Search for new physics with giant stars in globular clusters after Gaia

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QUARKS-2026
XXIII INTERNATIONAL SEMINAR ON HIGH-ENERGY PHYSICS
Petrozavodsk , Russia
18-23 May 2026

Search for new physics with giant stars in globular clusters after Gaia

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Supported by the Russian Science Foundation, project 22-12-00253

РНФ Российский научный фонд

Stellar evolution affected by axions

light particles with very suppressed interactions remove energy from stellar interiors
evolutionary timescales shorten
*
light particles with stronger but suppressed interactions result in energy transfer between parts of a star
mechanical construction of a star changes

white-dwarf luminosity function
average rate of WD cooling
Blinnikov, Vysotsky 1990

HB stars to red giants ratio
time scale of helium burning
Dicus et al. 1978

pulsating white dwarf period change
rate of individual WD cooling
Isern et al. 1992

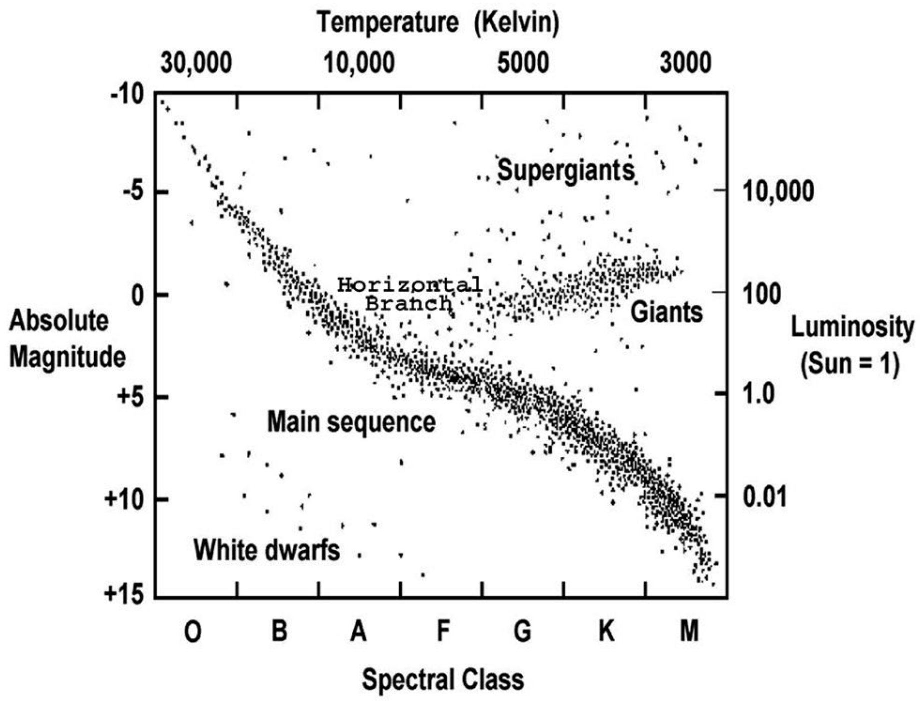
tip of the red-giant branch
time of helium ignition
Raffelt 1990

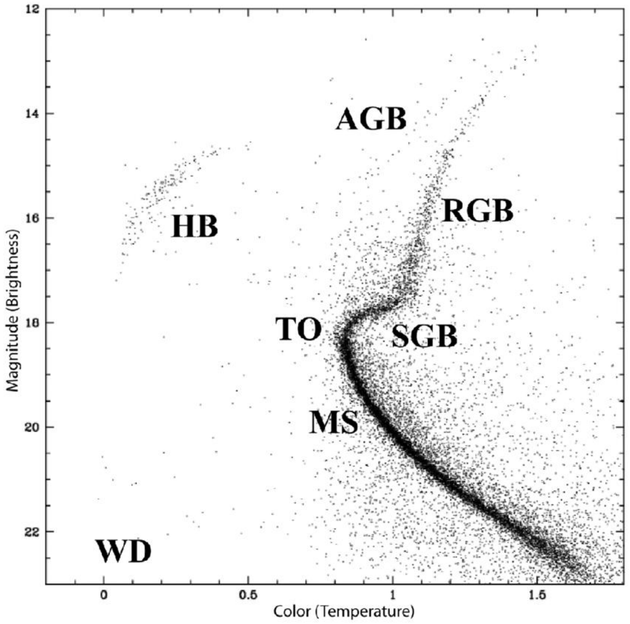
constrains much stronger than from laboratory experiments

reviews: *Raffelt 1996 (book), Giannotti et al. 2015, 2017, Caputo & Raffelt 2024*

Globular clusters

- millions of stars formed at the same time from the same gas
- star formation stopped (remaining gas blown by supernova explosions)
- color-magnitude diagram shows evolutionary tracks of very similar stars
- fast evolution when H exhausted in the center: red giants
- He ignition and burning: horizontal branch





Tip of the Red Giant Branch (TRGB)

• the brightest red giant indicates the moment of the helium ignition
• extra losses due to axions make the brightest red giant brighter than expected
• important to know the distance (GAIA parallaxes change the game)

- axion-electron interactions
- neutrino magnetic moment
- millicharged particles

…

The R parameter (ratio of HB to RG stars)

• ratio of the number of He burning stars to the number of red giants
• CMD gives a "stroboscopic" view of the evolutionary track
• many uncertainties cancel in the ratio
• losses due to axions accelerate He burning and reduce R

- axion-photon interactions
- nuclear processes

…

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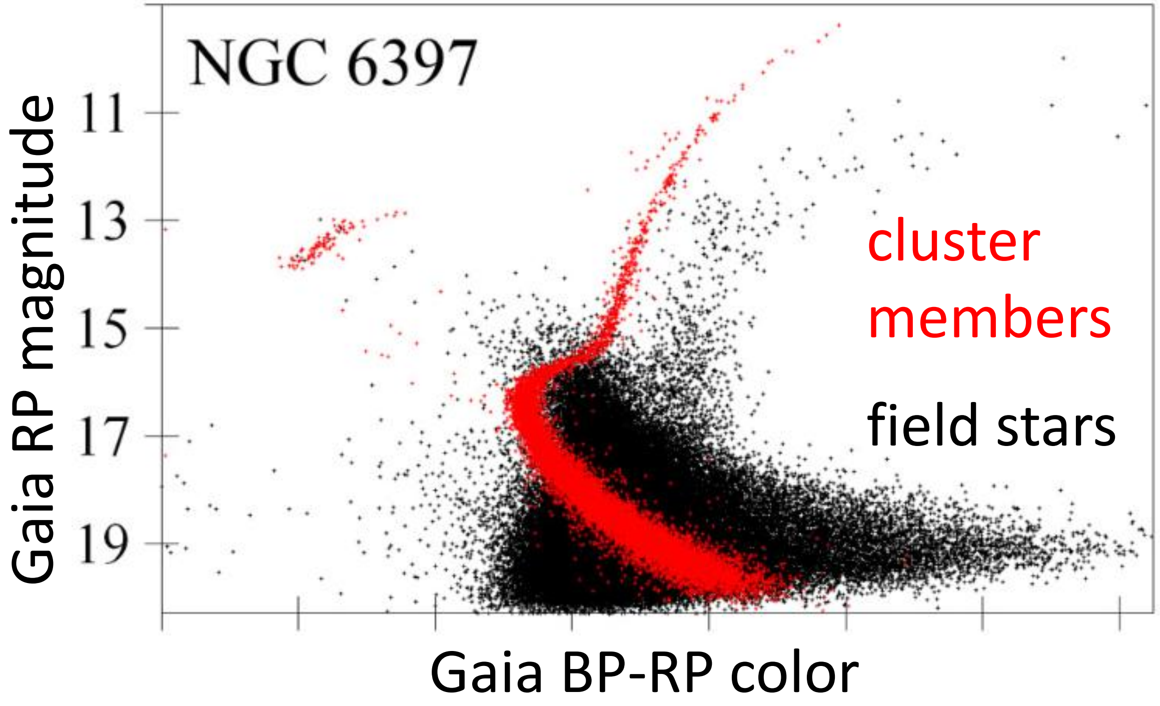
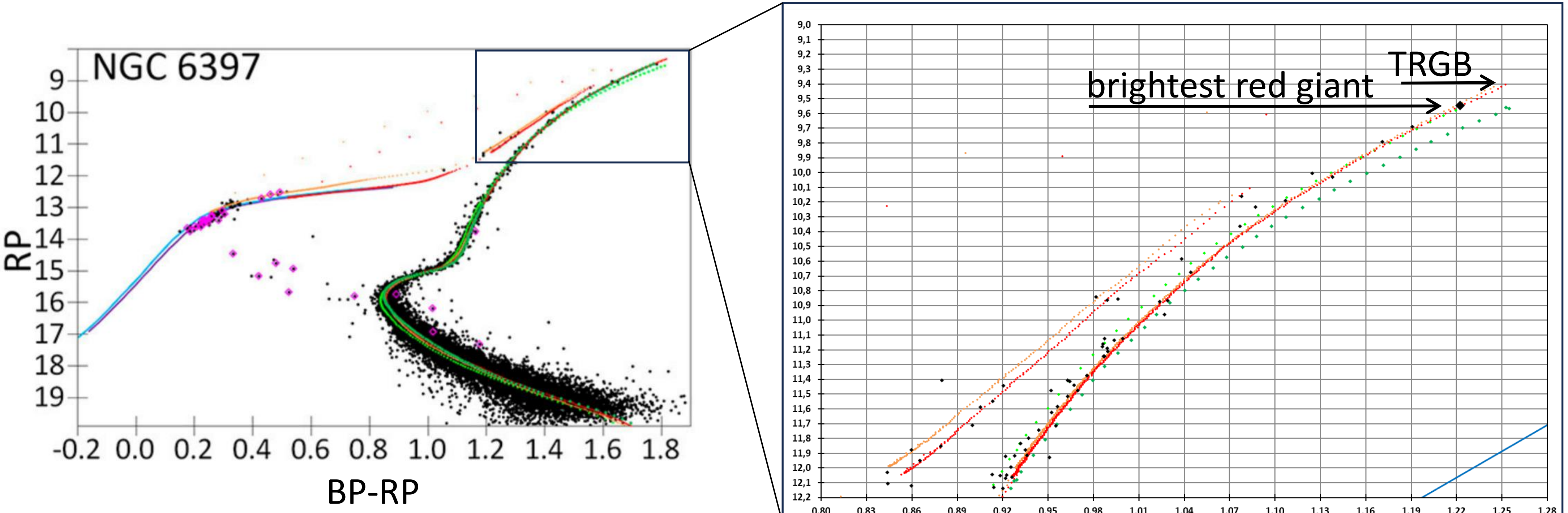
Globular clusters with Gaia

- Gaia DR3: parallaxes and proper motions for 1.9 billion stars
- easy selection of confirmed cluster members
- combination with HST and terrestrial photometry (Stetson) to resolve the very center



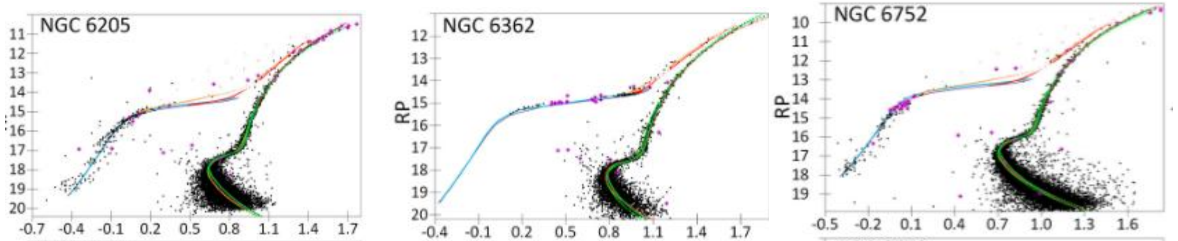
Isochrone fitting

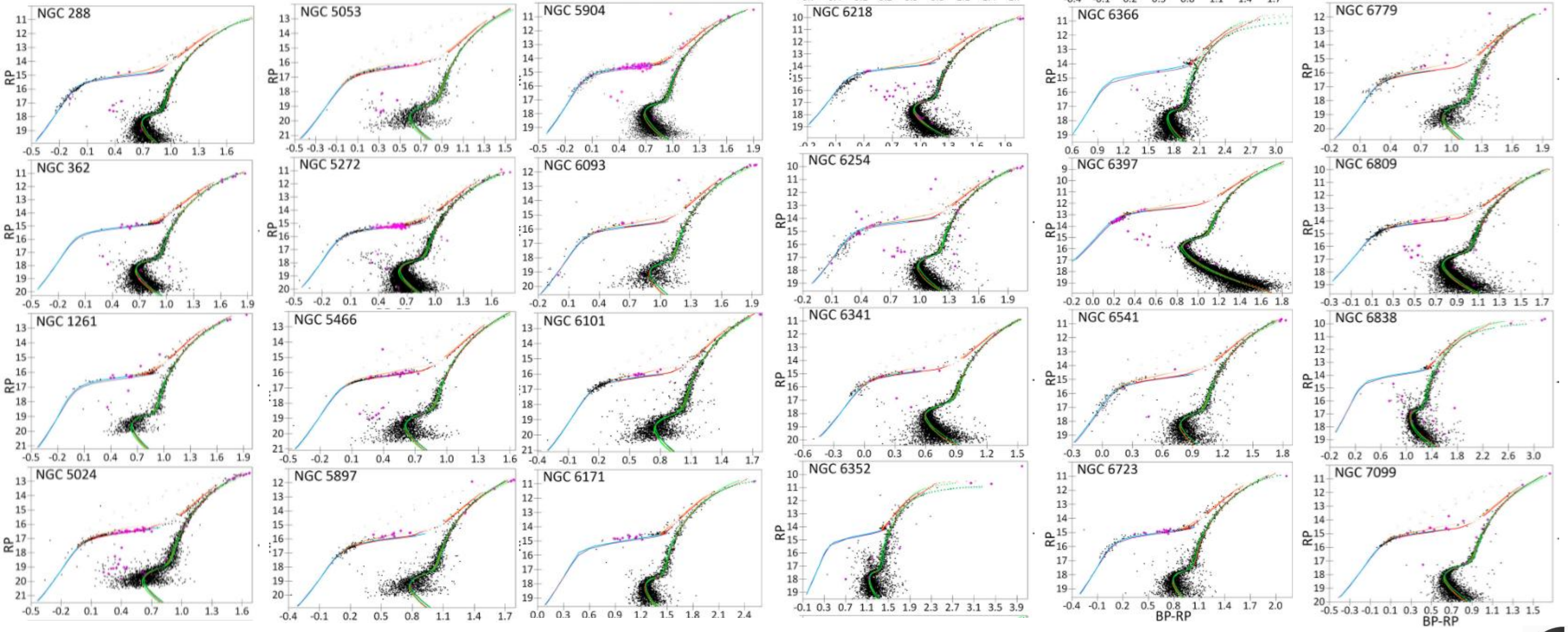
- isochrone: model color-magnitude diagram (CMD) for a cluster as it is observed
- depends on cluster parameters, is produced by stellar evolution codes
- fits of the observed clean CMD ➡ the set of **parameters of each cluster**



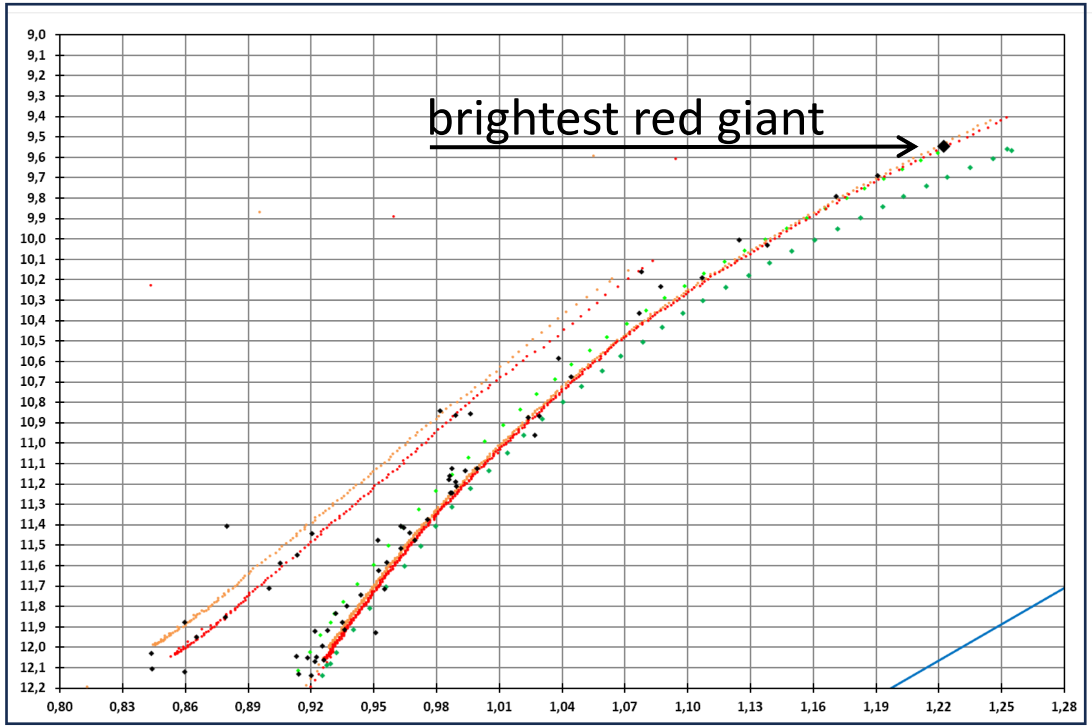
best-fit isochrone: red line

Homogeneous sample:
27 globular clusters





Brightest star luminosity & uncertainties



- use model best-fit isochrone value instead of the bolometric correction
- star projected to isochrone if does not fit exactly
- evil is in the uncertainties!

To estimate systematic uncertainties, we vary for each brightest star:

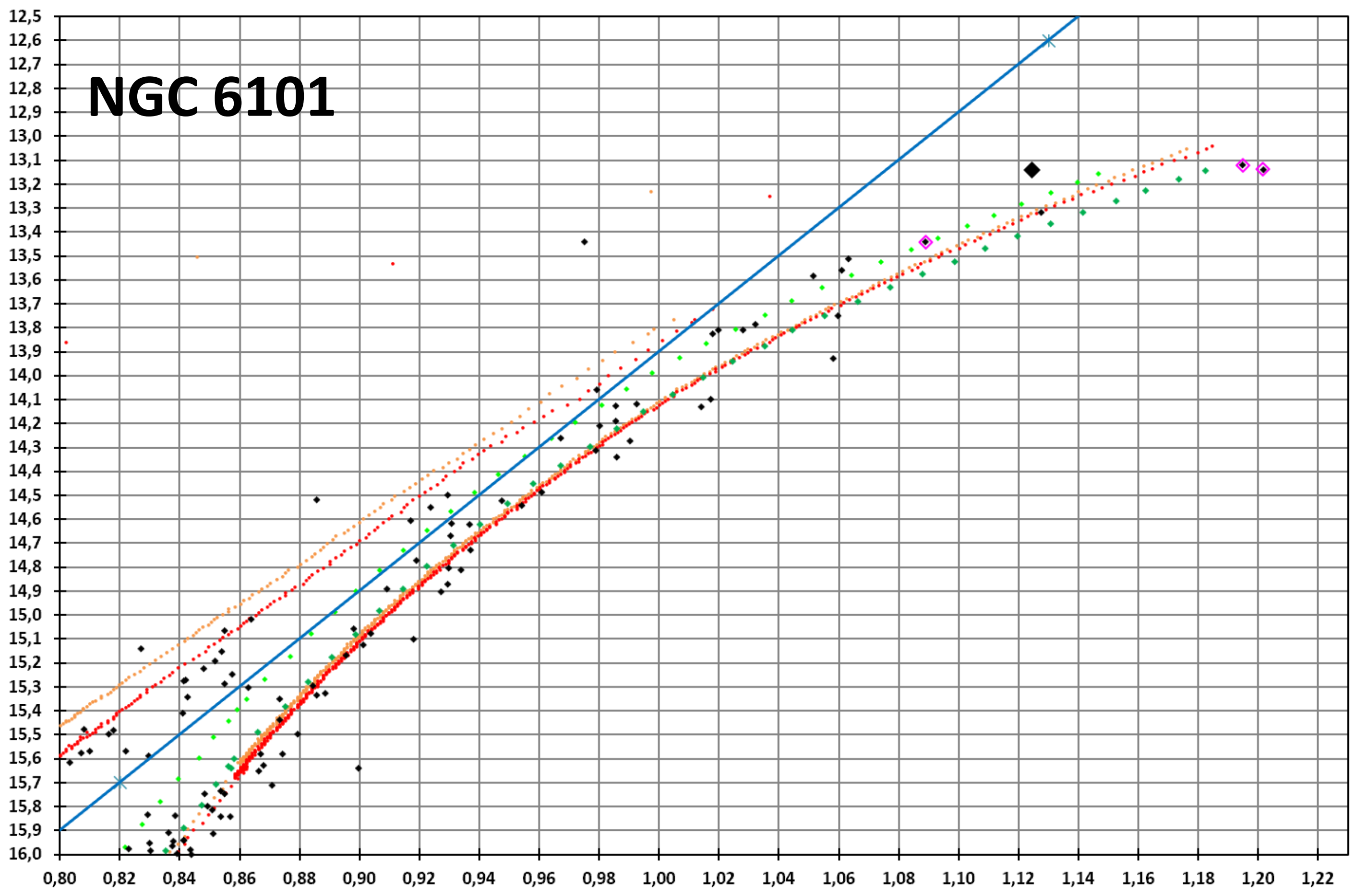
- method of the luminosity calculation (2 isochrones + direct integration of multiwavelength fluxes)
- Galactic extinction (2 models)
- distance (parallax vs. best-fit isochrone)
- age (2 independent estimates)
- chemical composition (2 sets of spectroscopic observations)

✓ brightest red giant luminosities
✓ with uncertainties
✓ for 27 clusters

Variable stars

- the brightest star may be variable
- snapshot Gaia or HST observation may not be representative

➢ remove the variables!
➢ when many observations available, use for cross check



Correction for discreteness

- the brightest star has not yet reached the tip
- the brightest non-variable is not the brightest star (*k* variables dropped)
- rich cluster – better tip coverage (*N* red giants)

➢ perform Monte-Carlo simulation of the difference between the brightest star and the tip
   - ✓ take a typical track
   - ✓ throw *N* stars, remove *k* brightest
   - ✓ get the difference
   - ✓ determine the correction and its two-side uncertainty

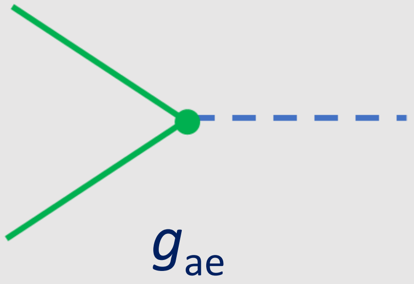
➢ add this correction (*N*,*k*) to the brightest-star luminosity

➢ add this uncertainty to its uncertainty

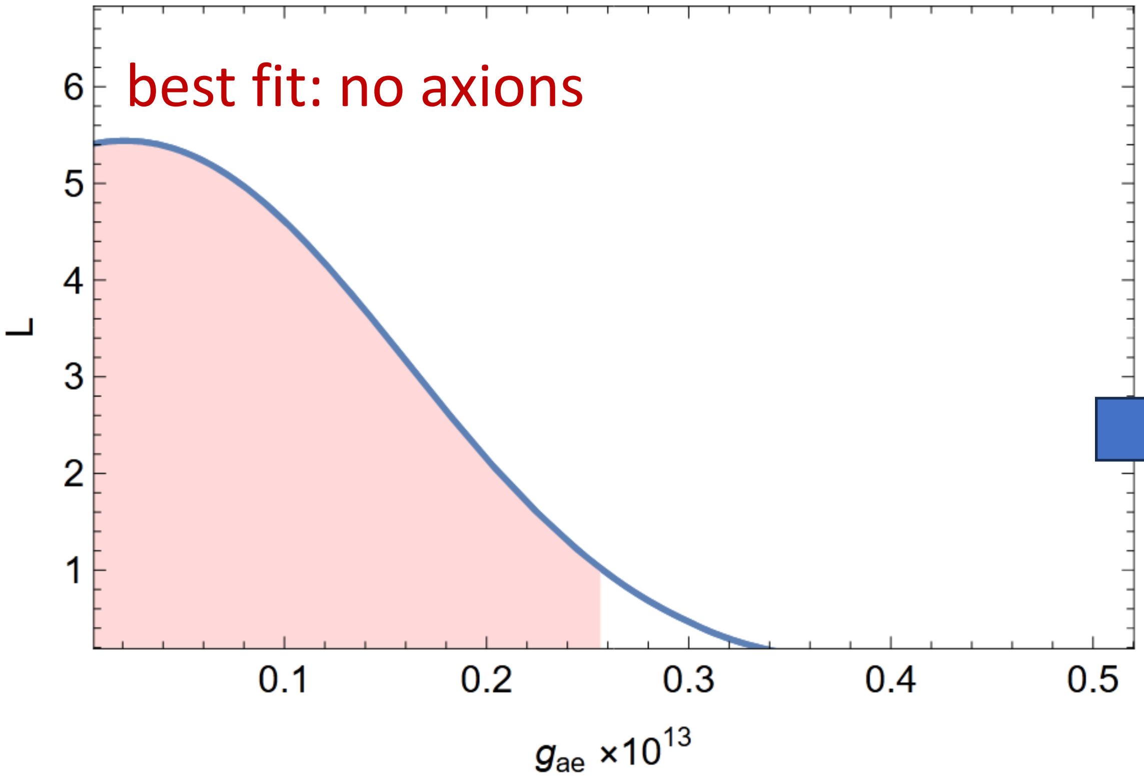
✓ TRGB luminosities
✓ with uncertainties
✓ for 27 clusters

Constraints on the axion coupling from the combination of clusters

- for each of 27 clusters, take MESA simulation with and without axions
- construct the combined likelihood – function of the coupling g_{ae}
- determine best-fit value or put upper limits on g_{ae}



$$\sim \frac{m_\psi}{f_A} a \bar{\psi} \gamma_5 \psi$$



$$g_{ae} < 2.6 \times 10^{-14} \ (95\% \ \mathrm{CL})$$

Gontcharov et al. 2026
(this work, preliminary)

Summary

- world-best limit on the axion-electron coupling $g_{ae} < 2.6 \times 10^{-14}$ (95% CL)
- essential differences from previous studies:
  - each cluster treated individually, both in data and simulations
  - removal of variable stars (compensated by the discreteness correction)
  - clean cluster membership selection from Gaia DR3
  - account of the mass loss in simulations
  - ….
- stay tuned for:
  - neutrino magnetic moment
  - millicharged particles
  - axion-photon coupling

Thank you!

BACKUP SLIDES

Individual problematic clusters: the likelihood analysis treats them correctly