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

My mum’s family is from Rugby, Warwickshire

My mum's family is from Rugby, Warwickshire

On my dad's side...

My mum's family is from Rugby, Warwickshire

On my dad's side...

My mum's family is from Rugby, Warwickshire

On my dad's side...

Weakly interacting slim particles

Weakly interacting slim particles

slender

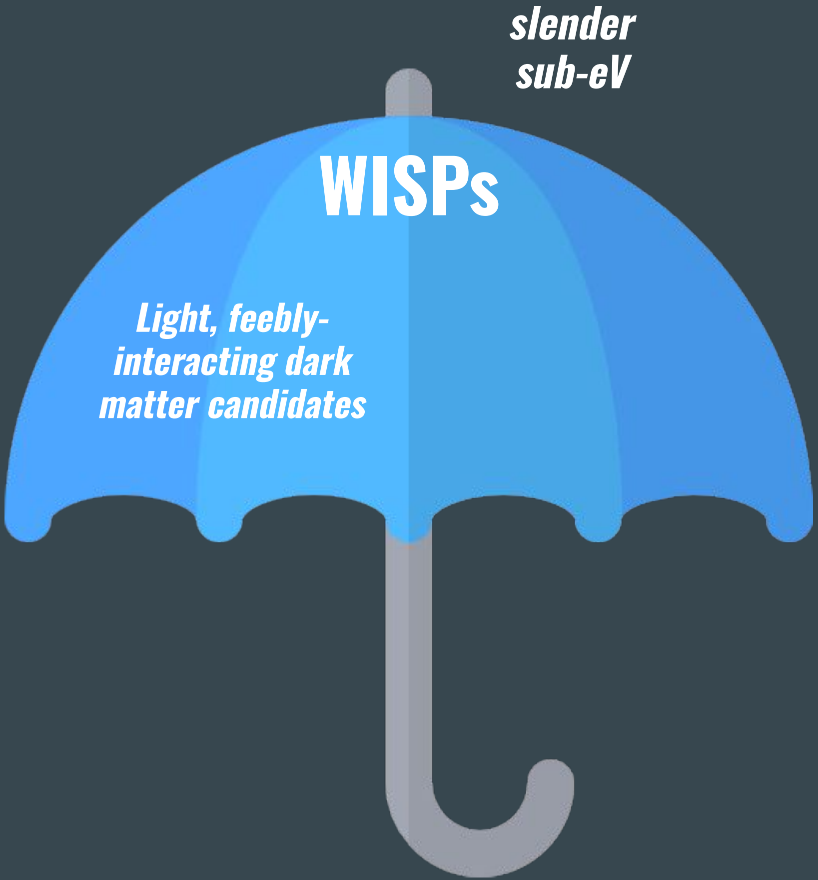
Weakly interacting slim particles

slender
sub-eV

Weakly interacting slim particles

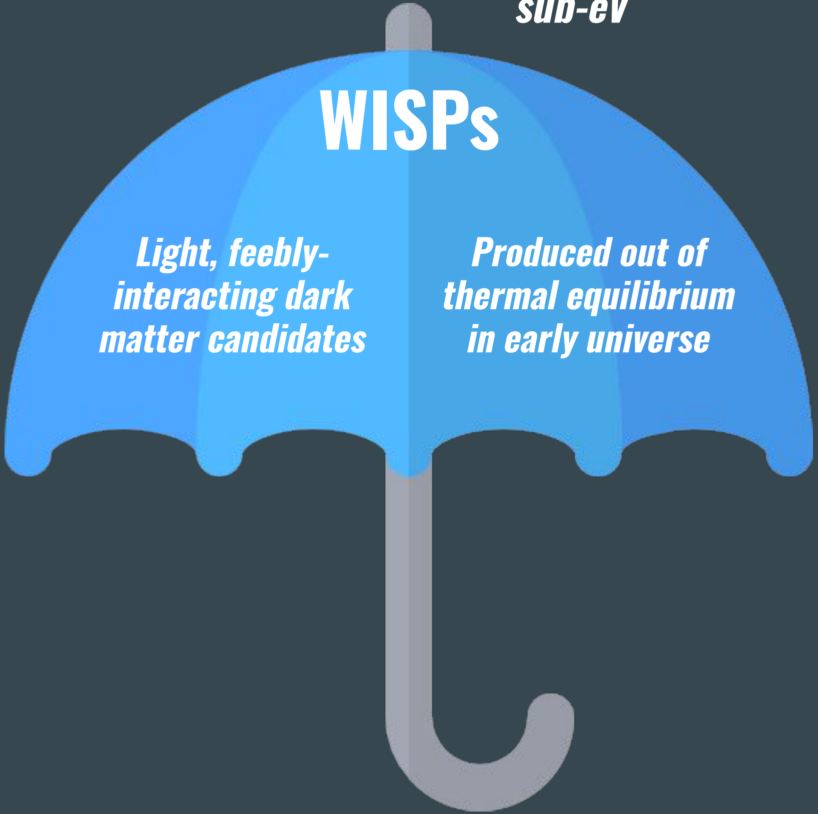
slender
sub-eV

Weakly interacting slim particles

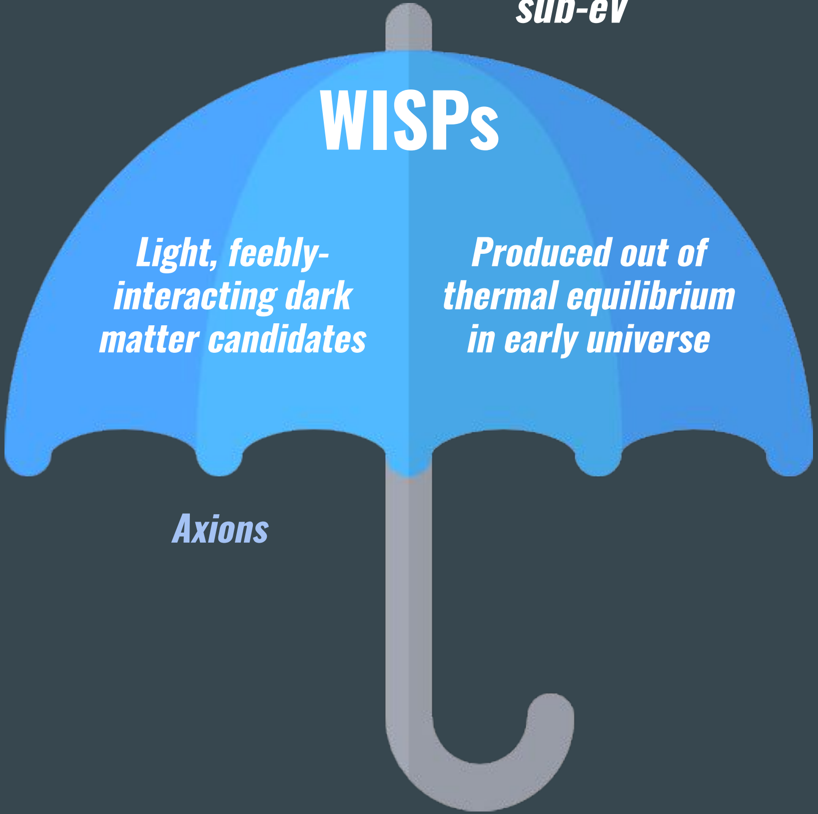


Weakly interacting slim particles

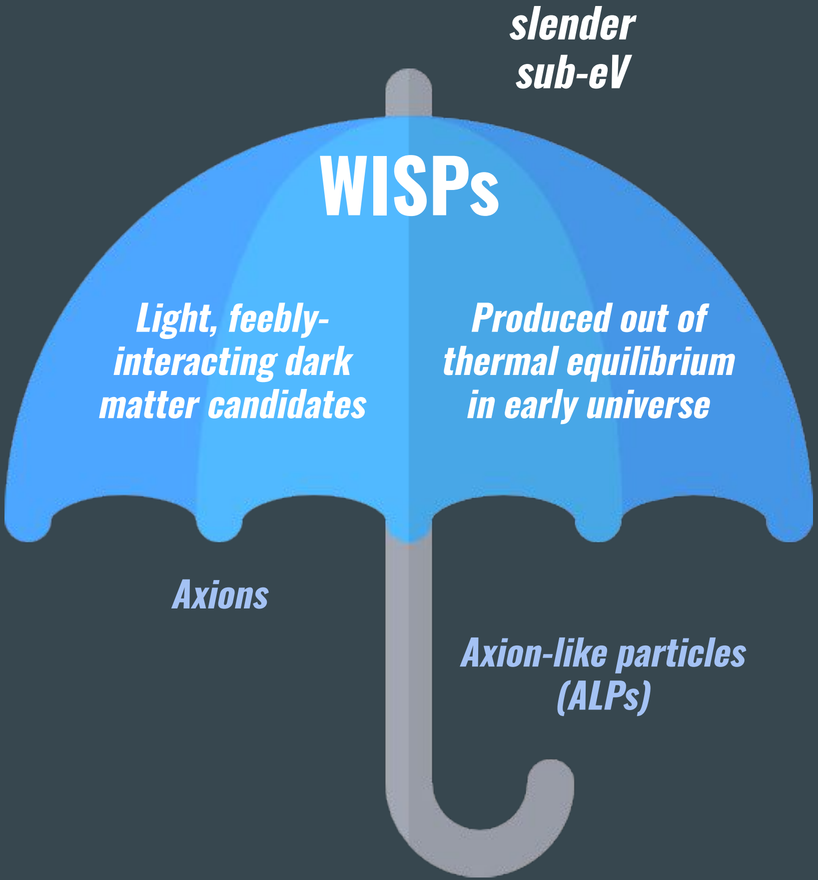
slender
sub-eV



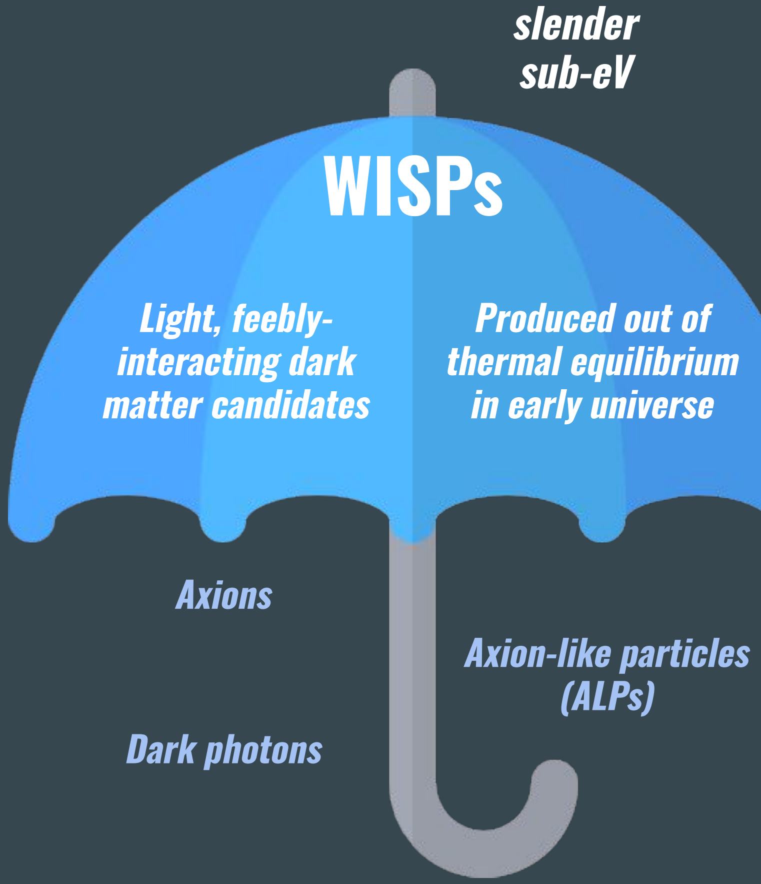
Weakly interacting slim particles



Weakly interacting slim particles



Weakly interacting slim particles



Advancing stellar constraints

WISPs affect stars because...

Advancing stellar constraints

WISPs affect stars because...

Their production can drain energy from the deep stellar interior

Advancing stellar constraints

WISPs affect stars because…

Their production can drain energy from the deep stellar interior

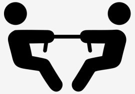
Accelerates progression of nuclear-burning evolutionary phase

Advancing stellar constraints

WISPs affect stars because…

Their production can drain energy from the deep stellar interior

Accelerates progression of nuclear-burning evolutionary phase



Leads to tension between theory and observation

Advancing stellar constraints

WISPs affect stars because...

Their production can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

Advancing stellar constraints

WISPs affect stars because...

Their production can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

The energy-loss argument has been applied with increasing sophistication for the last 40 years

Advancing stellar constraints

WISPs affect stars because…

Their production can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

The energy-loss argument has been applied with increasing sophistication for the last 40 years

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

Advancing stellar constraints

WISPs affect stars because…

Their production can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

The energy-loss argument has been applied with increasing sophistication for the last 40 years

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

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

Advancing stellar constraints

THE UNIVERSITY OF MELBOURNE

WISPs affect stars because...

Their production can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

The energy-loss argument has been applied with increasing sophistication for the last 40 years

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

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

Stage is nevertheless set for the advancement of these limits using the following general set of tactics

Advancing stellar constraints

WISPs affect stars because...

Their production can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

The energy-loss argument has been applied with increasing sophistication for the last 40 years

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

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

Stage is nevertheless set for the advancement of these limits using the following general set of tactics

Target underutilised evolutionary phases

Advancing stellar constraints

WISPs affect stars because…

Their production can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

The energy-loss argument has been applied with increasing sophistication for the last 40 years

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

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

Stage is nevertheless set for the advancement of these limits using the following general set of tactics

Target underutilised evolutionary phases

Recompute static limits using dedicated stellar evolution simulations

Advancing stellar constraints

WISPs affect stars because…

Their production can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

The energy-loss argument has been applied with increasing sophistication for the last 40 years

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

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

Stage is nevertheless set for the advancement of these limits using the following general set of tactics

- **Target underutilised evolutionary phases**
- **Recompute static limits using dedicated stellar evolution simulations**
- **Search for variations of the energy-loss argument**

Advancing stellar constraints

WISPs affect stars because...

Their production can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

The energy-loss argument has been applied with increasing sophistication for the last 40 years

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

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

Stage is nevertheless set for the advancement of these limits using the following general set of tactics

- **Target underutilised evolutionary phases**
- **Recompute static limits using dedicated stellar evolution simulations**
- **Search for variations of the energy-loss argument**
- **Address any known issues with existing bounds**

Advancing stellar constraints

WISPs affect stars because...

Their **production** can drain energy from the deep stellar interior

Energy-loss argument

Accelerates progression of nuclear-burning evolutionary phase

Leads to tension between theory and observation

The energy-loss argument has been applied with increasing sophistication for the last 40 years

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

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

Stage is nevertheless set for the advancement of these limits using the following general set of tactics

Target underutilised evolutionary phases

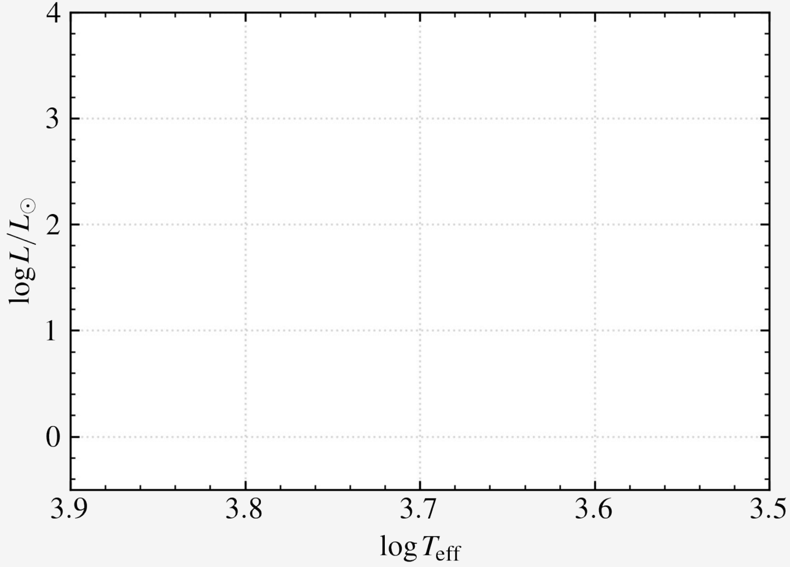
Recompute static limits using dedicated stellar evolution simulations

Search for variations of the energy-loss argument

Address any known issues with existing bounds

Evolution of low mass stars

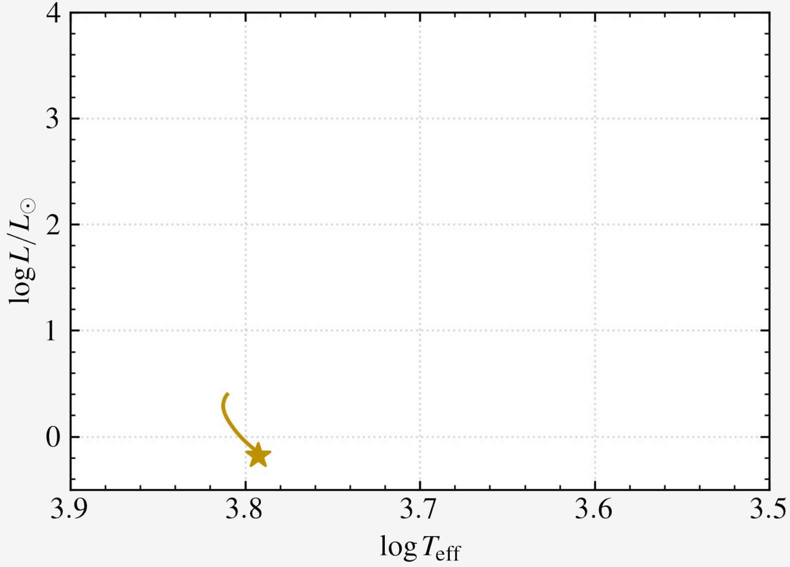
Helpful to go over the evolution of low mass stars



Evolution of low mass stars

Helpful to go over the evolution of low mass stars

Main sequence (MS)
Star burns hydrogen into helium in core. Longest evolutionary phase.



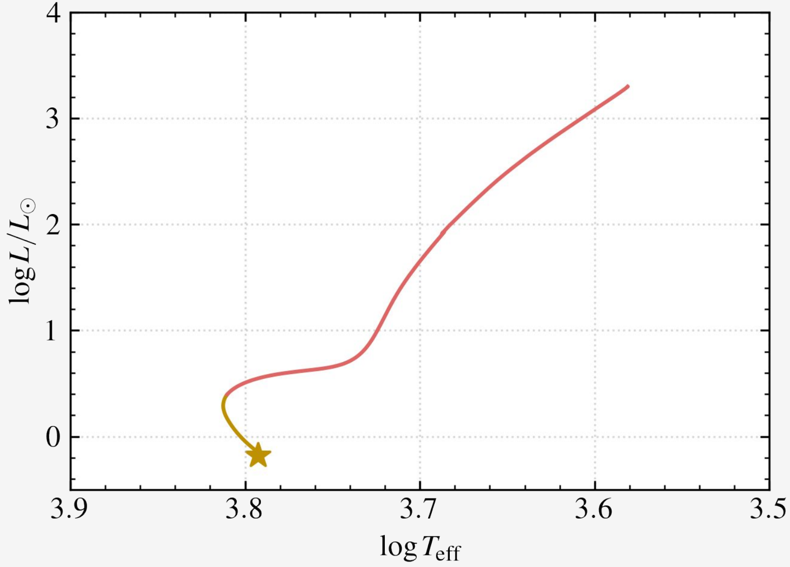
THE UNIVERSITY OF MELBOURNE

Helpful to go over the evolution of low mass stars

Main sequence (MS)
Star burns hydrogen into helium in core. Longest evolutionary phase.

→

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



Evolution of low mass stars

THE UNIVERSITY OF MELBOURNE

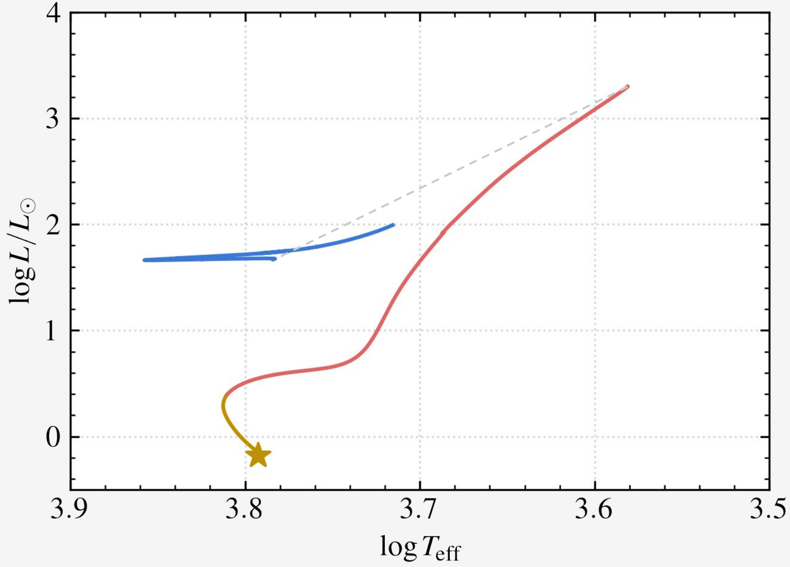
Helpful to go over the evolution of low mass stars

Main sequence (MS)
Star burns hydrogen into helium 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.



Evolution of low mass stars

Helpful to go over the evolution of low mass stars

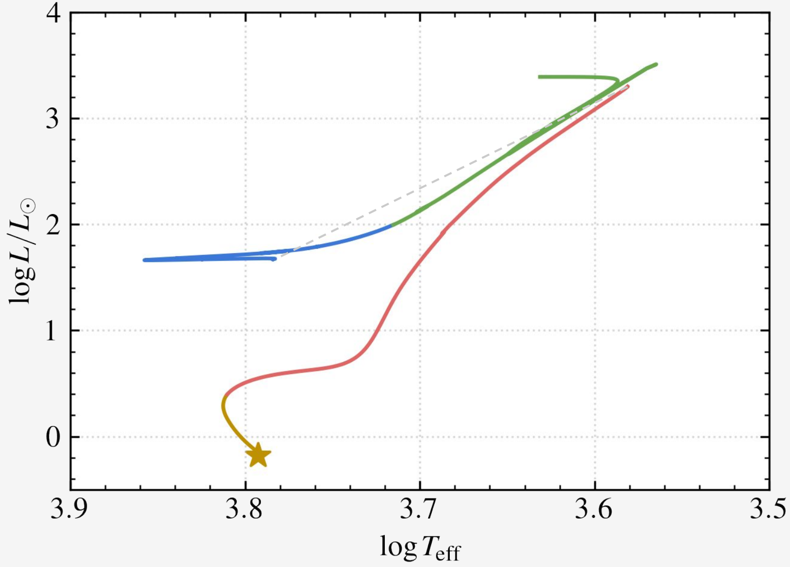
Main sequence (MS)
Star burns hydrogen into helium in core. Longest evolutionary phase.

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 low mass stars

Helpful to go over the evolution of low mass stars

Main sequence (MS)
Star burns hydrogen into helium in core. Longest evolutionary phase.

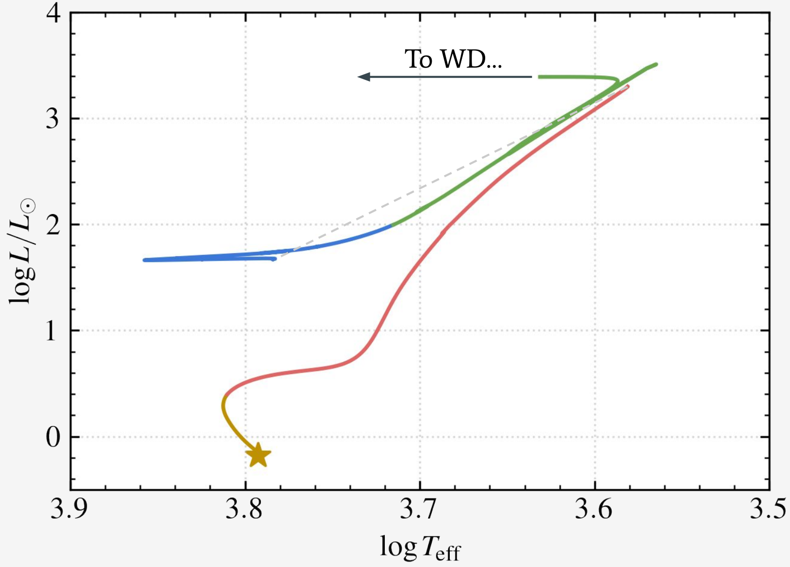
Red giant branch (RGB)
Hydrogen-burning continues in off-centre shell surrounding inert, degenerate core of helium

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



Evolution of low mass stars

Helpful to go over the evolution of low mass stars

Main sequence (MS)
Star burns hydrogen into helium in core. Longest evolutionary phase.

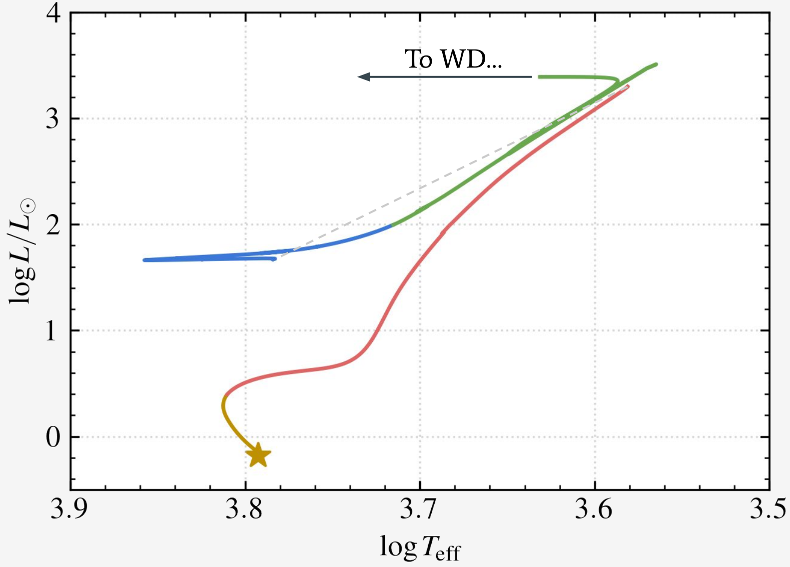
Red giant branch (RGB)
Hydrogen-burning continues in off-centre shell surrounding inert, degenerate core of helium

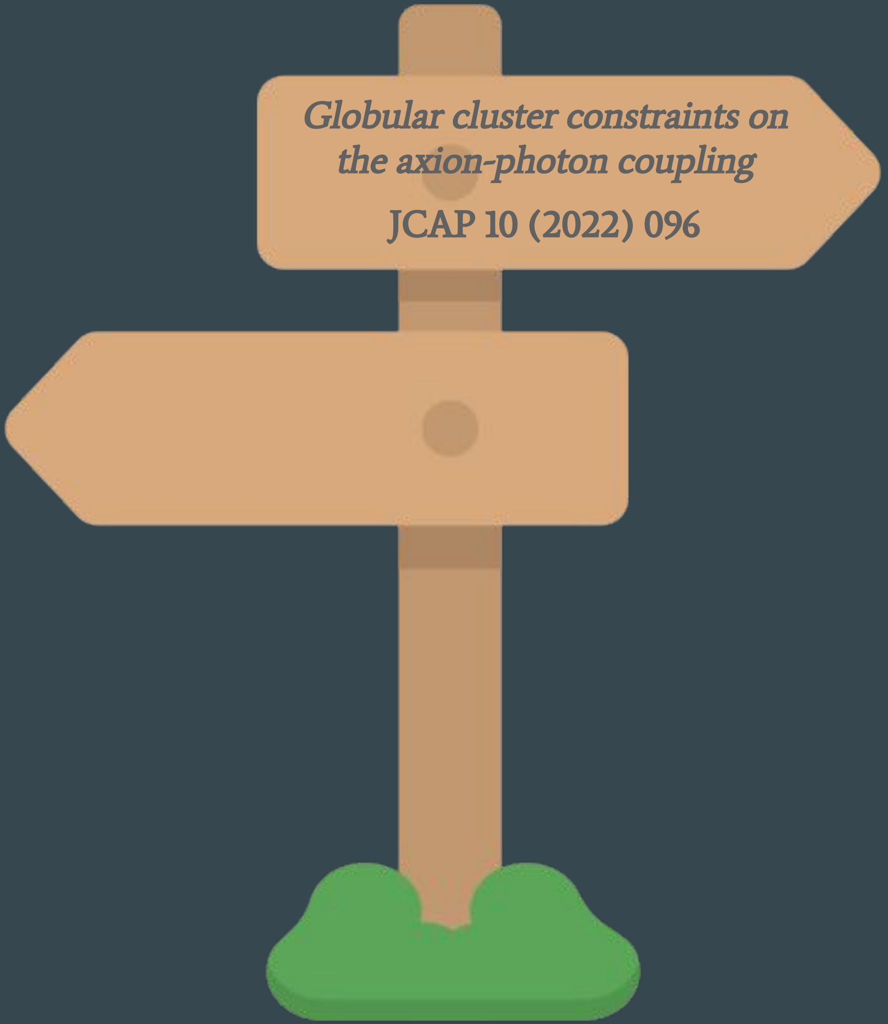
Helium ignition

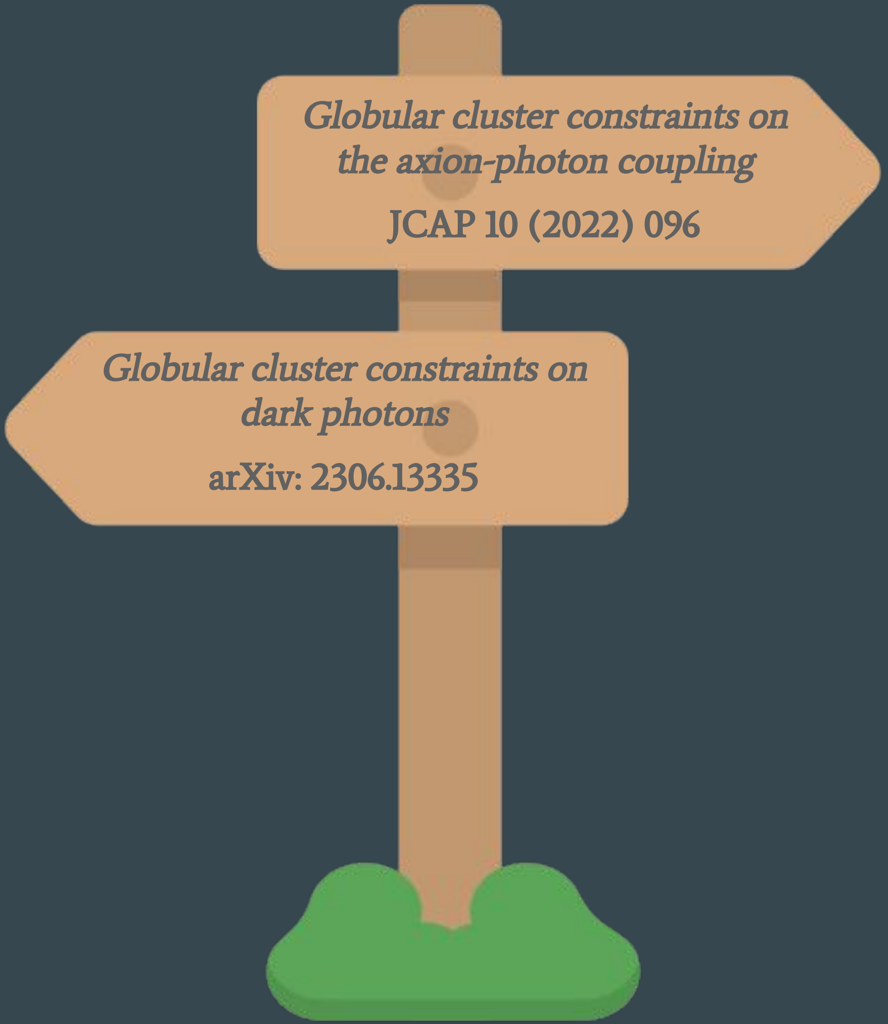
Horizontal branch (HB)
Central helium-burning phase. Helium converted to carbon/oxygen in convective core.

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

White dwarf



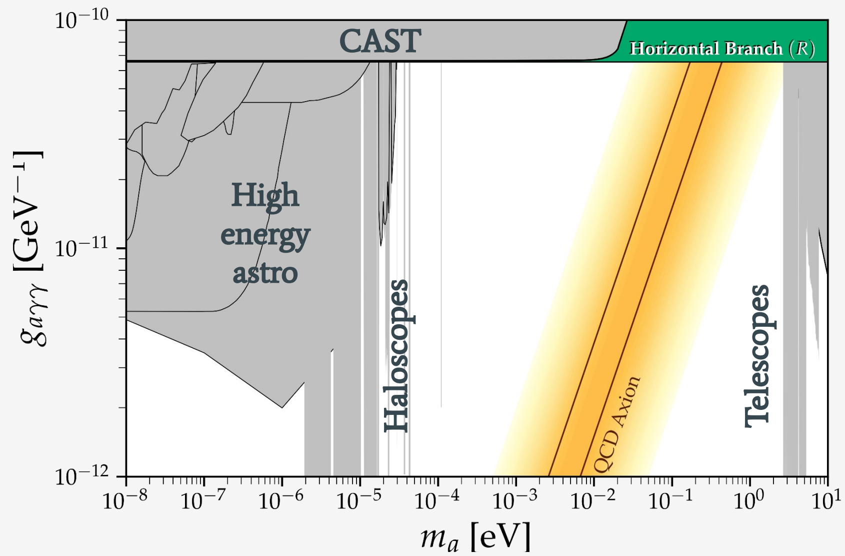

Globular cluster constraints on the axion-photon coupling
JCAP 10 (2022) 096


Globular cluster constraints on the axion-photon coupling
JCAP 10 (2022) 096
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

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



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

cajohare/AxionLimits

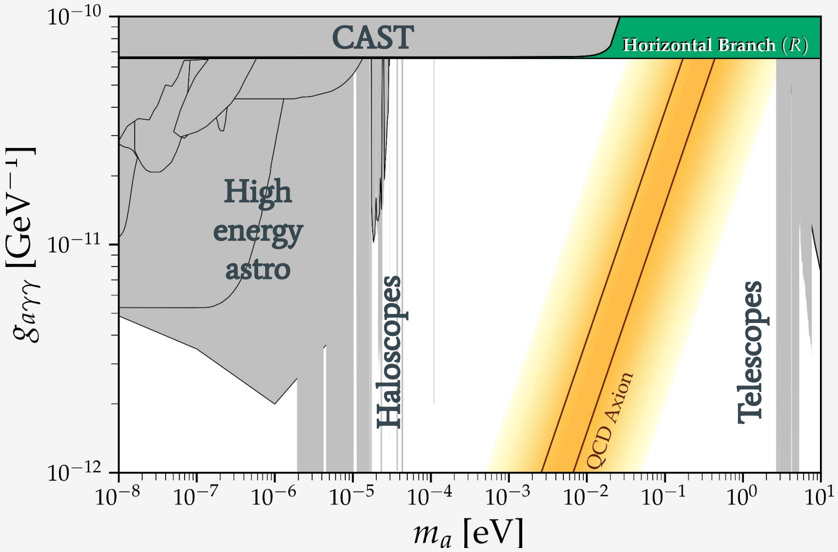
The *R*-parameter constraint

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

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

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

Primakoff process: $\epsilon_a \sim \dfrac{g_{a\gamma\gamma}^2 T^7}{4\pi\rho}$



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

cajohare/AxionLimits

The R-parameter constraint

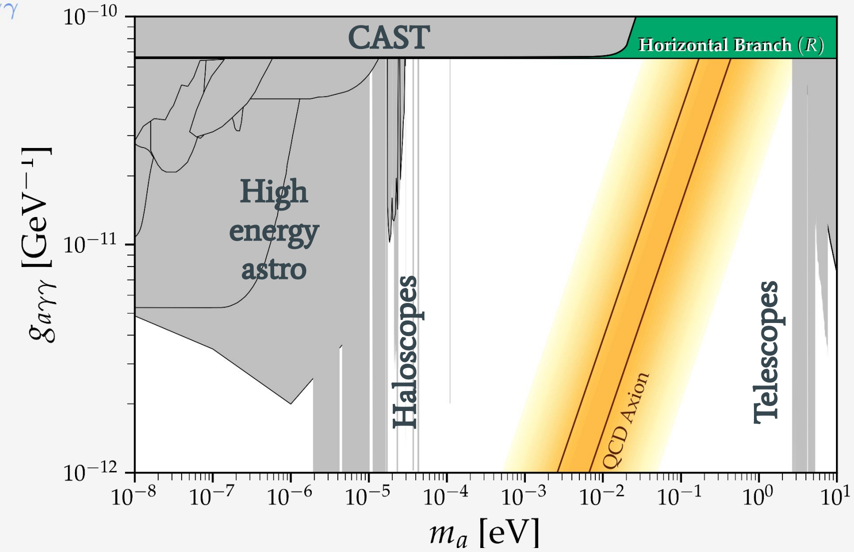
The leading stellar constraint on the axion-photon coupling comes from the R-parameter of globular clusters

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

Decreases with increasing $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

Primakoff process: $\epsilon_a \sim \dfrac{g_{a\gamma\gamma}^2 T^7}{4\pi\rho}$



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

cajohare/AxionLimits

The R-parameter constraint

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

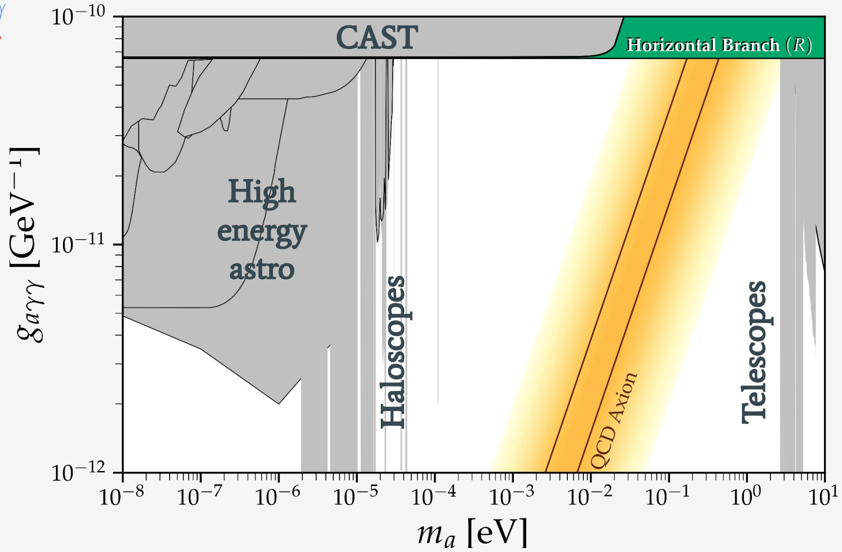
$$R = \frac{N_{\rm HB}}{N_{\rm RGB}} \simeq \frac{\tau_{\rm HB}}{\tau_{\rm RGB}}$$

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

Primakoff process: $\epsilon_a \sim \dfrac{g_{a\gamma\gamma}^2 T^7}{4\pi\rho}$



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

cajohare/AxionLimits

The *R*-parameter constraint

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

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

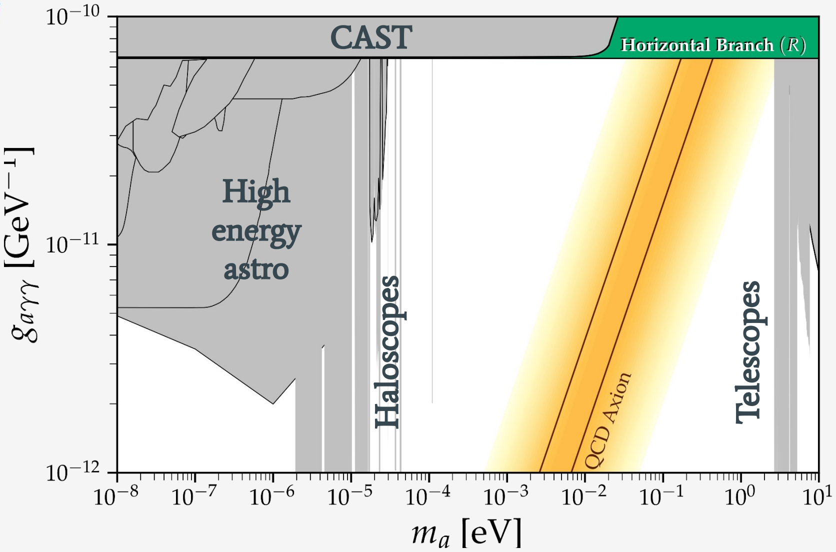
Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

Primakoff process: $\epsilon_a \sim \dfrac{g^2_{a\gamma\gamma}T^7}{4\pi\rho}$



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

cajohare/AxionLimits

The R-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

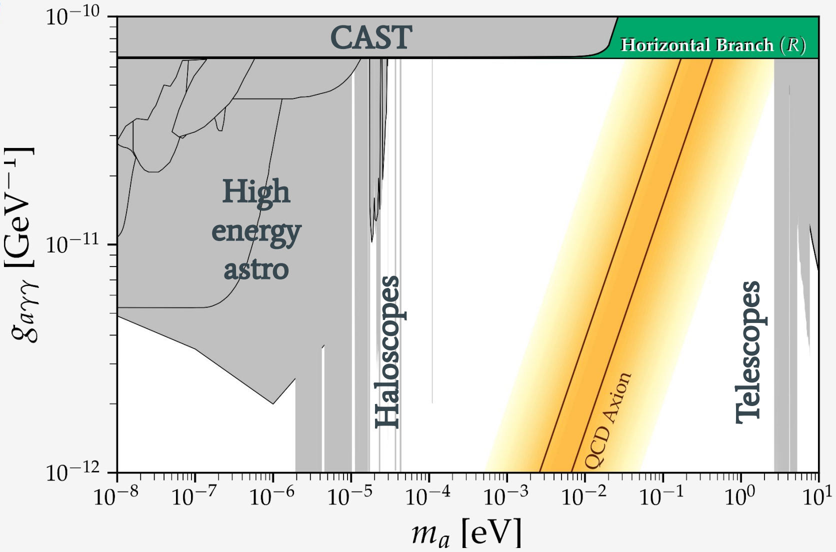
Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

Issue!

Primakoff process: $\epsilon_a \sim \dfrac{g_{a\gamma\gamma}^2 T^7}{4\pi\rho}$



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

cajohare/AxionLimits

The R-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

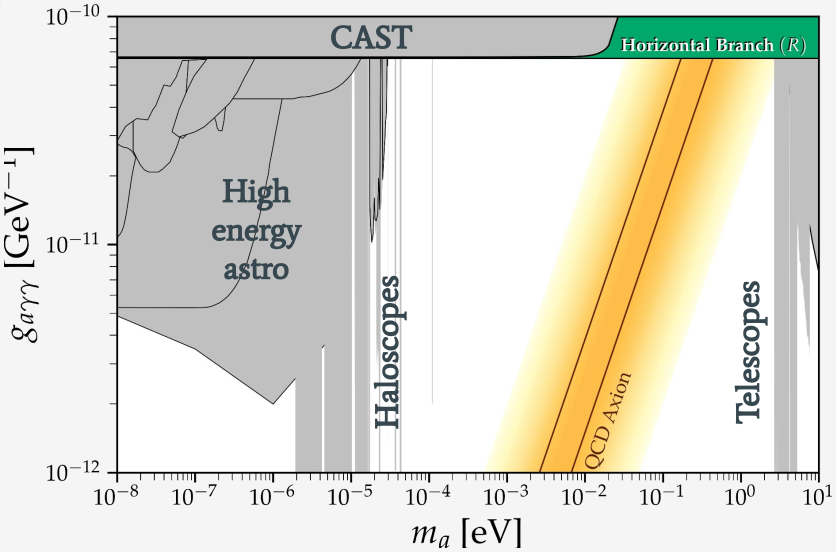
Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

Issue!

Theoretical predictions for HB duration suffer from stochastic and systematic uncertainty

Primakoff process: $\epsilon_a \sim \dfrac{g_{a\gamma\gamma}^2 T^7}{4\pi\rho}$



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

cajohare/AxionLimits

The R-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

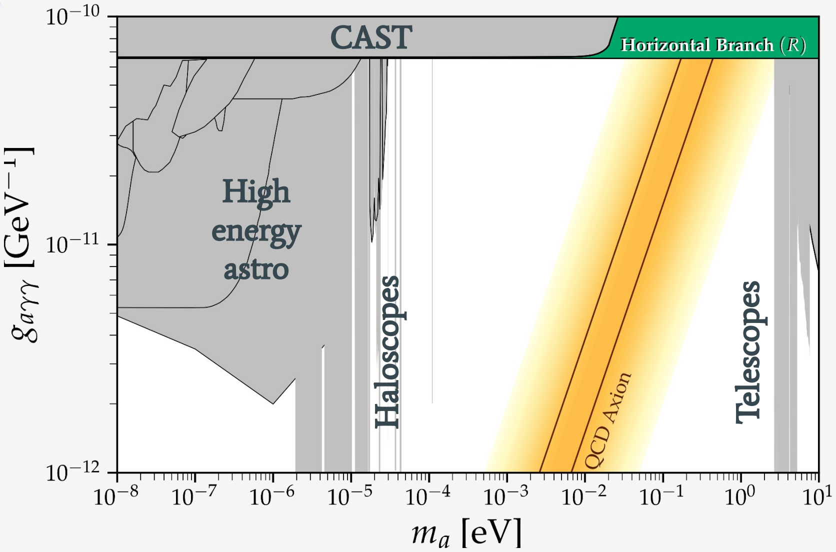
For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

Issue!

Theoretical predictions for HB duration suffer from stochastic and systematic uncertainty

Caused by **mixing across convective boundaries** in HB stars

Primakoff process: $\epsilon_a \sim \frac{g_{a\gamma\gamma}^2 T^7}{4\pi\rho}$



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

cajohare/AxionLimits

The R-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

---

Issue!

Theoretical predictions for HB duration suffer from stochastic and systematic uncertainty

Caused by **mixing across convective boundaries** in HB stars

How does this affect the bound you get?

The R-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

---

Issue!

Theoretical predictions for HB duration suffer from stochastic and systematic uncertainty

Caused by **mixing across convective boundaries** in HB stars

How does this affect the bound you get?

Illustrate with stellar evolution code `MESA`

The *R*-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, *R* will fall outside observed range

Issue!

Theoretical predictions for HB duration suffer from **stochastic** and systematic uncertainty

Caused by **mixing across convective boundaries** in HB stars

HB simulations are not computationally stable

The R-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

---

Issue!

Theoretical predictions for HB duration suffer from **stochastic** and systematic uncertainty

Caused by **mixing across convective boundaries** in HB stars

HB simulations are not computationally stable

Calculate R as a function of axion-photon coupling 20 times, varying temporal and spatial resolution

The R-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

---

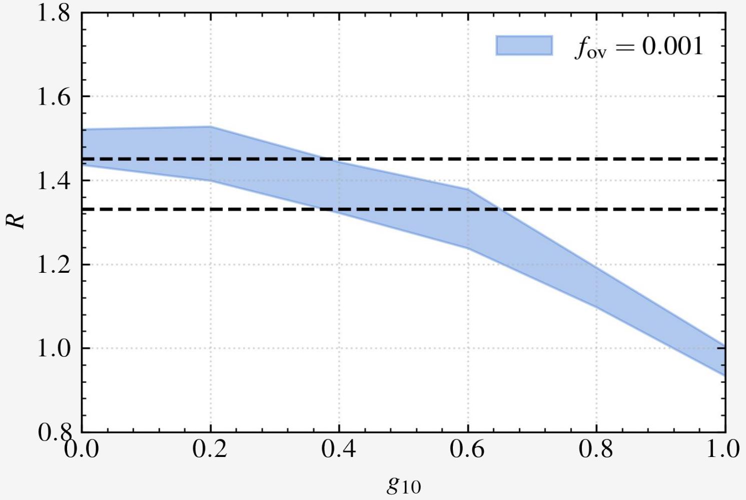
Issue!

Theoretical predictions for HB duration suffer from **stochastic** and systematic uncertainty

Caused by **mixing across convective boundaries** in HB stars

HB simulations are not computationally stable

Calculate R as a function of axion-photon coupling 20 times, varying temporal and spatial resolution



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

The R-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

---

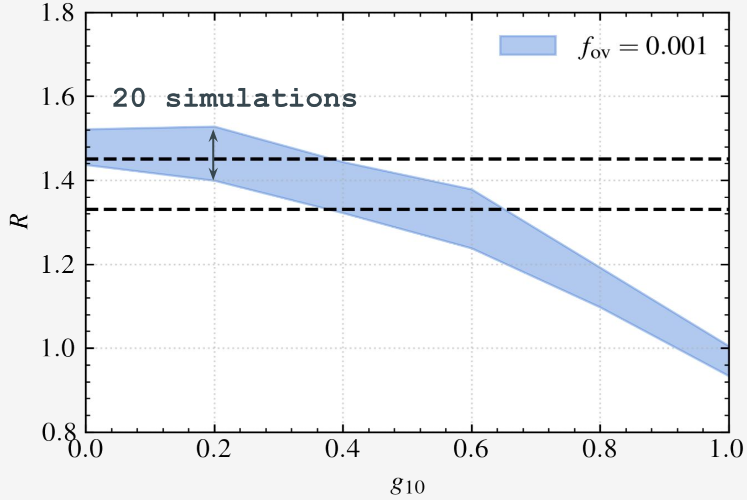
Issue!

Theoretical predictions for HB duration suffer from **stochastic** and systematic uncertainty

Caused by **mixing across convective boundaries** in HB stars

HB simulations are not computationally stable

Calculate R as a function of axion-photon coupling 20 times, varying temporal and spatial resolution



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

The *R*-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

---

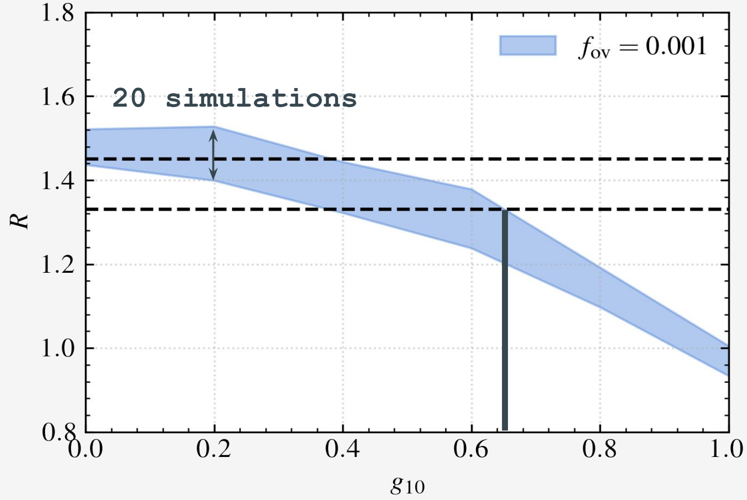
Issue!

Theoretical predictions for HB duration suffer from **stochastic** and systematic uncertainty

Caused by **mixing across convective boundaries** in HB stars

HB simulations are not computationally stable

Calculate R as a function of axion-photon coupling 20 times, varying temporal and spatial resolution



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

The *R*-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

---

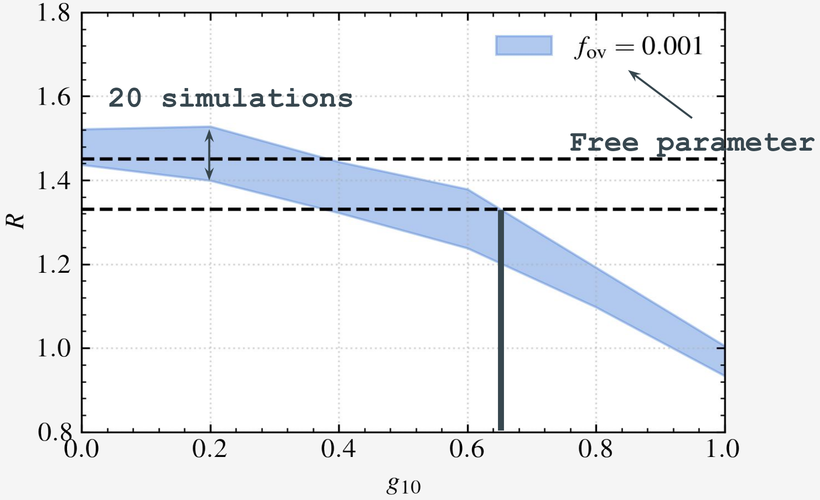
Issue!

Theoretical predictions for HB duration suffer from stochastic and **systematic** uncertainty

Caused by **mixing across convective boundaries** in HB stars

HB simulations are not computationally stable

Calculate R as a function of axion-photon coupling 20 times, varying temporal and spatial resolution



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

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

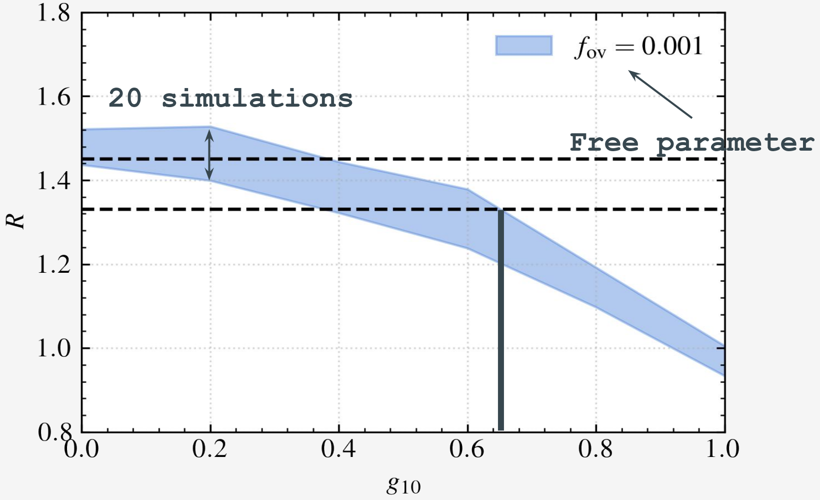
Issue!

Theoretical predictions for HB duration suffer from stochastic and **systematic** uncertainty

Caused by **mixing across convective boundaries** in HB stars

HB simulations are not computationally stable

Calculate R as a function of axion-photon coupling 20 times, varying temporal and spatial resolution



Varying free parameter(s) shifts implied limit

The *R*-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

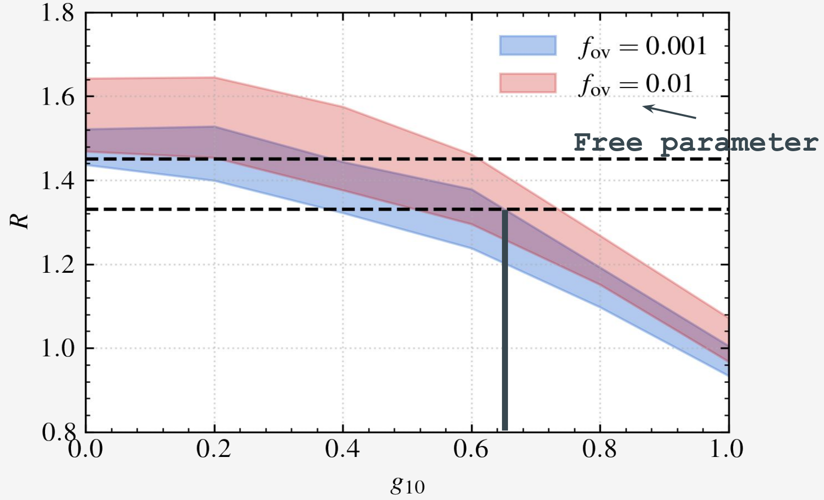
Issue!

Theoretical predictions for HB duration suffer from stochastic and **systematic** uncertainty

Caused by **mixing across convective boundaries** in HB stars

HB simulations are not computationally stable

Calculate R as a function of axion-photon coupling 20 times, varying temporal and spatial resolution



Varying free parameter(s) shifts implied limit

The R-parameter constraint

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

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

Decreases with increasing $g_{a\gamma\gamma}$

Independent of $g_{a\gamma\gamma}$

Energy-loss to axion photoproduction is efficient in HB cores, but not in RGB stars

For large enough values of $g_{a\gamma\gamma}$, R will fall outside observed range

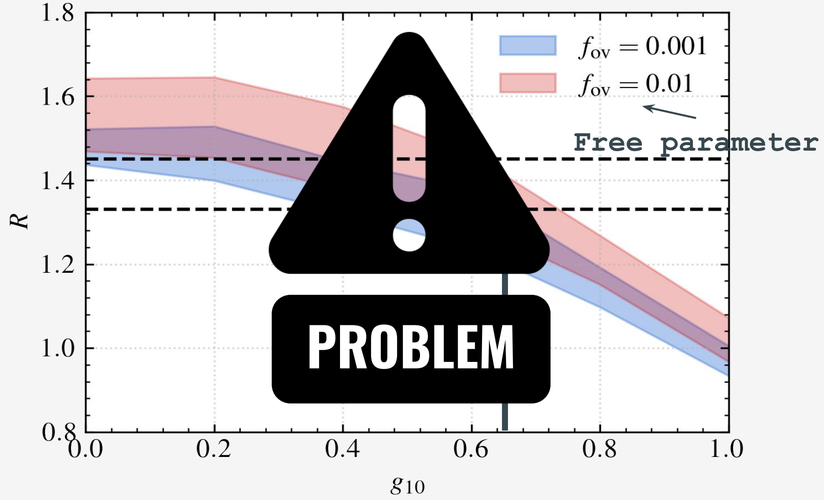
Issue!

Theoretical predictions for HB duration suffer from stochastic and **systematic** uncertainty

Caused by **mixing across convective boundaries** in HB stars

HB simulations are not computationally stable

Calculate R as a function of axion-photon coupling 20 times, varying temporal and spatial resolution



Varying free parameter(s) shifts implied limit

The R_2-parameter

Fortunately, other globular cluster parameters exist which can set complementary constraints on $g_{a\gamma\gamma}$

The R_2-parameter

Fortunately, other globular cluster parameters exist which can set complementary constraints on $g_{a\gamma\gamma}$

A particularly strong candidate for this is the **R_2-parameter** - the ratio of AGB to HB stars

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

The R_2-parameter

Fortunately, other globular cluster parameters exist which can set complementary constraints on $g_{a\gamma\gamma}$

A particularly strong candidate for this is the **R_2-parameter** - the ratio of AGB to HB stars

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

AGB He-B shell is hotter and less dense than HB core $\Rightarrow$ more sensitive to axion energy-loss than HB ($\epsilon_a \sim T^7/\rho$)

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

The R_2-parameter

Fortunately, other globular cluster parameters exist which can set complementary constraints on $g_{a\gamma\gamma}$

A particularly strong candidate for this is the **R_2-parameter** - the ratio of AGB to HB stars

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

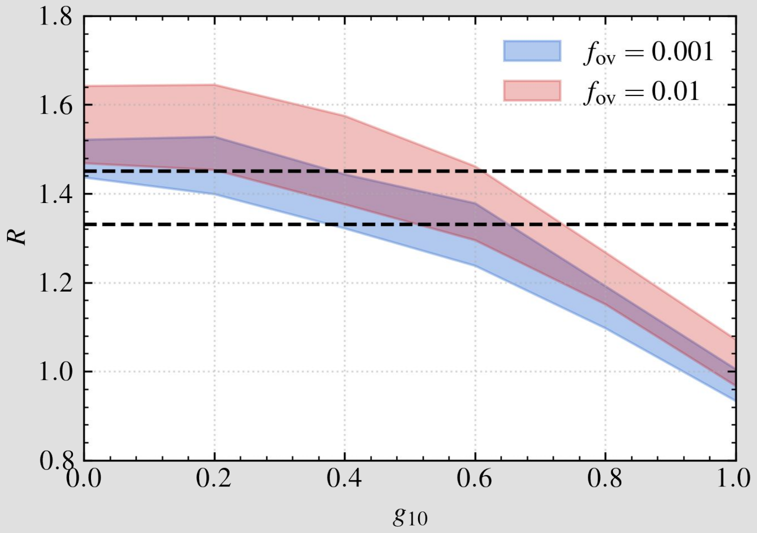
AGB He-B shell is hotter and less dense than HB core $\Rightarrow$ more sensitive to axion energy-loss than HB ($\epsilon_a \sim T^7/\rho$)

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

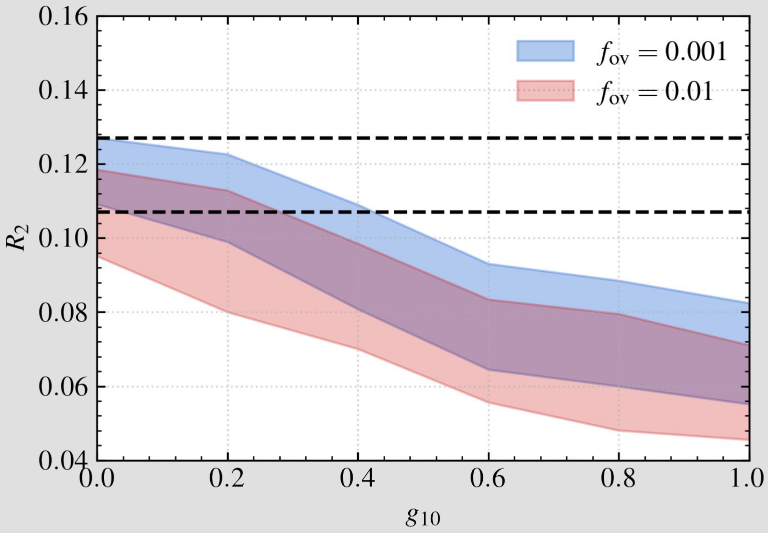
Historically used to constrain mixing across convective boundaries during the HB

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

R versus R_2

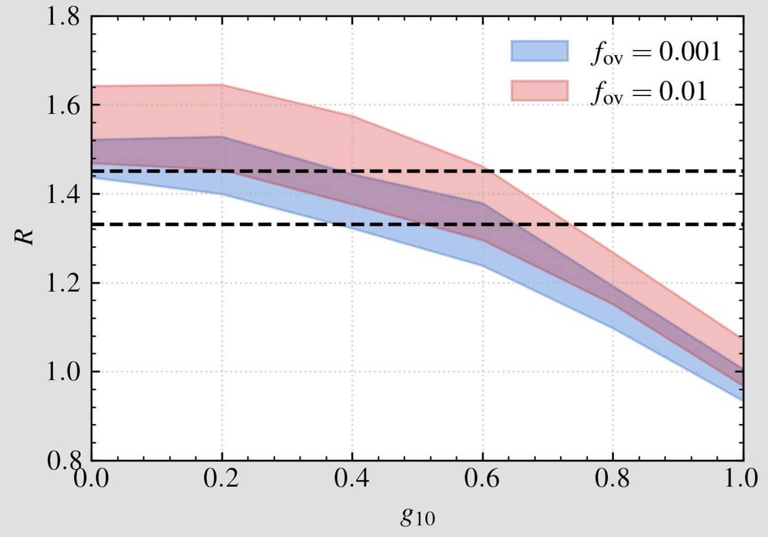


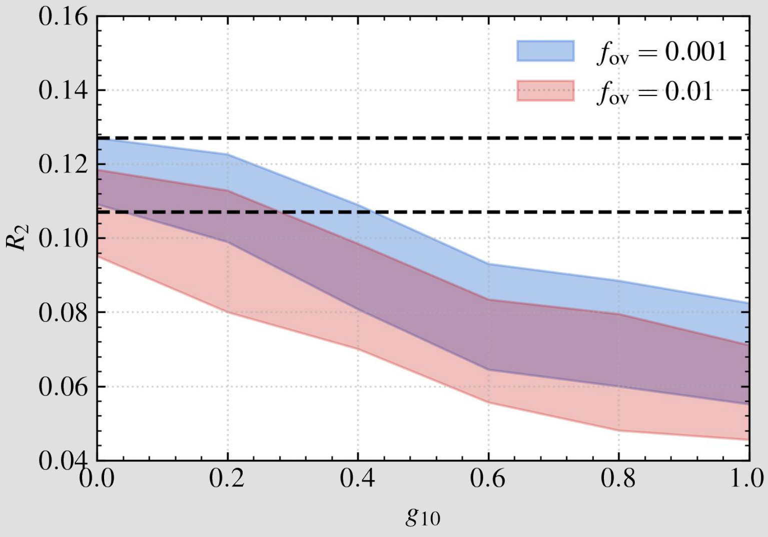
1.8
1.6
1.4
1.2
1.0
0.8
0.0
0.2
0.4
0.6
0.8
1.0
R
g_{10}
$f_{ov} = 0.001$
$f_{ov} = 0.01$



0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.0
0.2
0.4
0.6
0.8
1.0
R_2
g_{10}
$f_{ov} = 0.001$
$f_{ov} = 0.01$

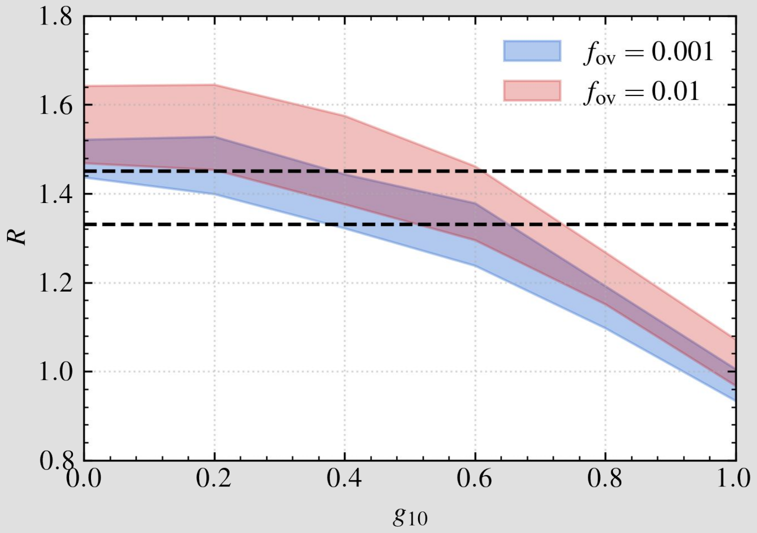
R versus R_2

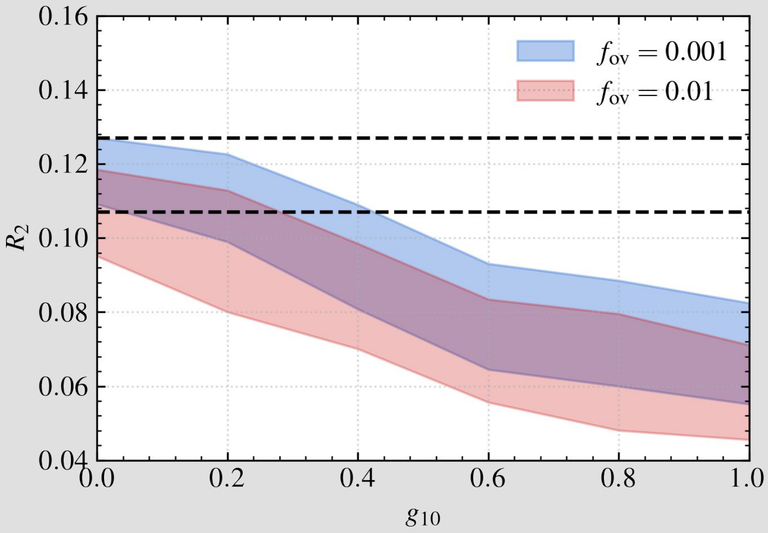




Varying convective boundary model parameter(s) has opposite effect on each constraint

R versus R_2

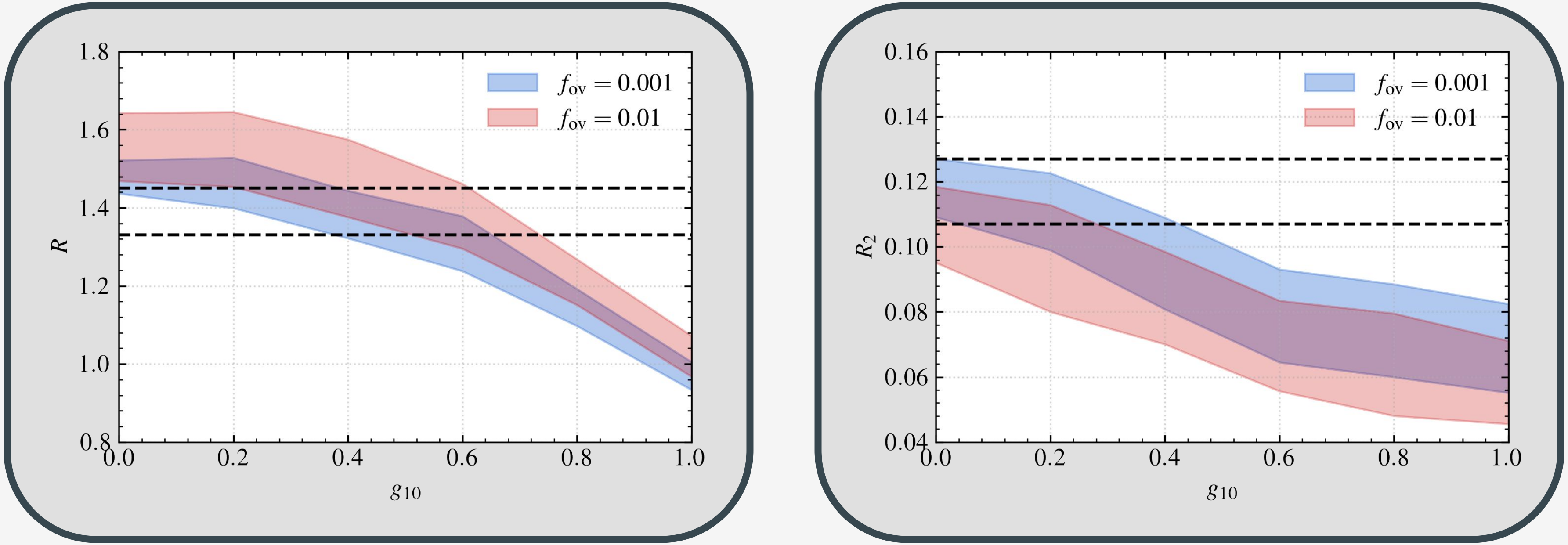




Varying convective boundary model parameter(s) has opposite effect on each constraint

Both R and R_2 decrease with increasing g_{10}

R versus R_2

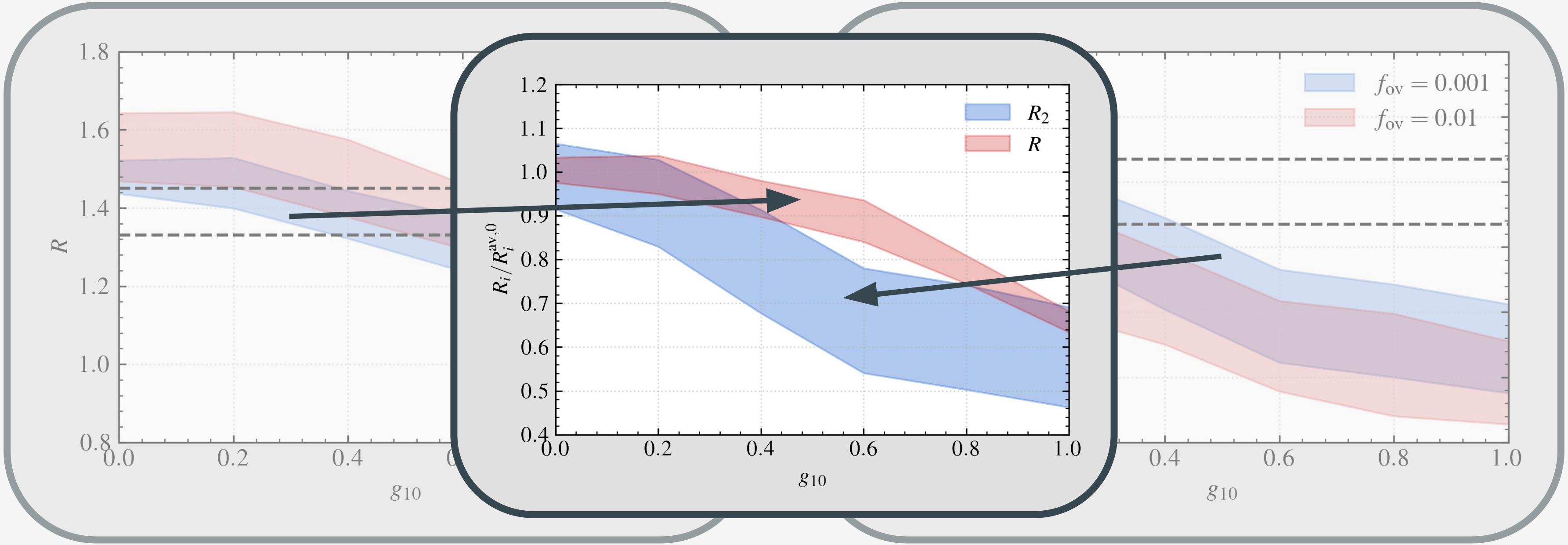


Varying convective boundary model parameter(s) has opposite effect on each constraint

Both R and R_2 decrease with increasing g_{10}

R_2 more sensitive to low values of g_{10}

R versus R_2



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

Both R and R_2 decrease with increasing g_{10}

R_2 more sensitive to low values of g_{10}

R versus R_2

Original idea: leverage R and R_2 against one another to compute a total limit which marginalises over the uncertainty associated with convective boundaries

R versus R_2

Original idea: leverage R and R_2 against one another to compute a total limit which marginalises over the uncertainty associated with convective boundaries

Reality: R_2 will always give you the strongest limit

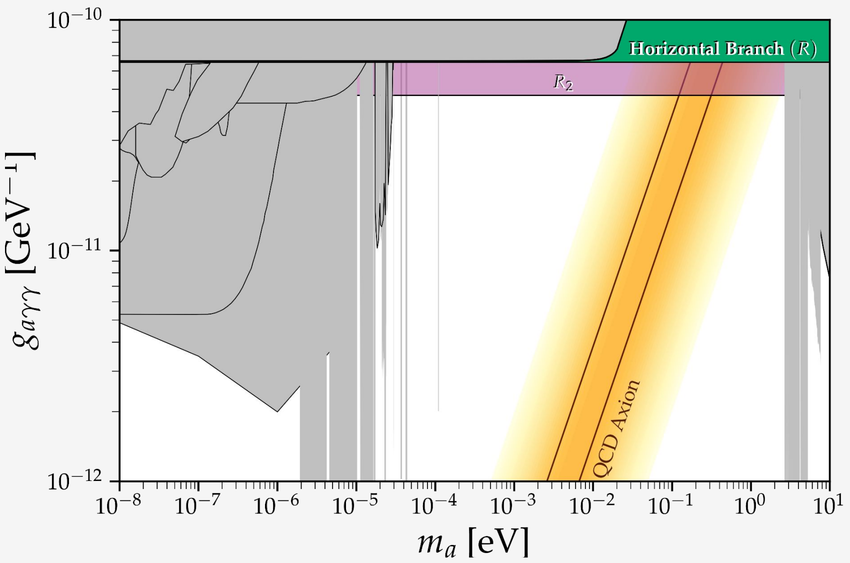
R versus R_2

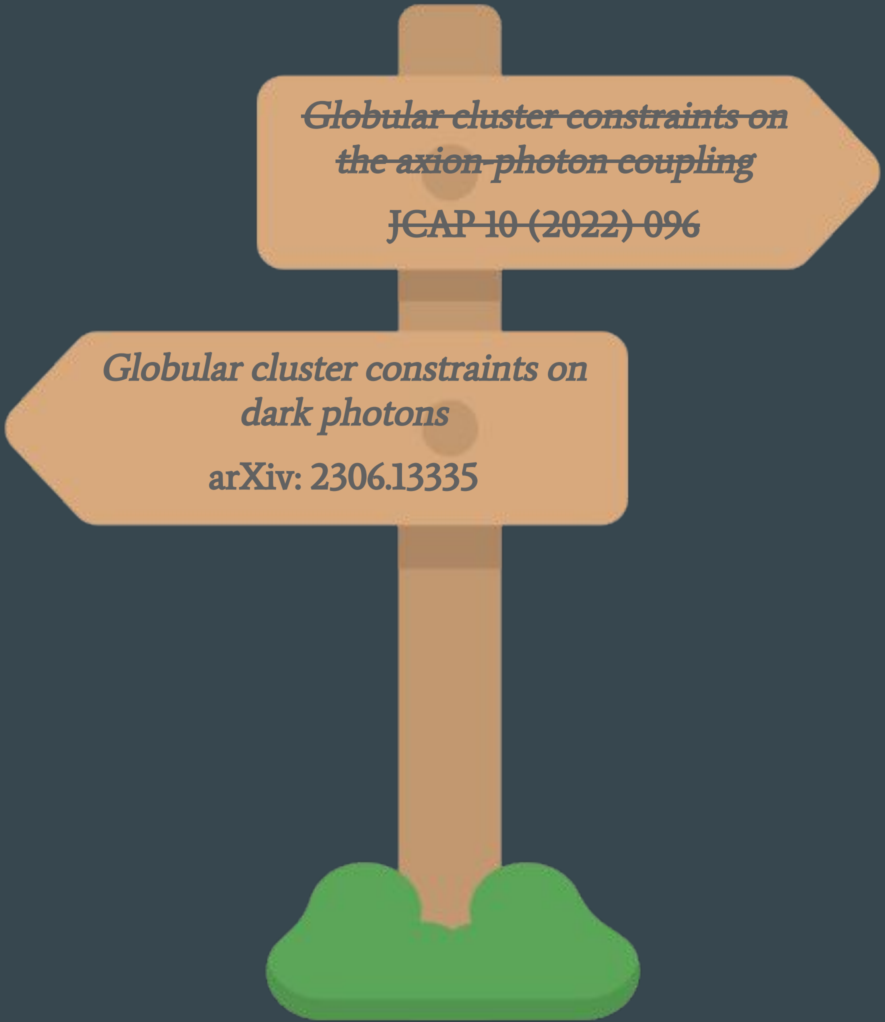
Original idea: leverage R and R_2 against one another to compute a total limit which marginalises over the uncertainty associated with convective boundaries

Reality: R_2 will always give you the strongest limit

New limit is both stronger and more robust than its predecessor

$$g_{10} < 0.47$$




~~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

Dark photons

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

Interact with the SM via kinetic mixing with the visible photon

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

Dark photons

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

Interact with the SM via kinetic mixing with the visible photon

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

Can constitute dark matter, or act as a mediator between the dark and visible sectors

Dark photons

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

Interact with the SM via kinetic mixing with the visible photon

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

Can constitute dark matter, or act as a mediator between the dark and visible sectors

Their parameter space is defined by their mass

Dark photons

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

Interact with the SM via kinetic mixing with the visible photon

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

Can constitute dark matter, or act as a mediator between the dark and visible sectors

Their parameter space is defined by their mass and kinetic mixing parameter

Dark photon stellar cooling constraints

Stellar limits on dark photons exist, e.g. those from the Sun, RGB stars, the *R*-parameter

Dark photon stellar cooling constraints

THE UNIVERSITY OF MELBOURNE

Stellar limits on dark photons exist, e.g. those from the Sun, RGB stars, the *R*-parameter

However, these limits are *static*, i.e. they have been derived by:

Dark photon stellar cooling constraints

Stellar limits on dark photons exist, e.g. those from the Sun, RGB stars, the *R*-parameter

However, these limits are *static*, i.e. they have been derived by:

1

Convert existing bounds on axions/neutrinos to upper limits on novel energy-loss

Dark photon stellar cooling constraints

Stellar limits on dark photons exist, e.g. those from the Sun, RGB stars, the *R*-parameter

However, these limits are *static*, i.e. they have been derived by:

1 Convert existing bounds on axions/neutrinos to upper limits on novel energy-loss

2 Demand that DP energy-loss be less than this when integrated/averaged over a **static** stellar profile

Dark photon stellar cooling constraints

Stellar limits on dark photons exist, e.g. those from the Sun, RGB stars, the *R*-parameter

However, these limits are *static*, i.e. they have been derived by:

1. Convert existing bounds on axions/neutrinos to upper limits on novel energy-loss
2. Demand that DP energy-loss be less than this when integrated/averaged over a **static** stellar profile

The reliability of static limits can only be guaranteed if dark photons affect stellar evolution in a similar fashion to the original target

Dark photon stellar cooling constraints

Stellar limits on dark photons exist, e.g. those from the Sun, RGB stars, the *R*-parameter

However, these limits are *static*, i.e. they have been derived by:

1 Convert existing bounds on axions/neutrinos to upper limits on novel energy-loss

2 Demand that DP energy-loss be less than this when integrated/averaged over a **static** stellar profile

The reliability of static limits can only be guaranteed if dark photons affect stellar evolution in a similar fashion to the original target

This is not the case for transverse dark photons: production in star localised to region with plasma frequency equal to the dark photon mass - **resonant production region (RPR)**

*transverse

Dark photon stellar cooling constraints

Stellar limits on dark photons exist, e.g. those from the Sun, RGB stars, the *R*-parameter

However, these limits are *static*, i.e. they have been derived by:

1. Convert existing bounds on axions/neutrinos to upper limits on novel energy-loss
2. Demand that DP energy-loss be less than this when integrated/averaged over a **static** stellar profile

The reliability of static limits can only be guaranteed if dark photons affect stellar evolution in a similar fashion to the original target

This is not the case for transverse dark photons: production in star localised to region with plasma frequency equal to the dark photon mass - **resonant production region (RPR)**

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...

Selected results

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

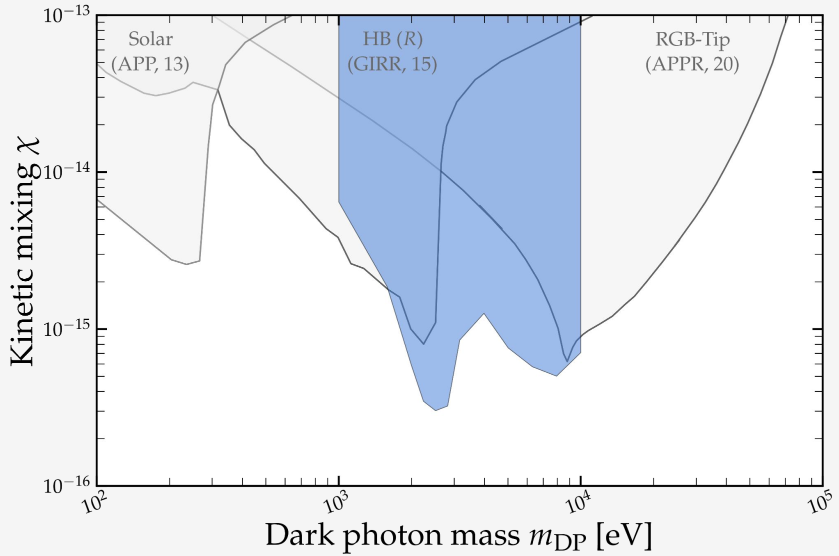
We found...

Selected results

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

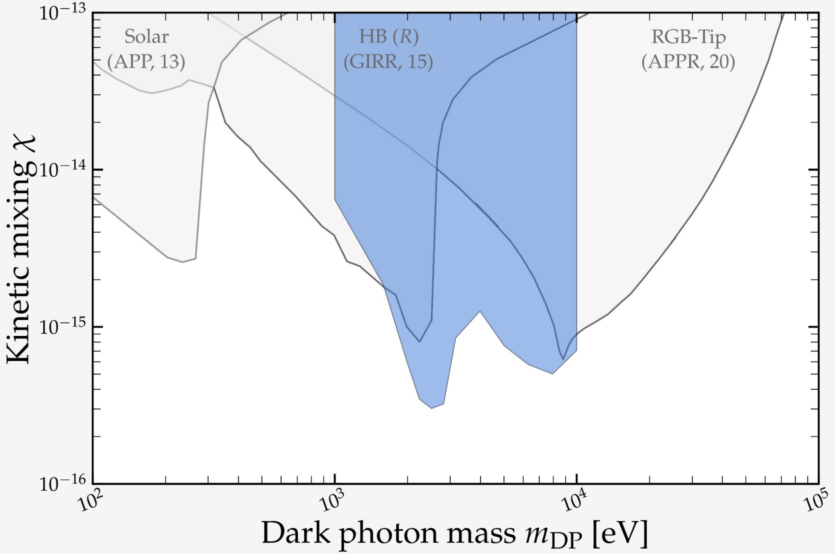
We found...

R_2 is particularly well-placed to constrain this



Selected results

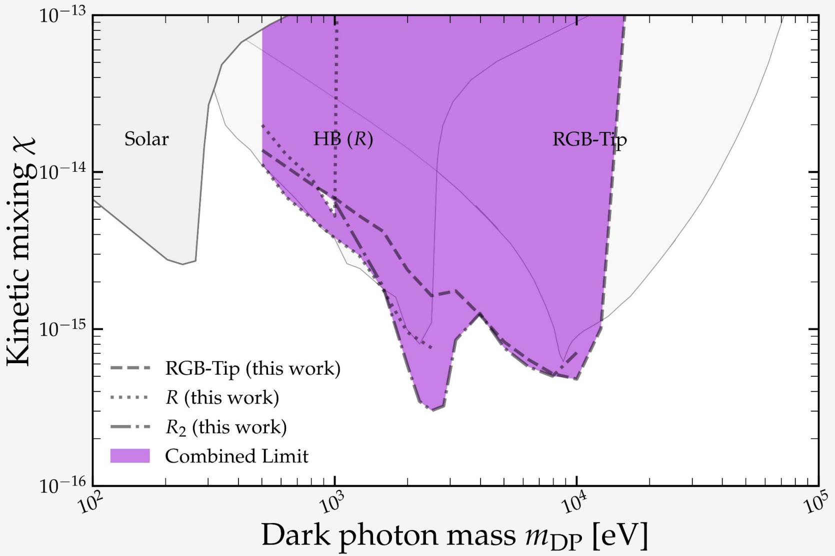
Supplement with updated limits from R and the RGB-tip luminosity



Selected results

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

Yields our **combined constraint**

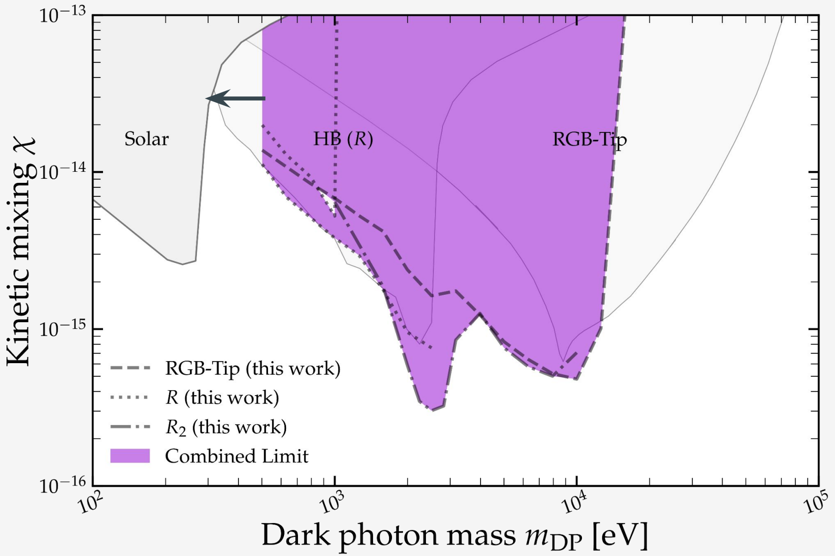


Selected results

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

Yields our **combined constraint**

Could not extend bound below 400 eV in mass due to complications with simulating main sequence evolution



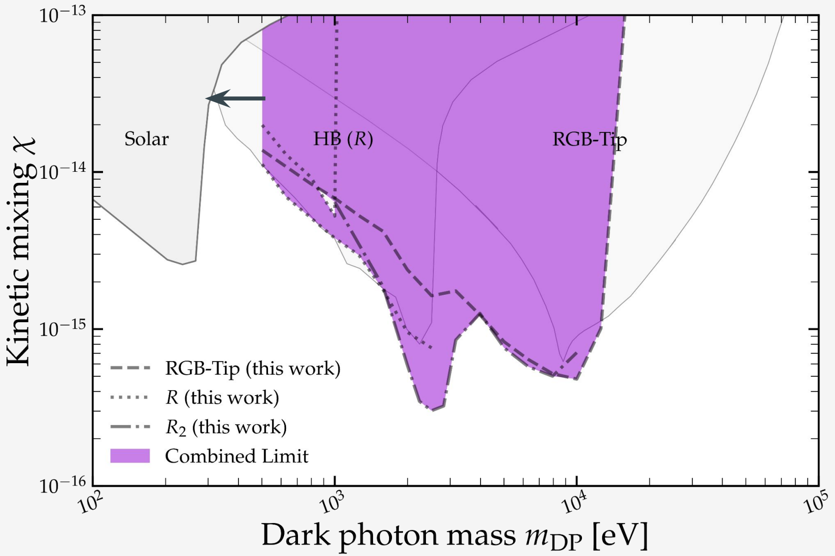
Selected results

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

Yields our **combined constraint**

Could not extend bound below 400 eV in mass due to complications with simulating main sequence evolution

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

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

THE UNIVERSITY OF MELBOURNE

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

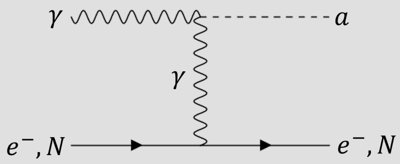
Increasing g_{10} reduces R - for high enough values it will contradict observation

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

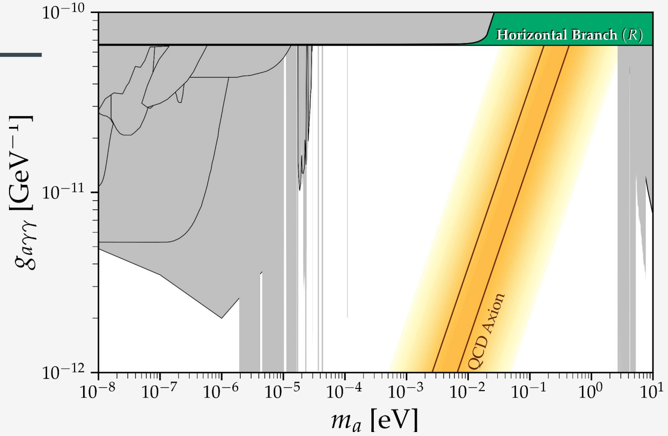
Ayala, et al., *Phys. Rev. Lett.* **113** (2014) 191302

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

Primakoff production



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



Aside: The HB convective core boundary (convective overshoot)

THE UNIVERSITY OF MELBOURNE

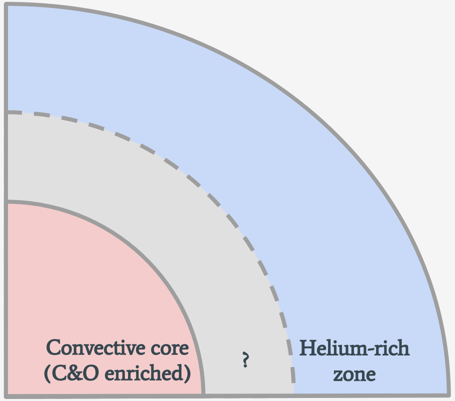
Formally, the convective boundary (CB) is the location at which **acceleration** (but not momentum) of convective elements falls to zero

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 $\nabla_{\rm rad}$ and growth of the convective core

Growth of core results in influx of helium into it - lowers $\nabla_{\rm rad}$ 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: $\omega \approx \omega_{\mathrm{p}}$

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

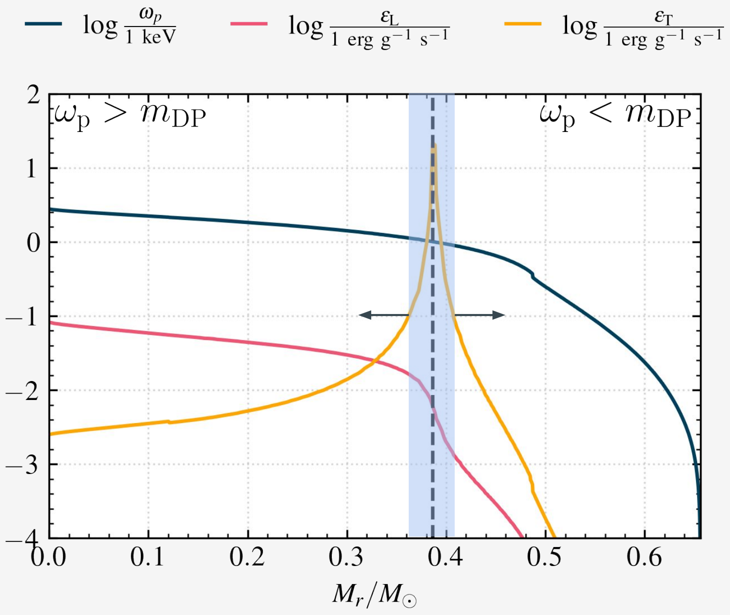
Resonant production when: $\omega_{\mathrm{p}} \approx m_{\mathrm{DP}}$

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

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