Constraining Axion–Electron Coupling with the TRGB

Based on the preprint [arXiv:2608.04801]:

Isochrone fitting of Galactic globular clusters – IX. Tip of the red-giant branch for 27 clusters and constraints on new particle physics

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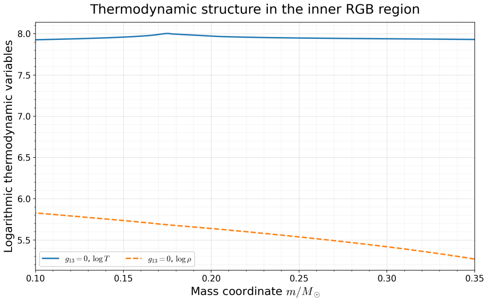
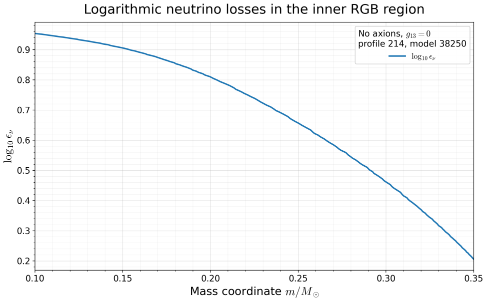
BASIS Foundation Summer School 2026 "Physics of Fundamental Interactions"

Outline

Neutrino Cooling and Off-Center Flash





Main point

- Central neutrino cooling shifts the temperature maximum away from the center.
- Therefore, the inner RGB structure is sensitive to additional weakly interacting cooling channels, e.g. axion-like particles.

Axion Implementation in MESA

Bremsstrahlung channel

$$\varepsilon_B^{(\mathrm{nd})} \simeq 47\, g_{ae}^2 T^{2.5} \frac{\rho}{\mu_e} \sum_j \frac{X_j Z_j}{A_j} \left(Z_j + \frac{1}{\sqrt{2}} \right)$$

$$\varepsilon_B^{(\mathrm{d})} \simeq 8.6 \times 10^{-7} F\, g_{ae}^2 T^4 \sum_j \frac{X_j Z_j^2}{A_j}$$

$$\varepsilon_B = \frac{\varepsilon_B^{(\mathrm{d})} \varepsilon_B^{(\mathrm{nd})}}{\varepsilon_B^{(\mathrm{d})} + \varepsilon_B^{(\mathrm{nd})}}$$

Local energy-loss term

$$\varepsilon_a = \varepsilon_B + \varepsilon_C, \qquad g_{13} \equiv \frac{g_{ae}}{10^{-13}}.$$

Compton-like channel

$$\varepsilon_C^{(\mathrm{nd})} \simeq 2.7 \times 10^{-22} g_{ae}^2 \frac{1}{\mu_e} \left(\frac{n_e^{\mathrm{eff}}}{n_e} \right) T^6$$

$$F_{\mathrm{deg}} = \frac{n_e^{\mathrm{eff}}}{n_e} = \frac{3 E_F T}{p_F^2}, \qquad S_{\mathrm{deg}} = \left(1 + F_{\mathrm{deg}}^{-2} \right)^{-1/2}$$

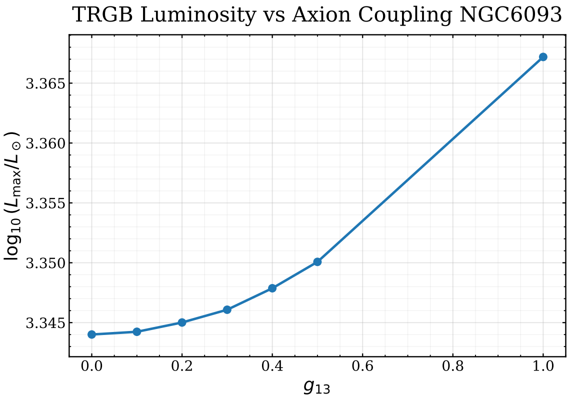
$$\varepsilon_C = \varepsilon_C^{(\mathrm{nd})} S_{\mathrm{deg}}$$

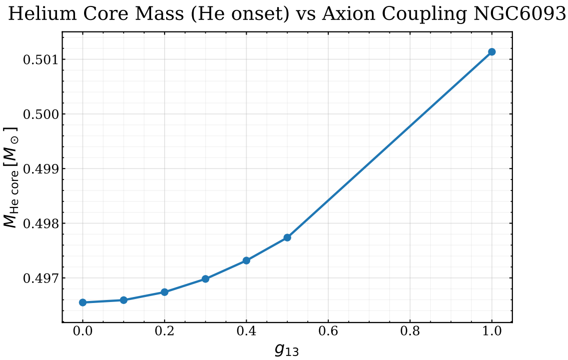
Numerical implementation

The additional losses were added as a local cooling contribution in the MESA `neu` microphysics module. Integrated over the stellar model value.

$$L_a = \int \varepsilon_a \, dm$$

TRGB Luminosity and Helium-Core Mass: NGC6063





TRGB luminosity

Increasing g_{13} makes the TRGB brighter.

Helium-core mass

Axion cooling delays helium ignition, allowing the He core to grow.

Uncertainty Budget

$$\delta \equiv \Delta \log_{10}(L_{\mathrm{TRGB}}/L_{\odot}), \qquad d_M \equiv \frac{|\Delta M_{\mathrm{ini}}|}{0.01\ M_{\odot}}$$

All values are in dex. **U**: uniform; **SN**: split normal; **SSN**: shifted split normal.

Common model uncertainties

Source	Dist.	δ_0	δ_-	δ_+
Numerical resolution	U	0	0.0010	0.0010
Convection	U	0	0.0110	0.0056
Electron conduction	U	0	0.0130	0
Radiative opacity	U	0	0.0080	0.0073
Atmospheric boundary	U	0	0	0.0002

Source	Dist.	δ_0	δ_-	δ_+
^{14}N$(p,\gamma)^{15}$O rate	SSN	$+0.0011$	0.0023	0.0021
Triple-α rate	SSN	$+0.0033$	0.0022	0.0022
Equation of state	U	0	0	0.0028
Electron screening	U	0	0.0114	0
Thermal-neutrino rates	U	0	0.0018	0.0037

Cluster-dependent RGB winds

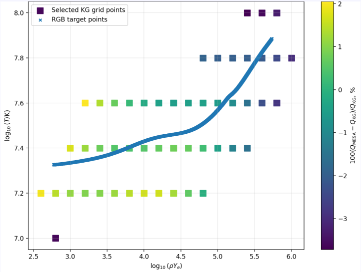
Cluster	Dist.	δ_0	δ_-	δ_+
NGC 288 (canonical)	SN	0	0.0023	0.0015
NGC 6366	SN	0	0.0304	0.0092
NGC 6752	SN	0	0.0166	0.0035
NGC 6352	SN	0	0.0309	0.0111

Initial stellar mass

Mass interval	Dist.	δ_0	δ_-	δ_+
$d_M < 1$	–	0	0	0
$1 \leq d_M \leq 2$ (NGC 5024)	U	0	0	0.0008
$2 < d_M \leq 3$ (NGC 6809)	U	0	0	0.0017
$d_M > 3$ (NGC 6341, NGC 6541)	U	0	0	0.0026
Hot-flasher clusters	U	0	0.0050	0.0050

Thermal Neutrino Losses and Electron Conduction

Microphysics uncertainties in the degenerate He core



RGB-core points of Cantor-Gusakov table used to compare with MESA plasmon-neutrino rate approximation formula(Itoh et al. 1996).

Plasmon-neutrino uncertainty.
The comparison over the RGB-core region gives

$$-3.72\% \ \leq \ \delta_\nu \ \leq \ +2.05\%.$$

This corresponds to the following coefficient before neutrino losses ($\frac{1}{1+\delta}$):

$$\boxed{r_\nu = 0.98,\ 1.04} \quad \Longleftrightarrow \quad {}^{+4\%}_{-2\%} \ \left(\Delta \log L_{\mathrm{TRGB}} = {}^{+0.0030}_{-0.0018}\ \mathrm{dex}\right).$$

Electron conduction.
MESA combines the Cassisi et al. (2007) conductive opacities with the Blouin et al. (2020) correction for *moderately degenerate* electrons: $\theta \equiv \frac{T}{T_{\mathrm{F}}} \sim 0.1 - 1.$
This regime is relevant mainly in the outer part of the degenerate RGB helium core (Blouin use qLFP method).
Cassisi et al. (2021) showed that the interpolation between

$$\underbrace{\text{Blouin/qLFP}}_{\text{moderate degeneracy}} \quad \text{and} \quad \underbrace{\text{C07 tables}}_{\text{strong degeneracy}}$$

changes predicted TRGB luminosity.
Their preferred interpolation is the **weak-damping prescription**:

$$D_{\mathrm{weak}}(\theta) = \left[1 + \left(\frac{0.01}{\theta}\right)^2\right]^{-1},$$

Adopted uncertainty: the difference between the weak-damping interpolation and the original Blouin interpolation:

$$\boxed{\Delta \log L_{\mathrm{TRGB}} = \log L_{\mathrm{weak}} - \log L_{\mathrm{B20}} = -0.013}.$$

Monte Carlo Simulation

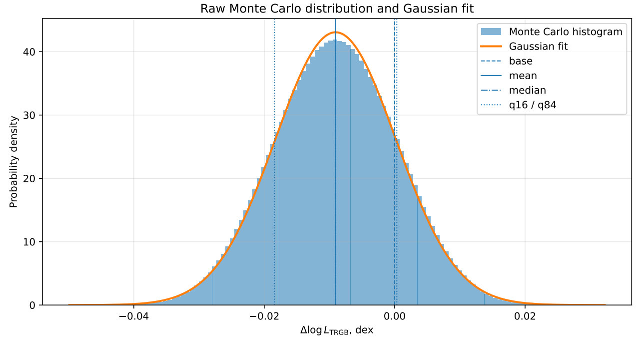
Median Monte Carlo shifts

$$d_M \equiv \frac{|\Delta M_{\rm ini}|}{0.01\,M_\odot}$$

Median shifts with central 68% intervals; all values are in dex.

Cluster class or mass category	$\Delta_{\rm MC}$
Canonical clusters	
$d_M \leq 3$	$-0.009^{+0.009}_{-0.009}$
$d_M > 3$	$-0.008^{+0.009}_{-0.009}$
Hot-flasher clusters	
NGC 6366	$-0.023^{+0.020}_{-0.026}$
NGC 6752	$-0.018^{+0.013}_{-0.015}$
NGC 6352	$-0.022^{+0.021}_{-0.027}$

Combined Monte Carlo distribution



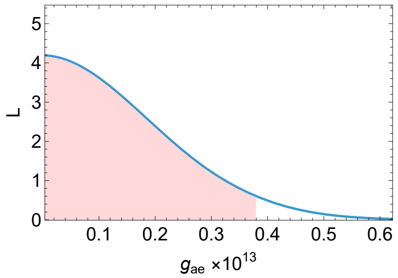
TRGB Luminosity: MESA vs Observations

Cluster	$\log L_{\mathrm{MESA}}$	$\log L_{\mathrm{obs}}$	Cluster	$\log L_{\mathrm{MESA}}$	$\log L_{\mathrm{obs}}$
NGC6205	$3.3352^{+0.0094}_{-0.0094}$	$3.0440^{+0.0580}_{-0.0652}$	NGC5904	$3.3637^{+0.0094}_{-0.0094}$	$3.2488^{+0.0464}_{-0.0472}$
NGC6218	$3.3637^{+0.0094}_{-0.0094}$	$3.3912^{+0.1096}_{-0.2236}$	NGC6341	$3.2912^{+0.0094}_{-0.0094}$	$3.2264^{+0.0476}_{-0.0524}$
NGC6093	$3.3354^{+0.0094}_{-0.0094}$	$3.3560^{+0.0644}_{-0.0856}$	NGC0362	$3.3695^{+0.0094}_{-0.0094}$	$3.3728^{+0.0672}_{-0.0884}$
NGC0288	$3.3635^{+0.0094}_{-0.0094}$	$3.0412^{+0.0572}_{-0.0808}$	NGC5053	$3.2934^{+0.0094}_{-0.0094}$	$2.9320^{+0.0808}_{-0.1140}$
NGC6171	$3.3805^{+0.0094}_{-0.0094}$	$3.1812^{+0.0960}_{-0.1456}$	NGC5466	$3.3119^{+0.0094}_{-0.0094}$	$3.2440^{+0.0564}_{-0.1160}$
NGC6352	$3.3780^{+0.0211}_{-0.0265}$	$3.1872^{+0.0684}_{-0.1220}$	NGC6779	$3.3121^{+0.0094}_{-0.0094}$	$3.3608^{+0.0560}_{-0.0772}$
NGC6838	$3.4052^{+0.0094}_{-0.0094}$	$3.3116^{+0.1412}_{-0.3196}$	NGC6101	$3.3143^{+0.0094}_{-0.0094}$	$3.3748^{+0.0892}_{-0.1736}$
NGC7099	$3.3051^{+0.0094}_{-0.0094}$	$3.3784^{+0.0772}_{-0.1448}$	NGC1261	$3.3619^{+0.0094}_{-0.0094}$	$3.3312^{+0.0640}_{-0.0868}$
NGC6723	$3.3831^{+0.0094}_{-0.0094}$	$3.1744^{+0.0700}_{-0.0864}$	NGC6752	$3.3334^{+0.0134}_{-0.0153}$	$3.3248^{+0.0824}_{-0.0924}$
NGC6362	$3.3839^{+0.0098}_{-0.0098}$	$3.2632^{+0.0500}_{-0.0664}$	NGC6809	$3.3241^{+0.0094}_{-0.0094}$	$3.2892^{+0.0356}_{-0.0532}$
NGC5897	$3.3195^{+0.0094}_{-0.0094}$	$3.4956^{+0.1268}_{-0.1932}$	NGC6541	$3.3240^{+0.0094}_{-0.0094}$	$3.2880^{+0.0388}_{-0.0468}$
NGC6366	$3.3815^{+0.0201}_{-0.0257}$	$3.1532^{+0.0700}_{-0.1256}$	NGC6254	$3.3396^{+0.0094}_{-0.0094}$	$3.3256^{+0.0624}_{-0.0992}$
NGC5024	$3.3212^{+0.0094}_{-0.0094}$	$3.2732^{+0.0368}_{-0.0404}$	NGC6397	$3.3195^{+0.0094}_{-0.0094}$	$3.2896^{+0.0536}_{-0.0868}$
NGC5272	$3.3422^{+0.0094}_{-0.0094}$	$3.3144^{+0.0452}_{-0.0500}$			

Conclusions

Main results

- We computed the TRGB luminosities and other stellar parameters for 27 globular clusters using MESA.
- For each cluster, we constructed a grid of models with different values of the axion–electron coupling.
- The results are consistent with the theoretical picture.
- Theoretical uncertainties were estimated using Monte Carlo simulations, and g_{13} was constrained through a likelihood analysis.



Statistical results

Minimum median shift for canonical clusters:

$$\Delta_{\mathrm{MC}}^{\mathrm{min}} = -0.009^{+0.009}_{-0.009}\ \mathrm{dex}$$

Our statistical bound:

$$\boxed{g_{13} < 0.38 \quad (95\%\ \mathrm{CL})}$$

To the best of our knowledge, this is the strongest published constraint on g_{ae} in this mass range.