Searching for axions with X-rays from magnetic white dwarf stars

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this talk is based on 1903.05088 & 2104.12772 with Ben Safdi & Chris Dessert

Do magnetic white dwarf stars emit hard X-rays? (>~ few keV)

We don't know!

They're not supposed to,

but we've never checked.

How would axions lead to X-ray emission from magnetic white dwarf stars?

White dwarf fact sheet

Formation

-- old stars that have exhausted their fuel

Properties

-- mass: $M = (0.5\text{-}1.3)\ M_{sun}$

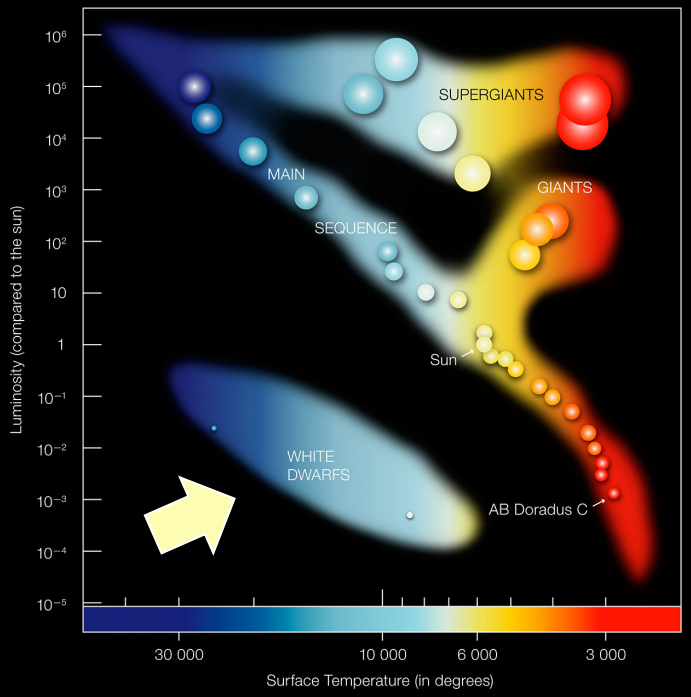
-- radius: $R = (1\text{-}2)\ R_{earth} = (0.8 – 2\%)\ R_{sun}$

-- luminosity: $L < 10^{-4}\ L_{sun}$

-- surface temp: $T_{eff} < (0.8\text{-}4.0) * 10^4$ K

-- core temp: $T_{core} \sim 10^7$ K

-- surface B-field: $B \sim (10^6 – 10^8)$ G



Composition

-- degenerate e^- + enough nuclei to give Q = 0

Structure

-- degenerate e^- core extends out to r = 0.99 R

-- non-degenerate "atmosphere" is remaining 1%

Population

-- closest WD to Earth is Sirius B at 8.6 ly

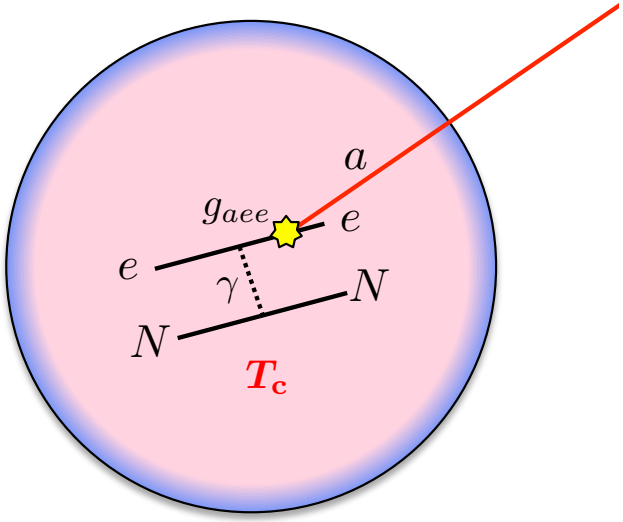
-- 97% of stars in the Milky way are expected to be WDs

Axion emission from a white dwarf

[Krauss, Moody, & Wilczek (1984)]
[Raffelt (1986)]
[Nakagawa, Adachi, Kohyama, & Itoh (1987,88)]

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

Compact stars are "glowing" in axions!



Implications

[Miller Bertolami et. al. (2014)]

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

(2) cooling hints: $g_{a\gamma\gamma} \simeq 1.4 \times 10^{-11}\ {\rm GeV}^{-1}$

$g_{aee} \simeq 1.5 \times 10^{-13}$ [Giannotti et. al. (2017)]

Detecting astrophysical ALPs at Earth

Can we detect the radiated ALPs when they reach Earth?

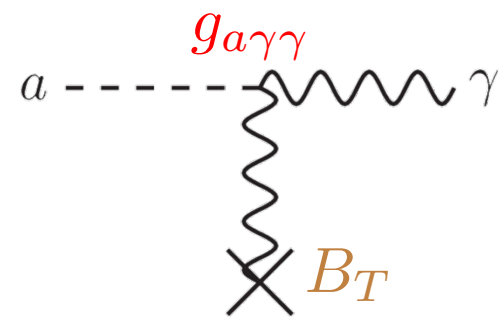
➔ Axion energy flux density at Earth:

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

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 (~ 10^{-18} counts / sec):

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

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

A stronger B-field at the source!

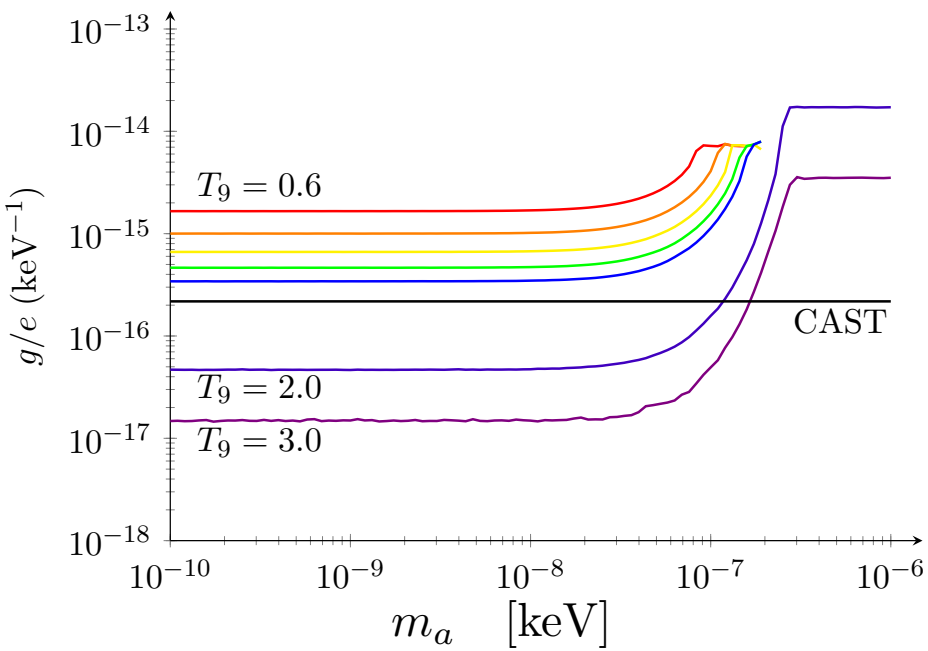
Often compact stars already sustain strong B-fields

- ➔ 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!

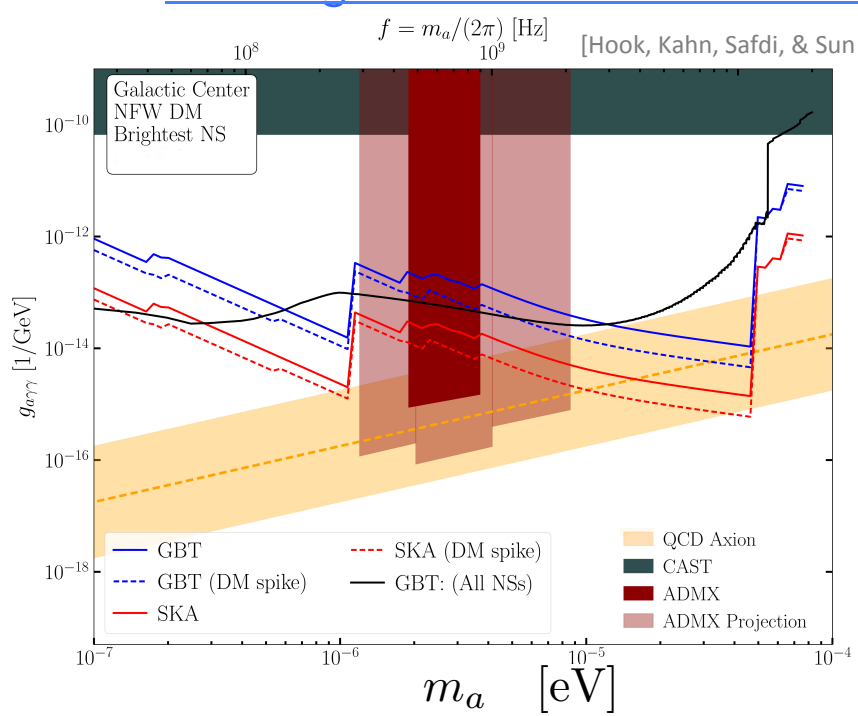
hard X-ray signals from magnetars

[Fortin & Sinha, (2018)]



radio signals from ALP dark matter

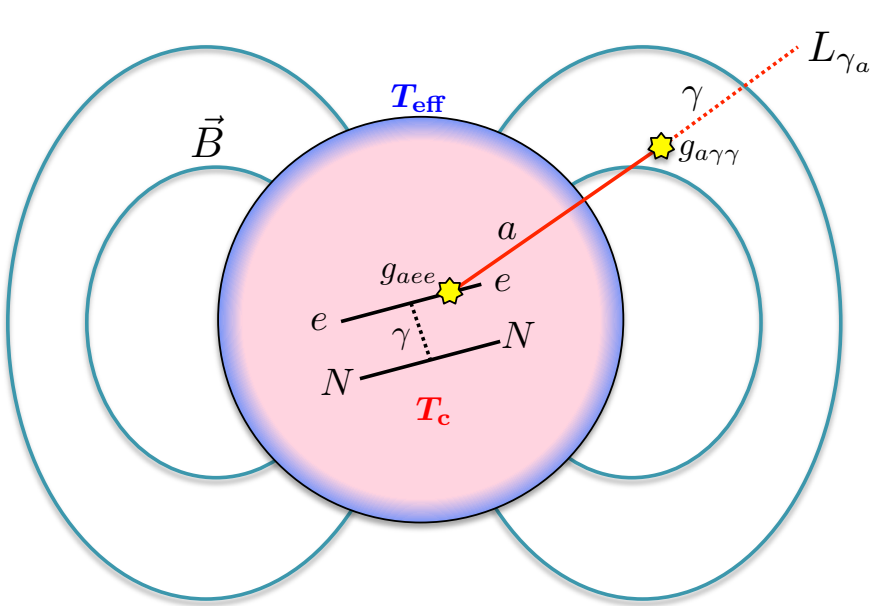
[Hook, Kahn, Safdi, & Sun (2018)]



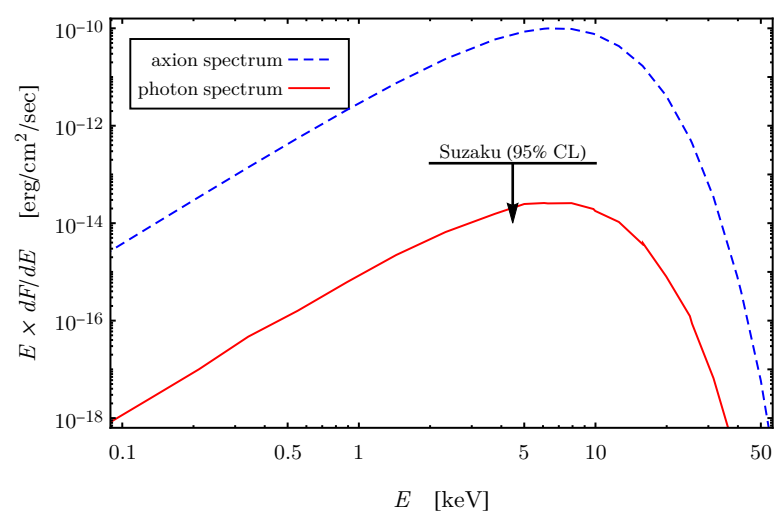
Axion conversion in MWD magnetosphere

[D. E. Morris (1986); Raffelt & Stodolsky (1987)]
see also: [Gill & Heyl (2011)]

Axions convert to X-ray photons as they exit the star



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



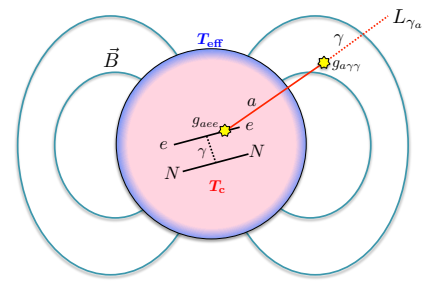
[Dessert, AL, & Safdi (1903.05088)]

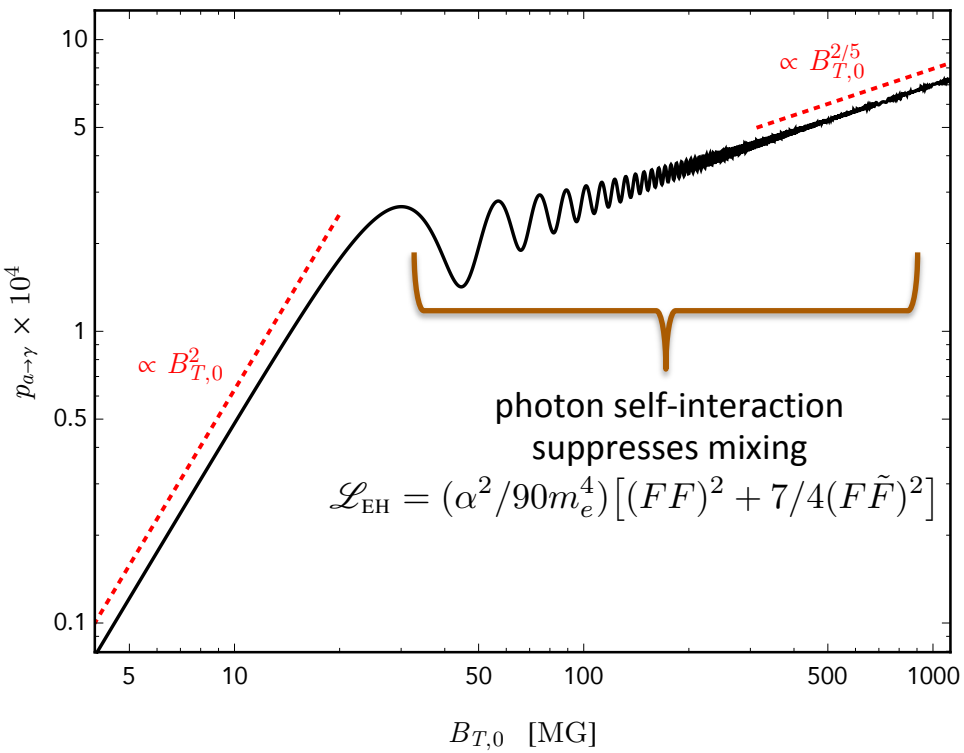
Non-resonant axion-photon conversion probability

For a dipole B-field profile & small m_a

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

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





Where should we look
for this signal?

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)

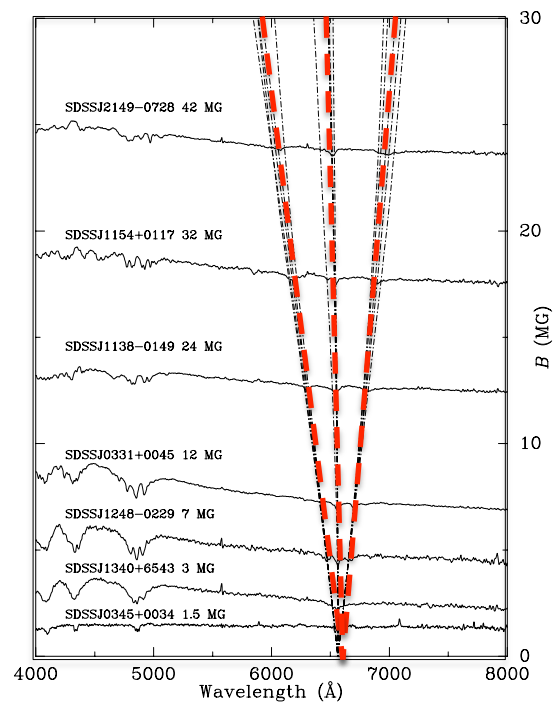
The number of known MWDs is far fewer

- ➔ 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

	$M_{\rm WD}$ $[M_\odot]$	$R_{\rm WD}$ $[R_\odot]$	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}

predicted X-ray flux
from 2-10 keV

(for $m_a = 10^{-9}$ eV and $|g_{aee}\, g_{a\gamma\gamma}| = 10^{-24}$ GeV^{-1})

RE J0317-853

Mon. Not. R. Astron. Soc. **277**, 971–985 (1995)

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

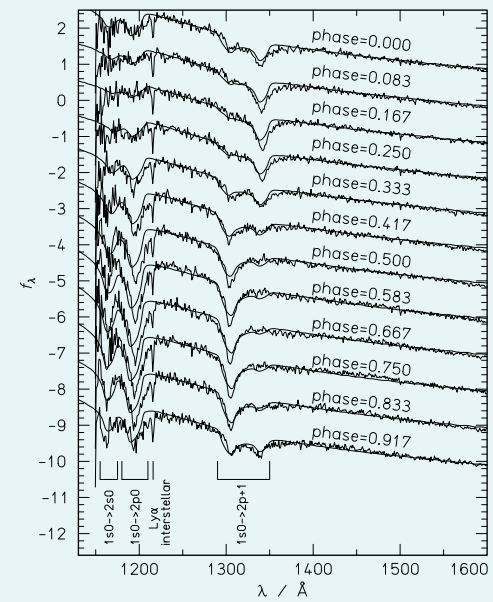
M. A. Barstow,[1★] S. Jordan,[2] D. O'Donoghue,[3] M. R. Burleigh,[1★] R. Napiwotzki[4] and M. K. Harrop-Allin[3]
[1] *Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH*
[2] *Institut für Astronomie und Astrophysik der Universität, D-24098 Kiel, Germany*
[3] *Department of Astronomy, University of Cape Town, Rondebosch 7700, South Africa*
[4] *Dr.-Remeis-Sternwarte, Universität Erlangen-Nürnberg, Sternwartstrasse 7, D-96049 Bamberg, Germany*

Observed in EUV (soft X-ray) by ROSAT

$$0.423 \pm 0.058 \text{ ct/sec} \quad \text{in} \quad 0.1 - 0.4 \text{ keV}$$

Optical & FUV spectra indicate B-field ➔

as the star rotates, we see a different B-field strength along the line of sight & the Zeeman splitting varies



Not seen in hard X-ray

- ➔ Suzaku (60 ks exposure)
- ➔ 2-10 keV band

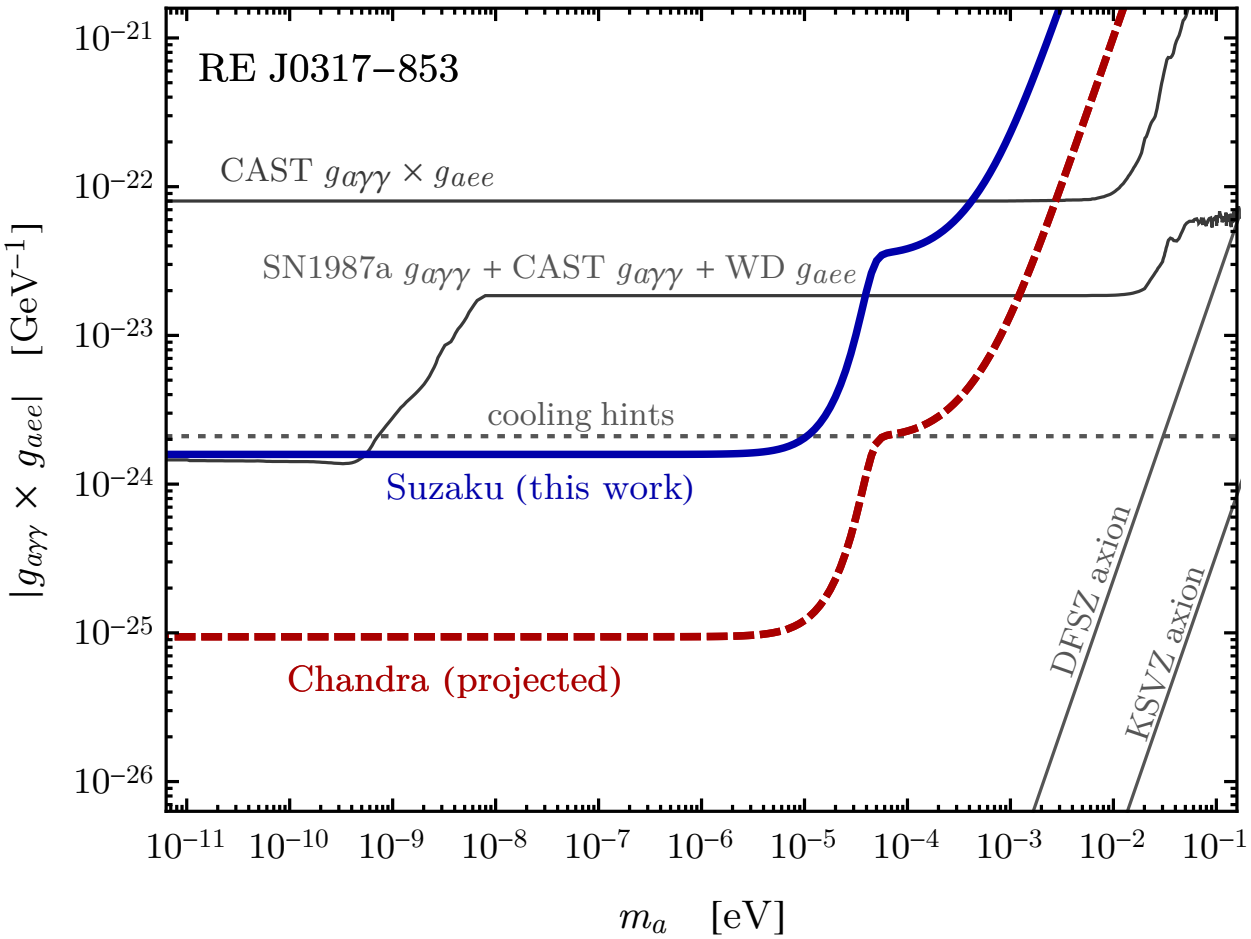
$$F_\gamma < 1.7 \times 10^{-13} \text{ erg/cm}^2\text{/sec}$$

An ideal target for axion-induced X-ray emission!

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

Constraining ALPs

[Dessert, Long, & Safdi (2019)]

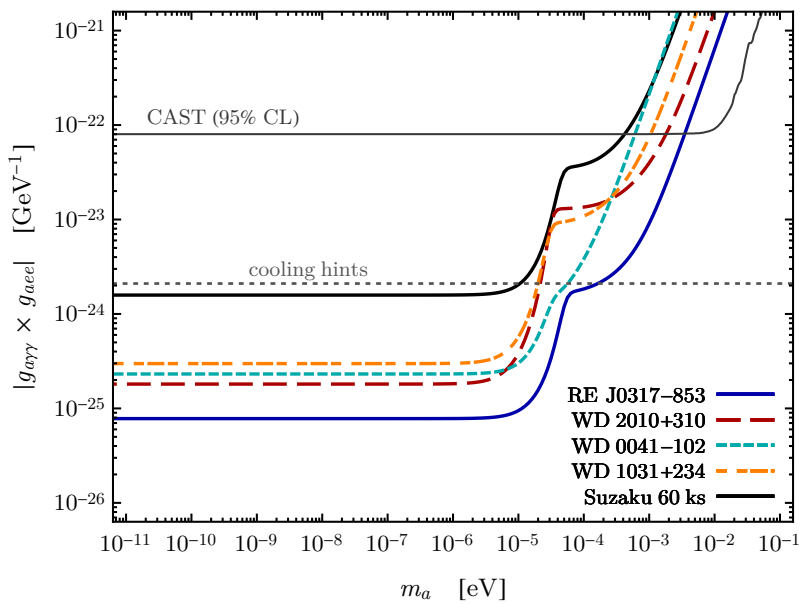


More than one order of magnitude improvement over previous limits (CAST).
Fiducial model for cooling hints is excluded up to $m_a \sim 10^{-5}$ eV @ 95% CL

Can we do better?

Chandra X-ray Observatory

- ➔ Better point source sensitivity than Suzaku.
- ➔ A stronger limit is possible even w/ a shorter exposure (20-40 ks).



What will we learn?

- ➔ definitely: extend limits by over x10
- ➔ and test cooling hints
- ➔ maybe: discover some new physics!

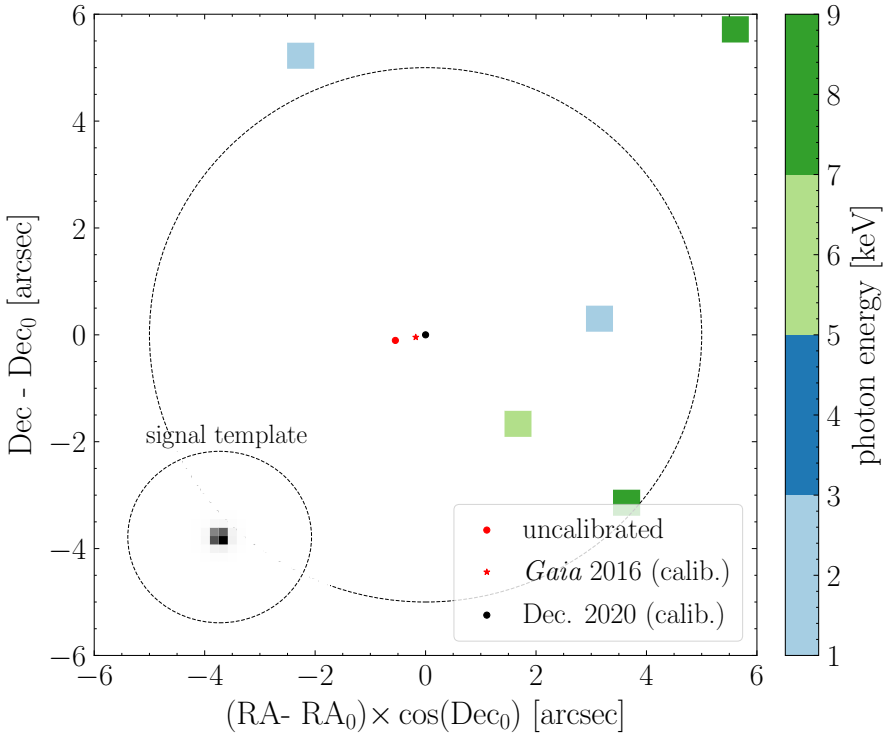
What have we learned from Chandra's observations?

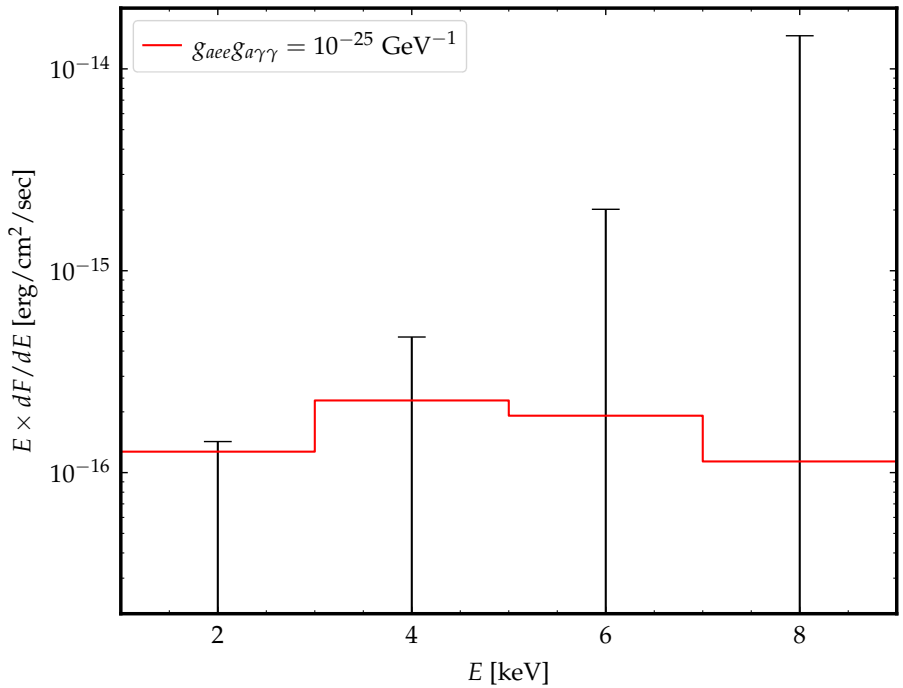
data taking on Dec 18, 2020
(artist's impression)

Chandra observation + data

Chandra observation

- ➔ 37.42 ks (~10 hr) of data taken on Dec 18, 2020
- ➔ No photon counts observed near the source



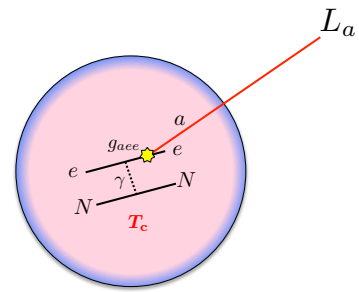


Towards a limit on axions

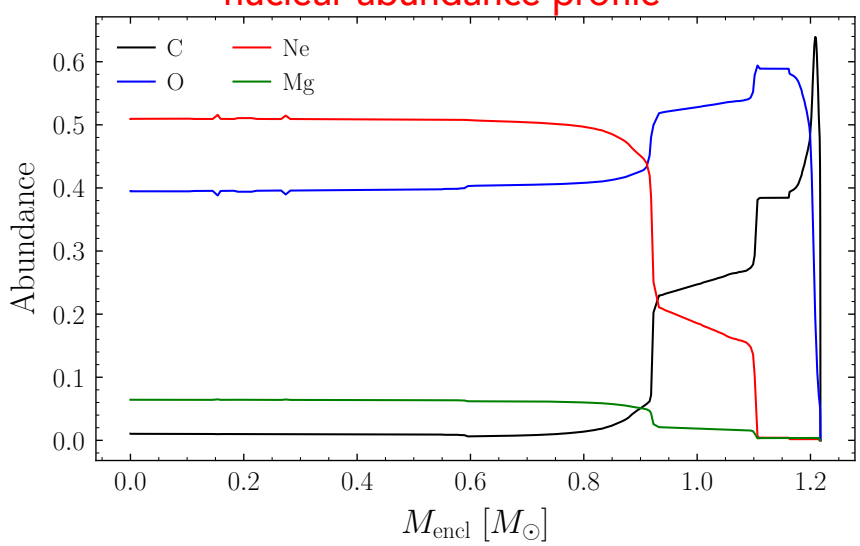
Improved WD modeling

➔ Use WD cooling sims to infer the nuclear composition, core temperature, and density profile of RE J0317-853

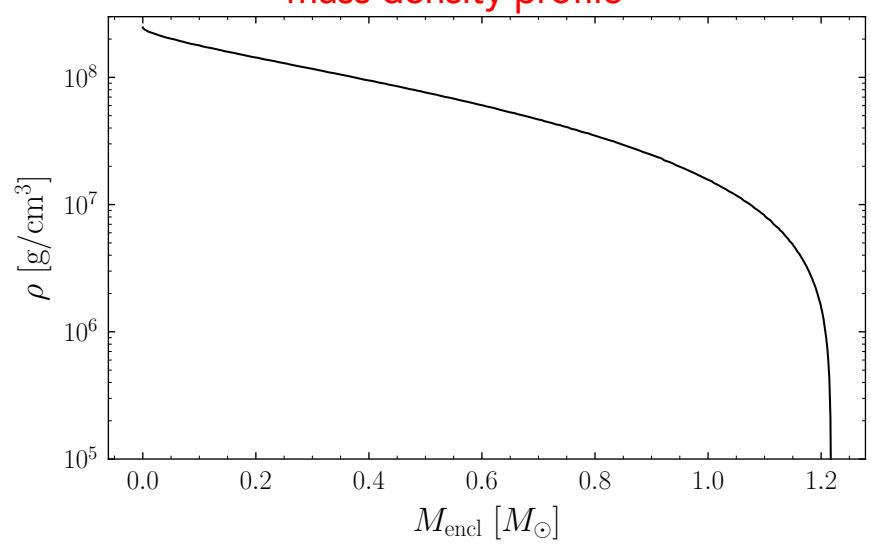
$$\frac{d\varepsilon_a}{d\omega} = \frac{\alpha_{\rm EM}^2 \alpha_{aee}}{\pi^2 m_e^2} \frac{\omega^3}{e^{\omega/T} - 1} \sum_s \frac{Z_s^2 \rho_s F_s}{A_s u}$$



nuclear abundance profile



mass density profile



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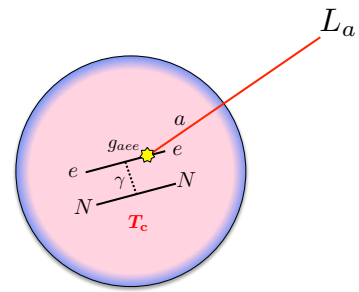
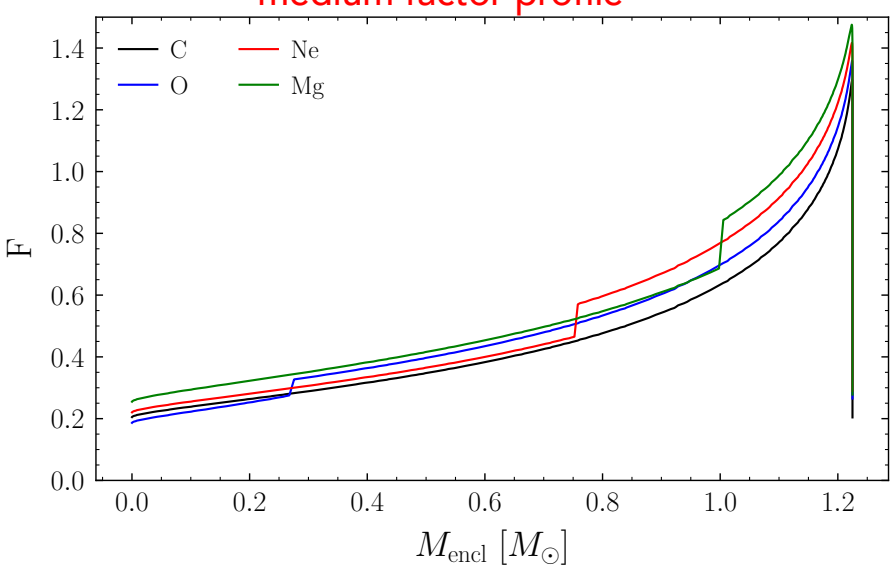
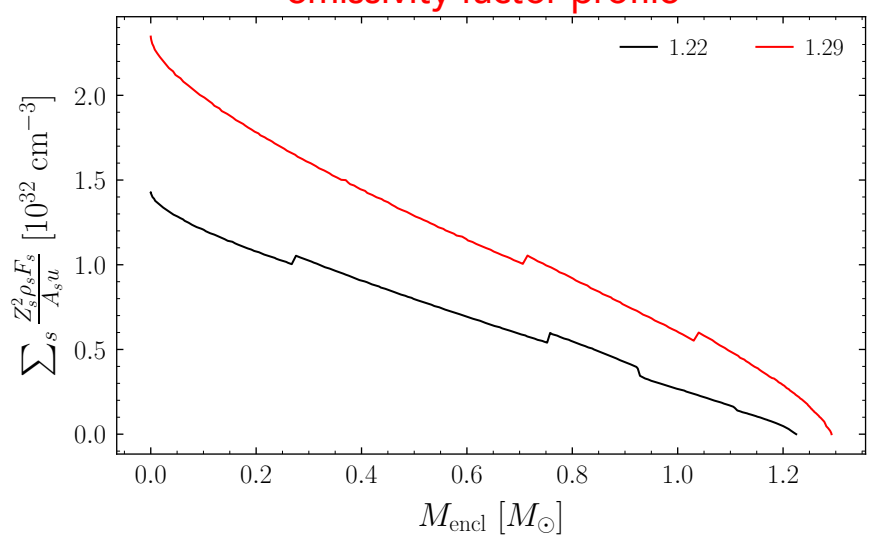


medium factor profile



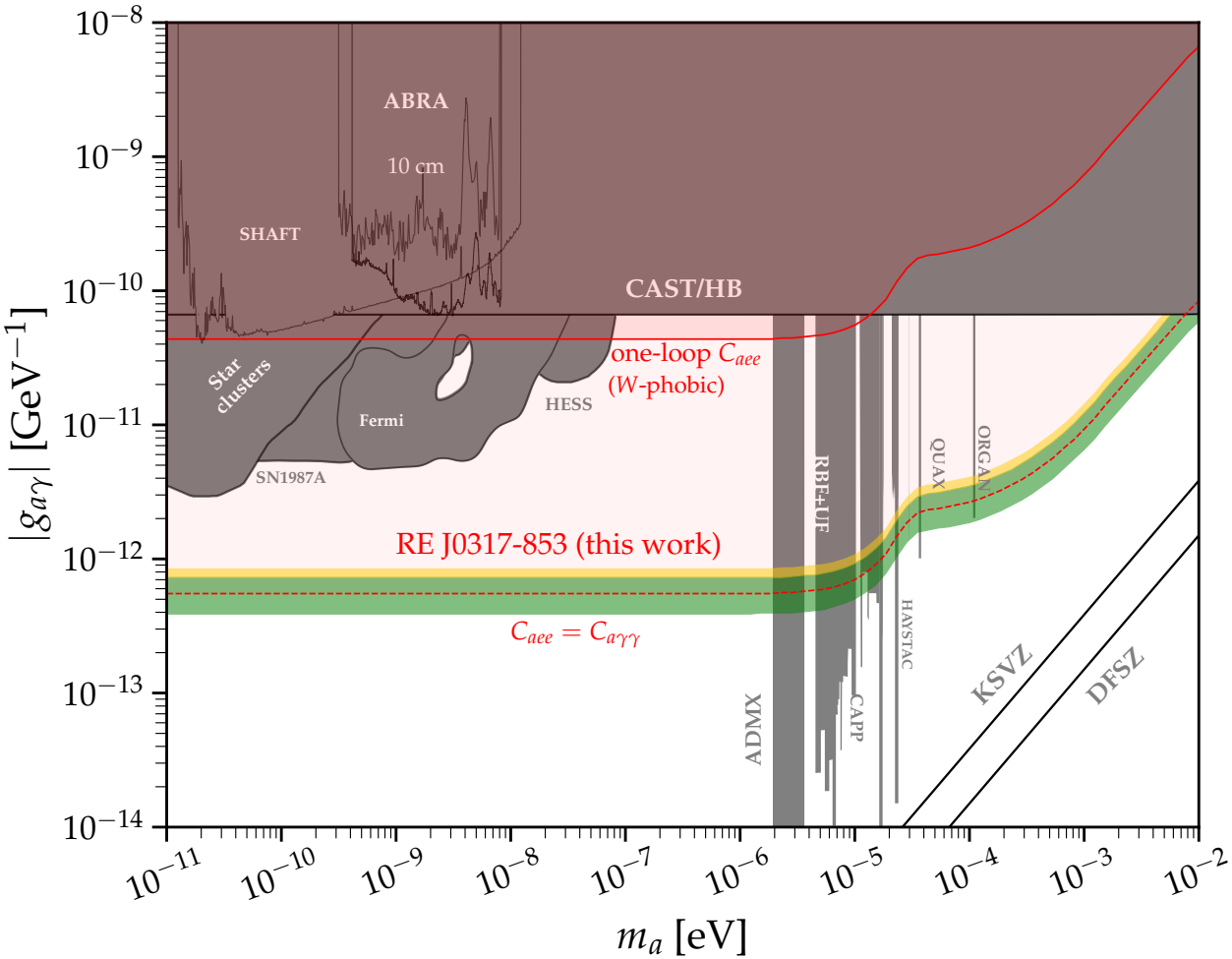
emissivity factor profile



Interpretation

Constraints on the axion-photon coupling

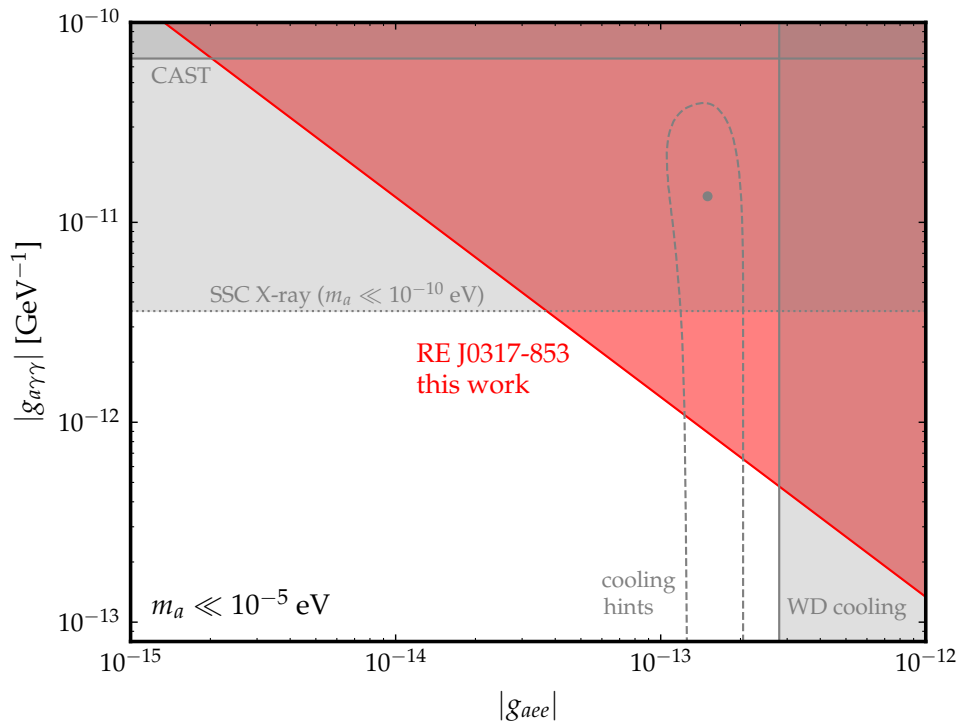
- ➔ Axion-electron coupling g_{aee} is radiatively-generated from $g_{a\gamma\gamma}$
- ➔ We also place model-dep constraints on $g_{a\gamma\gamma}$ alone



Interpretation

Implications for axion emission

➔ Absence of X-ray emission constrains axion-matter couplings



What have we learned?

➔ Best constraint to date on g_{aee}*$g_{a\gamma\gamma}$ (10x better than previous)

➔ Strong tension with best-fit point for cooling hints

Discussion

What happens if there's a signal?

Could it be astrophysics?

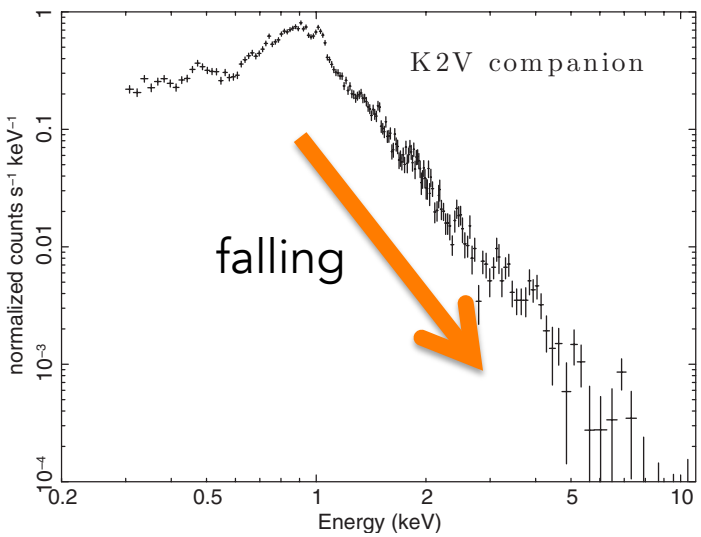
- ➔ An isolated MWD is expected to have negligible hard X-ray flux.
- ➔ Hard X-ray may result from accretion or a binary companion.

But we'd also see this in IR. Plus the spectrum is falling. Plus disks are rare.

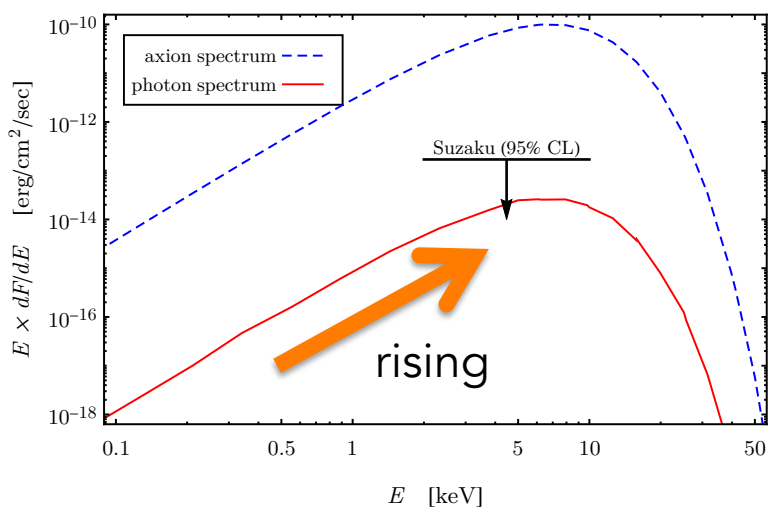
White dwarfs (WDs) represent the final evolutionary stage of intermediate- and low-mass stars. Depending on their effective temperature ($T_{\rm eff}$) and composition, or opacity, their photospheric emission can be observed from near-infrared (IR) up to soft X-rays ($\lambda \gtrsim 25$ Å, $h\nu \lesssim 0.5$ keV), but no detectable hard X-ray emission (>0.5 keV) is expected from single WDs.

[Bilikova et al (2010)]

background



signal



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But we'd also see this in IR. Plus the spectrum is falling. Plus disks are rare.

Could it be axions?

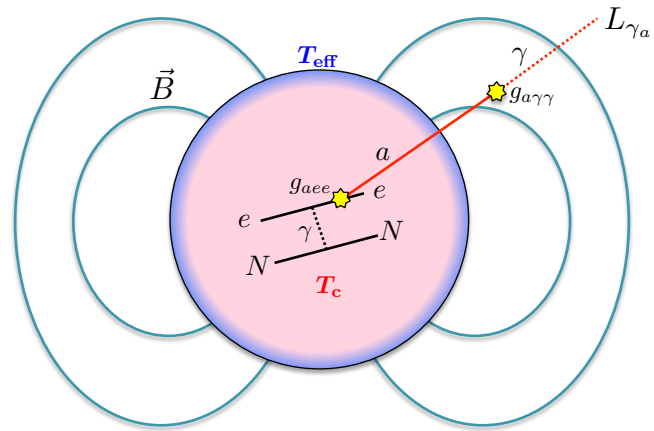
- ➔ Predicts *rising spectrum* of hard X-rays
- ➔ Predicts flux ratios in different stars
- ➔ Predicts periodic time-dependence
- ➔ Predicts polarized X-rays

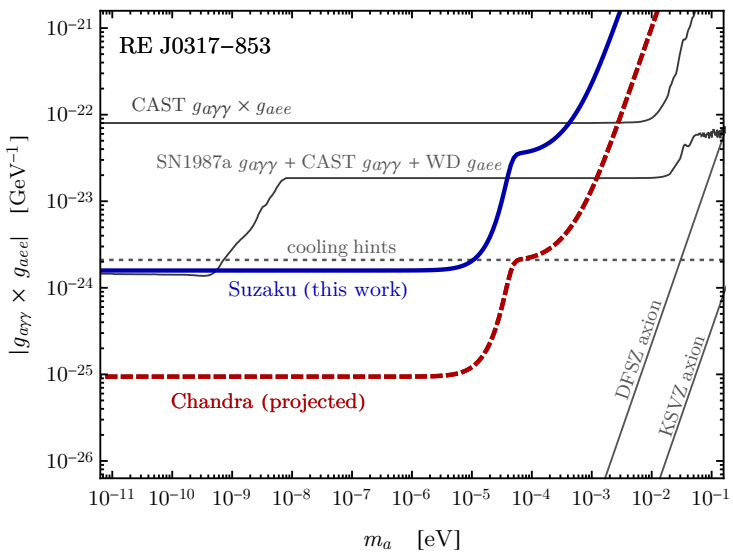
There will be several ways to discriminate an astrophysical X-ray flux from an axion-induced X-ray flux!

Summary

Axion emission from compact stars will induce a hard X-ray signature.

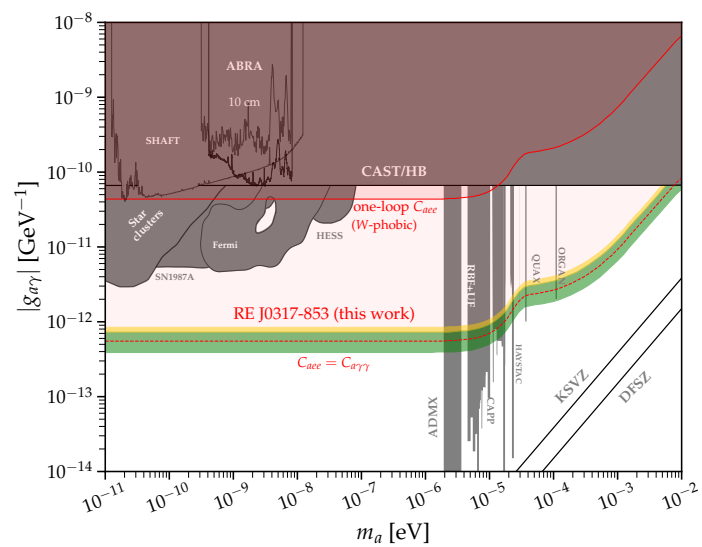
➔ A direct test of cooling "hints"





Existing X-ray data on RE J0317-853 leads to strongest constraint at low m_a.

➔ We identify good candidate MWDs

X-ray observations by *Chandra* find no evidence for X-ray emission (2-10 keV)

➔ Strong constraints on axion-matter couplings. Prospects favorable for future observations.