Axion-like particles and hidden photons: Hints from XENON1T and stellar cooling

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Based on **arXiv:2006.11243** in collaboration with Gonzalo Alonso-Álvarez, Fatih Ertas, Joerg Jaeckel and Lennert Thormaehlen

and **arXiv:2007.05517** in collaboration with Peter Athron, Csaba Balázs, Ankit Beniwal, Eliel Camargo-Molina, Andrew Fowlie, Tomás Gonzalo, Sebastian Hoof, Doddy Marsh, Markus Prim, Pat Scott, Wei Su, Martin White, Lei Wu and Yang Zhang

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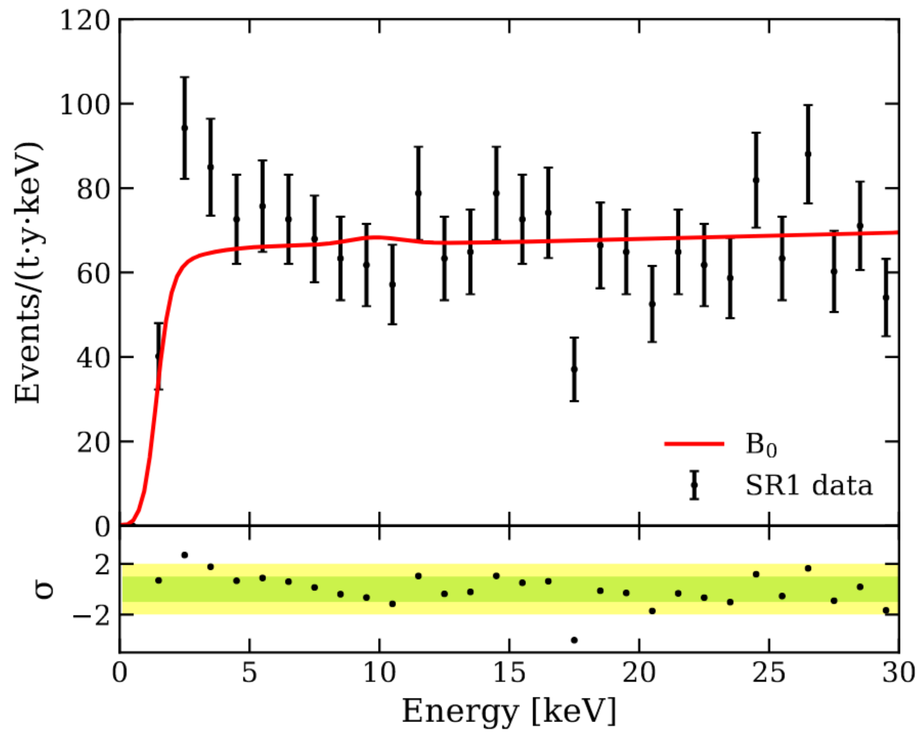
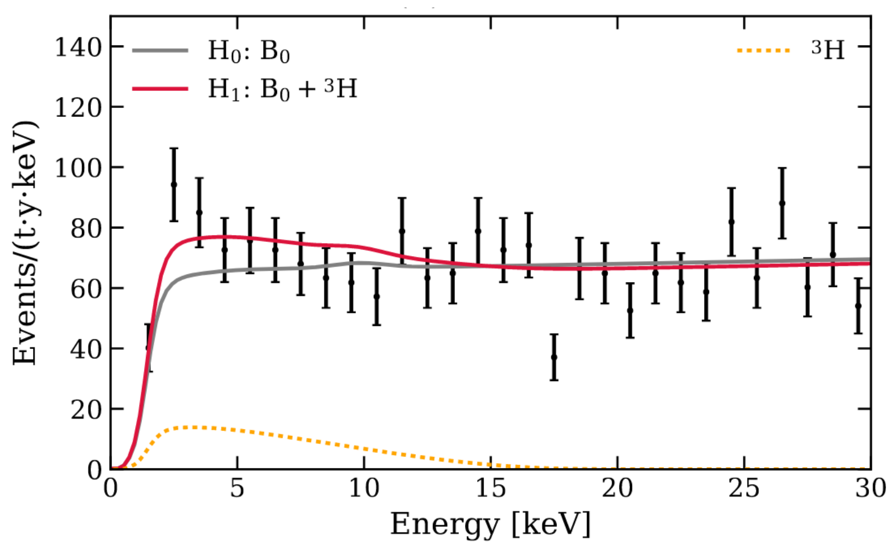
Electronic recoil events in XENON1T

- The XENON Collaboration has recently announced an excess in electronic recoil events with energy in the range 1-7 keV over known backgrounds

arXiv:2006.09721

- For several different signal hypotheses the significance is >3σ





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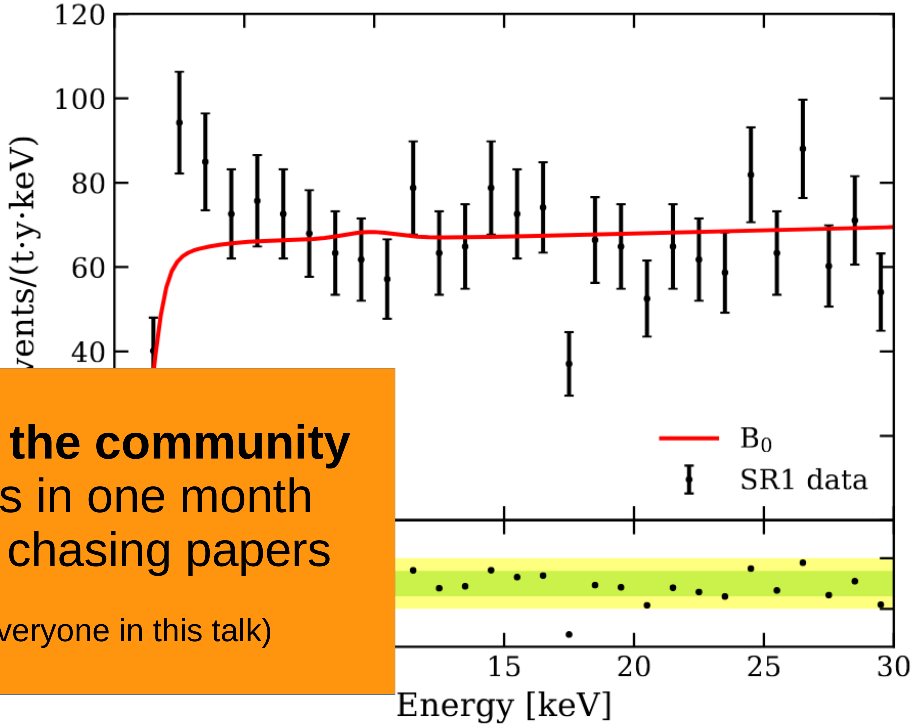

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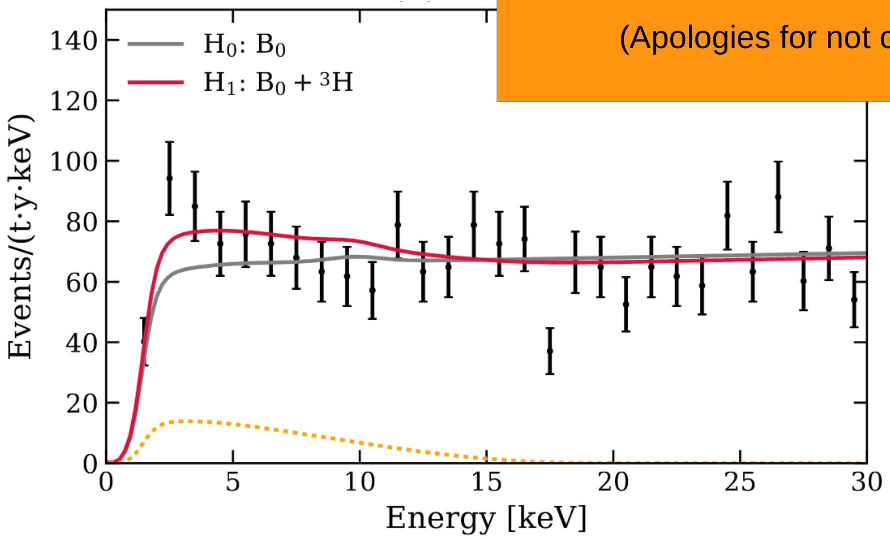
Huge excitement in the community
Almost 100 citations in one month
Over 50 ambulance chasing papers

(Apologies for not citing everyone in this talk)



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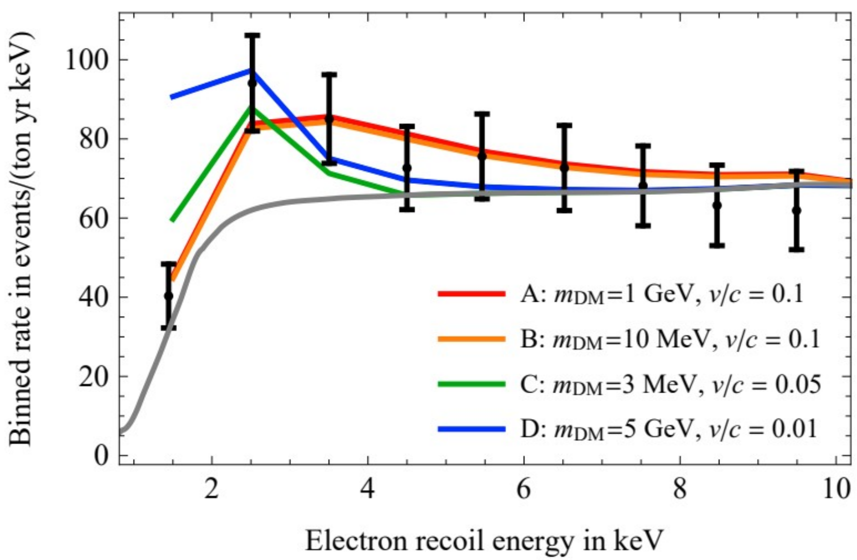
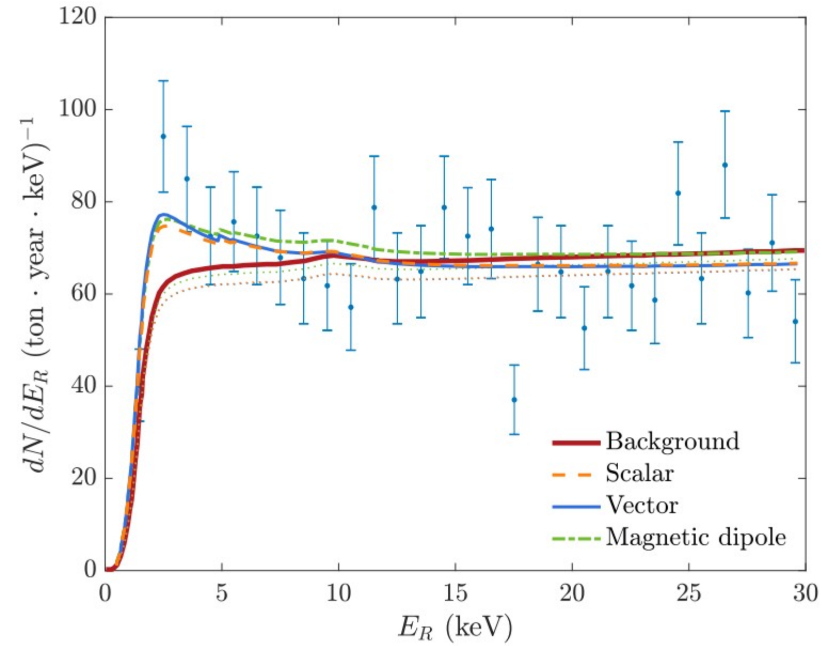
Possible explanation: Relativistic particles

- The XENON1T excess can be explained in terms of the scattering or absorption of particles produced or accelerated in astrophysical systems
  - QCD axions produced in the Sun
  - Solar neutrinos with non-standard interactions
  - Boosted dark matter particles with velocity > 0.1 c
  - Products of dark matter annihilation or decay

Boosted DM, Kannike et al., arXiv:2006.10735



Solar neutrinos, Bœhm et al., arXiv:2006.11250



Possible explanation: Non-relativistic scatters

- Can the XENON1T excess also be explained in terms of non-relativistic particles that are gravitationally bound to the Milky Way and contribute to the local DM density?

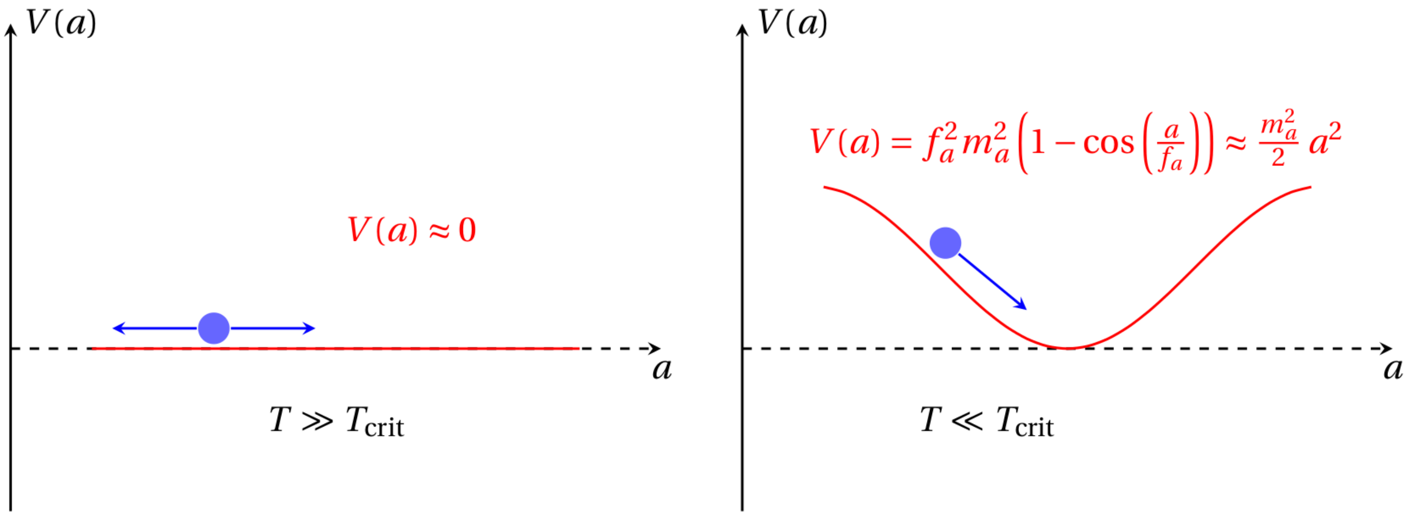
- Elastic DM-electron scattering does not give a good fit to data (even for momentum-dependent interactions)

Bloch et al., arXiv:2006.14521

- Possible alternative: Additional energy release in the detector
  - Exothermic DM ($X^* + e^- \rightarrow X + e^-$) — Baryakhtar et al., arXiv:2006.13918
  - Rayleigh DM ($X + N \rightarrow X + N + \gamma$) — Paz et al., arxiv:2006.12462
  - Luminous DM ($X^* \rightarrow X + \gamma$) — Bell et al., arXiv:2006.12461
  - ...

Possible explanation: Dark matter absorption

- A much simpler possibility is that the XENON1T signal is due to the absorption of keV-scale bosonic DM particles
- Two well-motivated candidates:
  - Axion-like particles with suppressed couplings to photons
  - Dark (or hidden) photons that kinetically mix with the visible photon
- These particles can be produced in the early Universe via the misalignment mechanism and potentially constitute all of DM



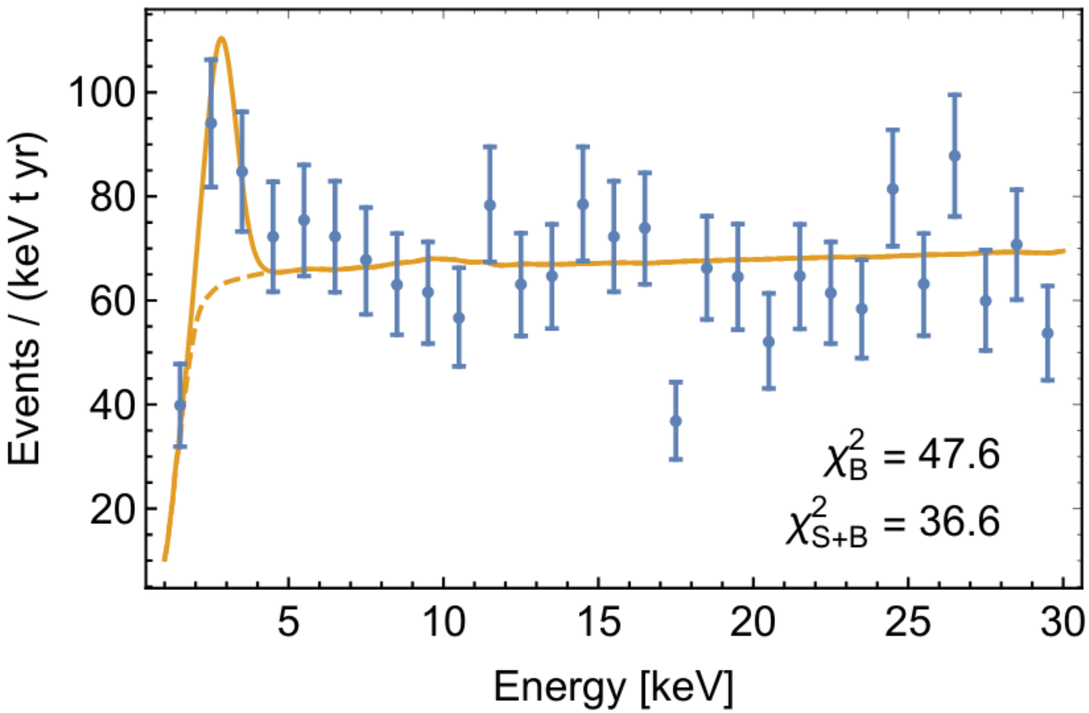
Note: For hidden photons, misalignment production requires non-minimal coupling to gravity

Alonso Álvarez et al., arXiv:1905.09836

Dark matter absorption in XENON1T

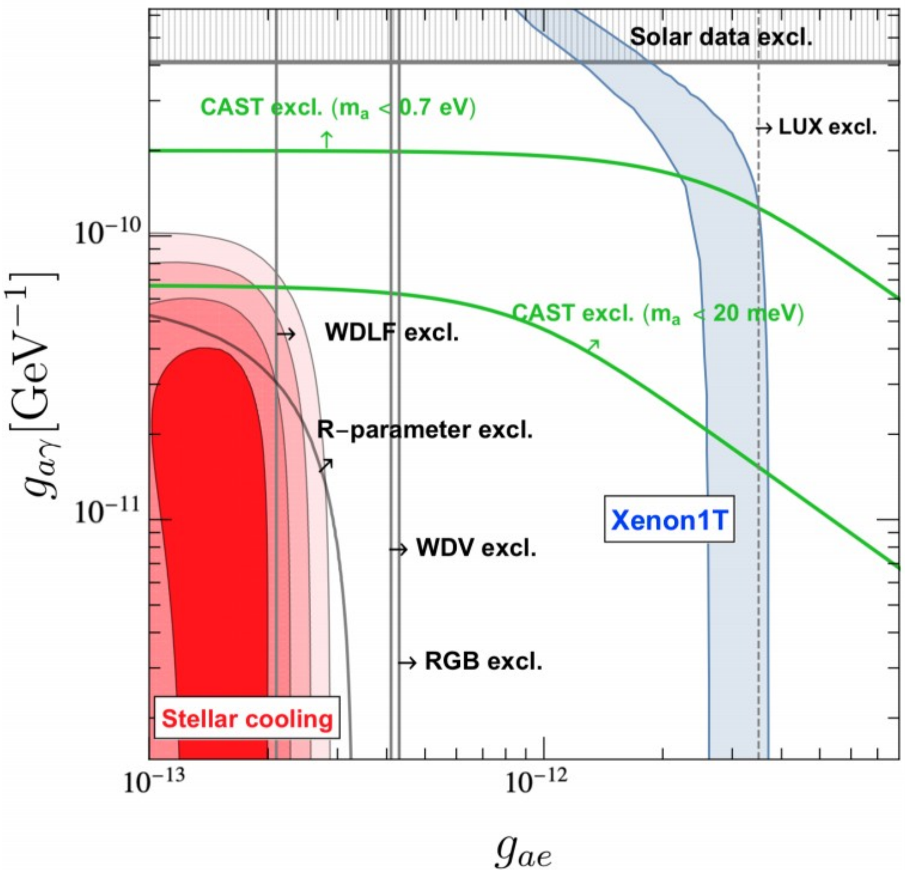
- The expected signal in XENON1T is then an electron recoil with energy equal to the rest mass of the DM particle
- Due to the finite energy resolution of the detector, this signal ends up giving a good fit to the observed data

Alonso-Álvarez, FK et al., arXiv:2006.11243



Stellar cooling: Constraints

- Many of the particles that can explain the XENON1T excess would also be produced in astrophysical systems through their couplings to photons and/or electrons
- Such particle production increases the energy losses and enhances stellar cooling rates in
  - White dwarfs (WD)
  - Red giants (RGB)
  - Horizontal branch stars (HB)
- As a result, many models are in strong tension with astrophysical constraints
- In particular the solar axions interpretation of XENON1T is robustly excluded



Di Luzio et al., arXiv:2006.12487

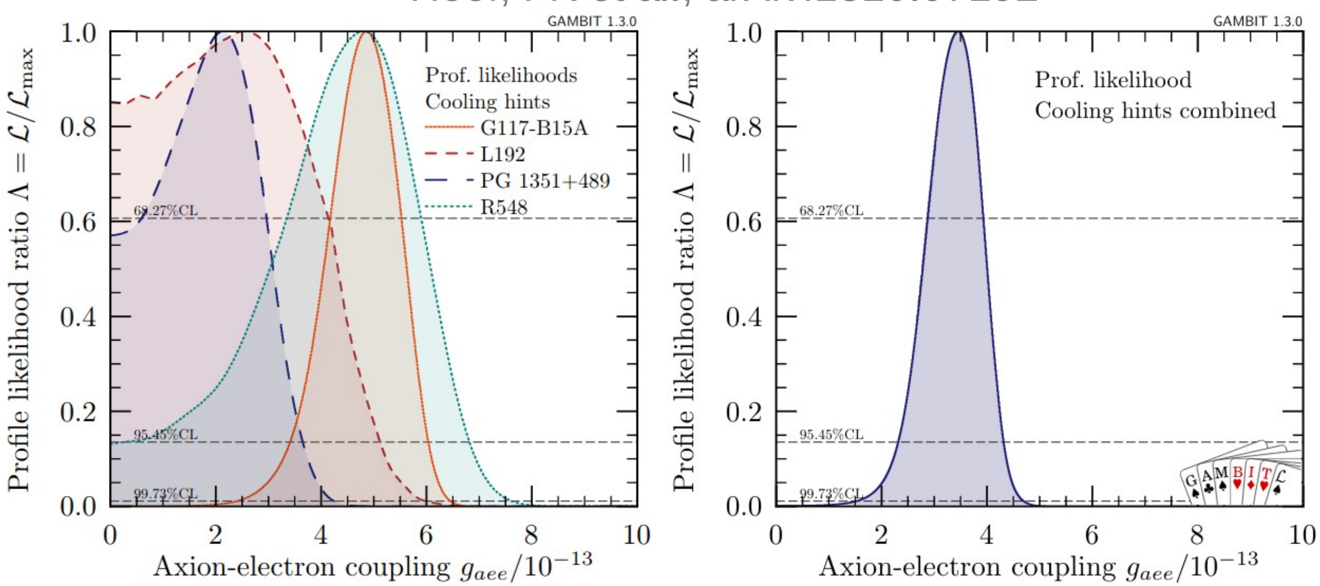
Stellar cooling: Hints

- At the same time, various astrophysical objects are observed to cool faster than expected from Standard Model processes
  - The R parameter ($R = N_{HB} / N_{RGB}$) is observed to be slightly smaller than expected, leading to a small preference for additional cooling contributions

Giannotti et al., arXiv:1512.08108

  - The observed cooling rates of WDs (measured via the decrease in the pulsation period) is significantly larger than expected, consistent with the production of exotic particles coupling to electrons

Hoof, FK et al., arXiv:1810.07192



XENON1T and stellar cooling: Hidden photons

- For m ~ 2 keV the hidden photon mass is comparable to the plasma frequency in the cores of HB stars and the production of hidden photons is resonantly enhanced

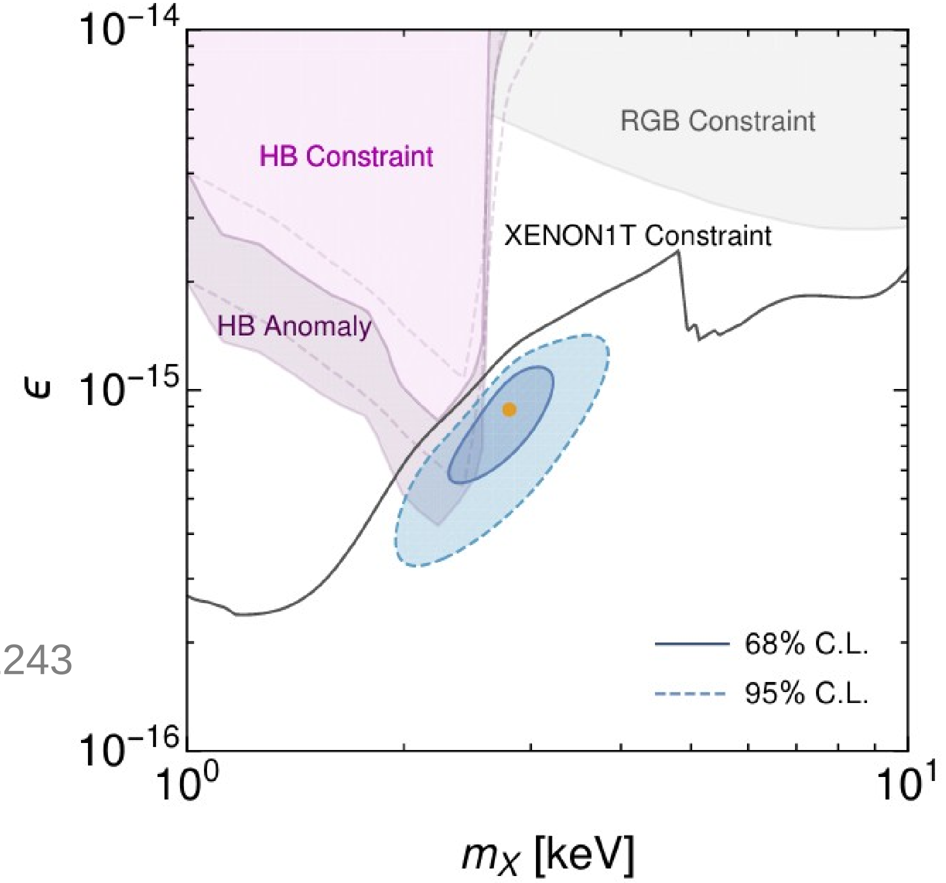
An et al., arXiv:1412.8378

- The mass and coupling strength required to fit the XENON1T signal predict a non-negligible contribution to the cooling rates of HB stars

- Hidden photons constituting all of DM can potentially account for both the XENON1T excess and the HB Anomaly

- Negligible contribution to WD cooling

Alonso-Álvarez, FK et al., arXiv:2006.11243



XENON1T and stellar cooling: ALPs

- The electron coupling inferred from the XENON1T excess is too small for ALPs to contribute significantly to stellar cooling rates and astrophysical constraints are easily satisfied

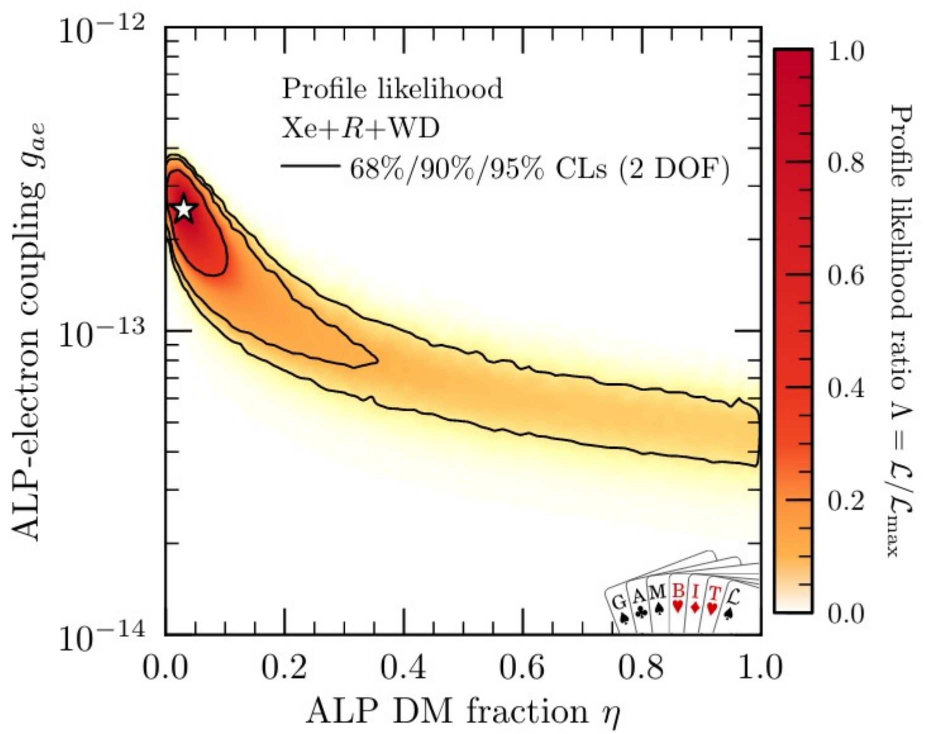
Takahashi et al., arXiv:2006.10035

- However, if ALPs are assumed to constitute only a fraction η of the local DM density, larger couplings are necessary to explain the XENON1T excess

- For η < 20% the ALP-electron coupling is large enough to contribute to the WD cooling rates

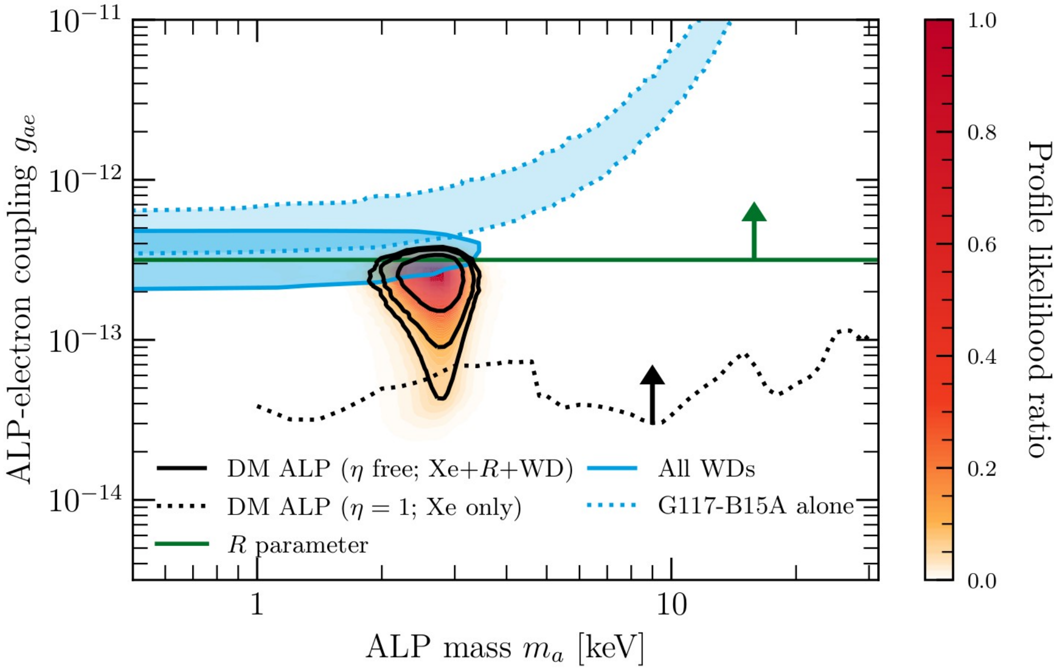
- In this case it is possible to simultaneously fit XENON1T and the WD cooling hints

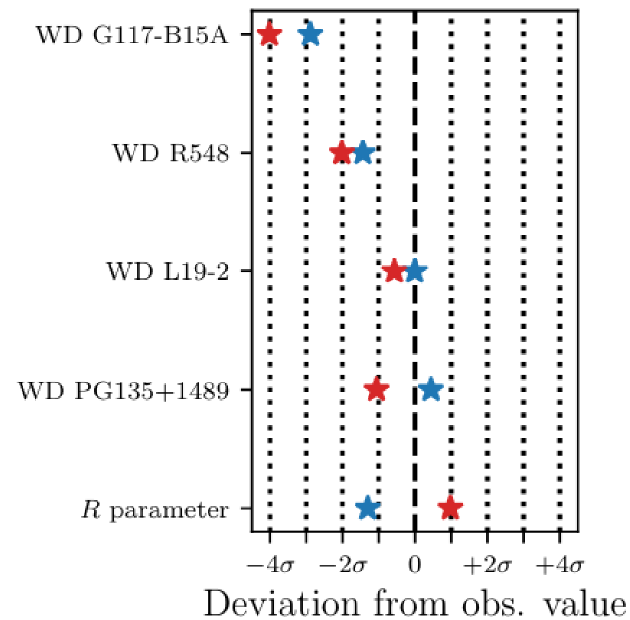
Athron, FK, et al., arXiv:2007.05517



XENON1T and stellar cooling: Combined fit

Athron, FK, et al., arXiv:2007.05517





	XENON1T	XENON1T + R parameter	XENON1T + R parameter + WD cooling hints
Axion-like particles	$\Delta\chi^2 = 16.8$	$\Delta\chi^2 = 17.7$	$\Delta\chi^2 = 23.1$
Axion-like particles + ^3H	$\Delta\chi^2 = 8.6$	$\Delta\chi^2 = 9.4$	$\Delta\chi^2 = 15.0$

How strong is the evidence for ALPs?

- Local $\Delta\chi^2$ values are difficult to interpret in terms of *p*-values for the ALP hypothesis
- To understand whether the ALP model is preferred over the background hypothesis, it is useful to calculate **Bayesian evidences**

$$\mathcal{Z}(\mathcal{M}) \equiv \int \mathcal{L}(D|\theta) P(\theta)\, d\theta$$

Prior distribution of θ

Likelihood of data D given parameter θ

- If the data *D* is in good agreement with the typical expectation for model *M*, the evidence will be large, otherwise it will be reduced
- We can then calculate the **Bayes factor** between two different models M_1 and M_2:

$$\frac{P(\mathcal{M}_1|D)}{P(\mathcal{M}_2|D)} = \frac{\mathcal{Z}(\mathcal{M}_1)}{\mathcal{Z}(\mathcal{M}_2)} \frac{P(\mathcal{M}_1)}{P(\mathcal{M}_2)}$$

Prior beliefs

How does this work in practice?

- Step 1: Choose **prior probabilities** to encode general expectations and previous knowledge
- Step 2: Combine all available experimental information to obtain **global likelihood functions**
- Step 3: Calculate **Bayesian evidence** using specialised sampling algorithms like MultiNest

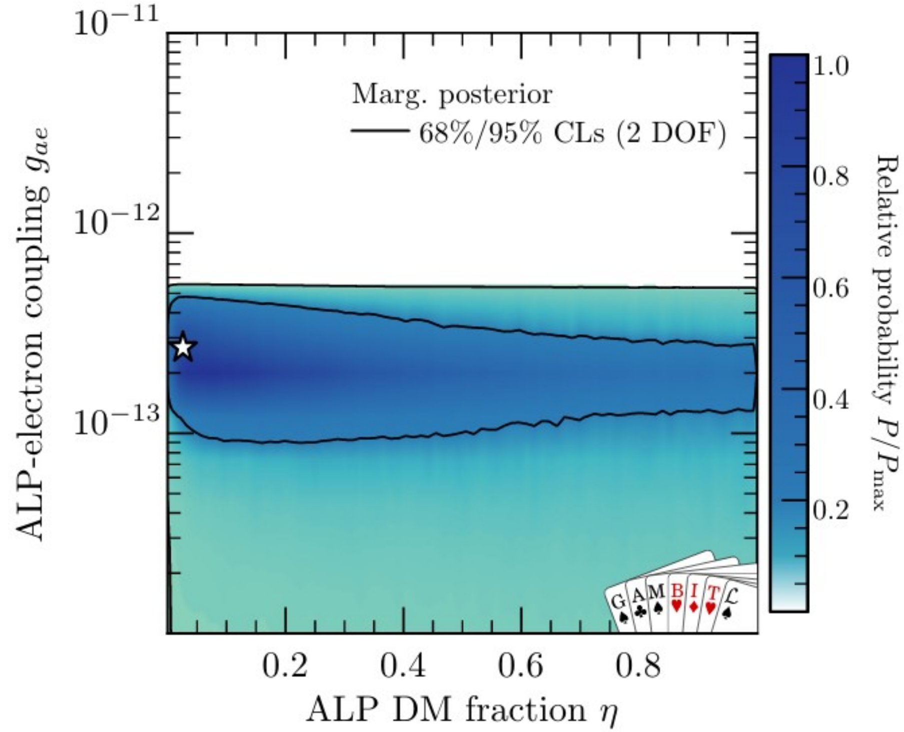
Parameter	Prior
ALP models	
m_a/keV	Uniform, $(1, 30)$
g_{ae}	Log, $(10^{-20}, 10^{-3})$
$g_{a\gamma}/\mathrm{GeV}^{-1}$	Log, $(10^{-20}, 10^{-3})$
g_{aN}^{eff}	Log, $(10^{-20}, 10^{-3})$
XENON1T nuisance parameters	
α_b	Gaussian, 1 ± 0.026
ϵ	Gaussian, 1 ± 0.03
XENON1T tritium component	
α_t	Log-normal, $\log_{10}\left(\frac{\alpha_t}{1\,\mathrm{mol/mol}}\right) = -27 \pm 3$
DM ALP nuisance parameters	
ρ_0	Log-normal, $\log_{10}\left(\frac{\rho_0}{1\,\mathrm{GeV/\,cm^3}}\right) = \log_{10}(0.4) \pm 0.138$
η	Uniform, $(0, 1)$

Process largely automated in the global fitting framework GAMBIT!

Results from Bayesian analysis

- Bayesian approach includes an automatic **Occam penalty**, i.e. a model is penalised for making very unspecific predictions (regarding e.g. the magnitude or location of a signal)
- As a result we find a Bayes factor of **0.92**, i.e. slight evidence *against* the ALP model, when neglecting the possible tritium background contribution
- Including a tritium background reduces the Bayes factor further
- Different prior choices (in particular smaller coupling ranges) can enhance the Bayes factor slightly, leading to a small preference *for* ALPs

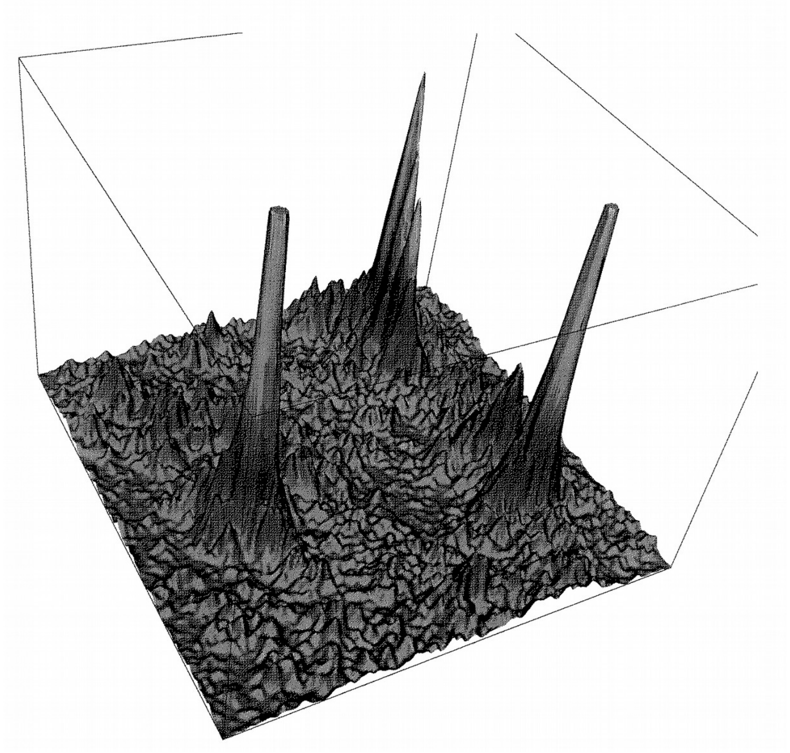
Athron, FK, et al., arXiv:2007.05517



- Bottom line: ALPs can fit the XENON1T signal, but they certainly did not predict it!

Outlook

- If the excess is confirmed by future direct detection experiments, it will be essential to measure its time dependence
- In contrast to DM scattering, the absorption of bosonic DM does not exhibit an annual modulation
- However, models of hidden photons and axion-like particles predict large inhomogeneities on small scales (such as axion mini-clusters)
- Expect substantial boosts of the event rate for a few seconds when a substructure crosses the detector



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Conclusions

- There are many ways to interpret the XENON1T excess in terms of new physics
- Particularly interesting is the possibility that XENON1T sees the absorption of bosonic particles from the local DM density
- Axion-like particles and hidden photons are well-motivated and cosmologically viable models that give a good fit to data and satisfy astrophysical constraints
- Moreover, both types of particles can give a relevant contribution to stellar cooling rates and account for small differences between predictions and observations
- Although the local preference for these models is quite large, there's no preference for them from a Bayesian point of view because of their unspecific predictions
- The next few years will be very exciting for direct detection experiments!