X-ray signatures of axion emission from compact stars

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RICE

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.

The data is here!

We have now completed the scientific and technical evaluation of proposals received in response to the CXC Call For Proposals, released 14 December 2018, for participation in the Chandra Cycle 21 General Observer Program. I am pleased to inform you that the Stage 1 science peer review panel has recommended that your proposal, entitled, SEARCHING FOR X-RAY SIGNATURES OF AXIONS IN MAGNETIC WHITE DWARF STARS, be implemented as part of the Chandra observing program. Based upon the panel's recommendation, one or more of the targets contained in your proposal will be included on the list of targets to be scheduled during Cycle 21 of the Chandra mission. While Cycle 21 officially extends from January/Feburary 2020 to January/Feburary 2021, some observations may be made outside this date range.

The targets and times approved for this proposal are:

```
                                Detector/  Approved Time(ks)
R.A./Dec.            Target Name            Grating    Cycle 21
-------------------------------------------------------------------
03:17:15.85/-[illegible].56 RE J0317-853        ACIS-I/NONE   40.00
```

Chandra spent 11 hours looking at my new favorite star!
Will they see any hard X-rays? What will we learn about axions?

Outline

① What’s an axion & who needs it?

② Why would axions lead to X-rays from magnetic white dwarf stars?

③ What can these stars teach us?

④ Can a recently-detected anomalous X-ray signal in neutron stars be due to axions coupling to muons?

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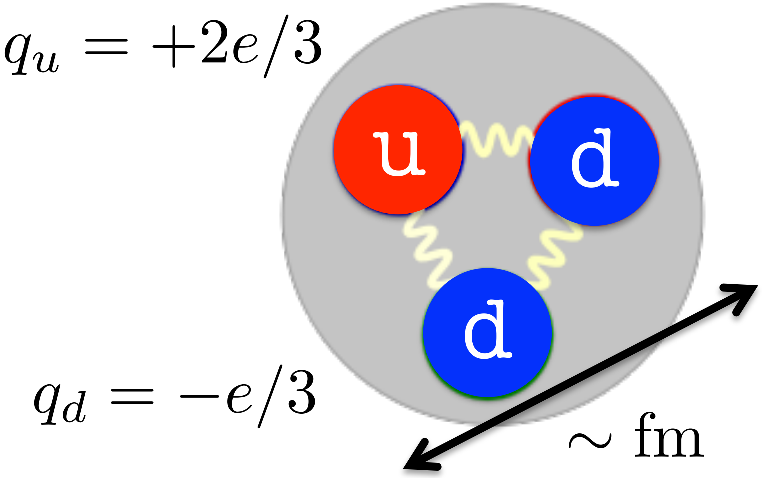
A problem with the neutron's EDM

What is the neutron's electric dipole moment? $\vec{d} = \Sigma_i q_i \vec{x}_i$



naïve dimensional analysis suggests…

$$d_n \sim e \times \mathrm{fm} \sim 10^{-13} e\,\mathrm{cm}$$

but experiment tells us …

$$d_n < 10^{-26} e\,\mathrm{cm}$$

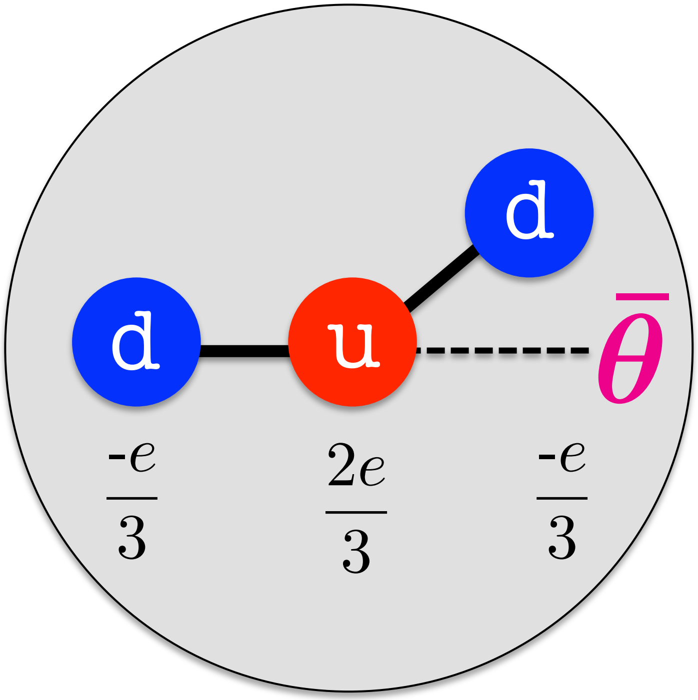
[Abel et. al., 2001.11966 + PRL]

That's a big problem!

A problem with the neutron's EDM

[Baluni (1979); Crewther,
DiVecchia, Veneziano,
& Witten (1979)]

There is a special configuration
with a parity symmetry:



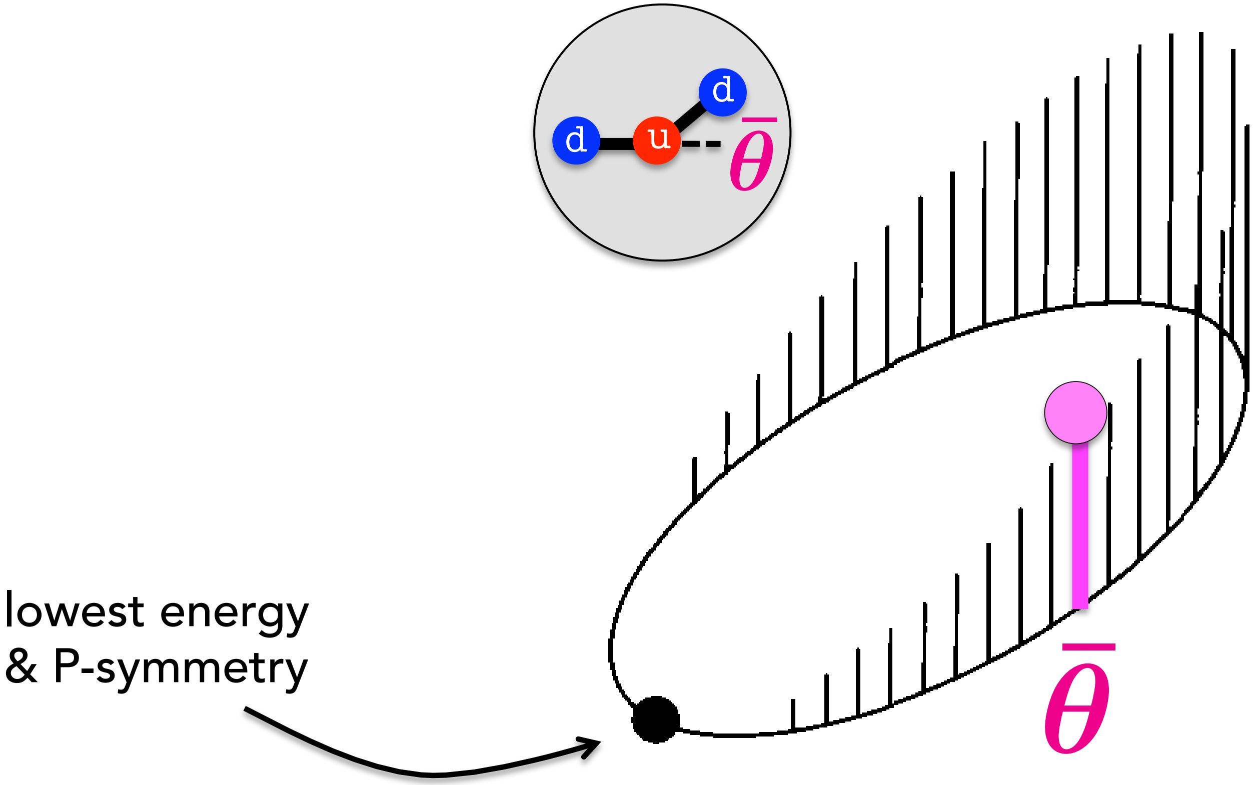
$$d_n \propto \sin \bar{\theta}$$

data says: $\bar{\theta} < 10^{-11}$

The price of symmetry breaking

[t'Hooft (1976)], [DiVecchia & Veneziano (1980)], [Gross, Pisarski, & Yaffe (1981)]
[Peccei & Quinn (1977)]

A nonzero angle costs energy:

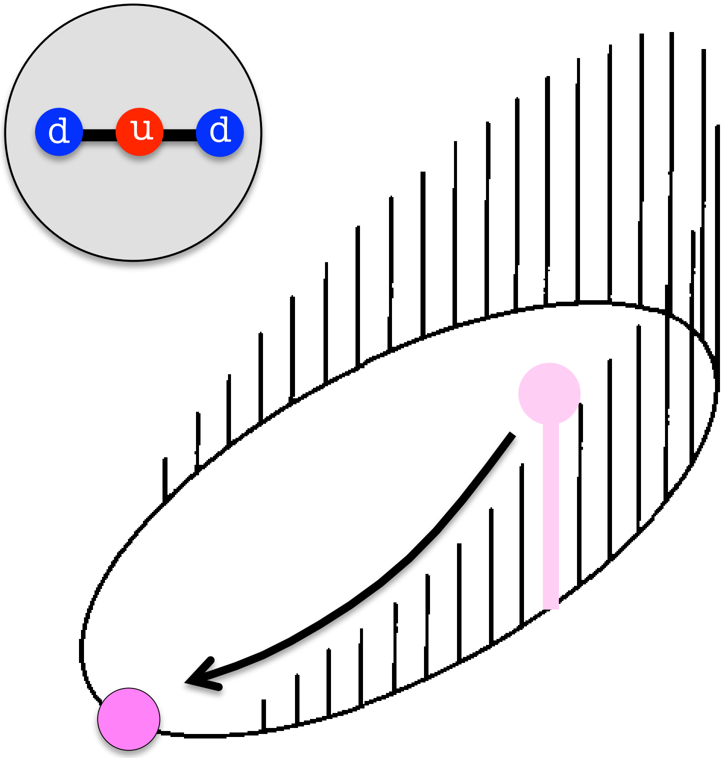


lowest energy
& P-symmetry

The price of symmetry breaking

[t'Hooft (1976)], [DiVecchia & Veneziano (1980)], [Gross, Pisarski, & Yaffe (1981)]
[Peccei & Quinn (1977)]

promote: $\bar{\boldsymbol{\theta}} \longrightarrow \boldsymbol{\theta}(t)$



$\boldsymbol{\theta} \approx 0$

Say hello to the axion

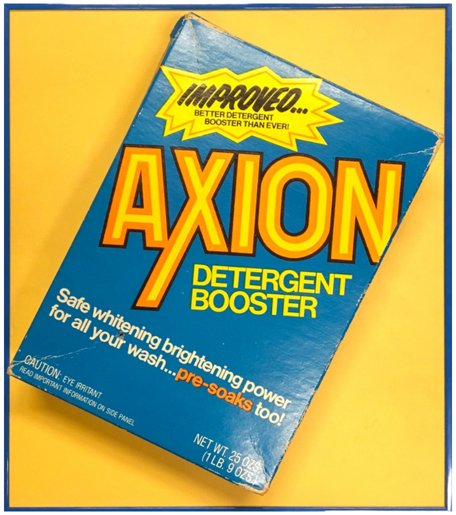
[Peccei & Quinn (1977)], [Weinberg (1978)], [Wilzcek (1977)]

This new degree of freedom corresponds to a hypothetical particle – the axion

$$\mathscr{L} = -\frac{\alpha_s}{8\pi}\left(\bar{\theta} - \frac{a(x)}{f_a}\right) G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Predicted properties:

$$S(a) = 0$$
$$\mathsf{Q}_{\text{parity}}(a) = -1$$
$$\mathsf{Q}_{\text{em}}(a) = 0$$
$$\mathsf{Q}_{\text{color}}(a) = 0$$



Say hello to the axion … and its friends

[Svrcek & Witten (2006)], [Arvanitaki, Dimopoulos, Dubovsky, Kaloper, & March-Russell (2010)]

Axion-like particles

- ➔ Light & weakly-coupled pseudoscalars are generic
- ➔ E.g., the "string axiverse"
- ➔ Could be dark matter (but doesn't have to be here)

Interactions with Standard Model particles

- ➔ Leading-order interactions are dimension-5 operators

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

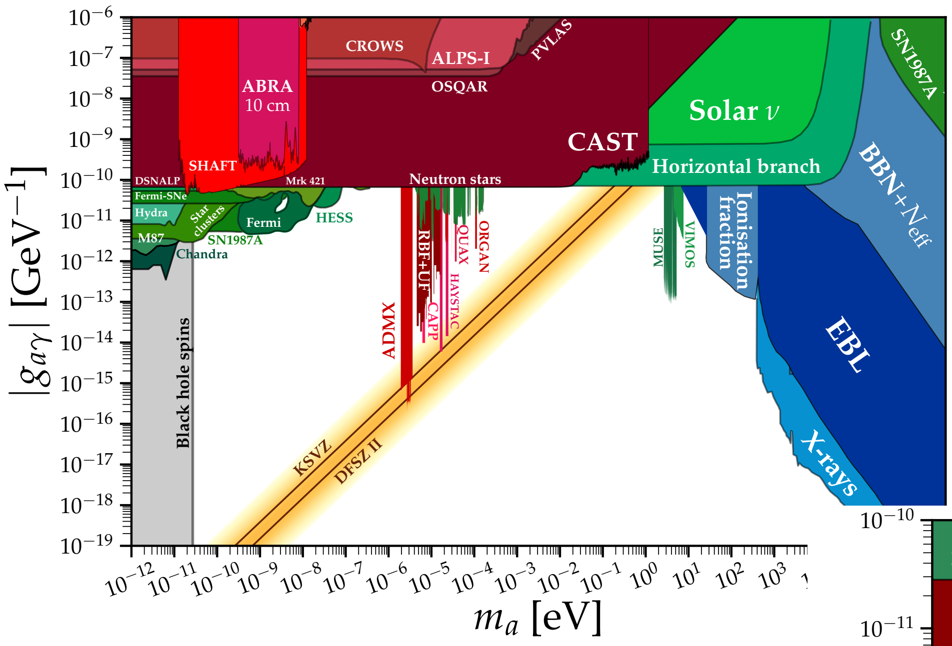
Connection to new physics scale

- ➔ Couplings arise from new physics at the scale f_a

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

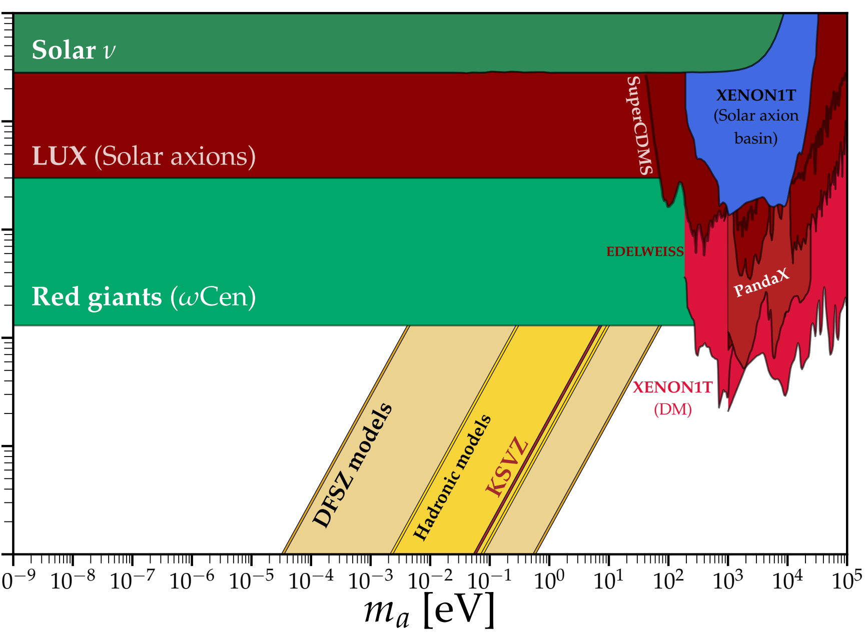
Still searching; Outlook: optimistic

[O'Hare, https://cajohare.github.io/AxionLimits/]



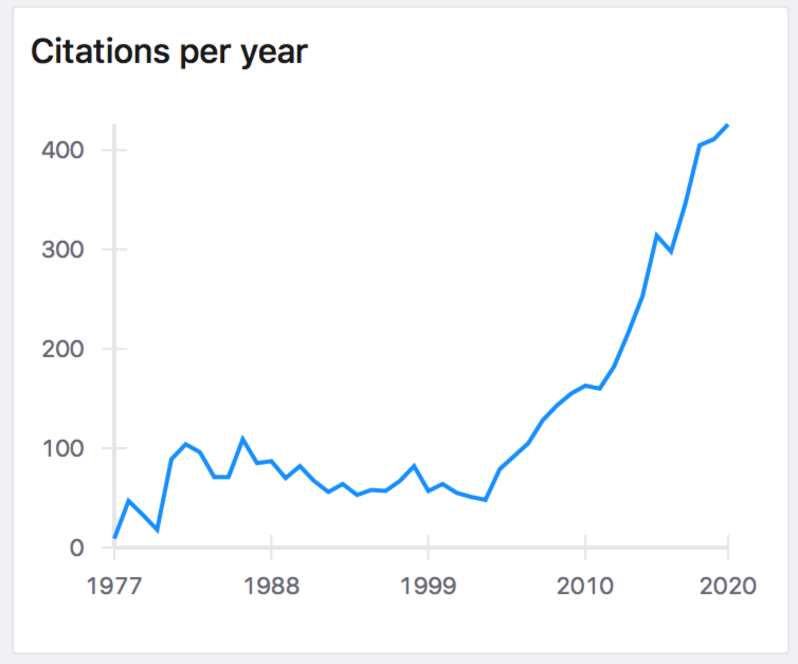
$$\mathscr{L}_{\rm int} = -\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$$

$$\mathscr{L}_{\rm int} = \frac{g_{aee}}{2m_e} \bar{\Psi} \gamma^\mu \gamma_5 \Psi \partial_\mu a$$

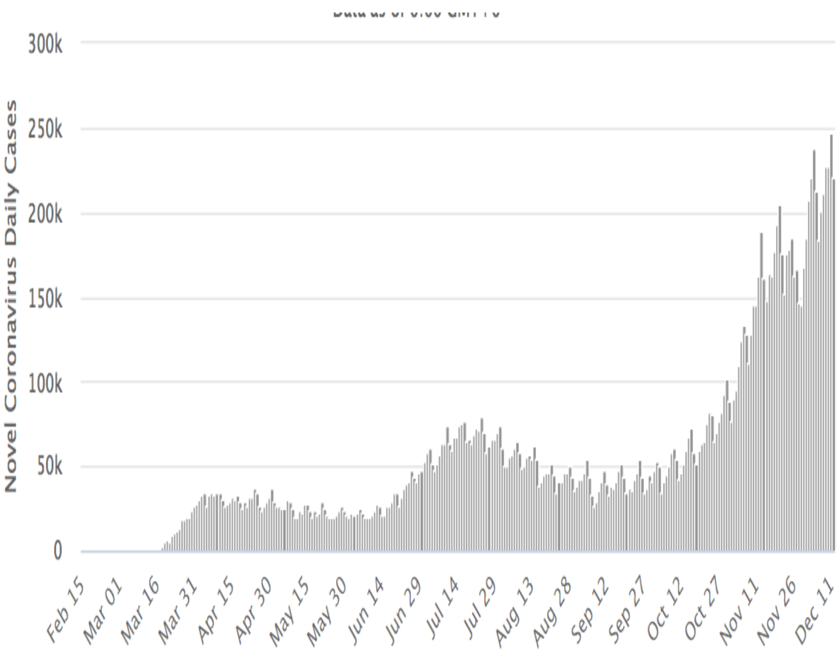


Sustained and growing interest for axions

cites to Peccei + Quinn (1977)



new daily cases of covid-19 in USA



Outline

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White dwarf fact sheet

Formation

-- old stars that have exhausted their fuel

Properties

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

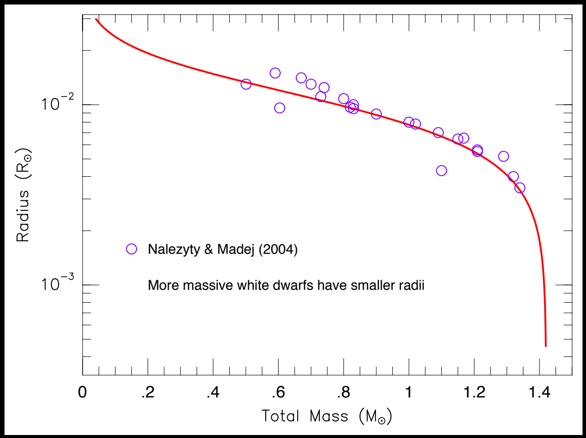
-- radius: $R = (1\text{-}2)\ R_{earth} = (0.8 – 2\%)\ R_{sun}$

-- 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

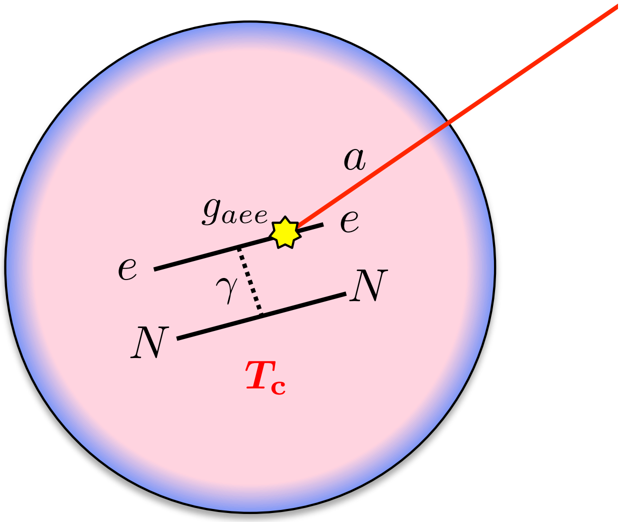
-- closest WD to Earth is Sirius B at 8.6 ly

-- 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)]

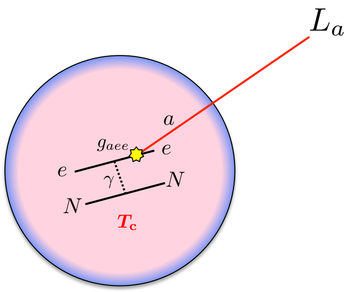
$$L_a \simeq (1.6 \times 10^{-4}\ L_\odot) \left(\frac{g_{aee}}{10^{-13}}\right)^2 \left(\frac{M_{\rm WD}}{1\ M_\odot}\right) \left(\frac{T_c}{10^7\ \rm K}\right)^4$$



Compact stars are “glowing” in axions!

Testing ALPs with white dwarf cooling

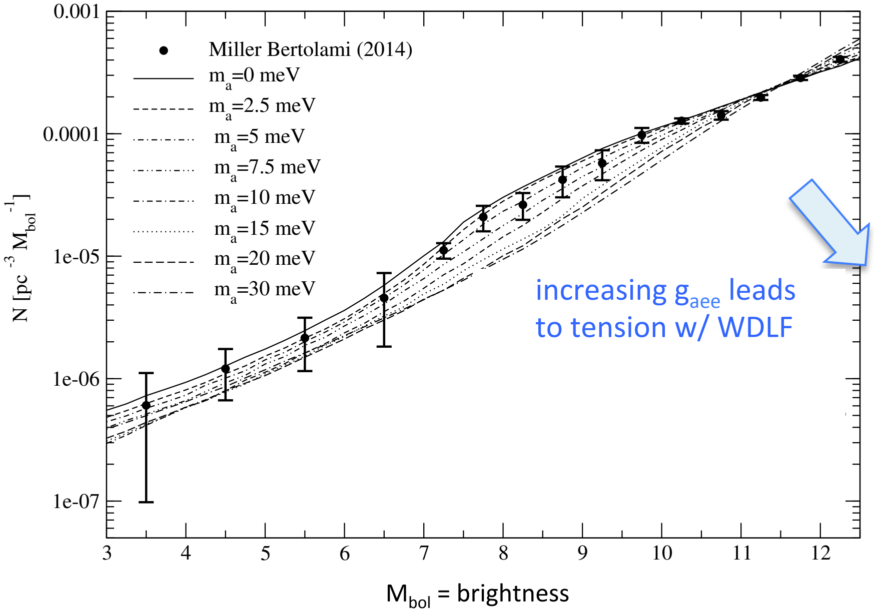
[Krauss, Moody, & Wilczek (1984)]
[Raffelt (1986)]
[Nakagawa, Adachi, Kohyama, & Itoh (1987,88)]



Axion emission causes WDs to cool

- ➔ Cooling is constrained by the white dwarf luminosity function
- ➔ WDLF = # stars versus brightness

[Miller Bertolami et. al. (2014)]



increasing g_{aee} leads to tension w/ WDLF

Leading to an upper limit on the axion-electron coupling:

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

[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

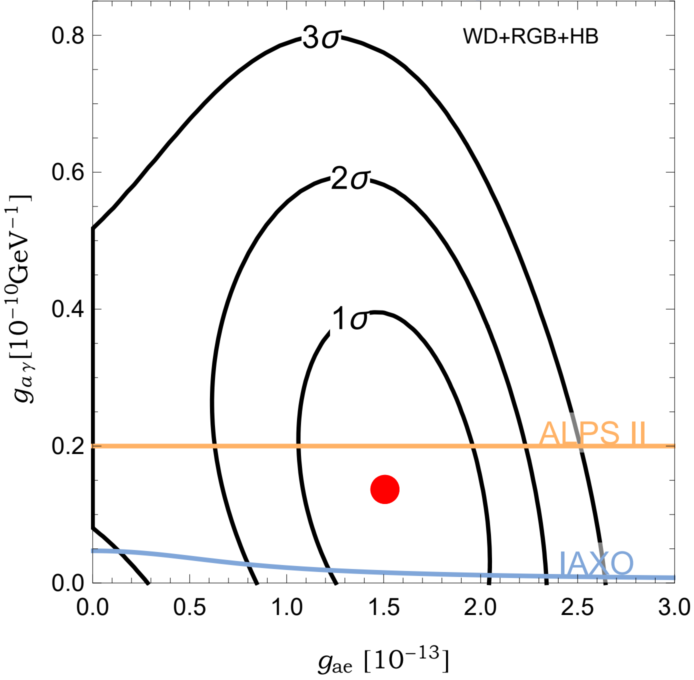
Evidence for ALPs?

- ➔ favored couplings are …

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

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

[Giannotti et. al. (2017)]



A target for future observations!

Detecting astrophysical ALPs at Earth

Can we detect the radiated ALPs when they reach Earth?

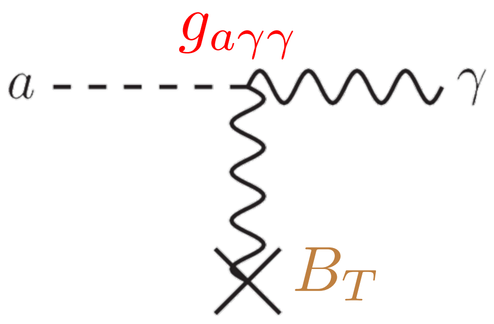
➔ Axion energy flux density at Earth:

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

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

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

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

A stronger B-field at the source!

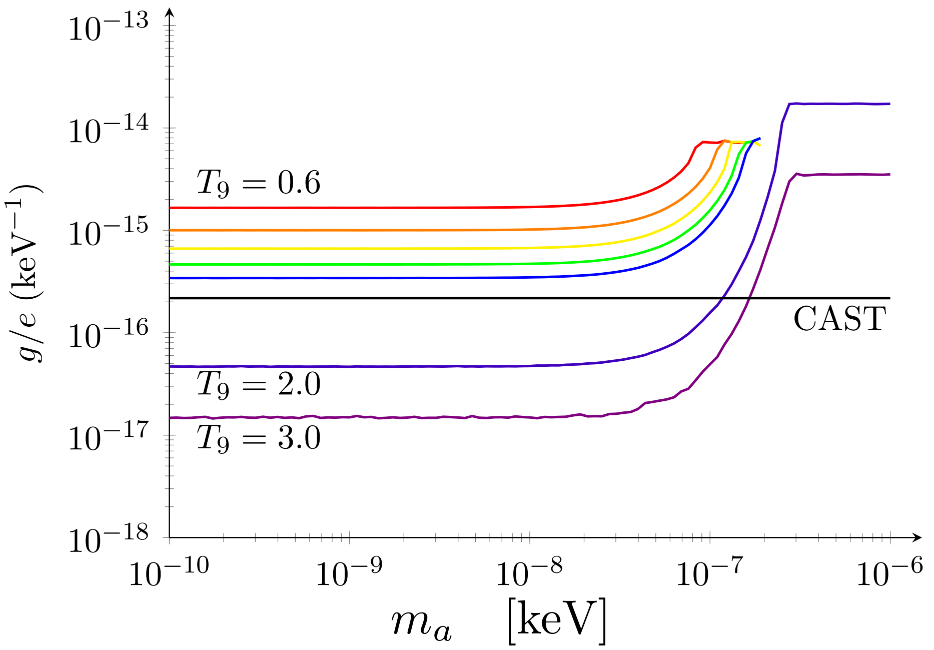
Often compact stars already sustain strong B-fields

- ➔ 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!

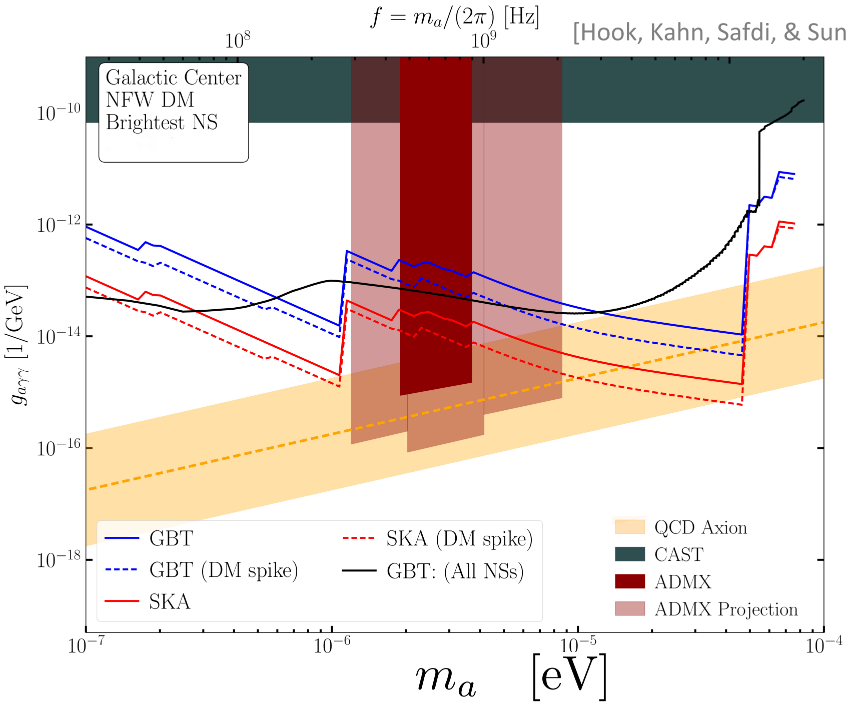
hard X-ray signals from magnetars

[Fortin & Sinha, (2018)]



radio signals from ALP dark matter

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

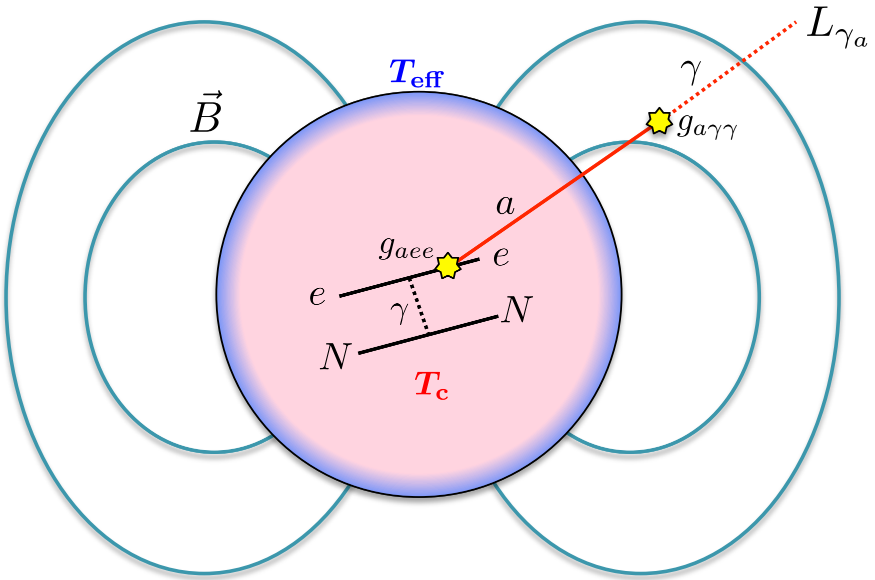


Axion conversion in MWD magnetosphere

[D. E. Morris (1986); Raffelt & Stodolsky (1987)]
[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 ($T_{\rm eff}$ ~ 10^4 K)

Axion-to-photon conversion

Axion-photon mixing in a background B-field

$$\mathscr{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} a F\tilde{F} = -g_{a\gamma\gamma} \underline{a\dot{\boldsymbol{A}}} \cdot \boldsymbol{B}$$

$$\mathscr{L}_{\text{EH}} = (\alpha^2/90m_e^4)\left[(FF)^2 + 7/4(F\tilde{F})^2\right]$$

Field equation in
the WKB approx.

$$-i\partial_\zeta \begin{pmatrix} \tilde{a} \\ i\tilde{A}_x \\ i\tilde{A}_y \end{pmatrix} = \begin{pmatrix} \Delta_a & \boxed{\Delta_{ax} \quad \Delta_{ay}} \\ \boxed{\Delta_{ax}} & \Delta_x \quad \Delta_{xy} \\ \boxed{\Delta_{ay}} & \Delta_{xy} \quad \Delta_y \end{pmatrix} \begin{pmatrix} \tilde{a} \\ i\tilde{A}_x \\ i\tilde{A}_y \end{pmatrix}$$

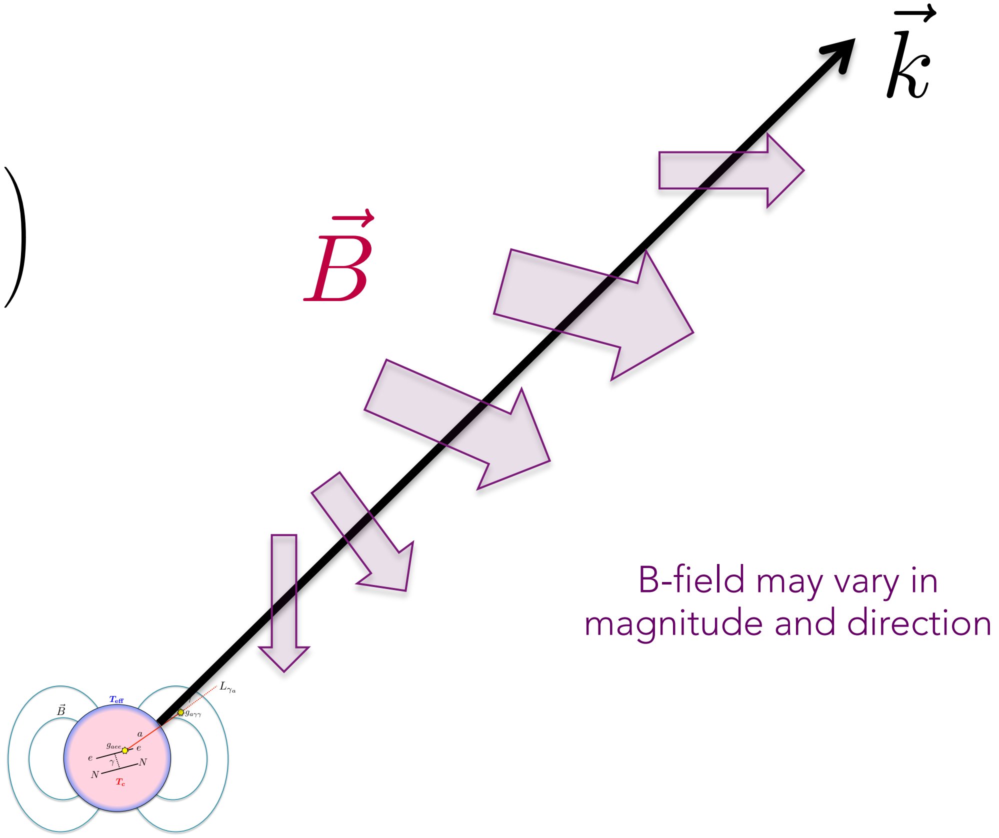
$$\Delta_a \equiv \frac{1}{2k}(\omega^2 - k^2 - m_a^2)$$

$$\Delta_x \equiv \frac{1}{2k}(\omega^2 - k^2 - m_A^2) + \frac{8\alpha^2}{45\,m_e^4}\left(\frac{7}{4}\frac{\omega^2}{k}B_x^2 + kB_y^2\right)$$

$$\Delta_y \equiv \frac{1}{2k}(\omega^2 - k^2 - m_A^2) + \frac{8\alpha^2}{45\,m_e^4}\left(\frac{7}{4}\frac{\omega^2}{k}B_y^2 + kB_x^2\right)$$

$$\boxed{\begin{aligned} \Delta_{ax} &\equiv \frac{1}{2} g_{a\gamma\gamma} \frac{\omega}{k} B_x \\ \Delta_{ay} &\equiv \frac{1}{2} g_{a\gamma\gamma} \frac{\omega}{k} B_y \end{aligned}} \quad \propto g_{a\gamma\gamma}$$

$$\Delta_{xy} \equiv \frac{8\alpha^2}{45\,m_e^4}\left(\frac{7}{4}\frac{\omega^2}{k} - k\right)B_x B_y$$

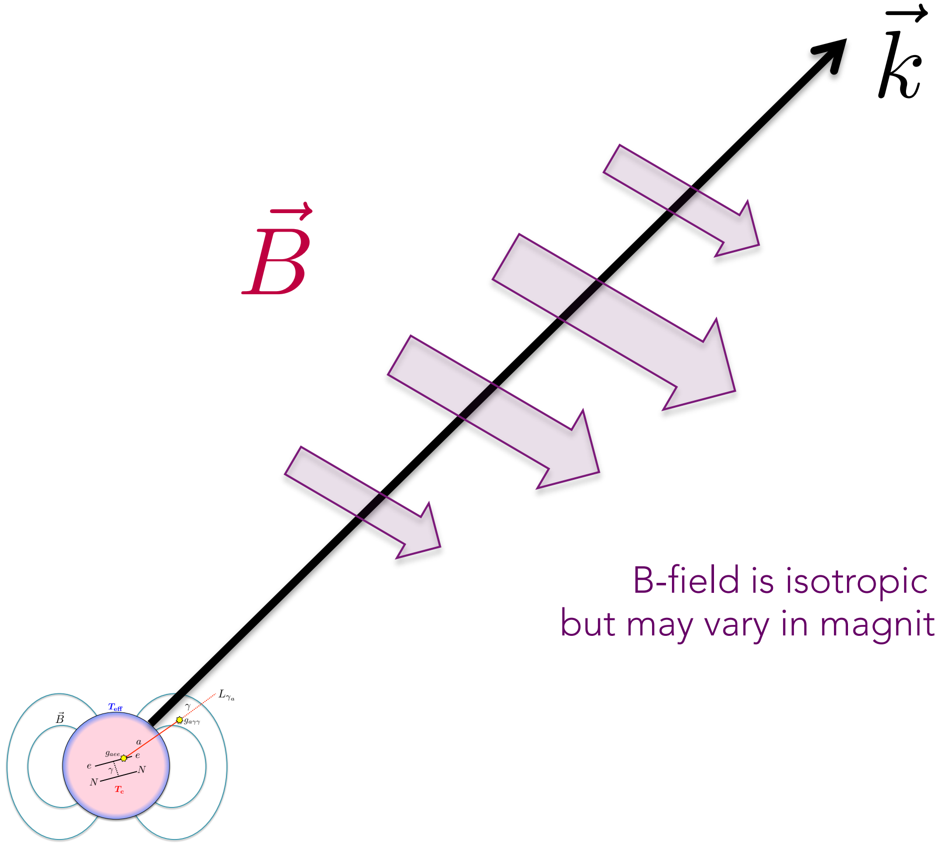


B-field may vary in
magnitude and direction

Axion-to-photon conversion

Axion-photon mixing in a background B-field

$$\mathscr{L}_{\rm int} = -\frac{1}{4} g_{a\gamma\gamma} a F\tilde{F} = -g_{a\gamma\gamma} \underline{a\dot{\boldsymbol{A}}} \cdot \boldsymbol{B}$$



B-field is isotropic
but may vary in magnitude

Assume an isotropic
magnetic field

$$-i\partial_\zeta \begin{pmatrix} \tilde{a} \\ i\tilde{A}_\parallel \\ i\tilde{A}_\perp \end{pmatrix} = \begin{pmatrix} \Delta_a & \boxed{\Delta_B} & 0 \\ \boxed{\Delta_B} & \Delta_\parallel & 0 \\ 0 & 0 & \Delta_\perp \end{pmatrix} \begin{pmatrix} \tilde{a} \\ i\tilde{A}_\parallel \\ i\tilde{A}_\perp \end{pmatrix}$$

$$\Delta_a \equiv \frac{1}{2k}(\omega^2 - k^2 - m_a^2)$$

$$\Delta_\parallel \equiv \frac{1}{2k}(\omega^2 - k^2 - m_A^2) + \frac{7}{2}\frac{\alpha}{45\pi}\frac{\omega^2}{k}\frac{B_T^2}{B_c^2}$$

$$\Delta_\perp \equiv \frac{1}{2k}(\omega^2 - k^2 - m_A^2) + 2\frac{\alpha}{45\pi}k\frac{B_T^2}{B_c^2}$$

$$\boxed{\Delta_B \equiv \frac{1}{2} g_{a\gamma\gamma}\frac{\omega}{k}B_T} \quad \propto g_{a\gamma\gamma}$$

Axion-to-photon conversion

Axion-photon mixing in a background B-field

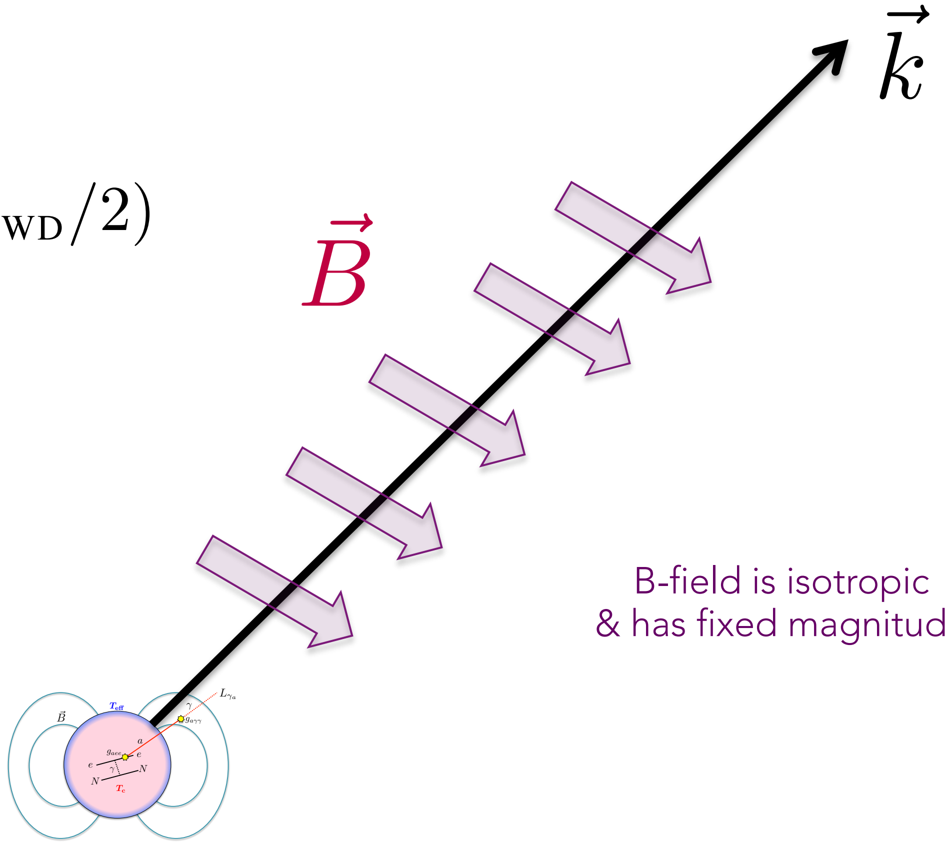
$$\mathscr{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} a F\tilde{F} = -g_{a\gamma\gamma} \underline{a\dot{\boldsymbol{A}}} \cdot \boldsymbol{B}$$

Assume isotropic & homogeneous field (out to r = 2 R_{WD})

$$p_{a\to\gamma} = \sin^2 2\theta \, \sin^2(\Delta_{\text{osc}} R_{\text{WD}}/2)$$

$$\tan 2\theta = \frac{2\Delta_B}{\Delta_\parallel - \Delta_a}$$

$$\Delta_{\text{osc}} = \frac{\Delta_\parallel - \Delta_a}{\cos 2\theta}$$

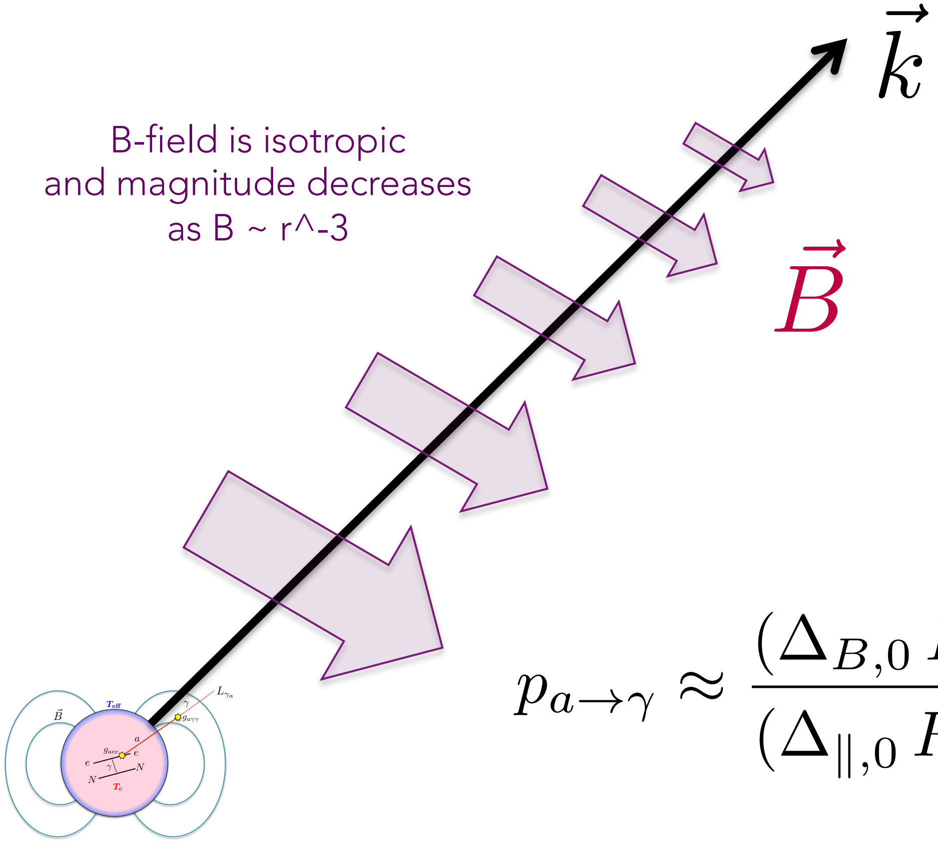


B-field is isotropic
& has fixed magnitude

Axion-to-photon conversion

Axion-photon mixing in a background B-field

$$\mathscr{L}_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} a F\tilde{F} = -g_{a\gamma\gamma} \underline{a\dot{\boldsymbol{A}}} \cdot \boldsymbol{B}$$



B-field is isotropic
and magnitude decreases
as B ~ r^-3

Assume an isotropic
magnetic field with
a dipolar profile

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

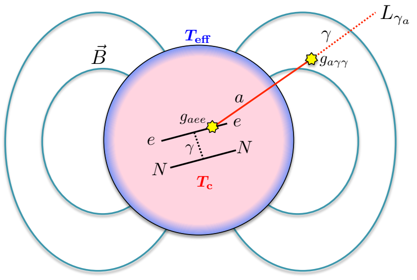
$$p_{a\to\gamma} \approx \frac{(\Delta_{B,0}\,R_{\text{WD}})^2}{(\Delta_{\|,0}\,R_{\text{WD}})^{\frac{4}{5}}} \left| \frac{\Gamma(\frac{2}{5}) - \Gamma(\frac{2}{5}, -\frac{i}{5}\Delta_{\|,0} R_{\text{WD}})}{5^{3/5}} \right|^2$$

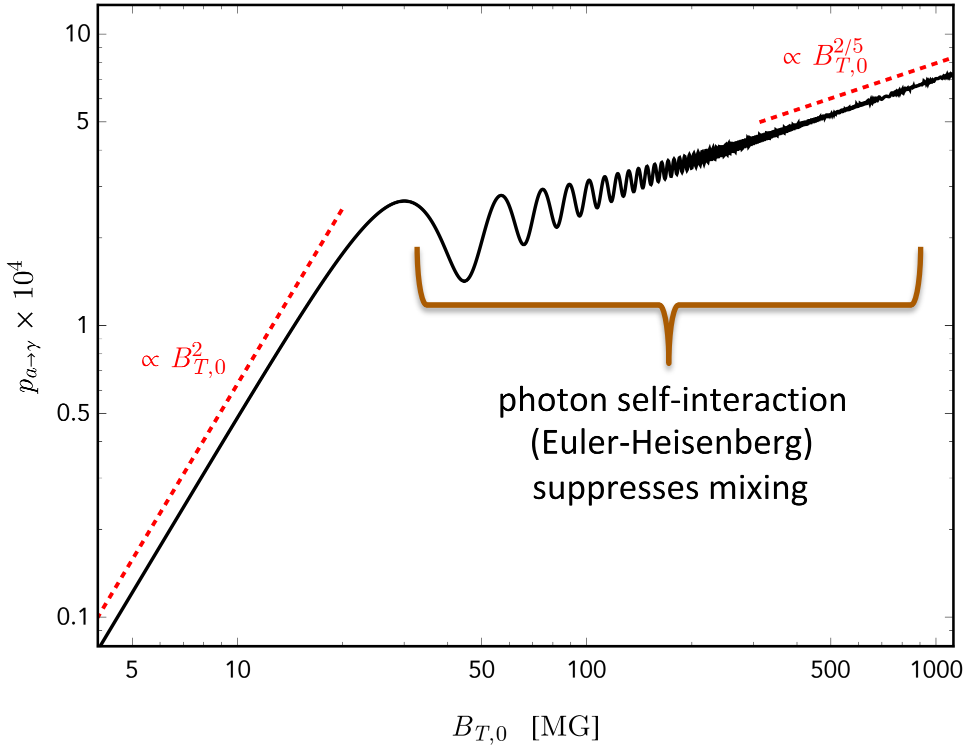
Conversion probability (dipolar B-field)

For a dipole B-field profile & small m$_a$

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

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





photon self-interaction
(Euler-Heisenberg)
suppresses mixing

A quasi-thermal X-ray spectrum

The spectrum of bremm'd axions

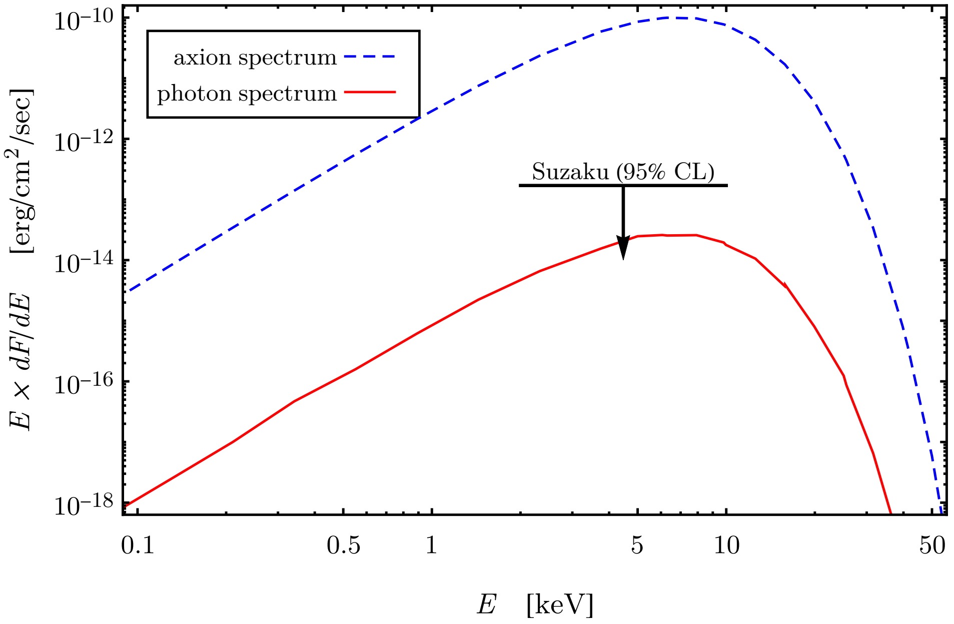
- ➔ Very close to thermal @ core temperature T_c

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

The spectrum of secondary (X-ray) photons

- ➔ Very slight energy modulation by axion-photon conversion

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



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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)

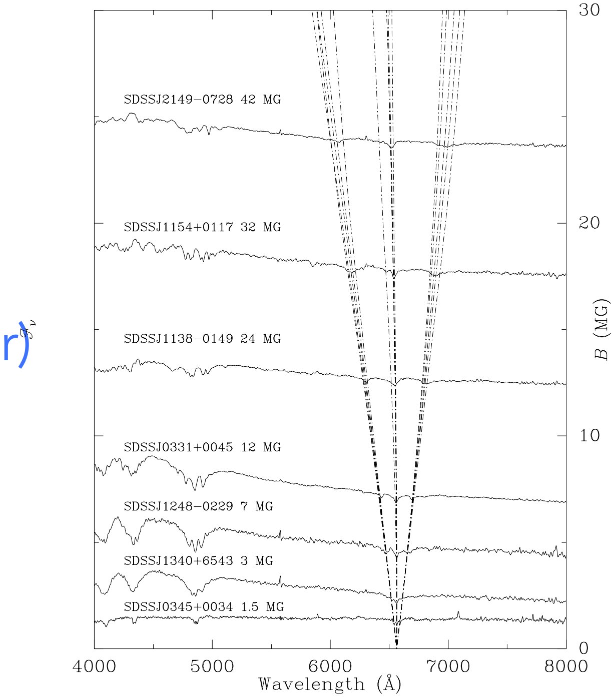
The number of known MWDs is far fewer

- ➔ 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

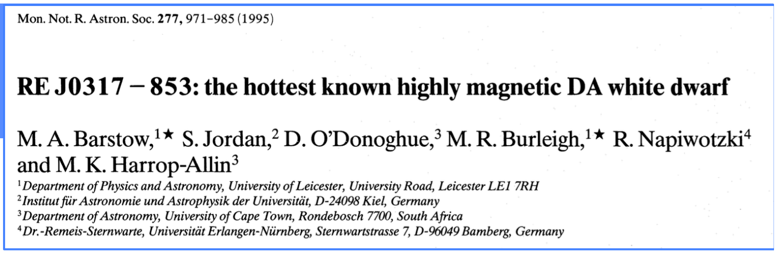
Top 10 MWD candidates

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

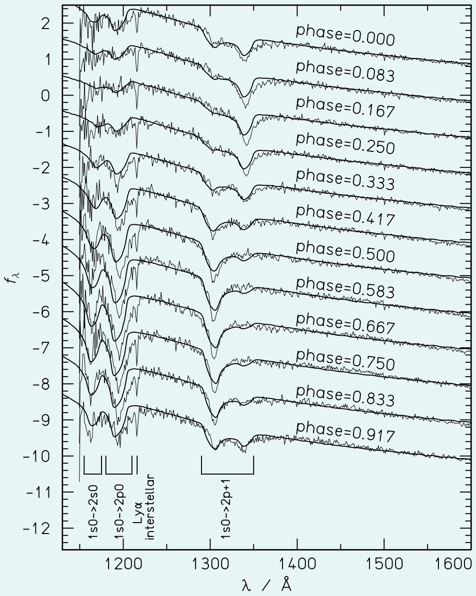
M. A. Barstow,[1]* S. Jordan,[2] D. O'Donoghue,[3] M. R. Burleigh,[1]* R. Napiwotzki[4]
and M. K. Harrop-Allin[3]
[1] *Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH*
[2] *Institut für Astronomie und Astrophysik der Universität, D-24098 Kiel, Germany*
[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

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

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

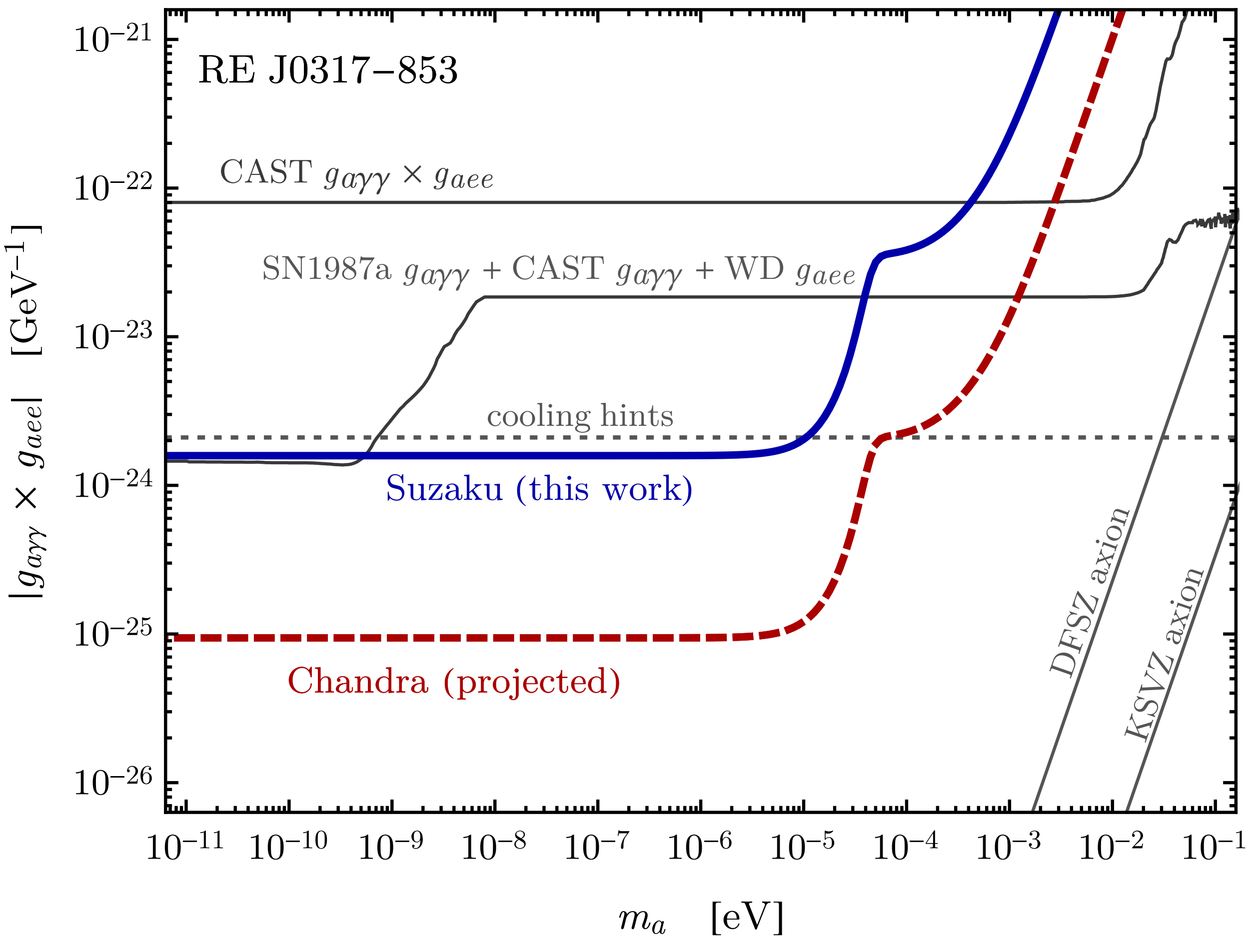
$$F_\gamma < 1.7 \times 10^{-13}\ \mathrm{erg/cm^2/sec}$$

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

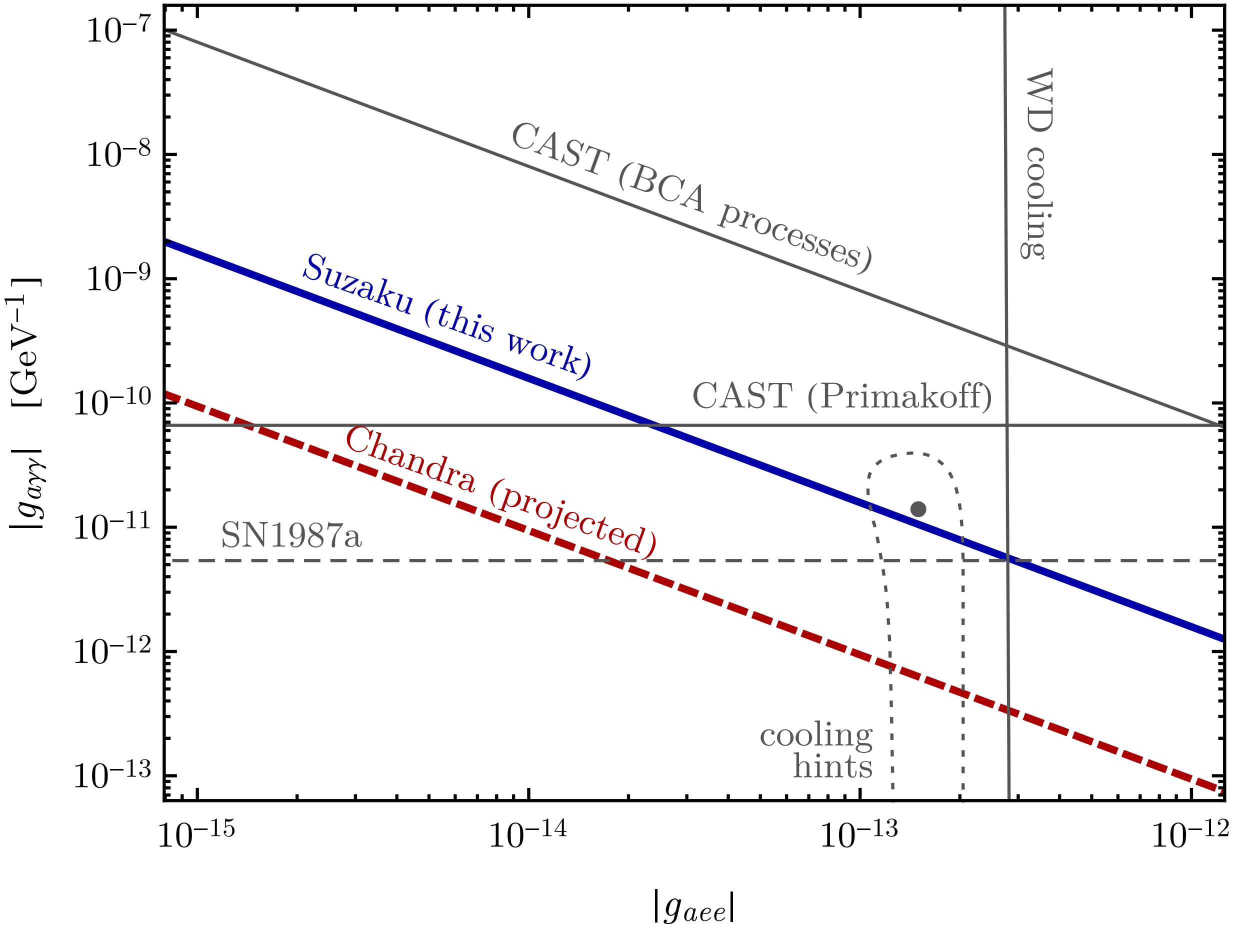
[Dessert, Long, & Safdi (2019)]



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

Constraining ALPs

[Dessert, Long, & Safdi (2019)]

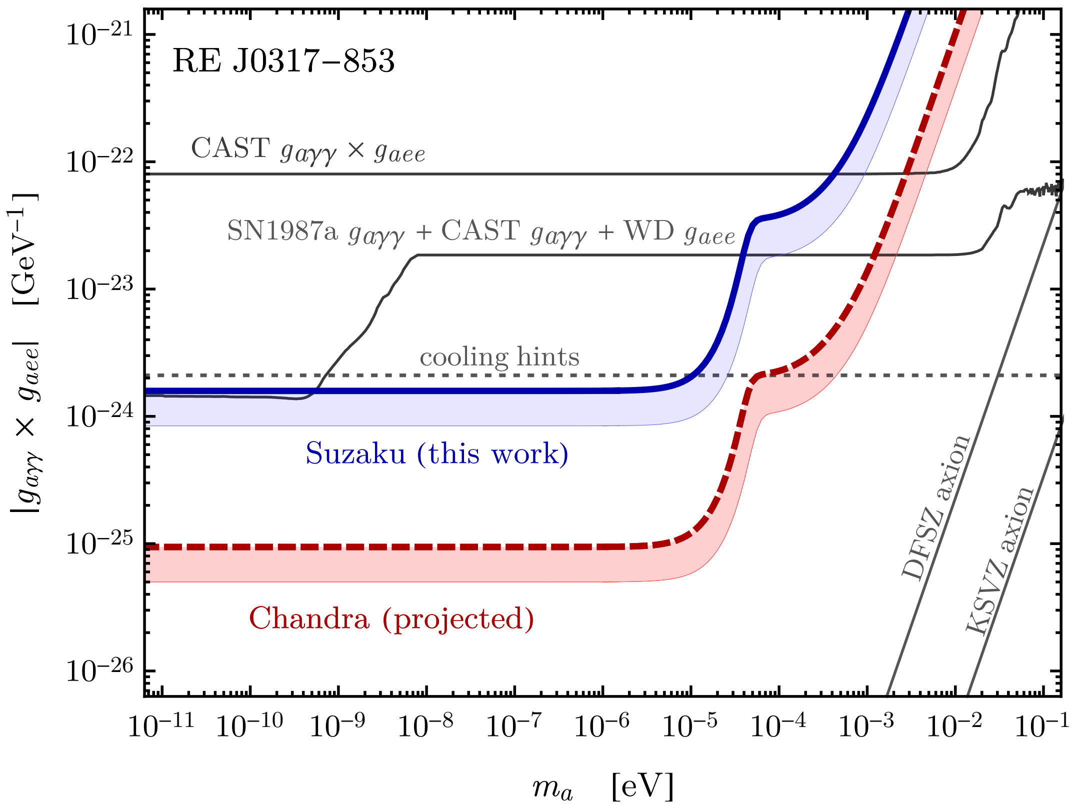


Limits become insensitive to axion mass for $m_a < 10^{-5}$ eV.
All upper limits at 95% CL. Dotted shows the cooling hints favored region (1σ).

Estimating uncertainties

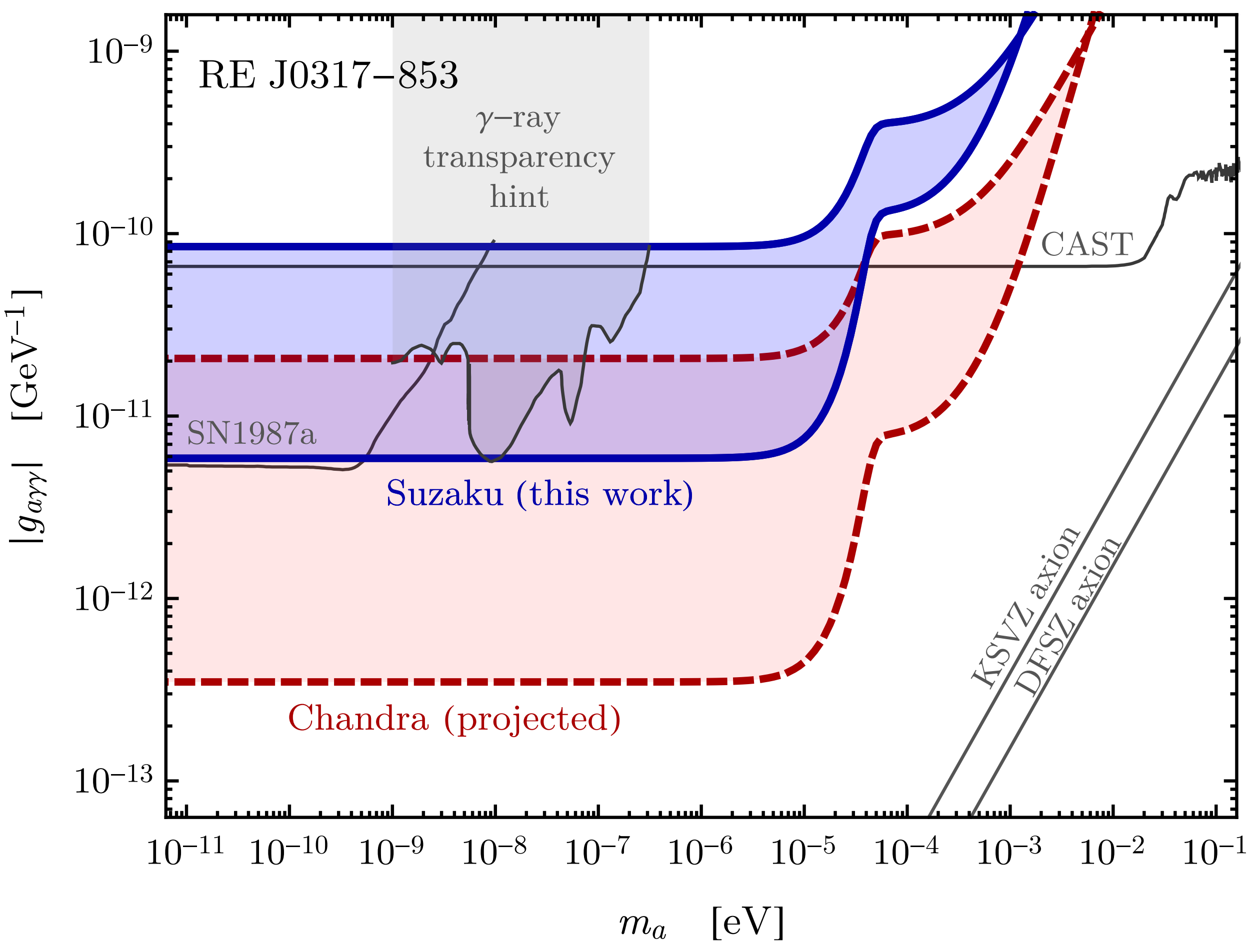
[Kulebi et. al. (2010)]

	M_{WD} $[M_\odot]$	R_{WD} $[0.01\ R_\odot]$	L_γ $[L_\odot]$	T_{eff} [K]	B [MG]	d_{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}



Constraining ALPs

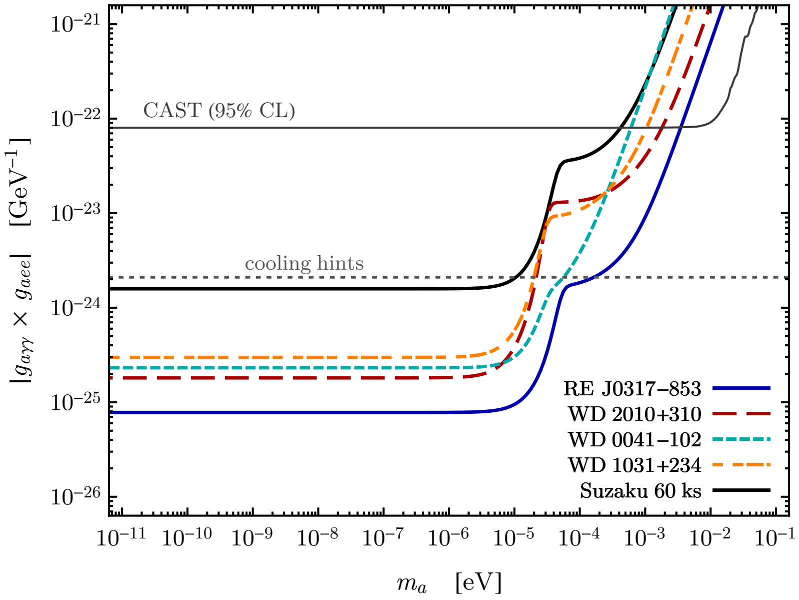
[Dessert, Long, & Safdi (2019)]



Can we do better?

Chandra X-ray Observatory

- We have submitted an observing proposal.
- Better point source sensitivity than Suzaku.
- A stronger limit is possible even w/ a shorter exposure (20-40 ks).



What will we learn?

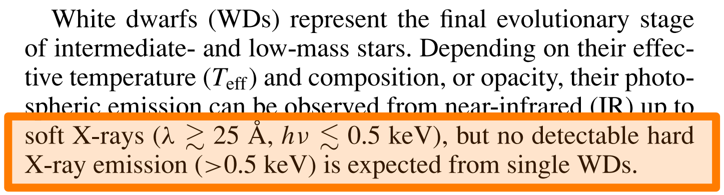
- definitely: extend limits by over x10
- definitely: test cooling hints
- maybe: discover some new physics!

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.

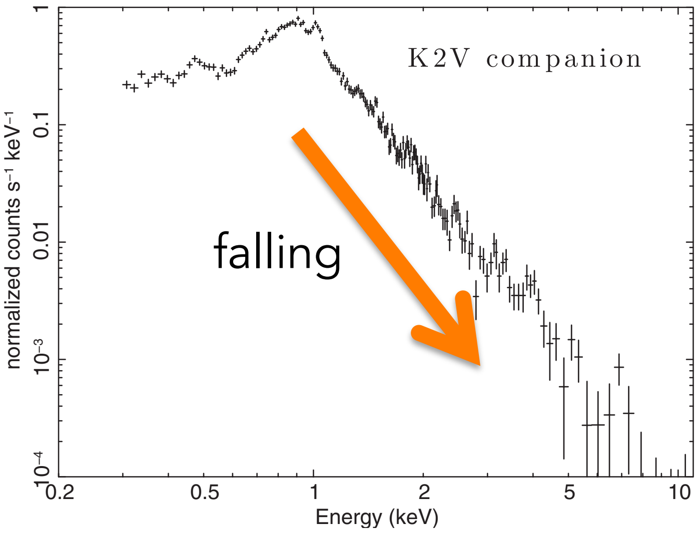
But we'd also see this in IR. Plus the spectrum is falling. Plus disks are rare.



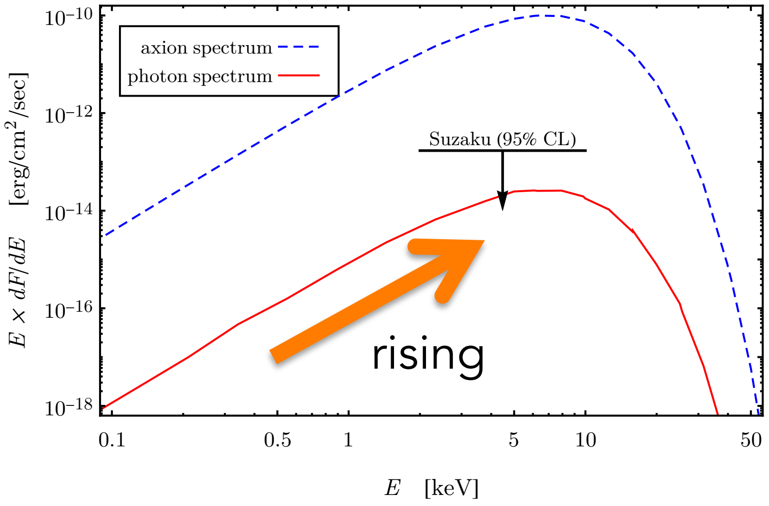
White dwarfs (WDs) represent the final evolutionary stage of intermediate- and low-mass stars. Depending on their effective temperature ($T_{\rm eff}$) and composition, or opacity, their photospheric emission can be observed from near-infrared (IR) up to soft X-rays ($\lambda \gtrsim 25$ Å, $h\nu \lesssim 0.5$ 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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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

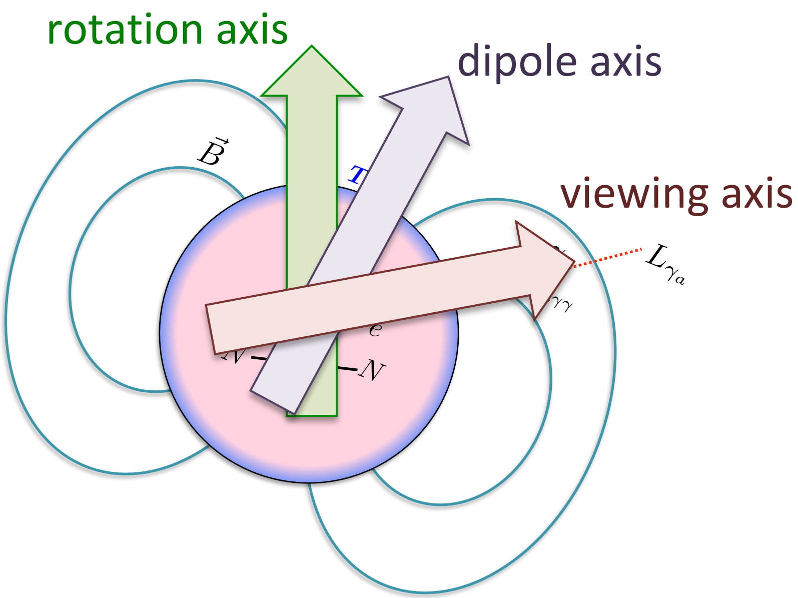
There will be several ways to discriminate an astrophysical X-ray flux from an axion-induced X-ray flux!

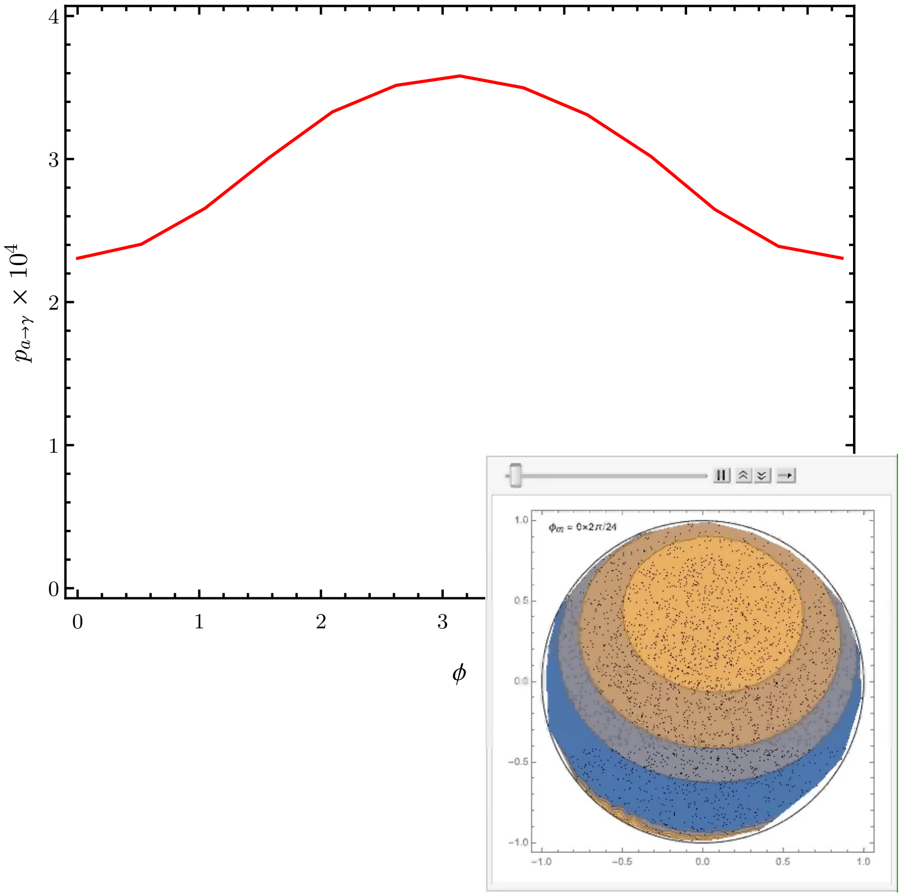
Time-varying flux

[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%)





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

Outline

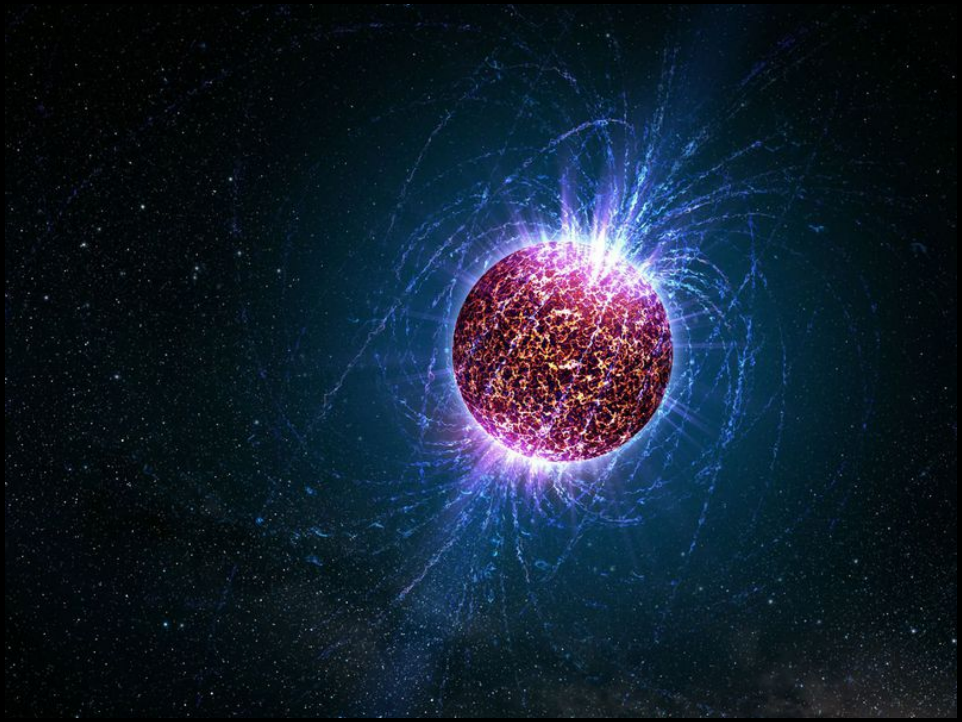
① What's an axion & who needs it?

② Why would axions lead to X-rays from magnetic white dwarf stars?

③ What can these stars teach us?

④ Can a recently-detected anomalous X-ray signal in neutron stars be due to axions coupling to muons?

Another target: neutron stars



Properties

-- mass: $M = M_{sun}$
-- radius: $R \sim 10$ km
-- core temp: $T \sim 10^8$ K ~ 10 keV
-- surface B-field: $B \sim (10^{10} - 10^{13})$ G

Composition

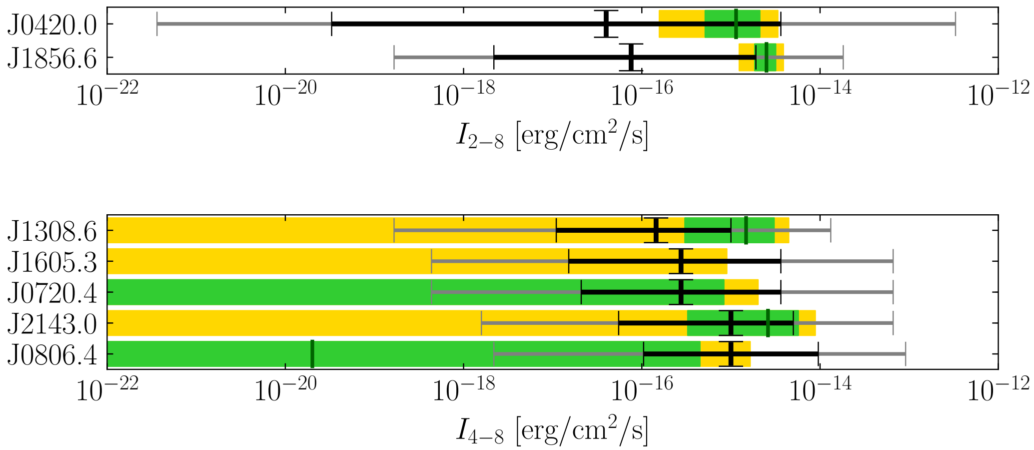
-- degenerate neutrons, protons, electrons, & muons

Magnificent 7

-- isolated, young, cooling neutron stars
-- discovered 1992-2001 by ROSAT (soft X-ray)
-- distance: 100-500 pc from Earth

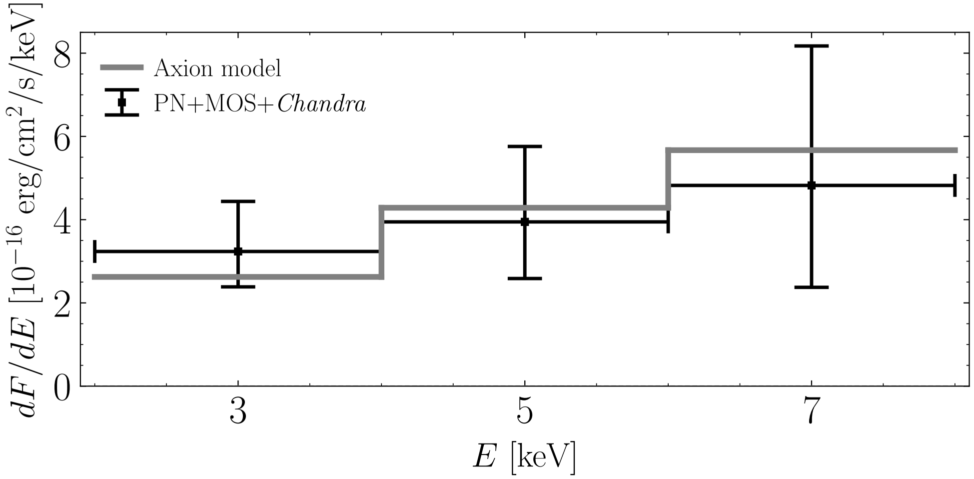
Evidence of hard X-rays from isolated neutron stars!

[Buschmann, Co, Dessert, & Safdi (2019)]



Strongest signal in 2 NS's out of the Magnificent 7

Rising excess over background at 2-8 keV

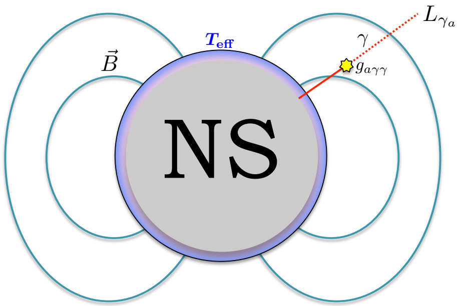


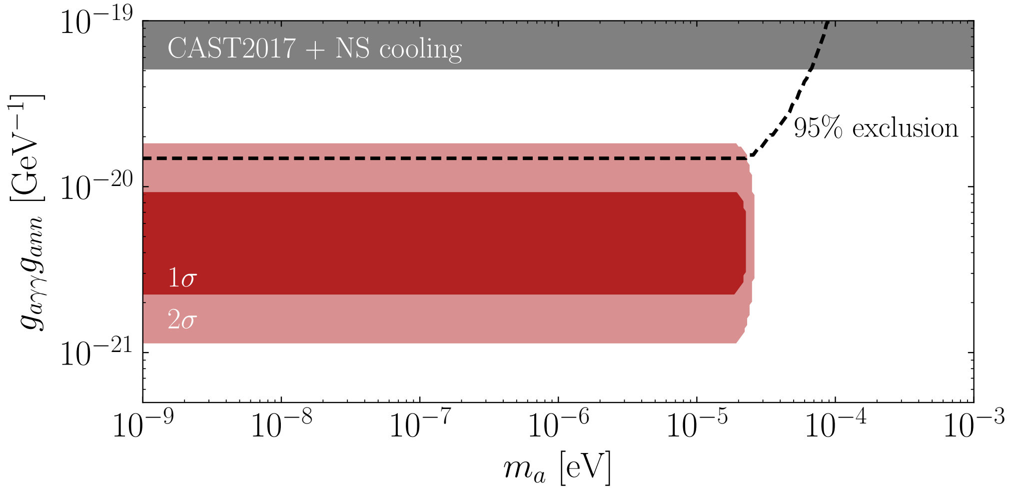
Evidence of hard X-rays from isolated neutron stars!

[Buschmann, Co, Dessert, & Safdi (2019)]

The excess can be interpreted as resulting from ALP emission from the stellar core & conversion in the magnetosphere

➔ Most efficient channels for axion emission: nucleon bremstrahlung





Axion emission from *muons*?

Since a neutron star is so dense, the Fermi momentum is large:

$$p_F \sim 200 \text{ MeV}$$

compare: $m_\mu \sim 100 \text{ MeV}$

There is a thermal population of muons in the NS core.

➔ A new channel for axion emission!

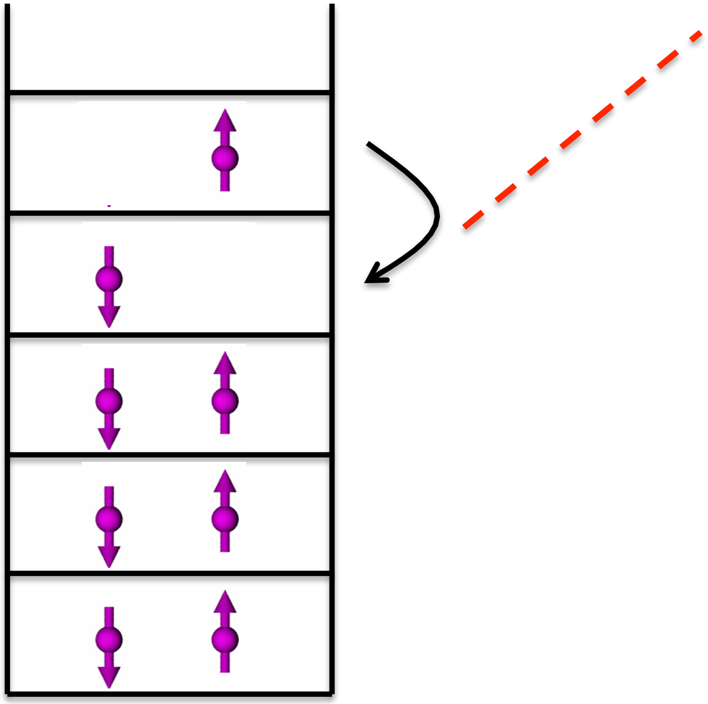
Axion synchrotron emission

[Borisov & Grishina (1994)]
[Kachelriess, Wilke, & Wunner (1996)]

Axion emission can accompany a transition btwn Landau levels

➔ More efficient than bremstrahlung for large B-field

$$E_N(p_z) = \sqrt{2eB\,N + p_z^2 + m^2}$$



$$L_a \sim \alpha_{a\mu\mu} \frac{2(eB)^4 T p_F}{9\pi m^5} R_{\rm NS}^3$$

More efficient than bremstrahlung

$$T \sim 10^8 \text{ K} \sim 10 \text{ keV}$$

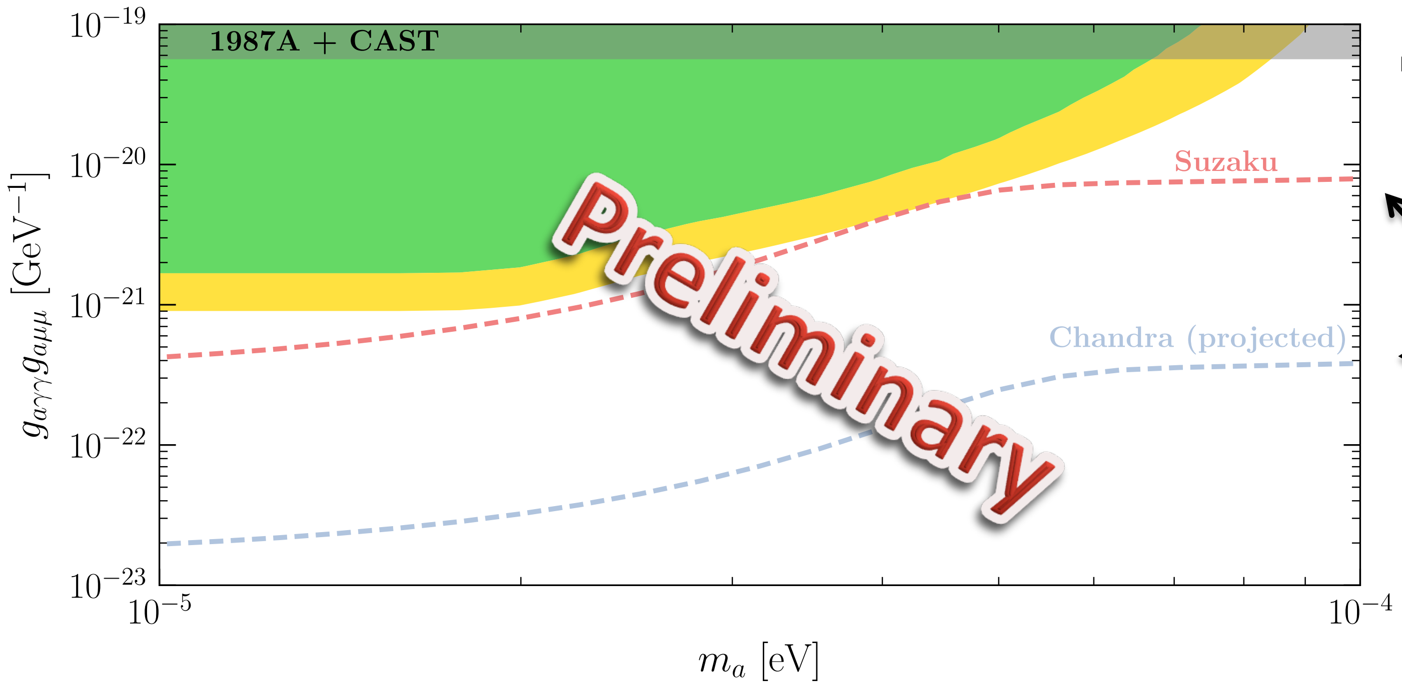
$$B \sim 10^{13} \text{ G} \sim (440 \text{ keV})^2$$

Axion interpretation

[Buschmann, Dessert, AL, & Safdi (to appear ~ Mar 2021)]

Strong limits on axion-muon & axion-photon couplings from M7

➔ It may be possible to explain the M7 signal



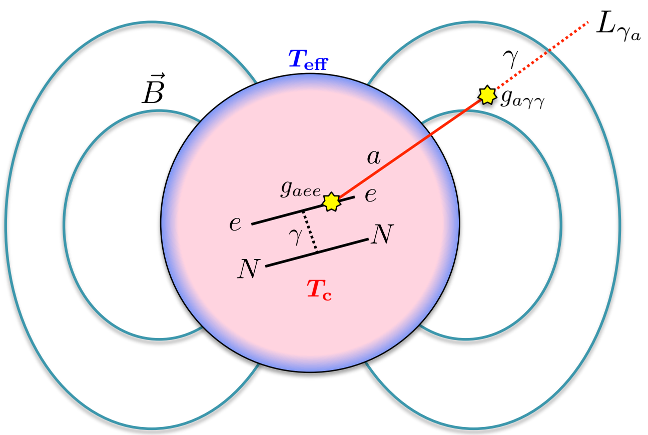
rescaled MWD limit assuming

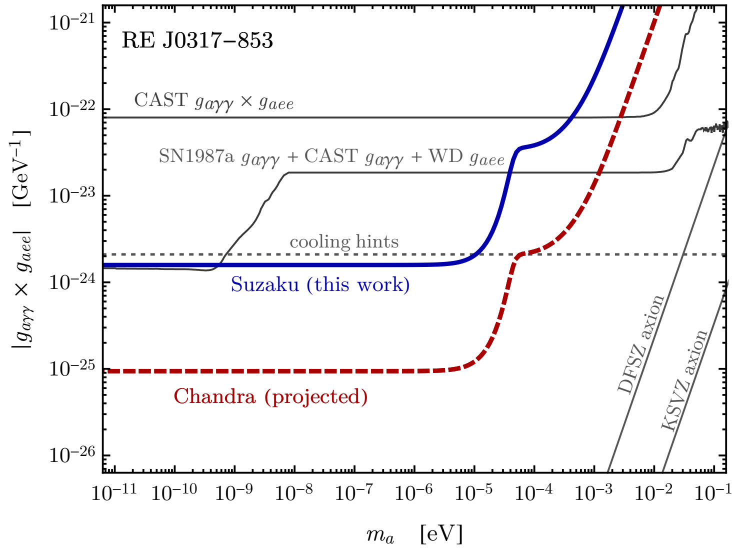
$g_{a\mu\mu} = (m_\mu/m_e)\, g_{aee}$

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.

➔ New data is here!

X-ray emission from M7 neutron stars, explained by ALP-muon coupling.

➔ Keep an eye our for the paper!