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Hidden Photon Dark Matter in the Light of XENON1T and Stellar Cooling

Based on arxiv:2006.11243 in collaboration with
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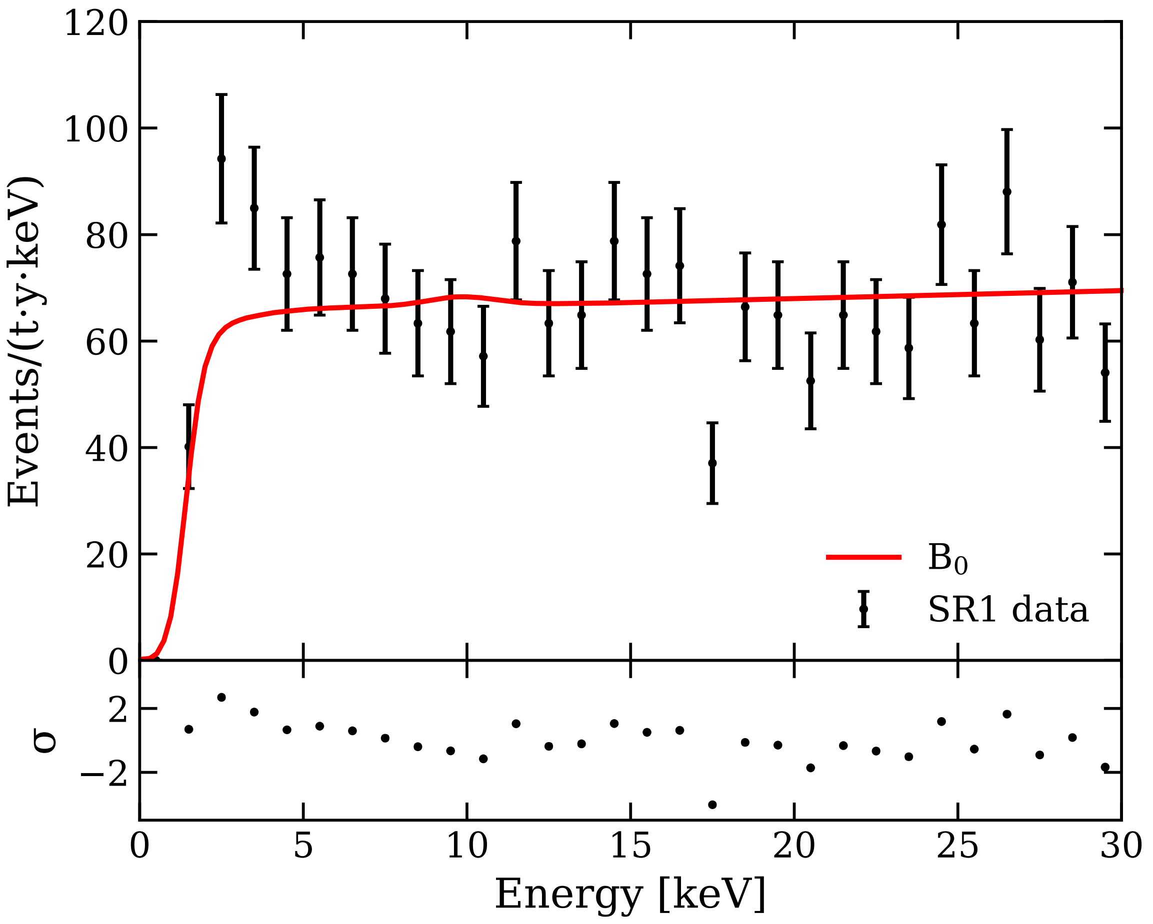
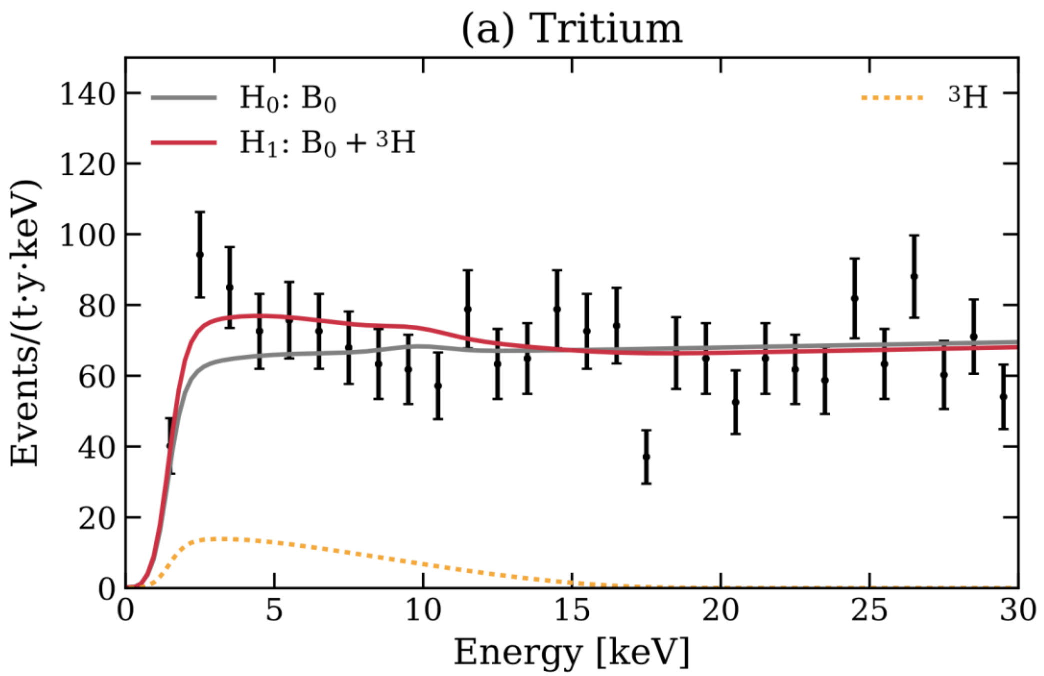
THE XENON1T EXCESS

- XENON1T observed an excess in electron recoil events
  [arXiv:2006.09721]
- 3.5 σ significance
- Energy Resolution ~20 % in signal region
- Upgrade XENONnT will confirm or rule out the observed excess



POSSIBLE EXPLANATIONS

- After XENON1T announced their results, many possible explanations were suggested:
  - Additional background from Tritium contamination
  - Solar axions
  - Neutrino magnetic moment
  - Inelastic DM
  - Boosted DM
  - …
  - **and hidden photon DM**



Key Questions in this Talk

1. Can hidden photon DM explain the XENON1T excess?
2. Would such a hidden photon be a viable DM candidate?
3. How does it compare with stellar cooling limits and hints?

Hidden Photons

- A hidden photon (HP) is a gauge boson of a new U(1) symmetry with gauge field X^μ.
- The HP can kinetically mix with the SM photon:

$$\mathcal{L} \supset -\frac{1}{2}\epsilon F^{\mu\nu} X_{\mu\nu} - \frac{1}{2} m_X^2 (X^\mu)^2 - j^\mu A_\mu$$

- After a suitable field redefinition:

$$\mathcal{L} \supset -\frac{1}{2} m_X^2 (X^\mu)^2 - j^\mu (A_\mu - \epsilon X_\mu)$$

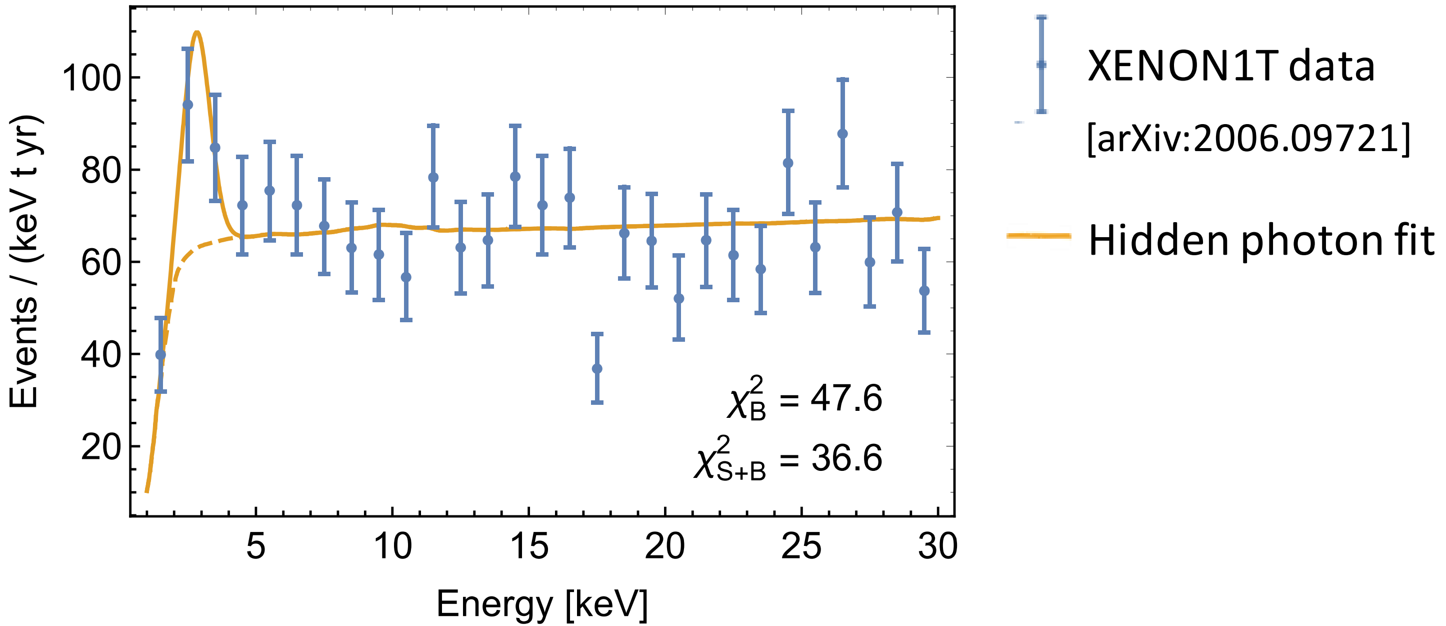
- HP couples weakly to SM electromagnetic current

Hidden Photons in XENON1T

- Absorption rate of non-relativistic HPs in xenon

$$R = \epsilon^2 \frac{\rho_{DM}}{m_X} \frac{\sigma_\gamma}{m_N}$$

- Monoenergetic peak is smeared out by the detector resolution



Hidden Photons in XENON1T

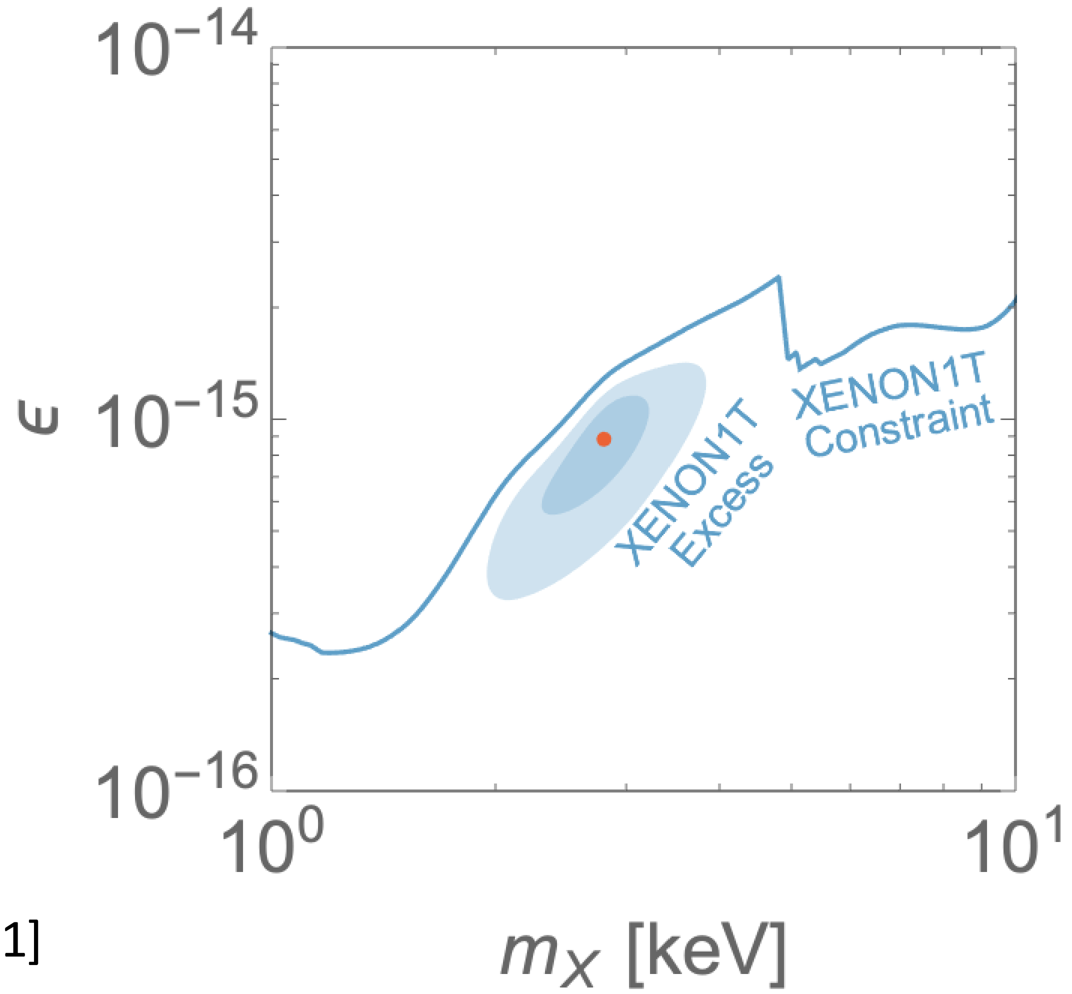
- Best fit:

$$m_X = 2.8 \text{ keV}$$
$$\epsilon = 8.6 \times 10^{-16}$$

- Global significance:

$$\sim 2\ \sigma$$

- Lower significance than solar axion in large parts due to look-elsewhere
- Results confirmed by [arXiv:2006.13159, 2006.13929, 2006.14521]



Hidden Photons as DM

- Light DM cannot be produced thermally
- Non-thermal production mechanisms:
  a) Misalignment (large initial field values) [arXiv:1201.5902]
  b) Fluctuations during inflation [arXiv:1504.02102]

$$m_X = 2.8 \ \text{keV}, \qquad H_I \sim 7 \times 10^{11} \ \text{GeV}$$

Higher inflation scales possible by including non-minimal coupling to gravity
[arXiv:1905.09836]

$$\mathcal{L} \supset \frac{1}{6}\kappa R(X^\mu)^2, \qquad \kappa \sim 0.6 - 0.8$$

$$m_X = 2.8 \ \text{keV}, \qquad H_I \sim 3 \times 10^{12} \ \text{GeV} - 10^{14} \ \text{GeV}$$

<u>Strong small scale fluctuations expected!</u>

  c) Decay product of e.g. axion field, dark Higgs, inflaton, cosmic strings etc.
[arXiv:1810.07188]

HIDDEN PHOTONS AS DM

- Stability is ensured
- Dominant decay channels:
  a) $X \longrightarrow \gamma\gamma\gamma$

$$\Gamma_{X\to3\gamma} = \frac{17\alpha^4\epsilon^2}{11664000\pi^3}\frac{m_X^9}{m_e^8} \simeq 1.4\times10^{-29}\,\mathrm{Gyr}^{-1}\left(\frac{m_X}{2.8\,\mathrm{keV}}\right)^9\left(\frac{\epsilon}{10^{-15}}\right)^2$$

[arXiv:0811.0326]

  b) $X \longrightarrow \nu\nu$

$$\Gamma_{X\to\nu\bar{\nu}} = \frac{\alpha\epsilon^2}{8\cos^4\theta_W}\frac{m_X^5}{m_Z^4} \simeq 2\times10^{-28}\,\mathrm{Gyr}^{-1}\left(\frac{m_X}{2.8\,\mathrm{keV}}\right)^5\left(\frac{\epsilon}{10^{-15}}\right)^2$$

[arXiv:1912.12152]

$\Longrightarrow$ A hidden photon of 2.8 keV is a viable DM candidate!

STELLAR COOLING

- Stars can produce new light bosons in large abundances
- Stellar cooling supplies strong constraints **but** anomalous cooling is observed

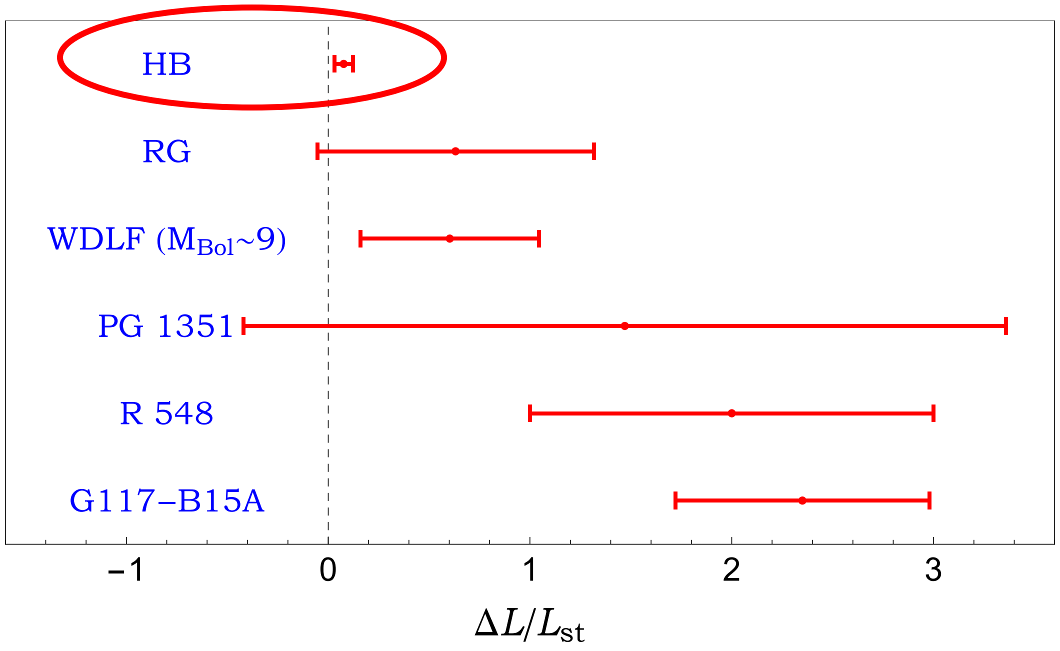


Figure taken from Giannotti, Irastorza, Redondo, Ringwald 2015 [arXiv:1512.08108]

HIDDEN PHOTONS AND HB STARS

- Transverse modes resonantly convert to HPs if

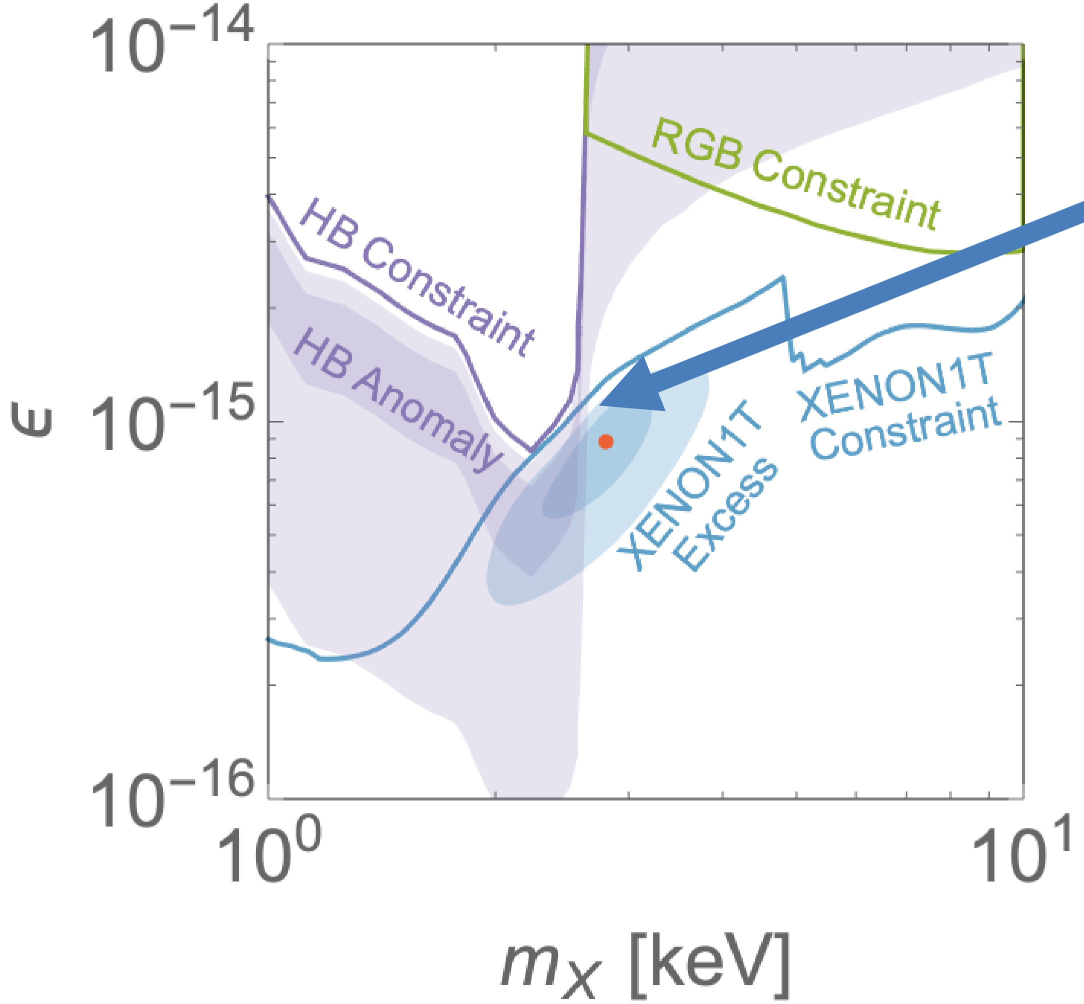
$$\omega_P \sim m_X$$

- For significant cooling, resonance condition needs to be fulfilled in some spherical shell inside HB stars.
- Maximal plasma frequency is reached at the core

$$\omega_P(r=0) \sim 2.6 \text{ keV}$$

Hidden Photons and HB Stars

- HB anomaly and XENON1T excess have a significant overlap



Sharp edge from resonance condition

$$\omega_P(r=0) \sim 2.6 \text{ keV}$$

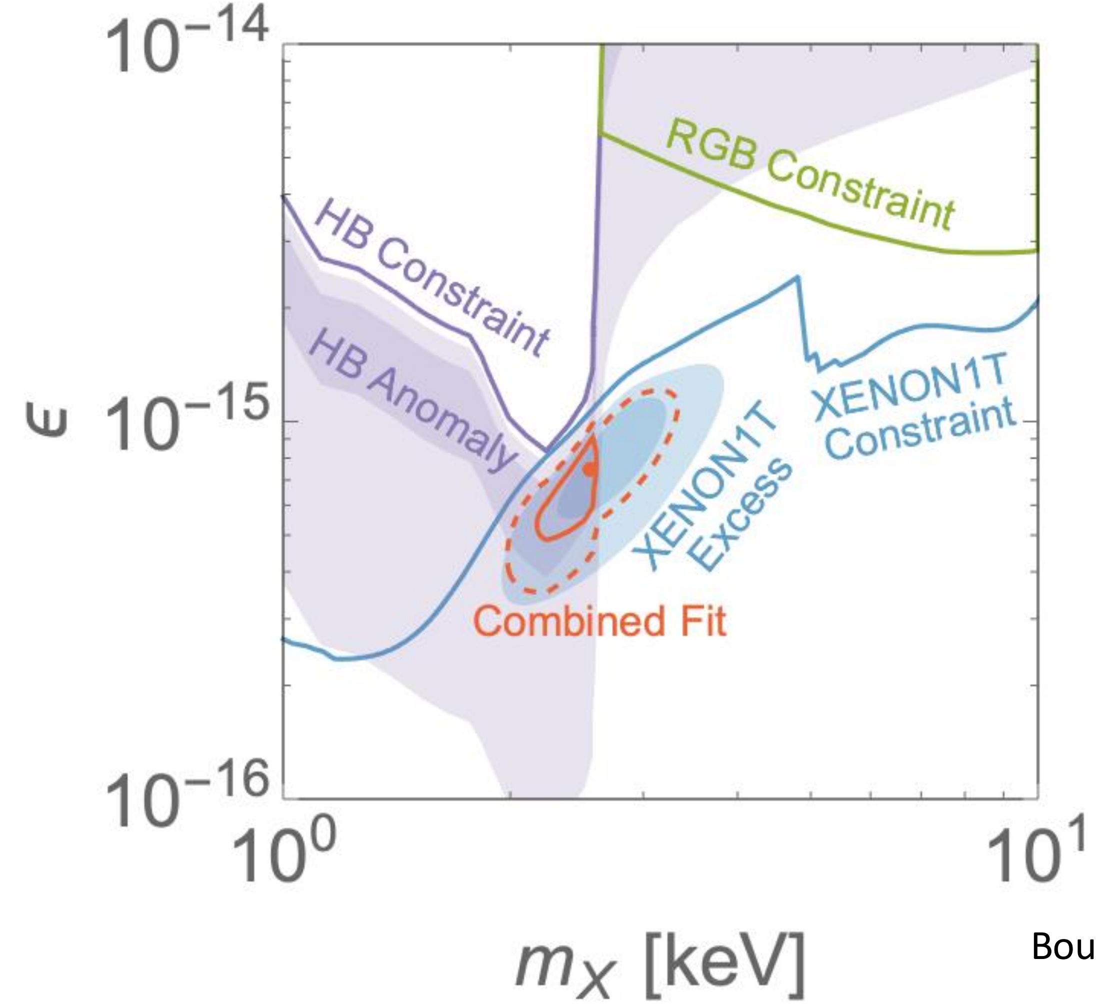
Note:

- Axion hint translated to hidden photons
- The hint from the *R*-parameter could be customised for HPs.

Bounds and Hints from: [arxiv:1512.08108] & [arxiv:1412.8379]

Hidden Photons and HB Stars

- Combined analysis gives shifts the best fit point to 2.5 keV.



Significance of combined analysis:

3.3 σ

Including unconstrained Tritium abundance:

2.2 σ

Bounds and Hints from: [arxiv:1512.08108] & [arxiv:1412.8379]

BAYESIAN ANALYSIS

- We can treat the HB exclusions and anomalies as prior knowledge in the HP parameter space $p(m_X, \epsilon \mid \mathrm{HP})$
- Can assign a prior distribution to the Tritium abundance $p(n_T)$
- Bayes factor:

$$K = \frac{\int \mathrm{d}m_x \; \mathrm{d}\epsilon \; \mathrm{d}n_T \; p(n_T) \; p(m_X, \epsilon \mid \mathrm{HP}) \; p(D \mid m_X, \epsilon, n_T, \mathrm{HP})}{\int \mathrm{d}n_T \; p(n_T) \; p(D \mid n_T, \mathrm{H\!\!\!/P})}$$

- Result:

$$K = 3.63$$

- This is commonly interpreted as **substantial evidence**!

CONCLUSION

- A hidden photon of (2 -3) keV could explain the XENON1T excess.
- Such a particle could constitute all of the dark matter.
- Additional motivation comes from the HB cooling anomaly $m_X \lesssim 2.6\ \mathrm{keV}$
- There is substantial evidence for the HP explanation of the XENON1T excess compared to the assumption of a tritium background
- To-Do's:
  - Build larger, more sensitive xenon detector!
  - Evaluate HB hint in detail for hidden photons
  - Investigate the time dependence of the signal