New signals in dark matter detectors

Joachim Kopp

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Fermilab

based on arXiv:1202.6073 (with Roni Harnik, Pedro Machado)
and work in progress with Wolfgang Altmannshofer, Felix Yu

Outline

1. Direct dark matter detection
2. New ν signals in dark matter detectors
3. Multi-Hit signals from dark matter
4. Conclusions

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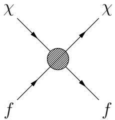
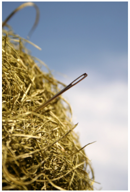
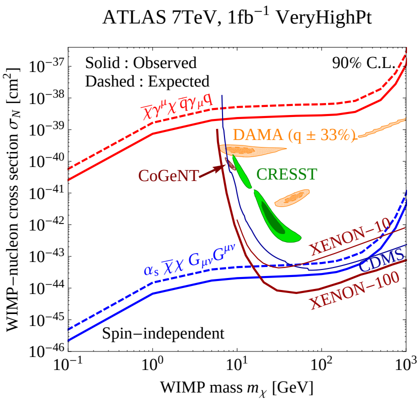
Direct dark matter detection

Search for feeble nuclear recoil from dark matter scattering.



The name of the game:
Background rejection!





compilation from Fox Harnik JK Tsai 1109.4398

Thick lines:
Collider bounds from monojet + MET search

Assumptions here:

- Elastic DM scattering $\propto$ target mass
- For collider limits: Effective field theory valid, flavor-universal couplings

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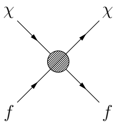
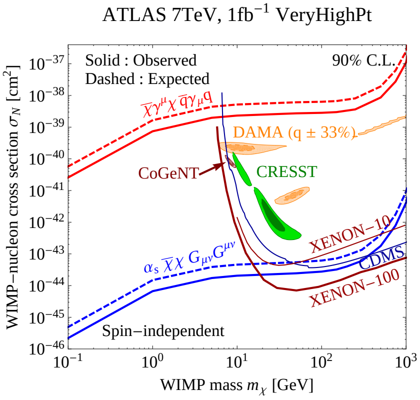


The name of the game:
Background rejection!

- Veto cosmic rays
- Fiducial volume cuts
- Attempt to distinguish electron recoils from nuclear recoils
- Reject multi-hit events
- Look for annual modulation
- ...



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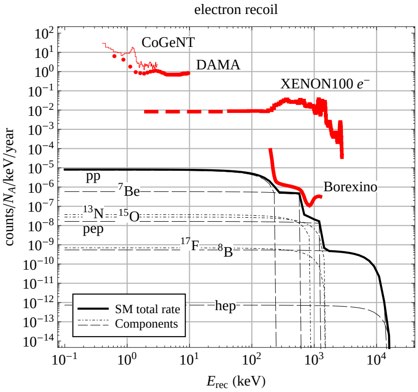
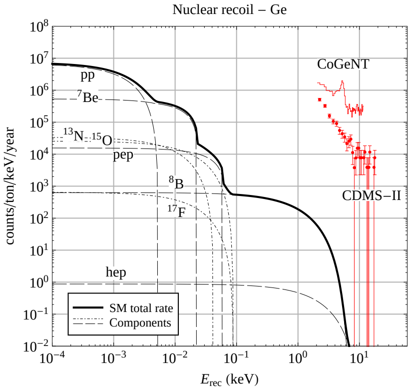
Neutrinos and direct dark matter detection

Solar neutrinos are a well-known background to future direct DM searches:

see e.g. Gütlein et al. arXiv:1003.5530

$$\frac{d\sigma_{\rm SM}(\nu N \to \nu N)}{dE_r} = \frac{G_F^2 m_N F^2(E_r)}{2\pi E_\nu^2}\Big[A^2 E_\nu^2 + 2AZ(2E_\nu^2(s_w^2 - 1) - E_r m_N s_w^2) + 4Z^2(E_\nu^2 + s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_N)) + s_w^2(E_r m_N - 2E_\nu^2))\Big],$$





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SM signal will only become sizeable in multi-ton detectors

But: New physics can enhance the rate

$\Rightarrow$ DM detectors can search for new physics in the ν sector

$\Rightarrow$ New ν physics can be confused with a dark matter signal

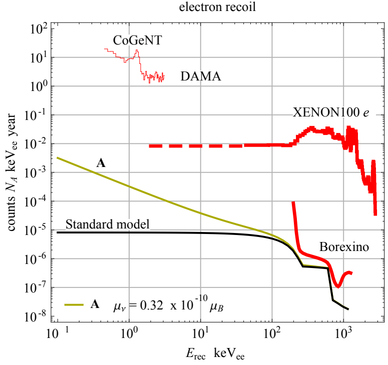
Example 1: Neutrino magnetic moments

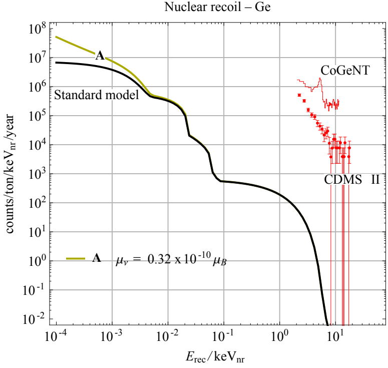
Assume neutrinos carry an enhanced magnetic moment

$$\mathcal{L}_{\mu_\nu} \supset \mu_\nu \, \bar{\nu} \sigma^{\alpha\beta} \partial_\beta A_\alpha \nu \,, \qquad \mu_\nu \gg \mu_{\nu,\text{SM}} = 3.2 \times 10^{-19} \mu_B$$

Cross section large at low energies due to photon propagator $\propto q^{-2}$

$$\frac{d\sigma_\mu(\nu e \to \nu e)}{dE_r} = \mu_\nu^2 \alpha \left(\frac{1}{E_r} - \frac{1}{E_\nu} \right) ,$$





Example 2: A not-so-sterile 4th neutrino

Introduce a new $U(1)'$ gauge boson A' (hidden photon) and a light sterile neutrino ν_s

Related model with gauged $U(1)_B$ first discussed in Pospelov 1103.3261
detailed studies in Harnik JK Machado 1202:6073 and Pospelov Pradler 1203.0545

- ν_s charged under $U(1)'$ $\rightarrow$ direct coupling to A'
- SM particles couple to A' only through kinetic mixing

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu} + \bar{\nu}_s i\partial\!\!\!/ \nu_s + g'\bar{\nu}_s\gamma^\mu\nu_s A'_\mu \\ - \overline{(\nu_L)^c} m_{\nu_L}\nu_L - \overline{(\nu_s)^c} m_{\nu_s}\nu_s - \overline{(\nu_L)^c} m_{\text{mix}}\nu_s$$

A small fraction of solar neutrinos can oscillate into ν_s

ν_s scattering cross section in the detector given by

$$\frac{d\sigma_{A'}(\nu_s e \to \nu_s e)}{dE_r} = \frac{\epsilon^2 e^2 g'^2 m_e}{4\pi p_\nu^2 (M_{A'}^2 + 2E_r m_e)^2}\left[2E_\nu^2 + E_r^2 - 2E_r E_\nu - E_r m_e - m_\nu^2\right]$$

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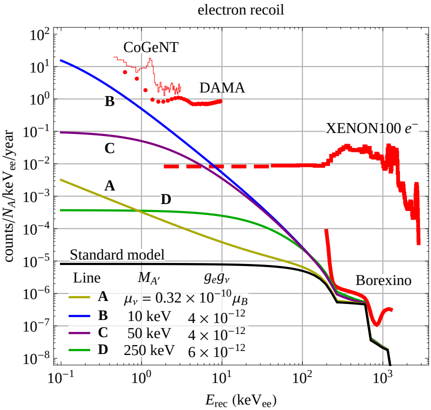

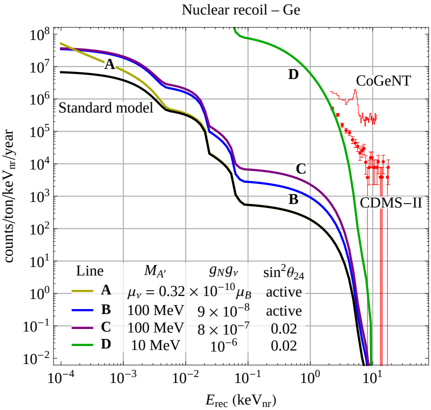

A: ν magnetic moment
B, C, D: kinetically mixed A' + sterile ν_s

A: ν magnetic moment
B: $U(1)_{B-L}$ boson
C: kinetically mixed $U(1)'$ + sterile ν
D: $U(1)_B$ + sterile ν charged under $U(1)_B$

proposed in Pospelov 1103.3261, details in Pospelov Pradler 1203.0545

- Enhanced scattering at low E_r for light A'
- Negligible compared to SM scattering ($\sim g^4 m_T / M_W^4$) at energies probed in dedicated neutrino experiments

Temporal modulation of neutrino signals

Signals of new light force mediators and/or sterile neutrinos can show seasonal modulation:

- The Earth–Sun distance: Solar neutrino flux peaks in winter.

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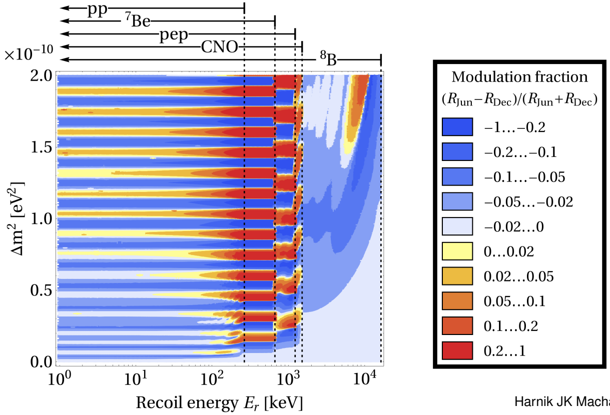

Harnik JK Machado, arXiv:1202.6073

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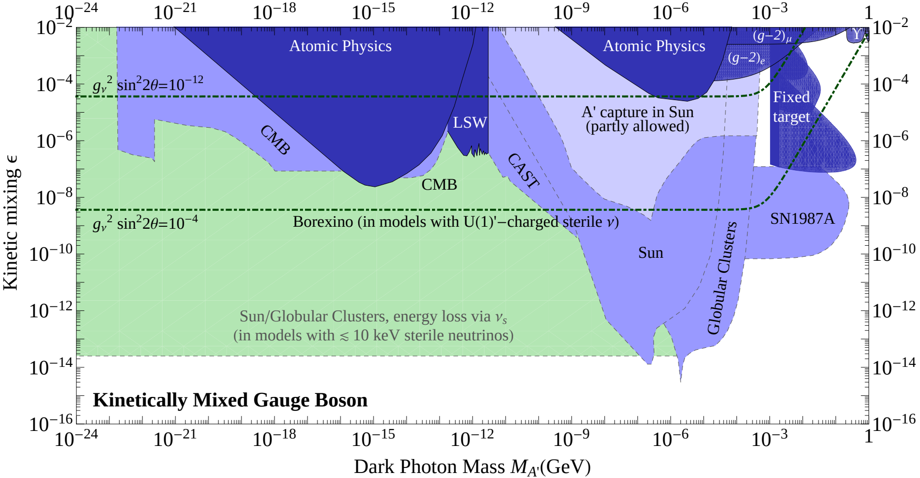
- Earth matter effects: An MSW-type resonance can lead to modified flux of certain neutrino flavors at night. And nights are longer in winter.

Hidden photons

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu} + \bar{\nu}_s i\partial\!\!\!/ \nu_s + g'\bar{\nu}_s\gamma^\mu\nu_s A'_\mu$$



Constraints from Jaeckel Ringwald 1002.0329, Redondo 0801.1527,
Bjorken Essig Schuster Toro 0906.0580, Dent Ferrer Krauss 1201.2683, Harnik JK Machado 1202.6073

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Multi-hit signatures from dark matter

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However, consider the following toy model (complete models: ask offline)

- Two dark sector particles χ^0 and χ^+
- χ^+ charged under $U(1)'$ gauge group
- $U(1)'$ gauge boson A' is light ($\ll$ 1 GeV)
- Coupling to the SM via kinetic mixing of $U(1)'$ and $U(1)_{\text{em}}$
- $U(1)'$ breaking leads to small mixing of χ^0 and χ^+.

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu} + i\bar{\chi}^+ \not{D}'_\mu \chi^+ + i\bar{\chi}^0 \not{\partial}_\mu \chi^0 - (\chi^0, \chi^+) \begin{pmatrix} m_{00} & m_{0+} \\ m_{+0} & m_{++} \end{pmatrix} \begin{pmatrix} \chi^0 \\ \chi^+ \end{pmatrix} .$$

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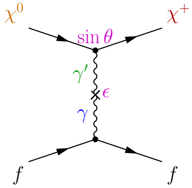
Phenomenology:

- Primary interaction leads to excitation $\chi^0 \to \chi^+$
- Suppressed by small $U(1)'$ breaking, (which leads to mixing $\propto \sin\theta$ of χ^0, χ^+)



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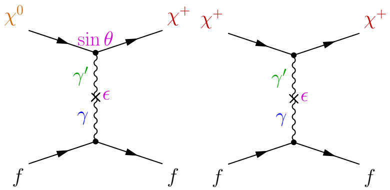
Phenomenology:

- Primary interaction leads to excitation $\chi^0 \to \chi^+$
- Suppressed by small $U(1)'$ breaking, (which leads to mixing $\propto \sin\theta$ of χ^0, χ^+)
- Subsequent interactions of χ^+ only suppressed by kinetic mixing parameter ε

$\Rightarrow$ Signature is multi-hit events



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Conclusions

Many interesting, unexplored signals possible in direct dark matter searches

- Neutrino–electron scattering and neutrino–nucleus scattering can be enhanced by several orders of magnitude at low energy ...
- ... for instance by
  - Magnetic moments
  - A 4th neutrino interacting through a new gauge force

- In some DM models, the only signal in direct detection is multi-hit events
  - The primary interaction can excite the DM to a more strongly interacting state
  - Multi-hit signatures don't *have* to be background

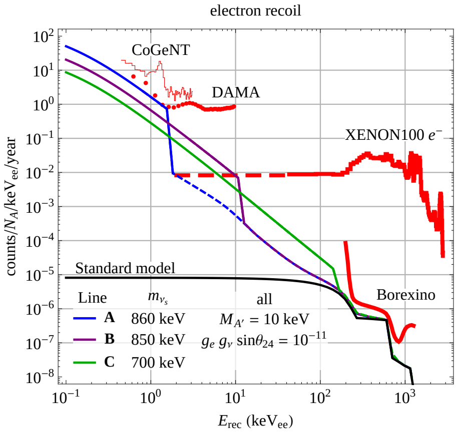
Thank you!

Bonus material

Heavier sterile neutrinos

Sterile neutrinos with mass close to a kinematic threshold in the Sun lead to different recoil spectra

Example: $m_{\nu_s} \sim 861$ keV (energy of solar Be-7 line: $^7\text{Be} + e^- \to {}^7\text{Li} + \nu$)



Anomalous energy loss in stars and supernovae

- A' bosons can be produced by plasmon oscillations in stars + supernovae

see e.g. Redondo 0801.1527 and references therein

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$$= -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \epsilon m_{A'}^2 A'_\mu A^\mu + \frac{1}{2}\epsilon^2 m_{A'}^2 A_\mu A^\mu + A_\mu j^\mu$$

Equations of motion:

$$(k^2 g^{\mu\nu} - \Pi^{\mu\nu}(k) - \epsilon^2 m_{A'}^2)A_\nu + \epsilon m_{A'}^2 A'^\mu = 0$$
$$(k^2 g^{\mu\nu} - m_{A'}^2)A'^\mu + \epsilon m_{A'}^2 A^\mu = 0$$

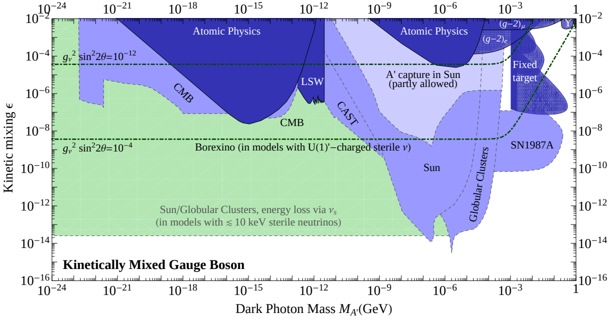
($\Pi^{\mu\nu}(k)$ = polarization tensor, depends on plasma frequency ω_P and on the inverse bremsstrahlung and Compton scattering rates)

Three regimes

- Low $m_{A'}$: A' production suppressed by small mixing $\sim m_{A'}^4/\omega_P^4$
- $m_{A'} \sim \omega_P$: Resonant A' production
- High $m_{A'}$: Thermal A' production

Anomalous energy loss in stars and supernovae

- A' bosons can be produced by plasmon oscillations in stars + supernovae
  see e.g. Redondo 0801.1527 and references therein
- Interesting features:
  - Resonant enhancement when $M_{A'} \sim$ plasmon mass
  - In general: Non-resonant A' production everywhere in the star (not just in the outer photosphere)
  - But: For very large ϵ, small optical depth even for A' $\rightarrow$ reduced production, weaker limit
- Require $P_{\text{invisible}} < P_{\text{visible}}$ to set limit



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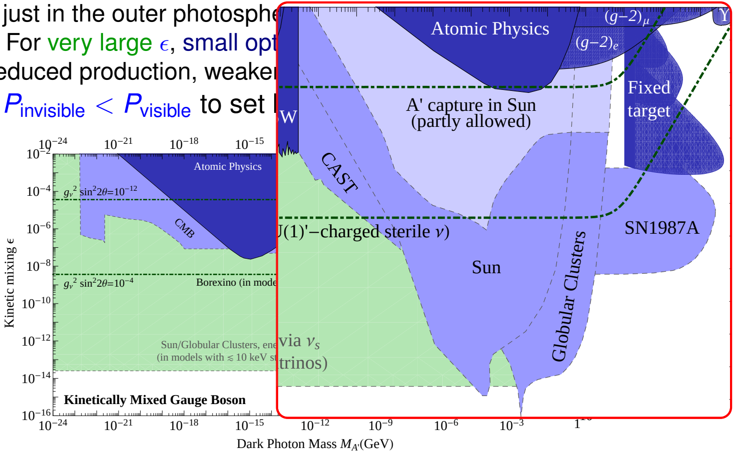

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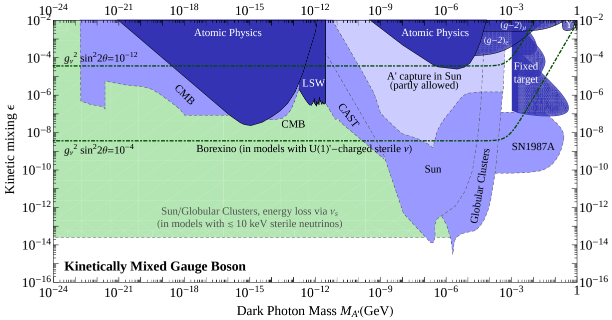
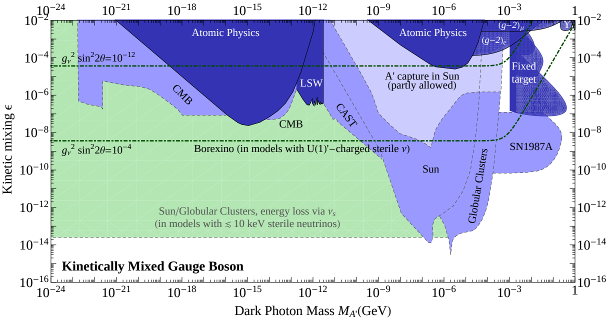


- Muon and electron $g - 2$
- Atomic physics: Test $1/r^2$ scaling of electromagnetic force
- Light shining through walls
- Fixed target experiments: A' production in beam dump, decay to SM
  - Expect significant improvement from APEX

Other constraints (2)



- CMB: Distortions to the black body spectrum
- Axion telescopes (e.g. CAST): Look for A' from the Sun oscillating to A
- B-factories: $e^+e^- \to A' +$ something,
  A' detected as $\not{E}$ or via its decay products
- In models with light sterile neutrinos:
  - ν_s production in stars + supernovae
  - $\nu_s e$ scattering in Borexino