Migdal effect: improving the sensitivity to light matter with liquid Argon experiments

Based on:

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

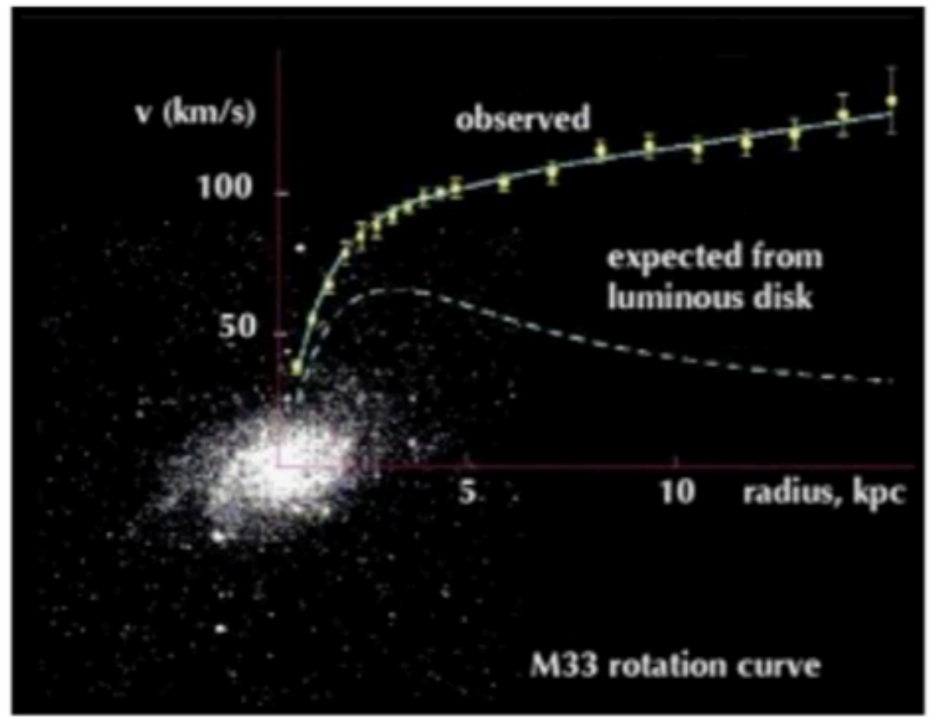
Marcel Grossmann Meeting - July 5-10, 2021

Andrea Messina - Sapienza Università di Roma & INFN

July 6, 2021

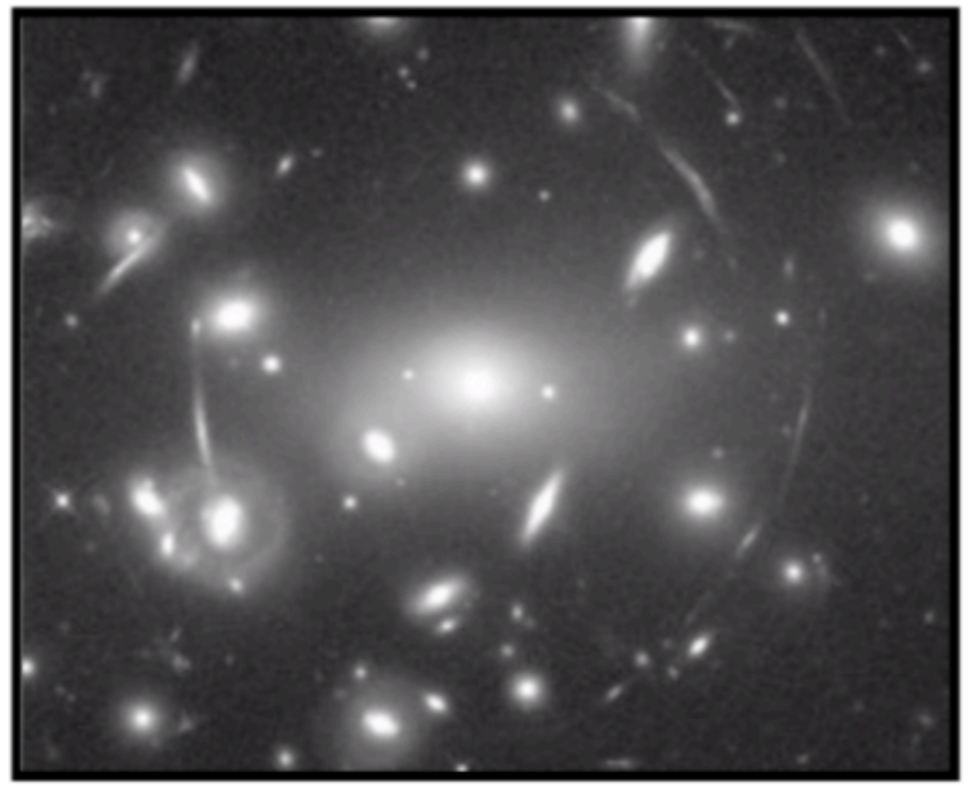
Compelling evidence for Dark Matter at all scales

Galaxies

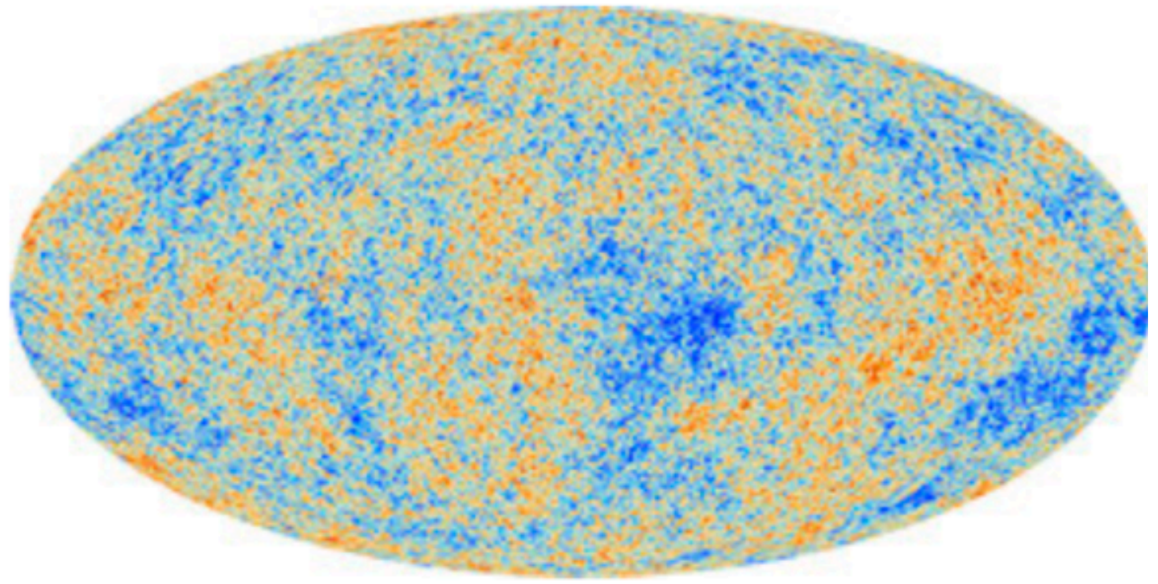


Bullet cluster

Lensing



Cosmic Microwave Background



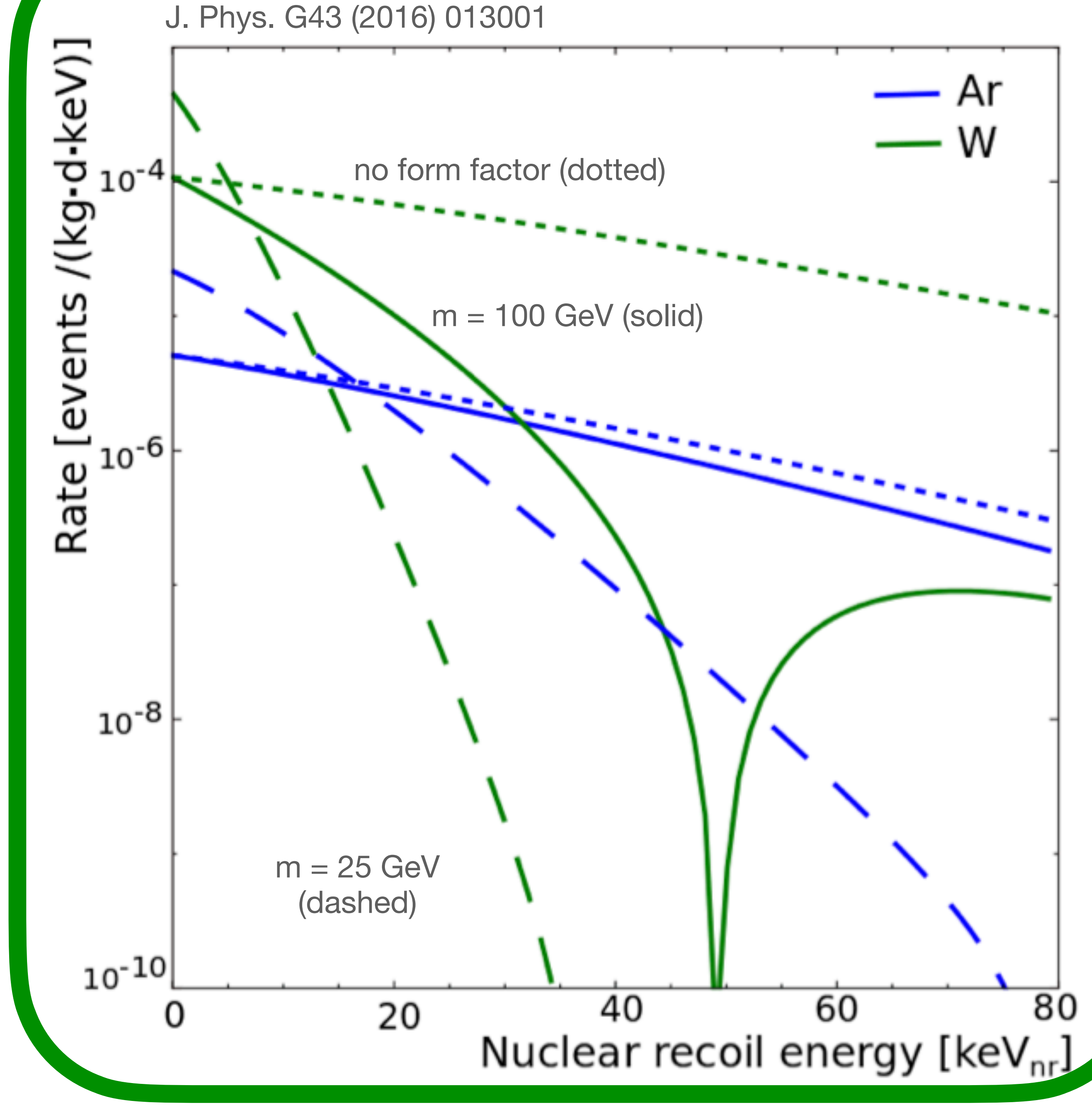
Larger scales

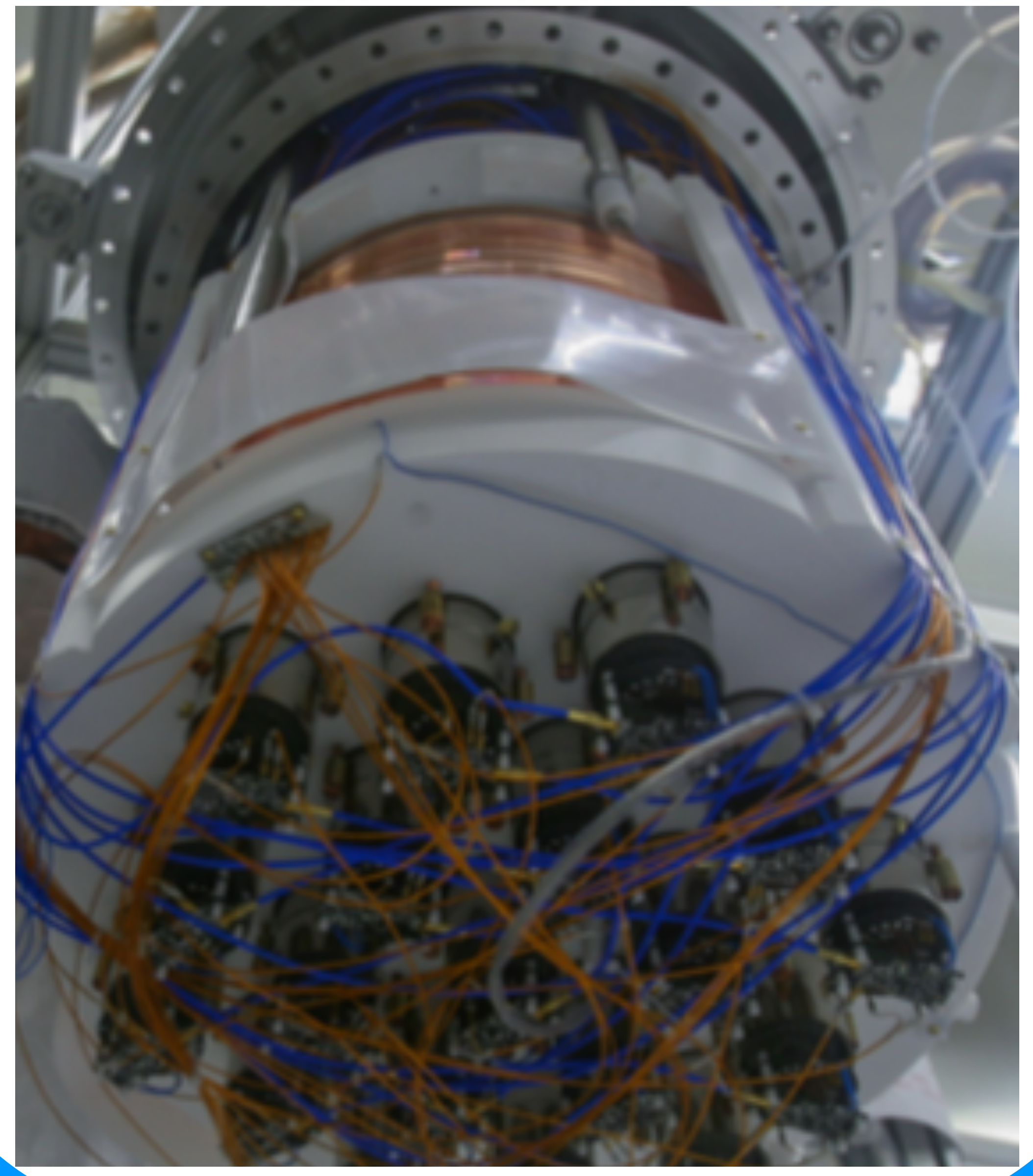
Dark Matter direct detection

Interaction rate

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

Credit: ESO/L. Calçada

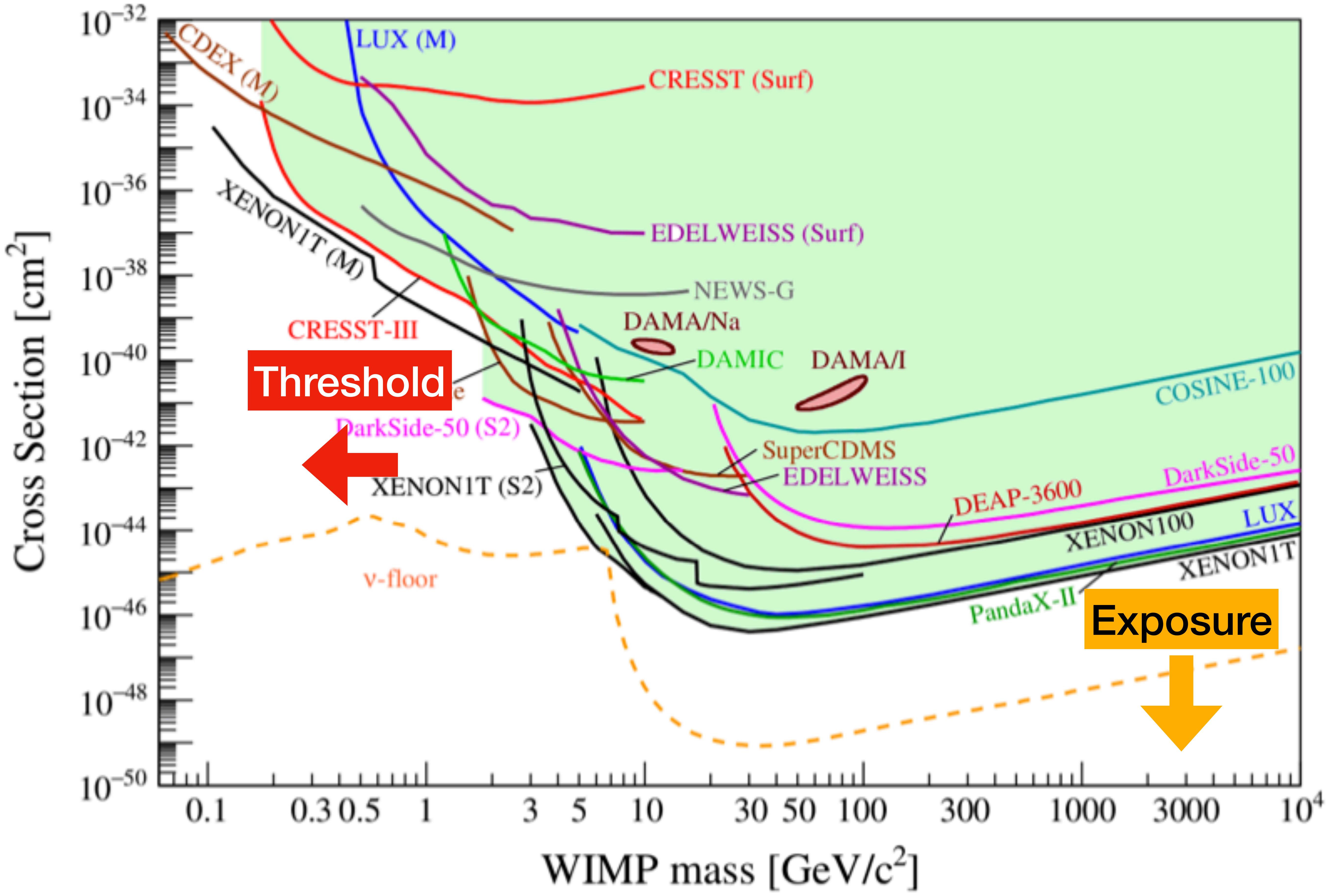




Dark Matter direct detection

WIMP search status

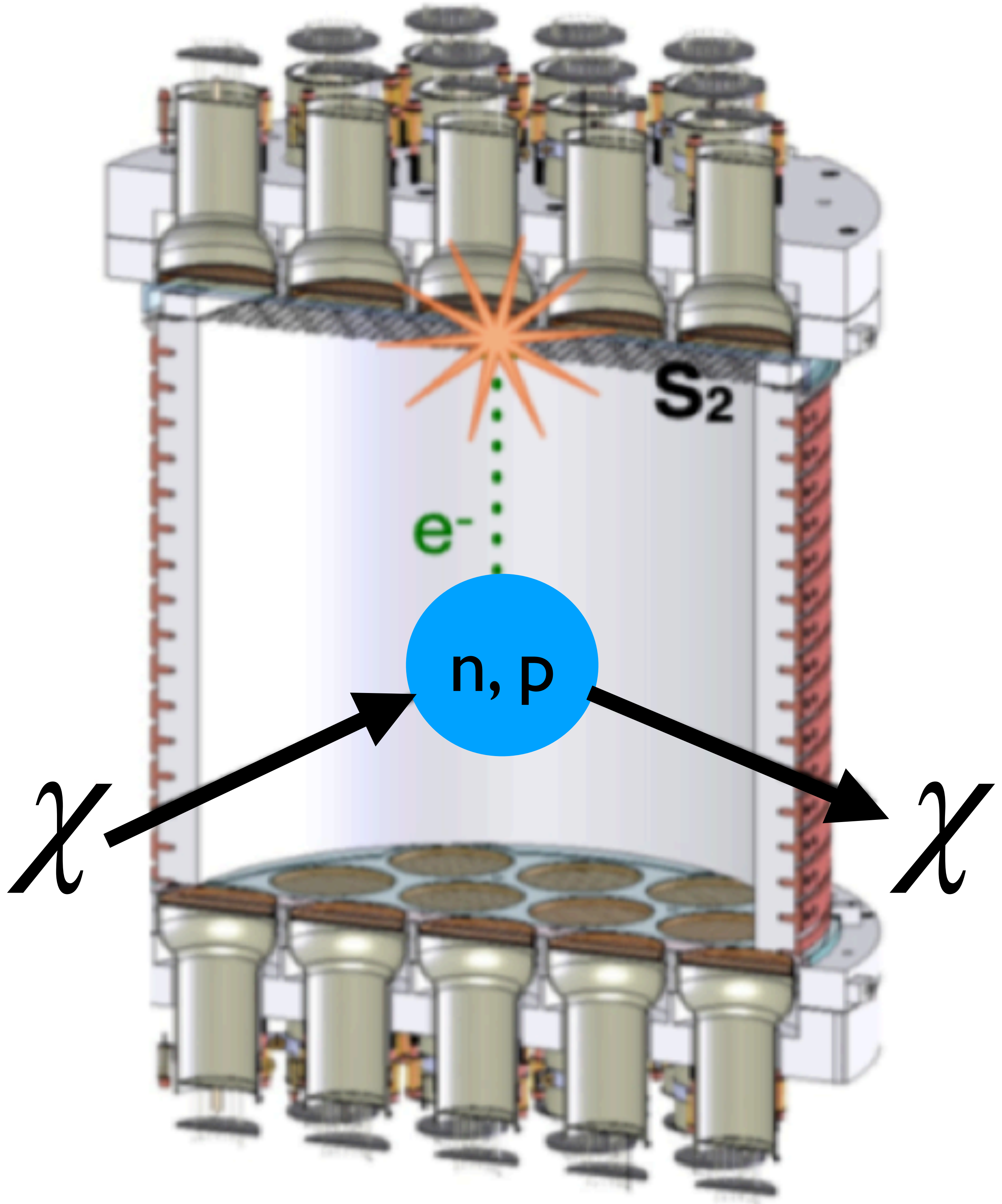
Direct Detection of Dark Matter - APPEC Committee Report
arXiv:2104.07634[hep-ex]



Detecting principle for light DM with noble liquids

Nuclear Recoil: simplistic picture

- elastic scattering with nucleus ($\frac{1}{q} \simeq$ 10 fm)
- the nuclear recoil (NR) kinetic energy is (partially: $q_{NR,Ar}$~0.25) absorbed by the detector active material and the event revealed
- typical experimental threshold few ionisation electrons $\lesssim 1$ keV_{NR}



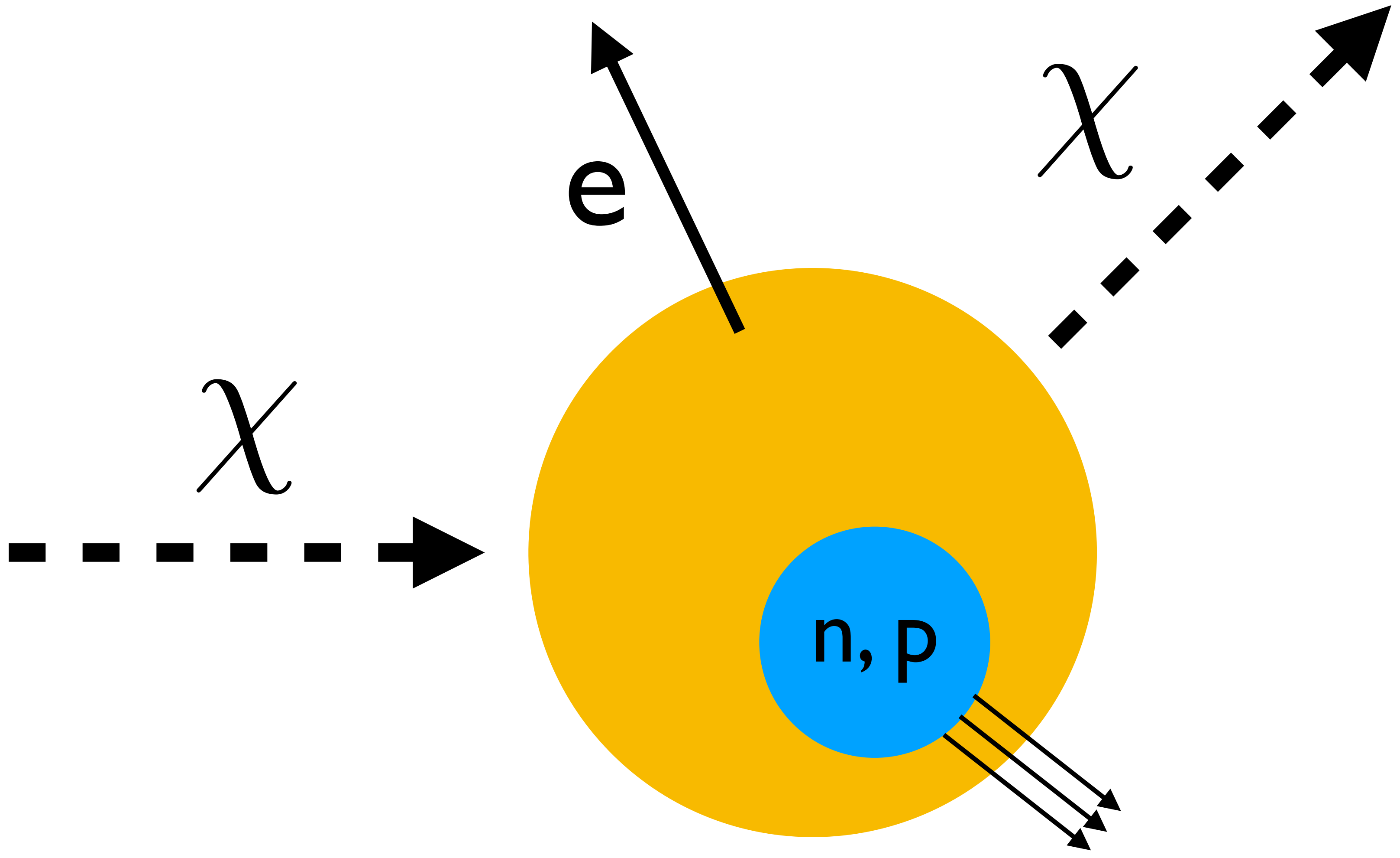
Assumption: the electron cloud follows instantaneously the nucleus after the collision.

The Migdal effect

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

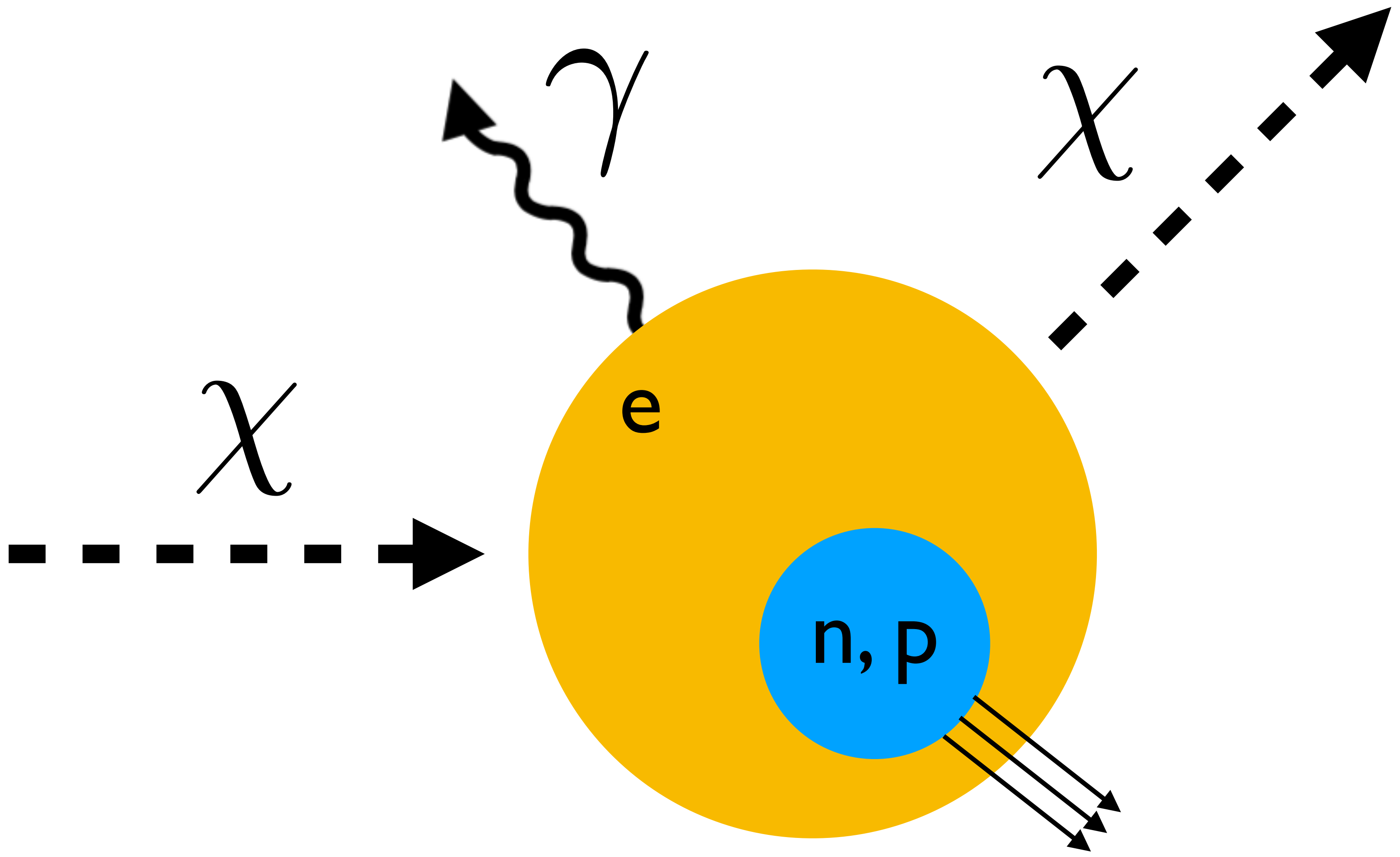
More accurate picture

relevant at small momentum transfer



The atom emits an electron
(Migdal effect)

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)

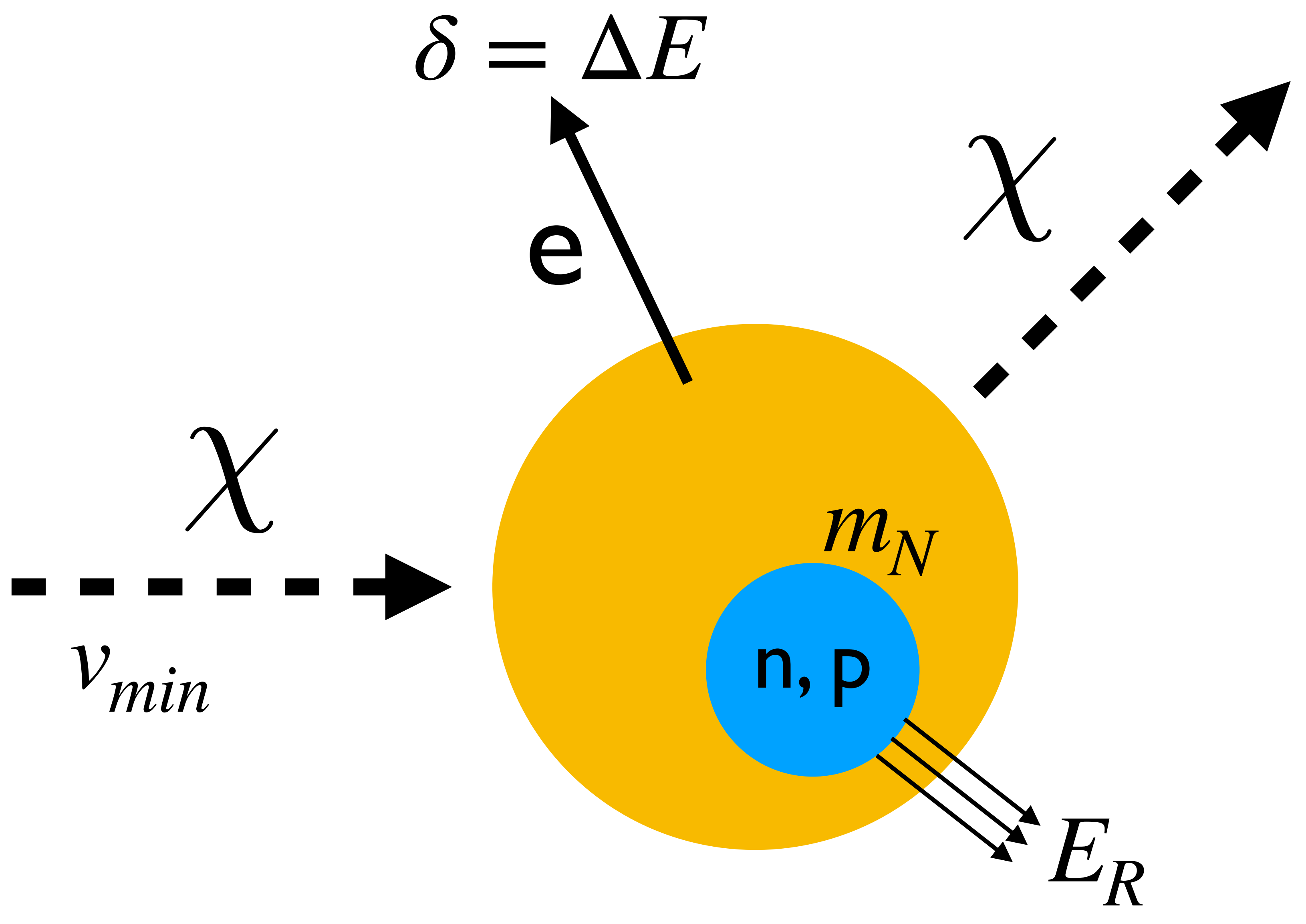


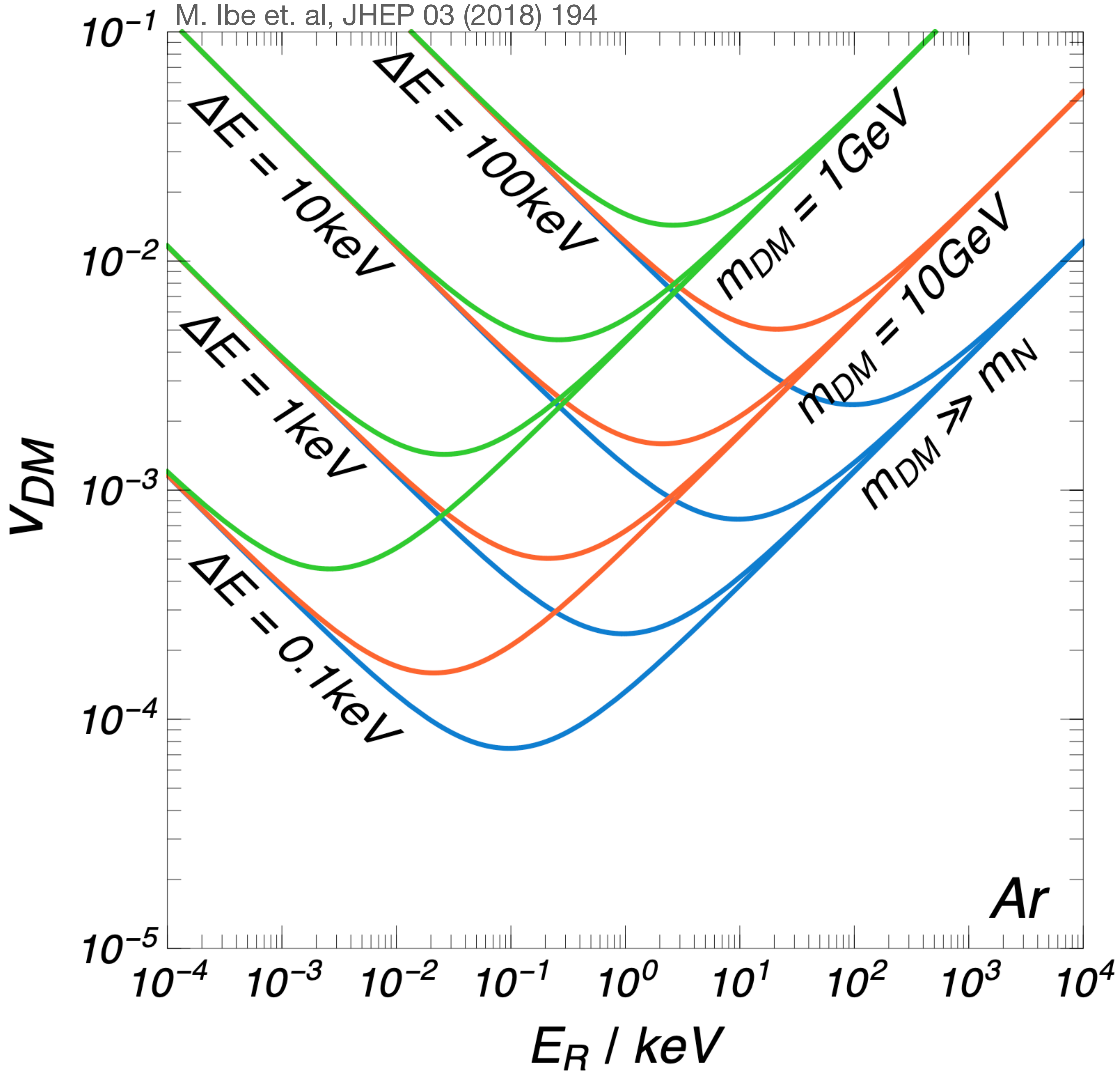
The polarised atom emits a photon
(Bremsstrahlung)

C. Kouvaris, J. Pradler, Phys. Rev. Lett. 118, 031803 (2017)

Kinematics

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



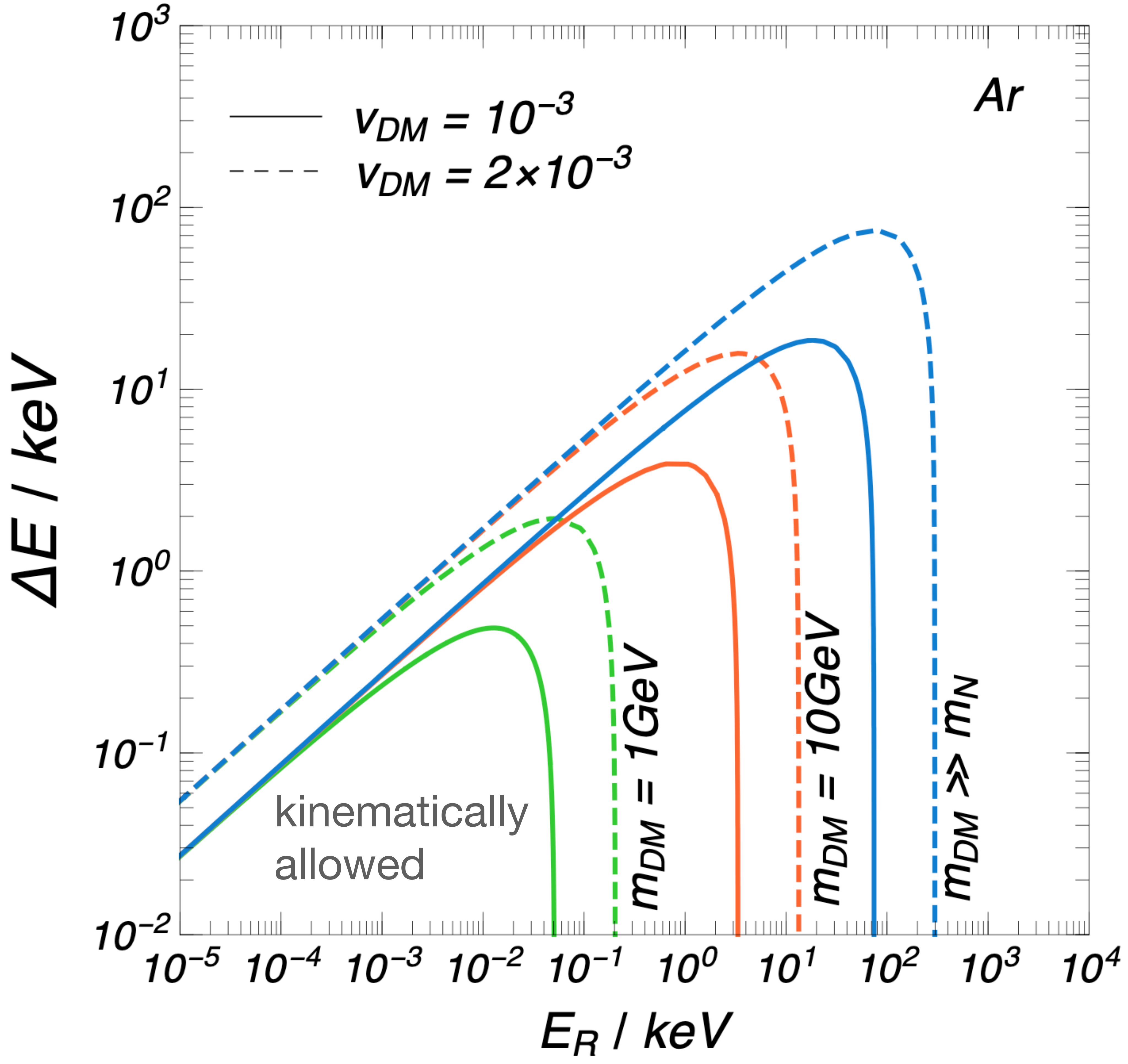


Kinematics

$$E_{R,\max} = \frac{2\mu_N^2 v_{\max}^2}{m_N^2}\,; \qquad \delta_{\max} = \frac{\mu_N v_{\max}^2}{2}$$

- threshold E $\lesssim 1$keV$_{NR}$;
- loss of sensitivity for $m_\chi \lesssim$ GeV;
- $\delta_{\max} > E_{R,\max}$ for $m_\chi \ll m_N$, (suppression factor μ_N/m_N);
- Migdal effect sensitive to sub-GeV.

M. Ibe et. al, JHEP 03 (2018) 194



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

Kinematics

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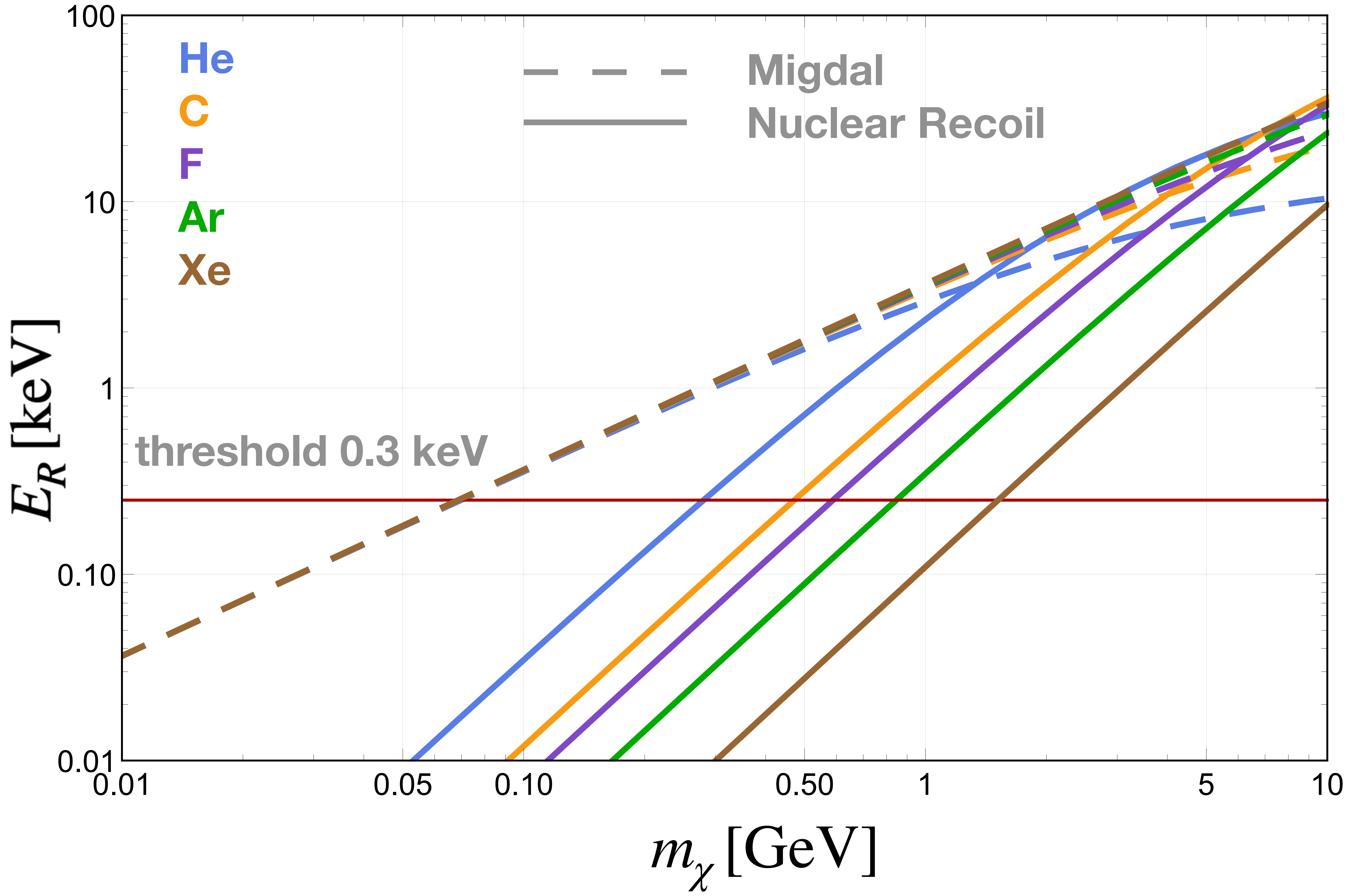


The heavier the nucleus the more significant the Migdal contribution at small DM masses

Rates

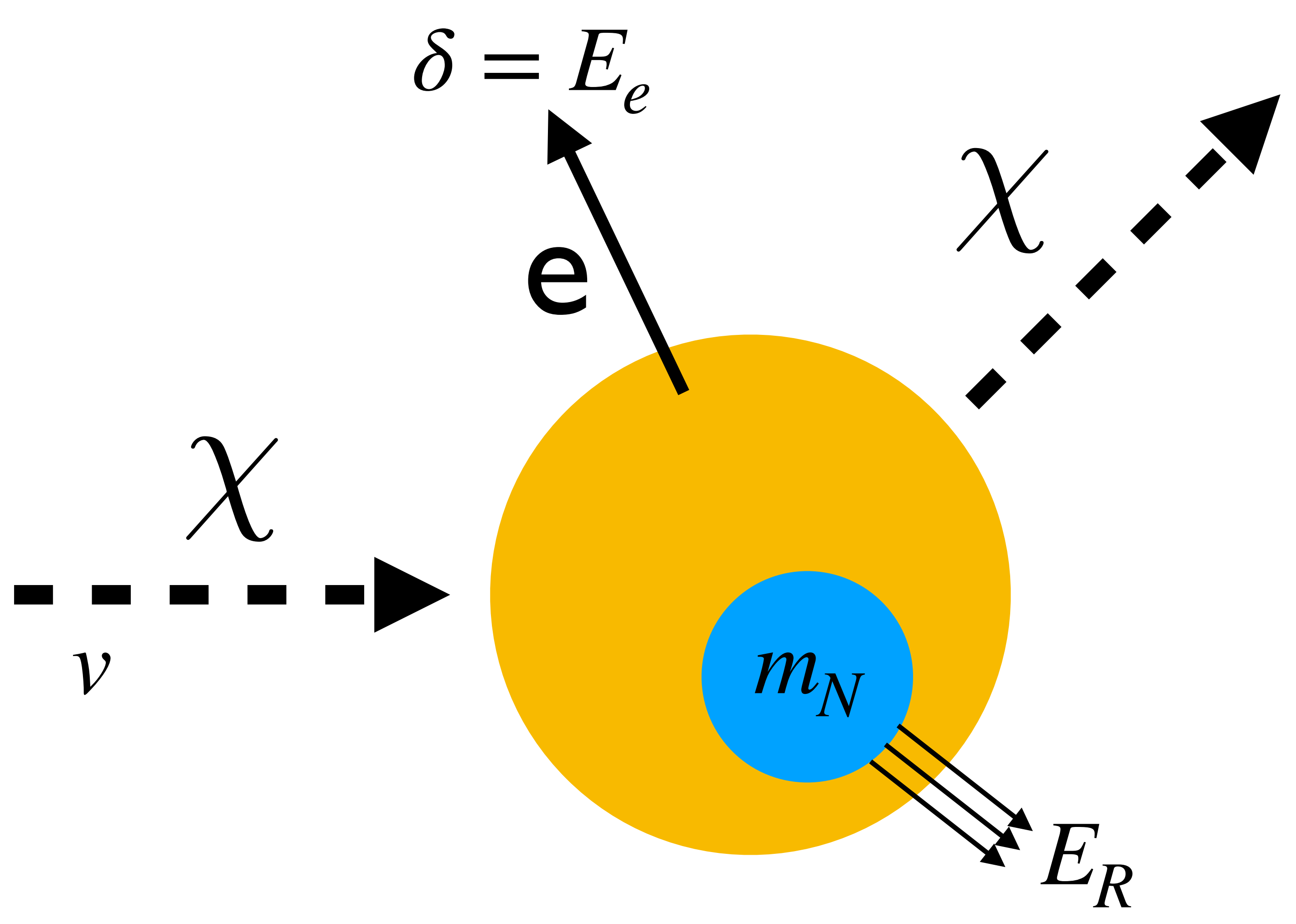
From the NR to a more complete picture

Usual nuclear recoil rate

$$\frac{d^2R}{dE_R dv} = \frac{d^2R_{NR}}{dE_R dv} |Z|^2$$

NR — de-excitation: negligible

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



Ionization probability

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

Computed in

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

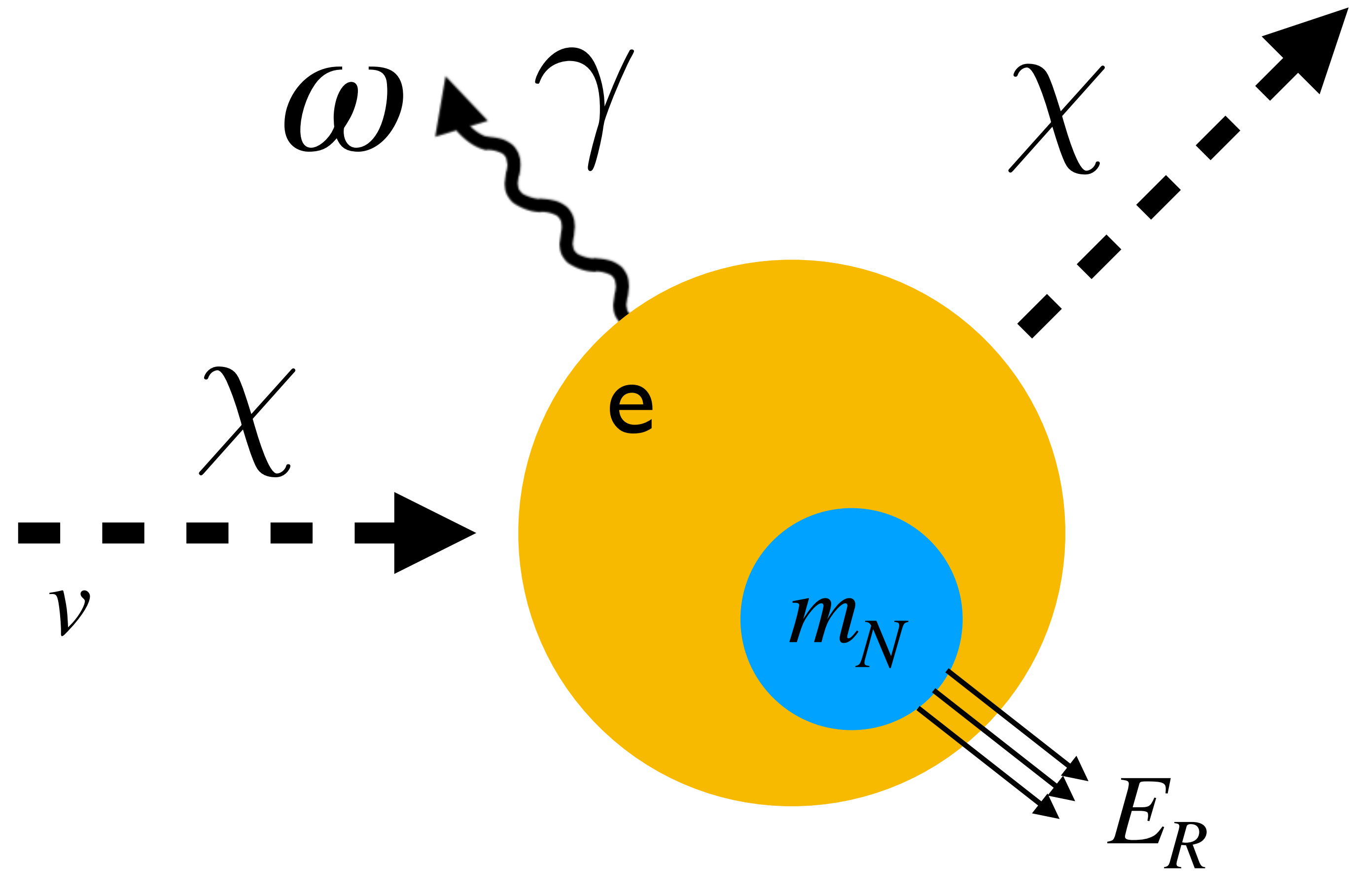
Photon bremsstrahlung

C. Kouvaris, J. Pradler, Phys. Rev. Lett. 118, 031803 (2017)

Usual nuclear recoil rate

Atomic scattering factors

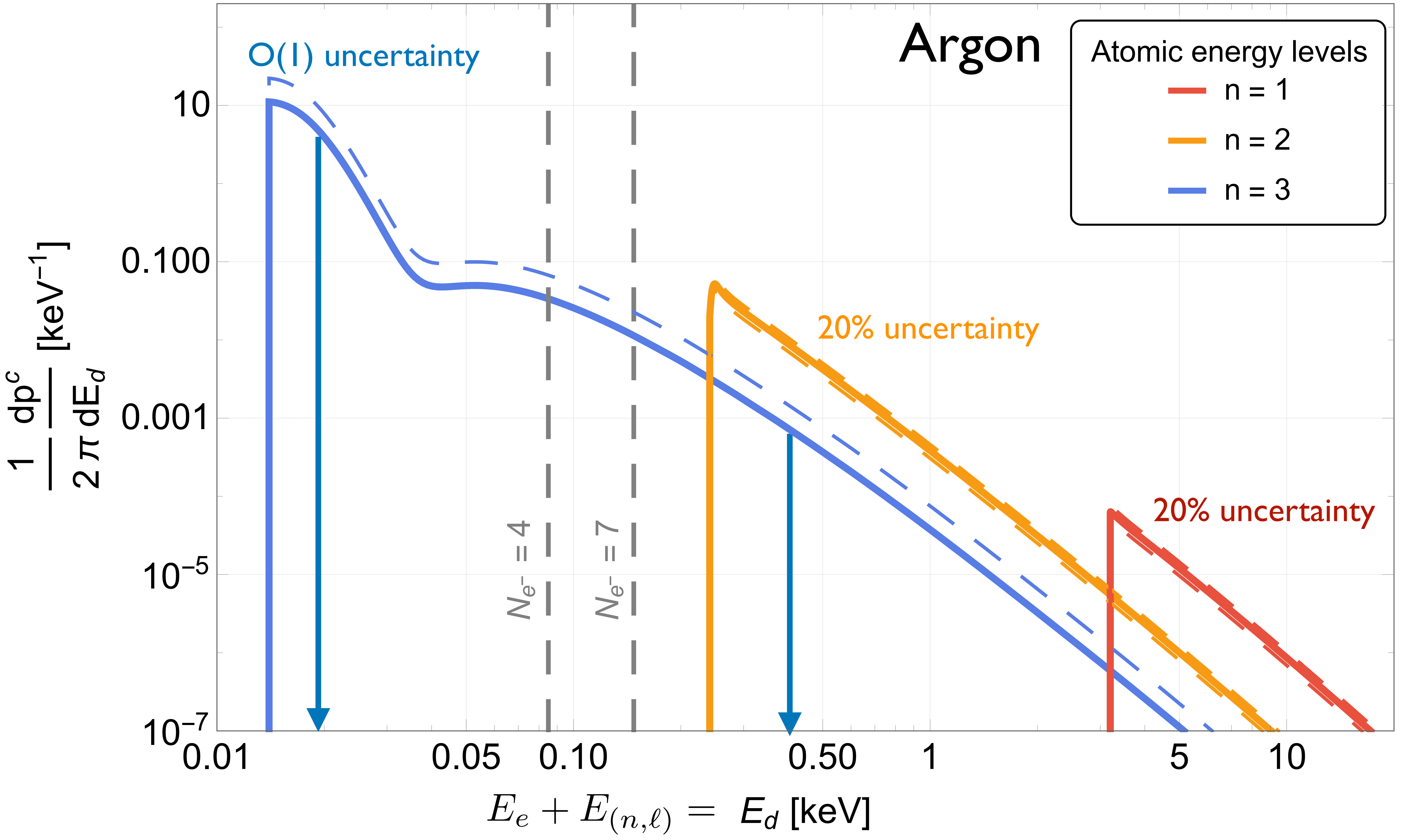
$$\frac{d^3R}{dE_R d\omega dv} = \frac{d^2R_{NR}}{dE_R dv} \frac{4\alpha |f(\omega)|^2}{3\pi\omega} \frac{E_R}{m_N}$$



Price to pay for argon $\sim \frac{2.5 \times 10^{-8}}{\omega} \frac{E_R}{1\,\mathrm{keV}}$

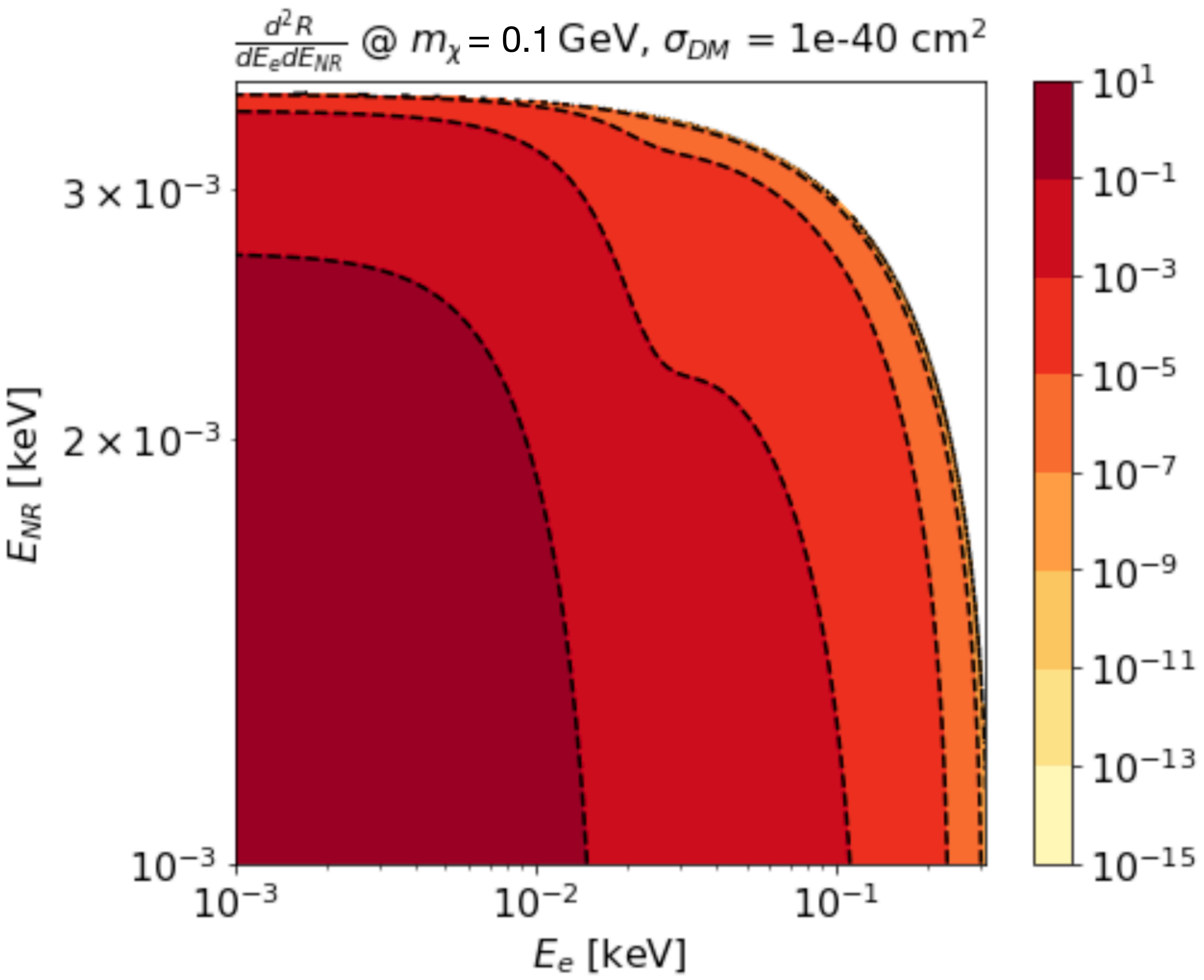
Migdal electron emission probabilities

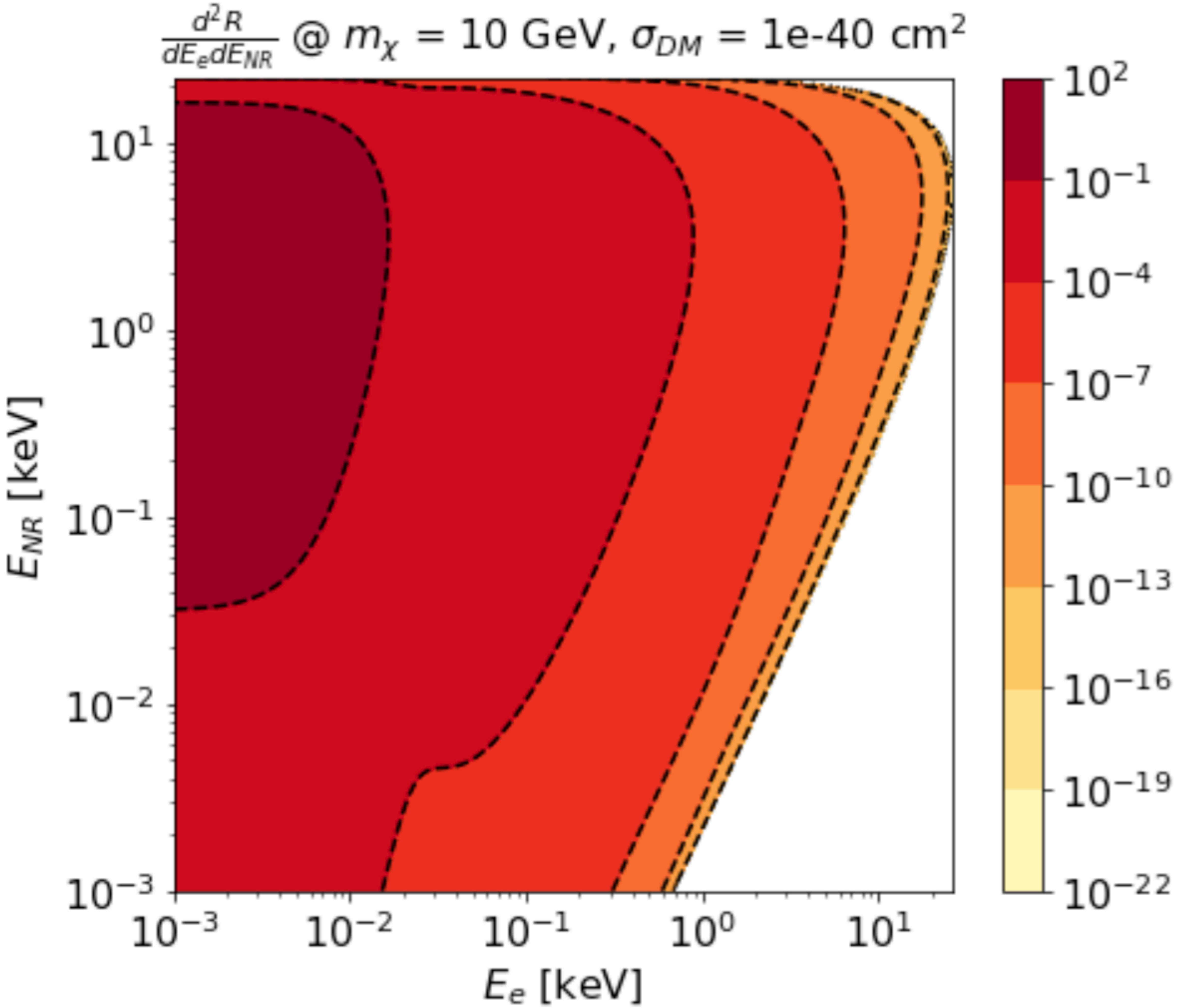
- Computed[1] for a number of isolated atoms in non-relativistic QM using the Flexible Atomic Code[2] (FAC);
- The outer shell is potentially affected by large uncertainties;
- Migdal emission can be rigorously related[3] to photo-absorption, thus anchored to exp. input which reduces theoretical uncertainties.



[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.

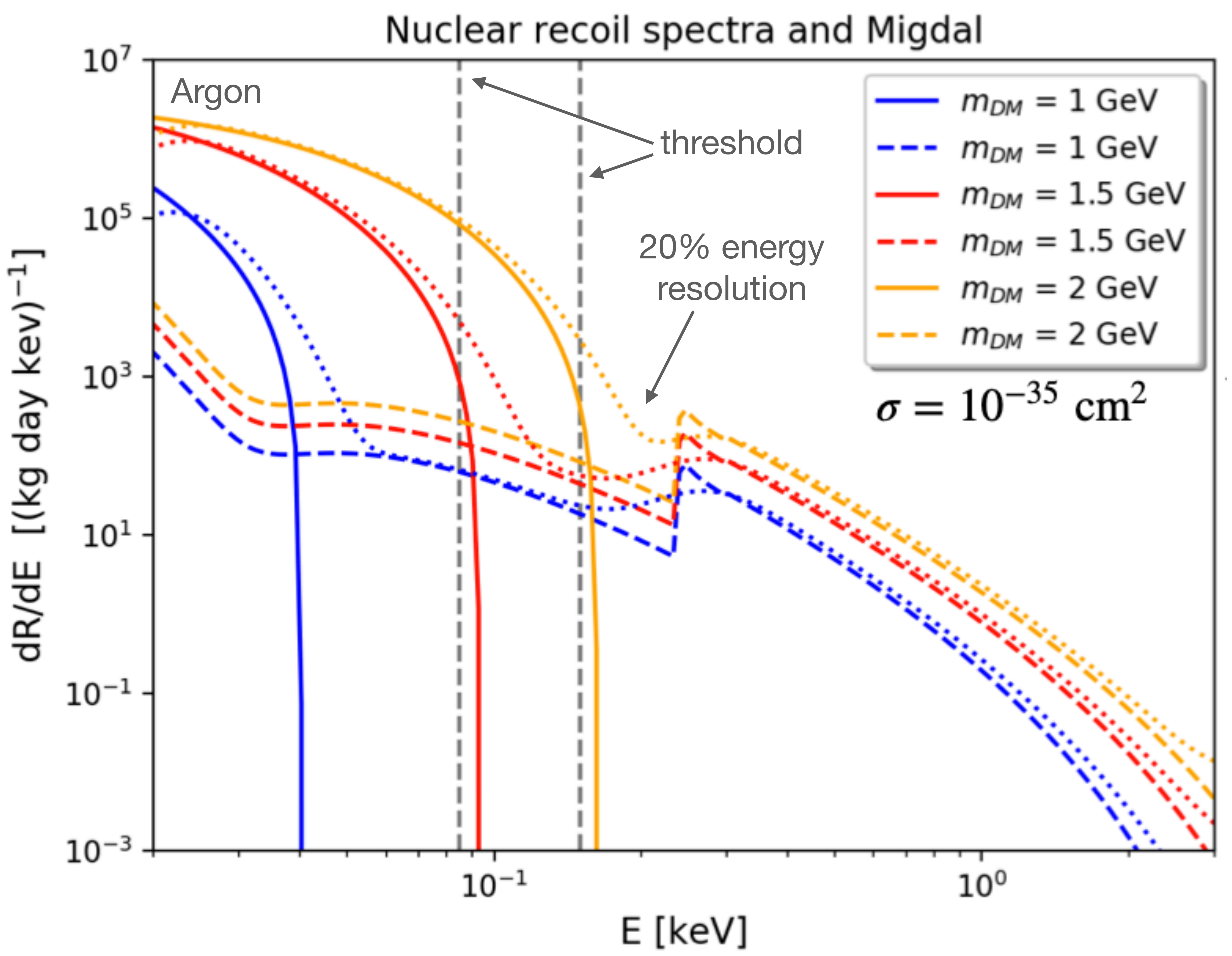
Double differential rates for Ar





Rates

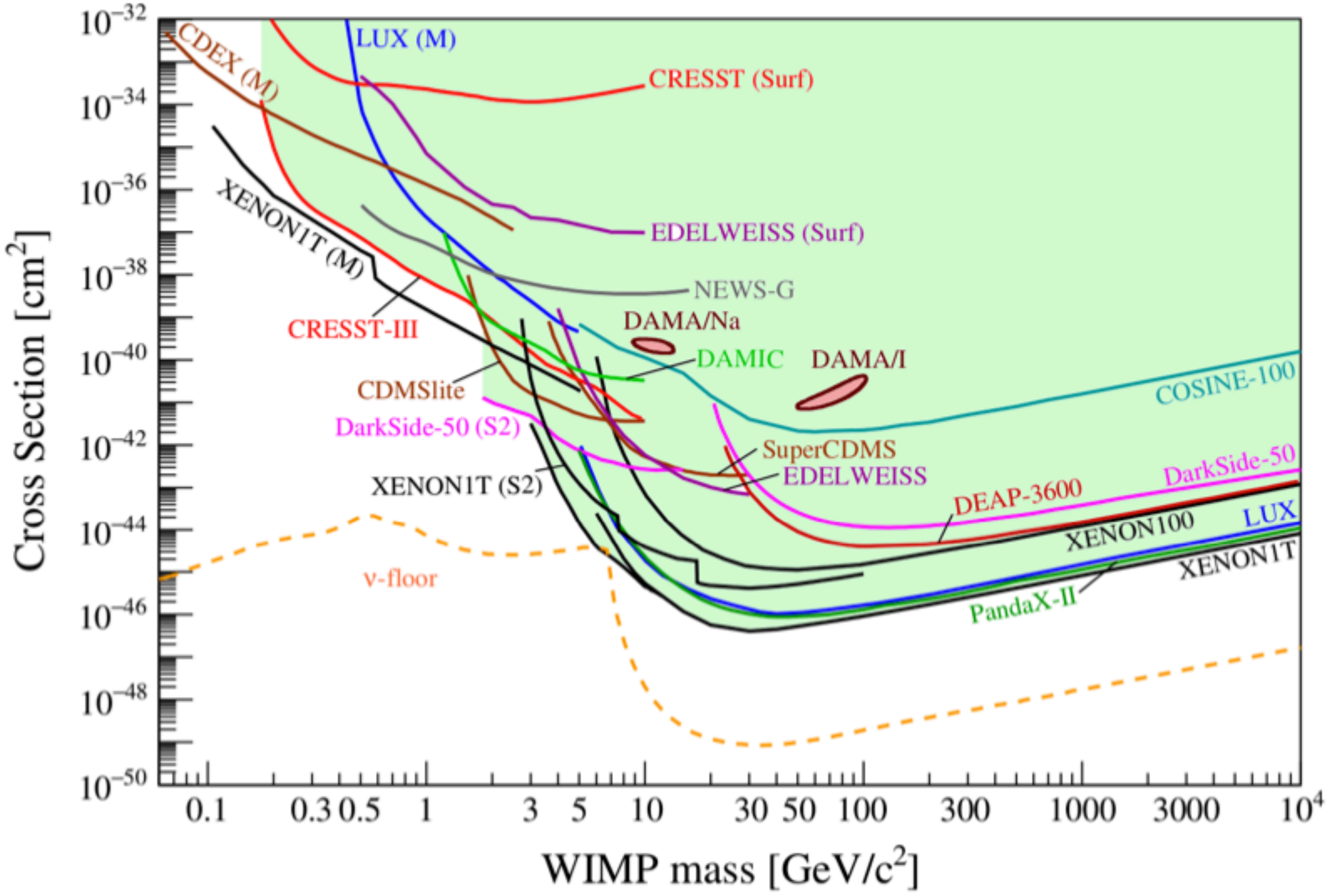
- NR is around or below threshold for $m_\chi \lesssim 2\,\mathrm{GeV}$;
- The Migdal electron rate extends to the keV region. Around threshold is only a factor 10 smaller than the NR one.
- Energy resolution effects help to move few events above threshold;



Has the Migdal effect been considered by current experiments?

- CDEX: solid state Germanium
- LUX: Liquid Xenon
- XENON1T: Liquid Xenon

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



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

TEALAB: a case study inspired to DarkSide-50

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

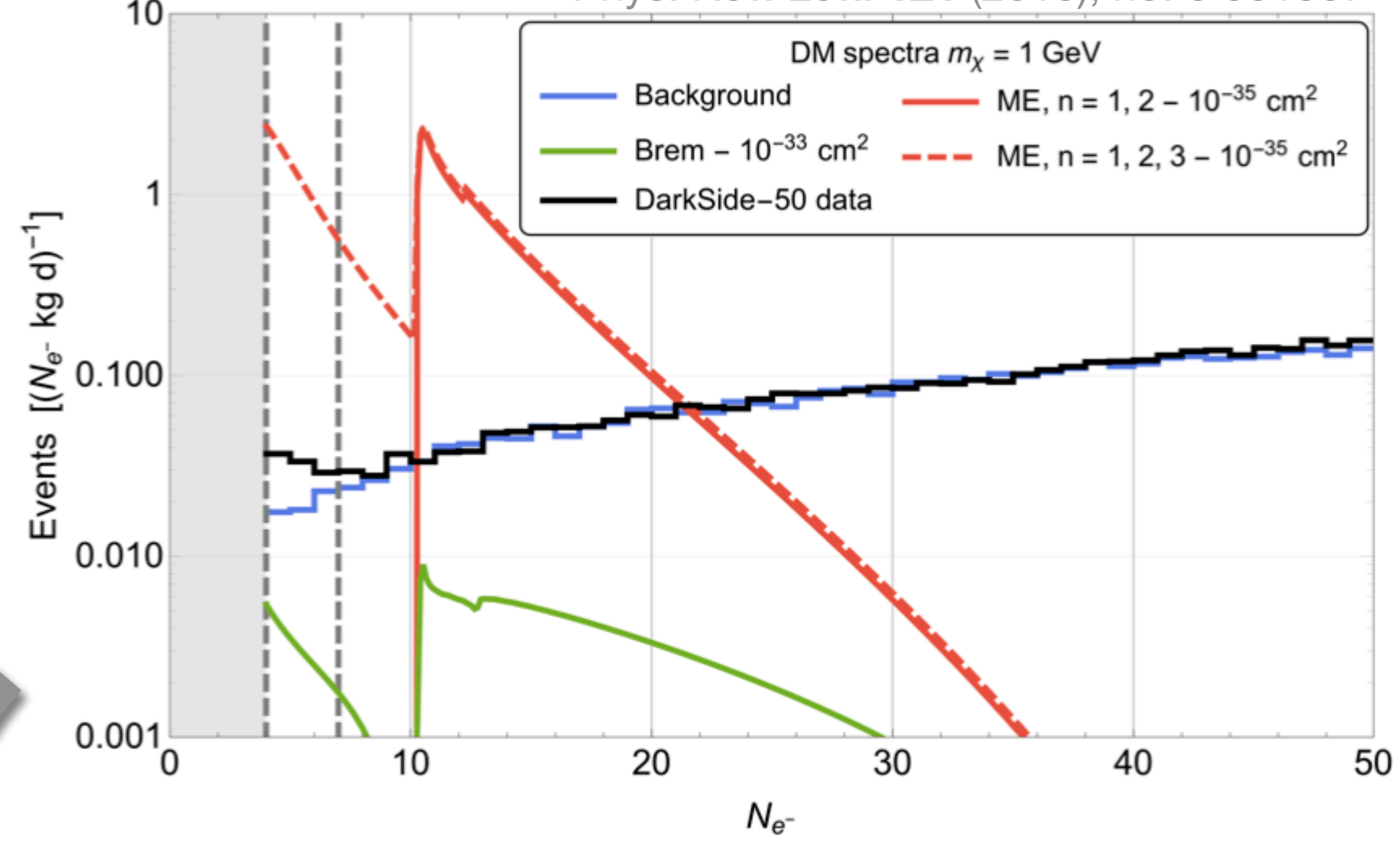
To exploit the Migdal prediction for liquid argon we used a simulated experiment called TEALAB.

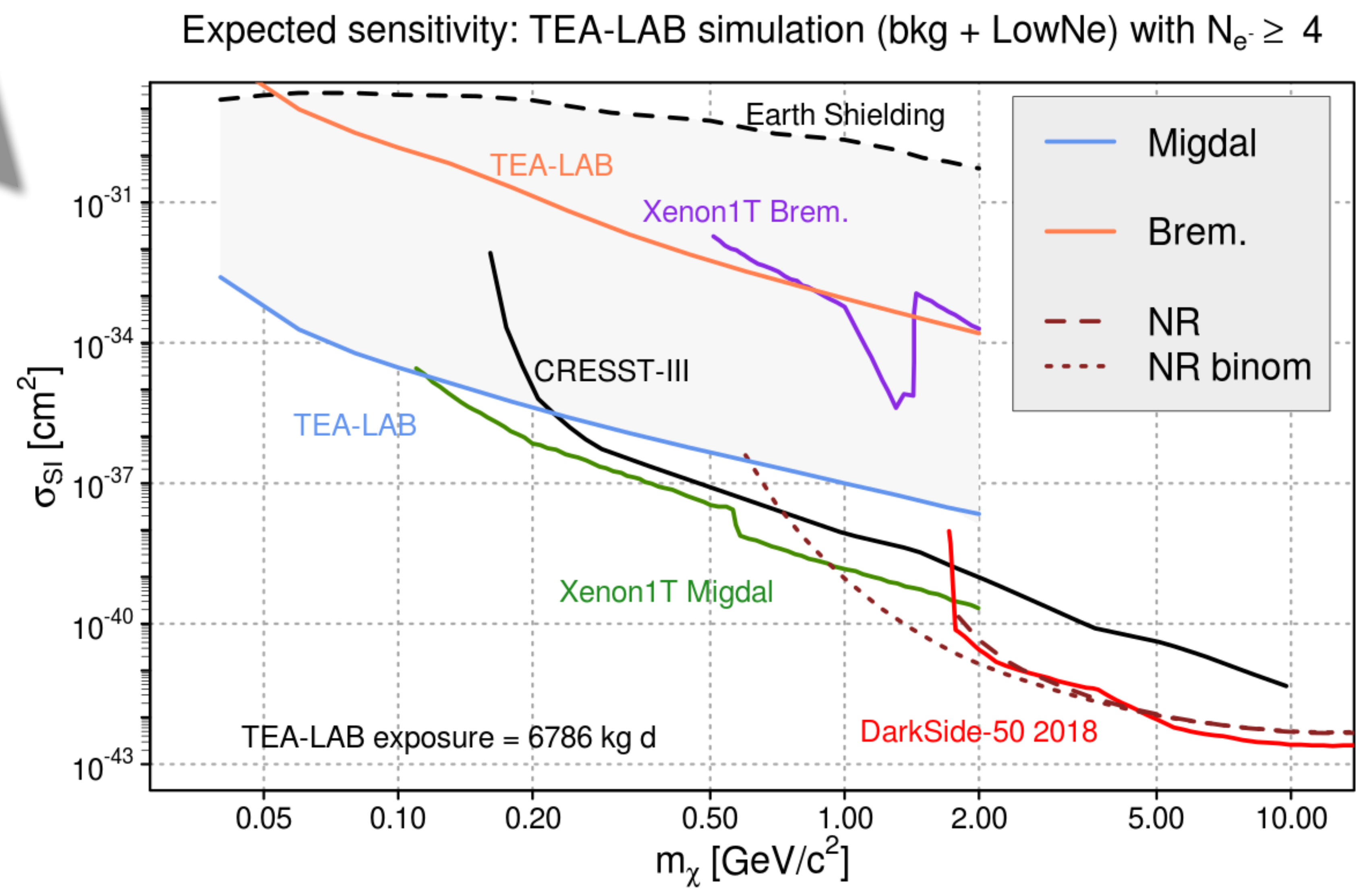
Analysis inputs:

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

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

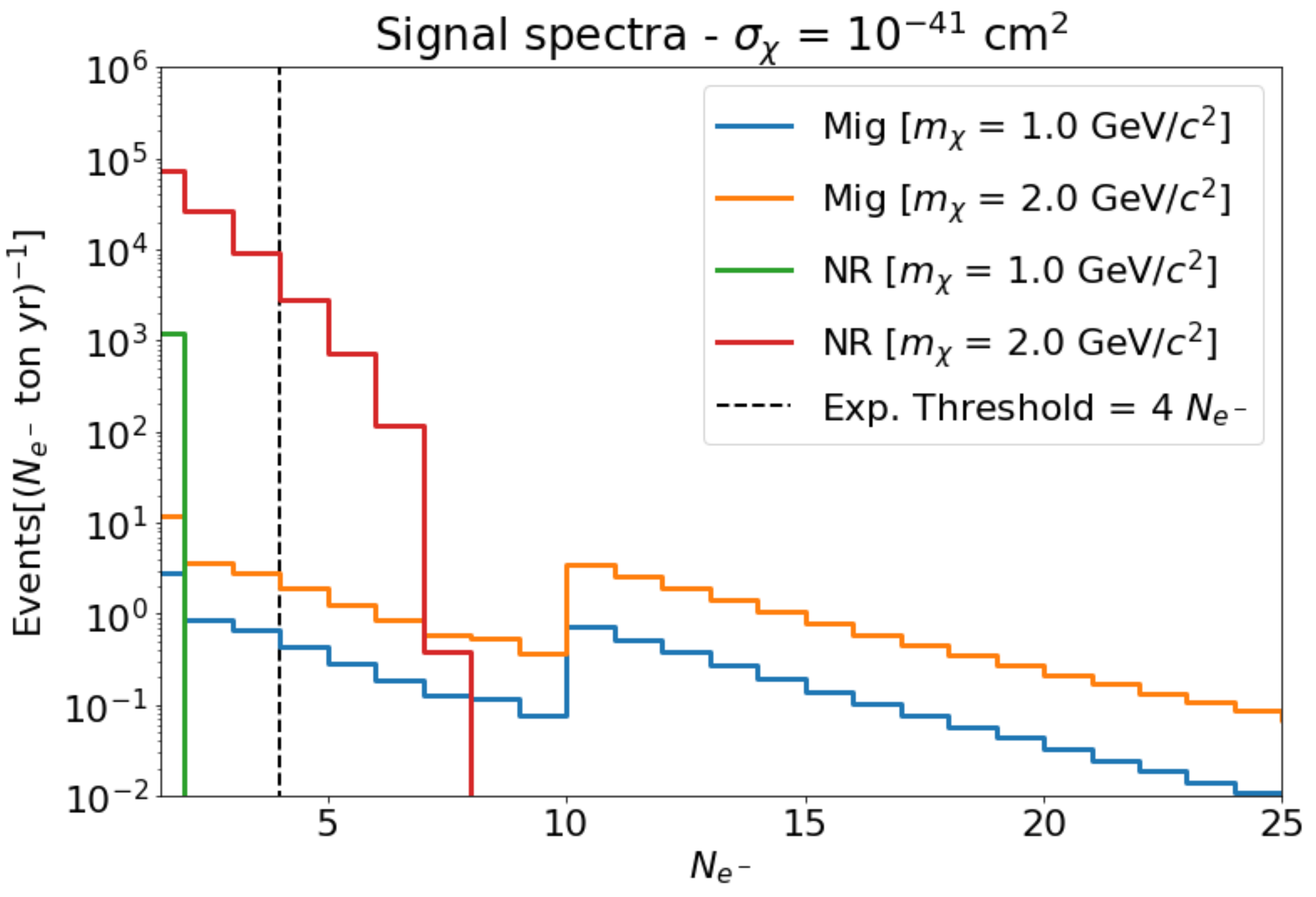
Phys. Rev. Lett. **121** (2018), no. 8 081307



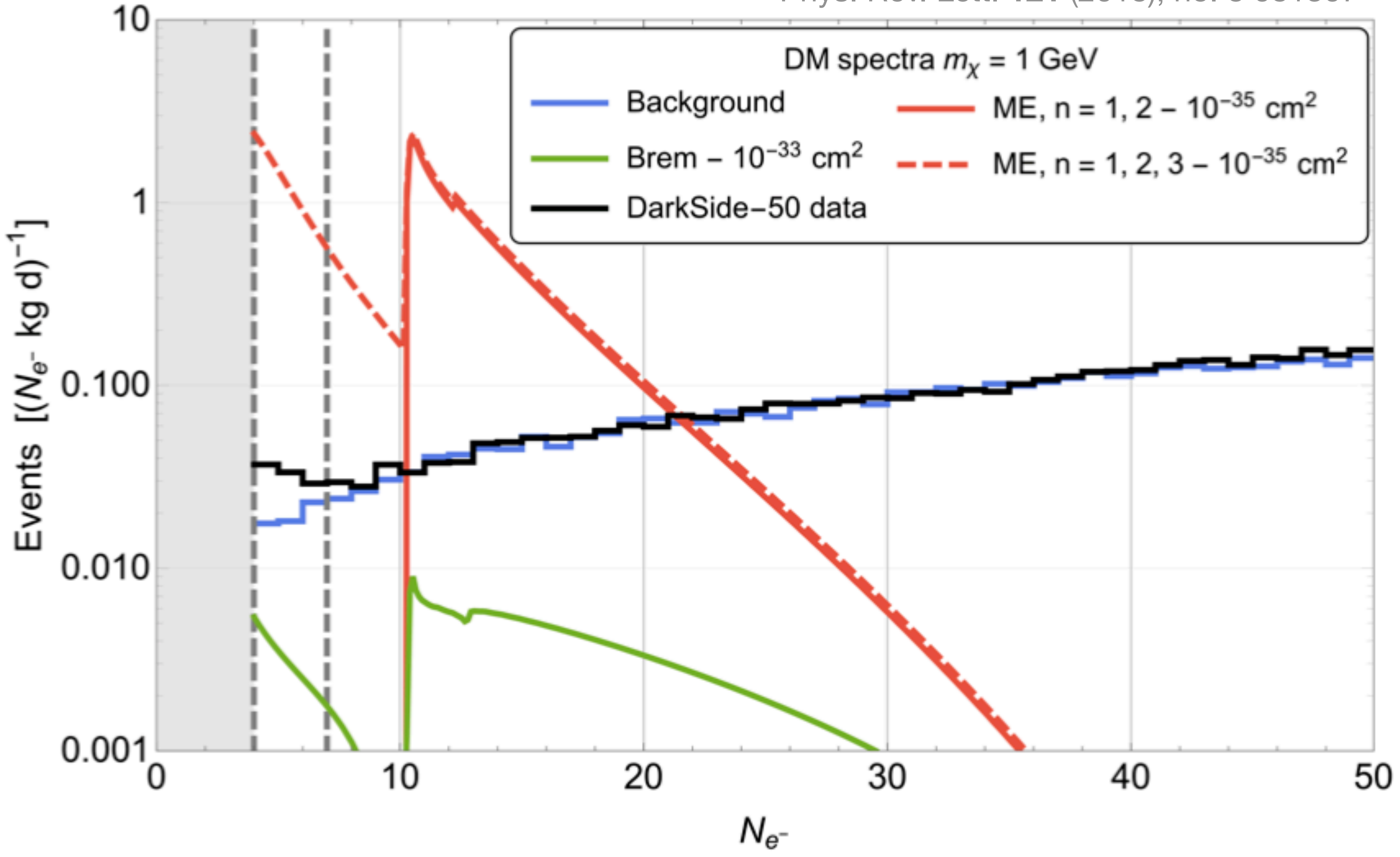


Event spectra

Signal, relevant backgrounds, and detector response



Phys. Rev. Lett. **121** (2018), no. 8 081307



The TEA-LAB likelihood

- binned **Poisson likelihood**;
- intensity controlled by the expected bkgd and signal rates;
- additional **nuisance parameters** to account for detector effects and sig/bkg uncertainties;

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

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

with:

$$\lambda_i = E\,[\underbrace{r_S\, S_i}_{\text{signal}} + \underbrace{r_B\,(B_i + LowNe_i)}_{\text{background}}]$$

$$\mathcal{L}_B = \prod_{\{bkgd\}} \prod_{i=1}^{Nbin} \mathcal{N}(\mu = bkgd_i, \sigma = \sigma_{bkgd_i})$$

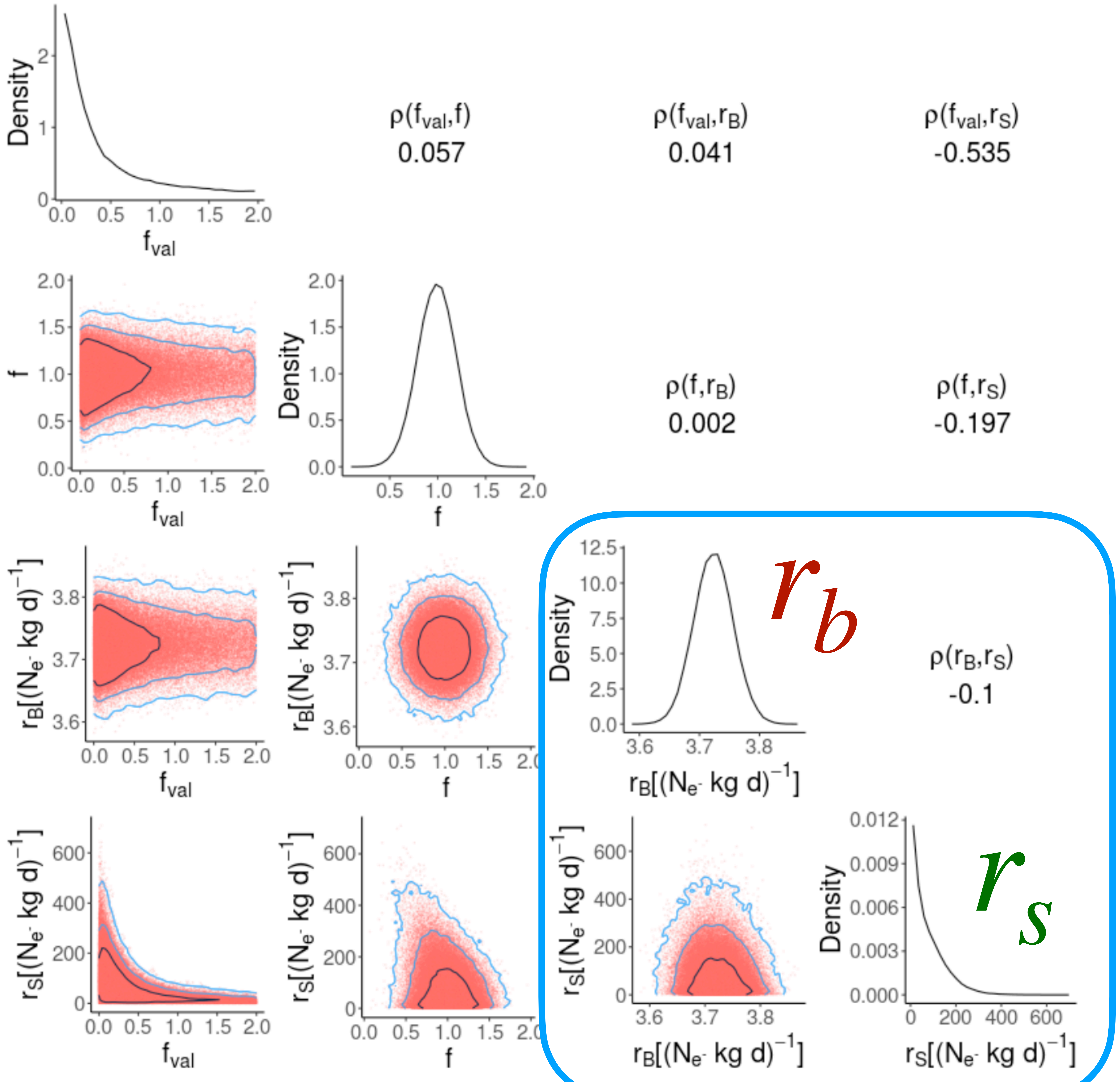
$$\mathcal{L}_S = \delta[S_i - S_i(\mathbf{f}, N_{e^-}^{max}, \epsilon)]$$

Posterior joint p.d.f.

- background-only pseudo-data;
- Used **MCMC** Gibbs sampler as implemented in JAGS to integrate the posterior;
- Explored different assumptions for signal and background templates
- Explored reasonable choices of prior p.d.f.

$$p(r_S, \boldsymbol{\theta} \,|\, \{x_i\}, H_{r_S}) = \frac{p(\{x_i\} \,|\, r_S, \boldsymbol{\theta}, H_{r_S}) \pi(r_S, \boldsymbol{\theta} \,|\, H_{r_S})}{\int_\Omega \int_0^\infty p(\{x_i\} \,|\, r_S, \boldsymbol{\theta}, H_1) \pi(r_S, \boldsymbol{\theta} | H_1) dr_S d\boldsymbol{\theta}},$$

$$\mathcal{L}(r_s, \boldsymbol{\theta}) \equiv p(\{x_i\} \,|\, r_S, \boldsymbol{\theta}, H_{r_S}).$$



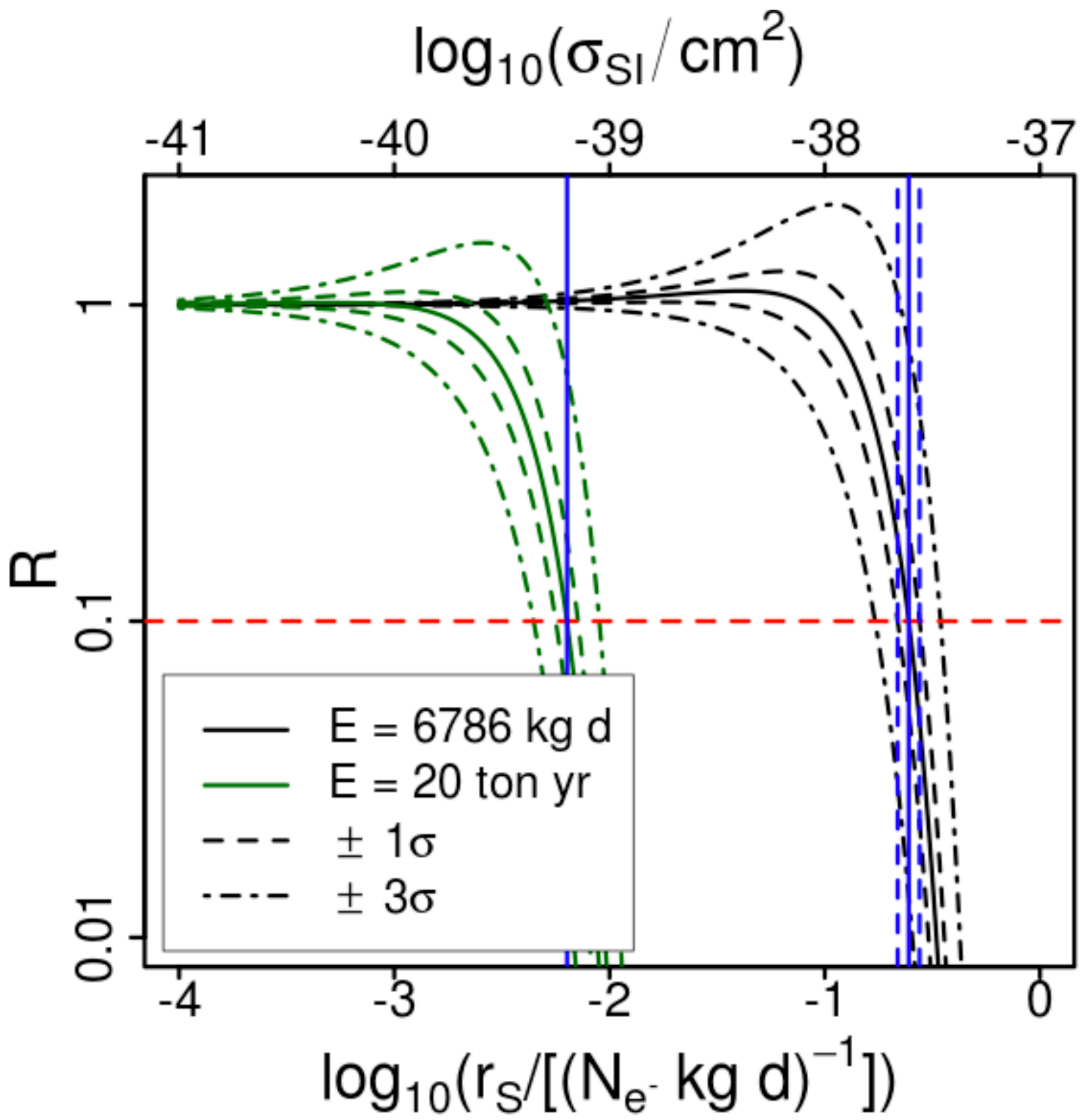
Sensitivity bounds to new signals

- The posterior $p(r_s \,|\, x, r_b)$ can be normalised to $p(r_s = 0 \,|\, x, r_b)$:

$$\frac{p(r_S \,|\, x,\, r_B)}{p(r_S = 0 \,|\, x,\, r_B)} = \frac{\mathcal{L}(r_S \,|\, r_B)}{\mathcal{L}(r_S = 0 \,|\, r_B)} \cdot \frac{\pi(r_S)}{\pi(r_S = 0)}$$

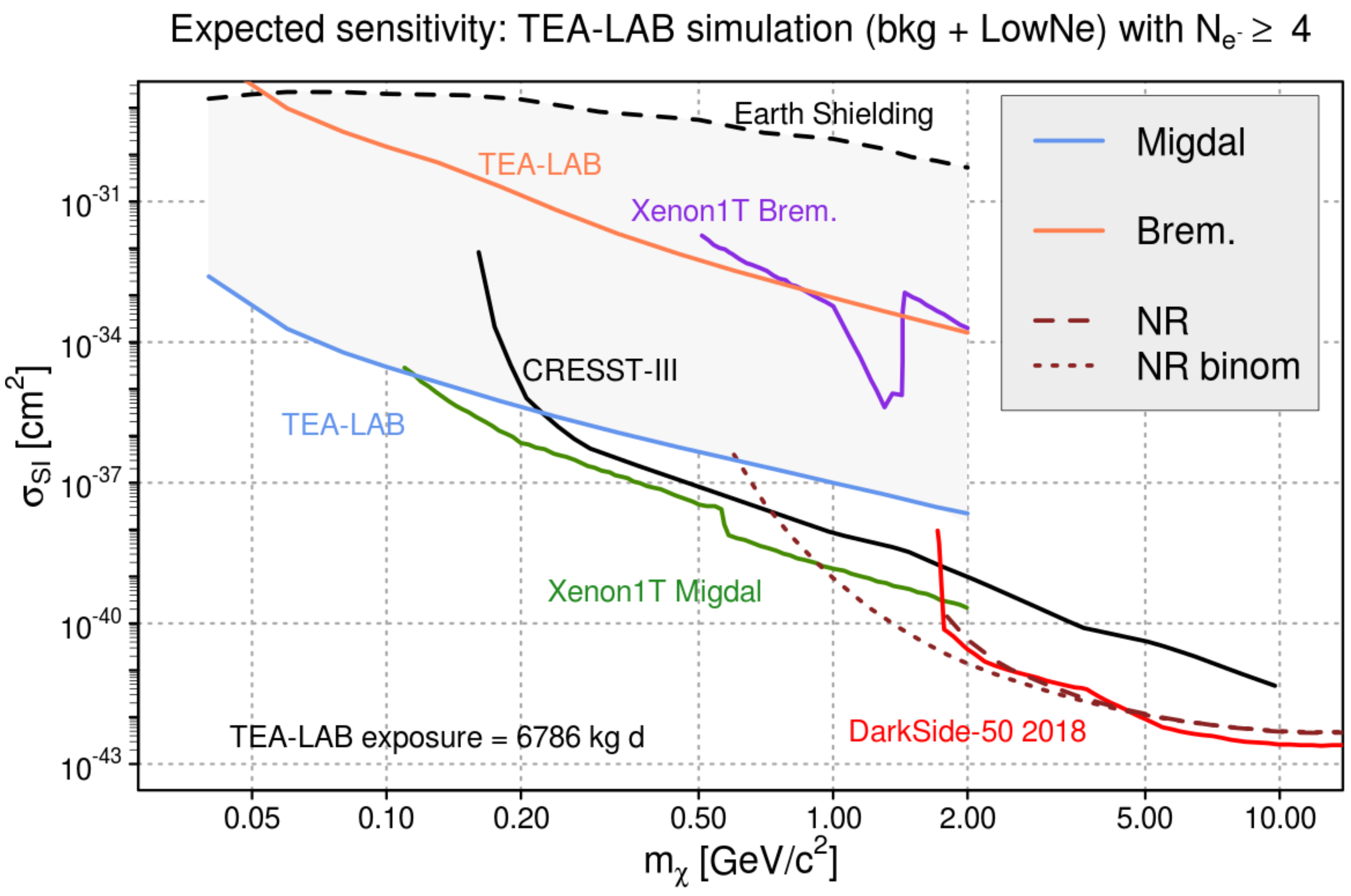
$$\mathcal{R}(r_S \,|\, x,\, r_B) = \frac{\mathcal{L}(r_S \,|\, r_B)}{\mathcal{L}(r_S = 0 \,|\, r_B)}.$$

- $\mathcal{R}$ has the **probabilistic interpretation of hypotheses belief updating ratio**
- $\mathcal{R}(r_S) = 0.10$ corresponds to a probability update ratio of 10% with respect to the null hypothesis.



TEA-LAB projected sensitivity to low mass DM

- Able to reproduce DarkSide-50 2018 limits;
- It is possible to extend the experimental sensitivity from $m_\chi \geq 1.8$ GeV/c² down to **masses** $\mathbf{m_\chi \lesssim 0.1}$ **GeV/c²**.



Estimation of Earth shielding

VERNE code
[Kavanagh, 2017]

$$\frac{d\langle E_\chi \rangle}{dx} = -\sum_i n_i(\mathbf{r}) \int_0^{E_R^{\max}} dE_R \, E_R \frac{d\sigma}{dE_R}$$

$$\kappa = -\frac{\sigma_p}{m_\chi \mu_p^2} \left(\sum_i n_i(\mathbf{r}) \frac{\mu_i^4 A_i^2}{m_i} \right)$$

$$f_{\mathrm{det}}(v_\chi^{\mathrm{fin}}) = e^{2\kappa d} f(e^{\kappa d} v_\chi^{\mathrm{fin}})$$

$d \sim 1400 \text{ m}$

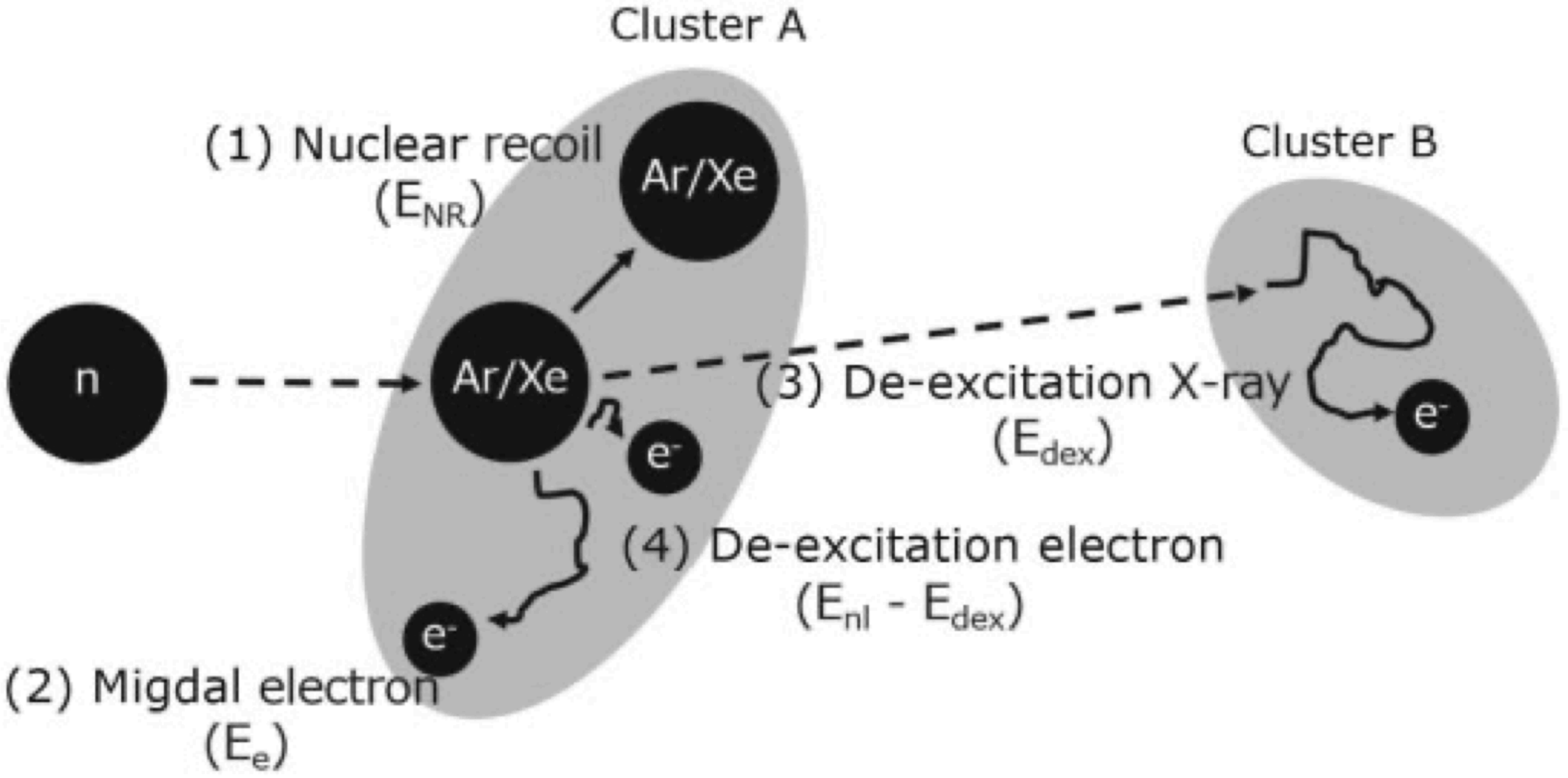
$$v_{\max}(m_\chi, \sigma) = \sqrt{\frac{2\,\delta_{\max}}{\mu_N}}$$

Ideas on how to measure the Migdal effect

Interesting signature in Ar

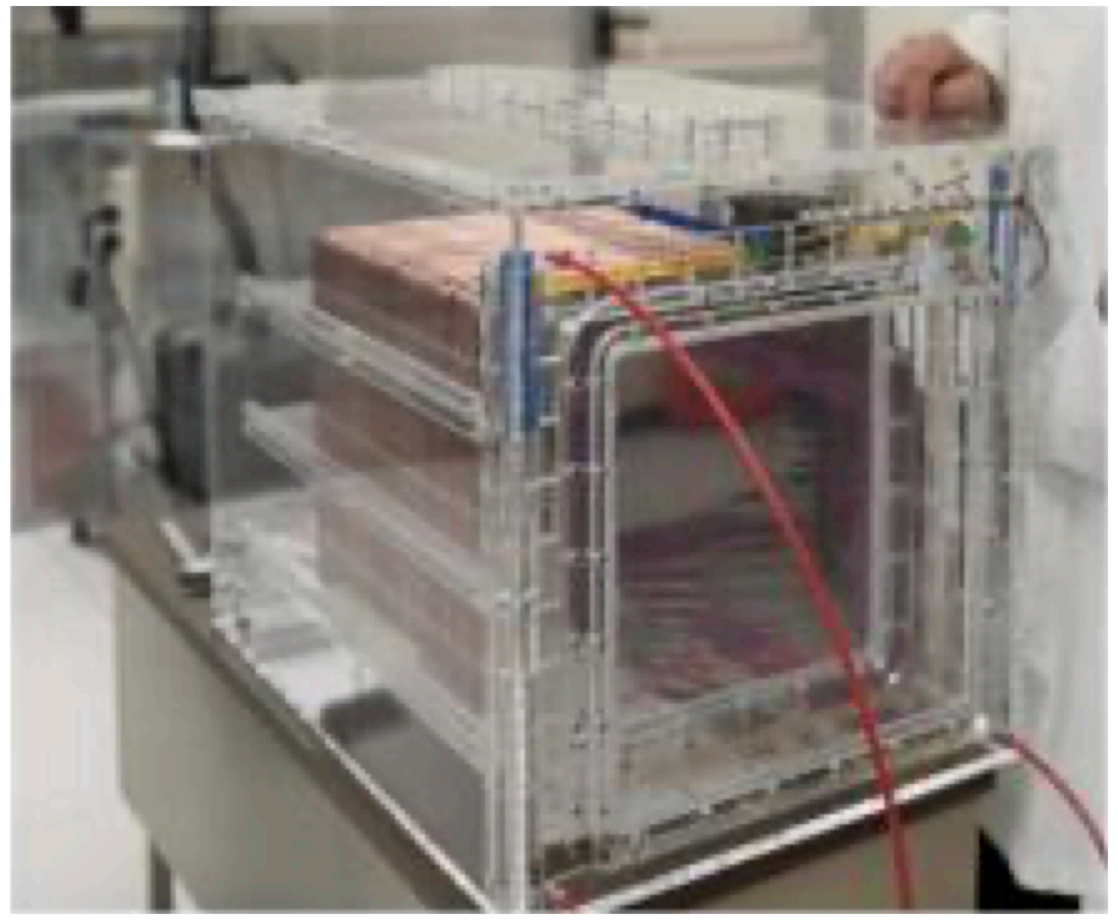
- MeV neutrons can induce energetic NR (high intensity source);
- ~10^{-4} probability the atom emits a Migdal electron from the n=1 shell;
- The atom will fill the hole reaching the ground state by the emission of a X-ray (K-line @ 3 keV);
- Event tag: will be a vertex with an energetic NR (few 100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

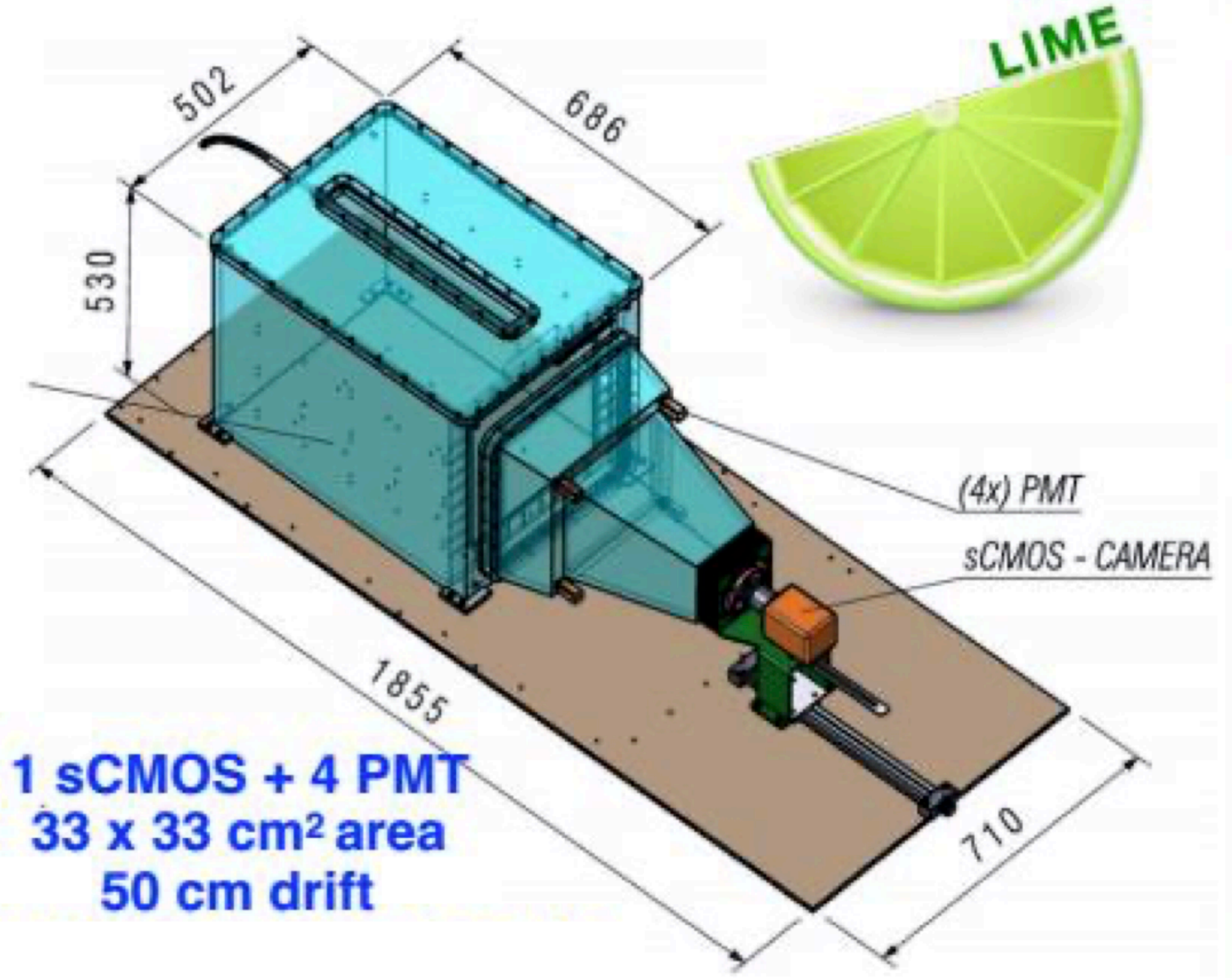
K. D. Nakamura et al., PTEP **1** (**2021**) 013C01

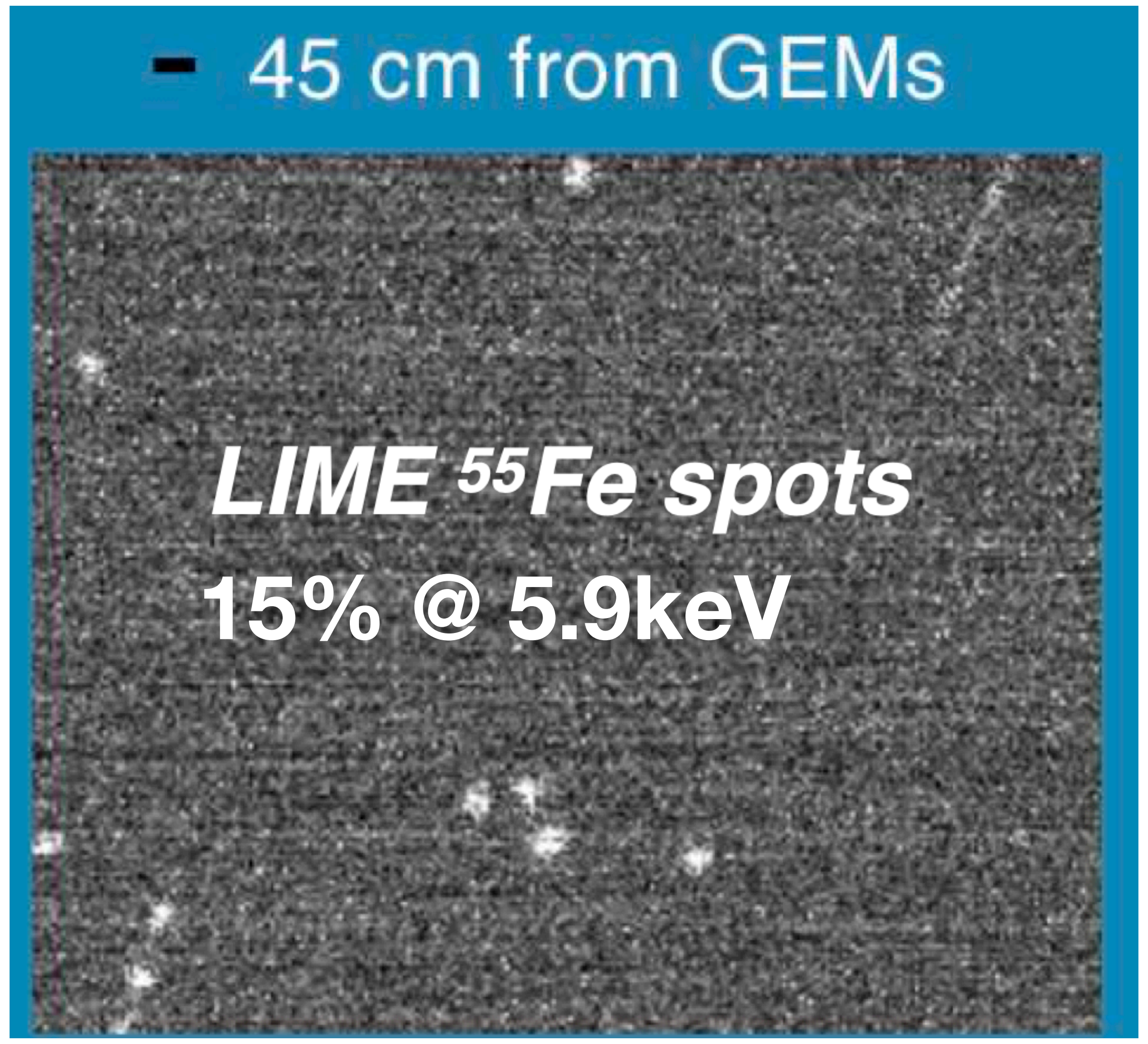


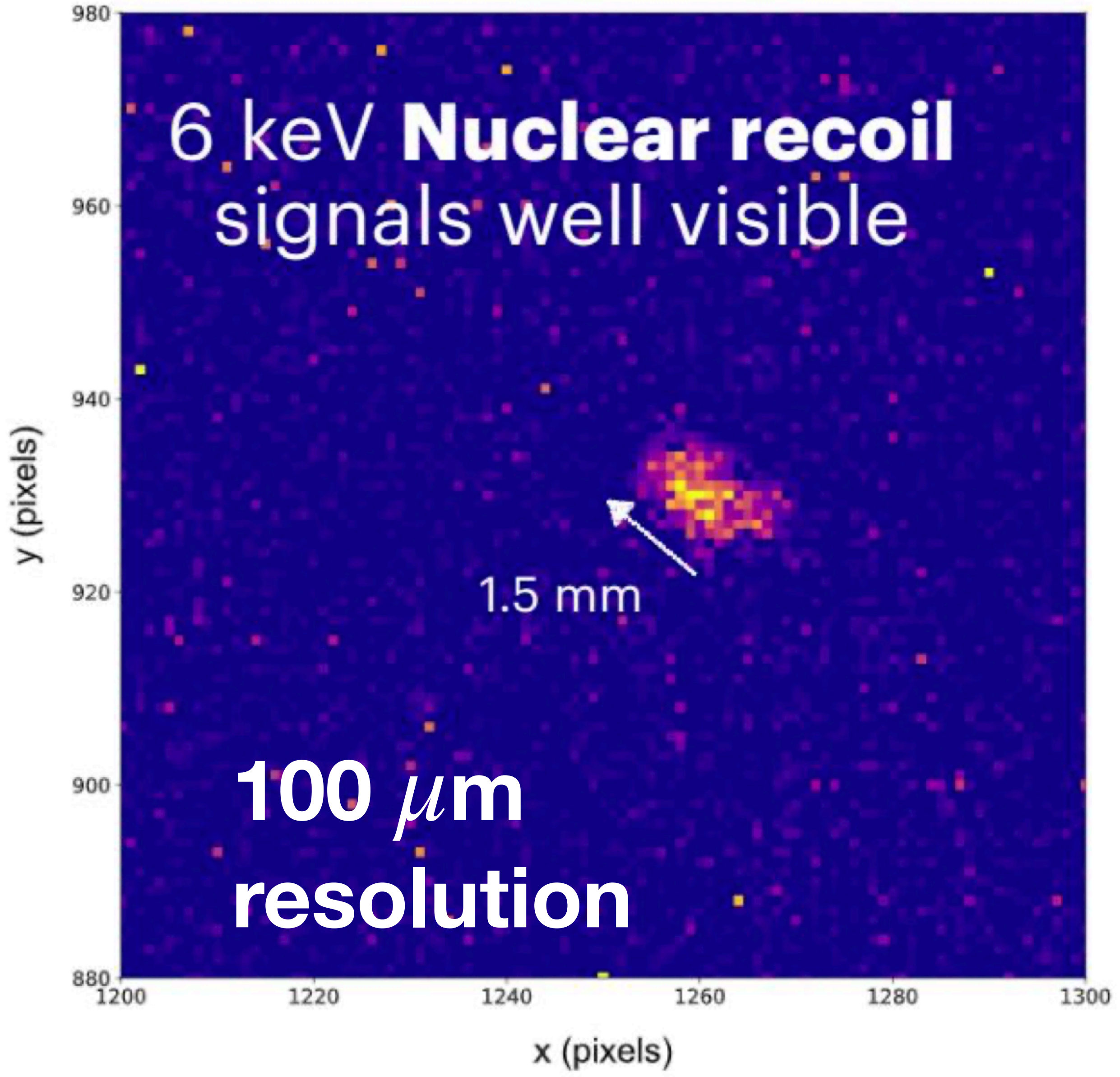
The CYGNO TPC[1] could see such events?

- **50L TPC with He/CF4** at atmospheric pressure;
- 3-**GEM** amplification stage;
- **Optical readout** of visible light by sCMOS camera;
- **Photodetectors** readout 3rd coordinate
- **Very good tracking capabilities and resolution** both for NR[2] and ER[3].
- Working on defining the detector configuration (gas mix, shielding, neutron source) for a **dedicated run to look for Migdal events**.









[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.

Conclusions

- The NR process has a **reacher phenomenology at small momentum transfers**;
- The **Migdal effect could improve the sensitivity to light dark matter** by more than an order of magnitude (from GeV to MeVs);
  - some experimental limits are based on the Migdal effect;
  - waiting for the others (in particular LAr experiments);
- It is **important to observe the Migdal effect** and confirm its relevance in DM;
  - there are **promising experimental opportunities** using fast neutrons and TPCs.

Thank you!