COMPACT STARS AS AXION LABORATORIES

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Axion-like particles versus QCD Axion

$$\mathcal{L} = \frac{-g^2}{32\pi^2}\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{C_\gamma \alpha_{\mathrm{EM}}}{8\pi f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \sum_f \frac{C_f}{2 f_a}\partial_\mu a \bar{f}\gamma^\mu\gamma_5 f$$

$$-\frac{1}{2} m_{\mathrm{bare}}^2 a^2$$

QCD axion only!

$$m_a^{\mathrm{QCD}} \gg m_{\mathrm{bare}}$$

small

Sring Axiverse: *N* pseudo-scalars -> *N-1* ALPs + 1 QCD axion

Axion interactions with Matter

Axion EM coupling: $$\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4} = g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$$

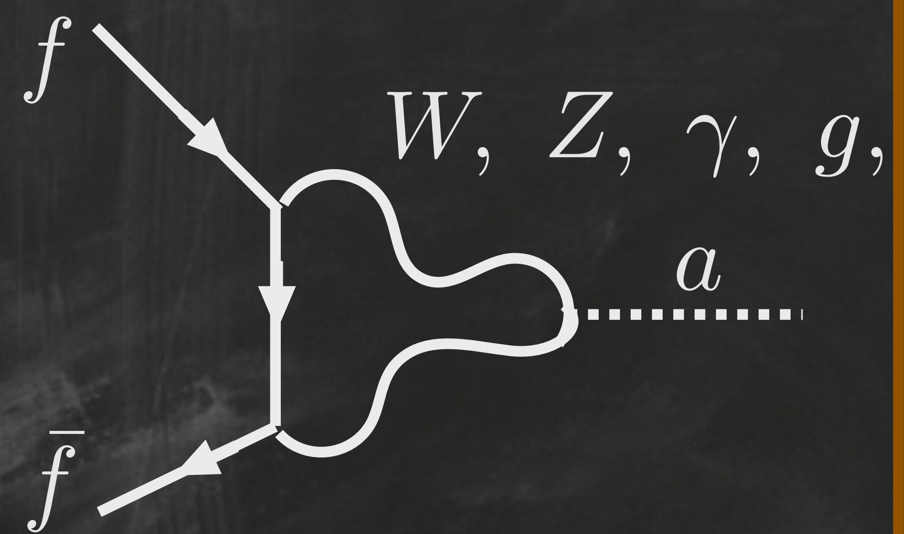
$$g_{a\gamma\gamma} = \frac{C_\gamma \alpha_{\rm EM}}{2\pi f_a}\,, \qquad C_\gamma \sim \mathcal{O}(1)$$

Axions fermion couplings: $$\mathcal{L} = \frac{C_f}{2f_a}(\partial_\mu a)\bar{f}\gamma^\mu\gamma_5 f$$

Dimensionless coupling: $$g_{aff} = \frac{C_f m_f}{f_a}$$

flavor changing also possible

IR and/or UV contributions to g_{aff}

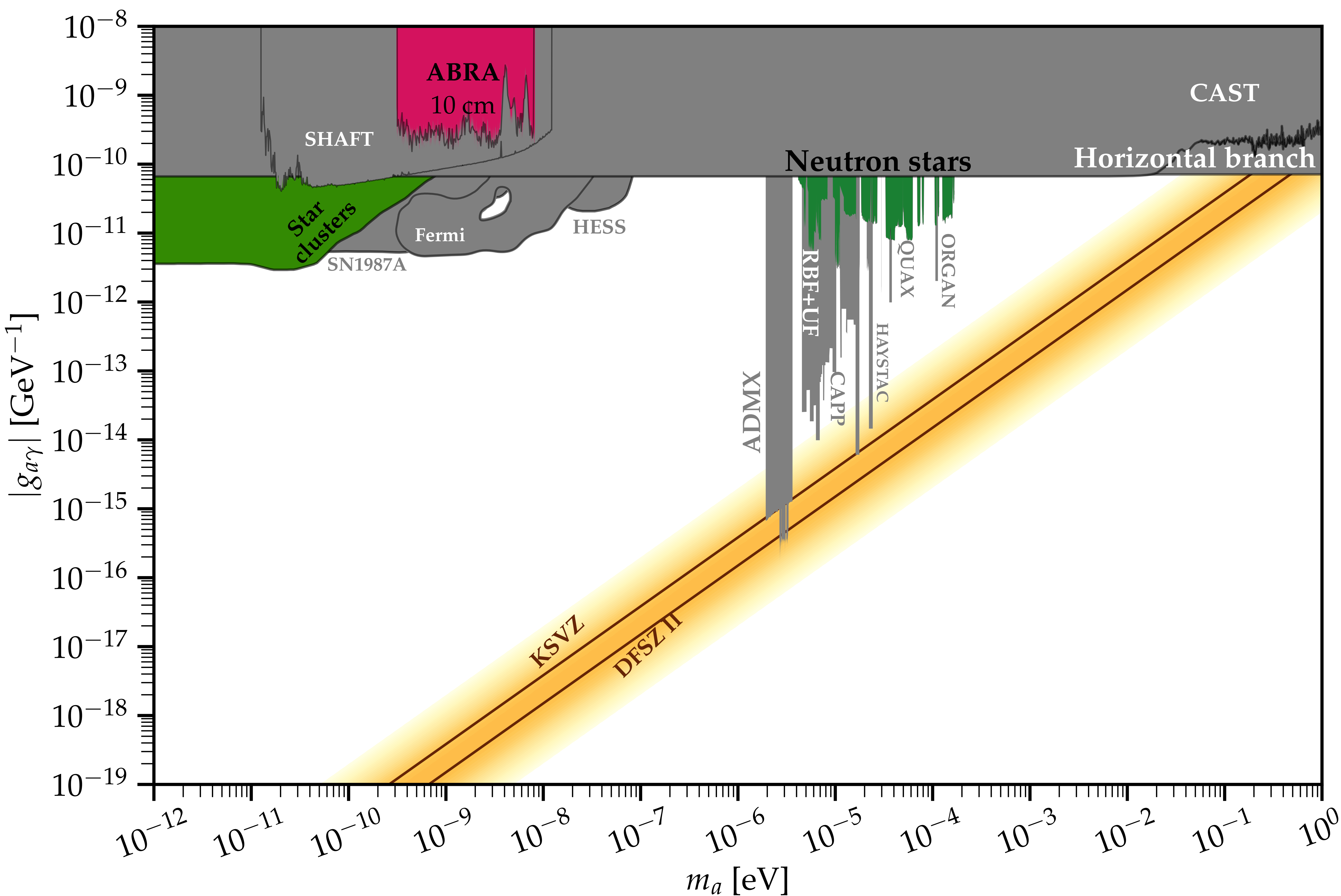


$$C_e^{\rm IR} \approx C_e^{\rm UV} + 5\times 10^{-4}C_W + 2\times 10^{-4}C_B$$

$$C_\gamma = C_W + C_B$$

non-zero electron PQ charge (DFSZ-type models)

Existing Constraints: $\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4}$



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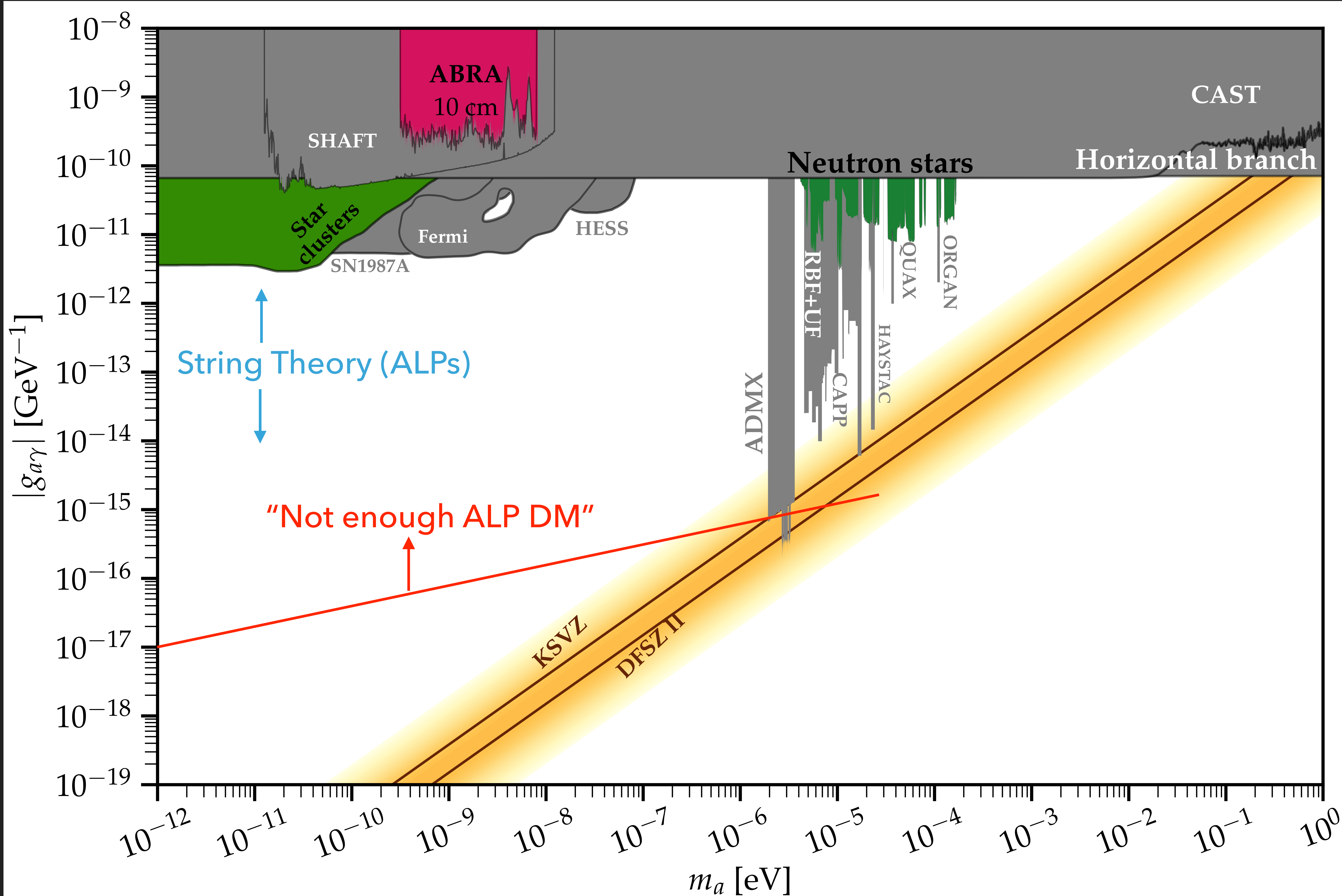

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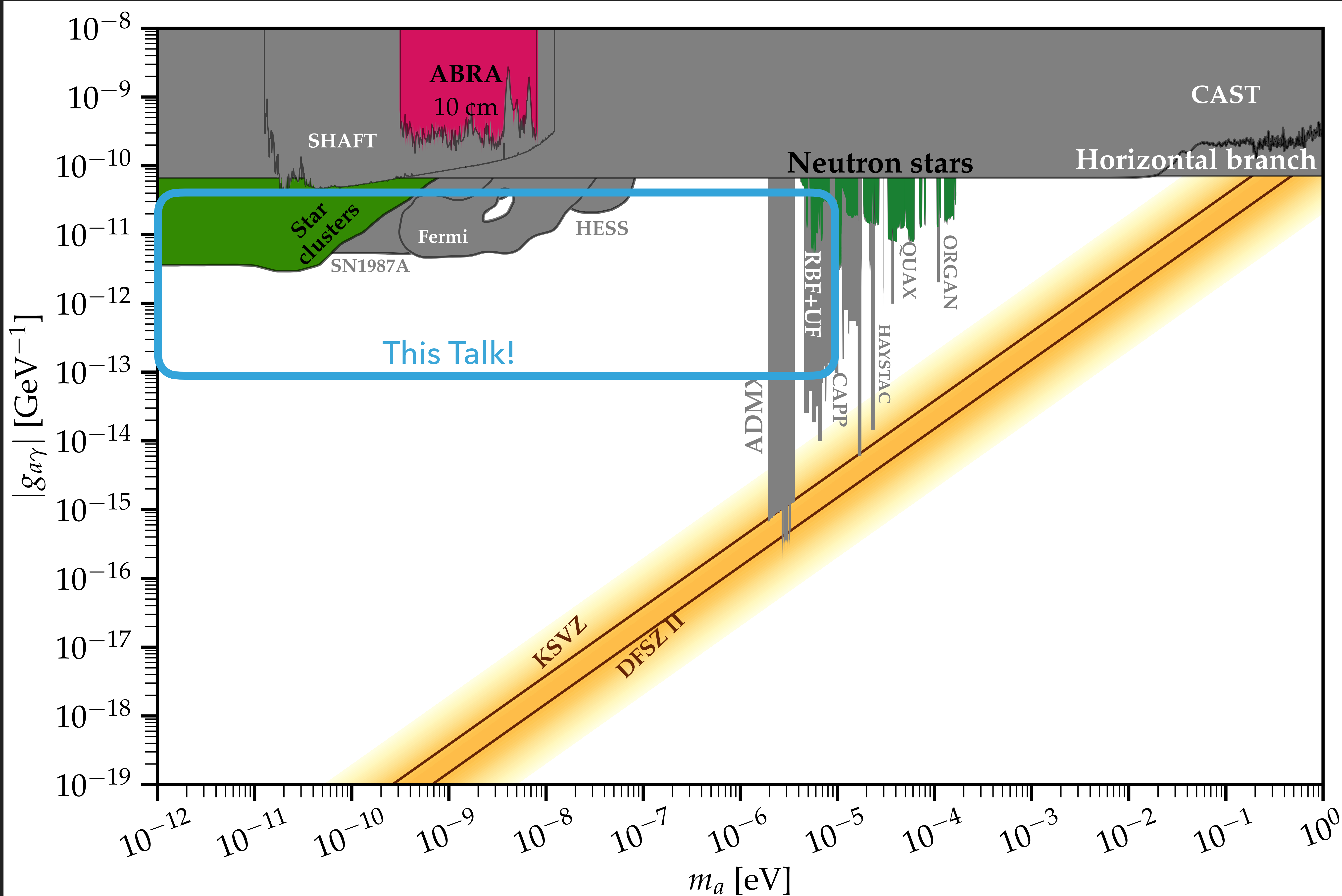

Outline

1. Axions with X-ray observations of white dwarfs and neutron stars (theory)
2. X-ray data: neutron star data (M7 anomaly)
3. X-ray data: white dwarfs data (RE J0317-853)

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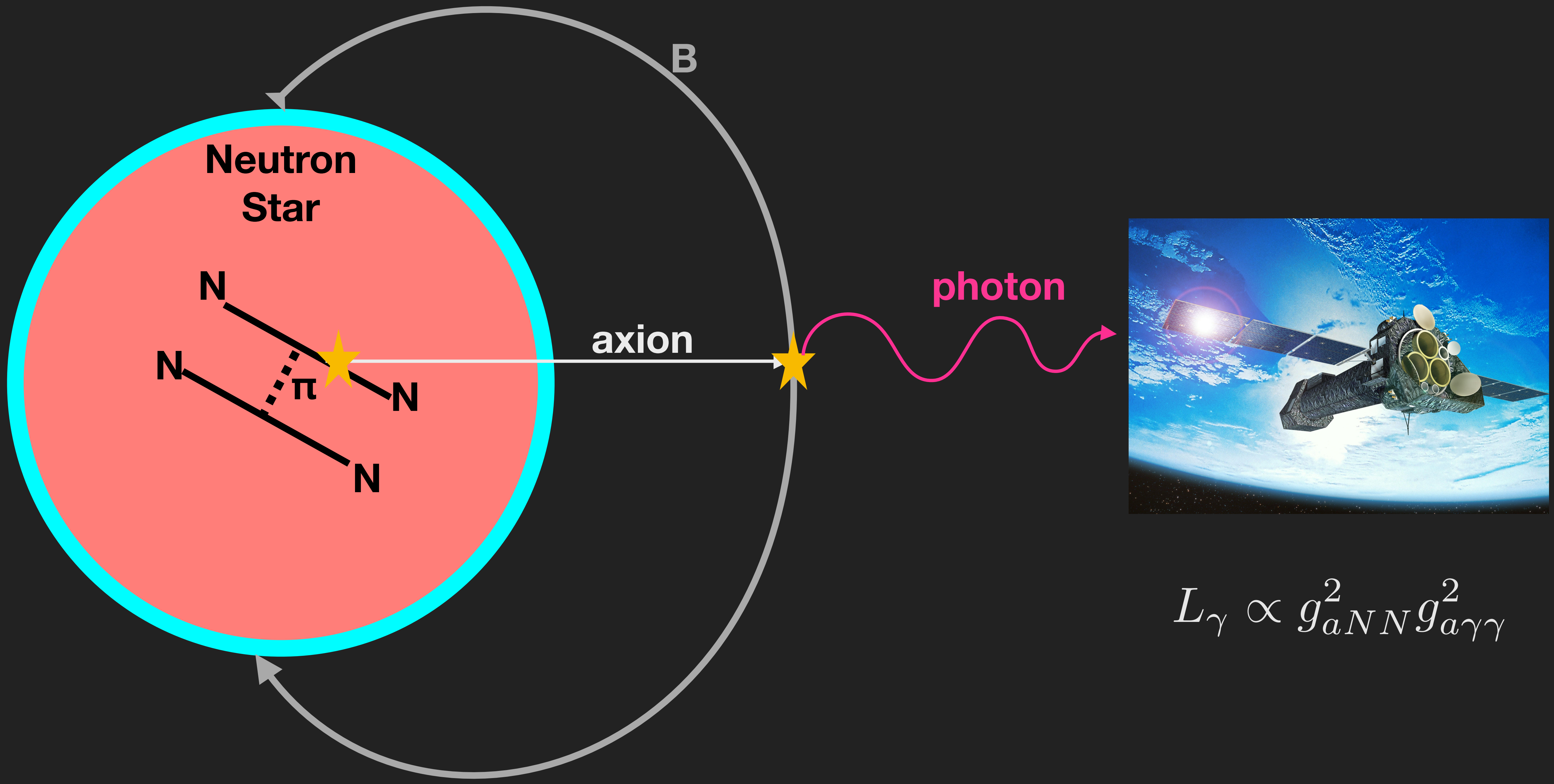
Dessert et al. 2104.12772, Dessert et al. 2008.03305 (PRL), Buschmann et al. 1910.04164 (PRL), Dessert et al. 1910.02956 (ApJ), Dessert et al. 1903.05088 (PRL)

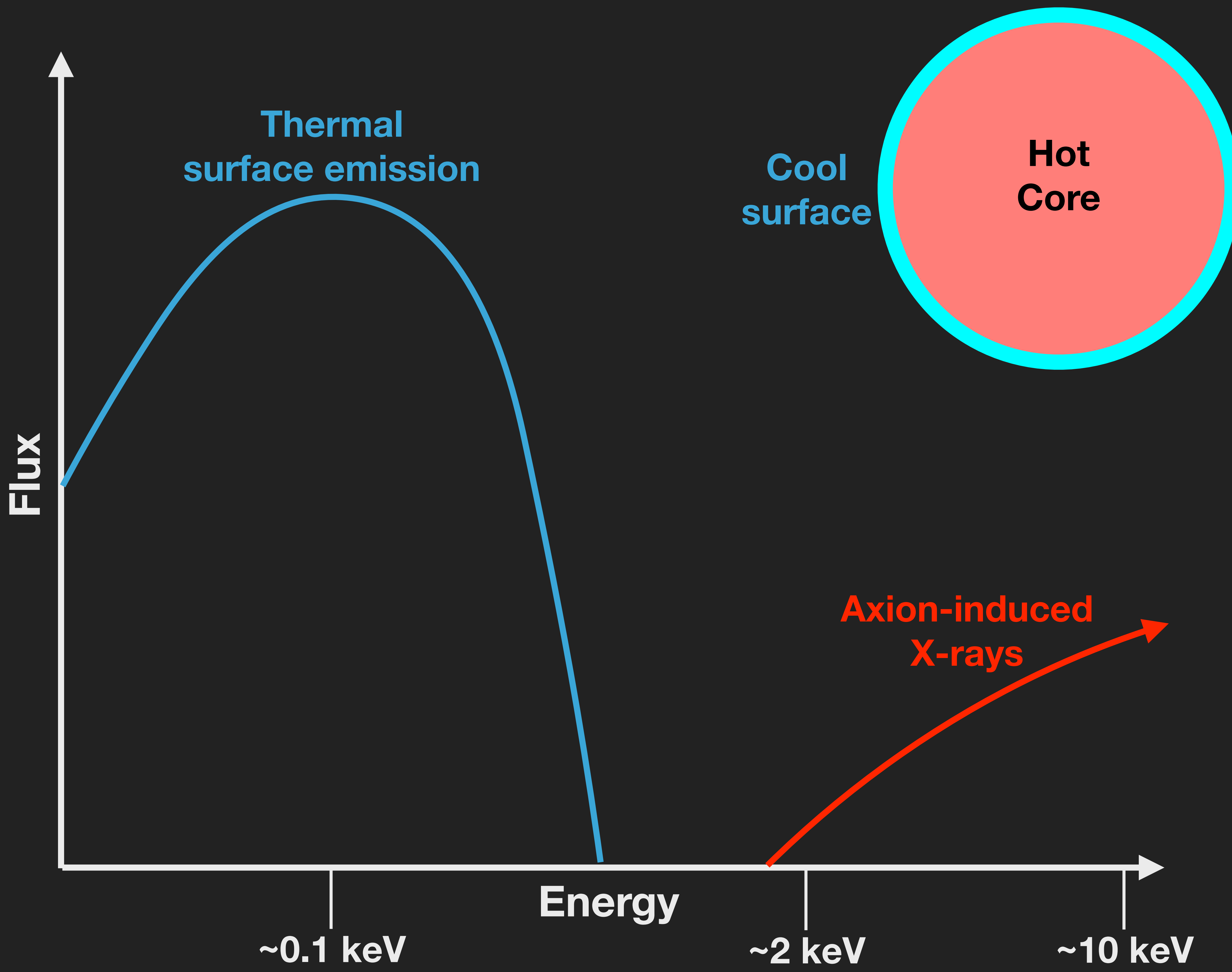
Chris Dessert

Neutron Star Overview



$$L_\gamma \propto g_{aNN}^2 g_{a\gamma\gamma}^2$$

Neutron Star Overview



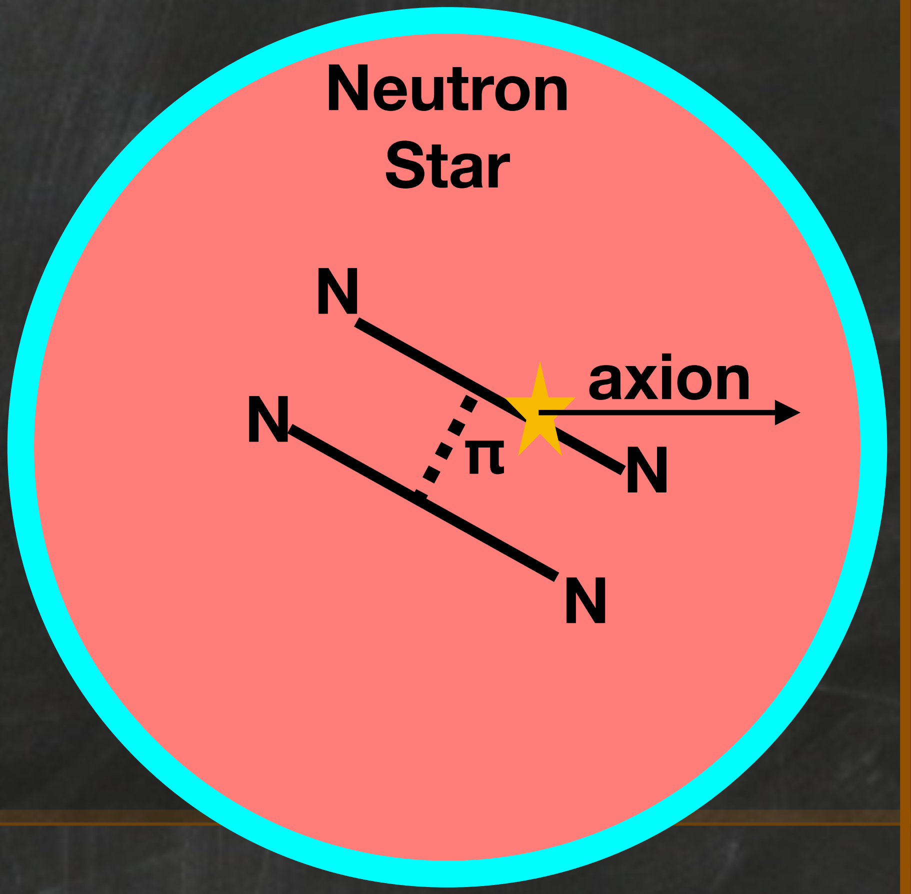
Axions Production in Neutron Star Cores from Brem.

Axion Luminosity:

$$L_a \approx 0.05 L_\odot \left(\frac{g_{ann}}{10^{-10}}\right)^2 \left(\frac{T_c}{10^8\ K}\right)^6$$

~thermal spectrum at: $T_c \approx 10$ keV

surface temperature ~0.1 keV

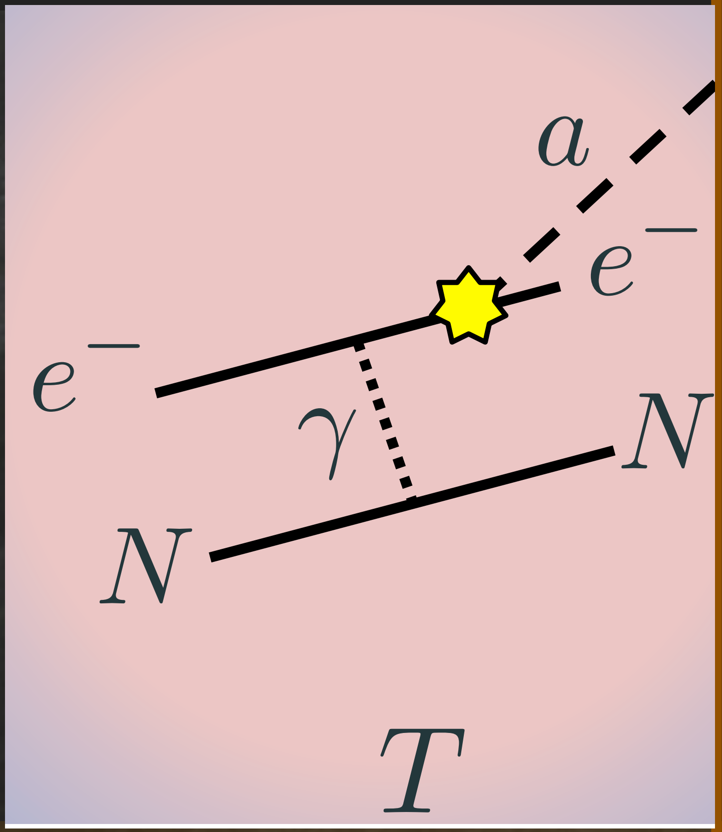


understanding factors of T_c

1. double neutron degeneracy: $(T_c/p_f)^4$ $(p_f \sim 0.3$ GeV$)$
2. cross-section: $\sigma \sim T_c$
3. energy: $E_a \sim T_c$

additional complication: superfluidity (*ask after for details)

Axions Production in White Dwarf Cores from Brem.



Axion Luminosity:

$$L_a \approx 2 \times 10^{-4} L_\odot \left(\frac{g_{aee}}{10^{-13}}\right)^2 \left(\frac{T_c}{10^7\ \mathrm{K}}\right)^4$$

~thermal spectrum at: $T_c \sim 1\ \mathrm{keV}$

surface temperature ~few eV

single electron degeneracy $(T_c/p_f)^2$ $(p_f \sim 0.5\ \mathrm{MeV})$

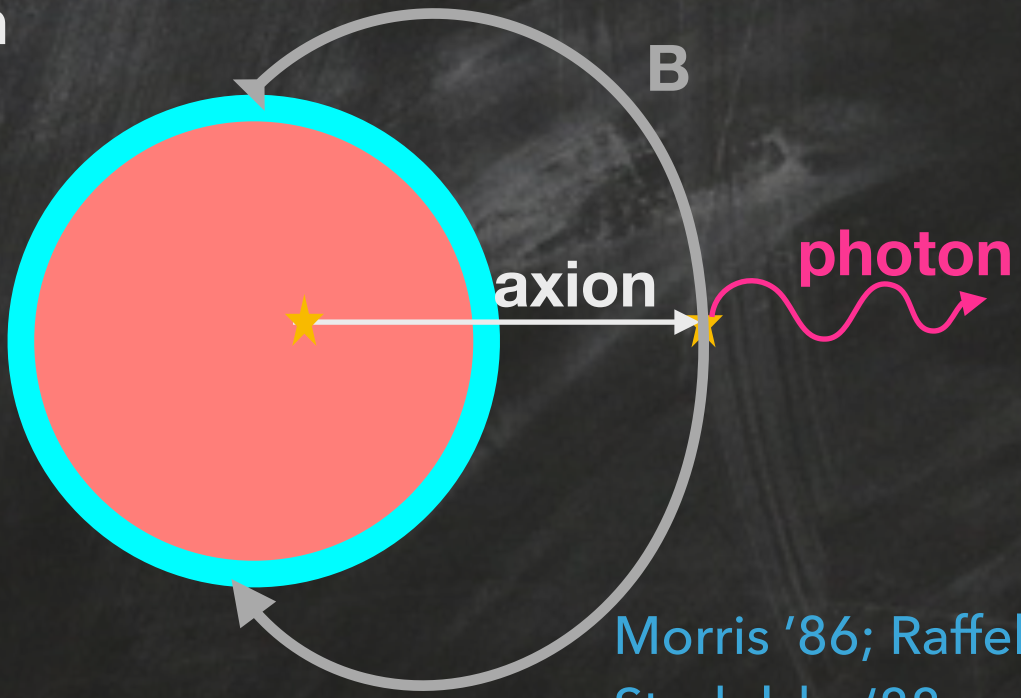
(additional complication: ionic correlation effects)

- Suppressed luminosity by factor ~few
- *ask after if interested in details

Axion-Photon Conversion in Dipole Field

Strong-field QED -> Euler Heisenberg Lagrangian

$$\mathcal{L}_{\rm EH} \supset \frac{\alpha_{\rm EM}^2}{90 m_e^4}\left[(F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right]$$



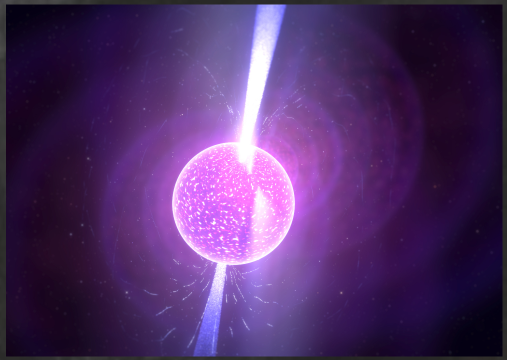
Axion-photon mixing:

$$\left[\omega + \begin{pmatrix} \Delta_{\rm EH} & \Delta_B \\ \Delta_B & \Delta_a \end{pmatrix} - i\partial_r\right]\begin{pmatrix} A_{||} \\ a \end{pmatrix} = 0$$

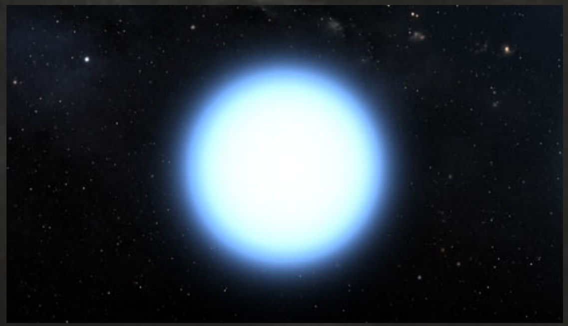
Morris '86; Raffelt & Stodolsky '88

$$p_{a\to\gamma} \sim 10^{-4}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ {\rm GeV}^{-1}}\right)^2\left(\frac{1\ {\rm keV}}{\omega}\right)^{4/5}\left(\frac{B_0}{10^{13}\ {\rm G}}\right)^{2/5}\left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{6/5}$$

typical NS: $p_{a\to\gamma} \sim 10^{-4}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ {\rm GeV}^{-1}}\right)^2$



typical MWD: $p_{a\to\gamma} \sim 5\times 10^{-3}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ {\rm GeV}^{-1}}\right)^2$



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3. X-ray data: white dwarfs data (RE J0317-853)

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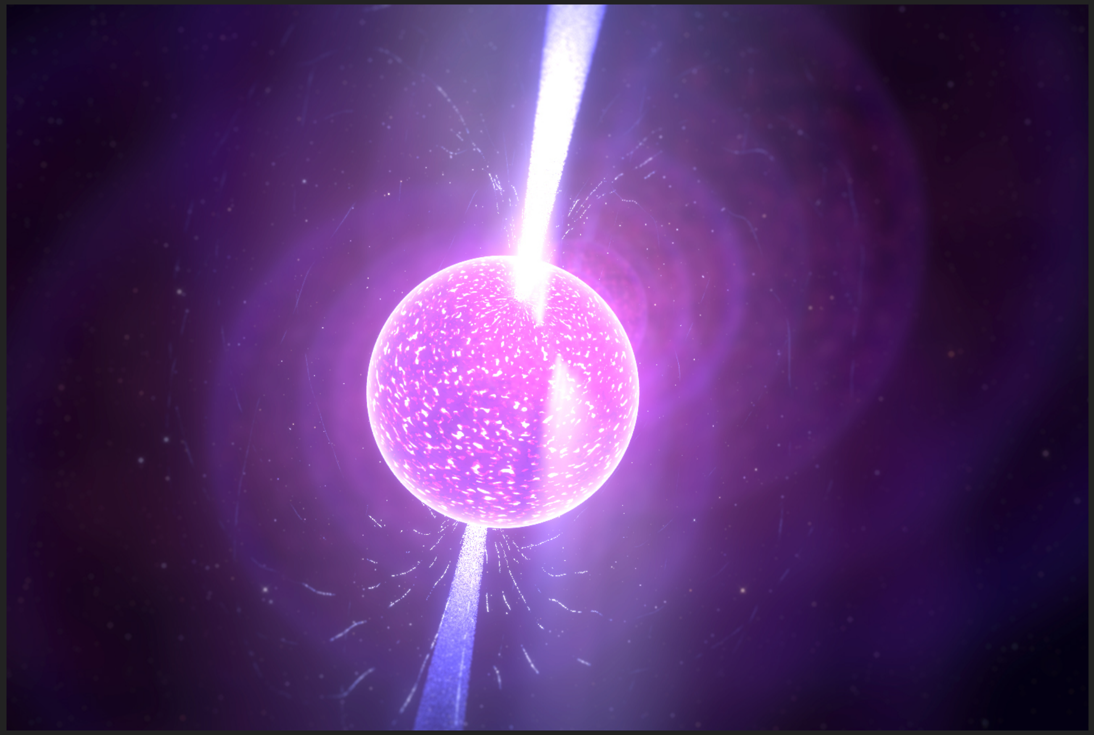
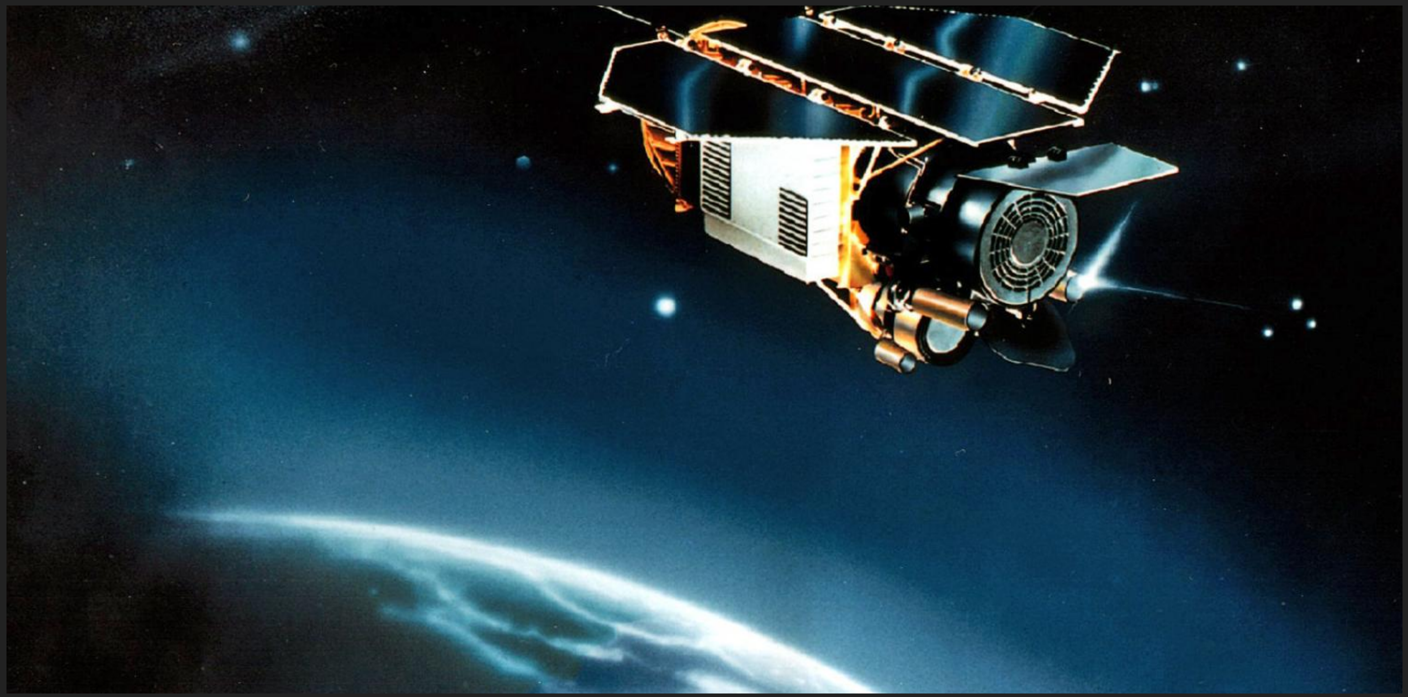
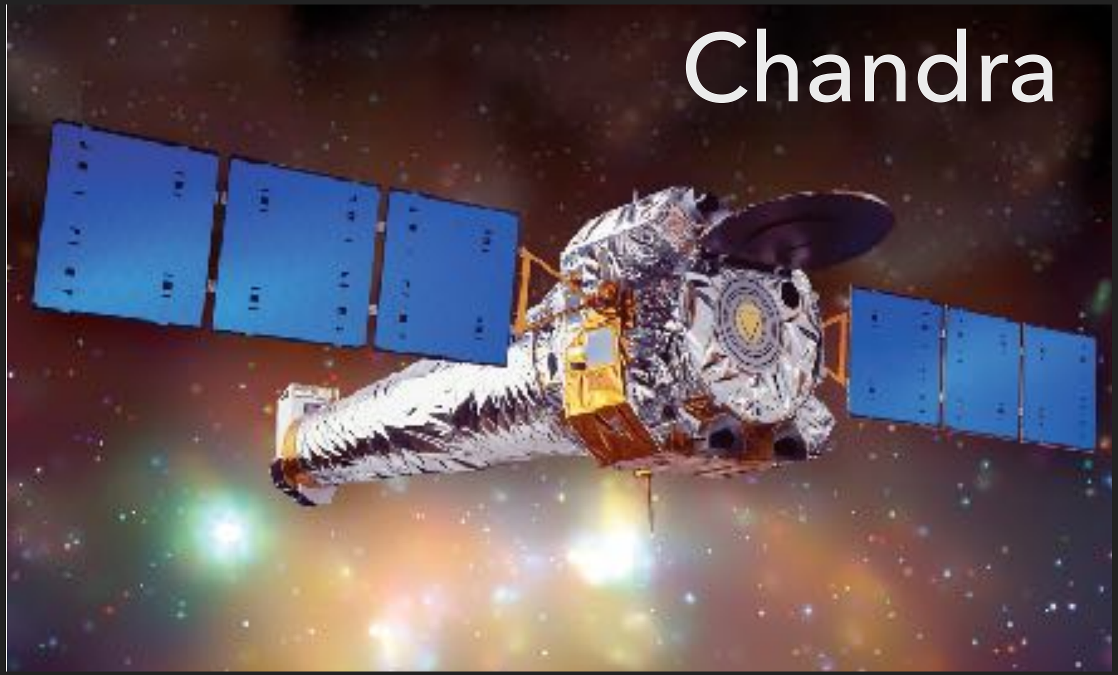
M7 hard X-ray excess





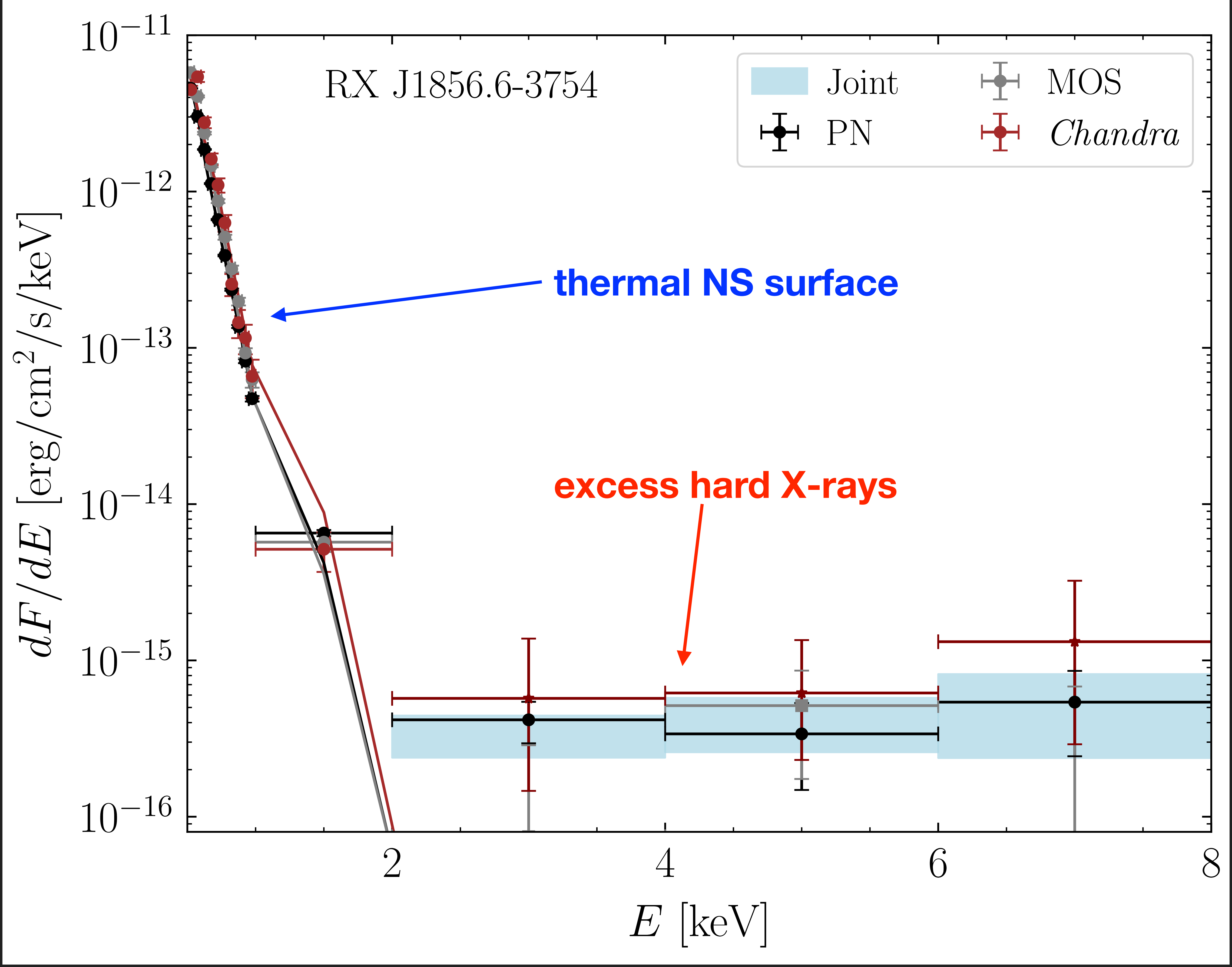
- 7 NSs between ~100 - 500 pc from Sun
- Discovered with ROSAT full-sky X-ray survey
- Surface: B ~ 10^{13} G (spindown)
- T_{surf} ~ 100 eV
- Non previous detection of non-thermal emission
- All old ~0.1 - 1 Myr and isolated

M7 hard X-ray excess

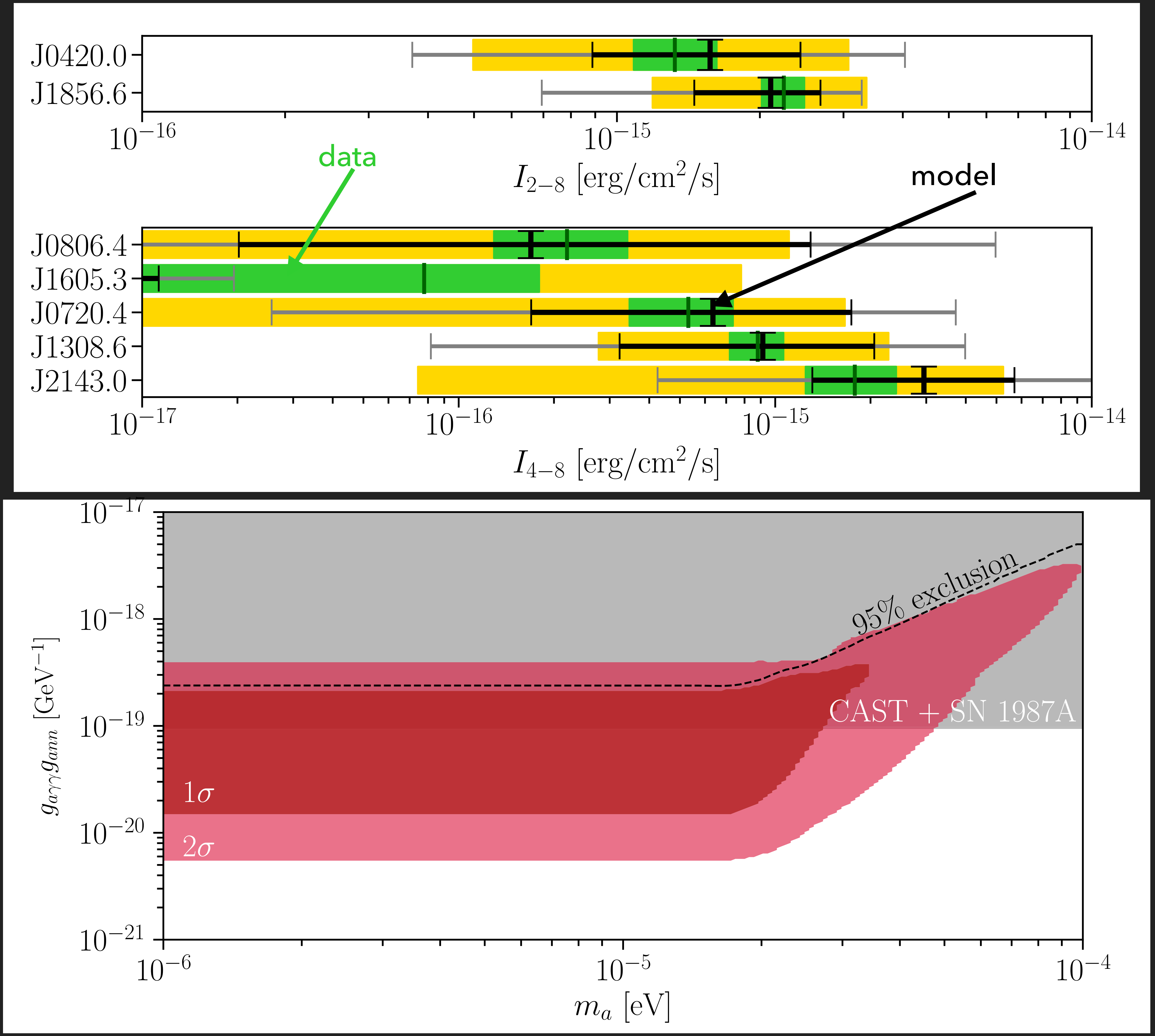


- data from ~2 - 8 keV
- XMM-Newton (PN and MOS)
    - ~50′′ angular resolution
- Chandra
    - ~1′′ angular resolution

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



All M7 hard X-ray data



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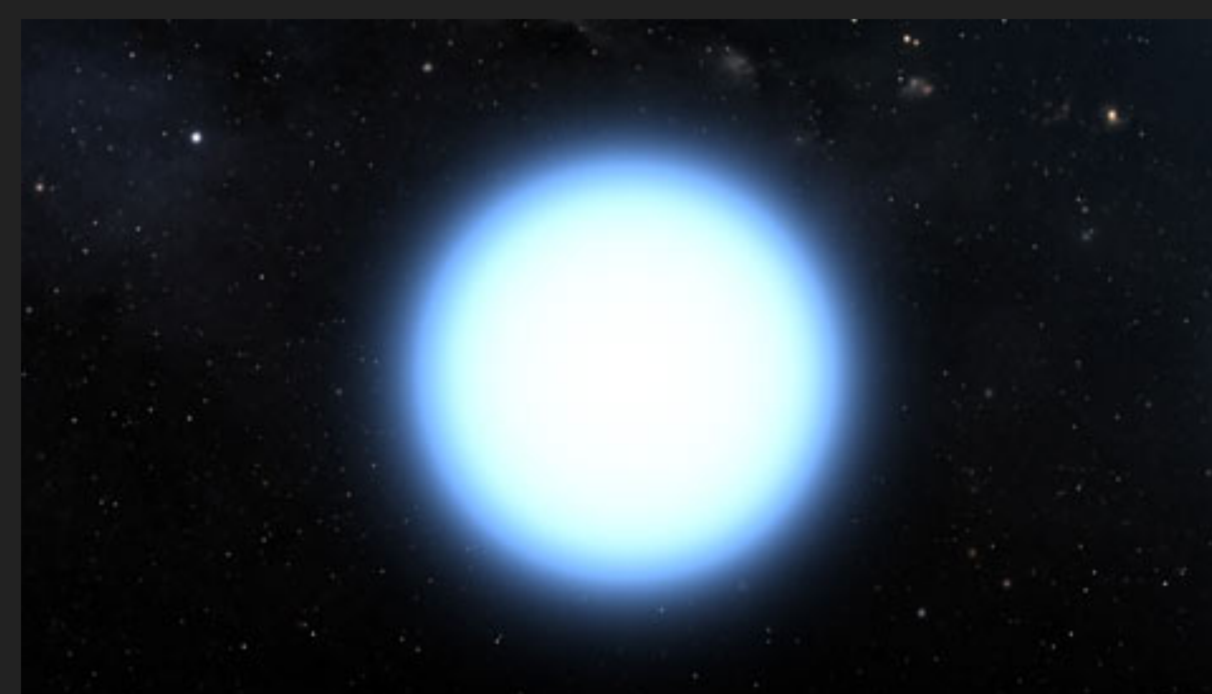
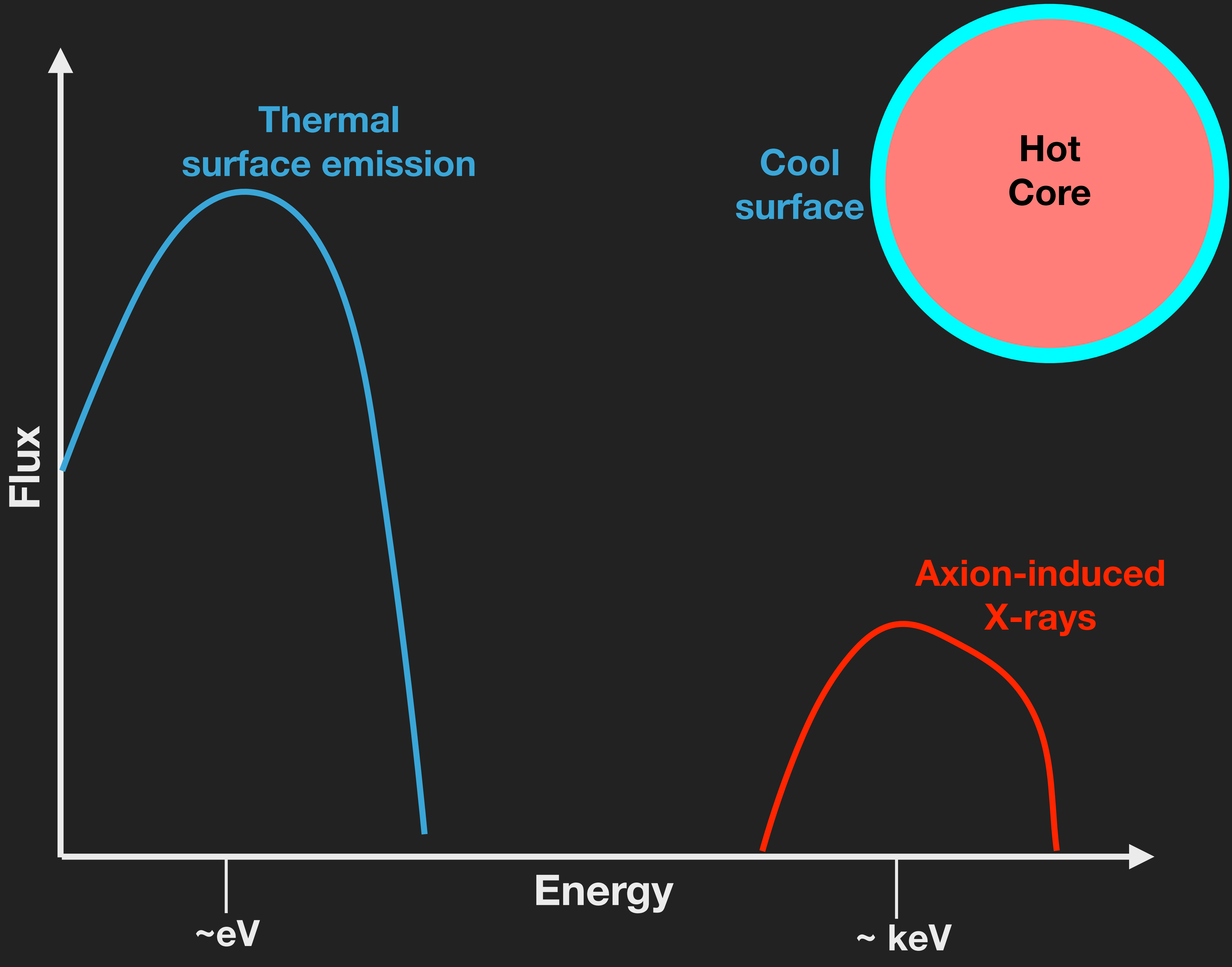
Fast forward to New Years 2021

*postponed during pandemic

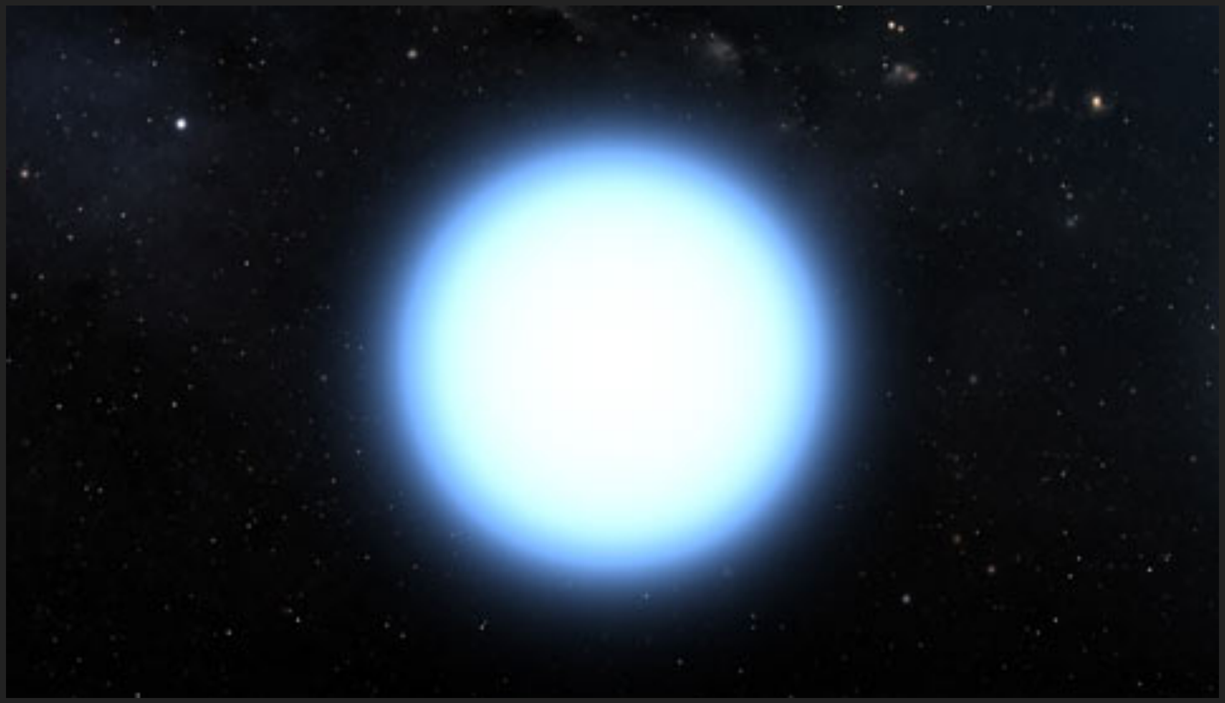
Our holiday present: long-awaited dedicated data from Chandra observation of magnetic white dwarf RE J0317-853



Magnetic white dwarfs are ultra-clean

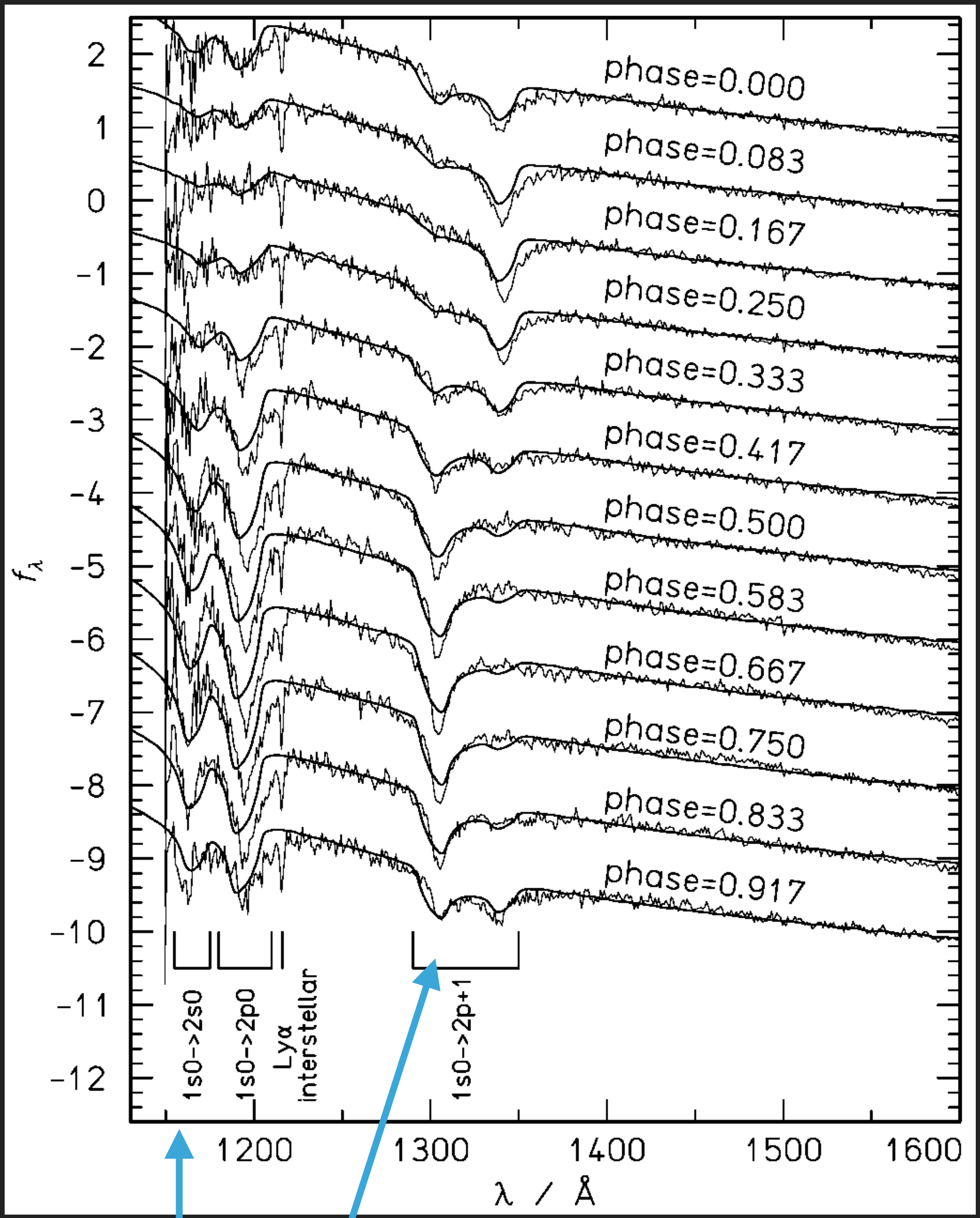


RE J0317-853 Facts

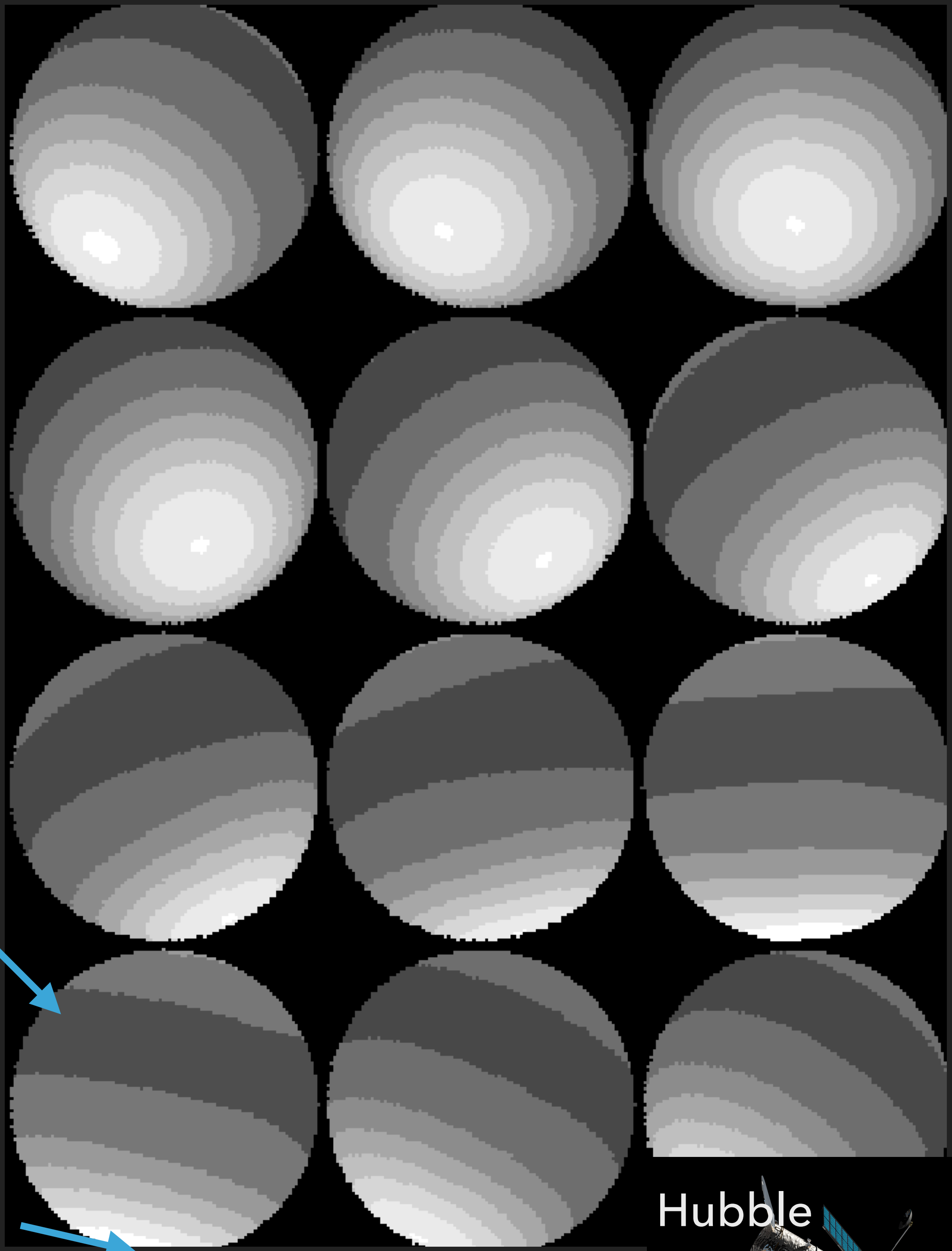


- "hottest" magnetic white dwarf (T_{surf} ~5 eV) -> high core T
- ~29.38 pc (Gaia parallax)
- Surface: B ~ 5×10^8 G (Zeeman splitting and circular pol.)
- T_{core} = 1.39 +- 0.01 keV (dedicated cooling sequences compared to Gaia luminosity data, ask after if interested)
- No previous dedicated X-ray observations

RE J0317-853 Magnetic Field



Zeeman splitting



*consistent B-field from optical circular polarization

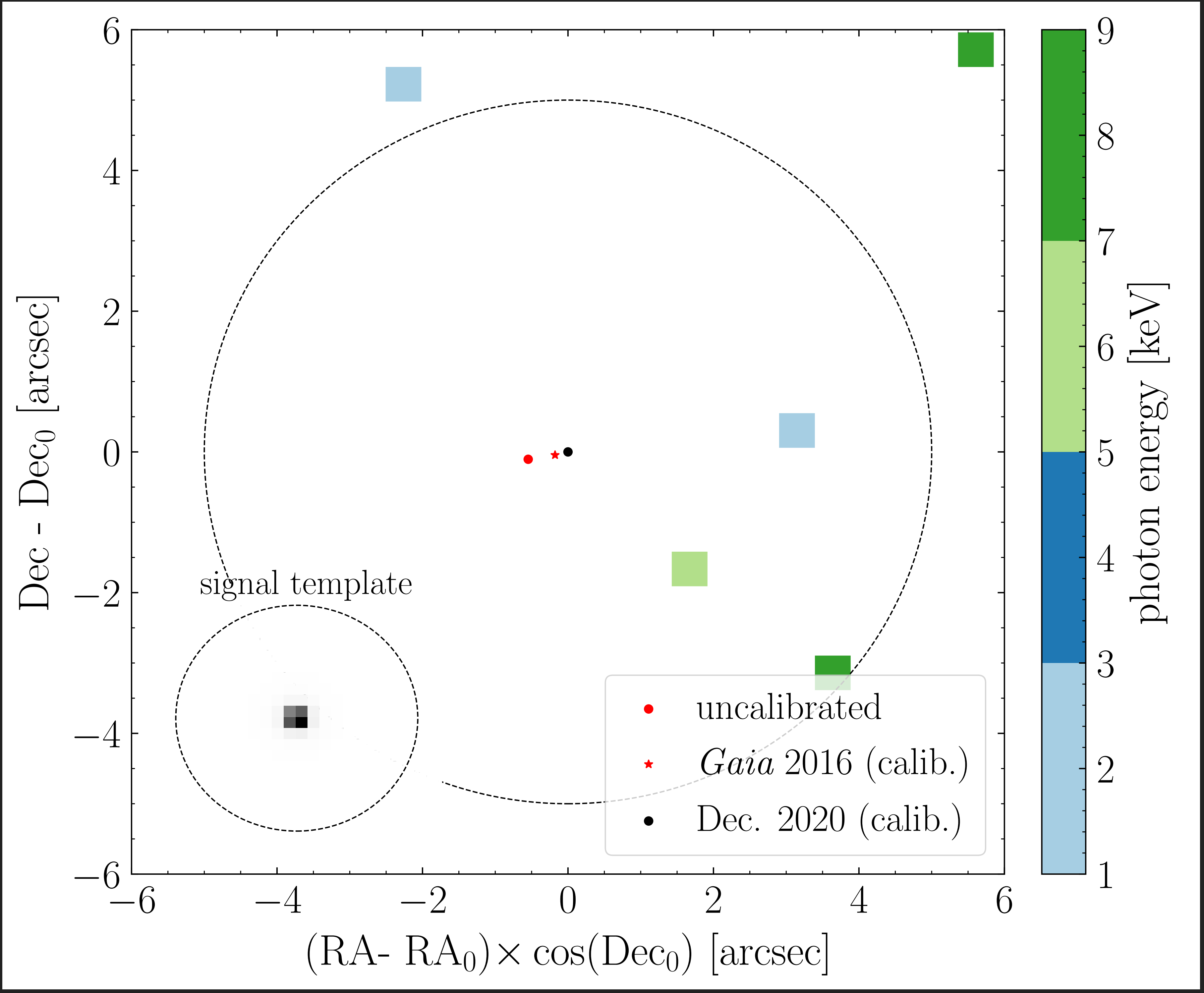
We assume B_0=200 MG dipole (conservative w.r.t. more realistic models, but dependence small)

Burleigh et al., ApJL 1999

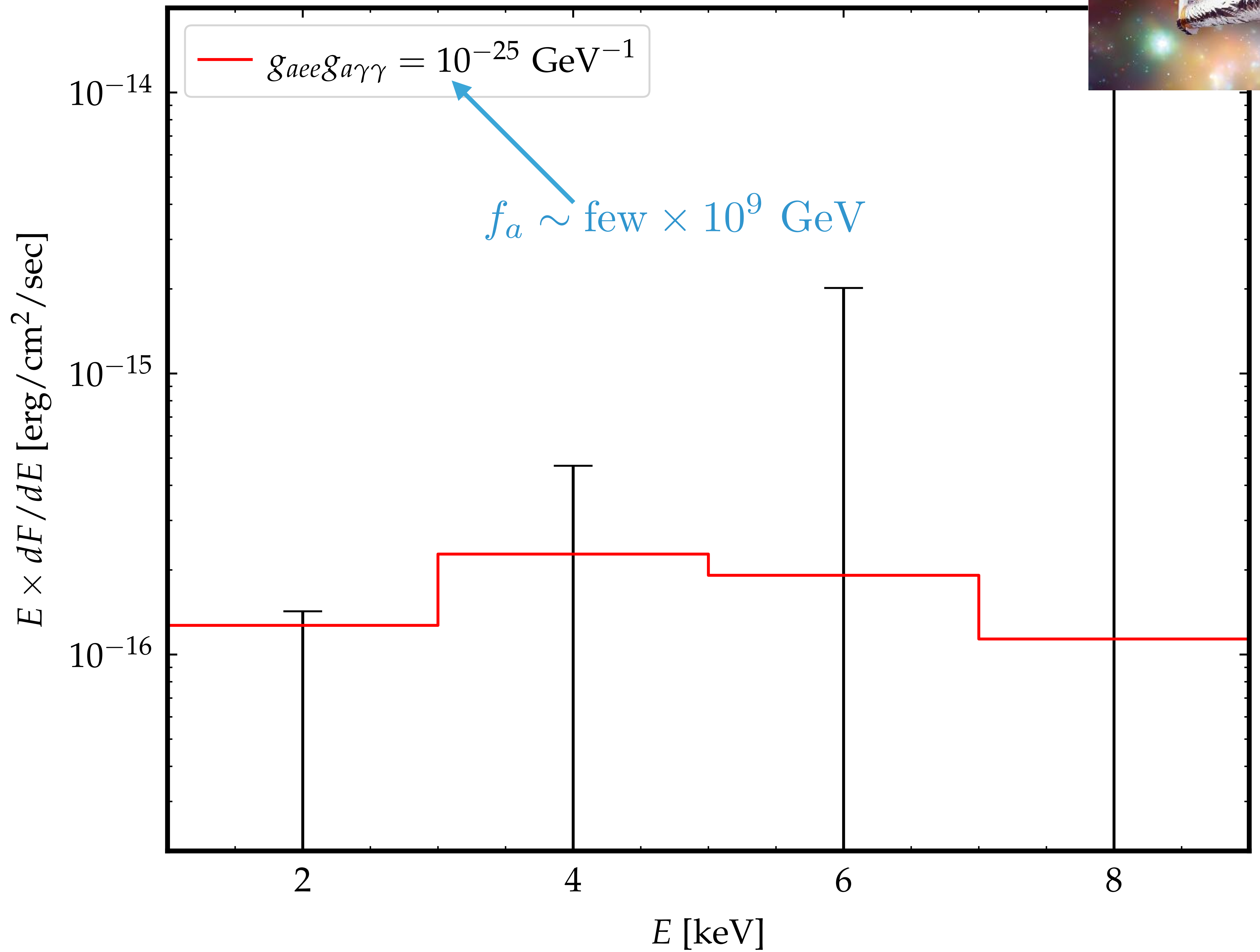
RE J0317-853 Chandra X-Ray Data

- ~40 ks with ACIS-I, no grating (18-12-2020)
- 1-9 keV

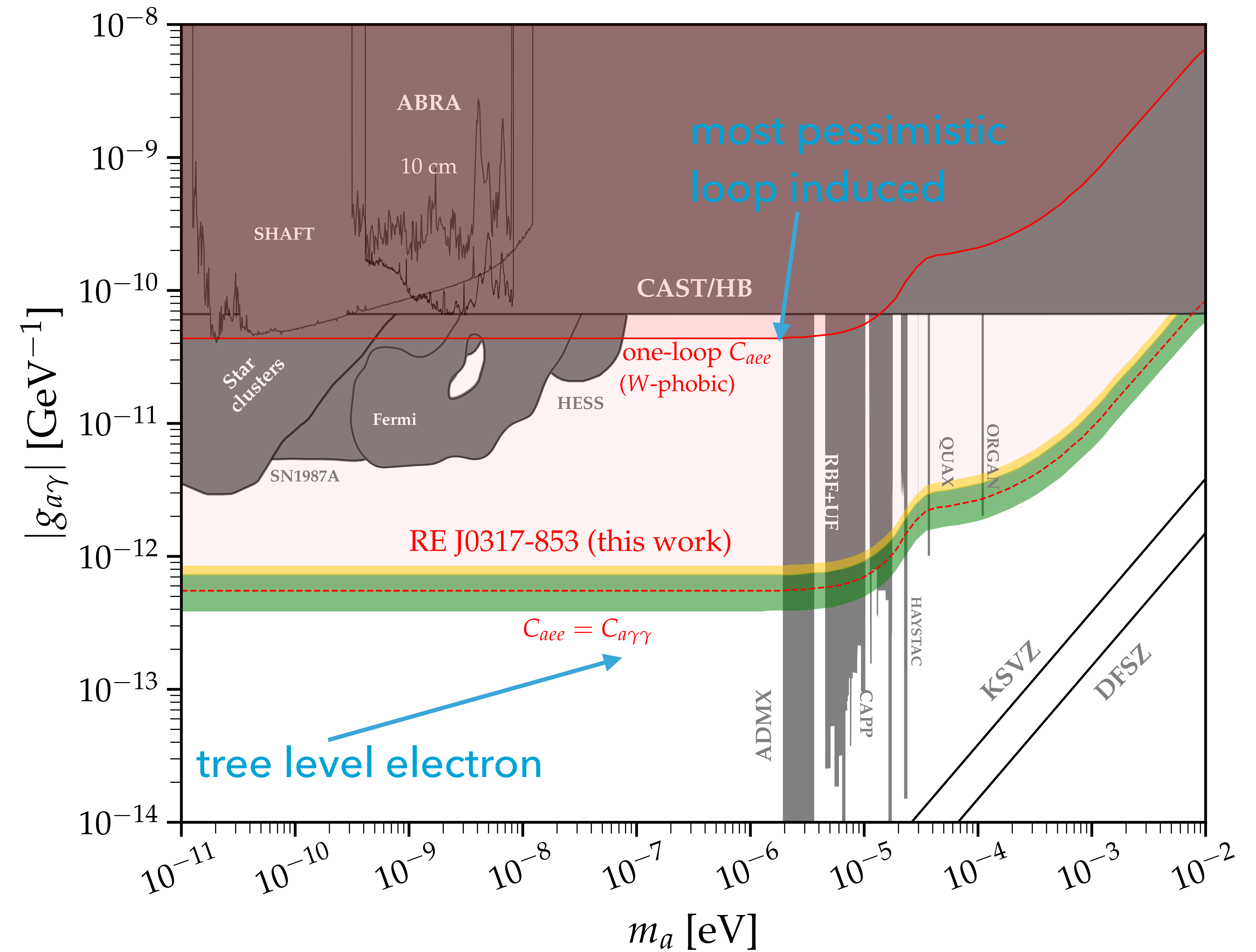
We saw absolutely nothing! :-(



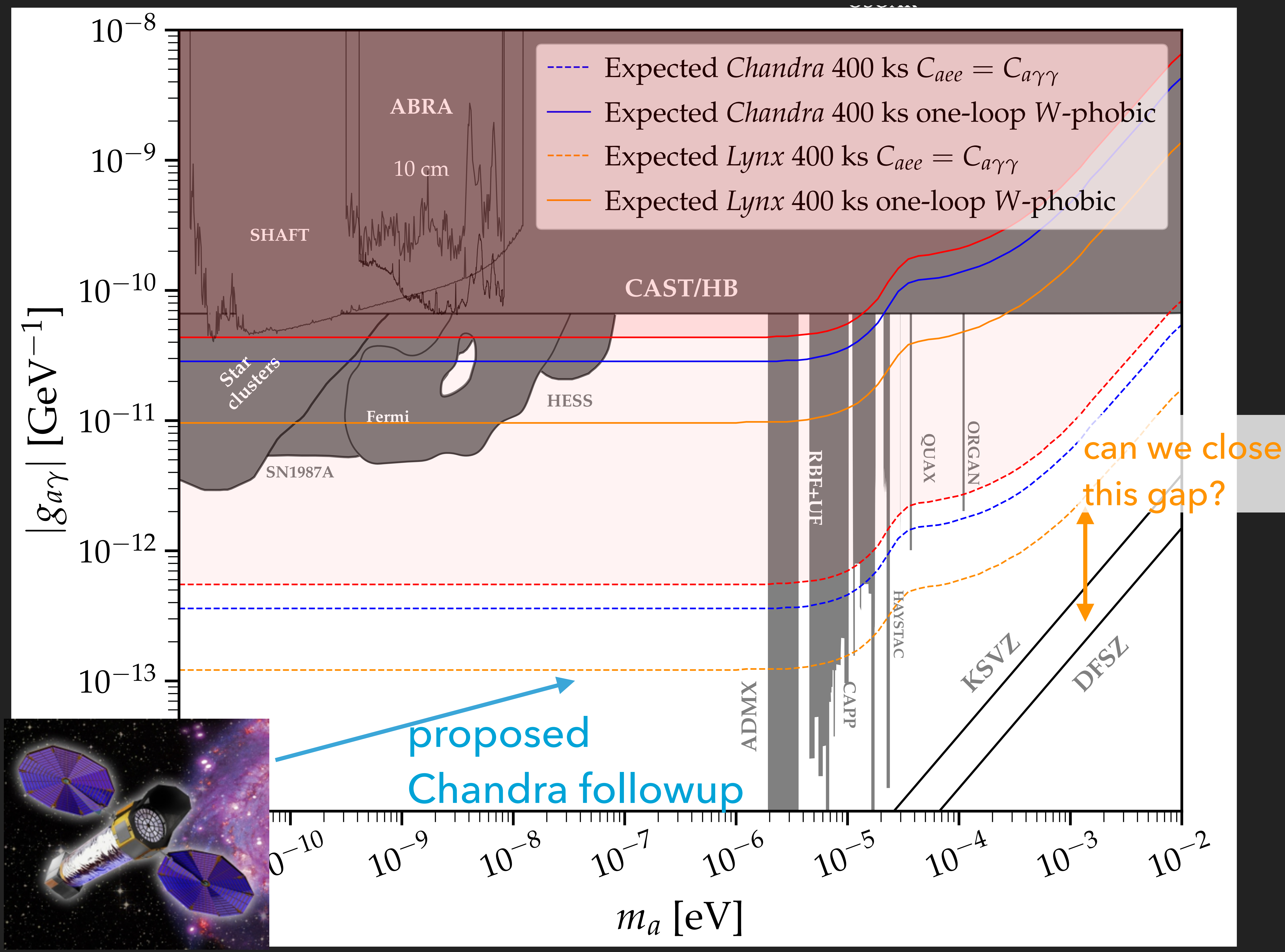
RE J0317-853 Chandra X-Ray Data



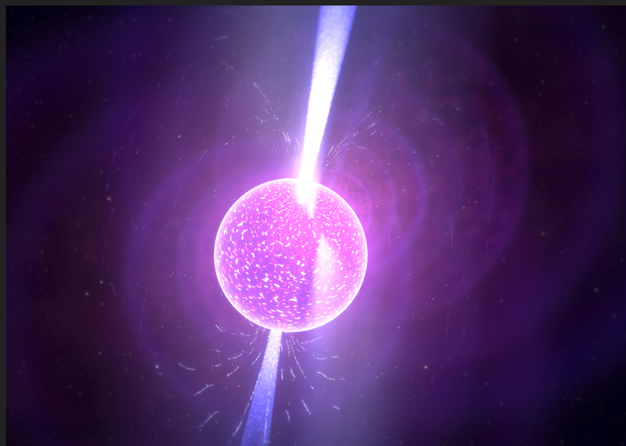
Results in terms of axion-photon coupling

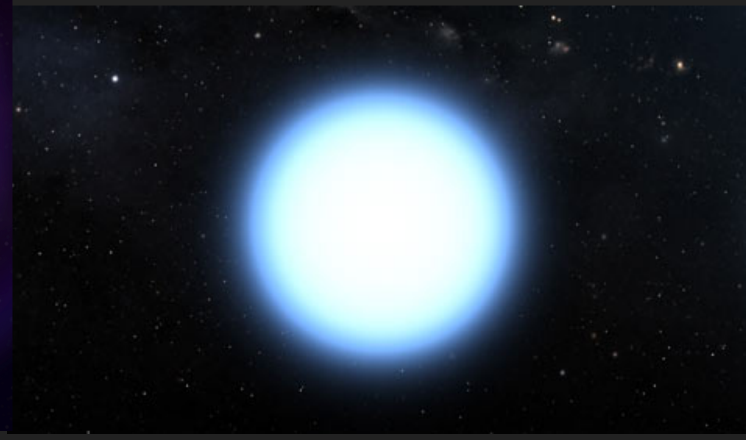


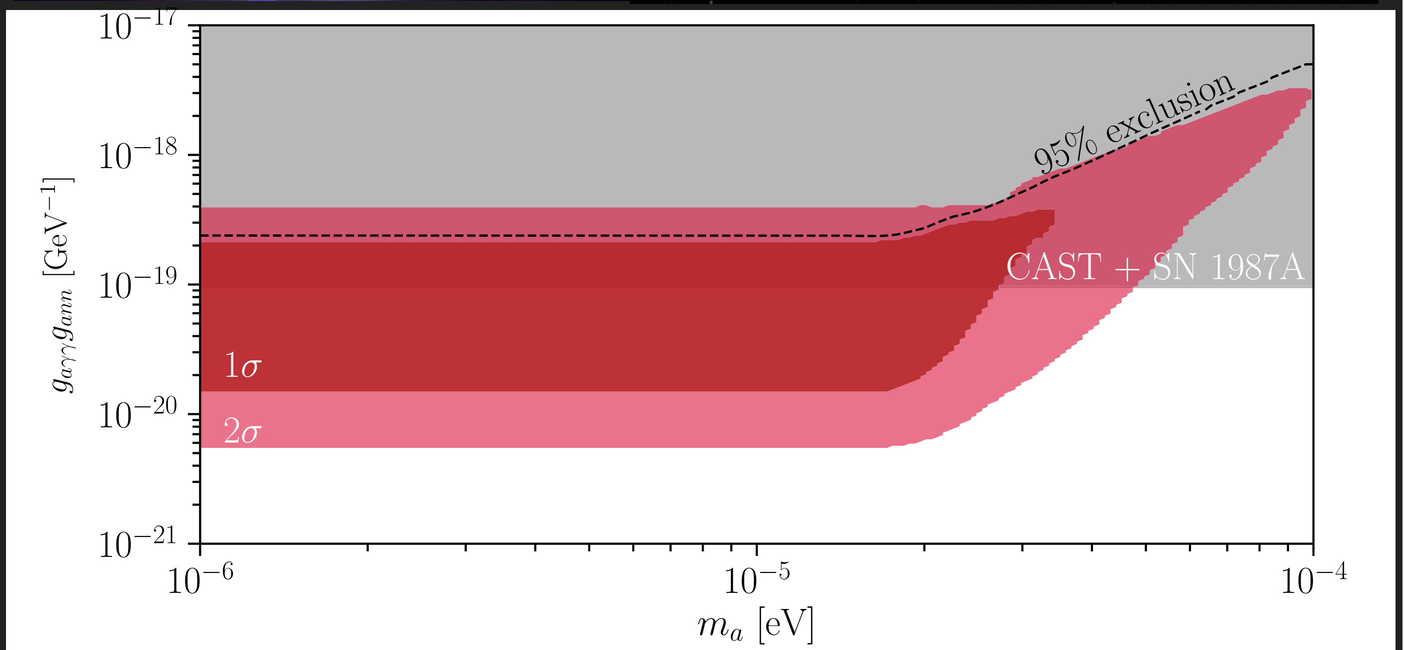
Future Searches Towards RE J0317-853

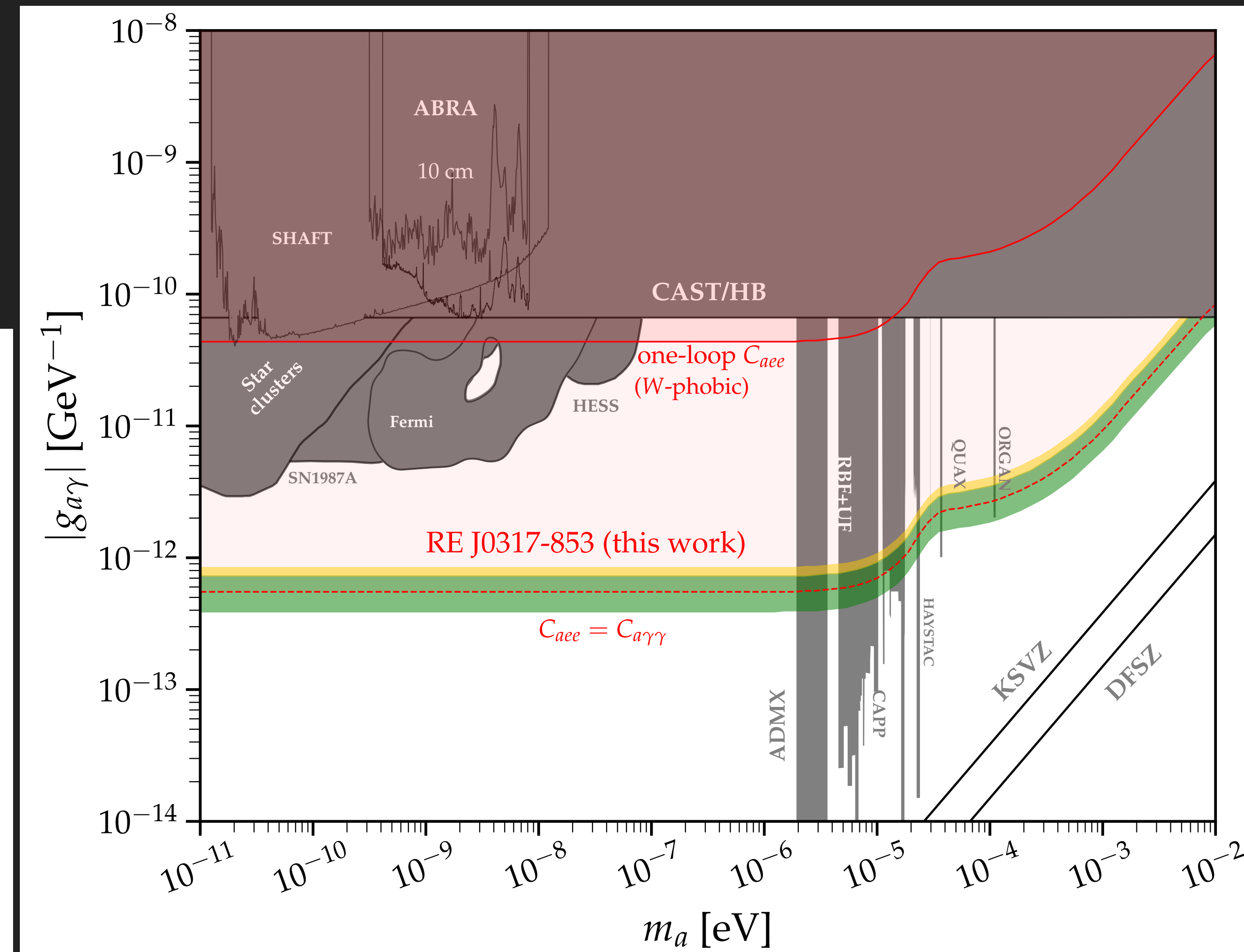


M7 Excess in light of RE J0317-853









need electrophobic / nucleophilic axion

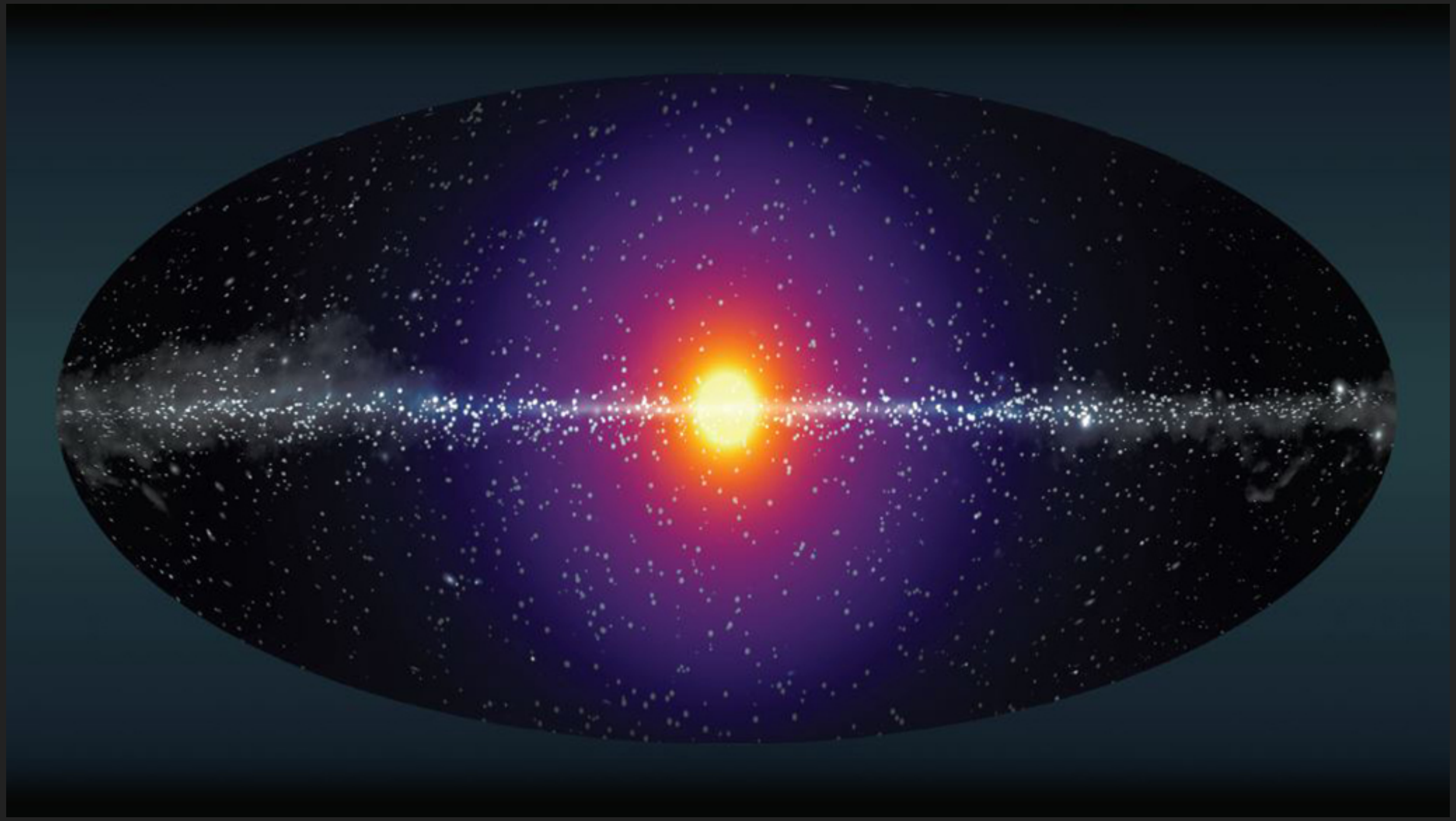
$$\frac{C_{aee}}{C_{aNN}} \lesssim 0.1$$

← not most generic expectation for ALP!

Question: Can alt. processes dominate axion rate in NSs? In progress

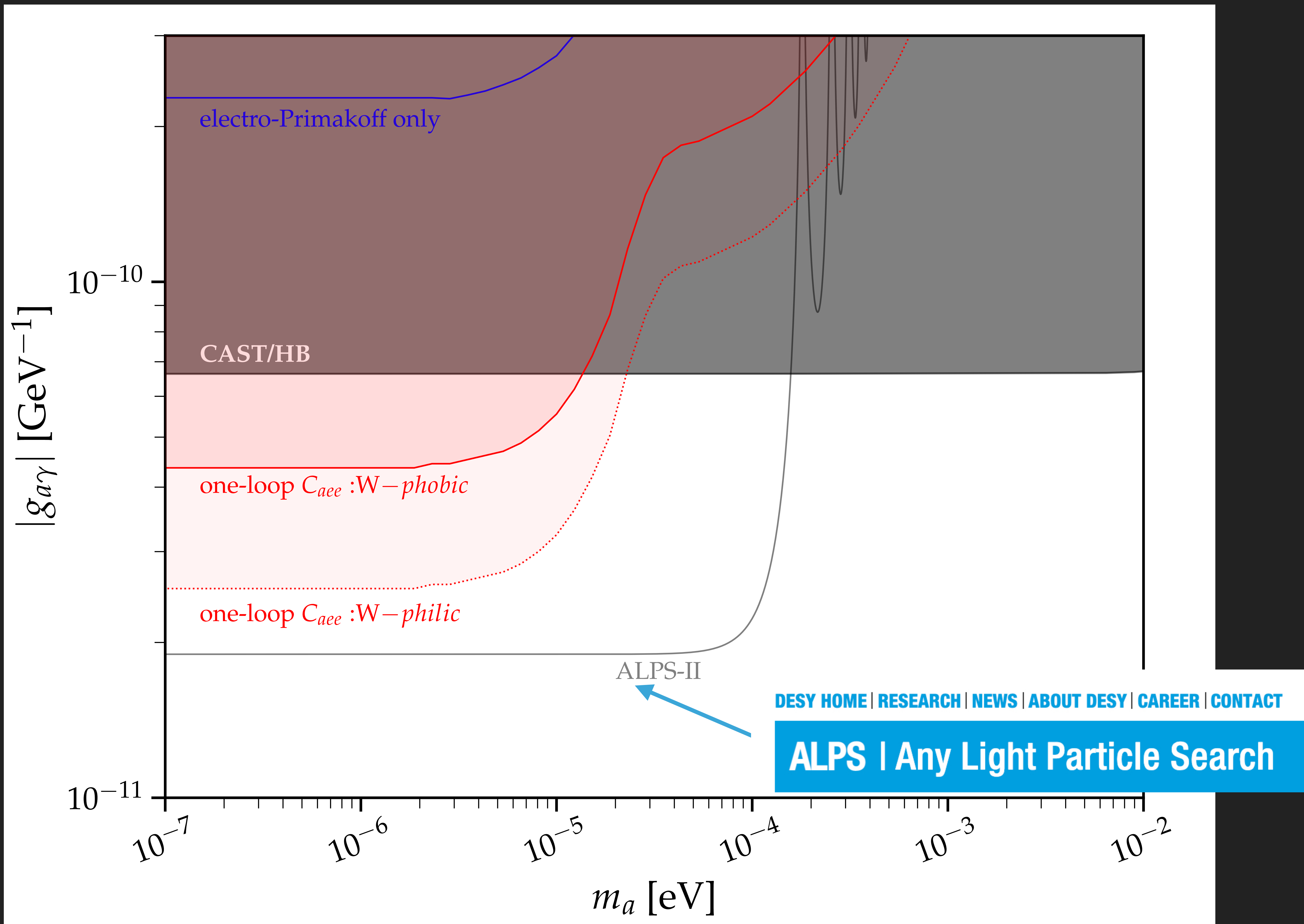
1. muon/proton cyclotron off of internal B-field
2. pion/kaon condensate production? quark-gluon plasma prod?

Questions?

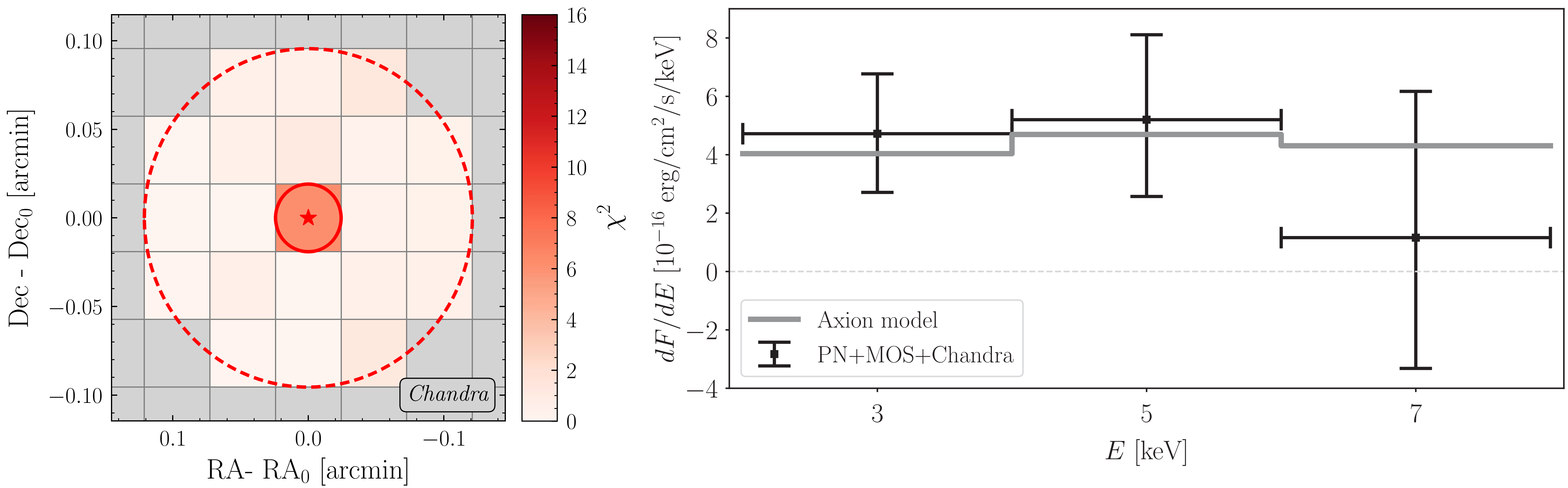


Backup Slides

One-loop axion-photon coupling

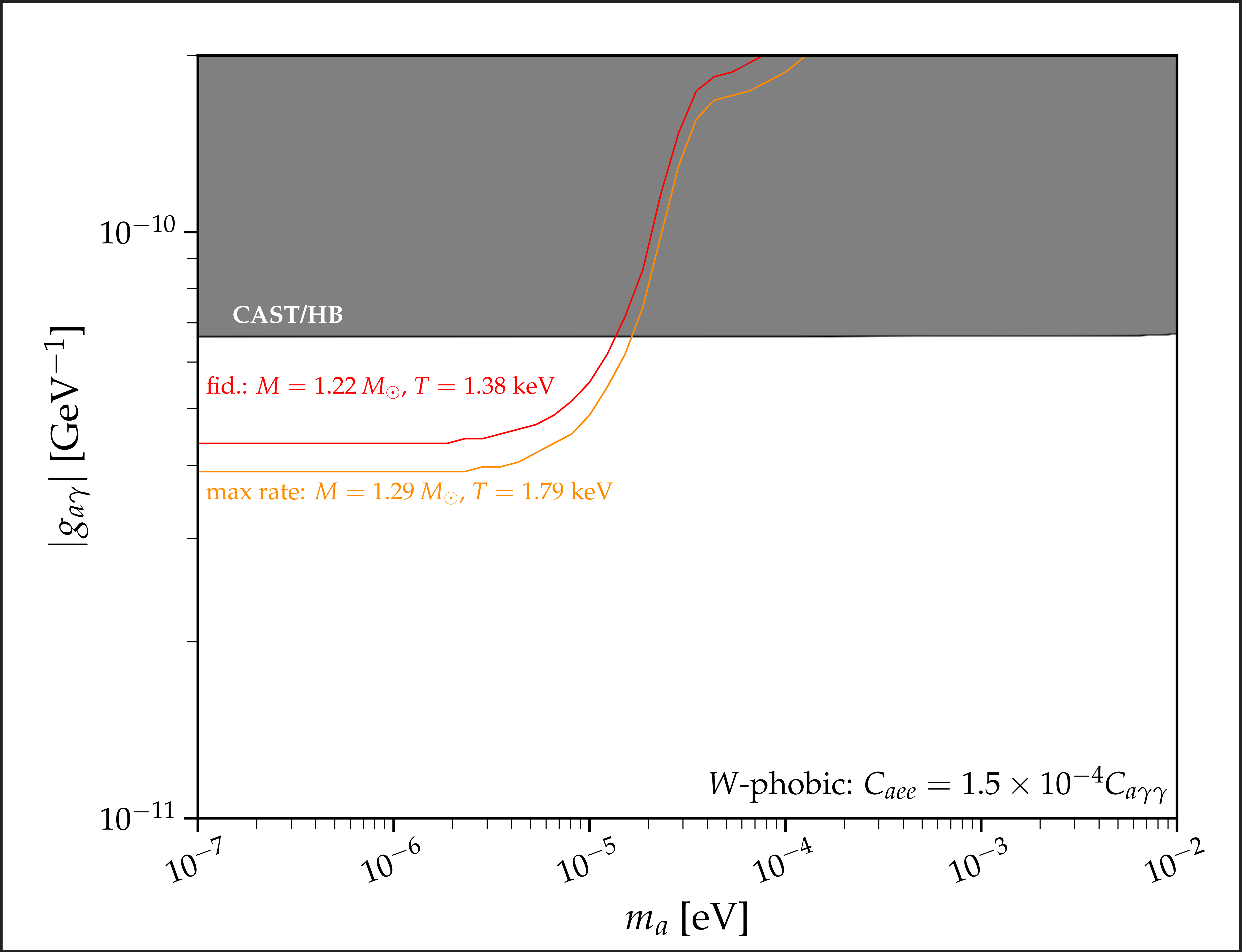


Hard X-ray excess from RX J1856.6-3754

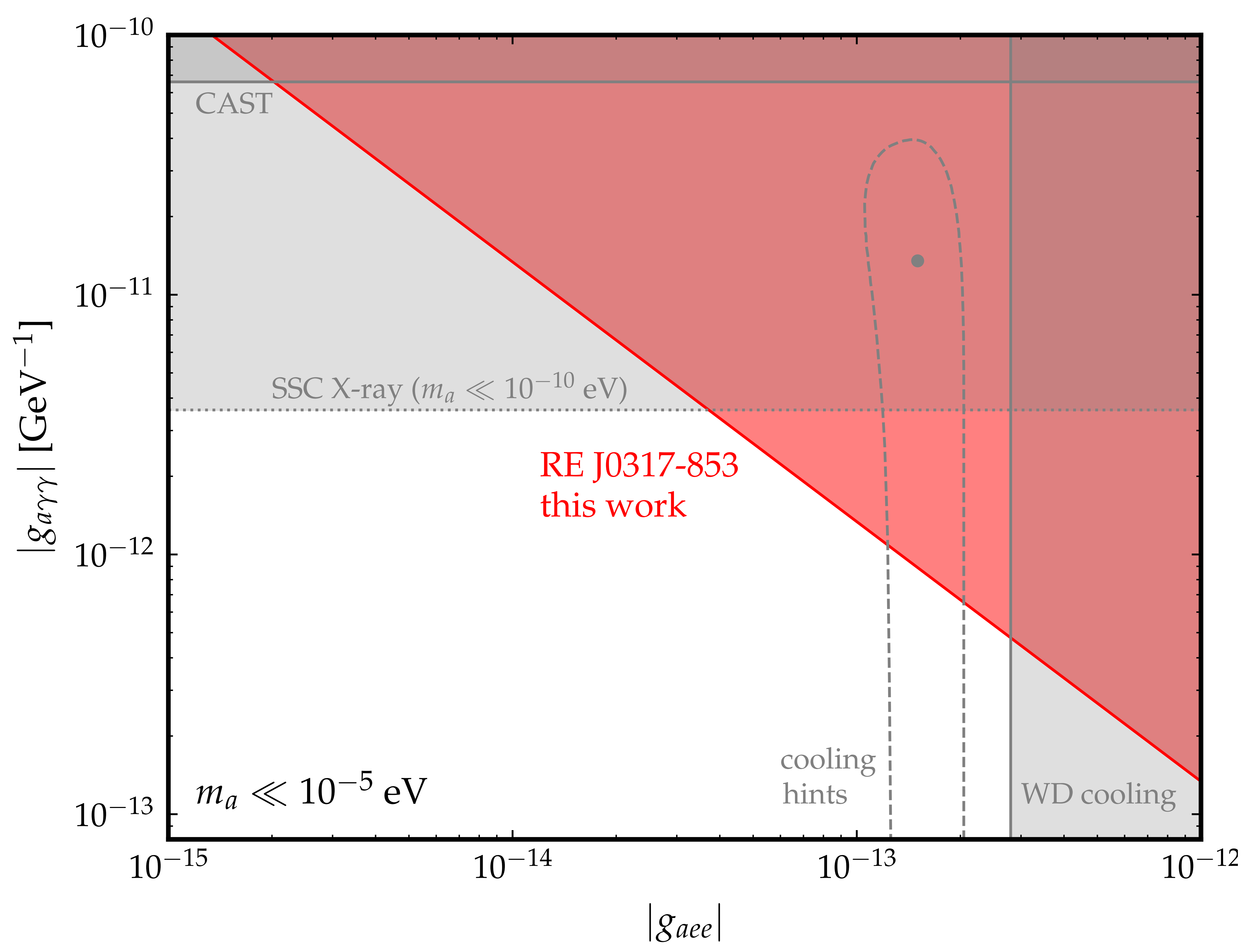


- No obvious astrophysical explanation

Stellar modeling systematics

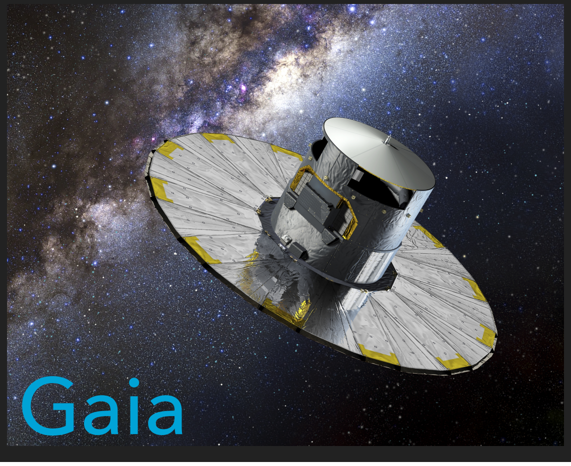


$|g_{aee} g_{a\gamma\gamma}| < 1.3 \times 10^{-25}\ \mathrm{GeV}^{-1}$ at 95% C.L. (low mass)



RE J0317-853 Core Temperature/Composition

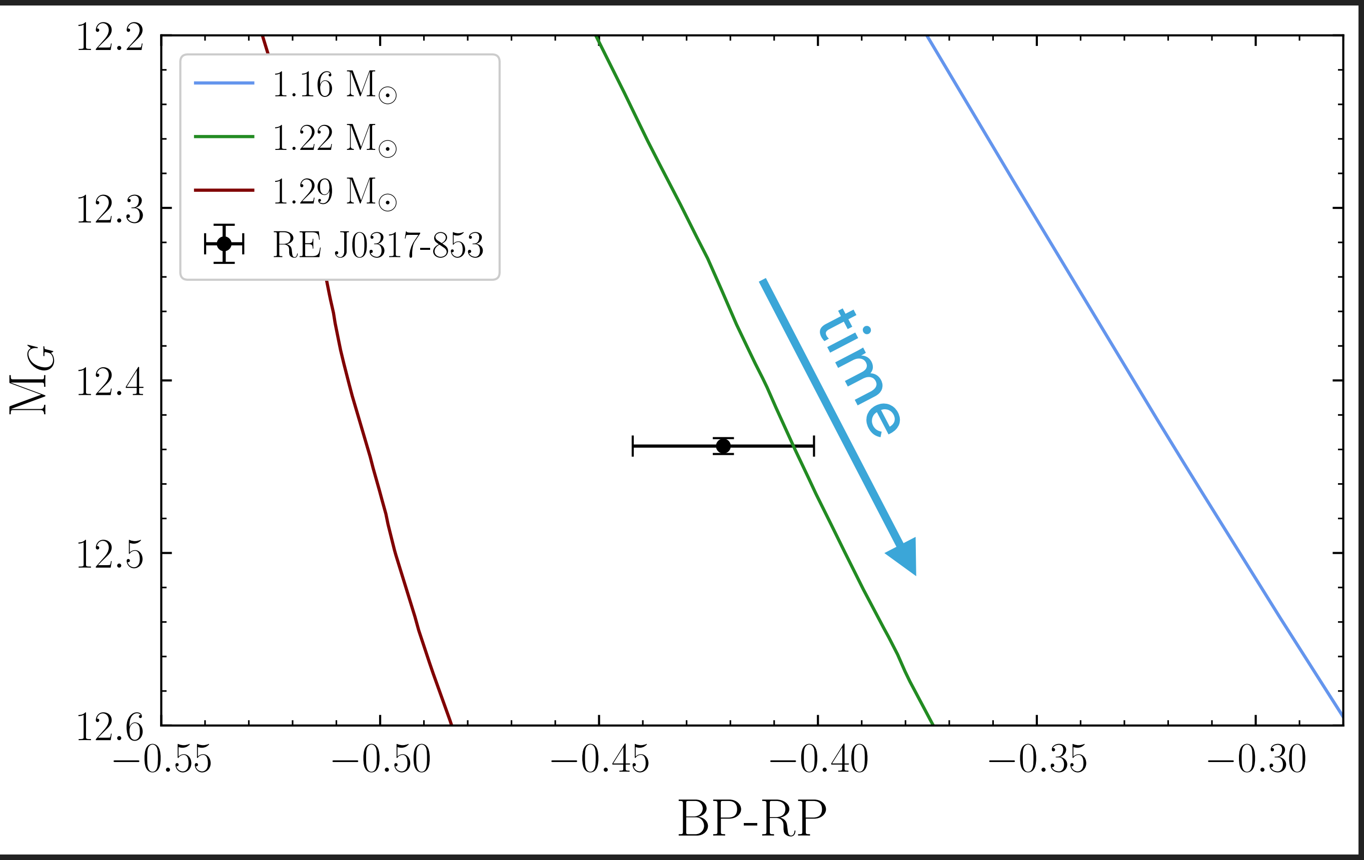
- Use Gaia measured Color (BP - RP) and Magnitude (M_G)
- Compare to dedicated WD cooling sequences that predict Gaia colors/magnitudes (Camissasa et al., A&A 2019)
- Combine with own dedicated MESA simulations for composition profiles

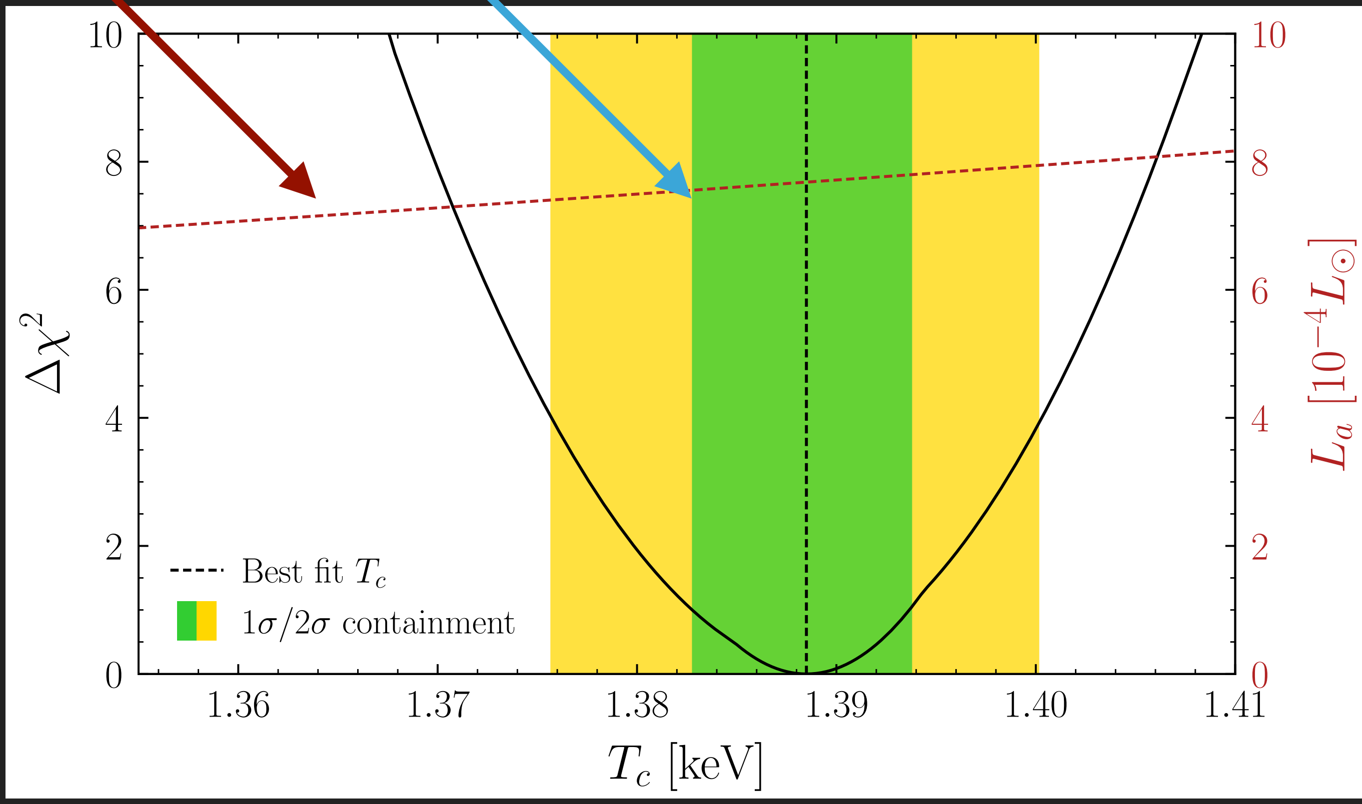


*consistent T_c base on binary companion age only + cooling theory

axion lum.

fiducial T_c





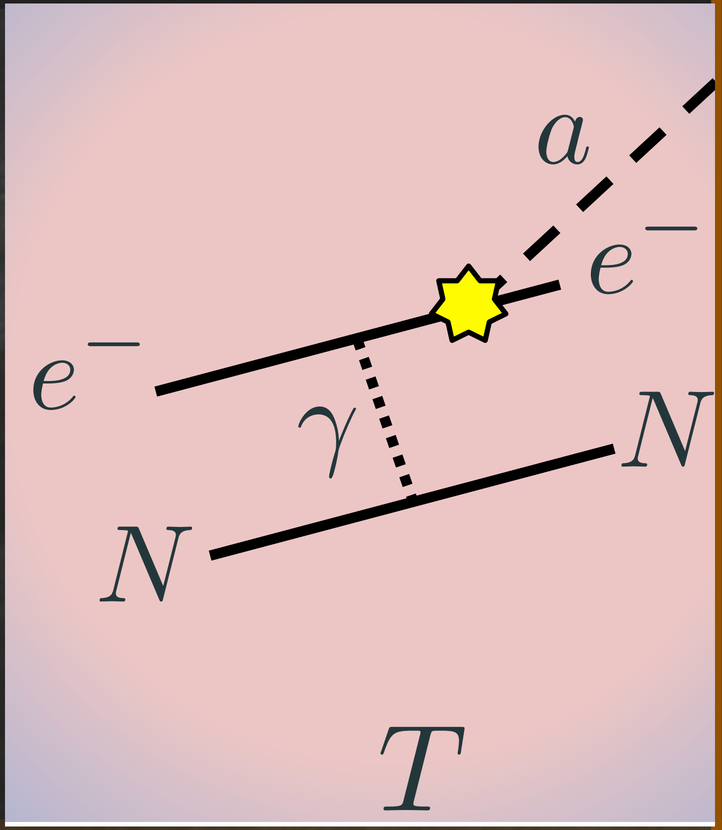
Axions Production in White Dwarf Cores from Brem.

Axion Luminosity:

$$L_a \approx 2 \times 10^{-4} L_\odot \left(\frac{g_{aee}}{10^{-13}}\right)^2 \left(\frac{T_c}{10^7\ \mathrm{K}}\right)^4$$

~thermal spectrum at: $T_c \sim 1\ \mathrm{keV}$

surface temperature ~few eV



single electron degeneracy $(T_c/p_f)^2$ $(p_f \sim 0.5\ \mathrm{MeV})$

(additional complication: ionic correlation effects)

Nakagawa, Kohyama, Itoh; Raffelt (1980's)

$$\frac{d\epsilon_a}{d\omega} = \frac{\alpha_{\mathrm{EM}}^2 g_{aee}^2}{4\pi^3 m_e^3} \frac{\omega^3}{e^{\omega/T} - 1} \sum_s Z_s^2 n_s F_s$$

erg/cm³/s/keV

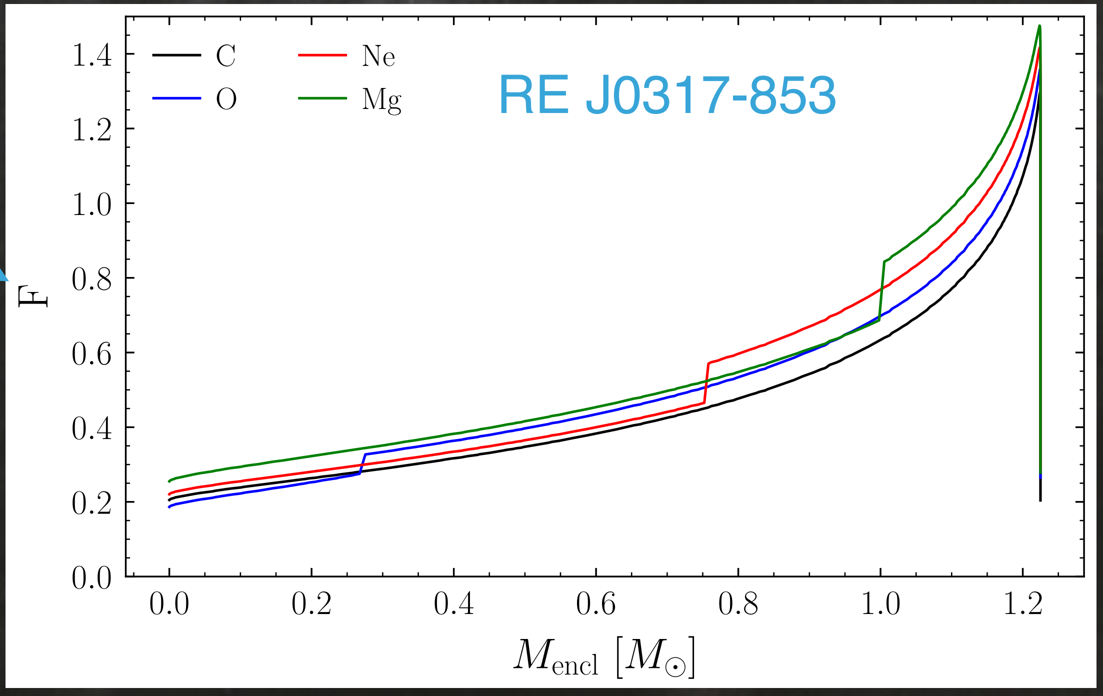
thermal spectrum

atomic number

nuclear species

number density

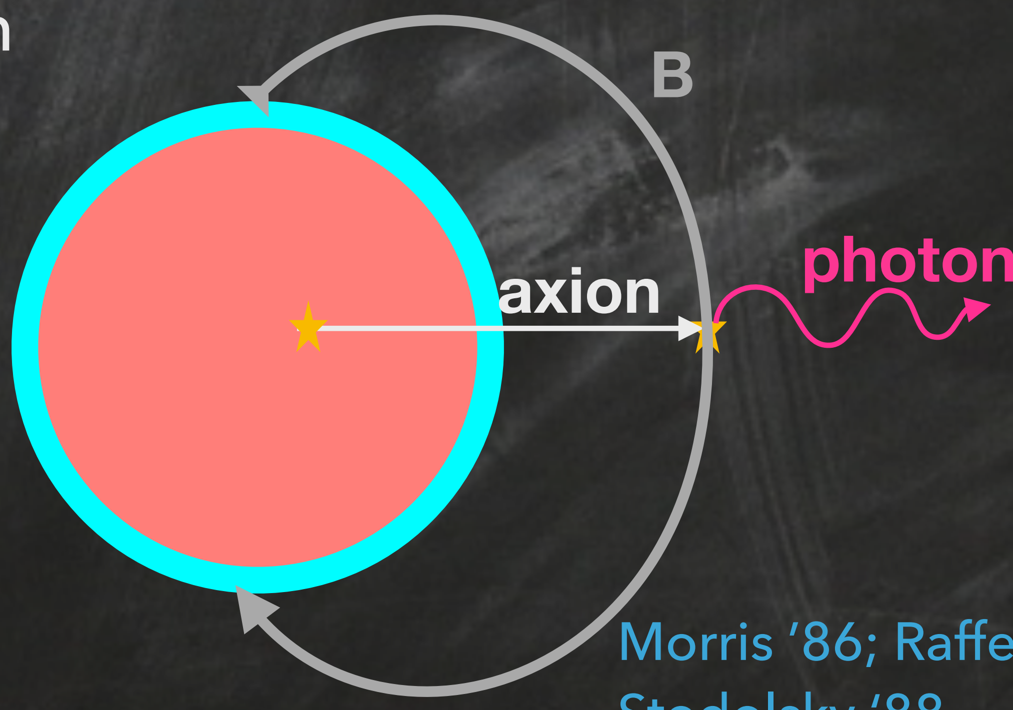
dimensionless ionic + Fermi



Axion-Photon Conversion in Dipole Field

Strong-field QED -> Euler Heisenberg Lagrangian

$$\mathcal{L}_{\rm EH} \supset \frac{\alpha_{\rm EM}^2}{90 m_e^4}\left[(F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right]$$



Morris '86; Raffelt & Stodolsky '88

Axion-photon mixing:

$$\left[\omega + \begin{pmatrix} \Delta_{\rm EH} & \Delta_B \\ \Delta_B & \Delta_a \end{pmatrix} - i\partial_r\right]\begin{pmatrix} A_{||} \\ a \end{pmatrix} = 0$$

$$\Delta_{\rm EH} \sim \omega \left(\frac{B}{B_C}\right)^2 \qquad \left(B_c = \frac{m_e^2}{e} \sim 4\times 10^{13}\ mG\right)$$

suppress mixing

$$\Delta_a \sim \frac{m_a^2}{\omega}$$

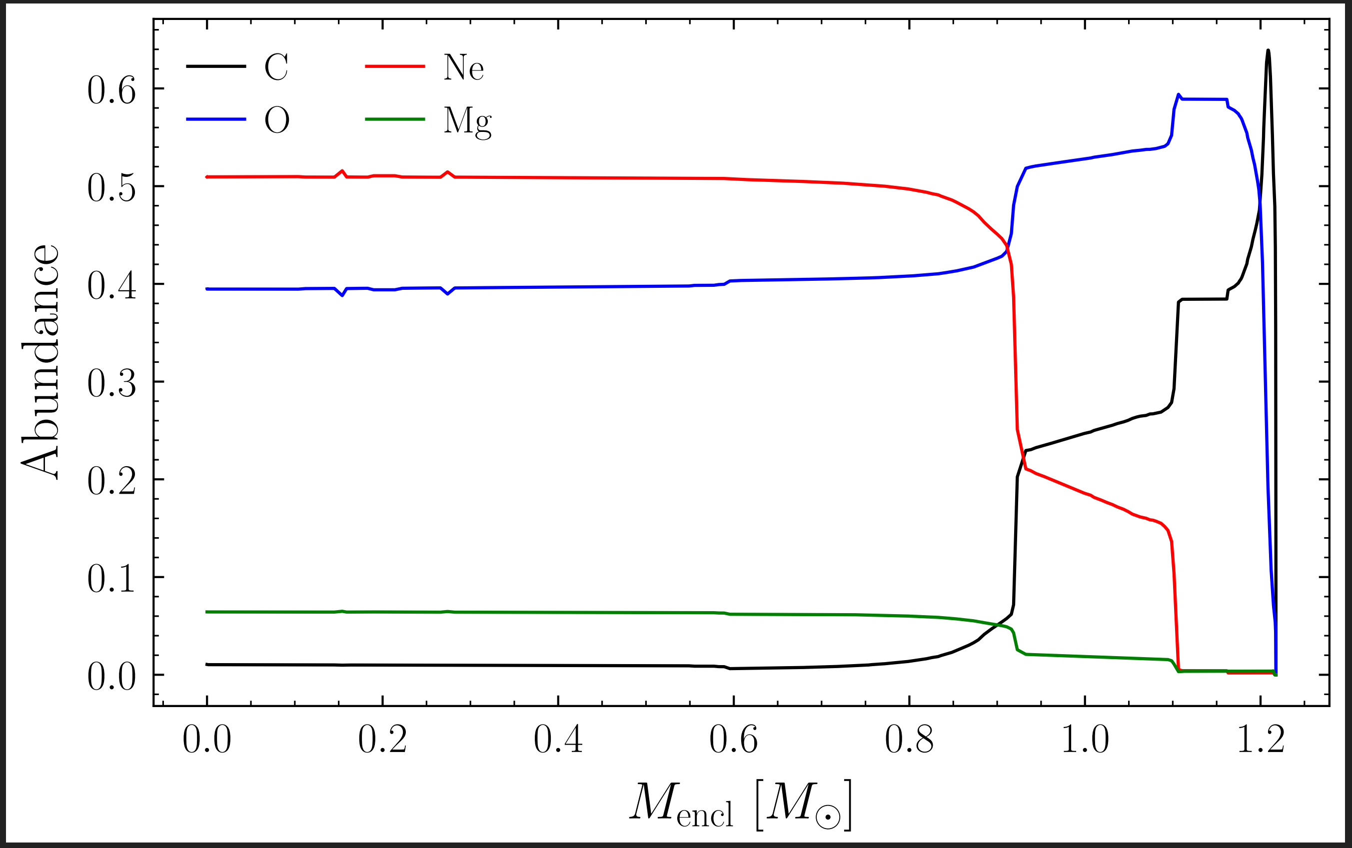
$$\Delta_B \sim g_{a\gamma\gamma} B$$

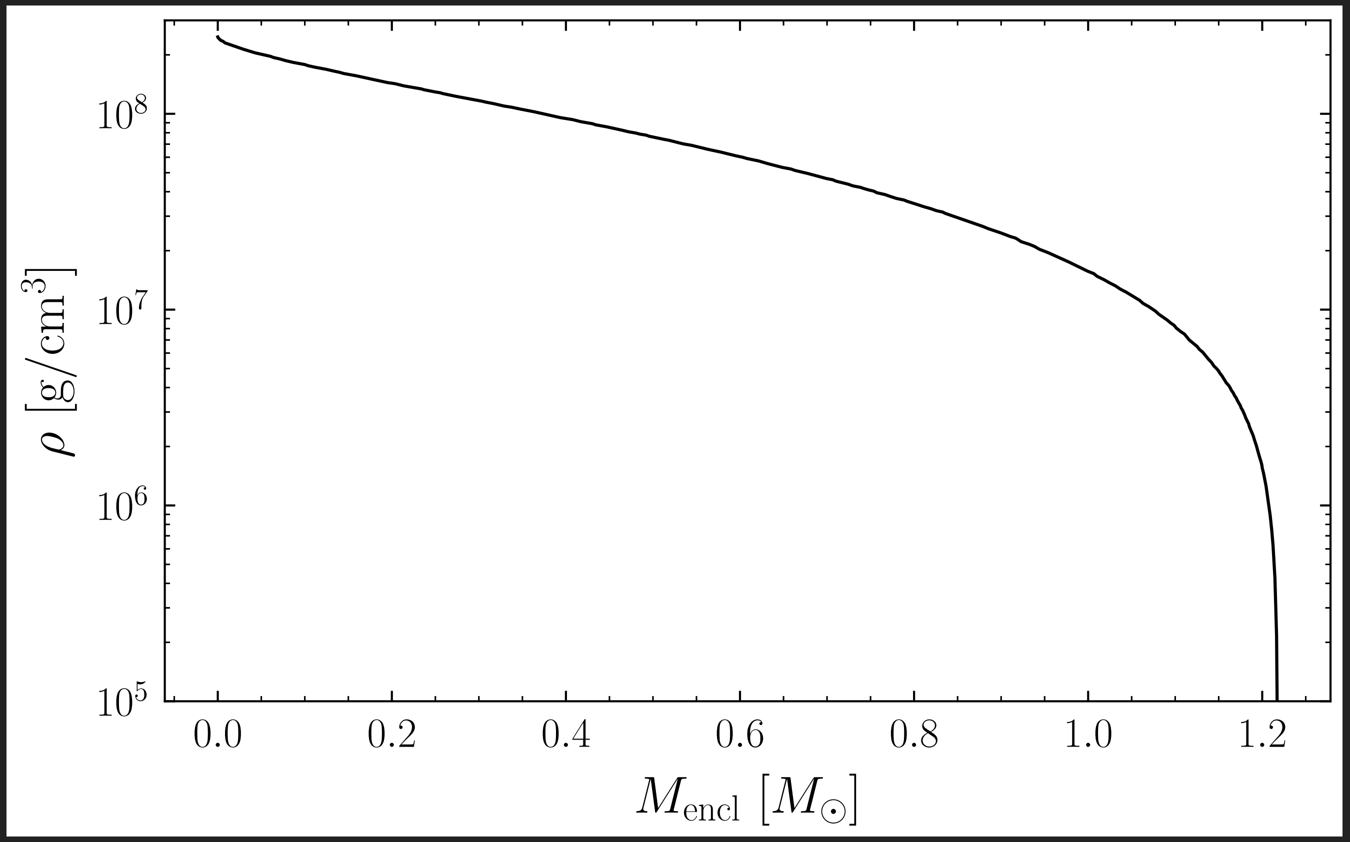
induces mixing

$$p_{a\to\gamma} \sim 10^{-4}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ {\rm GeV}^{-1}}\right)^2 \left(\frac{1\ {\rm keV}}{\omega}\right)^{4/5}\left(\frac{B_0}{10^{13}\ {\rm G}}\right)^{2/5}\left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{6/5}$$

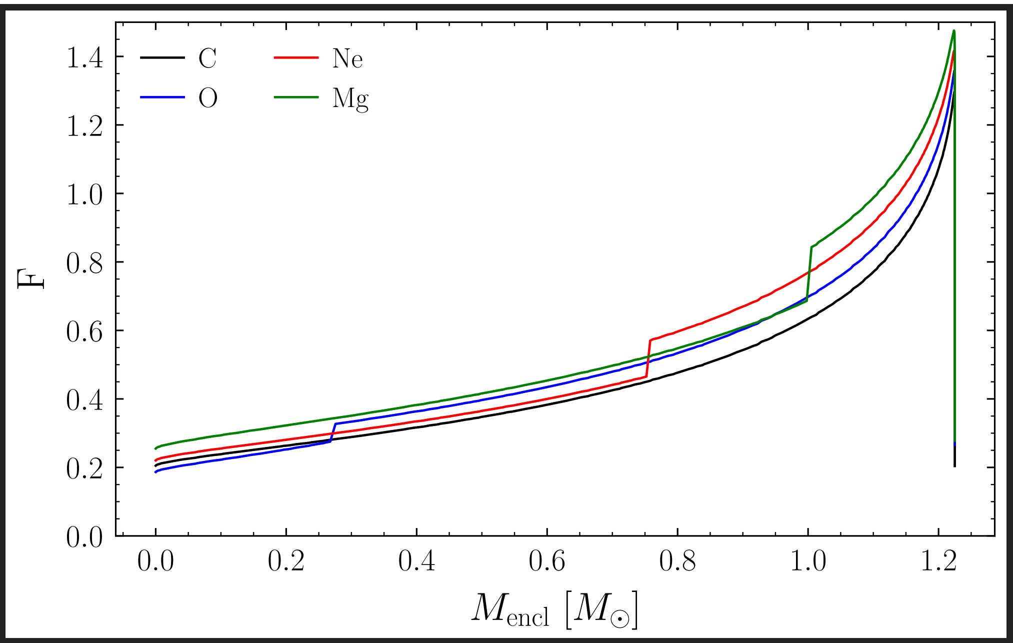
RE J0317-853 Core Temperature/Composition

- MESA: start with ~10 Msun star before WD phase
  - end up with oxygen-neon core because carbon depletion (standard expectation for ~1.2 - 1.3 Msun WD)

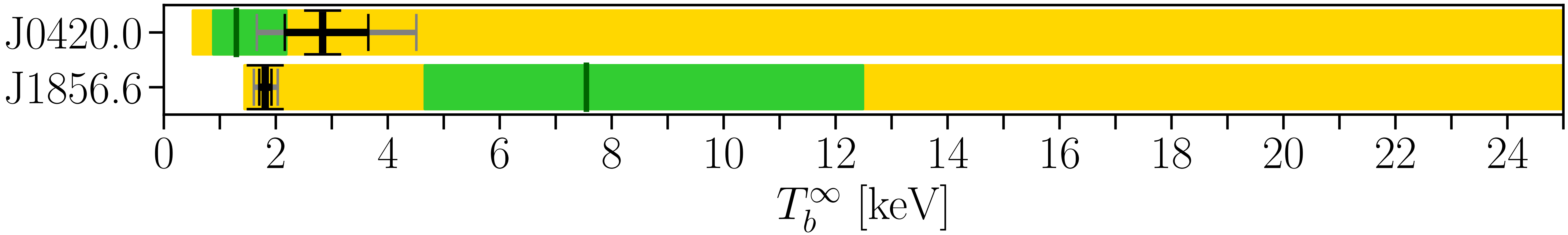




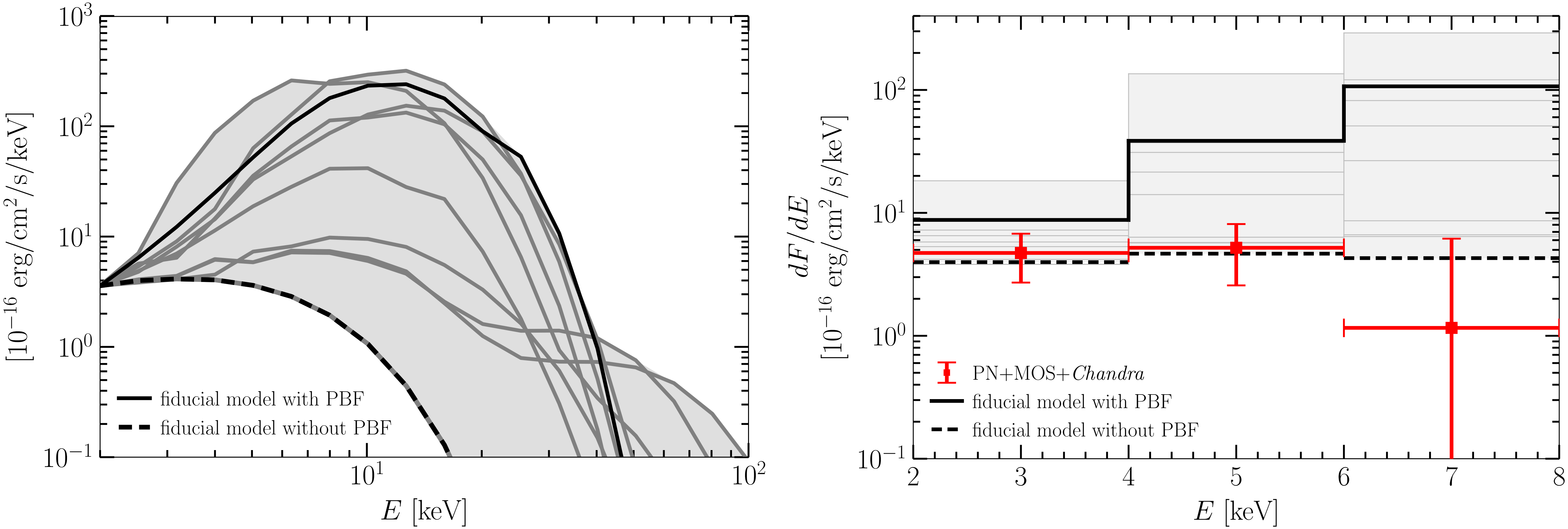
$$\frac{d\epsilon_a}{d\omega} = \frac{\alpha_{\rm EM}^2 g_{aee}^2}{4\pi^3 m_e^3} \frac{\omega^3}{e^{\omega/T} - 1} \sum_s Z_s^2 n_s F_s$$



NS X-ray Backup



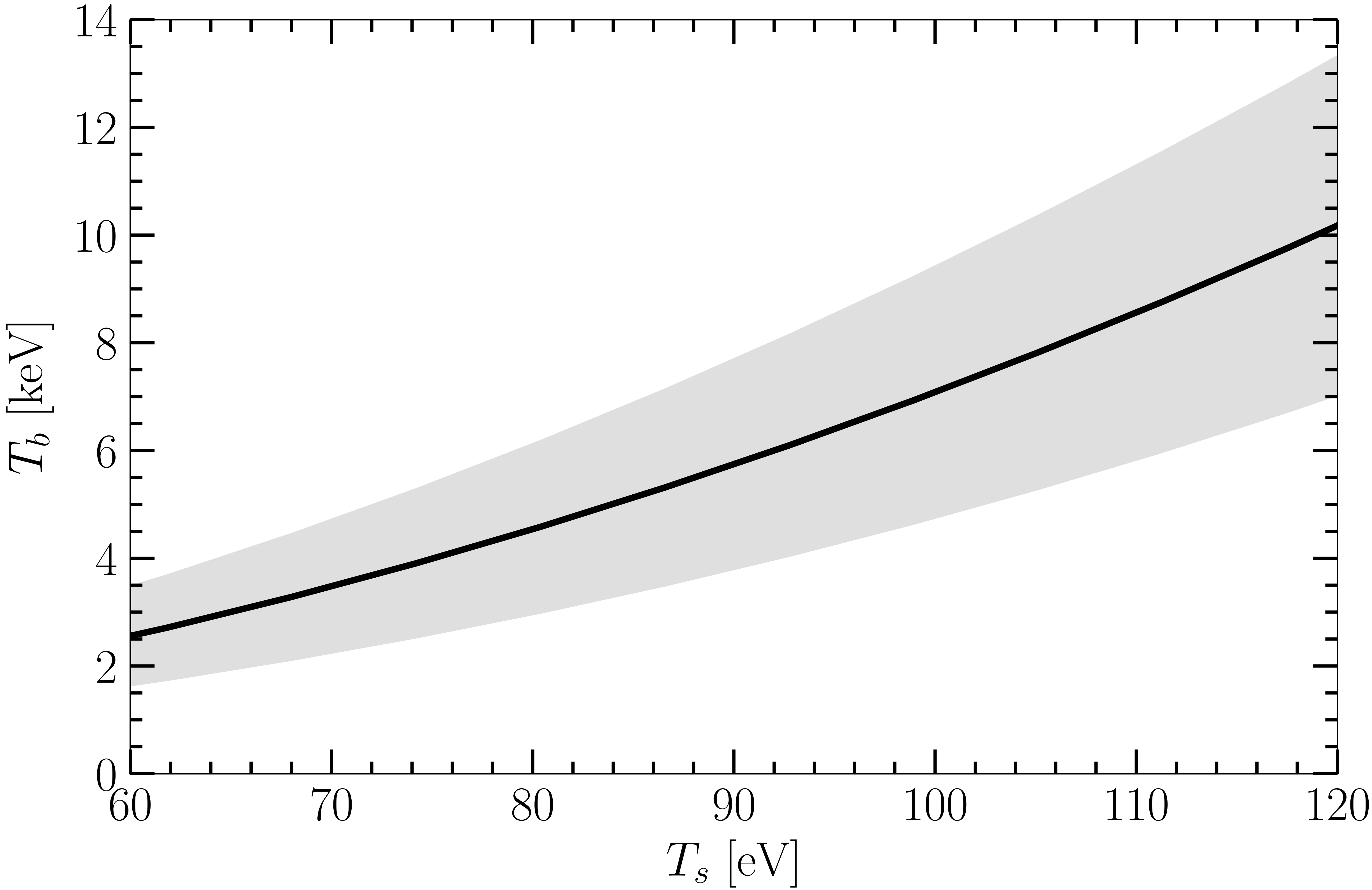
J0420.0
J1856.6
0
2
4
6
8
10
12
14
16
18
20
22
24
T_b^∞ [keV]



10^3
10^2
10^1
10^0
10^{-1}
dF/dE
$[10^{-16}$ erg/cm^2/s/keV]
fiducial model with PBF
fiducial model without PBF
10^1
10^2
E [keV]
10^2
10^1
10^0
10^{-1}
dF/dE
$[10^{-16}$ erg/cm^2/s/keV]
PN+MOS+*Chandra*
fiducial model with PBF
fiducial model without PBF
2
3
4
5
6
7
8
E [keV]

Core temperature / surface temperature relation

(large uncertainties here)



Core temperatures based off of kinematic ages