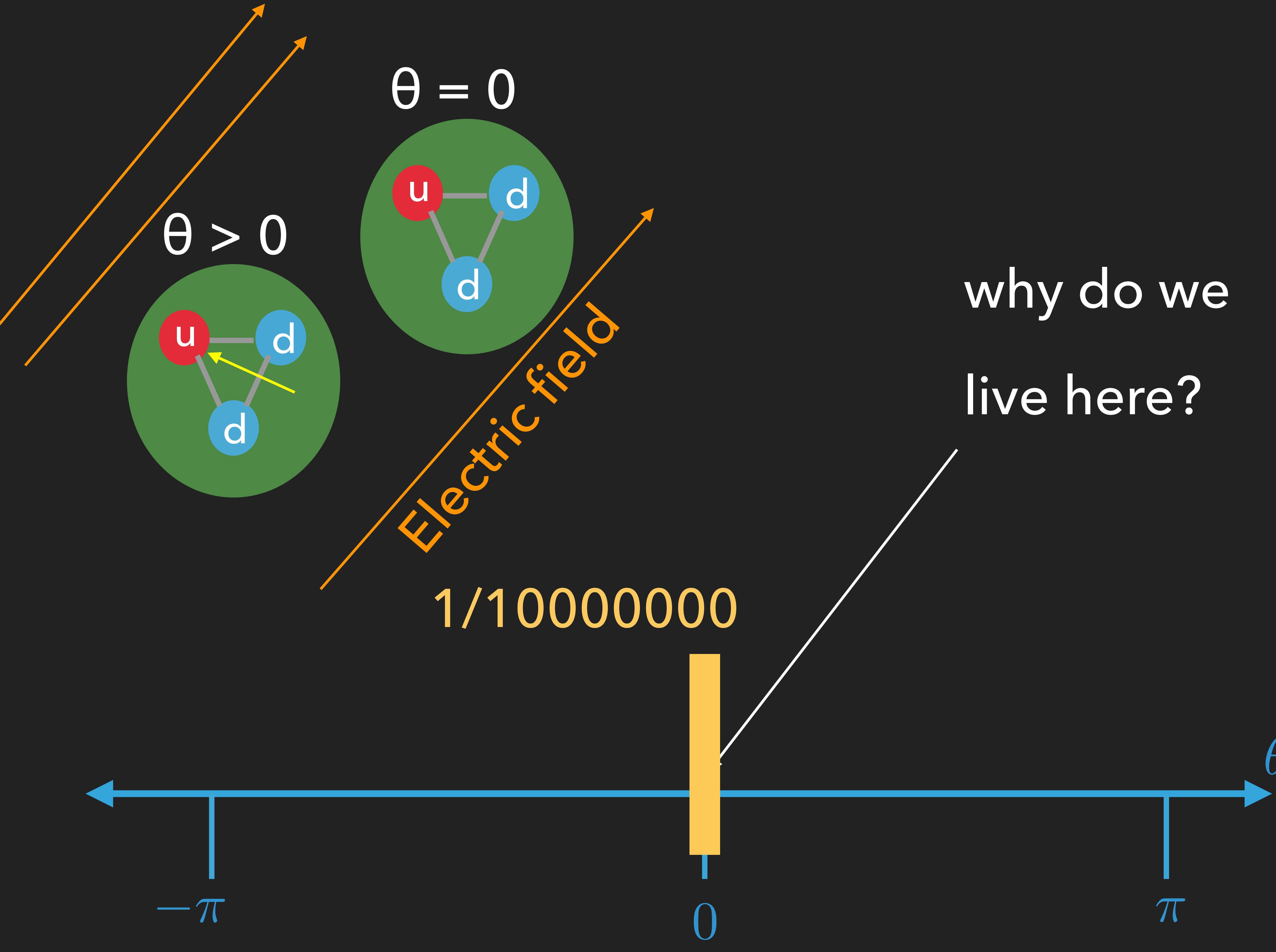
COMPACT STARS AS AXION LABORATORIES

BEN SAFDI

BERKELEY CENTER FOR THEORETICAL PHYSICS
UNIVERSITY OF CALIFORNIA, BERKELEY
LAWRENCE BERKELEY NATIONAL LABORATORY

The strong CP problem: no neutron EDM?

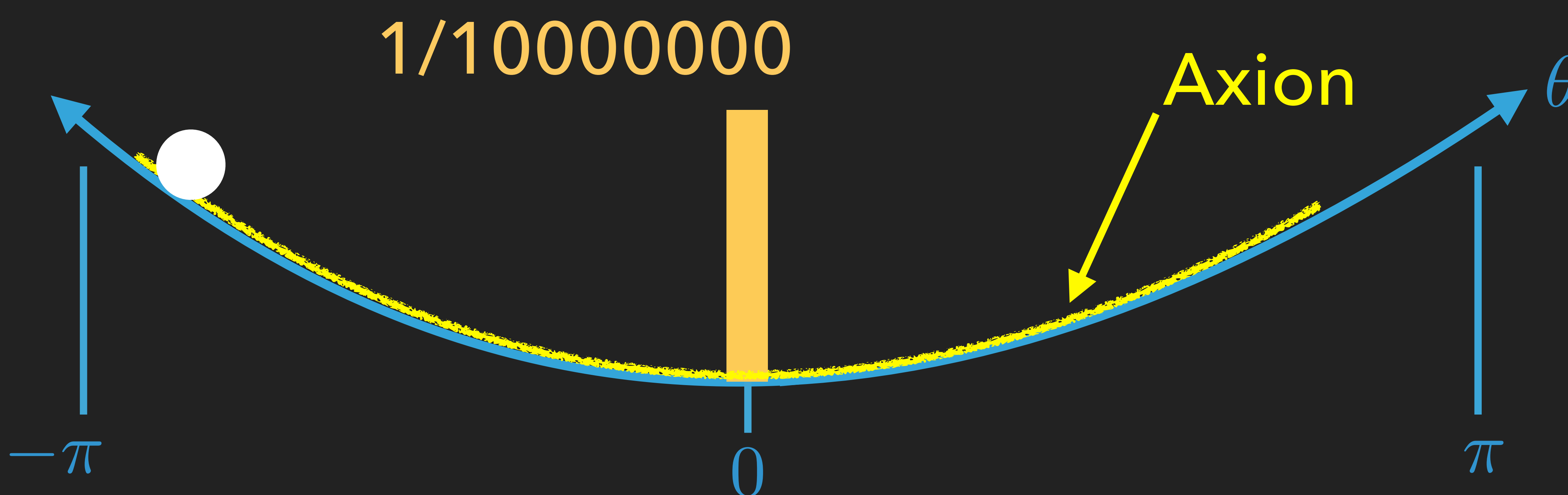


The neutron electric dipole moment puzzle

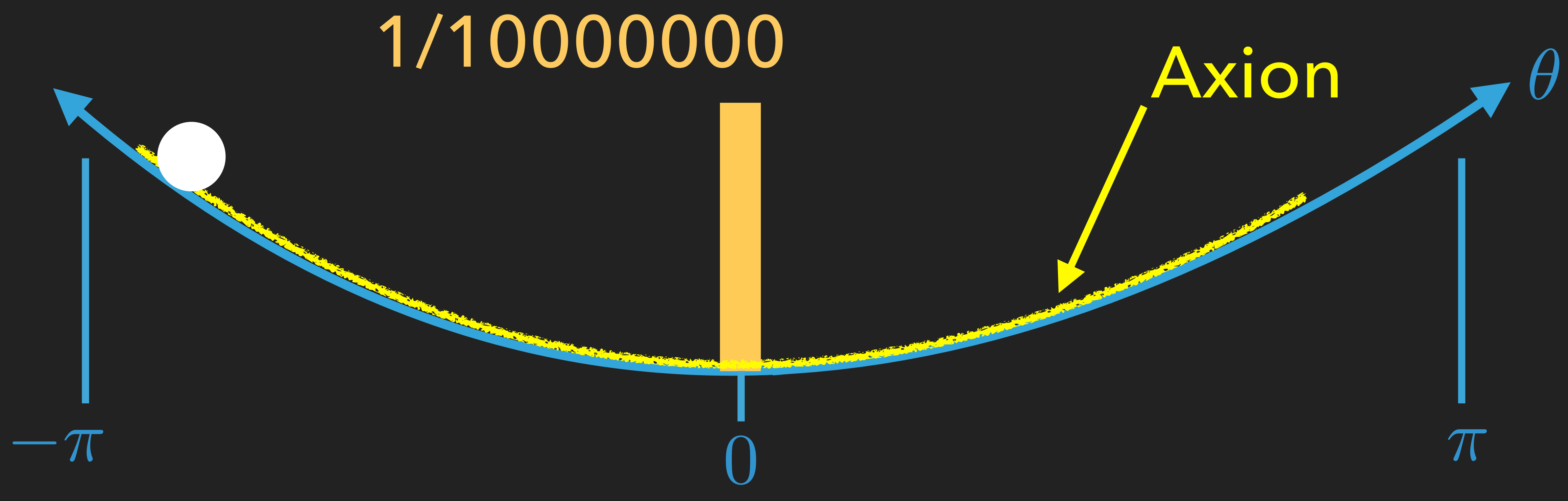
Roberto Peccei

Helen Quinn

1977



Axion Solution to Strong CP (more precisely)



$$\mathcal{L} = -\frac{g^2}{32\pi^2}\left(\bar{\theta} + \frac{a}{f_a}\right) G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$f_a \gtrsim 10^9 \text{ GeV}$$

$$d_n \propto \left(\bar{\theta} + \frac{a}{f_a}\right)$$

$$V(a) \approx \frac{1}{2}\Lambda^4_{\text{QCD}}\left(\bar{\theta} + \frac{a}{f_a}\right)^2$$

Axion Solution to Strong CP (more precisely)

$$\mathcal{L} = -\frac{g^2}{32\pi^2}\left(\bar{\theta} + \frac{a}{f_a}\right) G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\downarrow$$

$$V(a) \approx \frac{1}{2}\Lambda_{\rm QCD}^4 \left(\bar{\theta} + \frac{a}{f_a}\right)^2$$

Axion mass: $m_a \approx \frac{\Lambda_{\rm QCD}^2}{f_a} \approx 10^{-5}\ {\rm eV}\left(\frac{10^{12}\ {\rm GeV}}{f_a}\right)$

Axions also couple to EM: $\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4} = g_{a\gamma\gamma}\, a\mathbf{E}\cdot\mathbf{B}$

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

Axion interactions with Matter

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

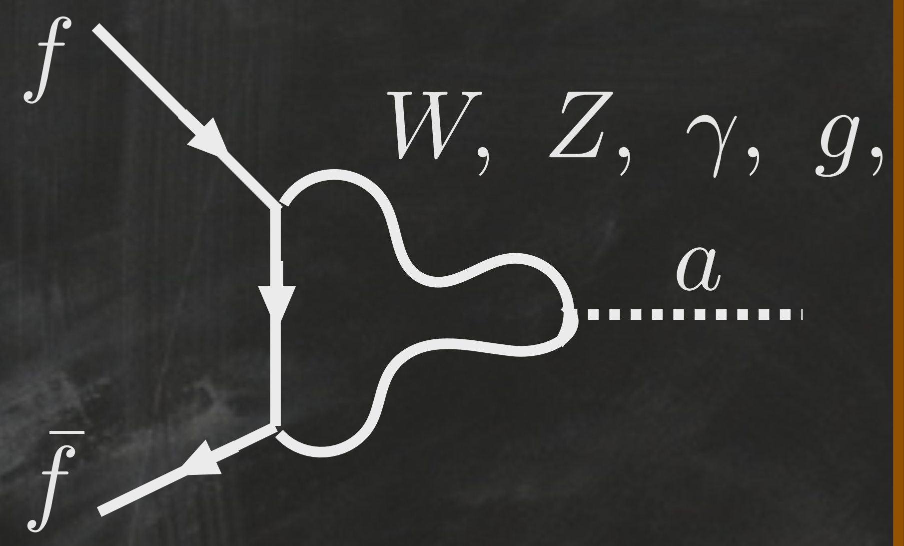
$$g_{a\gamma\gamma} = \frac{C_\gamma \alpha_{\rm EM}}{2\pi f_a}\ , \qquad C_\gamma \sim \mathcal{O}(1)$$

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}



$$C_e^{\rm IR} \approx C_e^{\rm UV} + 5\times10^{-4}C_W + 2\times10^{-4}C_B$$

$$C_\gamma = C_W + C_B$$

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

Axion-like particles versus QCD Axion

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

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

QCD axion only!

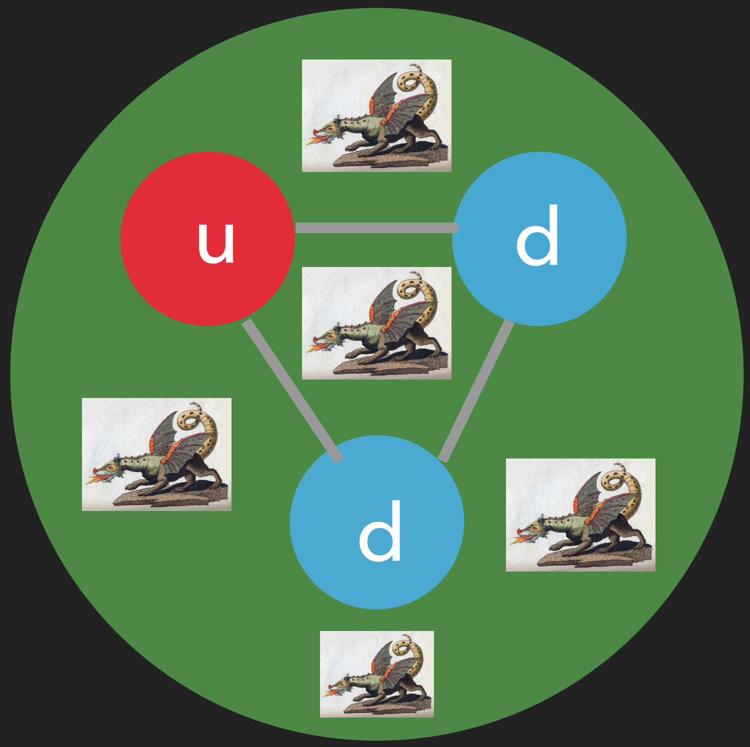
$m_a^{\rm QCD} \gg m_{\rm bare}$

small

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

axion timeline

neutron



dark matter

experiment

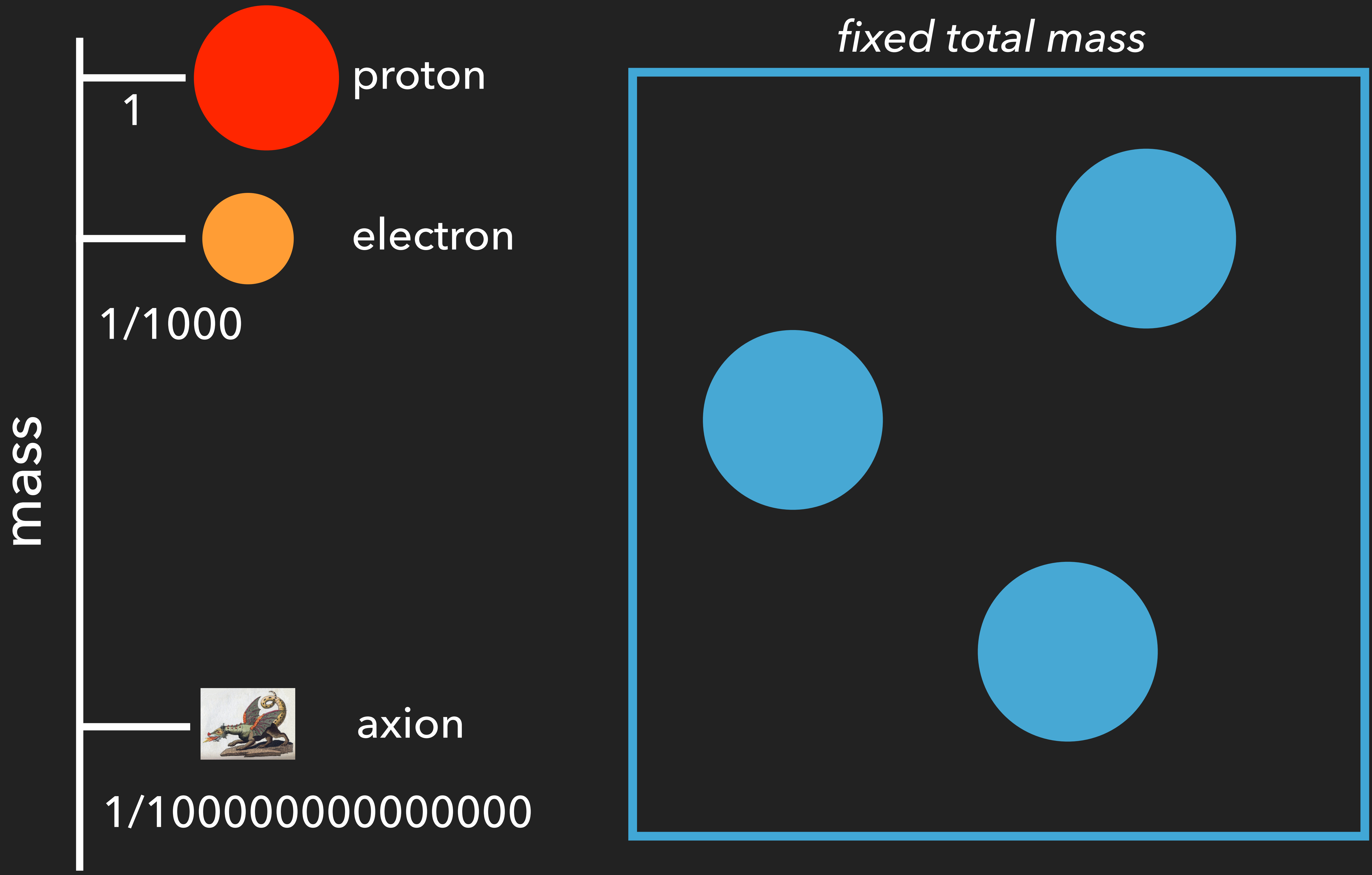
1977

1983

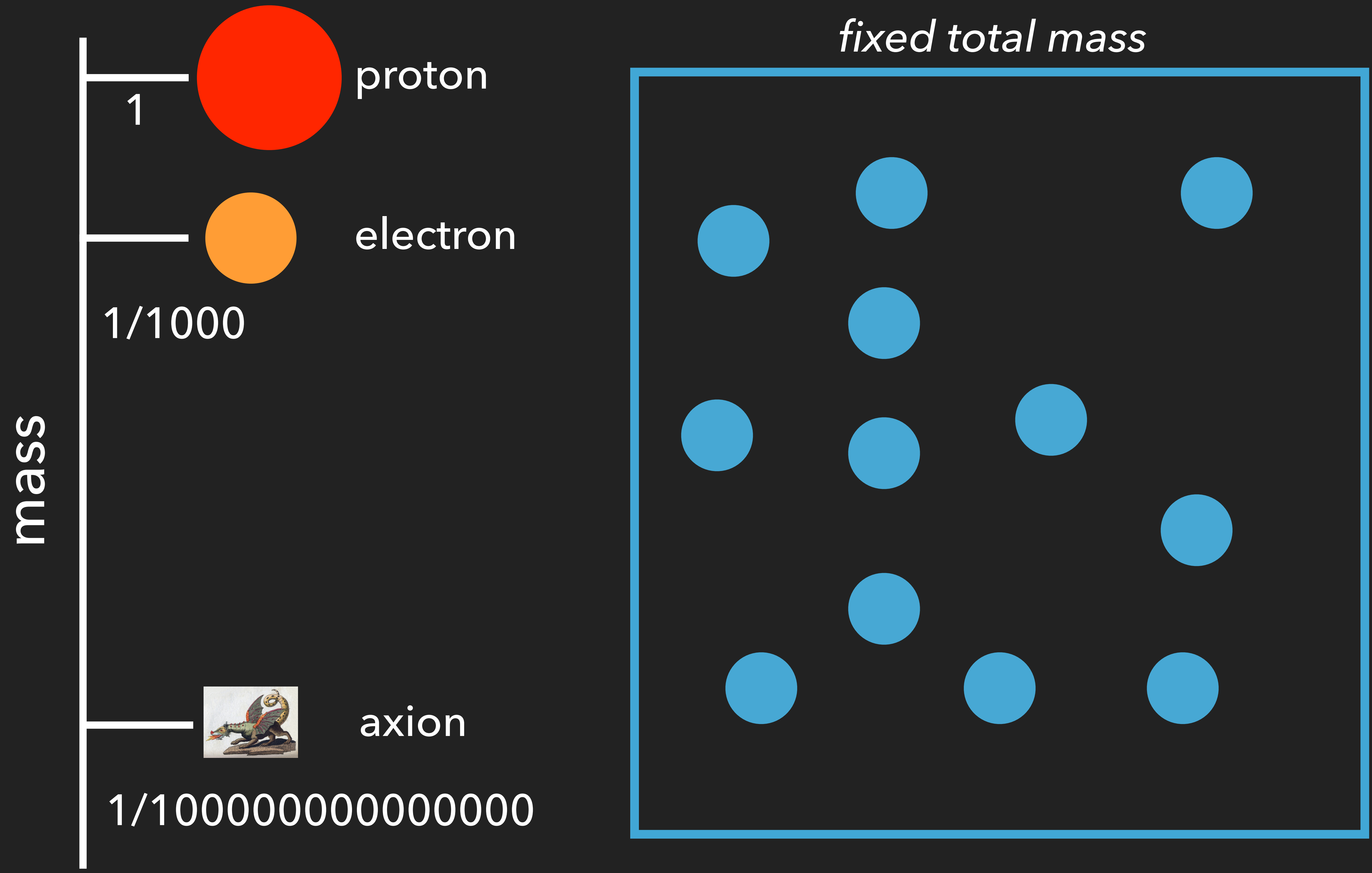
ALPs

today

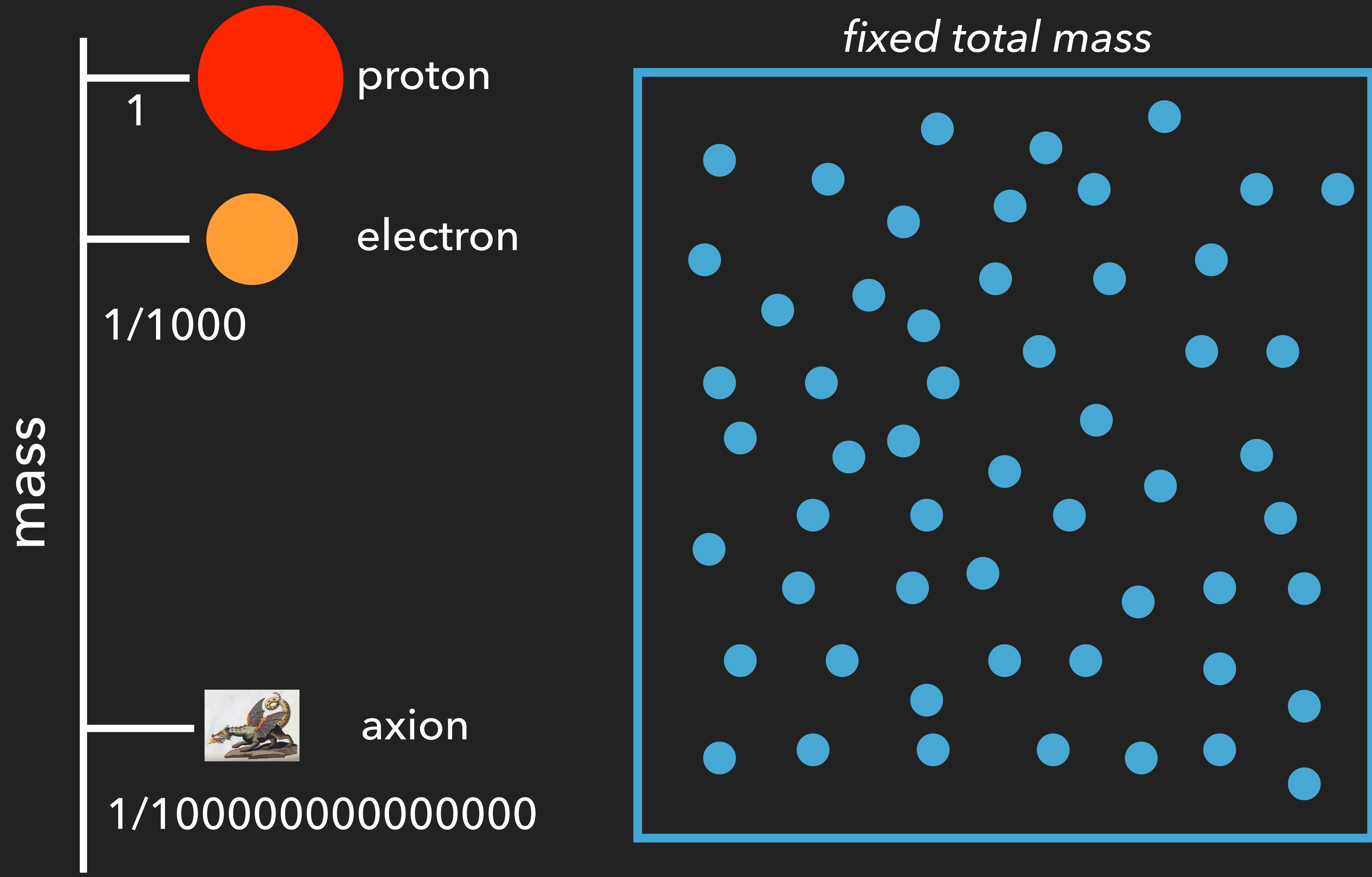
axion dark matter



axion dark matter



axion dark matter



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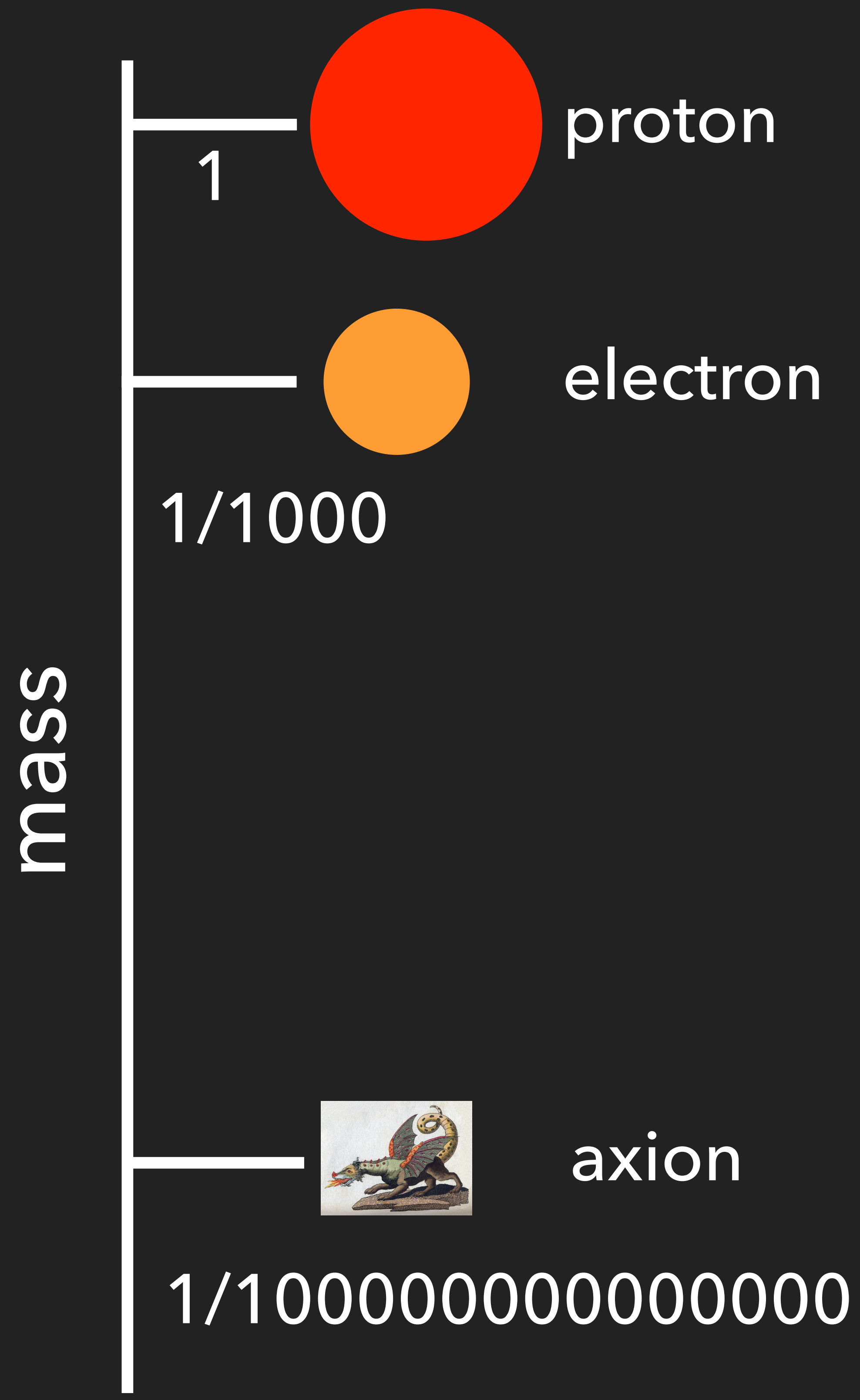
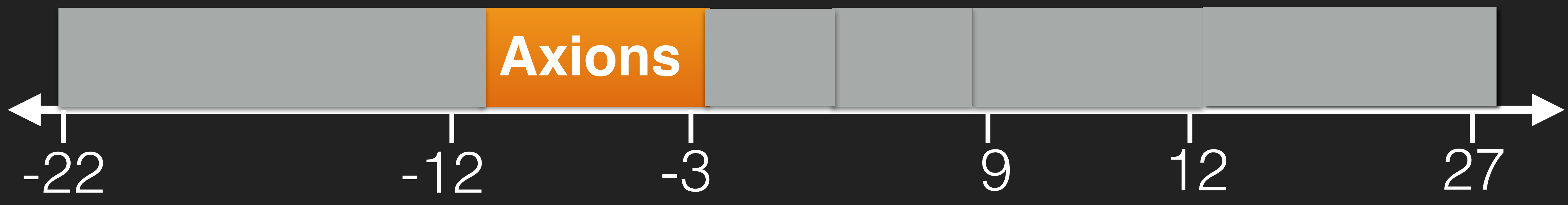
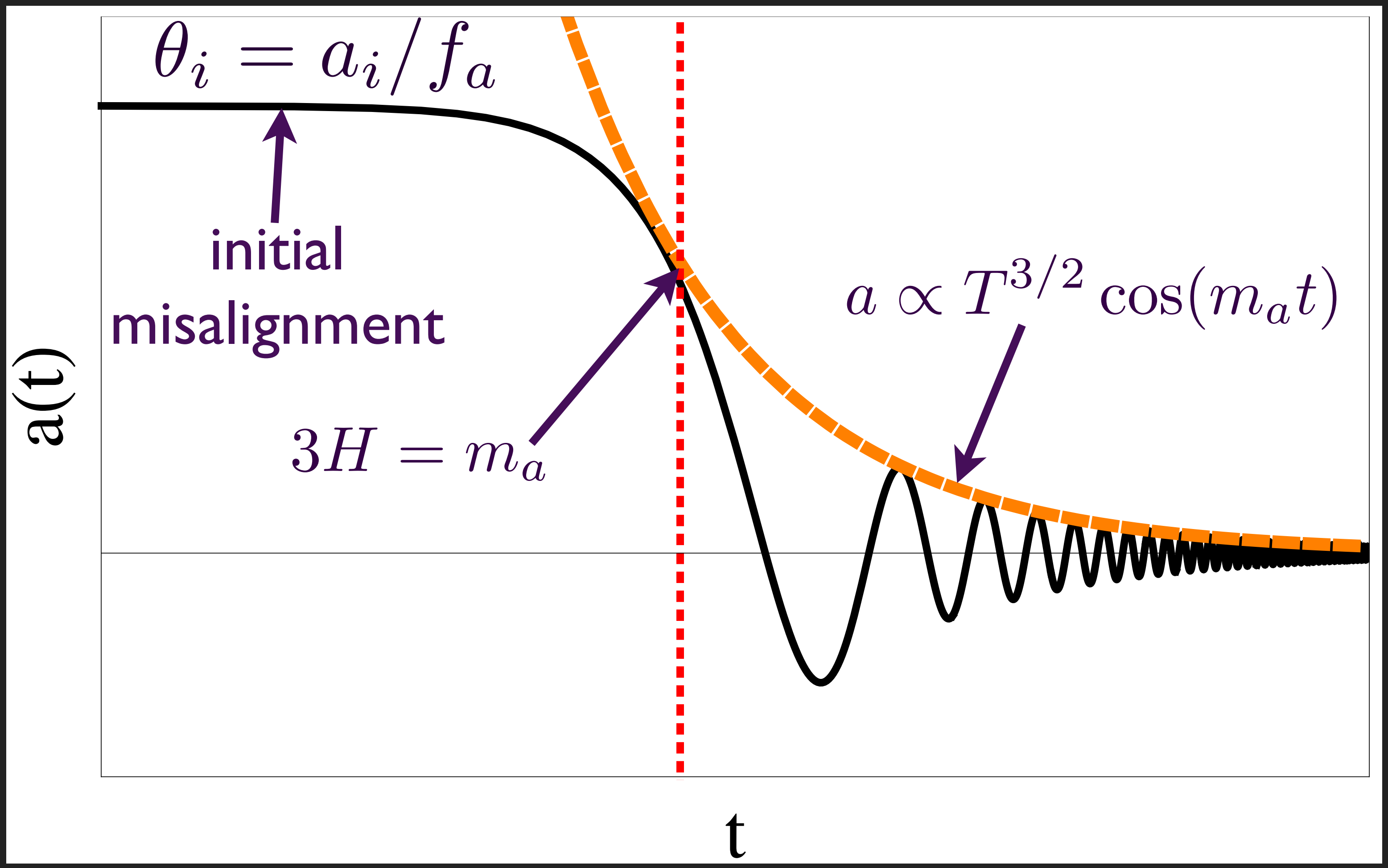


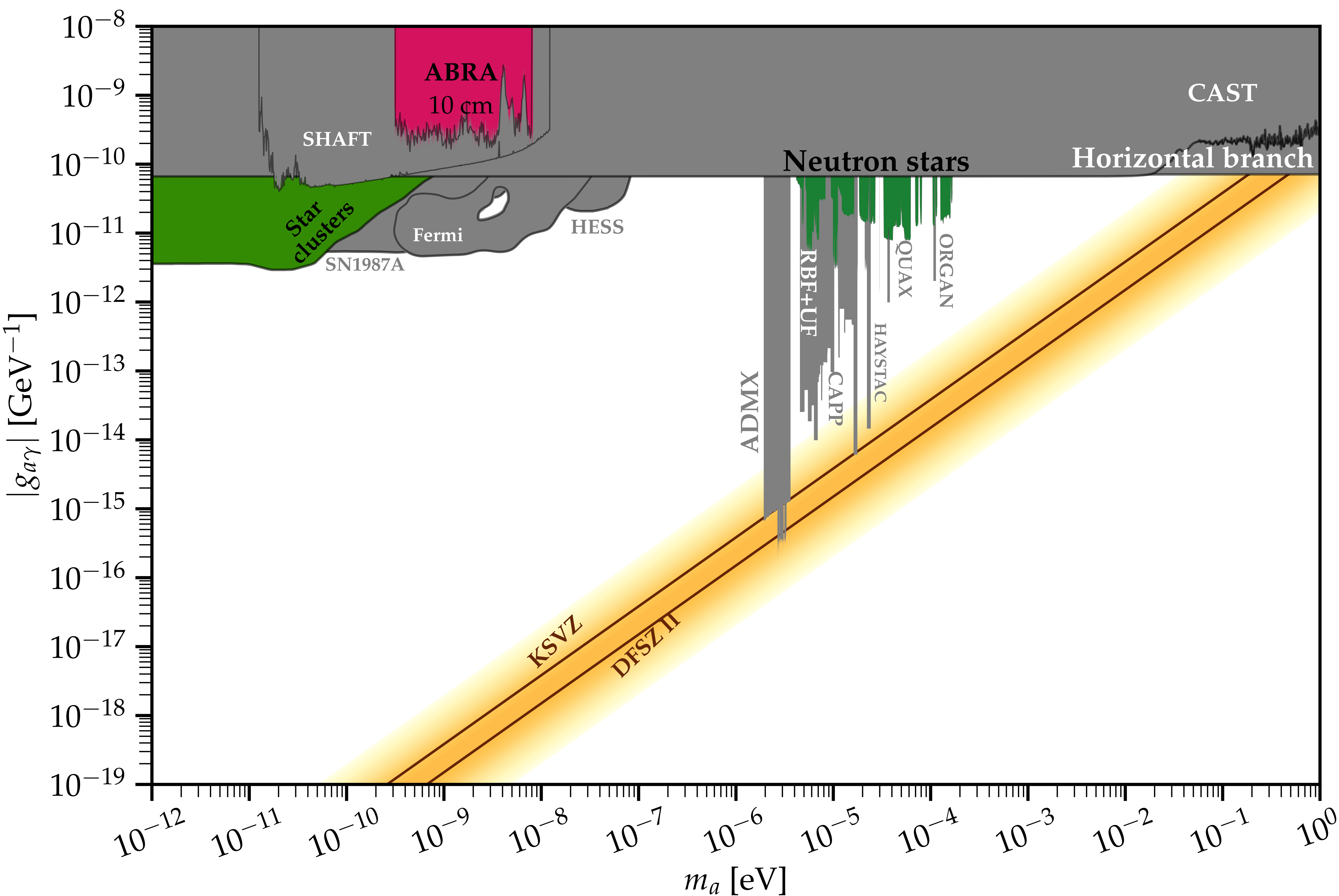


$$\sin a/f_a \sim a/f_a \quad : \qquad \ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



QCD axion: $\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \theta_i^2$

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



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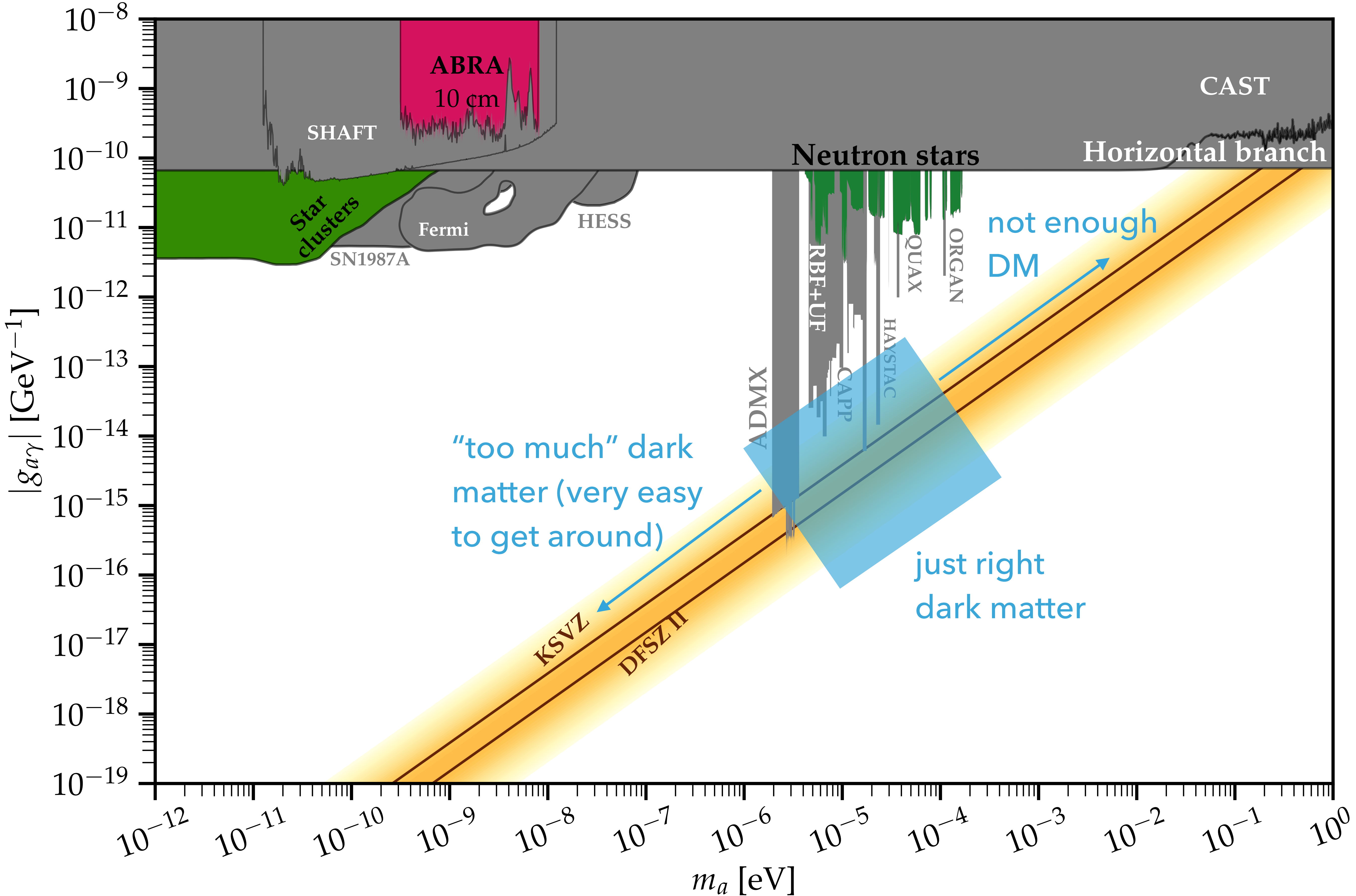

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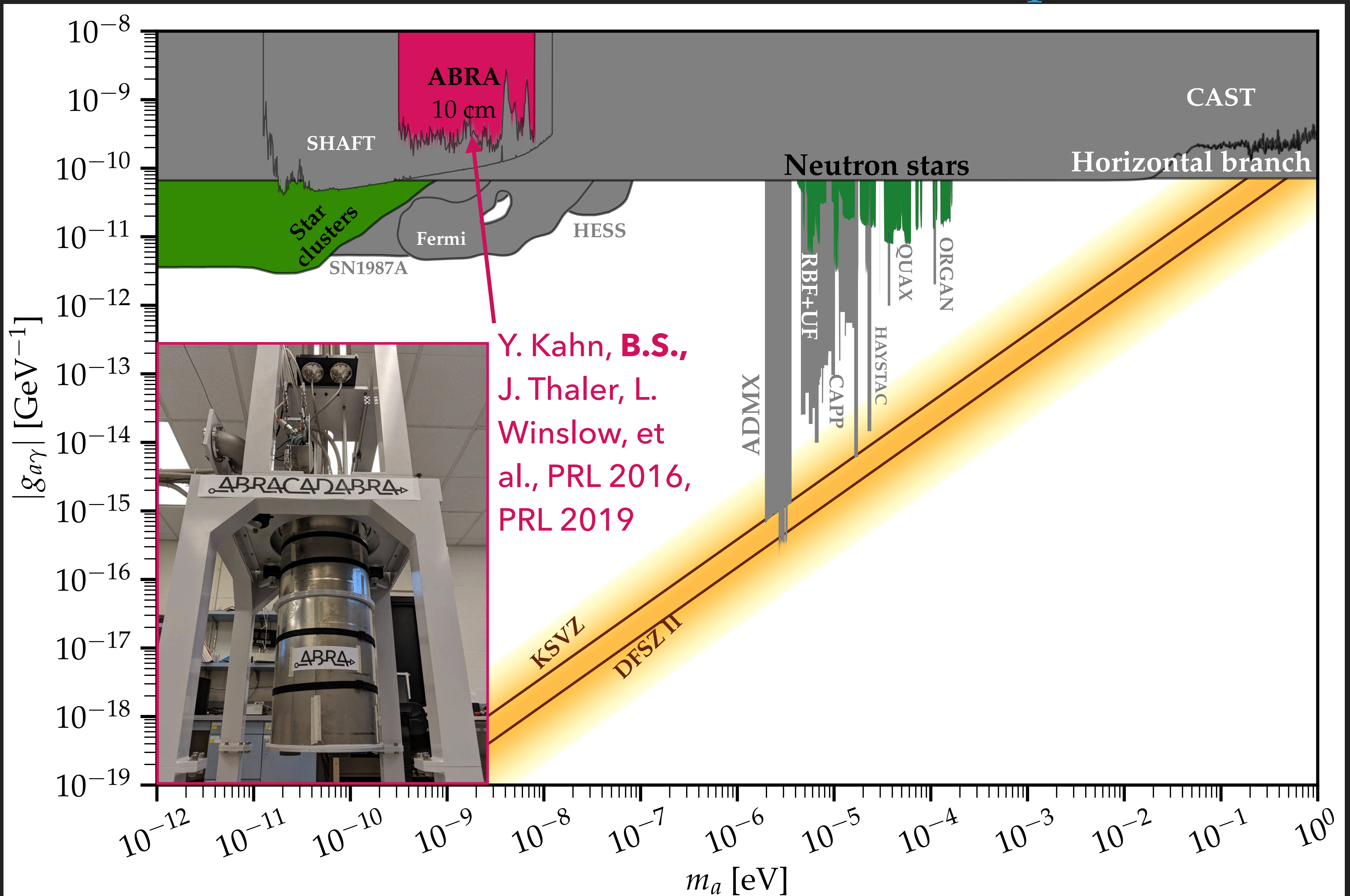

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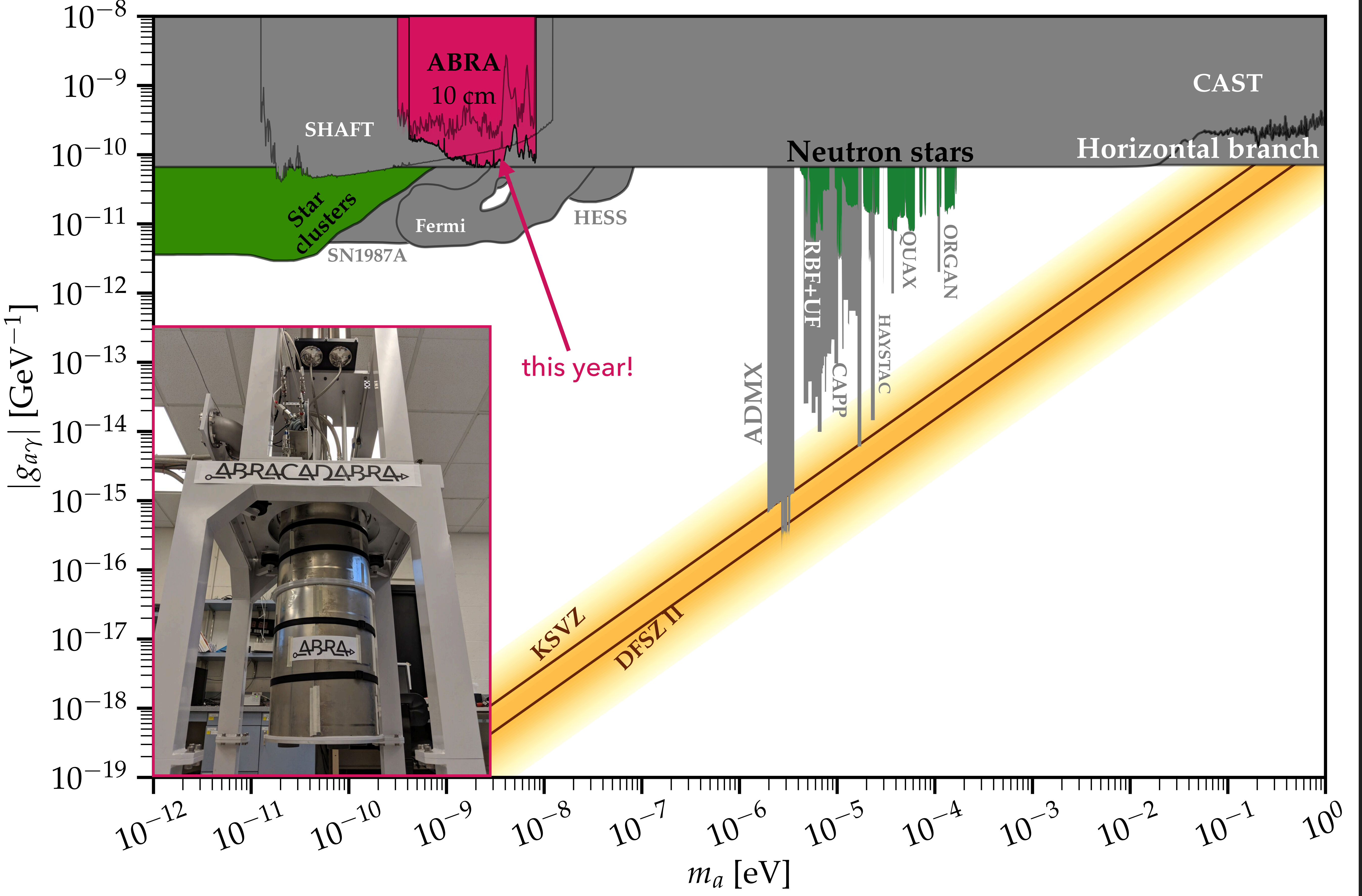

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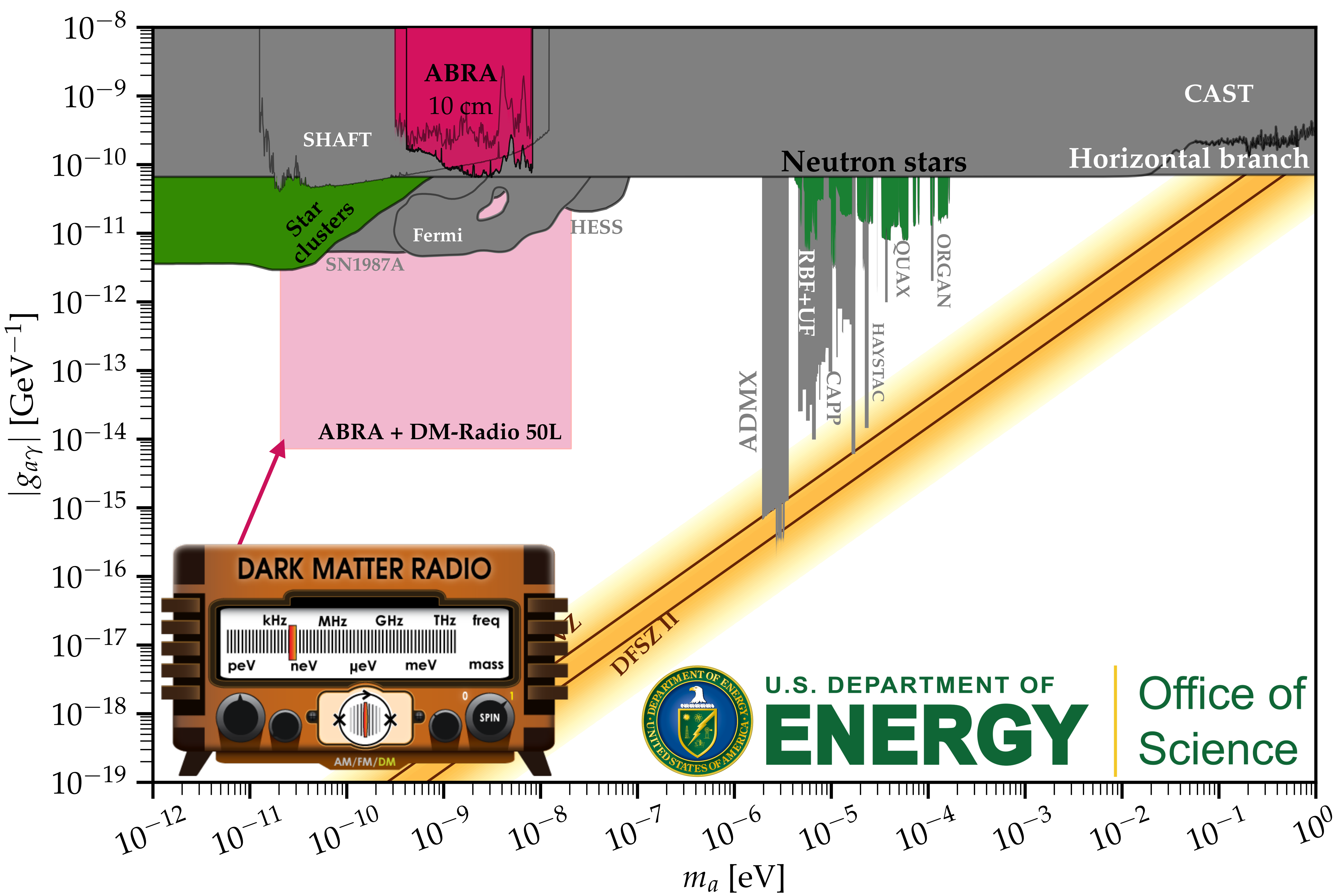

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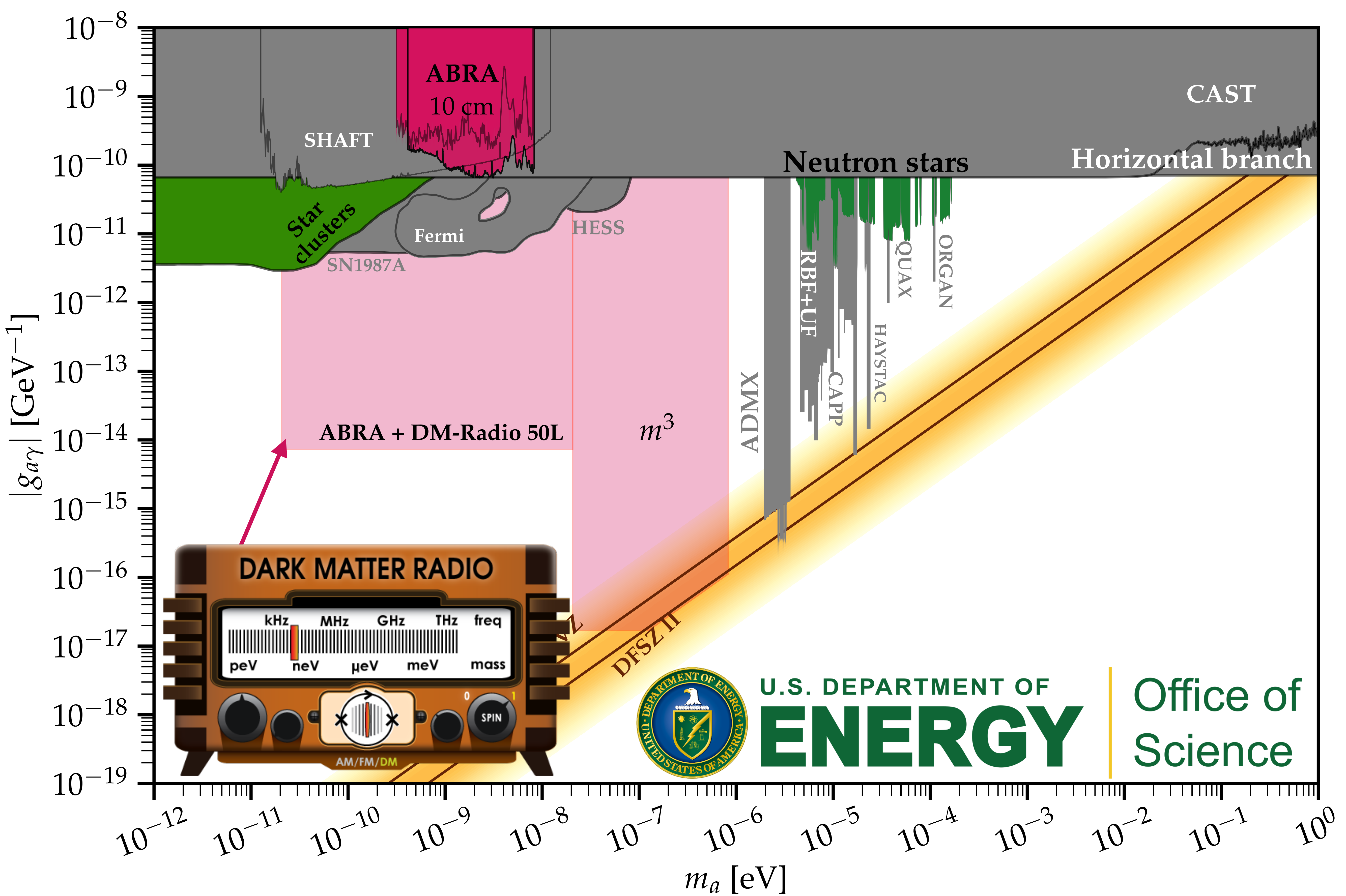

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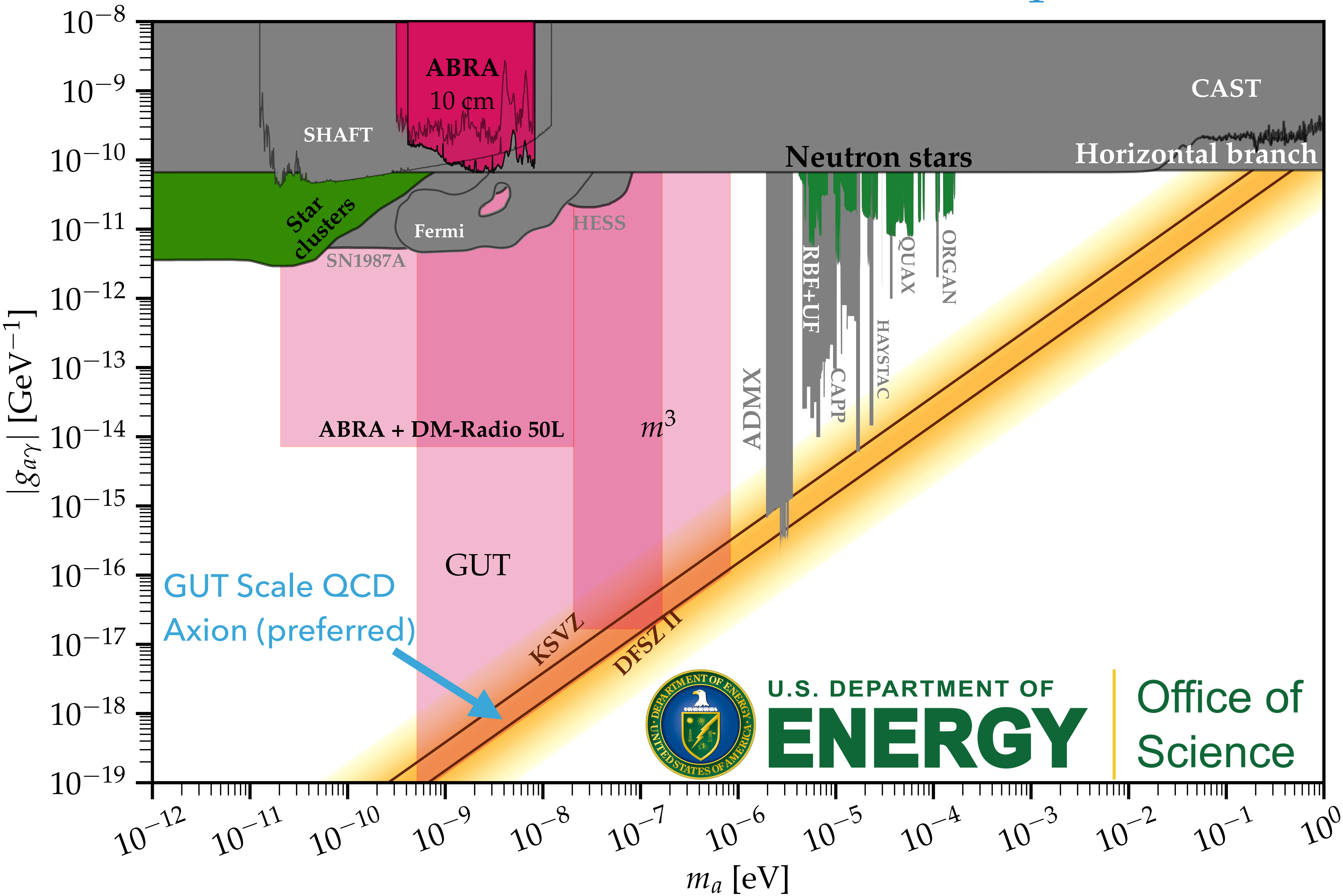

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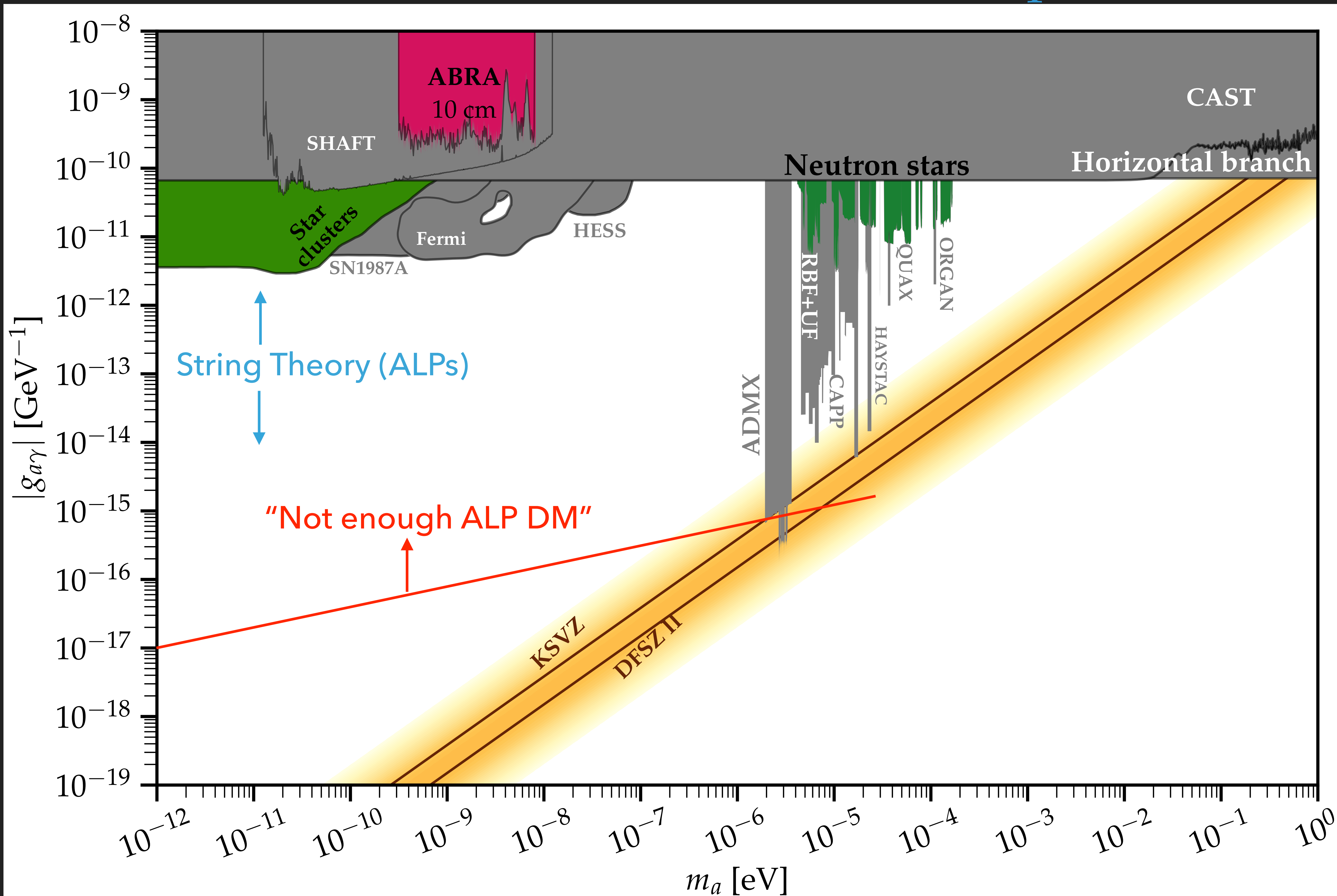

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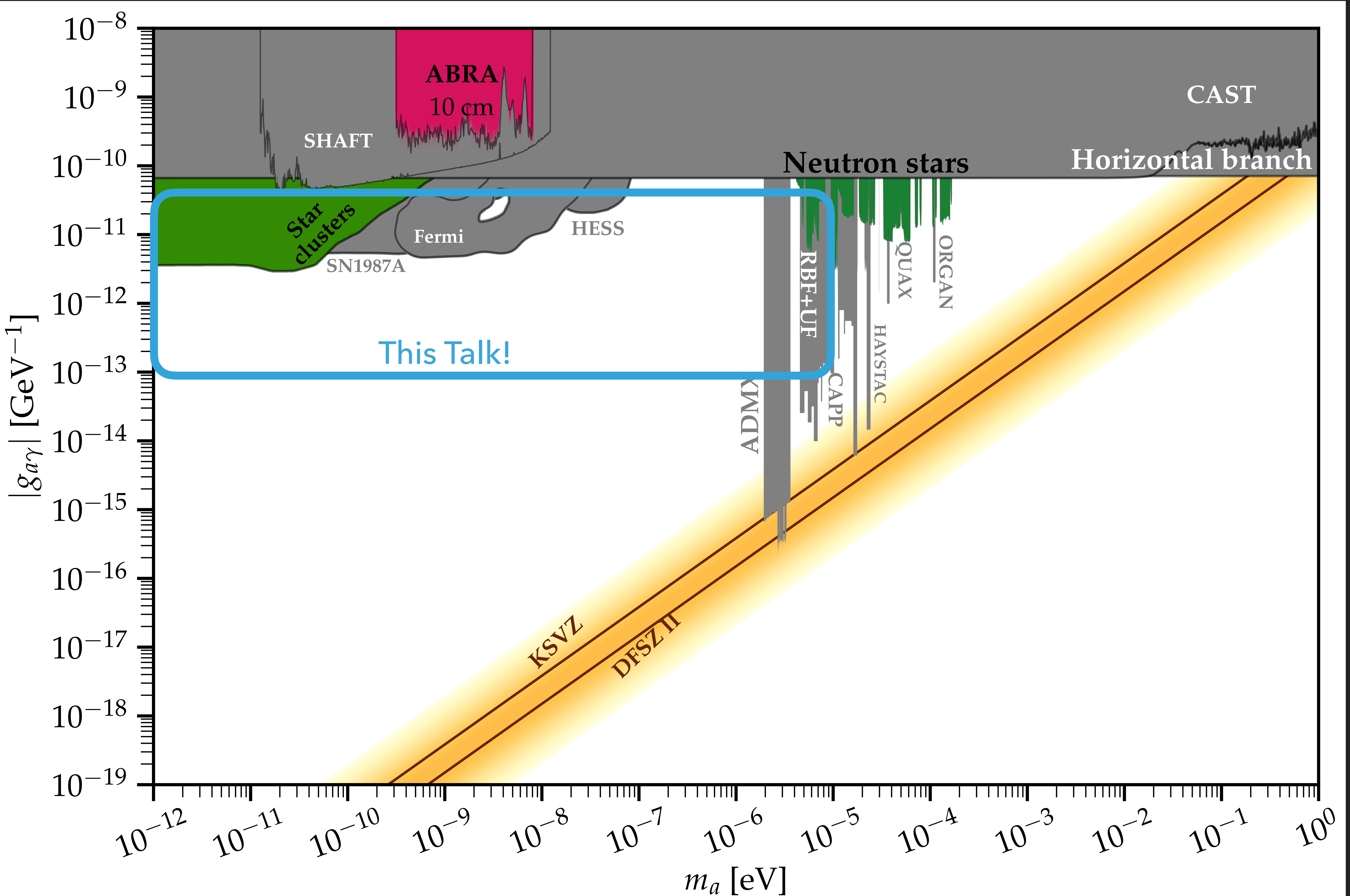

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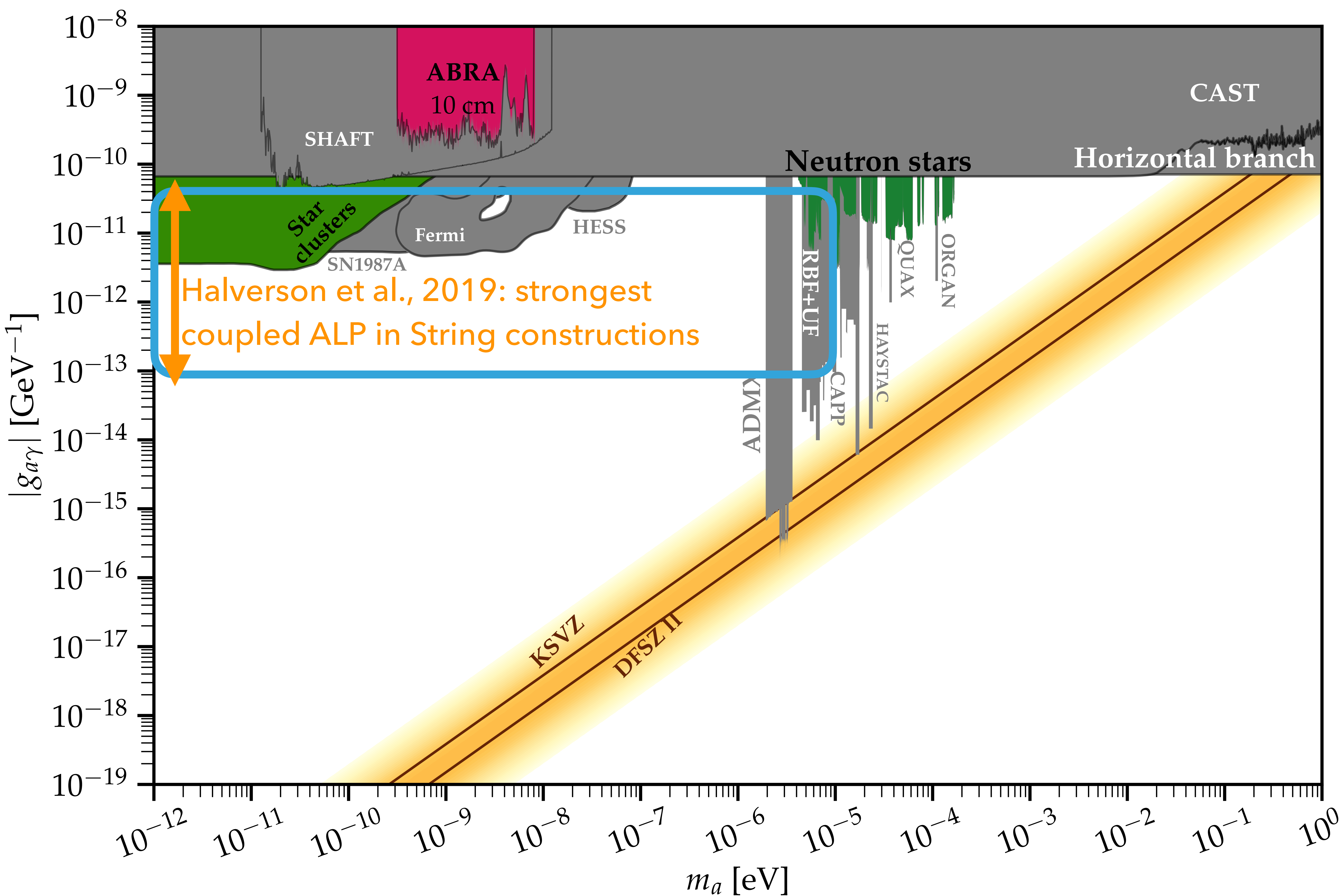

Outline

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)
4. Possible future work

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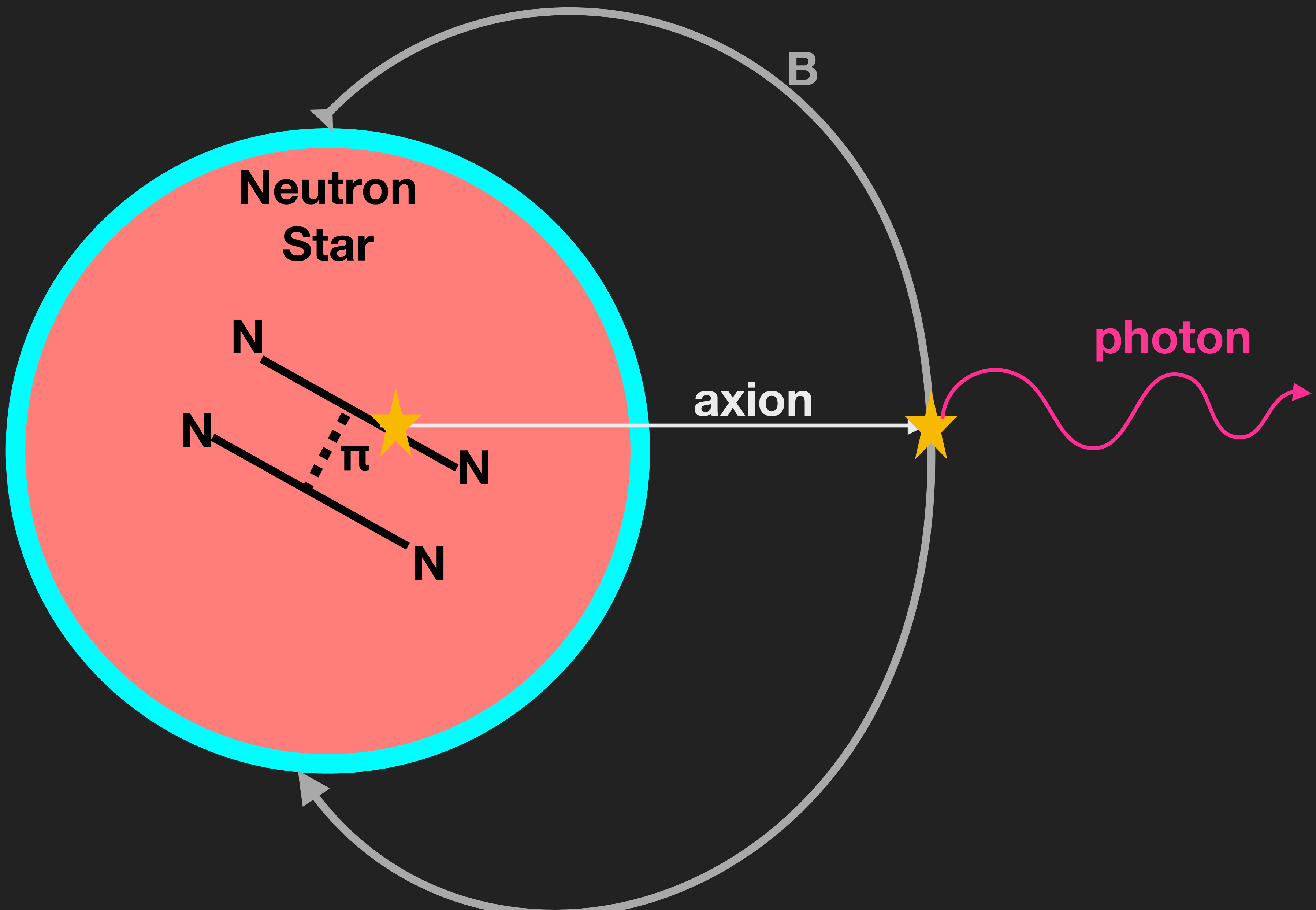
Dessert et al. 2104.12772, Dessert et al. 2008.03305 (PRL), Buschmann et al. 1910.04164 (PRL), Dessert et al. 1910.02956 (ApJ), Dessert et al. 1903.05088 (PRL)

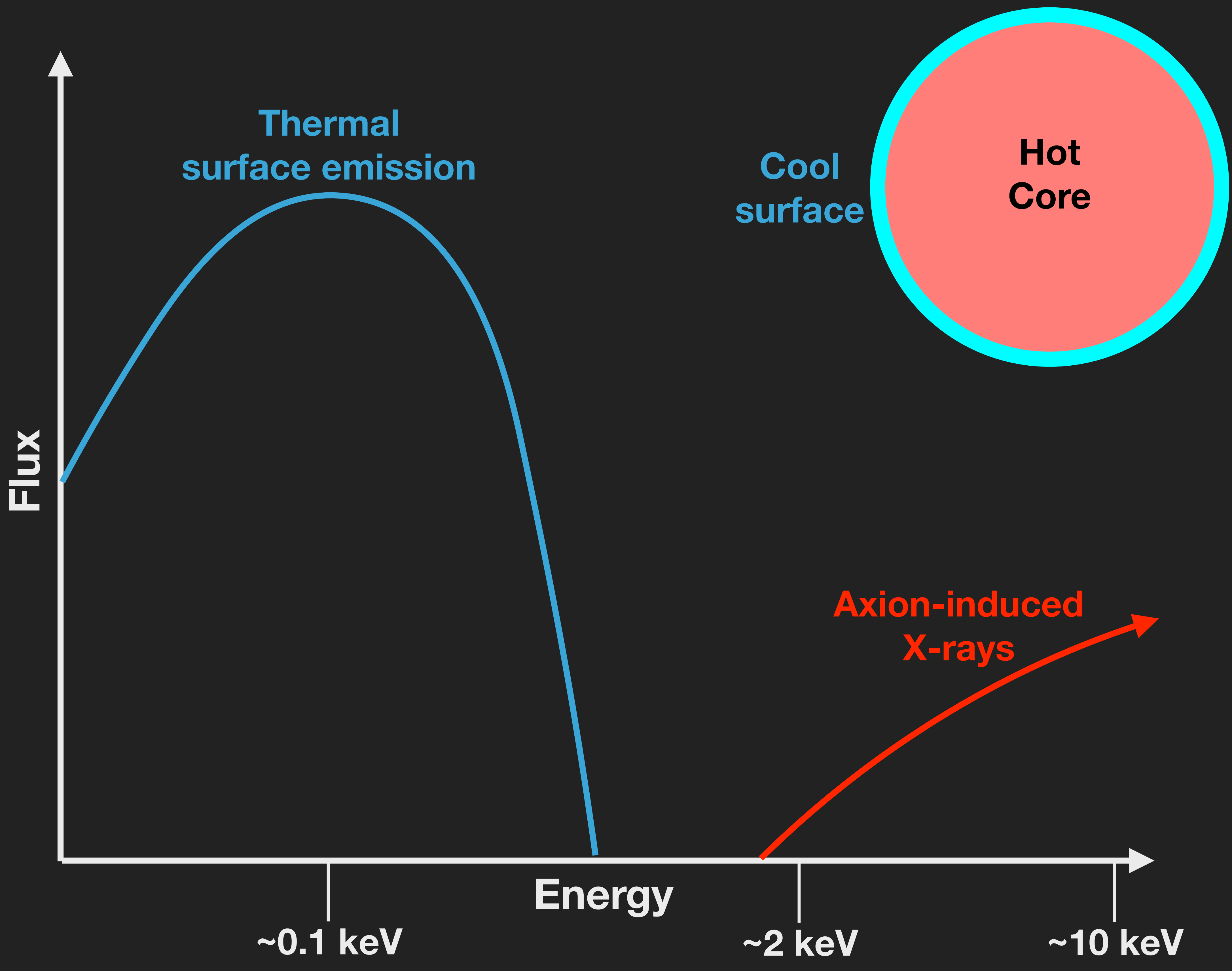
Chris Dessert

Neutron Star Overview



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

Neutron Star Overview



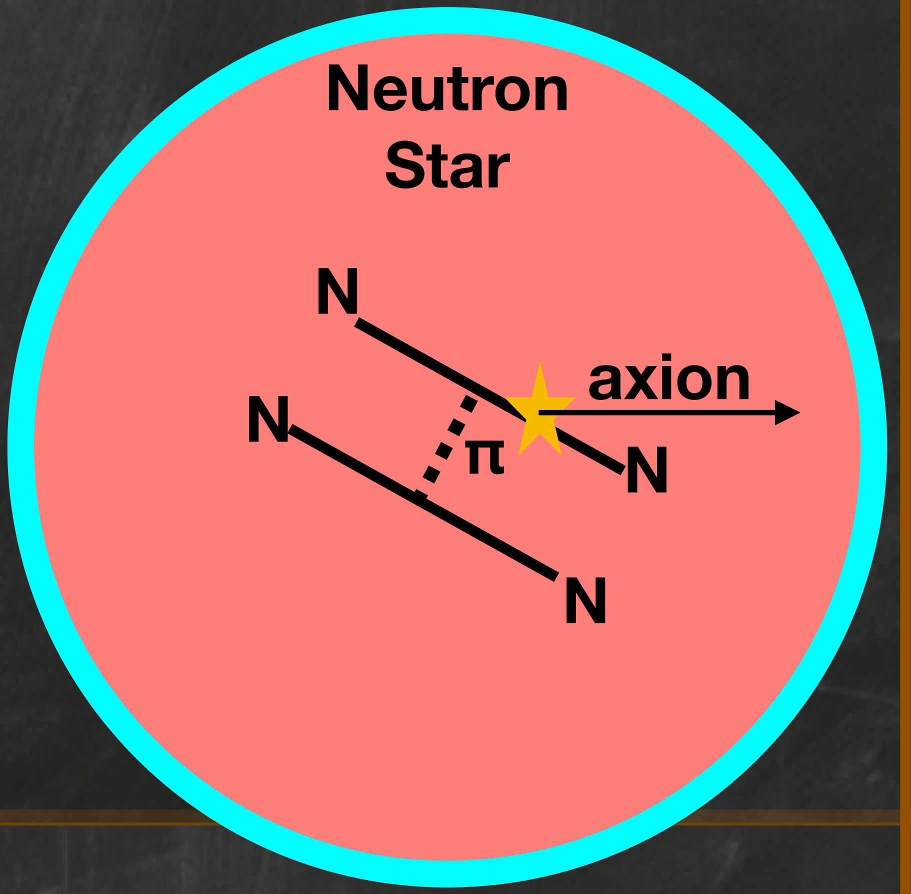
Axions Production in Neutron Star Cores from Brem.

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: $E_a \sim T_c$

Brem. rate exponentially suppressed, but new Cooper pair breaking/ formation channel open

additional complication: superfluidity $T_{\rm superfluid} \sim$ few $\times\, 10^8$ K

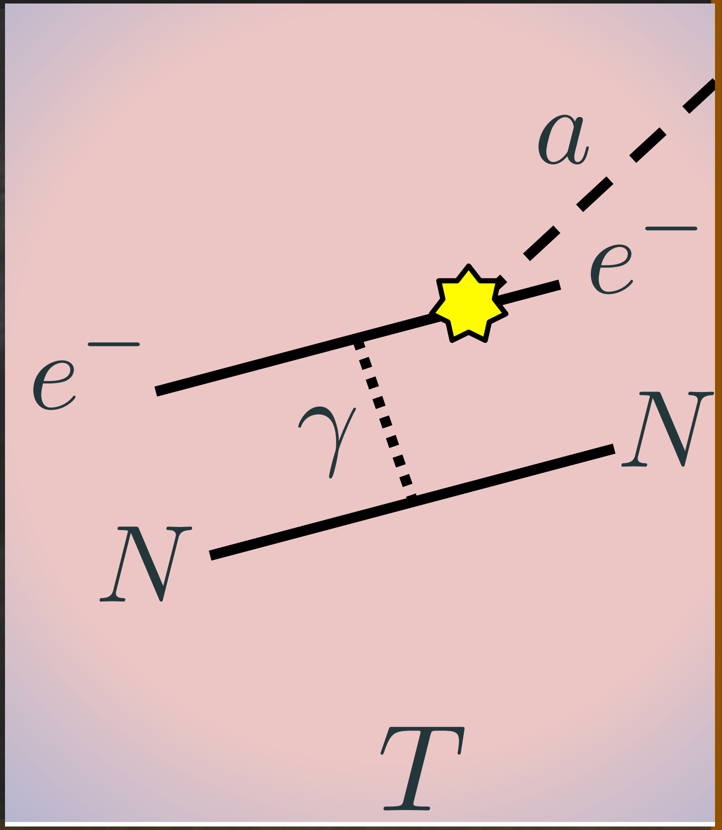
Axions Production in White Dwarf Cores from Brem.

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)

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

nuclear species

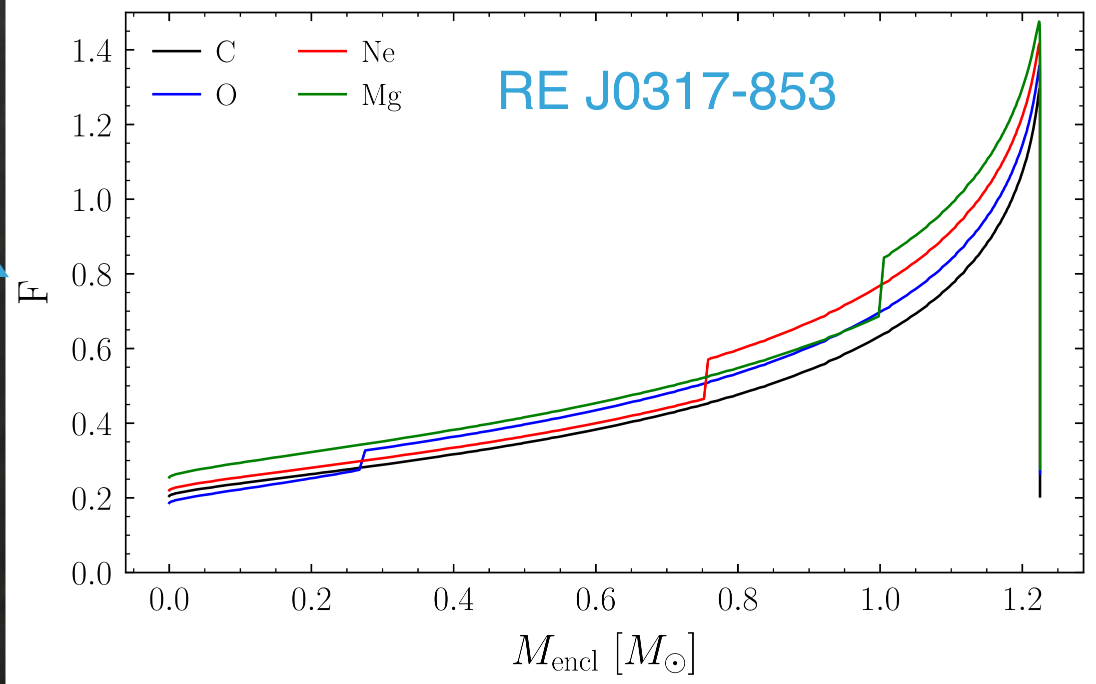
dimensionless ionic + Fermi

thermal spectrum

number density

erg/cm³/s/keV

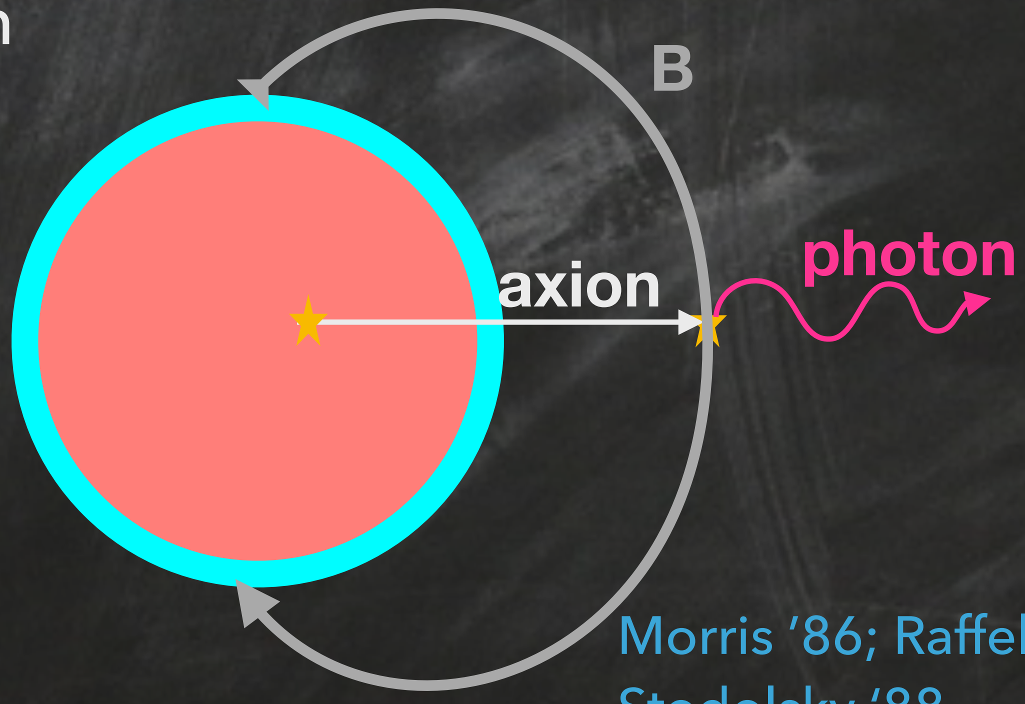
atomic number



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

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

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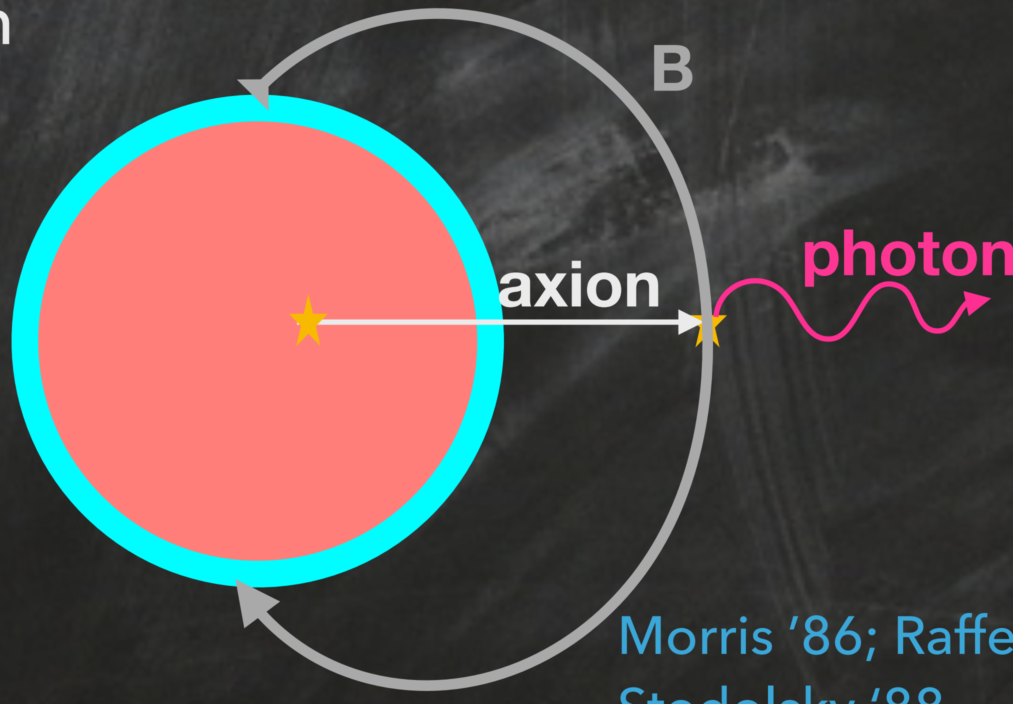

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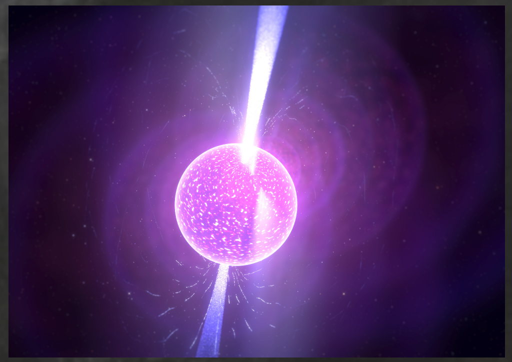
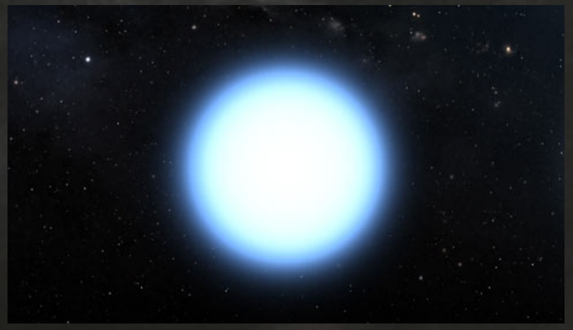
typical NS: $p_{a\to\gamma} \sim 10^{-4}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ {\rm GeV}^{-1}}\right)^2$



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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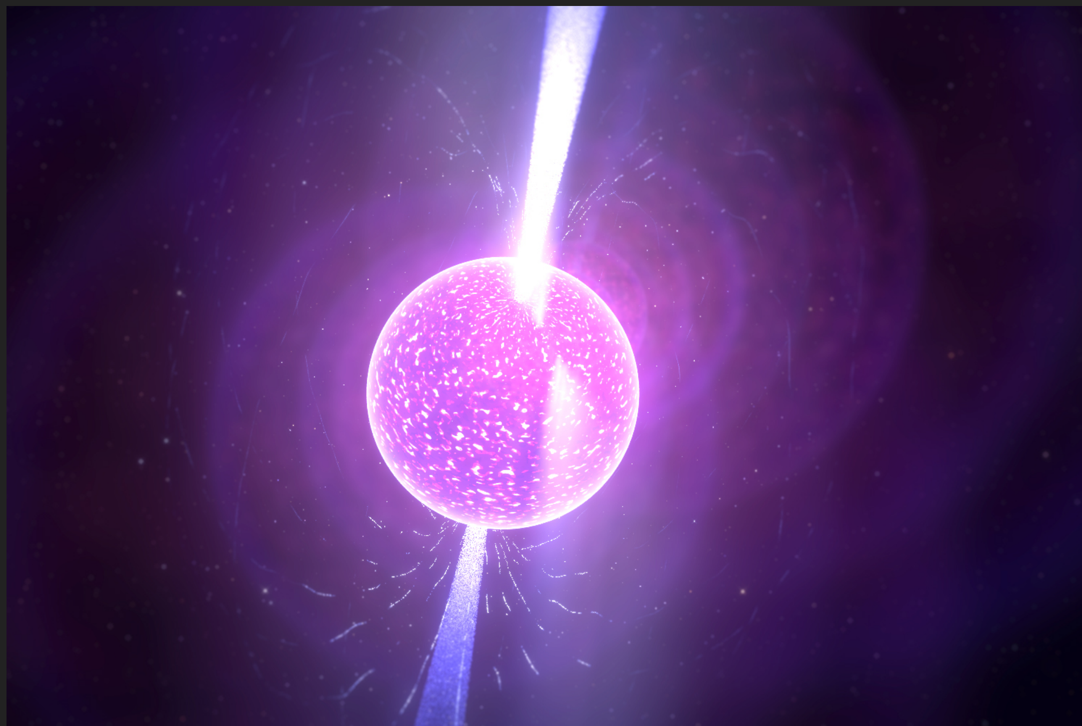
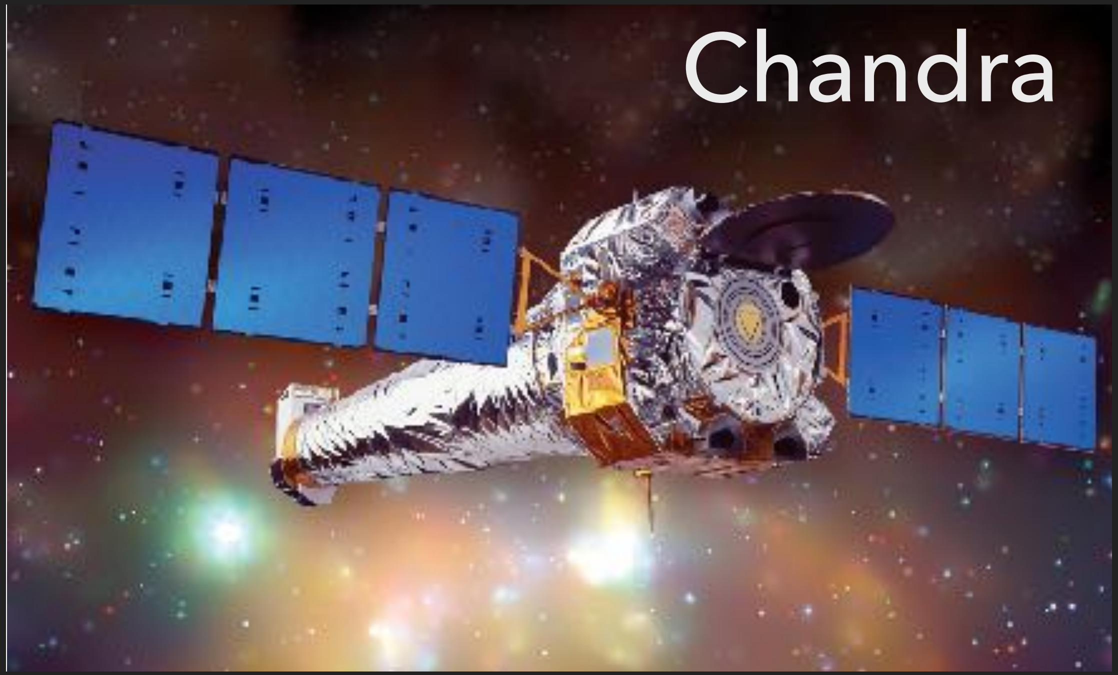
M7 hard X-ray excess



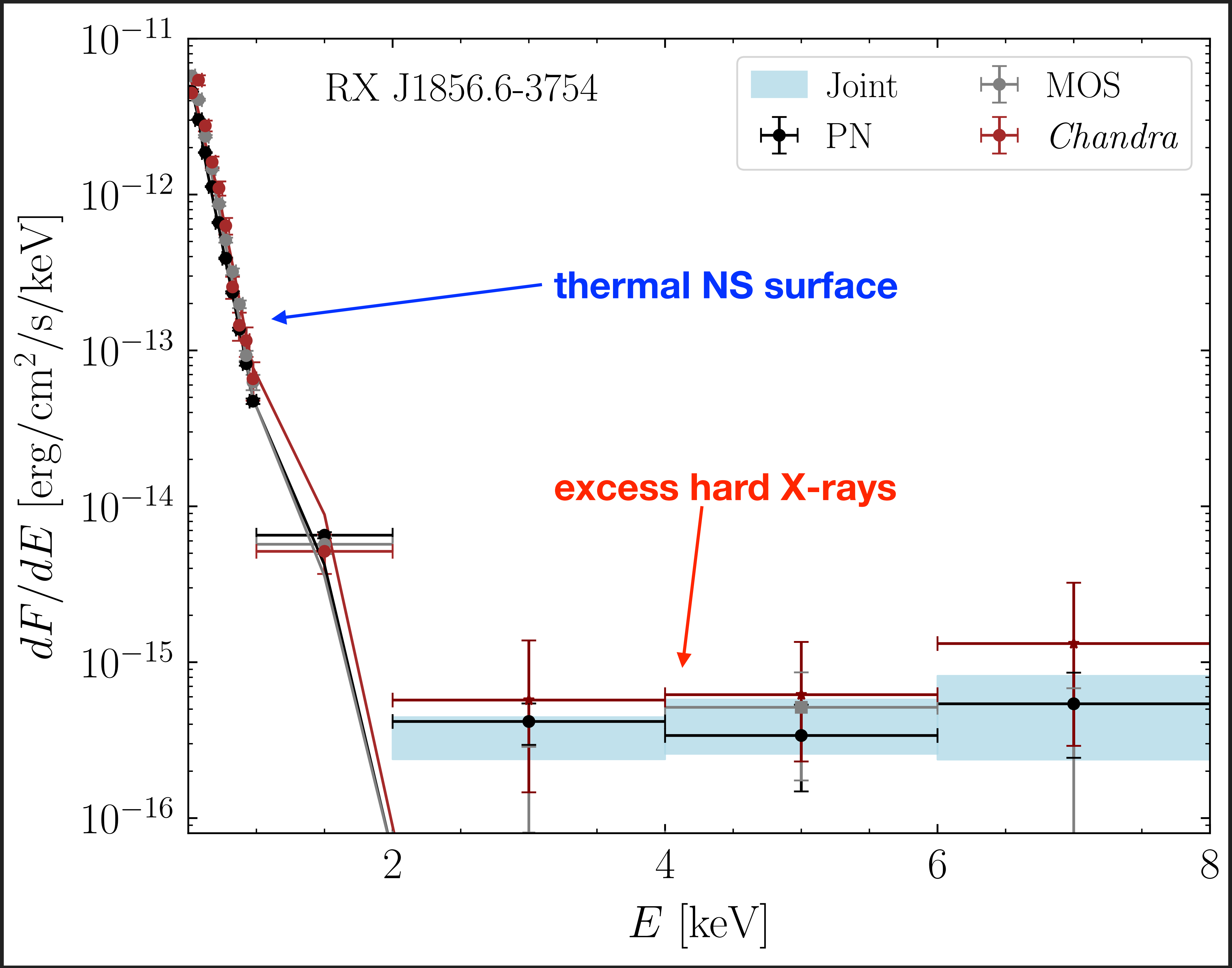
- 7 NSs between ~100 - 500 pc from Sun
- Discovered with ROSAT full-sky X-ray survey
- Surface: B ~ 10^{13} G (spindown)
- T_{surf} ~ 100 eV
- Non previous detection of non-thermal emission
- All old ~0.1 - 1 Myr and isolated

M7 hard X-ray excess

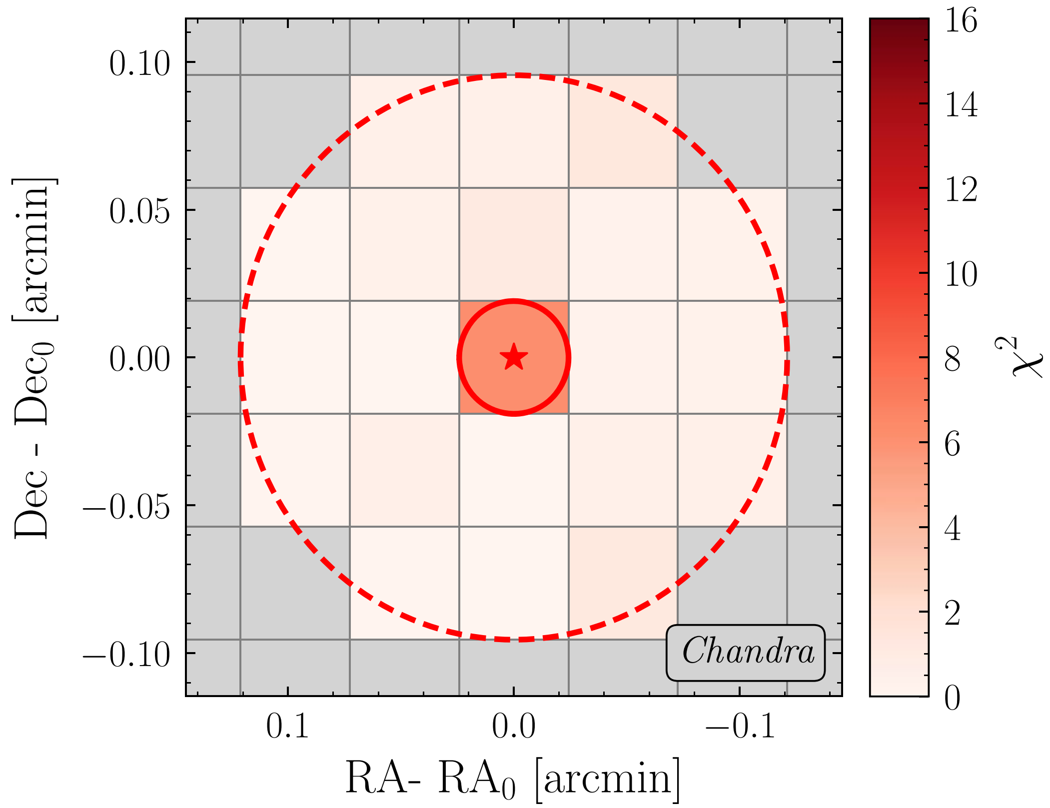


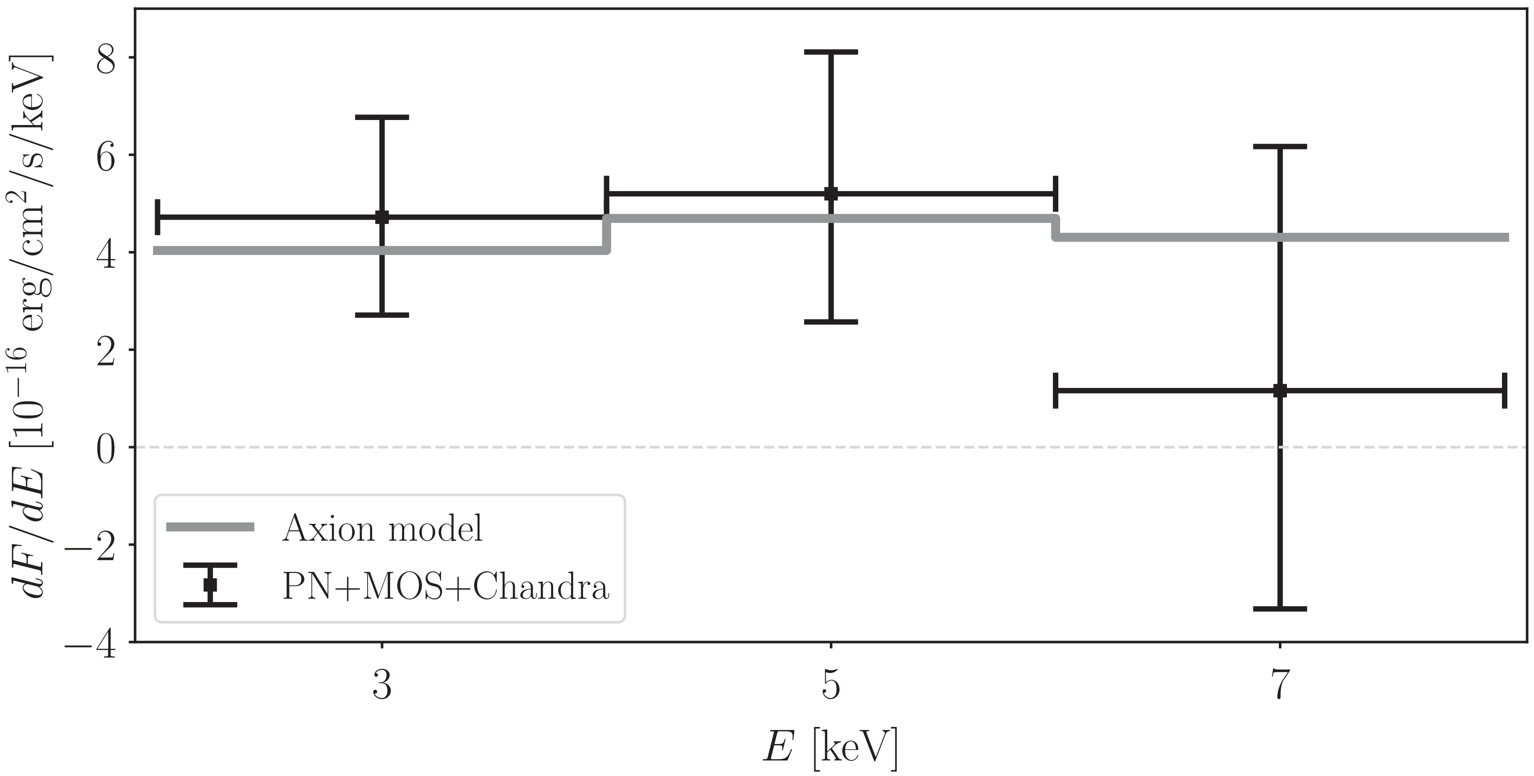
- data from ~2 - 8 keV
- XMM-Newton (PN and MOS)
  - ~50″ angular resolution
- Chandra
  - ~1″ angular resolution

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



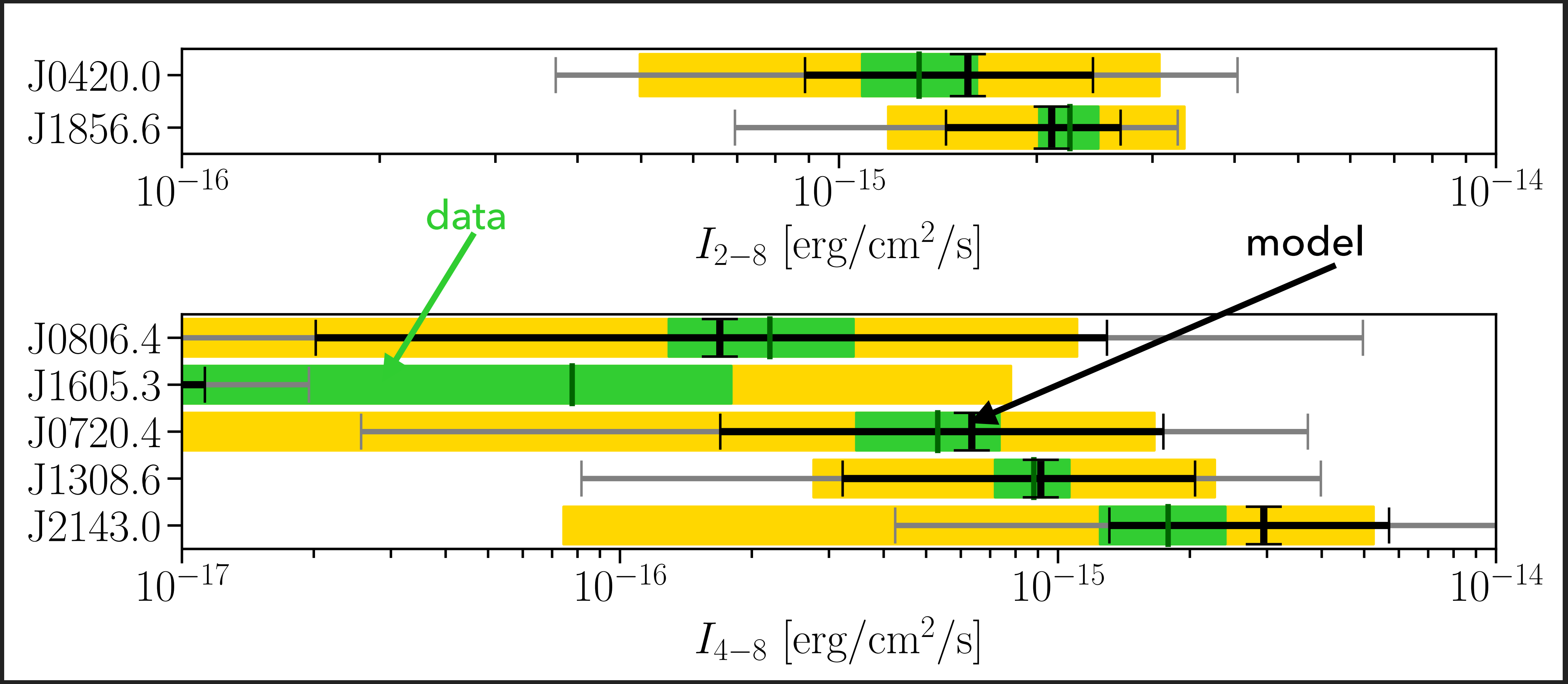
Hard X-ray excess from RX J1856.6-3754

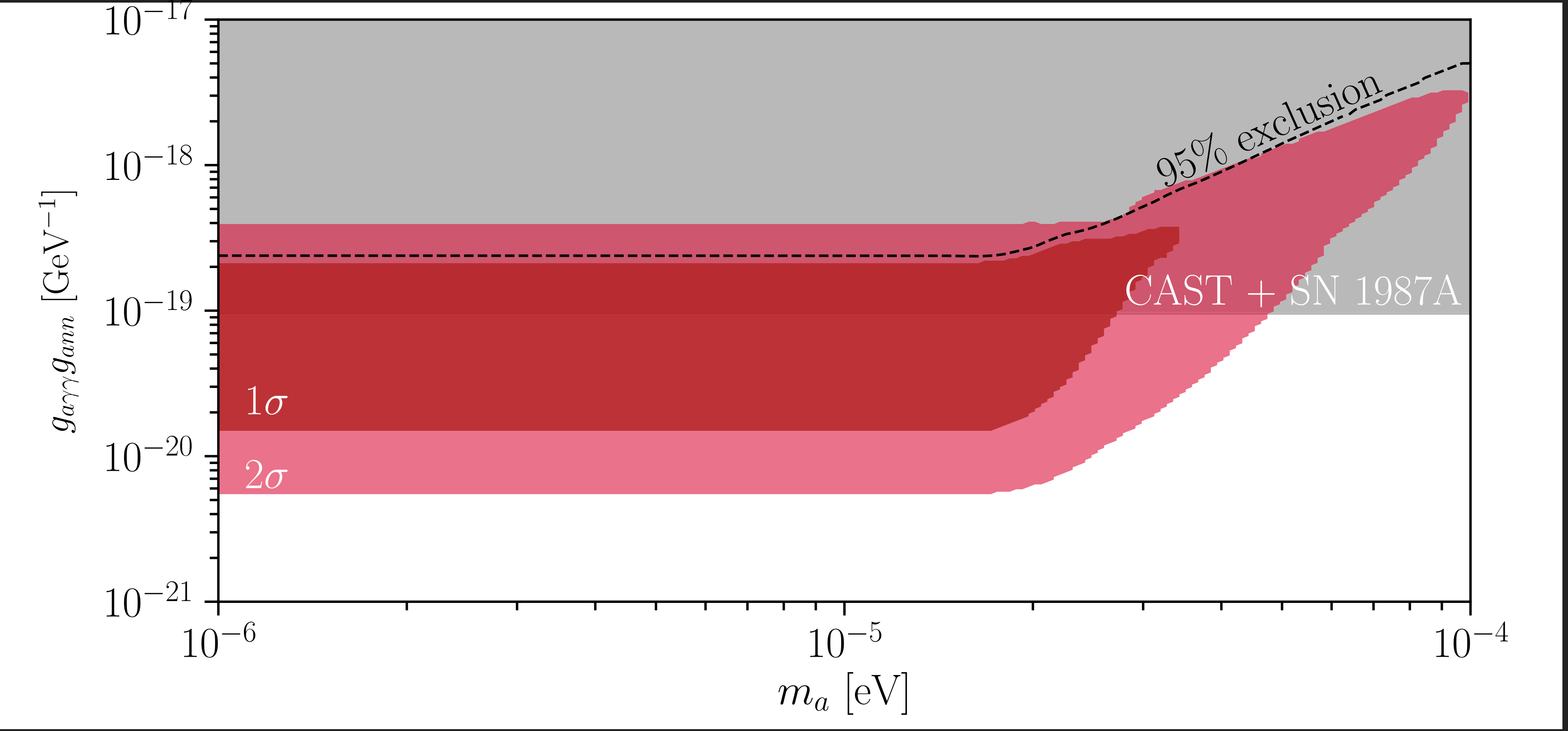




- No obvious astrophysical explanation

All M7 hard X-ray data





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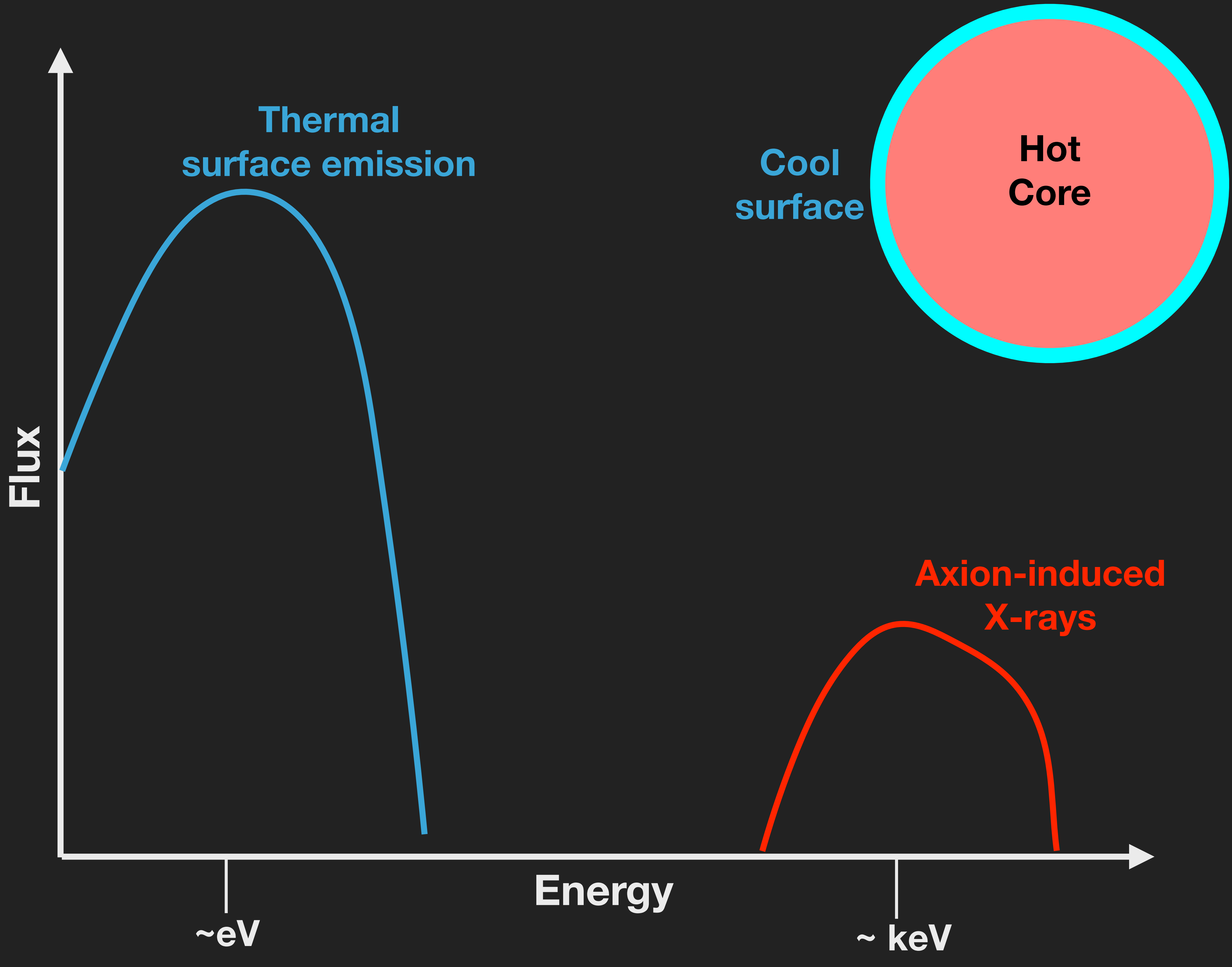
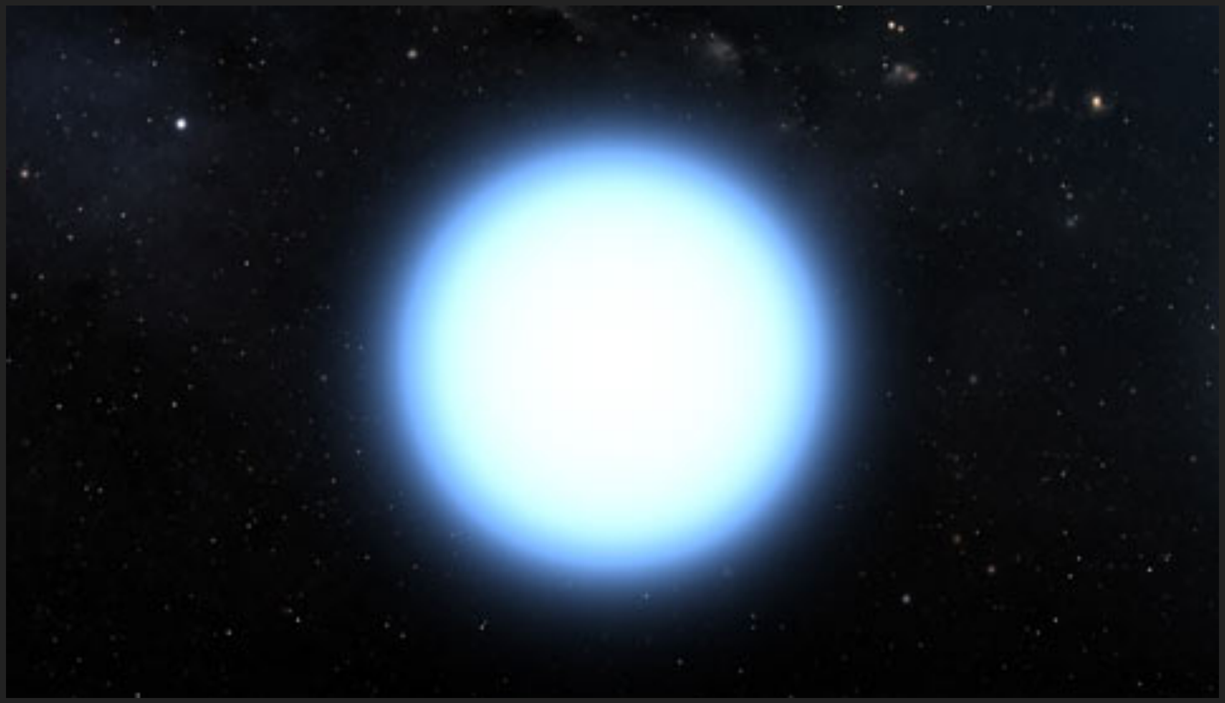
Magnetic white dwarfs are ultra-clean

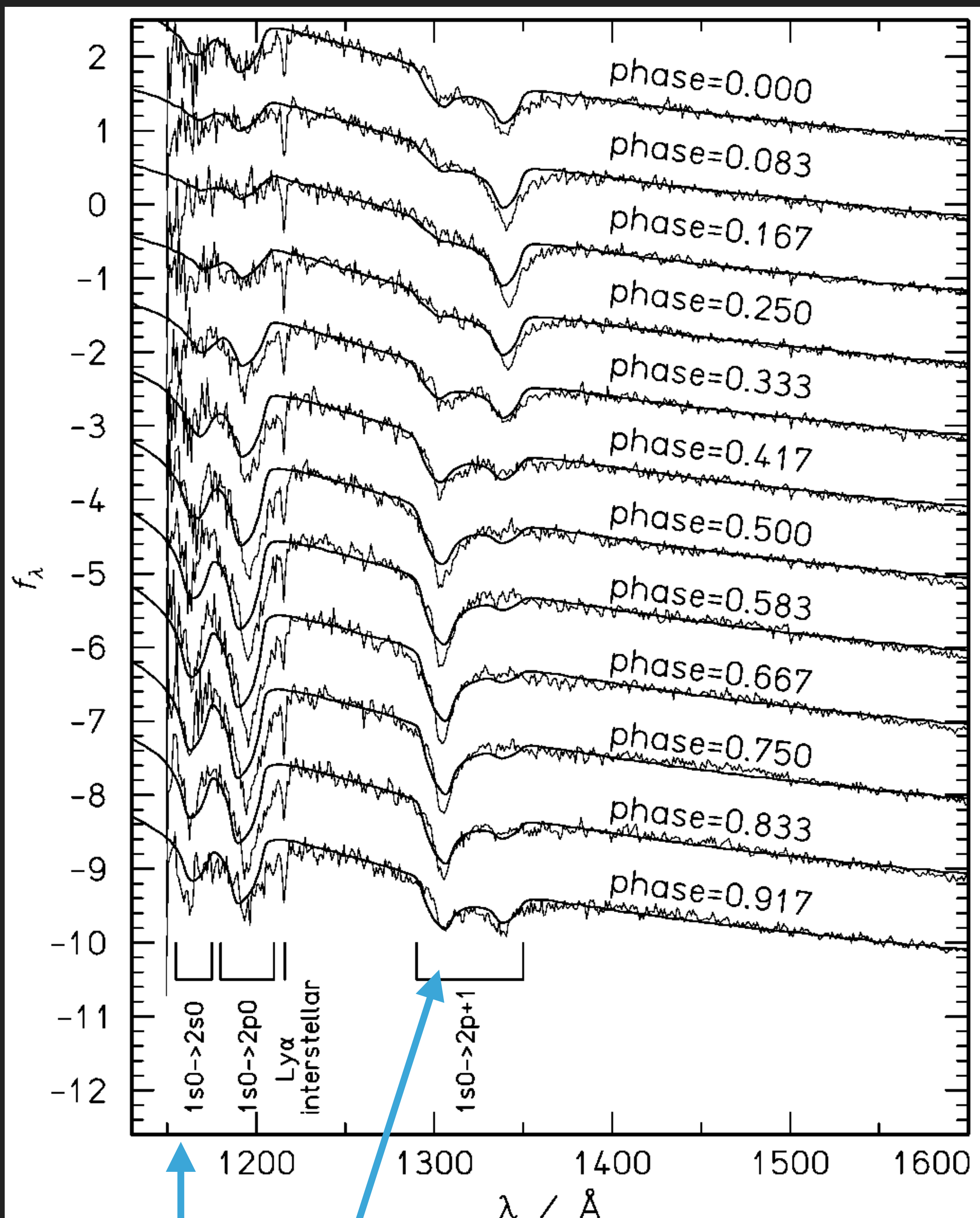


RE J0317-853 Facts



- "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} ~ 1.5 keV
- No previous dedicated X-ray observations

RE J0317-853 Magnetic Field

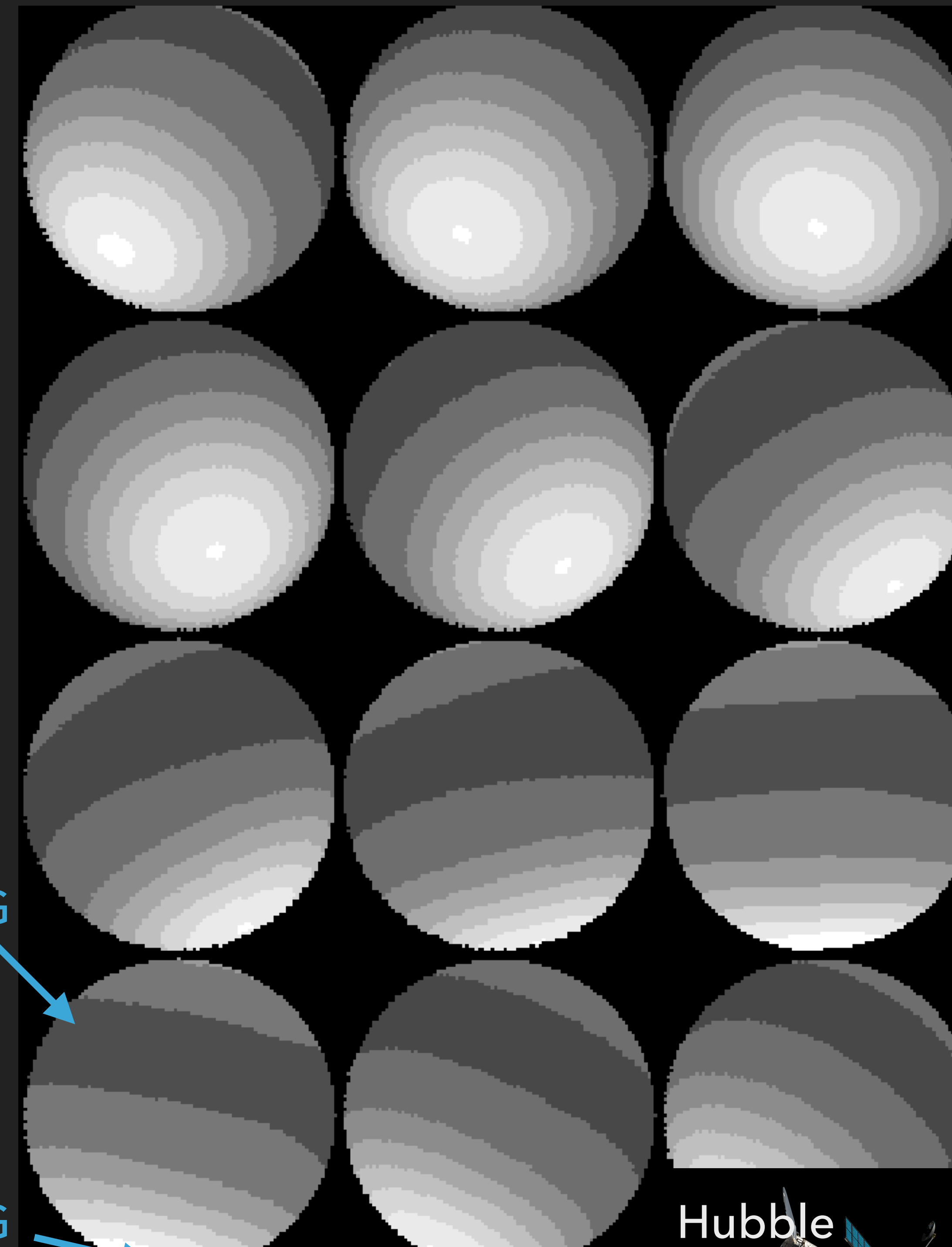


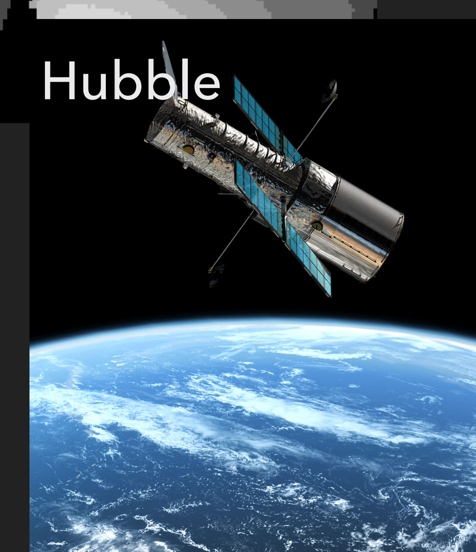
Zeeman splitting

Burleigh et al., ApJL 1999

100 MG

900 MG



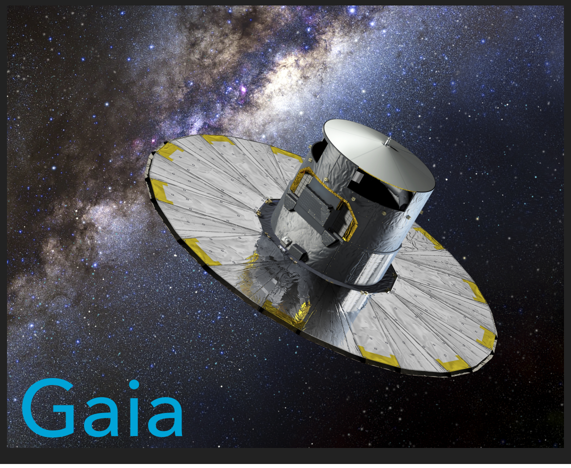


*consistent B-field from optical circular polarization

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

RE J0317-853 Core Temperature/Composition

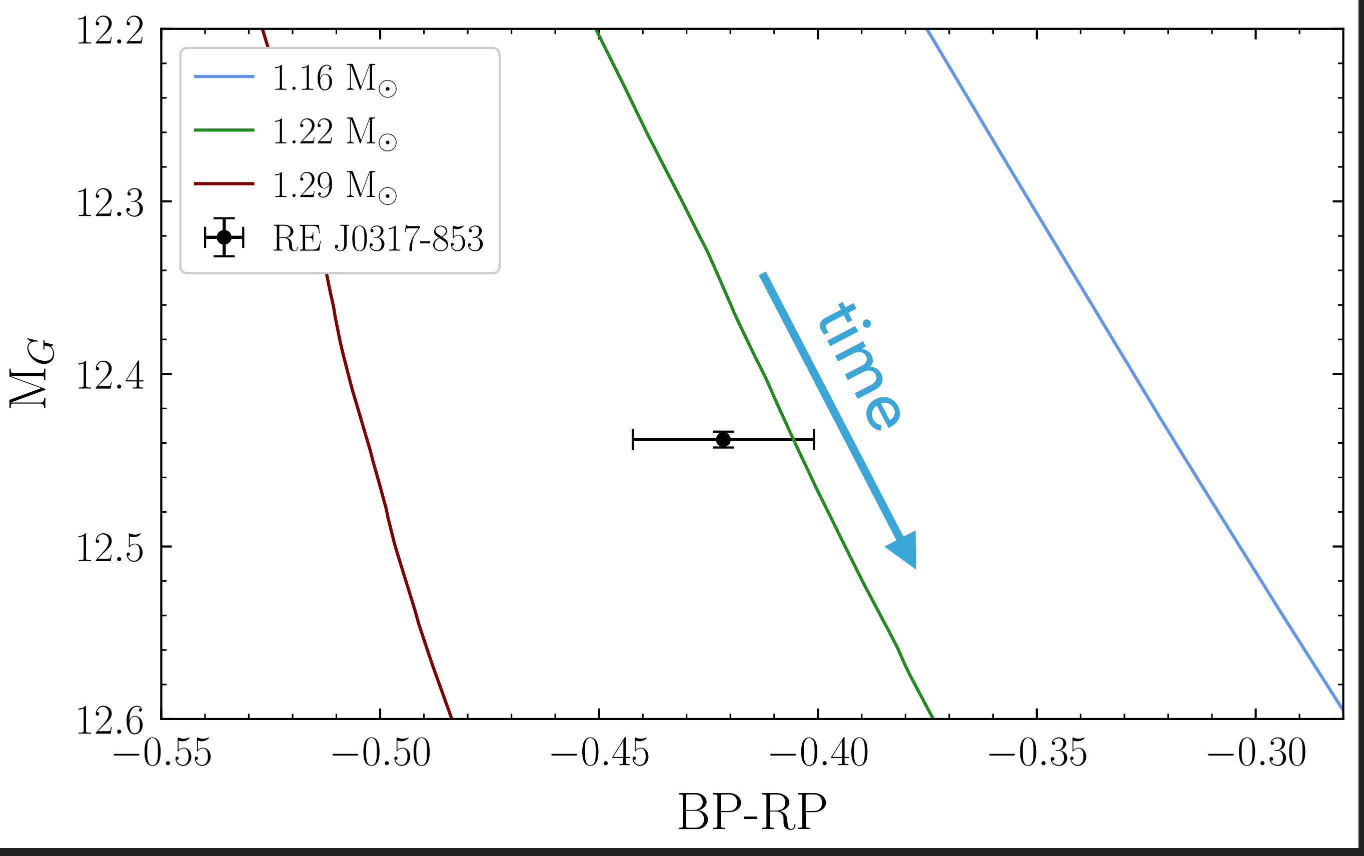
- Use Gaia measured Color (BP - RP) and Magnitude (M_G)
- Compare to dedicated WD cooling sequences that predict Gaia colors/magnitudes (Camissasa et al., A&A 2019)
- Combine with own dedicated MESA simulations for composition profiles

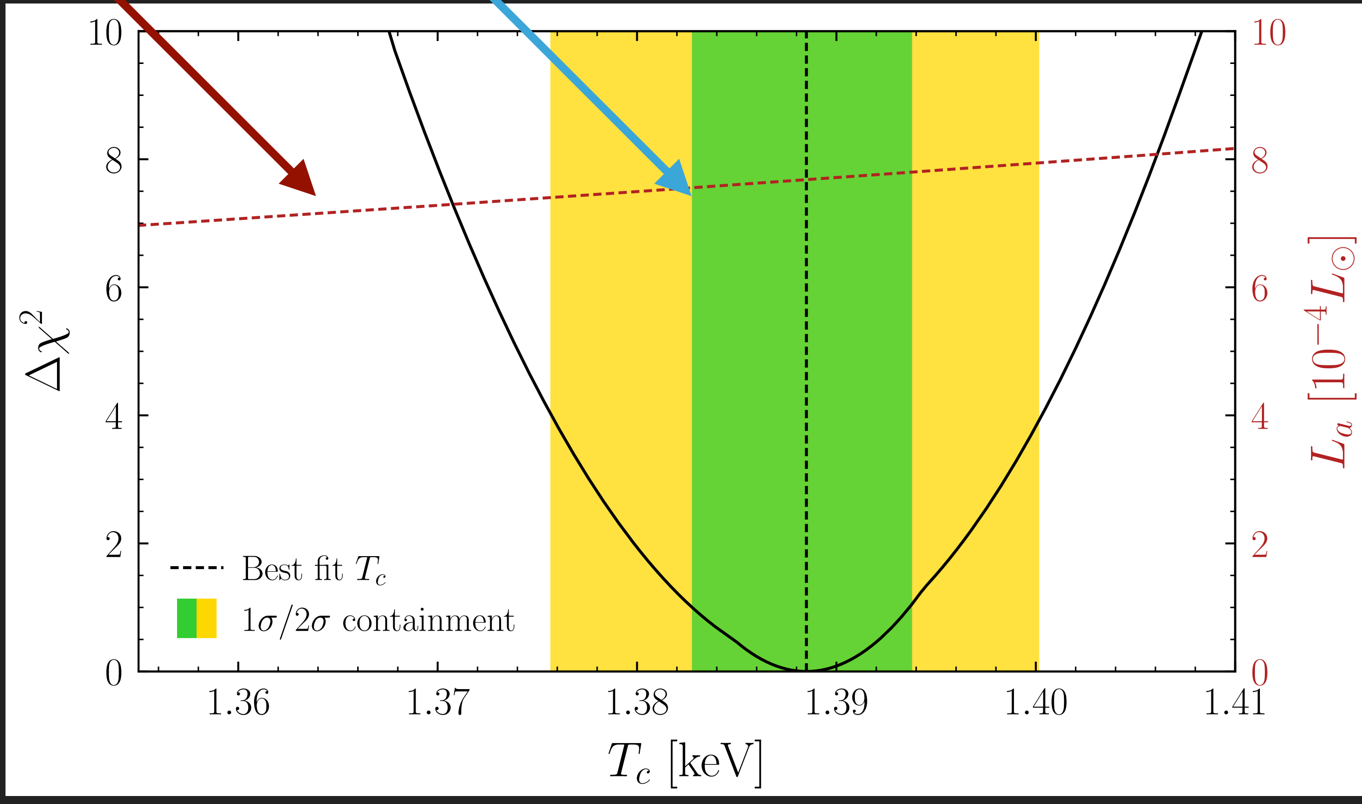


*consistent T_c base on binary companion age only + cooling theory

axion lum.

fiducial T_c

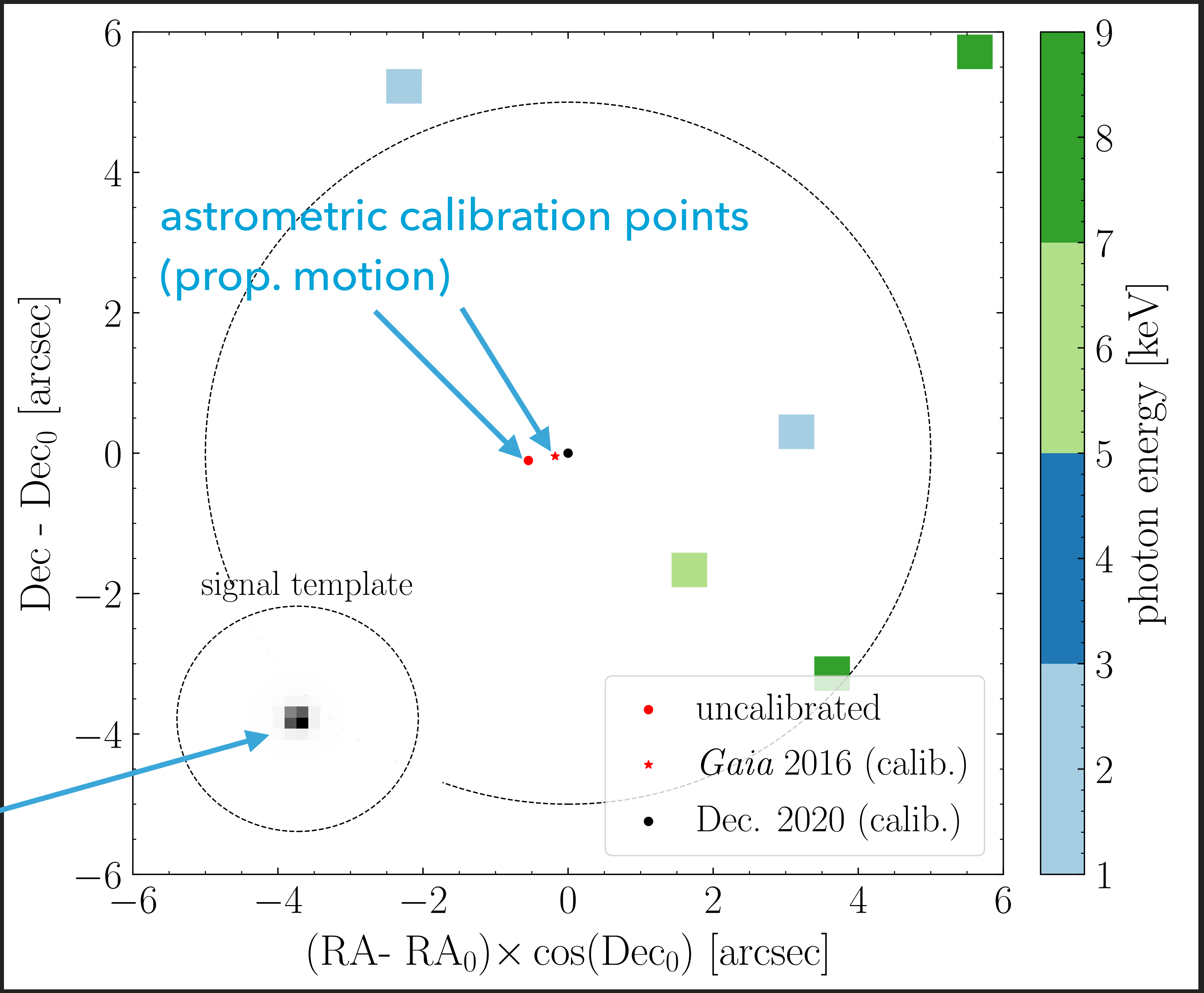




RE J0317-853 Chandra X-Ray Data

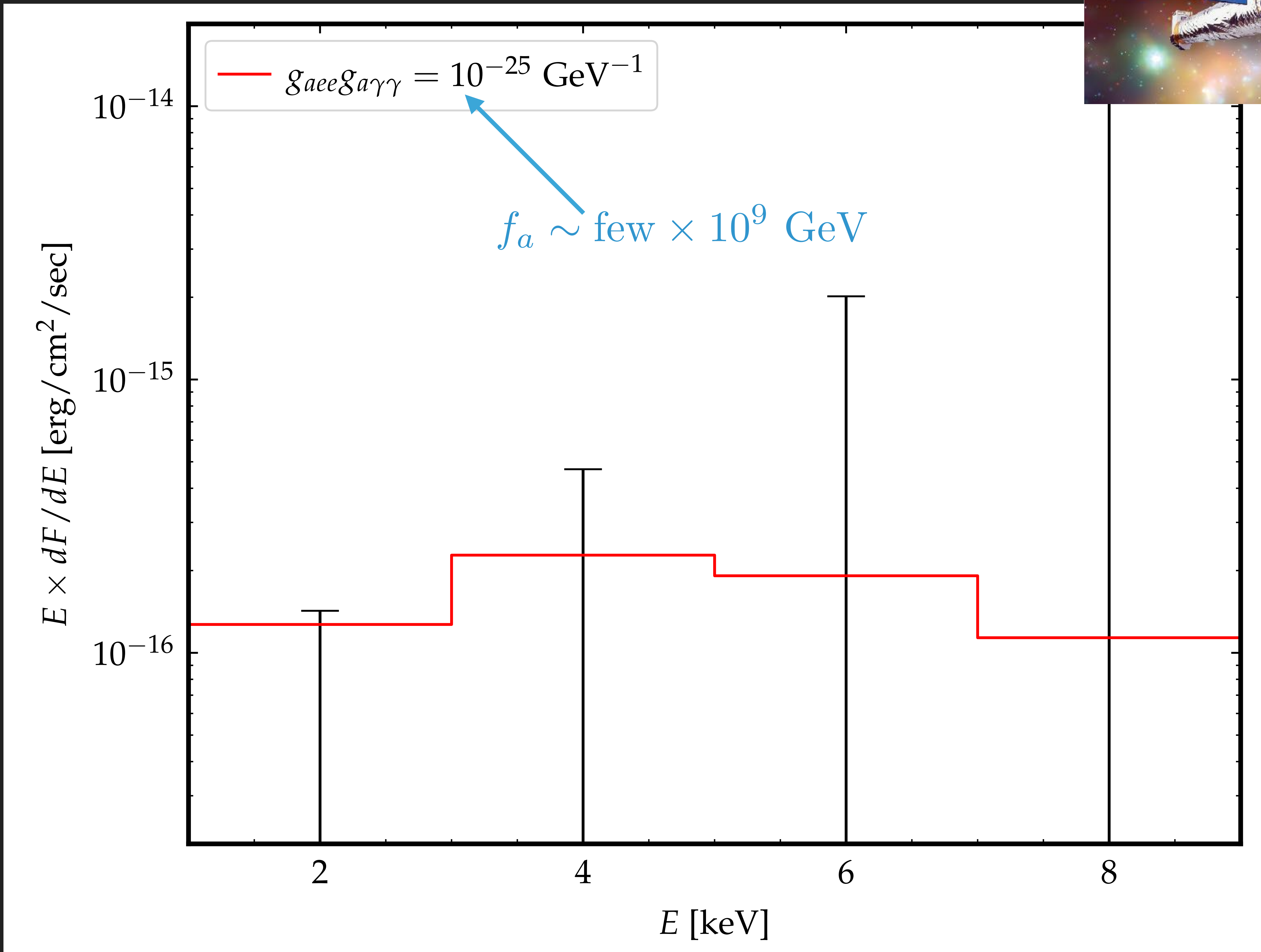
- ~40 ks with ACIS-I, no grating (18-12-2020)
- 1-9 keV

We saw absolutely nothing! :-(

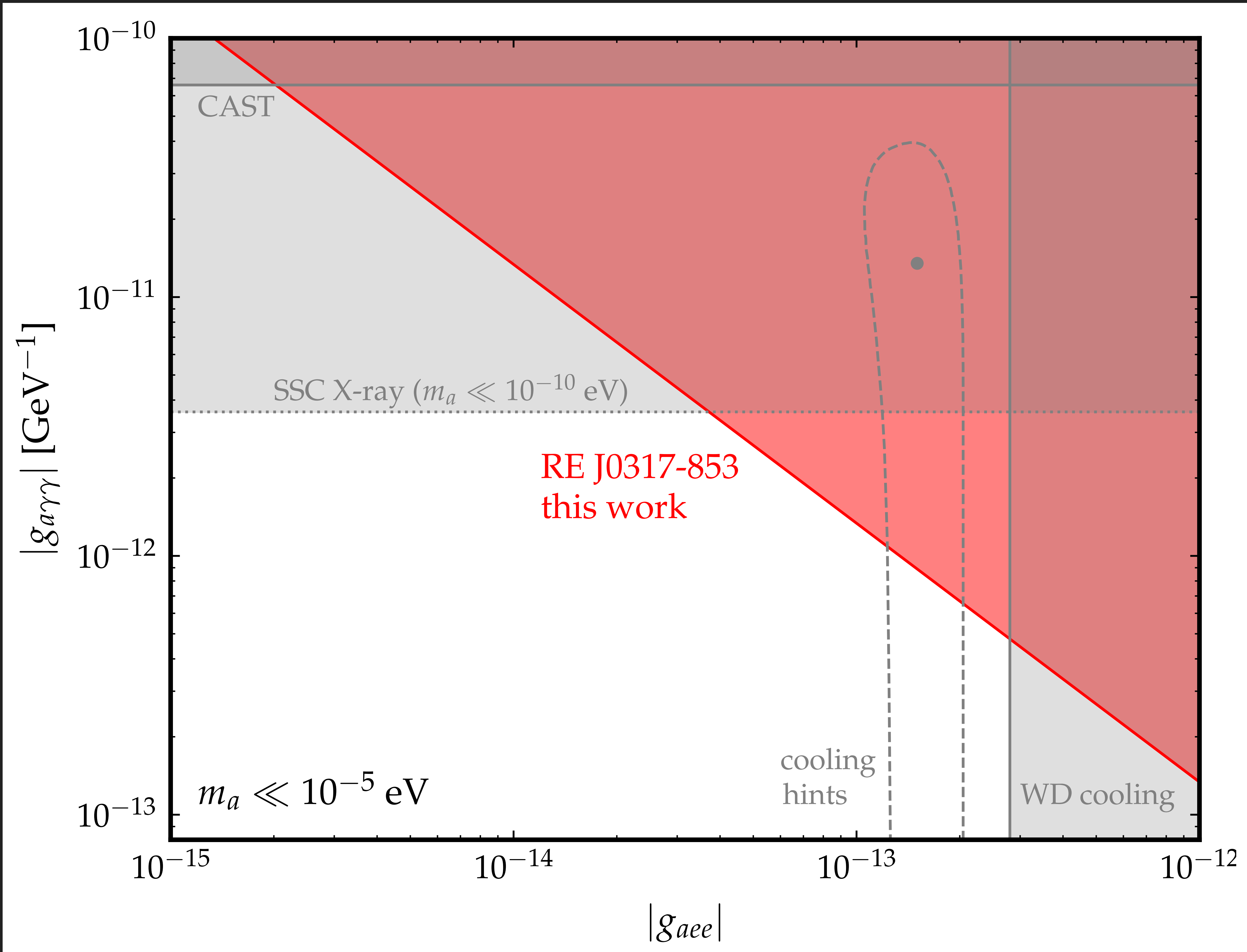


angular res.

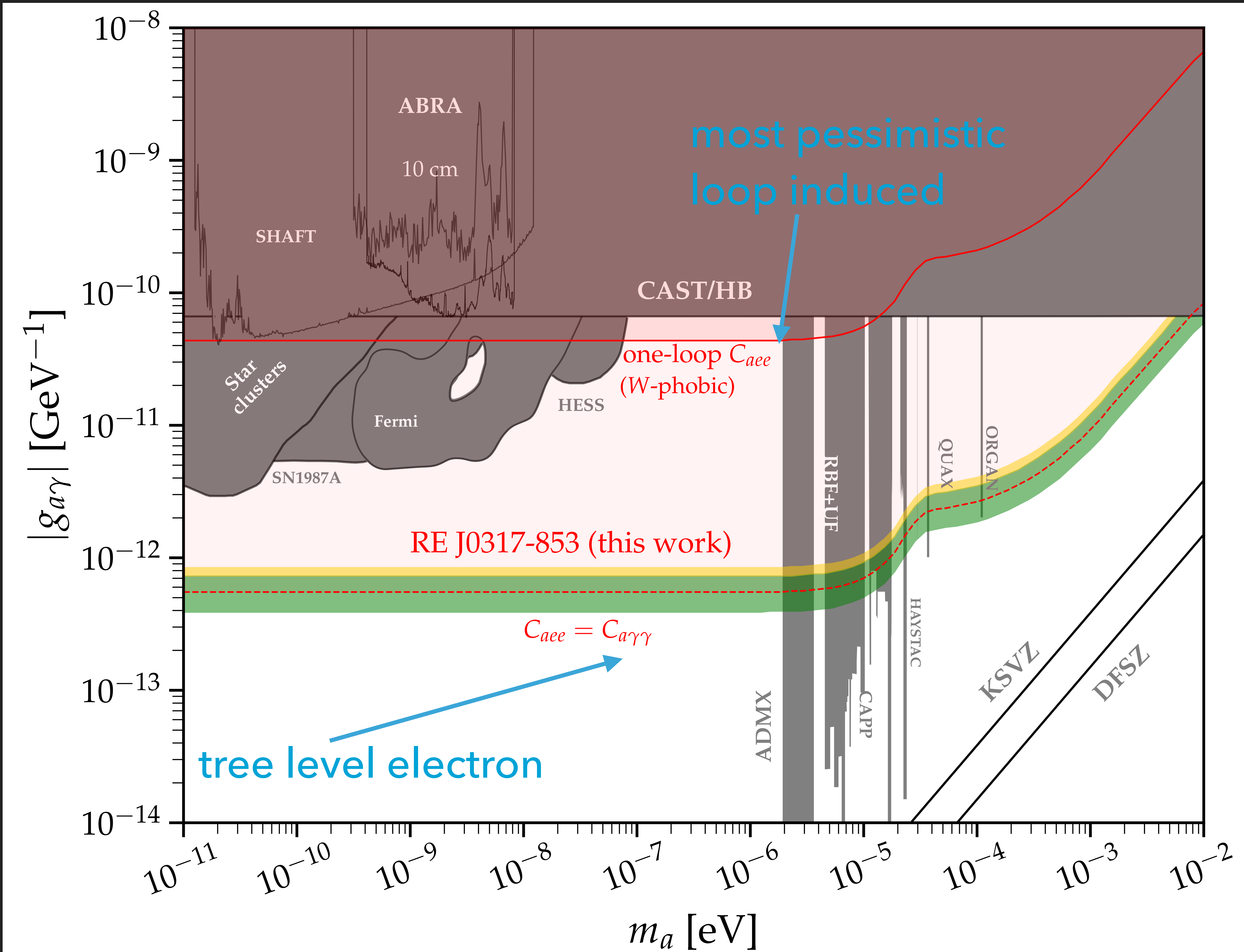
RE J0317-853 Chandra X-Ray Data



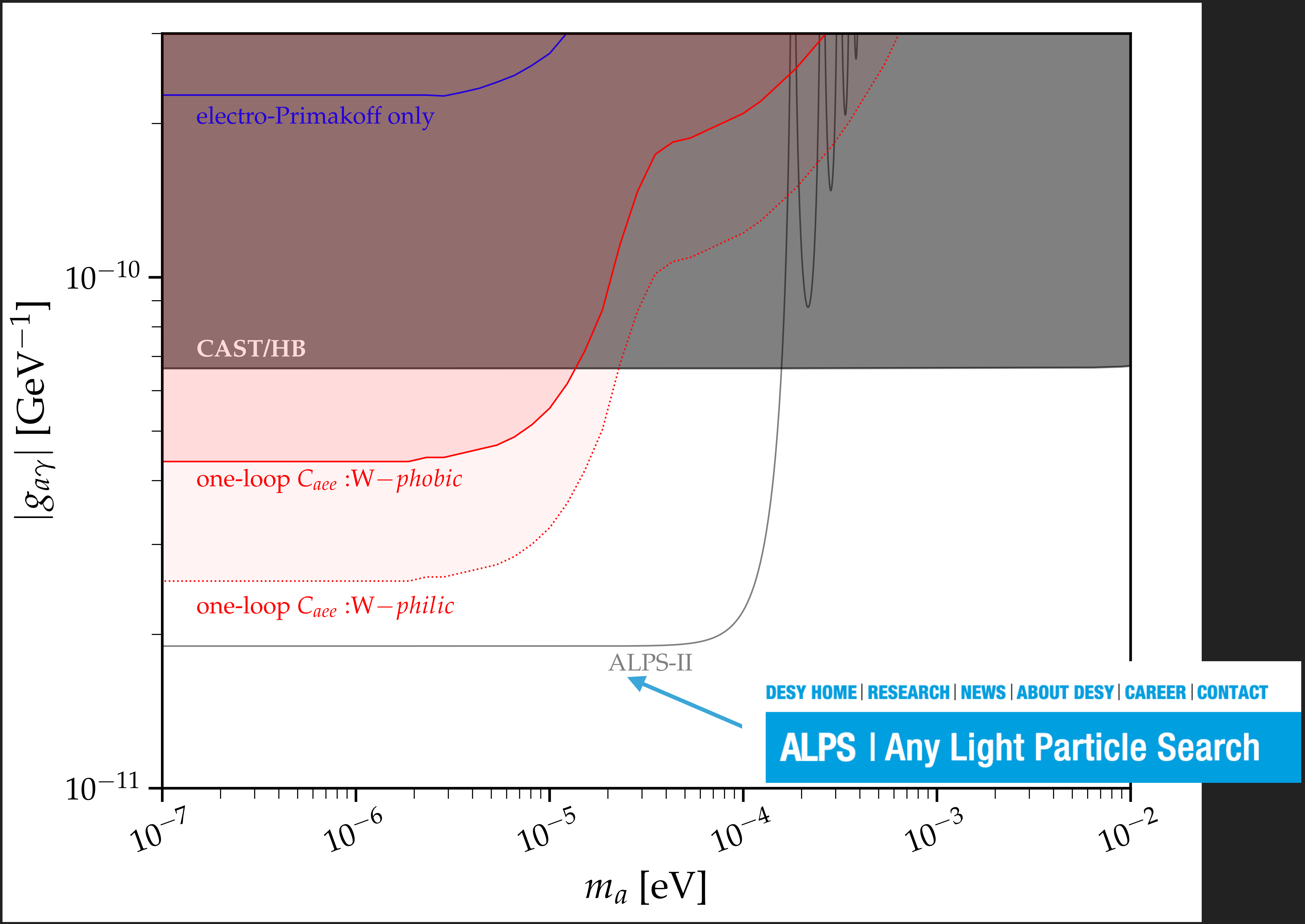
$|g_{aee}g_{a\gamma\gamma}| < 1.3 \times 10^{-25}\ \mathrm{GeV}^{-1}$ at 95% C.L. (low mass)



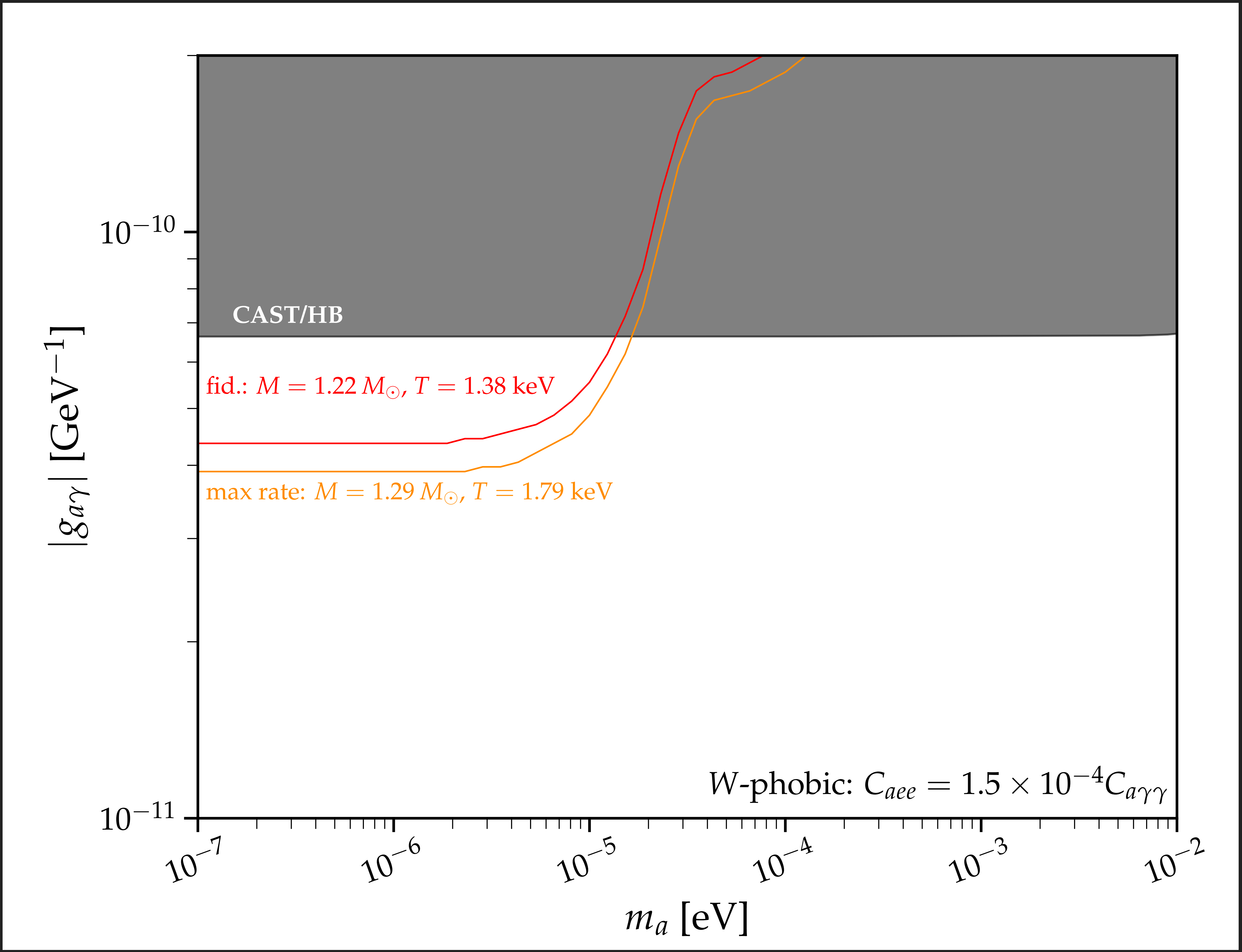
Results in terms of axion-photon coupling



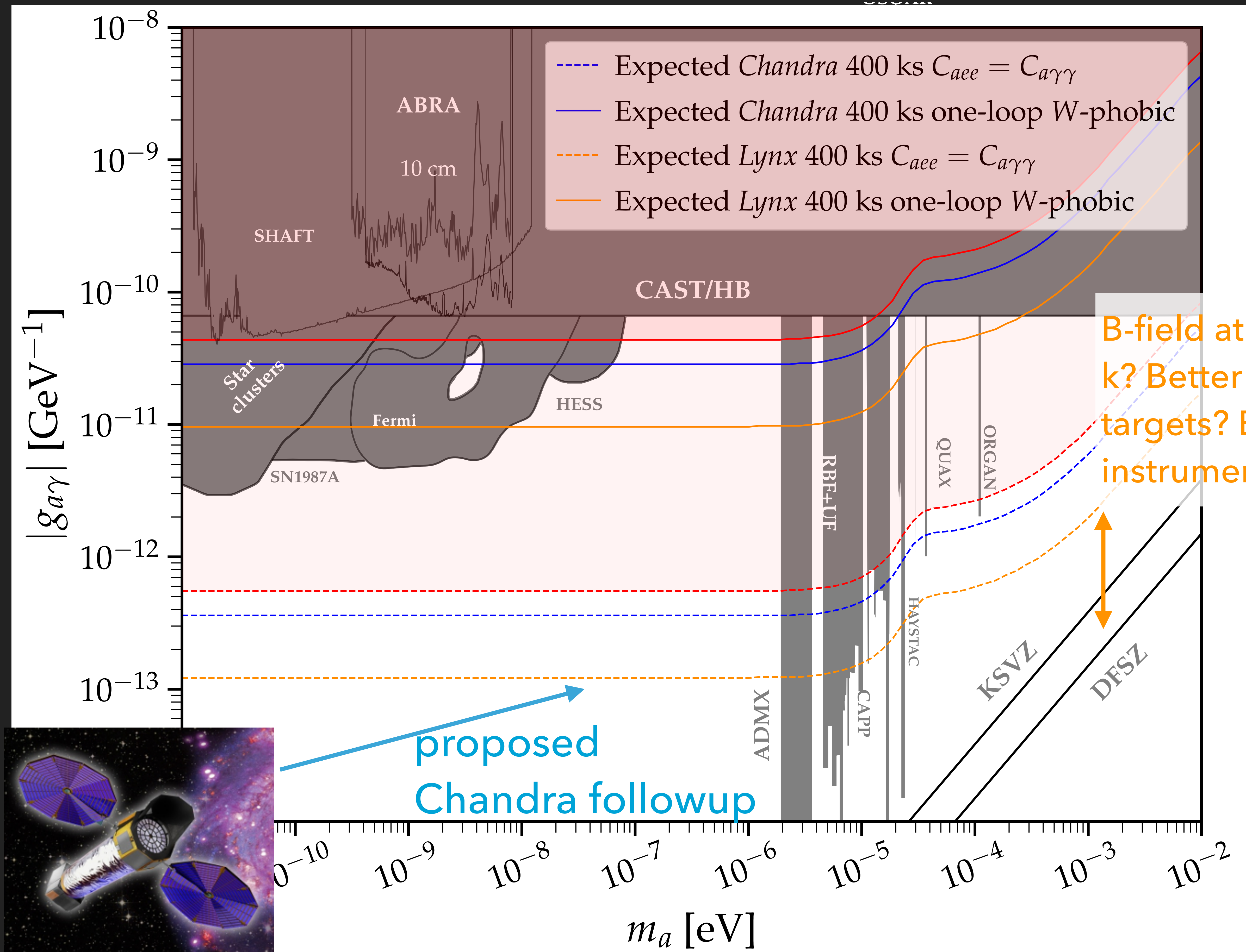
One-loop axion-photon coupling



Stellar modeling systematics



Future Searches Towards RE J0317-853



B-field at higher k? Better targets? Better instruments?

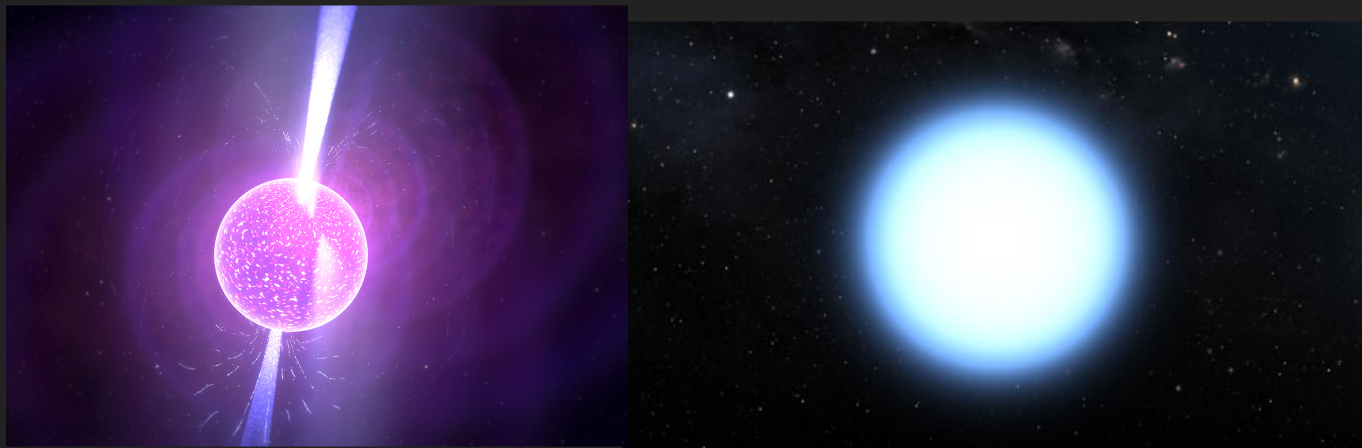
proposed Chandra followup

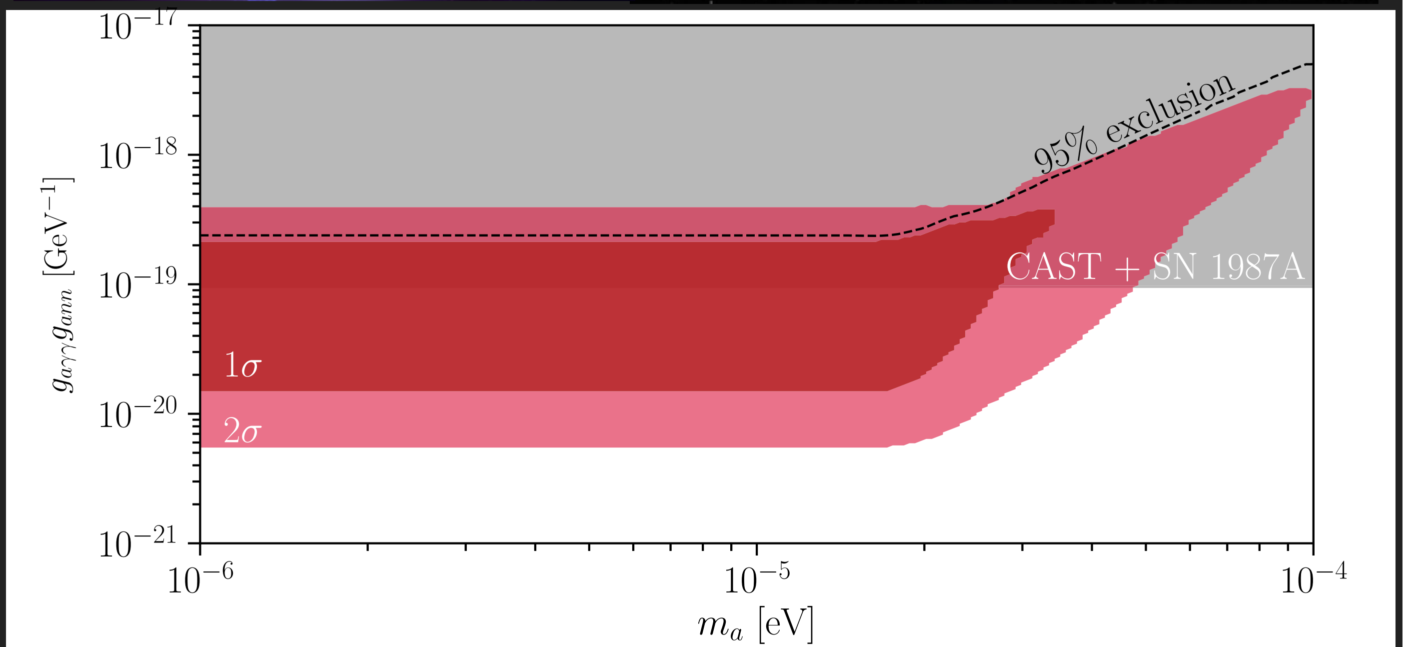
Outline

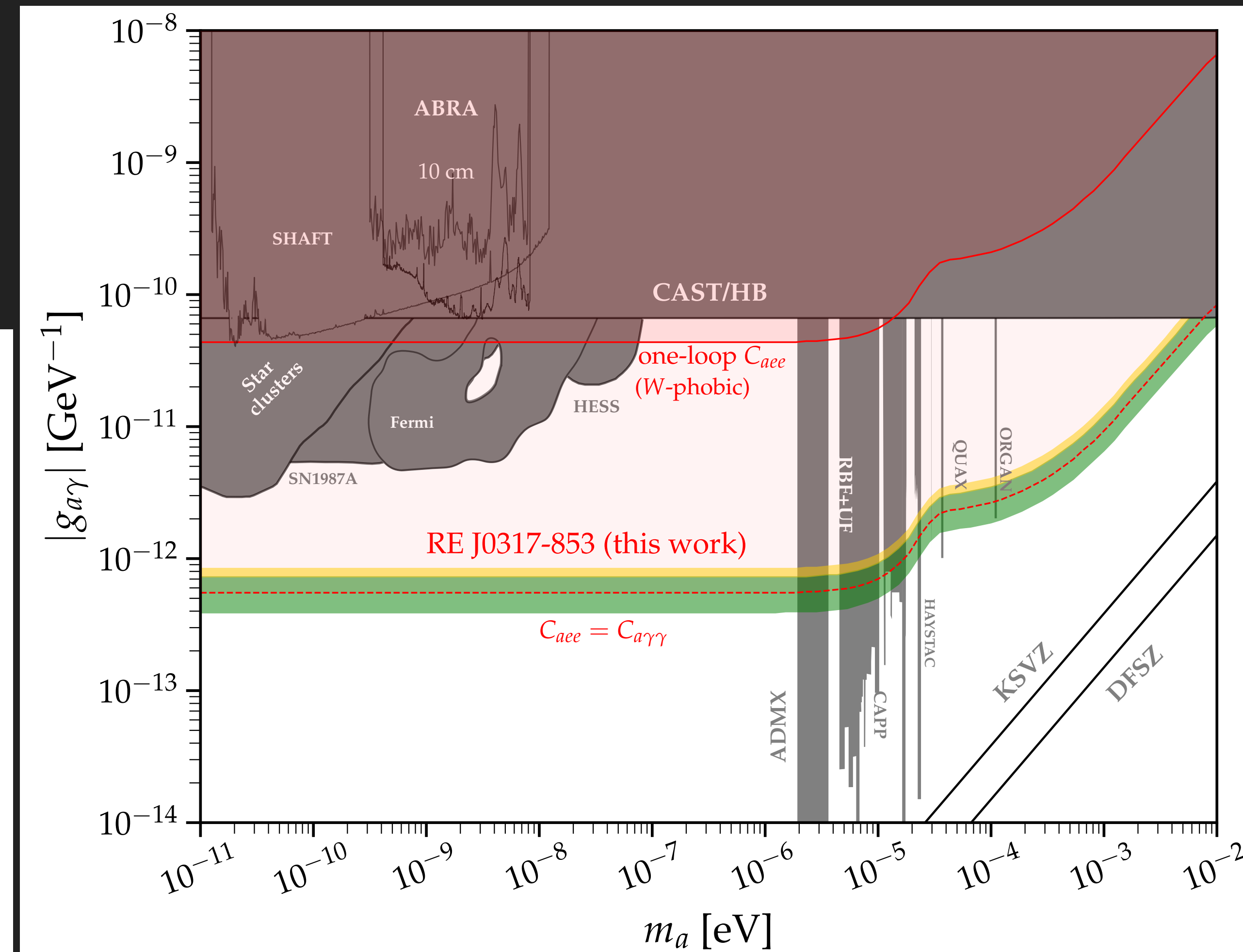
1. Axions with X-ray observations of white dwarfs and neutron stars (theory)
2. X-ray data: neutron star data (M7 anomaly)
3. X-ray data: white dwarfs data (RE J0317-853)
4. Future work and in progress

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)

M7 Excess in light of RE J0317-853







need electrophobic / nucleophilic axion

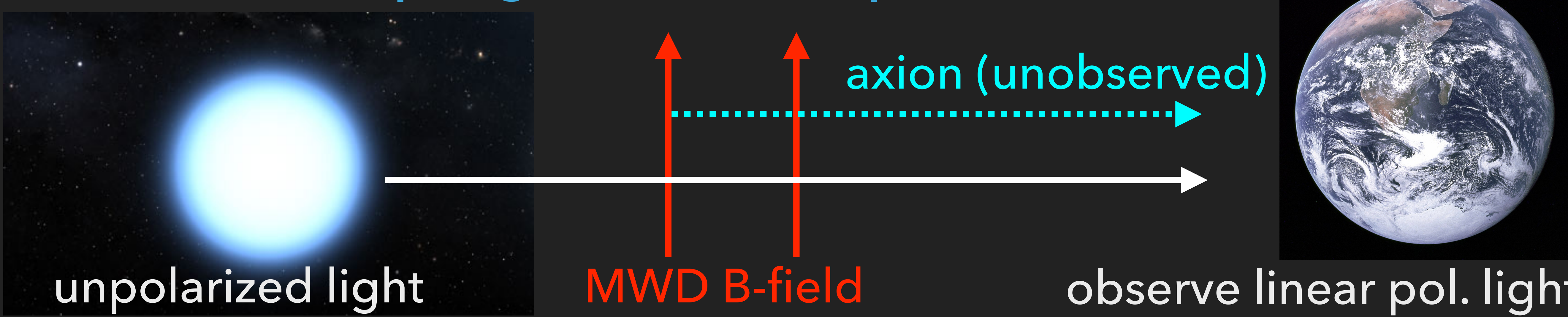
$$\frac{C_{aee}}{C_{aNN}} \lesssim 0.1$$

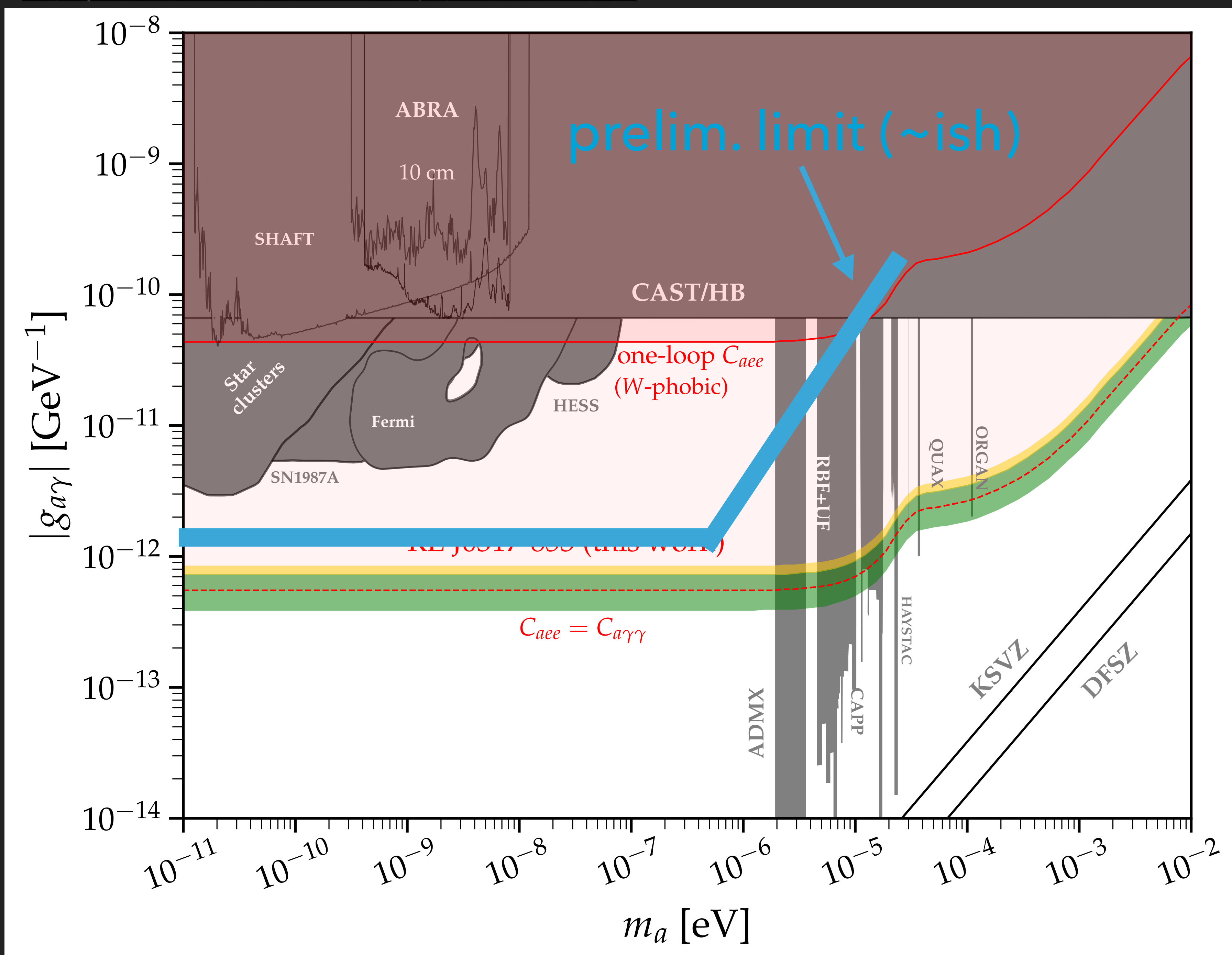
← not most generic expectation for ALP!

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?

In progress: MWD polarization





basic idea: Gill, Heyl 2011

our work (in progress):

1. Improved modeling
2. Dedicated and modern MWD polarization data towards optimal targets

Conclusion

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)

In progress and thoughts for future work

1. polarization studies from white dwarfs and neutron stars (in progress)
2. Additional white dwarfs and more X-ray data
3. Can axions (or other BSM) explain M7 NSs and be consistent with other WD constraints?
    1. Enhance axion NS production (cyclotron, meson condensates, QGP, …)

Questions?