Improving the sensitivity to light dark matter with the Migdal effect

Giovanni Grilli di Cortona

grillidc@lnf.infn.it

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

based on: G^{2}dC, Andrea Messina, Stefano Piacentini, *Migdal effect and photon Bremsstrahlung: improving the sensitivity to light dark matter of liquid argon experiments*, **JHEP 11 (2020) 034**, arXiv: 2006.02453

SUSY 2021

Outline

- Introduction and motivation
- The Migdal effect
- Impact of the Migdal effect in LAr experiments
- Detecting the Migdal effect in nuclear scattering
- Conclusions

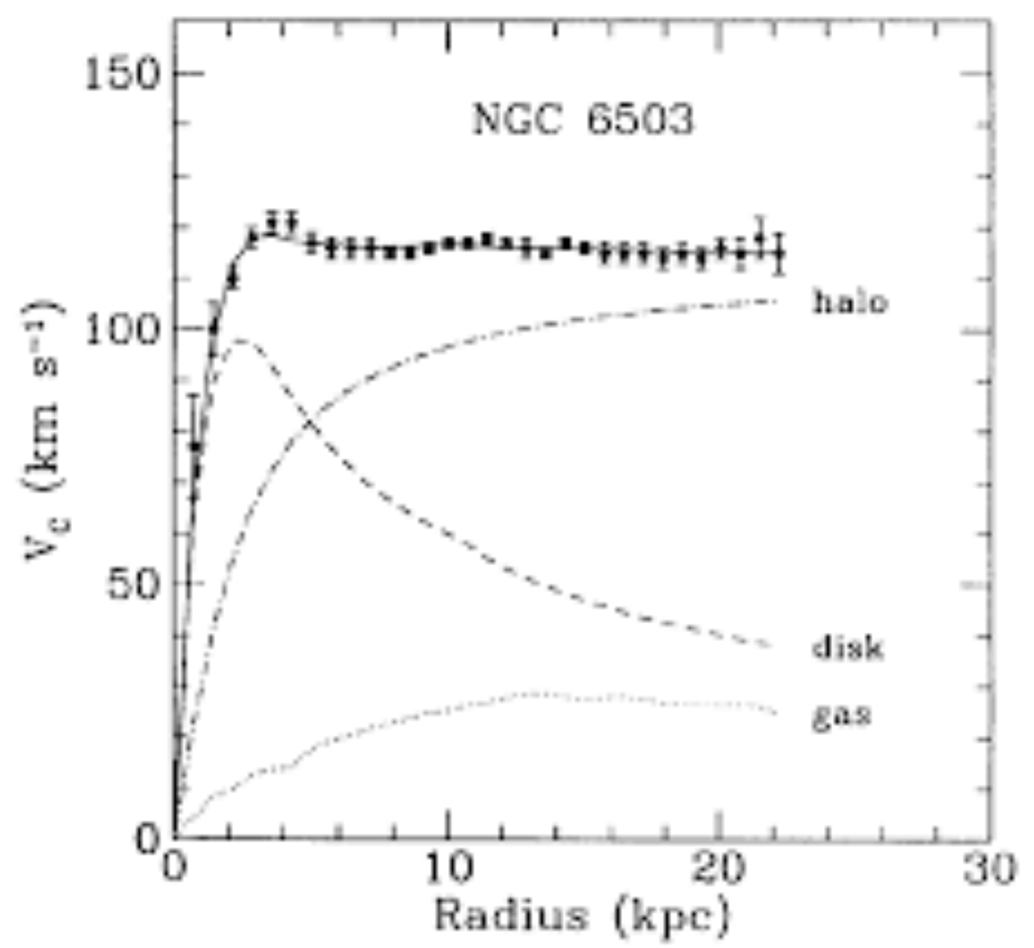
Introduction

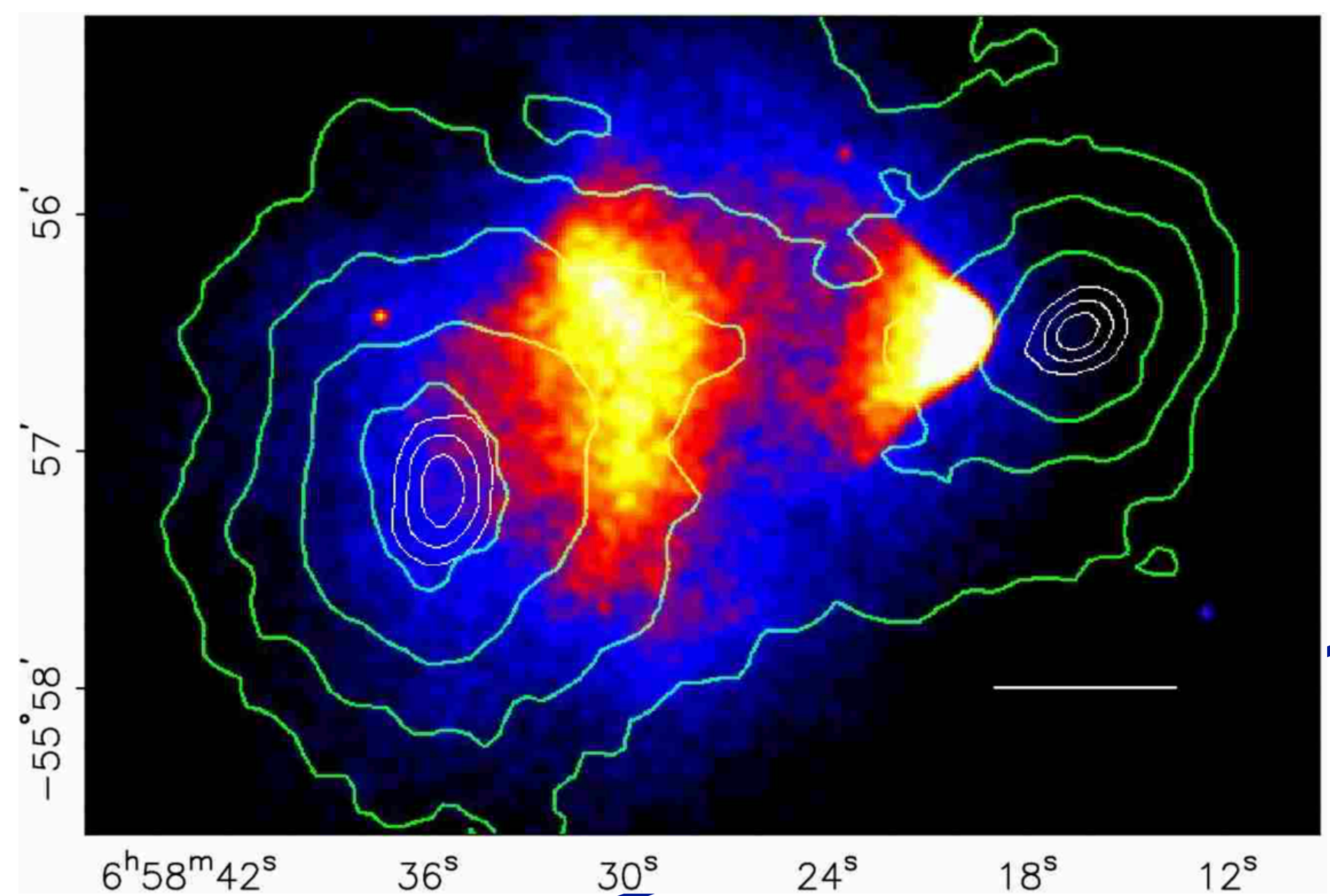
Introduction and motivation

Galaxies

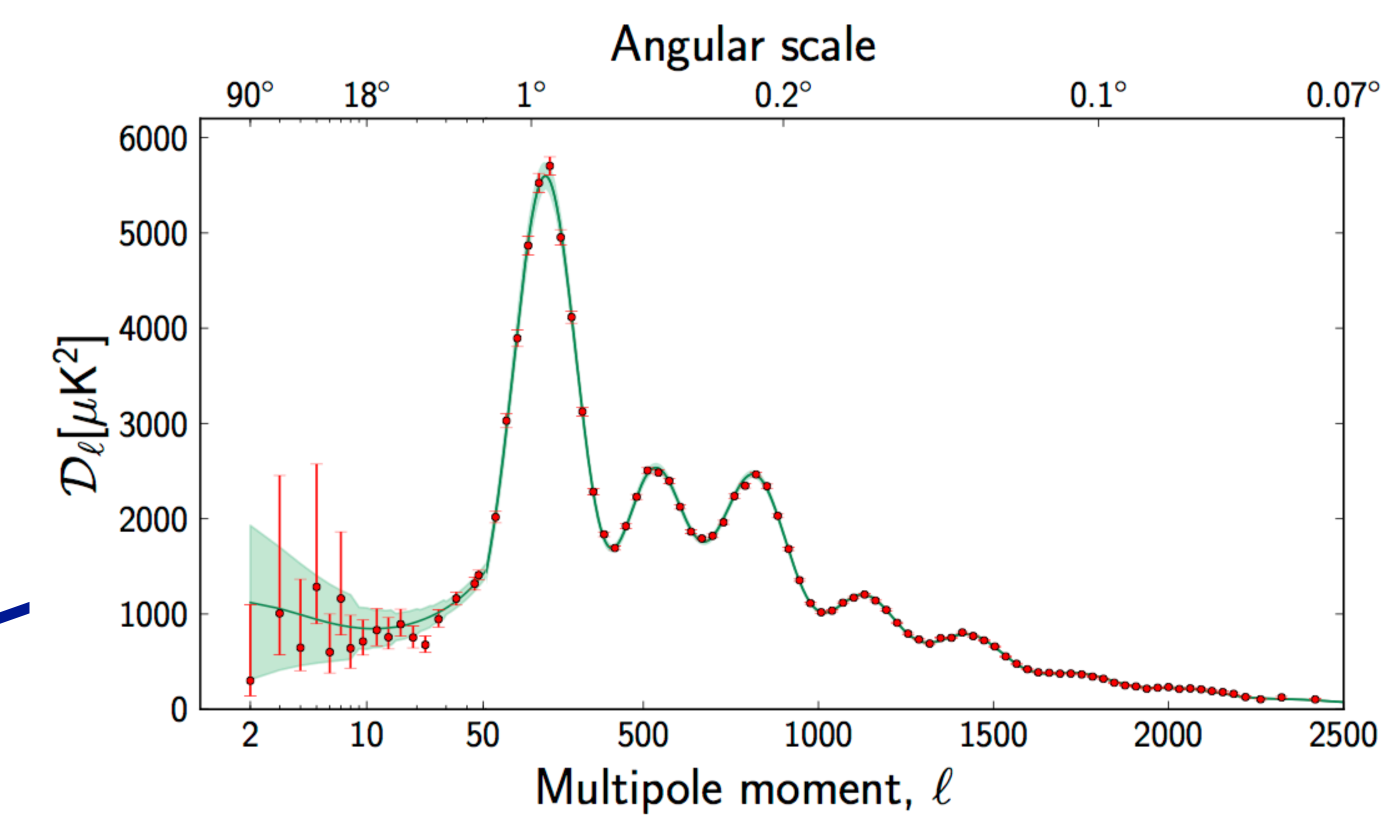
Clusters

Cosmic Microwave Background





[Clowe et al., APJL 648 (2006) L109-L113]

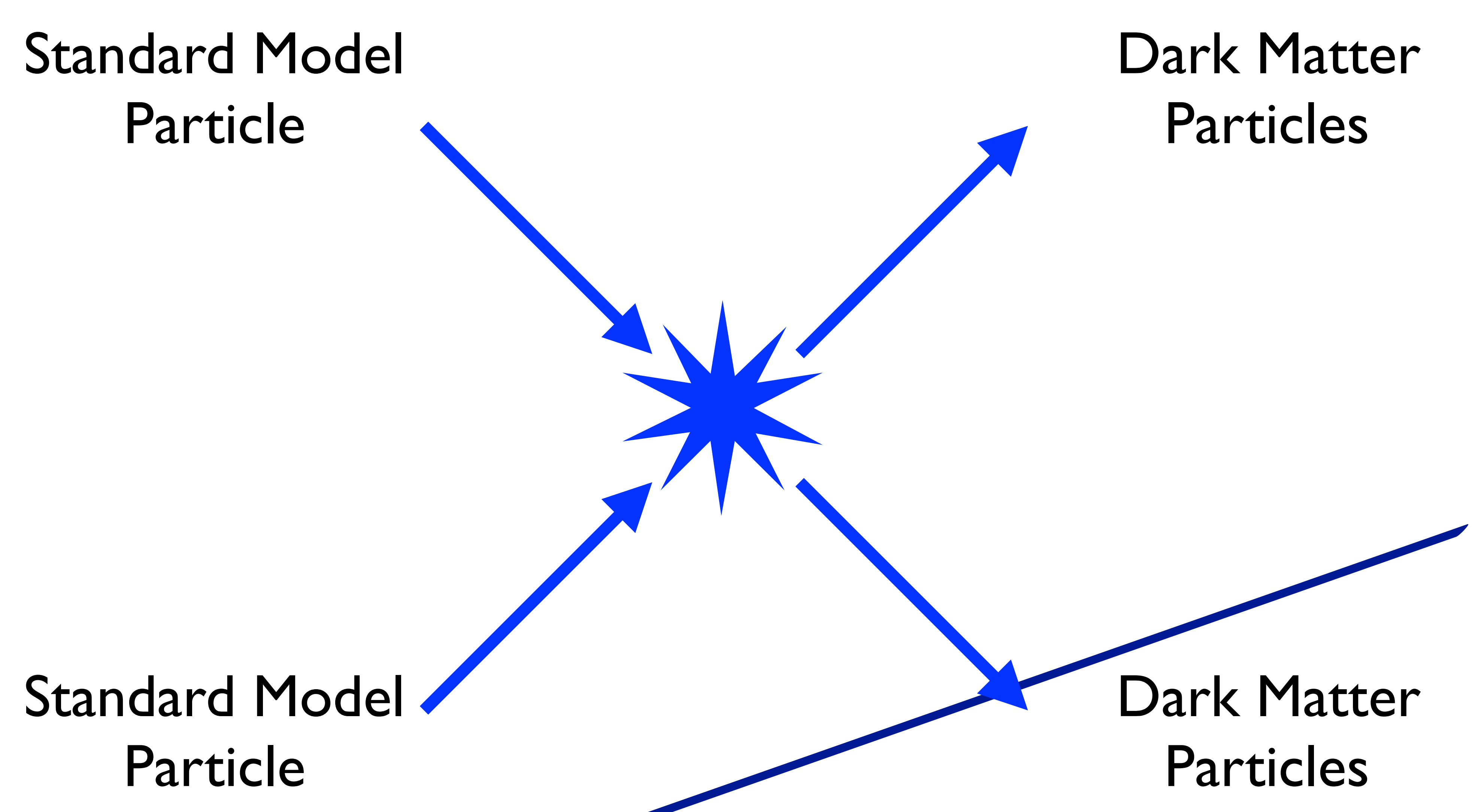


[Planck]

Small scales → Large scales

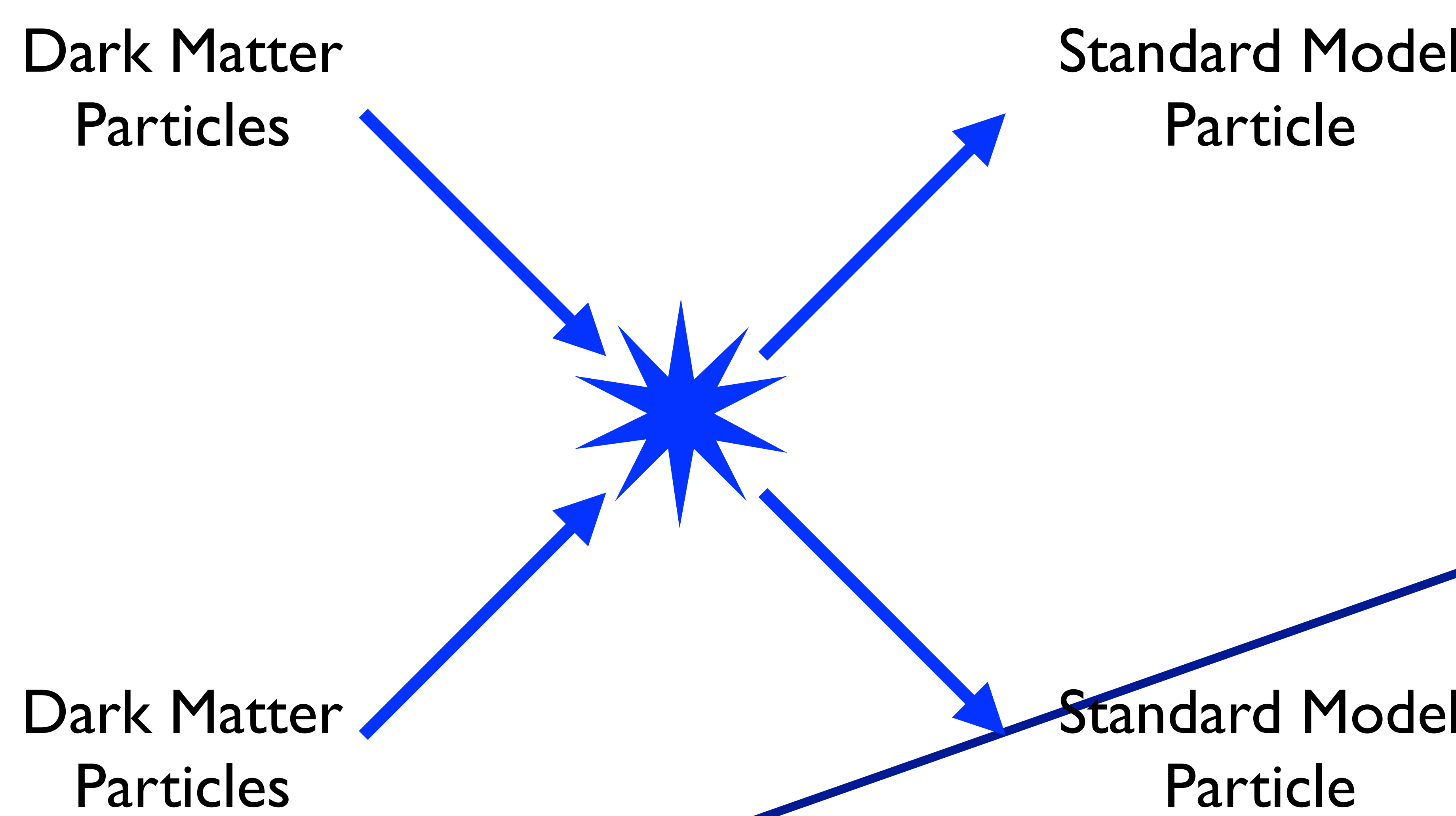
Introduction and motivation

Colliders



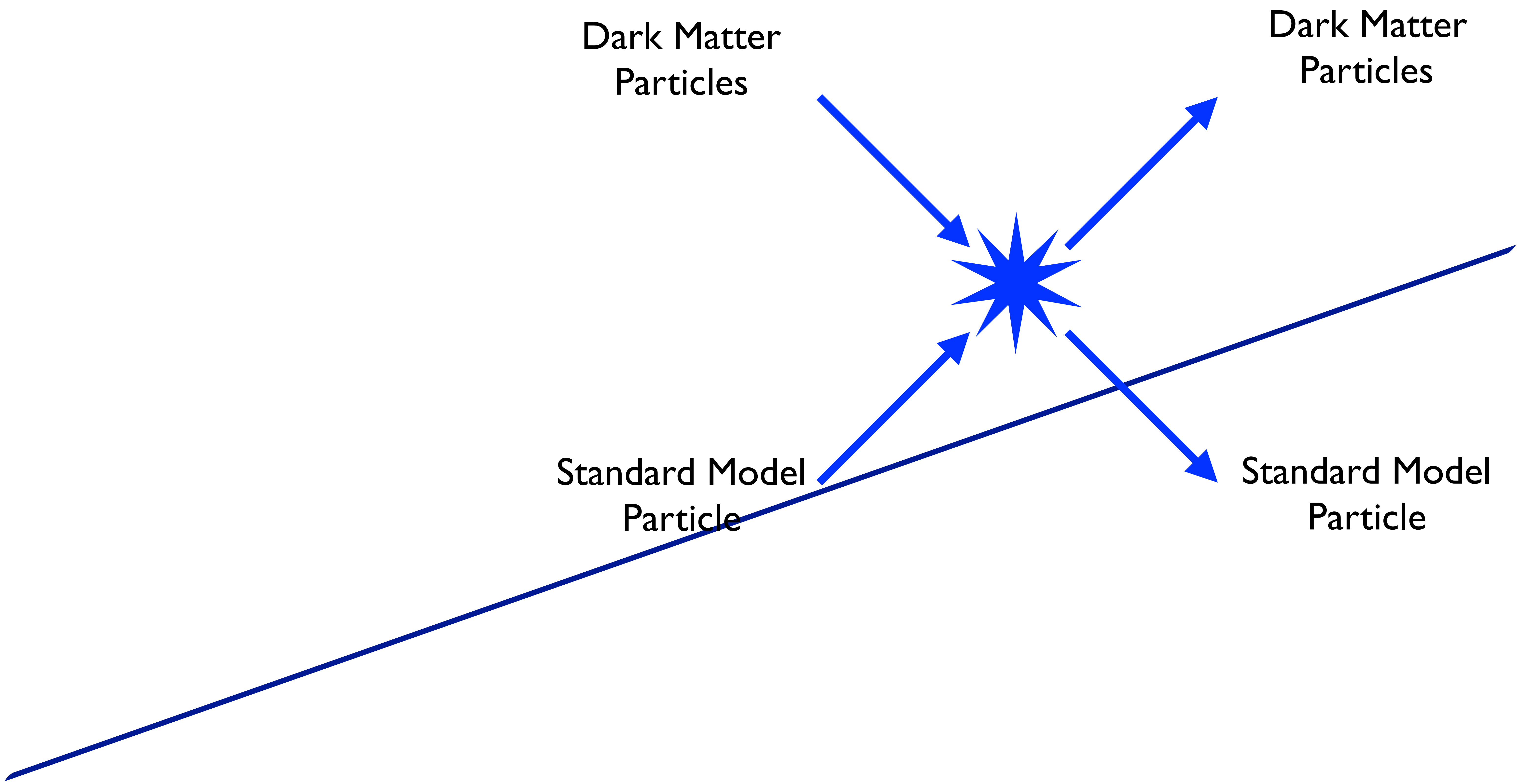
Introduction and motivation

Indirect detection

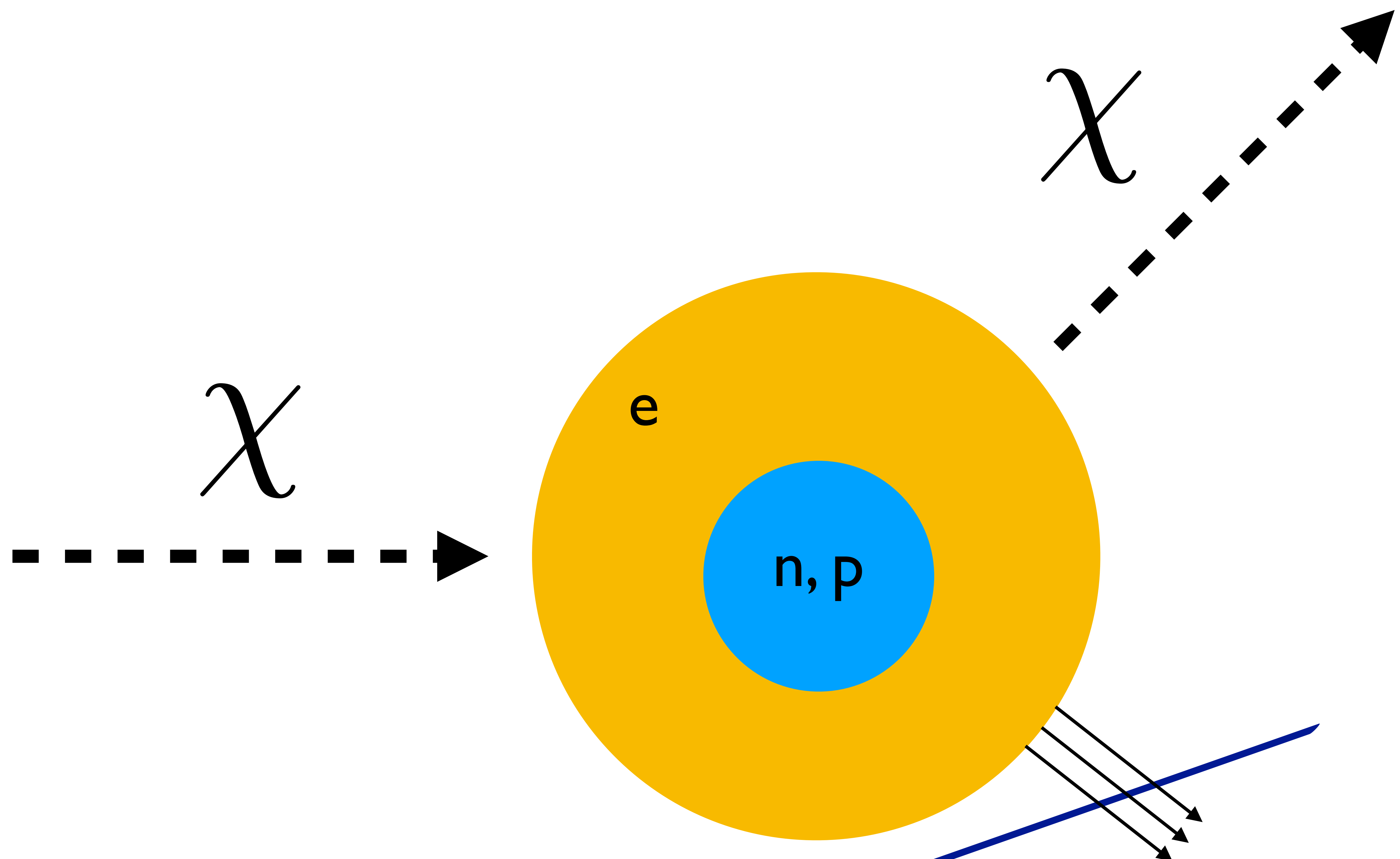


Introduction and motivation

Direct detection



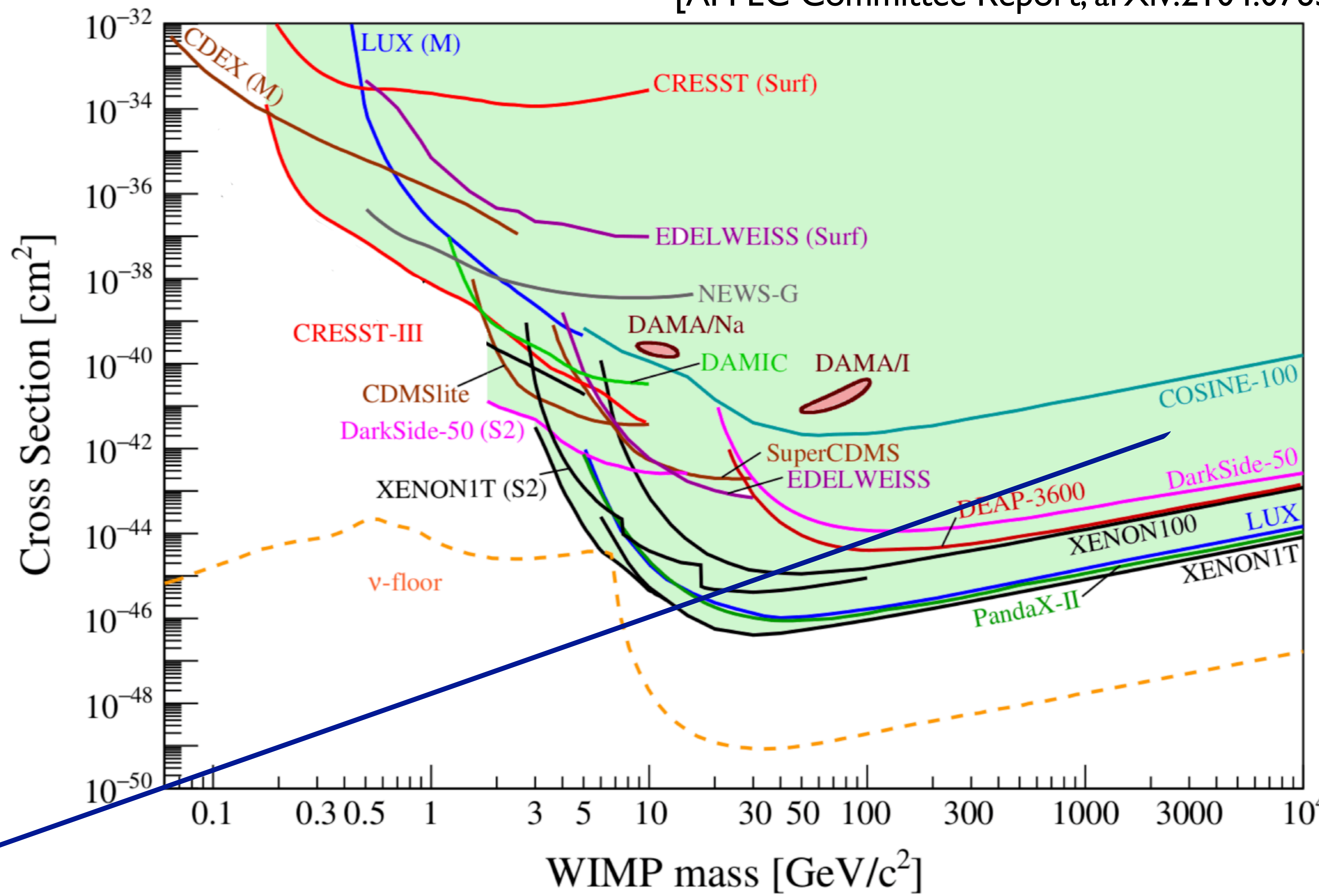
Direct detection



$$\frac{dR}{dE_R} = \frac{\rho_0 M_{\rm det}}{m_N m_\chi} \int_{v>v_{\rm min}} v f(v) \frac{d\sigma}{dE_R} dv$$

Direct detection

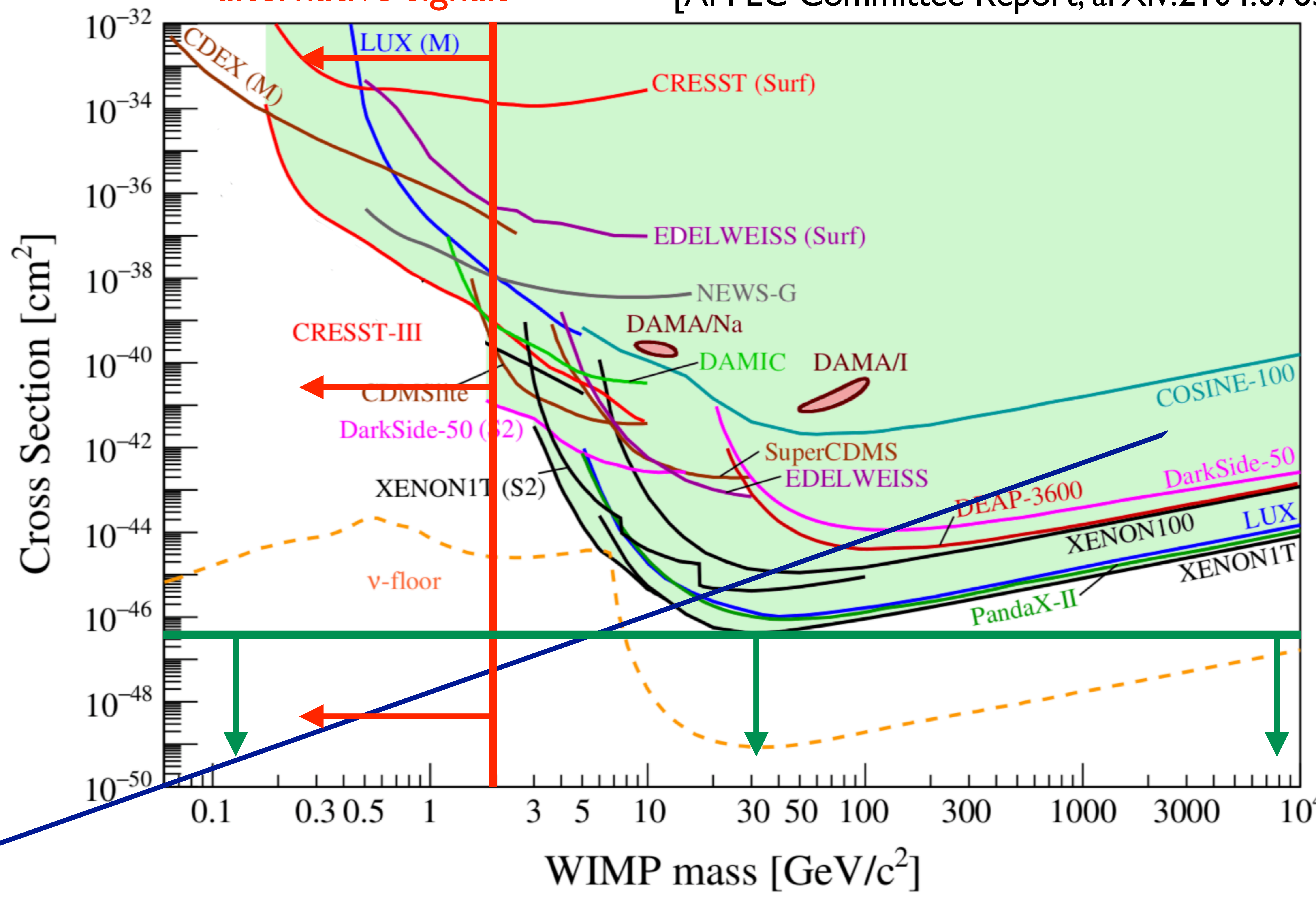
[APPEC Committee Report, arXiv:2104.07634]



Direct detection

lower threshold,
alternative signals

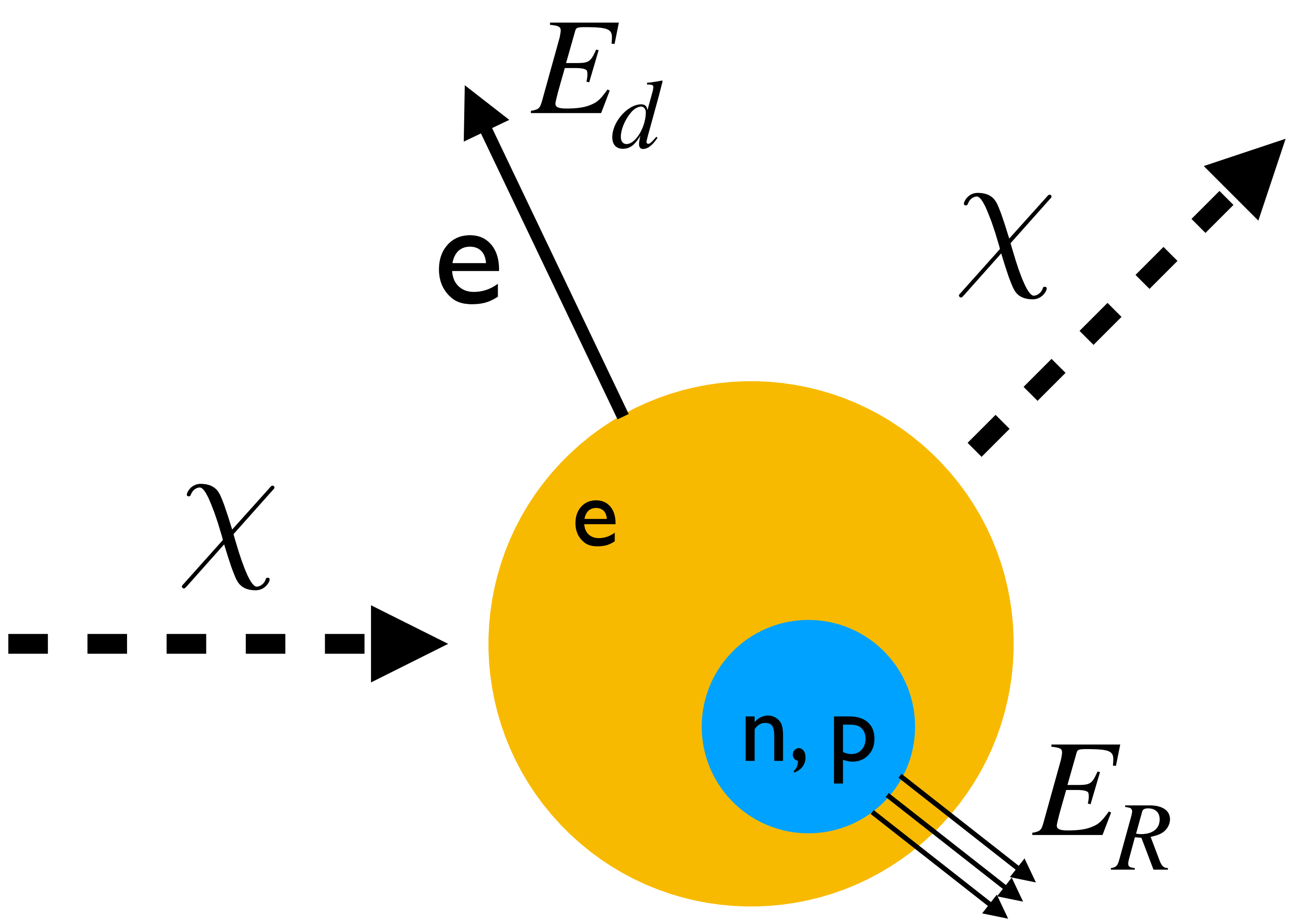
[APPEC Committee Report, arXiv:2104.07634]



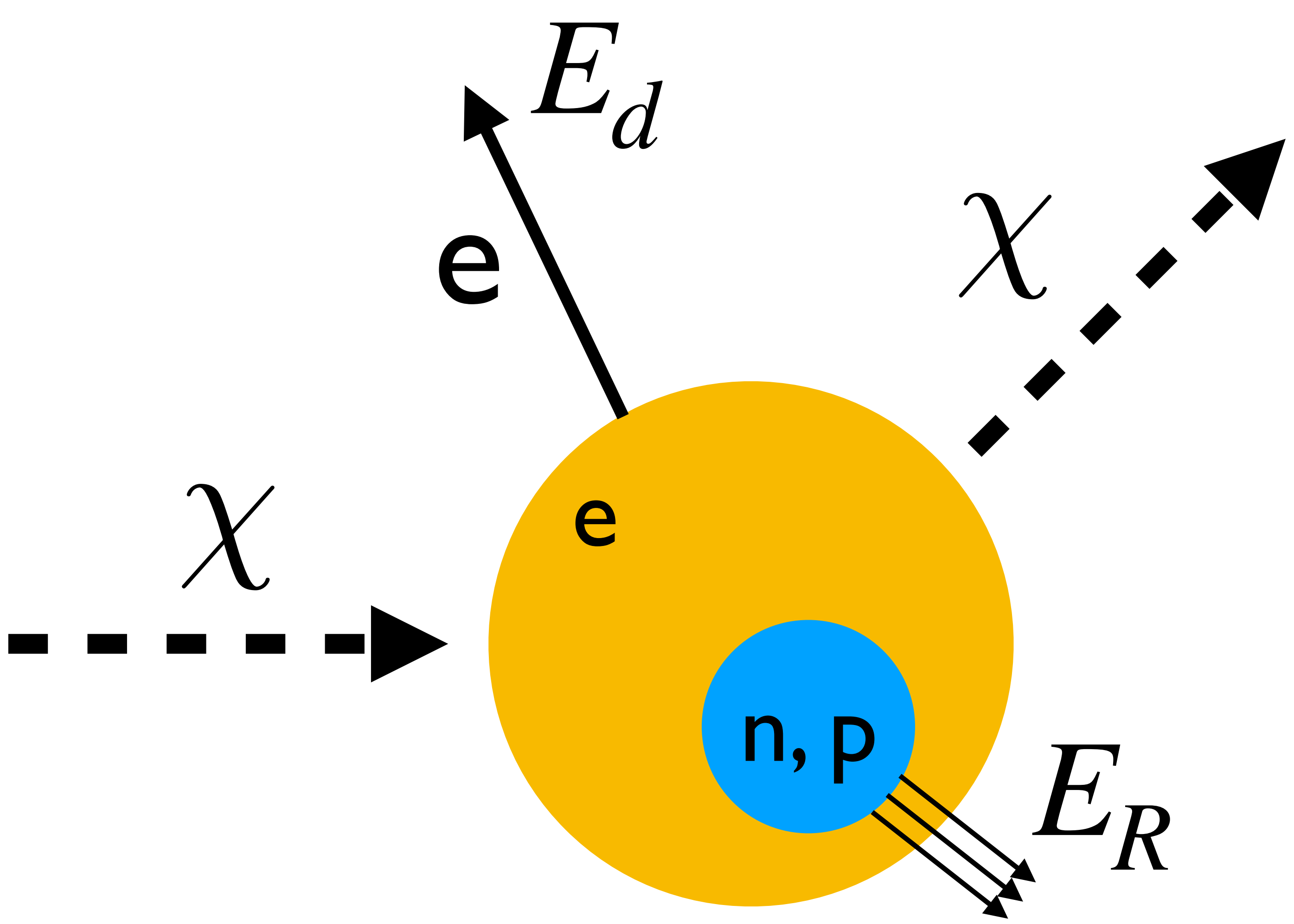
increase exposure or
volume of the
experiment

The Migdal effect

The Migdal effect



The Migdal effect



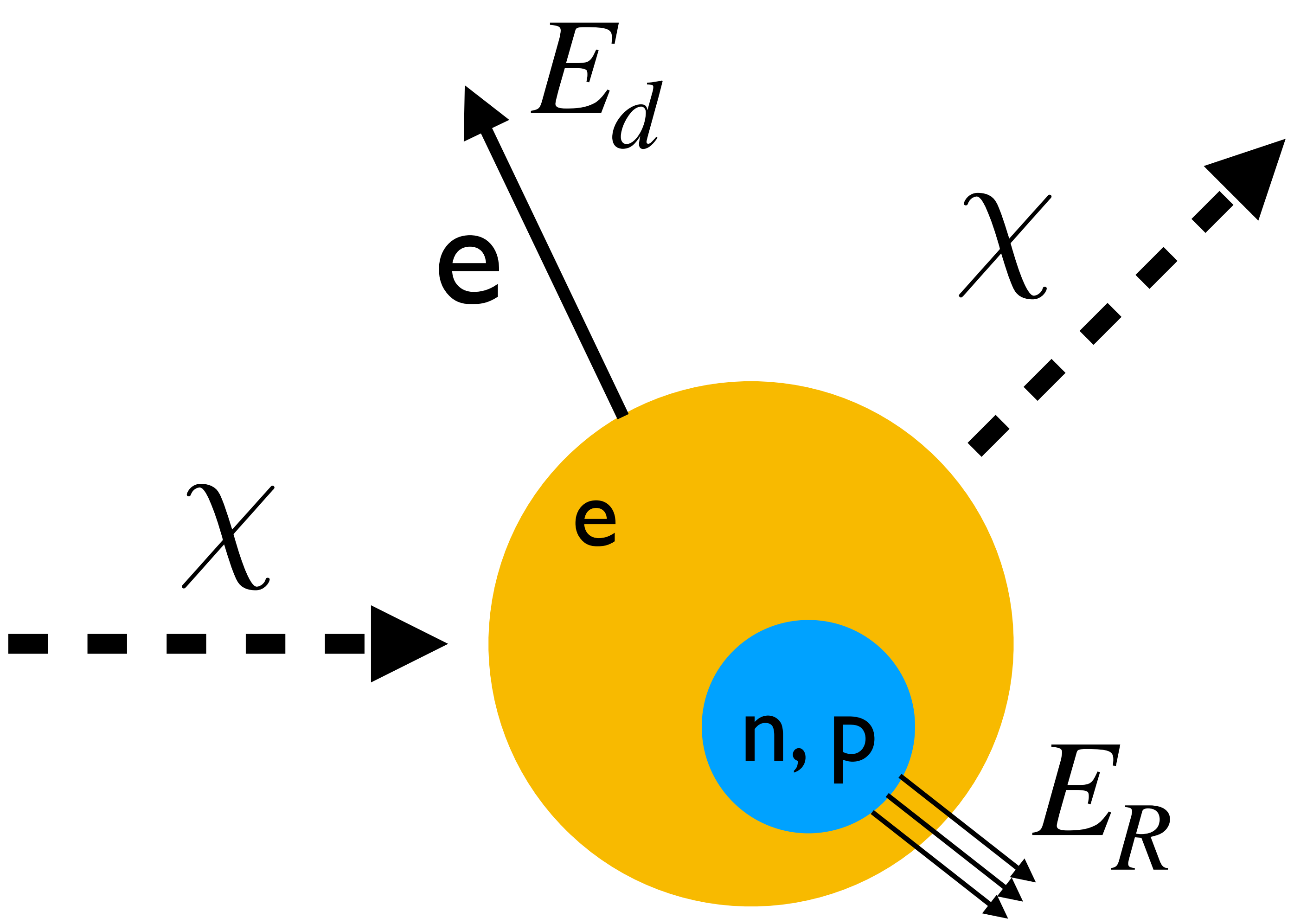
Kinematics

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} + \frac{E_d}{\sqrt{2 m_N E_R}}$$

$$E_R^{\max} = \frac{2\,\mu_N^2\, v_{\max}^2}{m_N}$$

$$E_d^{\max} = \frac{\mu_N\, v_{\max}^2}{2}$$

The Migdal effect



Kinematics

Nuclear recoil energy

Electron detected energy

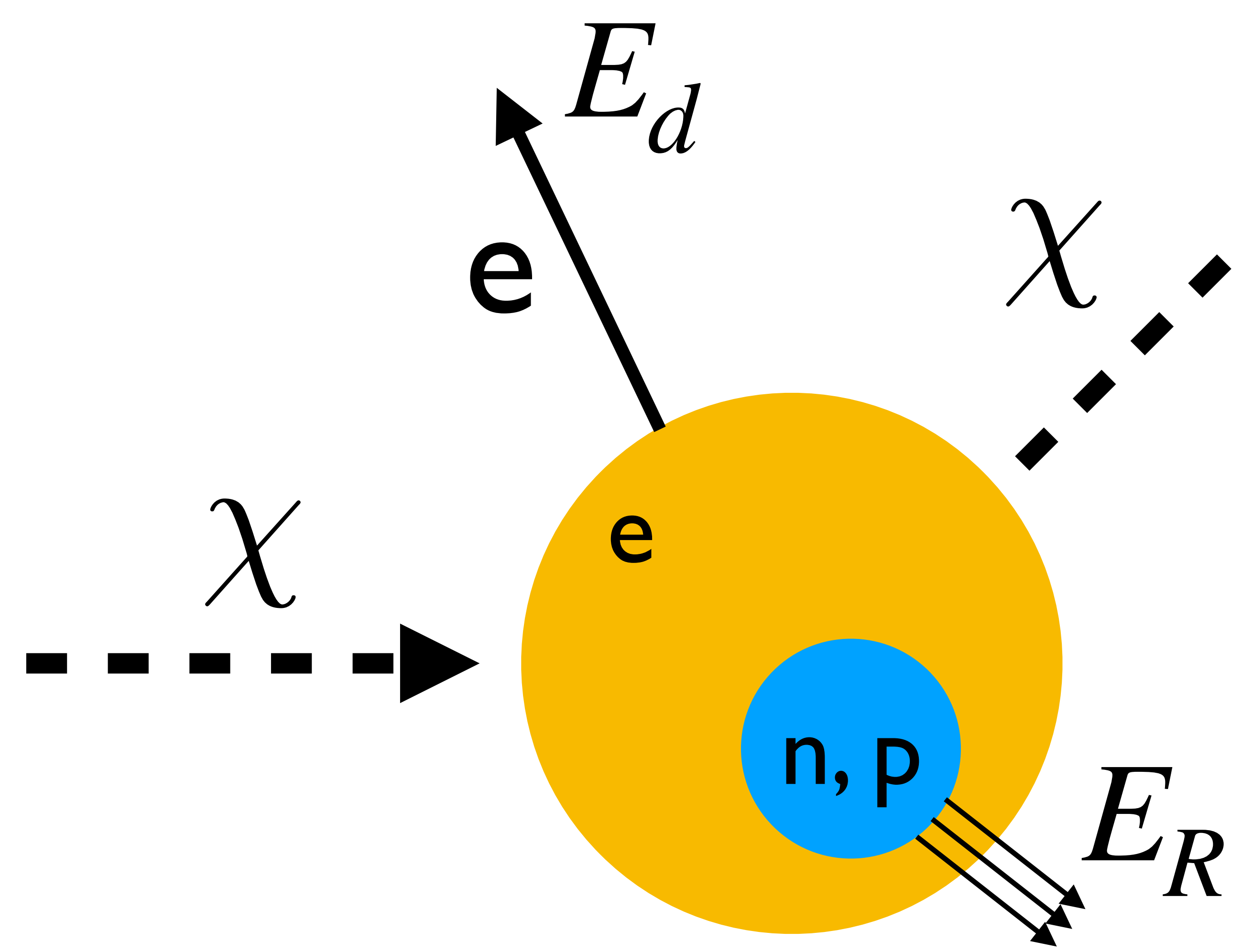
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} + \frac{E_d}{\sqrt{2 m_N E_R}}$$

DM-nucleus reduced mass

nucleus mass

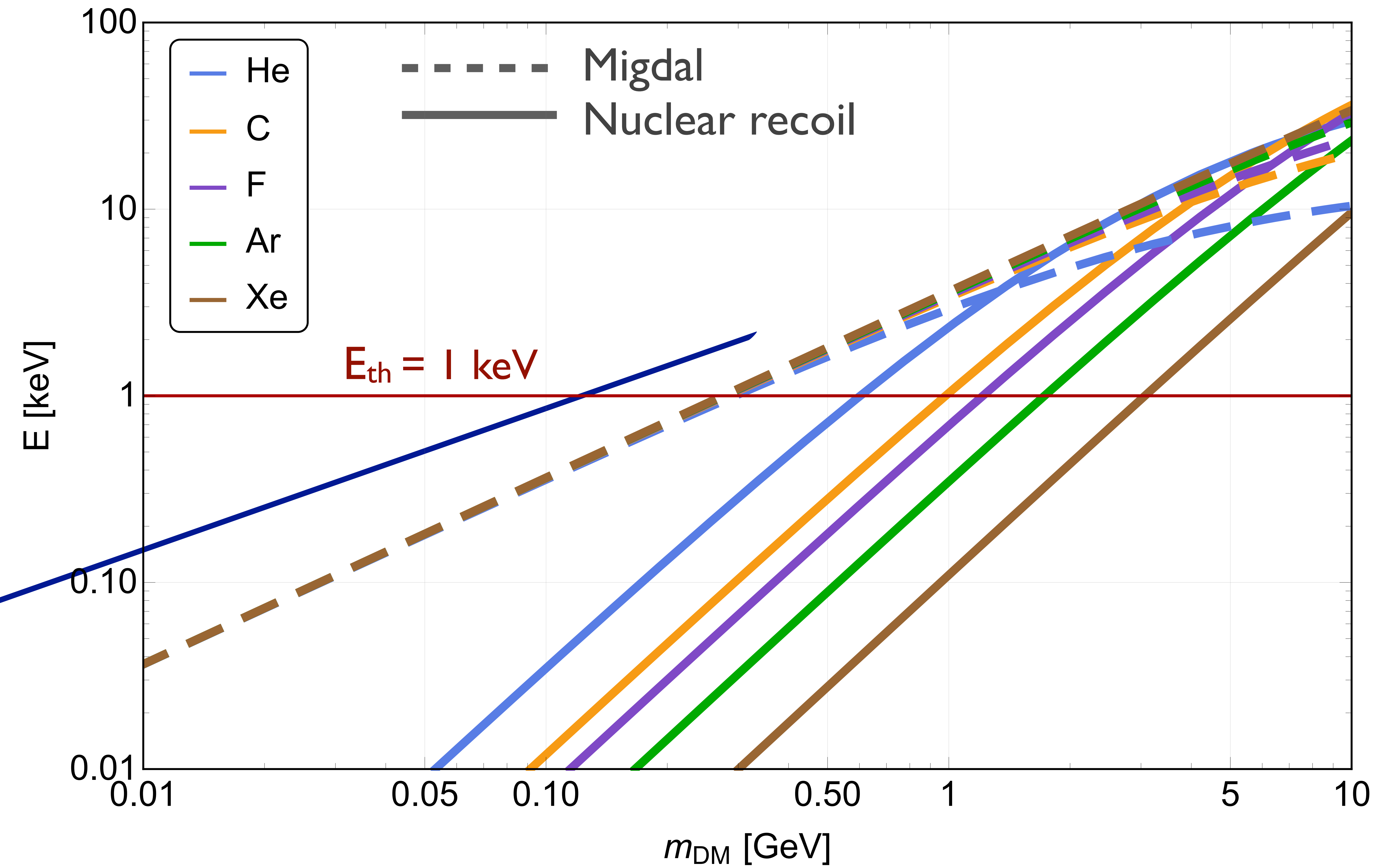
$$E_R^{\max} = \frac{2\,\mu_N^2\, v_{\max}^2}{m_N} \qquad E_d^{\max} = \frac{\mu_N\, v_{\max}^2}{2}$$

The Migdal effect



Kinematics

$$E_R^{\max} = \frac{2\,\mu_N^2\,v_{\max}^2}{m_N} \qquad E_d^{\max} = \frac{\mu_N\,v_{\max}^2}{2}$$



1. Threshold $E \lesssim 1$ keV
2. Sensitivity loss for $m_{DM} \lesssim 2\,\mathrm{GeV}$
3. $E_d^{\max} > E_R^{\max}$ for $m_{DM} \ll m_N$
4. The Migdal effect is sensitive to sub-GeV masses

The Migdal effect

$$\frac{d^2R}{dE_R dE_e} = \frac{dR}{dE_R} |Z(E_R, E_e)|^2$$

The Migdal effect

$$\frac{d^2R}{dE_R dE_e} = \boxed{\frac{dR}{dE_R}} |Z(E_R, E_e)|^2$$

DM nuclear recoil

The Migdal effect

$$\frac{d^2R}{dE_R dE_e} = \frac{dR}{dE_R} |Z(E_R, E_e)|^2$$

DM nuclear recoil

$$|Z(E_R, E_e)|^2 \simeq 1 + |Z_{\rm de}|^2 + |Z_{\rm ion}|^2$$

NR

de-excitation: negligible

ionization rate

The Migdal effect

$$\frac{d^2R}{dE_R dE_e} = \frac{dR}{dE_R} |Z(E_R, E_e)|^2$$

DM nuclear recoil

NR

de-excitation: negligible

ionization rate

$$|Z(E_R, E_e)|^2 \simeq 1 + |Z_{\rm de}|^2 + |Z_{\rm ion}|^2$$

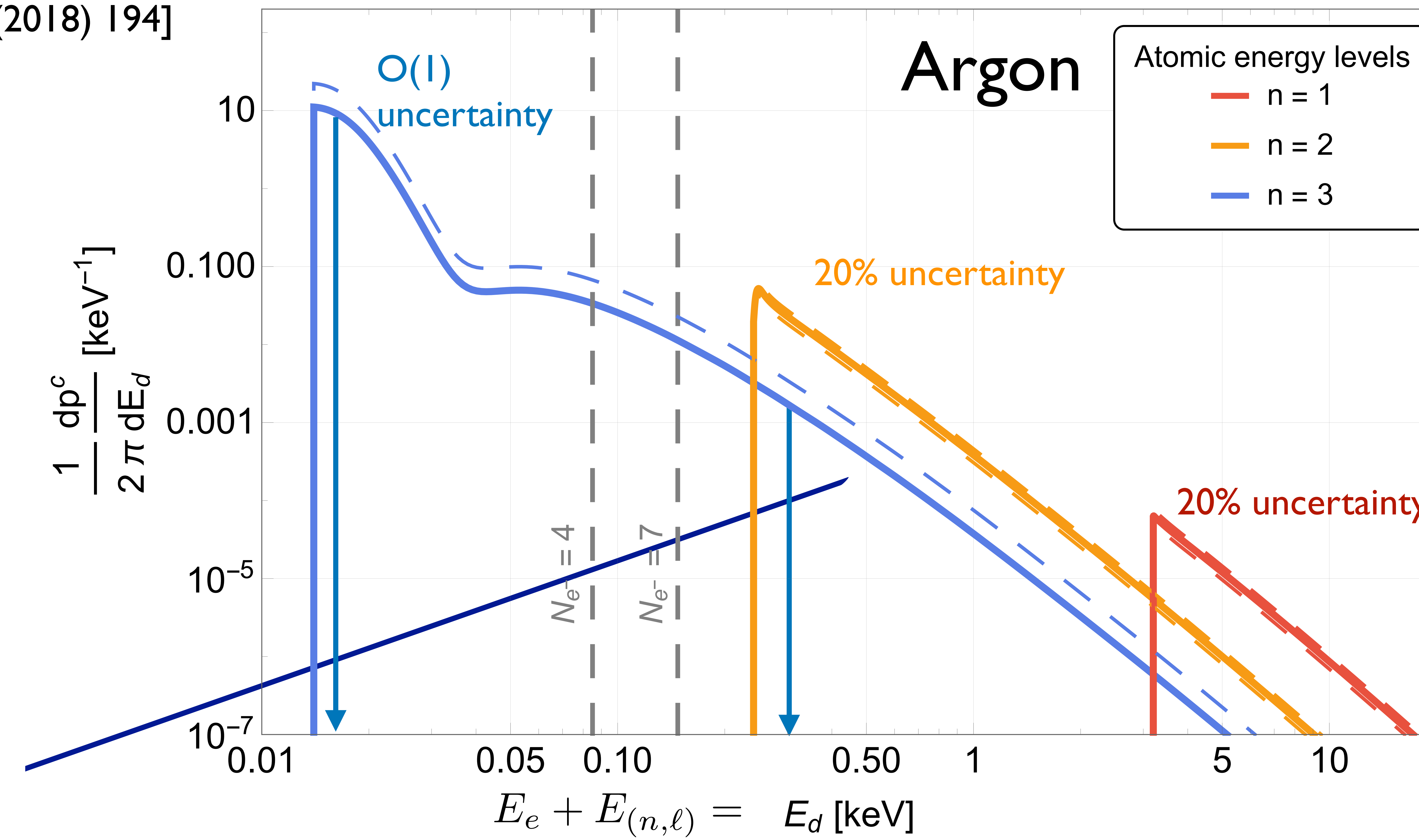
$$|Z_{\rm ion}(E_R, E_e)|^2 = \frac{1}{2\pi} \sum_{n,\ell} \int dE_e \frac{dp^c_{q_e}(n\ell \to E_e)}{dE_e}$$

Migdal

Computed in
[Ibe et al. JHEP03(2018)194]

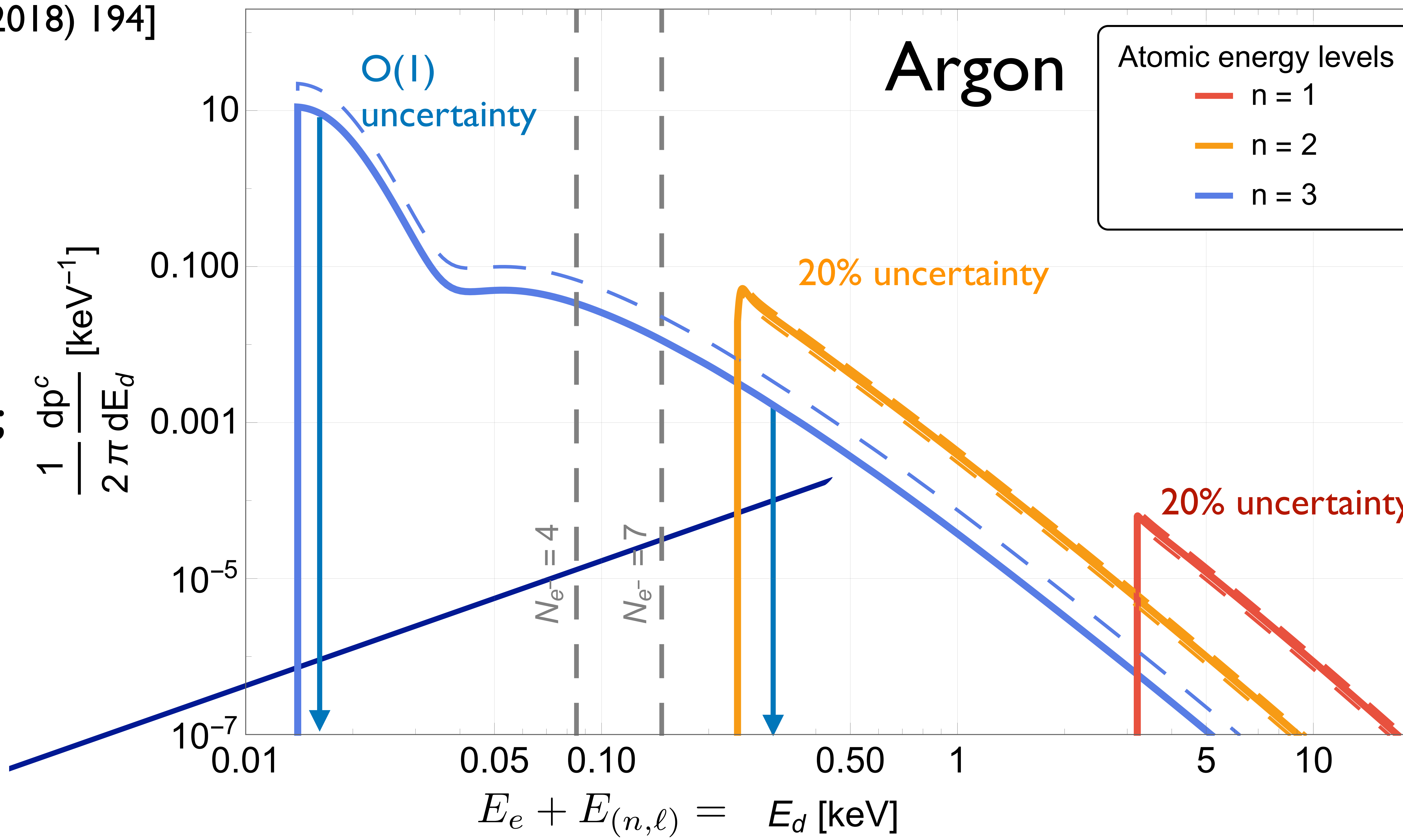
The Migdal effect

- Computed by [Ibe et al., JHEP 03 (2018) 194] for isolated atoms using the Flexible Atomic Code [Gu, Canadian Journal of Physics 86(2008)675];



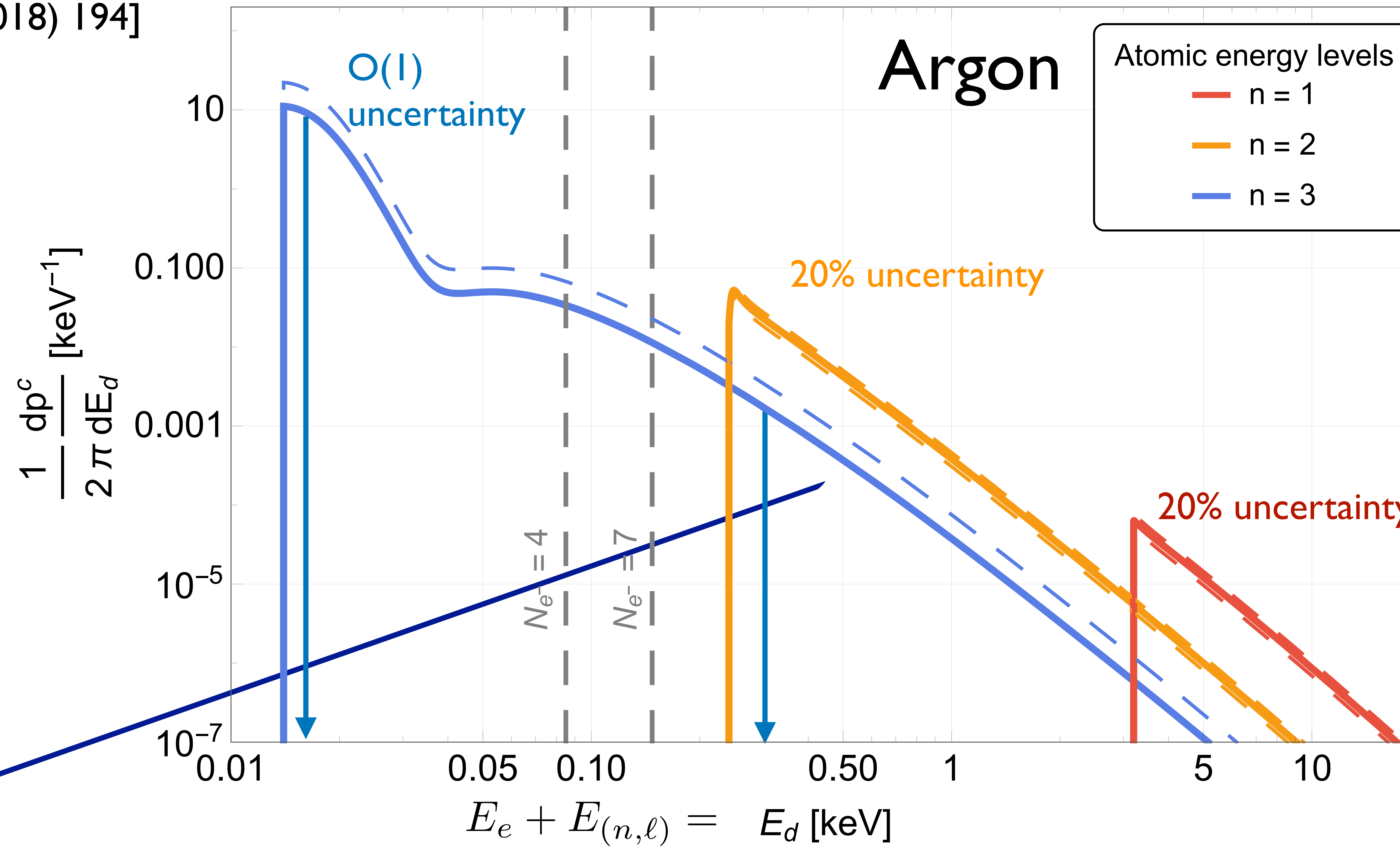
The Migdal effect

- Computed by [Ibe et al., JHEP 03 (2018) 194] for isolated atoms using the Flexible Atomic Code [Gu, Canadian Journal of Physics 86(2008)675];
- The outer shell is potentially affected by large uncertainties;



The Migdal effect

- Computed by [Ibe et al., JHEP 03 (2018) 194] for isolated atoms using the Flexible Atomic Code [Gu, Canadian Journal of Physics 86(2008)675];
- The outer shell is potentially affected by large uncertainties;
- The Migdal emission can be rigorously related to photo-absorption, thus relating the probability to experimental input and reducing the theoretical uncertainties [Liu et al., Phys. Rev. D 102 (2020) 121303]

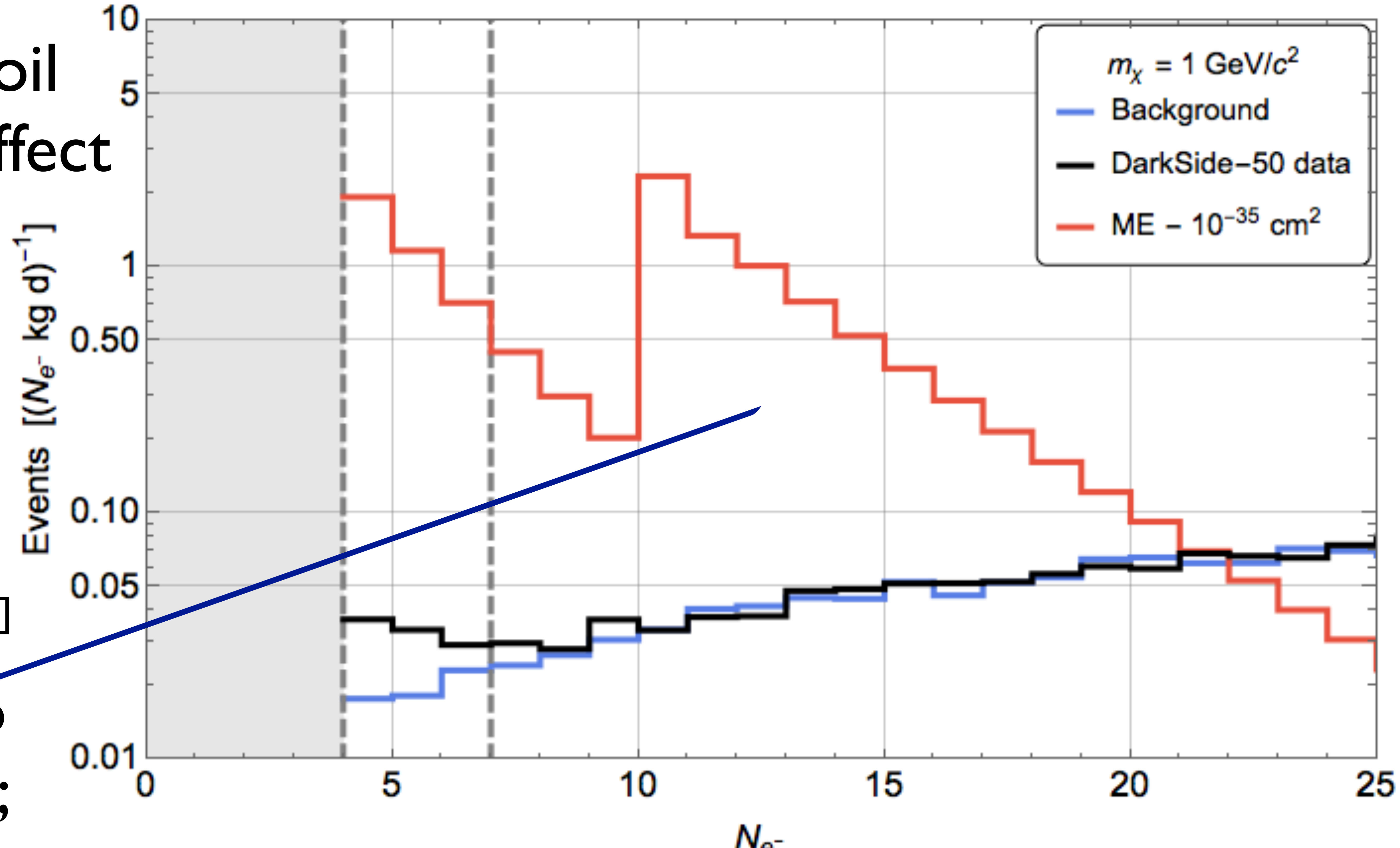


Migdal effect in LAr

LAr simulated experiment

Inputs:

- Signal templates (nuclear recoil and Migdal) and systematic effect treatment;
- Realistic LAr spectra and parametrisation of detector effects;
[DarkSide, Phys. Rev. Lett. 121 (2018) no. 8081307]
- Bayesian statistical analysis to extract the sensitivity curves;



Public repository at: https://github.com/piacent/LAr-MigdalLimits

Bayesian analysis

$$\mathcal{L} = \mathcal{L}_C \times \mathcal{L}_B \times \mathcal{L}_S$$

Bayesian analysis

$$\mathcal{L} = \mathcal{L}_C \times \mathcal{L}_B \times \mathcal{L}_S$$

$$\mathcal{L}_C(r_S, r_B, \theta; \{x_i\}) = p(\{x_i\}|r_S, r_B, \theta, H) = \prod_{i=1}^{N_{\rm bin}} \frac{\lambda_i^{x_i}}{x_i!} e^{-\lambda_i}$$

Bayesian analysis

$$\mathcal{L} = \mathcal{L}_C \times \mathcal{L}_B \times \mathcal{L}_S$$

$$\mathcal{L}_C(r_S, r_B, \theta; \{x_i\}) = p(\{x_i\}|r_S, r_B, \theta, H) = \prod_{i=1}^{N_{\rm bin}} \frac{\lambda_i^{x_i}}{x_i!} e^{-\lambda_i}$$

$$\lambda_i = E[r_S\, S_i + r_B(B_i + LowN_{e_i})]$$

Bayesian analysis

$$\mathcal{L}_B = \prod_{\{bkg\}} \prod_{i=1}^{N_{\rm bin}} \mathcal{N}(\mu = bkg, \sigma = \sigma_{bkg_i})$$

$$\mathcal{L} = \mathcal{L}_C \times \mathcal{L}_B \times \mathcal{L}_S$$

$$\mathcal{L}_C(r_S, r_B, \theta; \{x_i\}) = p(\{x_i\}|r_S, r_B, \theta, H) = \prod_{i=1}^{N_{\rm bin}} \frac{\lambda_i^{x_i}}{x_i!} e^{-\lambda_i}$$

$$\lambda_i = E[r_S\, S_i + r_B(B_i + LowN_{e_i})]$$

Bayesian analysis

$$\mathcal{L}_B = \prod_{\{bkg\}} \prod_{i=1}^{N_{\rm bin}} \mathcal{N}(\mu = bkg, \sigma = \sigma_{bkg_i})$$

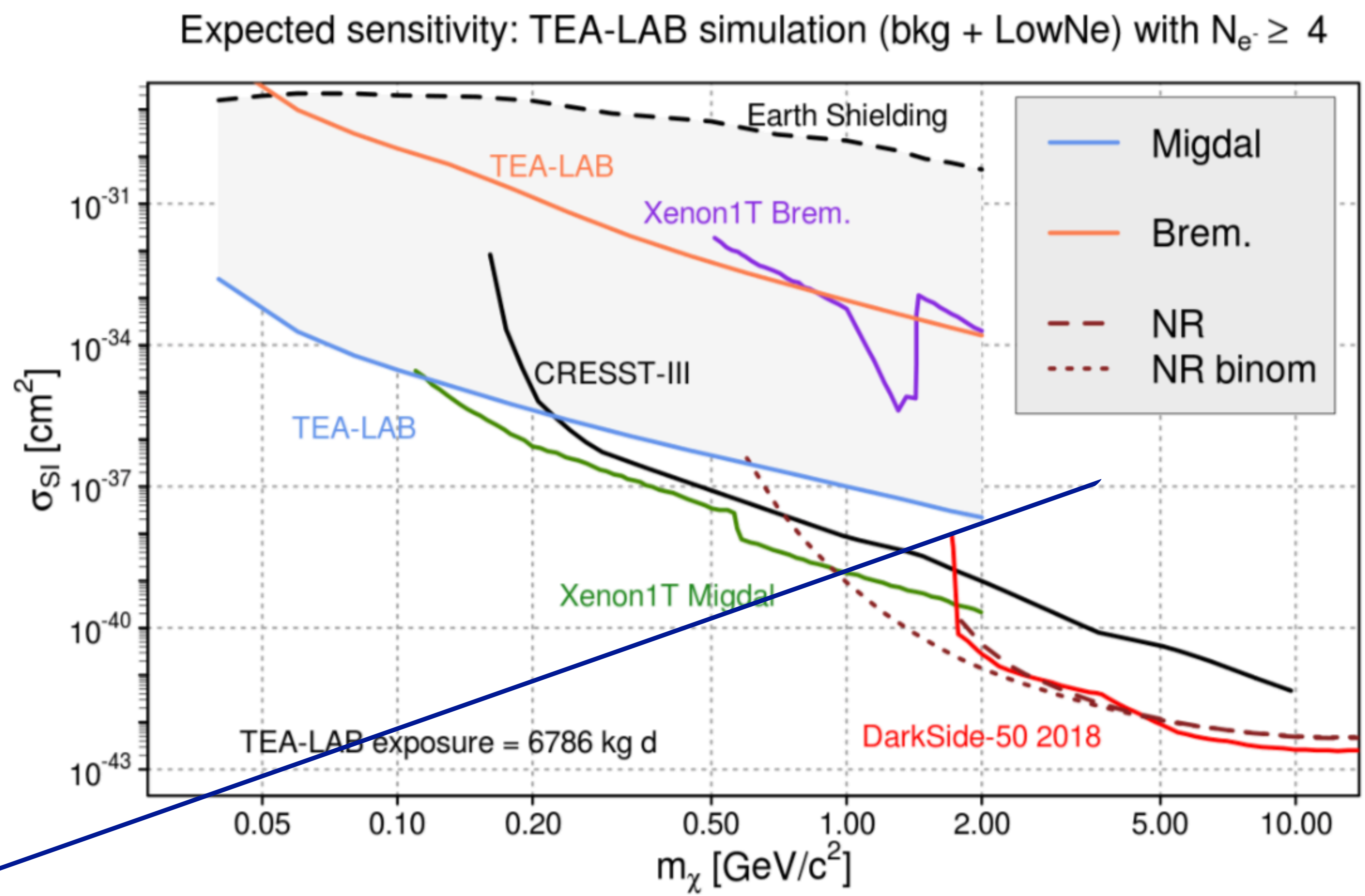
$$\mathcal{L}_S = \delta[S_i - S_i(f, N_{e^-}^{\rm max}, \epsilon)]$$

$$\mathcal{L} = \mathcal{L}_C \times \mathcal{L}_B \times \mathcal{L}_S$$

$$\mathcal{L}_C(r_S, r_B, \theta; \{x_i\}) = p(\{x_i\}|r_S, r_B, \theta, H) = \prod_{i=1}^{N_{\rm bin}} \frac{\lambda_i^{x_i}}{x_i!} e^{-\lambda_i}$$

$$\lambda_i = E[r_S\, S_i + r_B(B_i + LowN_{e_i})]$$

Expected sensitivity

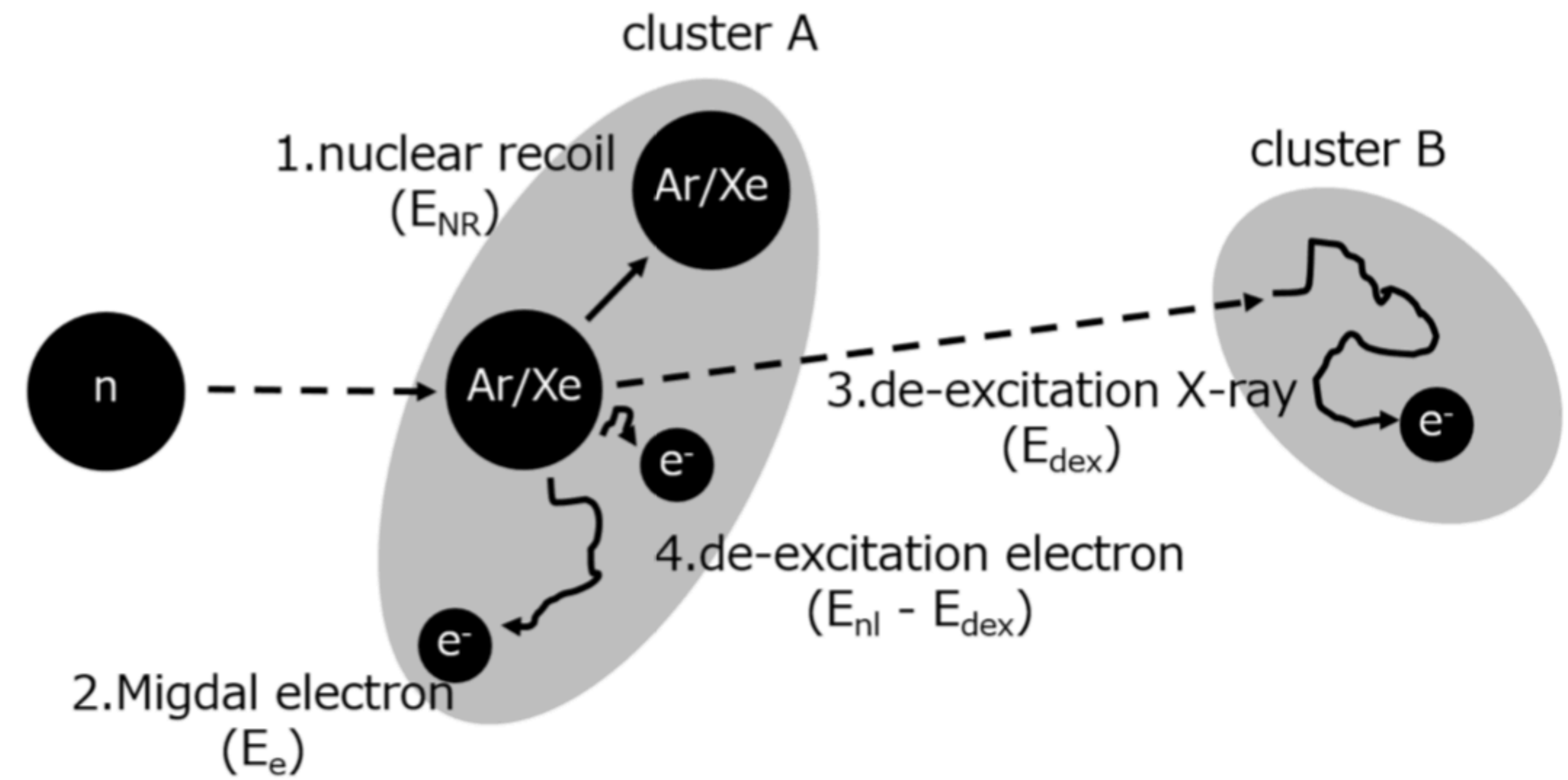


How to measure the Migdal effect in nuclear scattering?

Possible signatures

1. Neutrons can induce energetic NR;

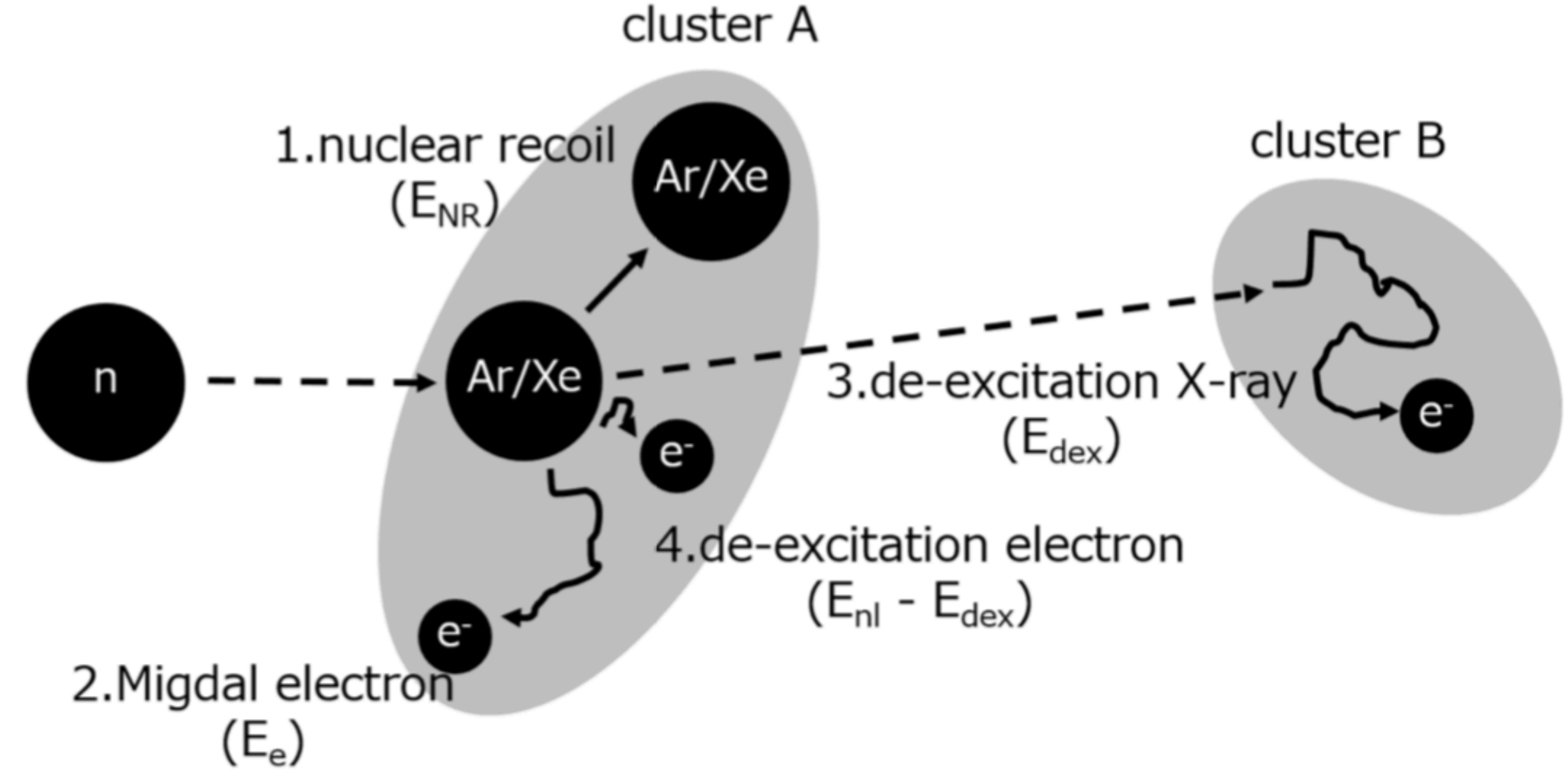
[Nakamura et al., PTEP 1 (2021) 013C01]



Possible signatures

1. Neutrons can induce energetic NR;
2. An atom can emit a Migdal electron from the 1s shell with a small probability (10^{-5}-10^{-4});

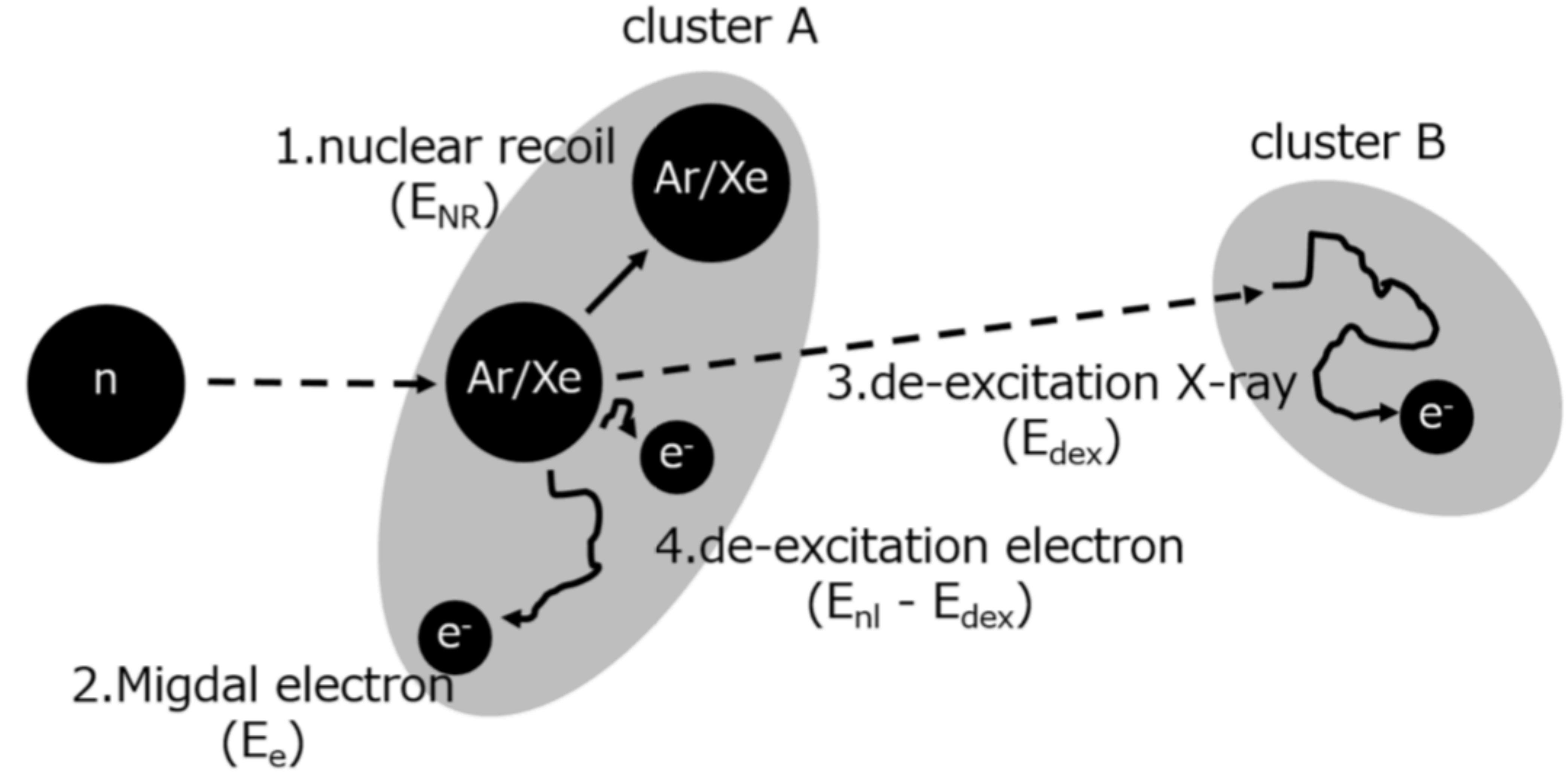
[Nakamura et al., PTEP 1 (2021) 013C01]



Possible signatures

1. Neutrons can induce energetic NR;
2. An atom can emit a Migdal electron from the 1s shell with a small probability (10^{-5}-10^{-4});
3. Atoms will fill the hole emitting an X-ray (~3 keV for Ar, ~30 keV for Xe);

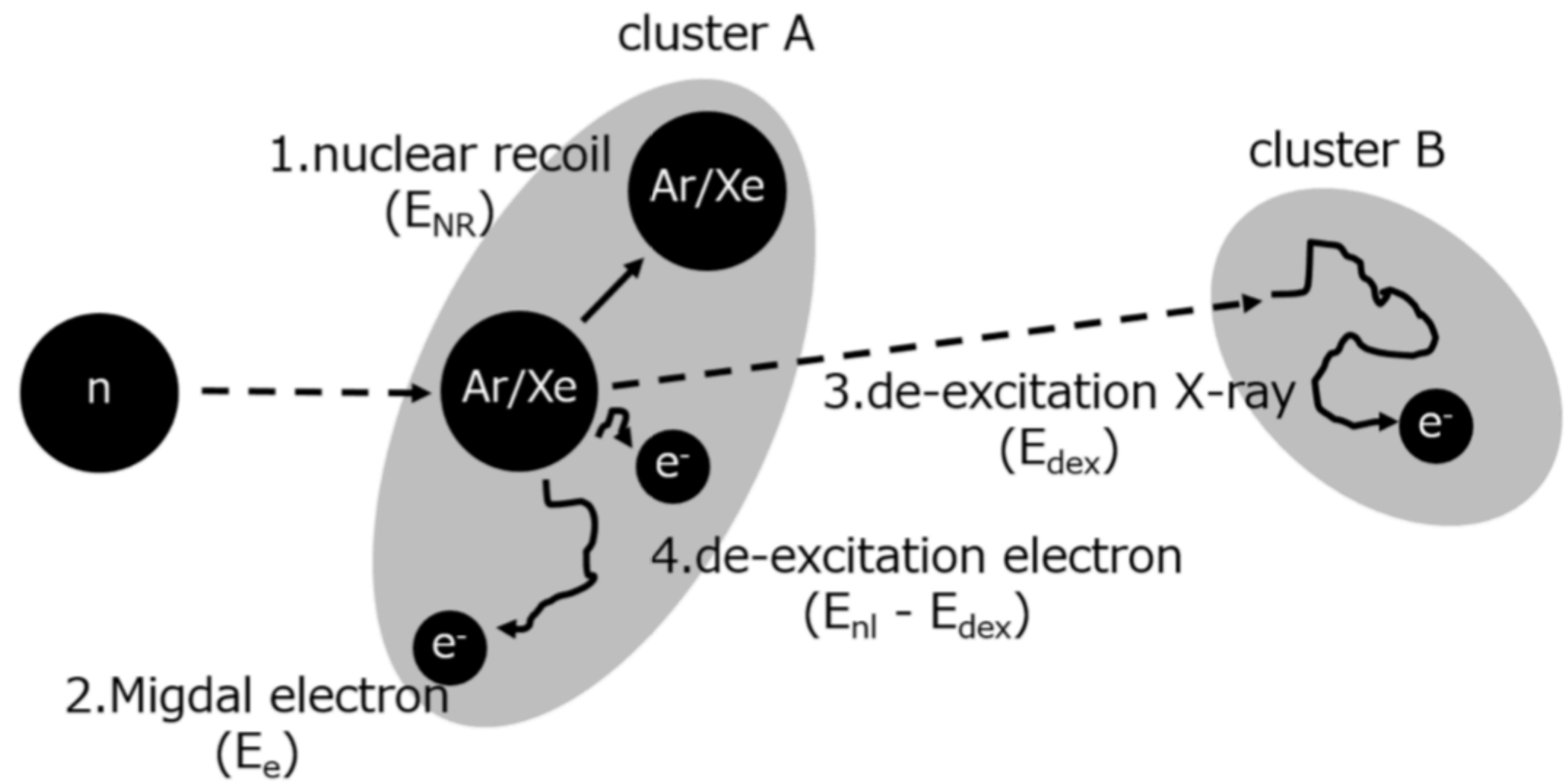
[Nakamura et al., PTEP 1 (2021) 013C01]



Possible signatures

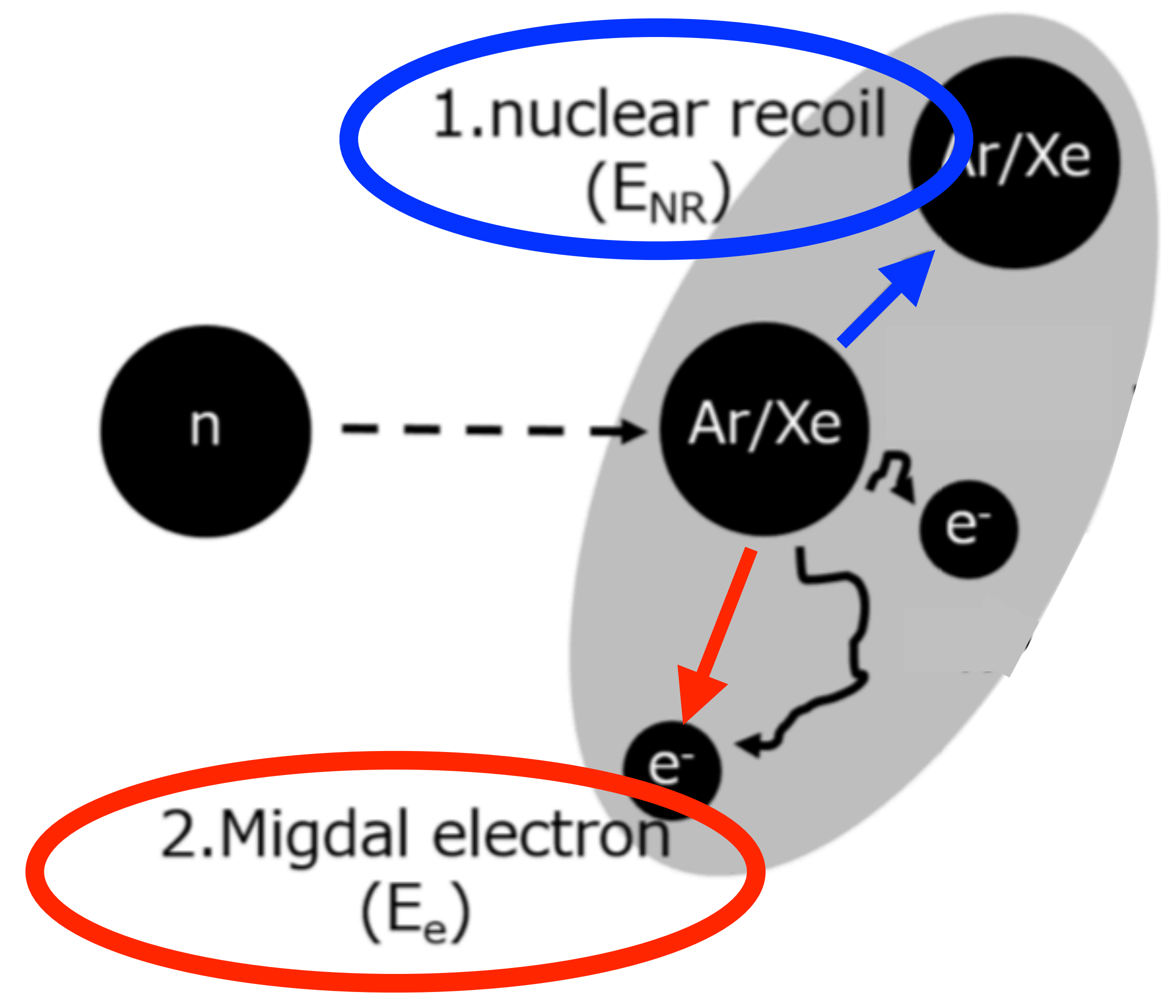
1. Neutrons can induce energetic NR;
2. An atom can emit a Migdal electron from the 1s shell with a small probability (10^{-5}-10^{-4});
3. Atoms will fill the hole emitting an X-ray (~3 keV for Ar, ~30 keV for Xe);
4. The signature is a vertex with an energetic NR and a few keV X-ray absorbed after a few cm;

[Nakamura et al., PTEP 1 (2021) 013C01]



Possible signatures

Or just detect the Migdal electron exploiting all the atomic shells: it needs to be able to reconstruct a nuclear recoil track and an electron recoil track starting from the same vertex.



Used also to discriminate between signal and background events.

Experimental opportunity

for Cygno details see A. Messina talk tomorrow

[Baracchini et al., *Measur.Sci.Tech.* 32 (2021) 2, 025902]

- Cygno Phase 0 TPC (LIME): 50 litres of He/CF_4 or Ar/CF_4 with very good 3-d tracking capability and resolution both for NR and ER;
- Possibility to exploit available neutron sources at 2.5 MeV and 14 MeV;

Experimental opportunity

X-ray signature

$$N_{\rm events} = N_T\,\Phi\,\sigma_{Ar}\,f_{Ar}\,q_e^2\,{\rm BR}_{\rm Mig}$$

Experimental opportunity

X-ray signature

7.5×10^{23}

$3.2 \times 10^{-24}\,\text{cm}^2$

$10^{-4} - 10^{-5}$

$$N_{\text{events}} = N_T \, \Phi \, \sigma_{Ar} \, f_{Ar} \, q_e^2 \, \text{BR}_{\text{Mig}}$$

Flux for a 2.5 MeV neutron source

$113\ \text{s}^{-1}\text{cm}^{-2}$

0.14

Fluorescence yield

$$\frac{2\, m_e^2 E_R}{m_N}$$

Experimental opportunity

X-ray signature

7.5×10^{23} $3.2 \times 10^{-24}\,\mathrm{cm}^2$ $10^{-4} - 10^{-5}$

$$N_{\rm events} = N_T\, \Phi\, \sigma_{Ar}\, f_{Ar}\, q_e^2\, \mathrm{BR}_{\rm Mig} \simeq 400\,/\,\mathrm{day}$$

Flux for a 2.5 MeV neutron source $113\ \mathrm{s}^{-1}\mathrm{cm}^{-2}$

0.14 Fluorescence yield

$$\frac{2\, m_e^2 E_R}{m_N}$$

Experimental opportunity

X-ray signature

$$N_{\text{events}} = N_T \, \Phi \, \sigma_{Ar} \, f_{Ar} \, q_e^2 \, \text{BR}_{\text{Mig}} \simeq 400 \, / \, \text{day}$$

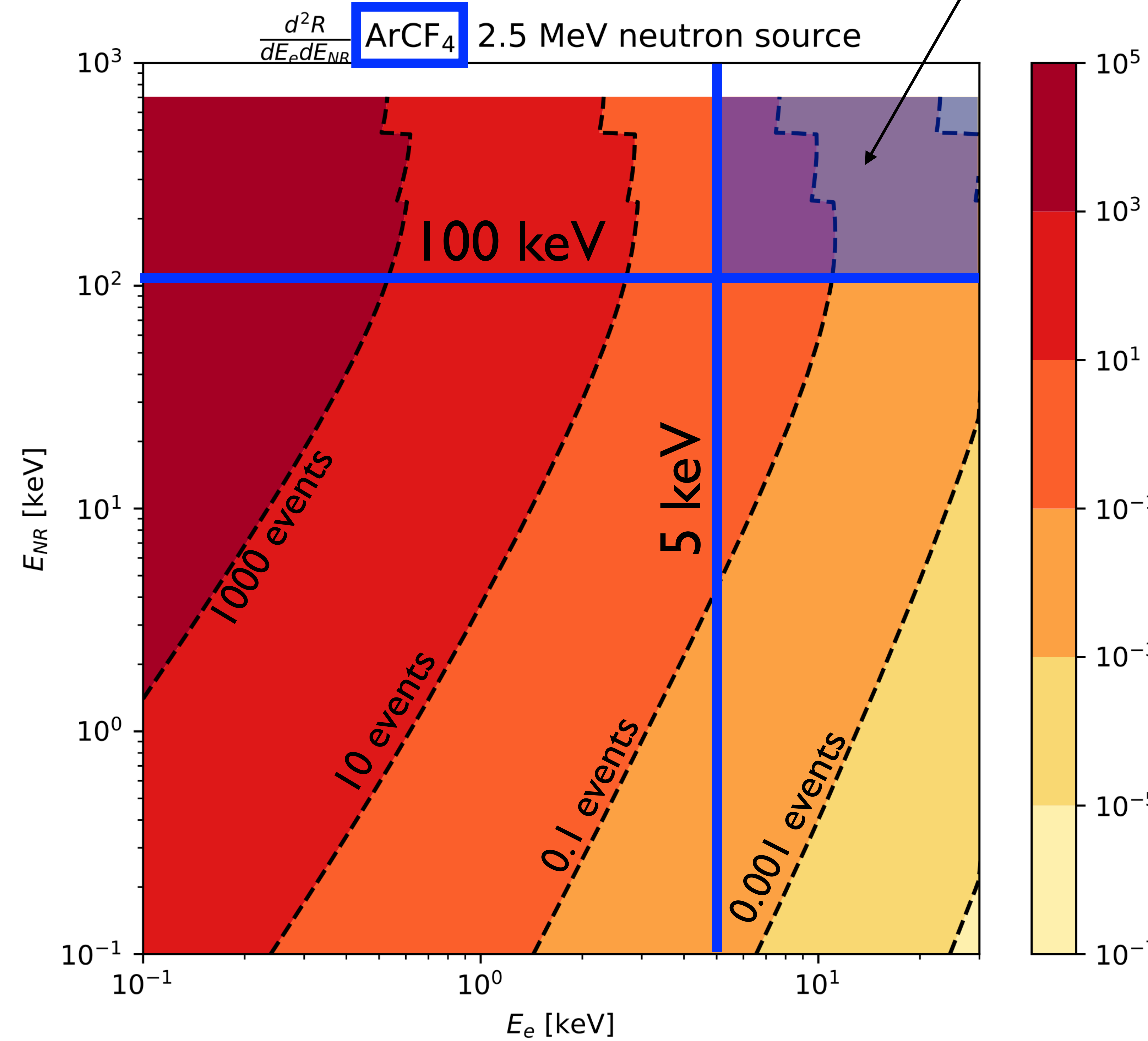
Expected absorption length for the X-ray: ~ 3 cm

Experimental opportunity

Migdal electron signature

- For large E_{NR} good tracking capability down to $E_e \sim 5$ keV.
- Potentially O(100) events per day for a realistic E_e energy threshold of 5 keV (integrating over $E_{NR} > 100$ keV), for a mixture 60:40 of $ArCF_4$;

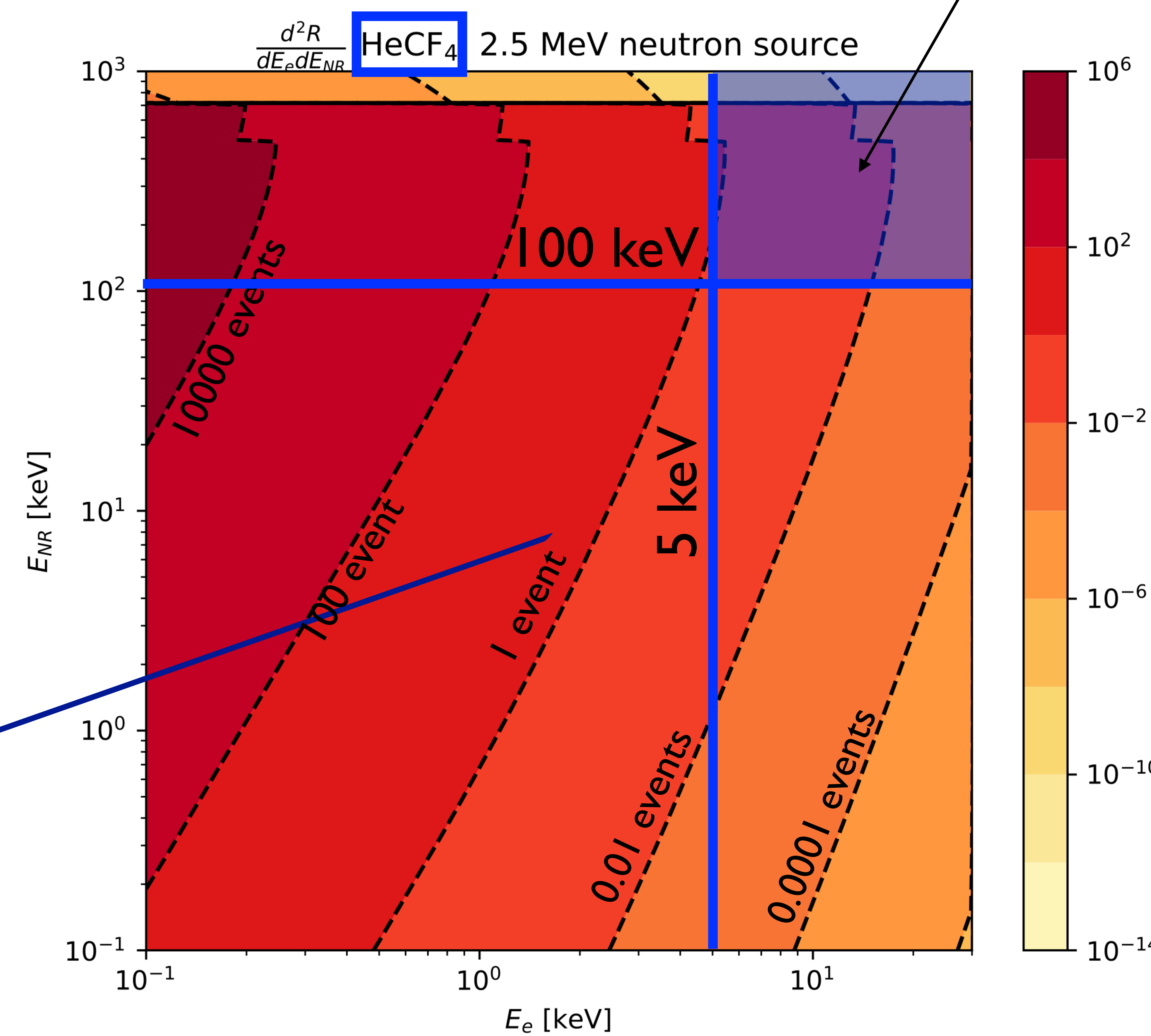
PRELIMINARY



Experimental opportunity

Migdal electron signature

- For large E_{NR} good tracking capability down to $E_e \sim 5$ keV.
- Potentially O(100) events per day for a realistic E_e energy threshold of 5 keV (integrating over $E_{NR} > 100$ keV), for a mixture 60:40 of $HeCF_4$;



Experimental opportunity

Working on signal and background simulations in order to define the optimal detector configuration (gas mix, shielding, neutron source) for a dedicated run to detect Migdal events exploiting (hopefully) both signatures.

Conclusions

Conclusions

- The Migdal effect has a great potential to improve the current sensitivity to light dark matter exploiting liquid argon detectors;

- It is important to observe the Migdal effect in nuclear scattering in order to confirm its relevance for dark matter experiments;

- There are promising signatures to be exploited and interesting experimental opportunities using fast neutrons and TPCs: simulations are currently ongoing.

Thank you!