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Non-standard neutrino interactions in light mediator models at reactor experiments

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MOTIVATIONS

- Neutrino mass and oscillations is a well known phenomenon. However, the neutrino mass generation mechanism remains unknown.

- So far, no experimental evidence for NSI of neutrinos, but if exist, directly indicate new physics beyond SM- well motivated from a phenomenological point of view.

- Recent interest in low-scale neutrino models containing new weakly coupled light mediating particles. Experiments such as GEMMA, Borexino, XENONnT constraint the parameter space.

- Ongoing/future reactor based neutrino experiments such as MINER, CONUS, CONNIE can investigate these low-scale models.

Low-scale NSI models at Reactor Experiments

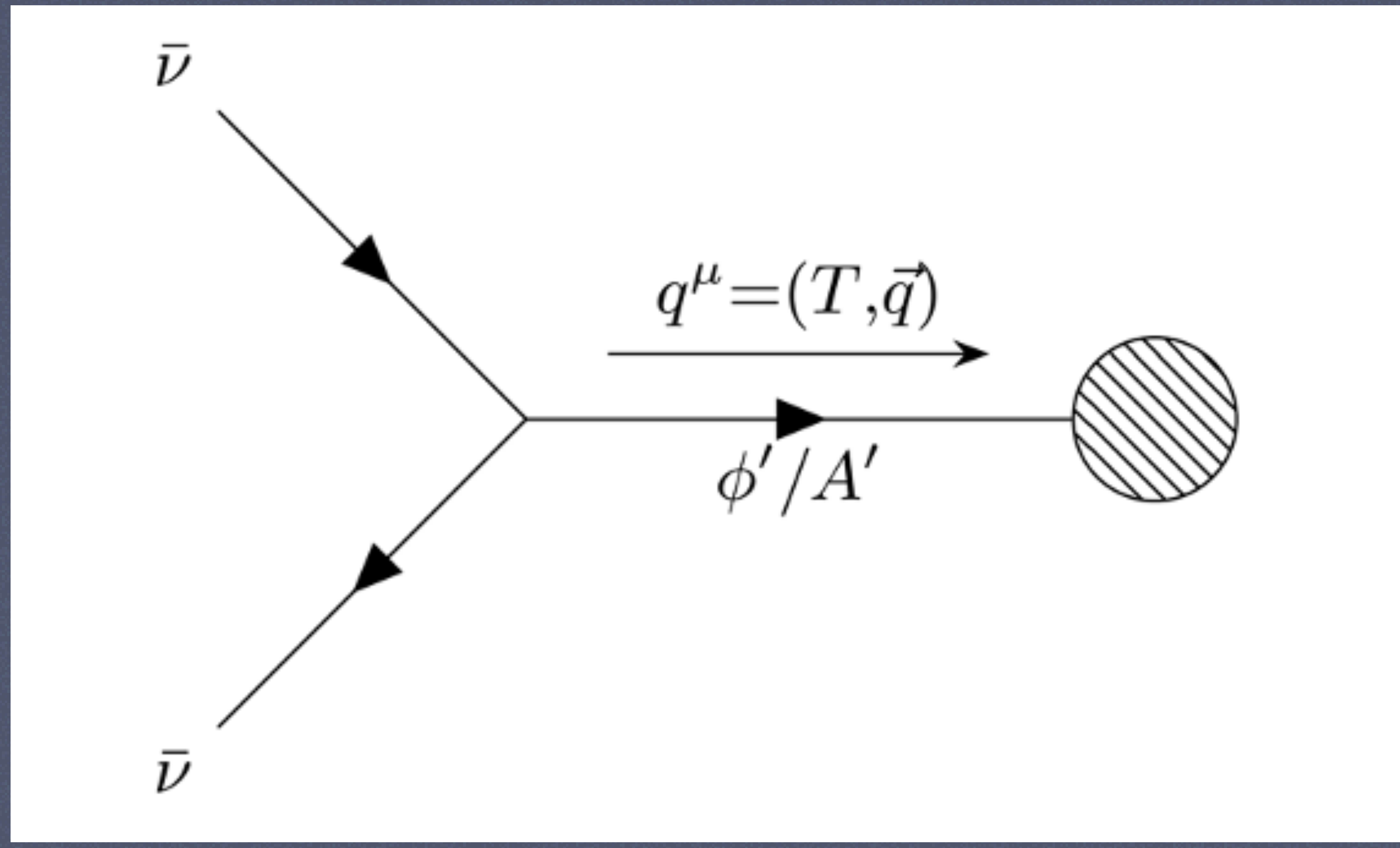
- Non-standard neutrino-electron interactions induced by light scalar/vector mediator arise naturally in many low-scale models.

- Our strategy → investigate these low-scale models in reactor based neutrino experiment with low threshold Ge/Si detectors and find the prospect of probing/ ruling out such models.

Non-standard neutrino-electron scattering

- Scalar NSI: $\mathscr{L}_S \supset g_{e,\phi}\bar{e}e\phi + g_{\nu,\phi}\bar{\nu}\nu\phi$

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



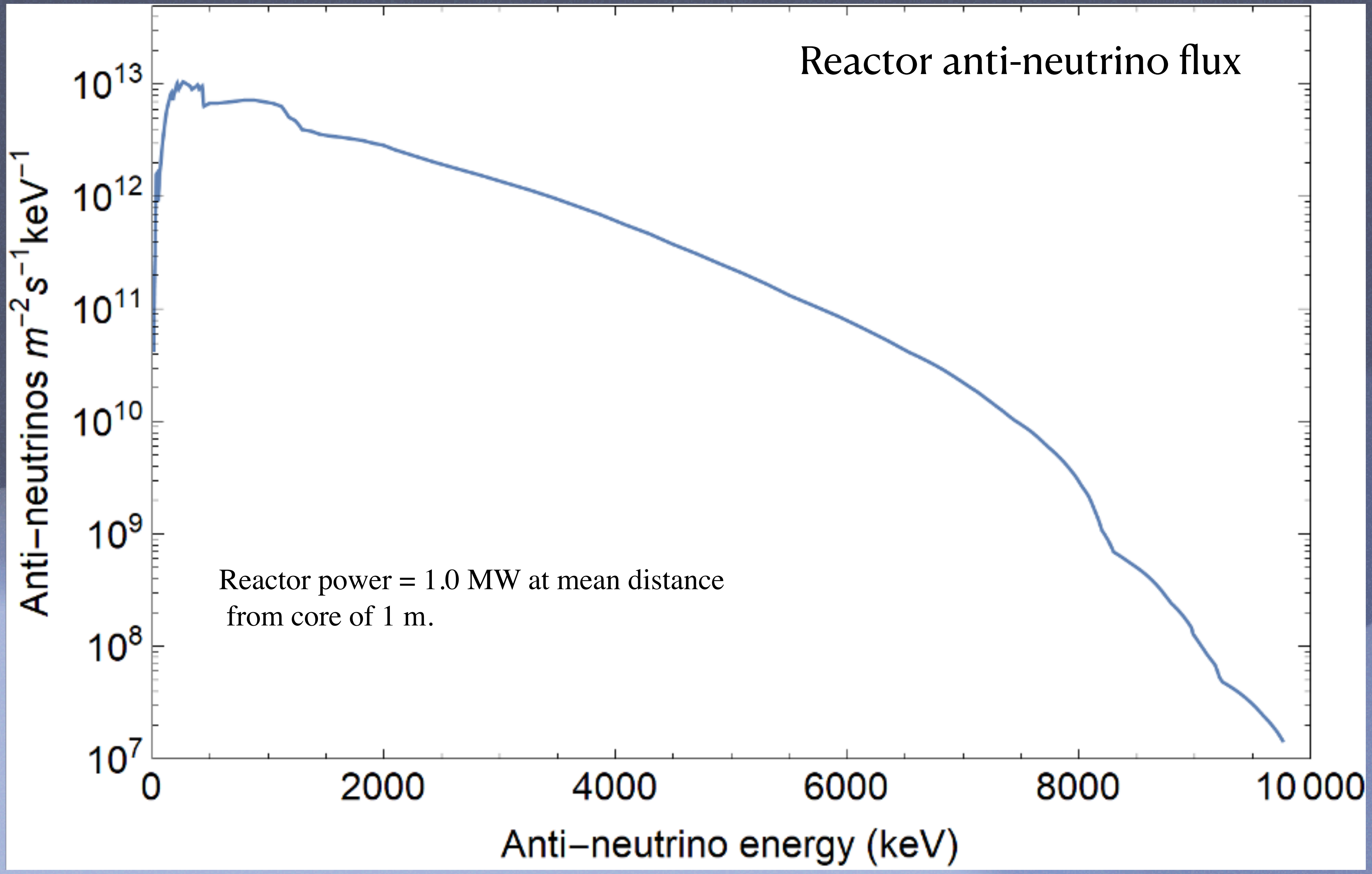
- Vector NSI: $\mathscr{L}_V \supset g_{e,A'}\bar{e}\gamma^\rho e A'_\rho + g_{\nu,A'}\bar{\nu}_L\gamma^\rho\nu_L A'_\rho$

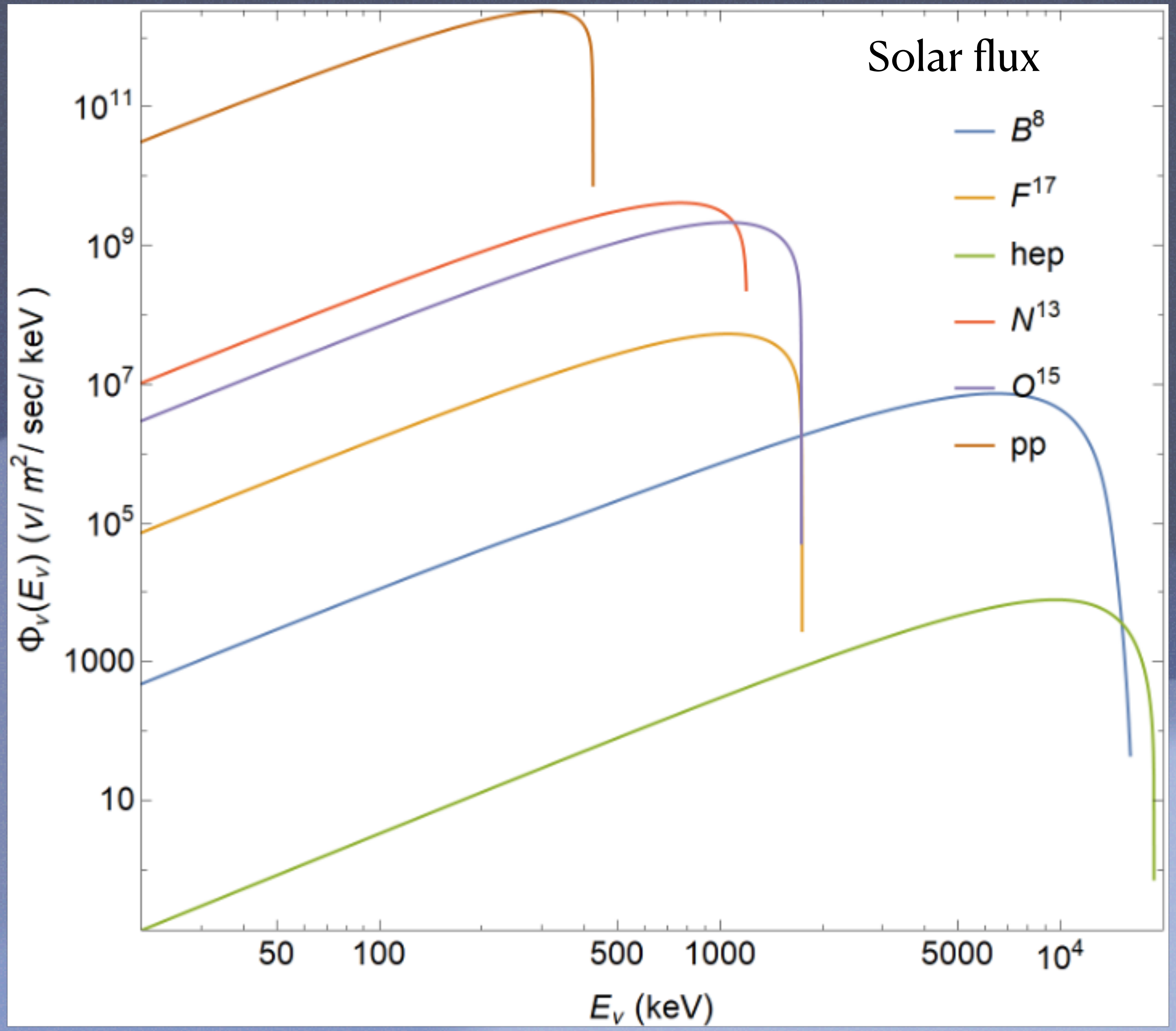
$$T_{max} = \frac{2E_\nu^2}{(m_N + 2E_\nu)}$$

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

REACTOR VS SOLAR NEUTRINO FLUX

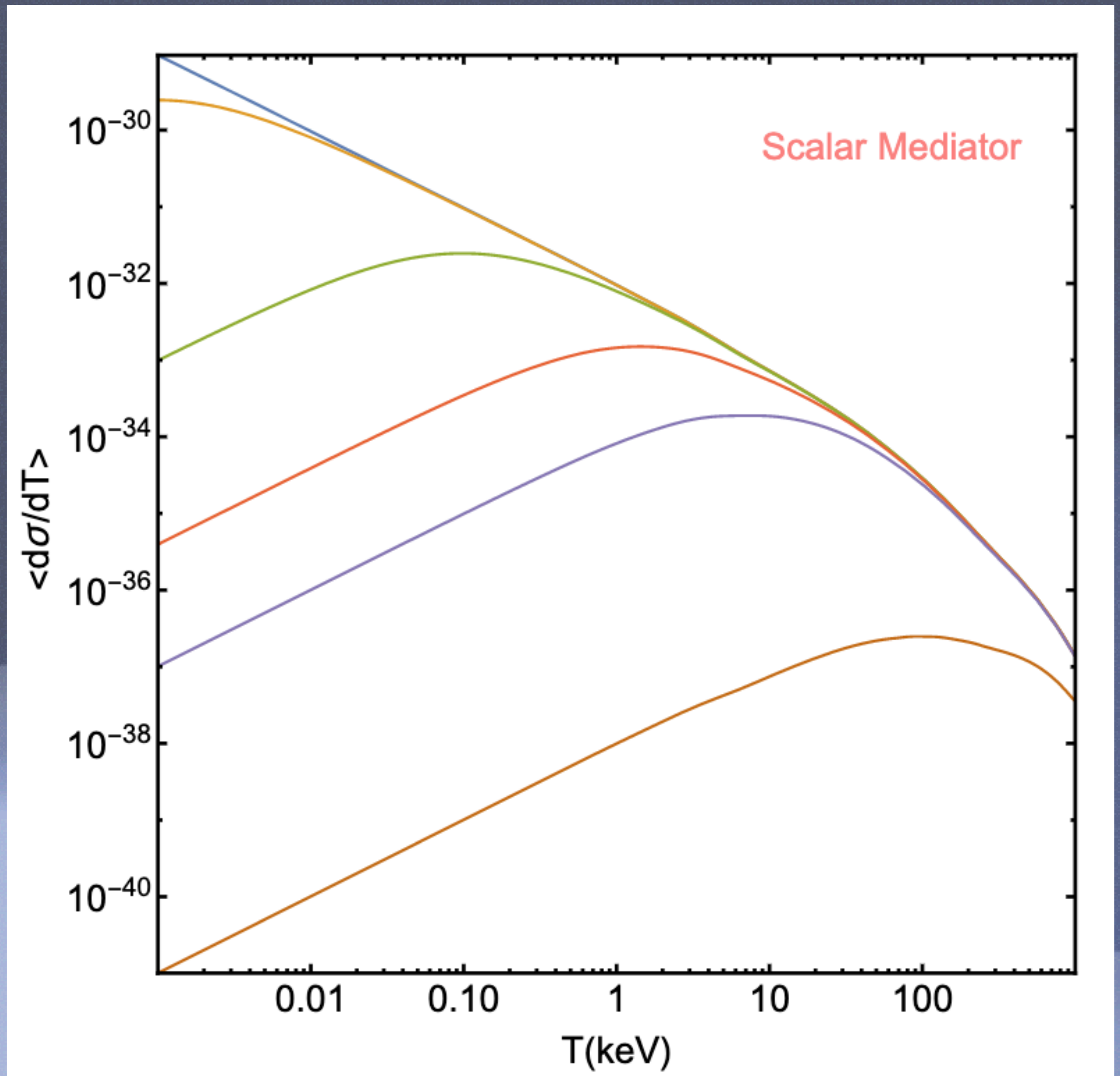
- MW reactor has similar energy profile to the solar neutrino flux with characteristic energy ≤ 1 MeV.
- Reactor antineutrino flux gets peaked around 200-300 keV and gives at least one order of magnitude more flux compared to solar flux at these keV energy scale.





Neutrino-Electron Scattering Cross-Section

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

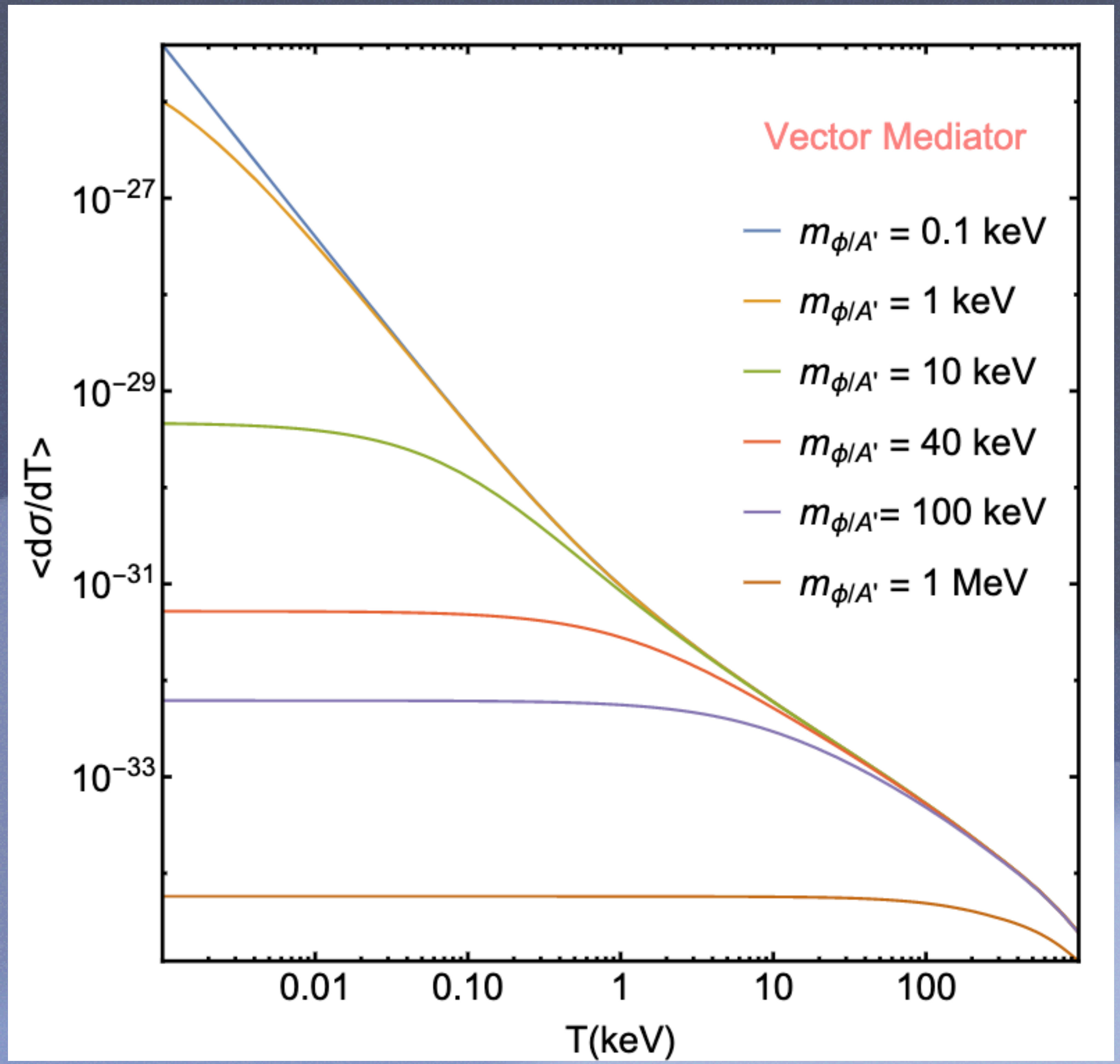


For scalar mediator:

$g_e = g_\nu = 5 \times 10^{-7}$

For vector mediator:

$g_e = g_\nu = 1.5 \times 10^{-7}$



Neutrino-Electron Scattering Rate in Detectors

- For incident neutrino energy less than the typical binding momentum of electron $\sim Zm_e\alpha$ in a hydrogen like atom, the FEA is not accurate. This would correspond to $\mathcal{O}(100)$ keV, typical neutrino energy from a MW reactor flux.
- For getting a better understanding of detector responses at low recoil one must include a proper treatment of many electron dynamics in atomic ionization that can be encapsulated in atomic ionization form factor.
- Si/Ge are crystal target with band structure with an energy gap between occupied valance band and unoccupied conduction band. At ultra-low energy transfers most of the transitions occurs from valance to conduction band. This is accounted for in the form of a crystal form factor.

Neutrino-electron Scattering Rate in Detectors

- The total rate is sum of the rates obtained for

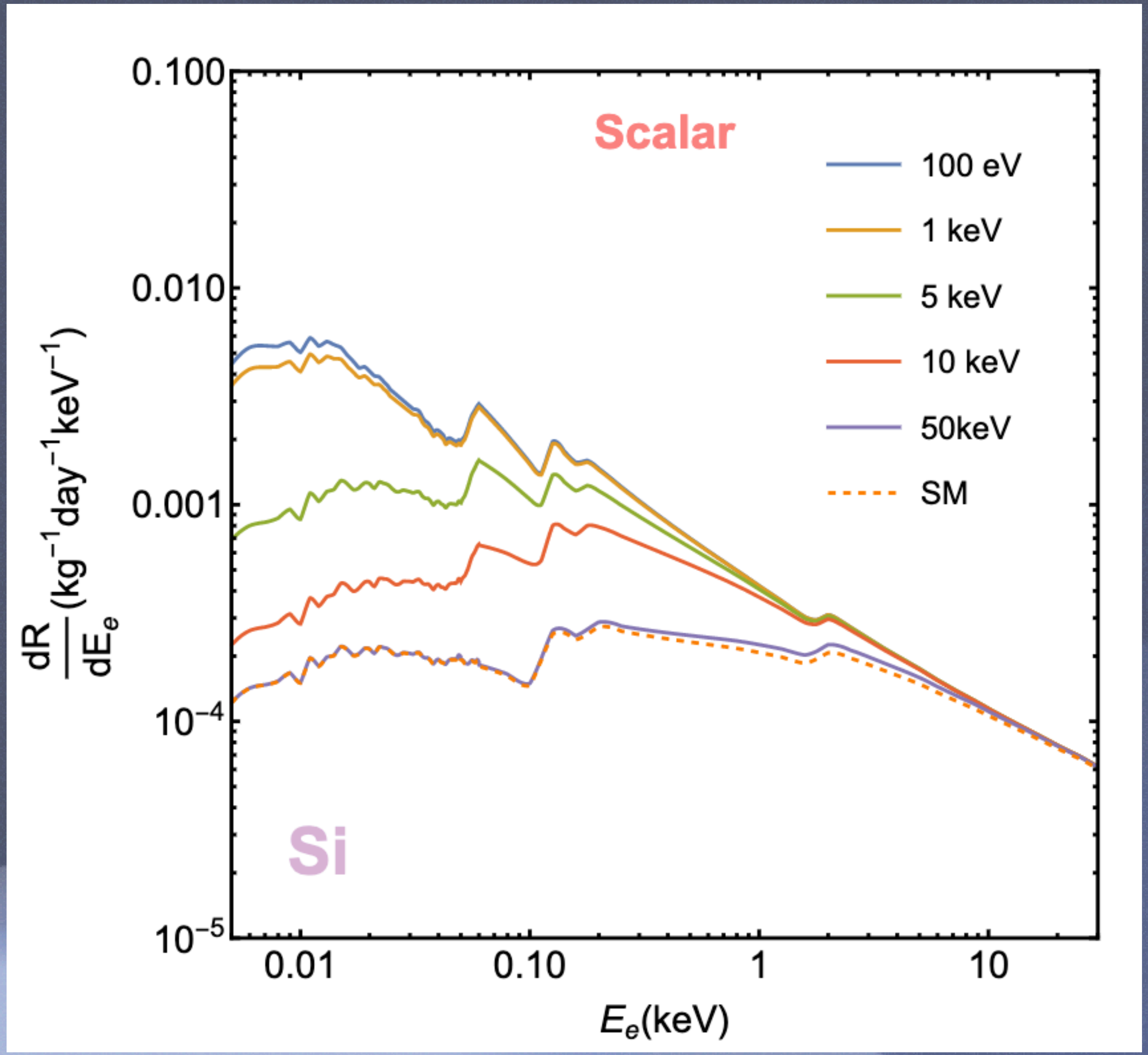
  — atomic states to free states transition for deposited energy $E_e > 60$ eV using atomic form factor from DarkARC code.

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

  — valance to conduction band transition for deposited energy $E_e \leq 60$ eV using crystal form factor from EXCEED-DM code.

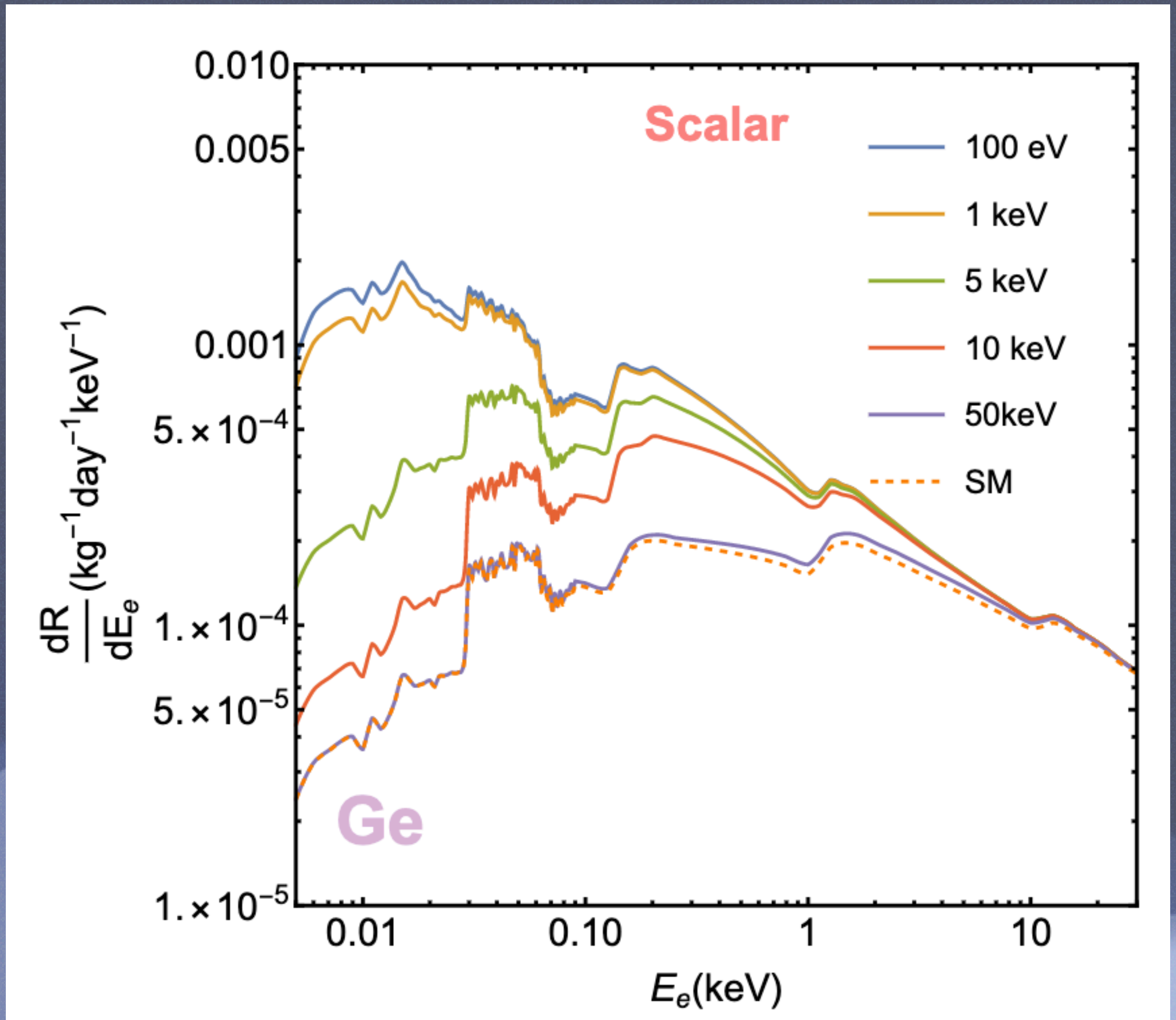
$$\frac{d\mathscr{R}_{v\to c}}{d\ln E_e} = N_{cell}\int dE_\nu \Phi\left(E_\nu\right)\int dq\frac{d\sigma_e}{dq}\left|f_{v\to c}\left(q,E_e\right)\right|^2$$

Recoil Spectra: Scalar Mediator

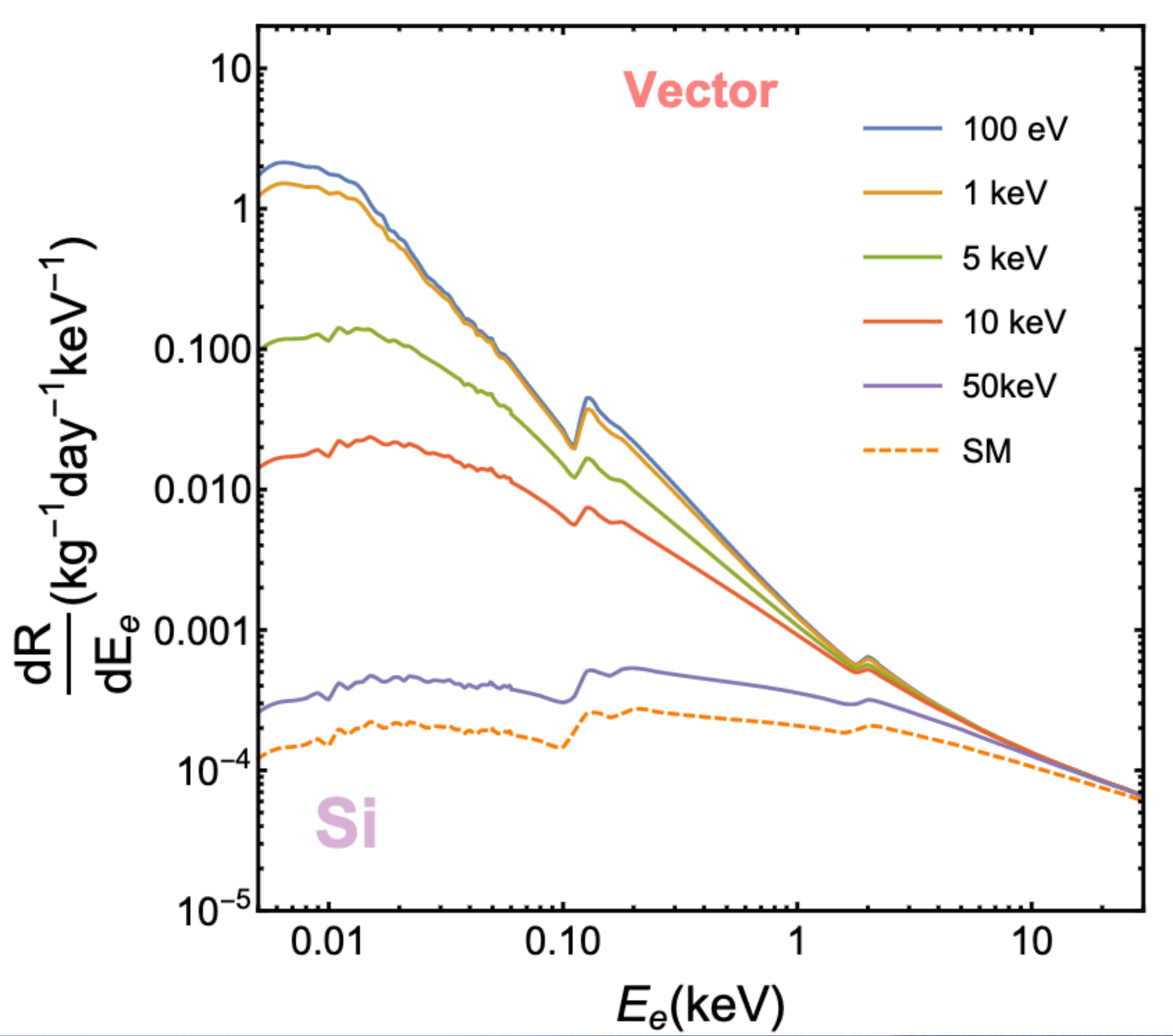


For scalar mediator:

$g_e = g_\nu = 5 \times 10^{-7}$

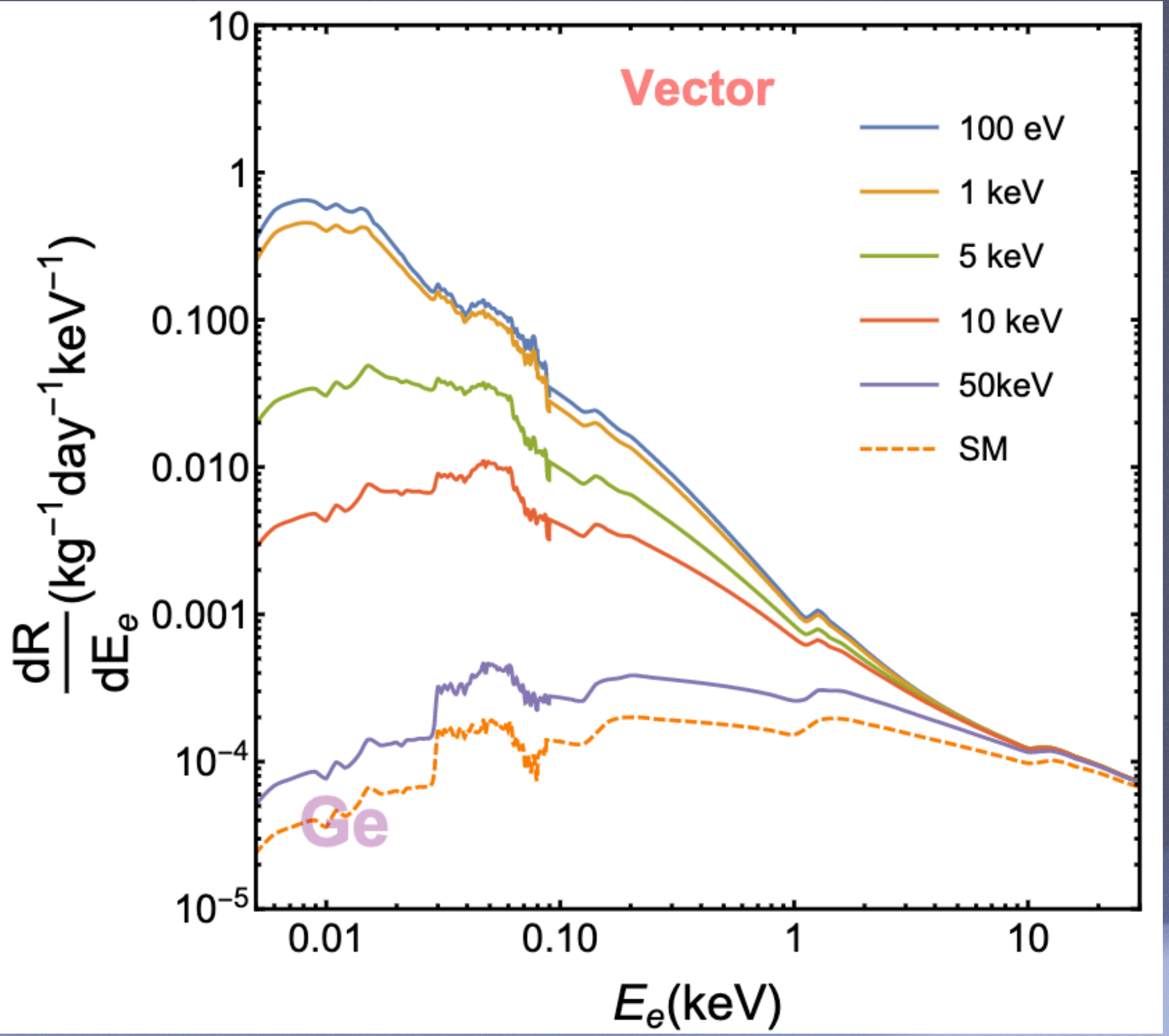


Recoil Spectra: Vector Mediator



For vector mediator:

$$g_e = g_\nu = 1.5 \times 10^{-7}$$



Result: Sensitivity curve

- To obtain the sensitivity curve

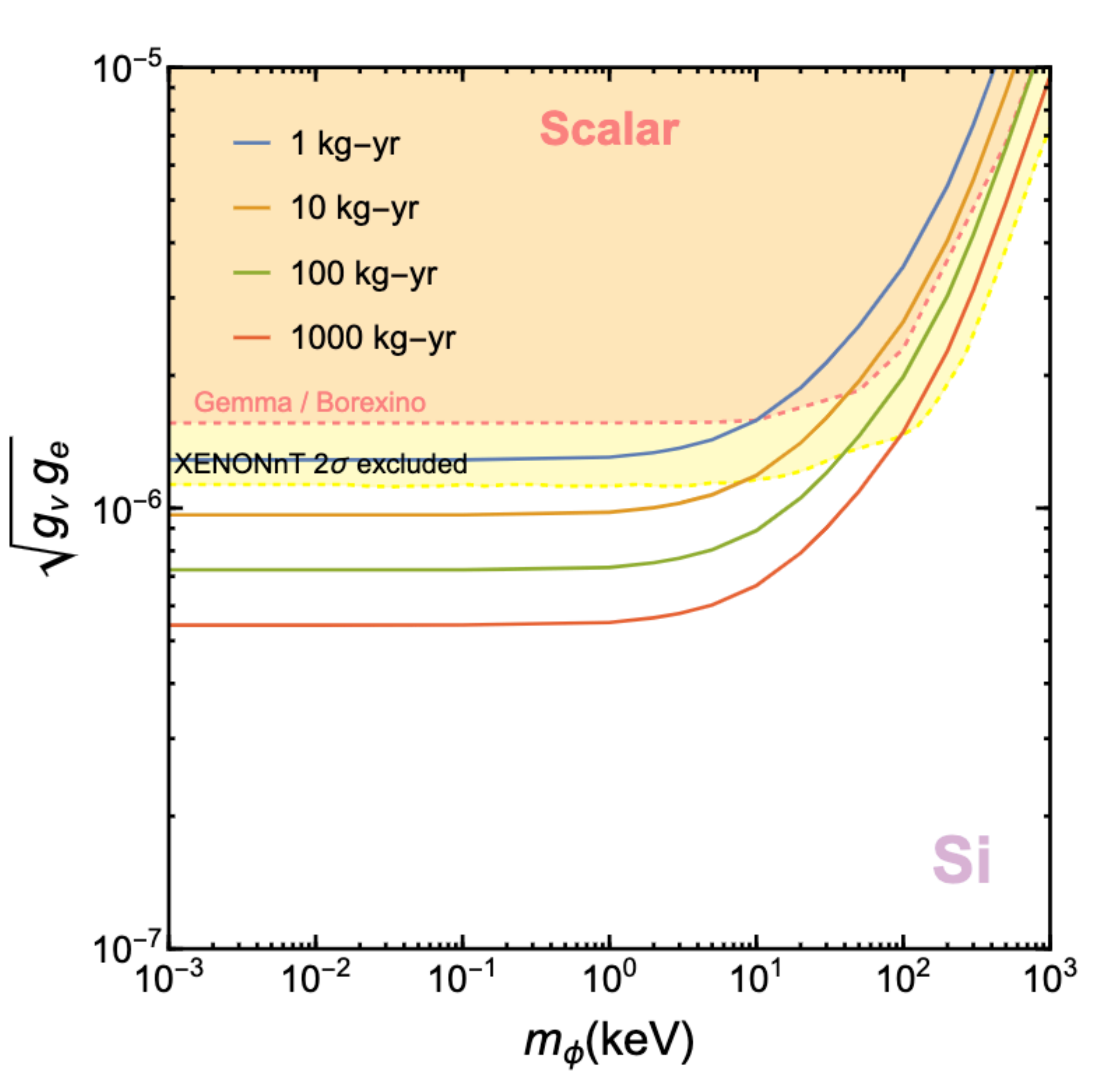
— we show projected sensitivity at 90% confidence level.

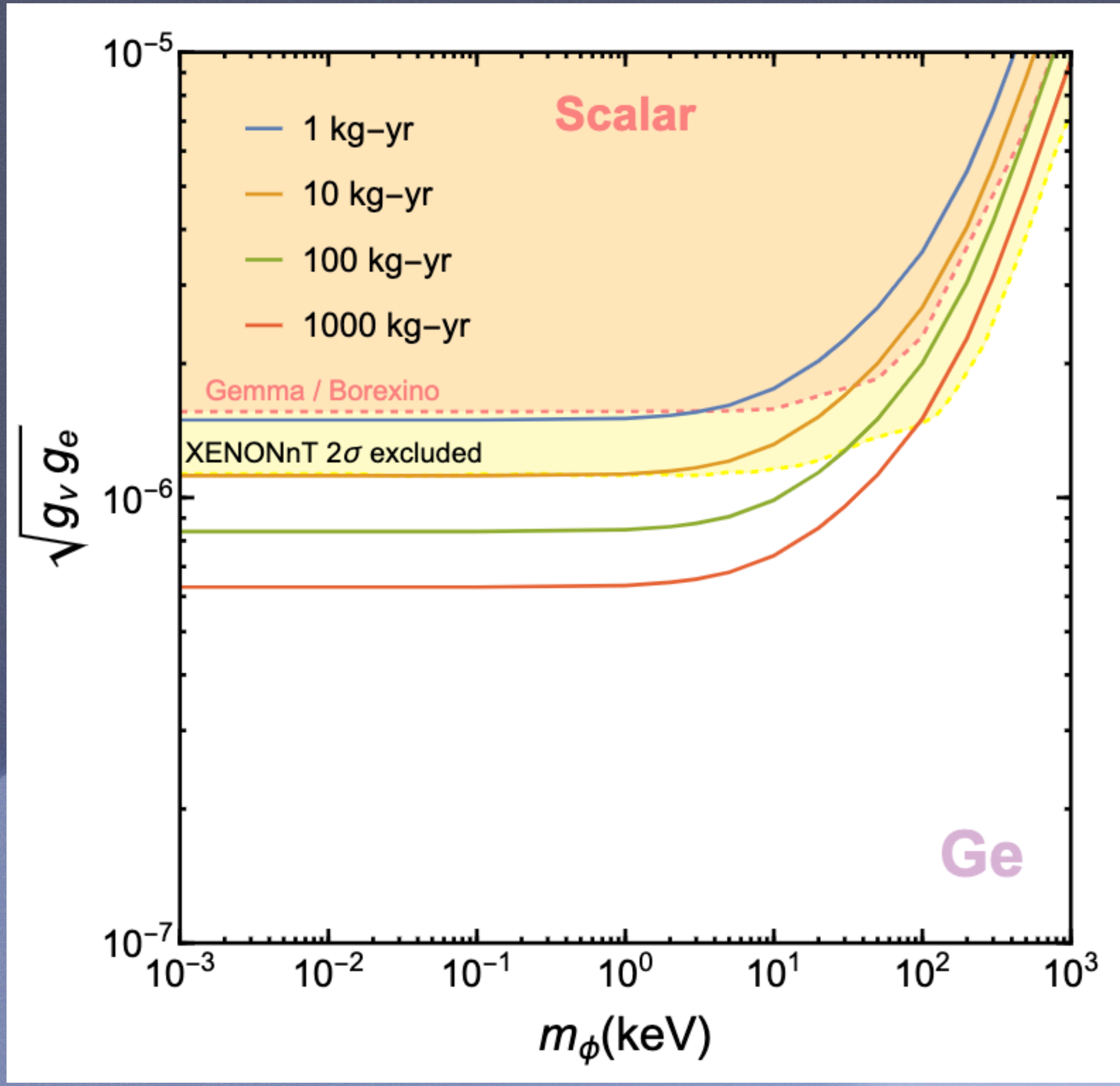
— corresponding constraints from Borexino, GEMMA and XENONnT are shown.

— we assume a constant background of 0.1 dru in addition to SM neutrino-electron background.

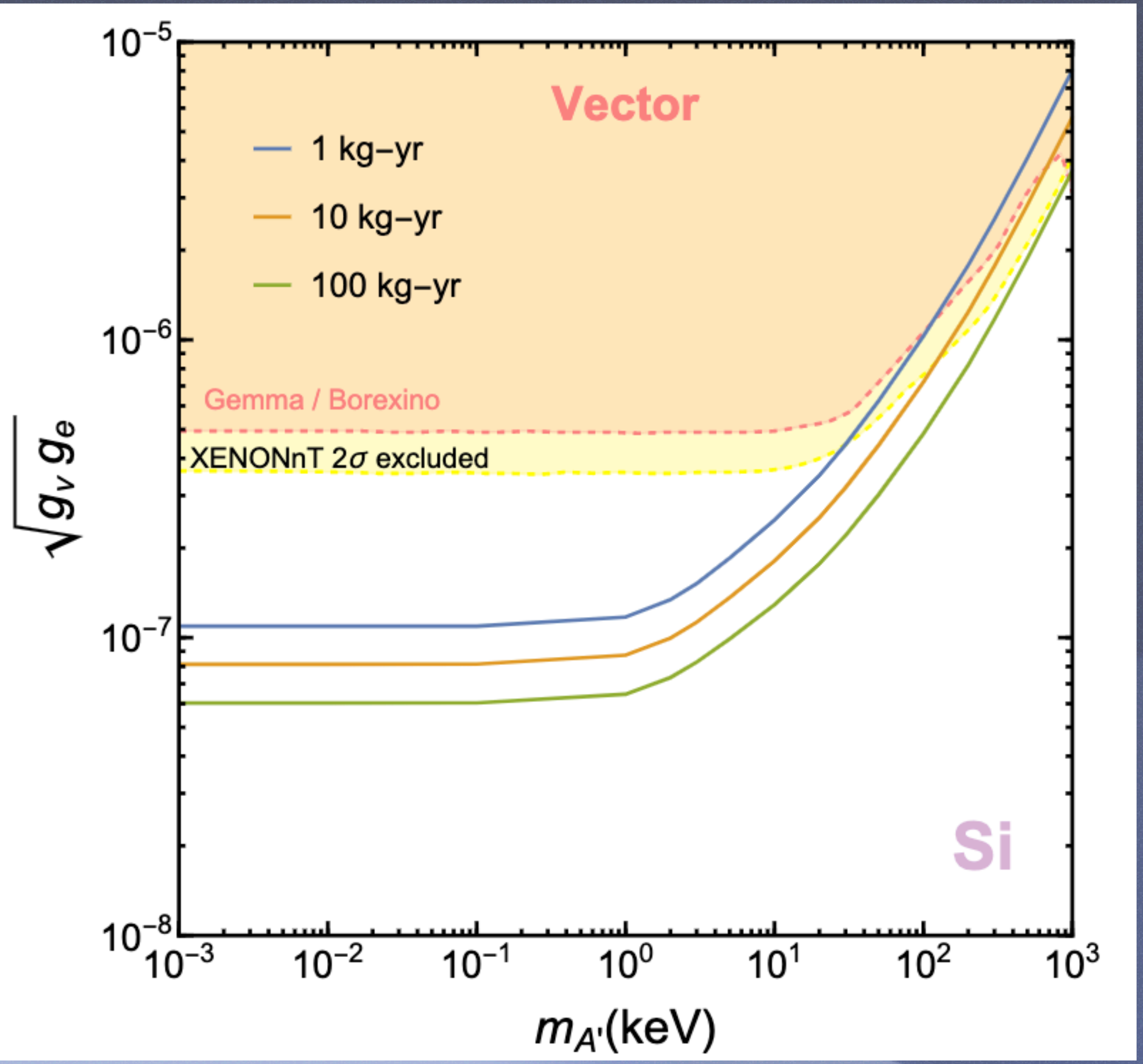
— we also assume the detector is capable of discriminating between ER and NR signals down to the threshold of 5 eV.

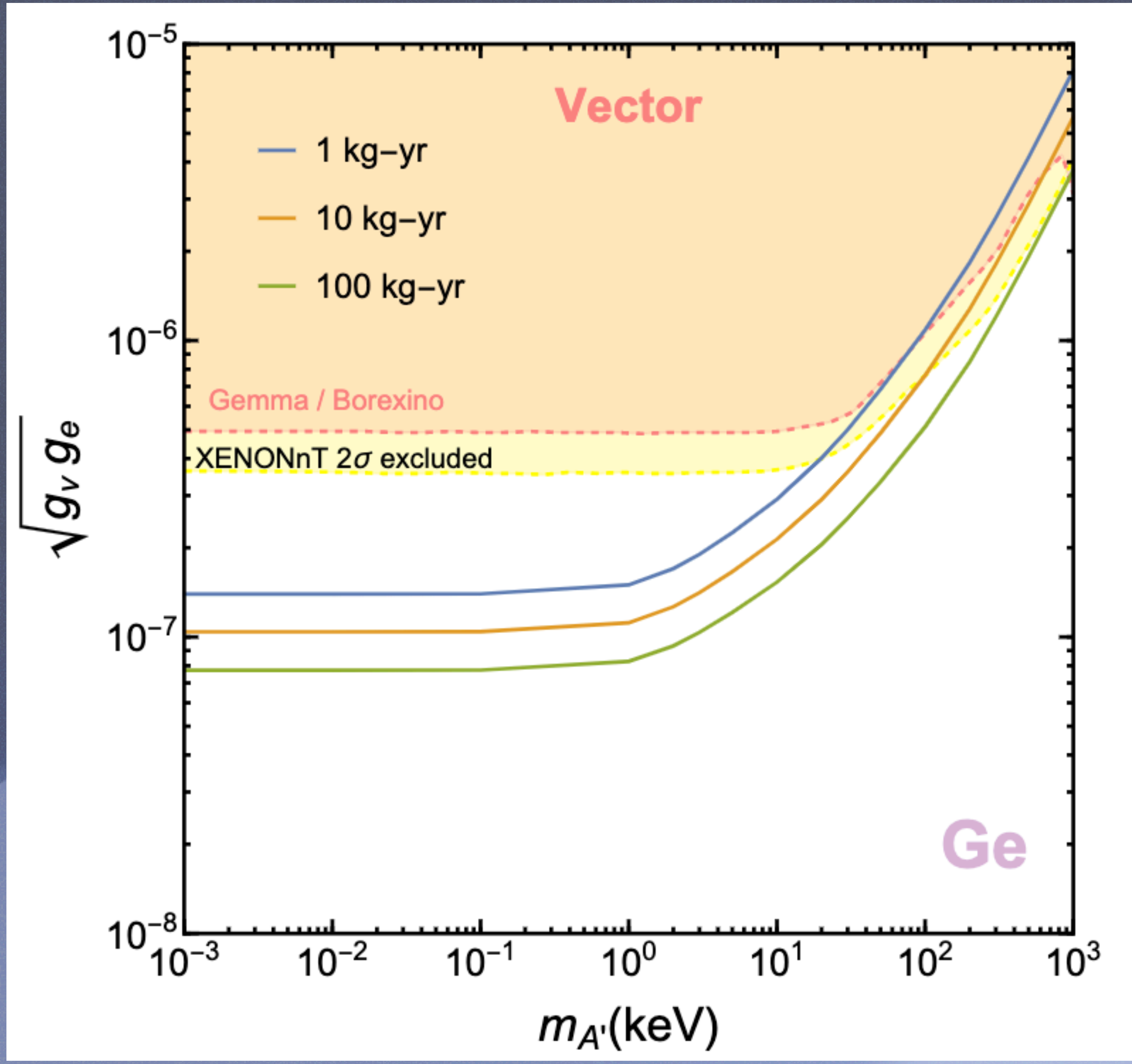
Sensitivity plot: scalar mediator





Sensitivity plot: Vector mediator





NATURE OF THE CURVE

- For heavier mediator masses:

— the coupling sensitivity decreases since for $q << M_{\phi/A'}$ it is Fermi like contact interactions.

— gives a line with a slope of 2 in the log-log space of the coupling vs mediator mass plot.

- For lighter mediator masses:

— the mediator mass can be neglected in the propagator for $q >> M_{\phi/A'}$.

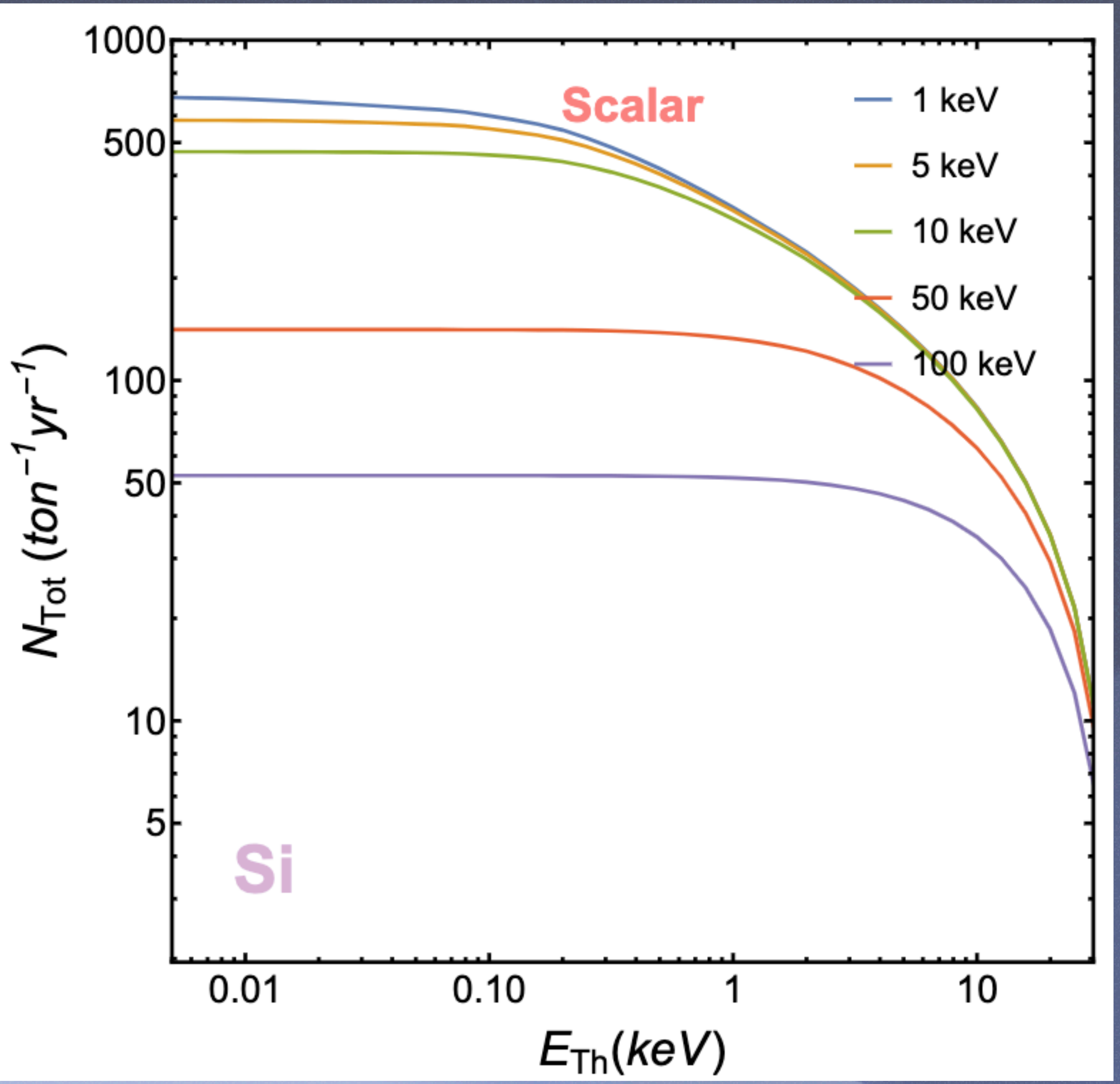
— sensitivity becomes flat in the log-log space of the coupling vs mediator mass plot.

Results

- Using a 10 kg-yr Ge detector and MW reactor one can probe coupling values of $\sqrt{g_e g_\nu} \sim 1 \times 10^{-6}$ and 1×10^{-7} for a scalar and vector mediator with masses below 1 keV respectively.

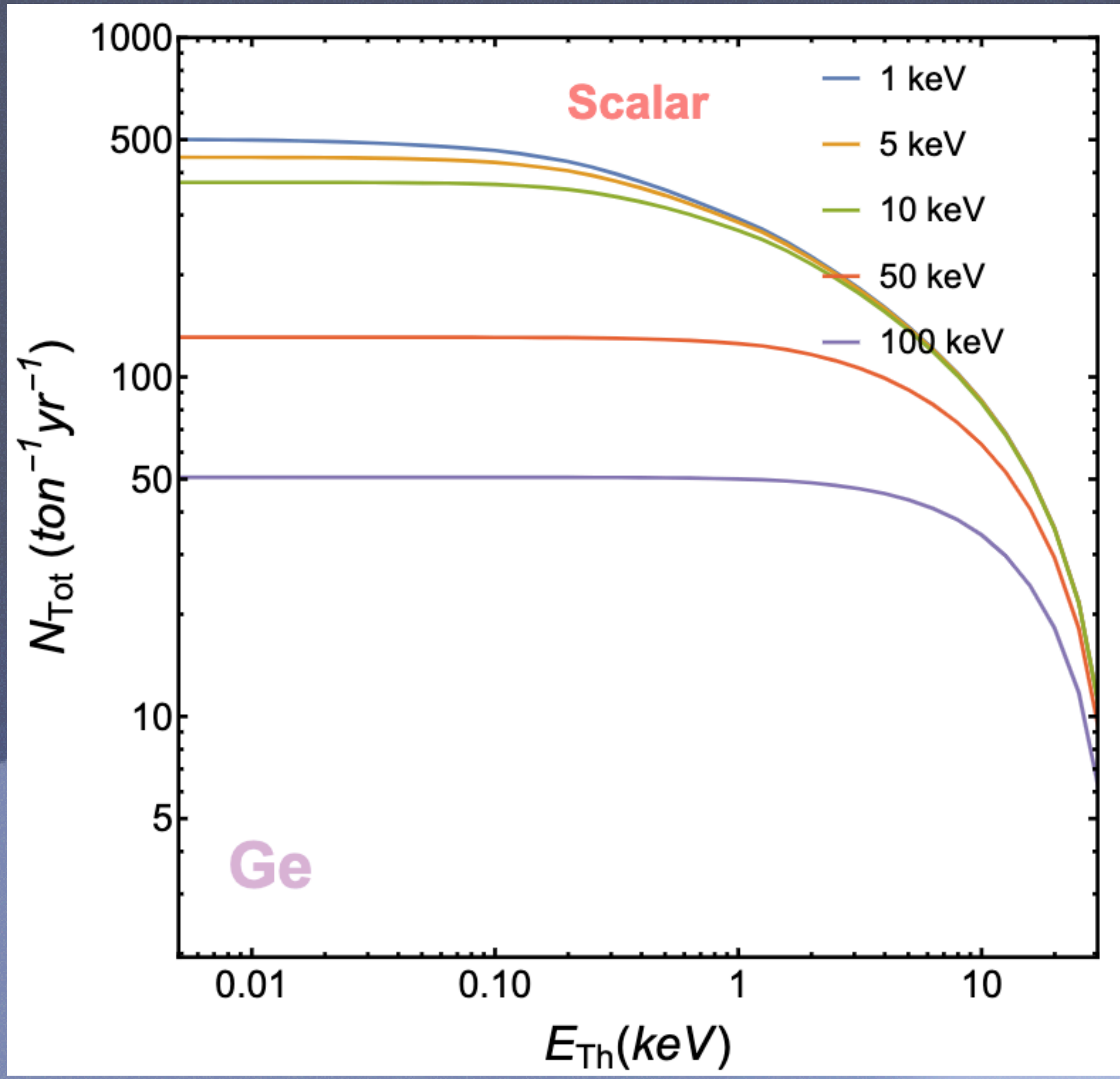
- The same exposure and setup for Si detector gives coupling reach of $\sqrt{g_e g_\nu} \sim 9.5 \times 10^{-7}$ and 8×10^{-8} for scalar and vector mediator with masses below 1 keV respectively.

Integrated Events: Scalar Mediator

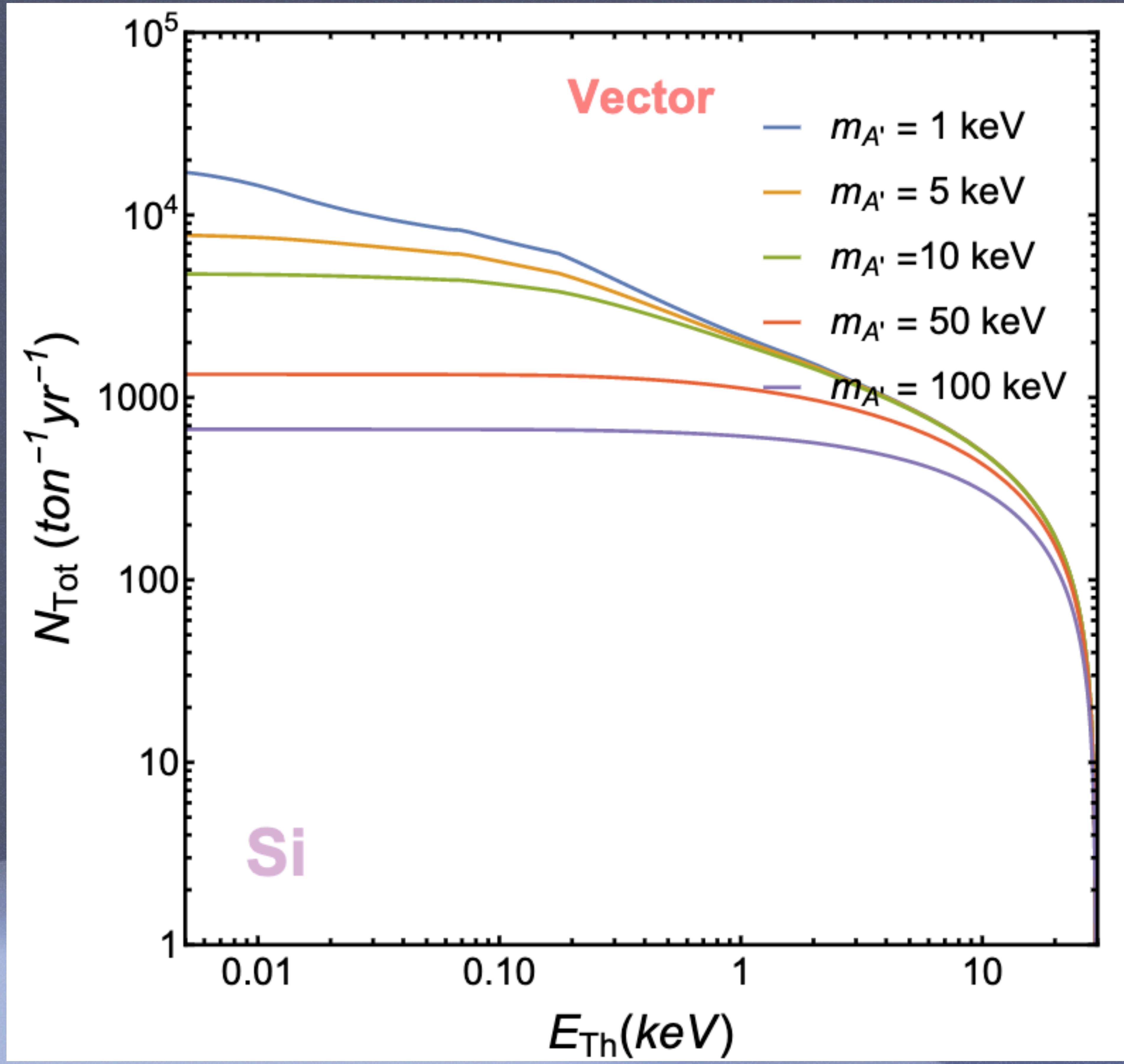


For scalar mediator:

$g_e = g_\nu = 5 \times 10^{-7}$

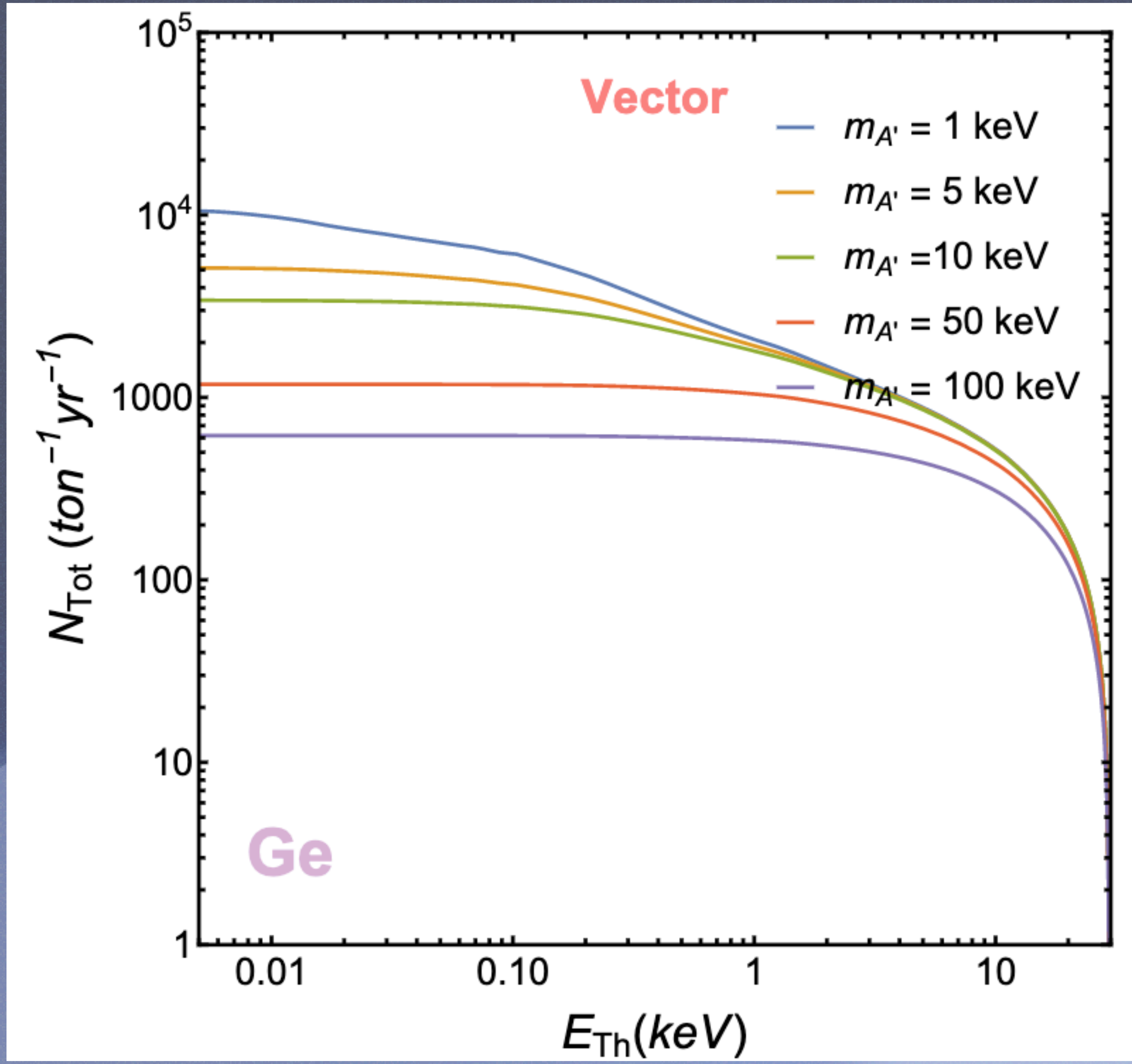


Integrated events: Vector Mediator



For vector mediator:

$$g_e = g_\nu = 1.5 \times 10^{-7}$$



Light Mediator Models: Examples

- Light scalar mediator models: we propose one

  — by extending the SM scalar sector by

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

  — mixing in the scalar sector give rise to one $\mathcal{O}(1)$ keV scalar particle.

  — Yukawa term $\bar{l}'^{c}_{L_i}(y')_{ij} i\sigma_2 \Delta l'_{L_j}$ gives NSI of neutrinos .

- Light vector models: the extension of SM by an anomaly-free $U(1)$ gauge group such as, $U(1)_{L_i - l_j}$, $U(1)_{B-L}$, $U(1)_{T3R}$ etc.

Light Mediator Models: Constraints

- Neutrino-neutrino, neutrino-electron and electron-electron interactions induced by the new light mediator:

— Borexino and GEMMA are quite sensitive to the modification of the scattering cross-section by NSI with low mass mediators.

— different astrophysical processes such as energy loss of SN1987A, solar cooling process and cooling of star in globular clusters can putt bounds. Can be evaded by Chameleon effect

— contribution to ΔN_{eff} can also put bounds.

— vector NSI induces flavor dependent matter potential and scalar NSI gives a correction to neutrino mass matrix. Can affect oscillations and scattering experiment.

Conclusions

- A well-motivated phenomenological approach to search for new physics, in neutrino sector, is that of NSI.
- At neutrino energy around 200 keV reactor anti-neutrino flux is one order of magnitude larger than the solar flux. Also atomic physics effects becomes important at this energy scale.
- With ER and NR discrimination and low background, the low threshold Si/Ge detector placed in reactor based experiment can probe large promoter space of light mediator induced NSI models.