Constraining the Axion-Photon Coupling with Massive Stars

Maurizio Giannotti, *Barry University*

(Mostly) Based on:
Phys.Rev.Lett. 110 (2013) 061101
with A. Friedland and M.Wise

9th PATRAS Workshop

Schloss Waldthausen, Mainz, June 2013

Stars as Laboratories

For 50 years stars have been excellent laboratories for light, weakly interacting particles. In fact, stars are sensitive to very rare processes, e.g.,

J. Bernstein et al., Phys. Rev. 132, 1227 (1963)

$$\gamma \rightarrow \nu + \bar{\nu}$$

and

$$e^{+} + e^{-} \rightarrow \nu + \bar{\nu}$$

which are extremely rare but play a fundamental role in stellar cooling.

Examples of models strongly constrained by stars include majorons, extra-dimensional photons, novel baryonic or leptonic forces, unparticles, etc.

H.M. Georgi, S.L. Glashow, and S. Nussinov, Nucl. Phys. B193, 297 (1981)

A. Friedland and M. Giannotti, Phys. Rev. Lett. 100, 031602 (2008)

Grifols and E. Masso, Phys. Lett. B 173, 237 (1986)

S. Hannestad, G. Raffelt, and Y.Y.Y. Wong, Phys. Rev. D76, 121701 (2007)

A considerable improvement in astrophysical observations analysis is now leading to revision and improvement of stellar bounds (*see talk by N. Viaux* on Thursday)

Axion and Axion-Like Particles (ALPs)

A particularly interesting example of light, weakly interacting particle is the **axion**, hypothetical particle whose existence is a prediction of the Peccei-Quinn solution of the Strong CP problem (*see talk by P. Sikivie/D. Tanner*) and prominent dark matter candidate (*see talk by P. Sikivie on Thursday*).

Peccei and Quinn (1977),
Weinberg (1978),
Wilczek (1978)

Preskill, Wise and Wilczek (1983)
Abbott and Sikivie (1983)
Dine and Fischler (1983)

In the *standard* (QCD) *axion models* the axion interaction with matter and photons and the axion mass are related through the Peccei-Quinn constant f_a

$$L_{\text{int}} = -i\frac{C_i m_i}{f_a} a\bar{\psi}\gamma_5\psi - \frac{1}{4} g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Axion-photon coupling

$$m_a \approx \frac{6\,\text{eV}}{f_a/10^6\,\text{GeV}}$$

$$g_{a\gamma} = \xi \frac{\alpha_{em}}{2\pi\ f_a}$$

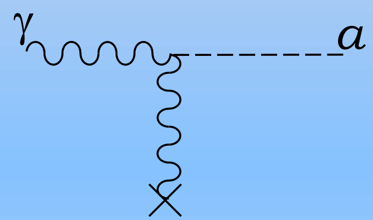
In more general models (**ALPs**), couplings and the mass are unrelated (discussed in more detail on Friday)

Axions and Stellar Evolution

Light ALPs can be produced in stars through various mechanisms, e.g.

Primakoff conversion

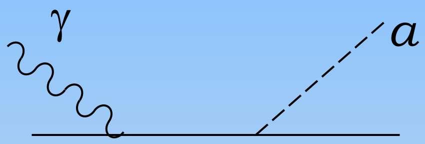
$$\gamma + Ze \rightarrow a + Ze$$



Relevant in He-burning stars

Compton scattering

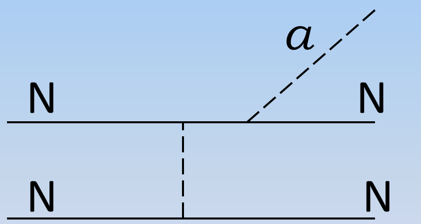
$$\gamma + e \rightarrow a + e$$



Relevant in RG and WD

Nucleon Bremsstrahlung

$$N + N \rightarrow N + N + a$$



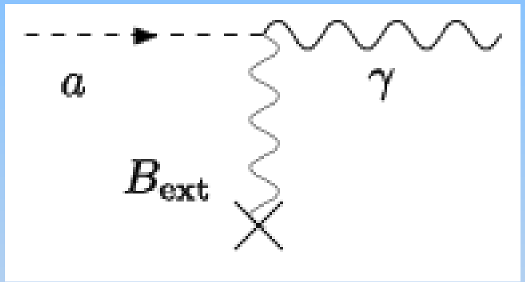
Relevant in SN and neutron stars

The emission of axions could lead to an *overly efficient energy drain*, inconsistent with observations. This leads to bounds on the axion couplings with photons, electrons and nuclei.

Axion detection: the role of the Axion-Photon Coupling

Most of the modern axion searches are based on the microwave cavity detection proposed by P. Sikivie, which relays on the axion-photon coupling. Axions can be converted into photons in an external magnetic filed. These bounds depend on the axion mass.

P. Sikivie, Phys.Rev.Lett. 51, 1415 (1983)



Axion-photon vertex

A strong terrestrial bound on the axion (ALPs)-photon coupling comes from the Cern Axion Solar Telescope (**CAST**)

$$g_{a\gamma} \leq 0.88\times10^{-10}\mathrm{GeV}^{-1}$$

The bound is however weakened at masses >0.02eV (in the QCD –axion region)

Experimental Axion (and ALPs) Search

- **Vacuum Phase**

  $m_a \leq 0.02\,eV$

  → $g_{a\gamma}$ (95%) < 0.88 x 10^{-10} GeV^{-1}
  → Phys.Rev.Lett.94:121301, 2005
  → JCAP 04 (2007) 010

- **^{4}He Phase**

  $0.02\,eV \leq m_a \leq 0.39\,eV$

  → g_{ag} (95%) < 2.2 x 10^{-10} GeV^{-1}
  → JCAP 02 (2009) 008

- **^{3}He Phase: first results**

  $0.39\,eV \leq m_a \leq 0.65\,eV$

  → $g_{a\gamma}$ (95%) < 2.3 x 10^{-10} GeV^{-1}
  → Phys.Rev.Lett. 107:261302, 2011

- **^{3}He Phase: preliminary results**

  $0.65\,eV \leq m_a \leq 1.18\,eV$

  → Publication in preparation

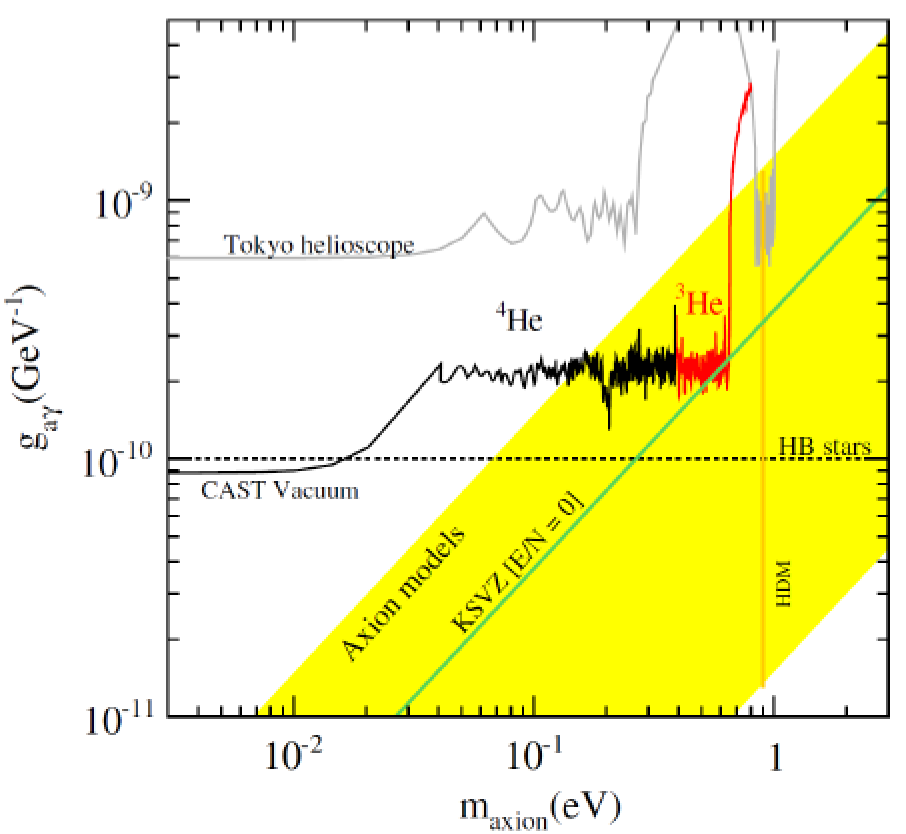
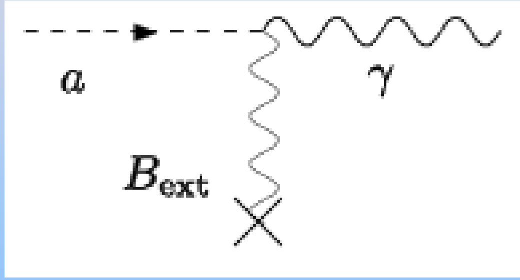


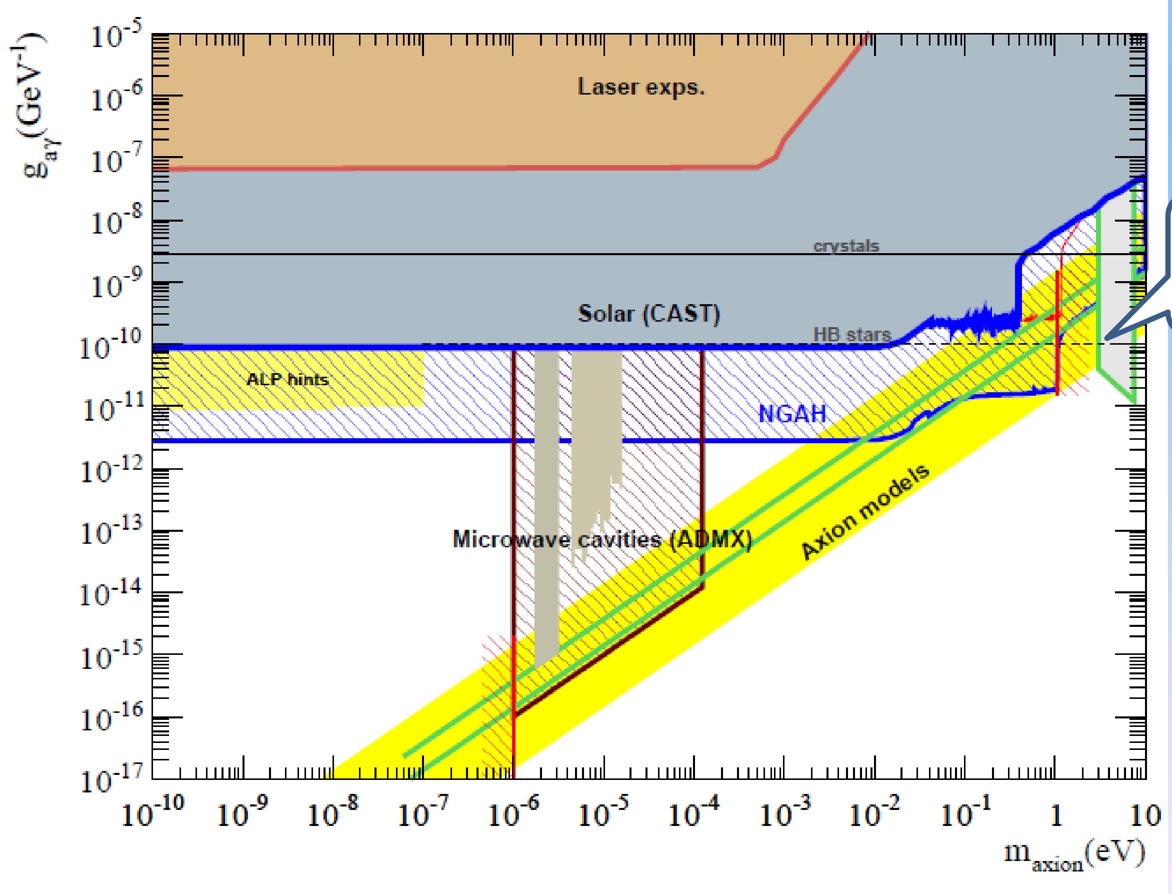
Image and data from Julia Vogel (LLNL), CAST

Experimental Axion (and ALPs) Search

The Next Generation Axion Helioscopes (NGAH) are expected to improve the bounds by over an order of magnitude (*See talk by B. Lakic, later today*)



Axion-photon vertex

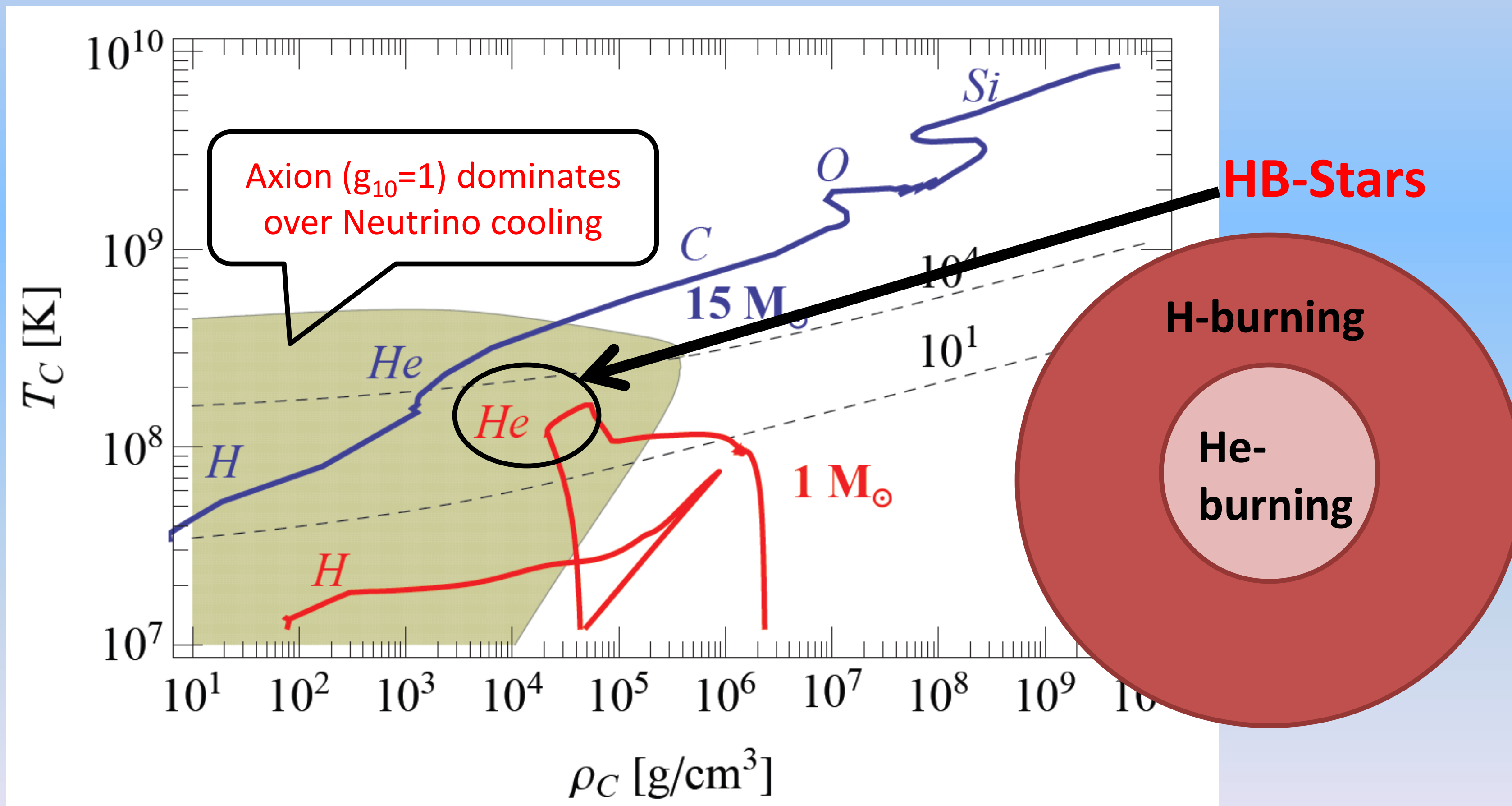


HB-bound, g_{10}=1.
Raffelt and Dearborn (1987)

from I. G. Irastorza et al., *Latest results and prospects of the CERN Axion Solar Telescope*, Journal of Physics: Conference Series **309 (2011) 012001**

The HB bound on the axion-photon Coupling

Axions can be produced in the core of a star from photons interacting with the electric field of the nuclei (**Primakoff process**).



Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

The HB bound on the axion-photon Coupling

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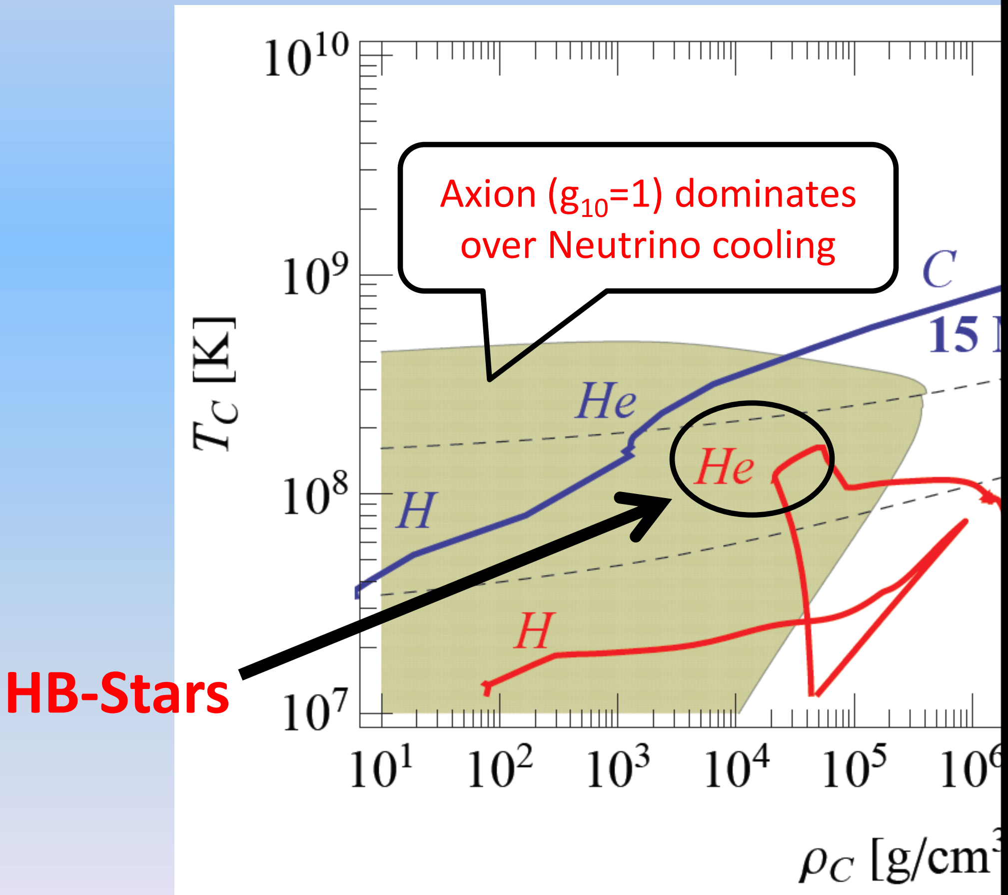
interacting with the electric field of the



Friedland, Giannotti, Wise, **Phys. Rev.**

Axions coupled too strongly to photons would <u>speed up the consumption of He in the HB star core and reduce the HB lifetime</u>.

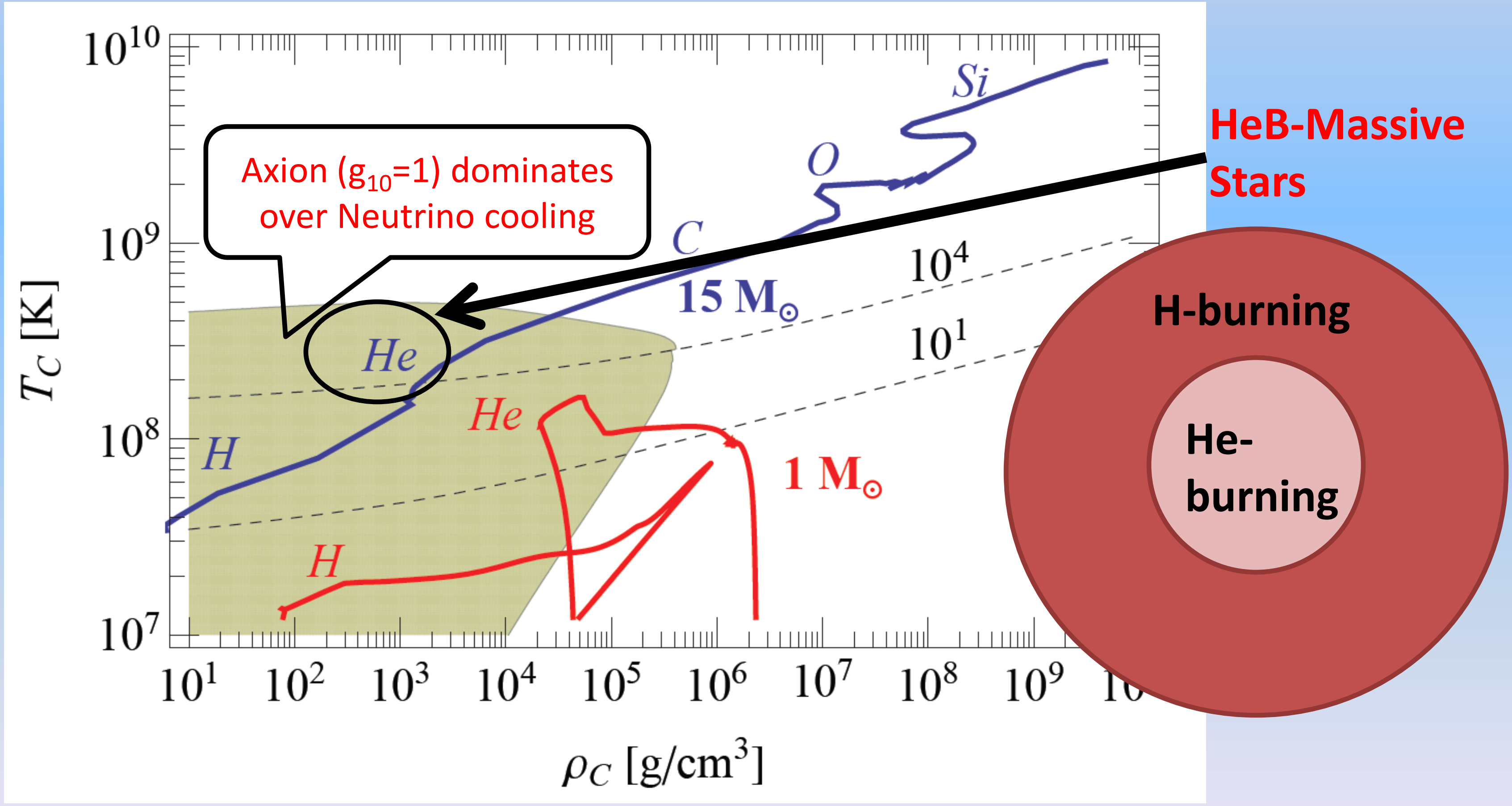
Observational constrains come from the <u>comparison of the number of HB vs. RG stars</u>.

The bound $g_{a\gamma} \leq 10^{-10}\mathrm{GeV}^{-1}$ [G.G. Raffelt and D.S.P. Dearborn, **Phys. Rev. D36, 2211(1987)**] (which is the one currently reported in the PDG) corresponds to a <u>reduction of the HB star lifetime by 30%</u>.

The bound applies to axion masses <30 keV or so.

Axion and He-burning massive stars

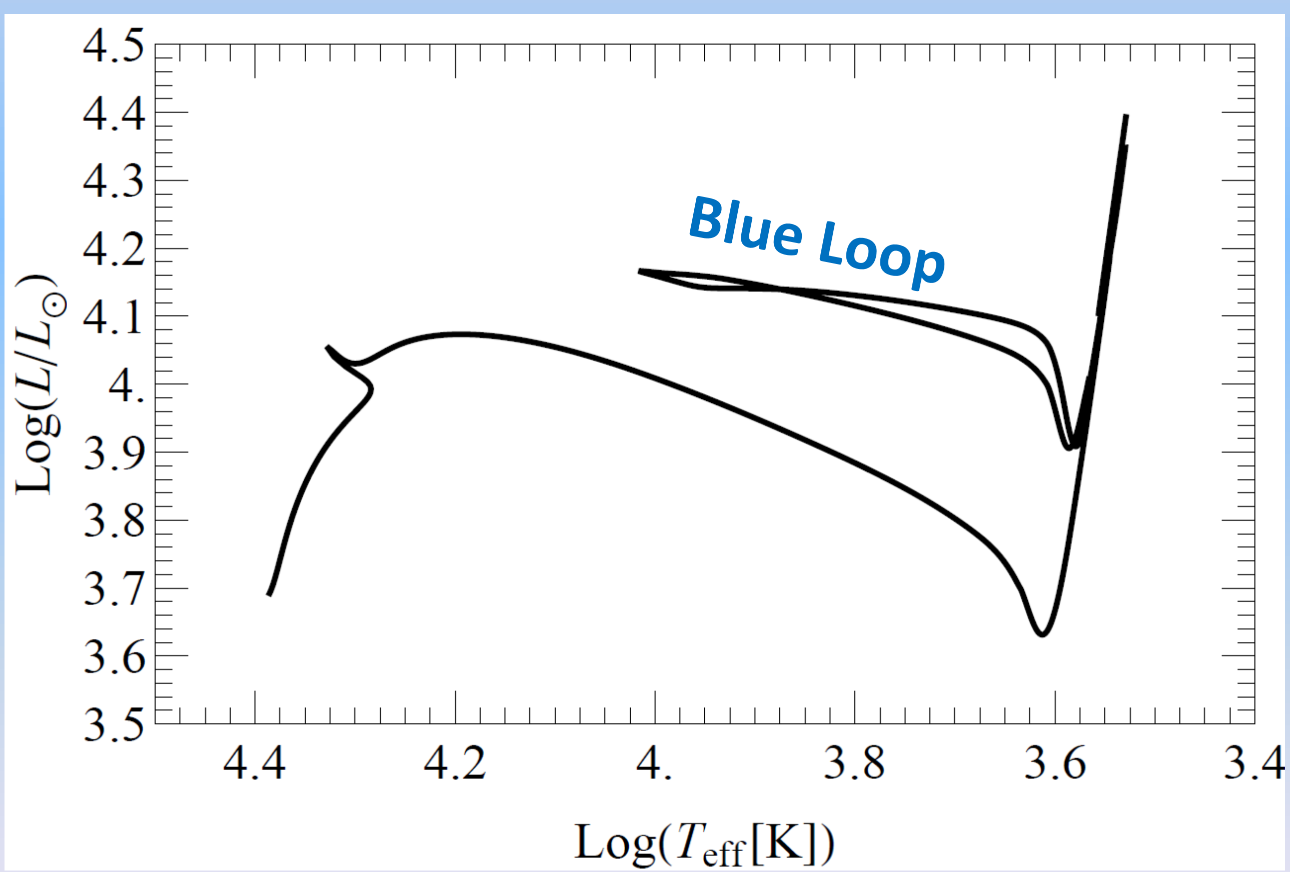
However, the currently strongest bound on the axion-photon coupling comes from the analysis of the evolution of He-burning massive stars



Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

The Blue Loop

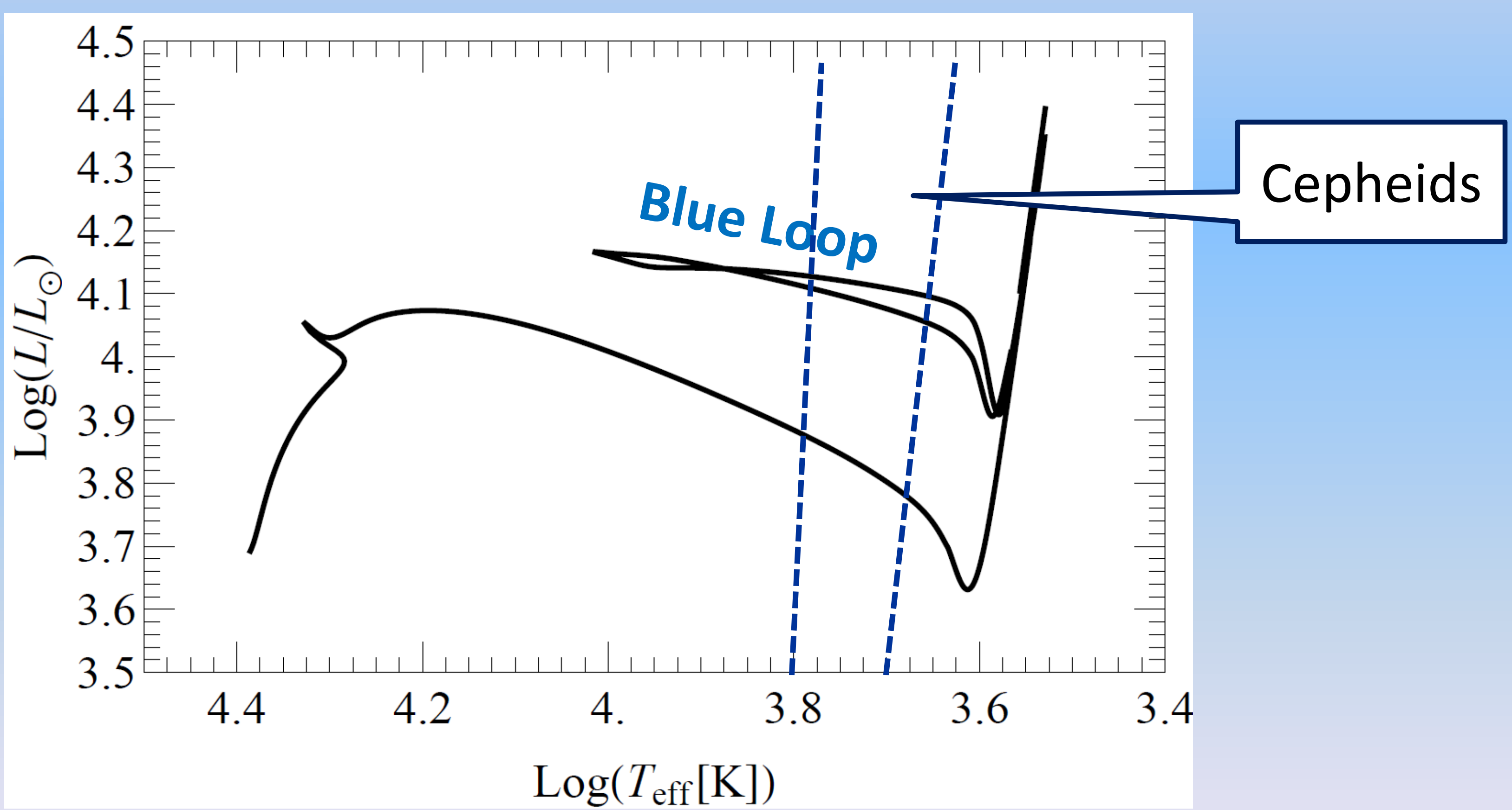
The HR diagram shows the luminosity v.s. surface temperature of a star.
The **blue loop** is a prominent feature of the evolution of a massive star.



Simulations for a 9.5$M_\odot$, solar metallicity, from main sequence to end of He-burning.
MESA (Modules for Experiments in Stellar Astrophysics), Paxton et al. *ApJ Suppl*. **192** 3 (2011) [arXiv:1009.1622]

The Blue Loop and the Cepheids

The blue loops are necessary to explain the existence of the Cepheids



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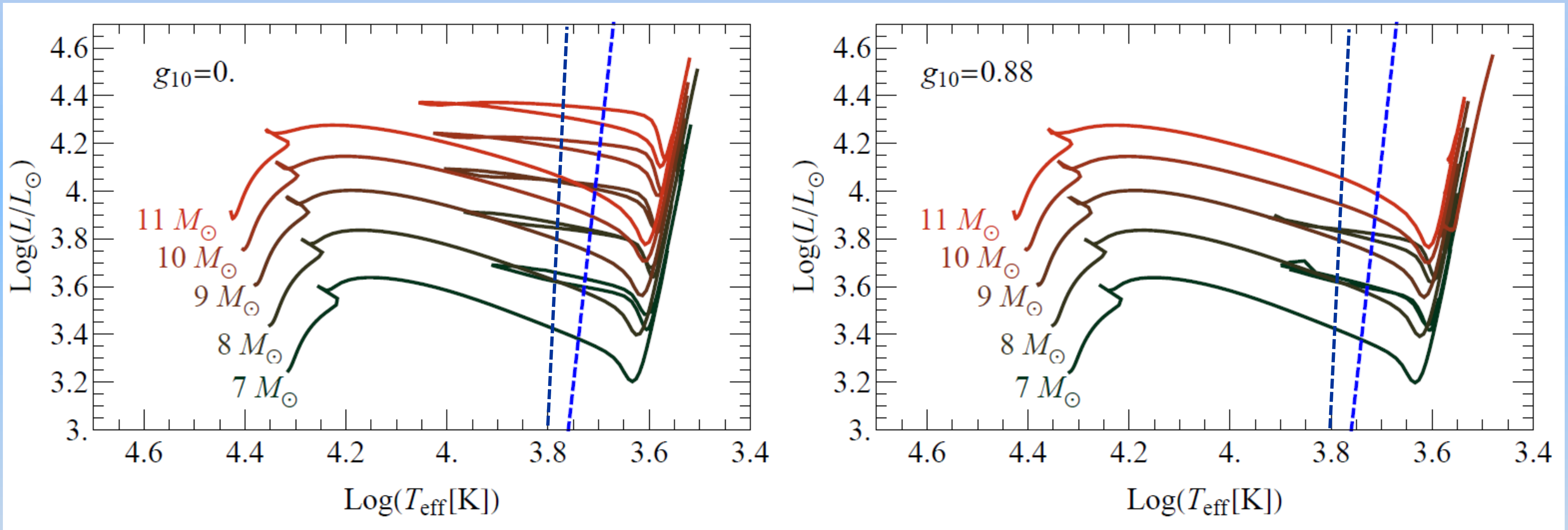
MESA (Modules for Experiments in Stellar Astrophysics), Paxton et al. *ApJ Suppl*. **192** 3 (2011) [arXiv:1009.1622]

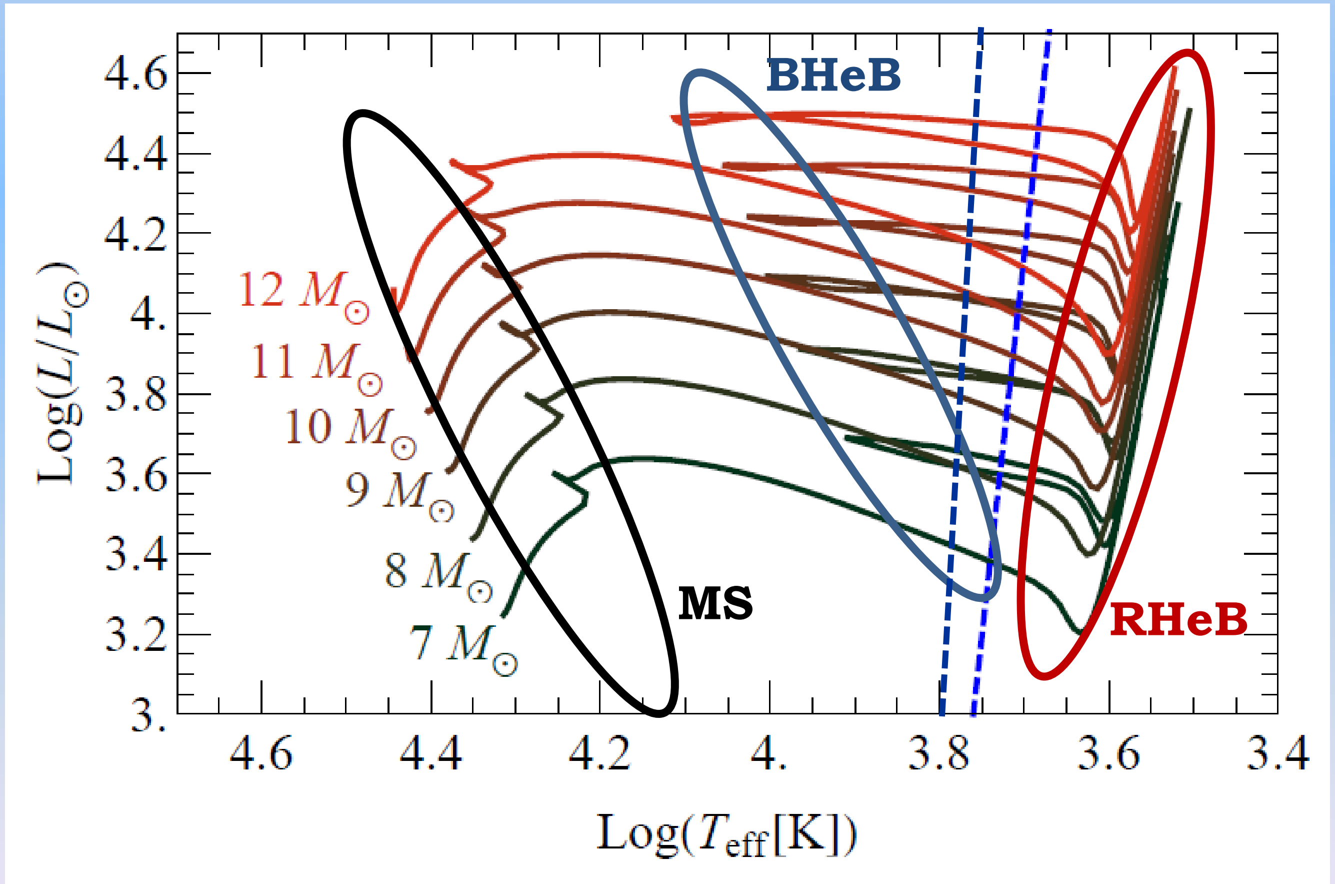
Axions effects on the Blue Loop

The value g_{10}=0.88 corresponds to the current CAST bound on the axion-photon coupling.



A value of g_{10}=0.8 would provide qualitative changes in the stellar evolution. In particular, it would eliminate the blue loop stage of the evolution, leaving one without an explanation for the existence of Cepheid stars in a broad range of pulsation periods.

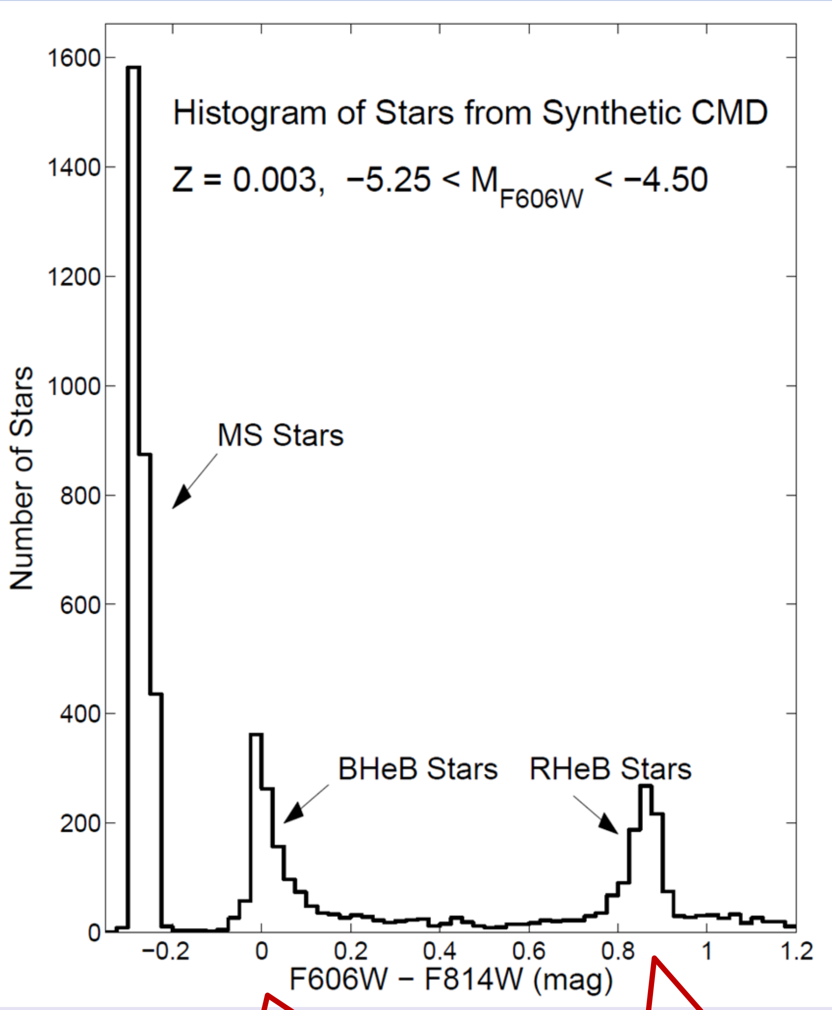
Observations of massive stars: Main, Blue and Red Sequences



Simulations of evolution in H-R diagram of stars with solar metallicity, from main sequence to end of He-burning. **[MESA]**

Most of the star life-time is spent in one of the three sequences: the **Main Sequence** (central H-burning), the **Red** central **He-Burning** sequence, and the **Blue** central **He-Burning** sequence

Observable evolutionary Phases: Central H- and He-burning



Log T[k]=4

Log T[k]=3.7

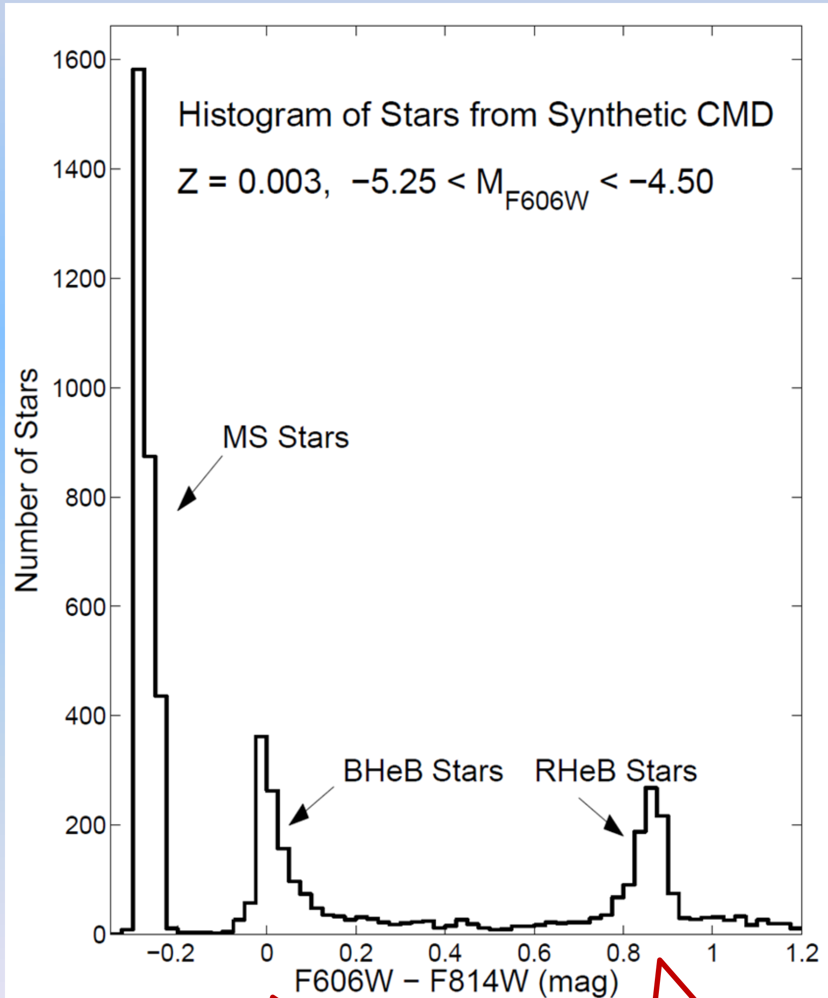
Blue stars have been observed for many decades and measurements are very accurate.

The contamination from MS stars transitioning to BHeB is conservatively estimated to be less than 10% (Dohm-Palmer & Skillman 2002).

The complete disappearance of all blue stars in certain luminosity regions is physically unacceptable.

From Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)

Observable evolutionary Phases: Central H- and He-burning



Log T[k]=4

Log T[k]=3.7

Result:

A value of g_{10} above 0.8 would be incompatible with the current observations of HeB sequences.

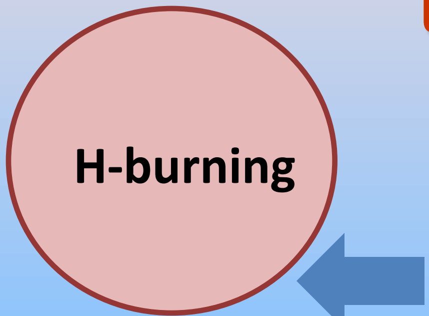
This analysis provides the *strongest bound to date* on the axion-photon coupling.

A.Friedland, M.G., and M.Wise,
Phys. Rev. Lett. 110, 061101 (2013)

See also
G. Raffelt, **http://physics.aps.org/articles/v6/14**

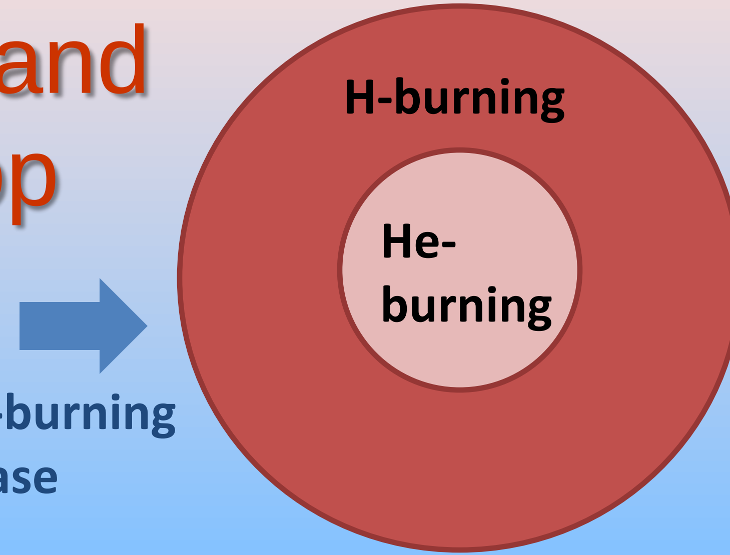
Astrophys.J. 740 (2011)

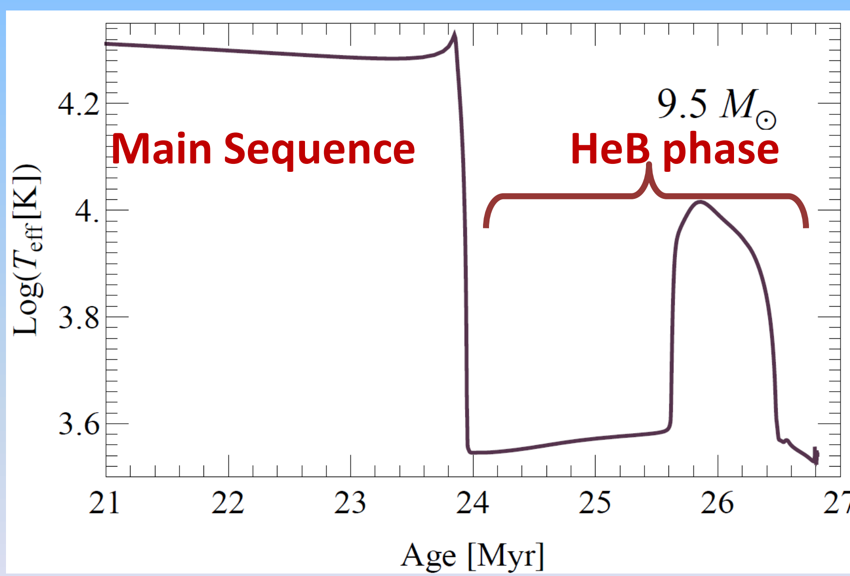
Massive stars and the Blue Loop

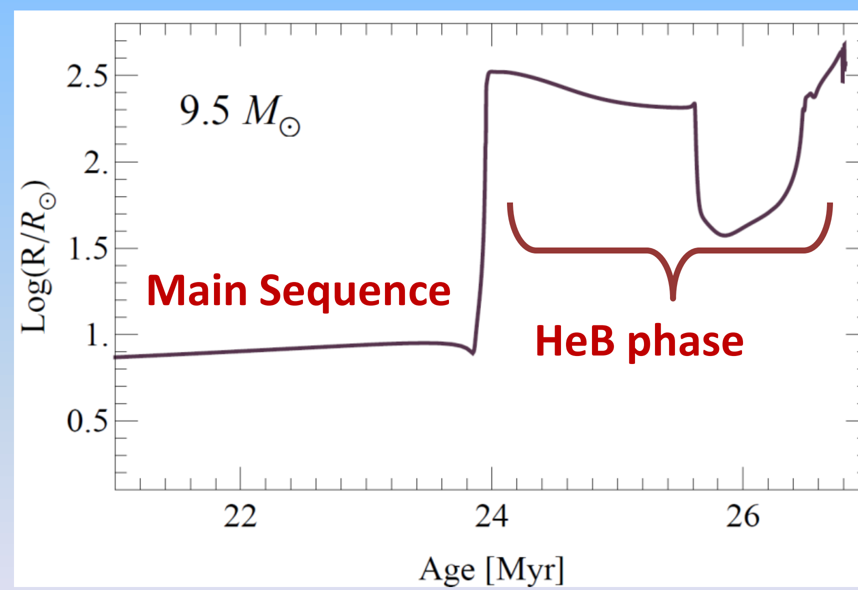


H-burning phase (Main Sequence)

He-burning phase







Simulations for a 9.5$M_\odot$, solar metallicity, from main sequence to end of He-burning.

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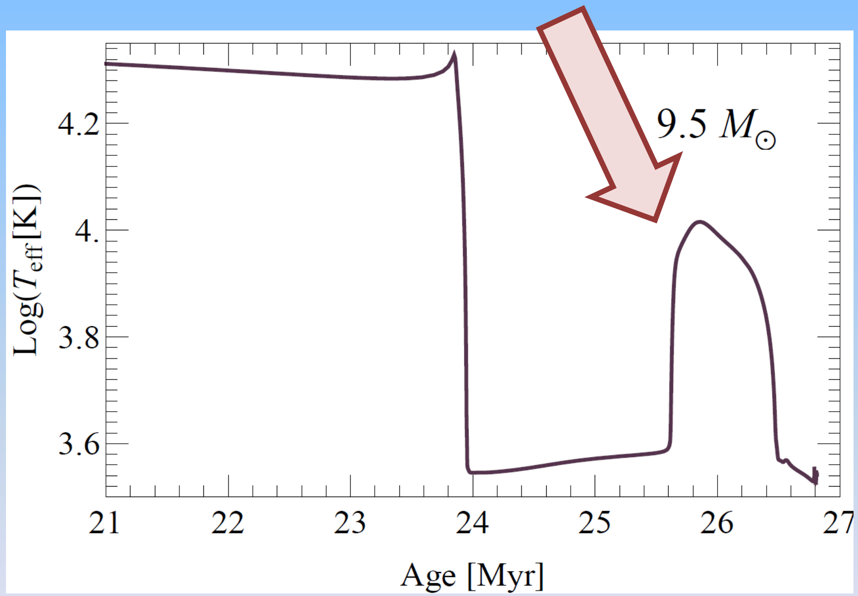
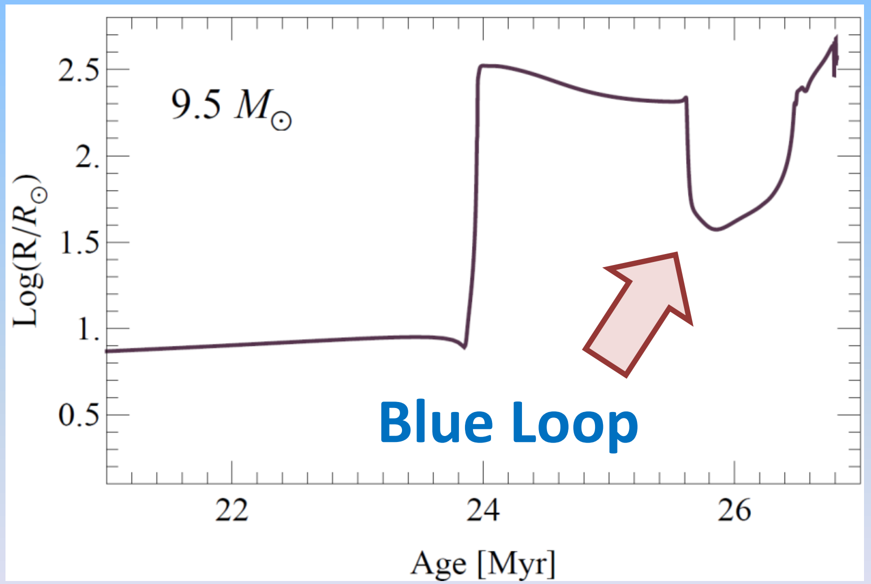
The Blue Loop

The journey of the star toward the hotter regions and back is called the **blue loop**. It happens for stars of a few solar masses during the He-burning stage.

Blue Loop





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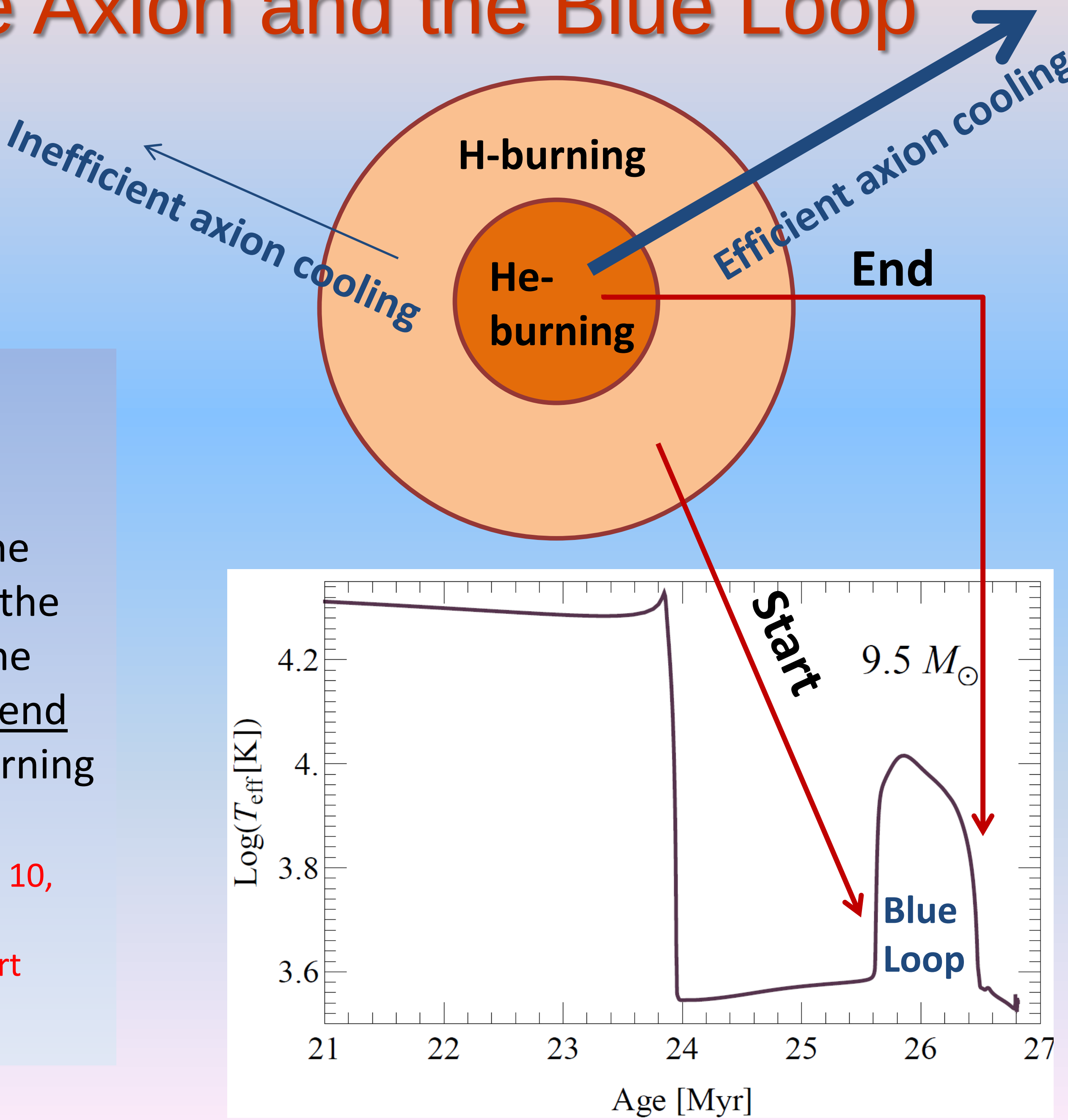
The Axion and the Blue Loop

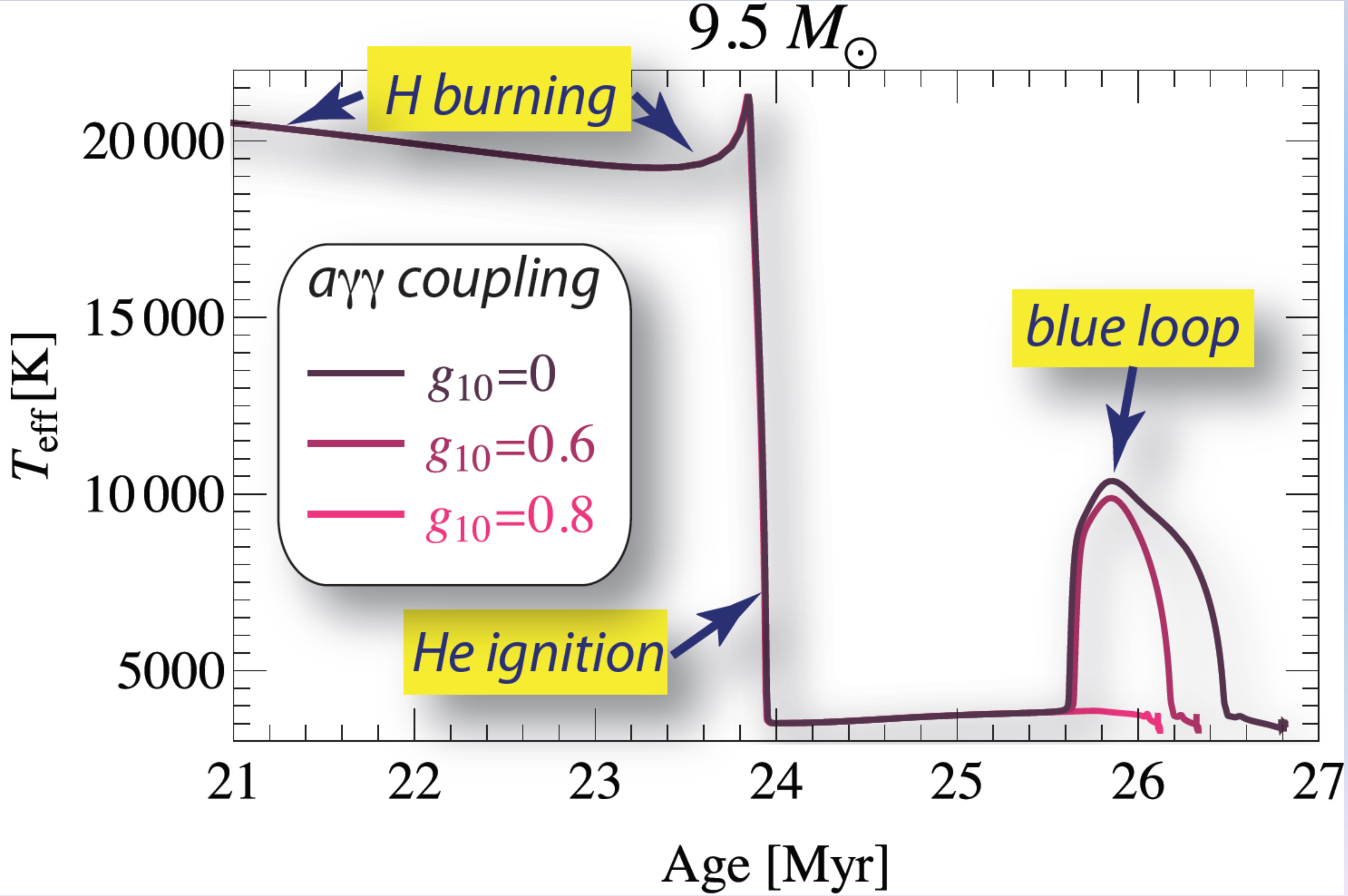


Blue Loop:

the <u>beginning</u> of the blue loop is set by the H-burning shell time scale whereas the <u>end</u> is set by the He-burning core time scale

[Lauterborn et al., A&A 10, (1971), Kippenhahn and Weigert (1994)]

The Axion and the Blue Loop



A.Friedland, M.G., and M.Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

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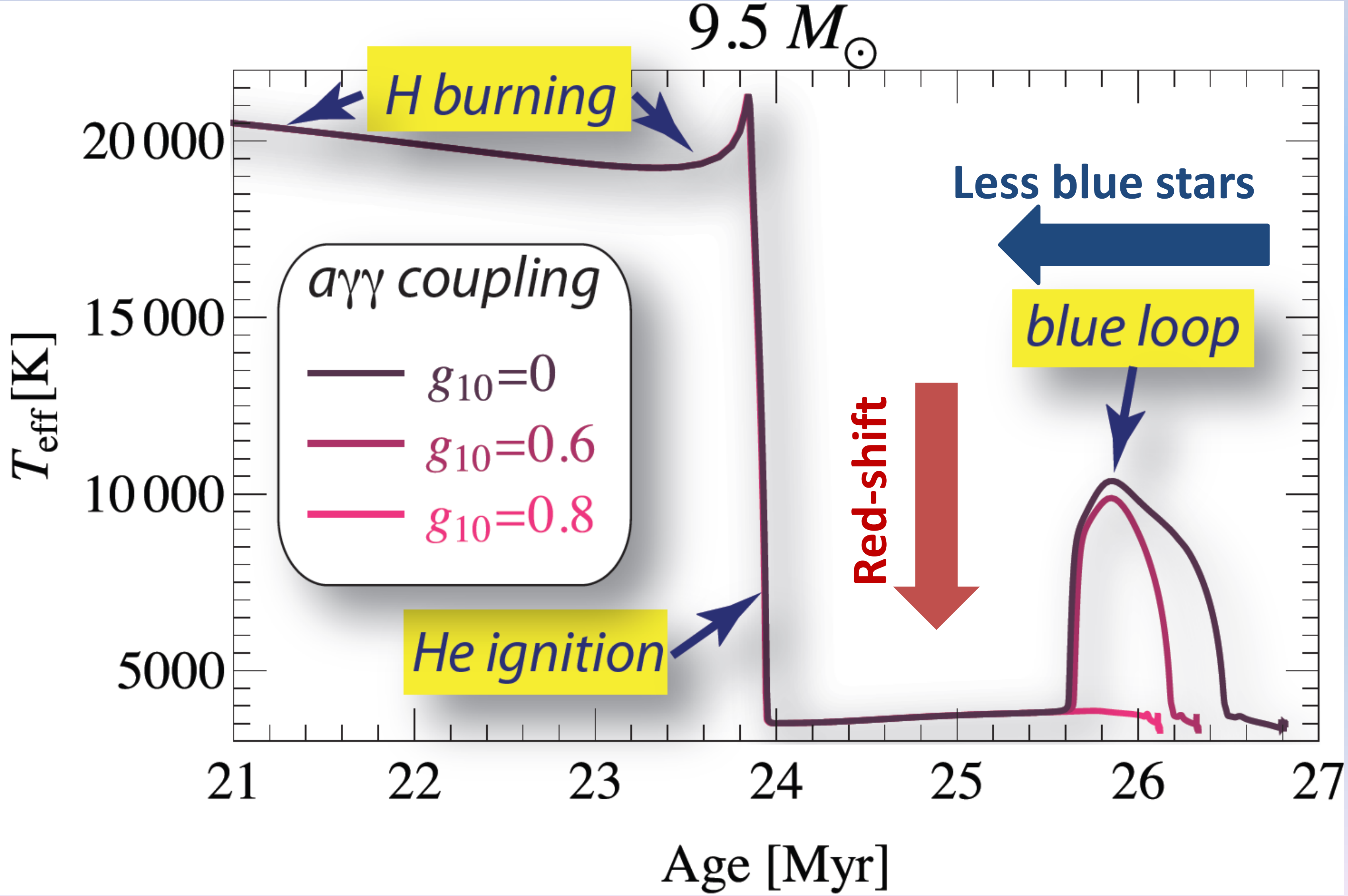


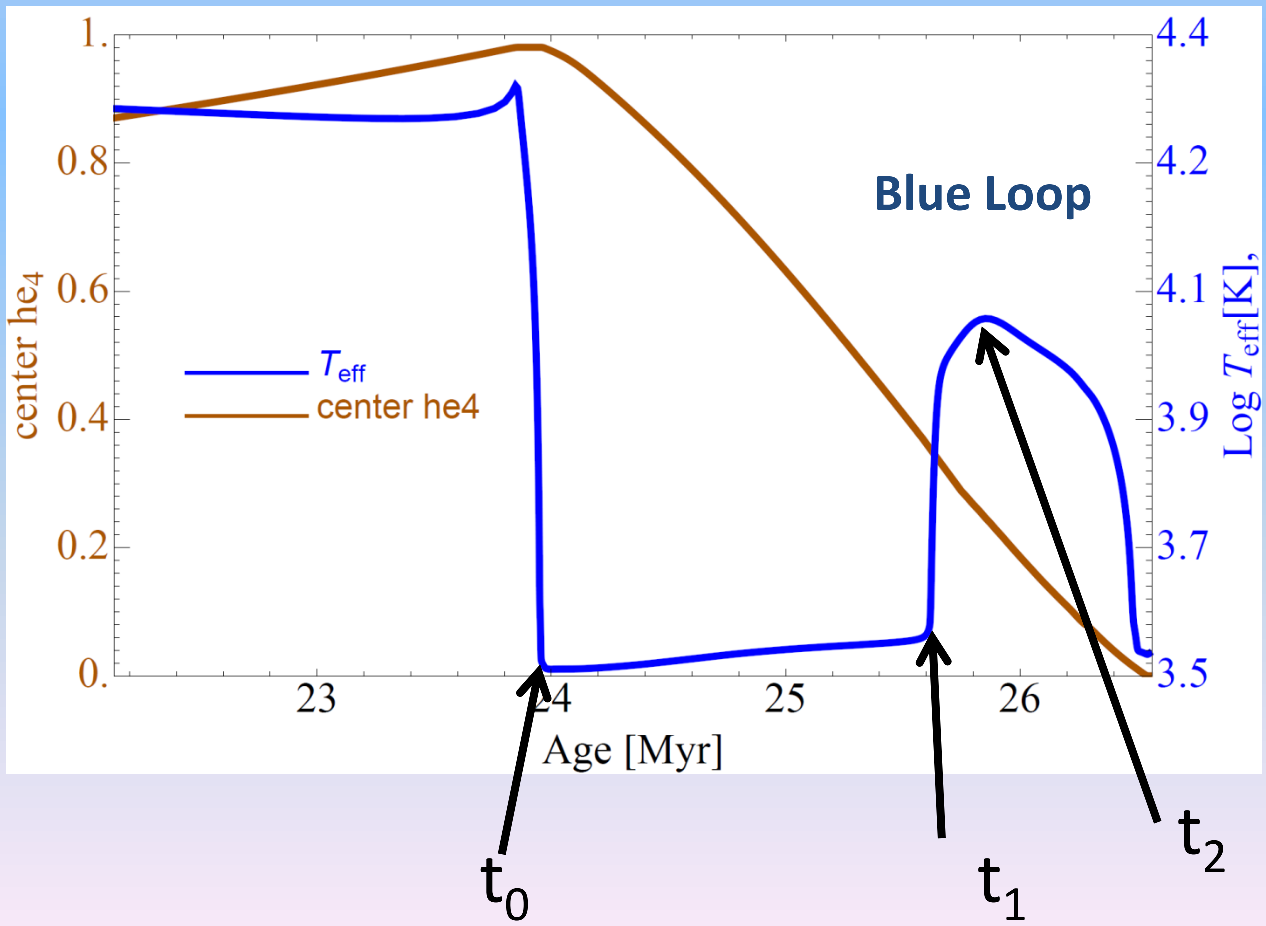
A.Friedland, M.G., and M.Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Blue loop as a probe for Fundamental Physics

When the He content in the core reaches a certain lower value (t_2), the surface temperature stops increasing and goes back to the red region of the HR diagram.

Speeding up the core evolution would eliminate the blue loop phase

[Lauterborn et al., A&A 10, (1971), E. Hofmeister, Z.F.A. 67, (1967)]



Characteristic times:

t_0: beginning of the core *He-burning phase*

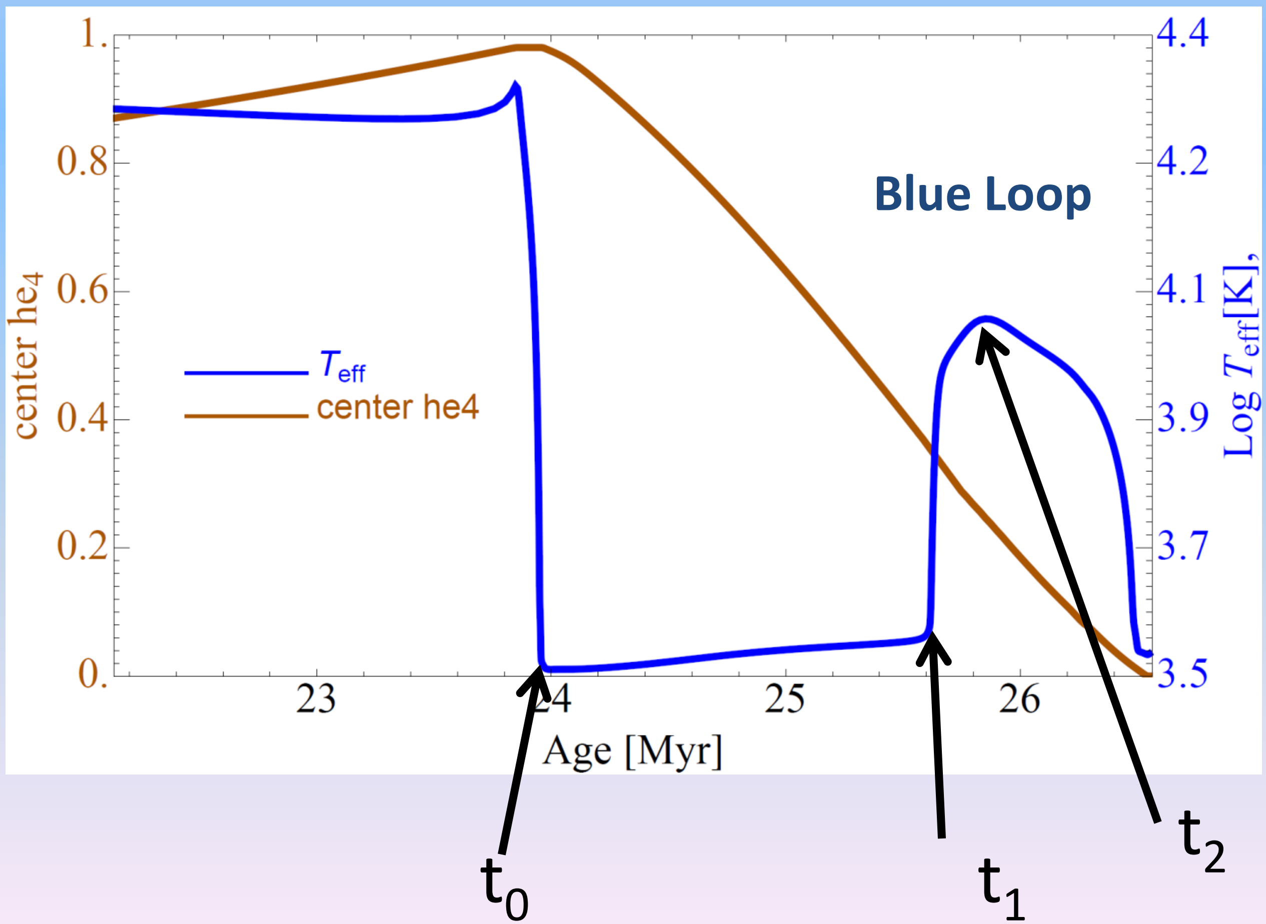
t_1: beginning of the *blue loop phase*

t_2: *turning point*

Blue loop as a probe for Fundamental Physics

A possible criteria: *A novel cooling mechanism which changes the he-burning time from t_{He} to t'_{He} would eliminate the blue loop phase if:*

$$\frac{t'_{He}}{t_{He}} \leq \frac{t_1 - t_0}{t_2 - t_0}$$



This criteria is independent from convection prescriptions and other possible uncertainties.

A conservative requirement for stars around 9-11 $M_\odot$ is that

$$t'_{He}/t_{He} \leq 0.8$$

is not allowed by observations.

Astro Labs: Massive vs. HB stars

HB and massive stars offer two different criteria for probing exotic processes which are efficient during the He-burning stage:

HB stars:

Lower core temperature, higher core density;

Relatively low energy production during he-burning:

$$\varepsilon_x \approx 80\,\mathrm{ergs\,g^{-1}\,s^{-1}}$$

Observations require:

$$t'_{He}/t_{He} \geq 0.7$$

[cfr. PDG and G.Raffelt in Axions, Springer (2010), chapter 3]

Massive stars:

Higher core temperature, lower core density;

High energy production during he-burning:

$$\varepsilon_x \approx \text{a few } 10^3\,\mathrm{ergs\,g^{-1}s^{-1}}$$

Observations require:

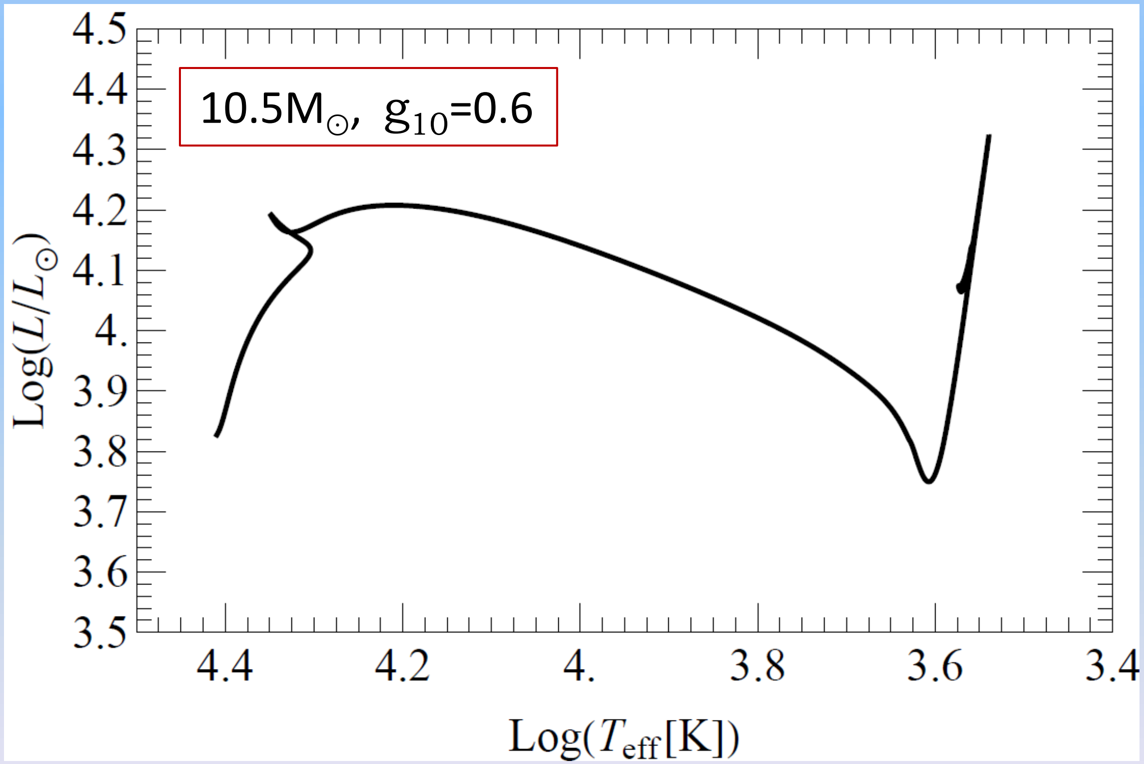
$$t'_{He}/t_{He} \geq 0.8$$

Massive stars are hotter and less dense. The maximal exotic cooling allowed by observation is larger than HB stars.

Exotic processes which are very sensitive to temperature are likely to be constrained more efficiently from massive stars. Otherwise, HB stars offer a better lab

Even Stronger Bounds?

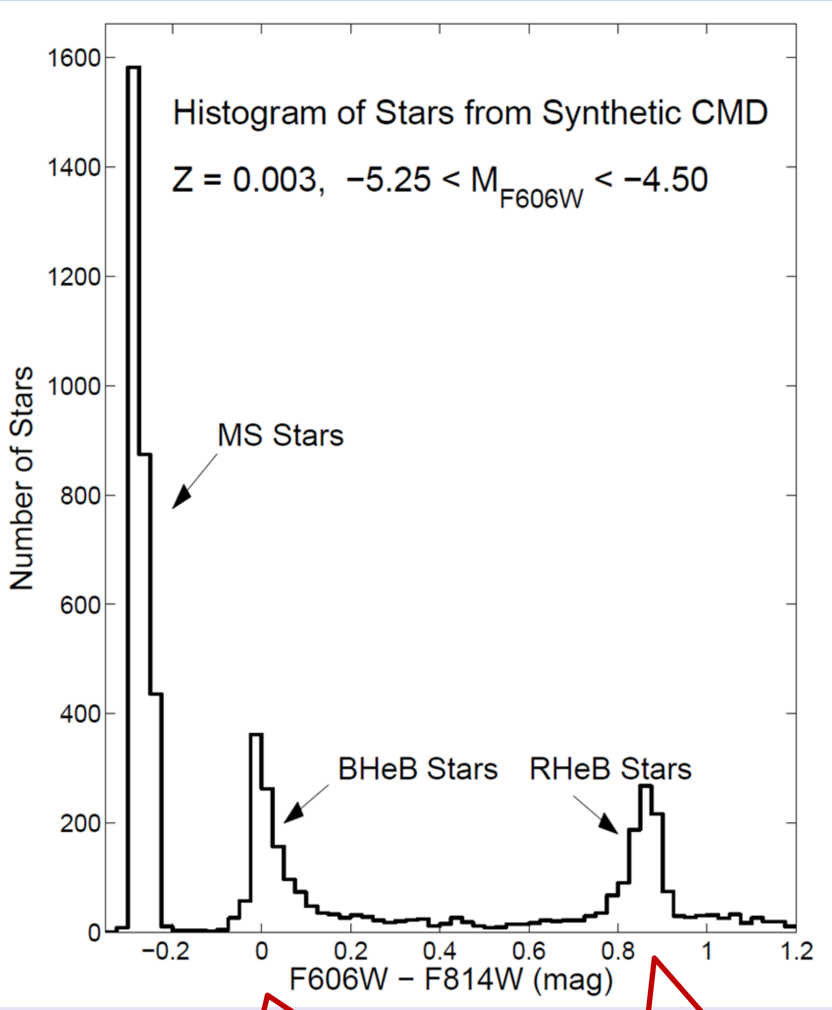
Other stars showed an even stronger response to axion cooling. (Friedland, M.G., Wise, work in progress).



Stars of mass between $10.5M_\odot$ and $11.5M_\odot$ don't show a loop already for g_{10}=0.6.

Stars of even larger mass are somewhat harder to model.

Even Stronger Bounds?



Log T[k]=4

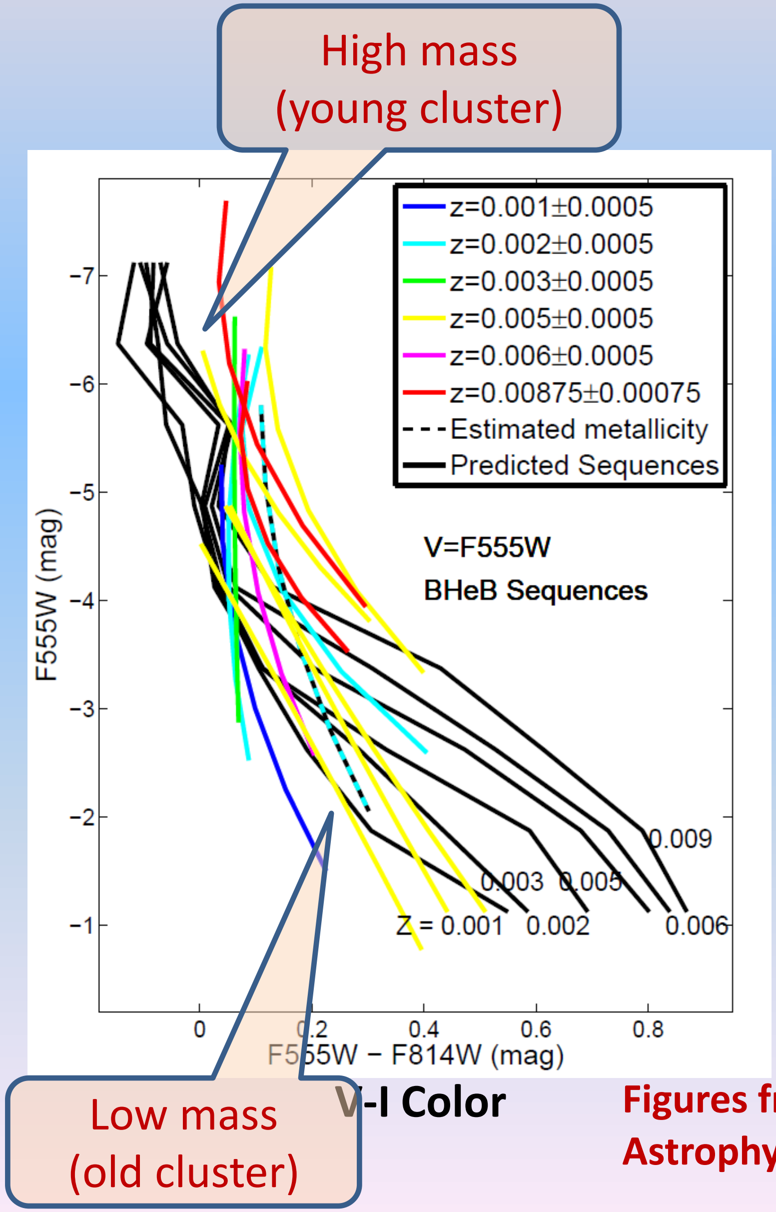
Log T[k]=3.7

In addition, the requirement that we used to derive the g_{10}=0.8 bound is conservative.

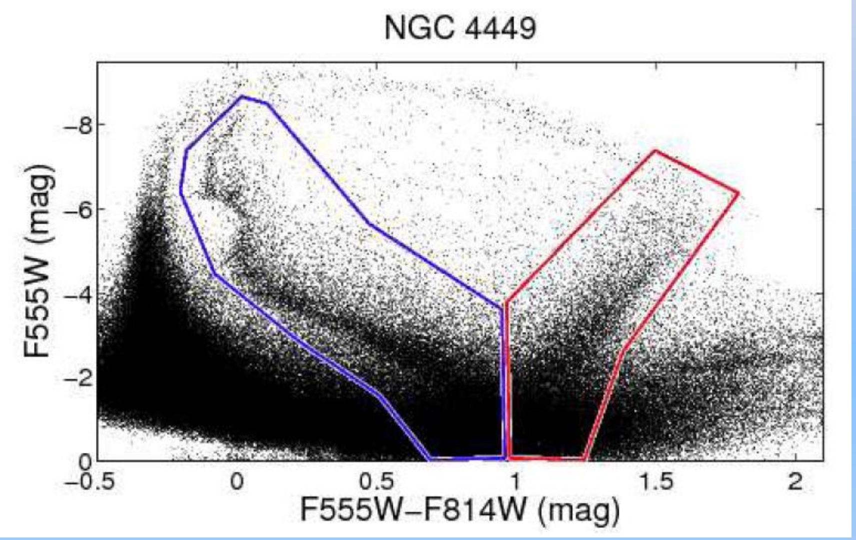
Given accurate counts, it may be possible to check whether the number of stars in the blue loop phase is reduced.

For example, g_{10} = 0.6 would reduce the time a 9.5 $M_{\odot}$ star spends on the blue loop by a factor of two or so. To get the same sensitivity for g_{10} from solar-mass stars requires knowing the numbers of HB stars to a 10% precision.

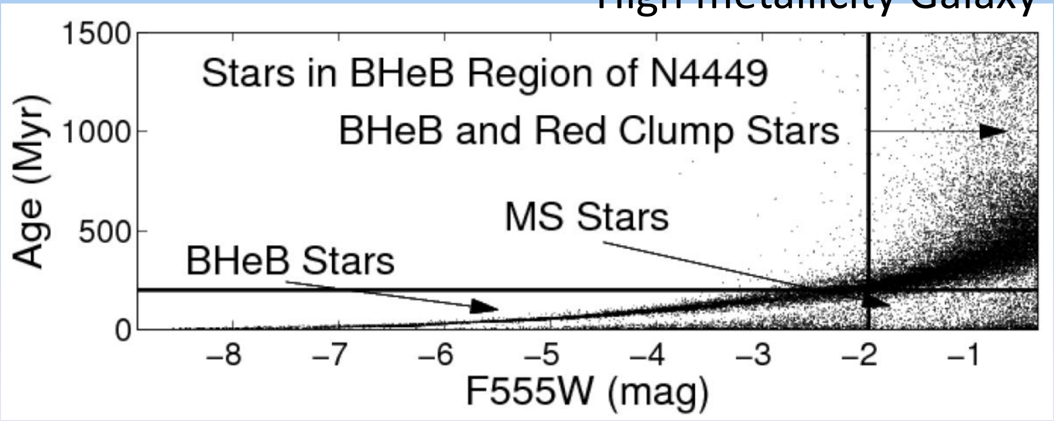
Experimental Evidence for Blue Sequences



V-I Color

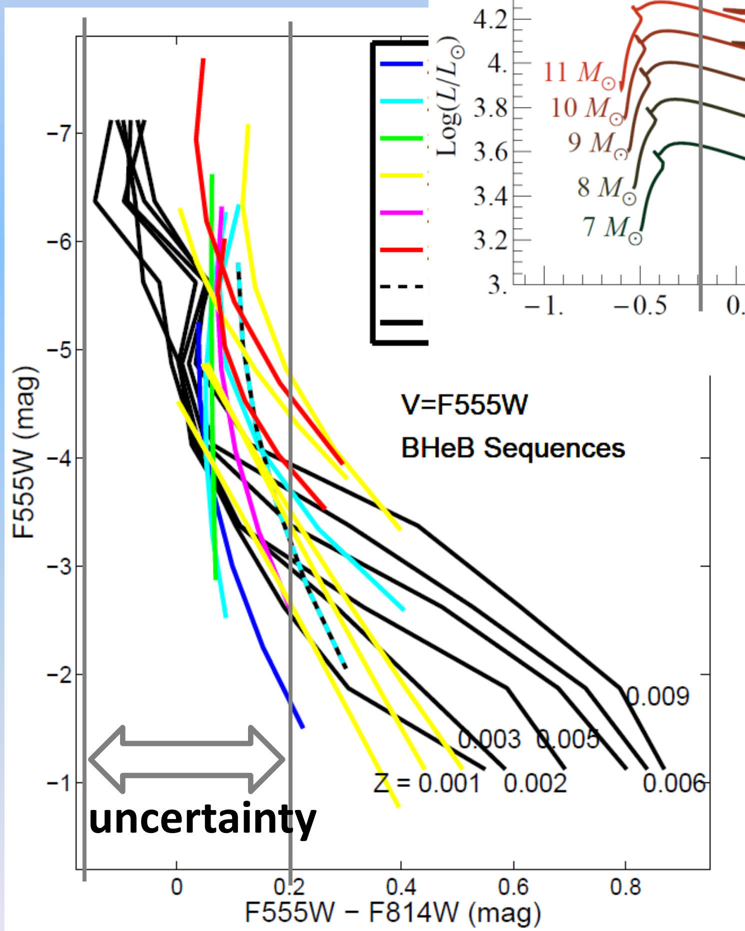


High metallicity Galaxy



Figures from Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)

Experimental Evidence for Blue Sequences



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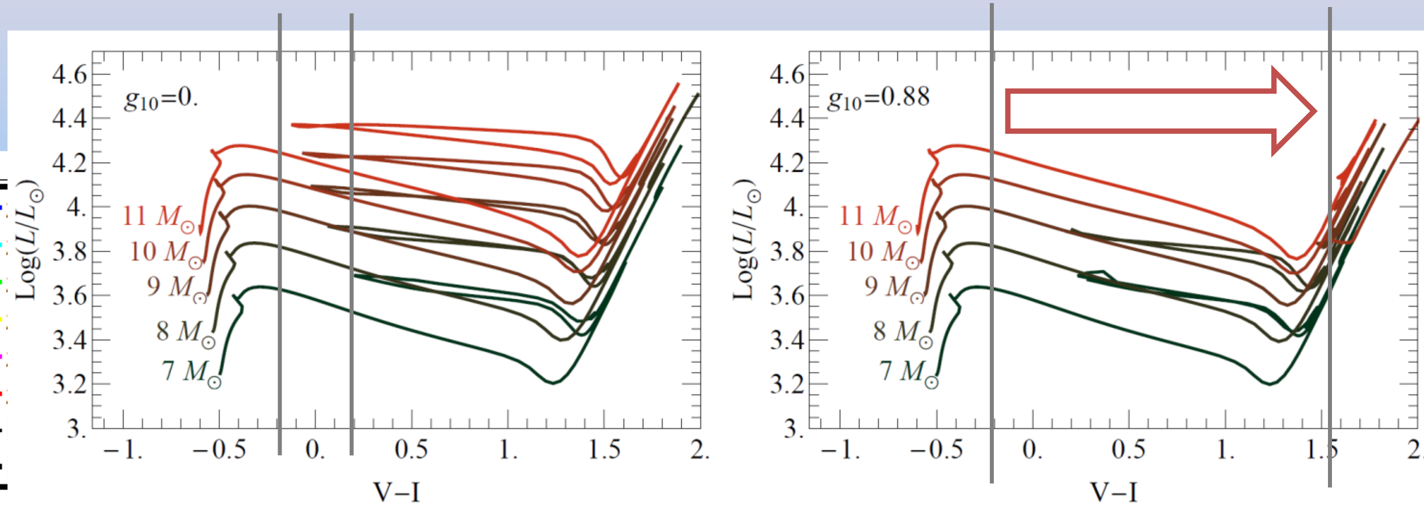

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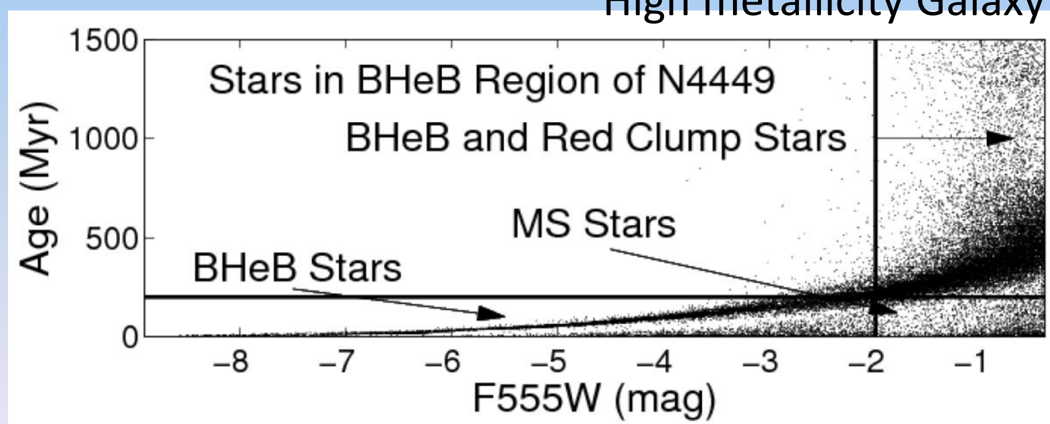
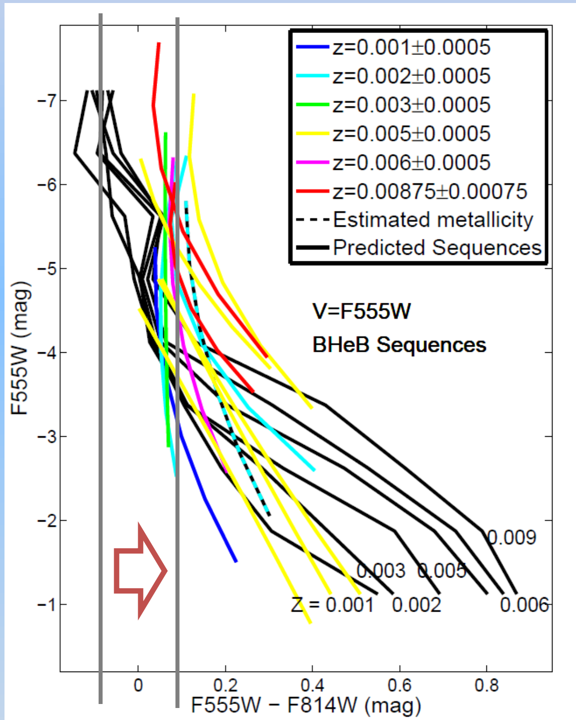


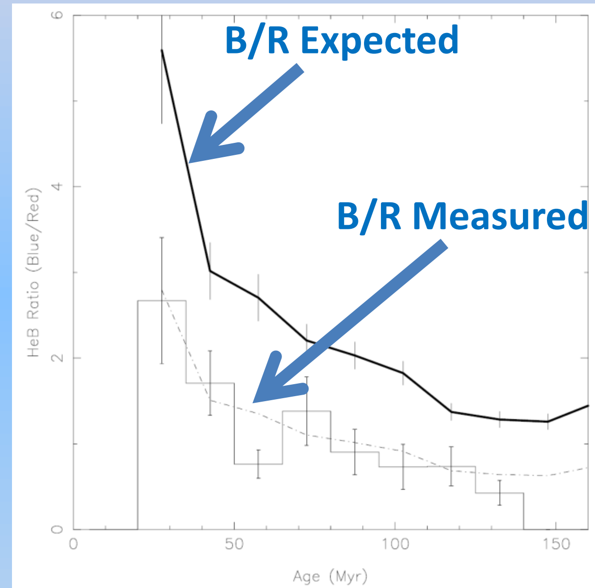
Figures from Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)

Two interesting astrophysical problems: is there a hint to new physics?



V-I Color

Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)



R. C. Dohm-Palmer and E. D. Skillman, The Astronomical Journal, 123 (2002)

From Palmer, Skillman (2002):

"Note how well the functional form of the observations matches that of the model. However, the model values are twice as large as the observations."

Current observations show:

1) a small red-shift of the bluest point of the blue loop in the high luminosity region of the CMD and

2) too many blue stars (B/R problem).

An axion-photon coupling a little below the current bound would reduce (*eliminate*?) both problems.

Conclusions and future directions

- Low and intermediate mass stars offer good laboratories to study models of weakly interacting particles.

- Axions have a strong impact on the evolution of low and intermediate mass stars during the core He-burning stage.

- Massive stars offer an efficient novel probe to test new physics. For axions they provide a bound of g_{10}=0.8 (up to m_a<40 keV or so). A strong bound could possibly be derived from a more accurate analysis of observations.

- Observations of red and blue massive stars show some anomalies and it looks like an axion with of g_{10} between ~0.1 and ~0.8 would help reducing these anomalies. Though it is still premature to draw precise conclusions, maybe new physics will be necessary to solve these problems.

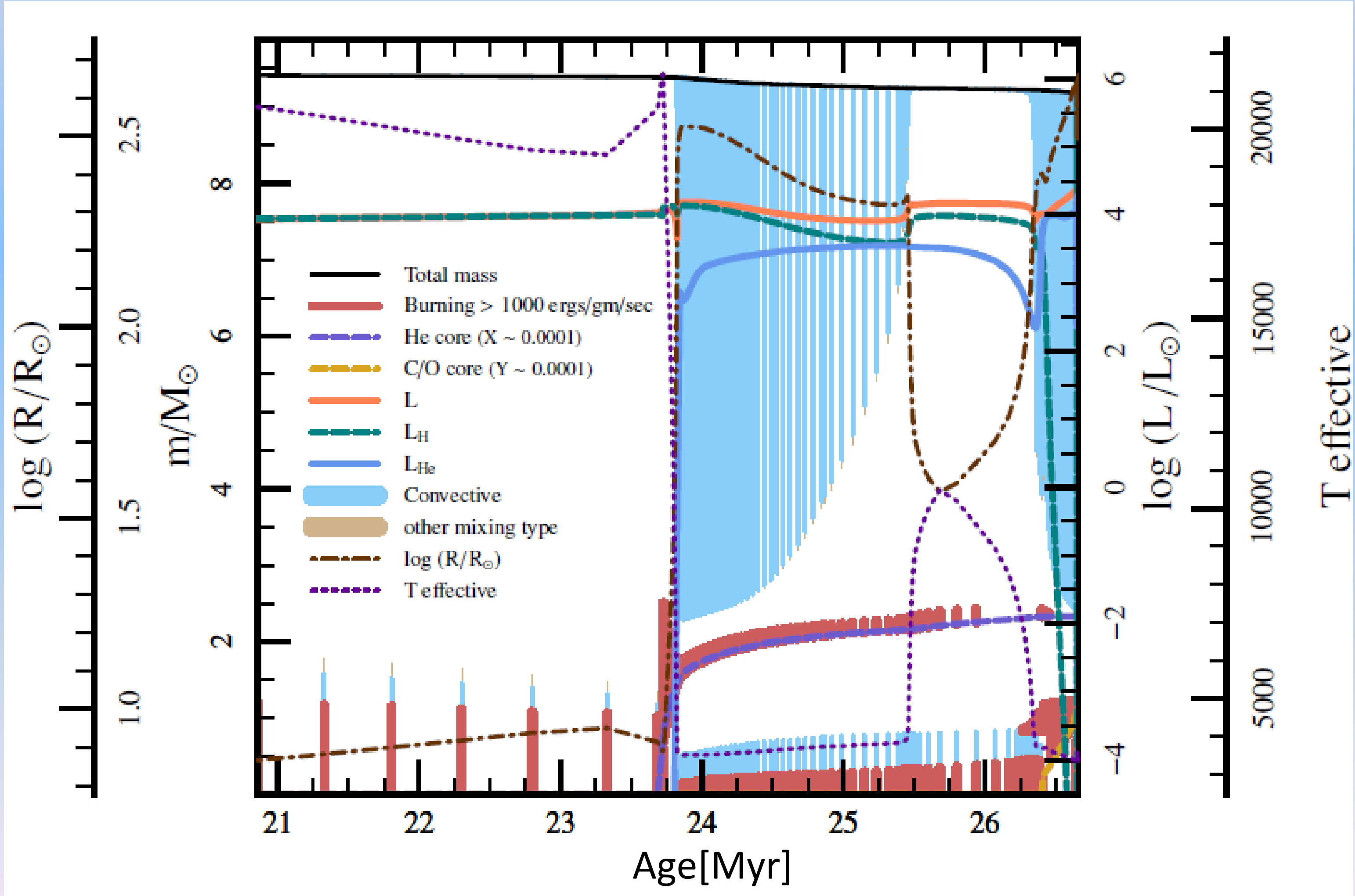
Thank

You

Extra Slides

Axions effects on the Blue Loop

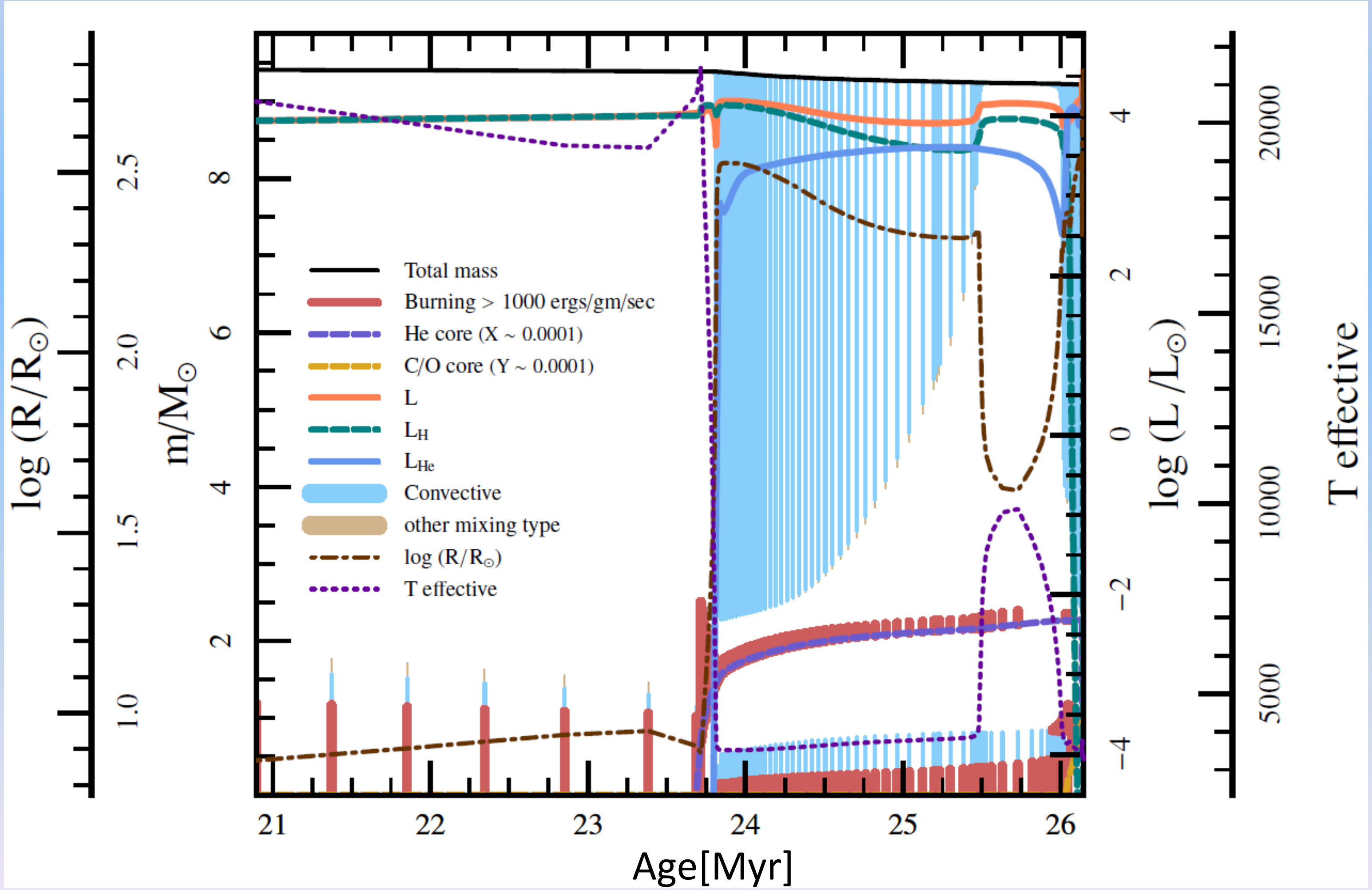
9.5 $M_\odot$ star, g_{10}=0 (No Axion)



MESA Simulation. Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Axions effects on the Blue Loop

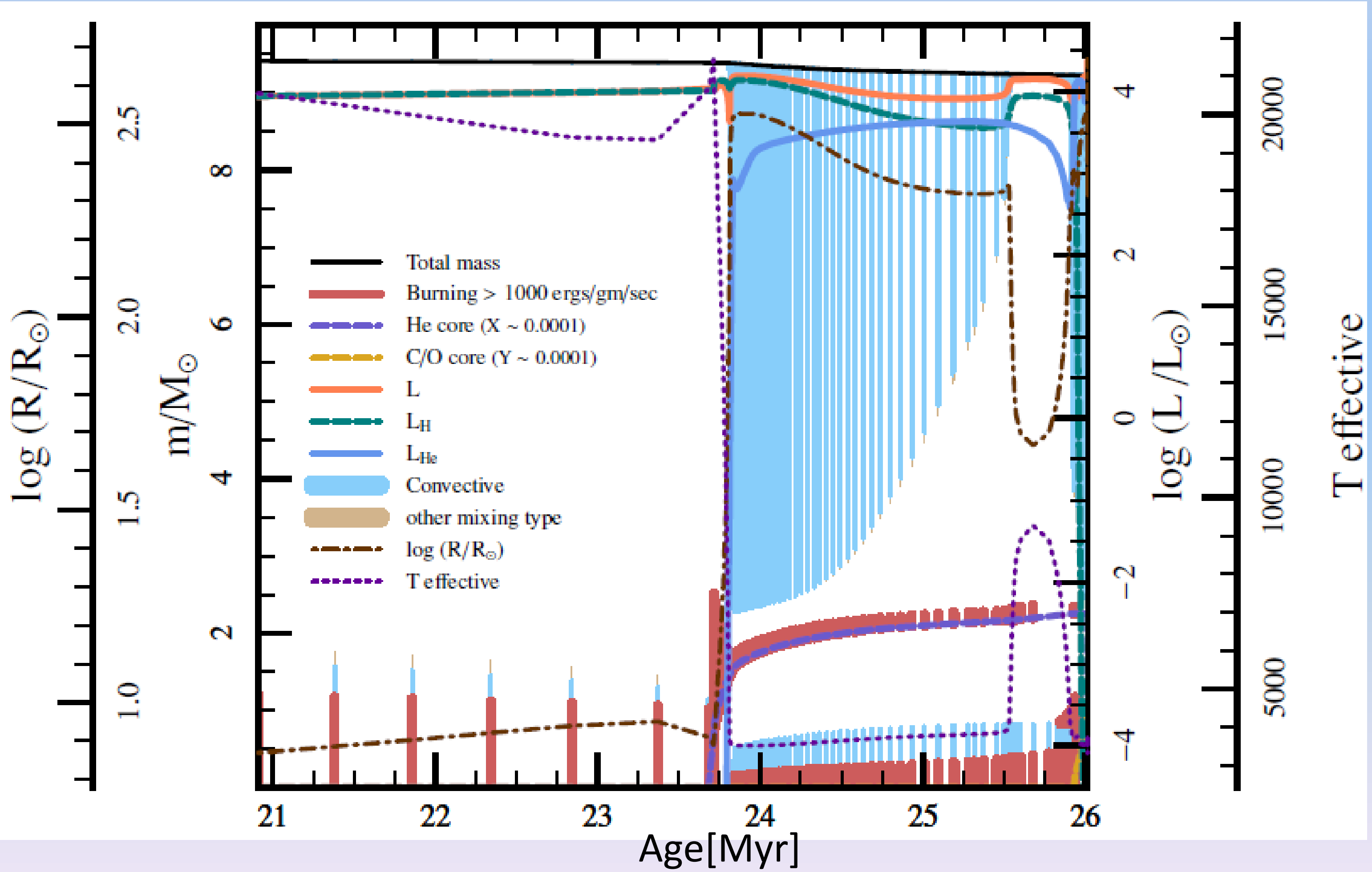
9.5 $M_\odot$ star, g_{10}=0.6



MESA Simulation. Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Axions effects on the Blue Loop

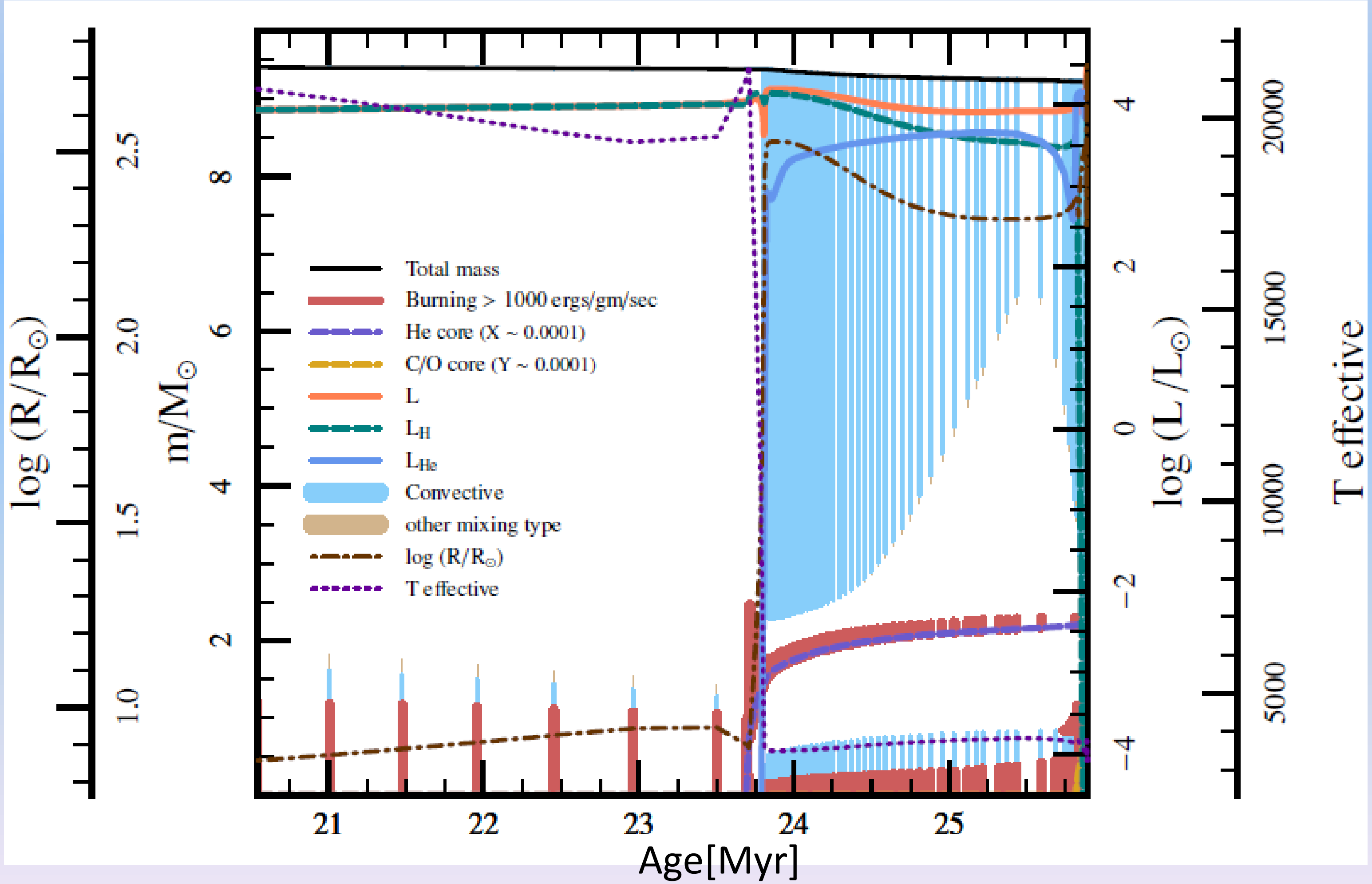
9.5 $M_\odot$ star, g_{10}=0.7



MESA Simulation. Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Axions effects on the Blue Loop

9.5 $M_\odot$ star, g_{10}=0.8

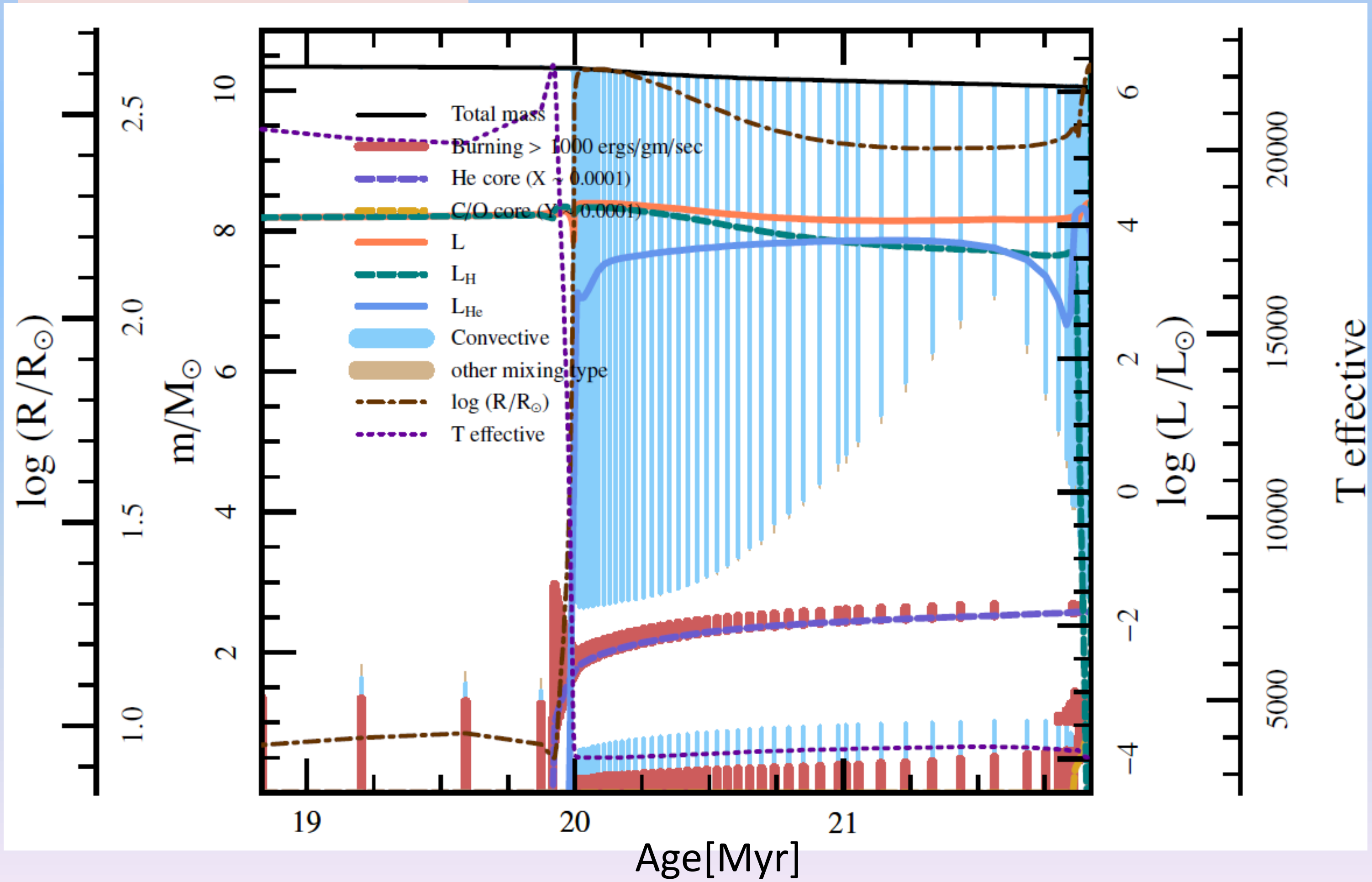


MESA Simulation. Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Even Stronger Bounds?

Other stars showed an even stronger response to axion cooling. (Friedland, M.G., Wise, work in progress).

$10.5M_\odot$ star, g_{10}=0.6



Stars as Laboratories

For a particle physicist, stellar interiors represent extremely hermetic detectors, sensitive to very rare processes. For example, the process

$$\gamma \rightarrow \nu + \bar{\nu}$$

E. Braaten, D. Segel
Phys.Rev. D48 (1993)

plays a fundamental role in stellar cooling though the probability of this decay to occur between successive interactions of the plasmon is only ~ 10^{-26}.

The same for

$$e^{+} + e^{-} \rightarrow \nu + \bar{\nu}$$

e.g., D. D. Clayton, "Principles of Stellar Evolution and Nucleosynthesis", Chicago (1994)

whose branching ratio with respect to the corresponding photon production is 10^{-19}

Summary Bounds (QCD-Axion)

Stars are extraordinary powerful labs for axion bounds

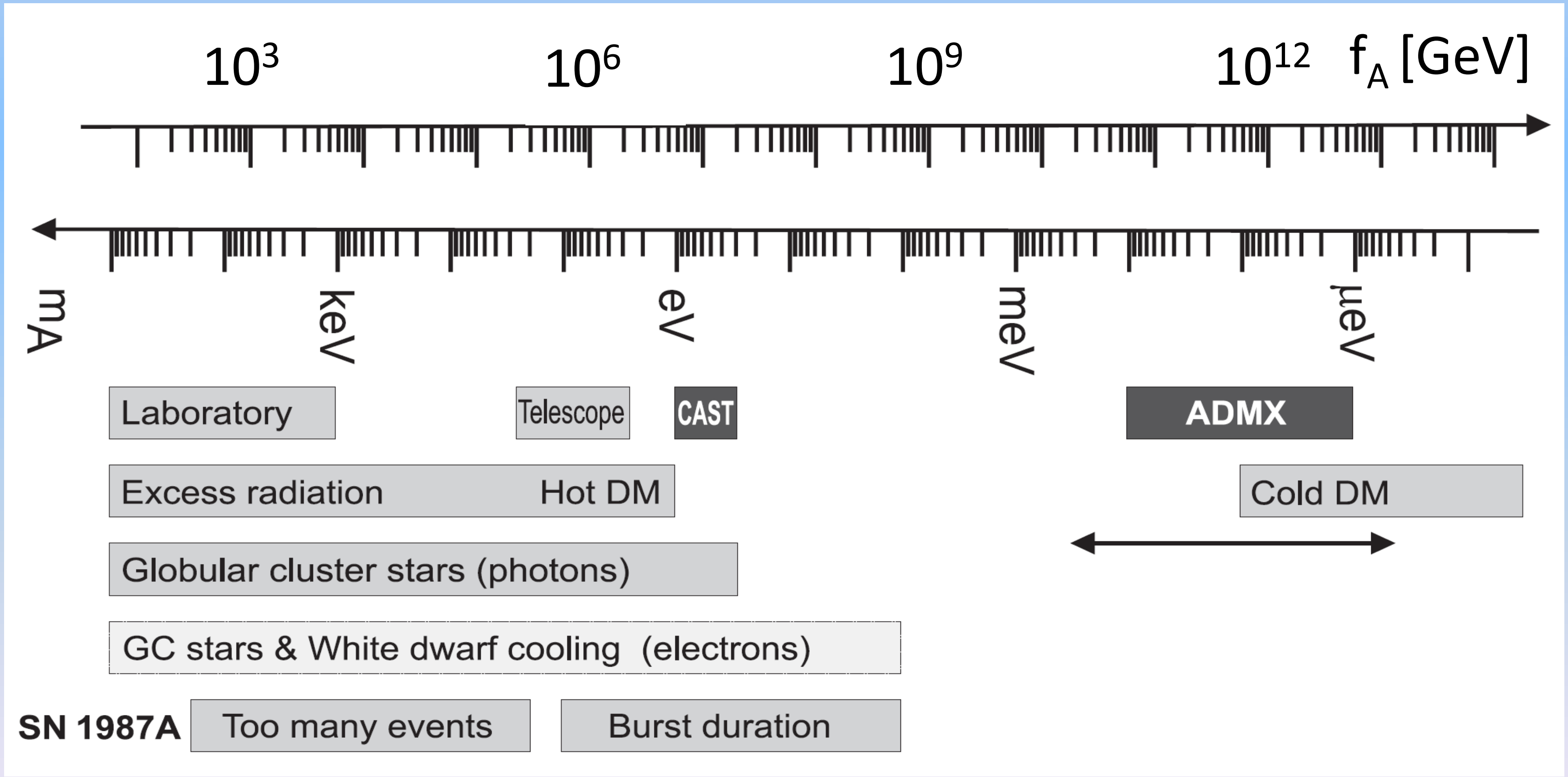


Figure from the PDG

Axion-Like Particles (ALPs)

In the standard axion models the axion interactions and mass are related in terms of the Peccei-Quinn constant f_{a}.

However, recently there has been an effort to study more general models where the coupling constants and the mass are unrelated (**ALPs**).

In the case of ALPs, the different coupling are unrelated.

$$L_{int} = - g_{ai} \frac{\partial_{\mu} a}{2m_i} \overline{\psi}_i \gamma_5 \gamma_{\mu} \psi_i - \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

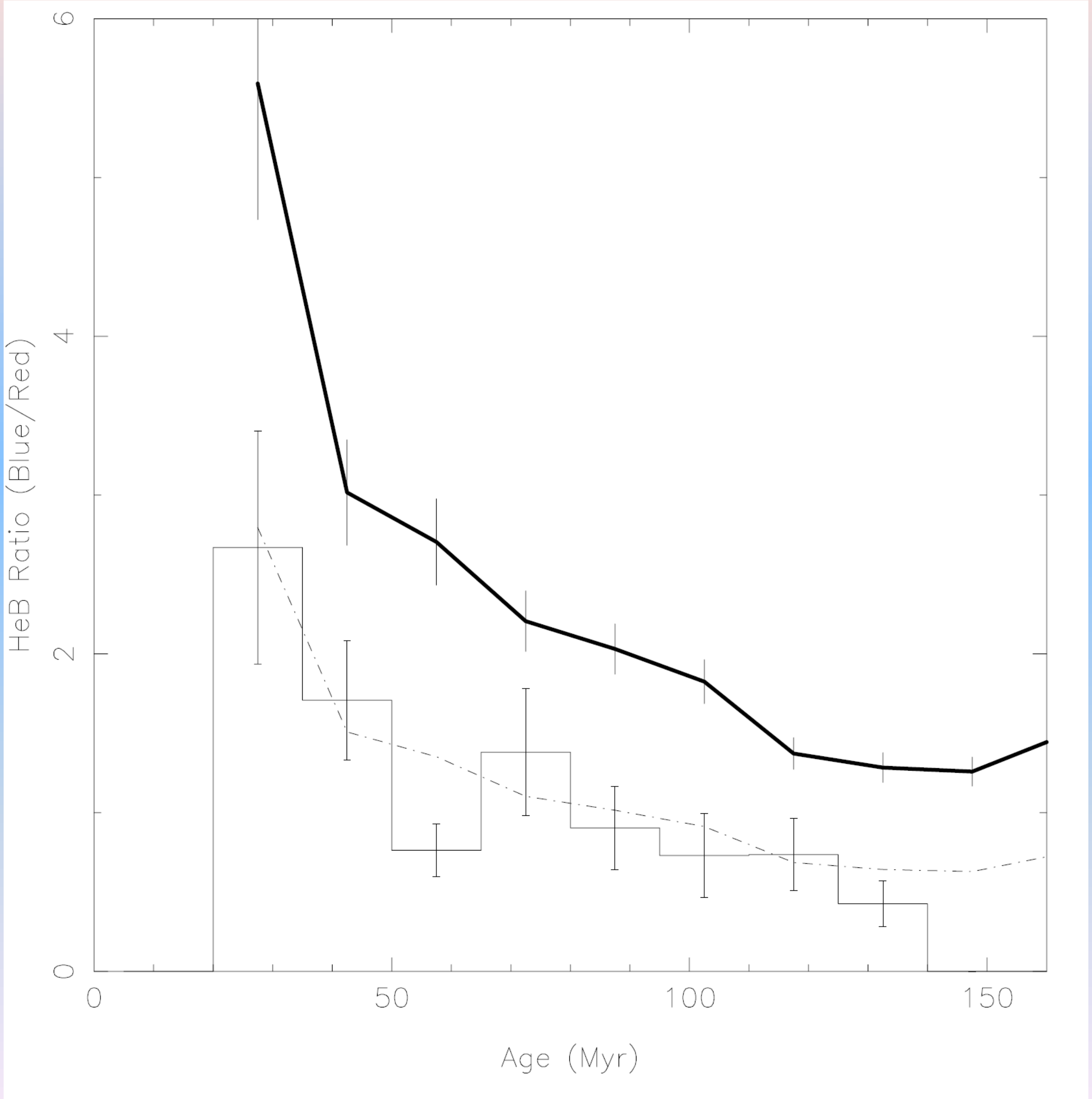
A. Ringwald,
Phys.Dark Univ. 1 (2012)

D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D.Montanino, M. Roncadelli, Phys. Rev. D 86, 075024 (2012)

J. Jaeckel and A. Ringwald, Ann. Rev. Nucl.Part.Sci. 60,405 (2010)

I. Irastorza, F. Avignone, S. Caspi, J. Carmona, T. Dafni, et al.,
JCAP 1106, 013 (2011)

D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D. Montanino, et al.,
Phys.Rev. D86, 075024 (2012)



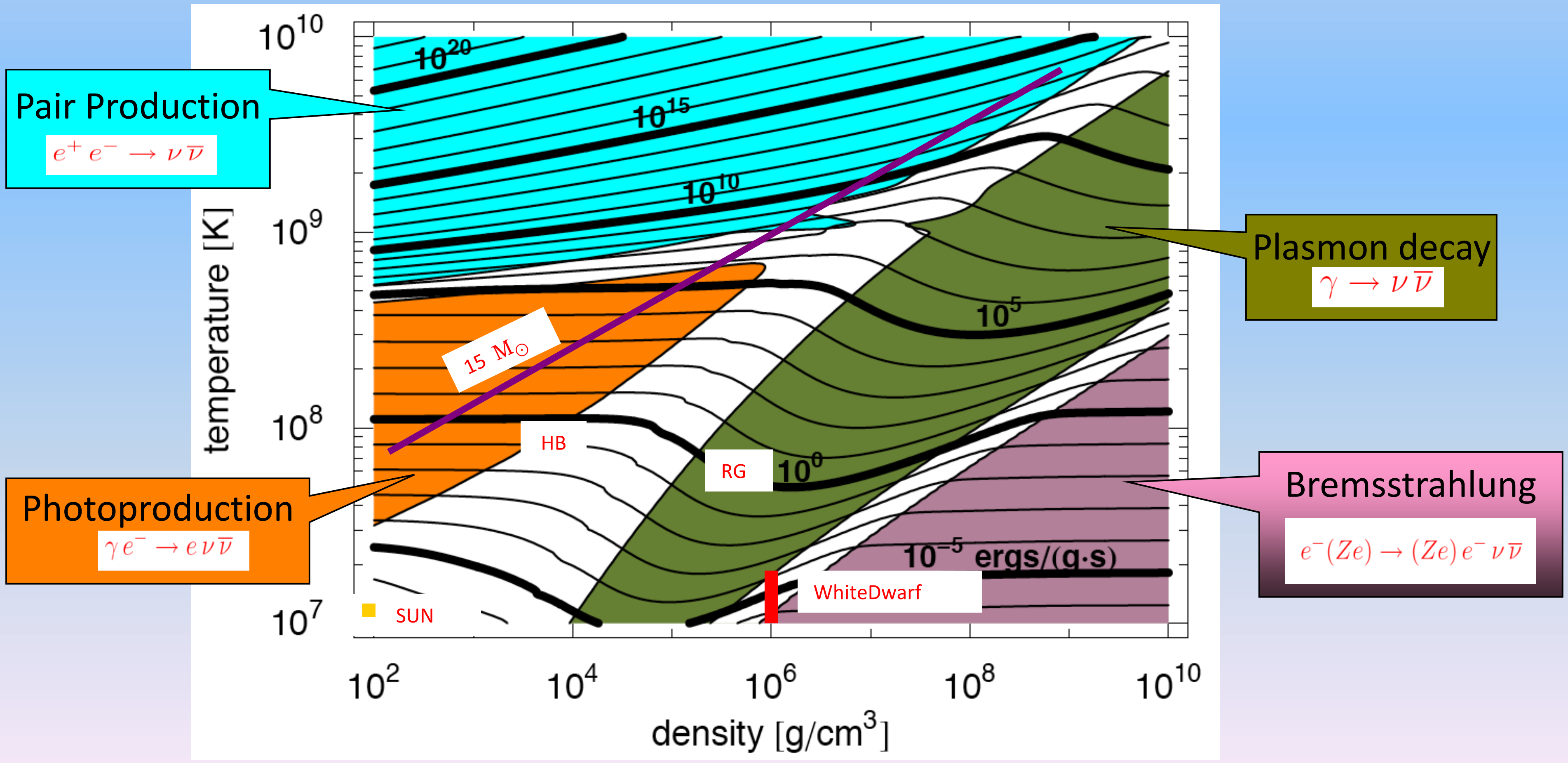
HeB Ratio (Blue/Red)
Age (Myr)
0
2
4
6
0
50
100
150

Stars as Laboratories

Standard Cooling: photons and neutrinos

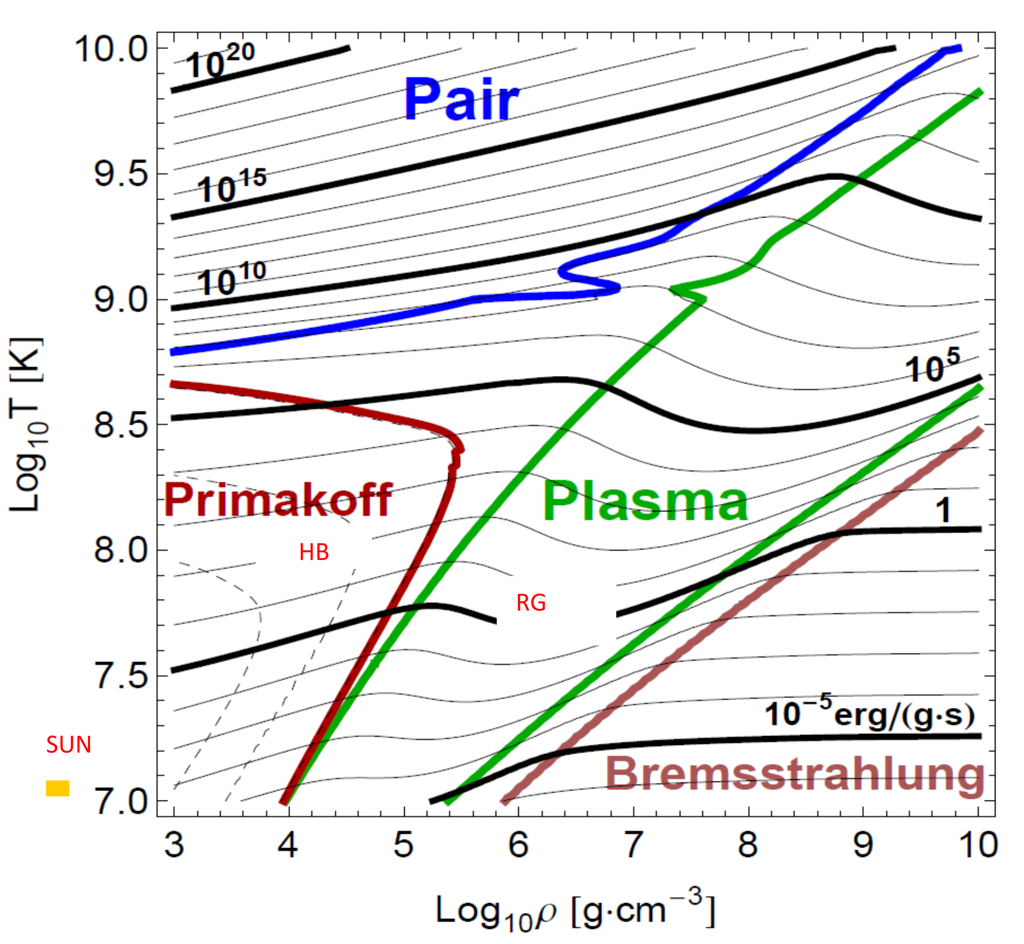
Photon cooling is relevant in the non-degenerate region, below T~5×10⁸K

The labels refer to the star core



Primakoff production of Axions in Stars

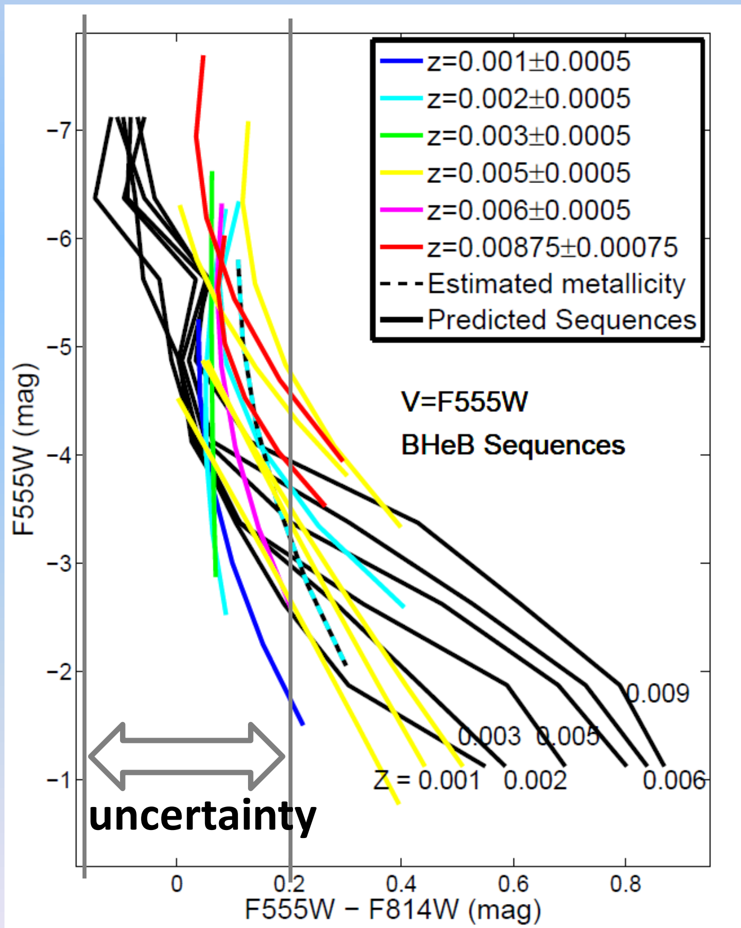
Axions can be produced in the core of a star through Primakoff photon conversion, $\gamma + (Ze) \rightarrow a + (Ze)$, in the field of a nucleus.



The axion energy loss is very sensitive to the temperature.

HB stars are, evidently, in the region where axion dominates over neutrino cooling

Experimental Evidence for Blue Sequences

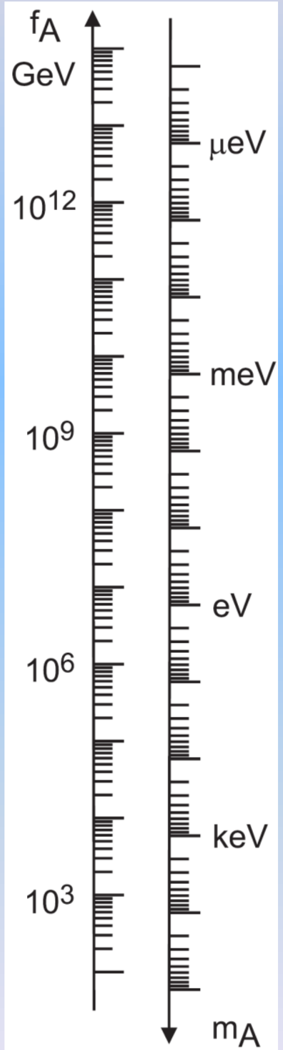


V-I Color

Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)

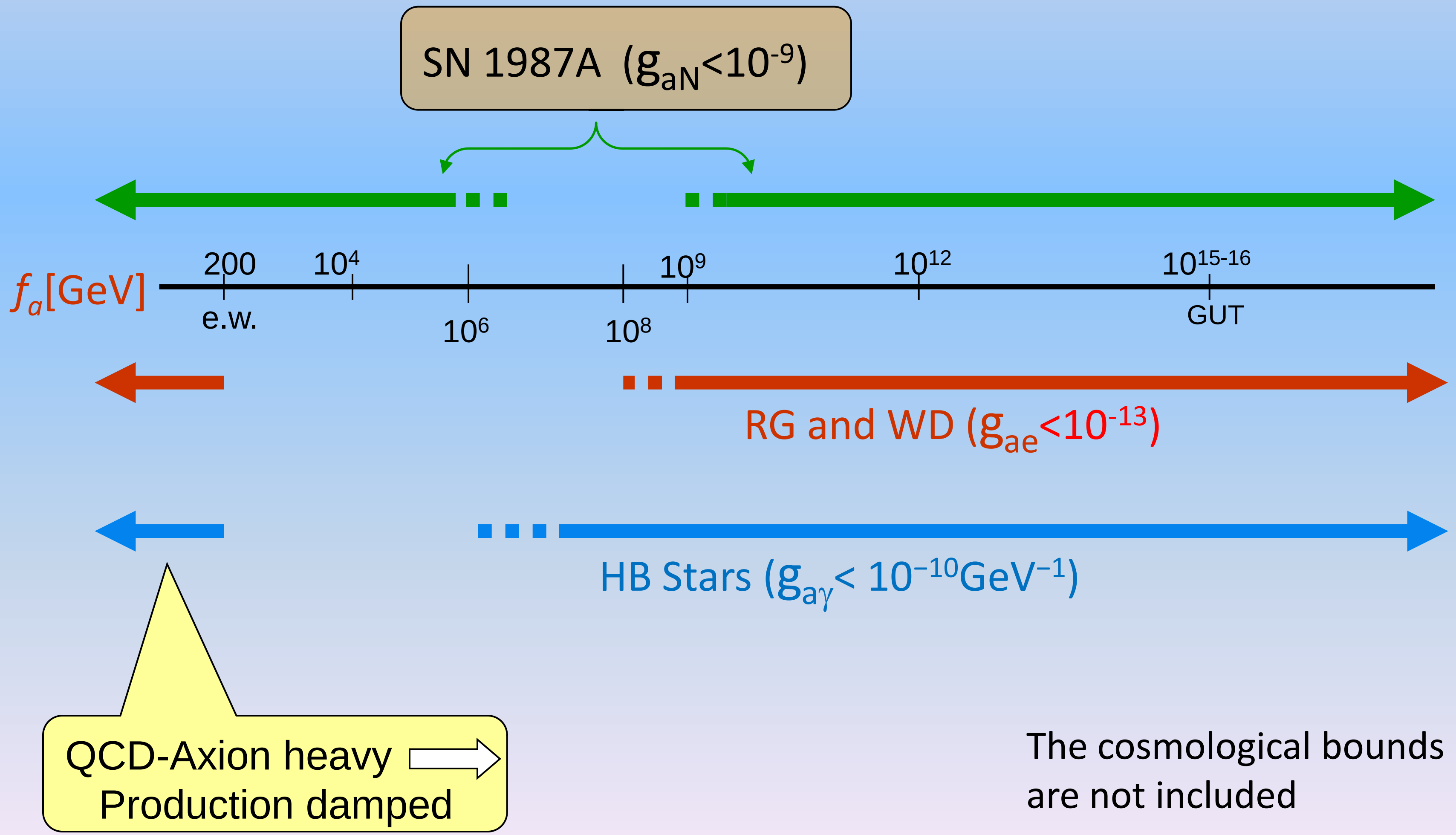
Result:

A value of g_{10} above 0.8 (optimistically, 0.5) seems to be incompatible with the current observations of HeB sequences.

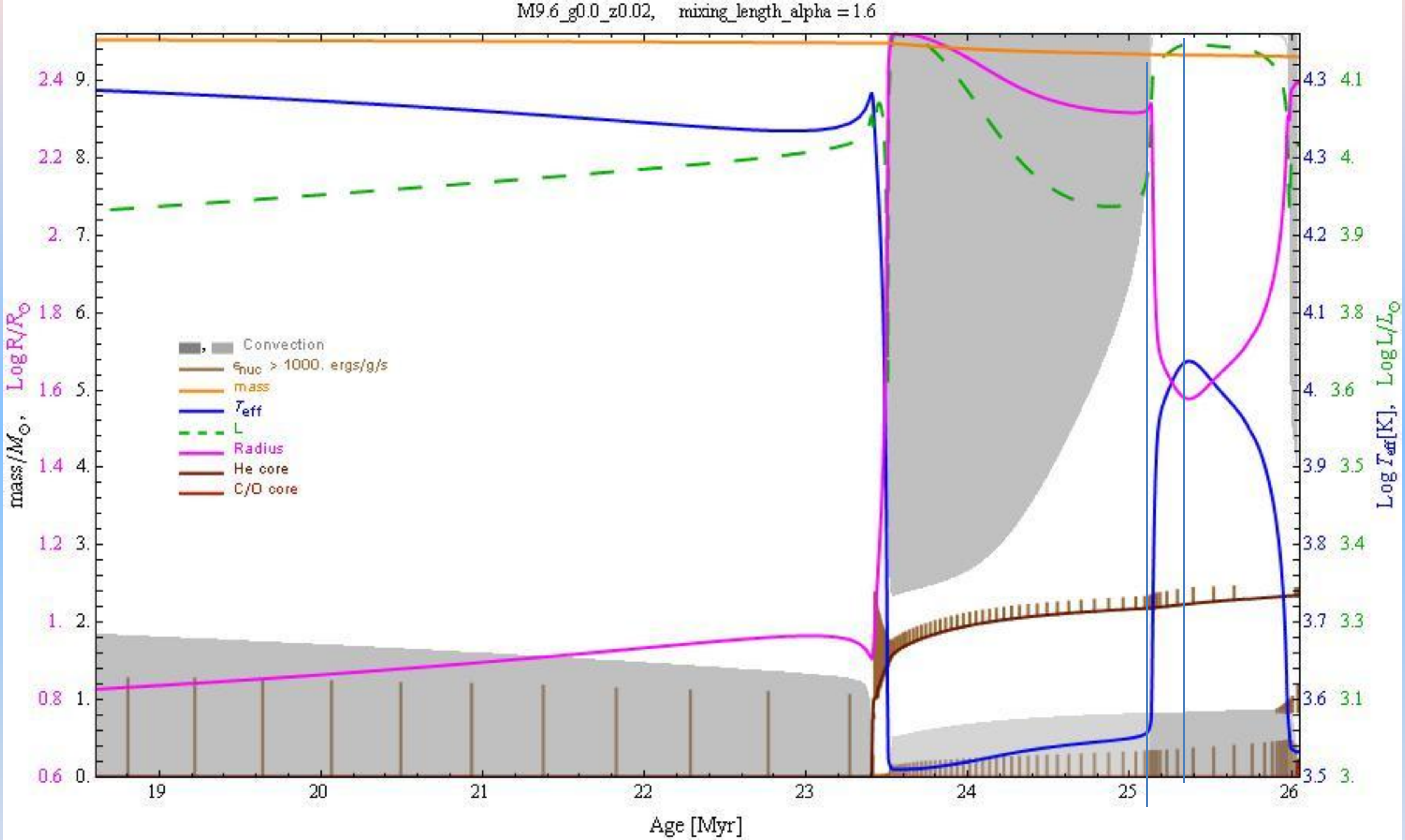


At this point observations are not good enough to draw conclusions about a possible exotic (axion?) signature. We use the data only to constraint $g_{a\gamma}$.

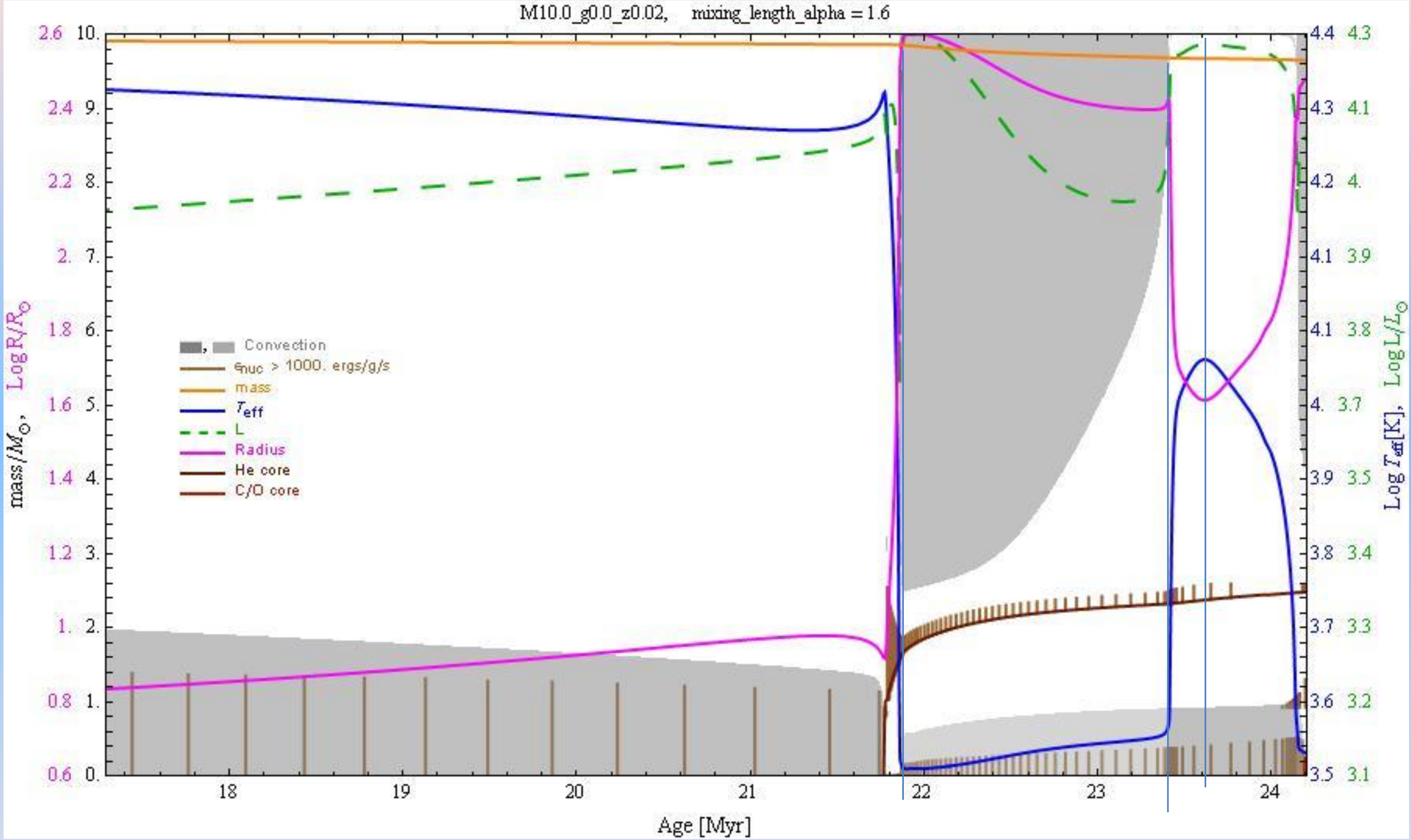
Summary of the stellar bounds (QCD-Axion)



The cosmological bounds are not included



M9.6_g0.0_z0.02, mixing_length_alpha = 1.6
mass/$M_\odot$, Log R/$R_\odot$
Log T_{eff}[K], Log L/$L_\odot$
Age [Myr]
Convection
ϵ_{nuc} > 1000. ergs/g/s
mass
T_{eff}
L
Radius
He core
C/O core
19
20
21
22
23
24
25
26



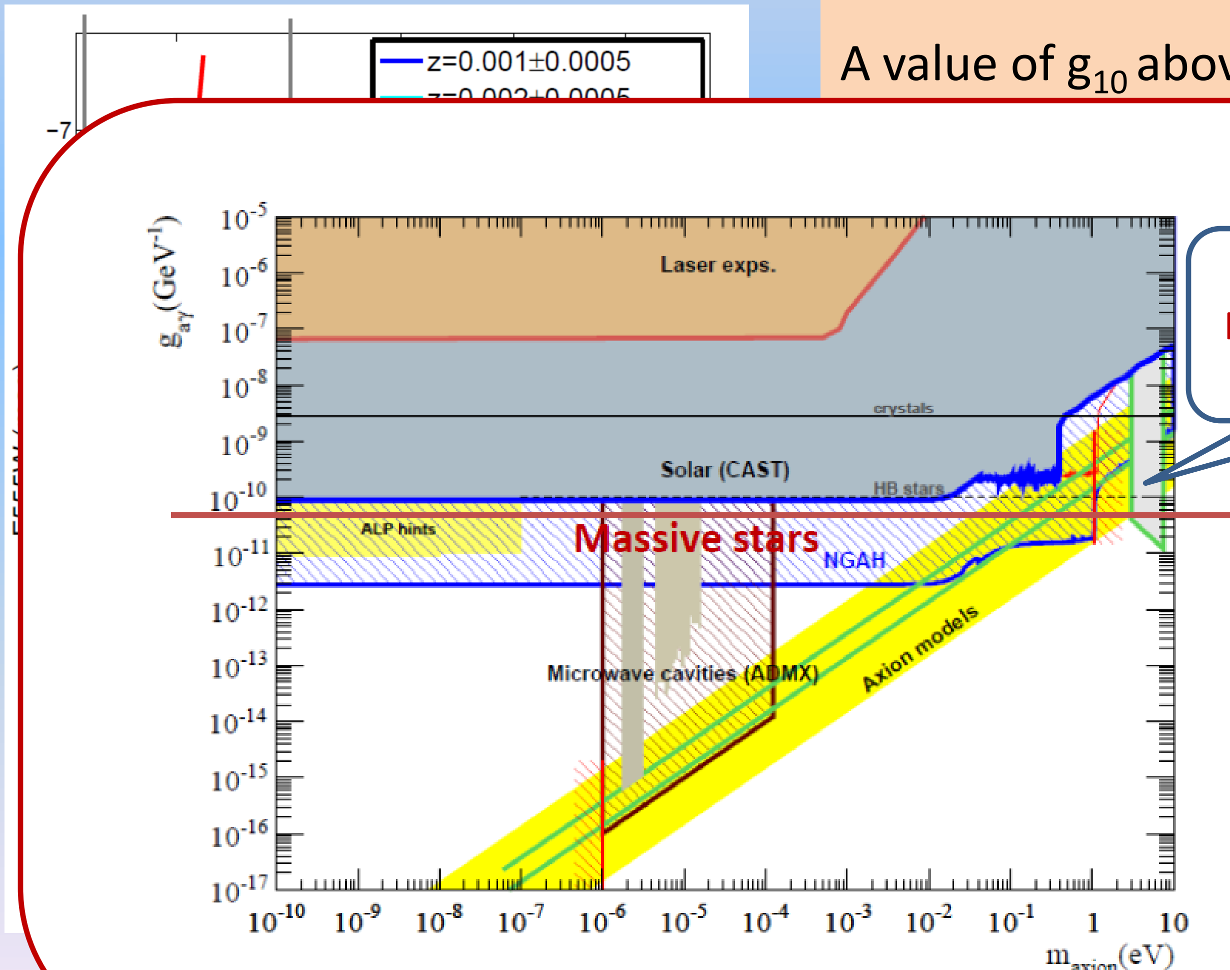
M10.0_g0.0_z0.02, mixing_length_alpha = 1.6
Convection
ϵ_{nuc} > 1000. ergs/g/s
mass
T_{eff}
L
Radius
He core
C/O core
Age [Myr]
mass/$M_\odot$, Log R/$R_\odot$
Log T_{eff}[K], Log L/$L_\odot$

Experimental Evidence for Blue Sequences

Result:

A value of g_{10} above 0.8 (optimistically, 0.5)

current



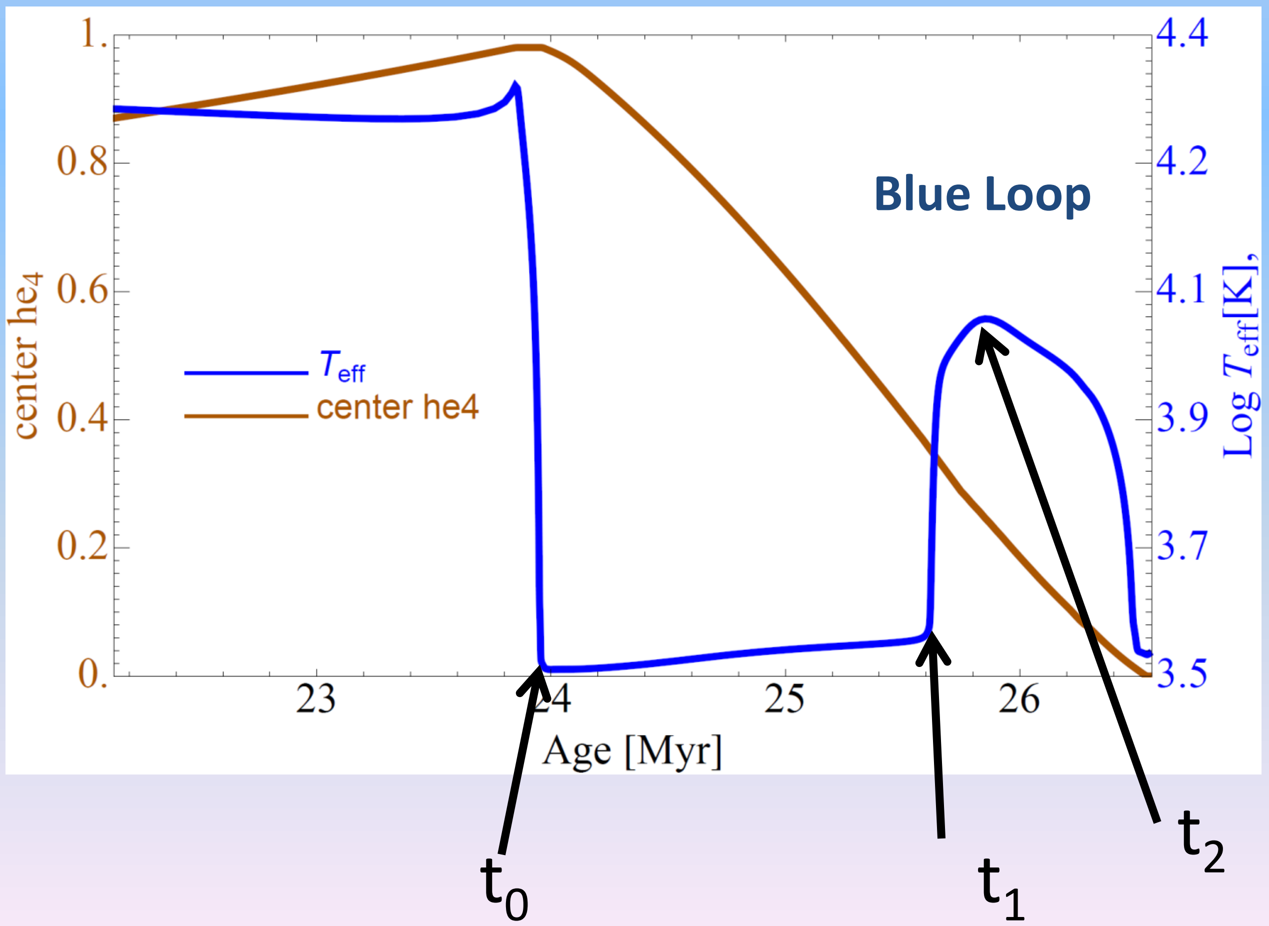
HB-bound,
Raffelt and Dearborn
(1987)

I. G. Irastorza et al.,
Journal of Physics:
Conference Series
309 (2011) 012001

Kr

Blue loop as a probe for Fundamental Physics

When the He content in the core reaches a certain lower value (t_2), the surface temperature stops increasing and goes back to the red region of the HR diagram.
[Lauterborn et al., A&A 10, (1971)]



Since the start of the loop (t_1) does not depend on the physics of the core, we can define a model independent criteria for the disappearance of the blue loop:

An additional cooling mechanism prevents the blue loop to happen if it moves t_2 before t_1

Stars as Laboratories

Exactly 50 years ago Bernstain, Ruderman and Feinberg studied the effects of electromagnetic properties of neutrinos for the cooling of the sun. Their bound on the neutrino magnetic moment was better than the experimental bound at that time.

J. Bernstein et al., Phys. Rev. 132, 1227 (1963)

Since then, stars have proven to be excellent laboratories to test physics scenarios with ***light, weakly interacting* particles**. Examples include majorons, extra-dimensional photons, novel baryonic or leptonic forces, unparticles, etc.

H.M. Georgi, S.L. Glashow, and S. Nussinov, Nucl. Phys. B193, 297 (1981)

A. Friedland and M. Giannotti, Phys. Rev. Lett. 100, 031602 (2008)

Grifols and E. Masso, Phys. Lett. B 173, 237 (1986)

S. Hannestad, G. Raffelt, and Y.Y.Y. Wong, Phys. Rev. D76, 121701 (2007)

Outline

- ❑ Stars and particle physics
- ❑ The Horizontal Brunch (HB) bound on the axion-photon coupling
- ❑ Bound on the axion-photon coupling from massive stars
- ❑ Conclusions