Solar axion detection and the inverse Primakoff process

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09/24/2020 Mini-workshop @CHEP, Peking University

The axion and the Strong CP problem

$$\mathscr{L} \supset -\frac{\theta g_s^2}{32\pi^2} G\tilde{G} - \left(\bar{u}_L M_u u_R + \bar{d}_L M_d d_R + \mathrm{h.c.}\right)$$

- The CKM matrix
  - CP violating phase ~ 1.2 radian
- QCD induced CP violating phase

$$\theta_{\mathrm{QCD}} = \theta + \arg\left[\det\left[M_u M_d\right]\right]$$

- Invariant under quark chiral rotation
- According to neutron EDM experiment

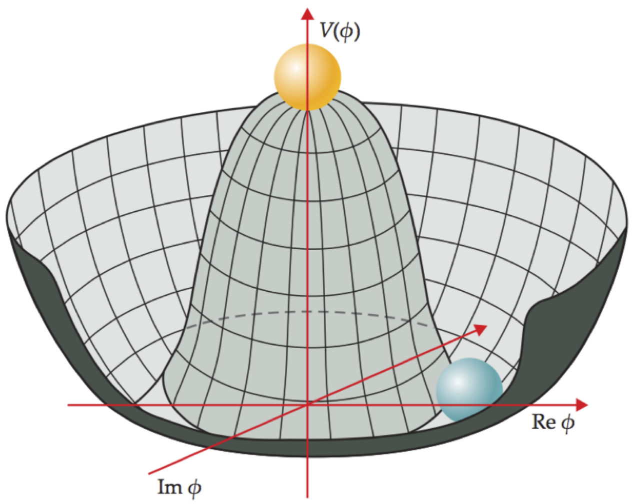
$$d^n_{\mathrm{EDM}} \sim \theta \times 10^{-16}\ \mathrm{e\ cm}$$

$$d^n_{\mathrm{exp}} < 10^{-26}\ \mathrm{e\ cm}$$

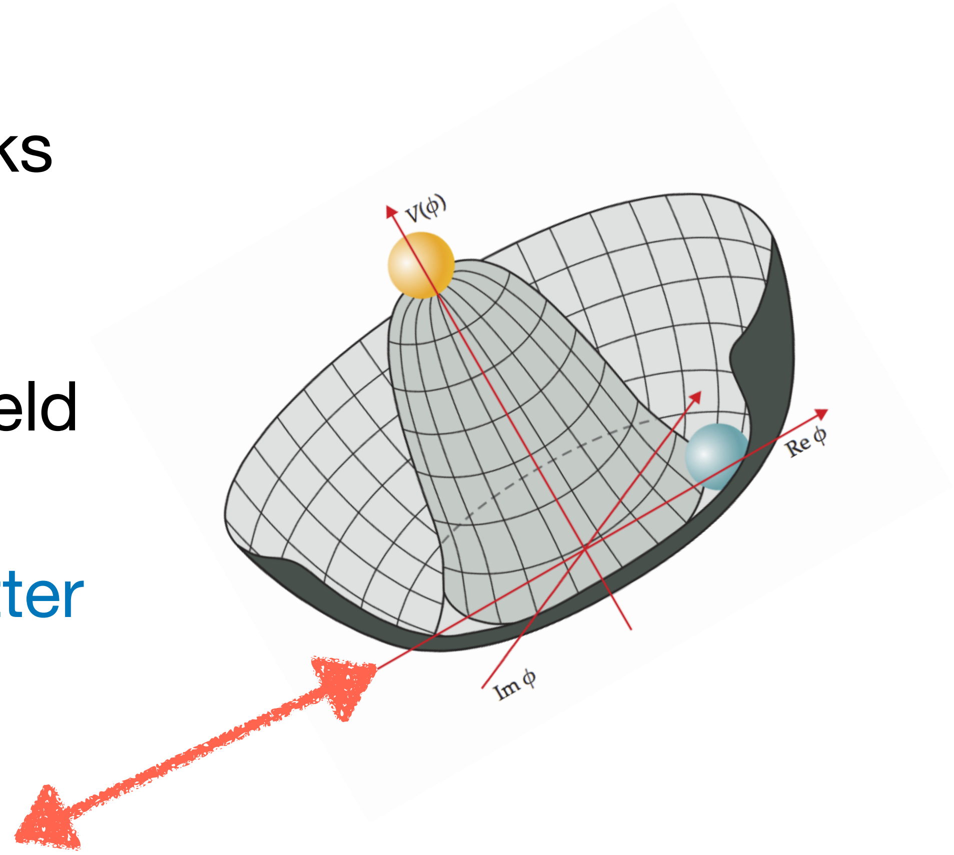
$$\theta_{\mathrm{QCD}} \lesssim 1.3 \times 10^{-10}\ \mathrm{radian}$$

Axion: the Strong CP problem and Dark Matter

- Global $U(1)_{PQ}$ symmetry
  - Spontaneous broken leads to massless goldstone (Axion)



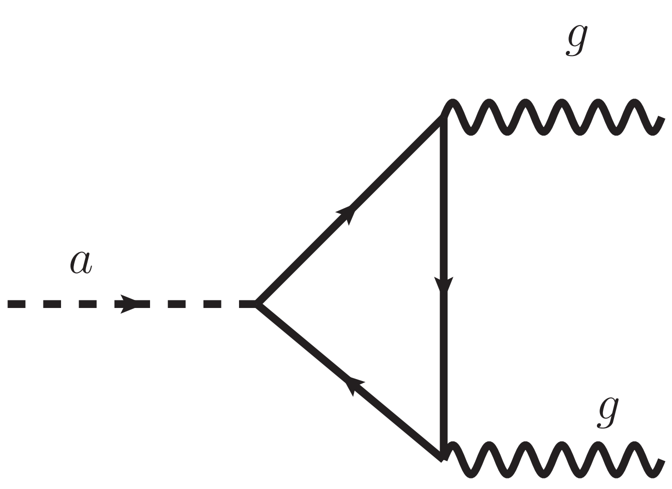
- At QCD scale ~ O(1) GeV,
  - Potential from Chiral Lagrangian explicitly breaks the symmetry leads to massive axion
  - Energy stored in coherent oscillation of axion field
  - When mass ~ Hubble, becoming cold dark matter
  - QCD vacuum picks

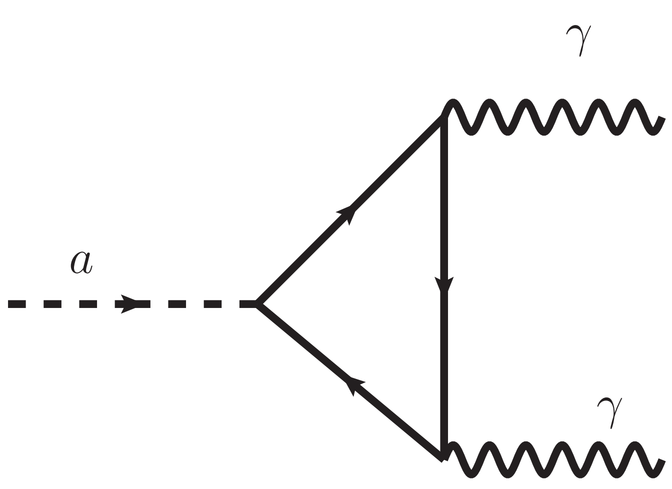


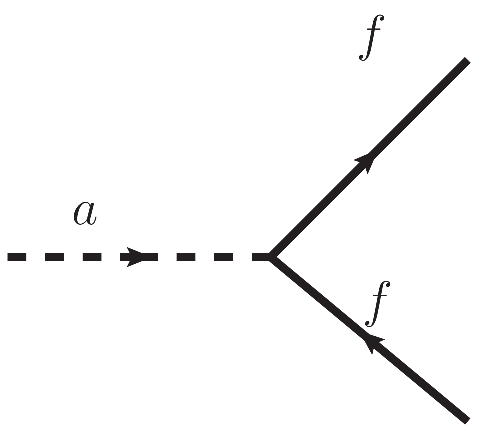
$$\Theta = \theta_{\rm QCD} + \xi \langle a \rangle / f_a = 0$$

Motivation for axion and axion-like particles

- Strong CP problem
- Dark Matter
- Stellar cooling/ TeV transparency

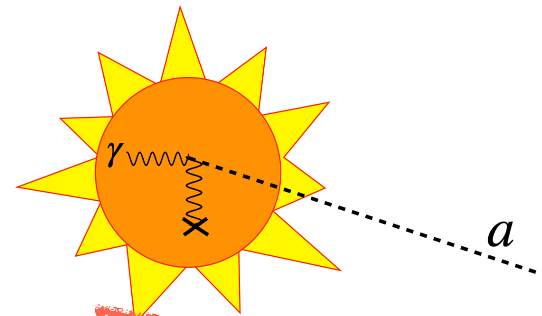


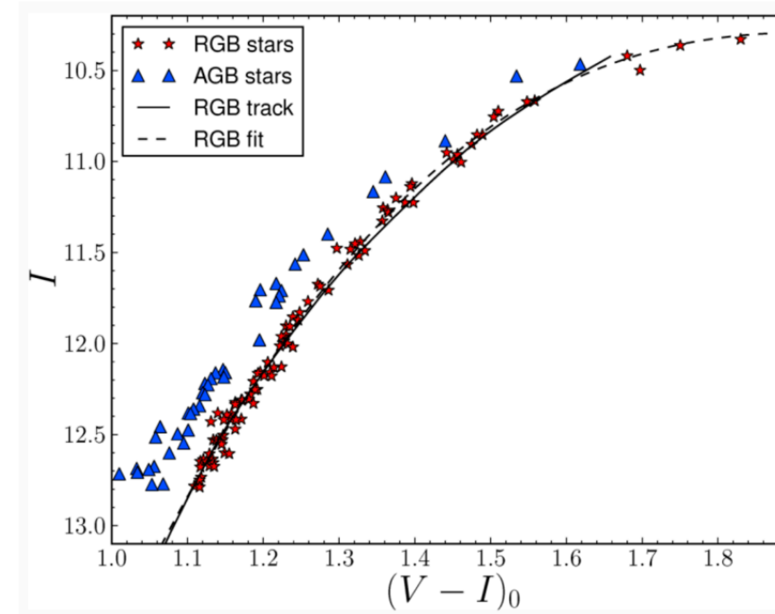


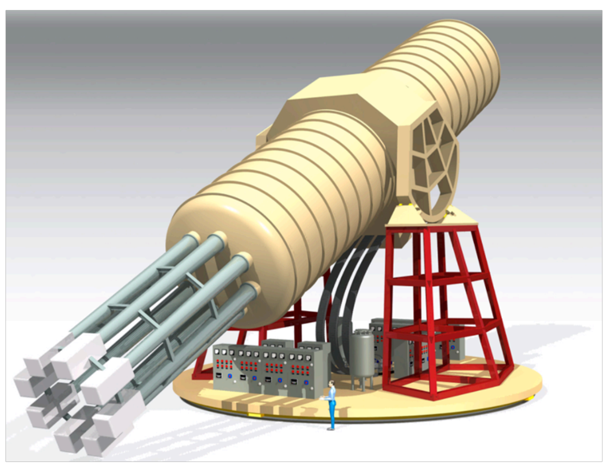


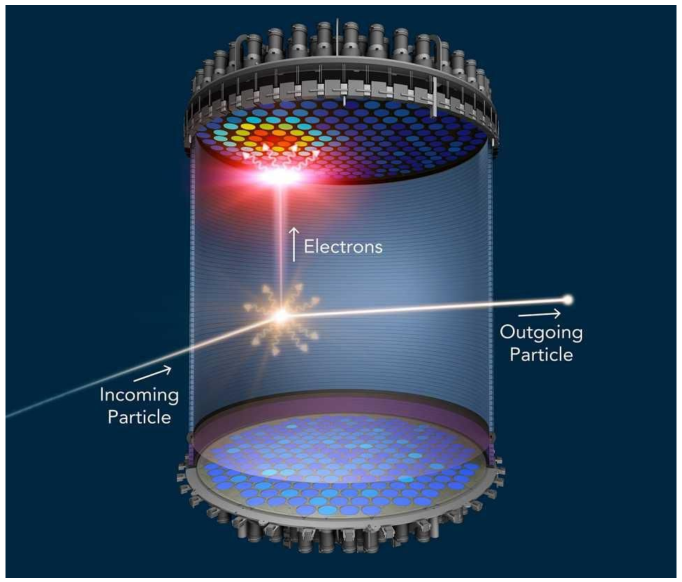
Experimental approaches

- Dark Matter Axion: haloscopes …
- Axion independent searches:
  - Rare meson decays
  - Stellar cooling
  - Supernova
  - Helioscopes: solar axion (CAST, IAXO, or DM direct detection searches)
  - Light shining through walls
  - Polarization
  - Fifth force
  - Etc..





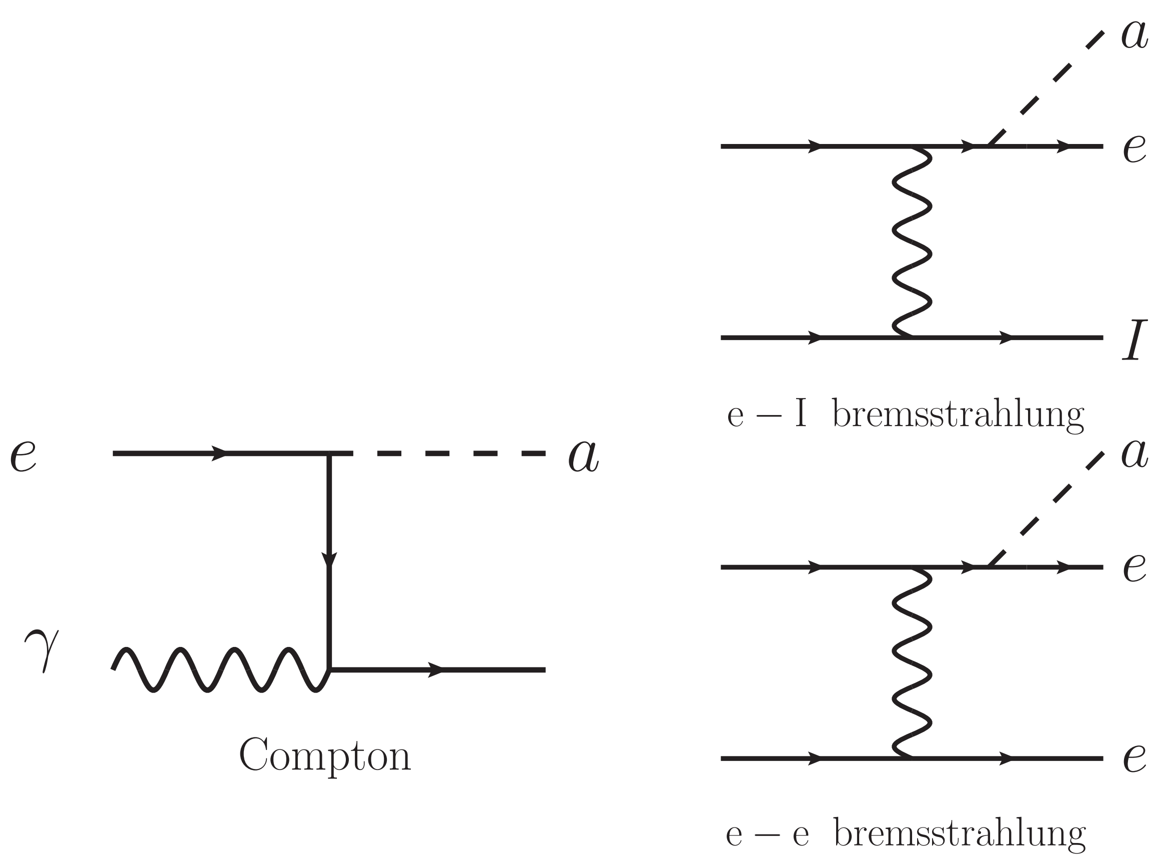




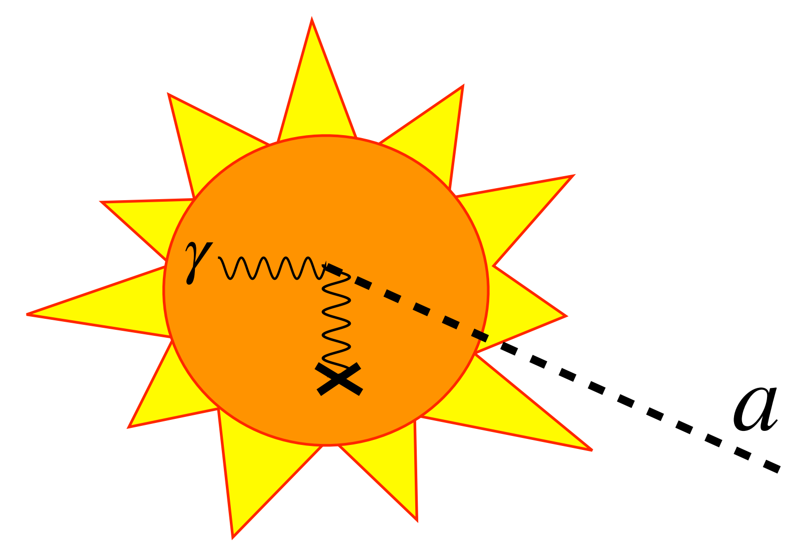
Helioscope: solar axion production

- The axion produced in the Sun via photon, electron or nucleon interactions

Atomic recombination and deexcitation, Bremsstrahlung, and Compton (ABC) interactions



Primakoff process



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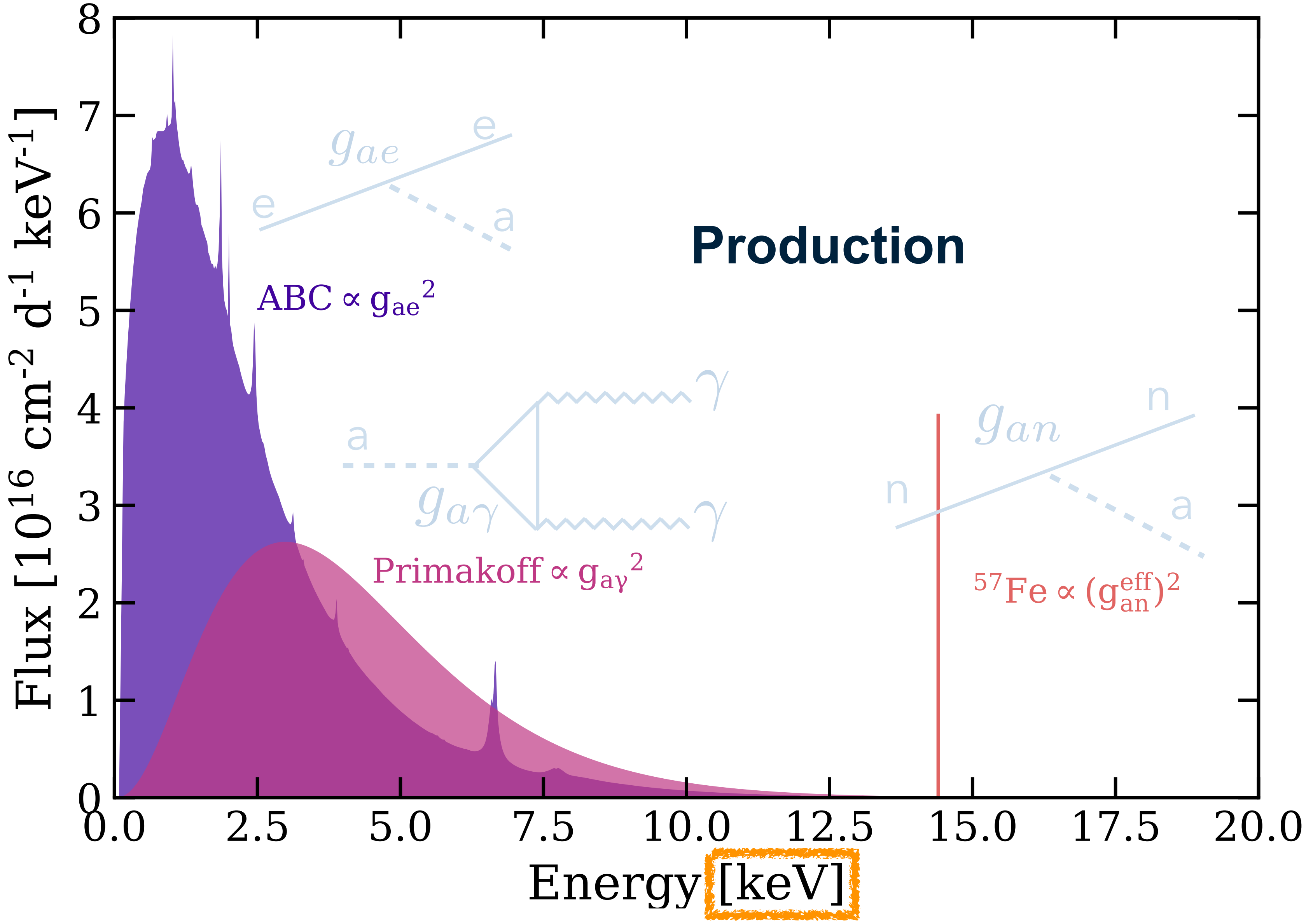
Solar axion production

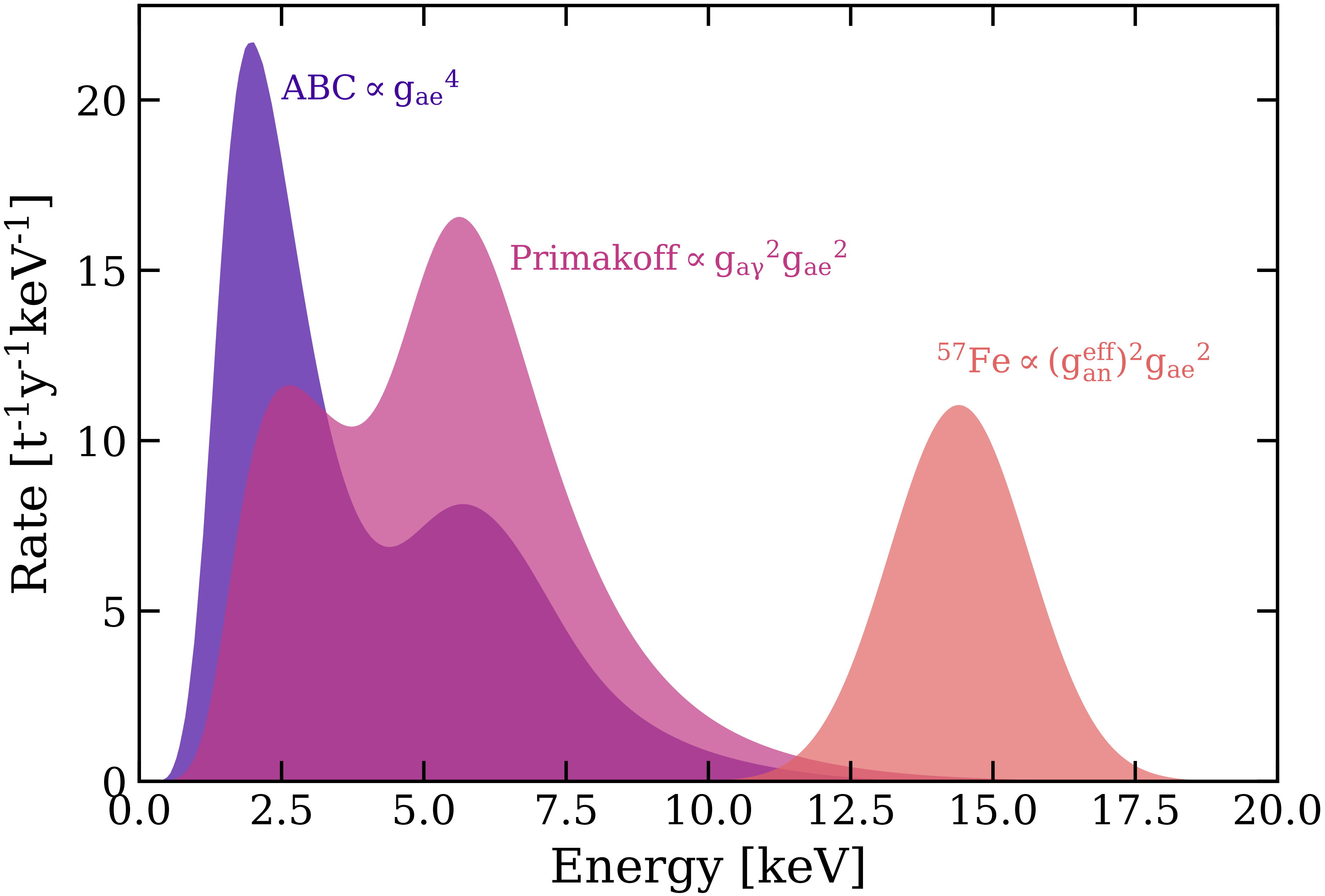
- The axion produced in the Sun via photon, electron or nucleon interactions



Naturally fall into keV range: solar core temperature ~ 15 million K.

Solar axion detection

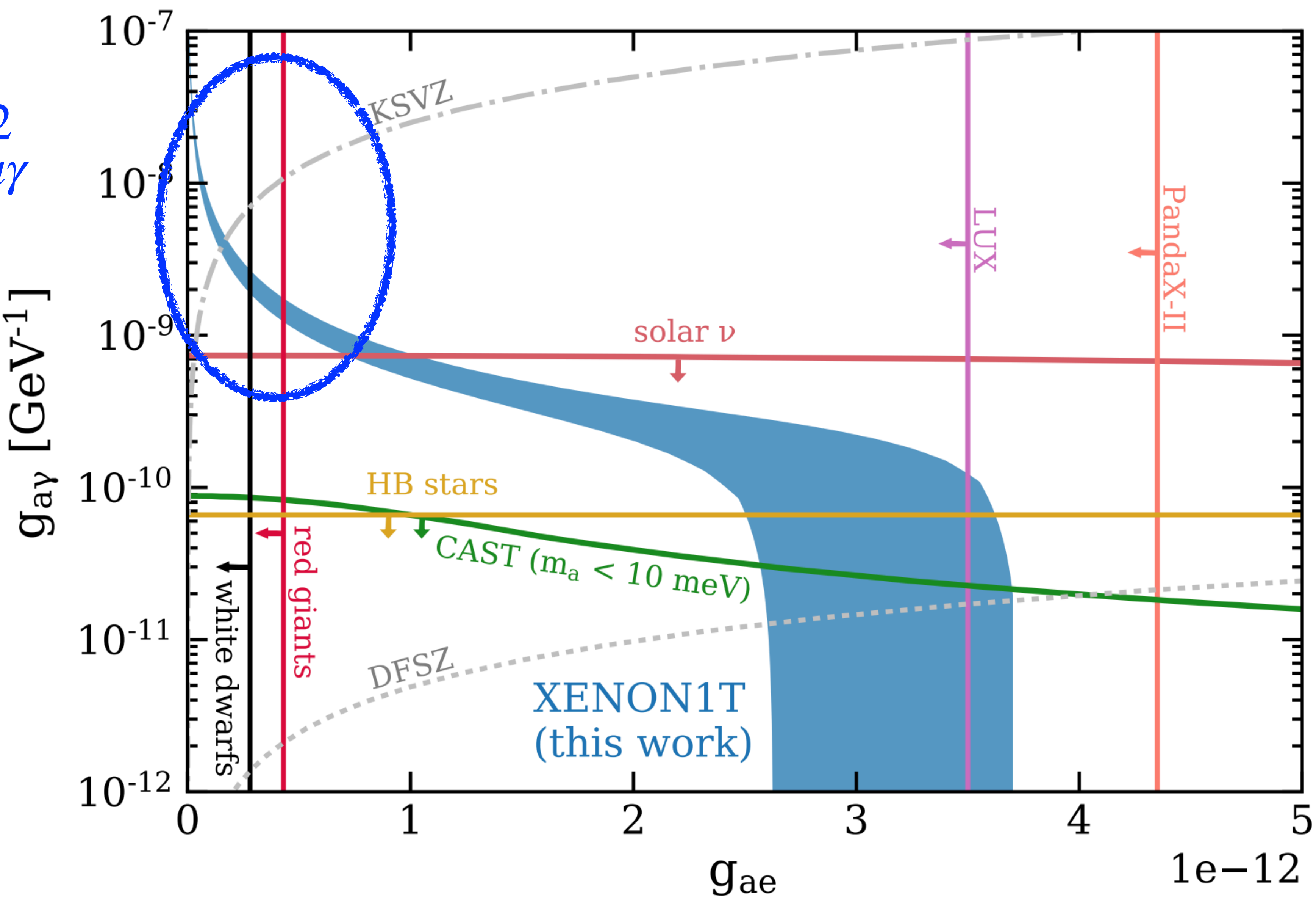
- Axio-electric effect $$\mathcal{L} \supset -g_{ae}\frac{\partial_\mu a}{2m_e}\bar{e}\gamma^\mu\gamma_5 e - \frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$
  - keV axions are absorbed by electrons



The results from axio-electric effect

- Confronting stellar cooling constraints

$g_{ae}^2 \times g_{a\gamma}^2$



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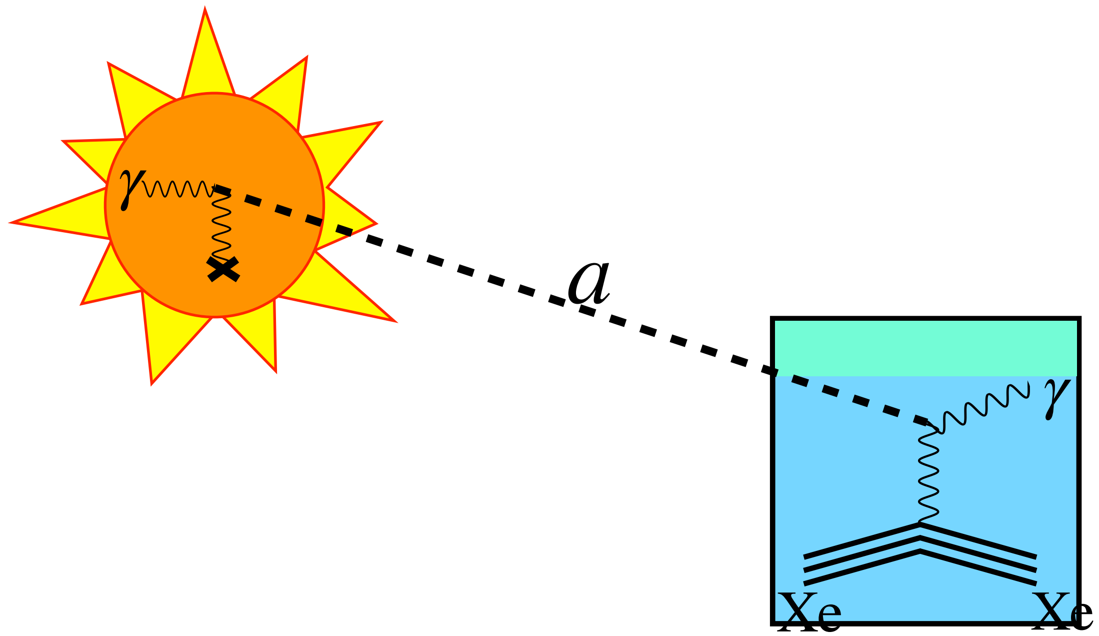
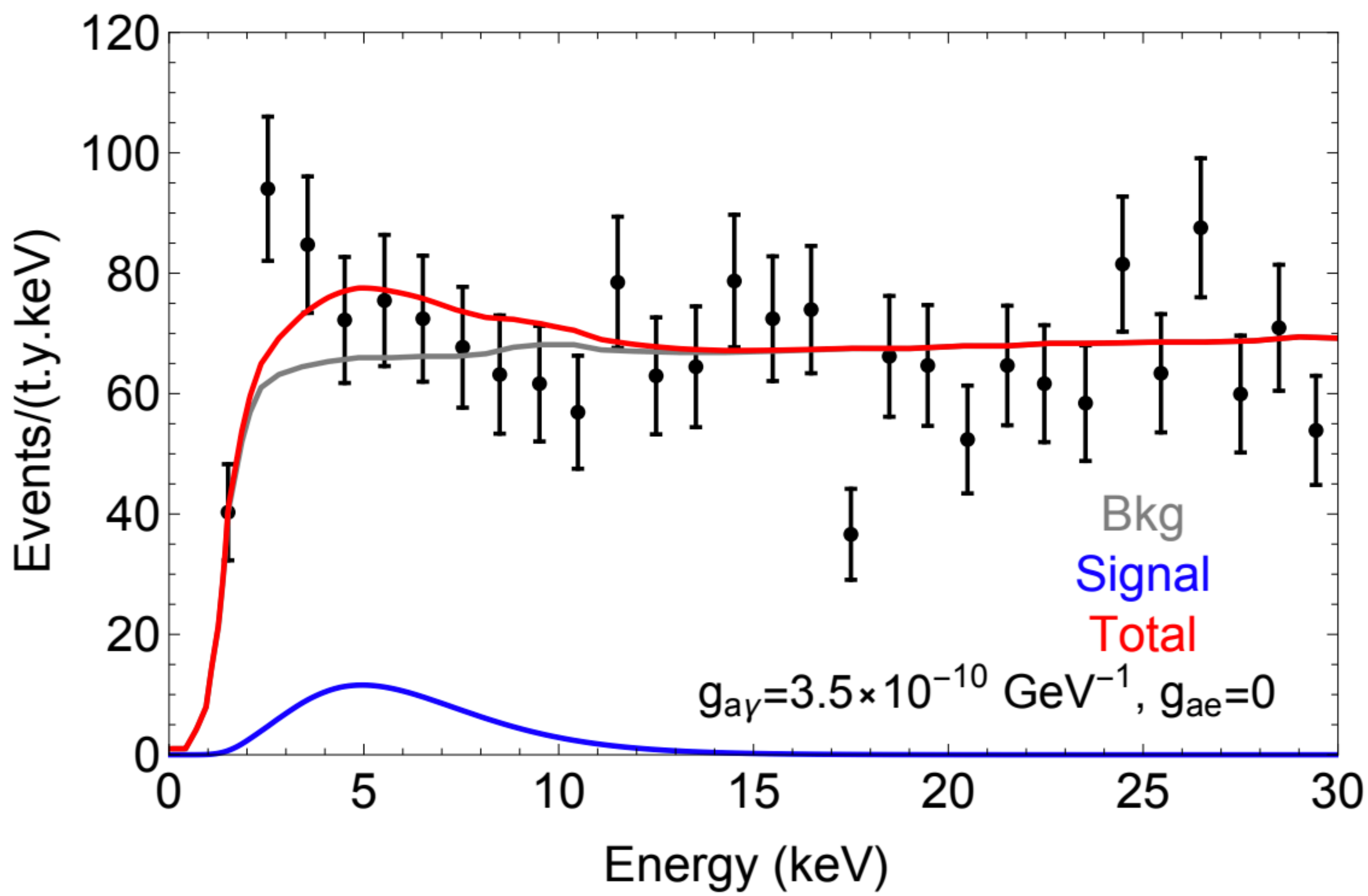
Inverse Primakoff effect

$$\frac{d\sigma_{a\to\gamma}^{\text{invPrim}}}{d\Omega} = \frac{\alpha}{16\pi} g_{a\gamma}^2 \frac{\boldsymbol{q}^2}{\boldsymbol{k}^2} \left(4 - \boldsymbol{q}^2/\boldsymbol{k}^2\right) F_a^2(\boldsymbol{q}^2)$$



Form factor: $F_a(q^2) = Zk^2/(r_0{}^2 + q^2)$

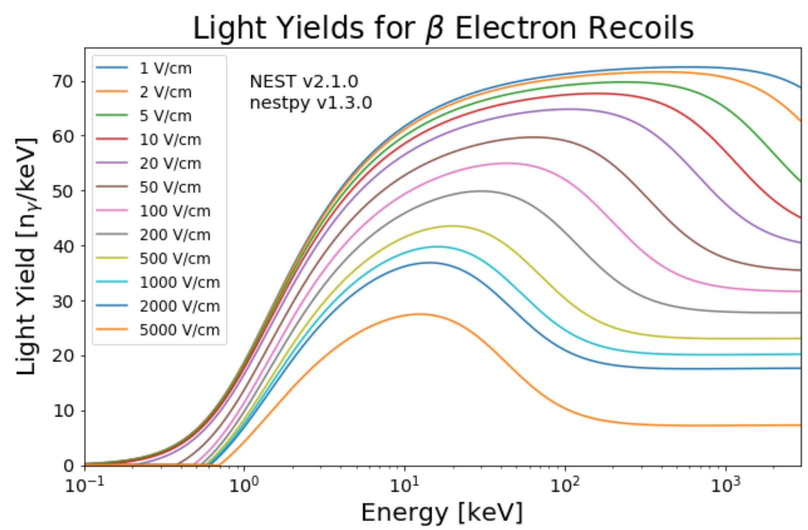
Screening effect: $r_0^{-1} = 4\ \text{keV}$

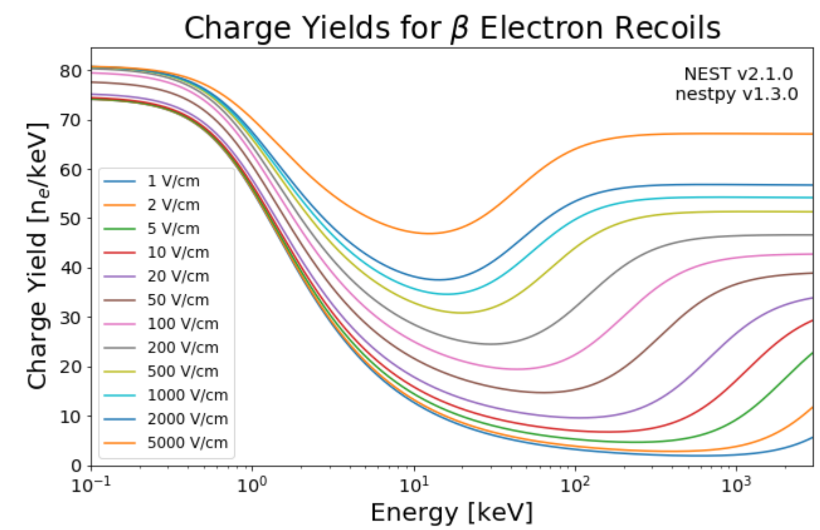


Photon and electron signal in xenon

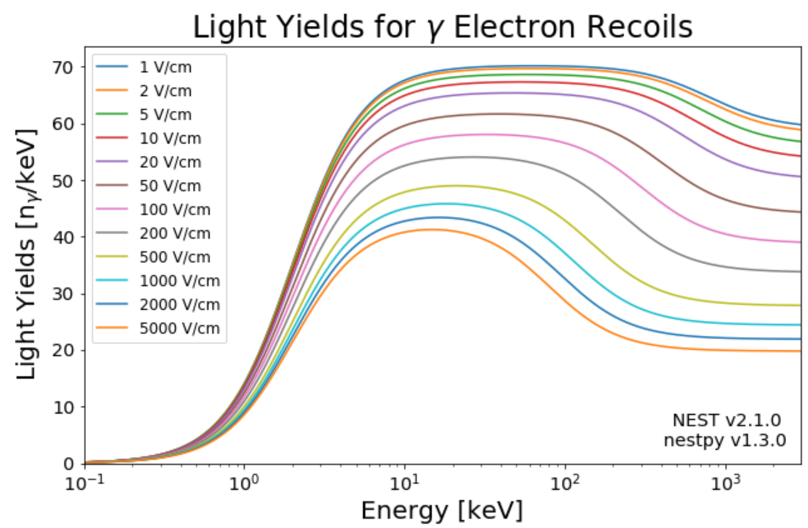
- keV photon ionizes Xe.
  - XENON can hardly distinguish keV photon signal from Electron Recoil

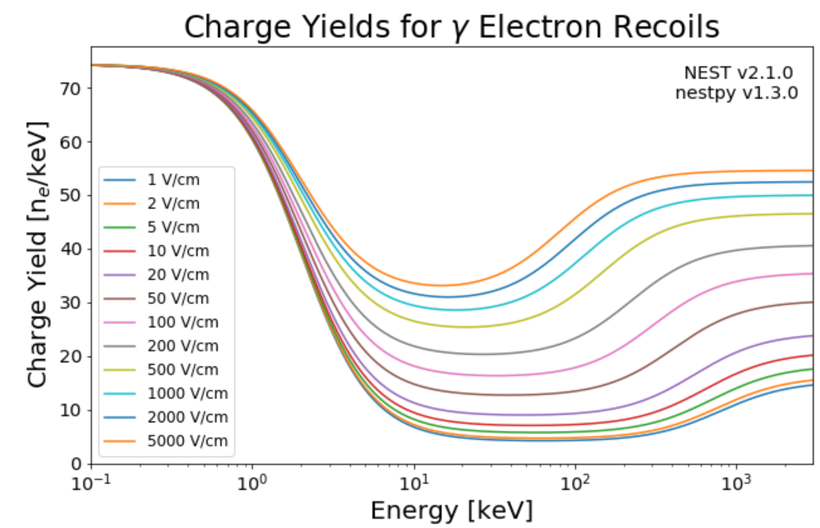
e





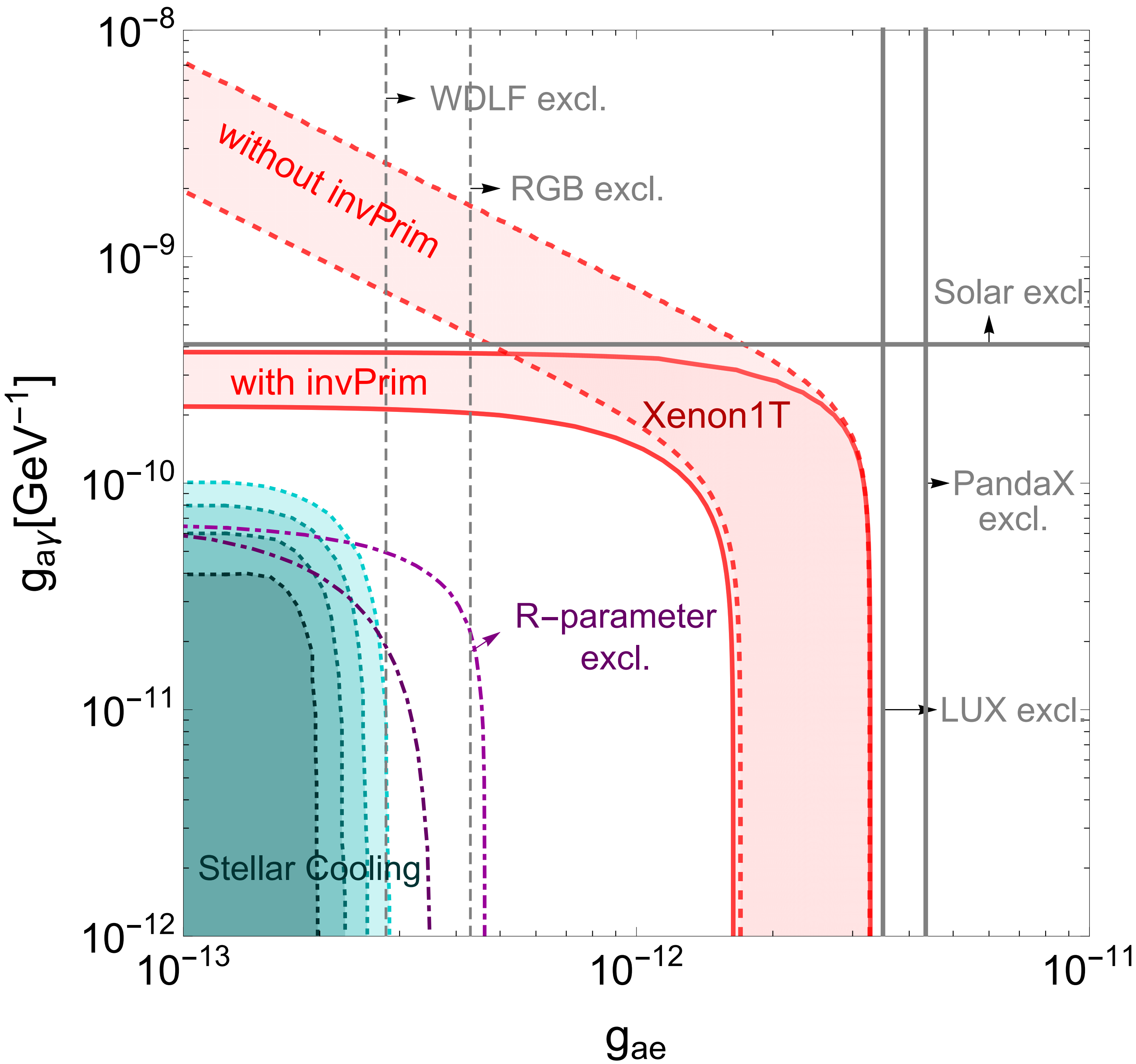
γ





http://nest.physics.ucdavis.edu/benchmark-plots

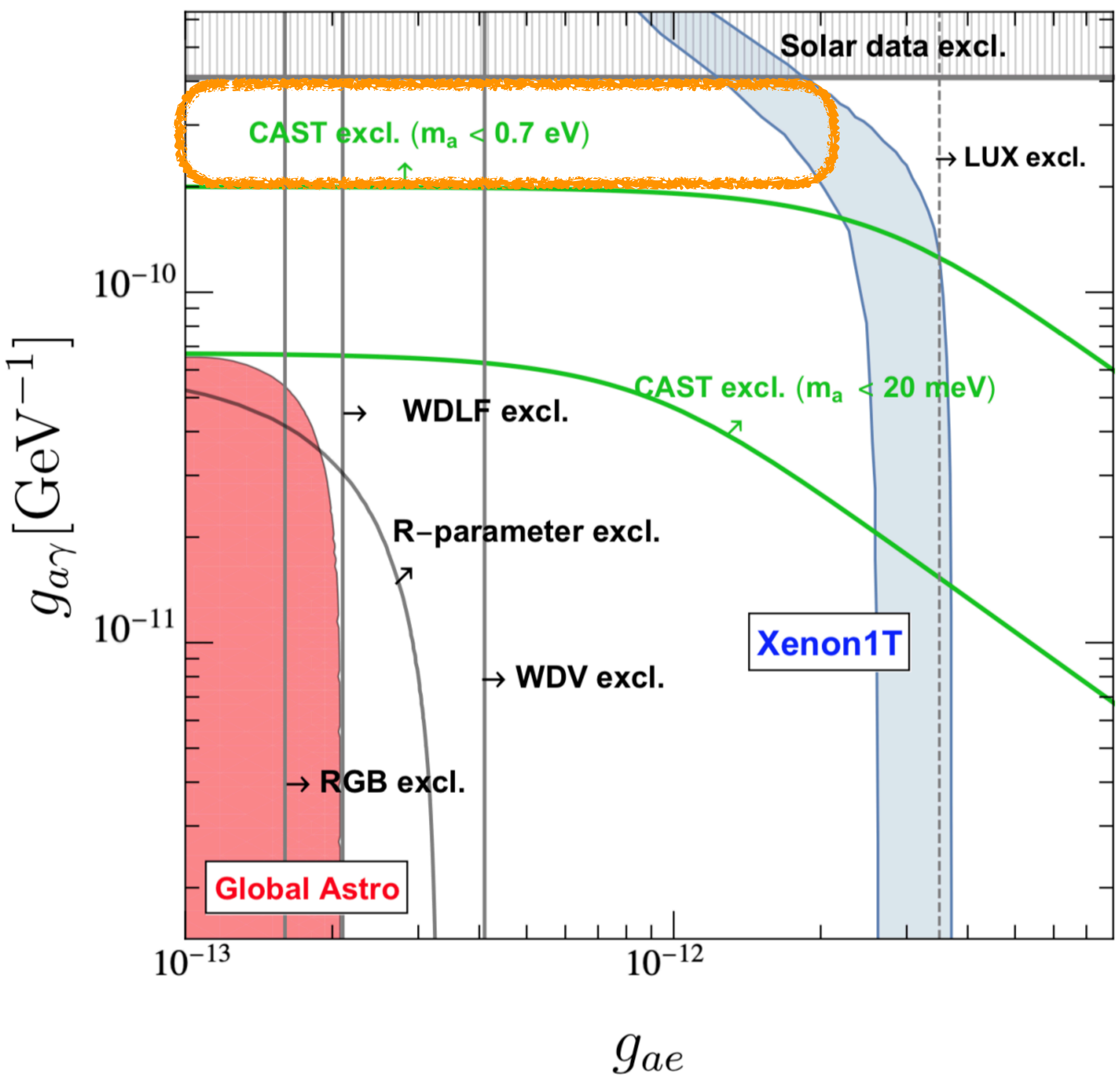
Inverse Primakoff effect should be included!



2006.14598 Gao, ***JL***, Wang, Wang, Xue, Zhong
see also 2006.15118 Dent, Dutta, Newstead, Thompson

The effect of Inverse Primakoff effect

- An important effect should not be missed
- Alleviated the stellar constraints



Observable	Measured	Expected	Tension
R-parameter	1.39 ± 0.03	$\leq 0.83\ (g_{e13} = 9)$	$19\sigma^{\star}$

R-parameter constraints: Discrepancy exceeds 19 σ, but if with inverse Primakoff, decreased to 8 σ.

PRL 125, 131804

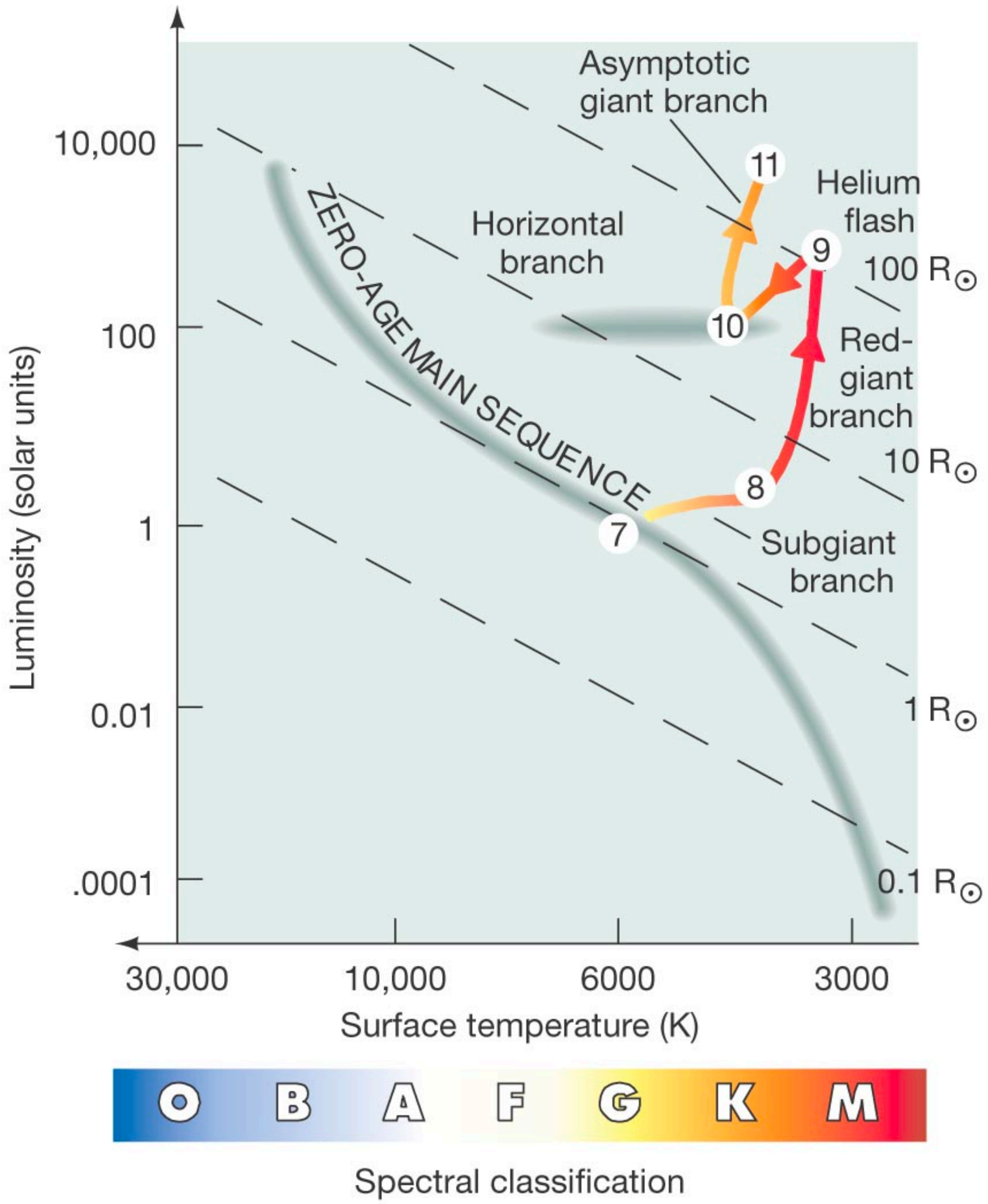
Luzio, Fedele, Giannotti, Mescia, and Nardi

Solar Axions Cannot Explain the XENON1T Excess

End of the story?

The R-parameter

$$R \equiv N_{HB}/N_{RGB} \simeq \tau_{HB}/\tau_{RGB}$$



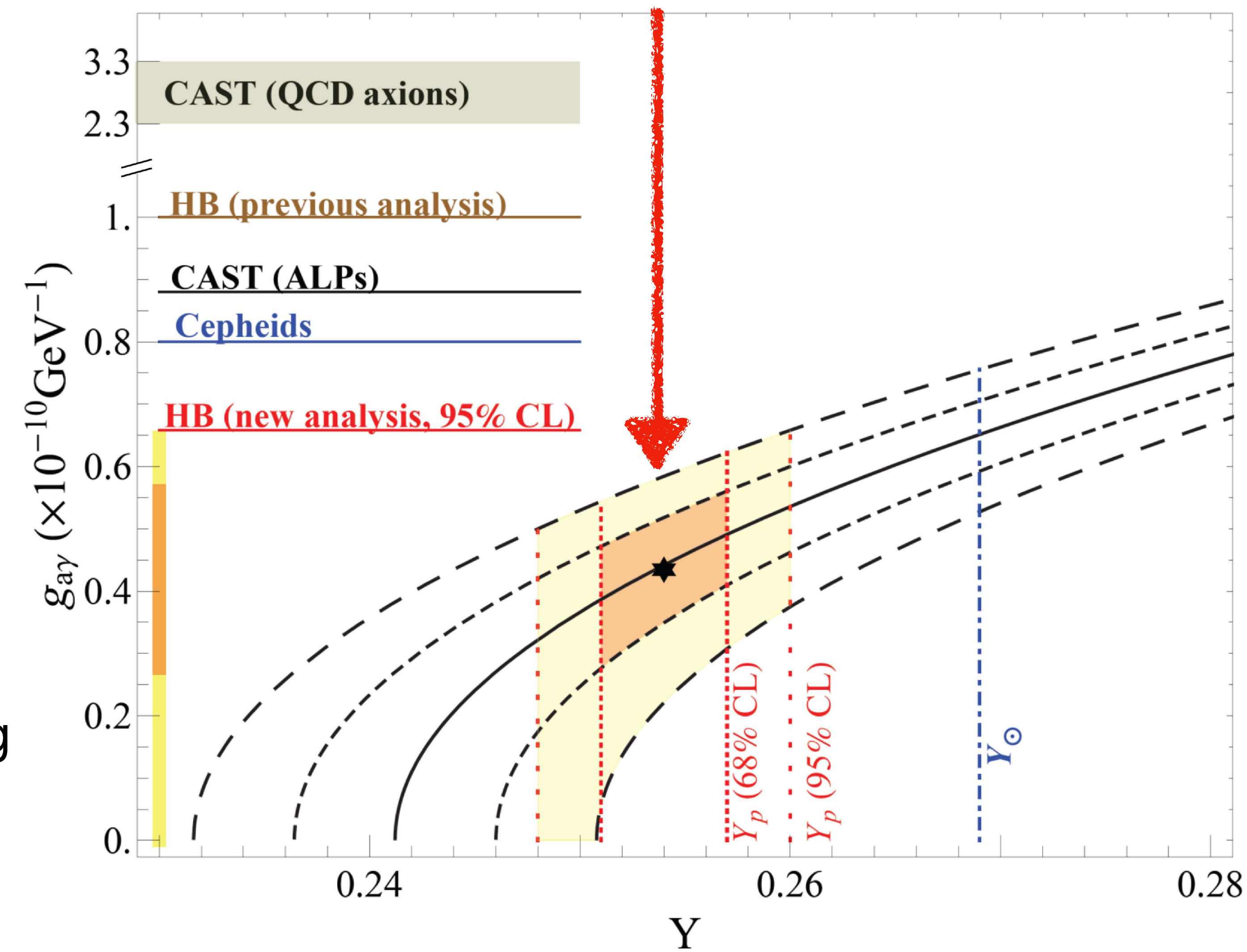
The R-parameter

$$R \equiv N_{HB}/N_{RGB} \simeq \tau_{HB}/\tau_{RGB}$$

$$R_{\rm th}(g_{a\gamma}, Y) = 6.26\,Y - 0.41\,g_{10}^2 - 0.12$$

- Used state-of-art stellar evolution models
- Primakoff process emitting axion will decrease R
- sensitive to He abundance Y
- He abundance measurement is challenging
- Choosing observed R from 39 clusters out of 57, biased R_{obs} ?

Stellar cooling anomaly



19 σ?

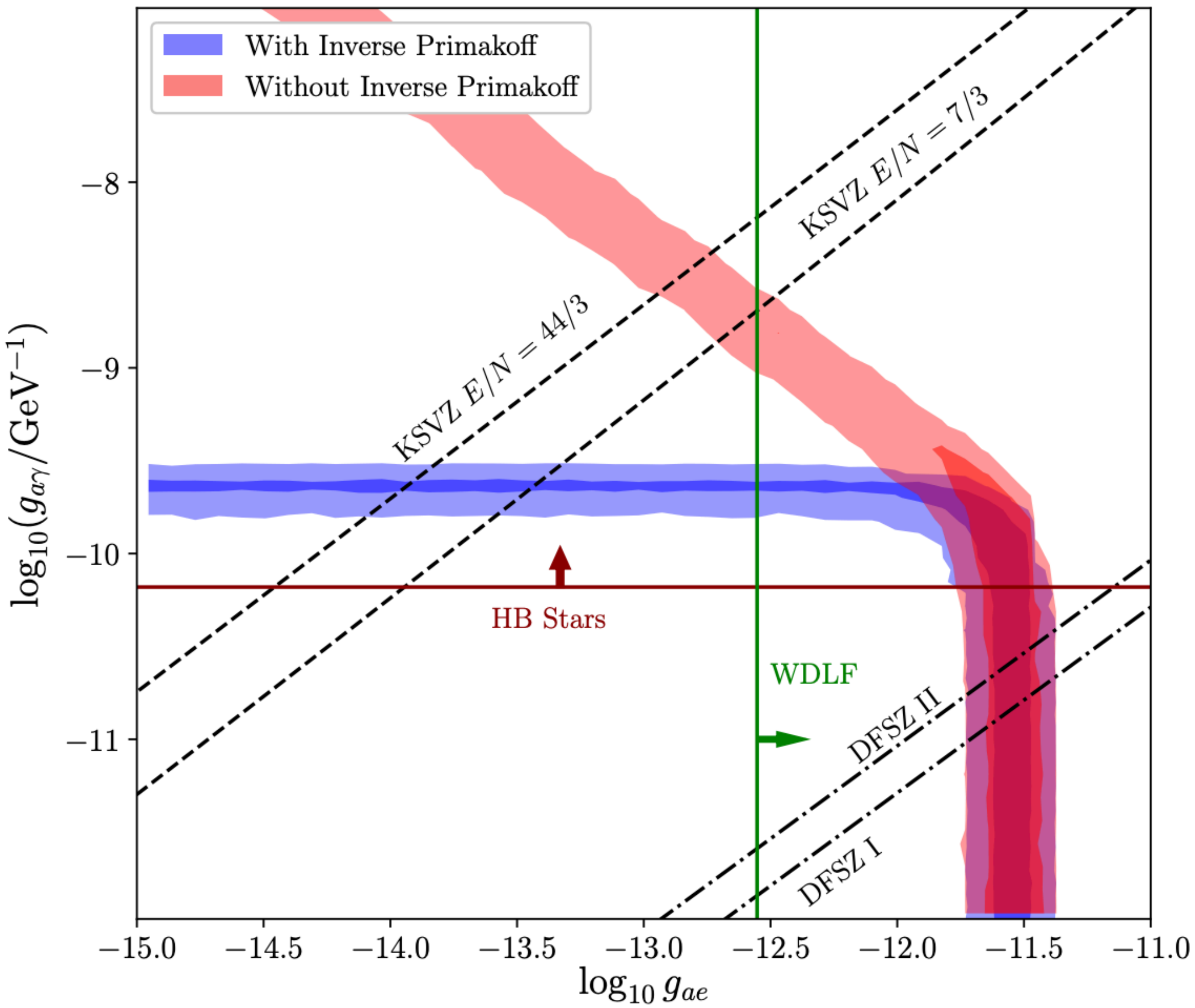
1406.6053, Ayala, Dominguez, Giannotti, Mirizzi, Straniero

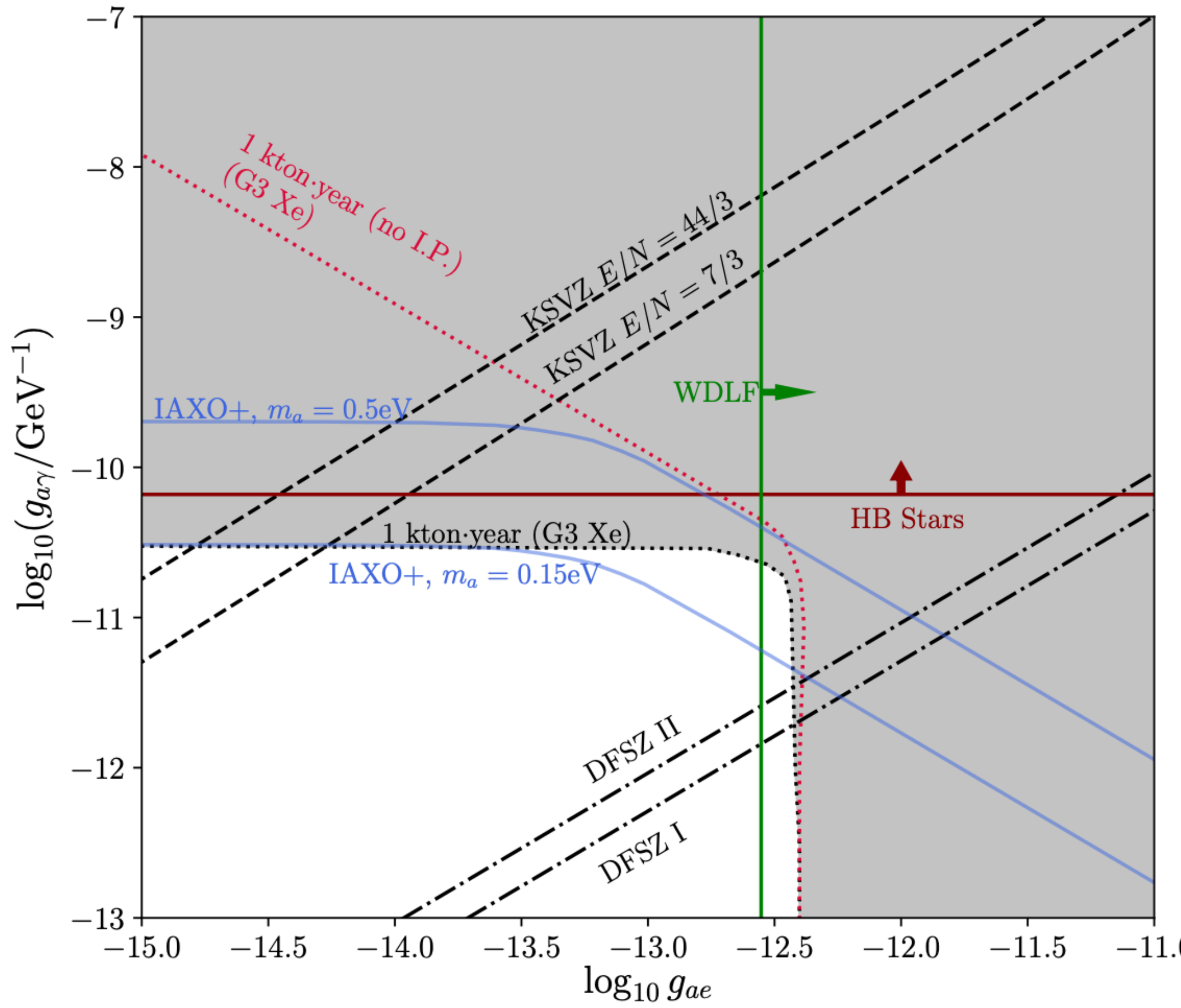
Summary

- The inverse Primakoff effect is important for solar axion
- The stellar cooling tension can be alleviated
- May further alleviate the tension via environment dependent mass (see 2006.15112)
- The uncertainties in the stellar cooling calculation should be checked
- Future experiments like XENONnT, PandaX and LZ can further explore the solar axion properties

Thank you!

Backup slides





2006.15118 Dent, Dutta, Newstead, Thompson