New results on axions in astrophysics

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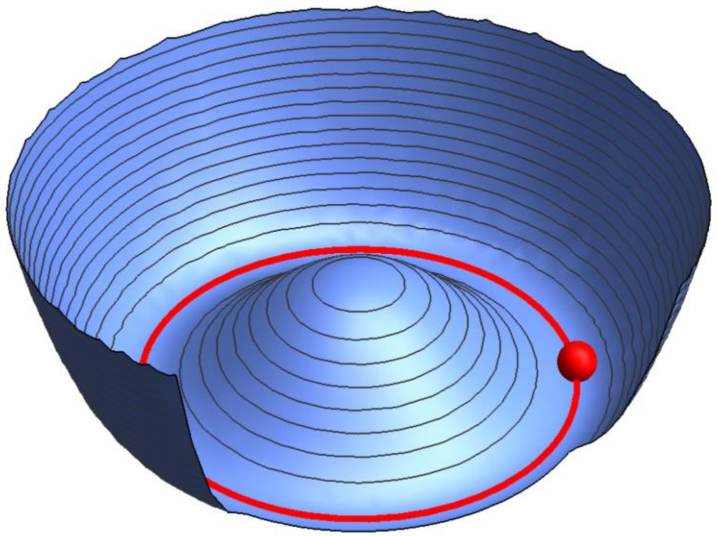
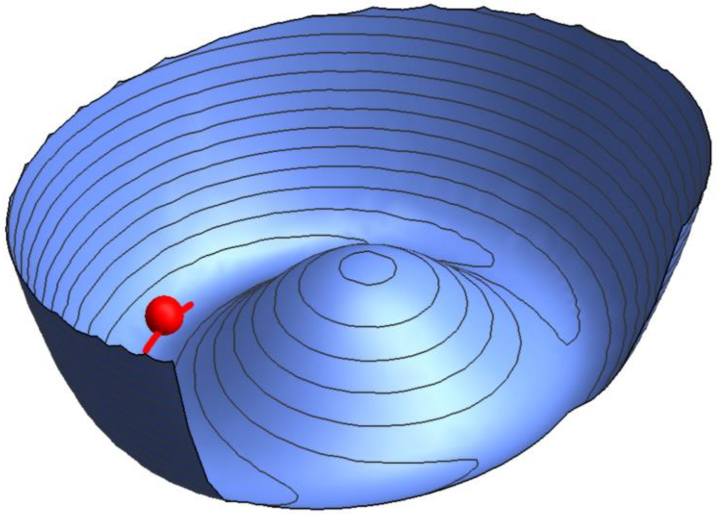
Axions and axion-like particles



spontaneous breaking of U(1):
Goldstone boson (massless)

(one scale)

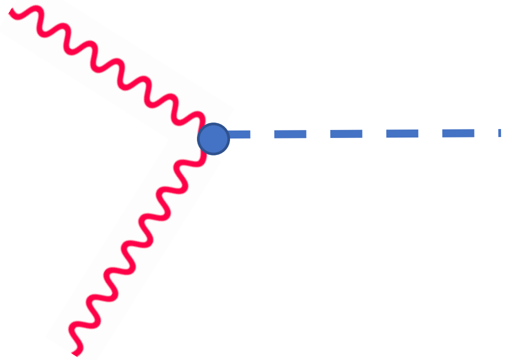


spontaneous + small explicit breaking:
pseudo-Goldstone boson (light)

(two scales)

ALP-photon interaction

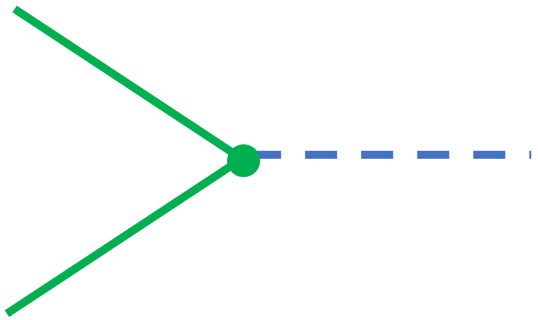
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}m^2a^2 - \frac{1}{4}gaF_{\mu\nu}\tilde{F}^{\mu\nu}$$



- allowed by all symmetries, hence appears
- dimensionful coupling g suppressed by the U(1) breaking scale
  - ✓ related to the ALP mass for a particular model, e.g. the QCD axion
- photon/ALP mixing in the external magnetic field
- conversion probability depends on the mass, coupling, energy and field

$$\frac{a}{M}F_{\mu\nu}\tilde{F}_{\mu\nu}, \quad M \sim f_A \sim \frac{\Lambda^2_{\rm QCD}}{m}$$

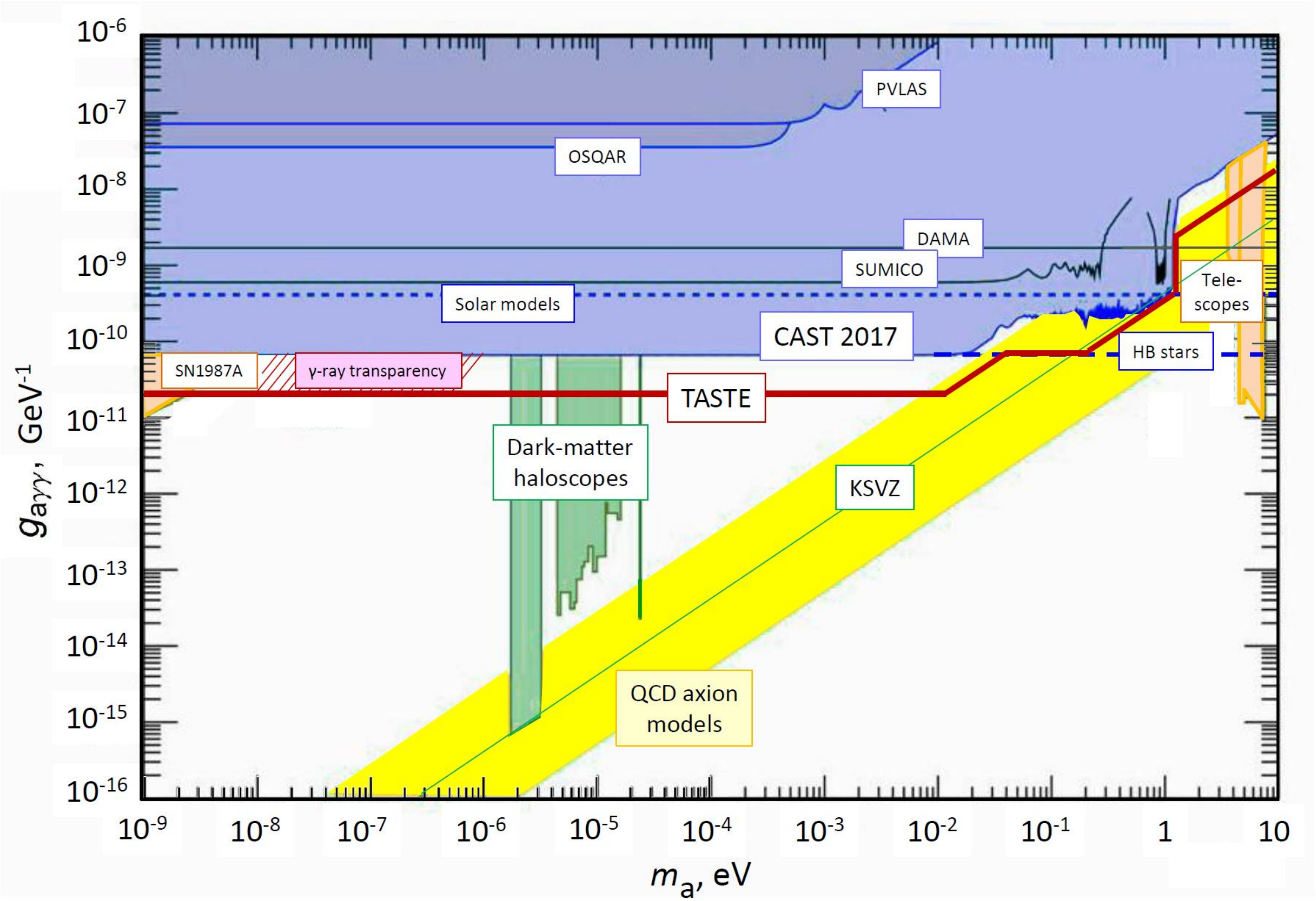
ALP-fermion interaction



- coupling of a (pseudo)Goldstone boson determined by the current algebra
- dimensionless coupling suppressed by the U(1) breaking scale
  - ✓ related to the ALP mass for a particular model, e.g. the QCD axion
- zero or not, depending on particular quantum numbers
- electron-ALP coupling of particular interest

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

ALP parameters



Paths to the axion discovery

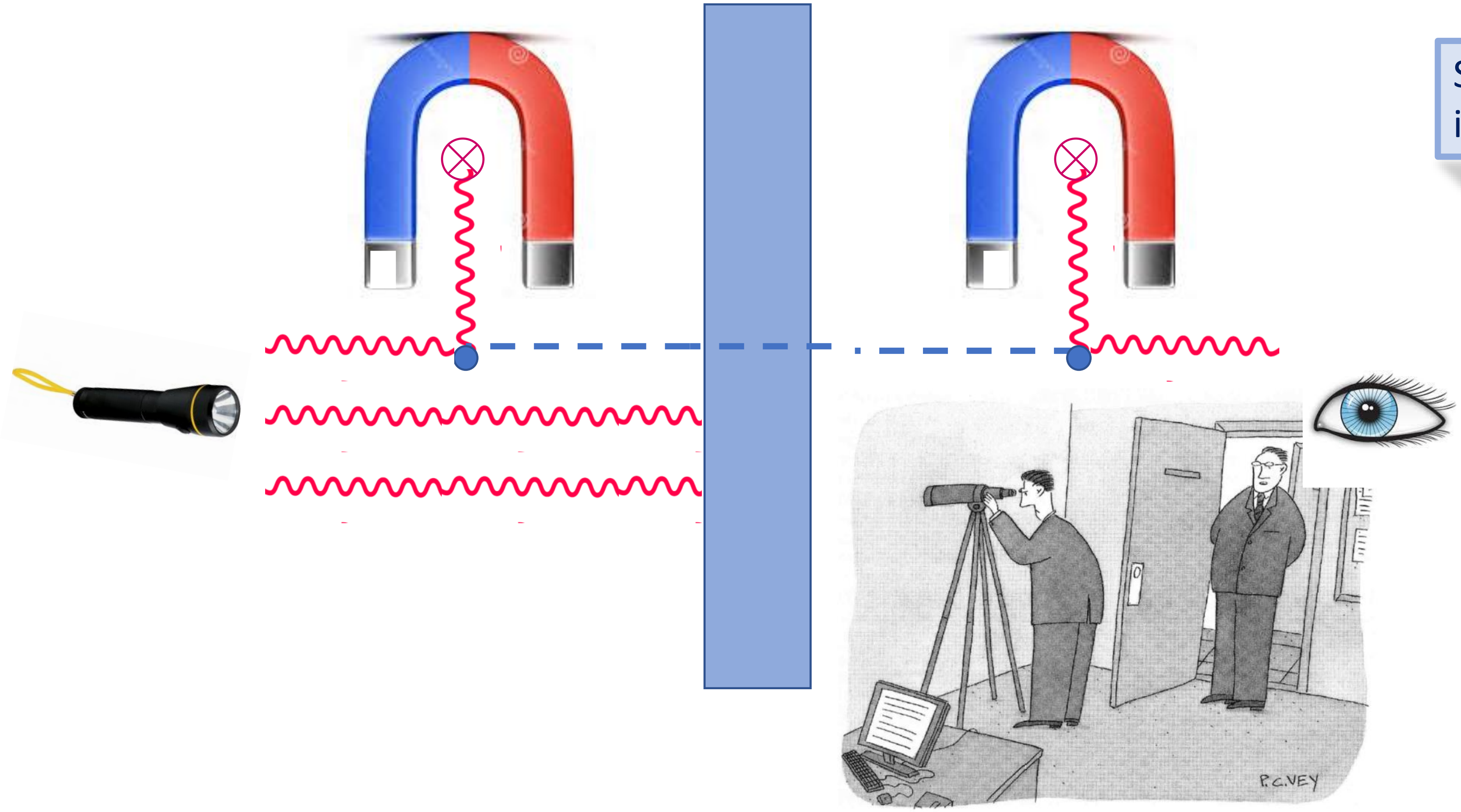
- production and detection in a lab
  - ✓ light shining through walls
  - ✓ polarization
  - ✓ cavities*

- production in astrophysical objects, detection in a lab
  - ✓ helioscopes

- production and detection in astrophysical objects:
  - ✓ stellar energy losses: light particles are produced in hot media, bring energy away (compete with neutrinos)
  - ✓ conversion and reconversion to photons in astro magnetic fields

* do not require axions to be the dark matter

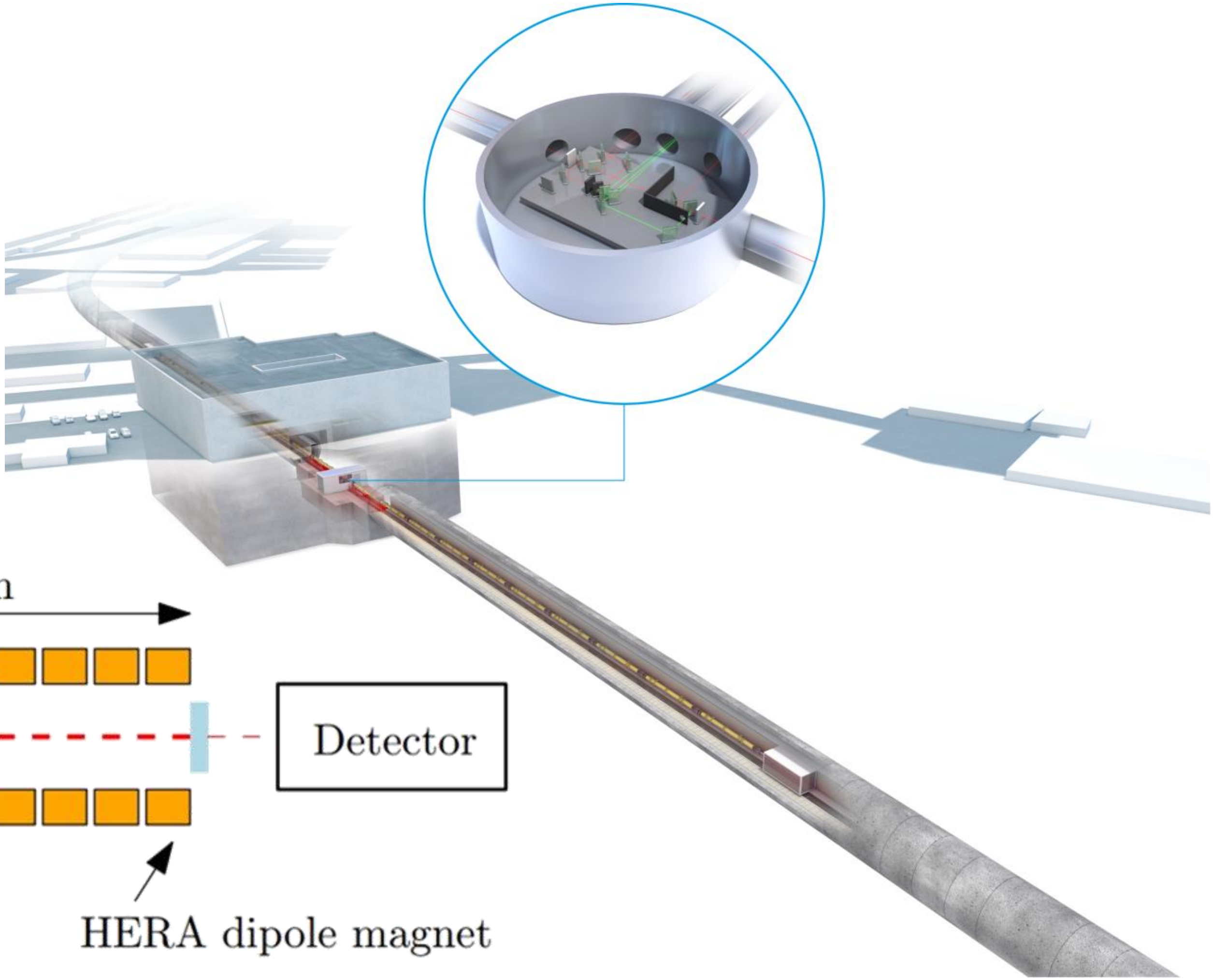
ALP-photon: shining light through walls

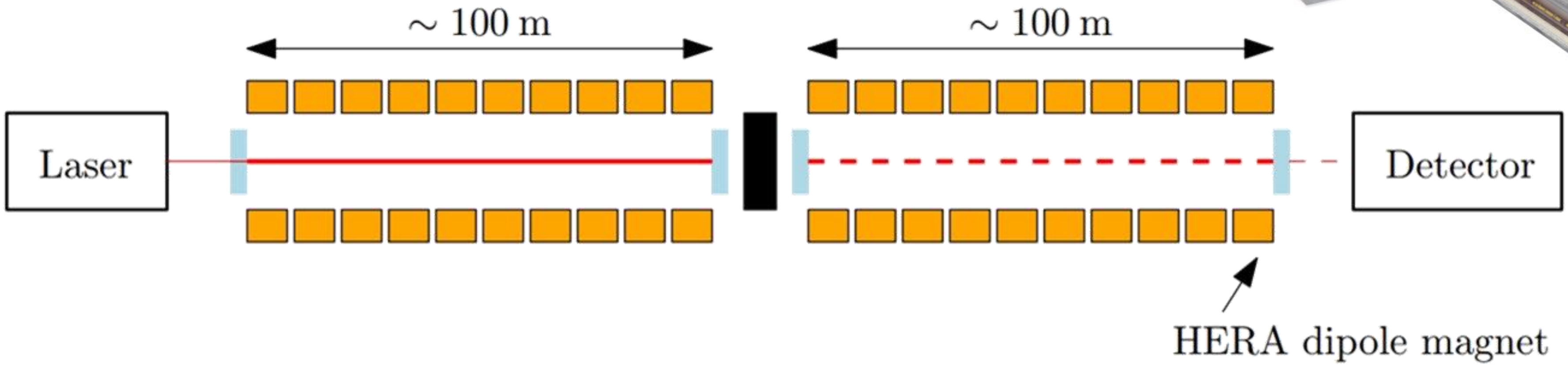


Search for axions
in a laboratory

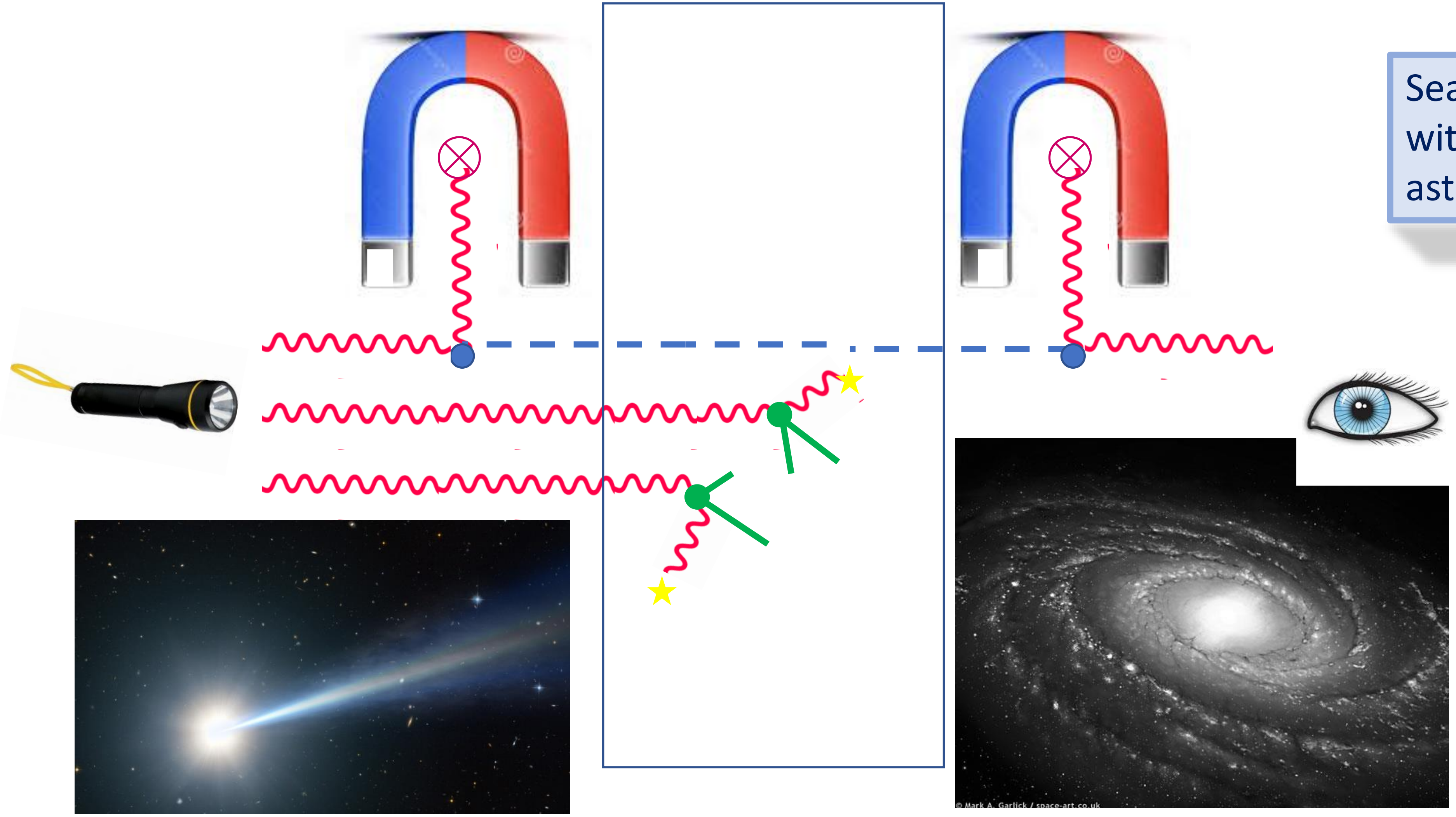
Purely laboratory axion experiment: ALPS-IIc

- light shining through the wall
- straightened HERA magnets
- locked cavities
  (resonant generation and regeneration)
- data taking soon



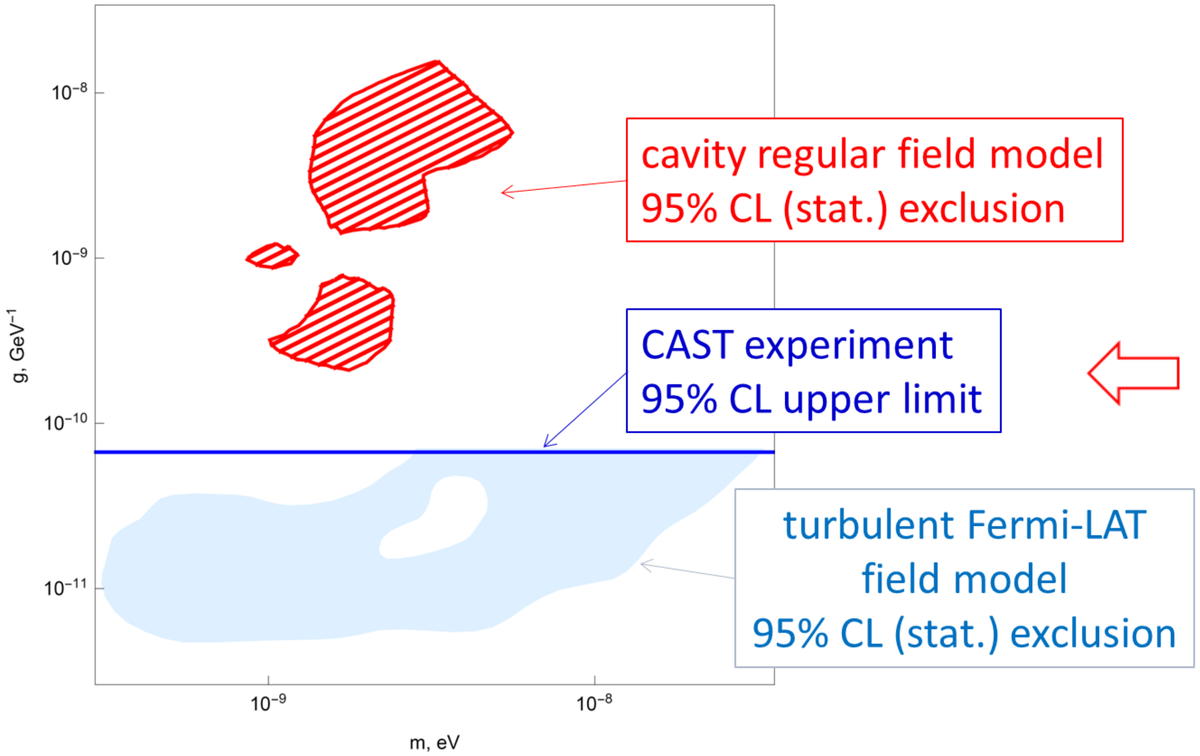


ALP-photon: shining light through the Universe



Search for axions with gamma-ray astronomy

Caution: we do not know astrophysical magnetic fields



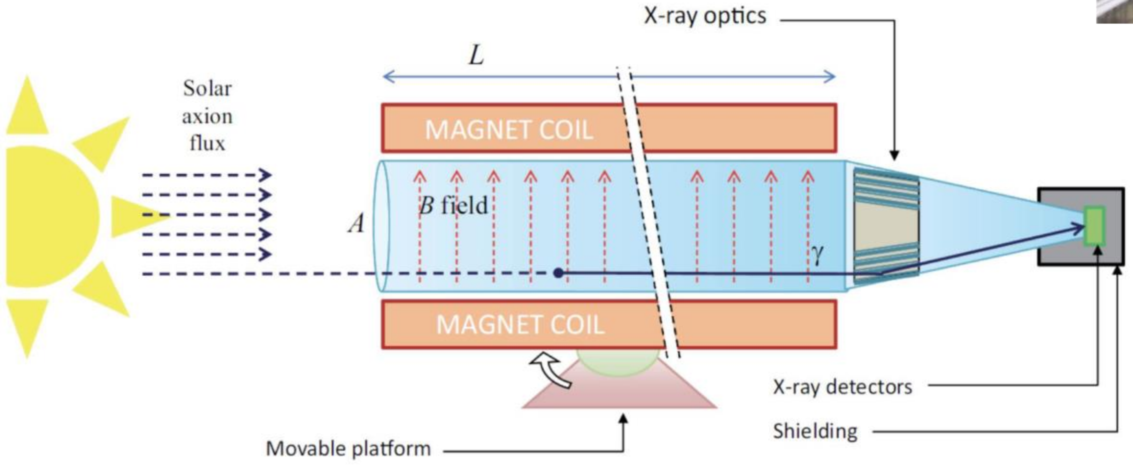
the actual field is an unknown combination of regular and turbulent components

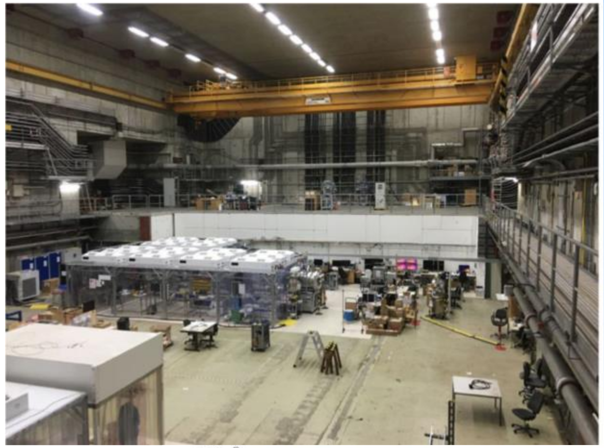
the actual constraint is somewhere in between

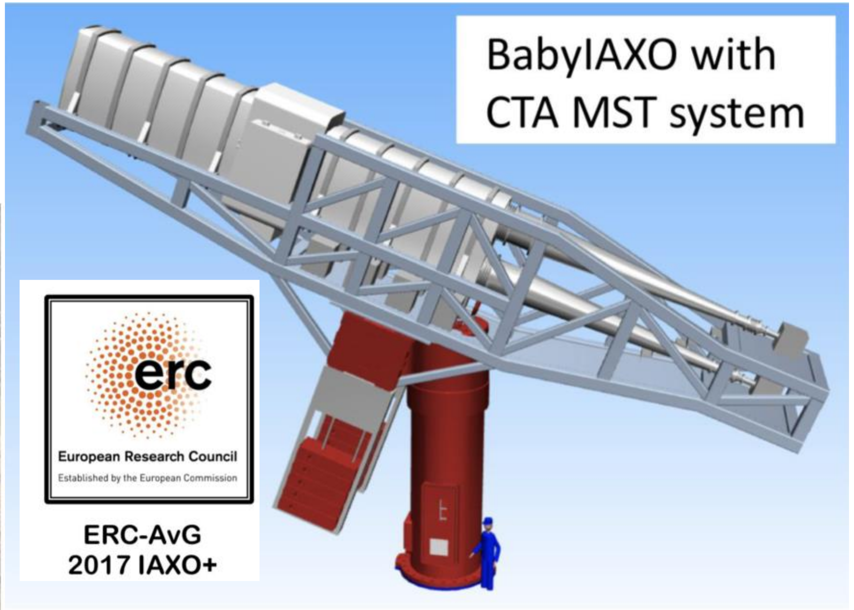
Libanov, ST 2020

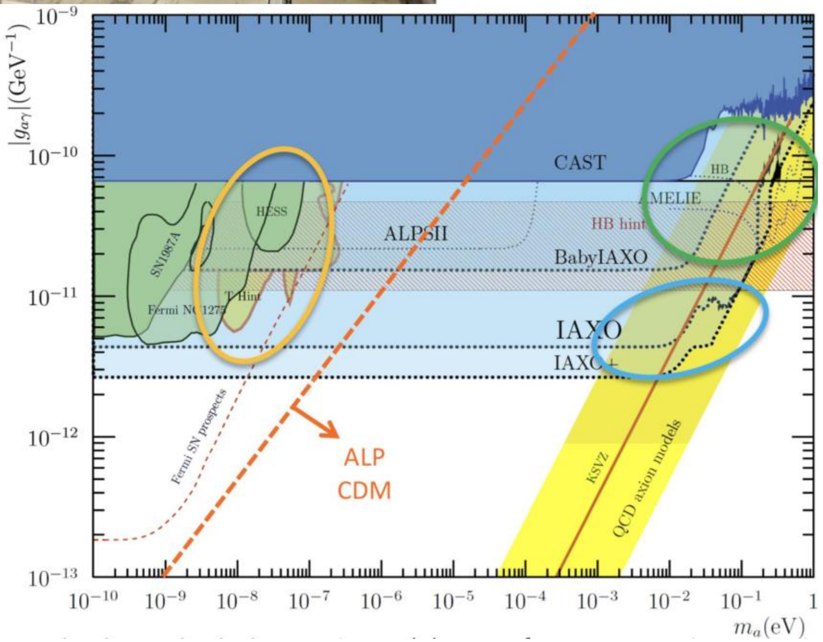
Solar axion detection: from CAST to babyIAXO

- axions produced in the solar central zone
- convert to X-ray photons in a lab magnet
- CERN Axion Solar Telescope (CAST)
- babyIAXO under construction in DESY
- future plans for IAXO









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

relevant for the electron coupling:

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

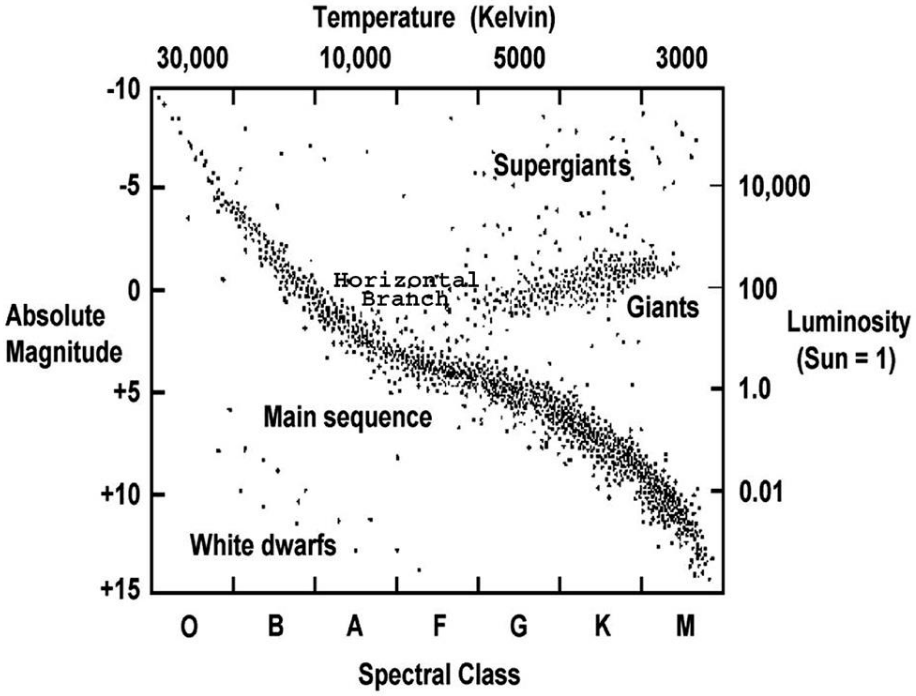
tip of the red-giant branch
time of helium ignition
Raffelt 1990

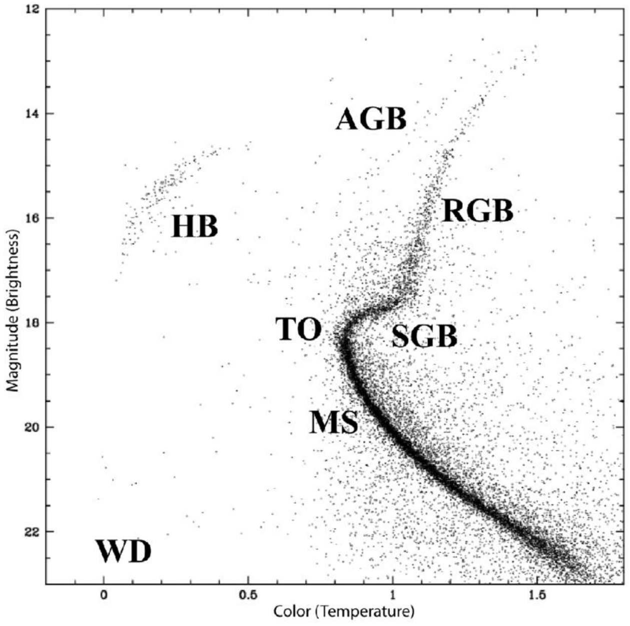
constrains much stronger than from laboratory experiments

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

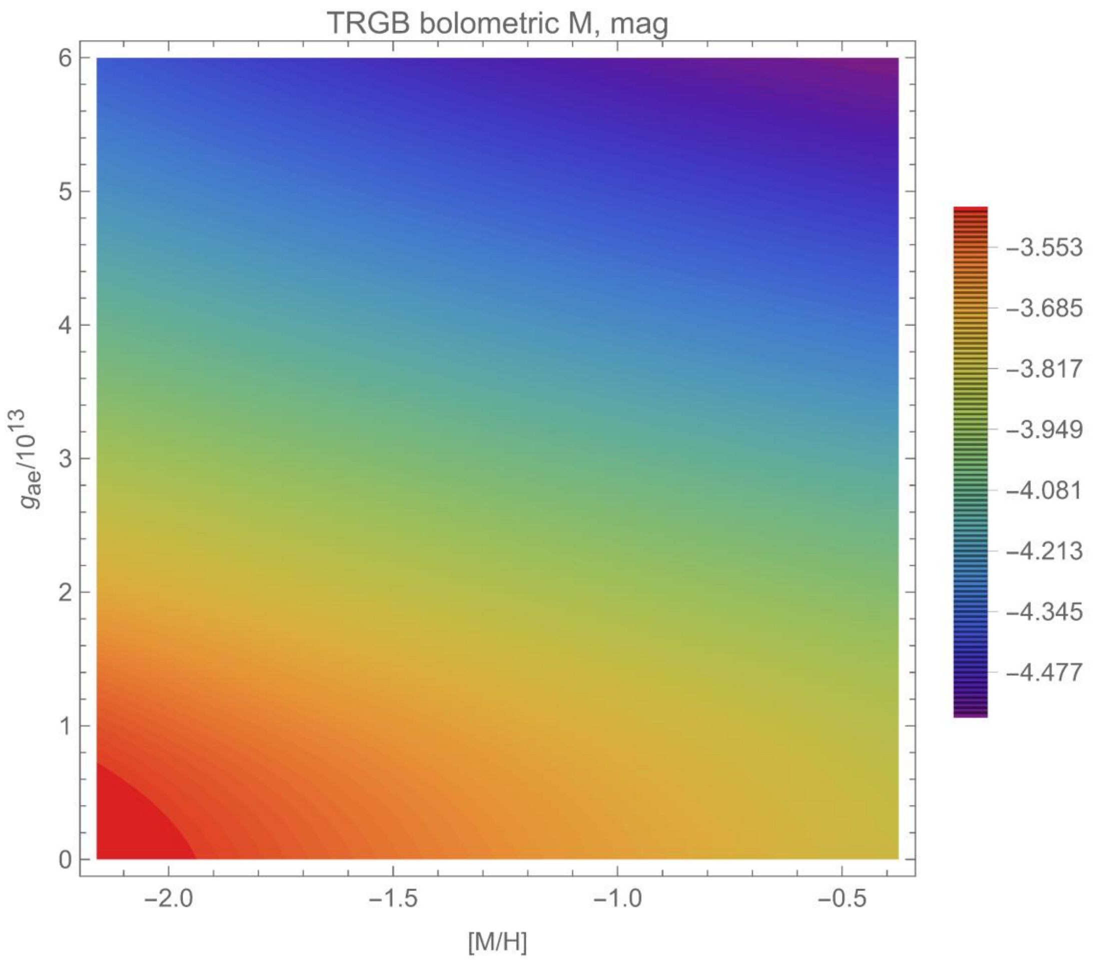




Tip of the Red Giant Branch (TRGB)

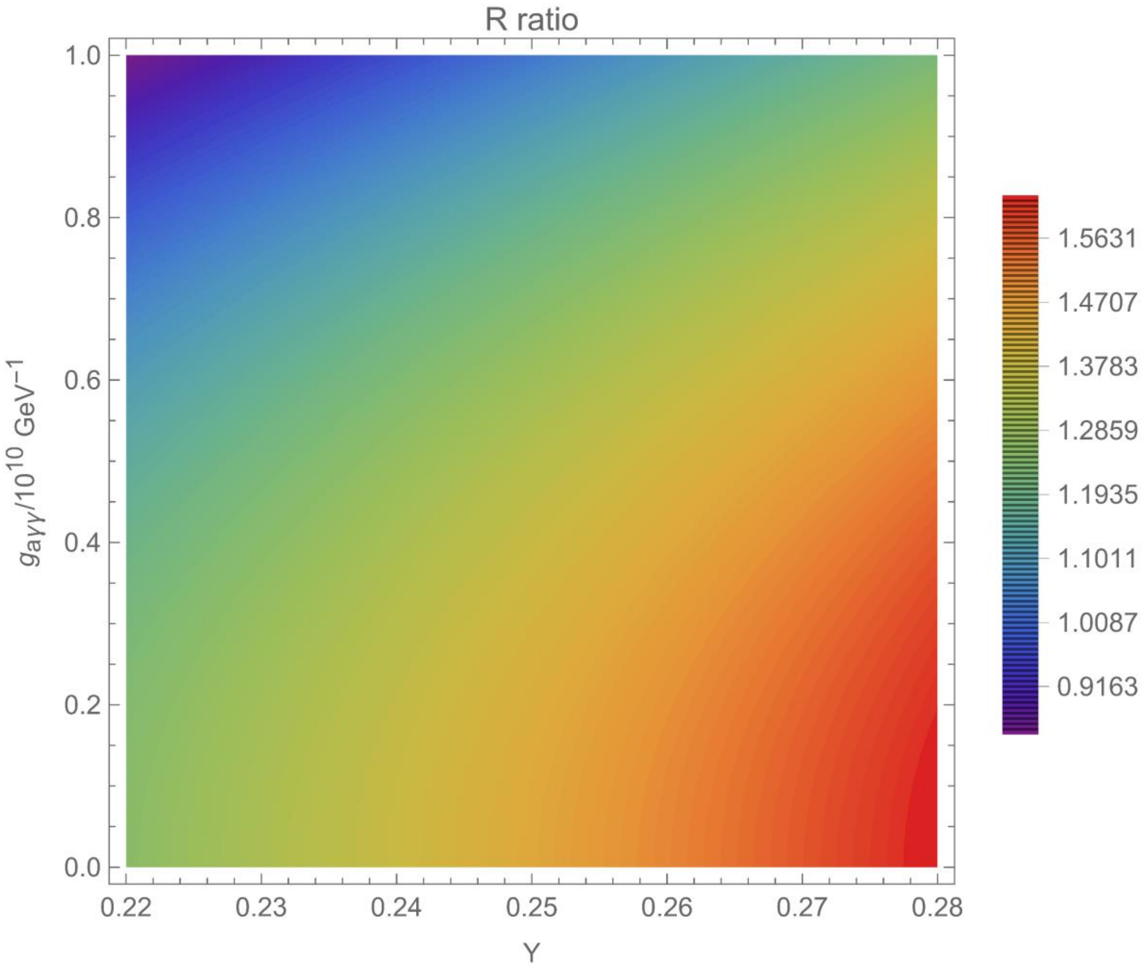
- the brightest red giant indicates the moment of the helium ignition
- extra losses due to axions make the brightest red giant brighter than expected
- important to know the distance (GAIA parallaxes change the game)

Straniero et al. 2020



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

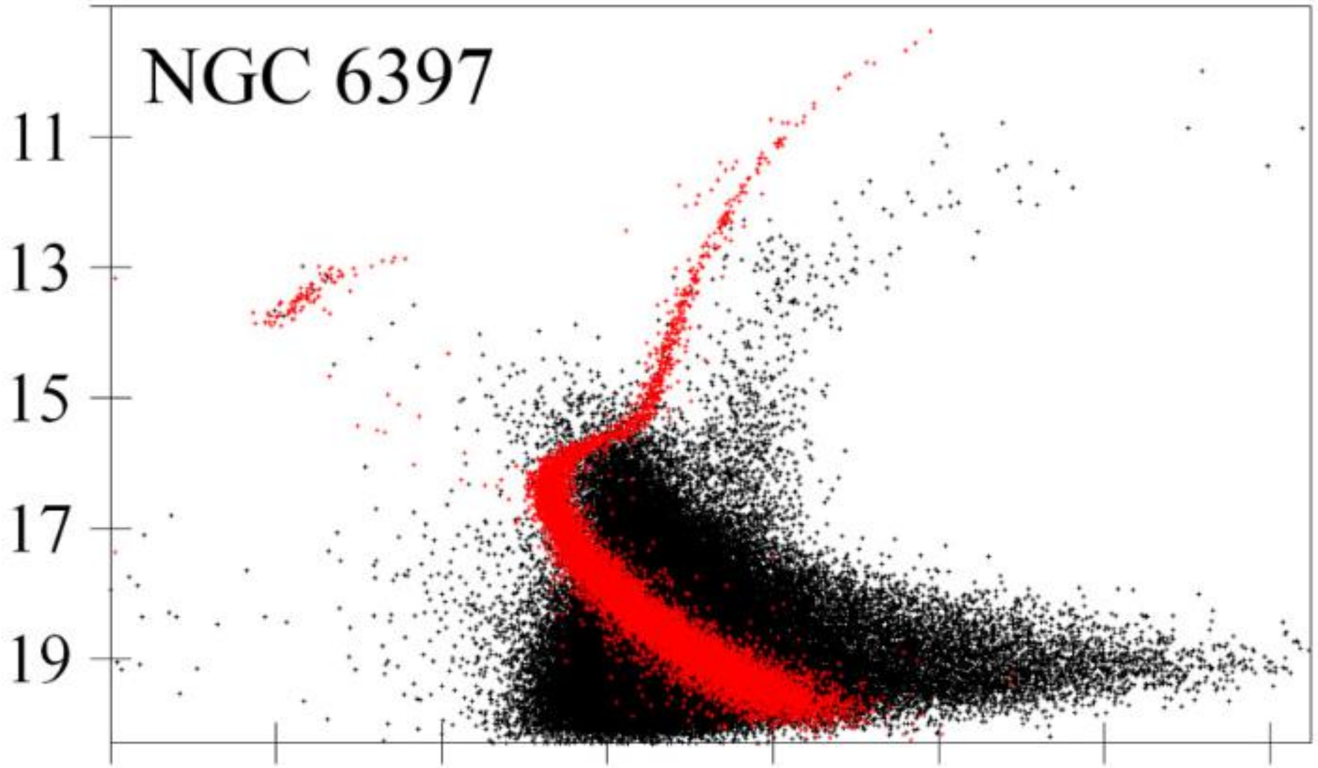


Ayala et al. 2014

Globular clusters with GAIA

- GAIA measured parallaxes and proper motions for 1.9 billion stars
- easy selection of confirmed cluster members
- troubles with crowded fields overcome in DR3 (2022) and in dedicated studies

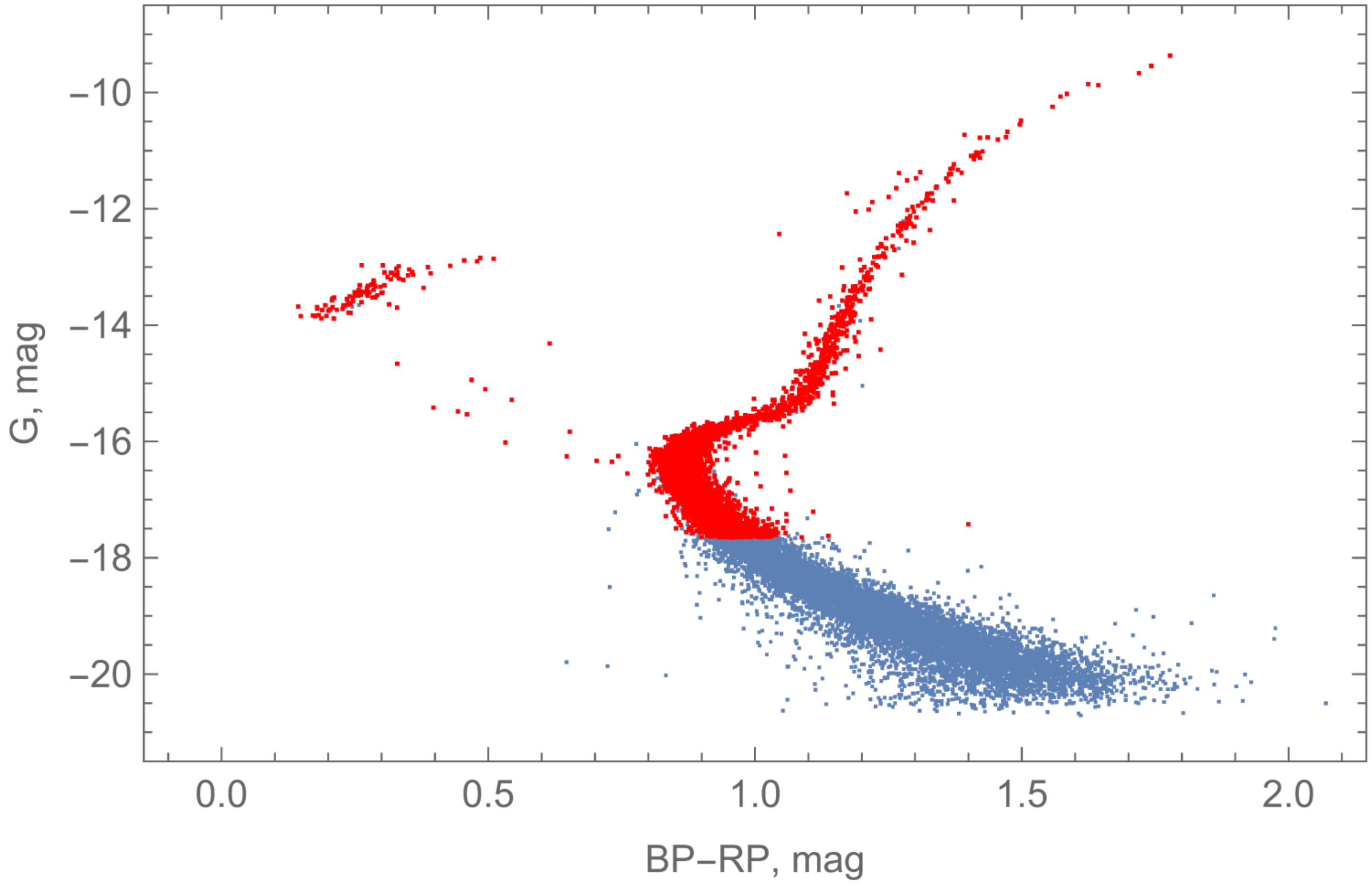
Gontcharov et al. 2024



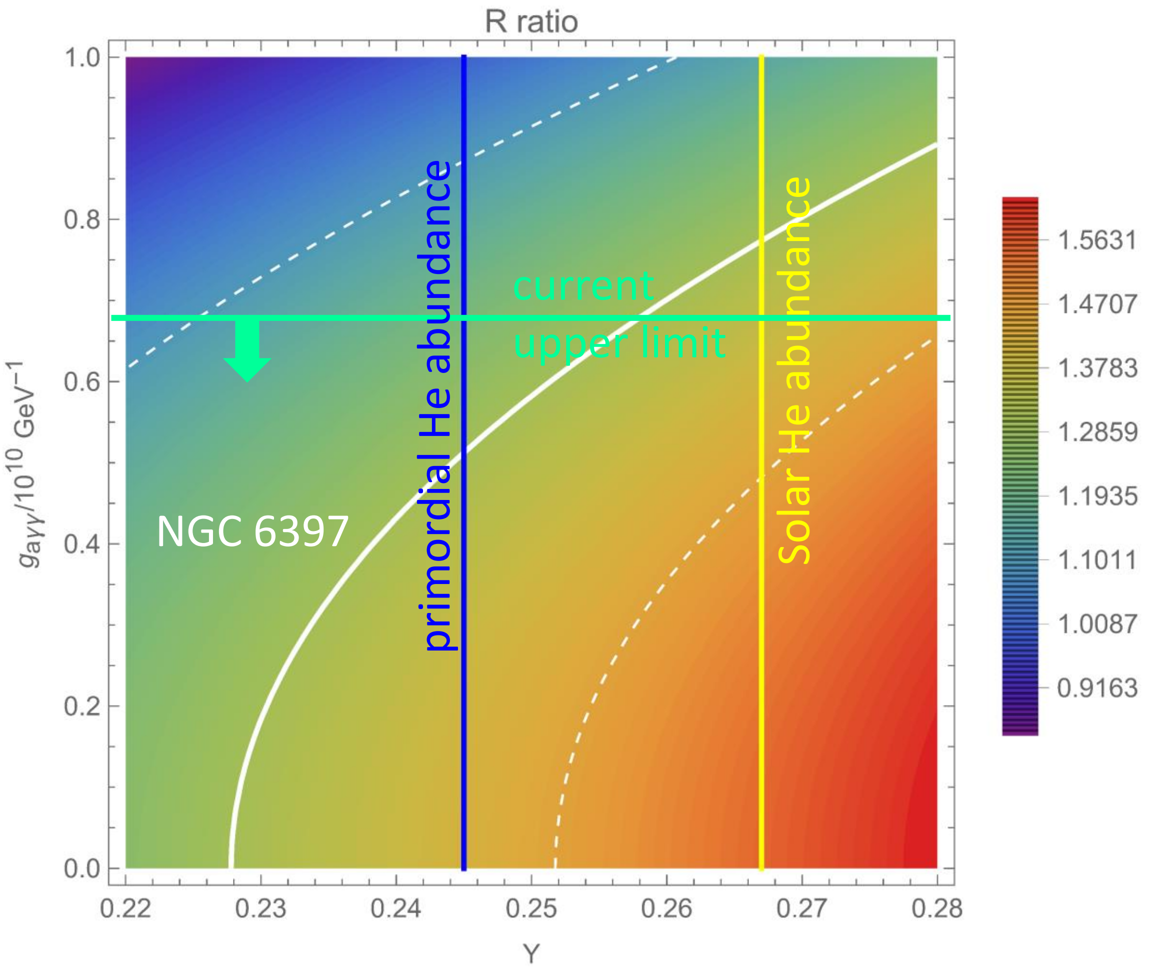
Example: NGC 6397

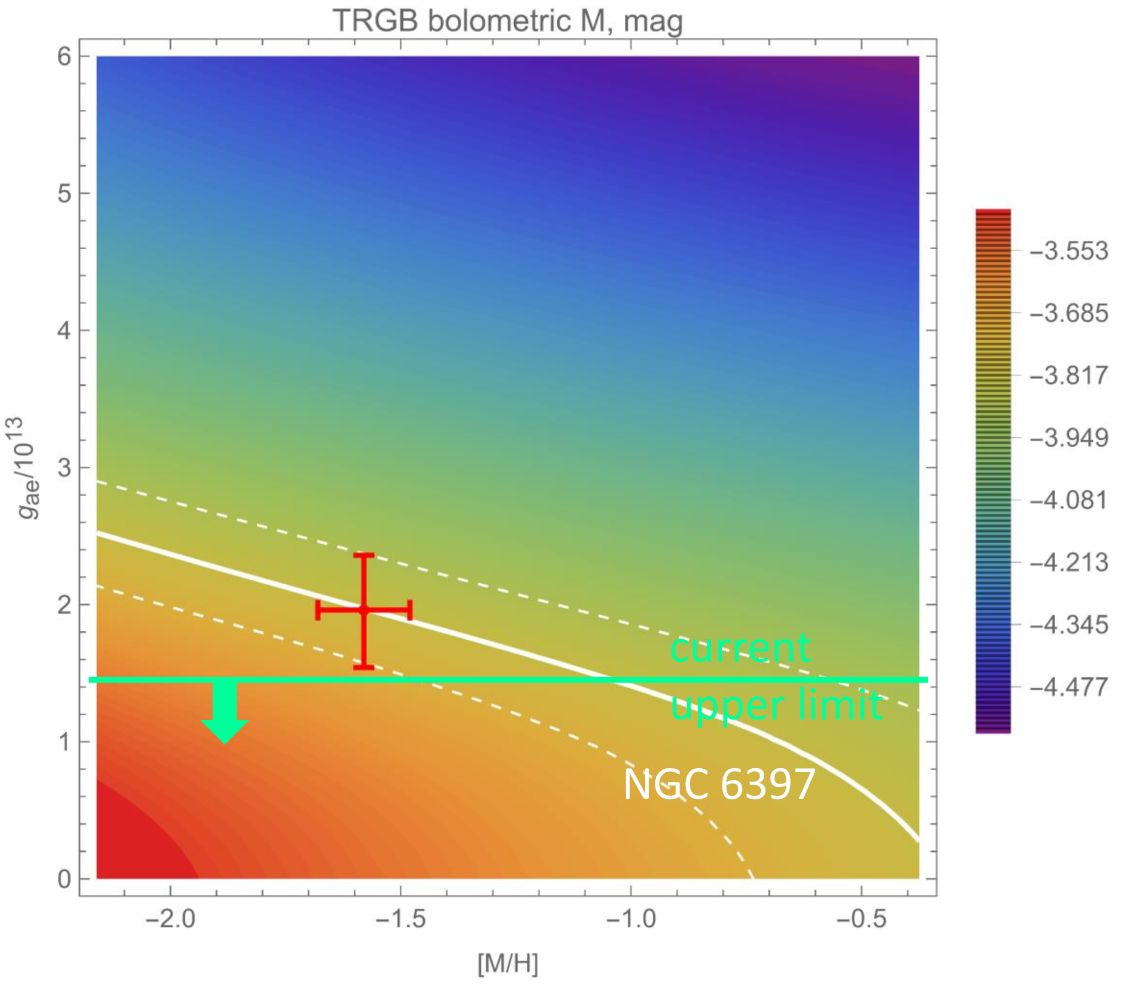
- GAIA DR3 selected cluster members (blue) *Gontcharov et al. 2024*
- have GAIA synthetic photometry (red)

GAIA 2023



Example: NGC 6397, results





Conclusions:

- GAIA DR3 offers precise determination of membership of Galactic globular clusters
- GAIA DR3 offers precise determination of distances to Galactic globular clusters
- hypothetical stellar energy losses due to axions would change evolution of bright stars
- RGB tip constrains axion-electron coupling
- ratio of HB to RGB star numbers constrains axion-photon coupling
- preliminary results confirm previous weak indications to nonzero anomalous losses

Coming:

- more clusters are being processed
- simulate in terms of direct GAIA observables
- GAIA white-dwarf luminosity function (constrains electron-axion coupling)
- hidden photons, millicharged particles, heavy ALPs,…

BACKUP SLIDES

ALP-photon oscillations

$$A(\mathbf{x},t) \quad \mapsto \quad A(\mathbf{x})\mathrm{e}^{-i\omega t}, \quad \omega^2+\partial_z^2 \quad \mapsto \quad 2\omega\left(\omega - i\partial_z\right)$$

$$\Downarrow$$

$$\left(i\partial_z+\omega+\mathcal{M}\right)\begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix} = 0$$

where $\mathcal{M} \equiv \begin{pmatrix} \Delta_p+\Delta_{\mathrm{Q},\|} & 0 & \Delta_{Mx} \\ 0 & \Delta_p+\Delta_{\mathrm{Q},\perp} & \Delta_{My} \\ \Delta_{Mx} & \Delta_{My} & \Delta_m \end{pmatrix}$

ALP-photon oscillations

$$\Delta_p = \frac{\omega_p^2}{2\omega}$$

plasma frequency

$$\omega_p^2 = 4\pi\alpha\frac{n_e}{m_e}$$

$$\mathcal{M} \equiv \begin{pmatrix} \Delta_p + \Delta_{Q,\parallel} & 0 & \Delta_{Mx} \\ 0 & \Delta_p + \Delta_{Q,\perp} & \Delta_{My} \\ \Delta_{Mx} & \Delta_{My} & \Delta_m \end{pmatrix}$$

QED contribution

$$\Delta_M = \frac{B}{2M}$$

$$\Delta_m = \frac{m^2}{2\omega}$$

ALP-photon oscillations

$$i\frac{d\rho(y)}{dy} = [\rho(y), \mathcal{M}(E,y)]\,, \qquad \mathcal{M} = \frac{1}{2}\begin{pmatrix} 0 & 0 & -igB_\theta \\ 0 & 0 & -igB_\phi \\ igB_\theta & igB_\phi & \frac{m^2}{E} \end{pmatrix}$$

$$\rho(0) = \mathrm{diag}\,(1/2, 1/2, 0) \quad \Rightarrow \quad \rho_{11}(y) + \rho_{22}(y)$$

conversion probability for constant B, n_e:

$$P = \frac{4\Delta_M^2}{\left(\Delta_p + \Delta_{Q,\perp} - \Delta_m\right)^2 + 4\Delta_M^2}\sin^2\left(\frac{1}{2}L\Delta_{\rm osc}\right)$$

где $\Delta_{\rm osc}^2 = \left(\Delta_p + \Delta_{Q,\perp} - \Delta_m\right)^2 + 4\Delta_M^2$