Neutron stars as axion laboratories

Benjamin Safdi

June 11, 2020

Leinweber Center for Theoretical Physics
University of Michigan

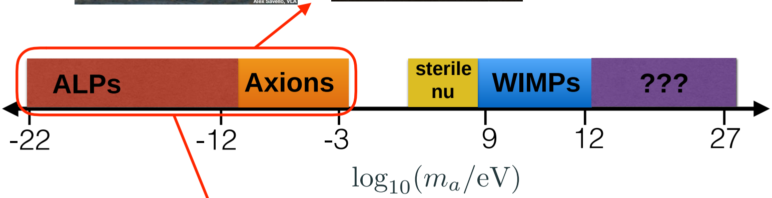
X**-rays:** 1903.05088 (PRL 2019), 1910.02956, 1910.04164

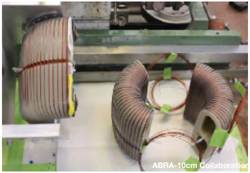
Radio: 1804.03145 (PRL 2018), 1811.01020 (PRD 2019), 2004.00011

M. Buschmann, R. Co, C. Dessert, J. Foster, A. Long, Z. Sun

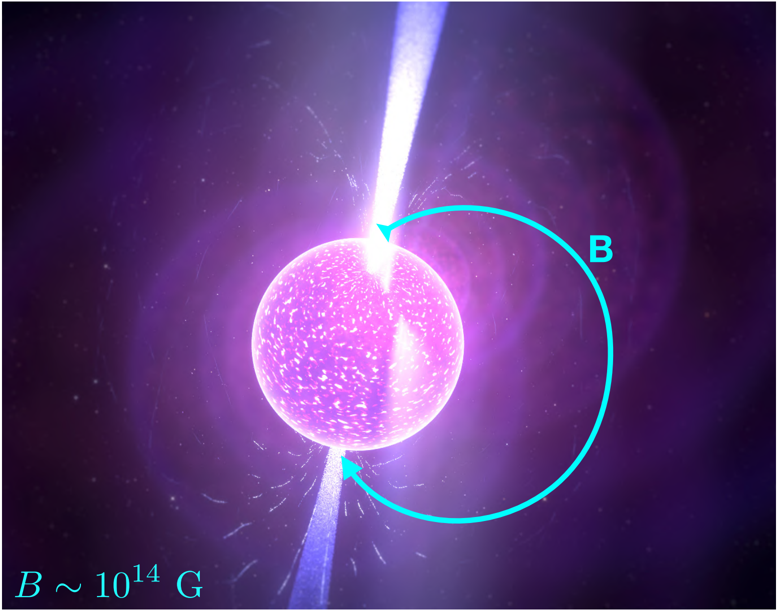
Complementarity between indirect and direct detection

This Talk:
- Indirect detection for axions





Neutron stars as B-field laboratories for axions



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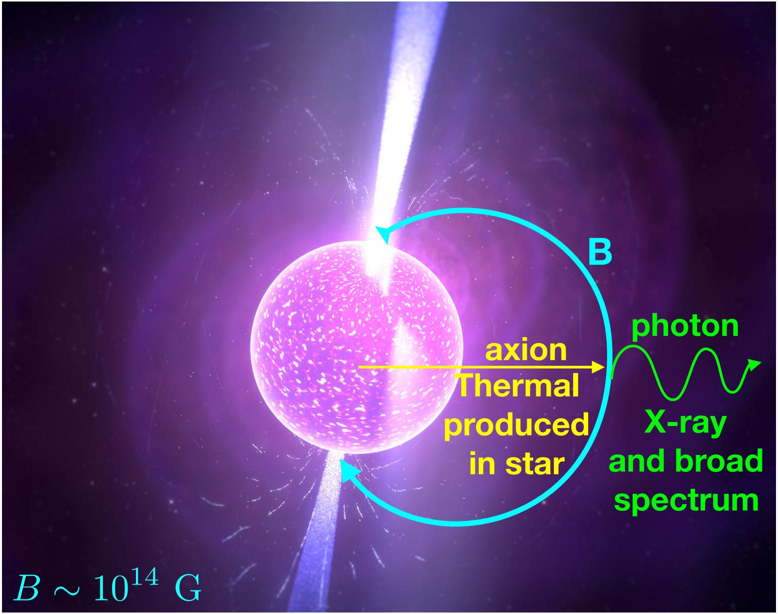
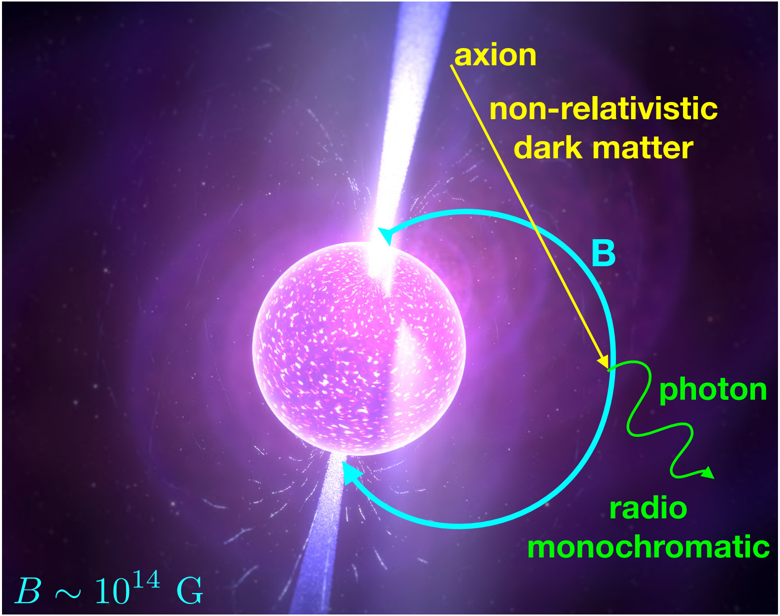
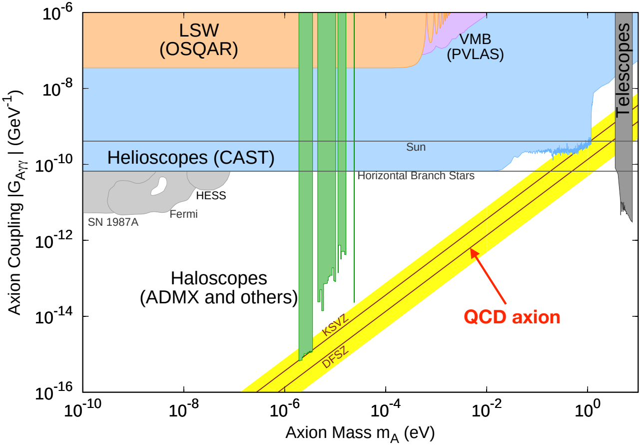


Neutron stars as B-field laboratories for axions



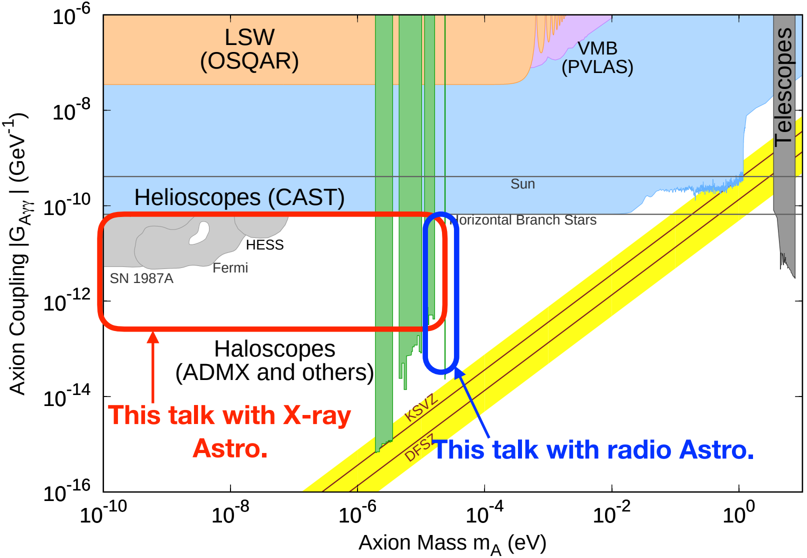
Axion-photon interactions

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{g_{aff}}{2m_e}\bar{\psi}_f \gamma^\mu \gamma_5 \psi_f \partial_\mu a - \frac{g_{a\gamma\gamma}}{4} a F \tilde{F} - \frac{1}{2} m_a^2 a^2 + \cdots$$

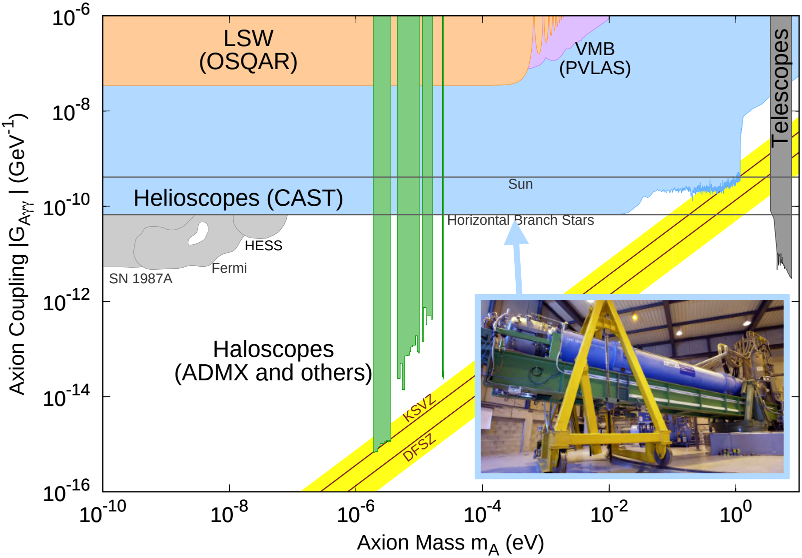


- String theory ALP constructions (1909.05257, Halverson *et al.*):
  $g_{a\gamma\gamma} \sim 10^{-12} - 10^{-10}$ GeV^{-1} for strongest-coupled ALP

Axion-photon interactions

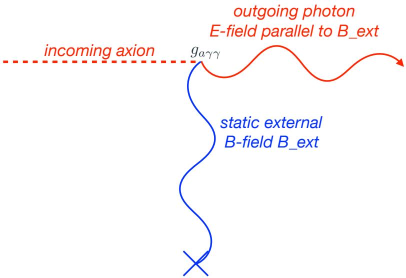


Existing axion-photon constraints



Axion-photon mixing

- $\mathcal{L} = g_{a\gamma\gamma} \underbrace{a}_{\text{dynam.}} \underbrace{\mathbf{E}}_{\text{dynam.}} \cdot \underbrace{\mathbf{B}}_{\text{ext.}}$



- $P_{a\to\gamma} \sim B_{\text{ext}}^2 g_{a\gamma\gamma}^2 L^2$
- L determined by B_{ext} geometry and axion wavelength m_a^{-1}

Example: CAST

High B field converts axions -> photons

- $P_{a\to\gamma} \sim B_{\text{ext}}^2 g_{a\gamma\gamma}^2 L^2$: what is L?

Example: CAST

Sun

keV plasma produces axions

relativistic axions

High B field converts axions -> photons

X-rays

- $P_{a\to\gamma} \sim B_{\text{ext}}^2 g_{a\gamma\gamma}^2 L^2$: what is L?
- Axion and photon have same energy ω, but momentum mismatch $\delta k \sim m_a^2/\omega$

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- $\delta k \ll L_{\text{CAST}}^{-1}$: $L \sim L_{\text{CAST}}$ ☺

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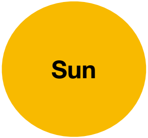

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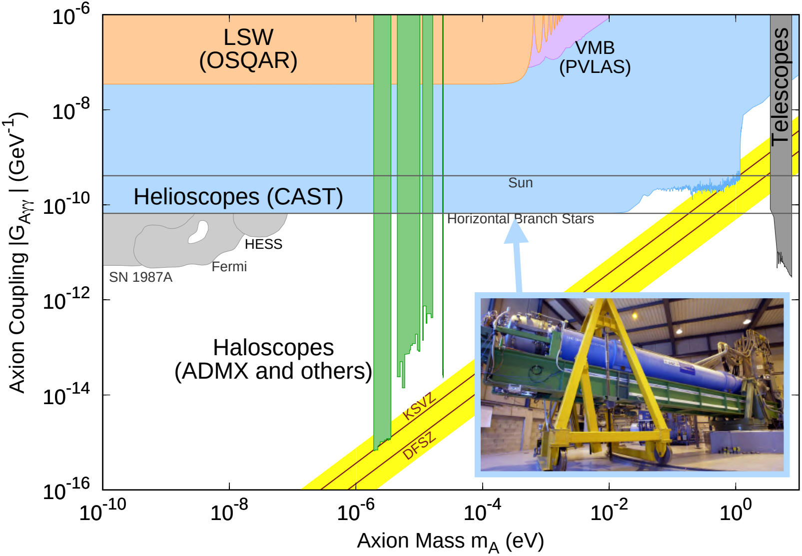
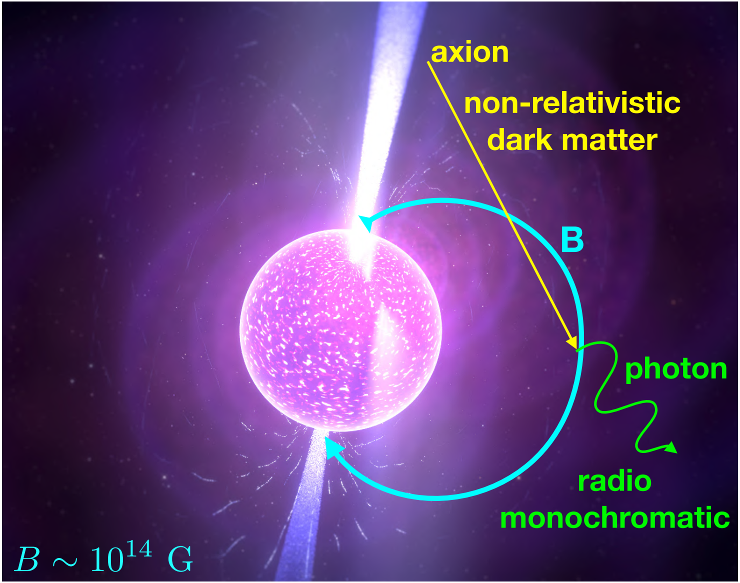
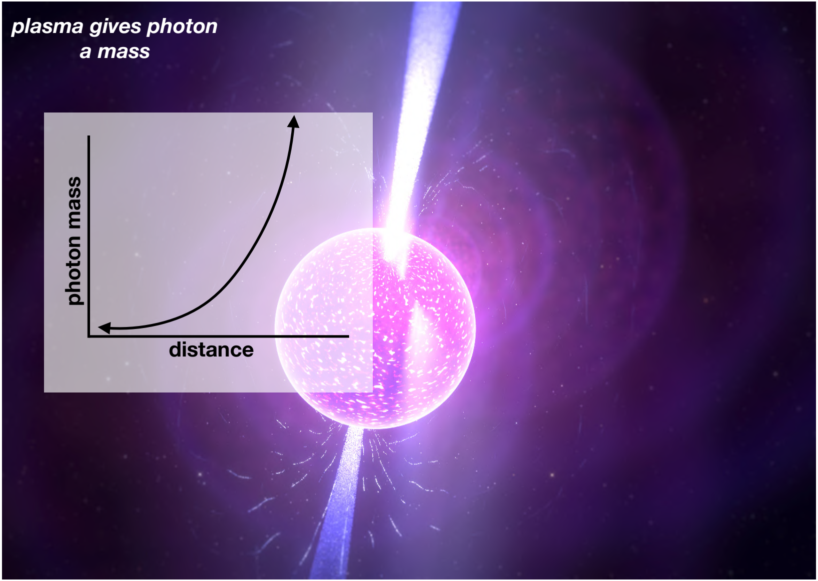
- Axion and photon have same energy ω, but momentum mismatch $\delta k \sim m_a^2/\omega$
- $\delta k \ll L_{\text{CAST}}^{-1}$: $L \sim L_{\text{CAST}}$ ☺
- But if $\delta k \gg L_{\text{CAST}}^{-1}$, $L \sim \delta k^{-1} \ll L_{\text{CAST}}$ ☹
  - $P_{a\to\gamma} \sim B_{\text{ext}}^2 g_{a\gamma\gamma}^2 \dfrac{\omega^2}{m_a^4}$

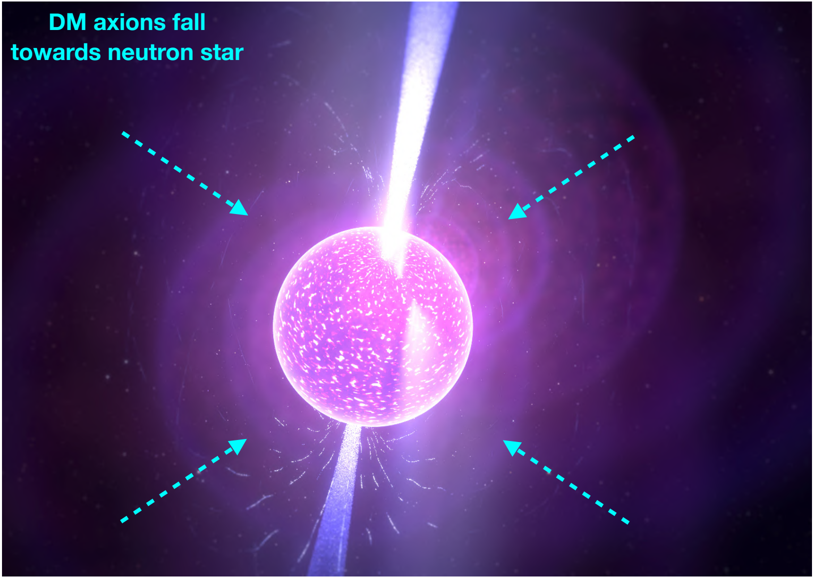
Existing axion constraints

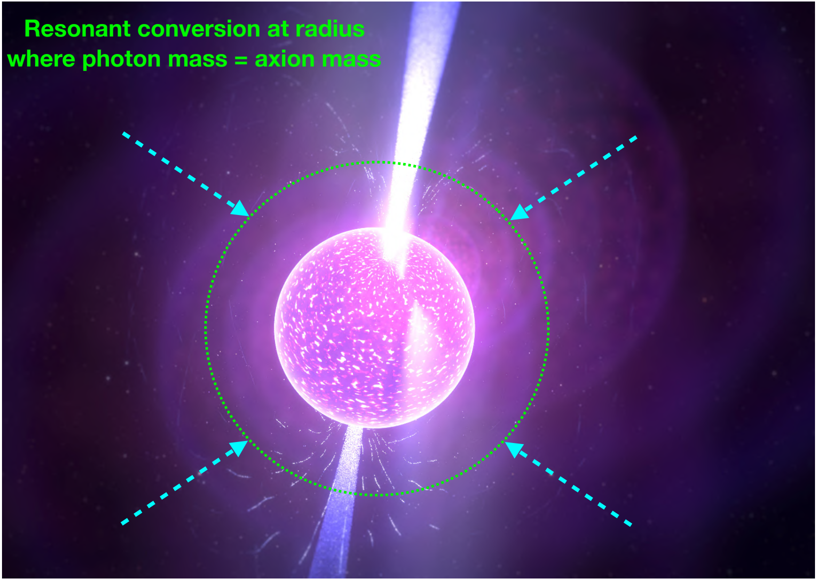


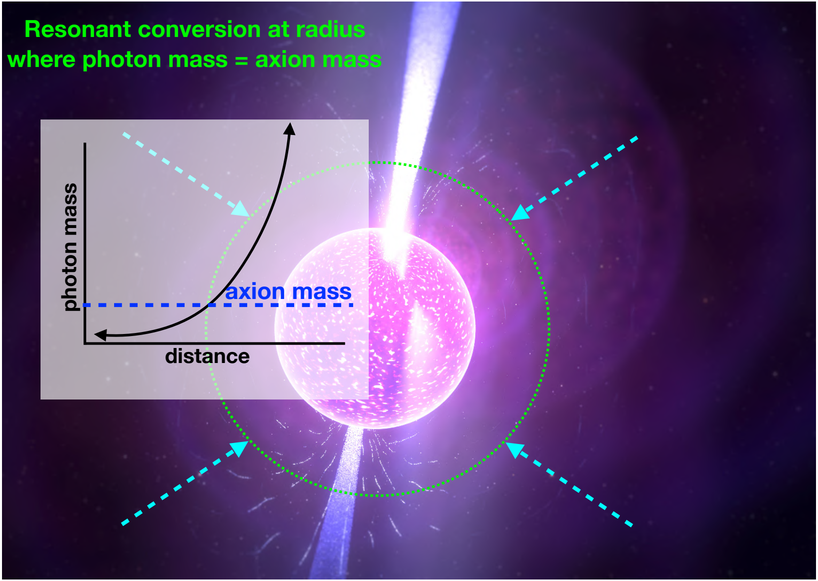
Part 1: Radio Searches for axion DM

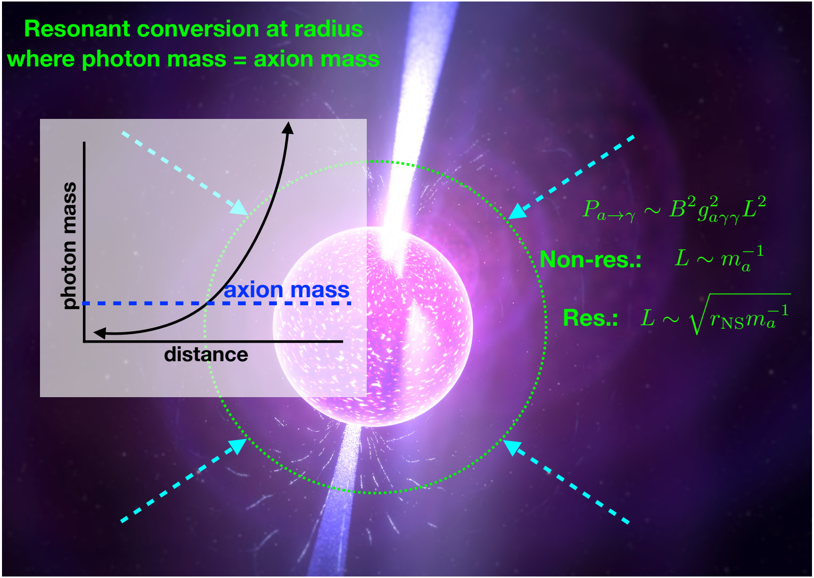



plasma gives photon a mass
photon mass
distance

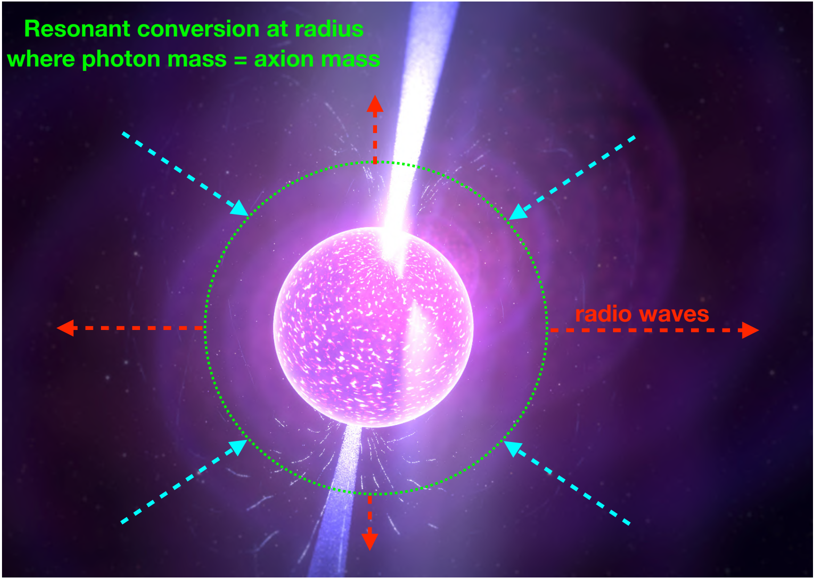

DM axions fall
towards neutron star

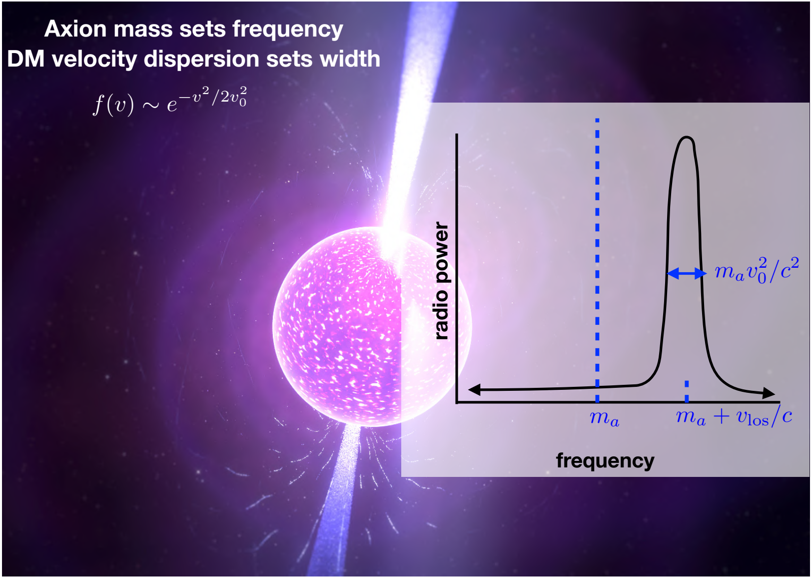

Resonant conversion at radius
where photon mass = axion mass


Resonant conversion at radius
where photon mass = axion mass
photon mass
axion mass
distance



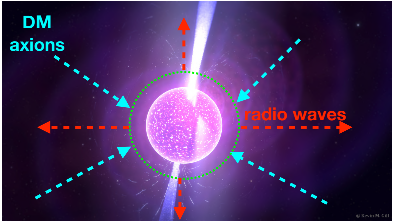
Resonant conversion at radius
where photon mass = axion mass
photon mass
axion mass
distance
$P_{a\to\gamma} \sim B^2 g_{a\gamma\gamma}^2 L^2$
Non-res.: $L \sim m_a^{-1}$
Res.: $L \sim \sqrt{r_{\rm NS} m_a^{-1}}$


Resonant conversion at radius
where photon mass = axion mass
radio waves



Axion mass sets frequency
DM velocity dispersion sets width
$f(v) \sim e^{-v^2/2v_0^2}$
radio power
$m_a v_0^2/c^2$
m_a
$m_a + v_{\rm los}/c$
frequency

NS with strong B-field and surrounding plasma



DM axions resonantly convert to radio waves when $m_a = m_\gamma$

radio waves

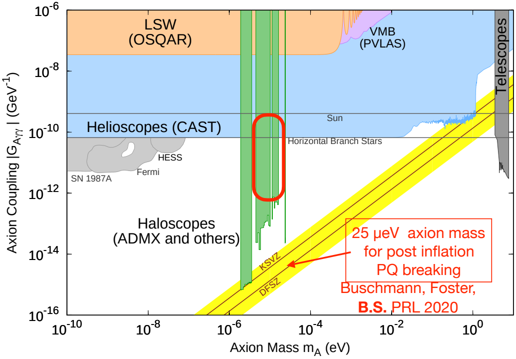
radio emission propagates to Earth

Narrow radio line detectable at Earth with $f = m_a/(2\pi)$.

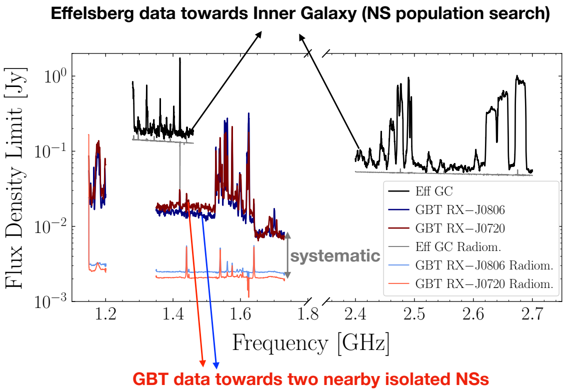
First data results appeared in 2020

Green Bank and Effelsberg Radio Telescope Searches for Axion Dark Matter Conversion in Neutron Star Magnetospheres

Joshua W. Foster,[1,*] Yonatan Kahn,[2] Oscar Macias,[3,4] Zhiquan Sun,[1] Ralph P. Eatough,[5,6] Vladislav I. Kondratiev,[7,8] Wendy M. Peters,[9] Christoph Weniger,[4,†] and Benjamin R. Safdi[1,‡]

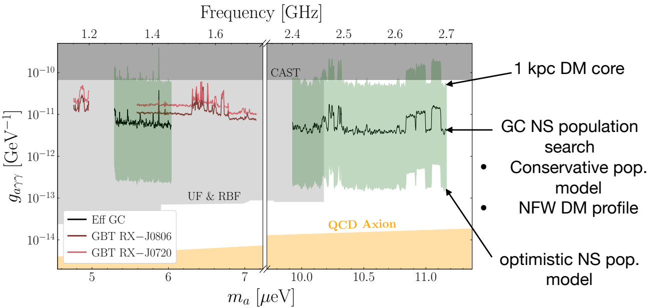


First data results appeared in 2020



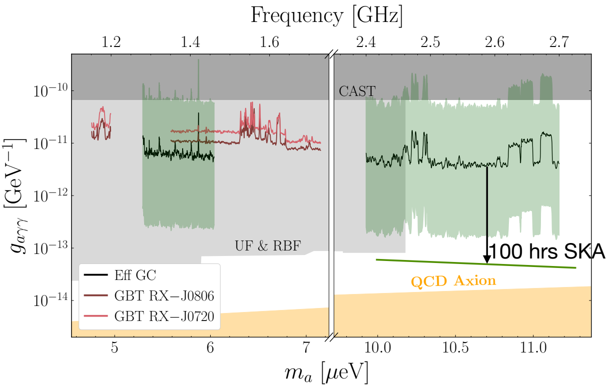
- Signal is ∼10 kHz wide (bump hunt in sliding window)
- Have ON and OFF data (∼1 hr each) for vetoing radio-frequency interference
- NO evidence for axion signals (data consistent with null)

First data results appeared in 2020



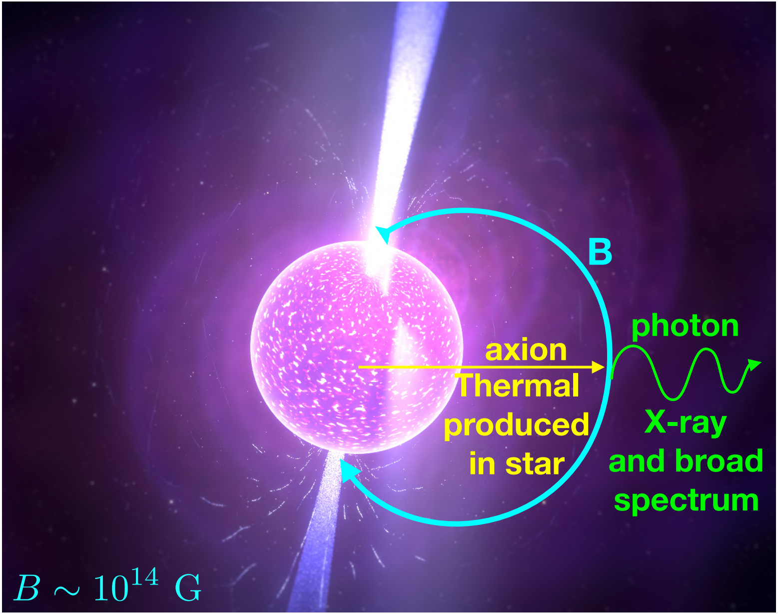
- NS Pop mode systematic: how do B-fields of old NSs decay?
- DM systematic: DM density in inner $\sim$1 pc - $\sim$1 kpc
- Magnetosphere systematic: pair multiplicity in lobes of NS magnetopsheres?
- Current theory limitation: Full 3D simulation of axion + NS conversion not available (see 1912.08815 for best attempt)

Radio search future



- Square Kilometer Array (SKA): bigger telescope + spatial information
  - Have data already on Murchison Widefield Array (MWA)
- GBT/Effelsberg: Acquiring more data at higher frequencies ($m_a \sim 25\ \mu$eV)

X-ray search for axions from neutron stars



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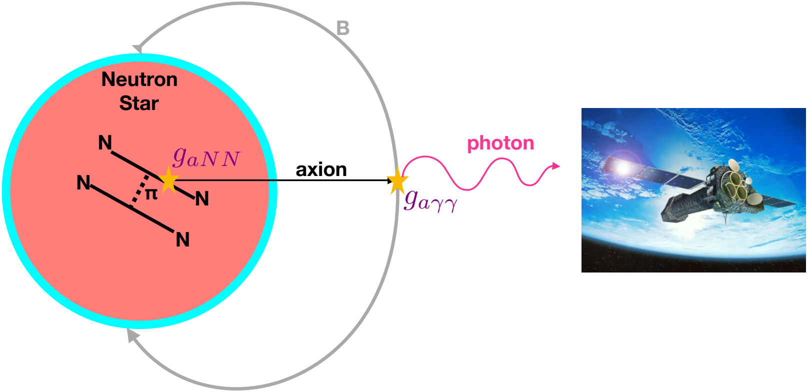

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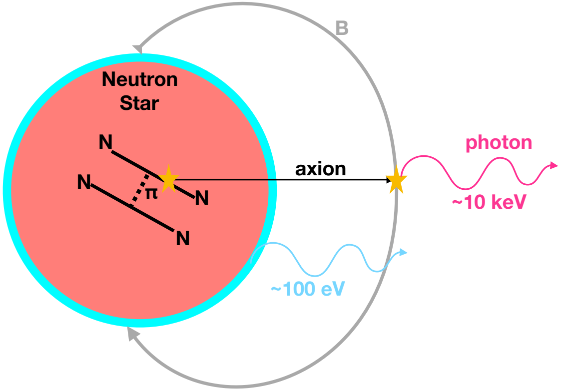

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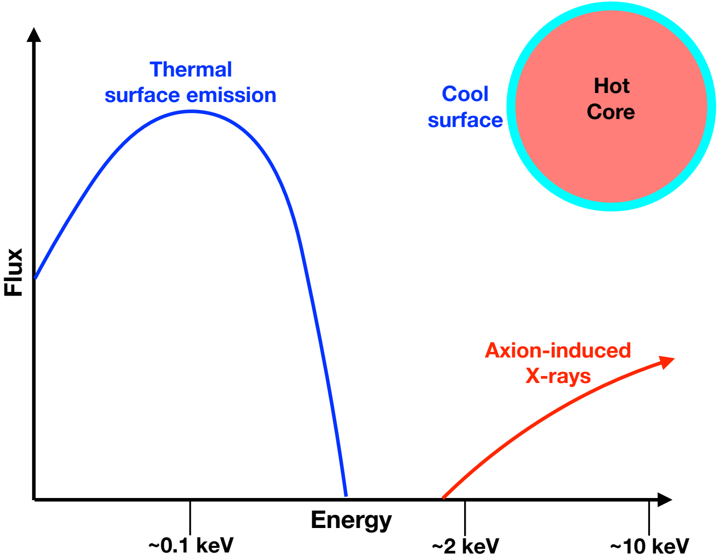
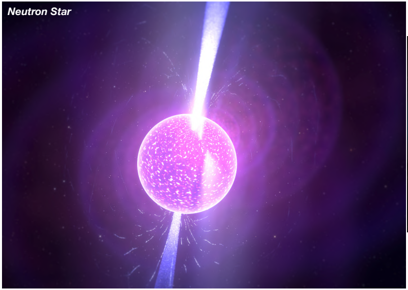


Theory ingredients for axion-induced X-rays

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{g_{aqq}}{2m_q}\bar{\psi}_q\gamma^\mu\gamma_5\psi_q\partial_\mu a - \frac{g_{a\gamma\gamma}}{4}aF\tilde{F} - \frac{1}{2}m_a^2a^2 + \cdots$$

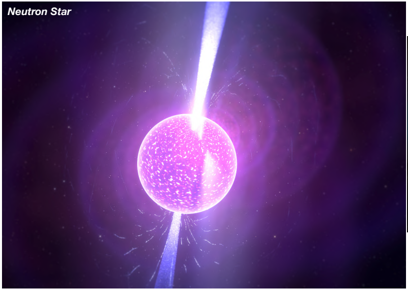
- NS core temperature T_b^∞: $dF/dE \sim E^{3-4/5}/(e^{E/T_b^\infty} - 1)$
- NS equation of state
- NS superfluidity model (*e.g.*, transition temperature)
- Magnetic field (typically well measured)

The magnificent seven isolated neutron stars



- 7 neutron stars between $\sim$100 - 500 pc away
- Discovered with ROSAT full-sky X-ray survey (90's)

The magnificent seven isolated neutron stars



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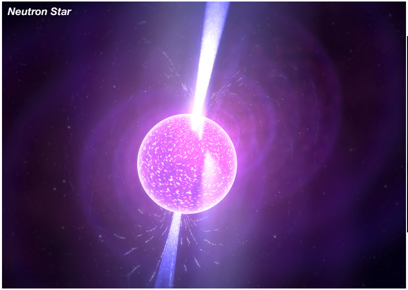

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- surface: $B \sim 10^{13}$ G (spindown)
- $T_{\rm surf} \sim 100$ eV
- Non non-thermal emission detected (no radio, no $E > 1\,\mathrm{keV}$)

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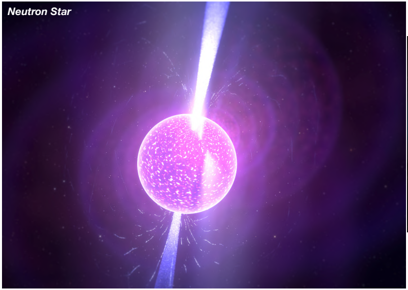

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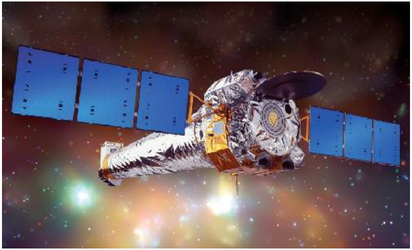
Magnificent seven datasets: *XMM-Newton* and *Chandra*

Chandra

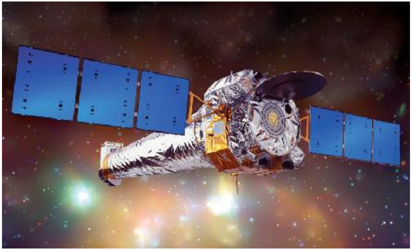


XMM-Newton

- Use data from $2-8$ keV

Magnificent seven datasets: *XMM-Newton* and *Chandra*

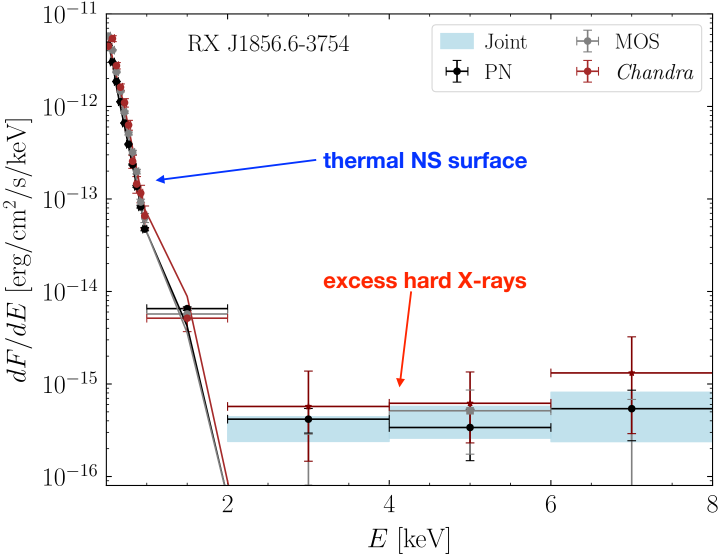
Chandra



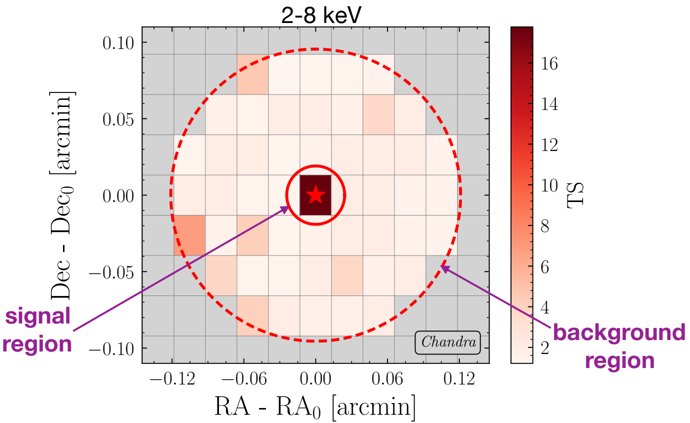
XMM-Newton

- Use data from $2-8$ keV
- *XMM-Newton* (PN and MOS)
  - 90% containment radius: $\sim$50”
- *Chandra* (ACIS)
  - 90% containment radius: $\sim$1” (signal limited)

Hard X-ray excesses from RX J1856.6-3754



RX J1856.6-3754: *Chandra*

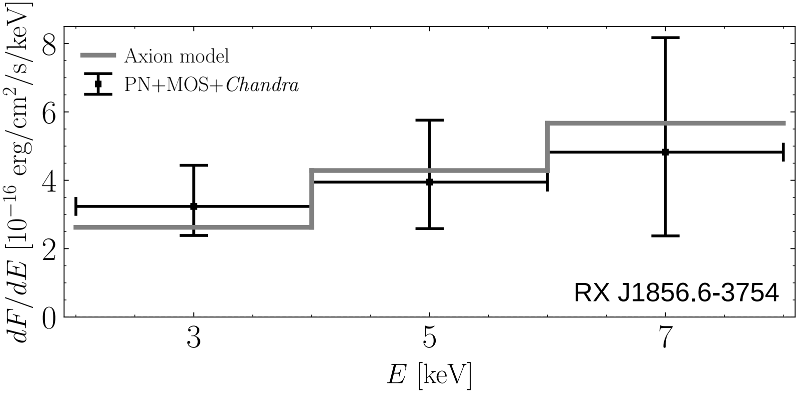


- *Chandra* only: $>3\sigma$ evidence for 2-8 keV flux
- *PN* only: $\sim 4\sigma$ evidence for 2-8 keV flux
- *MOS* only: $\sim 1\sigma$ evidence for 2-8 keV flux
- Excesses in 4 of 7 NSs, 3 consistent with null

- Does axion model fit data?
- Is there another explanation?

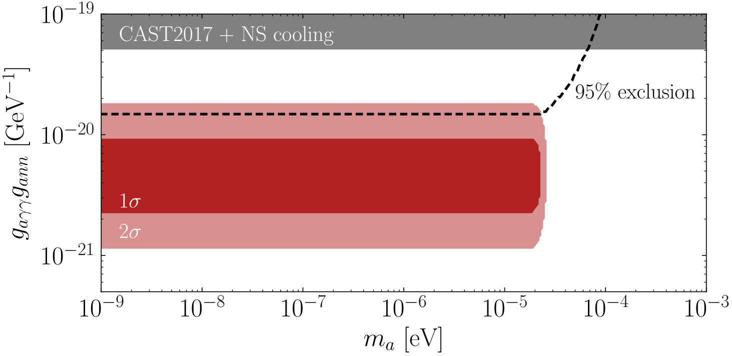
M7 spectra versus axion prediction

- Does axion spectrum $dF/dE \sim E^{3-4/5}/(e^{E/T_b^\infty} - 1)$ fit?



- M7 intensities consistent w/ axion?: yes (short answer)

Axion interpretation



- More than 5σ statistical significance: axion model versus null hypothesis
    - Instrumental systematics and other astrophysical emission mechanisms more important than statistics

- Does axion model fit data?
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Other astrophysical explanations for M7 excess (1910.02956)

- More complicated atmosphere model?
    - Doesn't seem to work: hard to get X-rays above 2 keV from surface ($T_{\rm surf} \sim 100$ eV)

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- Non-thermal emission from pulsar jet?
  - Luminosities appear much too large
- Accretion of interstellar medium?
  - Luminosities and energies appear too high

X-ray conclusions

- Found excess of hard X-rays in M7 neutron stars, could arise from axion-like particles

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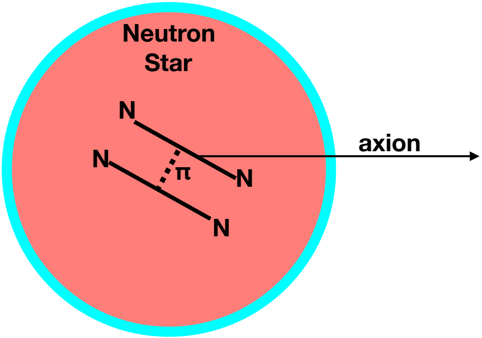
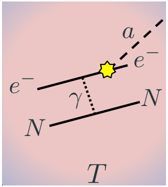
- Future experiments will probe this: IAXO, ALPS-II, ...
- My theory wishlist
  - Other models for M7 excess? (dark photons, etc.)
  - We have not modeled inner core! (axions from exotic matter: quark gluon plasma, strange matter, muons?)

Questions?

Step 1: axion production (neutron star or white dwarf)



Axion production in White Dwarfs



- $\mathcal{L}_{aee} = \frac{g_{aee}}{2m_e}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$
- $L_{\mathrm{WD},a} \approx 2 \times 10^{-4} L_\odot \left(\frac{g_{aee}}{10^{-13}}\right)^2 \left(\frac{T_c}{10^7\ \mathrm{K}}\right)^4$
- Axions $\sim$thermal at $T_c \sim \mathrm{keV}$

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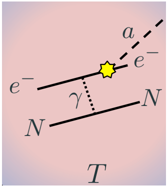

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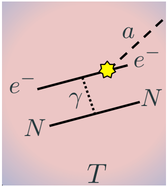

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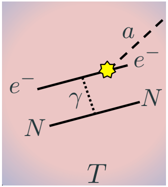
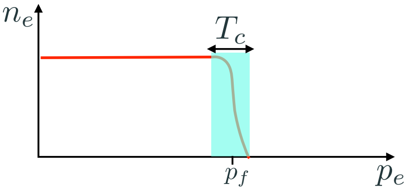
  - $E_a \sim T_c$

Axion production in White Dwarfs



- $\mathcal{L}_{aee} = \frac{g_{aee}}{2m_e}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$
- $L_{\mathrm{WD},a} \approx 2 \times 10^{-4} L_\odot \left(\frac{g_{aee}}{10^{-13}}\right)^2 \left(\frac{T_c}{10^7\ \mathrm{K}}\right)^4$
- Axions $\sim$thermal at $T_c \sim \mathrm{keV}$

- $L_{\mathrm{WD},a}$ factors of T_c:
  - $\sigma \propto T_c$
  - $E_a \sim T_c$
  - Electron degeneracy: $(T_c/p_f)^2$ ($p_f \sim 0.5$ MeV)



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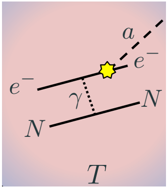

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- $g_{aee} < 3\times 10^{-13}$ (WD cooling, e.g. 1406.7712)
- WD, RG, HB Cooling hints (see *e.g.* 1708.02111) :
  - $g_{aee} = 1.5\times 10^{-13}$
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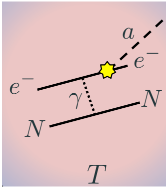

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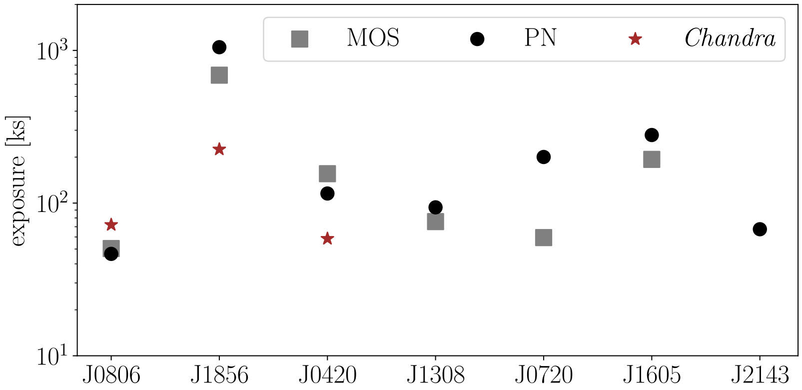
- NS production: degenerate neutron/proton scattering
  - $T_c \sim 10$ keV
  - $g_{ann} < 7.7 \times 10^{-10}$: Cas A NS cooling (1806.07151)

Magnificent seven data



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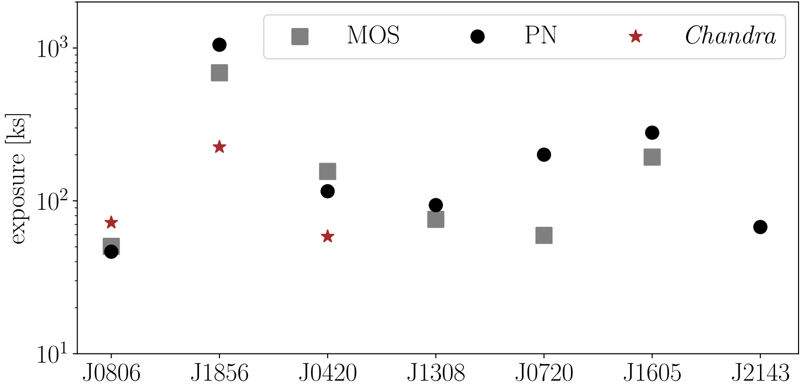
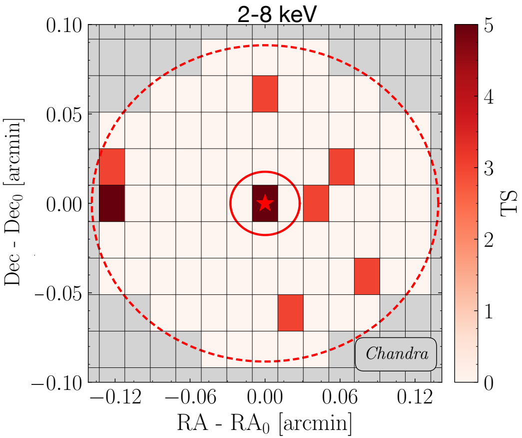


- RX J1856.6-3754 has *by far* most exposure
- Also closest of the M7 ($d \approx 100$ pc)
- $T_{\text{surf}} \approx 70$ eV / thermal luminosity relatively low (pileup not concern for *Chandra*)

RX J0420.0-5022



- $\sim 2\sigma$ evidence *Chandra*, $\sim 1\sigma$ PN, $\sim 1\sigma$ MOS
- No chance of pileup for *Chandra* (lowest count rates of M7)
- $\sim 1\sigma$ excesses from 2 other M7, 3 consistent with null

M7 data needed to predict signal

M7 Name	$\log(B_0/\,\mathrm{G})$	$\log(T_b^\infty/\,\mathrm{keV})$	d [pc]
RX J0806.4-4123	13.40 ± 0.13	1.2 ± 0.3	240 ± 25
RX J1856.6-3754	13.18 ± 0.05	0.9 ± 0.2	123 ± 13
RX J0420.0-5022	13.00 ± 0.06	0.9 ± 0.4	345 ± 200
RX J1308.6+2127	13.68 ± 0.04	1.2 ± 0.3	663 ± 137
RX J0720.4-3125	13.53 ± 0.05	1.2 ± 0.3	361 ± 130
RX J1605.3+3249	13.00 ± 0.20	1.2 ± 0.3	393 ± 219
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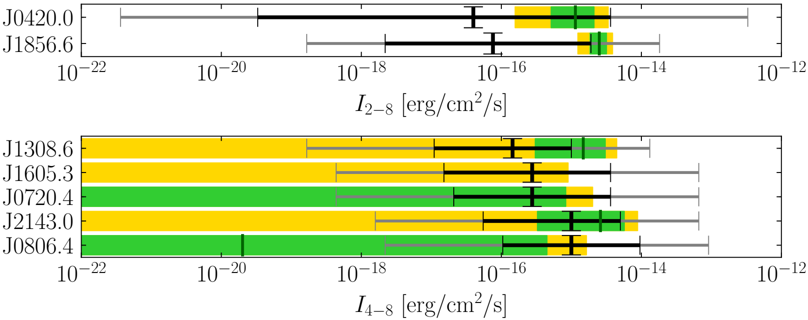
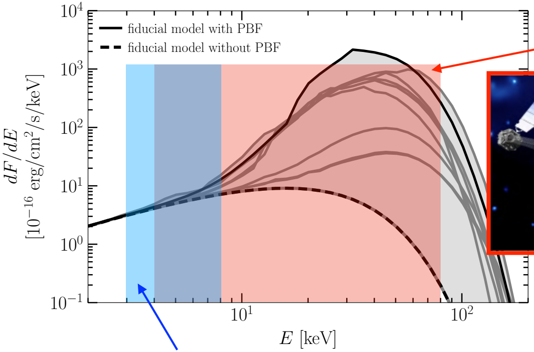
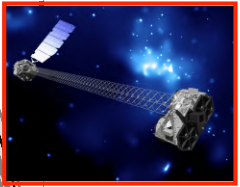
M7 intensities versus axion prediction



- green/yellow: 1(2)σ measurement from X-ray data
- black/gray: 1(2)σ estimate from axion + NS model (at best-fit $g_{a\gamma\gamma}g_{ann}$)
- Dom. mod. uncertainty: T_b^∞ ($I \sim T_b{}^6$ + superfluid suppr.)

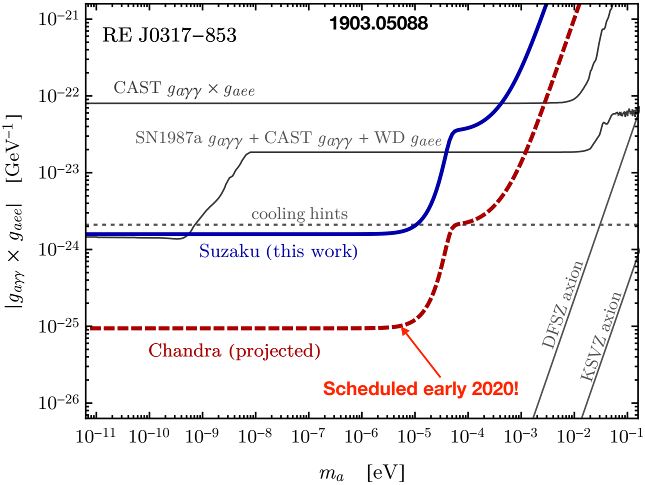
Future hard X-ray NuSTAR observations would be useful





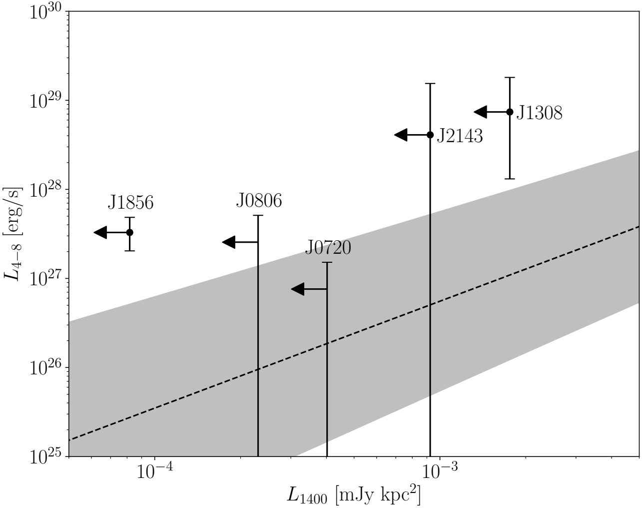
- Axions might gain energy from breaking Cooper pairs
  - Signal sensitive to neutron superfluid gap model
- Dedicated NuSTAR observation towards RX J1856 should detect high-E flux in any scenario (NuSTAR proposal in)

Upcoming *Chandra* observations of magnetic white dwarf

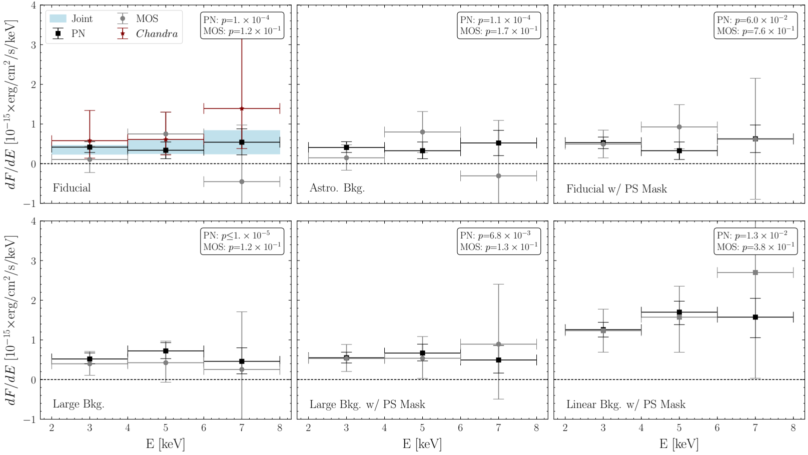


- WD surface temperatures ∼eV: no (good) archival data
- Upcoming *Chandra* observation: March 2020

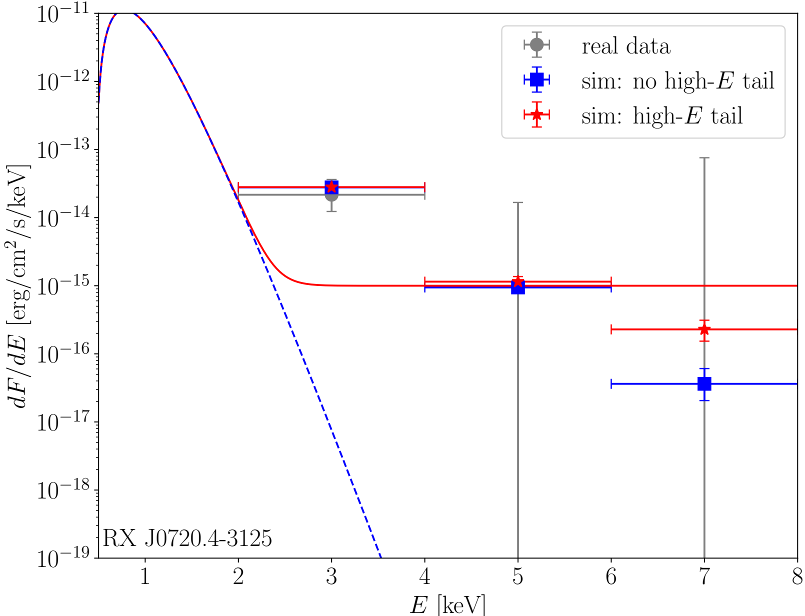
Radio constraints on pulsar-like emission



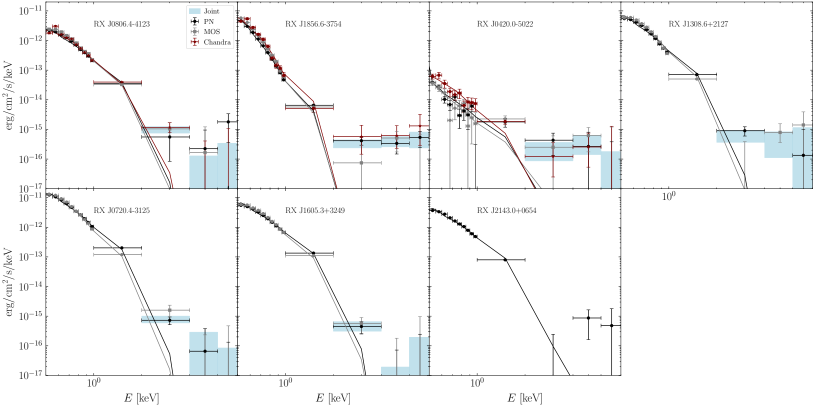
Systematic tests for RX J1856



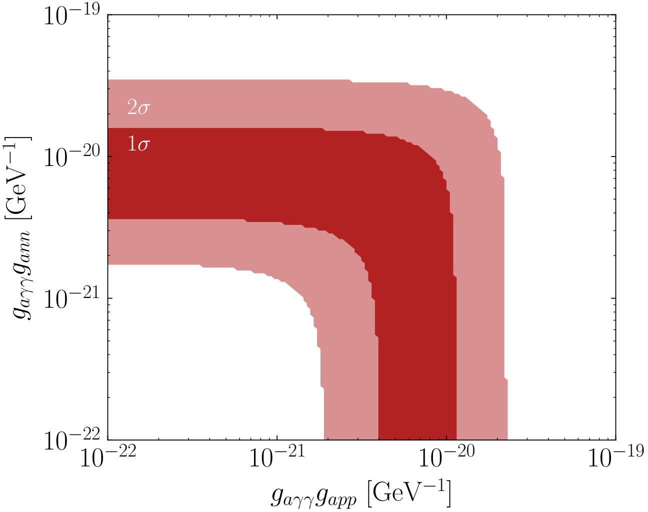
Chandra pileup example



Spectrum of all M7



Best-fit at low m_a



Best-fits and significances