Probing NSI with low energy neutrino-electron elastic scattering in reactor experiments

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Motivation

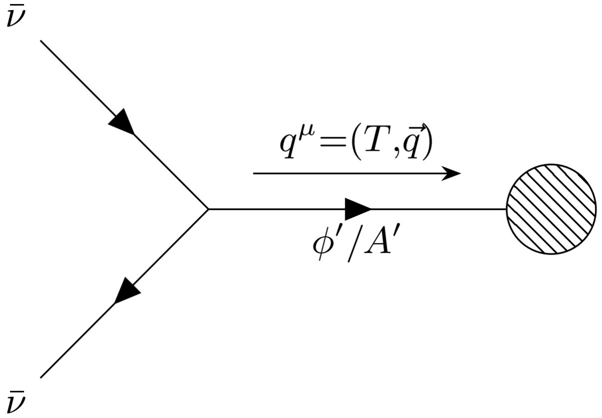
- Leptophilic interactions occur in many extensions of the Standard model such as $\boldsymbol{L_\mu - L_e}$, $\boldsymbol{L_e - L_\tau}$, light scalar models etc. These models include NSI with new weakly coupled mediating particles.
  R. Foot, **Mod. Phys. Lett. A 6, 527 (1991) ,**
  X. G. He, G. C. 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.

Neutrino-electron scattering



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

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

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

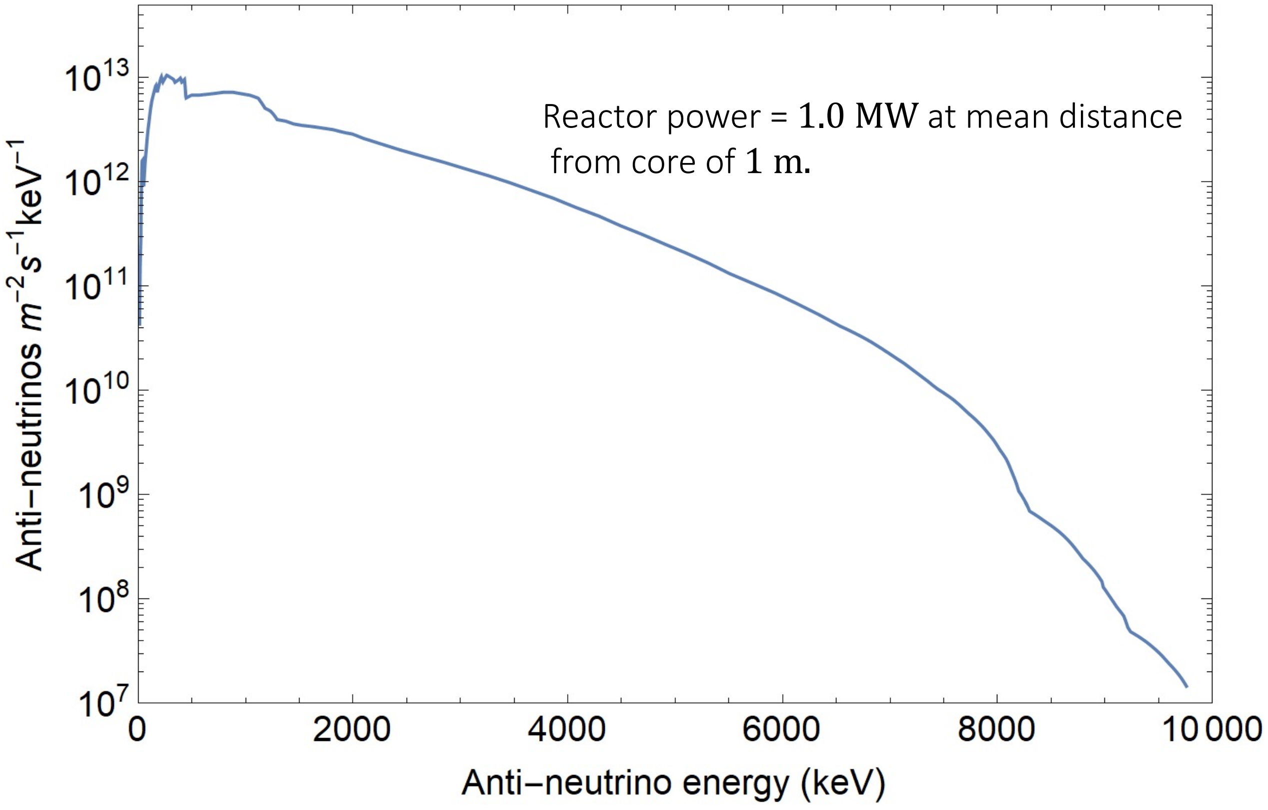
Vector NSI: $\mathcal{L}_V \supset A'_\mu\left(g_{\nu,Z'}\bar{\nu}_L\gamma^\mu\nu_L + g_{\ell,Z'}\bar{\ell}\gamma^\mu\ell\right)$

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

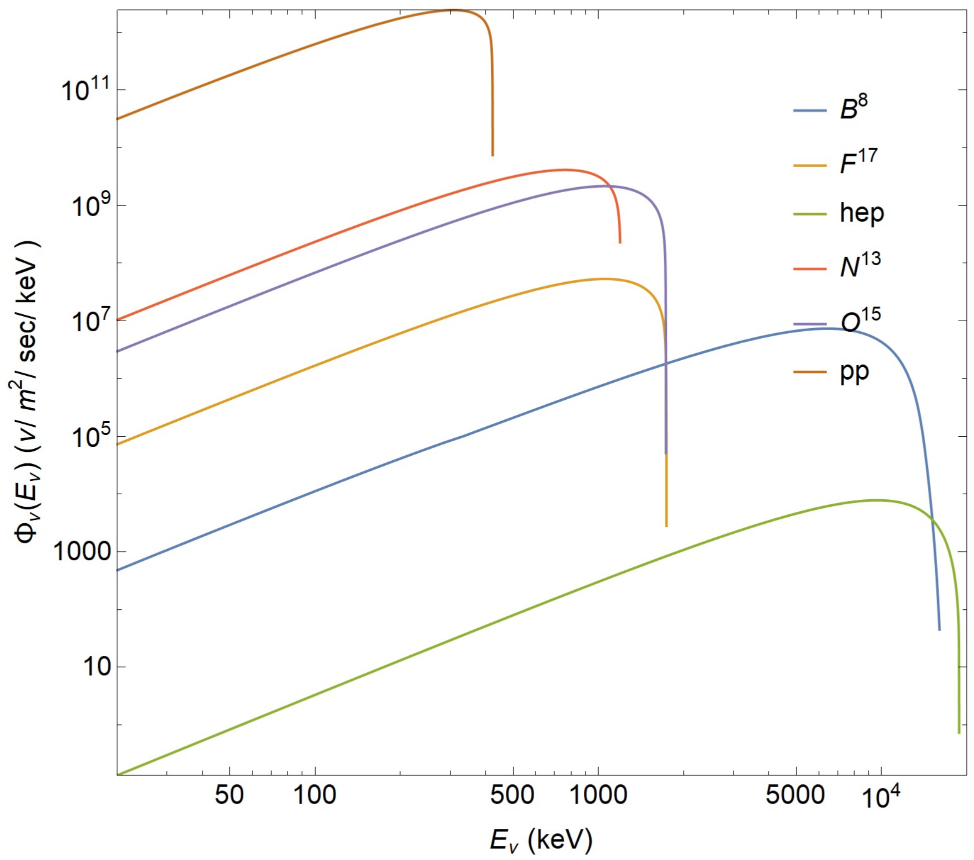
Reactor and Solar Neutrino Flux

- 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

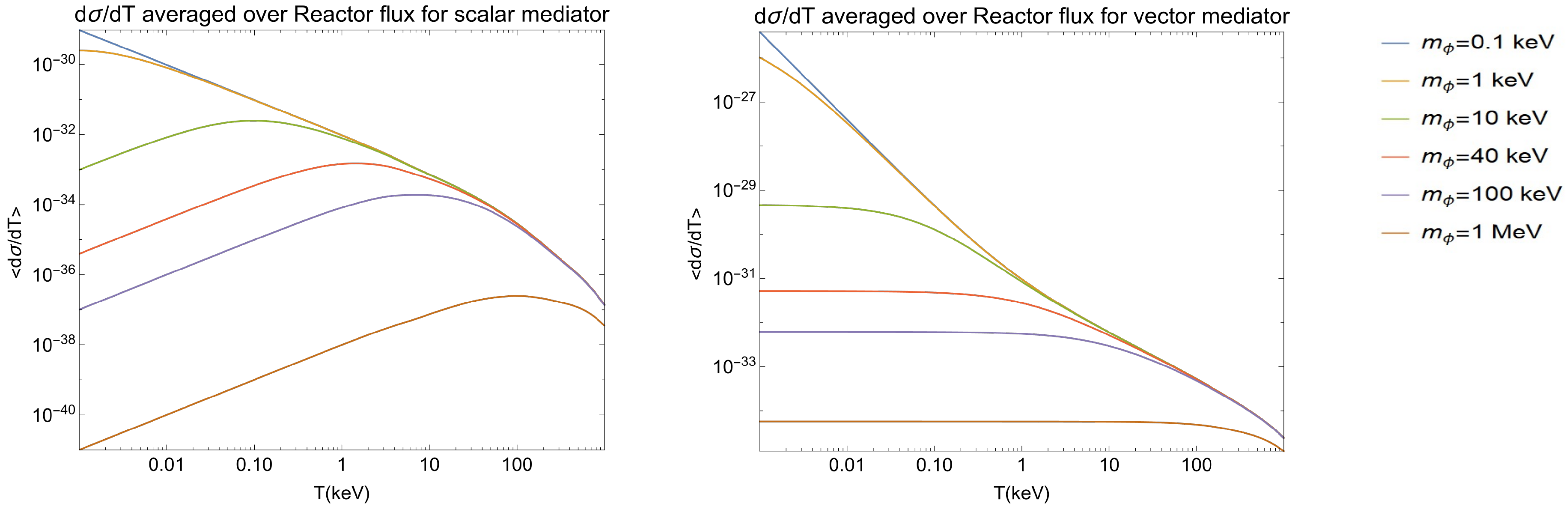


Solar flux



Neutrino-electron scattering

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



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.
-

$$\frac{dR}{d\ln E_e} = \frac{N_T}{4}\int dE_\nu \Phi(E_\nu)\int dq\left(\frac{d\sigma}{dq}\right)\left|f_{\text{ion}}^{n,l}(E_e,q)\right|^2$$

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

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

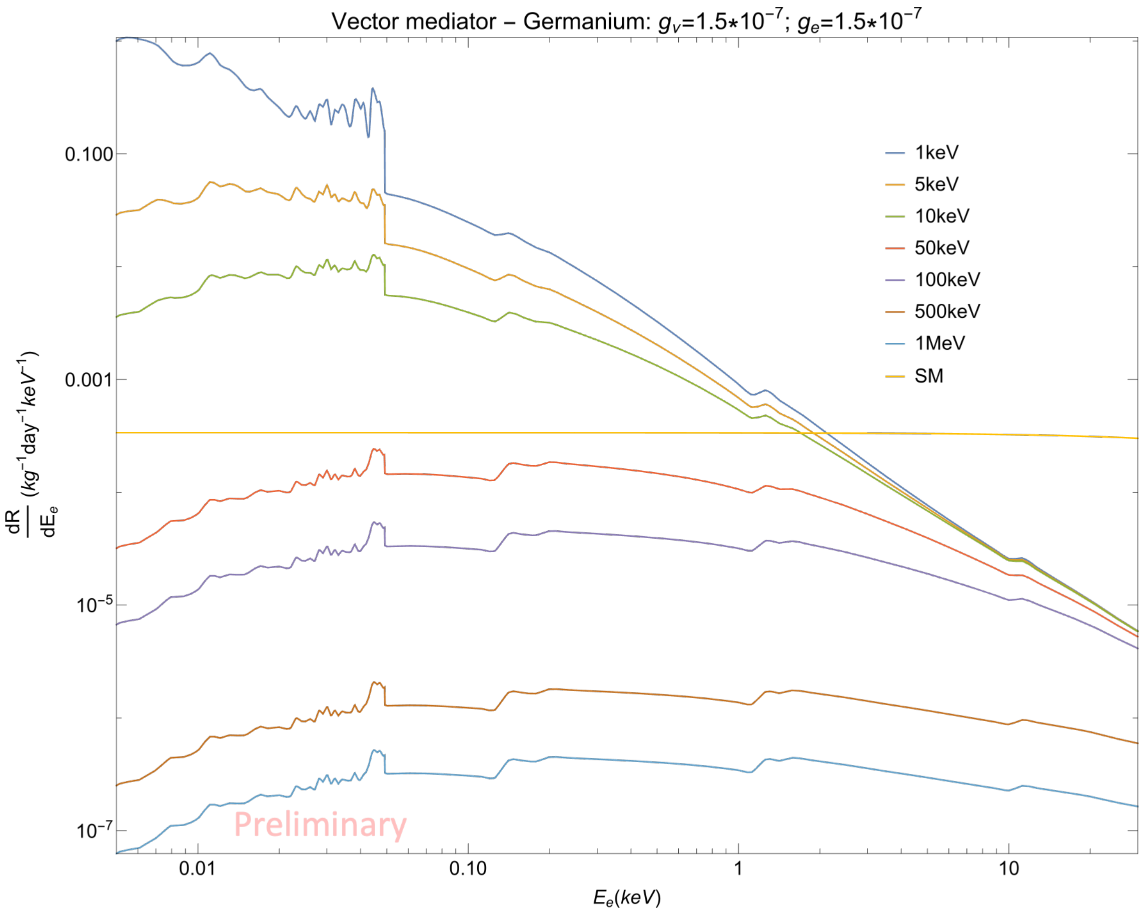
$$\frac{dR}{d\ln E_e} = \frac{N_{cell}}{4}\int dE_\nu \Phi(E_\nu)\int dq\left(\frac{d\sigma}{dq}\right)\times\frac{8\alpha m_e^2 E_e}{q_e^3}\left|f_{\text{crystal}}(E_e,q)\right|^2$$

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.

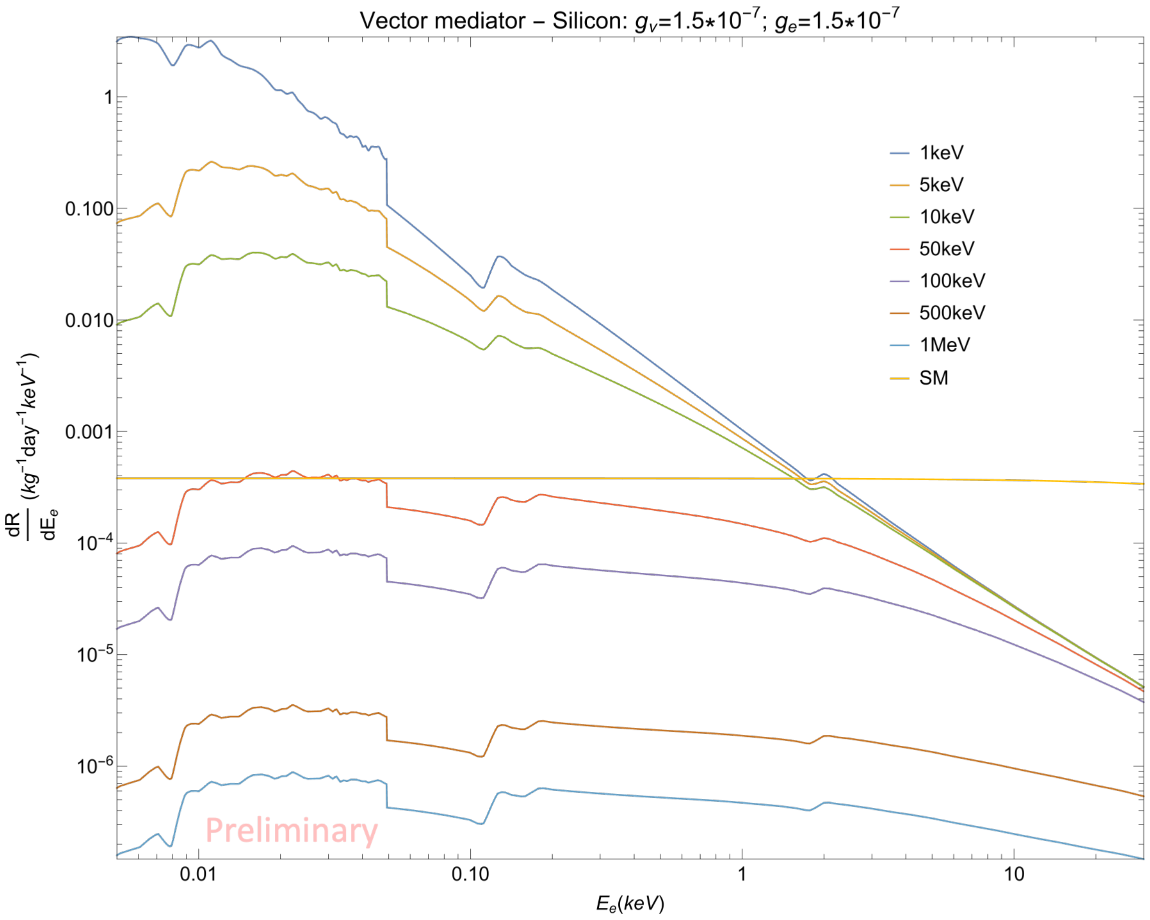
$$\left|f_{\text{ion}}^{n\ell}(k',q)\right|^2 = V\frac{4k'^3}{(2\pi)^3}\sum_{\ell'=0}^{\infty}\sum_{m=-\ell}^{\ell}\sum_{m'=-\ell'}^{\ell'}\left|\int\frac{\mathrm{d}^3k}{(2\pi)^3}\psi_2^*(\mathbf{k}+\mathbf{q})\psi_1(\mathbf{k})\right|^2$$

$$\left|f_{\text{crystal}}(q,E_e)\right|^2 = \frac{2\pi^2\left(\alpha m_e^2 V_{\text{cell}}\right)^{-1}}{E_e}\sum_{ii'}\int_{\text{BZ}}\frac{V_{\text{cell}}\,d^3k}{(2\pi)^3}\frac{V_{\text{cell}}\,d^3k'}{(2\pi)^3}\times E_e\delta\left(E_e - E_{i'\vec{k}'} + E_{i\vec{k}}\right)\sum_{\vec{G}'}q\delta\left(q - \left|\vec{k}' - \vec{k} + \vec{G}'\right|\right)\left|f_{\left[i\vec{k},i'\vec{k}',\vec{G}'\right]}\right|^2$$

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



Vector mediator – Germanium: $g_v=1.5*10^{-7}$; $g_e=1.5*10^{-7}$



Vector mediator – Silicon: $g_v=1.5*10^{-7}$; $g_e=1.5*10^{-7}$

Conversion from Deposited Energy to Ionization signal

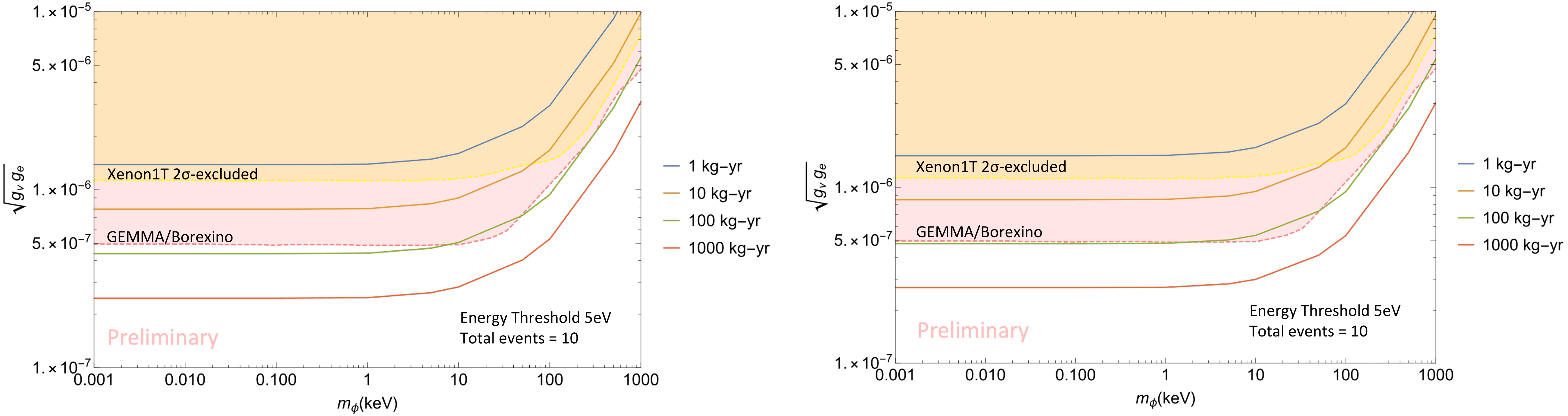
- The experiments measure the ionization signal Q i.e., the number of electron hole pairs produced in an event rather than the deposited energy itself .
- The deposited energy and the ionization signal are related by a complicated chain of secondary scattering processes which rapidly redistributes the 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.

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

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

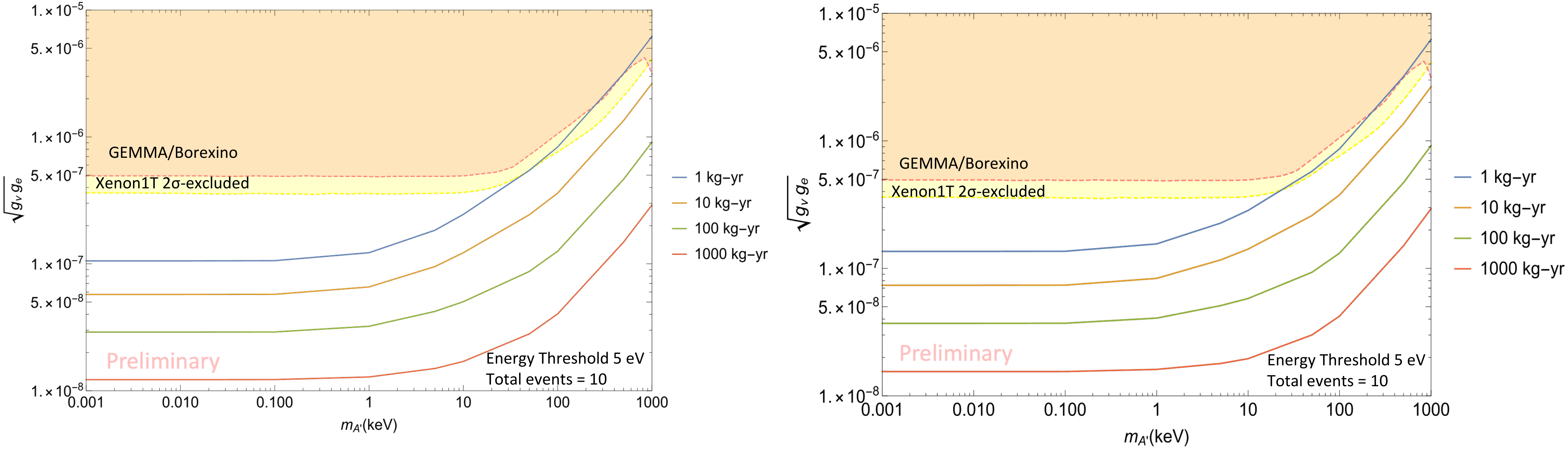
Results: Scalar mediator

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

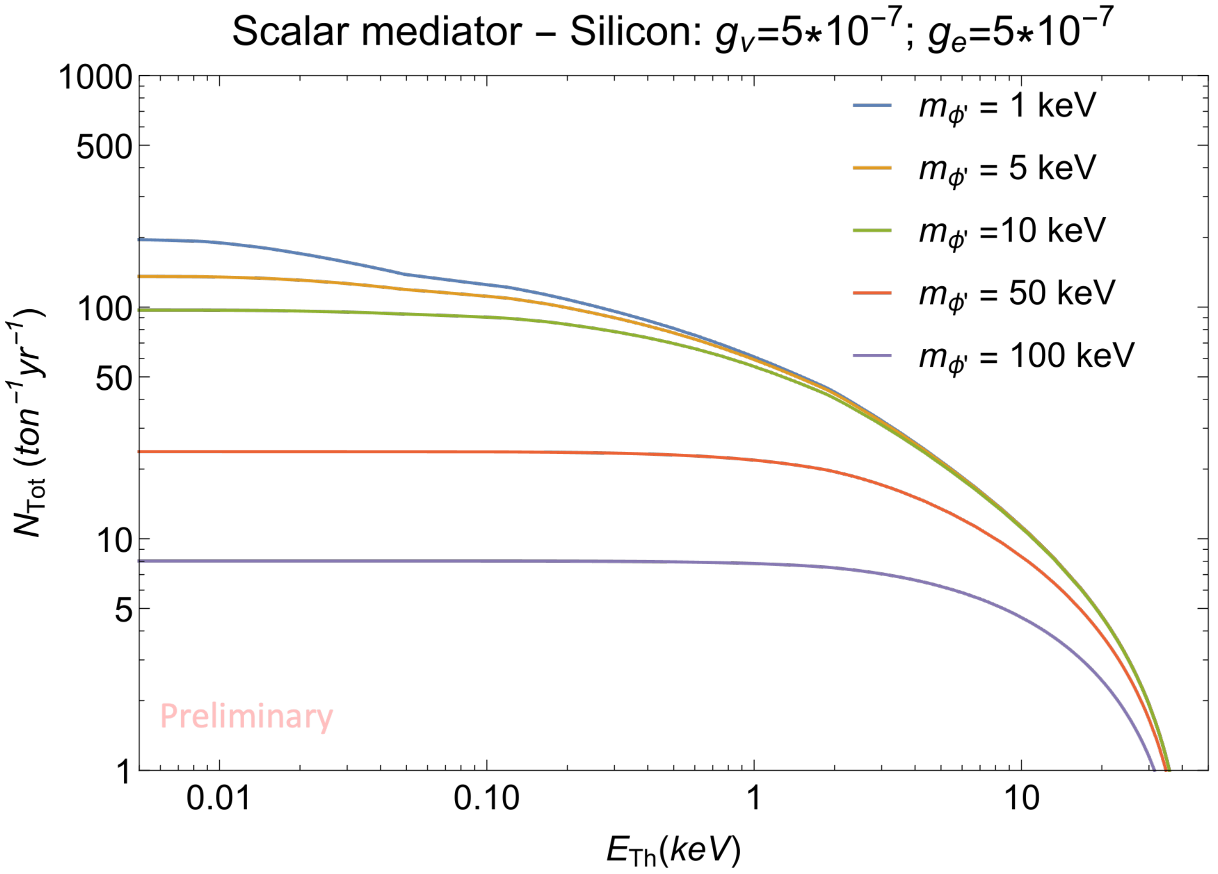


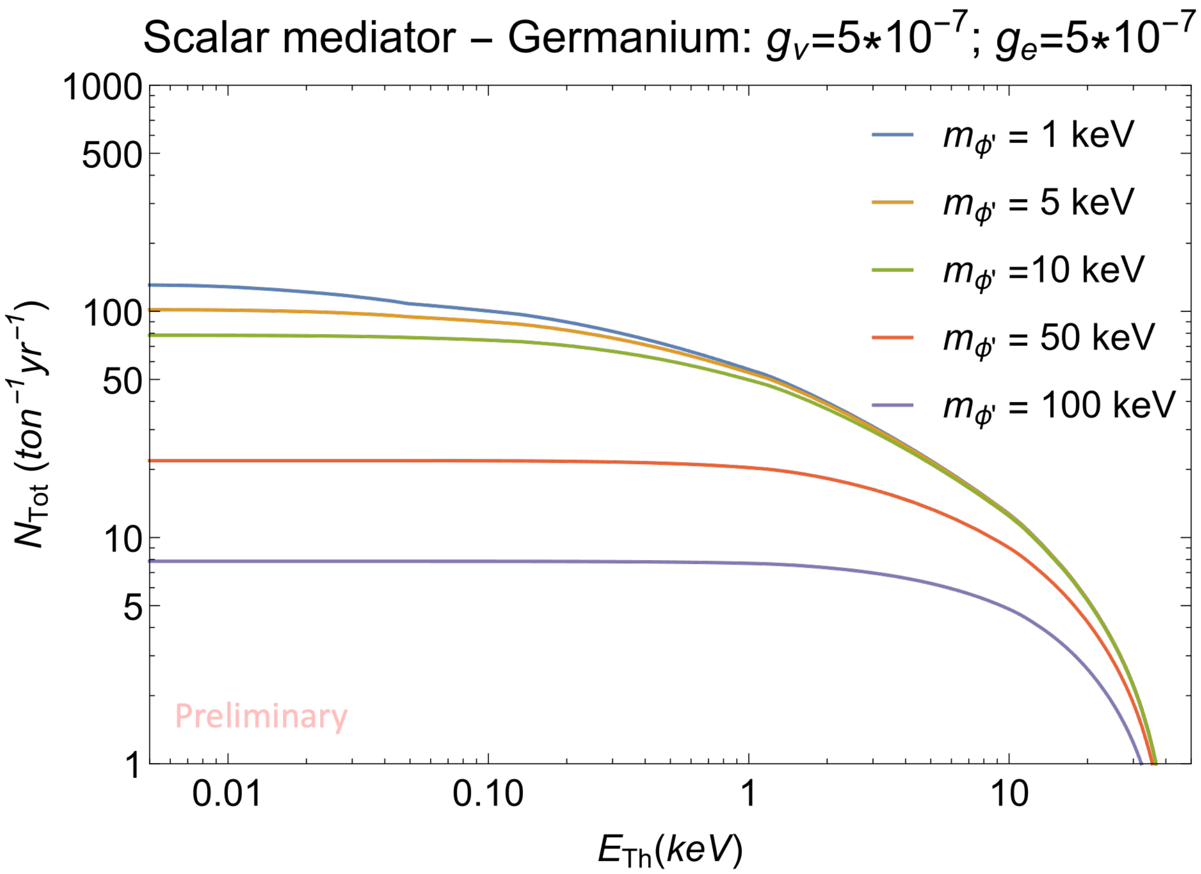
Result: Vector mediator

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

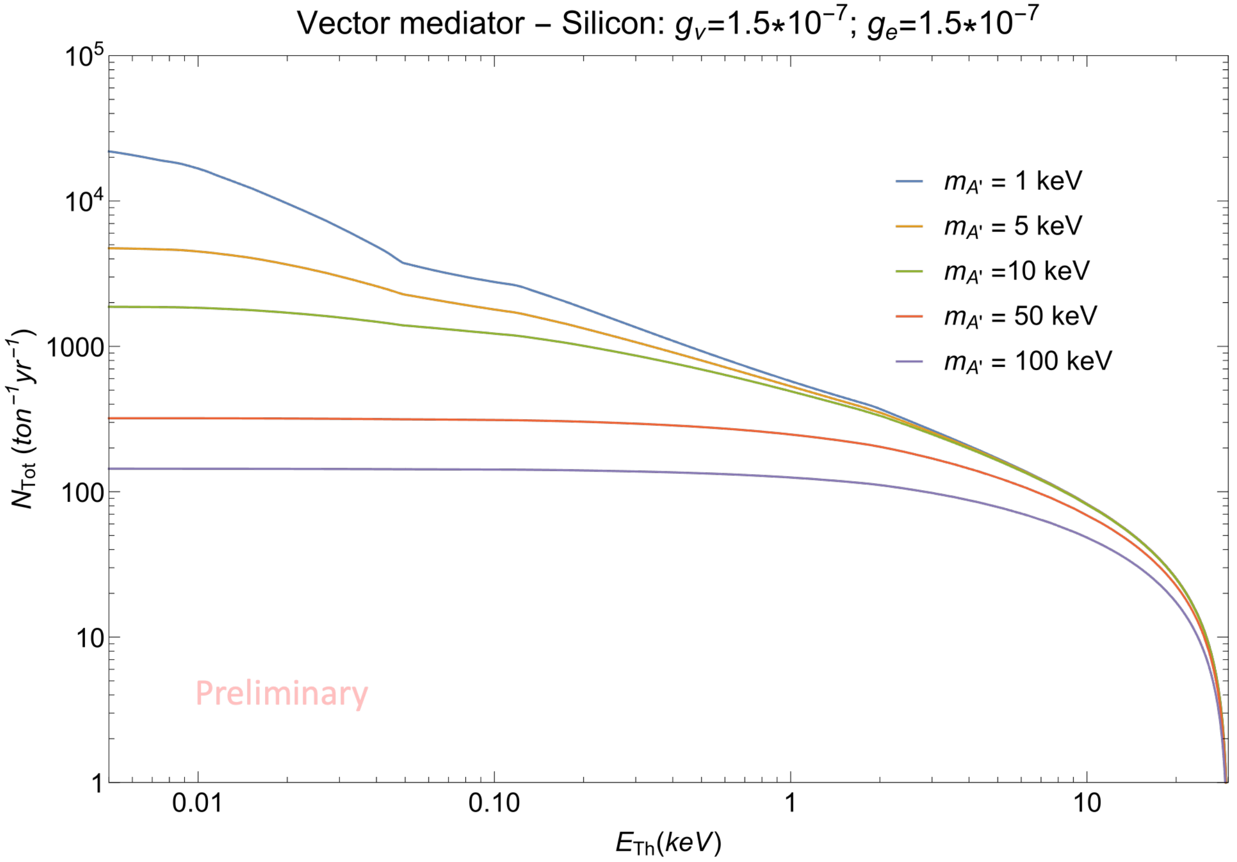


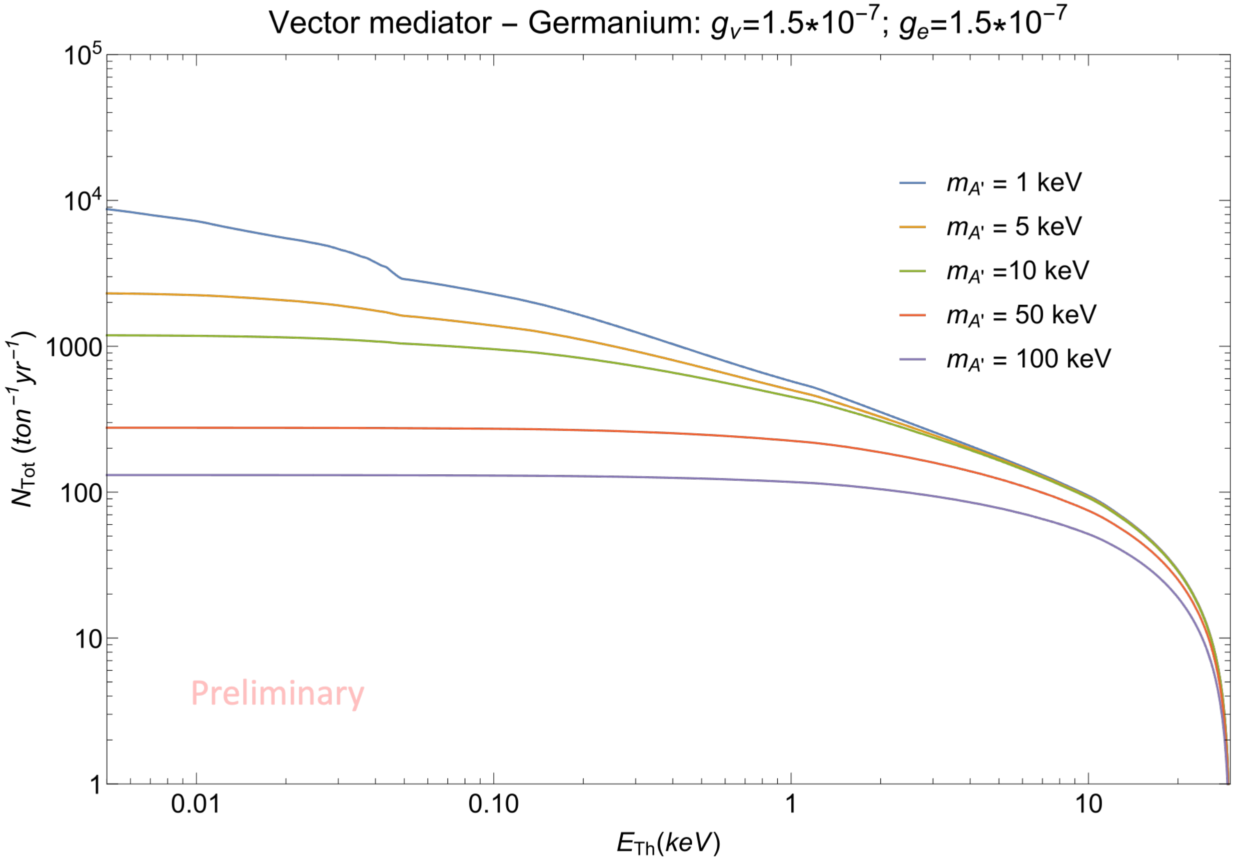
Electron recoil integrated rates as a function of Experimental Threshold energy





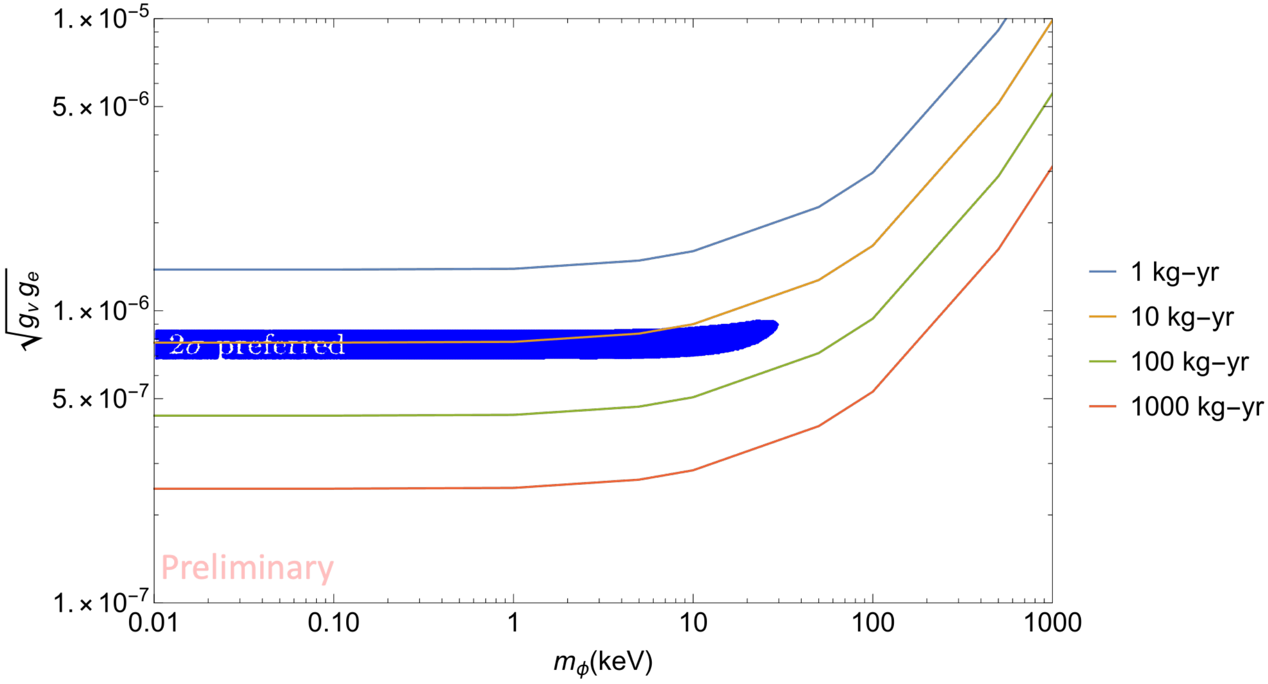
Electron recoil integrated rates as a function of Experimental Threshold energy



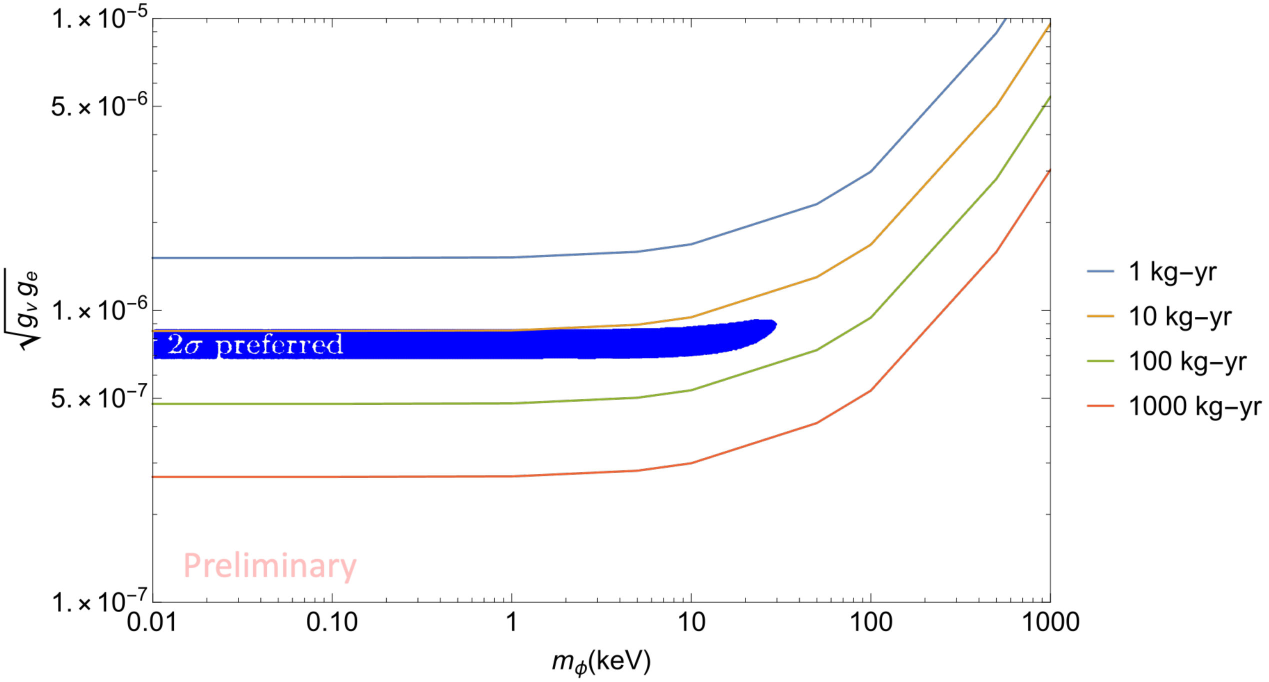


Xenon1T excess at Reactor based experiments

Sensitivity projections for Silicon detector for scalar mediator



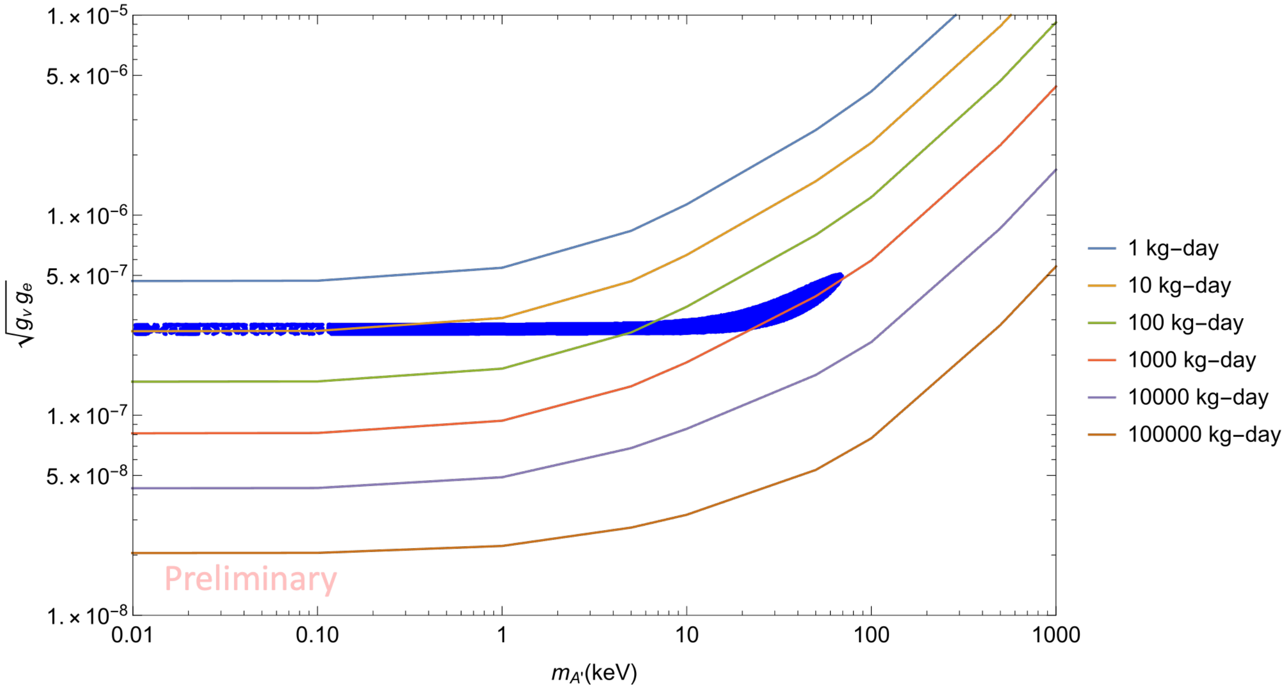
Sensitivity projections for Germanium detector for scalar mediator



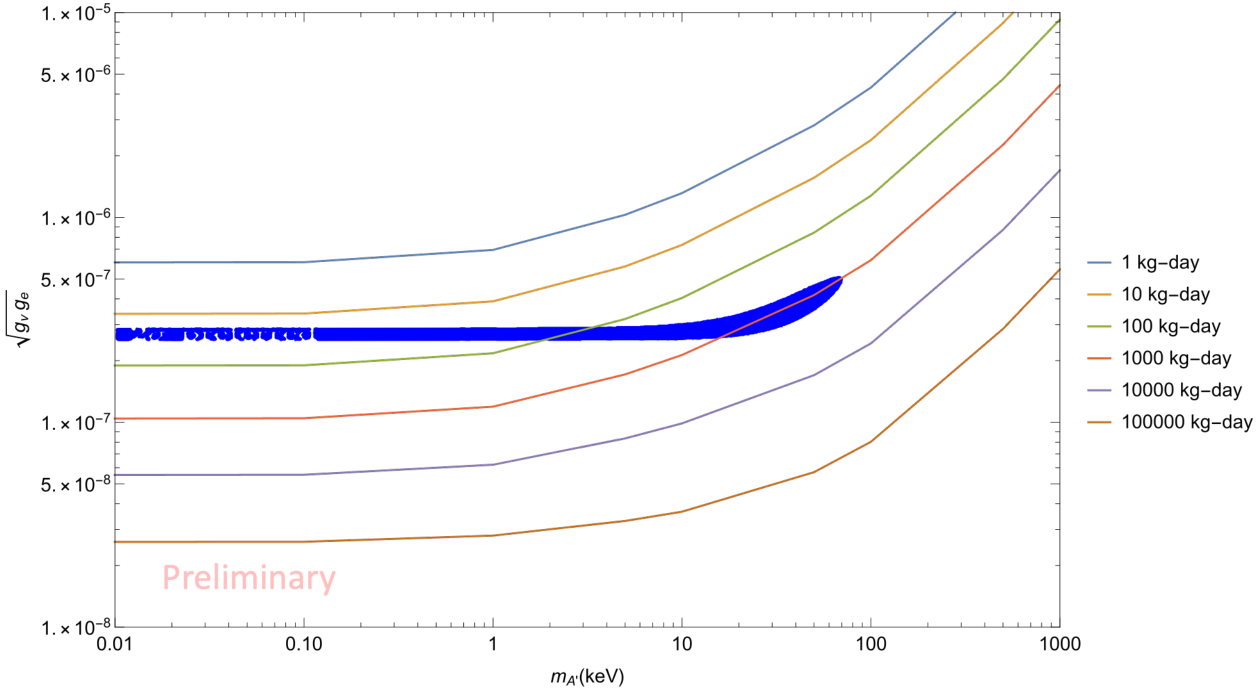
● Xenon1t 2σ−preferred region

Xenon1T excess at Reactor based experiments

Sensitivity projections for Silicon detector for vector mediator



Sensitivity projections for Germanium detector for vector mediator



● Xenon1t 2σ−preferred region

Ongoing work and future improvements

- NSI can arise in extended Higgs sector model such as one introduced in Dutta, B. et.al *Phys. Rev. D* **102**,055017 (2020) which has sterile neutrinos coupling with a light scalar. We will be working on a similar model which includes a Higgs triplet and a doublet (in addition to the SM Higgs doublet) and assigns a larger NSI to active neutrinos. These models will be constrained by various low energy experiments including reactor experiments.

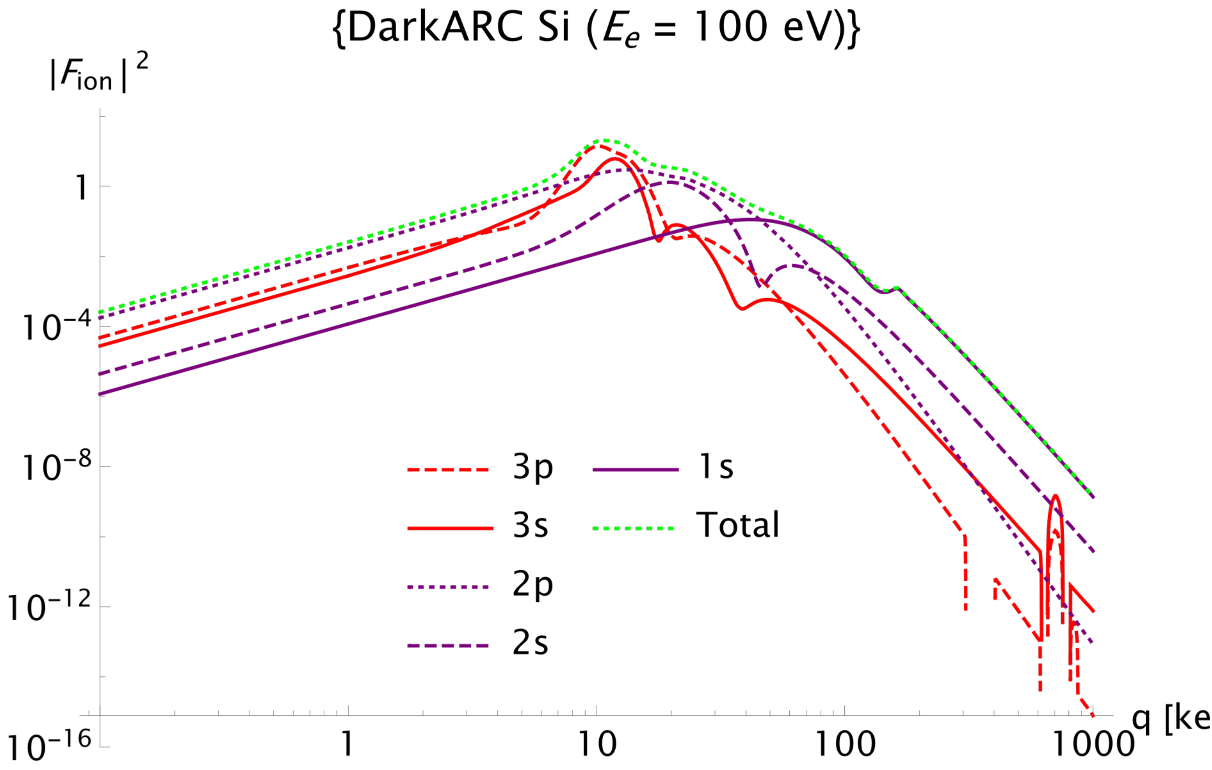
- We will be working on including core to conduction transition rates and more accurate calculations of the neutrino induced valence to free, valence to conduction transitions in semiconductor targets as has been done for the DM induced ionization rate calculations in Griffin, S. M. *et al.* (2021), *arXiv:2105.05253*

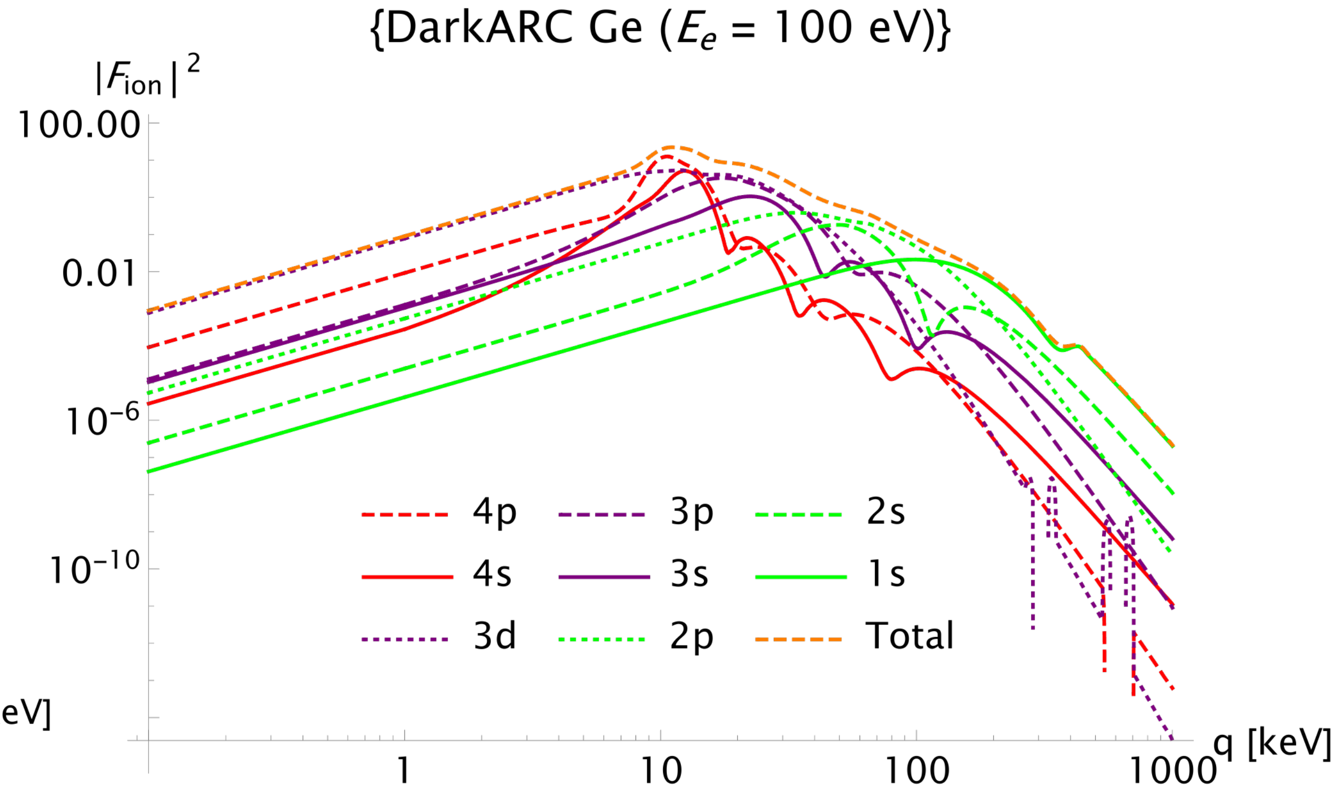
Conclusion

- 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.

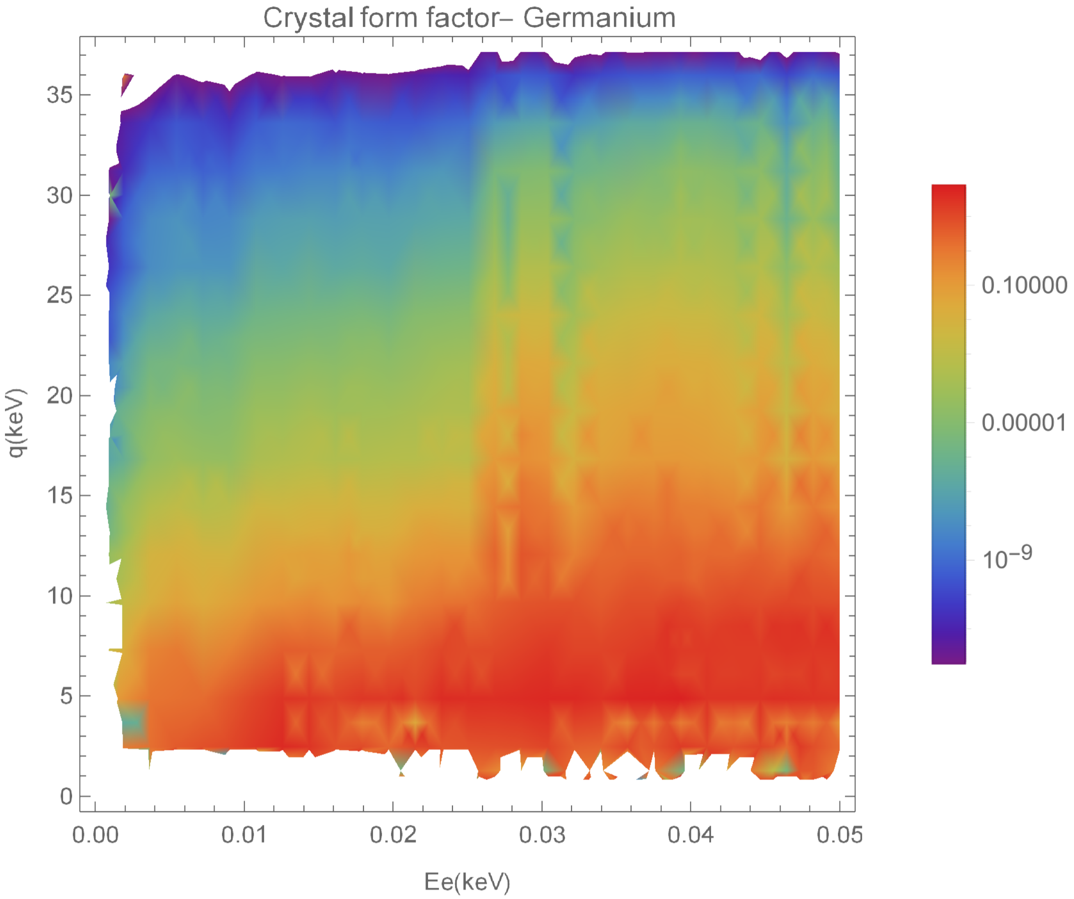
Backup

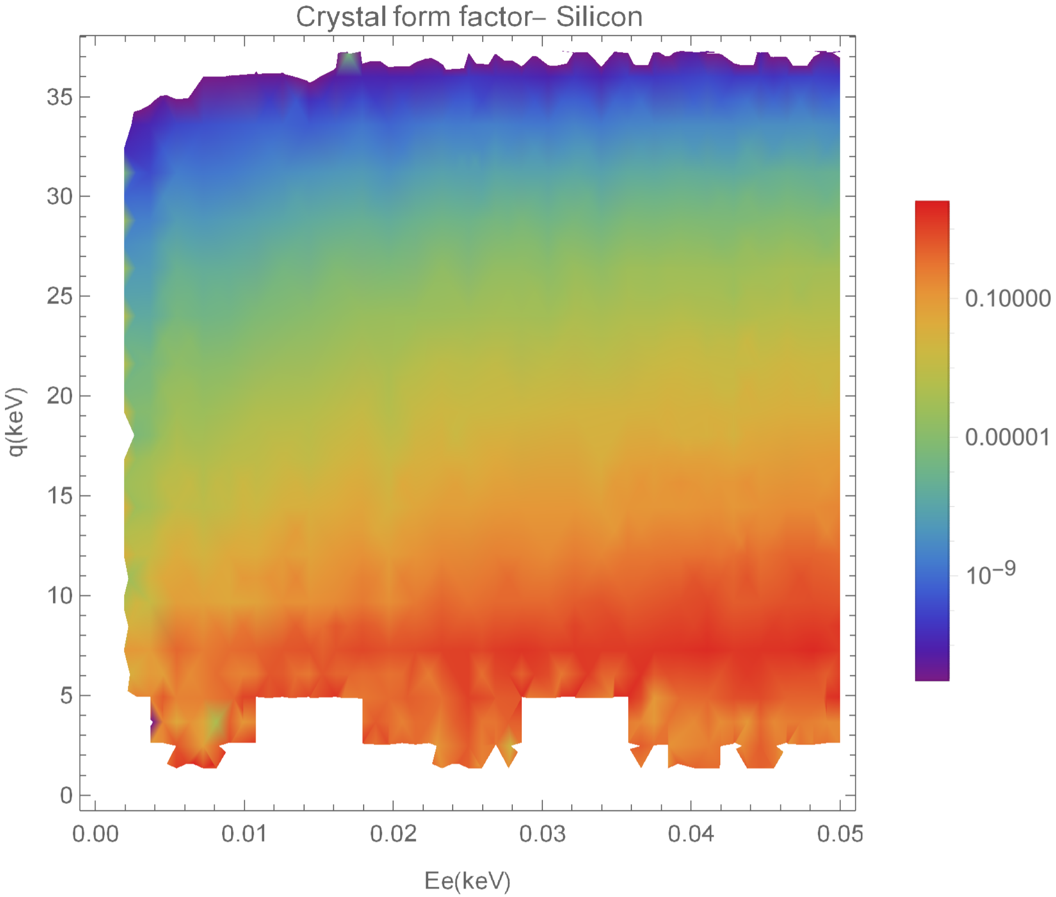
Ionization Form factor for Germanium and Xenon



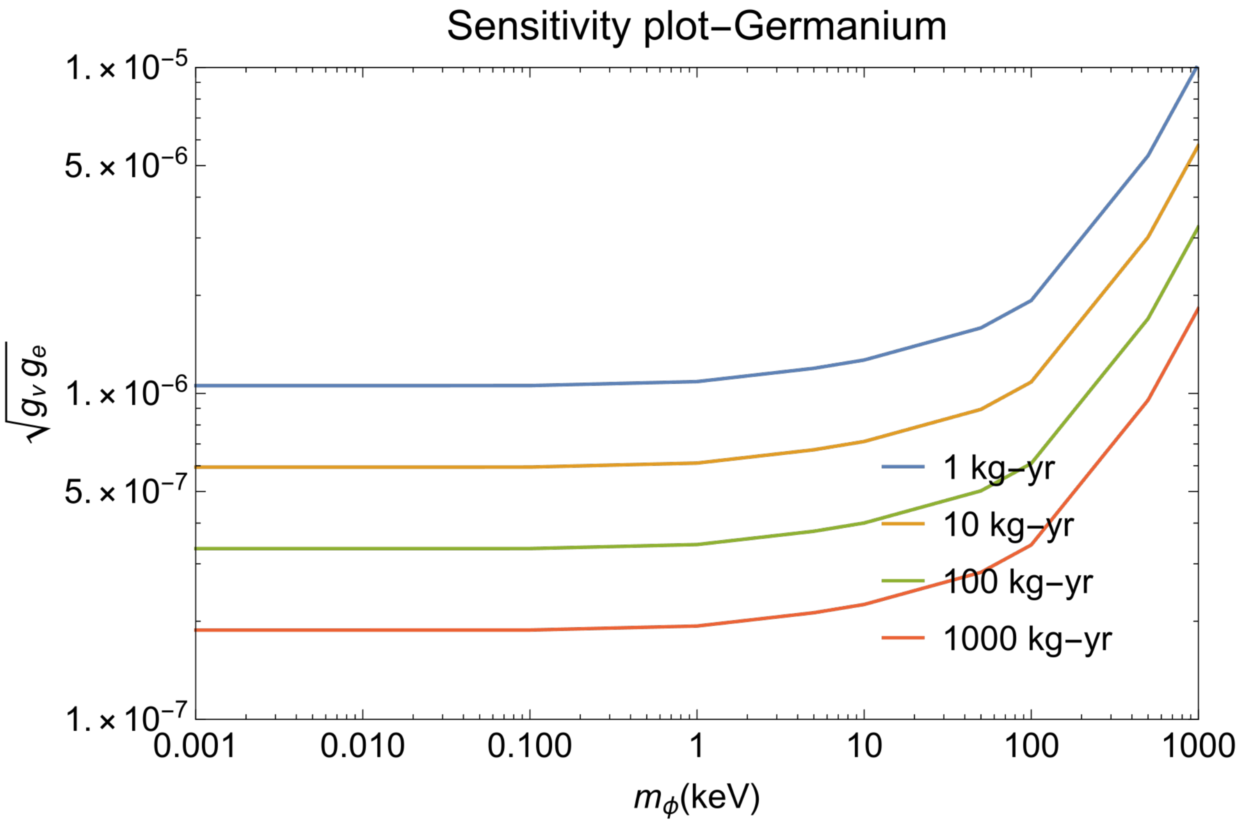


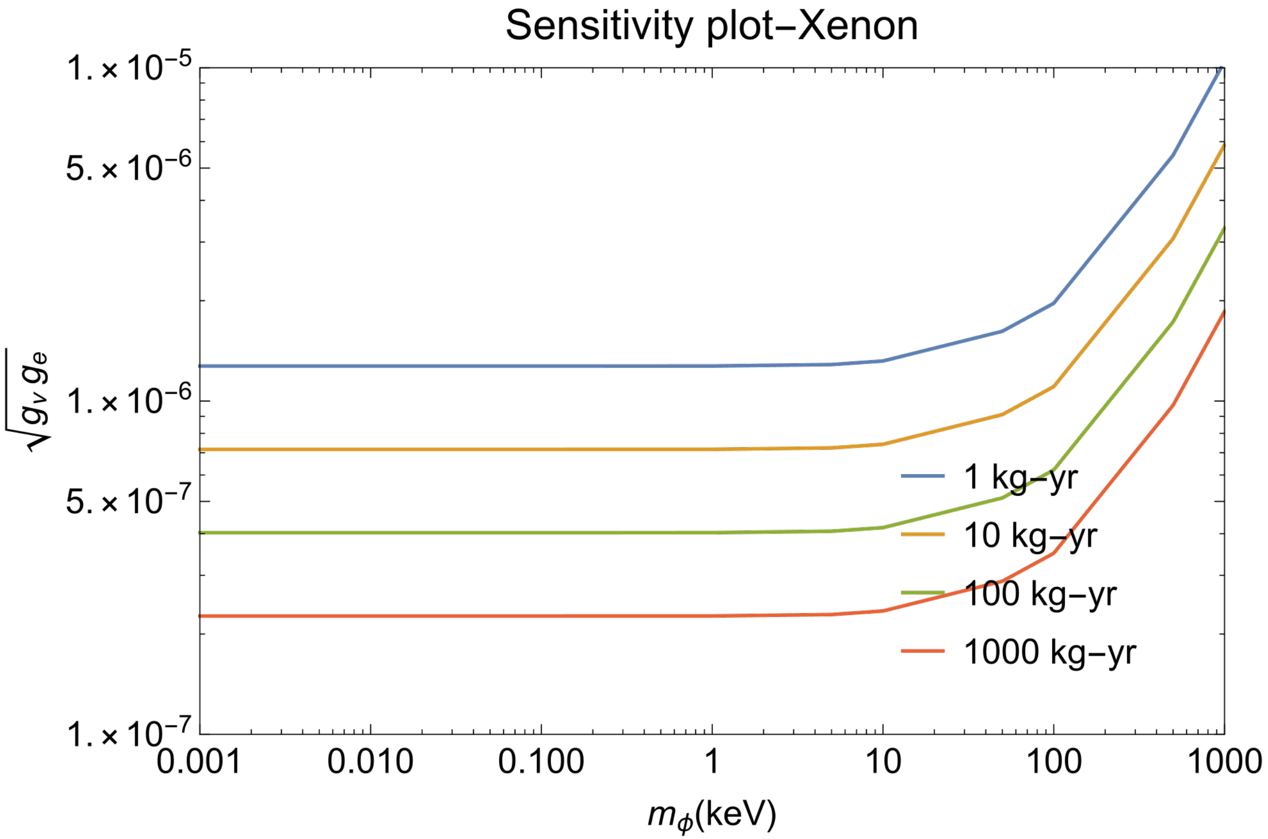
Crystal Form factor for Germanium and Silicon



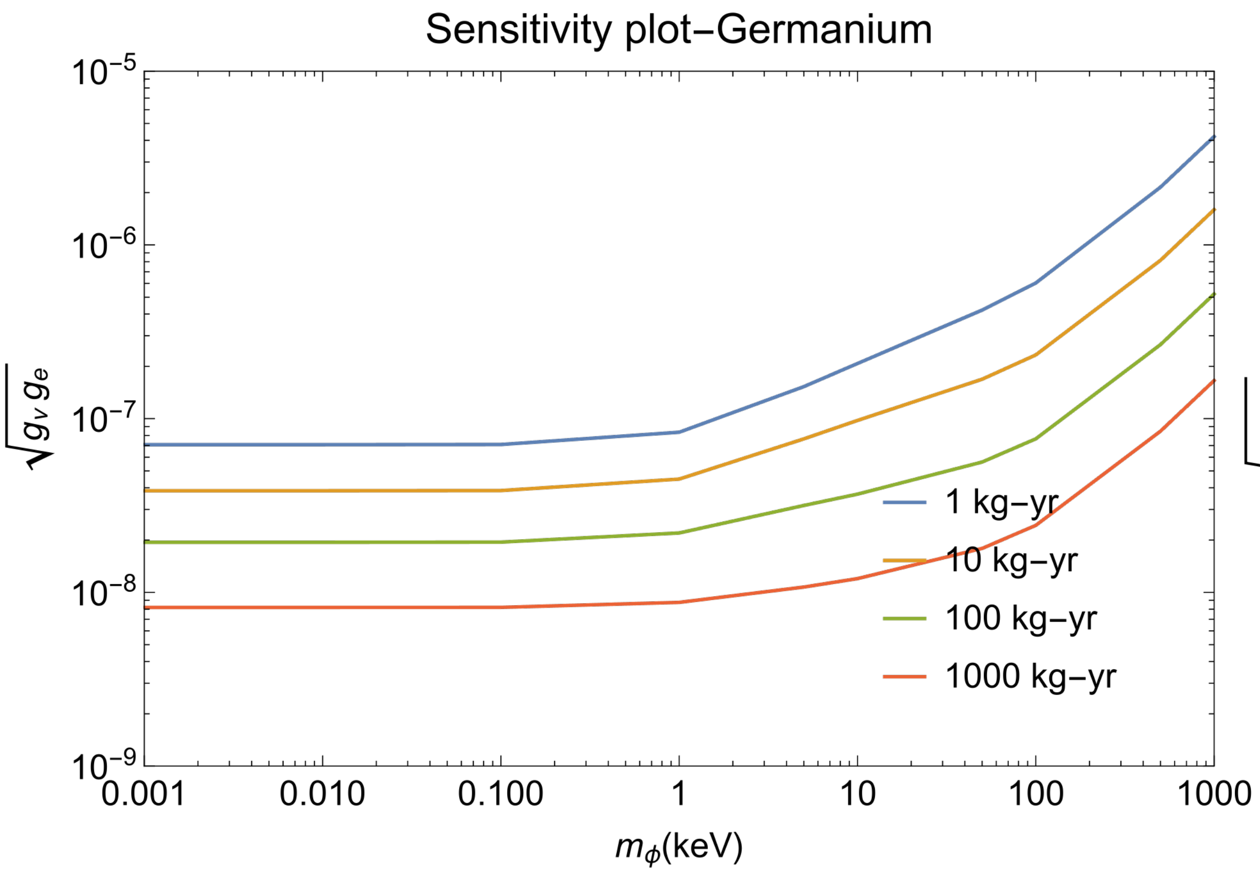


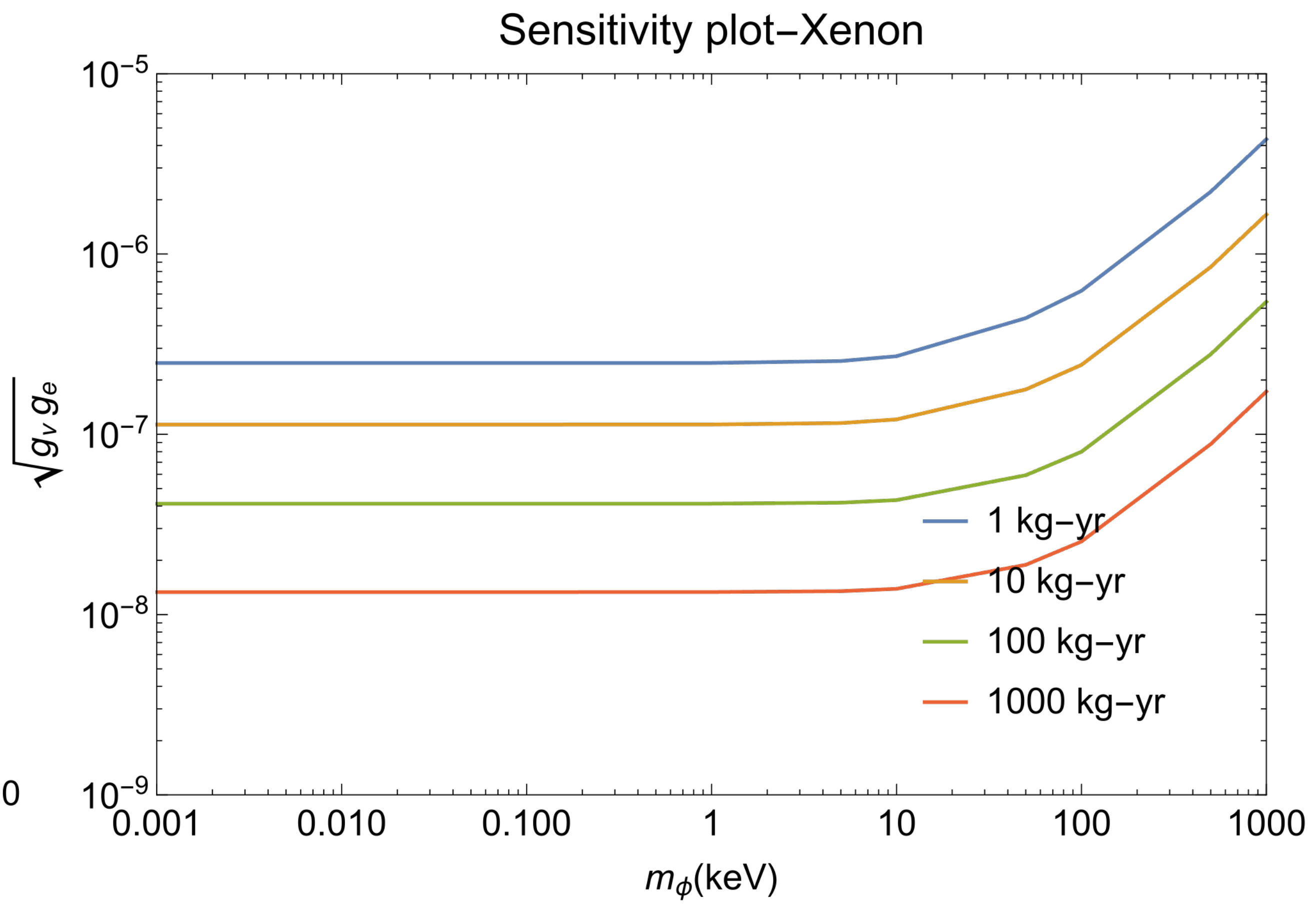
Sensitivity plots for scalar mediator(FEA)



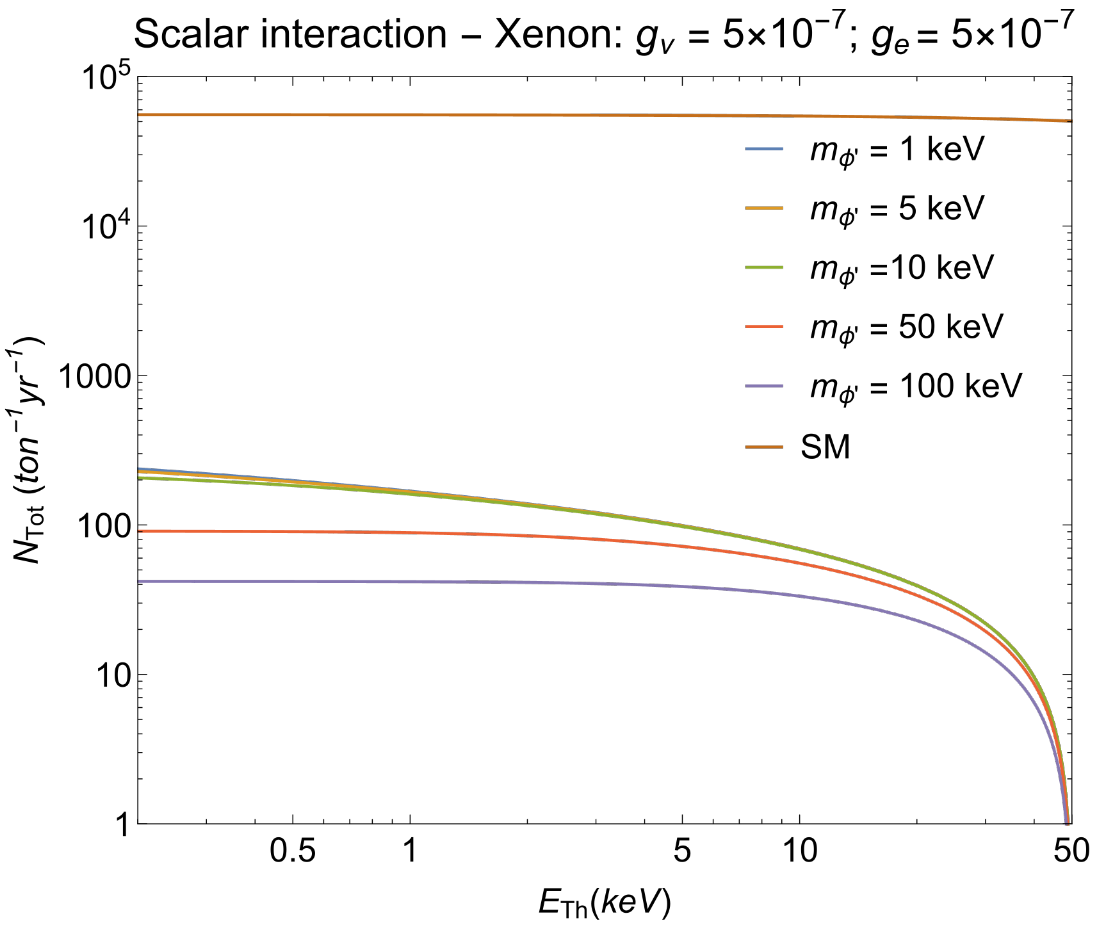


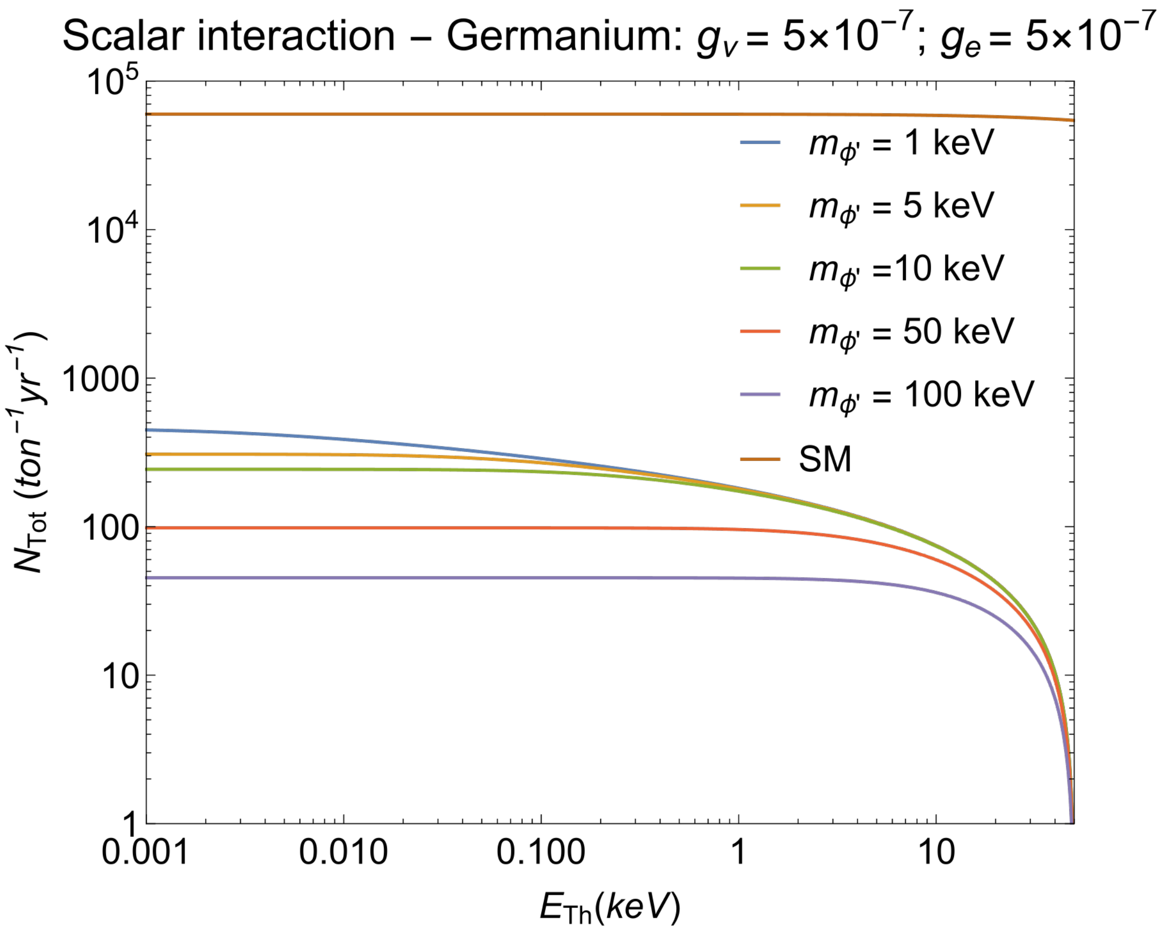
Sensitivity plots for vector mediator(FEA)





Electron recoil integrated rates as a function of Experimental Threshold energy (FEA)





Electron recoil integrated rates as a function of Experimental Threshold energy (FEA)