Axion constraints from white dwarf cooling in 47 Tuc

Leesa Fleury

University of British Columbia

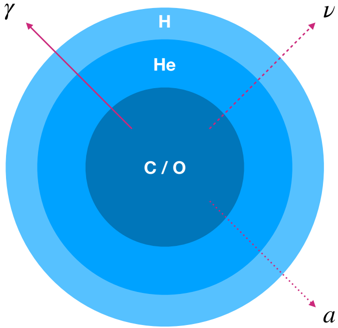
lfleury@phas.ubc.ca

In collaboration with Jeremy Heyl

19th Patras Workshop on Axions, WIMPs and WISPs
20 Sept 2024, Patras, Greece

What is a White Dwarf?

- Final evolutionary stage of stars not massive enough to burn C
- Cool by emission of photons, neutrinos, and potentially axions
- No nuclear burning in core
- Core is electron-degenerate
- Composition of typical WD ($M_{\mathrm{WD}} \sim 0.6\ M_\odot$):
  - C/O core (isothermal)
  - He layer
  - Thinner outer H envelope*
- Mass and envelope thickness affect cooling evolution



* Envelope thickness parameterised by relative mass: $q_H \equiv M_H / M_{\mathrm{WD}}$

Globular Clusters

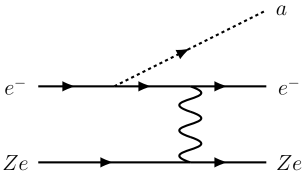
- Group of stars tightly bound by gravity, spherically-distributed in space
- Typically very old and well-populated with WDs
- Provide populations of WDs whose progenitor stars formed from the same protostellar material at the same time
- The WDs have approximately the same mass and a constant birthrate
- This is in contrast to WDs in the Galactic disc, which have different masses and a time-varying birthrate
- 47 Tucanae is a very well-populated and well-studied globular cluster

For WD population in a globular cluster:

$$\frac{\mathrm{d}N}{\mathrm{d}L} = \dot{N}\,\frac{\mathrm{d}t}{\mathrm{d}L}$$

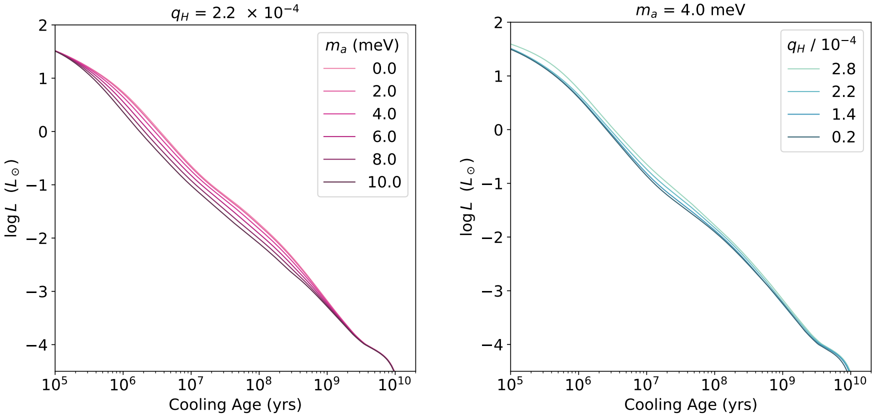
Axions and White Dwarf Cooling

Axion bremsstrahlung from electrons scattering on ions:



- Axion-electron coupling enables the production of axions in the electron-degenerate core of a WD through axion bremsstrahlung
- Emission of axions provides additional WD energy loss mechanism
- Affects cooling rate ($\mathrm{d}L/\mathrm{d}t$) at early cooling times → modifies $\mathrm{d}N/\mathrm{d}L$
- Axions have been suggested as explanation of cooling anomaly for white dwarfs in Galactic disc

Cooling Models



Example cooling curves shown for $M_{\mathrm{WD}} = 0.5388\ M_\odot$

- Stellar evolution simulations performed using MESA
- Cooling model parameter grid: M_{WD}, $\log_{10} q_H$, and m_a
- Degeneracy between axion mass and envelope thickness

Magnitudes

Luminosity:

$$L = 4\pi r^2 \int F_\lambda \, \mathrm{d}\lambda$$

Apparent magnitude (measured at detector):

$$m_\lambda - m_{\lambda,\mathrm{Vega}} = -2.5 \log_{10} \left(\frac{F_\lambda}{F_{\lambda,\mathrm{Vega}}} \right)$$

Absolute magnitude (measured at distance of 10 pc):

$$M_\lambda = m_\lambda - 5 \log_{10} \left(\frac{d}{10 \ \mathrm{pc}} \right) - A_\lambda$$

F_λ = energy flux of photons from source
A_λ = extinction due to absorption and scattering from interstellar dust
d = distance of source from detector (i.e. distance to cluster)

Bolometric Corrections

Move models from theory space to observation space:

- Telescopes measure flux through bandpass filter (label: i)
- Calculate model-predicted magnitude for filter i from luminosity (L) using bolometric corrections (BC_i)

Bolometric correction:

$$\mathrm{BC}_i \equiv M_{\mathrm{bol}} - M_i$$

Bolometric magnitude (measures flux of all wavelengths):

$$M_{\mathrm{bol}} = M_{\mathrm{bol},\odot} - 2.5 \log_{10}\left(\frac{L}{L_\odot}\right)$$

Model-predicted magnitude for filter i:

$$m_i = M_{\mathrm{bol}} - \mathrm{BC}_i + 5 \log_{10}\left(\frac{d}{10\ \mathrm{pc}}\right) + A_i$$

This is before accounting for photometric errors.

Unbinned Likelihood

$$\ln \mathcal{L}(\theta) = \sum_{i \in \text{data}} \ln f\left(m_{1i}, m_{2i}, R;\, \theta\right) - \iint\limits_{\text{data space}} f\left(m_1, m_2, R;\, \theta\right) \mathrm{d}m_1 \, \mathrm{d}m_2$$

$$f(m_1, m_2, R;\, \theta) = \dot{N} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\mathrm{d}t}{\mathrm{d}m_1'} \, \delta\left[m_2' - m_{2,\mathrm{mod}}\left(m_1';\, \theta_M\right)\right] \times E\left(m_1 - m_1', m_2 - m_2', R;\, m_1', m_2'\right) \mathrm{d}m_1' \, \mathrm{d}m_2'$$

f = number density distribution → model prediction in data space
E = photometric error distribution → move from theory to data space

Data:

$\{m_1, m_2\}$ = magnitudes (a measure of luminosity) in two filters
R = radial distance from cluster centre (in projection)

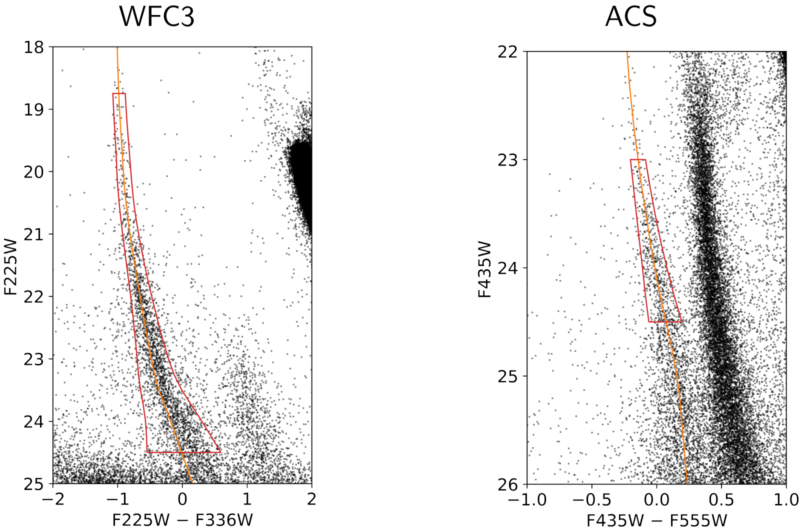
Parameters:

$\theta = \{\theta_M, \dot{N}\}$, $\theta_M = \{M_{\mathrm{WD}}, \log_{10} q_H, m_a\}$, $\dot{N}$ = WD birthrate

Data Analysis

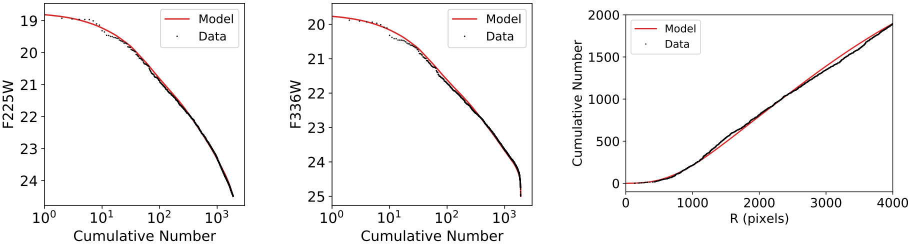
- Use unbinned likelihood analysis to find best-fitting model and constrain parameters
- Combined analysis of two sets of HST data of young WDs in 47 Tuc
    - WFC3 observations of centre (inner field)
    - ACS observations of surrounding ring (outer field)
- Account for energy loss due to axion emission in cooling models
    - axion bremsstrahlung from electrons
    - most generally parameterised by axion-electron coupling, g_{aee}
    - equivalently parameterised by DFSZ axion mass, m_a
- Use priors for M_{WD} and $\log_{10} q_H$ from similar analysis of old white dwarfs in 47 Tuc and uniform priors for everything else
    - helps break degeneracy between $\log_{10} q_H$ and m_a

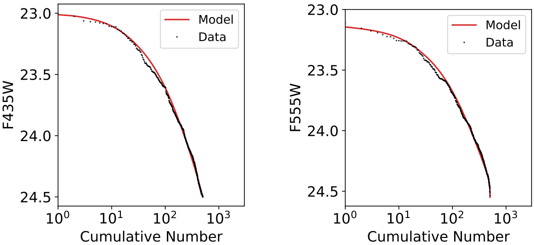
Data Space



F###W = magnitude for HST filter with effective wavelength $\lambda = ###$ nm

Best-Fitting Model





$$\dot{N}_{\mathrm{WFC3}} = 6.91^{+0.82}_{-0.23}\ \mathrm{Myr}^{-1}$$

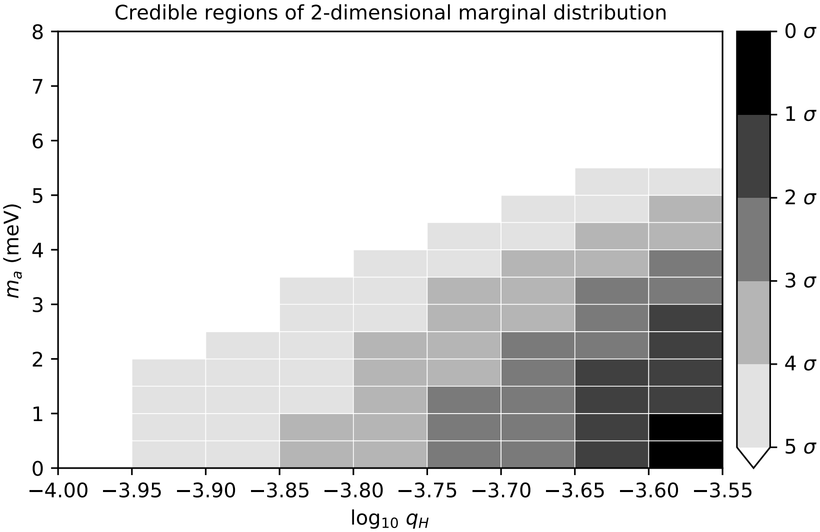
$$\dot{N}_{\mathrm{ACS}} = 3.73^{+0.62}_{-0.24}\ \mathrm{Myr}^{-1}$$

$$M_{\mathrm{WD}} = 0.5388^{+0.0000}_{-0.0106}\ M_{\odot}$$

$$\log_{10} q_H = -3.55^{+0.00}_{-0.12}$$

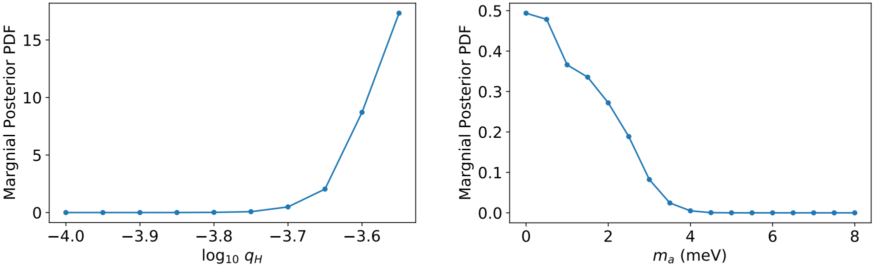
$$m_a = 0.00^{+2.85}_{-0.00}\ \mathrm{meV}$$

Joint Credible Regions



1D Marginal Posterior Probability Density Functions

After marginalising over all other parameters.



95% credible regions from these distributions:

$$\log_{10} q_H \geq -3.67 \quad , \quad m_a \leq 2.85\ \mathrm{meV}$$

Final Axion Constraints

New bound from this work (95% confidence): $g_{aee} \leq 0.81 \times 10^{-13}$

Previous bounds and hints:

- Red giant branch tip of globular clusters: $g_{aee} \leq 1.5 \times 10^{-13}$
- Galactic white dwarf luminosity function: $g_{aee} \leq 2.1 \times 10^{-13}$
- Hints from Galactic white dwarf cooling: $g_{aee} \sim (1.1 - 2.8) \times 10^{-13}$

Comparison:

- Improves upon previous leading bound by nearly a factor of 2
- Excludes parameter range hinted at by Galactic white dwarfs

Future work:

- Could improve bound further by using non-uniform birthrate priors
- May require modelling cluster relaxation effects