Supernova Remnants II
Chania, Greece
June 3-7 2019

Type Ia supernova subclasses and their progenitors

Ashley J. Ruiter
ARC Future Fellow / Senior Lecturer
School of Science
University of New South Wales Canberra
@ the Australian Defence Force Academy
ashley . ruiter [@] adfa . edu . au
@growzchilepeps

Australian Government
Australian Research Council

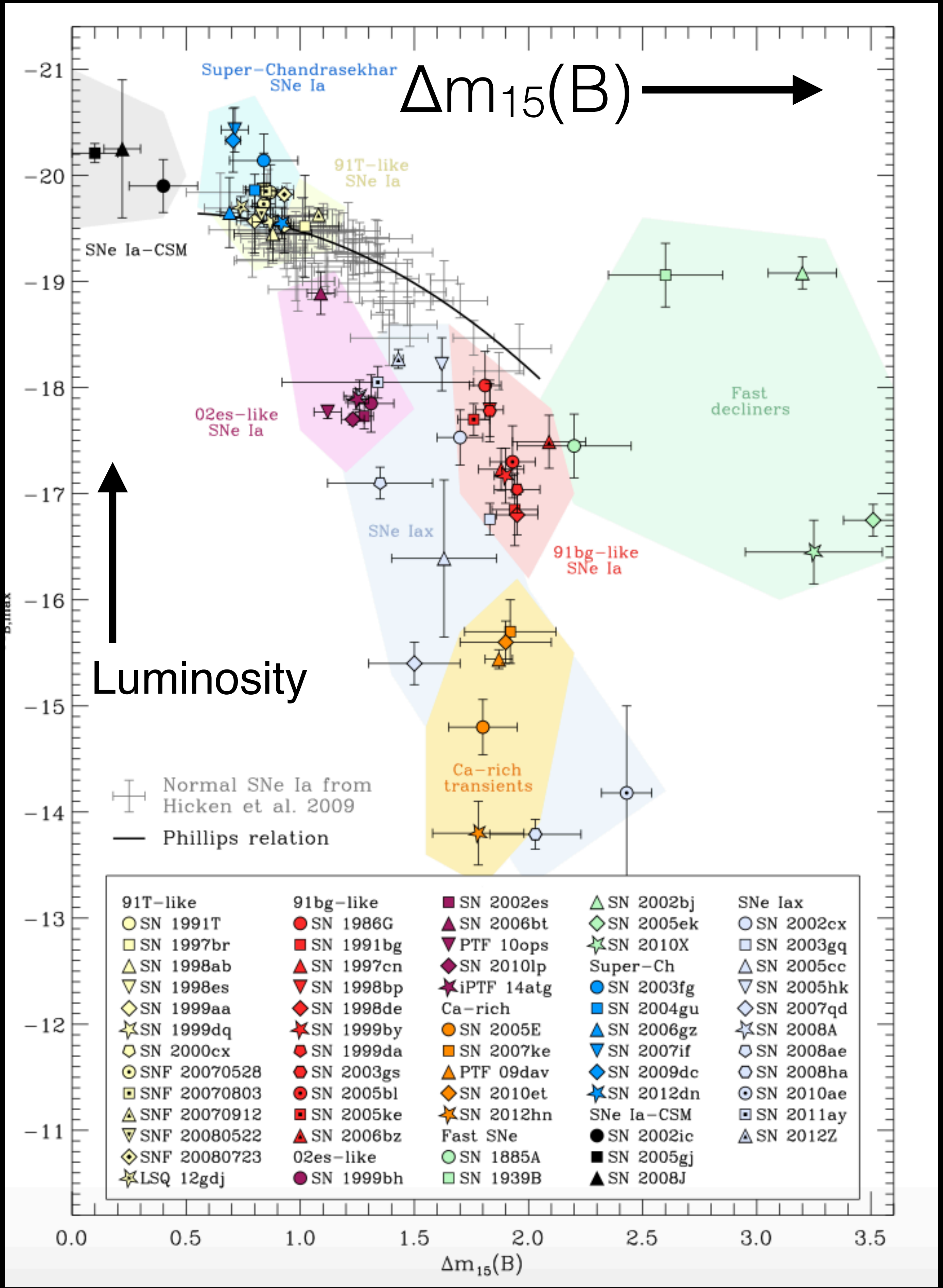
NCI
NATIONAL COMPUTATIONAL INFRASTRUCTURE

UNSW
THE UNIVERSITY OF NEW SOUTH WALES
CANBERRA

Thermonuclear supernovae and their subclasses

- Phillip's relation: black line. But only ~70% of SNe Ia are "normal".
- (Normal == used for cosmology…)
- Likely 2+ formation channels and/or explosion mechanisms make up normal SNe Ia. But there are lots of "abnormal" SNe Ia! e.g. Ca-strong/rich transients, 91bg-likes, 91T-likes, SNe Iax…
- This plot keeps changing… finding faster & fainter thermonuclear transients. But what make them?

$$M_{\max}(B) = -21.726 + 2.698\Delta m_{15}(B).$$

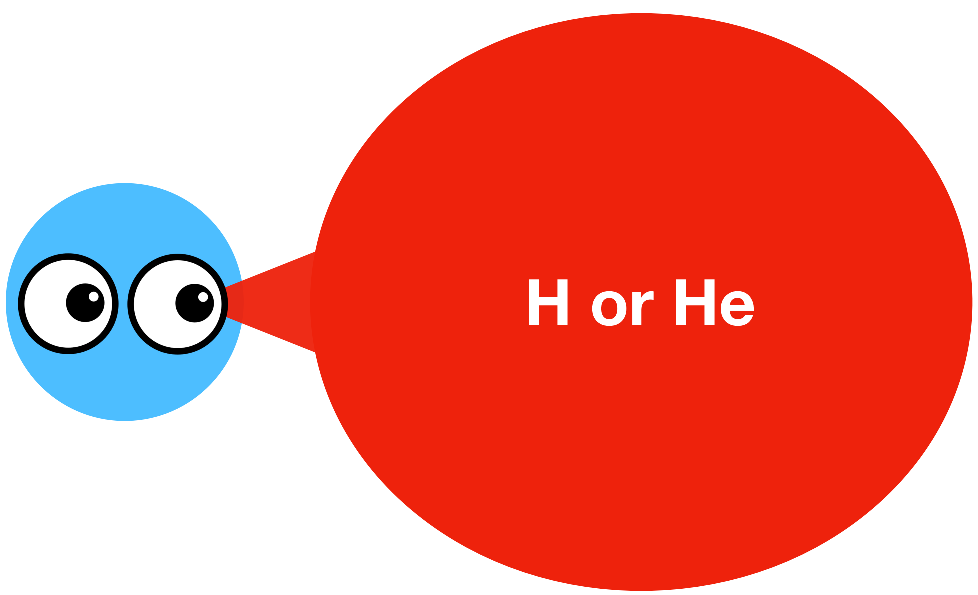


Taubenberger 2017

Type Ia SN progenitors

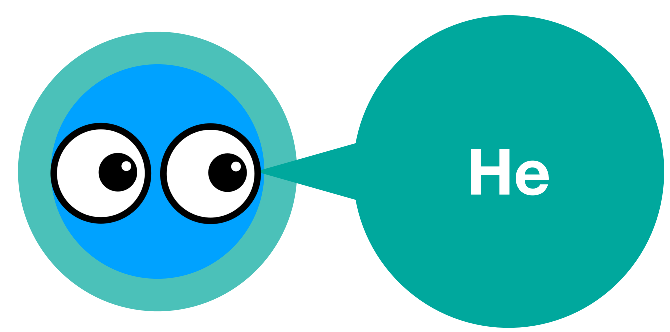
Nutshell synopsis of formation channel + explosion mechanism mish-mash

2 main channels,
1 explosion mechanism



Chandrasekhar mass WD (MCh)
& Single* Degenerate
(hydrogen or helium donor)
***technically could be DD but v. rare**

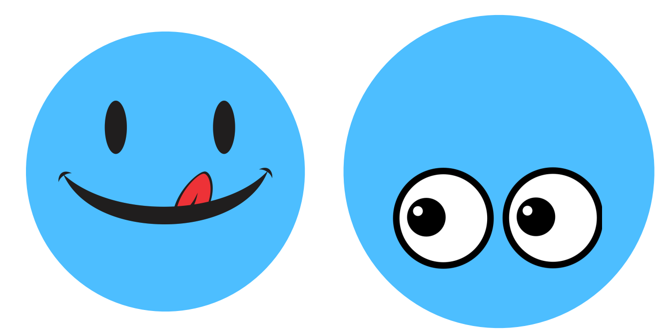
2 main channels,
1 explosion mechanism



Sub-Chandra mass WD
& Single OR Double Degenerate
(requires helium)

WD mergers:
2 explosion mechanisms

CO WDs(?)



Sub-Chandra OR MCh WD
& Double Degenerate
(probably some helium)

Paradigm shift with Pakmor et al. 2010 Nature paper on WD mergers that showed sub-Chandrasekhar mass WDs can produce light-curves & spectra that look like those of SNe Ia.

Type Ia SN progenitor channels

- Various SN Ia outcomes (Chandrasekhar mass, sub-Chandrasekhar mass with and without mergers) calculated with binary evolution population synthesis code *StarTrack.*

- Results presented here assume the **common envelope** prescription ‘New CE’ in Ruiter et al. 2019: Binding energy parameter λ depends on evolutionary state of star + some dependence on metallicity (cf. Xu & Li 2010, Domenik et al. 2012).

$$\alpha\left(\frac{GM_{rem}M_2}{2a_f} - \frac{GM_{giant}M_2}{2a_i}\right) = \frac{GM_{giant}M_{env}}{\lambda R_{giant}}$$

Thomas Reichardt

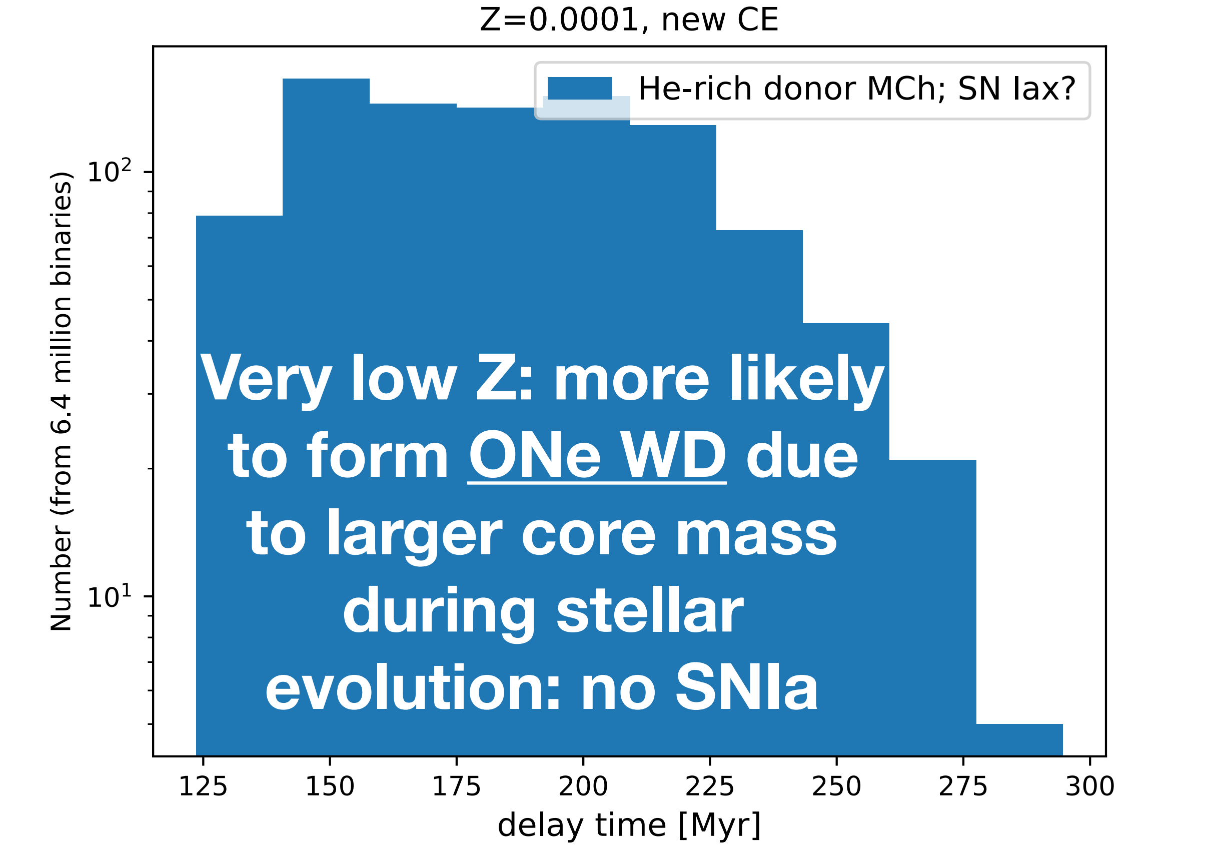
Some plots (preliminary): 2 Chandrasekhar mass channels as f(Z)

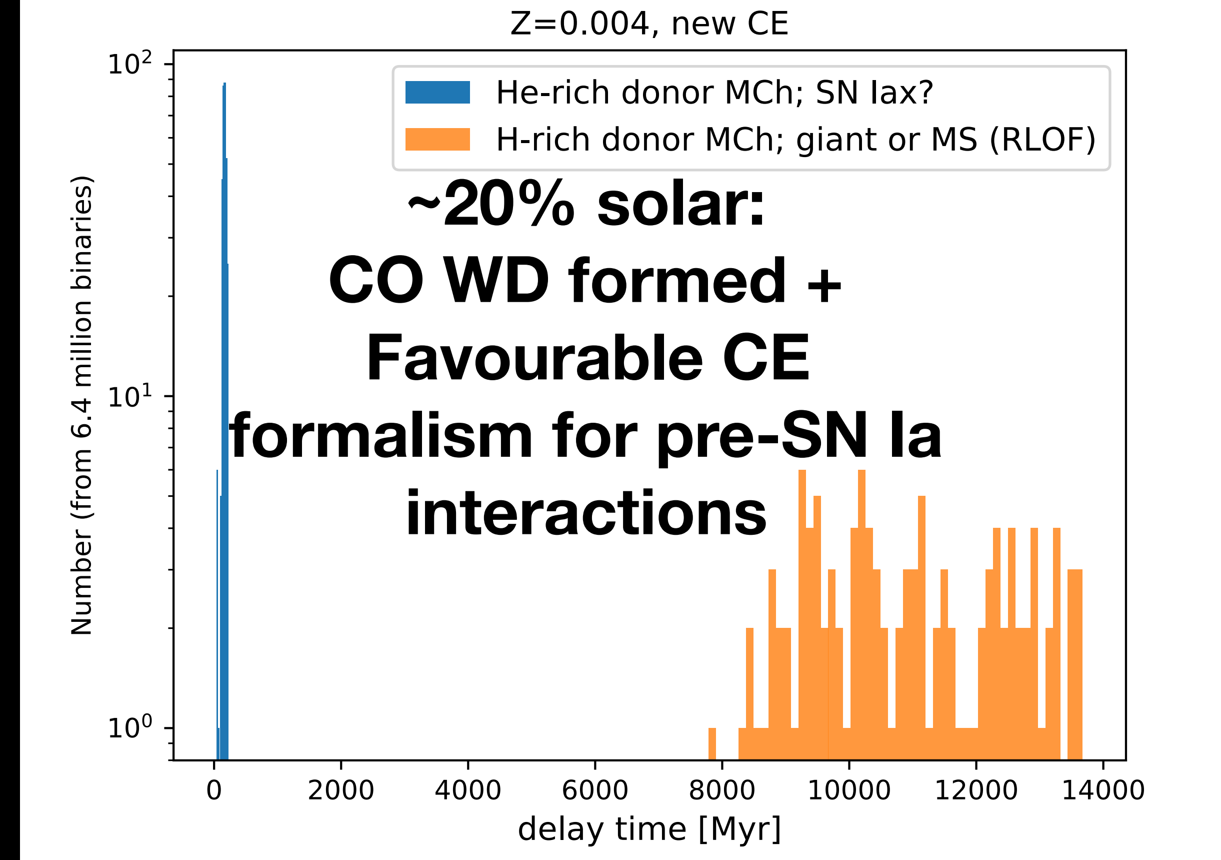
- *Nucleosynthesis*: WD explosions near the Chandrasekhar mass are likely needed to explain the **solar abundance of manganese** (Seitenzahl et al. 2013).

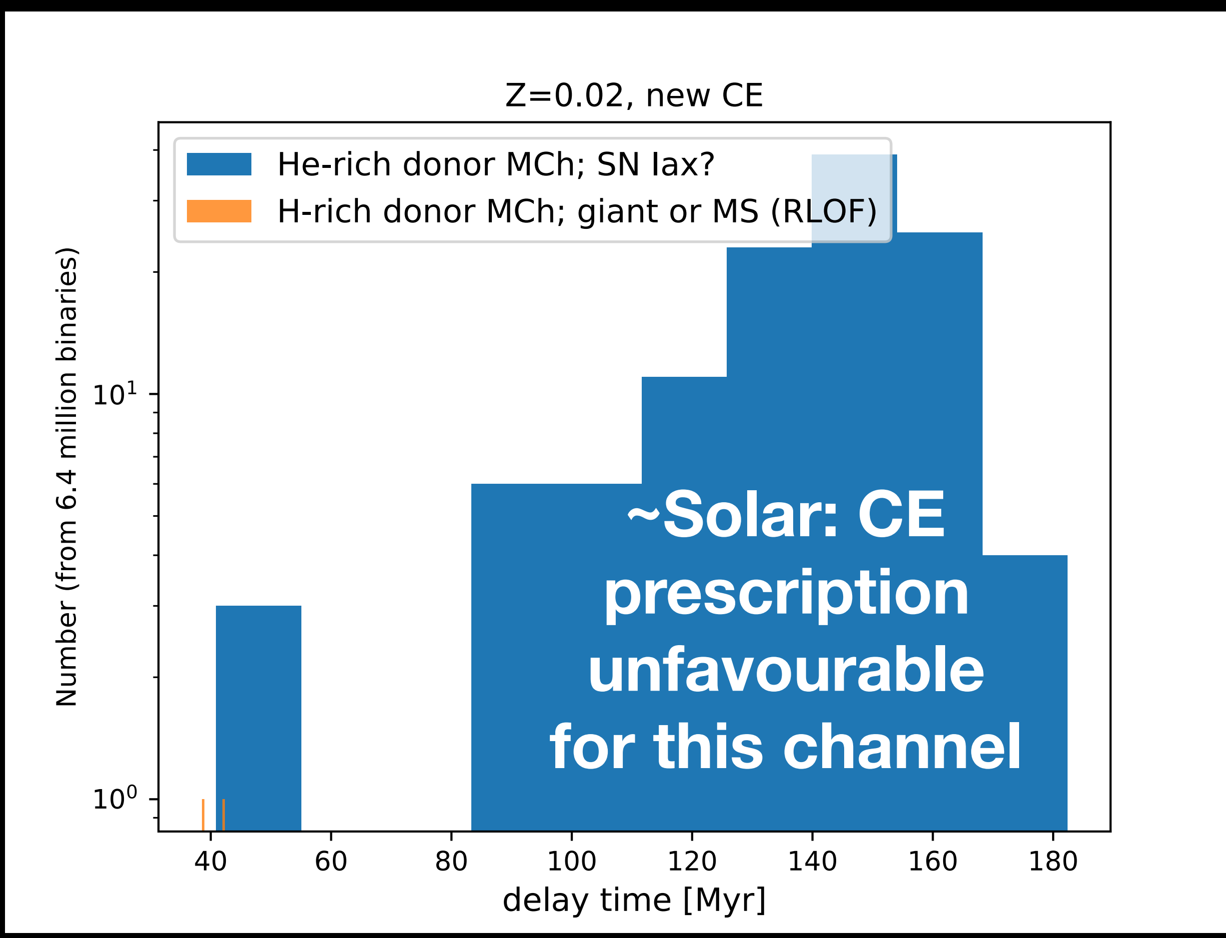
- **Explosions of ~MCh CO WDs (possibly CONe WDs):** promising scenario is ***pure deflagrations*** (e.g. SN2002cx and other **SN Iax** events; e.g. Jha et al. 2017). Probably **helium donors** given their young nature. **Hydrogen donors**: via stable RLOF or perhaps accrete from evolved stellar wind (—> short delay times).

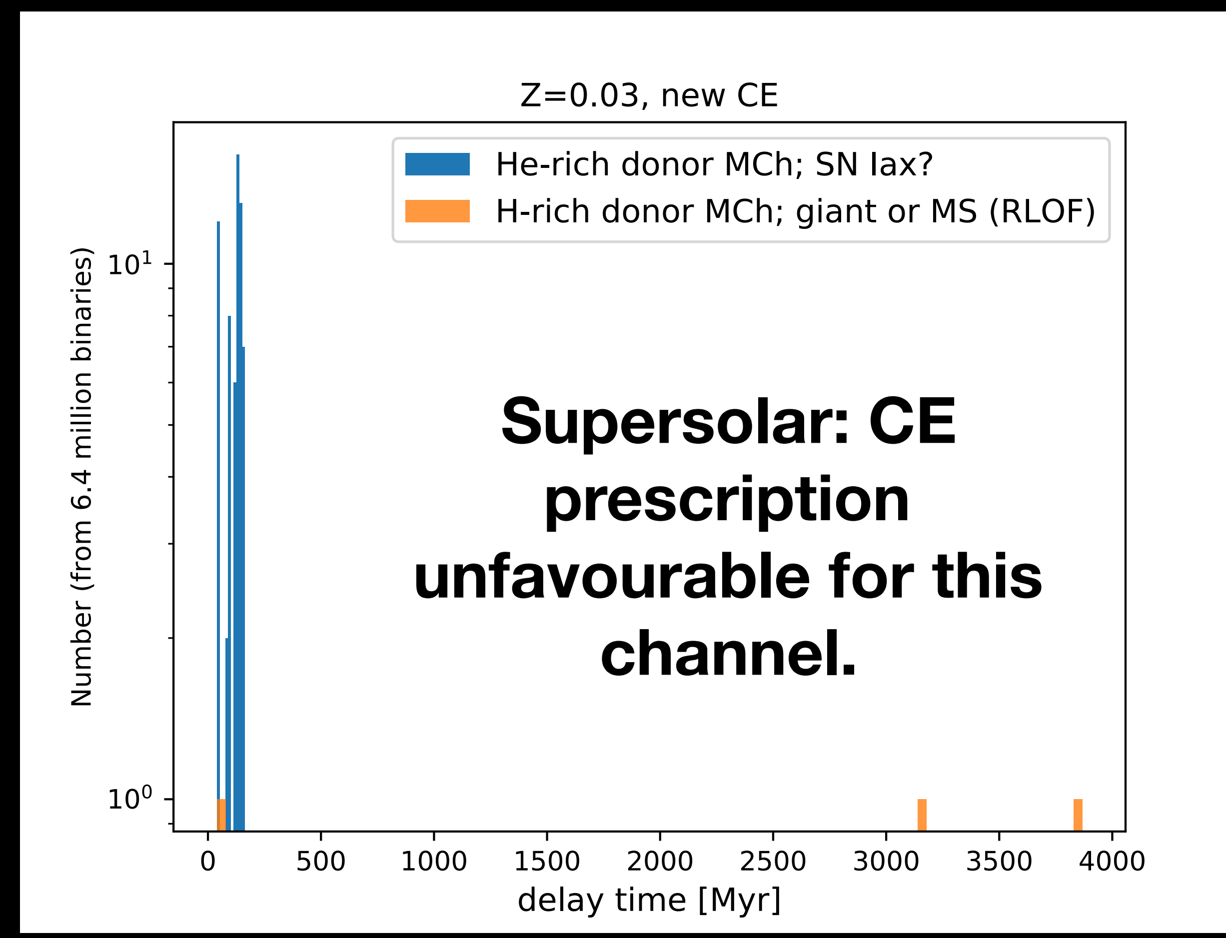
- How do delay times and rates change with metallicity Z? e.g. **delay time distributions** (progenitor ages):

discussing H-donor MCh channel:









MCh progenitors: non-mergers (RLOF only)

- H-stripped, He-burning star donors: *rate increases with decreasing Z*. Delay times typically always < 300 Myr.

- <u>Usual channel for stripped, He-burning donor</u> involves 2 CEs + one stable RLOF phase.

- H-rich RLOF channel: difficult to make these (accretion efficiency); more prominent at sub-solar but not at high Z (*none* at very low Z). **Why?** Preferentially make ONe WD instead of CO WD.

- <u>Usual channel for H-rich donor</u> involves 1 CE + one stable RLOF phase.

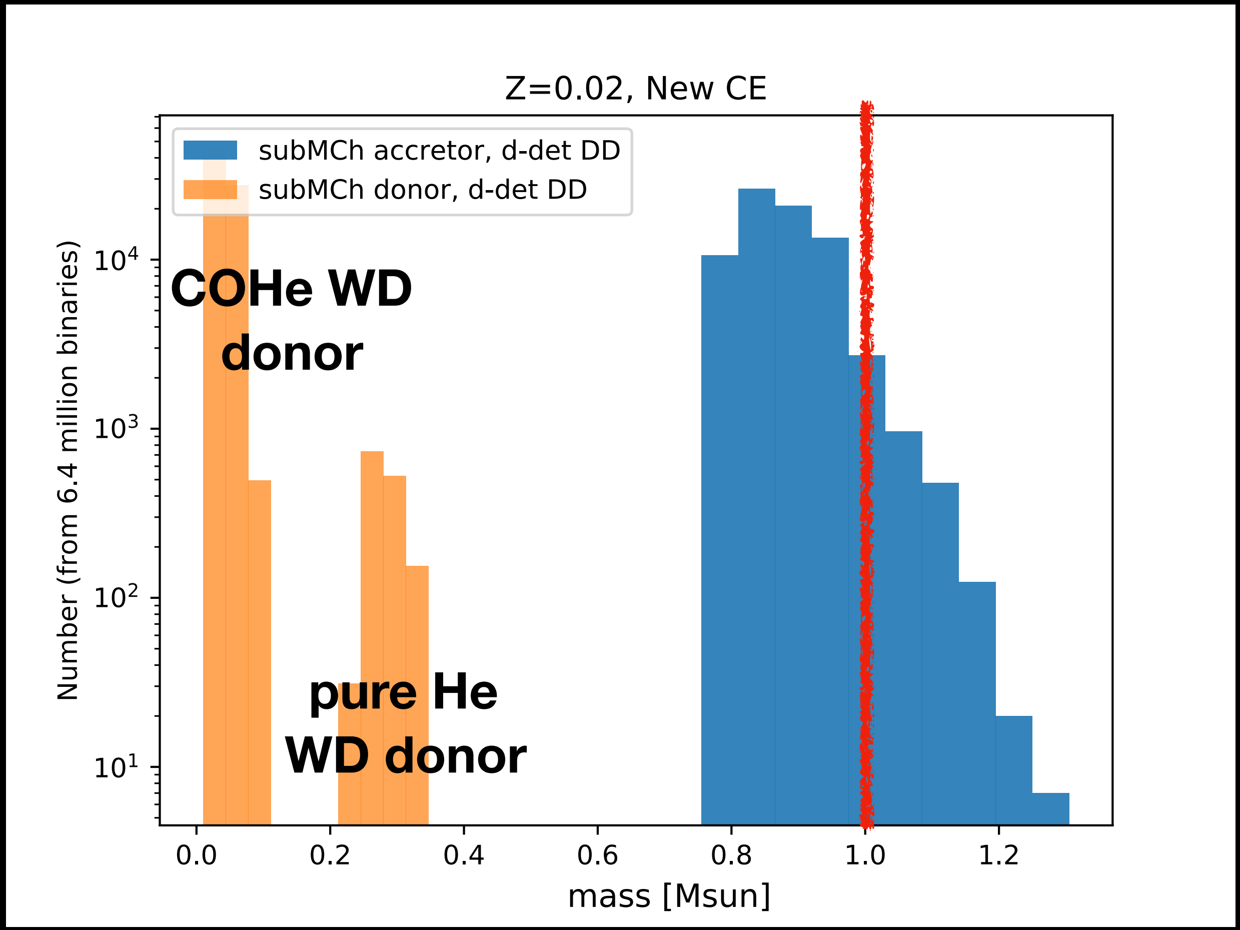
sub-Chandrasekhar mass channels ($M_{explode}$<1.4 Msun)

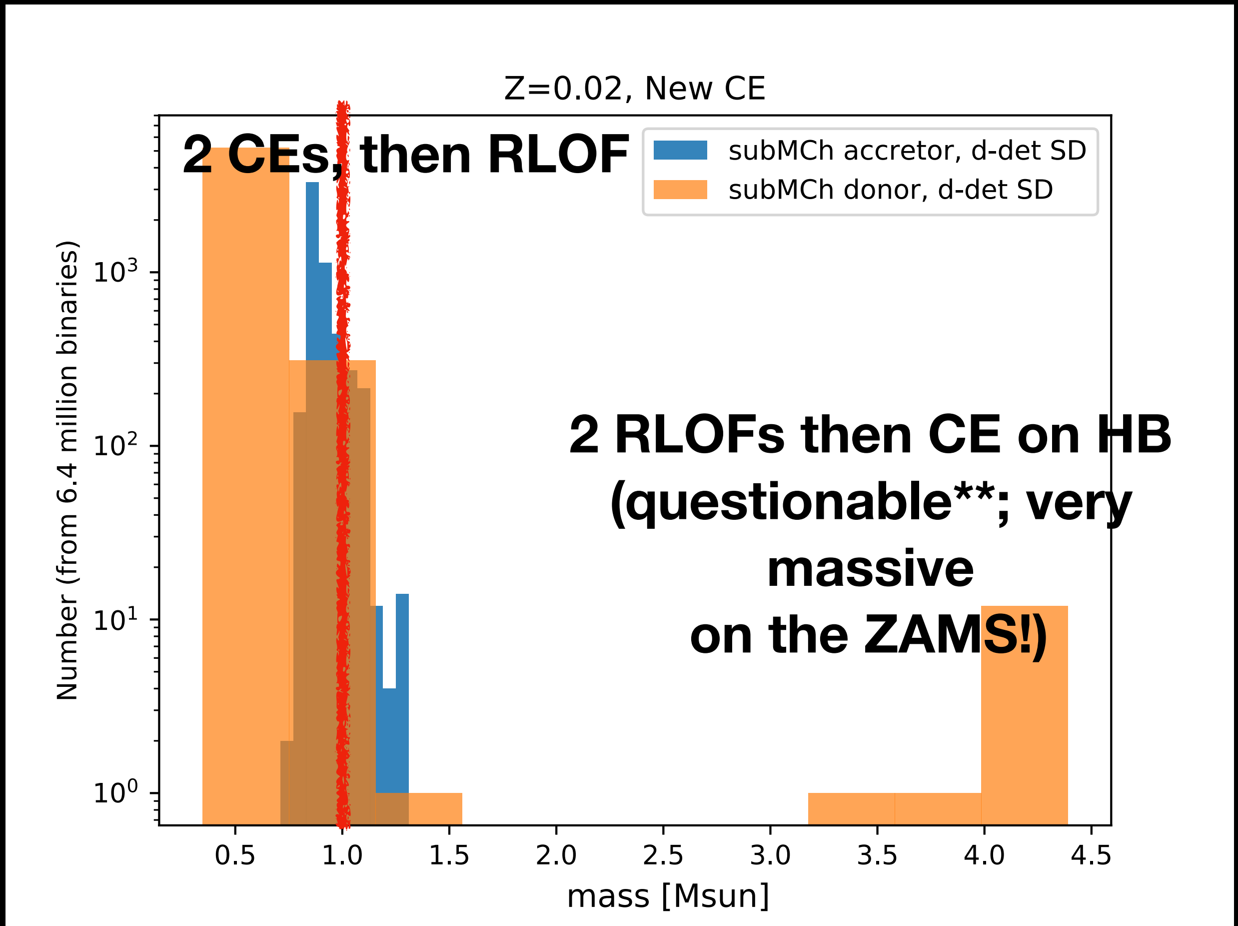
- **Sub-Chandra non-mergers:** or *'classic' double-detonation with ~0.01-0.05 Msun* **helium** *shells detonating on CO WD.* How much helium can this progenitor have and still look like a SN Ia? cf. recent FOE meeting poster by Abigail Polin: possible 'thick' helium shell explosion SN 2018byg.

- Theoretical delay time distribution is bimodal (e.g. Ruiter et al. 2014) but there are slight changes with metallicity. SD channel has short delay times, DD channel has longer delay times.

‘classic’ sub-MCh double detonation masses: nature of the donors (orange)

Left: Double Degenerate Right: Single Degenerate





**Need to investigate this rare ‘heavy donor’ channel further: donor star loses ~5-6 Msun before it reaches the Hertzsprung gap (mostly in RLOF to MS companion).

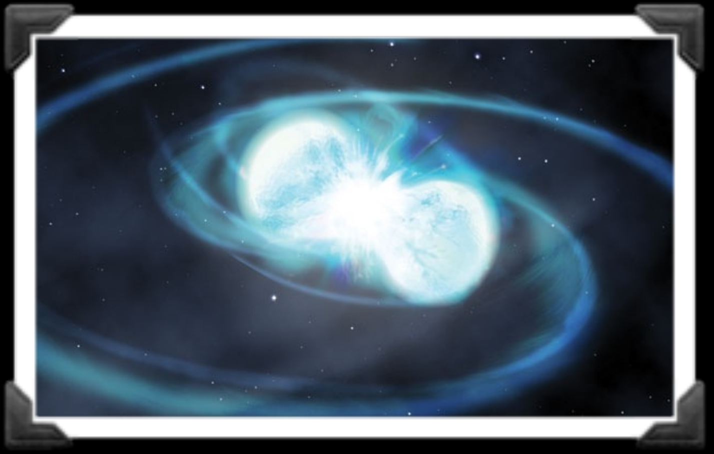
Accretor masses (blue hist) need to be ~1.0 Msun+ to look like regular SNe Ia (nickel-56).

WD mergers

(Helium WDs are only made via binary evolution, e.g. RGB star stripped of its H-envelope)

- **CO-CO WD mergers:** Solves most 'issues'. Delay time distribution ~t^(-1), peak brightness distribution (Ruiter et al. 2013), robust explosion achievable (Pakmor et al. 2012), theoretical merger rates are roughly on par with predictions inferred from observations (Moaz, Hallakoun & Badenes 2018).

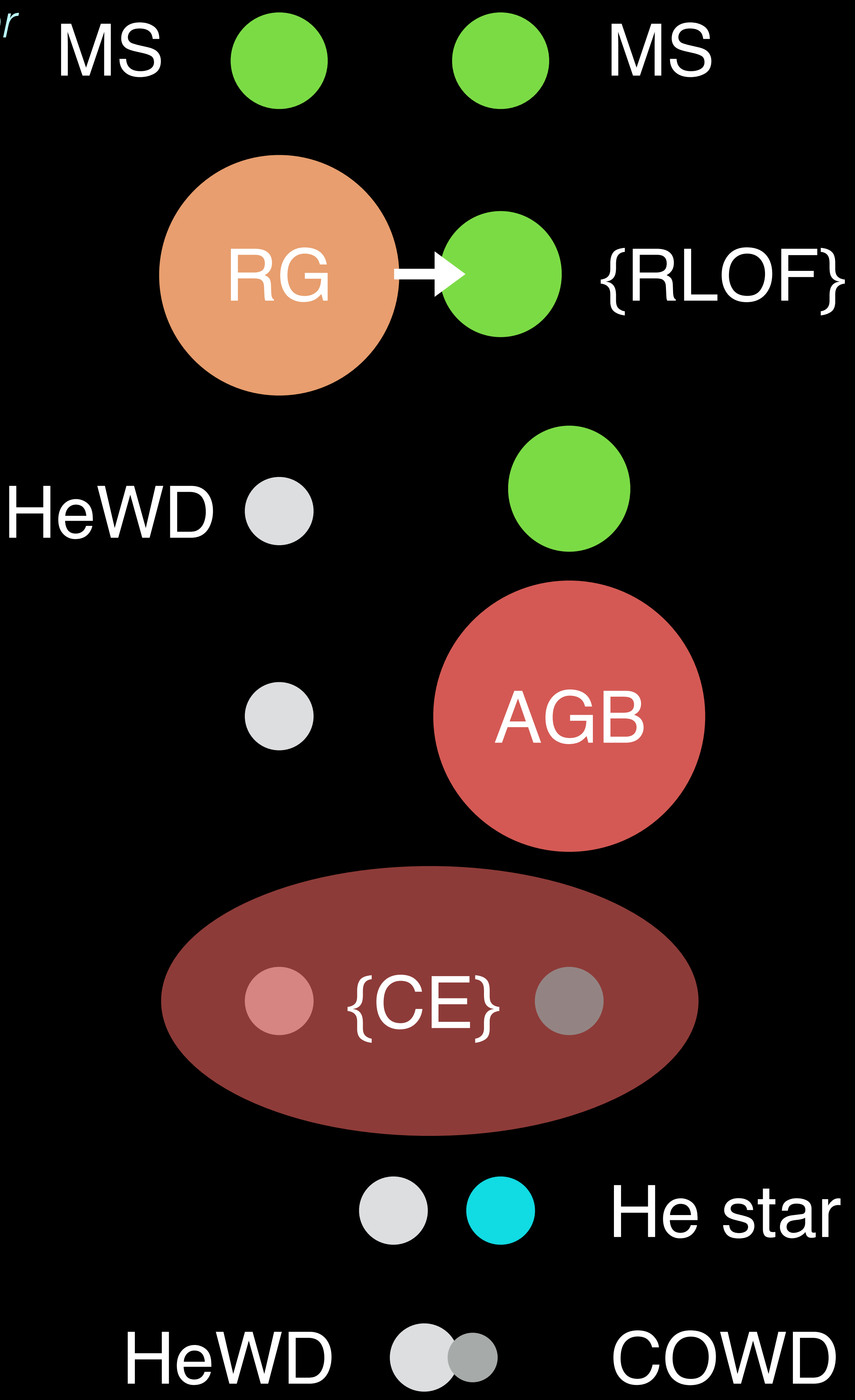
- **HeCO WD mergers:** some could make **1991bg-likes;** delay time works out since mergers kick in >few Gyr (see Crocker, Ruiter, Seitenzahl et al. 2017, Nature Astronomy). But not *all* channels will have long delay time.



Typical formation channel of HeWD+COWD merger found in Karakas, Ruiter & Hampel 2015

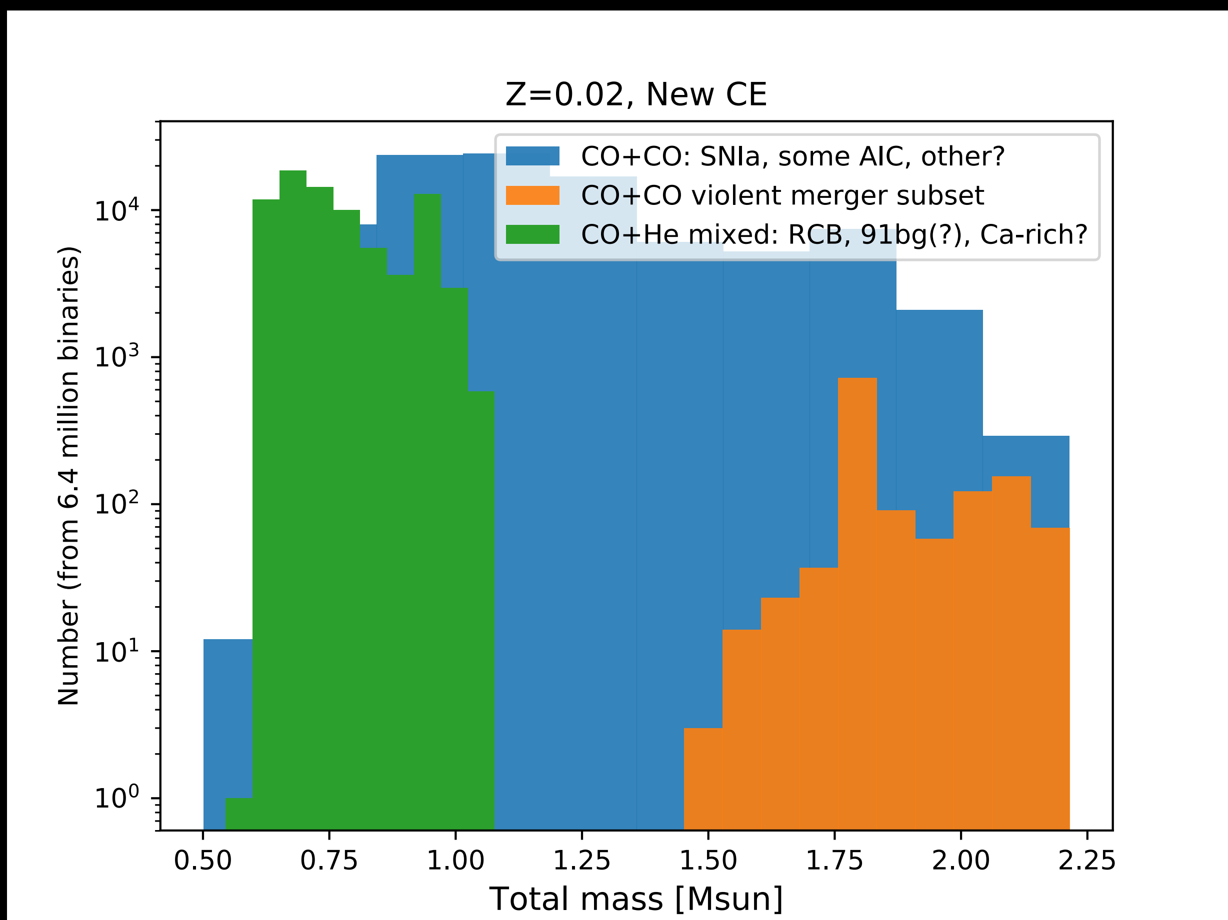
- Binary evolution population synthesis (binaries evolved in the field, e.g. no N-body / triples)
- *StarTrack* code evolutionary channel leading to He-CO double WD merger (cf. Crocker, Ruiter Seitenzahl et al. 2017).

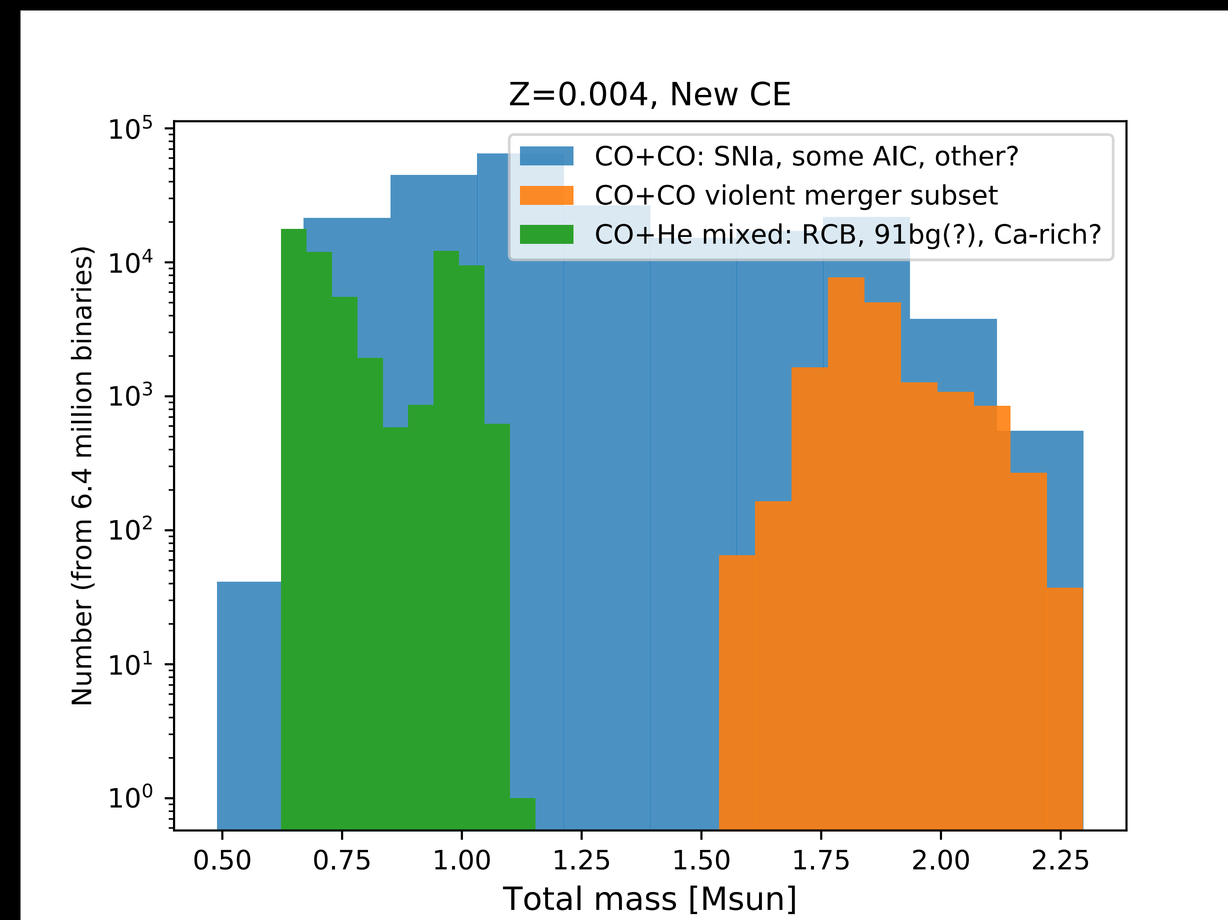
1. ZAMS masses ~1.3 - 2.5 Msun
2. low-mass (~0.3 - 0.4 Msun) **He WD** forms first via RLOF envelope stripping
3. **CO WD** (~0.4 - 0.55 Msun) forms later after (not during) CE event on the RGB or AGB
4. WD-WD merger delay time range ~500 Myr to Hubble time after star formation.



medium-heavy WD mergers:
simulated number vs. total merger mass (relative rates)

Usual assumption: explosion occurs before exploding WD reaches MCh





Orange systems: more likely to look like normal SNe Ia

Some “Galactic” WD merger rates:

MW COCO merger rate: ~0.005/yr (Z=0.02)

MW COCO merger rate: ~0.01/yr (Z=0.004)

Summary

- Chandrasekhar mass SNe Ia: two main channels of helium-rich donor and hydrogen-rich donor (e.g. Ruiter et al. 2009), but metallicity and choice of CE prescription affect the relative rates. Difficult to make MCh SNe via H-rich donor at low Z (cf. Chiaki Kobayashi chemical evolution). ***Currently best candidate for explaining SNe Iax.***

- Non dynamically-driven Sub-Chandrasekhar mass double-detonations (e.g. non-mergers): if both SD and DD channels occur in nature, delay time distribution is bimodal depending on donor type. Formation pathway is dictated by stellar masses and metallicity seems to have an influencing effect here. ***How much mass in helium shell is acceptable?***

- WD mergers with sub-MCh exploders: **CO+CO** mergers **may explain many 'normal' SNe Ia** (brightness distribution, rates pretty good, delay time too). Subset of He+CO mergers have long delay times: if these systems undergo helium detonations, they could explain the Galactic positron annihilation signal and plausibly account for the 1991bg SNe (Crocker et al. 2017, Panther et al. 2019).

- **Q: Can remnant observations help to delineate between some of these different channels??** (see Seitenzahl talk Wed. morning).

Our Astrophysics Group is accepting PhD student applications at UNSW Canberra!

(note: *different location from UNSW Sydney Physics*)!

- Current **Postdocs:** Fiona Panther, Nigel Maxted*, Simon Murphy.
  Current **Faculty:** Warrick Lawson (head of School of Science), Ashley Ruiter, Ivo Seitenzahl. **We are interested in stellar explosions and their progenitors (SNe and novae), binary evolution, supernova remnants, and gravitational wave sources (e.g. *LISA sources in our Galaxy*).**

*Maxted posters: S4.9, S10.13

- Rolling deadlines; for international applicants and scholarship information: https://www.unsw.adfa.edu.au/degree/postgraduate-research/physics-phd-1892

- Successful applicants receive a **scholarship of $35,000 AUD annually** for the 3.5 year PhD program (+ travel funds). PhD research program contains no formal coursework.

- Some more info on my website: **https://ashleyruiterastro.wordpress.com/** under “Student Projects”.

Dr Ashley J. Ruiter @growzchilepeps

What about the He-rich donor MCh channel?
Likely SN Iax candidates e.g. 2008ha, 2012Z

- SN Iax: "weirdo" class of SNe Ia. Lower luminosities, lower ejecta velocities.
- **Currently favoured model for SN Iax**: A ~**1.4 Msun CO or CONe WD** that undergoes a thermonuclear ignition, but the explosion does not unbind the star ("failed deflagration" or actually, a *failed detonation*). e.g. Jordan et al. 2012, Kromer et al. 2013.
- ~A few x 0.1 Msun of material is ejected. Some may fall back on WD and leave unusual nucleosynthetic signatures (e.g. Vennes et al. 2017).
- *Right*: *StarTrack* CONe WDs that approach Chandrasekhar mass limit with H-stripped, helium-burning star donors (blue) and other donors (red).

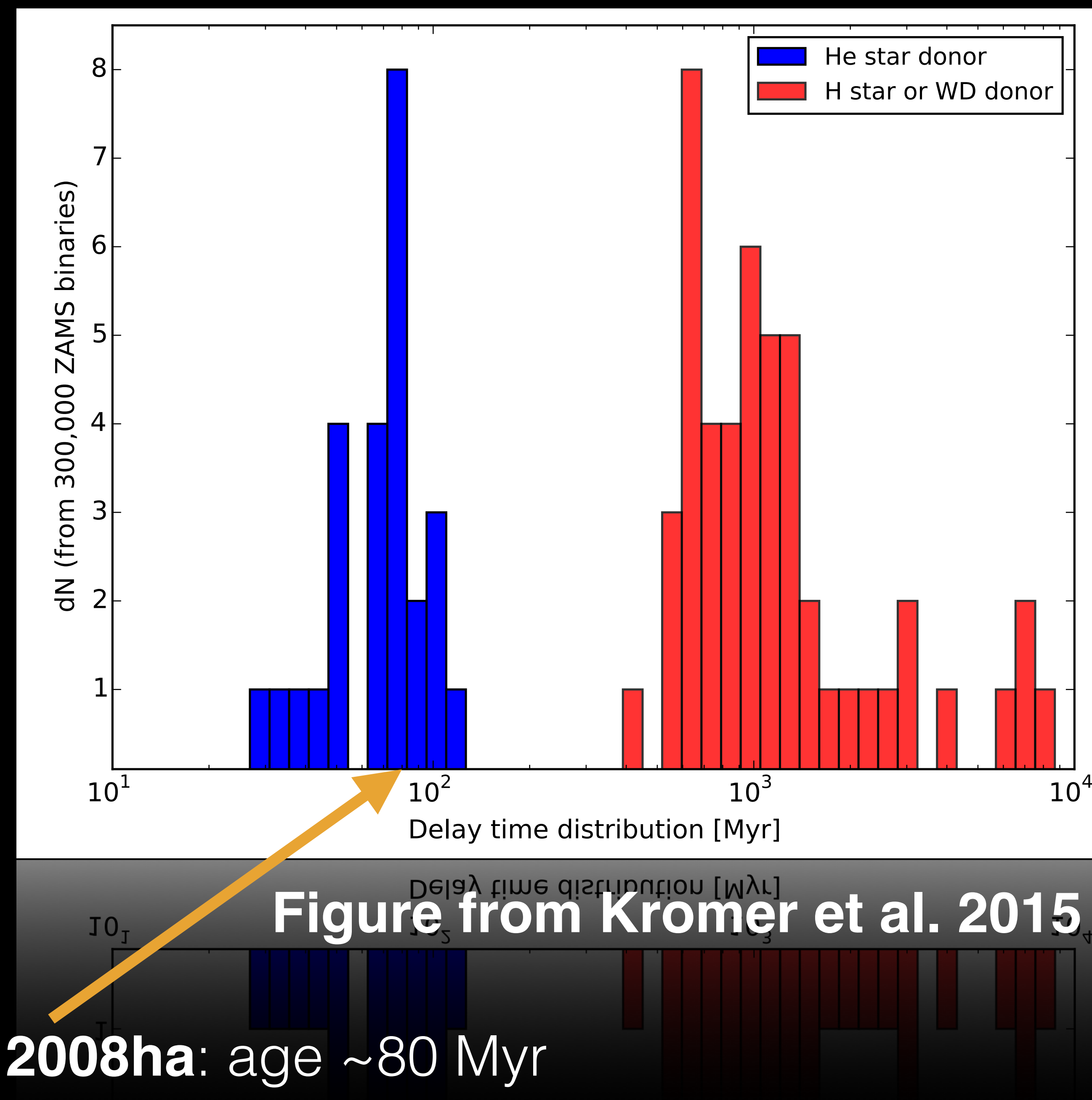
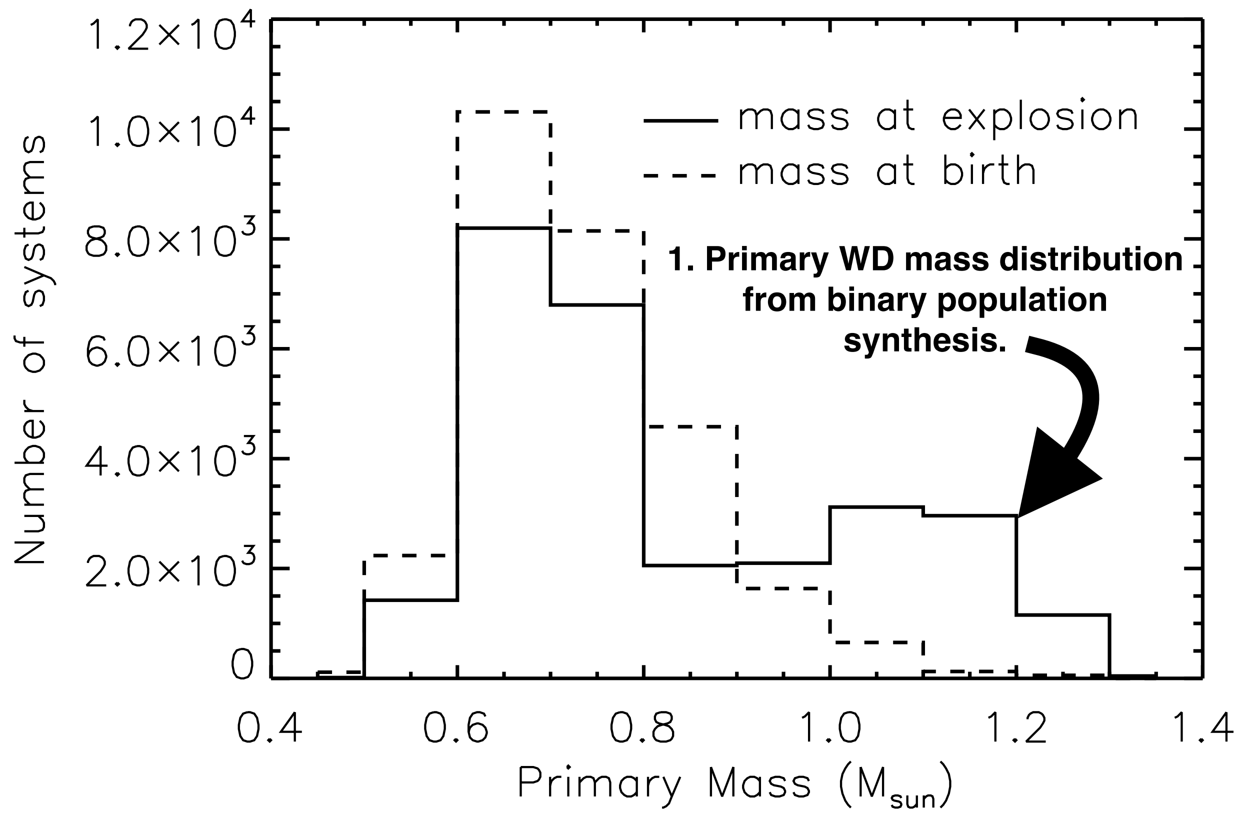


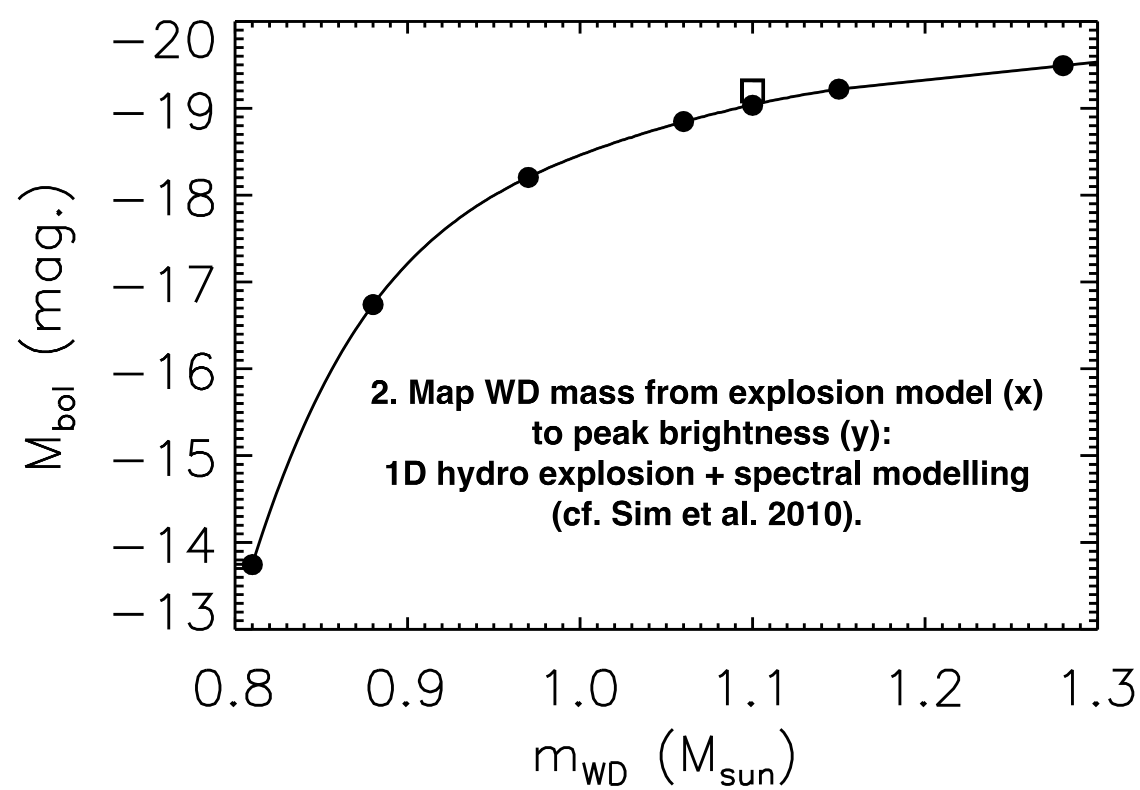
Figure from Kromer et al. 2015

Very faint SN **2008ha**: age ~80 Myr

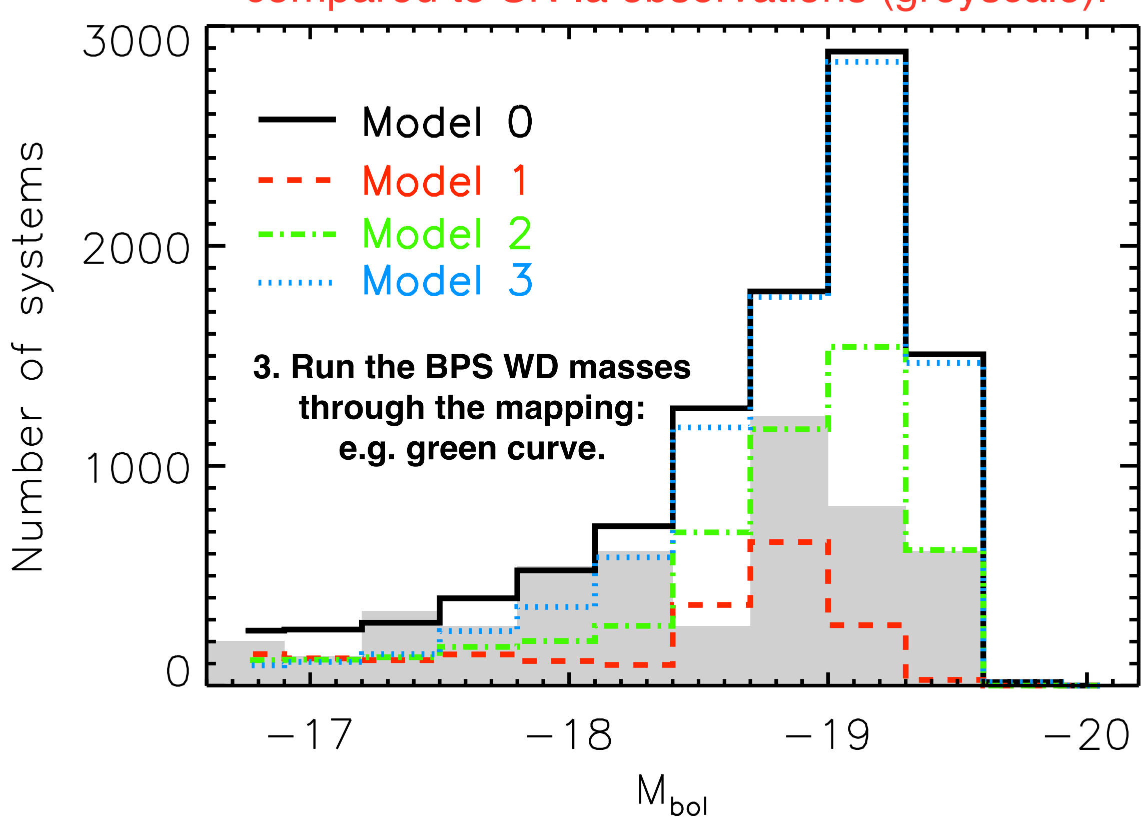
CO+CO mergers at Z=0.02 metallicity; Ruiter et al 2013.



Result:
Theoretical peak brightness distribution of merging white dwarfs matches the peak brightness distribution of SNe Ia.
Ruiter et al. 2013



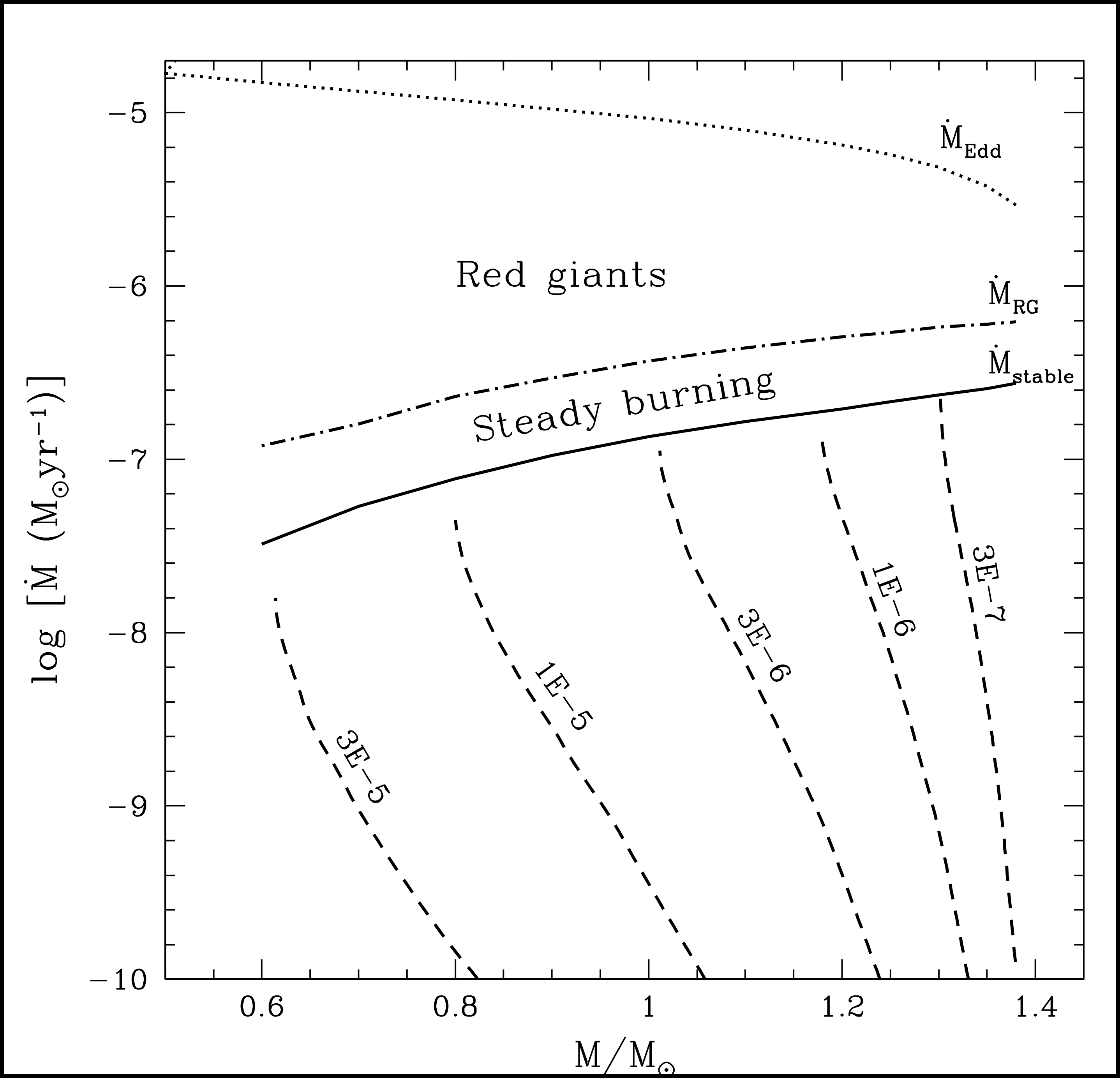
Peak brightness of merging WDs (coloured lines) compared to SN Ia observations (greyscale).



Implications:
1. Substantial fraction of SNe Ia result from sub-Chandrasekhar mass WDs (~1 M⊙).
2. New formation channel revealed (WD mass is 'beefed up' before merger).

SDS with H-rich donors: why is it so difficult to make them?

- Narrow region of Mdot-M_WD space where stable, efficient burning occurs.
- Outside of this region you have no or unstable burning (flashes): many CVs, not many SNe.
- Accretion efficiency more favourable for helium donors.

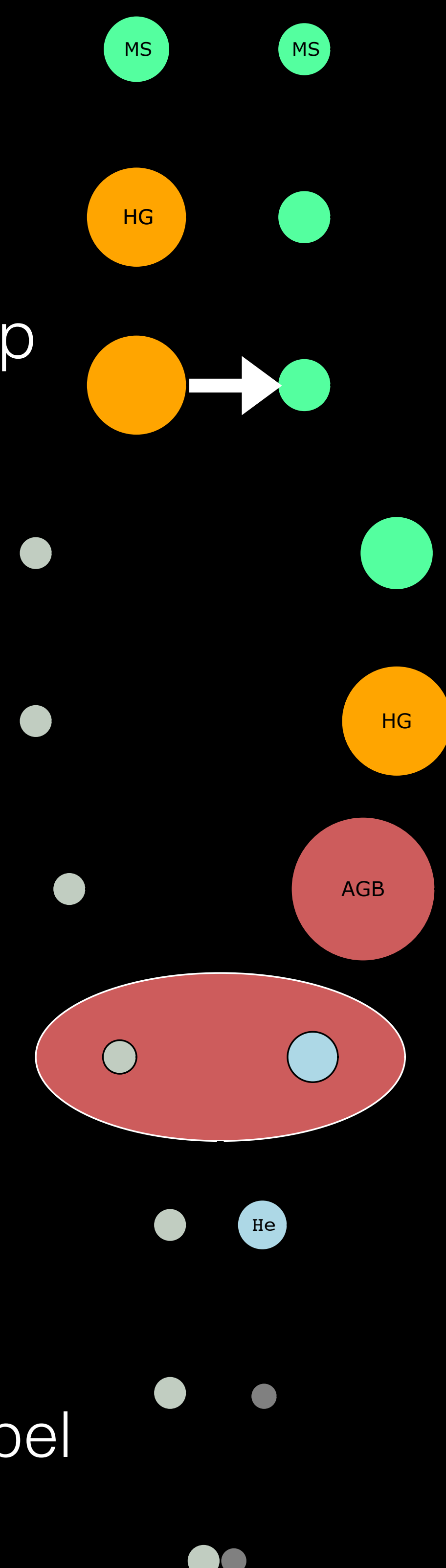


Hydrogen accretion on WDs; Nomoto et al. 2007

Two WD merger formation channels with *StarTrack*: CO+He and CO+CO

R Coronae Borealis and/or 1991bg-like SN: merger between HeWD + COWD (whether binary ends up as RCB or 91bg depends on *initial masses).*

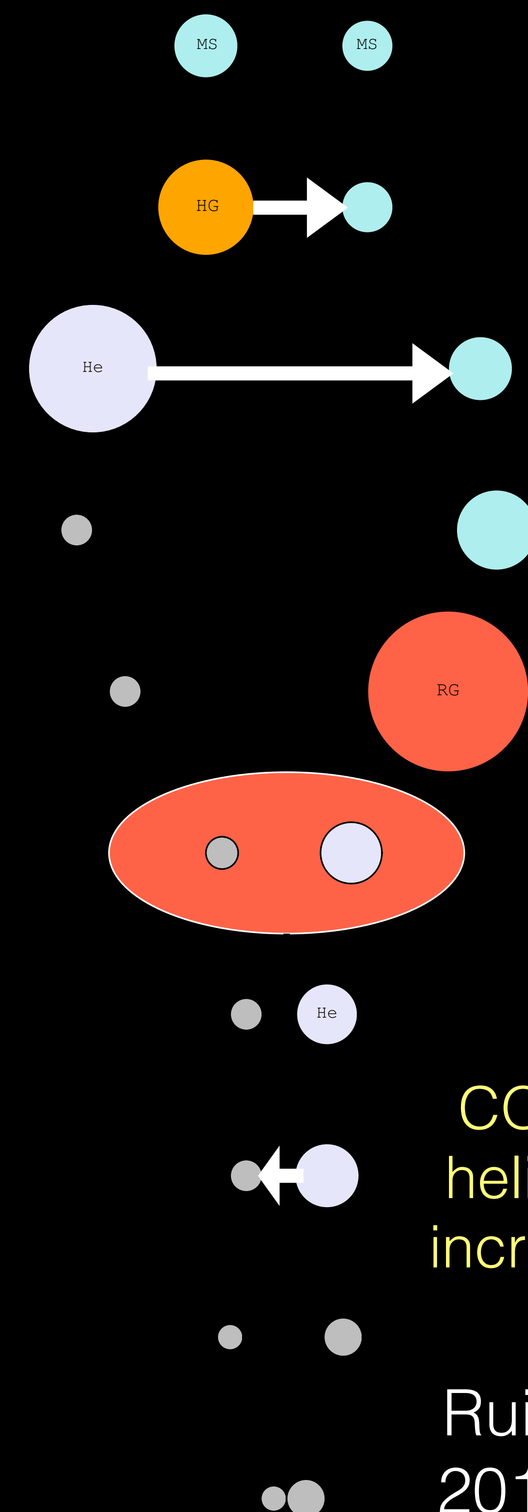
common envelope



Karakas, Ruiter & Hampel 2015, ApJ 809, 184

Type Ia Supernova: merger between COWD + COWD

common envelope



CO primary accretes from helium-burning secondary: increase in mass ~0.2 Msun

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