On formation and evolution of extremely low-mass white dwarfs (ELMs)

Alina Istrate

a.istrate@astro.ru.nl

Radboud University

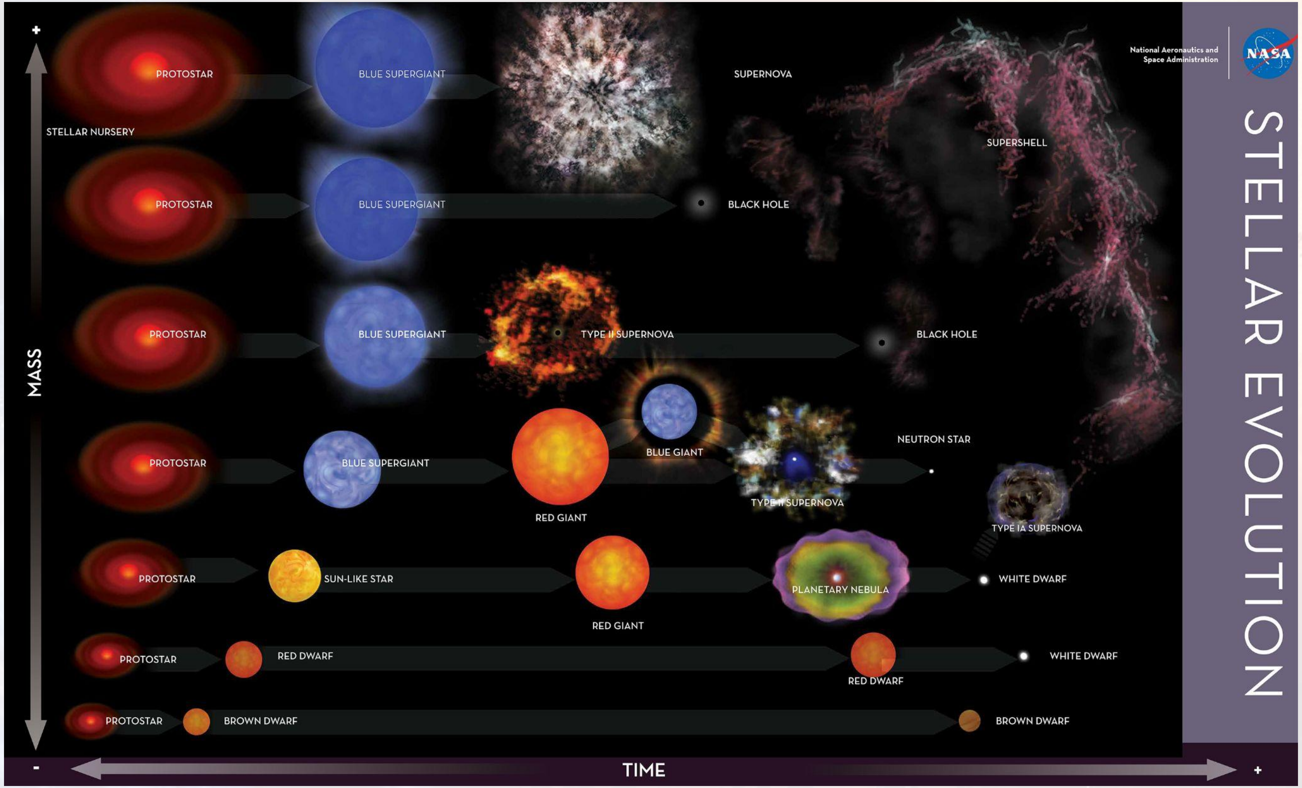
IN·DEI·NOMINE·FELICITER

Collaborators

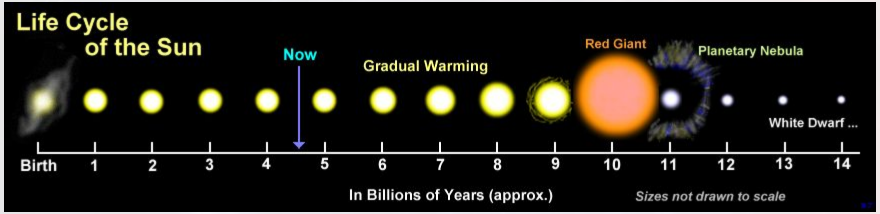
Thomas Tauris (AAlborg University), Norbert Langer (Argelander Institute for Astronomy), Pablo Marchant (KU Leuven), Luca Grassitelli (Argelander Institute for Astronomy), Gijs Nelemans (Radboud University), Ingrid Pelisoli (Warwick University), Alejandra Romero (Universidade Federal de Rio Grande do Sul, Brazil), Stephan Justham (University of Amsterdam) + others

23rd March 2022, Astronomical Institute of the Romanian Academy seminar

Binary interactions can completely change the picture of stellar evolution



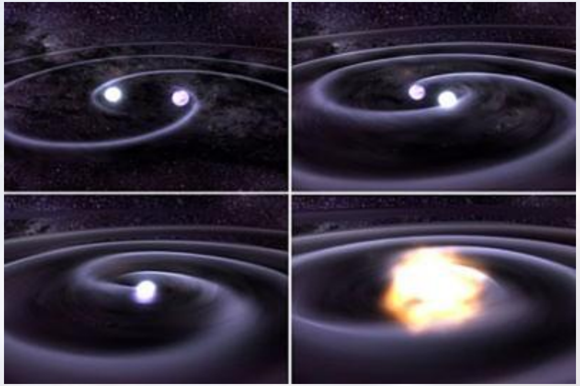
White dwarfs as stellar corpses



➔ the most common outcome of stellar evolution

➔ 10^{10} WDs in our Galaxy, about 2.5 x 10^{8} in DWD binaries (**Nelemans et al.2001**)

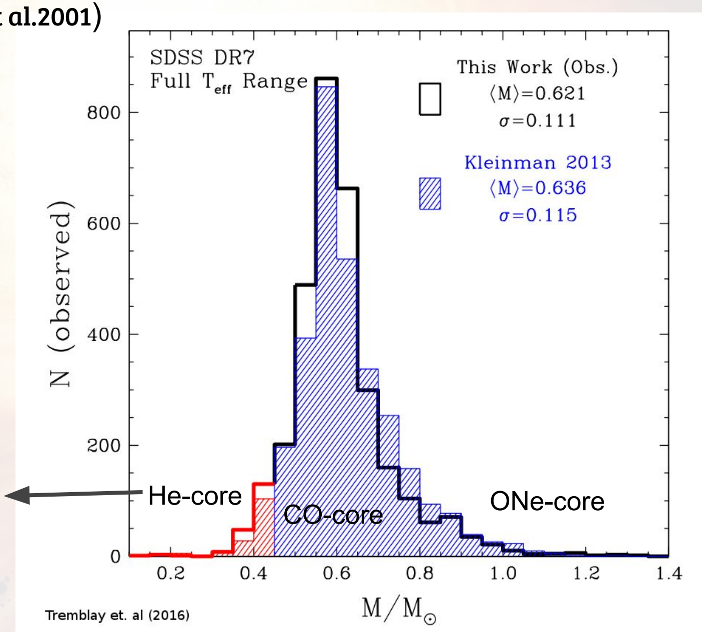
➔ populate the transient Universe: e.g. type Ia supernovae, novae, Ca-rich transients ...



Credit: GSFC/Dana Berry

"Low-mass white dwarfs need friends"

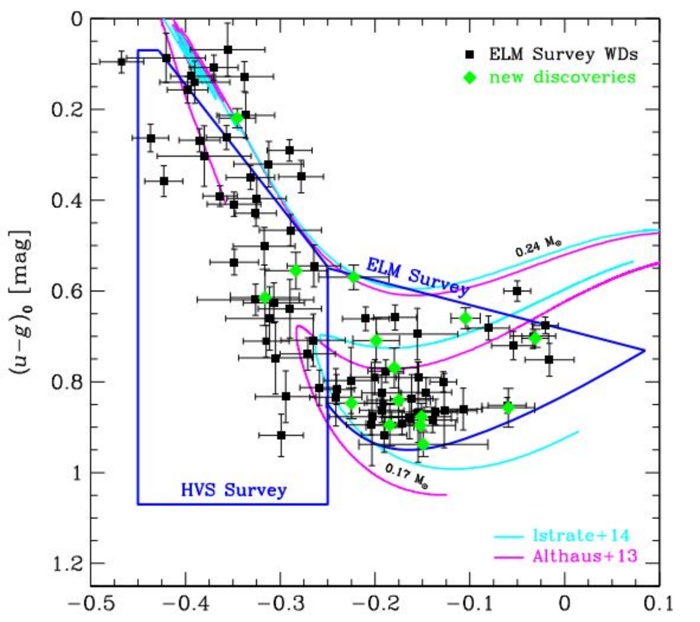
(**Marsh et al. 1995, MNRAS**)



➔ sources of gravitational waves in the mHz regime (eLISA)

➔ most isolated white dwarfs ~ 0.62 $M_\odot$

The ELM survey (Brown et al. 2010, 2012, Kilic et. al 2011, 2012, Brown et.al 2013, Gianninas et. al 2015, Brown et. al 2016a, b)



(Brown et al. 2016)

"Happy" by-product of the Hypervelocity Star Survey

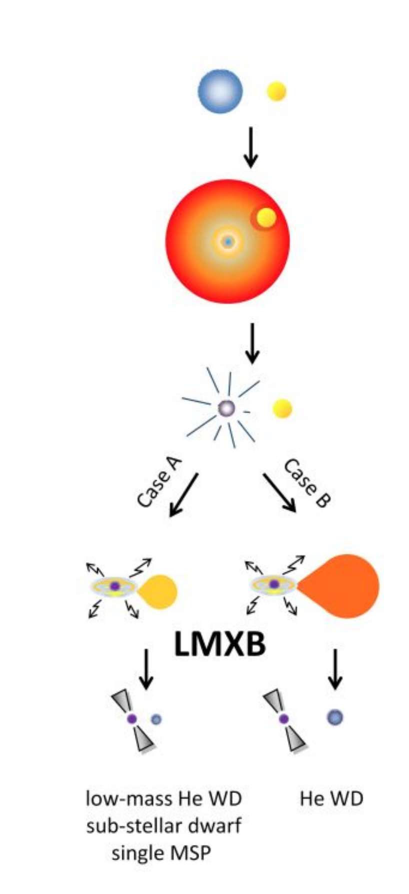
- since 2010, targeted spectroscopic survey for candidates with
  - $5 < \log g < 7$ and $8000 \text{ K} < T_{eff} < 22000$ K
  - WD mass $< 0.3 M_\odot$
  - short-period radial velocity variability
  - high proper motion (Pelisoli et al 2018- "the sdA problem")
- discovered around 100 objects
- Orbital periods of < 1 day
- Companion diversity :
  - the majority-> double degenerate systems: ELM + CO WD
  - millisecond pulsar systems
  - subdwarf stars
  - A-type stars (EL CVn stars)
- Kinematics:
  - The majority members of the Galactic Disk
  - A non-negligible fraction are members of the Galactic halo

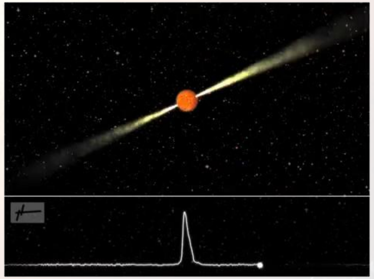
Most important question: ***why should we care about ELMs*** ?

- study the population of short-period binary WDs
  - e.g J0651+2844: 12.75 min orbital period eclipsing system (Brown et al. 2011c)
    - orbital decay due to gravitational waves radiation > 3.8 times Hulse-Taylor binary pulsar
    - tidal distortions -> clues about dynamical tides (Fuller et. al 2013)
- piece of the puzzle in stellar and binary evolution
  - formation: common envelope physics constraints (e.g Nandez et. al 2015)
  - future evolution
    - gravitational wave foreground at mHz frequencies -> eLISA (Amaro-Seoane et al. 2012)
    - possible progenitors of merger/“exotic” systems: extreme helium stars, R Corona Borealis, AM CVn, hot subdwarfs
  - properties -> clues into internal processes, e.g. mixing as well as binary mass transfer
- independent “clock” in millisecond pulsar systems
- probe the regime of intermediate mass black holes through tidal disruption events (Law-Smith et. al 2017)

Formation of ELMs through the low-mass X-ray binary channel

➢ ELM WDs first observed in millisecond pulsar systems





Evolutionary scenario for ELM in double degenerate systems

Li et al.

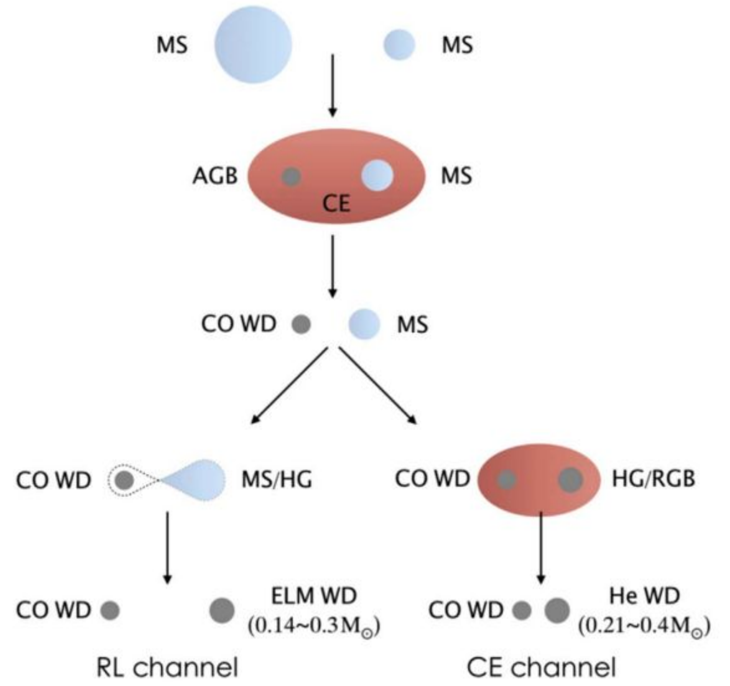
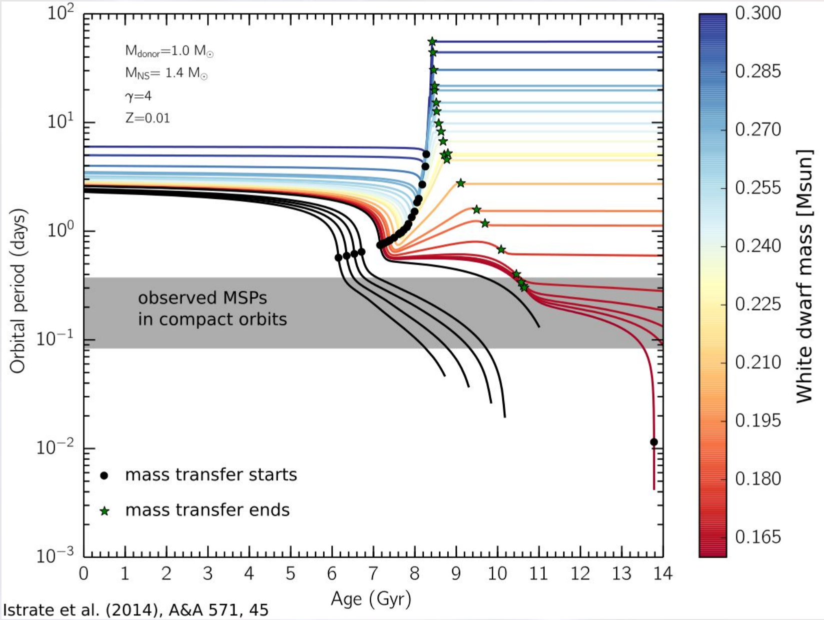


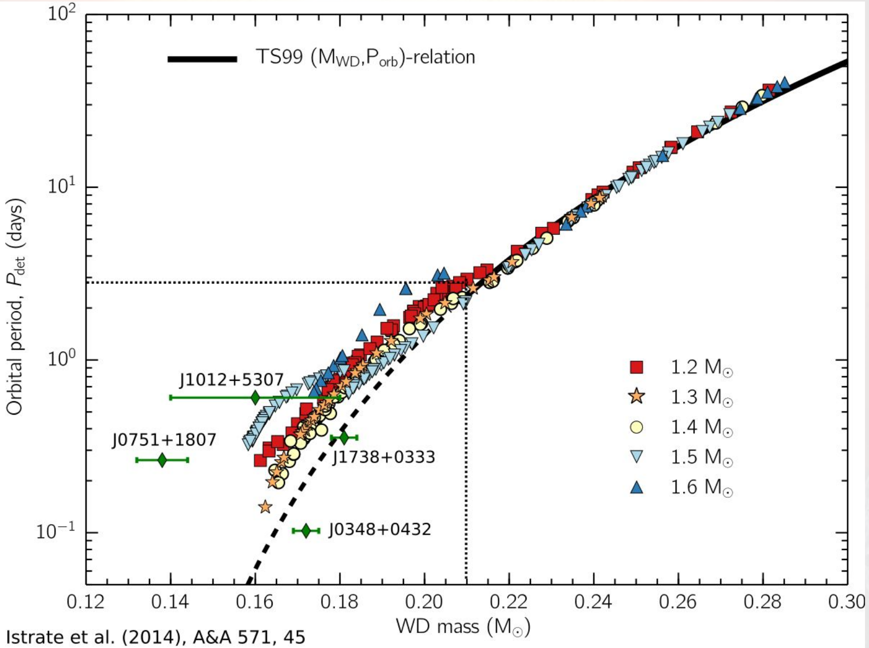
Figure 2. Sketch map for the formation of DDs with ELM WDs. MS—main sequence, AGB—asymptotic giant branch, CE—common envelope, HG—Hertzsprung gap, RGB—red giant branch.

Modelling of LMXB systems

Bonn stellar evolution code
(BEC/STERN)



Istrate et al. (2014), A&A 571, 45



Istrate et al. (2014), A&A 571, 45

Stable mass transfer versus common envelope evolution

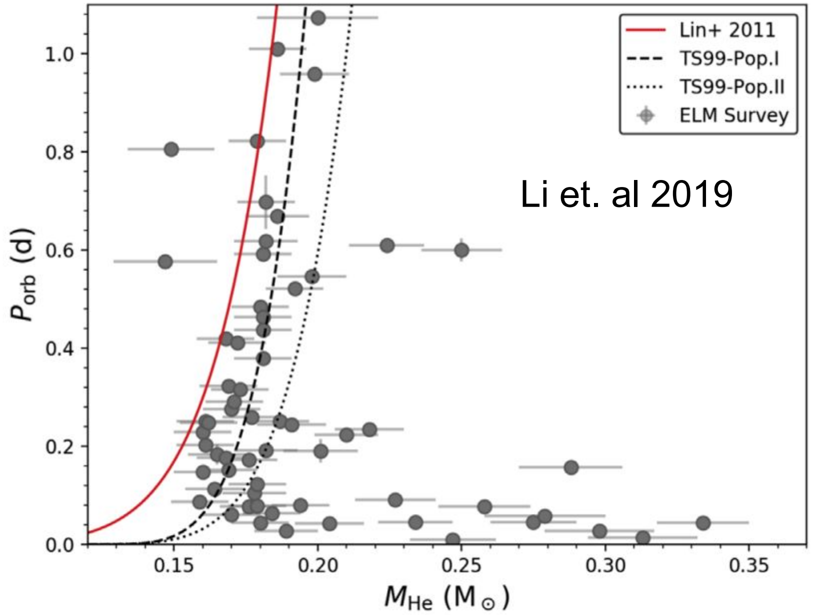
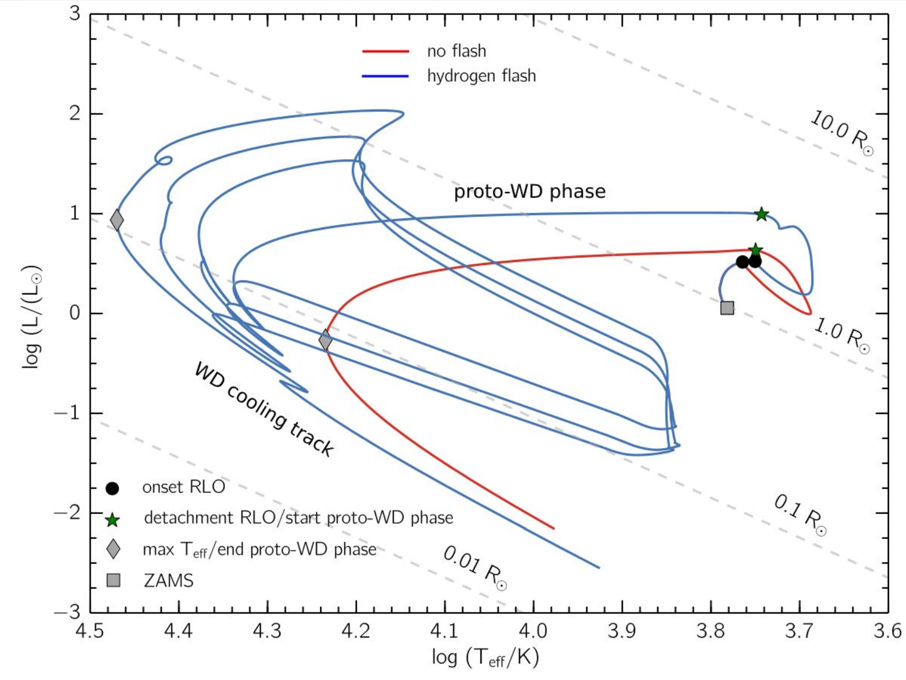
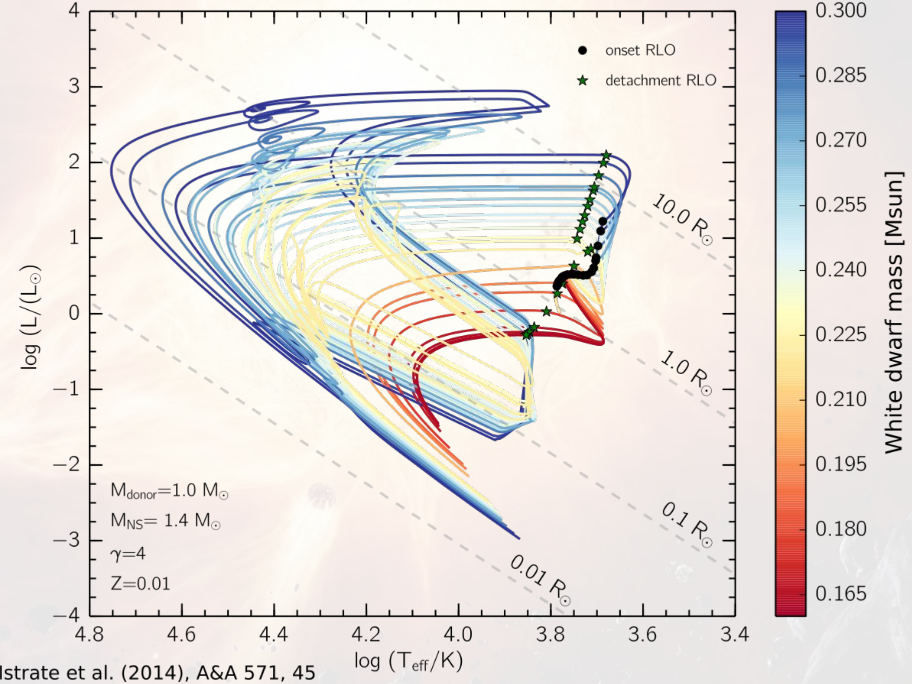


Figure 1. The ELM WD mass vs. orbital period for ELM WDs in the clean sample from Brown et al. (2016a). The red solid line is from Lin et al. (2011) based on detailed binary evolution calculation, and the black lines are from Tauris & Savonije (1999) for Population I ($Z = 0.02$; dashed) and Population II ($Z = 0.001$; dotted) stars.

To flash or not to flash: that is the question!

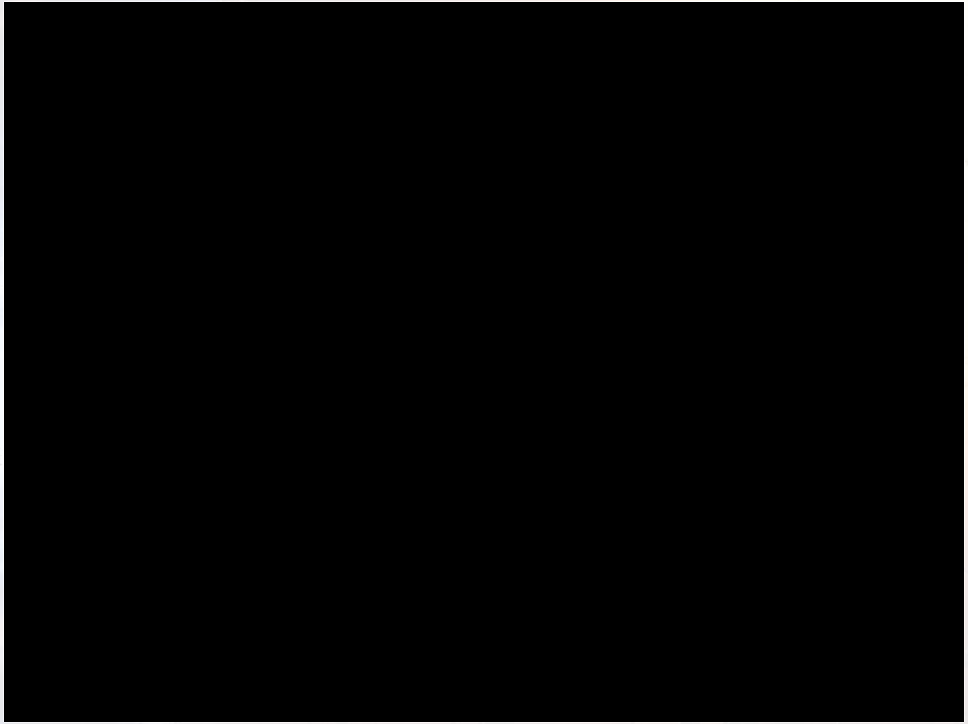
Bonn stellar evolution code
(BEC/STERN)





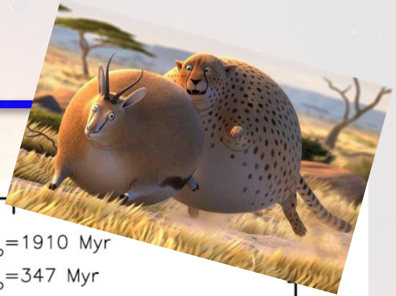
Istrate et al. (2014), A&A 571, 45

Stellar evolution modeling in a nutshell



“Bloated” WDs aka proto (pre-) WDs

Bonn stellar evolution code (BEC/STERN)

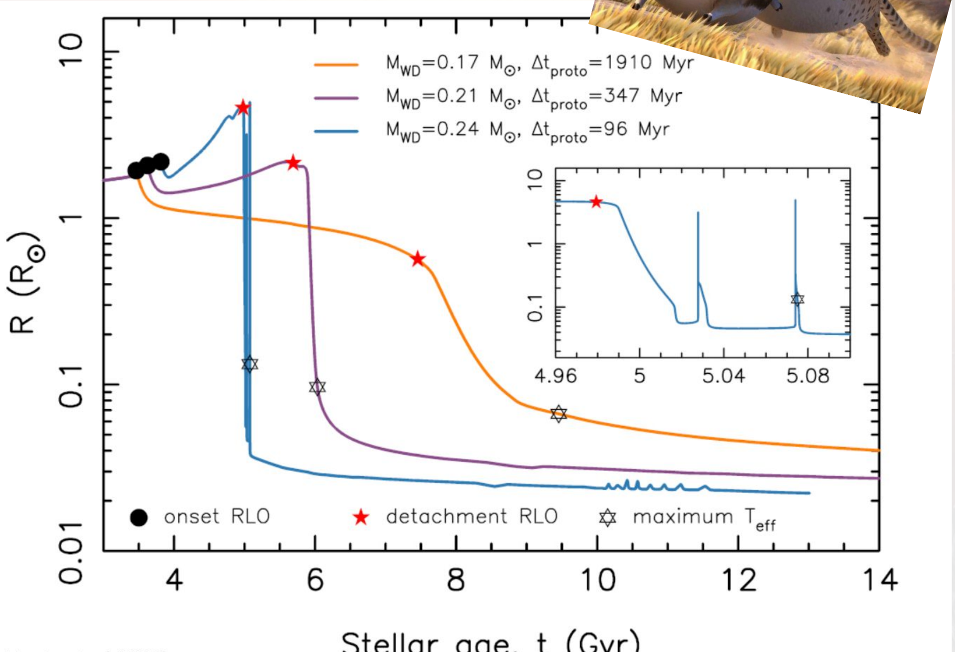


Motivation: PSR J1816+4510

- log (g) = 4.9 ± 0.3
- T_{eff} = 16000 ± 500 K
- metal rich (lines of He, Ca, Si, Mg)

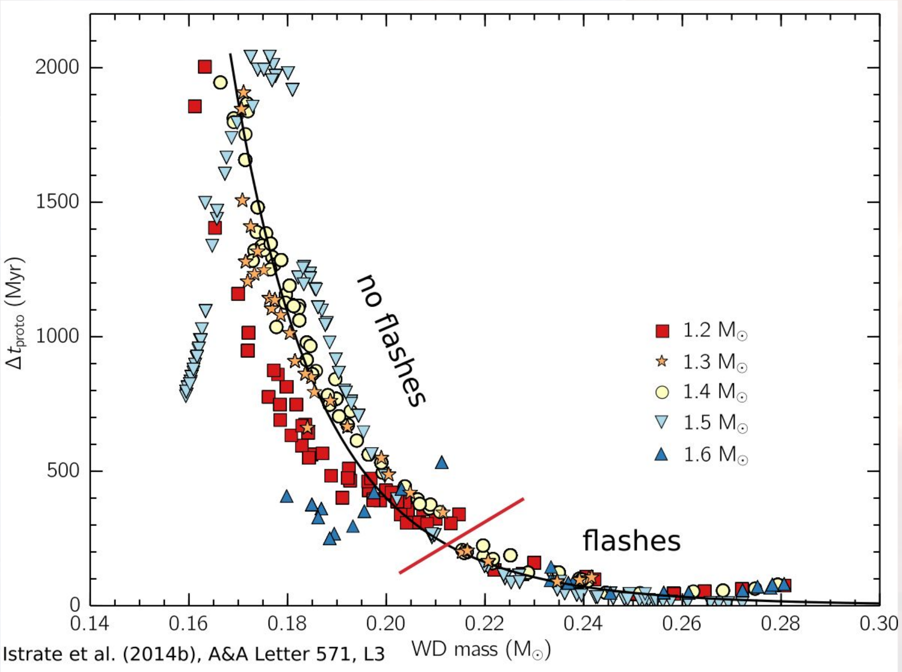
“We discuss the companion in relation to other sources, but find that we understand neither its nature nor its origins. Thus, the system is interesting for understanding unusual stellar products of binary evolution, as well as, independent of its nature, for determining neutron-star masses”.

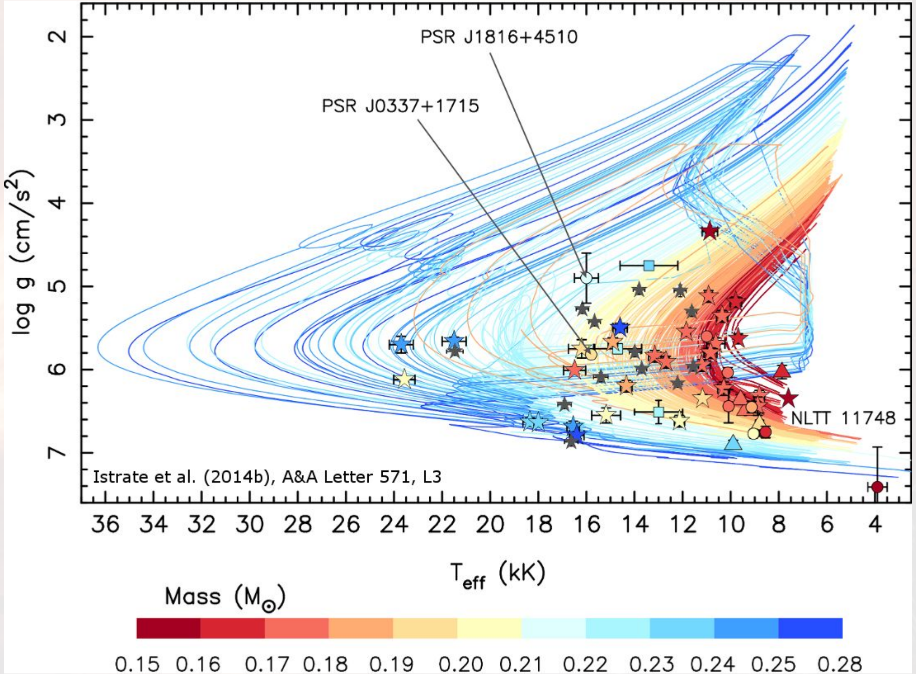
(**Kaplan et. al 2013**)



Istrate et. al 2014b

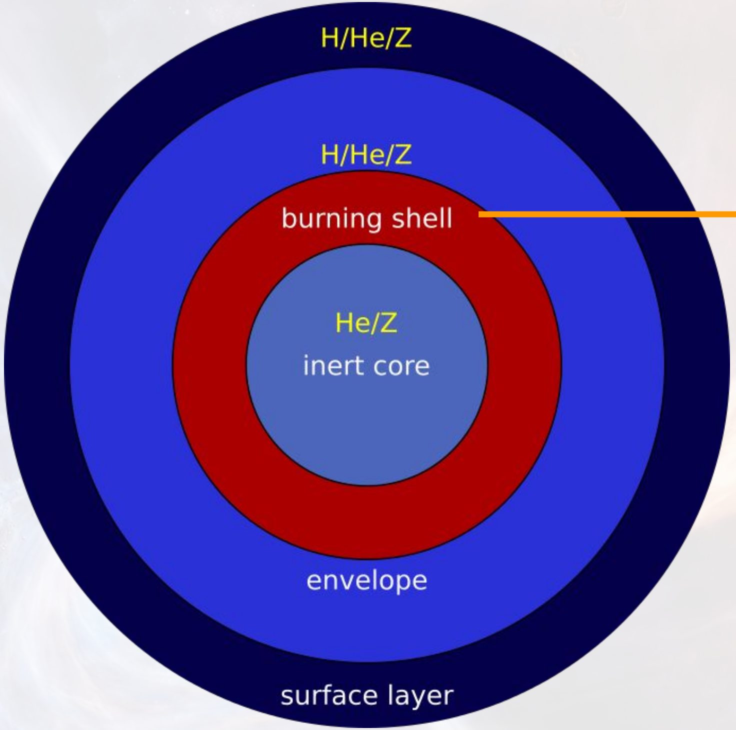
Evolutionary timescale for the proto-WD phase





$$\Delta t_{proto} \simeq 400\ \ \text{Myr}\ \left(\frac{0.20\ M_\odot}{M_{WD}}\right)^7$$

The structure of the donor star after the mass transfer phase

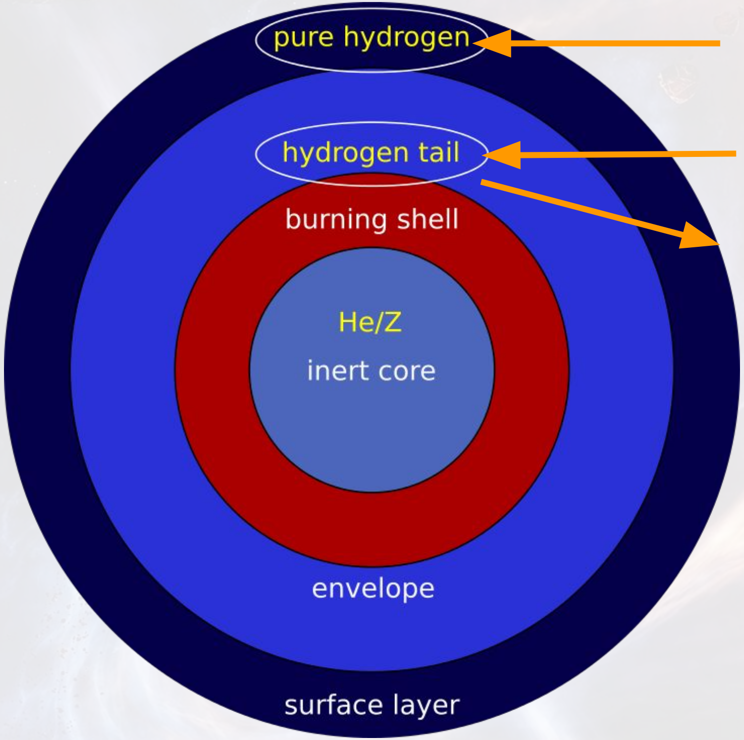


stable/unstable (runaway process)

hydrogen shell flash

occurs in a certain WD mass range (metallicity dependent + physics included dependent)

Element diffusion in the proto-WD evolution (Althaus et al. 2001, 2013)



gravitational settling

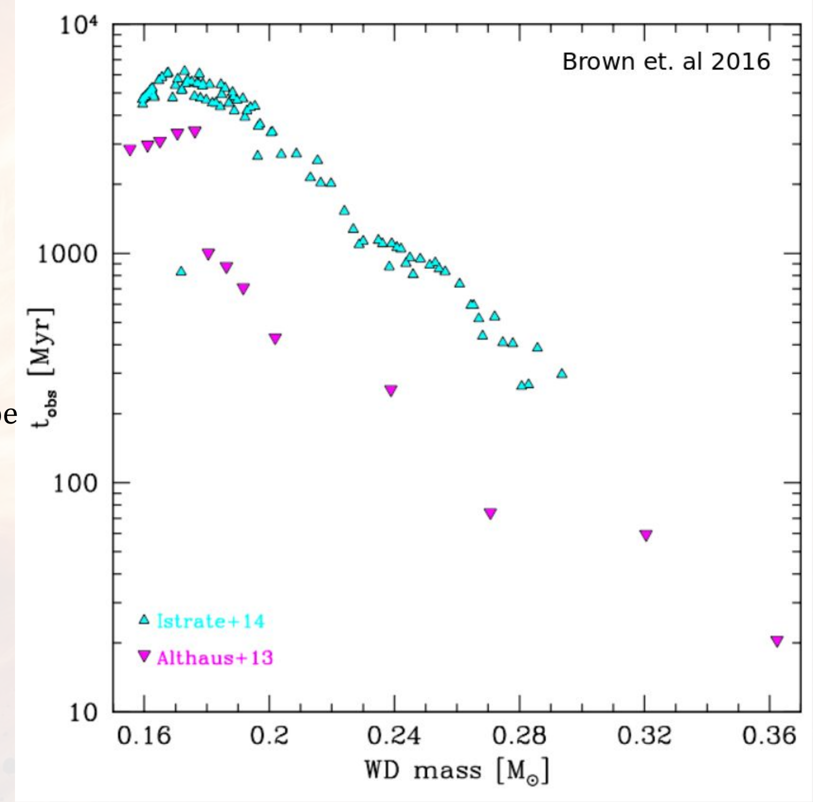
chemical diffusion

induces additional hydrogen shell flashes

thin hydrogen envelope on the cooling track

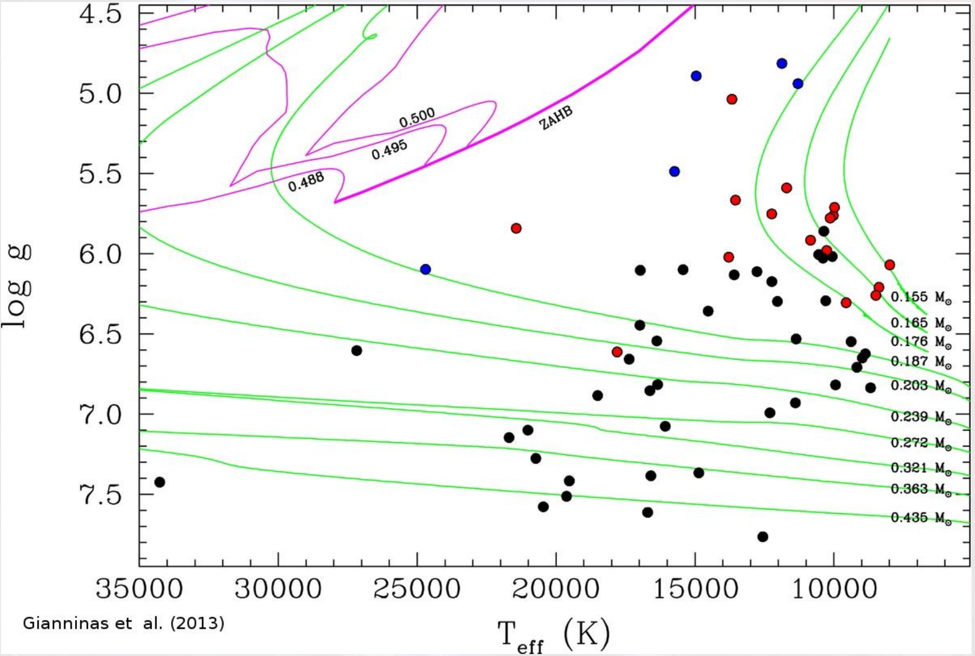
faster cooling

cooling dichotomy



Puzzling presence of metals

➢ all ELMs with log g < 5.9 (proto-ELMs) show evidence of Ca lines in their spectra



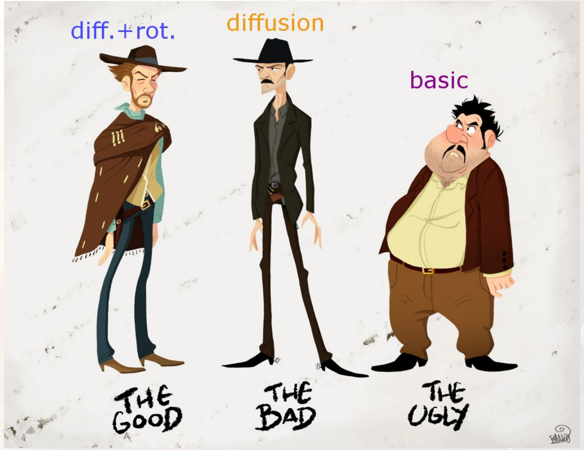
➢ possible explanations:

- result of a recent flash
  - diffusion timescales for metals much shorter than the evolutionary timescale
- ongoing accretion from circumstellar debris disks
  - no infrared excess
  - too close orbits -> dynamical unstable
- radiative levitation
  - minimal radiative support for Ca, far less than required to explain the observed Ca abundance
- rotational mixing

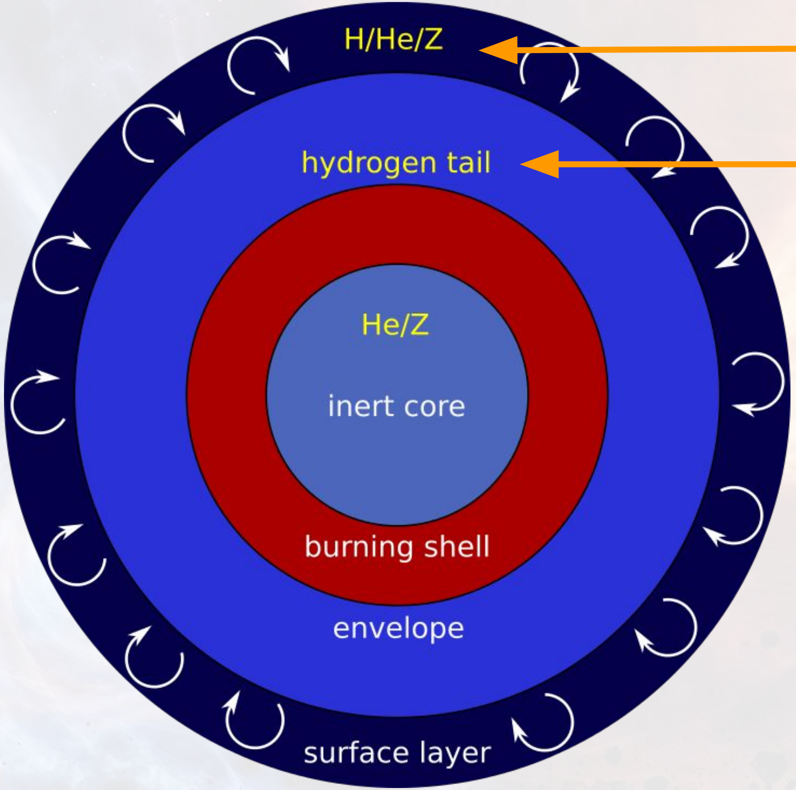
First evolutionary models for ELMs including rotational mixing !

MESA

- account for the cooling times discrepancies → include element diffusion
  - at the surface, gravitational settling → pure hydrogen composition
  - close to He-core boundary, thermal and chemical diffusion → diffusive hydrogen tail
- account for the presence of metals → include rotational mixing
  - basic : no element diffusion nor rotational mixing
  - diffusion: element diffusion included
  - diffusion+rotation : element diffusion + rotational mixing
- include metallicity dependence: Z=0.02, 0.01, 0.001, 0.0002
- WDs with masses between 0.16-0.44 $M_\odot$



Rotational mixing in the proto-WD evolution

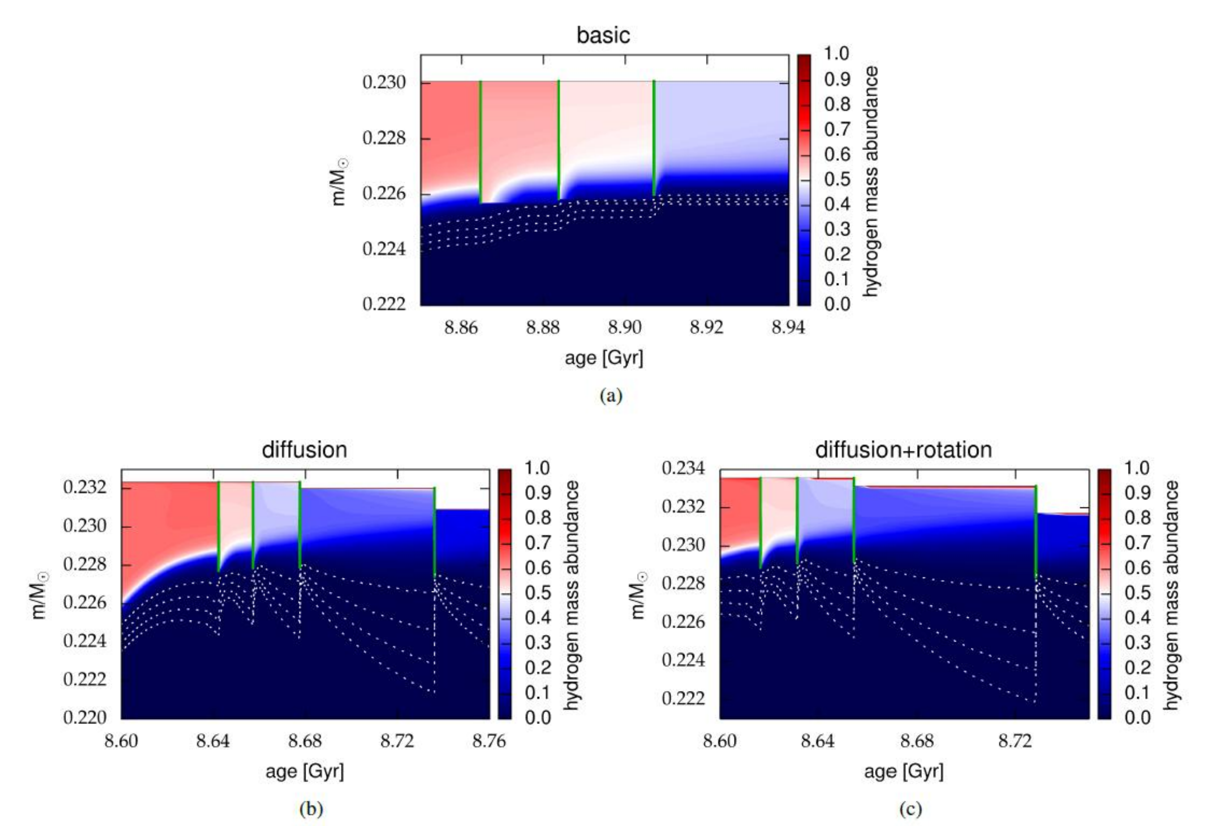


counteracts gravitational settling

does not affect the hydrogen tail

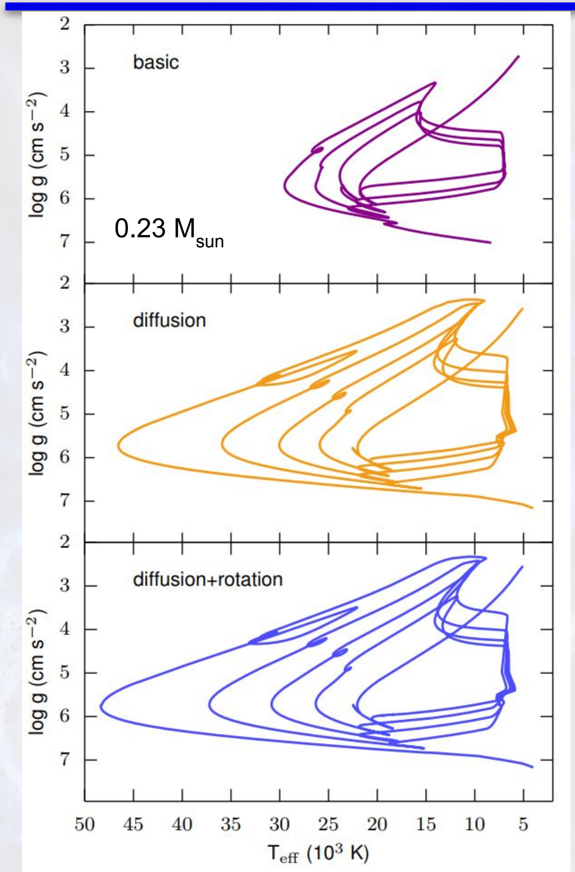
preserves the cooling dichotomy

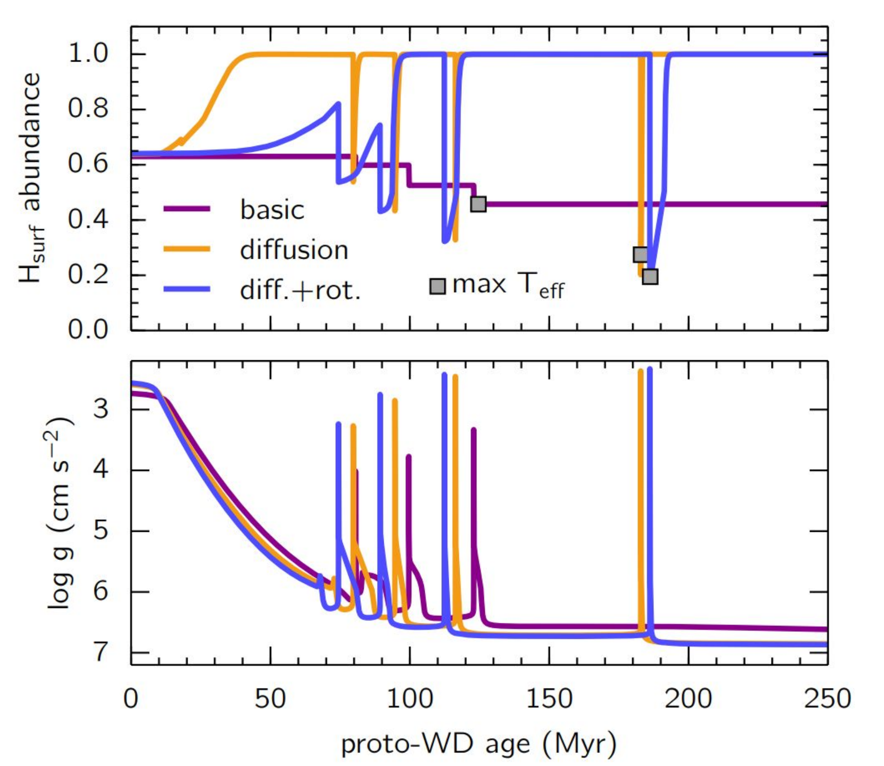
➢ Rotational mixing preserves the diffusive hydrogen tail



Istrate et al. (2016a)

Importance of physics in the proto-WD phase

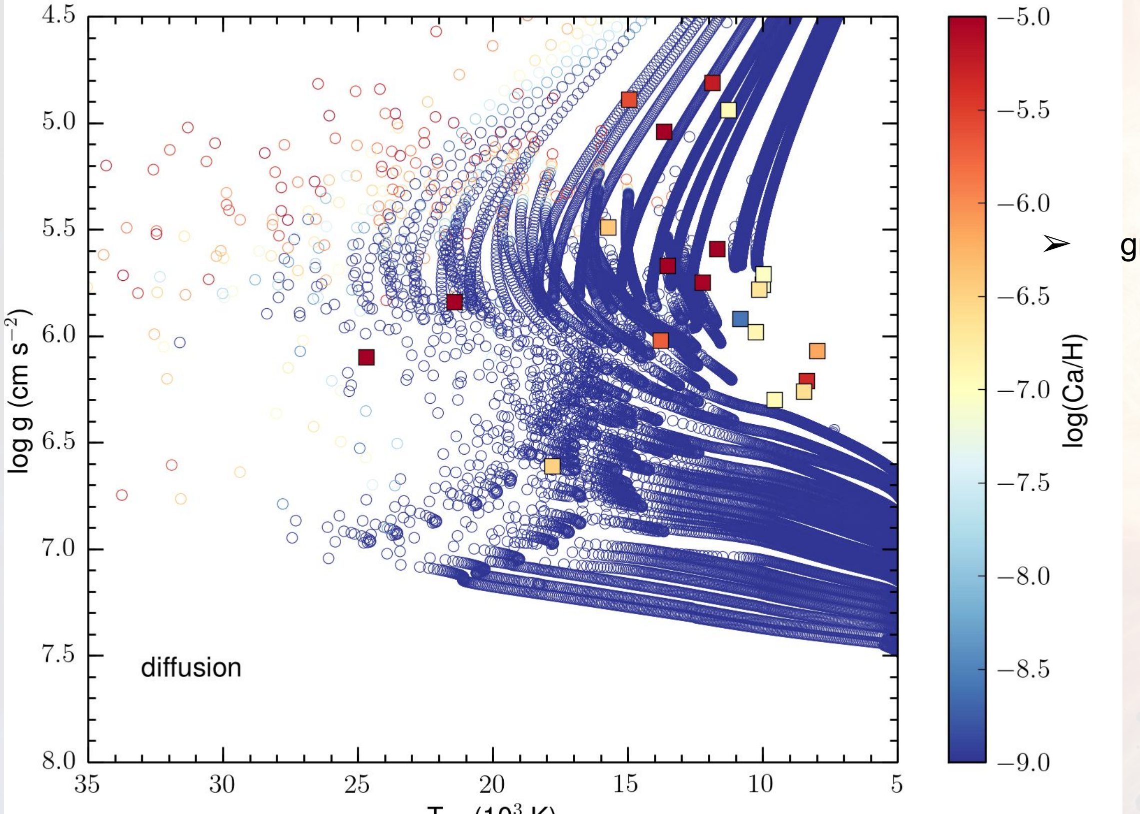




Istrate et al. (2016a)

Metals in the surface layers of ELM proto-WDs

MESA

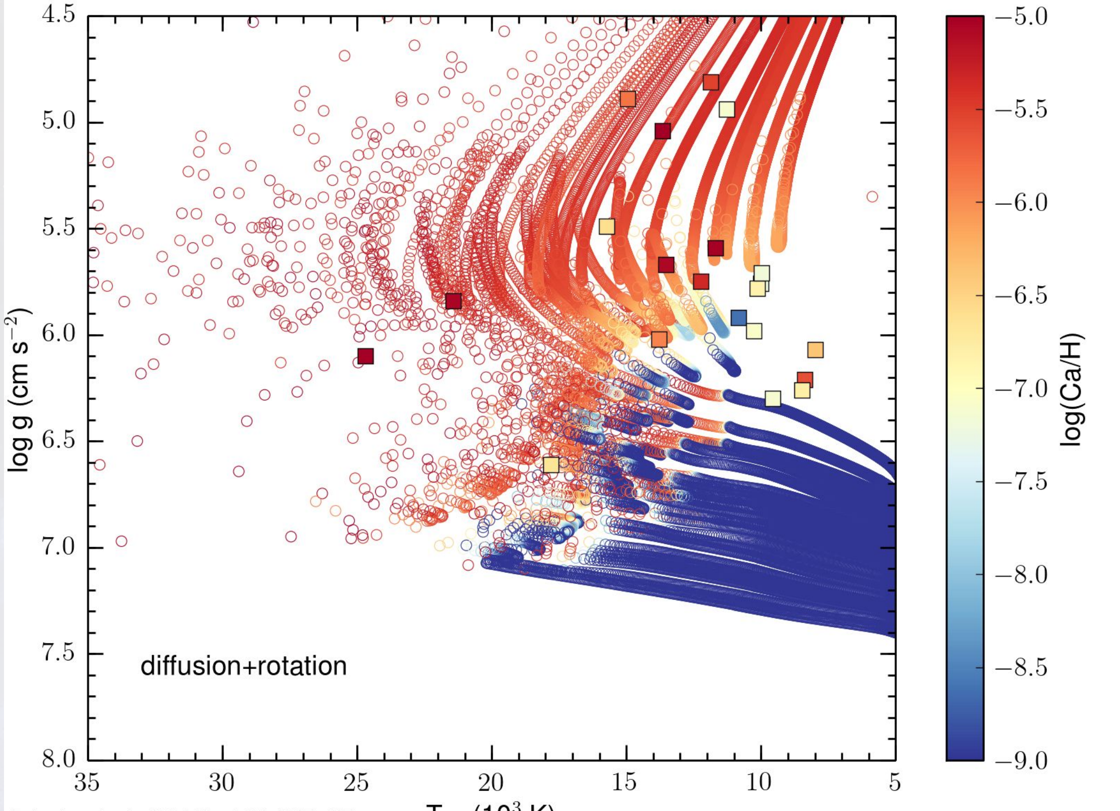


Istrate et al. (2016), A&A 595, 35

➢ gravitational settling-> pure hydrogen surface layers !

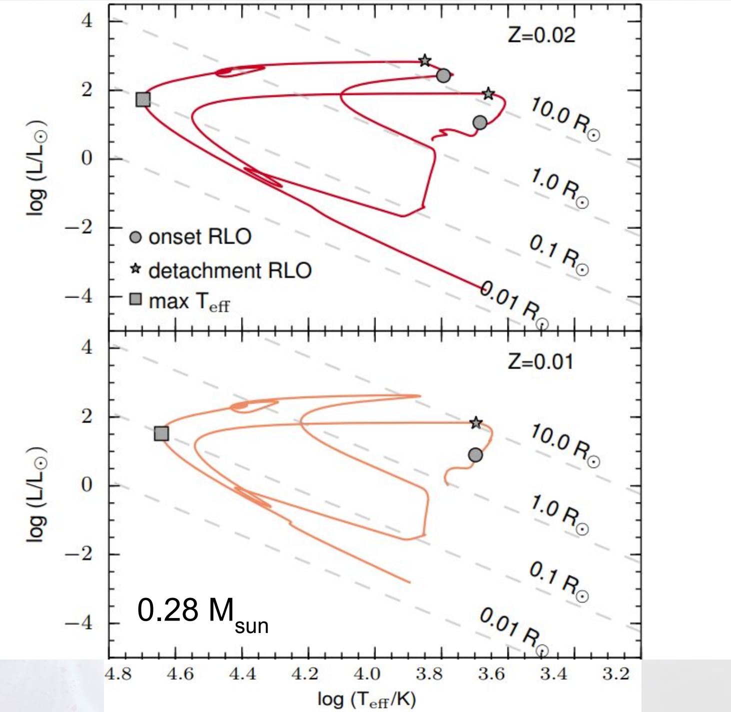
Metals in the surface layers of ELM proto-WDs

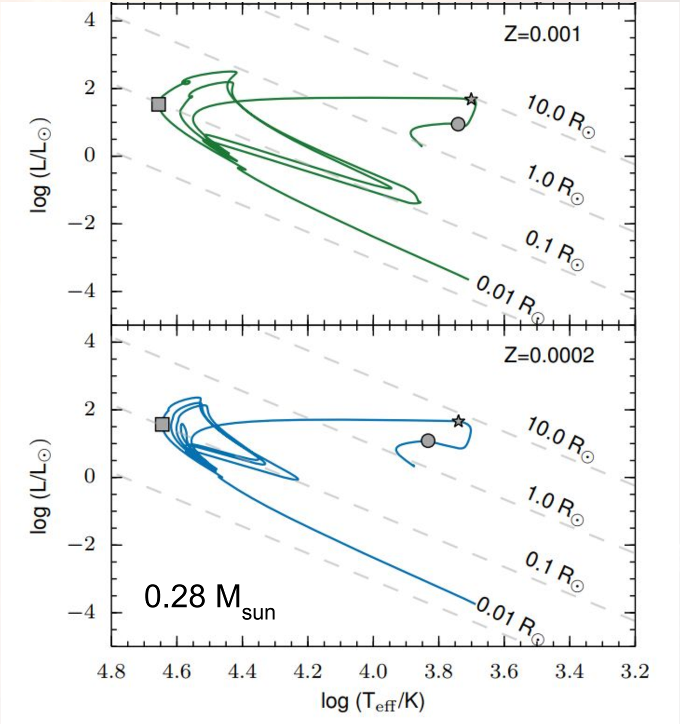
MESA



Istrate et al. (2016), A&A 595, 35

- rotational mixing: key process in determining the surface composition



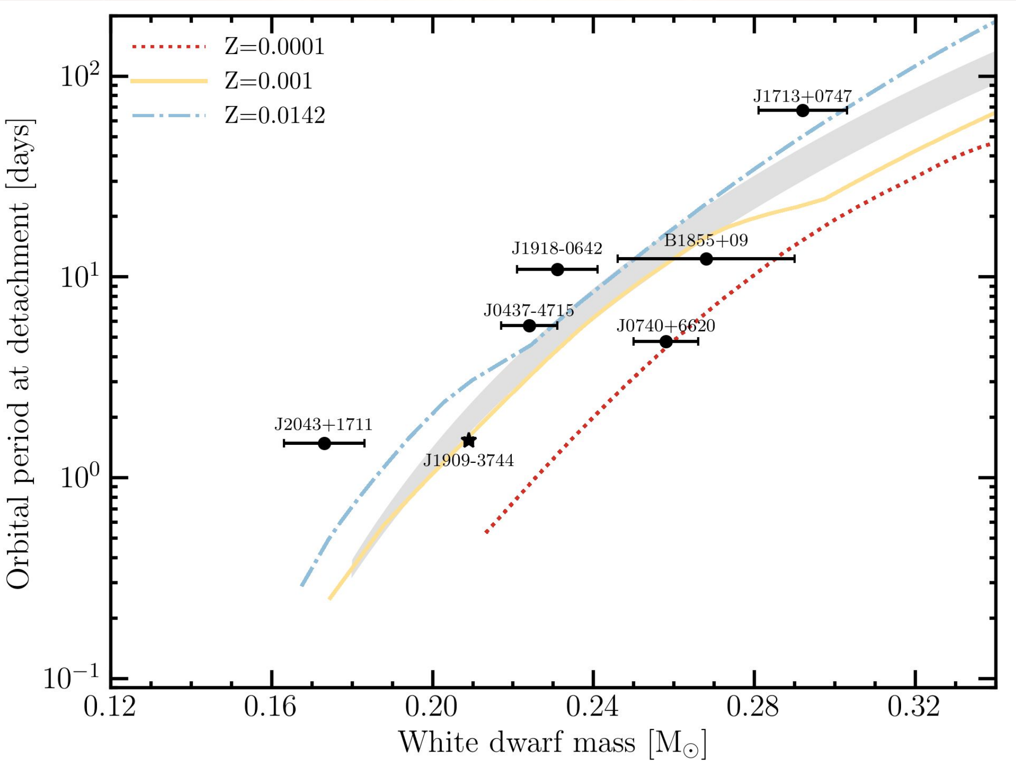


Metallicity needs to be taken into account when looking at individual objects!

Towards precision modelling of ELMs: the case of PSR J1909-3744

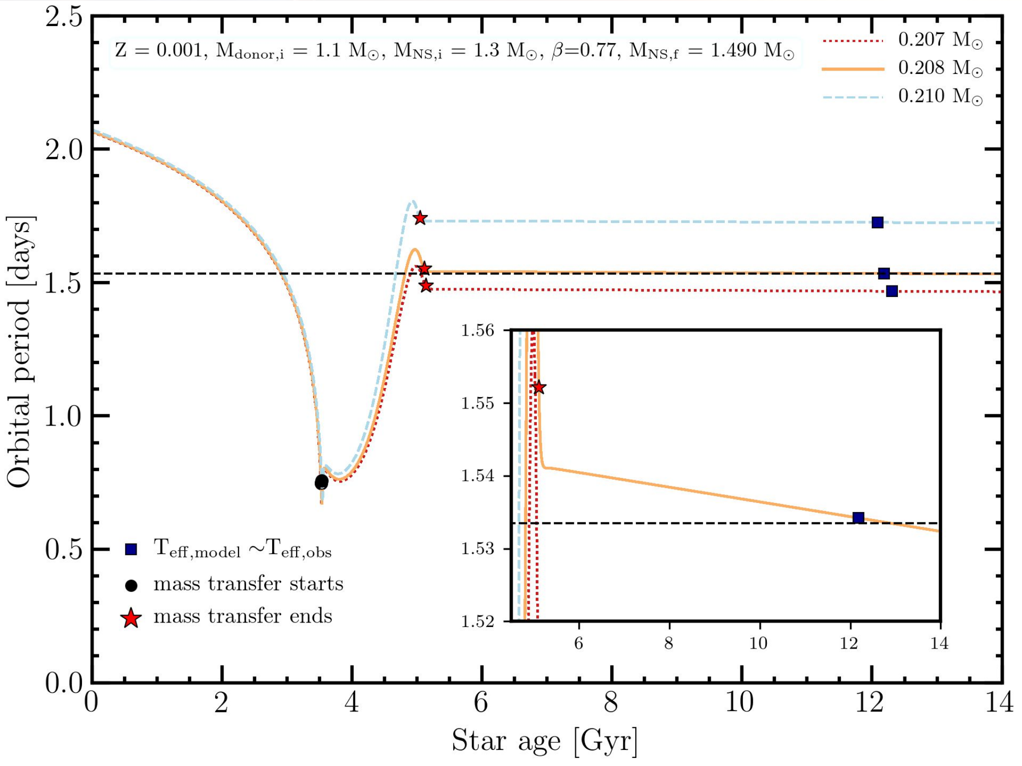
- ✓ Pulsar mass = 1.492 $M_\odot$
- ✓ ELM mass= 0.209 $M_\odot$
- ✓ Orbital period = 1.533 days

Aim: find an evolutionary model that simultaneously fit the orbital parameters and the WD properties



Towards precision modelling of ELMs: the case of PSR J1909-3744

Liu, Guillemot, Istrate et al 2020



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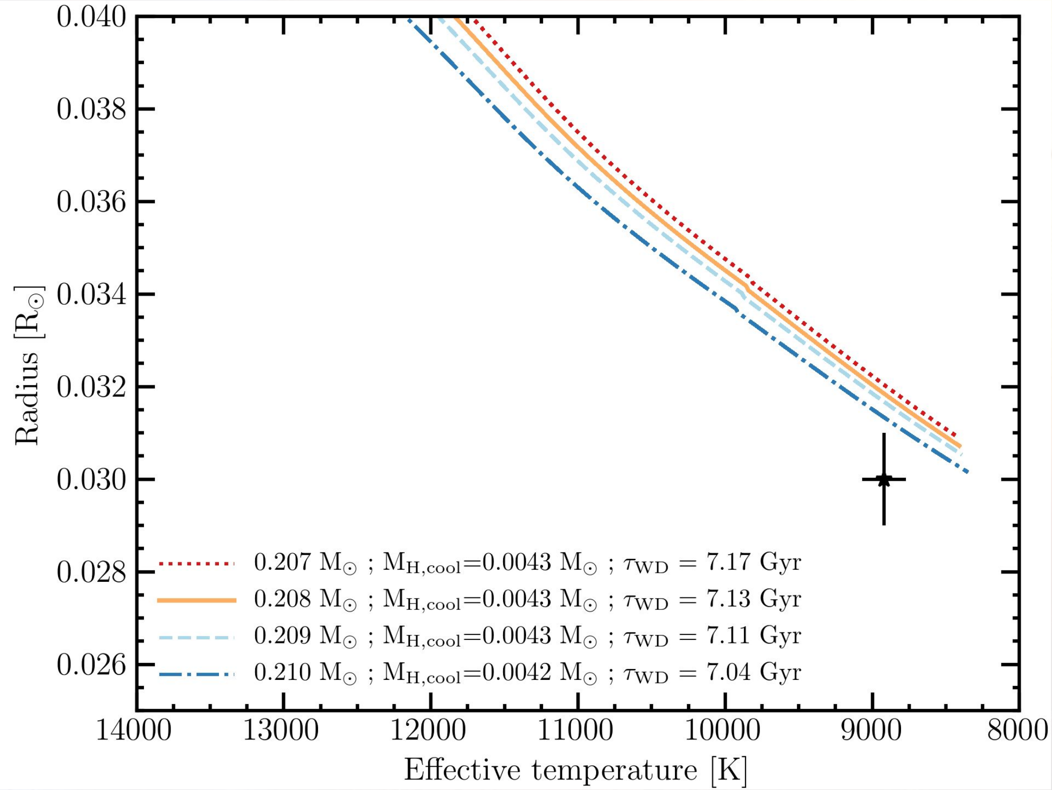
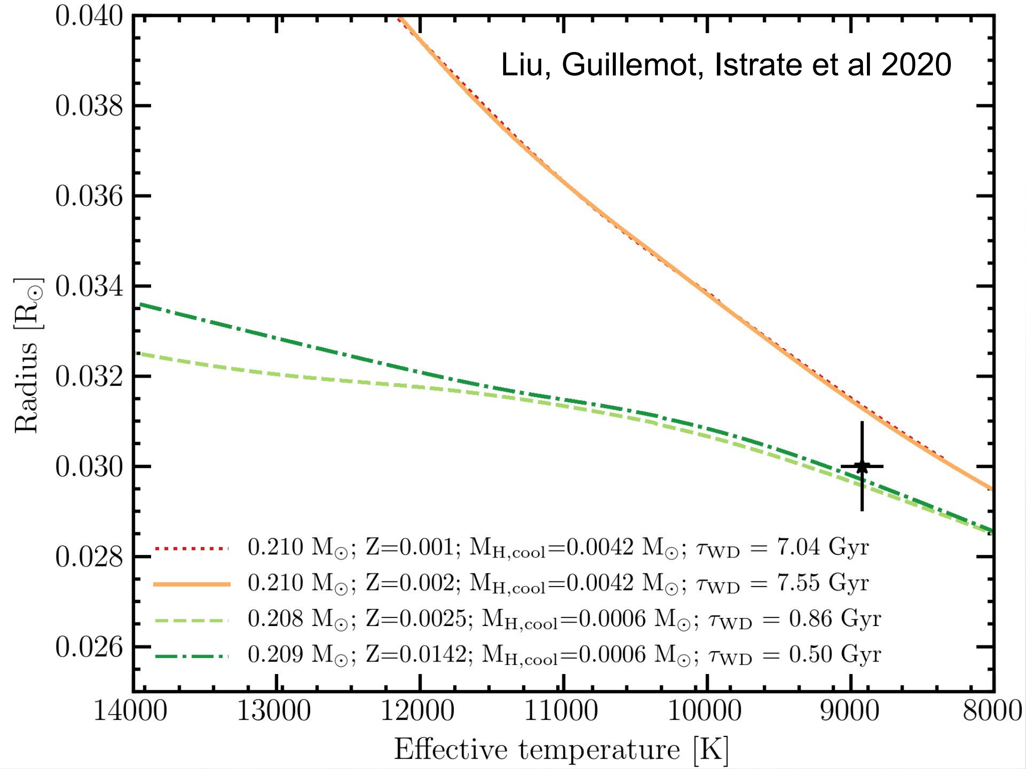
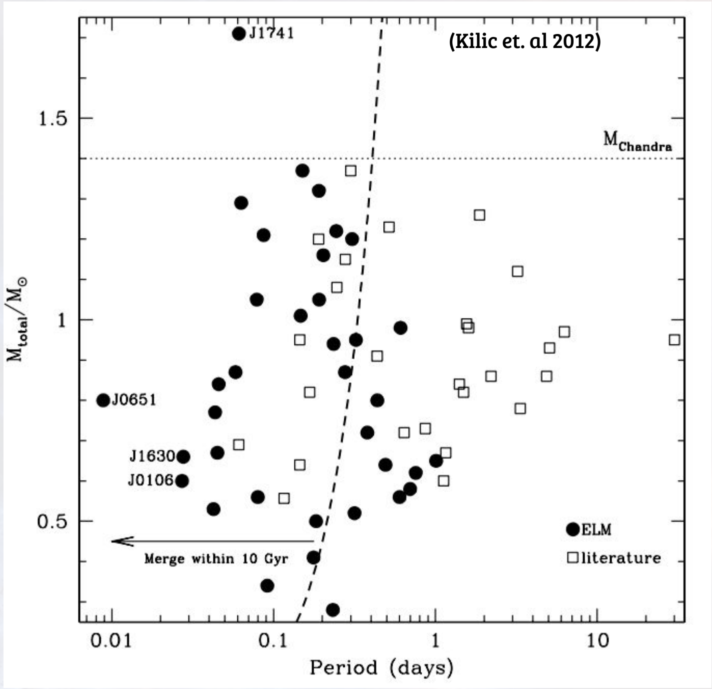


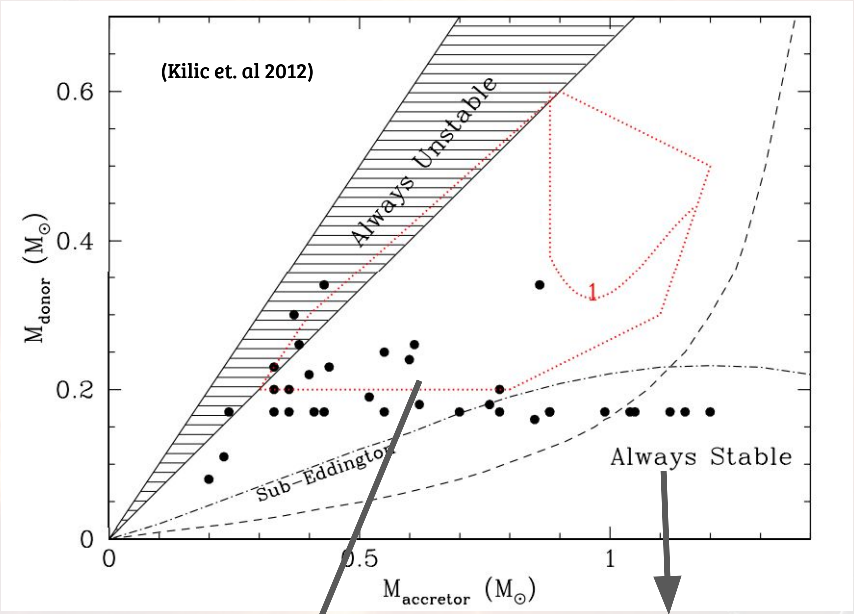
Towards precision modelling of ELMs: the case of PSR J1909-3744

Orbital period evolution and WD cooling properties don't match !



What the future looks like for ELM WD systems?



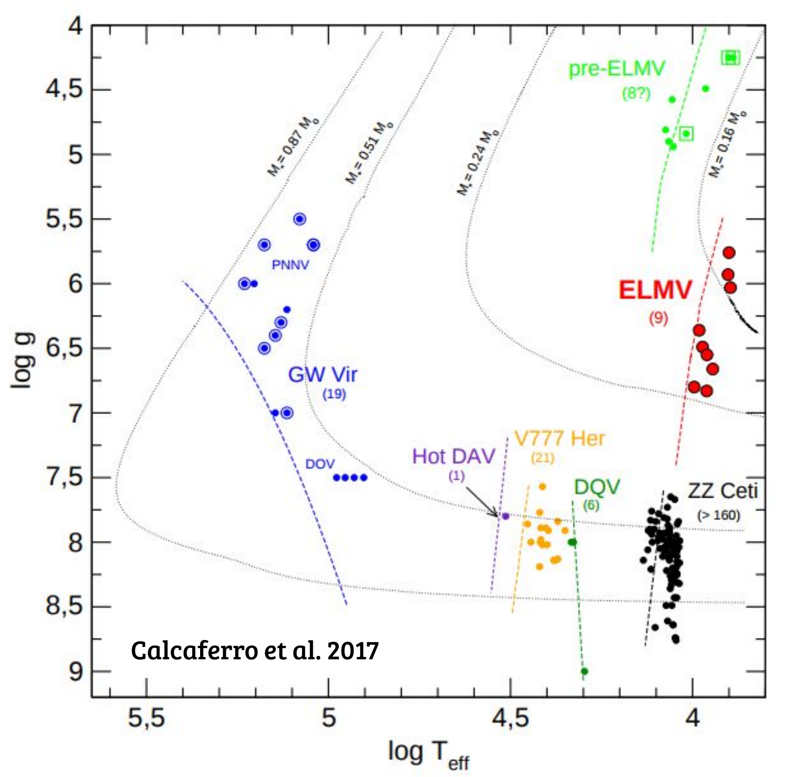


~ half of the observed ELMs will merge in less than 6 Gyr

progenitors of extreme helium stars, single subdwarfs, or massive WDs (?)

progenitors of AM CVns and .Ia supernovae

ELMs and asteroseismology



proto/pre ELMVs pulsators

- ★ (10+) so far discovered

  (**Maxted et al. 2013, 2014; Zhang et al. 2016; Gianninas et al. 2016; Corti et al. 2016**)

- ★ mixed modes: 300-600 s
- ★ excitation mechanism: κ-mechanism (second ionization of He)

ELMVs pulsators

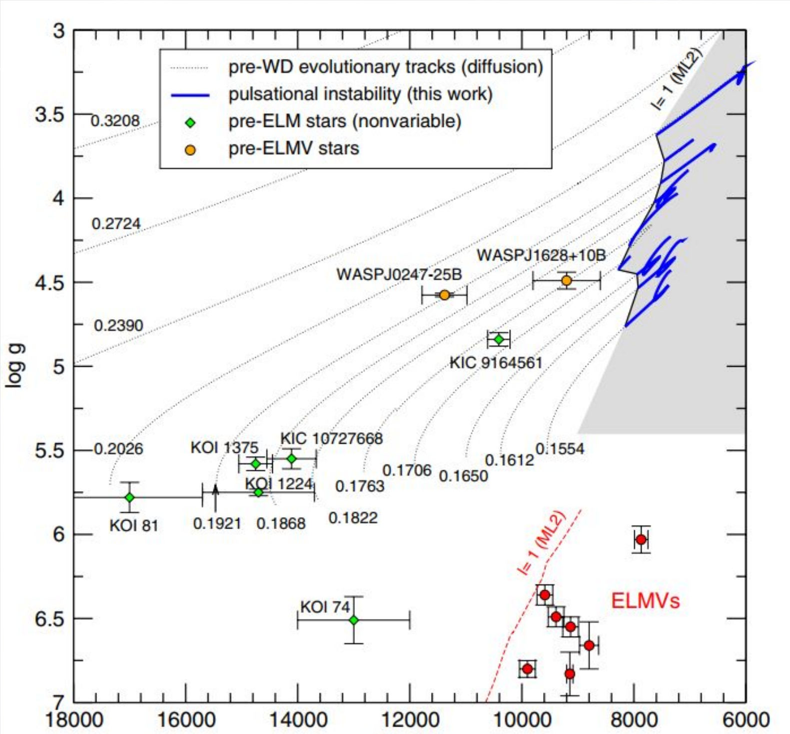
- ★ (12+) discovered so far

  (**Hermes et al. 2012, 2013b,a; Kilic et al. 2015; Bell et al. 2015, 2017**)

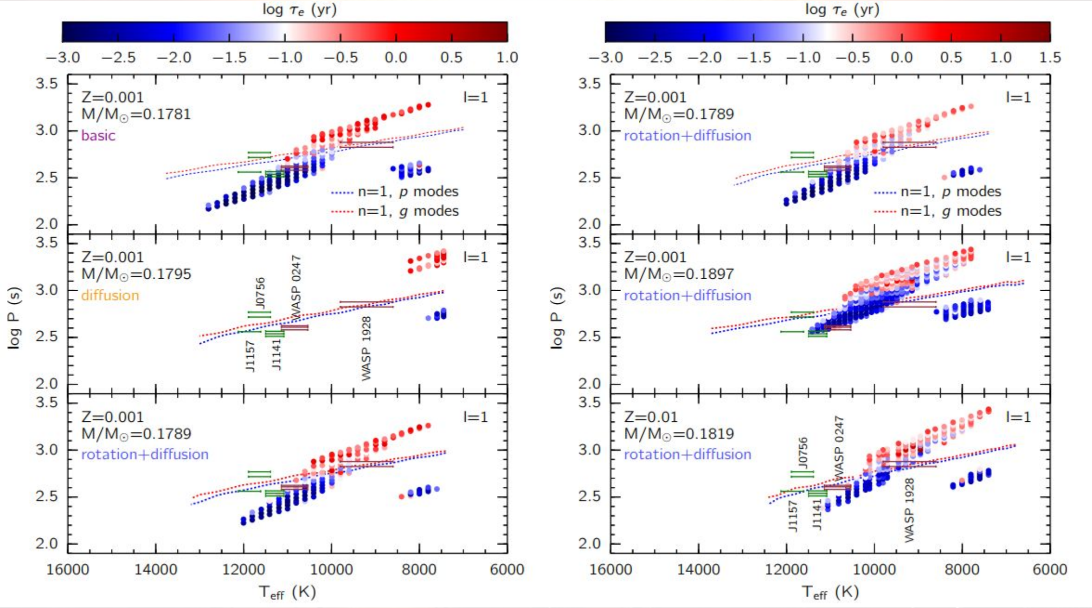
- ★ long g-modes : 1000-6000 s
- ★ excitation: mainly κ-mechanism (H ionization region)

Instability strip of proto-ELMs

➢ element diffusion alone: cannot explain the existence of proto-ELMV pulsators



Corsico et al. (2016)



Istrate et al 2017

Take-away message

- ELM WDs in close binaries are benchmark stellar objects for a variety of astrophysical problems
- we can explain now *some* of their observed properties:
  - the large number of bloated objects (proto-WDs)
  - (qualitatively) the presence of metals in their atmosphere
  - the existence of proto-WD pulsators
- element diffusion and rotational mixing play an important role in their evolution
- However…there is an increasing number of systems that cannot be explained with current models

Future work

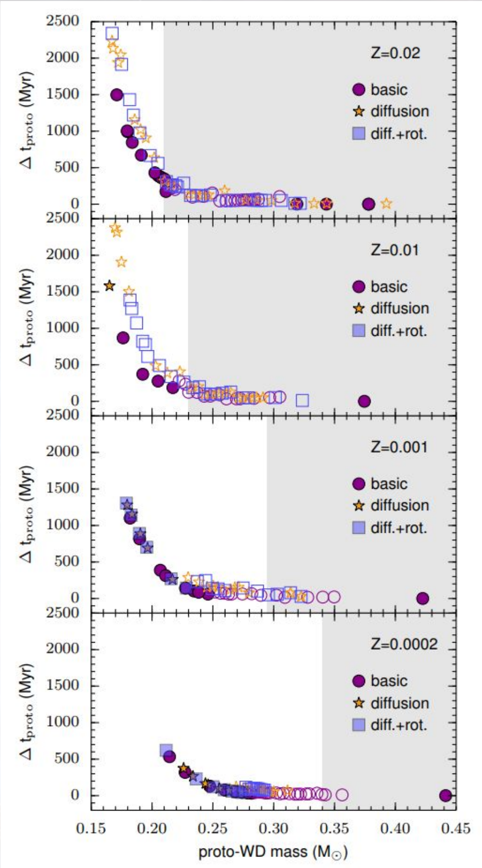
- ➢ Tailored modelling of individual systems
  - The hydrogen poor ELM system in 20 min orbital period (Burdge et. al 2019)
  - Peculiar system that does not match the mass-orbital period (Masuda et al.2019)
- ➢ Investigate the mixing processes on the proto-WD phase
  - Rotational mixing + gravitational settling + radiative levitation case applied to GALEX J1717+6757 (Hermes et al., 2014)
  - map out the instability strips for both proto-ELMs and ELMs pulsators
- ➢ Investigate the future evolution of ELM + WD systems

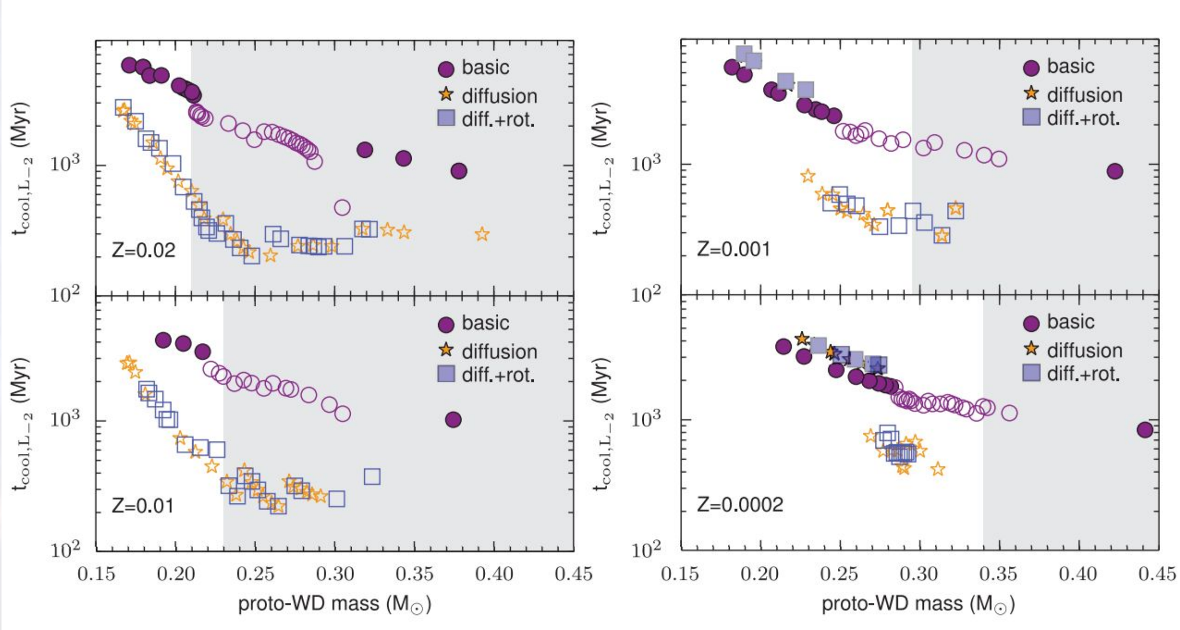

THANK YOU
FOR YOUR
ATTENTION

Table 1. Measured and derived timing parameters of PSR J1909–3744.

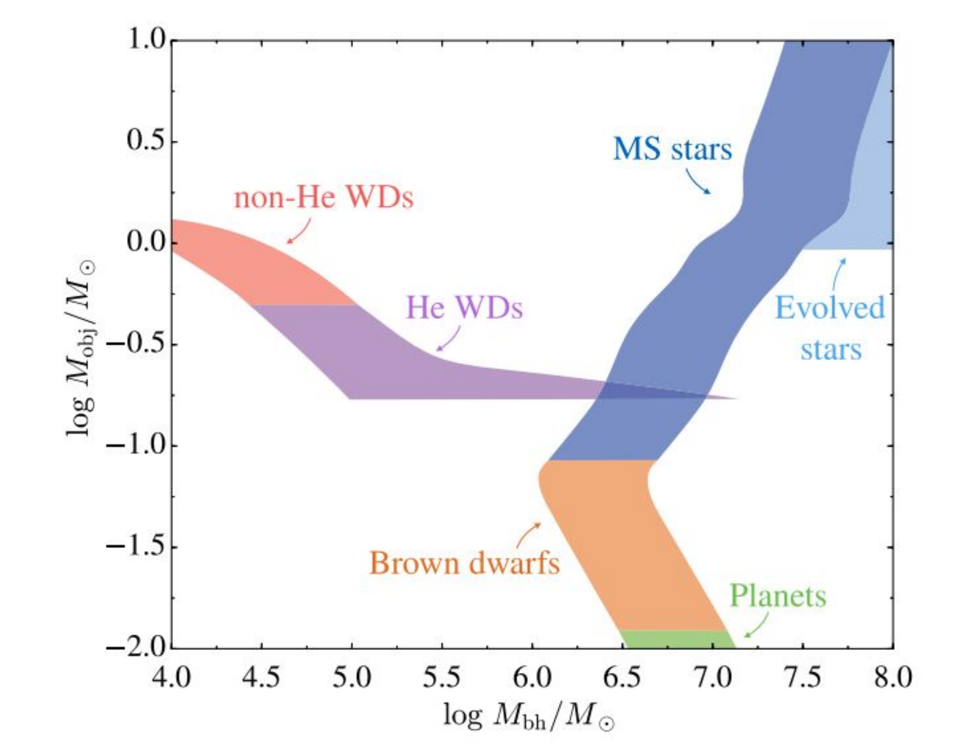
Parameter	Value
MJD range	53368–58693
Number of TOAs	846
Timing residual rms (μs)	0.103
Reference epoch (MJD)	55000
Measured parameter	
Right ascension, α (J2000)	19:09:47.4335812(6)
Declination, δ (J2000)	−37:44:14.51566(2)
Proper motion in α, μ_α (mas yr^{-1})	−9.512(1)
Proper motion in δ, μ_δ (mas yr^{-1})	−35.782(5)
Parallax, π (mas)	0.861(13)
Spin frequency, ν (Hz)	339.315687218483(1)
Spin frequency derivative, $\dot{\nu}$	$-1.614795(7) \times 10^{-15}$
DM (cm^{-3} pc)	10.3928(3)
DM1 (cm^{-3} pc yr^{-1})	−0.00035(5)
DM2 (cm^{-3} pc yr^{-2})	$2.2(7) \times 10^{-5}$
Orbital period, P_b (d)	1.533449474305(5)
Epoch of ascending node (MJD), T_{asc}	53113.950742009(5)
Projected semi-major axis, x (s)	1.89799111(3)
$\hat{x}$ component of the eccentricity, κ	$4.68(98) \times 10^{-8}$
$\hat{y}$ component of the eccentricity, η	$-1.05(5) \times 10^{-7}$
Orbital period derivative, $\dot{P}_b$	$5.1087(13) \times 10^{-13}$
Derivative of x, $\dot{x}$	$-2.61(55) \times 10^{-16}$
Shape of Shapiro delay, s	0.998005(65)
Range of Shapiro delay, r (μs)	1.029(5)
Derived parameter (assuming GR)	
Galactic longitude, l (deg)	359.7
Galactic latitude, b (deg)	−19.6
Longitude of periastron, ω (deg)	156(5)
Orbital eccentricity, e	$1.15(7) \times 10^{-7}$
Pulsar mass, m_p ($M_\odot$)	1.492(14)
Companion mass, m_c ($M_\odot$)	0.209(1)
Parallax distance, d_π (kpc)	1.16(2)
kinematic distance, d_k (kpc)	1.158(3)
Spin period, P (ms)	2.94710806976663(1)
Spin period derivative, $\dot{P}$ ($\times 10^{-21}$)	14.02521(6)
$\dot{P}_{Gal}$ ($\times 10^{-21}$)	0.0587(2)
$\dot{P}_{Shk}$ ($\times 10^{-21}$)	11.36(3)
$\dot{P}_{Int}$ ($\times 10^{-21}$)	2.60(3)
Characteristic age, τ_c (Gyr)	18.0
Surface magnetic field, B (G)	8.9×10^7

Evolutionary timescales for (proto) ELM WDs



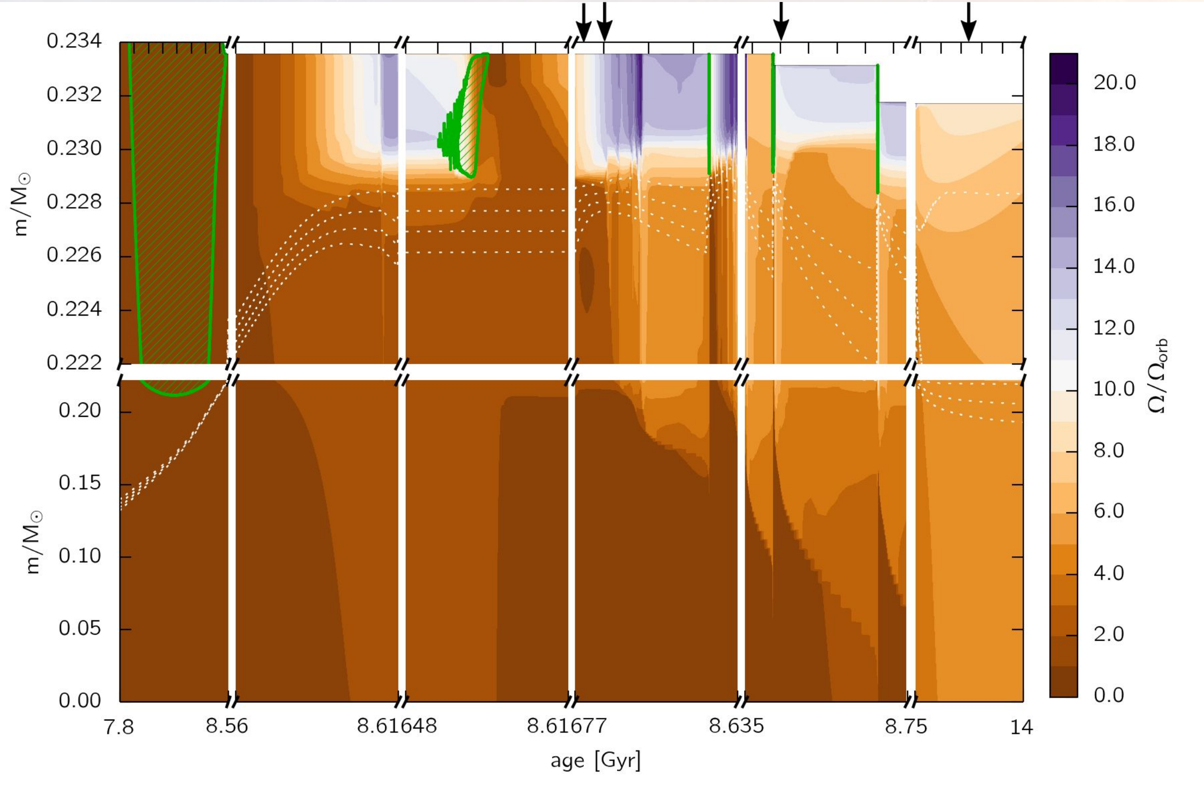


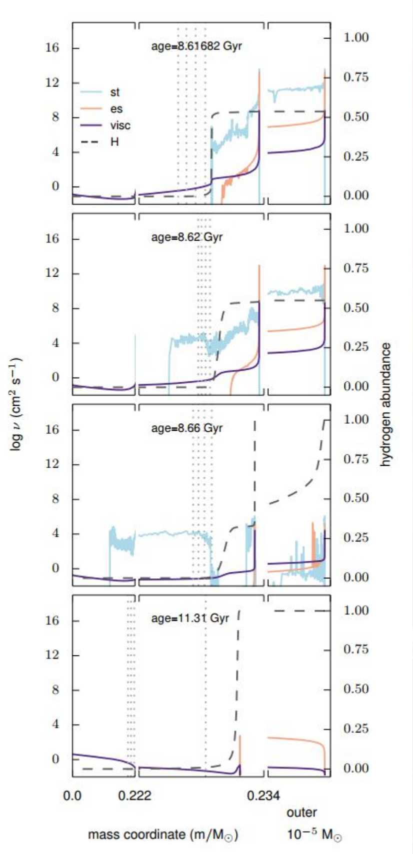
Tidal disruption menu



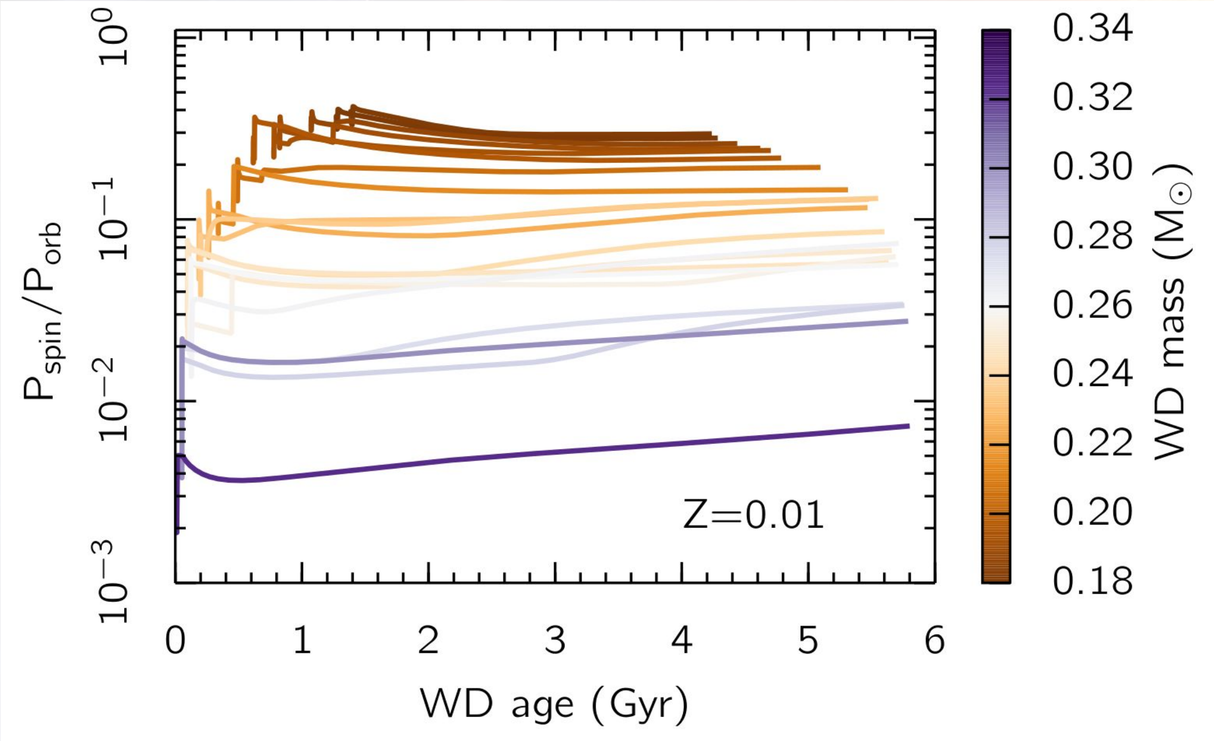
Law-Smith et al. 2017

Rotational mixing



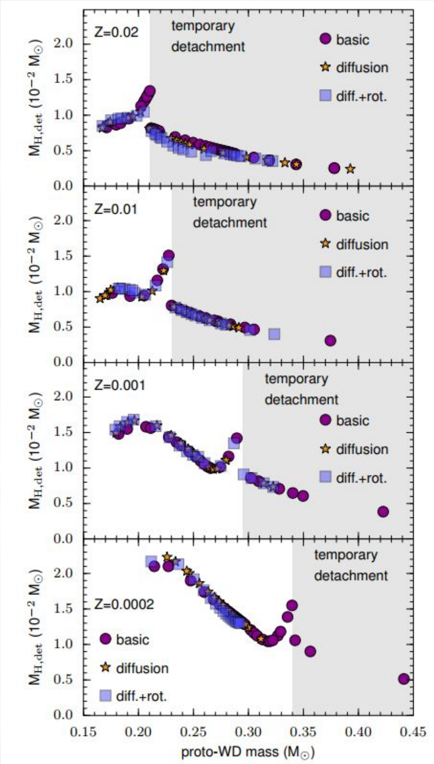


WD rotation period vs orbital period

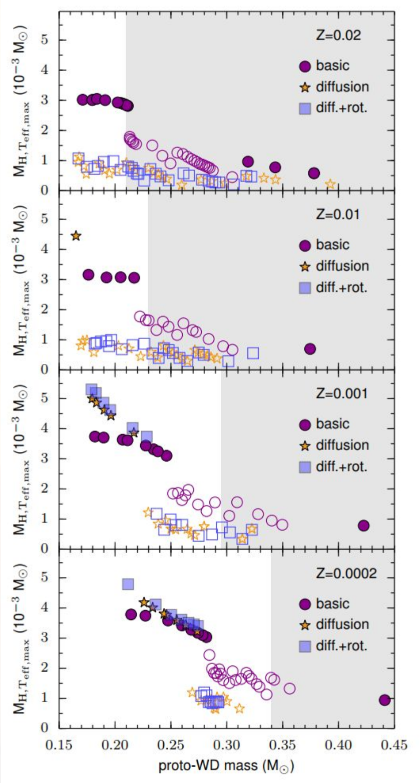


Hydrogen envelopes

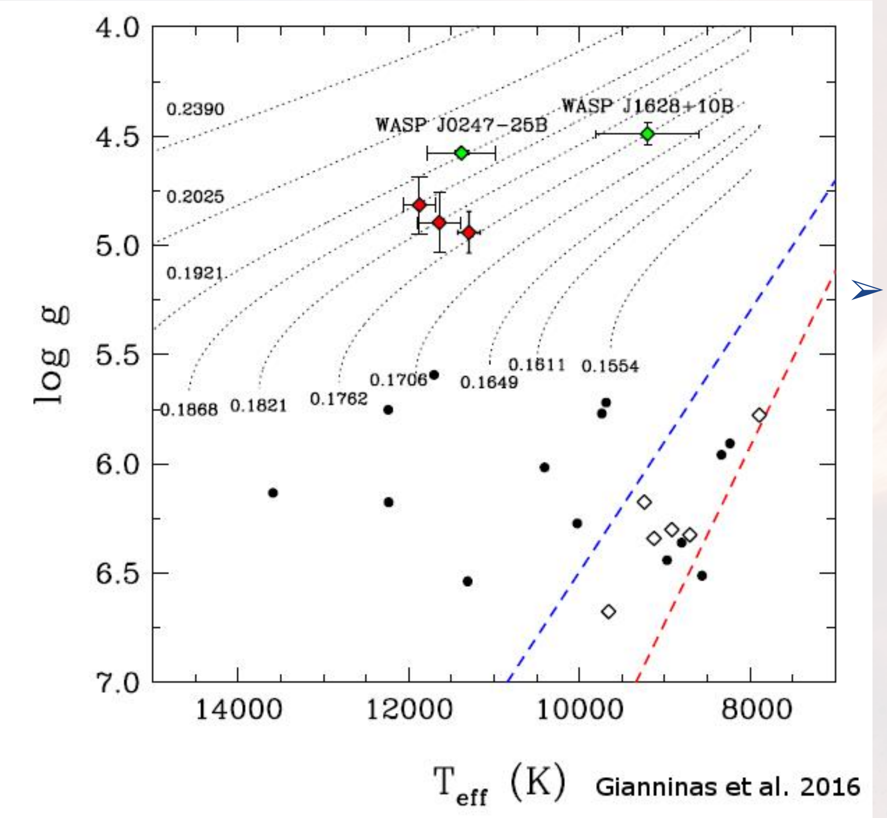
- after mass transfer



- after proto-WD phase



Discovery of helium rich proto-ELM pulsators



➢ first empirical evidence that pulsations in proto-ELMs can only occur if a significant amount of He is present in their atmosphere