What are white dwarfs telling us about the structure and evolution of the Galaxy

Jordi Isern

Institute for Space Sciences

ICE (CSIC-IEEC)

Supernovae: a survey of current research
Cambridge, June-July 1981

[redacted]

White dwarf cooling

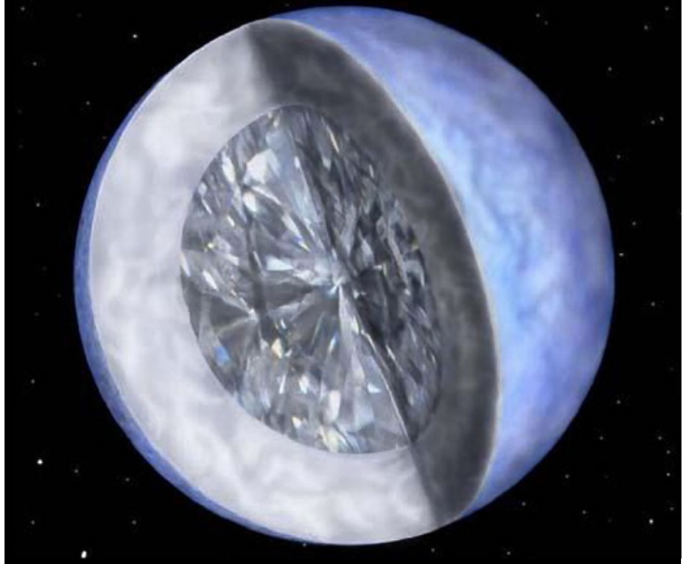
$$L + L_\nu = -\int_{M_{WD}} c_V \frac{dT_C}{dt} dm - \int_{M_{WD}} T \left(\frac{\partial P}{\partial T} \right)_{V,x} \frac{dV}{dt} dm + (l_s + e_s)\dot{m}_e + \dot{\varepsilon}$$

A L(T_C) relationship is necessary to solve this equation

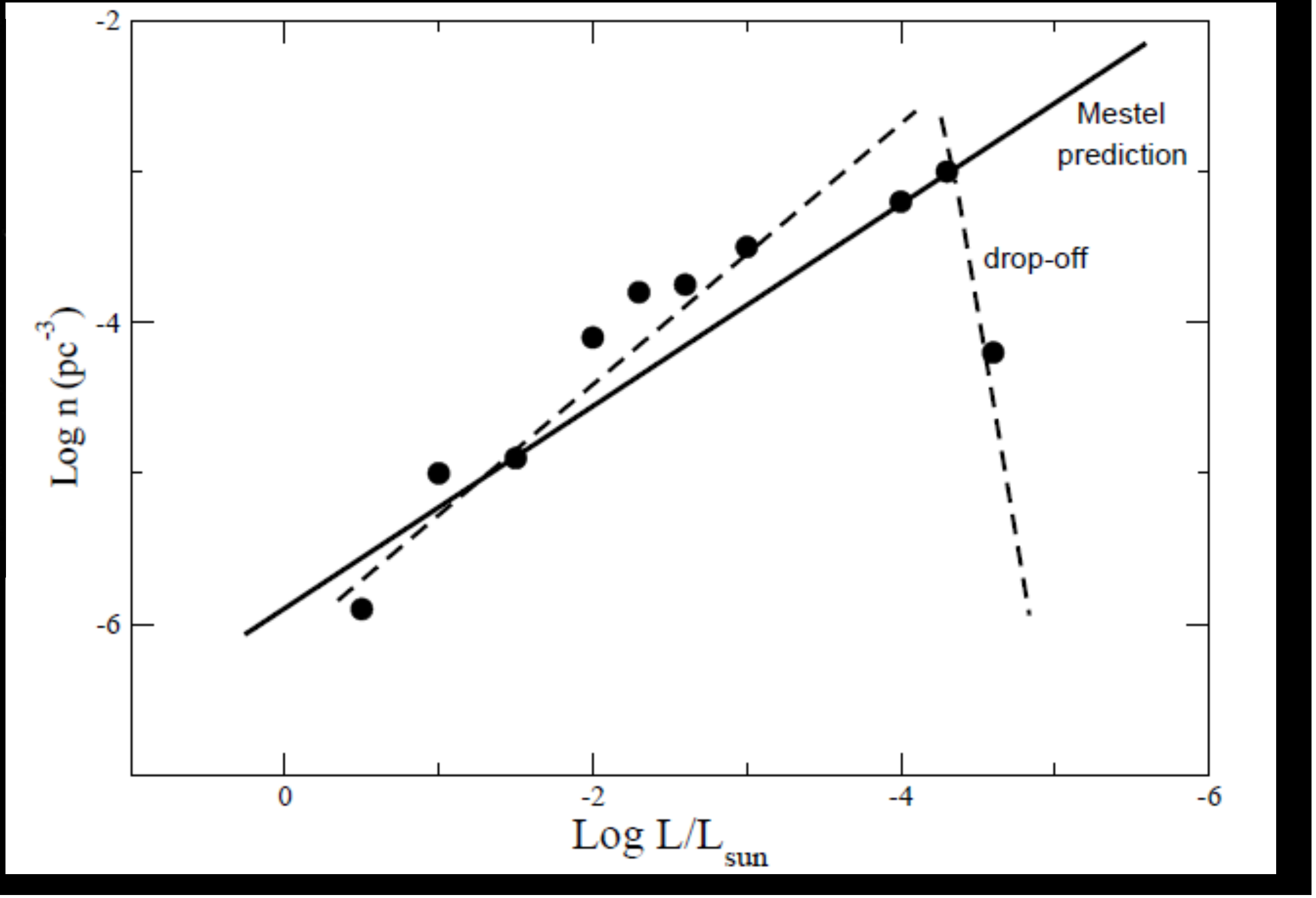
It depends on the properties of the envelope.

$$L \propto T^\alpha$$

$$\alpha \approx 2.5 - 2.7$$



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

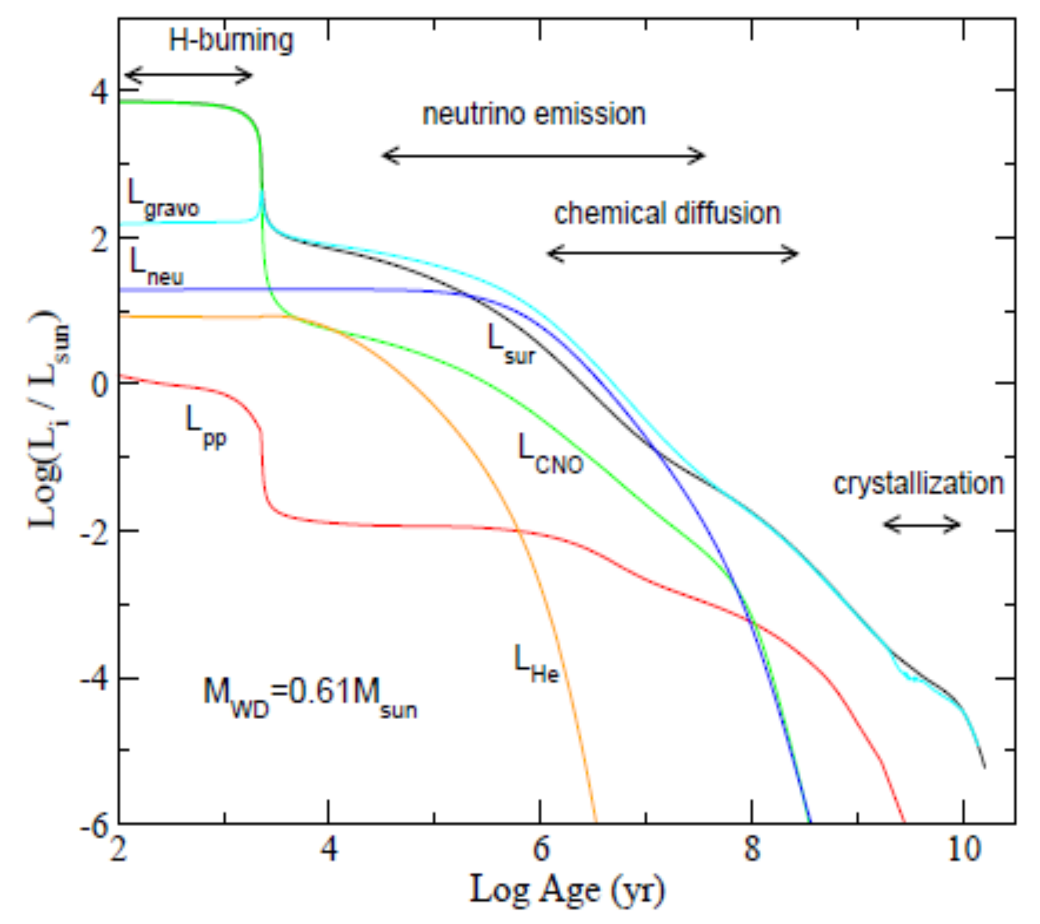
t_{PS} is the lifetime of the progenitor

τ_{cool} is the characteristic cooling time

hidden an IMFR

If n(L) and the evolutionary sequences are known it is possible to use the WDLF to obtain information about the Galaxy

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.

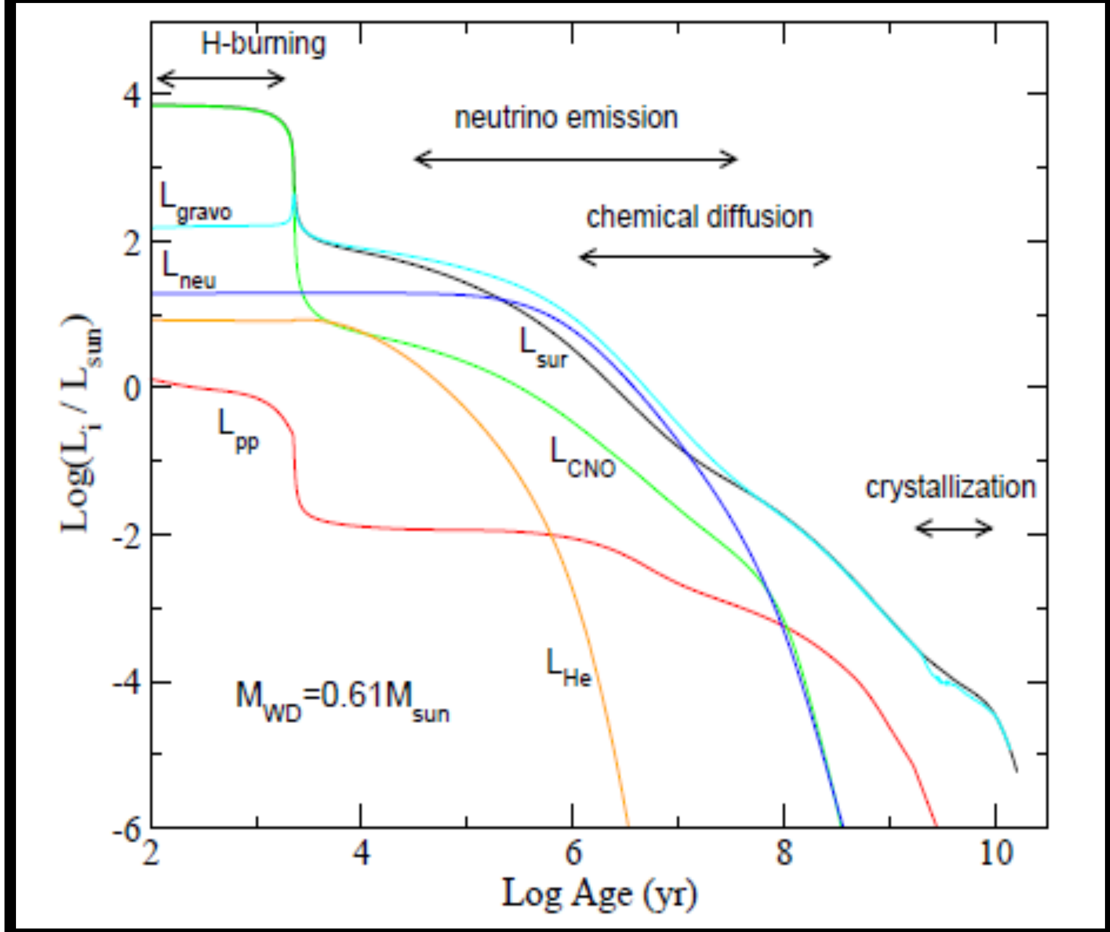
Neutrinos dominate & thermal structures converge

Very short epoch (< 10^8 yr)

The cooling process (II)

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

Gravothermal energy



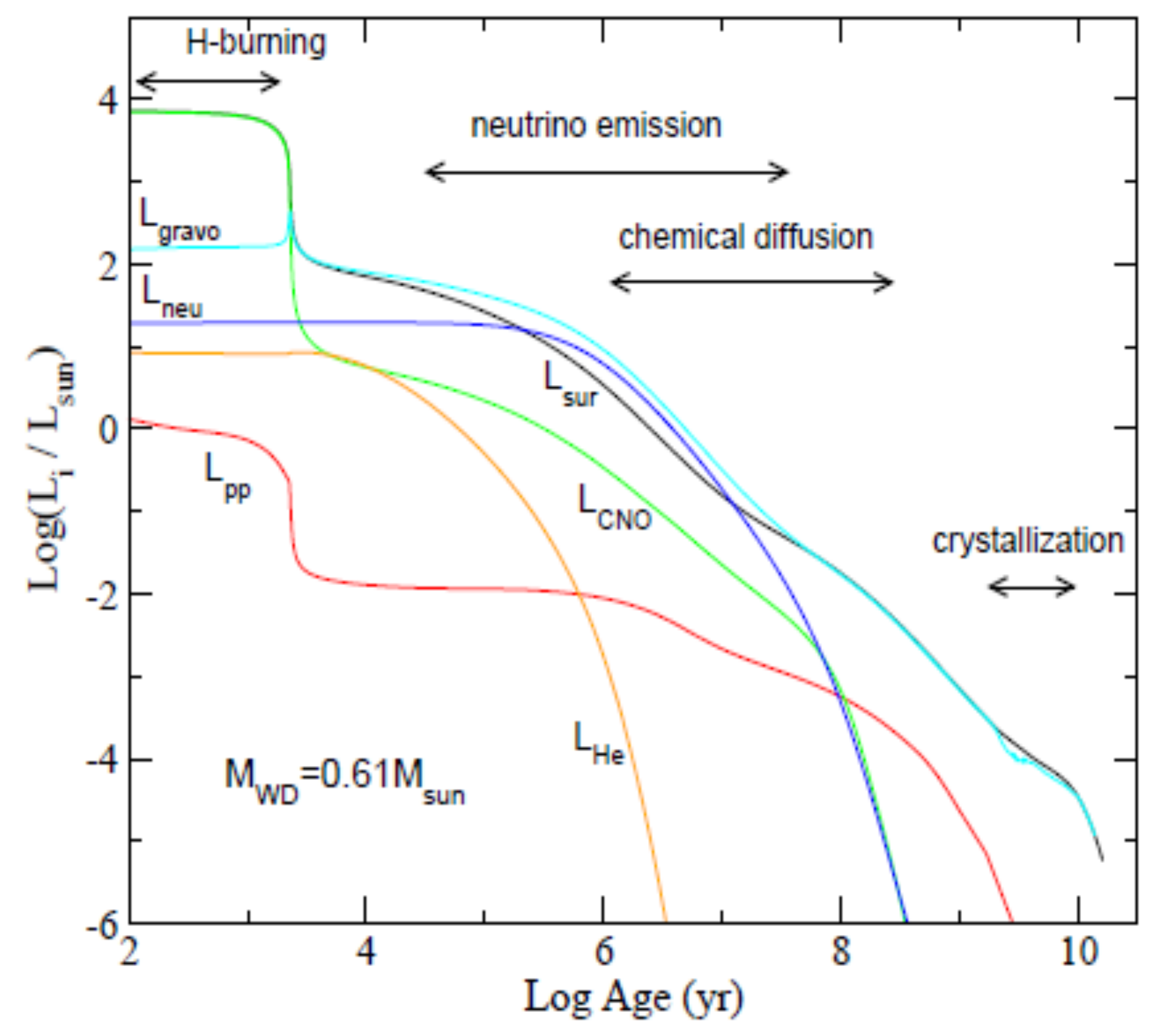
Coulomb plasma

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 [$-3 > \log(L/L_o) > -4.5$]

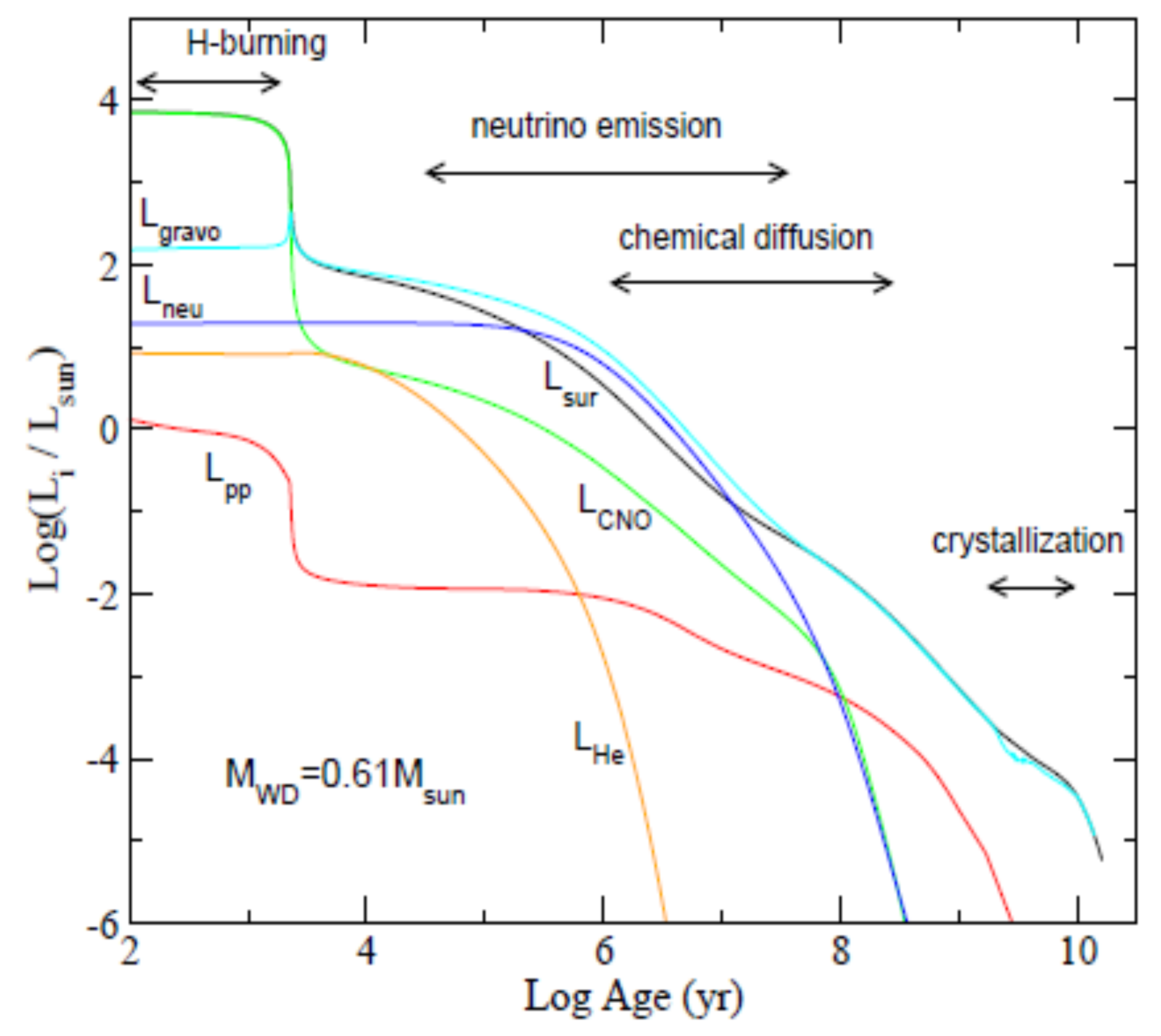


Latent heat
(≈ kT_s per particle)

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

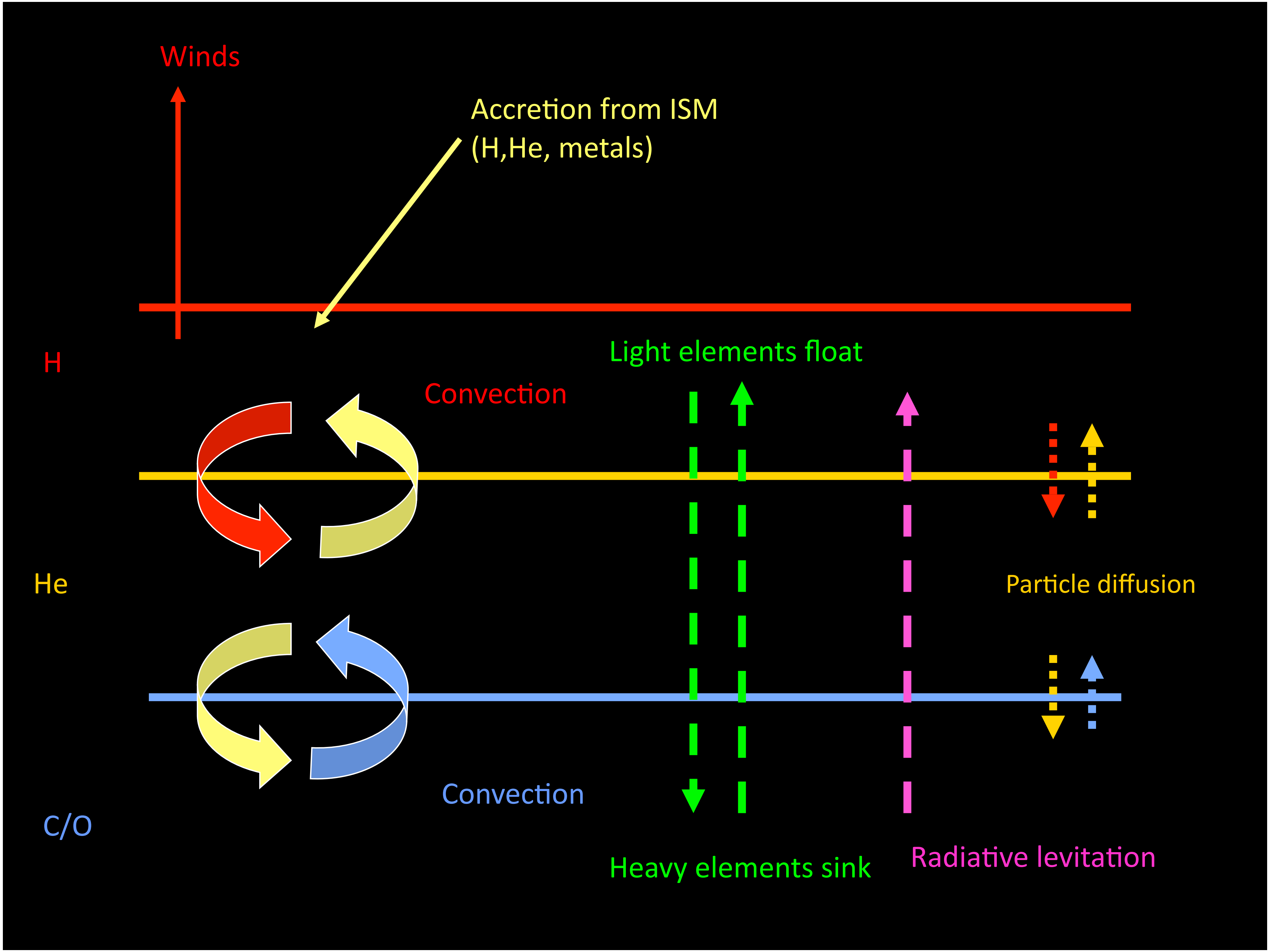
The cooling process (IV)

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

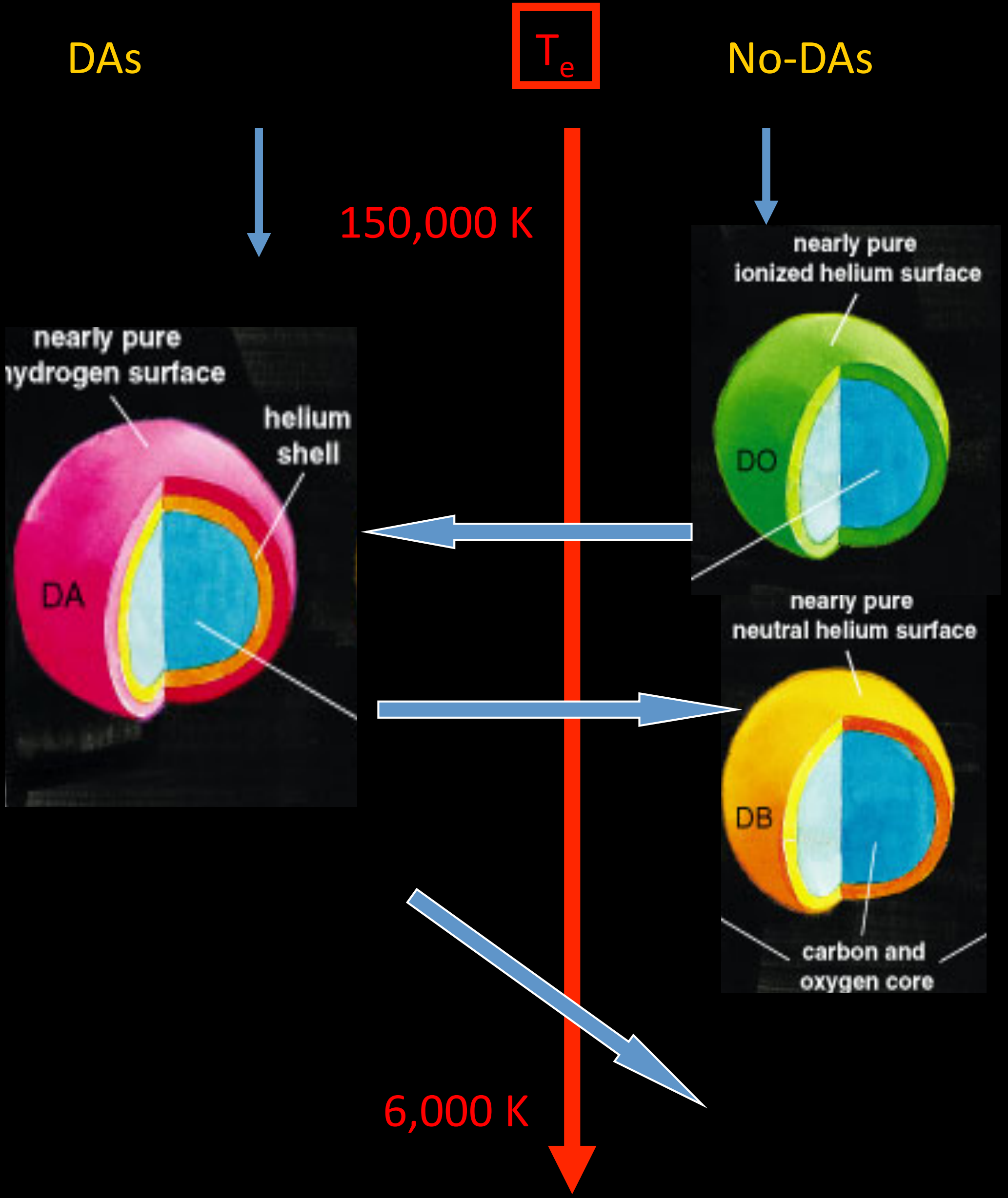


At low temperatures, the specific heat follows the Debye law

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


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



DAs

T_e

No-DAs

150,000 K

6,000 K

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

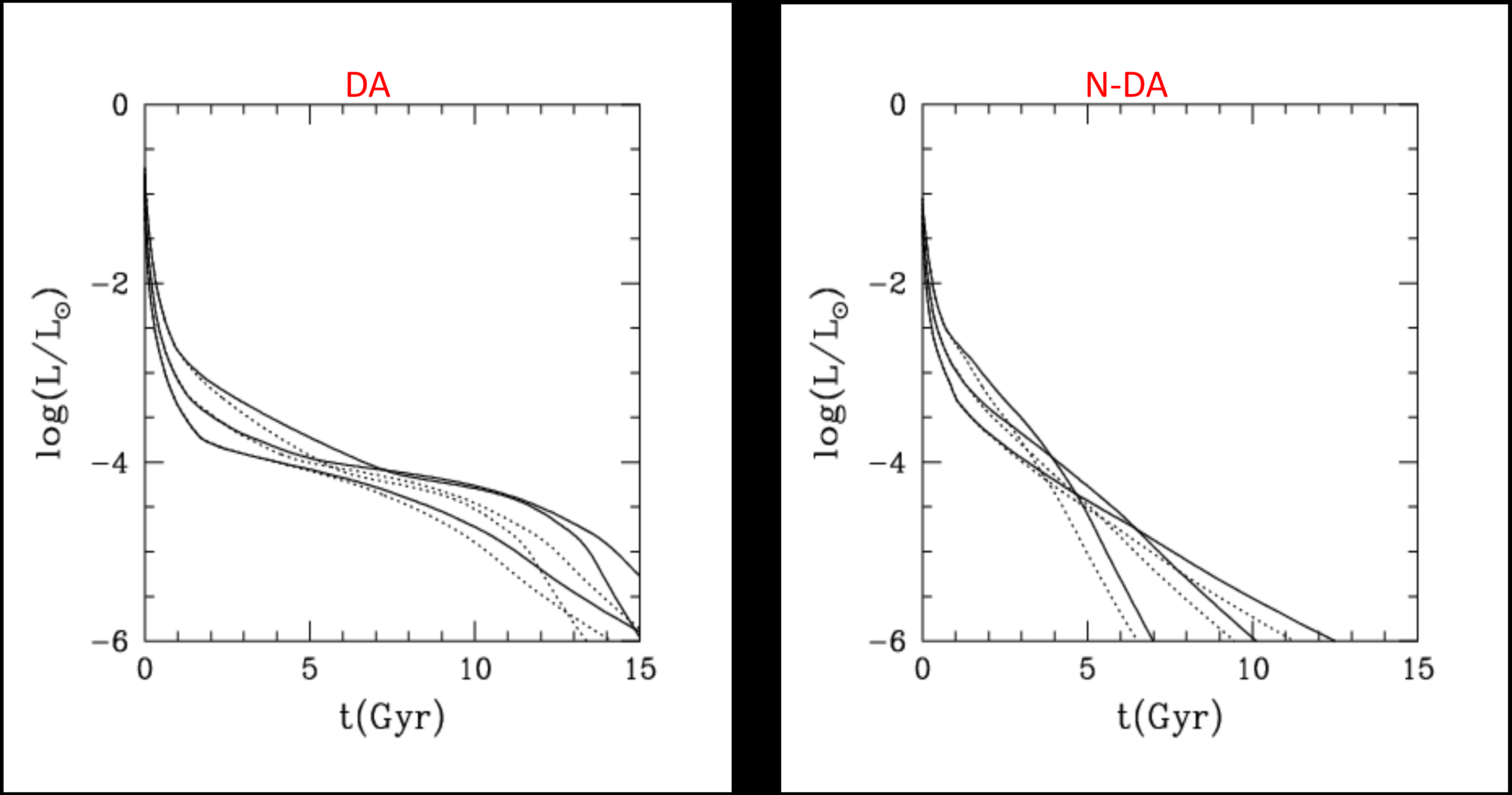
The He layer

- 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

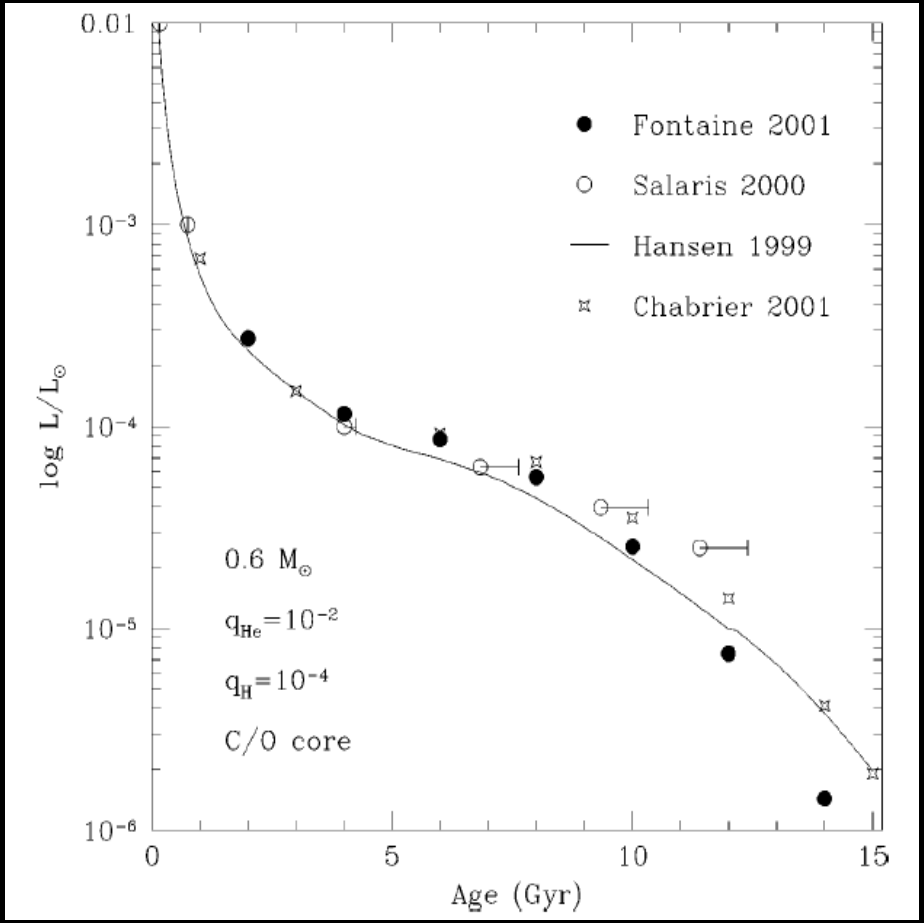
Is the origin of the DA, n-DA character:

- primordial ?
- mixing?
- both?

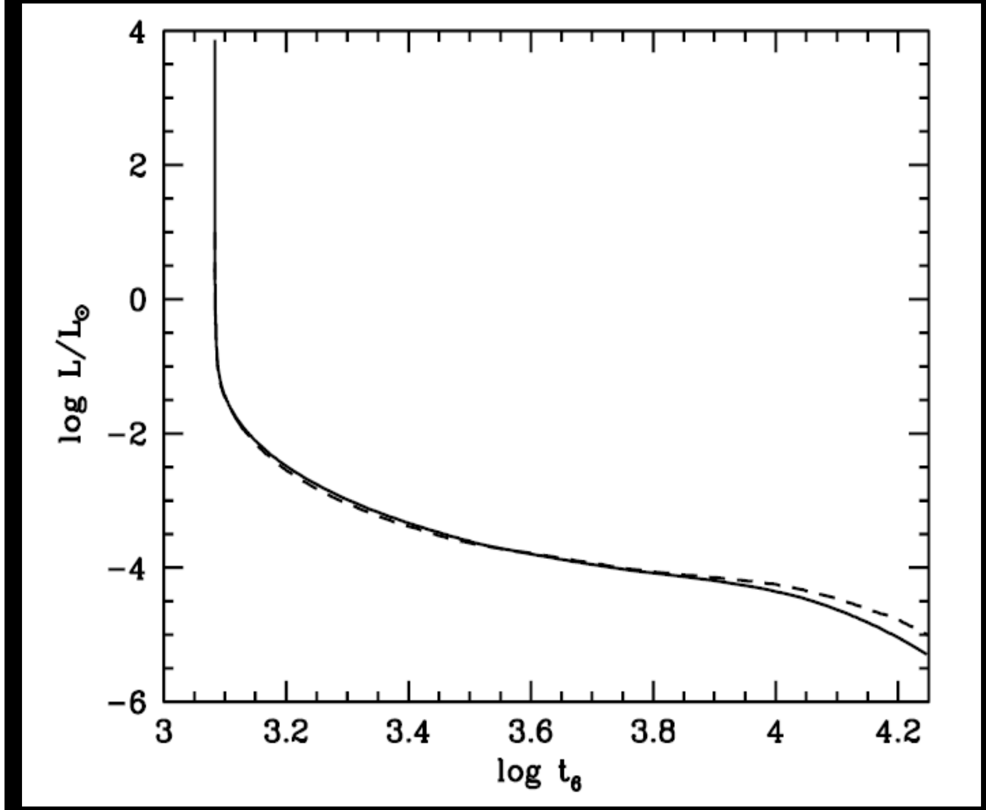
Luminosity versus time
(dotted lines without sedimentation)



Comparison between cooling models

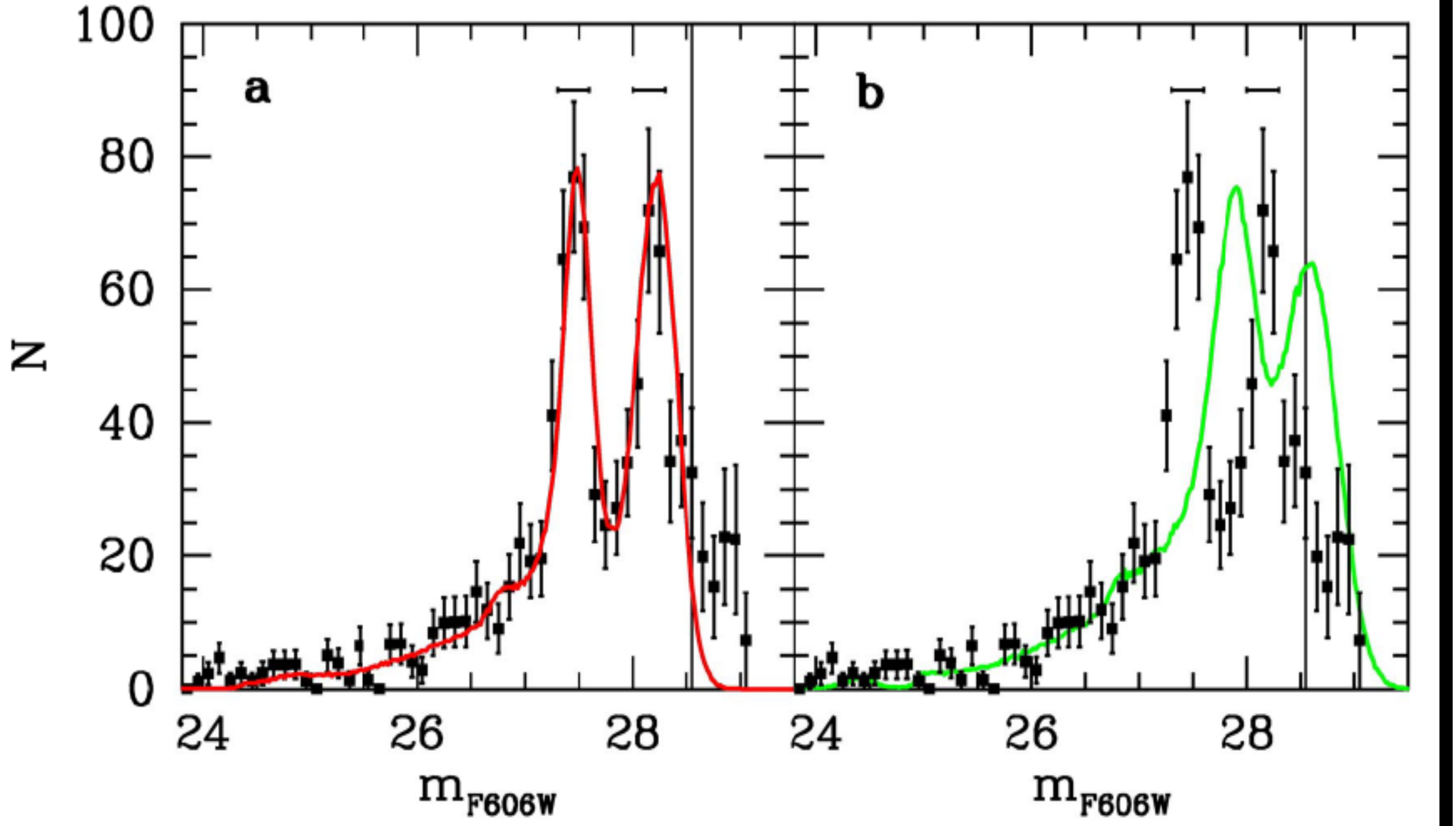


Hansen & Liebert'03



___: Renedo et al 2010

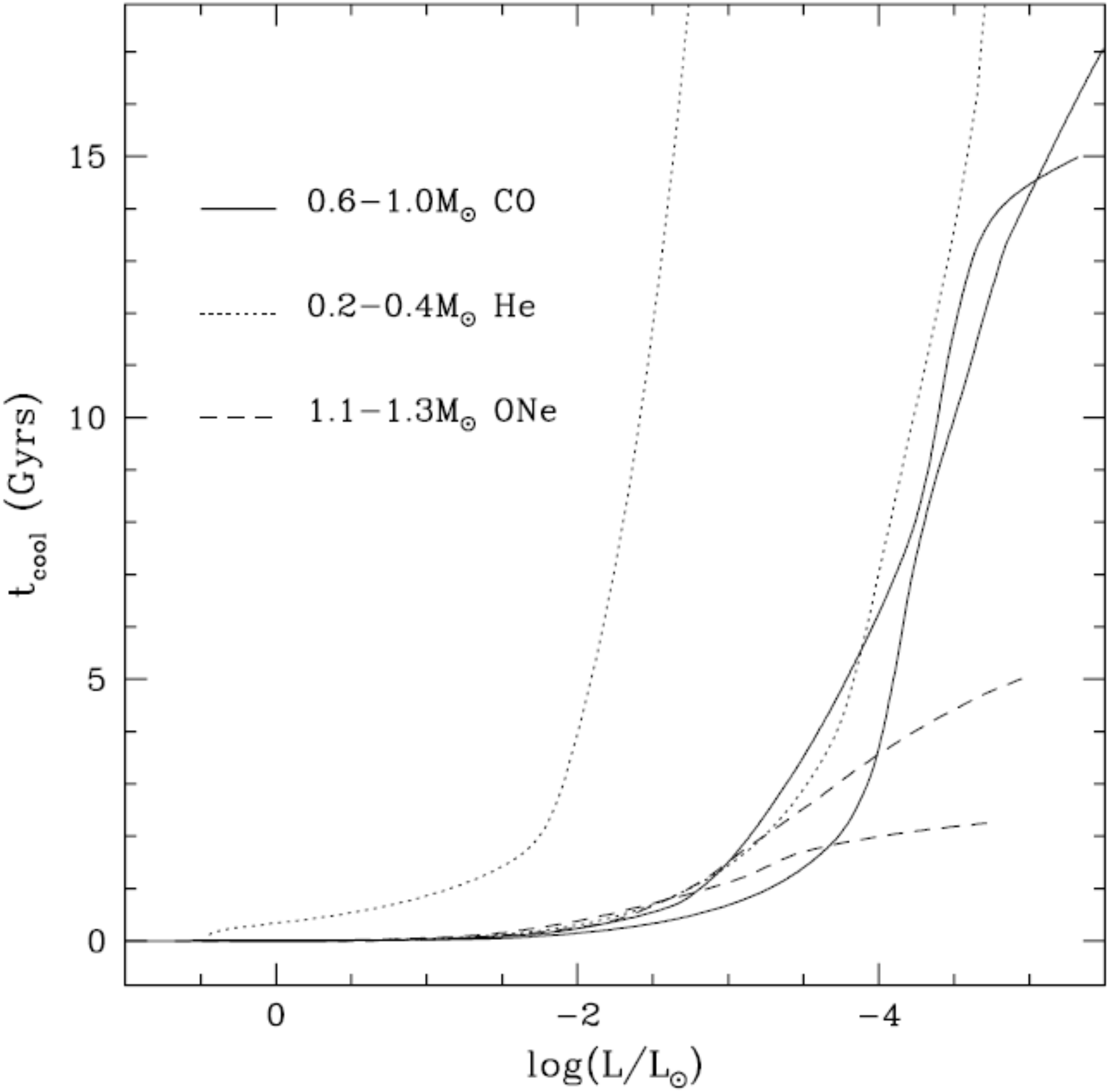
---- : Salaris et al 2010



Luminosity function of NGC6791

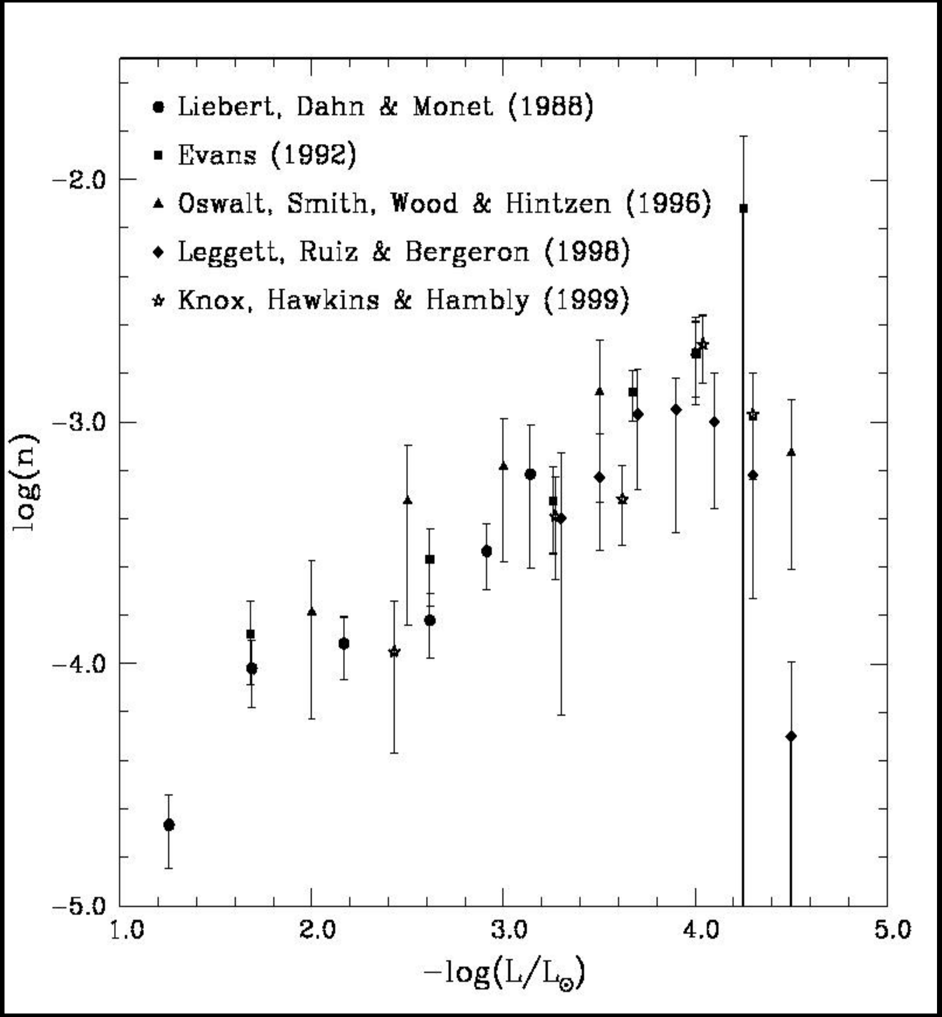
García Berro et al'10, NatureGarcía Berro et al'10,
Nature, 465,194,465,194

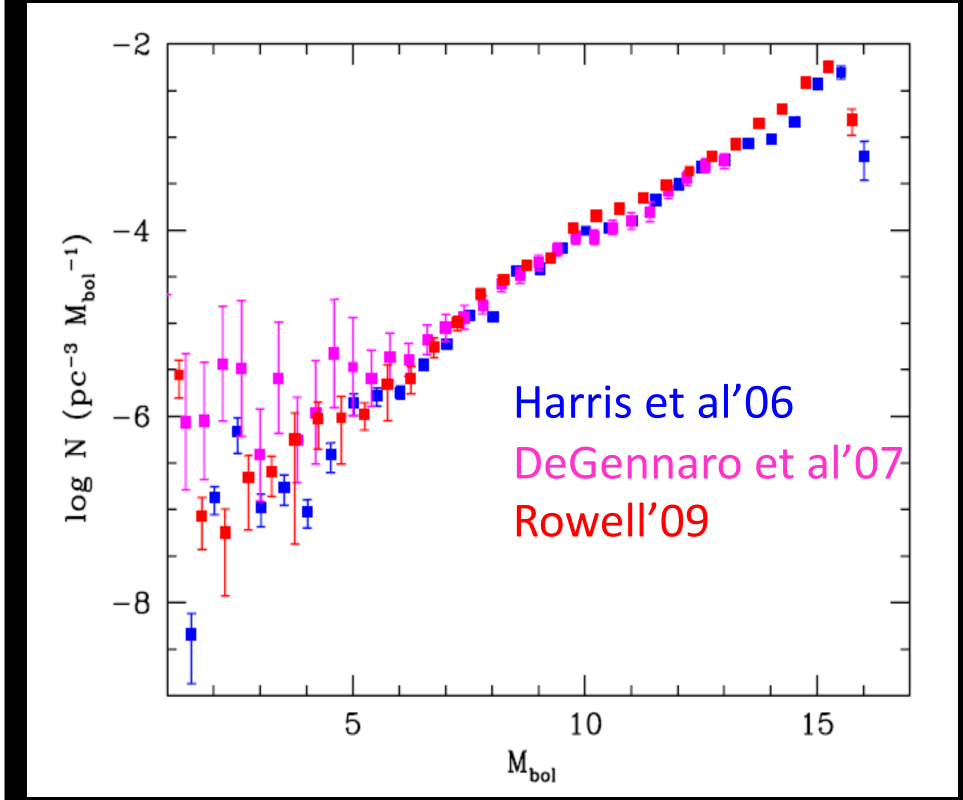
Age of NGC6791
Turn off Main Sequence: 8 Gyr
WD age (no sed) : 6 Gyr (green)
WD age (sed): 8 Gyr (red)


t_{cool} (Gyrs)
15
10
5
0
0
−2
−4
$\log(L/L_\odot)$
0.6−1.0$M_\odot$ CO
0.2−0.4$M_\odot$ He
1.1−1.3$M_\odot$ ONe

Surveys are more and more accurate and significative

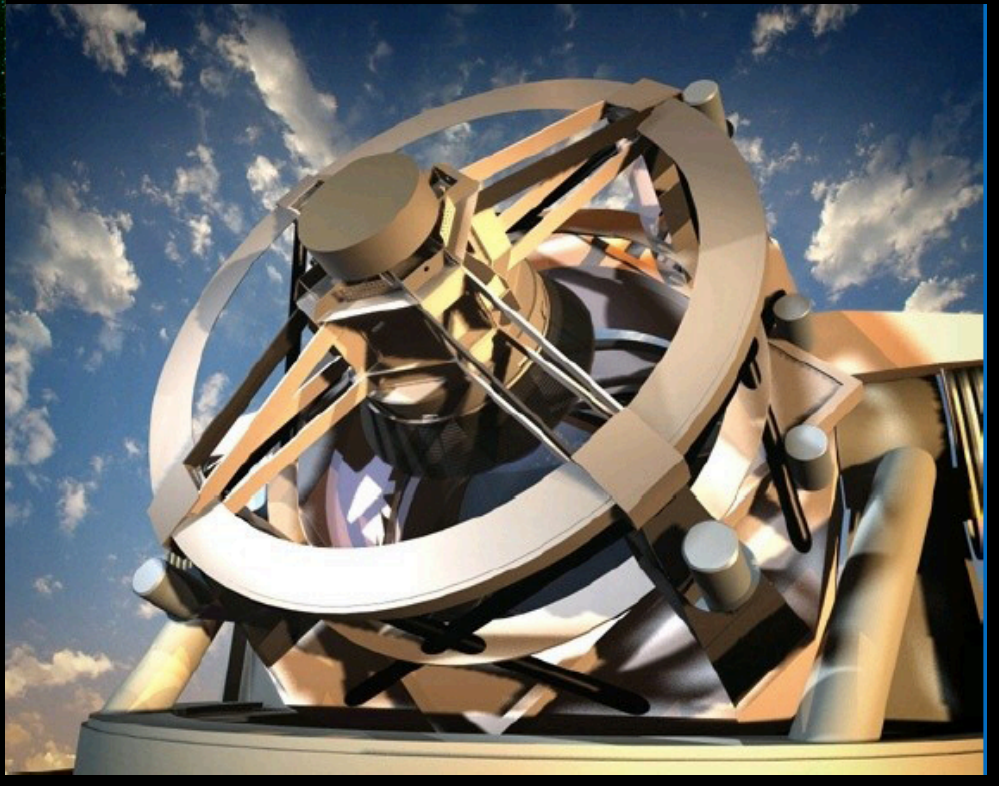
Sample of WD:
High precision LF





400,000 WD

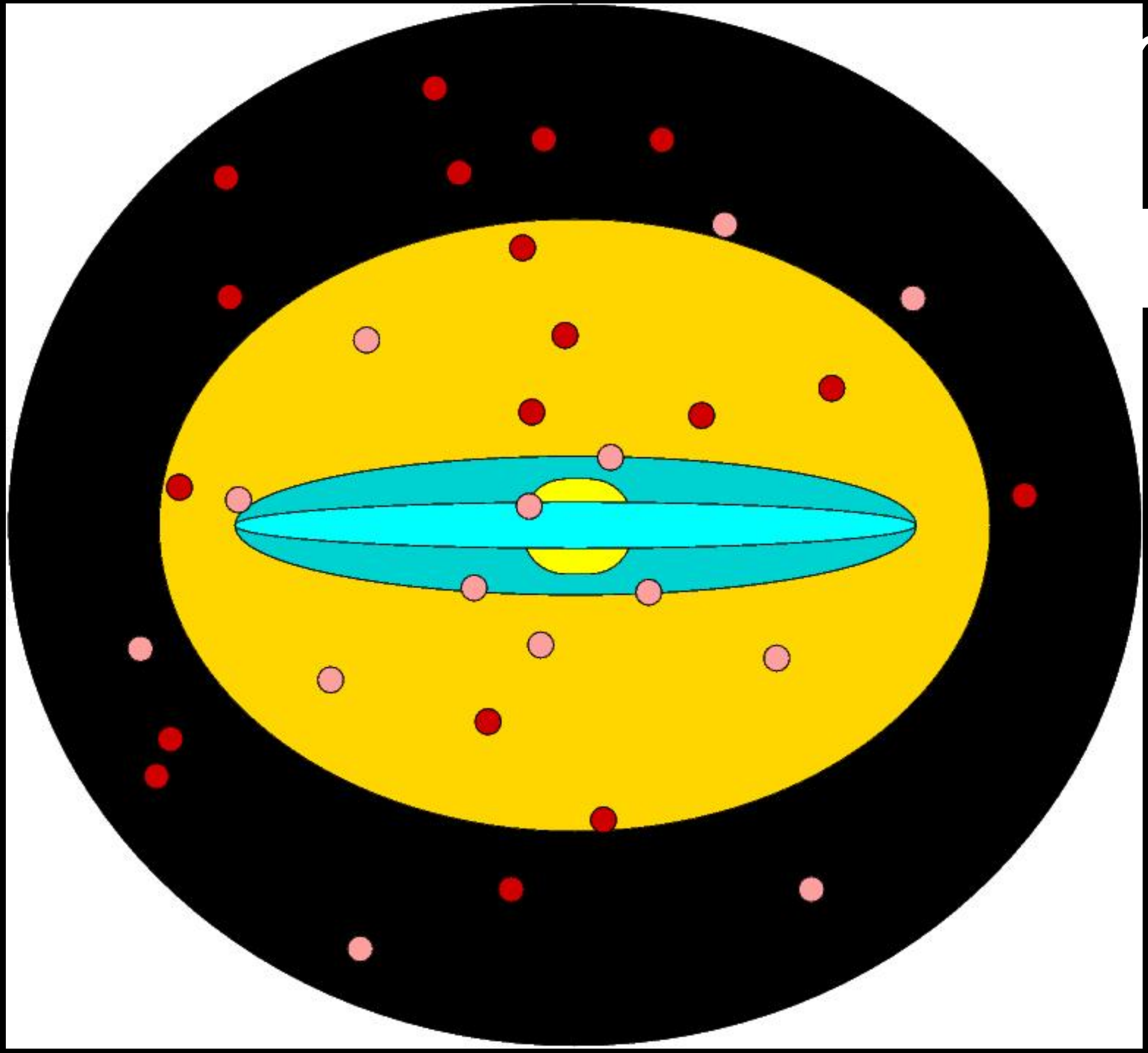
Large Synoptic Survey Telescope (LSST)



50,000,000 WD
r > 27.5 mag

First light: 2015 ???
Start Science: 2017

Overview of the Milky Way



Globular clusters

alo

stellar halo

thick disk

thin disk

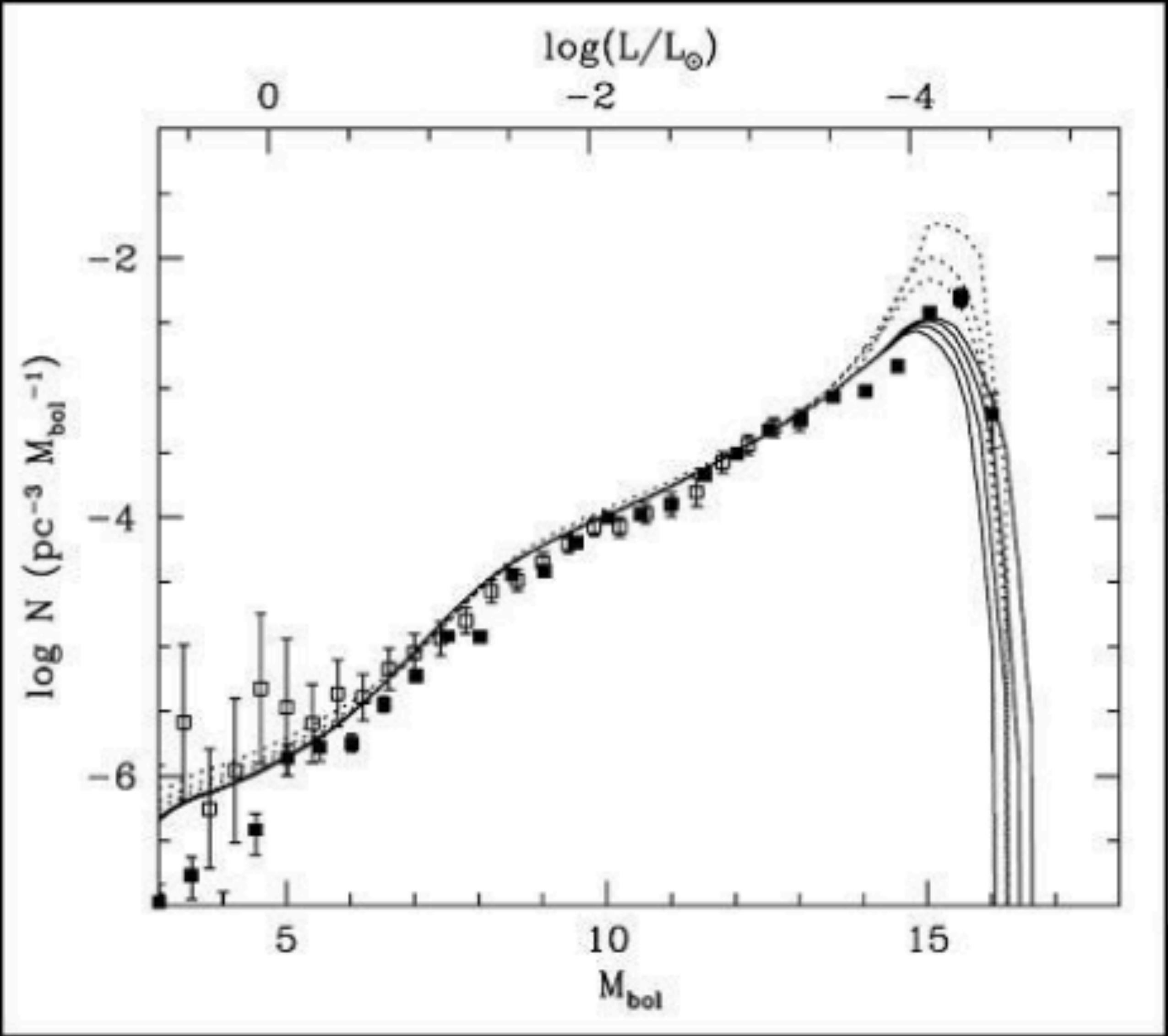
bulge

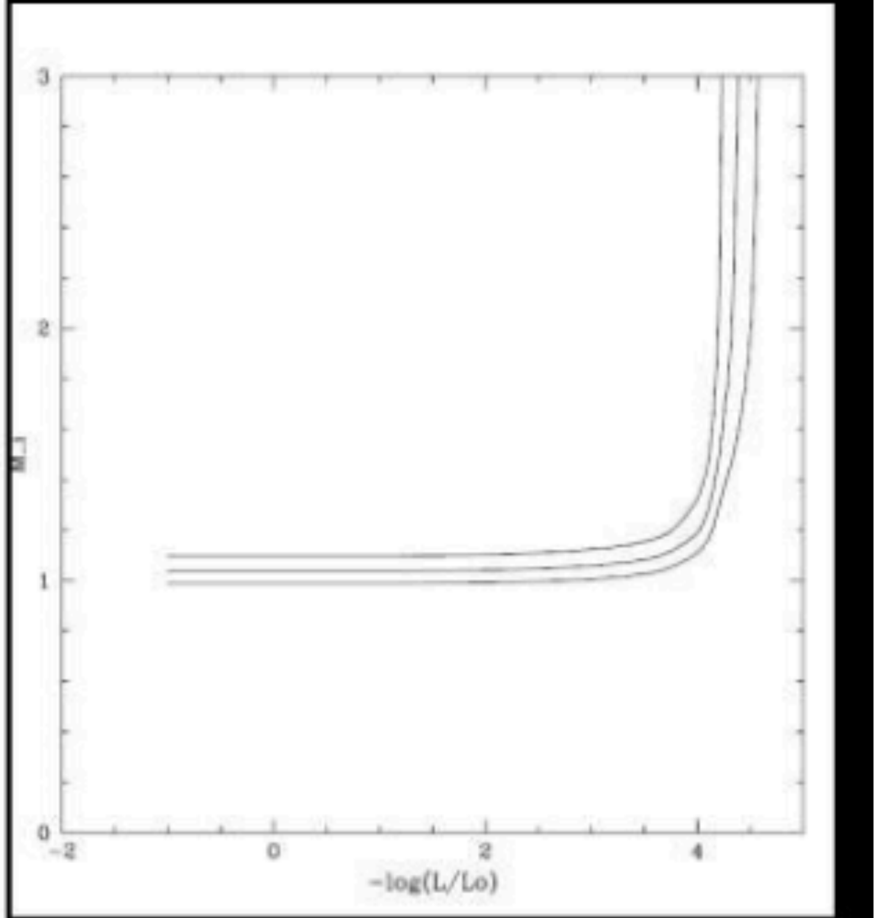
Evolution of the Milky Way (Reid'05)

- t ~12-13 Gyr. Formation of the primitive halo
- t ~11-12 Gyr. Minor mergers of satellite systems
- t ~ 10-11 Gyr. Formation of the disk
- t ~ 9-10 Gyr . A major merge induces the formation a thick disk (or mergers plus migration Chiappini'12)
- t ~ 8 - Gyr. Thin disk

Identification criteria:

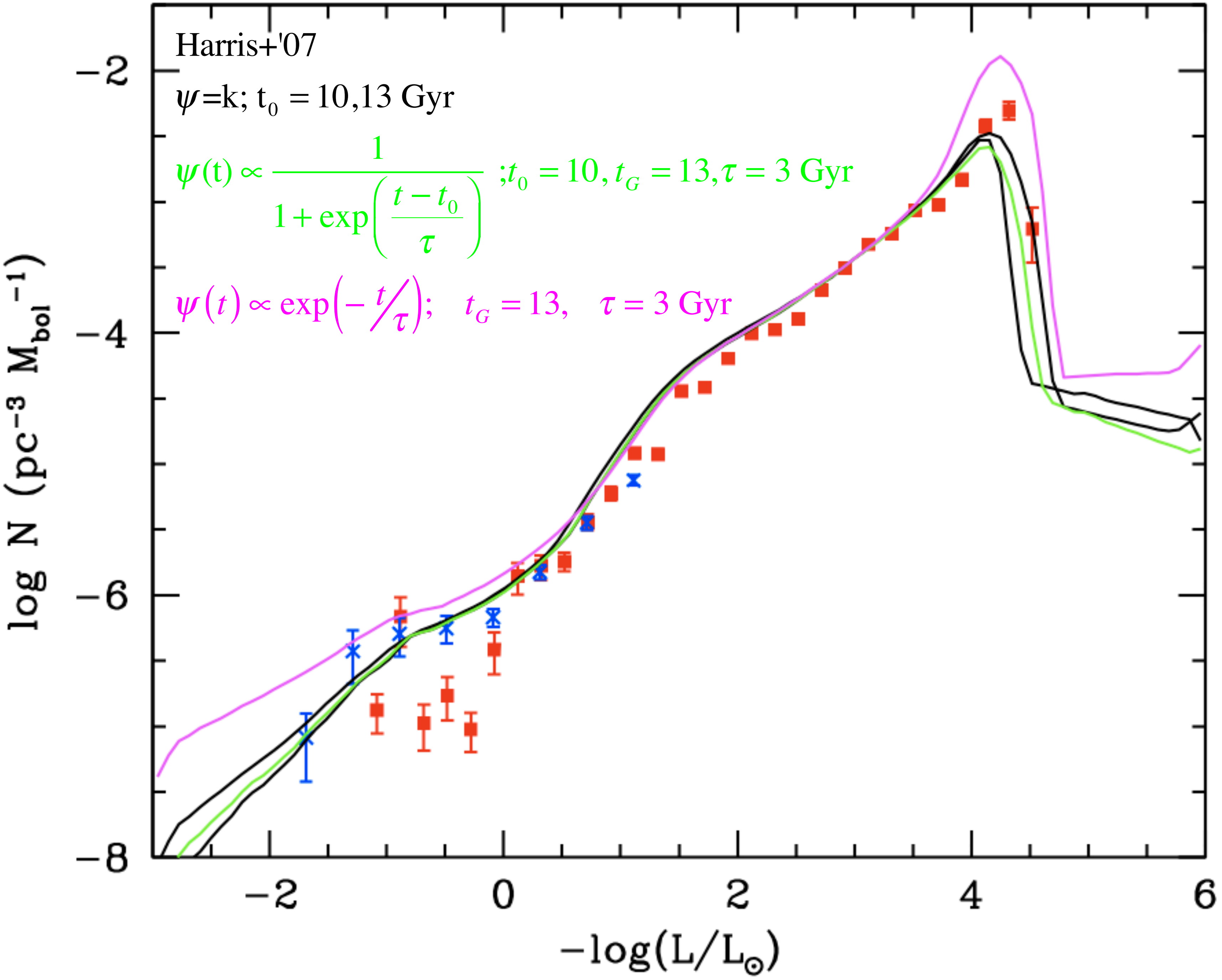
Kinematics
Age
Chemical abundances

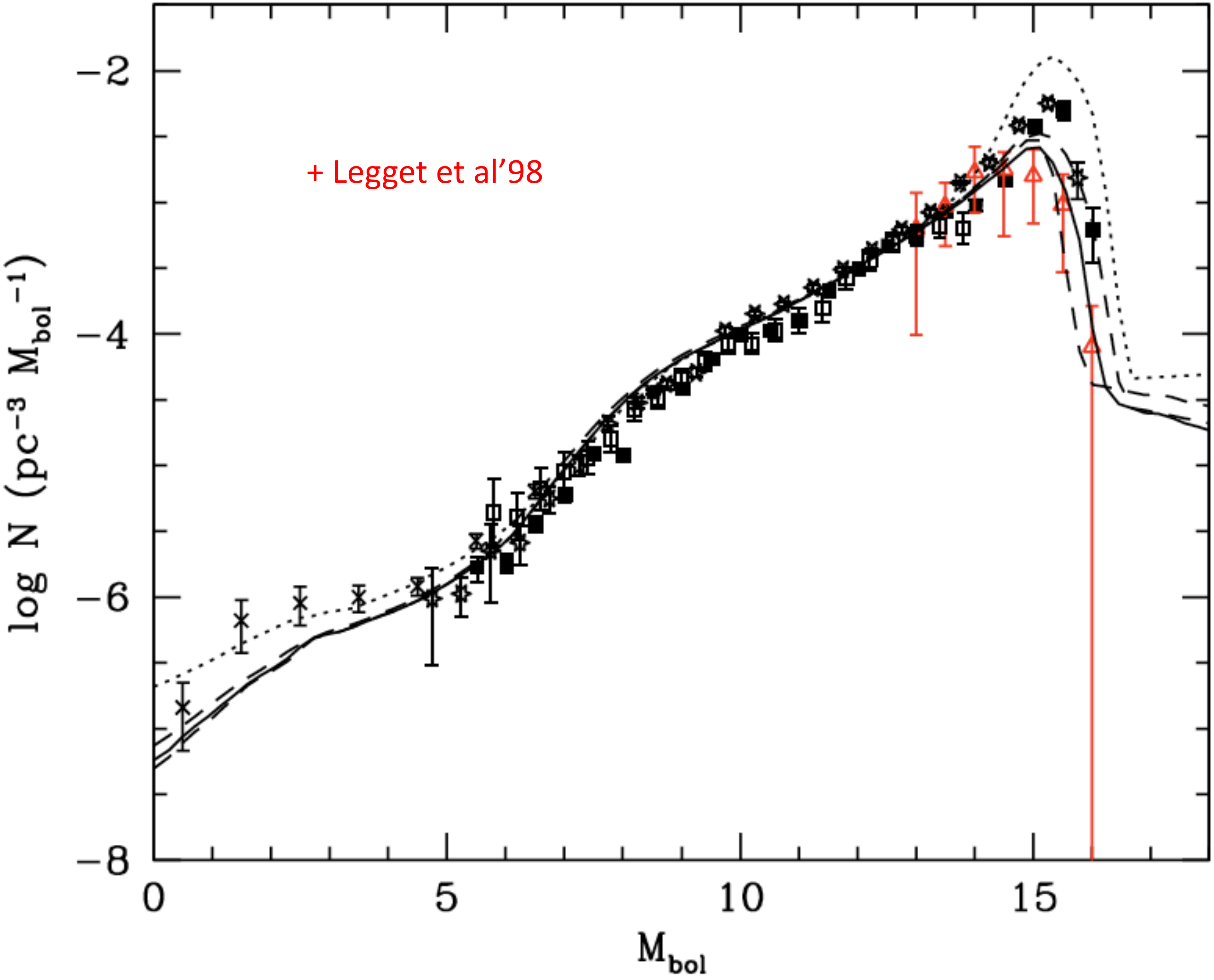


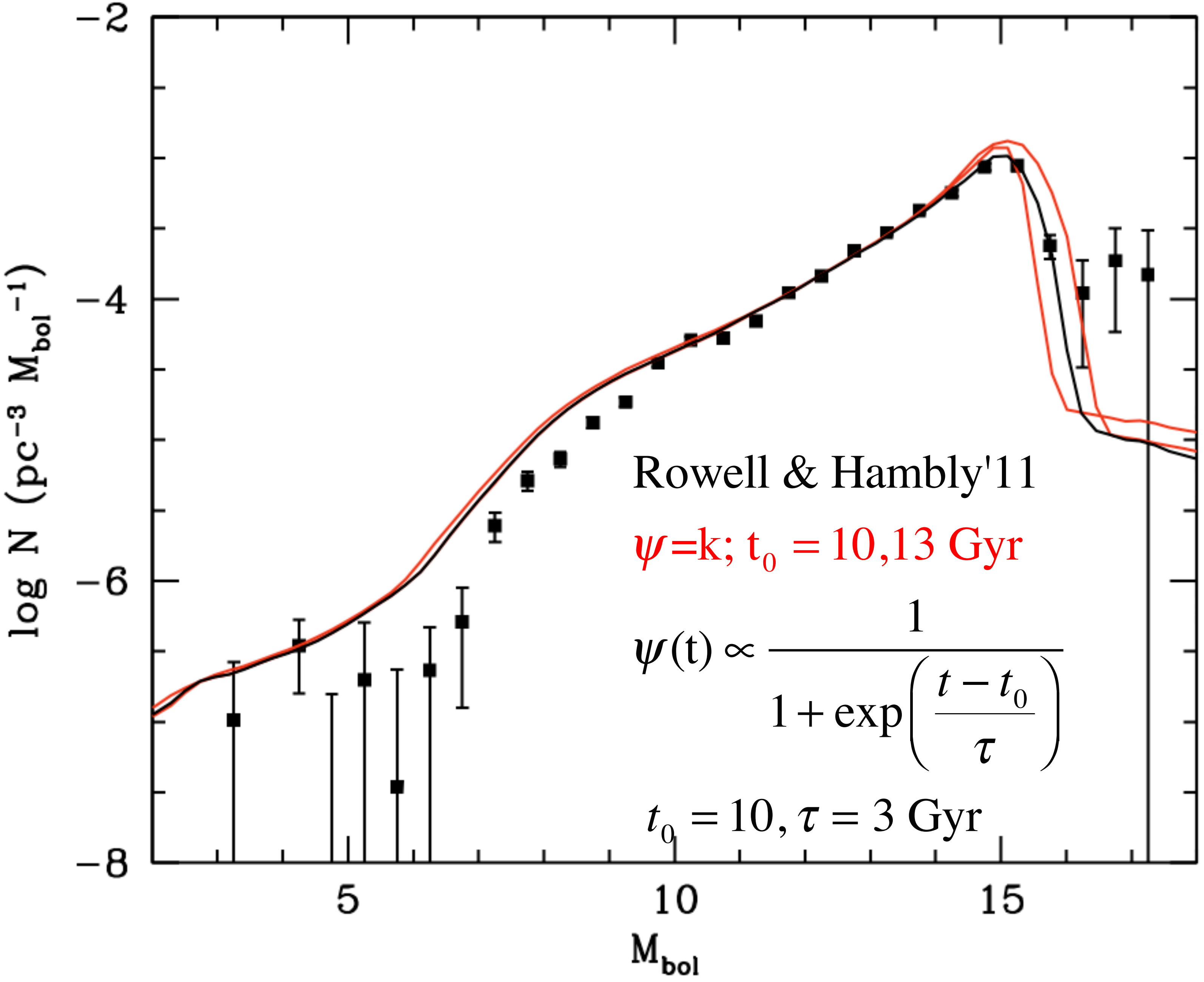


$$n(l) \propto \langle \tau_{cool} \rangle \int_{M_i}^{M_{\max}} \Phi(M)\Psi(\tau)dM$$

Isern & Garcia-Berro'08


Harris+'07
ψ=k; $t_0 = 10,13$ Gyr
$\psi(t) \propto \frac{1}{1+\exp\left(\frac{t-t_0}{\tau}\right)}$;$t_0 = 10, t_G = 13, \tau = 3$ Gyr
$\psi(t) \propto \exp\left(-t/\tau\right)$; $t_G = 13$, $\tau = 3$ Gyr
−2
−4
−6
−8
log N (pc^{-3} M$_{bol}$$^{-1}$)
−2
0
2
4
6
−log(L/L$_\odot$)


+ Legget et al'98
log N (pc^{-3} M$_{bol}$$^{-1}$)
M$_{bol}$
−2
−4
−6
−8
0
5
10
15



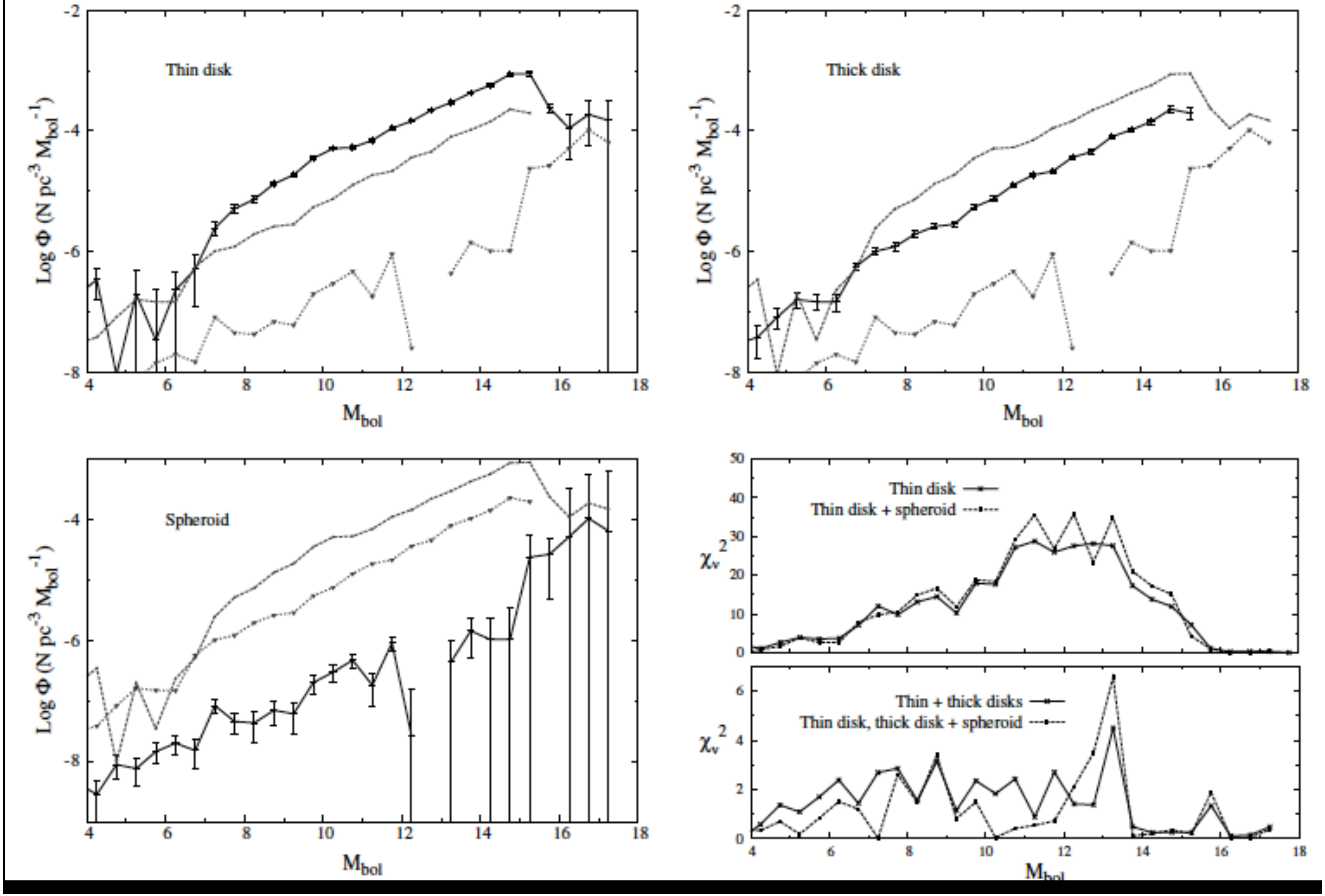
Rowell & Hambly'11

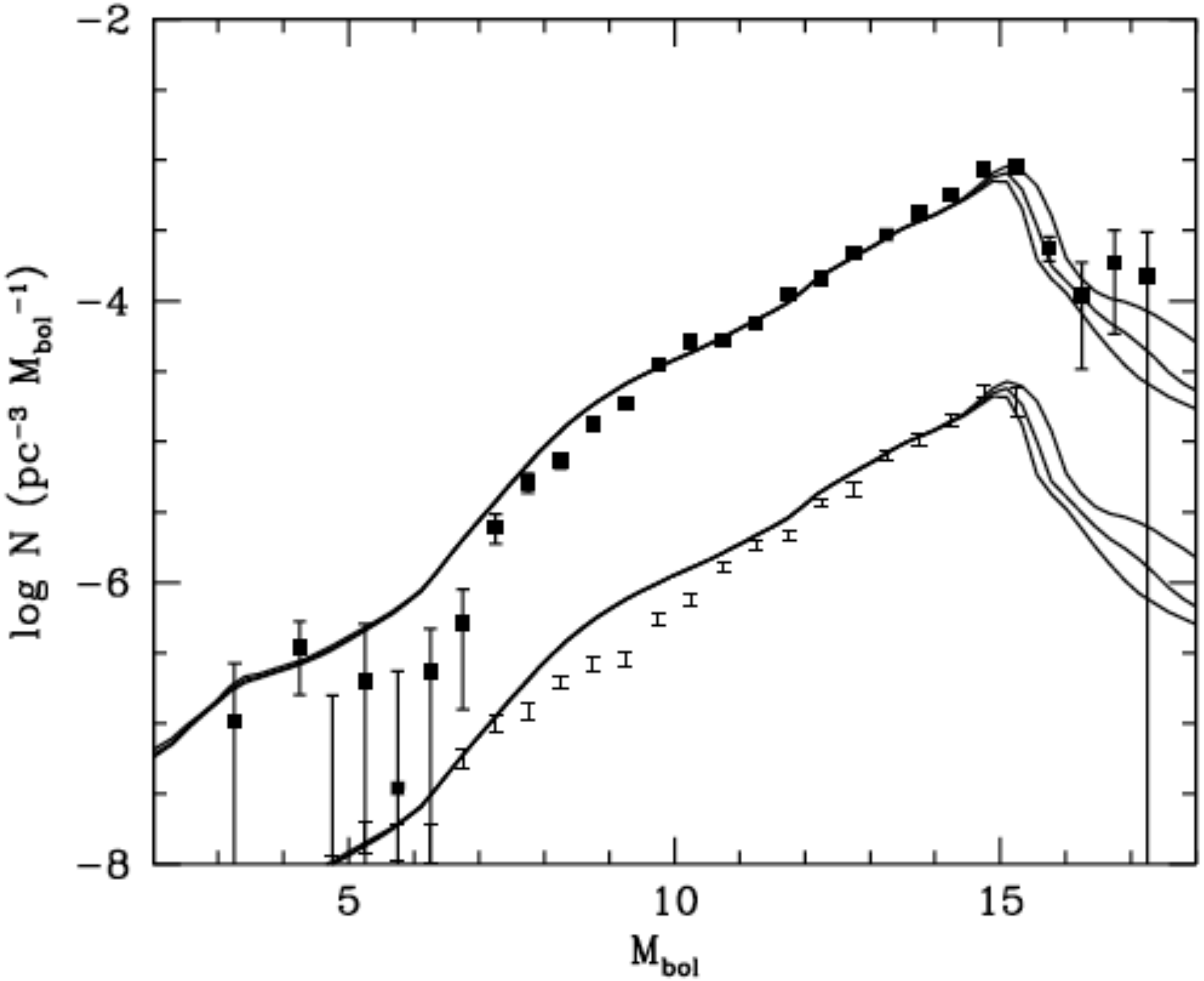
ψ=k; t_0 = 10,13 Gyr

$$\psi(\mathrm{t}) \propto \frac{1}{1+\exp\left(\frac{t-t_0}{\tau}\right)}$$

$t_0 = 10, \tau = 3$ Gyr

Rowell & Hambley'11





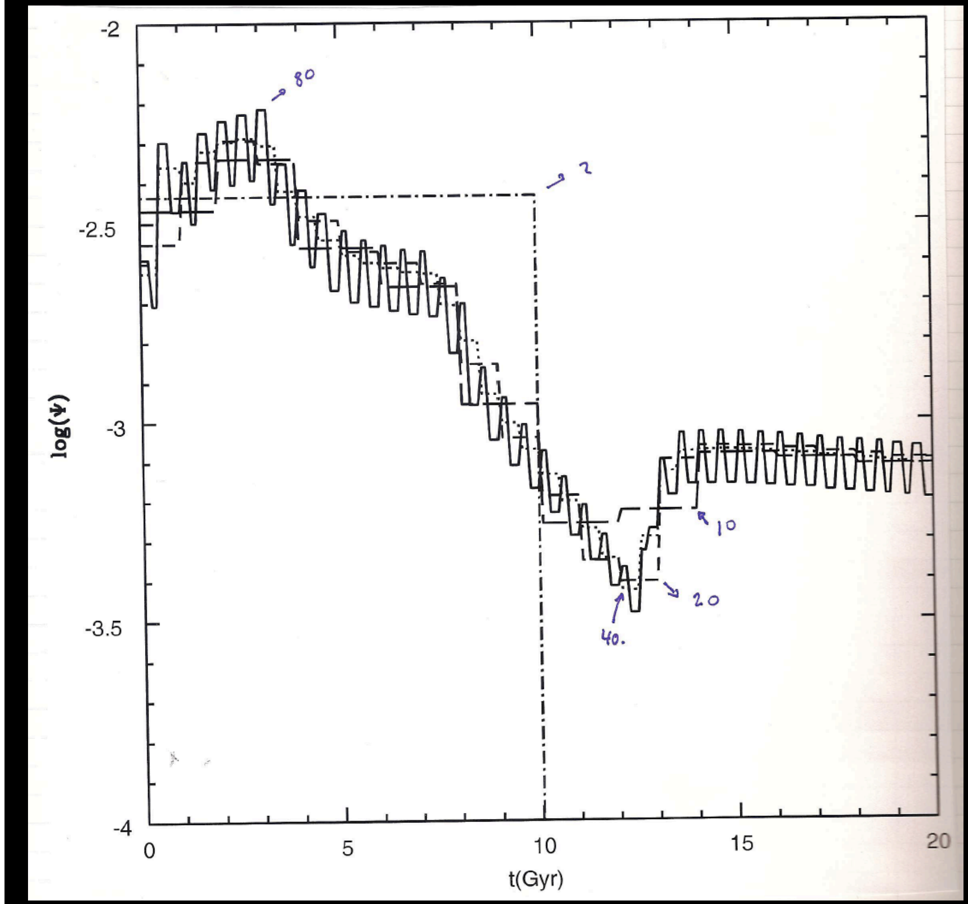
Isern+’12

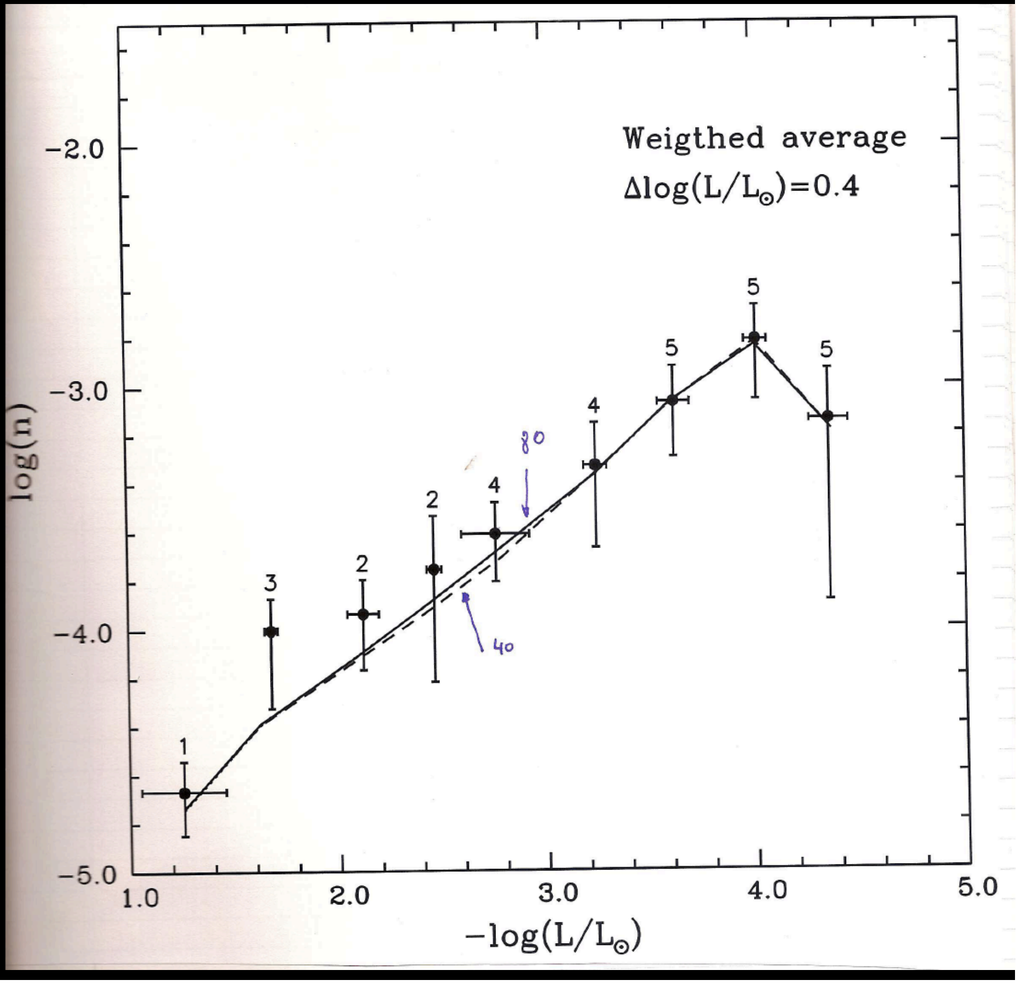
Fig. 6. White dwarf luminosity function of the thin (upper curves) and thick (lower curves) disks [18]. The data corresponding to the thick disk have been shifted by a quantity of -1 for a seek of clarity. The theoretical function have been computed for a constant star formation rate and ages of 10, 11 and 13 Gyr (from left to right respectively).

$$\Psi = \sum_i \psi_i(t)$$

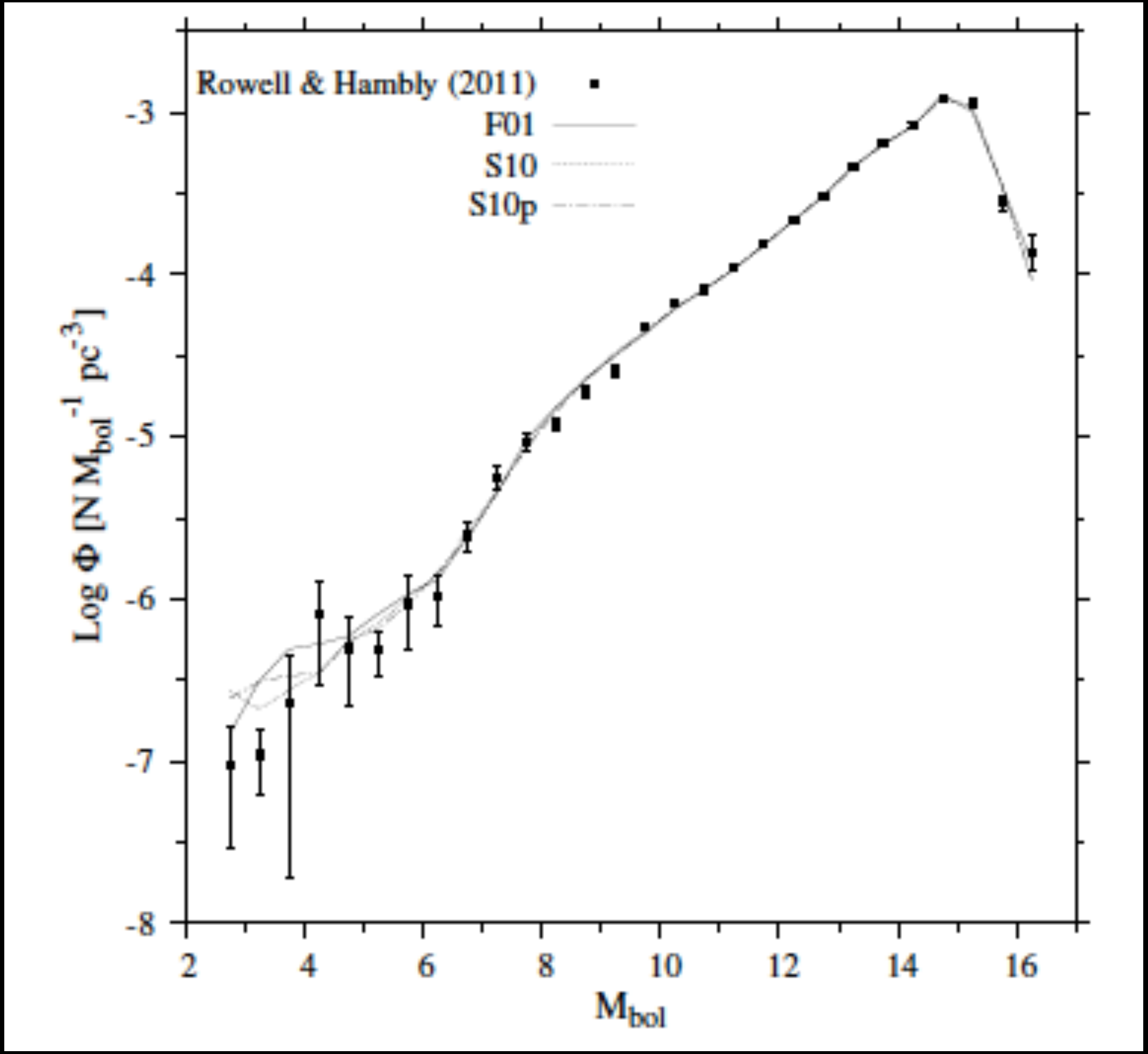
$$\psi_i(t) = \left\{ \begin{matrix} \psi_i^0 \text{ if } t_i \le t \le t_i + \Delta t \\ 0 \end{matrix} \right\}$$

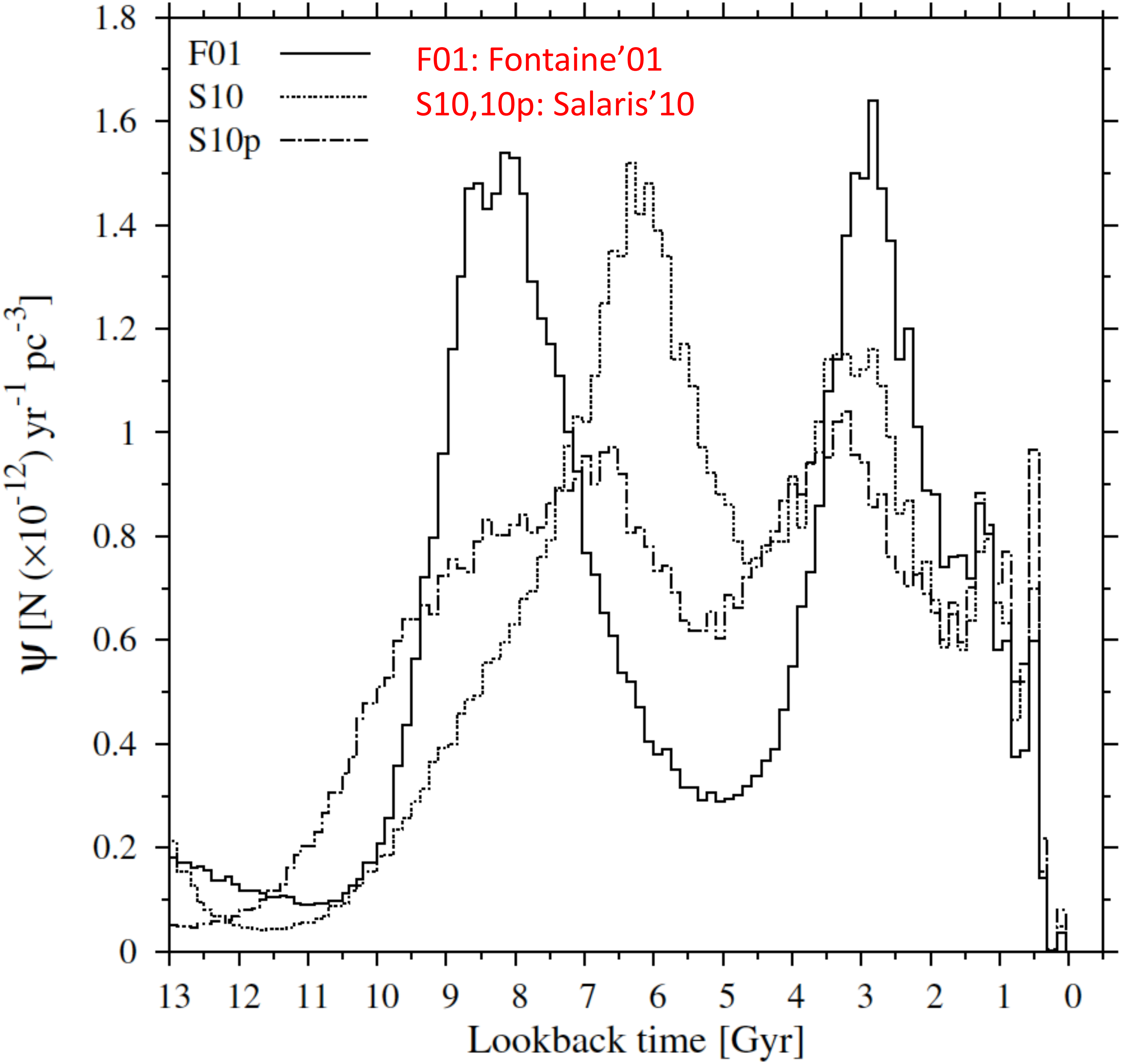
Isern'01





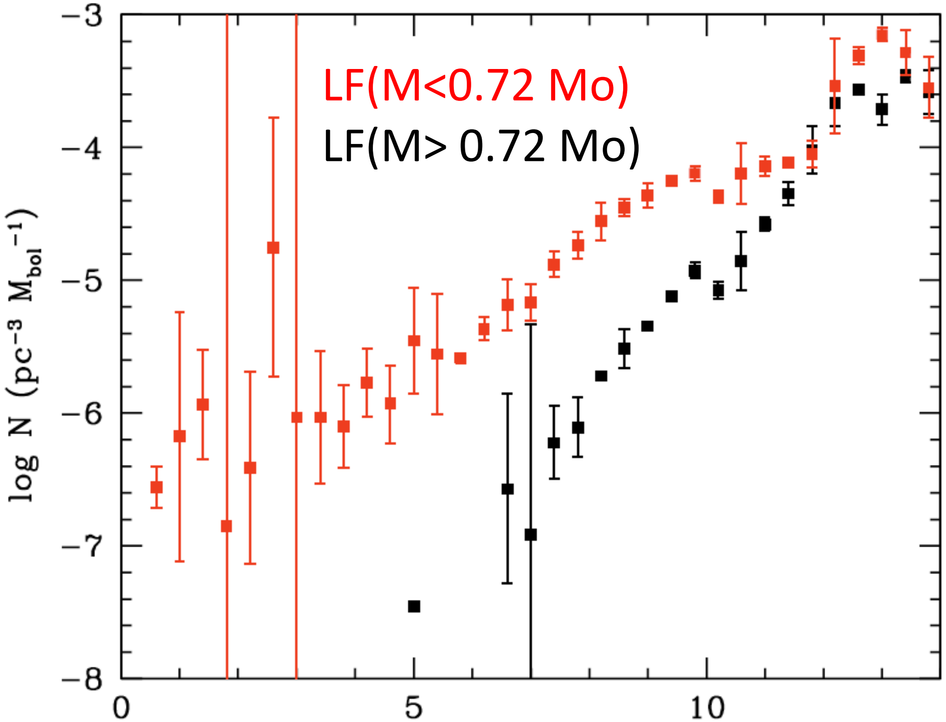
$\Psi \sim 8 \times 10^{-3}$ pc^{-3}





F01: Fontaine’01

S10,10p: Salaris’10



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

In the case of massive WD

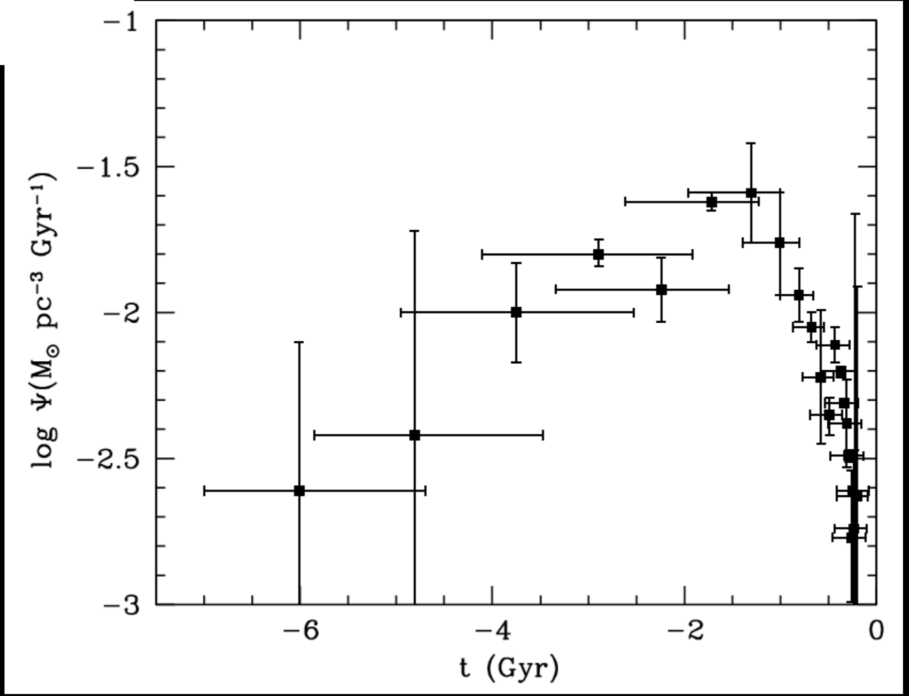
$$t_{SP}\ll t_{cool}$$

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

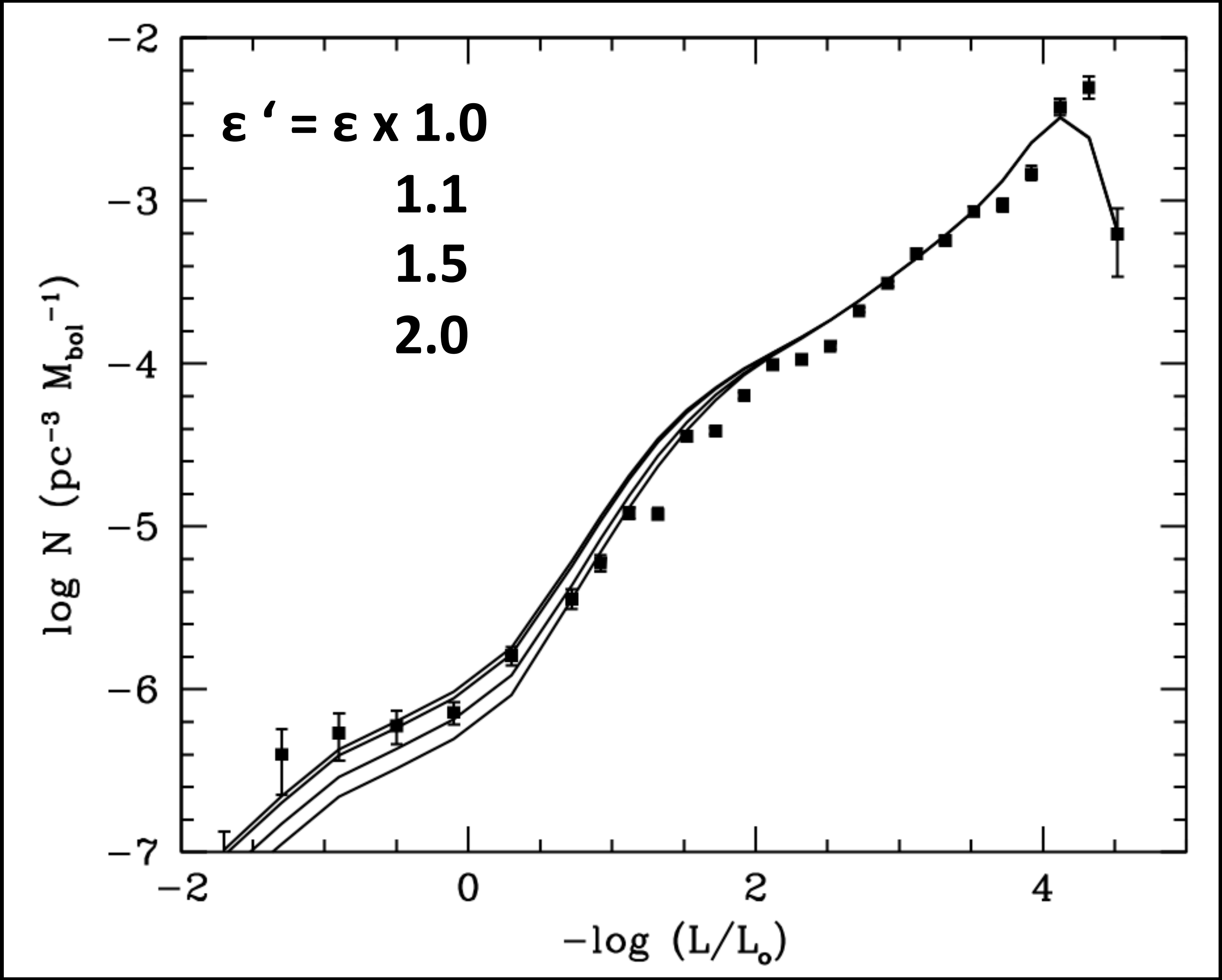
Kepler’12, private communication

The luminosity function of massive WD closely follows The SFR

Irregularities are detectable!



Neutrinos



How did the halo form?

- By the monolithic collapse of an initial mass of gas?
- By accretion of tidally disrupted satellite galaxies?
- A mixture of both?

Probably the halo WD population can provide some insight about the problem

WDs may have three origins:

- Primitive halo
- Capture from the exterior
- Expelled from the disc

Identification criteria:

- Kinematics
- Age

The age depends on the lifetime in the main sequence: $t_{MS}(Z)$ and on the cooling time τ_{cool} (Z).

Influence of the metallicity

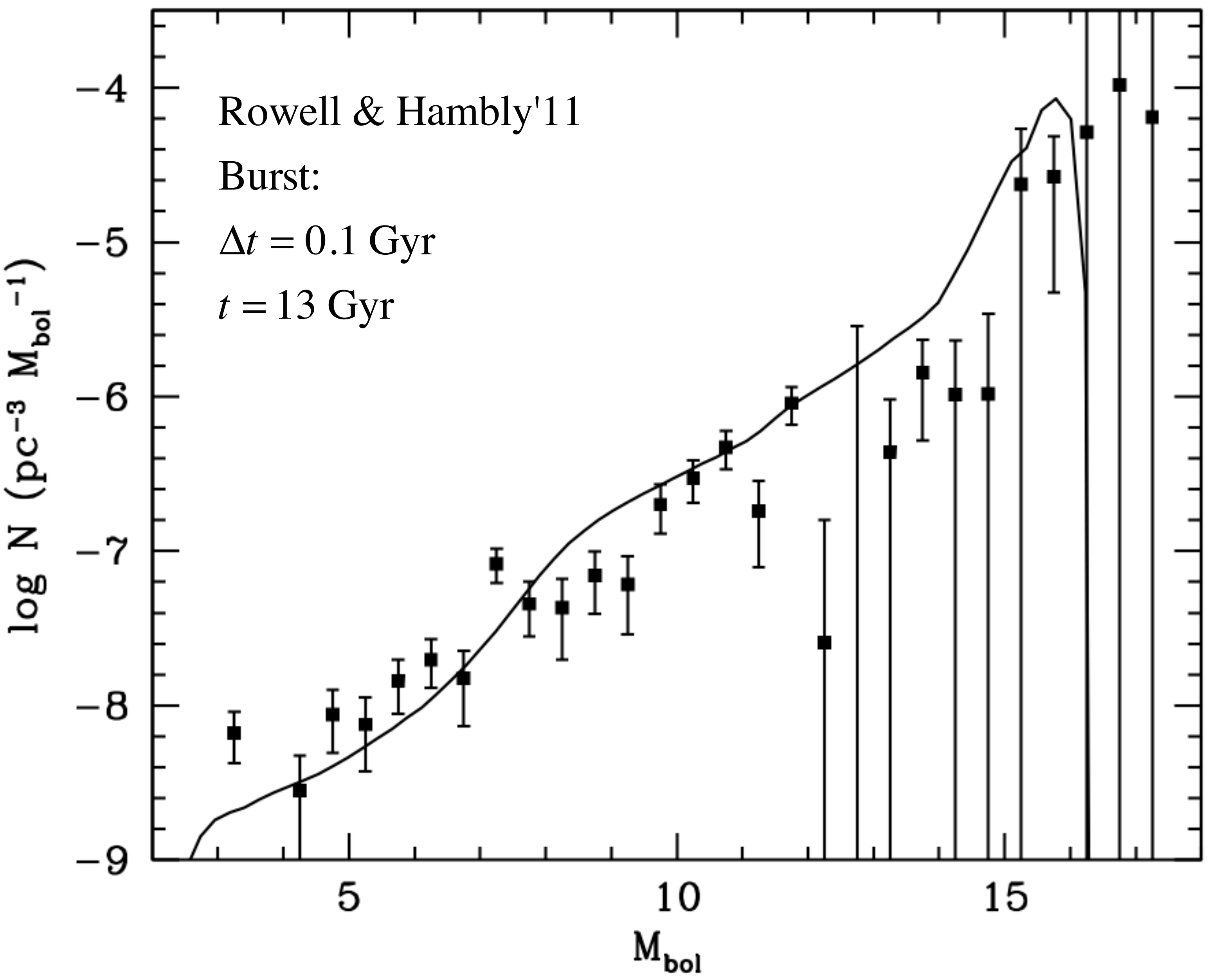
- Pre-white dwarf lifetime
- Initial-final mass relationship
- C/O profiles:
  - Larger specific heat
  - Lower latent heat
  - Higher sedimentation energy
  - Energy release at lower temperatures
- Sedimentation of impurities

$$Z \downarrow \Rightarrow C \uparrow$$

$$c_v \propto \mu^{-1}$$

$$l \propto T_s$$

$$L \propto T_c^{\alpha} \qquad \alpha > 1$$



Rowell & Hambly'11

Burst:

$\Delta t = 0.1$ Gyr

$t = 13$ Gyr

Conclusions

Several problems remain:

Noticeable differences in the models specially at low luminosities.

  Multiple origins:

    - Boundary conditions
    - Size and physics of the envelope

Understanding the origin and evolution of the DA, non-DA character

Properly determine the luminosity function of dim WD

Contamination from binary systems (He-WD, mergers, tidal heating…)

Luminosity functions from separate populations and interpretation within a global model of Galaxy