Axions and White Dwarfs

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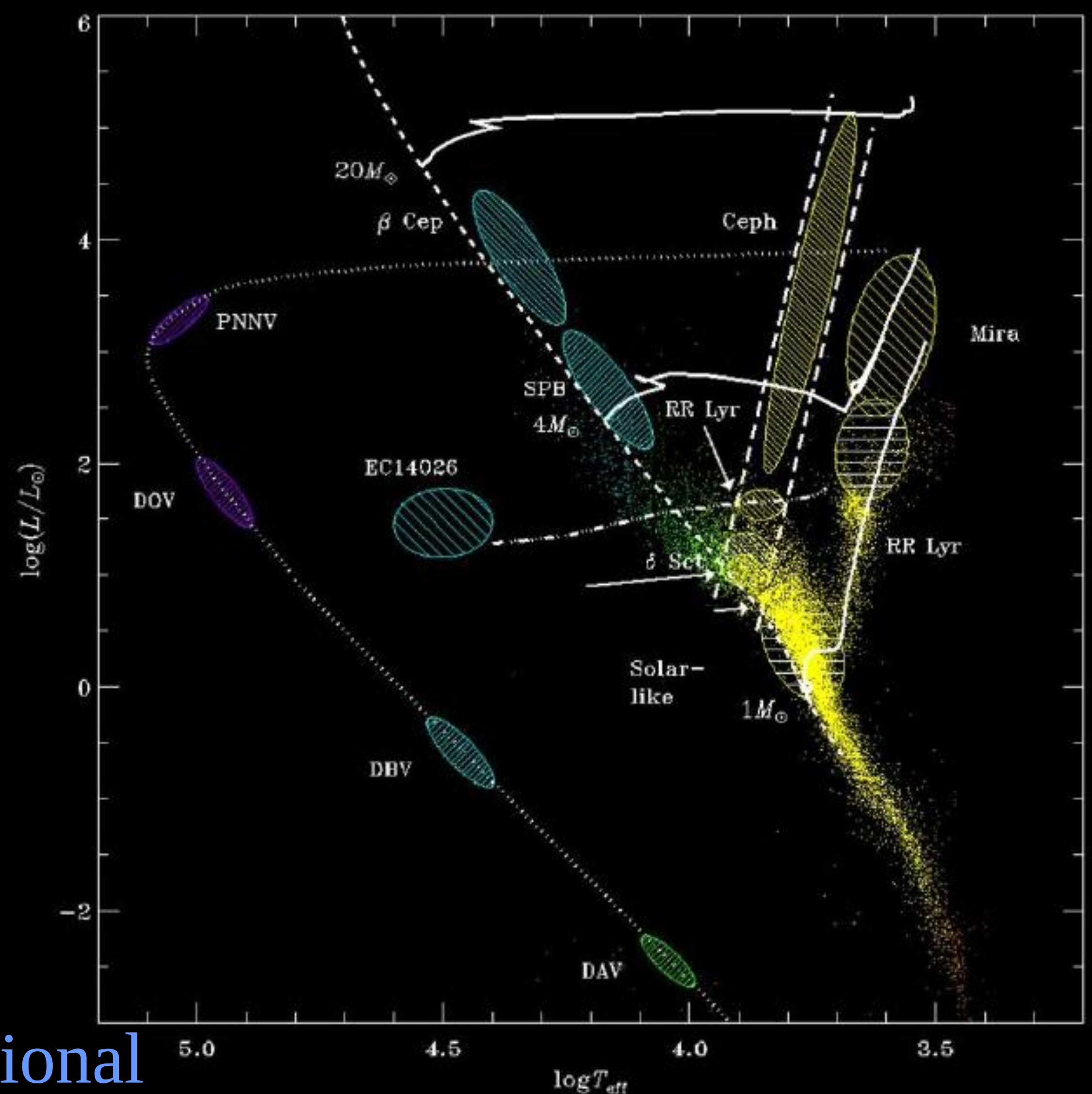
The white dwarf population is one of the best studied!

They are the end stage of low and intermediate-mass stars
Their evolution is just a cooling process
The basic physical ingredients of their evolution are well identified (not all has been satisfactorily solved yet)
Impressively solid observational background for testing theory.



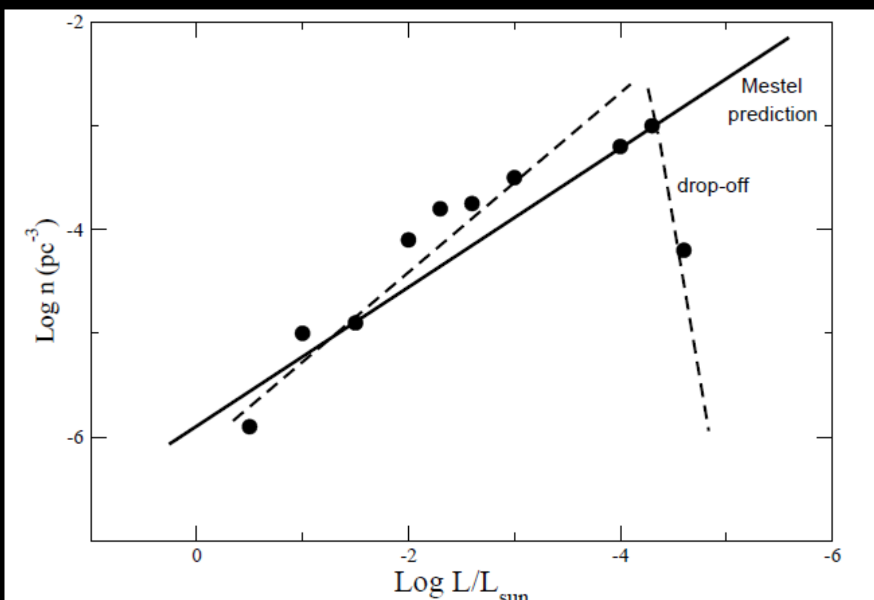
Courtesy of Christensen-Dalgaard

White Dwarf Cooling

$$L + L_\nu = -\int_{M_{WD}} c_V \frac{dT_c}{dt}\, dm - \int_{M_{WD}} T\left(\frac{\partial P}{\partial T}\right)_{V,x_0} \frac{dV}{dt}\, dm + \left(l_s + e_s\right)\dot{m}_c$$

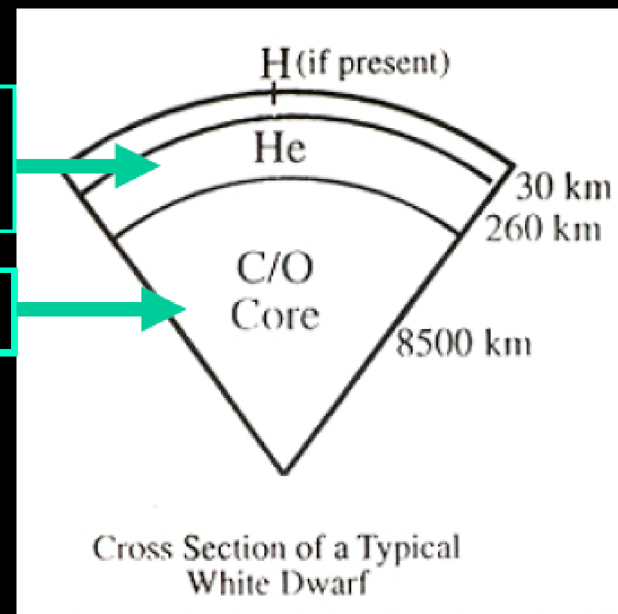
$+ L_e$ $\qquad$ $+ \varepsilon_e$

To solve this equation it is necessary a $L(T_C)$ relationship that depends on the properties of the envelope

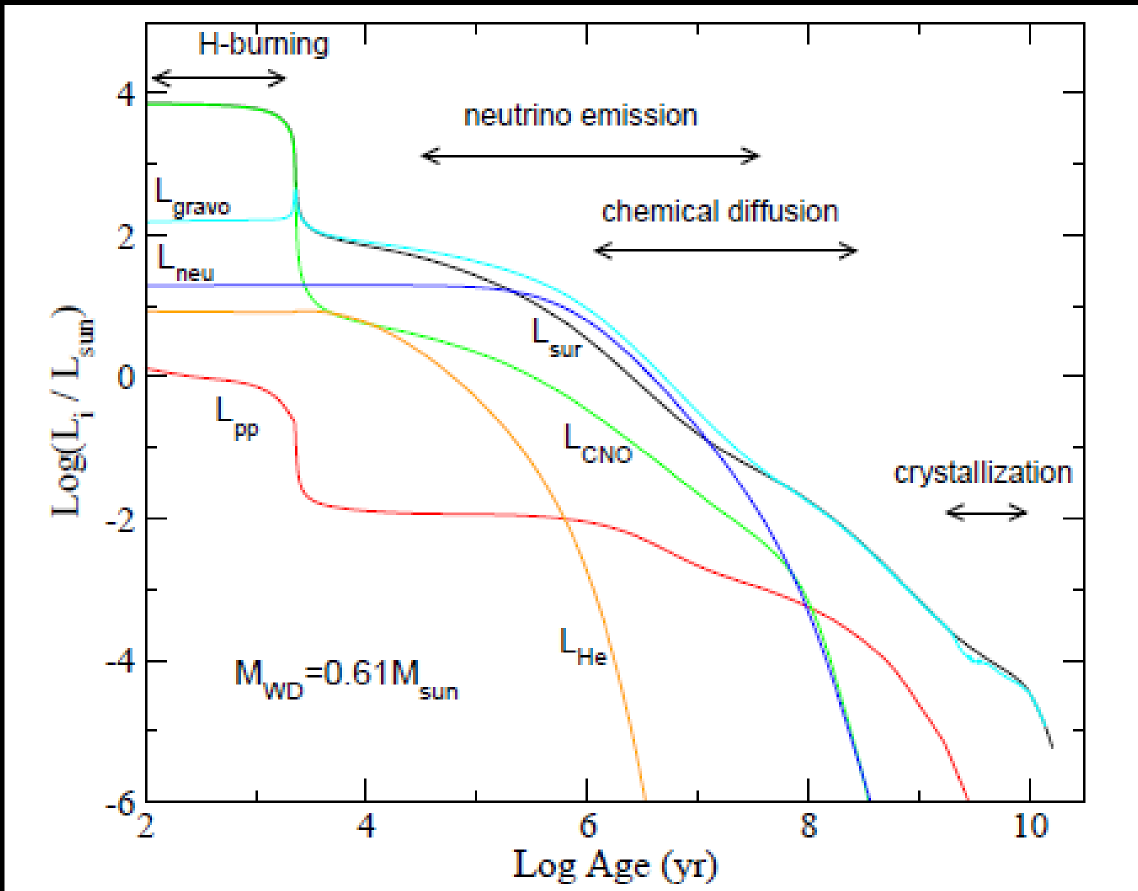


Energy flux control

Energy reservoir



The cooling process (I)



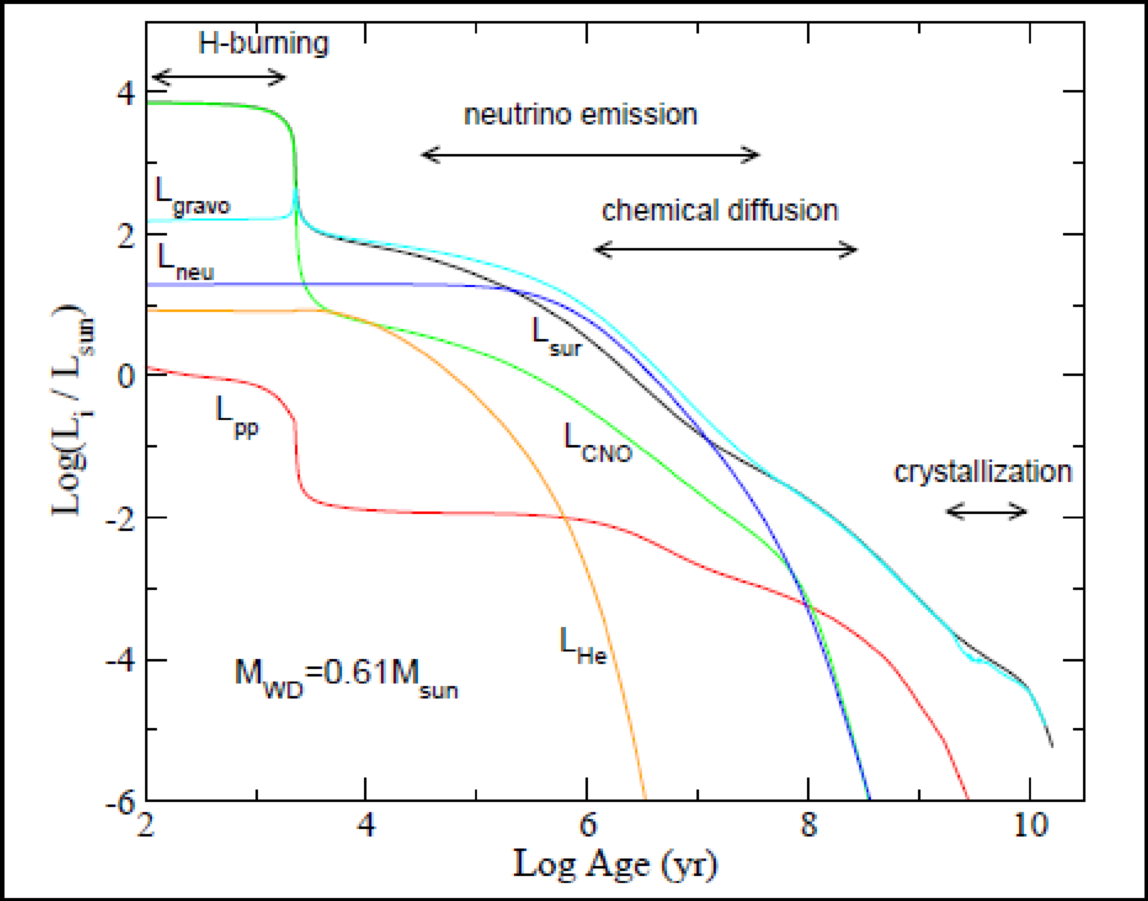
Neutrino cooling [log(L/L_o) > -1.5]

- Is the must complicated phase because the initial conditions are unknown.
- Neutrinos dominate & thermal structures converge
- Very short epoch (< 10^8 yr)

Fluid cooling [-1.5 > log(L/L_o) > -3]

- Gravothermal energy
- Coulomb plasma
- The main uncertainty comes from the C/O abundances that depend on the $^{12}C(\alpha,\gamma)^{16}O$ reaction , Z, & the treatment of convection

The cooling process (II)

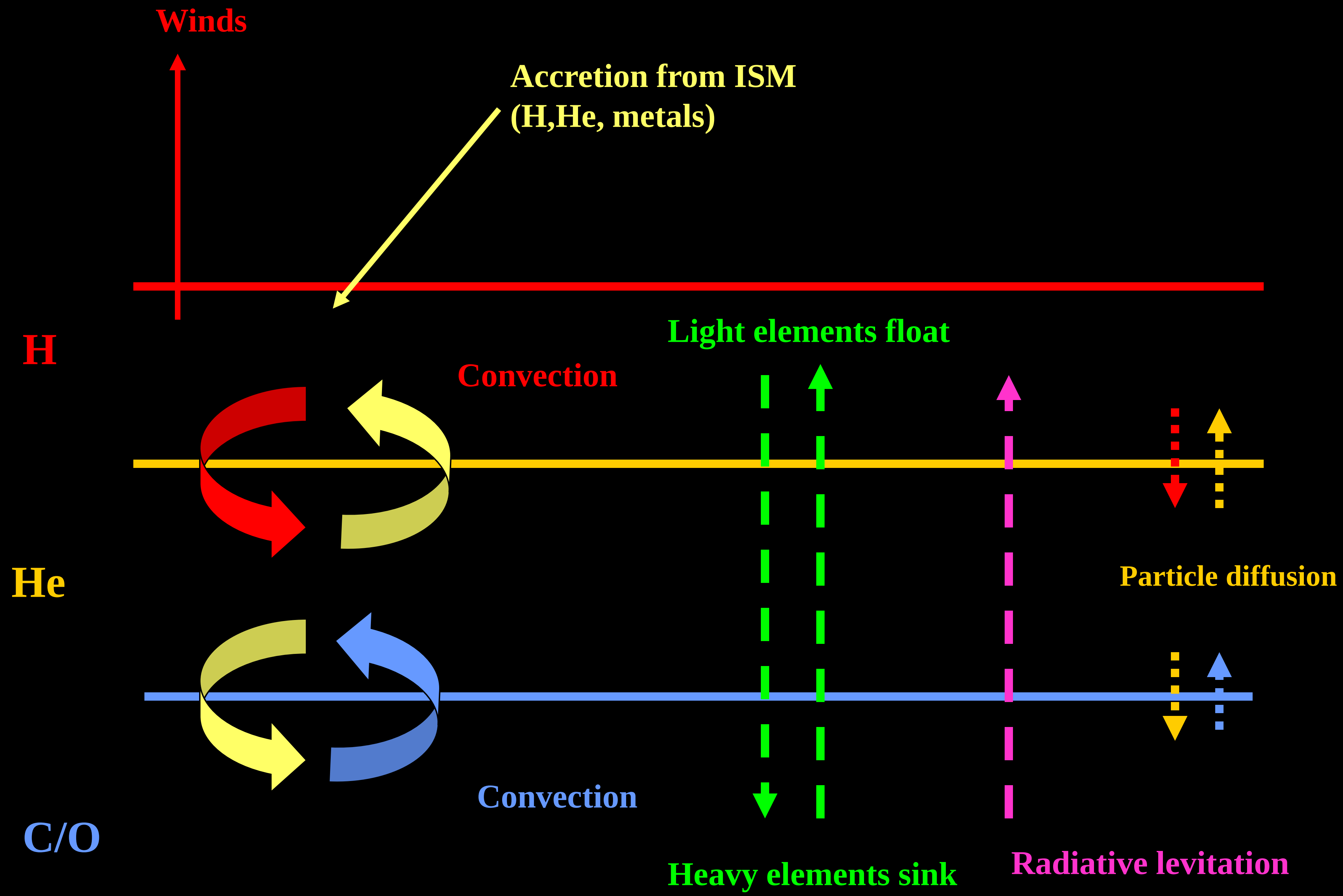


Crystallization [-3 > log(L/L$_o$) > -4.5]

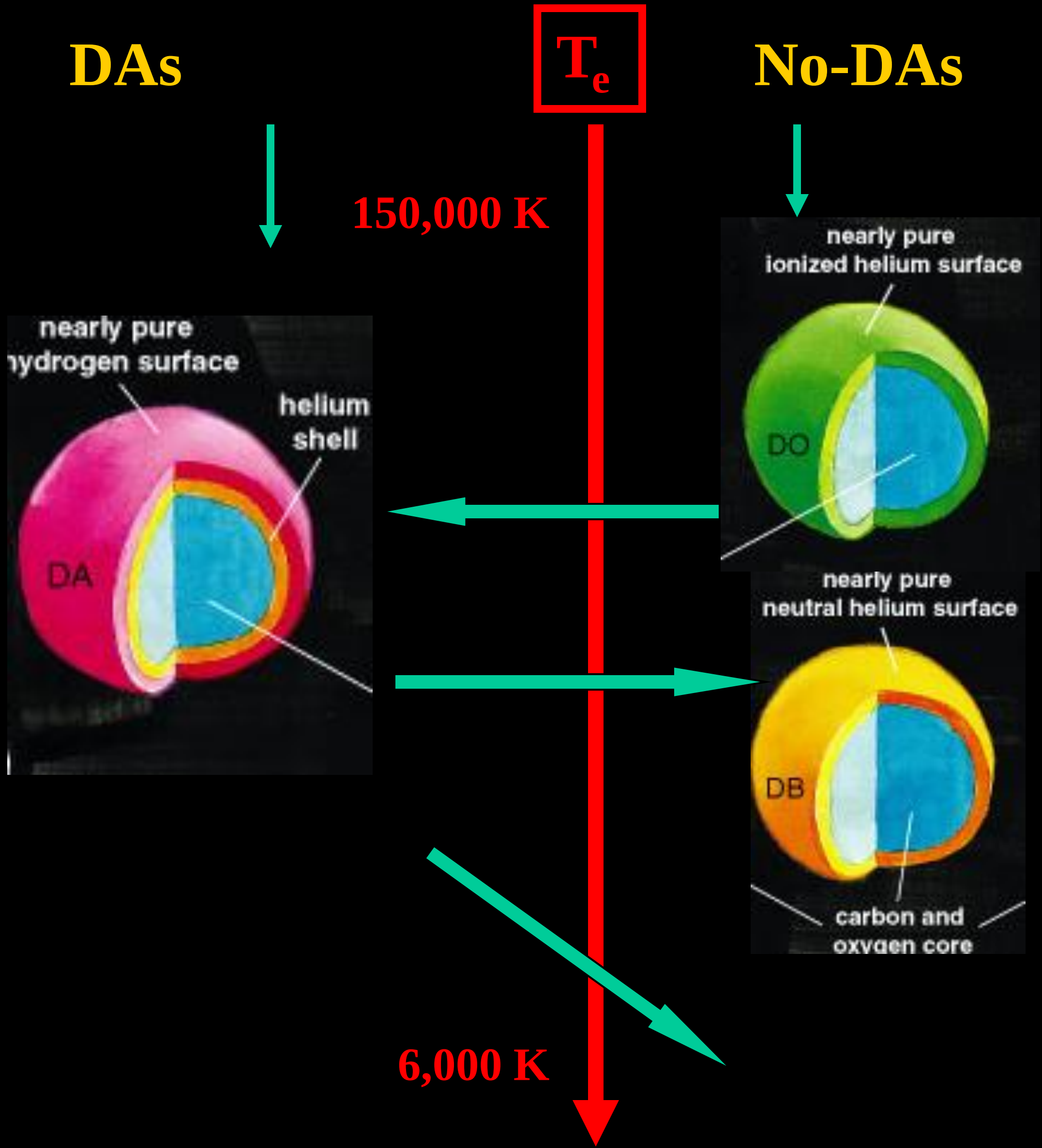
- Latent heat (~ kT$_s$ per particle)
- Sedimentation upon crystallization that depends on the chemical profile and phase diagrams

Debye cooling [-4.5 > log(L/L$_o$)]

- At low temperatures, the specific heat follows the Debye law
- Compression of outer layers is the main source of energy & prevents the sudden disappearence of the white dwarf


Winds
Accretion from ISM
(H,He, metals)
H
Convection
Light elements float
He
Particle diffusion
Convection
C/O
Heavy elements sink
Radiative levitation

Two families of white dwarf envelopes



The H layer:

- Acts as a source of opacity
- If its mass is larger than $2x10^{-4}$ M_o, H-burning
- Evolution predicts 10^{-4} M_o

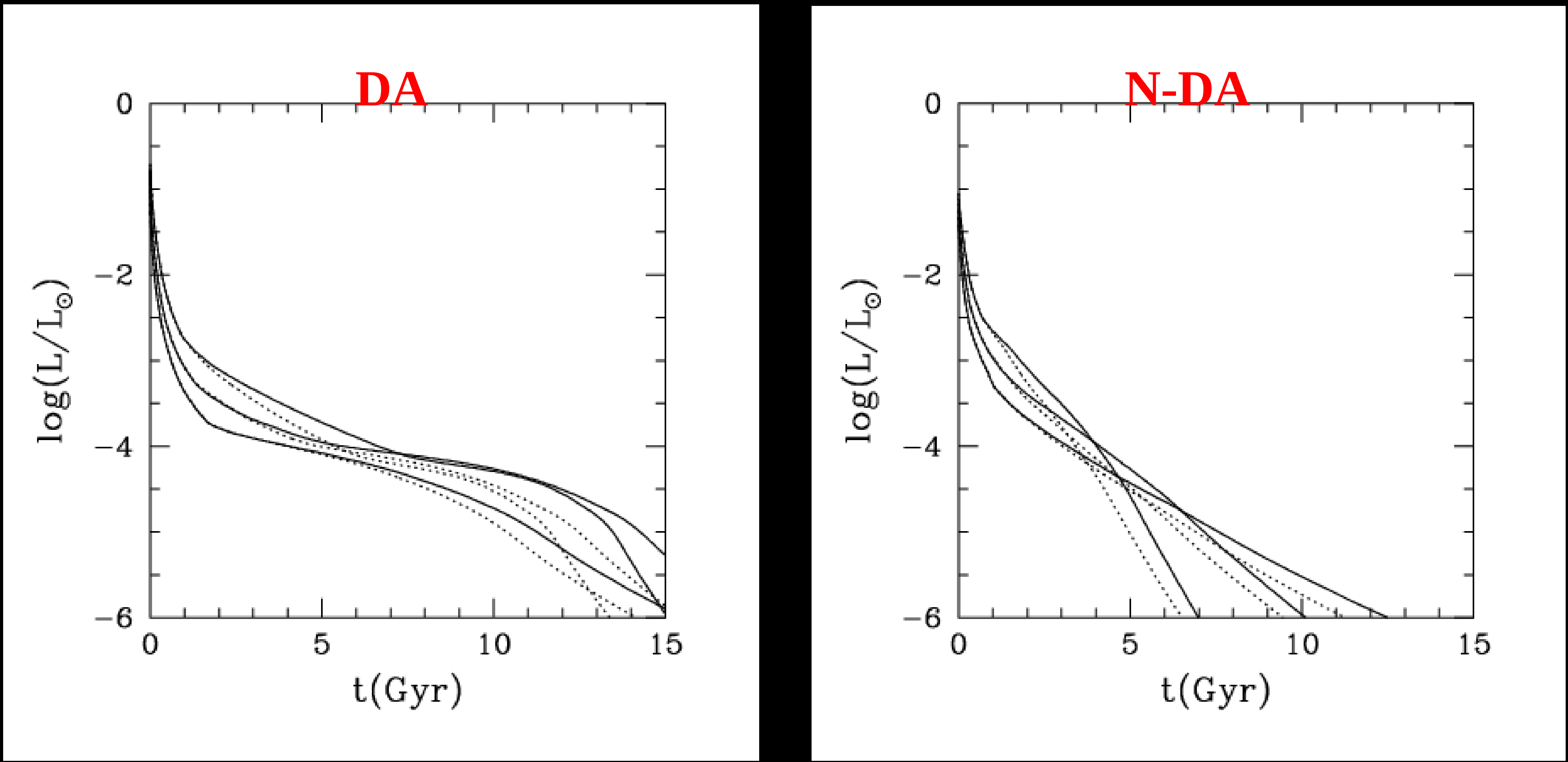
The He layer

- Important source of energy at very low T_e
- Low opacity (n-Das cool much faster)
- Controls the diffusion of H inwards (DA-nDA)
- Controle the diffusion of C outwards (DB-DQ)
- Evolution predicts 10^{-2} M_o

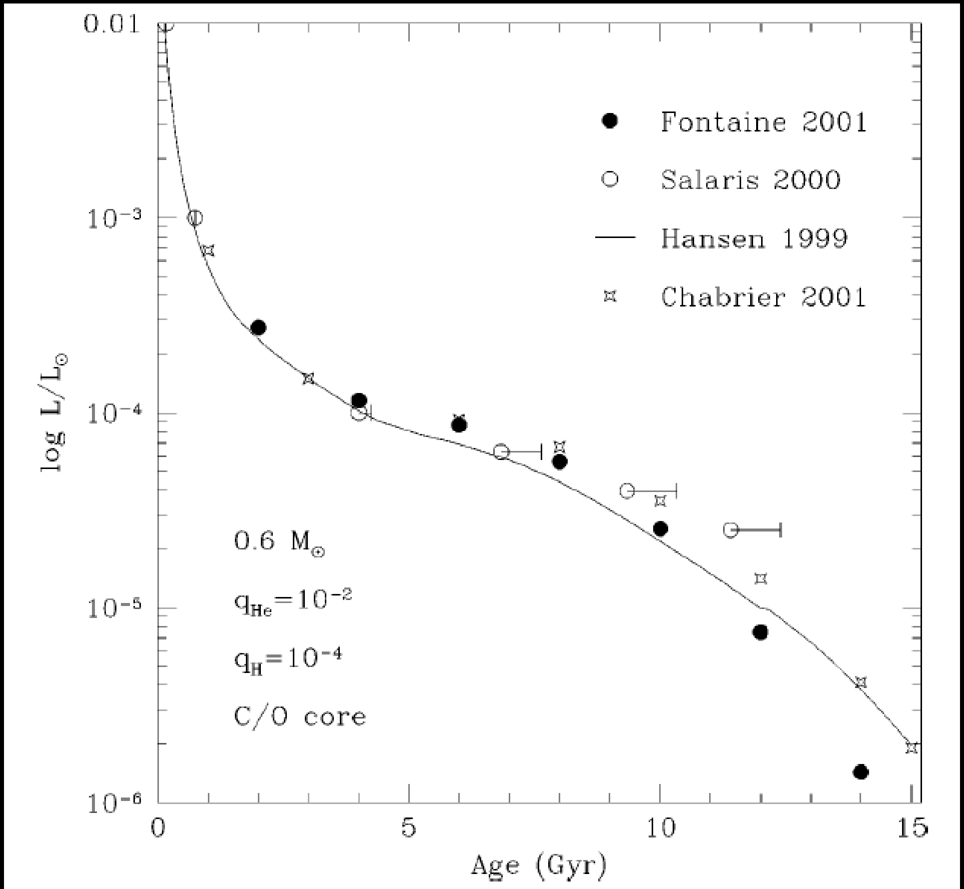
Is the origin of the DA, n-DA character:

- **primordial ?**
- **mixing?**
- **both?**

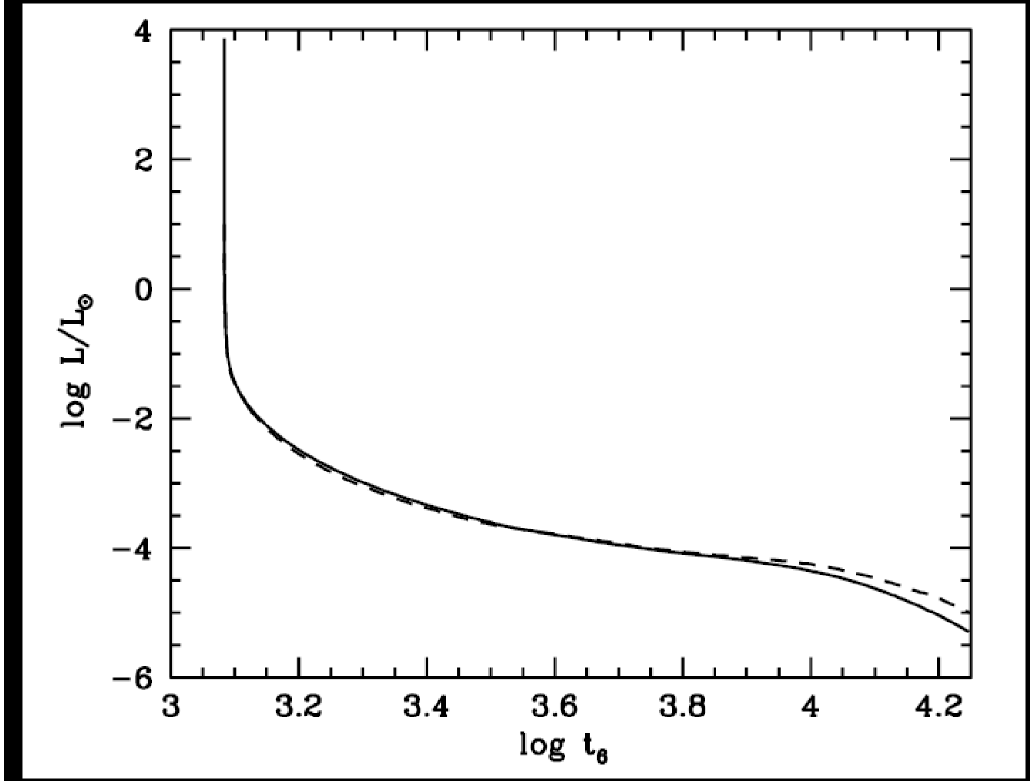
Luminosity versus time
(dotted lines without sedimentation)



Comparison between cooling models



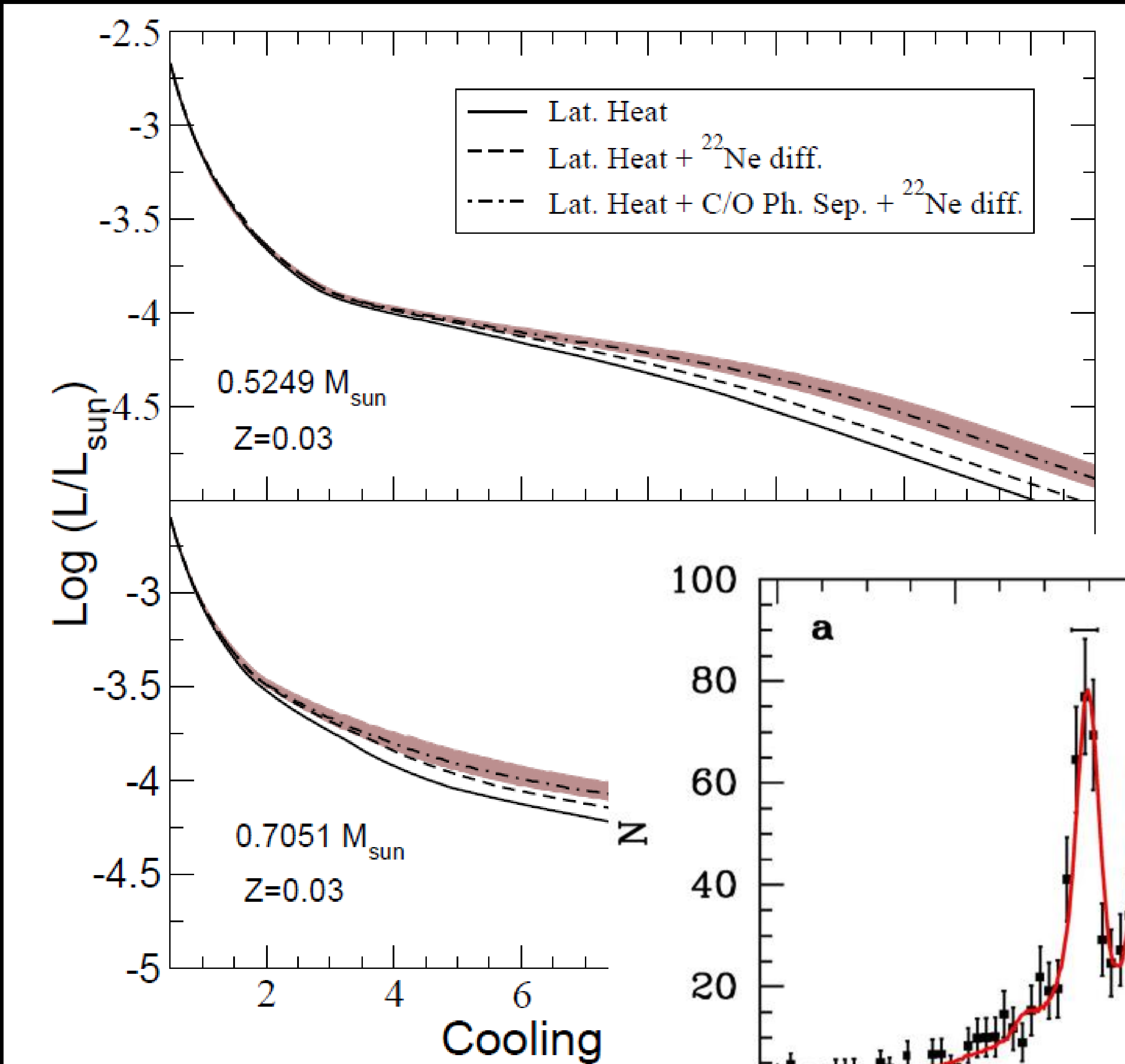
Hansen & Liebert'03

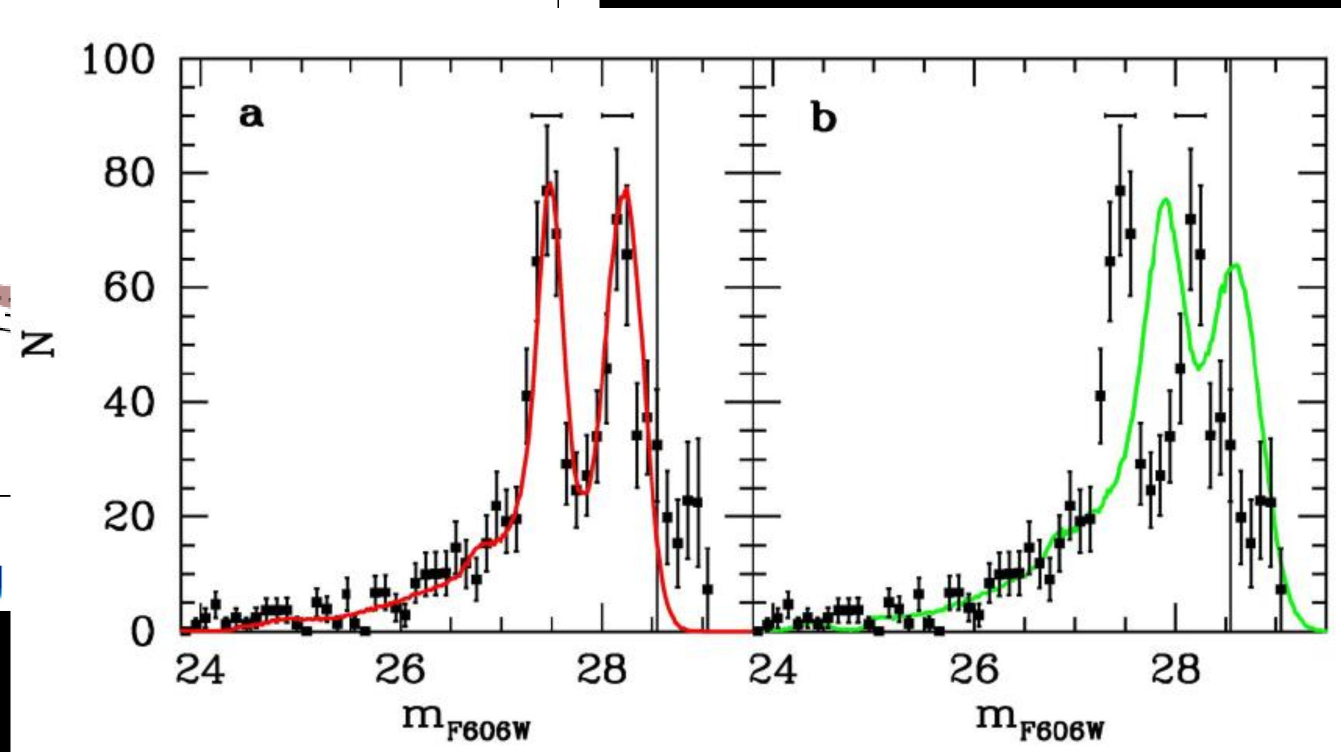


___: Renedo et al 2010
---- : Salaris et al 2000

Age of NGC6791

Turn off Main Sequence: 8 Gyr
WD age (no sed) : 6 Gyr (green)
WD age (sed): 8 Gyr (red)





Garcia Berro et al'10, ApJ, in press
García Berro et al'10, Nature, 465,194

Is it possible to test the cooling of white dwarf stars?

… certainly yes!

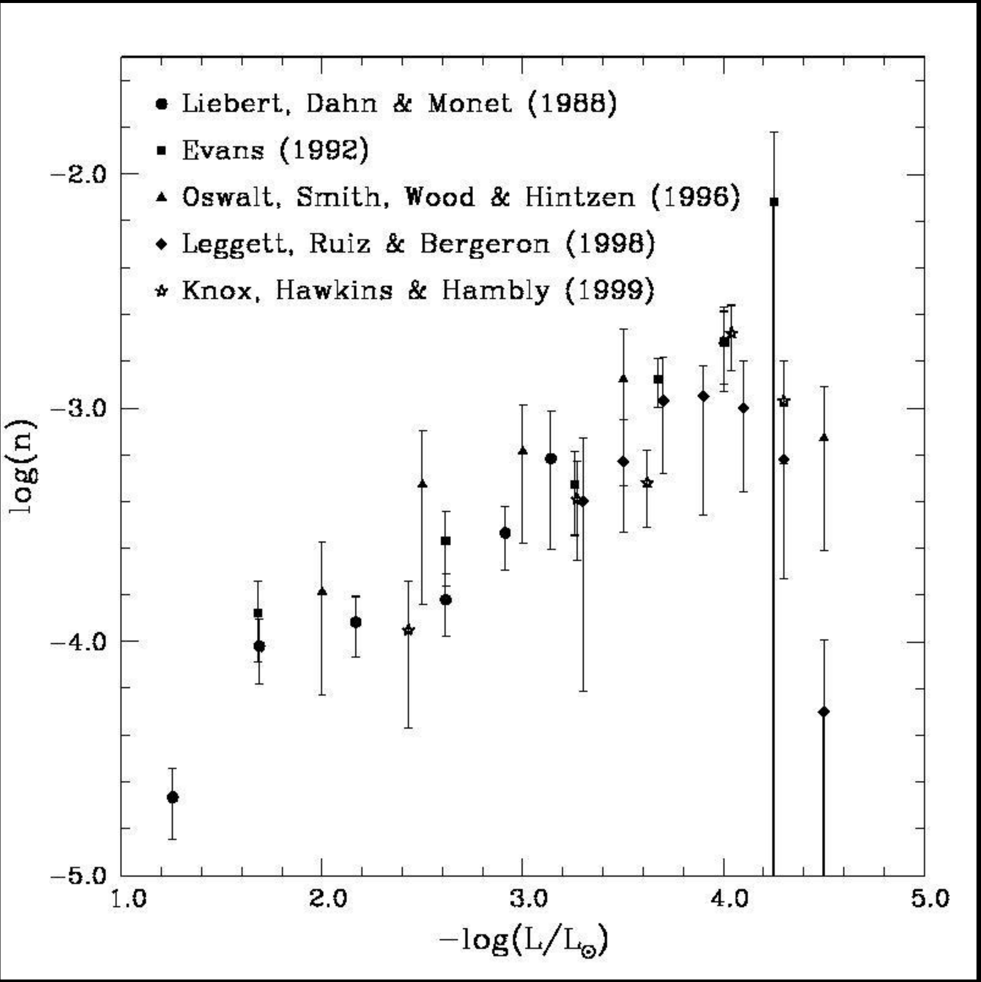
The luminosity function

$$n(L) = \int_{M_l}^{M_U} \Phi(M)\Psi(t_{Gal} - t_{cool} - t_{MS})\tau_{cool}\, dM$$

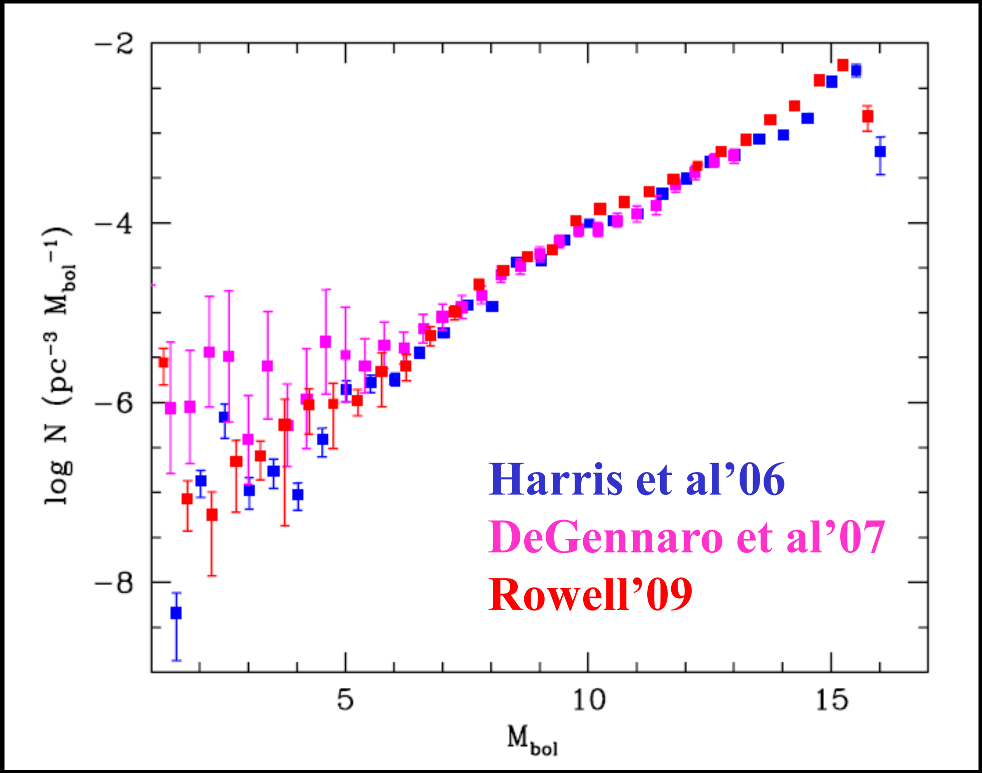
1. n(L) is the observed distribution
2. Φ is the IMF, Ψ is the SFR, t_{Gal} is the age of the Galaxy
3. T_{cool} is the cooling time, t_{MS} lifetime progenitor, τ_{cool} characteristic cooling time, and hidden there is the IFMR

If the 3 ingredients are reasonably well known, it is possible to use the WDLF to test new physics

Surveys are more and more accurate and significative



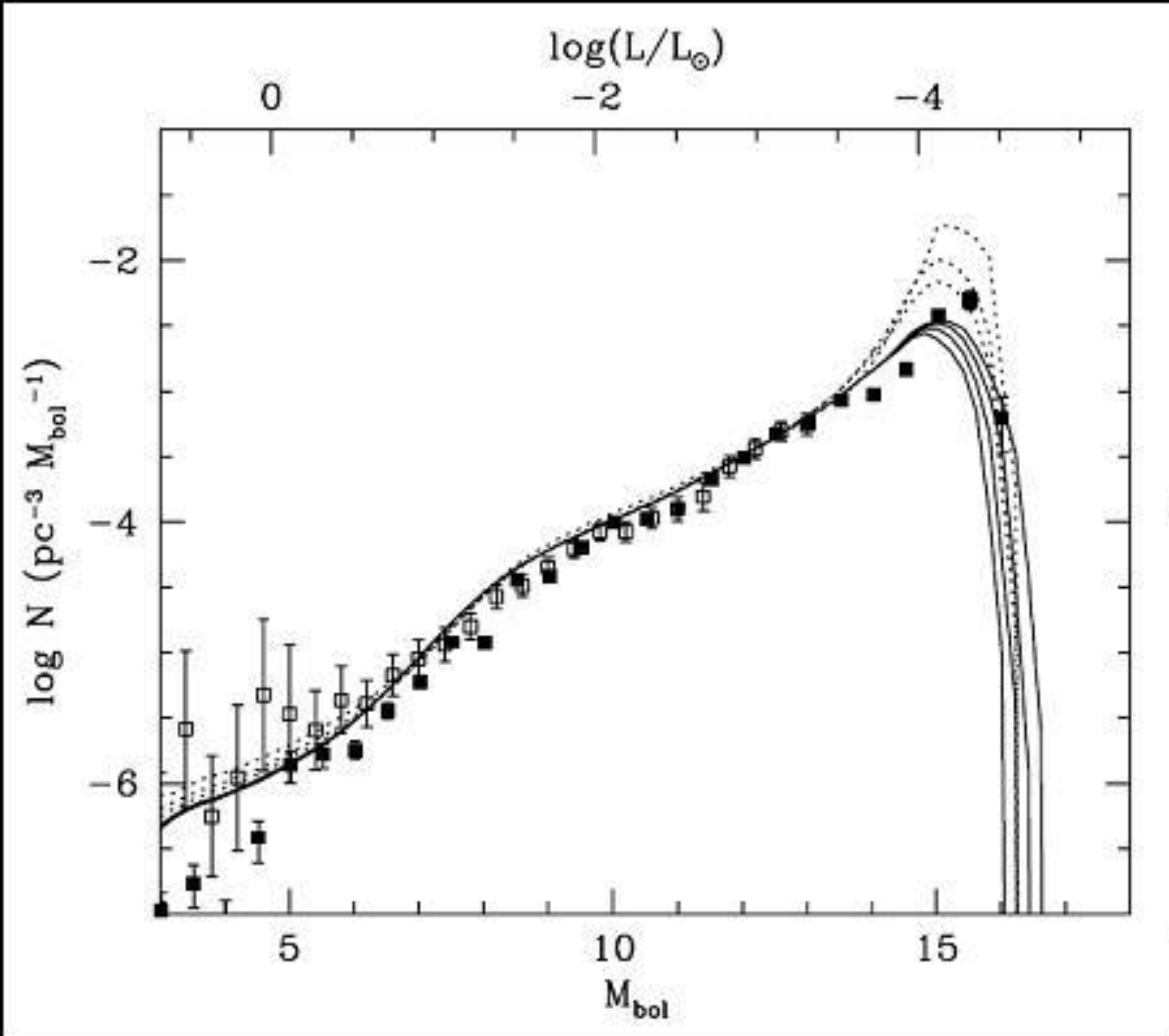
Sloan sample of WD:
High precision LF

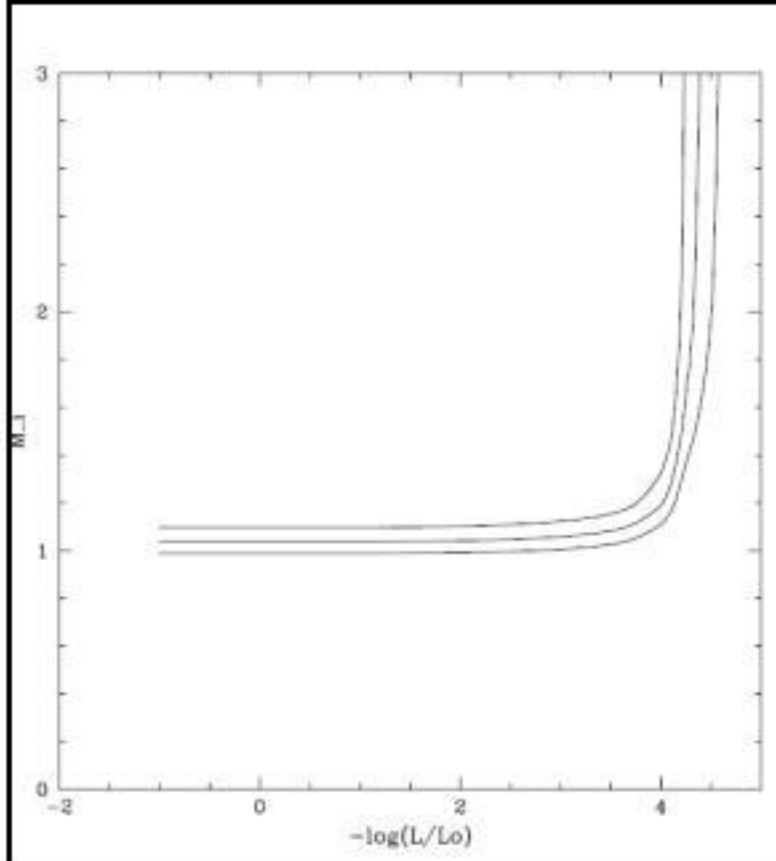


GAIA:

~ 300,000 disc WD

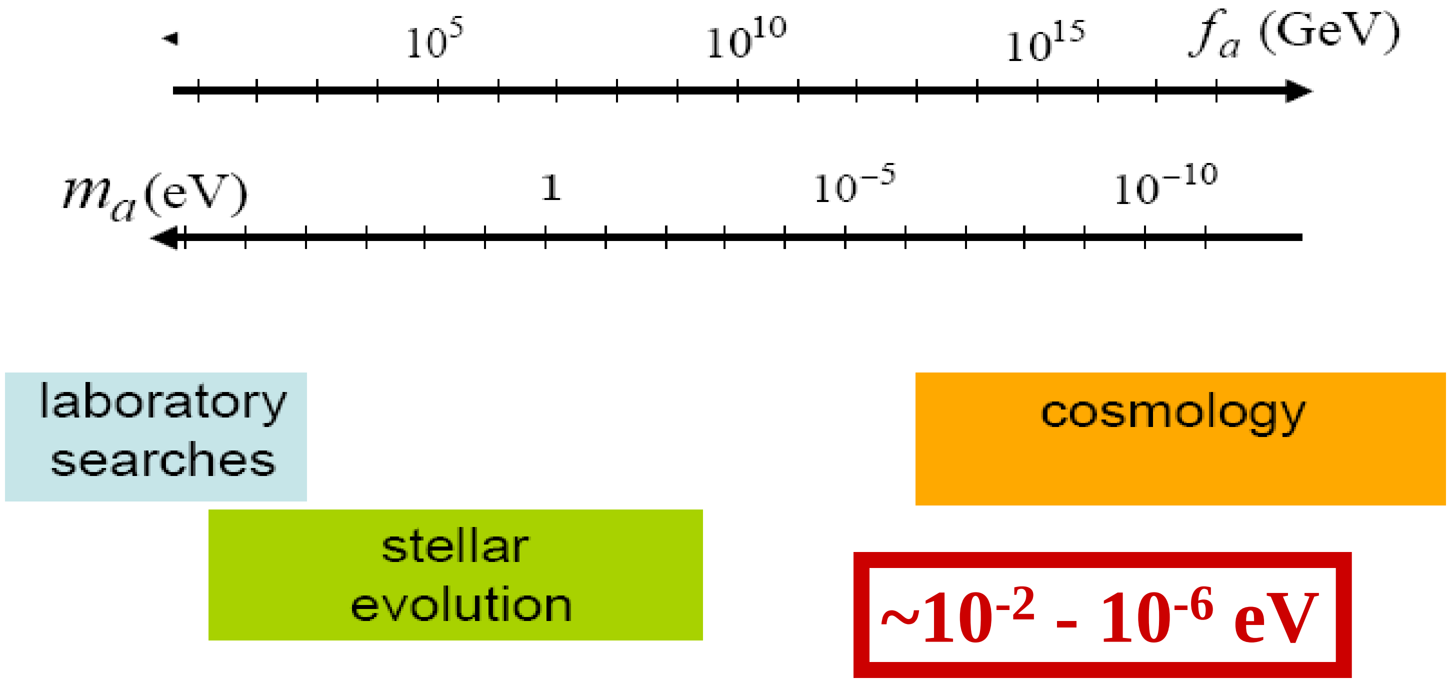
~ 90,000 halo WD





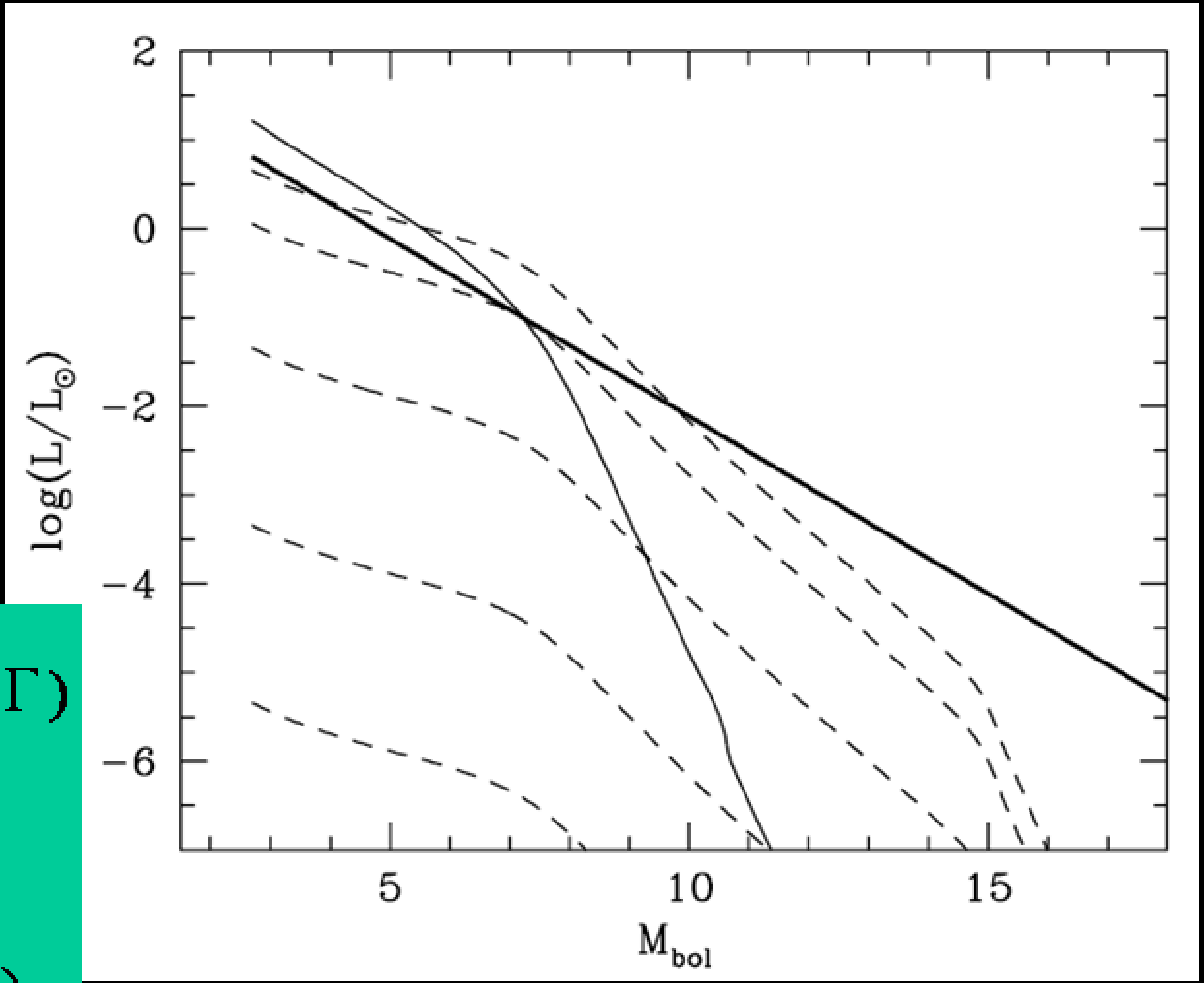
$$n(l) \propto \langle \tau_{cool} \rangle \int_{M_i}^{M_{max}} \Phi(M)\Psi(\tau)dM$$

The remaining axion window



For these masses, axions can freely escape from stars
They can be treated as a sink of energy

$$M_{bol} = -2.5 \log L + ctn$$



$$\varepsilon_a = 1.08 \cdot 10^{23} \alpha \frac{Z^2}{A} T_7^4 F(\Gamma)$$

$$\alpha = \frac{g_{ae}^2}{4\pi}$$

$$g_{ze} = 8.5 \cdot 10^{-11} c_e \left(m_a / 1eV \right)$$

$$c_e = \frac{\cos^2 \beta}{3}$$

DFSZ axions

Bremmsstrahlung is dominant

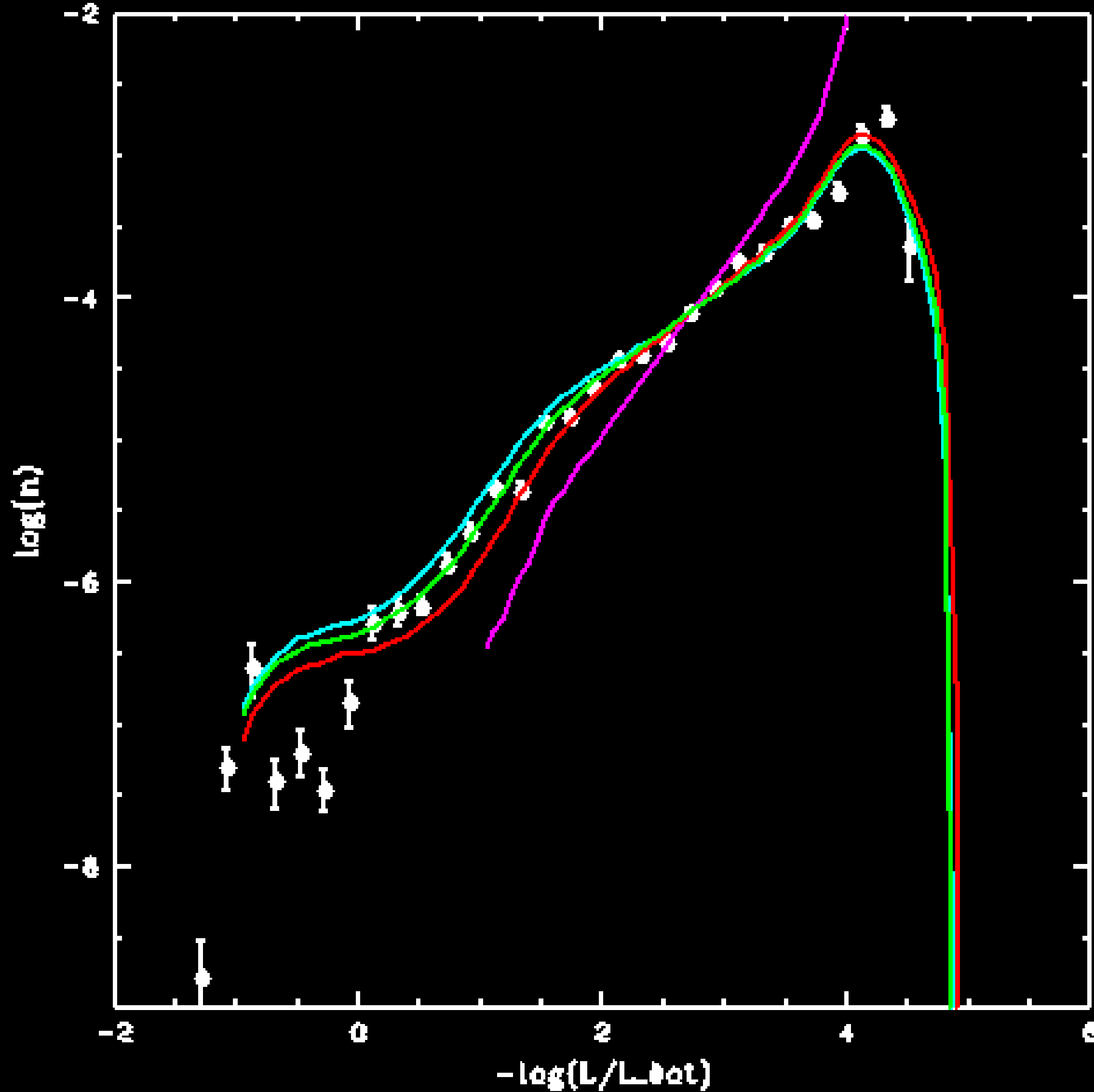
Nakagawa et al 1987, 1988

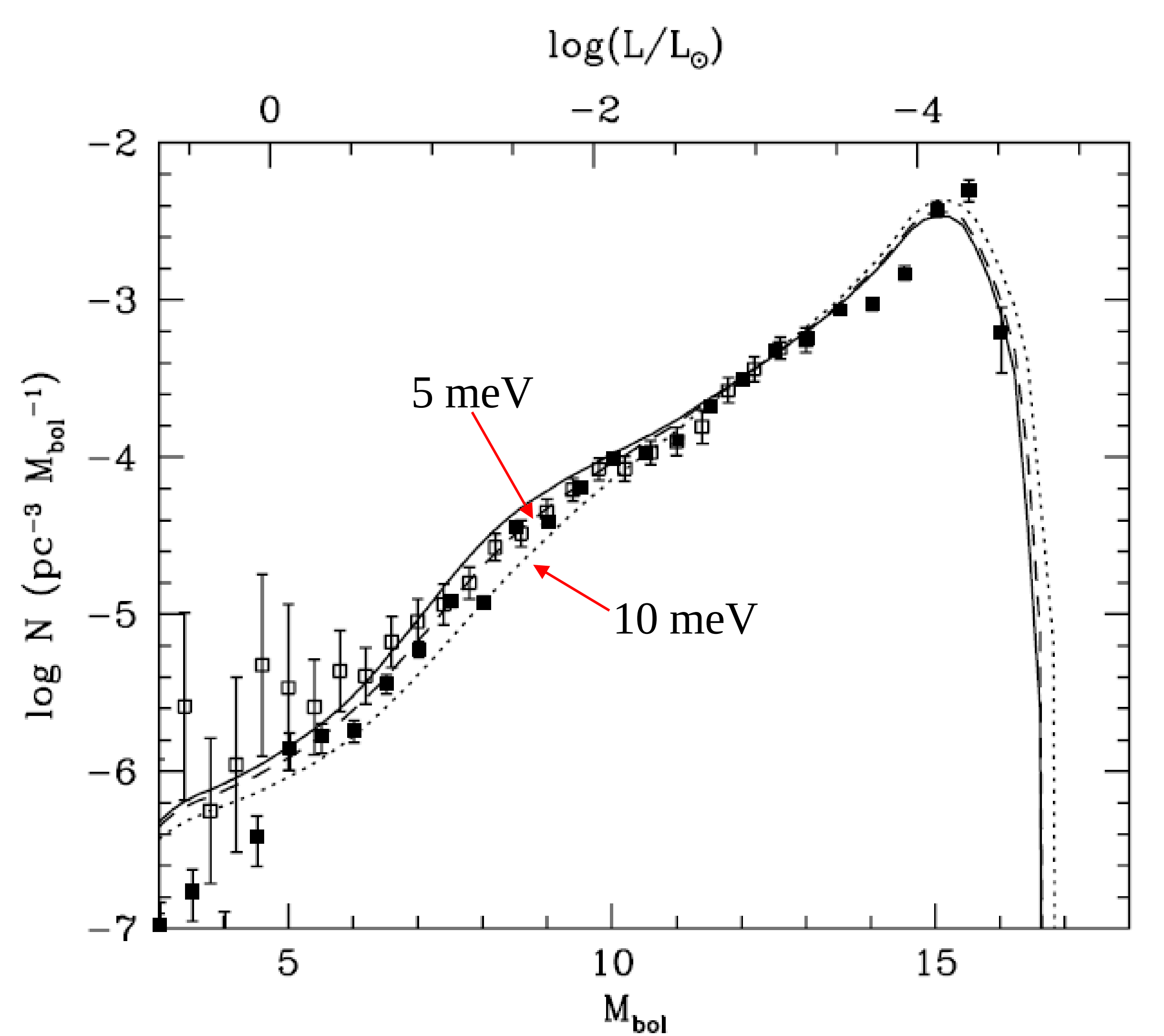
$m_a \cos^2\beta = 0$

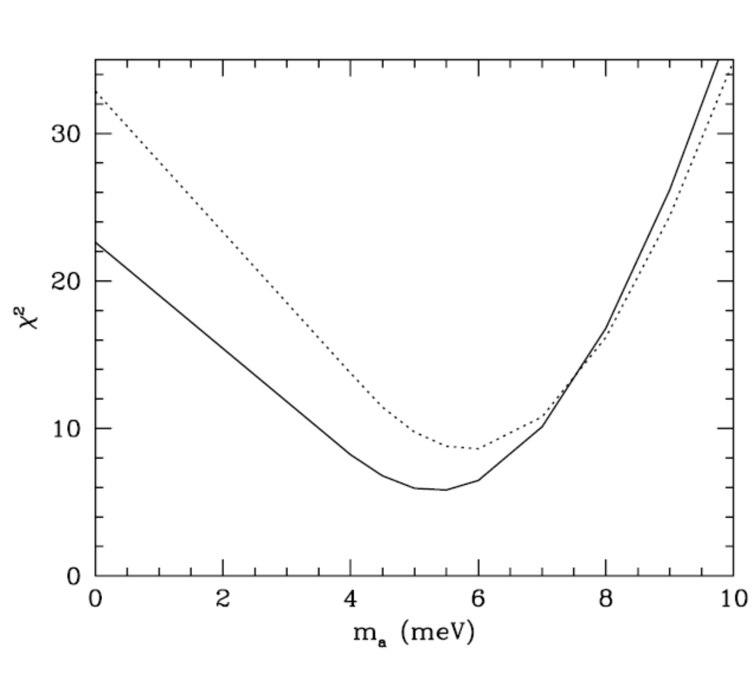
$m_a \cos^2\beta =$ very large

$m_a \cos^2\beta = 10$ meV

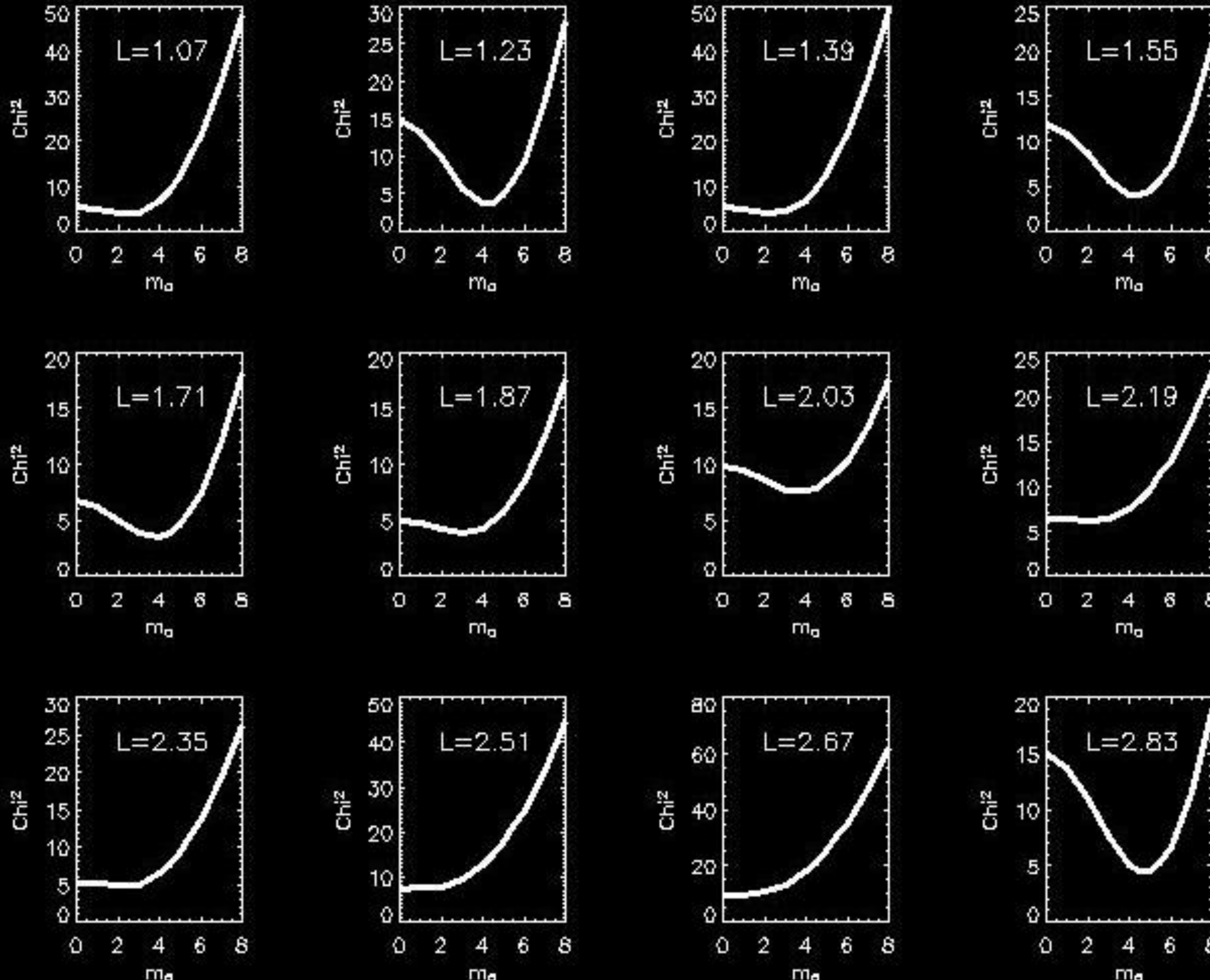
$m_a \cos^2\beta = 4$ meV







The best fit is obtained for $m_a \cos^2\beta \sim 5$ meV



L=1.07
L=1.23
L=1.39
L=1.55
L=1.71
L=1.87
L=2.03
L=2.19
L=2.35
L=2.51
L=2.67
L=2.83
Chi2
ma

Uncertainties:

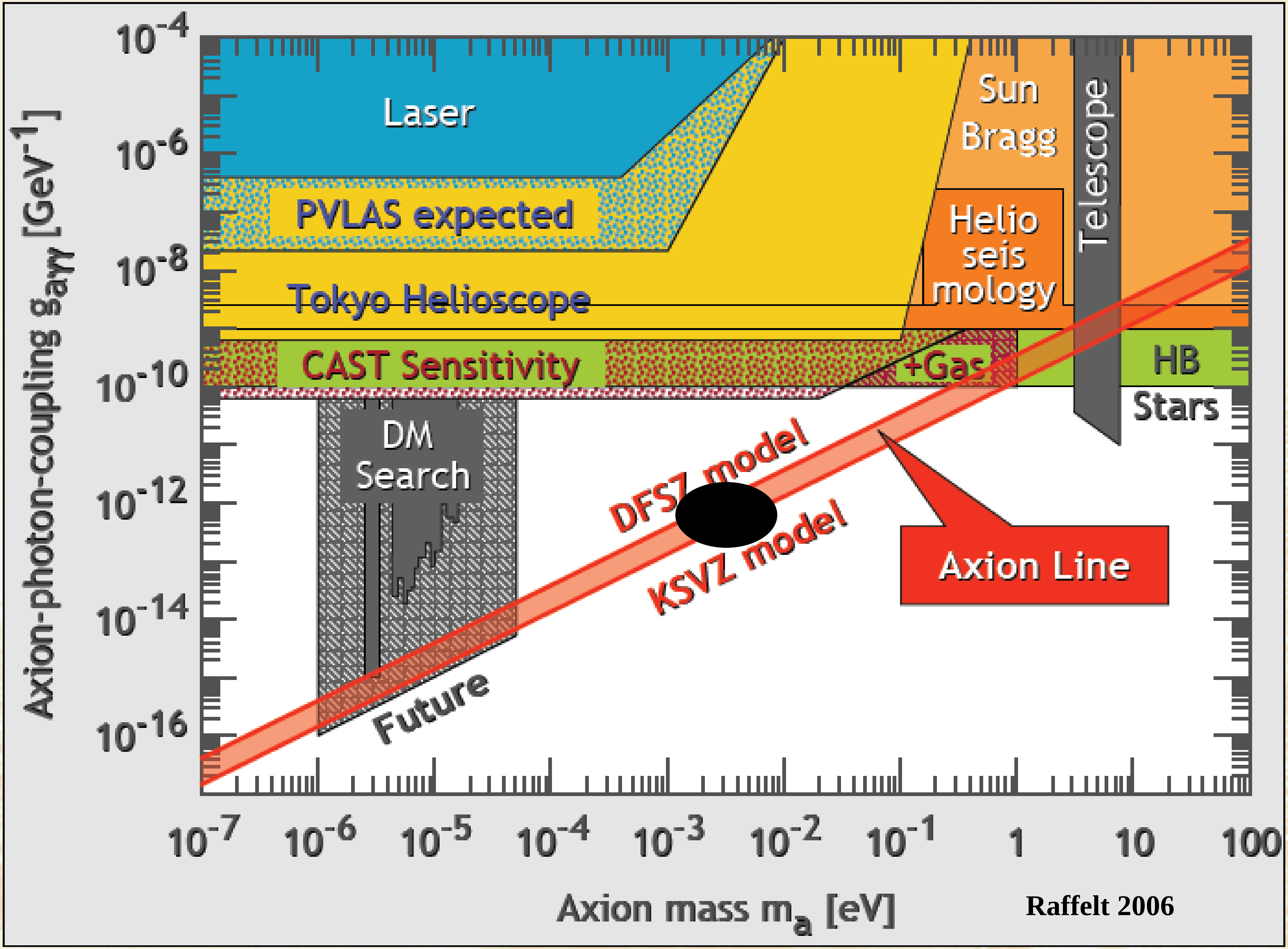
- Internal structure
- Emission rates
- Transparency of the envelope
- Initial-final mass relationship
- IMF
- Pathological SFR
- Ages of MS progenitors
- Metallicities
- Observational systematics
- ....

This result suggests that if axions (DFSZ ones) are included, the luminosity function of white dwarf stars is better fited

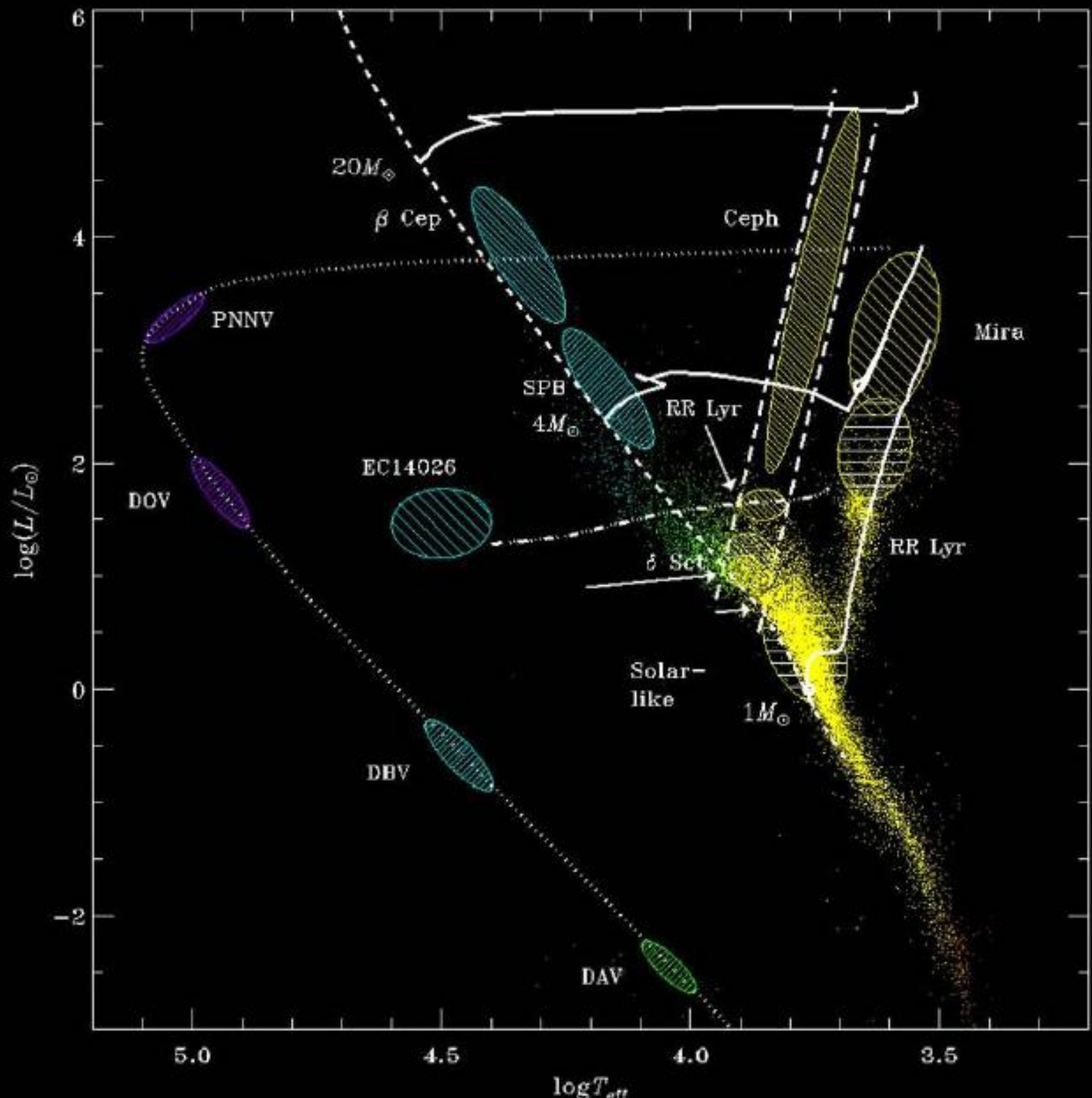
In the worst case they provide a very strong upper limit

Tasks to do:

Coincidence between the different cooling models
Improvement of models. Is there any “classical” effect that could account for this extra-cooling?
Improvement of the observational luminosity function.
Predictions
Contradictions



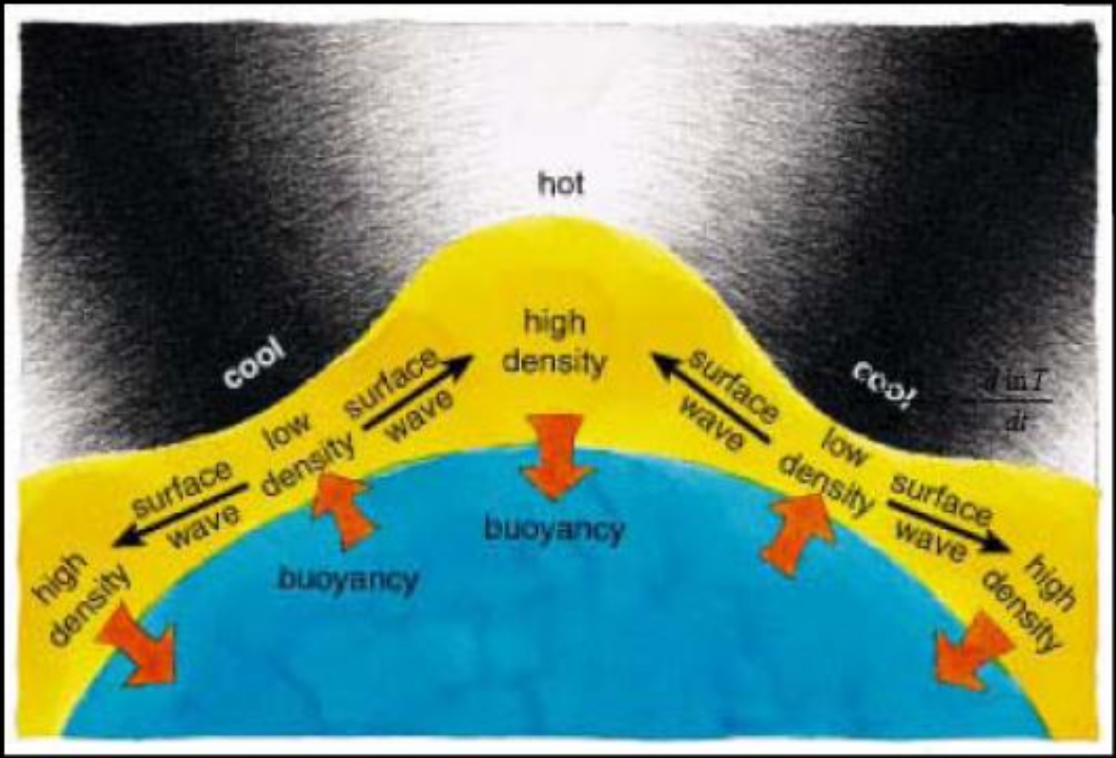
Laser
PVLAS expected
Tokyo Helioscope
CAST Sensitivity
+Gas
Sun Bragg
Helio seis mology
Telescope
HB
Stars
DM Search
Future
DFSZ model
KSVZ model
Axion Line
Axion-photon-coupling $g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 100
Axion mass m_a [eV]
Raffelt 2006



6
4
2
0
−2
log(L/L⊙)
5.0
4.5
4.0
3.5
log T_eff
20M⊙
β Cep
Ceph
PNNV
Mira
SPB
4M⊙
RR Lyr
EC14026
DOV
RR Lyr
δ Sct
Solar-
like
1M⊙
DBV
DAV

Variable WD

Non-radial g-modes



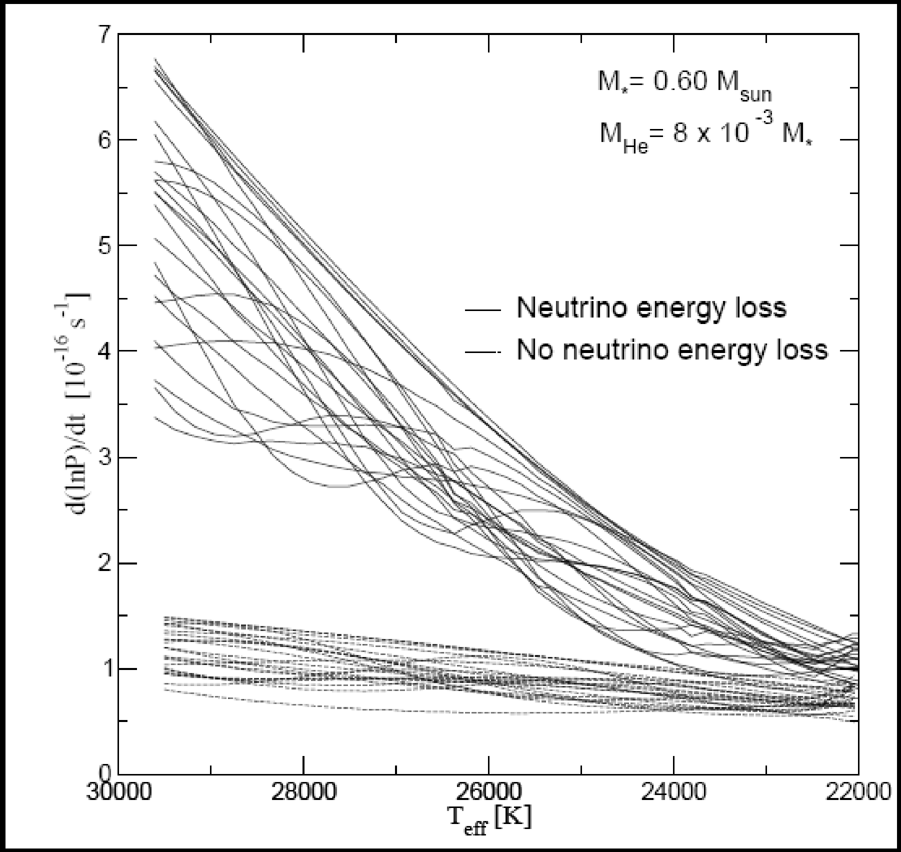
- Long period waves ~ 10^2 - 10^3 s
- Gravity is the restoring force

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

The period increases as the star cools down and decreases as it contracts.

The radial term can be neglected for cool enough stars (DAV, DBV)

- DOV variables: the drift can be positive or negative depending on the mode
  - PG1159-35: P = 516 s and dP/dt=13.07 +/-0.3 x 10^{-11} s/s
- DBV variables: the drift is always positive. dP/dt ~ 10^{-13} – 10^{-14} s/s. No drift measurements
- DAV variables: the drift is always positive.
  - G117-B15A: P=215.2 s, dP/dt = 3.57x10^{-15} s/s (Kepler et al 2005)
  - R548: P =213.13 s, dP/dt </= 5.5 x 10^{-15} s/s

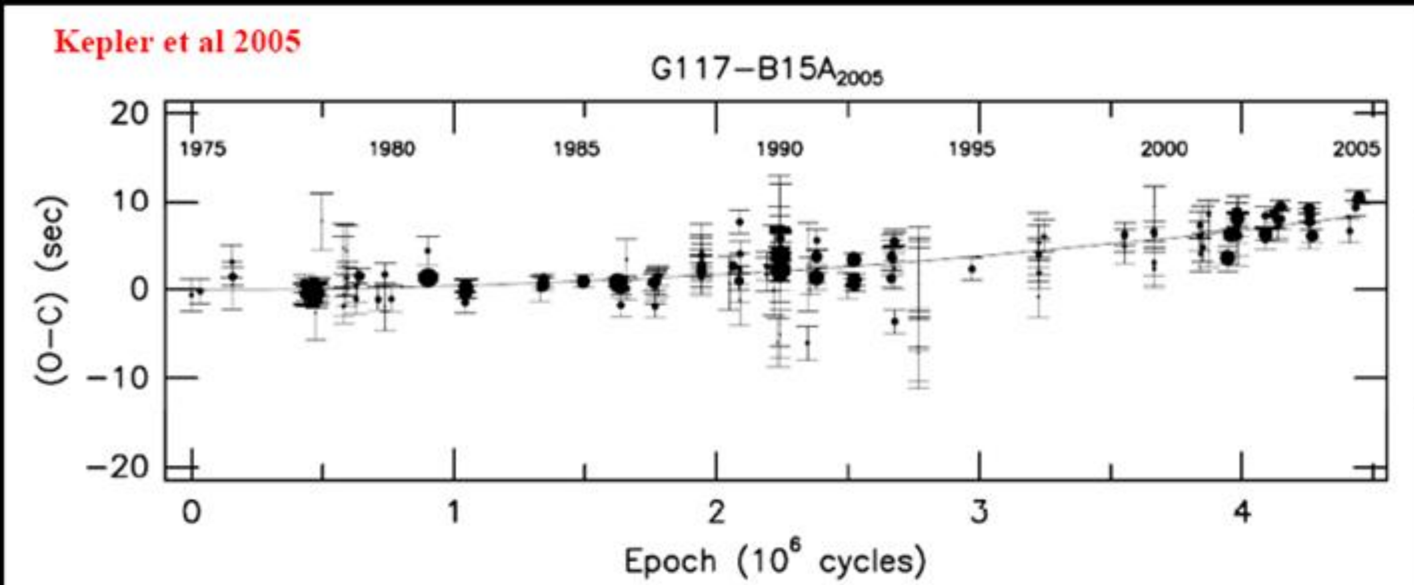


Còrsico and Athaus, 2004

$$\dot{\Pi} = (12.0 \pm 3.5) \times 10^{-15} \text{ s/s}$$

The first value (Kepler et al'91) was a factor of 2 larger than expected.
Three solutions:

- **Observational error**
- **White dwarfs with "IME" cores**
- **Exotic source of cooling**



$$P = 215.1973888 \pm 0.0000004 \quad s$$

$$dP/dt = (4.27 \pm 0.80) \times 10^{-15} \quad s/s$$

With proper motion correction:

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

$4.07 \pm 0.59 \times 10^{-15}$ s/s (Kepler'09)

Possible additional corrections:

Reflex motion caused by the companion
Resonances caused by the different compositions layers

$$M_{bol} = -2.5\log L + ctn$$

$$\varepsilon_a = 1.08\cdot 10^{23}\alpha \frac{Z^2}{A} T_7^4 F(\Gamma)$$

$$\alpha = \frac{g_{ae}^2}{4\pi}$$

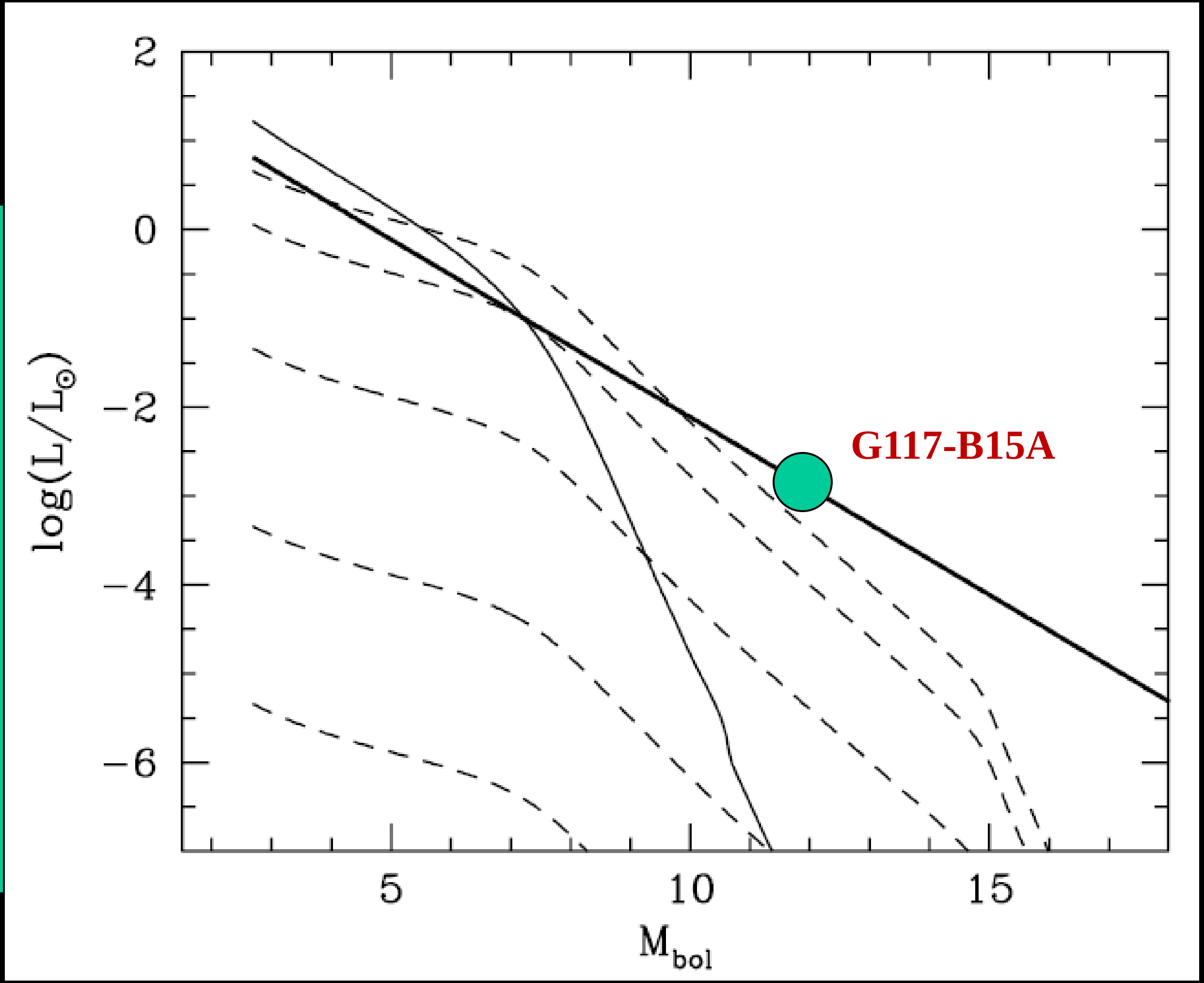
$$g_{ze} = 8.5\cdot 10^{-11} c_e \left({m_a}/{1eV} \right)$$

$$c_e = \frac{\cos^2\beta}{3}$$

$$\frac{\dot{\Pi}_{obs}}{\dot{\Pi}_{\mathrm{mod}}} \simeq \frac{L_{\mathrm{mod}} + L_x}{L_{\mathrm{mod}}}$$

Isern et al 1993

$$m_a \cos^2\beta \simeq 8.5 \text{ meV}$$



DFSZ axions
Bremmsstrahlung is dominant

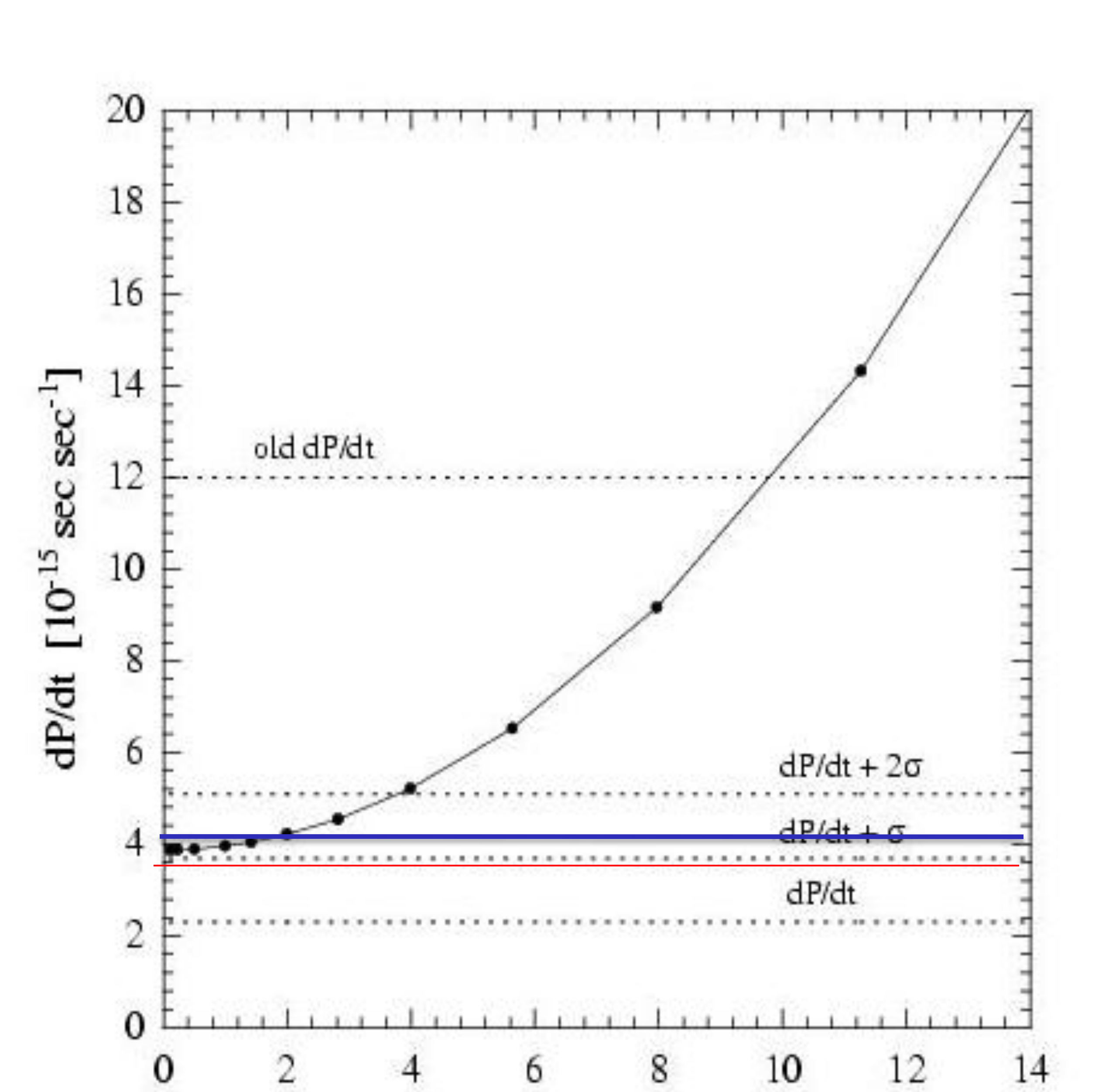
Nakagawa et al 1987, 1988

Fiducial model & error budget

P_F=210.4 s
dP/dt =3.9×10^{-15} ss^{-1}

Error budget

Source	ΔP(s)	$\Delta dP/dt$ $(ss^{-1})\times10^{15}$
Mode identification	6	1.0
M_*	6	1.0
Chemical profile	4	0.1
T_{eff}	2	0.2



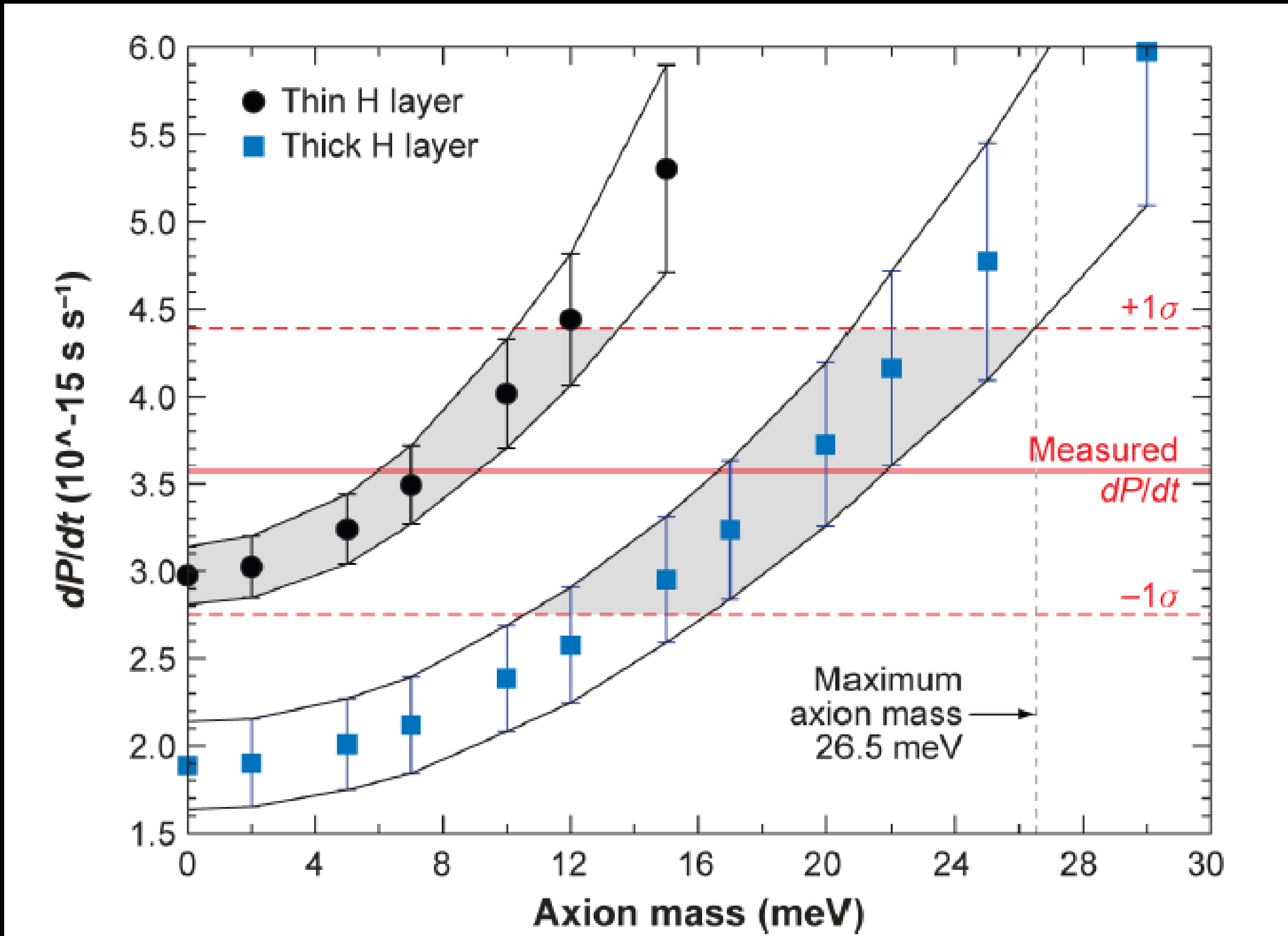
$m_a \cos^2 \beta$ [meV]

Corsico et al 2001:
$m_a = 0$
$P_F = 210.4 \pm 18$ s
$dP/dt = (3.9 \pm 2.3) \times 10^{-15} ss^{-1}$

$m_a = 5$ meV ;
$dP/dt \sim 6 \times 10^{-15}\ ss^{-1}$

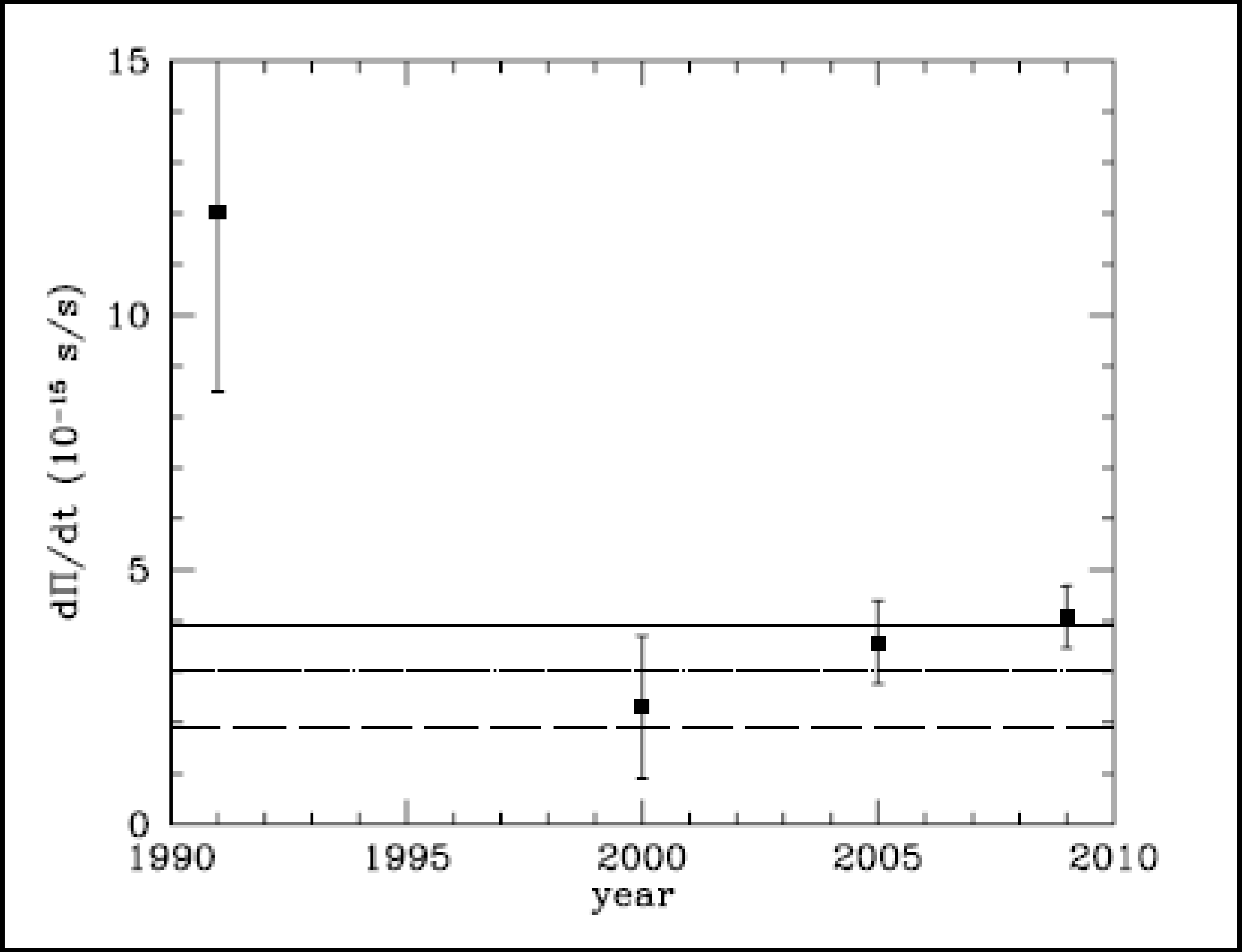
Kepler et al 2009

Kepler et al 2005



Bischoff-Kim et al 2008:
$m_a < 13 – 26$ meV

Observed and predicted secular drift of G117-B15A



Corsico et al'91 (________)
Bishkof-Kim et al'08
thick envelope (-·-·-·-)
thin envelope (_ _ _ _)

PREDICTION

In the case of the DBV (Corsico & Althaus, 2004):

dP/dt ~ $10^{-13} – 10^{-14}$ s

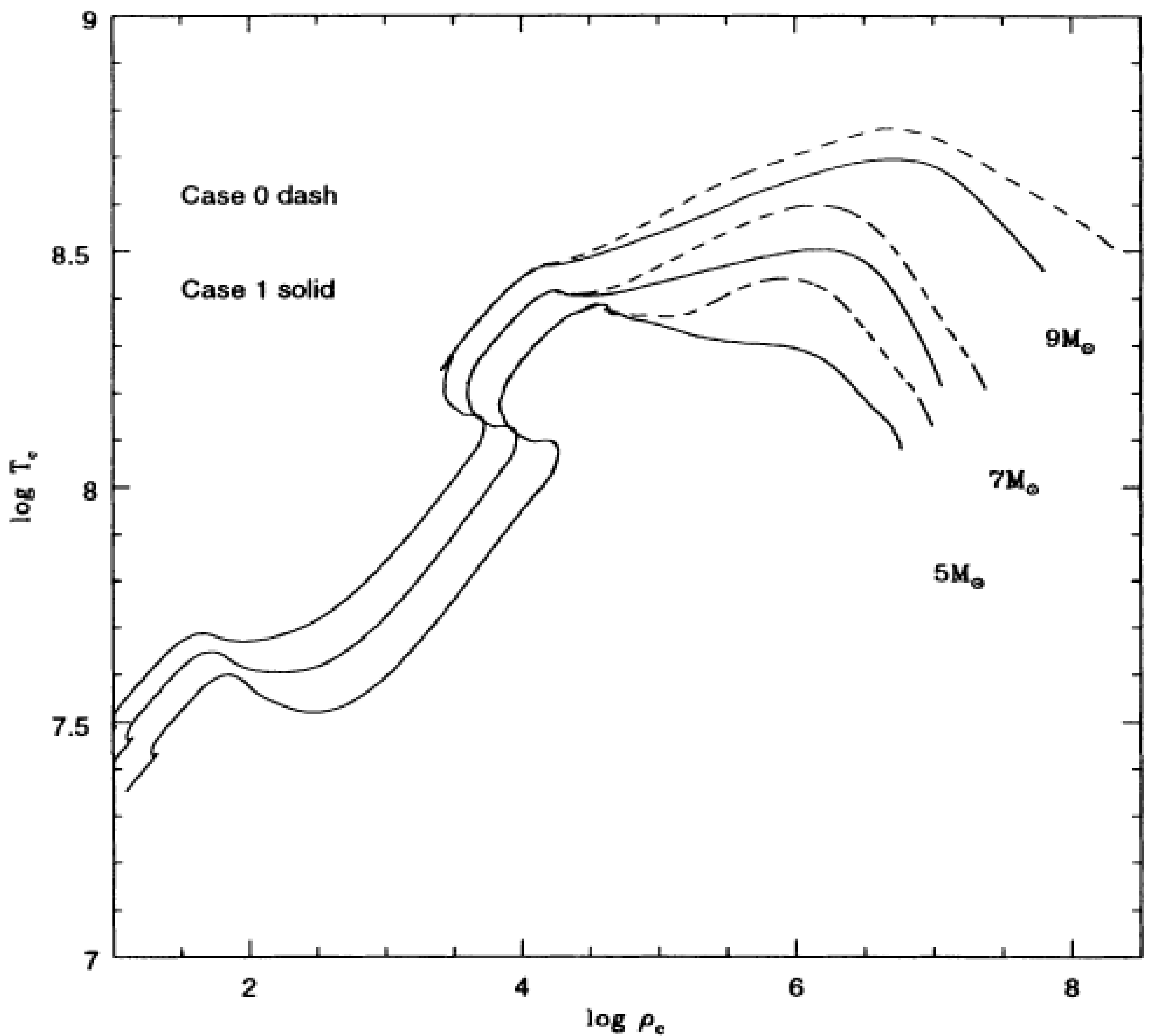
Axions with m_a ~ 5 would modify dP/dt by a factor 1.5 (it strongly depends on the temperature of the core)

Influence on the AGB evolution

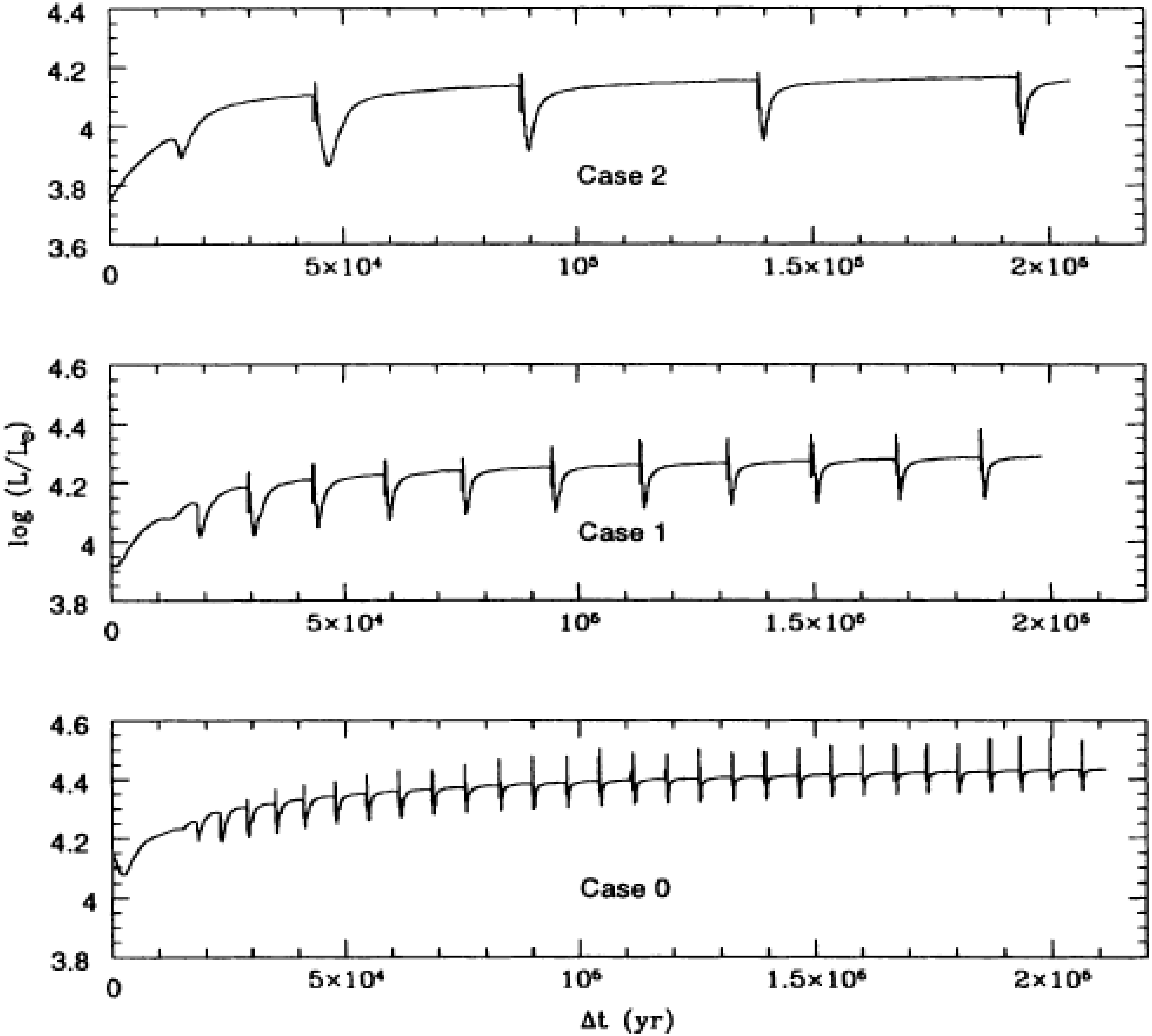
Table 1. Properties of the models during the HB and E-AGB phases.

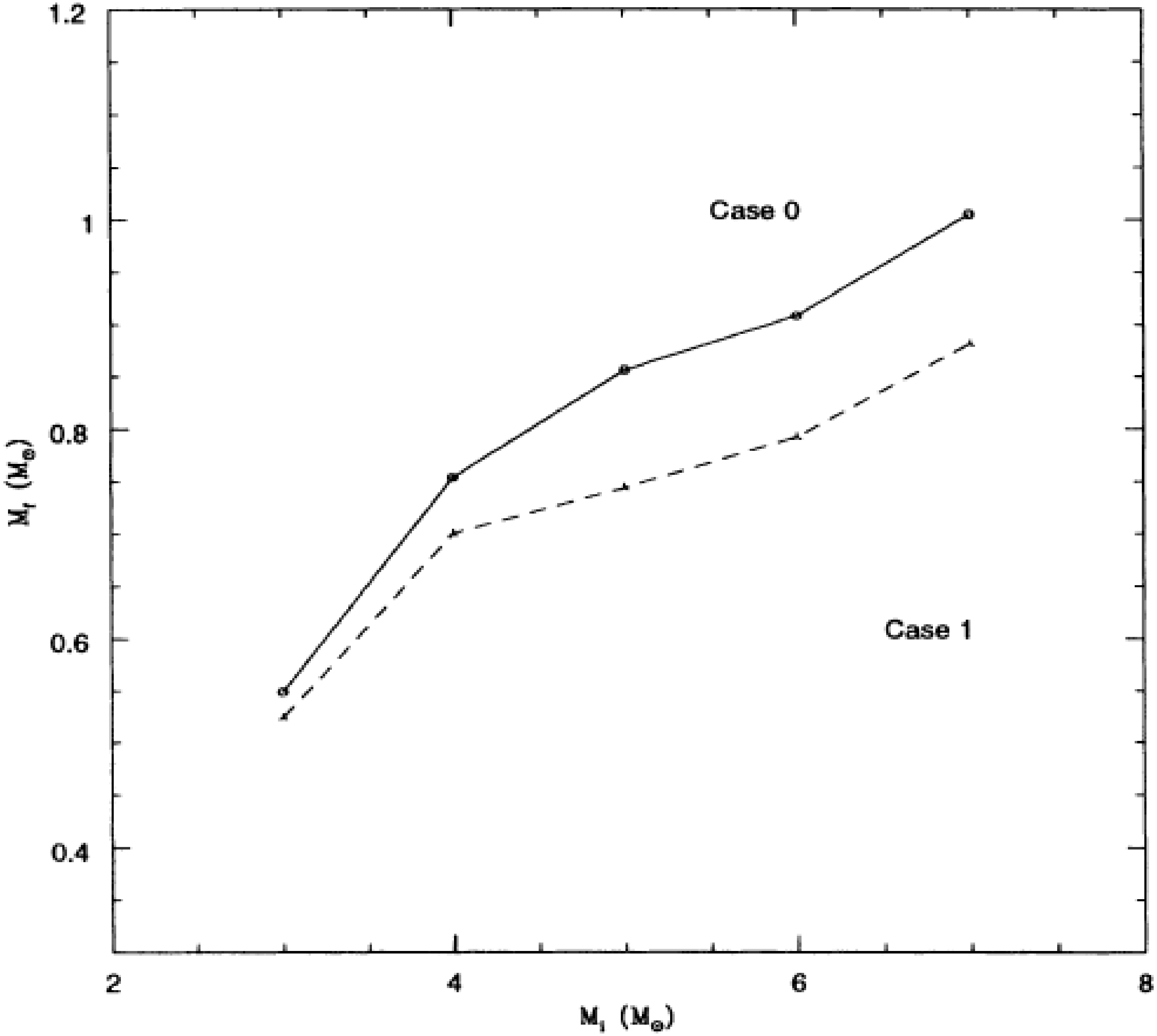
M_T	M_{ax}	He_s^1	$\log L_{tip}$	M_{He}^1	Δt_{He}	M_{He}^2	$\Delta t_{E\text{-}AGB}$	He_s^2	M_{CO}
	0.0	0.298	3.451	0.479	...	...	...	...	...
0.8	8.5	0.298	3.559	0.501	...	...	...	...	...
	20.	0.299	3.750	0.544	...	...	...	...	...
	0.0	0.294	3.445	0.477	...	...	...	...	...
1.5	8.5	0.294	3.561	0.500	...	...	...	...	...
	20.	0.295	3.765	0.547	...	...	...	...	...
	0.0	0.296	2.560	0.378	141	0.545	9.2	0.296	0.549
3.0	8.5	0.296	2.587	0.378	127	0.530	6.6	0.296	0.524
	20.	0.298	2.707	0.378	85.6	0.479	5.0	0.298	0.459
	0.0	0.296	3.186	0.654	20.8	1.024	1.20	0.324	0.856
5.0	8.5	0.296	3.187	0.651	20.0	1.014	0.75	0.340	0.744
	20.	0.297	3.192	0.648	16.6	0.968	0.51	0.347	0.645
	0.0	0.296	3.685	1.001	7.3	1.591	0.39	0.366	1.005
7.0	8.5	0.298	3.686	1.001	7.05	1.579	0.240	0.377	0.881
	20.	0.299	3.688	1.001	6.2	1.537	0.115	0.381	0.787
	0.0	0.300	3.881	1.201	5.1	1.882	C-ignition	...	...
8.0	8.5	0.300	3.882	1.201	5.1	1.889	C-ignition	...	...
	20.	0.301	3.883	1.201	4.64	1.585	C-ignition	...	...
	0.0	0.301	4.052	1.422	4.1	2.217	C-ignition	...	...
9.0	8.5	0.301	4.053	1.422	4.1	2.209	C-ignition	...	...
	20.	0.302	4.055	1.422	3.9	2.165	C-ignition	...	...

Domínguez, Straniero, Isern’99



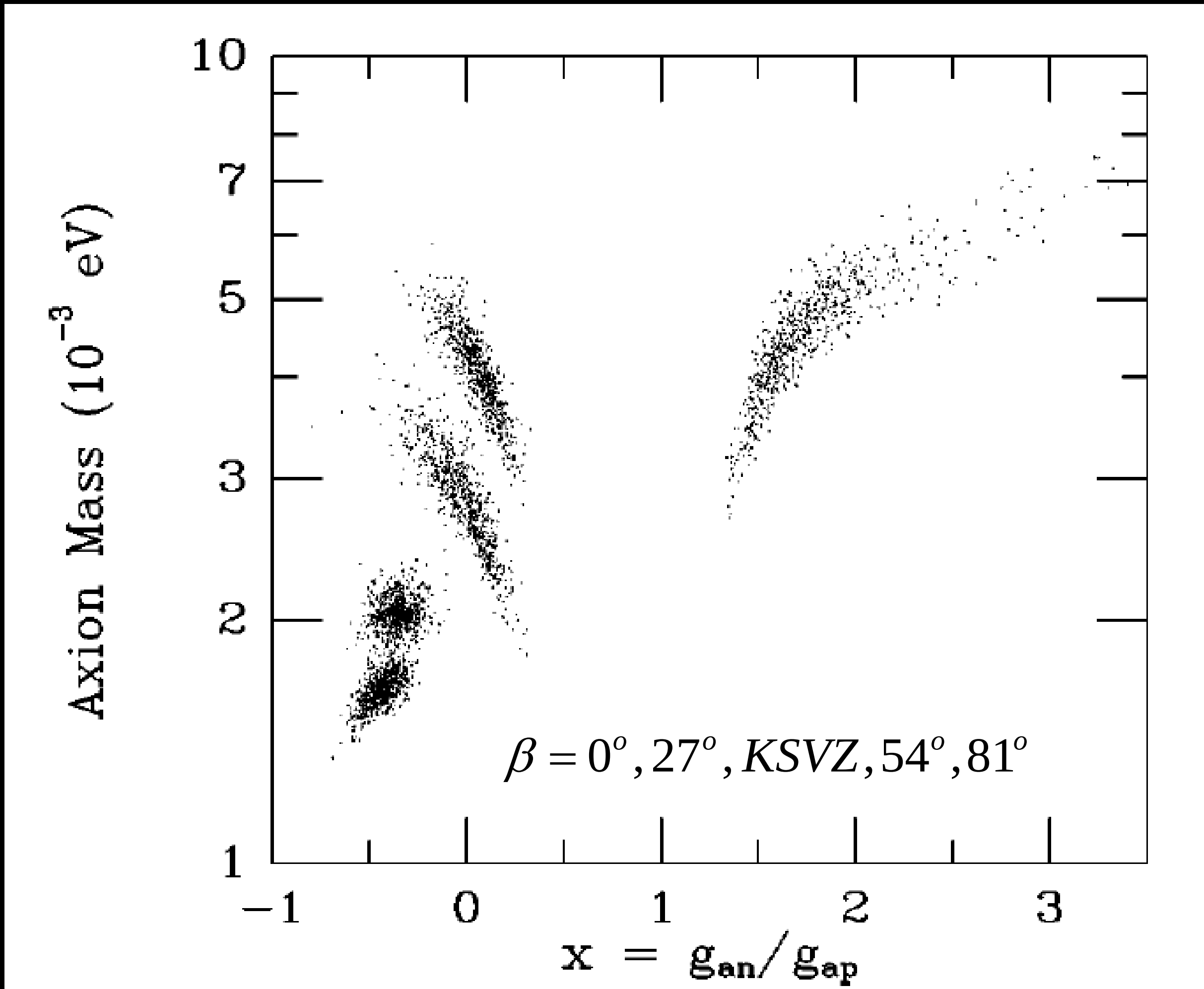
Case 0 dash
Case 1 solid
9M⊙
7M⊙
5M⊙
log T_c
log ρ_c
9
8.5
8
7.5
7
2
4
6
8


Case 2
Case 1
Case 0
log (L/L⊙)
Δt (yr)
0
5×10⁴
10⁵
1.5×10⁵
2×10⁵
3.6
3.8
4
4.2
4.4
4.6



1.2
1
0.8
0.6
0.4
2
4
6
8
Case 0
Case 1
M_f ($M_\odot$)
M_i ($M_\odot$)

Influence on core collapse supernovae



Keil et al '97

Raffelt'06
m_a(KSVZ) < 16 meV
m_a (DFSZ) ?

Nucleon bremsstrahlung is dominant

Conclusions:

Because of their simplicity, WDs are excellent complementary laboratories for testing new physics.
The recent luminosity functions and the measurement of the secular drift of the pulsation period of DAV suggest that WDs cool dowm more quickly than expected . Axions could account for this discrepancy.
Nevertheless, more conventional explanations have to be explored before:

Improvement of the observational WDLF

Effects of the metallicity on the internal chemical composition

Evolution of the envelope: DA-noDA exchange...

...