Interpretations of the XENON1T excess

Felix Kahlhoefer

7. KAT-Strategietreffen, online

4 December 2020

Including results from **arXiv:2006.11243** and **arXiv:2007.05517** in collaboration with Gonzalo Alonso-Álvarez, Peter Athron, Csaba Balázs, Ankit Beniwal, Eliel Camargo-Molina, Fatih Ertas, Andrew Fowlie, Tomás Gonzalo, Sebastian Hoof, Joerg Jaeckel, Doddy Marsh, Markus Prim, Pat Scott, Wei Su, Lennert Thormaehlen, Martin White, Lei Wu and Yang Zhang

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

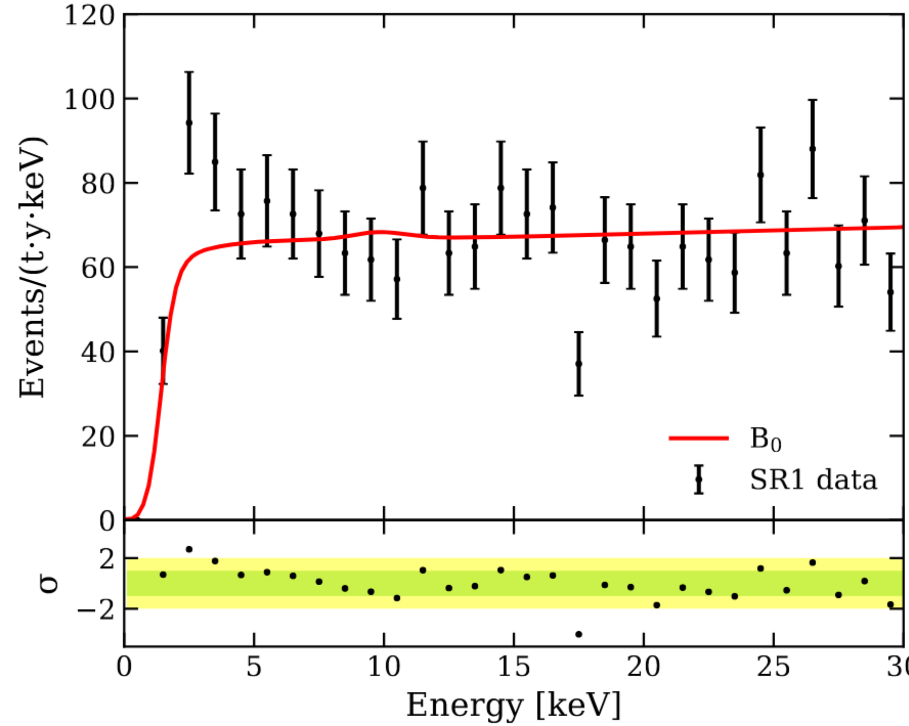
TTK Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

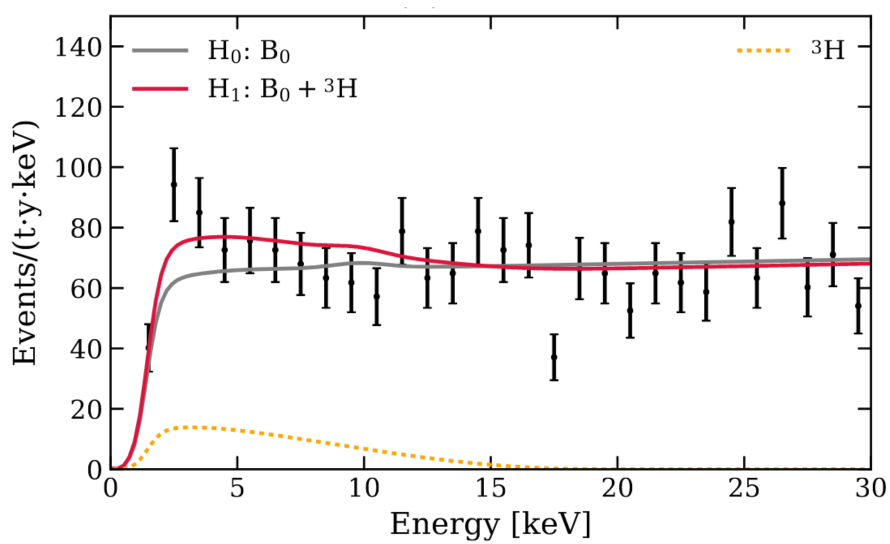
Electronic recoil events in XENON1T

- 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





- A more conventional explanation of the signal is that it is due to an unaccounted tritium component

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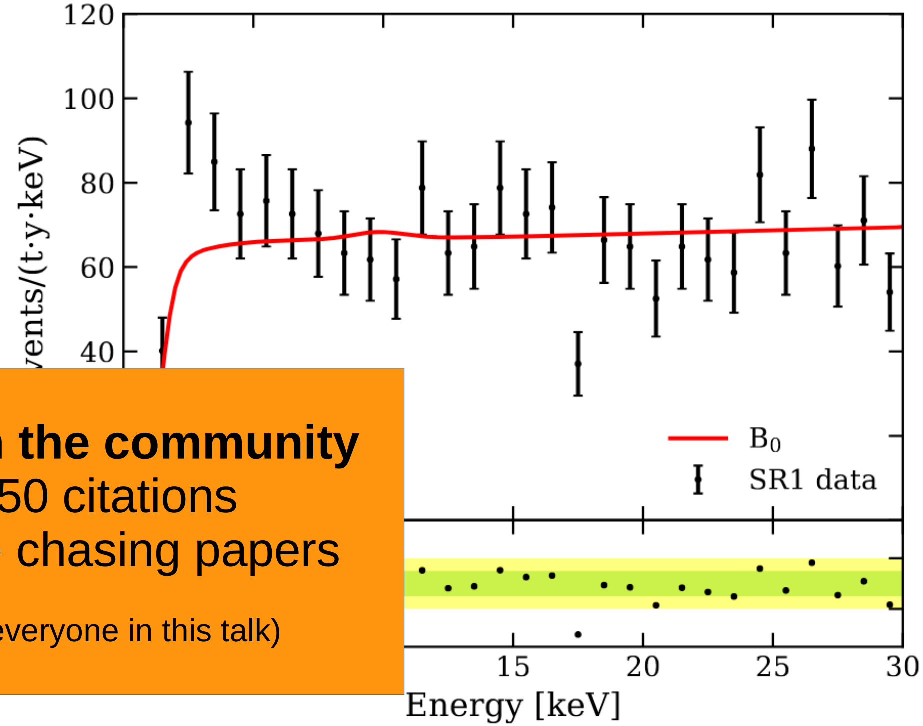
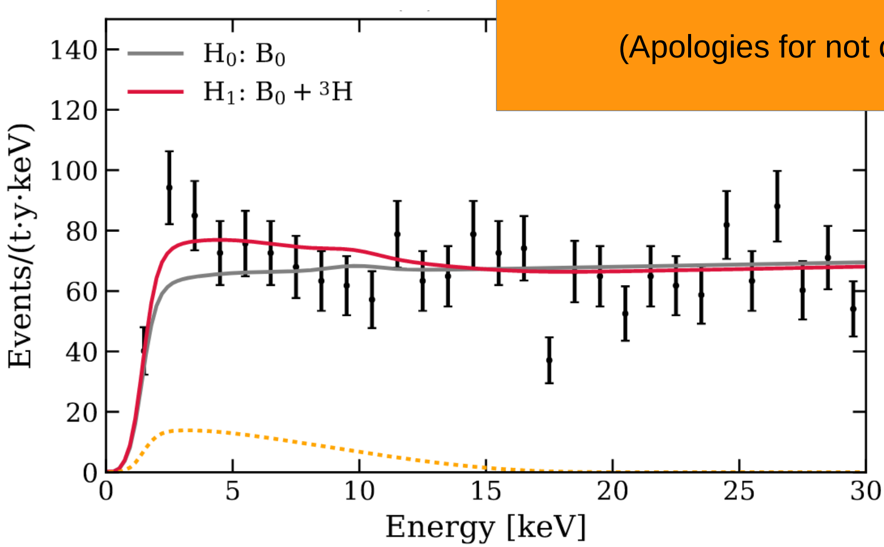


- For several different the significance is >3

Huge excitement in the community
Already over 150 citations
Over 50 ambulance chasing papers

(Apologies for not citing everyone in this talk)



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Overview of possible interpretations

Production mechanism

Detection mechanism

	Particles from the local DM density	**Particles produced in the Sun**	**Particles accelerated in astrophysical processes**
Elastic scattering on electrons	*No good fit to data* arXiv:2006.14521	Neutrinos with non-standard interactions arXiv:2006.11250	Boosted dark matter arXiv:2006.10735
Absorption (photoelectric effect)	Axion-like particles arXiv:2006.10035 Hidden photons arXiv:2006.11243	QCD axions arXiv:2006.12487	Products of dark matter annihilation or decay arXiv:2006.12488
Inelastic scattering, nuclear scattering, etc.	Exothermic DM arXiv:2006.13918 Luminous DM arXiv:2006.12461	*Unnecessarily complicated*	

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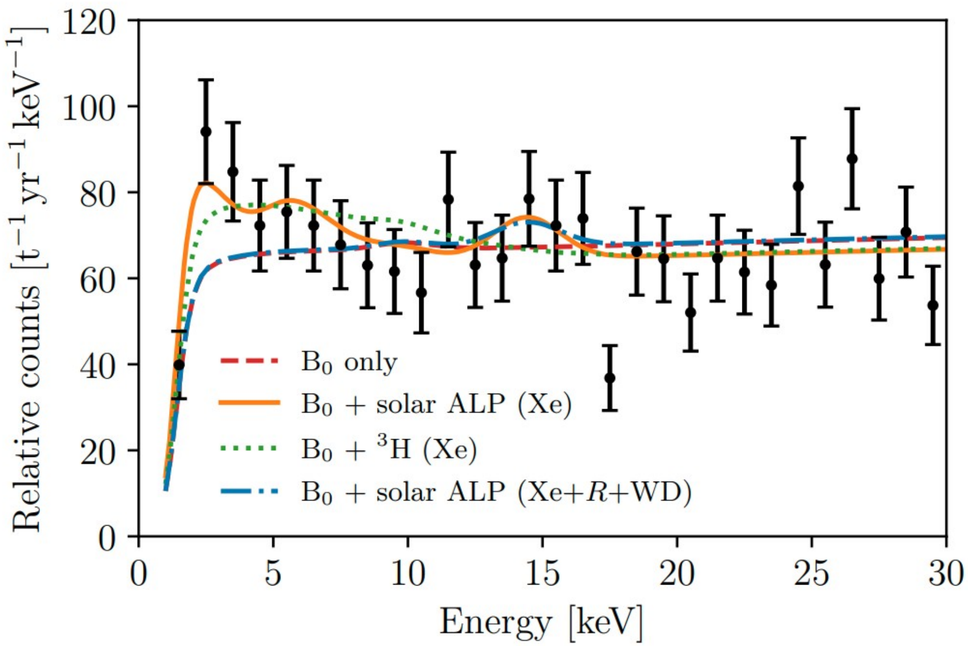
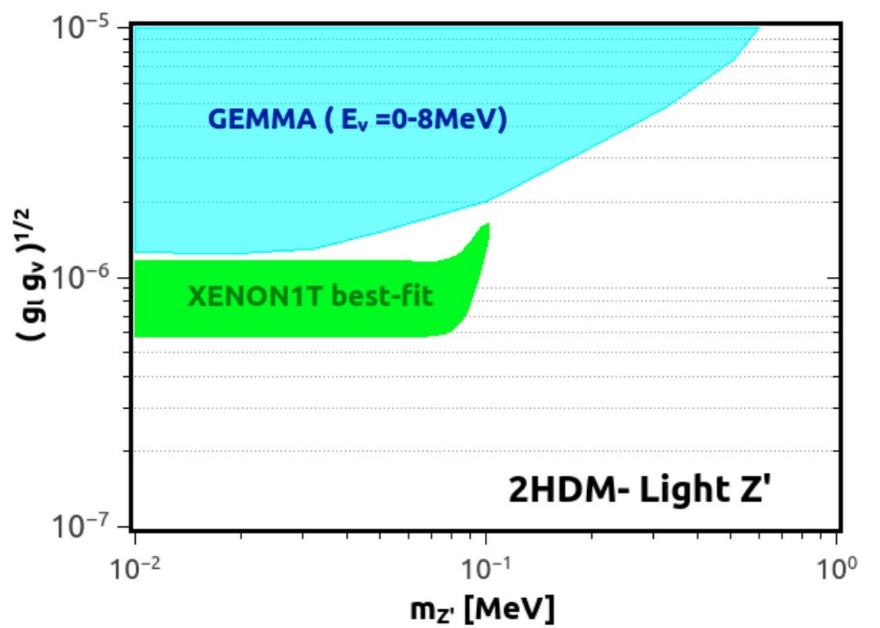
Particles produced in the Sun

- Both solar axions and solar neutrinos give a good fit to the XENON1T excess
- Example: Solar axions have $\Delta\chi^2 = 14.7$ with 3 degrees of freedom
- The shape of the signal is largely dictated by the temperature of the Sun
- Few fit parameters + no look-elsewhere-effect → strong signal preference

Solar axions, Athron, FK et al., arXiv:2006.11250



Solar neutrinos, Lindner et al., arXiv:2006.14590



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Constraints from stellar cooling

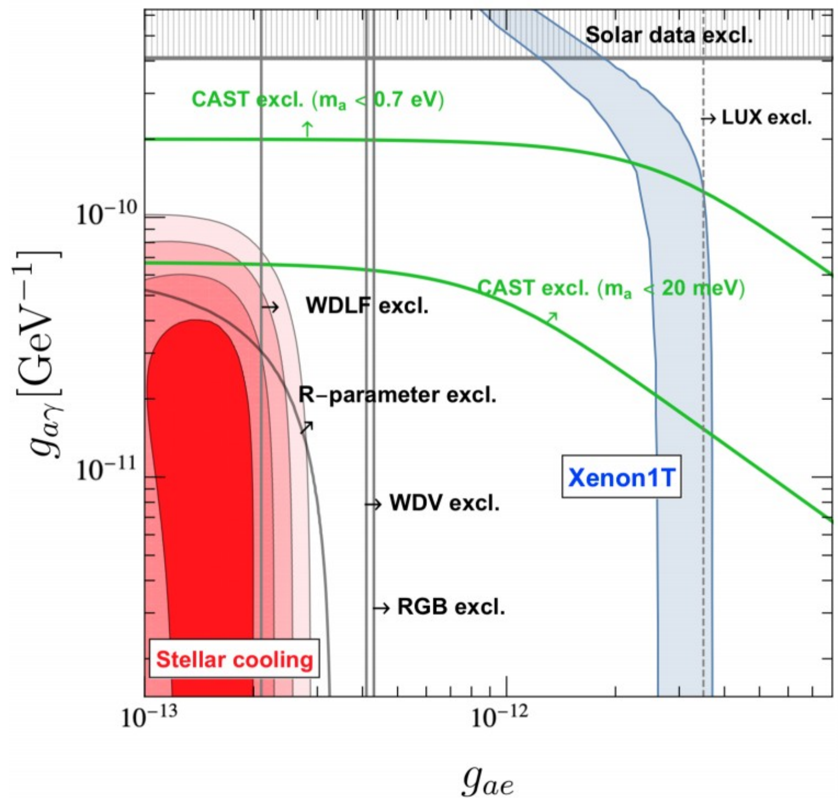
- Particles produced in the Sun can also be produced in other astrophysical systems

- Such particle production increases the energy losses and enhances stellar cooling 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



Alternative: Non-relativistic scatters

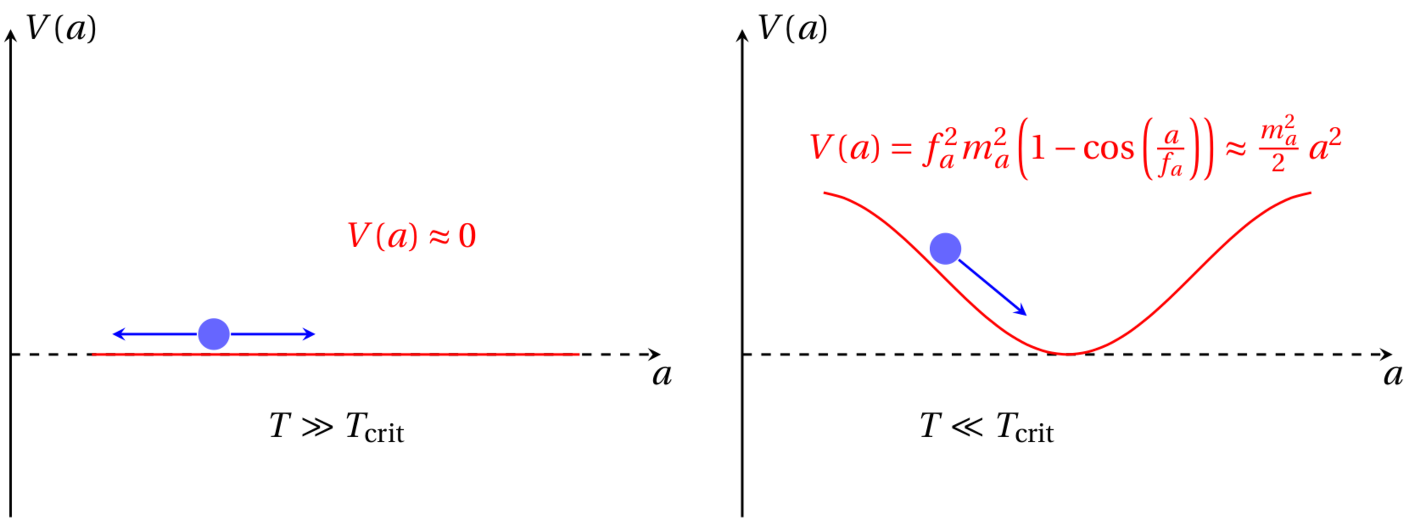
- Can the XENON1T excess also be explained in terms of non-relativistic particles that are gravitationally bound to the Milky Way and contribute to the local DM density?
- Elastic DM-electron scattering does not give a good fit to data (even for momentum-dependent interactions)

  Bloch et al., arXiv:2006.14521
- Possible alternative: DM particles "store" energy, which they release in the detector
  - Exothermic DM ($X^* + e^- \to X + e^-$) — Baryakhtar et al., arXiv:2006.13918
  - Luminous DM ($X^* \to X + \gamma$) — Bell et al., arXiv:2006.12461
- Requires a slightly heavier state, which is populated either in the early universe or through up-scattering

  Aboubrahim et al., arXiv:2011.08053
  Eby et al., arXiv:1904.09994

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 that couple dominantly to electrons
  - Dark (or hidden) photons that mix with the visible photon
- These particles can be produced in the early Universe via the misalignment mechanism and potentially constitute all of DM

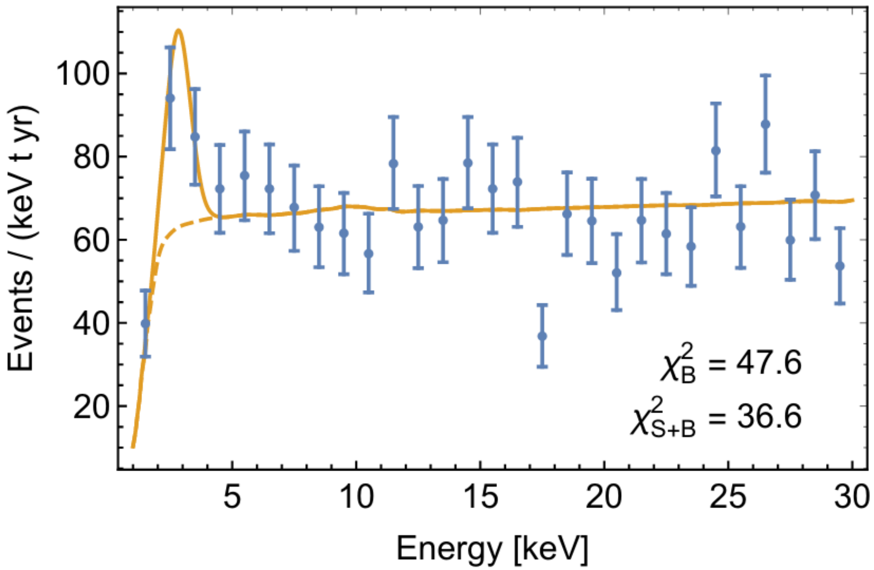


Note: For hidden photons, misalignment production requires non-minimal coupling to gravity

Alonso Álvarez et al., arXiv:1905.09836

Dark matter absorption in XENON1T

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



- 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
- Since the signal does not rely on particle production in the Sun, astrophysical constraints can be satisfied

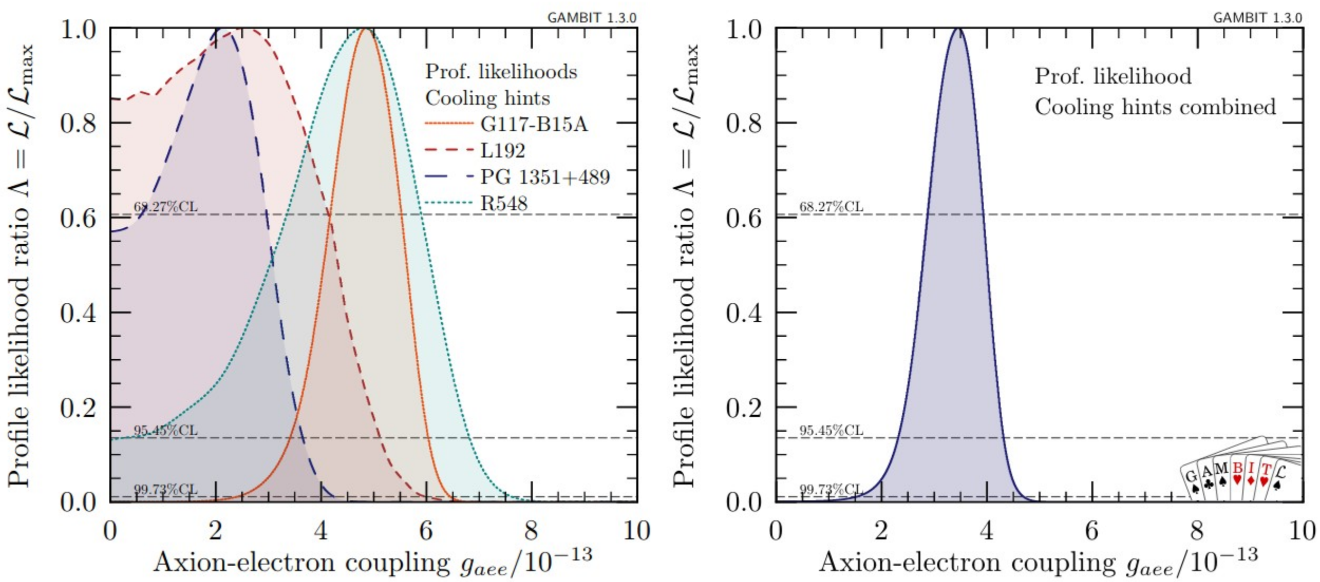
Stellar cooling hints

- However, astrophysical observations not only provide bounds on new particles beyond the Standard Model, but also some hints for anomalous cooling mechanisms
  - 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 increase 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

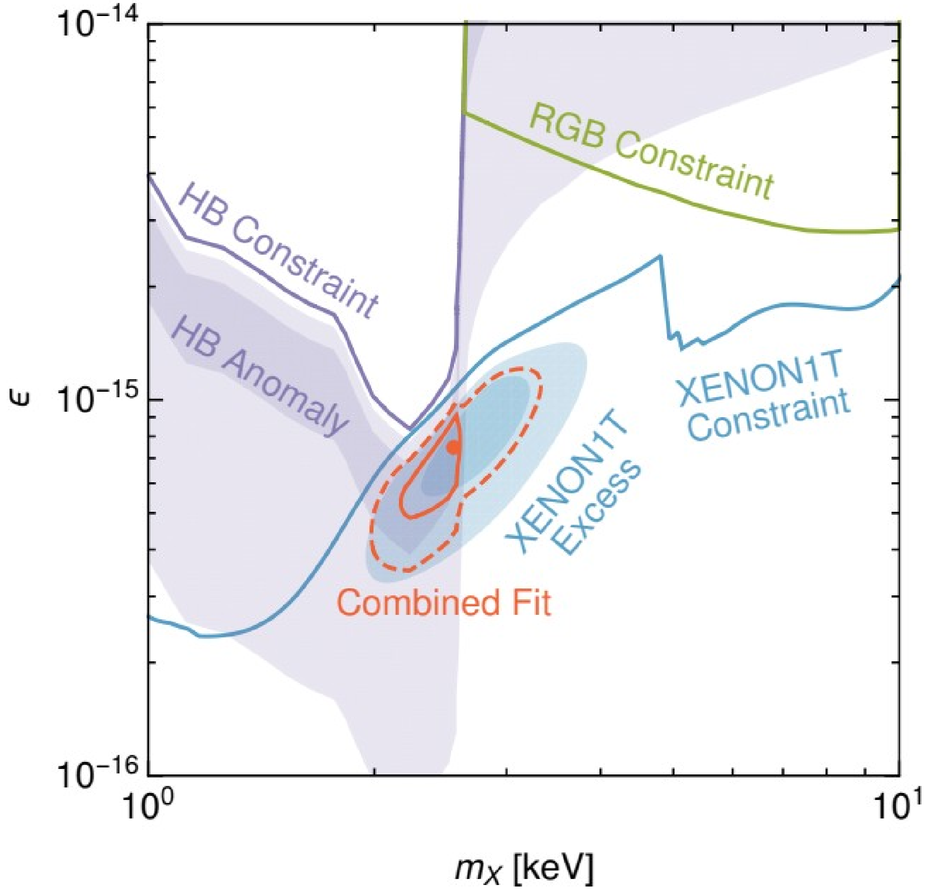
An et al., arXiv:1412.8378

- 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

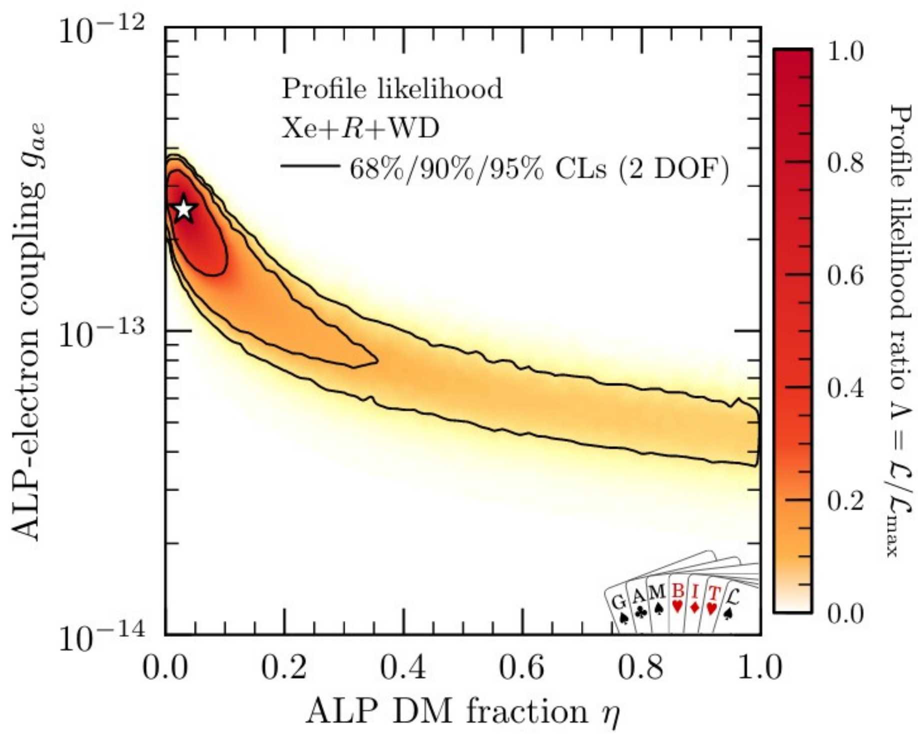
Takahashi et al., arXiv:2006.10035

- 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

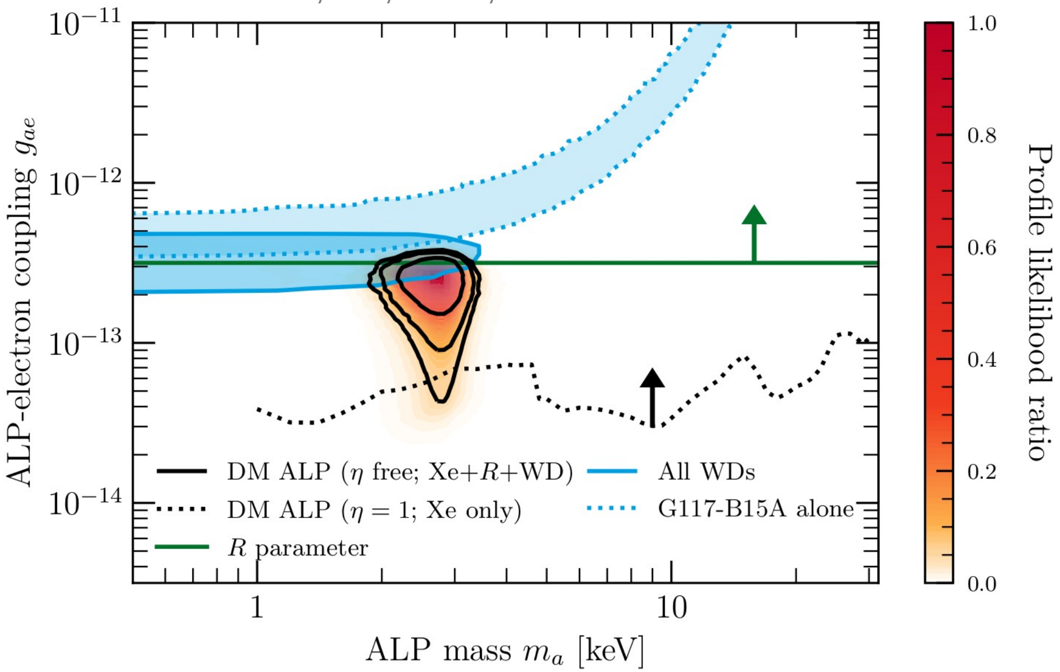
- In this case it is possible to simultaneously fit XENON1T and the WD cooling hints

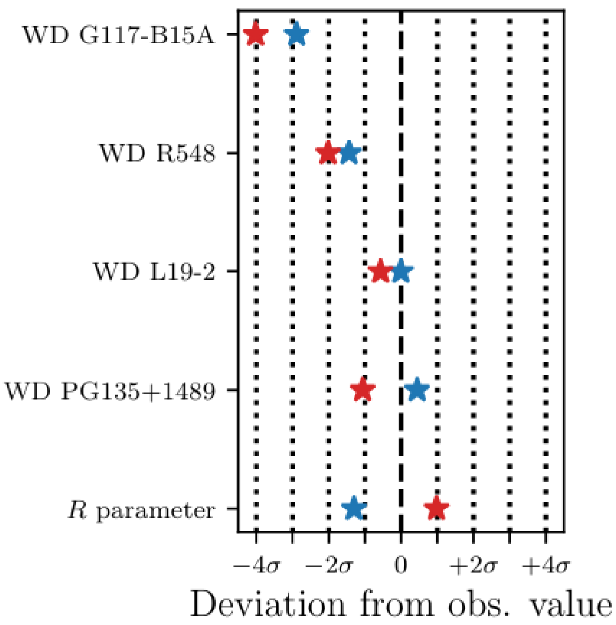
Athron, FK, et al., arXiv:2007.05517



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 + ^{3}H	$\Delta\chi^2 = 8.6$	$\Delta\chi^2 = 9.4$	$\Delta\chi^2 = 15.0$

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**

Prior distribution of θ

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

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

- Process largely automated in the global fitting framework GAMBIT!

Results from Bayesian analysis

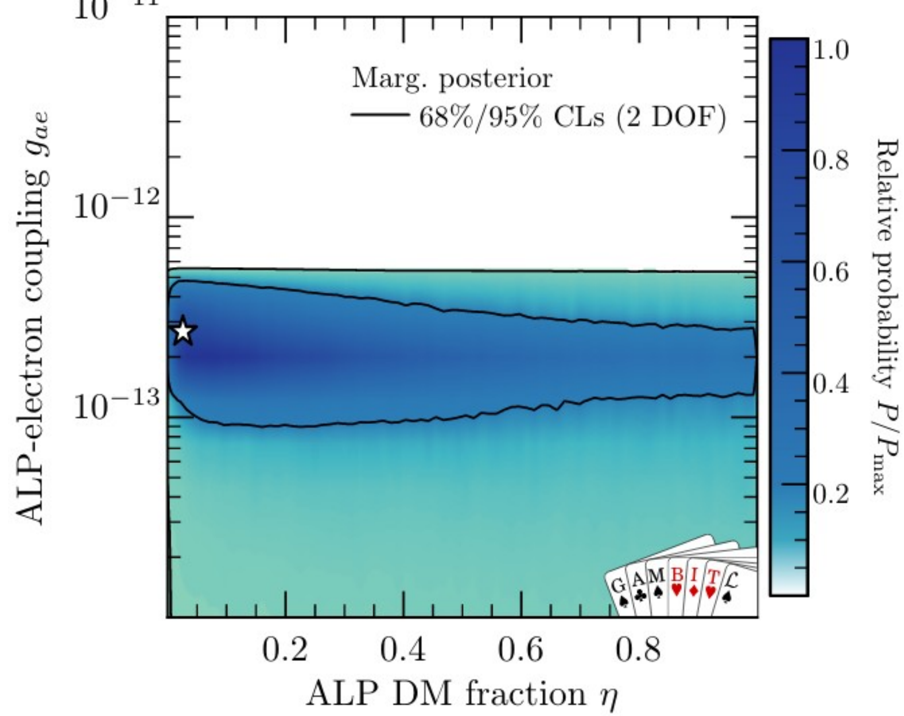
- Bayesian approach includes an automatic **Occam penalty**, i.e. a model is penalised for making very unspecific predictions (regarding the magnitude or location of a signal)

- As a result we find Bayes factor of order unity, i.e. *no clear evidence* for the ALP model

- When including a tritium background the ALP model is in fact *disfavoured*

- Different prior choices (in particular smaller coupling ranges) can enhance the Bayes factor, leading to a *small preference* for ALPs

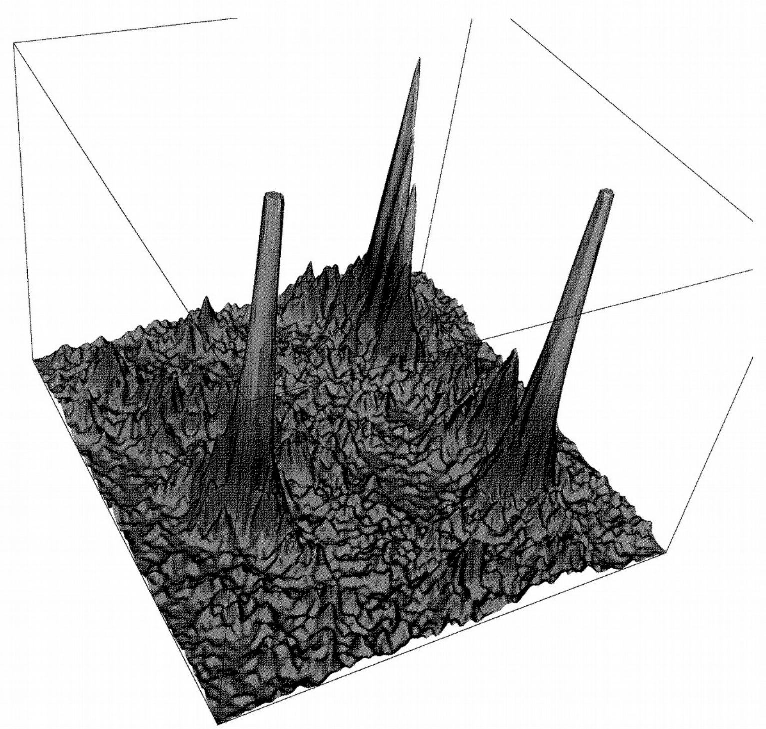
Athron, FK, et al., arXiv:2007.05517



- **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



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!