Fifty-One Erg
Raleigh, May 20-24 2019
NCSU

Type Ia supernova subclasses and progenitor origin

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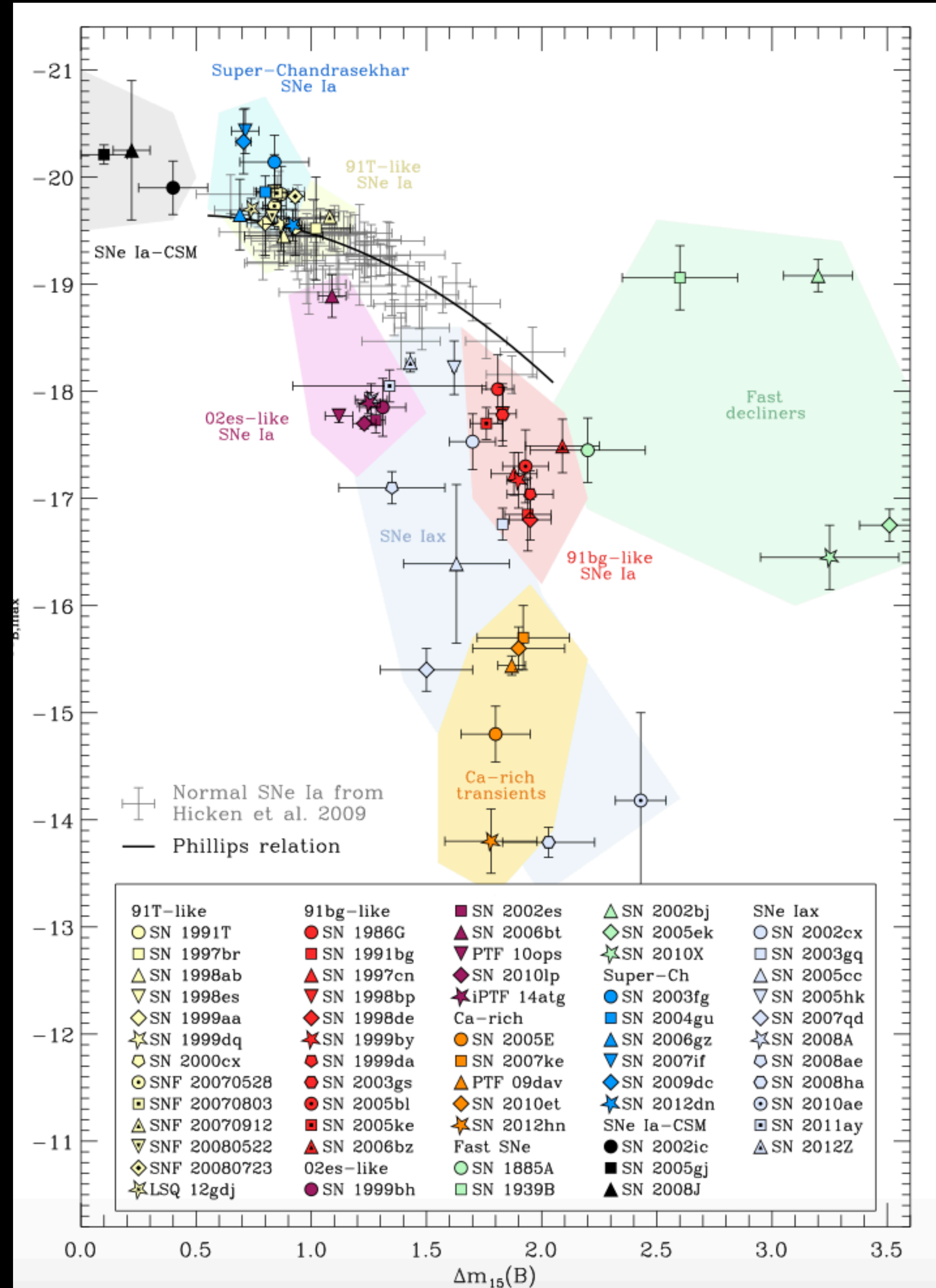
Thermonuclear supernovae and their subclasses

- 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. And then there's all the other stuff! Ca-strong/rich transients, 91bg-likes, 91T-likes, "one" Eh X (Iax)…
- This plot keeps changing… finding faster & fainter thermonuclear transients. But what make them?

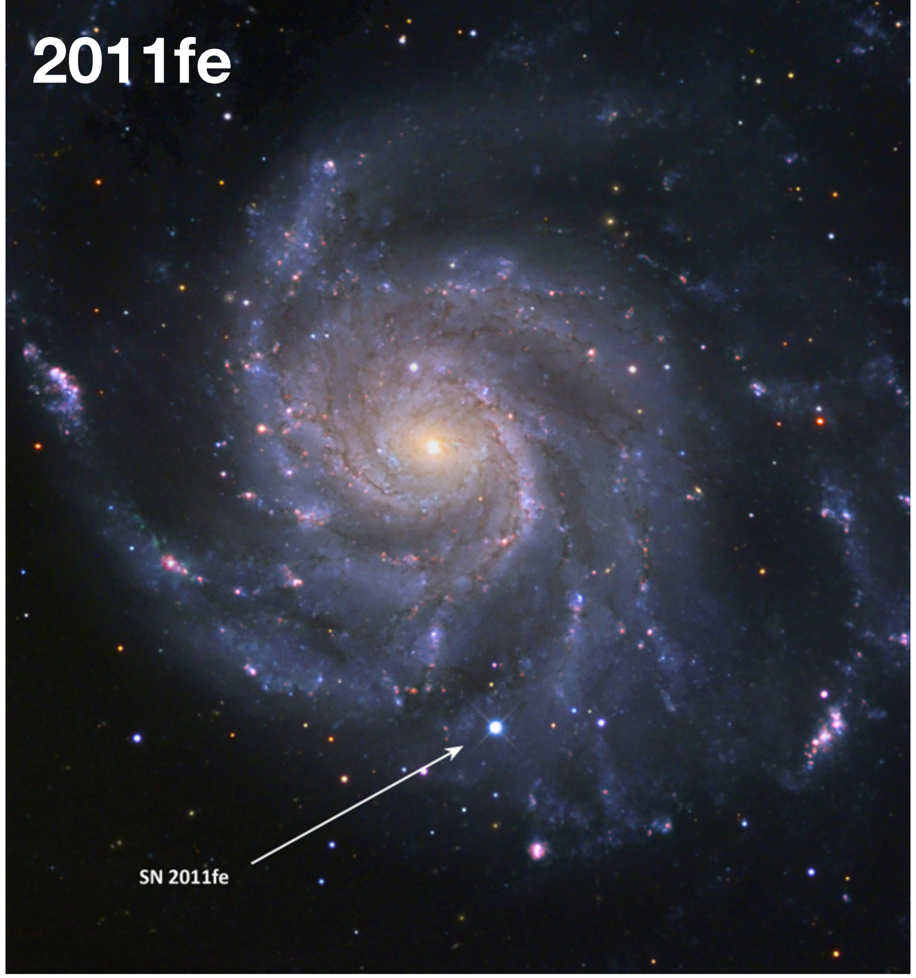
$$M_{\mathrm{max}}(B) = -21.726 + 2.698\Delta m_{15}(B).$$



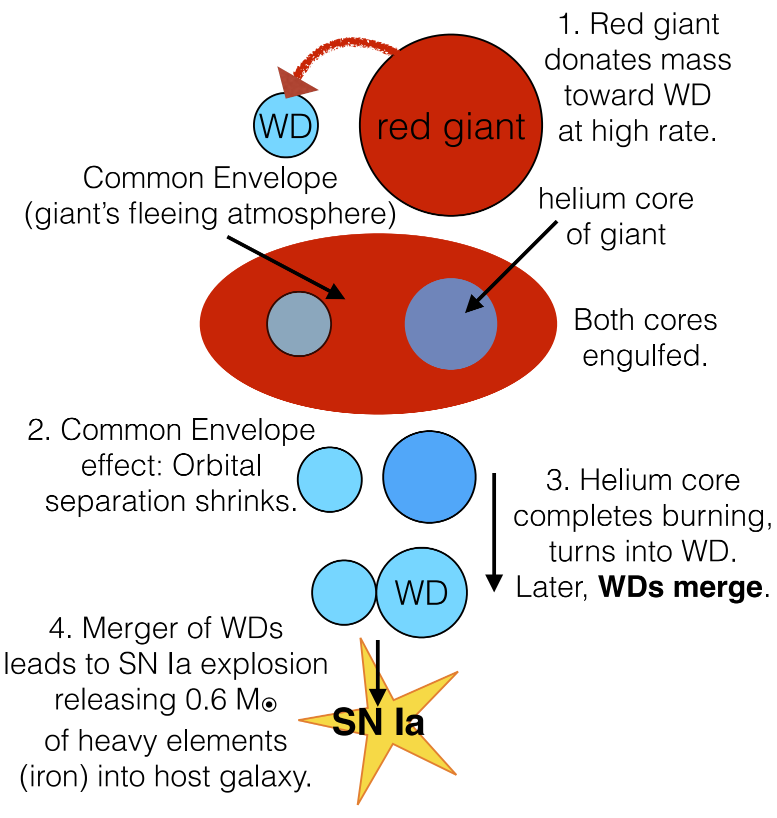
Taubenberger 2017

Detailed explosion model of a single configuration is useful, but need to **also** know *how often* said configuration would occur in Nature to explain population.

Properties of stellar populations (age, mass, rates) can explain/refute progenitor origin (or at least provide clues)!

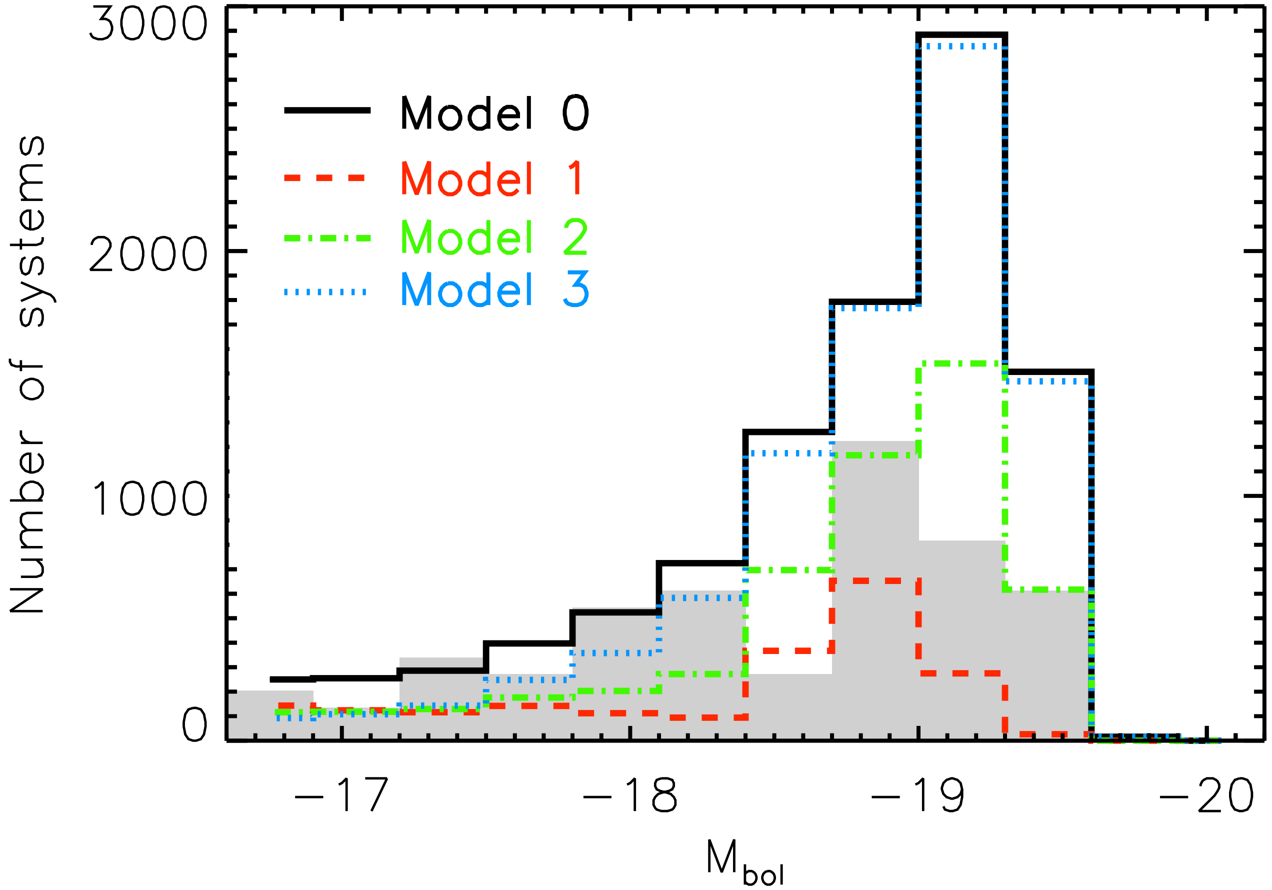


B. J. Fulton



Example of SN Ia evolutionary channel (*StarTrack*)

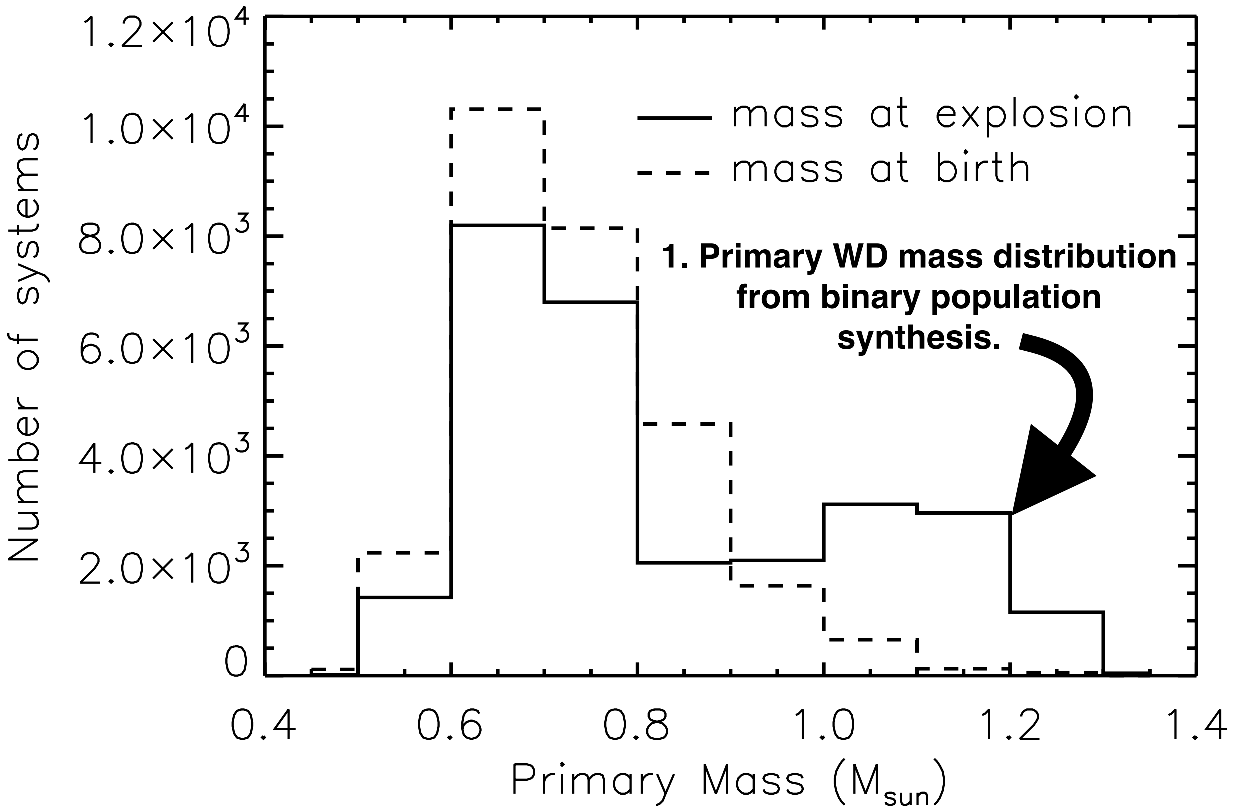
Peak brightness of merging WDs (coloured lines) compared to SN Ia observations (greyscale).



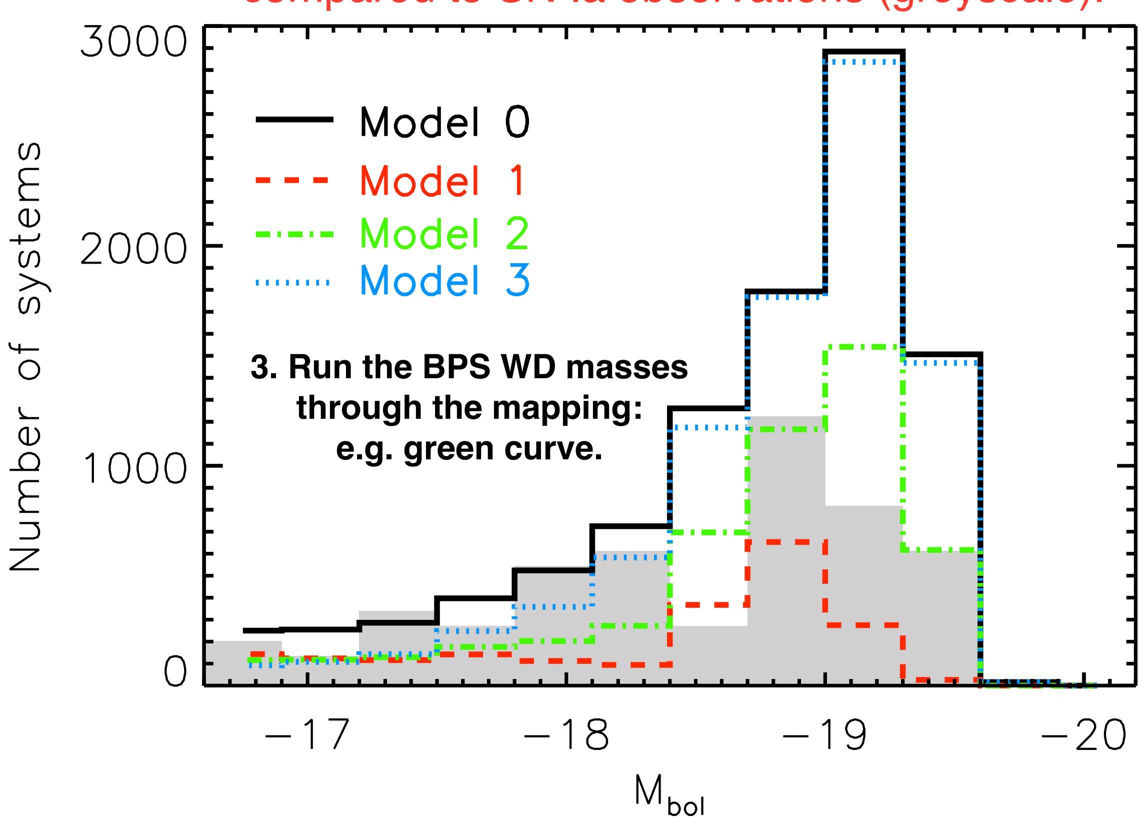
New formation channel revealed (helium star dumps mass on primary WD before explosion; Fig. 2 Ruiter et al. 2013).

Model peak luminosity distribution has same shape and characteristic peak as observed local SNe Ia (Li et al. 2011, LOSS survey within 80 Mpc; grey histogram).

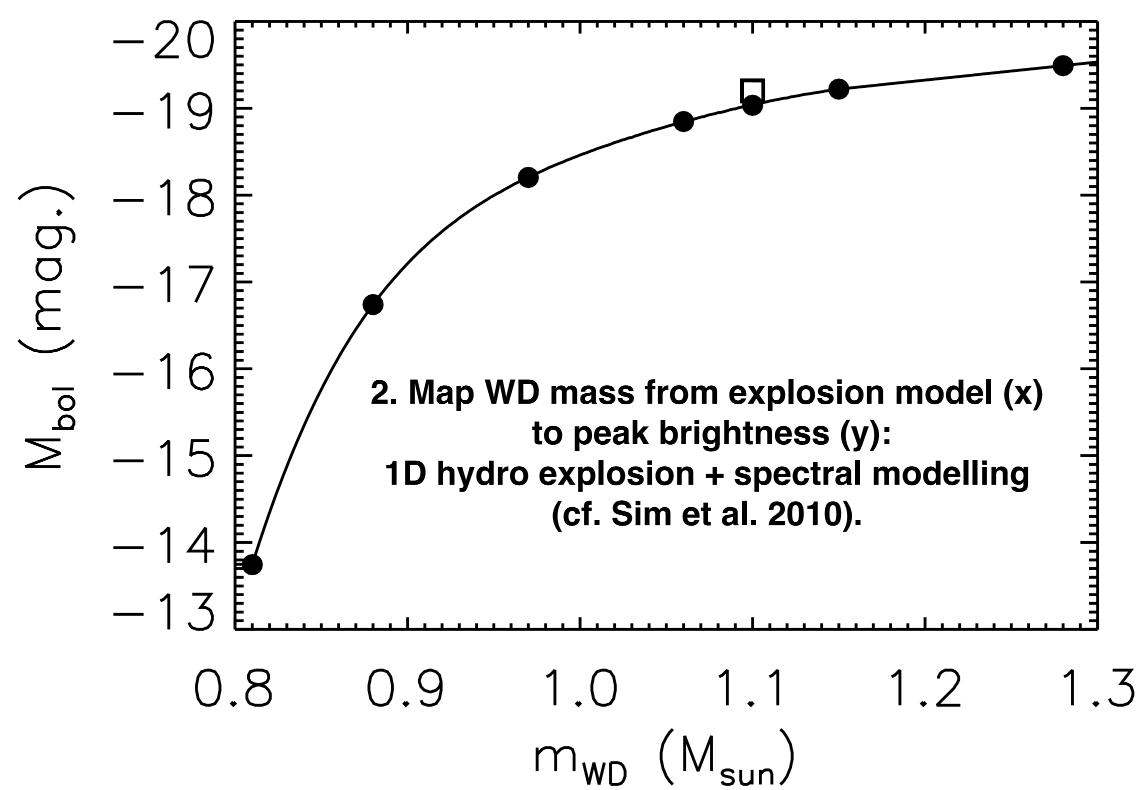
CO+CO mergers at Z=0.02 metallicity; Ruiter et al 2013.



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



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



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).

Type Ia SN progenitors

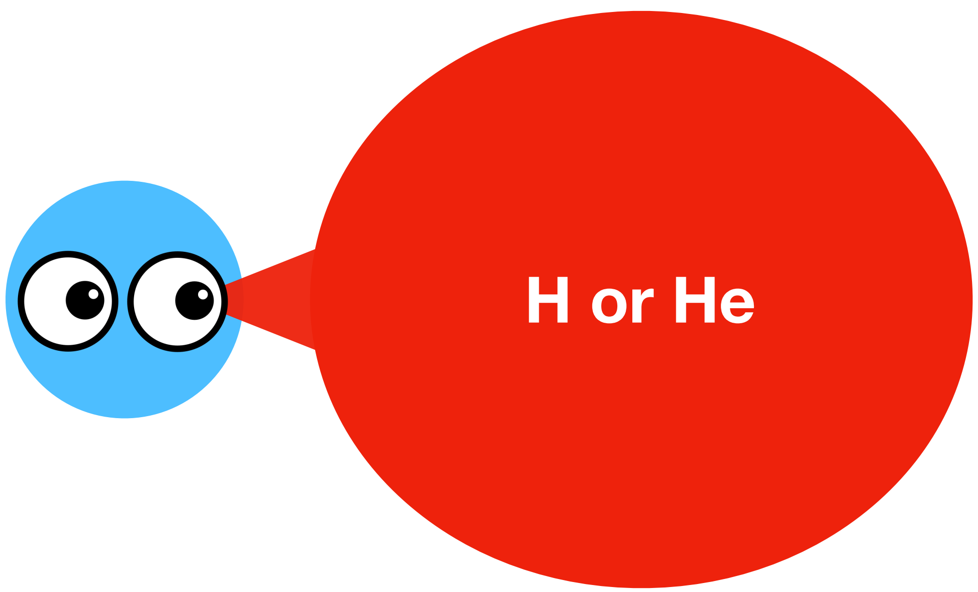
Nutshell synopsis of formation channel + explosion mechanism mish-mash

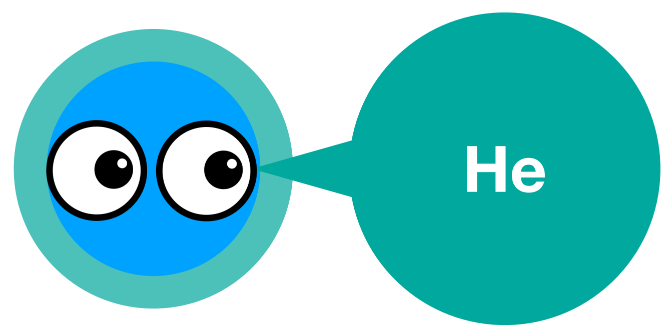
2 main channels, 1 explosion mechanism

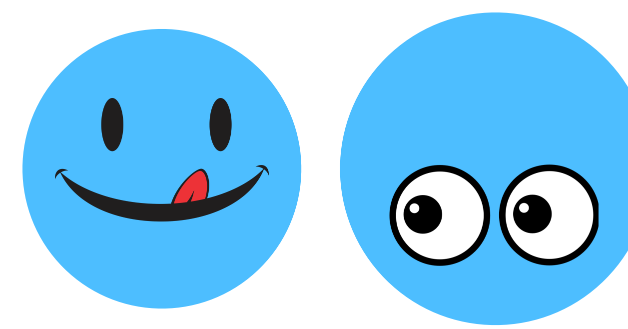
2 main channels, 1 explosion mechanism

WD mergers: 2 explosion mechanisms

CO WDs(?)







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

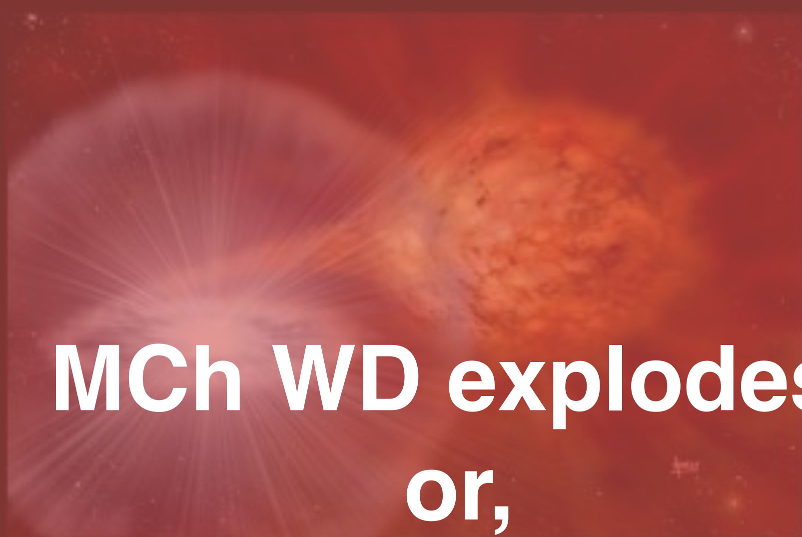
Sub-Chandra mass WD
& Single OR Double Degenerate
(requires helium)

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

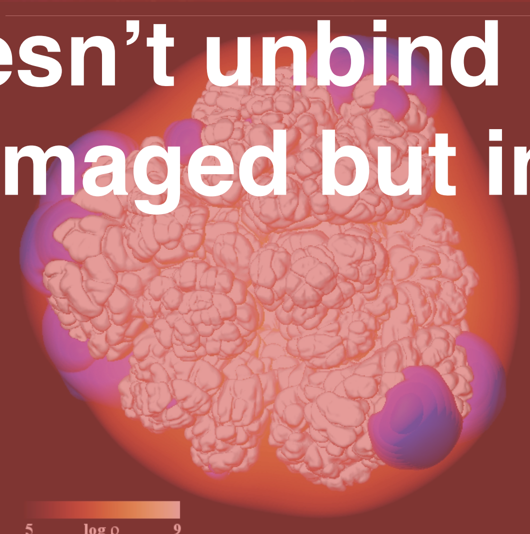
Paradigm shift with Pakmor et al. 2010 Nature paper on WD mergers that showed sub-Chandrasekhar mass WDs can produce light-curves & spectra that look like those of SNe Ia.

Some SN Ia progenitor (& explosion) scenarios (CO WD accretor, donor = ?)

WD approaches Chandrasekhar mass (via RLOF). Explosion may unbind star, or not.



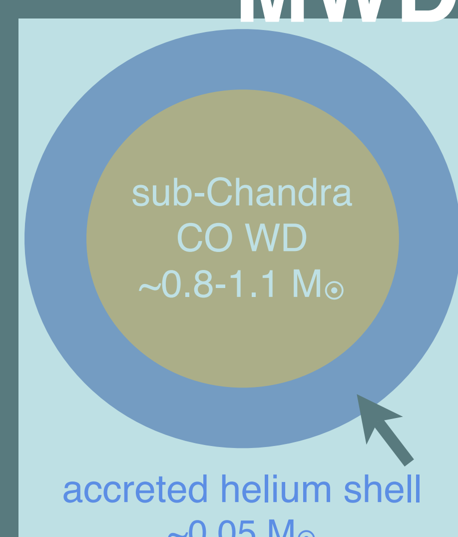
MCh WD explodes, or, doesn't unbind -> WD damaged but in tact



N100 model of Seitenzahl et al. Central C ignition of 1.4 M_{sun} WD: **Go see VR simulation upstairs!**

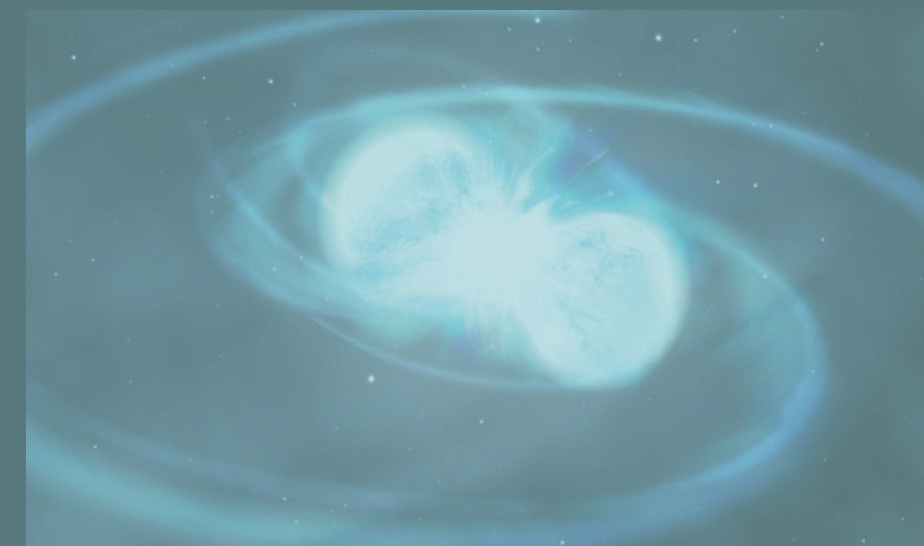
RLOF

WD gains mass from He-rich companion. He-layer ignites before WD is MCh -> detonation near centre.

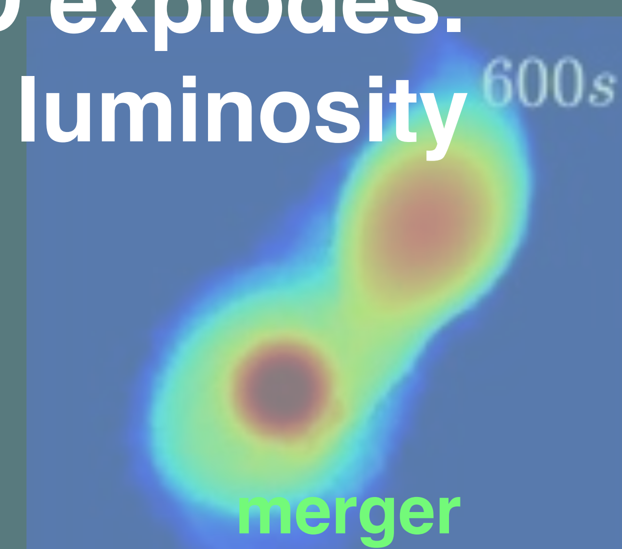


'classic' double-detonation

Merger of two WDs. Both CO? Or maybe one CO, one He?



sub-MCh WD explodes. MWD ~ peak luminosity



merger "prompt detonation" favoured model: WD explodes below MCh

CO+CO simulation of Pakmor et al.

See also Pakmor et al. 2013

Common Envelope (CE) prescription is important: some channels change more than others

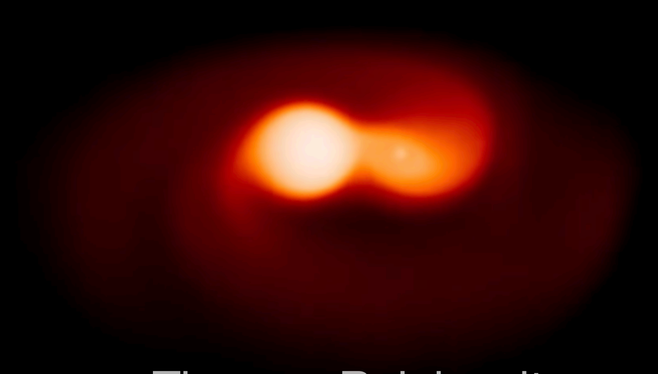
- In **binary population synthesis** (BPS), the common envelope (CE) phase cannot be explicitly calculated; it must be parametrized in some way.

- Separation after common envelope (CE) is determined by energy reservoirs available. What are those? Internal, ionisation… enthalpy ? The unknown physics is contained in **binding energy parameter λ** (and **α**), typically we equate binding energy of envelope-losing star to orbital energy of the binary and can **solve for a_f** (separation post-CE).

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

- *This `Classic' Webbink (1984) prescription where binding energy parameter λ is constant for all H-rich stars: α x λ ~ 1. Previously the 'canonical' model in BPS.* Perhaps not as realistic? (see recent paper by Iaconi & De Marco for comparison of observations and simulations).

- Our 'New' prescription with <u>variable λ</u> based on Xu & Li (2010) (see also Domenik et al. 2012) employs evolutionary stage-dependent λ, **α**=1, + enthalpy argument from Ivanova & Chaichenets (2010). *Example*:, λ is ~1 for sub-giants, can be ~3-10+ for extremely evolved stars like AGB.



Thomas Reichardt

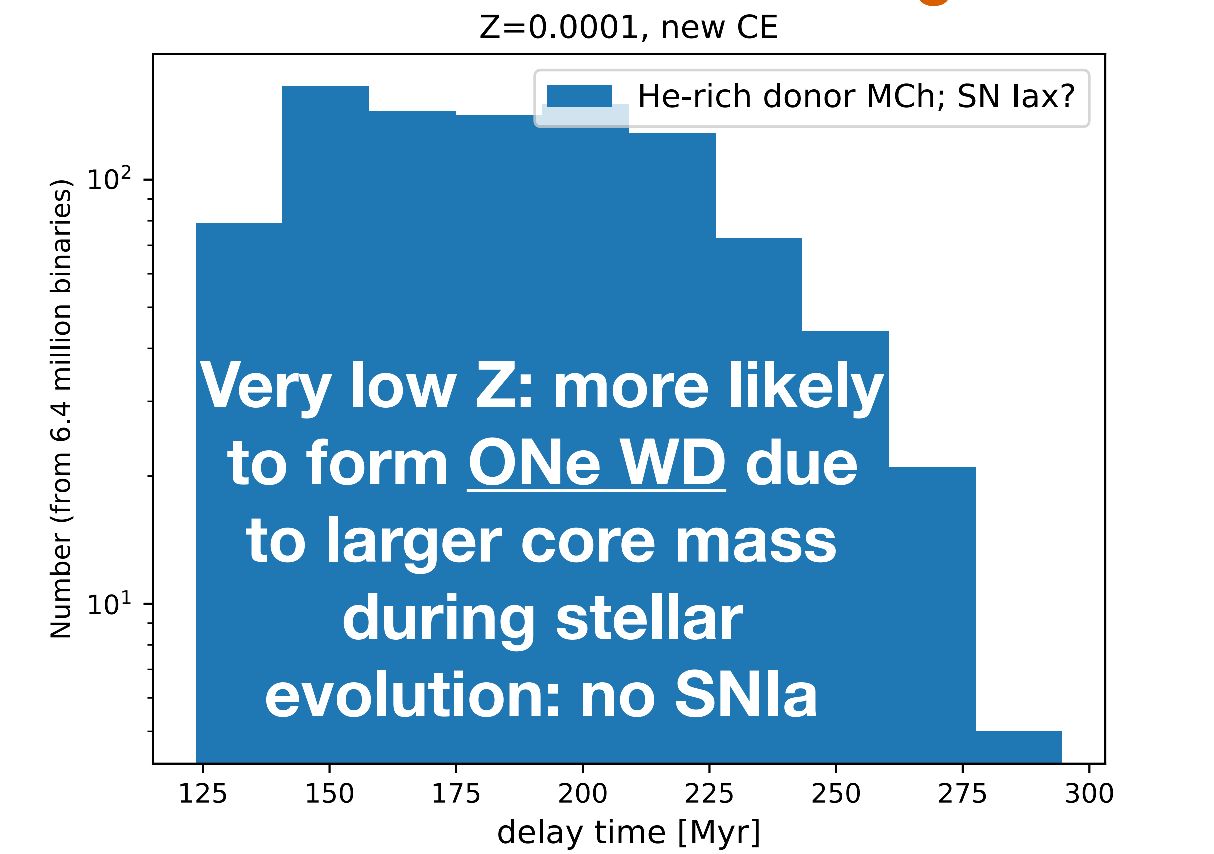
Some plots (preliminary): 2 Chandrasekhar mass channels as f(Z) (RLOF)

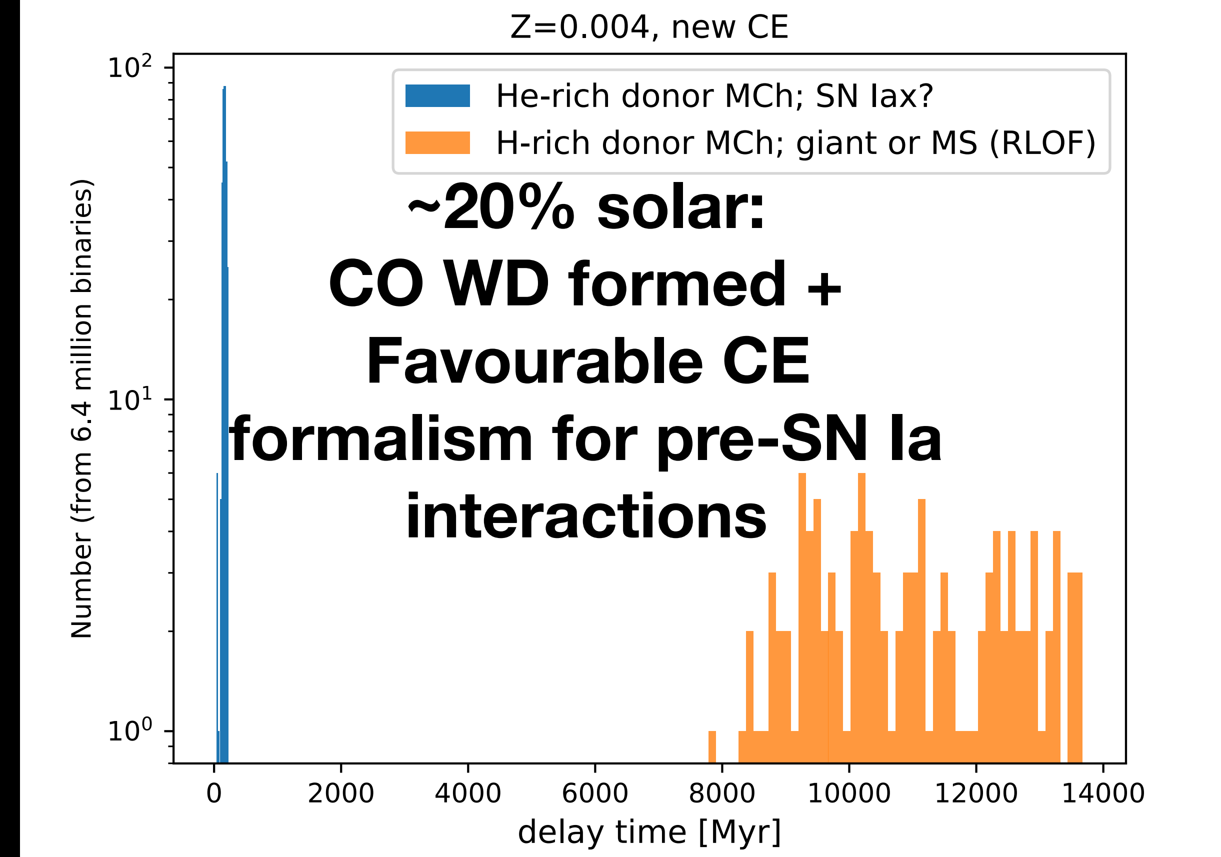
- **Explosions of ~MCh CO WDs (possibly CONe WDs):** promising scenario is ***pure deflagrations*** (e.g. SN2002cx and other **SN Iax** events; e.g. Jha et al. 2017). Probably **helium donors**. **Hydrogen donors**: via RLOF (can have longer delay time) or perhaps accrete from evolved stellar wind (short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

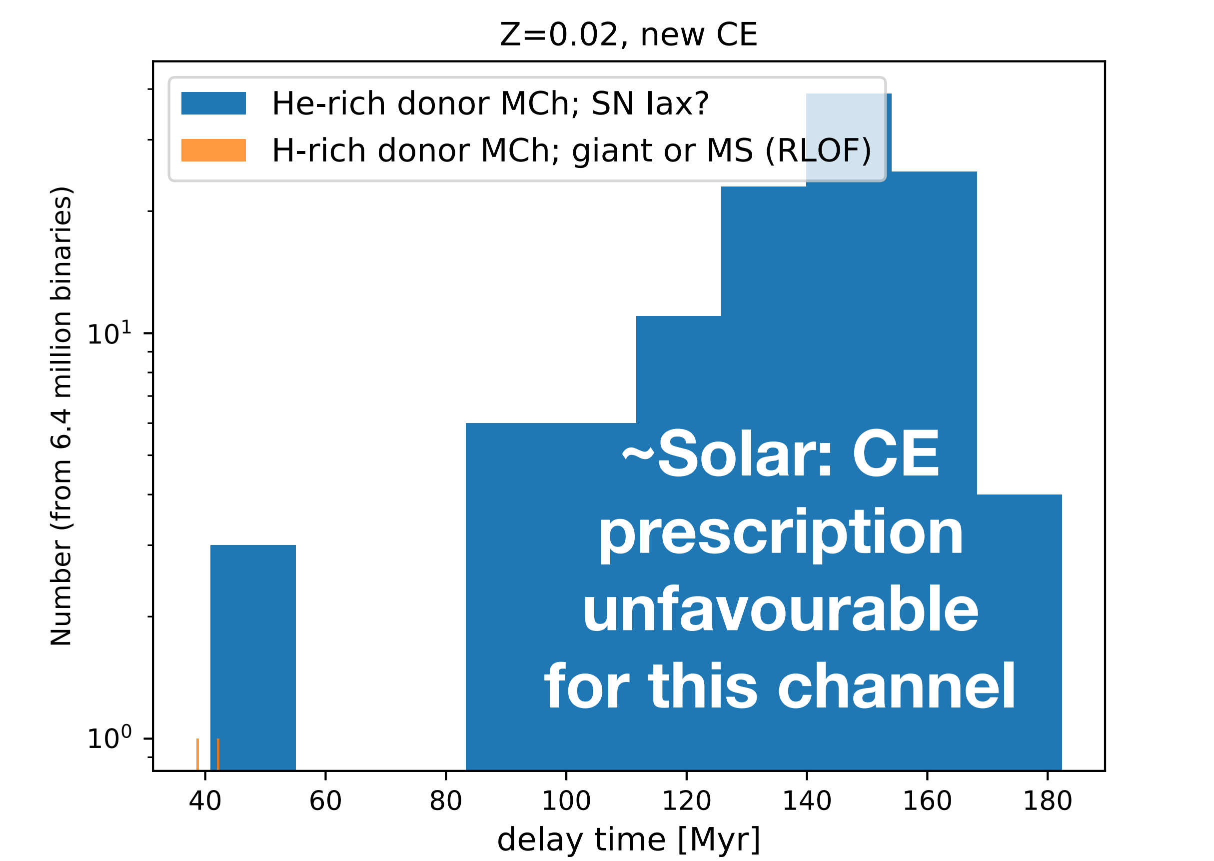
- *nucleosynthesis*: WD explosions near the Chandrasekhar mass are likely needed to explain the **solar abundance of manganese** (Seitenzahl et al. 2013).

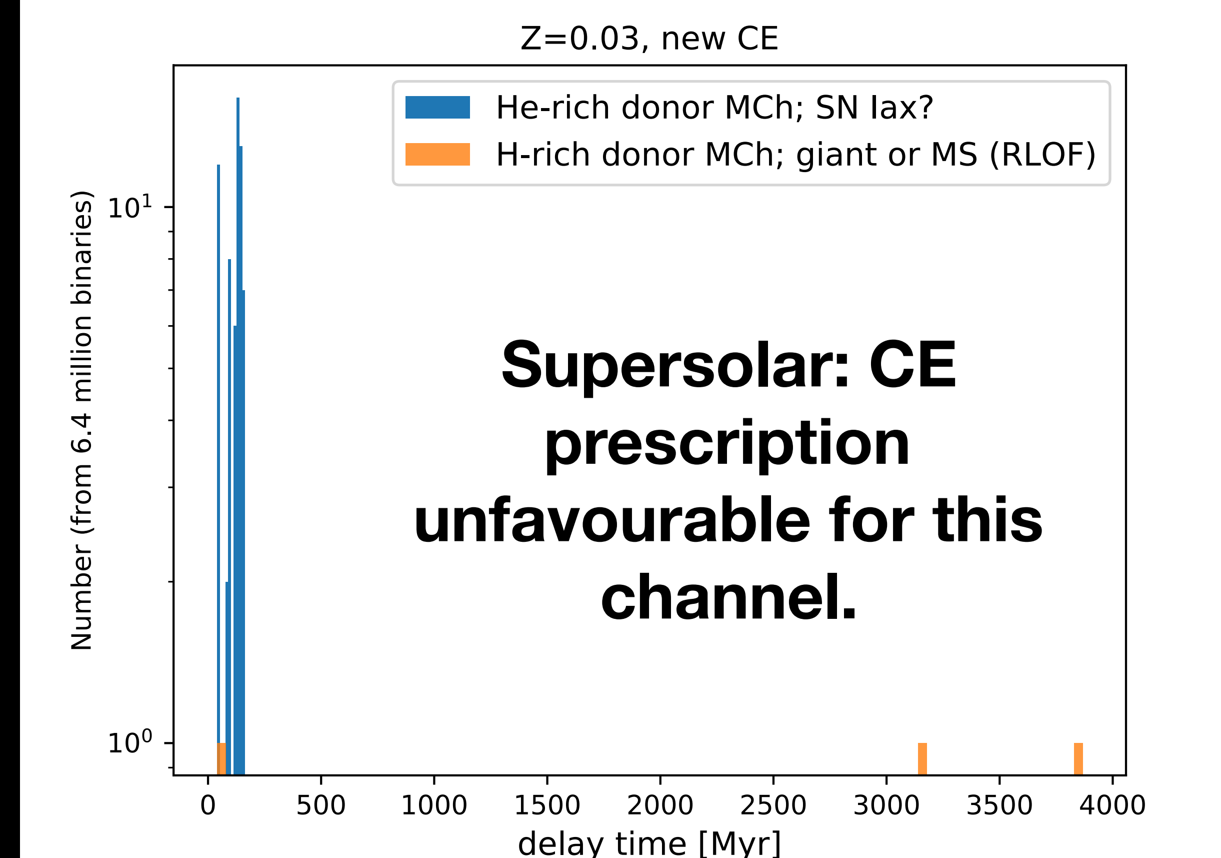
- How do delay times and rates change with metallicity Z?

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 < 300 Myr for all Z (more massive on ZAMS -> evolve off MS faster).

- Usual channel for stripped, He-burning donor 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.

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

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 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 helium-burning star donors (blue) and other donors (red).

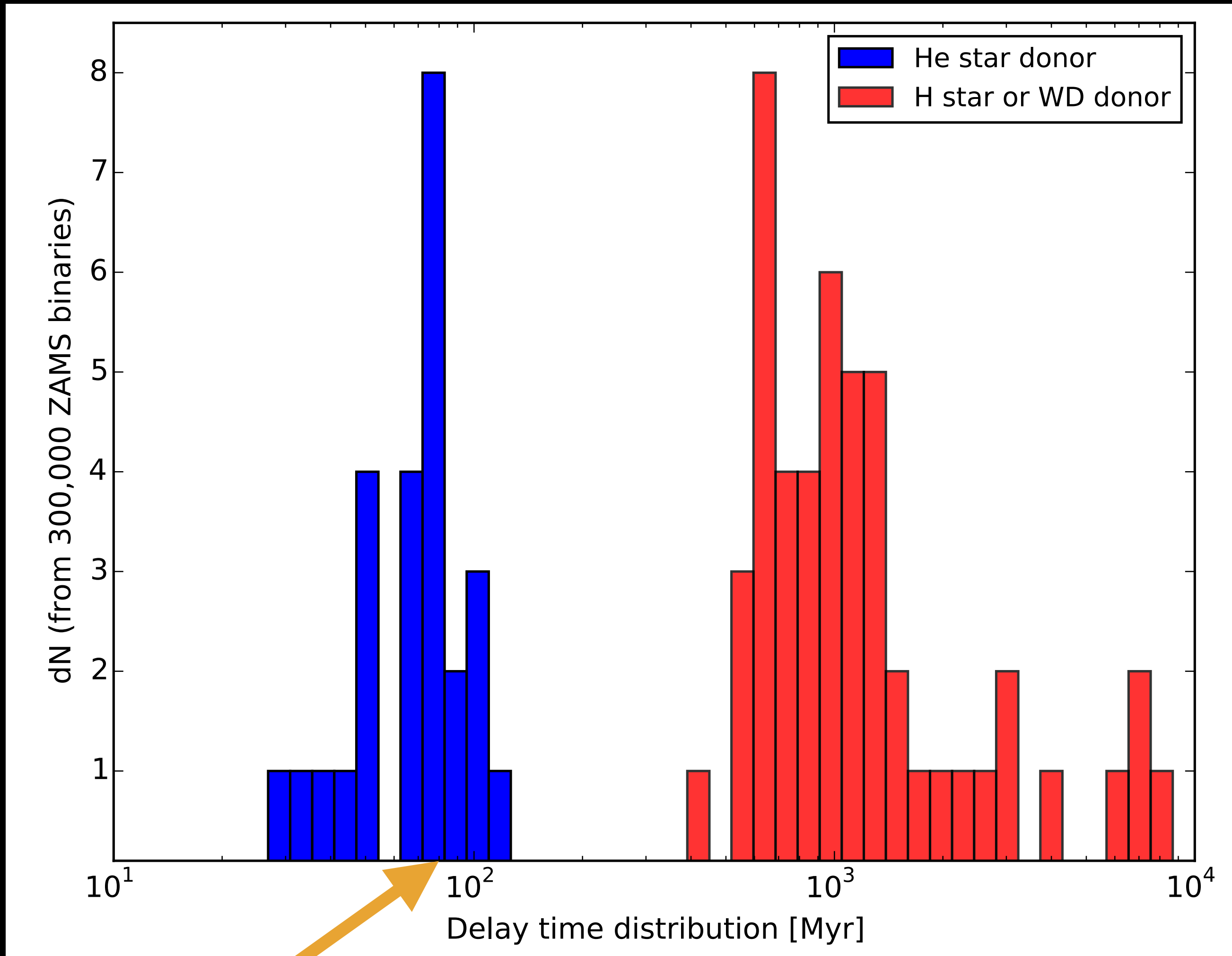


Figure from Kromer et al. 2015

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

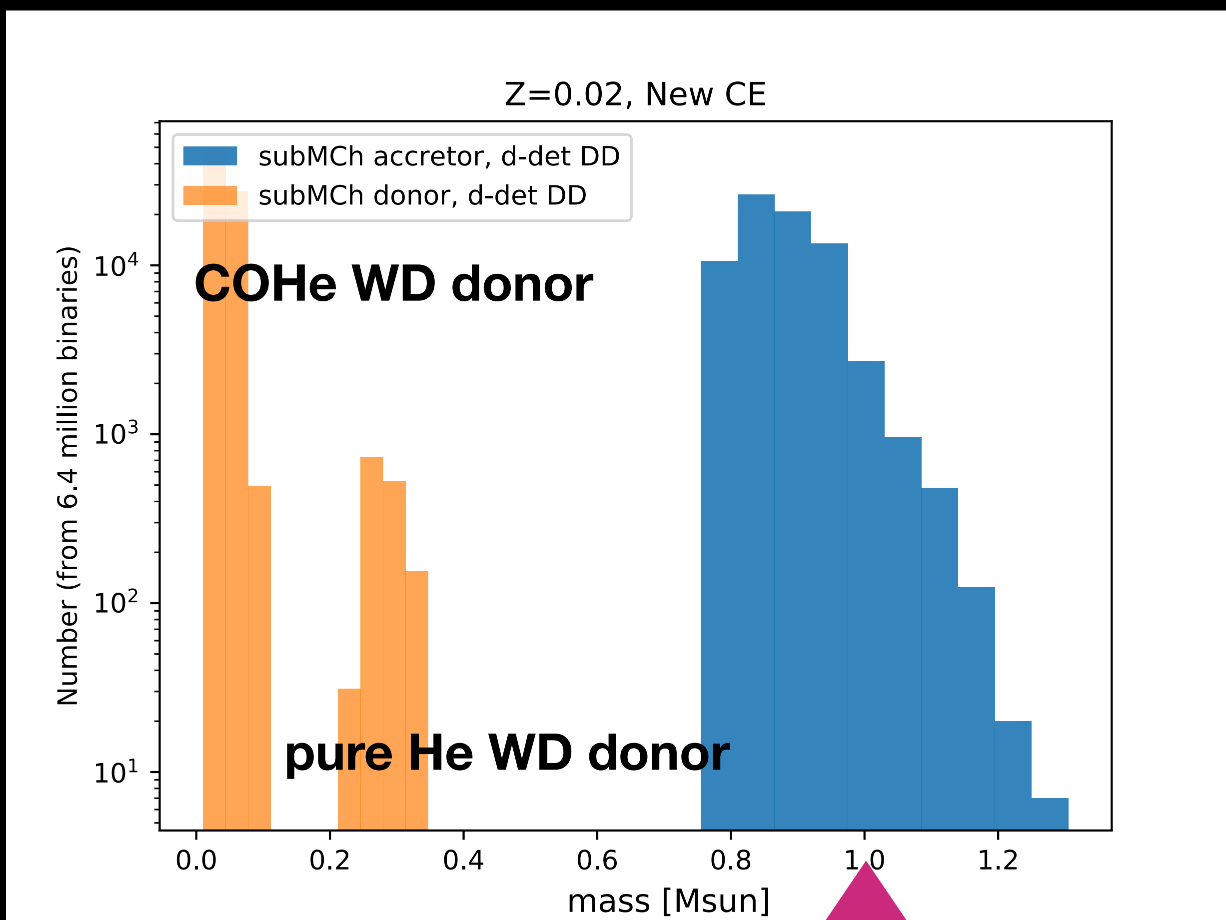
sub-Chandrasekhar mass channels (M<1.4 Msun)

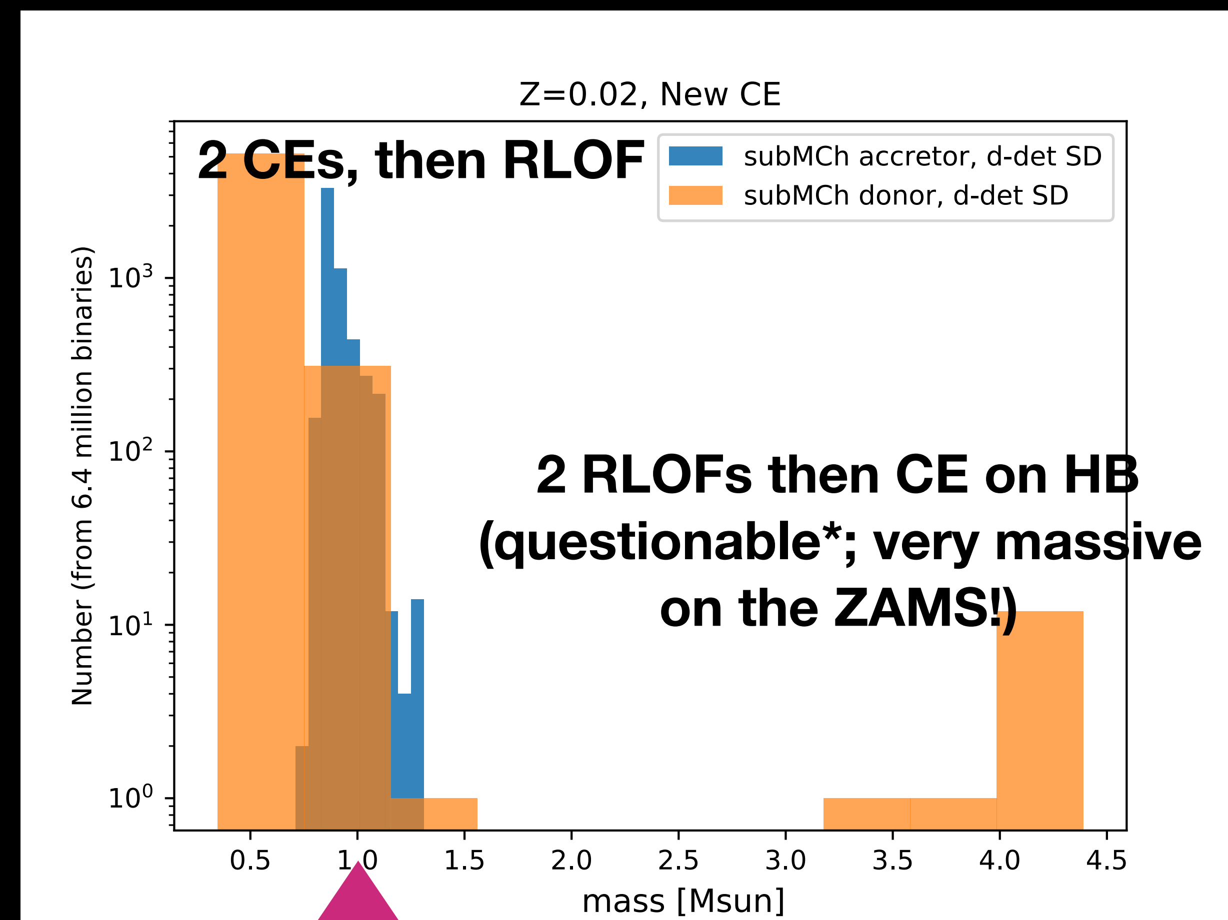
- **Sub-Chandra non-mergers:** or *'classic' double-detonation with ~0.01-0.05 Msun* **helium** *shells detonating on CO WD.* How much helium can this progenitor have and still look like a SN Ia? (see A. Polin's poster for new & interesting candidate)!

- DTD is bimodal (e.g. Ruiter et al. 2014) but there are slight changes with metallicity.

‘classic’ sub-MCh double detonations: nature of the donors

Left: DD Right: SD





*Need to investigate ‘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

(He 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), rates are roughly on par (for astro)!
- **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)

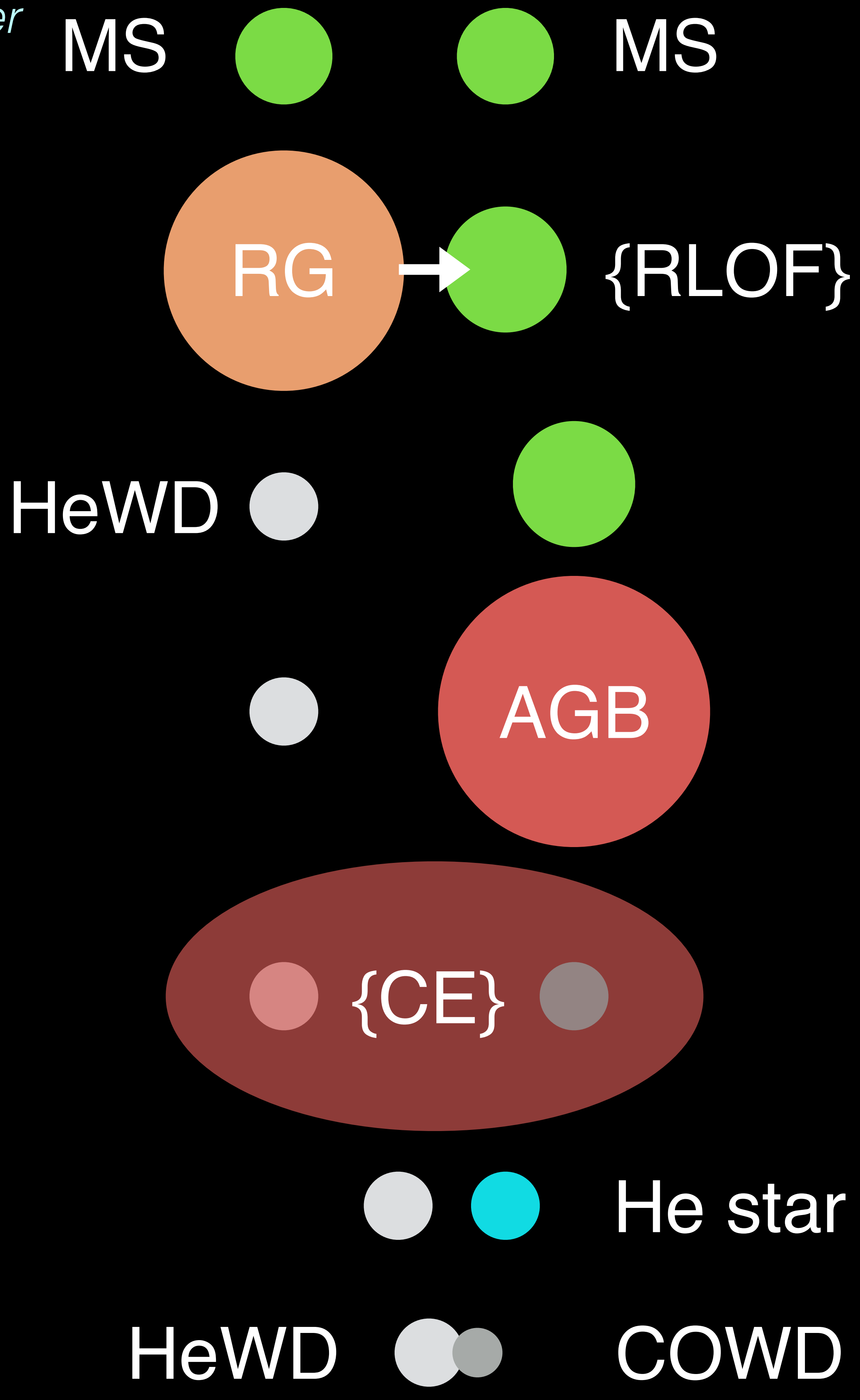
- *StarTrack* code evolutionary channel leading to He-CO double WD merger (cf. Crocker, Ruiter Seitenzahl et al. 2017).

1. ZAMS masses ~1.3 - 2.5 Msun

2. low-mass (~0.3 - 0.4 Msun) **He WD** forms first via RLOF envelope stripping

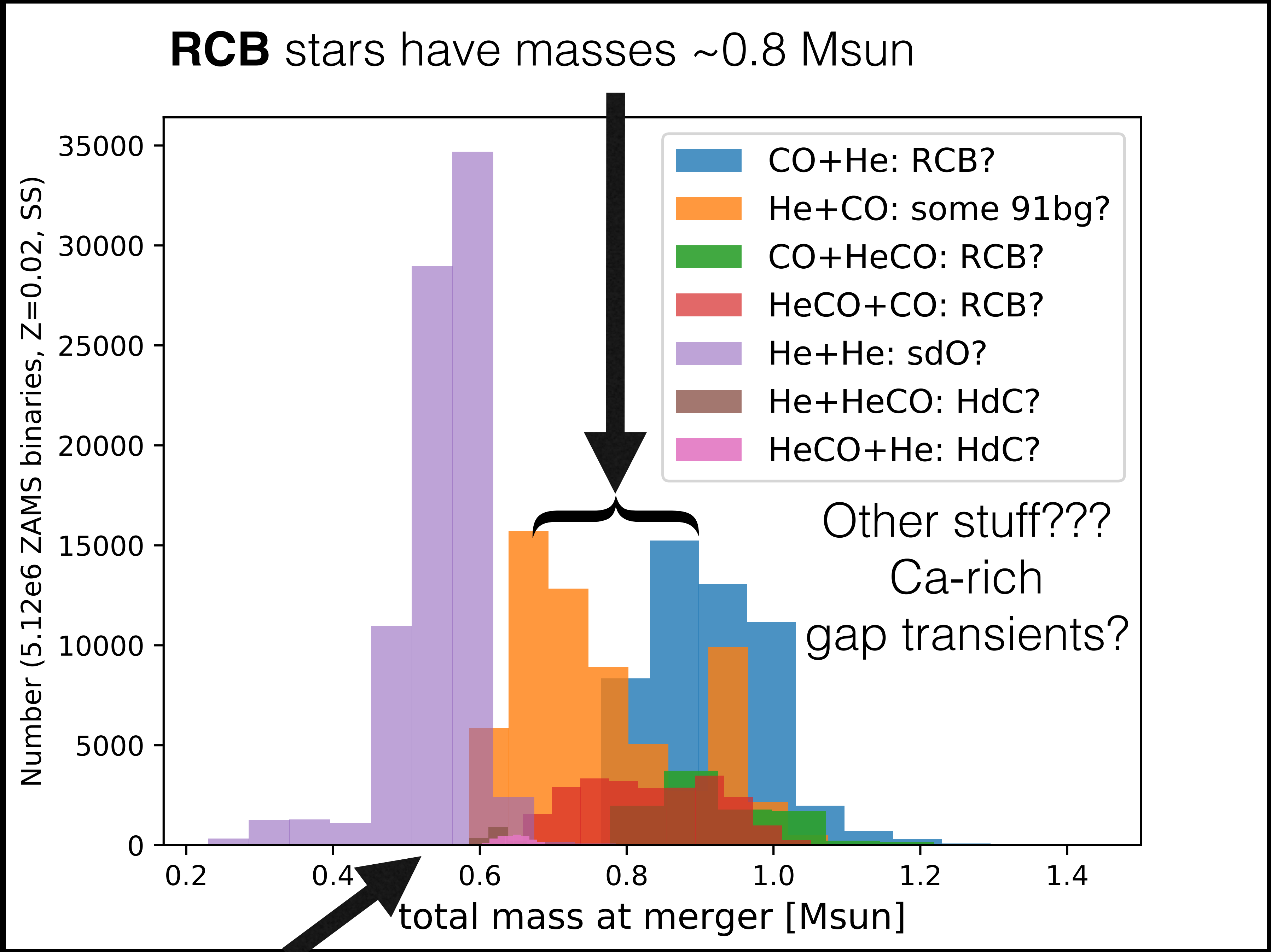
3. **CO WD** (~0.4 - 0.55 Msun) forms later after (not during) CE event on the RGB or AGB

4. WD-WD merger delay time range ~500 Myr to Hubble time after star formation.



Total mass (M1 + M2) of some WD-WD mergers

(most of these **won't make SNe Ia** but will make R Coronae Borealis, etc.)

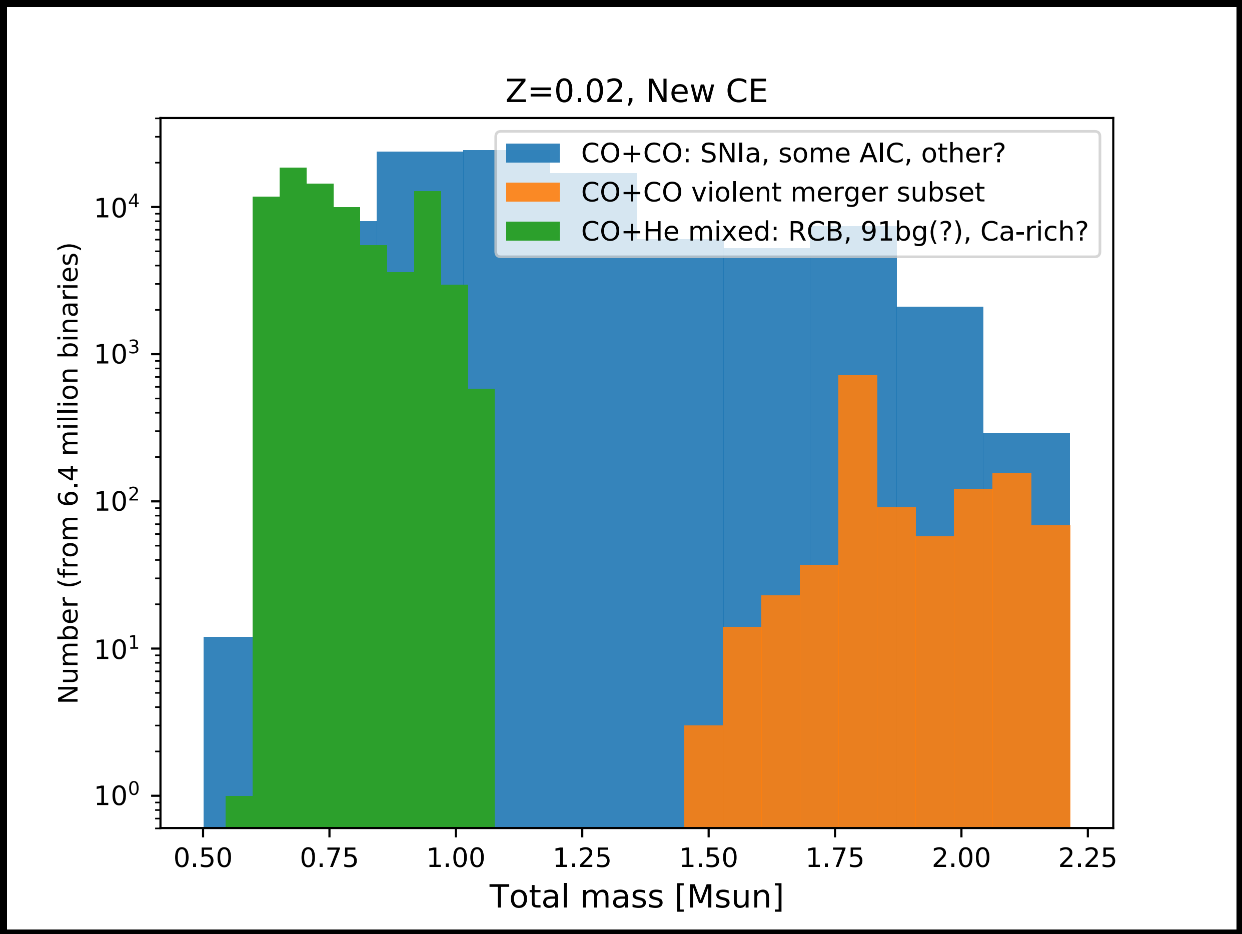


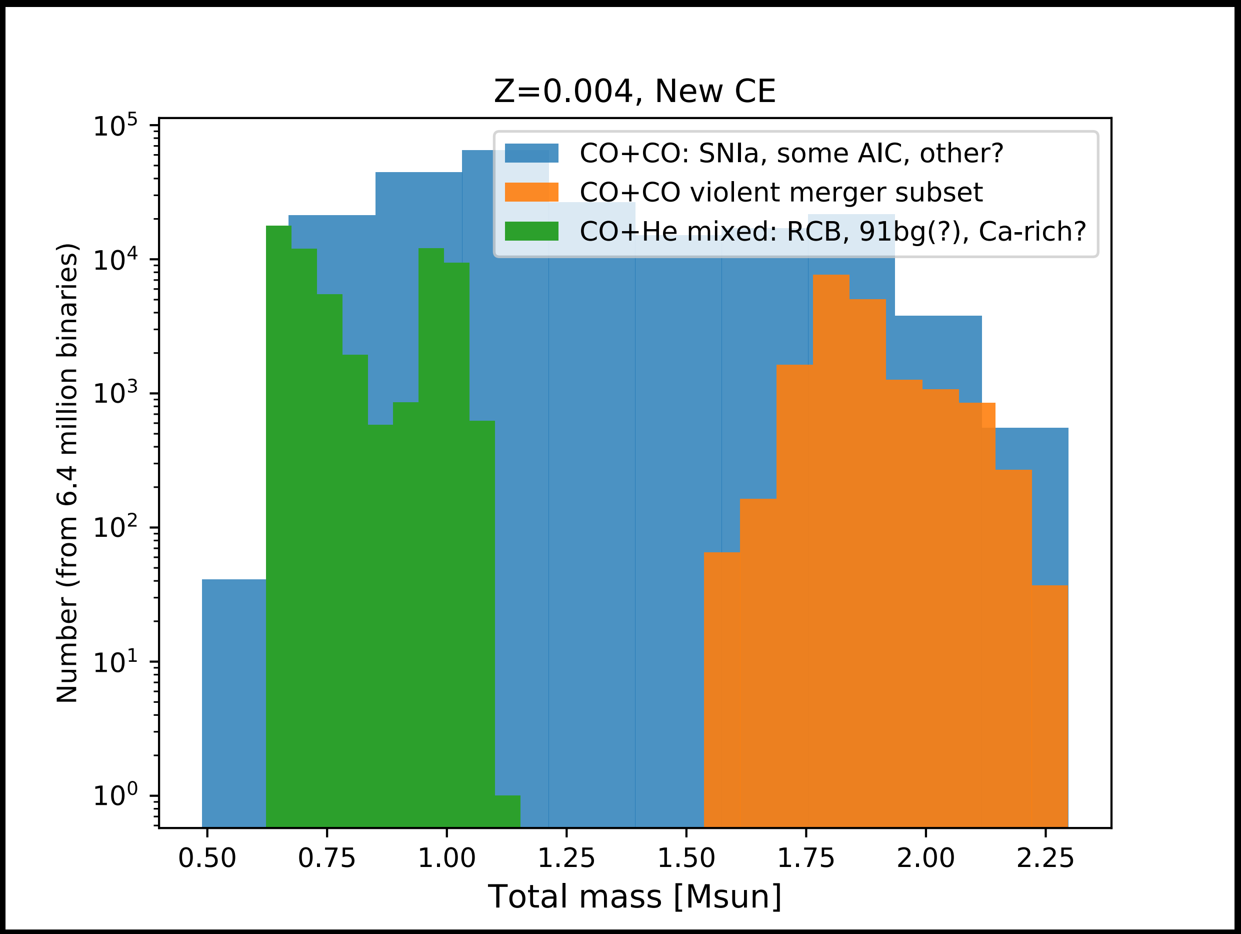
sdO stars have masses ~0.5 Msun

1991bg-like SNe, need long delay times > 2-3 Gyr; see Crocker et al. 2017, Panther et al. 2019. This would correspond to many He+CO with Mtot > 0.9 Msun

DOI: 10.5281/zenodo.1436923

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





Some "Galactic" WD merger rates:

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

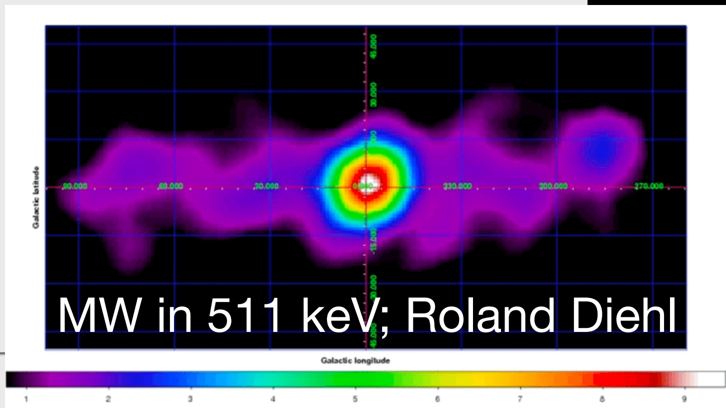
MW COCO merger rate: ~0.01/yr
(Z=0.004)

1991bg-like SNe arise from old stars. Some background:

- Some type of source with characteristic delay time of ~few Gyr is needed to explain the positron annihilation signal in the MW (511 keV gamma rays), which traces the (old) stars (see Crocker et al. 2017 for details).
- Most plausible explanation of this source is helium detonations in star systems. Normal SNe Ia delay times too short; 91bg-likes postulated to occur mostly among old stellar populations. *StarTrack* simulations show **HeCO WD mergers** could be the source (have right — late enough — delay time distribution).
- Nuclear burning of **helium** can plausibly give the amount of **titanium-44** that can explain antimatter (positron signal) in the Milky Way. (cf. Woosley et al. 1986). Ti->Sc->Ca.
- WiFeS IFU observations ~1 kpc surrounding region where 1991bg-like SN exploded (since faded) to rule out presence of young stars. Spectral synthesis modelling shows **average ages are >1-2 (nominally ~9-10) Gyr**.

SN1991bg-like supernovae are associated with old stellar populations

https://arxiv.org/abs/1904.10139



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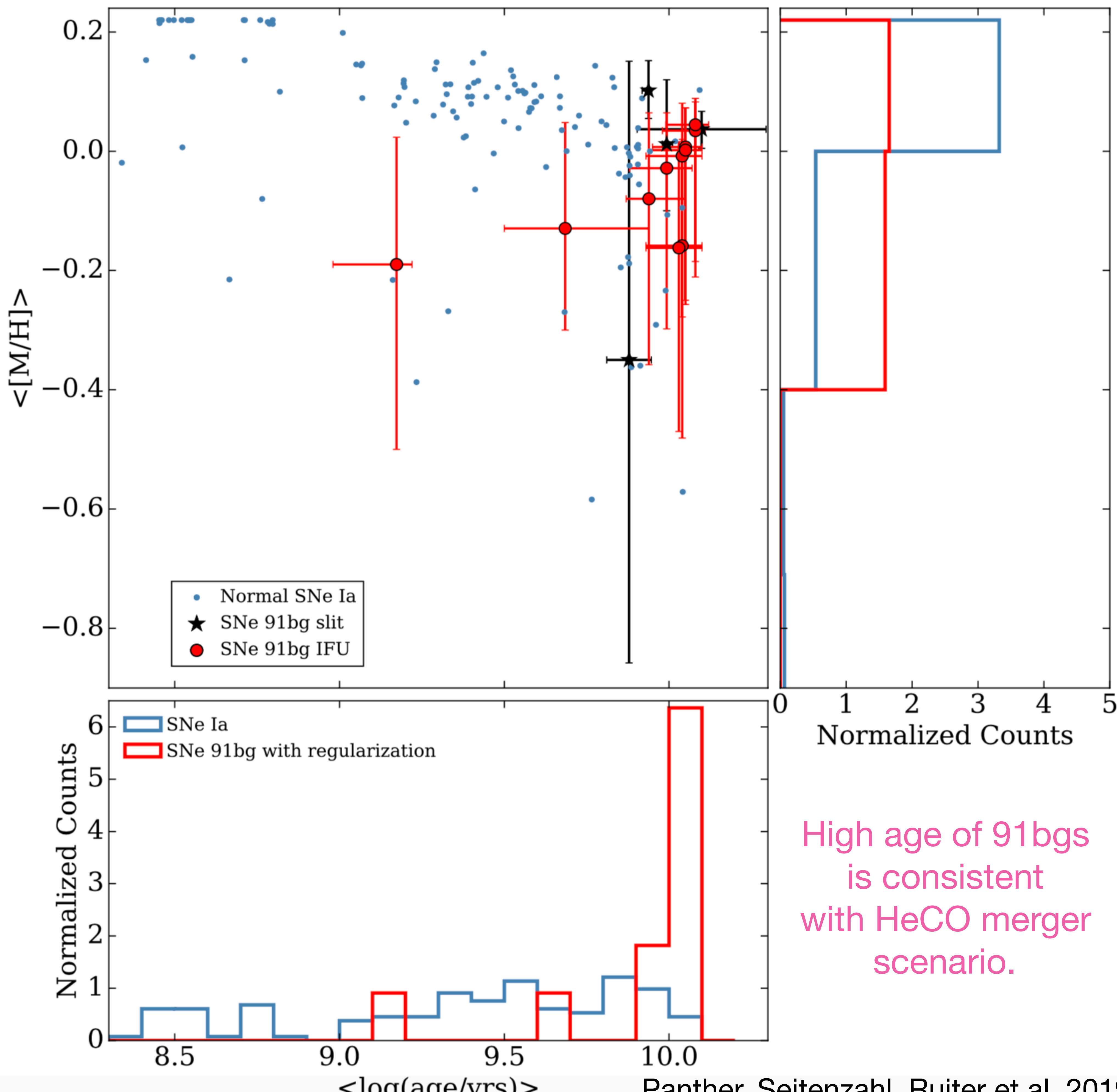

High age of 91bgs is consistent with HeCO merger scenario.

Panther, Seitenzahl, Ruiter et al. 2019

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: if both 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 <u>**may explain many `normal' SNe Ia**</u> (brightness distribution, rates pretty good, delay time too). Some **He+CO** mergers could make other thermonuclear transients such as 91bg or Ca-rich gap transients. <u>Subset of He+CO mergers have long delay times:</u> if these systems undergo helium detonations, they could explain the Galactic antimatter signal and plausibly account for the 1991bg SNe.

- Did not explore wind-accretion in this talk, but possibly this channel may contribute something at early delay times (cf. Ruiter et al. 2019).

- So which results work best? Next step is calibrating the models by comparing post-CE binary models with real post-CE binary systems.

- **Population Synthesis: <u>understanding common envelope</u> is most important for figuring out nature and origin of SN Ia progenitors (and related transients) than it is for getting rough rate predictions right (maybe that is different for heavier compact objects, though)…**

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

(note: *different 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 (SNe and novae), binary evolution, supernova remnants, and gravitational wave sources (e.g. *LISA*).**

- 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”.

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