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Probing Supernova Neutrino Boosted Dark Matter with Collective Excitation

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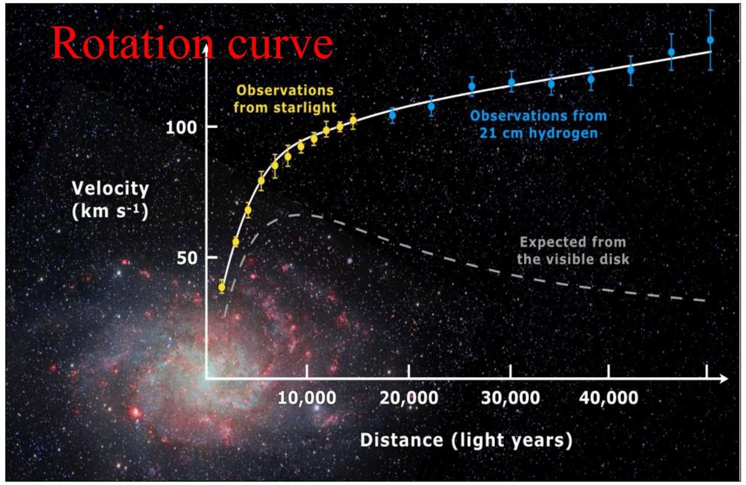
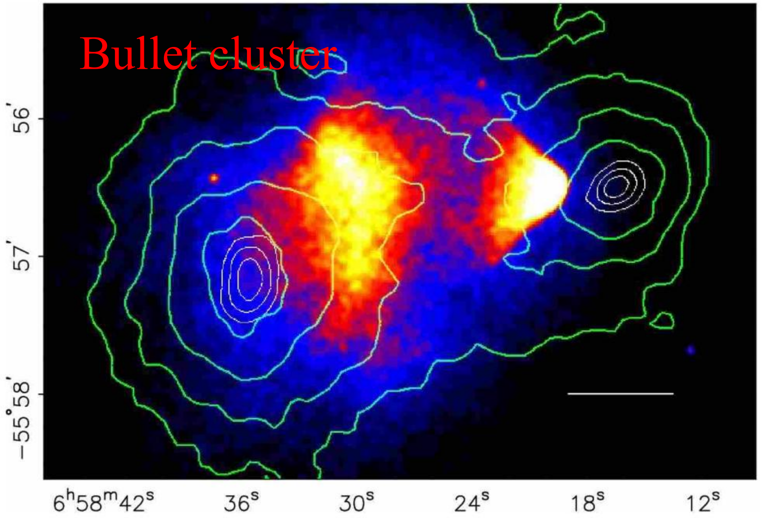
DM and Neutrino Focus Week, TDLI, 2025.08.22

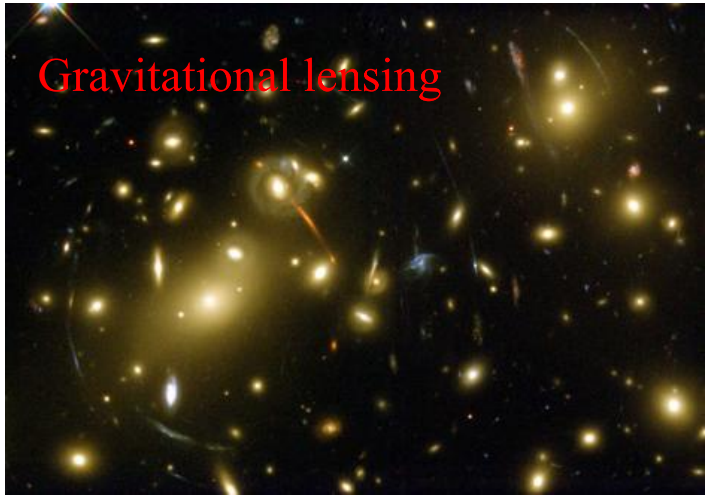
CONTENT

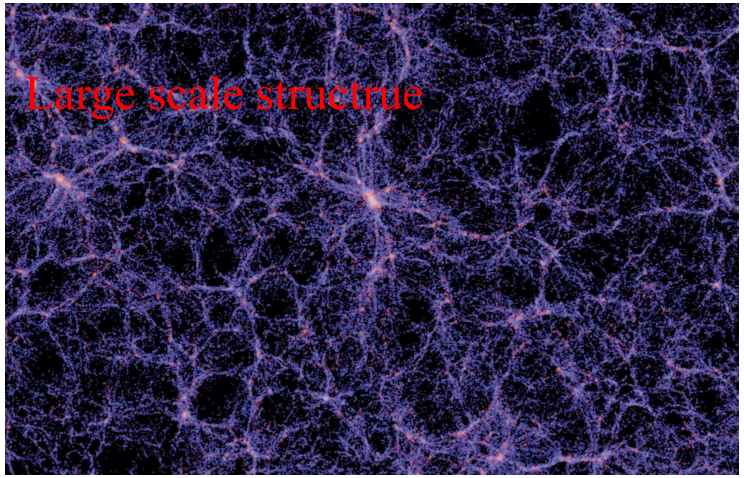
- **Introduction**
- Galactic Supernova neutrinos
- Boosted dark matter
- Direct detection with plasmon
- Summary

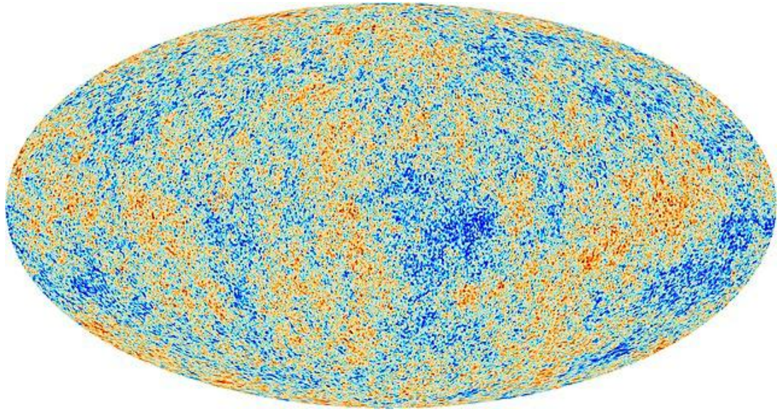
Dark Matter



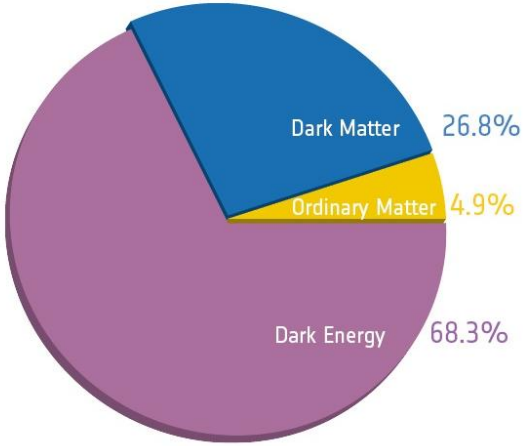








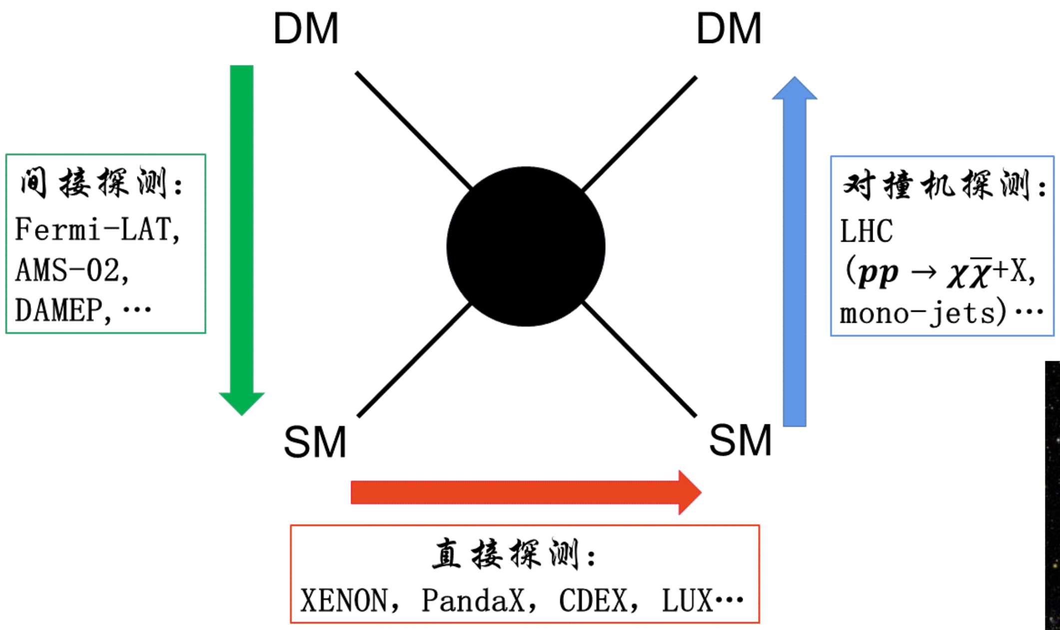
CMB

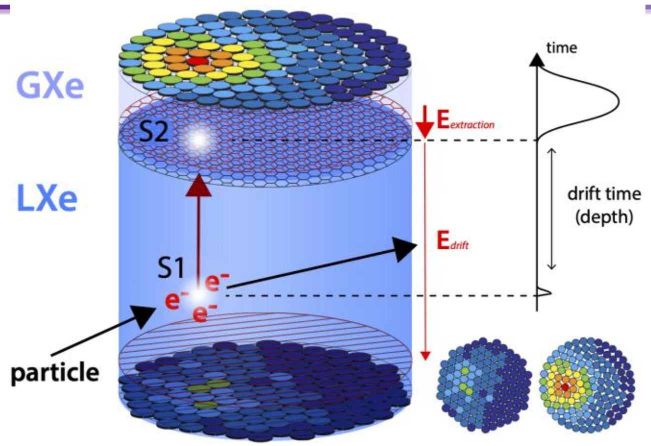


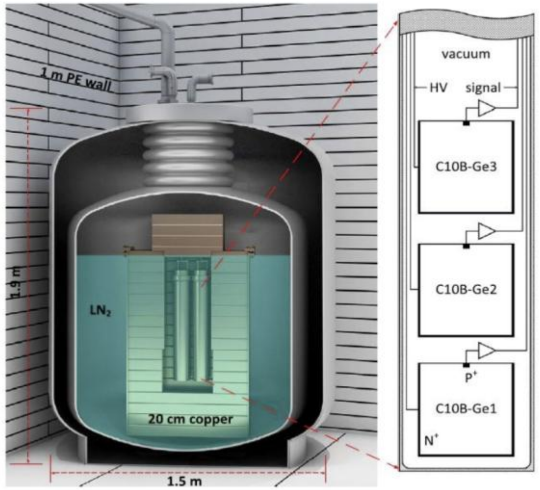
Planck, arXiv:1303.5062

DM Detection

Three detection methods

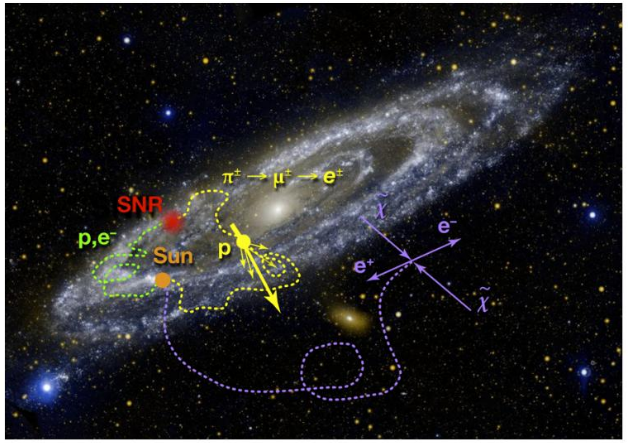




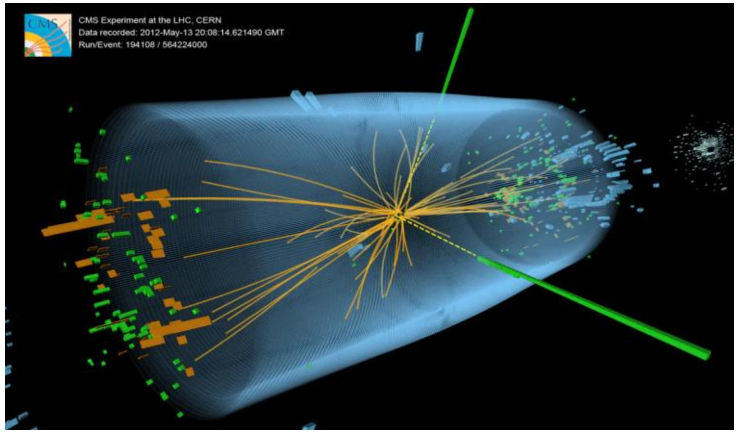


Direct

No clear dark matter signal has been found



Indirect



Collider

Difficult in direct detection

Can not constraint small mass

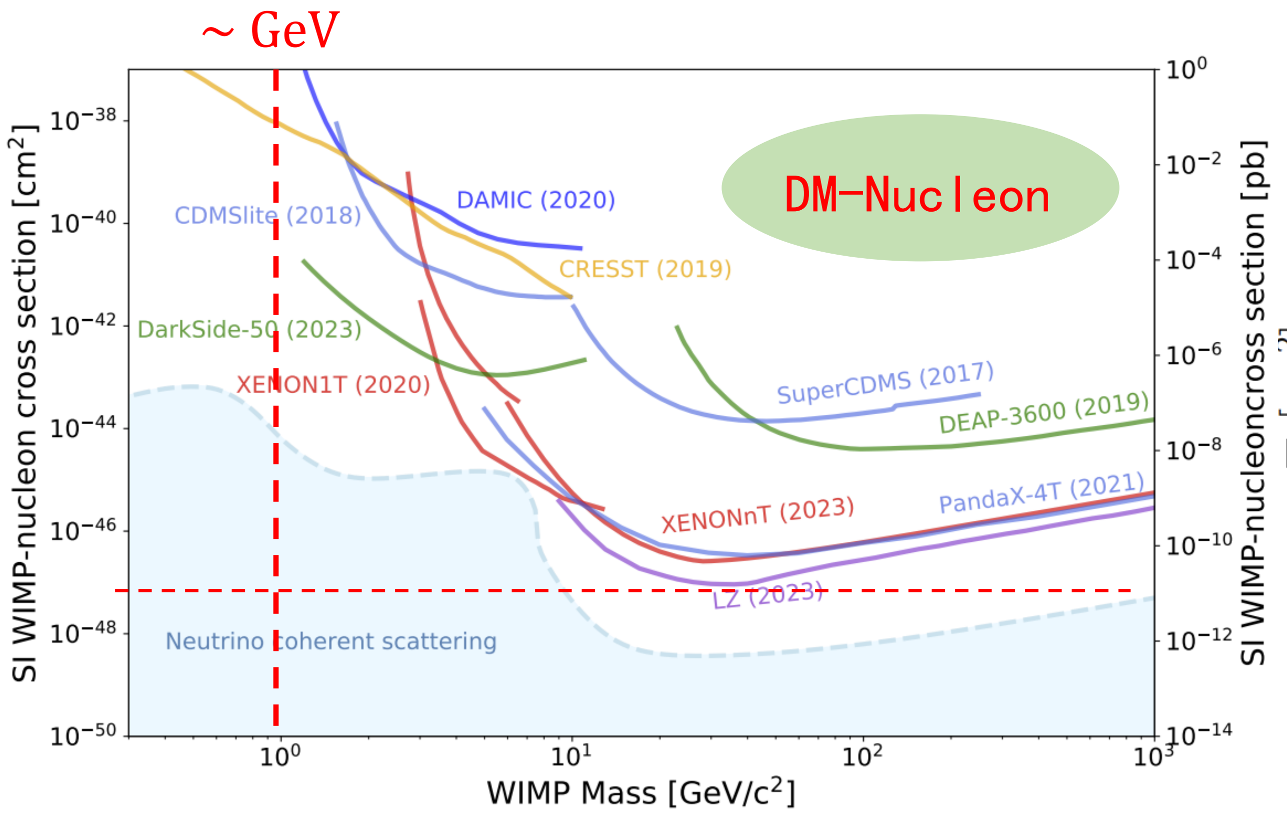
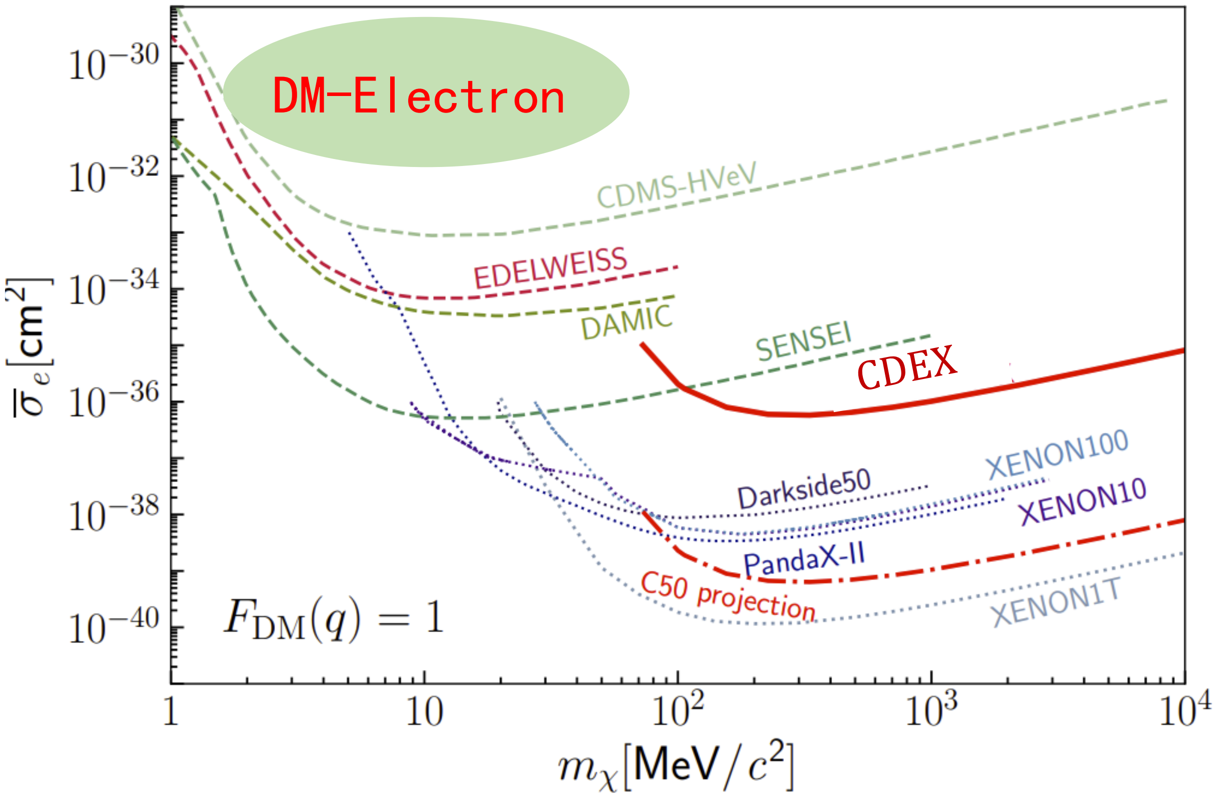
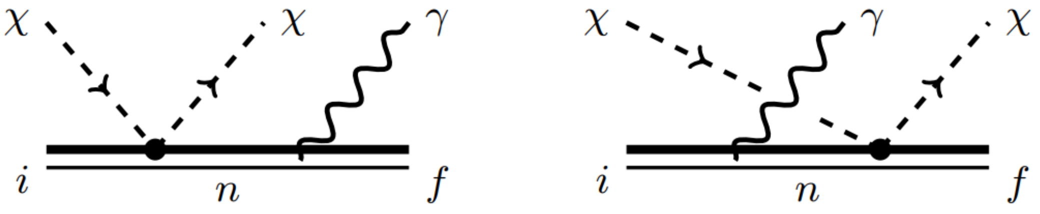


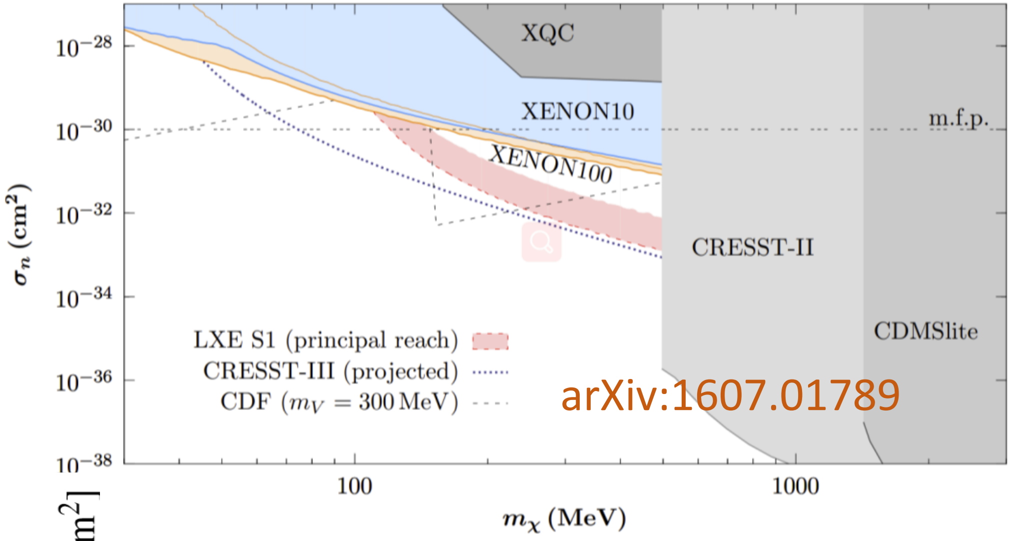
Figure 27.1: Upper limits on the SI DM-nucleon cross section as a function of DM mass.



How to overcome it?

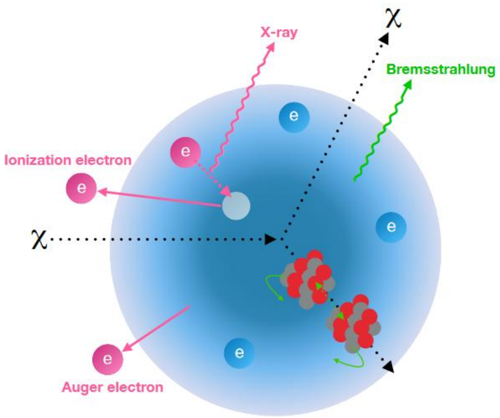
- Improve threshold
  - Extra Photon during Bremsstrahlung

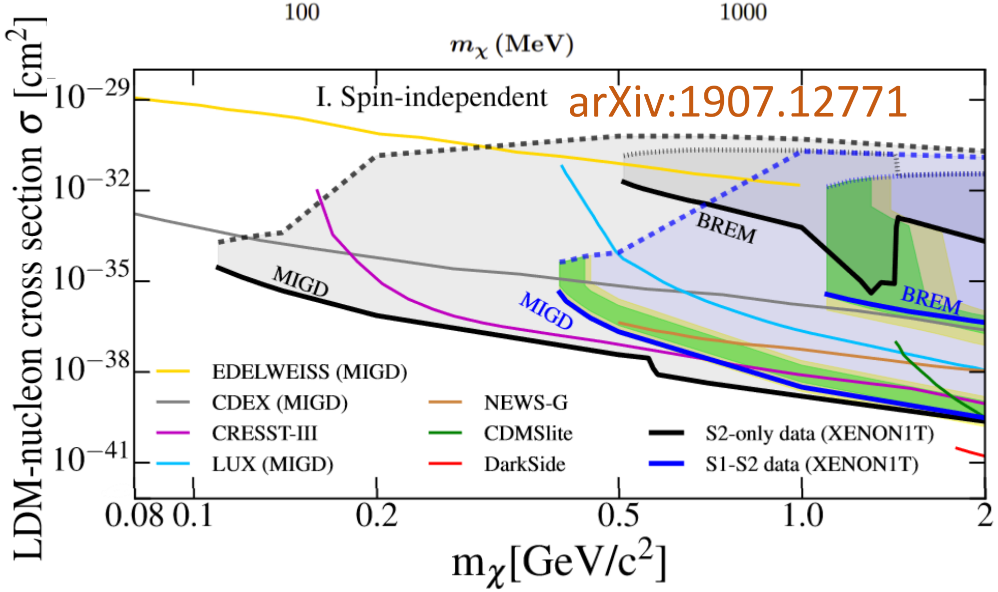




arXiv:1607.01789

  - Migdal effect

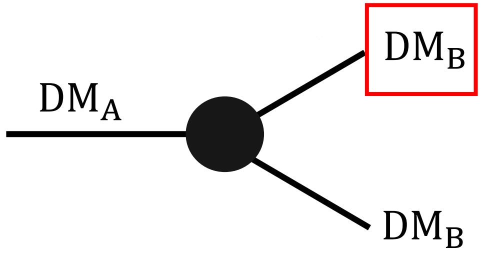




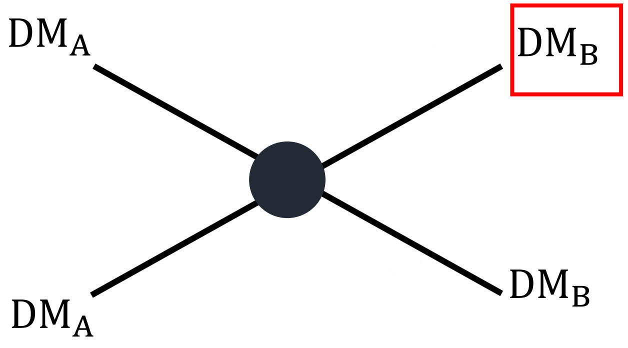
arXiv:1907.12771

Boosted DM

- By annihilation or decay

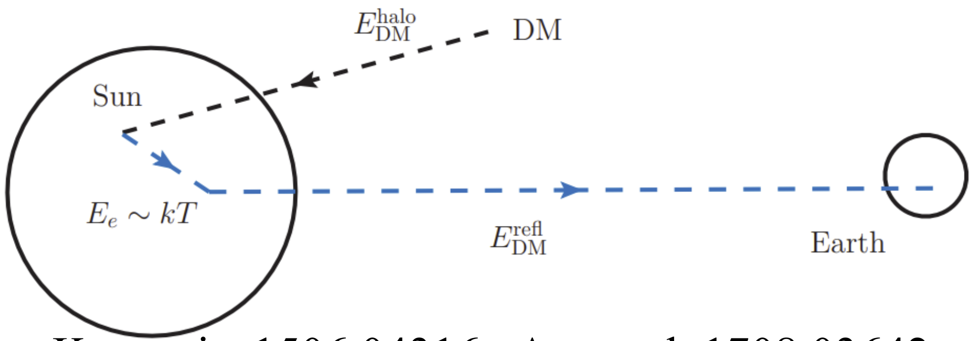


JHEP04(2015)105

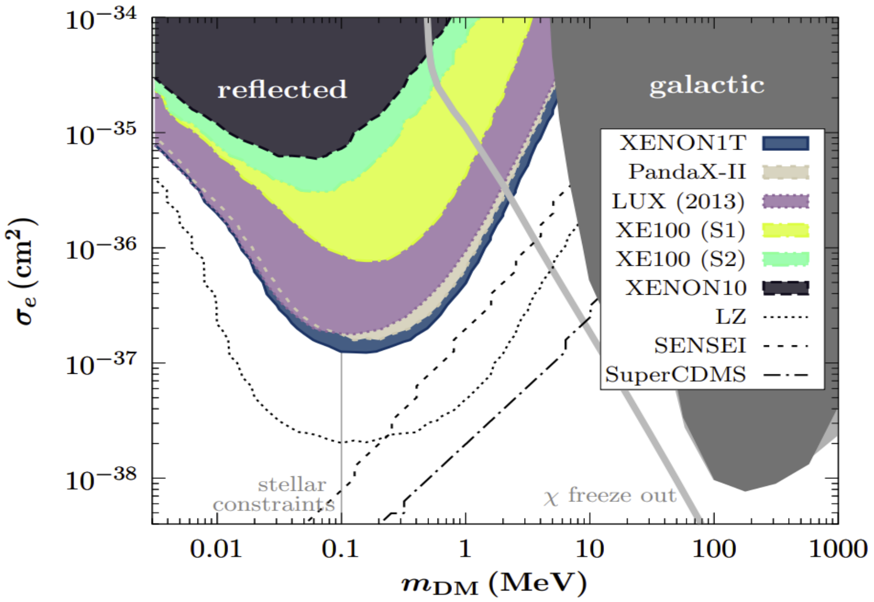


arXiv: 1405.7370

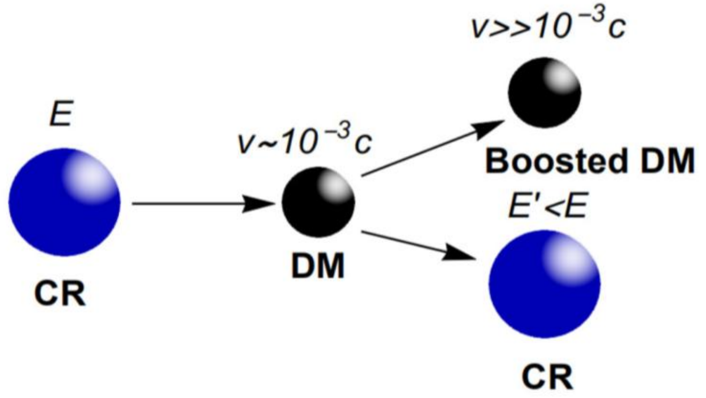
- Solar reflect

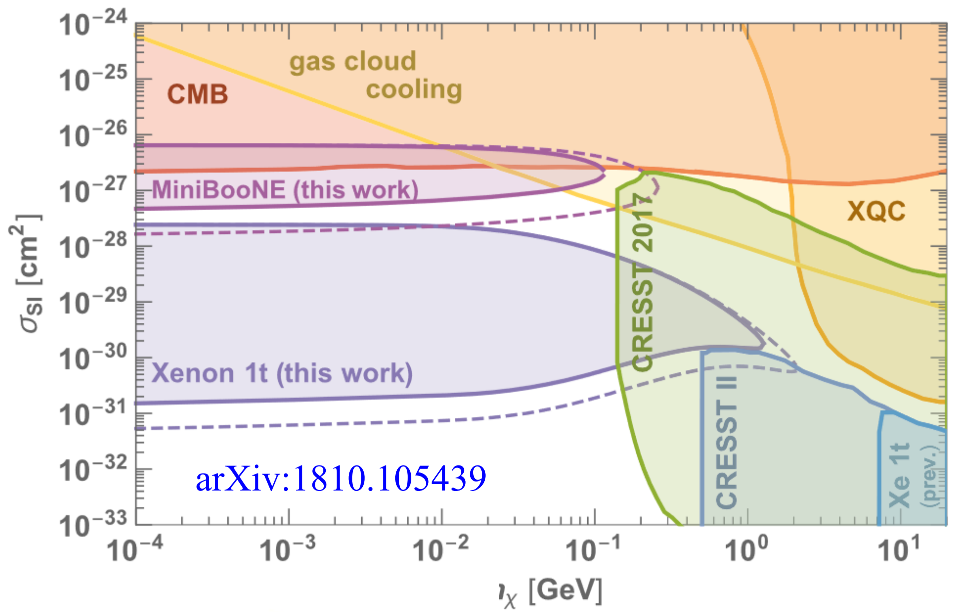


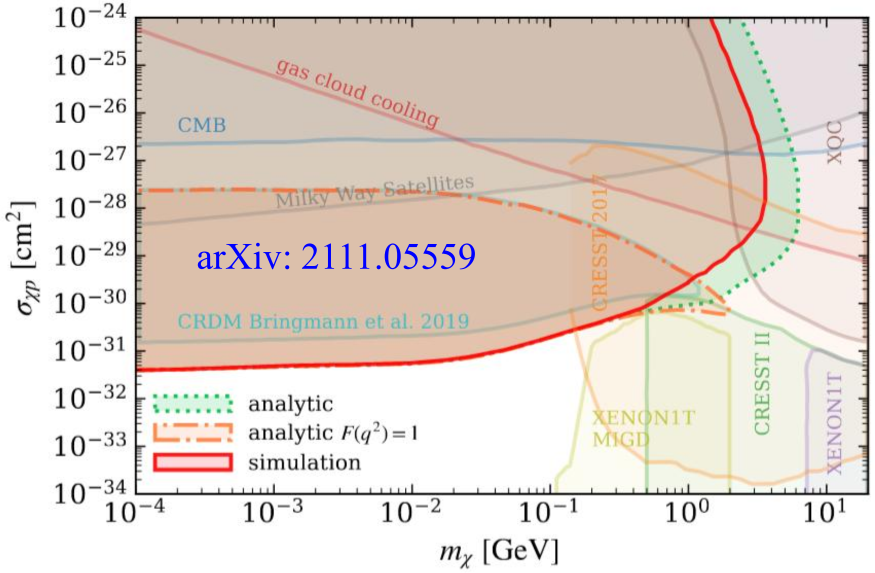
Kouvaris, 1506.04316; An, et al, 1708.03642.

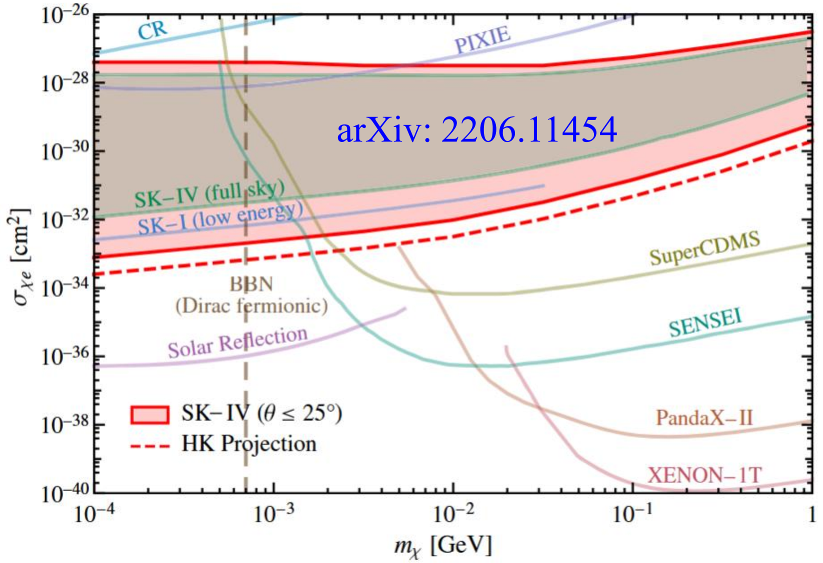


- Cosmic ray boost









W. Wang, L. Wu, J. M. Yang, H. Zhou, and B. Zhu, arXiv:1912.09904

W. Wang, L. Wu, W.-N. Yang, and B. Zhu, arXiv:2111 .04000.

S.-F. Ge, J. Liu, Q. Yuan, and N. Zhou, arXiv:2005.09480.

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Galactic core-collapse supernova neutrinos (CC SNe)

- Single explosion

The spectrum (particle number per unit energy) can be parameterized as:

Total energy

$$\frac{dN}{dE_{\nu_i}} = \frac{E^{\nu}_{\rm tot}(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)} \frac{E^{\alpha}_{\nu}}{\langle E_\nu \rangle^{2+\alpha}} \exp\left[-(1+\alpha)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$

Average energy

shape parameter

Total neutrino spectrum:

$$\frac{dN}{dE_\nu} = \frac{dN}{dE_{\nu_e}} + \frac{dN}{dE_{\nu_{\bar{e}}}} + 4\frac{dN}{dE_{\nu_x}}$$

$$\nu_x \equiv \{\nu_\mu, \nu_{\bar{\mu}}, \nu_\tau, \nu_{\bar{\tau}}\}$$

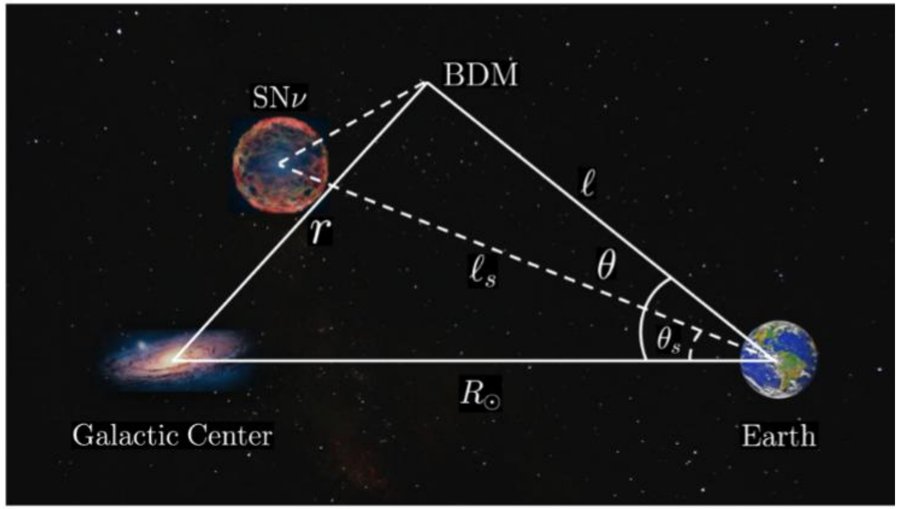
ν	$E^{\nu}_{\rm tot}$ (erg)	$\langle E_\nu \rangle$ (MeV)	α
ν_e	6×10^{52}	13.3	3.0
$\nu_{\bar{e}}$	4.3×10^{52}	14.6	3.3
ν_x	2×10^{52}	16	3

From Ref. S. Horiuchi et al, arXiv: 1709.06567

- Neutrino flux (explosion occurring at $\boldsymbol{\ell}_s$) at $\boldsymbol{\ell}$ is

$$\frac{d\phi_\nu}{dE_\nu} = \dot{N}\frac{dN_\nu}{dE_\nu}\frac{1}{4\pi|\boldsymbol{\ell}-\boldsymbol{\ell}_s|^2}$$

$\dot{N}$: explosion rate, is $\frac{1}{\tau}$ for single explosion



Multiple explosion

Then, the total flux should be obtained by integrating over the entire space after multiplying by the supernova probability density function $f(\boldsymbol{\ell}_s)$,

$$\frac{d\phi_\nu(\boldsymbol{\ell})}{dE_\nu} = \dot{N}_{\rm CC}^{\rm gal}\frac{dN_\nu}{dE_\nu}\int\frac{f(\boldsymbol{\ell}_s)}{4\pi|\boldsymbol{\ell}-\boldsymbol{\ell}_s|^2}d^3\ell_s$$

Dependent on both position and energy

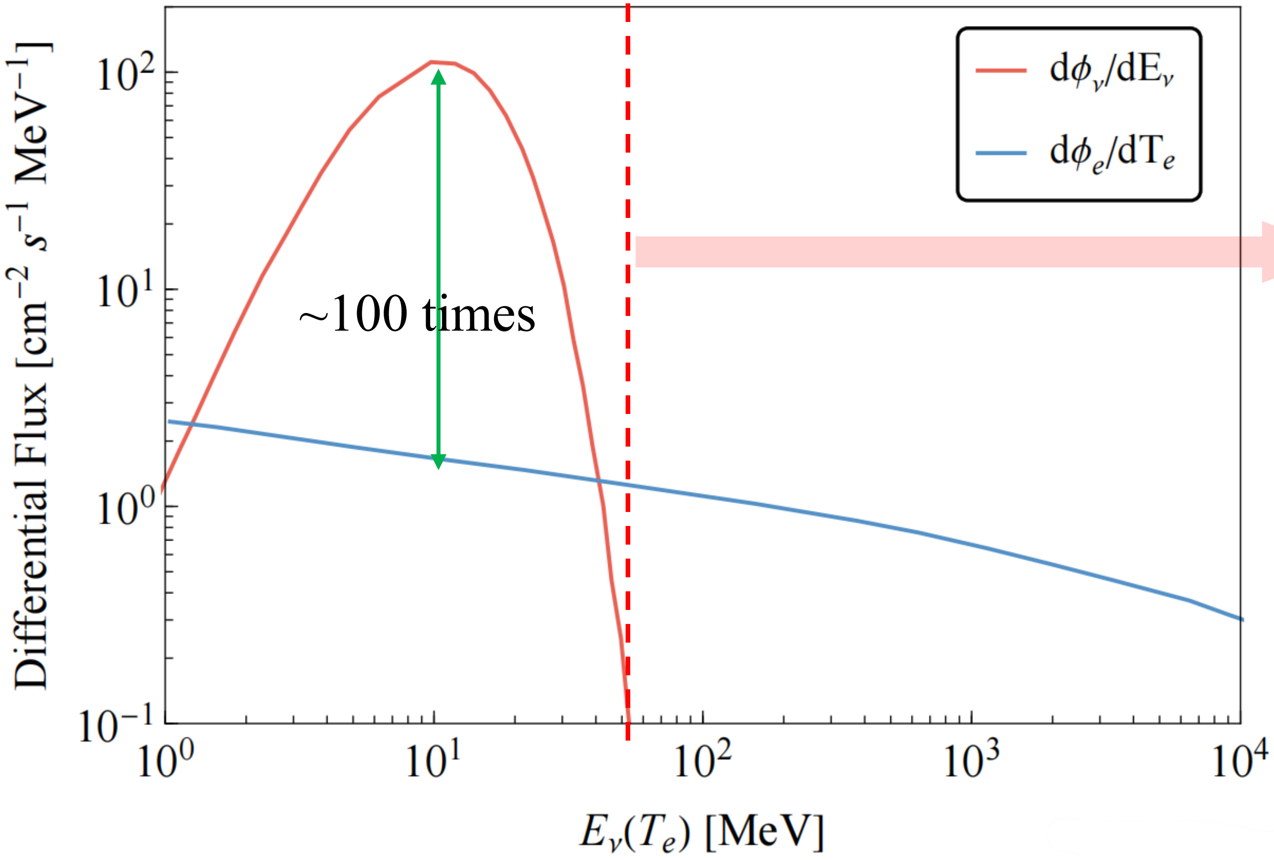
$$\dot{N}_{\rm CC}^{\rm gal} = 2.3\times10^{-2}\ \rm yr^{-1}$$

$$f(\boldsymbol{\ell}_s) = \frac{1}{\mathcal{N}}\exp\left[-\frac{R(\ell_s,\theta_s,\phi_s)}{R_d} - \frac{|z(\ell_s,\theta_s,\phi_s)|}{z_H}\right]$$

From Ref. 1306.0559

Why consider CC SNe?

Flux of CC SNe vs Cosmic Ray, at the Earth surface



$$\exp\left[-(1+\alpha)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

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Benchmark Model

Couple via vector boson Z'_μ:

$$\mathcal{L} \supset g_\nu \bar{\nu} \gamma^\mu \nu Z'_\mu + g_e \bar{e} \gamma^\mu e Z'_\mu + g_\chi \bar{\chi} \gamma^\mu \chi Z'_\mu .$$

Cross section:

$$\frac{d\sigma_{\chi\nu}}{dT_\chi} = \frac{g_\nu^2 g_\chi^2 m_\chi [2E_\nu^2 - (2E_\nu + m_\chi)T_\chi + T_\chi^2]}{4\pi E_\nu^2 (m_{Z'}^2 + 2m_\chi T_\chi)^2},$$

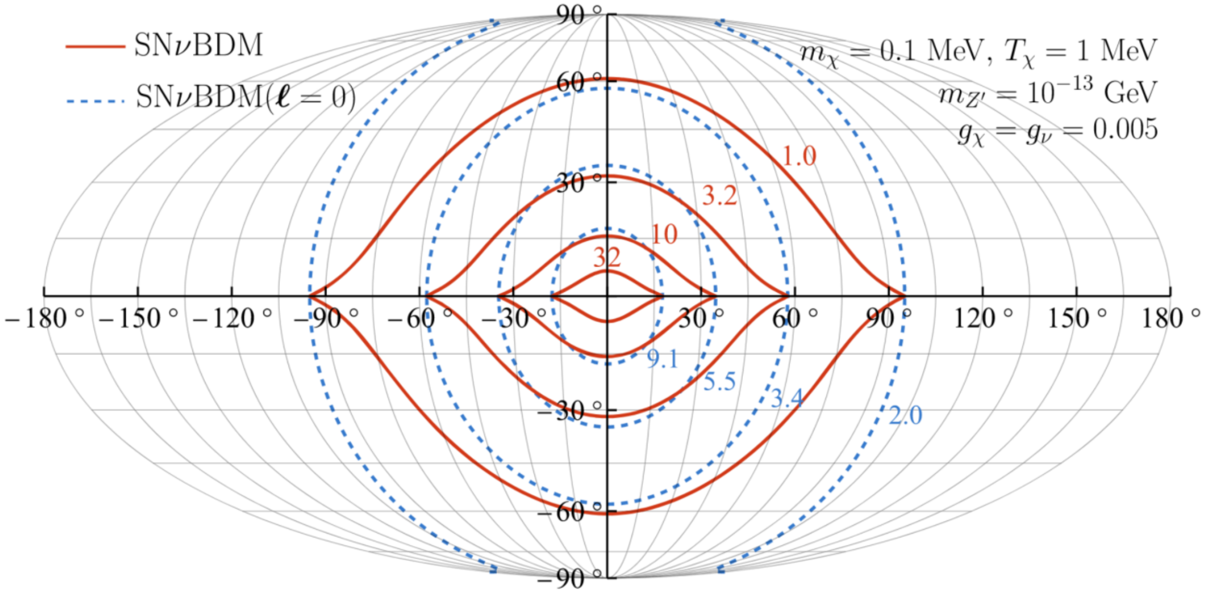
$$\frac{d\sigma_{\chi e}}{dT_\chi} = \frac{g_e^2 g_\chi^2 [2E_e'^2 m_\chi - (m_e^2 + m_\chi(2E_e' + m_\chi))T_\chi + m_\chi T_\chi^2]}{4\pi (E_e'^2 - m_e^2)(m_{Z'}^2 + 2m_\chi T_\chi)^2},$$

Supernova neutrino boosted dark matter (SNνBDM)

- Angular distribution of BDM flux

$$\frac{d\phi_\chi}{dT_\chi d\Omega} = \iint \frac{\rho_\chi(\boldsymbol{r})}{m_\chi}\frac{d\sigma_{\chi\nu}}{dT_\chi}\frac{d\phi_\nu(\boldsymbol{\ell})}{dE_\nu}dE_\nu d\ell \;= D(\hat{\boldsymbol{\ell}})\frac{\rho_\chi^{\rm loc}}{m_\chi}\int_{E_\nu^{\rm min}}\frac{d\sigma_{\chi\nu}}{dT_\chi}\frac{d\phi_\nu^{\rm loc}}{dE_\nu}dE_\nu$$

where $D(\hat{\boldsymbol{\ell}}) = \frac{1}{4\pi}\int_{\rm LOS}\frac{K(\boldsymbol{\ell})}{K(0)}\frac{\rho_\chi(\boldsymbol{r})}{\rho_\chi^{\rm loc}}d\ell$ with $K(\boldsymbol{\ell}) = \int \frac{f(\boldsymbol{\ell}_s)}{4\pi|\boldsymbol{\ell}-\boldsymbol{\ell}_s|^2}d^3\ell_s.$



Effective Distance

Total flux from all direction is

$$\frac{d\phi_\chi}{dT_\chi} = D_{\text{eff}} \frac{\rho_\chi^{\text{loc}}}{m_\chi} \int \frac{d\sigma_{\chi\nu}}{dT_\chi} \frac{d\phi_\nu^{\text{loc}}}{dE_\nu} dE_\nu,$$

- Effective distance

$$D_{\text{eff}} = \int D(\hat{\boldsymbol{\ell}}) d\Omega = \frac{1}{4\pi} \int_{\text{LOS}} \frac{K(\boldsymbol{\ell})}{K(0)} \frac{\rho_\chi(\boldsymbol{r})}{\rho_\chi^{\text{loc}}} d\ell \, d\Omega = \boxed{10.7 \text{ kpc}}$$

more accurate value

- If ignore neutrino position dependent

$$\widetilde{D}_{\text{eff}} = \frac{1}{4\pi} \int_{\text{LOS}} \frac{\rho_\chi(\boldsymbol{r})}{\rho_\chi^{\text{loc}}} d\ell \, d\Omega = 16.4 \text{ kpc}$$

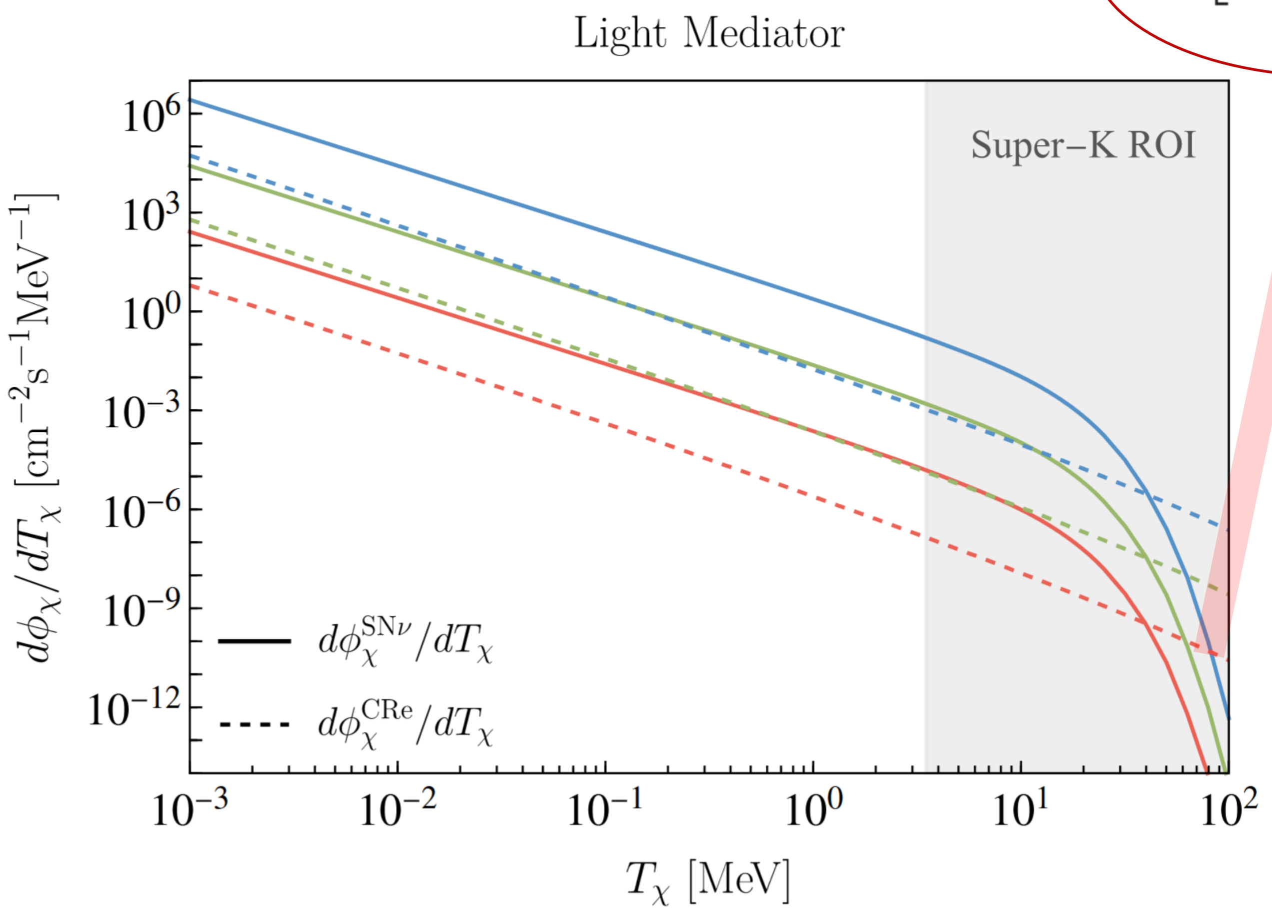
overestimated the results

Boosted DM flux

- $m_\chi = 0.01$ MeV
- $m_\chi = 0.1$ MeV
- $m_\chi = 1$ MeV
- Super-Kamiokande-IV region of interest
- $g_\chi = g_\nu = g_e = 0.005$
- Light mediator

  $m_{Z'} = 10^{-13}$ GeV

$$\exp\left[-(1+\alpha)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$



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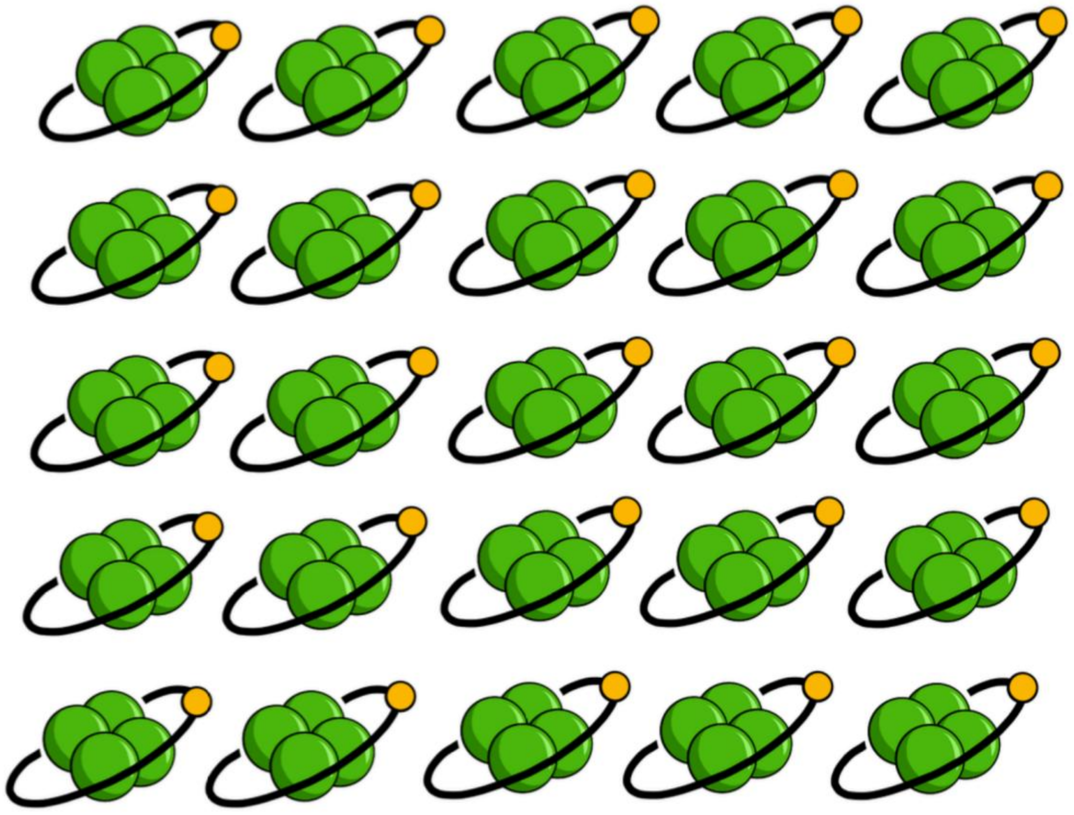
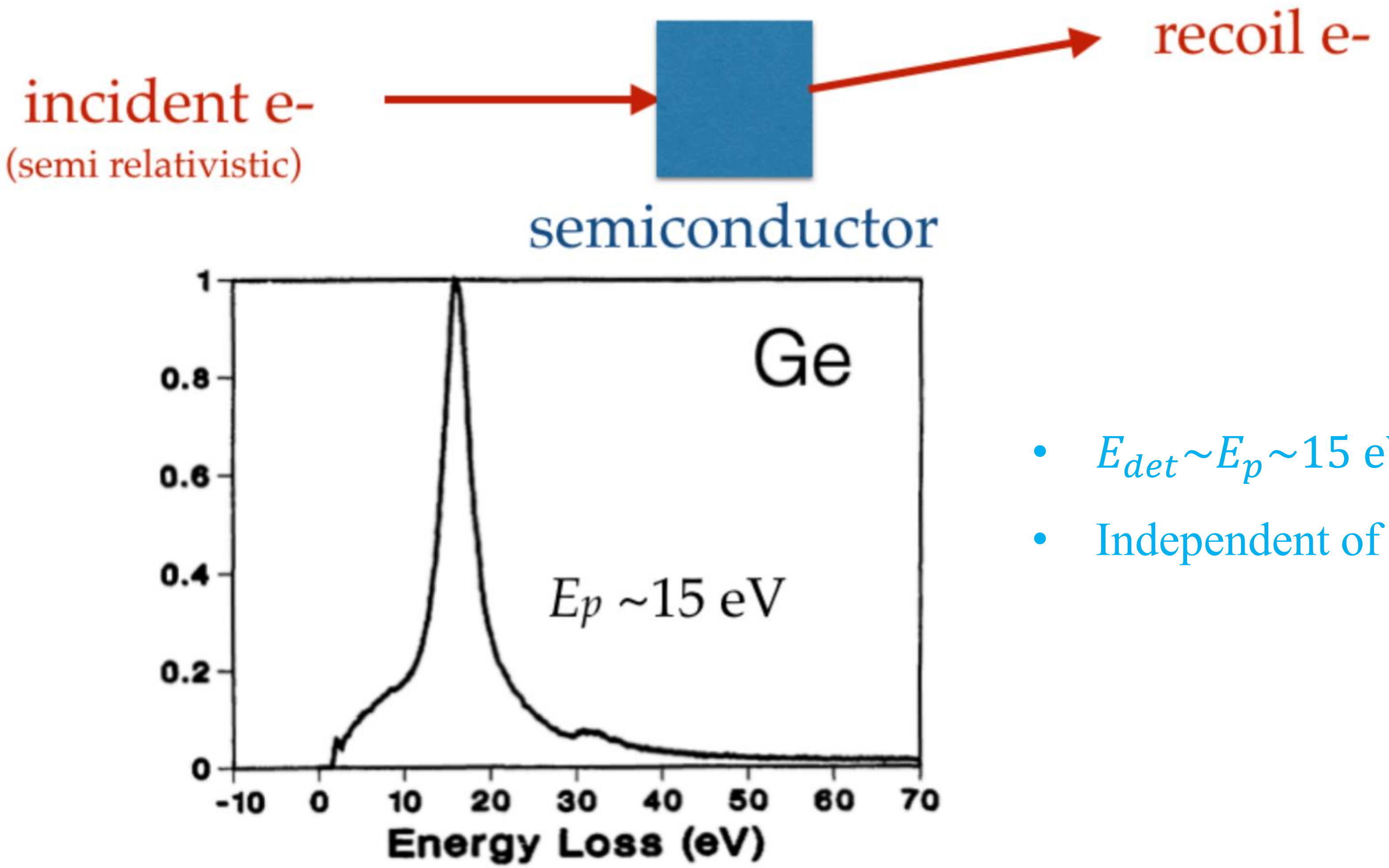
What is Plasmon?

A collective oscillation of electrons, like phonons being collective mode of nucleus



Electron Energy-Loss Spectroscopy (EELS)



- $E_{det} \sim E_p \sim 15$ eV
- Independent of initial velocity

MK Kundmann PHD thesis 1988

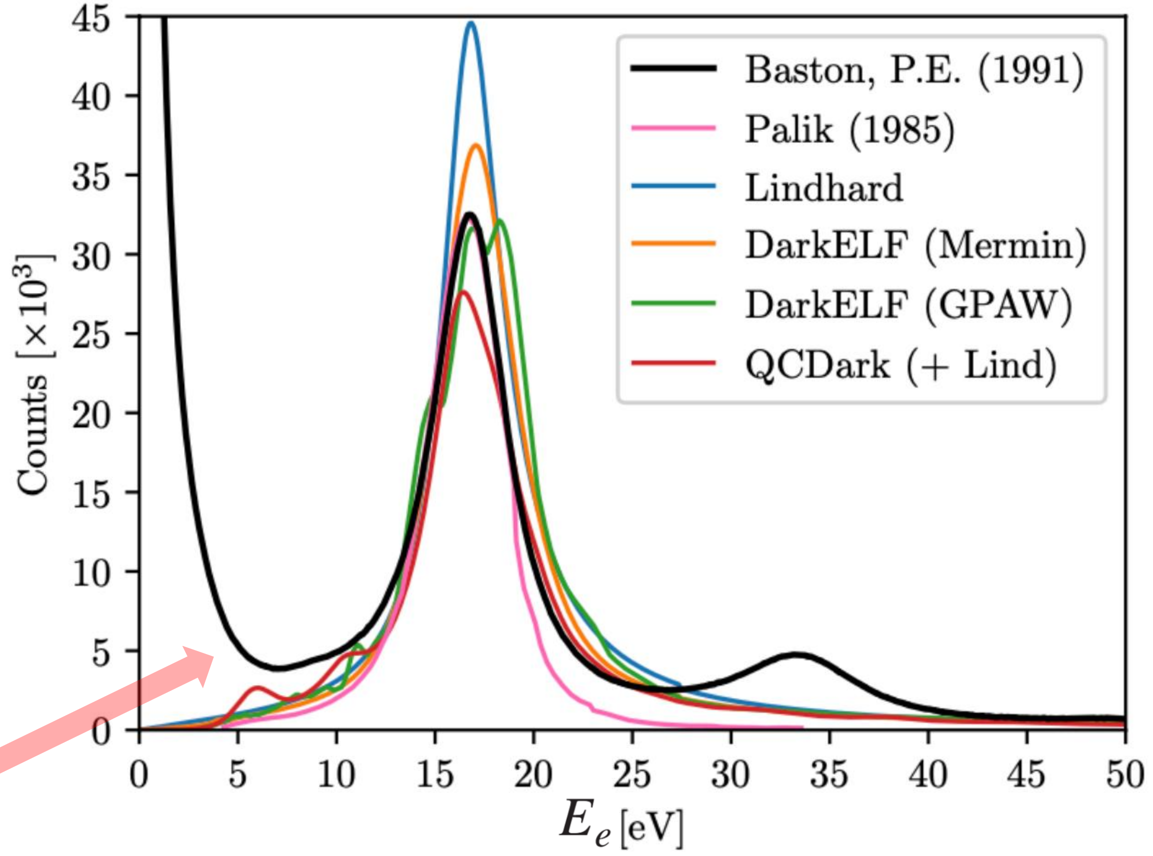
Cross section and energy loss function

- $$\mathcal{L}_e^{\mathrm{eff}} \supset g_e A_0' \psi_e^* \psi_e + \frac{i g_e}{2 m_e} \mathbf{A}' \cdot (\psi_e^* \overrightarrow{\nabla} \psi_e - \psi_e^* \overleftarrow{\nabla} \psi_e) + \cdots$$
- $$|\mathcal{M}|^2 = \frac{g_e^2 g_\chi^2}{(Q^2 - E_e^2 + m_{Z'}^2)^2} \frac{1}{2} \sum_{\bar{u}' u} \bar{u}_\chi' \gamma^0 u_\chi \bar{u}_\chi \gamma^0 u_\chi' \times \sum_{i,f} \mathcal{P}_i \langle i | e^{-i\mathbf{Q}\cdot\hat{\mathbf{x}}} | f \rangle \langle f | e^{i\mathbf{Q}\cdot\hat{\mathbf{x}}} | i \rangle .$$
- $$\frac{d\sigma_{\chi e}^{\mathrm{Si}}}{dE_e} = 2 N_{\mathrm{cell}} V_{\mathrm{cell}} \frac{\bar{\sigma}_{\chi e} \pi}{\mu_{\chi e}^2} \int \frac{d\mathbf{Q}^3}{(2\pi)^3} \frac{Q^2}{4\pi\alpha} \frac{(2E_\chi - E_e)^2 - Q^2}{4 p_\chi^2} \times F_{\mathrm{DM}}(Q)^2 \, \mathrm{Im}\left[\frac{-1}{\epsilon(\mathbf{Q}, E_e)}\right],$$

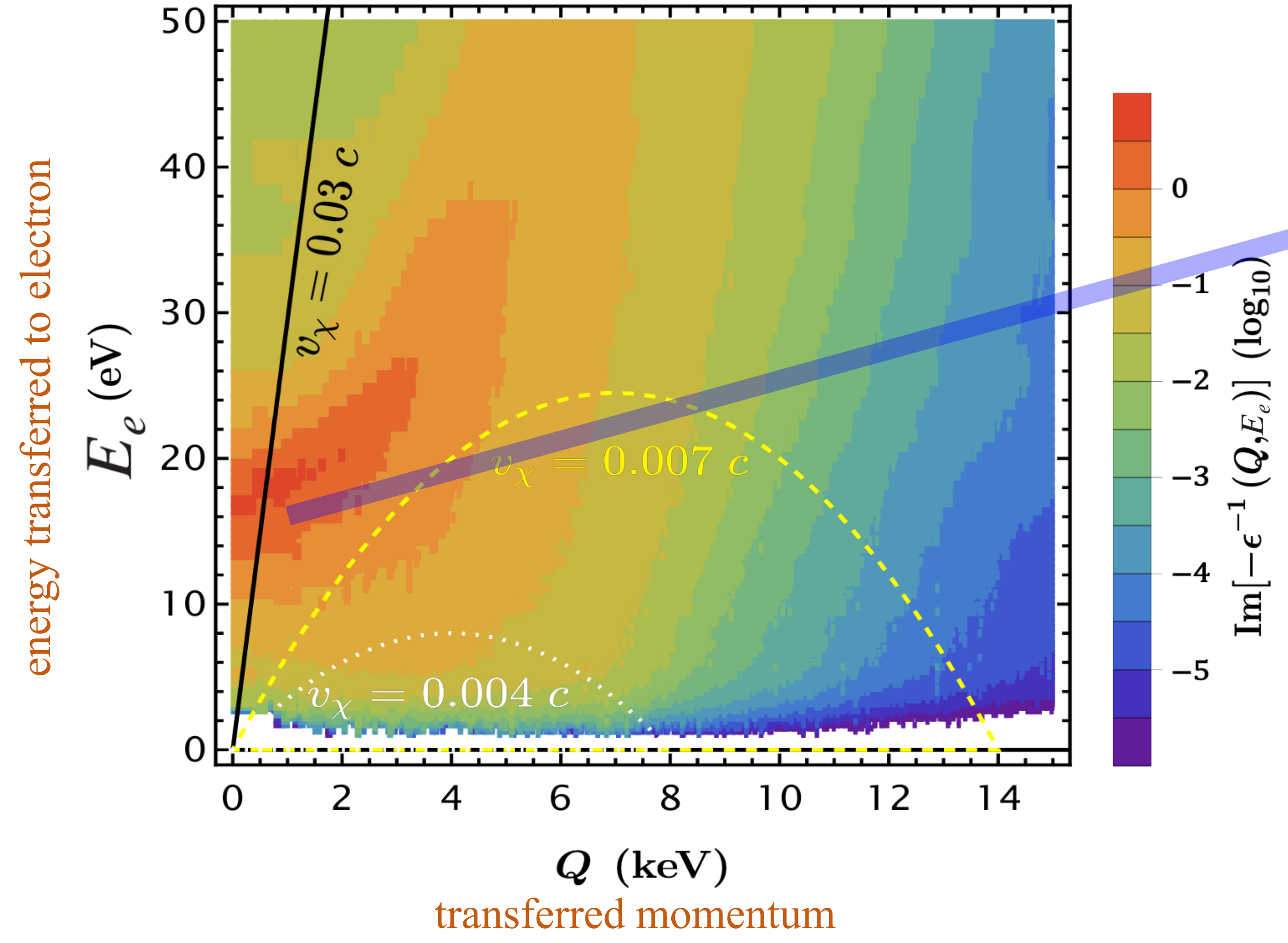
Please see 2401.11971 for details

$$\mathrm{Im}\left[\frac{-1}{\epsilon(\mathbf{Q}, E_e)}\right] = \frac{\pi e^2}{q^2} \sum_f \left| \langle f | \hat{\rho}(\mathbf{Q}) | 0 \rangle \right|^2 \delta\left(\omega_f - \omega\right),$$

There are many methods to calculate it



Boosted DM’ s advantage



For excite significant plasmon

$v_\chi \sim 10^{-2} c$

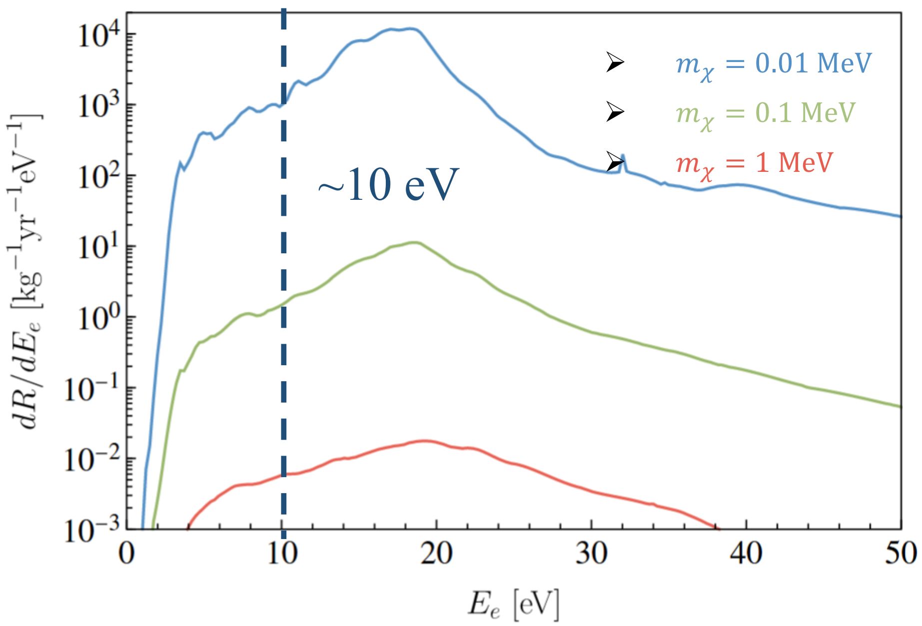
Calculated by the *DarkELF* package (2104.12786).

Numerical Results

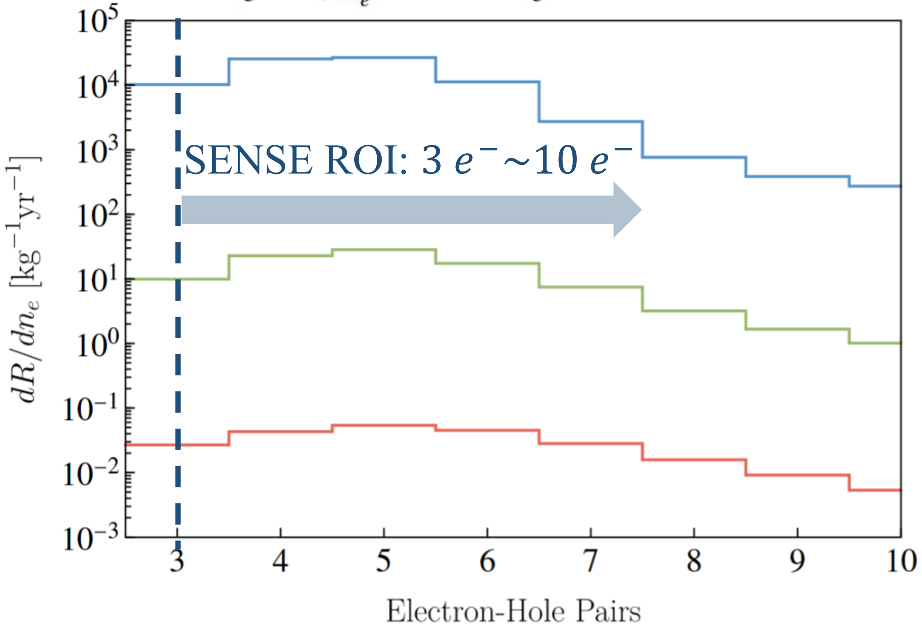
Differential rate

$$\frac{dR}{dT_\chi dQ dE_e} = \bar{\sigma}_{\chi e} \frac{N_{\text{cell}} V_{\text{cell}}}{8\pi^2 \alpha \mu_{\chi e}^2} \frac{((2E_\chi - E_e)^2 - Q^2) Q^3}{4 p_\chi^2} \left(\frac{\alpha^2 m_e^2 + m_{A'}^2}{Q^2 - E_e^2 + m_{A'}^2} \right)^2 \mathrm{Im}\left[\frac{-1}{\epsilon(Q, E_e)} \right] \frac{d\phi_\chi}{dT_\chi},$$

$$\frac{dR}{dE_e} = \int_{T_\chi^{\min}}^{\infty} dT_\chi \int_{Q_{\min}}^{Q_{\max}} dQ \frac{dR}{dT_\chi dQ dE_e}$$



$$\frac{dR}{dn_e} = \int_{E_e^{\min}}^{\infty} dE_e \frac{dR}{dE_e} P(n_e, E_e)$$



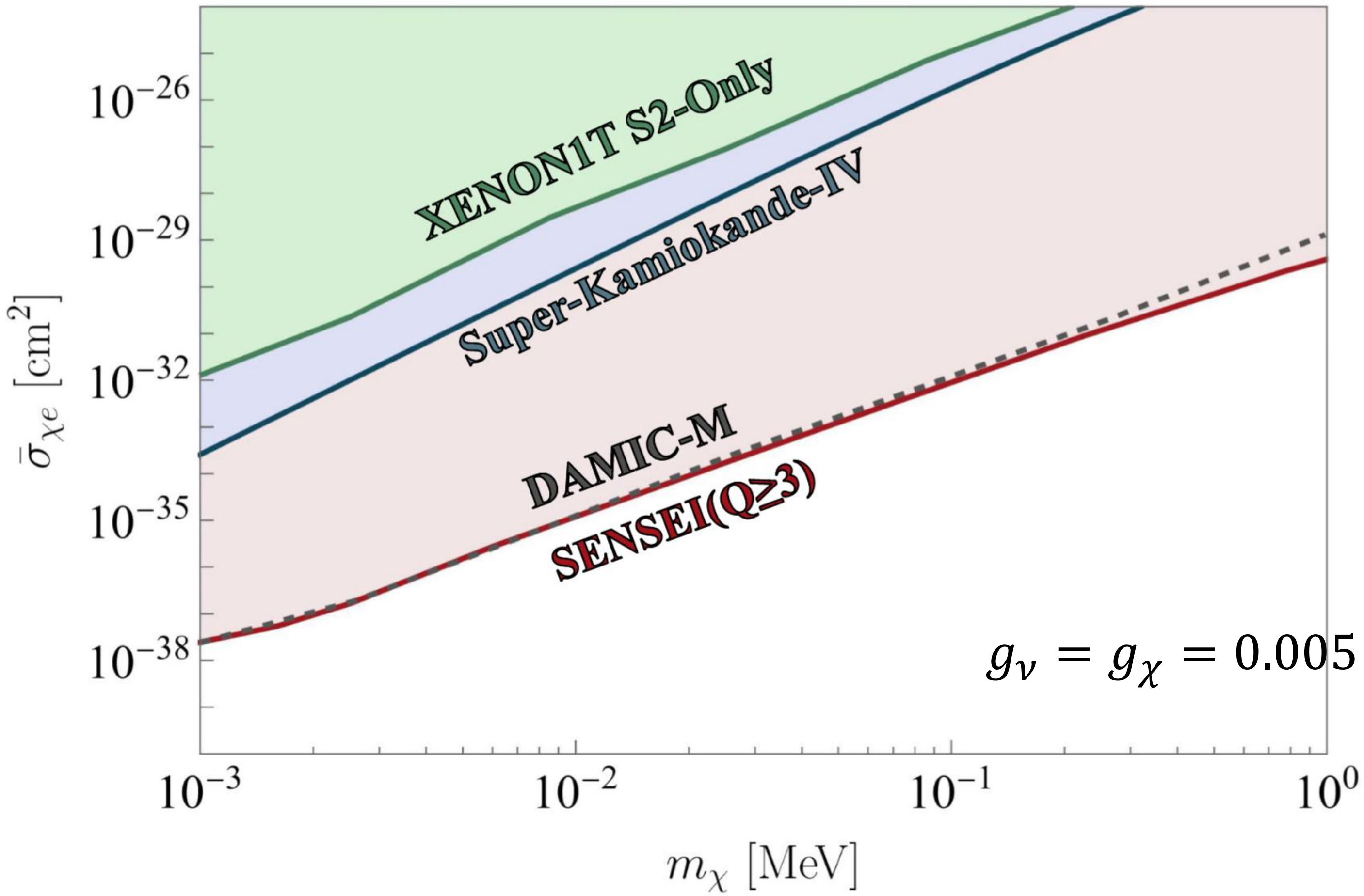
- Experiment threshold

  XENON1T: 186 eV

  Super-K: 3.9 MeV

Upper Limit

SENSEI vs Super-Kamiokande-IV vs XENON-1T only S2 signals



$$\bar{\sigma}_{\chi e} = \frac{\mu_{\chi e}^2}{\pi}\left(\frac{g_\chi g_e}{\alpha^2 m_e^2 + m_{Z'}^2}\right)^2$$

Summary

- We give the computational framework for computing CC SNνBDM and provide more relatively accurate results for the effective distance D_{eff}.
- Compared with cosmic ray electron boosted dark matter, SNνBDM has higher flux.
- For detecting BDM, considering Plasmon Resonance Techniques can have a better exclusion capability

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