Hydrogen Deficient Carbon-Rich (HdC) Supergiant Stars

Tracing their Atmospheres Rich in ^{18}O to their White Dwarf Merger Origin

No exoplanets were ever found around such type of stars !

Patrick Tisserand *(IAP, Paris)* & Advait Mehla *(Caltech)*

Collaborators: Courtney Crawford, Geoff Clayton, Jamie Soon, Ashley Ruiter, Viraj Karambelkar, Mansi Kasliwal, ..

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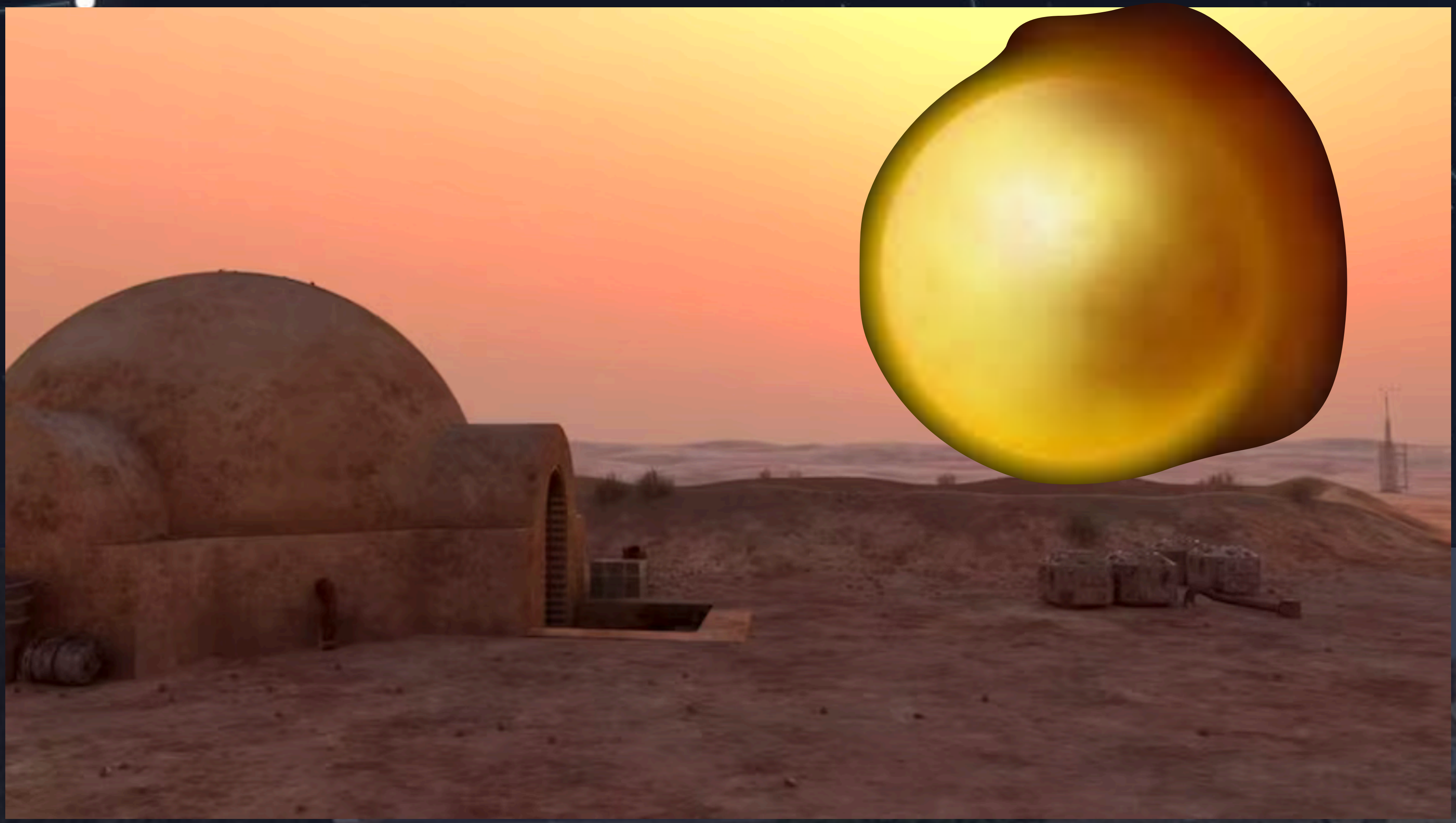

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"The Kiss" by Gustave Klimt (1907)

Plan:

- Summary of what we know !
  - Expectation from Simu: Evolution and Pop. Synth.
  - HdC stars from observations
  - RCB stars
- Oxygen Isotopic ratios $^{16}O/^{18}O$ in HdC stars
  - Mehla et al. (2025) : IR High-res spectroscopy
  - $^{16}O/^{18}O$ and the masses of the WD system

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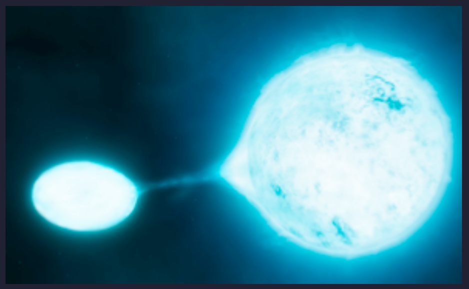
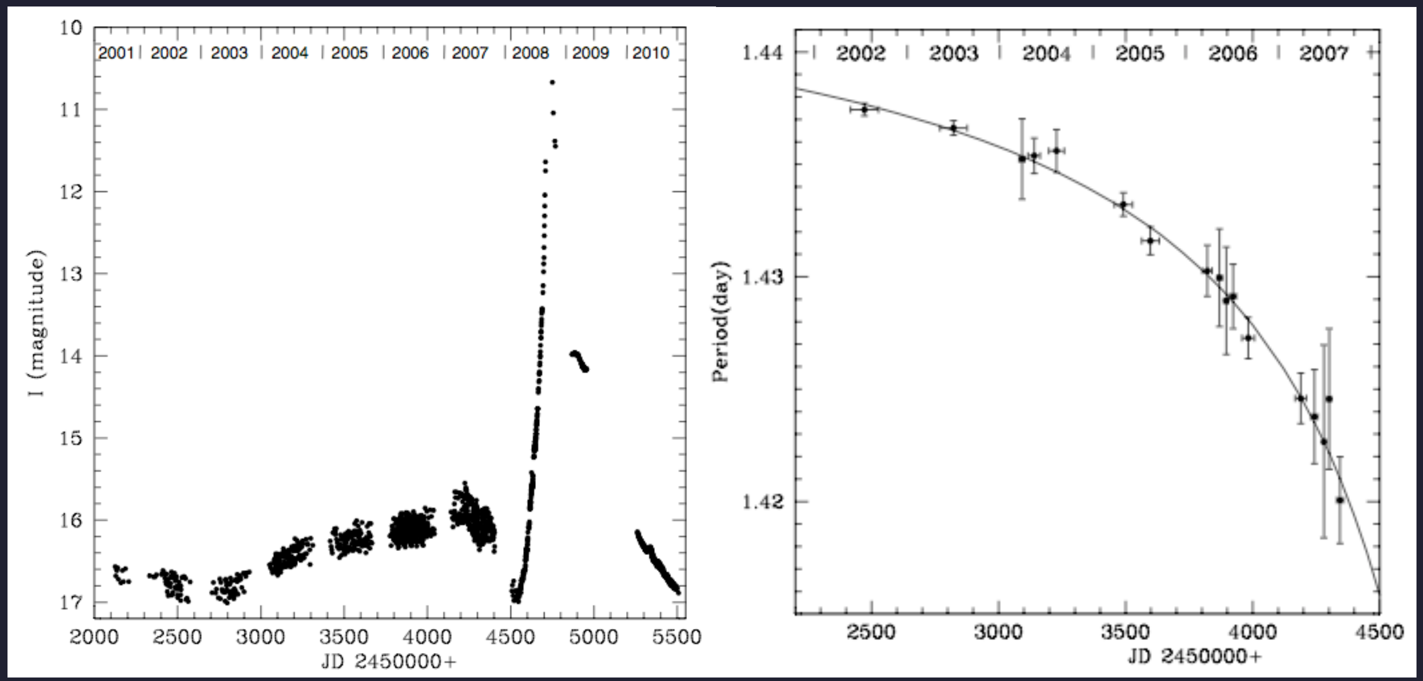
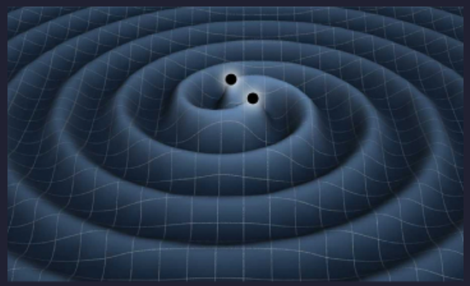
Mergers exist !

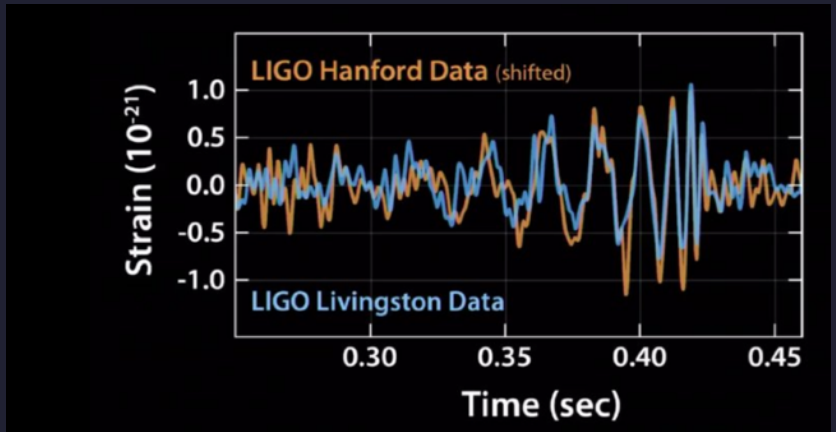


OGLE discovery: V1309 Sco *Tylenda et al., 2011*

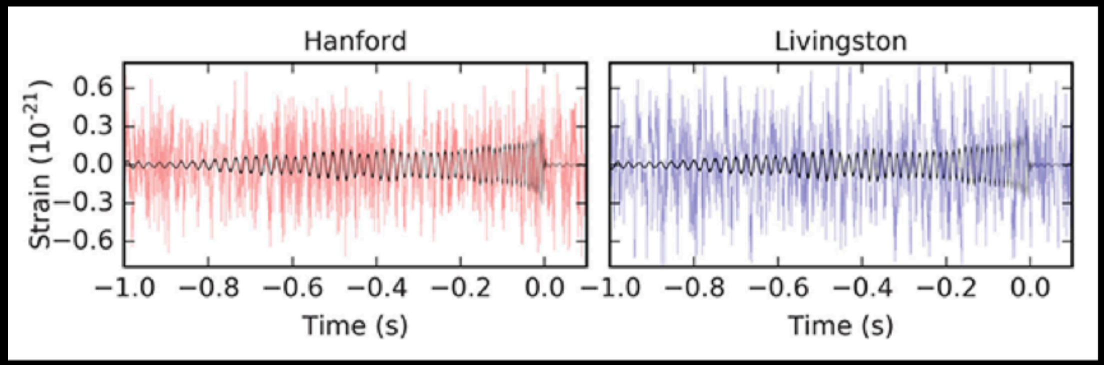


Gravitational Waves





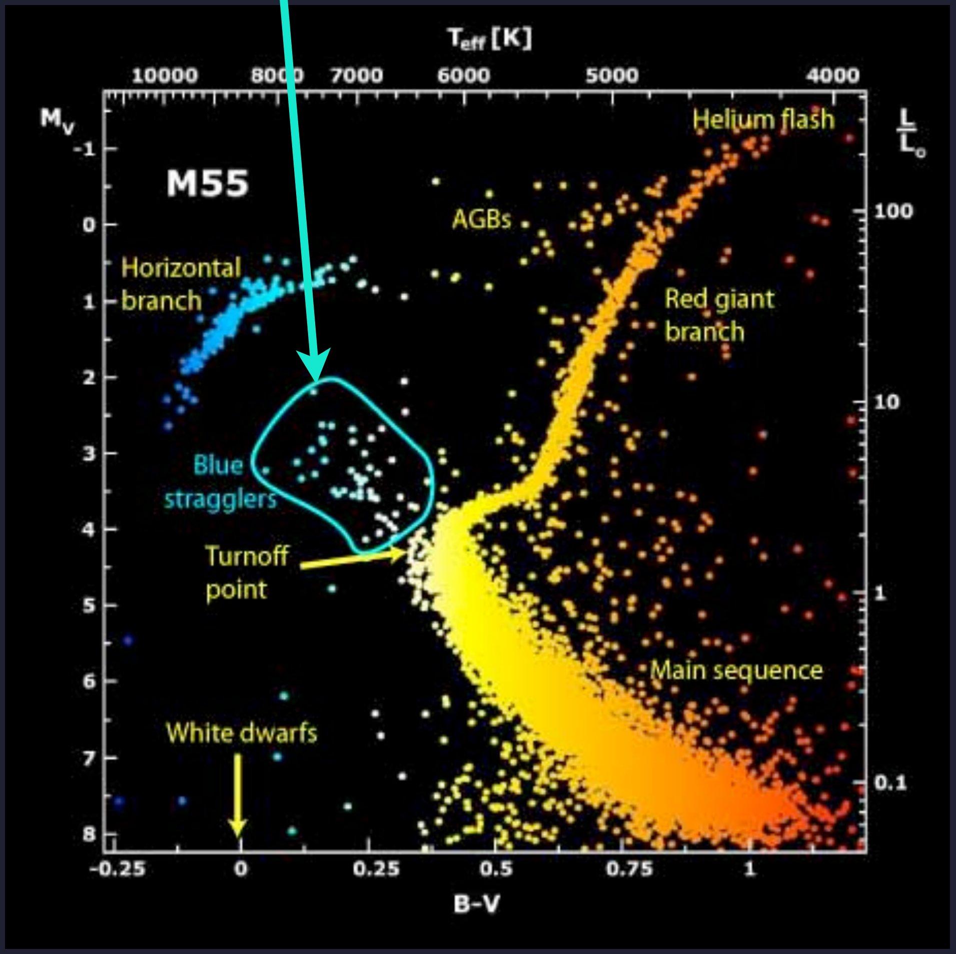
GW150914: Two ~30 M⊙ BH at ~400 Mpc



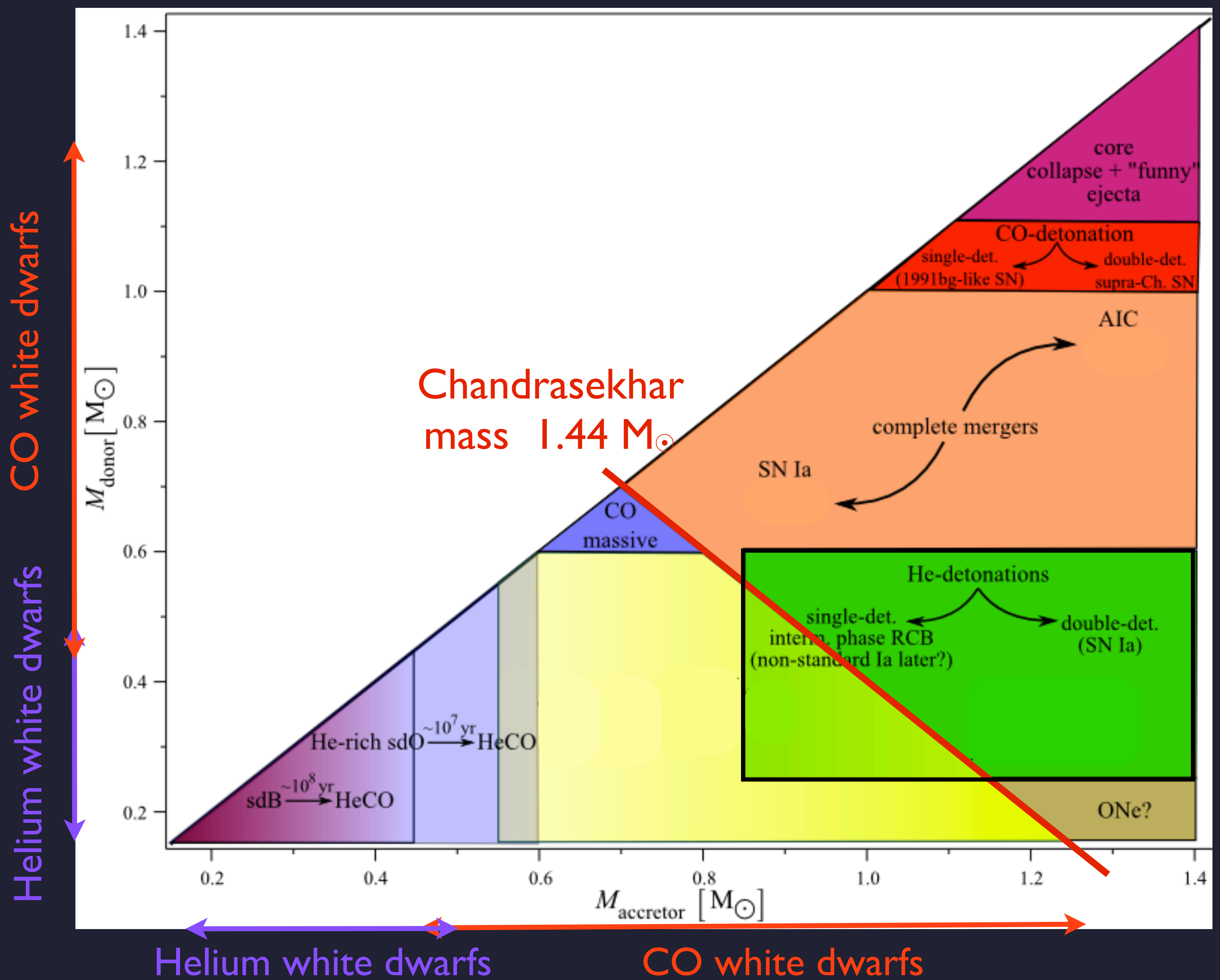
GW151226: ~14 + 8 M⊙ BH at ~430 Mpc

Abbott *et al.* (2016)

Blue stragglers
[No spectroscopic companion]

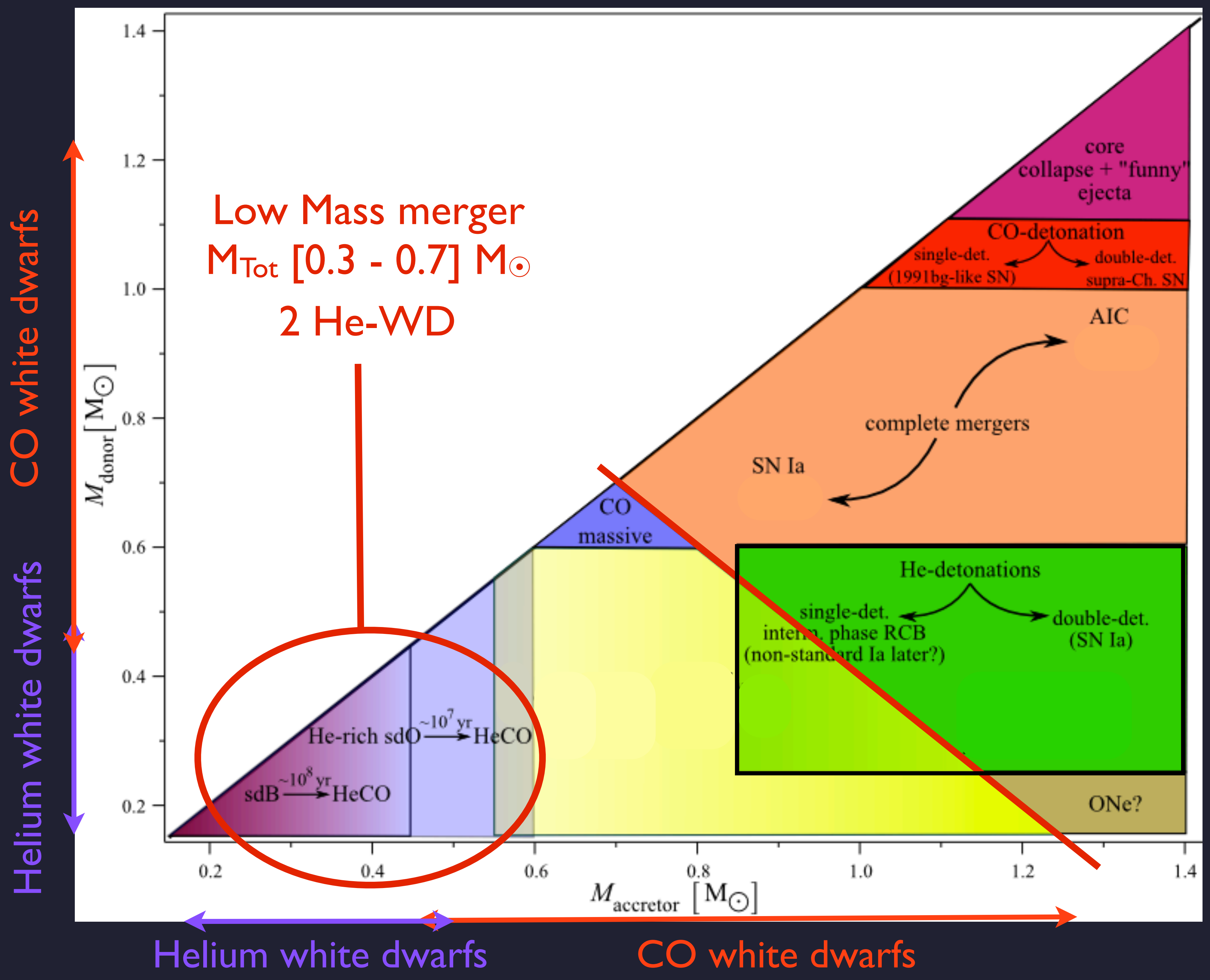


WD mergers



core collapse + "funny" ejecta
CO-detonation
single-det. (1991bg-like SN)
double-det. supra-Ch. SN
AIC
complete mergers
SN Ia
CO massive
He-detonations
single-det. interm. phase RCB (non-standard Ia later?)
double-det. (SN Ia)
ONe?
He-rich sdO ~10^7 yr → HeCO
sdB ~10^8 yr → HeCO
Chandrasekhar mass 1.44 M☉
1.4
1.2
1.0
0.8
0.6
0.4
0.2
M_donor [M☉]
M_accretor [M☉]
CO white dwarfs
Helium white dwarfs

WD mergers


Low Mass merger
M_Tot [0.3 - 0.7] M☉
2 He-WD
CO white dwarfs
Helium white dwarfs
core collapse + "funny" ejecta
CO-detonation
single-det. (1991bg-like SN)
double-det. supra-Ch. SN
AIC
complete mergers
SN Ia
CO massive
He-detonations
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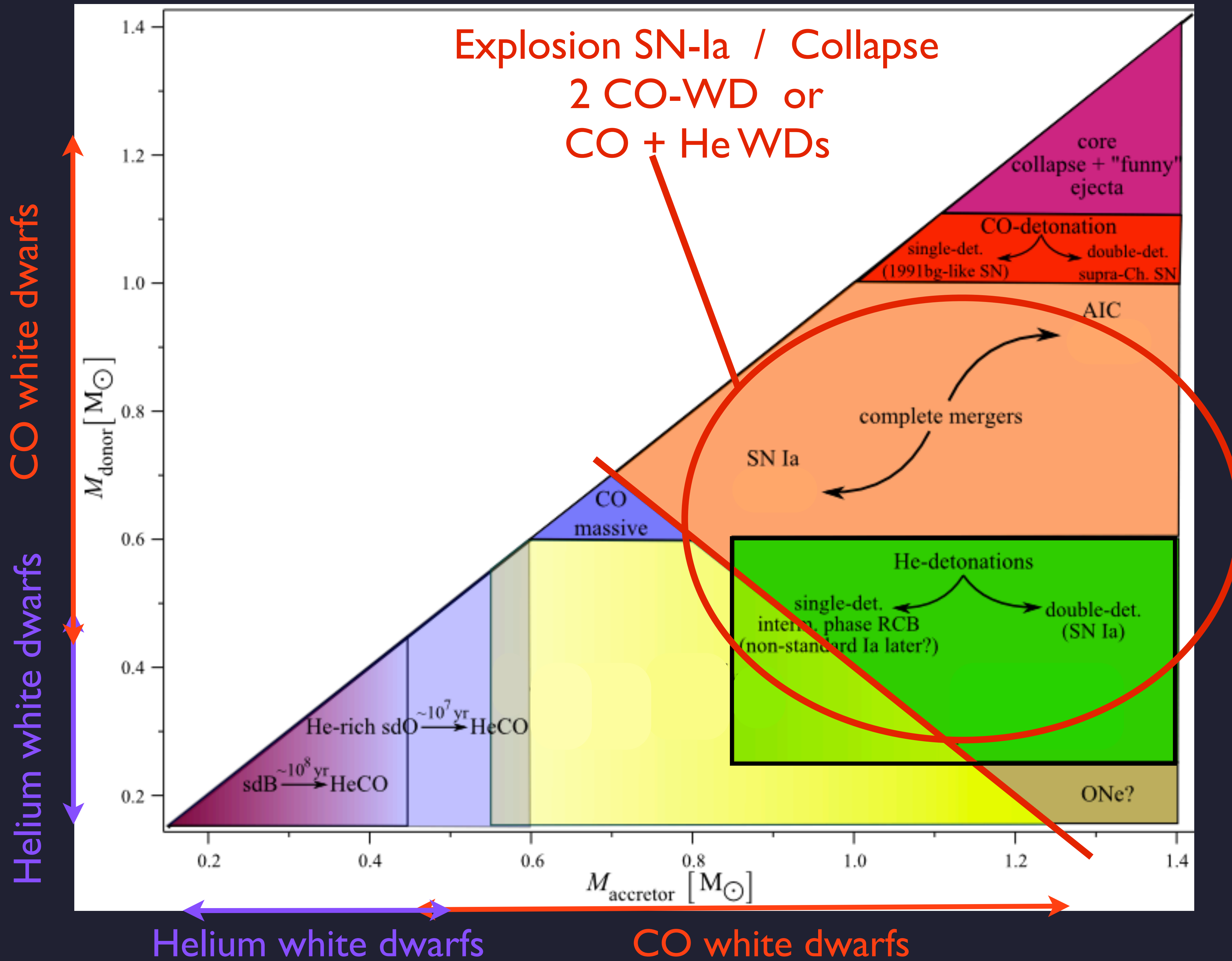
ONe?
M_donor [M☉]
M_accretor [M☉]
Helium white dwarfs
CO white dwarfs

WD mergers



Explosion SN-Ia / Collapse
2 CO-WD or
CO + He WDs
core
collapse + "funny"
ejecta
CO-detonation
single-det.
(1991bg-like SN)
double-det.
supra-Ch. SN
AIC
complete mergers
SN Ia
CO
massive
He-detonations
single-det.
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He-rich sdO ~10^7 yr HeCO
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M_donor [M⊙]
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1.4
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1.0
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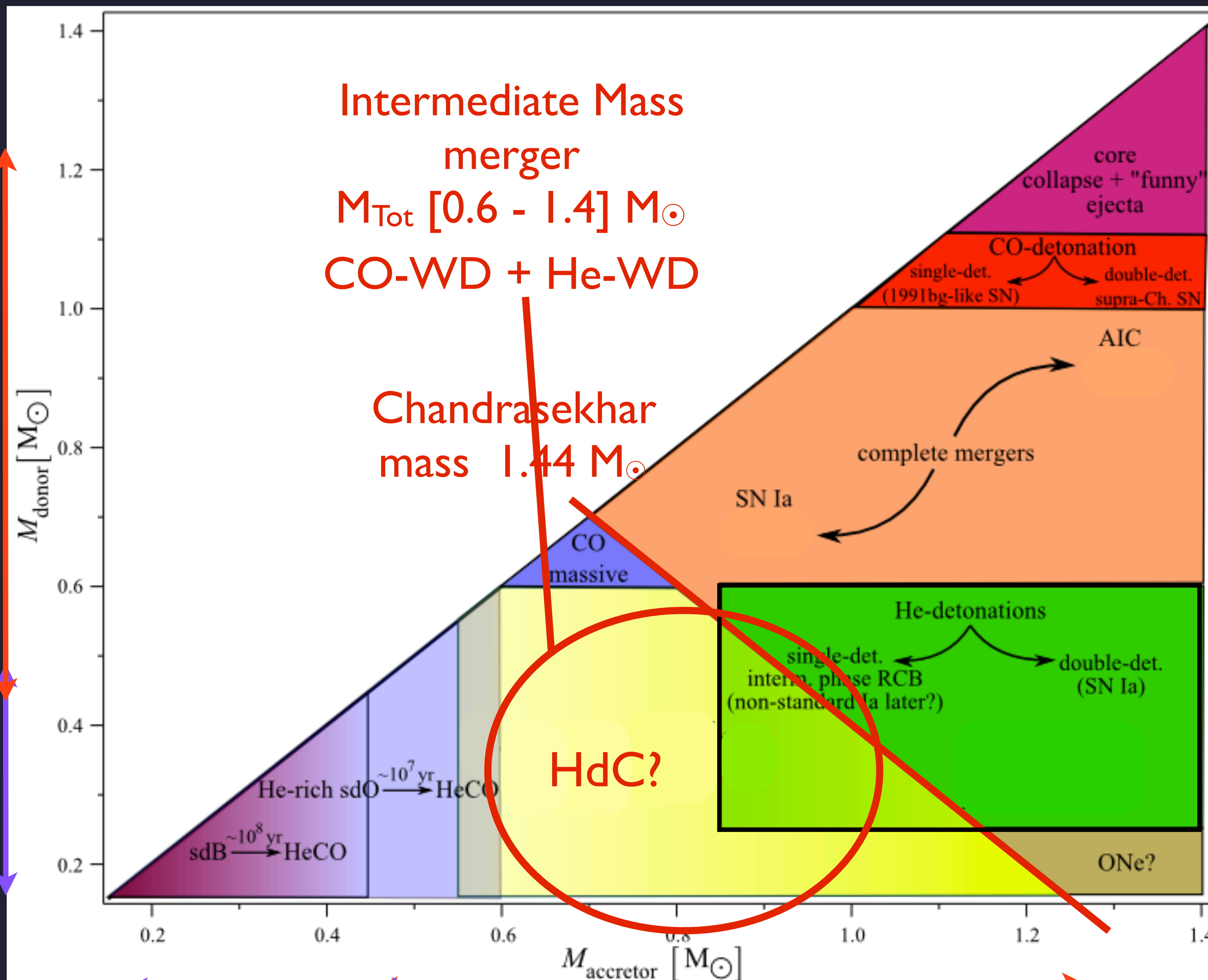
CO white dwarfs
Helium white dwarfs
Helium white dwarfs
CO white dwarfs

WD mergers



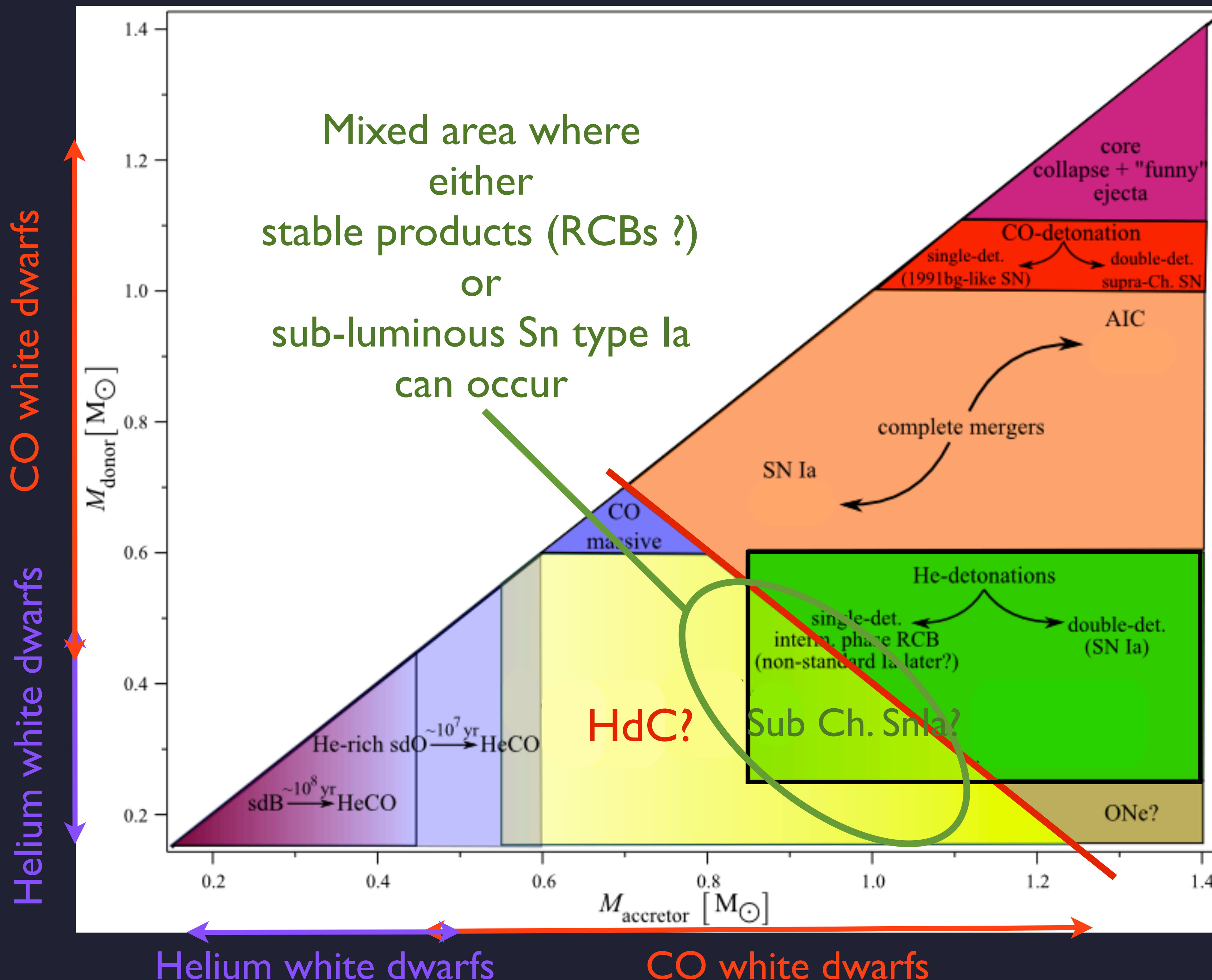
CO white dwarfs

Helium white dwarfs

Helium white dwarfs

CO white dwarfs

WD mergers


Mixed area where
either
stable products (RCBs ?)
or
sub-luminous Sn type Ia
can occur
core
collapse + "funny"
ejecta
CO-detonation
single-det.
(1991bg-like SN)
double-det.
supra-Ch. SN
AIC
complete mergers
SN Ia
CO
massive
He-detonations
double-det.
(SN Ia)
HdC?
Sub Ch. SnIa?
ONe?
He-rich sdO $\xrightarrow{\sim 10^7 yr}$ HeCO
sdB $\xrightarrow{\sim 10^8 yr}$ HeCO
M_{donor} [$M_\odot$]
$M_{accretor}$ [$M_\odot$]
1.4
1.2
1.0
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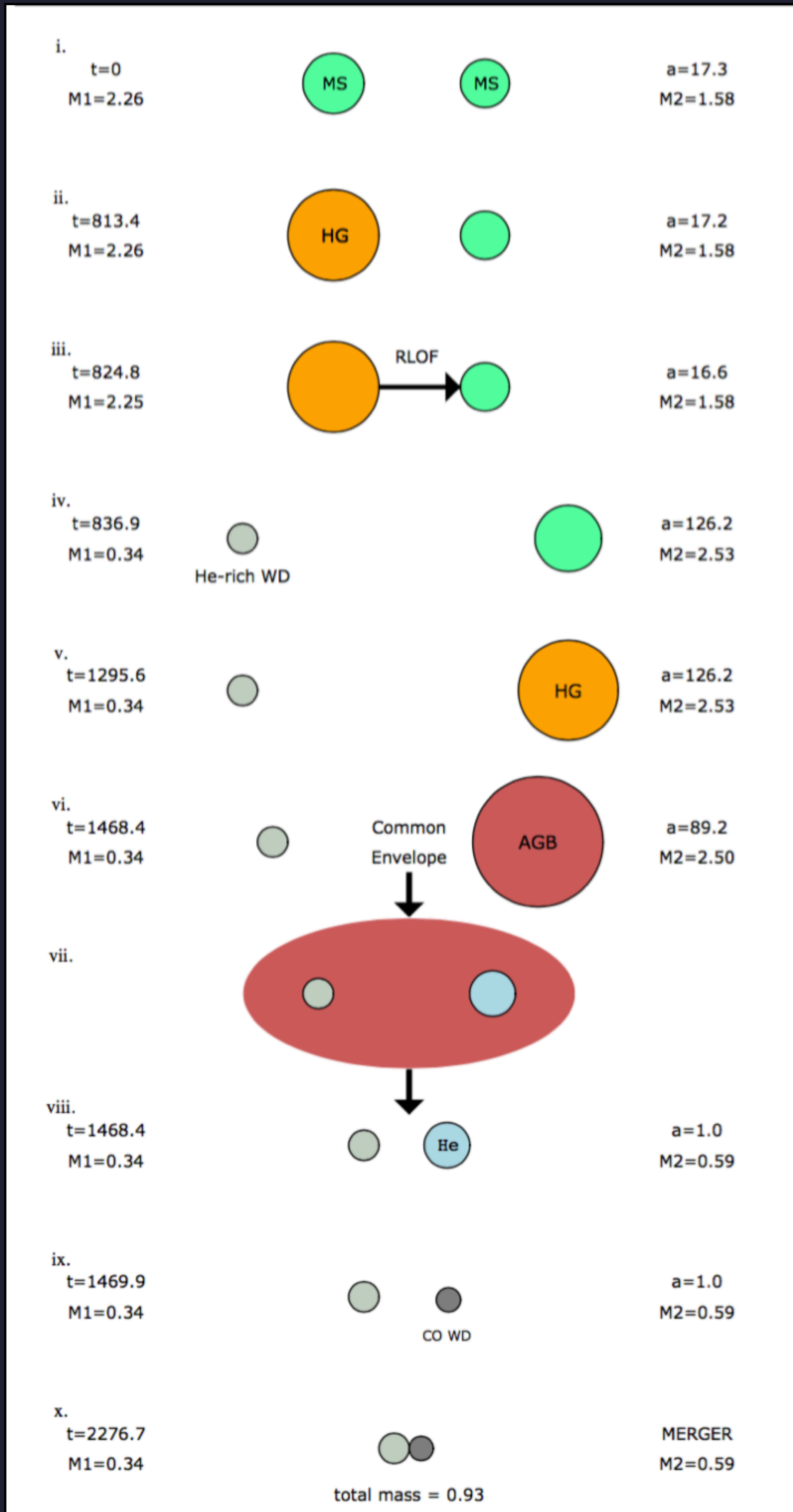
0.6
0.4
0.2
CO white dwarfs
Helium white dwarfs
Helium white dwarfs
CO white dwarfs

Close binary evolution

Typical evolutionary path expected



Karakas, A., Ruiter, A. J. and Hampel, M.(2015)

— First star evolve off the MS

— Mass transfer

— He-WD created (Hydrogen envelope stripped away)

— Second star evolve off the MS

— Second star move on the AGB phase

— Common envelope phase

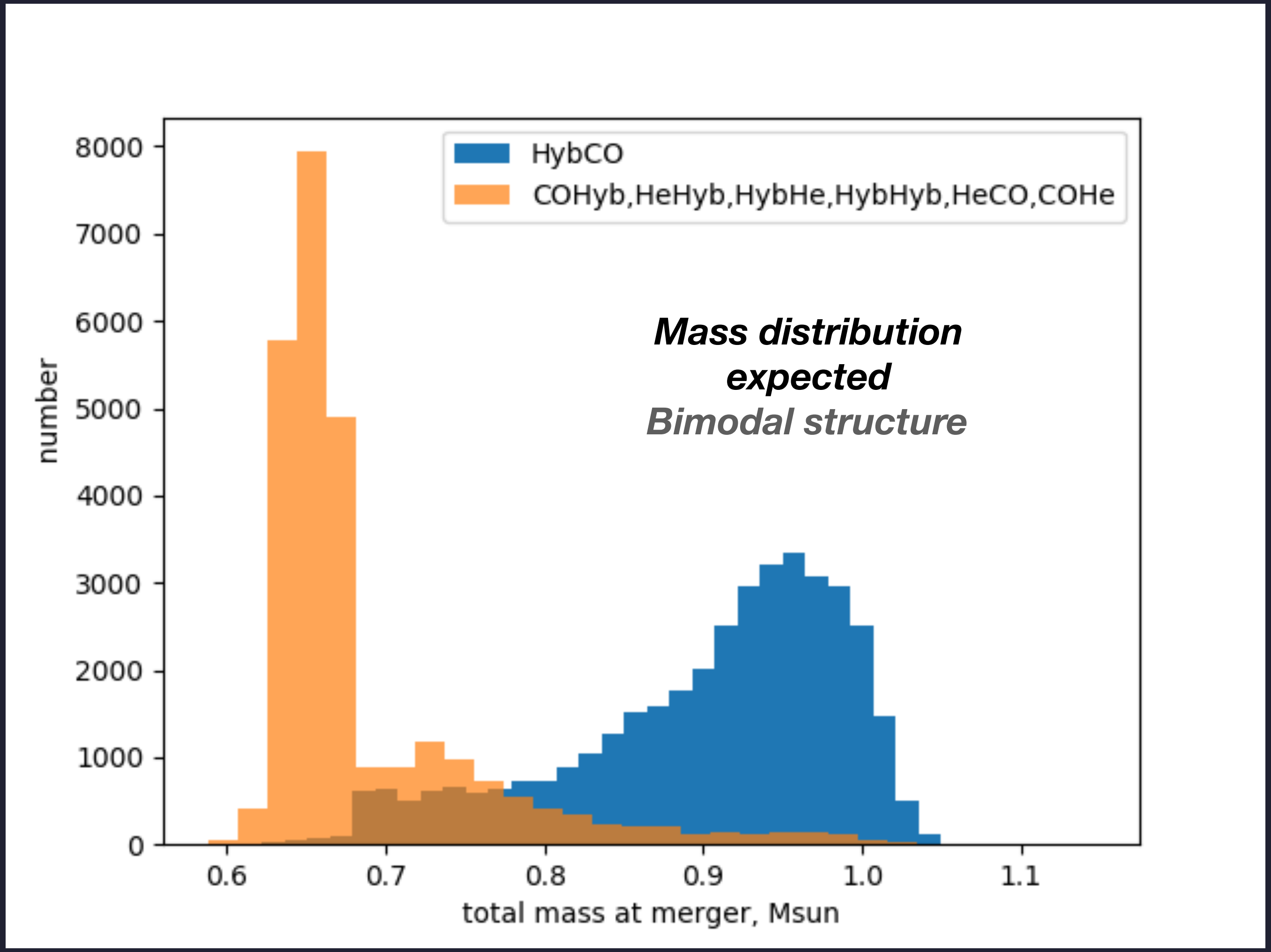
— White dwarf binary system on close distance

— CO-WD created

— Merger !

Supergiant

Expected Mass distribution



Tisserand et al. (2022)

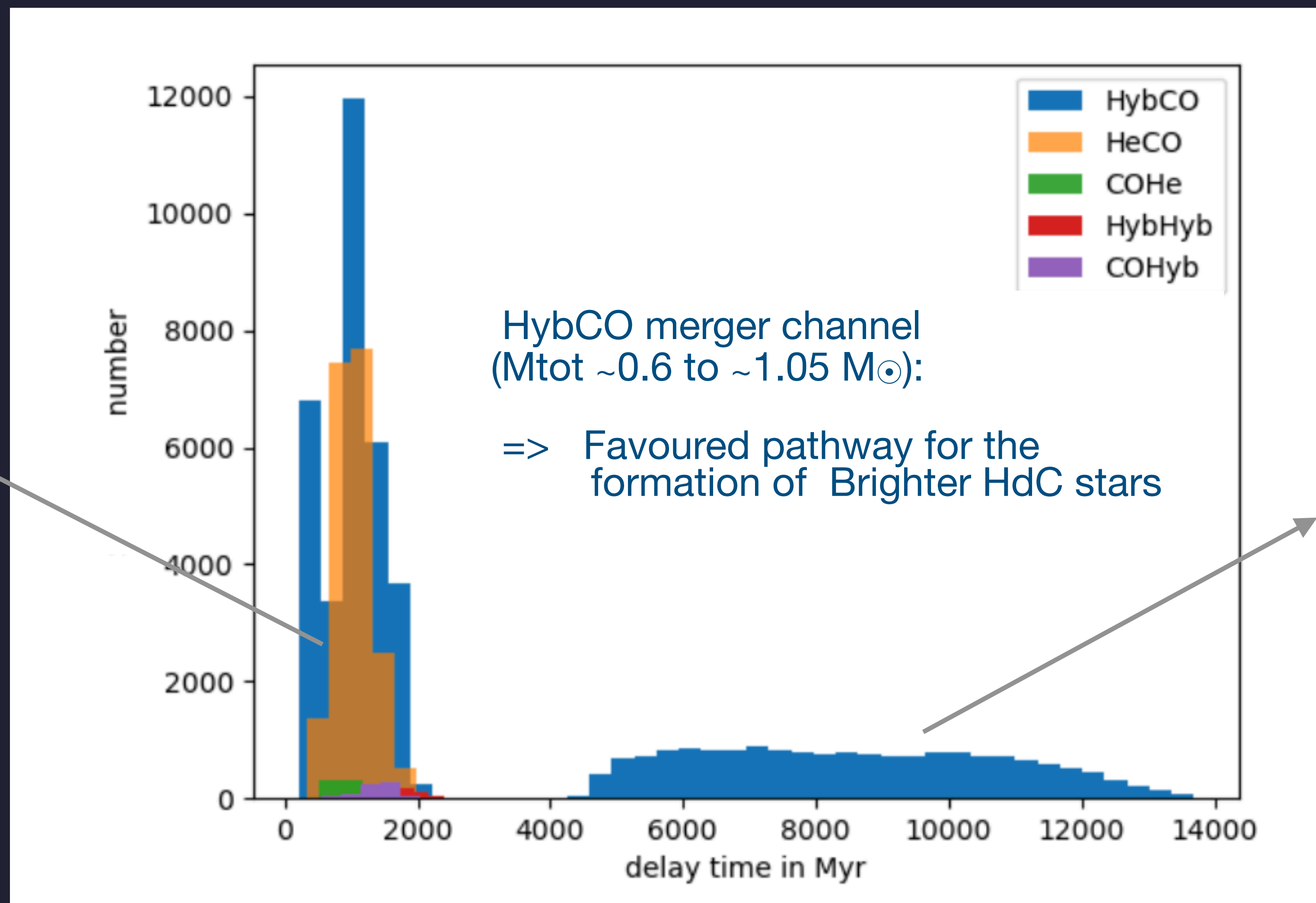
RCBs can lose up to 0.1 $M_\odot$ in a life time because of dust production

+ 0.1 $M_\odot$ can be expelled at the time of the merger.

Delay time :

When the original M-S stars system were created ?

Young population created ~ 1 billion years ago



Old population > 5 billions years old

Tisserand et al. (2022)

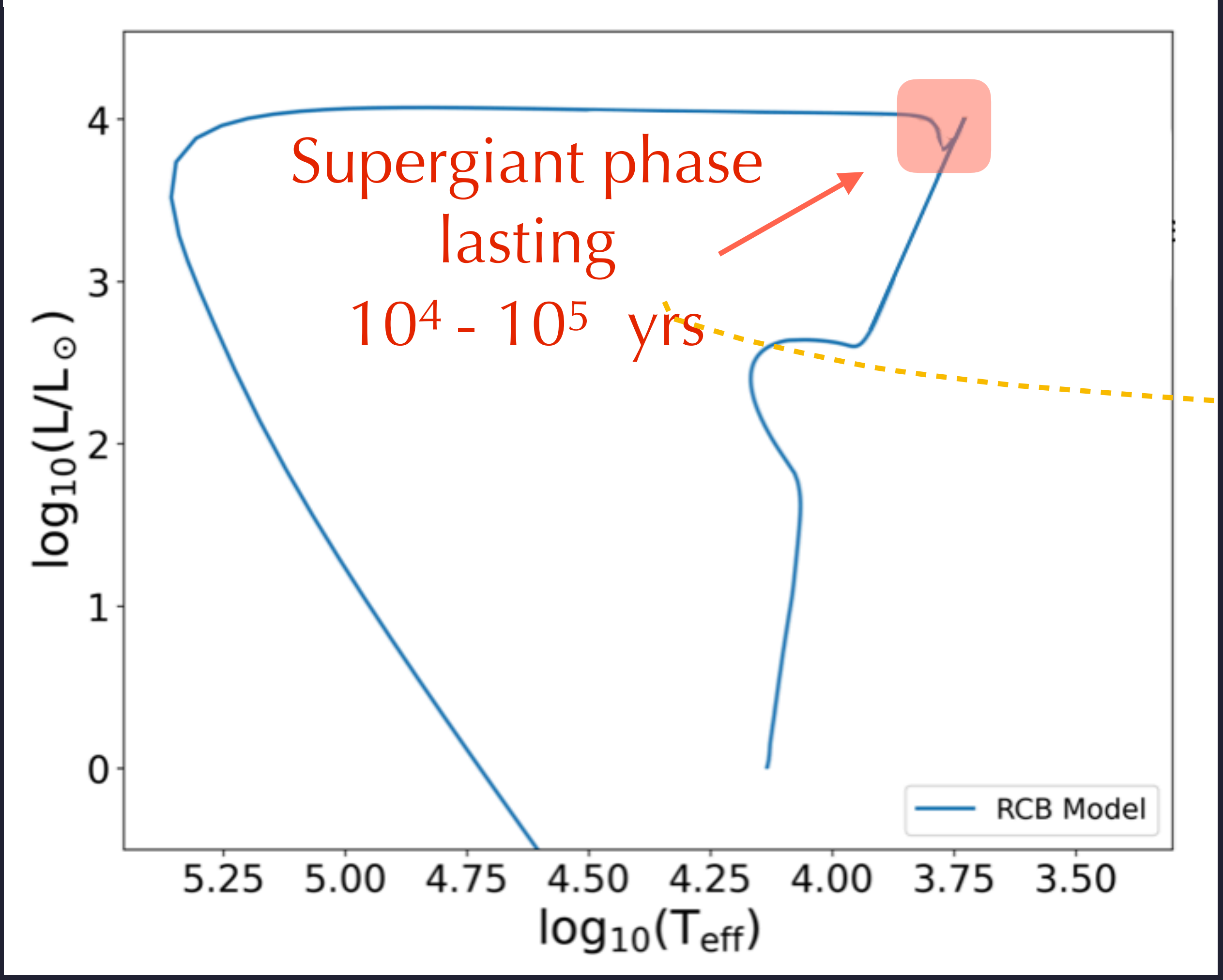
How many of them can we expect?

- ***Formation rate:***

	Total Mass	Rate (Ruiter, 2009)
WD-He + WD-He => sdB/O stars	~0.5 $M_\odot$	~0.8 /100 yrs
WD-He + WD-CO => HdC stars	~0.9 $M_\odot$	~0.5 /100 yrs
WD-CO + WD-CO => SnIa, WR	> ~1.2 $M_\odot$	~0.9 /100 yrs (0.3 for Mass >M_{ch})

- ***Lifetime:***

MESA model: 0.6 $M_\odot$ CO-WD + 0.3 $M_\odot$ He-WD



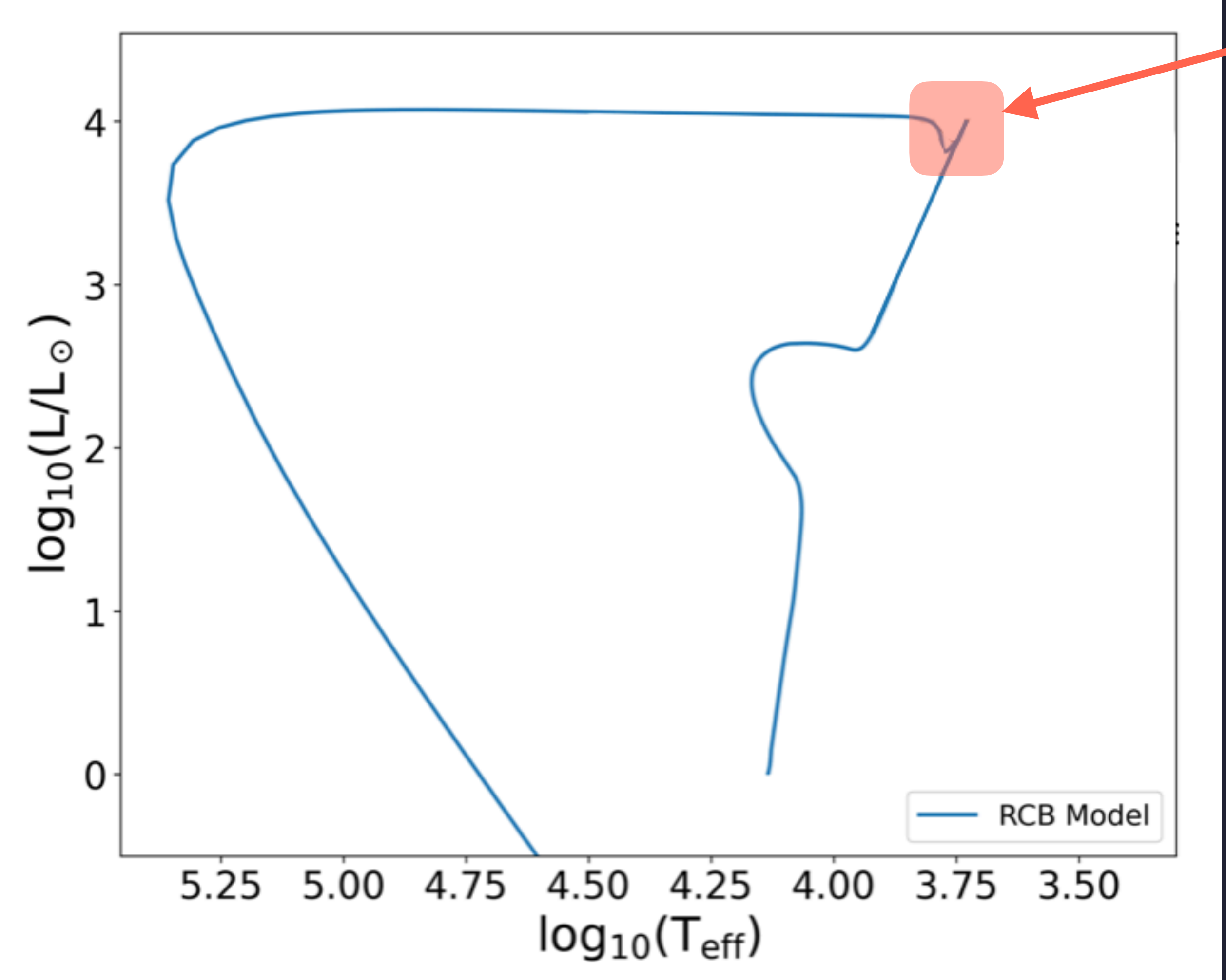
Crawford et al. (2024)

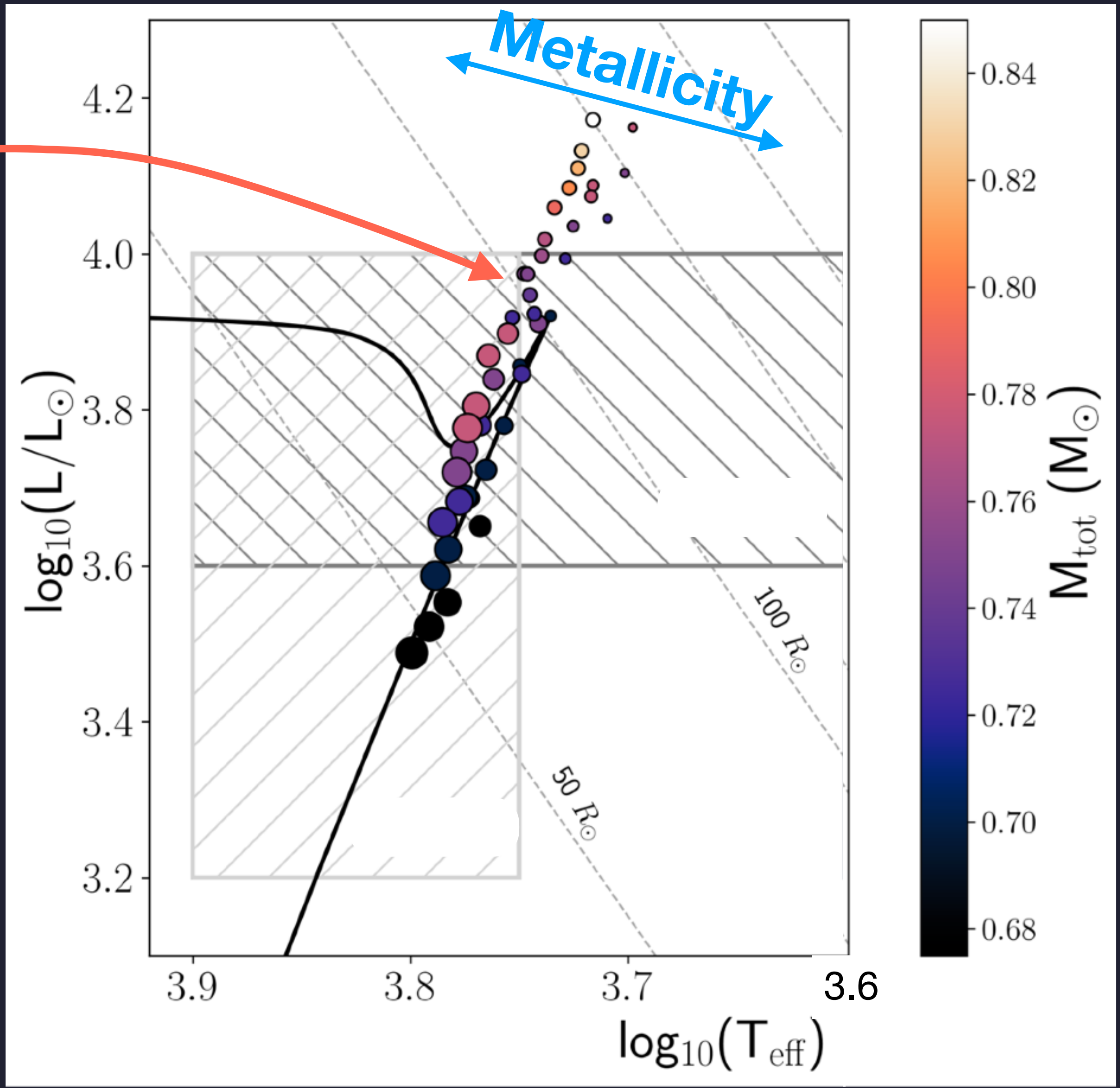
We expect
~500 stars in our Galaxy
(between 300 to 2000
depending on models)

MESA models for various Total mass & WD mass ratio

Lower M_{tot} and higher $q = M_{donor} / M_{accretor}$ creates a less luminous star !

MESA model: 0.6 M⊙ CO-WD + 0.3 M⊙ He-WD



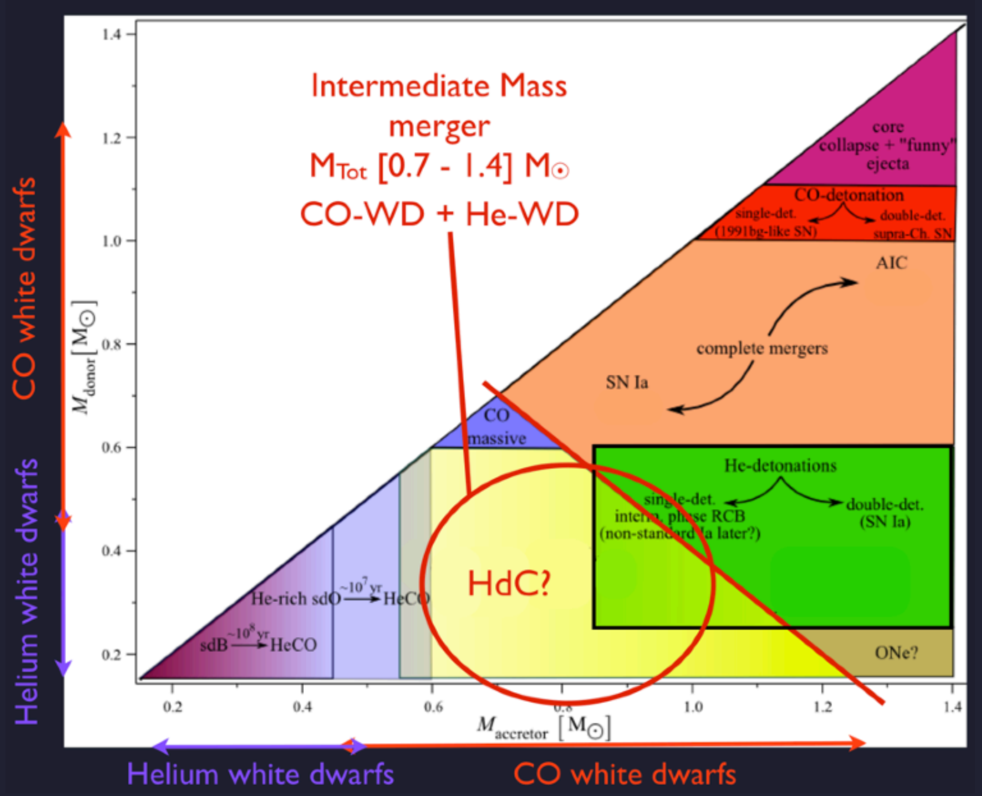


Crawford et al. (2024)

==> We should observe Supergiant stars with a range of Luminosities and Temperatures

What to expect so far ?

From Pop. synthesis, and WD merger simulations



Intermediate Mass WD mergers:

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- Of lower mass [0.6 - 0.8] $M_\odot$ <=> *Fainter !*
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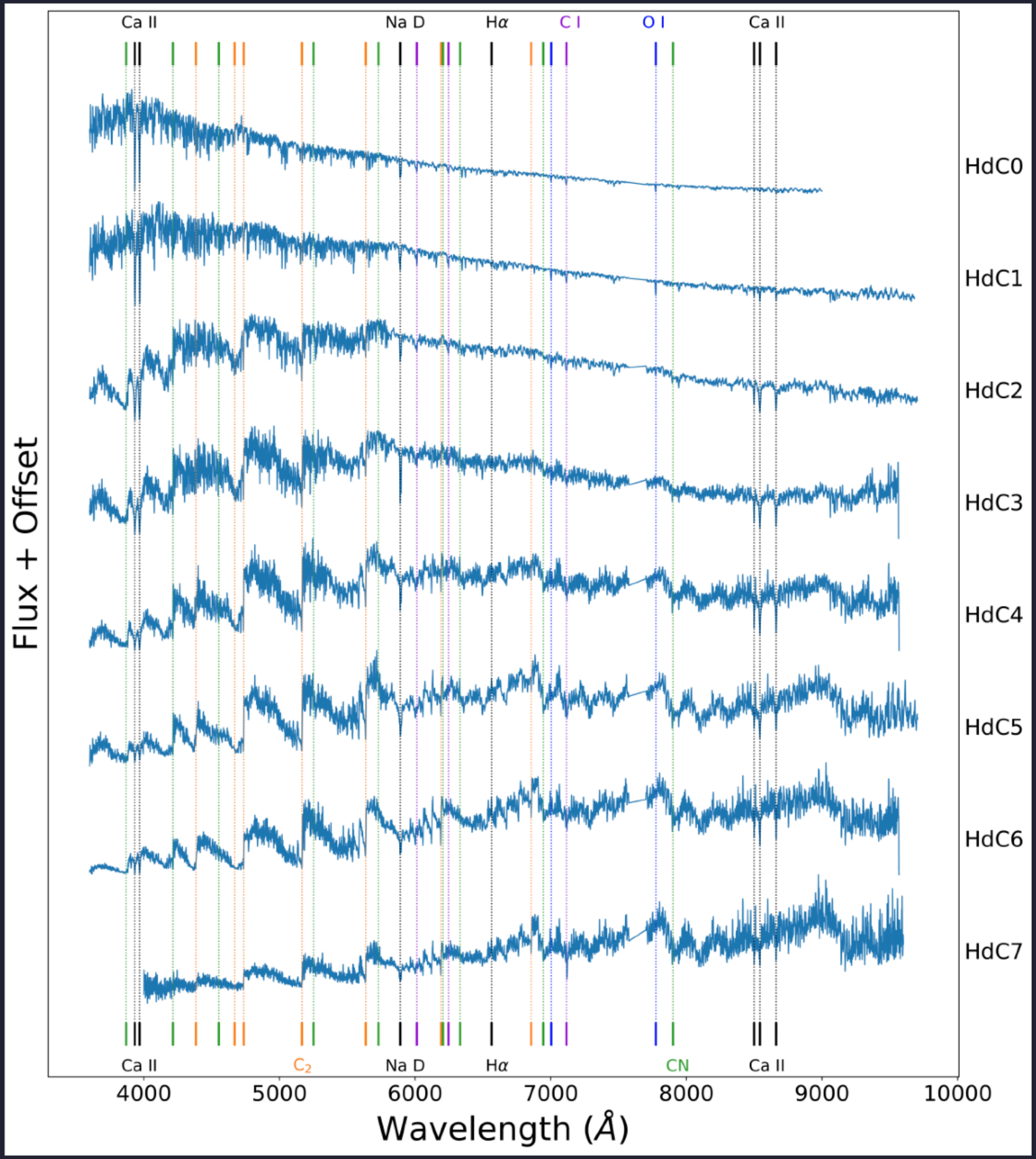
<u>HdC</u>: Hydrogen Deficient Carbon-Rich Supergiant Stars

- **Hydrogen-deficient**
  (<1% H by mass)
- **Carbon-rich**
  (C/O > 1)
- **Metal-poor**
  (-2 < [Fe/H] < -0.5)



~8000K

~3500K

Crawford+ (2023)

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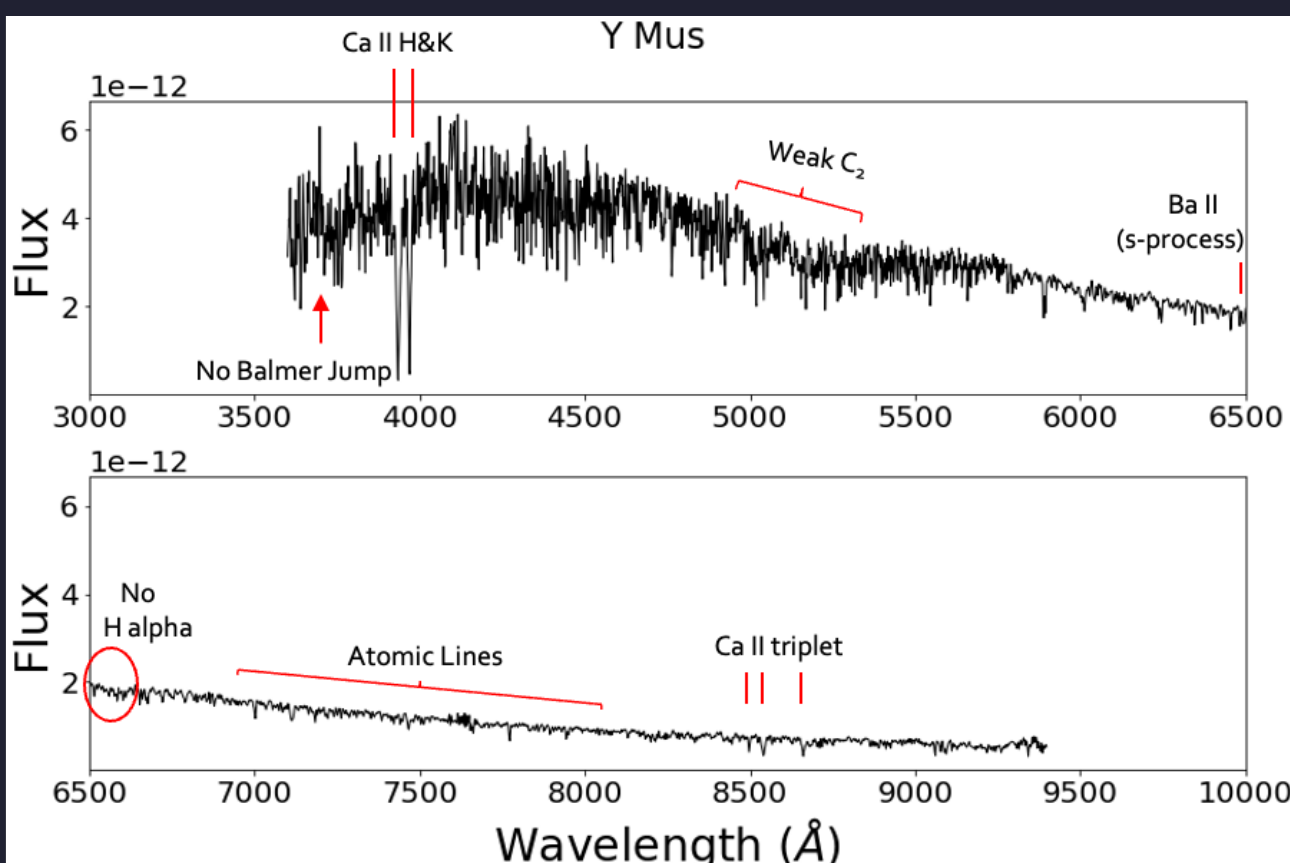
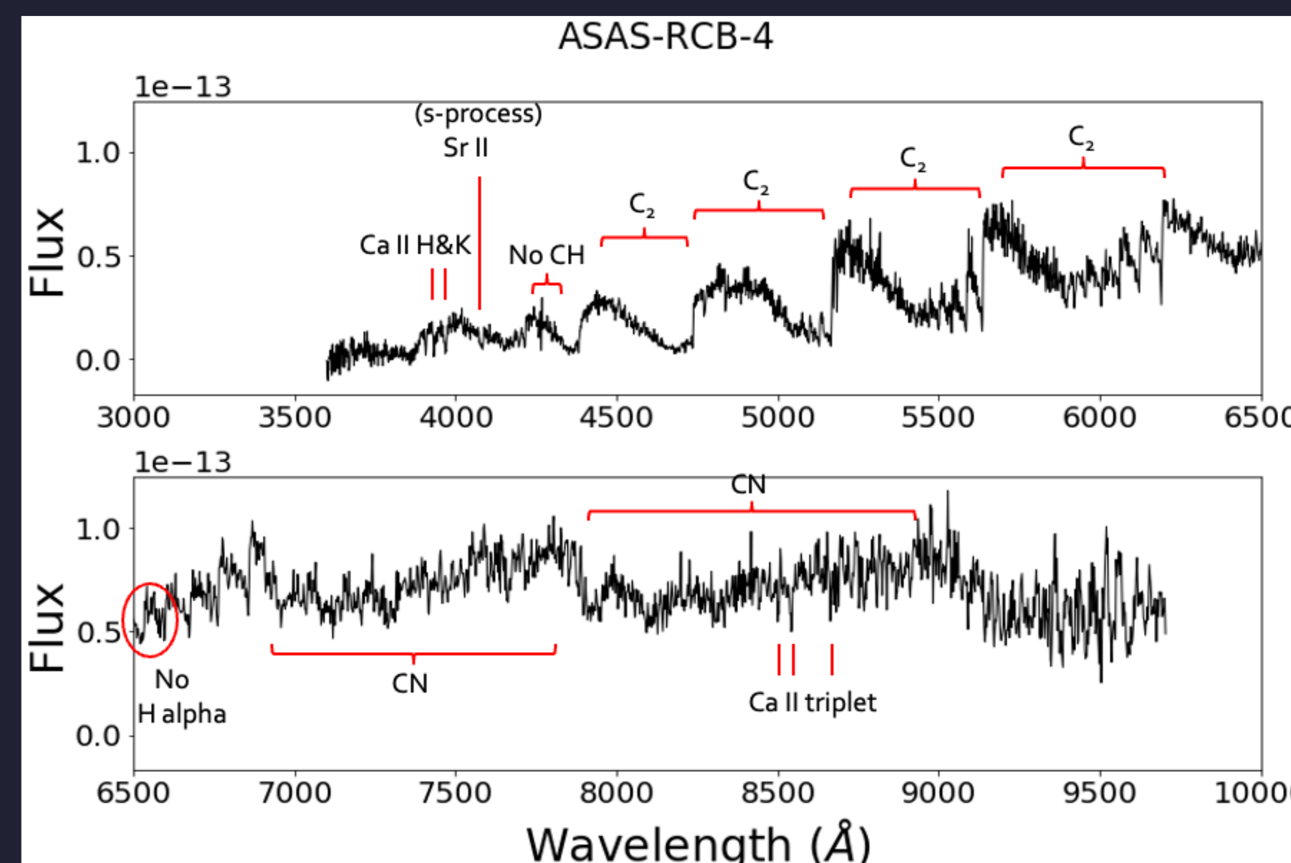
Warm HdC (~8000K)



Cool HdC (~3500K)



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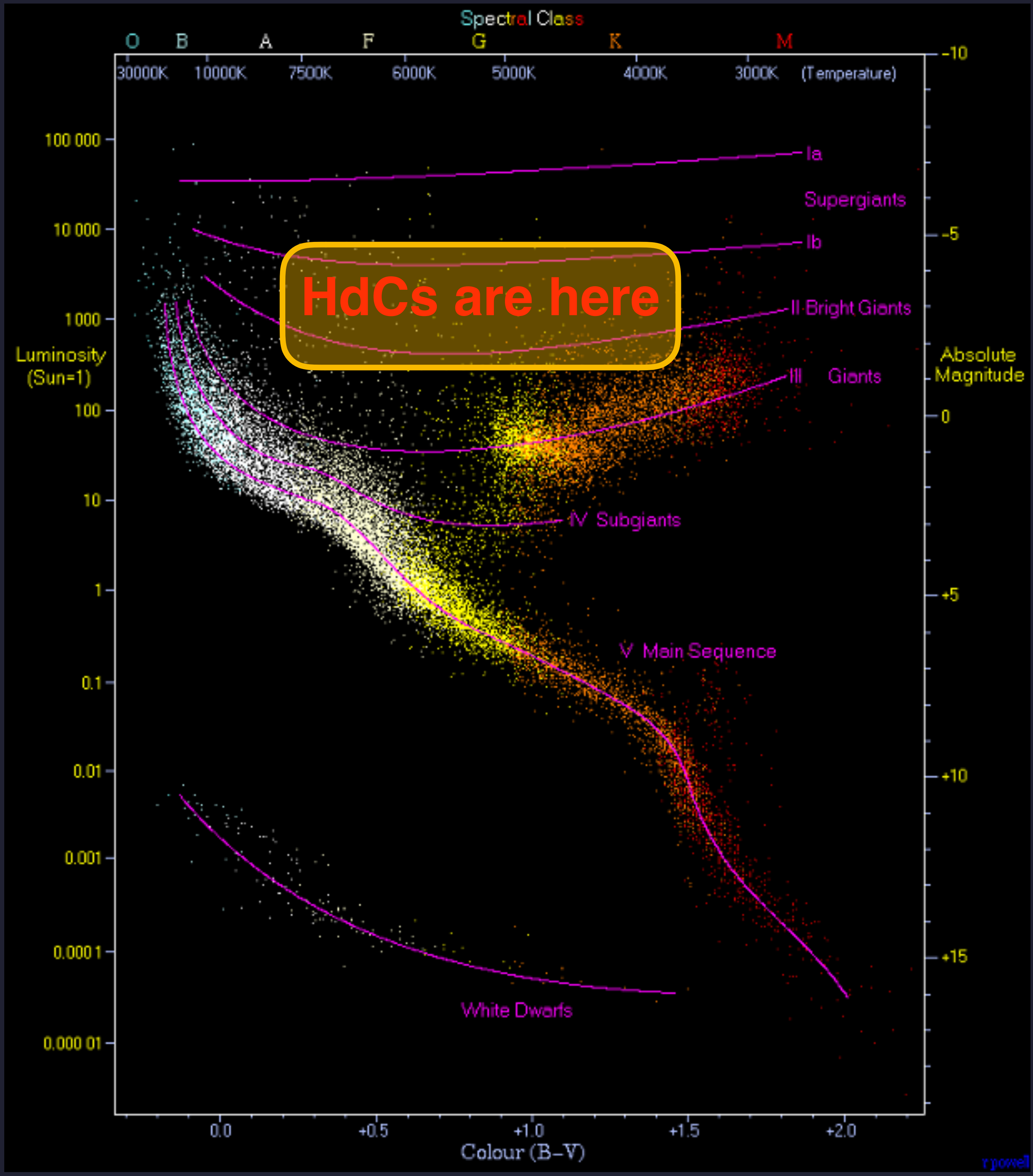
- **Supergiant Luminosity**
  $-5 \le M_V \le -2$ mag
- **T_{eff} ~ 3500 - 8000 K**
  Spectral type: F to K



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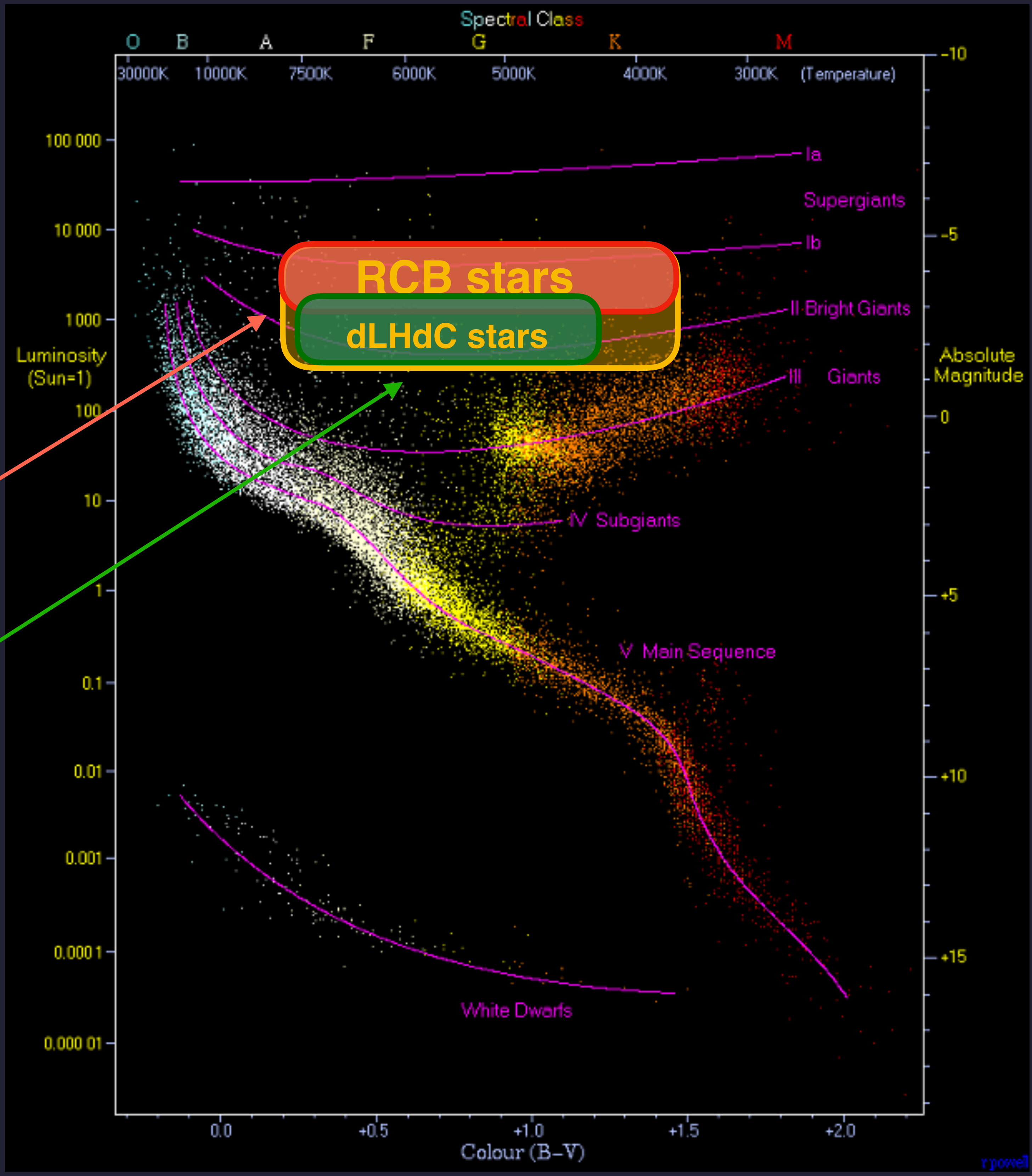
- **2 sub-groups:**
  - ✳ RCB stars - Bright
    Heavy dust-producer
  - ✳ dustless HdC - Fainter
    (dLHdC)
    No or low dust-producer



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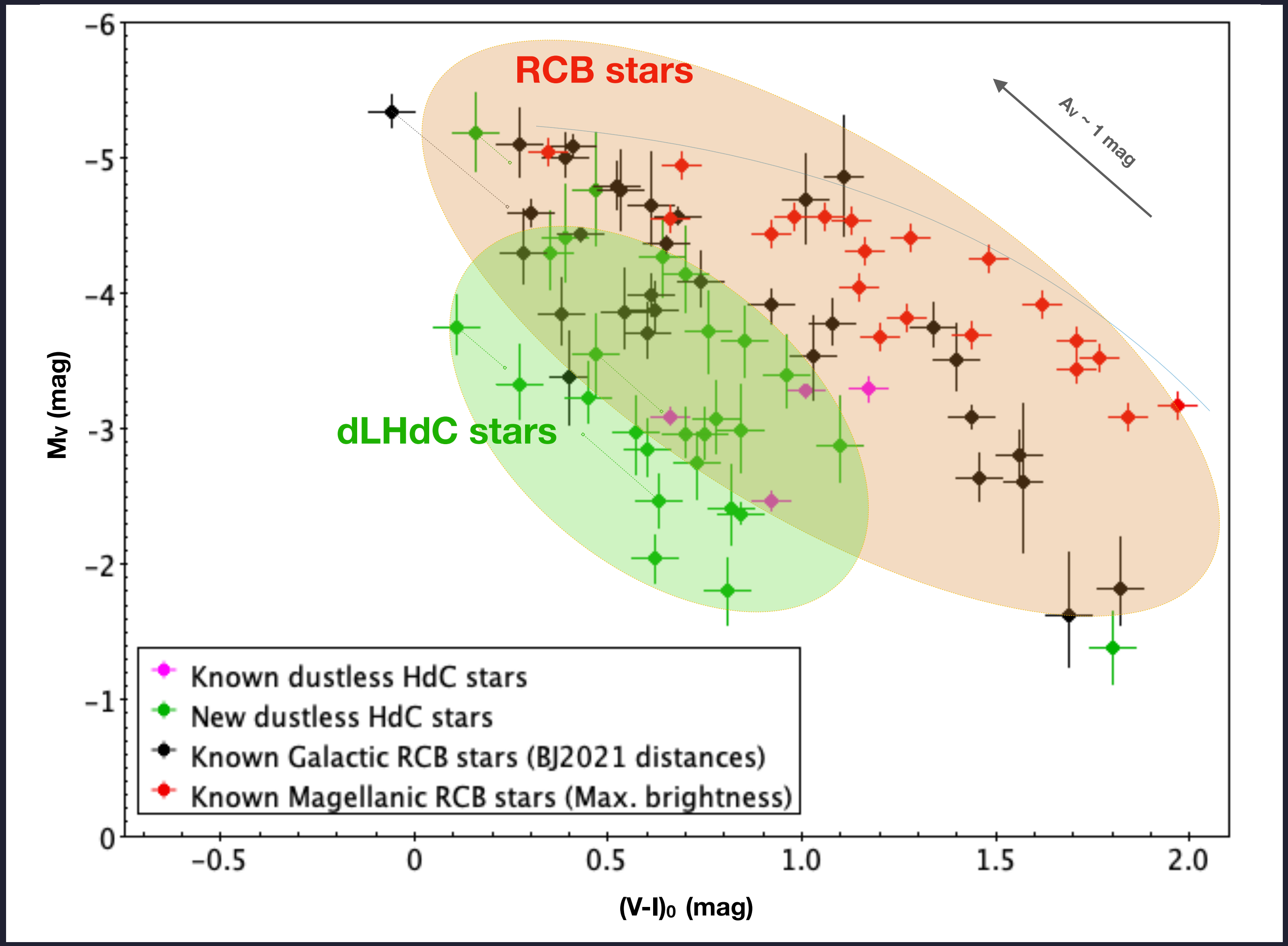


Tisserand et al. (2022)

Oscillations:

- RCB: P~[20-60] days, Amp~0.4 mag
- dLHdC: P~10 days, Amp~0.1 mag max

dLHdC stars are presumably a different population of HdC stars resulting from lower mass WD mergers

HdC: Hydrogen Deficient Carbon-Rich Supergiant Stars

- **Rare !**

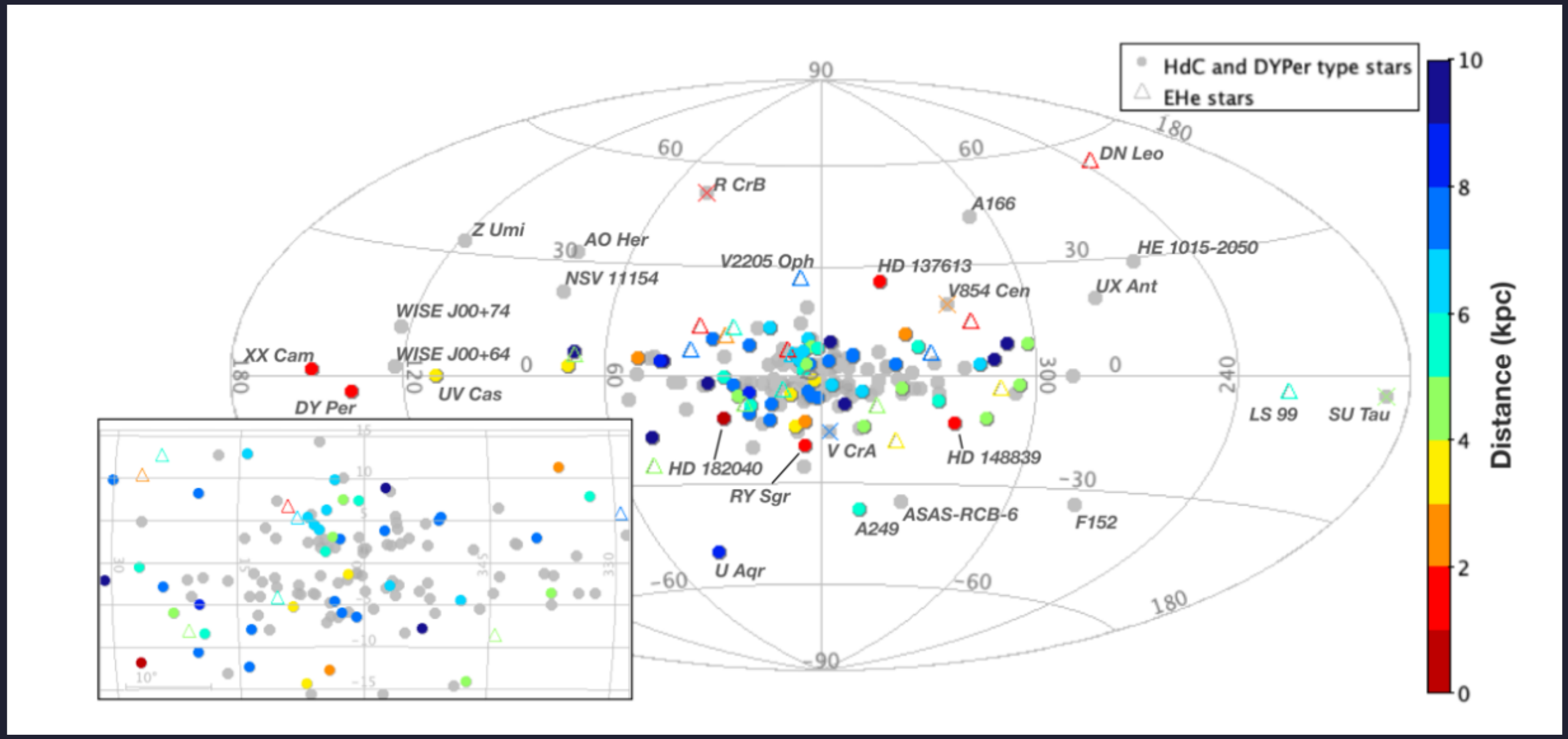
We did an ALL-sky spectroscopic search using WISE, 2MASS, Gaia + monitoring surveys (MACHO, EROS, OGLE, ASAS, ATLAS..)

Found: **RCB stars** : 162 known (135 Galactic, 29 in LMC/SMC)
dLHdC stars : 34 known (all Galactic)

~30 were known in 2000

Estimate:

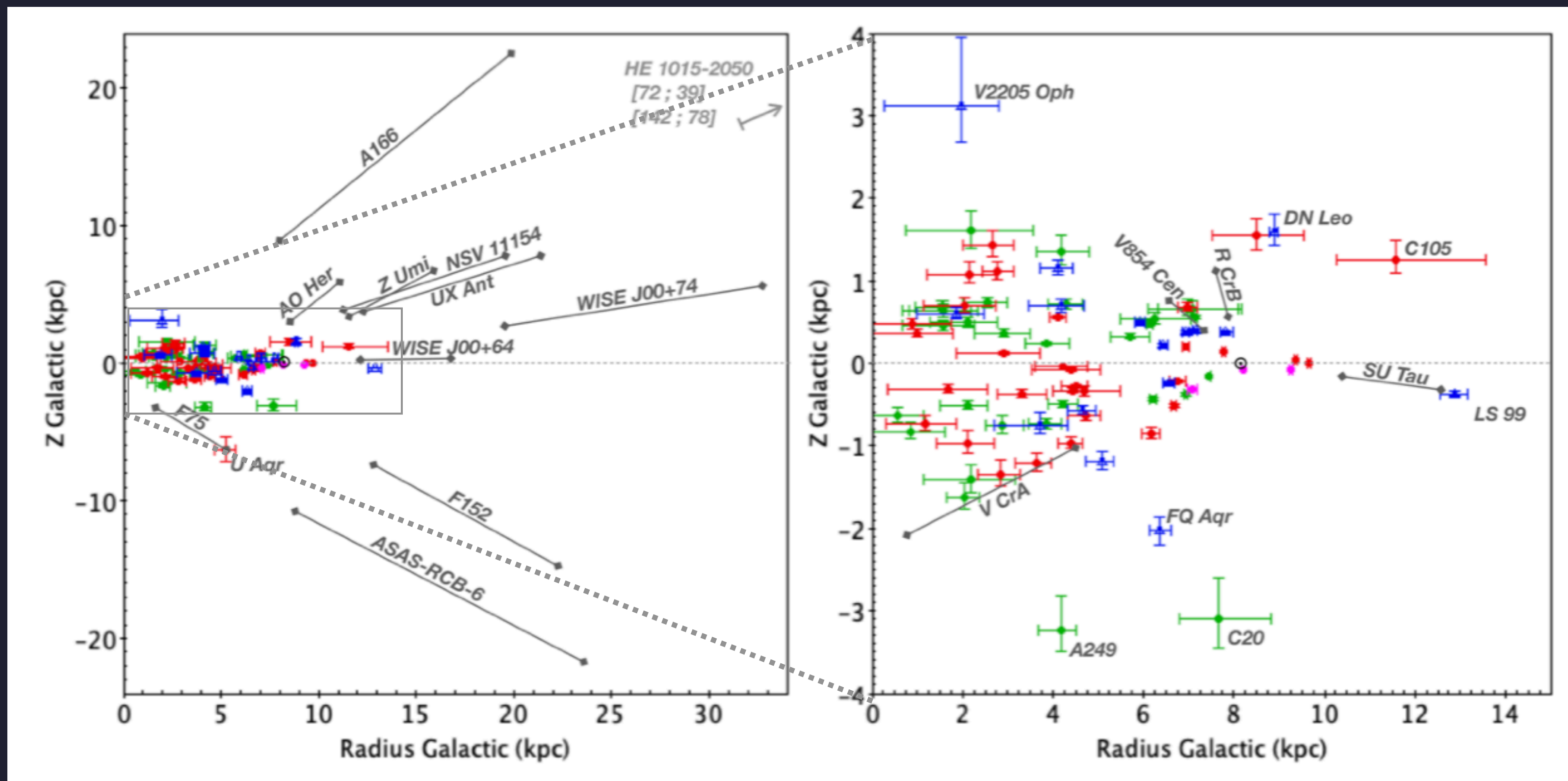
- Between 300-500 RCB stars should exist in the Galaxy.
- Hard to imagine more than 500 dLHdC stars also..

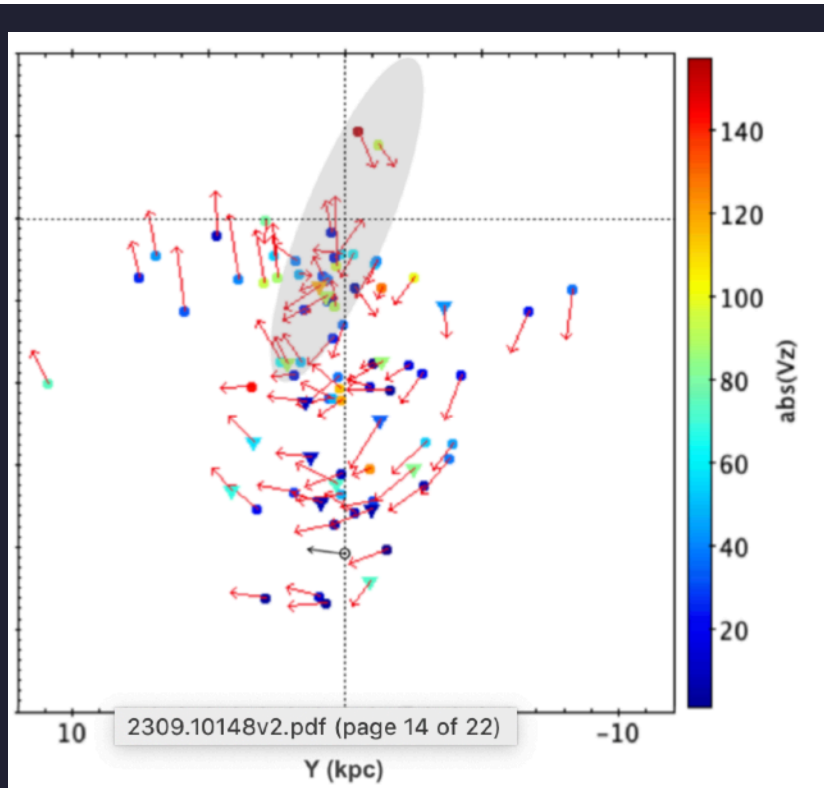


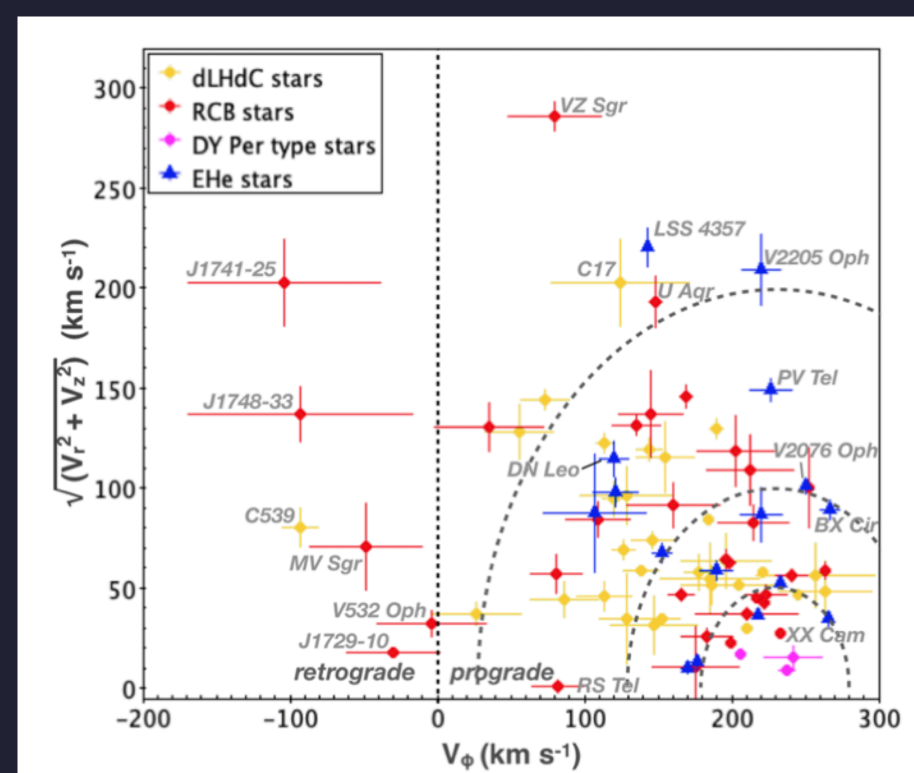
Tisserand et al. (2012, 2020, 2022, 2024a)
Karambelkar et al. (2021, 2022)

HdC: Hydrogen Deficient Carbon-Rich Supergiant Stars

Position and Dynamic from Gaia DR3







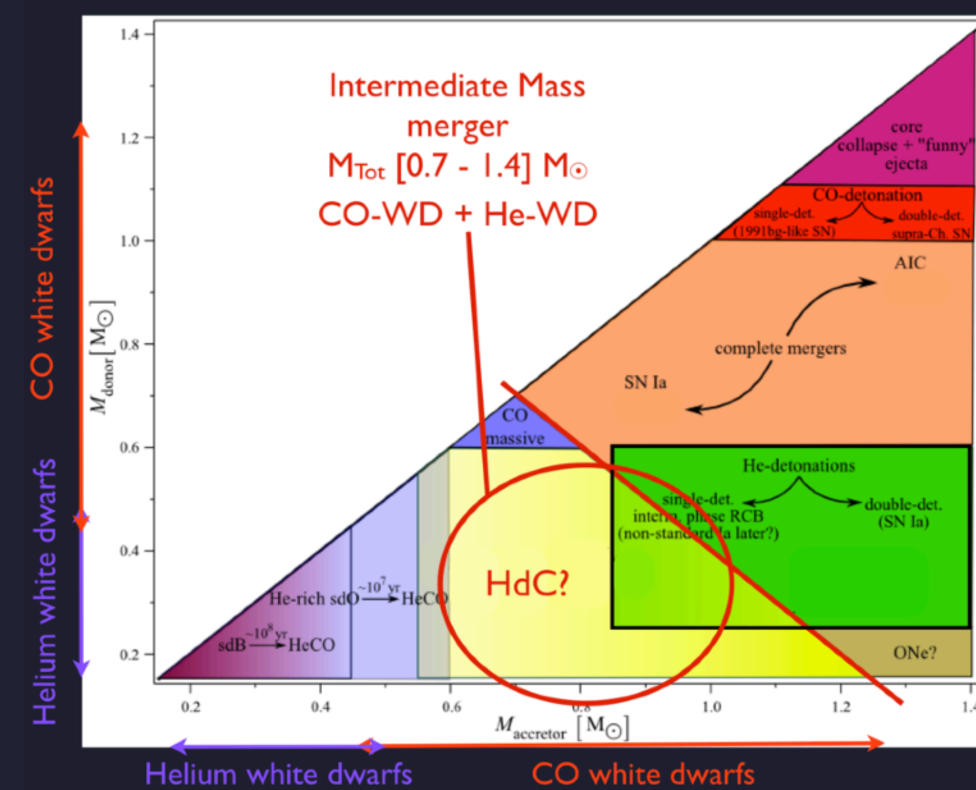
We found RCB and dLHdC stars in all stellar populations

- ***Thin disk***
- ***Thick disk***
- ***Bulge***
- ***Halo***

Tisserand et al. (2024a)

What to expect so far ?

From Pop. synthesis, and WD merger simulations



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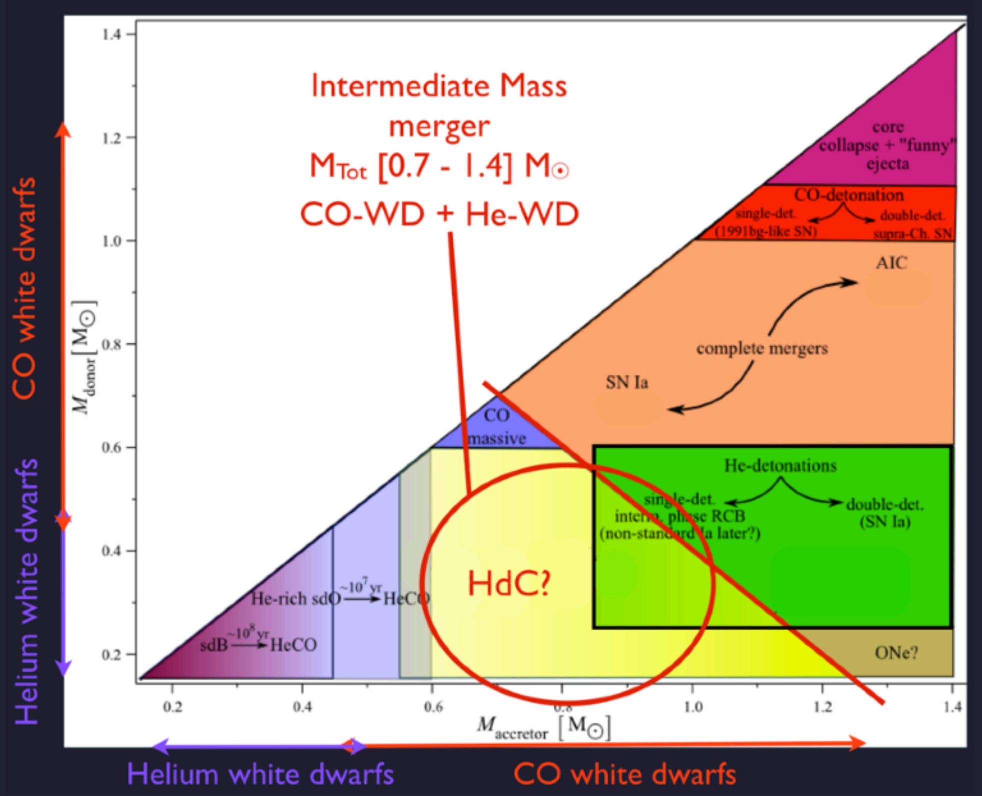

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    — **RCB stars**
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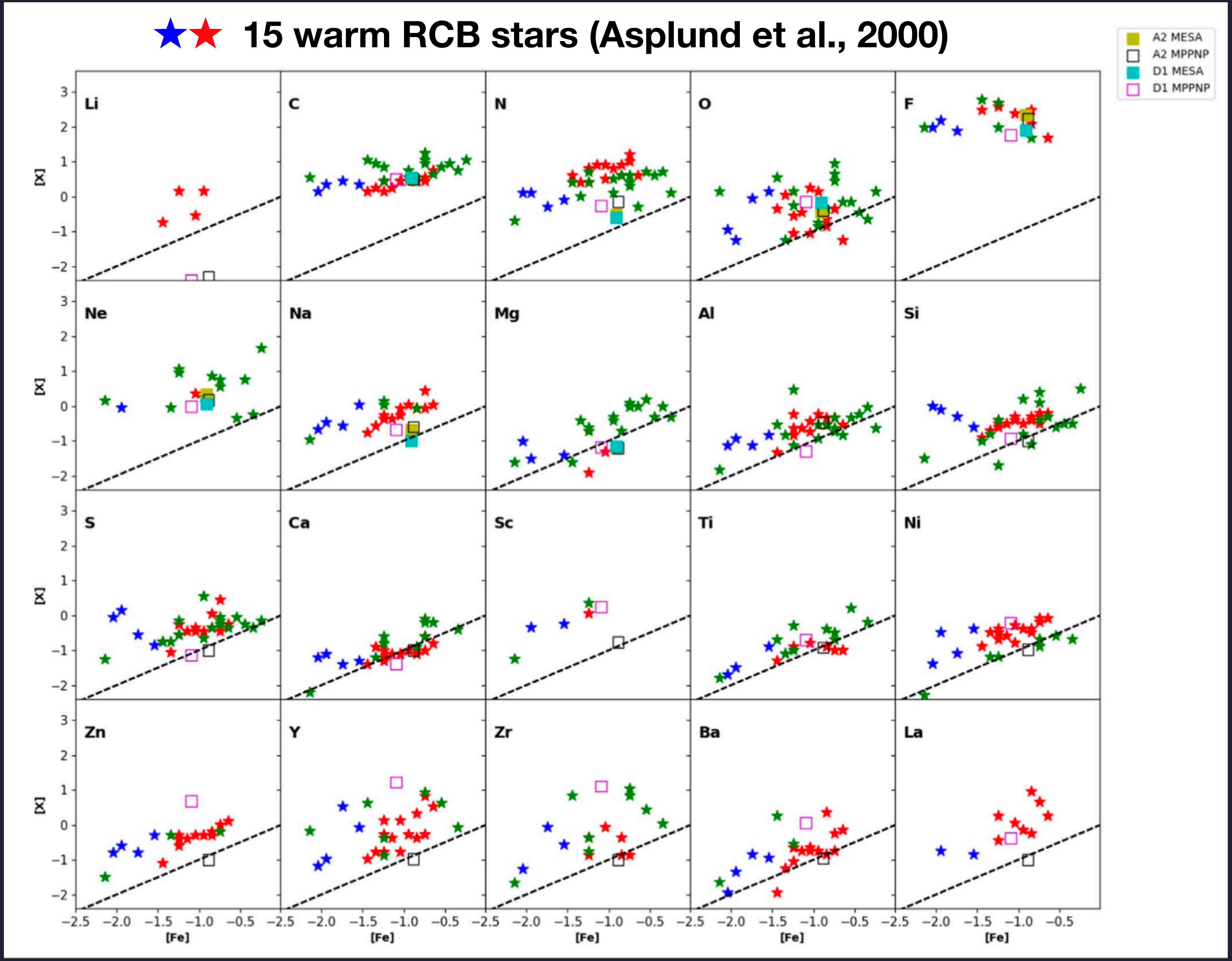
    with characteristic of Young stellar populations
    — **dLHdC stars**

HdC: Hydrogen Deficient Carbon-Rich Supergiant Stars

Abundances of warm RCB stars

Stars = observations
Boxes = models
Line = solar mixture

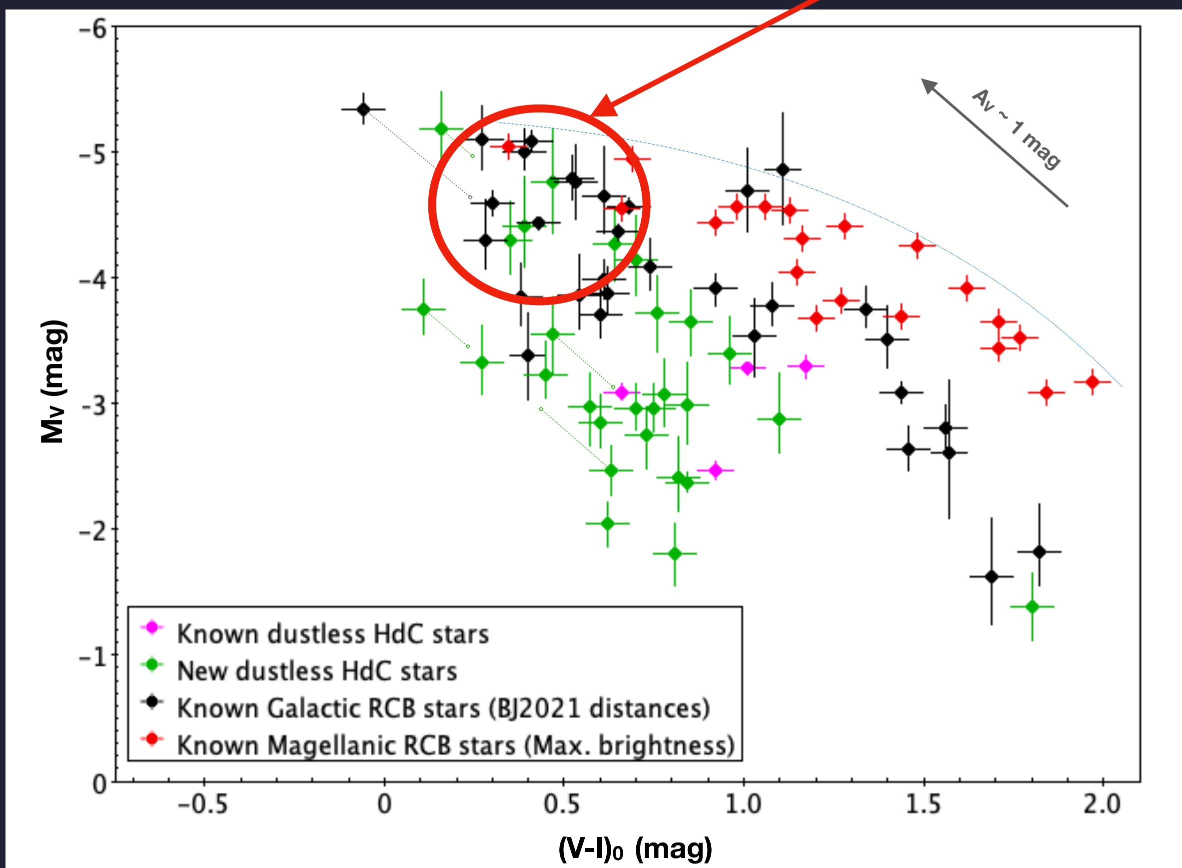
- Metal-poor
  (-2 < [Fe/H] < -0.5)
- C/O ~ [5-100]
- High [N]
- 4 Li-rich stars
  (strange!)
- Strongly F-enriched
- s-process enriched



Munson+ (2022), Jeffery+ (2011), Asplund (2000)

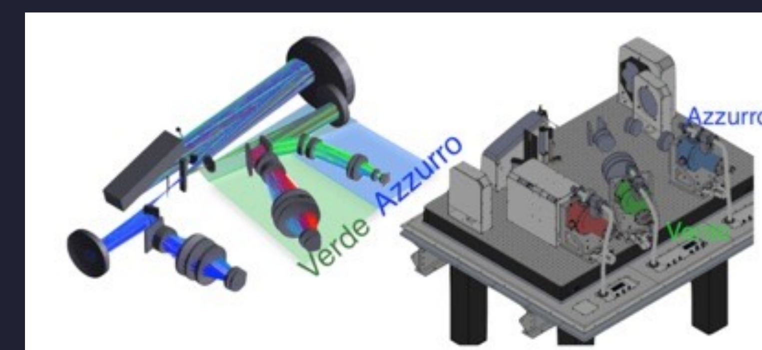
HdC: Hydrogen Deficient Carbon-Rich Supergiant Stars

Abundances of warm RCB stars



We gathered High-res spectra of 50+ Galactic RCB and dLHdC stars of all Lum. / Temp. using AAT/VELOCE , R~80000

Azzurro 391-431nm
Verde 431-590nm
Rosso 590-930nm
+ Laser comb !



Analysis: **special H-def MARCS models**

- Original grid made by Kjell Eriksson in 2013 (Upsalla)
- Extension (x50) ongoing with Bertrand Plez (Montpellier)

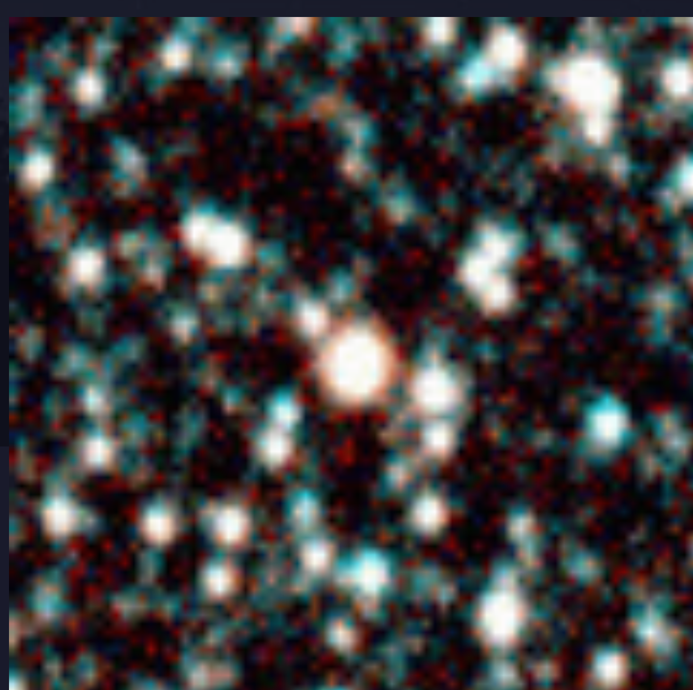
RCB stars

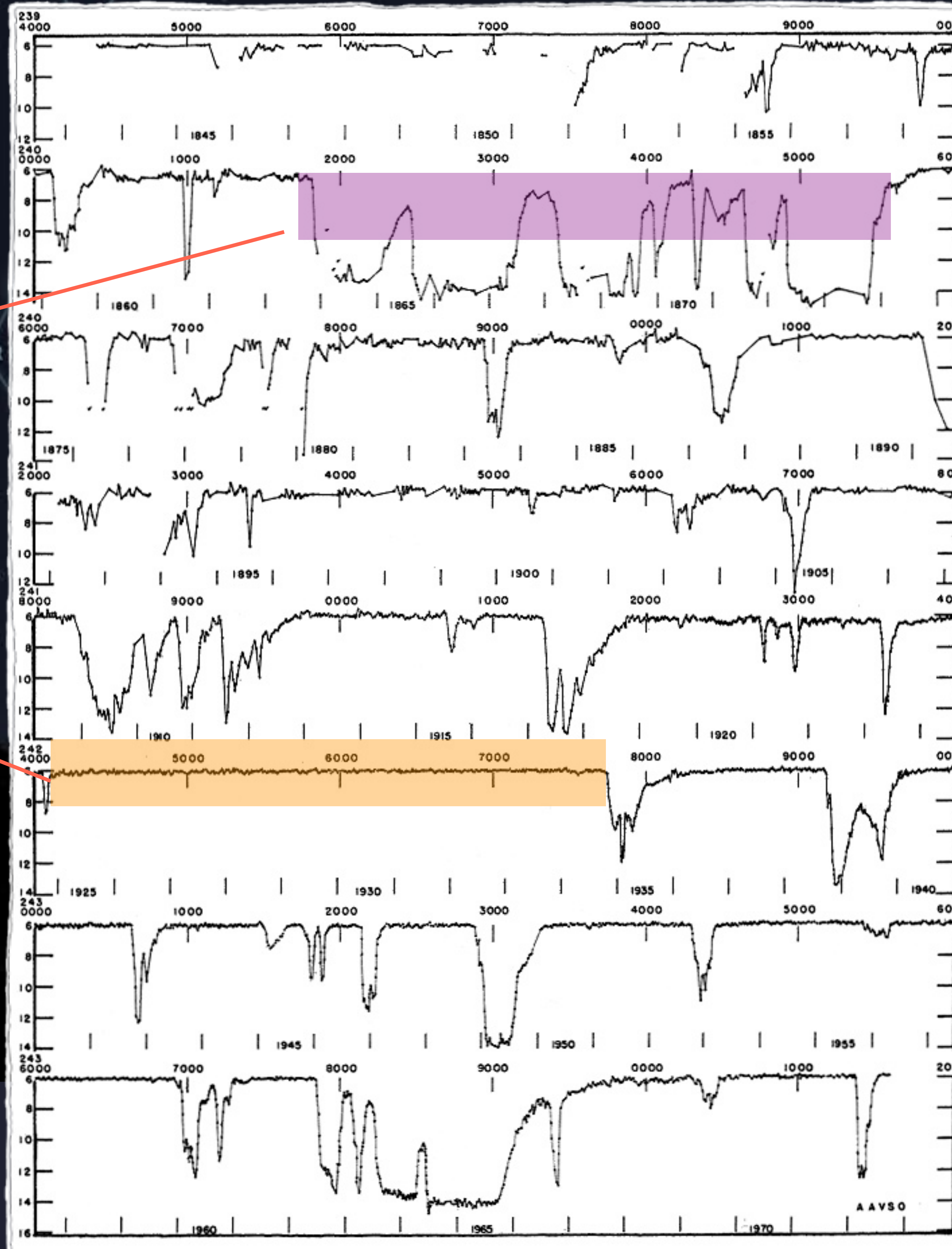
RCB stars

Characteristic unpredictable photometric declines down up to 9 mag in 2-3 weeks !

Period of strong activity

Remained bright for ~10 yrs continuously.





R CrB light curve (1843-1972)

RCB stars

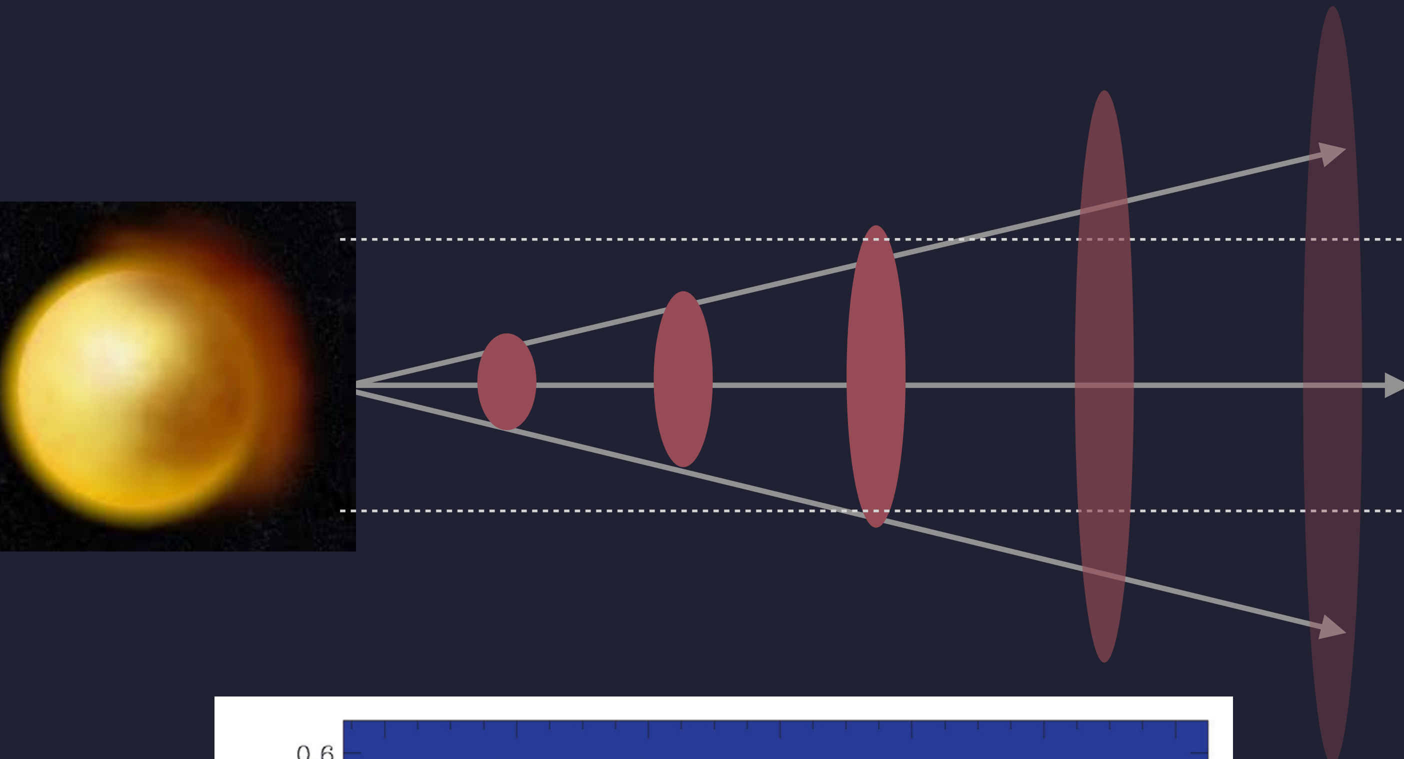
Dust clouds

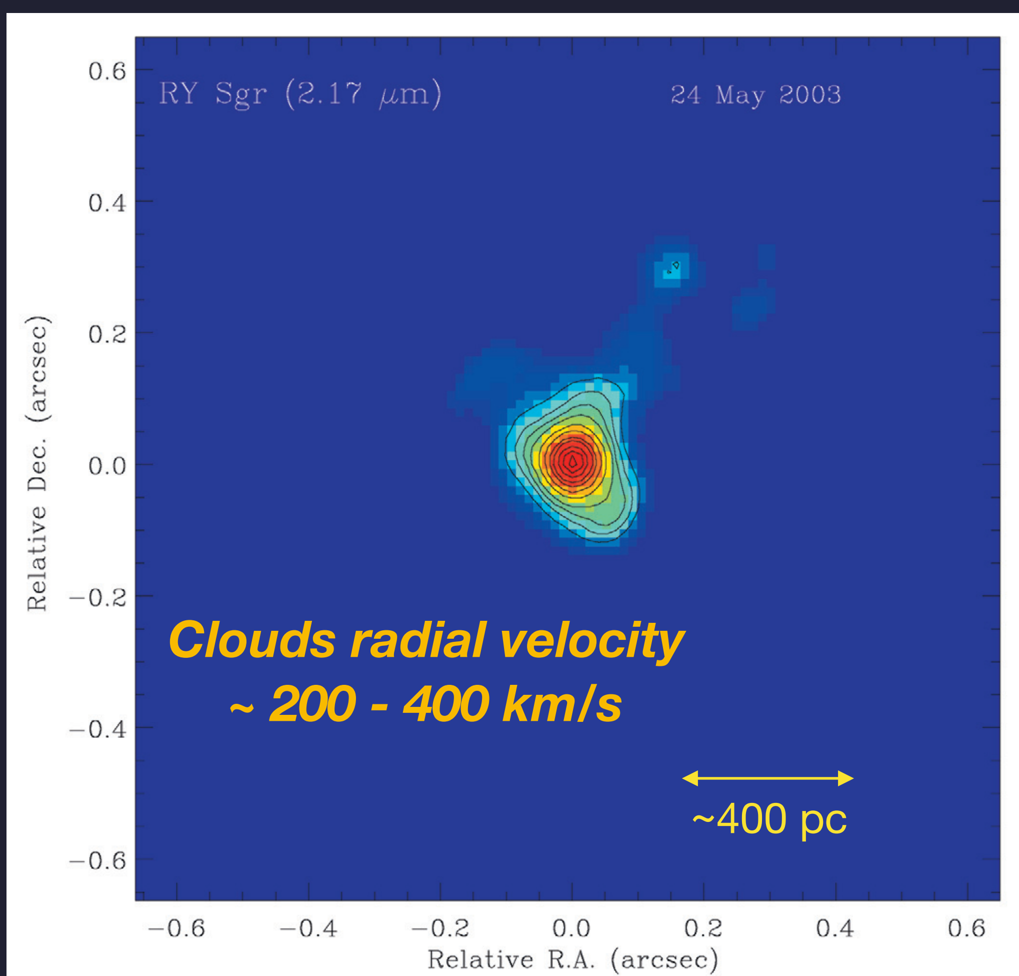
Dust production rate :

10^{-7} - 10^{-6} $M_{\odot}$ / year

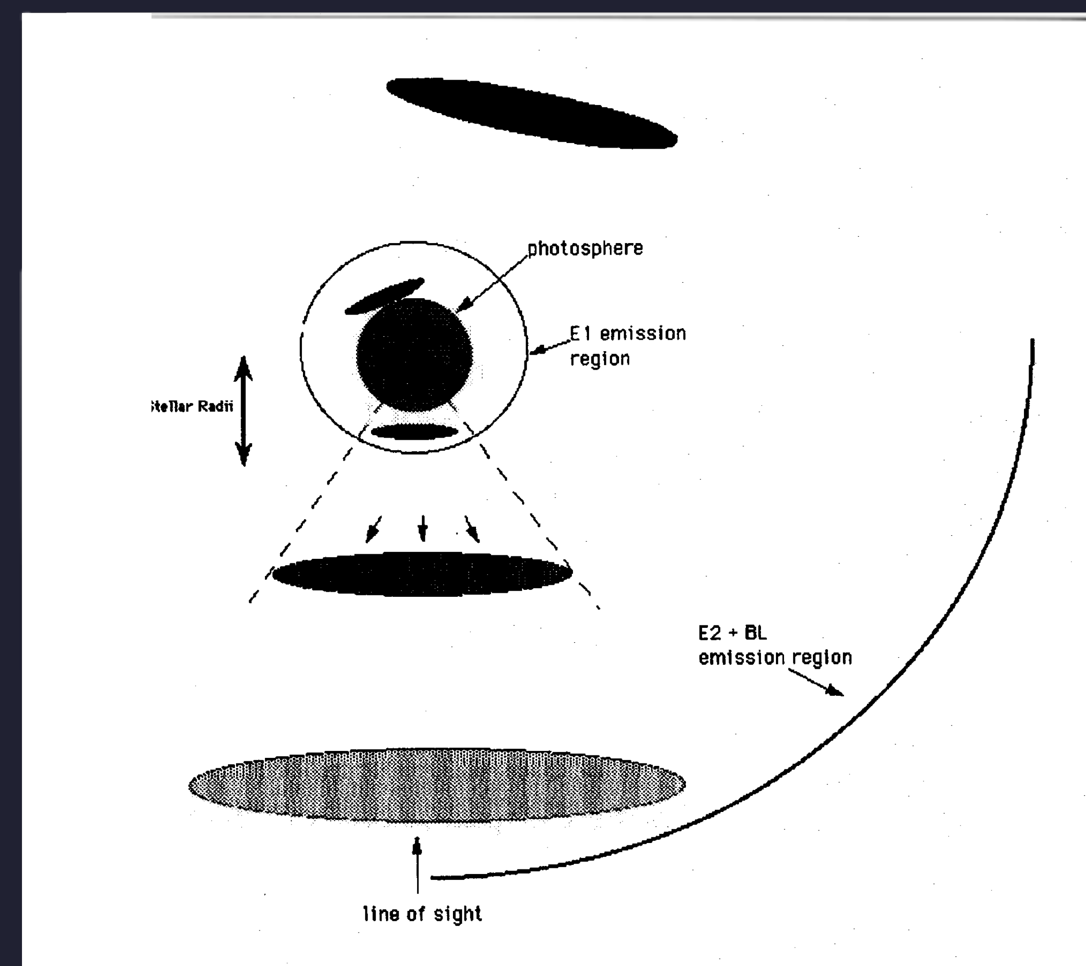
~ Earth mass every 1 - 10 years

or ~ Moon mass every 1 - 10 days





de Laverny et al. (2004)

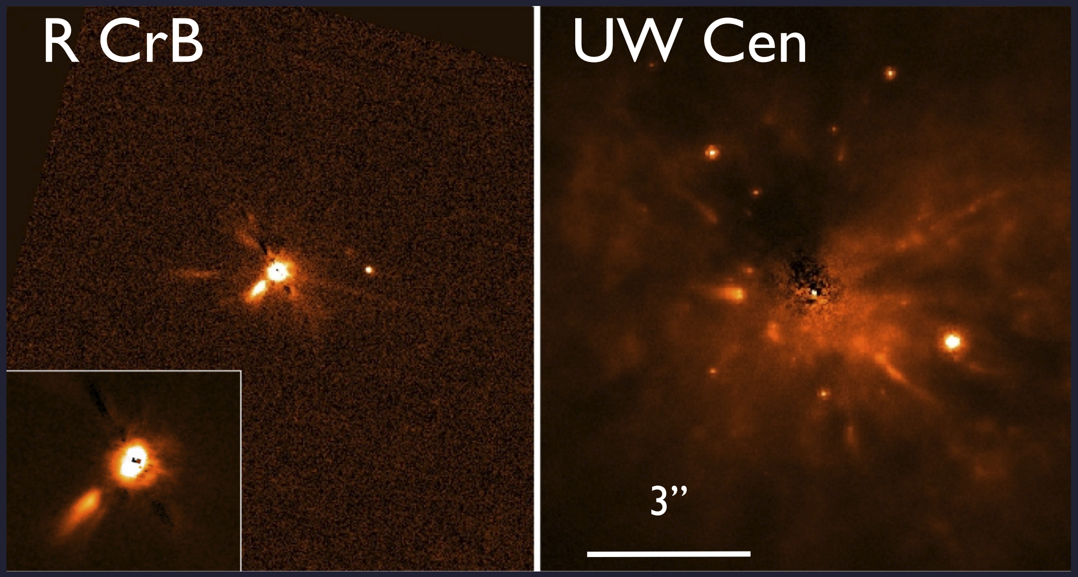


Clayton, 1996

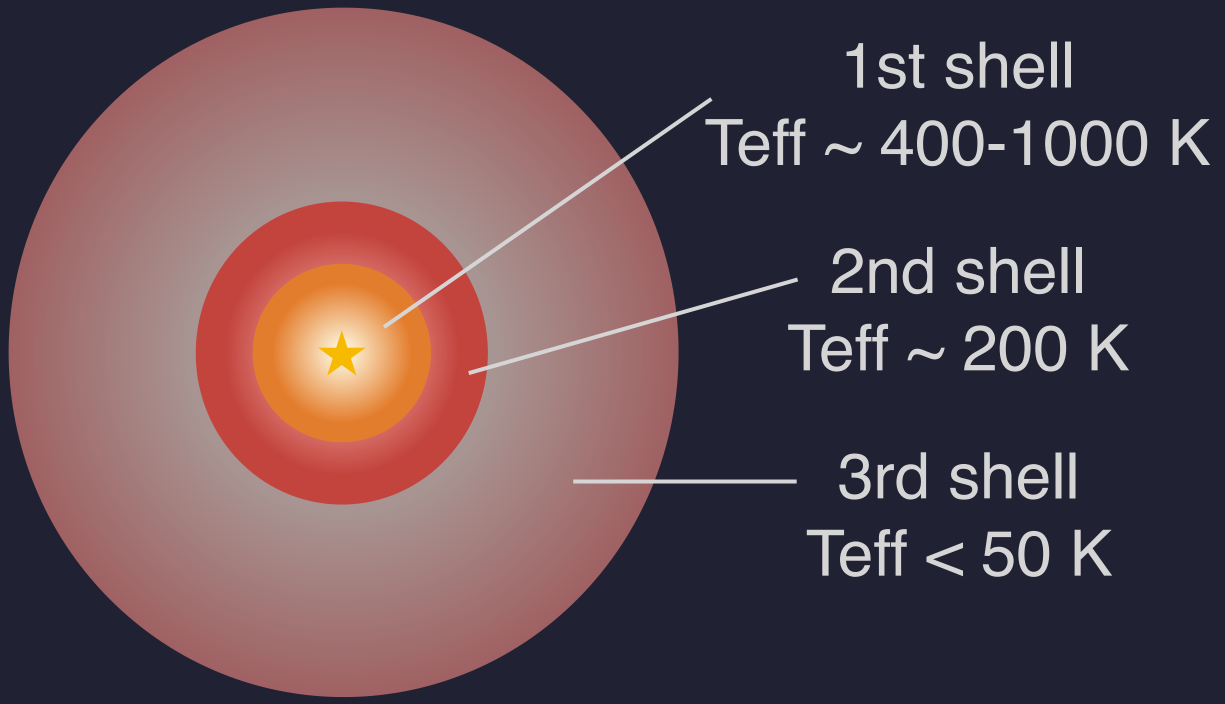
RCB stars

Circumstellar dust shell

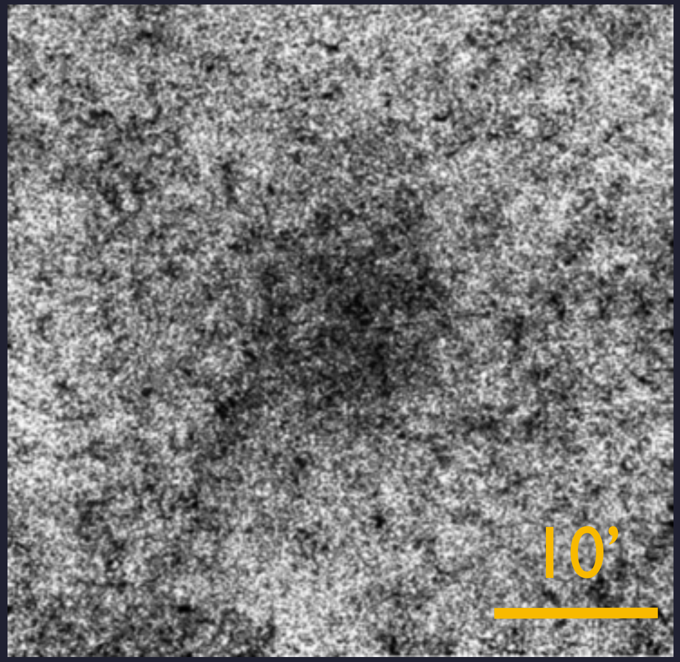
Small scale structures



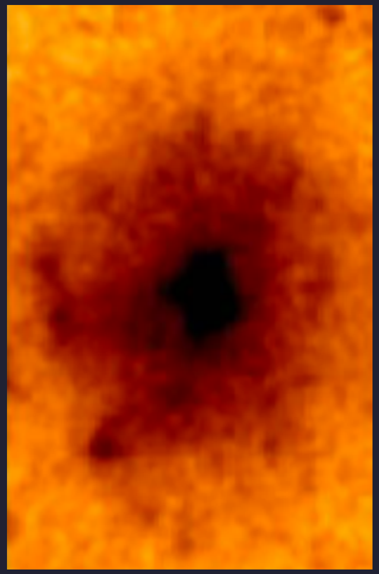
HST *Clayton et al., 2011 (~V band)*



Large scale structures… ~2 pc radius

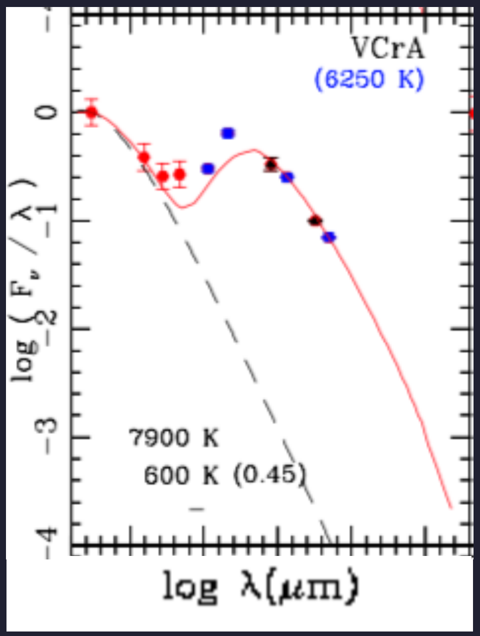


R CrB *Clayton et al., 2012*

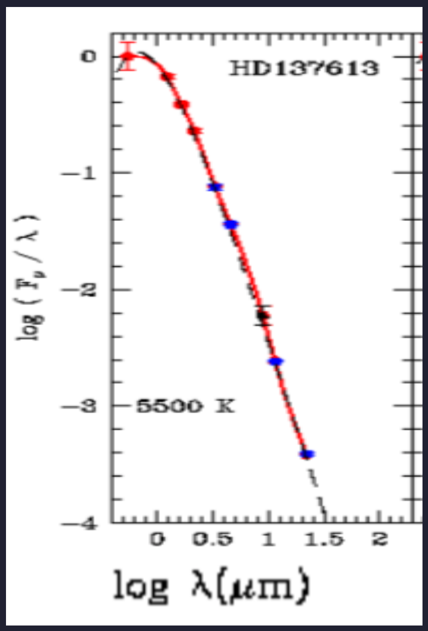


RY Sgr *Herschel*

RCB



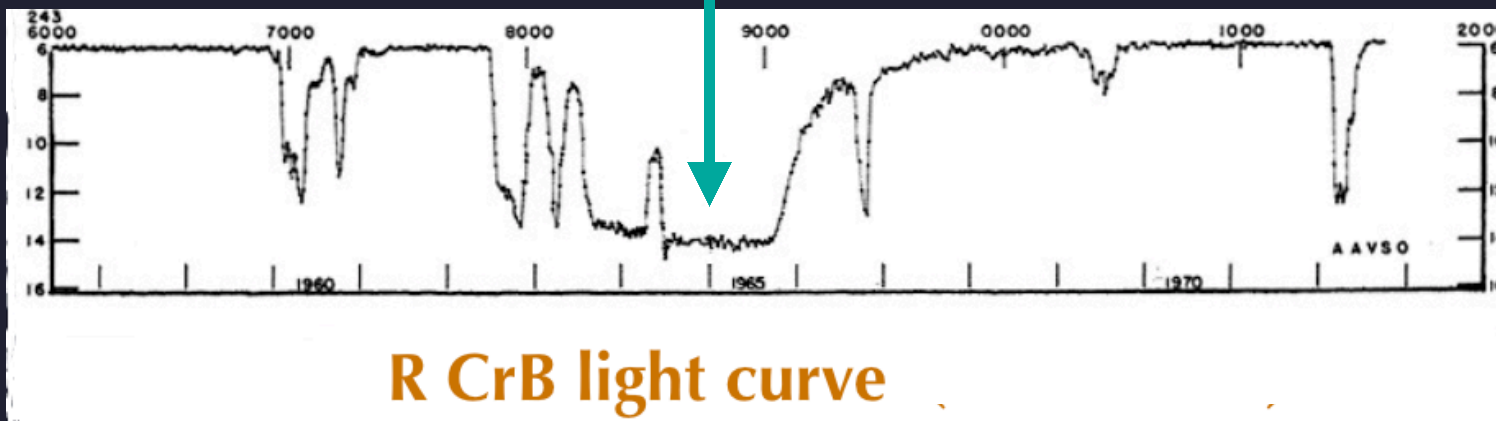
dLHdC

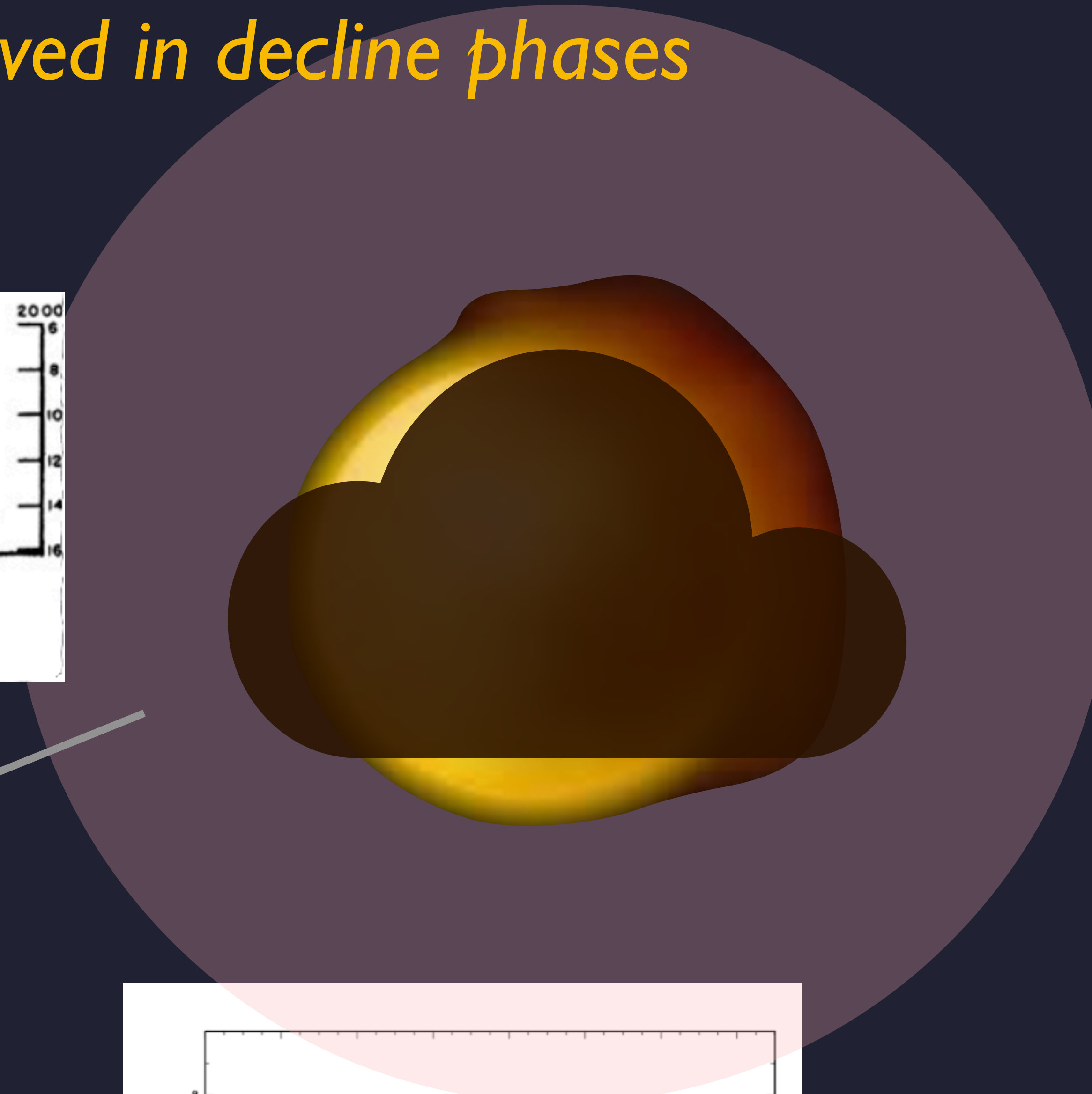


RCB stars

Broad band emissions observed in decline phases

Natural Coronagraph !!





Allow observation of immediate surrounding !

=> circumstellar gas, ...

- **Broad band emission features :**

Most common: Ca II H and K, Na I D lines
+ [N II] (5755, 6548, 6583 Å), He I (5876, 7065 Å),
Ca II IR triplet, and [Ca II] (7291, 7323 Å),
[O I] (6300, 6363 Å), [S II] (6717, 6731 Å) ,
K I (7664, 7699 Å), and the C2 Swan bands.

Kameswara Rao et al. (2004, 2006)

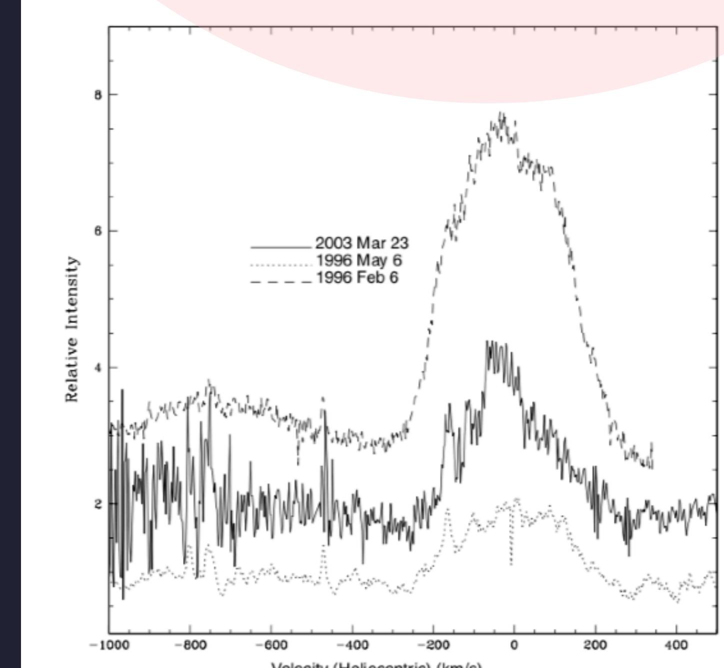
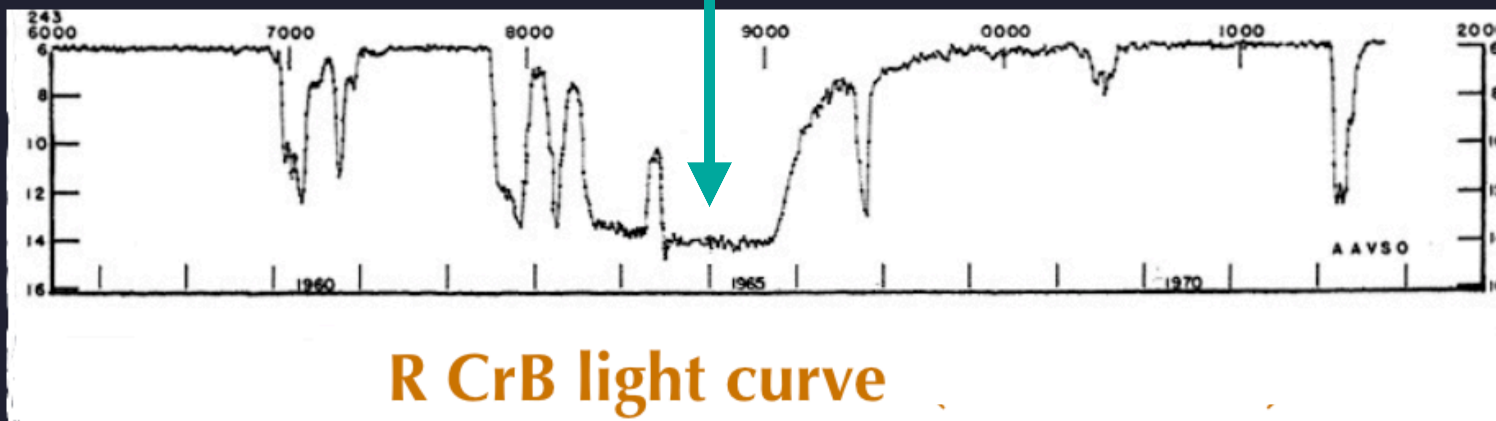


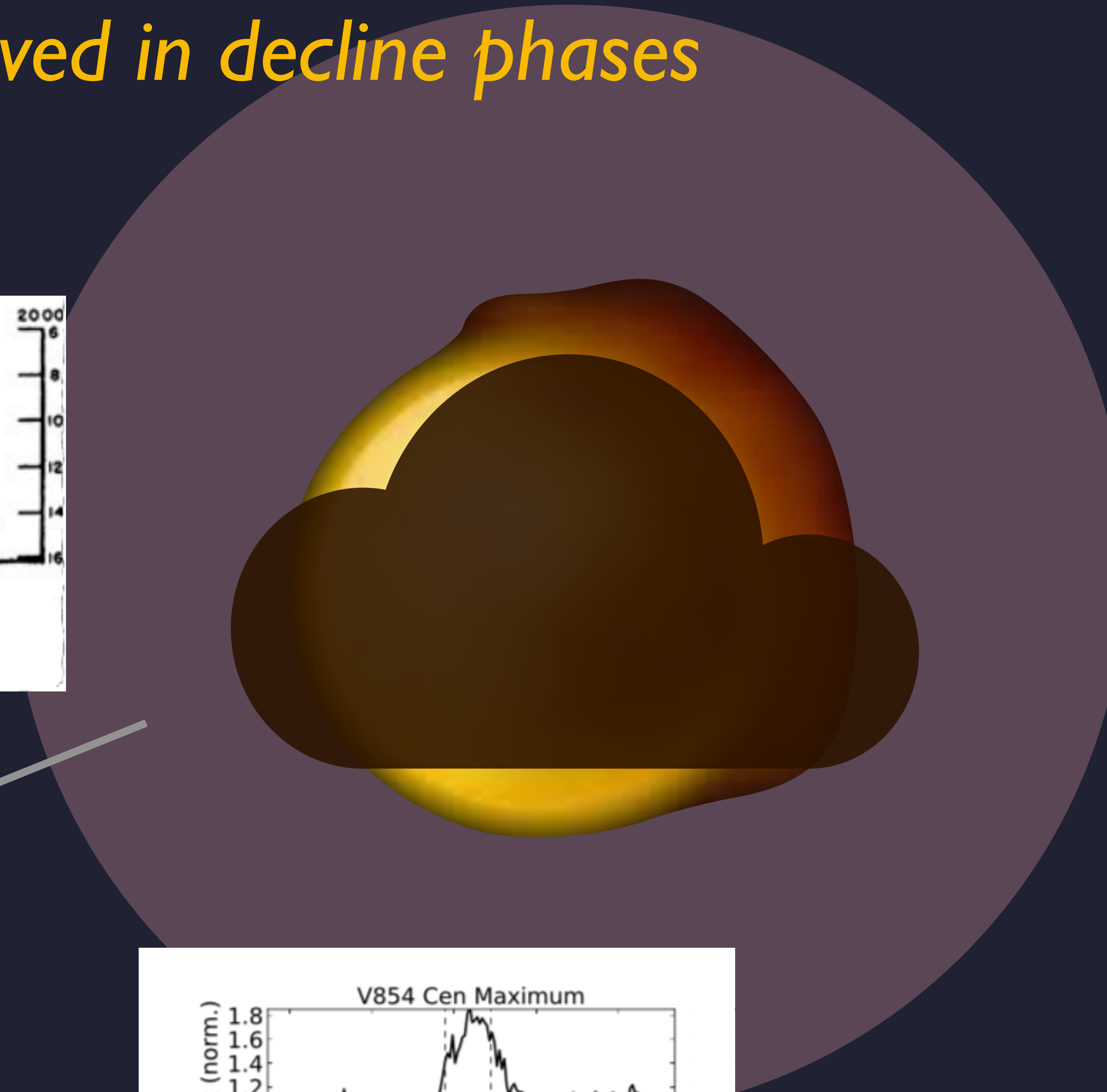
Figure 3. The He I line at 3889 Å on 2003 March 23 (solid line), on 1996 May 6 (dotted line) and on 1996 February 6 (dashed line).

RCB stars

Broad band emissions observed in decline phases

Natural Coronagraph !!





Allow observation of immediate surrounding !

=> circumstellar gas, …

- **Broad band emission features :**

Oostrum et al. (2018) using ESO / X-shooter
report of unidentified visual emission features (UFs)
=> Chemical and physical nature is still a mystery !

More specifically: new feature at 8692 Å
=> likely of a carbonaceous molecular nature

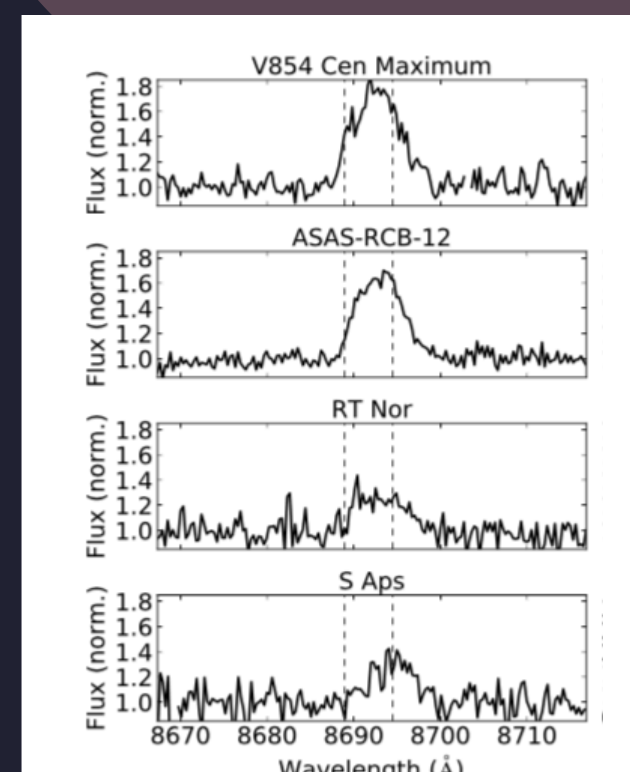
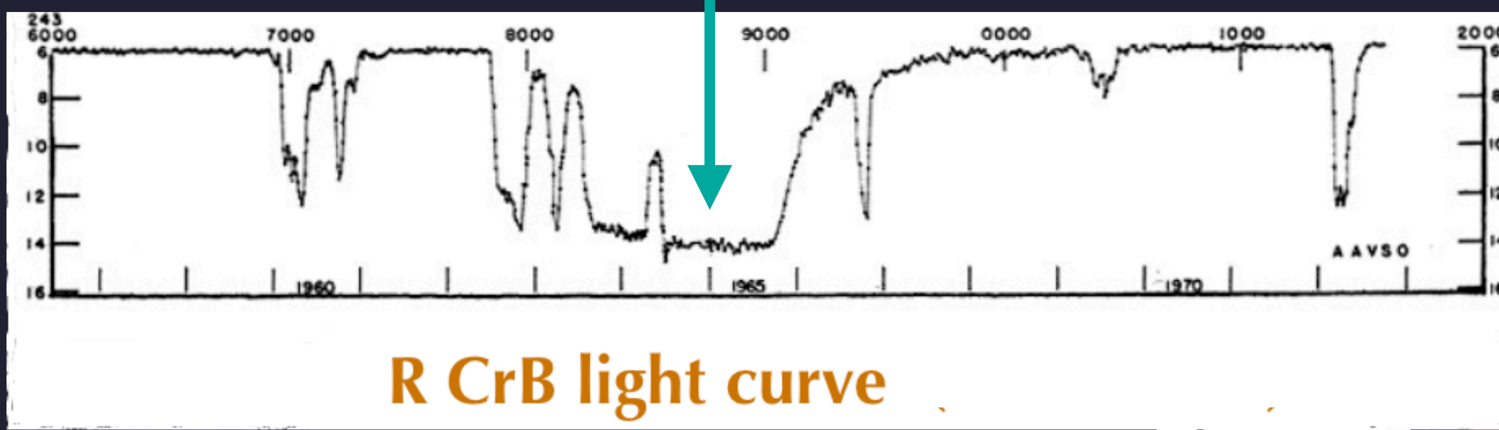


Fig. 2. λ8692 unidentified feature (UF)

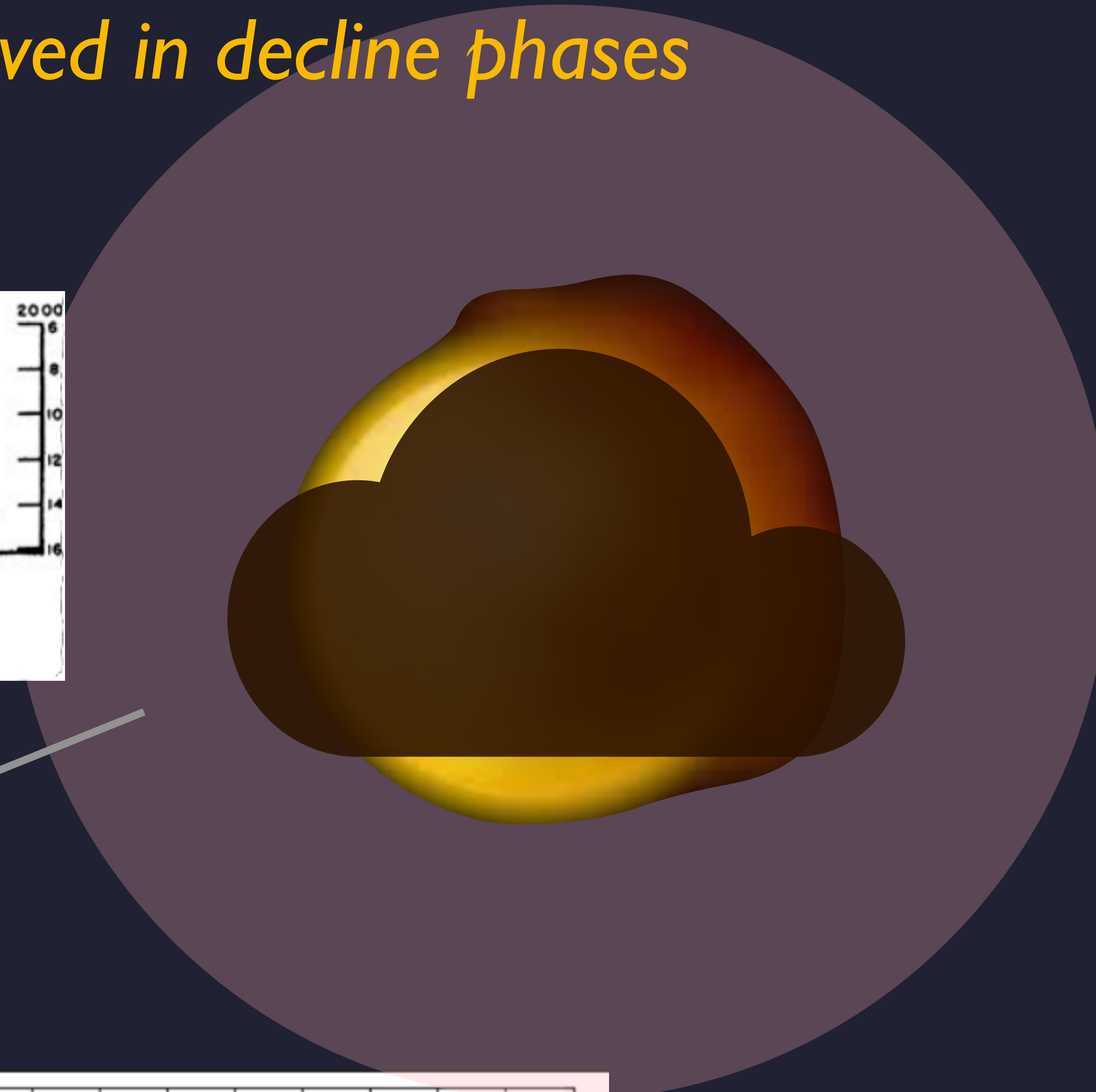
RCB stars

Broad band emissions observed in decline phases

Natural Coronagraph !!



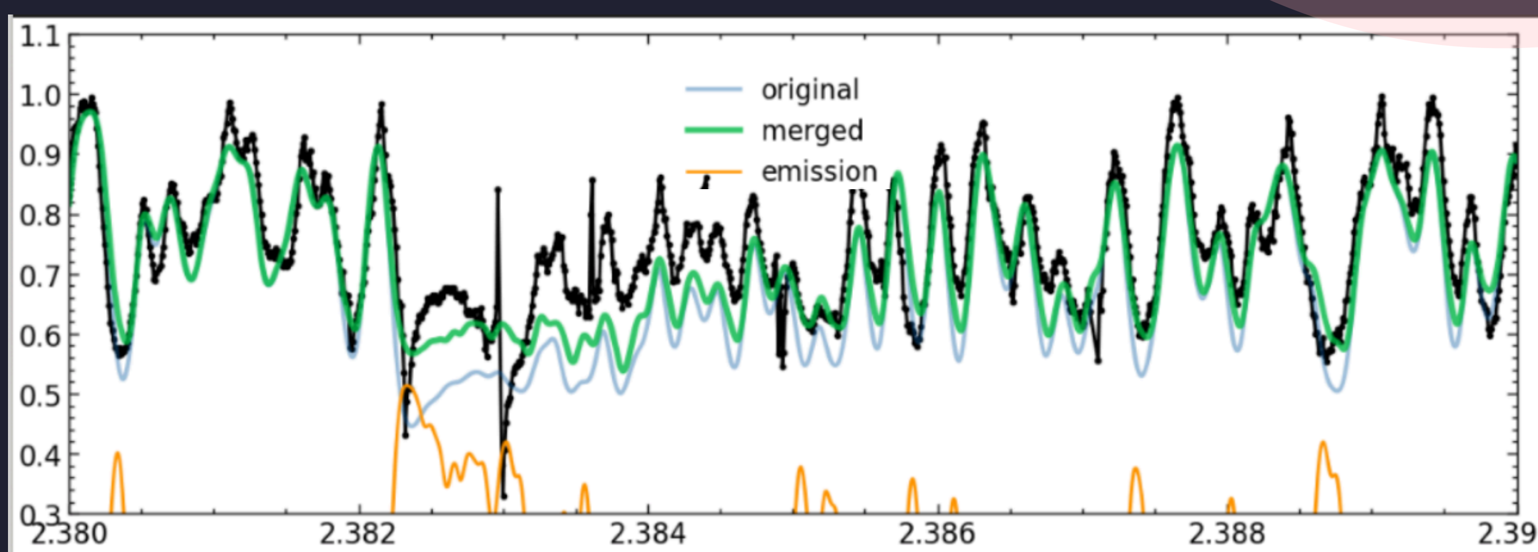
R CrB light curve



Allow observation of immediate surrounding !

=> circumstellar gas, ...

- **Broad band emission features :**



Mehla et al. (2025): CO Emission + shift of 250 km/s was needed for some RCB stars

Oxygen isotopic $^{16}O/^{18}O$ ratios of HdC Stars

Advait Mehla

pHd student, Caltech

Contact
at amehla@caltech.edu for questions

Mehla et al. 2025 in PASP

Oxygen Isotope Ratios in Hydrogen-deficient Carbon Stars: A Correlation with Effective Temperature and Implications for White Dwarf Merger Outcomes

Advait Mehla[1], Mansi M. Kasliwal[2], Viraj Karambelkar[2,7], Patrick Tisserand[3], Courtney Crawford[4], Geoffrey Clayton[5], Jamie Soon[6], and Varun Bhalerao[1]

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- IRTF / IShell NIR spectrograph: R = 75,000 (2.26 - 2.48 μm)
- 6 RCBs and 6 dLHdCs
- ExoMol linelists: CN, CO, C_2
- First NIR High-Res observations of few dLHdC stars

$^{16}O/^{18}O$ ratios of HdC Stars

Past Low-res observations:

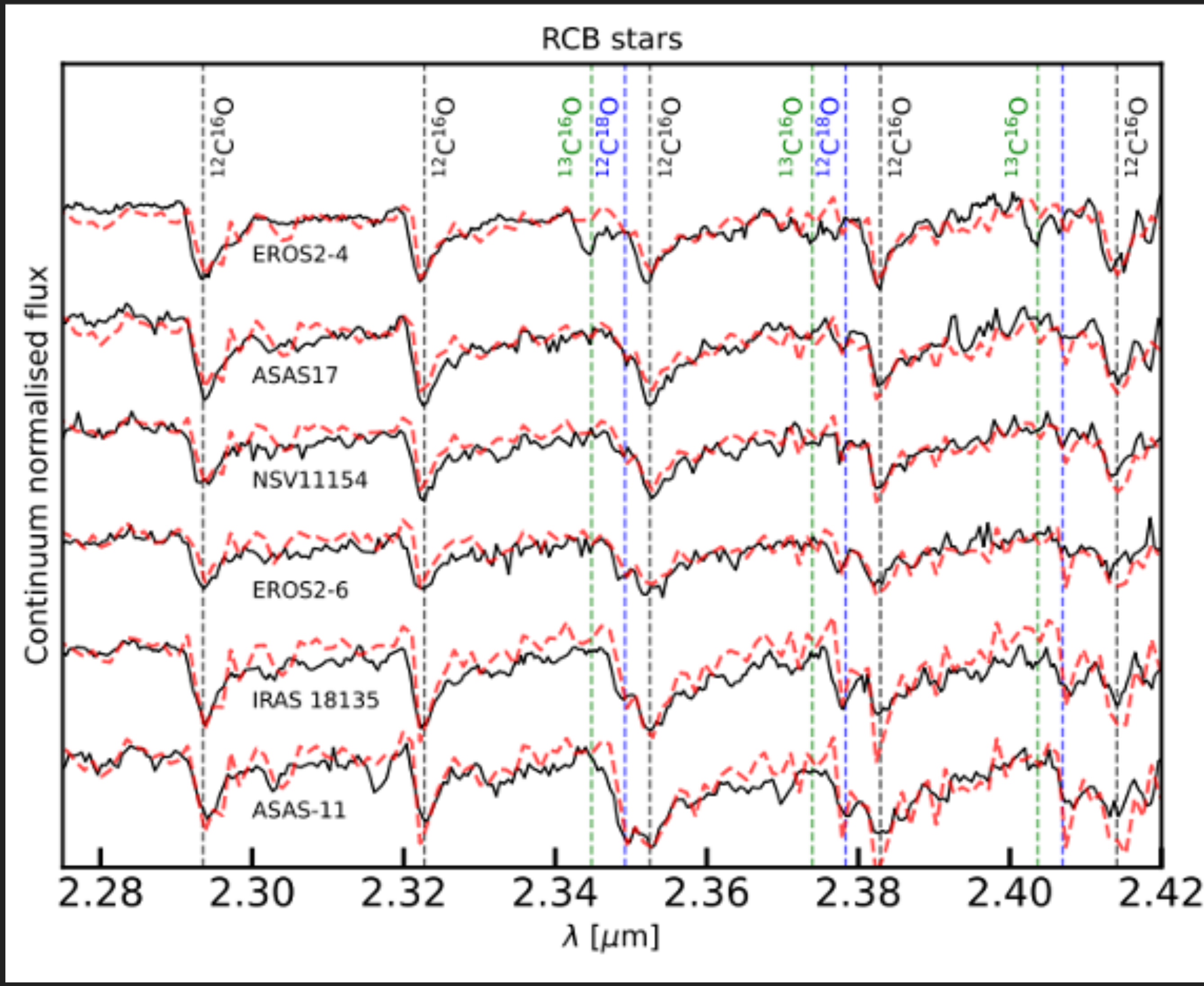
- HdC stars are strongly enhanced ^{18}O

  HdC: $^{16}O/^{18}O \simeq$ 1-30

  Sun: $^{16}O/^{18}O \simeq$ 500

- Smoking gun for the Double white dwarf mergers scenario !!

- Process that can create this amount of ^{18}O without converting it to ^{22}Ne



Karambelkar et al. (2023)

Clayton et al. (2005, 2007)

Garcia-Hernandez et al. (2009, 2010)

Alpha capture reaction chain :

$$^{14}N(\alpha,\gamma)^{19}F(\beta^+)^{18}O\ (\alpha,\gamma)^{22}Ne$$

=> Need the right amount of energy to do the first half but NOT the second half during WD merger

$^{16}O/^{18}O$ ratios of HdC Stars

Procedure

- Modified version of TSFitPy package used for fitting using chi^2 minimization
  => Python wrapper around Turbospectrum
  => Modifications were made to enable fitting of isotope ratios

- H-def MARCS Atmospheric models grid (60 models):
  - T_{eff} = 4000-7500K (step 250 K)
  - A(C) = 9.5, A(O) = 8.8
  - A(N) = 7.5, 8.0, 8.5, 9.4
  - log(g) = 1.0

- Initial T_{eff} estimated using colour-temperature calibration (Crawford 2023)

$^{16}O/^{18}O$ ratios of HdC Stars

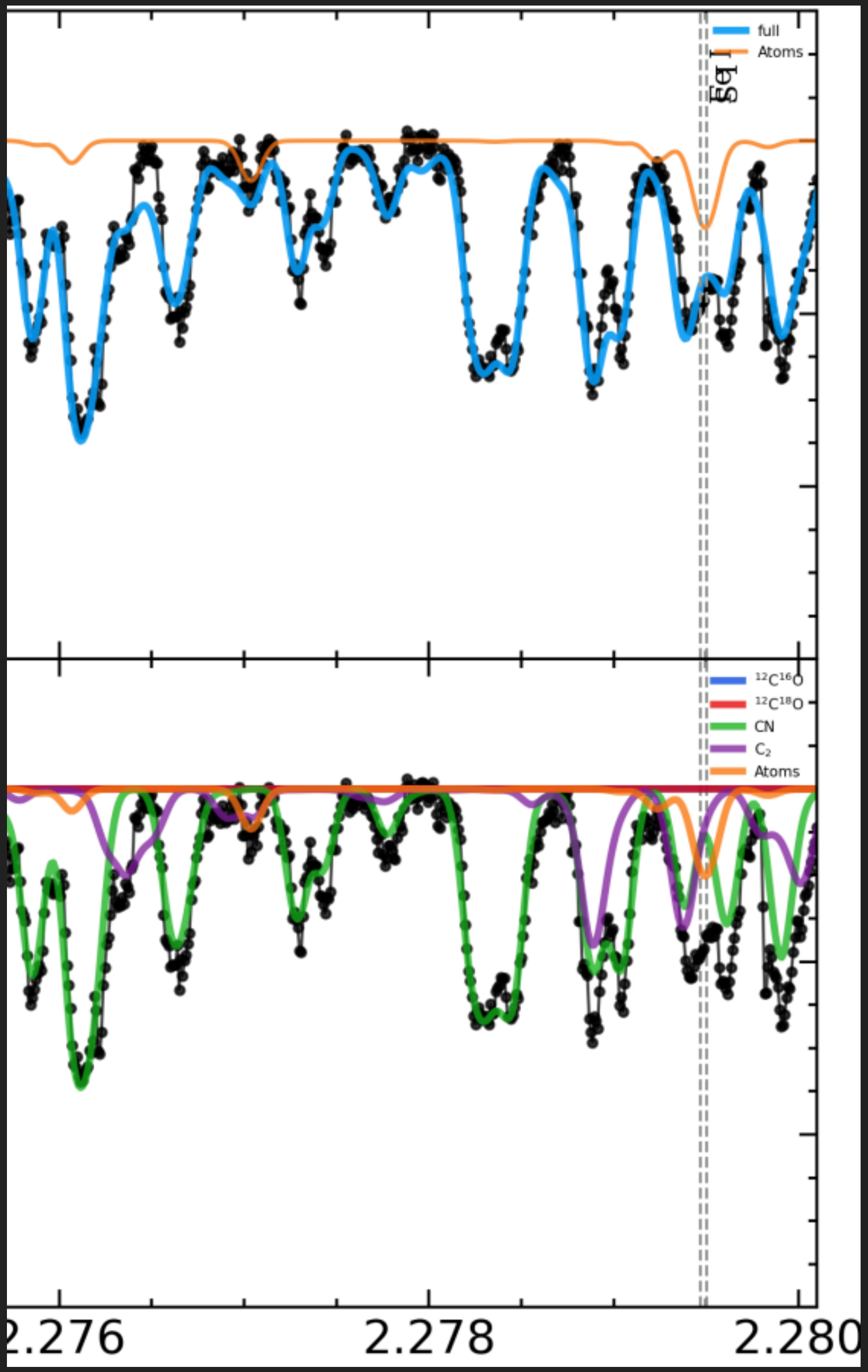
Procedure

- A(C) and A(N) are fitted together
  Region: < 2.38 um, outside the CO
- Majority of the C_2 lines blended with CN

=> first: get an initial A(C) estimate using few unblended C_2

=> use this to find A(N), and feed this back to find A(C) again full set of blended lines

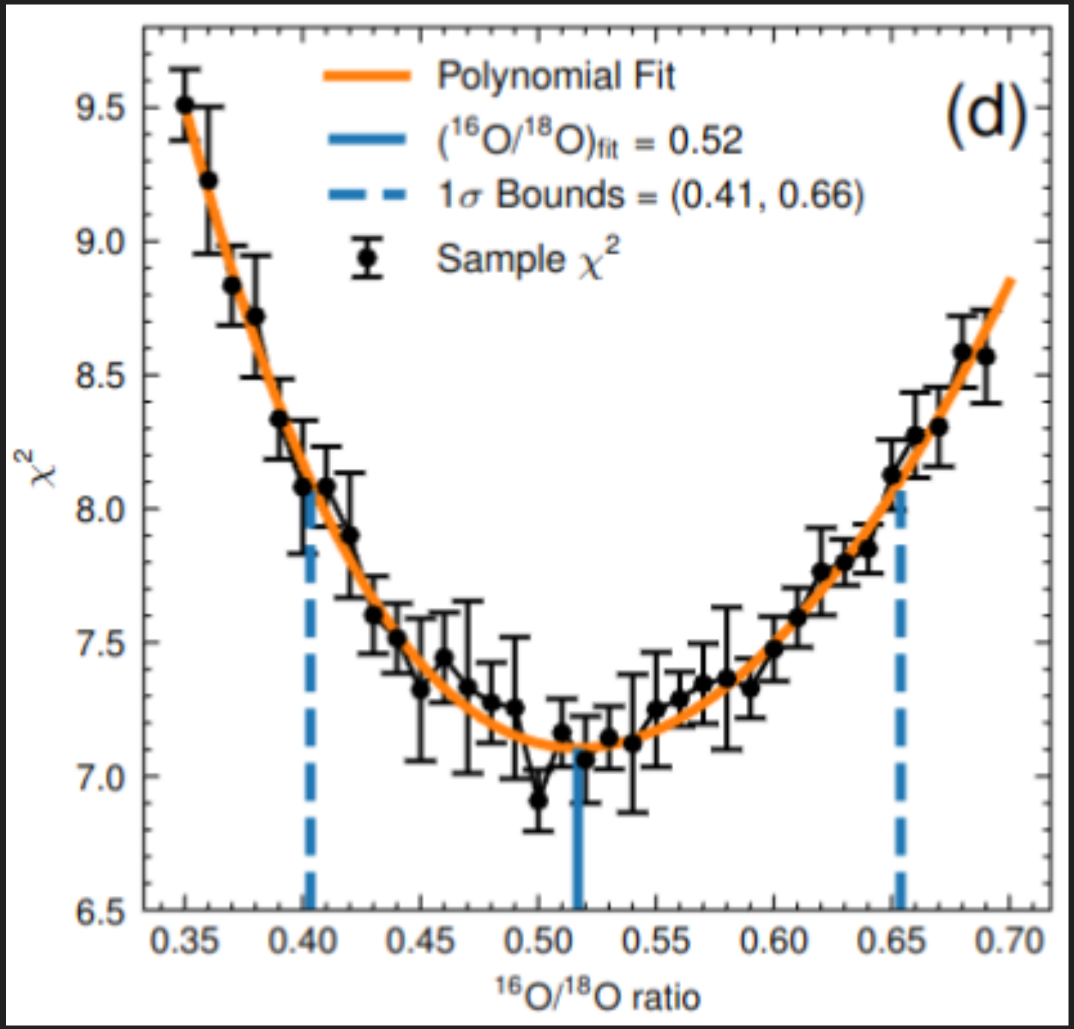
- Iterate this process until values converge

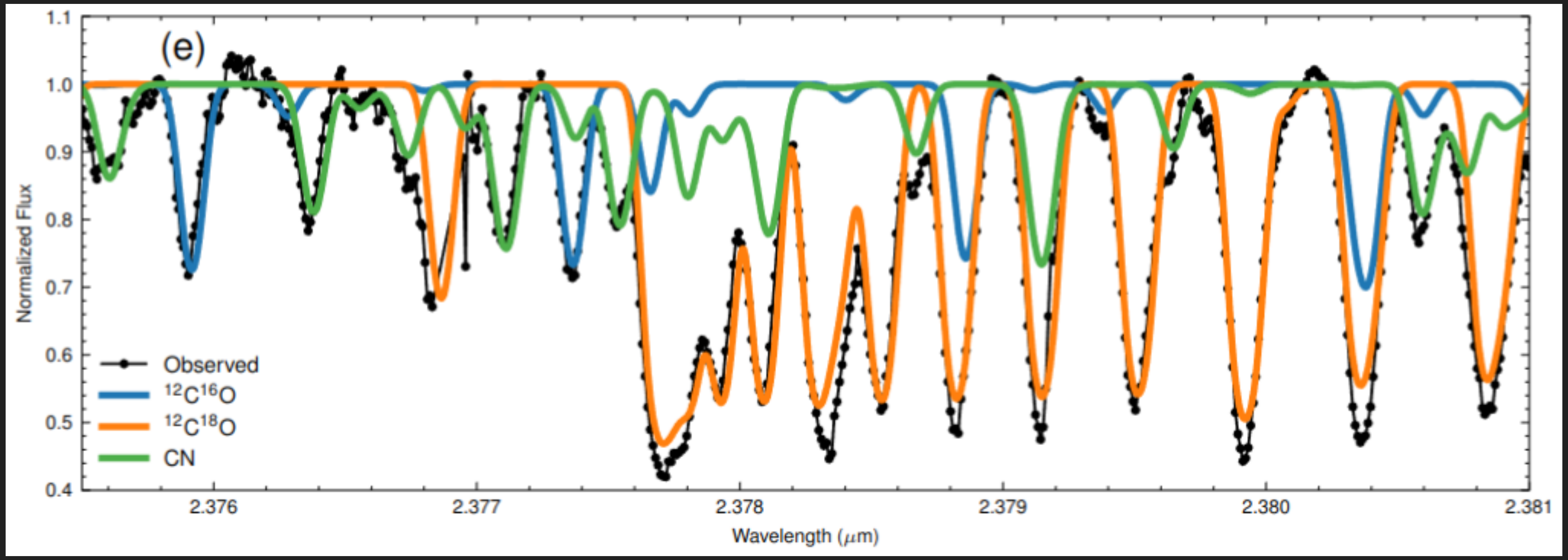


$^{16}O/^{18}O$ ratios of HdC Stars

Procedure

- Next, a combined CO linemask with isotopologues was used
- A list of input isotope ratios are fitted to find the best-fit (reduced) χ^2 for each
- Isotope ratio and 1σ bounds are estimated from the minimum and $\Delta\chi^2 = 1$ condition





$^{16}O/^{18}O$ ratios of HdC Stars

Results

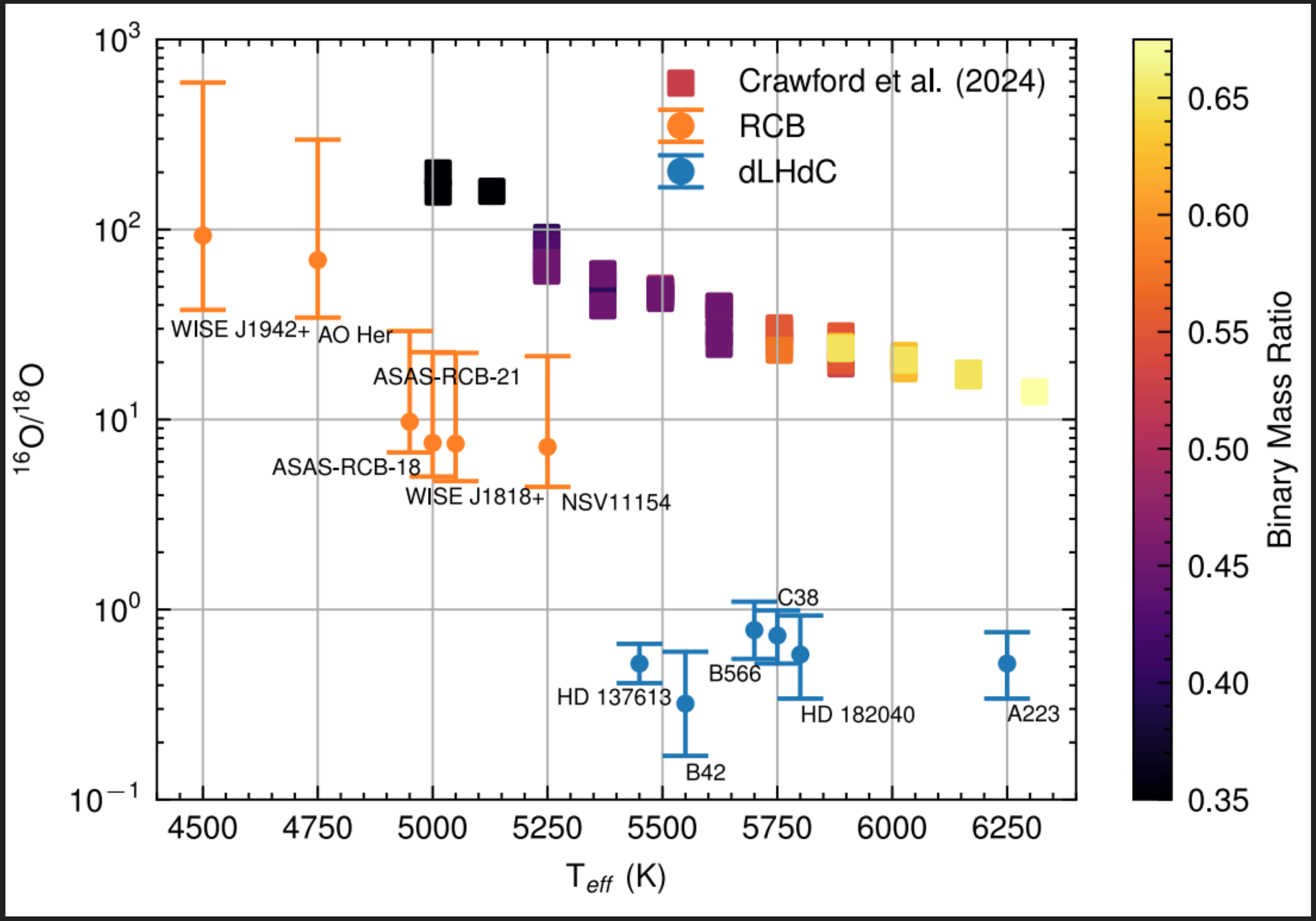
Name	$T_{\rm eff}$	A(C)	A(N)	A(O)	$^{16}O/^{18}O$	[Fe]	[Mg]	[Na]	[Ca]	[S]	[Si]
HD 137613	5500	9.86 ± 0.12	9.24 ± 0.06	8.72 ± 0.08	$0.52^{+0.14}_{-0.11}$	-0.19	0.43	0.32	-0.22	-0.19	-0.38
HD 182040	5750	9.90 ± 0.13	9.08 ± 0.08	7.99 ± 0.06	$0.58^{+0.35}_{-0.24}$	-0.45	0.17	-0.02	-0.4	-0.15	-0.21
B566	5750	10.03 ± 0.25	9.09 ± 0.10	8.55 ± 0.10	$0.78^{+0.32}_{-0.23}$	0.23	0.74	0.62	0.04	0.18	0.20
C38	5750	10.32 ± 0.16	9.47 ± 0.08	8.99 ± 0.10	$0.73^{+0.26}_{-0.21}$	-0.78	-0.12	-0.12	-0.78	-0.38	-0.65
A223	6250	9.48 ± 0.24	8.73 ± 0.09	8.20 ± 0.09	$0.60^{+0.24}_{-0.19}$	-0.29	0.02	0.02	-0.52	-0.10	0.33
B42	5500	10.17 ± 0.14	9.18 ± 0.14	8.81 ± 0.1	$0.32^{+0.28}_{-0.15}$	-0.31	0.34	0.29	0.06	-0.10	0.03
NSV11154	5250	8.90 ± 0.06	7.45 ± 0.15	7.19 ± 0.10	$7.18^{+6.38}_{-2.76}$	-0.92	-1.37	-1.18	-1.11	-0.61	-1.11
ASAS-RCB-21	5000	8.86 ± 0.06	7.74 ± 0.09	7.77 ± 0.16	$6.85^{+2.30}_{-1.77}$	-0.80	-1.20	-1.56	-1.54	-0.12	-0.83
ASAS-RCB-18	5000	9.15 ± 0.05	7.83 ± 0.19	8.01 ± 0.14	$9.73^{+4.89}_{-3.02}$	-1.03	-1.28	-1.52	-1.74	-0.33	-0.14
WISE J1818+	5000	8.93 ± 0.06	7.60 ± 0.12	7.55 ± 0.10	$7.47^{+4.27}_{-2.73}$	-0.92	-1.23	-1.75	-1.56	0.01	-0.57
AO Her	4750	8.95 ± 0.05	6.95 ± 0.11	7.76 ± 0.14	69.03^{+228}_{-35}	-0.69	-1.22	-1.01	-0.90	-0.89	-0.38
WISE J1942+	4500	8.72 ± 0.06	6.59 ± 0.13	7.42 ± 0.10	92.93^{+500}_{-55}	-0.69	-1.31	-1.27	-0.86	-0.16	-1.00

- RCBs have $^{16}O/^{18}O > 4$ & dLHdCs have < 1 in this sample
- Exist a sub-population of cold RCBs with $^{16}O/^{18}O \sim 100$

$^{16}O/^{18}O$ ratios of HdC Stars

Results

Evolution with Temperature !!

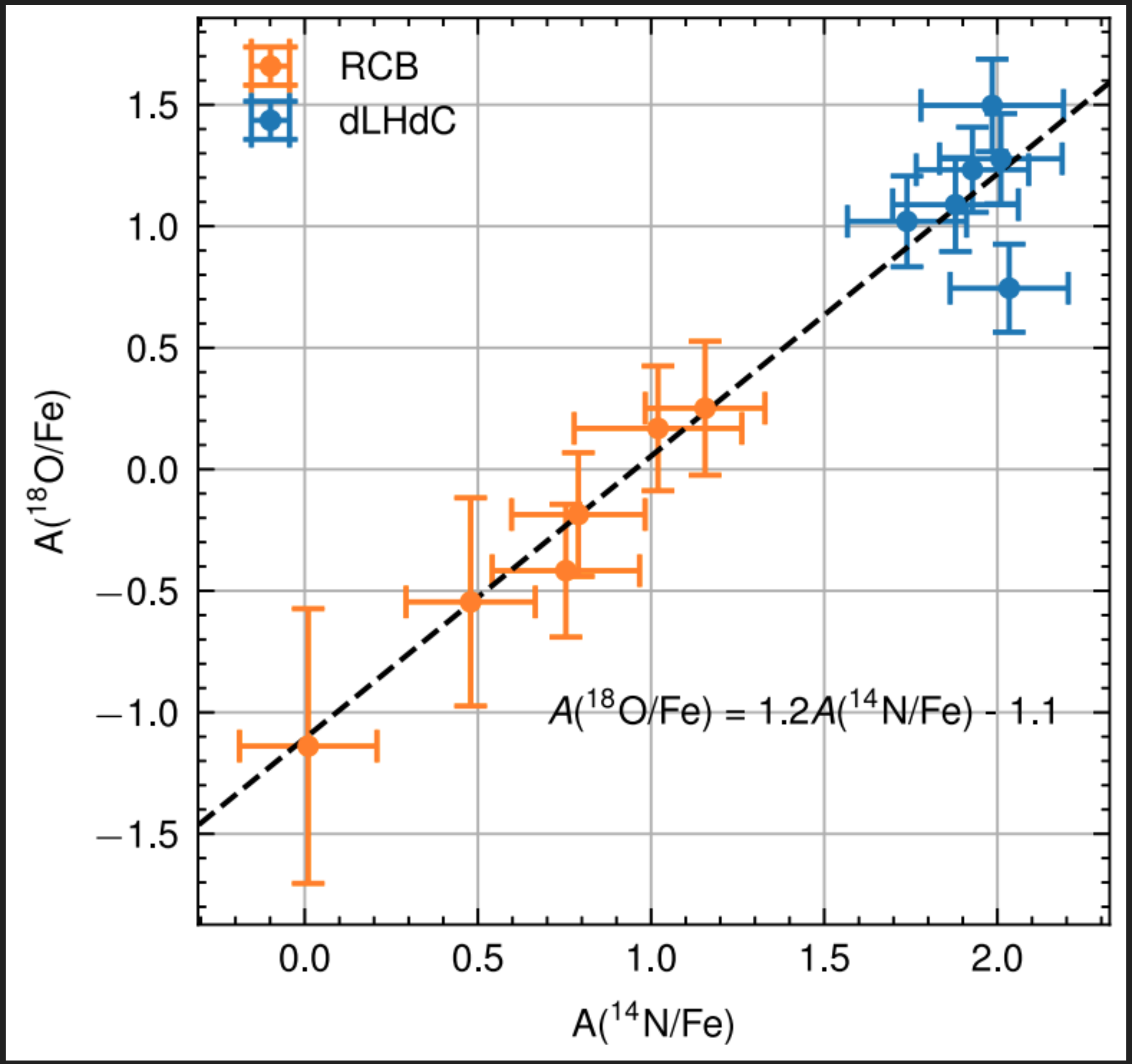


Binary Mass ratio
q = M_{donor} / $M_{accretor}$

- Matches trend predicted by MESA theoretical simulations
- Theoretical models overprediction: by ~100 !
- Binary mass ratio might play a role in deciding which class is formed

$^{16}O/^{18}O$ ratios of HdC Stars

Results



Correlation between $A(^{18}O)$ and A(N)

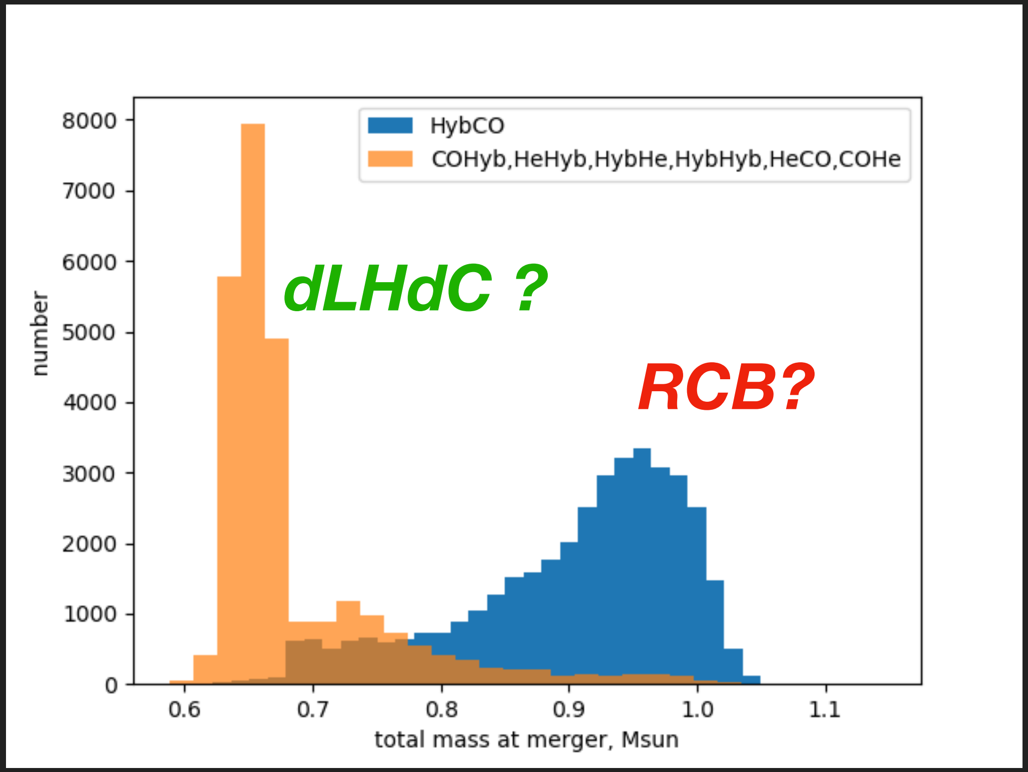
A fixed and small amount (≈8%) of the original ^{14}N is converted to ^{18}O in all HdC stars

Alpha capture reaction chain

$$^{14}N(\alpha,\gamma)^{19}F(\beta^{+})^{18}O\ (\alpha,\gamma)^{22}Ne$$

Conclusion

- We start to uncover trends between
  T_{eff}, $^{16}O/^{18}O$, Abundances and Metallicities..



- *More advanced models* will be required to replicate the diversities HdC stars
- *Future spectral studies* on larger samples of HdC stars with variation in parameters like temperature

Thanks for listening!