Hints of ALPs from the sky?

Cooling anomalies and the case for ALPs

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Stars as Laboratories

For over 50 years stars have proven to be excellent laboratories to test physics scenarios with ***light, weakly interacting*** **particles**. Examples include *ALPs, nonstandard neutrino properties, majorons, extra-dimensional photons, novel baryonic or leptonic forces, unparticles*, etc.

Stars are complementary labs to terrestrial experiments, sometime sensitive to extremely weak couplings or rare processes.

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

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

N. Viaux et. al., Phys.Rev.Lett. 111 (2013) 231301

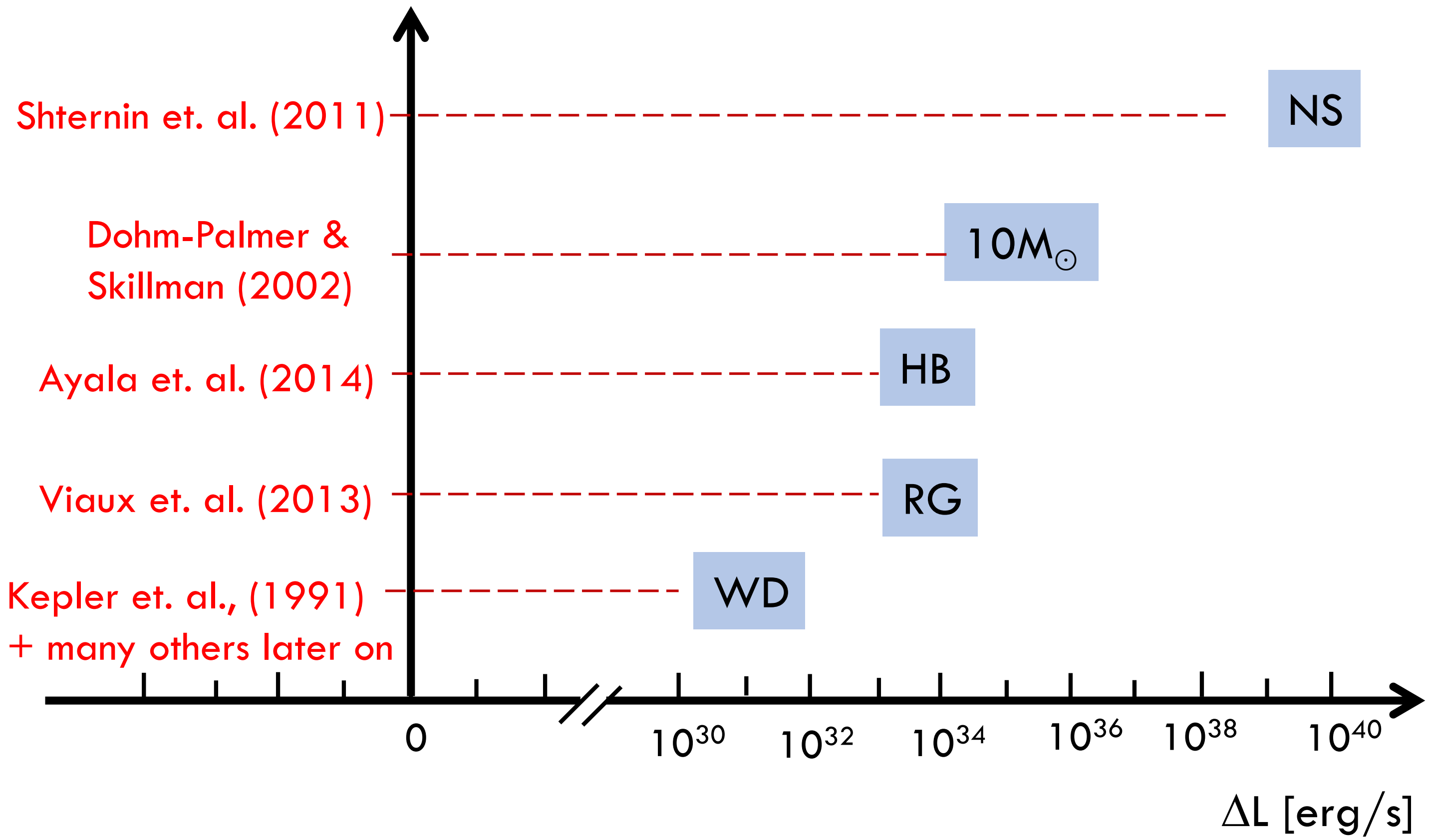
N. Viaux et. al., Astron.Astrophys. 558 (2013) A12

A. Ayala et. al., Phys.Rev.Lett. 113 (2014) 19, 191302

J. Redondo, G. Raffelt, JCAP 1308 (2013) 034

Cooling Anomalies

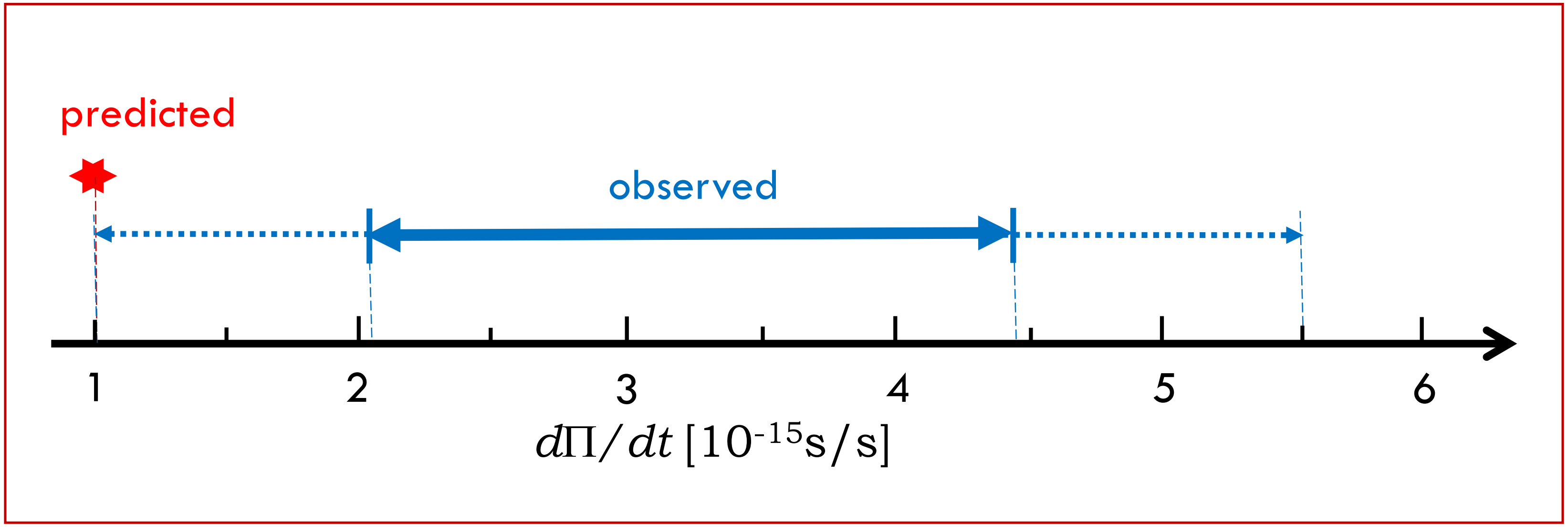
Practically every stellar system seems to be cooling faster than predicted by the models.



White Dwarfs

Already in 1991, measurements of the **period decrease** $\dot{\Pi}/\Pi$ showed an unexpectedly fast cooling of the star G117-B15A, a pulsating WD of the class ZZ Ceti [Kepler et. al., 1991].

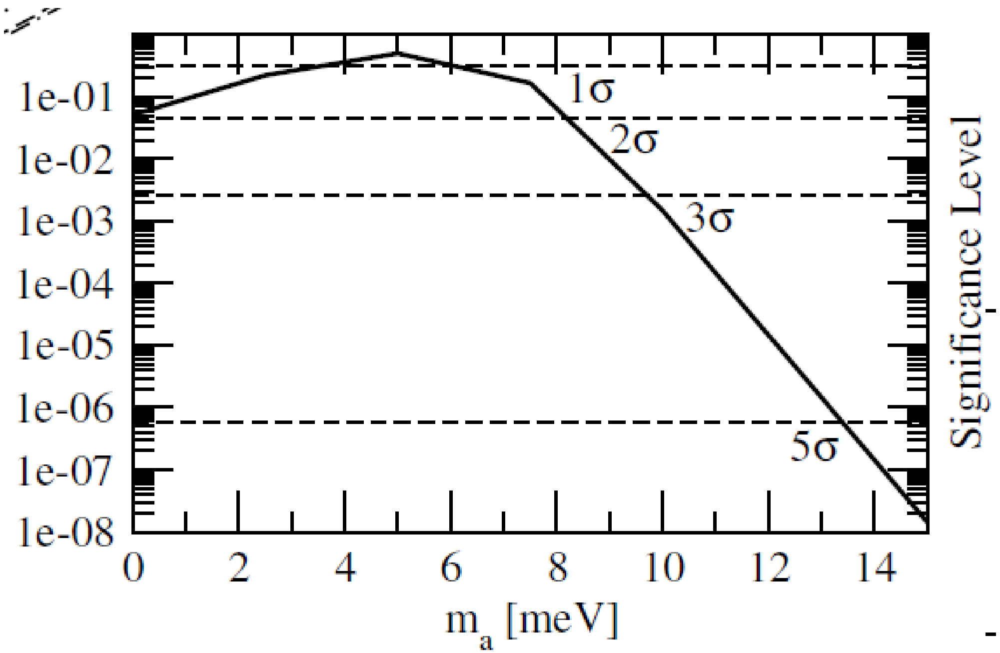
$\dot{\Pi}/\Pi$ is practically proportional to the cooling rate $\dot{T}/T$, indicating that this specific WD is cooling substantially faster than what expected from standard pulsation theory.



data from: Corsico et. al., JCAP 1212 (2012). WD: R548. Results for G117-B15A are similar.

White Dwarfs

In addition, the **<u>white dwarf luminosity function</u> (WDLF)** which shows the number of WDs per luminosity bin, is not well fitted (within 1σ) by the standard cooling theory. Additional cooling increases the accuracy of the fit.



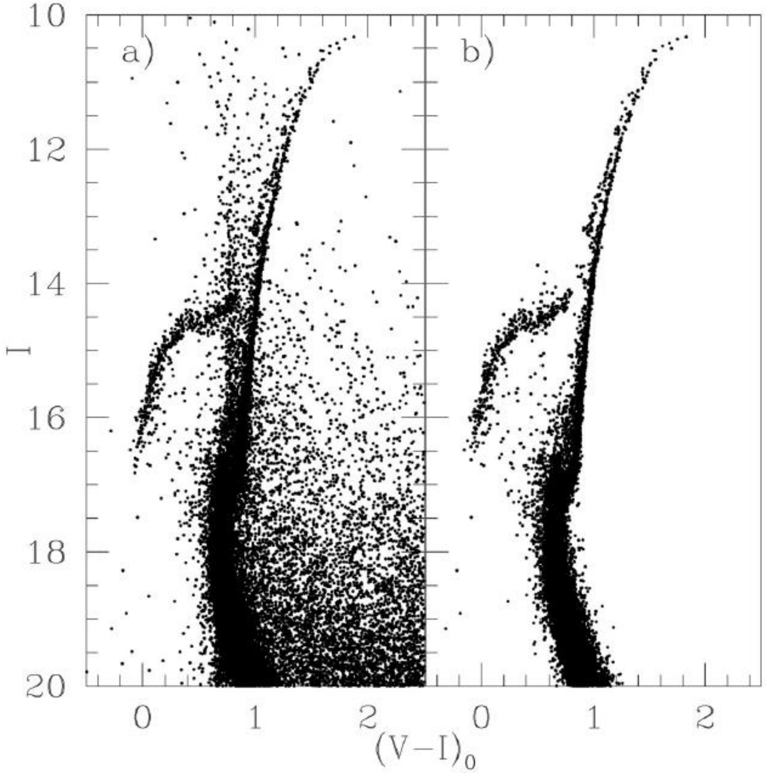
The continuous line shows the significance level at which different values of the axion mass are discarded by a χ^2-test

Bertolami et. al., JCAP 1410 (2014) 10

$$g_{ae} = 2.8\times10^{-14} m_{a,meV}$$

RG Cooling

A particularly useful observable in the CMD is the brightness of the tip of the RG branch.



Viaux et. al. Astron.Astrophys. 558 (2013) A12: Color-magnitude diagram of M5. Left: Original. Right: After field star decontamination.

Additional cooling would give rise to a brighter RGB tip.

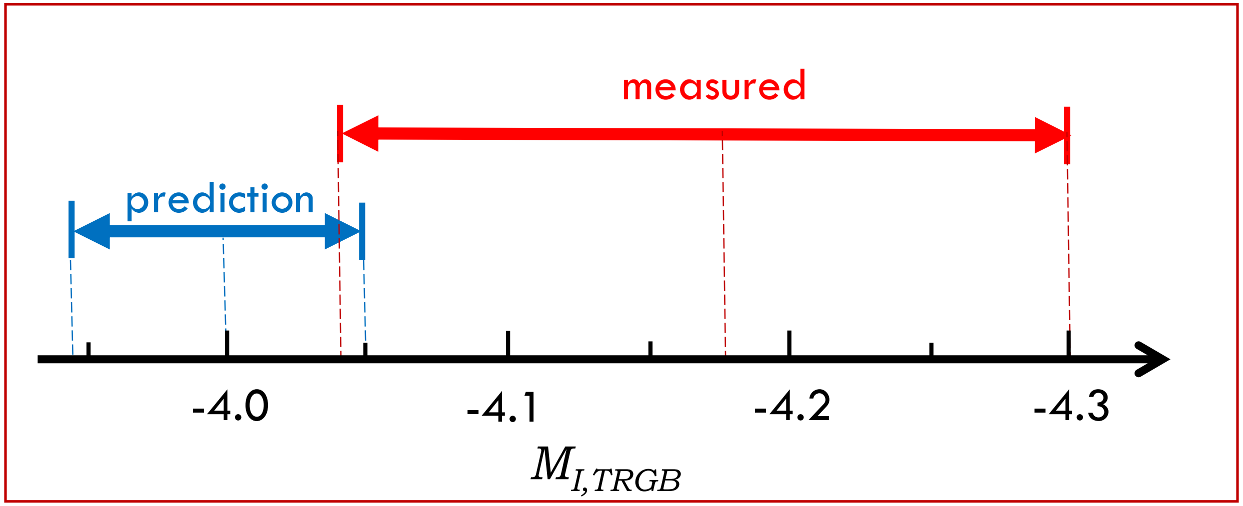
In two recent papers Viaux et. al. showed that, indeed, the luminosity of the RGB tip for the M5 cluster is slightly more luminous than expected, even though the discrepancy can be accounted for by the combination of theoretical and observational errors.

RG Cooling

The blue band shows the theoretical predictions (at 1σ) assuming only standard cooling.

The red band shows the measured value, including the 1σ uncertainties.

The numerical analysis seem to be lacking about 10^{34} erg/s additional cooling, in order to match the observations



The observational uncertainty is mostly due to the cluster distance and will likely be substantially reduced with the GAIA mission.

Viaux et. al., Phys.Rev.Lett. 111 (2013)

HB Cooling

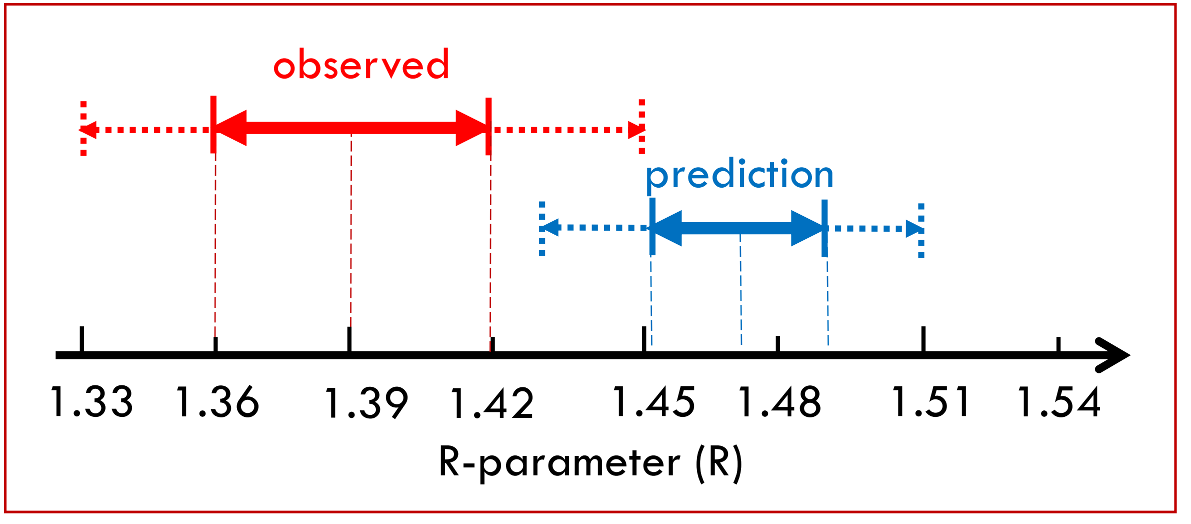
The R-parameter:

$$R = N_{HB}/N_{RG}$$

See Straniero's talk, tomorrow

compares the number of stars in the HB (N_{HB}) and in the upper portion of the RGB (N_{RG}).

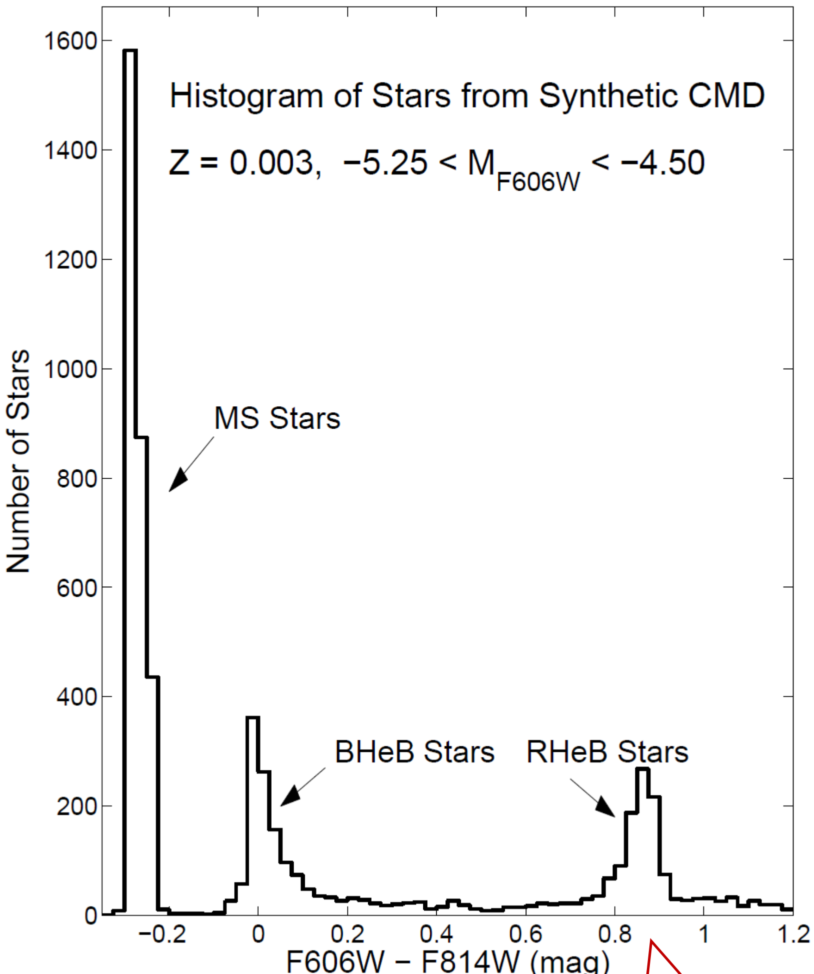
A recent analysis of 39 GC showed a slight discrepancy (at 1 σ) between the predicted and observed R-parameter.



Ayala, Dominguez, M.G., Mirizzi, Straniero, PRL (2014)

Using recent measurements of the helium mass fraction one would predict $R = 1.47$, a value somewhat higher than the observed $R = 1.39 \pm 0.03$.

Open Clusters and Massive Stars



Log T[k]=4

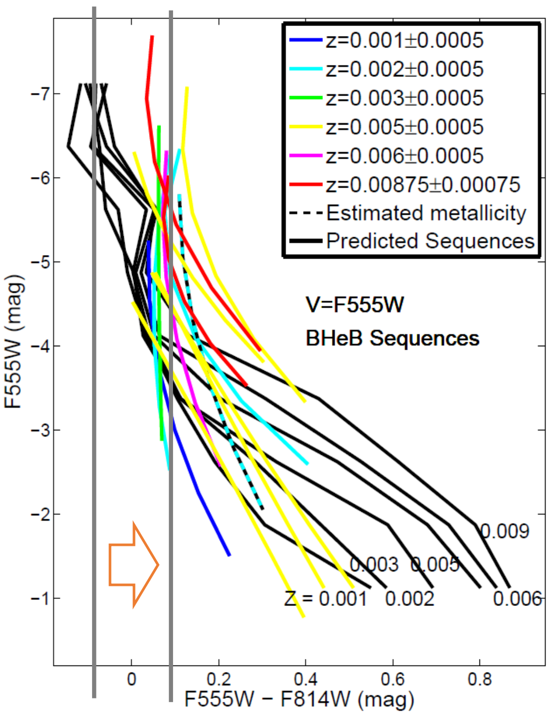
Log T[k]=3.7

Blue and red stars have been observed and studied for many decades. Measurements are very accurate.

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

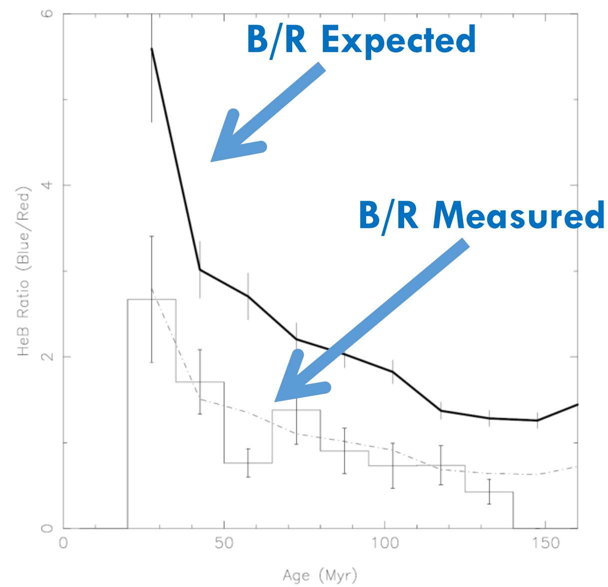
From Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)

Open Clusters and Massive Stars



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):

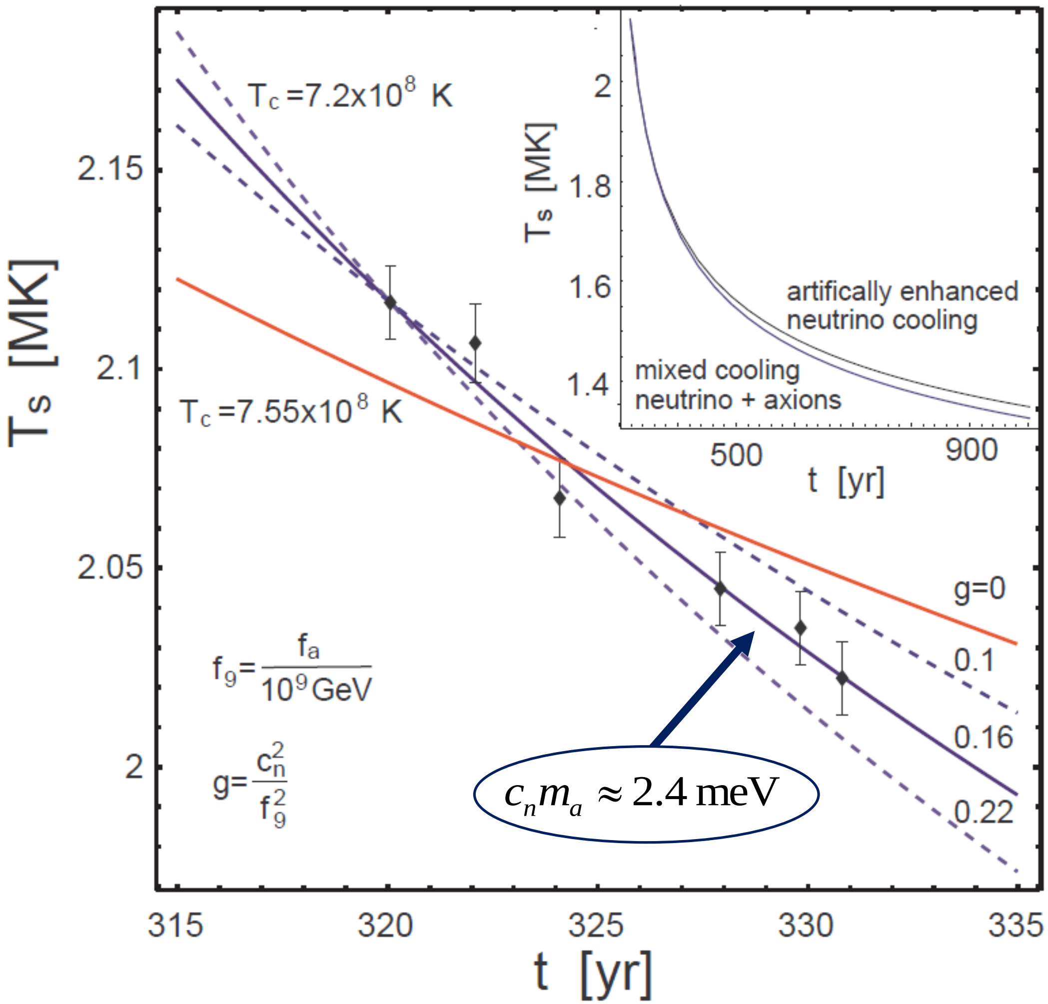
"Note how well the functional form of the observations matches that of the model. However, the model values are twice as large as the observations."

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).

NS cooling



Measured surface temperature over 10 years of the NS in Cas A reveals unusually fast cooling rate.

The thermal energy losses are approximately twice more intensive than it can be explained by the neutrino emission.

Shternin et. al., Mon. Not. R. Astron. Soc. 412 (2011)

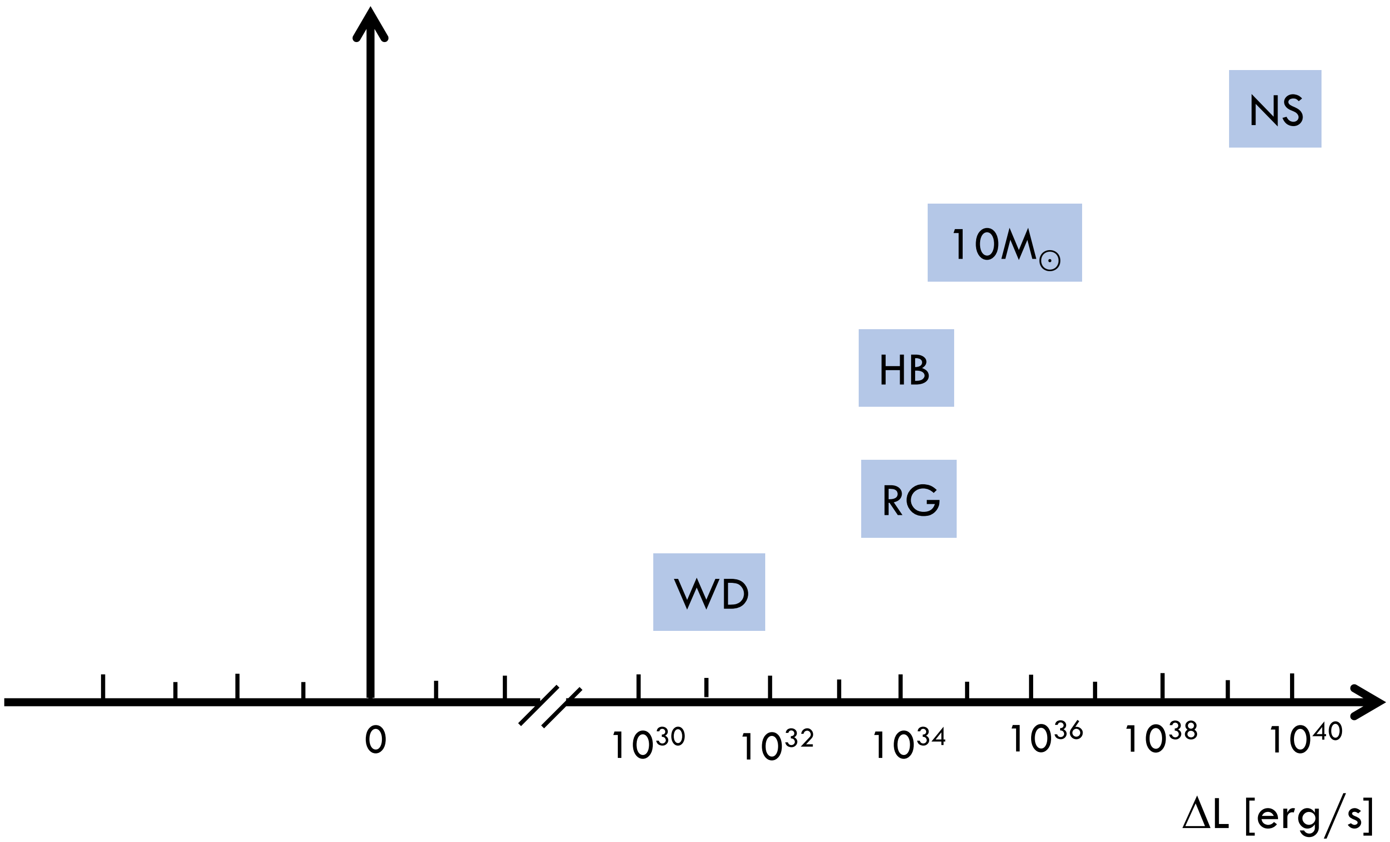
Leinson, JCAP 1408 (2014)

FACTS: There are aspects of stellar evolution which are not well understood. Observational anomalies from different stellar systems indicate the need for additional cooling.

SPECULATIONS:

- This is the result of the difficulty in numerical modeling stellar evolution
- This is the result of poor observations.
- This is due to a poor statistical analysis.
- …..
- This is a hint to new physics

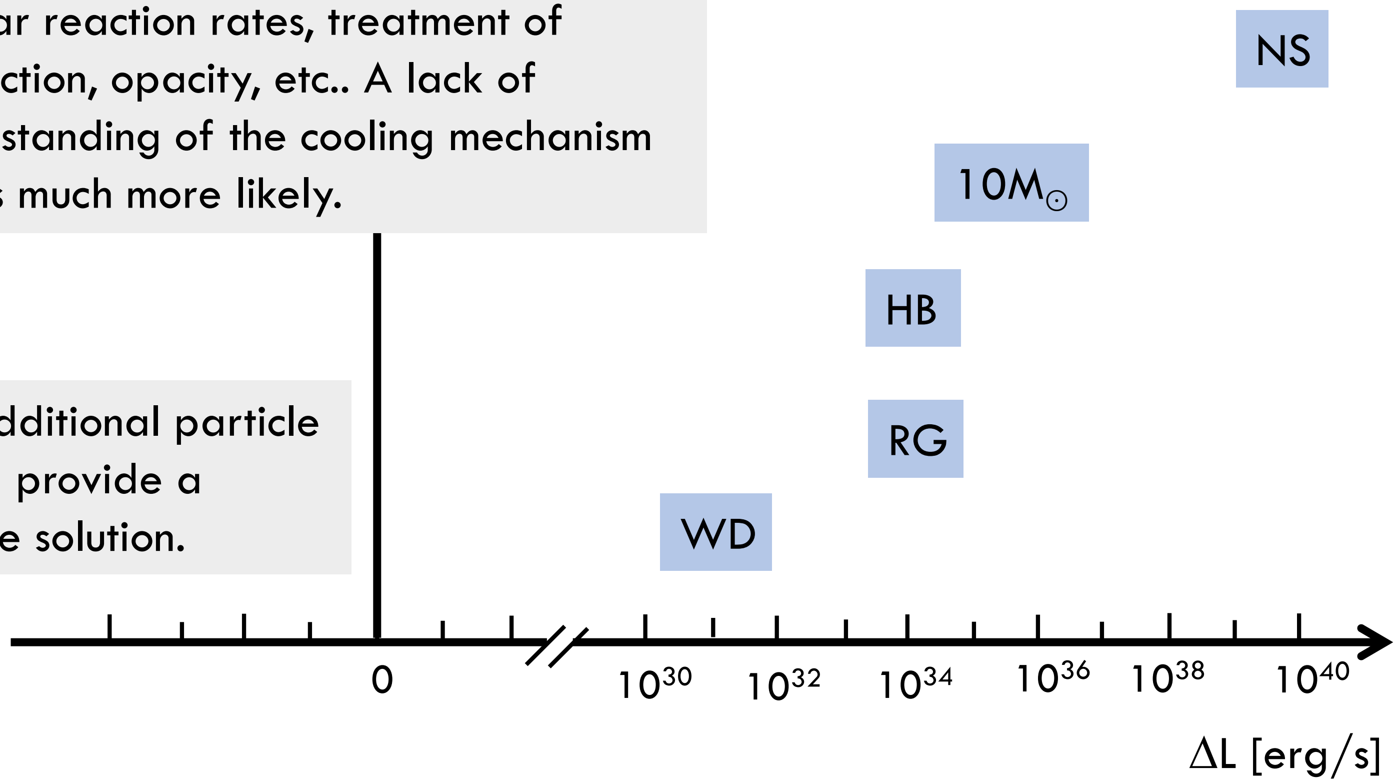
The tendency of different stellar systems to show the need for additional cooling indicates a systematic problem.



The tendency of different stellar systems to show the need for additional cooling indicates a systematic problem.

The recurrence in different stellar systems seems to disfavor options like EOS, nuclear reaction rates, treatment of convection, opacity, etc.. A lack of understanding of the cooling mechanism seems much more likely.

An additional particle could provide a simple solution.



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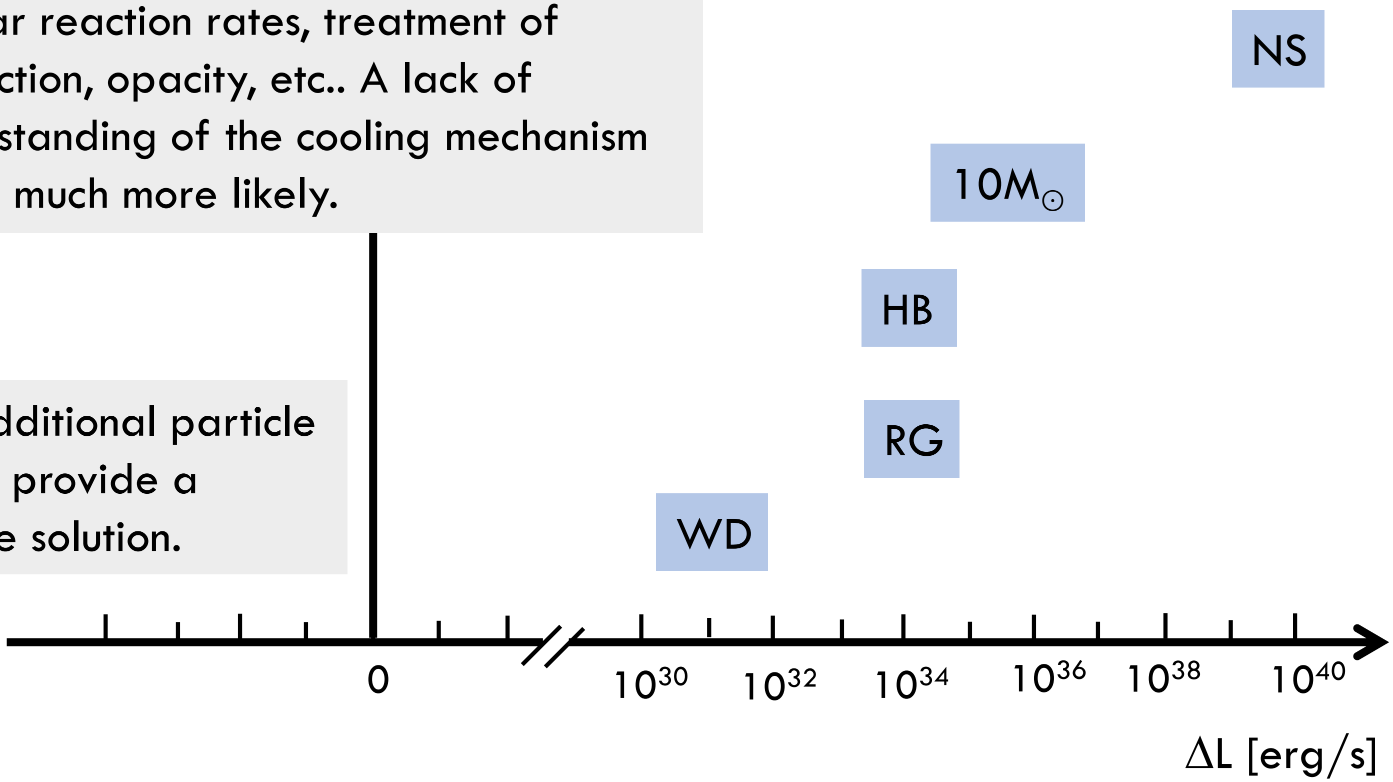


If it is new physics, what are the most likely candidates ?

Candidates: WD and RG

Both white dwarfs an RG are very dense. The RG core is hotter.

Dark Photons: not appropriate temperature dependence.

ALP-photon: cannot compete with plasmon decay into neutrino for any reasonable value of the coupling constant.

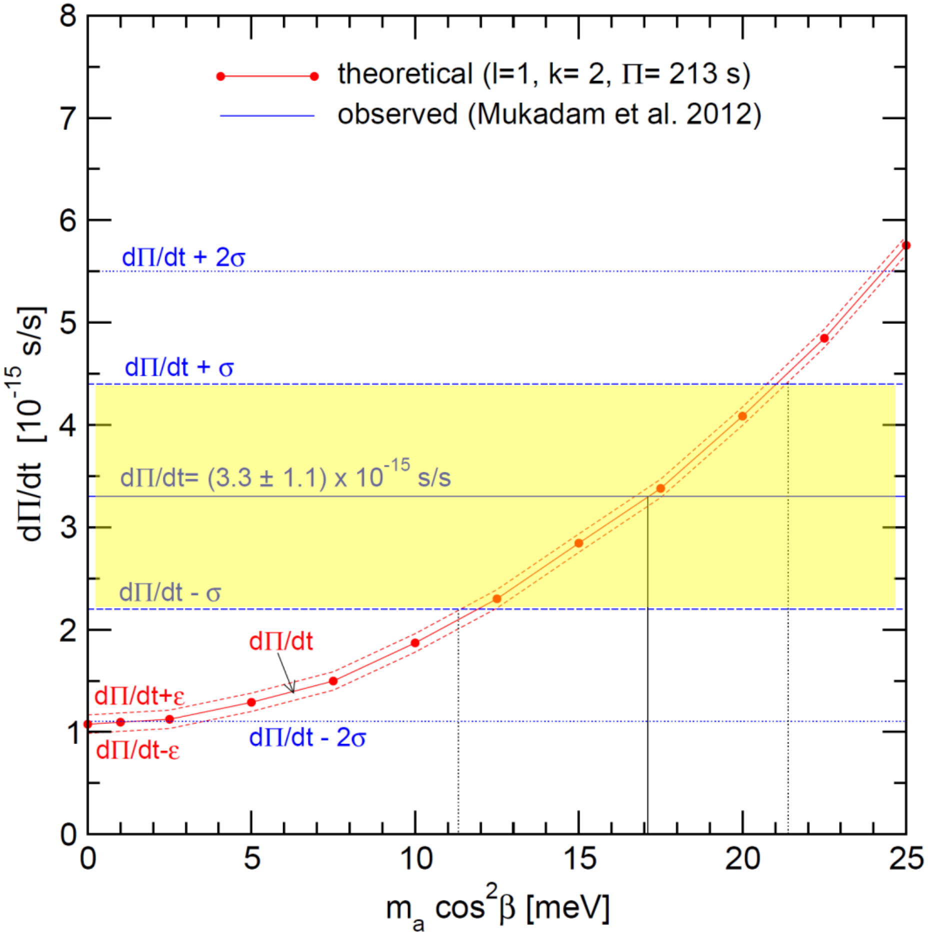
millicharged fermions: same as ALP-γ.

The best candidates are

- ALPs coupled to electrons
- neutrinos with an anomalous magnetic moment

Both could explain RG as well as the WD period anomaly.
However, only an ALP-electron coupling can easily account for the WDLF
[Bertolami, Melendez, Althaus, Isern (2014), 1410.1677]

WD Period



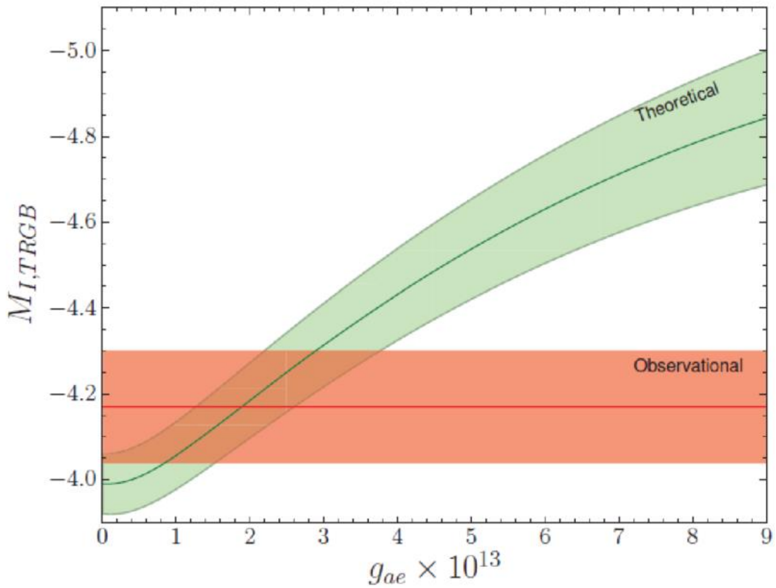
Corsico et. al., JCAP 1212 (2012).

WD: R548. Results for G117-B15A are similar.

RG AND WDLF

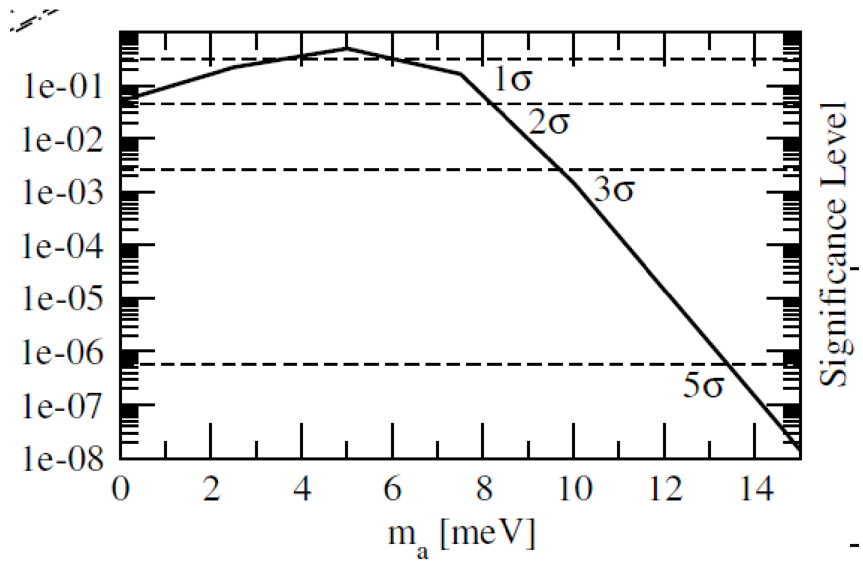
The best fit in both cases is for $g_{ae} \approx$ a few$\times10^{-13}$

RG



Viaux et. al., Phys.Rev.Lett. 111 (2013)

WDLF



Bertolami et. al., JCAP 1410 (2014) 10

Candidates: He-burning stars

Massive and low mass helium burning stars are much less dense than WD and RG, and have a nondegenerate core. The more massive stars are hotter and less dense.

ALP coupled to electrons would not be helpful in such environment. Neither would be an anomalous neutrino magnetic moment.

A millicharged neutrino is a better candidate but the temperature dependence of the production rate is too weak to simultaneously explain the results from low and massive stars.

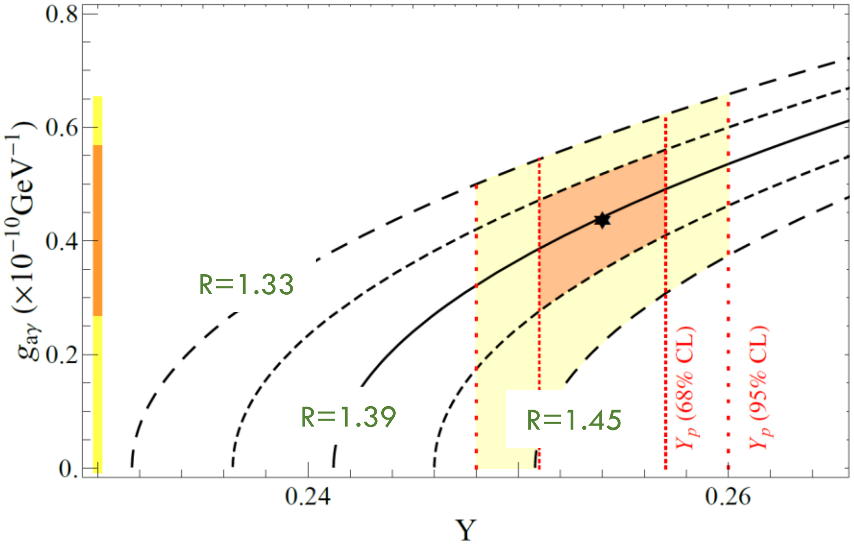
Dark Photons could not work for both HB and higher mass stars. They are produced resonantly at the mass equal to the plasma frequency (transverse mode dominates). However, the plasma frequency profiles of low and higher mass stars are very different.

An ALP coupled to photons: appears to be the only candidate.

He-burning stars

A coupling of the order of $g_{a\gamma} \approx$ a few$\times 10^{-11}$ GeV^{-1} could alleviate the observed anomalies

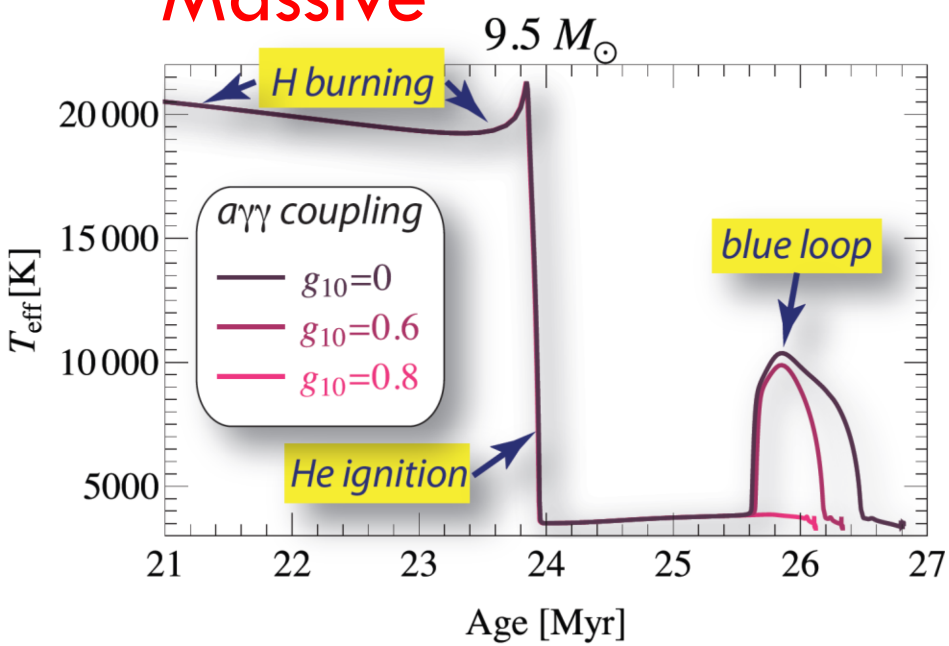
HB



Ayala, Dominguez, M.G., Mirizzi, Straniero, PRL (2014),

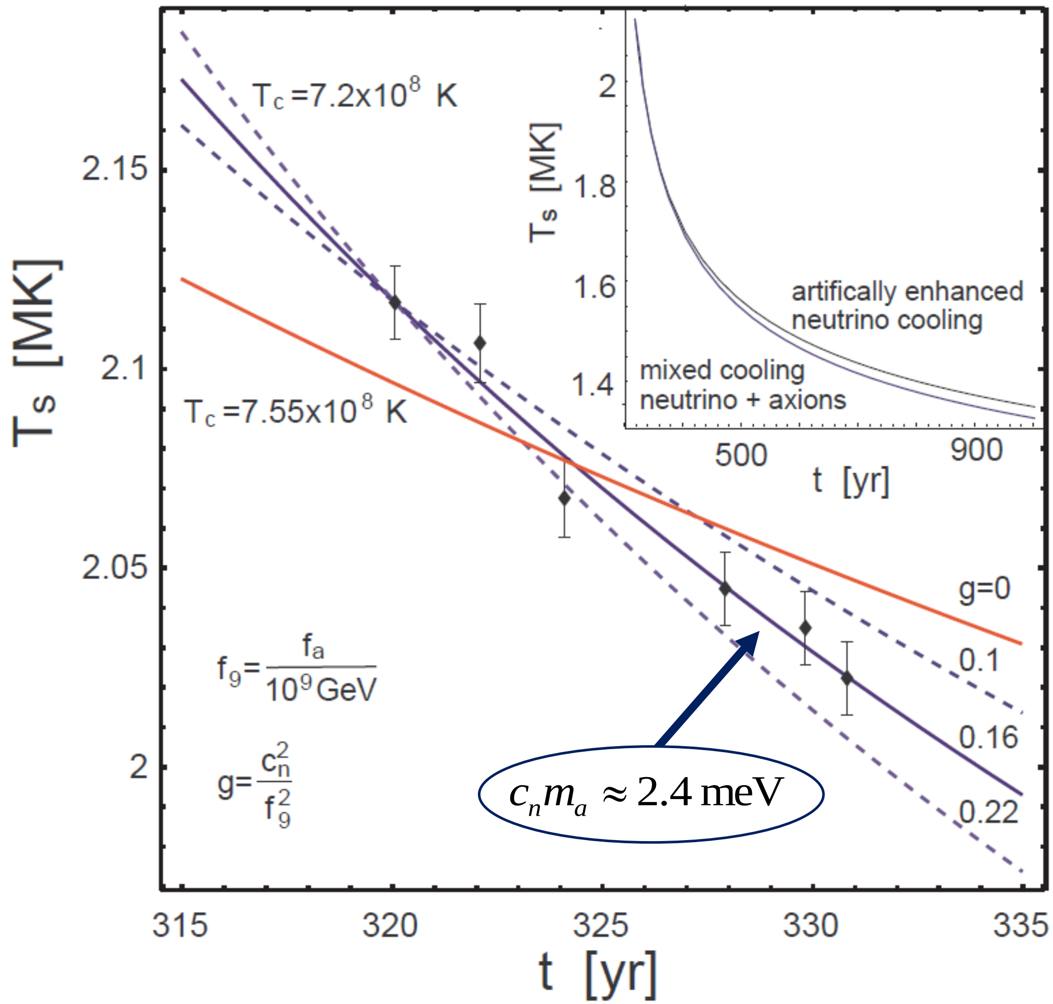
Updated results in Oscar Straniero's talk, tomorrow evening

Massive



A. Friedland, M.G., M. Wise, PRL (2013)

ALPs and NS cooling



Leinson, JCAP 1408 (2014)

The additional cooling could be explained by arbitrarily enhancing the neutrino rates [Shternin et. al., Mon. Not. R. Astron. Soc. 412 (2011)]

or by introducing an ALP coupled to nucleons [Leinson, JCAP 1408 (2014)]

New Physics around the corner?

<u>These are just hints!</u>

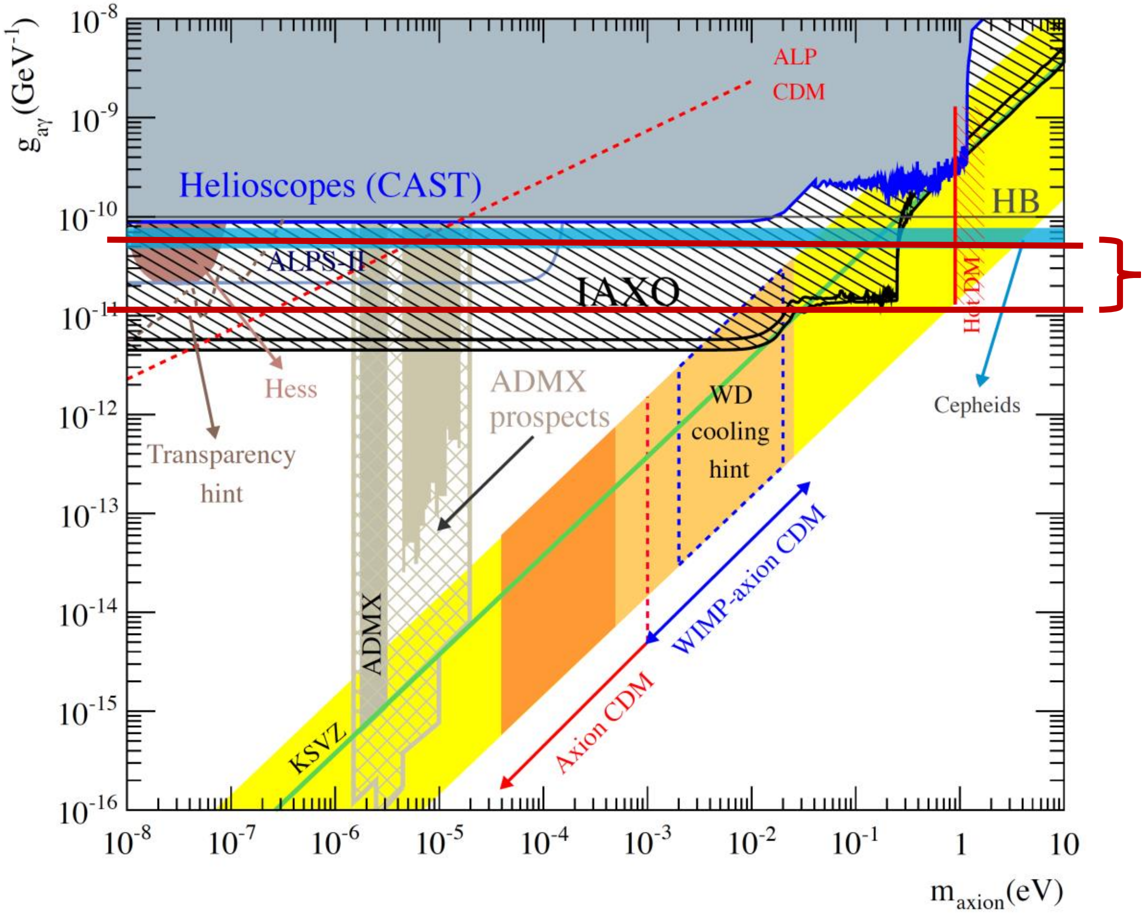
Some of the <u>uncertainties</u>, especially in some of the nuclear reaction rates and in the treatment of convection <u>are still not completely quantifiable</u>.

<u>Experimental investigation</u> is essential to decide whether or not there is new physics around the corner.

ALPS II and especially IAXO have the potential to explore the interesting parameter region.

Discussion

Some particularly interesting areas can be identified in the ALP parameter space



Interesting area from analysis of HB and massive stars

ALPS II and especially IAXO have potential to explore large portions of these areas

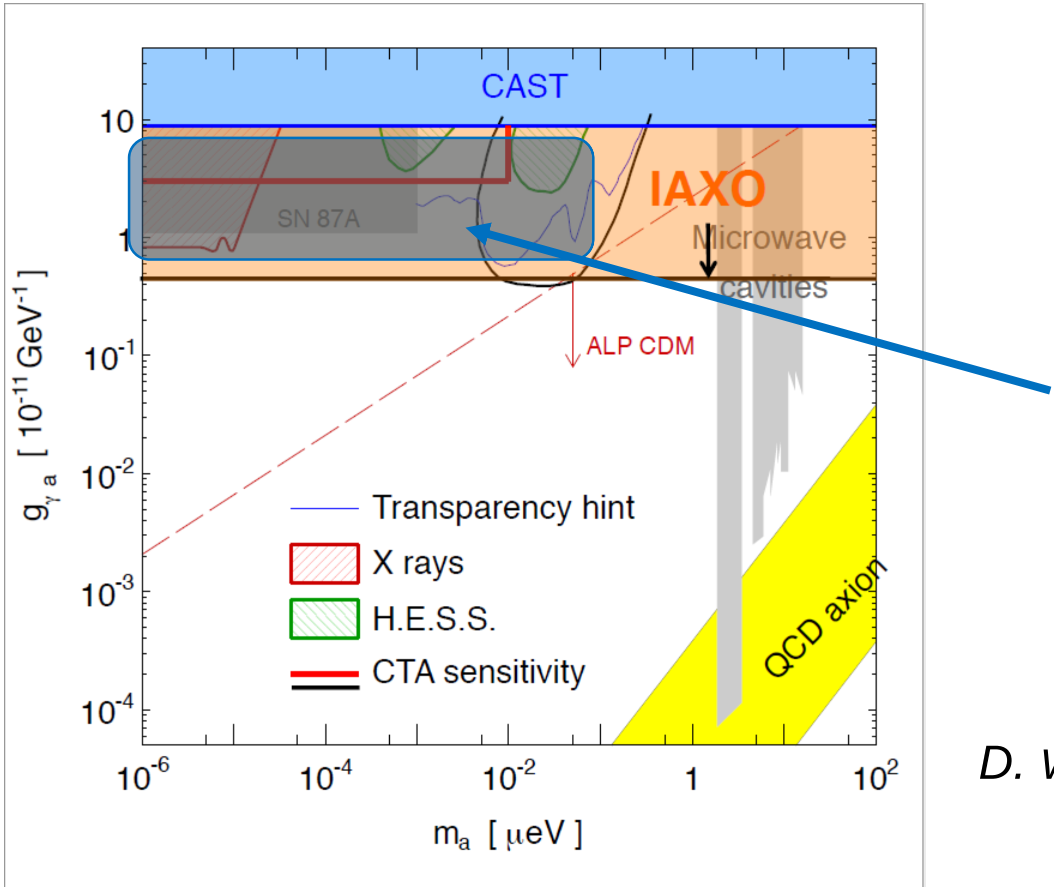
Discussion

Astrophysical hints (including the transparency hints) can be explained by an ALP with

A. Ringwald, Karlsruhe colloquium, 2014

A. Ringwald, XVI International Workshop on Neutrino Telescopes, 2015

$$f_a \approx 10^8\,\mathrm{GeV}, C_{a\gamma} \approx 1, C_{ae} \approx C_{an} \approx 10^{-2} \text{ and } m_a \leq 0.1\,\mu\mathrm{eV}$$



This region is completely accessible to IAXO

D. Wouters & P.B., JCAP 2014

Conclusions

- ✓ Stars have provided for years an excellent tool to understand the physics of light, weakly interacting particles.

- ✓ Several observational anomalies seem to indicate the need for additional cooling.

- ✓ An ALP coupled to photons, electrons and nucleons seems to provide the easiest solution. Interestingly, the required ALP parameters could also apply to other astrophysical observations, e.g., transparency hints. However, no definite conclusion can be extracted without a complete experimental investigation

- ✓ The current astrophysical analysis hints to a specific region in the parameter space. This region would be accessible to IAXO.

- ✓ If ALPs were to be found in this range, the discovery would be transformative not only for particle physics and probably for cosmology, but also for TeV gamma ray astronomy and for stellar evolution.