Testing keV sterile neutrino dark matter in future direct detection experiments.

Miguel Campos

work done in collaboration with
Werner Rodejohann.

Based on [*arXiv:1605.02918*]

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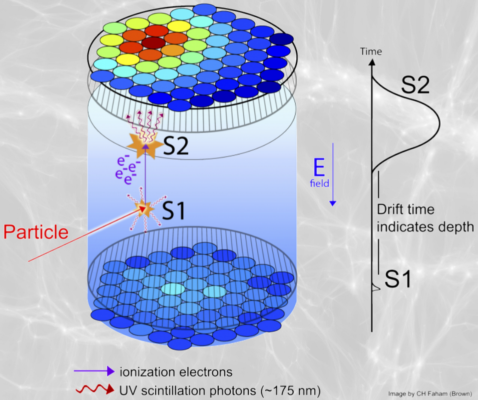
DESY-2016, 28 Sept.

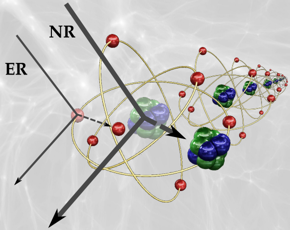
Introduction

Direct Detection Experiments



[Scheme from LUX Collaboration]

Electron Recoil vs Nuclear Recoil



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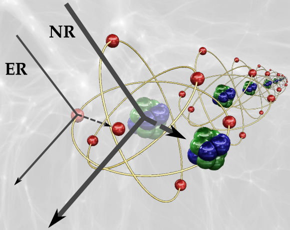
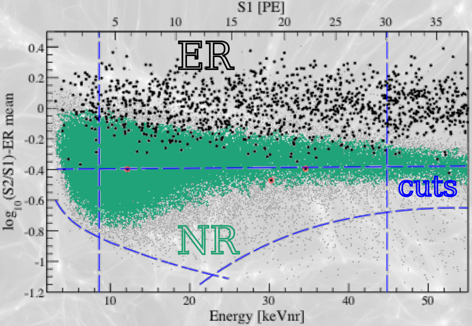
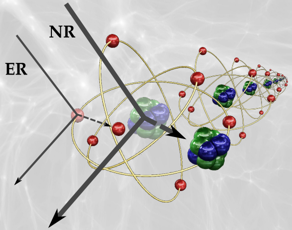
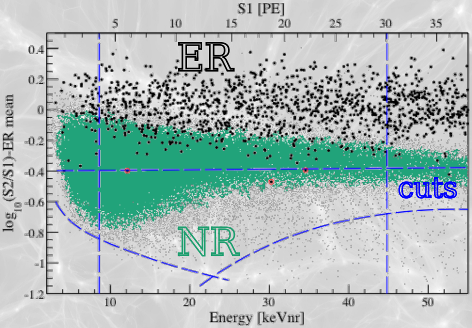




[XENON100 results from 2011]

Electron Recoil vs Nuclear Recoil

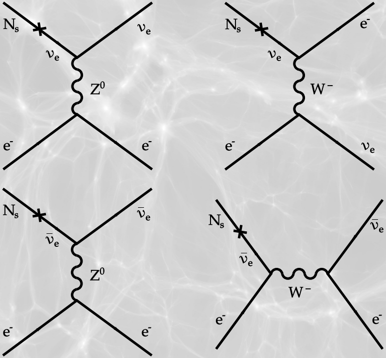




[XENON100 results from 2011]

In an attempt to use the discarded ER, one needs a signal that can be discriminated from this background.

The Process



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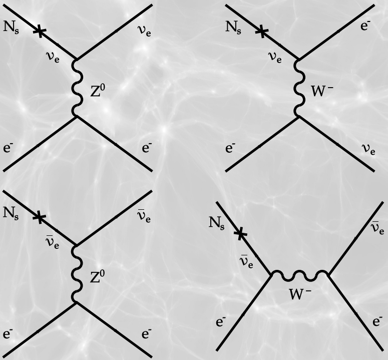

This process is suppressed due to the mixing angle between the sterile and the active neutrinos:

$$|U_{Se}|^2 \ll 1. \tag{1}$$

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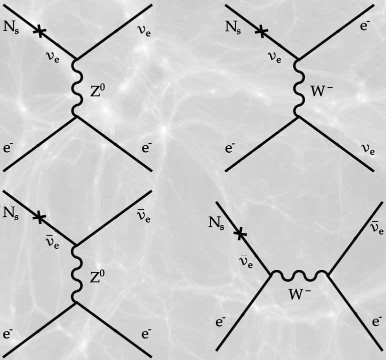

This process is suppressed due to the mixing angle between the sterile and the active neutrinos:

$$|U_{Se}|^2 \ll 1. \tag{1}$$

On the other hand if we assume here that the sterile neutrinos constitute all Dark Matter the estimated local density of 0.3 GeV/cm^3 implies a high flux. Also, as they are non-relativistic

$$E_\nu \approx m_S. \tag{2}$$

The Analysis

To calculate the cross sections we used the Roothan-Hartree-Fock method considering an effective mass for the bound electron as

$$\tilde{m} := E_B^2 - |\vec{p}_B|^2 \text{ where } E_B = m_e - \varepsilon.$$

[Based on method developed in *Phys. Lett. B* **525**, *63 (2002)*.]

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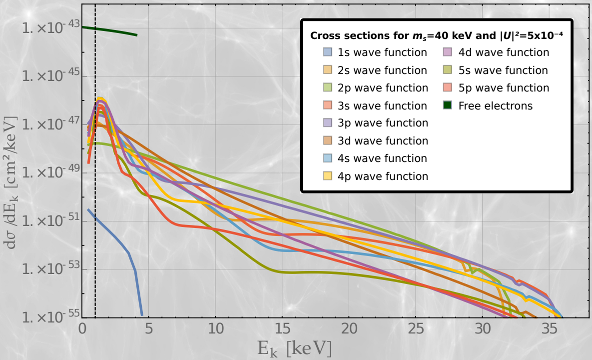

Relevant quantities

We calculate the differential event rate as:

$$\frac{dR_t}{dE_k}(m_S, |U_{Se}|^2) = \frac{\rho_0}{m_S} n_e \int \frac{d\sigma_t}{dE_k}(m_S, |U_{Se}|^2) f(v) v dv. \tag{3}$$

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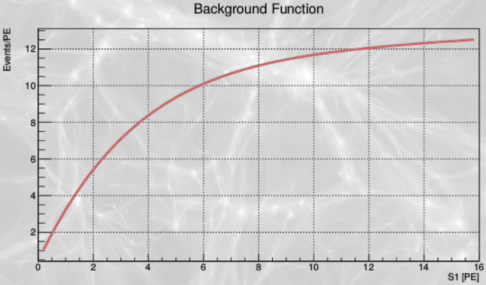
measured in DRU's = [kg×day×keV]$^{-1}$.
If T is the exposure time and M the mass of the detector we can define the differential number of events as:

$$\frac{dN_t}{dE_k}(m_S, |U_{Se}|^2) = M \cdot T \cdot \frac{dR_t}{dE_k}(m_S, |U_{Se}|^2) \, . \quad (4)$$

Detector input

To take into account the background, it is necessary to consider the intrinsic β decays of ^{222}Rn and ^{85}Kr present in xenon. From calibration data it is possible to obtain a background model.



Extracted from [*Phys. Rev. D* **90**, *no. 6, 062009 (2014)*]

Detector input

We must also consider the **conversion function** $\mathrm{Conv}(E_k)$ that relates the measured PE with the recoil energy of the scattered electrons E_k and the **acceptance** of the detector for ER $\mathrm{Acc}(\mathrm{PE})$.

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The differential number of events is then

$$\frac{dN_T}{dE_k}(m_S, |U_{Se}|^2) = \sum_t \mathrm{Acc}(\mathrm{Conv}(E_k)) n_t \frac{dN_t}{dE_k}(m_S, |U_{Se}|^2)\,,$$

where n_t is the number of electrons in the t state.

Statistical Method

In the region in which the signal is above than the background we can integrate and define:

$$N_s := \int_{E_{Th}}^{E_0} \frac{dN}{dE_k} dE_k,$$
$$N_b := \int_{E_{Th}}^{E_0} F_b dE_k. \tag{5}$$

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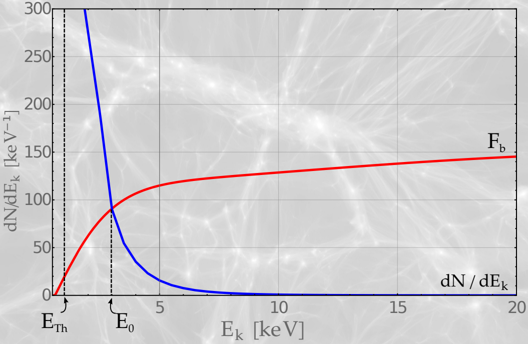


XENON1T differential number of events for $m_S = 40$ keV and $|U_{Se}|^2 = 5 \times 10^{-4}$

Statistical Method

From this simple block space analysis, we define the significance in terms of a χ^2 distribution, as a function of N_s and N_b:

$$\chi^2(m_S, |U_{Se}|^2) := \frac{(N_s(m_S, |U_{Se}|^2) - N_b(m_S, |U_{Se}|^2))^2}{N_b(m_S, |U_{Se}|^2)}. \tag{6}$$

Imposing that $\chi^2 \geq 4.60$ (13.82) for 90% (99.9%) C.L. we obtain the region in terms of m_S and $|U_{Se}|^2$ that can be excluded in the different experiments.

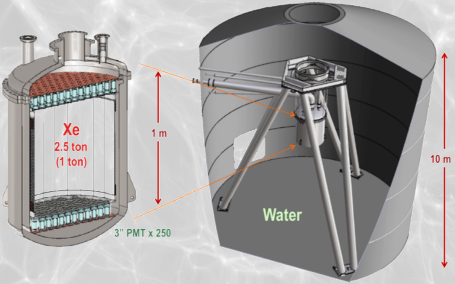
Detector characteristics: XENON100

Characteristics

- Bckgr $\sim 3 \times 10^{-3}$ [kg$\times$day$\times$keV^{-1}]
- $T = 224.6$ live days.
- $M = 34$ kg fiducial mass.
- $E_{Th} = 2$ keV$_{\mathrm{er}}$ threshold energy.

From [*Phys. Rev. Lett.* **109**, *181301 (2012)*]

Detector characteristics: XENON1T



Characteristics

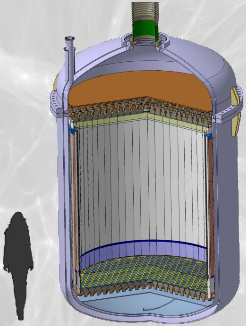
- Bckgr $\sim 1.8 \times 10^{-4}$ [kg×day×keV^{-1}]
- $T = 2 * 365$ live days.
- $M = 1000$ kg fiducial mass.
- $E_{Th} = 1$ keV$_{\rm er}$ threshold energy.

From [*JCAP* **1604**, *no. 04, 027 (2016)*]

Detector characteristics: DARWIN

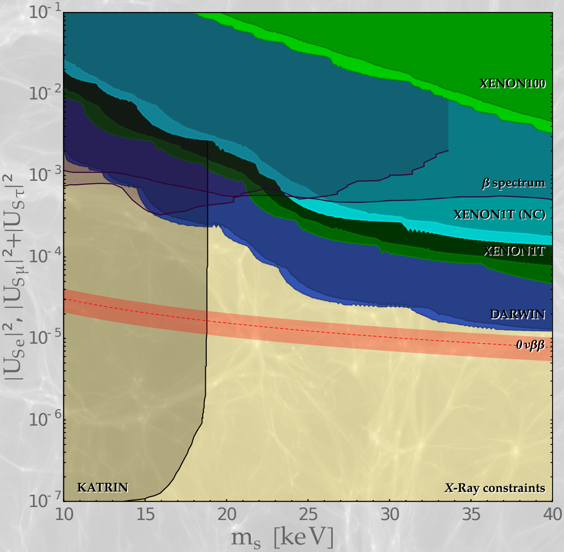
Characteristics

- Bckgr $\sim 2.05 \times 10^{-5}$ [kg$\times$day$\times$keV^{-1}]
- $M \cdot T = 200$ year$\times$ton
- $E_{Th} = 1$ keV$_{\mathrm{er}}$ threshold energy.

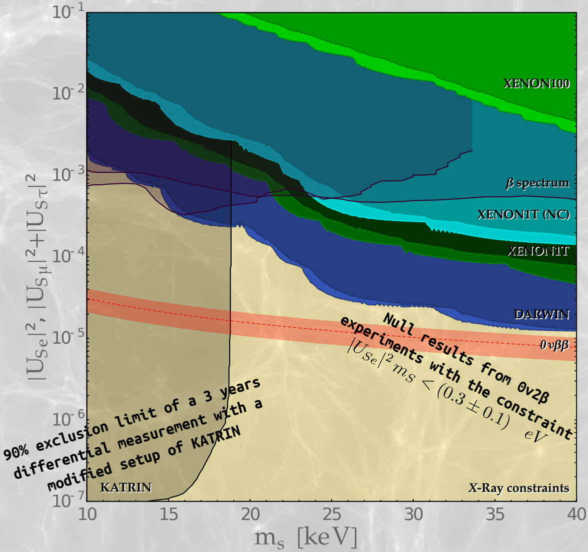


From [*arXiv:1606.07001 [astro-ph.IM]*.]

Results


XENON100
β spectrum
XENON1T (NC)
XENON1T
DARWIN
0νββ
KATRIN
X-Ray constraints
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10 15 20 25 30 35 40
$|U_{Se}|^2, |U_{S\mu}|^2+|U_{S\tau}|^2$
m_s [keV]

Results

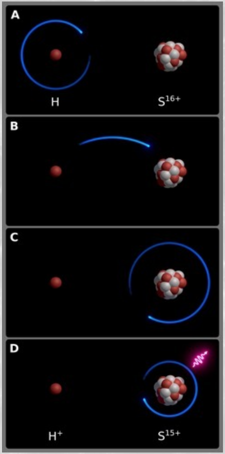

XENON100
β spectrum
XENON1T (NC)
XENON1T
DARWIN
0νββ
Null results from 0v2β experiments with the constraint $|U_{Se}|^2 m_S < (0.3 \pm 0.1)$ eV
90% exclusion limit of a 3 years differential measurement with a modified setup of KATRIN
KATRIN
X-Ray constraints
$|U_{Se}|^2, |U_{S\mu}|^2 + |U_{S\tau}|^2$
m_s [keV]


Thanks !
ν_τ
ν_μ
ν_e

Backup Slides: The mysterious 7.1 keV line

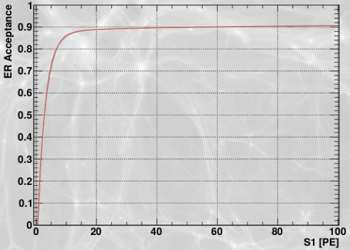
Using an electron beam ion trap the research group from the Max-Planck-Intitut für Kernphysik demonstrated that bare Sulphur ions (S^{16+}) can emit gamma lines at around 3.47 keV from Hydrogen atoms, an effect not considered before and published in

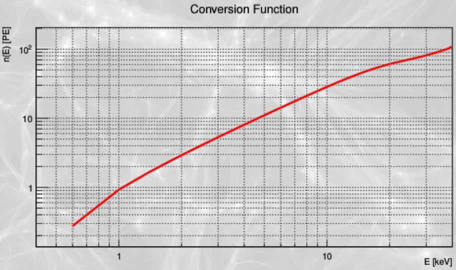
[arXiv:1608.04751 [astro-ph.HE]] .



From [MPIK webpage]

Backup Slides: Acceptance & Conversion Functions





Both extracted from [*Phys. Rev. D* **90**, *no. 6, 062009 (2014)*]

Backup Slides: Incoherent Scattering

If $m_S \approx \mathcal{O}(10 - 50)$ keV, then $\lambda_S \approx \mathcal{O}(10^{-8} - 10^{-9})$ cm.
As $R_{Xe} \sim 1.1 \times 10^{-8}$ cm the electron-neutrino scattering is incoherent and all the bound electrons in the xenon atom must be considered.
When considering just free electrons one would need masses higher than ~ 20 keV to go beyond the minimum threshold of the detector hence entering the incoherent regime.

Backup Slides: Cross sections

For free electrons the cross section with a sterile neutrino is given by

$$\begin{aligned}\frac{d\sigma_{\text{free}}}{dE_k} =&2\frac{G_F^2}{\pi}|U_{Se}|^2\frac{m_e}{|\vec{p}_S|^2}\left[g_1^2 E_S\left(E_S+\frac{m_S^2}{2m_e}\right)\right. \\ &+g_2^2(E_S-E_k)\left(E_S-E_k+\frac{m_S^2}{2m_e}\right) \\ &\left.-\, g_1 g_2(m_e E_k+\tfrac{1}{2}m_S^2)\right]. \end{aligned} \tag{7}$$

where

$$g_1^{\nu}=g_2^{\bar{\nu}}:=1+\frac{1}{2}(g_V+g_A)\,,\ g_2^{\nu}=g_1^{\bar{\nu}}:=\frac{1}{2}(g_V-g_A)\,,$$

Backup Slides: Cross sections

For bound electrons in a state t ($t = 1s$, $2s$, $2p$,...) the cross section in the rest frame of the atom where (p_B, θ, ϕ) are the variables of the bound electron is

$$\frac{d\sigma_t}{dE_k} = \int \frac{p_B^2 dp_B d(\cos\theta) d\phi}{(2\pi)^3} \frac{|R_t(\vec{p}_B)|^2}{4\pi} \\ \frac{|\mathcal{M}|^2}{4E_S E_B|\beta - p_B/\tilde{m}|} \frac{1}{8\pi\lambda^{1/2}(s, m_S^2, \tilde{m}^2)} \left|\frac{du}{dE_k}\right|. \tag{8}$$

Here $R_t(\vec{p}_B)$ are radial wave functions normalized such that

$$\int_0^\infty \frac{k^2 dk}{(2\pi)^3} |R_t(k)|^2 = 1\,. \tag{9}$$

The function $\lambda(a, b, c) := a^2 + b^2 + c^2 - 2ab - 2bc - 2ca$ is the Källén function and s and u are the usual Mandelstam variables.

Backup Slides: The Roothaan-Hartree–Fock method

The **Hartree–Fock** method estimates the wave function and the energy of a quantum many-body system in a stationary state.
The **Roothaan equations** are a representation of the Hartree–Fock equation in a non orthonormal basis set which can be of Gaussian-type or Slater-type.