Low energy neutrino scattering in semiconductor detectors

Shuo-yu Xia
xiashuoyu@ihep.ac.cn

Yu-Feng Li and Shuo-yu Xia, JHEP 10 (2023) 021, Arxiv: 2211.11582
Yu-Feng Li and Shuo-yu Xia, Nucl.Phys.B 1006 (2024) 116632, Arxiv: 2310.05704

23^{rd} Sep, 2024

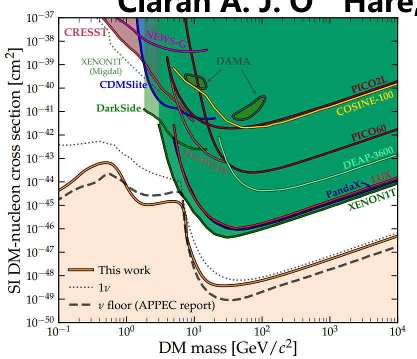
Outline

- Background
- Neutrino scattering in non-relativistic effective field theory (NR EFT)
- Low energy neutrino excitation in semiconductor
  - In-medium screening effect for neutrino-electron excitation
  - Migdal effect induced by neutrino-nucleus scattering
- Summary

Background

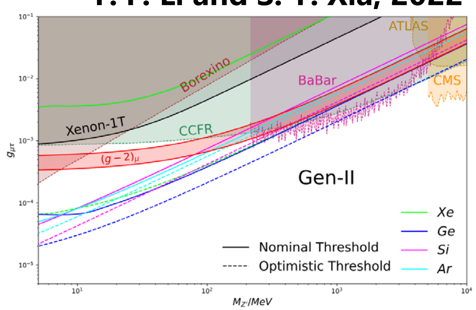
- Rich physics

Ciaran A. J. O’ Hare, 2022

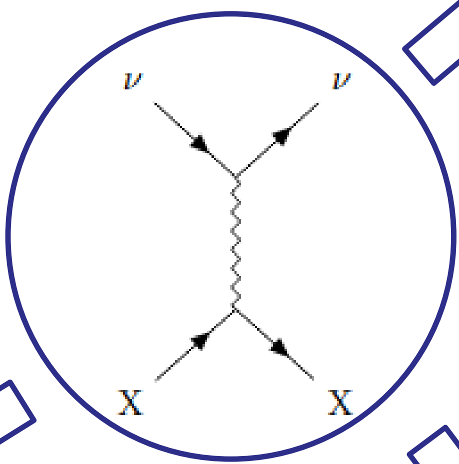


Neutrino Fog

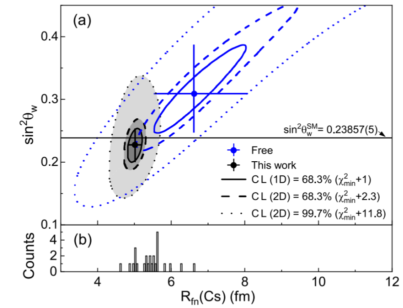
Y. F. Li and S. Y. Xia, 2022



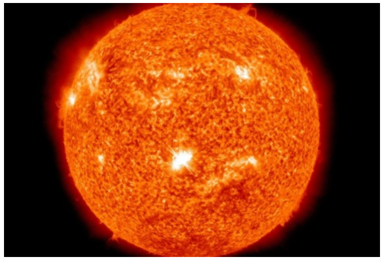
Neutrino Non-Standard Interaction



Y. Huang, et al., 2024

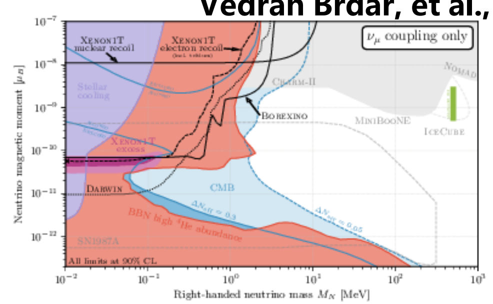


SM Precision Test

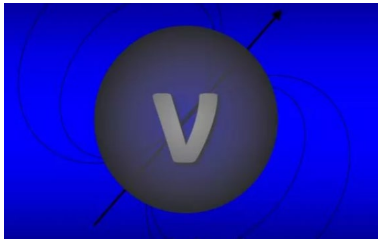


Solar Physics

Vedran Brdar, et al., 2021



Sterile Neutrino

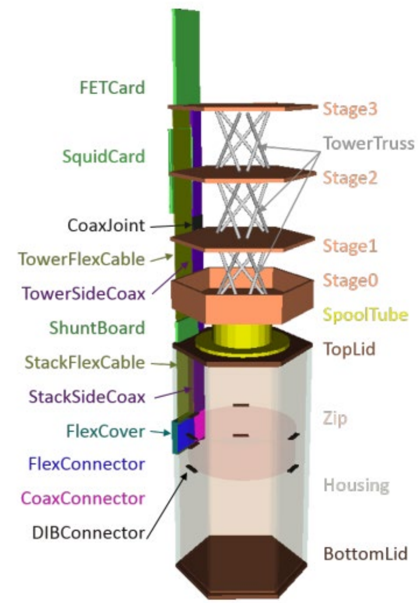


Neutrino Magnetic Moments

Background

- Neutrino detection in semiconductor detectors
  - Very low threshold
  - Detection via phonons and electrons
  - Several electron excitations

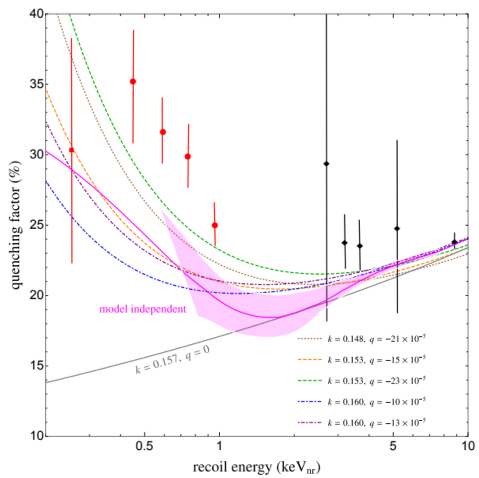
Barak, Liron and others,
Phys.Rev.Lett. 125 (2020) 17, 171802



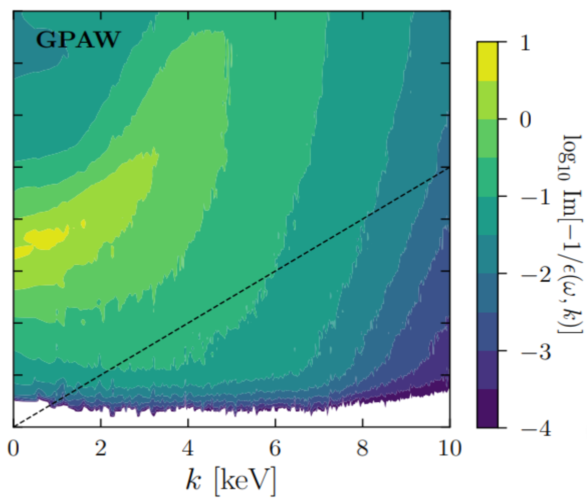
Agnese, R. and others,
Phys.Rev.D 95 (2017) 8, 082002

Background

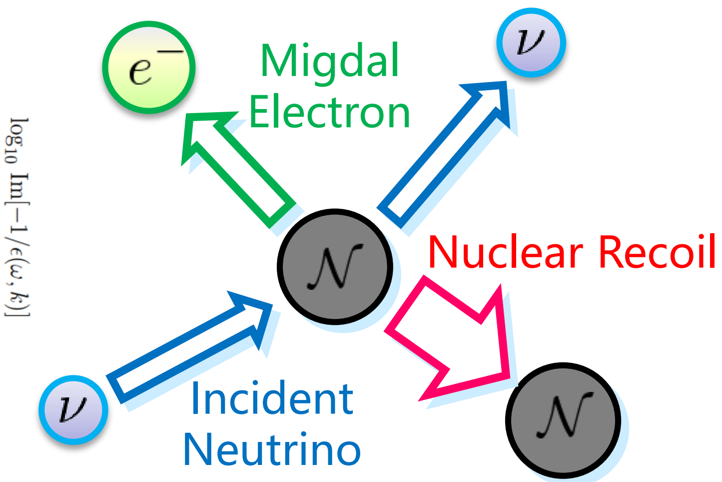
- low energy excitations in semiconductor
  - Quenching models at low energy
  - Migdal effect in nuclear recoil
  - Screening effect and other collective behavior
  - … …



Liao, Jiajun and others , Phys.Rev.D 104 (2021) 1, 015005



Knapen, Simon and others , Phys.Rev.D 105 (2022) 1, 015014



Migdal Effect

Neutrino scattering in NR EFT

Appendix of Arxiv: 2211.11582

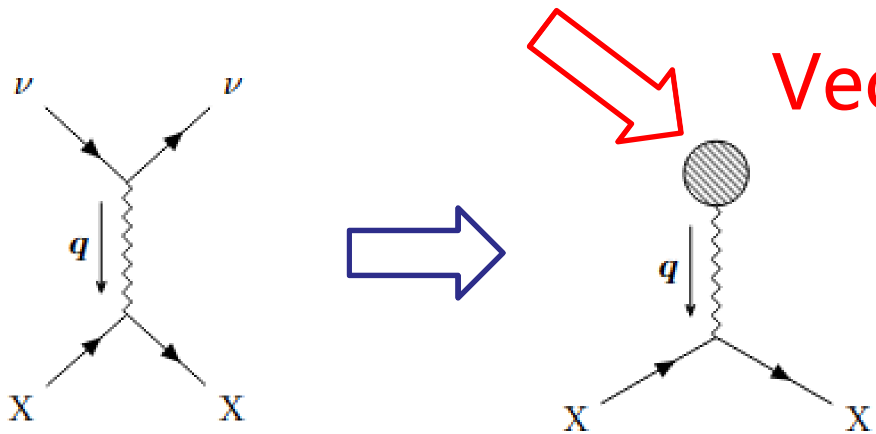
- Neutrino electron scattering Lagrangian in SM

$$\mathcal{L}_{\mathrm{E}\nu\mathrm{ES}} = -i\frac{G_F}{\sqrt{2}}\left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5)\nu_\alpha\right]\left[\bar{\phi}_e \gamma_\rho (g_{\alpha;\mathrm{V}} - g_{\alpha;\mathrm{A}}\gamma^5)\phi_e\right]$$

- Neutrino electron excitation in NR EFT

Andrea Mitridate, et al., JHEP 09 (2021) 123, Arxiv: 2106.12586

$$\mathcal{L}_{\mathrm{E}\nu\mathrm{ES}} = -i\sqrt{2}G_{\mathrm{F}}g_{\alpha;\mathrm{V}}\bar{\nu}_{\alpha,L}\gamma^0\nu_{\alpha,L}\phi_+^\dagger\phi_+$$



Vector Dominant Potential

Neutrino scattering in NR EFT

- Contribution of neutrino magnetic moment

$$\mathcal{L}_{\rm mag} = -i\mu_\nu \frac{m_\nu}{m_e}\frac{4\pi\alpha}{q^2}\left[\bar{\nu}_\alpha(1-\gamma^5)i\frac{\sigma^{\mu\nu}q_\nu}{2m_\nu}\nu_\alpha\right]\left[\bar{\phi}_e\gamma_\mu\phi_e\right]$$

- Neutrino magnetic moment (ER) in NR EFT
  - Isotropic structure of the crystal
  - Leading order interaction

$$\mathcal{L}_{\rm mag} = i\mu_\nu \frac{E_\nu}{m_e}\frac{8\pi\alpha}{q^2}\bar{\nu}_{\alpha,\rm L}\nu_{\alpha,\rm L}\phi_+^\dagger\phi_+$$

⇧

Leading Order Potential

Neutrino scattering in NR EFT

- Neutrino nucleus scattering in EFT
  - Enhancement from coherent effect

Coherent Effect

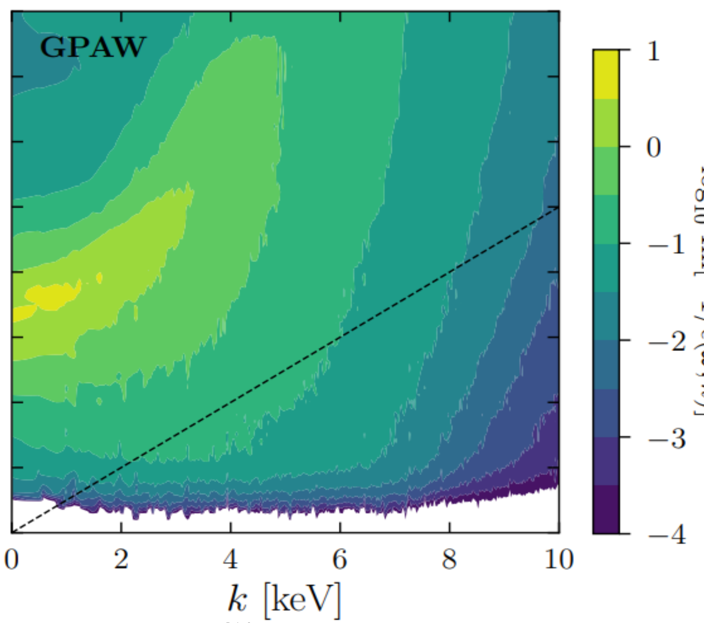
$$\mathcal{L}_{\rm eff} = -i\sqrt{2}G_{\rm F}[g_n N F_N^2(\vec{q}) + g_p Z F_Z^2(\vec{q})]\nu_{e,L}\gamma^0\bar{\nu}_{e,L}\phi_+^\dagger\phi_+$$

- Neutrino magnetic moment (NR) in NR EFT
  - Coherently coupled to Z

$$\mathcal{L}_{\rm mag} = iZF_Z^2(\vec{q})\mu_\nu \frac{E_\nu}{m_e}\frac{8\pi\alpha}{q^2}\bar{\nu}_{\alpha,\rm L}\nu_{\alpha,\rm L}\phi_+^\dagger\phi_+$$

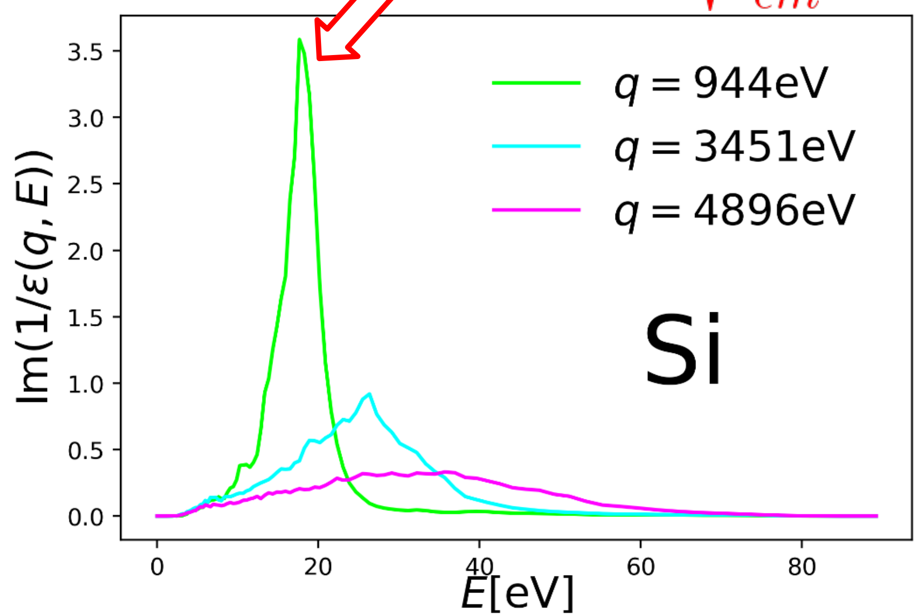
Screened neutrino excitation

- Describe excitation with energy loss function
  - Calculation based on Density Functional Theory
  - Inverse dielectric function



Knapen, Simon and others , Phys.Rev.D 105 (2022) 1, 015014

Plasmon @ $\sqrt{\frac{ne^2}{\epsilon m}}$



Data for silicon

Screened neutrino excitation

Yu-Feng Li and Shuo-yu Xia, JHEP 10 (2023) 021, Arxiv: 2211.11582

- Correlation function in EELS

$$S^{\hat{H}_I^\dagger \hat{H}_I}(\omega) = 2V|V_{\rm cou}(\boldsymbol{Q})|\,{\rm Im}\left[\frac{-1}{\epsilon(\mathrm{Q},\omega)}\right]$$

Coulomb Potential

Inverse Dielectric Function

- Dielectric response of neutrino

$$S^{\hat{H}_I^\dagger \hat{H}_I}(\omega) = 2V\frac{|V_{{\rm E}\nu{\rm ES}}|^2}{|V_{\rm cou}(\boldsymbol{Q})|}{\rm Im}\left[\frac{-1}{\epsilon(\mathrm{Q},\omega)}\right]$$

Effective Potential of Neutrino

Screened neutrino excitation

- Event rate with in-medium screening effect

Not Sensitive to Plasmon

$$R_{\rm SM} = \frac{N_{\rm cell}\Omega G_F^2 g_{\alpha;\rm V}^2}{\pi\alpha}\int \Phi(E_\nu)\,\mathrm{d}E_\nu \times \sum_G \int_{1\rm BZ} \frac{\mathrm{d}^3 q\,\mathrm{d}\omega}{(2\pi)^3} |\boldsymbol{G}+\boldsymbol{q}| \,\mathrm{Im}\left[\frac{1}{\epsilon_{\rm G,G}(\rm q,\omega)}\right] \times \left[\ldots\ldots\right]$$

Sensitive to Plasmon

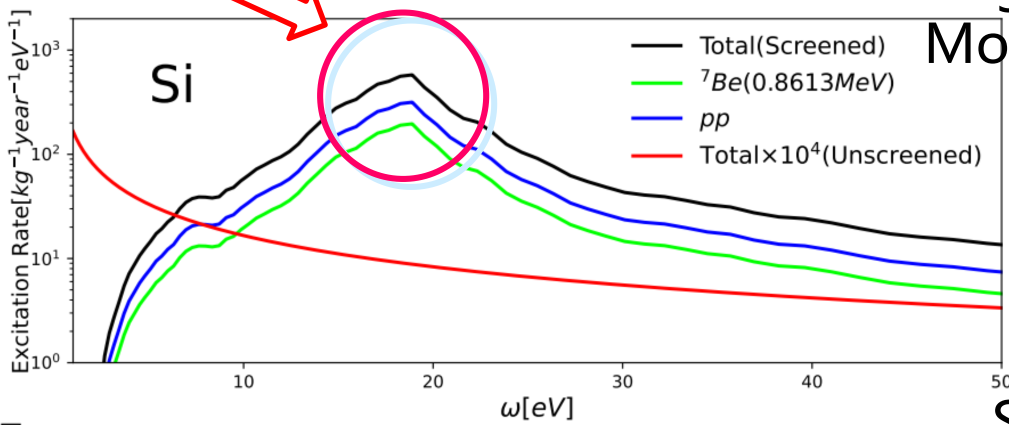
$$R_{\rm mag} = 32 N_{\rm cell}\Omega\mu_\nu^2 \frac{\pi\alpha}{m_e^2}\int \Phi(E_\nu)E_\nu^2\,\mathrm{d}E_\nu \times \sum_G \int_{1\rm BZ} \frac{\mathrm{d}^3 q\,\mathrm{d}\omega}{(2\pi)^3} \frac{1}{|\boldsymbol{G}+\boldsymbol{q}|^3} \,\mathrm{Im}\left[\frac{1}{\epsilon_{\rm G,G}(\rm q,\omega)}\right] \times \left[\ldots\ldots\right]$$

Screened neutrino excitation

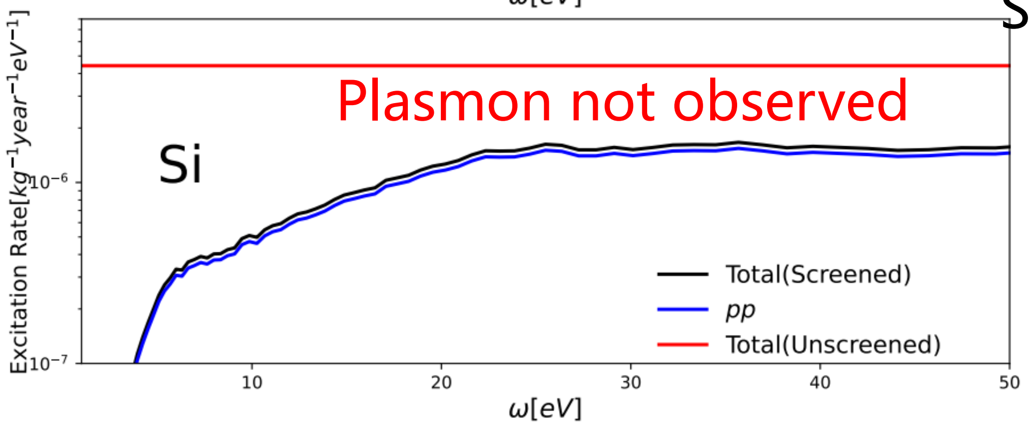
- Event rate with in-medium screening effect

Significant
Plasmon Enhancement

Magnetic
Moment

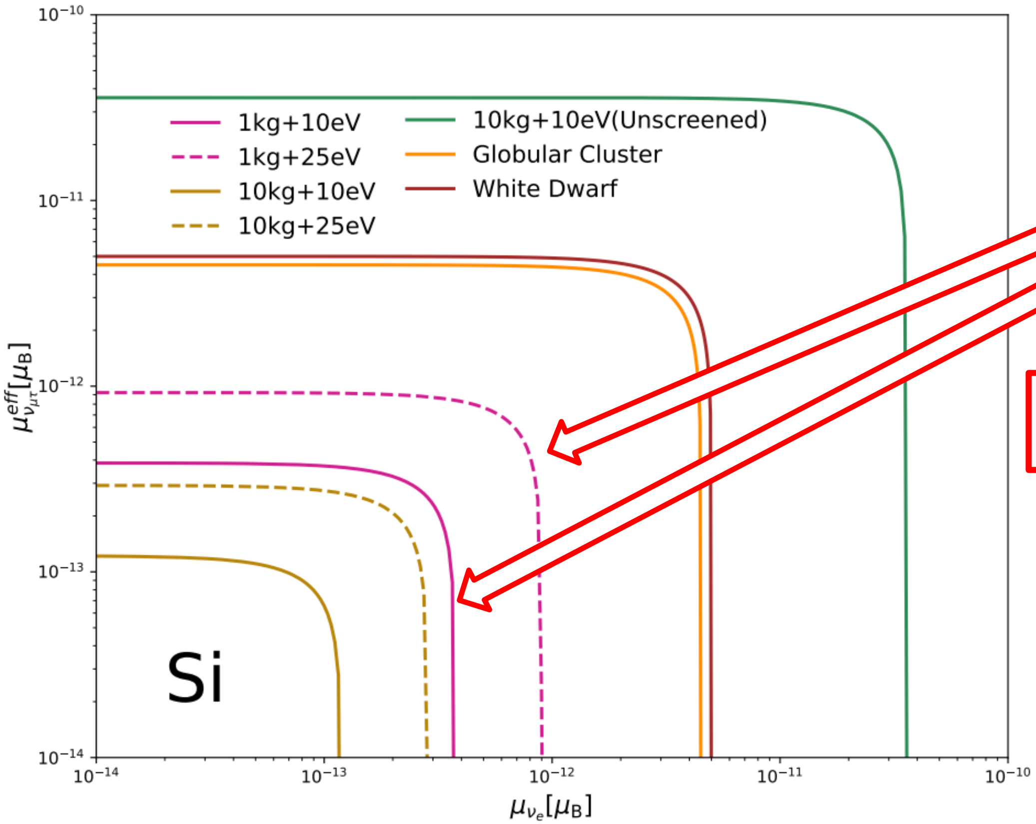


SM



Screened neutrino excitation

- Constraints on neutrino magnetic moment
  - Better than astrophysical constraints at near future



Detection of Plasmon is Important

Threshold < 20 eV

Neutrino induced Migdal effect

- The physical potential in Migdal effect
  - Additional electron emission for detection
  - Benefit from the coherent effect in CEνNS
  - Possible explanation for quenching model
- Experiments /Proposals
  - Neutron nucleus scattering

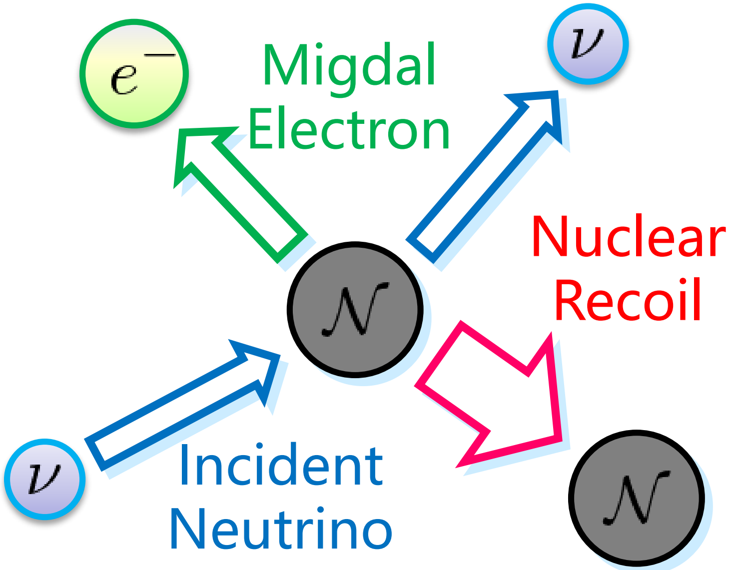
    Peter Cox, et al., Arxiv: 2208.12222

    Nicole F. Bell, et al., Arxiv: 2112.08514

    H.M. Araújo, et al., Arxiv: 2207.08284
  - Dark matter direct detection

    EDELWEISS collaboration, Arxiv: 2203.03993

    XENON Collaboration, Arxiv: 1907.12771

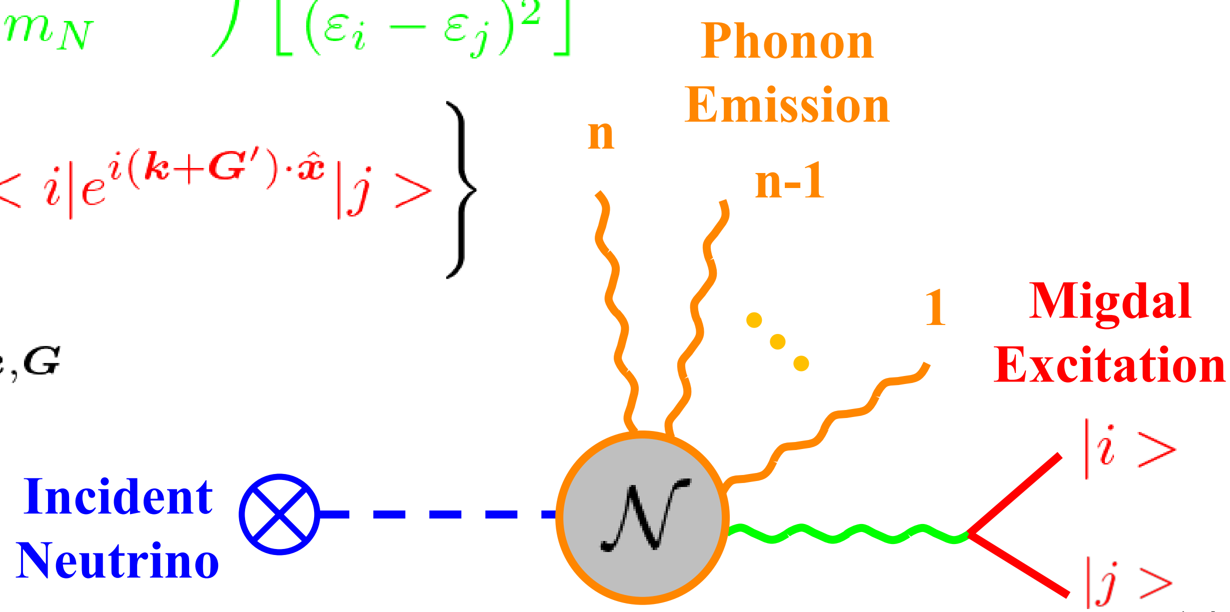


Neutrino induced Migdal effect

Yu-Feng Li and Shuo-yu Xia, Nucl.Phys.B 1006 (2024) 116632, Arxiv: 2310.05704

- Migdal effect as a multi-phonon process

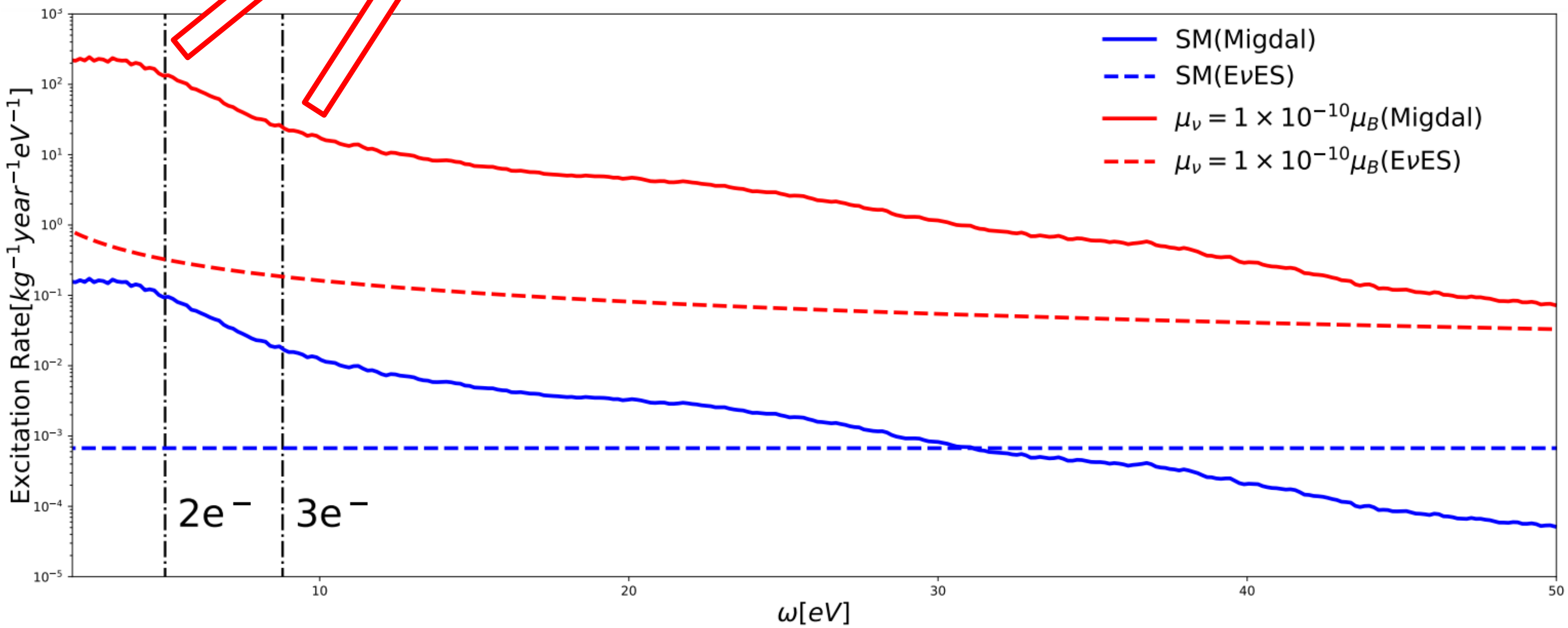
$$
\begin{aligned}
i\mathcal{M} = &- iV_{\mathrm{CE}\nu\mathrm{NS}}(\boldsymbol{q}) N e^{-W(\boldsymbol{q})} \prod_{s=1}^{n} \left(\frac{-i\boldsymbol{q}\cdot\boldsymbol{\epsilon}_{\boldsymbol{k}_s,\alpha_s}}{\sqrt{2Nm_N\omega_{\boldsymbol{k}_s,\alpha_s}}} \right) \\
&\times \sum_{\boldsymbol{G}'} \sum_{\boldsymbol{k}} \left\{ \left(\frac{\boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{G}')}{m_N} \right) \left[\frac{1}{(\varepsilon_i-\varepsilon_j)^2} \right] \right. \\
&\times \left. \left[\frac{Z_{ion}4\pi\alpha_e}{V|\boldsymbol{k}+\boldsymbol{G}'|^2} \right] < i|e^{i(\boldsymbol{k}+\boldsymbol{G}')\cdot\hat{\boldsymbol{x}}}|j > \right\} \\
&\times \sum_{\boldsymbol{G}} \delta_{\sum_s \boldsymbol{k}_s+\boldsymbol{G}+\boldsymbol{k},\boldsymbol{G}}
\end{aligned}
$$



Neutrino induced Migdal effect

- Event rate with the Migdal effect

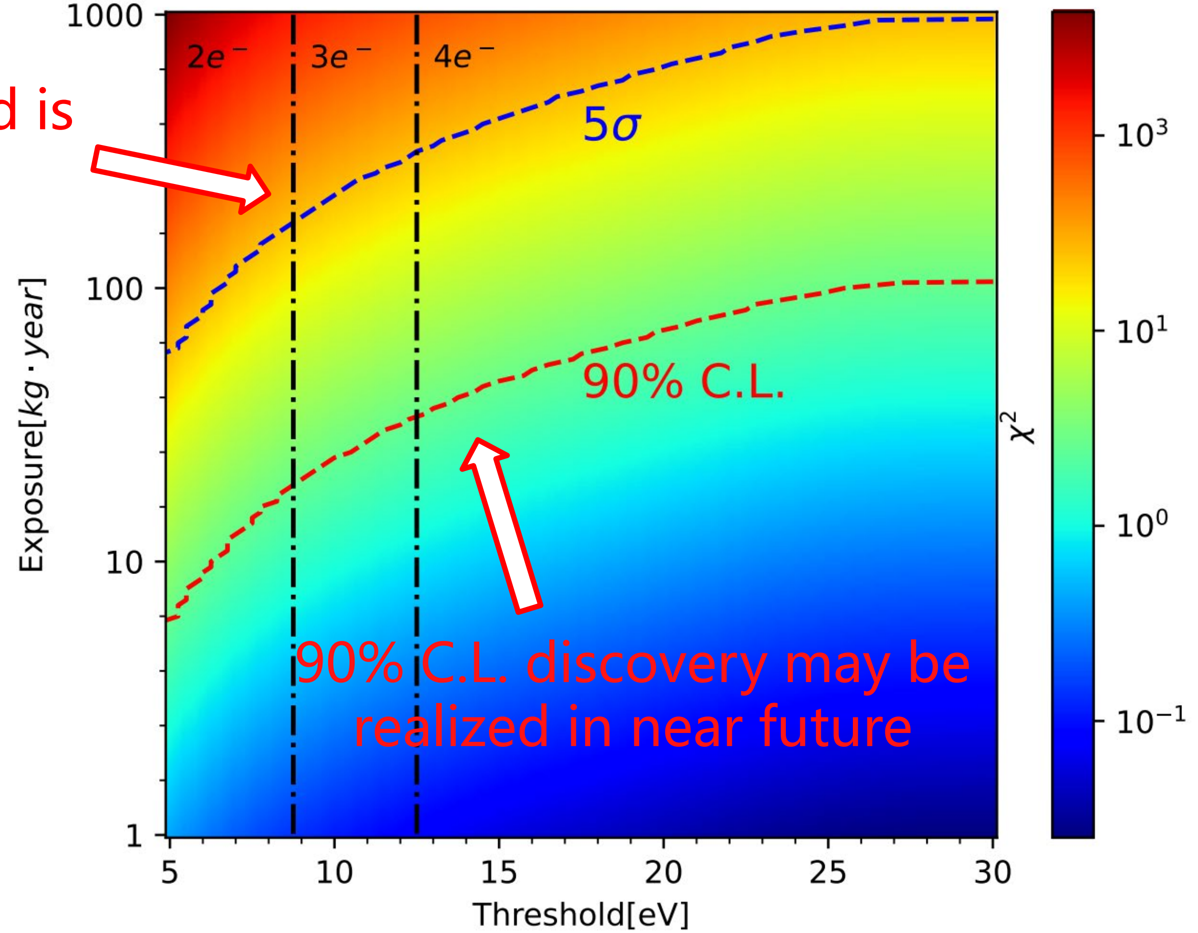
One order event rate increase
With threshold from 3e to 2e



Neutrino induced Migdal effect

- Sensitivity of the Migdal effect

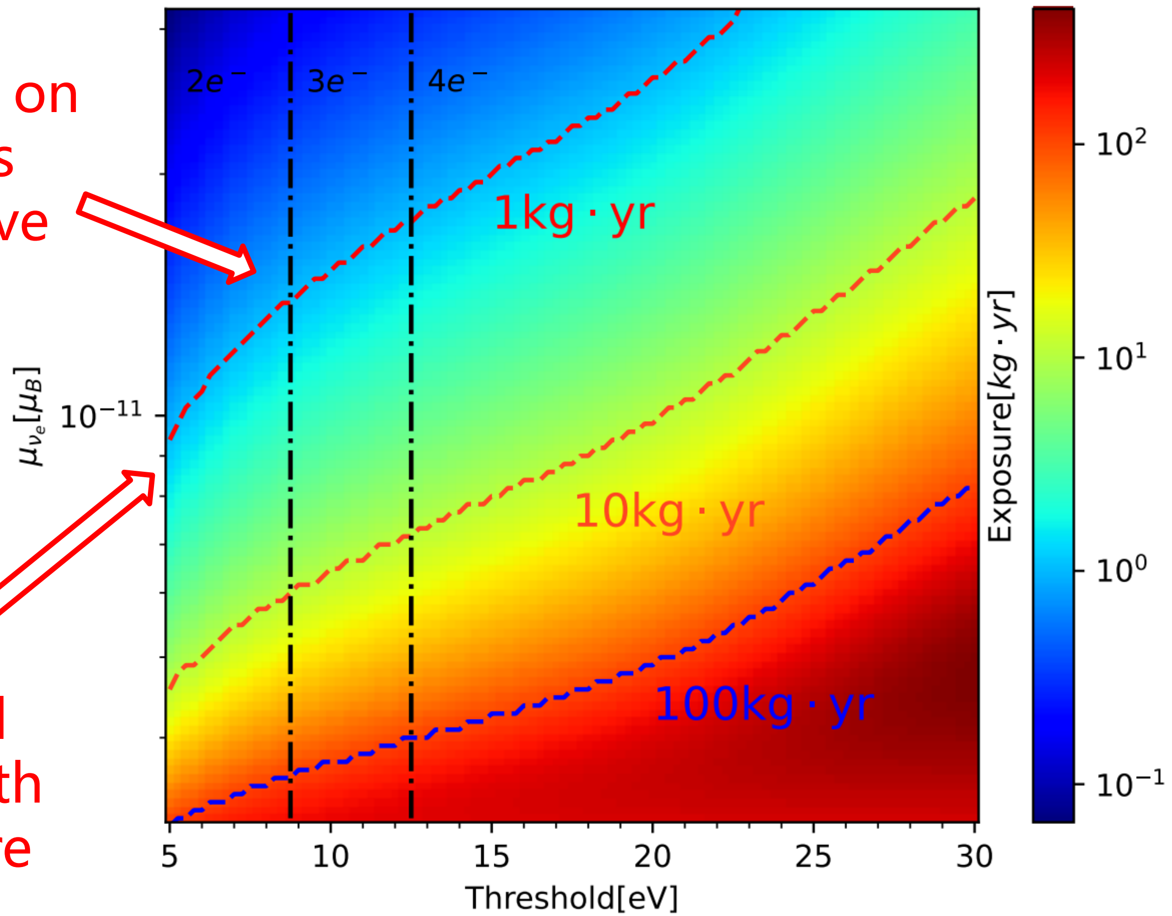
Low threshold is important



Neutrino induced Migdal effect

- Constraints on neutrino magnetic moment

Improvement on threshold is more effective



Similar to astrophysical constraints with small exposure

Summary

- Plasmon can enhance the observation of neutrino magnetic moment
- Migdal effect may improve the detection of low energy nuclear recoil
- Low threshold is important to detect low energy neutrino excitation
- Challenges
  - Background, resolution, experimental scale, ……
  - Dielectric response, excitation models, ……

Thank You For Your Attention