Galactic Origin of Relativistic Bosons and Xenon1T Excess

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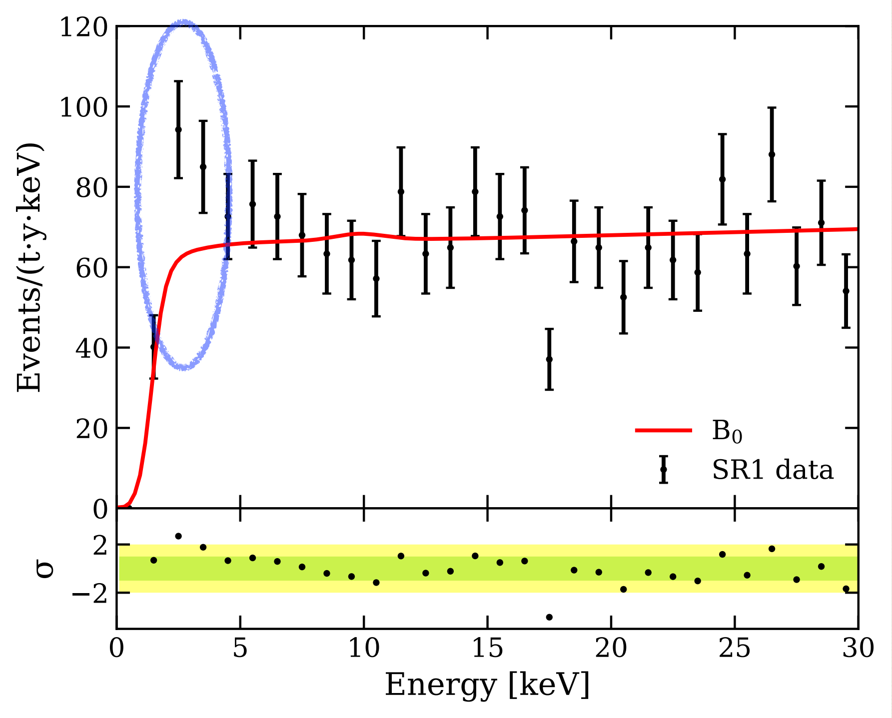
Based on work with Manuel Buen-Abad, Jatan Buch, and John Leung
2006.12488 [hep-ph], to appear in JCAP

Xenon1T low-energy electron recoil excess

~ 50 events;
peak at 2-3 keV



Xenon1T report: 2006.09721

Experimental anomalies come and go.

What new theoretical or experimental ideas can we learn from them?

Many roads lead to Rome

- Absorption of relativistic bosons with keV energy, in particular, solar axions;
- Absorption of non-relativistic bosons with keV mass;
- Scattering of relativistic particles with keV energy, e.g., solar neutrinos with an enhanced magnetic moments;
- Scattering of non-relativistic particles: semi-annihilation, fast initial particles such as boosted dark matter, inelastic scattering….
- ……

Many roads lead to Rome

- Absorption of relativistic bosons with keV energy, in particular, solar axions;
- Absorption of a non-relativistic boson with keV mass;
- Scattering of relativistic particles with keV energy, e.g., solar neutrinos with an enhanced magnetic moments;
- Scattering of non-relativistic particles off electrons: semi-annihilation, fast initial particles such as boosted dark matter....
- ……

free from look-elsewhere effects

Question for experimentalists: any other experimental information(e.g., in terms of S1/S2) to distinguish between relativistic and non-relativistic particles?

Production of solar axions

- Atomic recombination and deexcitation, Bremsstrahlung, Compton scattering (ABC);

$$\Phi_{\mathrm{a}}^{\mathrm{ABC}} \propto g_{\mathrm{ae}}^2$$

- Nuclear transition of Fe

$$\Phi_a^{\mathrm{Fe}} \propto g_{an}^2$$

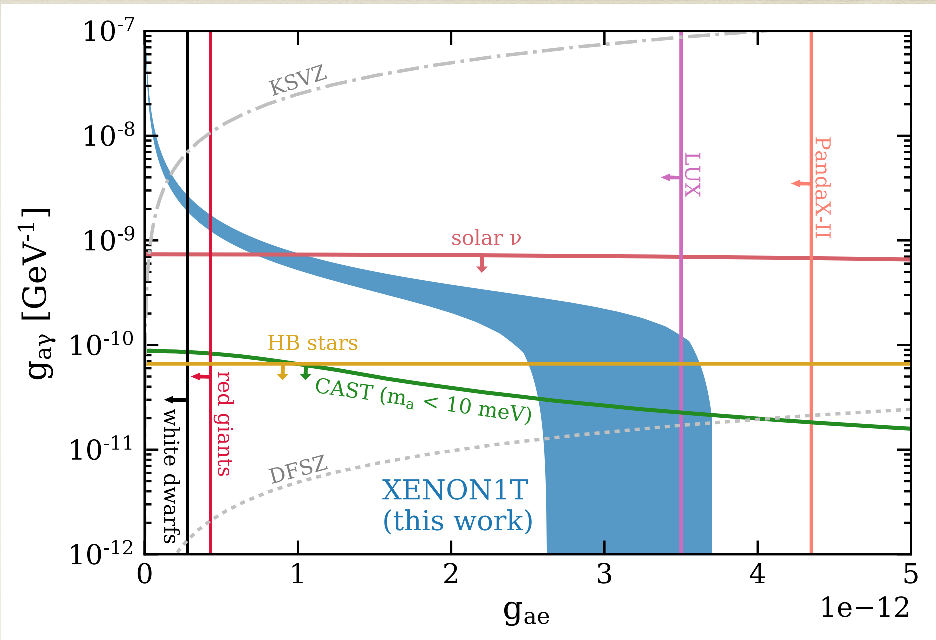
- Primakoff conversion of photons

$$\Phi_a^{\mathrm{Prim}} \propto g_{a\gamma}^2$$

Key feature: axion energy set by the core temperature of the Sun, ~KeV. Thus no look-elsewhere effects.

Detection of solar axions

Axio-electric effect: $\sigma_{ae} \propto g_{ae}^2$



Solar axion explanation is ruled out stellar cooling bounds

(one could build exotic models to get around the bounds: axion couplings are modified in stars…).

Given the stellar bound, the predicted number of events will be smaller **by a factor of 10^4**.

Similar story for solar dark photons.

A useful benchmark: given the stellar bounds, solar axion flux on earth is at most

$$\Phi \sim 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Other origins of relativistic bosons?

Decouple the production of bosons from the absorption process in direct detection.

In particular, production of ***relativistic*** bosons may dominantly come from a source different from the Sun and does not depend on their couplings to the SM.

Axions or dark photons from DM decays or annihilations.

Could they compete with the solar flux?

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Could they compete with the solar flux?

Yes, it is possible. Useful and simple model-independent upper bounds on the galactic flux of relativistic bosons (**independent of Xenon1T excess**).

Dark matter decays

Dark matter ϕ decays to relativistic bosons

fraction of decaying DM

$$\frac{d\Phi_d}{dE} = \left(\frac{dN_\psi}{dE}\right)_0 \frac{f_\phi}{4\pi\tau_\phi m_\phi} \int \rho_{\mathrm{DM}}(s)\mathrm{d}s\mathrm{d}\Omega,$$

energy spectrum, e.g. if DM decays to only two identical bosons in the final state, this is 2 $\delta(E-m_\phi/2)$

lifetime

decay J-factor: dominated by the Milky Way Halo

Dark matter decays

age of the Universe

$$\Phi_d \approx 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} f_\phi \left(\frac{4\ \mathrm{keV}}{m_\phi}\right)\left(\frac{\boxed{4\times 10^{17}\ \mathrm{s}}}{\tau_\phi}\right)\left[\int \left(\frac{dN_\psi}{dE}\right)_0 dE\right].$$

Stronger semi-model independent bound from CMB, assuming DM decays only to relativistic particles, $f_\phi/\tau_\phi < 2\times 10^{-19}\ \mathrm{s}$ (Poulin et. al 2016)

$$\Phi_d \lesssim 10^{9}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

One order of magnitude below the upper bound of solar axion flux.

Dark matter annihilations

Agnostic of the DM production mechanism (freeze-out, freeze-in, moduli decays …). Apply even when dark sector is completely secluded from the SM except through the weakly-coupled boson portal.

Assumptions:

1. DM relic abundance set (at redshift z_0) before matter-radiation equality;

$$z_0 \gtrsim z_{\rm eq}$$

2. $\langle\sigma v\rangle$ velocity independent.

$$\Gamma_{\rm ann}(z_0) = n_\phi(z_0)\langle\sigma v\rangle \lesssim H(z_0)\ , \quad \Rightarrow \langle\sigma v\rangle \lesssim 7\times 10^{-24}\,\frac{\rm cm^3}{\rm s}\, f_\phi^{-1}\left(\frac{m_\phi}{\rm keV}\right)$$

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weaker bound compared to thermal freeze out benchmark $3\times 10^{-26}\,{\rm cm^3/s}$

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$$\frac{d\Phi_2}{dE} = \left(\frac{dN_\psi}{dE}\right)_0 \frac{f_\phi^2\langle\sigma v\rangle}{8\pi m_\phi^2}\int \rho^2_{\rm dm}(s)\,{\rm d}s{\rm d}\Omega\ , \qquad \text{2-body,}$$

annihilation J-factor: dominated by the MW halo

$$\Rightarrow \boxed{\Phi_2 \lesssim 8\times 10^9\ {\rm cm^{-2}s^{-1}}\ f_\phi\left(\frac{4\ {\rm keV}}{m_\phi}\right)\left[\int\left(\frac{dN_\psi}{dE}\right)_0 dE\right]},$$

Comparable to the maximal solar axion flux.

Comments:

a. Bound get stronger for higher-body annihilations, e.g., 3-body annihilations;

$$\Phi_3 \quad \lesssim \quad 7 \times 10^5 \ \mathrm{cm}^{-2}\mathrm{s}^{-1} \ f_\phi \left(\frac{4 \ \mathrm{keV}}{m_\phi}\right) \left[\int \left(\frac{dN_\psi}{dE}\right)_0 dE\right]$$

b. Check Assumption 1: Γ < H before matter-radiation equality.

$$\frac{d\Phi_2}{dE} \quad = \quad \left(\frac{dN_\psi}{dE}\right)_0 \frac{f_\phi^2 \langle \sigma v \rangle}{8\pi m_\phi^2} \int \rho_{\mathrm{dm}}^2(s)\, \mathrm{d}s \mathrm{d}\Omega \ , \qquad \text{2-body,}$$

Increase <σv>, increase ϕ ?

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Increase <σv>, increase ϕ ?

No. Increase <σv>, Γ > H during matter domination and f_ϕ decreases. f_ϕ ~ 1/<σv>.

$$\Phi_2 \propto f_\phi^2\langle\sigma v\rangle \propto 1/\langle\sigma v\rangle$$

c. Check Assumption 2: <σv> velocity independent. **Larger cross section today!**

$$\langle \sigma v\rangle = \langle \sigma v\rangle|_{z_0}(v/v_0)^{-n},$$

average DM velocity at z0, e.g. v0~0.1

$$\Phi_{\text{2-body},\,\sigma\propto 1/v^2} \approx 10^{12}\ \mathrm{cm^{-2}s^{-1}}\ f_\phi\left(\frac{4\ \mathrm{keV}}{m_\phi}\right)\left[\int\left(\frac{dN_\psi}{dE}\right)_0 dE\right],$$

$$\Phi_{\text{2-body},\,\sigma\propto 1/v^4} \approx 10^{16}\ \mathrm{cm^{-2}s^{-1}}\ f_\phi\left(\frac{4\ \mathrm{keV}}{m_\phi}\right)\left[\int\left(\frac{dN_\psi}{dE}\right)_0 dE\right].$$

Considerably much larger flux allowed. Yet an enhanced cross section is subject to cosmological bounds, e.g. CMB bound on Sommerfeld enhancement (Bringmann et.al 2018). A possible caveat: more work needs to be done.

The conservative upper bounds derived are independent of the experimental excess, using simple requirements of DM that apply to generic models.

Now check whether that helps with the explanation of Xenon1T excess.

Axions

Given the stellar bounds, the solar axion flux on earth is at most

$$\Phi \sim 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

To get the number of observed events, we need a flux larger **by a factor of 10^4**.

On the other hand, the galactic source is at most comparable to the maximal solar axion flux. Could not help explain the excess.

Dark Photons

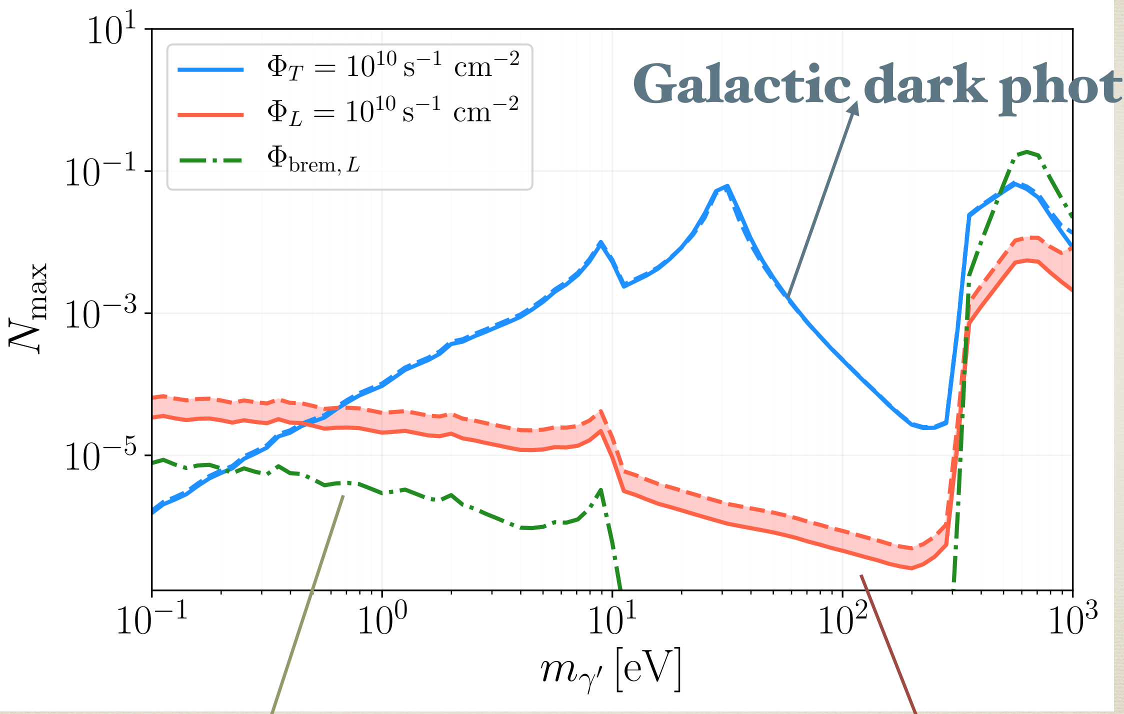
$$\epsilon F^{\mu\nu} F'_{\mu\nu}/2$$

Stueckelberg case: dark Higgs responsible for the breaking of dark U(1) is heavy and decoupled.

Solar production: $\gamma^{(*)} \to \gamma'$

Detection: $\gamma' + \mathrm{atom} \to \mathrm{atom}^+ + e^-$

Dark Photons



Galactic dark photon (transverse)

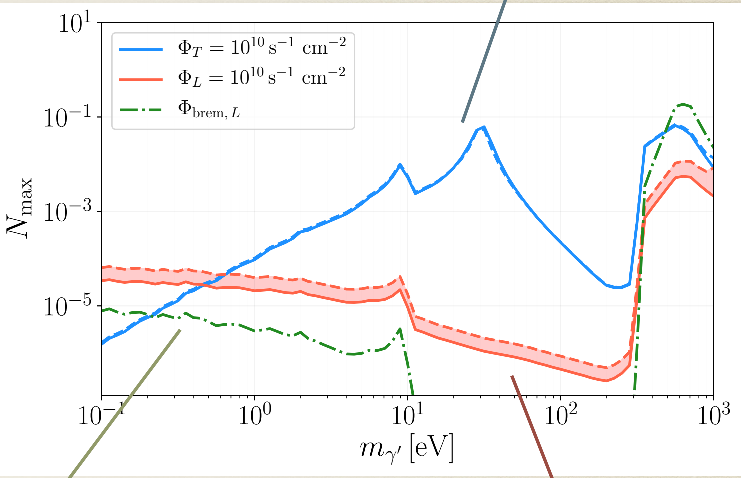
Solar dark photon

Galactic dark photon (longitudinal)

Dark Photons

1. Unlike the axion case, the galactic source of relativistic dark photons could dominate over the solar source.

2. Given the general bounds we derive before, the galactic source could only lead to O(0.1) events (compared to ~50 observed events). The only possible exception is the velocity dependent annihilation cross section.



Galactic dark photon (transverse)

Solar dark photon

Galactic dark photon (longitudinal)

Conclusions

Clearly we need more experimental efforts to confirm or rule out the Xenon1T excess.

Independent of Xenon1T excess, we have got some conservative generic upper bounds on galactic flux of relativistic weakly-coupled bosons. They could be comparable (axion case) or dominate over (dark photon case) the solar flux.

Questions for experimentalists:

Any other experimental information (e.g., in terms of S1:scintillation/S2:ionization) to distinguish between relativistic and non-relativistic particles?

Any way to collect directional information to tell the origin of the incoming particles?

Thank you !