with Chris Dessert & Ben Safdi (1903.05088)

Testing axion-like particles with X-ray emission from magnetic white dwarf stars

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@ Pheno 2019
May 6, 2019

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Axion-like particles

Interactions with Standard Model particles

- Leading-order interactions are dimension-5 operators

$$\mathscr{L}_{\mathrm{ALP}} = \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F \tilde{F} + \frac{g_{aee}}{2m_e}\, \bar{e}\gamma^\mu\gamma_5 e\, \partial_\mu a \cdots$$

Connection to new physics scale

- Couplings arise from new physics at the scale f_a
- Very weakly interacting!

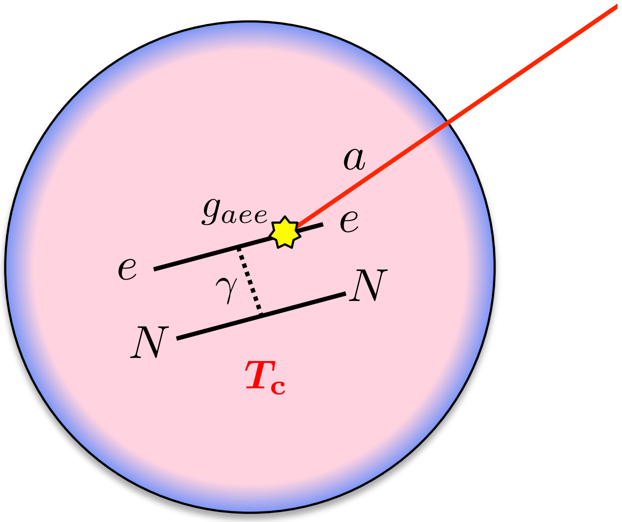
$$g_{a\gamma\gamma} = C_\gamma \frac{\alpha}{2\pi f_a} \qquad g_{aee} = C_e \frac{m_e}{f_a}$$

Testing ALPs with white dwarf cooling

[Raffelt (1986)]
[Nakagawa, Adachi, Kohyama, & Itoh (1987,88)]

Axions are produced via bremstrahlung

➔ axion luminosity:



$$L_a \simeq \left(1.6 \times 10^{-4}\ L_\odot\right) \left(\frac{g_{aee}}{10^{-13}}\right)^2 \left(\frac{M_{\rm WD}}{1\ M_\odot}\right) \left(\frac{T_c}{10^7\ {\rm K}}\right)^4$$

Axion emission causes WDs to cool

➔ constrains the axion-electron coupling:

$$g_{aee} < 3 \times 10^{-13} \quad (3\sigma)$$

[PDG & Miller Bertolami et al (2014)]

A hint of new physics!

Evidence of anomalous cooling?

- ➔ Seen in white dwarf, red giant branch, and horizontal branch stars

Evidence for ALPs?

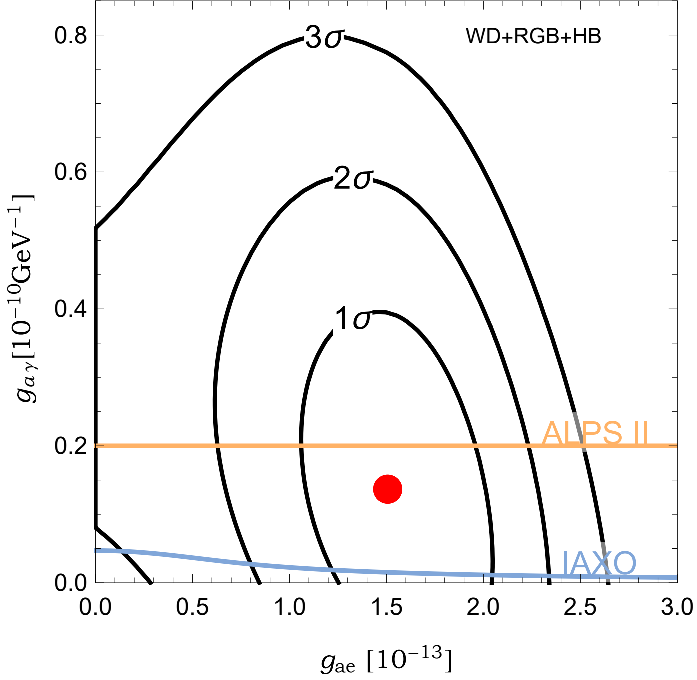
- ➔ favored couplings are …

$$g_{a\gamma\gamma} \simeq 1.4 \times 10^{-11}\ \mathrm{GeV}^{-1}$$

$$g_{aee} \simeq 1.5 \times 10^{-13}$$

A target for future observations!

[Giannotti et. al. (2017)]



Detecting astrophysical ALPs at Earth

Can we detect the radiated ALPs when they reach Earth?

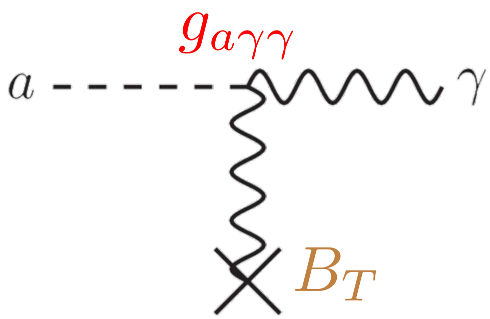
- ➔ Axion energy flux density at Earth:

$$F_a = L_a \,/\, (4\pi d_{\mathrm{WD}}^2)$$

Axions are converted into photons in a B-field

- ➔ Conversion probability is given by

$$p_{a\to\gamma} \approx g_{a\gamma\gamma}^2 B_T^2 L^2/4$$



Predicted signal (is very weak):

$$F_\gamma \simeq (4\times 10^{-31}\ \mathrm{erg/cm^2/sec}) \left(\frac{g_{aee}}{10^{-13}}\right)^2 \left(\frac{M_{\mathrm{WD}}}{1\ M_\odot}\right) \left(\frac{T_c}{10^7\ \mathrm{Kel}}\right)^4$$

$$\times \left(\frac{g_{a\gamma\gamma}}{10^{-11}/\mathrm{GeV}}\right)^2 \left(\frac{B_T}{5\ \mathrm{T}}\right)^2 \left(\frac{L}{100\ \mathrm{cm}}\right)^2 \left(\frac{d_{\mathrm{WD}}}{10\ \mathrm{pc}}\right)^{-2}$$

A stronger B-field at the source!

Often compact stars already sustain strong B-fields

- ➔ Neutron stars (magnetars): ~10^{12} – 10^{15} Gauss
- ➔ Magnetic white dwarfs: ~10^{6} – 10^{9} Gauss

The conversion of axions into photons will occur near the star!

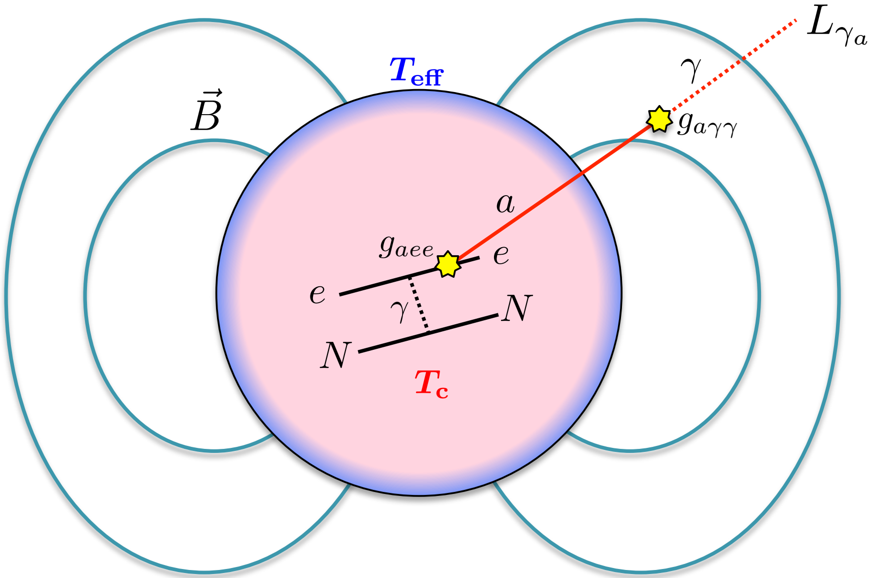
- ➔ Previous talk: Kuver Sinha
  … axions from *magnetars* produce an X-ray signal
- ➔ This talk: Andrew Long
  … axions from *magnetic white dwarfs* produce an X-ray signal
- ➔ Next talk: Josh Foster
  … dropping *axion dark matter* onto a magnetic neutron star produces a radio signal

Axion conversion in MWD magnetosphere

[D. E. Morris (1986); Raffelt & Stodolsky (1987)]
[Fortin & Sinha (2018)]
[Dessert, Long, & Safdi (2019)]

Focus on ALP production in magnetic white dwarfs (MWDs)

➔ ALPs convert to X-ray photons as they exit the star



signal = thermal X-ray emission (T_c ~ 10^7 K ~ keV)
background = surface emission negligible (T_{eff} ~ 10^4 K)

Conversion probability (refined calculation)

Axion-photon conversion in a weak & homogenous B-field

$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B_T^2 R_{\rm WD}^2$$

But more generally …

- ➔ The B-field falls off moving away from the star

$$\left[i\partial_r + E + \begin{pmatrix} \Delta_\parallel & \Delta_B \\ \Delta_B & \Delta_a \end{pmatrix} \right] \begin{pmatrix} A_\parallel \\ a \end{pmatrix} = 0$$

$$\text{boundary condition:} \quad A_\parallel(r=0) = 0$$

$$\begin{aligned} \Delta_B &= g_{a\gamma\gamma} B_T / 2 \\ \Delta_a &= -m_a^2/(2E) \\ \Delta_\parallel &= \frac{7}{2} E \frac{\alpha}{45\pi} \frac{B_T^2}{B_{\rm crit}^2} \end{aligned}$$

- ➔ Axion-to-photon conversion probability

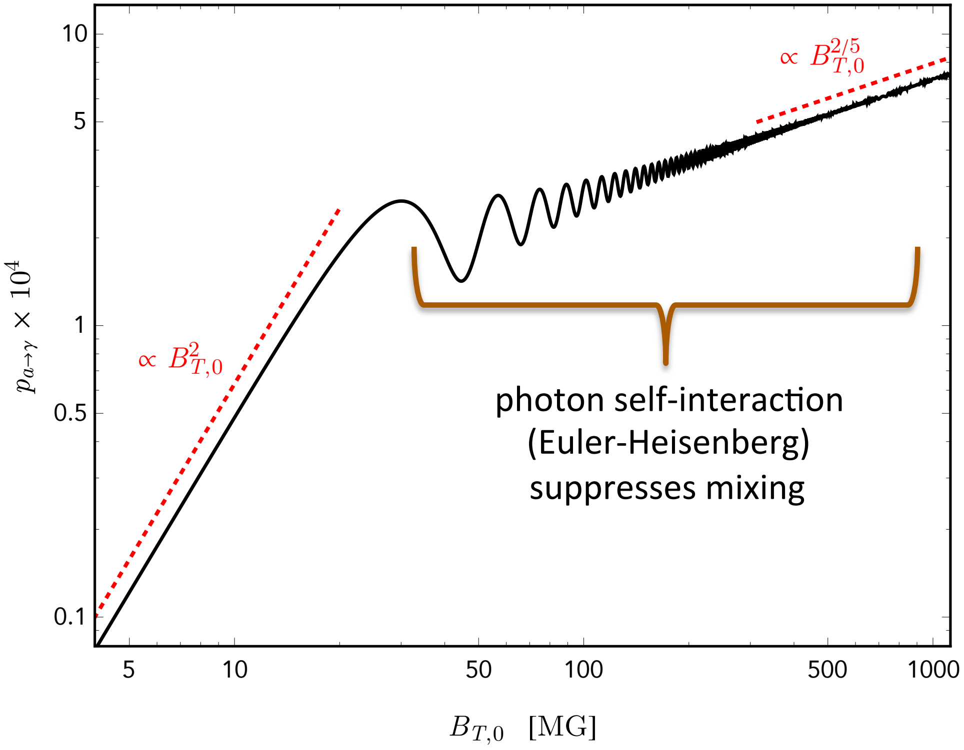
$$p_{a\to\gamma} \propto \left| A_\parallel(r=\infty) \right|^2$$

Conversion probability (refined calculation)

For a dipole profile B-field profile

$$B_T(r) = B_{T,0} \times \left(\frac{r}{R_{\rm WD}} \right)^{-3}$$

$$p_{a\to\gamma} \approx \frac{(\Delta_{B,0}\, R_{\rm WD})^2}{(\Delta_{\parallel,0}\, R_{\rm WD})^{\frac{4}{5}}} \left| \frac{\Gamma(\frac{2}{5}) - \Gamma(\frac{2}{5}, -\frac{i}{5} \Delta_{\parallel,0} R_{\rm WD})}{5^{3/5}} \right|^2$$



photon self-interaction (Euler-Heisenberg) suppresses mixing

A quasi-thermal X-ray spectrum

The spectrum of bremm'd axions

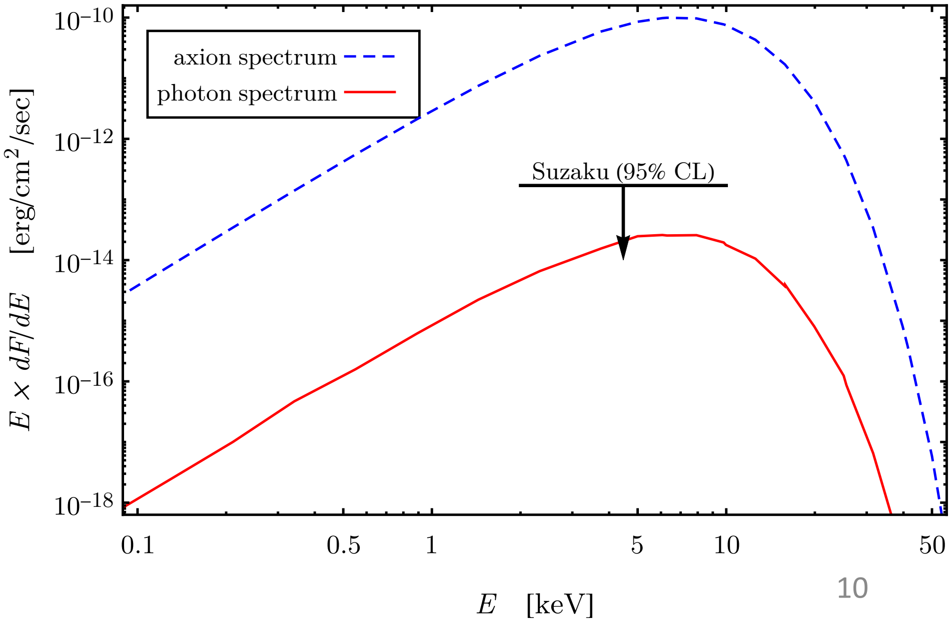
- ➔ Very close to thermal @ core temperature T_c

$$\frac{dL_a}{dE} \propto E^3 \,/\, (e^{E/T_c} - 1)$$

The spectrum of secondary (X-ray) photons

- ➔ Very slight energy modulation by axion-photon conversion

$$\frac{dF_{\gamma_a}}{dE} = \frac{dL_a}{dE}\,\frac{p_{a\to\gamma}(E)}{4\pi d_{\mathrm{WD}}^2}$$



How many MWDs are there?

The Gaia survey maps out nearby WDs

- ➔ Expects to see 100% of WDs with 100 pc of Earth.
- ➔ Current catalog contains ~70,000 WDs.

[Torres et. al. (2015)

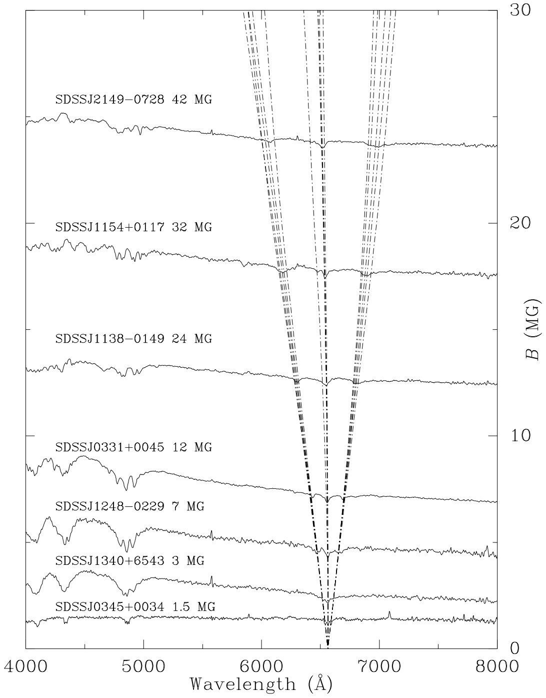
The number of known MWDs is far fewer

- ➔ Roughly 300-550 have been identified.

[Ferrario, deMartino, & Gansike (2015)]

B-field measured from spectra

① Measure the spectrum well
② MWD contains hydrogen (Balmer)
③ B-field induces Zeeman effect
④ Spectra splitting ⇔ B-field



Magnetic white dwarf candidates

Top 10 MWD candidates

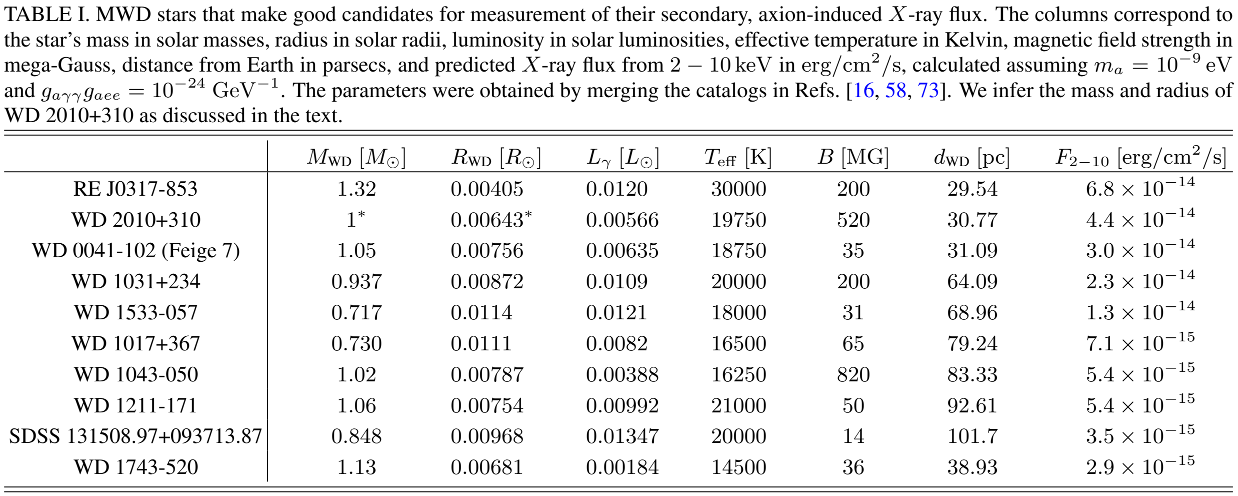
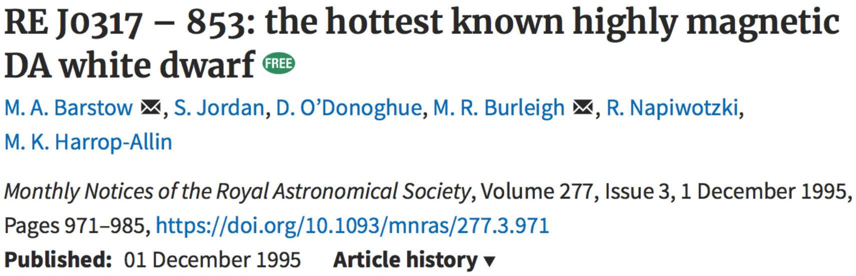


TABLE I. MWD stars that make good candidates for measurement of their secondary, axion-induced X-ray flux. The columns correspond to the star's mass in solar masses, radius in solar radii, luminosity in solar luminosities, effective temperature in Kelvin, magnetic field strength in mega-Gauss, distance from Earth in parsecs, and predicted X-ray flux from $2 - 10\,\mathrm{keV}$ in $\mathrm{erg/cm^2/s}$, calculated assuming $m_a = 10^{-9}\,\mathrm{eV}$ and $g_{a\gamma\gamma} g_{aee} = 10^{-24}\,\mathrm{GeV^{-1}}$. The parameters were obtained by merging the catalogs in Refs. [16, 58, 73]. We infer the mass and radius of WD 2010+310 as discussed in the text.

	$M_{\rm WD}$ $[M_\odot]$	$R_{\rm WD}$ $[R_\odot]$	L_γ $[L_\odot]$	$T_{\rm eff}$ [K]	B [MG]	$d_{\rm WD}$ [pc]	F_{2-10} [erg/cm^2/s]
RE J0317-853	1.32	0.00405	0.0120	30000	200	29.54	6.8×10^{-14}
WD 2010+310	1^*	0.00643^*	0.00566	19750	520	30.77	4.4×10^{-14}
WD 0041-102 (Feige 7)	1.05	0.00756	0.00635	18750	35	31.09	3.0×10^{-14}
WD 1031+234	0.937	0.00872	0.0109	20000	200	64.09	2.3×10^{-14}
WD 1533-057	0.717	0.0114	0.0121	18000	31	68.96	1.3×10^{-14}
WD 1017+367	0.730	0.0111	0.0082	16500	65	79.24	7.1×10^{-15}
WD 1043-050	1.02	0.00787	0.00388	16250	820	83.33	5.4×10^{-15}
WD 1211-171	1.06	0.00754	0.00992	21000	50	92.61	5.4×10^{-15}
SDSS 131508.97+093713.87	0.848	0.00968	0.01347	20000	14	101.7	3.5×10^{-15}
WD 1743-520	1.13	0.00681	0.00184	14500	36	38.93	2.9×10^{-15}

RE J0317-853

- ➔ M_{WD} = 1.32 M_{sun}
- ➔ R_{WD} = 0.00405 R_{sun}
- ➔ L_{gam} = 0.0120 L_{sun}
- ➔ T_{eff} = 30,000 Kelvin
- ➔ B = 200 MG
- ➔ d_{WD} = 29.54 pc (Gaia)
- ➔ **$F_{2\text{-}10}$ < 1.7e-13 erg/cm^2/sec @ 95% CL (Suzaku, 60 ks)**



RE J0317 – 853: the hottest known highly magnetic DA white dwarf FREE

M. A. Barstow ✉, S. Jordan, D. O'Donoghue, M. R. Burleigh ✉, R. Napiwotzki, M. K. Harrop-Allin

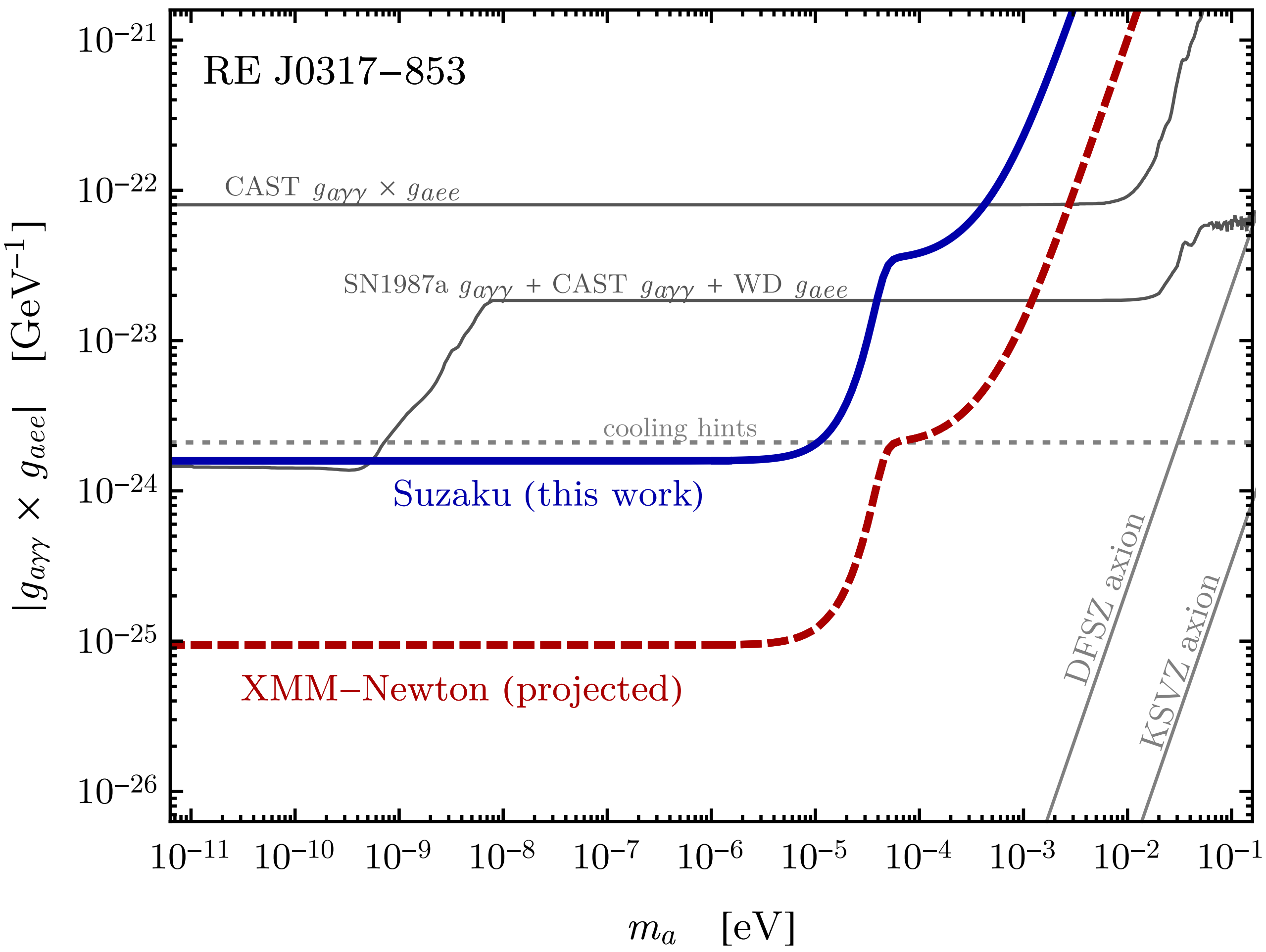
Monthly Notices of the Royal Astronomical Society, Volume 277, Issue 3, 1 December 1995, Pages 971–985, https://doi.org/10.1093/mnras/277.3.971

Published: 01 December 1995 **Article history ▾**

[Barstow et. al. (1995)]
[Burleigh et. al. (1999)]
[Kulebi et. al. (2010)]
[Suzaku (2013)]

Constraining ALPs

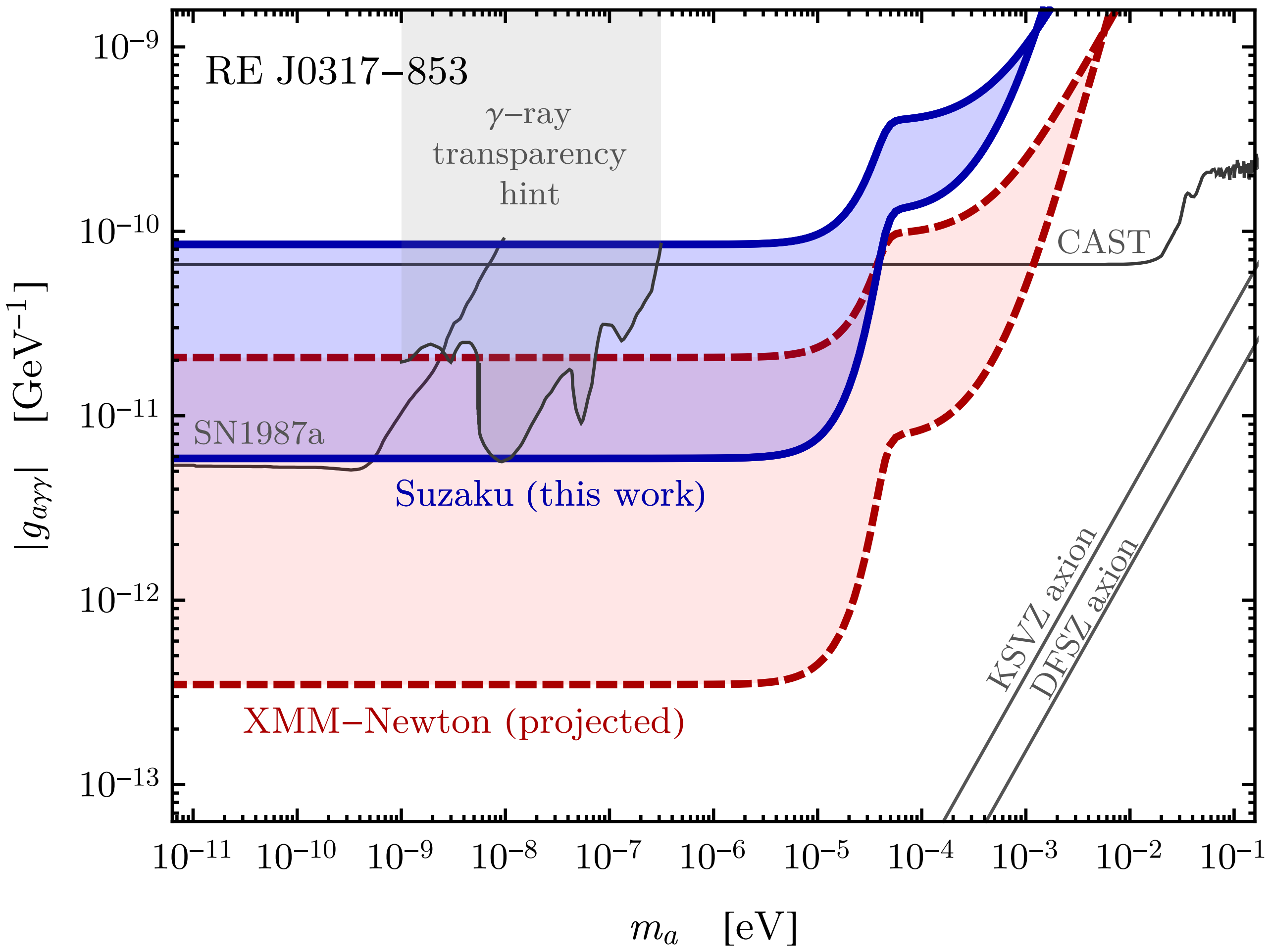
[Dessert, Long, & Safdi (2019)]



More than 1 order of magnitude improvement over previous limits (CAST).
Fiducial model for cooling hints is excluded up to $m_a \sim 10^{-5}$ eV @ 95% CL

Constraining ALPs

[Dessert, Long, & Safdi (2019)]



Summary

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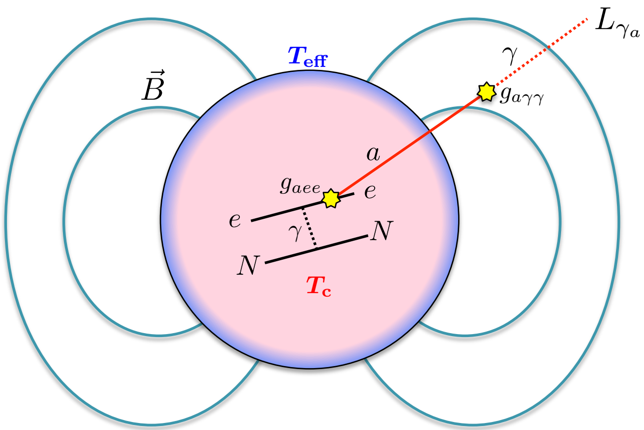
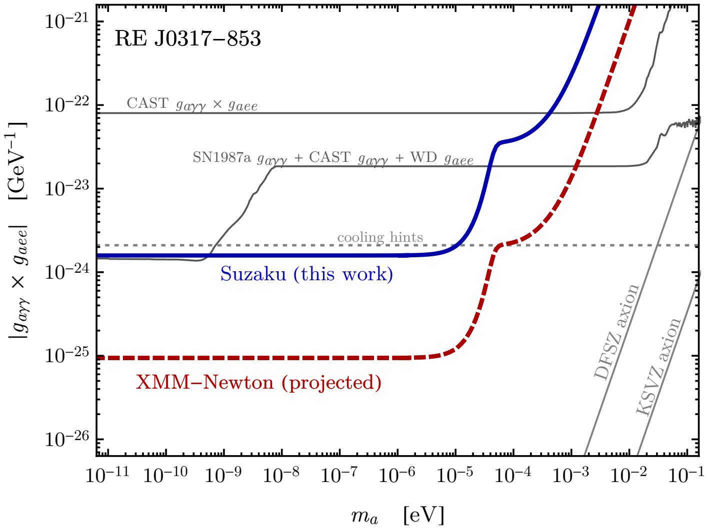
X-ray observations of magnetic white dwarf stars provide a new handle on axion-like particles.

➔ Complementary to probes of cooling (WD luminosity funcion)





This technique yields the strongest constraints to date on light ALPs.

Lots of room to improve the limits with more data!

BACKUP SLIDES

Estimating the core temperature

[Chabrier, Brassard, Fontaine, & Saumon (2000)]

There is no direct measurement of the WD core temperature

- ➔ E.g., photons produced inside do not escape

However there is extensive literature to model WD interiors

- ➔ A high electron thermal conductivity implies a nearly isothermal core.
- ➔ Core temperature is related to surface brightness (or effective temperature)

$$T_c \simeq (3\times10^6\ \mathrm{K})\left(\frac{L_\gamma}{10^{-4}L_\odot}\right)^{0.4}$$

$$\simeq (4\times10^6\ \mathrm{K})\left(\frac{T_\mathrm{eff}}{20{,}000\ \mathrm{K}}\right)^{1.6}\left(\frac{R_\mathrm{WD}}{0.01\ R_\odot}\right)^{0.8}$$

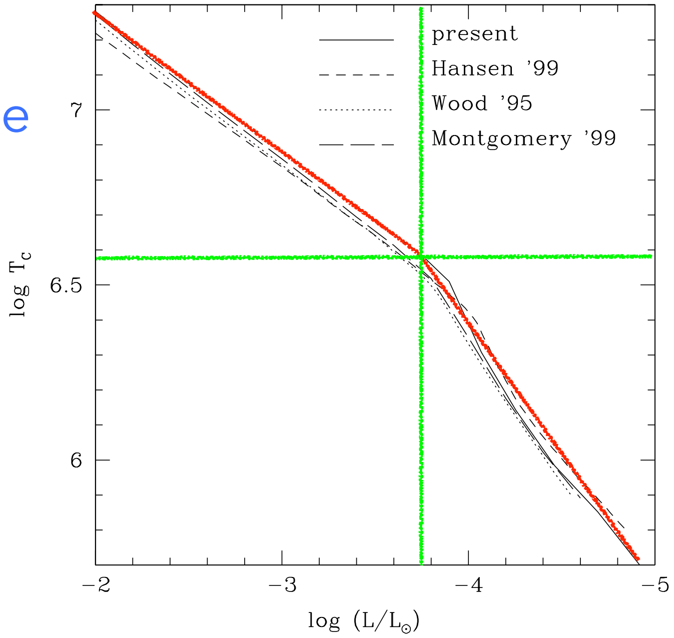


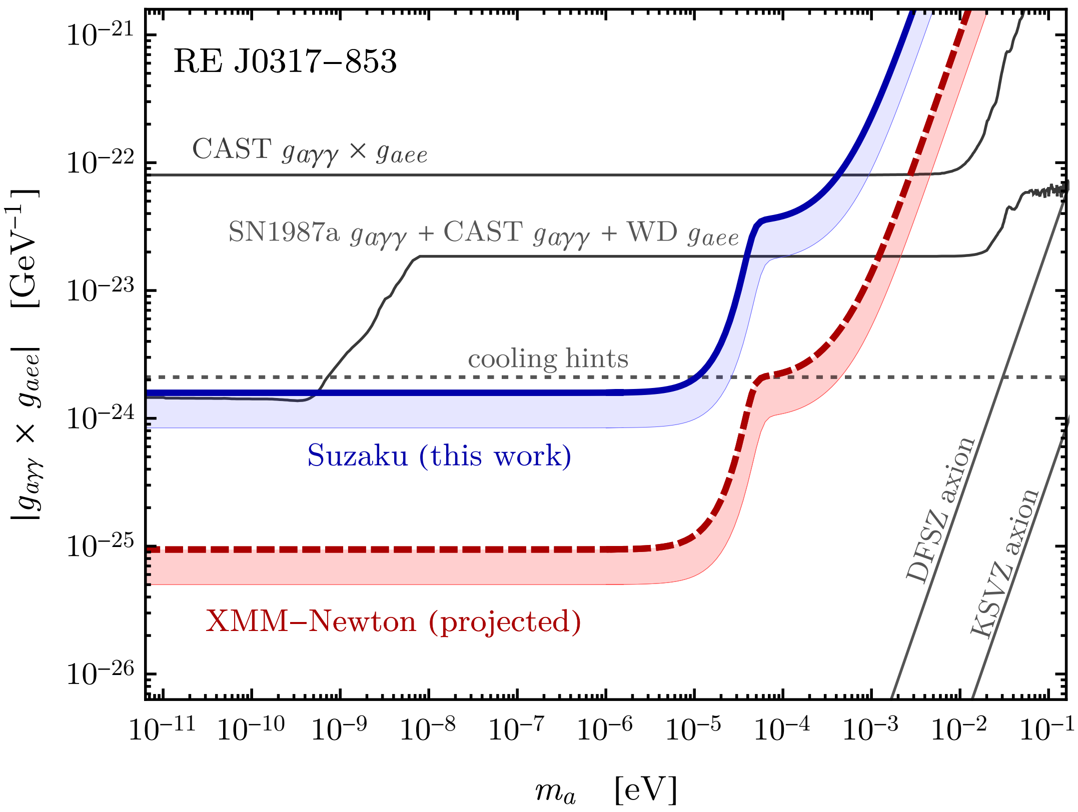
FIG. 2.—L-T_c relations from our calculations (*solid line*) and those of Hansen (1999) (*short-dashed line*), Wood (1995) (*dotted line*), and Montgomery et al. (1999) (*long-dashed line*) for a 0.6 $M_\odot$ WD with hydrogen and helium mass fractions $q(\mathrm{H}) = 10^{-4}$, $q(\mathrm{He}) = 10^{-2}$ and pure H atmosphere.

Estimating uncertainties

[Kulebi et. al. (2010)]

TABLE II. The X-ray flux of RE J0317-853 is calculated for different values of $M_{\rm WD}$, $R_{\rm WD}$, and $T_{\rm eff}$, which were determined by [60]. The luminosities, L_γ, are inferred from the Stefan-Boltzmann law. We calculate F_{2-10} for $m_a = 10^{-9}$ eV and $g_{a\gamma\gamma}g_{aee} = 10^{-24}$ GeV^{-1}.

	$M_{\rm WD}$ [$M_\odot$]	$R_{\rm WD}$ [0.01 $R_\odot$]	L_γ [$L_\odot$]	$T_{\rm eff}$ [K]	B [MG]	$d_{\rm WD}$ [pc]	F_{2-10} [erg/cm^2/sec]
CO-low-T	1.32 ± 0.020	0.405 ± 0.011	0.0120	30000	200	29.54	6.8×10^{-14}
CO-high-T	> 1.46	0.299 ± 0.008	0.0503	50000	200	29.54	2.4×10^{-13}
ONe-low-T	1.28 ± 0.015	0.416 ± 0.011	0.0126	30000	200	29.54	7.2×10^{-14}
ONe-high-T	1.38 ± 0.020	0.293 ± 0.008	0.0483	50000	200	29.54	2.2×10^{-13}

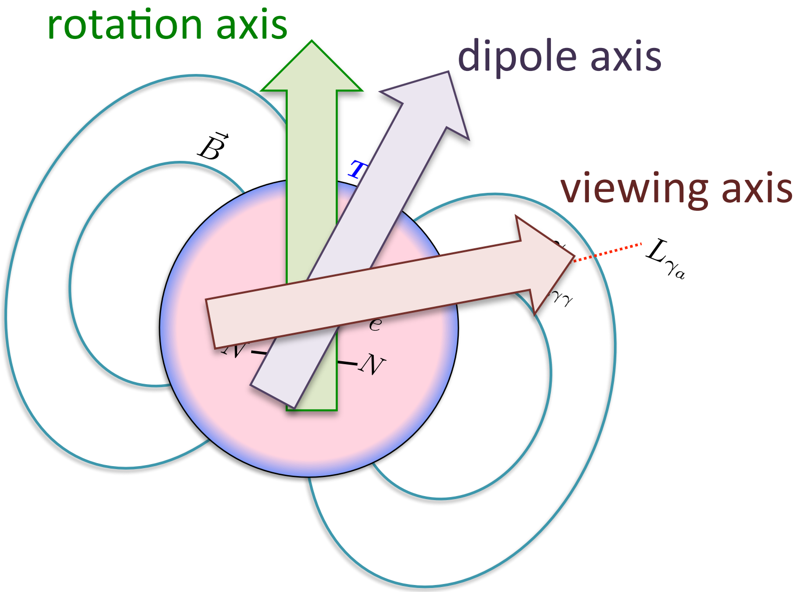


Time-varying flux

[Burleigh et. al. (1999)]

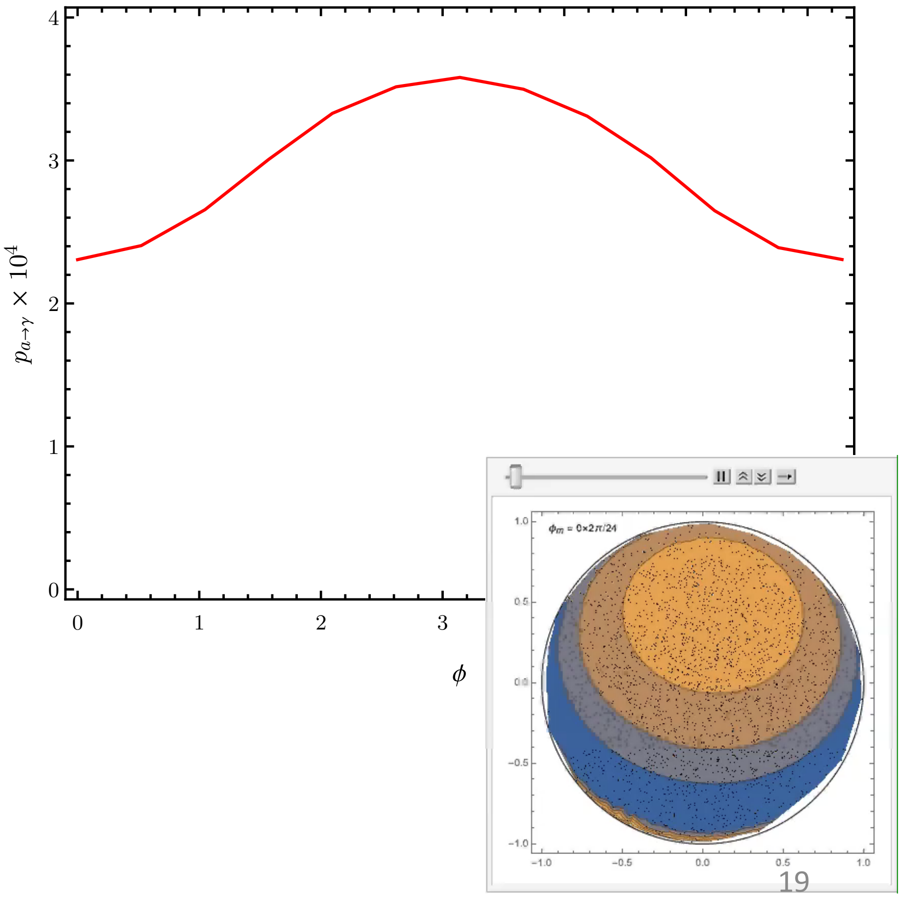
Time-resolved spectroscopy gives a model for the B-field structure

- ➔ Best described by an offset dipole
- ➔ Leads to time-varying flux at O(50%)


rotation axis

dipole axis

viewing axis



dipolar strength = 363 MG
rotation-to-dipole = 19 deg
rotation-to-viewing = 51 deg
dipole offset = -0.19 R_{WD}

Volume averaging

In the main text we assume …

- ➔ dipole profile (B ~ r^{-3})
- ➔ axion trajectories emerge radially (B_T does not change direction)

We can generalize these assumptions …