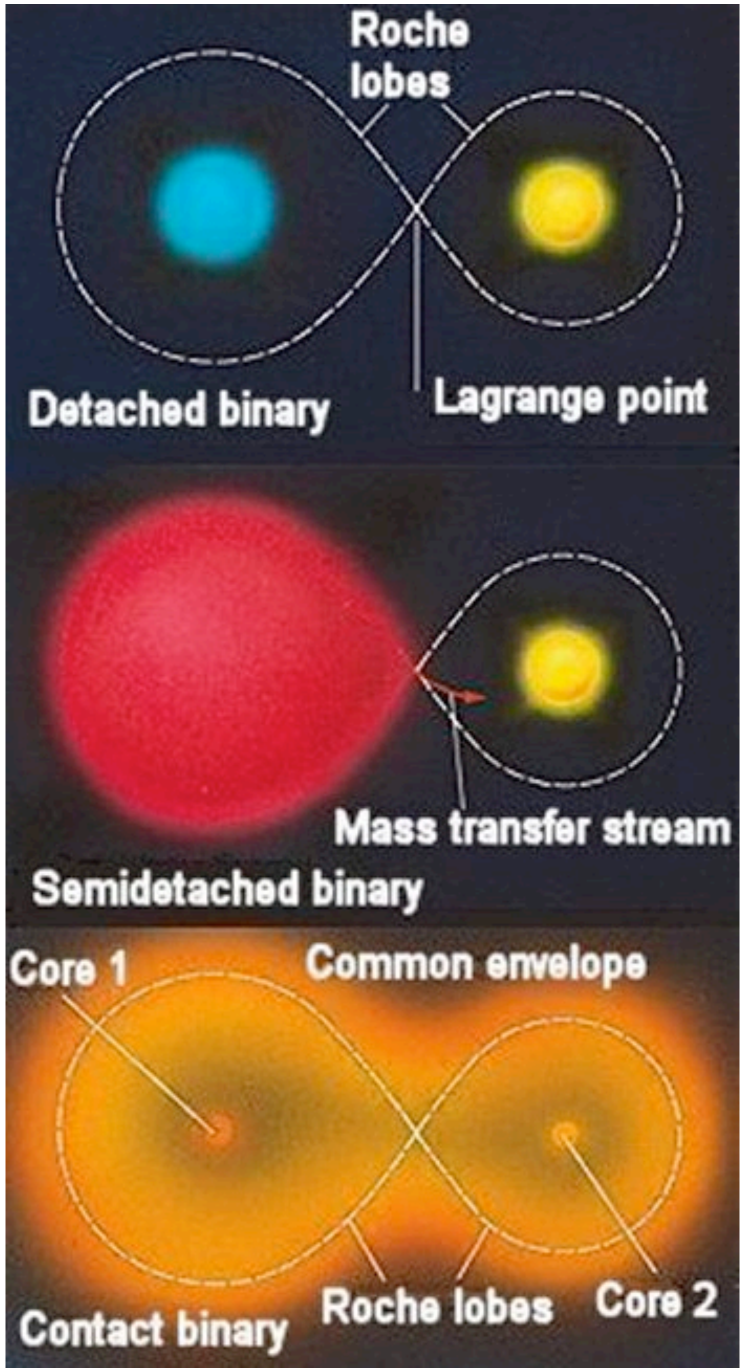
Stellar evolution

- Stellar winds

Stellar dynamics

- Stability of mass transfer
- Physics of mass transfer

Binary population synthesis

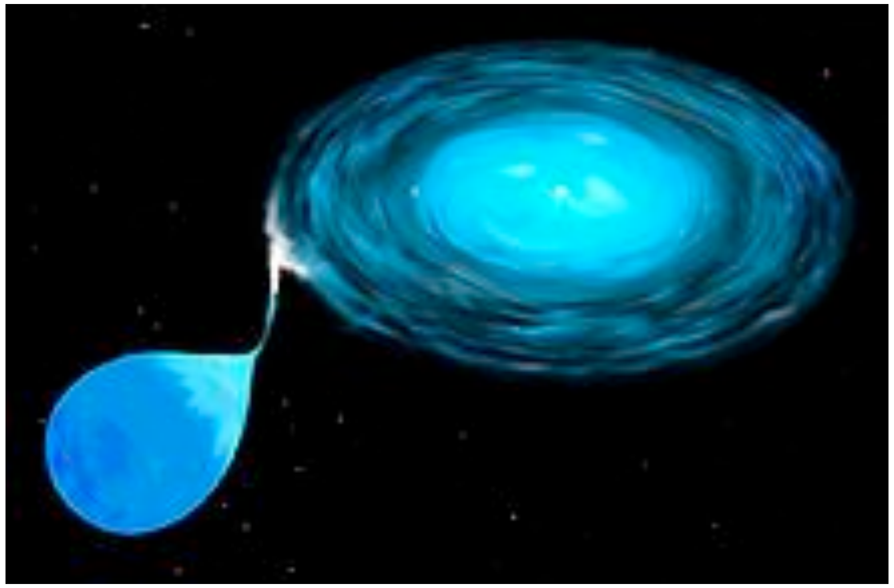


Stellar evolution

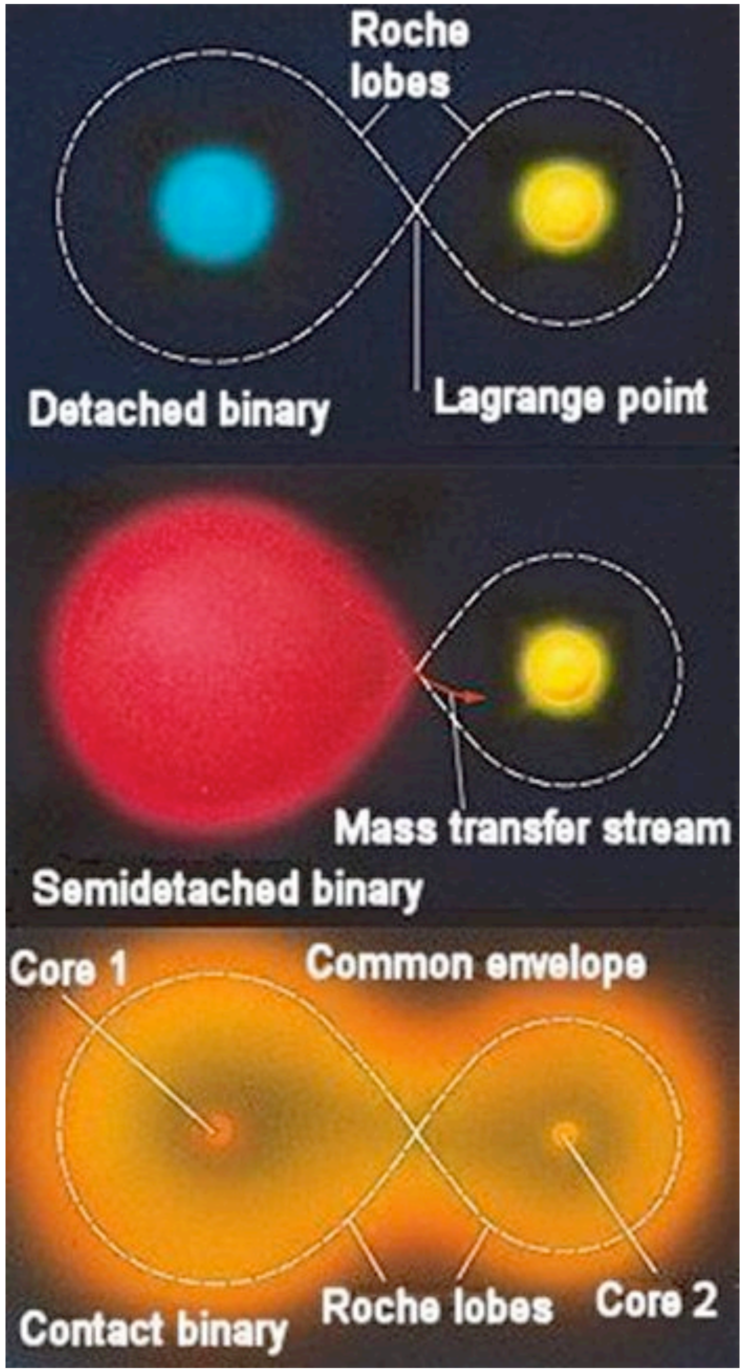
- Stellar winds

Stellar dynamics

- Stability of mass transfer
- Physics of mass transfer
- Mass loss and accretion

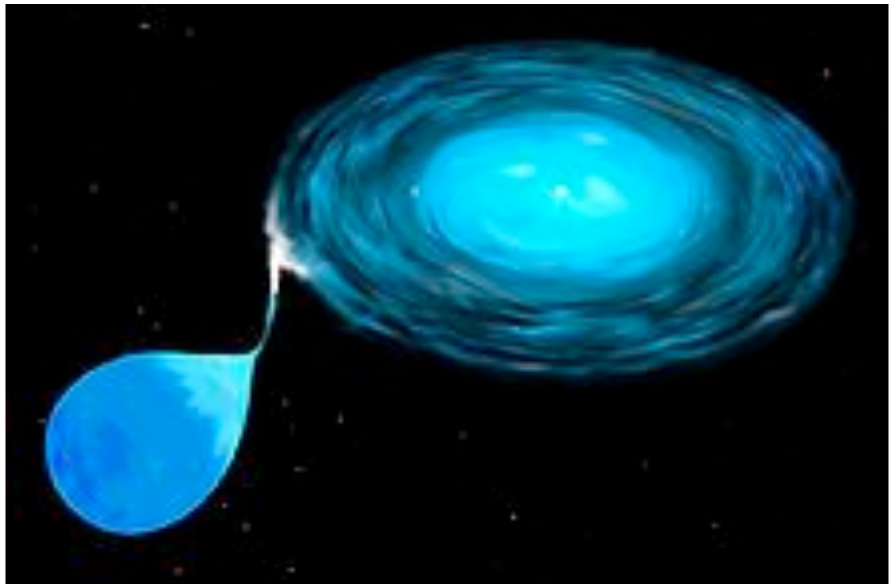


Binary population synthesis



Stellar evolution

- Stellar winds



Stellar dynamics

- Stability of mass transfer
- Physics of mass transfer
- Mass loss and accretion
- Angular momentum loss
- Mass loss
- Gravitational waves
- Magnetic braking
- Tidal effects

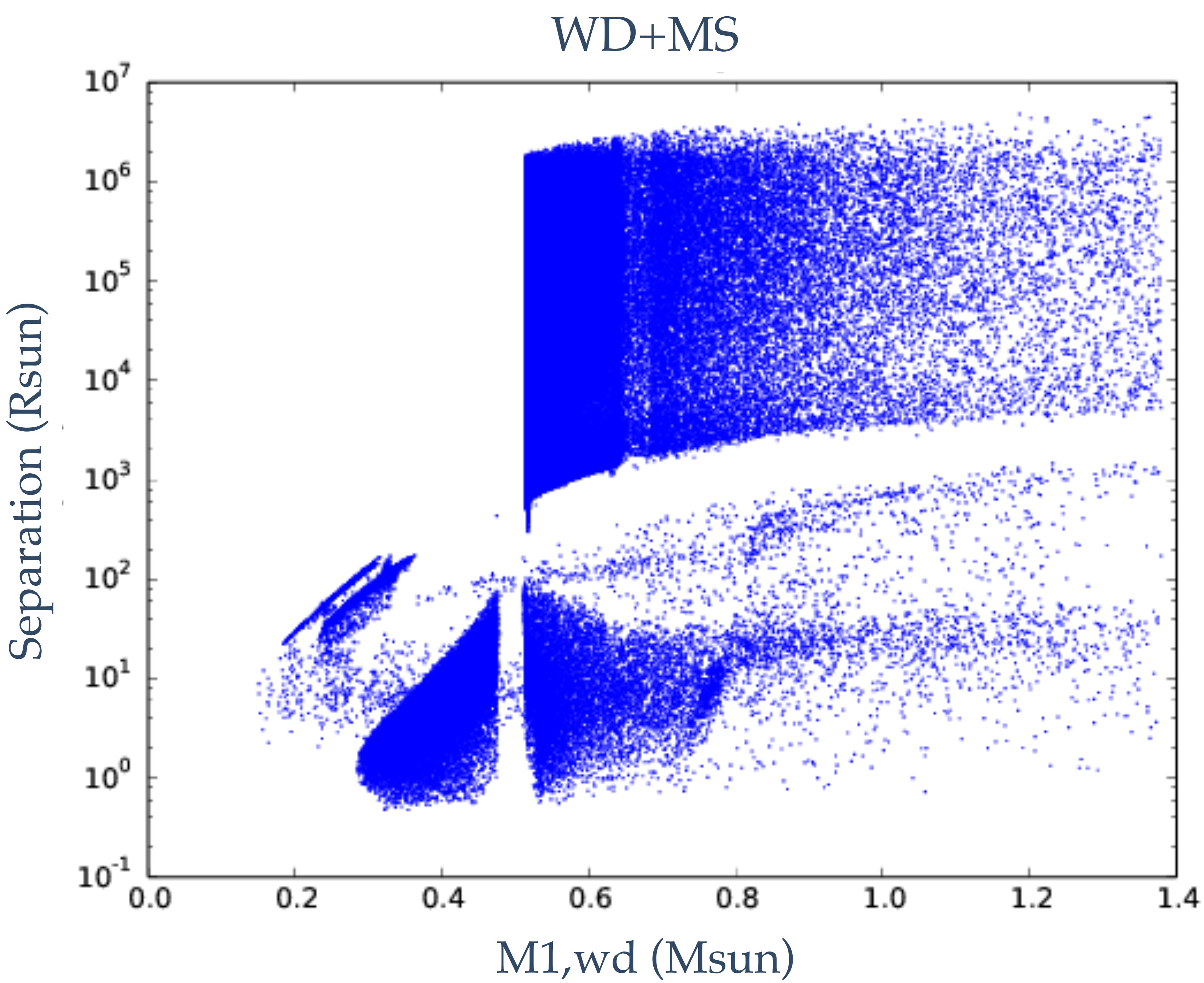
Binary population synthesis

- Study e.g.
  - characteristics of a binary population (e.g. mass ratio distribution, period distribution)
  - frequency of an astrophysical event
  - chemical enrichment of a region

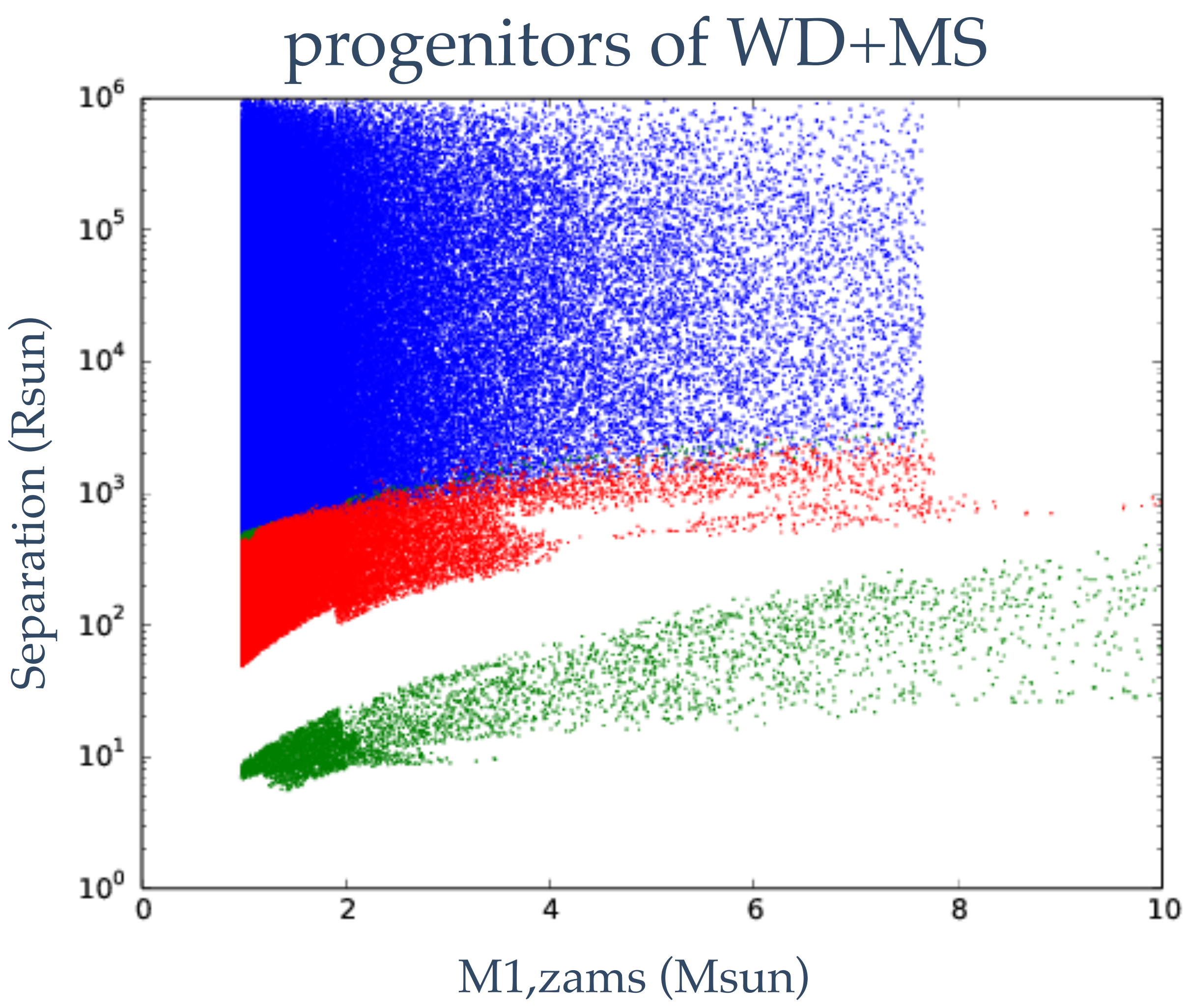
- Rapid calculation
- Simplifying assumptions (e.g. straightforward prescriptions for the stability and rate of mass transfer)

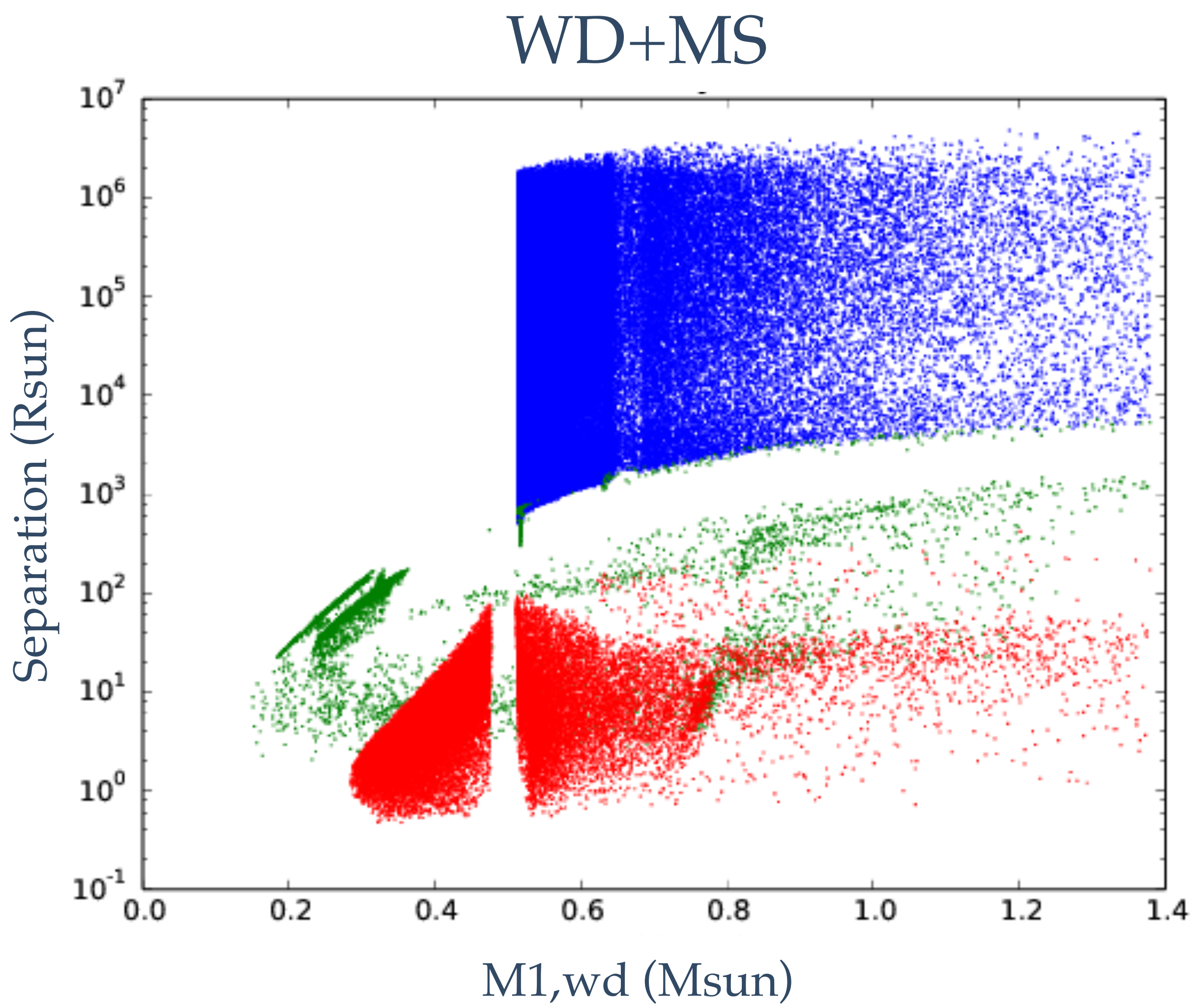
- Hybrid method:
  - Calculations with detailed stellar evolution code + population synthesis code (e.g. Chen+'14, Wang+'15, Liu+'16)

Binary population synthesis



Binary population synthesis





- No interaction
- Stable mass transfer
- Common-Envelope

Population synthesis comparison

Population synthesis comparison

PopCORN!

Are different results caused by

accuracy or assumptions?

PopCORN

Binary population synthesis codes:

- Binary_c (Izzard et al. 2004, 2006, 2009, Claeys et al. 2014. Based on Hurley et al.2000 & 2002)
- Brussels code (De Donder & Van Beveren et al. 2004, Mennekens et al. 2010)
- SeBa (Portegies Zwart & Verbunt 1996, Nelemans et al. 2001, Toonen et al. 2012, 2013)
- StarTrack (Belczynski et al. 2008, Ruiter et al. 2009)

Most simple comparison:

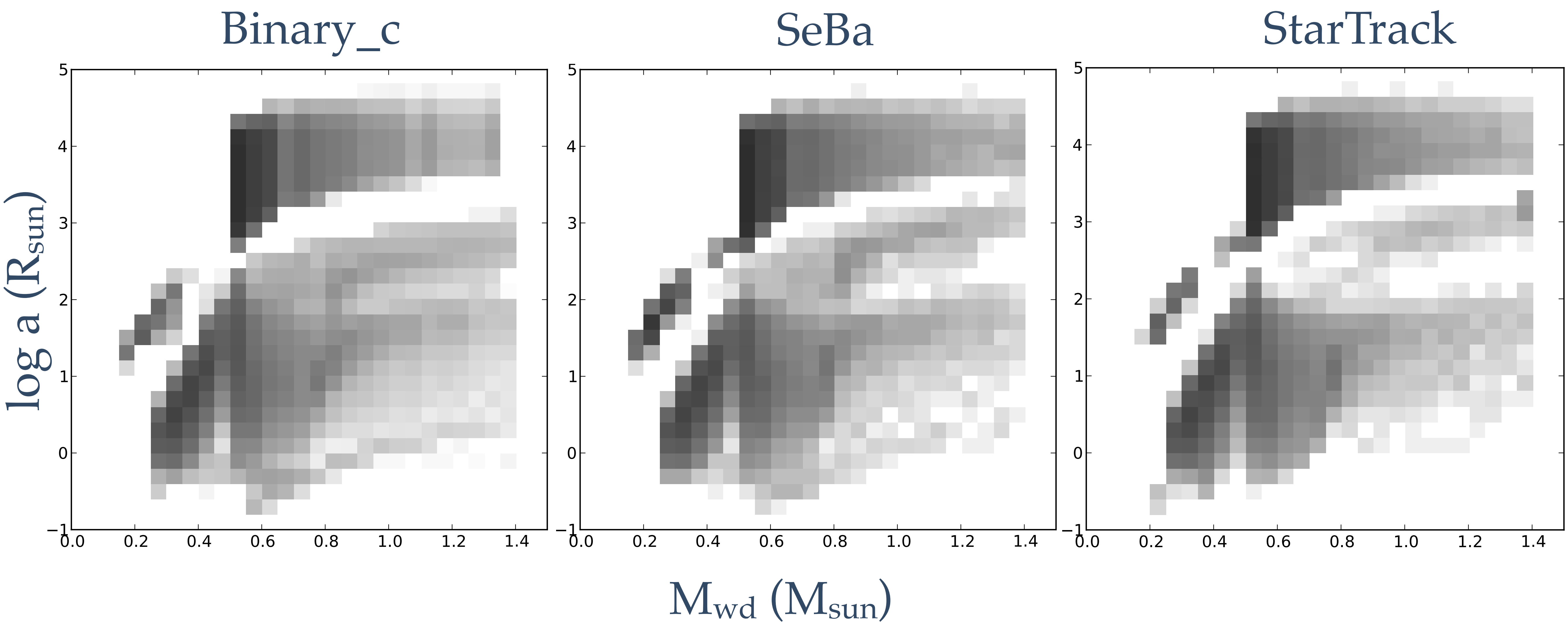
- Equalize assumptions where possible
- Study inherent differences in codes

Focus on two populations:

- Single white dwarf + non-degenerate companion
- Double white dwarf systems

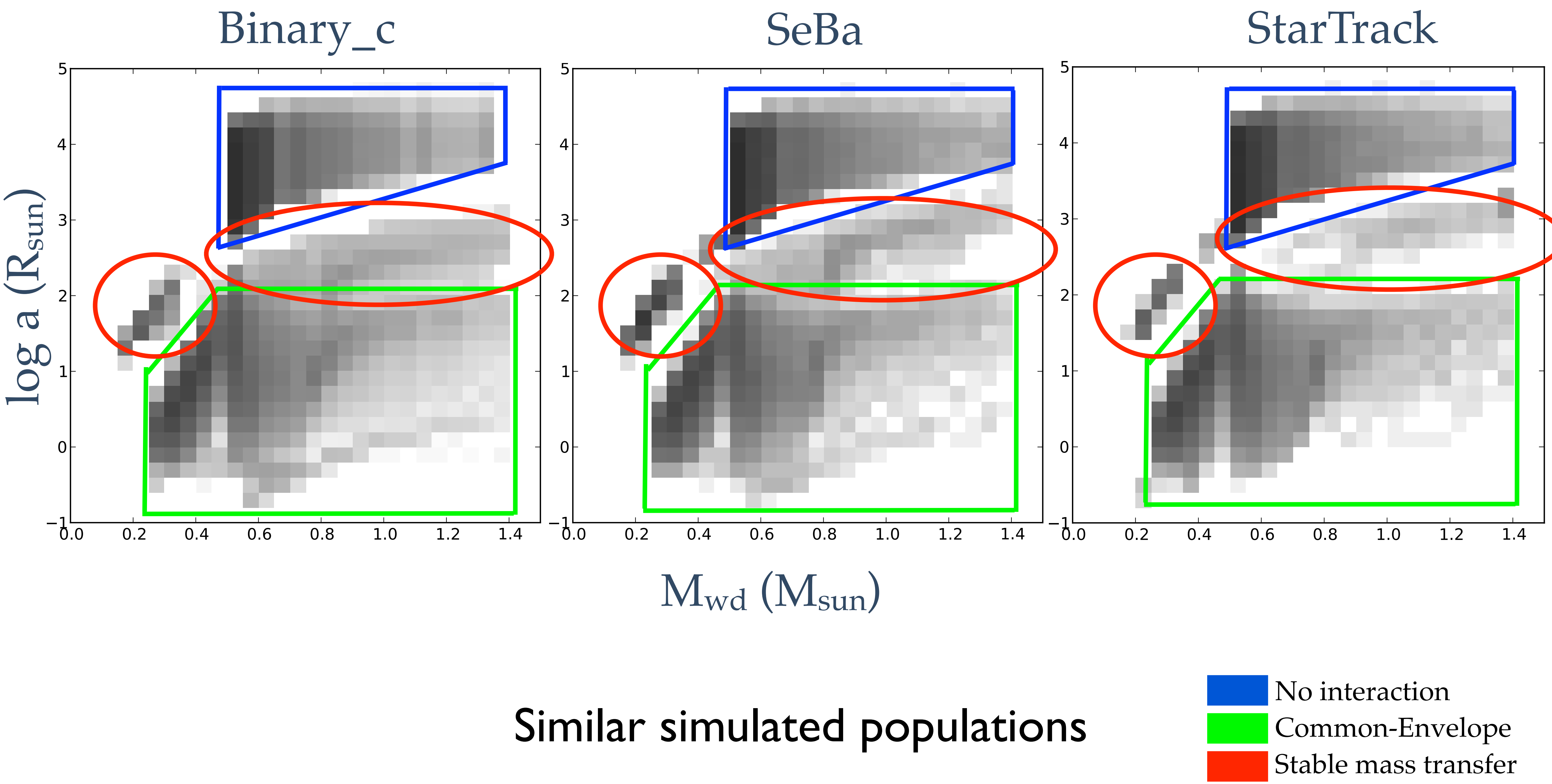
ref: Toonen et al. 2014

WD + non-degenerate star



Similar simulated populations

WD + non-degenerate star



Similar simulated populations

PopCORN

Small differences due to input physics:

Inherent to the codes:

- Initial-Final mass relation
- Stability criterion
- Mass transfer rate
- Wind prescription
- He star evolution

Assumptions of this study:

- Same initial distributions (primary mass, mass ratio, separation)
- Same star formation history
- Conservative mass transfer to all types of stars
- Common envelope evolution prescription
- No tides, magnetic braking, wind accretion, eccentricities

ref: Toonen, Claeys, Mennekens, Ruiter 2014

see also: www.astro.ru.nl/~silviato/popcorn

PopCORN

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PopCORN

- When input assumptions are equalized: different BPS codes give **similar** populations.

- Differences are **not** caused by **numerical** differences, **but** can be explained by differences in the **input physics**

ref: Toonen, Claeys, Mennekens, Ruiter 2014

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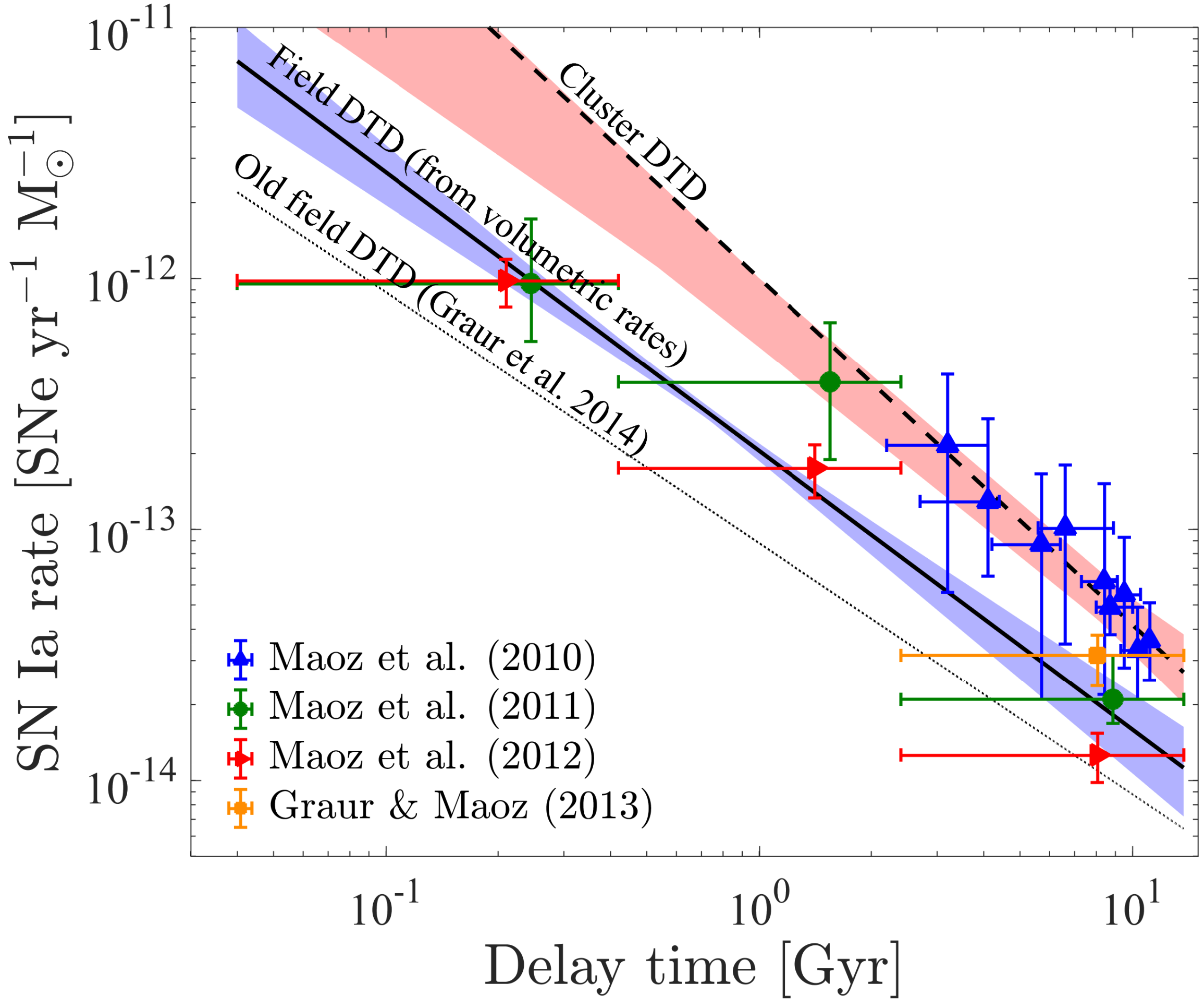
Rates of supernovae

Observational constraints

- Delay time distribution =
  SNIa rate per unit mass of created stars
  since a instantaneous starburst



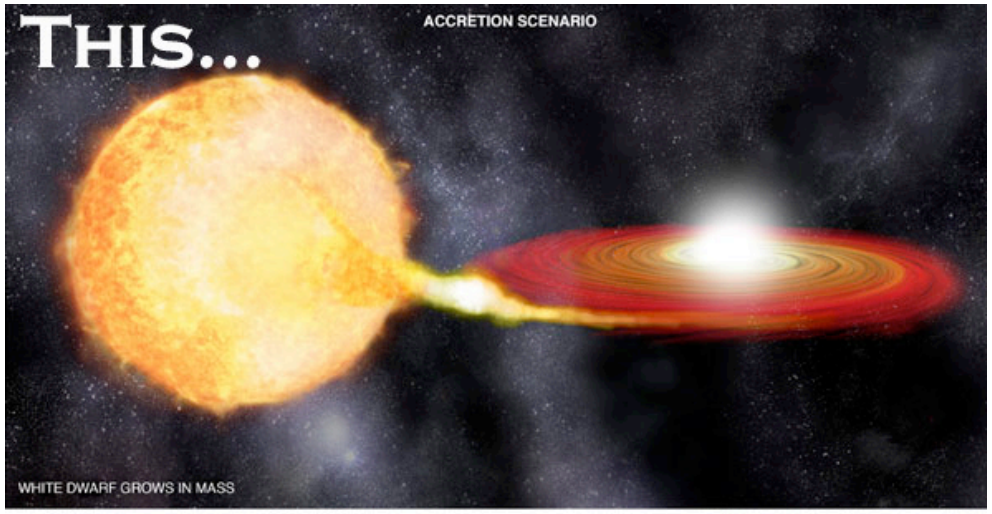
(Time) Integrated rate (per 10^4 Msun) (Maoz & Graur 2017)	
Field galaxies	11.3±2.4
Volumetric rates	12.5±1.0
Galaxy clusters	59±25

- Delay time distribution declines ~ $t^{-1.1}$
- Be careful with synthetic Galactic rate: Dependent on star formation rate

Formation channels

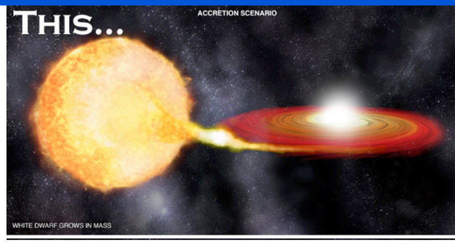
Traditionally:

- Single degenerate channel
  (Whelan & Iben '73)



- Double degenerate channel
  (Iben & Tutukov '84, Webbink '84)

Single-degenerate channel

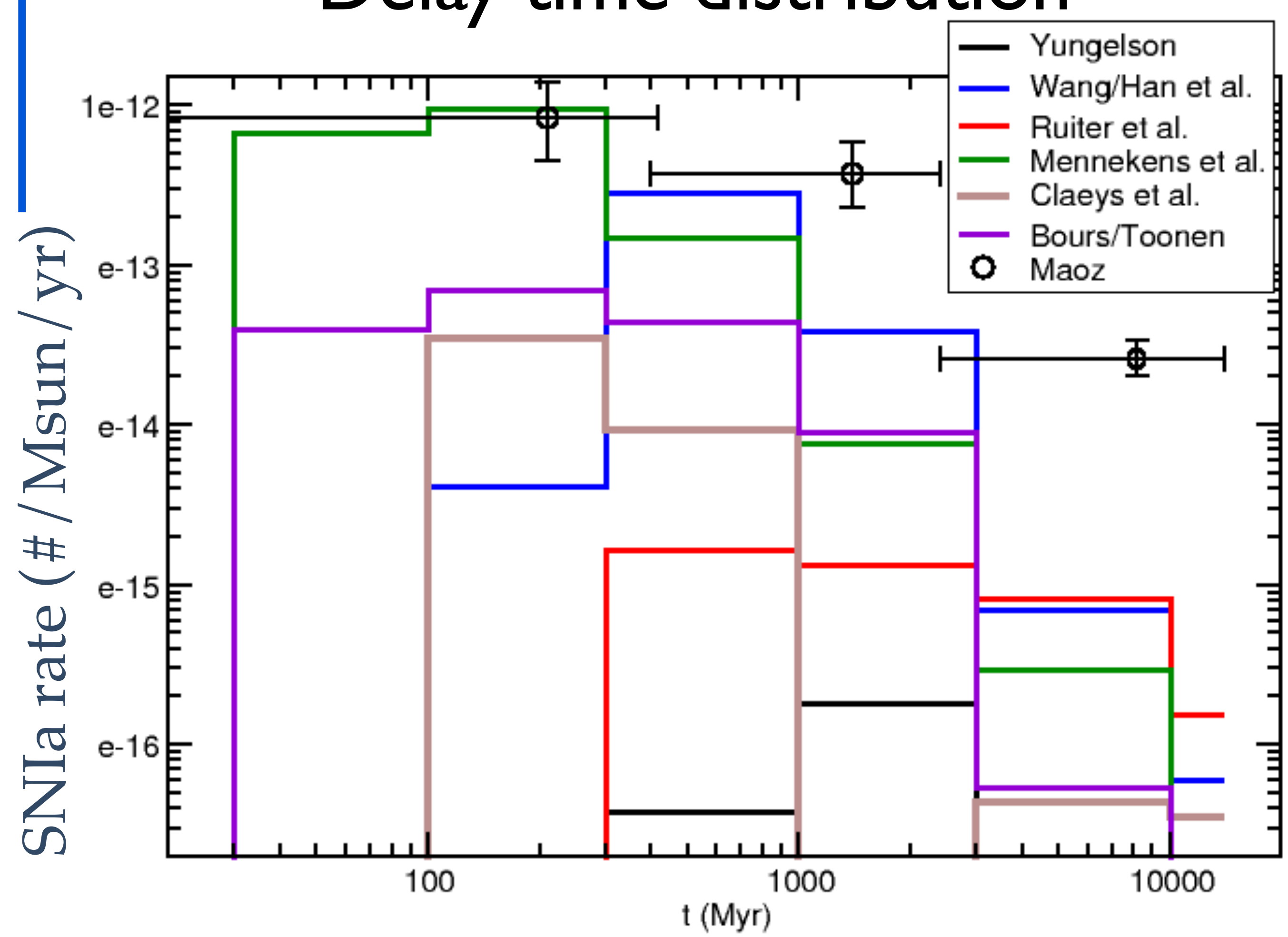


Single-degenerate channel

3 General characteristics:

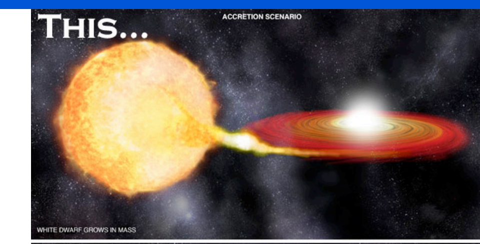
1. SD SNIa rates are low
   - Synthetic rate:
     - 0.006-3 per 10^4 Msun
   - Observed rate:
     - ~10-60 per 10^4 Msun
2. Rates vary by factor ≤5000

Delay time distribution



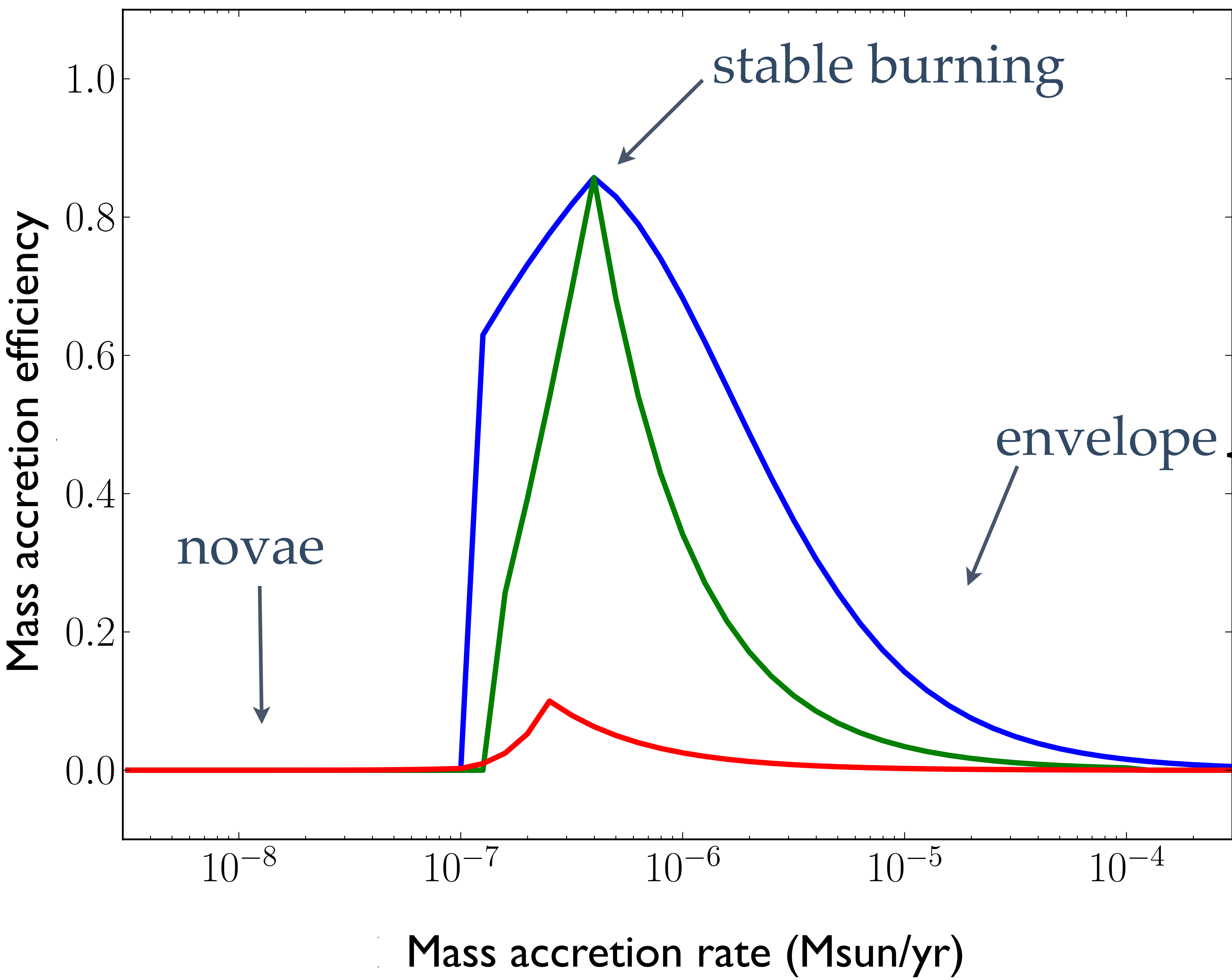
ref: Nelemans, Toonen, Bours 2013

Efficiency of mass accretion



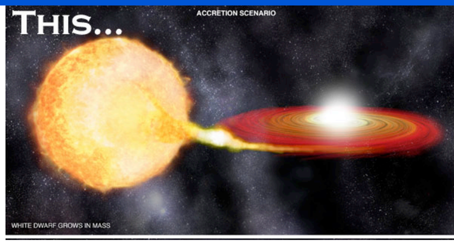
Large uncertainties stimulate new studies

(e.g. Idan+ 13, Newsham+ 13, Wolf+ 13, Hillman+ 15, Denissenkov+ 17)



- Common-envelope phase
- Optically thick wind
  (Hachisu+ 99, Nomoto+ 07, Kobayashi+ 09)
- Super-Eddington wind
  (Ma+ '13, Wang+ ' 15)

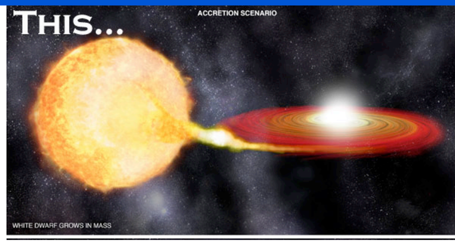
Single-degenerate channel



3 General characteristics:

1. SD SNIa rates are low
2. Rates vary by factor ≤ 5000, due to:
   - Accretion efficiency
     - factor >1000 (Bours+ 13)
     - **Crucial!**

Single-degenerate channel



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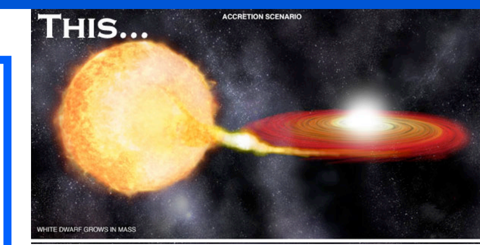
If completely conservative accretion:

- Synthetic rate:
  - ~13 per 10^4 Msun (Claeys+ 14)
- Observed rate:
  - ~10-60 per 10^4 Msun

Single-degenerate channel



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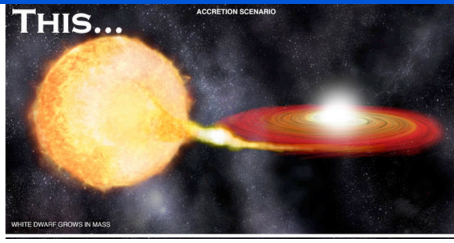
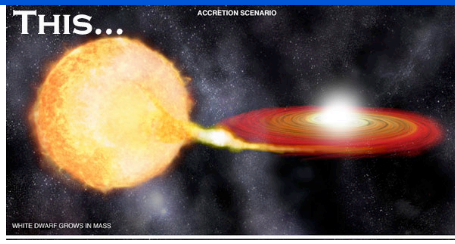
     - **Crucial!**
   - Accretion rates
     - factor ~~ 2-3 (Chen+ 2015)
   - Mass transfer cycles
     - factor ~ 2-3 (Wang+ 10, Toonen+ 14)
   - Prior evolution: Common-envelope phase
     - factor ~3-4 (e.g. Ruiter+09, Mennekens+ '10, Toonen+17)

Prior evolution



- Progress in understanding common-envelope evolution!
- Based on WD-MS systems from SDSS (Rebassa-Mansergas+ 07, Nebot Gómez-Morán+ 11, Zorotovic+ 11)
  - Observed period distribution: few hours - few days (Nebot+ 11)
    - Theory predict periods up to hundreds of days
    - Evolution! Not selection effects! (Toonen+ 13)
  - Orbits shrink more during common-envelope phase (Zorotovic+ 11,14, Toonen+ 13, Camacho+ 14)
- Not clear a priori that this result is applicable to SD SNIa progenitors (Toonen+ 17)

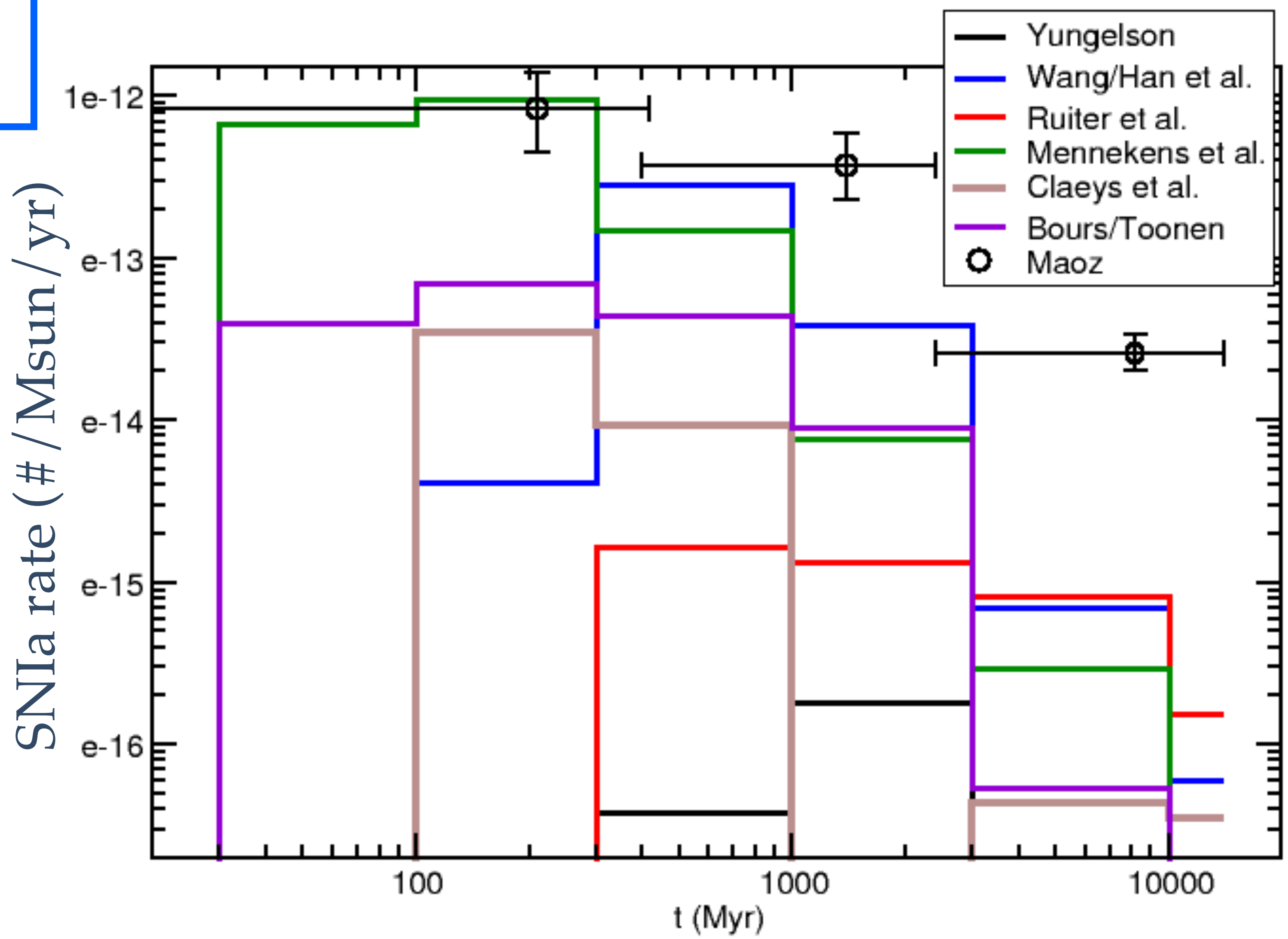
Single-degenerate channel



3 General characteristics:

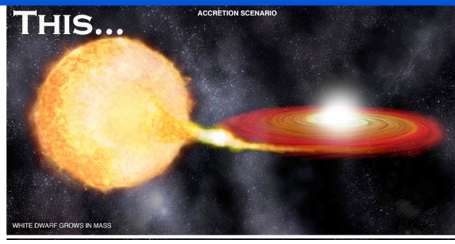
1. SD SNIa rates are low
2. Rates vary by factor ≤ 5000
3. few SNIa at long delay times
   > few Gyr

Delay time distribution



ref: Nelemans, Toonen, Bours 2013

Spin-up Spin-down

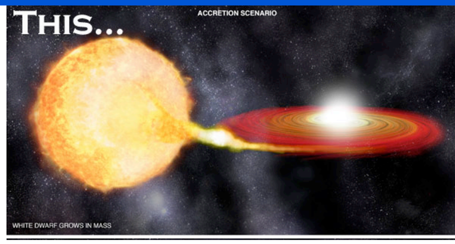


Accretion of angular momentum (Justham 11, Di Stefano+ 11, Hachisu+ 12):

- Spins up WD
- Increases critical mass M_{crit} for explosion
  - Differential rotation: M_{crit} ~2-4 M_{sun} (Ostriker+ 68, Yoon+ 04, 05)
  - Solid body rotation: M_{crit} ~1.43-1.5 M_{sun} (Saio+ 04, Piro+ 08)

- Prompt detonation if $M_{crit} < M_{wd}$ during mass transfer
- Delayed if $M_{chan} < M_{wd} < M_{crit}$
  - Delay can be significant (e.g. magnetodipole radiation: Ilkov+ 11: ~10^8-10^9 yr)
  - Frequent (Wang+14: 77% of SD, Benvenuto+ 15: 33% of SD)
  - Donor star has become a compact object (Justham 11, Di Stefano+ 11)
  - Range of WD masses & brightnesses (Hachisu+12)

Single-degenerate channel



3 General characteristics:

1. SD SNIa rates are low
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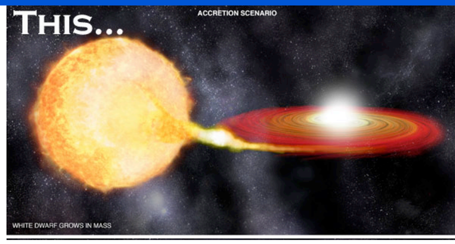
   > few Gyr

Single-degenerate channel



Hydrogen donors:

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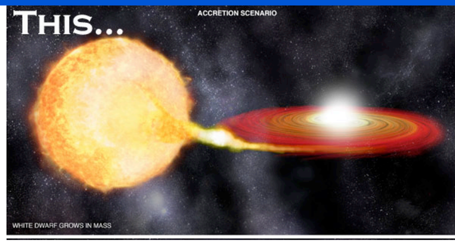
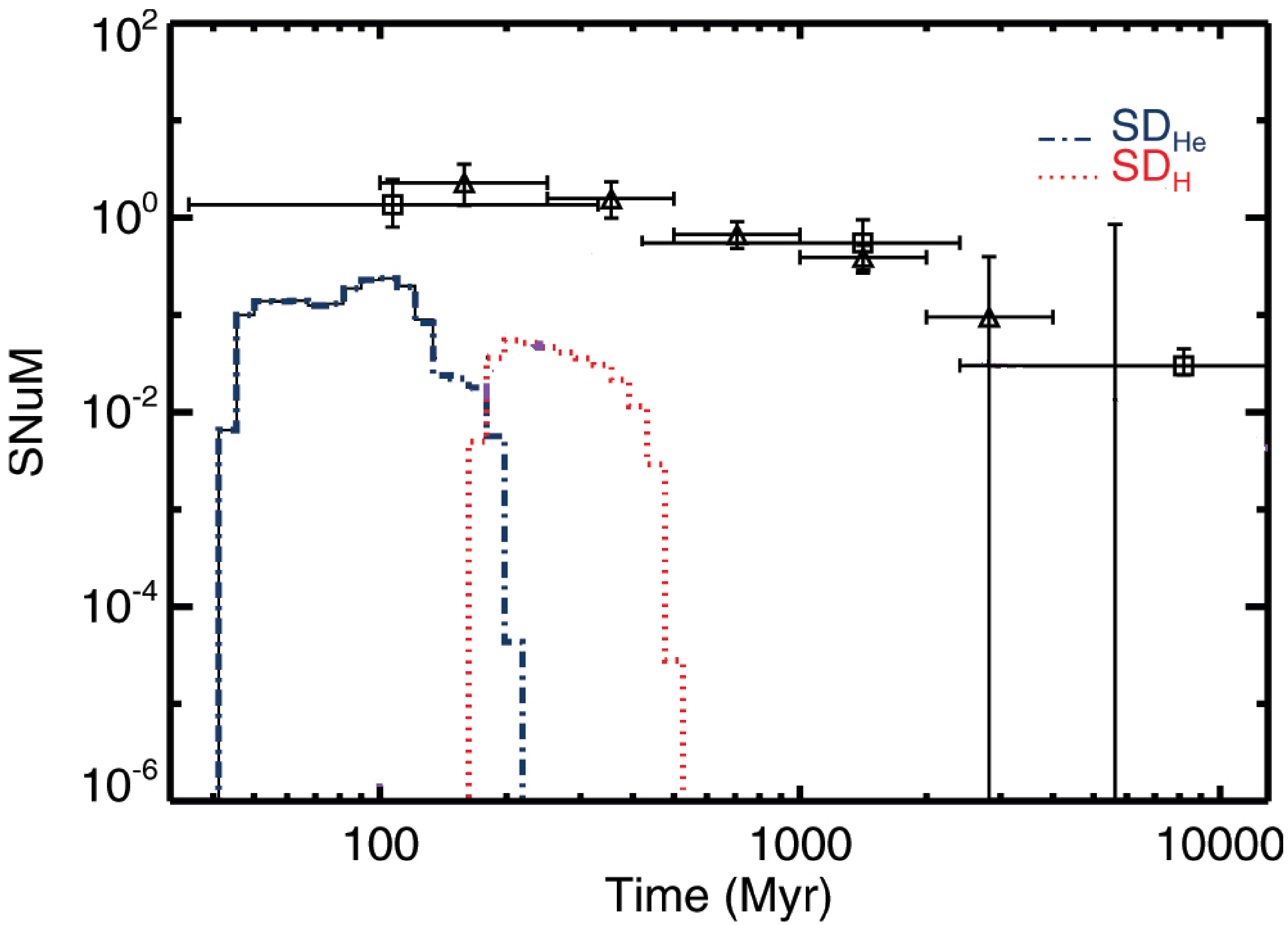
   > few Gyr

Single-degenerate channel



Hydrogen donors:

1. SD SNIa rates are low
2. Rates vary by factor ≤ 5000
3. few SNIa at long delay times > few Gyr



Helium-rich donors:

- SNIa Rates are low
  - 0.15 per 10^4 Msun
- Short delay times
  - few 100 Myr (Ruiter+ 09, Wang+ 09, Claeys+ 13)

ref: Claeys+ 13

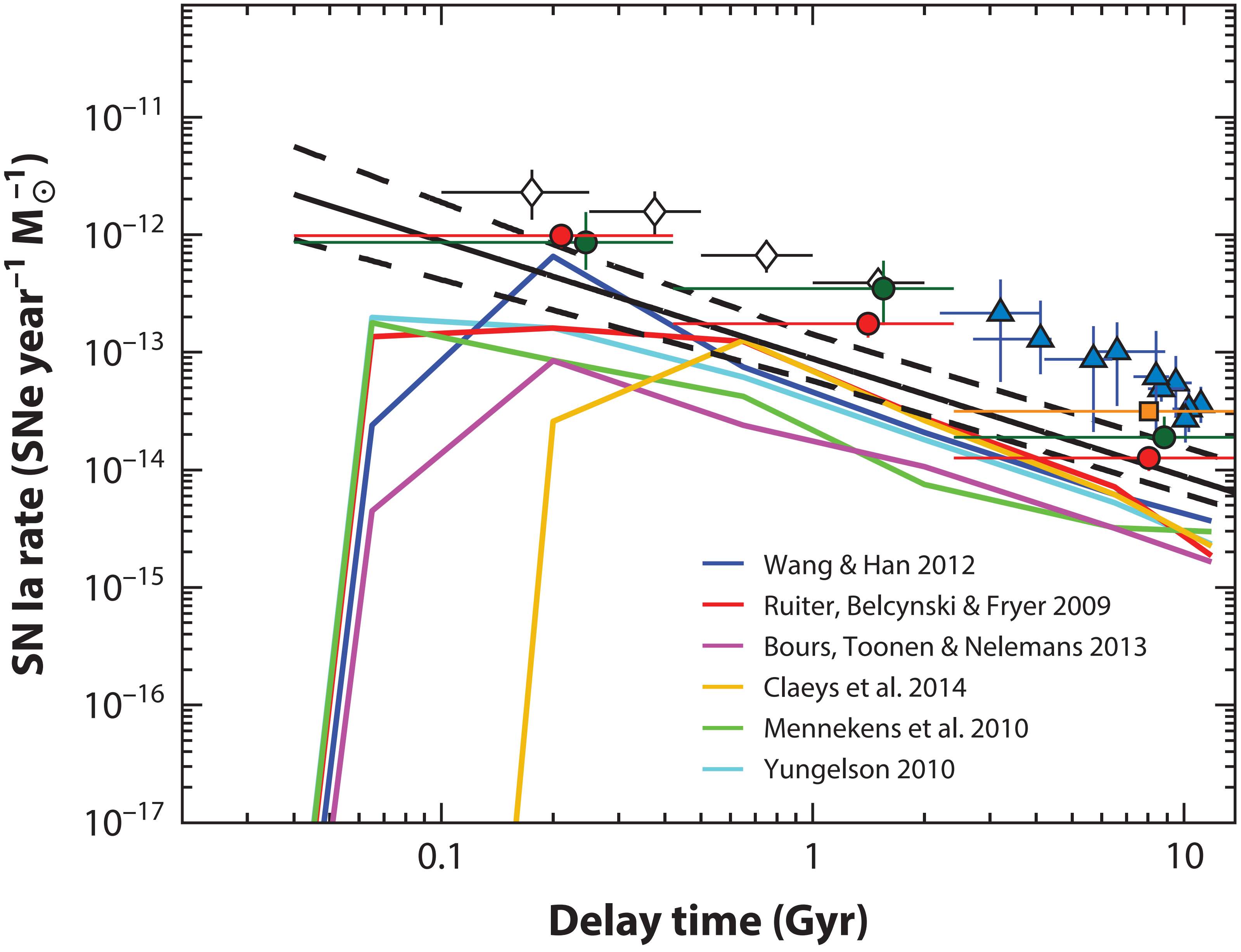
Double-degenerate channel

Double-degenerate channel

2 General characteristics:

- Consistent shape
  - amongst BPS studies
  - with observations
- DD rates are high-ish
  - Synthetic rate:
    - 2-6 per 10^4 Msun
  - Observed rate:
    - ~10-60 per 10^4Msun

Delay time distribution



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- DD rates are high-ish
  - Synthetic rate:
    - 2-6 per 10^4 Msun
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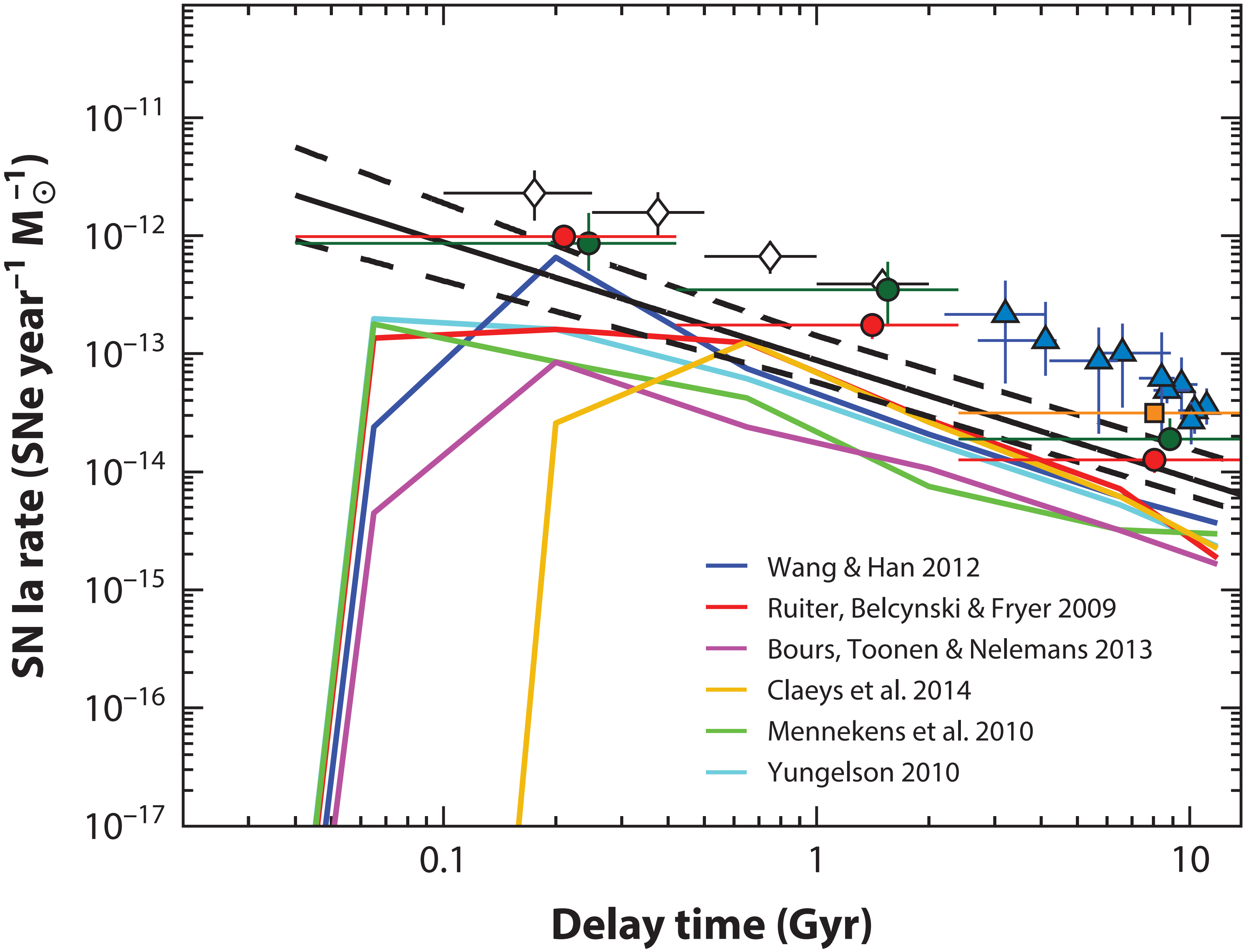
- But do DD mergers lead to SNIa ??

Delay time distribution

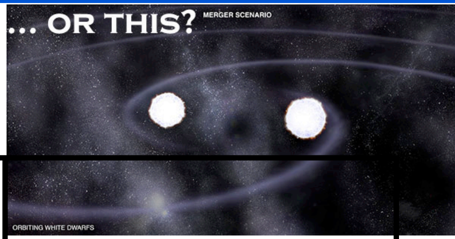


Violent merger models

Accretion induced collapse can be avoided:

- During merger phase
  (e.g. Pakmor+ 10,11,12, Guillochon +10, Moll+ 14, Sato+ 16)
- During remnant phase
  (e.g. van Kerkwijk+ 10, Raskin+ 14, Sato+ 15)

Violent merger models



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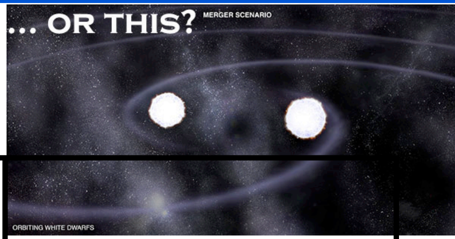
Integrated rate (per 10^4 Msun)		
Observations		10-60
Standard DD	M1+M2 >1.38	2-3.3
Pakmor+ 10,11,12		
Sato+ 15		
Sato+ 16		
v. Kerkwijk+ 10		
Sato+ 15		

Violent merger models



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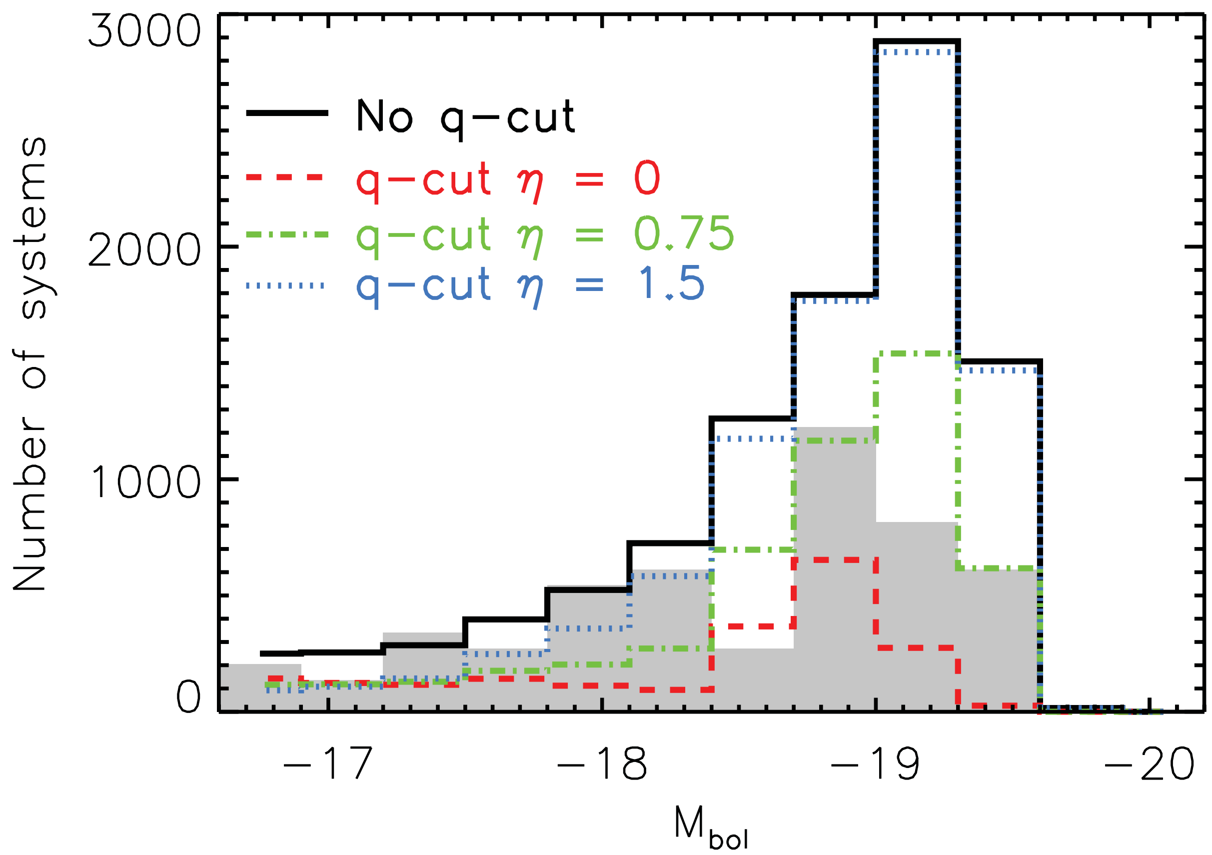
Rates as high or below standard DD channel

Integrated rate (per 10^4 Msun)		
Observations		10-60
Standard DD	M1+M2 >1.38	2-3.3
Pakmor+ 10,11,12	q>0.8, M1>0.8	0.8
	q>0.9, M1>0.8	0.4-0.5
Sato+ 15	0.9<M1,2<1.1	0.2
Sato+ 16	q>0.8 $M1^{-0.84}$	0.6
v. Kerkwijk+ 10	q>0.8	1.9-2.9
	q>0.9	0.7-1.1
Sato+ 15	0.7<M1<0.9, M1+M2>1.38	0.7-0.78

Violent merger models

- Luminosity of prompt mergers (Ruiter+ 12)
  - Luminosity related to ^{56}Ni produced in detonation primary WD
  - Good match between predicted & observed distribution of explosion brightness



- Depends critically on one specific evolutionary phase (see also Chen+ 16)
  - WD accretes from helium star

Other channels?

Integrated rate (per 10^4 Msun)	
Observed	10-60
Standard SD	0.6-0.8 (< ~3)
Standard DD	2-3.3
Violent mergers (Pakmor+10,11,12, Kerkwijk+ 10, Sato+ 15,16)	0.5-3

- What are we missing?
- How far do we need to go?

Other channels?

Integrated rate (per 10^4 Msun)	
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Violent mergers (Pakmor+10,11,12, Kerkwijk+ 10, Sato+ 15,16)	0.5-3
All CO-CO mergers (including sub-Chandrasekhar)	8-9
All He-CO mergers (including sub-Chandrasekhar)	8-11

- What are we missing?
- How far do we need to go?
- Other mergers of WDs?
  - Helium facilitates ignition
    (Pakmor+ 13)
  - High efficiency required
    (Yungelson+ 17, also observationally: Badenes + 12, Maoz+ 16)

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- Core-degenerate scenario
  - See Bo Wang's talk

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All CO-CO mergers (including sub-Chandrasekhar)	8-9
All He-CO mergers (including sub-Chandrasekhar)	8-11
All ONe-CO/ONe mergers (see also Marquardt+ 15)	0.8-1.8
Hybrid in SD channel (Chen+ 14, Wang+ 14)	0.1-1.5

- What are we missing?
- How far do we need to go?
- Other mergers of WDs?
  - Helium facilitates ignition (Pakmor+ 13)
  - High efficiency required (Yungelson+ 17, also observationally: Badenes + 12, Maoz+ 16)
- Core-degenerate scenario
  - See Bo Wang's talk
- Hybrid CO-ONe WD

Other channels?

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Standard SD	0.6-0.8 (< ~3)
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Violent mergers (Pakmor+10,11,12, Kerkwijk+ 10, Sato+ 15,16)	0.5-3
All CO-CO mergers (including sub-Chandrasekhar)	8-9
All He-CO mergers (including sub-Chandrasekhar)	8-11
All ONe-CO/ONe mergers (see also Marquardt+ 15)	0.8-1.8
Hybrid in SD channel (Chen+ 14, Wang+ 14)	0.1-1.5
Double detonations (Ruiter+ 11, Wang+ 13)	1-4

- What are we missing?
- How far do we need to go?
- Other mergers of WDs?
  - Helium facilitates ignition (Pakmor+ 13)
  - High efficiency required (Yungelson+ 17, also observationally: Badenes + 12, Maoz+ 16)
- Core-degenerate scenario
  - See Bo Wang's talk
- Hybrid CO-ONe WD
- Double detonation on sub-Chandrasekhar WDs

Other channels?

Integrated rate (per 10^4 Msun)	
Observed	10-60
Standard SD	0.6-0.8 (< ~3)
Standard DD	2-3.3
Violent mergers (Pakmor+10,11,12, Kerkwijk+ 10, Sato+ 15,16)	0.5-3
All CO-CO mergers (including sub-Chandrasekhar)	8-9
All He-CO mergers (including sub-Chandrasekhar)	8-11
All ONe-CO/ONe mergers (see also Marquardt+ 15)	0.8-1.8
Hybrid in SD channel (Chen+ 14, Wang+ 14)	0.1-1.5
Double detonations (Ruiter+ 11, Wang+ 13)	1-4

- Observed rate still hard to reach
  - Multiple channels contributing?
- Long delay times only reached by WD-WD mergers
  - But spin-up spin-down...

Conclusions

- Double-degenerate channel
  - The DD channel predicts rates and a delay time distribution that is comparable to observations
  - Do the rates of the violent merger channel match up?

- Single-degenerate channel
  - The SD channel is very sensitive to assumptions for the WD accretion efficiency and CE-evolution
  - Can enough WDs accrete up to the Chandrasekhar limit?

- Binary population synthesis
  - Differences in BPS results are not caused by numerical effects, but by different assumptions of input physics

Conclusions

- Questions?