White Dwarfs as Physics Laboratories: The Axion case

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Collaboration:

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Chicago, July 20th, 2012

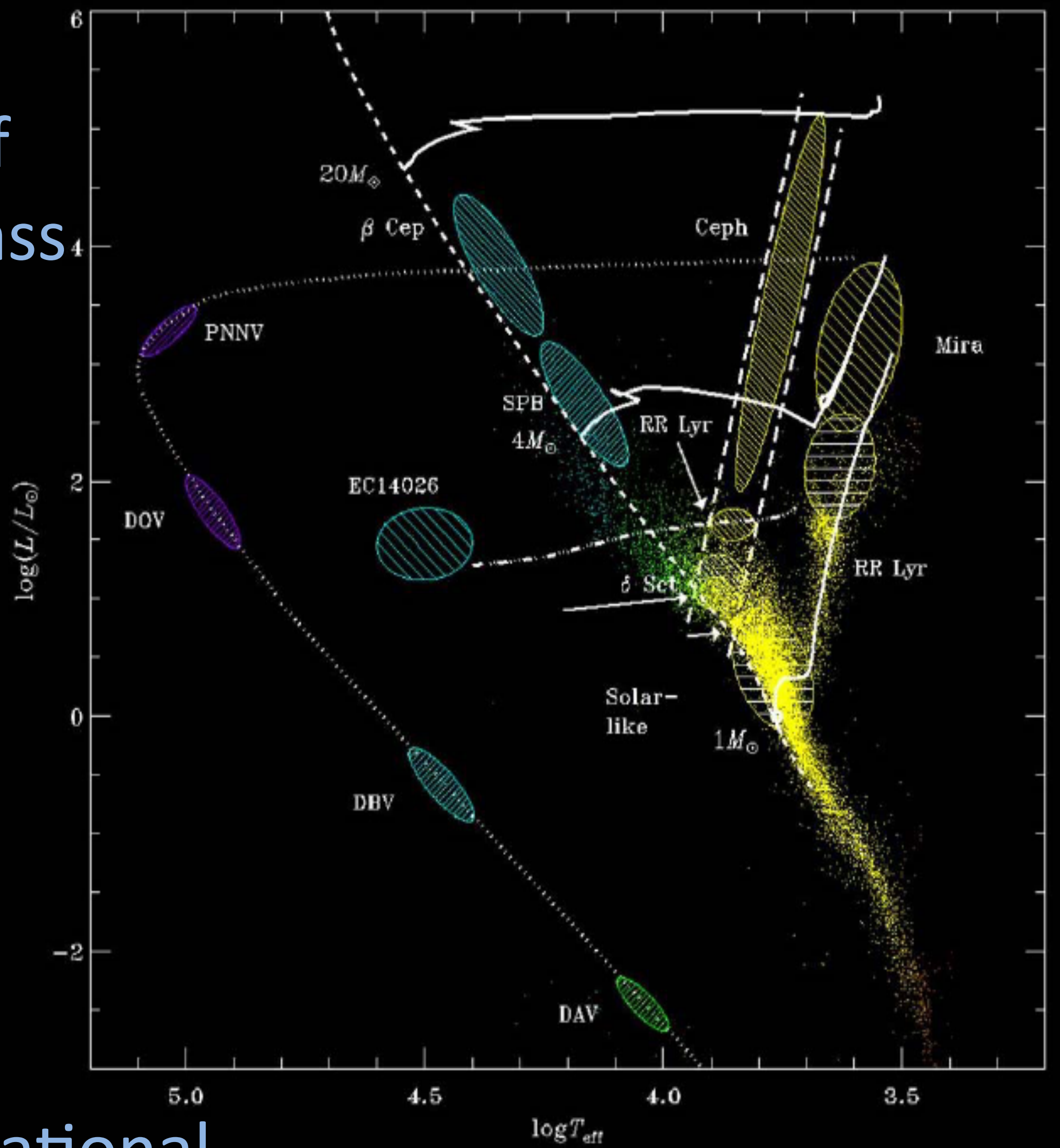
The white dwarf population is one of the best studied!

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

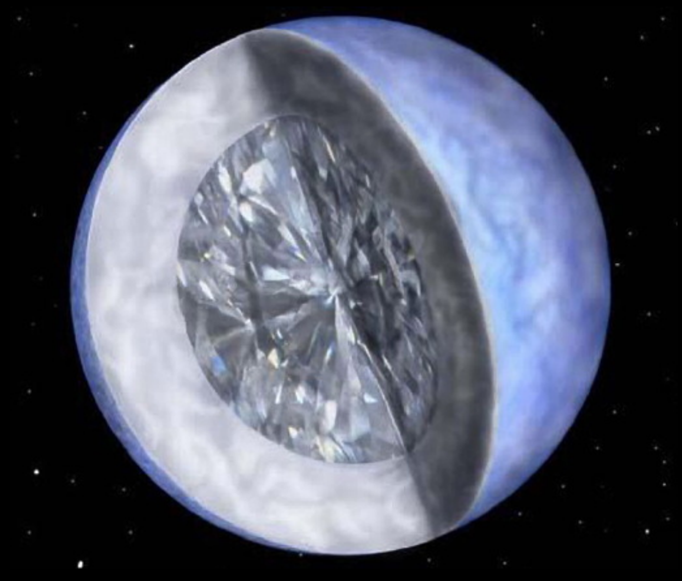
White dwarf cooling

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

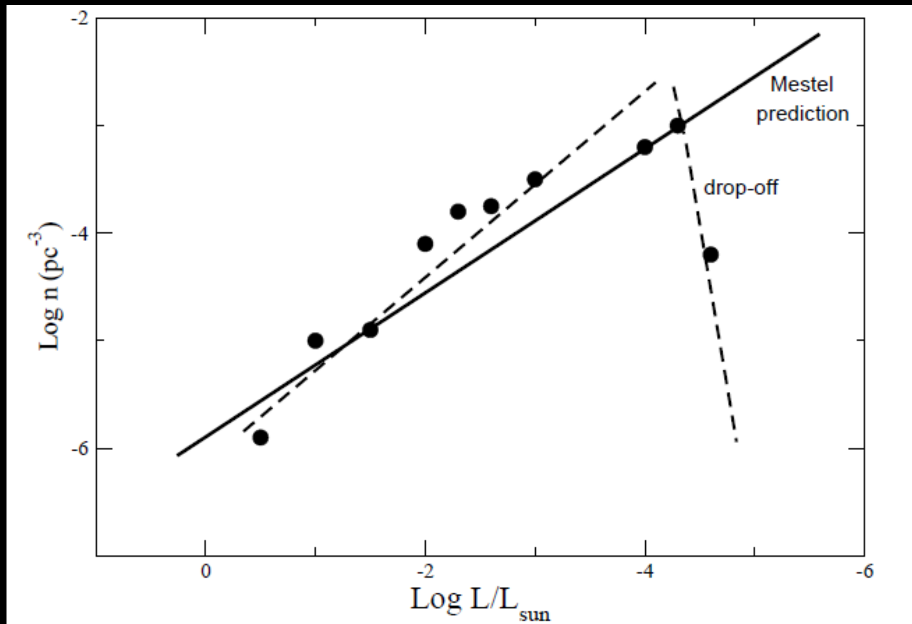
A $L(T_C)$ relationship is necessary to solve this equation
It depends on the properties of the envelope.

$$L \propto T^\alpha$$

$$\alpha \approx 2.5 - 2.7$$



CO.core/He-envelope/H-envelope



GAIA mission (2013-2018)

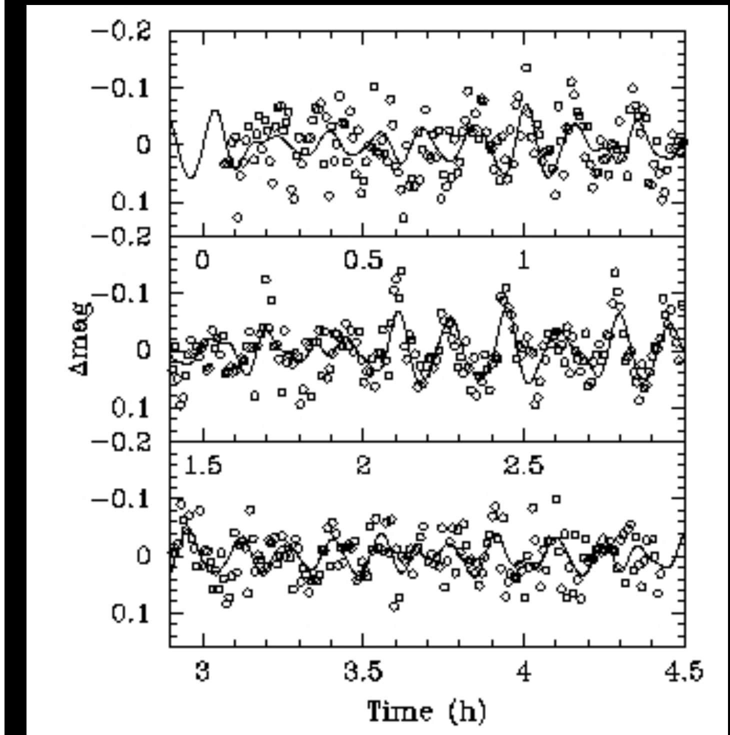
400,000 WD

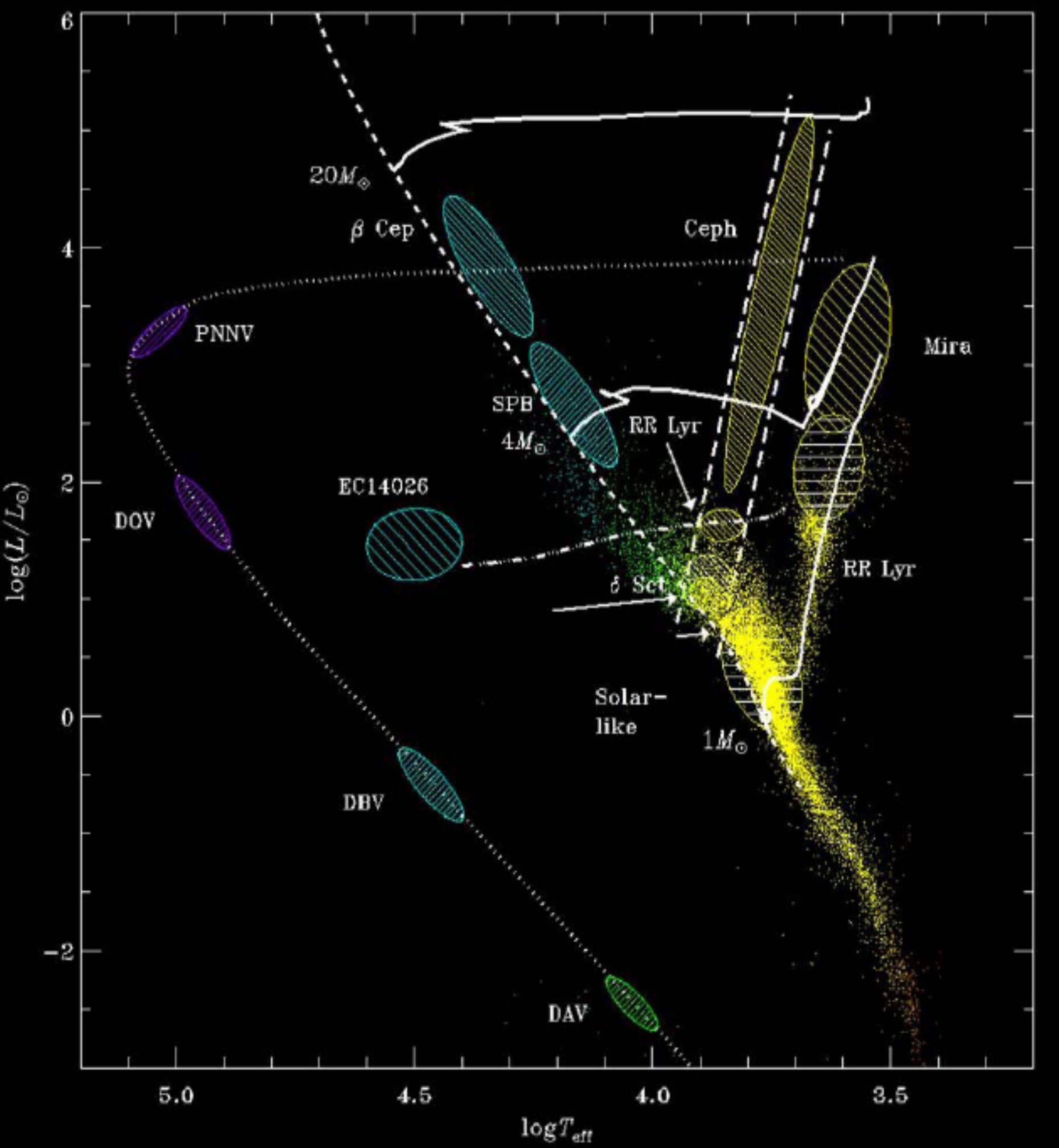
Large Synoptic Survey Telescope (LSST)

50,000,000 WDr > 27.5 mag

First light: 2015
Start Science: 2017

During their cooling,
WD find some instabilities
and they experience
Luminosity fluctuations:
DOV, DBV, DAV

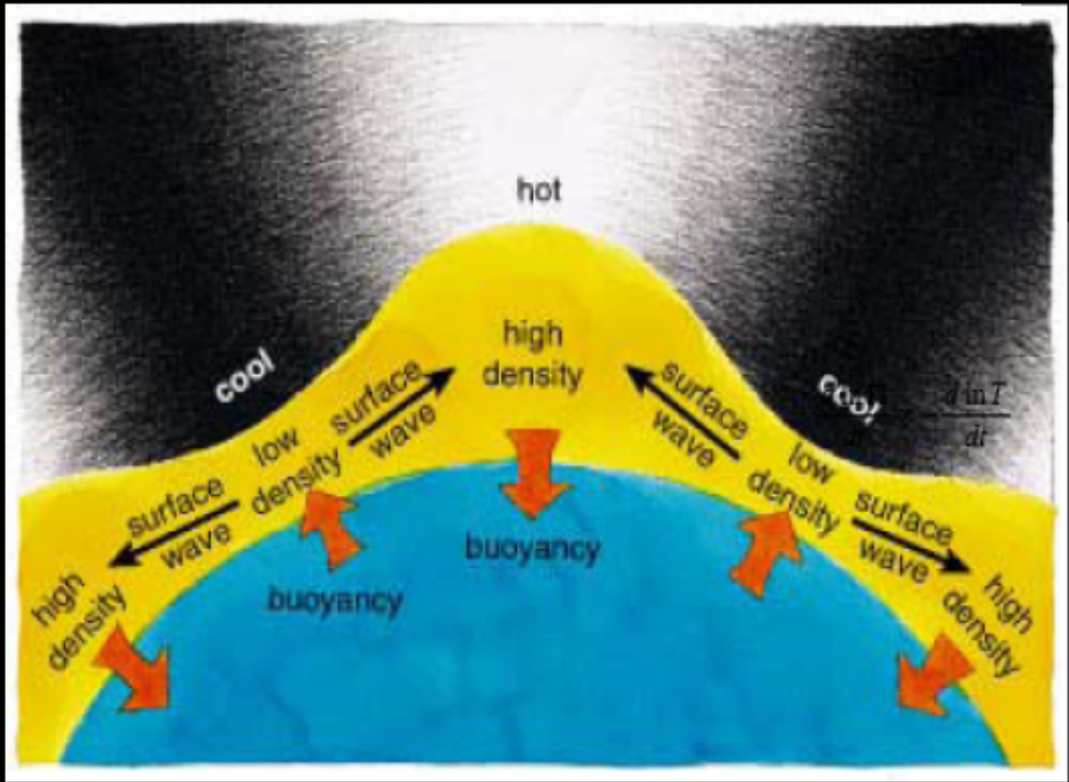




Courtesy of Christensen-Dalgaard

Non-radial g-modes

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

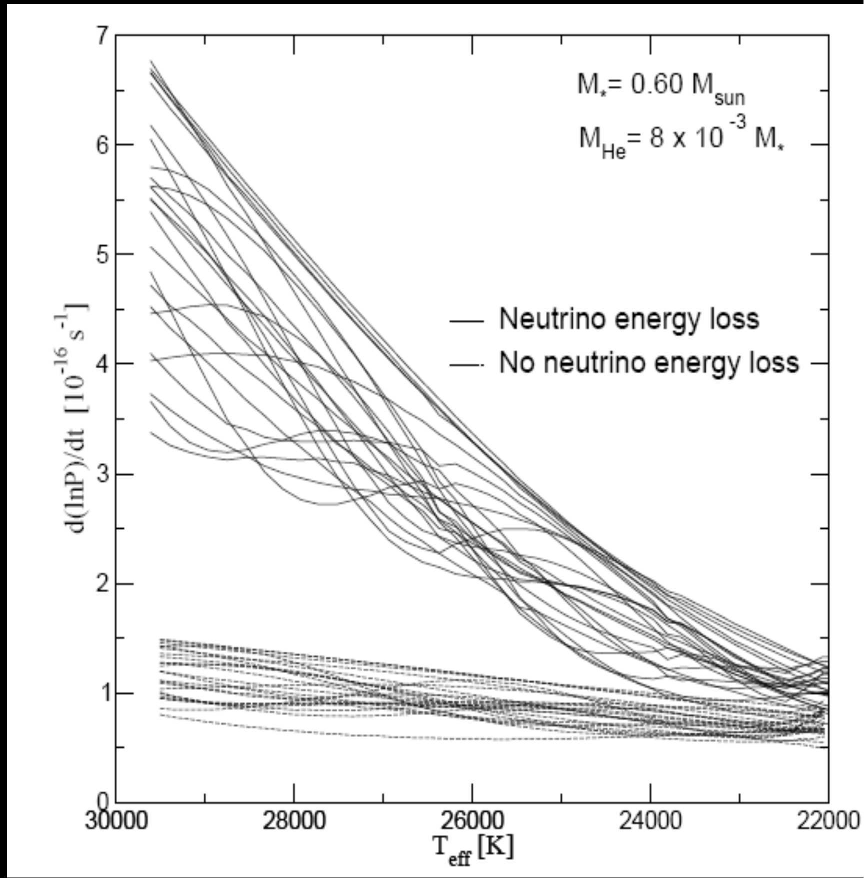


$$\frac{\dot{P}}{P} = -a\frac{\dot{T}}{T} + b\frac{\dot{R}}{R}$$

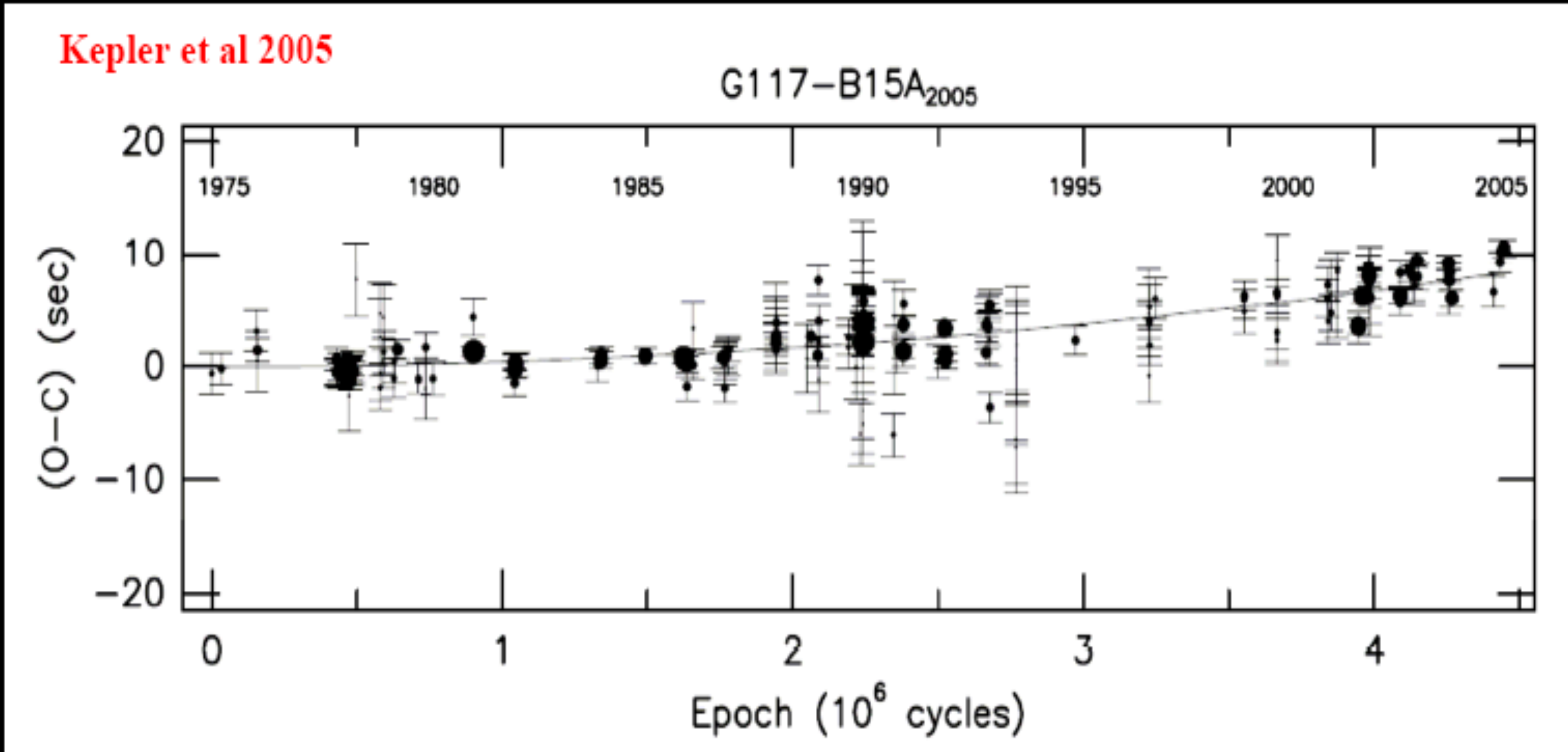
The period increases as the star cools down and decreases as it contracts.

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.

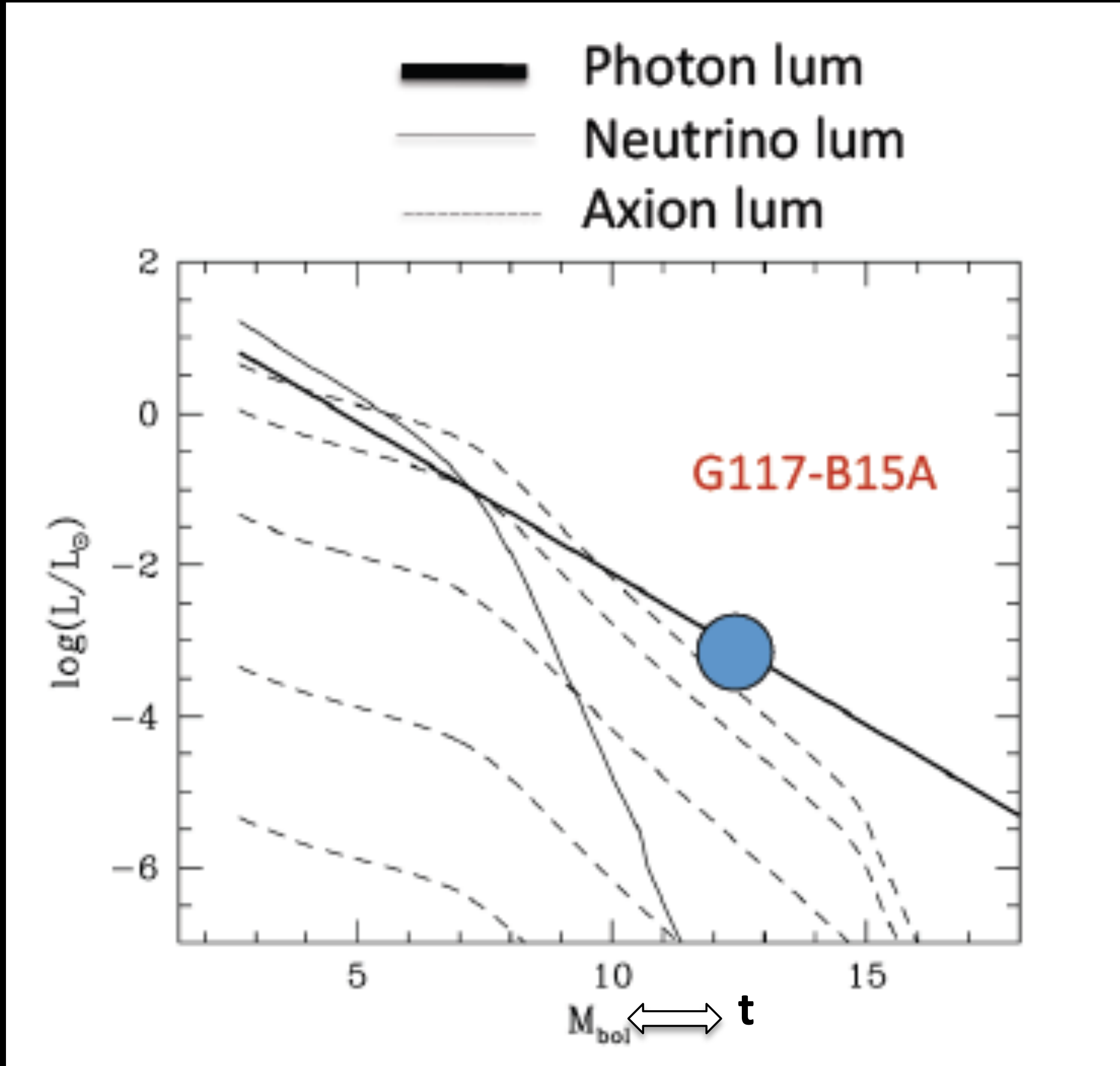
Three solutions:

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

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

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

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



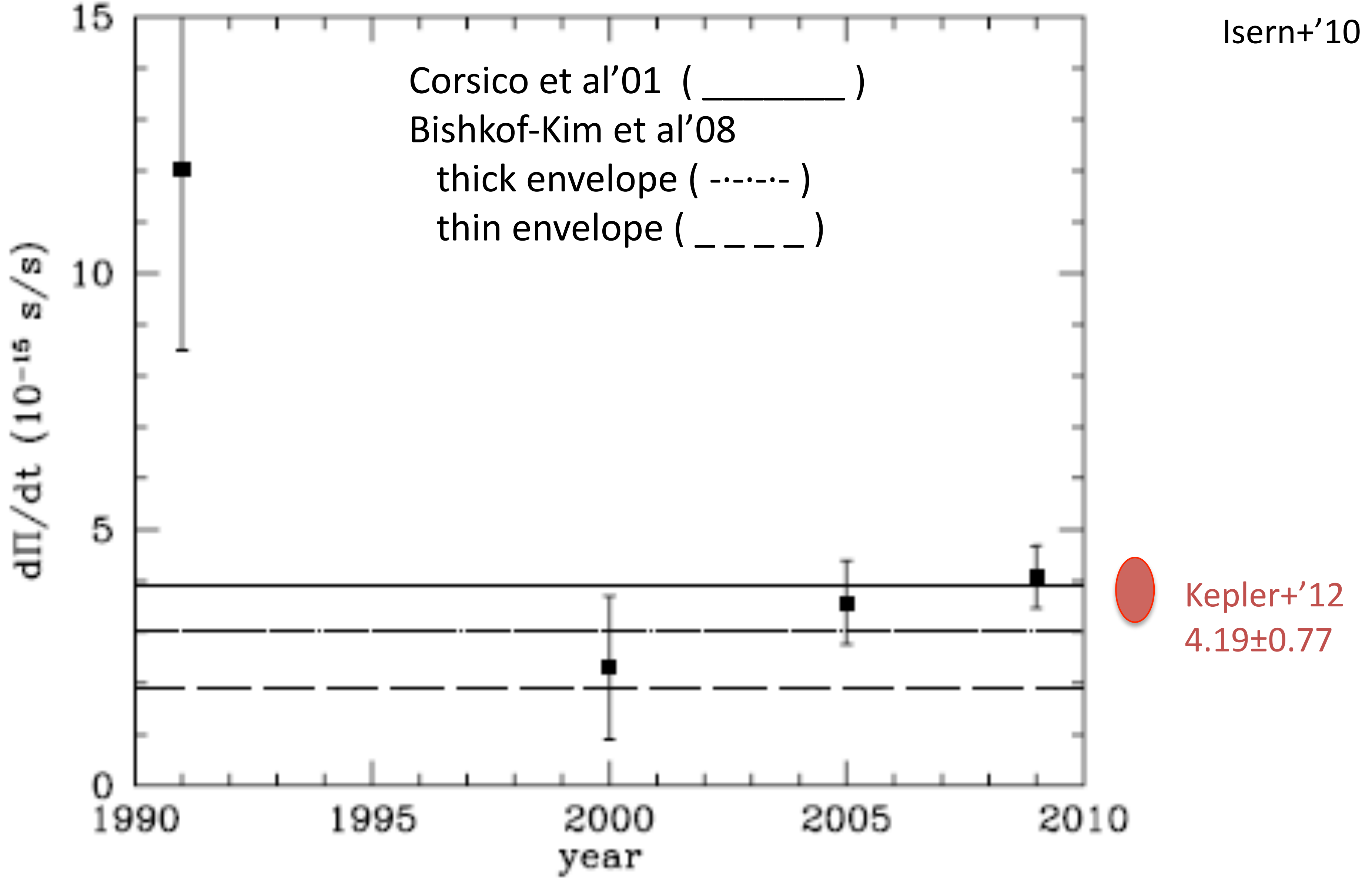
DFSZ axions

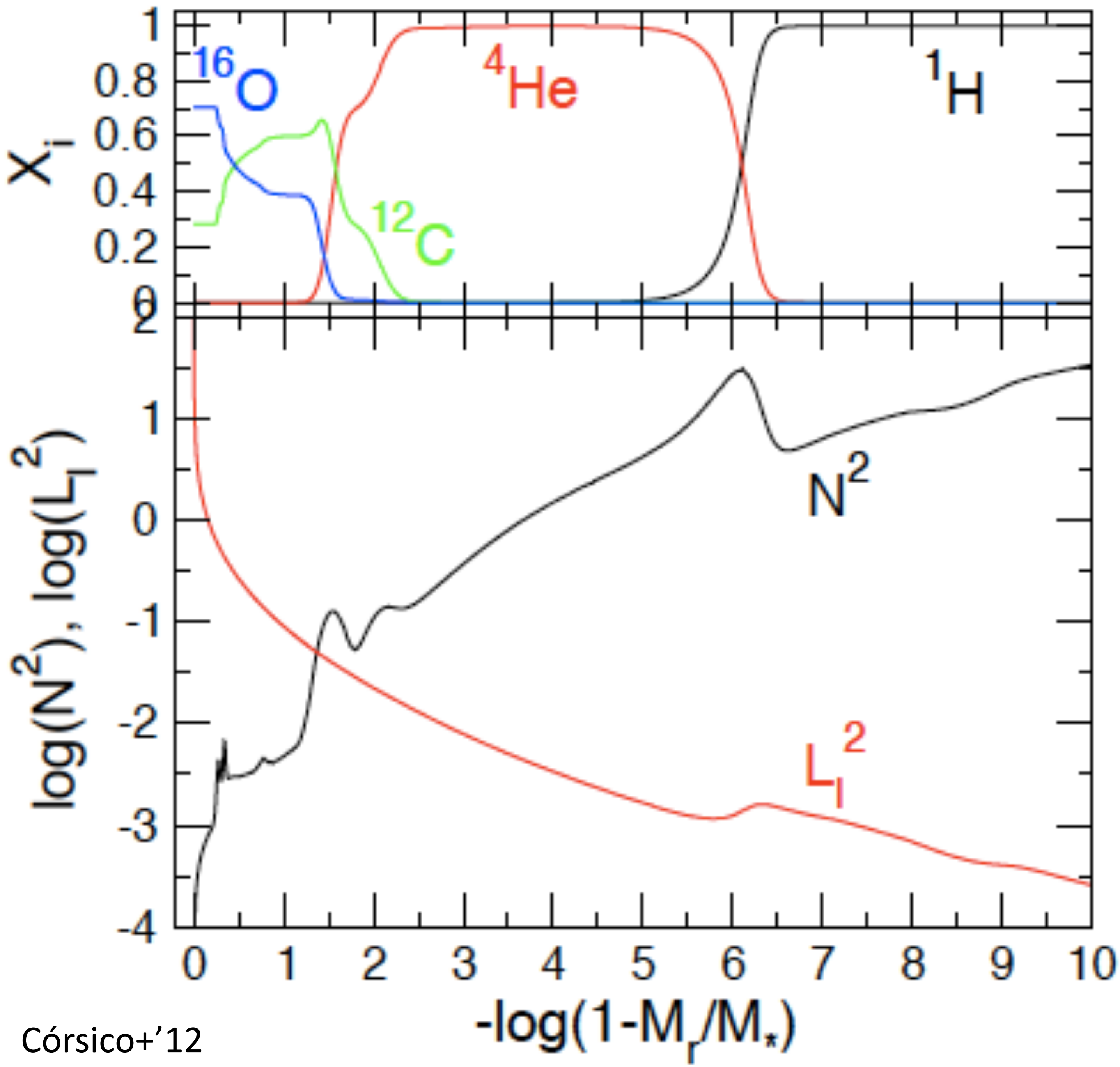
Bremmsstrahlung is dominant

Nakagawa et al 1987, 1988

$g_{ae} \sim 2.2 \times 10^{-13}$ ($m_a \sim 8$ meV) Isern+'92

Evolution of the measurements of the period of pulsation period drift of G117-B15A





^{16}O
^{4}He
^{1}H
^{12}C
X_i
1
0.8
0.6
0.4
0.2
0
2
1
0
-1
-2
-3
-4
N^2
L_l^2
log(N^2), log(L_l^2)
0 1 2 3 4 5 6 7 8 9 10
-log(1-M_r/M_*)

Córsico+'12

Table 1. Characteristics of G117−B15A as stated by spectroscopy and according to our asteroseismological model.

Quantity	Spectroscopy	Asteroseismological model
$T_{\rm eff}$ [K]	$11\,430 - 12\,500$	$11\,985 \pm 200$
$M_*/M_\odot$	$0.530 - 0.622$	0.593 ± 0.007
$\log g$	$7.72 - 8.03$	8.00 ± 0.09
$\log(R_*/R_\odot)$	—	-1.882 ± 0.029
$\log(L_*/L_\odot)$	—	-2.497 ± 0.030
$M_{\rm He}/M_*$	—	2.39×10^{-2}
$M_{\rm H}/M_*$	—	$(1.25 \pm 0.7) \times 10^{-6}$
$X_{\rm C}, X_{\rm O}$ (center)	—	$0.28, 0.70$

Note 1: the ranges of values in column 2 have been derived by taking into account the spectroscopic analysis of Robinson et al. (1995), Koester & Allard (2000), Koester & Holberg (2001), Bergeron et al. (1995, 2004).
Note 2: The quoted uncertainties in the asteroseismological model are the internal errors of our period-fit procedure.

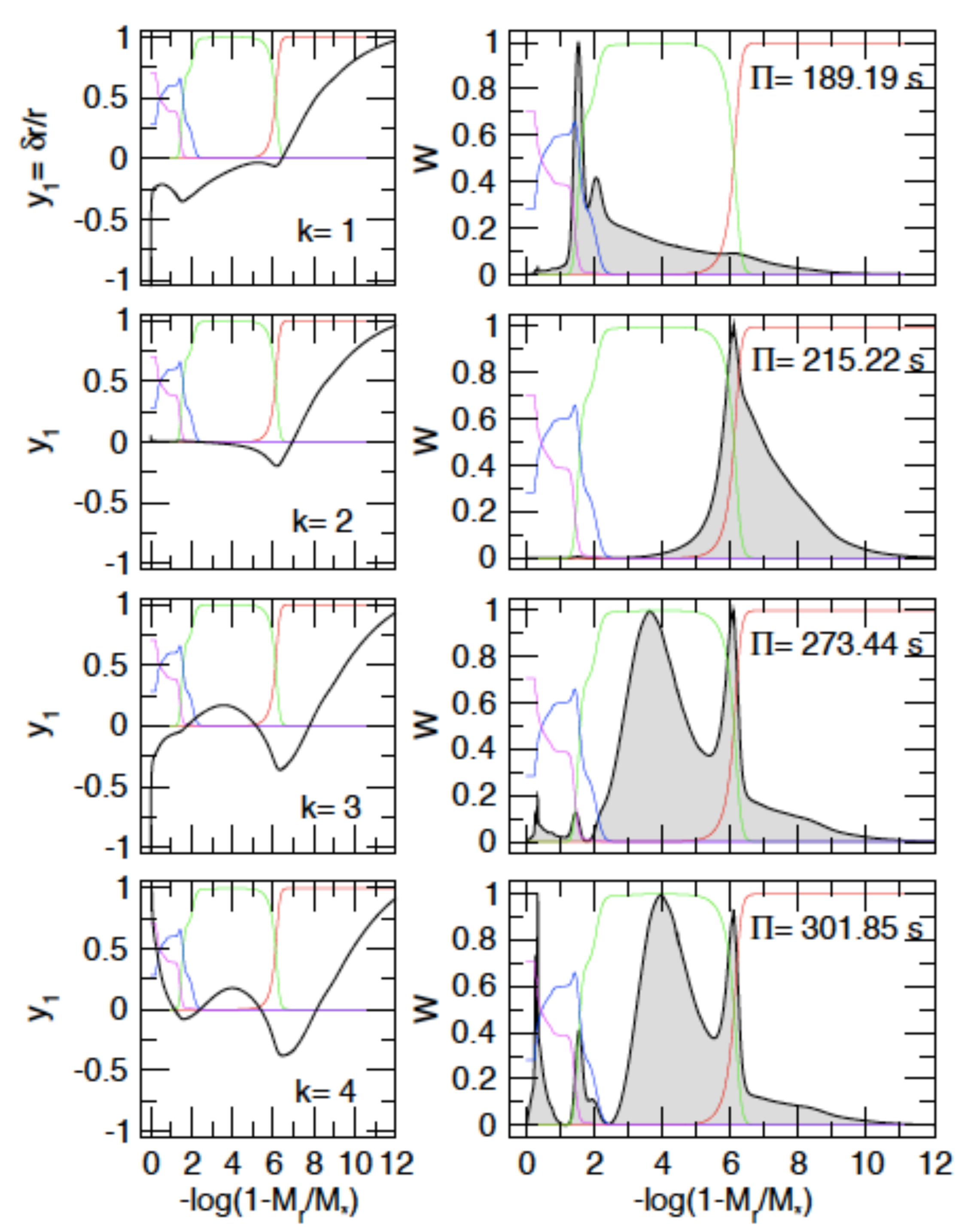
Córsico+'12

Table 2. The observed (G117–B15A) and theoretical (asteroseismological model) periods and rates of period changes.

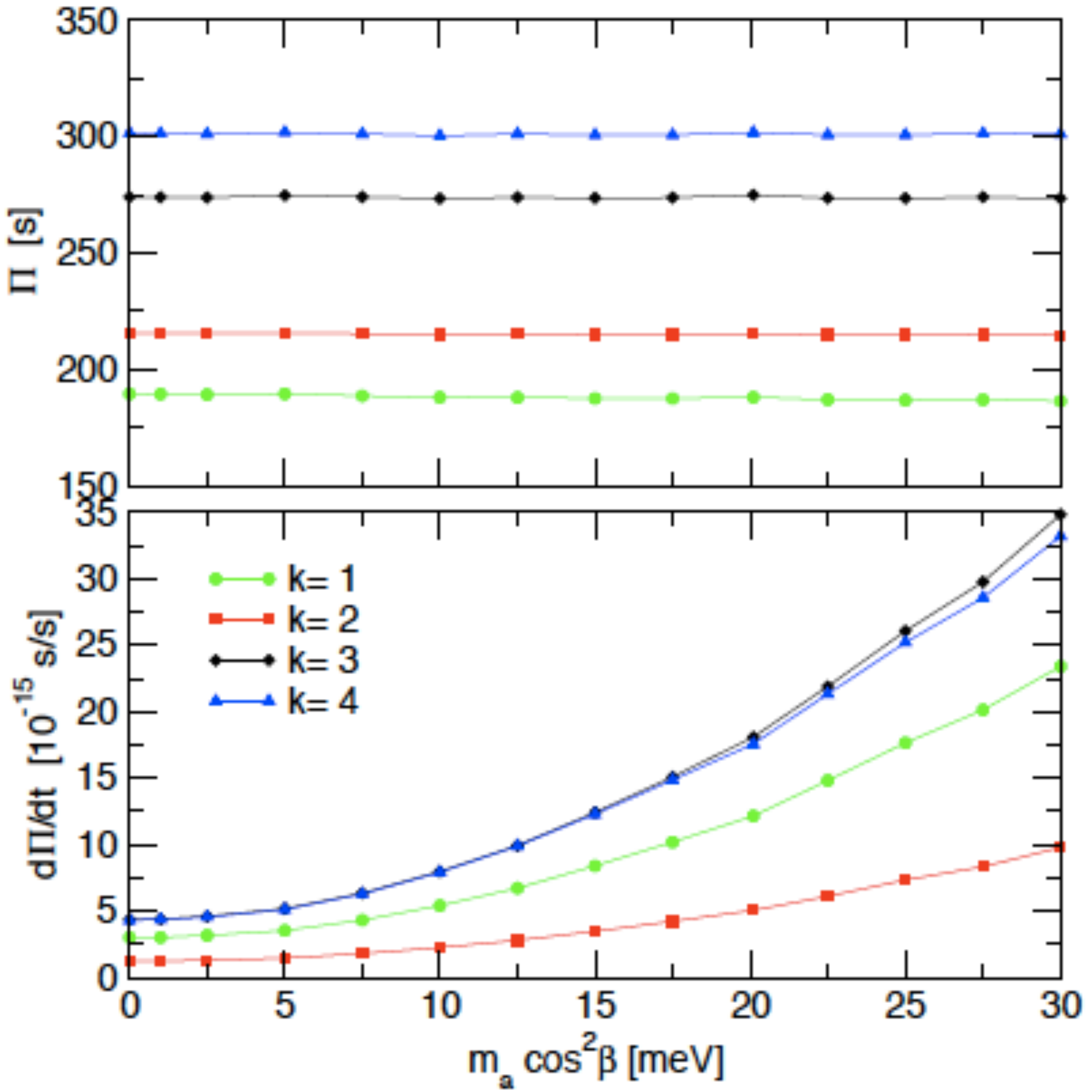
Π^o [s]	Π^t [s]	ℓ	k
—	189.19	1	1
215.20	215.22	1	2
270.46	273.44	1	3
304.05	301.85	1	4

$\dot{\Pi}^o$ [10^{-15}s/s]	$\dot{\Pi}^t$ [10^{-15}s/s]	ℓ	k
—	3.01	1	1
4.19 ± 0.53	1.25	1	2
—	4.43	1	3
—	4.31	1	4

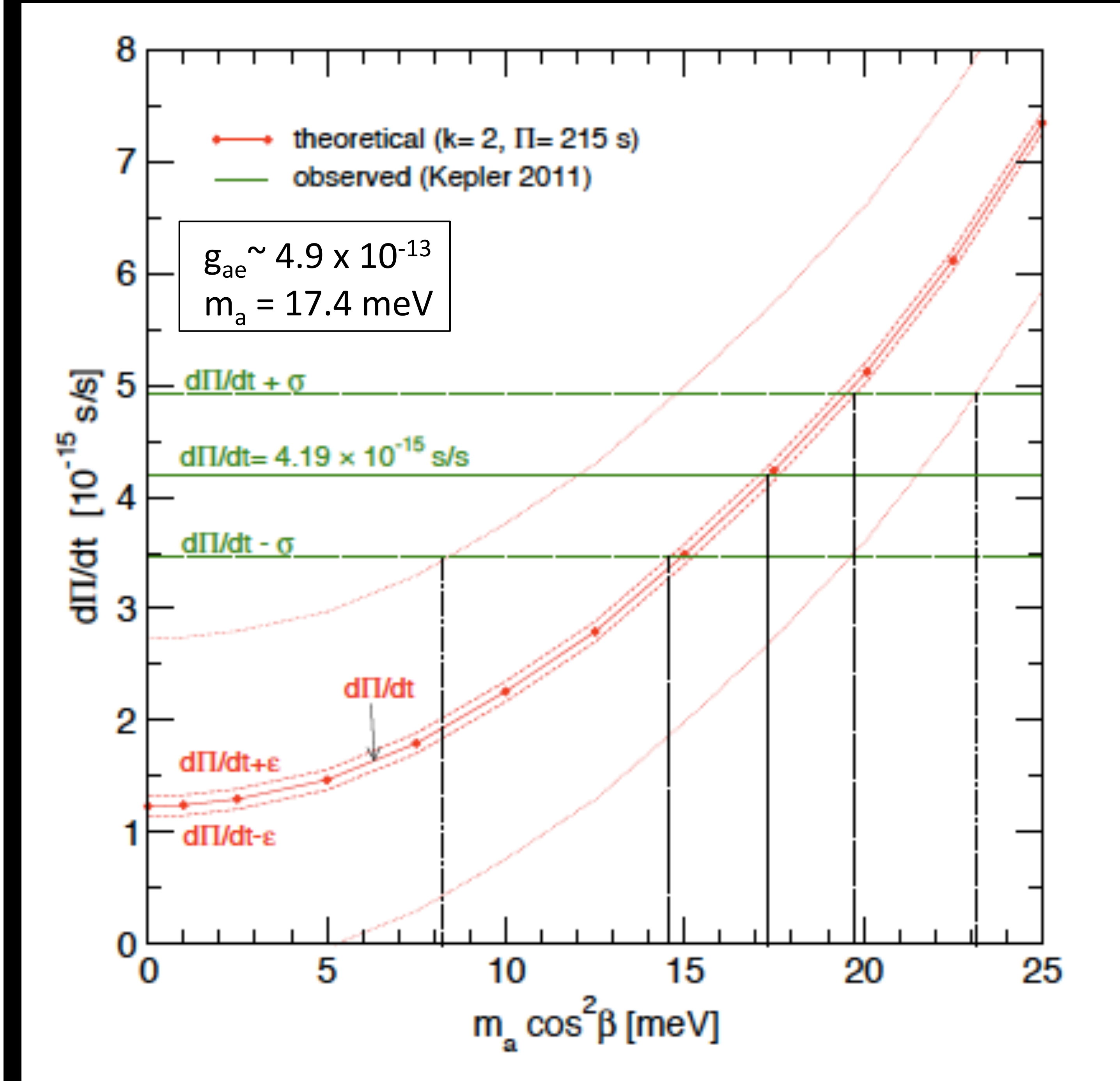
Kepler+'12



Weight function



350
300
250
200
150
Π [s]
35
30
25
20
15
10
5
0
dΠ/dt [10^-15 s/s]
k= 1
k= 2
k= 3
k= 4
0
5
10
15
20
25
30
m_a cos^2β [meV]



theoretical (k= 2, Π= 215 s)
observed (Kepler 2011)
g_ae ~ 4.9 x 10^-13
m_a = 17.4 meV
dΠ/dt + σ
dΠ/dt= 4.19 × 10^-15 s/s
dΠ/dt - σ
dΠ/dt
dΠ/dt+ε
dΠ/dt-ε
dΠ/dt [10^-15 s/s]
m_a cos^2β [meV]
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25

Other exemples:

DAV:

R548 (ZZ Ceti), Π =213 s, dΠ/dt ≈ 0.8 to 4.3 x 10^{-15} s/s

Mukadam +'09

DBV:

EC20058-5234, Π =257 s, dΠ/dt ≈ 8 x 10^{-13} s/s

D'Alessio+'10

KIC 8626021 (Kepler mission)

The luminosity function

Number of white dwarfs per unit of volume and magnitude versus luminosity

$$n(L) = \int_{M_l}^{M_u} \Phi(M)\Psi\left(T_G - t_{cool} - t_{ps}\right)\tau_{cool}\, dM$$

1.- n(L) is the observed distribution

2.- Φ,Ψ are the IMF and SFR respectively. T_G is the age of the Galaxy

3.- t_{cool} is the cooling time

t_{PS} is the lifetime of the progenitor

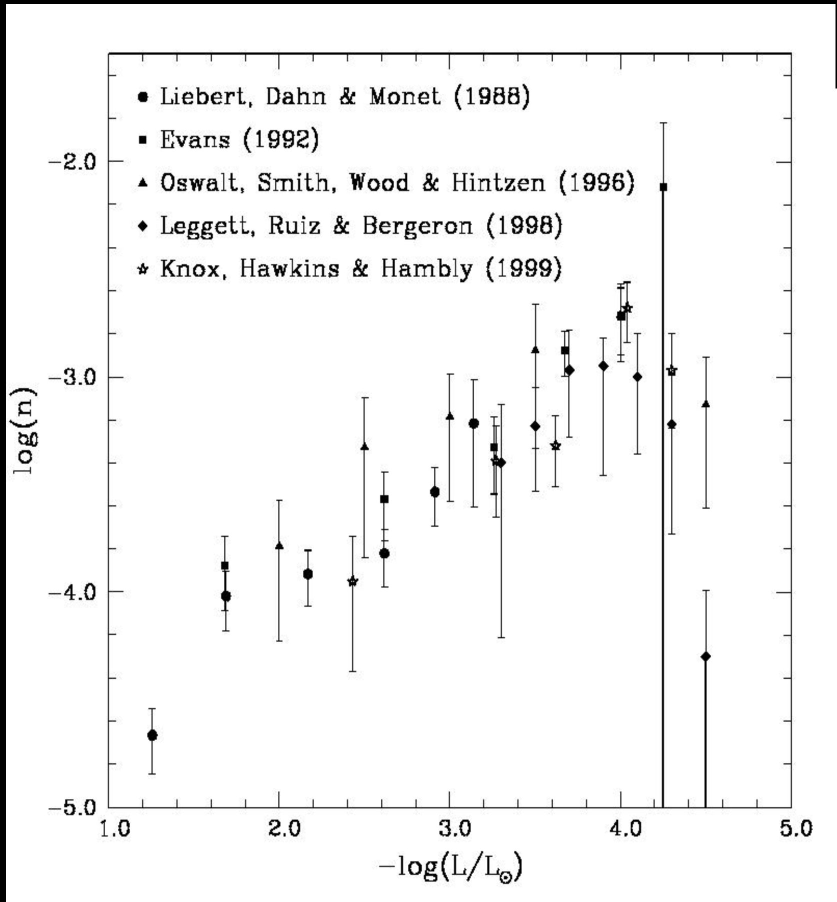
τ_{cool} is the characteristic cooling time

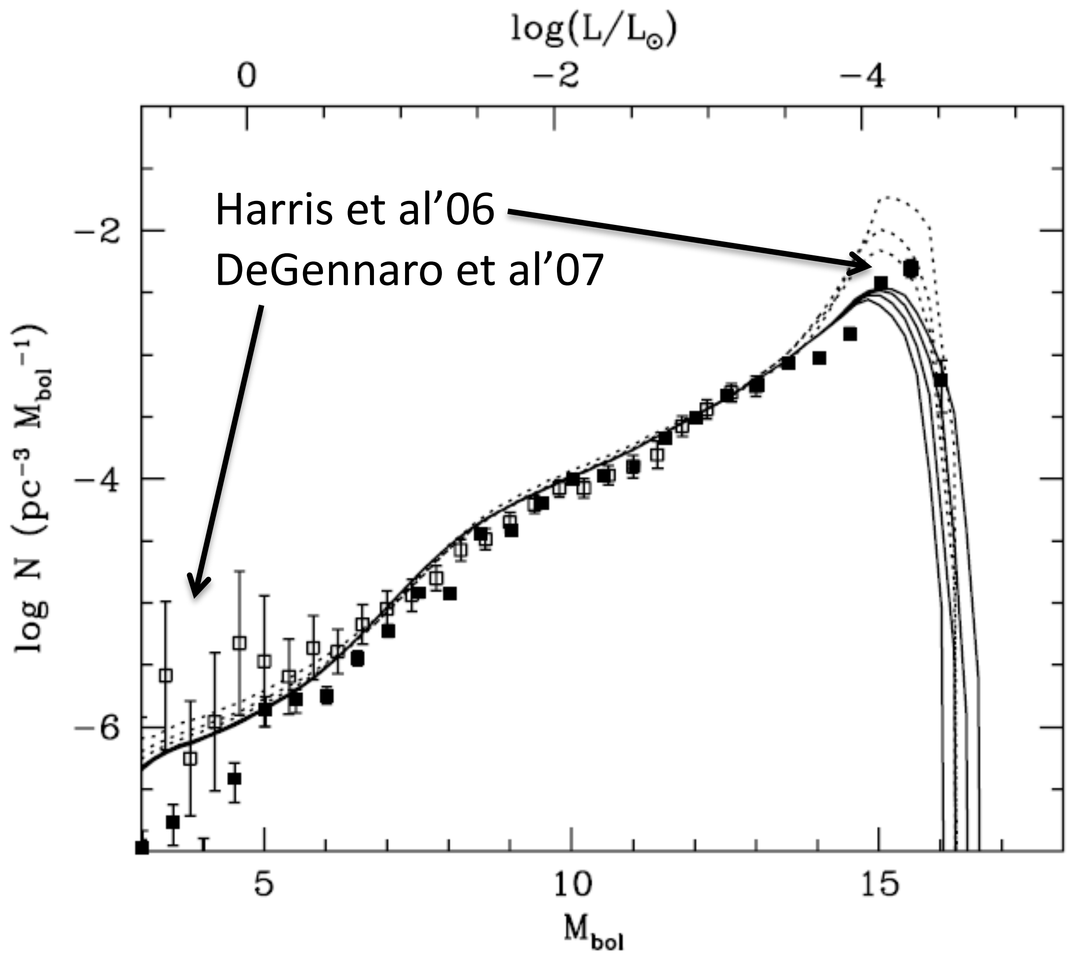
Hidden an IMFR

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

Surveys are more and more accurate and significative

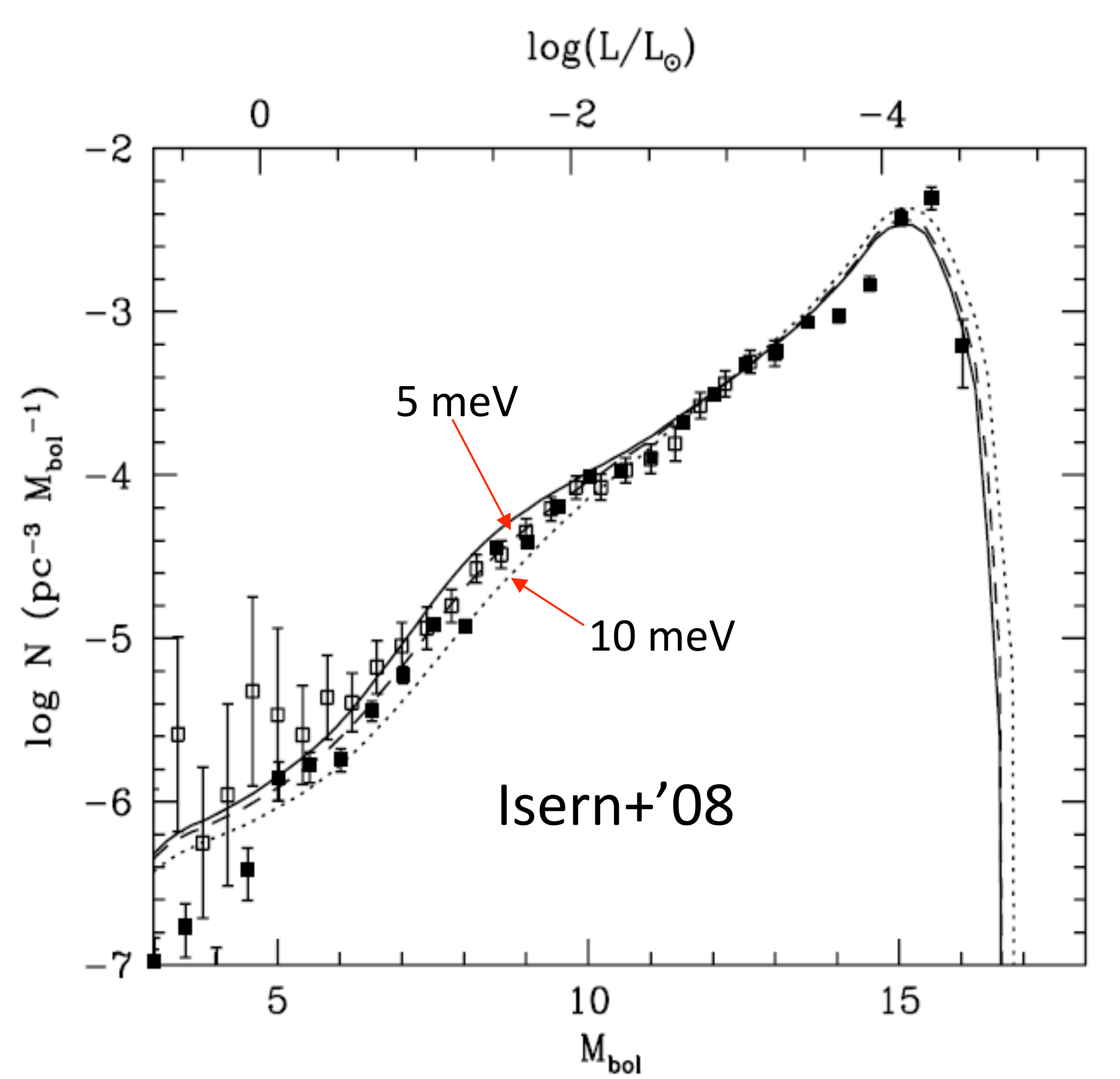
Sample of WD:
High precision LF

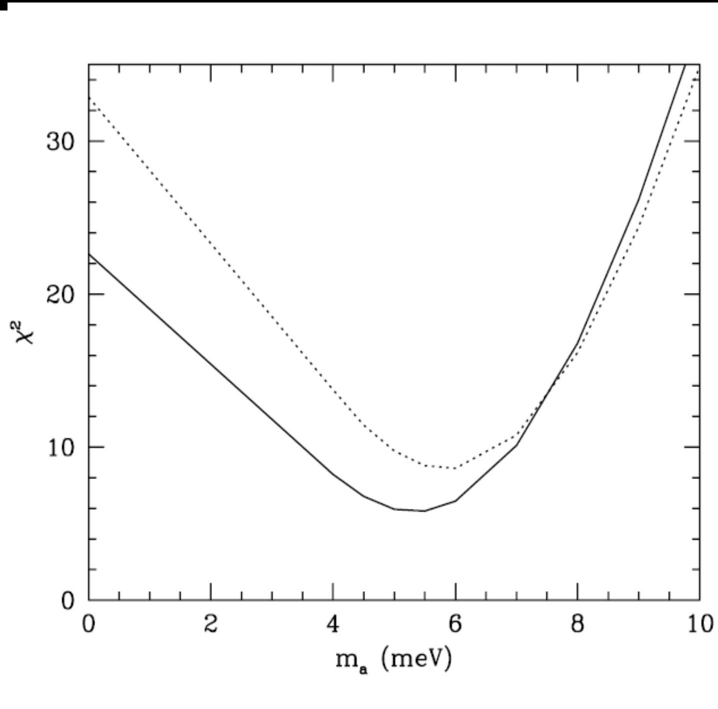




$$n(l) \propto \langle \tau_{cool} \rangle \int_{M_i}^{M_{max}} \Phi(M)\Psi(\tau)dM$$

Isern & Garcia-Berro'08





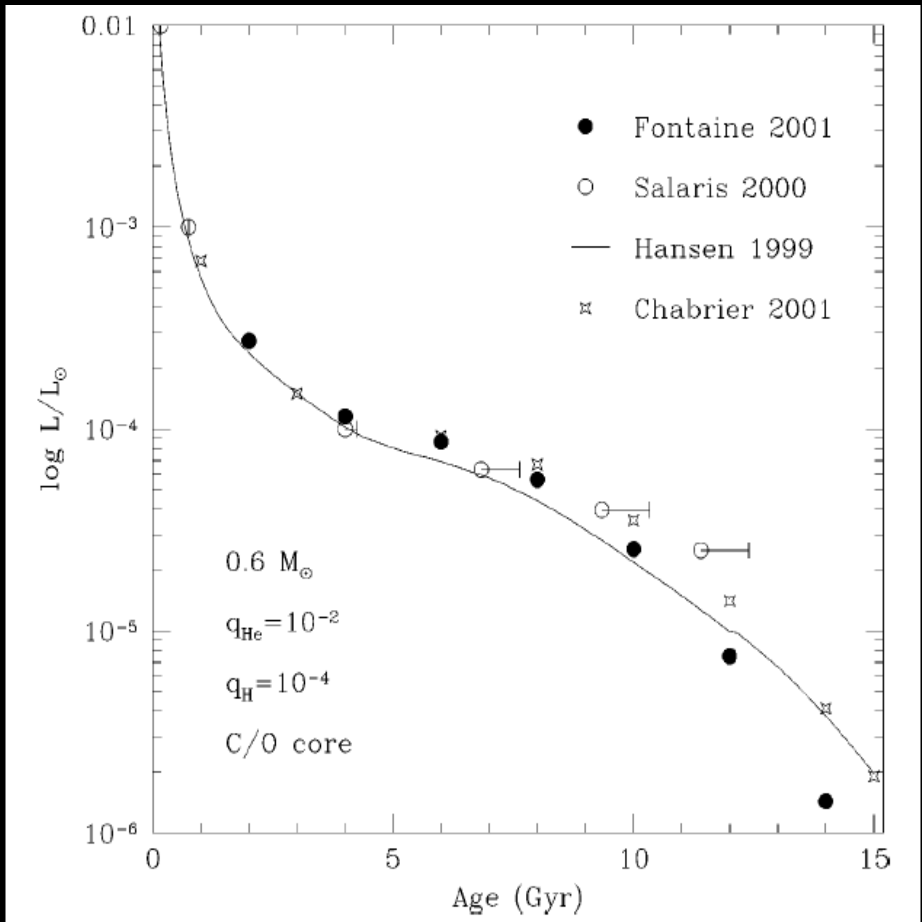
Many uncertainties:

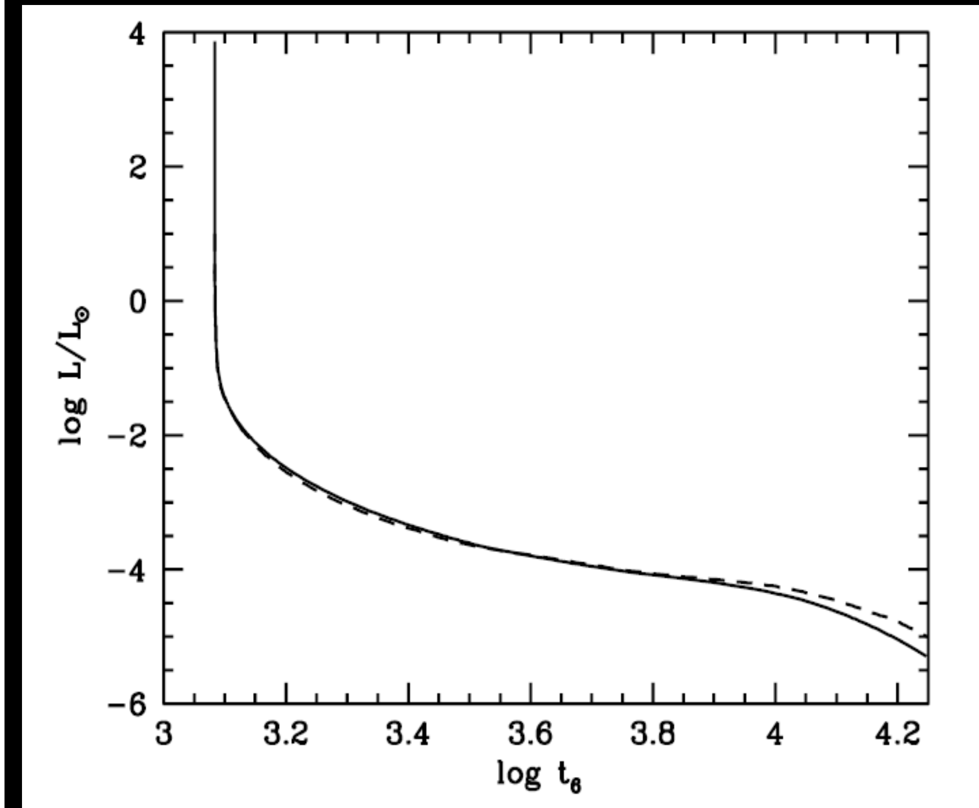
- Internal structure
- Emission rates
- Transparency of the envelope
- Initial-final mass relationship
- IMF
- Pathological SFR
- Ages of MS progenitors
- Metallicities
- ....

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

Models from Salaris+'00

Comparison between cooling models

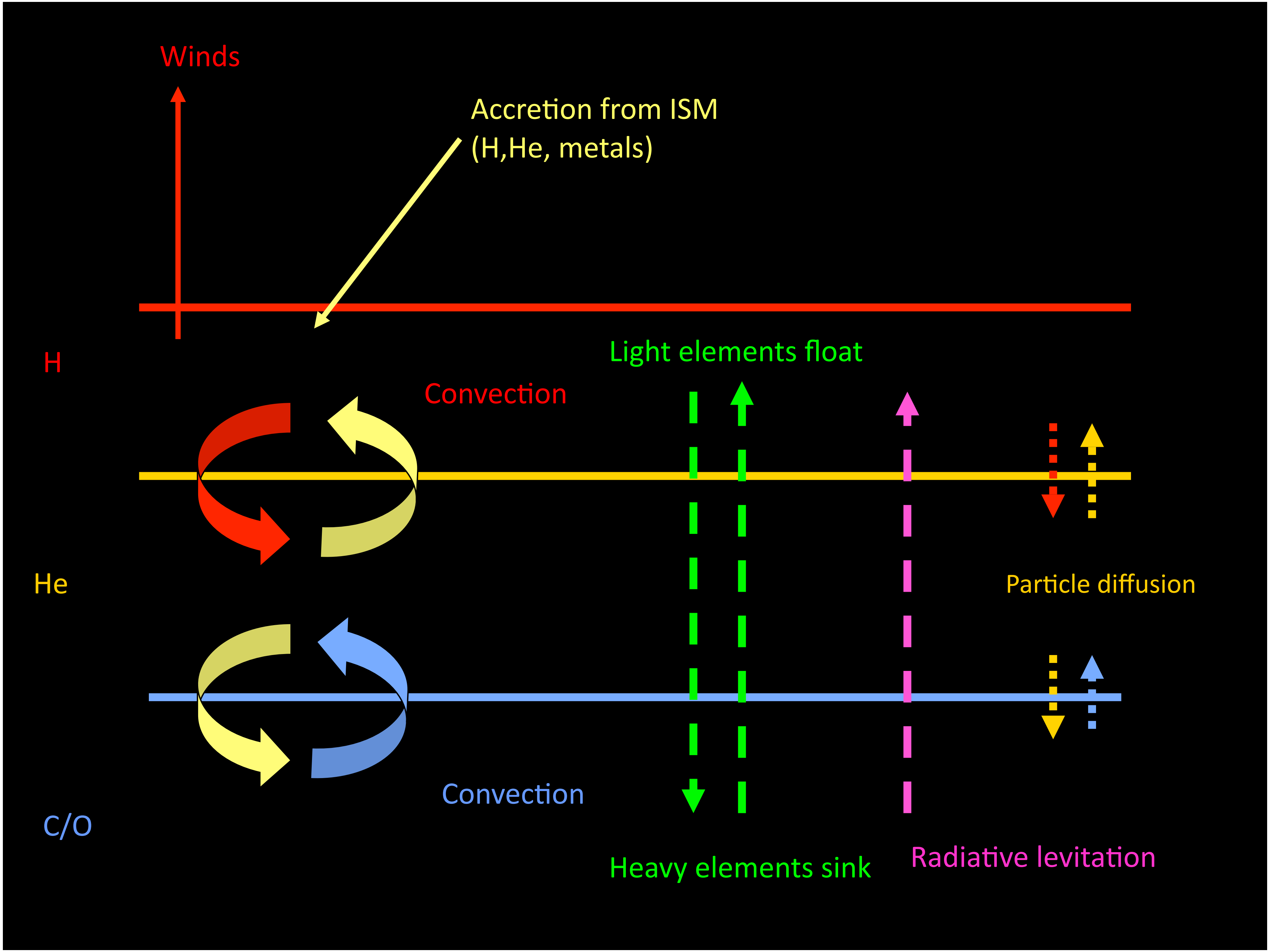




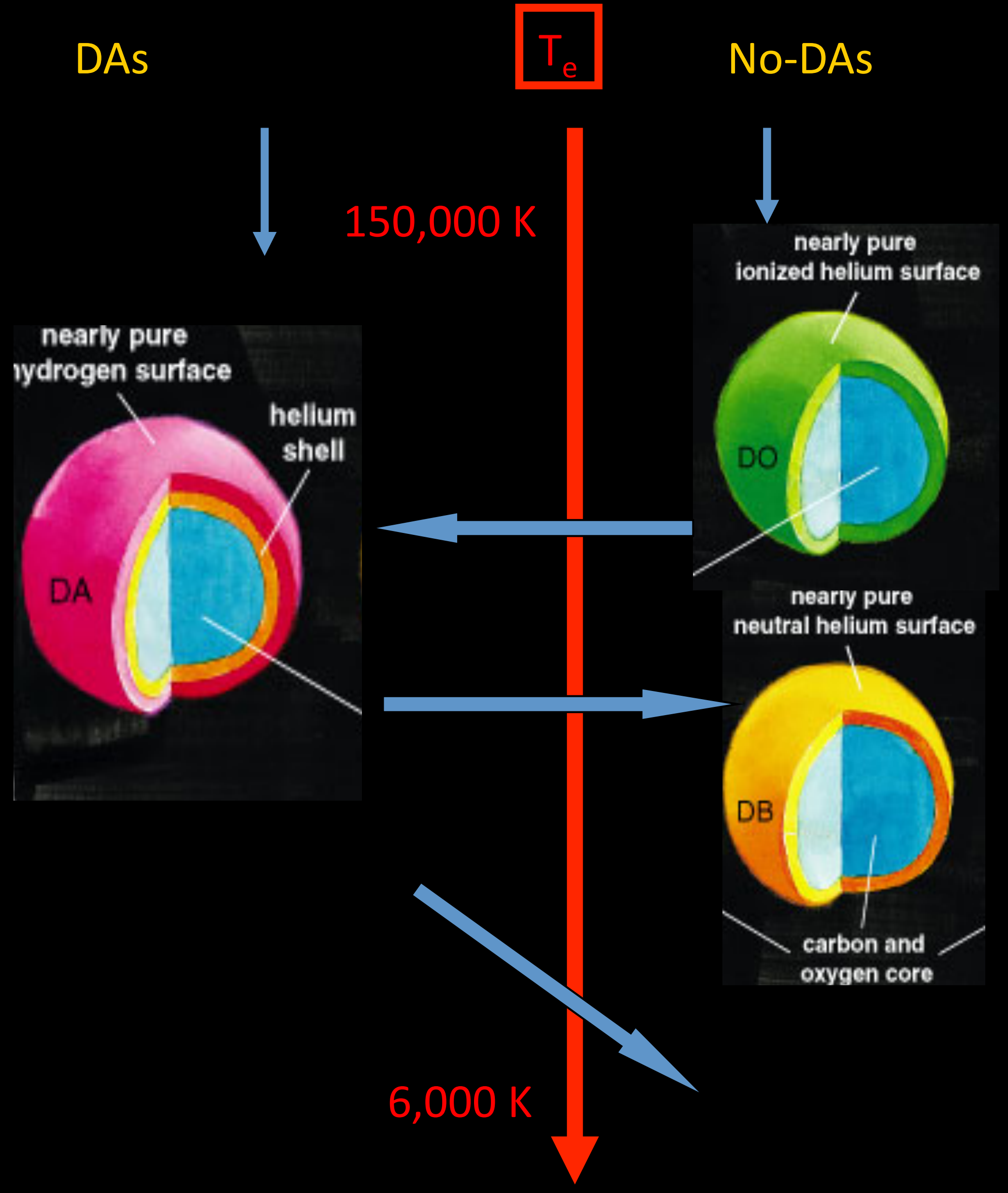
Hansen & Liebert'03

___: Renedo et al 2010

---- : Salaris et al 2010


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



<u>The H layer:</u>

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

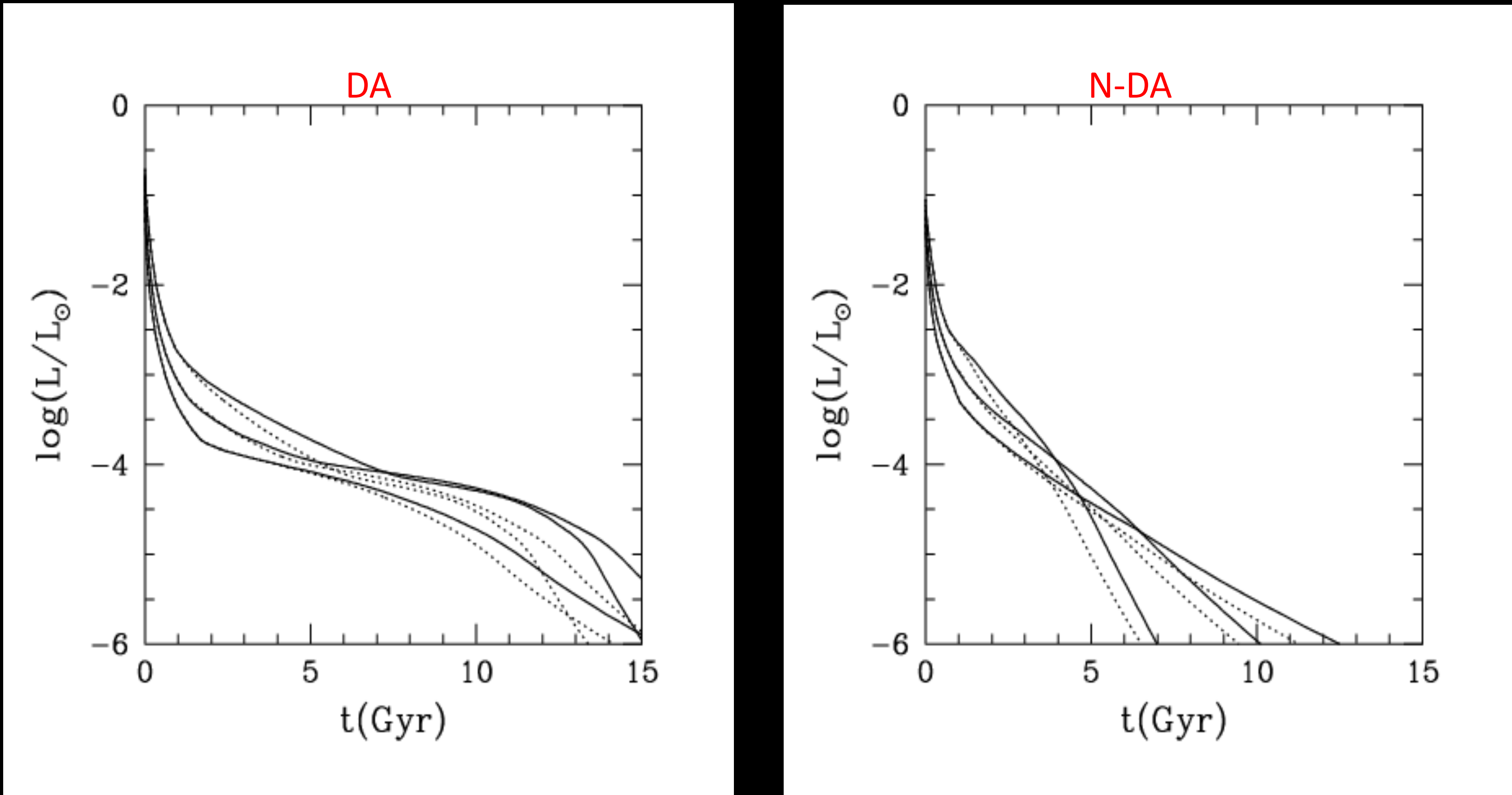
<u>The He layer</u>

- 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)



DA, non-DA influence

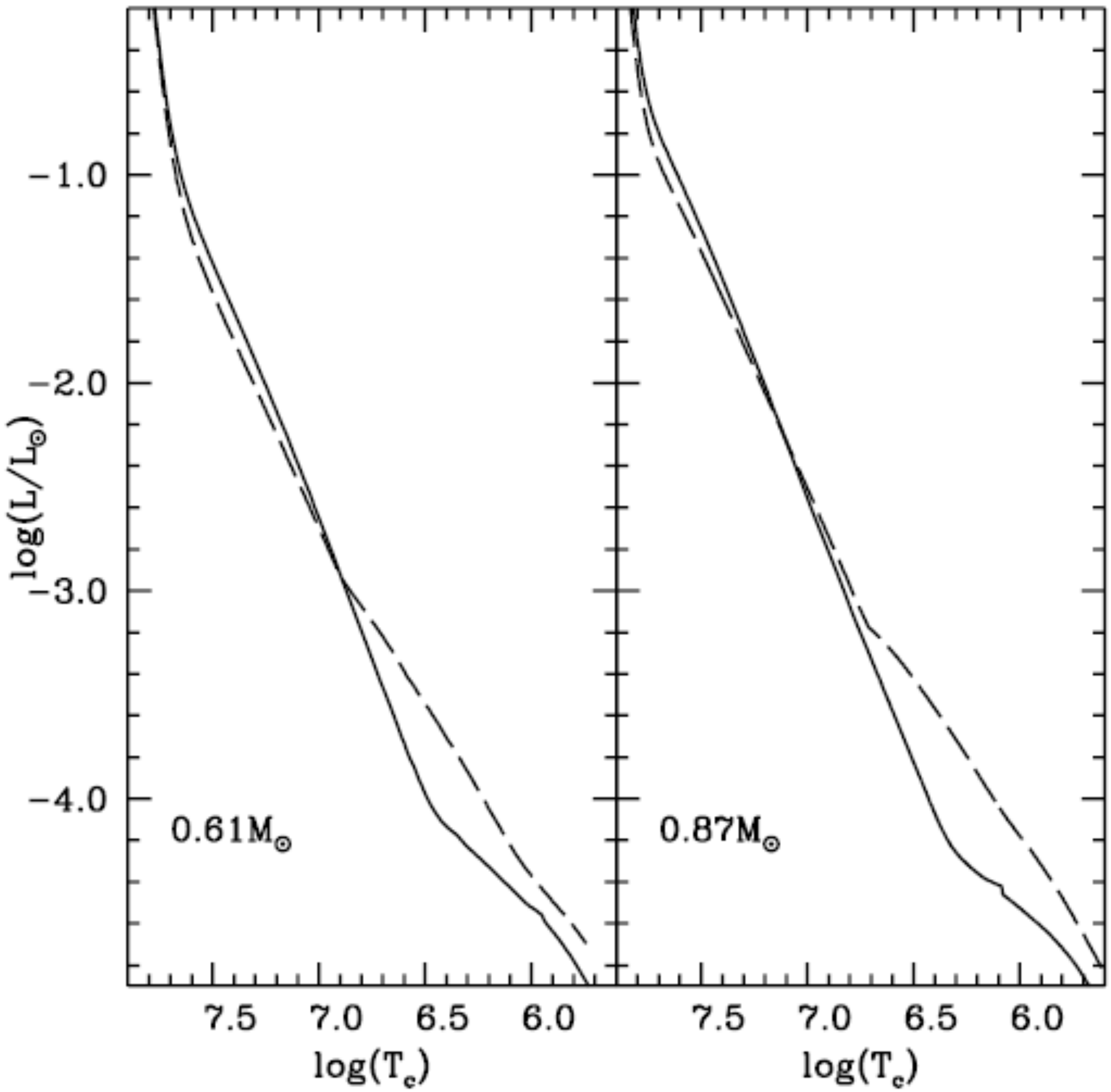


Fig. 1.— $L - T_c$ relationships for our 0.61 and 0.87 $M_\odot$ WD models (with phase separation not included). Solid lines denote H-atmosphere models, dashed lines He-atmosphere ones.

Assume that:

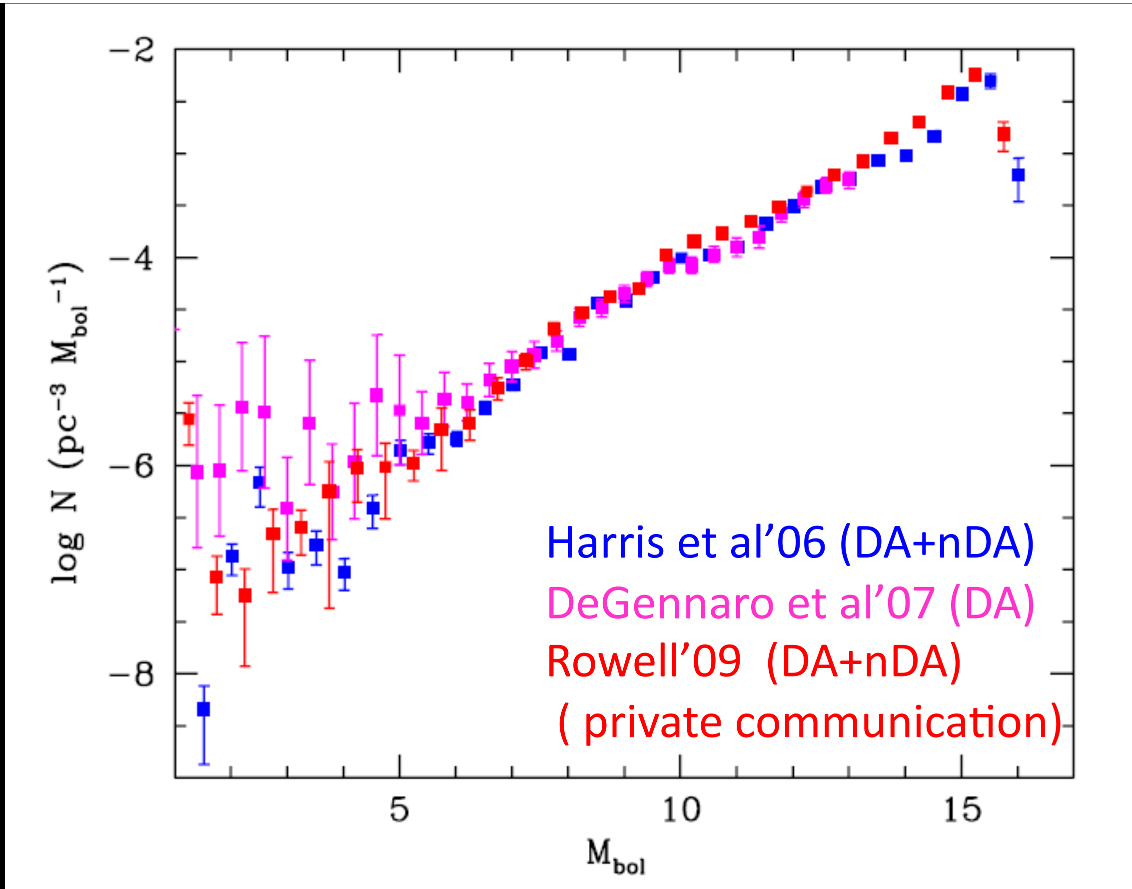
$$L = gT_C^\gamma$$

From the figure we see that:

$$\gamma_{DA} \approx \gamma_{nDA}$$

in the range

$$-3 \leq \log L \leq -1$$

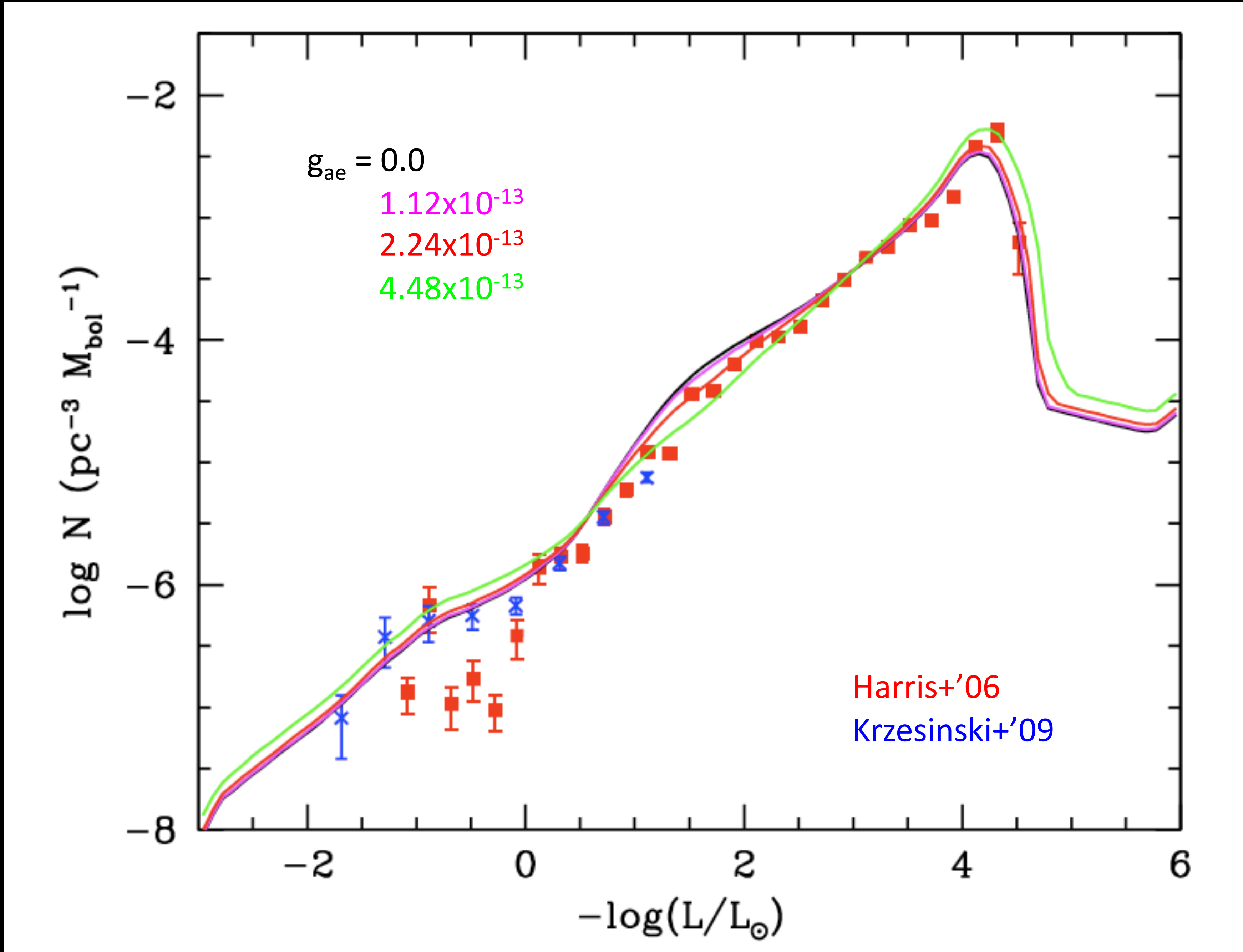


Since $\gamma_{DA} \approx \gamma_{nDA}$ the luminosity function of Das and nDAs coincide after normalization

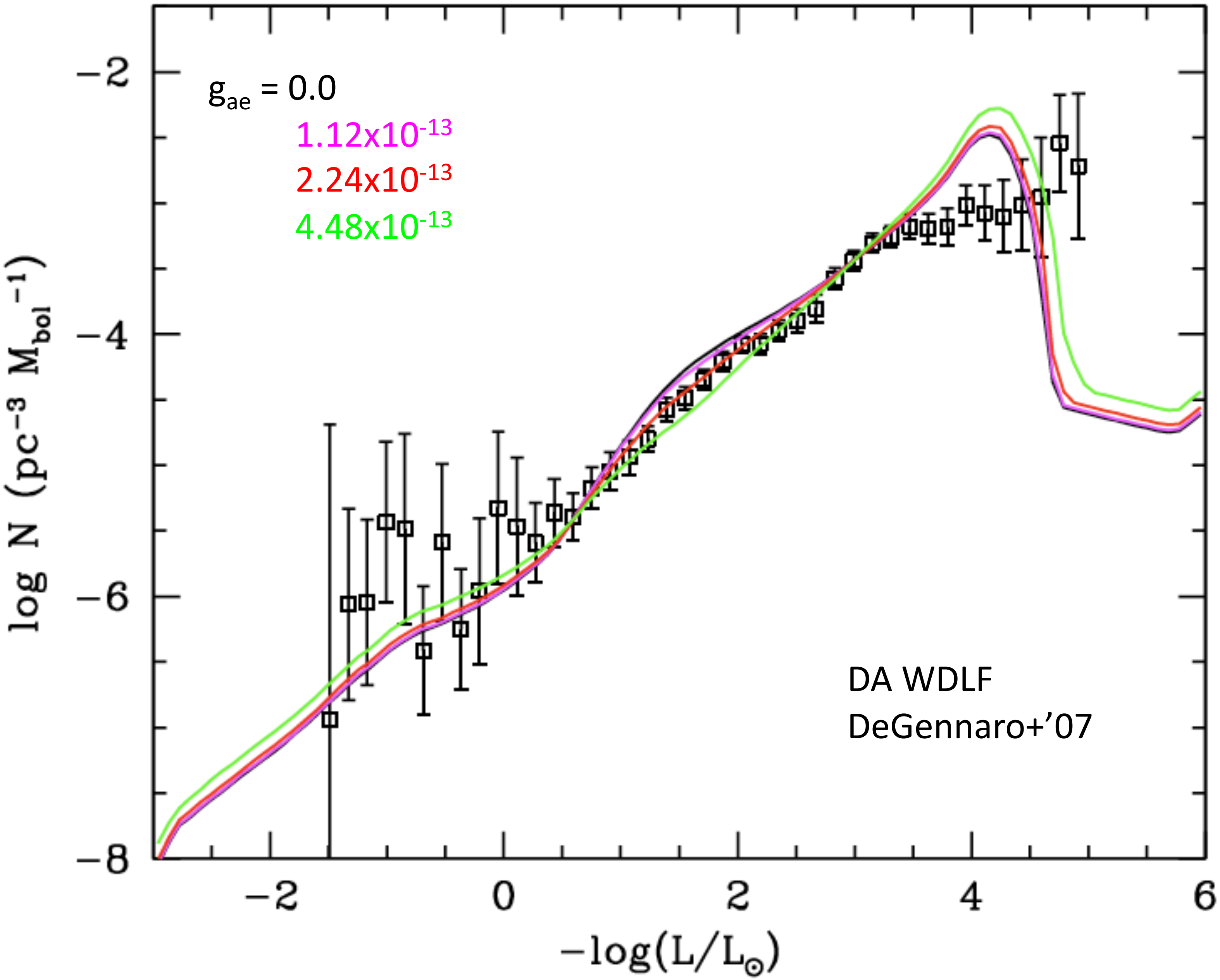
$$L \approx -\frac{dU}{dt} \approx -C_V \frac{dT_C}{dt} \text{ (we neglect the compression term)}$$

$$\frac{dL}{dt} = \gamma g T_C^{\gamma-1} \frac{dT_C}{dt} \text{ (from the L-}T_C\text{ relationship)}$$

$$N_{WD} \propto \dot{l}^{-1} = -\frac{L}{dL/dt} = \frac{C_V}{\gamma g} T_C^{1-\gamma}$$



g_ae = 0.0
1.12x10^-13
2.24x10^-13
4.48x10^-13
Harris+'06
Krzesinski+'09
log N (pc^-3 M_bol^-1)
−log(L/L⊙)
−2
−4
−6
−8
−2
0
2
4
6



g_ae = 0.0
1.12x10^-13
2.24x10^-13
4.48x10^-13
DA WDLF
DeGennaro+'07
log N (pc^-3 M_bol^-1)
−log(L/L_⊙)
−2
−4
−6
−8
−2
0
2
4
6

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 down more quickly than expected .

Axions or light bosons able to couple to electrons could account for this discrepancy ($g_{ae} \sim 2\text{-}5 \times 10^{-13}$)

The results seem robust (for the moment) but more refinements are needed:

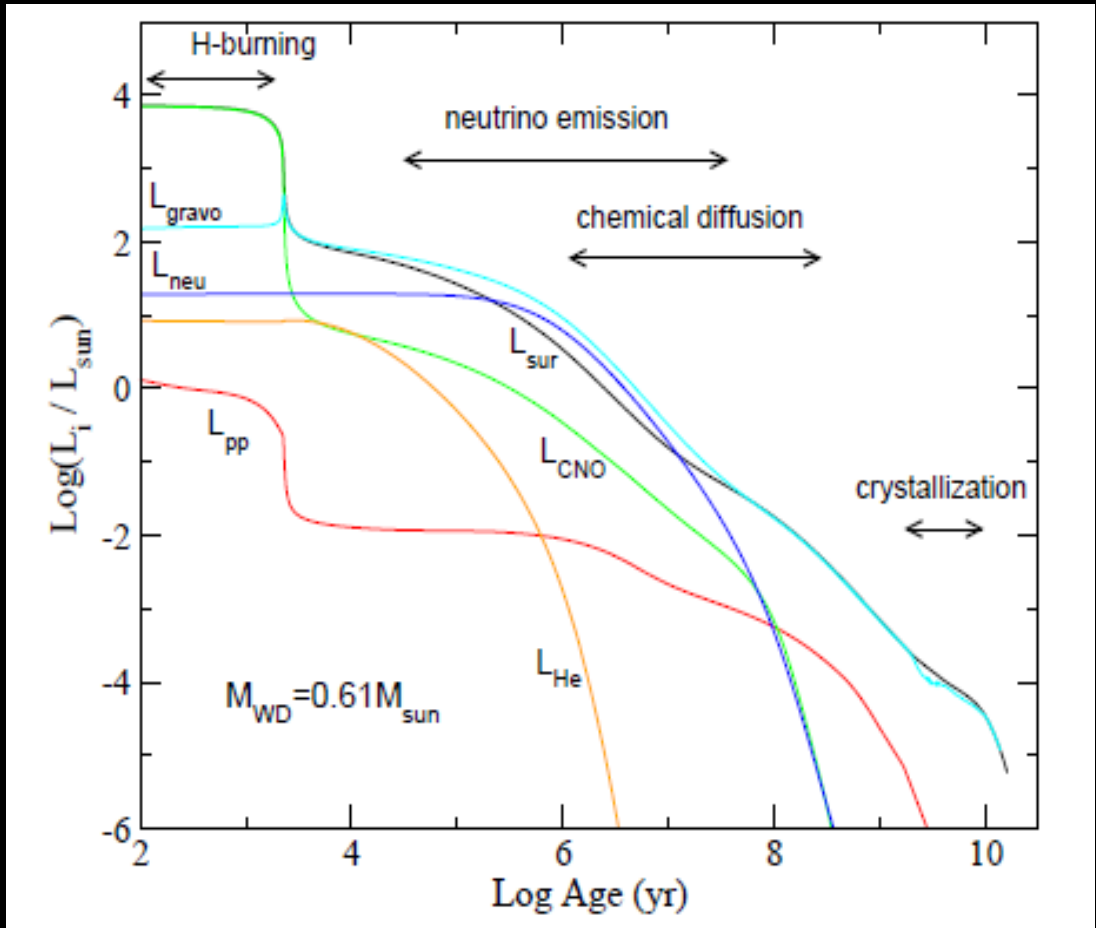
* Extend the observational LF to high and low luminosities
* Obtention of the LF for massive white dwarfs
* Improvement of the cooling models. Envelope is crucial
* Role of binaries

This method can be used in other problems

GAIA & LSST can provide the necessary precision & accuracy

Suplementary information

The cooling process (I)



Althaus+'10

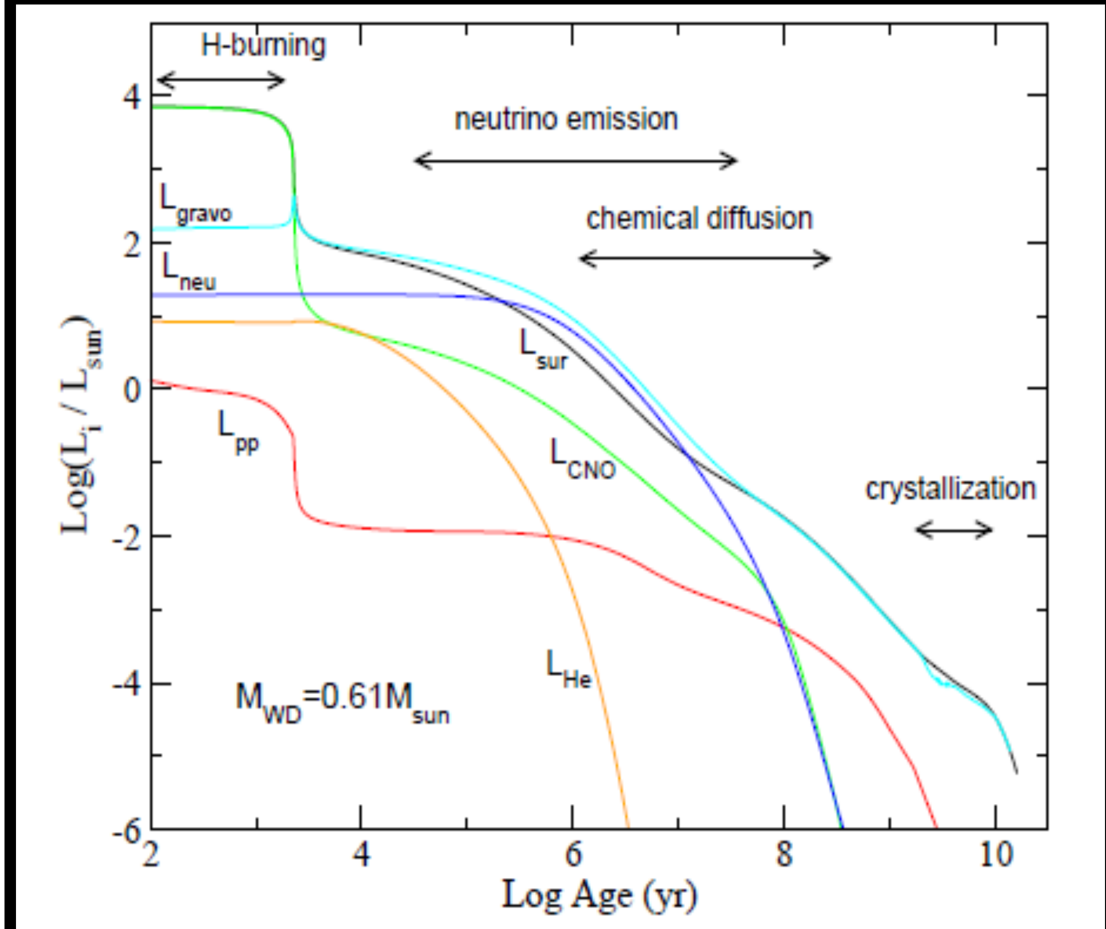
Neutrino cooling [$\log(L/L_o) > -1.5$]

Is the must complicated phase because the initial conditions are unknown.

Neutrinos dominate & thermal structures converge

Very short epoch (< 10^8 yr)

The cooling process (II)



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:

$^{12}C(\alpha,\gamma)^{16}O$ reaction ,

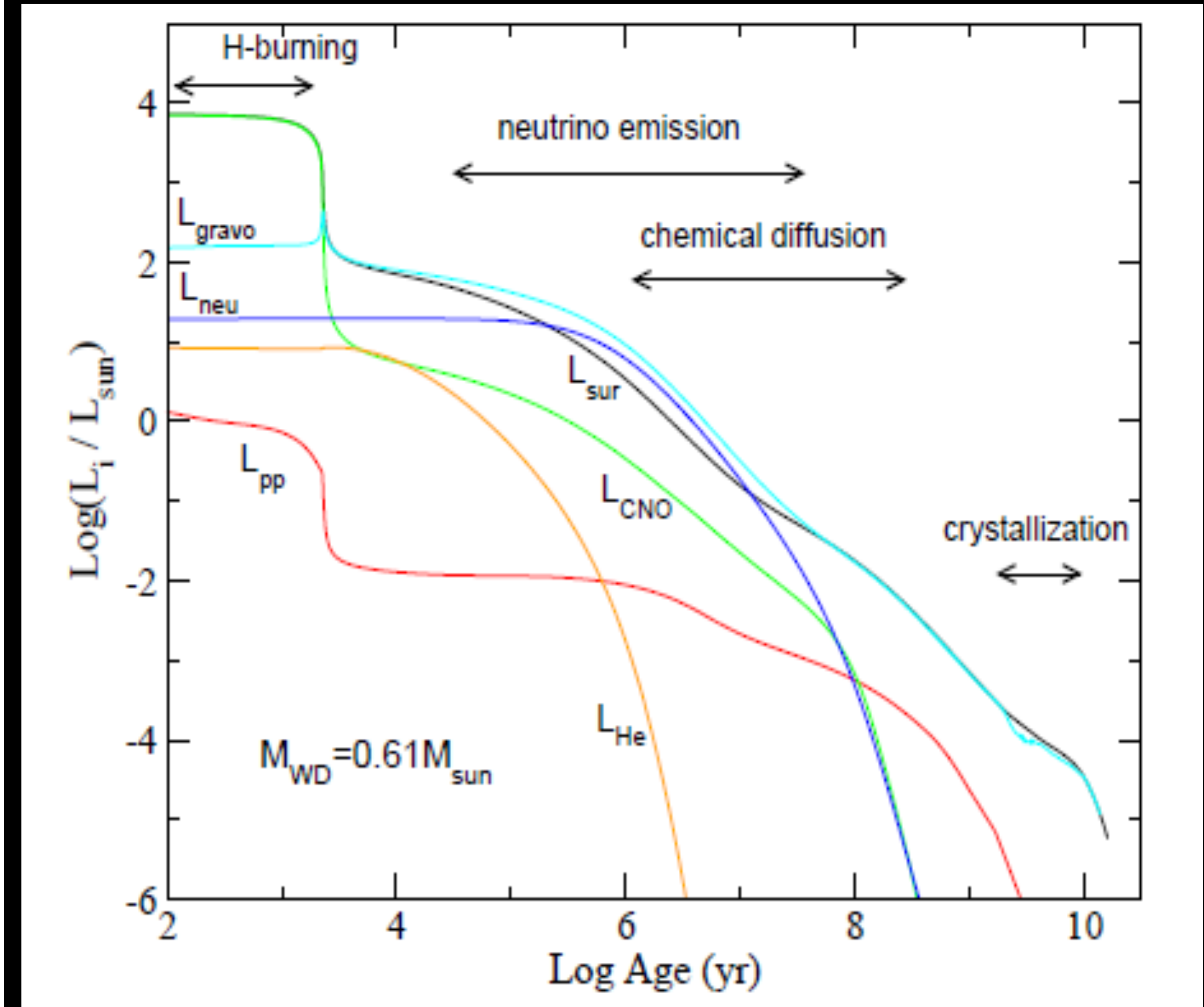
metallicity

treatment of convection

mass of the progenitor

The cooling process (III)

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

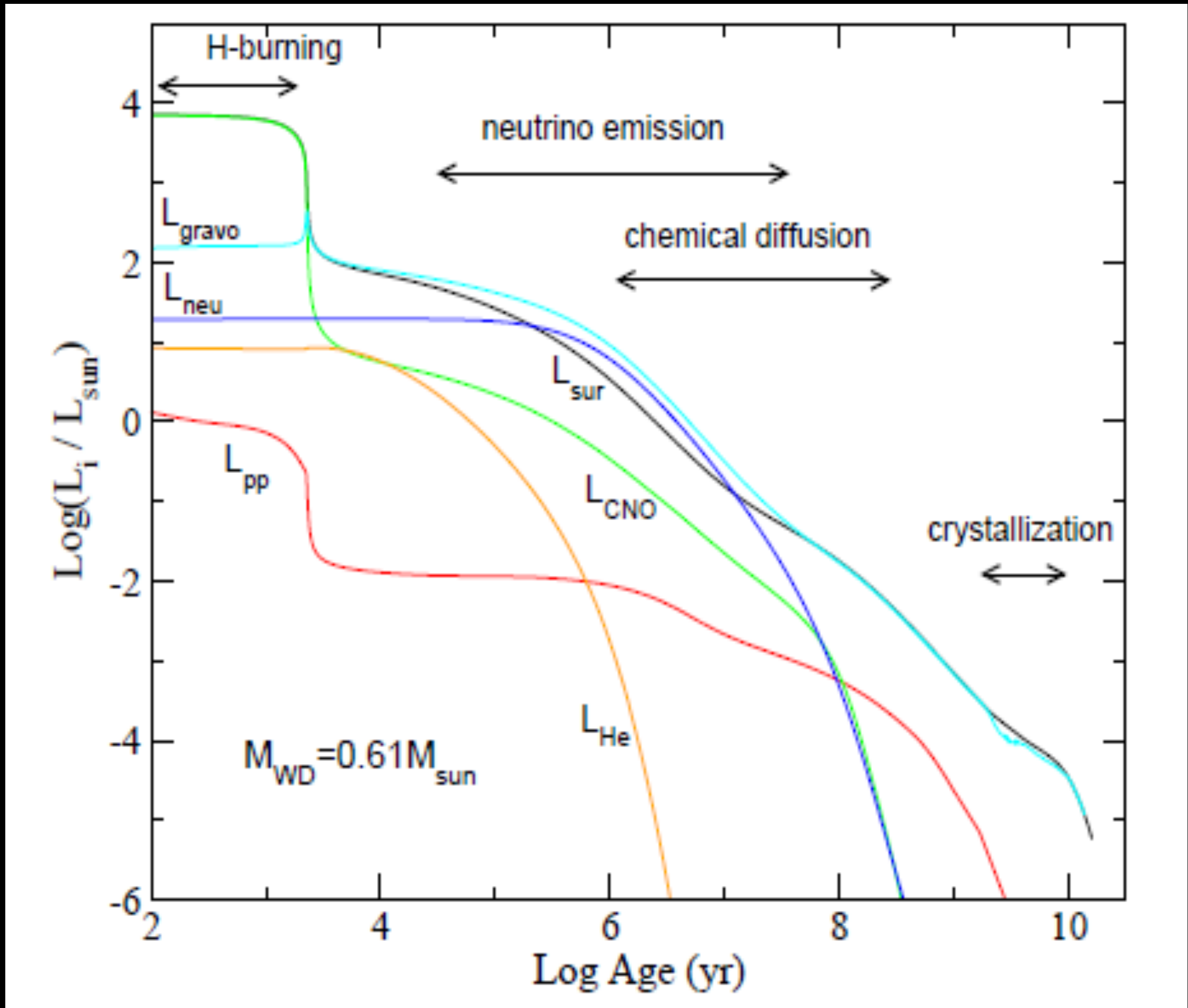


Latent heat
(≈ kT_s per particle)

Sedimentation upon crystallization that depends on the chemical profile and phase diagrams

The cooling process (IV)

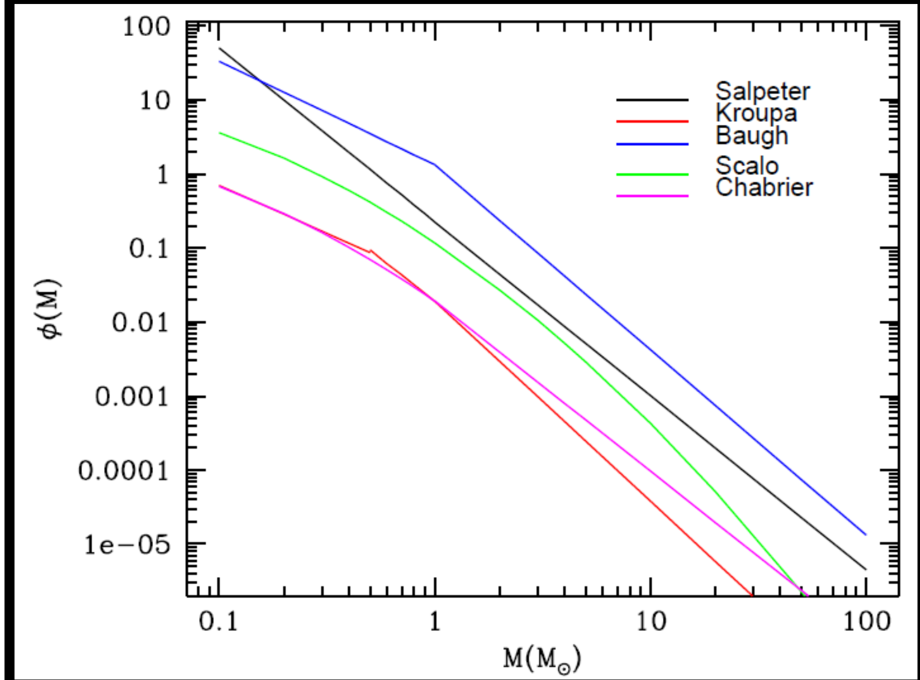
Debye cooling [-4.5 > log(L/L_o)]



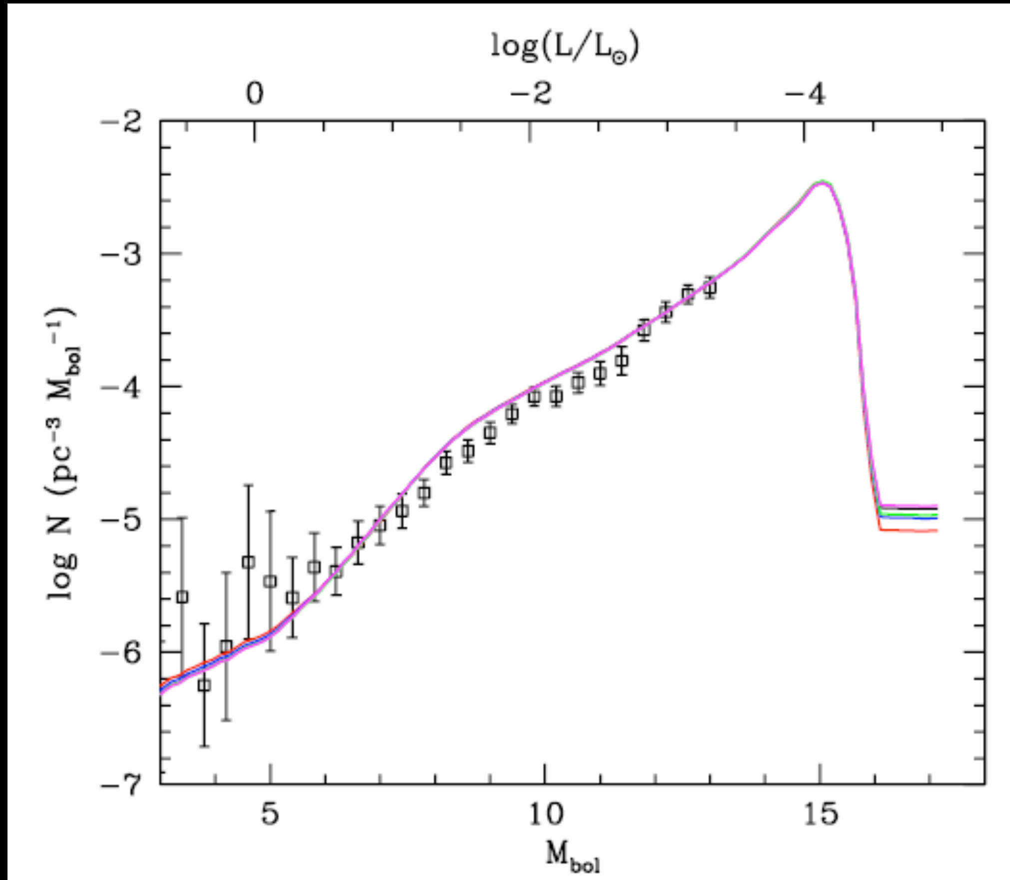
At low temperatures, the specific heat follows the Debye law

Compression of outer layers is the main source of energy & prevents the sudden disappearance of the white dwarf

Dependence on the IMF

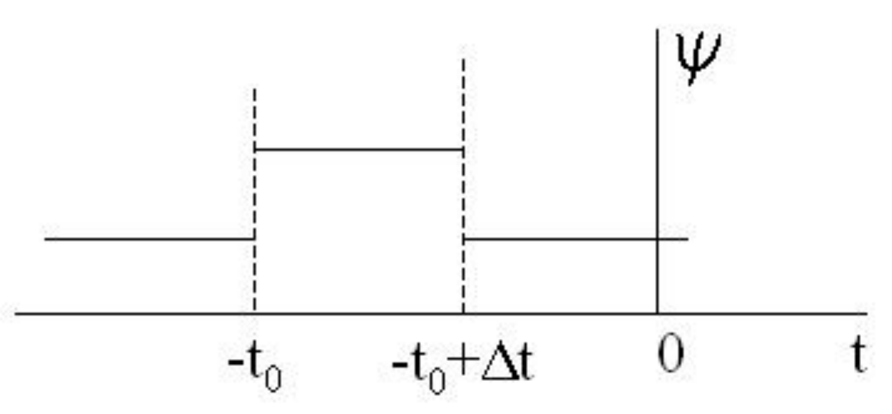


SFR=1 and the age=11 Gyr



The WDLF is not very dependent on the IMF as far as low mass stars are effectively produced.

Influence of the SFR

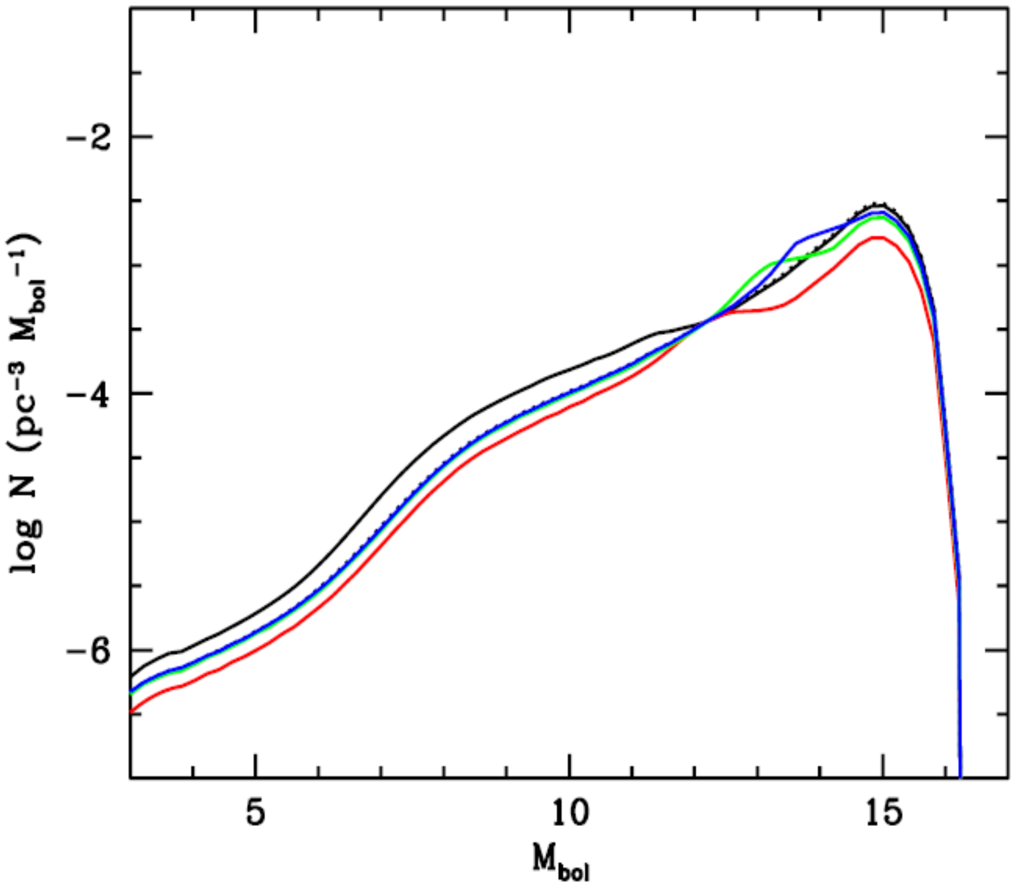


If the peak coincides with the normalization (red line) the bright branch falls below the standard

T_0	Color
0 (no bump)	Black dotted
-1	Black
-2	red
-3	Green
-4	Blue

$\psi = 3$, if $t_0 < t < t_0 + \Delta t$

$\psi = 1$, if $t < t_0$; $t > t_0 + \Delta t$

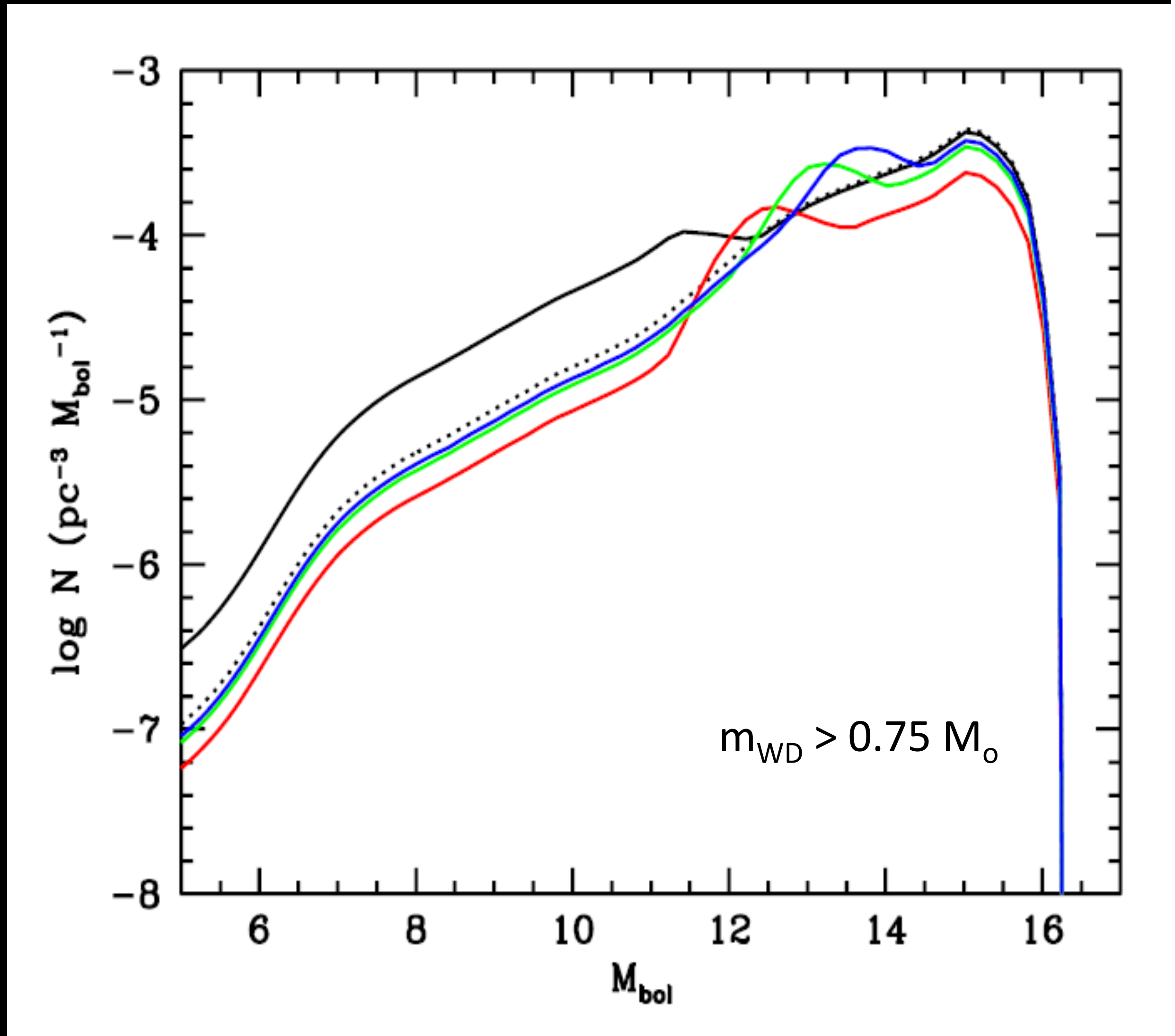


$$n(l) = \int_{M_{\min}}^{M_{\max}} \Phi(M)\Psi\left(T_{gal} - t_{cool} - t_{SP}\right)\tau_{cool}\, dM$$

In the case of massive WD

$$t_{SP} \ll t_{cool}$$

$$n(l) \propto \Psi\left(T_{gal} - t_{cool}\right)$$

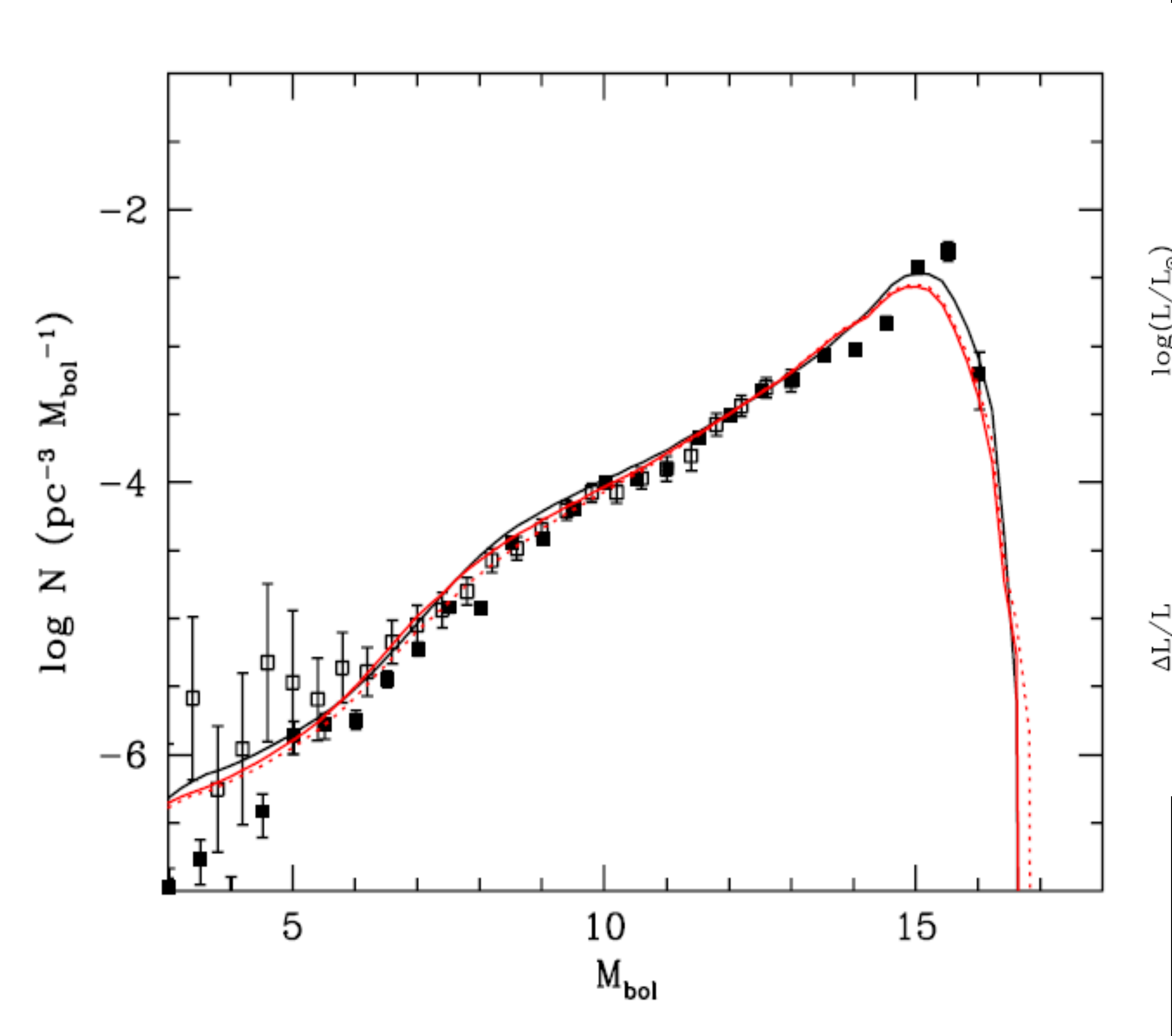


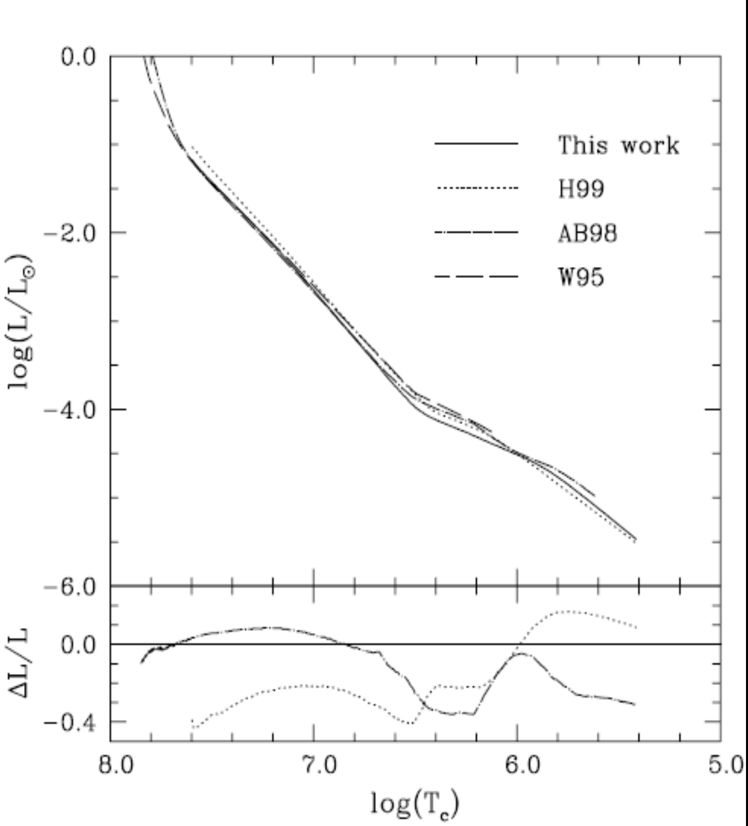
The luminosity function of massive WD closely follows the SFR.

Irregularities are detectable!

INFLUENCE OF THE ATMOSPHERE

Salaris et al 2000





$M_{He}/M_* = 10^{-2}$

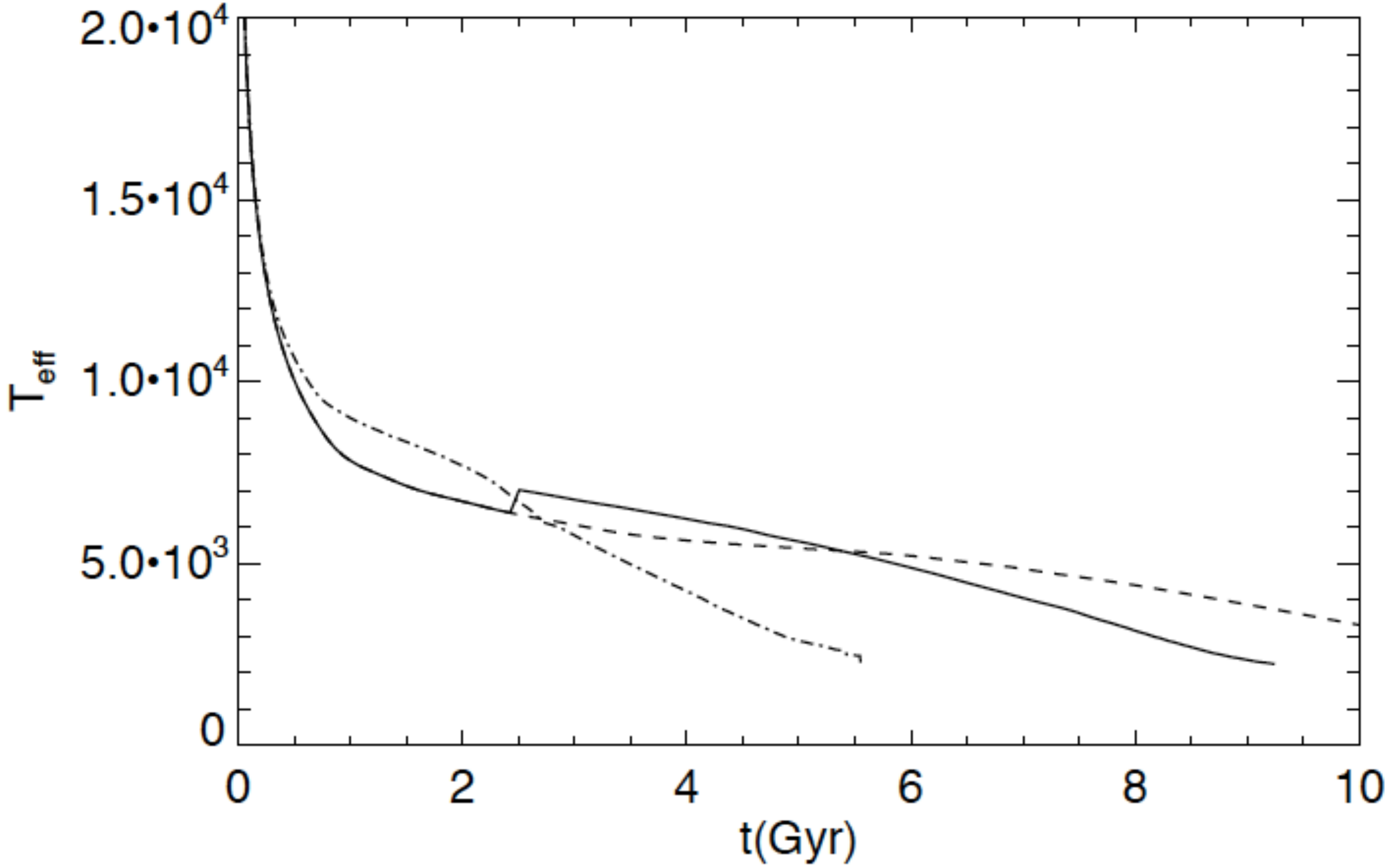
$M_H/M_* = 10^{-4}$

Models should be noticebly more luminous to mimic the extra cooling introduced by axions.

The evolution of the envelope is crucial!

Cheng & Hansen'11

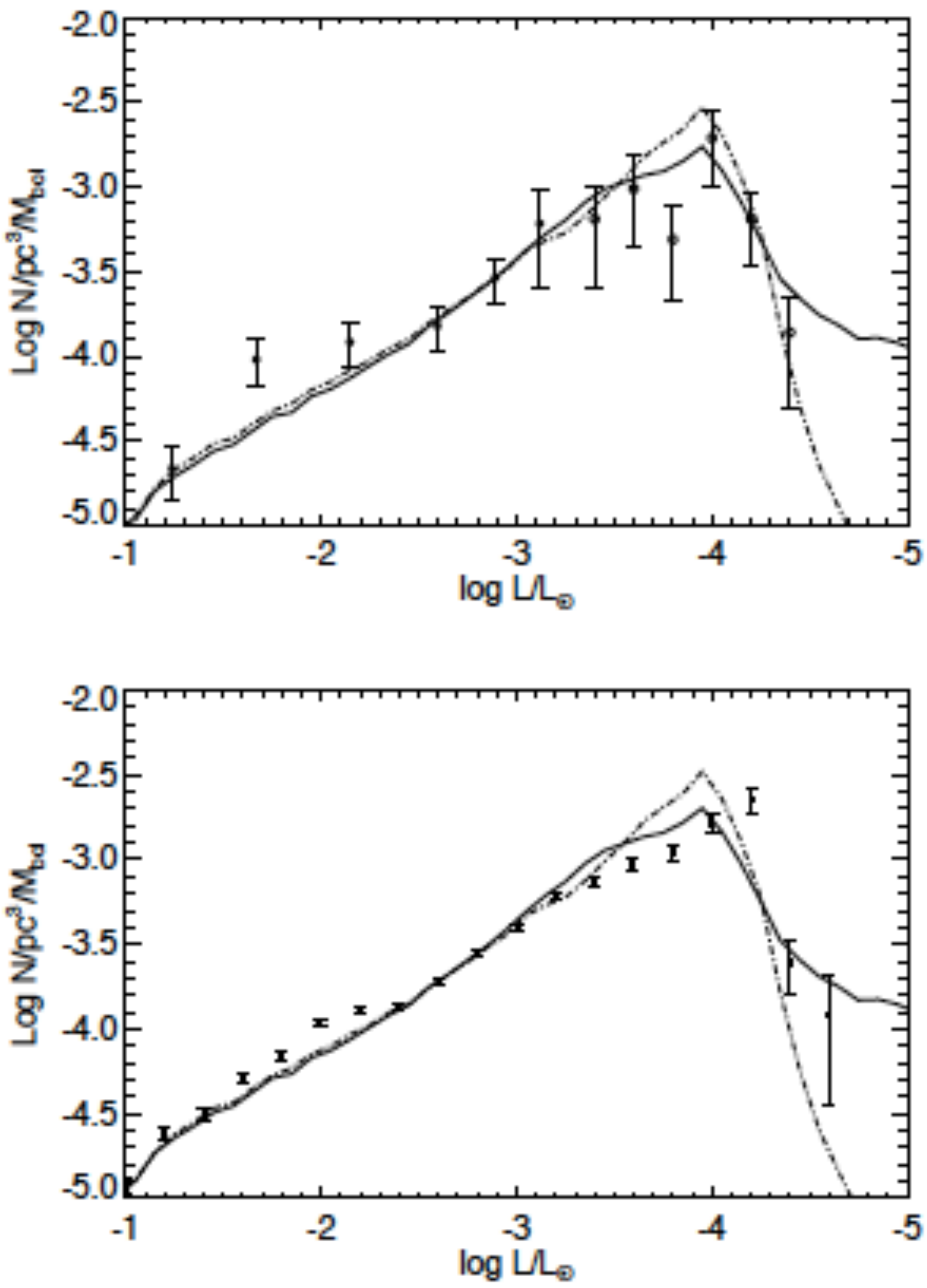
Thick WD (53%) $M_H \sim 10^{-4} M_*$ (dashed line)
Thin WD (32%) $M_H \sim 10^{-8} M_*$ (solid line)
He WD (15%) $M_H \sim 0 M_*$ (dot-dashed)



Cheng & Hansen'12
Solid line: mixture WD
Dash-dotted: thick H WD

Upper figure:
Solid circle: Liebert+'88
Hollow circle: Legget+'98

Lower figure:
Harris+'06



Influence of binaries:

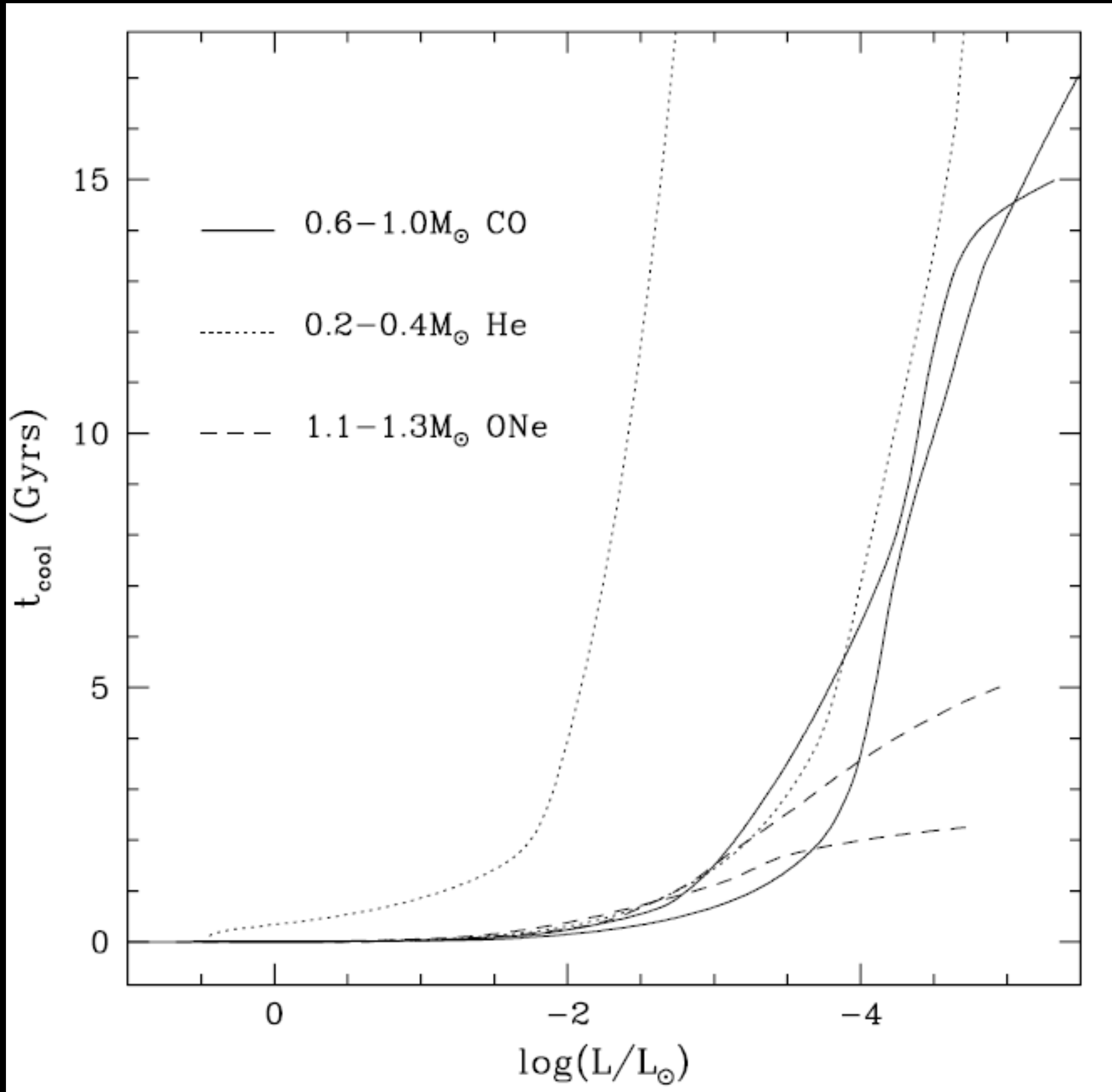
Presence of He-white dwarfs

Mergers

Tidal heating

Non resolved binaries

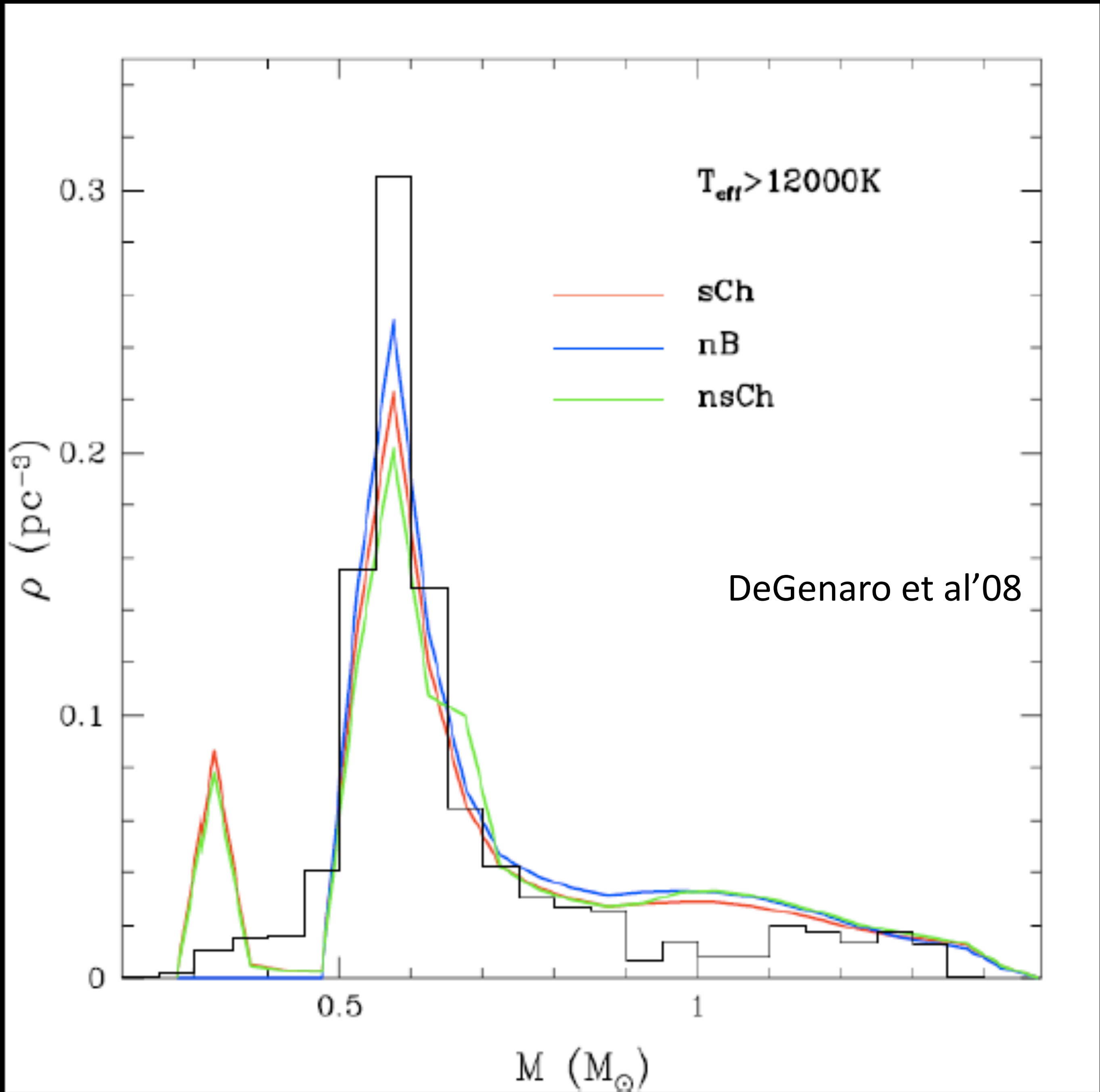
Contamination by He-WD



Birthrate calculation

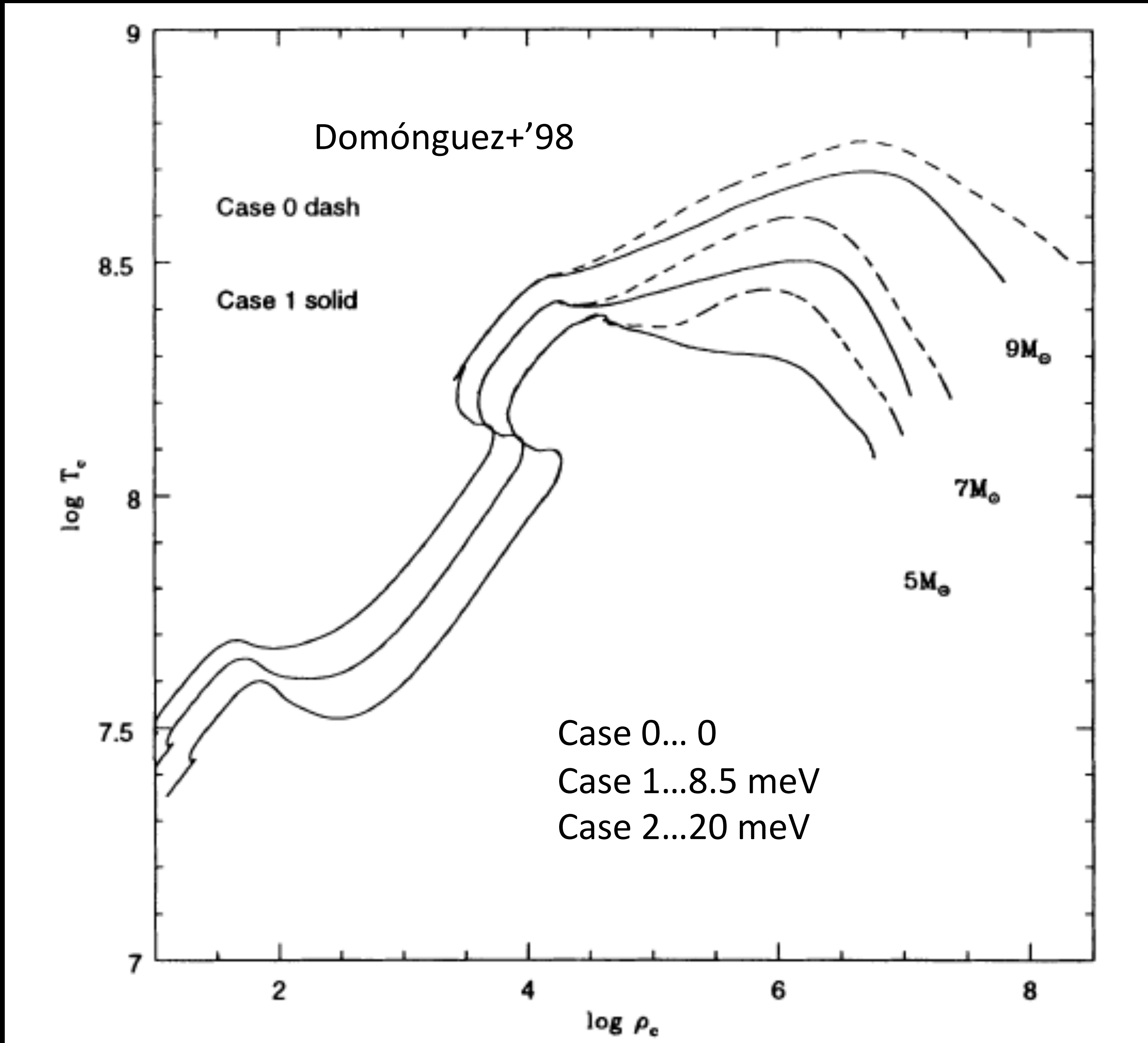
Isern et al,
Thermonuclear Supernovae,
Ed. Ruiz-Lapuente, Canal, Isern,
Kluwer p. 127 (1997)

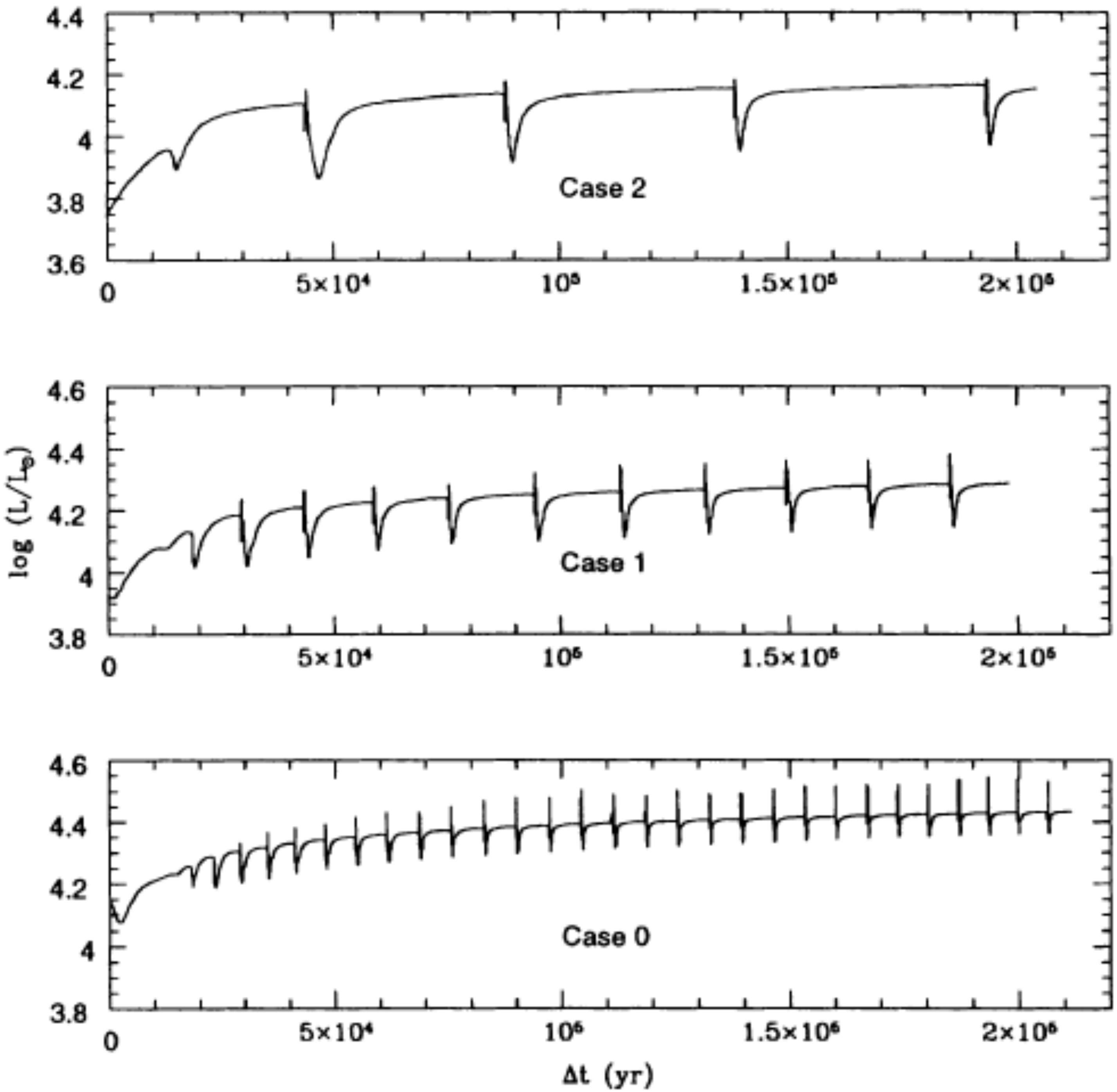
- Only evolutionary channels in which RLOF occurs when the envelope is convective
- Models obtained with FRANEC. Solar metallicity
- WD cooling models from Salaris et al 2000
- Catalán et al (2008) IFMR
- Common envelope treatment: Iben & Tutukov (1984)
- Magnetic breaking
- Salpeter's IMF for the primary,
- $F(q) \propto q$; $q = M_2/M_1$
- Distribution of initial separations: $H(A_0) \propto 1/A_0$
- During the merging ALL the mass of the secondary is transfered to the primary



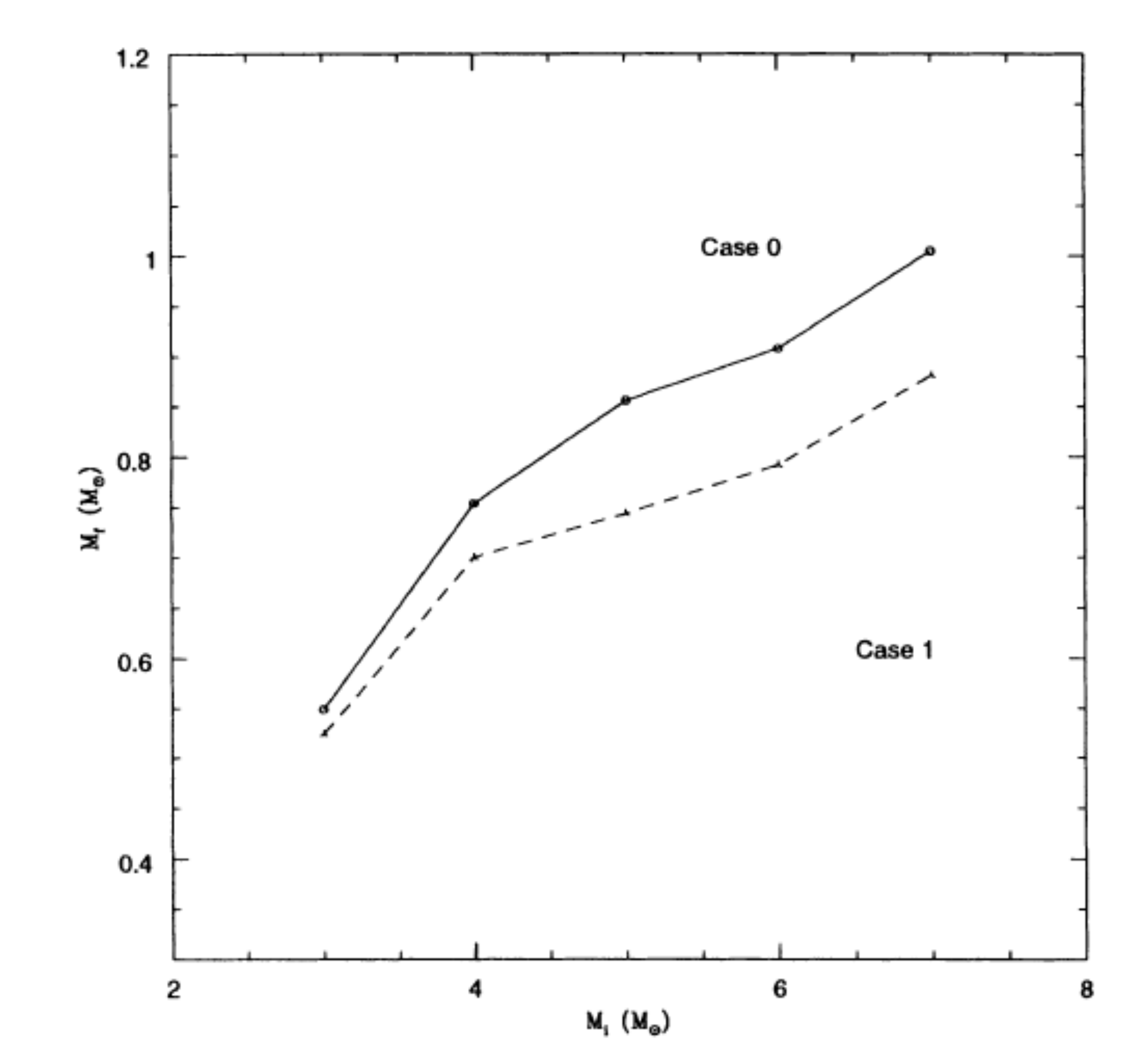
T_eff>12000K
sCh
nB
nsCh
ρ (pc⁻³)
0.3
0.2
0.1
0
0.5
1
M (M⊙)
DeGenaro et al'08

Influence on the previous evolution



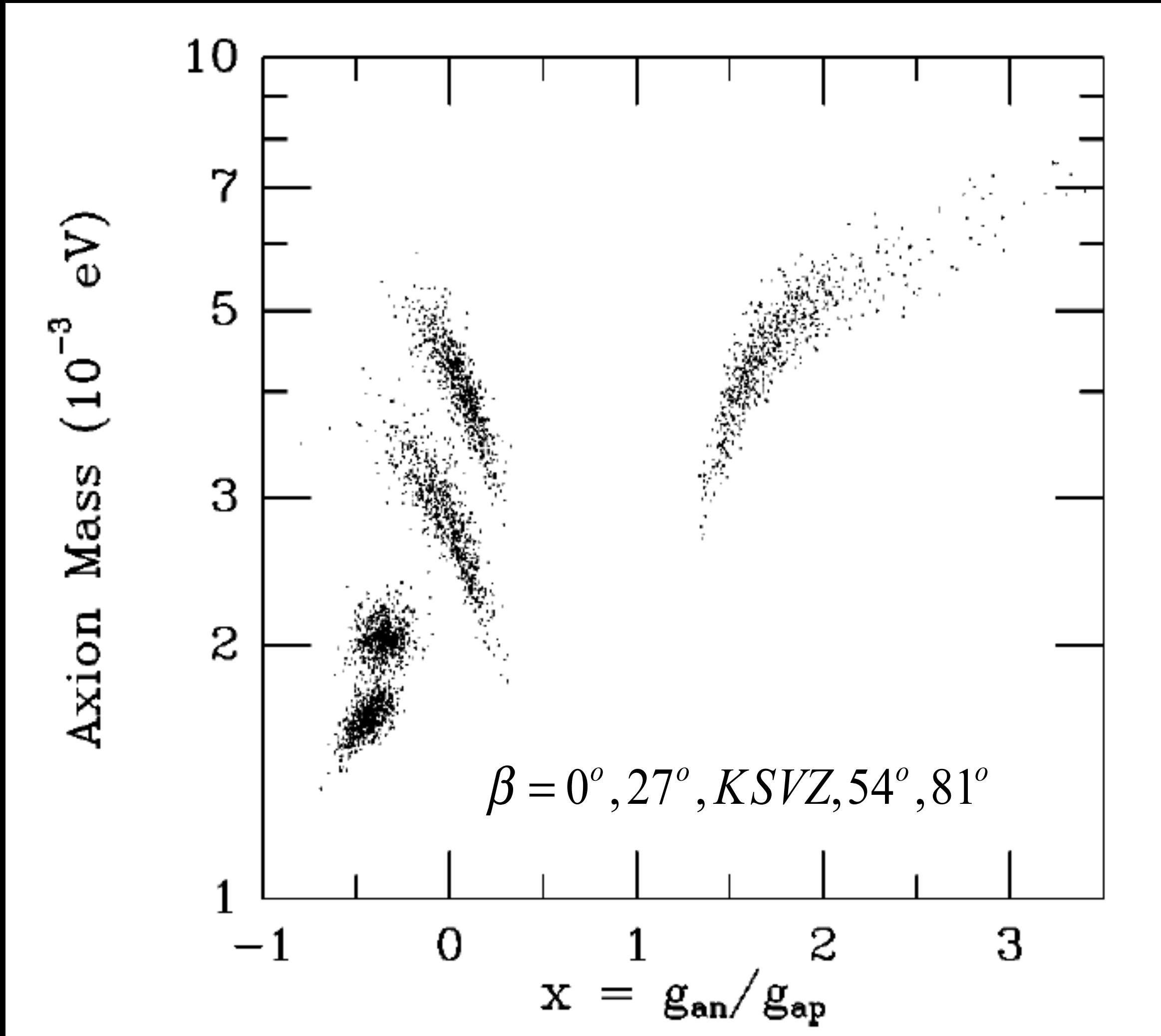


4.4
4.2
4
3.8
3.6
0
5×10⁴
10⁵
1.5×10⁵
2×10⁵
Case 2
4.6
4.4
4.2
4
3.8
log (L/L⊙)
Case 1
Case 0
Δt (yr)



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

Influence on core collapse supernovae



Keil et al '97

Nucleon bremsstrahlung is dominant

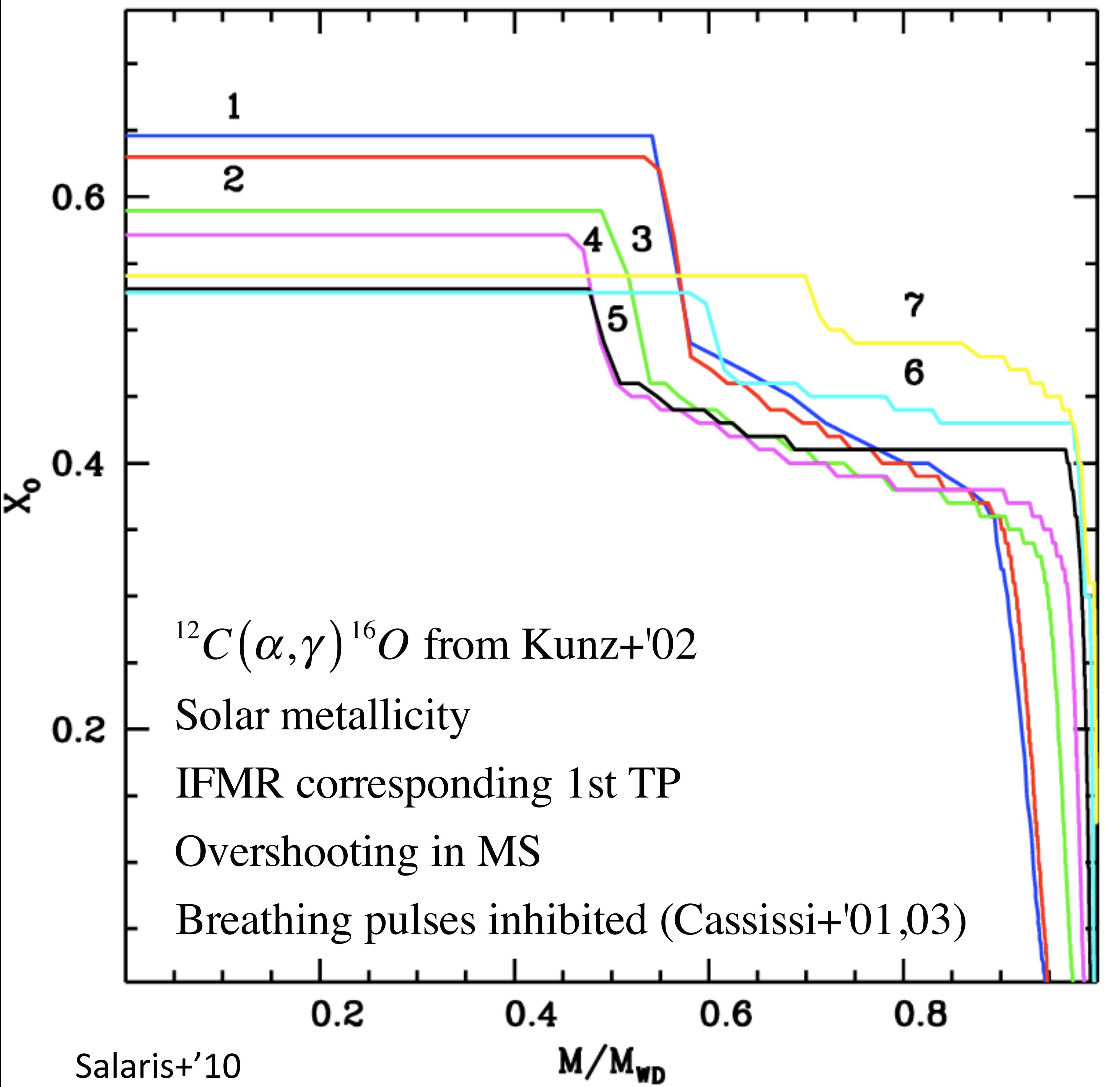
Raffelt'06

m_a(KSVZ) < 16 meV

m_a (DFSZ) ?

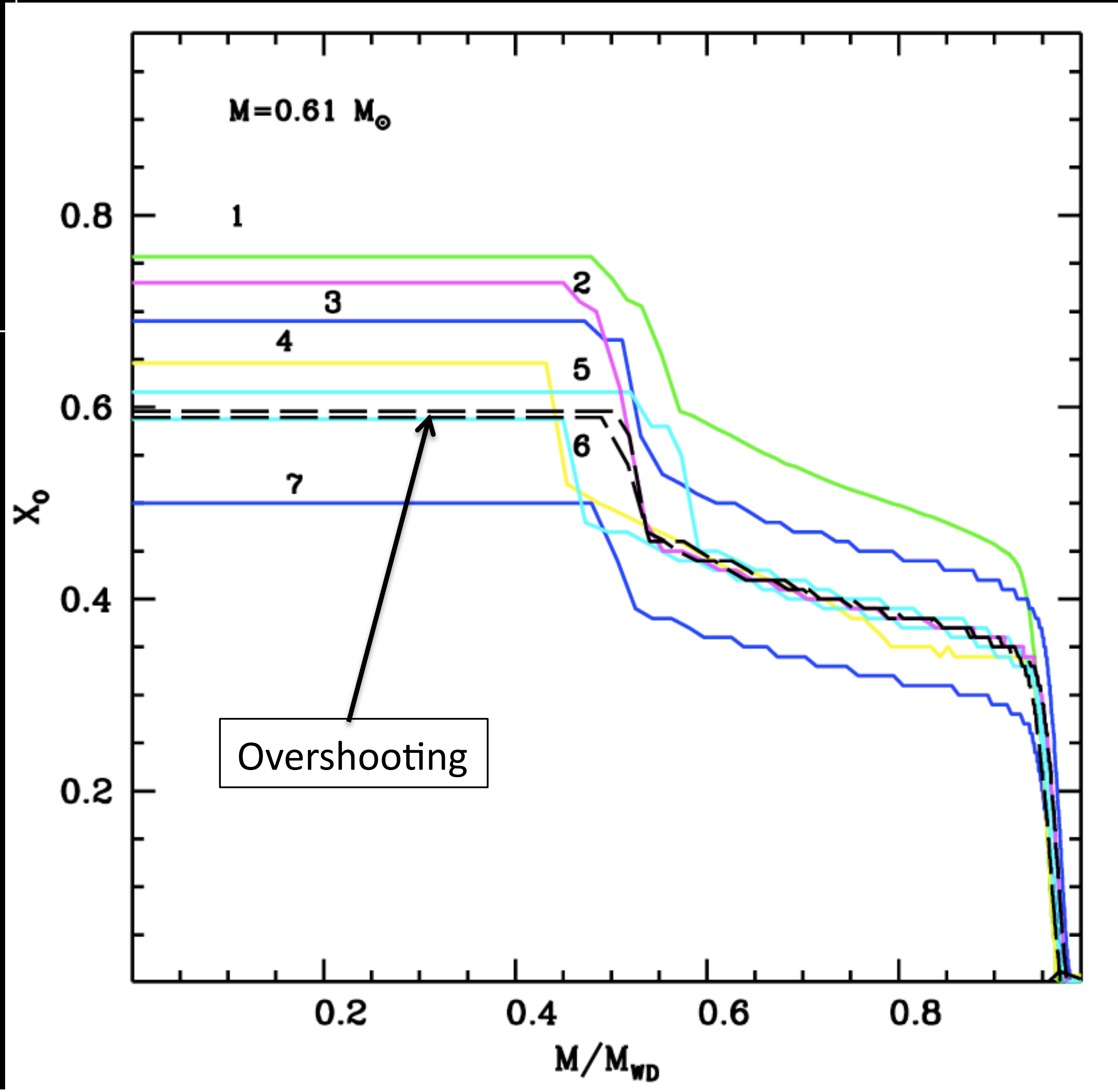
Chemical profiles

#	MWD
1	0.54
2	0.55
3	0.61
4	0.68
5	0.77
6	0.87
7	1.00



Salaris+'10

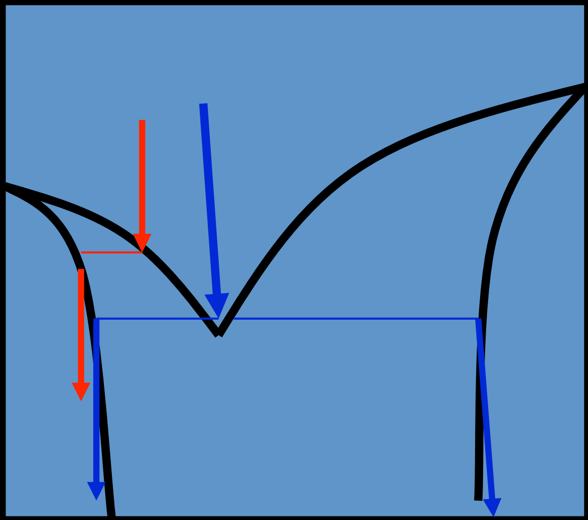
1) Salaris+'97
(Caughlan+'85)
2) Suppression breathing pulses
(Dorman & Rood'93)
3) Kunz+'02 lower limit
4) IFMR
5) Z=0.002
6) Z=0.04
7) Kunz+'02 upper limit



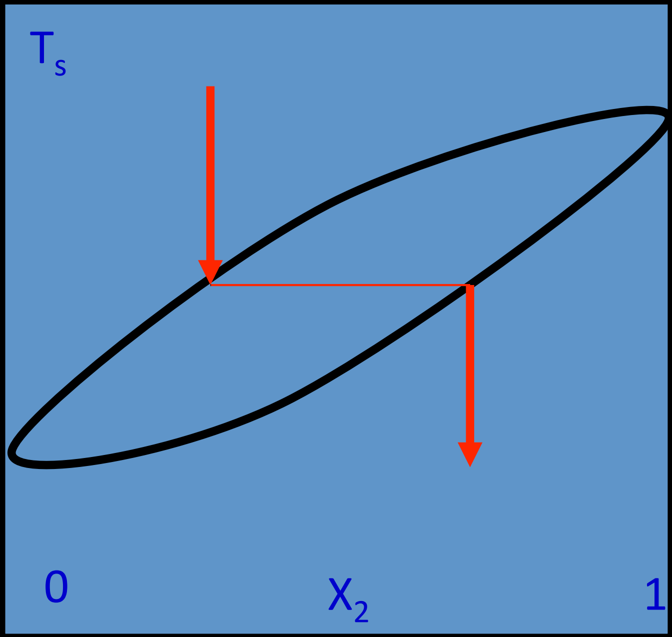
Behavior upon crystallization

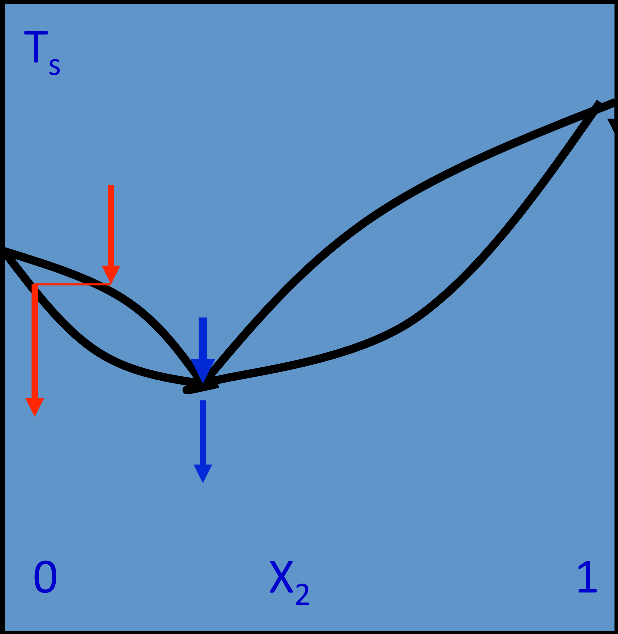
Hernanz+'94
Segretain+'94
Isern+'91
Isern+'97
Isern+'00

Eutectic



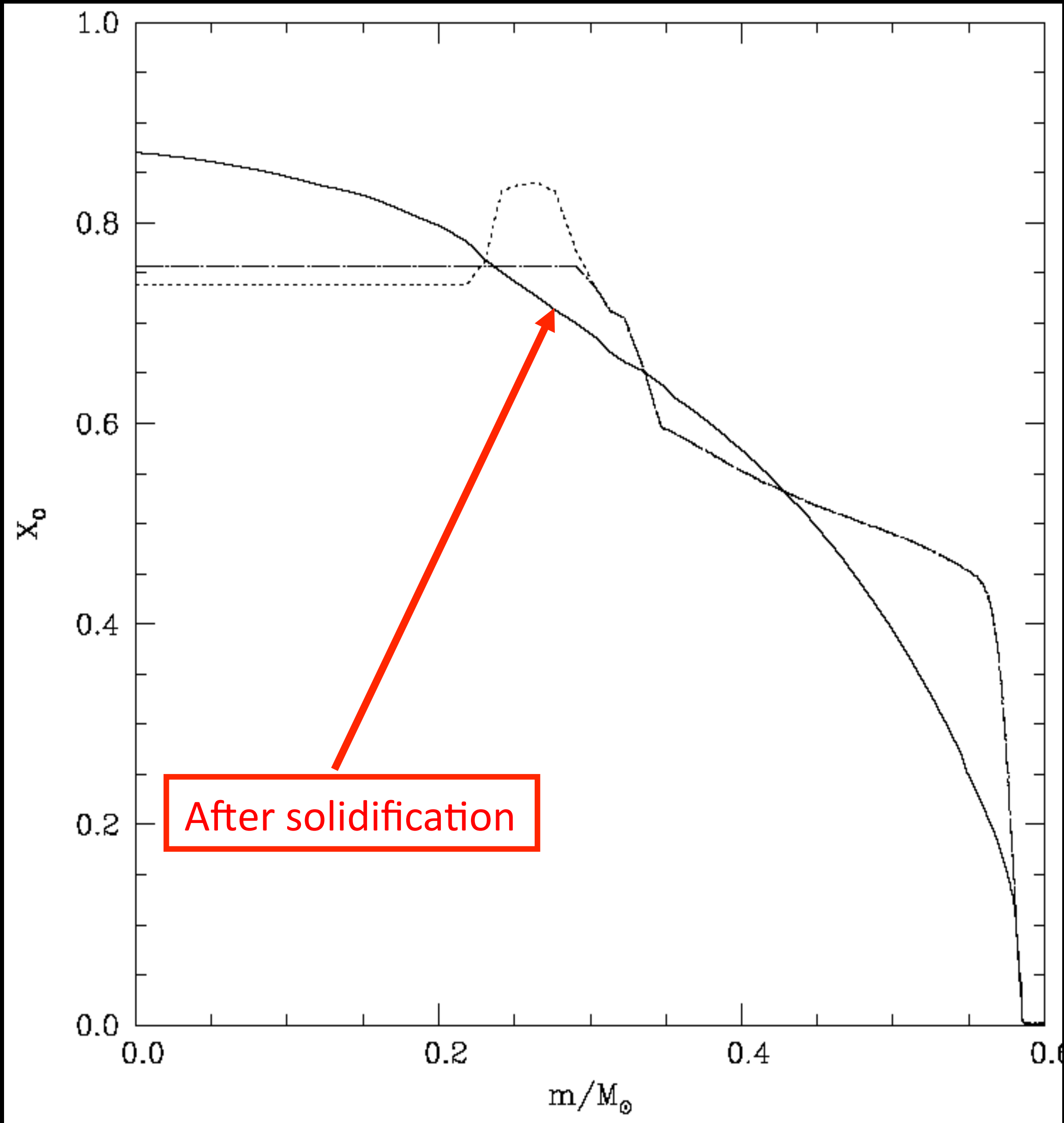
Spindle



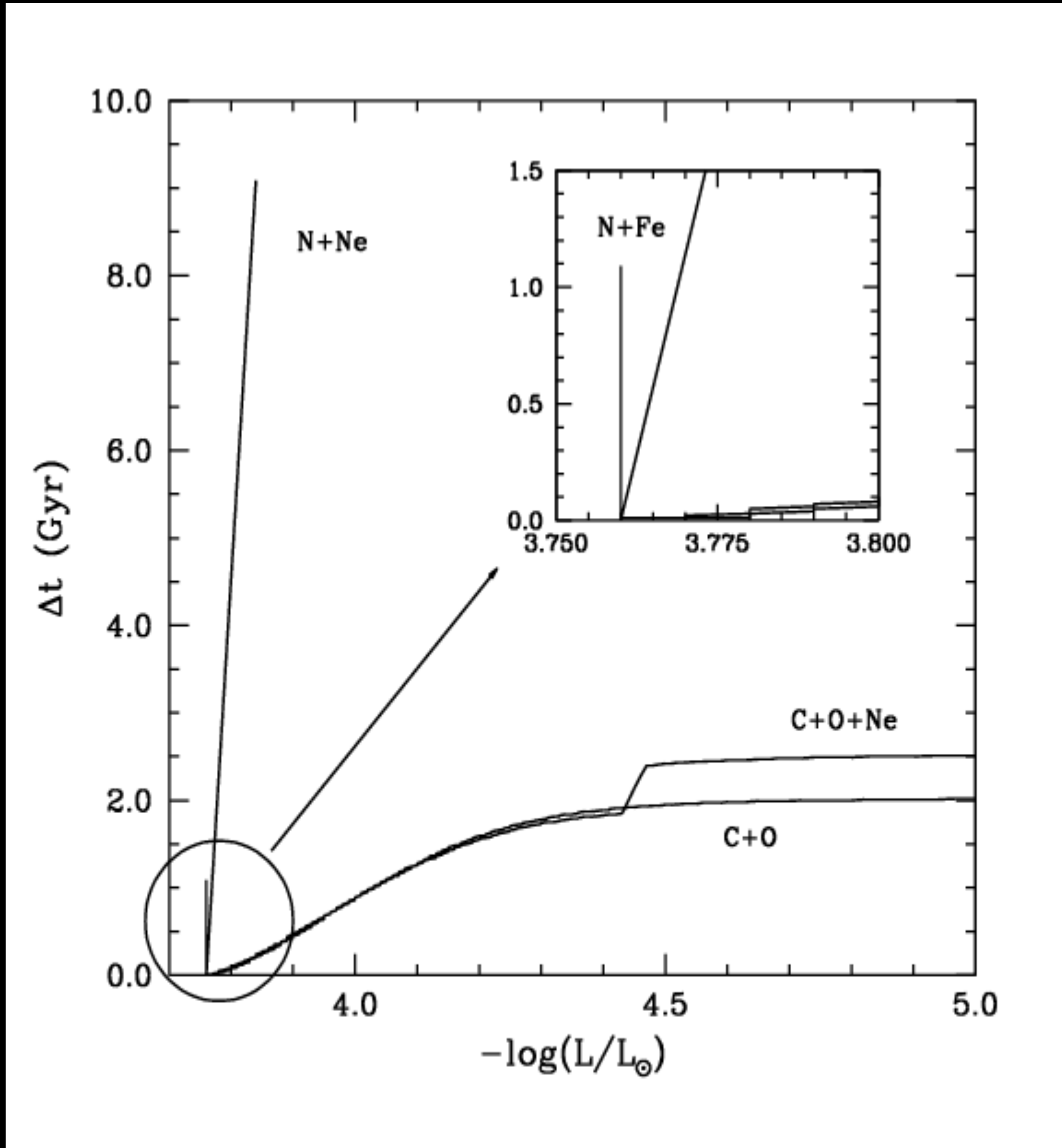


Azeotrope

Change of the chemical profile because of solidification

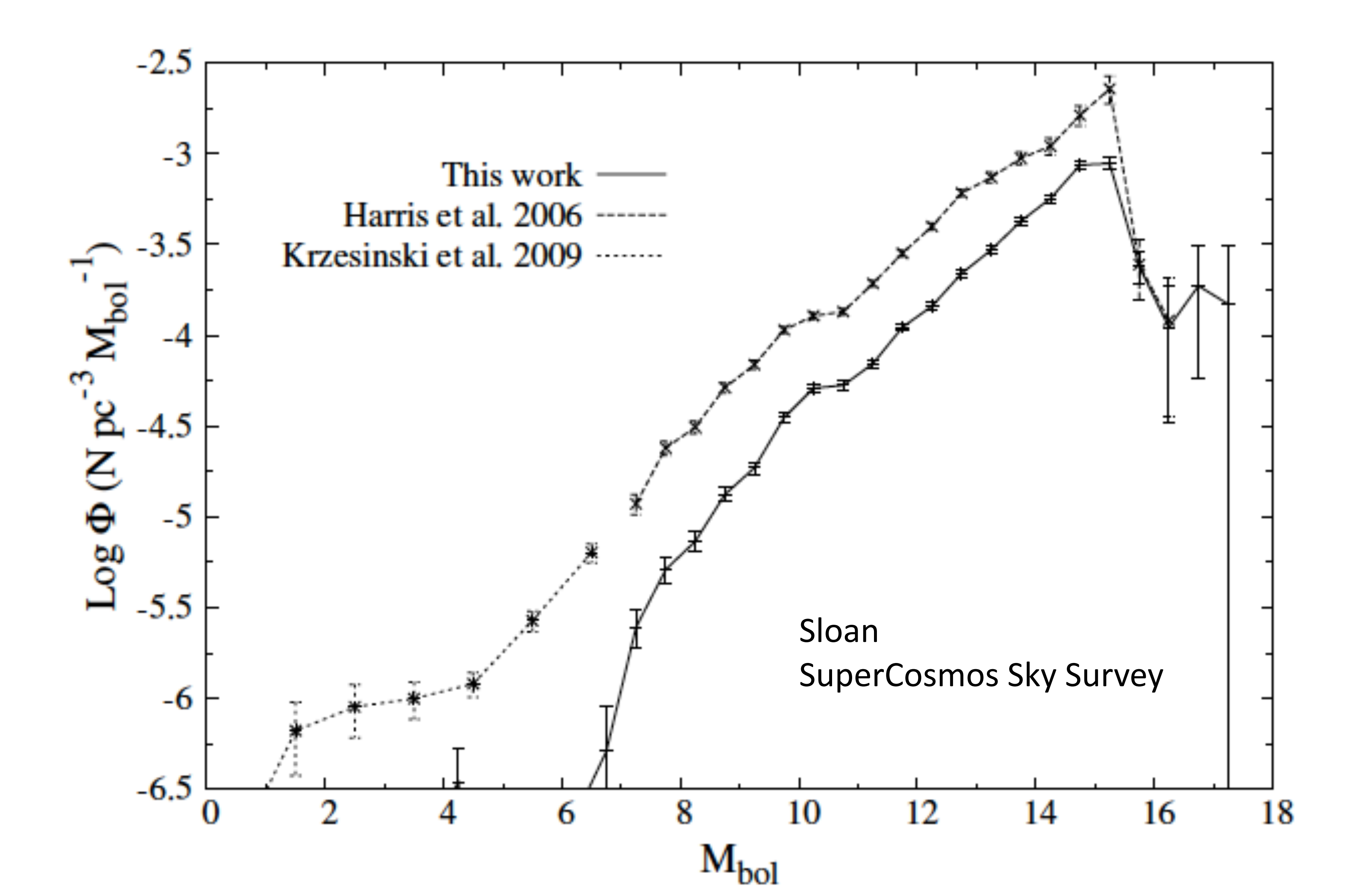


Delays introduced by crystallization



White dwarf envelopes

- DA: Pure H layers.
  - 90,000 K > T_e > 6,000 K, below this T Balmer lines are not seen
- DO: spectrum dominated by He II
  - 100,000 K > T_e > 45,000 K. They are the hottest
  - C,N,O,Si are present in the photosphere
  - The coolest are H-poor
- DB: He dominated armospheres
  - 30,000 K > T_e > 12,000 K
  - There is a gap betwee DO and DB!!!
- DQ: He dominated atmospheres
  - 12,000 K > T_e > 6,000 K
  - C abundances in the range of 10^{-7} - 10^{-2}
- DZ: only metallic features (Ca II H-K)
  - T to small to show the lines of the dominant elements
- DC: So cool that the dominant component is not seen
  - No lines deeper than 5%



Rowell & Hambley'11

Neutrinos