Sapienza Università di Roma

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Improving the sensitivity to light matter with the Migdal effect

Based on:

G. Grilli di Cortona, A. M., S. Piacentini - JHEP **11** *(2020) 034*

PANIC 2021 Conference
Lisbon, 5-10 September 2021

Andrea Messina - Sapienza Università di Roma & INFN

September 5, 2021

Outline

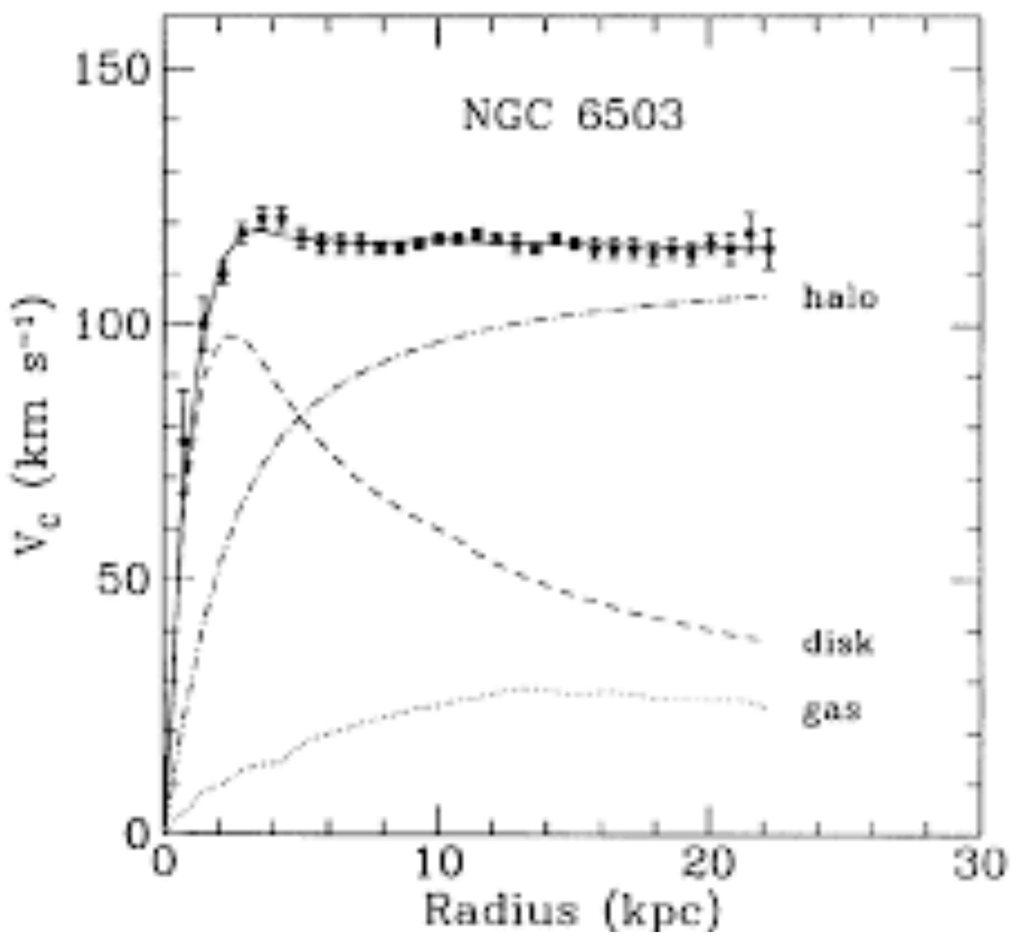
- Introduction and motivation
- The Migdal effect
- Impact of the Migdal effect on the DM sensitivity of LAr experiments
- Prospects to observe the Migdal effect in nuclear recoils
- Conclusions

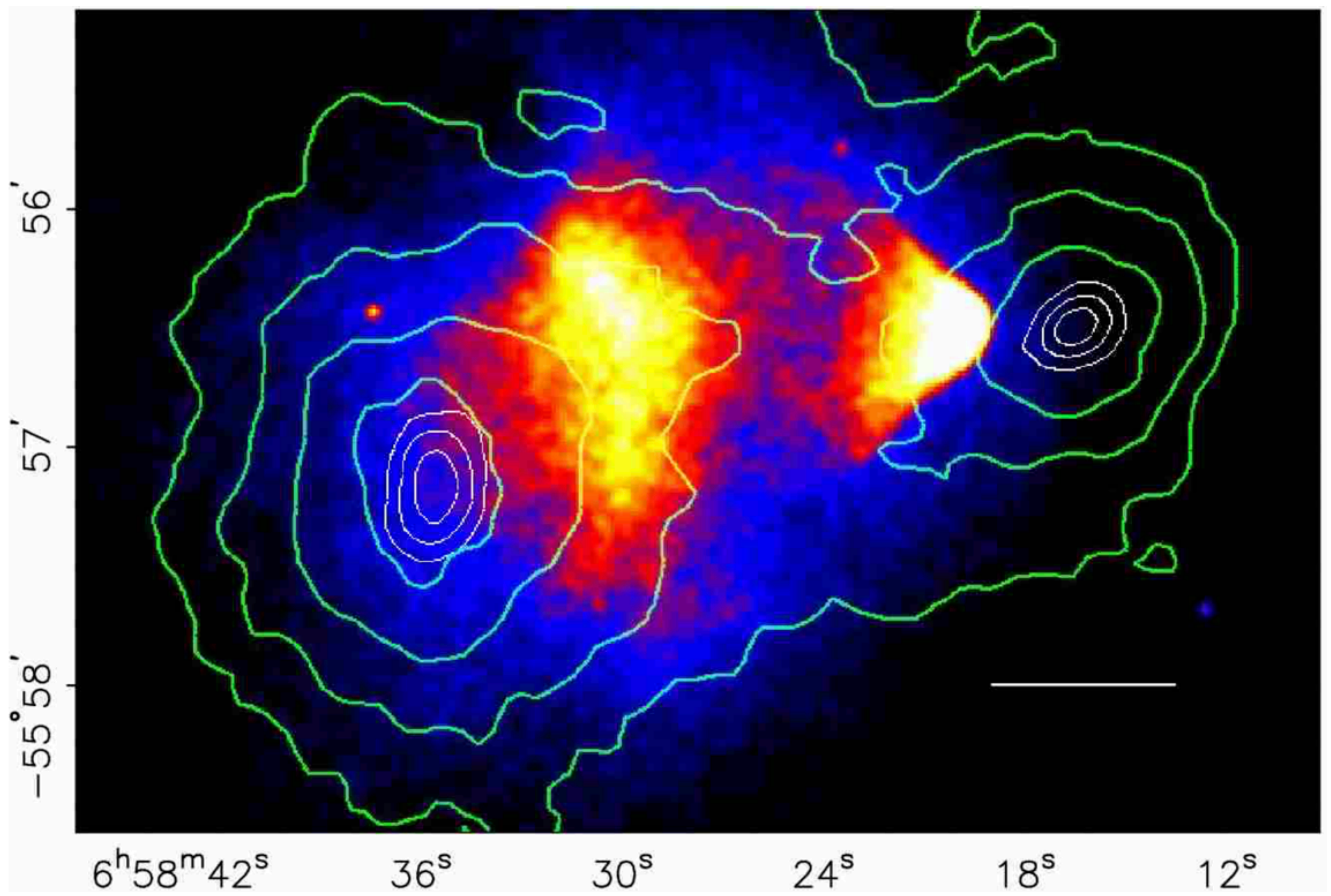
Compelling evidence for Dark Matter at all length scales

Galaxies

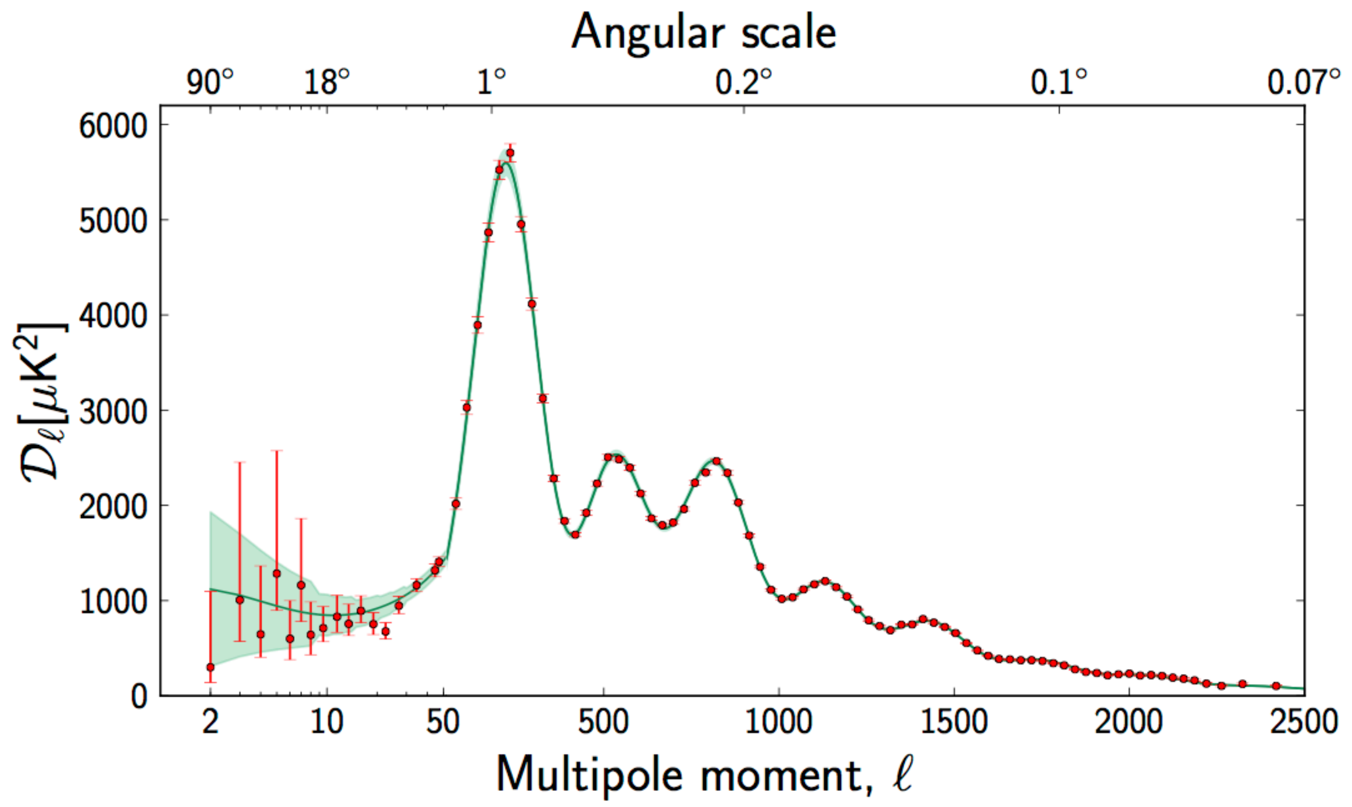
Clusters

Cosmic Microwave Background





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



[Planck]

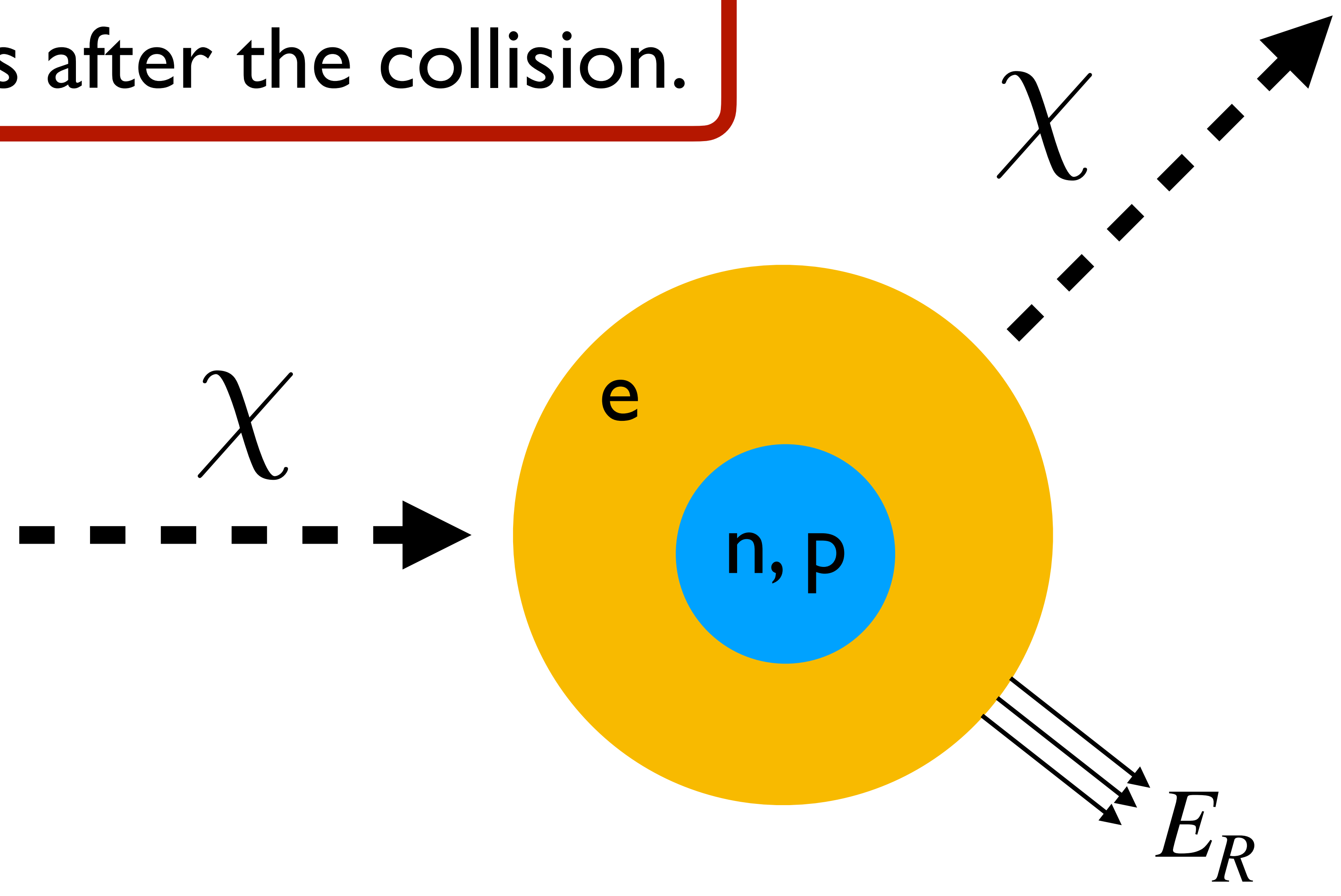
Small scales

Large scales

Dark Matter direct detection

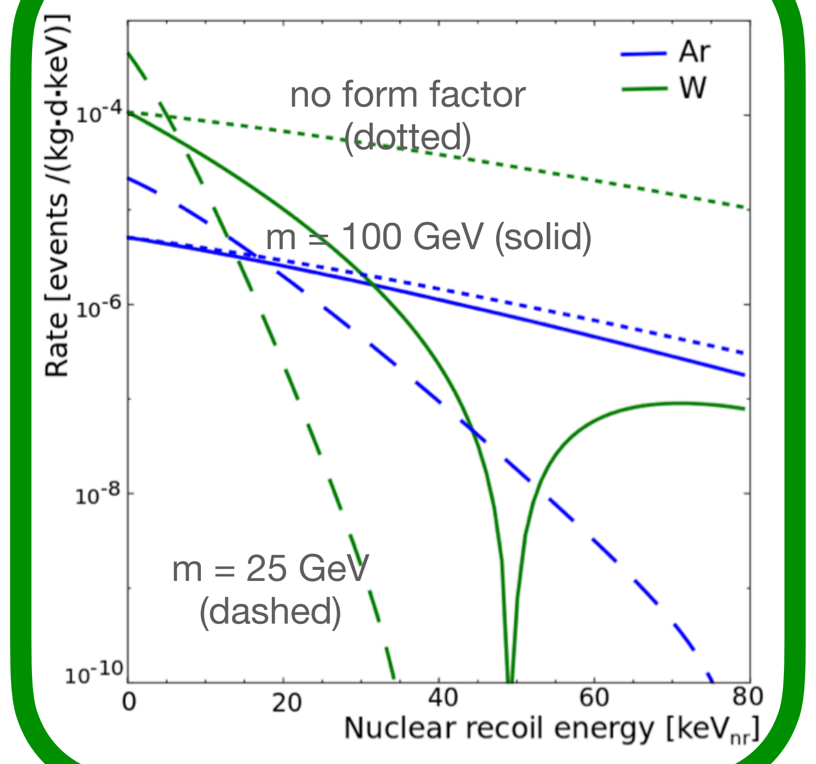
Interaction rate for elastic scattering on nuclei

Assumption: the electron cloud follows instantaneously the nucleus after the collision.



Credit: ESO/L. Calçada

J. Phys. G43 (2016) 013001



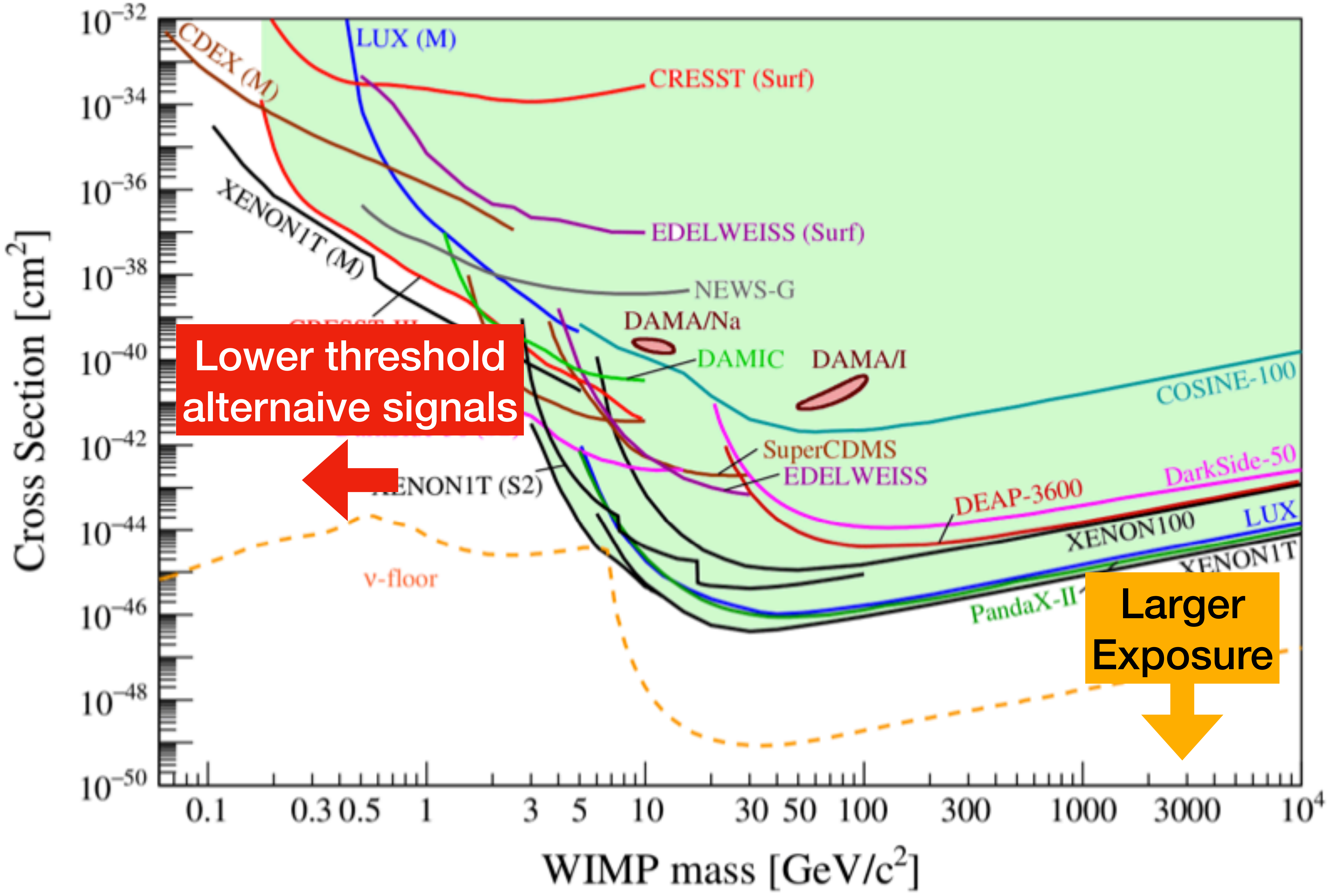
$$\frac{dR}{dE_r} \propto \frac{\rho_0}{m_\chi \mu^2}\sigma_0 F^2(E_r)\int_{v_{min}(E_r,\delta)}^{v_{esc}} d^3v \frac{f(\vec{v})}{v}$$

typical threshold ~ 1 keV

Dark Matter direct detection

WIMP search status

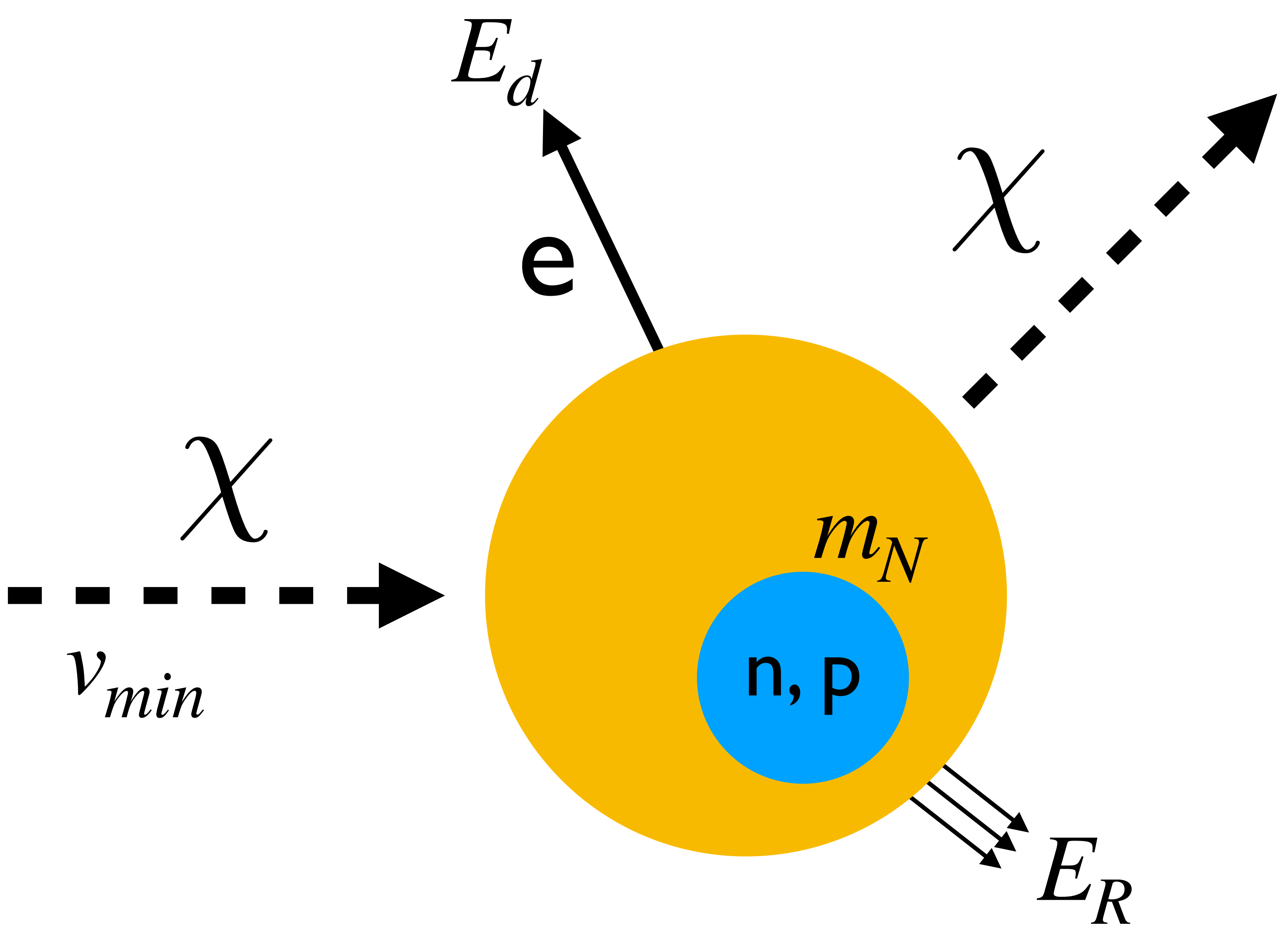
Direct Detection of Dark Matter - APPEC Committee Report
arXiv:2104.07634[hep-ex]



The Migdal effect

A. Migdal, "Ionization of atoms accompanying α- and β-decay", J. Phys. USSR 4 (1941) 449.

More accurate picture
relevant at small momentum transfer



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

The atom emits an electron (Migdal effect)

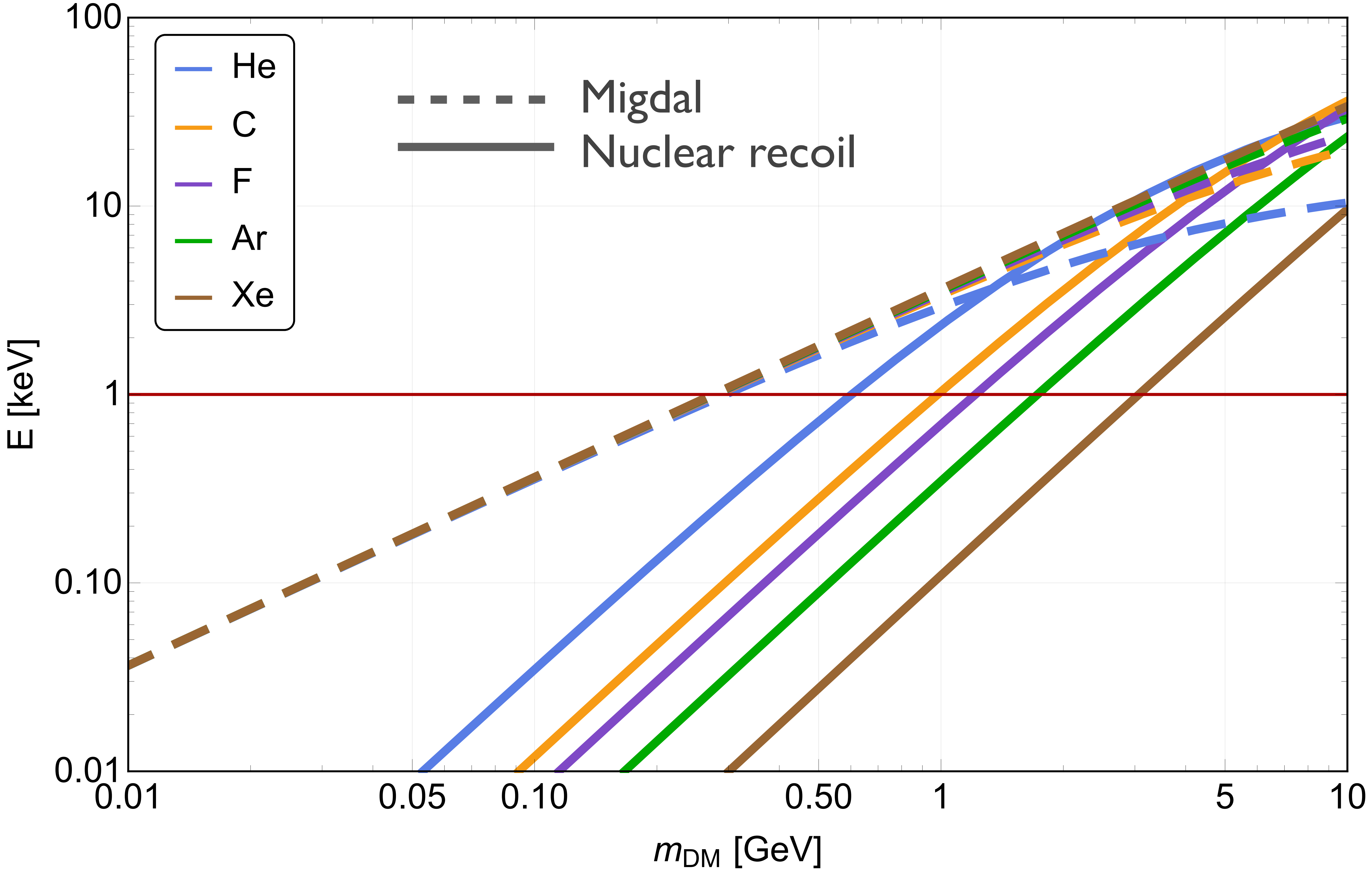
$$E_R^{\max} = \frac{2\,\mu_N^2\, v_{\max}^2}{m_N}; \qquad E_d^{\max} = \frac{\mu_N\, v_{\max}^2}{2}$$

R. Bernabei et al., Mod. Phys. A22 (2007) 3155-3168.
M. Ibe, W. Nakano, Y. Shoji, K. Suzuki et. al, JHEP **03** (2018) 194.
M.J. Dolan, F. Kalhoefer, C. McCabe, Phys. Rev. Lett. 121, 101801 (2018)

Kinematics

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

- threshold E $\simeq 1$ keV$_{NR}$;
- loss of sensitivity for $m_{\rm DM} \simeq$ GeV;
- Migdal effect sensitive to sub-GeV;
- $E_d^{\max} > E_R^{\max}$ for $m_{\rm DM} \ll m_N$, (suppression factor μ_N/m_N).



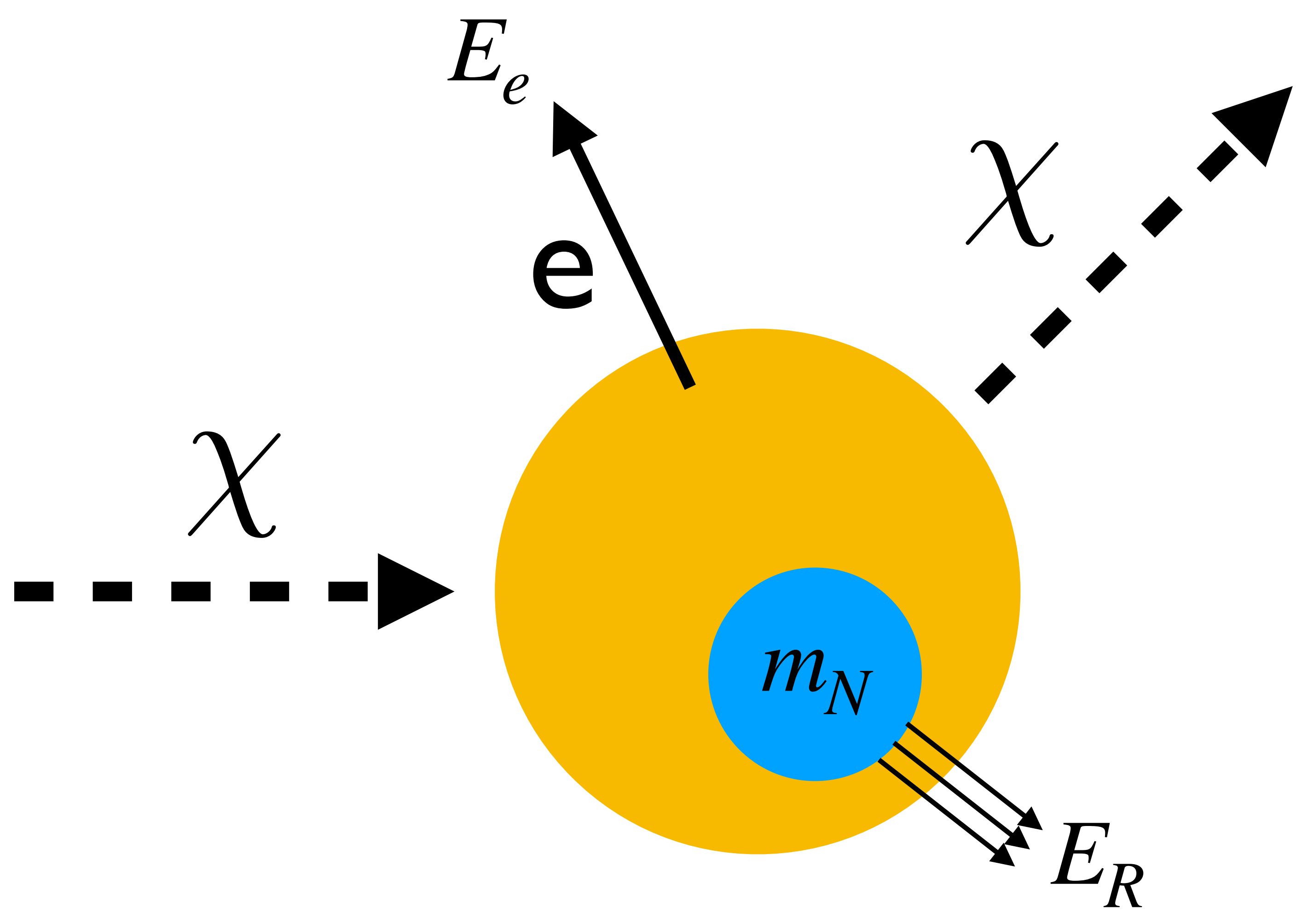
At low DM mass it is easier to detect a Migdal electron rather than a nuclear recoil

Rates

From the NR to a more complete picture

Usual nuclear recoil rate

$$\frac{d^2R}{dE_R dE_e} = \frac{dR_{NR}}{dE_R} |Z|^2$$



NR

de-excitation: negligible

$$|Z|^2 \simeq 1 + |Z_{\mathrm{de}}|^2 + |Z_{\mathrm{ion}}|^2$$

Ionization probability

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

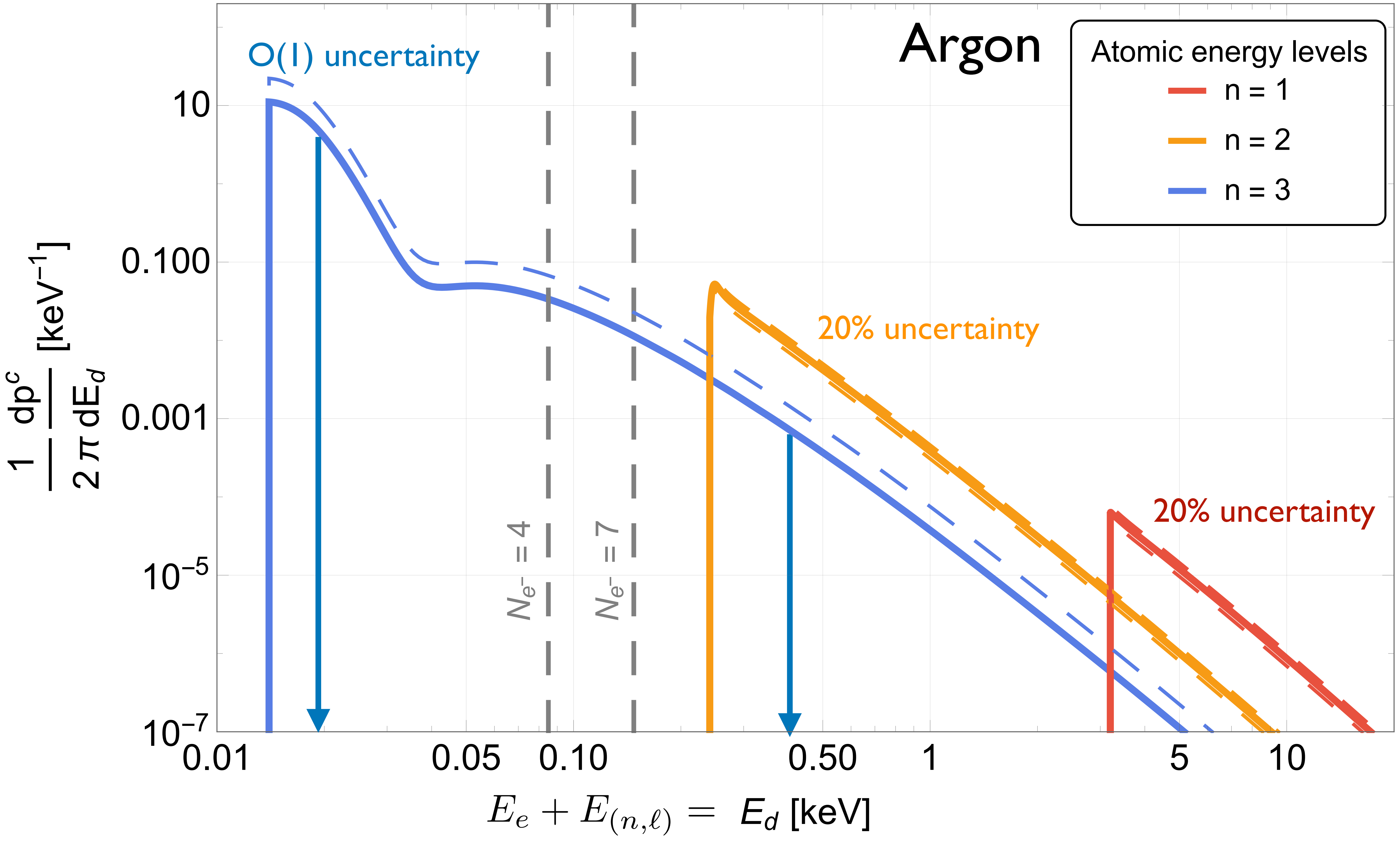
Migdal

Computed in

M. Ibe, W. Nakano, Y. Shoji, K. Suzuki et. al, JHEP **03** (2018) 194.

Migdal electron emission probabilities

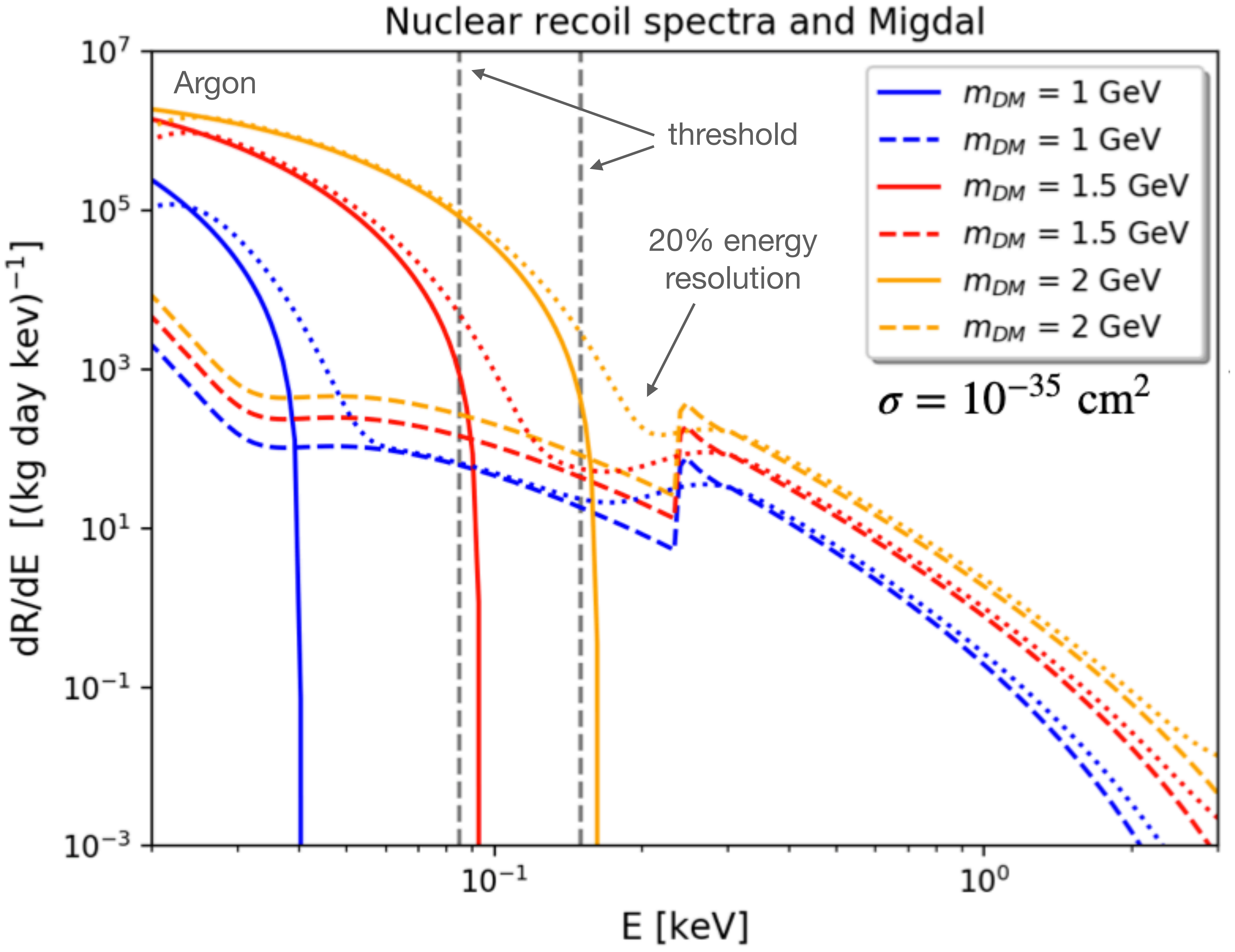
- Computed[1] for a number of isolated atoms in non-relativistic QM using the Flexible Atomic Code[2] (FAC);
- The outer shell is potentially affected by large uncertainties;
- Migdal emission can be rigorously related[3] to photo-absorption, thus anchored to exp. inputs which reduces theoretical uncertainties.



[1] M. Ibe, W. Nakano, Y. Shoji, K. Suzuki et. al, JHEP **03** (2018) 194.
[2] M. F. Gu, Canadian Journal of Physics **86** (2008) 675.
[3] C.-P. Liu, Chih-Pan Wu, Hsin-Chang Chi, Jiunn-Wei Chen, Phys. Rev. D 102 (2020) 121303.

Rates in LAr

- NR is around or below threshold for $m_\chi \lesssim 2\,\mathrm{GeV}$;
- **The Migdal electron rate extends to the keV region.**



What is the sensitivity of a liquid argon experiment exploiting the Migdal effect?

TEALAB: a LAr case study

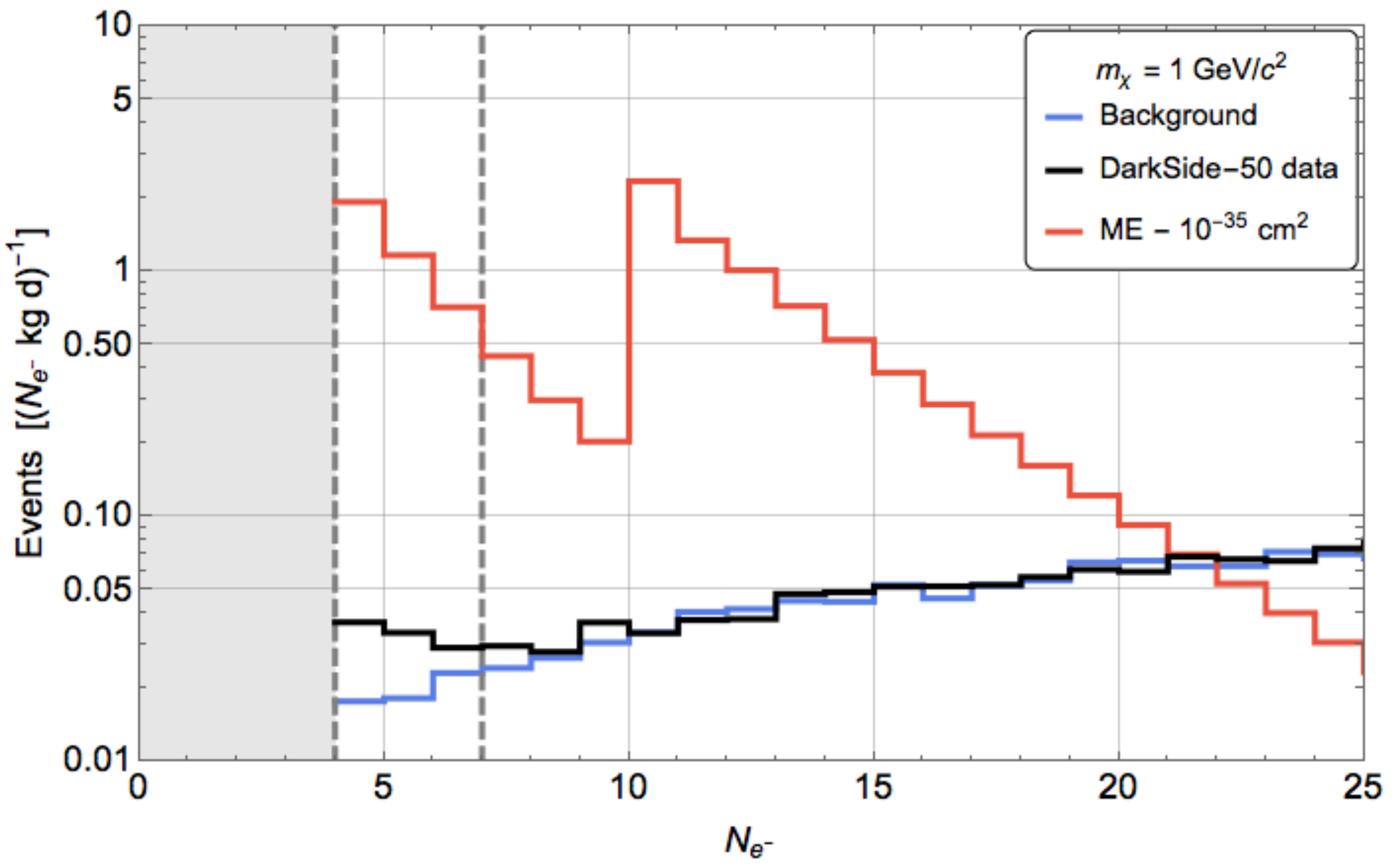
G. Grilli di Cortona, A. M., S. Piacentini - *JHEP* **11** (2020) 034

To exploit the Migdal prediction for liquid argon we used a simulated experiment called TEALAB.

Analysis inputs:

- Signal templates (Migdal and NR) and systematic effect treatment;
- Realistic LAr spectra and parametrisation of detector effects;
  [DarkSide-50 Low-mass: Phys. Rev. Lett. **121** (2018), no. 8 081307]
- Bayesian statistical analysis to extract the sensitivity bounds;

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



The TEALAB likelihood

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

- binned **Poisson likelihood**;

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

- intensity controlled by the expected bkgd and signal rates;

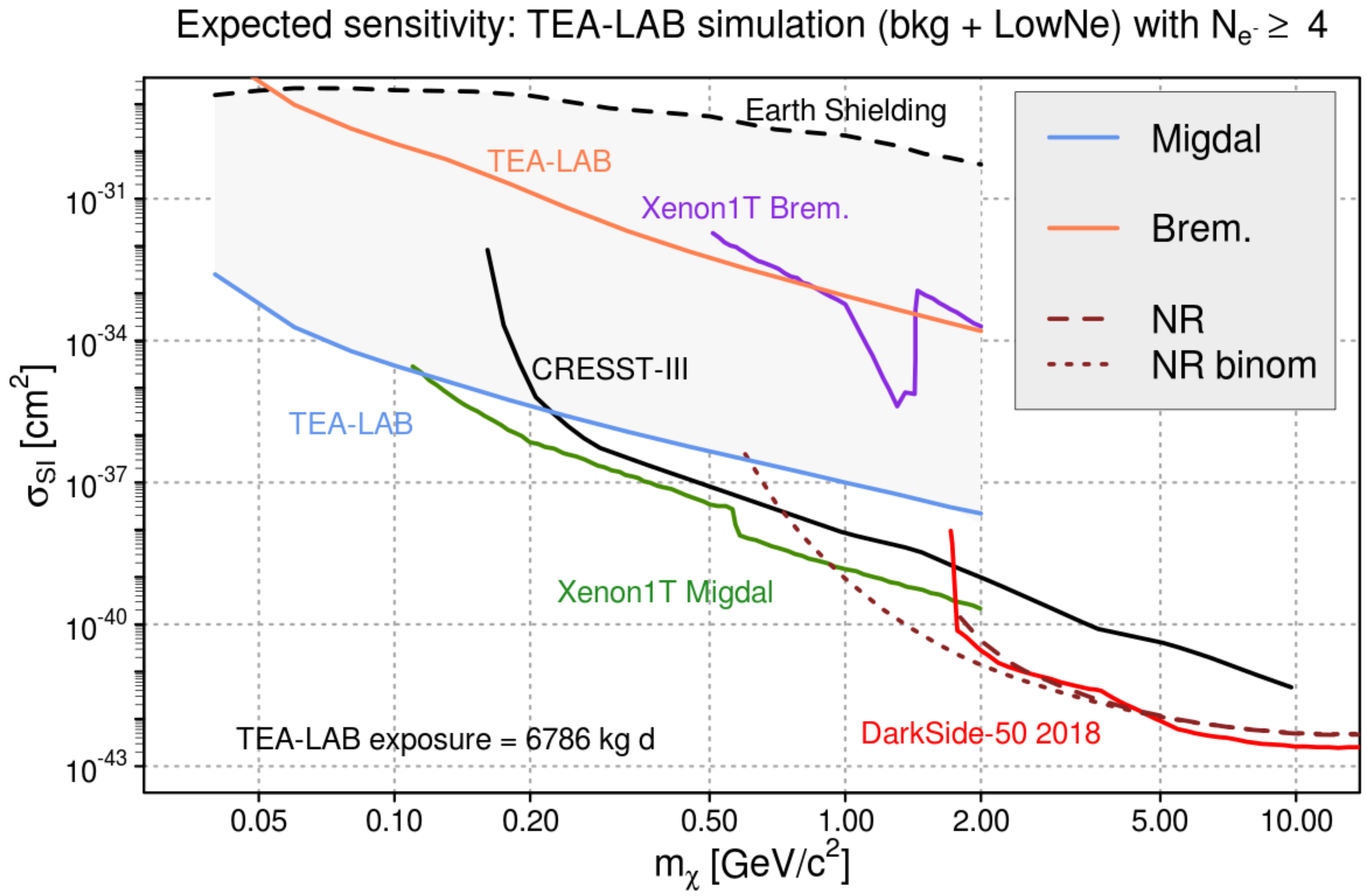
$$\lambda_i = E[r_S\, S_i + r_B(B_i + LowN_{e_i})]$$

- additional **nuisance parameters** to account for detector effects and sig/bkg uncertainties;

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

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

TEA-LAB projected sensitivity to low mass DM



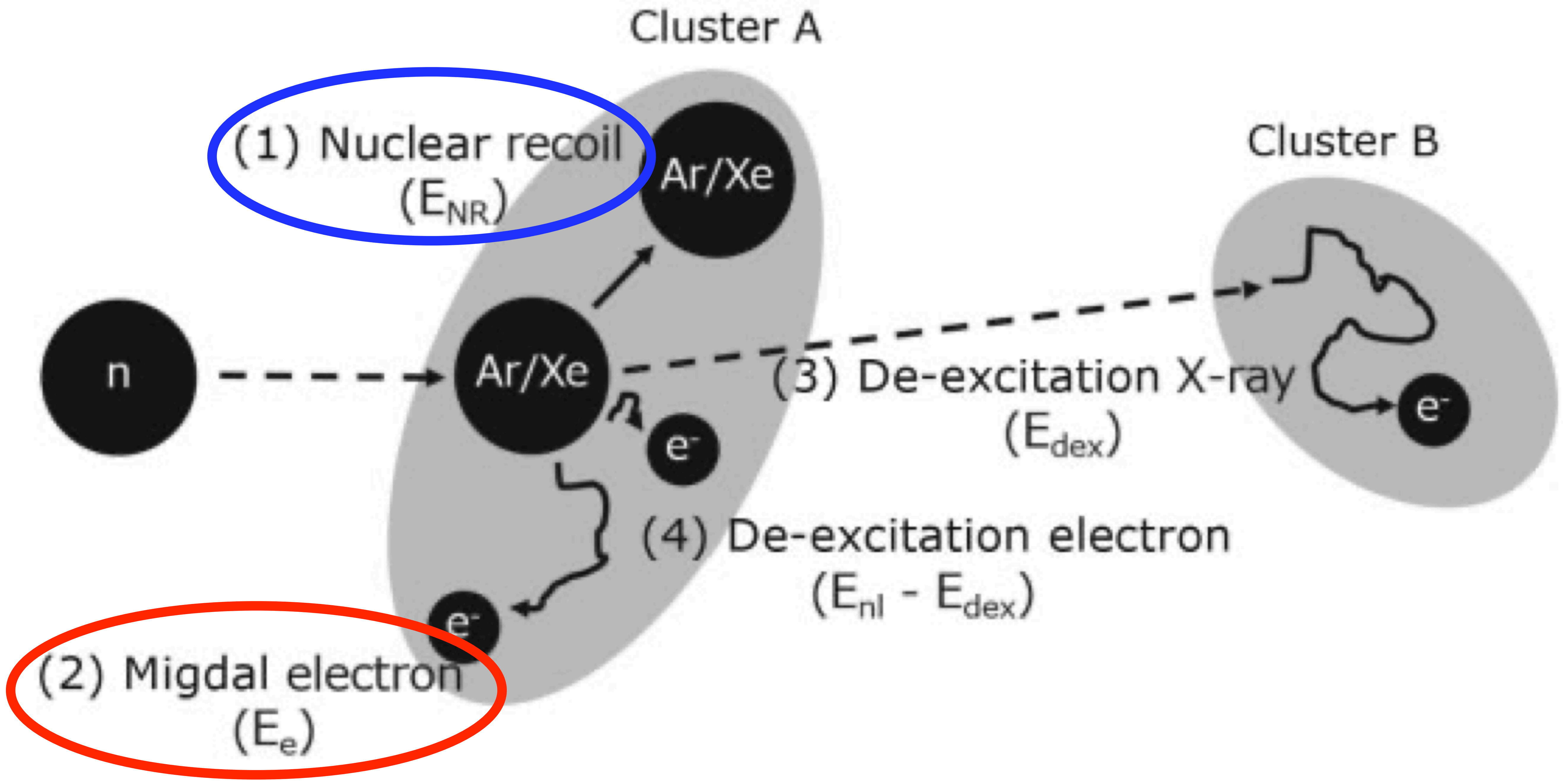
It is possible to extend the sensitivity down to **masses $m_\chi \lesssim$ 0.1 GeV/c²**.

Prospects to measure the Migdal effect in nuclear recoils

Interesting signatures in Ar

- MeV neutrons can induce energetic NR (high intensity source);
- With probability ~10^{-4}-10^{-5} the atom can emit a Migdal electron from the n=1 shell;
- The atom will fill the hole by emitting a X-ray (K-line @ 3 keV);
- **Event tag:** a vertex with an **energetic NR** (few 100 keV) and a **3 keV X-ray** absorbed after few cm.

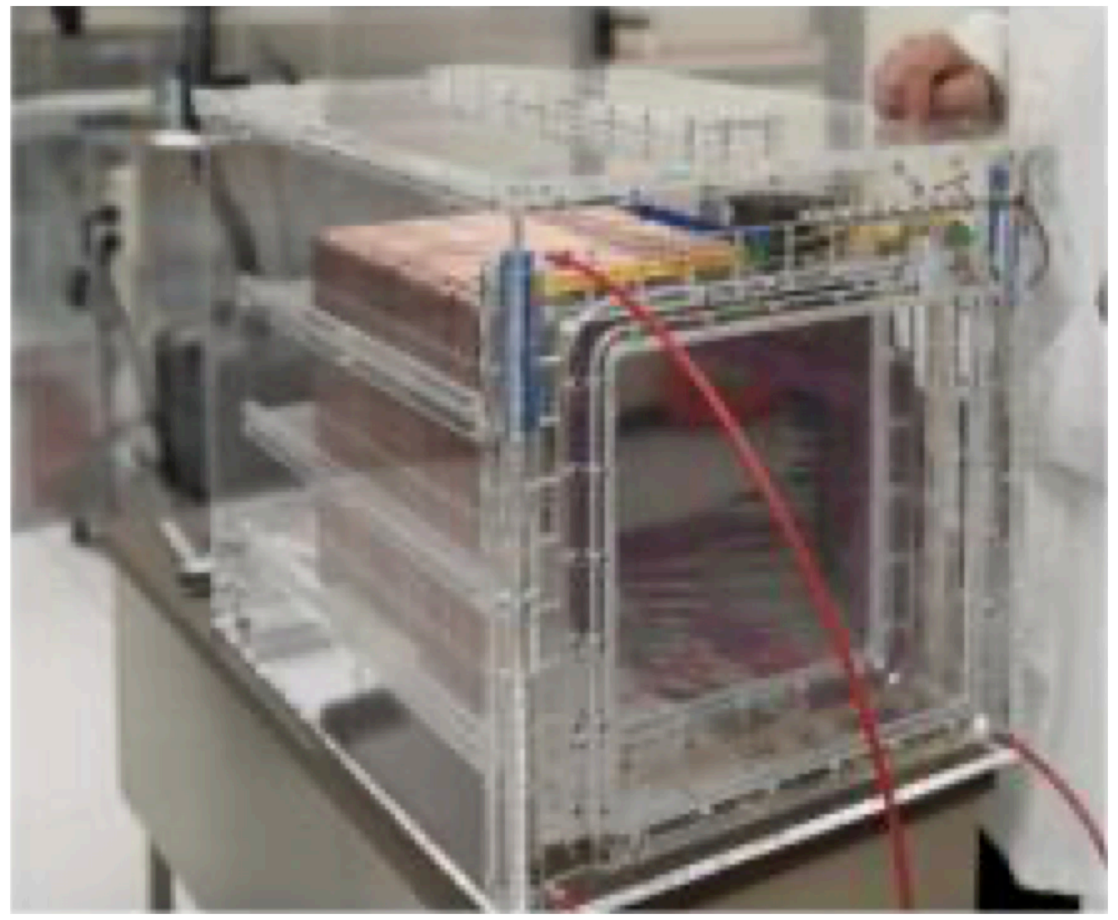
K. D. Nakamura et al., PTEP **1** (**2021**) 013C01

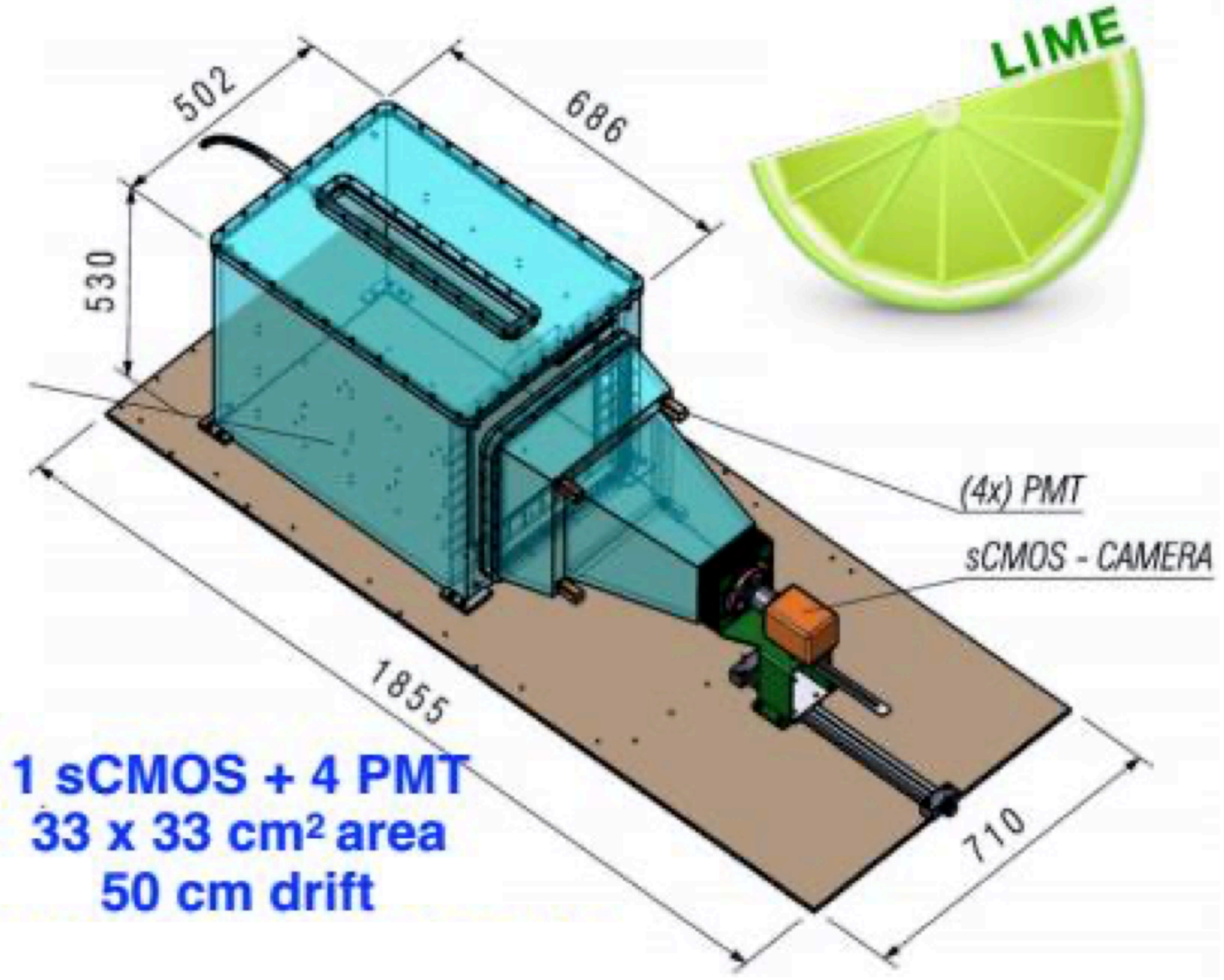


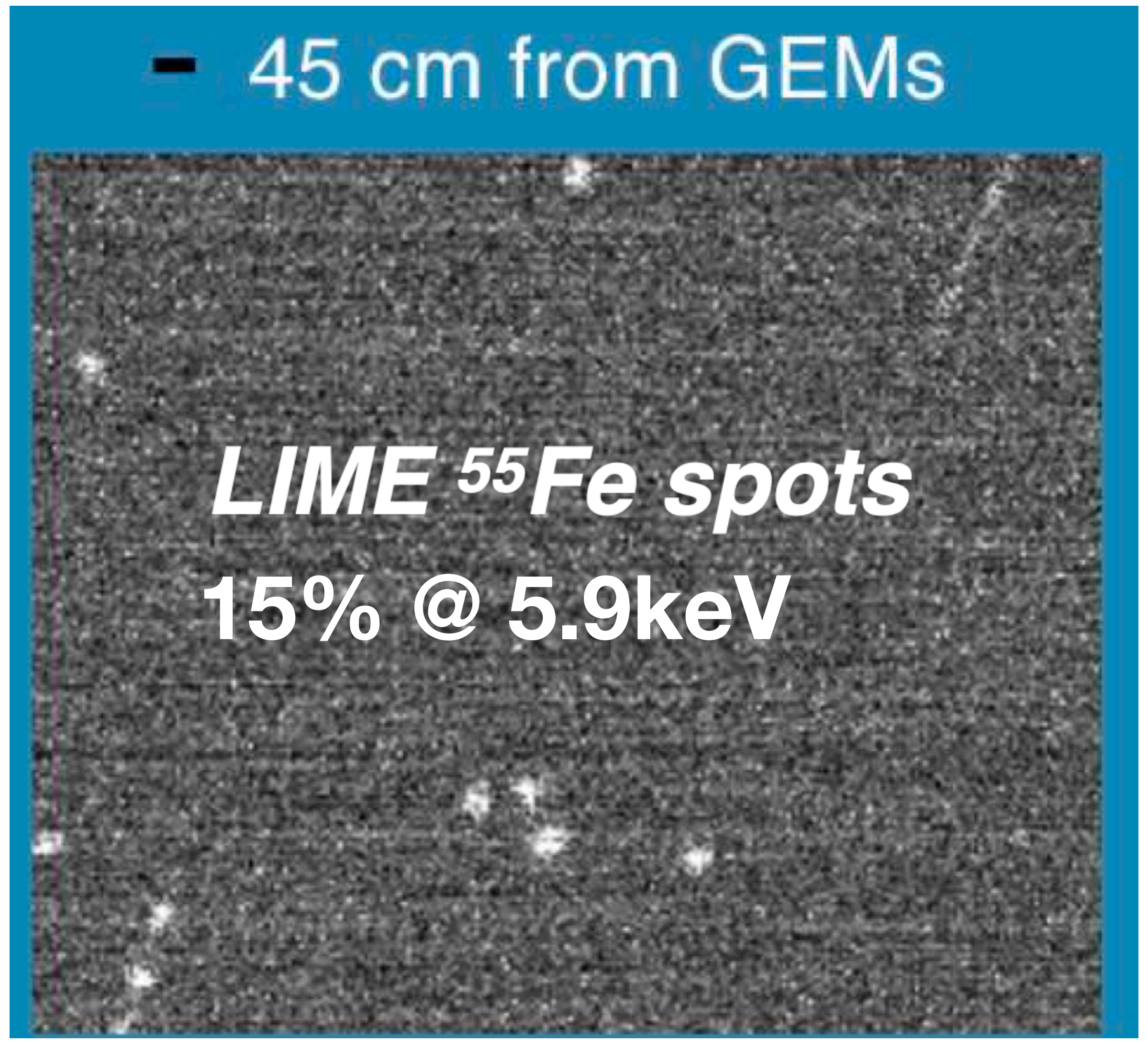
Or just **detect the Migdal electron** exploiting all atomic shells: it needs good tracking capabilities to reconstruct a nuclear recoil and an electron recoil originating from the same vertex.

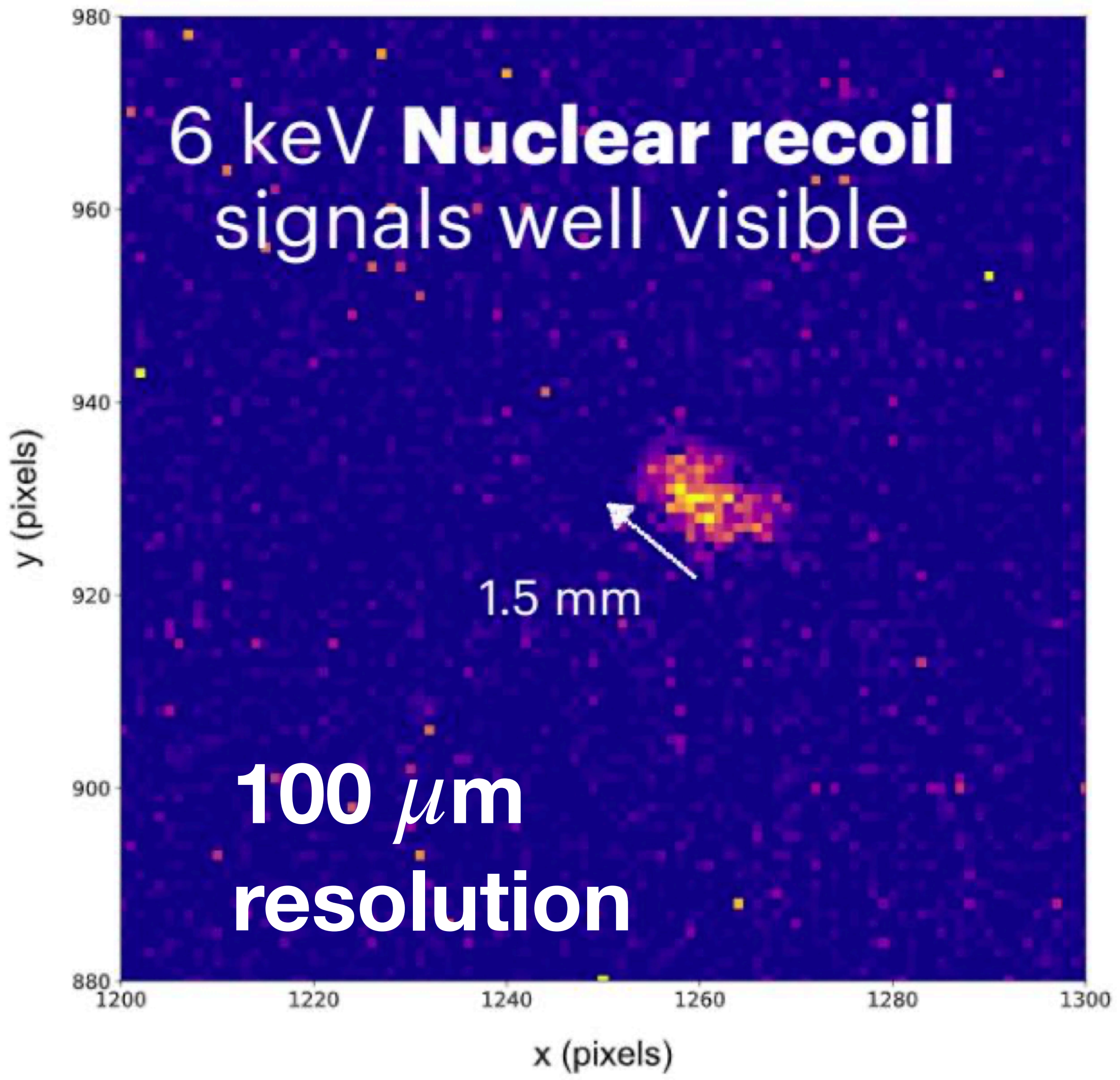
The CYGNO TPC[1] could see such events?

- **50L TPC with He(Ar)/CF_4** at atmospheric pressure, 3-**GEM** amplification stage;
- **Optical readout** of visible light by **sCMOS** camera and **Photodetectors;**
- **Very good tracking capabilities and resolution** both for NR[2] and ER[3];
- Possibility to use a neutron **source at 2.5 or 14 MeV**.
- Working on defining the detector configuration (gas mix, shielding, neutron source) for a **dedicated run to look for Migdal events**.









For CYGNO details see Stefano Piacentini's poster

[1] E. Baracchini et al., *JINST* 15 (2020) 07, C07036.
[2] E. Baracchini et al., *Measur.Sci.Tech.* 32 (2021) 2, 025902.
[3] E. Baracchini et al., *J.Phys.Conf.Ser.* 1498 (2020) 012017.

Signal event yield

1. X-ray signature

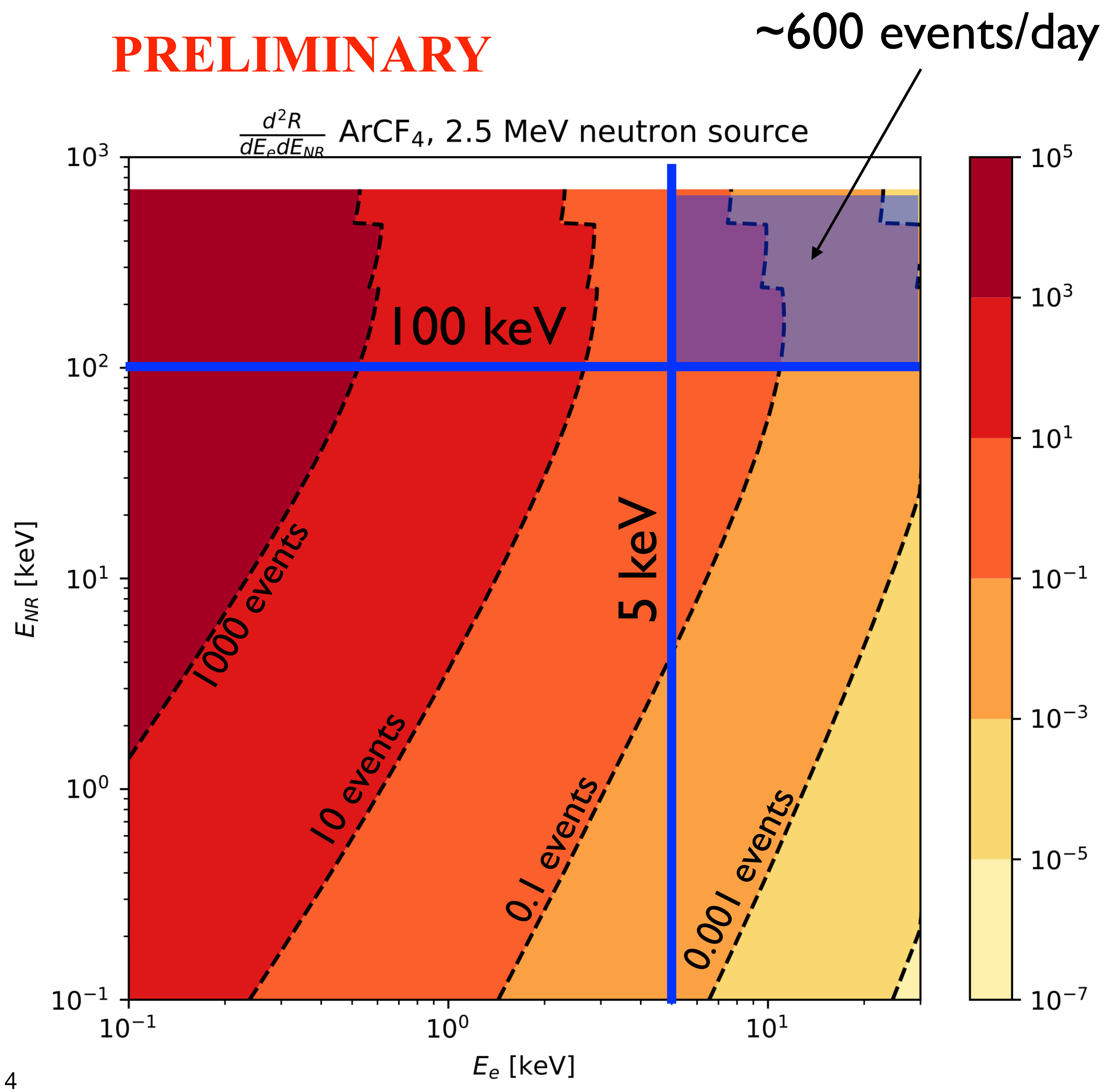
$$N_{\text{events}} = N_T \, \Phi \, \sigma_{Ar} \, f_{Ar} \, q_e^2 \, \text{BR}_{\text{Mig}}$$

- Number of target nuclei: $N_T = 7.5 \times 10^{23}$
- Flux for a 2.5 MeV neutron source: $\Phi = 113 \ \text{s}^{-1}\text{cm}^{-2}$
- $\sigma_{Ar} = 3.2 \times 10^{-24} \ \text{cm}^2$
- Fluorescence yield: $f_{Ar} = 0.14$
- $q_e^2 = \dfrac{2 \, m_e^2 E_R}{m_N}$
- $\text{BR}_{\text{Mig}} = 10^{-4} - 10^{-5}$

$$\simeq 400 \ \text{evt/day}$$

2. Migdal electron signature

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 $ArCF_4$;



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 the **CYGNO TPC**: simulations for the best experimental setup are currently ongoing.

Thank you!