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Migdal effect as an inelastic channel in dark matter direct detection

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Reference: Phys. Rev. D **102**, 121303(R) / arXiv:2007.10965

Dark Matter Direct Detection

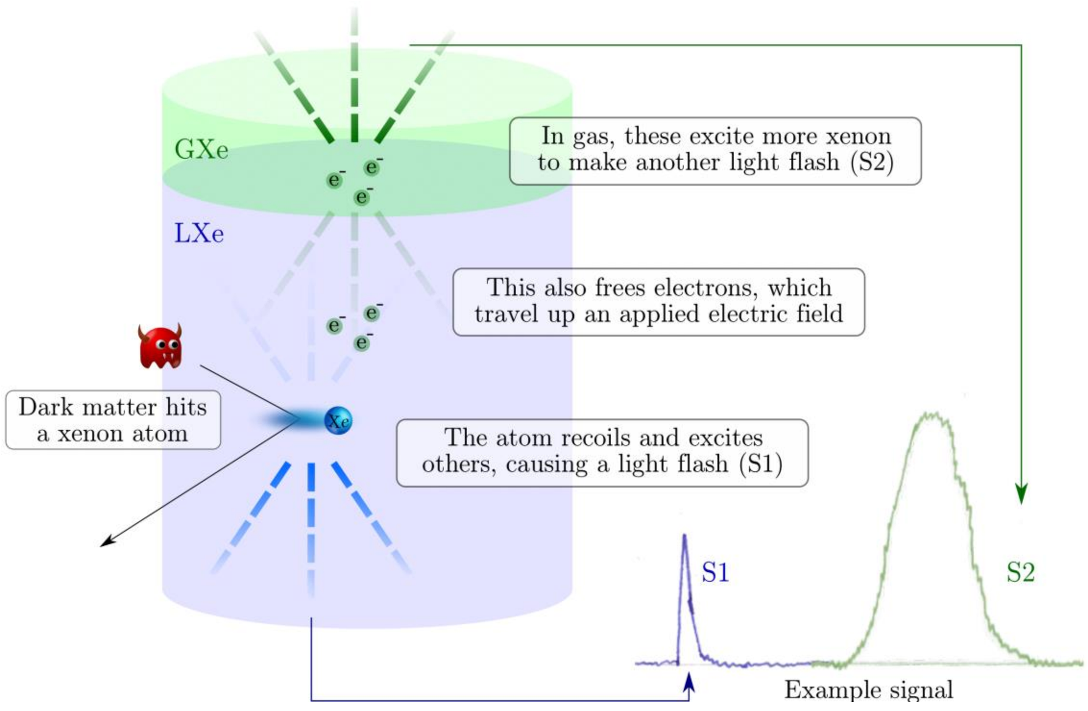
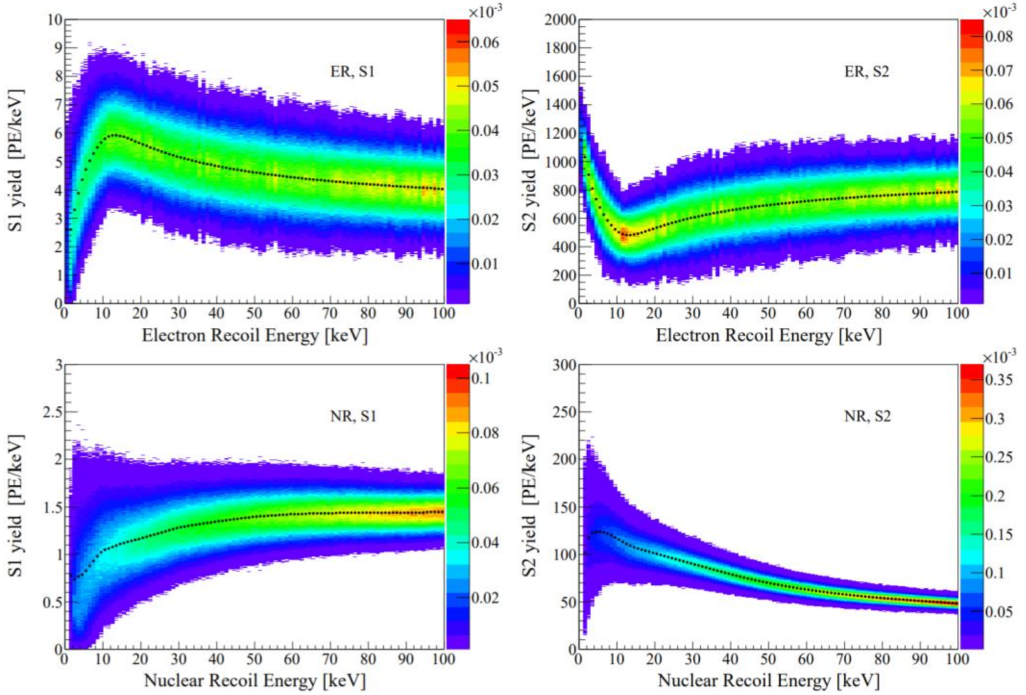


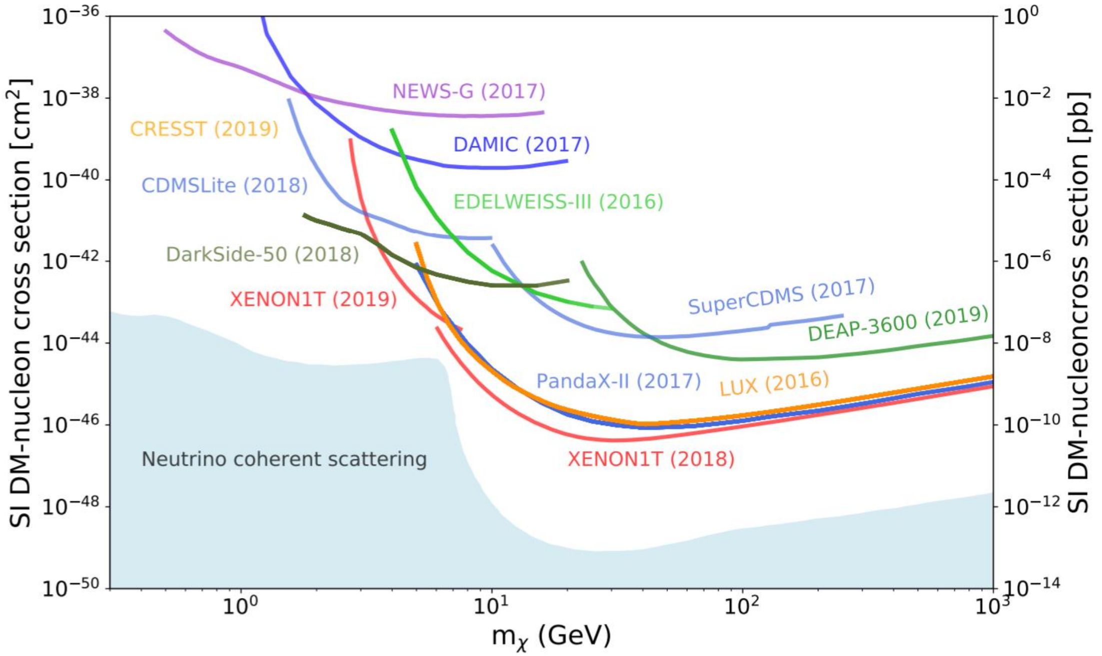
Photo from XENON Collaboration website.

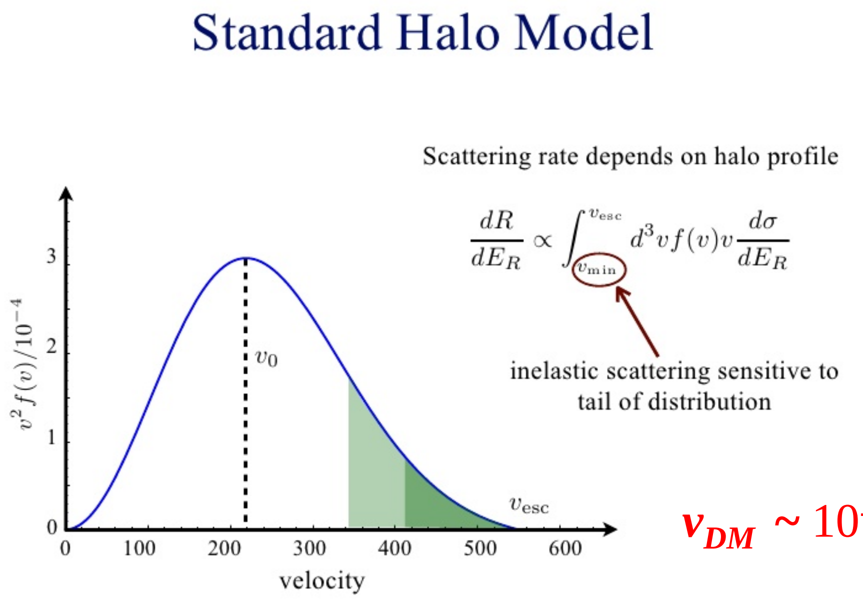
Discrimination of
Nuclear Recoil (NR) & Electronic Recoil (ER)



E. Aprile *et al*., Journal of Cosmology and Astroparticle Physics 2016, 027 (2016).

Restrictions on Light Dark Matter Search





$v_{DM} \sim 10^{-3}\, c$

GeV mass → keV kinematic energy

Nucleus (Atom) Mass $\sim A^* m_p \sim 100$ GeV

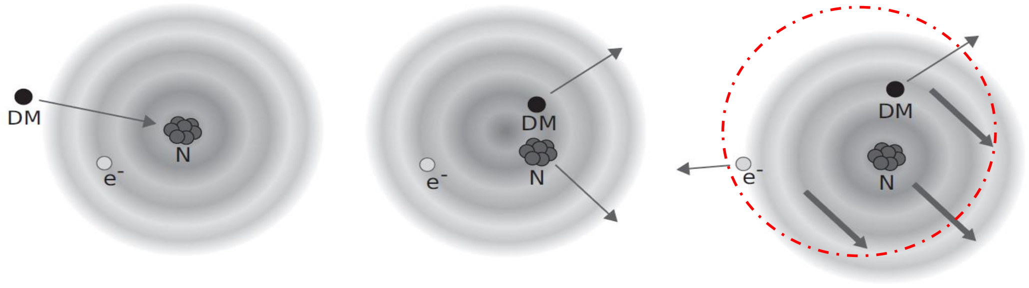
Efficiency of energy transfer: $r = \dfrac{4\, m_{inc}\, m_{tar}}{(m_{inc} + m_{tar})^2}$

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

$\langle n'l'm' \,|\, 1 \,|\, nlm \rangle = \delta_{nn'}\,\delta_{ll'}\,\delta_{mm'}$
$\langle n'l'm' \,|\, 0 \,|\, nlm \rangle = 0$

Migdal Effects

$$|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$$



The Migdal Factor:

$$\boxed{\mathbf{q}_e = m_e\mathbf{v} = m_e/m_A\mathbf{q}}$$

strongly suppressed by mass ratio

$$Z_{FI}(\mathbf{q}_e) = \int \prod_i d^3\mathbf{x}_i\, \Phi^*_{E^F_{ec}}(\{\mathbf{x}\})e^{-i\sum_i \mathbf{q}_e\cdot\mathbf{x}_i}\Phi_{E^I_{ec}}(\{\mathbf{x}\})$$

$$\sum_F |Z_{FI}|^2 = \underbrace{|Z_{II}|^2}_{\sim 1} + \sum_{n,\ell,n',\ell'} p^d_{q_e}(n\ell \to n'\ell') + \sum_{n,\ell}\int \frac{dE_e}{2\pi}\frac{d}{dE_e}p^c_{q_e}(n\ell \to E_e)$$

elastic *excitation* *ionization*

Masahiro Ibe, Wakutaka Nakano, Yutaro Shoji, and Kazumine Suzuki, J. High Energy Phys. **2018**, 194 (2018).

Migdal Effects – Inelastic Channel of DM detection

- Additional electron emission coming from the moving nucleus.
- Observed like an ER event but actually a NR.
  - Misleading NR/ER Distinguishment
  - Easier (More energetic signals produced) to be detected with given analyzable thresholds
  - Allowing more opportunity of low-mass DM exchanged enough amount of energy with heavy nuclei to be detected.

$$q^\mu J_\mu = 0$$

$$|\hat{J}_\perp|^2 \sim 2|\hat{J}_\parallel|^2 = 2\frac{\omega^2}{|\vec{q}|^2}|\rho|^2$$

Migdal-Photoabsorption Relation

transition matrix element

Migdal:

$$M_{FI} = \left\langle F \left| e^{-i\frac{m_e}{m_A}\vec{q}_A\cdot\sum_{i=1}^{Z}\vec{r}_i} \right| I \right\rangle$$

$$M_{FI}^{(1)} = -i\frac{m_e}{m_A}\vec{q}_A\cdot\vec{D}_{FI}$$

Photoabsorption:

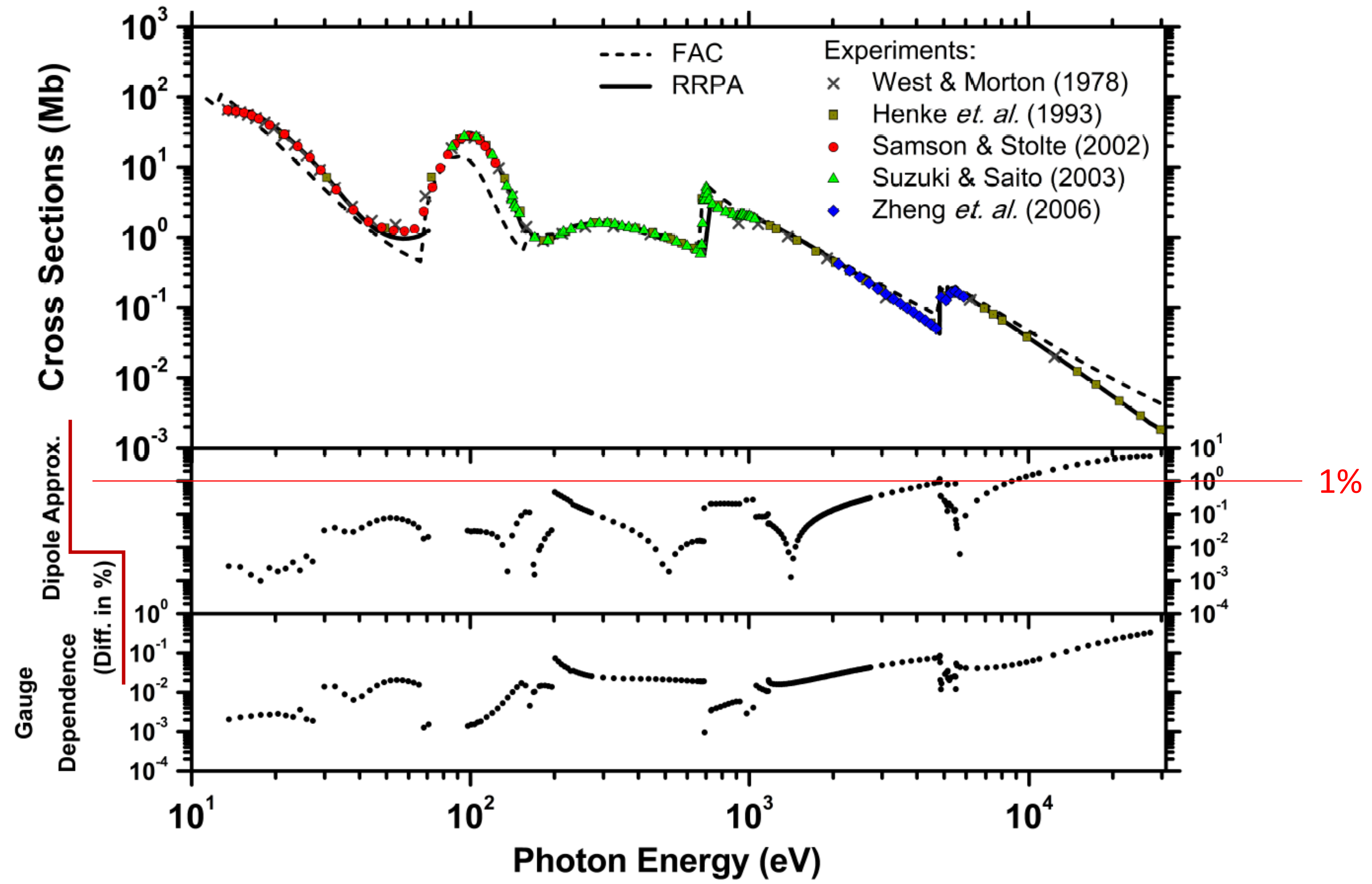
$$P_{FI} = \hat{\varepsilon}\cdot\left\langle F \left| \sum_{i=1}^{Z} \cancelto{1}{e^{i\vec{k}\cdot\vec{r}_i}}\,\vec{\alpha}_i \right| I \right\rangle \equiv \hat{\varepsilon}\cdot\vec{O}_{FI}$$

$$\vec{O}_{FI}^{(E1)} = iE_r\vec{D}_{FI}$$

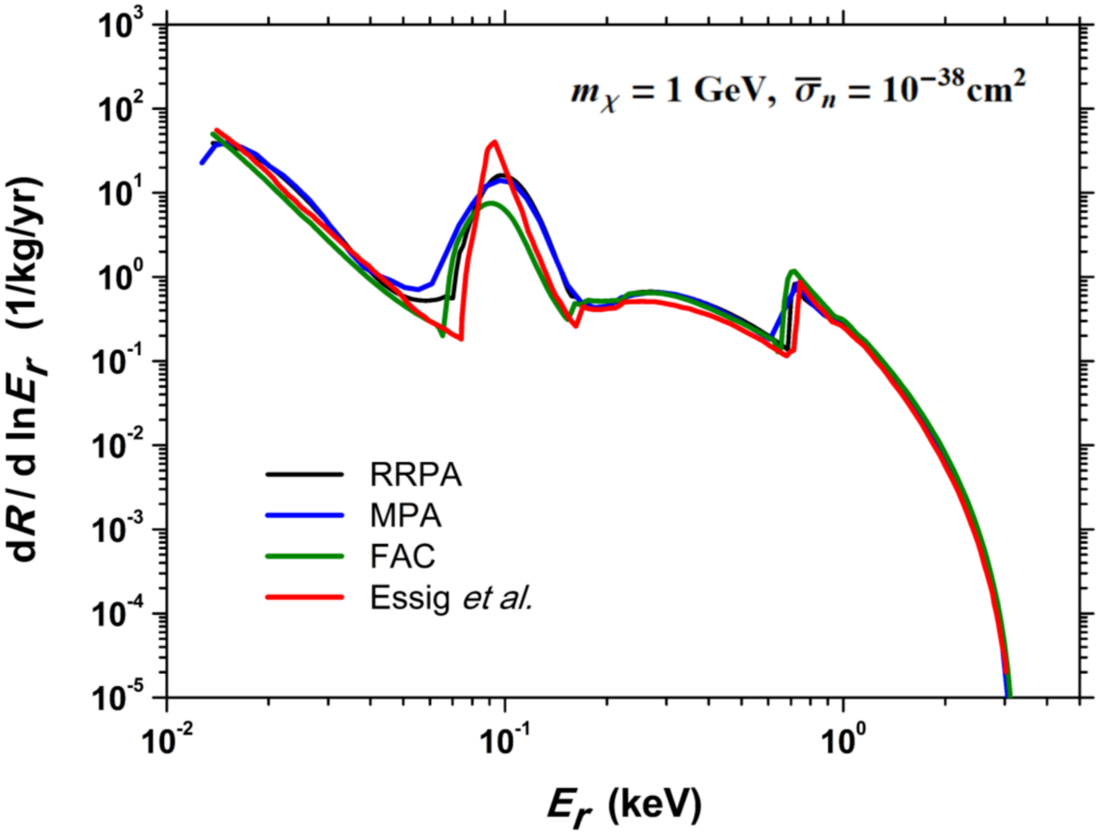
Dipole: $\vec{D}_{FI} \equiv \left\langle F \left| \sum_{i=1}^{Z} \vec{r}_i \right| I \right\rangle$

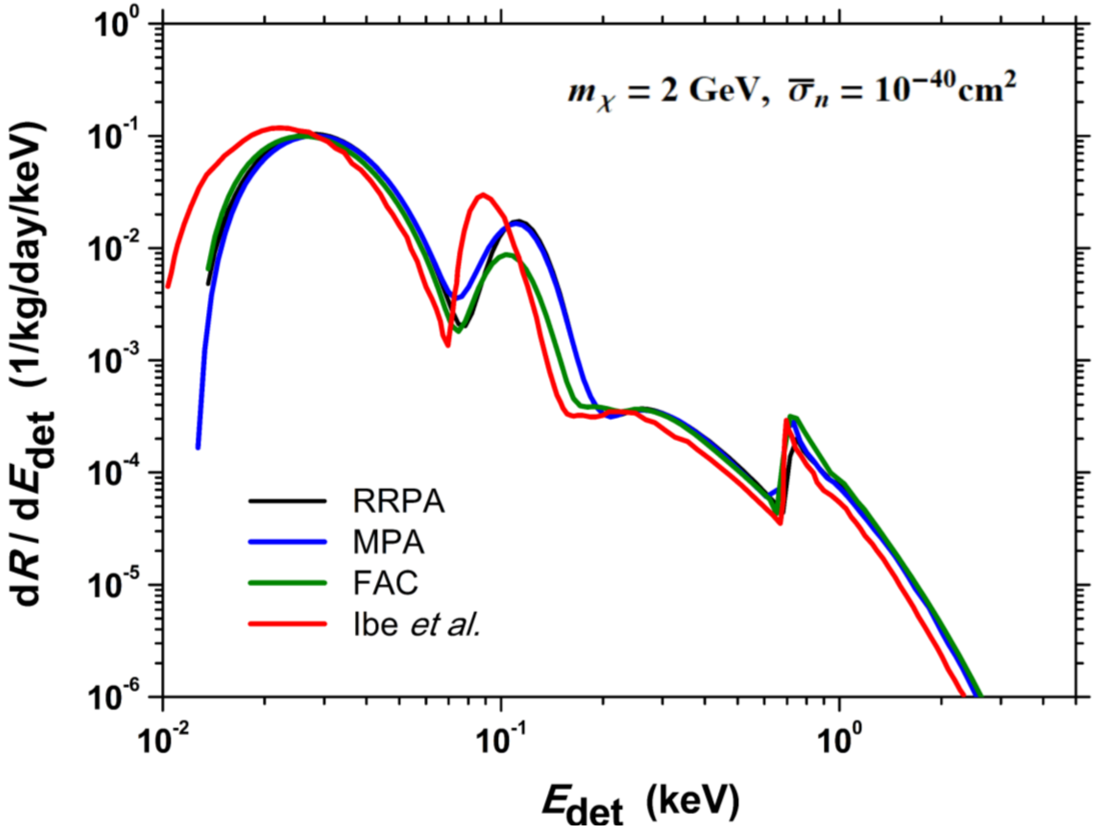
The leading order terms dominate when long wavelength limit valid. $e^{i\vec{k}\cdot\vec{r}} \to 1$

Dipole Approx. for Xenon Photoionization



Event Rates of Migdal Effects

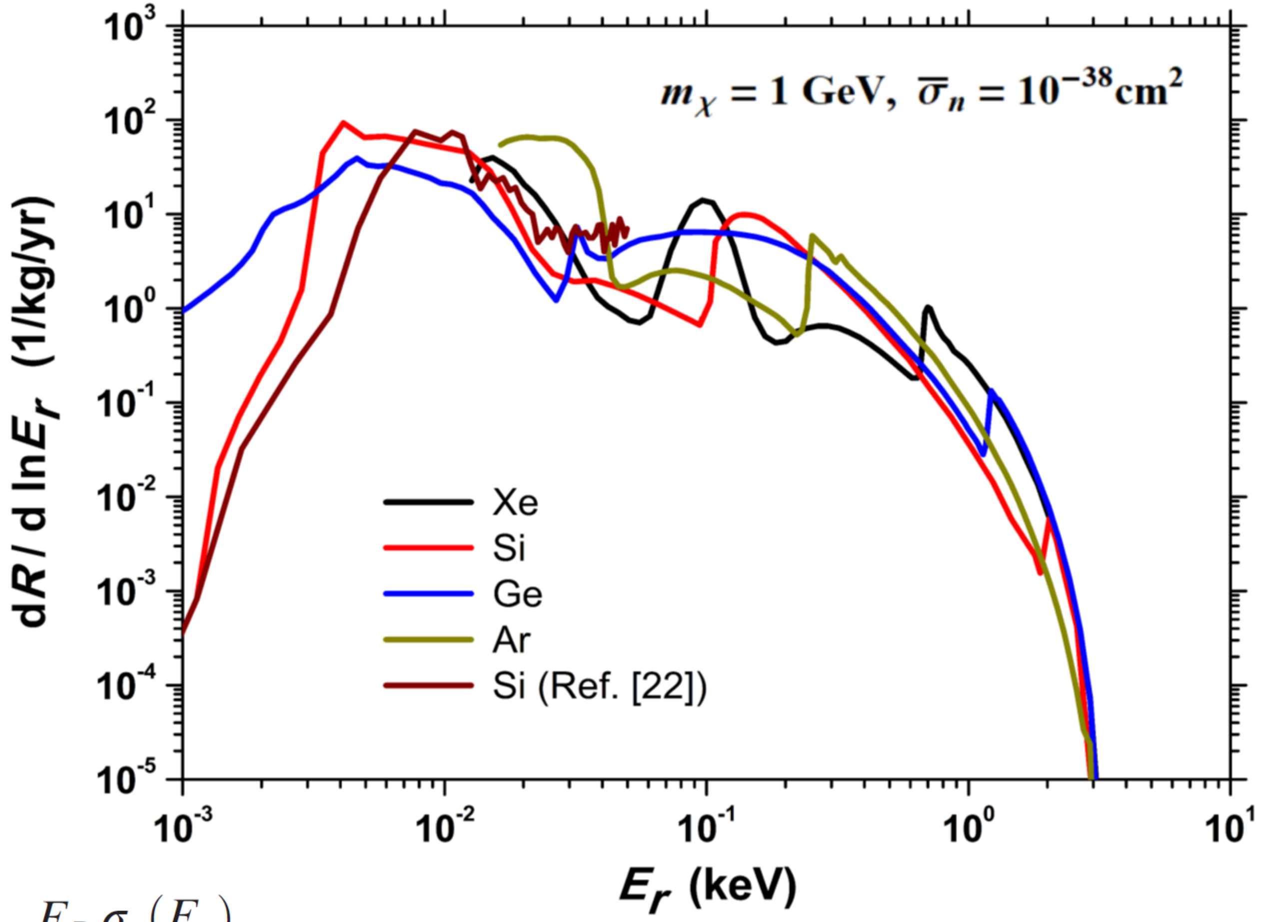




$$\frac{dR}{dE_r} = n_\chi N_T \frac{m_e^2}{\mu_N^2} \overline{D^2}_{FI} \int dE_R \, \tilde{\sigma}_N(q_A) E_R \eta(v_{\min})$$

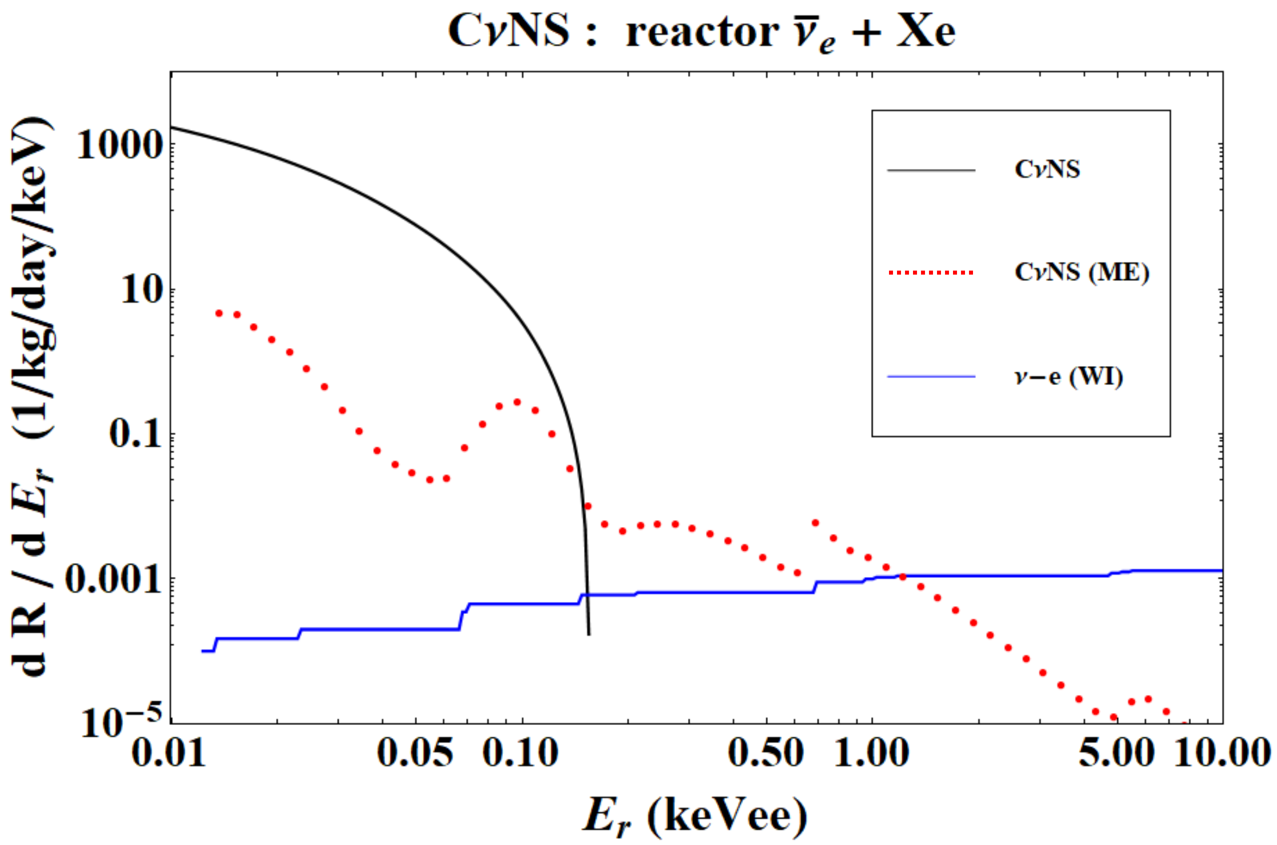
$$\frac{dR}{dE_{\rm det}} = \int dE_r \delta(E_{\rm det} - q_{\rm nr} E_R - E_r) \; \frac{dR}{dE_r}$$

Easily Applied for Other Atoms



$$\frac{d\sigma^{(\mathrm{MPA})}}{dE_R dE_r} = \frac{m_e^2}{\mu_N^2 v_\chi^2} \tilde{\sigma}_N(q_A) \frac{E_R}{E_r} \frac{\sigma_\gamma(E_r)}{4\pi^2 \alpha}$$

Another Application for Migdal Effect



$$\frac{d\sigma}{dE_R} \simeq \sum_{E_{ec}^F} \frac{d\sigma_{C\nu NS}}{dE_R} \times |Z_{FI}(q_e)|^2$$

$$\frac{dR}{dE_r} = \frac{G_F^2 Q_W^2}{4\pi} \frac{m_e^2}{E_r} \frac{\sigma_\gamma(E_r)}{4\pi^2\alpha} \int dE_\nu\, f(E_\nu) \int dE_R\, F_A^2(q_A) \left(1 - \frac{m_A E_R}{2E_\nu^2}\right) E_R$$

Thanks for your attention!

Reference: C.-P. Liu, Chih-Pan Wu, Hsin-Chang Chi, and Jiunn-Wei Chen,
"*Model-independent determination of the Migdal effect via photoabsorption*",
Phys. Rev. D **102**, 121303(R); arXiv:2007.10965