Probing non-standard neutrino interactions with low energy neutrino-electron elastic scattering in reactor experiments

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Motivation

- Leptophilic interactions occur in many extensions of the Standard model such as $\boldsymbol{L_\mu - L_e}$, $\boldsymbol{L_e - L_\tau}$, light scalar models etc. These models include NSI with new weakly coupled mediating particles.
  R. Foot, **Mod. Phys. Lett. A 6, 527 (1991) ,**
  X. G. He, G. C. Joshi, H. Lew and R. R. Volkas**, Phys. Rev. D 44, 2118 (1991)**
  X. G. He, G. C. Joshi, H. Lew and R. R. Volkas**, Phys. Rev. D 43, 22 (1991),**
  Dutta, Ghosh and Li**,2006.01319**

- Xenon1t , Borexino, GEMMA etc experiments provide constraints on the parameter space of such models. . Sierra *et al.*, 2020 **2006.12457,** Boehm *et al.* **2006.11250**

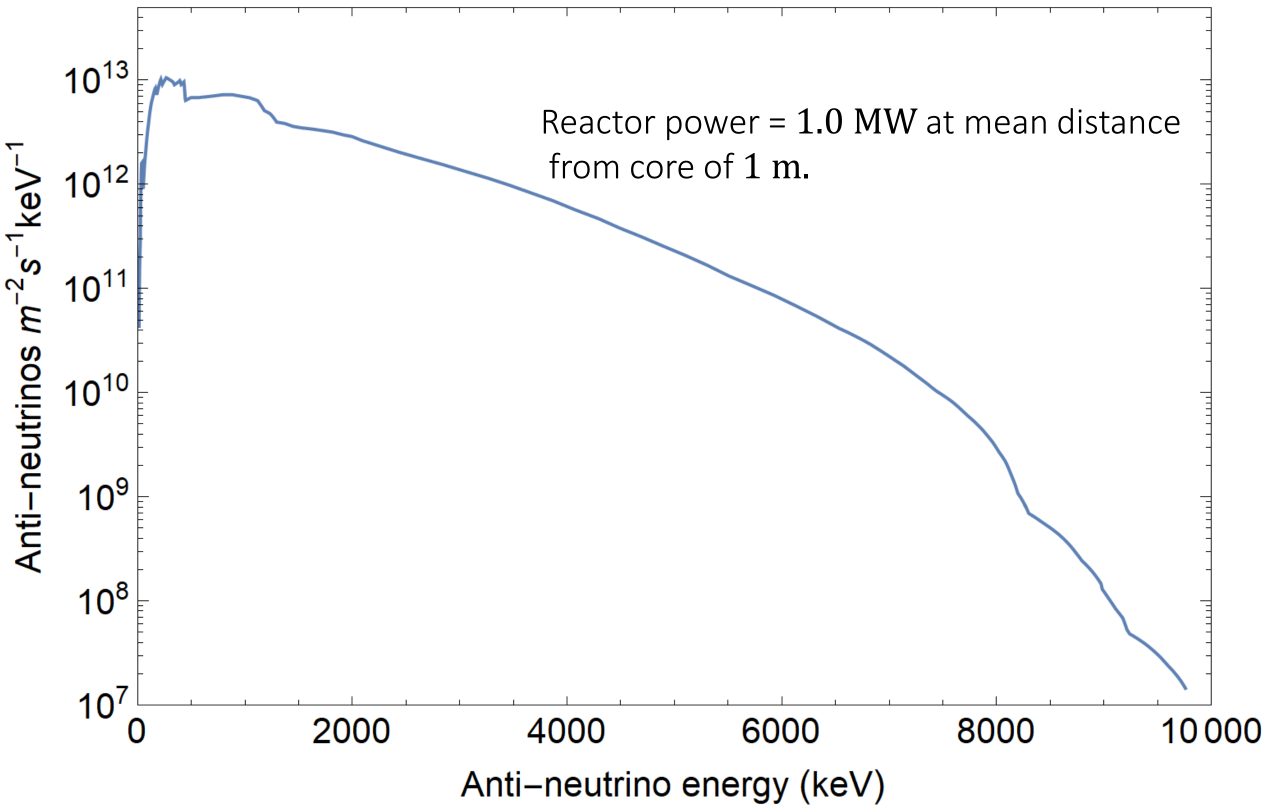
- Ongoing and future reactor experiments such as MINER, CONUS, CONNIE, VIOLETTA etc. can also provide a particularly important probe of such light mediator models.

- We study the prospects for probing Neutrino NSI via light scalar and vector mediators using reactor neutrino sources in combination with low threshold electron recoil detectors such as Si, Ge

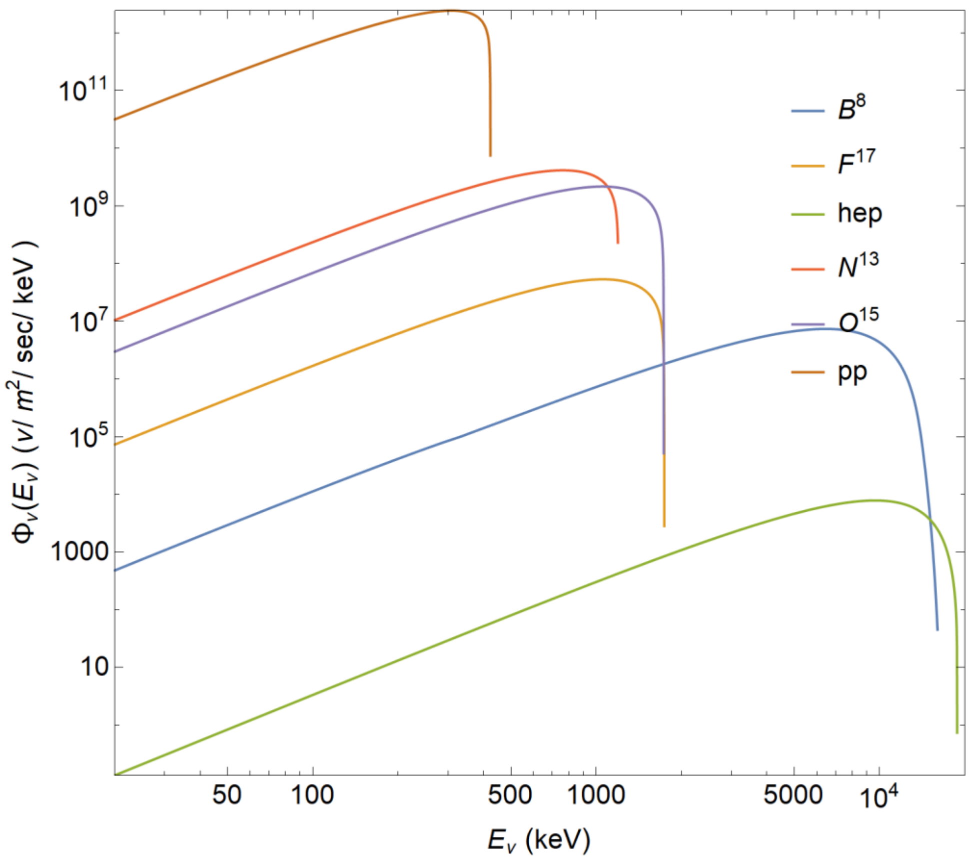
Reactor and Solar Neutrino Flux

- The MW reactors have a similar energy flux profile to solar neutrinos with characteristic neutrino energies <1 MeV
- At the typical incident neutrino energy $\lesssim$ 200keV atomic /crystal effects should be considered . (arXiv:1411.0574v1)

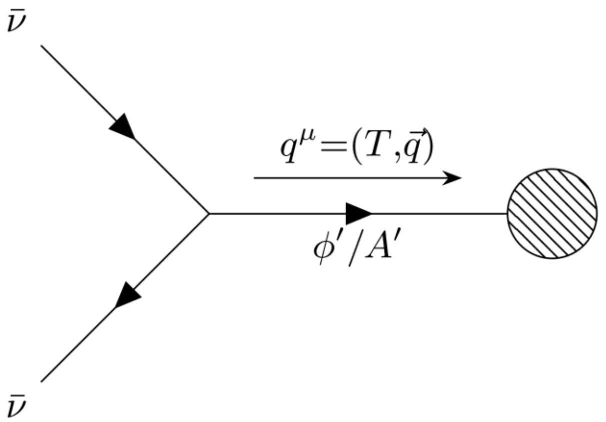
Reactor Antineutrino flux



Solar flux



Neutrino-electron scattering



$$T_{max} = \frac{2E_\nu^2}{(m_N + 2E_\nu)}$$

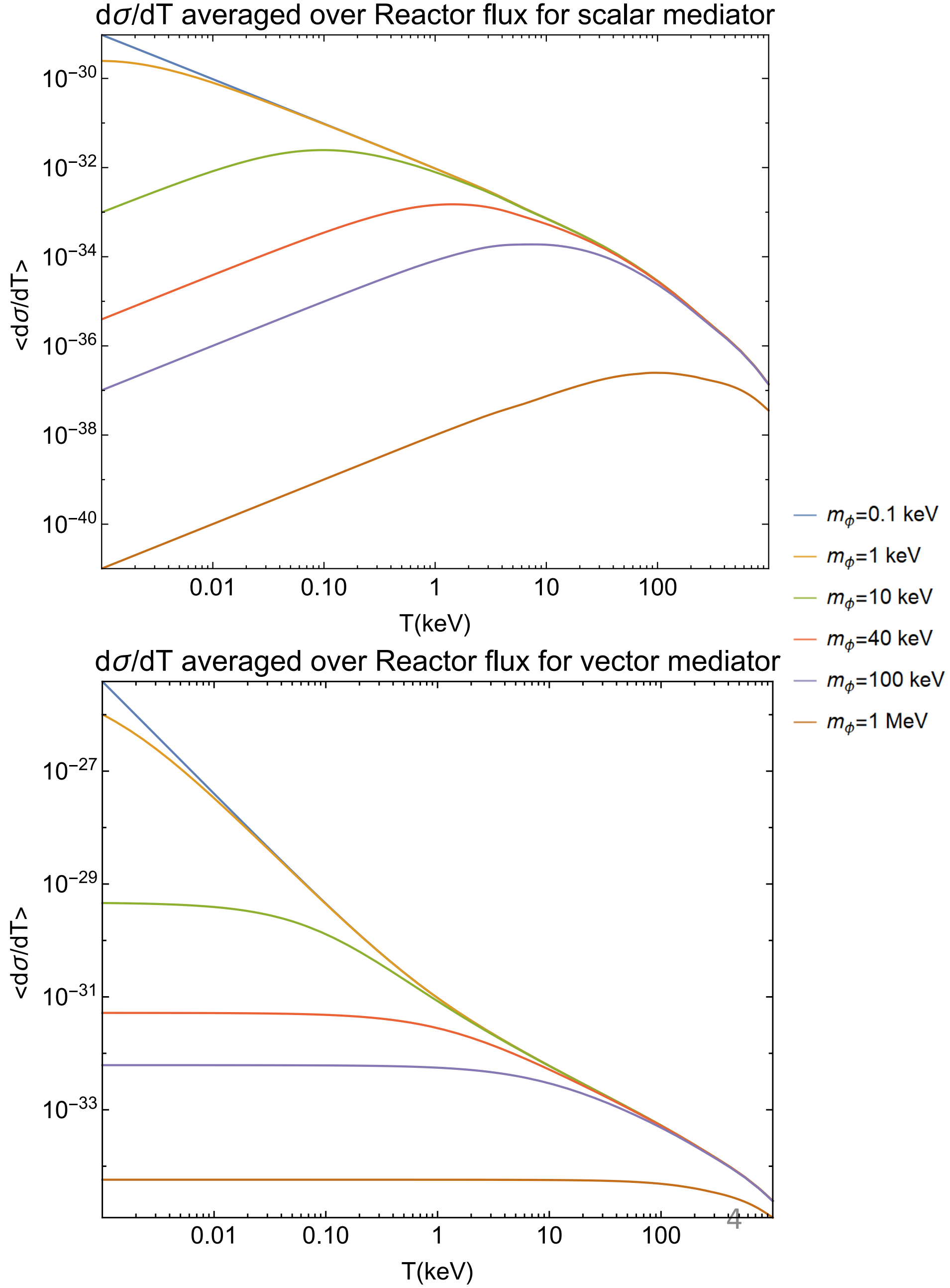
Scalar NSI: $\mathcal{L}_S \supset \phi\left(g_{\nu,\phi}\bar{\nu}\nu + g_{\ell,\phi}\bar{\ell}\ell\right)$

$$d\,\sigma_e/d\,T - d\,\sigma_e^{\rm SM}/d\,T = \frac{g_{\nu,\phi}^2 g_{e,\phi}^2 T m_e^2}{4\pi E_\nu^2\left(2Tm_e + m_\phi^2\right)^2}$$

Vector NSI: $\mathcal{L}_V \supset A'_\mu\left(g_{\nu,Z'}\bar{\nu}_L\gamma^\mu\nu_L + g_{\ell,Z'}\bar{\ell}\gamma^\mu\ell\right)$

$$d\,\sigma_e/d\,T - d\,\sigma_e^{\rm SM}/d\,T = \frac{\sqrt{2}G_F m_e g_\nu g_{\nu,A'} g_{e,A'}}{\pi\left(2Tm_e + m_{A'}^2\right)} + \frac{m_e g_{\nu,Z'}^2 g_{e,A'}^2}{2\pi\left(2Tm_e + m_{A'}^2\right)^2}$$

$$\left\langle \frac{d\sigma}{dT}\right\rangle = \frac{\int dE_\nu \phi(E_\nu)\frac{d\sigma}{dT}(E_\nu)}{\int dE_\nu \phi(E_\nu)}$$



Neutrino electron scattering rate in detectors

- Treating the atomic electrons as free (FEA) is considered a good approximation at higher energies (> few keVs) . But in the sub-keV regime, which is similar to atomic scales, proper treatment of many electron dynamics in atomic ionization becomes important for a better understanding of detector responses at these low energies.
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$$\frac{d\mathcal{R}_a}{d\ln E_e} = \frac{N_T}{4}\int dE_\nu \Phi(E_\nu)\int dq\left(\frac{d\sigma}{dq}\right)\left|f_{\text{ion}}^{n,l}(q,E_e)\right|^2$$

Ionization form factor-describes the likelihood that a given momentum transfer results in a particular electron recoil energy

$$\frac{d\mathcal{R}_{v\to c}}{d\ln E_e} = N_{cell}\int dE_\nu \Phi(E_\nu)\int dq\left(\frac{d\sigma_e}{dq}\right)|f_{v\to c}(q,E_e)|^2$$

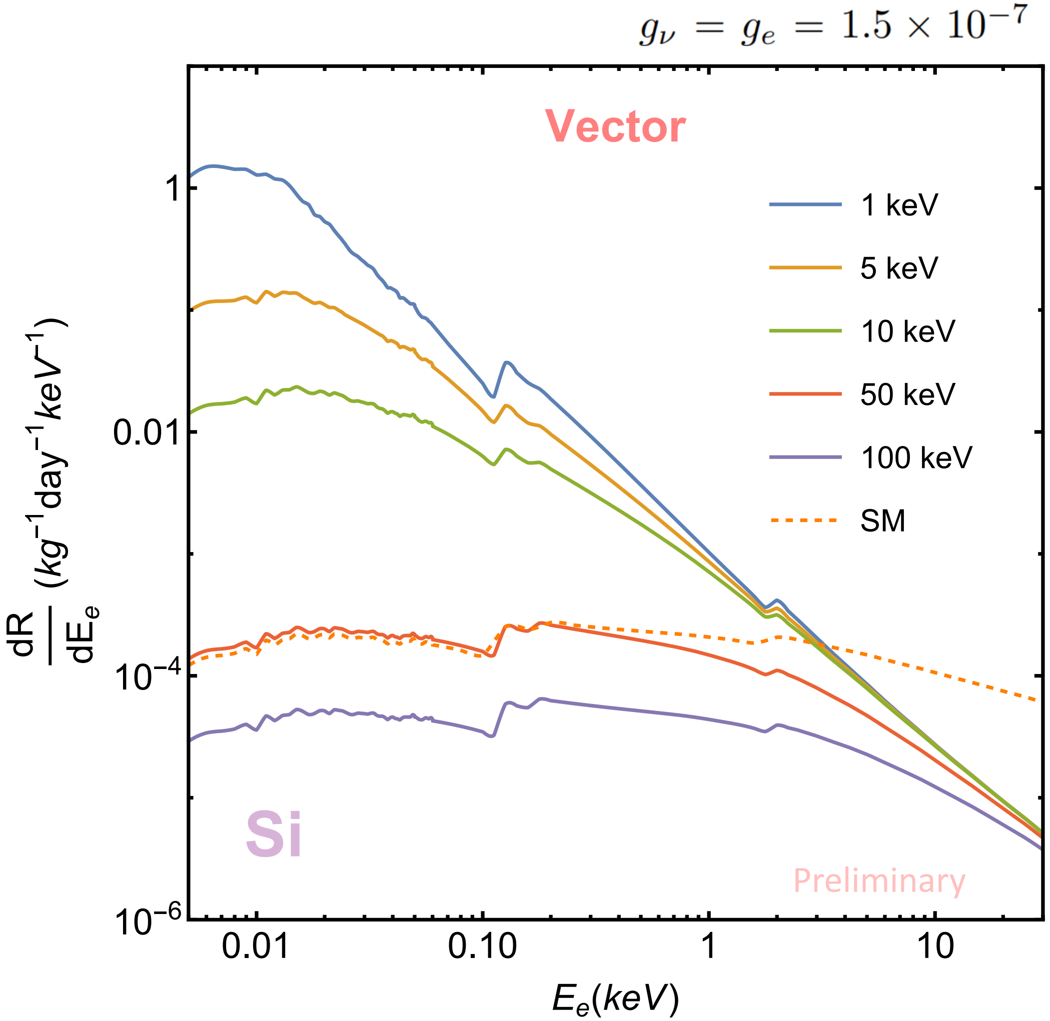
Crystal form factor-accounts for the semiconductor band structure and describes the likelihood that a given momentum transfer results in a transition from a state in valence band to conduction band.

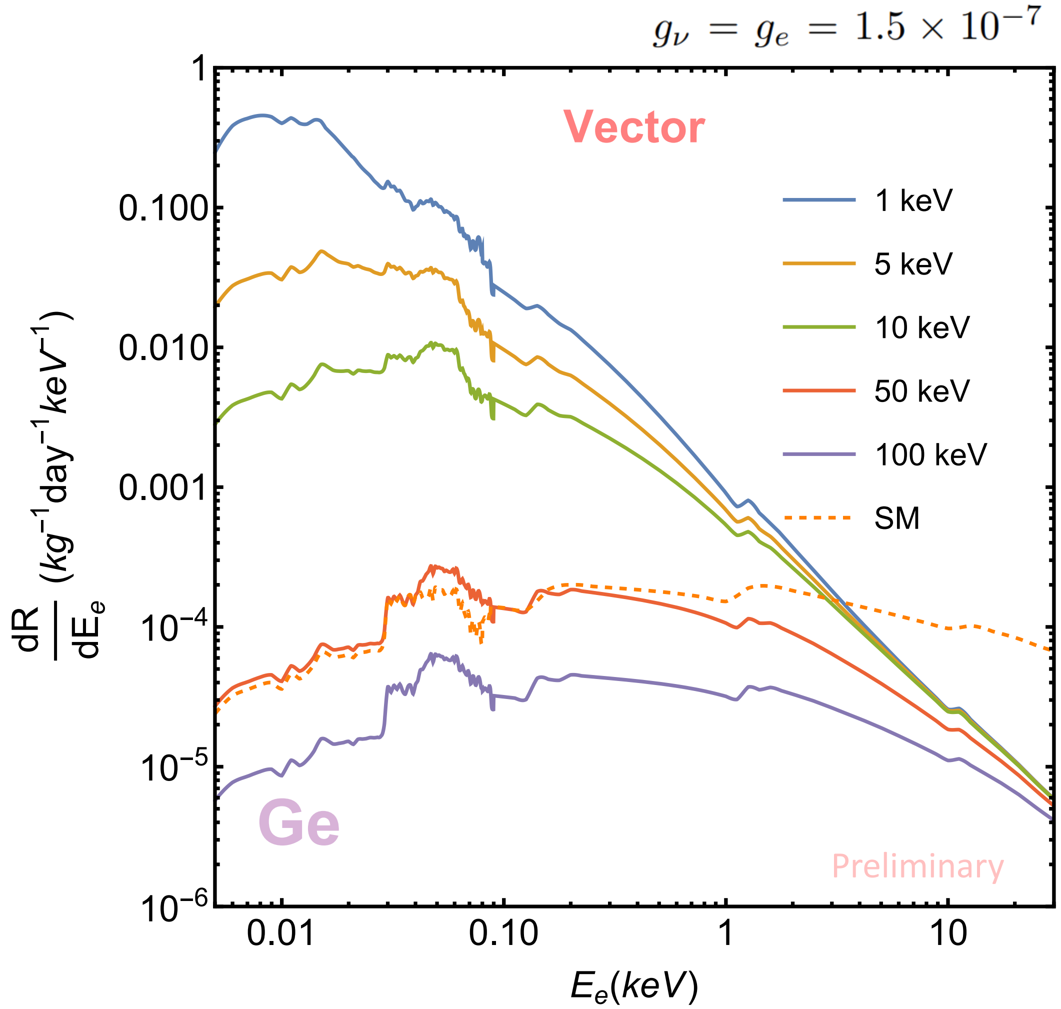
Catena *et al* **1912.08204**
Catena *et al* **2105.02233**
Griffin, S. M. *et al.* (2021) **2105.05253**
Essig, Mardon and Volansky, 2012 **1108.5383**
Essig *et al* **1509.01598**
Essig *et al.* **1908.10881**

$$\left|f_{\text{ion}}^{n\ell}(k',q)\right|^2 = V\frac{4k'^3}{(2\pi)^3}\sum_{\ell'=0}^{\infty}\sum_{m=-\ell}^{\ell}\sum_{m'=-\ell'}^{\ell'}\left|\int\frac{\mathrm{d}^3k}{(2\pi)^3}\psi_2^*(\mathbf{k}+\mathbf{q})\psi_1(\mathbf{k})\right|^2$$

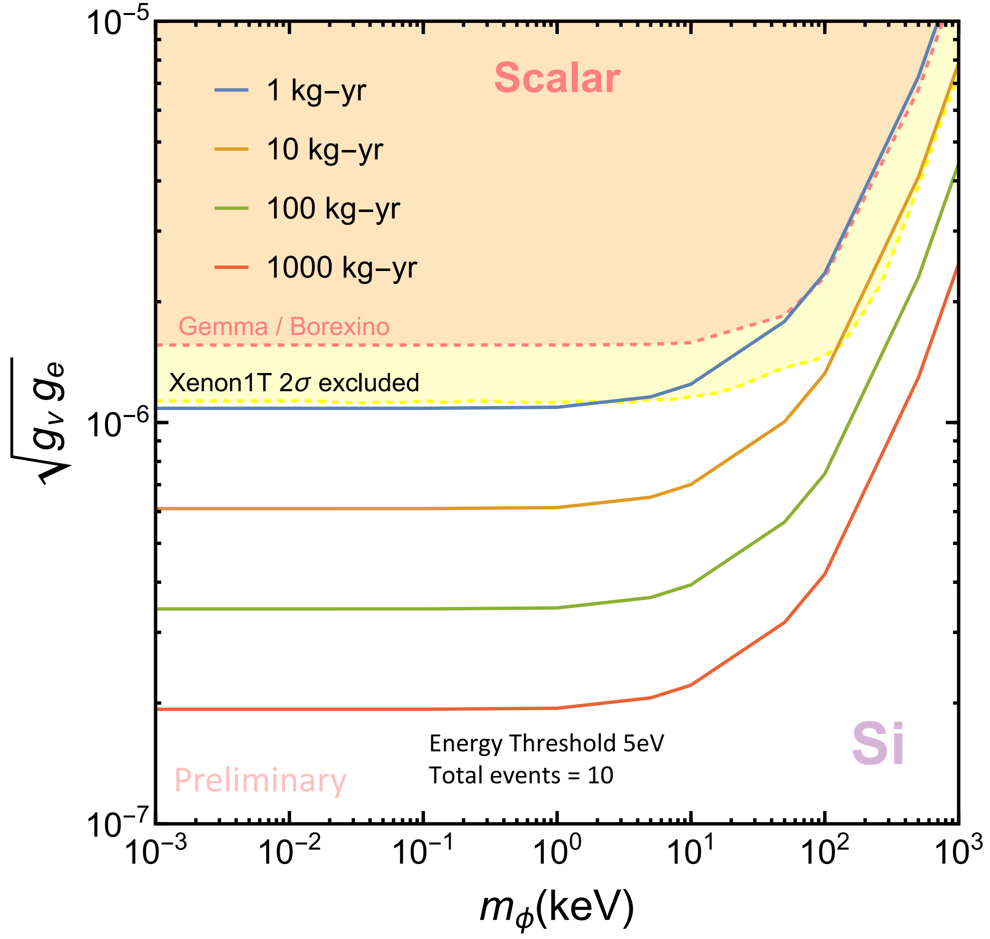
$$|f_{v\to c}(q,E_e)|^2 = \frac{4\pi^2\Omega}{q^3}\sum_{i,f}\int_{\text{BZ}}\frac{d^3k_i d^3k_f}{(2\pi)^6}E_e\delta(E_e - E_{f\mathbf{k}_f} + E_{i\mathbf{k}_i})\sum_{\mathbf{G}} q\delta(q - |\mathbf{k}_f + \mathbf{G} - \mathbf{k}_i|)\left|\frac{1}{\Omega}\int_{\text{cell}} d^3x e^{i\mathbf{G}\cdot\mathbf{x}}u_{f,\mathbf{k}_f}^*(\mathbf{x})u_{i,\mathbf{k}_i}(\mathbf{x})\right|^2$$

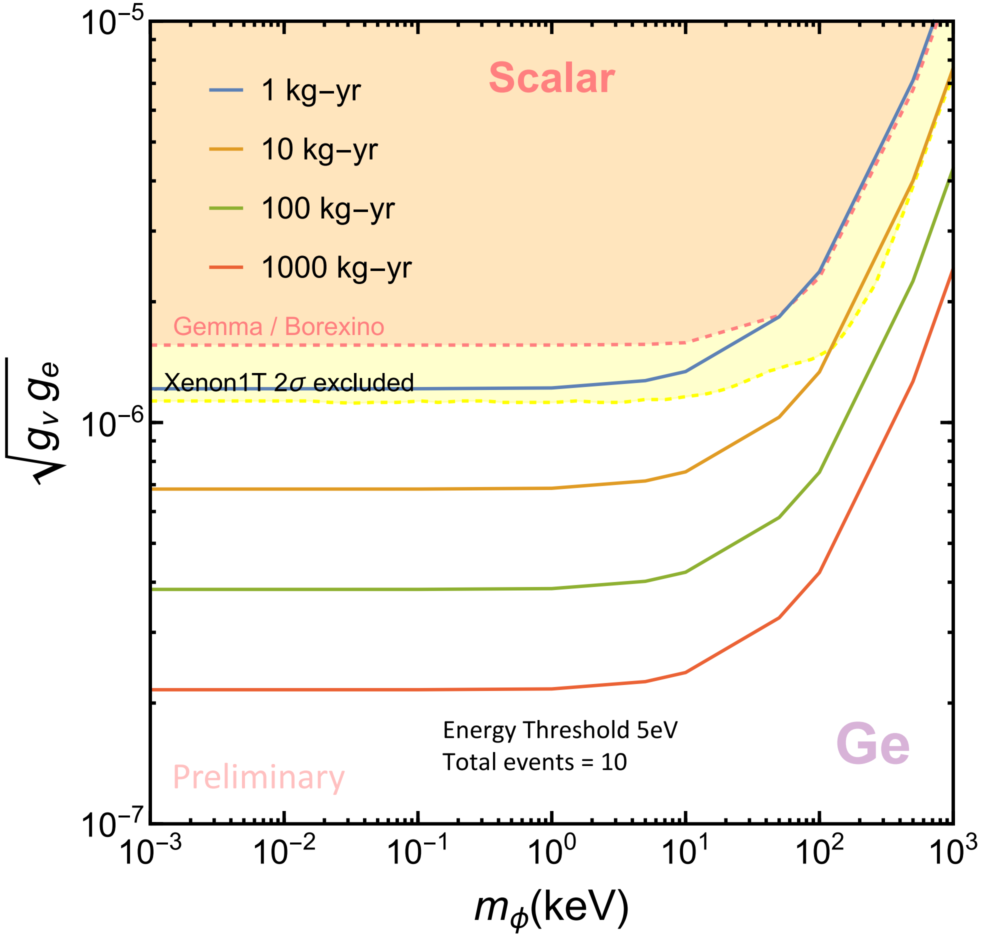
Scattering rate as a function of total energy deposited by the neutrinos



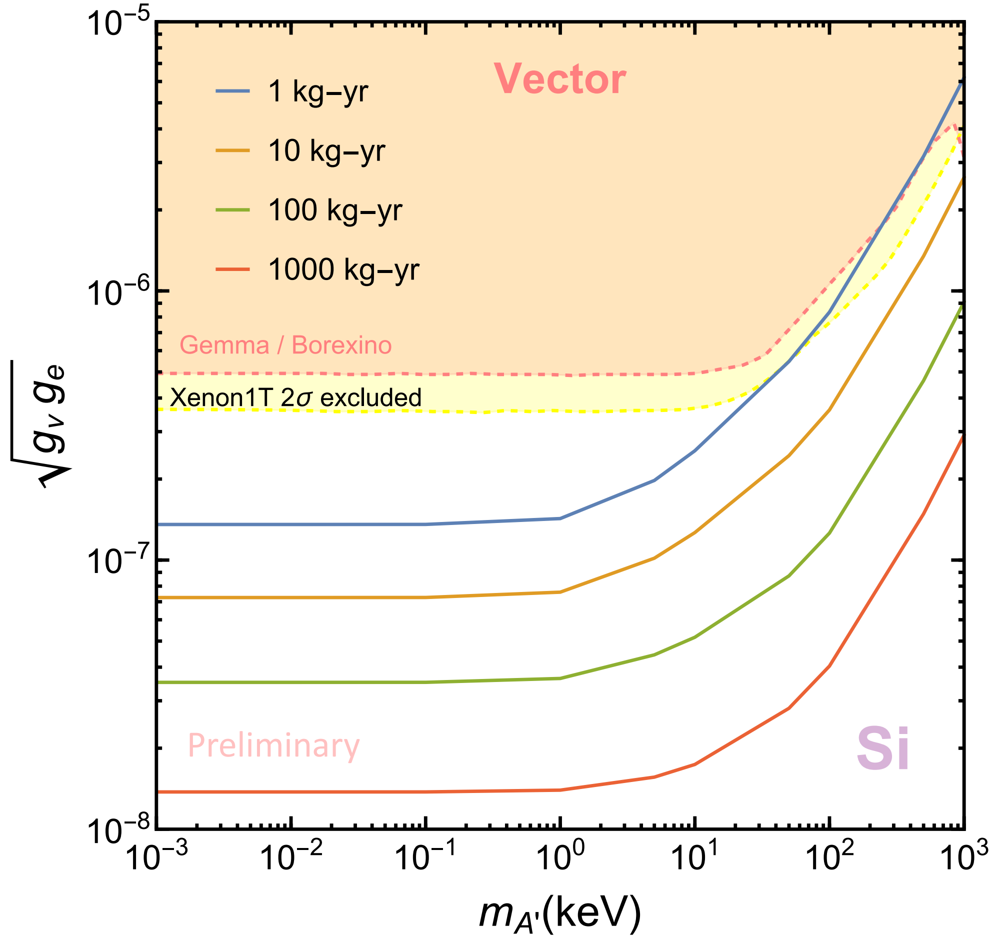


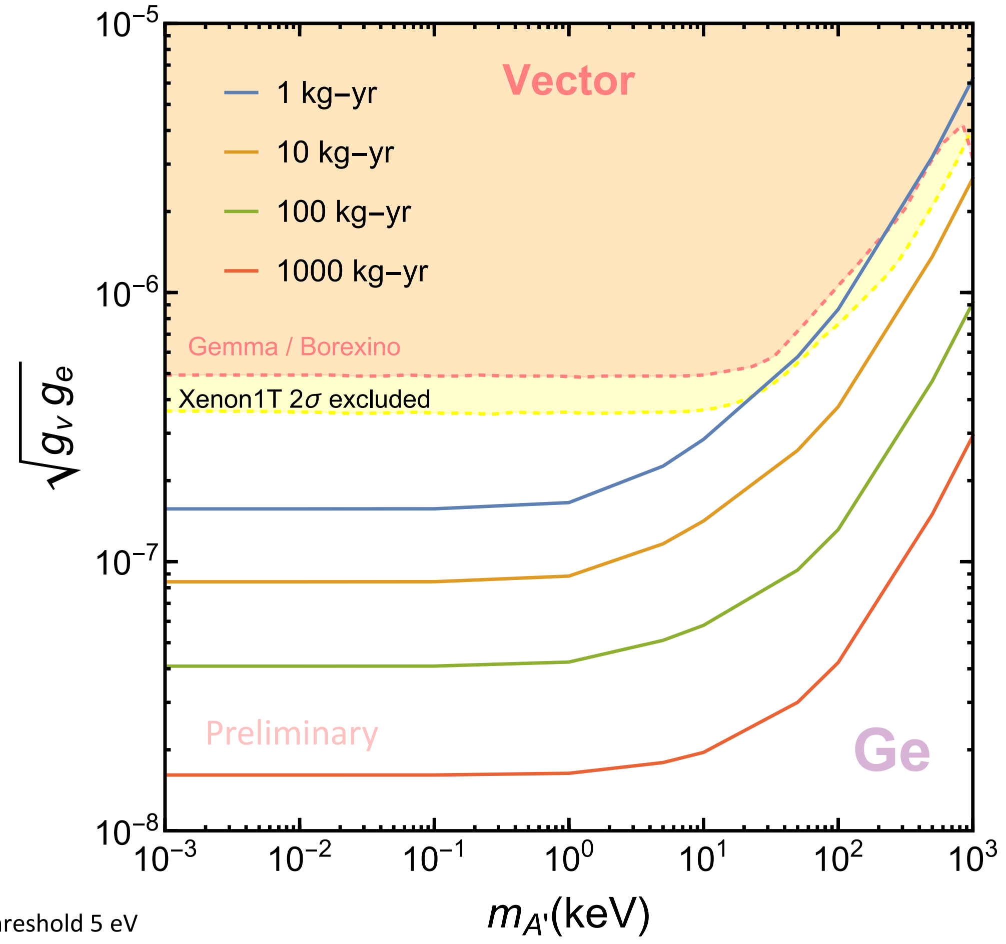
Results- Sensitivity projections for Silicon (left) Germanium (right) detector for scalar mediator





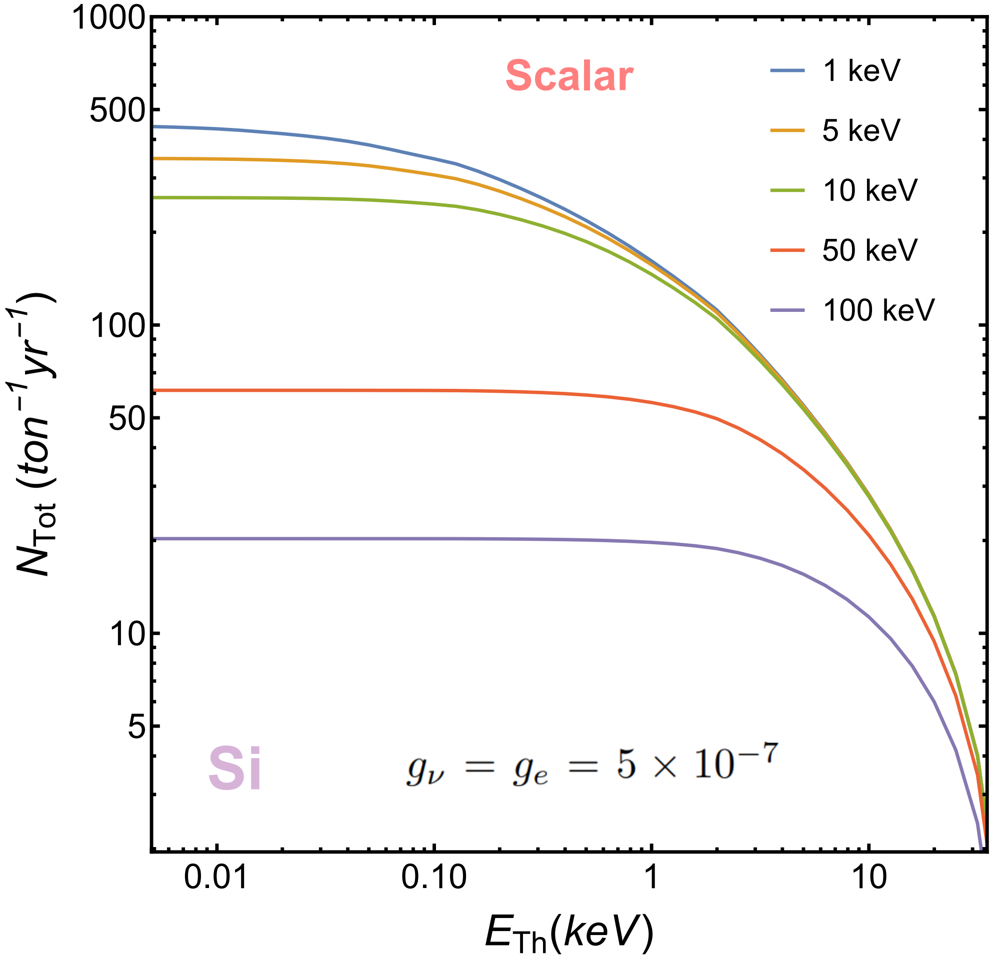
Results- Sensitivity projections for Silicon (left) Germanium (right) detector for vector mediator

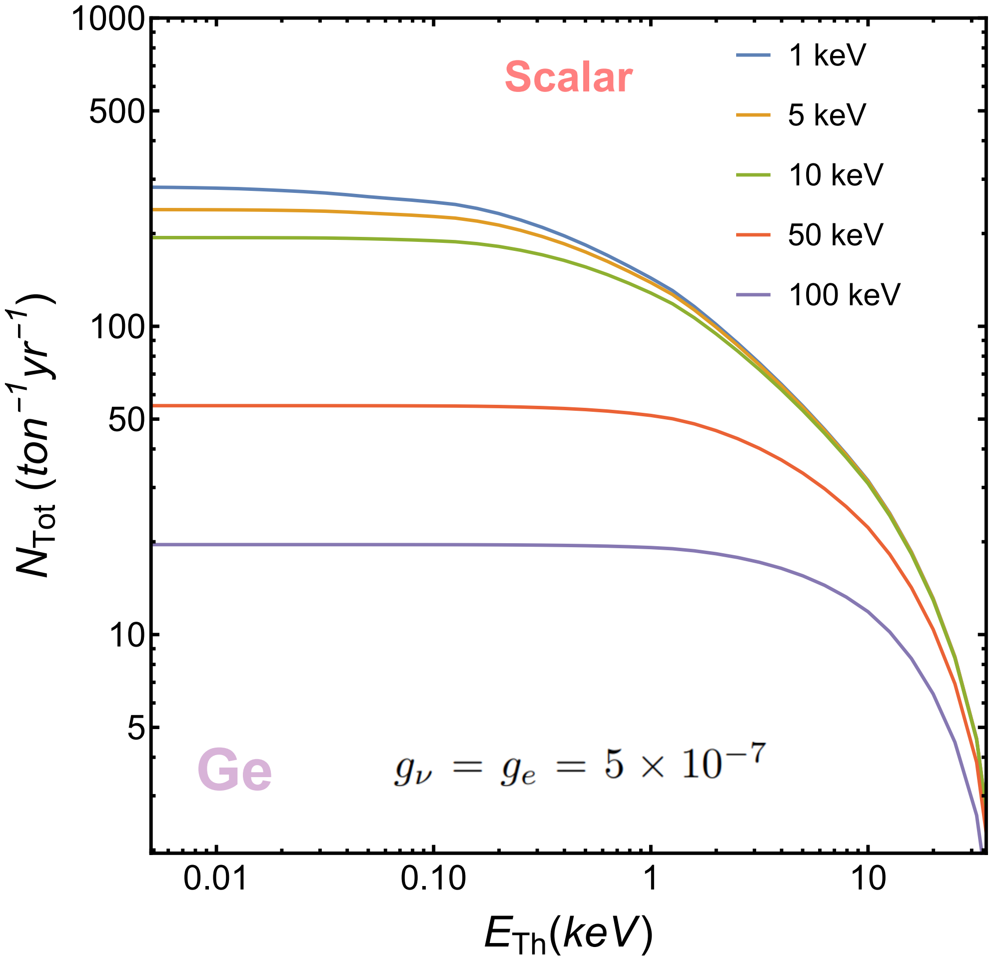




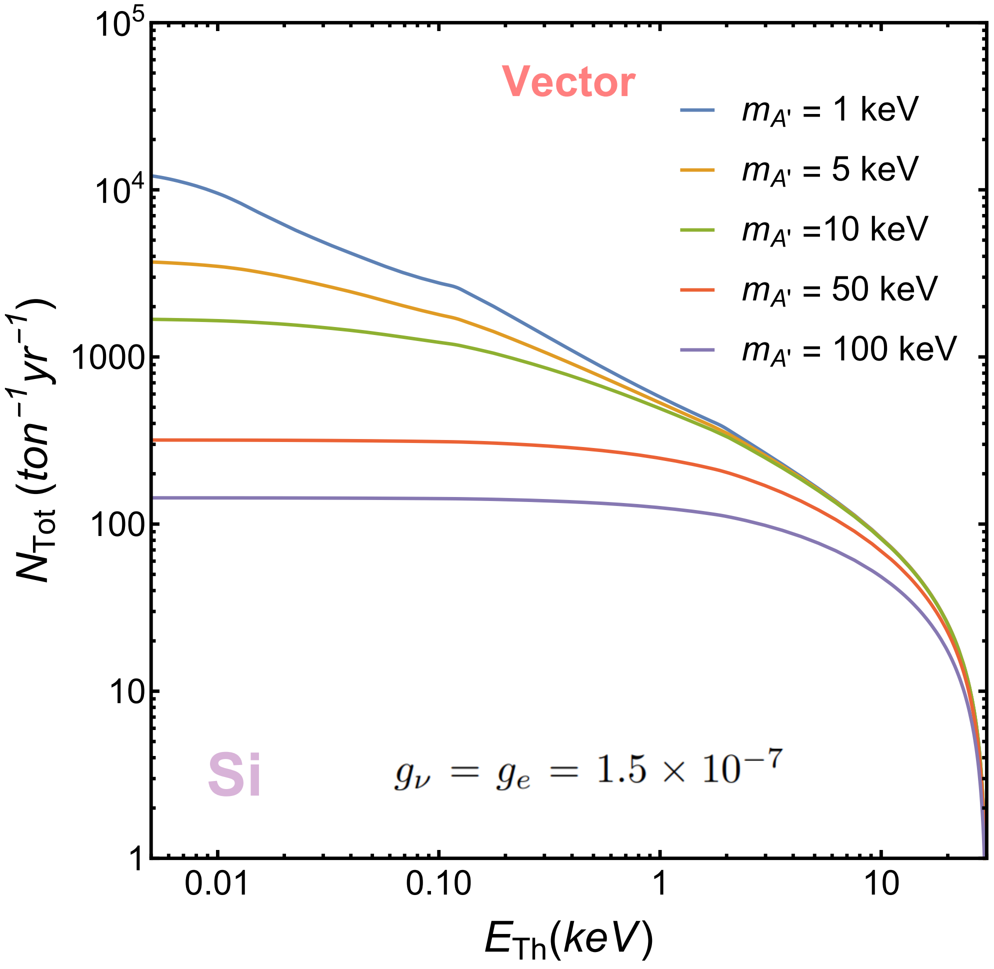
Energy Threshold 5 eV
Total events = 10

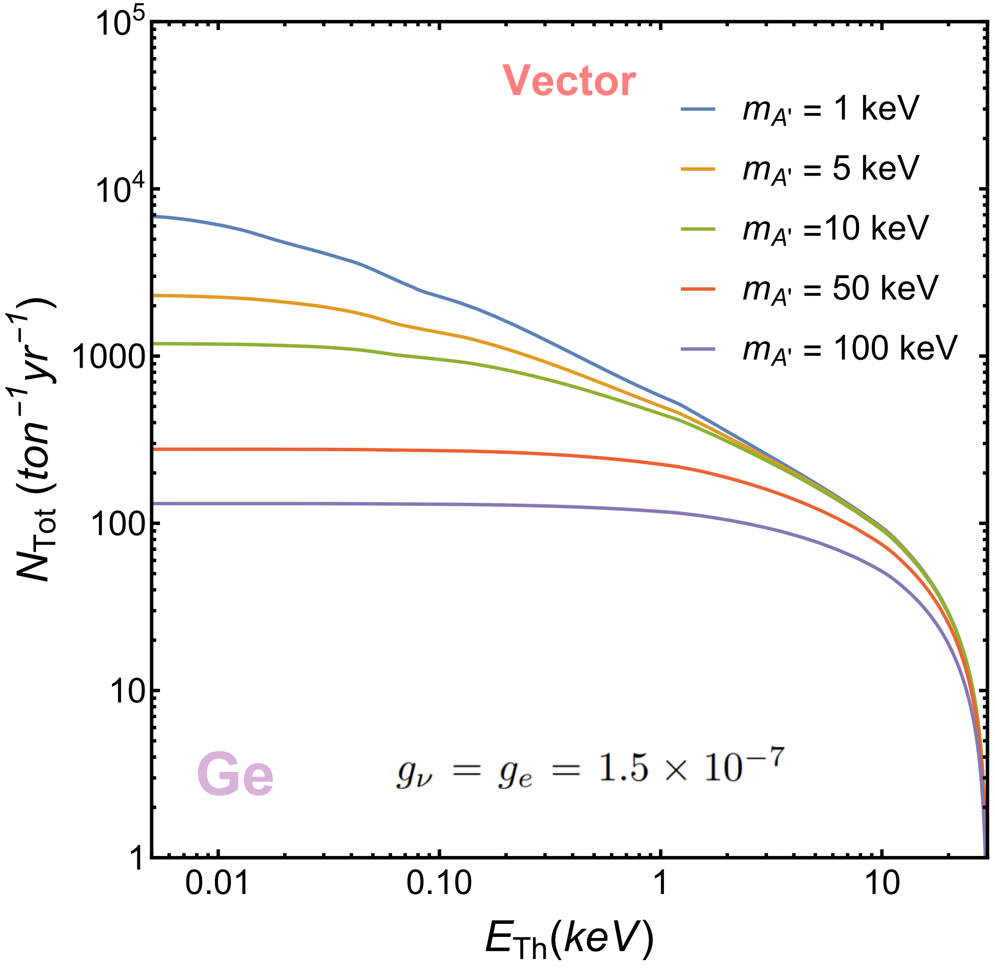
Electron recoil integrated rates as a function of Experimental Threshold energy





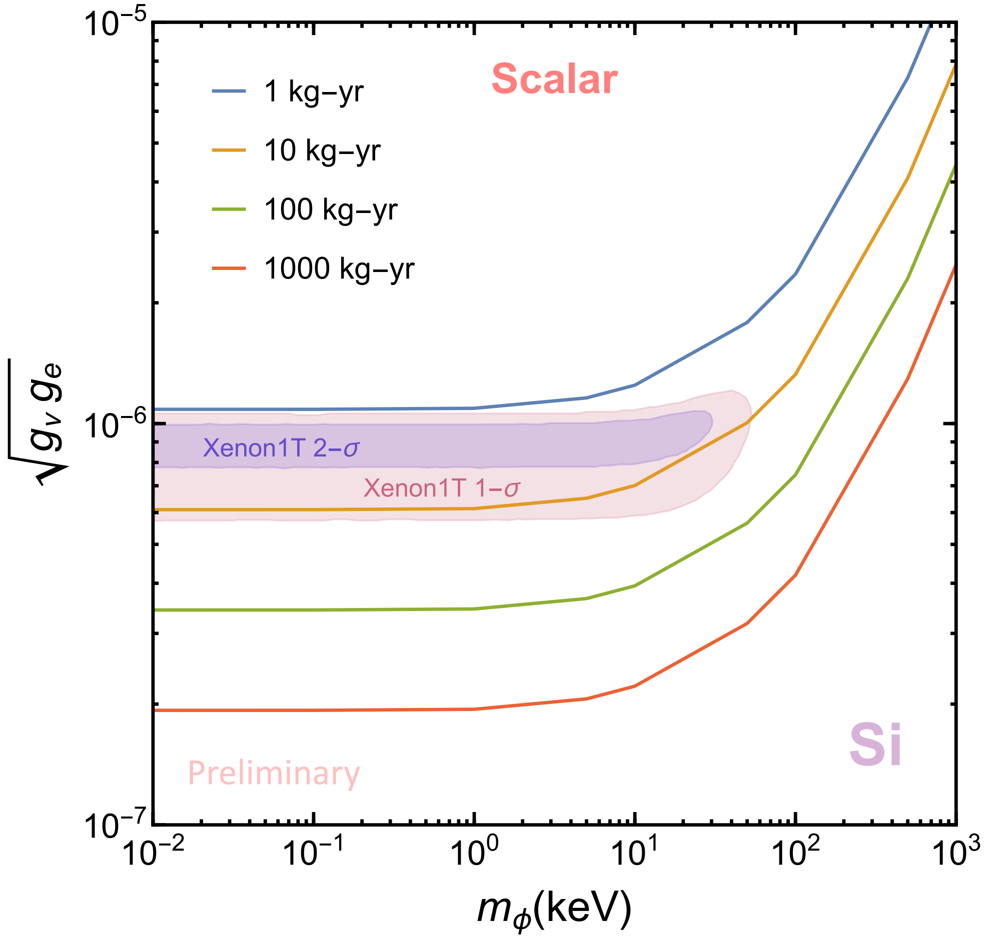
Electron recoil integrated rates as a function of Experimental Threshold energy



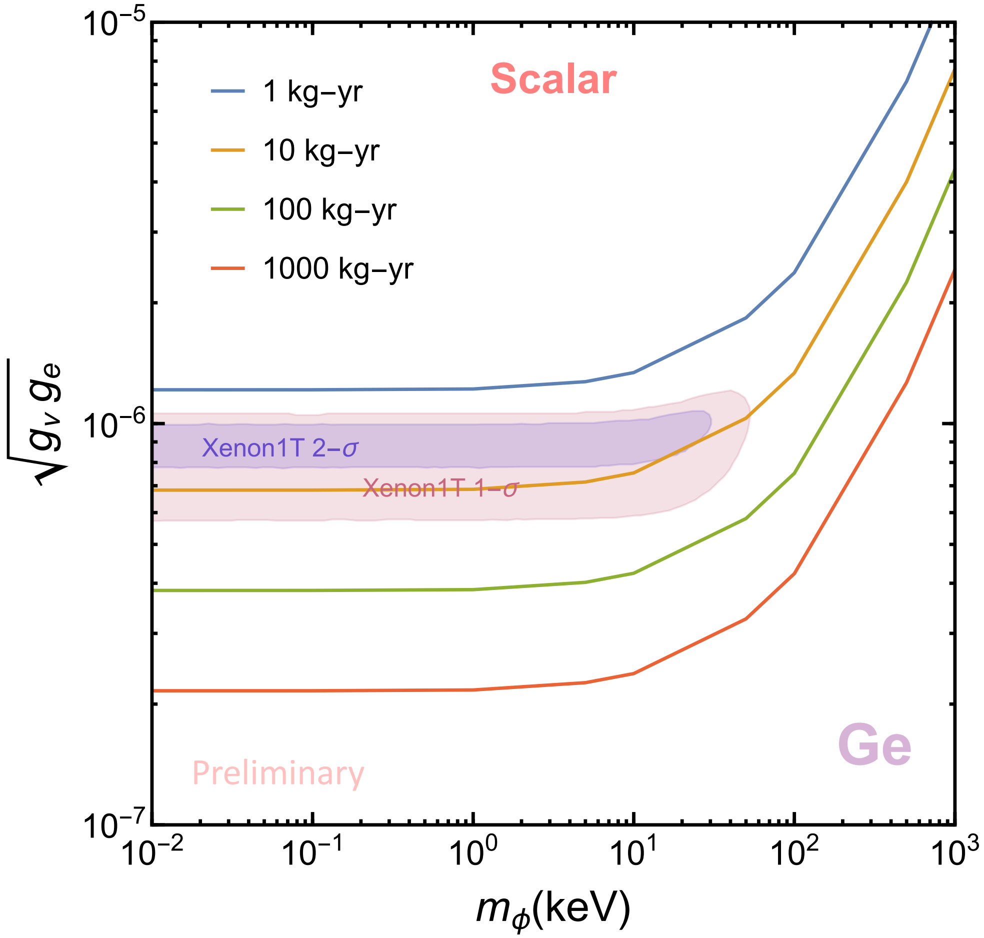


Xenon1T excess at Reactor based experiments

Sensitivity projections for Silicon detector for scalar mediator

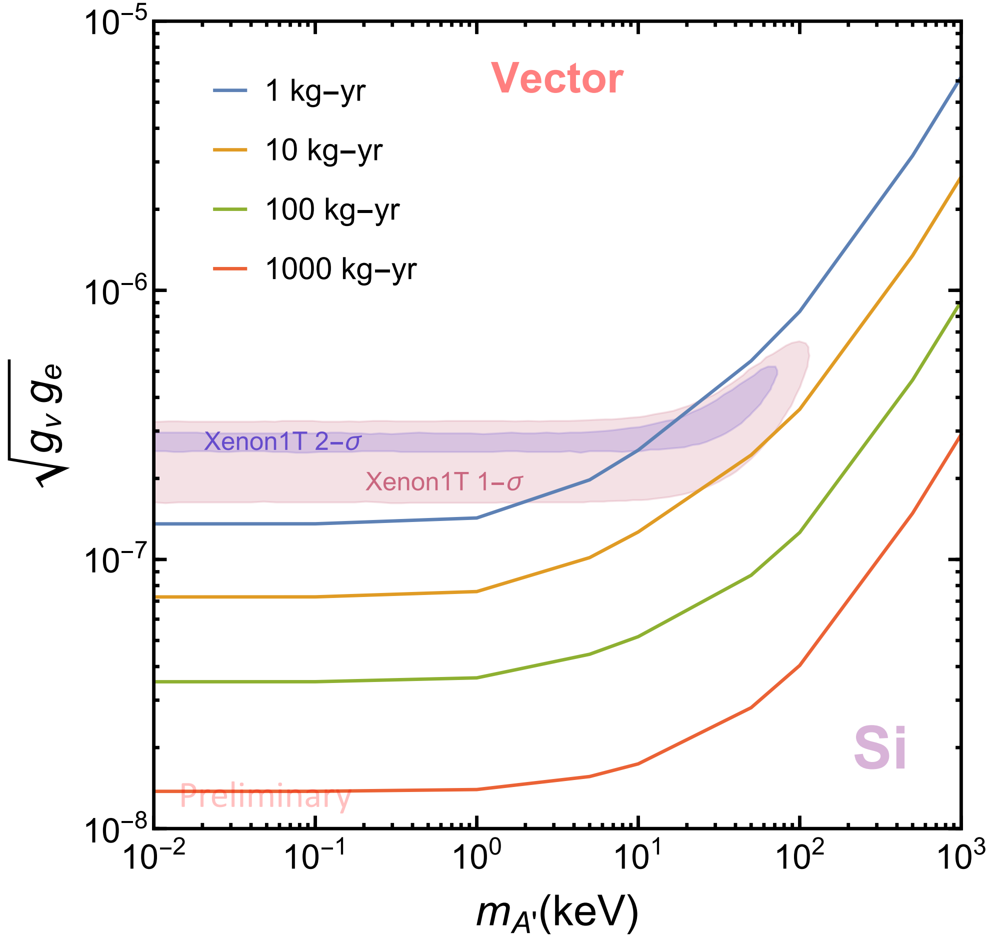


Sensitivity projections for Germanium detector for scalar mediator

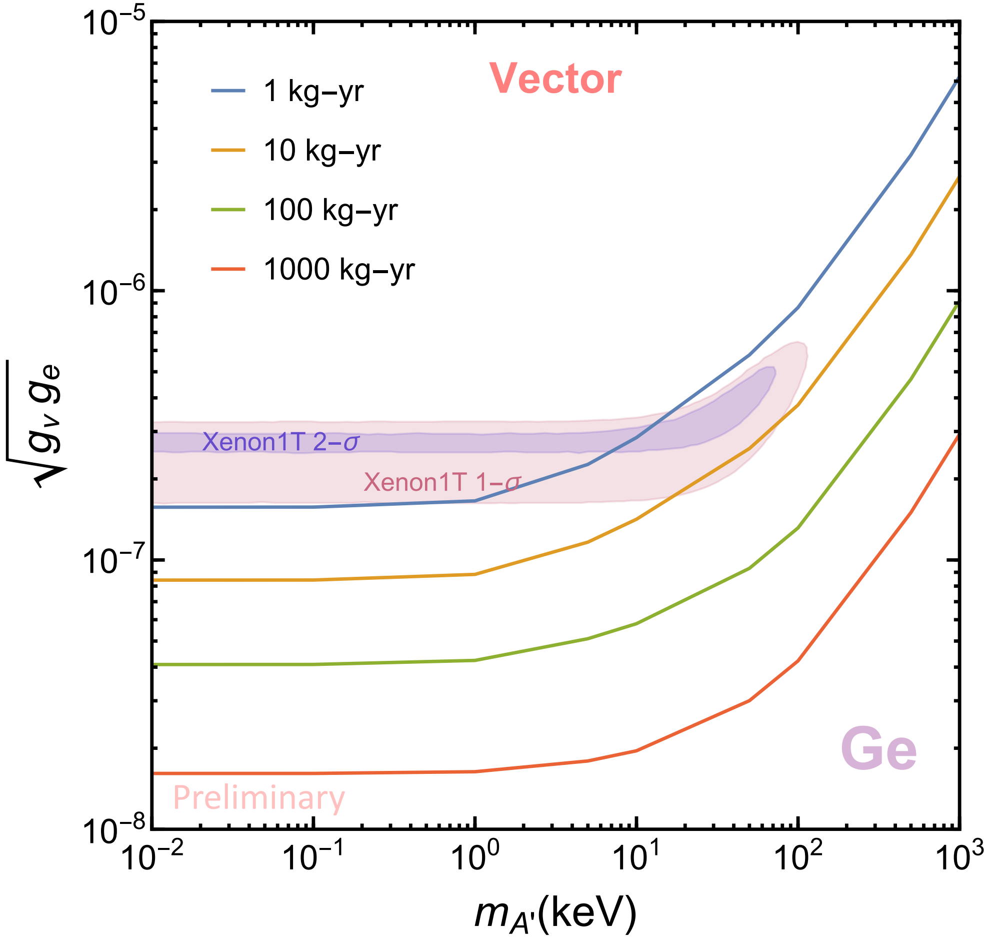


Xenon1T excess at Reactor based experiments

Sensitivity projections for Silicon detector for vector mediator



Sensitivity projections for Germanium detector for vector mediator



Light Mediator Models

- We also propose a model with a light scalar mediator by extending the Higgs sector of the Standard model by including an additional Higgs triplet, singlet and a doublet (in addition to the SM higgs doublet) that yields a larger NSI of neutrinos. The Yukawa sector Lagrangian in the interaction basis includes $\bar{l}^c_{L_i}(y)_{ij} i\sigma_2 \Delta l_{L_j}$ which gives rise to $\bar{\nu}\nu\phi$ term in the mass basis giving rise to non-standard neutrino scalar interaction.
- Our analysis is also applicable to light vector boson mediator of well studied U(1) extensions of SM such as $U(1)_{L_e-L_\mu}, U(1)_{L_e-L_\tau}, U(1)_{L_\mu-L_\tau}$ (loop suppressed coupling to electron) and $U(1)_{B-L}$
- The relevant parameter space is constrained by bounds from experiments like Gemma, Borexino, Xenon1t and different astrophysical events (SN1987A, solar cooling, globular cluster) and cosmological observations(ΔN_{eff})

Conclusion

- We investigated light leptophilic mediators via neutrino interactions at ongoing/upcoming reactor experiments.
- Including atomic and crystal effects we calculated the projected electron recoil event rates in low threshold detectors using reactor flux.
- We compared the parameter space sensitivity with the Xenon1T/Borexino experiment results which uses solar-pp flux. We find that ongoing reactor experiments can be sensitive to the parameter space which has not been probed by these experiments. These sensitivities could be further enhanced from a gigawatt-class reactor neutrino source.
- The explanation of the excess in the recent Xenon1t result can also be investigated at the reactor experiments.

Backup

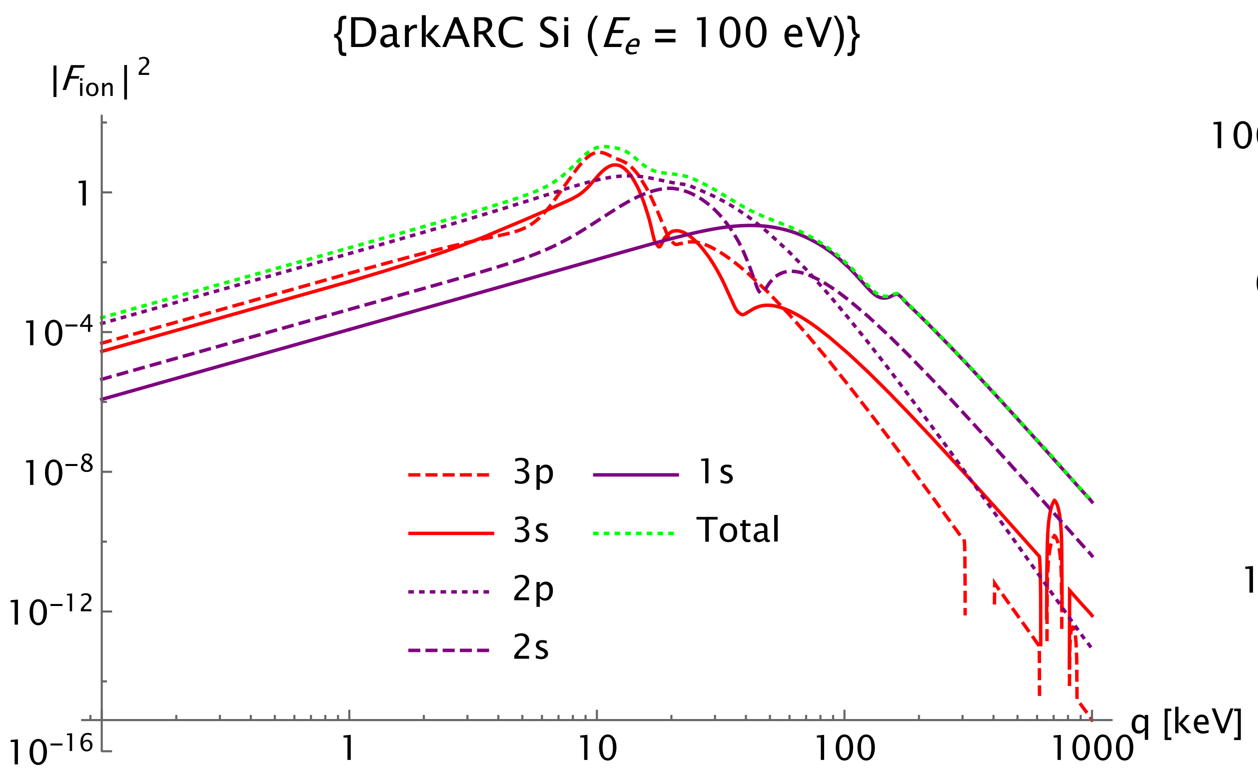
Conversion from Deposited Energy to Ionization signal

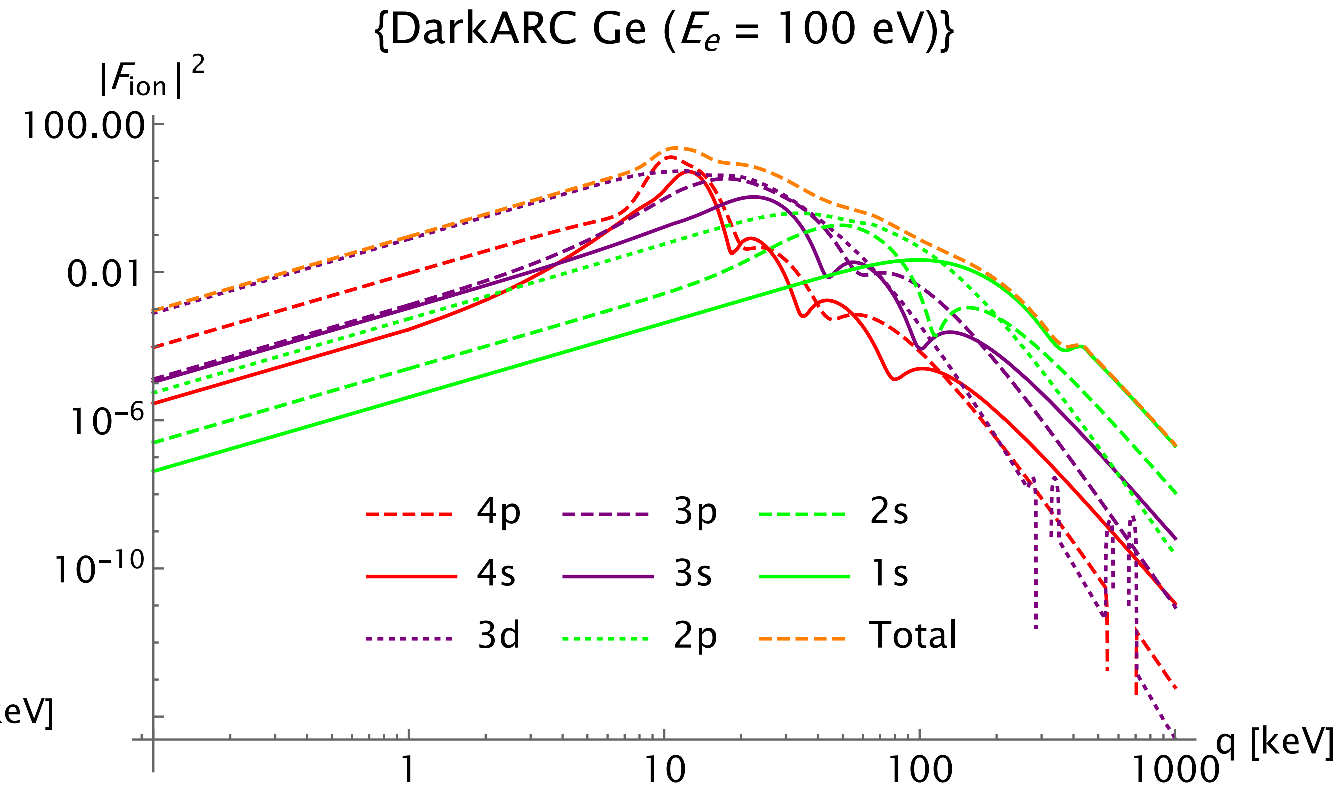
- The experiments measure the ionization signal Q i.e., the number of electron hole pairs produced in an event rather than the deposited energy itself .
- The deposited energy and the ionization signal are related by a complicated chain of secondary scattering processes which rapidly redistributes the energy deposited in the initial scattering into multiple low energy e^--h^+ pair ionizations.
- Assuming linear response, in addition to the primary electron-hole pair produced by the initial scattering, one extra electron-hole pair is produced for every extra ε of energy deposited above the band-gap energy. ε is the mean energy per electron-hole pair as measured in high energy recoils.

$$Q(E_e) = 1 + \lfloor (E_e - E_{\text{gap}})/\varepsilon \rfloor$$

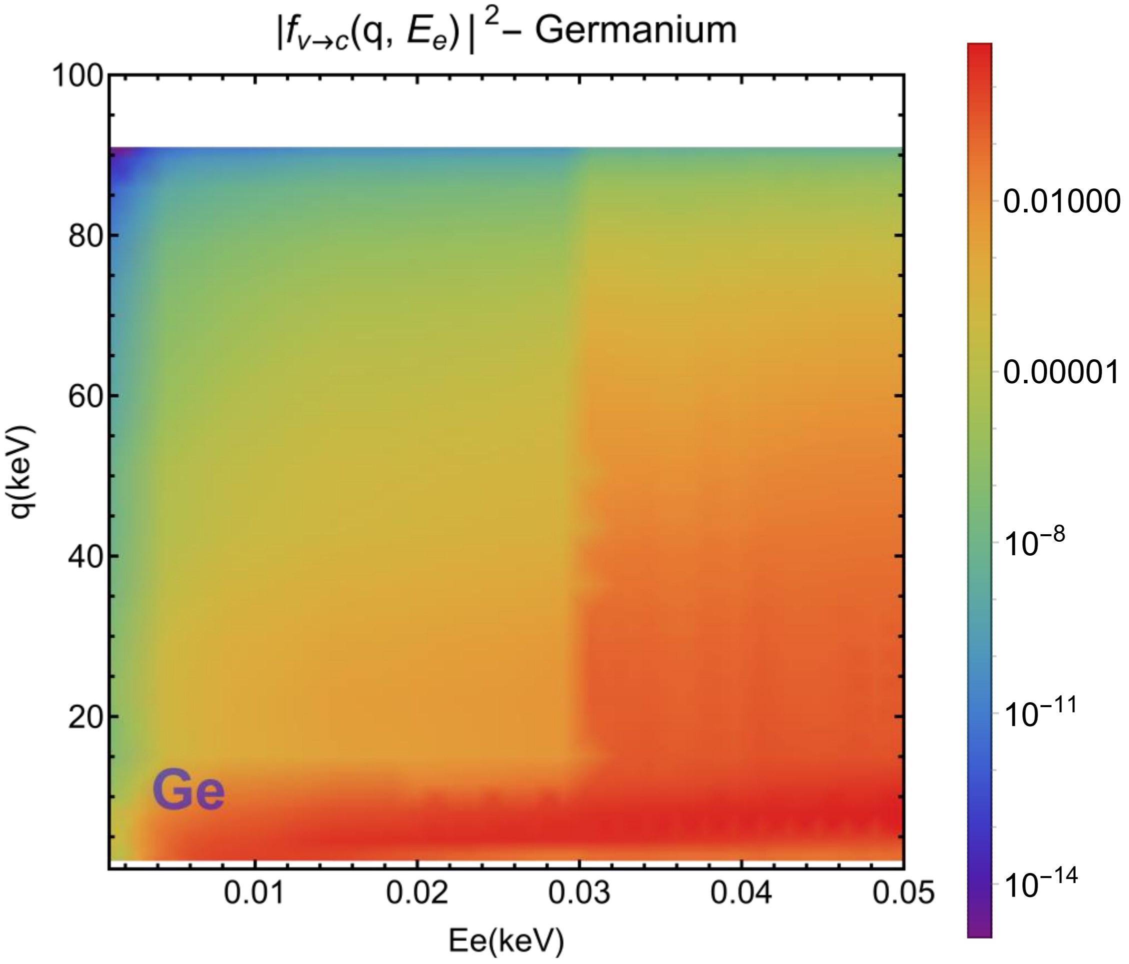
$$\varepsilon = \begin{cases} 3.6\text{eV} & \text{(silicon)} \\ 2.9\text{eV} & \text{(germanium)} \end{cases}, \quad E_{\text{gap}} = \begin{cases} 1.11\text{eV} & \text{(silicon)} \\ 0.67\text{eV} & \text{(germanium)} \end{cases}$$

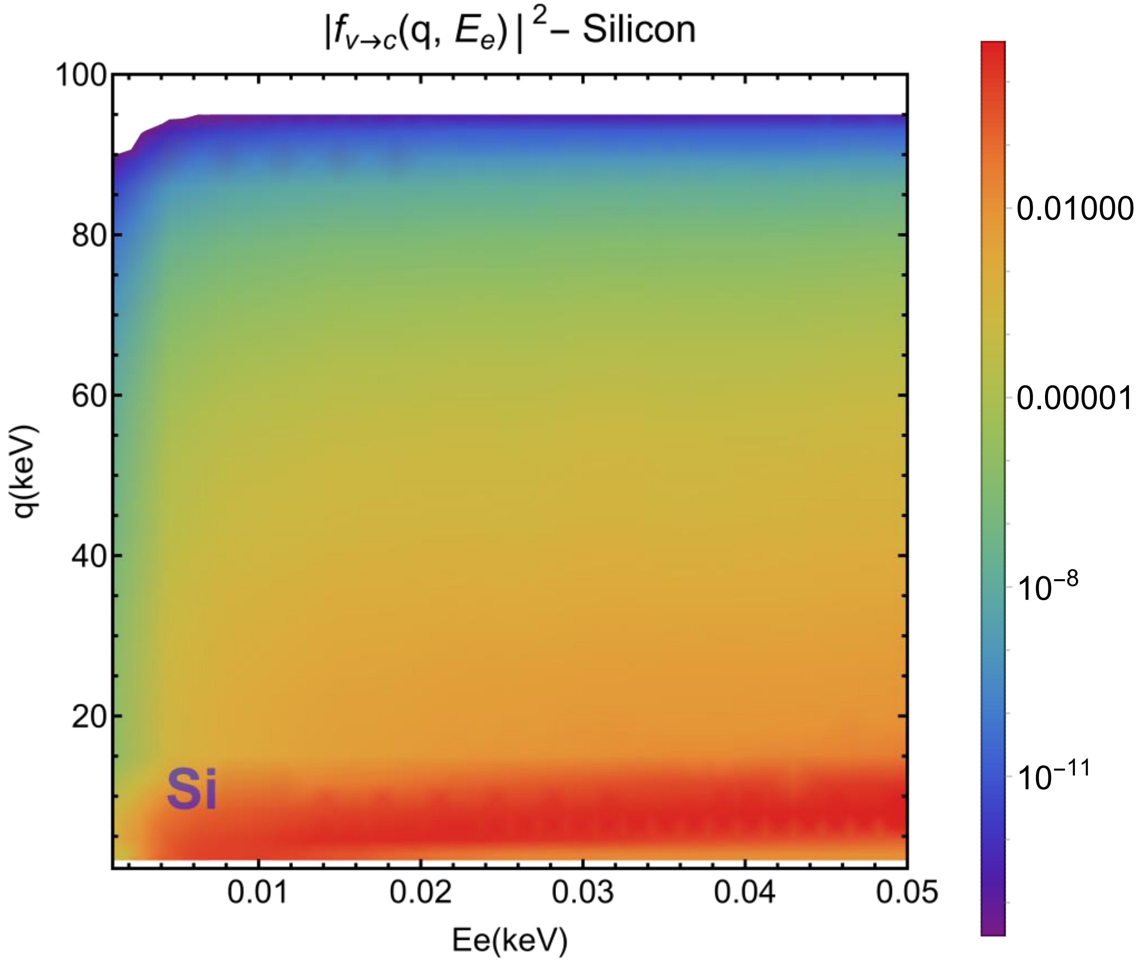
Atomic Ionization Form factor for Silicon and Germanium



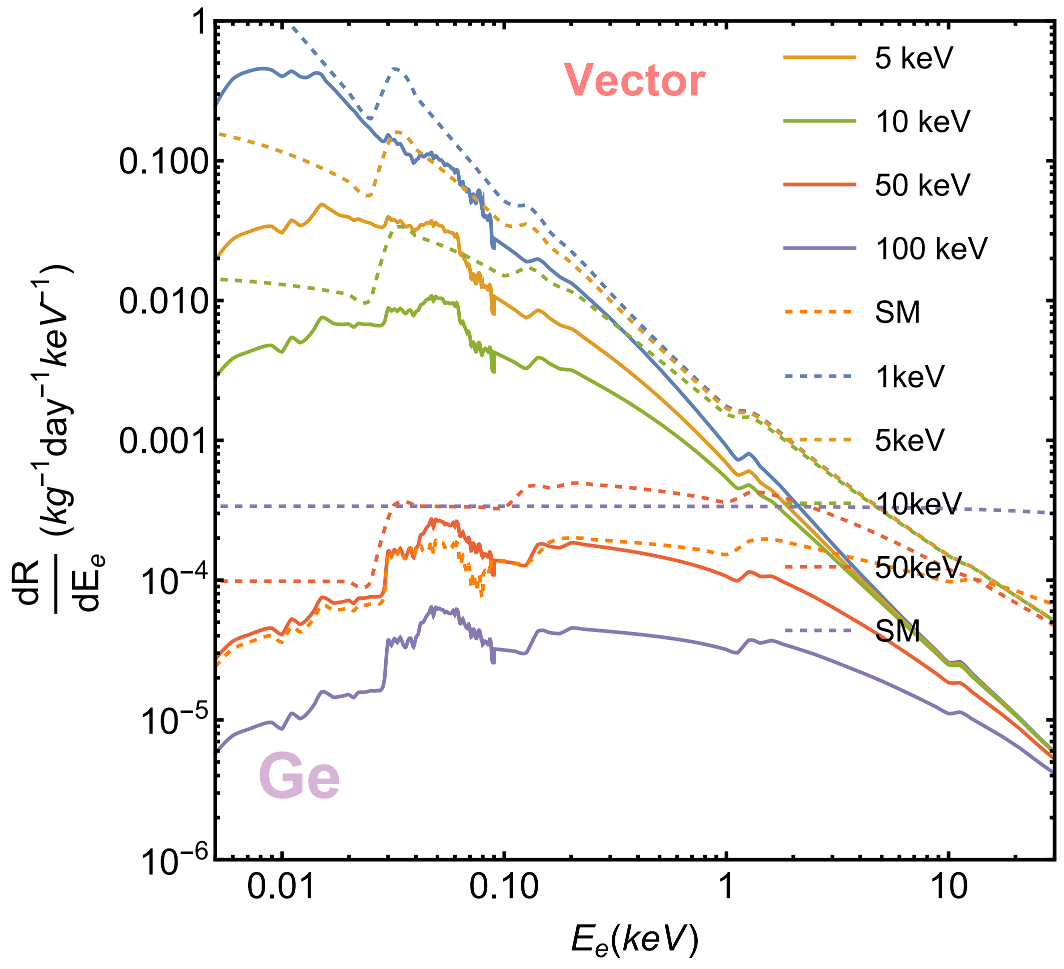


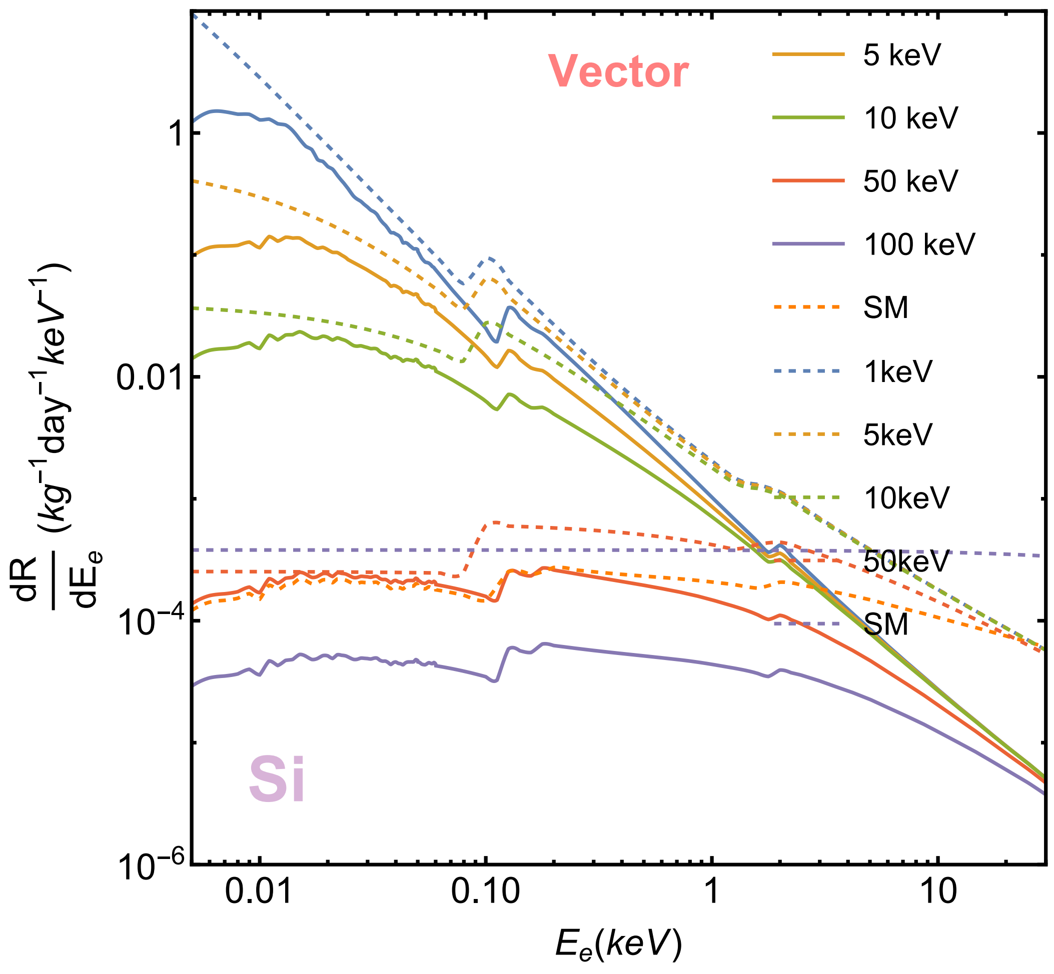
Crystal Form factor for Germanium and Silicon



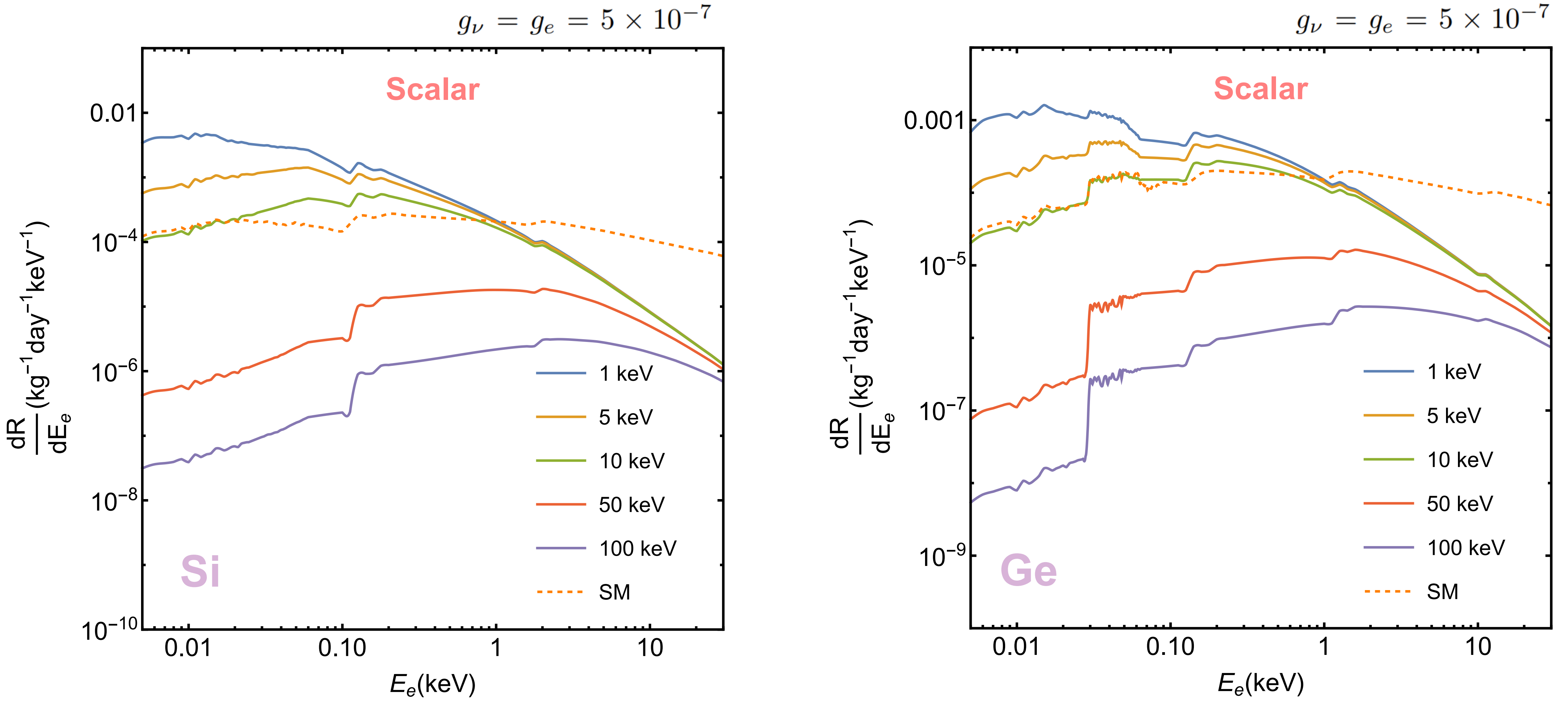


Comparison with FEA





Scattering rate as a function of total energy deposited by the neutrinos



Light Scalar Model

$$H_1 \sim (2, 1/2), \qquad H_2 \sim (2, 1/2),$$
$$\phi \sim (1, 0), \qquad \Delta \sim (3, 1)\ .$$

$$\begin{aligned}
V =\ & m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_\phi^2 \phi^\dagger\phi + m_{\phi'}^2(\phi^2 + \phi^{\dagger 2}) + m_\Delta^2 \,\mathrm{Tr}\, \Delta^\dagger\Delta + m_{12}^2(H_1^\dagger H_2 + H_2^\dagger H_1) \\
& + m_{11\phi} H_1^\dagger H_1(\phi^\dagger + \phi) + m_{22\phi} H_2^\dagger H_2(\phi^\dagger + \phi) + m_{12\phi}(H_1^\dagger H_2 + H_2^\dagger H_1)(\phi^\dagger + \phi) \\
& + m_{\Delta\Delta\phi}(\phi^\dagger + \phi)\mathrm{Tr}\, \Delta^\dagger\Delta + m_{3\phi}(\phi^3 + \phi^{\dagger^3}) + m'_{3\phi}(\phi^2\phi^\dagger + \phi^{\dagger^2}\phi) \\
& + m_{11\Delta}(H_1^T i\sigma_2\Delta^\dagger H_1 - H_1^\dagger\Delta i\sigma_2 H_1^*) + m_{22\Delta}(H_2^T i\sigma_2\Delta^\dagger H_2 - H_2^\dagger\Delta i\sigma_2 H_2^*) \\
& + m_{12\Delta}(H_1^T i\sigma_2\Delta^\dagger H_2 - H_2^\dagger\Delta i\sigma_2 H_1^*) + m_{21\Delta}(H_2^T i\sigma_2\Delta^\dagger H_1 - H_1^\dagger\Delta i\sigma_2 H_2^*) \\
& + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \frac{\lambda_\phi}{2}(\phi^\dagger\phi)^2 + \frac{\lambda'_\phi}{2}(\phi^{\dagger^3}\phi + \phi^3\phi^\dagger) + \frac{\lambda''_\phi}{2}(\phi^{\dagger^4} + \phi^4) + \frac{\lambda_\Delta}{2}(\mathrm{Tr}\, \Delta^\dagger\Delta)^2 \\
& + \frac{\lambda'_\Delta}{2}\mathrm{Tr}\, (\Delta^\dagger\Delta)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2\right] \\
& + \lambda_6\left[(H_1^\dagger H_1)(H_1^\dagger H_2) + (H_1^\dagger H_1)(H_2^\dagger H_1)\right] + \lambda_7\left[(H_2^\dagger H_2)(H_1^\dagger H_2) + (H_2^\dagger H_2)(H_2^\dagger H_1)\right] \\
& + \lambda_8(H_1^\dagger H_1)(\phi^\dagger\phi) + \lambda'_8(H_1^\dagger H_1)(\phi^{\dagger^2} + \phi^2) + \lambda_9(H_2^\dagger H_2)(\phi^\dagger\phi) + \lambda'_9(H_2^\dagger H_2)(\phi^{\dagger^2} + \phi^2) \\
& + \lambda_{10}(H_1^\dagger H_2 + H_2^\dagger H_1)\phi^\dagger\phi + \lambda'_{10}(H_1^\dagger H_2 + H_2^\dagger H_1)(\phi^{\dagger^2} + \phi^2) + \lambda_{11} H_1^\dagger\Delta\Delta^\dagger H_1 \\
& + \lambda_{12}(H_1^\dagger H_1)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_{13} H_2^\dagger\Delta\Delta^\dagger H_2 + \lambda_{14}(H_2^\dagger H_2)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_{15}\left[H_1^\dagger\Delta\Delta^\dagger H_2 + H_2^\dagger\Delta\Delta^\dagger H_1\right] \\
& + \lambda_{16}\left[(H_1^\dagger H_2)\mathrm{Tr}\, \Delta^\dagger\Delta + (H_2^\dagger H_1)\mathrm{Tr}\, \Delta^\dagger\Delta\right] + \lambda_{17}(\phi^\dagger\phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda'_{17}(\phi^{\dagger^2} + \phi^2)\mathrm{Tr}(\Delta^\dagger\Delta) \\
& + \lambda_{18}(H_1^T i\sigma_2\Delta^\dagger H_1 - H_1^\dagger\Delta i\sigma_2 H_1^*)(\phi^\dagger + \phi) + \lambda_{19}(H_2^T i\sigma_2\Delta^\dagger H_2 - H_2^\dagger\Delta i\sigma_2 H_2^*)(\phi^\dagger + \phi) \\
& + \lambda_{20}(H_1^T i\sigma_2\Delta^\dagger H_2 - H_2^\dagger\Delta i\sigma_2 H_1^*)(\phi^\dagger + \phi) + \lambda_{21}(H_2^T i\sigma_2\Delta^\dagger H_1 - H_1^\dagger\Delta i\sigma_2 H_2^*)(\phi^\dagger + \phi)\ . \qquad (4.2)
\end{aligned}$$

After the spontaneous symmetry breaking, the scalars can be expressed as

$$H_1 \sim \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + iG_0) \end{pmatrix}, \quad H_2 \sim \begin{pmatrix} {\phi_2}^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix},$$
$$\phi \sim \frac{1}{\sqrt{2}}(v_\phi + \rho_\phi + i\eta_\phi), \quad \Delta \sim \begin{pmatrix} \Phi^+ & \sqrt{2}\Phi^{++} \\ \frac{1}{\sqrt{2}}(v_\Delta + \rho_t + i\eta_t) & -\Phi^+ \end{pmatrix}.$$

$$\begin{aligned}
-\mathcal{L}_{Yukawa} =\ & \bar{q}'_{L_i}(y'_{1d})_{ij} d'_{R_j} H_1 + \bar{q}'_{L_i}(y'_{1u})_{ij} u'_{R_j}\tilde{H}_1 + \bar{l}'_{L_i}(y'_{1e})_{ij} e'_{R_j} H_1 + \bar{q}'_{L_i}(y'_{2d})_{ij} d'_{R_j} H_2 \\
& + \bar{q}'_{L_i}(y'_{2u})_{ij} u'_{R_j}\tilde{H}_2 + \bar{l}'_{L_i}(y'_{2e})_{ij} e'_{R_j} H_2 + \bar{l}'^c_{L_i}(y')_{ij} i\sigma_2\Delta l'_{L_j}\ ,
\end{aligned}$$

Light Scalar Model

Parameters	Descriptions	Benchmark values
m_1^2, m_2^2, m_ϕ^2, $m_{\phi'}^2$, m_Δ^2 and m_{12}^2	these are the mass square parameters $\sim [\mathcal{O}(100)\text{ GeV}]^2$	$m_1^2 = -(126)^2$ GeV^2, $m_2^2 = (843)^2$ GeV^2, $m_\phi^2 = m_\phi'^2 = -(54)^2$ GeV^2, $m_\Delta^2 = (703)^2$ GeV^2, $m_{12}^2 = -(100)^2$ GeV^2.
$m_{11\phi}$, $m_{22\phi}$, $m_{12\phi}$, $m_{\Delta\Delta\phi}$, $m_{3\phi}$, $m'_{3\phi}$, $m_{11\Delta}$, $m_{22\Delta}$, $m_{12\Delta}$ and $m_{21\Delta}$	the mass dimension of these parameters are one with values $\sim \mathcal{O}(0.1 - 10)$ GeV	$m_{11\phi} = 0.138$ GeV, $m_{11\Delta} = 11.54$ GeV and rest of them are -10 GeV.
λ_1, λ_2, λ_ϕ, λ'_ϕ, λ'_ϕ λ_Δ λ'_Δ, λ_3, λ_4, λ_5, λ_6, λ_7, λ_8, λ'_8, λ_9, λ'_9, λ_{10}, λ'_{10}, λ_{11}, λ_{12}, λ_{13}, λ_{14}, λ_{15}, λ_{16}, λ_{17}, λ'_{17}, λ_{18}, λ_{19}, λ_{20} and λ_{21}	these are the dimensionless couplings with values between $0.1 - 1.0$	$\lambda_1 = 0.53$, $\lambda_6 = 0.33$; rest of them are 0.1

Table 1: Brief descriptions and the necessary range of values for all the parameters that appear in the scalar potential in eq. 4.2. One particular benchmark scenario is shown. We use this benchmark to generate a light scalar of mass $\sim \mathcal{O}(1)$ keV along with other heavy physical scalars consistent with the LHC bounds. The values of the vev's are $v_1 = 246$ GeV, $v_2 = 0$ GeV, $v_\phi = 1$ GeV and $v_\Delta = 1$ GeV.

Physical particles	Mass values and descriptions
Neutral scalars: h, h_1, h_2 and h_3	$m_h = 125.5$ GeV, this is the SM Higgs; $m_{h_1} = 0.001$ GeV, very light scalar, neccessary for our analysis; $m_{h_2} = 500$ GeV, $m_{h_3} = 600$ GeV they satisfy the LHC bounds.
Neutral pseudo-scalars: s_1, s_2 and s_3	$m_{s_1} = 500$ GeV, $m_{s_2} = 500$ GeV, $m_{s_3} = 600$ GeV, they satisfy LHC bounds.
Single charged scalars: $h_1^\pm$, $h_2^\pm$	$m_{h_1^\pm} = 500$ GeV, $m_{h_2^\pm} = 600$ GeV, in agreement with LHC bounds.
Double charged scalars: $h_3^{\pm\pm}$	$m_{h_3^{\pm\pm}} = 500$ GeV, satisfying LHC limits.

Table 2: The physical scalar spectrum generated using the benchmark values from Table 1. The physical scalar h is identified as the SM Higgs scallar. The h_1 is the light scalar which will be identified as ϕ' in the rest of the paper. The scalar masses are consistent with the LHC bounds.