In memoriam
Tom Marsh

AM CVn STARS

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He-star donor AM CVn stars and their progenitors as LISA sources

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OUTLOOK

General properties, formation, evolution

He-star donor AM CVn stars as GWR sources

AM CVn stars ≡ Interacting Double Degenerates

Weak (V = 15-20 or *g* = 13.5-24) blue objects with He-lines, but without H-lines, in the spectra.

The threshold for H-detection [N(H)/N(He)] ~ (10^{-6} – 10^{-3}), the deficit of H is real (only 2 stars with traces of H are known).

The most compact known binaries: P_{orb}=5.4-65.6 min. (a ~ 1Rsun). Only UCXB have similar range of periods .

Variability – Dwarf Novae: Δm=(3.5-6)^m, P ~ (10 – 100) day, DIM-mech., nuclear outbursts(?), first predicted by Taam (1980), but not observed as yet.

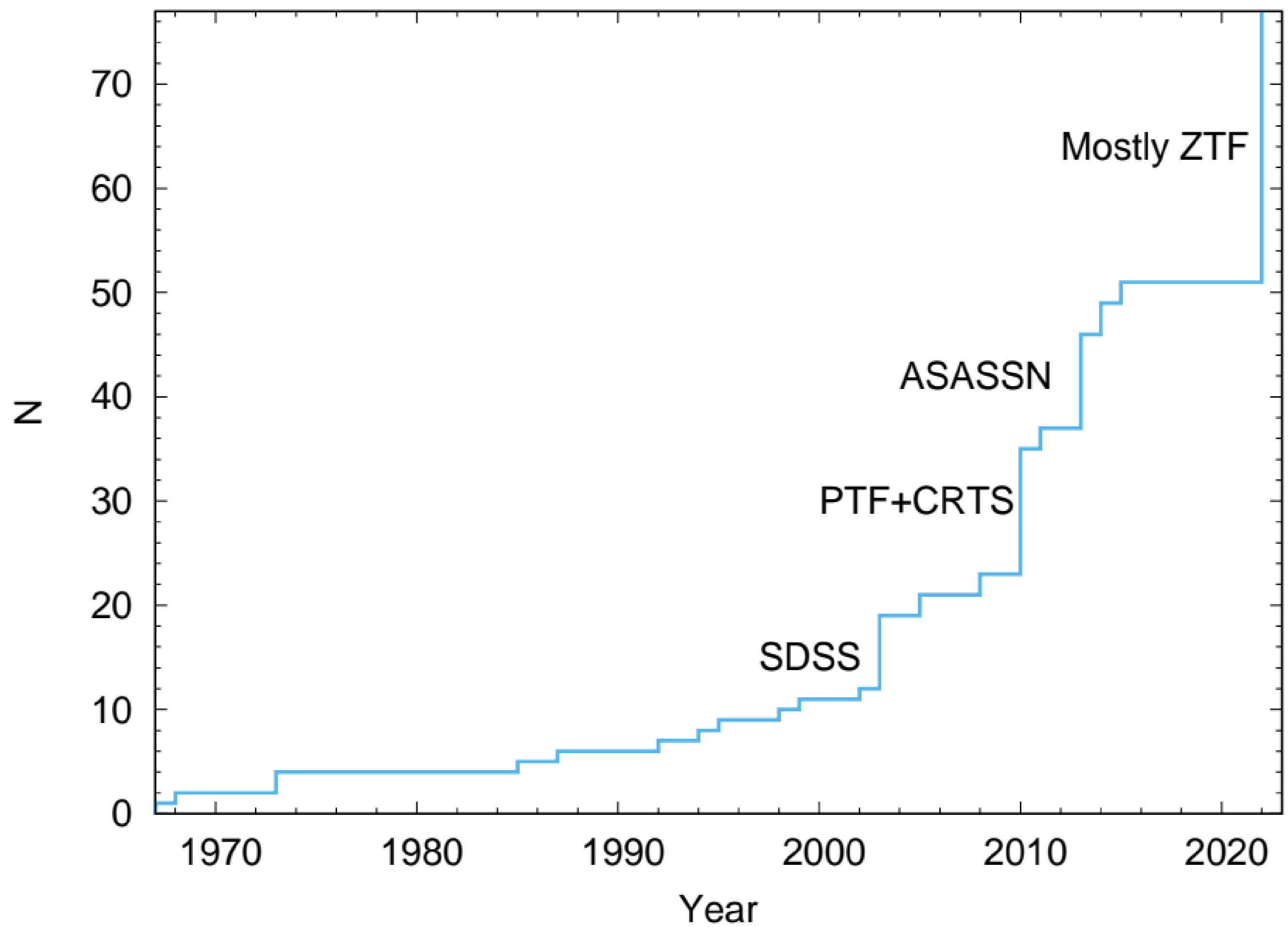
Supersoft X-ray sources (*ROSAT*, TY96).

The site of nuclear weak-*s* and *i*-processes? (Piersanti et al. 2019)

Lipunov, Postnov, Prokhorov (1987): detached close binary WD (DWD) may be the strongest sources of GW observed by lasers from space

Hellings (1996): interacting WD, i.e. AM CVns, may be observed too. But their number is small, if compared to DWD.

Before c. 2000 – serendipitous discoveries.
Progress – wide-field and transients surveys,
dedicated surveys, stimulated by planned LISA.



AM CVn itself:
discovered - 1936,
variability - 1967,
binarity - 2002

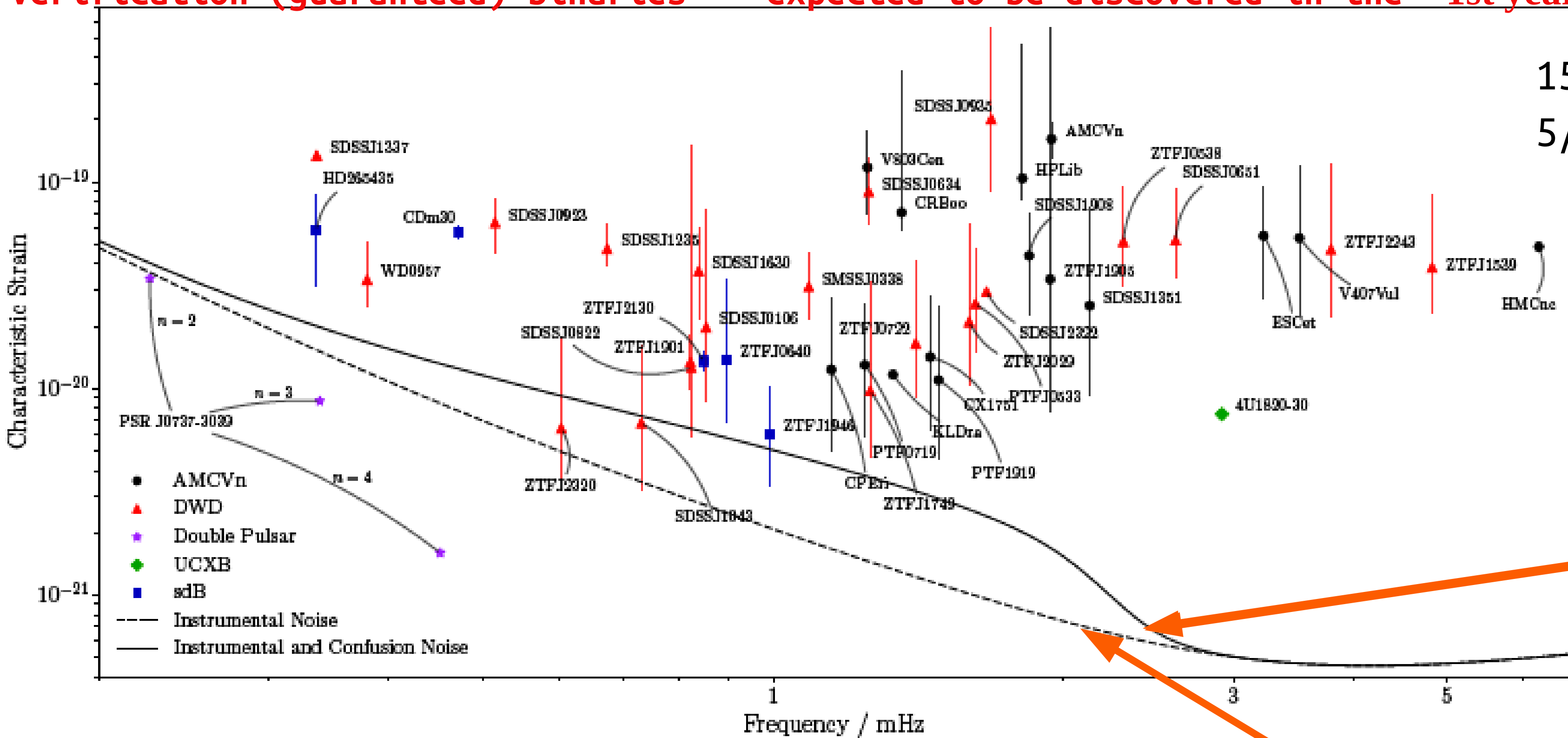
1967 - 1 star
2015 - 52 stars
2022 - 77 stars
and candidates
About
60 orbital periods
are measured.

Breedt (pre-2016)
+Yungelson (2022)

Estimated space density $\varrho > 7\times10^{-8}$ pc $^{-3}$ (Ramsay et al. 2018)

$\varrho = 6(-2,+6)\times10^{-7}$ pc $^{-3}$ (van Roestel et al. 2021)

Verification (guaranteed) binaries - expected to be discovered in the ~1st year of the mission



15/43 - AM CVns ●

5/43 - sdB+WD ■

Confusion noise+LISA noise

LISA noise

Finch et al. (2022)

VB: testing and tuning of detector

GW: amplitude of the signal

$$\mathcal{A} = \frac{2(G\mathcal{M}_c)^{5/3}(\pi f_0)^{2/3}}{Dc^4},$$

$\mathcal{M}_c = (m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$ – chirp mass, D – distance,
frequency $f_0 = 2/P$, time-derivative of GW frequency $\dot{f}$,
an inclination angle ι, ecliptic coordinates (b, l),
initial phase ϕ_0, polarisation angle ψ.

EM: f_0, (b, l), estimates of m_1 and m_2, D [Gaia!]

Evolutionary status of AM CVns: semidetached binaries

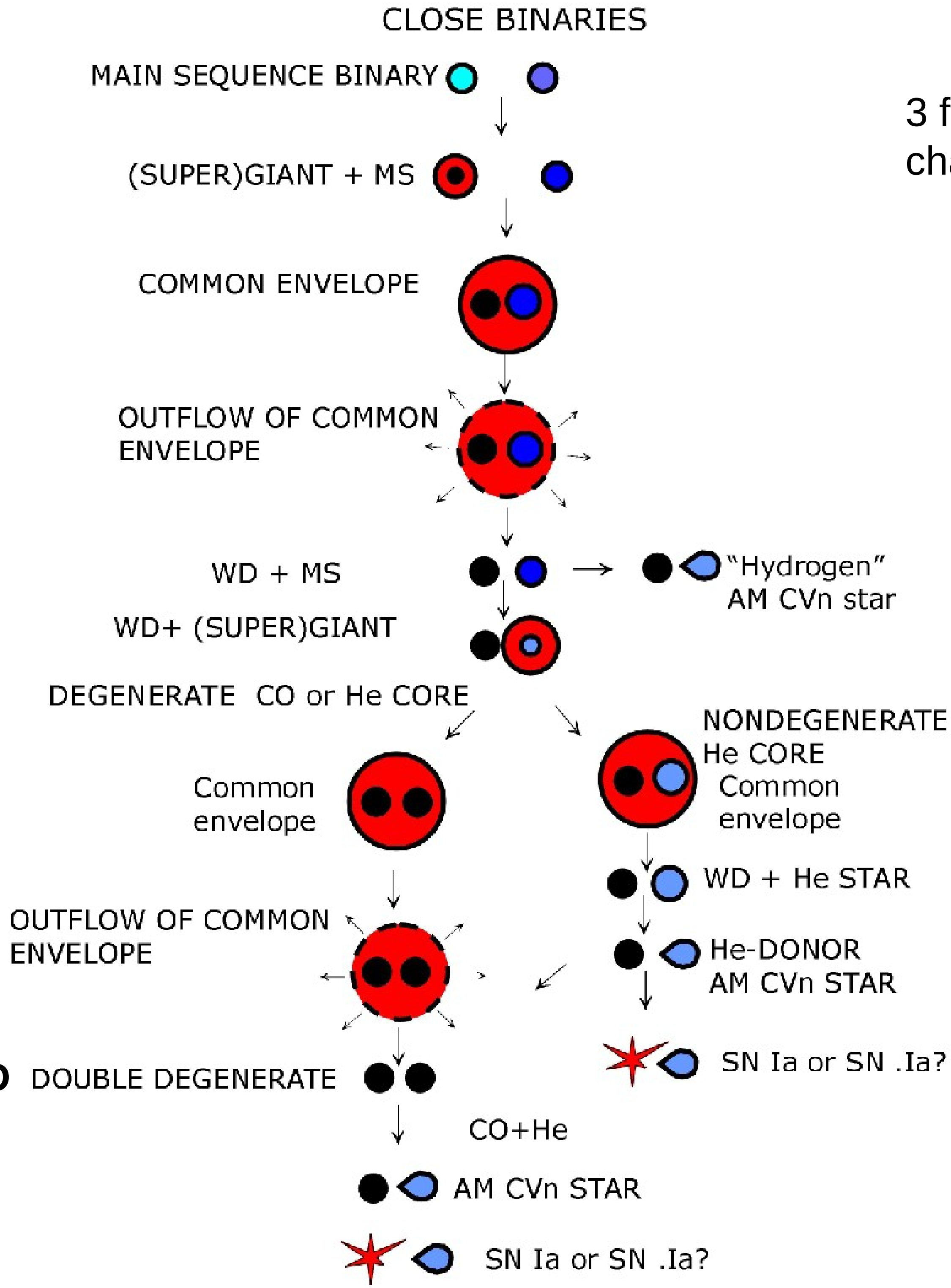
He WD donor+CO WD accretor (Paczynski 1967).

Low-mass stripped He-star donor + CO WD accretor (Faulkner et al. 1972, Savonije et al. 1986).

The core of strongly evolved (X_c<0.1) MS star + CO WD accretor (TFEY 1985).

Driving force of the evolution – AML via GWR (Paczynski 1967)

3 formation channels



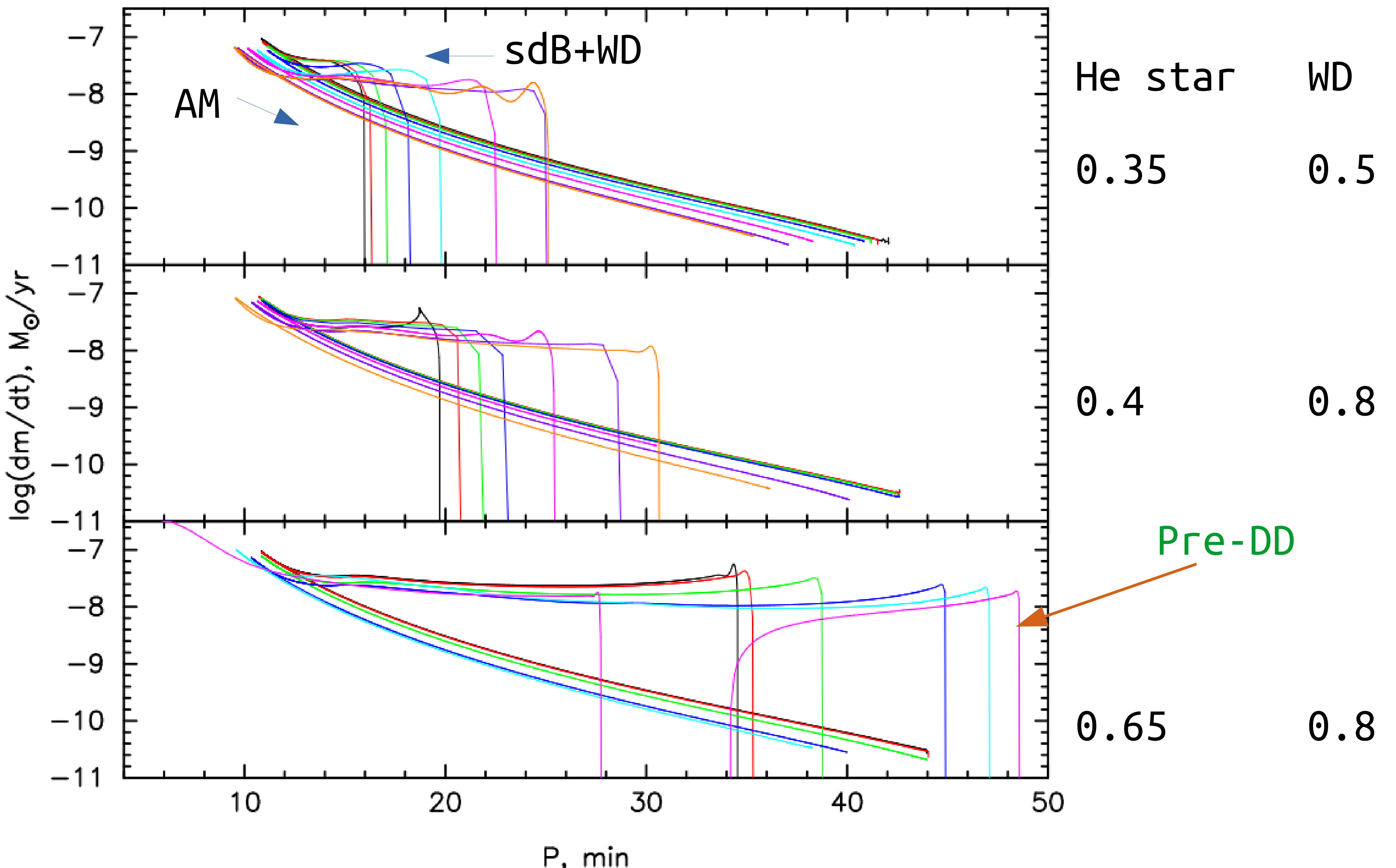
'Evolved' CV

He-star

WD

Postnov & Yungelson 2014

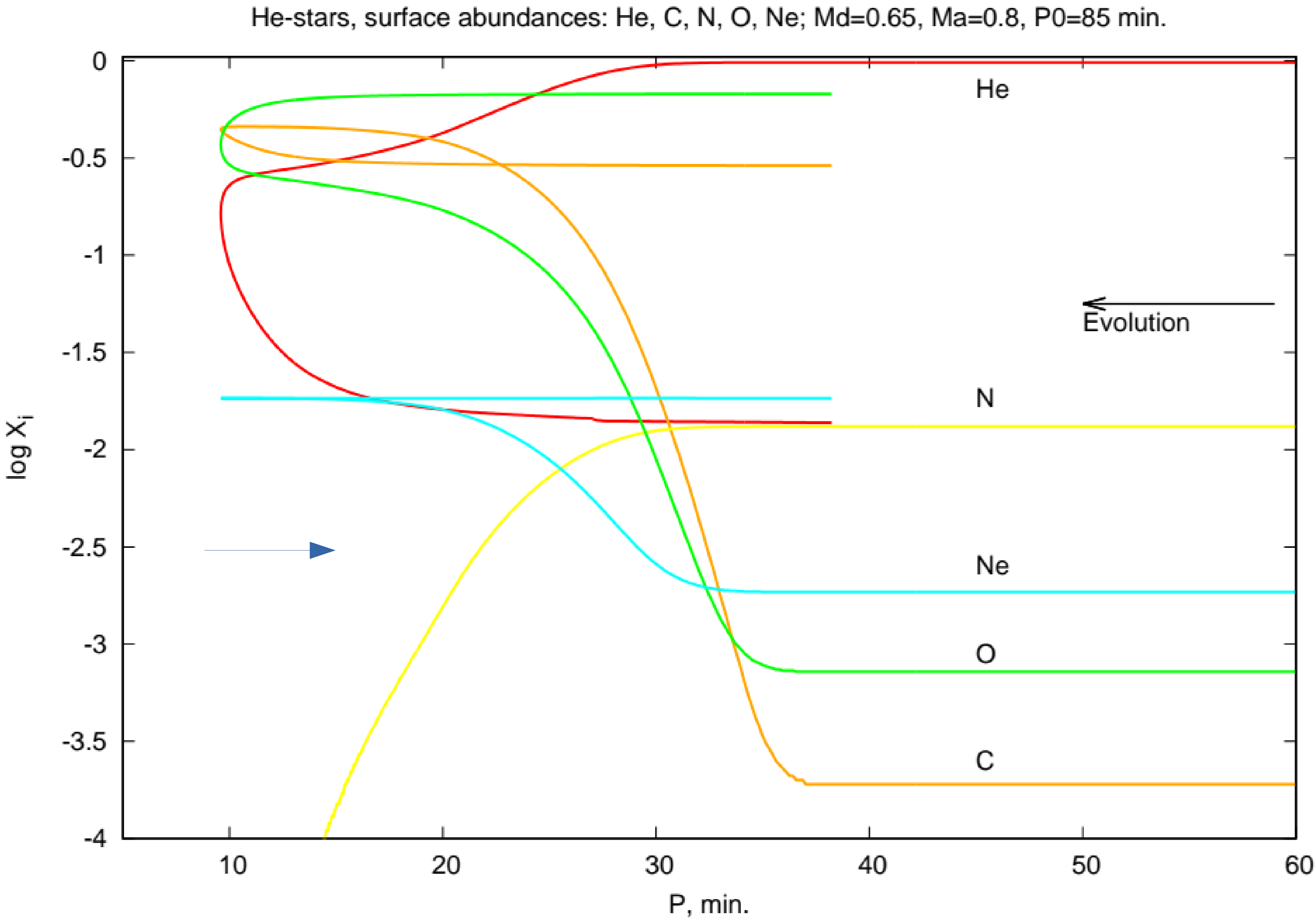
dm/dt as a function of the orbital period at RLOF



P_{min}- when the effect of AML becomes less pronounced than mass-transfer effect.

Lifetime - up to 600-700 Myr

Yungelson 2008



P_{form}=85min., P_{RLOF}≈47min., P_{fin}≈38min., M_{min}≈0.023 $M_{\odot}$

t_{AM}≈280Myr

At the surface first appear H-burning products (mostly He), later - He-burning products

Yungelson 2008

Wei-Min Liu, L. Yungelson & A. Kuranov work

Population synthesis for He-star donor AM CVn stars.
Earlier work: Nelemans et al. (2001, 2004)

Aim: model of the present day He-star AM CVn population in the Galaxy and a study of possibility of its detection by LISA.

Method: hybrid population synthesis – generation of a population of precursors of AM CVns by a fast BPS code and tracing their further evolution by a stellar evolutionary code.

1. BPS by an updated BSE (Hurley et al. 2002) provides birthrates of WD+nascent He-stars AM CVn candidates and their masses and separations

2. Ev. computations by STARS (Eggleton 2006) provide lifetimes of stars

3. Convolution with SFR=2$M_\odot$/yr (Chomiuk & Povich 2011) provides current number of stars and their distributions over parameters

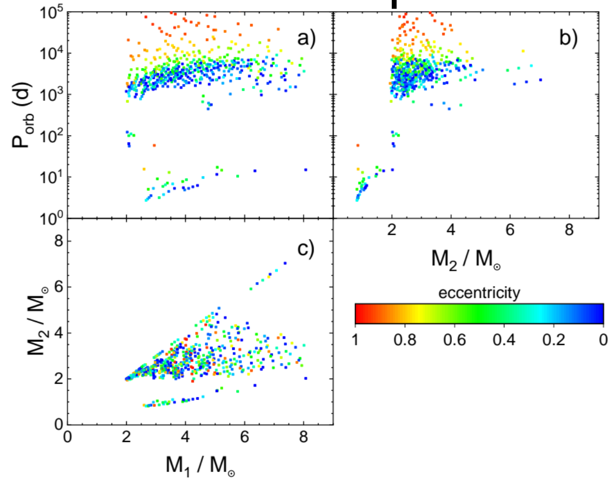
AM CVns belong predominantly to the thin disk population
Disk model:

$$\rho \propto \exp\left(-\frac{R}{R_d}\right)\operatorname{sech}^2\left(\frac{z}{z_d}\right),$$

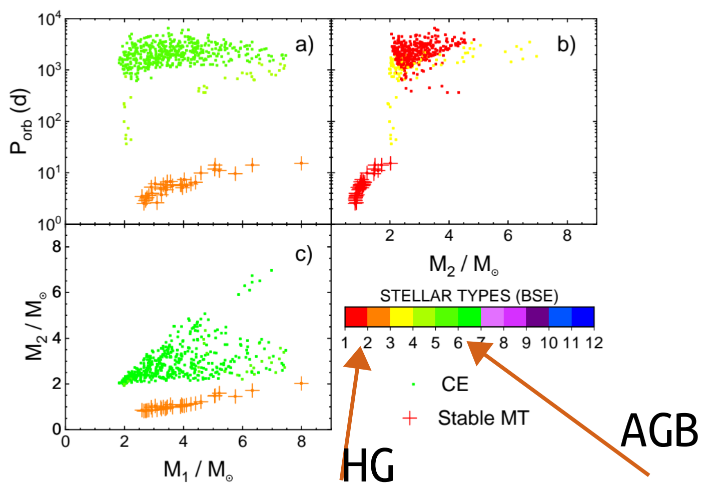
R_d =2.5 Kpc - disk radial scale, z_d=0.3 Kpc - disk vertical scale (Ivezic 2008)

Binarity rate - 50%; IMF - Salpeter; dN/dq=1; f(log P) ~ $(\log P)^{-0.55}$

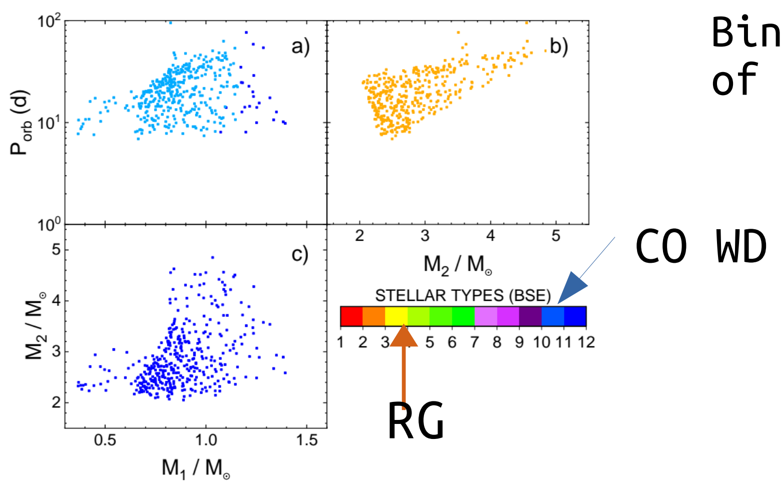
Evolution of the parameters of precursors of AM CVns



Initiated systems at ZAMS

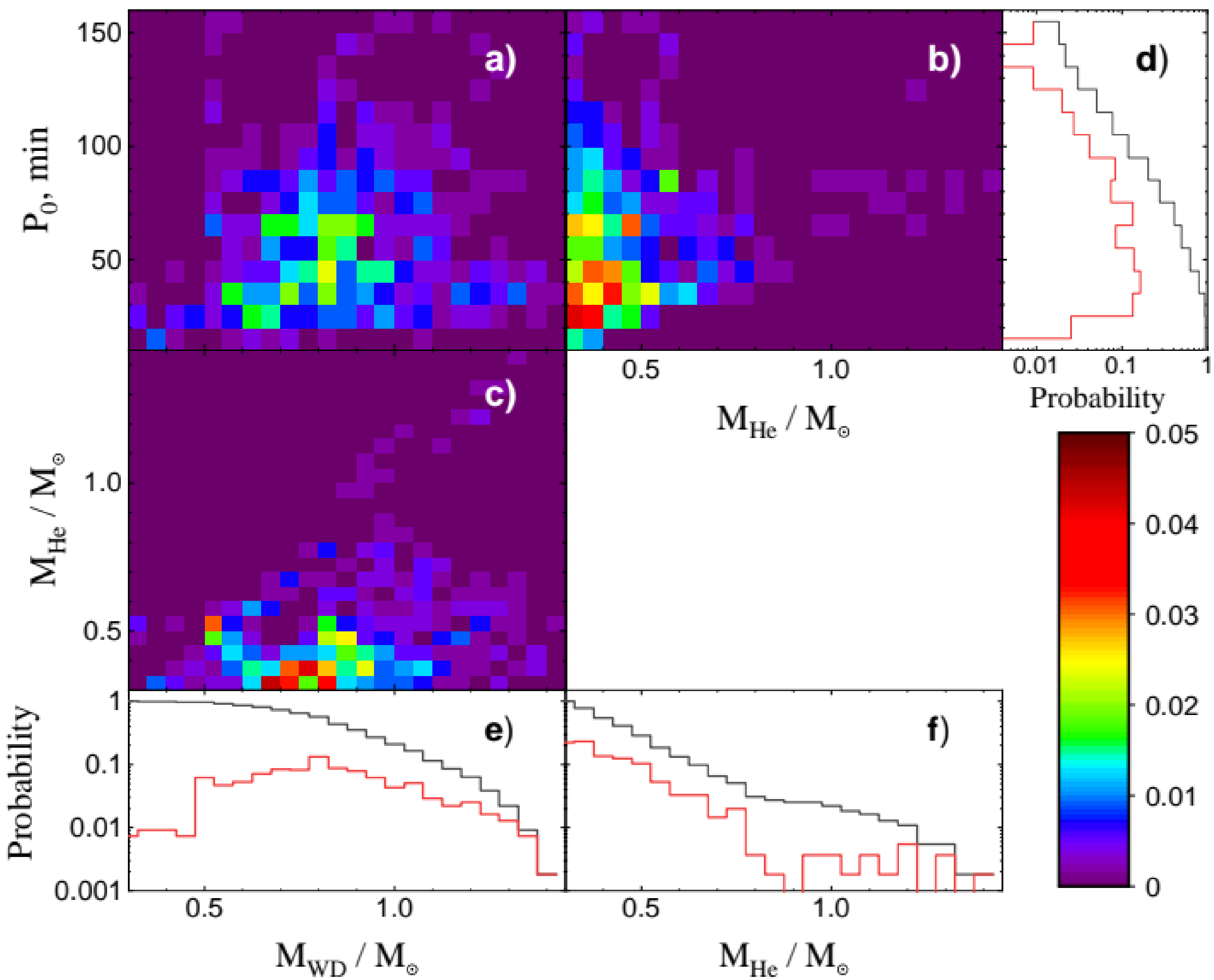


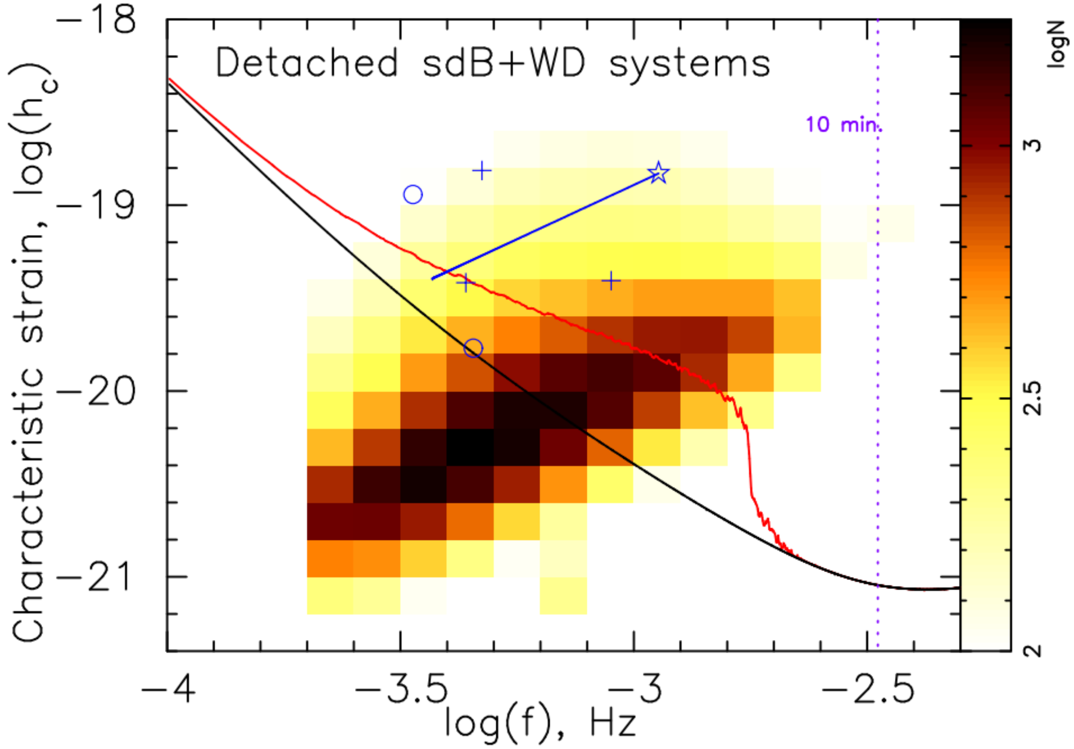
Binaries prior to the RLOF by progenitors of WD – HG/RG or AGB stars.
Dots → CE, crosses – stable RLOF.
Accretors (M2) are still MS stars (panel b).
Precursors of WD – (2-8)$M_\odot$ stars

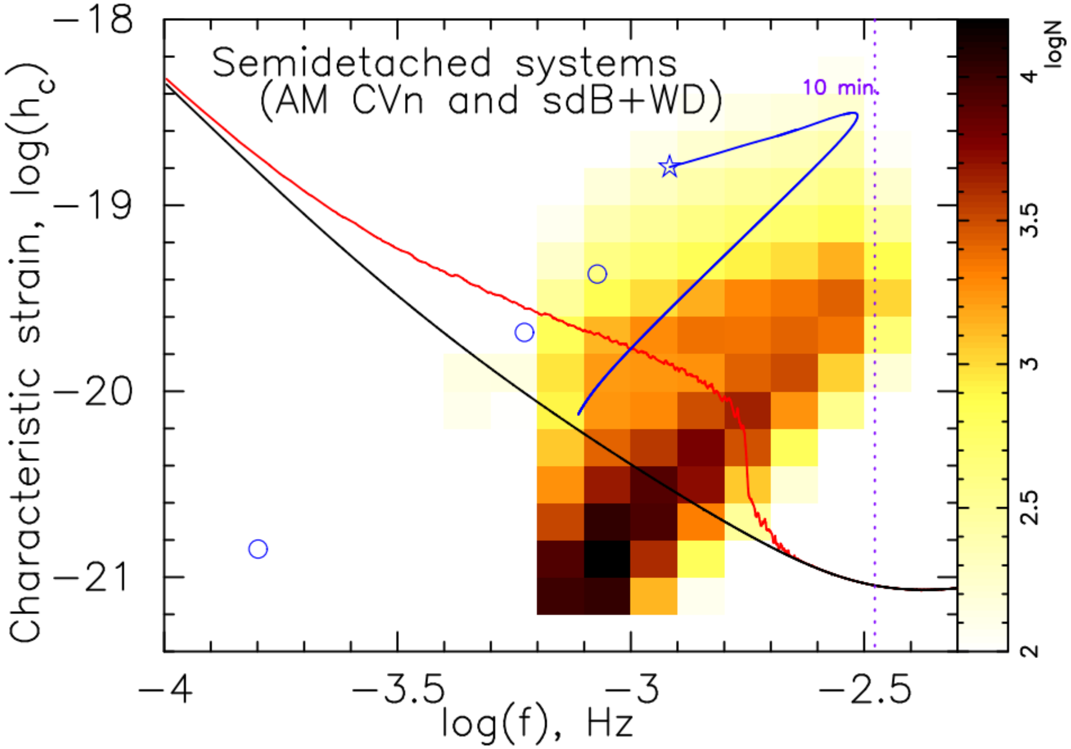


Binaries prior to the RLOF by precursors of He-stars - red giants. CE always.

Immediate precursors of AM CVns: post-RLOF systems (sdB+WD).
Relations between parameters: M_{wd}-M_{sdB}, M_{wd}-P, M_{he}-P
(Low-mass He star + low mass WD), short-period systems dominate.
P are limited by possibility of RLOF prior to exhaustion of He in the cores.







For a 4-yr long mission, S/N≥5

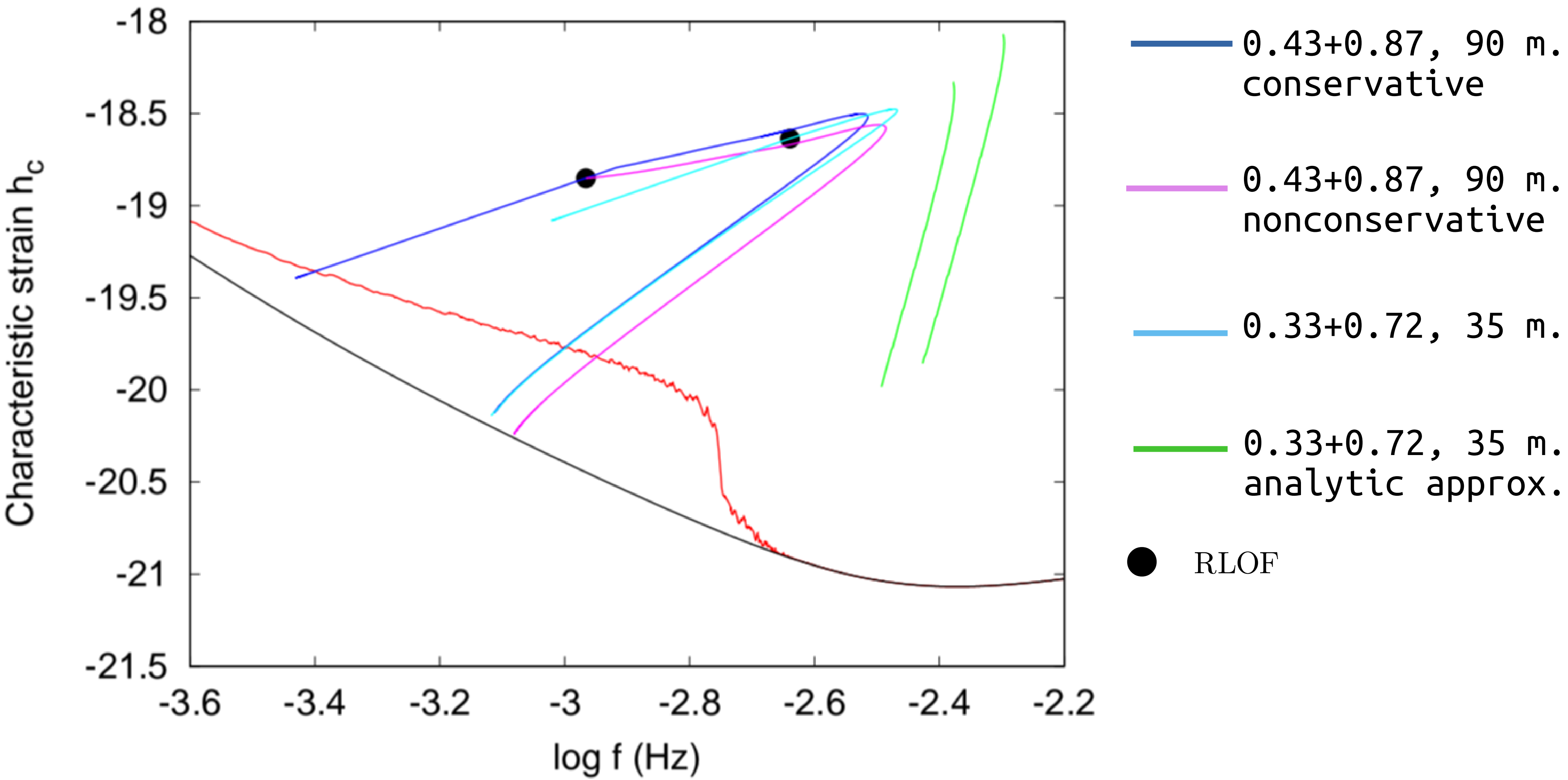
$$h_c \approx 3.75 \times 10^{-19} \left(\frac{f}{1\ \mathrm{mHz}}\right)^{\frac{7}{6}} \left(\frac{\mathcal{M}}{1\ M_\odot}\right)^{\frac{5}{3}} \left(\frac{1\ \mathrm{Kpc}}{D}\right)$$

Track for $(0.43+0.87)M_\odot$,
P_0=90 min. system at D=1Kpc

t_{RLOF}=36Myr
t_{Pmin}=42Myr
t_{AM}= 131Myr
t_{fin}=496Myr

+ will become He-star AM Cvn
○ will burn out He, become WD and may merge with companions or become DD AM CVns

Conf. noise+LISA noise
Korol et al. (2022),
“observations-driven”



<ins>The effects of nonconservative mass-transfer</ins>: longer time of evolution in the “AM CVn range”, weaker signal.

<ins>The effect of analytic approximation</ins>: overestimate of frequency, longer time of evolution in the “AM CVn range”.

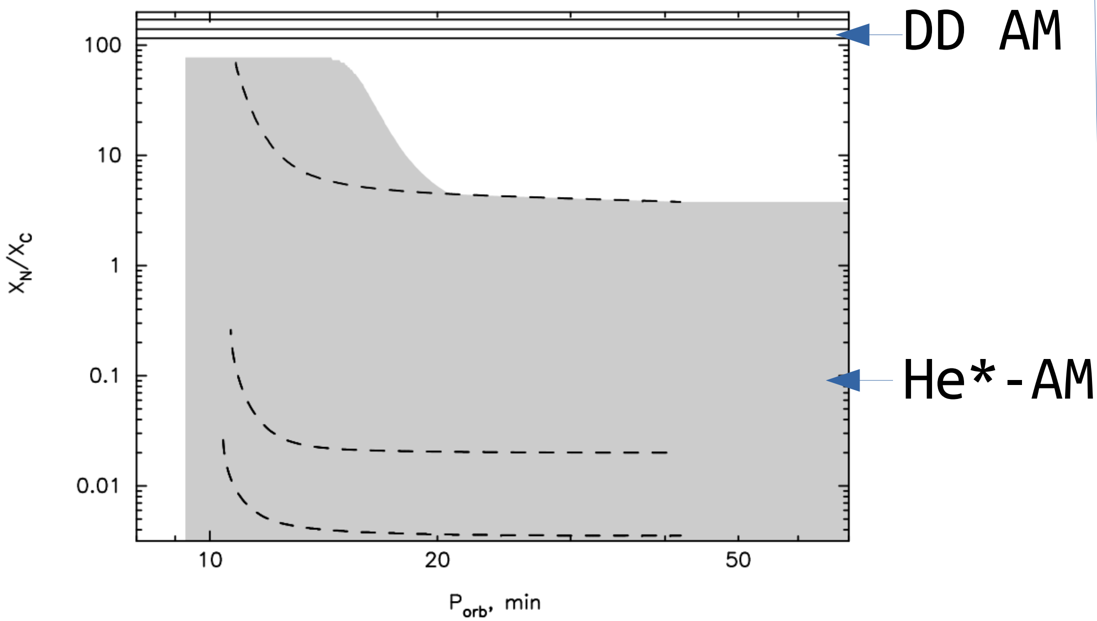
Birthrate [yr^{-1}]	N	LISA	Comment	Reference
4.6e-4	112000	500	AM, thin disk, S/N≥5	LYK 2022
	150	150	D ≤ 1Kpc	LYK 2022
	15000	75	Detached sdB+WD	LYK 2022
≤4.9e-3	≤460000		Galaxy. Depending on α_{CE}	TY 1996
2.7e-4 – 1.6e-3	<3.1e7	11200	All AM CVn; different Gal.models, IMF, SFH	Nelemans et.al. 2001, 2004
	<1.2e7	<120	1yr, ELD, different arm-length, S/N>5	Nissanke 2012
		5000	DD only, 1 yr, S/N>5	Ruiter et al. 2010
		19800 -8000	DD only, 1yr, S/N>3, different SFH	Yu & Jeffery 2013
		2700	DD only, S/N>5, negative chirp>0.1yr^{-2}	Kremer et al. 2017
		80 - 8300	Different assumptions on α_{CE} and λ, chirp<0	Breivik et al. 2018
		21400	DD, SN>7, 4 yr	Wilhelm et al. 2021

Despite very different assumptions predicted number of detections is in the same range of ~ (100 - 1000)

PROBLEMS!

Only 3-5 of well studied AM CVns probably have He-star donors!?

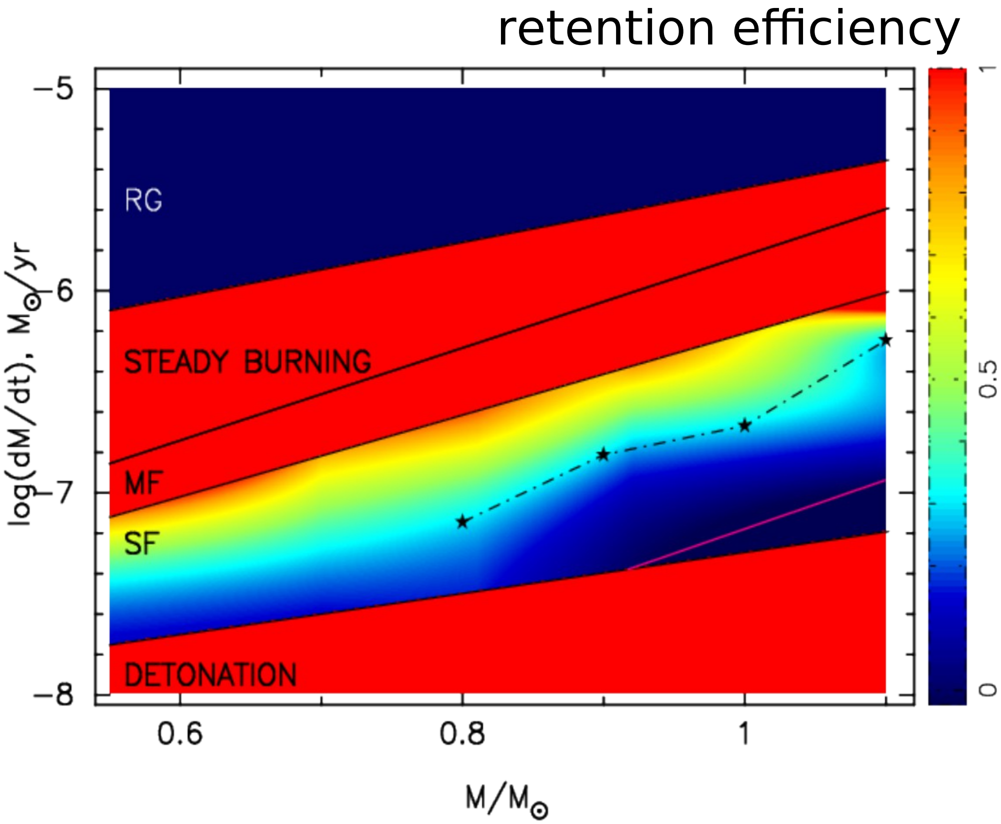
AM CVns formed via different channels have different surface abundances: H vs. He burning products.

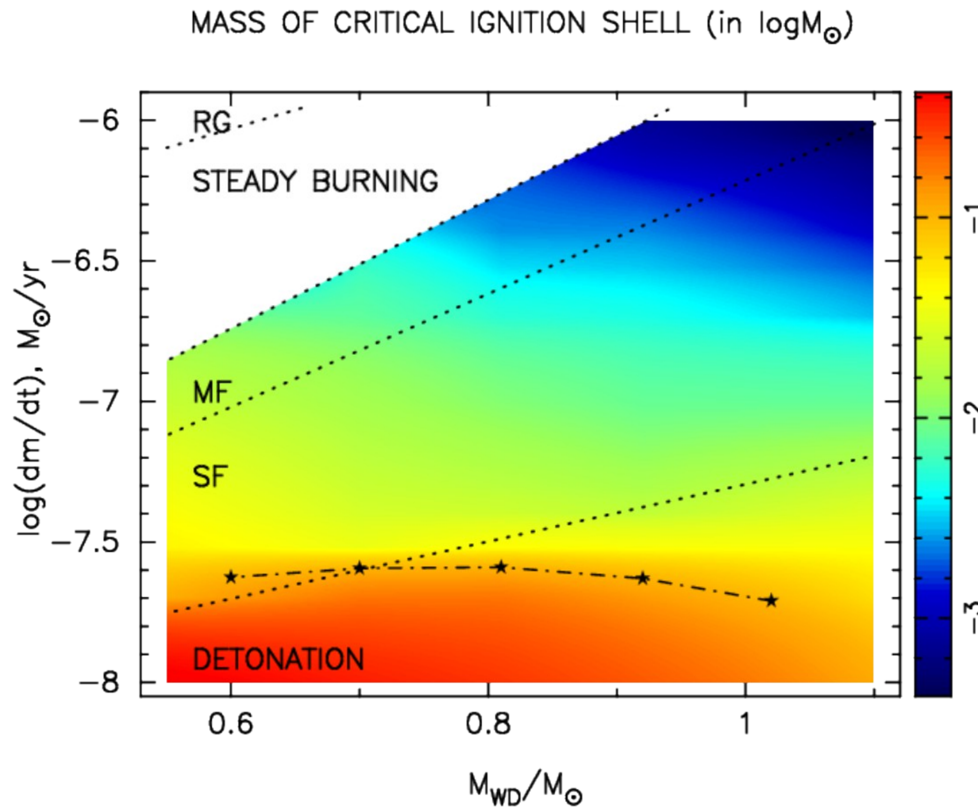


C/N/O abundances studies require analysis of UV spectra. Most studies are made for visual spectra, if at all.

Nelemans et al. (2010)

He-star AM CVns are exterminated by unstable He-burning?





Taam(1980), Nomoto (1982): Degenerate matter at the base of He-shell is heated by grav. energy release, cooled by neutrino.

As T_{He} increases, $\varepsilon_{nuc} > \varepsilon_\nu$, TNR starts; as $P_{ideal} > P_{deg}$ degeneracy is lifted, rapid expansion begins.

For low dM_{accr}/dt detonation becomes possible.

Piersanti et al. (2014), nonrotating models.

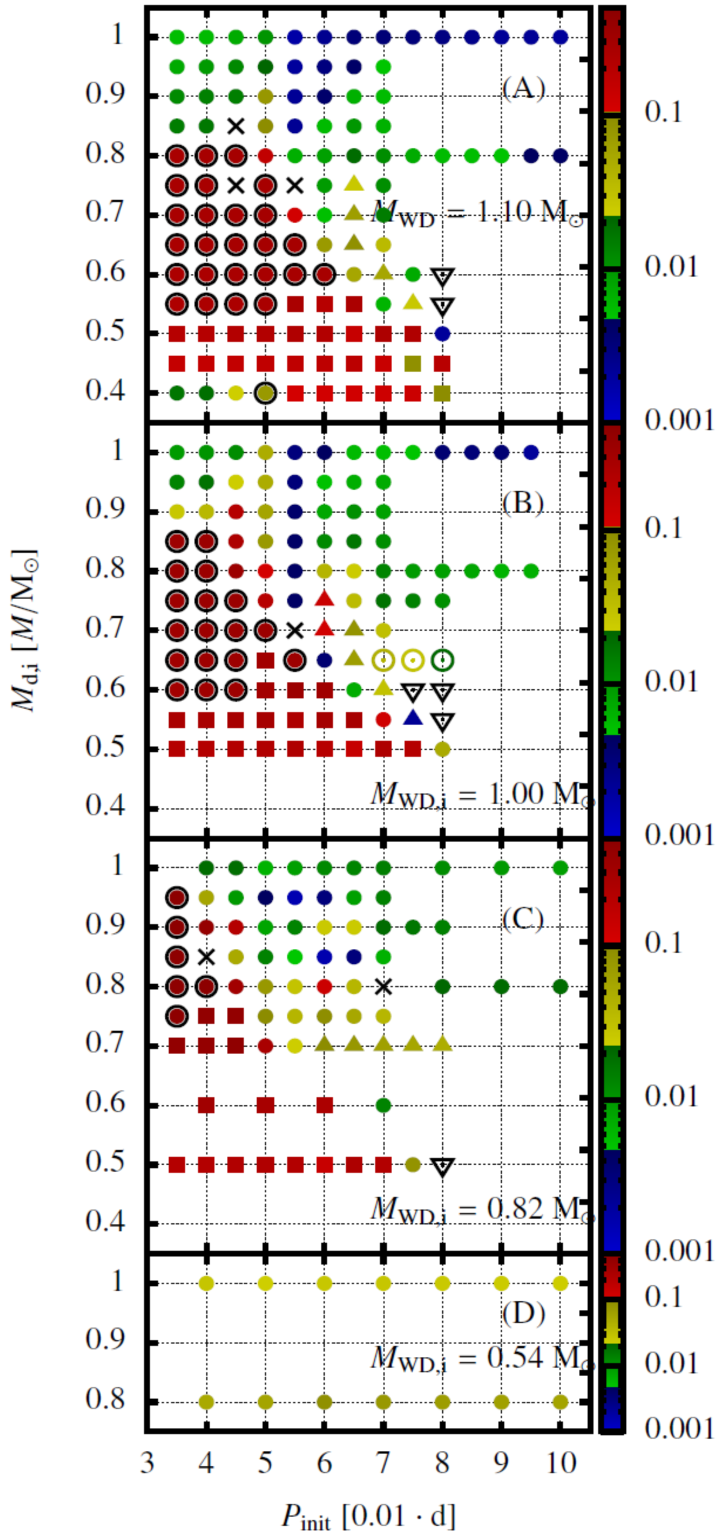
Rotating models

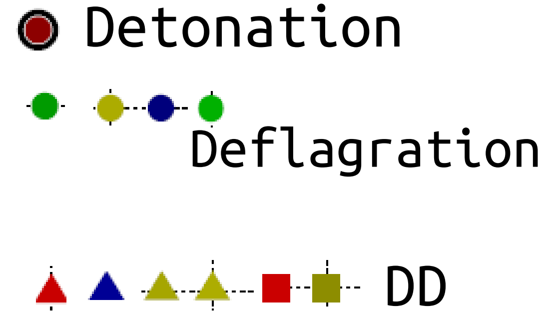
Evolution up to He ignition

Neunteufel et al.(2019)

Shear instability,
Solberg-Hoiland instability,
Eddington-Sweet circulation,
magnetic field

$0.4\,M_\odot \leq M_{\rm donor} \leq 1.0\,M_\odot$.





He-detonation definitely occurs if $M_{wd}>0.82M_\odot$, $M_{don}>0.55M_\odot$, $P_0<86$min.

We did not encounter such systems in our grid.

High-velocity sdB from disrupted AM CVns are not observed.

Shen, K. (2015): Every Interacting Double White Dwarf Binary May Merge

Merger due to frictional angular momentum loss in post-outbursts common envelopes

Response to this statement needs 3D hydrodynamic computations

He-star donor AM CVns are almost not observed

We do not properly estimate abundances in the accretion disks?

We do not understand evolution of close binaries?

We mistreat common envelopes?

We do not properly compute evolution of He-stars?

We do not properly compute evolution of rotating WD?

We do not properly treat explosive events?

Etc.

G. Ramsay, M. J. Green, T. R. Marsh, T. Kupfer, E. Breedt, V. Korol, P. J. Groot, C. Knigge, G. Nelemans, D. Steeghs, P. Woudt, and A. Aungwerojwit (A&A, 620, A141, 2018):

“ ...variability, the presence of emission lines and unusual colours have all been used to detect AM CVn stars. As a result, the sample is neither flux- nor volume-limited, but is instead affected by complex and often poorly understood selection effects. ”

THANK YOU FOR ATTENTION AND PATIENCE!