KITP Santa Barbara
White Dwarfs from Physics to Astrophysics
November 14-17, 2022

Mergers of white dwarfs as 'failed' Type Ia supernovae

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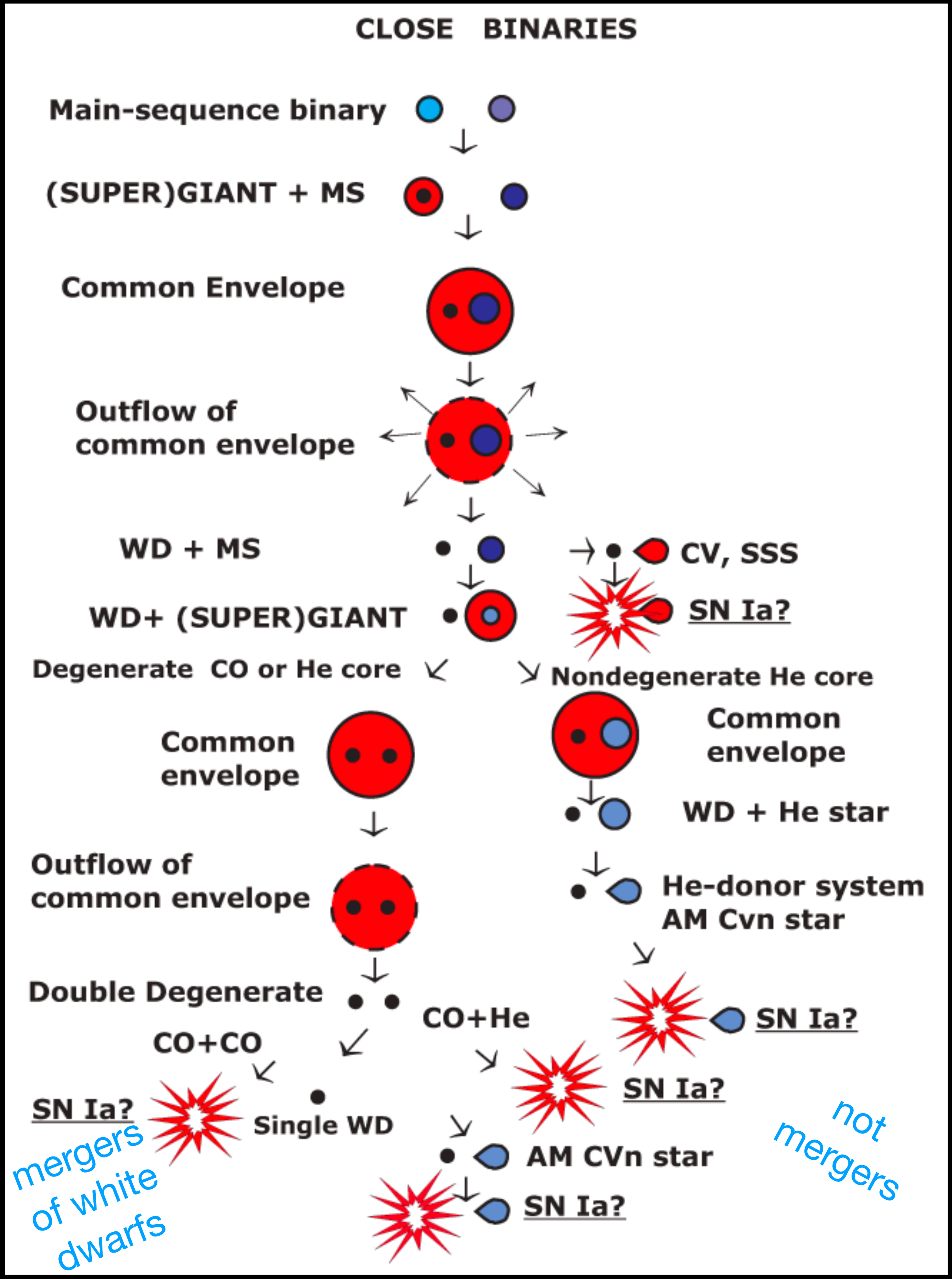
Binary star evolution leading to WDs



Left: figure shows some different formation channels that might lead to a Type Ia supernova or other transients (from Postnov and Yungelson, Living Reviews, "The Evolution of Compact Binary Star Systems").

We figure out which formation channels for various objects (i.e. transients) are viable and/or common using numerical methods, through rapid binary evolution population synthesis, or BPS.

https://www.emis.de/journals/LRG/Articles/lrr-2014-3/articlese7.html

What do double white dwarf mergers (maybe) make? Some ideas loosely based on mass:

- low-mass WDs (<0.3 Msun): Hydrogen-deficient Carbon stars (**HdC; more later in this talk!)**; hot subdwarf **sdB/O** stars, **extreme He** stars… (*are these separate channels, or part of a sequence*)?

- medium-mass WDs (~0.35 - 0.65 Msun): **R Coronae Borealis** (these are also HdC stars). Maybe some sub-luminous SNe Ia? (Crocker et al. 2017 Nat Astro). If 2 WDs merge —> WD of mass ~1.1 Msun **Single WD**s. High B field? *But what is the timescale for this to happen?* When will the WD look "normalish"? See also Kilic et al. 2022.

- higher mass WDs (>0.75 Msun): **SNe Ia** but which? "*Normal" ones*? *Weird ones? More than one subclass? (see Ruiter 2020 for short SNIa review).* Note that the exploding WD must be ~0.9 Msun or more massive to produce enough Ni-56 to "look like" a "normal" type Ia supernova (Ruiter et al. 2013, Shen et al. 2017, 2021).

- even higher mass WDs (>1.1 Msun): **merger-induced collapse** to **neutron stars**; possibly black holes (Margalit & Metzger). Sometimes called accretion-induced collapse (AIC) or merger-induced collapse (MIC) in case of WD mergers. See i.e. Brooks et al. 2017, Kashyap et al. 2018, Schwab 2021.

What are hydrogen-deficient carbon stars?

- Hydrogen-deficient (Hd) stars include a large number objects (including certain massive stars, hot subdwarfs, and WDs), but Hd carbon stars (HdC) have an under-abundance of H, and an over-abundance of carbon (between factors of a few to ~10; Warner, 1967).

- The R Coronae Borealis stars (RCB) are a probably the most well-known class of HdC stars (Clayton 1996; Jeffery 2008), with ~150 RCB stars now observationally confirmed (Tisserand et al. 2020), with likely another ~300+ lurking in the Galaxy.

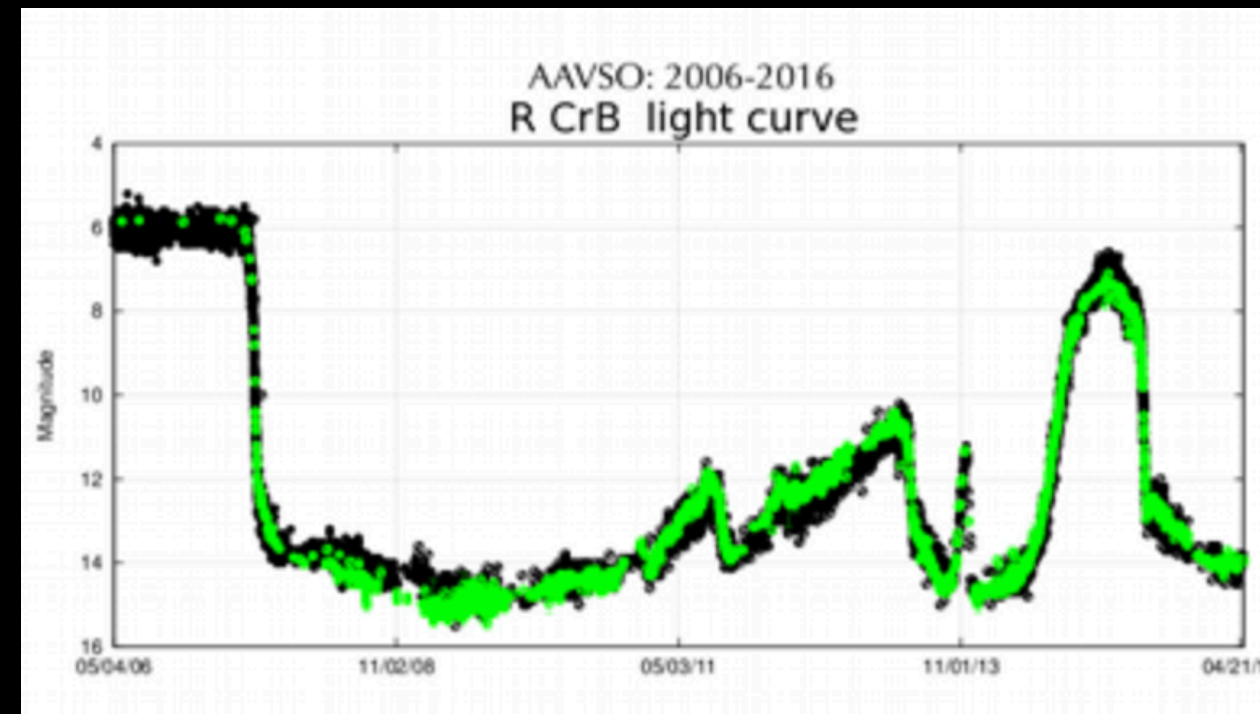
- RCB stars are thought to be the result of a merger of two WDs, likely a helium-rich WD and a CO WD (*helium-rich WDs are only created in binaries).*

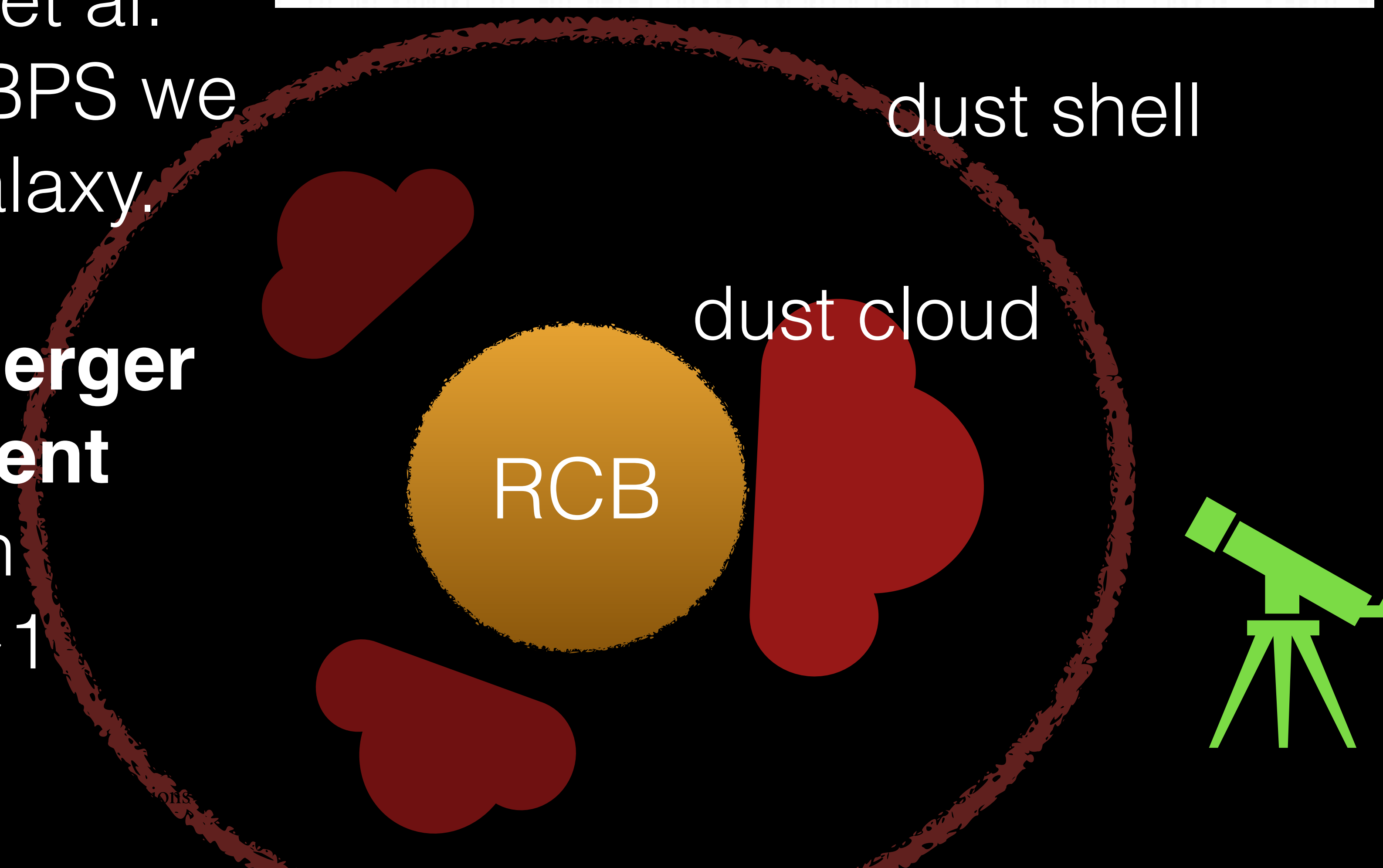
R Coronae Borealis stars

- H-deficient, C-rich, dusty supergiants that pulsate seemingly randomly (can vary by 9 mags). SED catalogue by Montiel, Clayton+ 2019.

- ~150 known (Tisserand et al. 2018, 2020). Based on BPS we expect up to ~500 in Galaxy.

- The most likely origin: **merger of two hydrogen-deficient objects (WDs)**. Oxygen abundances:16O/18O ~1 (Sun is ~500).





‘Dustless’ HdC stars: another class of HdC star

- RCBs produce a lot of dust (see also Karakas, Ruiter, & Hampel 2015). But there is another class of low-mass HdC star that are without dust shells. Until now, only 4 of these “dustless” HdC stars were known (since the 60s)! See also Saio & Jeffery (2002).

- A campaign was launched to uncover more (fainter) ’dustless’ HdC stars. *The result:* **27 of them** were found through Gaia eDR3 + 2MASS and WiFeS spectroscopic follow-up. Typical M_V ~-2 to -4.

- They are called dLHdC (dust-Less Hydrogen-deficient Carbon stars).

- dLHdC stars have a Galactic bulge-like distribution (like RCB stars), but they are less luminous and have no (very little) dust.

The dawn of a new era for dustless HdC stars with GAIA eDR3 ⋆

P. Tisserand[1], C. L. Crawford[2], G. C. Clayton[2], A. J. Ruiter[3], V. Karambelkar[5], M. S. Bessell[4], I. R. Seitenzahl[3], M. M. Kasliwal[5], J. Soon[4], T. Travouillon[4],

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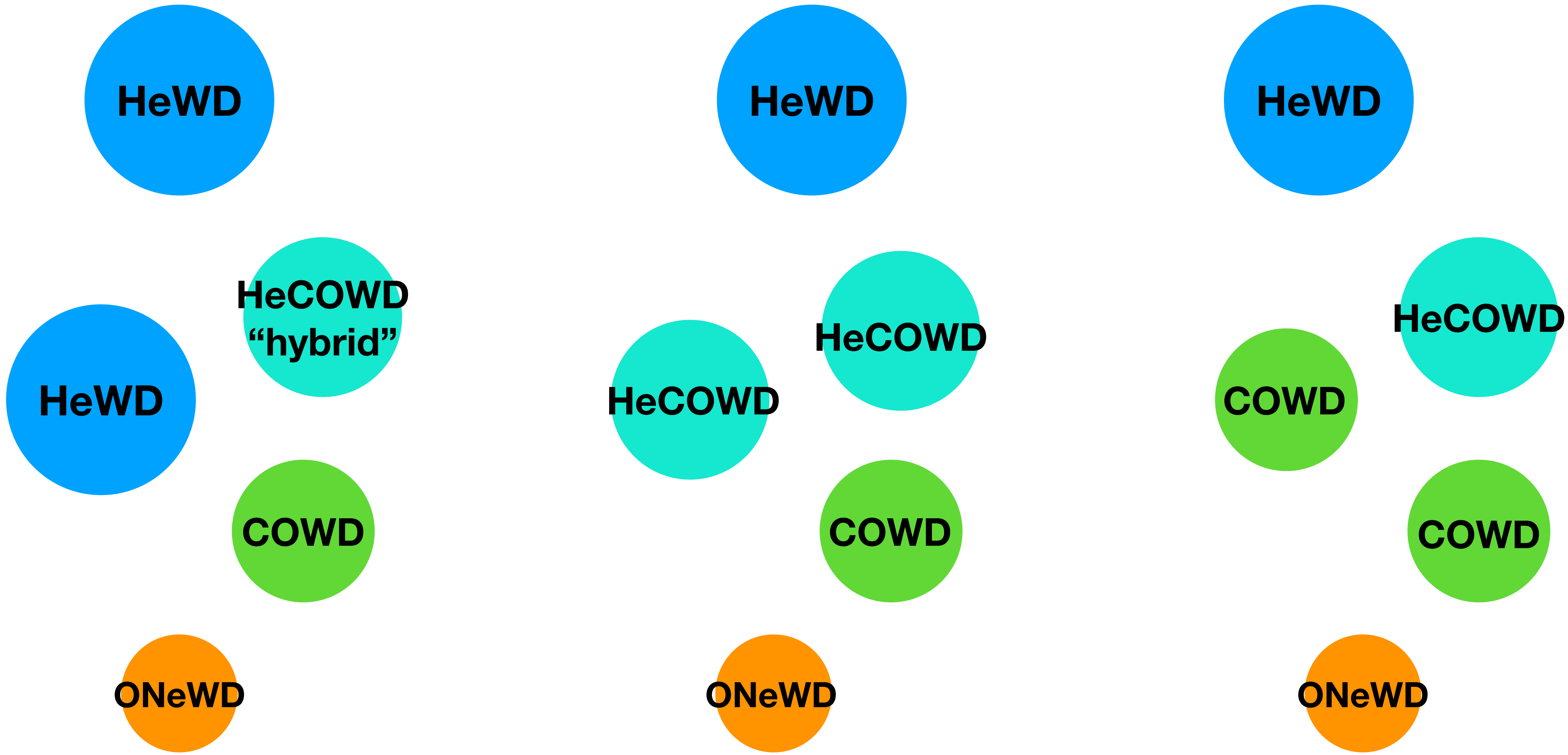
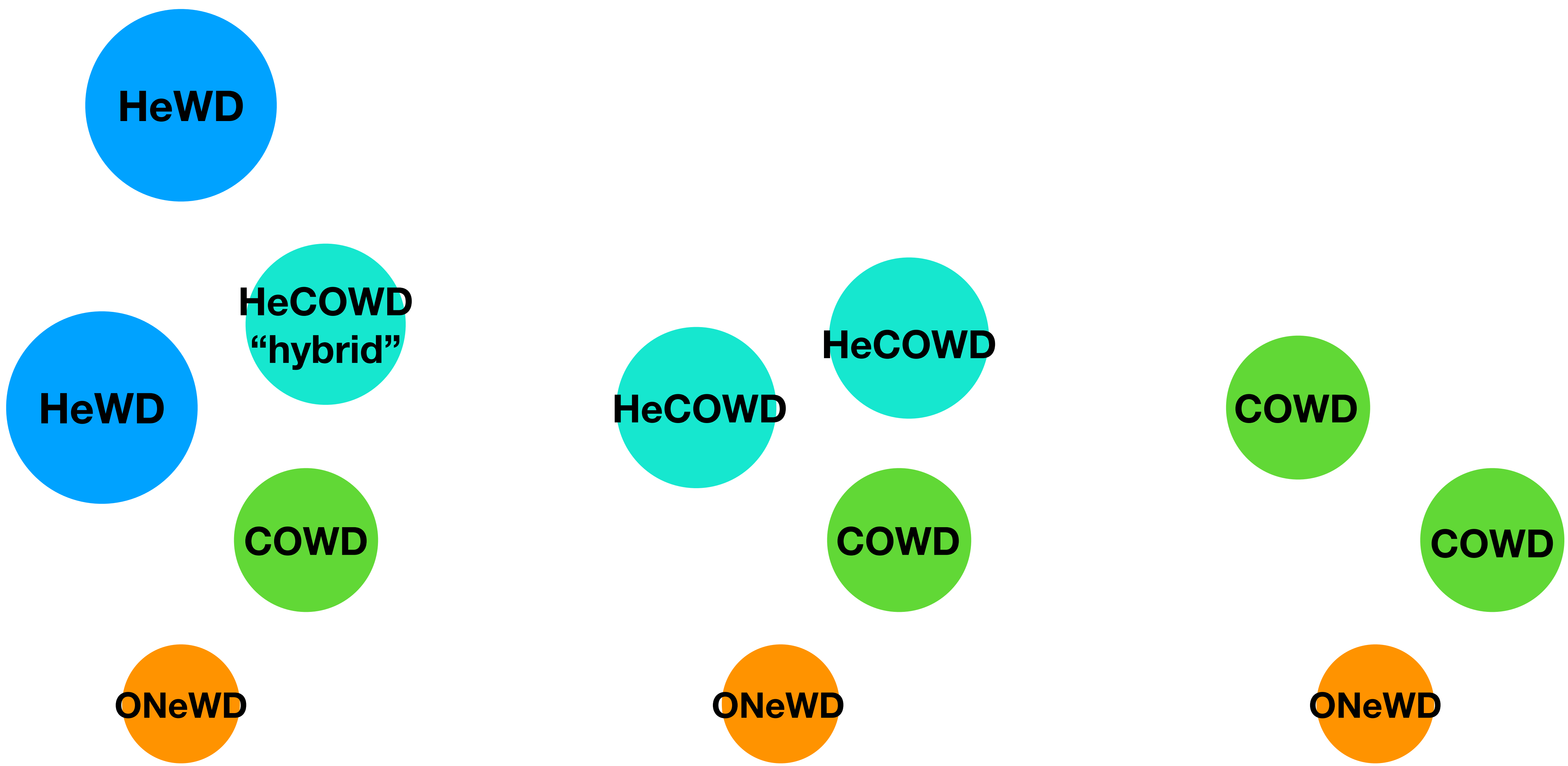
What are (some of) the different WD merger types (channels)?

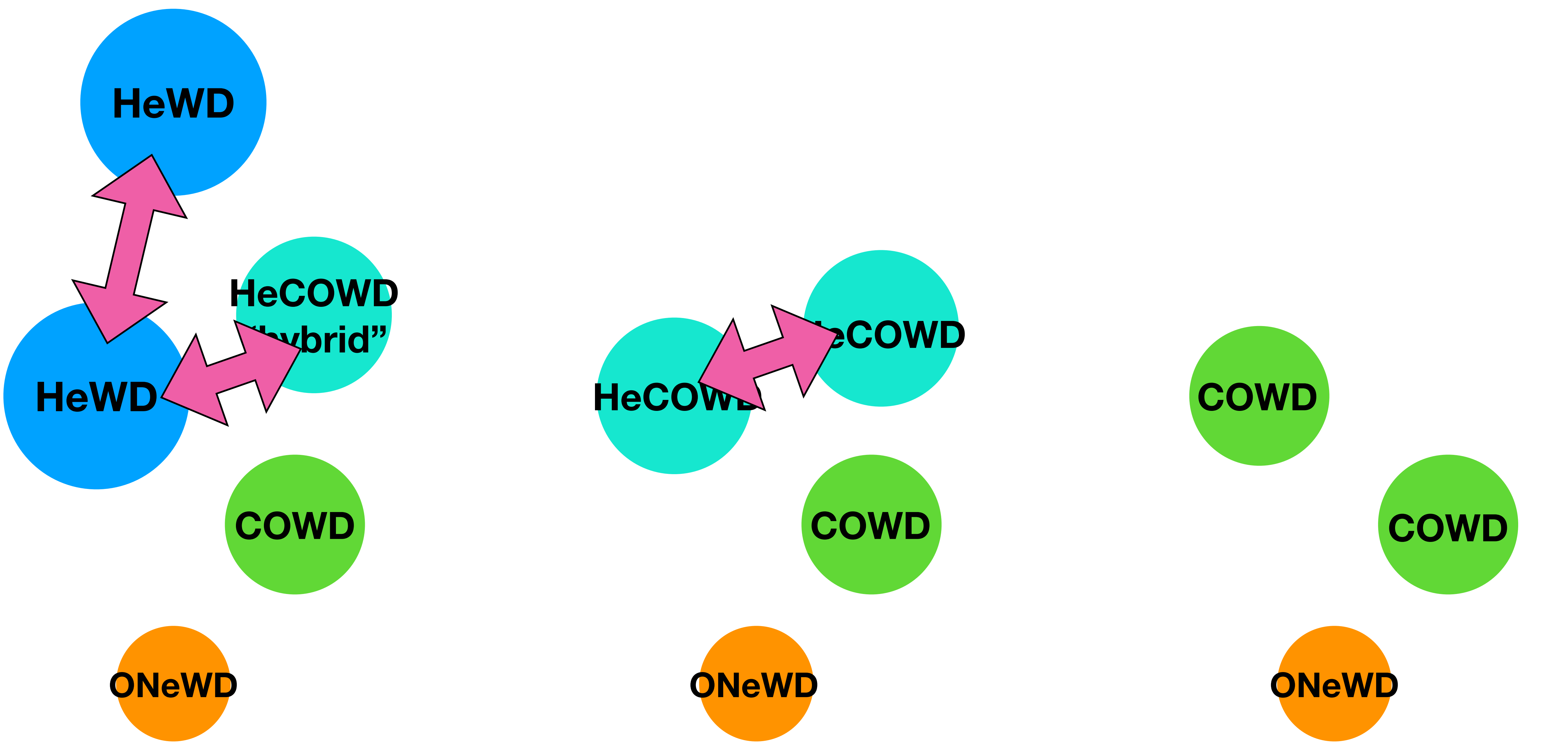
Left one merges with something on the right.



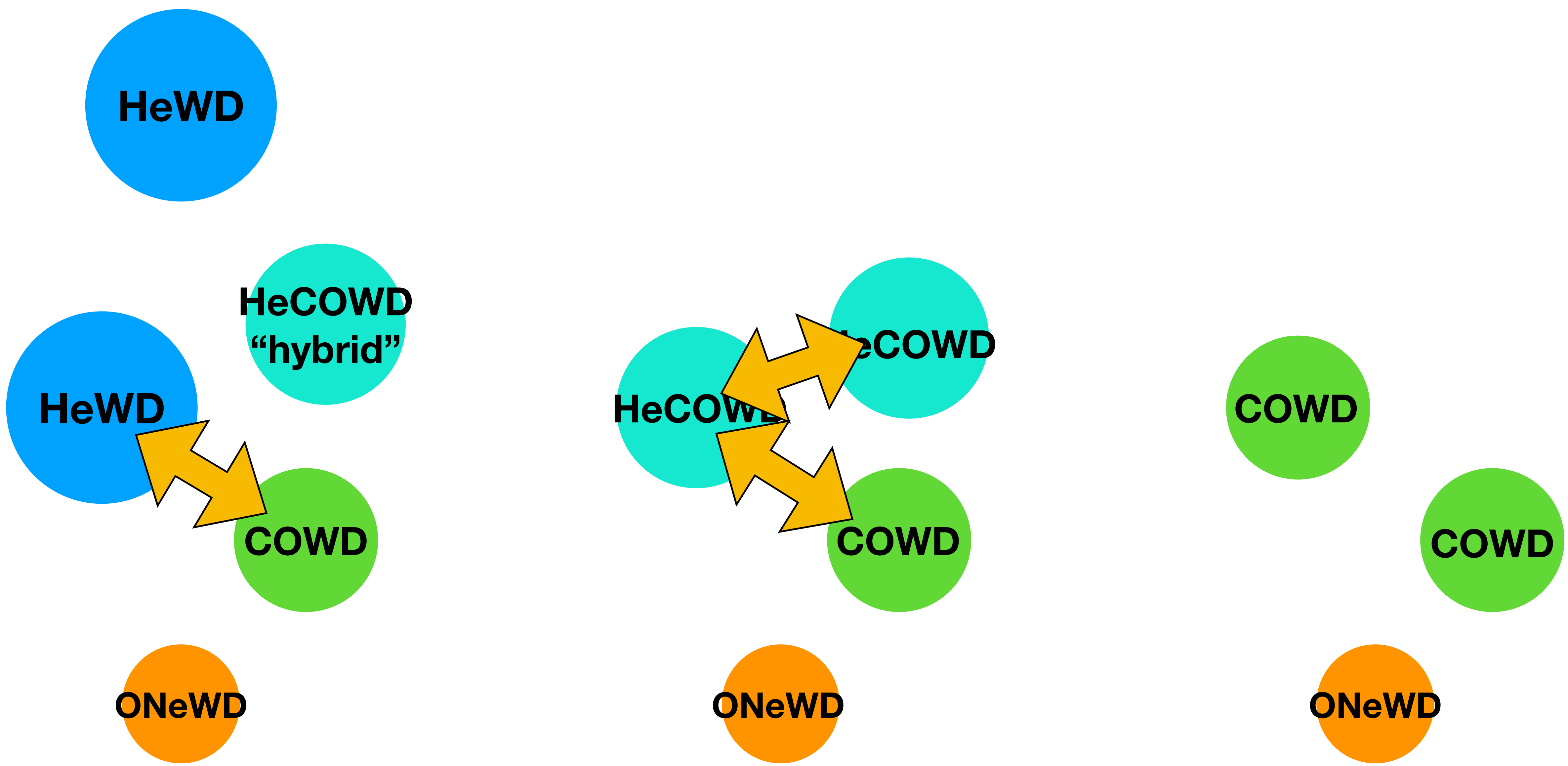
Let’s take away the ‘degenerate degenerates’



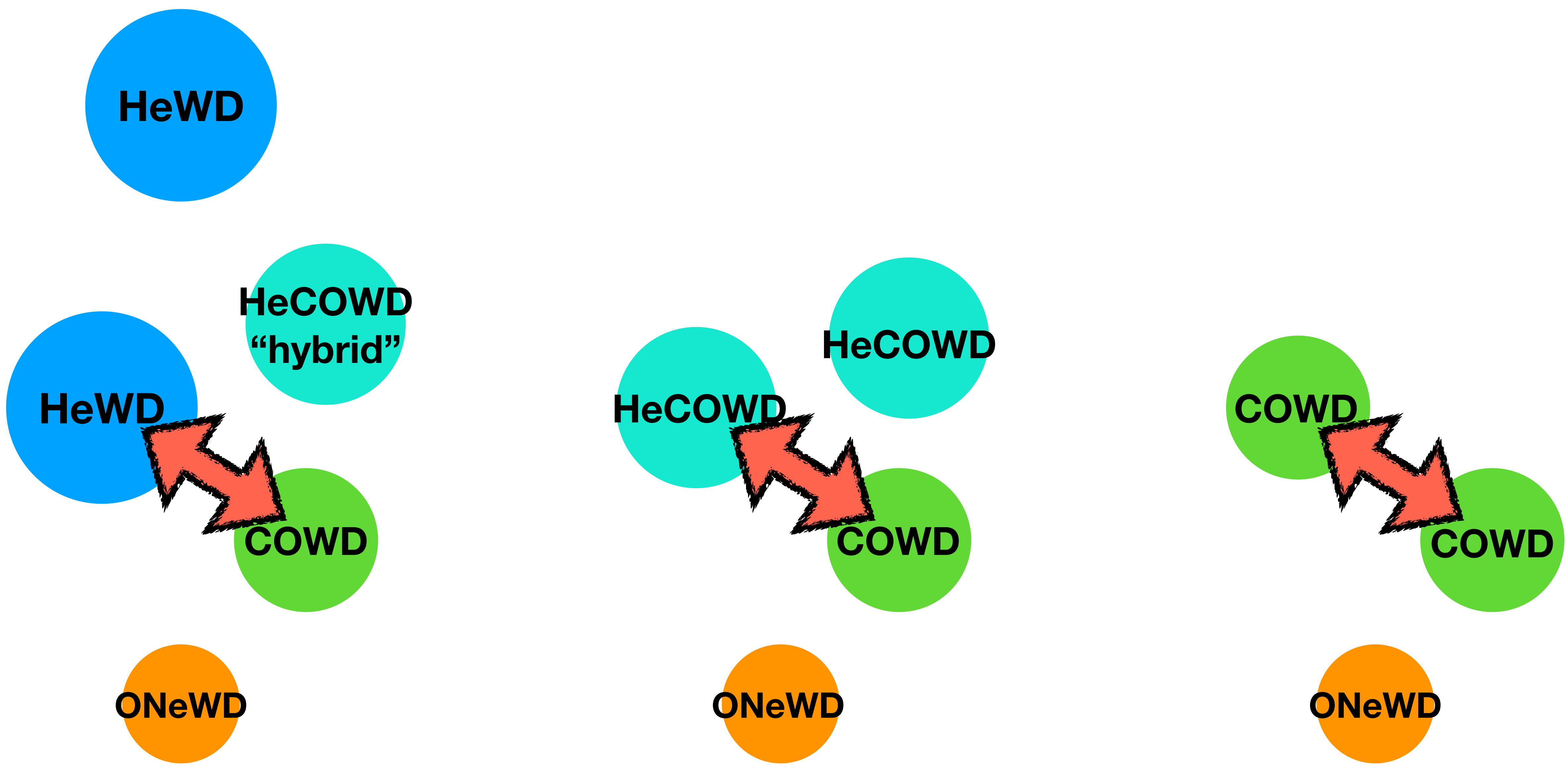
What may make some of the subdwarf population (sdB, sdO), probably more…



What may make the HdC stars (RCB and ‘dustless’ HdC stars) —> ignition of helium shell in accreted envelope during WD merger leads to a supergiant-like appearance (and usually dust, except those ~31 ‘dustless’ ones, which are fainter).



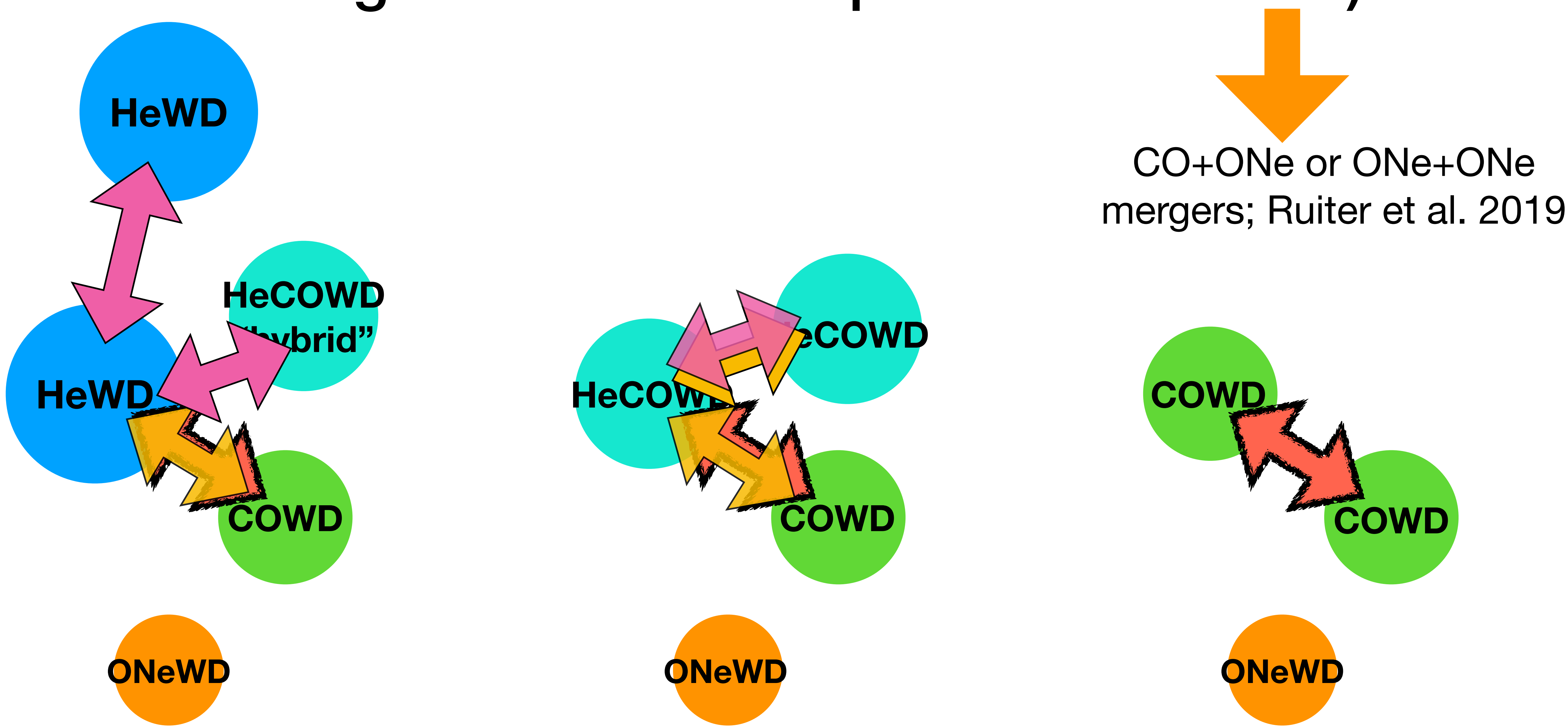
What might actually explode in a thermonuclear (SN type Ia-like) explosion?
Probably need a CO WD (maybe possible with ONe-rich WD? See Marquardt et al. 2015) with mass ~1 Msun or higher for a 'normal' SN Ia.



Putting them all together:

Some combos can probably make a lot of stuff 🧐

(still haven't touched on extreme helium stars, rapidly-spinning and/or highly magnetic WDs, or merger-induced collapse neutron stars).



What WD mergers may produce (M1 vs M2)

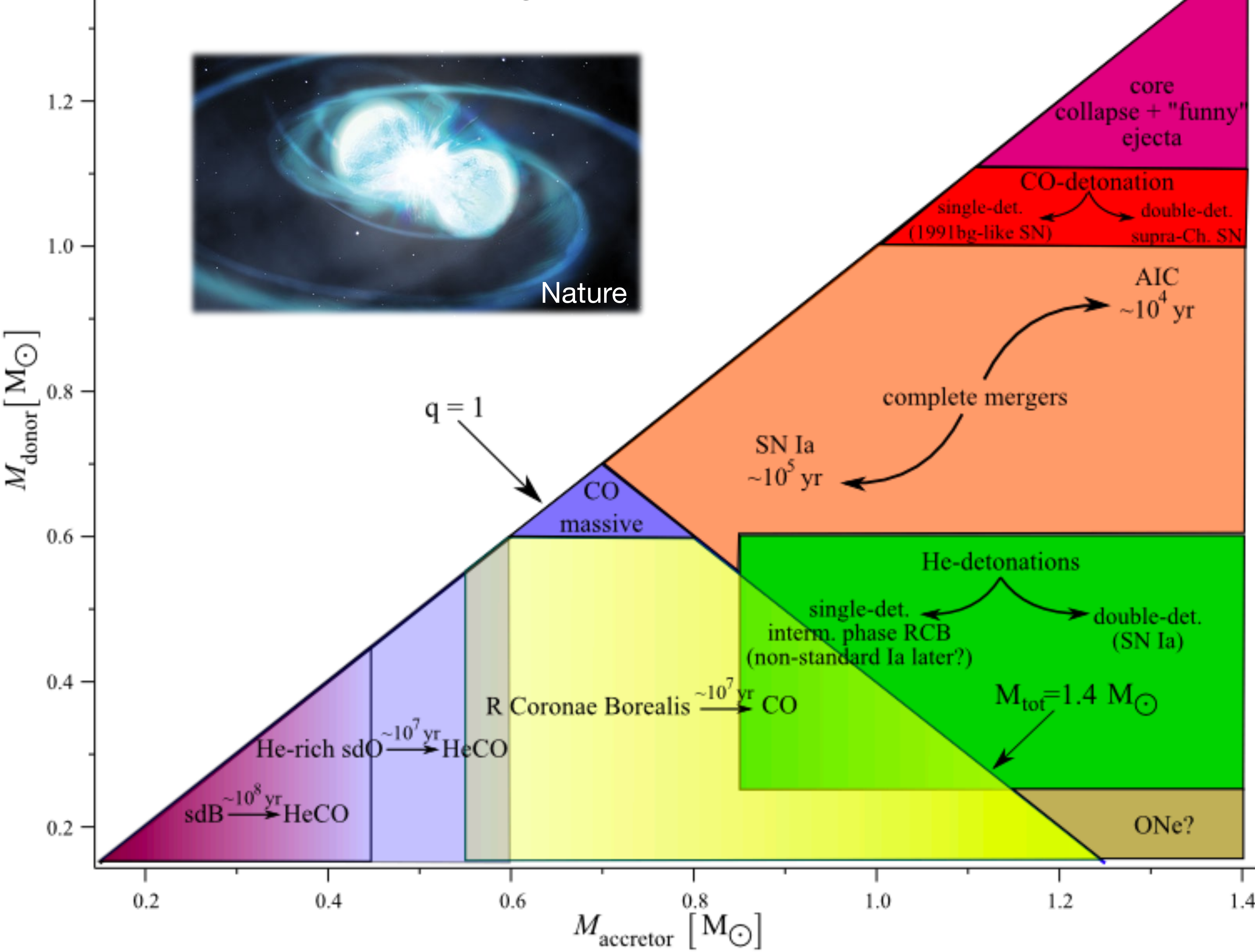


Figure by Marius Dan, courtesy of Patrick Tisserand

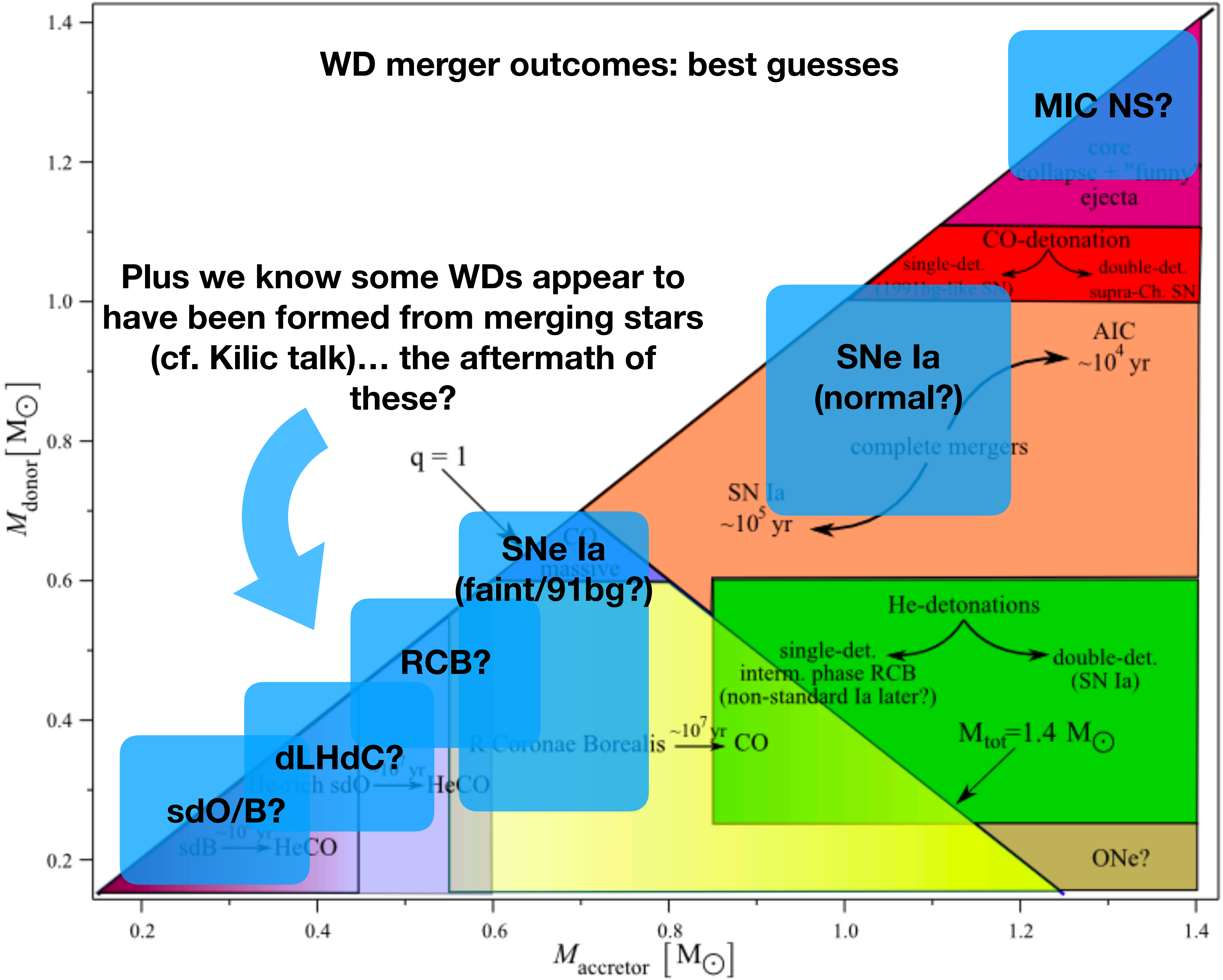
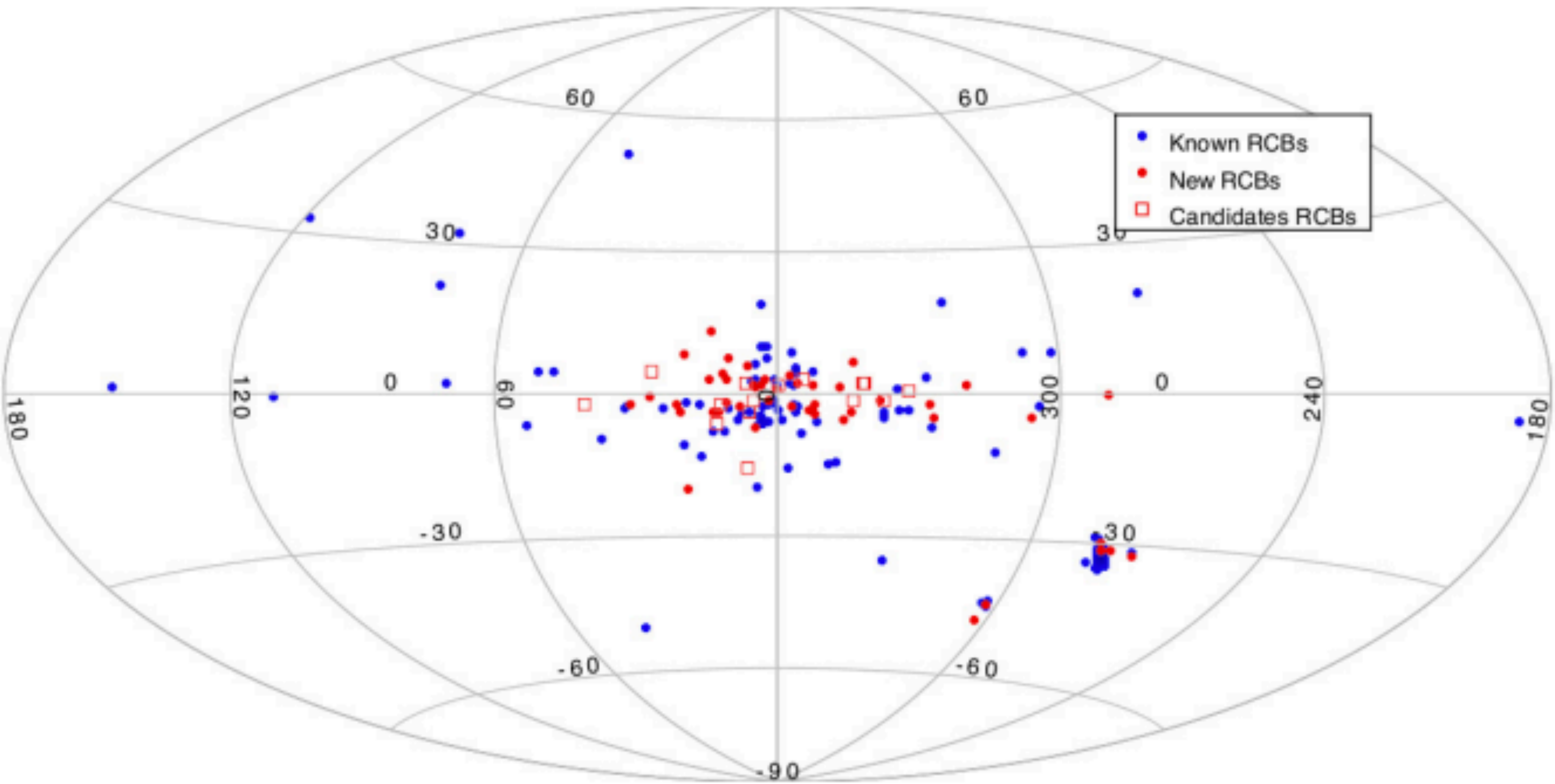
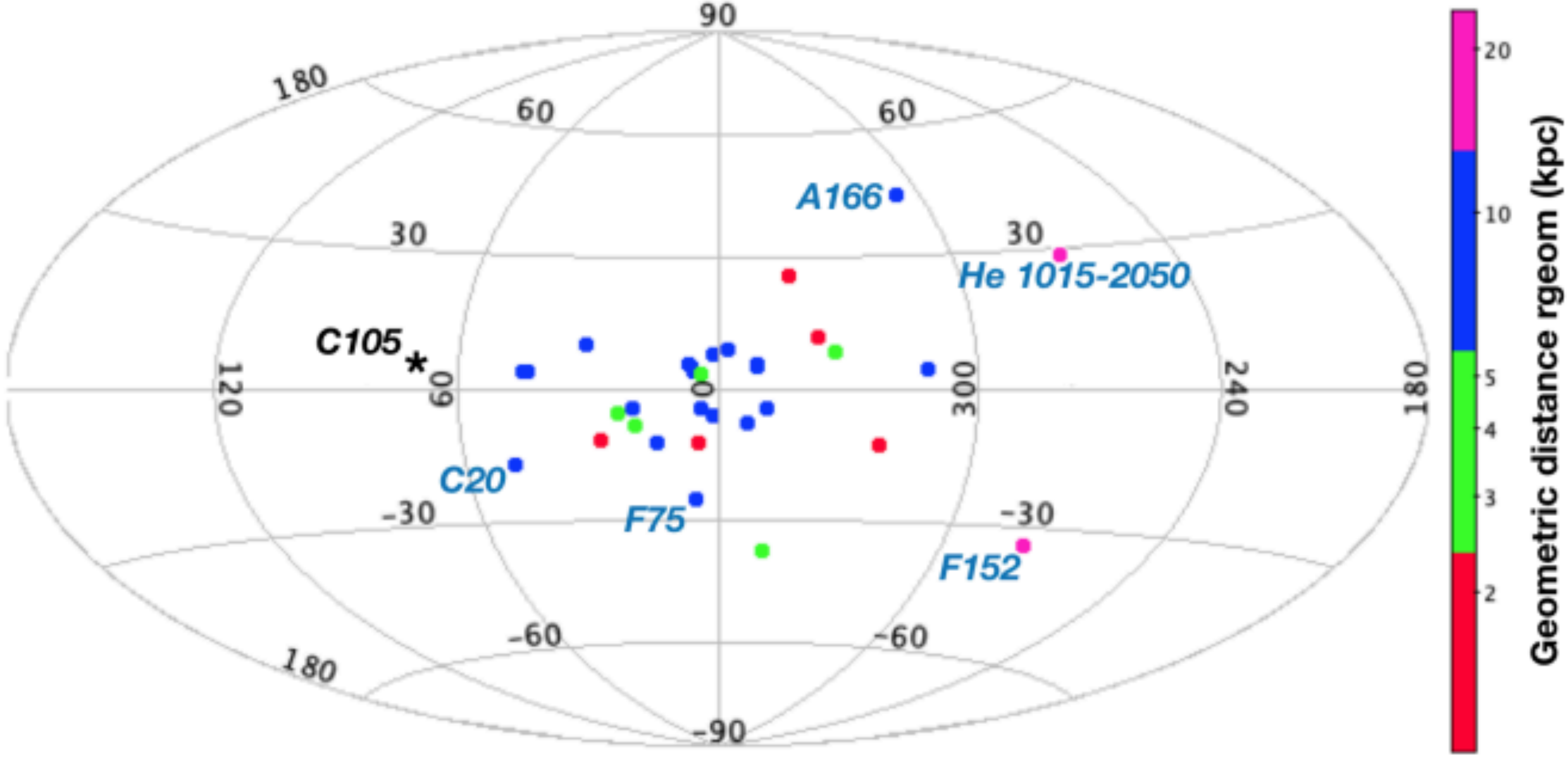


Figure by Marius Dan, modified by AJR

Galactic distribution of RCB stars from Tisserand et al. 2020: highly concentrated around the bulge (but also in the Magellanic Clouds)





Galactic distribution of **dLHdC stars** (most in bulge, some in halo). To weed out candidates, searched spectra for absence of CH band, weak or absent Balmer lines, and made comparison to other HdC (e.g. RCB) stars to confirm the HdC class (see 3.2 of paper).

Theoretical story…

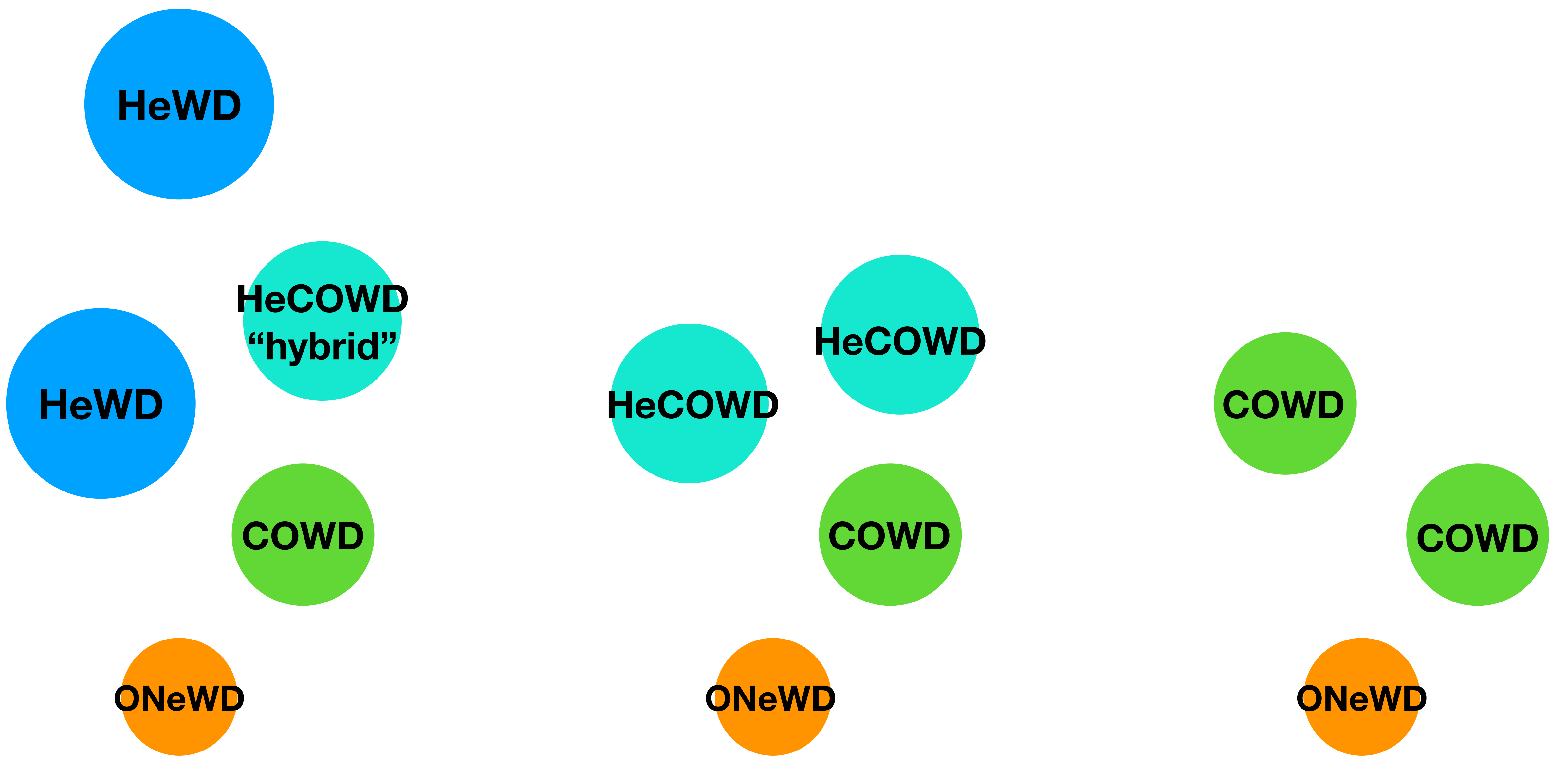
What is the origin of HdC stars?
(RCB, and dustless HdC, versions)

- Saio & Jeffery (2002) proposed that HdC stars (extreme helium stars in general) are formed via the merger of a HeWD + COWD (see also Webbink 1984, Iben & Tutukov 1984, Clayton 2012). SJ02 propose that the maximum luminosity post-merger will scale with the total mass. This could vary between ~2 mag for a total merger mass of 0.6 vs. 0.9 Msun.

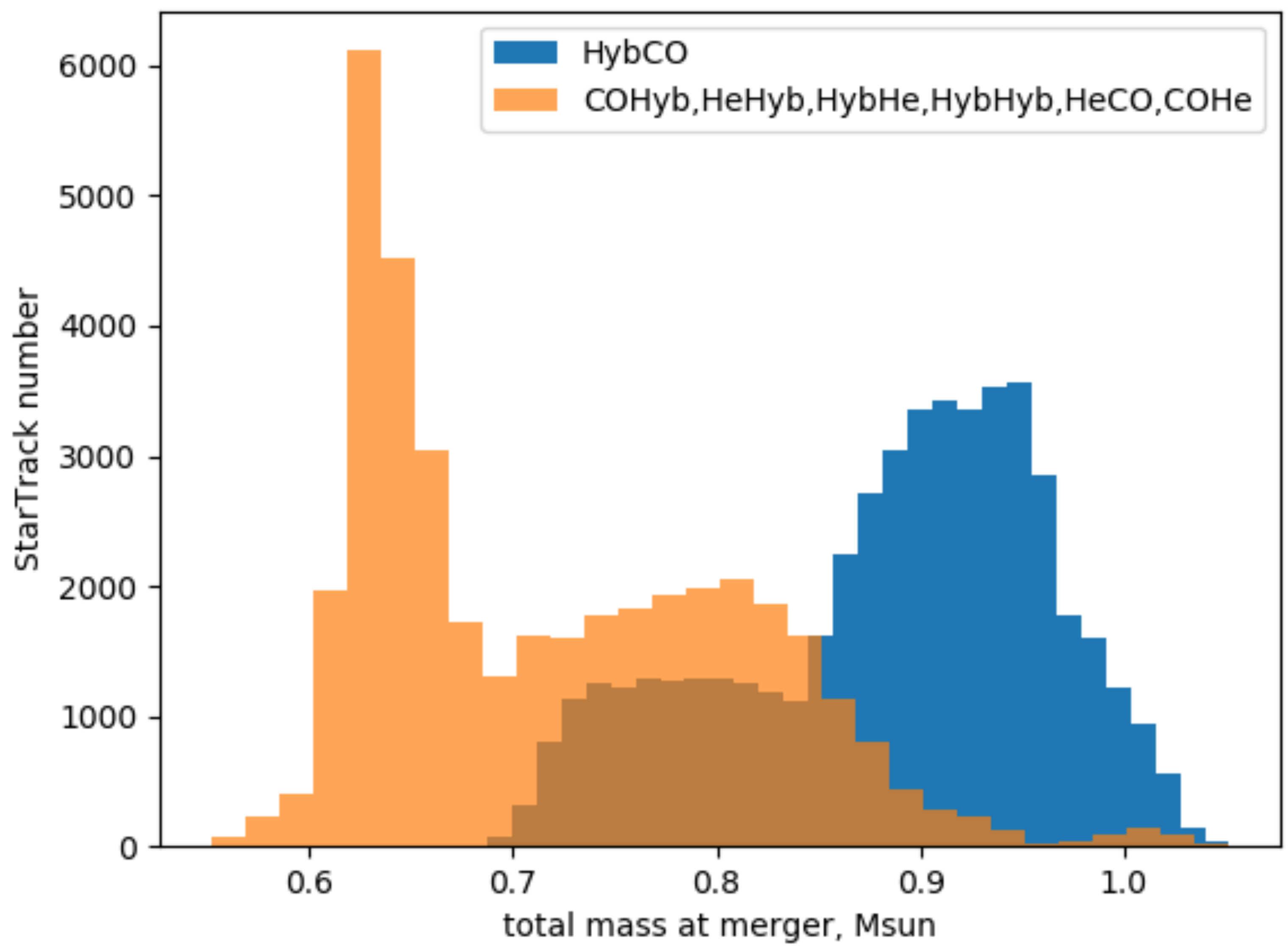
- How might these stars form? Are they part of the RCB evolutionary sequence? Or a different 'channel' altogether?

- Look at some He-rich WD + CO WD mergers with binary population synthesis…

What may make the HdC stars (RCB in particular)

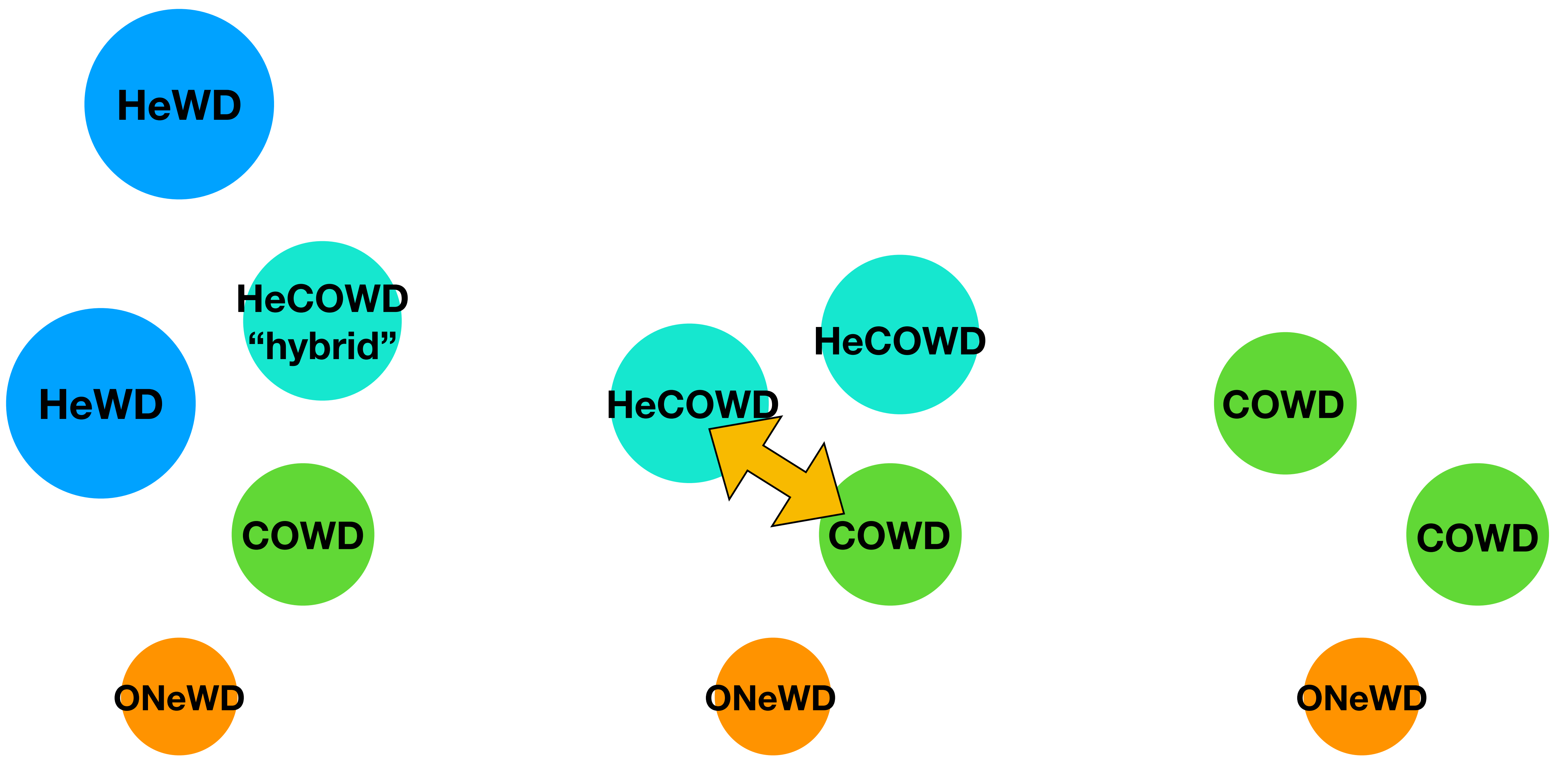


WD mergers with StarTrack: grouped by formation channel (number vs. mass of WDs at time of merger).



Showing HybCO channel (**syntax**: first-formed WD is hybrid HeCO) separated out (similar to fig. in Tisserand et al. 2022)

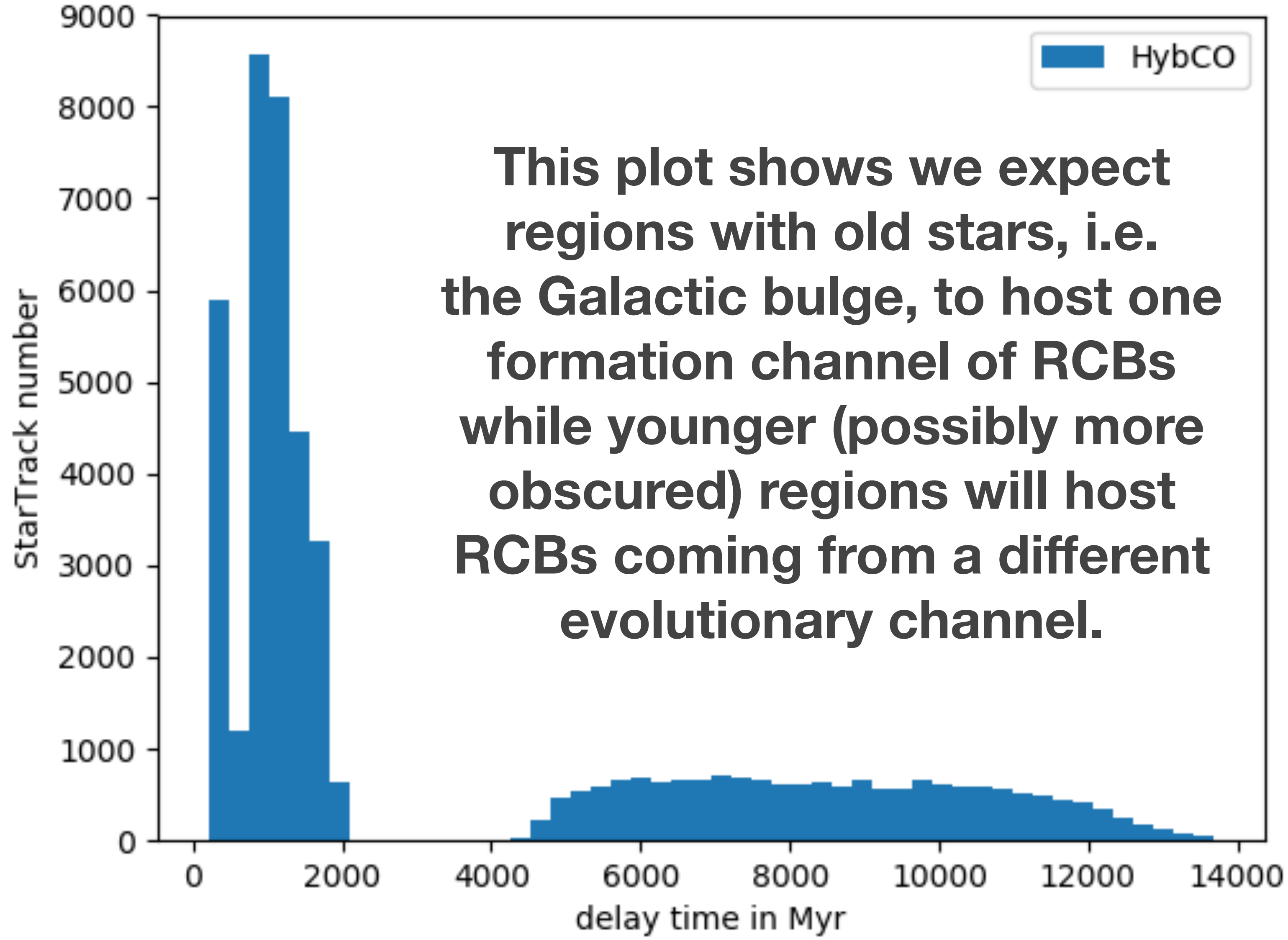
What may make the HdC stars (RCB and ‘dustless’ HdC stars) —> Showing channel from blue histogram.



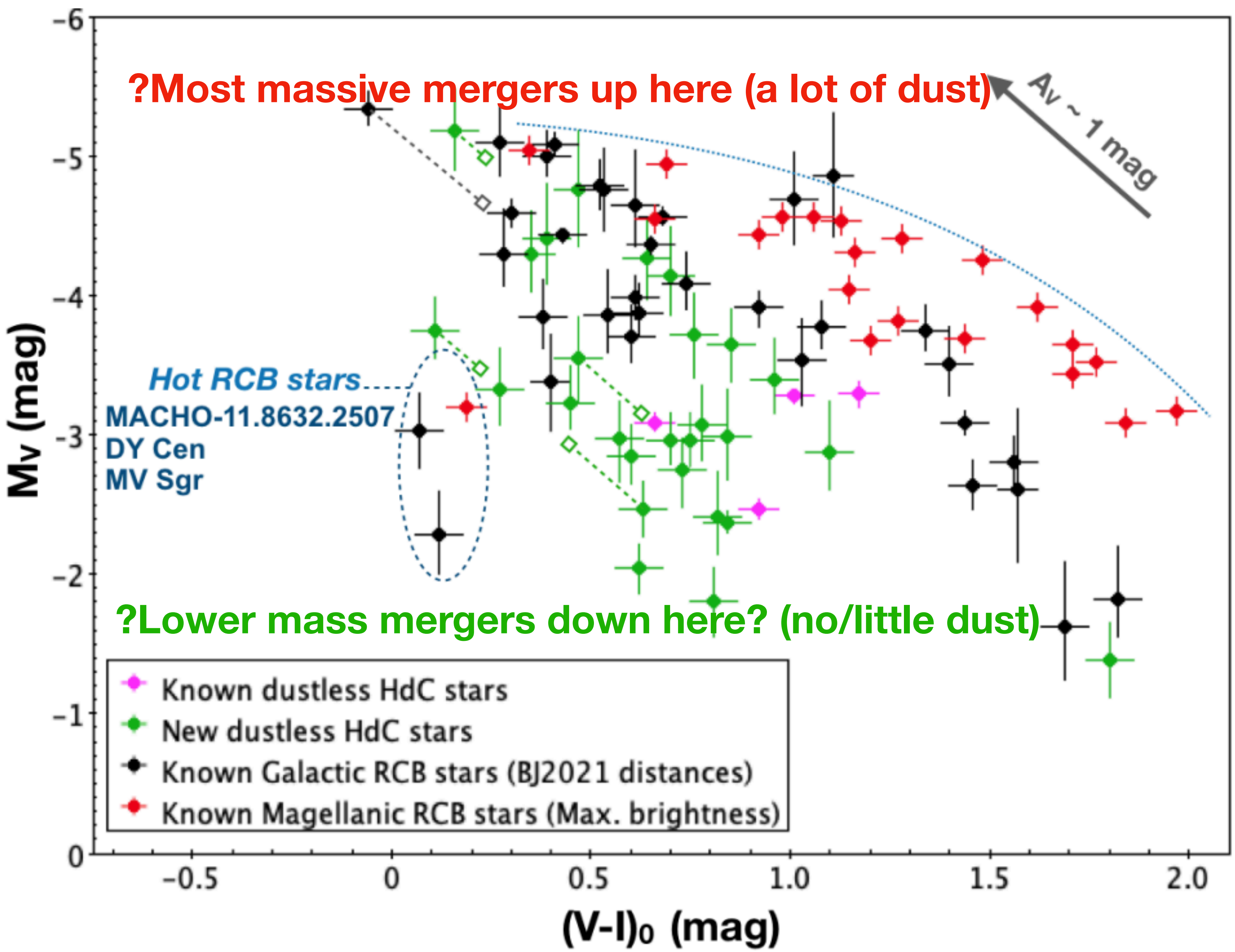
Theoretical delay times of HeCO+CO white dwarf mergers

The variable (R Coronae Borealis) phase that follows should last ~10,000 - 100,000 years.

Short DTD systems could easily be found in the LMC, SMC, or MW disc.
Long DTD systems are likely to be found in the bulge or halo.



DTD (delay time distribution) of “Hybrid” HeCOWD +COWD mergers (StarTrack BPS code). Clearly bi-model (or maybe trimodal!?)



Magellanic cold RCB stars are brighter.

Summary - WD mergers - delineation of outcomes: still a way to go… *LISA* should help

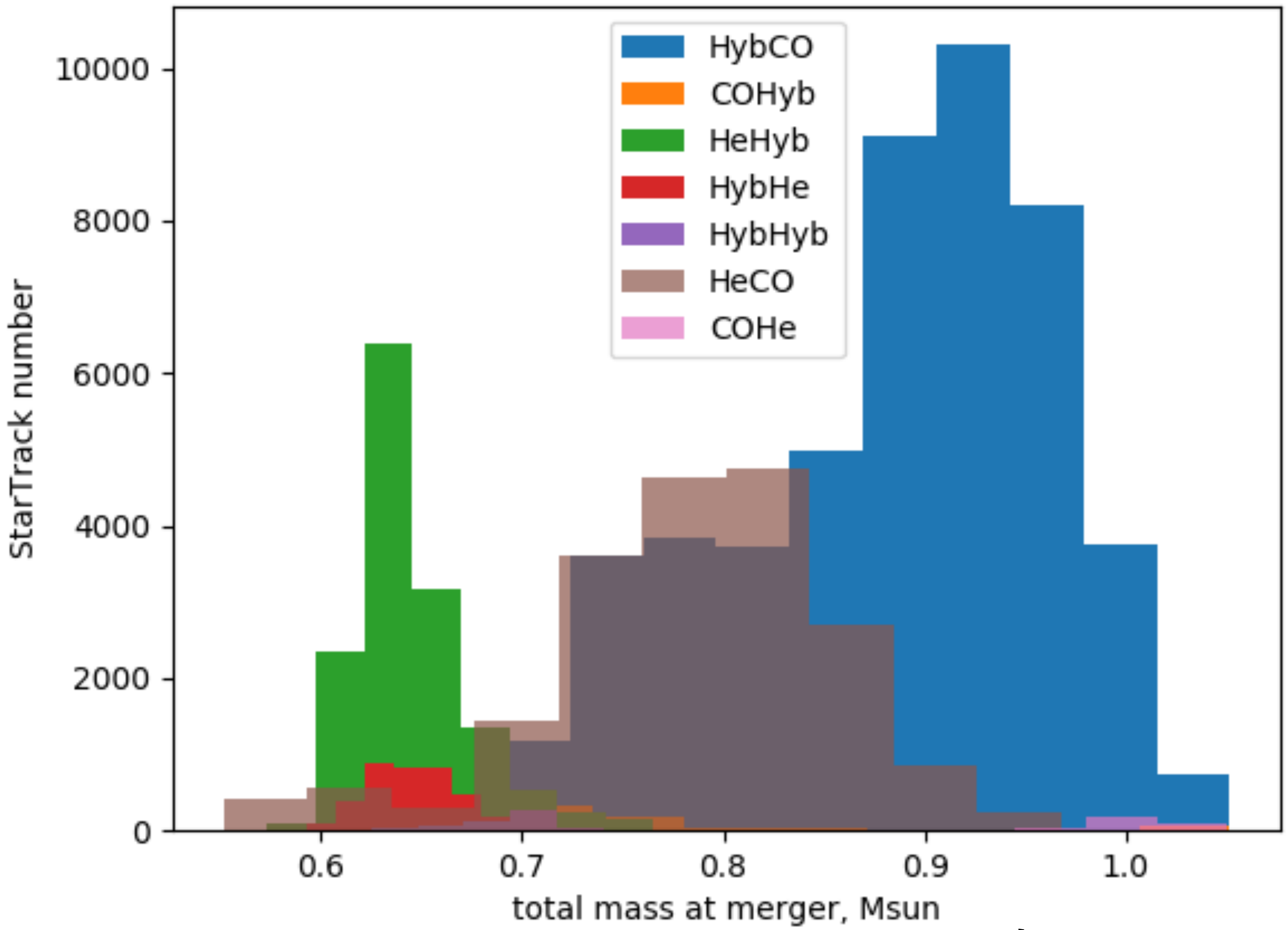
- **HeCO 'hybrid' +CO WD mergers:** Plausibly the main channel to make **H-deficient carbon stars (RCB ones that are dusty).**

- Our recent study (Tisserand, Crawford, Clayton, et al. 2022) shows a promising relationship between WD merger mass and maximum brightness, and ability to produce dust. But actually, a lot is still unclear! 🫠

- Using the above logic, the He+CO WD mergers (which have slightly lower merger mass) could be responsible for the fainter, dustless HdC stars (dLHdC observed population that is growing; green dots in prev slide).

- Next slide: channels broken down further.

Total merger mass of various double WDs
(from StarTrack BPS code). *HybCO 'channel' is most common*.
Could these Hybrid-COHe + CO mergers be the RCB stars?
HeCO maybe the dLHdC (dustless HdC) stars?



Not plotted: CO+CO and heavier!

Solar Z: many groups

Typical formation channel of HeWD+COWD merger

- 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 - could lead to formation of a hydrogen-deficient carbon star.

1. ZAMS masses ~1.3 - 2.5 Msun

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

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

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.