# Advancing globular cluster constraints on the axion-photon coupling

*Lepton Photon 2023*

*JCAP* 10 (2022) 096, arXiv:2207.03102

Matthew Dolan, **Frederick Hiskens**, Raymond Volkas

# Part One

## globular cluster constraints on the axion-photon coupling

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF MELBOURNE

# Part One

THE ISSUE WITH globular cluster constraints on the axion-photon coupling

Part Two

# Advancing globular cluster constraints on the axion-photon coupling

# Axions & stellar constraints

# Axions & stellar constraints

Axions are well-motivated extensions to the Standard Model of particle physics

# Axions & stellar constraints

Axions are well-motivated extensions to the Standard Model of particle physics

Strong CP problem

# Axions & stellar constraints

Axions are well-motivated extensions to the Standard Model of particle physics

Strong CP problem

DM candidate

# Axions & stellar constraints

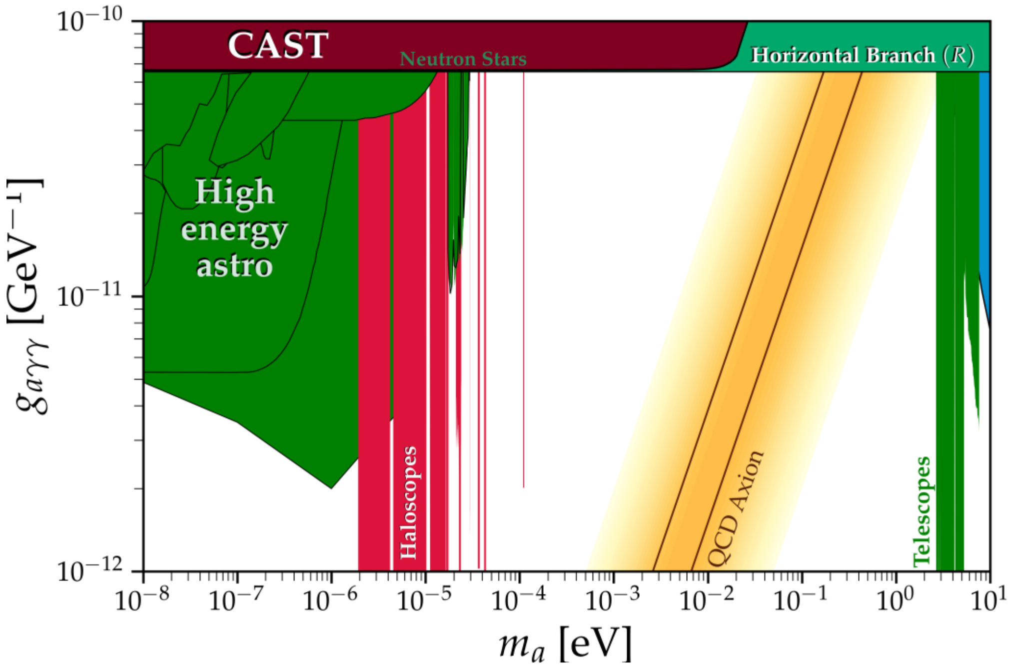
Axions are well-motivated extensions to the Standard Model of particle physics

Strong CP problem

DM candidate

Experimental, phenomenological and theoretical interest in axions has exploded over the last decade – e.g. in their coupling to photons

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$




cajohare/AxionLimits

# Axions & stellar constraints

THE UNIVERSITY OF MELBOURNE

Axions are well-motivated extensions to the Standard Model of particle physics

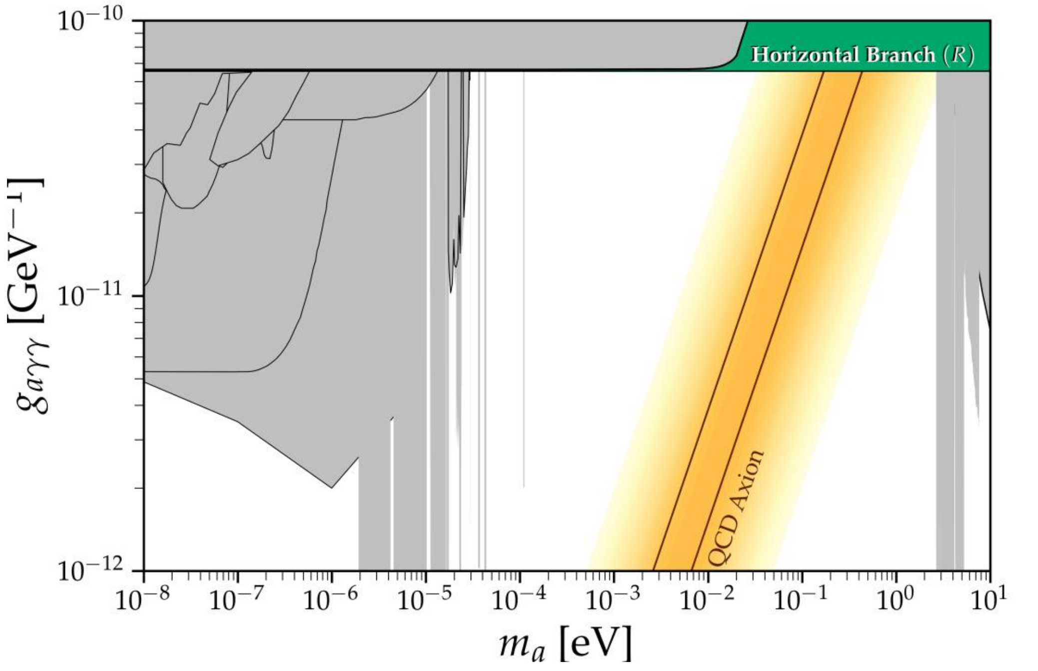
Strong CP problem

DM candidate

Experimental, phenomenological and theoretical interest in axions has exploded over the last decade – e.g. in their coupling to photons

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Amongst the oldest of the present limits are the stellar cooling constraints




ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

cajohare/AxionLimits

# Axions & stellar constraints

Axions are well-motivated extensions to the Standard Model of particle physics

Strong CP problem

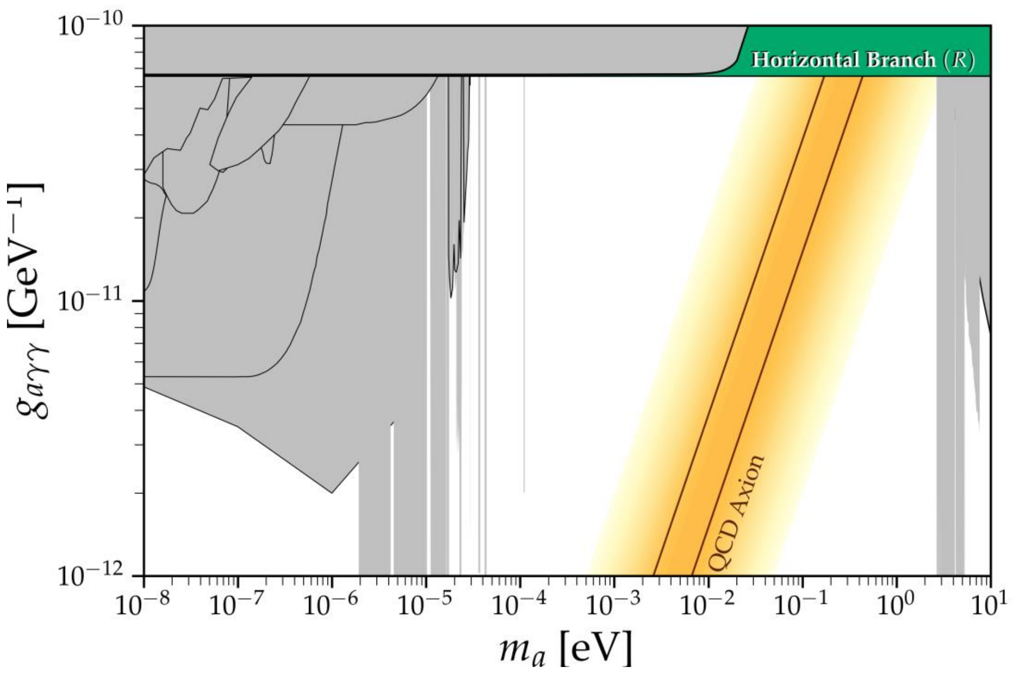
DM candidate

Experimental, phenomenological and theoretical interest in axions has exploded over the last decade – e.g. in their coupling to photons

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Amongst the oldest of the present limits are the stellar cooling constraints

Axions can drain energy from stars




cajohare/AxionLimits

# Axions & stellar constraints

Axions are well-motivated extensions to the Standard Model of particle physics

Strong CP problem

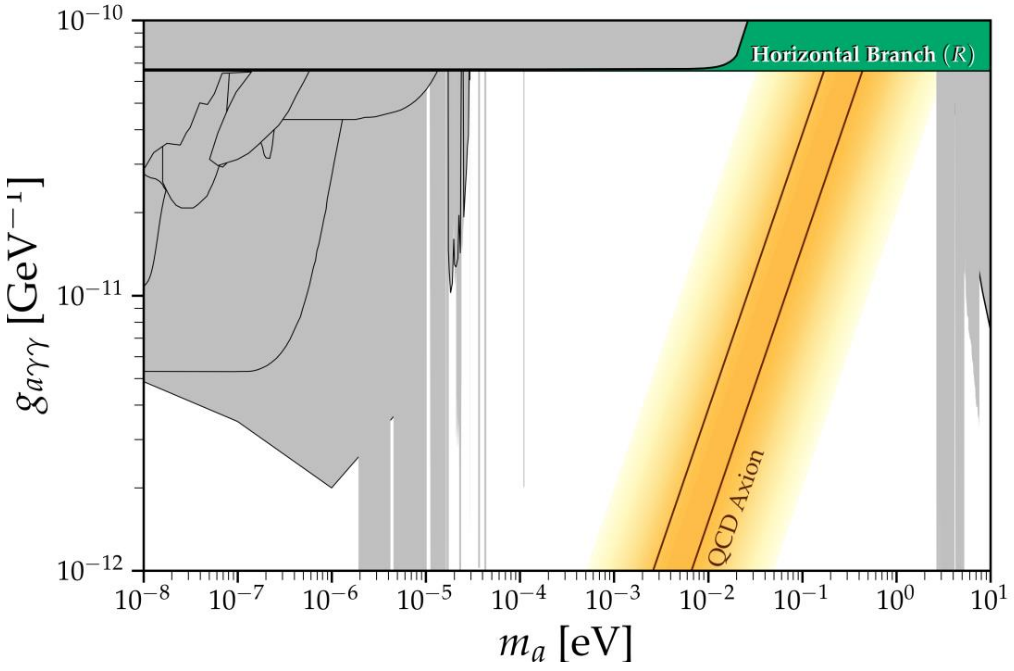
DM candidate

Experimental, phenomenological and theoretical interest in axions has exploded over the last decade – e.g. in their coupling to photons

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Amongst the oldest of the present limits are the stellar cooling constraints

Axions can drain energy from stars → Accelerates progression of nuclear-burning evolutionary phase




cajohare/AxionLimits

# Axions & stellar constraints

Axions are well-motivated extensions to the Standard Model of particle physics

Strong CP problem

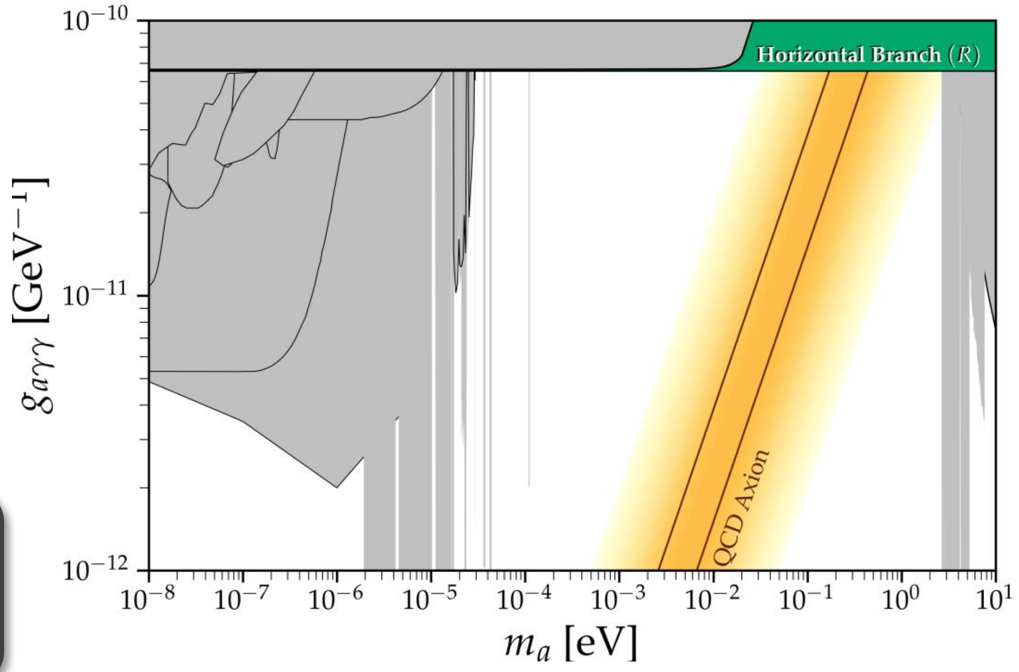
DM candidate

Experimental, phenomenological and theoretical interest in axions has exploded over the last decade – e.g. in their coupling to photons

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Amongst the oldest of the present limits are the stellar cooling constraints

Axions can drain energy from stars → Accelerates progression of nuclear-burning evolutionary phase → Tension between theory and observation




cajohare/AxionLimits

# Axions & stellar constraints

Axions are well-motivated extensions to the Standard Model of particle physics

- Strong CP problem
- DM candidate

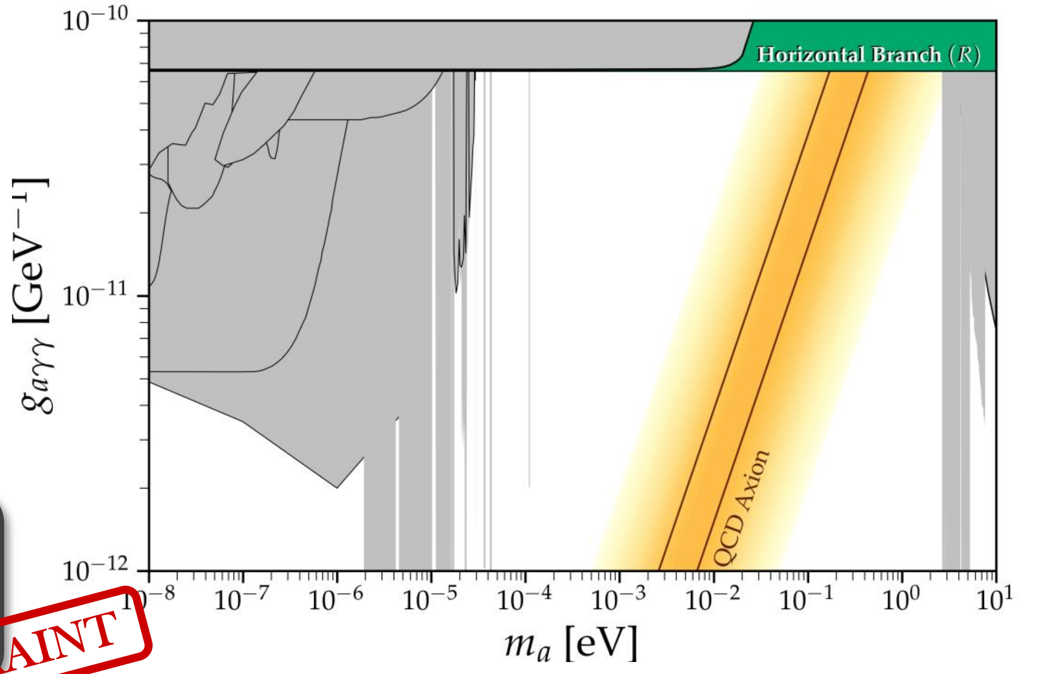
Experimental, phenomenological and theoretical interest in axions has exploded over the last decade – e.g. in their coupling to photons

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Amongst the oldest of the present limits are the stellar cooling constraints

Axions can drain energy from stars → Accelerates progression of nuclear-burning evolutionary phase → Tension between theory and observation

CONSTRAINT




cajohare/AxionLimits

# Axions & stellar constraints

Axions are well-motivated extensions to the Standard Model of particle physics

Strong CP problem

DM candidate

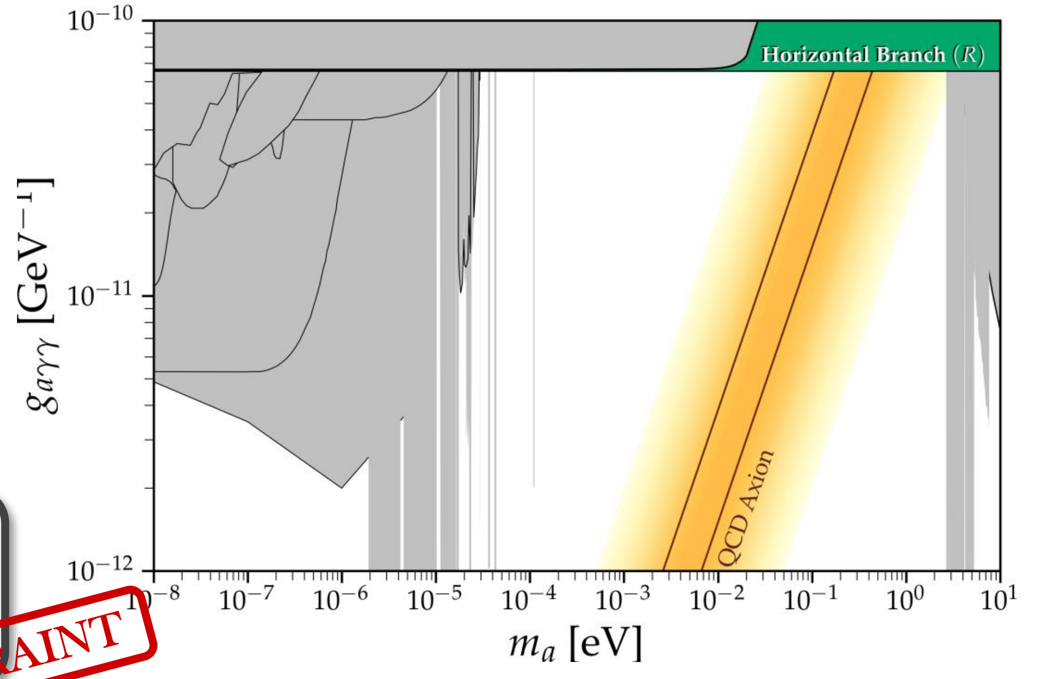
Experimental, phenomenological and theoretical interest in axions has exploded over the last decade – e.g. in their coupling to photons

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Amongst the oldest of the present limits are the stellar cooling constraints

Axions can drain energy from stars → Accelerates progression of nuclear-burning evolutionary phase → Tension between theory and observation

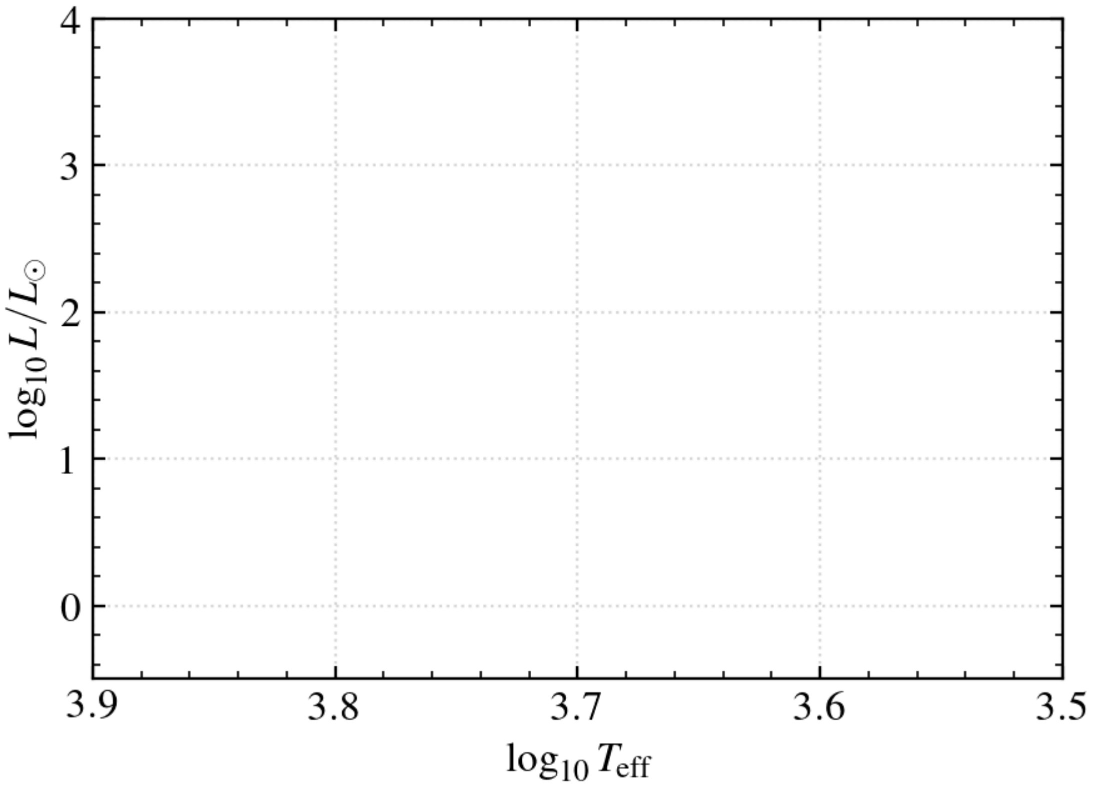
CONSTRAINT




Before continuing we must first take a detour through the evolutionary progression of low mass stars…

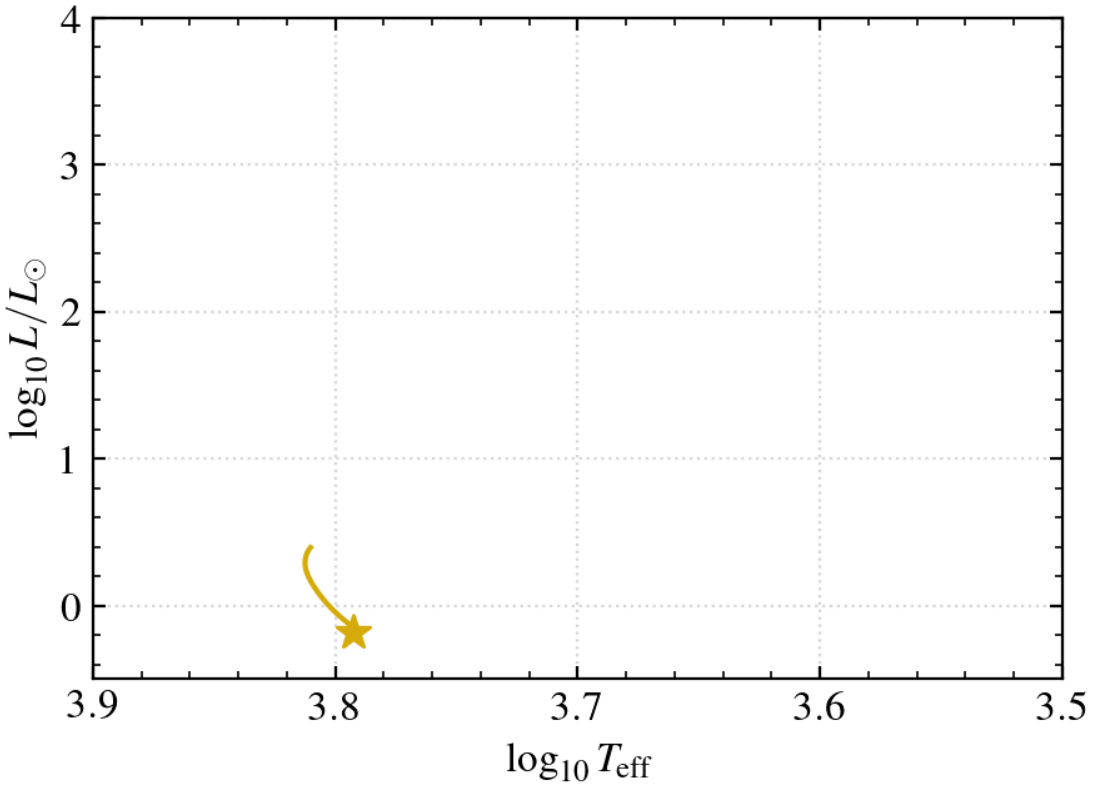
cajohare/AxionLimits

# Evolution of a low mass star ($\lesssim 1.5 M_\odot$)



# Evolution of a low mass star ($\lesssim 1.5 M_\odot$)

**Main Sequence (MS):**
Star burns hydrogen in core. Longest evolutionary phase.

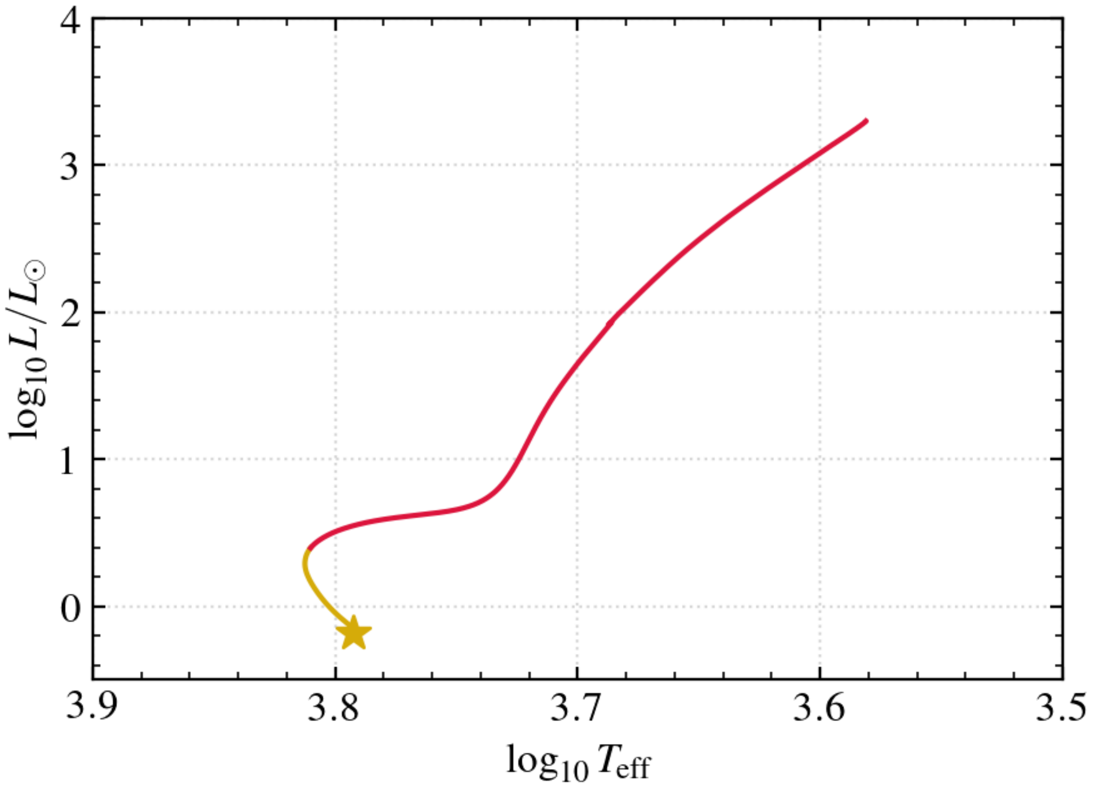


# Evolution of a low mass star ($\lesssim 1.5 M_\odot$)

**Main Sequence (MS):**
Star burns hydrogen in core. Longest evolutionary phase.

→

**Red giant branch (RGB):**
Hydrogen-burning continues in off-centre shell surrounding inert, degenerate core of helium



# Evolution of a low mass star ($\lesssim 1.5M_\odot$)

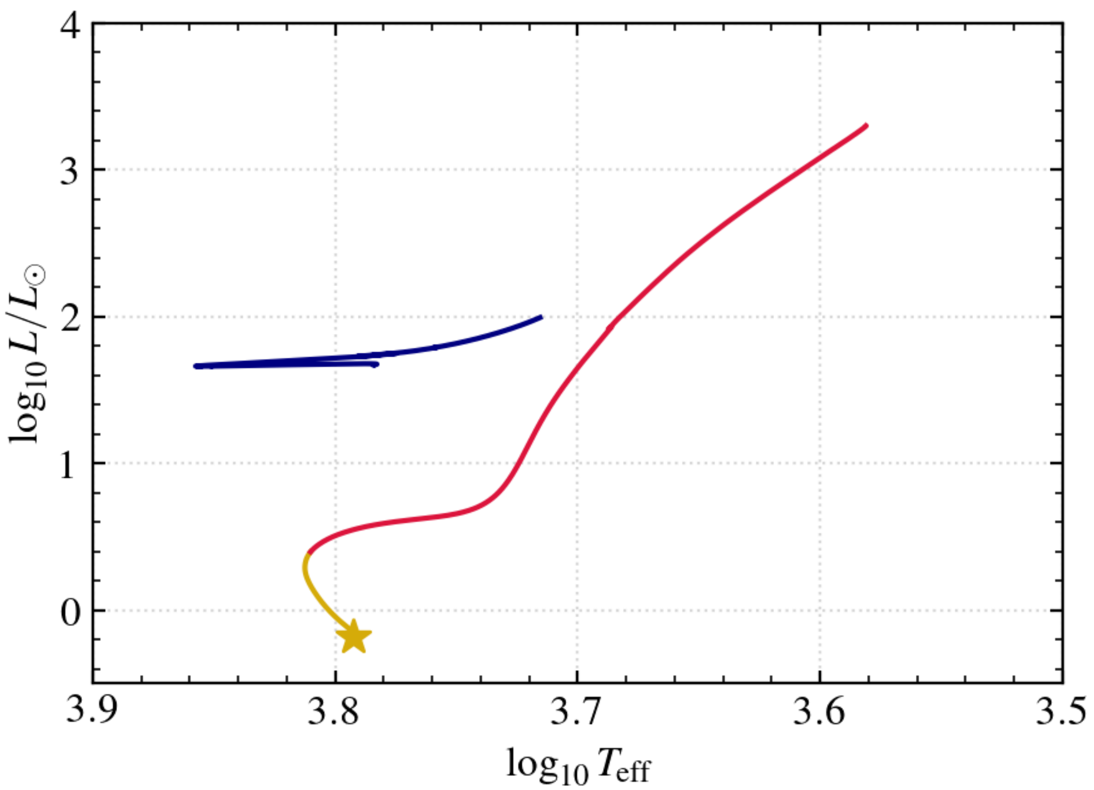
THE UNIVERSITY OF MELBOURNE

**Main Sequence (MS):**
Star burns hydrogen in core. Longest evolutionary phase.

**Red giant branch (RGB):**
Hydrogen-burning continues in off-centre shell surrounding inert, degenerate core of helium

Helium ignition

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




ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# Evolution of a low mass star ($\lesssim 1.5 M_\odot$)

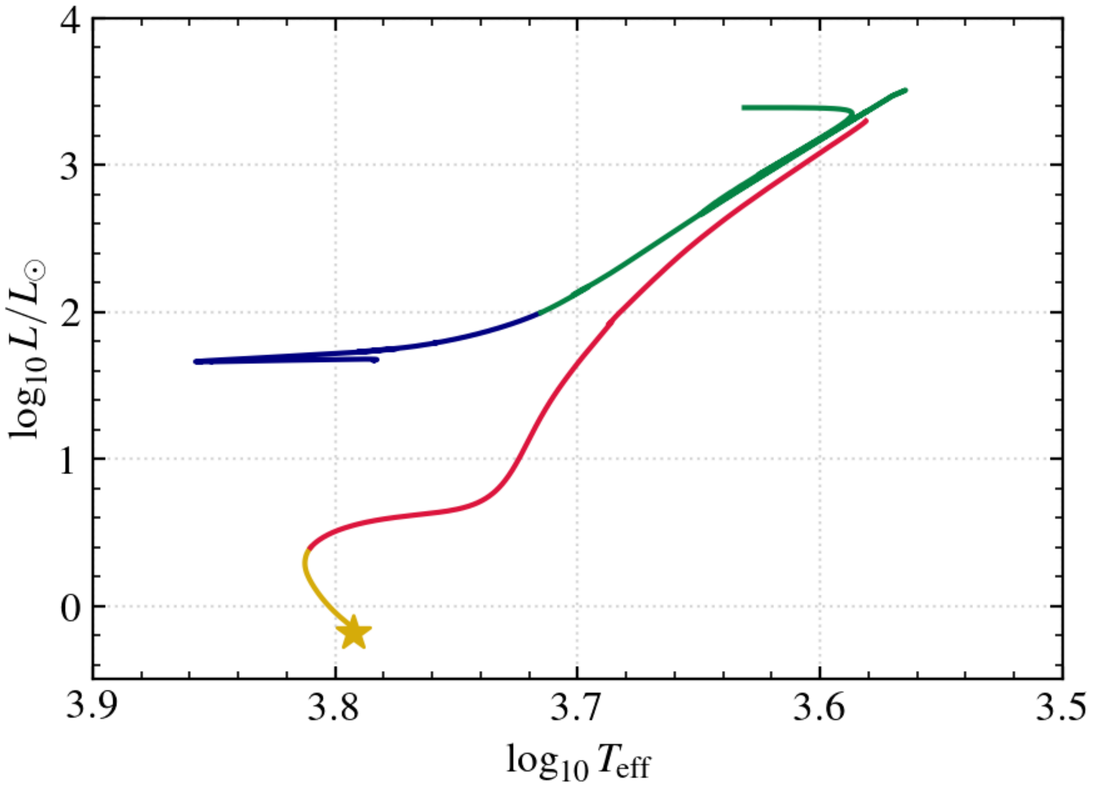
**Main Sequence (MS):** Star burns hydrogen in core. Longest evolutionary phase.

**Red giant branch (RGB):** Hydrogen-burning continues in off-centre shell surrounding inert, degenerate core of helium

Helium ignition

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

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



# Evolution of a low mass star ($\lesssim 1.5 M_\odot$)

THE UNIVERSITY OF MELBOURNE

**Main Sequence (MS):** Star burns hydrogen in core. Longest evolutionary phase.

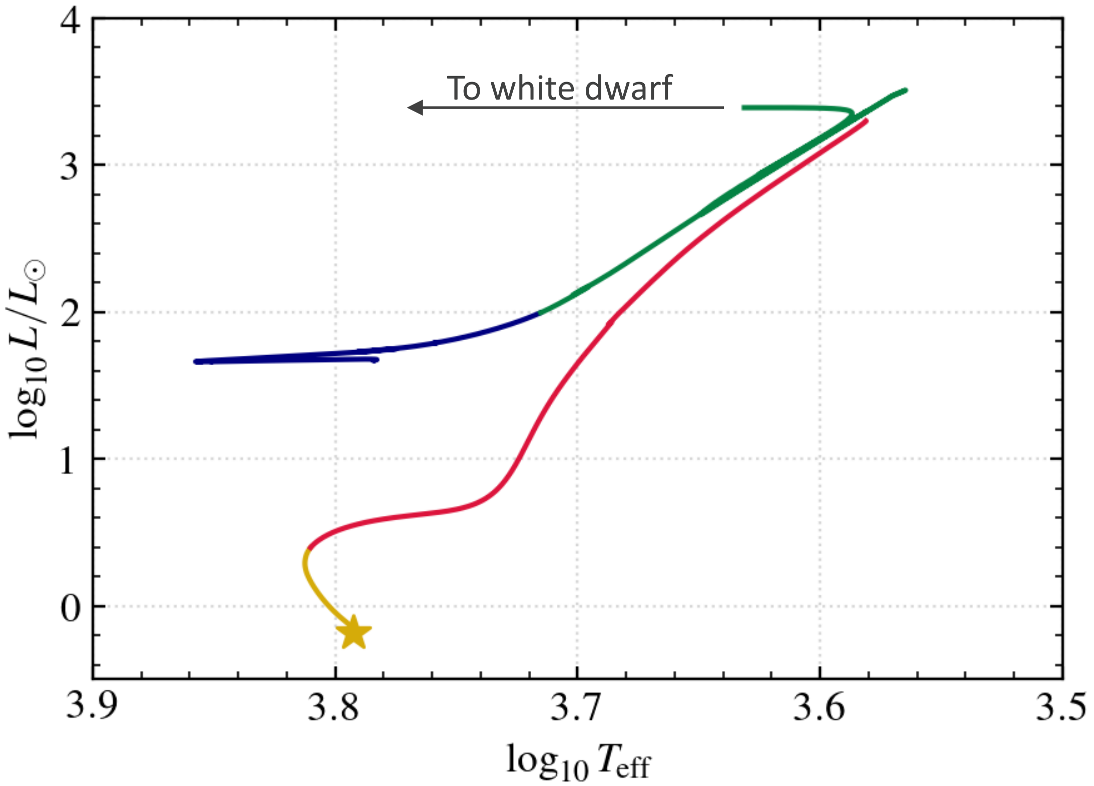
→ **Red giant branch (RGB):** Hydrogen-burning continues in off-centre shell surrounding inert, degenerate core of helium

→ Helium ignition →

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

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

→ white dwarf




Dolan, FJH, Volkas, *JCAP*, **2021** (2021) 010

Dominguez et al., *MNRAS* **456** (1999) L1

# Evolution of a low mass star ($\lesssim 1.5 M_\odot$)

**Main Sequence (MS):** Star burns hydrogen in core. Longest evolutionary phase.

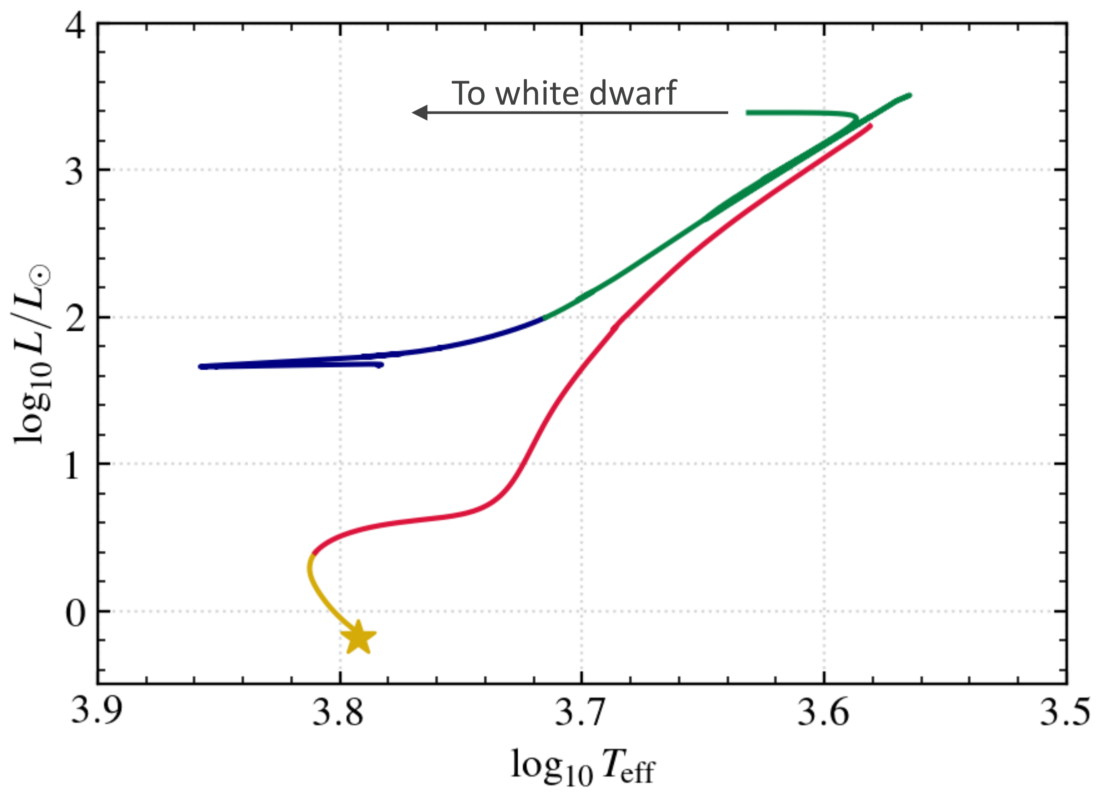
**Red giant branch (RGB):** Hydrogen-burning continues in off-centre shell surrounding inert, degenerate core of helium

Helium ignition

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

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

white dwarf

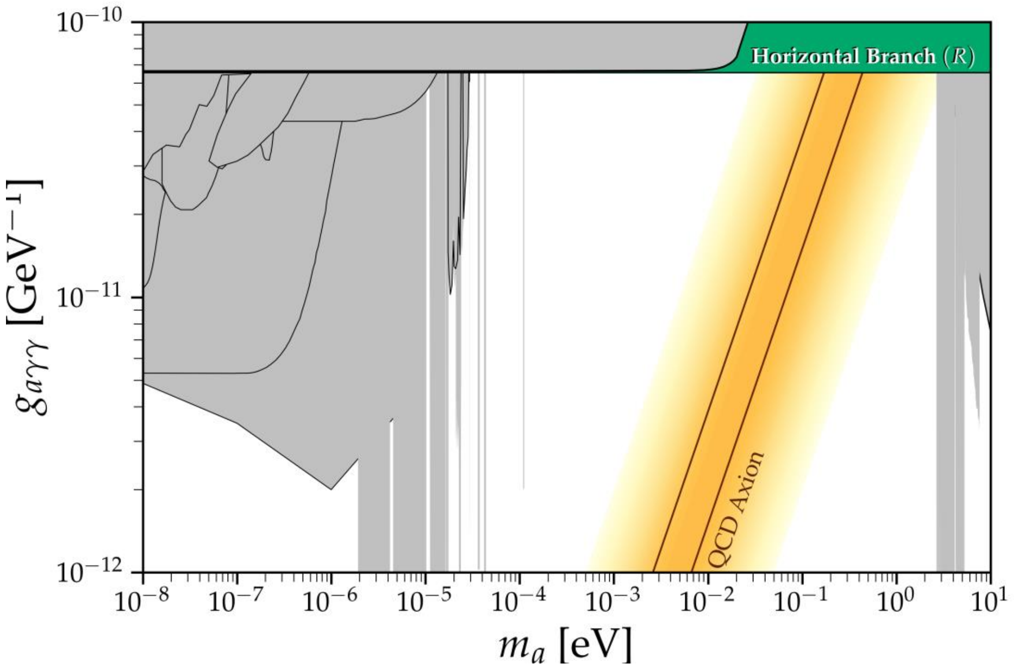



Dolan, FJH, Volkas, *JCAP*, **2021** (2021) 010
Dominguez et al., *MNRAS* **456** (1999) L1

# $R$-parameter constraint

# $R$-parameter constraint

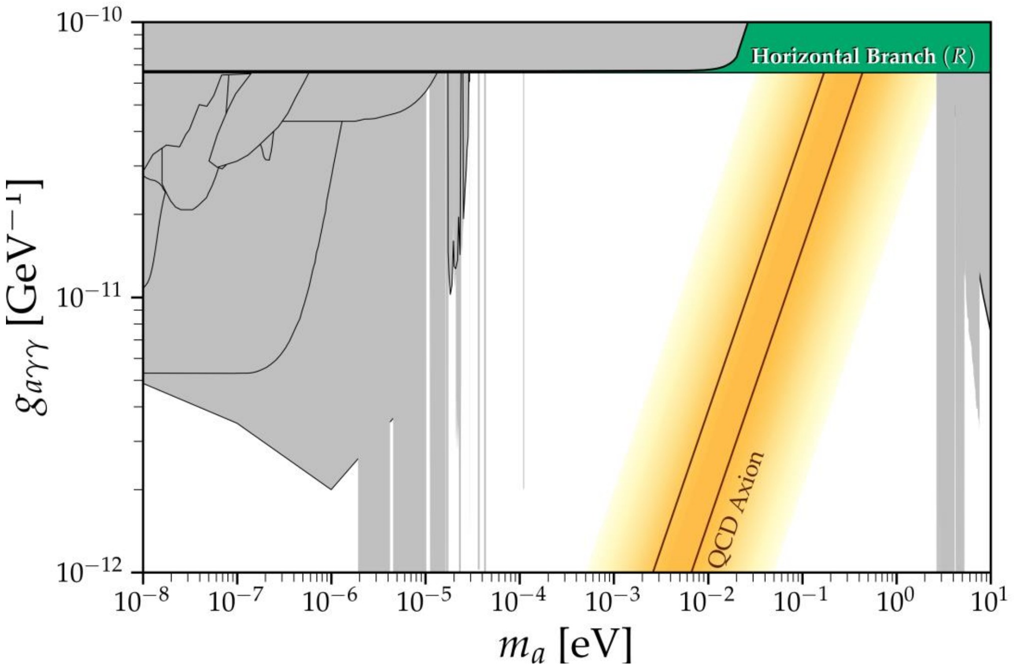
Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint



# $R$-parameter constraint

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

- **$R$-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

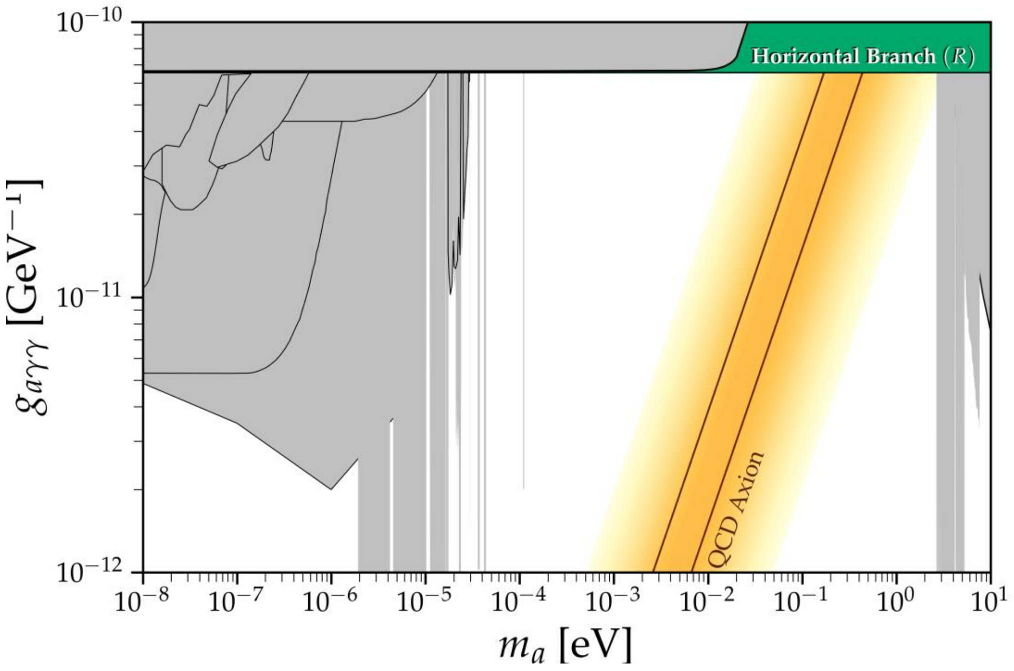


# $R$-parameter constraint

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

- **$R$-parameter:** the ratio of horizontal branch (HB) to red giant branch (RGB) stars in globular clusters

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



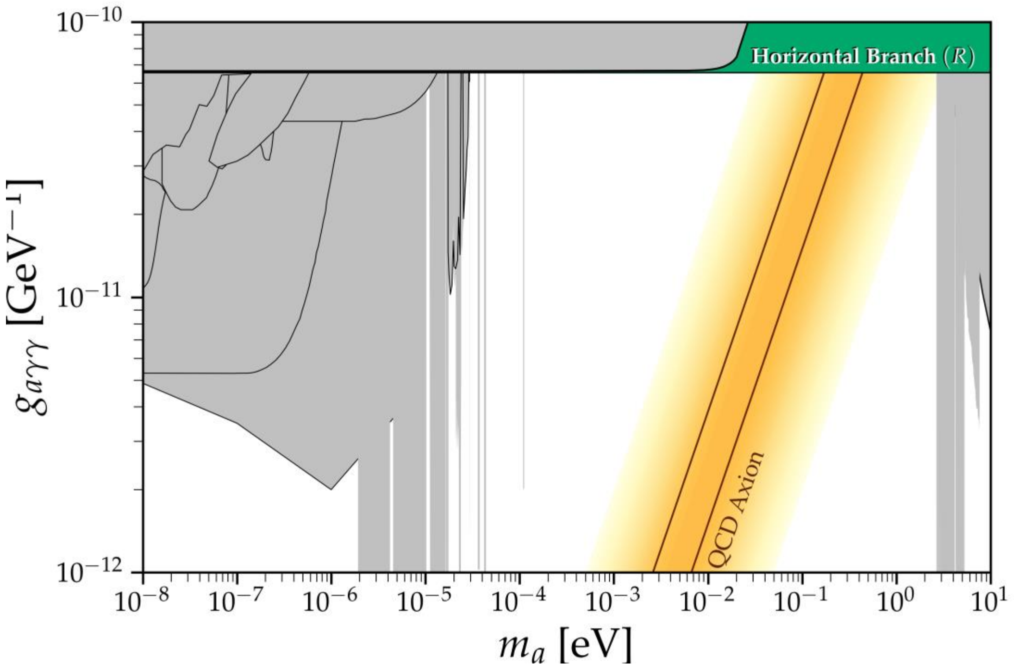
# $R$-parameter constraint

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

- **$R$-parameter:** the ratio of horizontal branch (HB) to red giant branch (RGB) stars in globular clusters

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

Globular cluster HB and RGBs populated by stars of approximately the same mass



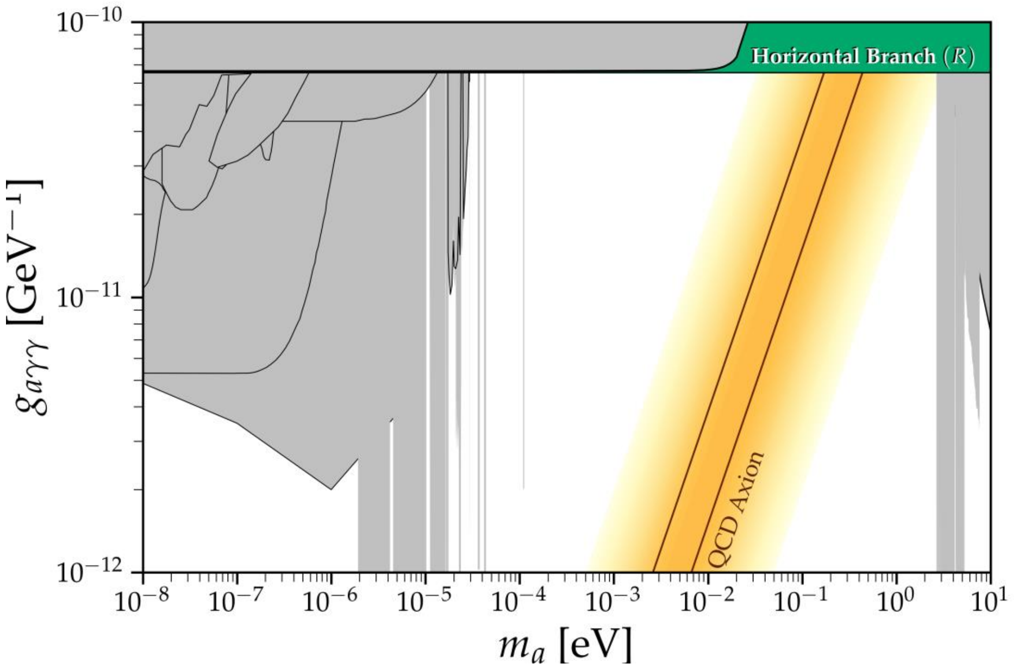
# $R$-parameter constraint

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

- ***R*-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

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

Globular cluster HB and RGBs populated by stars of approximately the same mass



# $R$-parameter constraint

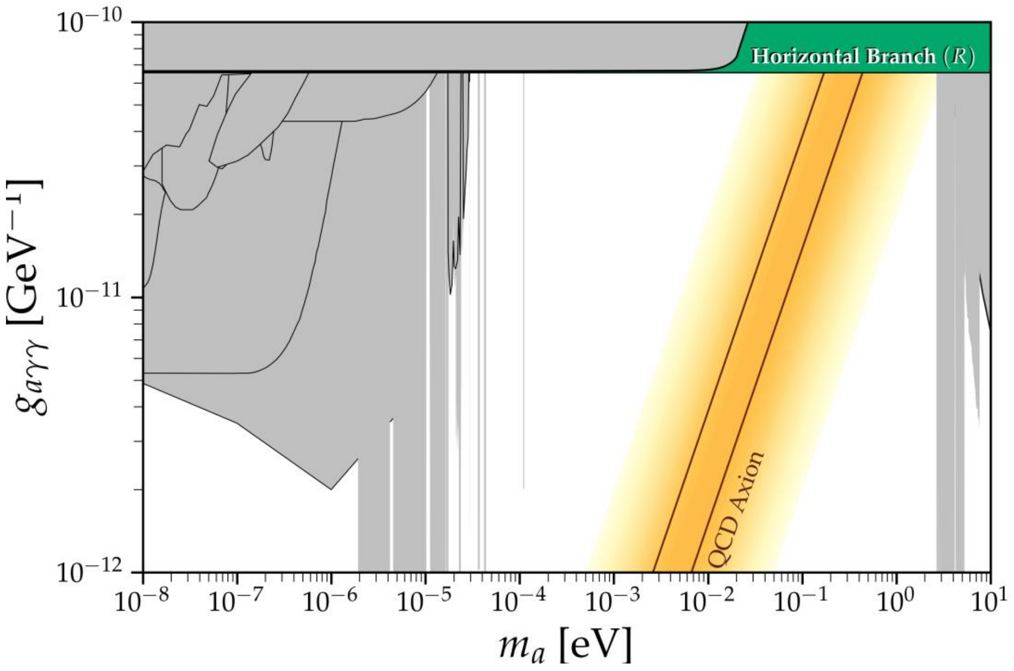
Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

- **$R$-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

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

↓ as $g_{a\gamma\gamma}$ increases

Globular cluster HB and RGBs populated by stars of approximately the same mass



# $R$-parameter constraint

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

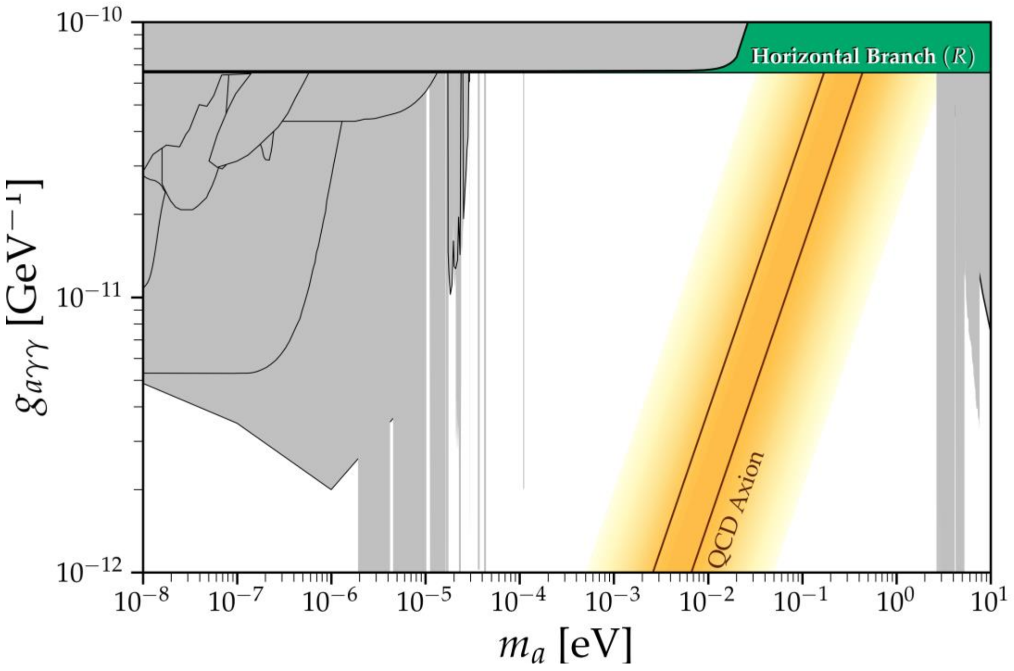
- **$R$-parameter:** the ratio of horizontal branch (HB) to red giant branch (RGB) stars in globular clusters

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

$\tau_{\rm HB}$: ↓ as $g_{a\gamma\gamma}$ increases

$\tau_{\rm RGB}$: insensitive to $g_{a\gamma\gamma}$

↑ Globular cluster HB and RGBs populated by stars of approximately the same mass



# $R$-parameter constraint

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

- **$R$-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

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

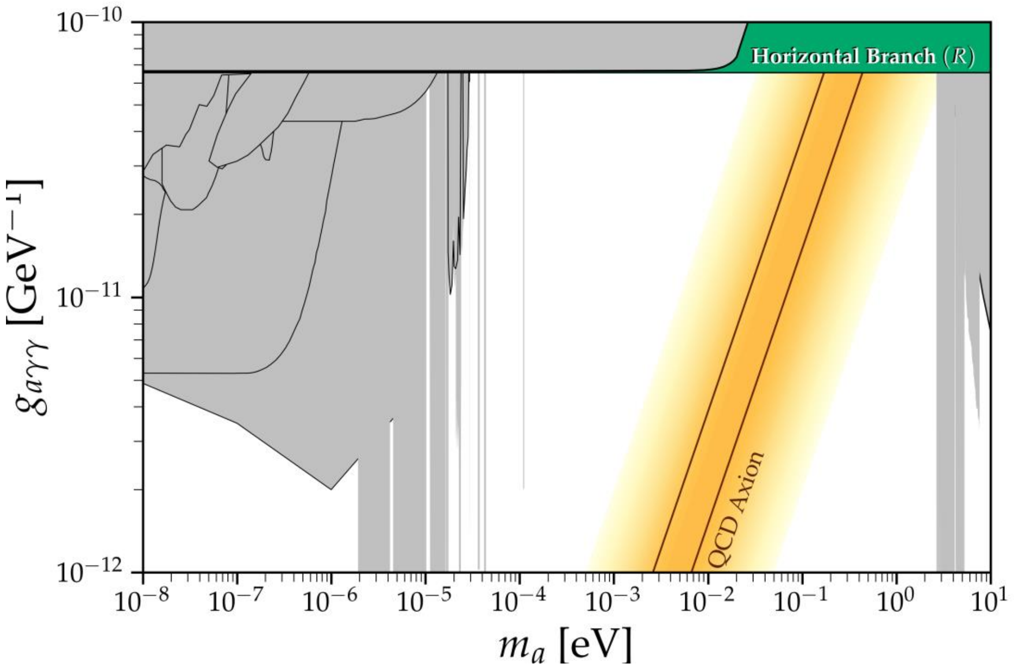
$\tau_{\rm HB}$: ↓ as $g_{a\gamma\gamma}$ increases

$\tau_{\rm RGB}$: insensitive to $g_{a\gamma\gamma}$

Globular cluster HB and RGBs populated by stars of approximately the same mass

- Increasing $g_{a\gamma\gamma}$ reduces $R$ until it can be excluded at $g_{10} = \frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}} = 0.66$

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



# $R$-parameter constraint

THE UNIVERSITY OF MELBOURNE

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

- **$R$-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

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

↓ as $g_{a\gamma\gamma}$ increases

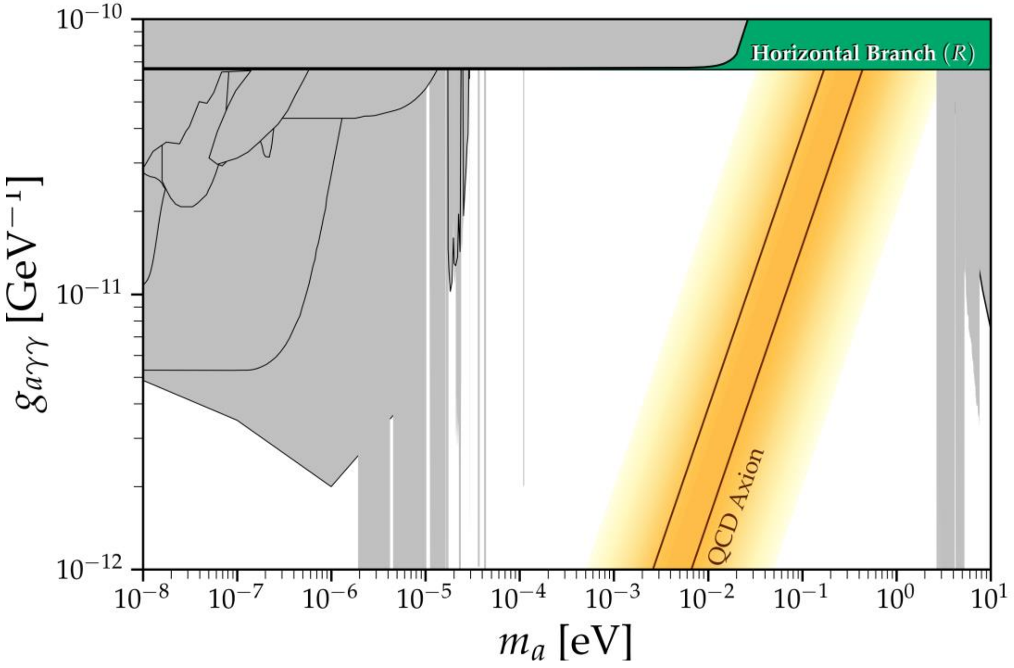
insensitive to $g_{a\gamma\gamma}$

Globular cluster HB and RGBs populated by stars of approximately the same mass

- Increasing $g_{a\gamma\gamma}$ reduces $R$ until it can be excluded at $g_{10} = \frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}} = 0.66$

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

ISSUE



# $R$-parameter constraint

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

***R*-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

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

$\tau_{\mathrm{HB}}$: ↓ as $g_{a\gamma\gamma}$ increases

$\tau_{\mathrm{RGB}}$: insensitive to $g_{a\gamma\gamma}$

↑ Globular cluster HB and RGBs populated by stars of approximately the same mass

Increasing $g_{a\gamma\gamma}$ reduces $R$ until it can be excluded at $g_{10} = \frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}} = 0.66$

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

ISSUE

Predictions for $\tau_{HB}$ suffer from large stochastic + systematic uncertainty

# $R$-parameter constraint

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

***R*-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

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

↓ as $g_{a\gamma\gamma}$ increases

insensitive to $g_{a\gamma\gamma}$

Globular cluster HB and RGBs populated by stars of approximately the same mass

Increasing $g_{a\gamma\gamma}$ reduces $R$ until it can be excluded at

$g_{10} = \frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}} = 0.66$

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

ISSUE

Predictions for $\tau_{HB}$ suffer from large stochastic + systematic uncertainty

Caused by **mixing** of helium-burning products across convective core boundary

# $R$-parameter constraint

THE UNIVERSITY OF MELBOURNE

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

**$R$-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

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

$\tau_{\rm HB}$: ↓ as $g_{a\gamma\gamma}$ increases

$\tau_{\rm RGB}$: insensitive to $g_{a\gamma\gamma}$

↑ Globular cluster HB and RGBs populated by stars of approximately the same mass

Increasing $g_{a\gamma\gamma}$ reduces $R$ until it can be excluded at

$$g_{10} = \frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}} = 0.66$$

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

ISSUE

Predictions for $\tau_{HB}$ suffer from large stochastic + systematic uncertainty

Caused by **mixing** of helium-burning products across convective core boundary

Mixing is a physical necessity – convective elements arrive at boundary with non-zero momentum

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# $R$-parameter constraint

THE UNIVERSITY OF MELBOURNE

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

***R*-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

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

$\tau_{\mathrm{HB}}$: ↓ as $g_{a\gamma\gamma}$ increases

$\tau_{\mathrm{RGB}}$: insensitive to $g_{a\gamma\gamma}$

↑ Globular cluster HB and RGBs populated by stars of approximately the same mass

Increasing $g_{a\gamma\gamma}$ reduces $R$ until it can be excluded at

$$g_{10} = \frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}} = 0.66$$

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

ISSUE

Predictions for $\tau_{HB}$ suffer from large stochastic + systematic uncertainty

Caused by **mixing** of helium-burning products across convective core boundary

Mixing is a physical necessity – convective elements arrive at boundary with non-zero momentum

Widely acknowledged in astrophysical literature – not included in previous stellar cooling bounds

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# $R$-parameter constraint

Historically, the *gold standard* stellar cooling limit on $g_{a\gamma\gamma}$ is the $R$-parameter constraint

**$R$-parameter:** the ratio of **horizontal branch (HB)** to **red giant branch (RGB)** stars in globular clusters

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

$\tau_{\rm HB}$: ↓ as $g_{a\gamma\gamma}$ increases

$\tau_{\rm RGB}$: insensitive to $g_{a\gamma\gamma}$

Globular cluster HB and RGBs populated by stars of approximately the same mass

Increasing $g_{a\gamma\gamma}$ reduces $R$ until it can be excluded at

$$g_{10} = \frac{g_{a\gamma\gamma}}{10^{-10}\ GeV^{-1}} = 0.66$$

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

ISSUE

Predictions for $\tau_{HB}$ suffer from large stochastic + systematic uncertainty

Caused by **mixing** of helium-burning products across convective core boundary

Mixing is a physical necessity – convective elements arrive at boundary with non-zero momentum

Widely acknowledged in astrophysical literature – not included in previous stellar cooling bounds

Helpful to see this in action…

# Example

# Example

**Example scheme:** *standard overshoot*

- Time-dependent diffusive process
- Diffusion coefficients decrease exponentially with distance from the convective boundary
- Scale of exponential decrease set by free parameter $f_{ov}$

# Example

**Example scheme:** *standard overshoot*

- Time-dependent diffusive process
- Diffusion coefficients decrease exponentially with distance from the convective boundary
- Scale of exponential decrease set by free parameter $f_{ov}$

Simulate the HB

- Location of the boundary is unstable
- Can spark dramatic **core breathing pulses** - large convective episodes which extend HB duration

# Example

**Example scheme:** *standard overshoot*

- Time-dependent diffusive process
- Diffusion coefficients decrease exponentially with distance from the convective boundary
- Scale of exponential decrease set by free parameter $f_{ov}$

Simulate the HB

- Location of the boundary is unstable
- Can spark dramatic **core breathing pulses -** large convective episodes which extend HB duration

NOT COMPUTATIONALLY STABLE

# Example

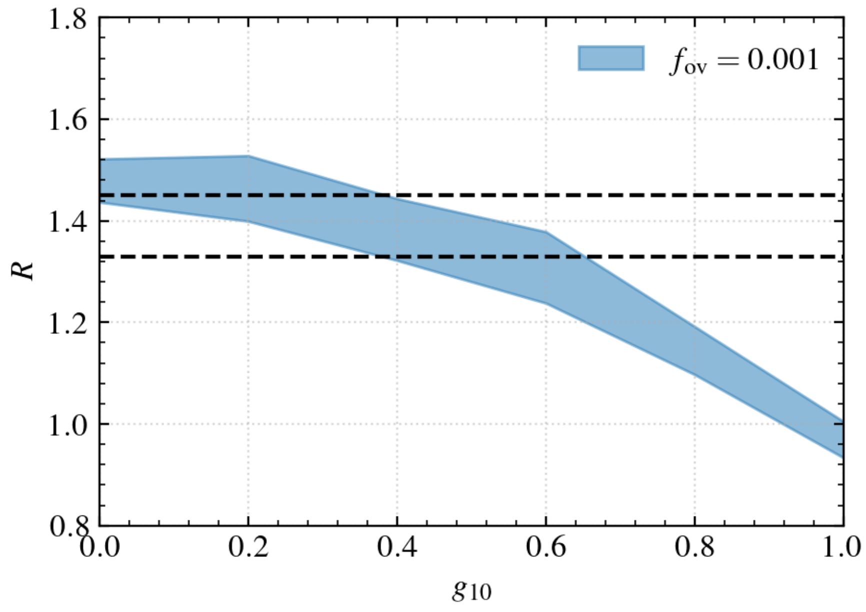
**Example scheme:** *standard overshoot*

- Time-dependent diffusive process
- Diffusion coefficients decrease exponentially with distance from the convective boundary
- Scale of exponential decrease set by free parameter $f_{ov}$

Simulate the HB

- Location of the boundary is unstable
- Can spark dramatic **core breathing pulses -** large convective episodes which extend HB duration

NOT COMPUTATI STAB




Source of stochastic variation in predictions of $R$ – examine in MESA

# Example

**Example scheme:** *standard overshoot*

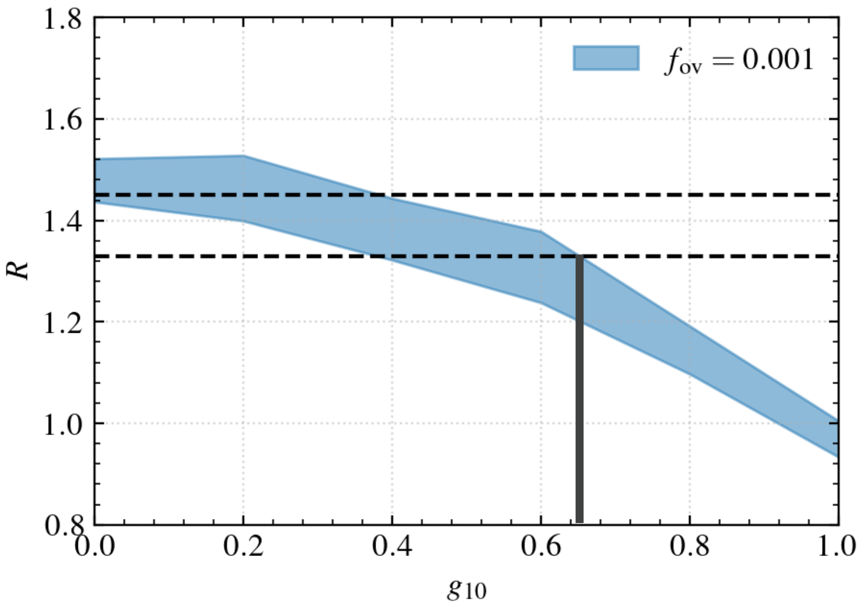
- Time-dependent diffusive process
- Diffusion coefficients decrease exponentially with distance from the convective boundary
- Scale of exponential decrease set by free parameter $f_{ov}$

Simulate the HB

- Location of the boundary is unstable
- Can spark dramatic **core breathing pulses -** large convective episodes which extend HB duration

NOT COMPUTATI STAB

Source of stochastic variation in predictions of $R$ – examine in MESA




Can only constrain when entire range falls below 95% CL

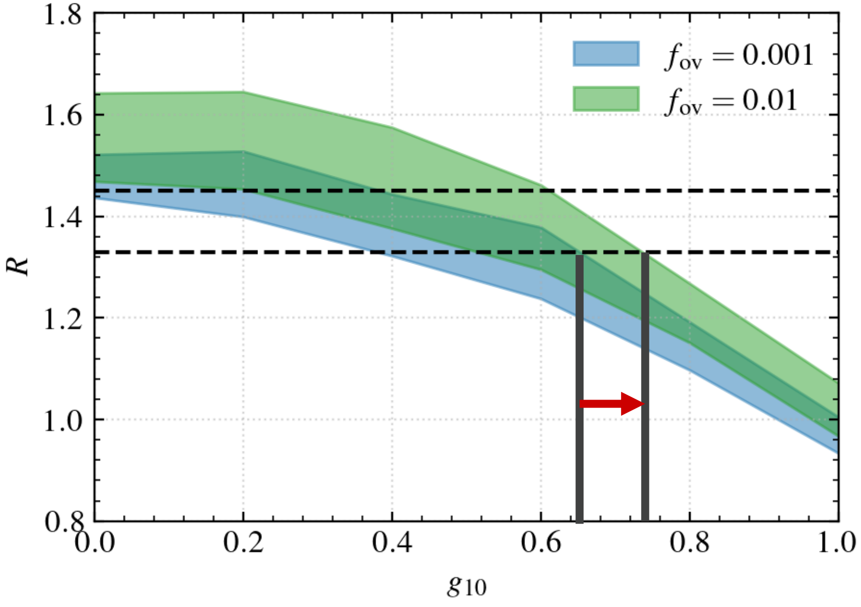
# Example

**Example scheme:** *standard overshoot*

- Time-dependent diffusive process
- Diffusion coefficients decrease exponentially with distance from the convective boundary
- Scale of exponential decrease set by free parameter $f_{ov}$

Simulate the HB

- Location of the boundary is unstable
- Can spark dramatic **core breathing pulses** - large convective episodes which extend HB duration


Source of stochastic variation in predictions of $R$ – examine in MESA

Choice of $f_{ov}$ systematically shifts $R$

Can only constrain when entire range falls below 95% CL

Which value of $f_{ov}$ do we take?

# Advancing globular cluster constraints on the axion-photon coupling

# The $R_2$-parameter

Other globular cluster parameters exist which can provide complementary constraints on $g_{a\gamma\gamma}$

# The $R_2$-parameter

Other globular cluster parameters exist which can provide complementary constraints on $g_{a\gamma\gamma}$

The ratio of AGB to HB stars – the $R_2$-parameter – is a particularly appealing candidate for this

$$R_2 = \frac{N_{\mathrm{AGB}}}{N_{\mathrm{HB}}} \sim \frac{\tau_{\mathrm{AGB}}}{\tau_{\mathrm{HB}}}$$

# The $R_2$-parameter

Other globular cluster parameters exist which can provide complementary constraints on $g_{a\gamma\gamma}$

The ratio of AGB to HB stars – the $R_2$-parameter – is a particularly appealing candidate for this

$$R_2 = \frac{N_{\mathrm{AGB}}}{N_{\mathrm{HB}}} \sim \frac{\tau_{\mathrm{AGB}}}{\tau_{\mathrm{HB}}}$$

AGB helium-burning shell is more sensitive to axion energy-loss ($\sim T^7/\rho$) than HB core. Possible to decrease $\tau_{AGB}$, but not $\tau_{HB}$

Dominguez et al., *MNRAS* **456** (1999) L1

# The $R_2$-parameter

Other globular cluster parameters exist which can provide complementary constraints on $g_{a\gamma\gamma}$

The ratio of AGB to HB stars – the $R_2$-parameter – is a particularly appealing candidate for this

$$R_2 = \frac{N_{\mathrm{AGB}}}{N_{\mathrm{HB}}} \sim \frac{\tau_{\mathrm{AGB}}}{\tau_{\mathrm{HB}}}$$

AGB helium-burning shell is more sensitive to axion energy-loss ($\sim T^7/\rho$) than HB core. Possible to decrease $\tau_{AGB}$, but not $\tau_{HB}$

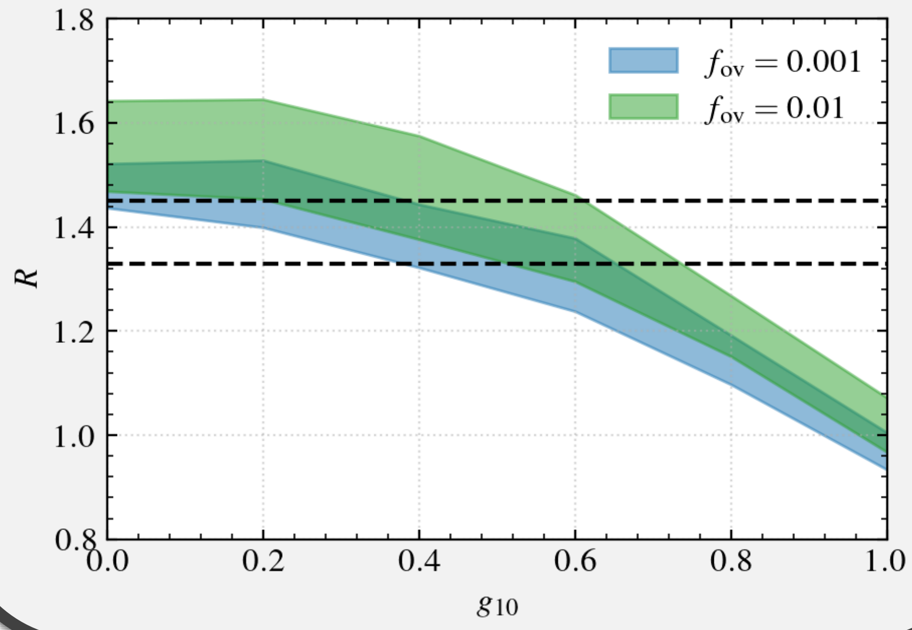
Dominguez et al., *MNRAS* **456** (1999) L1

Historically used to constrain the effects of mixing across convective boundaries

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

# Comparing $R$ and $R_2$

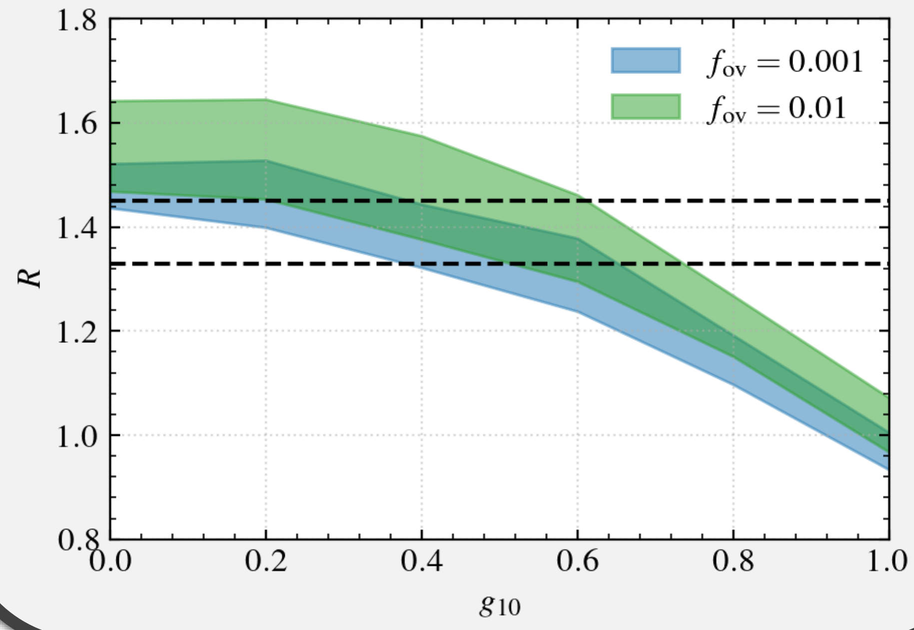
$R$



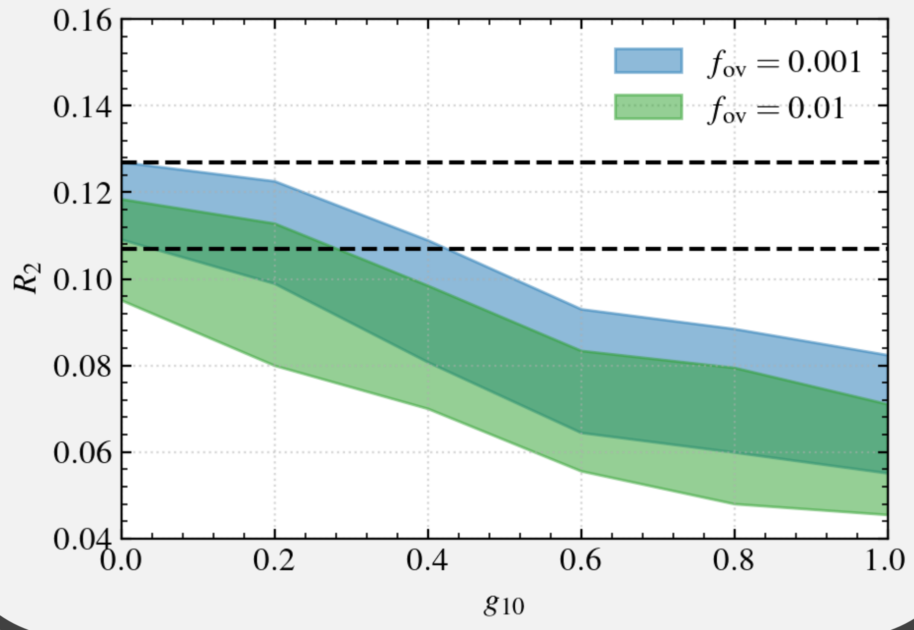

$R_2$

# Comparing $R$ and $R_2$

$R$

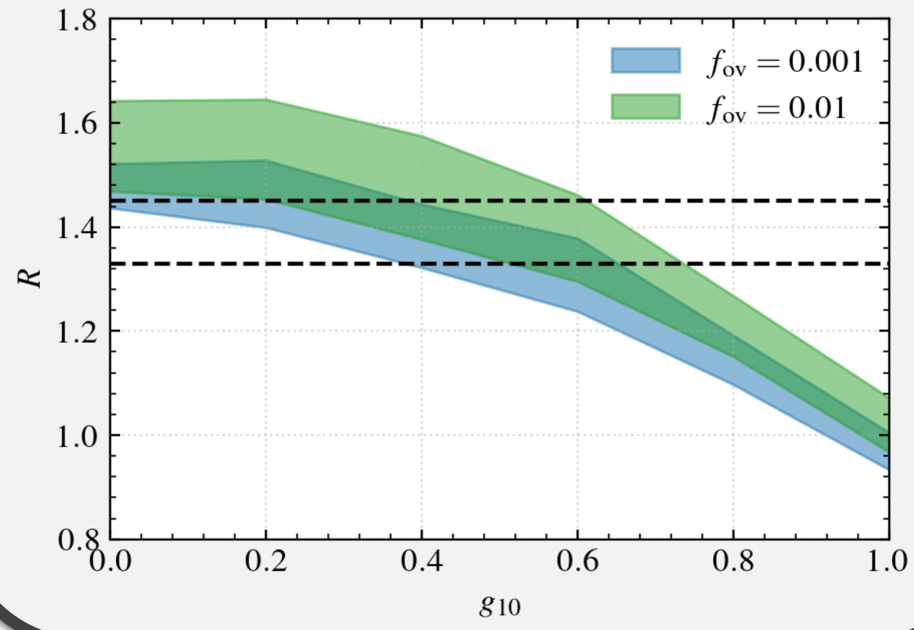



$R_2$

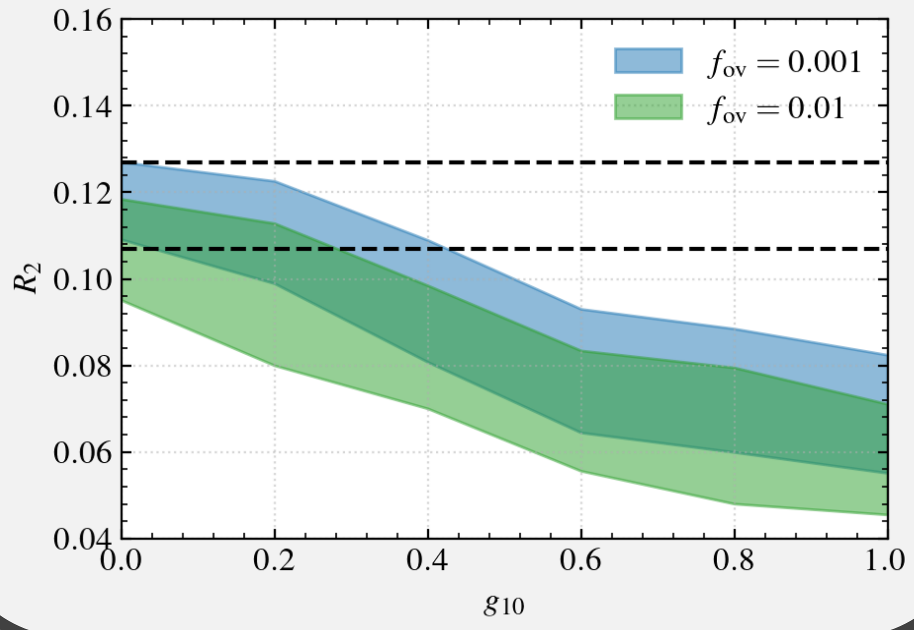


# Comparing $R$ and $R_2$

## $R$




## $R_2$

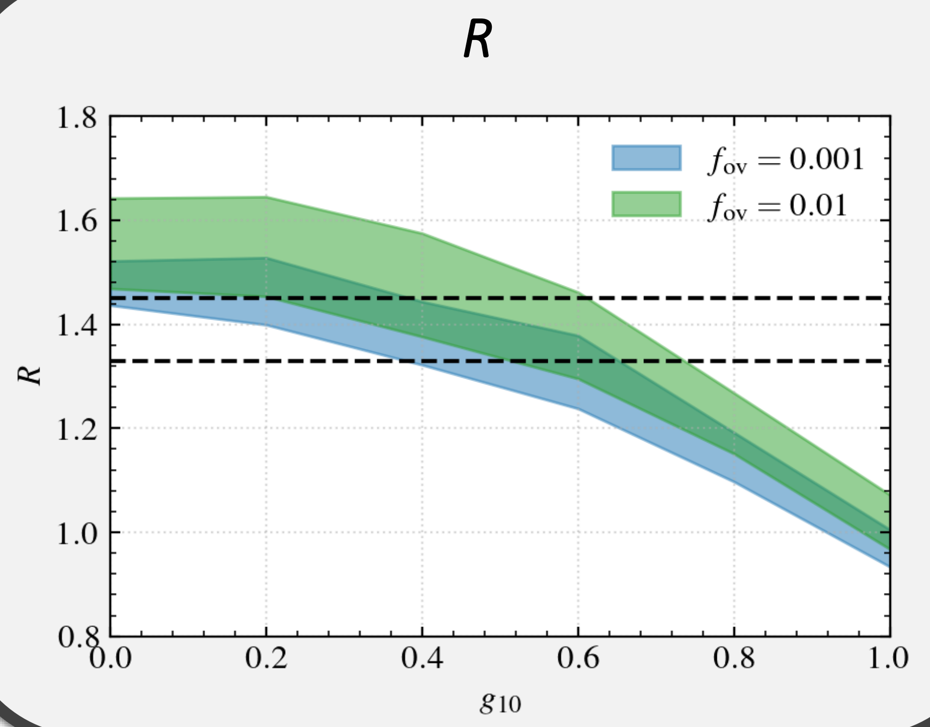


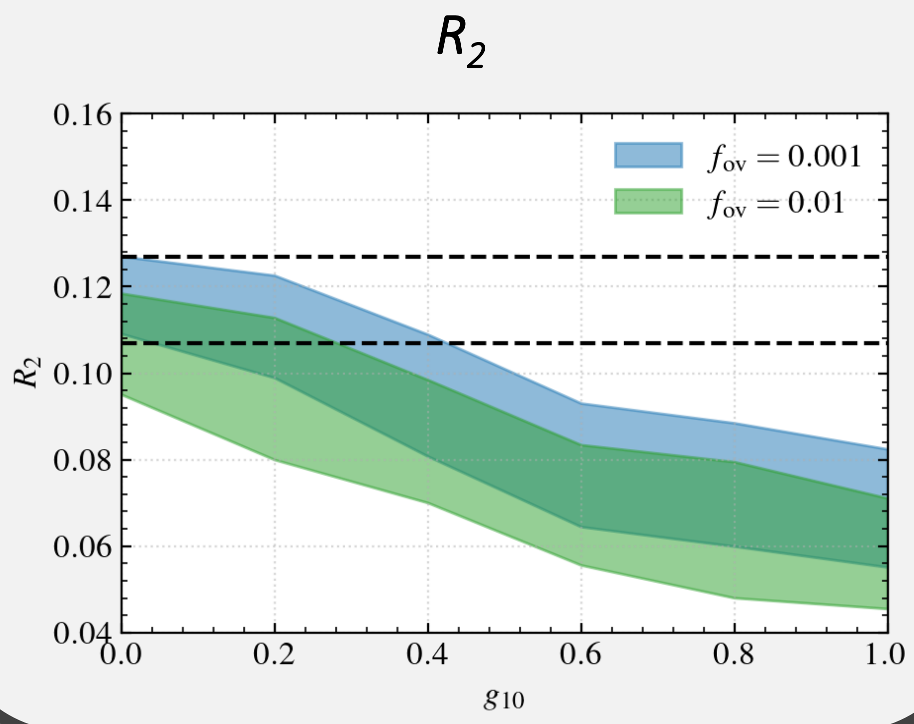

Convective boundary model parameter(s) affect constraints oppositely

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF MELBOURNE

# Comparing $R$ and $R_2$



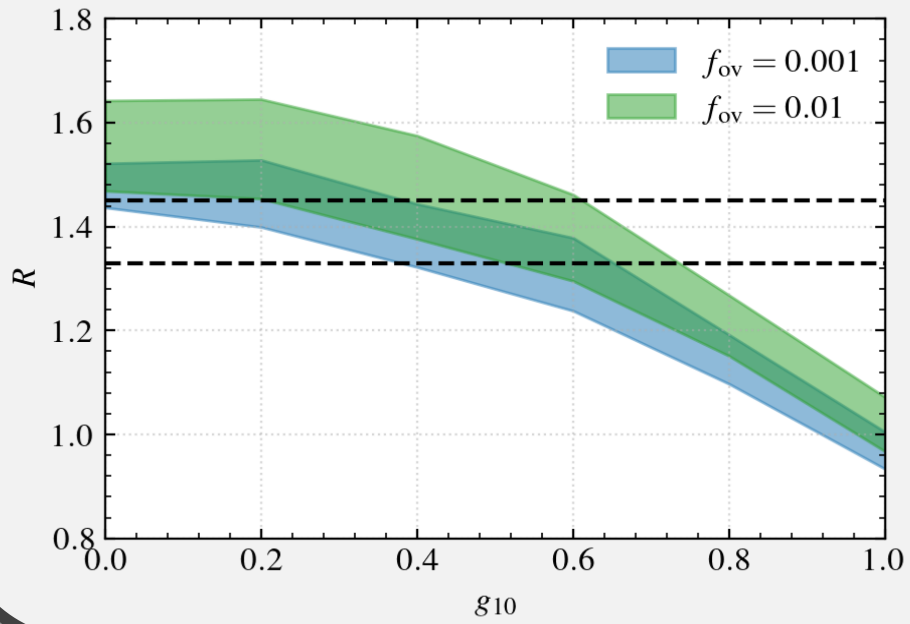




Convective boundary model parameter(s) affect constraints oppositely

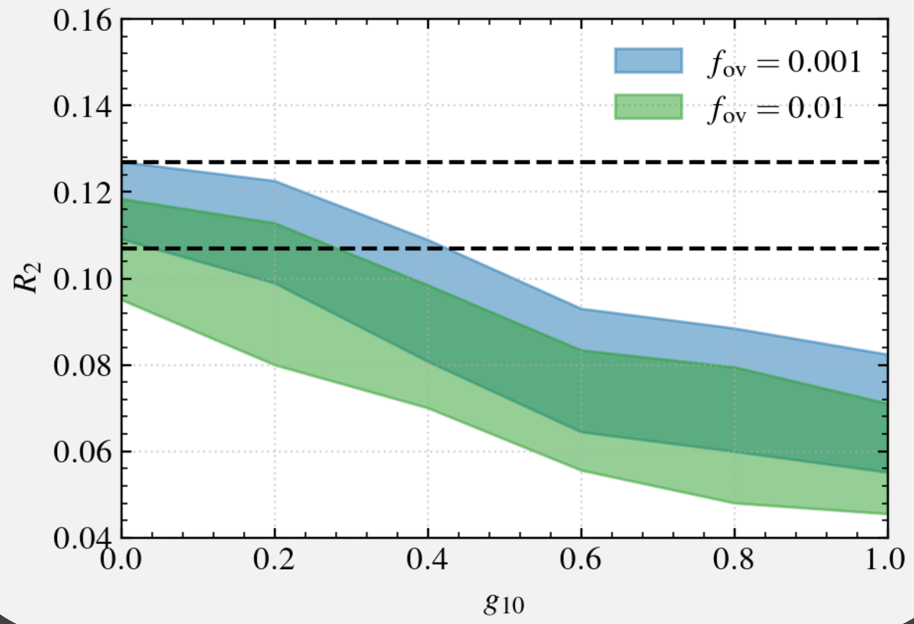
Both $R$ and $R_2$ decrease with $g_{10}$.

# Comparing $R$ and $R_2$

$R$




$R_2$



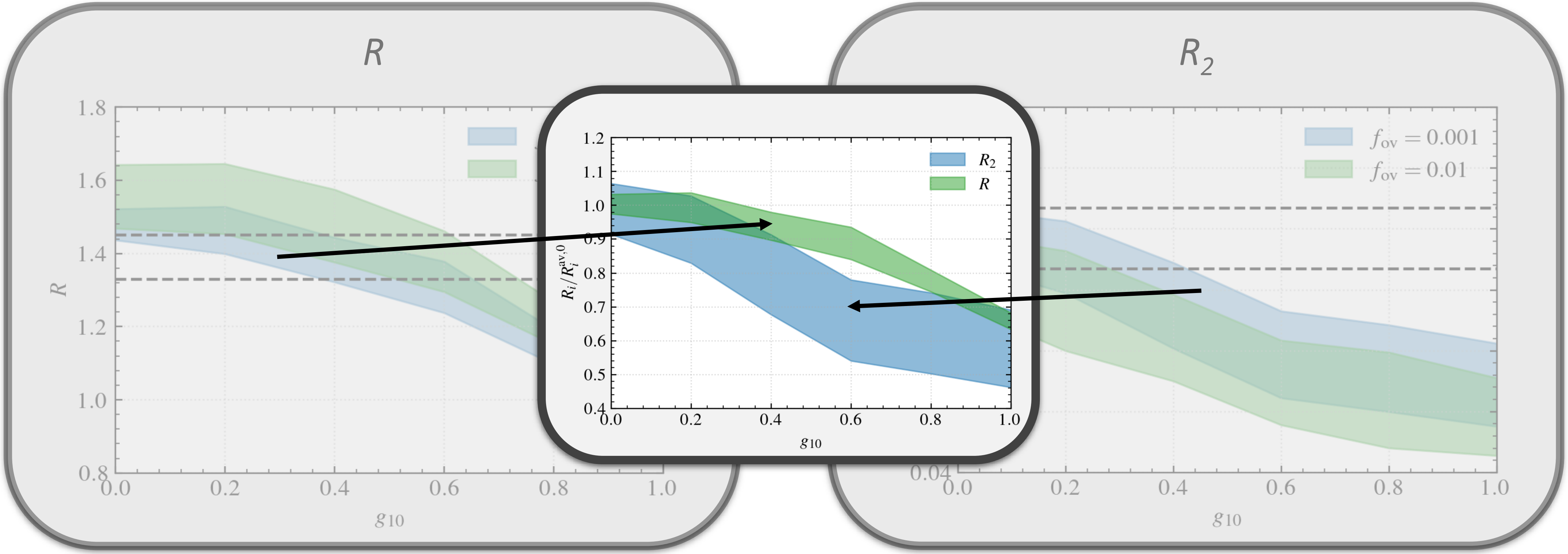

Convective boundary model parameter(s) affect constraints oppositely

Both $R$ and $R_2$ decrease with $g_{10}$.

$R_2$ more sensitive at low values of $g_{10}$

# Comparing $R$ and $R_2$

THE UNIVERSITY OF MELBOURNE




Convective boundary model parameter(s) affect constraints oppositely

Both $R$ and $R_2$ decrease with $g_{10}$.

$R_2$ more sensitive at low values of $g_{10}$

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# Calculating a robust bound

# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs

# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs

Pick CB scheme and model parameters (e.g. $f_{ov}$)

# Calculating a robust bound

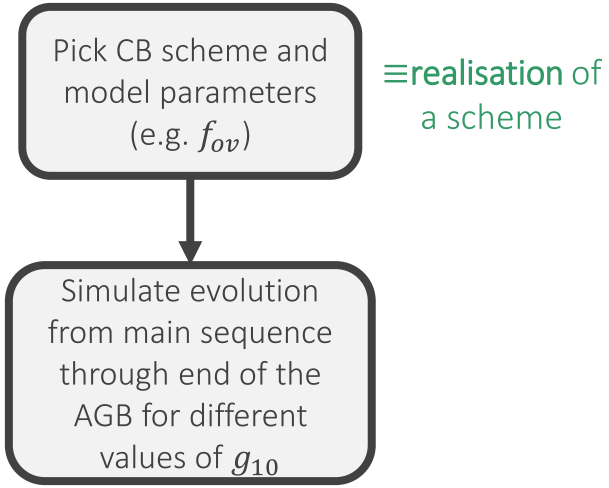
**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs

Pick CB scheme and model parameters (e.g. $f_{ov}$)

≡**realisation** of a scheme

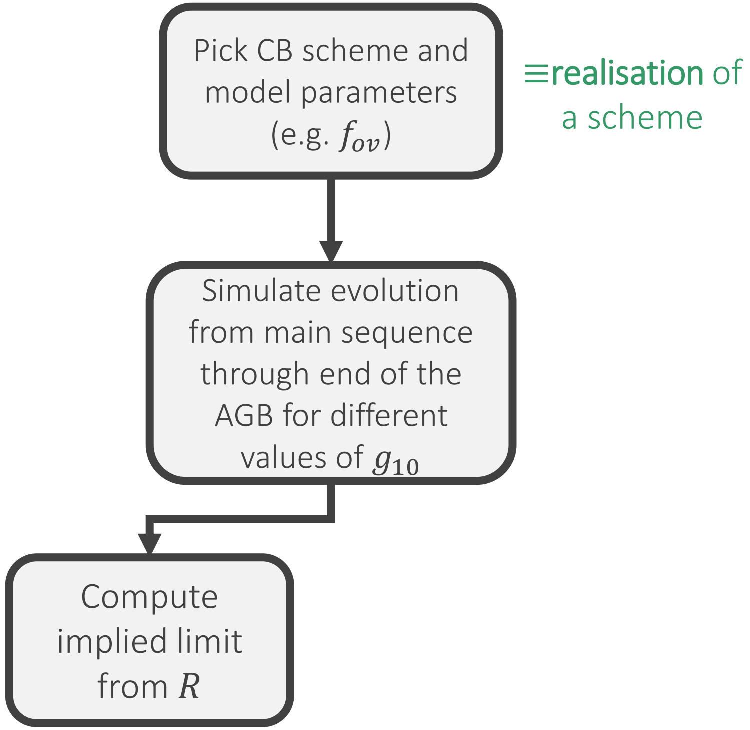
# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs



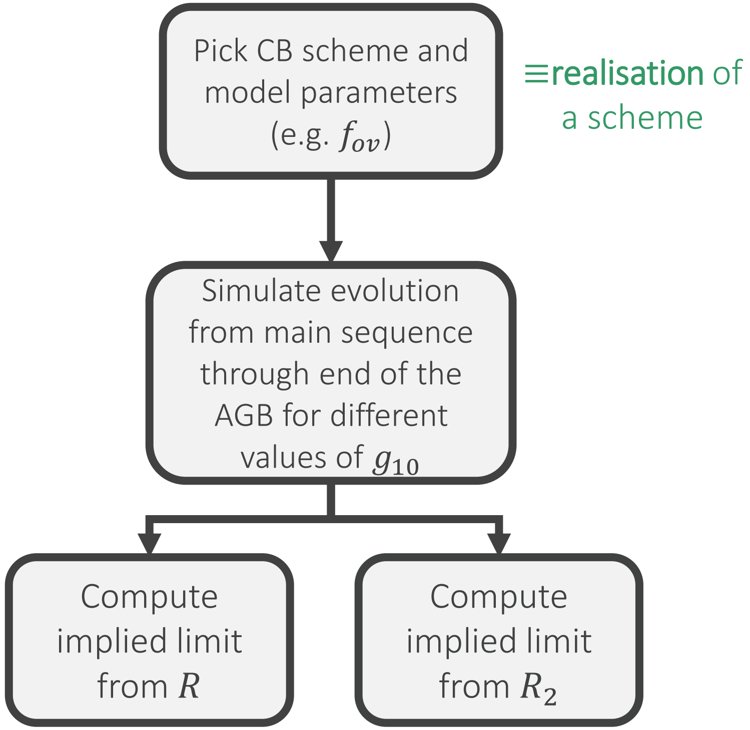
# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs



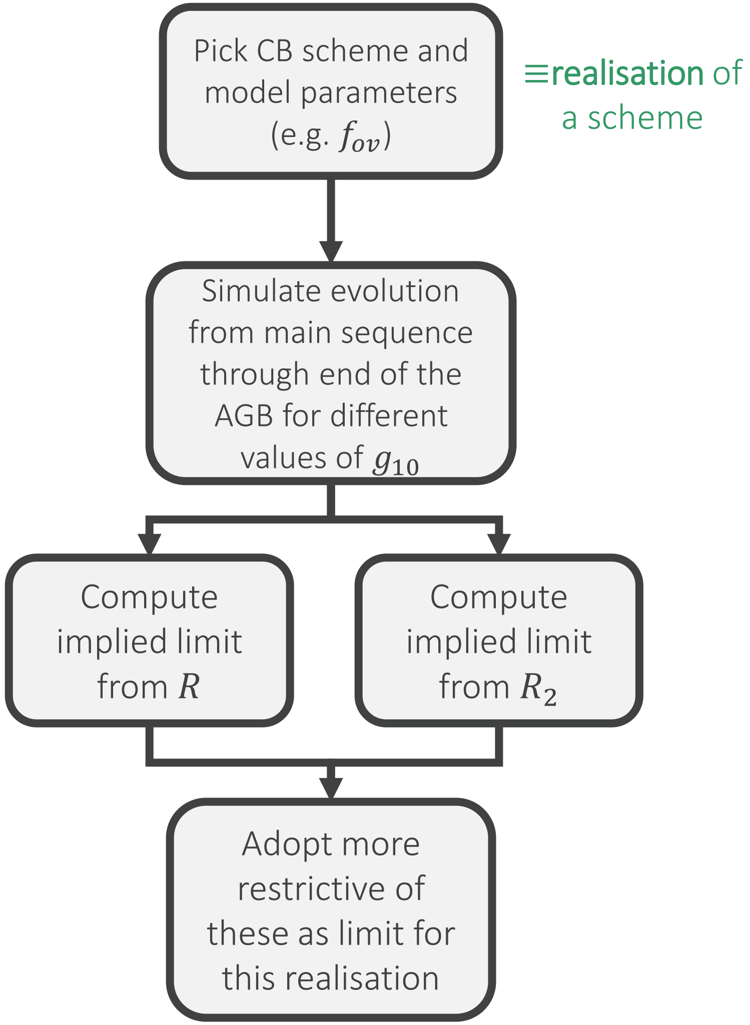
# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs



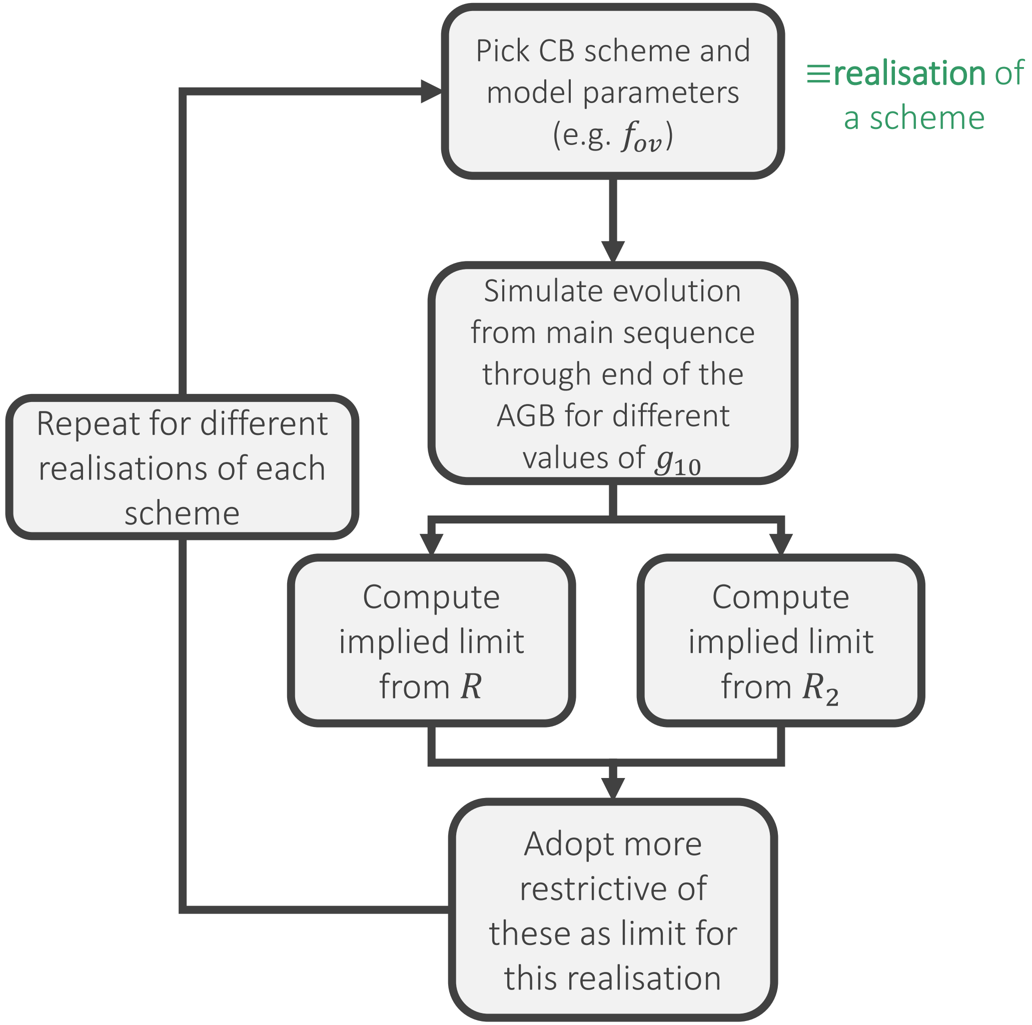
# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs



# Calculating a robust bound

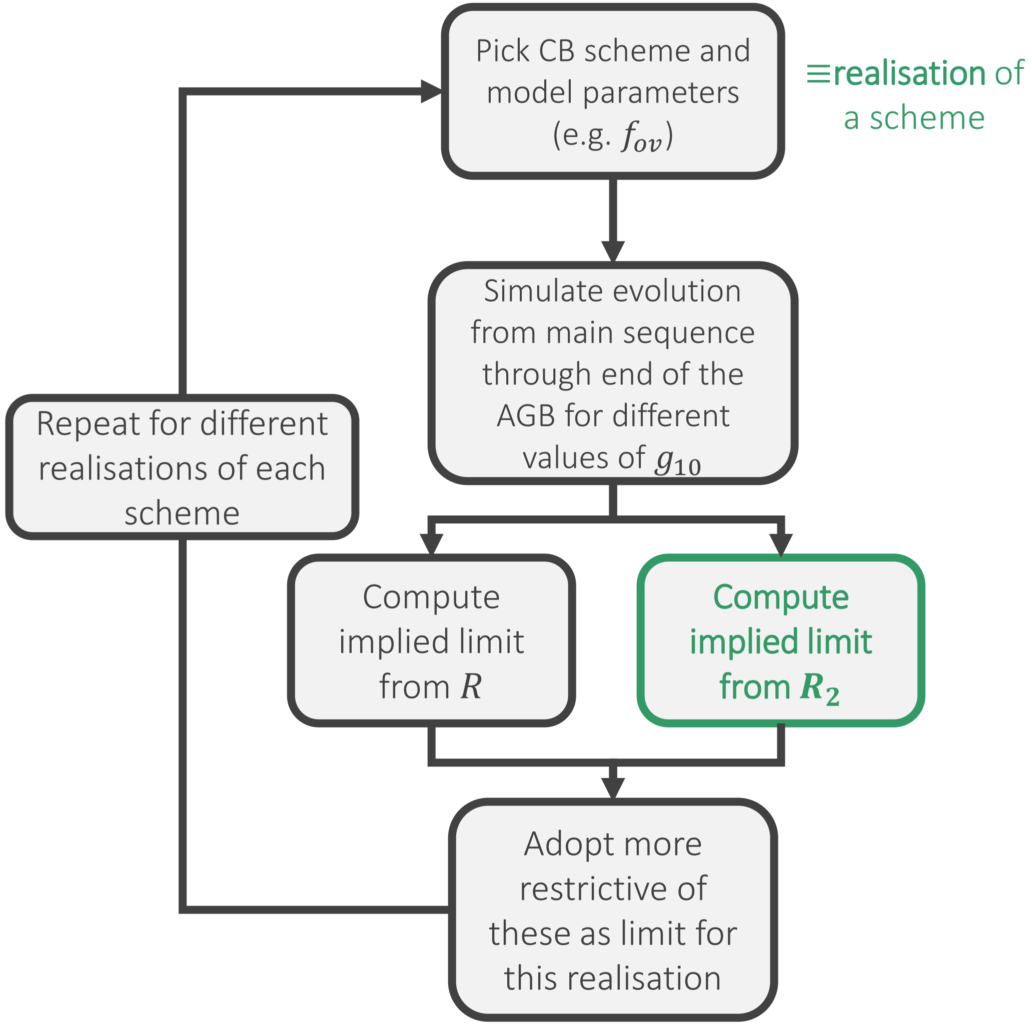
**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs



# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs

$R_2$ is more restrictive in all cases considered

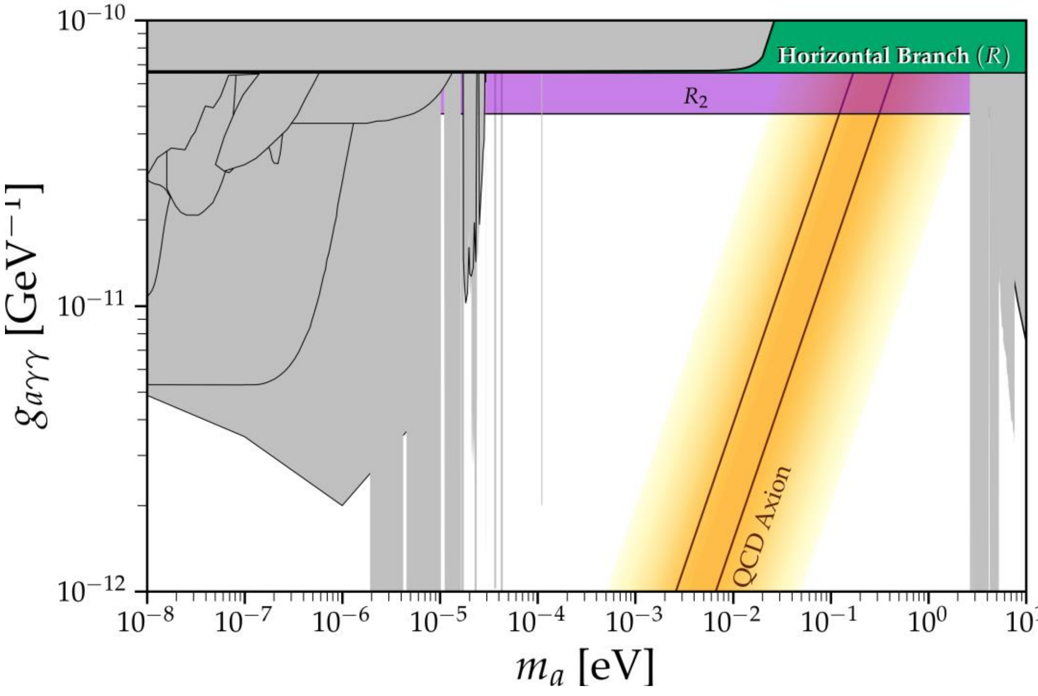


# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs

$R_2$ is more restrictive in all cases considered

Most conservative overall limit $g_{10} \leq 0.47$ – an improvement of 30%



# Calculating a robust bound

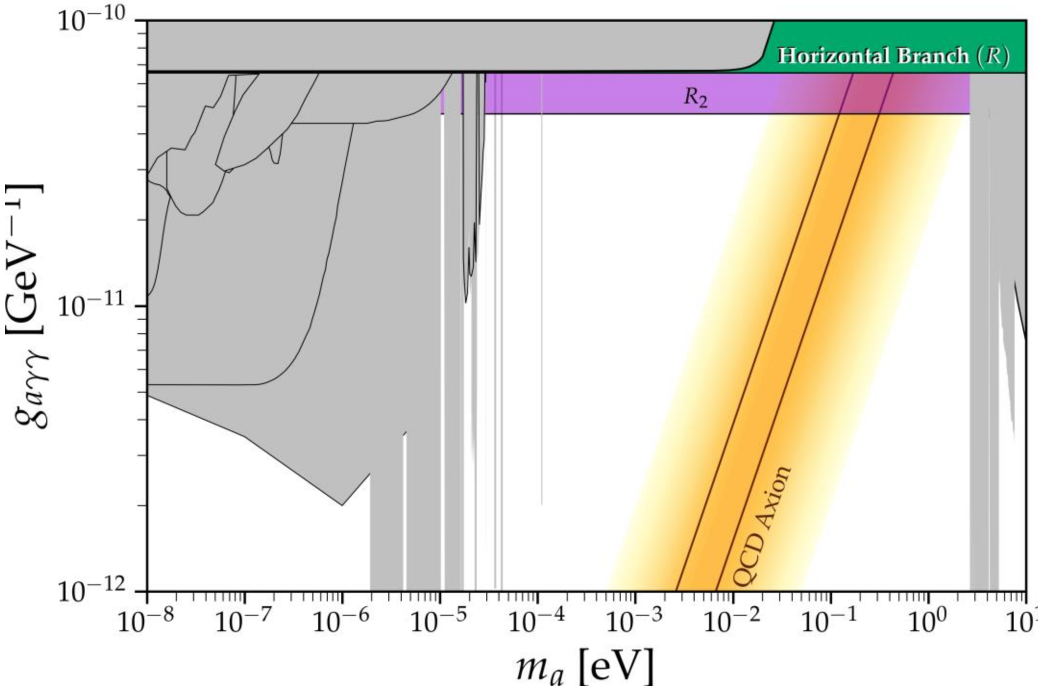
**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs

$R_2$ is more restrictive in all cases considered

Most conservative overall limit $g_{10} \leq 0.47$ – an improvement of 30%

Complementary constraints on HB convective structure from asteroseismology exist

Constantino et al., *MNRAS*, **452** (2015) 123



# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs

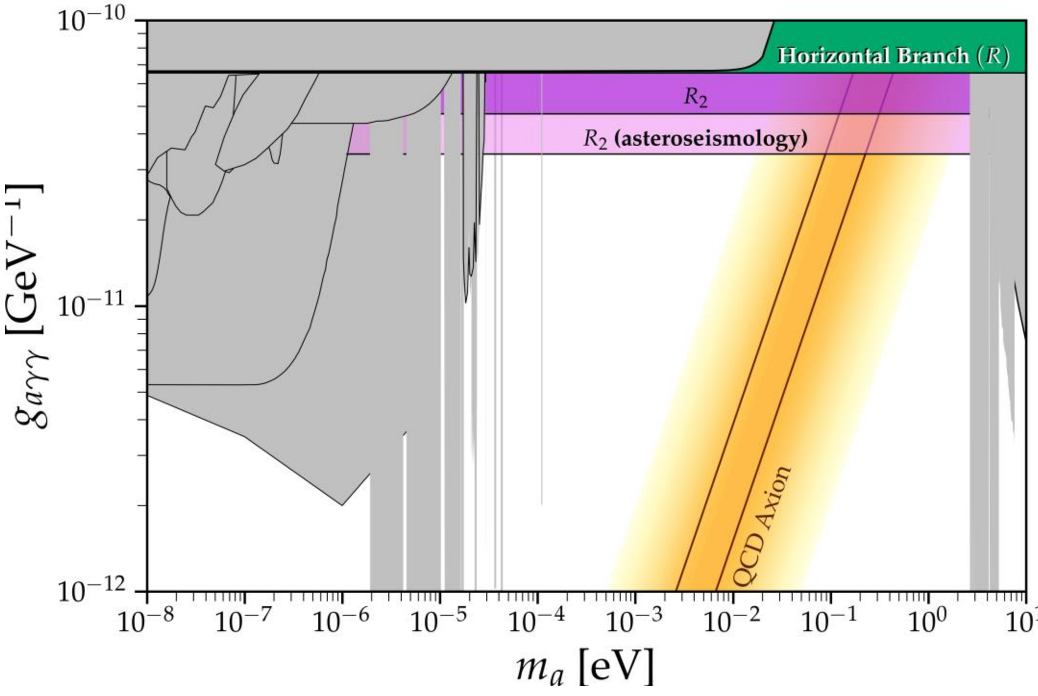
$R_2$ is more restrictive in all cases considered

Most conservative overall limit $g_{10} \leq 0.47$ – an improvement of 30%

Complementary constraints on HB convective structure from asteroseismology exist

Constantino et al., *MNRAS*, **452** (2015) 123

Limits from schemes supported by asteroseismology range between $g_{10} \leq 0.34$ and $g_{10} \leq 0.11$



# Calculating a robust bound

**The goal:** calculate a bound on $g_{10}$ which accounts for the sizeable uncertainty related to mixing across CBs

$R_2$ is more restrictive in all cases considered

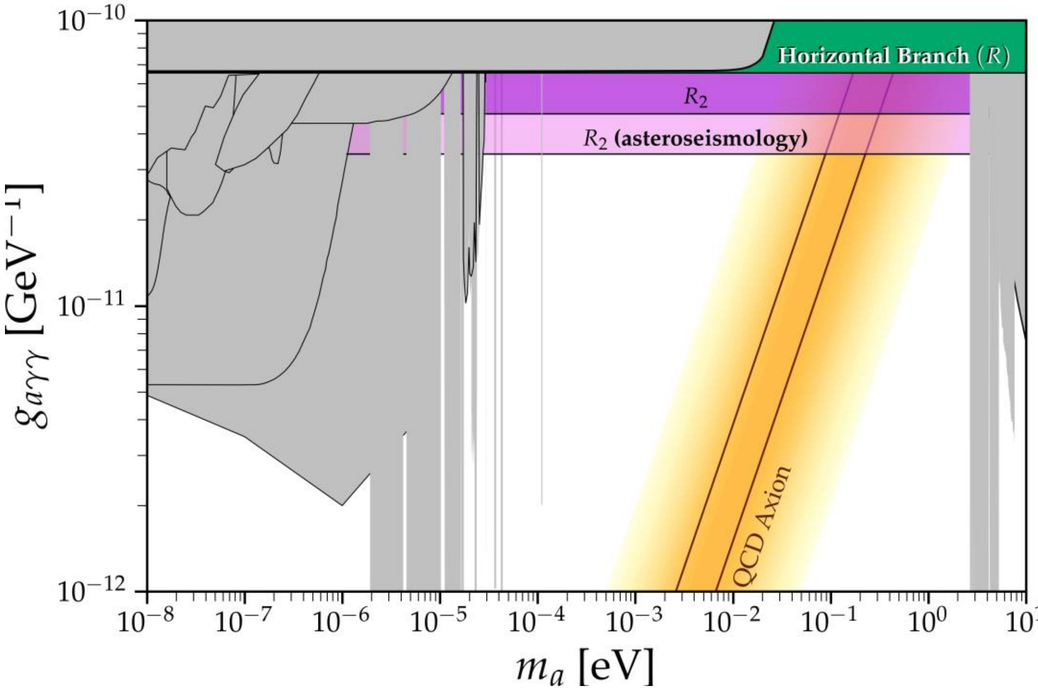
Most conservative overall limit $g_{10} \leq 0.47$ – an improvement of 30%

Complementary constraints on HB convective structure from asteroseismology exist

Constantino et al., *MNRAS*, **452** (2015) 123

Limits from schemes supported by asteroseismology range between $g_{10} \leq 0.34$ and $g_{10} \leq 0.11$

Evidence not yet conclusive…



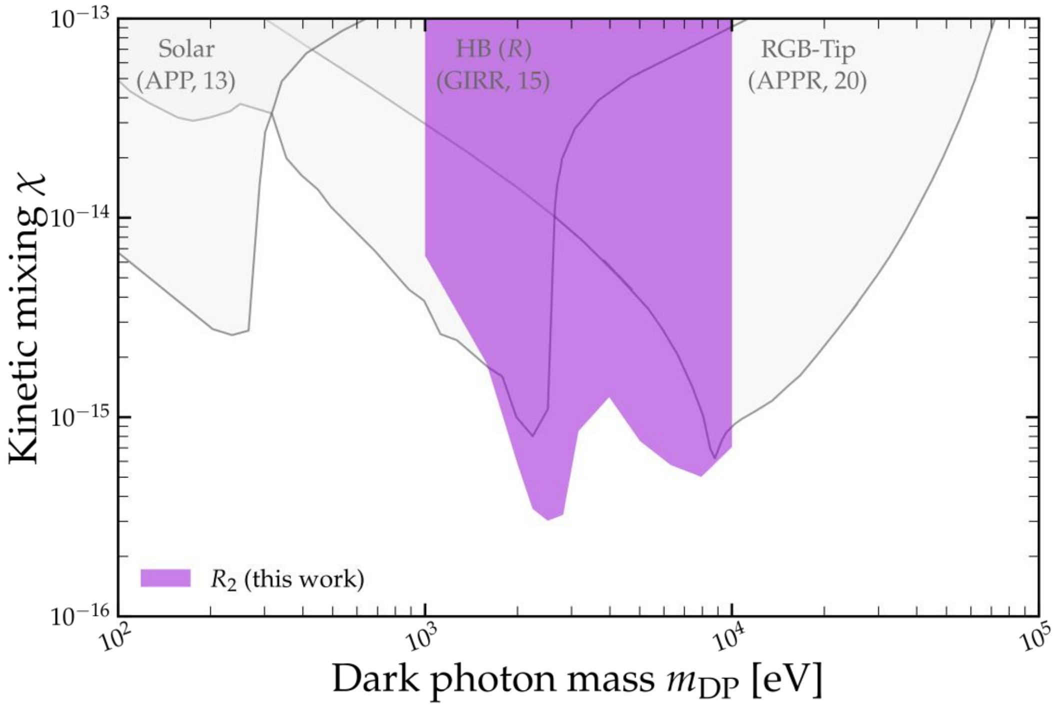
# Other applications of $R_2$

# Other applications of $R_2$

One imagines the limit from $R_2$ could be applied to other light, weakly interacting particles, e.g. dark photons

# Other applications of $R_2$

One imagines the limit from $R_2$ could be applied to other light, weakly interacting particles, e.g. dark photons

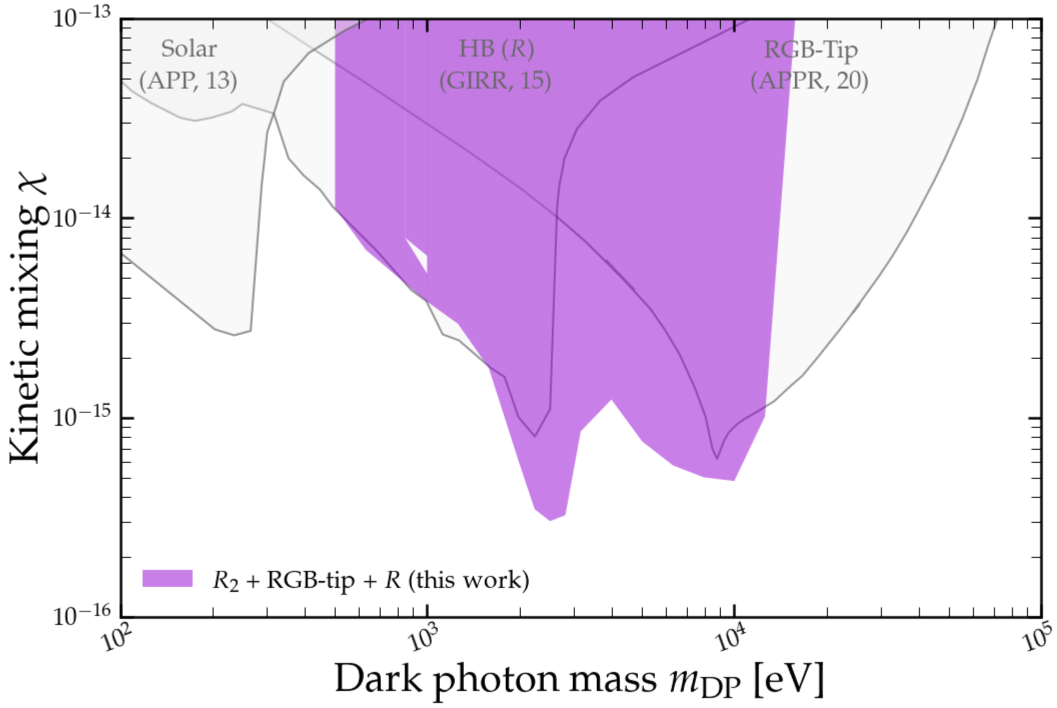



Dolan, FJH, Volkas 2306.13335

# Other applications of $R_2$

One imagines the limit from $R_2$ could be applied to other light, weakly interacting particles, e.g. dark photons

Complement with updated limits from $R$ and the red giant branch tip luminosity



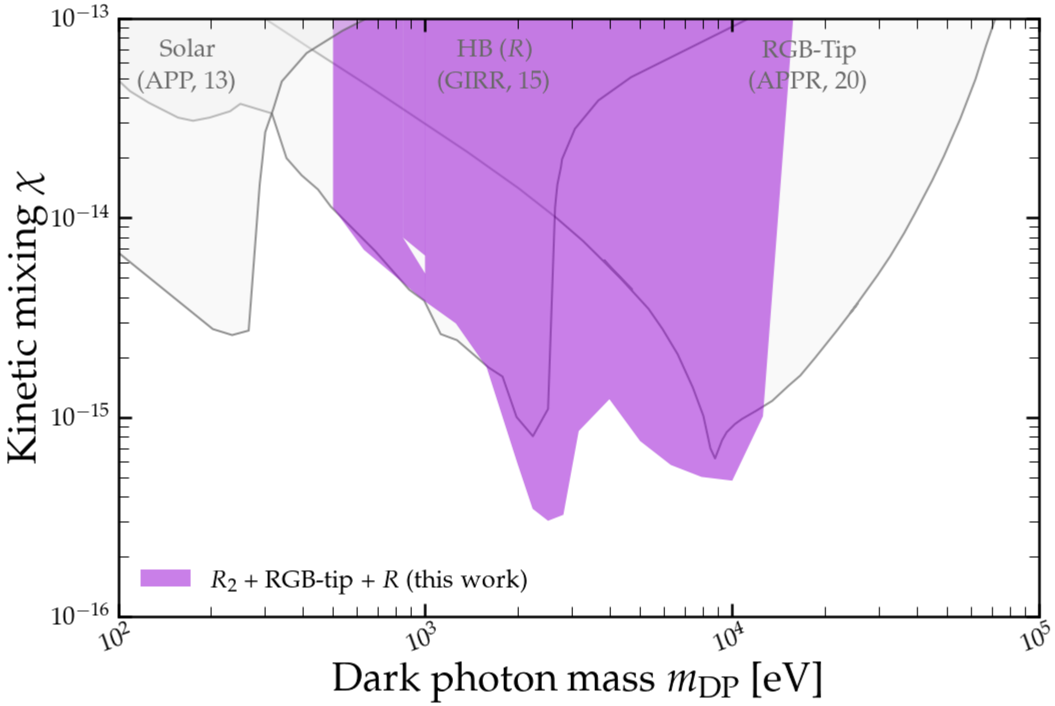

Dolan, FJH, Volkas 2306.13335

# Other applications of $R_2$

One imagines the limit from $R_2$ could be applied to other light, weakly interacting particles, e.g. dark photons

Complement with updated limits from $R$ and the red giant branch tip luminosity

Improve on previous bounds by up to an order of magnitude




Dolan, FJH, Volkas 2306.13335

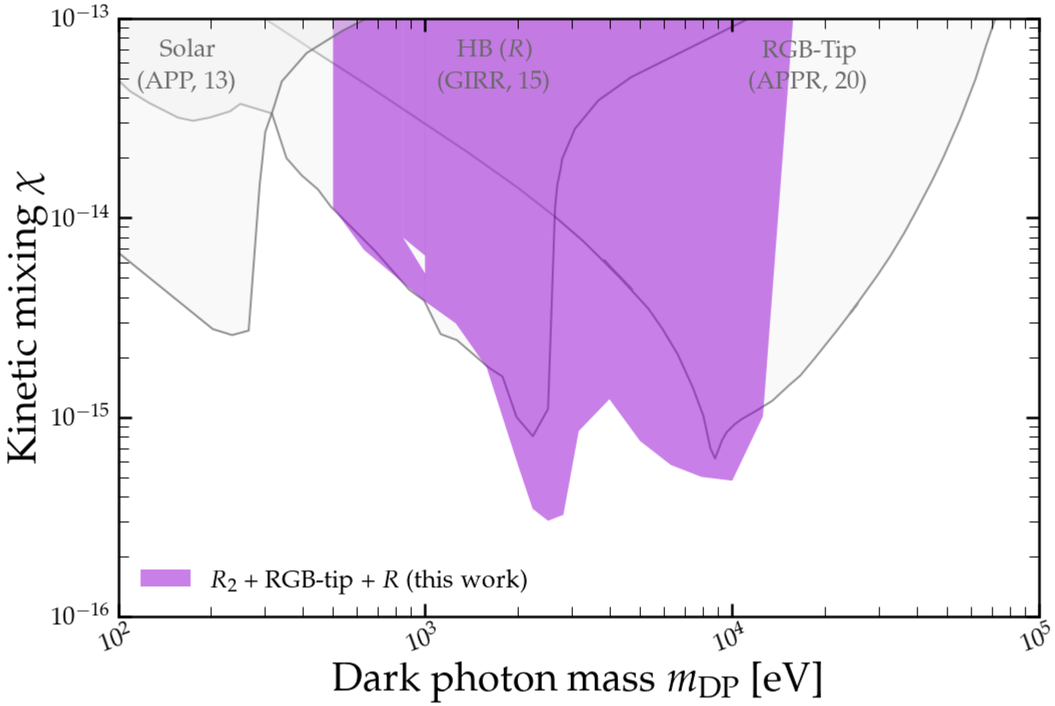
# Other applications of $R_2$

One imagines the limit from $R_2$ could be applied to other light, weakly interacting particles, e.g. dark photons

Complement with updated limits from $R$ and the red giant branch tip luminosity

Improve on previous bounds by up to an order of magnitude

Story is subtle and interesting…




Dolan, FJH, Volkas 2306.13335

# Concluding remarks

# Concluding Remarks

# Concluding Remarks

Observed limits on globular clusters have a strong pedigree for constraining axions

# Concluding Remarks

Observed limits on globular clusters have a strong pedigree for constraining axions

The most restrictive of these, based on the $R$-parameter, neglects sizeable uncertainty from the modelling of mixing across convective boundaries

# Concluding Remarks

Observed limits on globular clusters have a strong pedigree for constraining axions

The most restrictive of these, based on the $R$-parameter, neglects sizeable uncertainty from the modelling of mixing across convective boundaries

Confronting this leads one to consider the ratio of asymptotic giant branch to horizontal branch stars in globular clusters

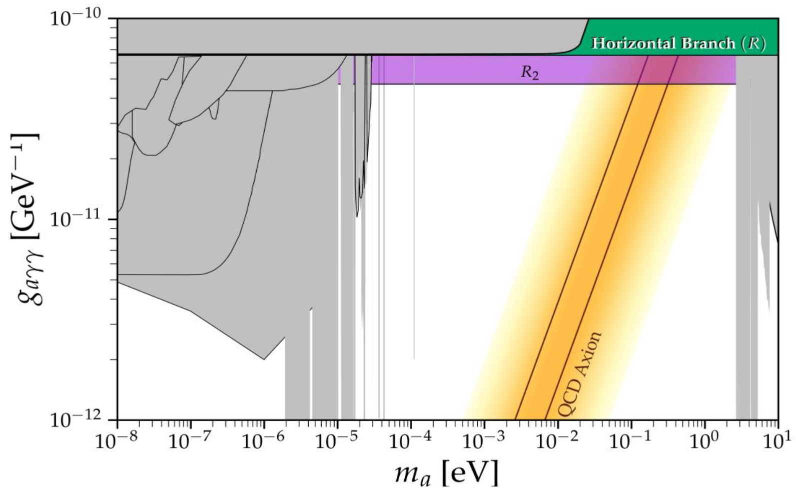
# Concluding Remarks

Observed limits on globular clusters have a strong pedigree for constraining axions

The most restrictive of these, based on the $R$-parameter, neglects sizeable uncertainty from the modelling of mixing across convective boundaries

Confronting this leads one to consider the ratio of asymptotic giant branch to horizontal branch stars in globular clusters

Using $R_2$ we can construct a new and more robust constraint of $g_{10} < 0.47$



# Concluding Remarks

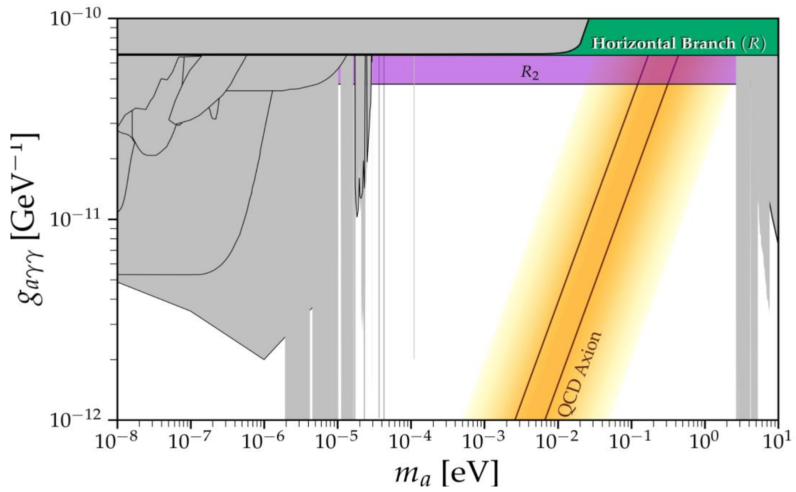
Observed limits on globular clusters have a strong pedigree for constraining axions

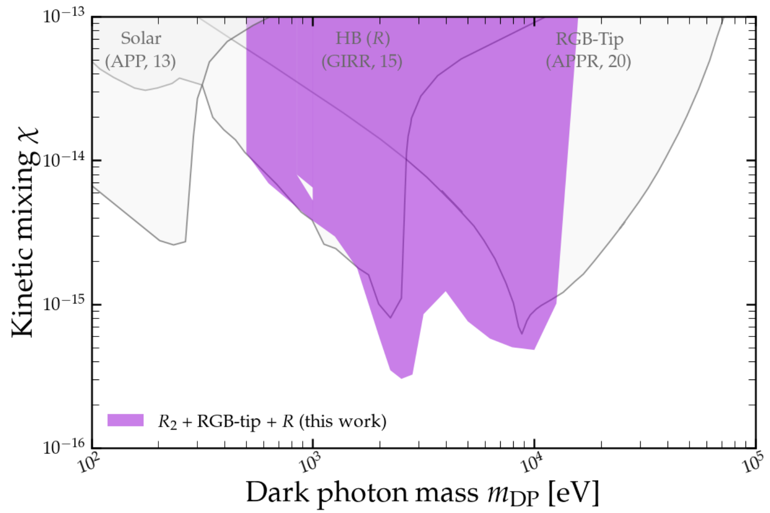
The most restrictive of these, based on the $R$-parameter, neglects sizeable uncertainty from the modelling of mixing across convective boundaries

Confronting this leads one to consider the ratio of asymptotic giant branch to horizontal branch stars in globular clusters

Using $R_2$ we can construct a new and more robust constraint of $g_{10} < 0.47$

Can be applied to other light, weakly interacting particles – e.g. dark photons [2306.13335]



# Backup Slides

# Stellar cooling bounds

Axions could be produced in deep stellar interiors, e.g. **Primakoff production** ($m_a \lesssim 1$ keV)

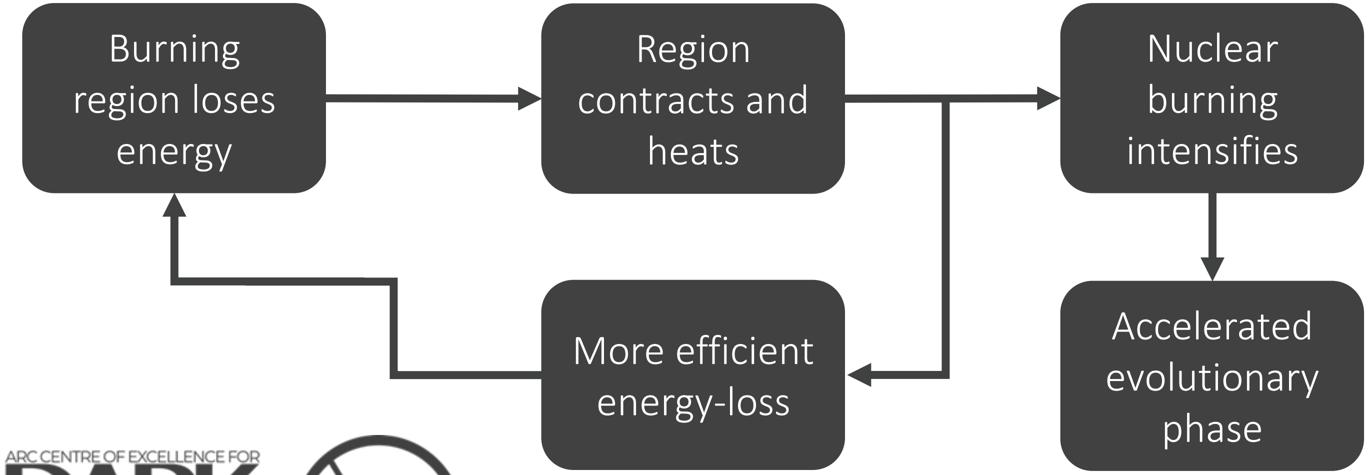
If sufficiently light and weakly interacting, they can freely escape the local stellar region – new source of energy-loss

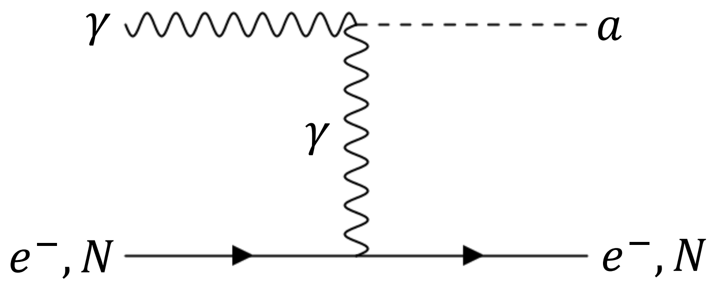
Constraints derived in this manner are examples of **stellar cooling** bounds

Debye screening

$$\epsilon_P = \frac{g_{a\gamma\gamma}^2 T^7}{4\pi\rho} G\left(\frac{k_{DH}}{T}\right)$$

Raffelt G., *Phys. Rev. D* **33** (1986) 897



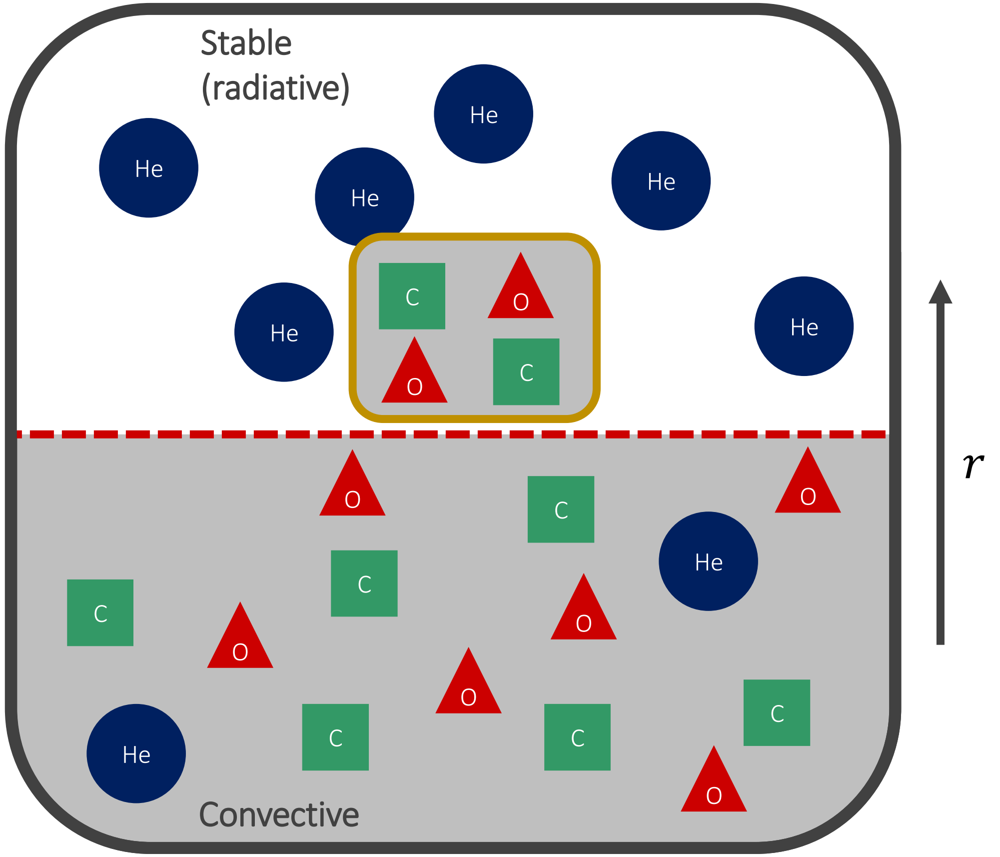
# Mixing across convective boundaries

Convective boundary separates C/O rich convective region below and He-rich stable region above

Convective elements arrive at the boundary with non-zero momentum and penetrate the stable region: **convective overshoot**

C/O are more opaque than He $\Longrightarrow$ convective region grows

Helium-burning core



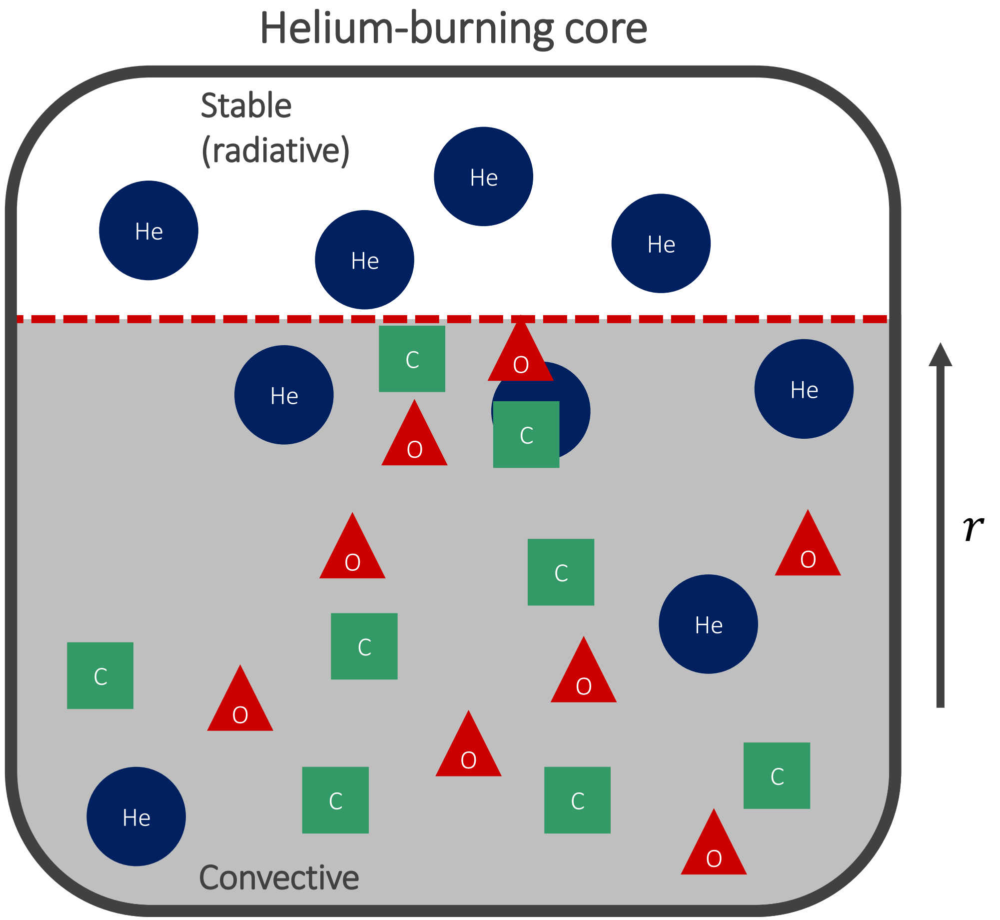
# Mixing across convective boundaries

Convective boundary separates C/O rich convective region below and He-rich stable region above

Convective elements arrive at the boundary with non-zero momentum and penetrate the stable region: **convective overshoot**

C/O are more opaque than He $\Longrightarrow$ convective region grows

Contents of new, larger convective region mix



# Mixing across convective boundaries

Convective boundary separates C/O rich convective region below and He-rich stable region above

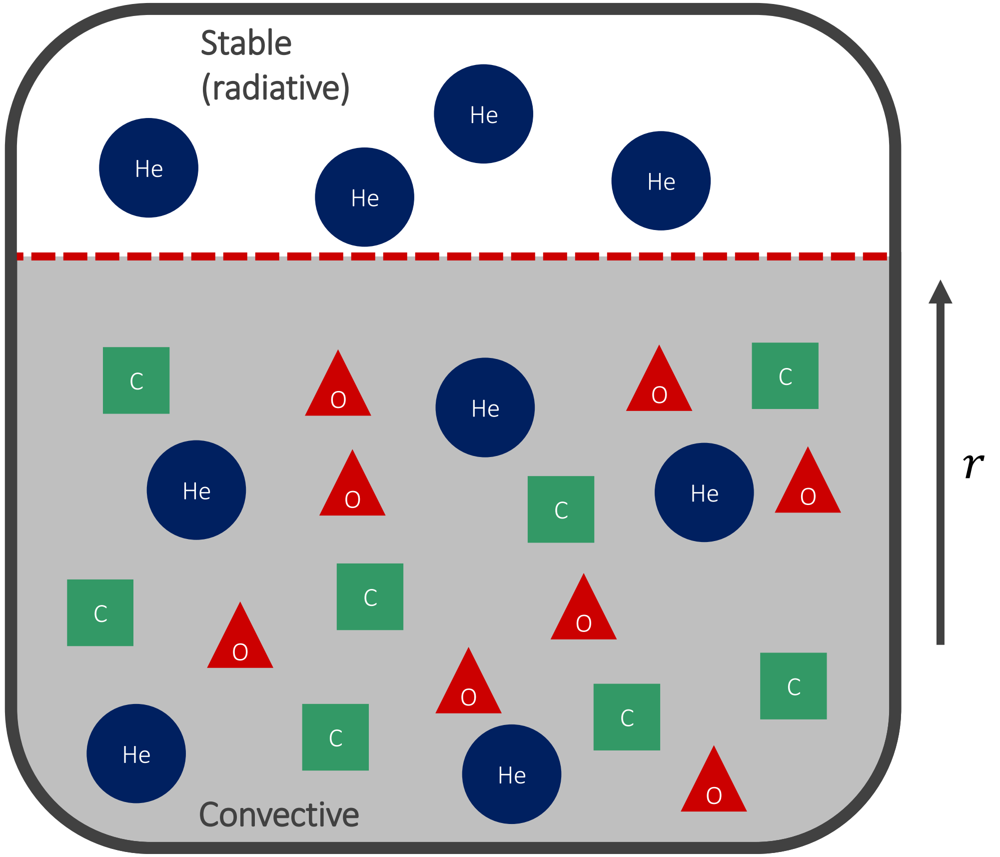
Convective elements arrive at the boundary with non-zero momentum and penetrate the stable region: **convective overshoot**

C/O are more opaque than He $\Longrightarrow$ convective region grows

Contents of new, larger convective region mix

Increased presence of He can cause the convective region to split giving rise to intermediate region

Helium-burning core



# Mixing across convective boundaries

Convective boundary separates C/O rich convective region below and He-rich stable region above

Convective elements arrive at the boundary with non-zero momentum and penetrate the stable region: **convective overshoot**

C/O are more opaque than He $\Longrightarrow$ convective region grows

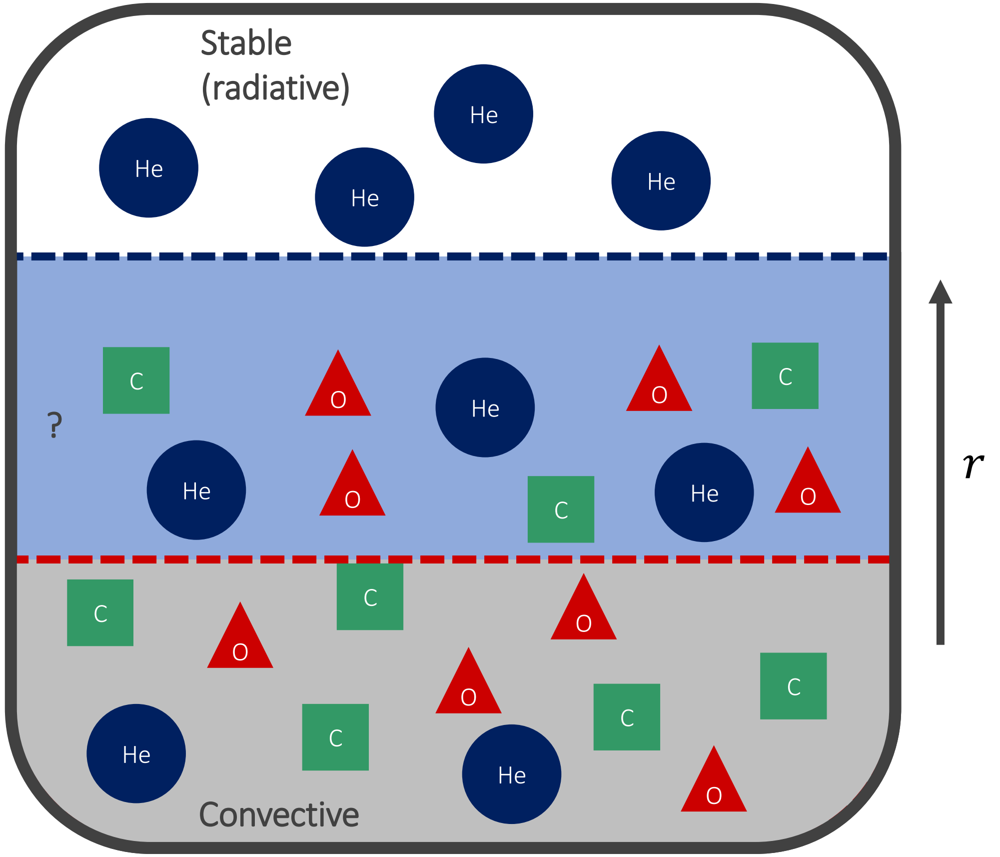
Contents of new, larger convective region mix

Increased presence of He can cause the convective region to split giving rise to intermediate region

**Result:** evolution of the core boundary is not stable

Effects are dire if they occur near the end of the HB $\Longrightarrow$ large convective episodes which significantly elongate the HB

Helium-burning core



# Calculating $R_2$

Simulate evolution of $\sim 0.8 M_\odot$ star through MS, RGB, HB and AGB

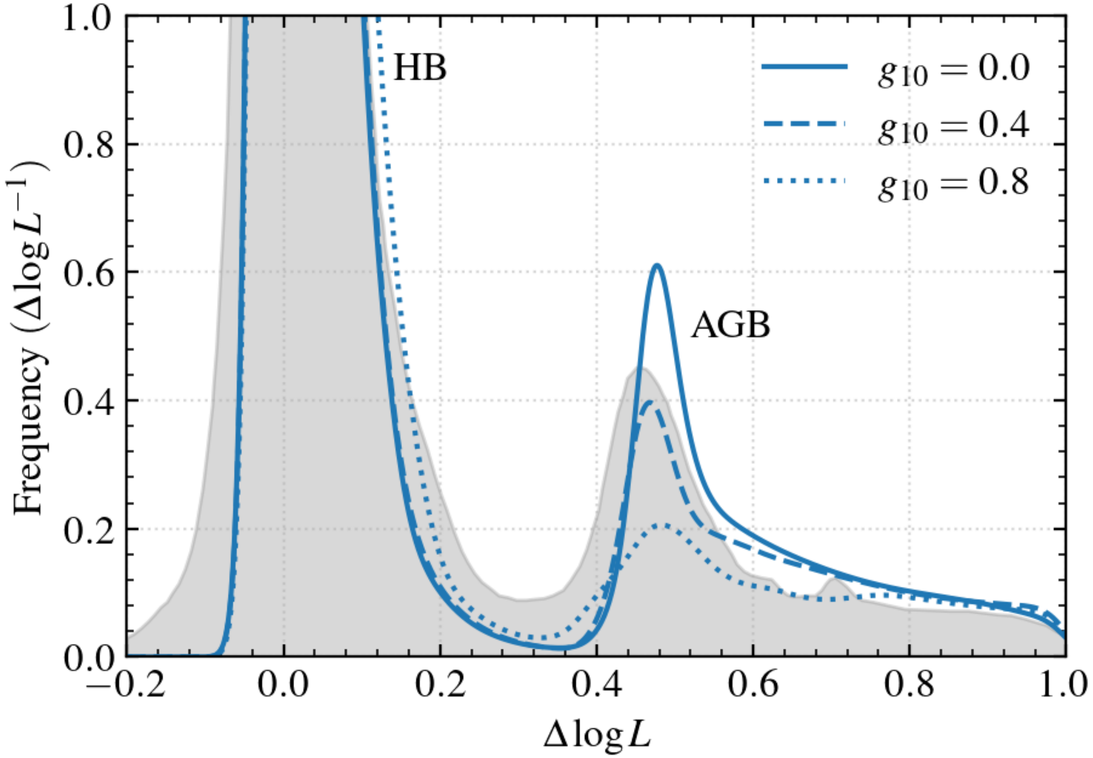
Convert results of simulation to probability density function of $\Delta\log_{10}L_{HB} = \log_{10}L - \log_{10}L_{HB}$

$$P(\Delta \log L) = \frac{1}{\tau}\sum_{i=1}^{n} \frac{\Delta t_i}{\sigma\sqrt{2\pi}} \exp\left( - \frac{(\Delta \log L - \Delta \log L_i)^2}{2\sigma^2} \right)$$

A clear minimum exists between HB and AGB peaks

Calculate $R_2$ as ratio of the areas either side of this minimum

Repeat for non-zero values of $g_{10}$



# Dark photons & stellar cooling

## Background

Dark photons are the gauge bosons associated with hypothesised new $U(1)$ gauge groups

DM candidate

Portal to dark sector

Interact with SM via kinetic mixing with the visible photon

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

Can have non-zero physical mass $m_{DP}$

If sufficiently light and weakly interacting, can be subject to the same suite of constraints as axions - including **globular cluster stellar cooling** limits

## Stellar production

Dark photons have both L and T polarisations

Nature of stellar dark photon production depends on polarisation being considered

Focused on **transverse** dark photon energy-loss

**Transverse** dark photons produced resonantly

Local plasma frequency

Resonant production if $\omega_{\rm p} = m_{\rm DP}$

≡ **resonant production region** (RPR)

RPR can be off-centre & **moves** throughout evolution

Existing constraints based on ***static*** stellar profiles are blind to many interesting effects of this

**Goal:** Calculate updated globular cluster constraints on dark photons from $\boldsymbol{R}$, $\boldsymbol{R_2}$ (and the RGB-tip luminosity)

# Results

**Bound from $R_2$**

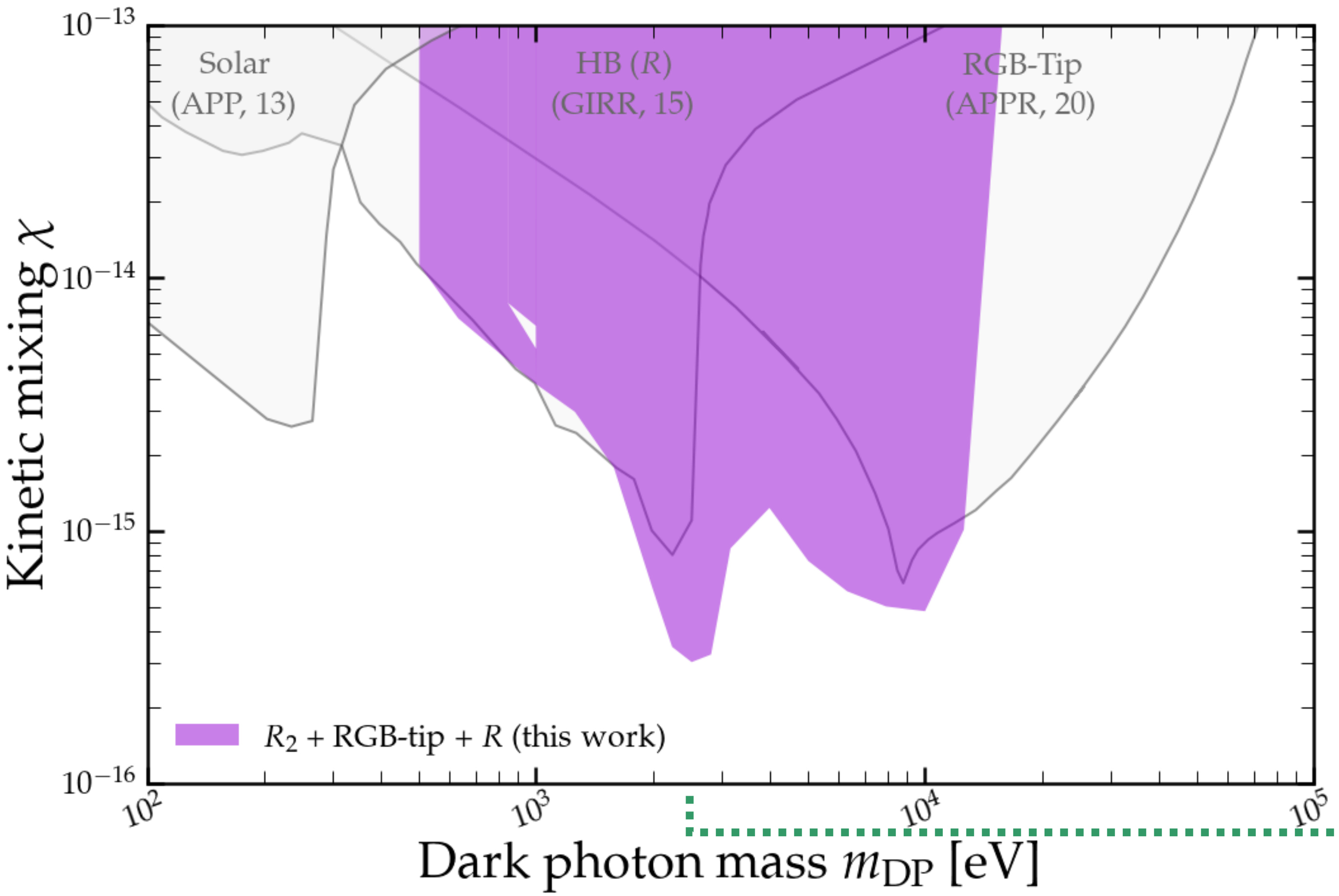
General improvement over existing bounds

Dynamic simulations necessary to capture full impact of moving RPR

Interplay between energy-loss and convective structure

Dark photons **cause** core breathing pulses

Strong constraint from $R_2$




**Complement with**

Updated limit from RGB-Tip luminosity & $R$

Stop at $m_{DP} = 500\ eV$

Less massive dark photons disrupt main sequence evolution

Full story in arXiv:2306.13335

$m_{\mathrm{DP}} \approx \omega_{\mathrm{P}}^{\mathrm{HB\ core}}$