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The cooling of white dwarfs and a varying gravitational constant

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Introduction

- Within the theoretical framework of some modern unification theories the constants of nature are functions of cosmological time.
- This contradicts the fact that for most astronomical applications we assume that these constants are independent of time (and of space location).
- In fact, the statement about the constancy of the fundamental “constants” of nature is just a hypothesis, though quite an important one, which deserves to be explored.
- In recent years, several constraints have been placed on the variation of the fine structure constant (Uzan 2003; García–Berro et al. 2007).

Introduction

- In sharp contrast with the vivid debate about whether (or not) there is evidence for a varying fine structure constant, very few studies have been devoted to study a hypothetical variation of the gravitational constant.
- White dwarf stars provide an independent way of testing the possibility of a hypothetical varying gravitational constant:

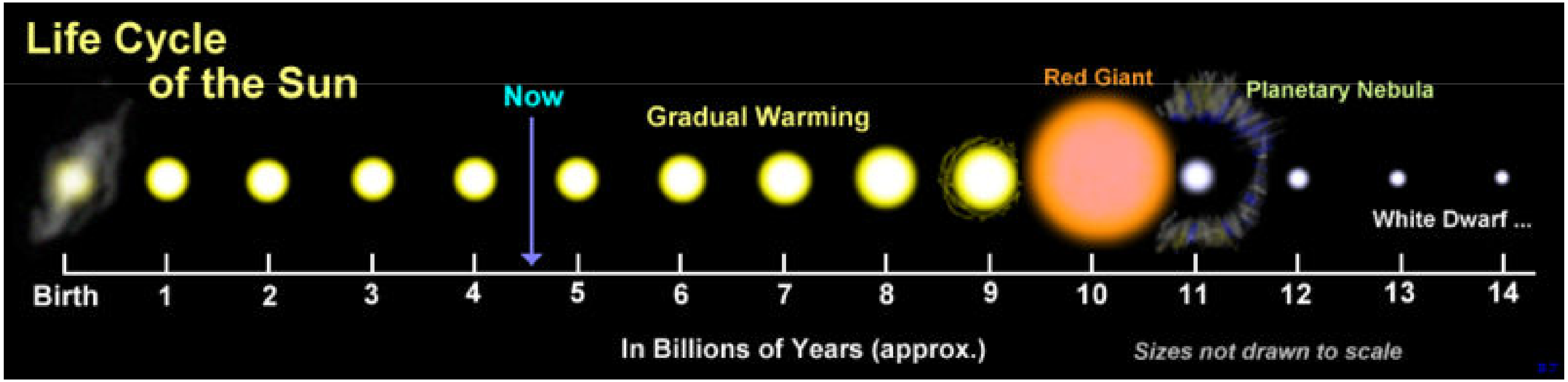
  1. White dwarfs are extremely long-lived stars. Thus, the effects of a varying gravitational constant can become prominent, even for very small secular rates of change.

Introduction

2. White dwarfs are the endpoint of stellar evolution for the vast majority of stars. Hence, the present Galactic populations contain substantial numbers of white dwarfs.
3. White dwarfs are rather compact objects. The pressure of degenerate electrons supports their mechanical structure, and this structure is very sensitive to the precise value of G.
4. The evolution of white dwarfs is relatively well understood, and can be fairly described as a simple gravothermal process. Hence, for sufficiently low temperatures their luminosity is derived entirely from a close balance between the thermal and the gravitational energies. Consequently, a secularly varying G largely affects the gravothermal balance of white dwarfs and, thus, their luminosities.

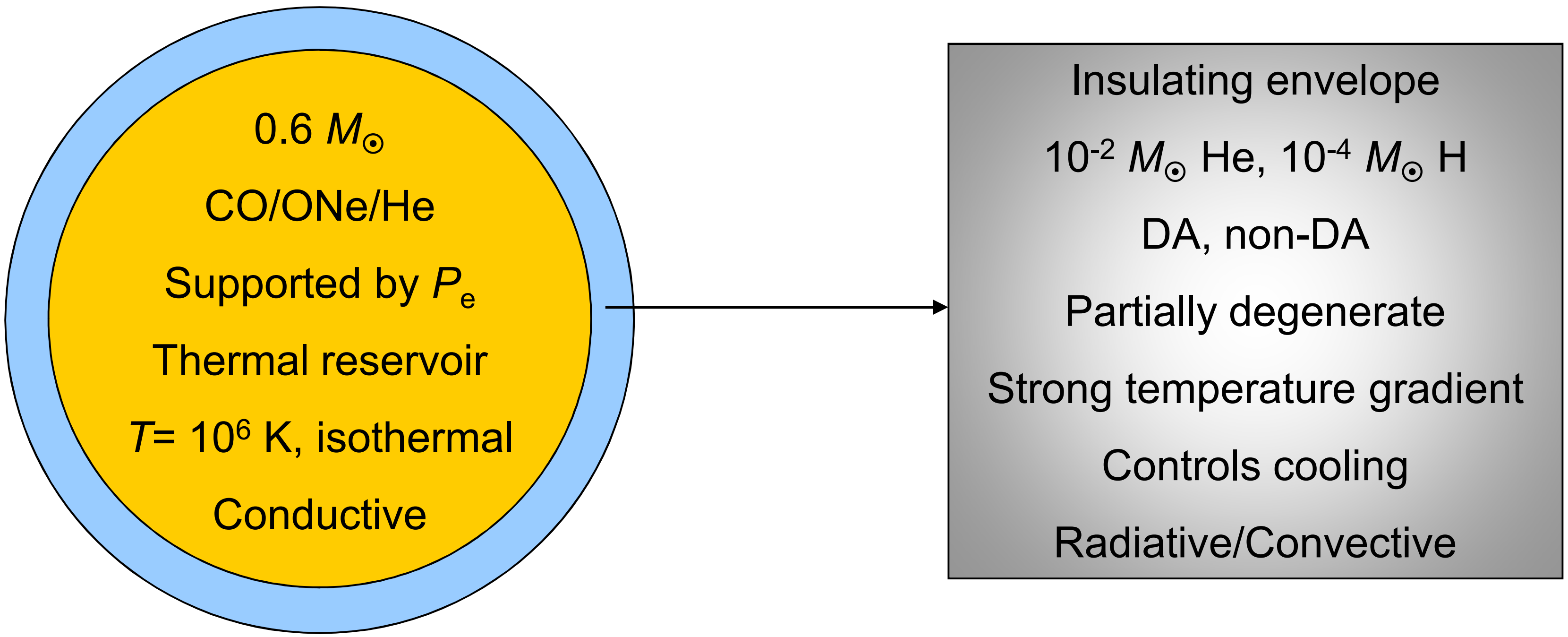
White dwarfs for non-astronomers

- Life of solar mass stars (98% of the stars):



White dwarfs for non-astronomers

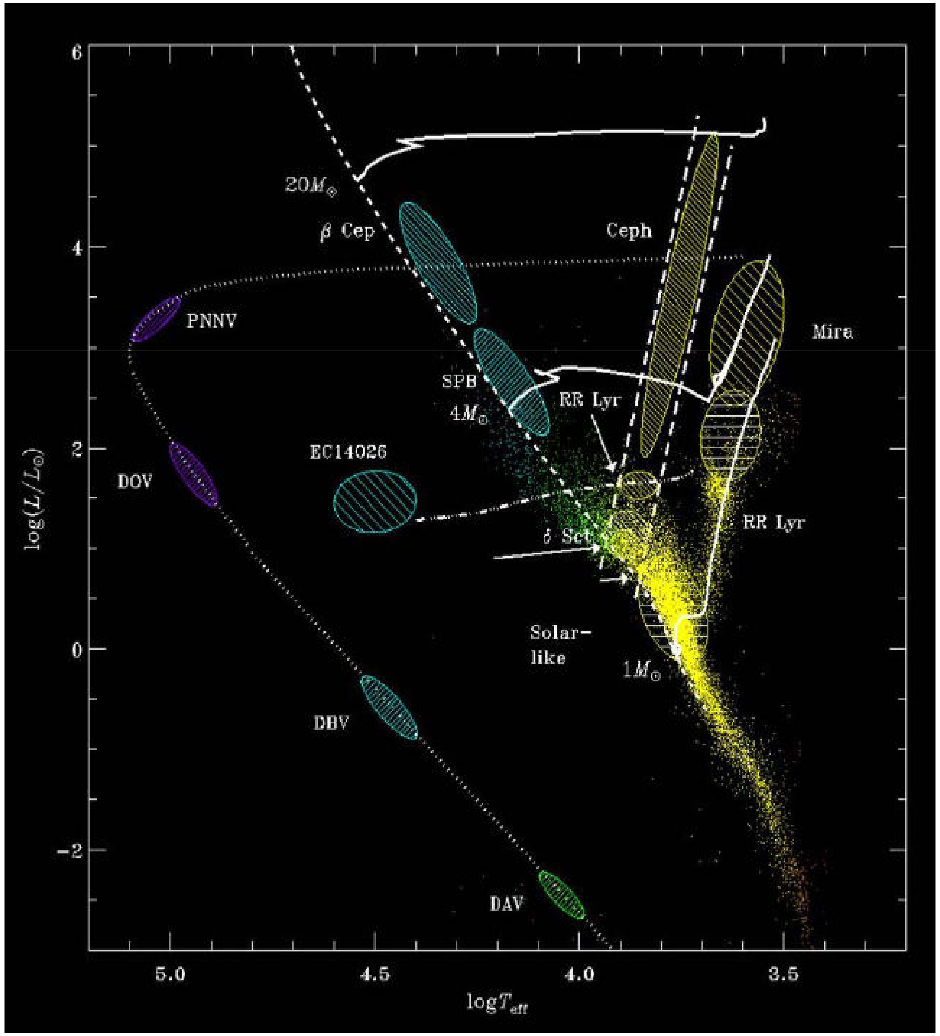
- The structure of white dwarfs is supported by the pressure of the degenerate electrons.
- No nuclear reactions for typical luminosities: cooling.
- Constant radius.



Pulsating white dwarfs

- Non-radial oscillations (toroidal or spheroidal)
- Either DAs: ZZ-Ceti, DBs: V777 Her, PG1159: GW Vir
- DAs: DAVs, DBs: DBVs, PG1159: DOVs
- Only *g*-modes (gravity), no *f*- nor *p*-modes in all cases
- DOVs: $T_{\rm eff}$ ~80000 K
- DBVs: $T_{\rm eff}$ ~27000 K
- DAVs: $T_{\rm eff}$ ~12000 K
- Typical periods: from 200 s to 2000 s

Pulsating white dwarfs



Pulsating white dwarfs

- G117-B15A is a ZZ Ceti star (DAV)
- The periods of the pulsations are 215.2 s, 271.0 s and 304.4 s
- The mode with period 215.2 s is the most stable optical clock known so far, with a stability better than most pulsars:

$$\dot{P} = (3.57 \pm 0.82) \times 10^{-15}$$

- The secular changes in the period are due to cooling:

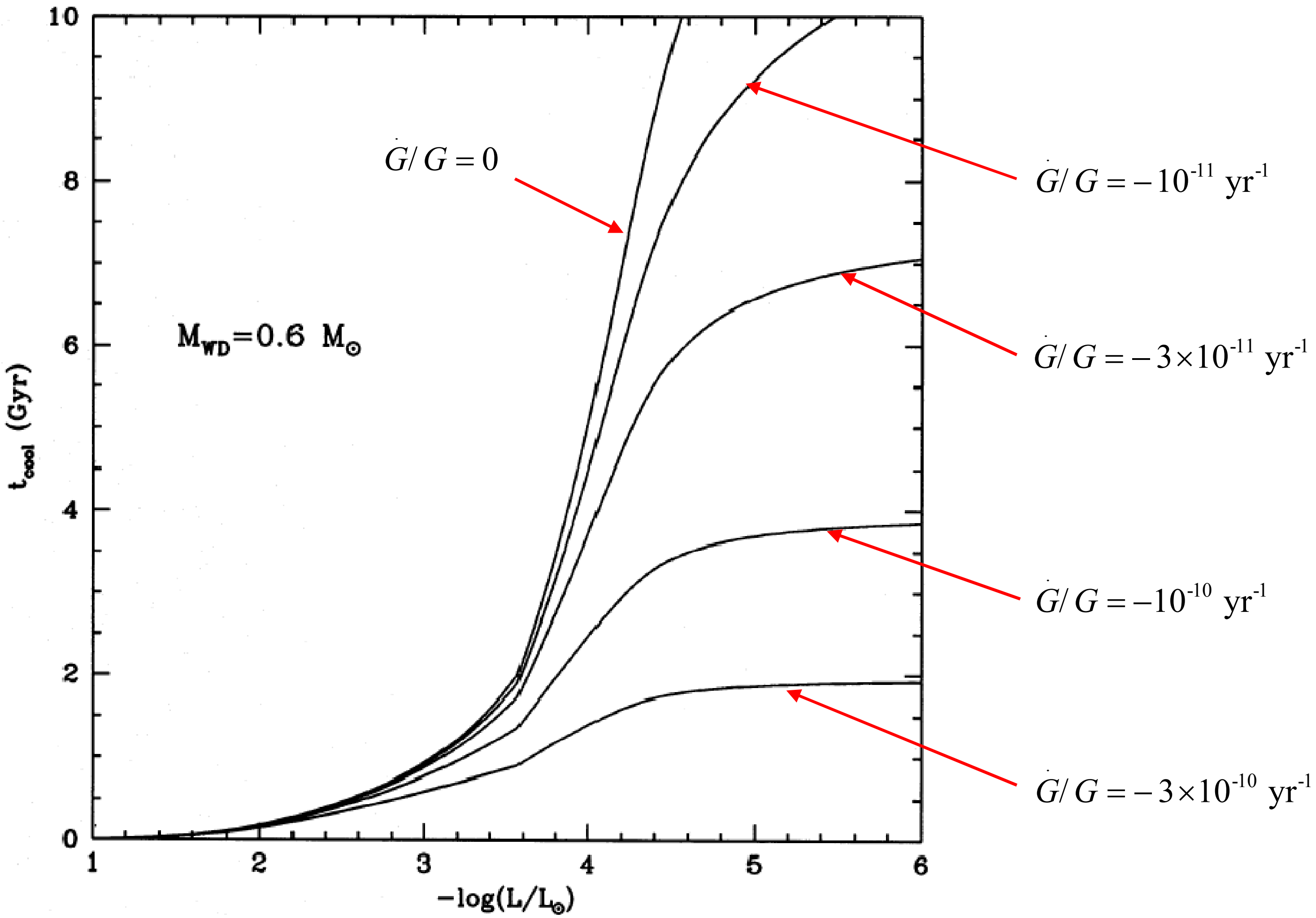
$$\frac{\dot{P}}{P} = -a\frac{\dot{T}}{T} + b\frac{\dot{R}}{R}$$

- Any additional source of cooling can be checked.
- For a varying *G*, the second term is not negligible.

Previous work

- The first one to use white dwarfs to constrain a possible variation of the gravitational constant was Vila (1976). However, due to the lack of good observational data and of reliable cooling models he could not arrive at a significant conclusion.
- Later, García–Berro et al. (1995) used a simplified treatment to check which could be the effects of a slowly varying *G* in the cooling of white dwarfs.
- Their treatment was based on a series of static models and not on fully evolutionary calculations. Nevertheless, they were able to set an upper limit.

Previous work



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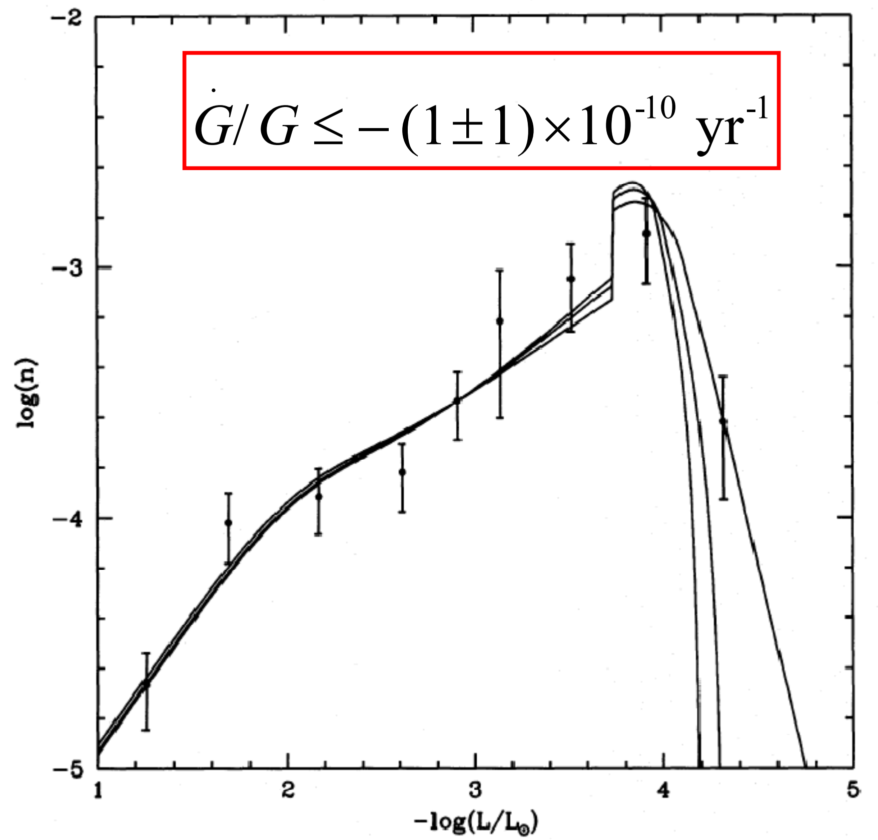
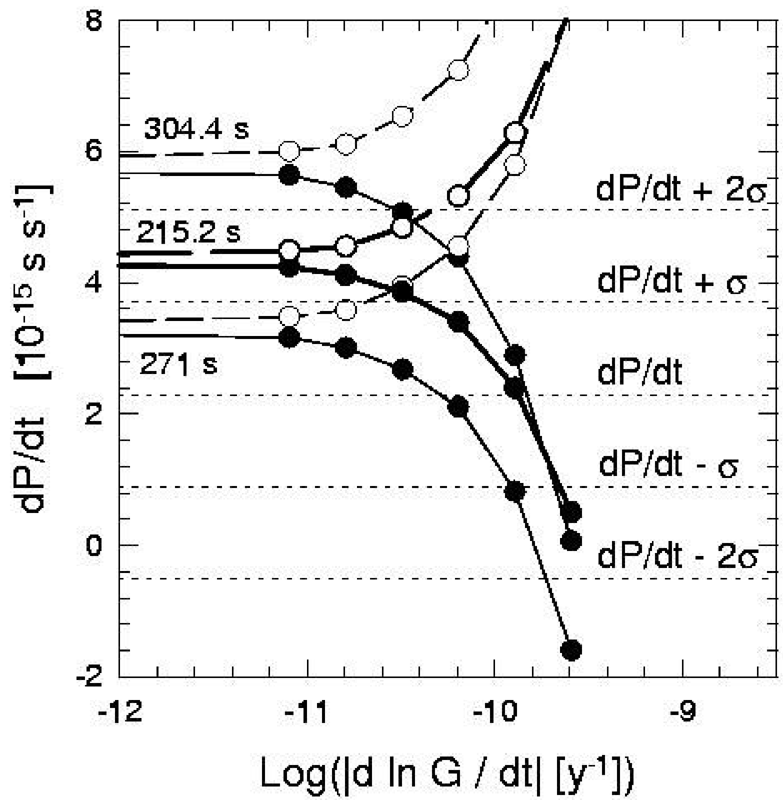
Previous work

- Using the white dwarf luminosity function (density of disk white dwarfs with a given luminosity) an upper limit can be placed:



Previous work

- Using the rate of period change of G117-B15A:



$$- 2.5\times10^{-10}\ \mathrm{yr}^{-1} \le \dot{G}/G \le 4.0\times10^{-11}\ \mathrm{yr}^{-1}$$

Our approach

- Although the evolutionary properties of white dwarfs could be potentially used to set upper bounds to the rate of variation of the gravitational constant, very few studies have been done up to now.
- We compute a new set of cooling sequences using a state-of-the-art (and very realistic) stellar evolutionary code.
- In the interests of simplicity, we have assumed that $\dot{G}/G$ remains constant with time.
- Issues like ^{22}Ne sedimentation in the liquid phase, carbon-oxygen phase separation upon crystallization, non-gray model atmospheres, element diffusion, reliable opacities and conductivities… are fully taken into account.

The energy equation

- The luminosity equation in the case of a varying *G* becomes (García–Berro et al. 1995):

$$L + L_{\nu} = -\frac{dB}{dt} + \frac{\dot{G}}{G}\Omega$$

B=*U*+Ω is the binding energy

U is the thermal energy

Ω is the gravitational energy

- Both *U* and Ω change as a result of a varying *G*:

$$\dot{\Omega} = -\int_0^{M_{WD}} \frac{P}{\rho^2}\dot{\rho}\, dm + \frac{\dot{G}}{G}\Omega$$

The energy equation

- These expressions were obtained under the assumption that the changes of the gravitational constant are so small that the white dwarf has time to adjust its mechanical structure to the actual value of *G* in a timescale much shorter than that of the cooling timescale.
- Given their global nature, these expressions are useful for studying the energetics of white dwarfs and allow to derive first-order approximations to the effects of a varying *G.*
- However, if more accurate results are to be obtained, a different approach must be used.
- We use the regular expression for the luminosity, and allow *G* vary.

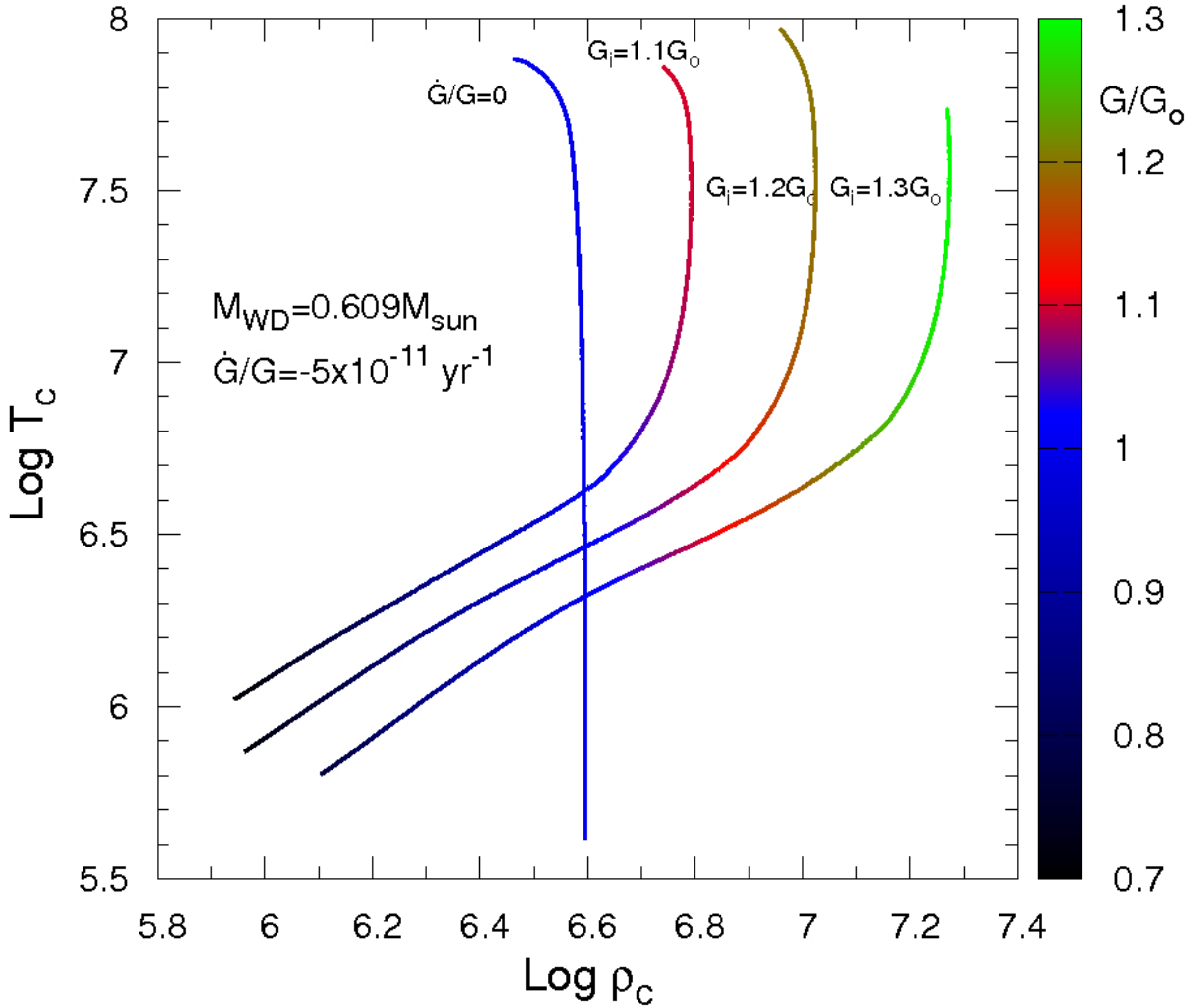
White dwarf evolutionary results

- Grid of white dwarf models with different initial values for *G*, different white dwarf masses and different rates of change of the gravitational constant:

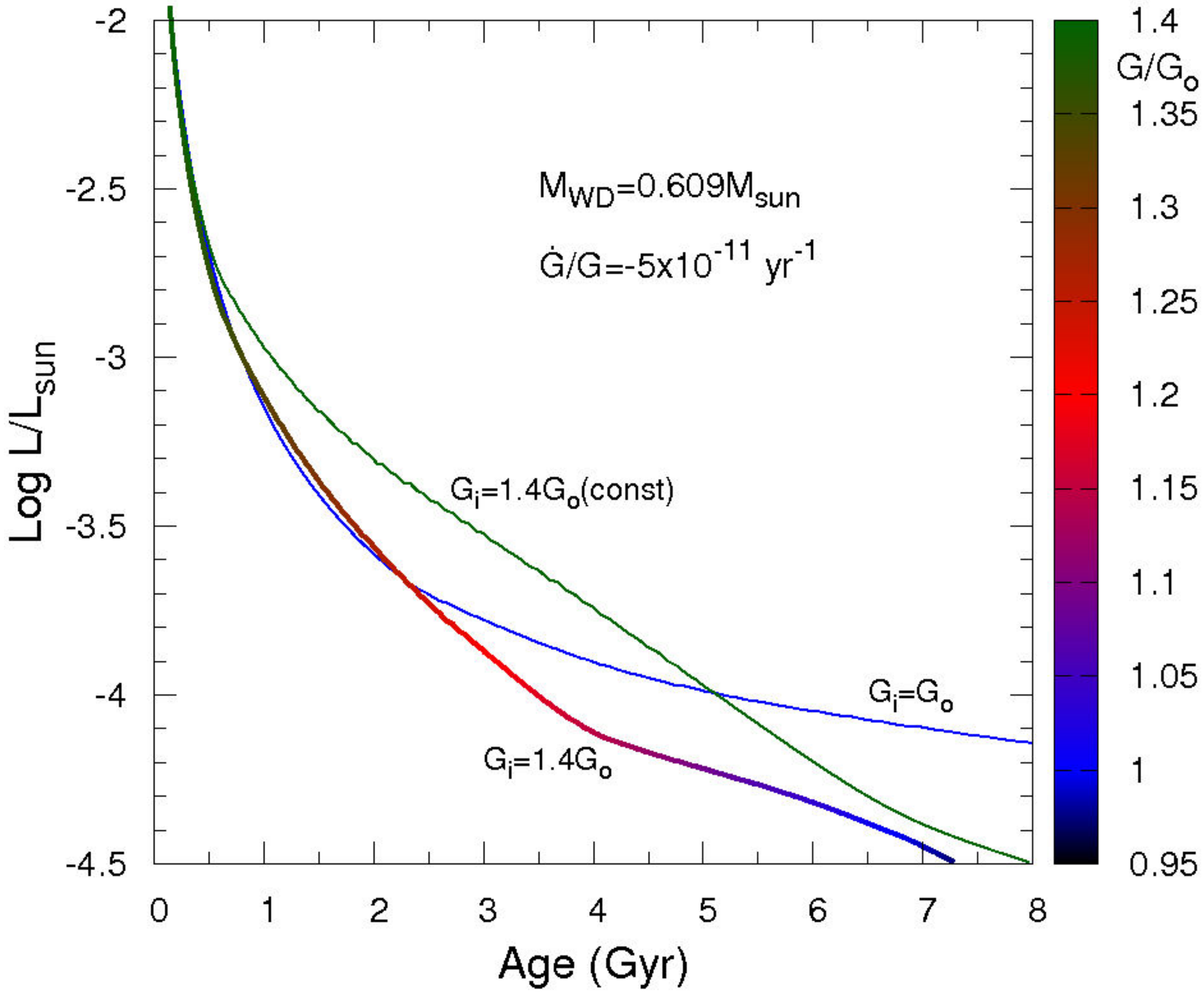
Table 1. White dwarf evolutionary sequences computed in this work. We list the white dwarf stellar mass (in solar units) and, for each value of the rate of change of the gravitational constant, G/G (in units of yr^{-1}), the initial value of G at the beginning of the white dwarf cooling phase, G_i/G_0, being G_0 the actual value of G. The numbers in brackets give the stellar luminosity ($\log(L/L_\odot)$) at which $G = G_0$ occurs.

$M_{\rm WD}/M_\odot$	G_i/G_0		
	$G/G = -5\times10^{-11}$	$G/G = -1\times10^{-11}$	$G/G = -1\times10^{-12}$
0.525	1.40 (−4.40)	1.10 (−4.37)	1.010 (−4.33)
0.525	1.30 (−4.20)	1.05 (−4.05)	1.005 (−4.00)
0.525	1.20 (−4.05)	1.02 (−3.66)	
0.525	1.10 (−3.77)		
0.609	1.50 (−4.83)	1.20 (< −5)	1.100 (< −5)
0.609	1.40 (−4.40)	1.10 (−4.30)	1.050 (< −5)
0.609	1.30 (−4.19)	1.05 (−4.02)	1.020 (< −5)
0.609	1.20 (−4.02)	1.02 (−3.60)	
0.609	1.10 (−3.68)		
1.000	1.24 (−4.64)	1.10 (−4.55)	1.020 (< −5)
1.000	1.20 (−4.12)	1.05 (−3.68)	1.010 (−4.30)
1.000	1.10 (−3.23)	1.02 (−3.10)	1.005 (−3.56)

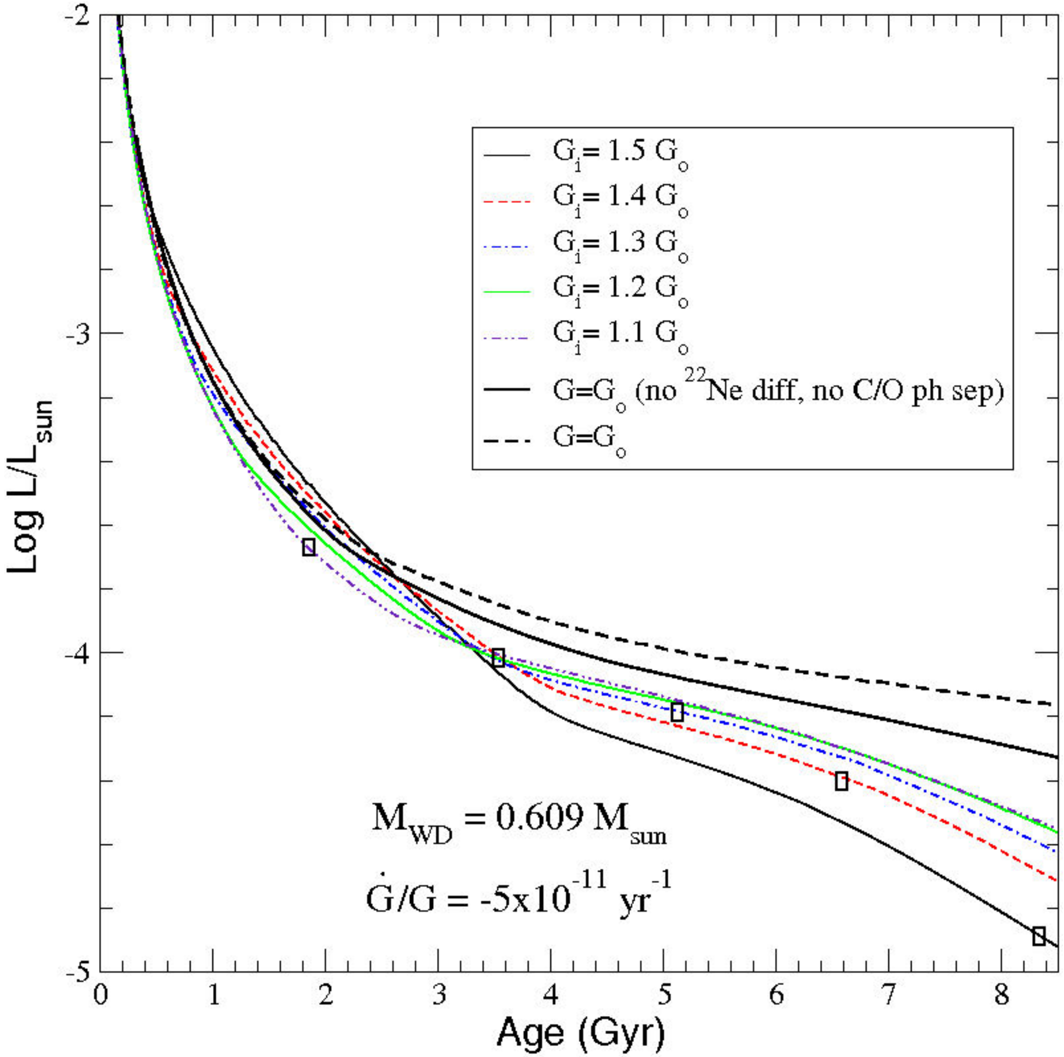
White dwarf evolutionary results



White dwarf evolutionary results



White dwarf evolutionary results



White dwarf evolutionary results

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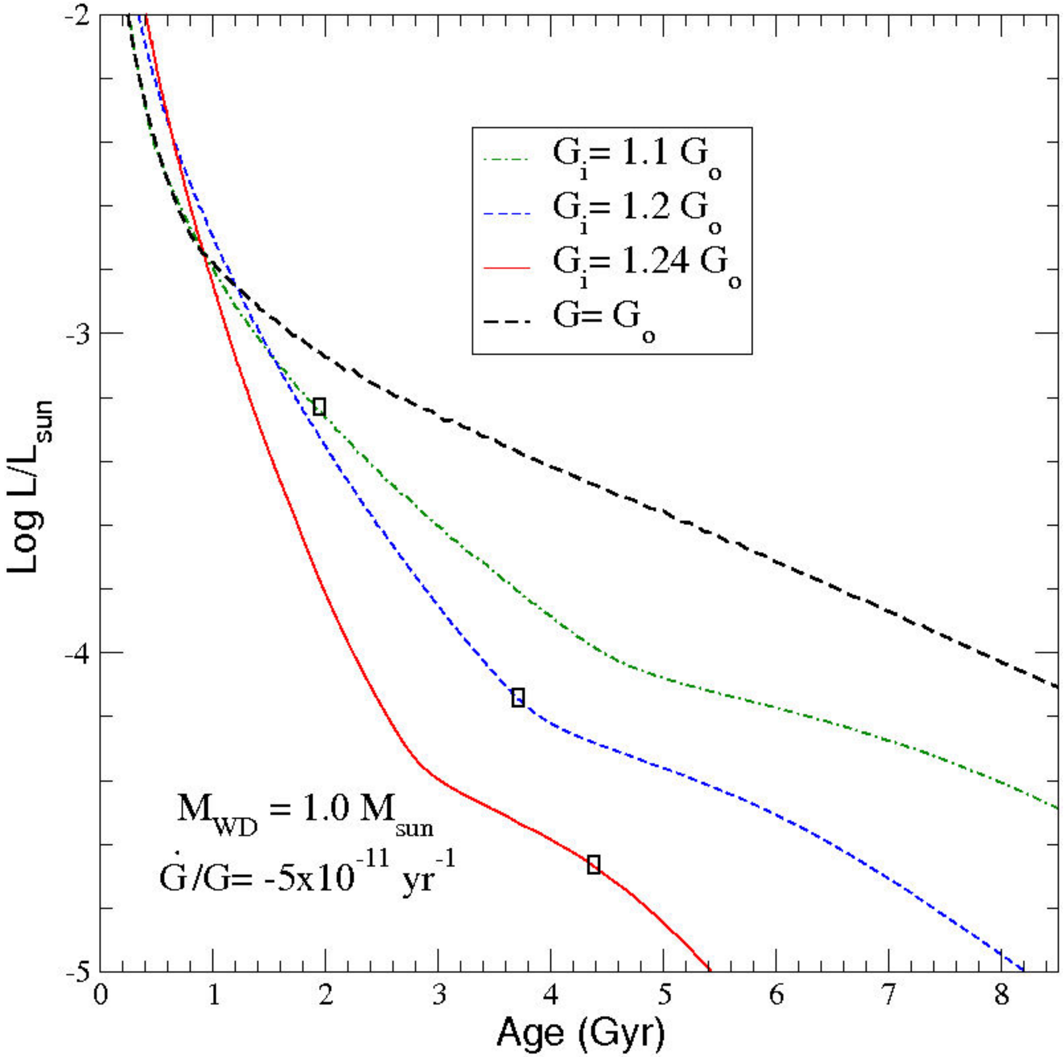
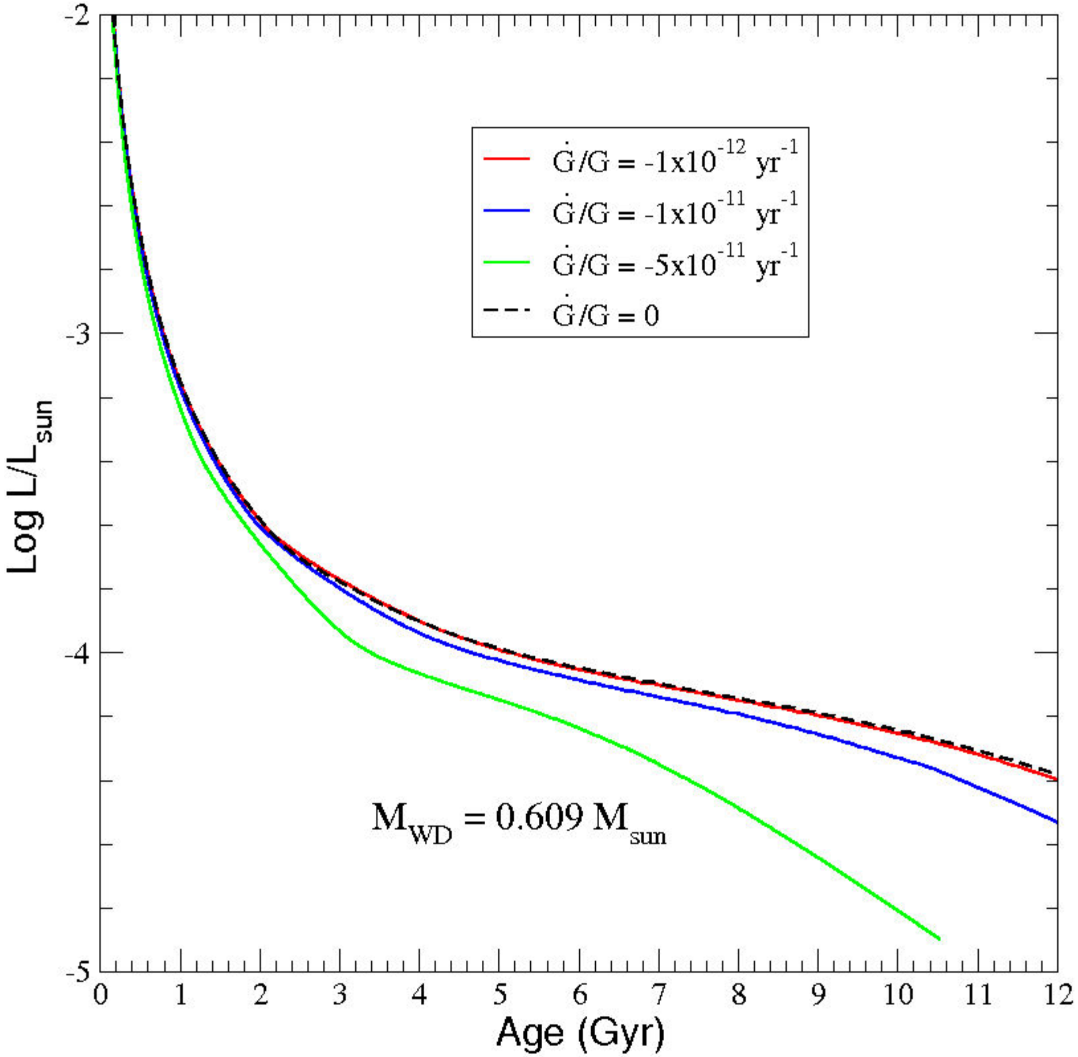
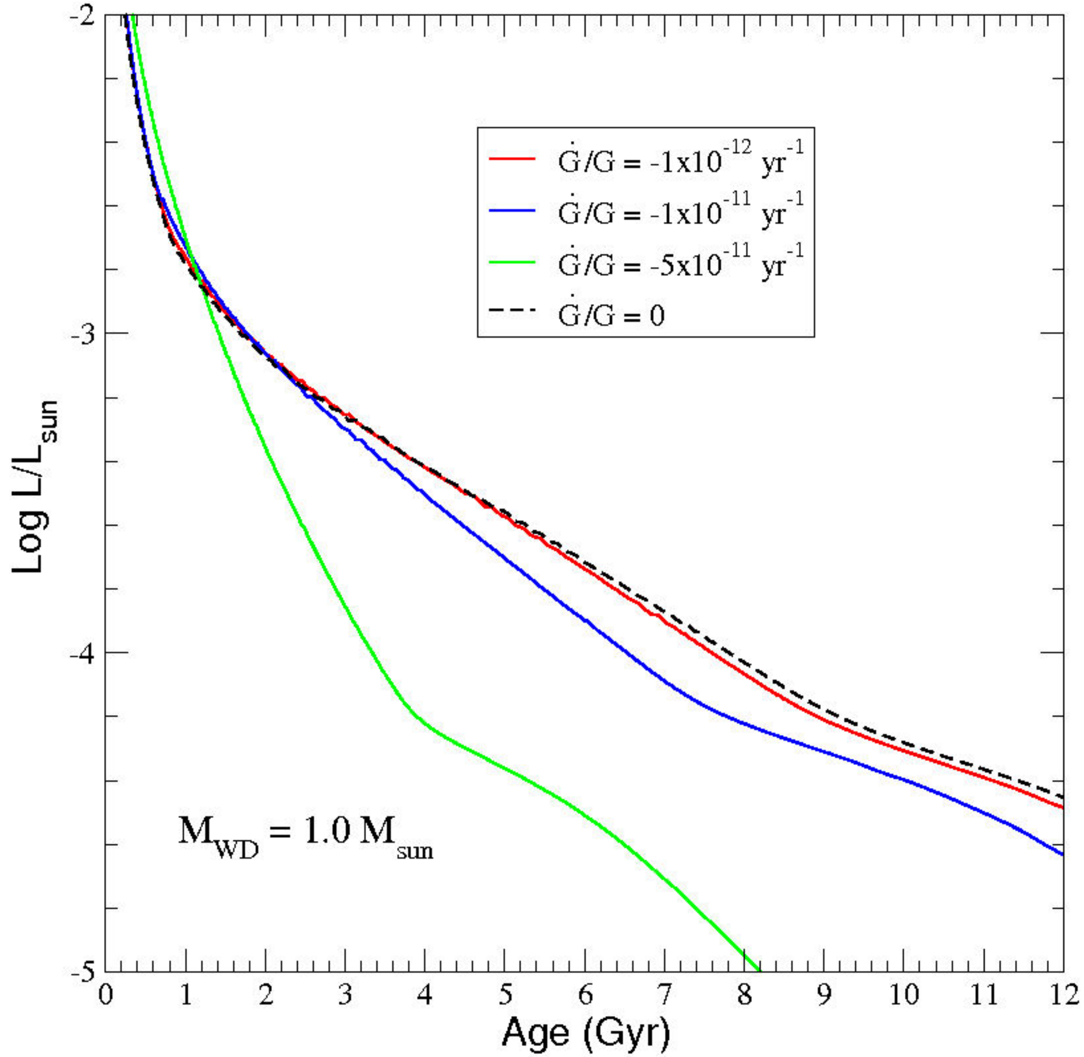


White dwarf evolutionary results



White dwarf evolutionary results



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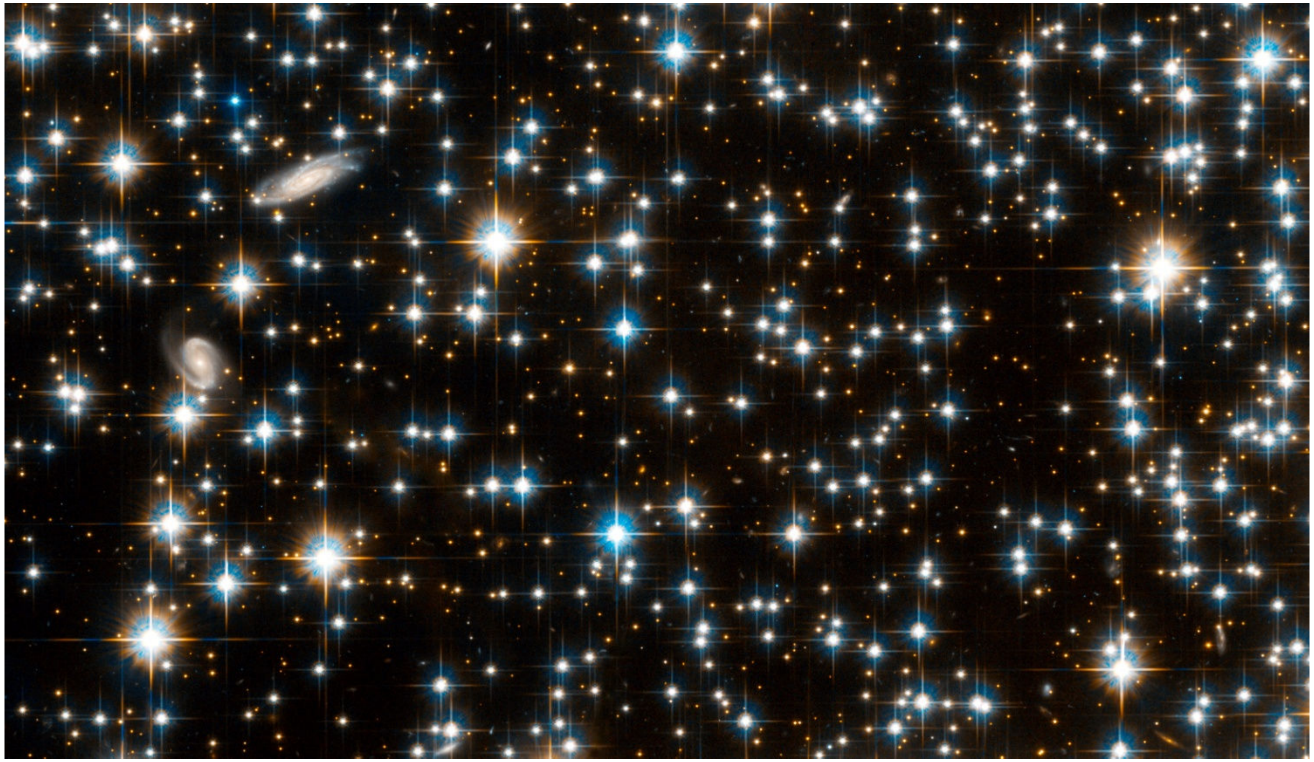
Possible targets

- NGC 6791 is a metal-rich ([Fe/H] $\approx$ +0.4), well populated (~3,000 stars) and very old (~8 Gyr).



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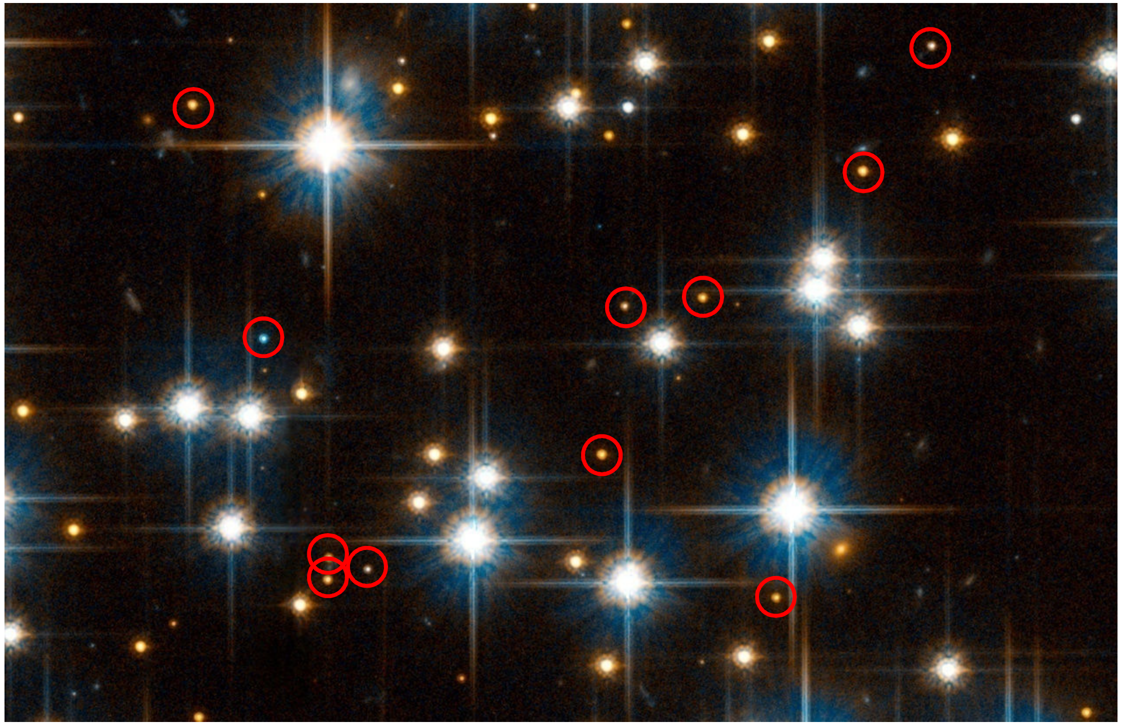
Possible targets

- The HST has imaged it down to luminosities below those of the faintest white dwarfs.



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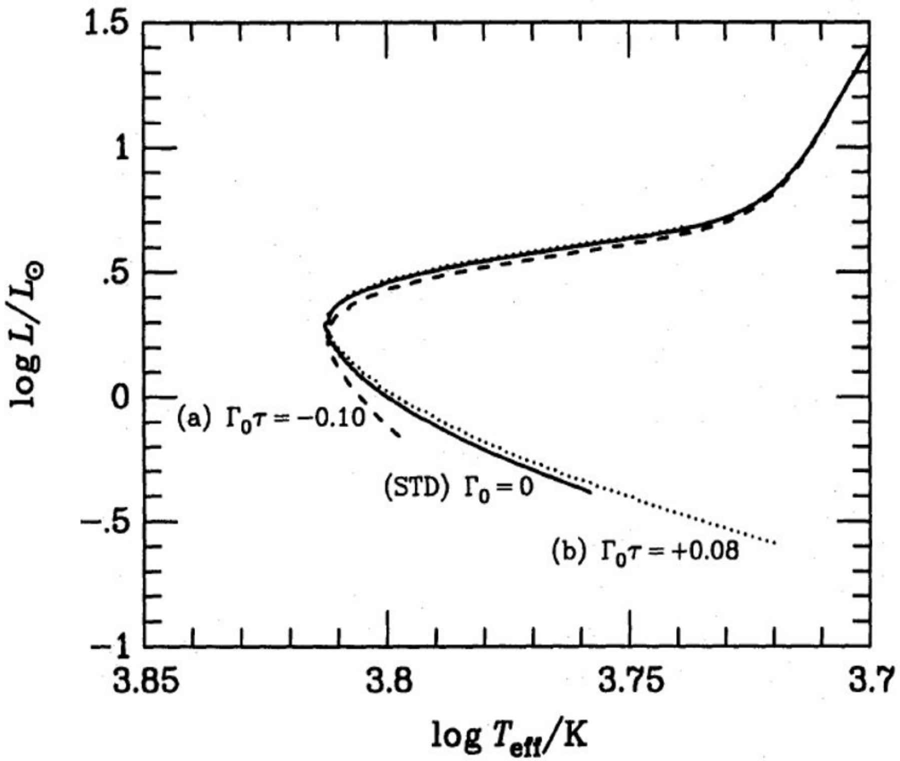
Possible targets

- This characteristic makes it a primary target to check the accuracy and consistency of the evolutionary sequences of non-evolved stars and white dwarfs.

- Moreover, we have a reliable white dwarf luminosity function, which can be used to constrain the rate of change of G.

Turn-off ages and CMD

- The shape of the isochrone is not affected, but the age changes:



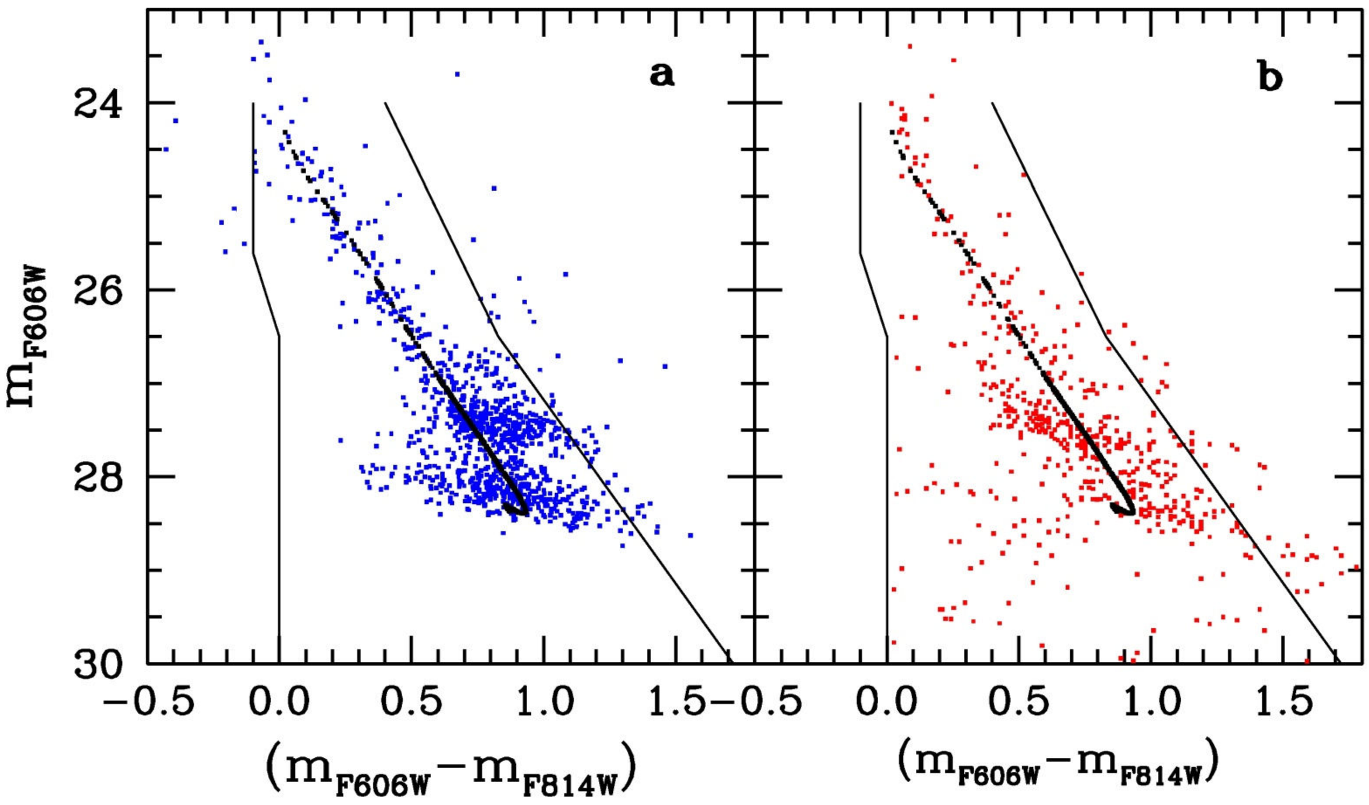
Turn-off ages and CMD

- For the case in which a constant rate of change of the gravitational constant is adopted it can be shown that:

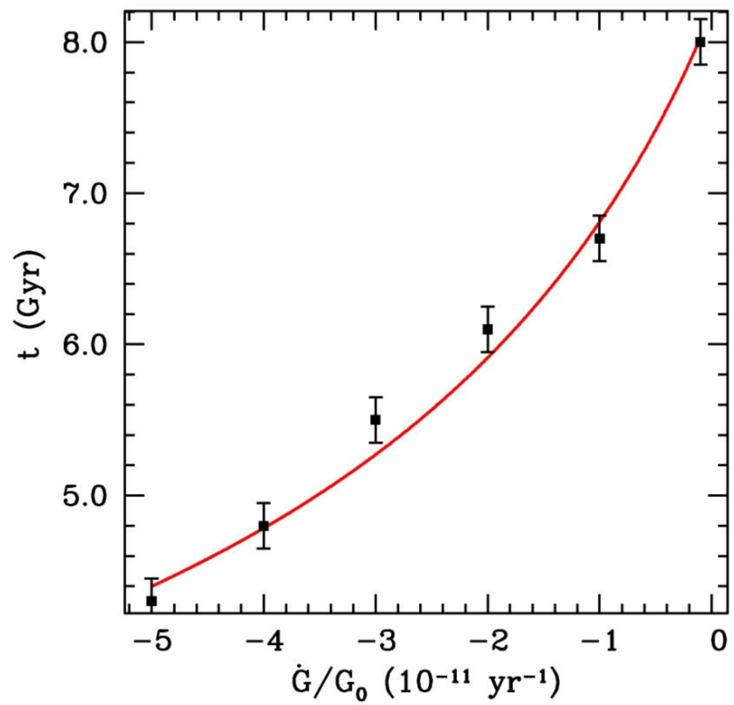
$$T_{TO} = \frac{1}{\gamma\left|\frac{\dot{G}}{G}\right|}\ln\left(\left|\frac{\dot{G}}{G}\right|\gamma T_{TO}^{0}+1\right)$$

where $\gamma \approx 5.6$

Color-magnitude diagram



The white dwarf luminosity function



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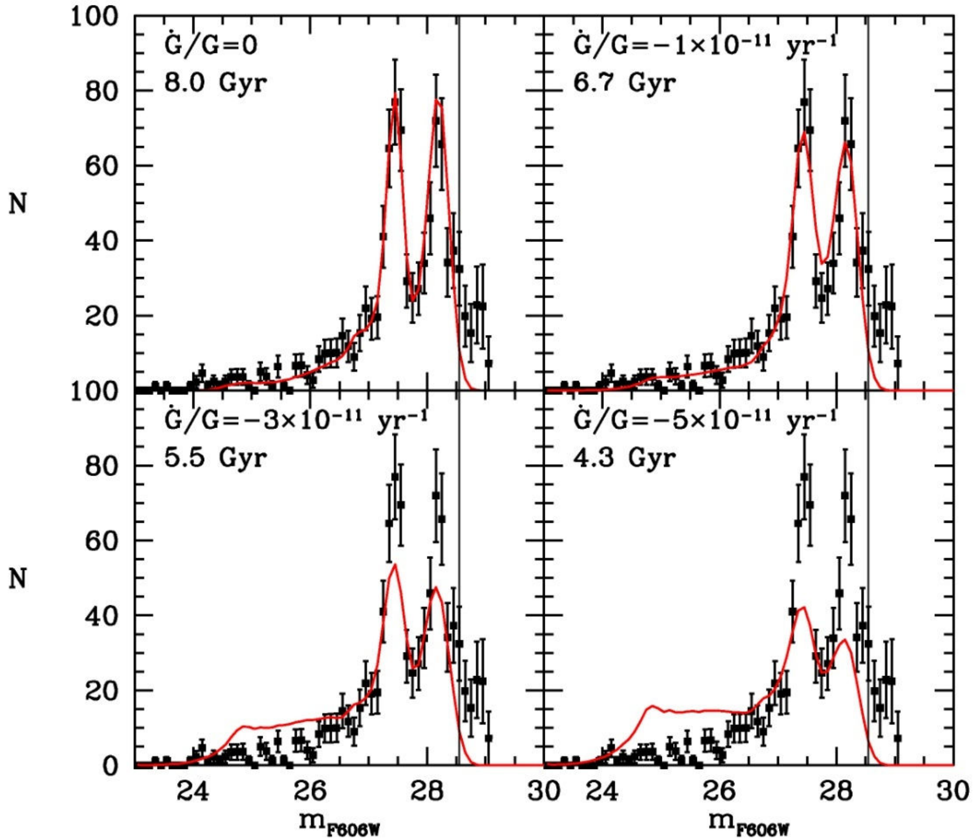
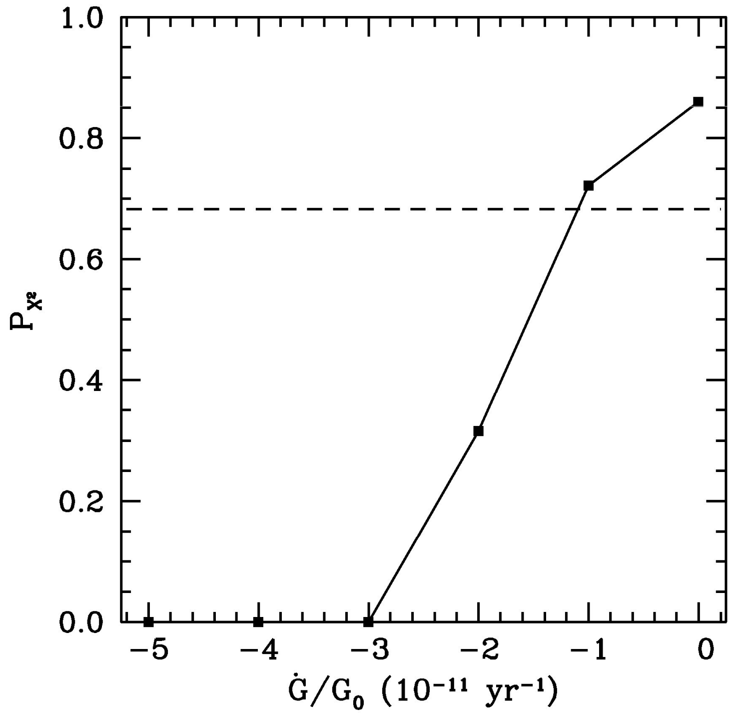
The white dwarf luminosity function



The white dwarf luminosity function



Conclusions

- In a step forward to use NGC 6791 to set constraints in the rate of variation of G, we have computed reliable cooling sequences which fully incorporate the effects of a varying G.
- We find that the mechanical structure and energy balance of cool white dwarfs are strongly modified when a slowly varying G is adopted.
- The white dwarf evolution is sensitive to the initial value of G at the beginning of the cooling phase.
- Tight constraints can be obtained using the white dwarf luminosity function of the old Galactic cluster NGC 6397.

Conclusions

- Additionally, we can use as well the variable DA white dwarf G117-B15A, using our updated evolutionary sequences.

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