Globular-cluster constraints on the axion-photon coupling

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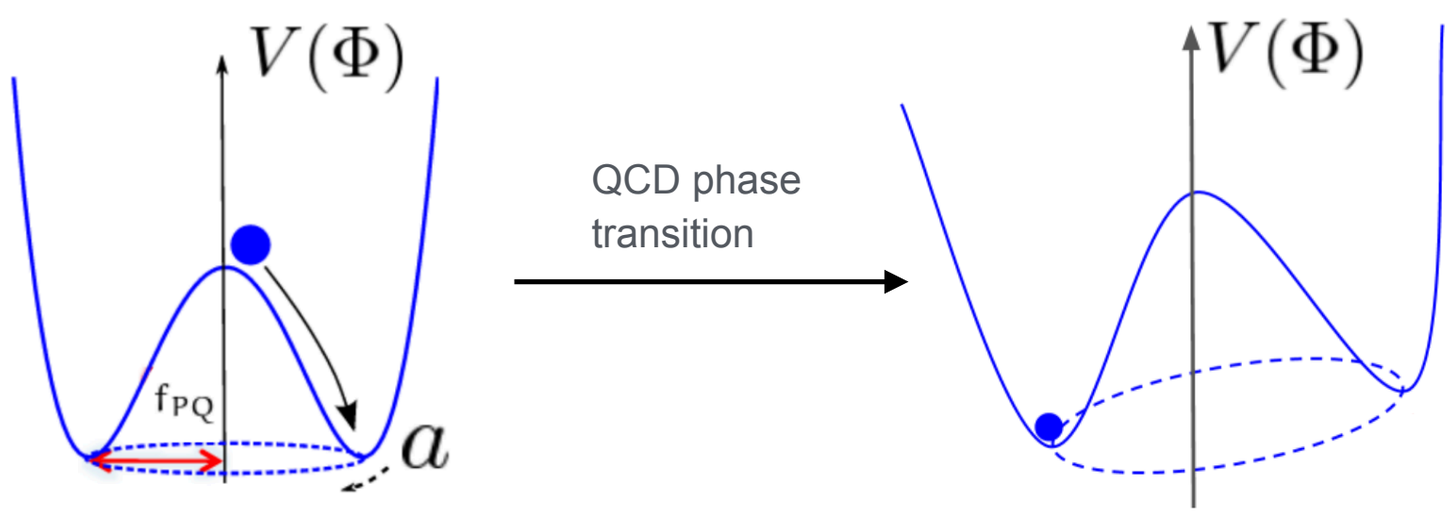
QCD axion

The strong CP problem: QCD Lagrangian contains an arbitrary CP-violating angle θ, but experimentally $|\theta| < 5 \times 10^{-11}$

Abel et al. 2001.11966

The Peccei-Quinn Mechanism: Peccei, Quinn (1977)

- Add a global $U(1)_{\mathrm{PQ}}$ symmetry to the QCD Lagrangian
- The axion is a pseudo-NG boson associated with the SSB of $U(1)_{\mathrm{PQ}}$ symmetry
- The axion field chooses a specific value during the QCD phase transition and the axion acquires a nonzero mass



Axion-like particles

The QCD axion: m_a and f_a are not independent

$$m_a = 5.691(51)\left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)\mathrm{meV}$$

Gorghetto, Villadoro, 1812.01008

The axion-like particle: m_a and f_a are independent

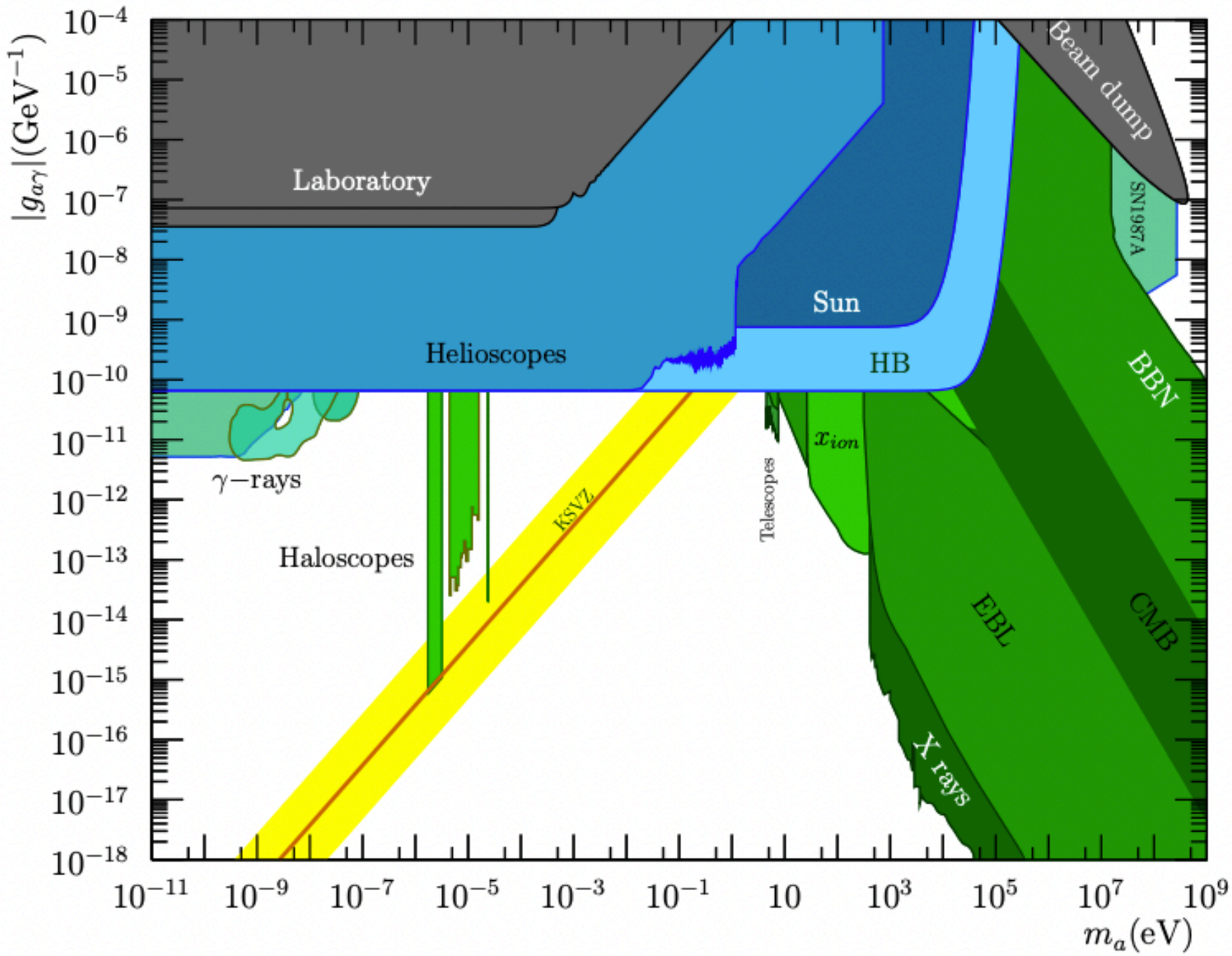
Motivations:

- string theory
  - ALPs are produced from moduli decays Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, 0905.4720
- dark matter
- R-axion Bellazzini, Mariotti, Redigolo, Sala, Serra, 1702.02152
- TeV gamma-ray transparency
  - an unexpected large TeV gamma-ray flux from the GRB can be explained by heavy ALPs

Meyer, Horns, Raue, 1302.1208

Constraints on $m_a - g_{a\gamma}$ plane

The axion-photon interaction term: $$\mathscr{L}_{\text{int}} = -\frac{g_{a\gamma}}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} a = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$



Irastorza, Redondo, 1801.08127

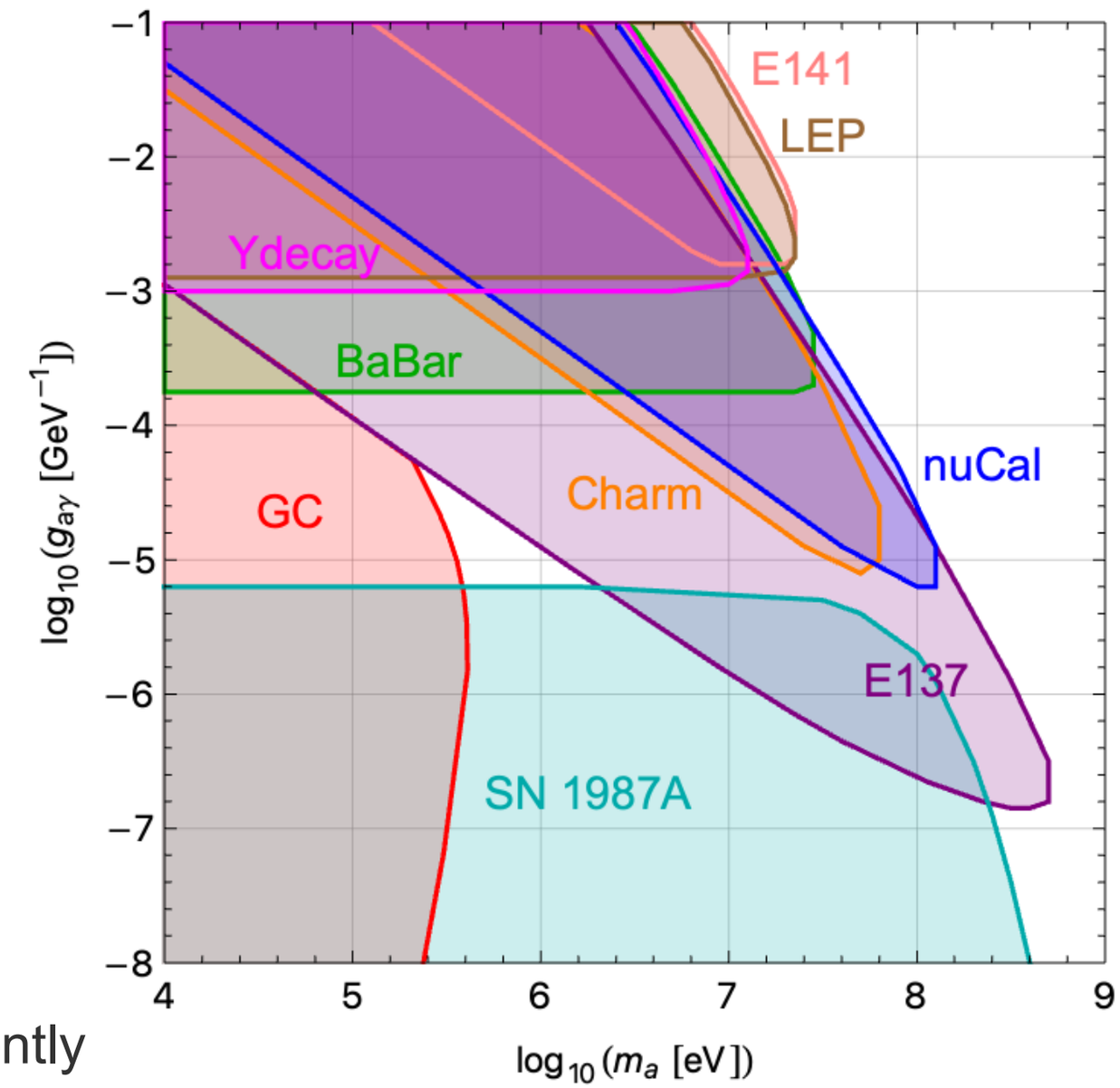
Cosmological triangle

- not excluded either by astrophysical phenomena or high-energy physics experiments
- excluded by cosmological observations

  Cadamuro, Redondo, 1110.2895
- However, can be weakened by a low reheating temperature

  Depta, Hufnagel, Schmidt-Hoberg, 2002.08370

Goal: placing constraints on the cosmological triangle independently from cosmological observations

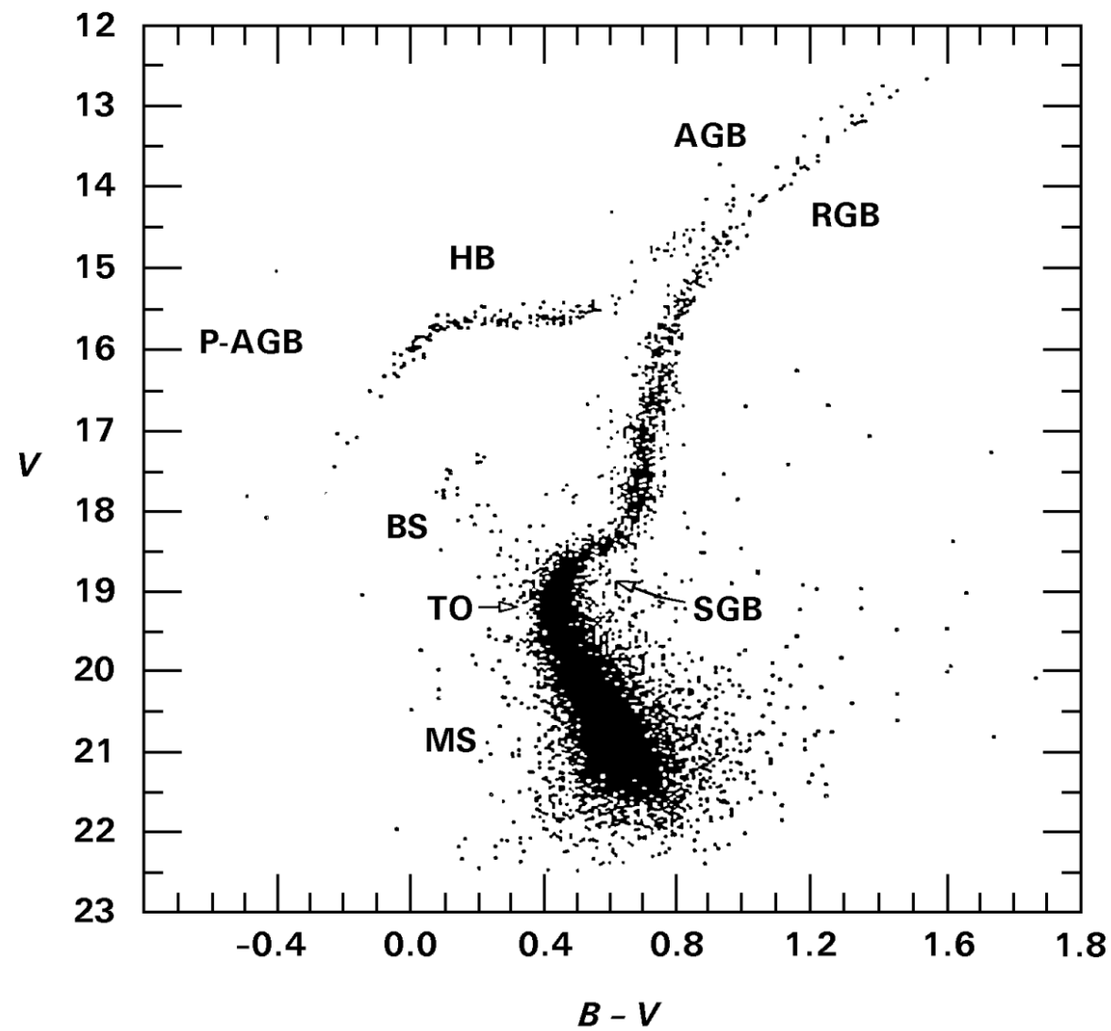


data are taken from Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, 1709.00009

Conventional globular-cluster constraints

a globular cluster: a system consists of old gravitationally bounded stars

- The lifetime of HB stars is sensitive to energy loss due to emissions of axions while that of RGB stars isn't
- parameters should be consistent with the observed number ratio $n_{\mathrm{HB}}/n_{\mathrm{RGB}}$



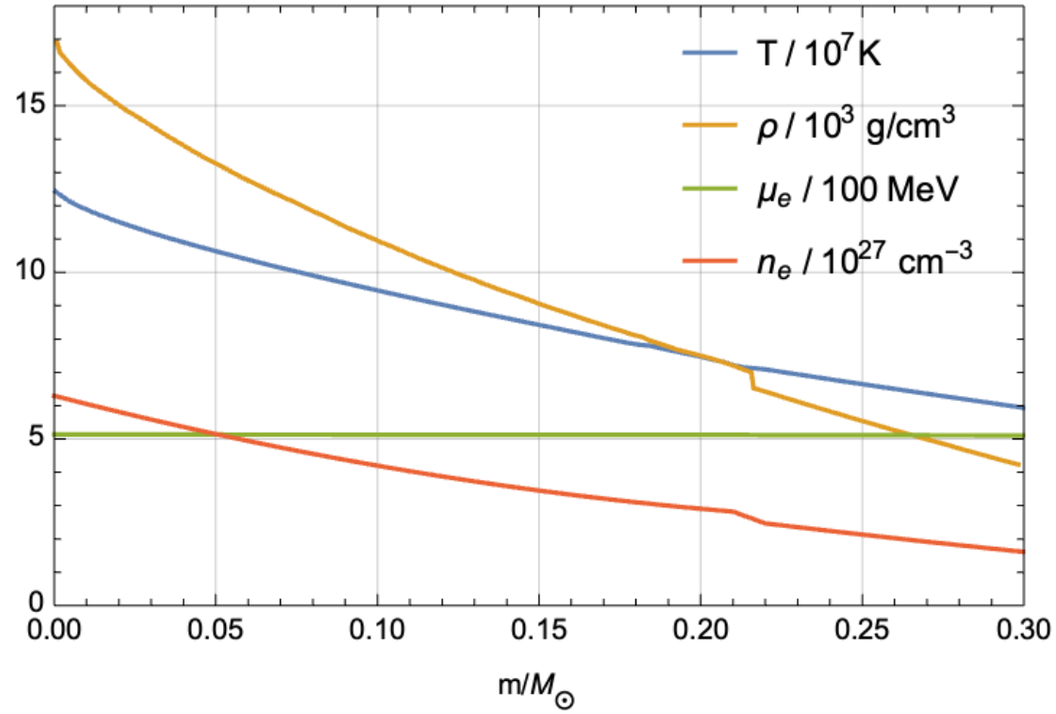
Raffelt, "Stars as laboratories for fundamental physics"

Our idea: observe photons from decays of axions produced in HB stars

HB stars

- a plasma temperature is high enough to produce heavy axions
  (a production rate is suppressed by the Boltzmann factor $e^{-E/T}$)
  (MS $\sim$ a few $\times 100$ eV, HB ~ 10 keV)

- possible to place constraints on the cosmological triangle
  (NS: Berenji, Gaskins, Meyer, 1602.00091 SN: Ferreira, Marsh, Müller, 2205.07896)



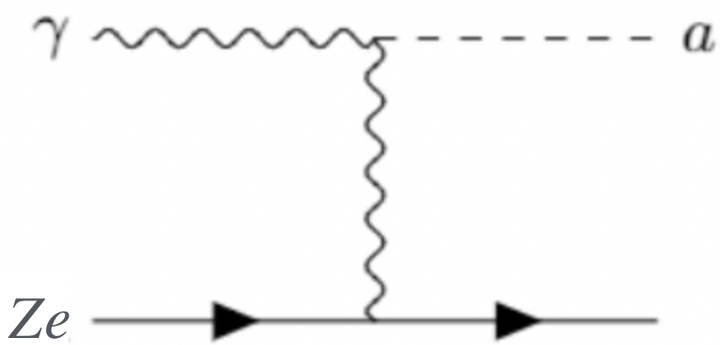
temperature, density, chemical potential, and electron density profiles of a He-core of a typical HB star. The only inner $0.3M_\odot$ region is shown.

Carenza, Straniero, Döbrich, Giannotti, Lucente, Mirizzi, 2004.08399

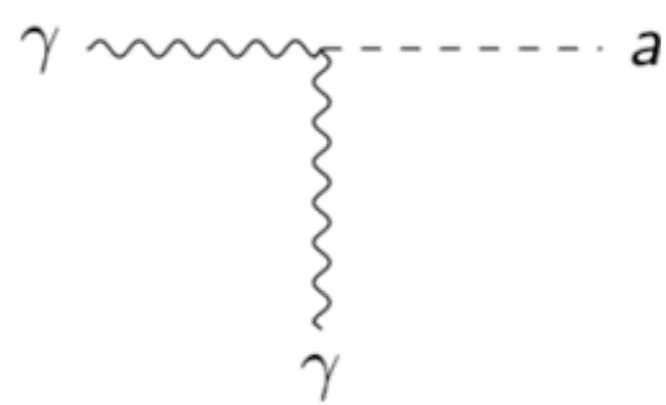
ALP productions in HB stars

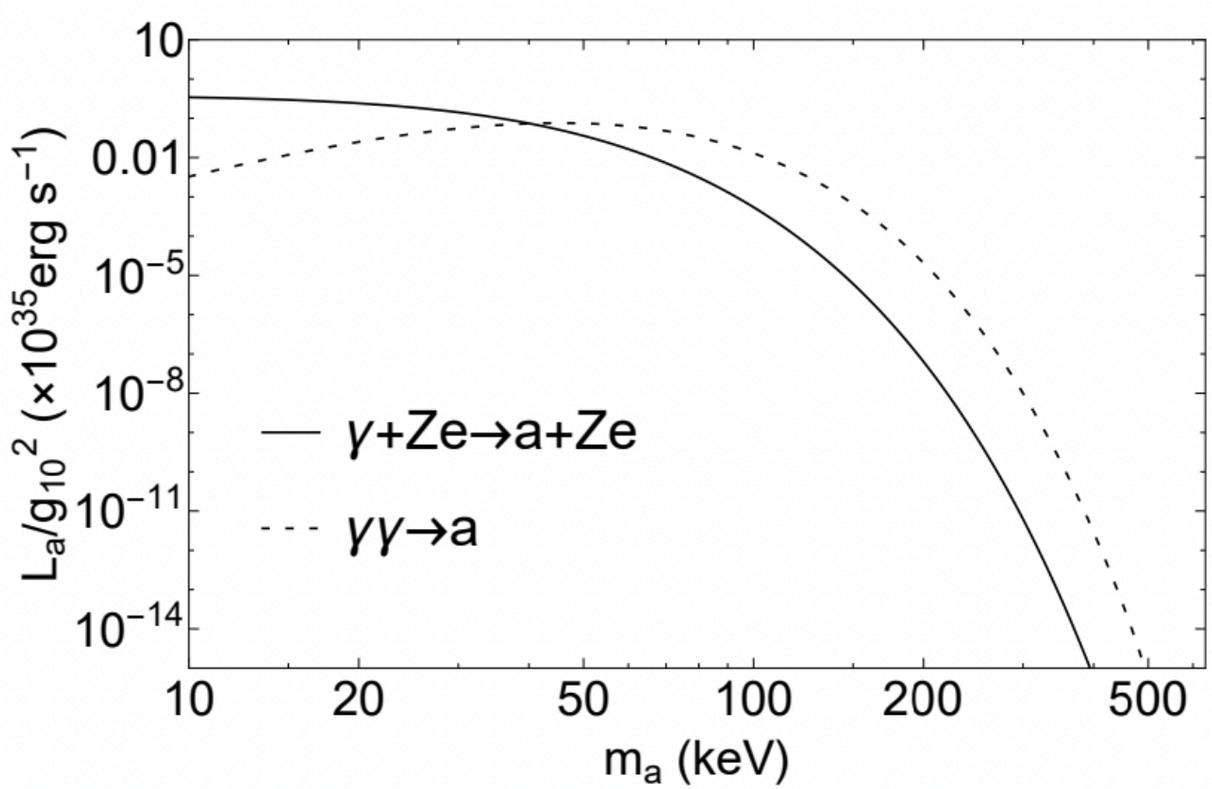
Relevant processes are:

The Primakoff process ($\gamma + Ze \rightarrow a + Ze$)



the photon coalescence ($2\gamma \rightarrow a$)





the energy loss rate due to axion emission in erg/s

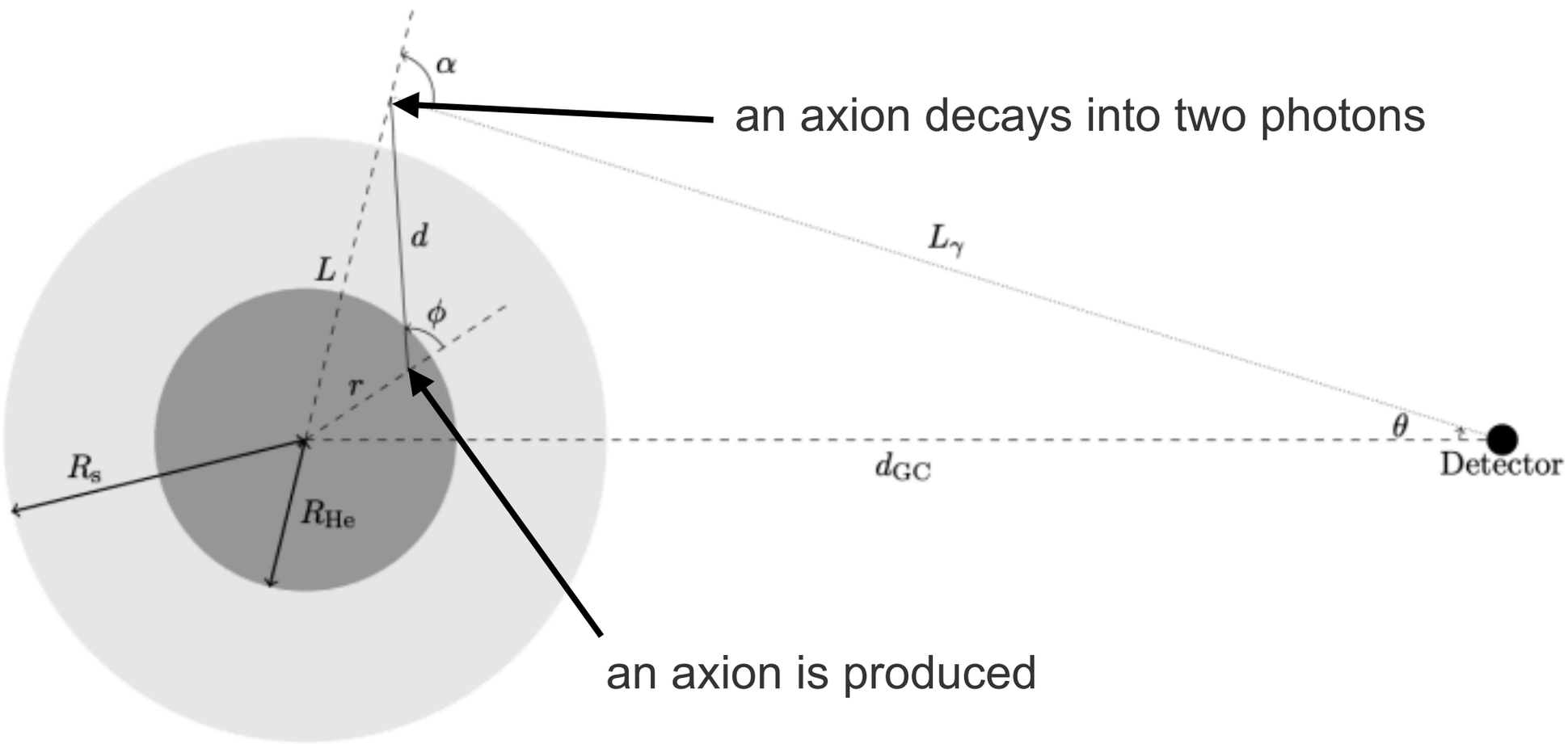
Carenza, Straniero, Döbrich, Giannotti, Lucente, Mirizzi, 2004.08399

Signature of axion productions

Produced axions spontaneously decay into two photons

If an axion decays outside the star, we might be able to observe photons otherwise photons are reabsorbed in a plasma

Geometry for photon detections:

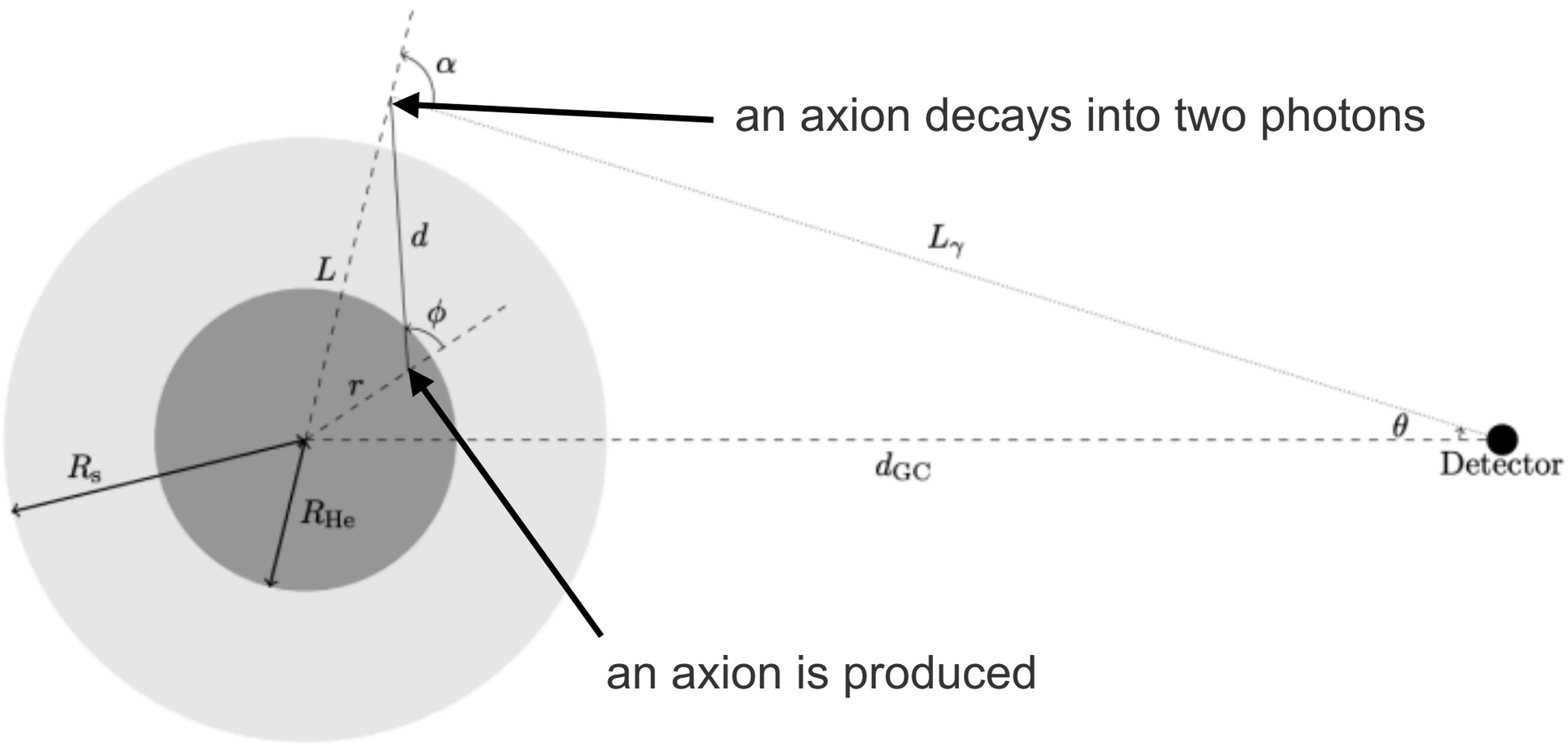


Signature of axion productions

The differention of the fluence $\tilde{F}_\gamma$ is given by

(the fluence: the total number of photons arriving at the detector per unit of surface area)

$$\mathrm{d}\tilde{F}_\gamma = 2 \cdot \frac{1}{4\pi d_{\mathrm{GC}}^2} \cdot \frac{\mathrm{d}N}{\mathrm{d}\omega}\, \mathrm{d}\omega \cdot f_{c_\alpha}\left(\omega, c_\alpha\right) \mathrm{d}c_\alpha \cdot \frac{\exp\left[-L/l_a(\omega)\right]}{l_a(\omega)} \mathrm{d}L \cdot e^{-R_s/\lambda}\, \Theta_{\mathrm{cons.}}\left(\omega, c_\alpha, L\right)$$



Choice of a globular cluster

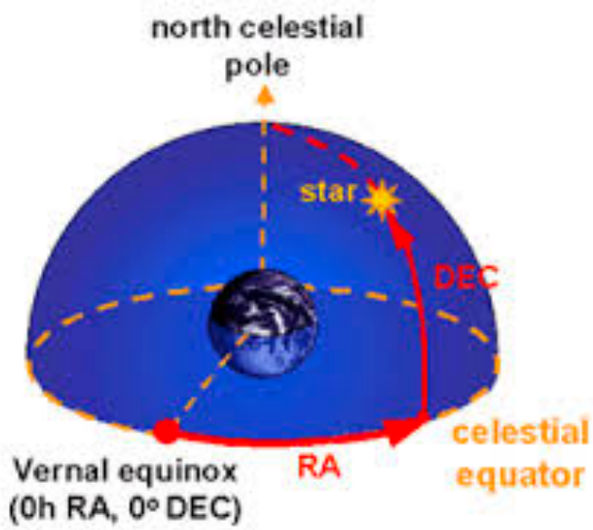
Most of HB stars are in globular clusters

In general, preferred GCs are

- heavy (many stars)
- near ($\text{fluence} \propto \text{distance}^{-2}$)
- not on the Galactic plane (at the direction where background is small)

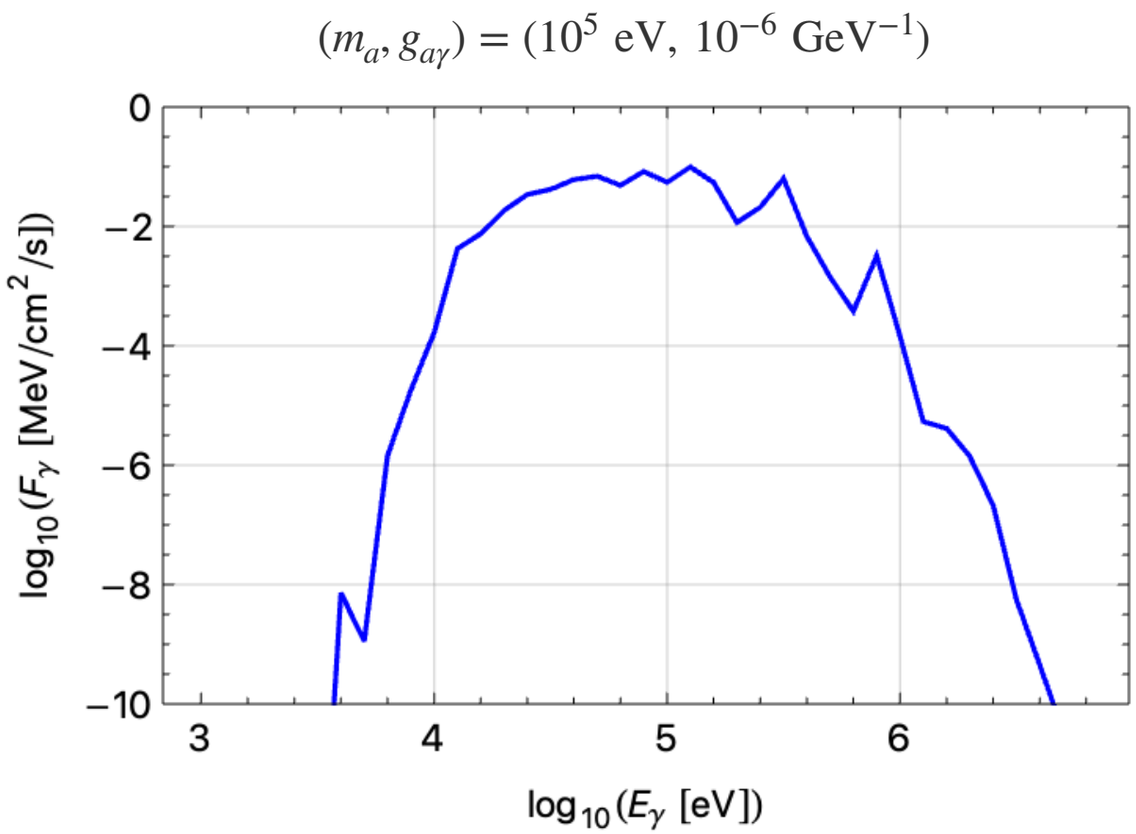
NGC 6397 is used as our axion laboratory

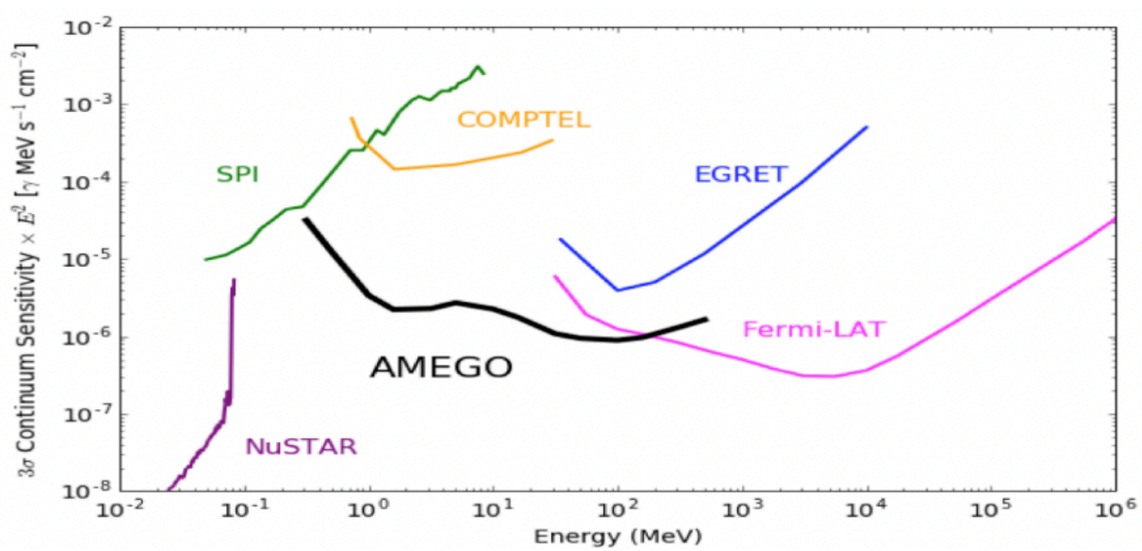
Name	Mass ($M_\odot$)	Radius (ly)	Distance (kly)	Right ascension	Declination
NGC 6397	1.14×10^5	34	7.8	$17^{\mathrm{h}}40^{\mathrm{m}}42.09$	$-53°40'27.6''$



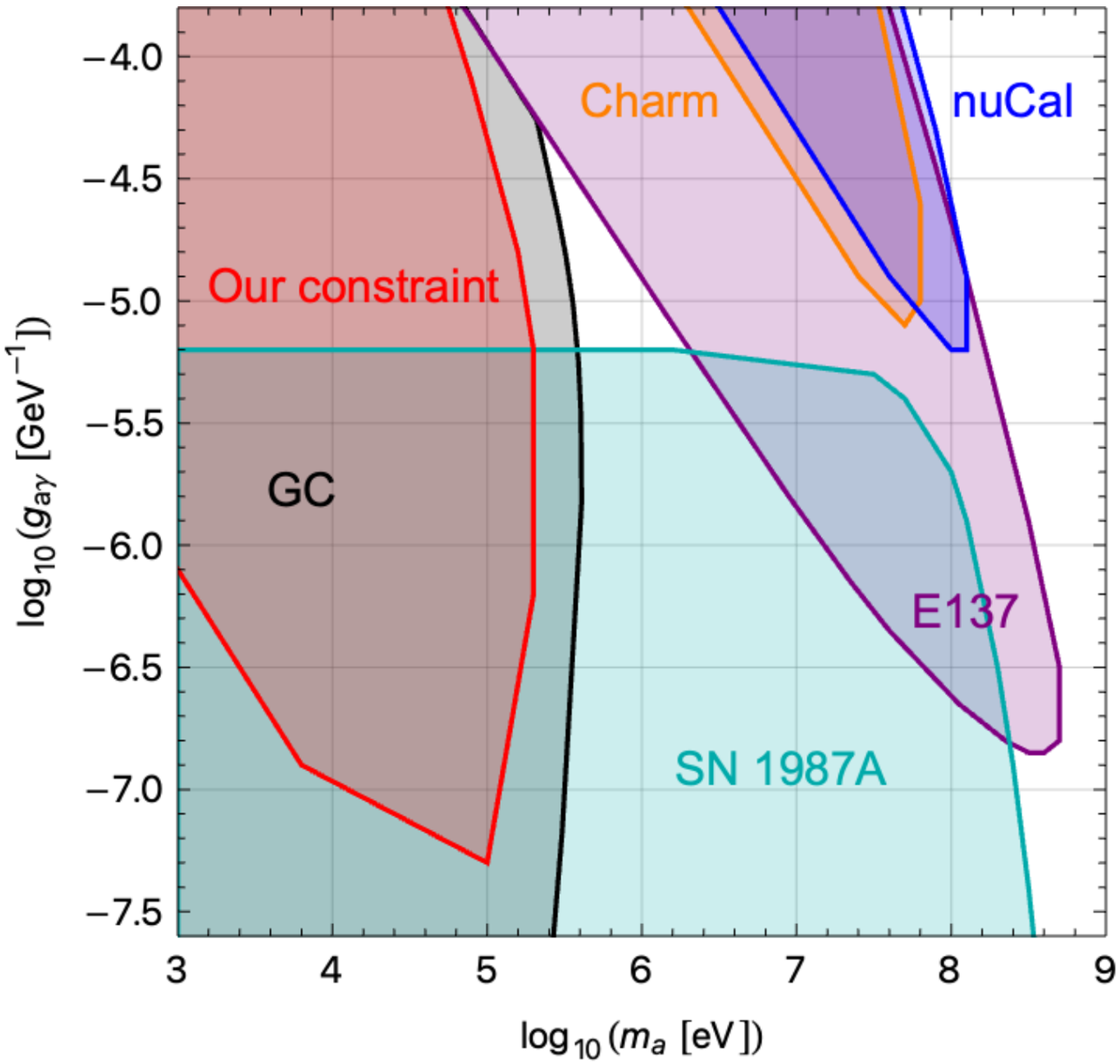
Detectability

- For a given pair of $(m_a, g_{a\gamma})$, a photon spectrum at the detector is computed
- Compare photon spectra to telescopes' sensitivities
- Assume 100 HB stars are in a field of view
- Assume future MeV gamma-ray telescopes have 100 times better sensitivity





Our constraint



- About to constrain the cosmological triangle
- Our constraints depend only on the core temperature of HB stars

Conclusion

- Cosmological triangle:
  the triangular region excluded neither by astrophysical phenomena nor HEP experiments

- Photons from decays of axions produced in HB stars might be observable in the temporary or the future gamma-ray telescopes

- Our constraints weakly depend on the model of globular clusters

- As a next step, we optimize a choice of a globular cluster