WISPers from the stars

Advancing stellar constraints on weakly interacting slim particles

Fred Hiskens

CDM Annual Workshop 2023

In collaboration with Prof. Raymond Volkas & A/Prof. Matthew Dolan

I’m from Melbourne, but...

My mum’s family is from Rugby, Warwickshire

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On my dad’s side…

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Weakly interacting slim particles

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slender

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sub-eV

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WISPs

Light, feebly-interacting dark matter candidates

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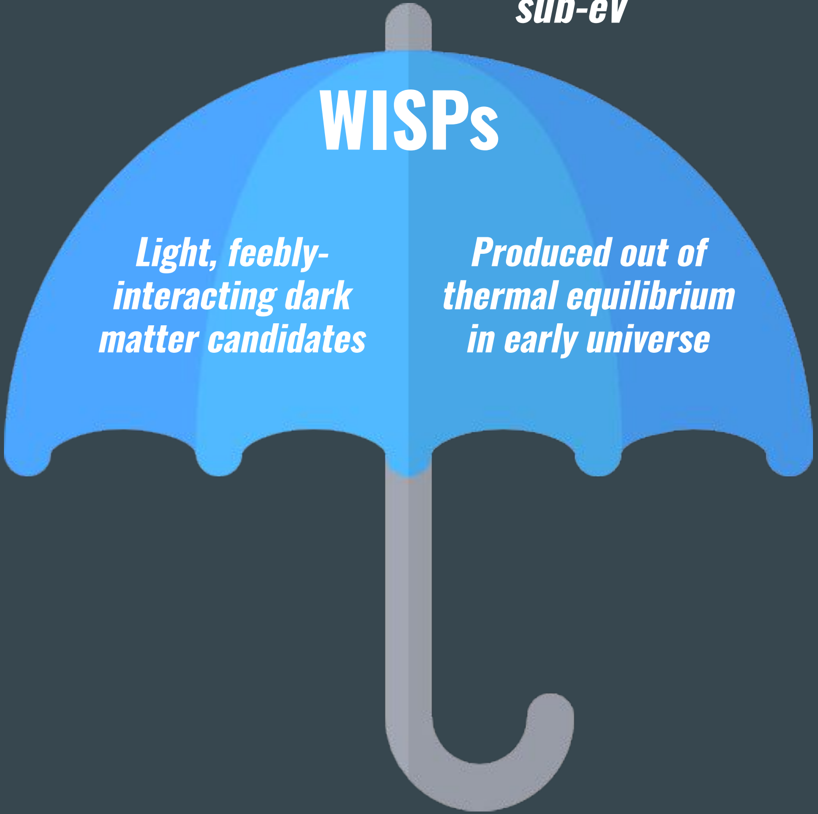

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Produced out of thermal equilibrium in early universe

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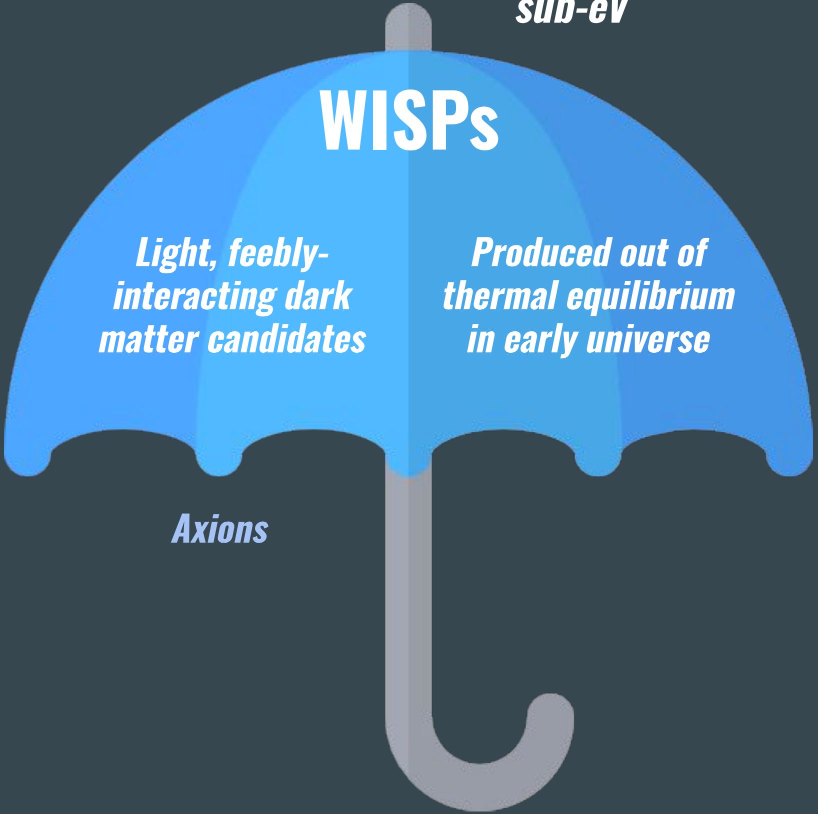

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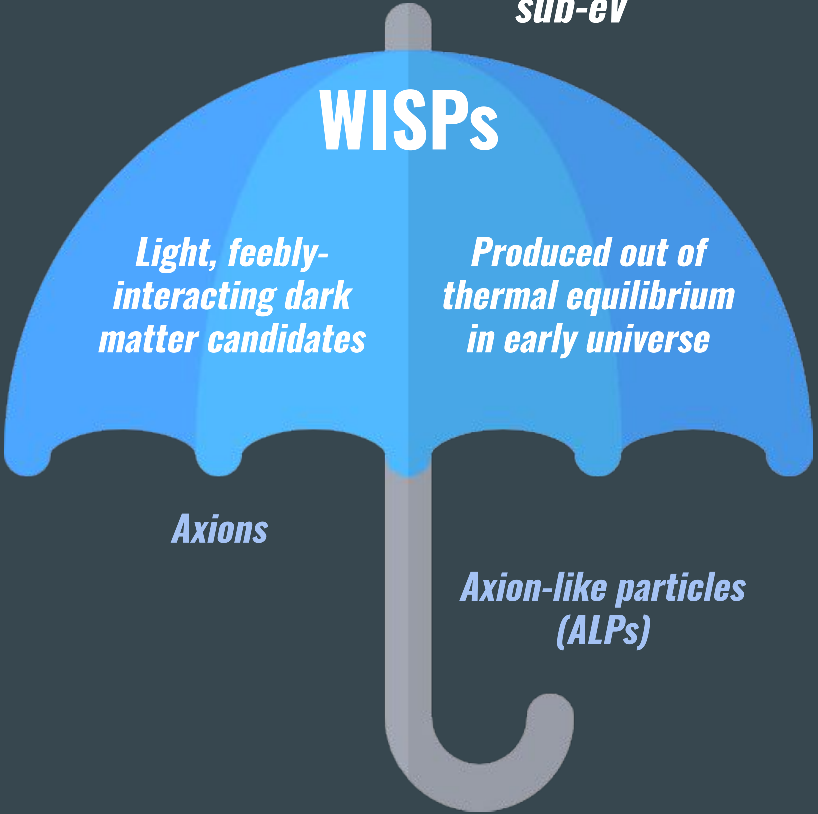

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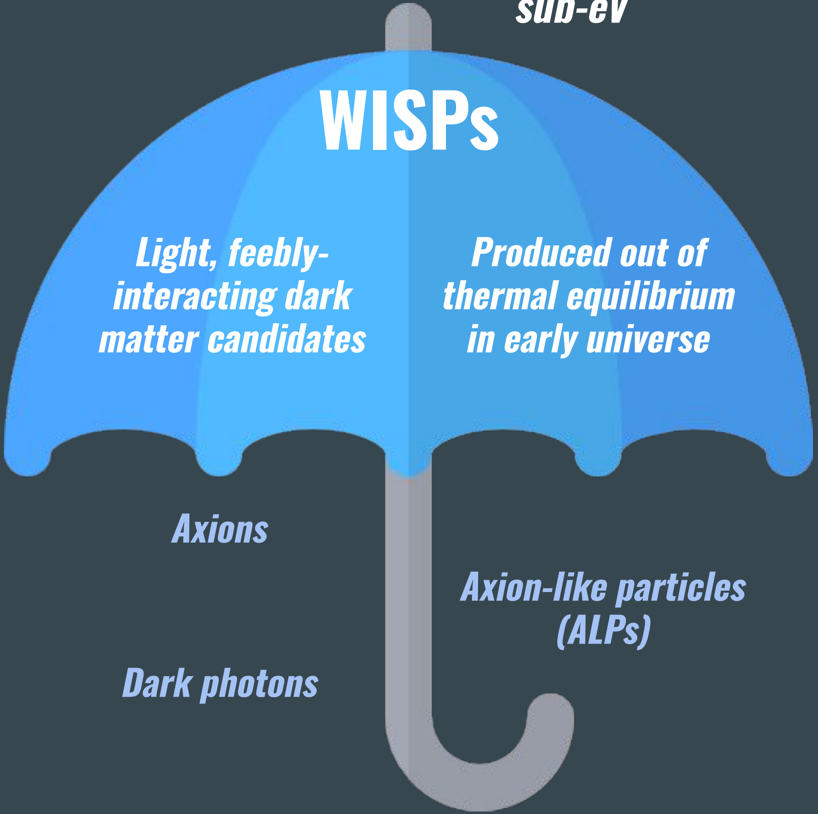

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Integrate novel energy-loss over stellar profile at a single moment in time

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Iteratively solve the **stellar structure equations** with WISP energy-loss included

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Address any known issues with existing bounds

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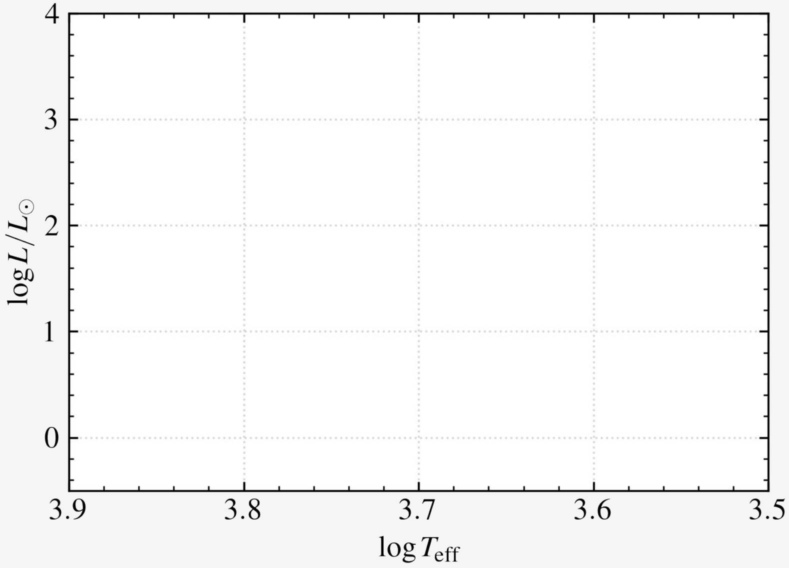
Evolution of low mass stars

Helpful to go over the evolution of low mass stars



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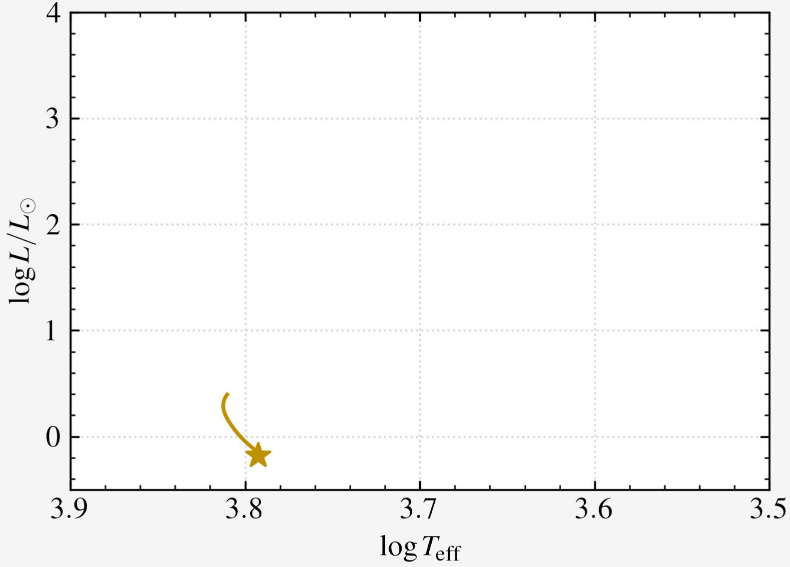
Star burns hydrogen into helium in core. Longest evolutionary phase.



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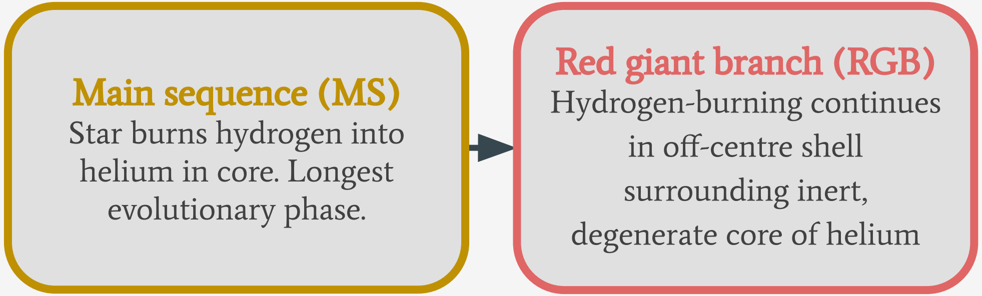

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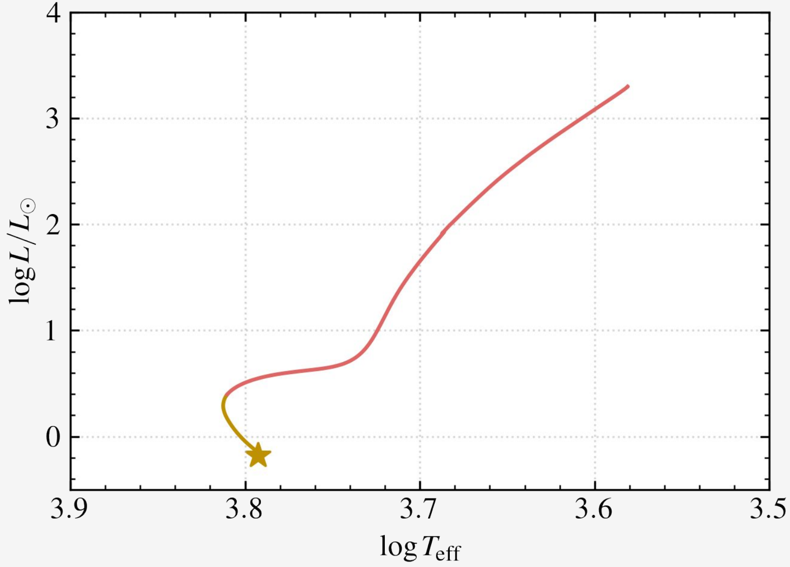

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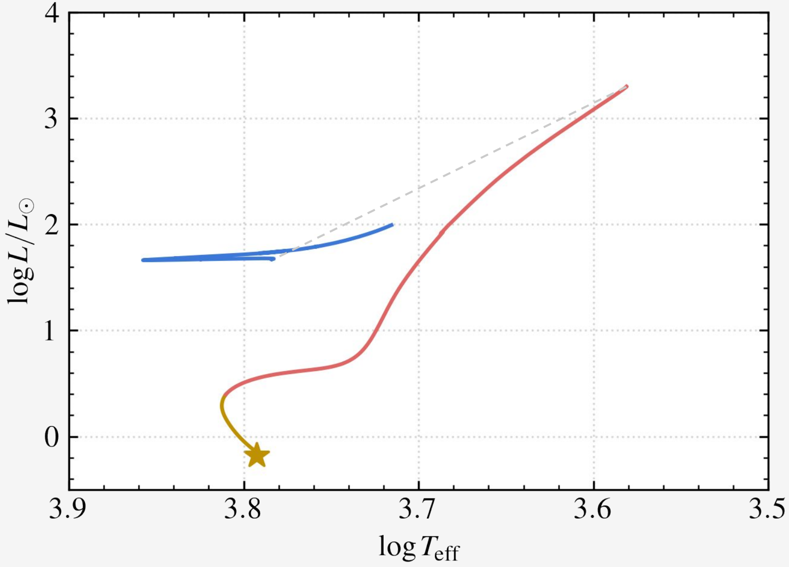
Horizontal branch (HB)
Central helium-burning phase. Helium converted to carbon/oxygen in convective core.



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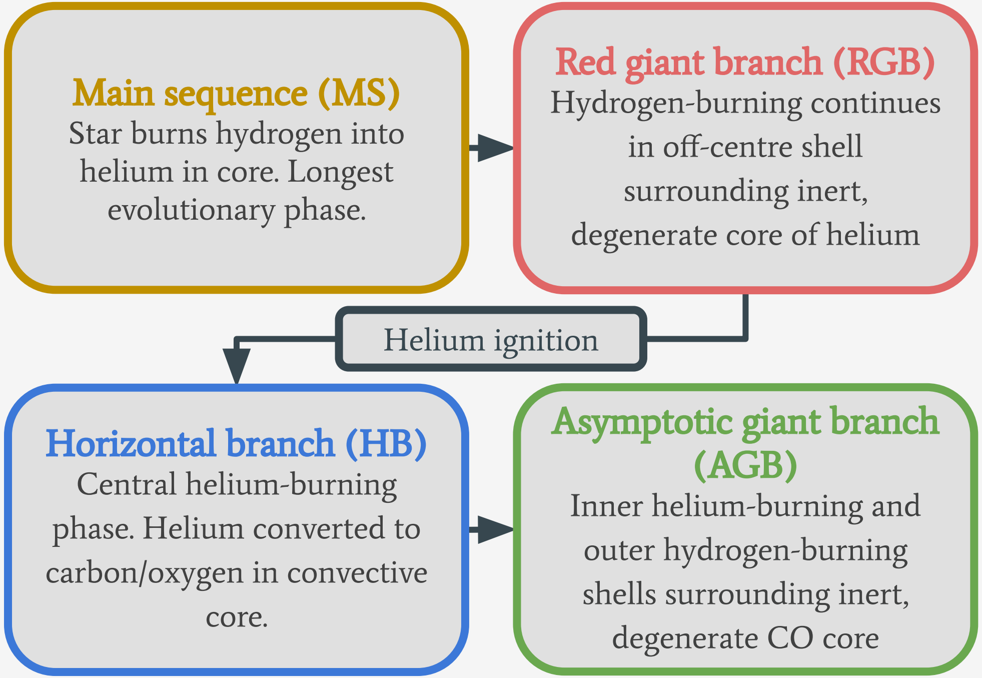

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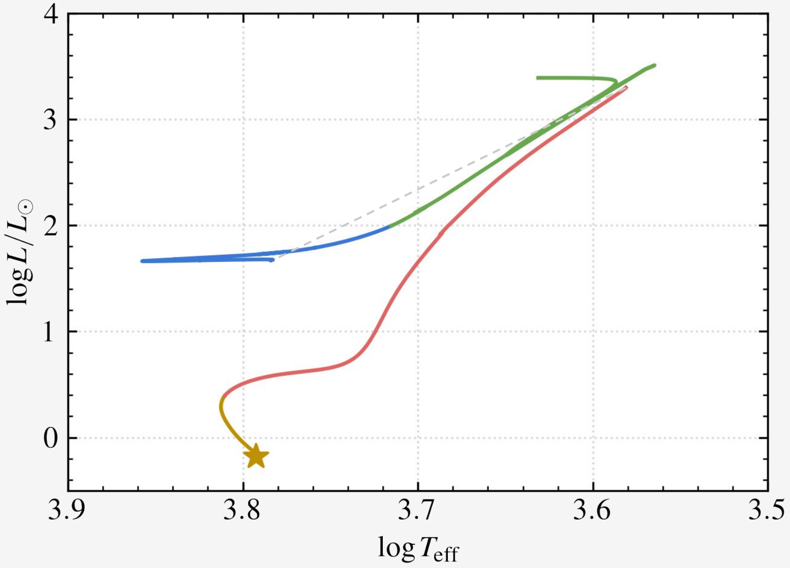
Asymptotic giant branch (AGB)
Inner helium-burning and outer hydrogen-burning shells surrounding inert, degenerate CO core



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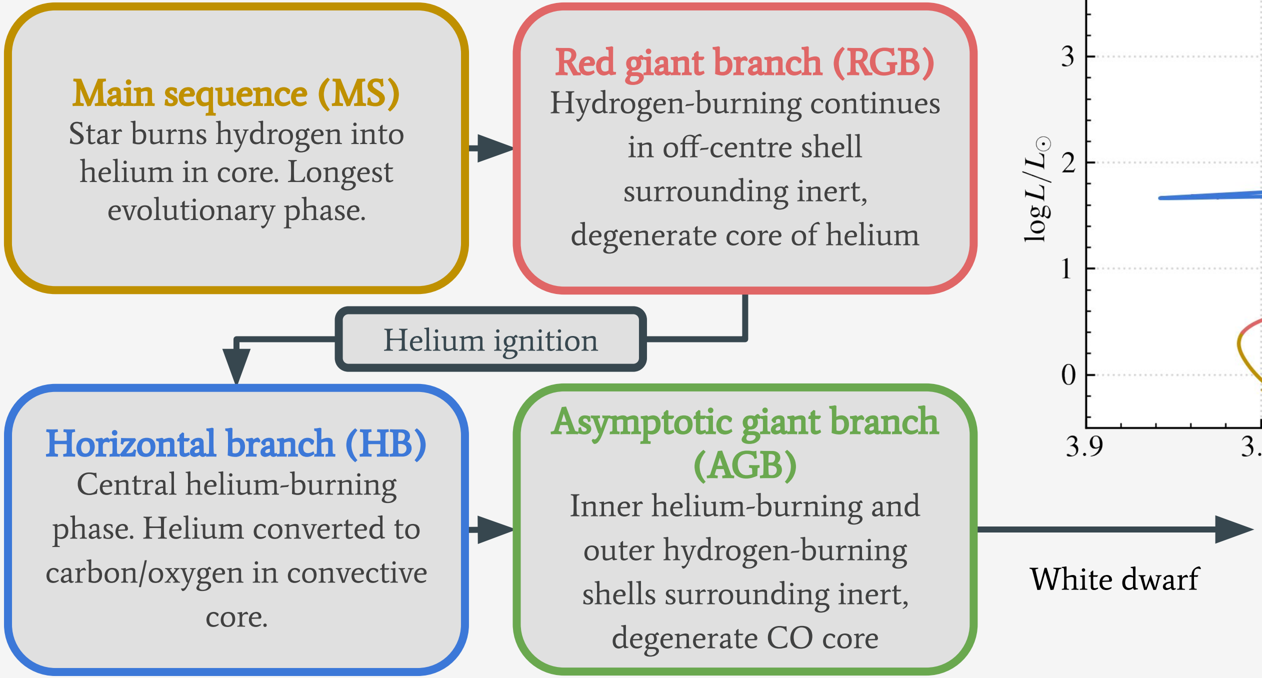

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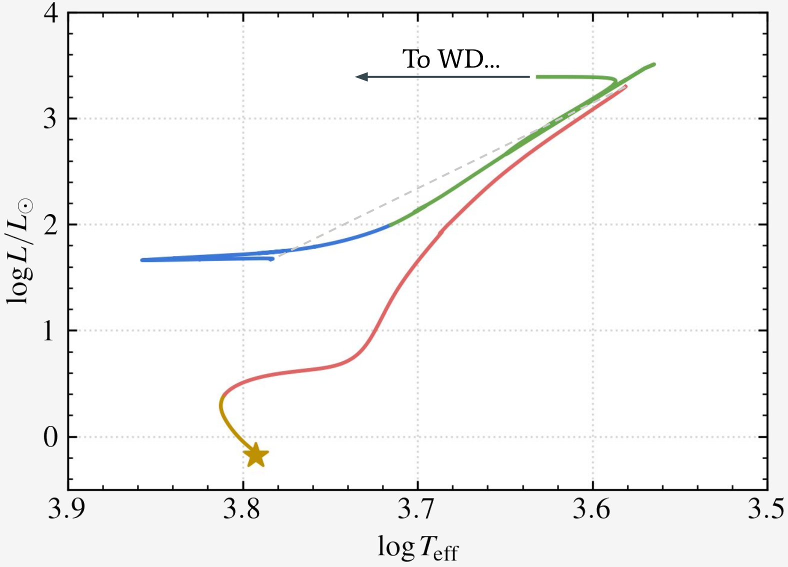

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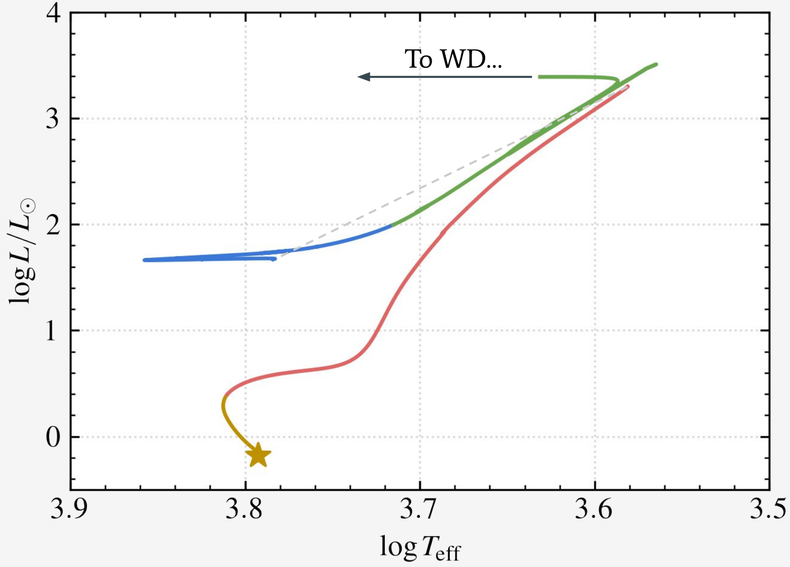
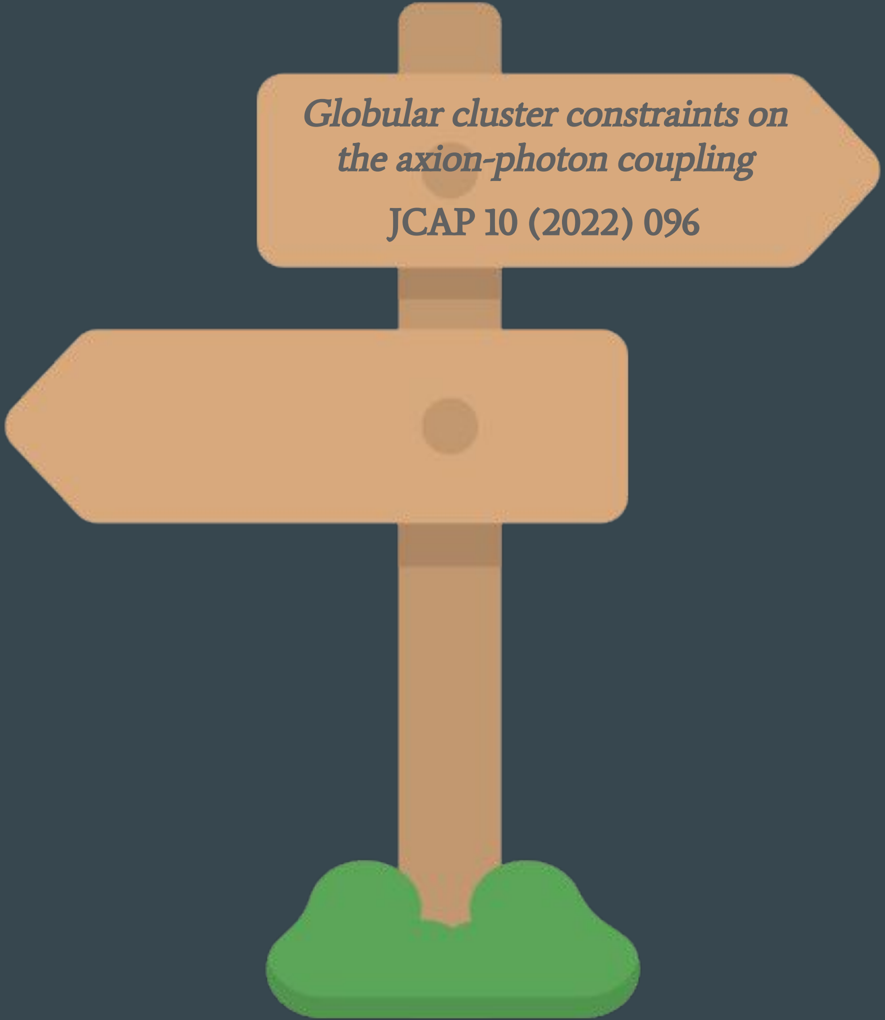
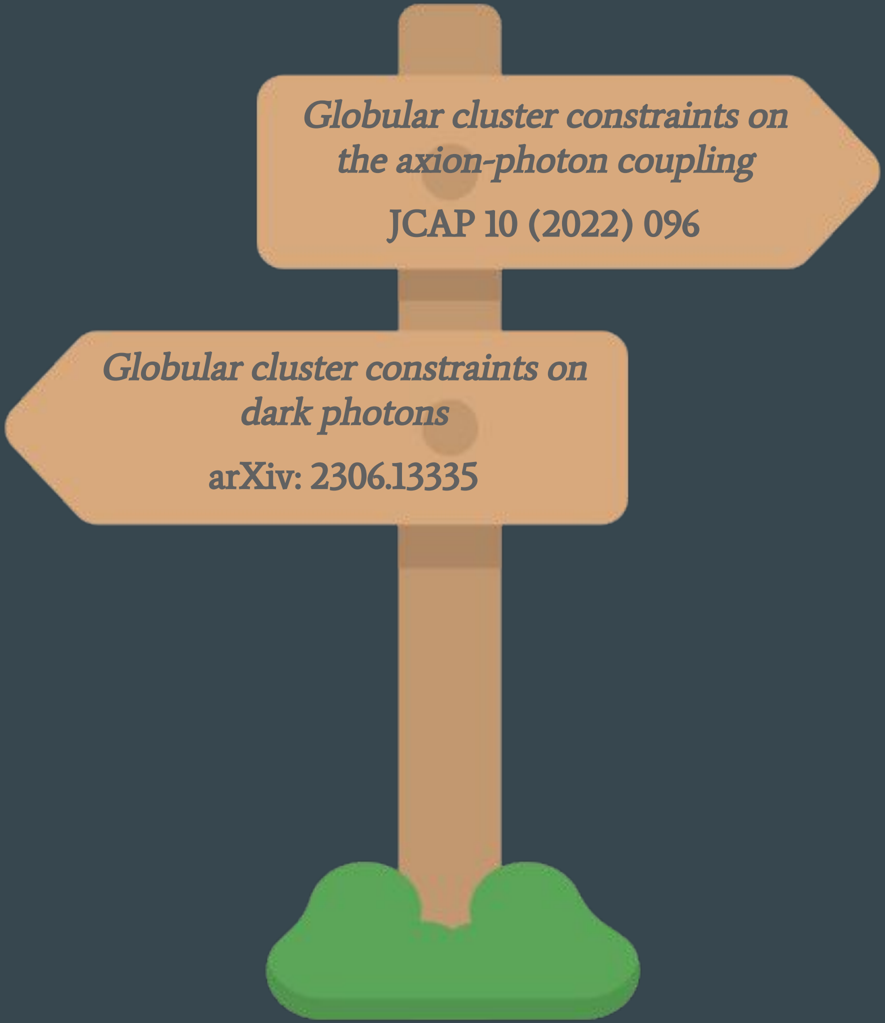




Globular cluster constraints on the axion-photon coupling

JCAP 10 (2022) 096



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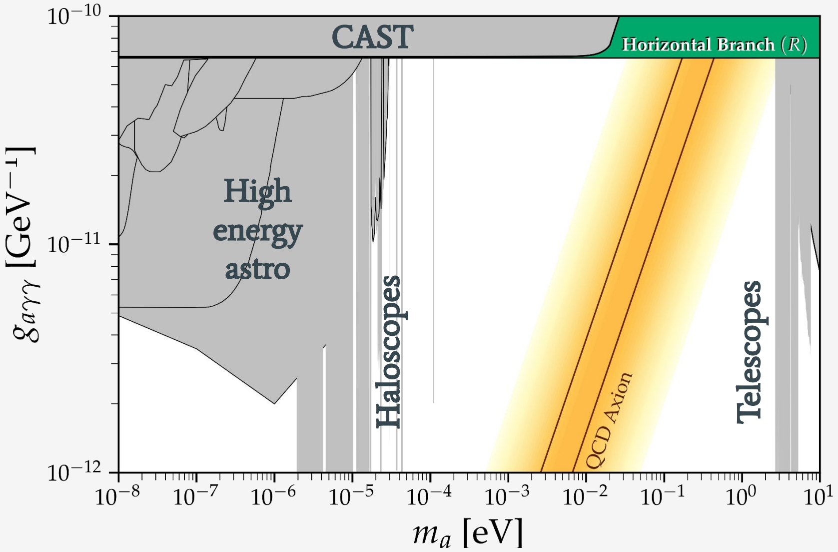
Globular cluster constraints on dark photons

arXiv: 2306.13335

The *R*-parameter constraint

The leading stellar constraint on the axion-photon coupling comes from the *R*-parameter of globular clusters

$$R = \frac{N_{\rm HB}}{N_{\rm RGB}} \simeq \frac{\tau_{\rm HB}}{\tau_{\rm RGB}}$$



Ayala, et al., *Phys. Rev. Lett.* **113** (2014) 19

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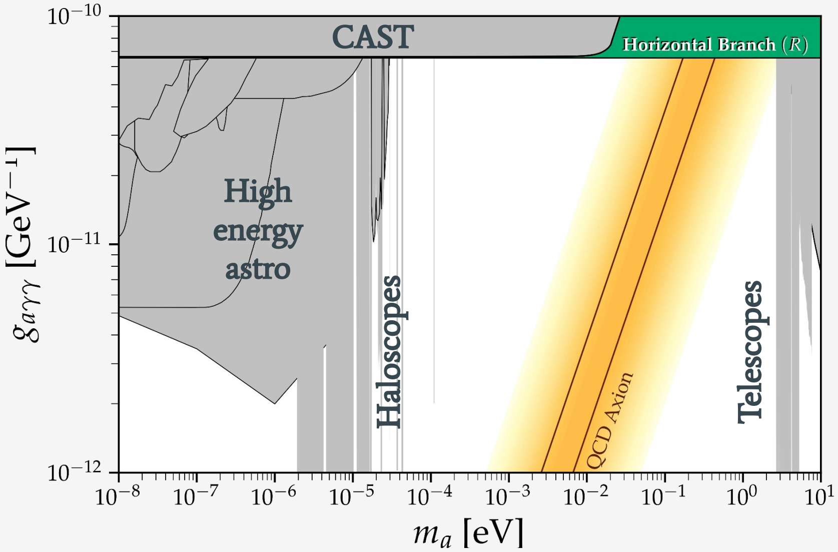

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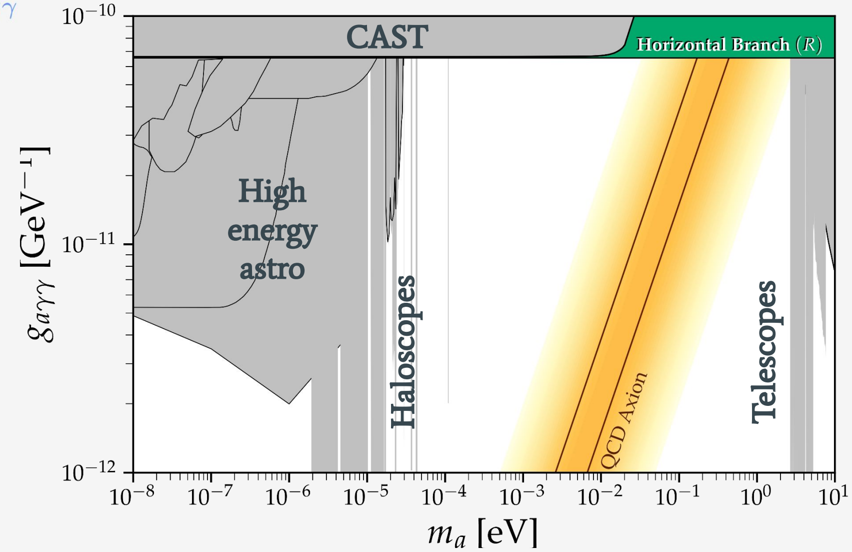

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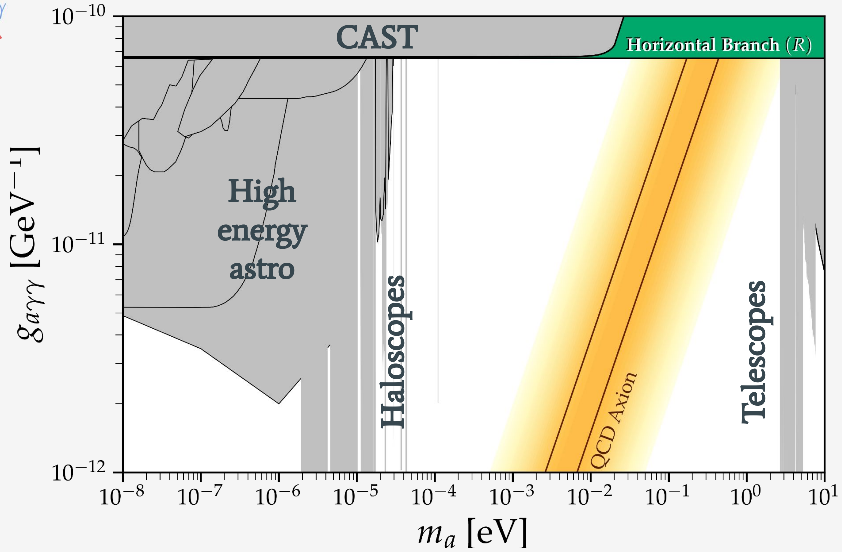

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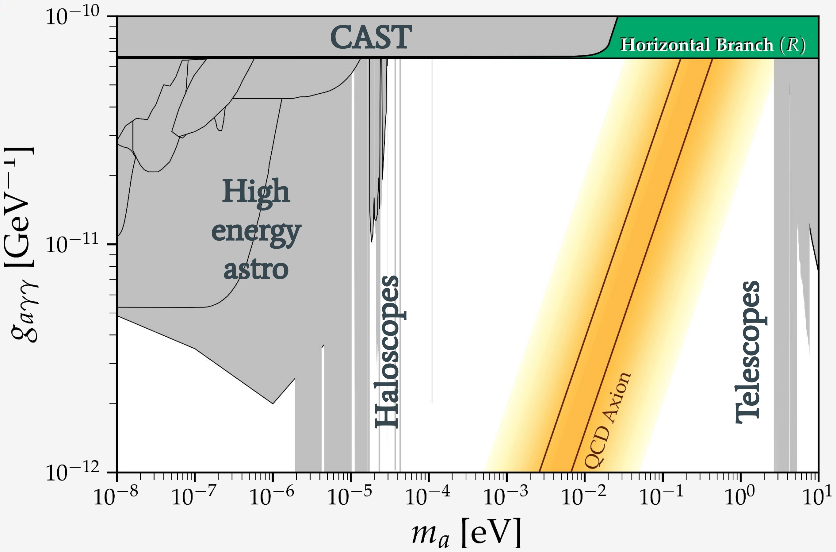

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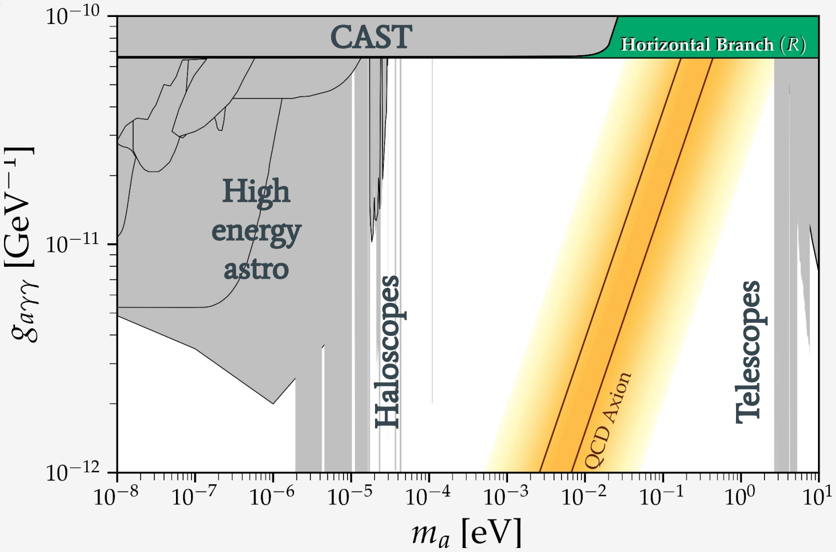

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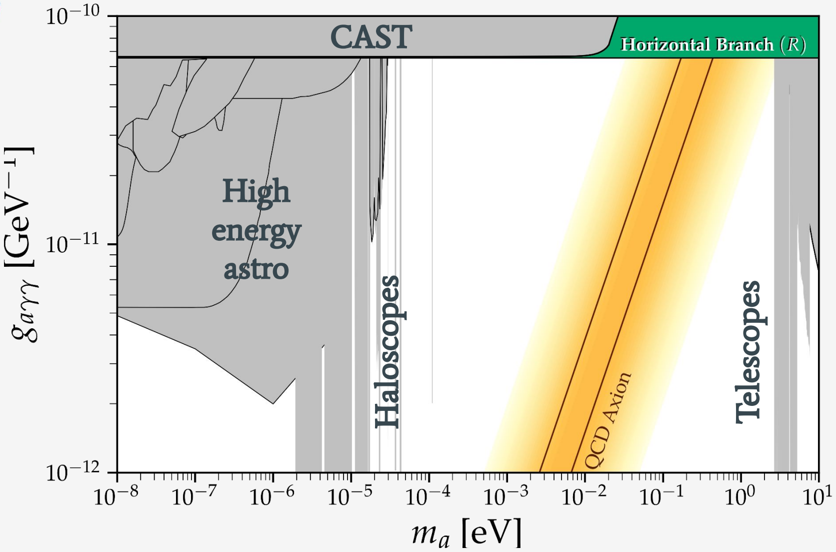

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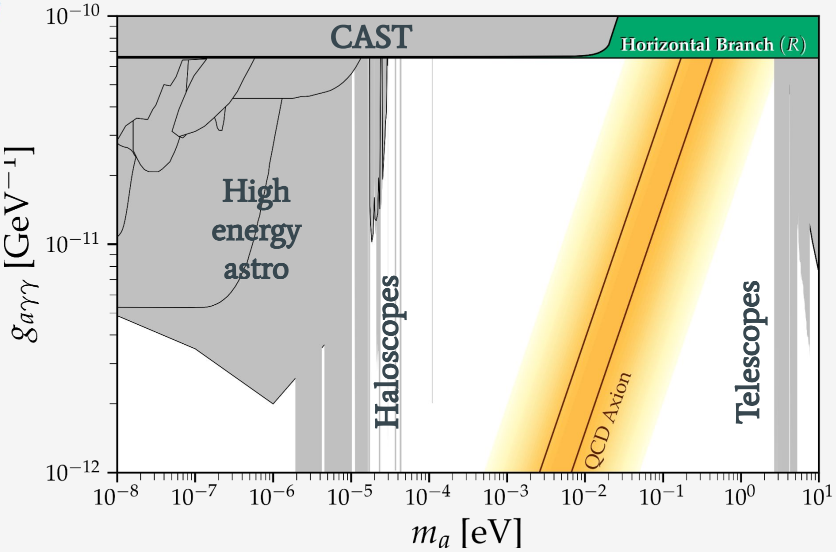

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Illustrate with stellar evolution code `MESA`

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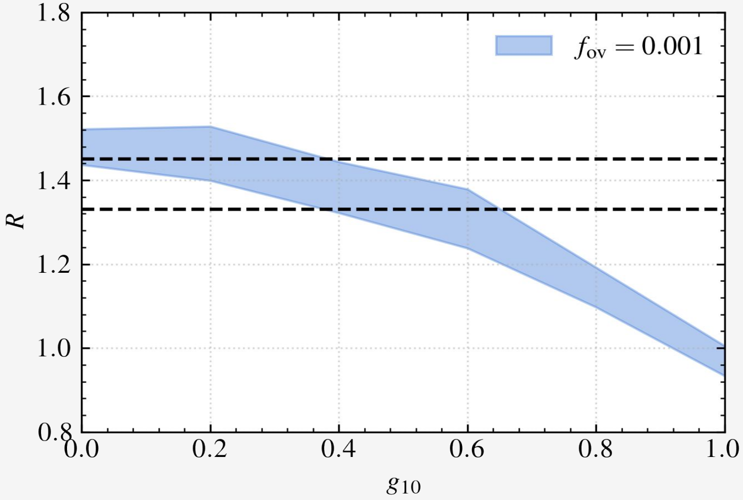

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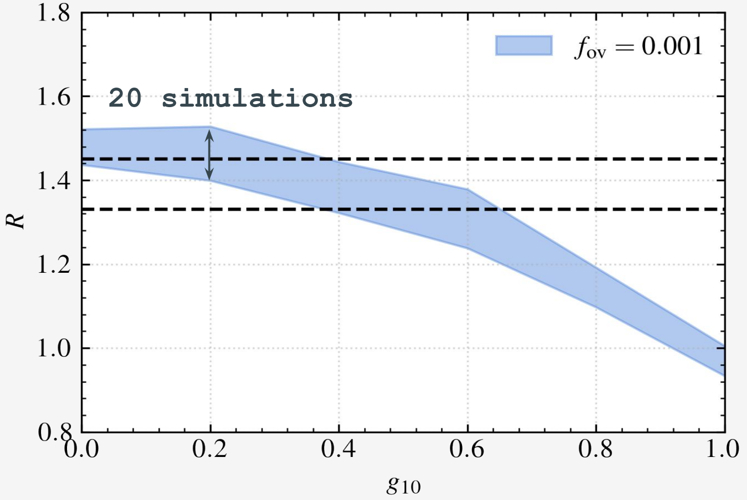

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The leading stellar constraint on the axion-photon coupling comes from the *R*-parameter of globular clusters

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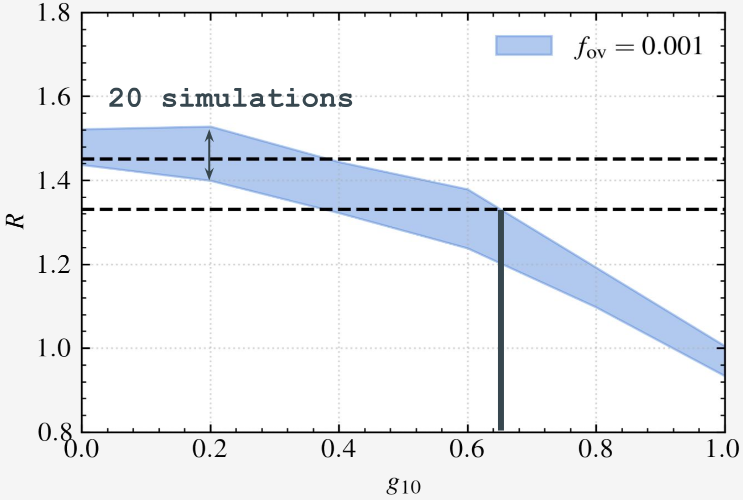

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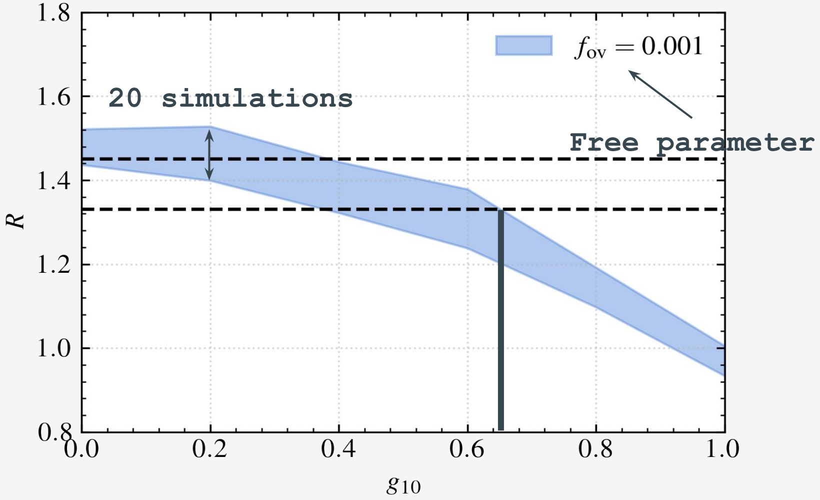

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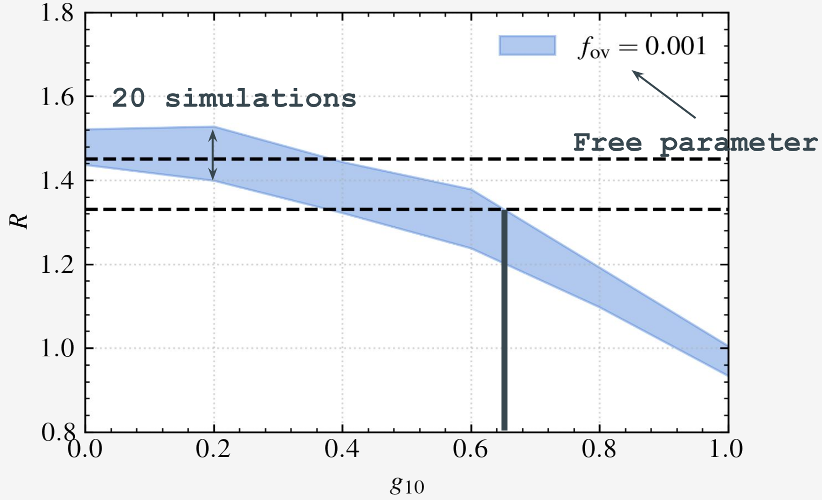

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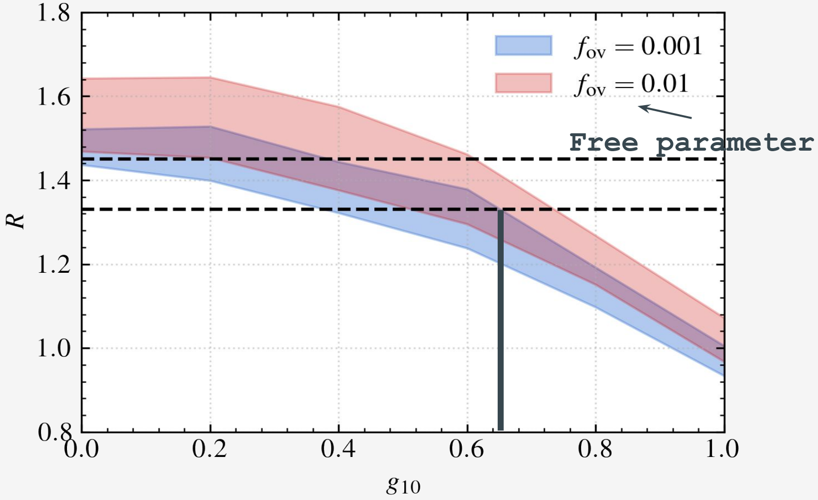

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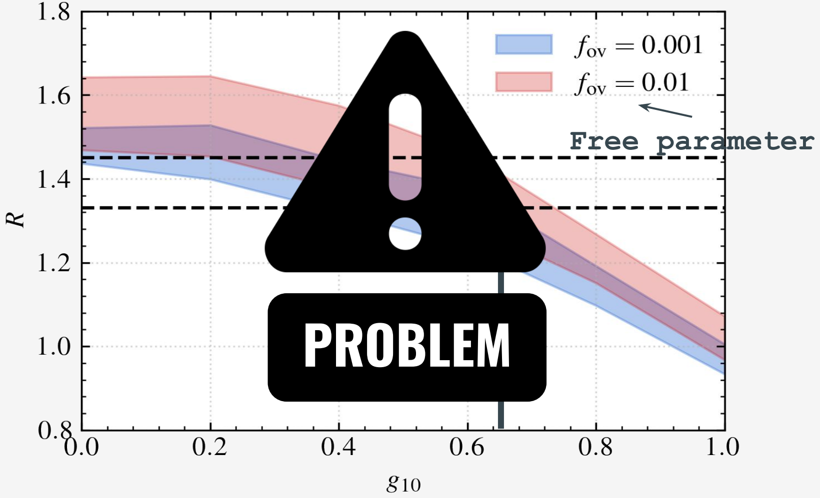

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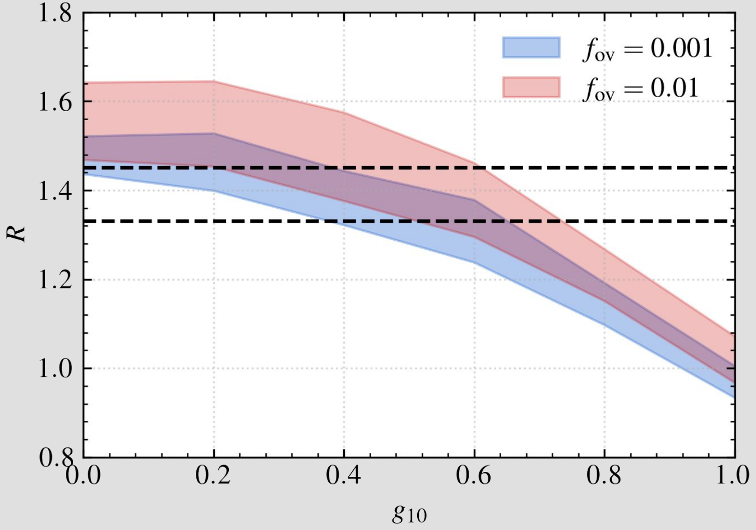
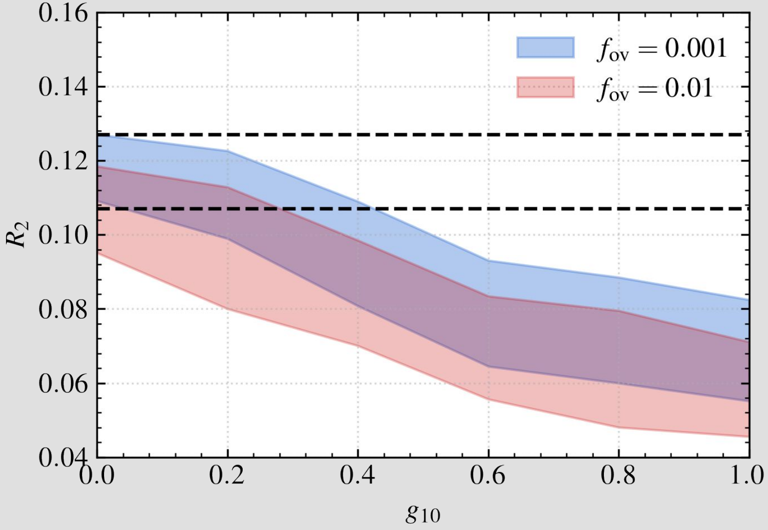
Historically used to constrain mixing across convective boundaries during the HB

Constantino, et al., *MNRAS*, **456** (2016) 3866

R versus R_2


1.8
1.6
1.4
1.2
1.0
0.8
R
0.0
0.2
0.4
0.6
0.8
1.0
g_{10}
$f_{\rm ov} = 0.001$
$f_{\rm ov} = 0.01$


0.16
0.14
0.12
0.10
0.08
0.06
0.04
R_2
0.0
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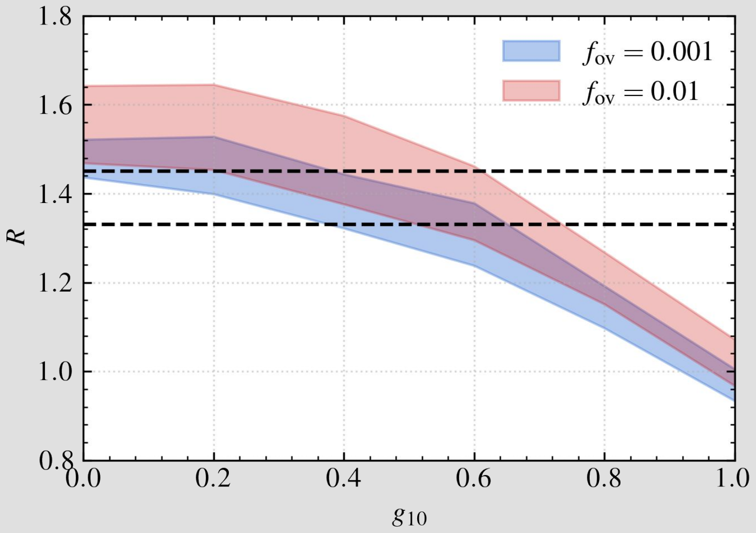

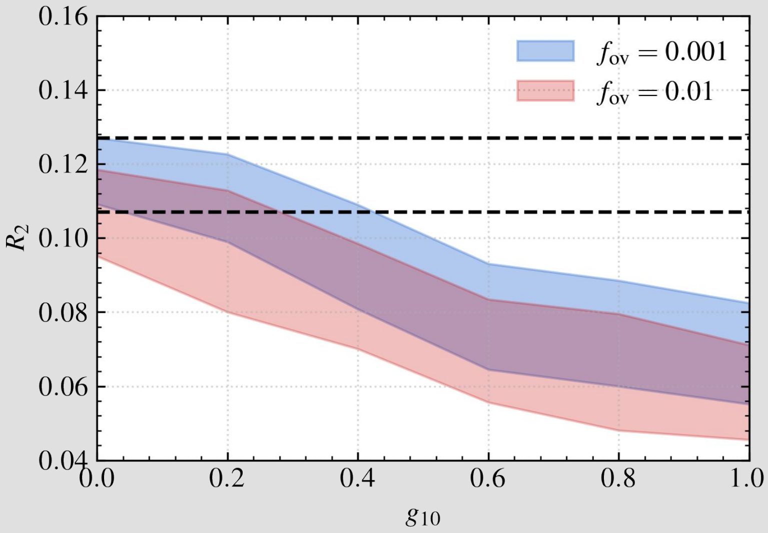

Varying convective boundary model parameter(s) has opposite effect on each constraint

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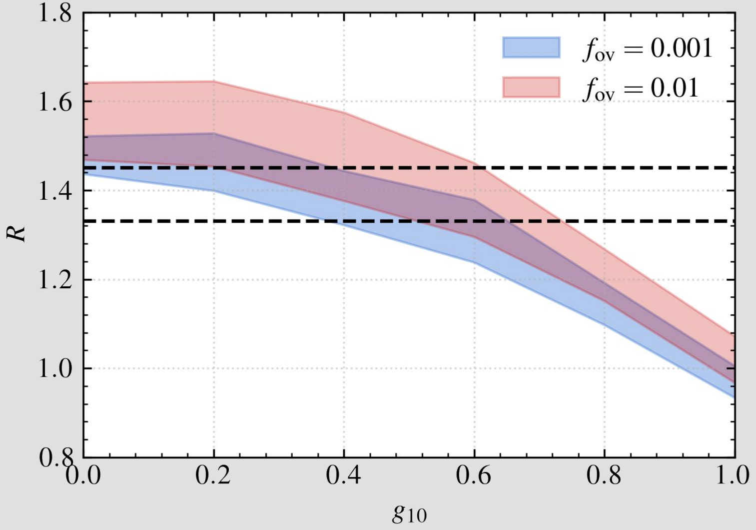

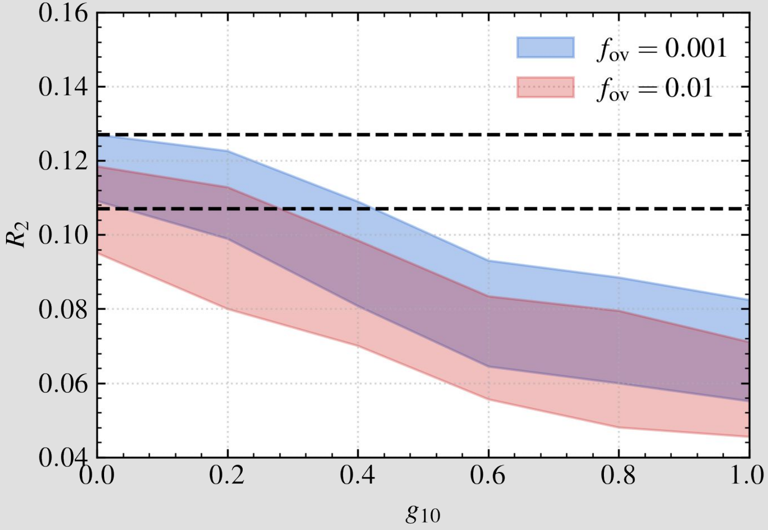

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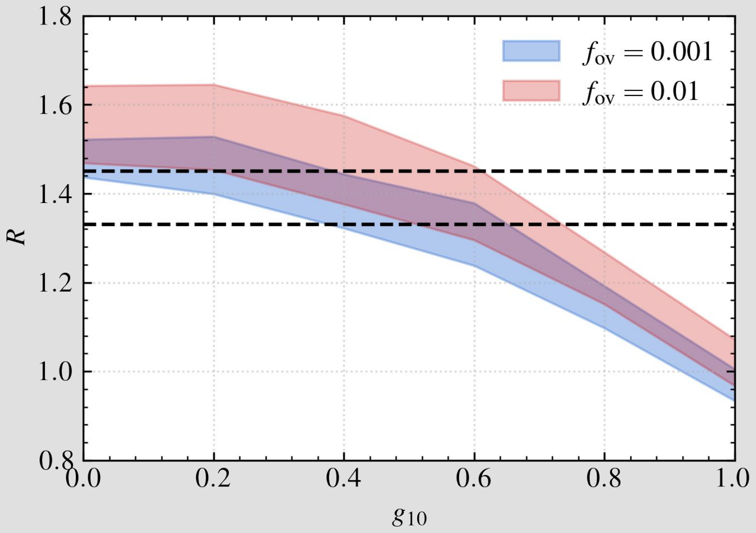

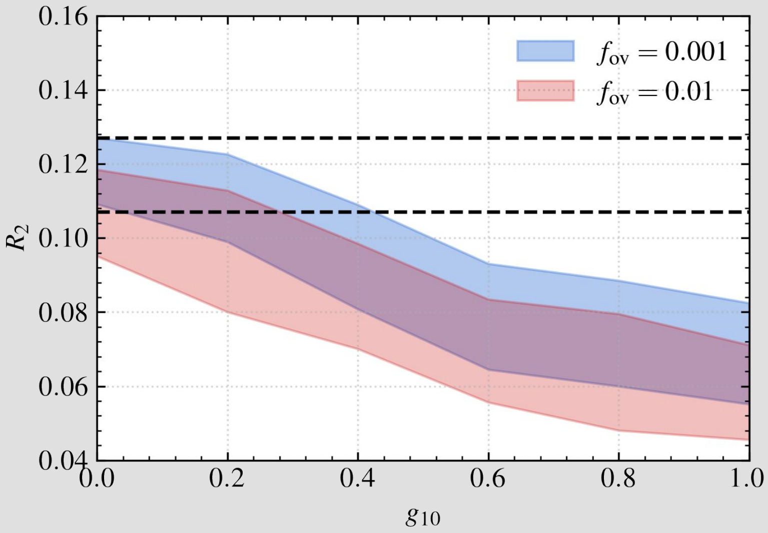

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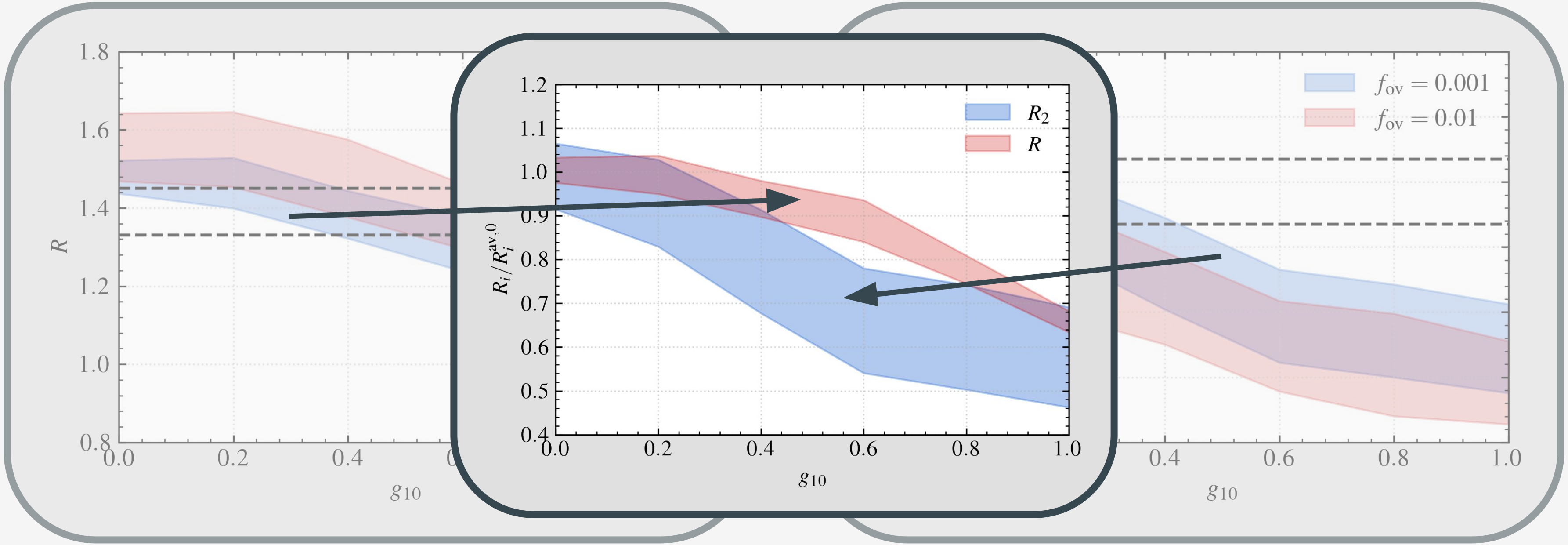

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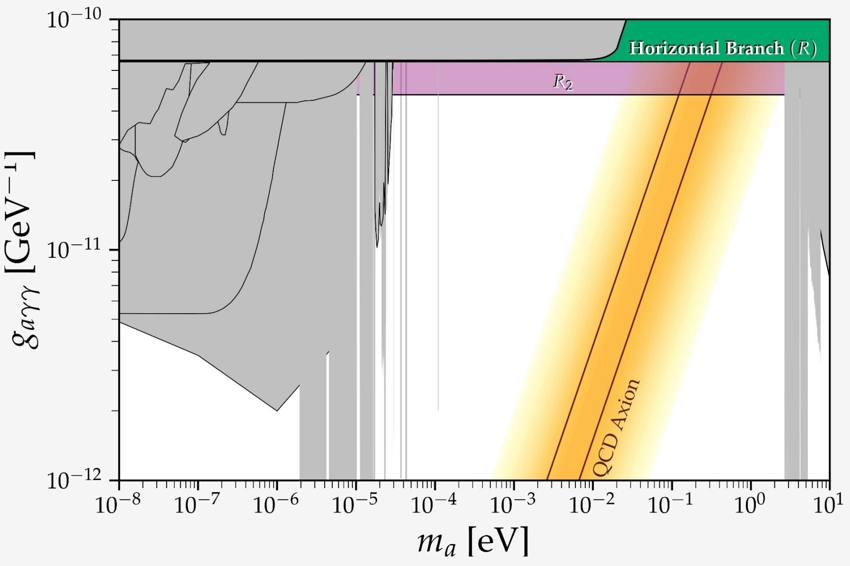
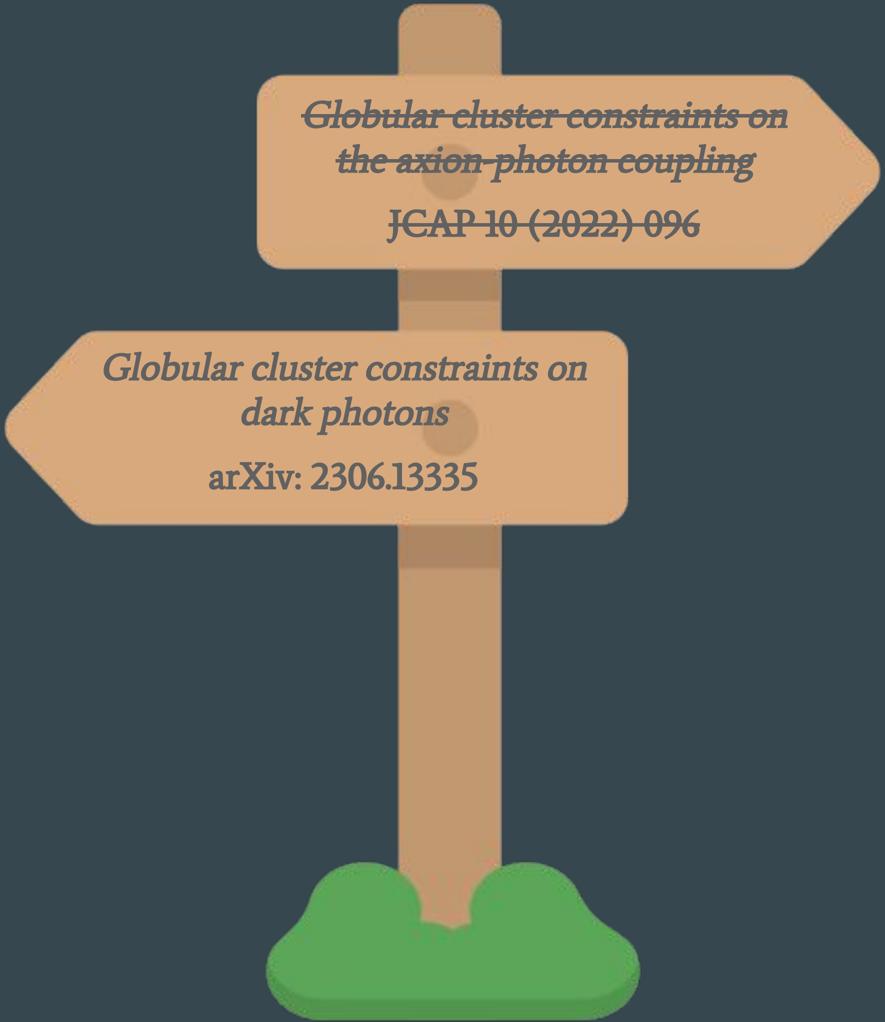
New limit of $g_{10} \leq 0.47$, which is both stronger and more robust than its predecessor





~~Globular cluster constraints on the axion-photon coupling~~

~~JCAP 10 (2022) 096~~

Globular cluster constraints on dark photons

arXiv: 2306.13335

Dark photons

Dark photons are gauge bosons associated with new *dark U(1)* gauge groups

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Interact with the SM via kinetic mixing with the visible photon

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{m_{\rm DP}^2}{2}V_\mu V^\mu - \frac{\chi}{2}F_{\mu\nu}V^{\mu\nu}}$$

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Goal: To use dynamic and self-consistent stellar evolution simulations to develop new dark photon constraints from R and R_2 (and RGB-tip)

Selected results

We found...

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Strong interplay between novel energy-loss and stellar convective structure when the RPR is in the stellar core near the end of HB evolution

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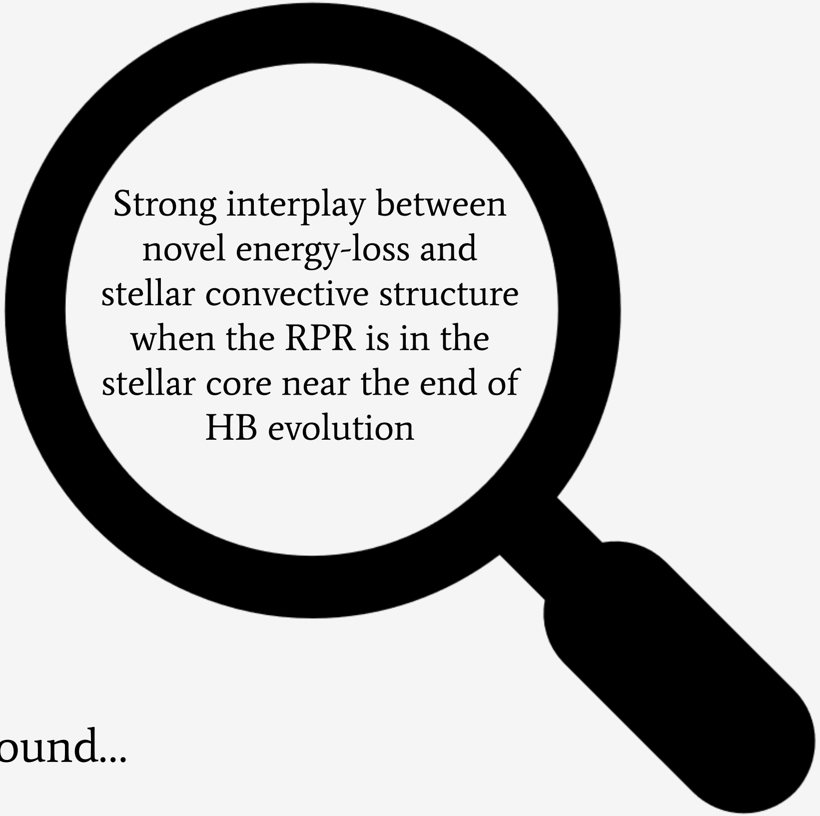

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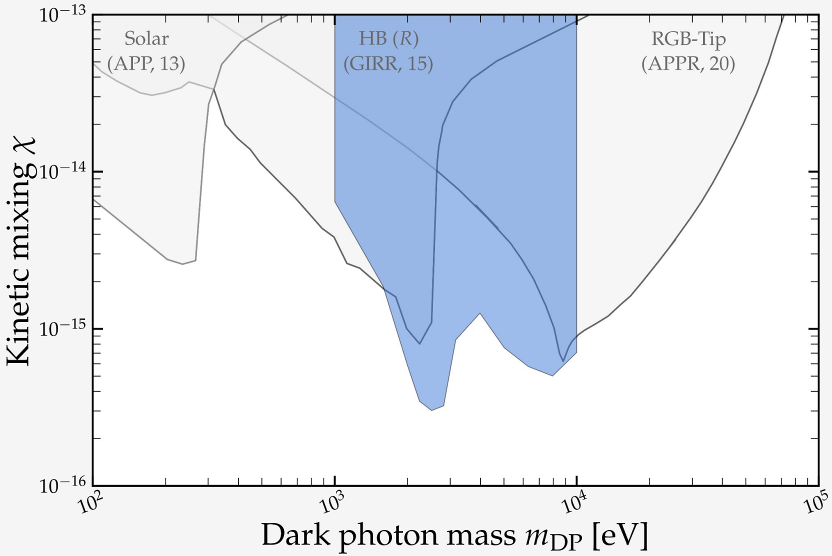
R_2 is particularly well-placed to constrain this



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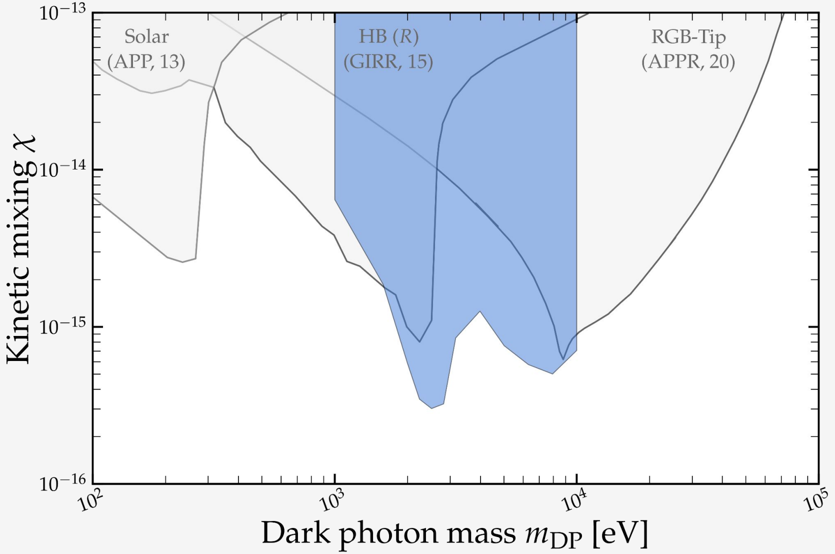
Supplement with updated limits from R and the RGB-tip luminosity



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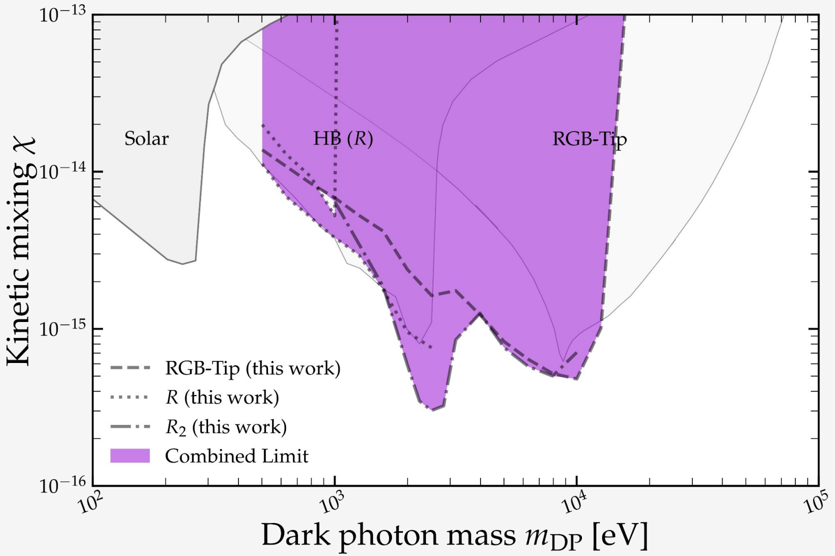

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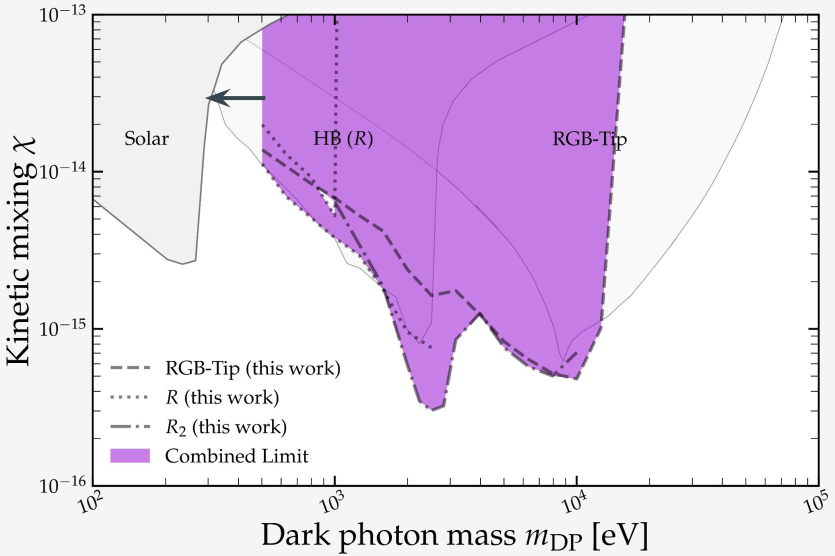

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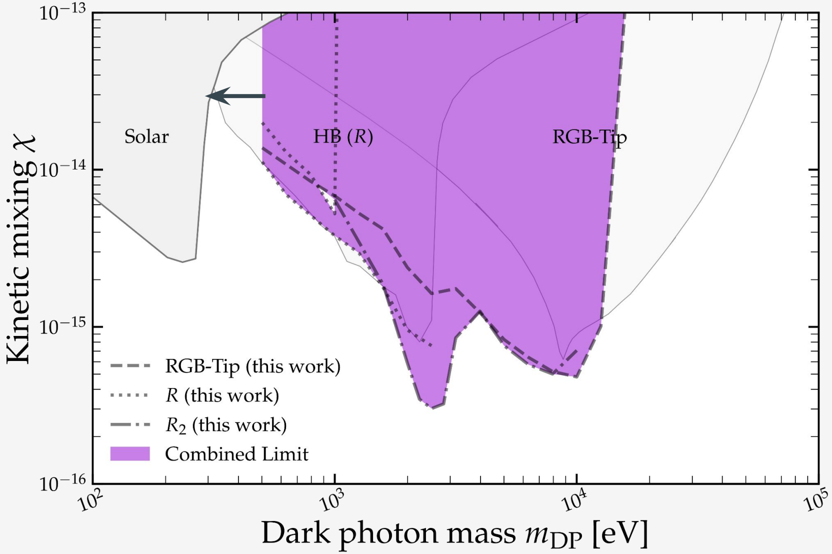
Subject of future work...



WISPers from the stars

Stellar evolution has been a rich source of constraint on weakly interacting slim particles for decades

Despite this, improving observational and theoretical capabilities make their advancement possible to this day

Using the stellar evolution code MESA and the R_2-parameter, we set a new limit on the axion-photon coupling which is both more robust and more restrictive than its predecessor

We developed new limits on dark photons from R, R_2 and the RGB-tip by including transverse dark photon production in stars (for the first time)

Thank you for your attention!

Backup Slides

R-parameter constraint

$$g_{10} \equiv \frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}$$

Historically, the most restrictive stellar cooling bound on the axion-photon coupling comes from the *R*-**parameter** of globular clusters

$$R = \frac{N_{\mathrm{HB}}}{N_{\mathrm{RGB}}} \simeq \frac{\tau_{\mathrm{HB}}}{\tau_{\mathrm{RGB}}}$$

Globular cluster HBs and RGBs populated with stars of approximately the same initial mass $M_{\mathrm{i}} \approx 0.8 M_{\odot}$

Observed limits on *R* constrain the relative lifetimes of the evolutionary phases

---

Axion photoproduction proceeds via the **Primakoff process**

For $g_{10} \sim 1$, energy-loss is efficient in HB stars but not during the RGB phase

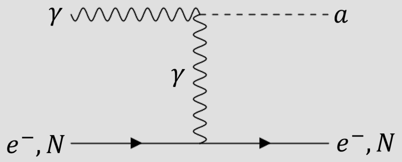
Increasing g_{10} reduces *R* - for high enough values it will contradict observation

Raffelt & Dearborn., *Phys. Rev. D* **36** (1987) 2211

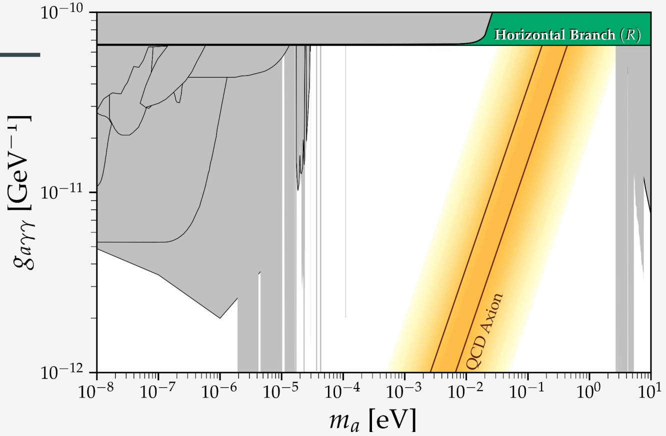
Ayala, et al., *Phys. Rev. Lett.* **113** (2014) 191302

This all sounds fine... but there's an issue!

Primakoff production



$$\epsilon_{\mathrm{P}} = \frac{g_{a\gamma\gamma}^2 T^7}{4\pi\rho} G\left(\frac{k_{\mathrm{D}}}{T}, \frac{\omega_{\mathrm{P}}}{T}\right)$$



Aside: The HB convective core boundary (convective overshoot)

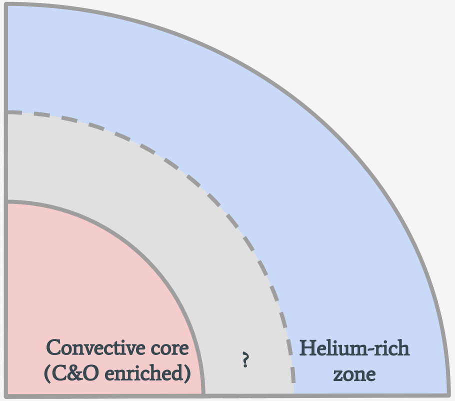
Formally, the convective boundary (CB) is the location at which **acceleration** (but not momentum) of convective elements falls to zero

Convective elements penetrate beyond the CB, mixing the products of helium-burning (C & O) across the boundary - **convective overshoot**

Carbon and oxygen are more opaque than helium - mixing leads to local increase in ∇_{rad} and growth of the convective core

Growth of core results in influx of helium into it - lowers ∇_{rad} profile

Further outward movement of CB results in **splitting** of the core



Repeated episodes of growth & splitting cause instability of CB boundary - source of **stochastic** & **theoretical** uncertainty ignored in previous bounds

Stellar dark photon production

$$\Gamma_{\mathrm{L}}^{\mathrm{Prod}} = \frac{\chi^2 m_{\mathrm{DP}}^2}{e^{\omega/T}-1}\frac{\omega^2\Gamma_{\mathrm{L}}^{\gamma}}{(\omega^2-\omega_{\mathrm{p}}^2)+(\omega\Gamma_{\mathrm{L}}^{\gamma})^2}$$

Resonant production when: $\omega \approx \omega_{\mathrm{p}}$

$$\Gamma_{\mathrm{T}}^{\mathrm{Prod}} = \frac{\chi^2 m_{\mathrm{DP}}^4}{e^{\omega/T}-1}\frac{\Gamma_{\mathrm{T}}^{\gamma}}{(m_{\mathrm{DP}}^2-\omega_{\mathrm{p}}^2)+(\omega\Gamma_{\mathrm{T}}^{\gamma})^2}$$

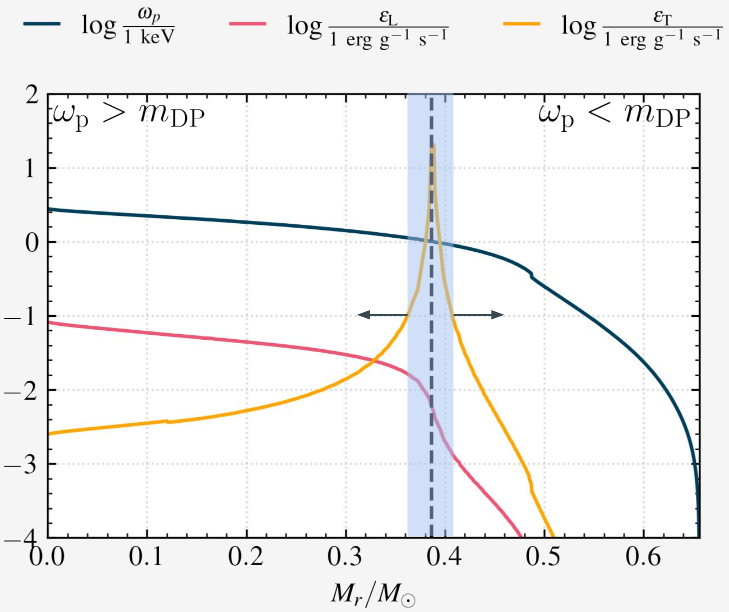
Resonant production when: $\omega_{\mathrm{p}} \approx m_{\mathrm{DP}}$

Atypical

Off centre

Free to move throughout evolution

Star can acquire RPR during evolution



Transverse energy loss only sizeable in region which satisfies resonance

Defines **resonant production region (RPR)**

Dominates over L if present

$$\omega_{\mathrm{p}} = \frac{4\pi\alpha n_e}{m_e} = \frac{4\pi\alpha Y_e\rho}{m_{\mathrm{amu}}m_e}$$