Astrophysical constraints to axion-photon coupling

Oscar Straniero *Italian National Institute of Astrophysics and INFN LNGS (Italy)*

Adrian Ayala *Granada & Rome Universities (Spain/Italy)*

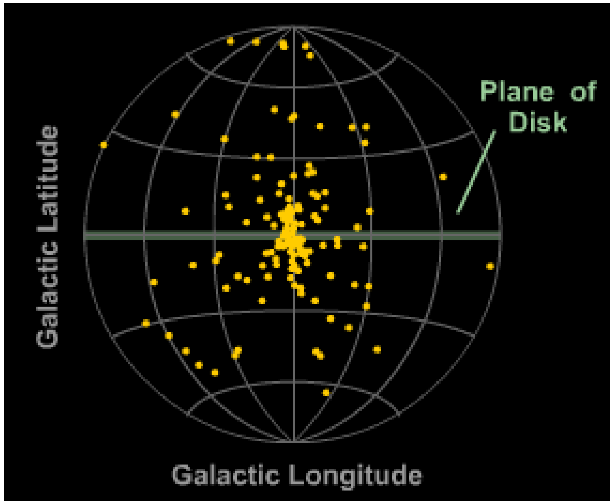
Maurizio Giannotti *Physical Sciences, Barry University (USA)*

Alessandro Mirizzi *II Institut fur Theoretische Physik, Universitat Hamburg (Germany) and University of Bari (taly)*

Inma Dominguez *University of Granada (Spain)*

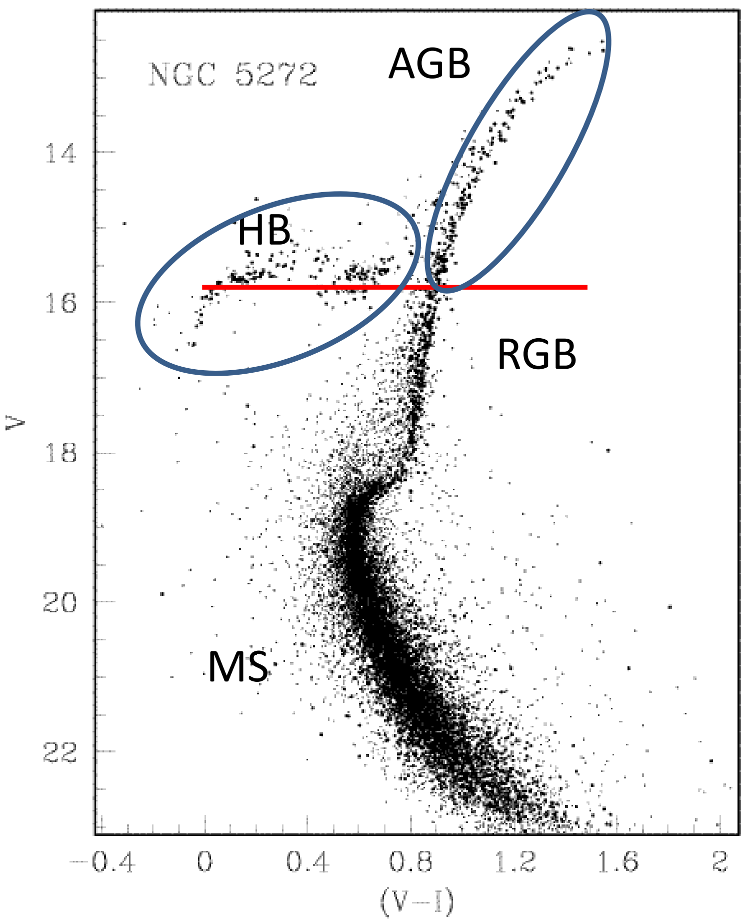
Globular Clusters

- **GCs are building blocks of any kind of galaxy.** They are found in giant spirals (such as the MW or M31), ellipticals (M87) as well as in Dwarfs Spheroidals or irregular galaxies (e.g. Magellanic Clouds).
- **Hundreds of GCs populate the galactic halo and bulge**. They are old (~13 Gyr) and contain up to 10^7 stars gravitationally bound.
- Most of their stars are nearly coeval. However, there exists a growing amount of observational evidences showing that they **host multiple stellar populations**, characterized by diverse chemical compositions. In a few extreme cases, multiple photometric sequences have been distinguished.



GC Color-Magnitude diagram: the R parameter

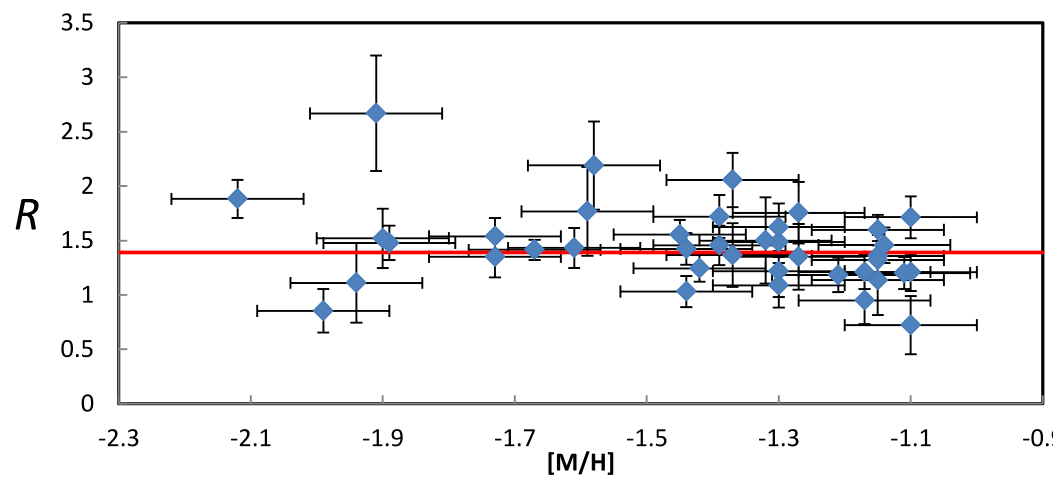
The number of stars observed in a given portion of the CM diagram is proportional to the time spent by a star in this region, e.g.: $N_{RGB}\ (or\ N_{HB}) \propto t_{RGB}\ (or\ t_{HB})$



$$R = \frac{N_{HB}}{N_{RGB}}$$

- R does **not depend on metallicity and age** of the cluster.
- R **depends on the original He** content (linearly)

39 GCs (from the Salaris et al 2004 catalog)



<R> = 1.39±0.03

Stellar structure: basic equations
1d hydrostatic model

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$

***Hydrostatic* equilibrium**

$$\frac{dr}{dM_r} = \frac{1}{4\pi r^2 \rho}$$

Mass continuity

$$\frac{dT}{dM_r} = -\nabla \frac{GM_r T}{4\pi r^4 P}$$

Energy transport

$$\frac{dL_r}{dM_r} = \varepsilon_{grav} + \varepsilon_{nucl} + \varepsilon_{\nu} + \varepsilon_{Ax}$$

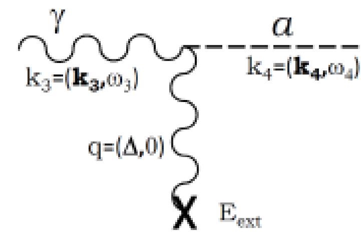
Energy conservation

$$\varepsilon_{grav} = -T\frac{dS}{dt} = -\frac{dE}{dt} + \frac{P}{\rho^2}\frac{d\rho}{dt}; \qquad \varepsilon_{nucl} = \sum_k Y_i Y_j \rho N_A \langle \sigma v \rangle_k Q_k;$$

$$\varepsilon_{\nu} = \text{neutrinos cooling}; \qquad \varepsilon_{Ax} = \text{axions cooling}$$

Axions energy loss (Primakoff)

Based on Raffelt and Dearborn 1987, Phys Rev D 36, 2211
+ revised intermediate (partial degenerate) regime



$$\varepsilon = 4.706 \times 10^{-31} g_{10}^2 T_{\rm K}^4 \frac{\rm erg}{\rm g \cdot s} \left[\sum_{\rm ions} (Z_j^2 + \theta_{\rm deg} Z_j) \frac{X_j}{A_j} \right] f(y_{\rm pl}, y_{\rm S}, y_m)$$

$$\begin{cases} \theta_{\rm deg} = 1\,, & \text{for} \quad z \le 5.45 \times 10^{-11}\,, \\ \theta_{\rm deg} = 0.63 + 0.3 \tan^{-1}\left(0.65 - 9316\, z^{0.48} + \frac{0.019}{z^{0.212}}\right), & \text{for} \quad 5.45 \times 10^{-11} < z \le 7.2 \times 10^{-8}\,, \\ \theta_{\rm deg} = 4.78 \times 10^{-6}\, z^{-0.667}\,, & \text{for} \quad z > 7.2 \times 10^{-8}\,. \end{cases}$$

$$z = \frac{\rho_{\rm cg}}{T_K^{3/2} \mu_e}$$

$$y_{\rm ions} = \frac{\kappa_{\rm ions}}{T} = 2.57 \times 10^{10} \left(\frac{\sum_{\rm ions} Z_j^2 X_j}{A_j} \right)^{1/2} \left(\frac{\rho_{\rm cg}}{T_{\rm K}^3} \right)^{1/2}$$

$$y_m = m_\phi / T,$$

$$y_{\rm el} = \frac{\kappa_{\rm el}}{T} = 2.57 \times 10^{10}\, \theta_{\rm deg} \left(\frac{\sum_{\rm ions} Z_j X_j}{A_j} \right)^{1/2} \left(\frac{\rho_{\rm cg}}{T_{\rm K}^3} \right)^{1/2}$$

$$g_{a\gamma} = 2 \times 10^{-10} \;\; {\rm GeV}^{-1} \zeta\, ({\rm m_a}/1\ {\rm eV})$$

$$y_{\rm S} = \sqrt{y_{\rm ions}^2 + y_{\rm el}^2}\,.$$

$$g_{10} = g_{\alpha\gamma}\, 10^{10}\, GeV^{-1}$$

$$y_{\rm pl} = \frac{\omega_{\rm pl}}{T} = \frac{3.33 \times 10^5}{T_{\rm K}} \frac{(\rho_{\rm cg}/\mu_e)^{1/2}}{(1 + (1.019 \times 10^{-6} \rho_{\rm cg}/\mu_e)^{2/3})^{1/4}}$$

$$f(y_{\rm pl}, y_{\rm S}, y_m) = \frac{100\,(1 + {y_{\rm pl}}^2)\,(1 + {y_m}^2)}{(1 + {y_{\rm S}}^2)\,(1 + e^{y_{\rm pl}})}\, g(y_{\rm pl}, y_{\rm S}, y_m)$$

$g(y_{pl}, y_S, y_m)$ Interpolated on a 3d table

Axion E-loss rate, T_8=0.5, 1, 2

$$g_{10} = \frac{g_{\alpha\gamma}}{10^{10}GeV} = 1$$

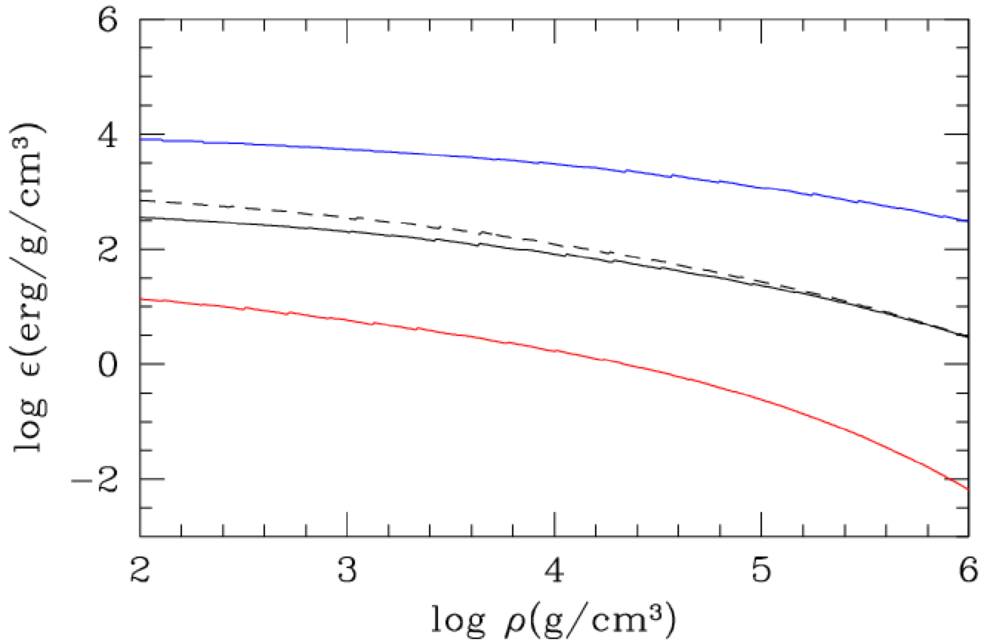
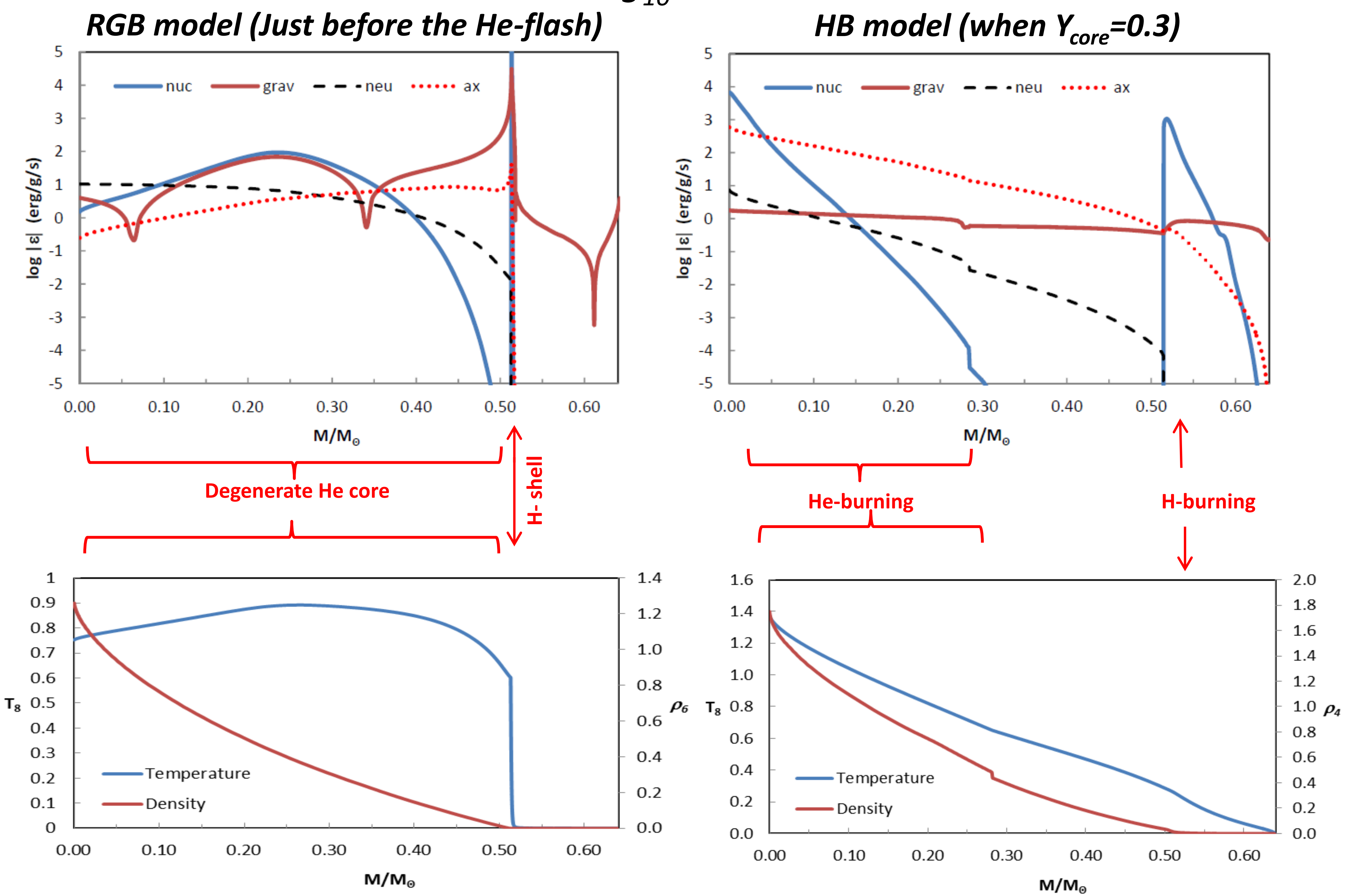


Fig. 2. Solid lines: axion production rate versus density for a pure He mixture and T= 5×10^7 K (red), 10^8 K (black) and 2×10^8 K (green). Dashed line: T= 10^8, but for pure C.

Energy sources and sinks: $M=0.82\ M_{\odot}$ $Y=0.248$ $Z=0.001$

$g_{10}=1$



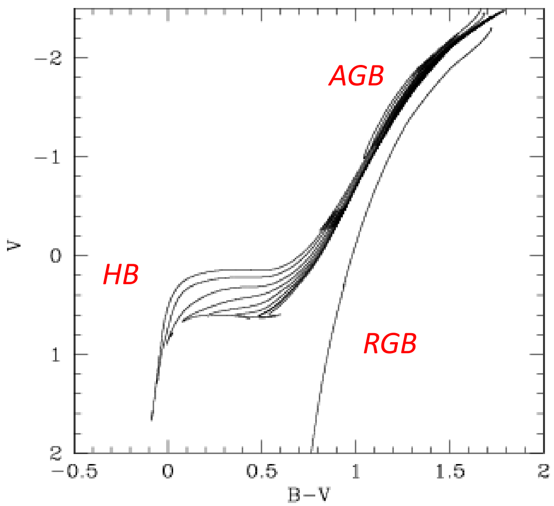
The theoretical R parameter: a new approach

- In Phys. Rev. Lett. 2014, 113, 191302, we have approximated the R parameter, by defining: R_{theory}= HB timescale/bright-RGB timescale.

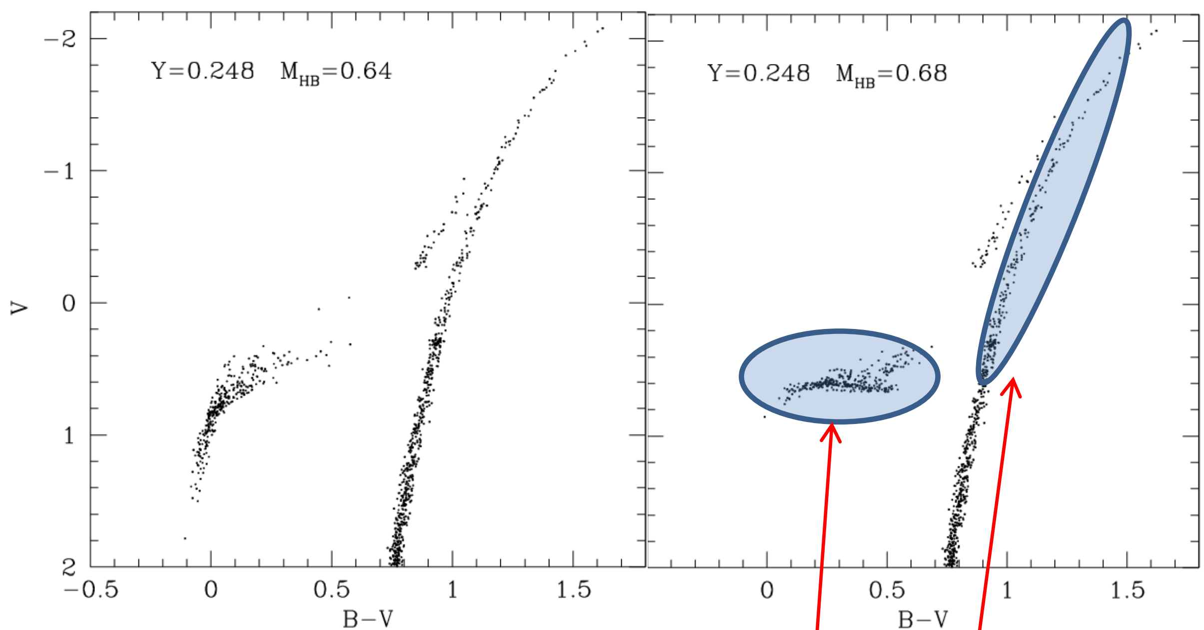
- To obtain a theoretical definition of R more similar to the measured one, we have developed a new tool to generate «synthetic» CM diagrams, basing on a more extended set of stellar models.

Synthetic CM diagrams

For each pair (Y, $g_{a\gamma}$) we calculate a set of evolutionary tracks: 1 RGB + 10 HB(AGB). The total mass of the HB models is varied from 0.58 to 0.76, to account for the RGB mass loss causing the observed HB color spread, while their ZAHB core mass is fixed to the value attained at the RGB tip



Montecarlo. N extractions, each one includes 3 parameters: time (uniform disrt.), HB mass (gaussian, only if $t>t_{RGB\ tip}$), photometric errors (gaussian) .



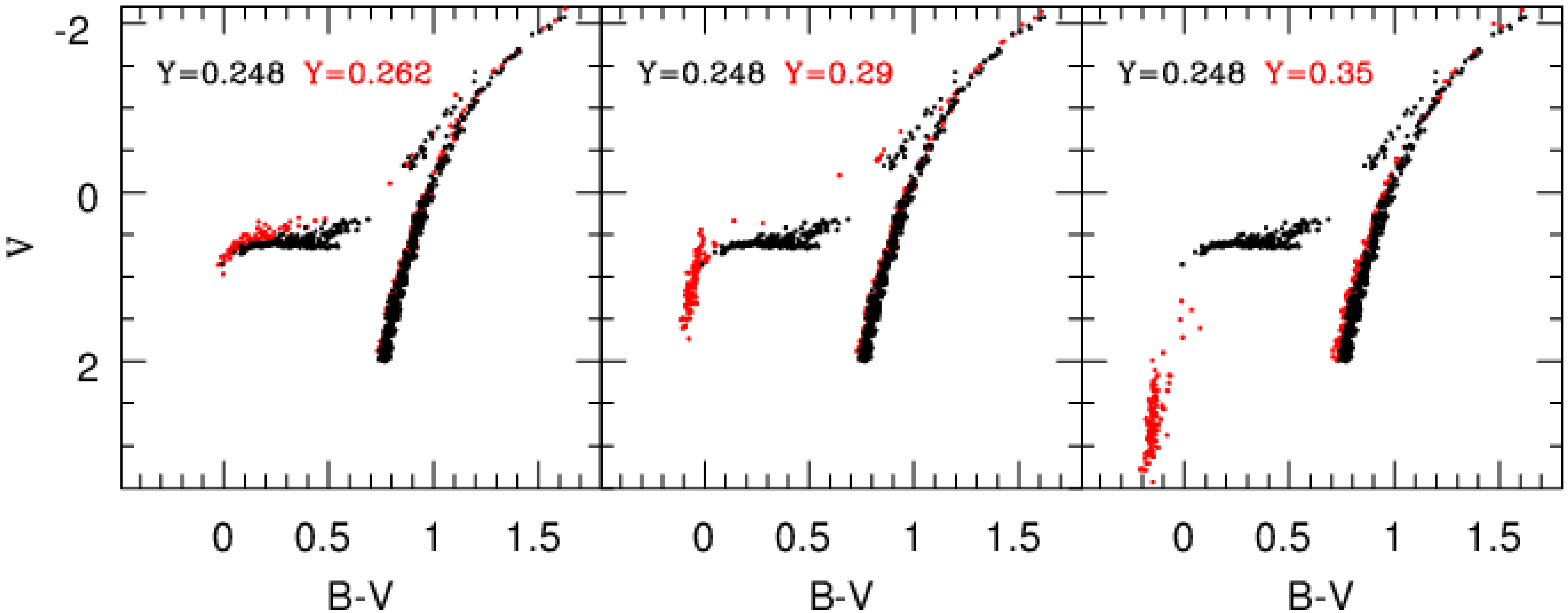
$\sigma(M_{HB})=0.1\ M_{\odot}$
$\sigma(V)=0.01$ mag
$\sigma(B\text{-}V)=0.014$ mag

$N=3\times10^5$ $\sigma_{stat}(R)<1\%$
but only 1000 synthetic stars plotted here.

$$R_{theo} = \frac{N_{HB}}{N_{RGB}}$$

Multiple populations

Examples of simulations with 30% of He enhanced stars



R=1.408 ***R=1.448*** ***R=1.548***

To be compared with single population ***R=1.408***

Clusters with blue HB tails not considered

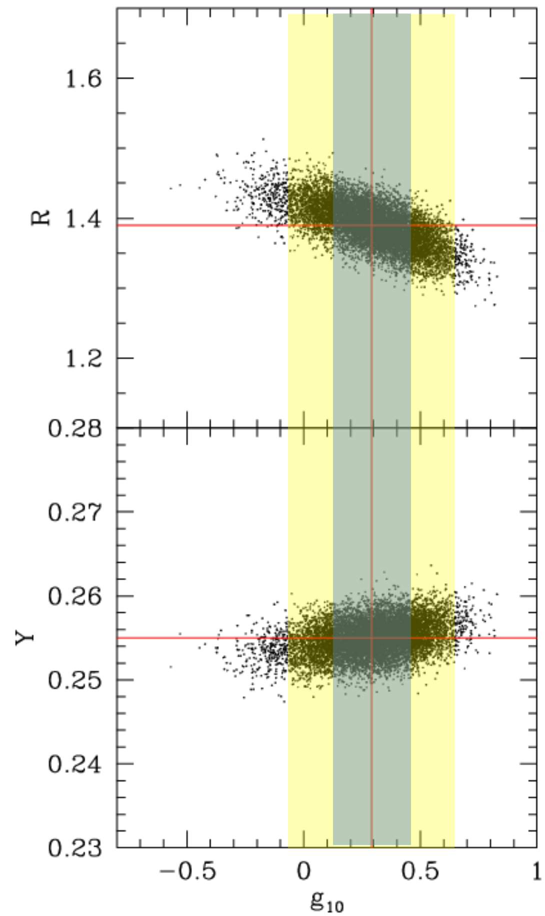
Model prescriptions and error budget

Measured parameters

Parameter	uncertainty	Reference
R	1.39±0.03	Ayala et al. 2014
Y	0.255±0.002	Izotov et al. 2015, Aver et al. 2014

Model Parameters: Nuclear reaction rates

Reaction	uncertainty	Reference
$^{4}N(p,\gamma)^{15}O$	7%	SF II , Adelberger et al. 2011 (LUNA 2005)
$^{4}He(2\alpha,\gamma)^{12}C$	10%	Angulo et al. 1999 (NACRE), Fymbo 2005
$^{12}C(\alpha,\gamma)^{16}O$	20%	Kunz et al. 2001 , Shurman et al. 2013



Treatment of convection (HB):

Induced overshoot (He -> C,O) + Semiconvection
(see Straniero et al 2003, ApJ 583, 878)

Plasma neutrinos (RGB):

Esposito et al. 2003, Nucl. Phys. B 658, 217
Haft et al. 1994 ApJ. 425, 222
Itoh et al. 1996, ApJ 470, 1015 .

5 PARAMETERS

$$g_{\alpha\gamma} = a\vartheta^2 + b\vartheta$$

$$\vartheta = R_{g=0} - R = cY + f(r1, r2, r3) + d - R$$

$$a = 5.2706 \qquad b = 4.675$$

$$c = 7.3306 \qquad d = -0.409$$

Summary and Conclusions

- By means of synthetic CM diagrams, we have calculated the relation between $g_{\alpha\gamma}$ and 5 parameters, namely Y, R, and the 3 more relevant nuclear rates affecting the HB timescale.
- By combining the uncertainties on this 5 parameters we find:

  $$g_{10}=0.29\pm0.18$$

  corresponding to a axion-photon upper bound:

  $$g_{10} < 0.65 \text{ (95\% CL)}$$

- The main source of uncertainty of the model is the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. This uncertainty is due to the possible interference between two subthreshold resonances in the ^{16}O ($j^{\pi}=1^{-}$, 2^{+}). Presently available measurements seem to exclude a constructive interference (within the quoted ±20% error), but not a destructive one. It this case, the reaction rate would be reduced down to the 50% of the suggested value. It would imply a decrease of the theoretical R, thus reducing or even cancelling the apparent need of an additional cooling process.New low-energy measurements are required. The $^{12}C(\alpha,\gamma)^{16}O$ reaction is among the main scientific cases of LUNA MV, a new nuclear astrophysics facility under construction at the Gran Sasso underground laboratory of INFN (LNGS).

WARNING:

- In our analysis, a key role is played by the adopted Y. He abundance determination are very difficult for Globular Cluster stars. because they are too cool to excites He atoms. Thus, we have used precise measurements of He abundances in extragalactic HII molecular regions (several paper by Aver et al., Izotov et al.) with metallicity in the same range of the GCs. In general, it Is expected that these environments experienced a limited chemical evolution (as the low Z testify), so that their Y should be very close to the cosmological one. Note that latest estimate of primordial Y from extragalactic HII clouds would imply a faster expansion rate of the primordial Universe (first 3 minutes) compared tothat predicted by stndard Big Bang Nucleosynthesis (3 neutrinos only). This is in contrast with recent claims from the PLANCK collaboration, who derived a lower primordial He, Y=0.24665±0.00063 . By adopting this lower Y:

$$g_{\alpha\gamma} = a\vartheta^2 + b\vartheta$$

$$\vartheta = R_{g=0} - R \approx 0 \quad \Rightarrow \quad g_{\alpha\gamma} \approx 0$$

Additional Material

Axion cooling competes with nuclear energy production

Gamow's peak energy $E_0 = \left(\frac{bKT}{2}\right)^{1/2}$

T = 70 MK shell-H nurning (RGB+HB)

^{14}N+p 65 KeV

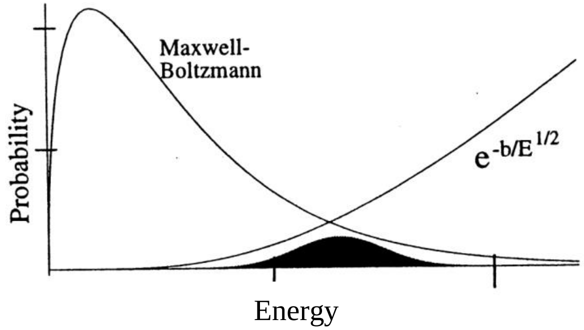
T = 100-200 MK core-He burning (HB)

3α and ^{12}C+α 200-300 KeV

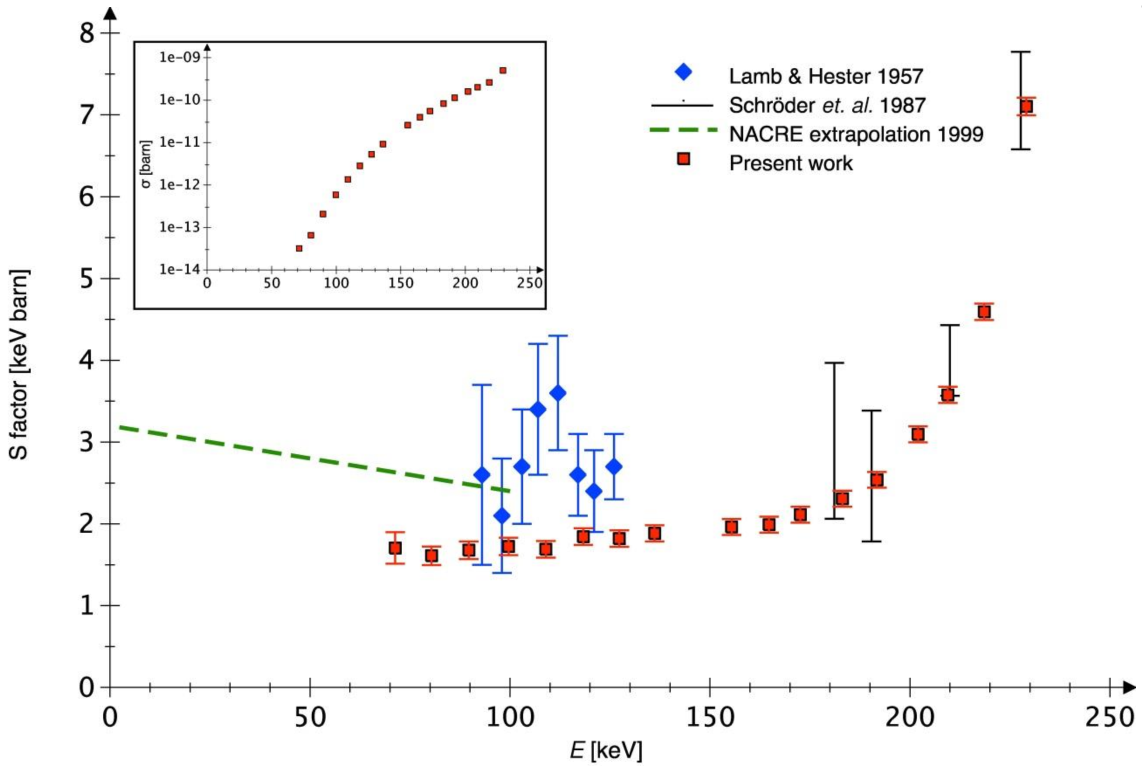
$$\sigma(E) = \frac{1}{E} S(E) \exp\left(-\frac{b}{E^{1/2}}\right)$$

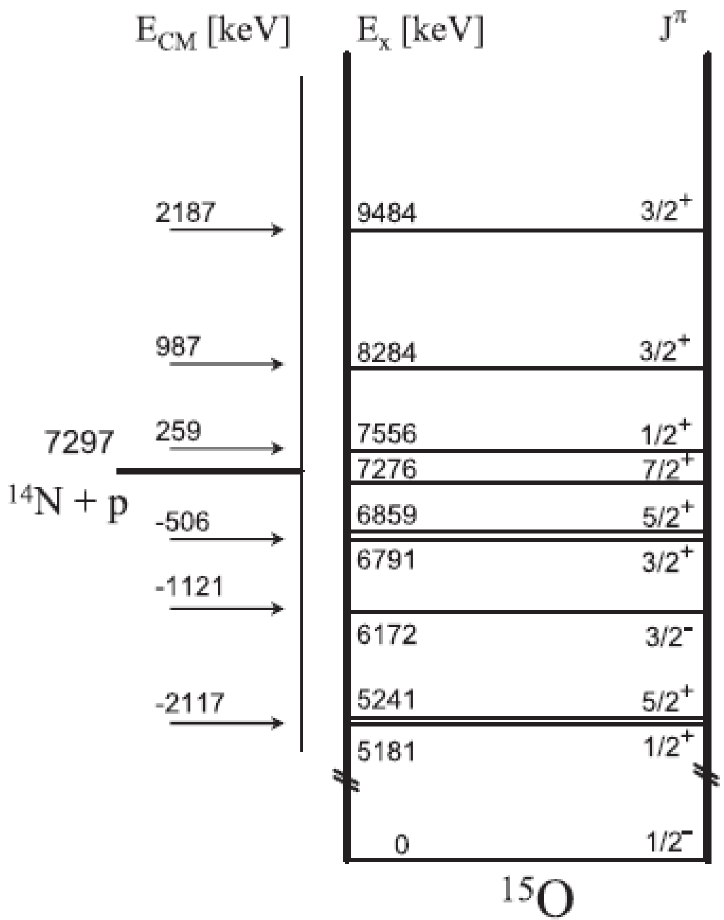
$$b = \frac{\sqrt{2}\pi Z_j Z_k e^2 \mu^{1/2}}{\hbar} = 0.99 Z_j Z_k \mu^{1/2} \;\; \mathrm{MeV}^{1/2}$$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right] dE$$



$^{14}N(p,\gamma)^{15}O$ the bottleneck of CNO





LUNA 400 KV

Formicola et al. 2005

Imbriani et al. 2005

$^{12}C(\alpha,\gamma)^{16}O$ (Shurman et al. 2013)

At the Gamow peak around E ~ 300 keV the cross section is dominated by ground state capture proceeding through two subthreshold resonances with $J^\pi = 1^-$ and 2^+. Those interfere with contributions from higher lying states and the direct capture process. In addition cascade transitions take place. The current estimates of the astrophysical cross section are based on R-Matrix analyses, taking into account direct measurements at higher energies (E > 1 MeV), elastic scattering data and the β–delayed α-spectrum of ^{16}N (providing information on the reduced width of the subthreshold 1^- state).

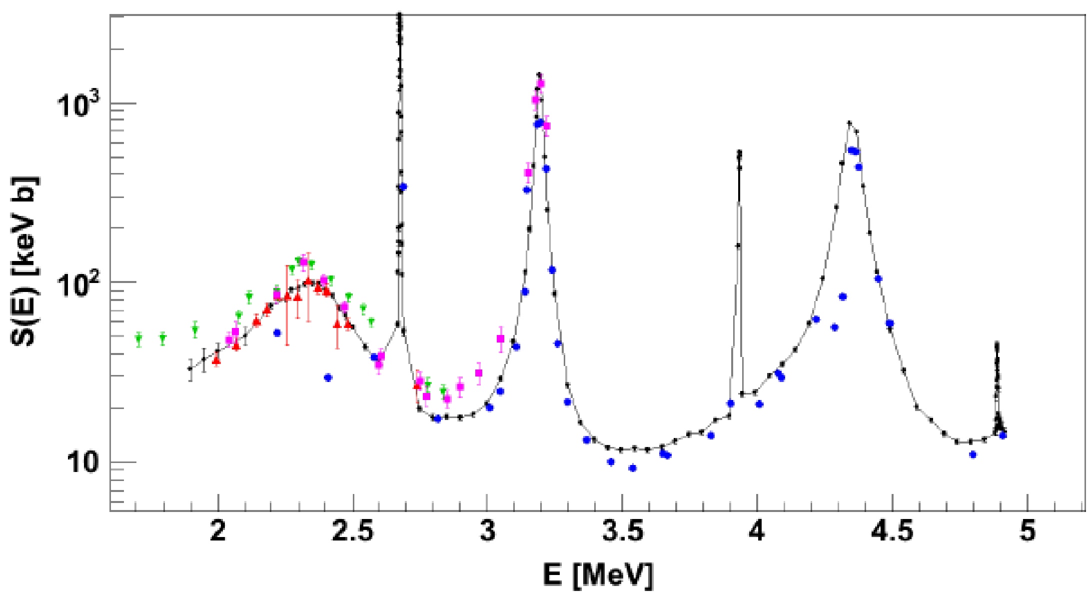


Figure 6 $^{12}C(\alpha,\gamma)^{16}O$ total cross section as measured by the RMS experiments ERNA (black dots with line to guide the eye, [5]) and DRAGON (solid blue circles, [21]) compared to the sum of all γ-ray transitions from the measurements of Kunz et al. (solid red triangles-up, [24][25]), Kettner et al. (solid magenta squares, [23]) and Redder et al. (solid green triangles-down, [22]). Good agreement is found between between ERNA and Kunz et al., while the DRAGON data points show larger deviations around the resonances at 2.4 and 4.4 MeV.