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*]

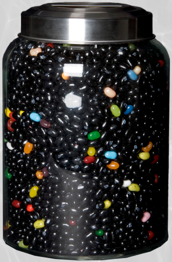
Max-Planck-Institut für Kernphysik
&
Heidelberg Universität

IMPRS Seminar, 04 Nov. 2016

Dark Matter.

What we do know

- Its approximate abundance.



(Chandra X-Ray Center/NASA)

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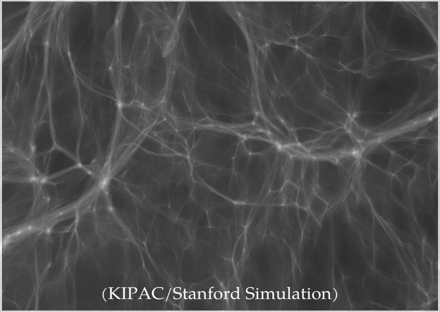

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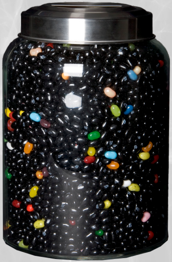

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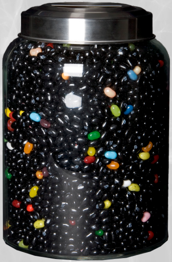
What we don't know

- What it actually is.



Dark Matter classification.

Three options

In general terms, we can classify (Particle) Dark Matter in three categories:

- Cold Dark Matter (CDM).
- Warm Dark Matter (WDM).
- Hot Dark Matter (HDM).

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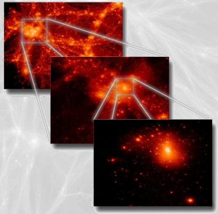
CDM is usually characterized by a heavy non-relativistic particle that would lead to the formation of small structures first.



Extracted from [*New Astron. Rev.* **58**, *1 (2014)*]

Cold Dark Matter.

Weakly Interacting Massive Particles (WIMPs) fall in this category and due to the absence of confirmed detection, only limits on its properties (mass and cross section) have been derived.

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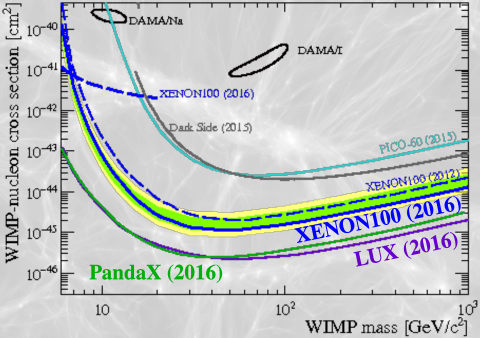

Extracted from [*arXiv:1609.06154 [astro-ph.CO]*]

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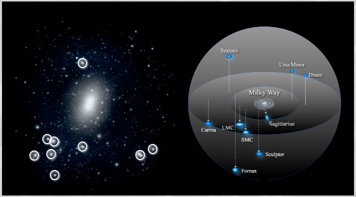

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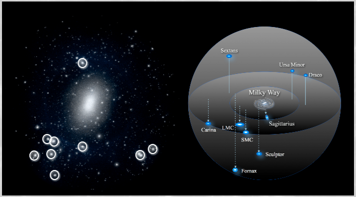

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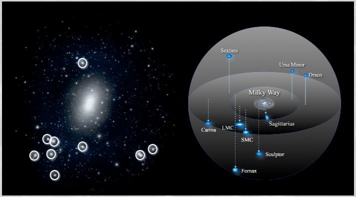

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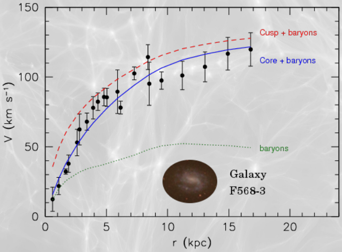

Extracted from [*Proc. Nat. Acad. Sci.* **112**, *12249 (2014)*]

Warm Dark Matter.

WDM particles are lighter than in the CDM case, usually in the order of $\sim$keVs.

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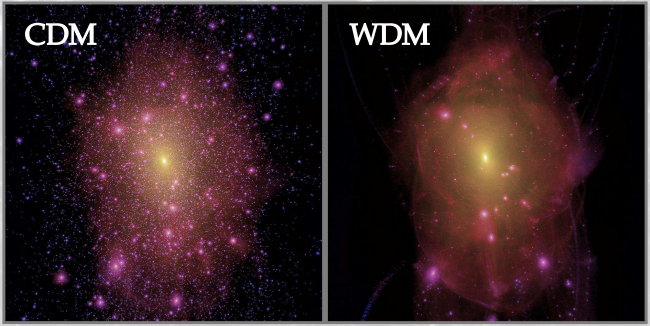
WDM behaves like CDM at large scales, but differs at small scales (less than 50 kpc) solving the missing satellites problem.



Extracted from [*Mon. Not. Roy. Astron. Soc.* **420**, *2318 (2012)*]

Sterile neutrinos as WDM

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- Don't perceive gauge SM interactions.
- Mix with the light active ones.
- Can generate neutrino masses through the (type I) seesaw mechanism (if $M \sim 10^{15}$ GeV).

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...as Dark Matter.

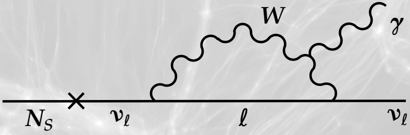
Constitute a DM candidate if $M \sim$ keV, when one specifies the production mechanism:

- Dodelson and Widrow mechanism.
- Shi-Fuller mechanism.
- Decay of heavier scalar singlets.

Signals of WDM.

One of the process proposed to measure sterile neutrinos as DM is using their 1-loop decay into an active-like neutrino and an X-ray photon, in which

$$E_\gamma = \frac{1}{2} M_\nu \qquad (1)$$



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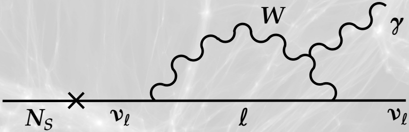
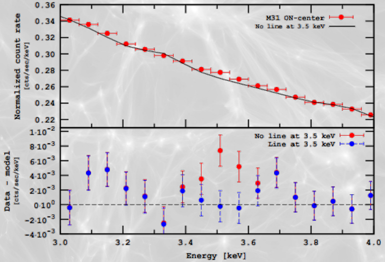
During 2014 a 3.5 keV line was detected using the measurements from the XMM-Newton satellite, but the DM explanation is still controversial.



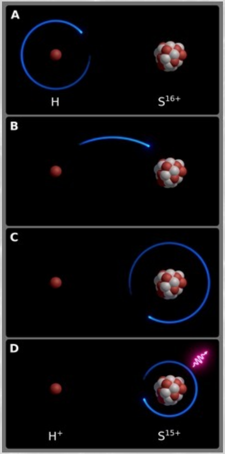


Extracted from [*Phys. Rev. Lett.* **113**, *251301 (2014)*]

The mysterious 3.5 keV line

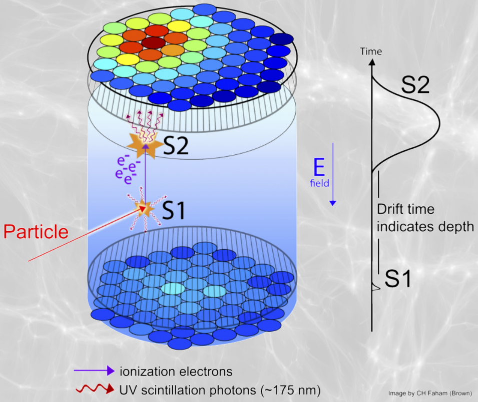
Using an electron beam ion trap the research group from the Max-Planck-Intitut für Kernphysik demonstrated that bare Sulphur ions (S^{16+}) can emit gamma lines at around 3.47 keV from Hydrogen atoms, an effect not considered before and published in

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



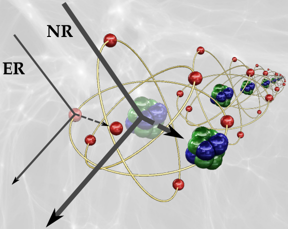
(MPIK)

Direct Detection Experiments



(LUX Collaboration)

Electron Recoil vs Nuclear Recoil



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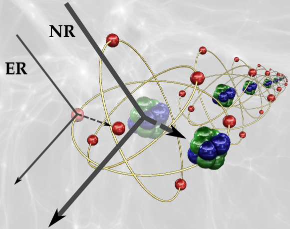

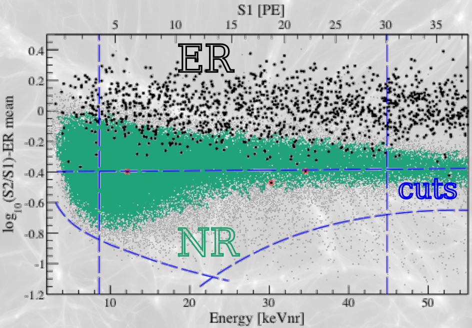

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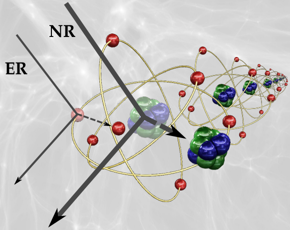
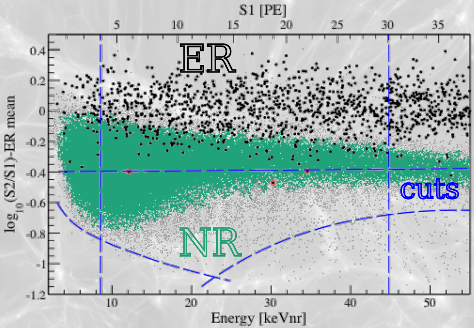
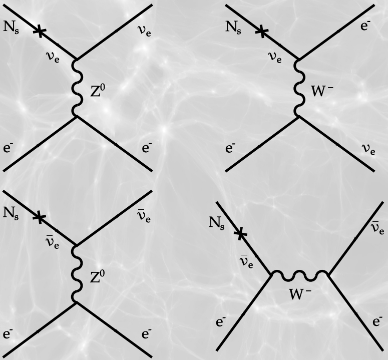




Extracted from [*Phys. Rev. Lett.* **107**, *131302 (2011)*]

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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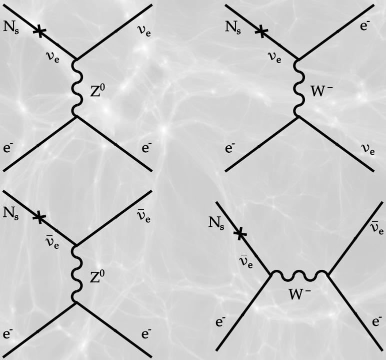
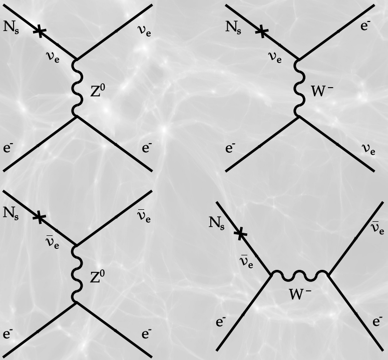


This process is suppressed due to the mixing angle between the sterile and the active neutrinos:

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

The Process



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

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

$$E_\nu \approx m_S. \tag{3}$$

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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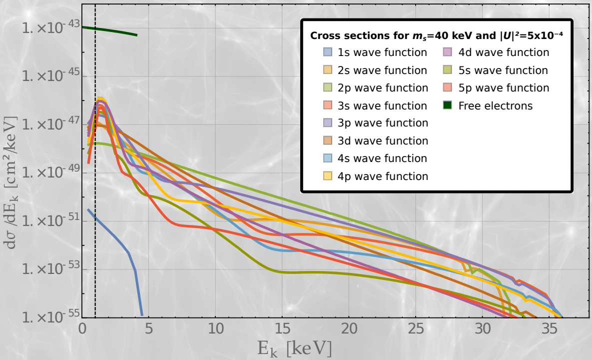

Relevant quantities

We calculate the differential event rate as:

$$\frac{dR_t}{dE_k}(m_S, |U_{Se}|^2) = \frac{\rho_0}{m_S} n_e \int \frac{d\sigma_t}{dE_k}(m_S, |U_{Se}|^2) f(v) v dv. \qquad (4)$$

measured in DRU's = $[\mathrm{kg} \times \mathrm{day} \times \mathrm{keV}]^{-1}$.

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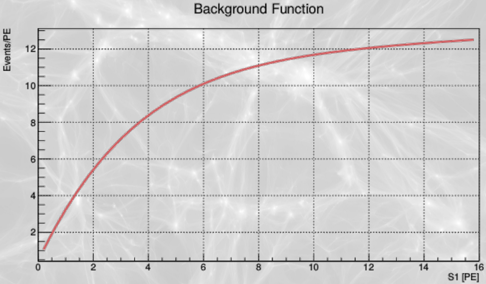
measured in DRU's = [kg×day×keV]$^{-1}$.
If T is the exposure time and M the mass of the detector we can define the differential number of events as:

$$\frac{dN_t}{dE_k}(m_S, |U_{Se}|^2) = M \cdot T \cdot \frac{dR_t}{dE_k}(m_S, |U_{Se}|^2)\,. \qquad (5)$$

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:

$$N_s := \int_{E_{Th}}^{E_0} \frac{dN}{dE_k} dE_k,$$
$$N_b := \int_{E_{Th}}^{E_0} F_b dE_k. \tag{6}$$

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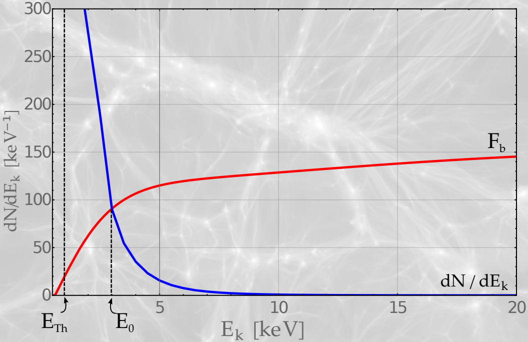


XENON1T differential number of events for $m_S = 40$ keV and $|U_{Se}|^2 = 5 \times 10^{-4}$

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:

$$\chi^2(m_S, |U_{Se}|^2) := \frac{(N_s(m_S, |U_{Se}|^2) - N_b(m_S, |U_{Se}|^2))^2}{N_b(m_S, |U_{Se}|^2)}. \qquad (7)$$

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.

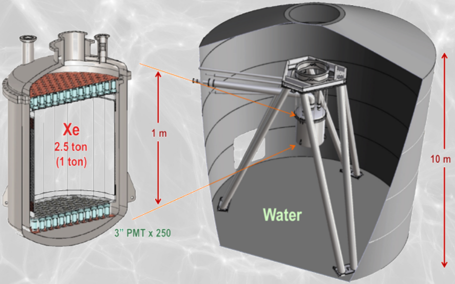
Detector characteristics: XENON100

Characteristics

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

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

Detector characteristics: XENON1T



Characteristics

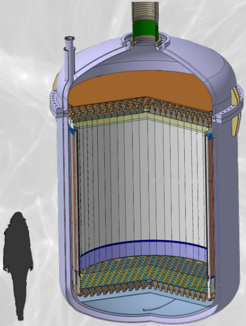
- Bckgr $\sim 1.8 \times 10^{-4}$ [kg×day×keV^{-1}]
- $T = 2 * 365$ live days.
- $M = 1000$ kg fiducial mass.
- $E_{Th} = 1$ keV$_{\rm er}$ threshold energy.

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

Detector characteristics: DARWIN

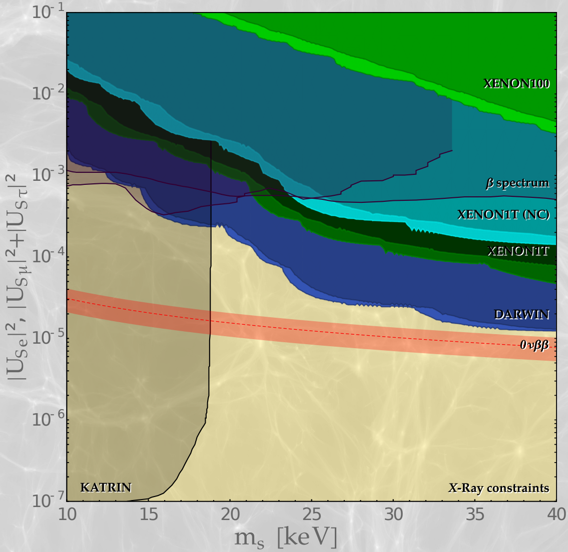
Characteristics

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

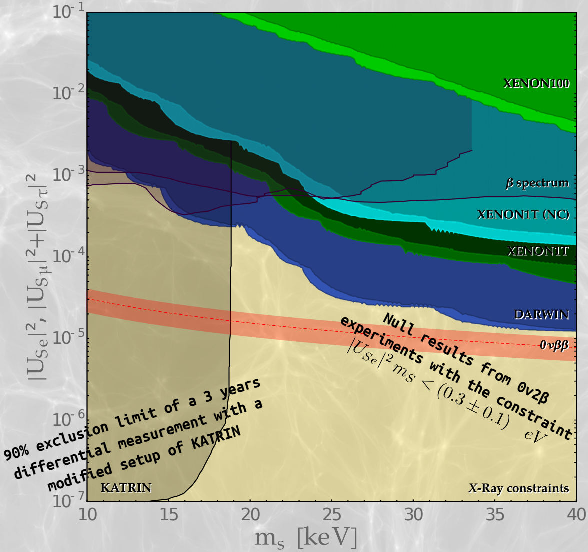


Data from [*arXiv:1606.07001 [astro-ph.IM]*]

Results

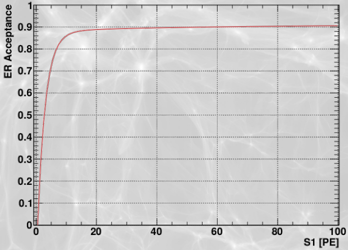

XENON100
β spectrum
XENON1T (NC)
XENON1T
DARWIN
0νββ
KATRIN
X-Ray constraints
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$|U_{Se}|^2, |U_{S\mu}|^2+|U_{S\tau}|^2$
10
15
20
25
30
35
40
m_s [keV]

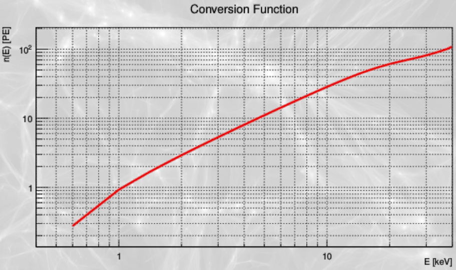
Results


XENON100
β spectrum
XENON1T (NC)
XENON1T
DARWIN
0νββ
Null results from 0ν2β 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]
10
15
20
25
30
35
40
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}


Thanks !
ν_τ
ν_μ
ν_e

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

$$\begin{aligned}\frac{d\sigma_{\text{free}}}{dE_k} =& 2\frac{G_F^2}{\pi}|U_{Se}|^2\frac{m_e}{|\vec{p}_S|^2}\left[g_1^2 E_S\left(E_S+\frac{m_S^2}{2m_e}\right)\right.\\ &+g_2^2(E_S-E_k)\left(E_S-E_k+\frac{m_S^2}{2m_e}\right)\\ &\left.-\,g_1 g_2(m_e E_k+\tfrac{1}{2}m_S^2)\right].\end{aligned} \tag{8}$$

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

$$\frac{d\sigma_t}{dE_k} = \int \frac{p_B^2 dp_B d(\cos\theta) d\phi}{(2\pi)^3} \frac{|R_t(\vec{p}_B)|^2}{4\pi} \\ \frac{|\mathcal{M}|^2}{4E_S E_B|\beta - p_B/\tilde{m}|} \frac{1}{8\pi\lambda^{1/2}(s, m_S^2, \tilde{m}^2)} \left|\frac{du}{dE_k}\right| . \tag{9}$$

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

$$\int_0^\infty \frac{k^2 dk}{(2\pi)^3} |R_t(k)|^2 = 1 \, . \tag{10}$$

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.