White Dwarfs as Physics Laboratories: The Axion case

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Collaboration:

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7th Patras Workshop on axions, WIMPs & WISPs
Mykonos, June 26th, 2011

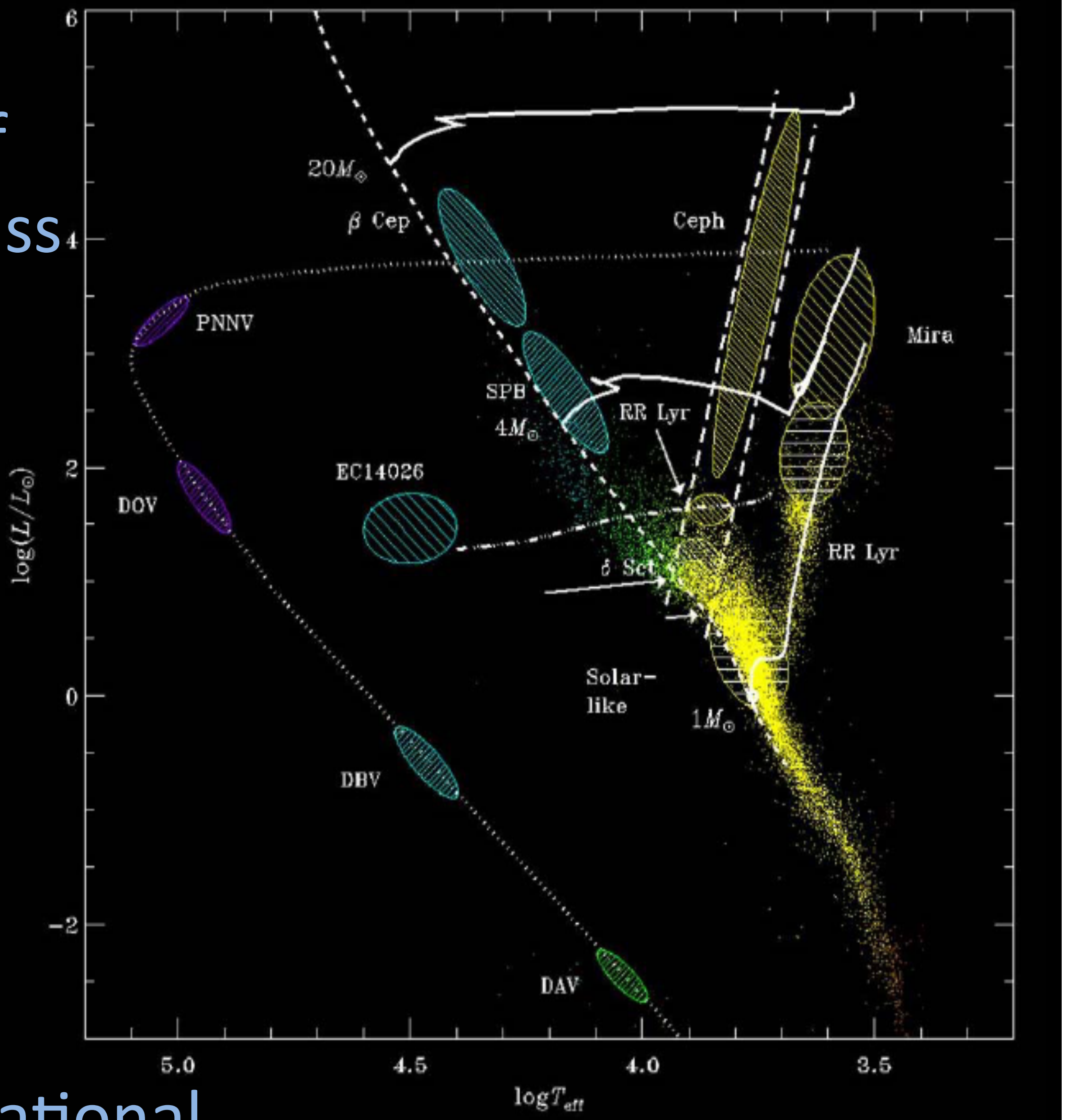
The white dwarf population is one of the best studied!

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)

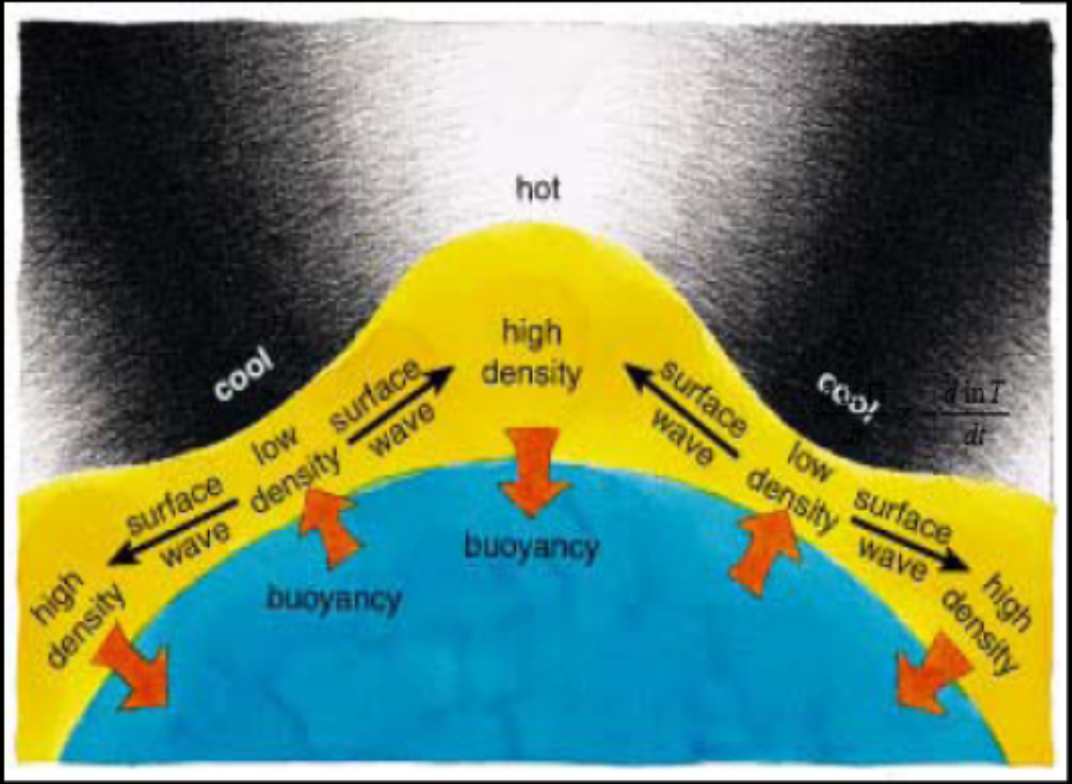
Impressively solid observational background for testing theory.



Courtesy of Christensen-Dalgaard

Non-radial g-modes

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

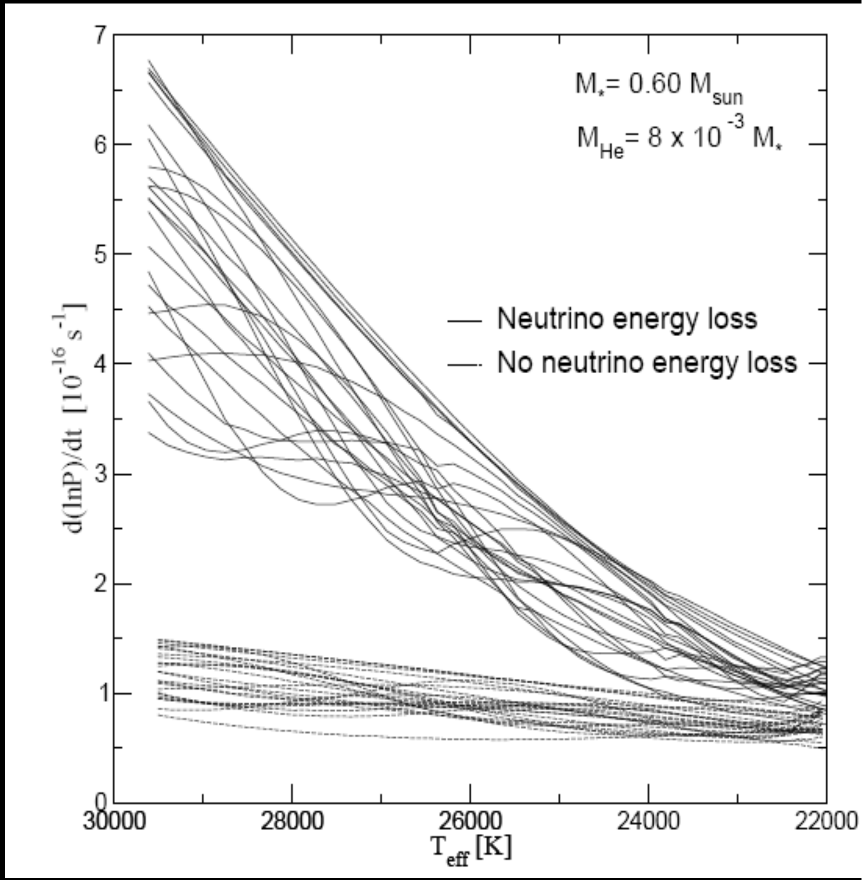


$$\frac{\dot{P}}{P} = -a\frac{\dot{T}}{T} + b\frac{\dot{R}}{R}$$

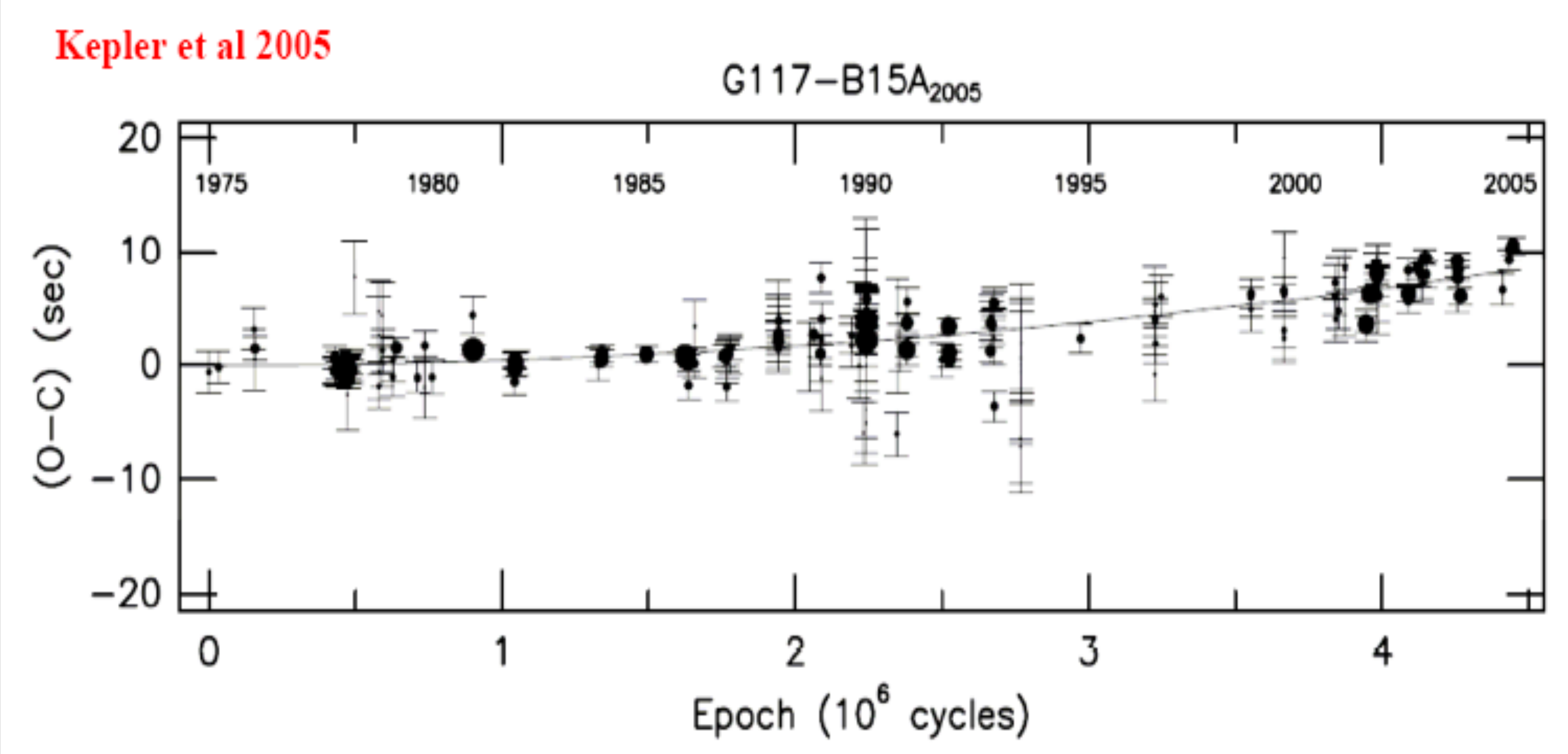
\# The period increases as the star cools down and decreases as it contracts.

\# 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.

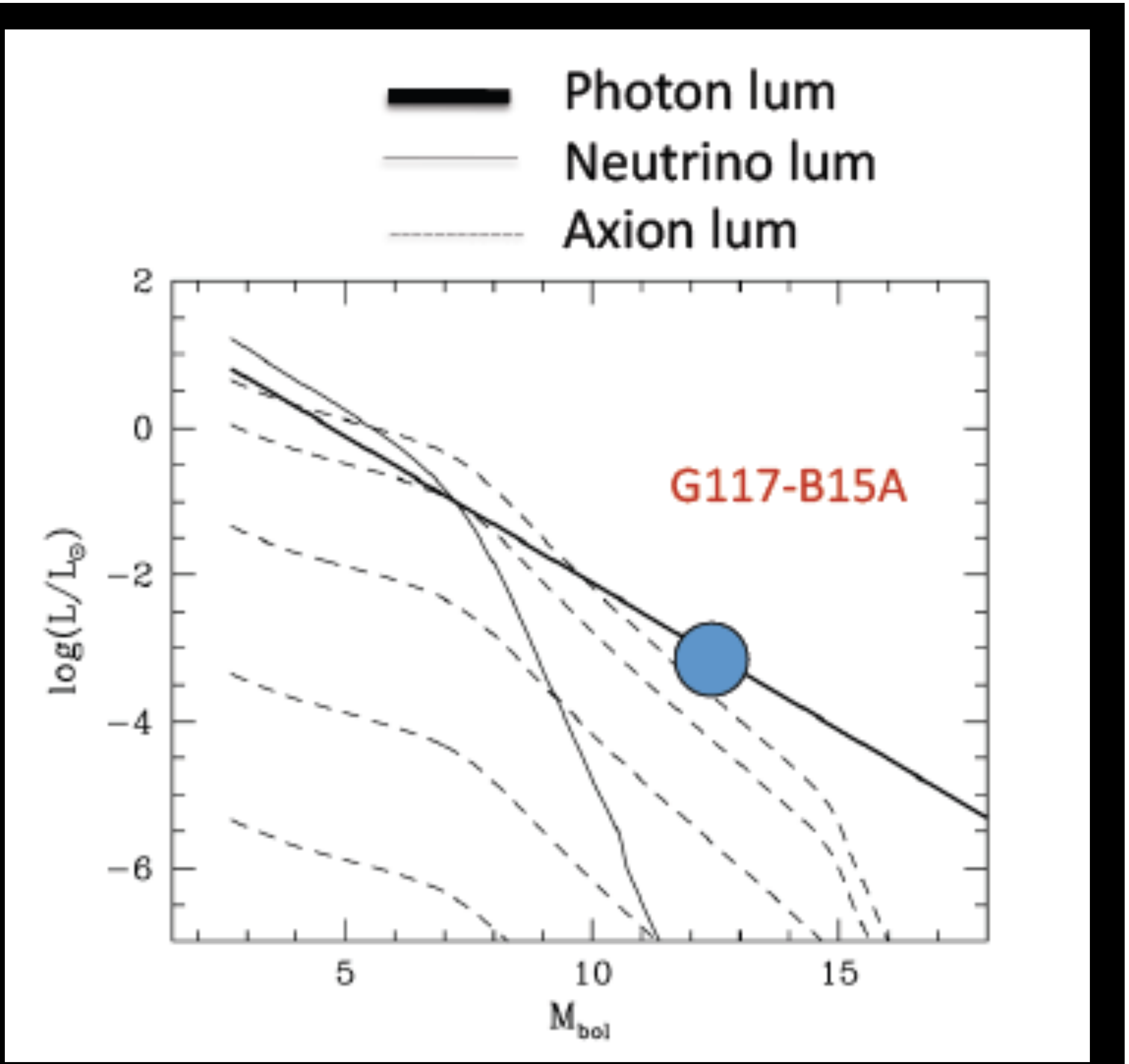
Three solutions:

- Observational error
- Whited warfs with “IME” cores
- Exotic source of cooling

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

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

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

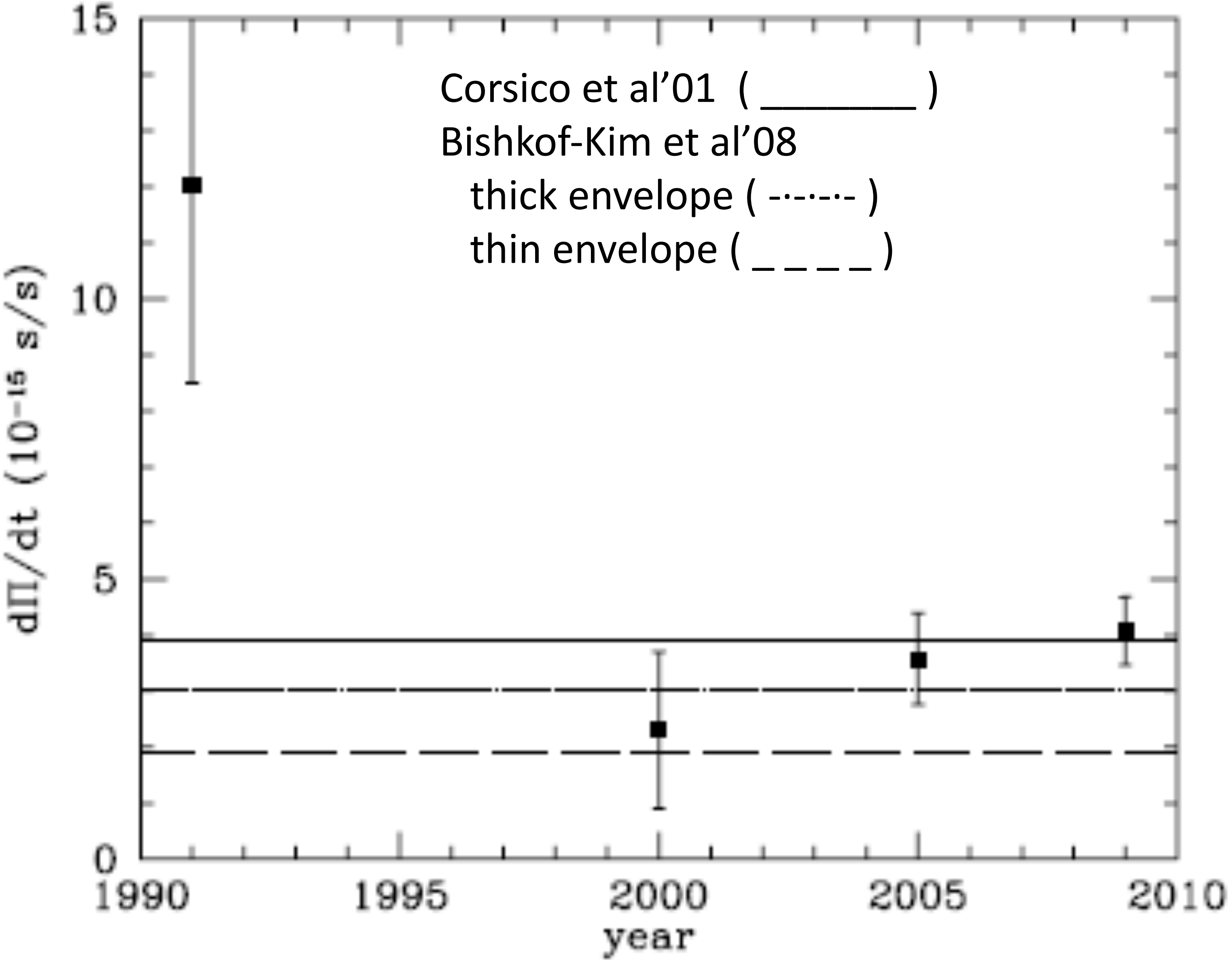


DFSZ axions
Bremmsstrahlung is dominant

Nakagawa et al 1987, 1988

g_{ae} ~ 2.2 x 10^{-13} (m_a ~ 8 meV) Isern+'92

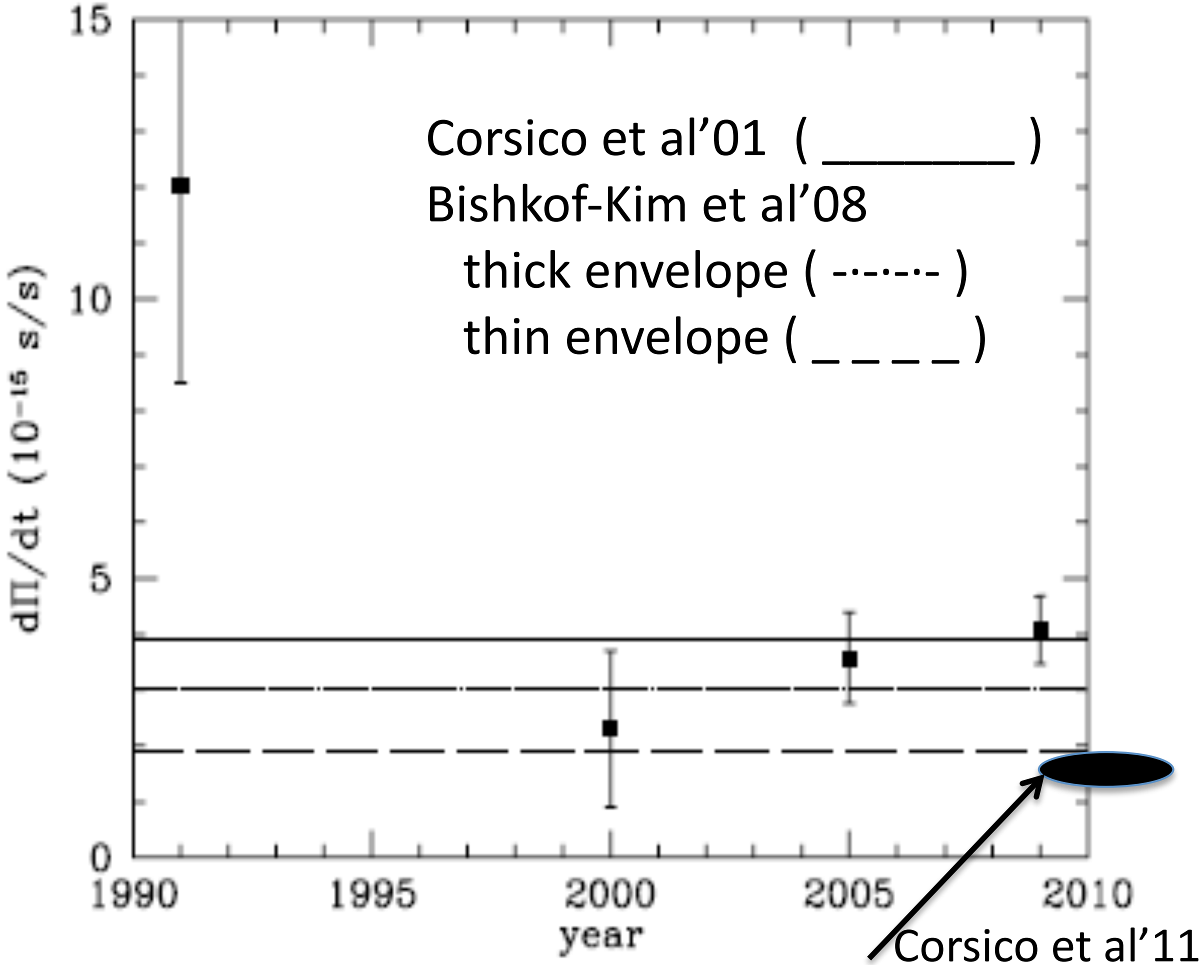
Evolution of the measurements of the period of pulsation period drift of G117-B15A



Corsico et al’01 (________)
Bishkof-Kim et al’08
thick envelope (-··-·-·-)
thin envelope (_ _ _ _)

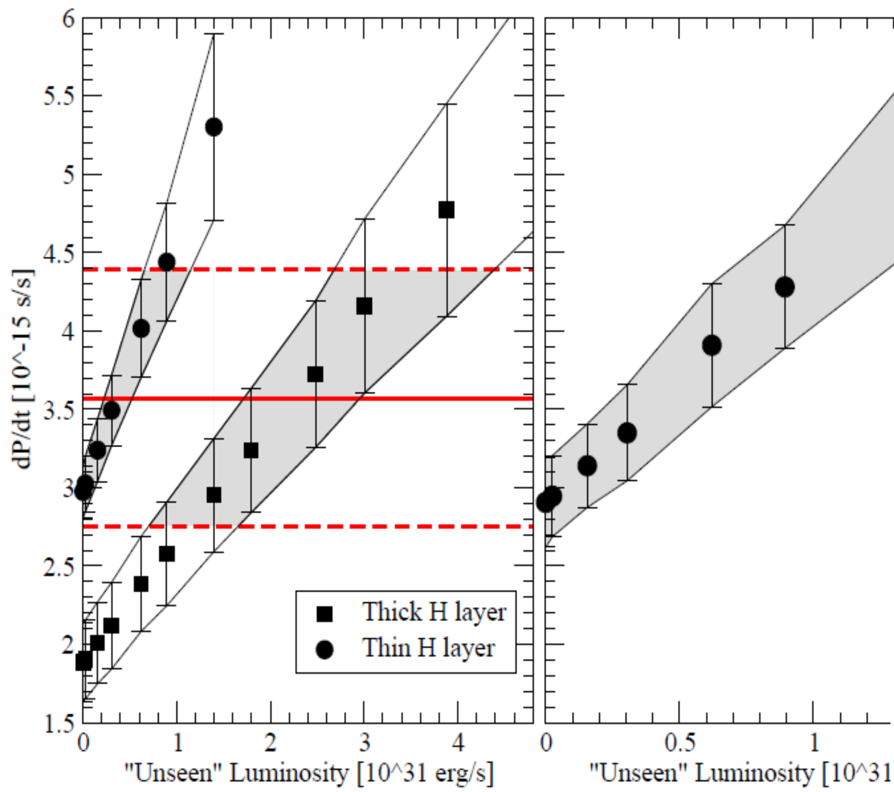
Isern+’10

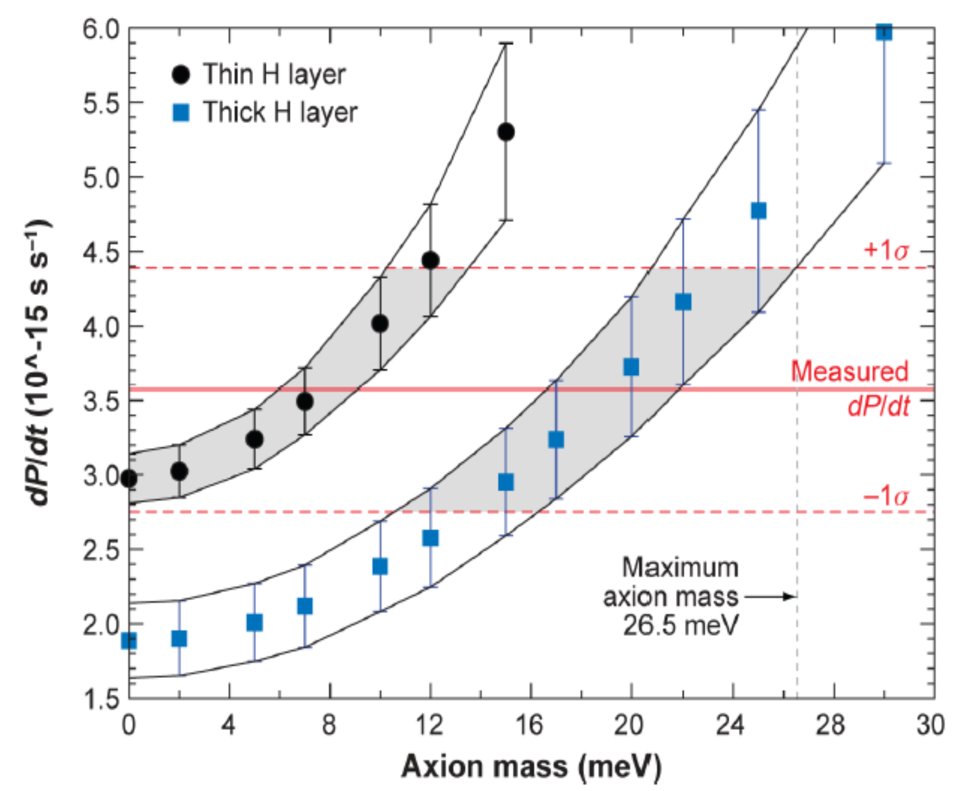
Observed and predicted secular drift of G117-B15A



Corsico et al’11

Comparison of the theoretical predictions (lines) with the observations. An extra cooling term seems necessary.

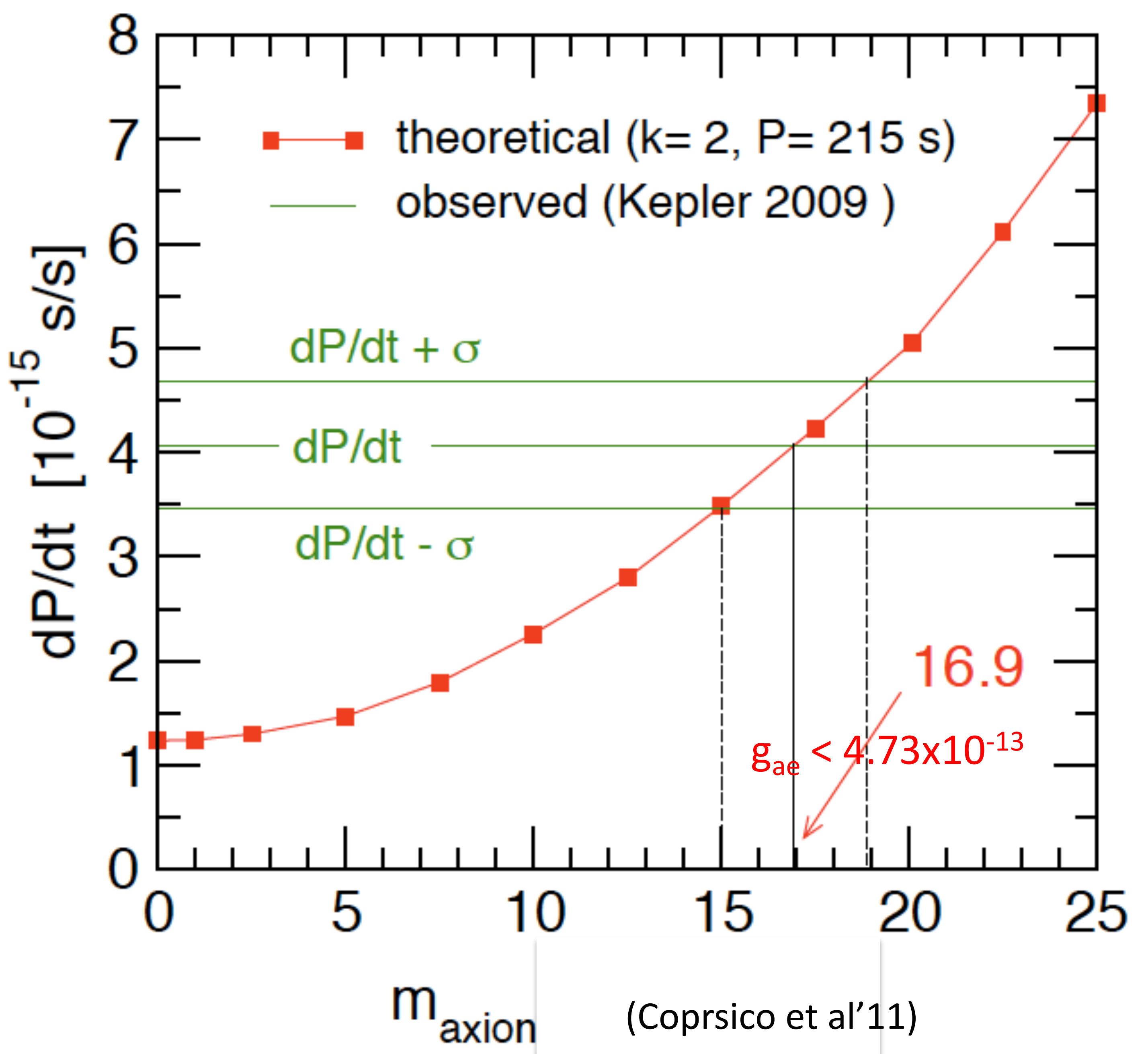




Bischoff-Kim et al 2008:

$m_a < 13 – 26$ meV

$g_{ae} < 3.64\mathrm{x}10^{-13}$-$7.28\mathrm{x}10^{-13}$



16.9

$g_{ae} < 4.73\text{x}10^{-13}$

(Coprsico et al'11)

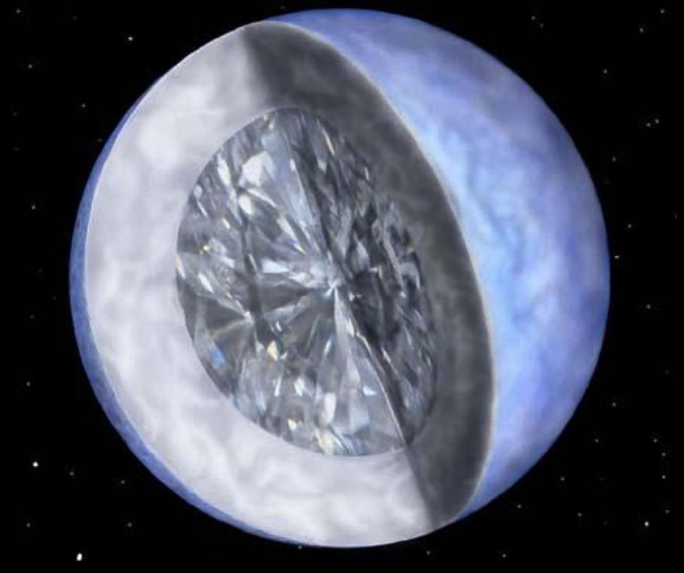
White dwarf cooling

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

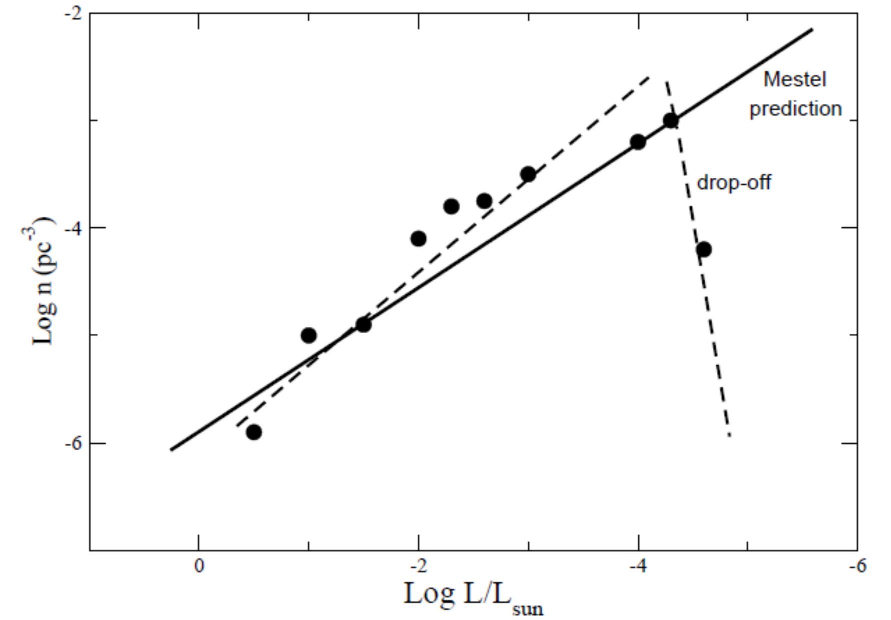
A $L(T_C)$ relationship is necessary to solve this equation
It depends on the properties of the envelope.

$$L \propto T^\alpha$$

$$\alpha \approx 2.5 - 2.7$$



CO.core/He-envelope/H-envelope



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

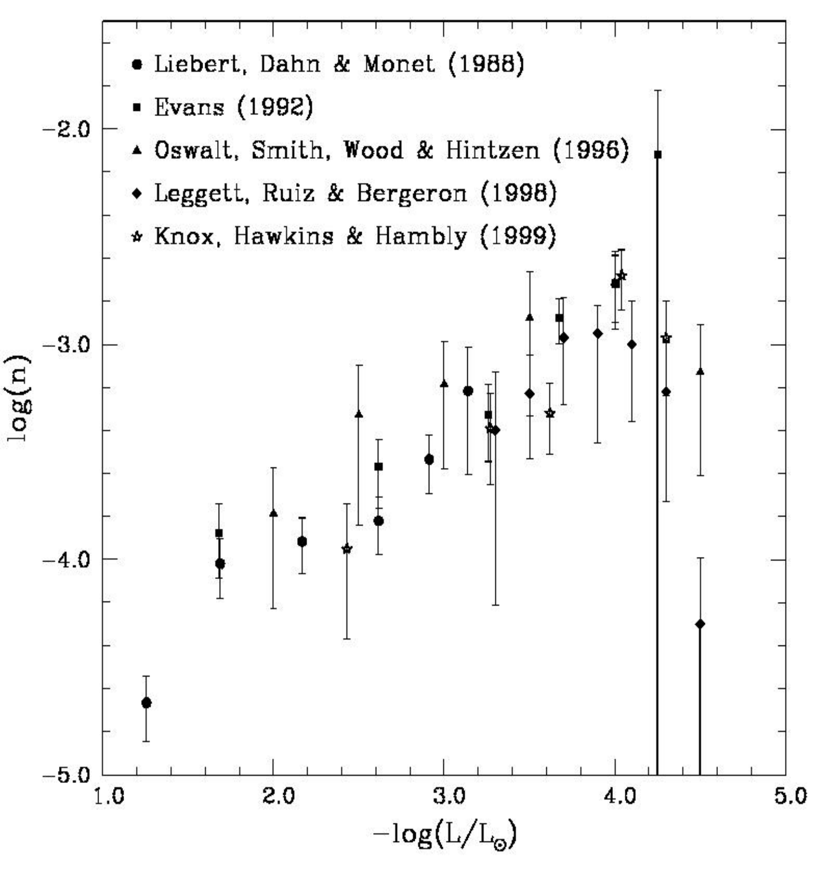
τ_{cool} is the characteristic cooling time

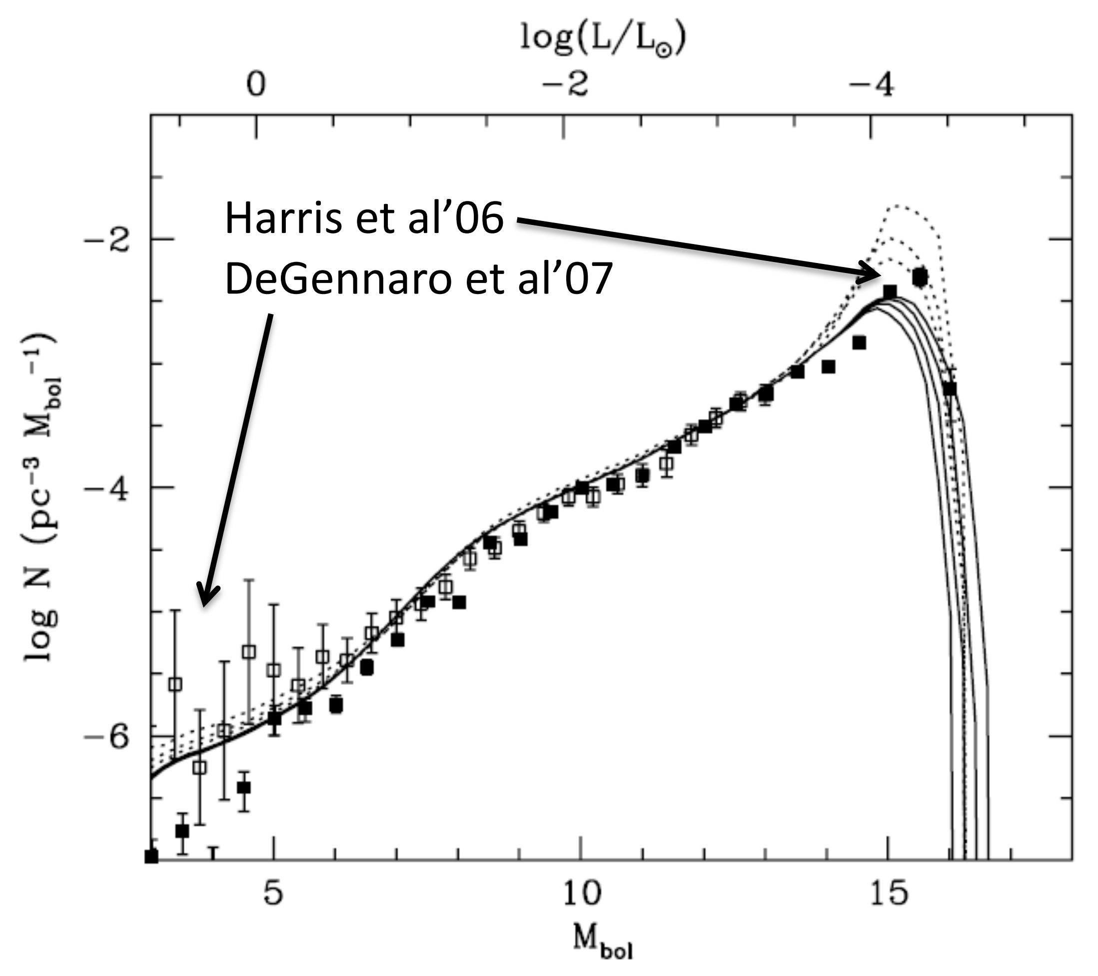
Hidden an IMFR

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

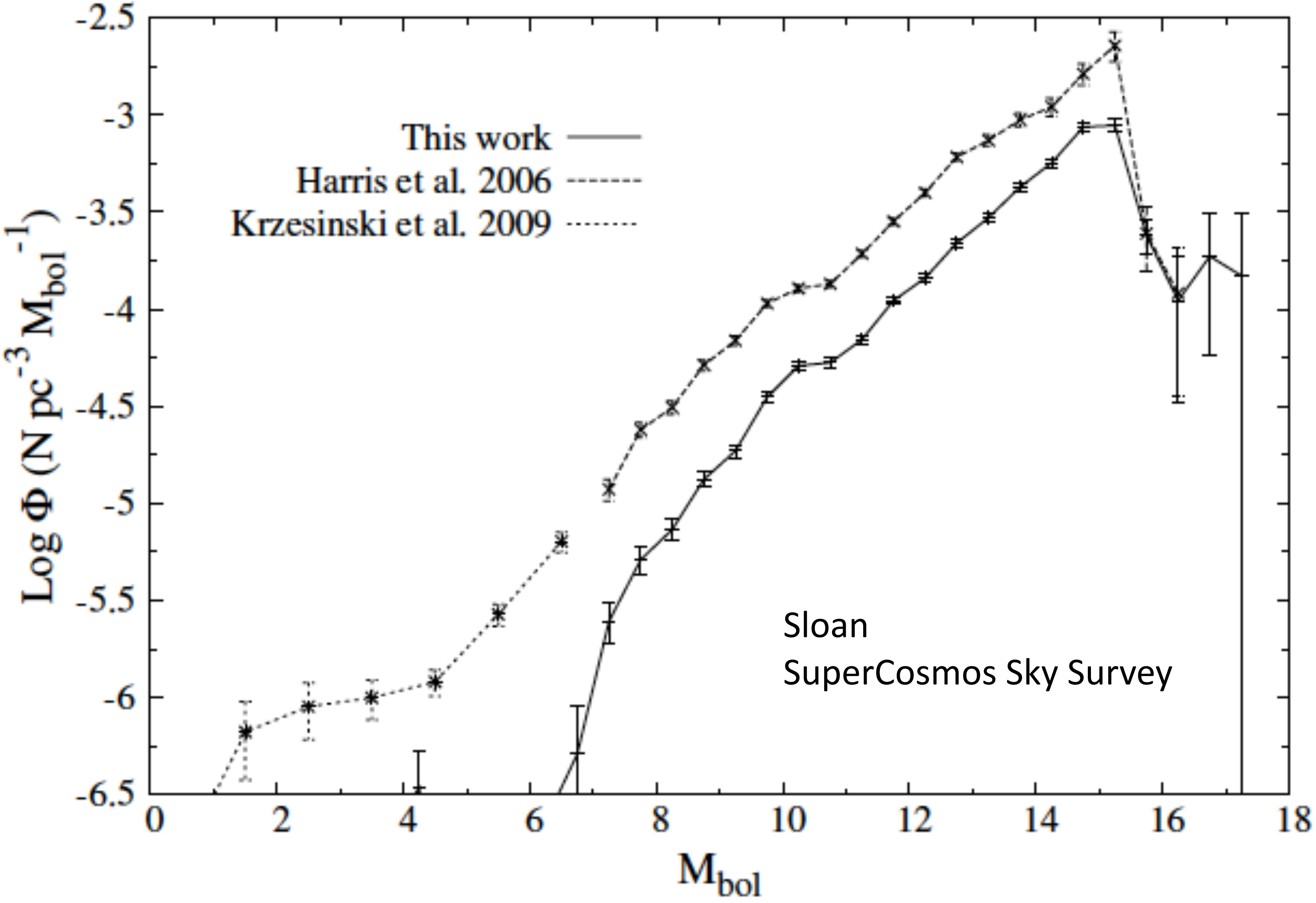



Harris et al'06

DeGennaro et al'07

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

Isern & Garcia-Berro'08

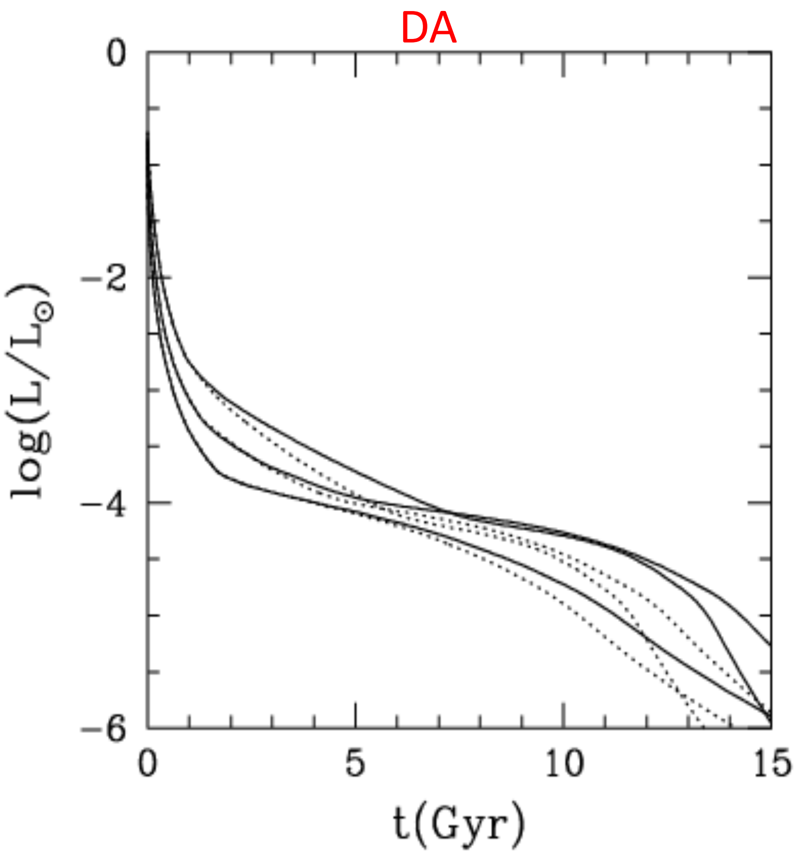


Sloan
SuperCosmos Sky Survey

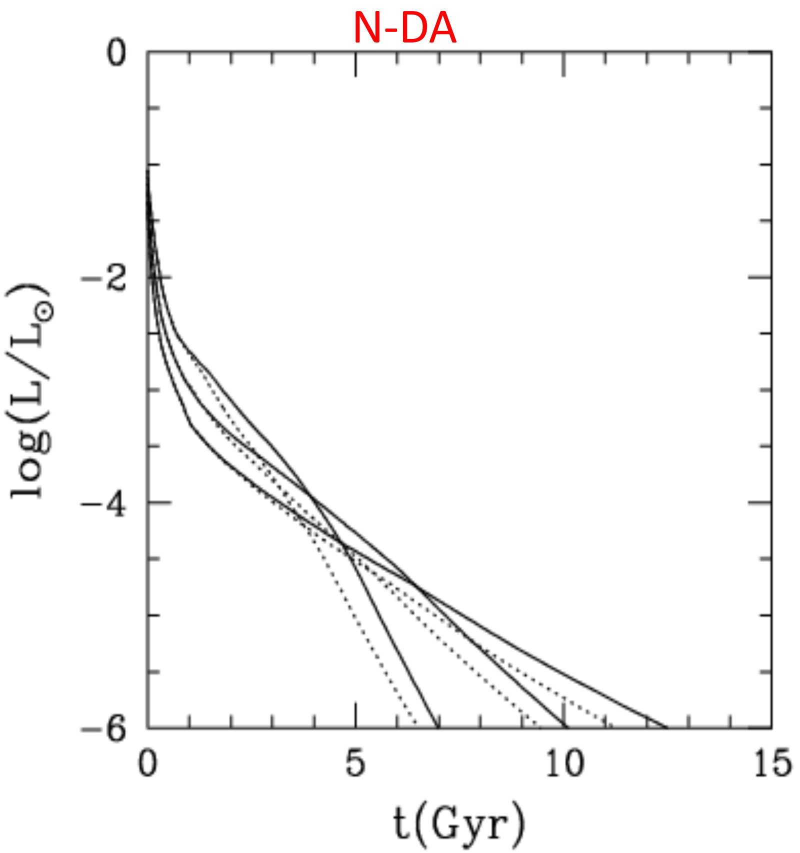
Rowell & Hambley'11

Luminosity versus time

(dotted lines without sedimentation)



DA



N-DA

DA, non-DA influence

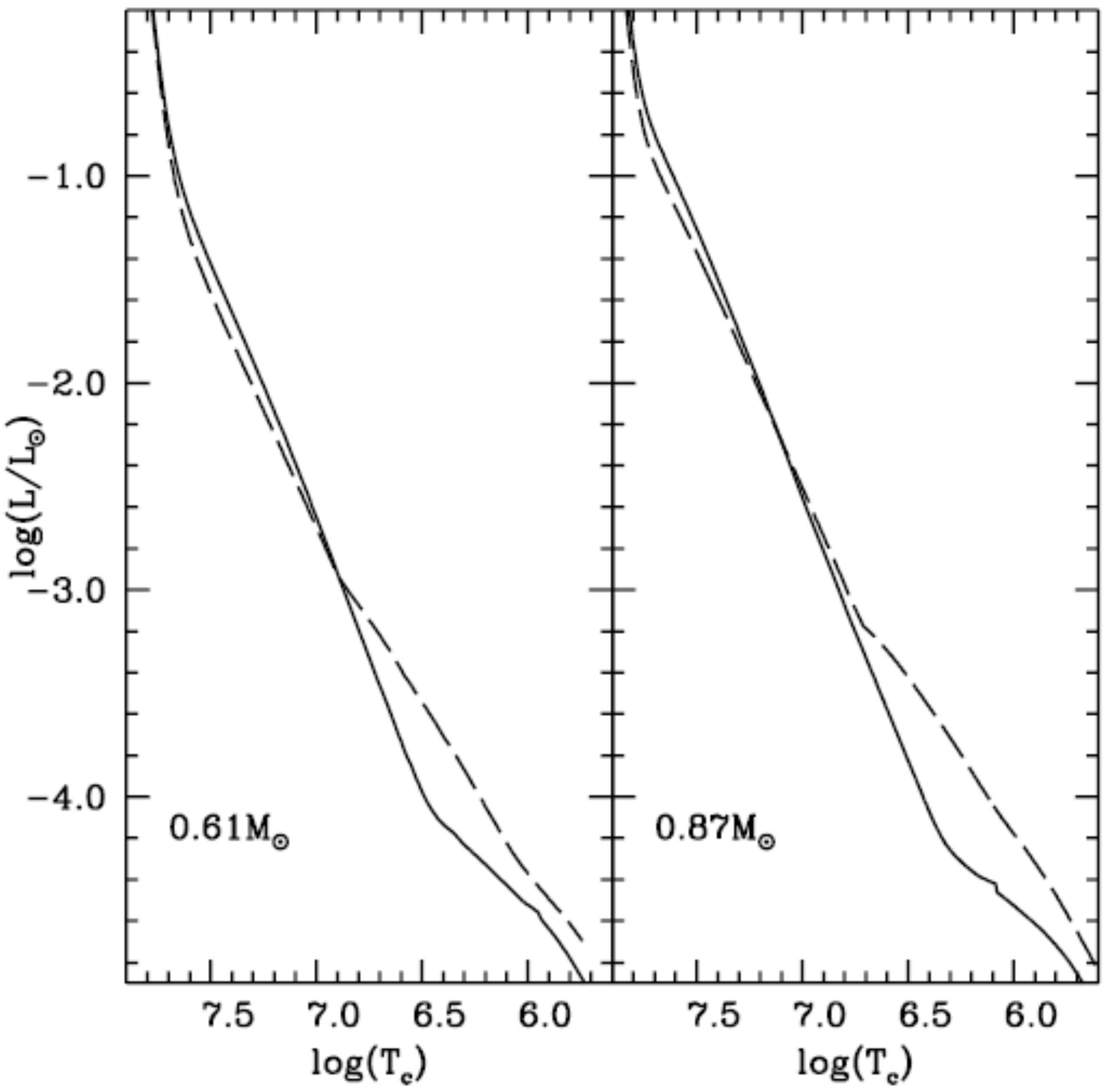


Fig. 1.— $L - T_c$ relationships for our 0.61 and 0.87 $M_\odot$ WD models (with phase separation not included). Solid lines denote H-atmosphere models, dashed lines He-atmosphere ones.

Assume that:

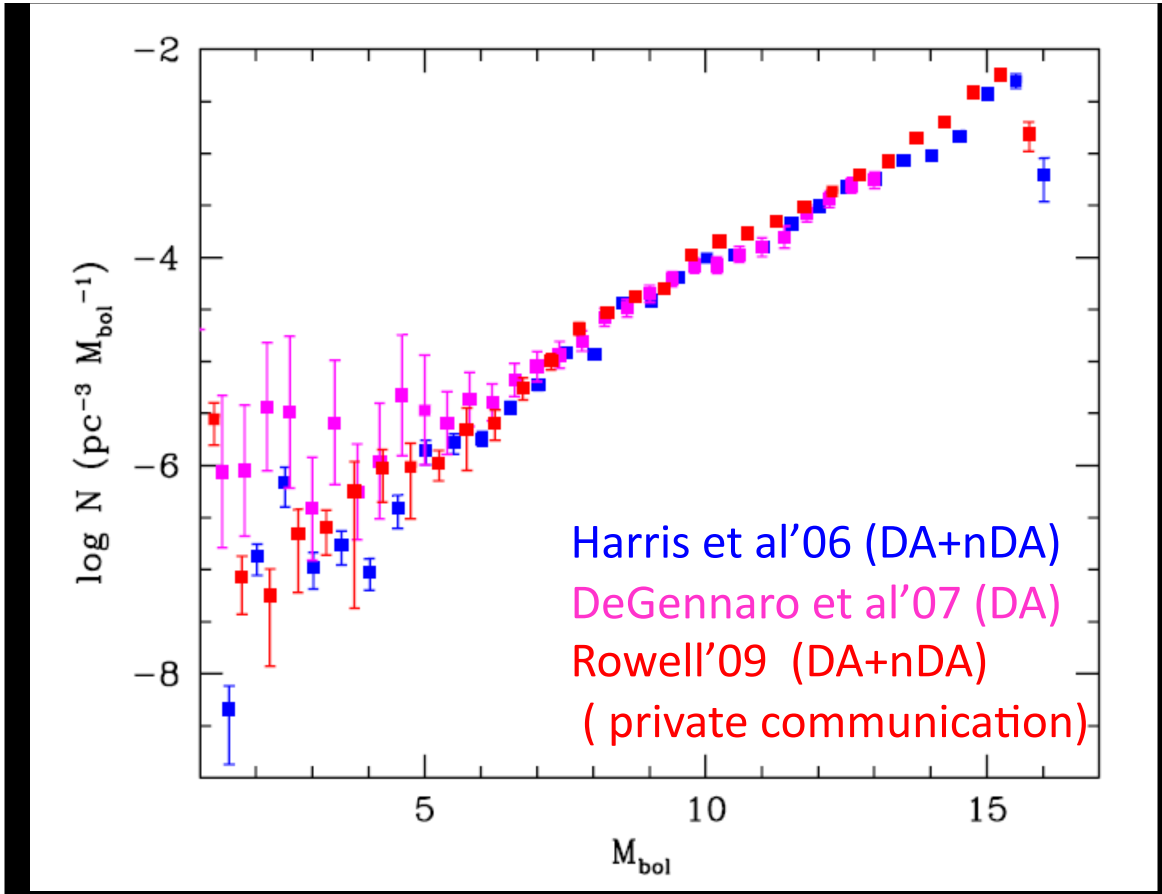
$$L = g T_C^{\gamma}$$

From the figure we see that:

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

in the range

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



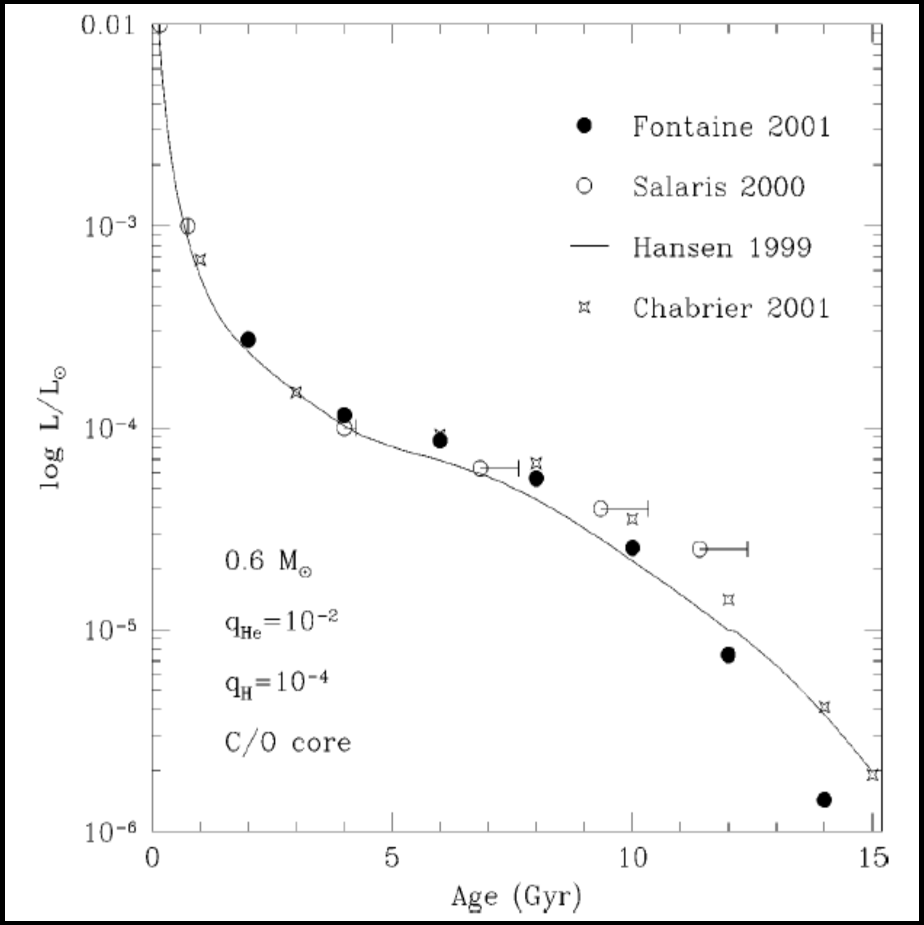
Since $\gamma_{DA} \approx \gamma_{nDA}$ the luminosity function of Das and nDAs coincide after normalization

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

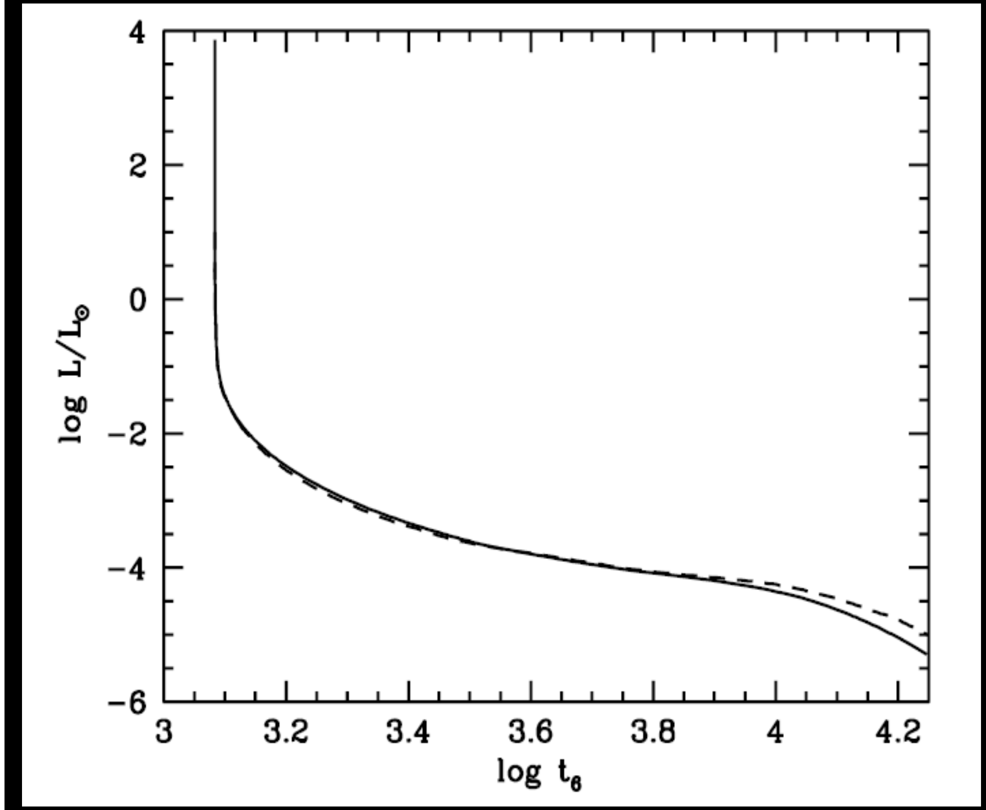
$$\frac{dL}{dt} = \gamma g T_C^{\gamma-1} \frac{dT_C}{dt} \quad \text{(from the L-}T_C\text{ relationship)}$$

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

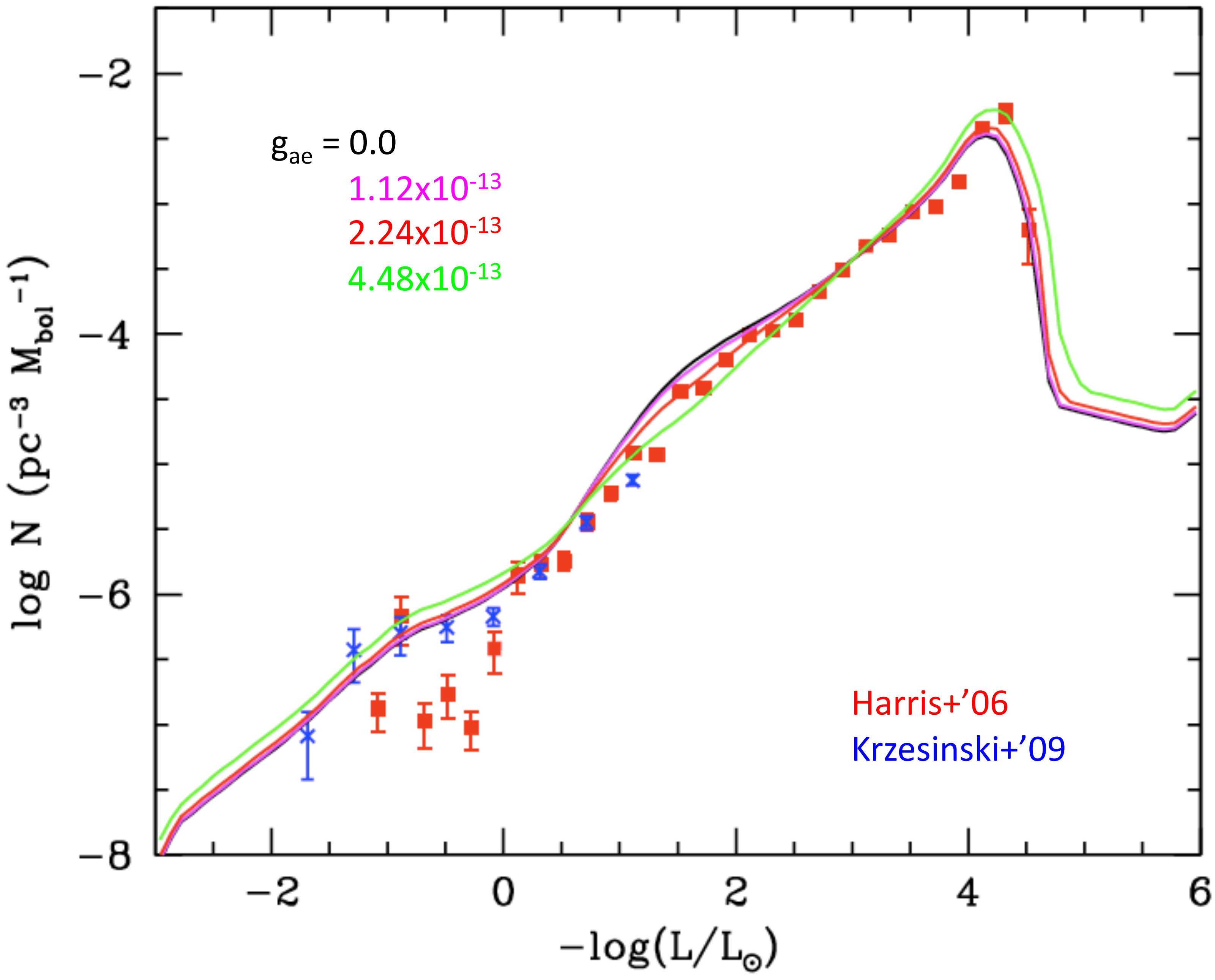
Comparison between cooling models

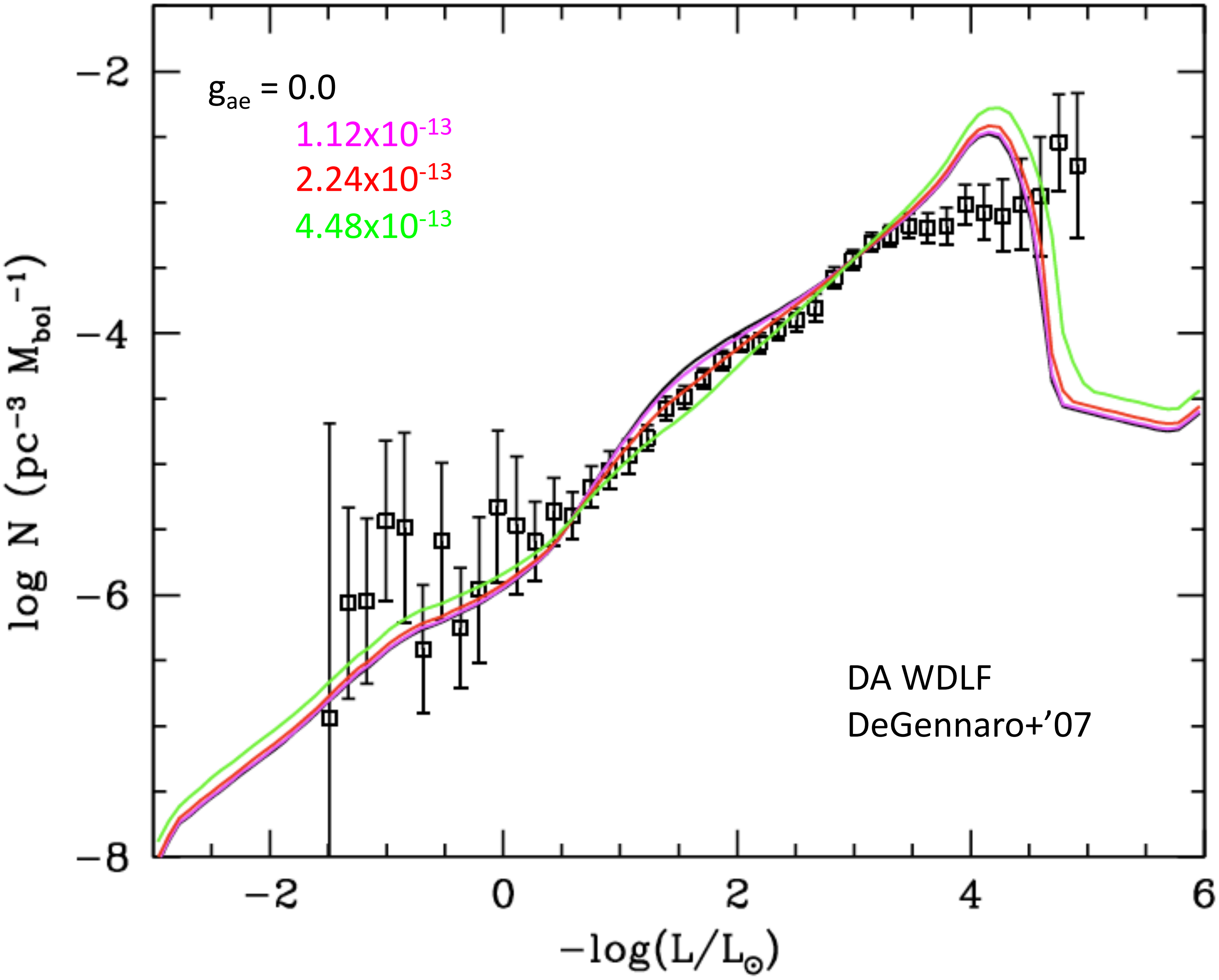


Hansen & Liebert'03



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


g_{ae} = 0.0
1.12×10^{-13}
2.24×10^{-13}
4.48×10^{-13}
Harris+'06
Krzesinski+'09
$\log N\ (\mathrm{pc}^{-3}\ M_{\mathrm{bol}}^{-1})$
$-\log(L/L_\odot)$
−2
−4
−6
−8
−2
0
2
4
6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$\log N\ (\mathrm{pc}^{-3}\ M_{\mathrm{bol}}^{-1})$
$-\log(L/L_\odot)$
−2
−4
−6
−8
−2
0
2
4
6

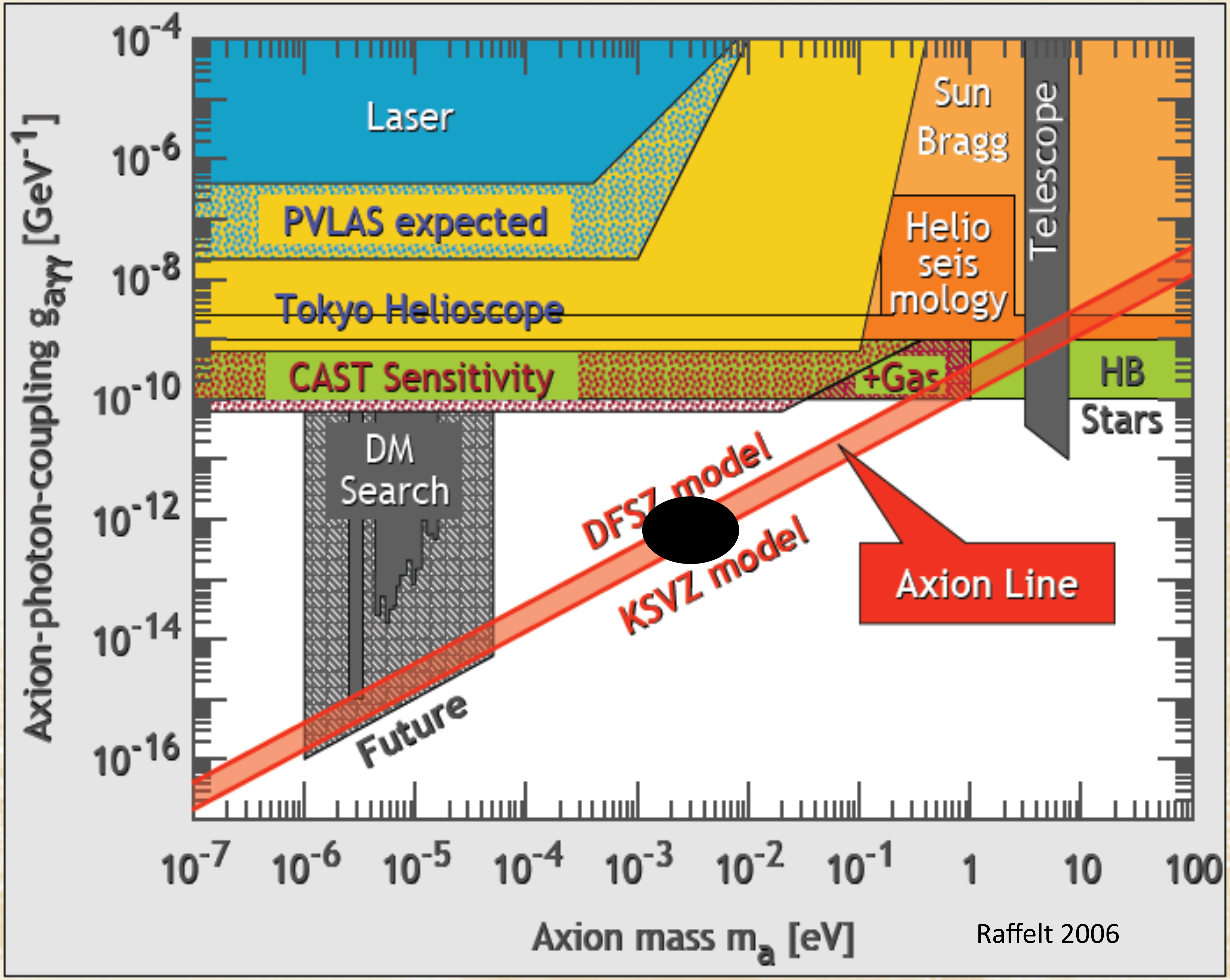
GAIA mission (2013-2018)

400,000 WD

Large Synoptic Survey Telescope (LSST)

First light: 2015
Start Science: 2017

50,000,000 WD
r > 27.5 mag



Raffelt 2006

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 ($g_{ae} \sim 2 \times 10^{-13}$)

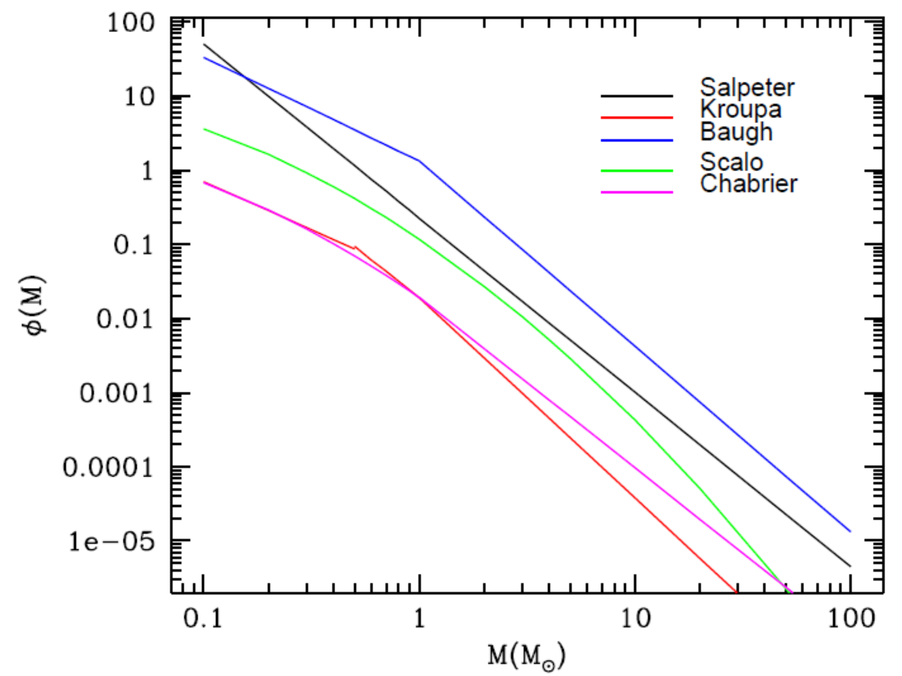
The results seem robust (for the moment) but more refinements are needed:

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

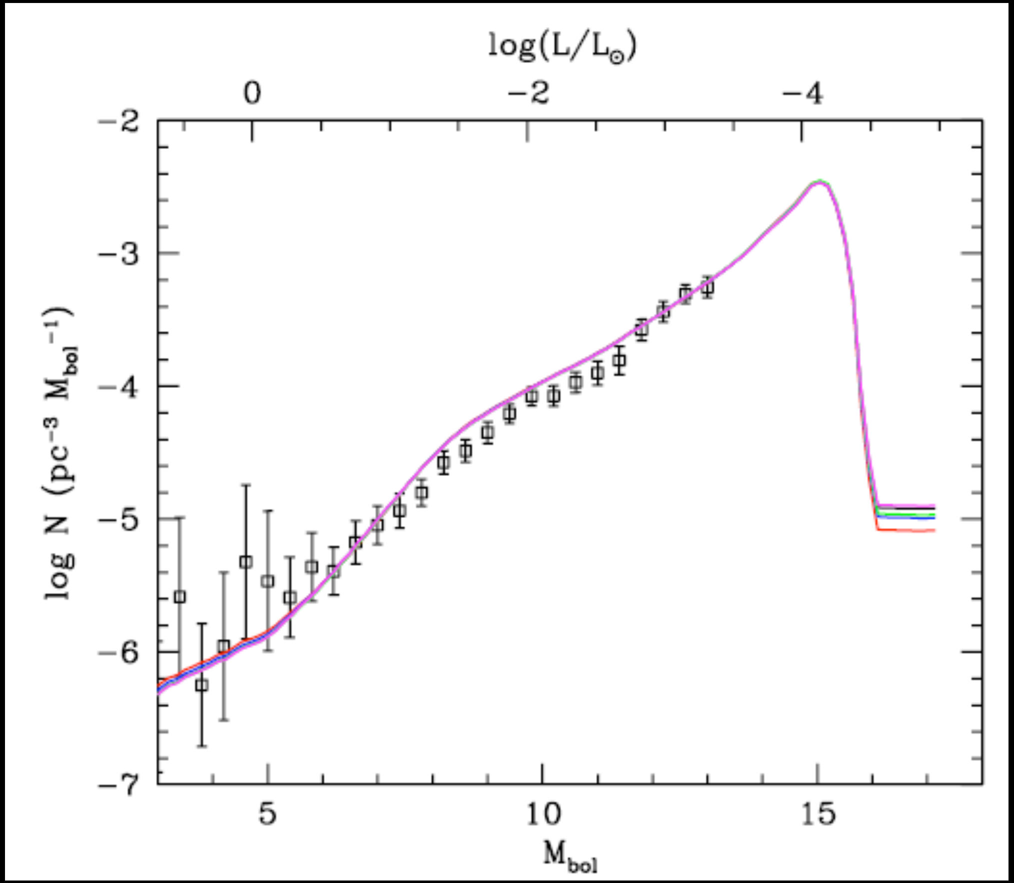
This method can be used in other problems

GAIA & LSST can provide the necessary precision & accuracy

Dependence on the IMF

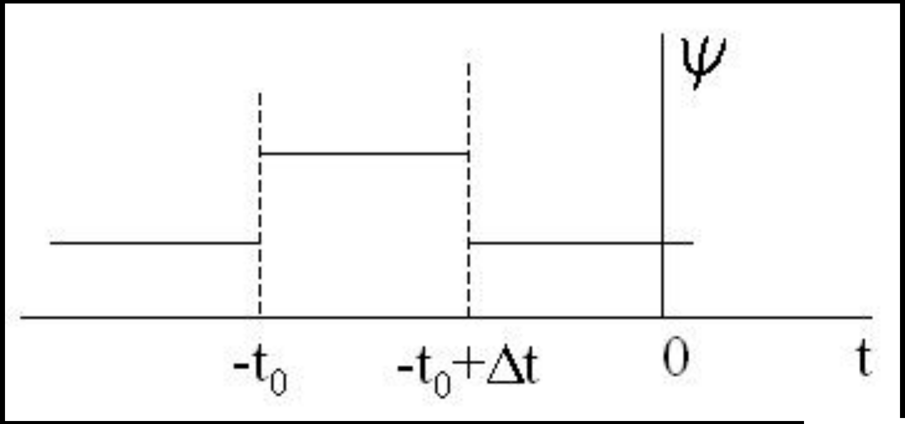


SFR=1 and the age=11 Gyr



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

Influence of the SFR

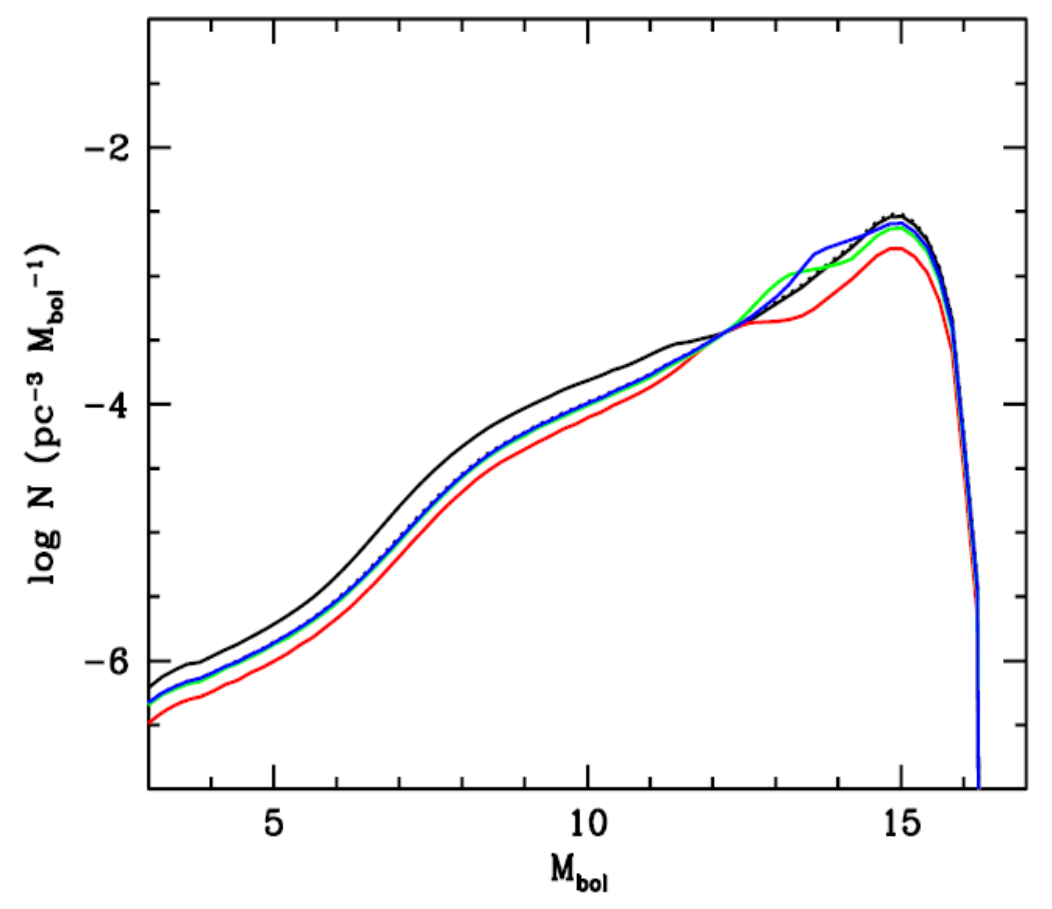


If the peak coincides with the normalization (red line) the bright branch falls below the standard

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 $t < t_0$; $t > t_0 + \Delta t$

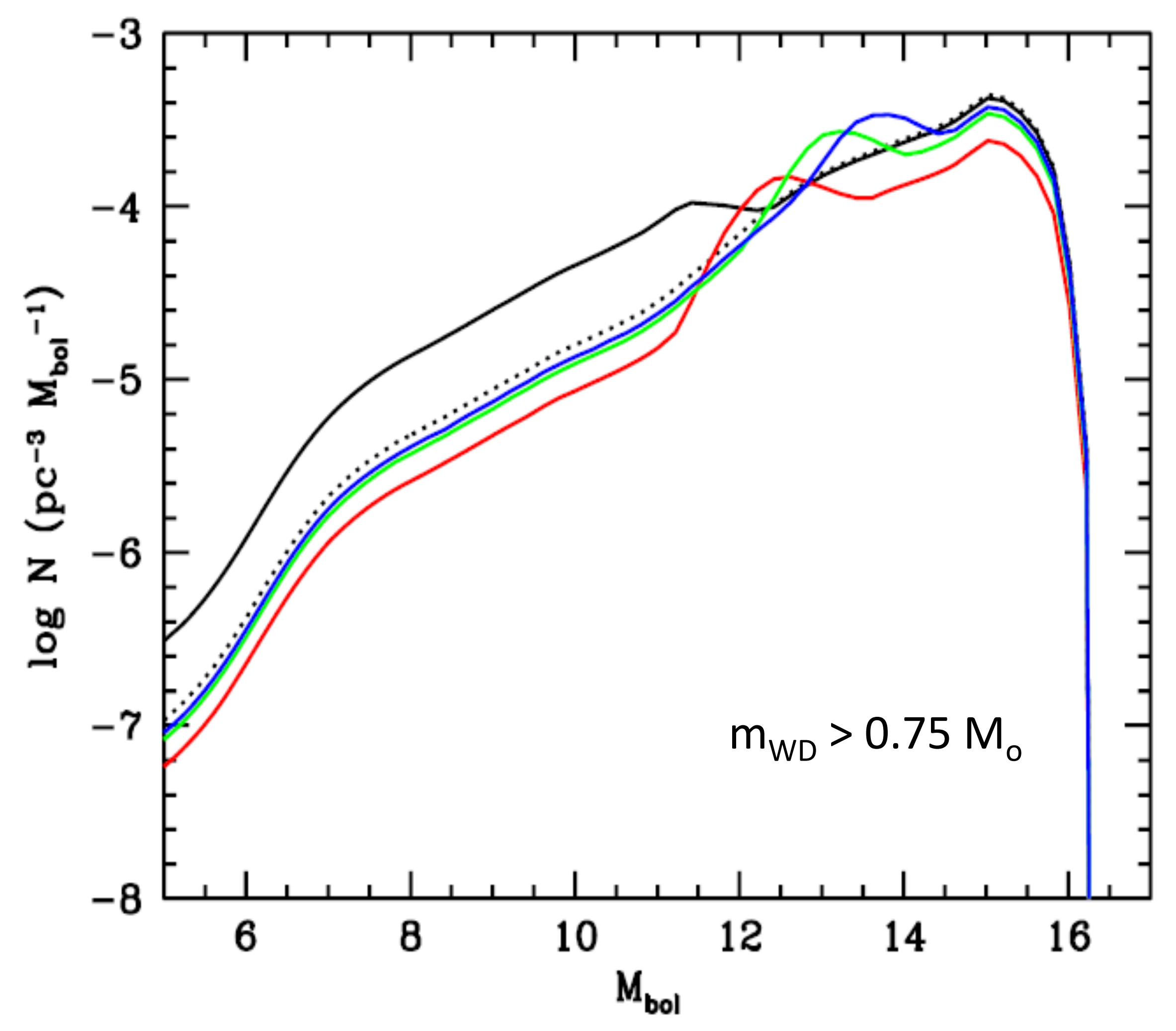


$$n(l) = \int_{M_{\min}}^{M_{\max}} \Phi(M)\Psi\left(T_{gal} - t_{cool} - t_{SP}\right)\tau_{cool}\, dM$$

In the case of massive WD

$$\mathrm{t}_{SP} \ll t_{cool}$$

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



The luminosity function of massive WD closely follows The SFR

Irregularities are detectable!

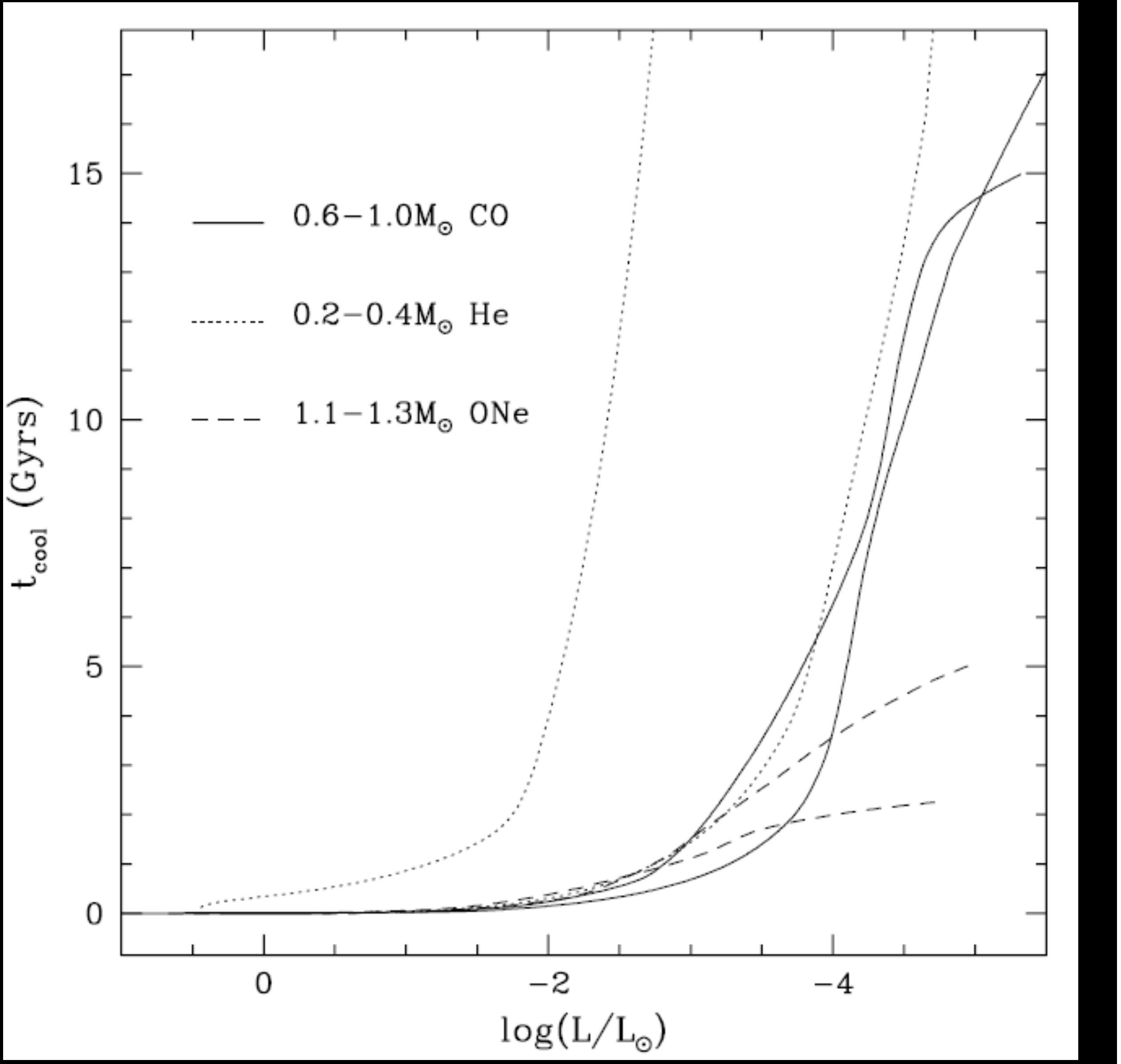
Influence of binaries:

Presence of He-white dwarfs

Mergers

Tidal heating

Non resolved binaries

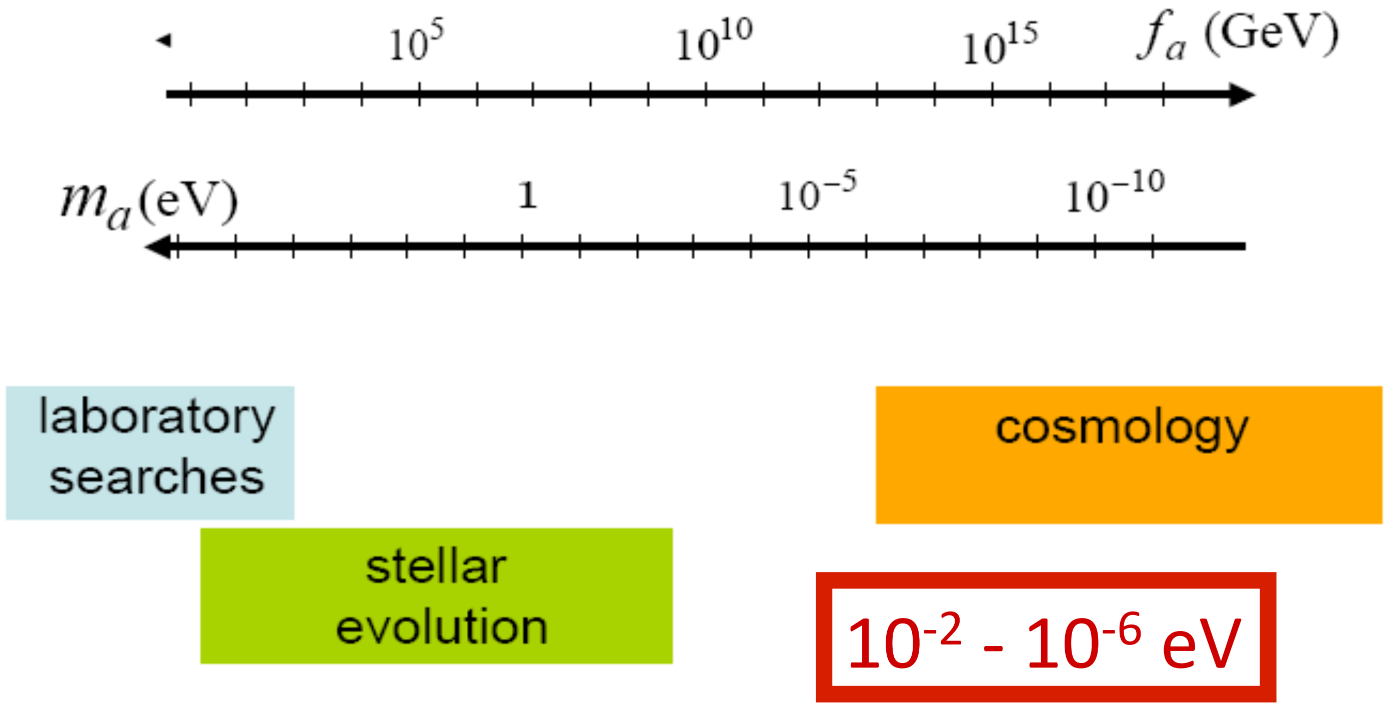


Contamination by He-WD

The axion case

- Axions were proposed as a solution to the strong CP problem
  - KVSZ model -> Axions couple to hadrons & photons
  - DFSZ model -> Axions also couple to electrons
- Coupling is determined by the Peccei-Quinn scale f_a which is related to the mass of the axion: $m_a = 6.0\ \mathrm{eV} \cdot (10^6\ \mathrm{GeV}/f_a)$
- Experiments have failed to detect axions
- Constraints from astrophysical arguments
  - Solar properties
  - Red giants (HB & AGB stars)
  - Core collapse supernovae
  - Cosmological considerations

The remaining axion window



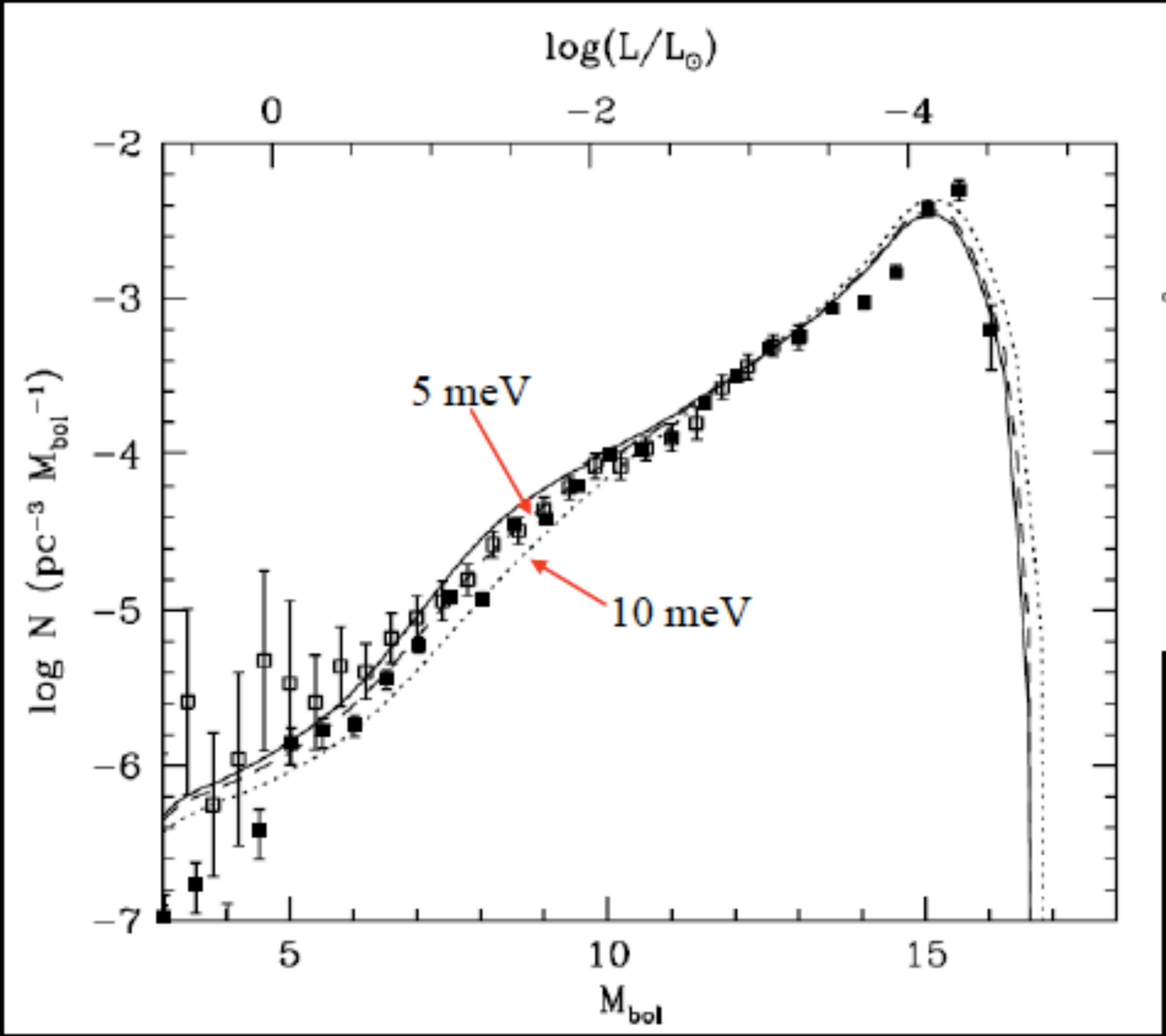
laboratory searches

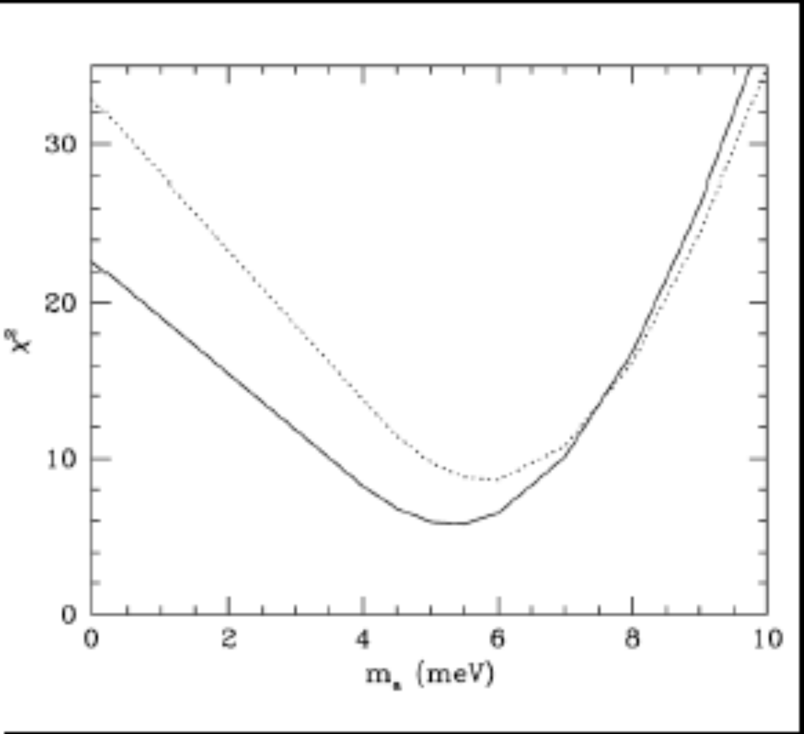
stellar evolution

cosmology

10^{-2} - 10^{-6} eV

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





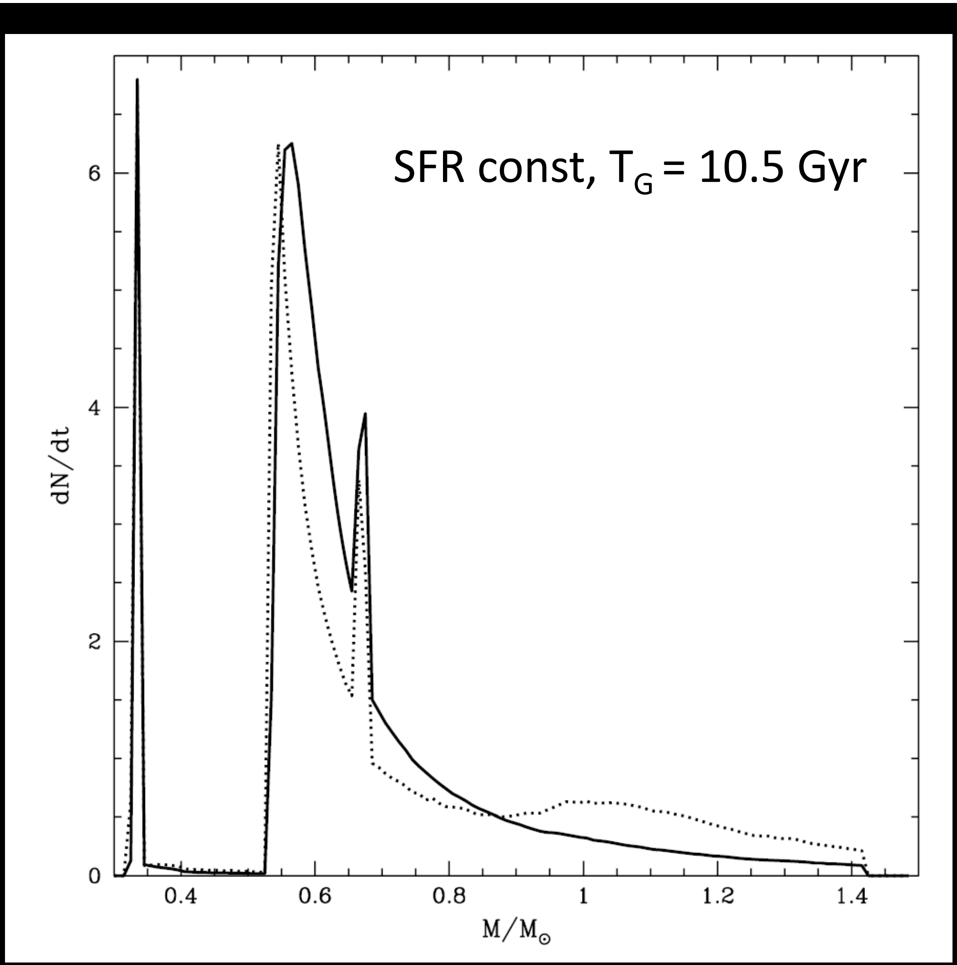
Isern et al’08

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

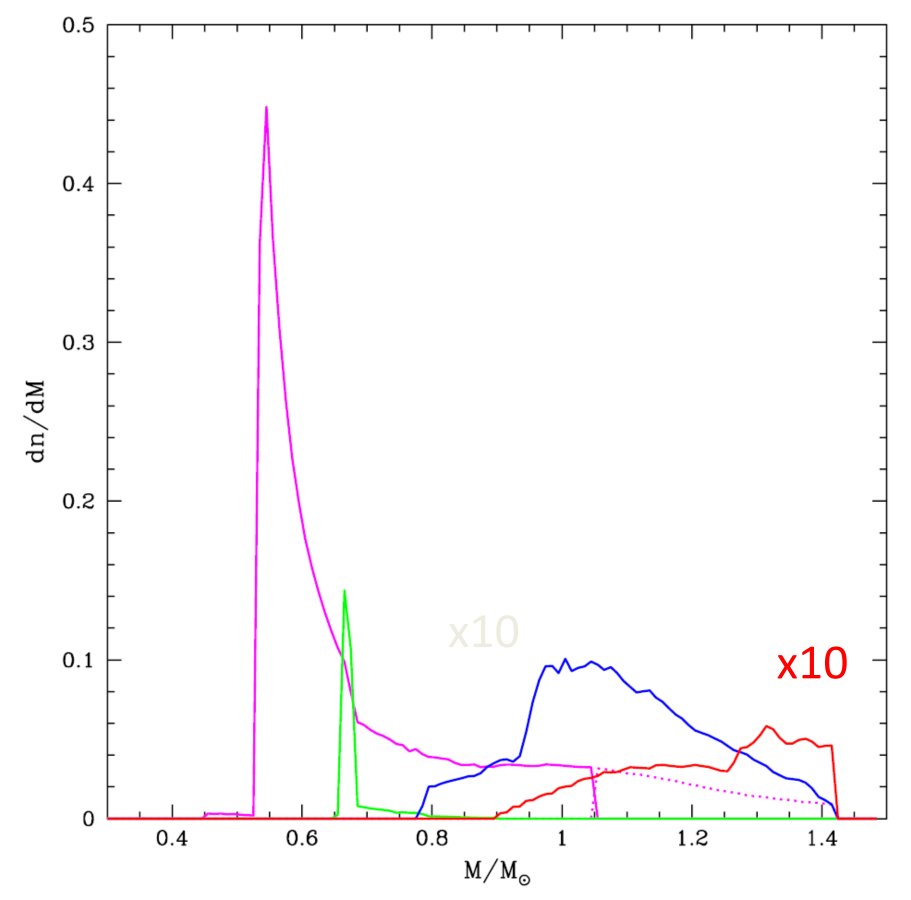
Birthrate calculation

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



SFR const, $T_G = 10.5$ Gyr

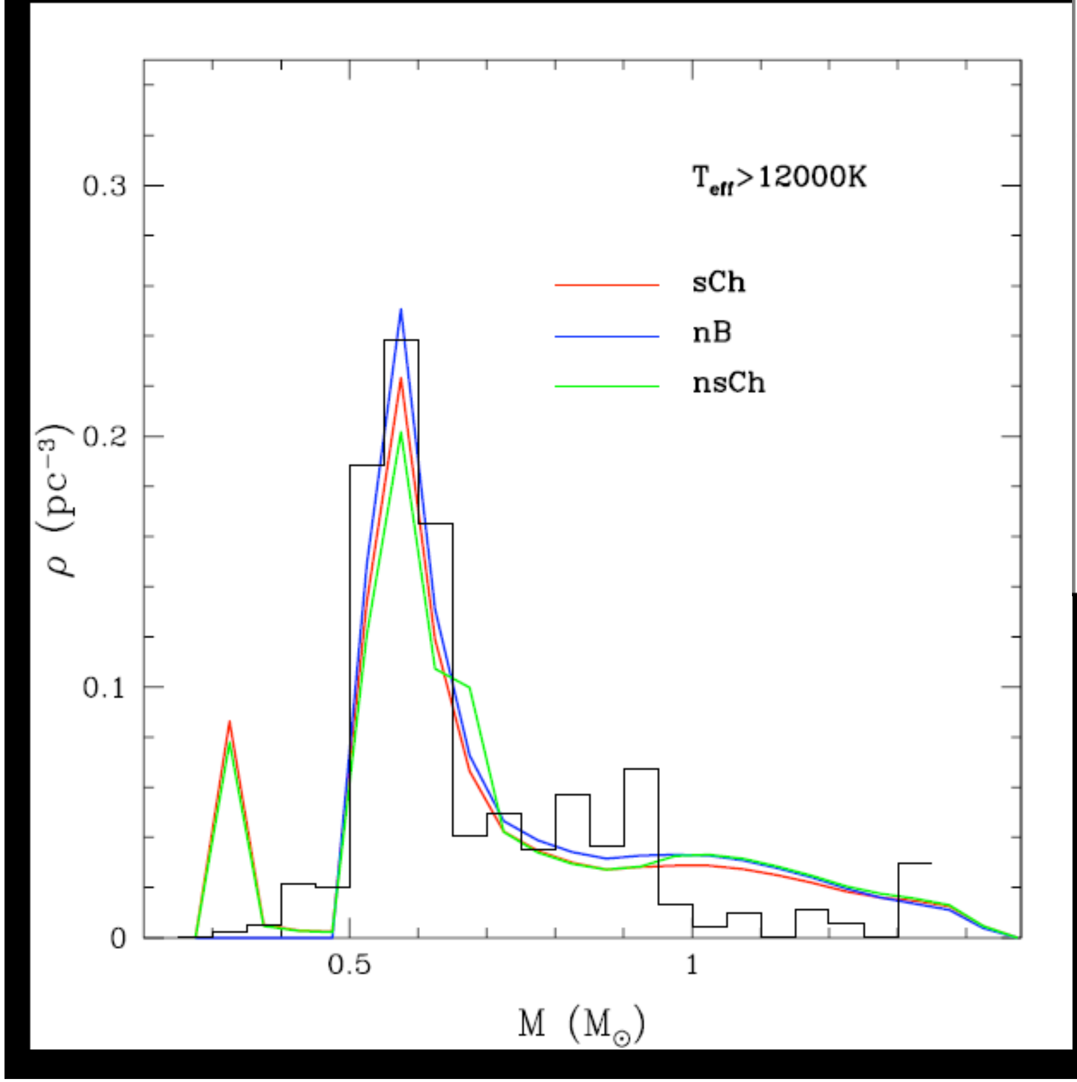


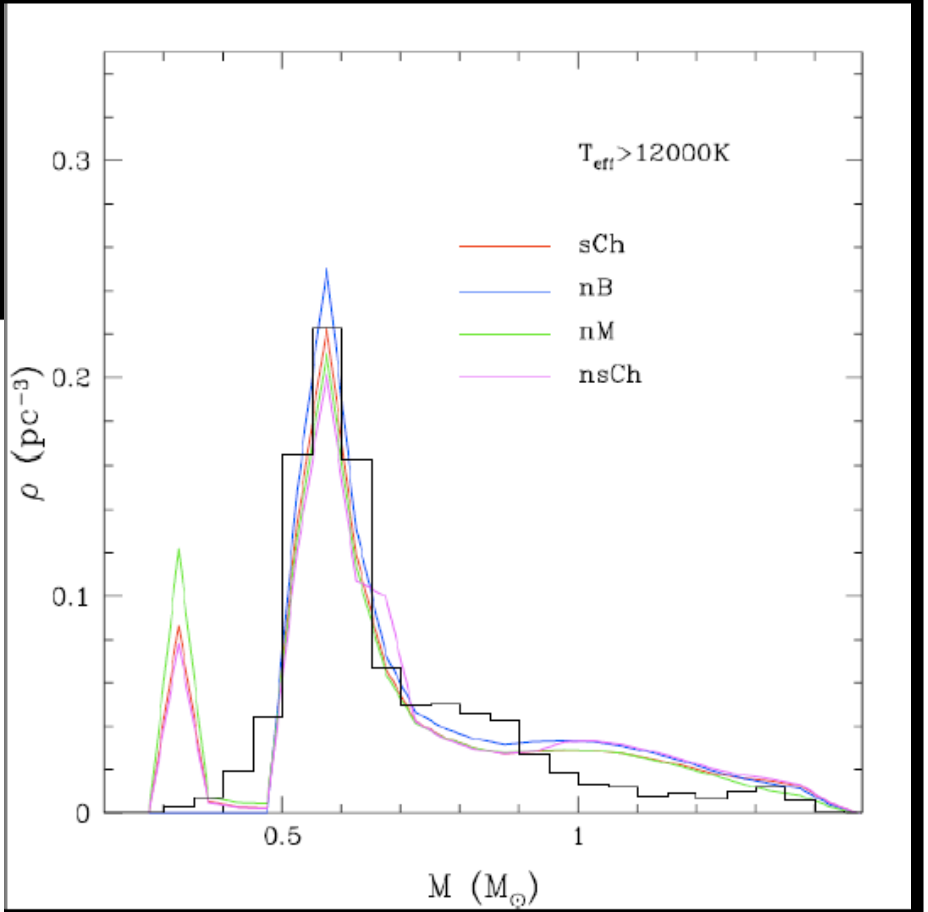
Single:
M=1.05

He + He
M=0.65
n_{HeHe} = 58%
n_{CO}= 42%

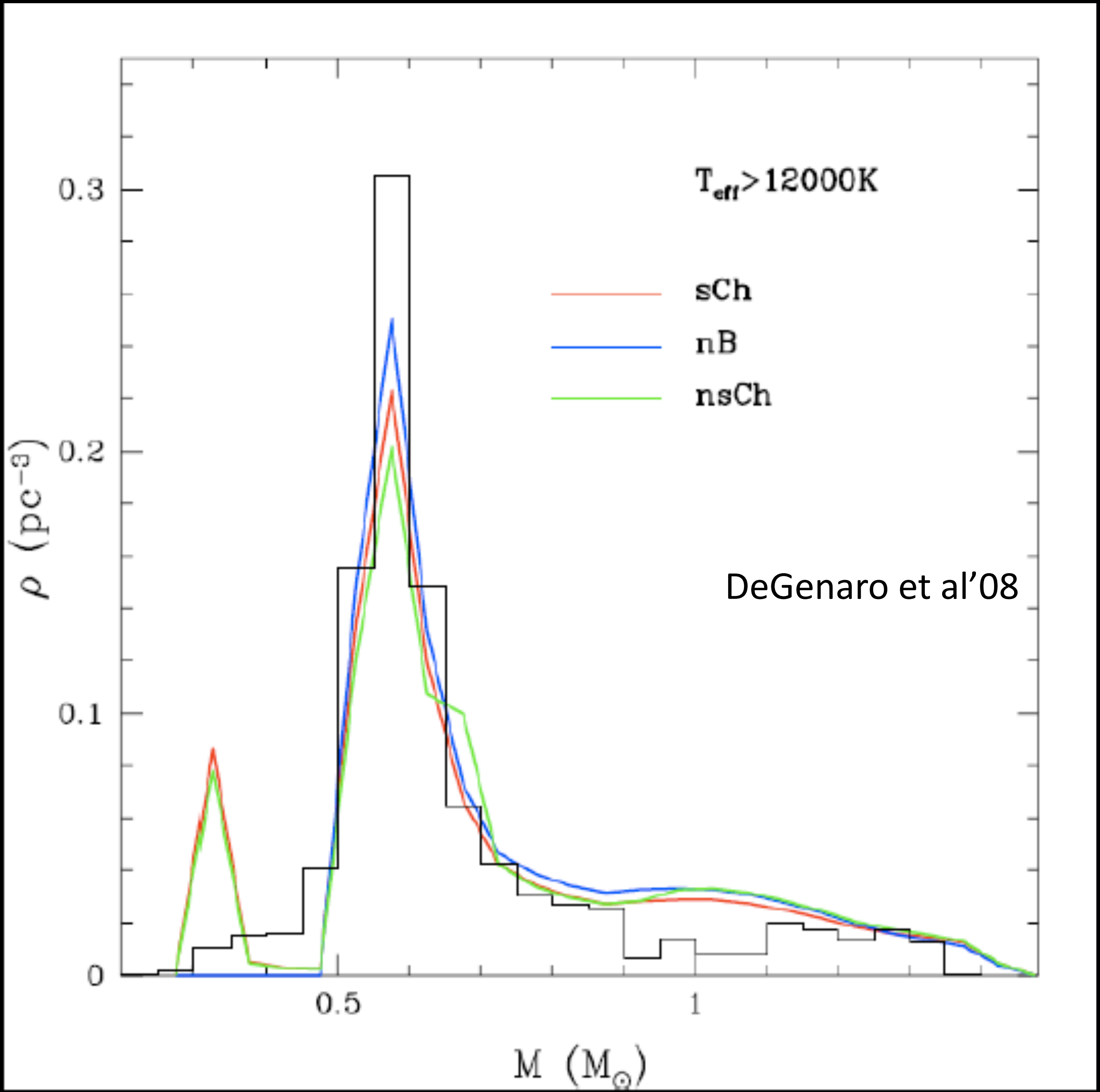
CO+He: ~ 20%
CO+Co: ~ 15%

Liebert et al'05
Bin average 0.05

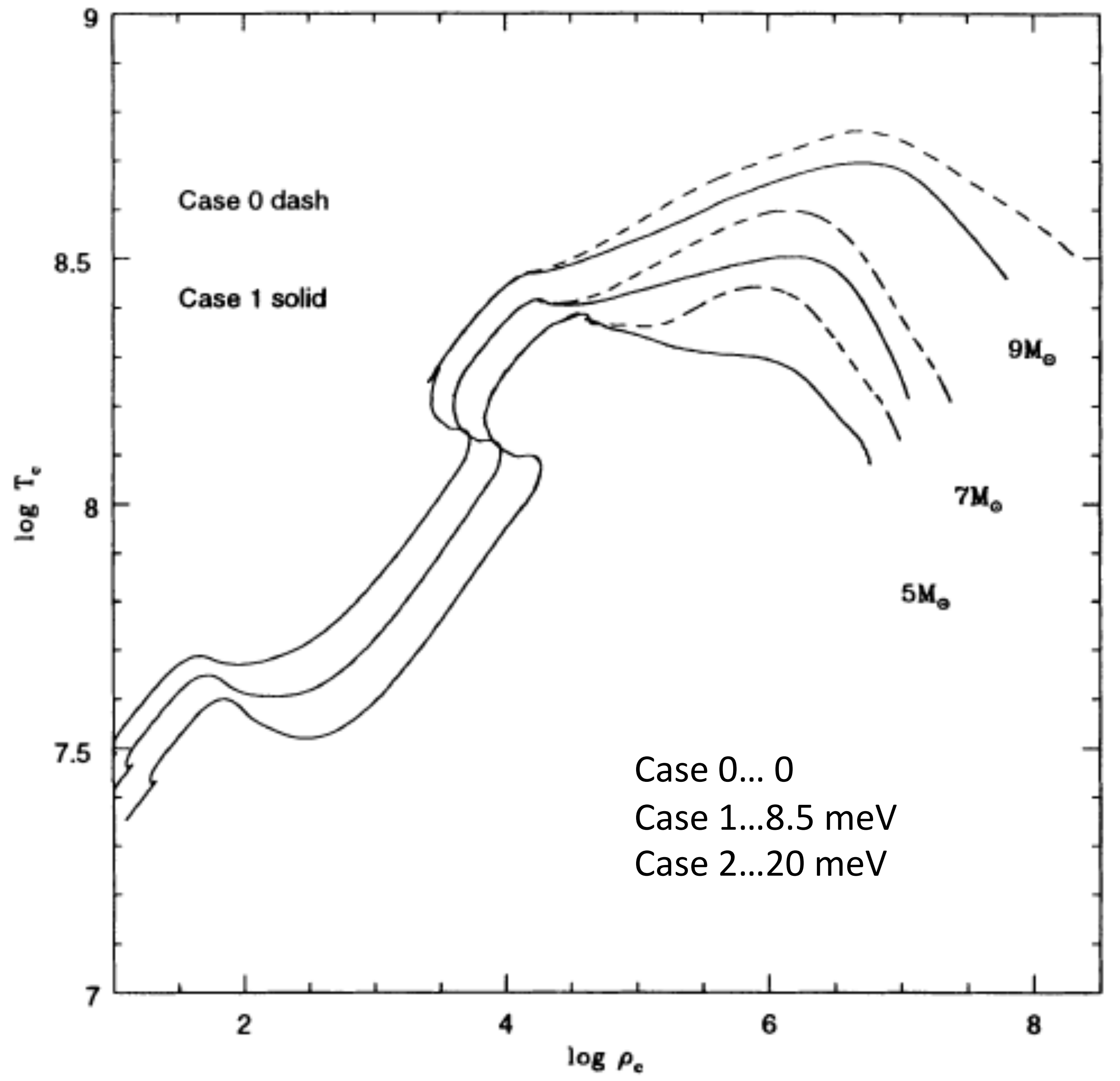




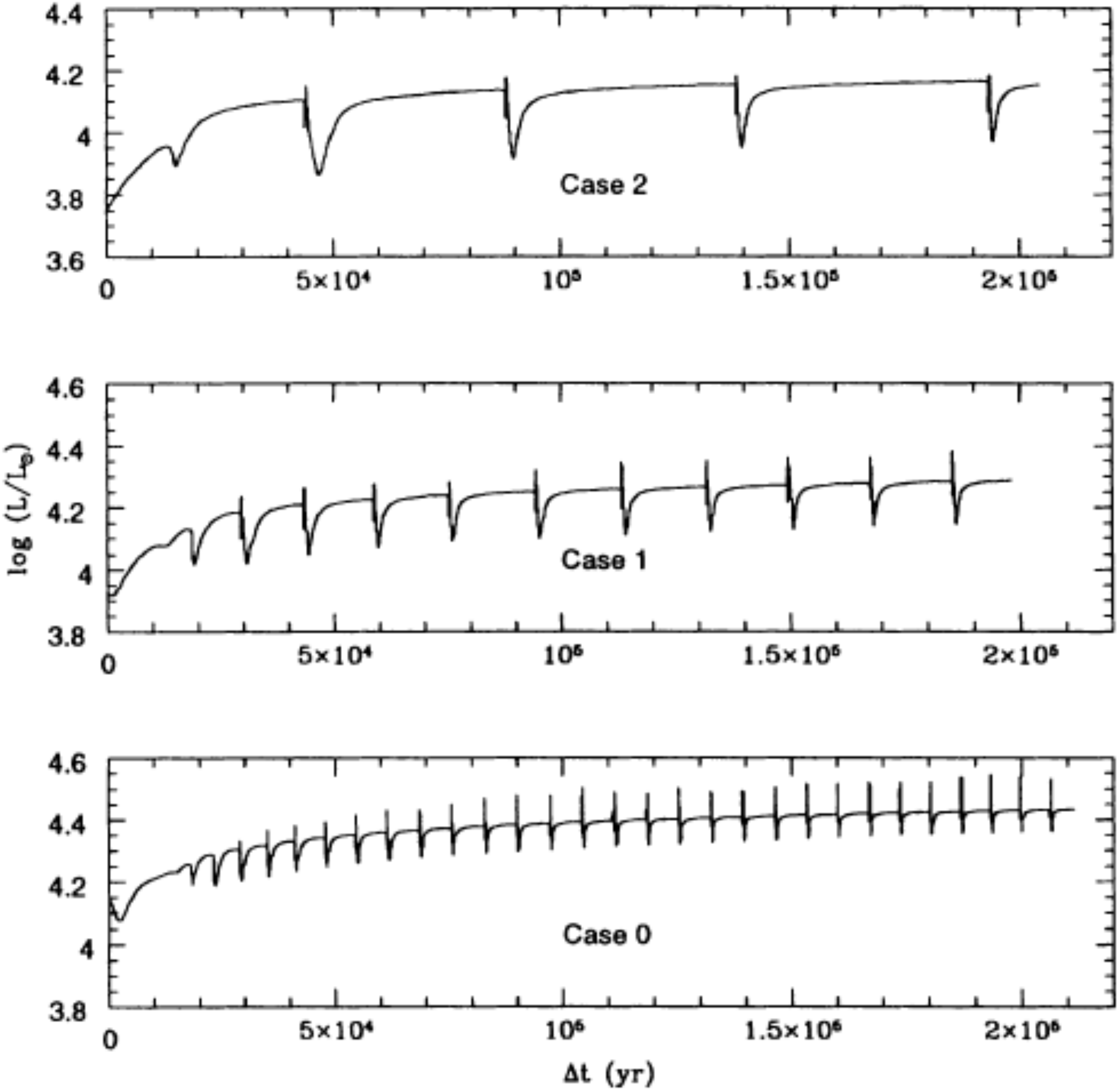
Gaussian errors included

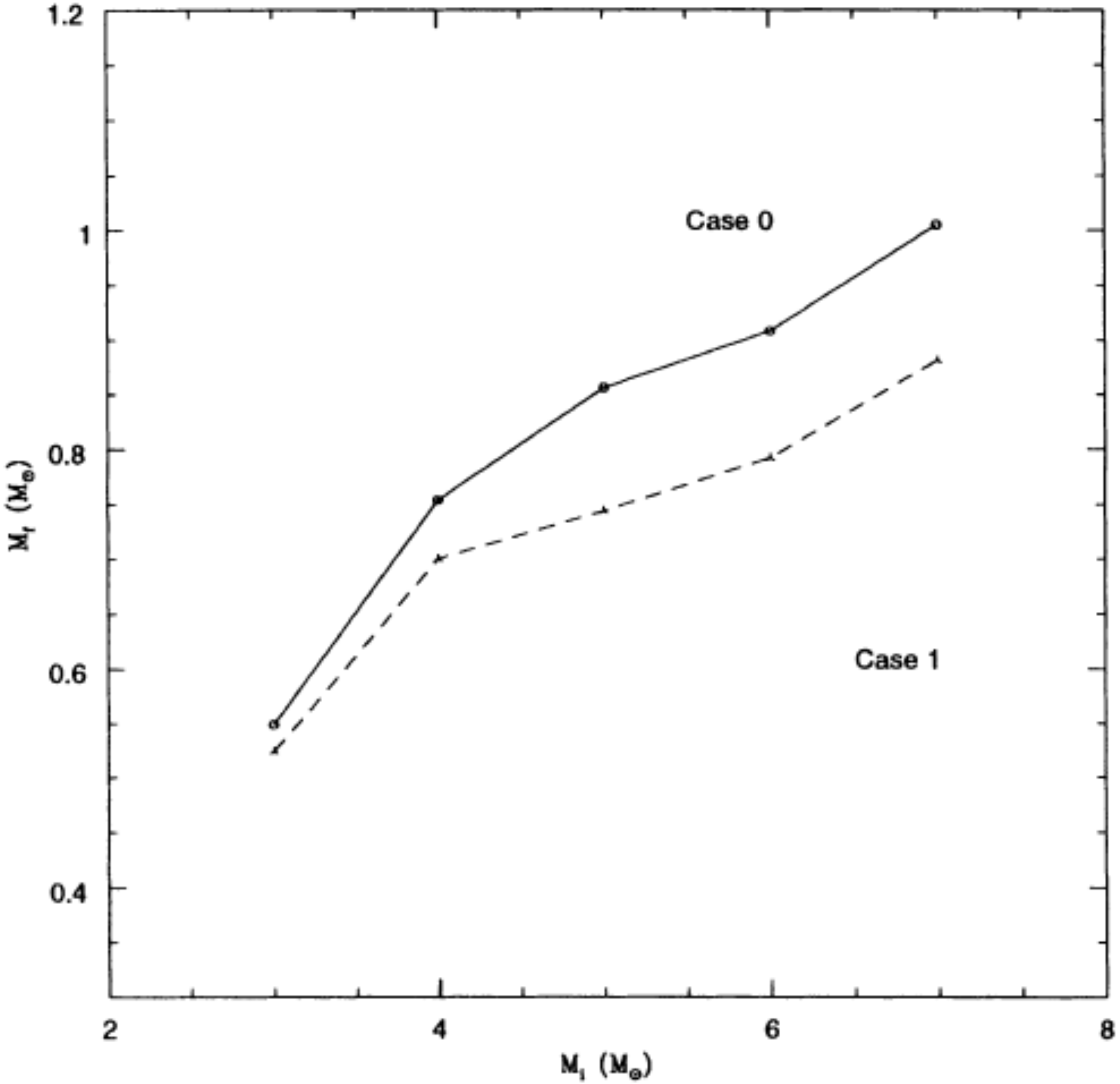


DeGenaro et al’08

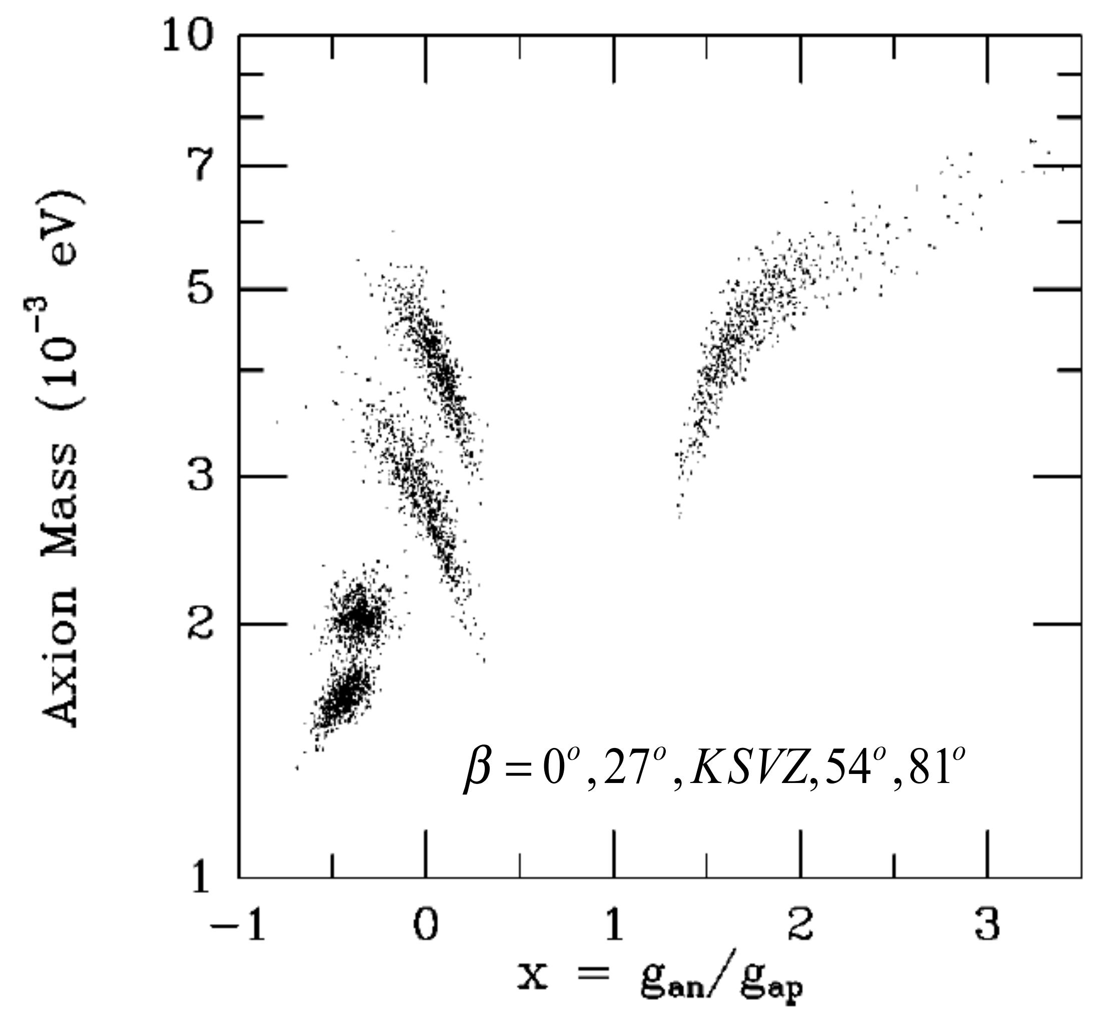


Case 0… 0
Case 1…8.5 meV
Case 2…20 meV


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


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

Influence on core collapse supernovae



Keil et al ‘97

Nucleon bremsstrahlung is dominant

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