The Migdal effect *(with neutral projectiles)*

Christopher McCabe

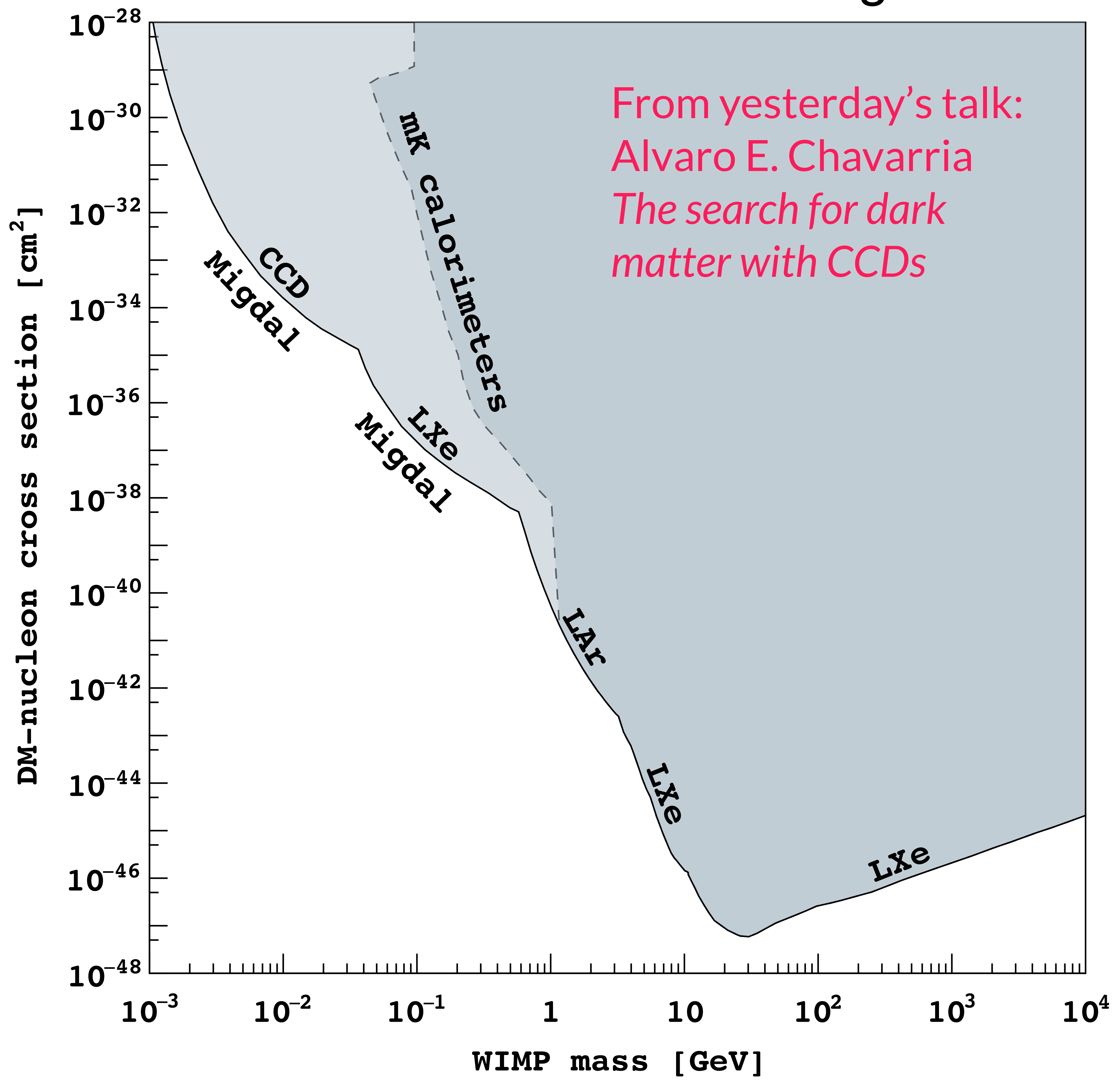
With Peter Cox, Matthew Dolan and Harry Quiney (Univ. of Melbourne)
and the MIGDAL Collaboration

LDMA 2025, 9 April 2025

Motivation

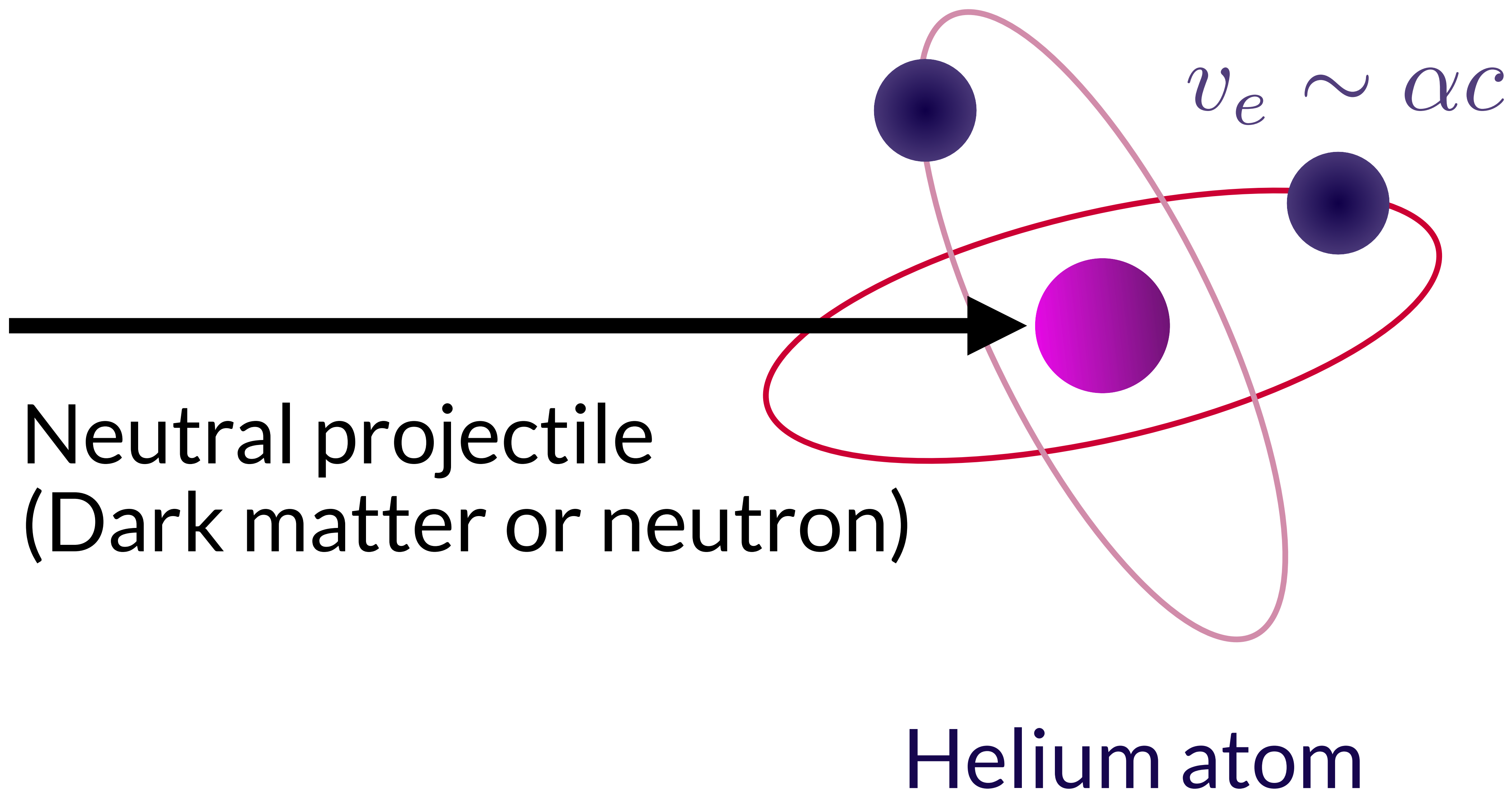
Migdal searches now dominate searches for DM lighter than ~ 1 GeV

DM-nucleus scattering



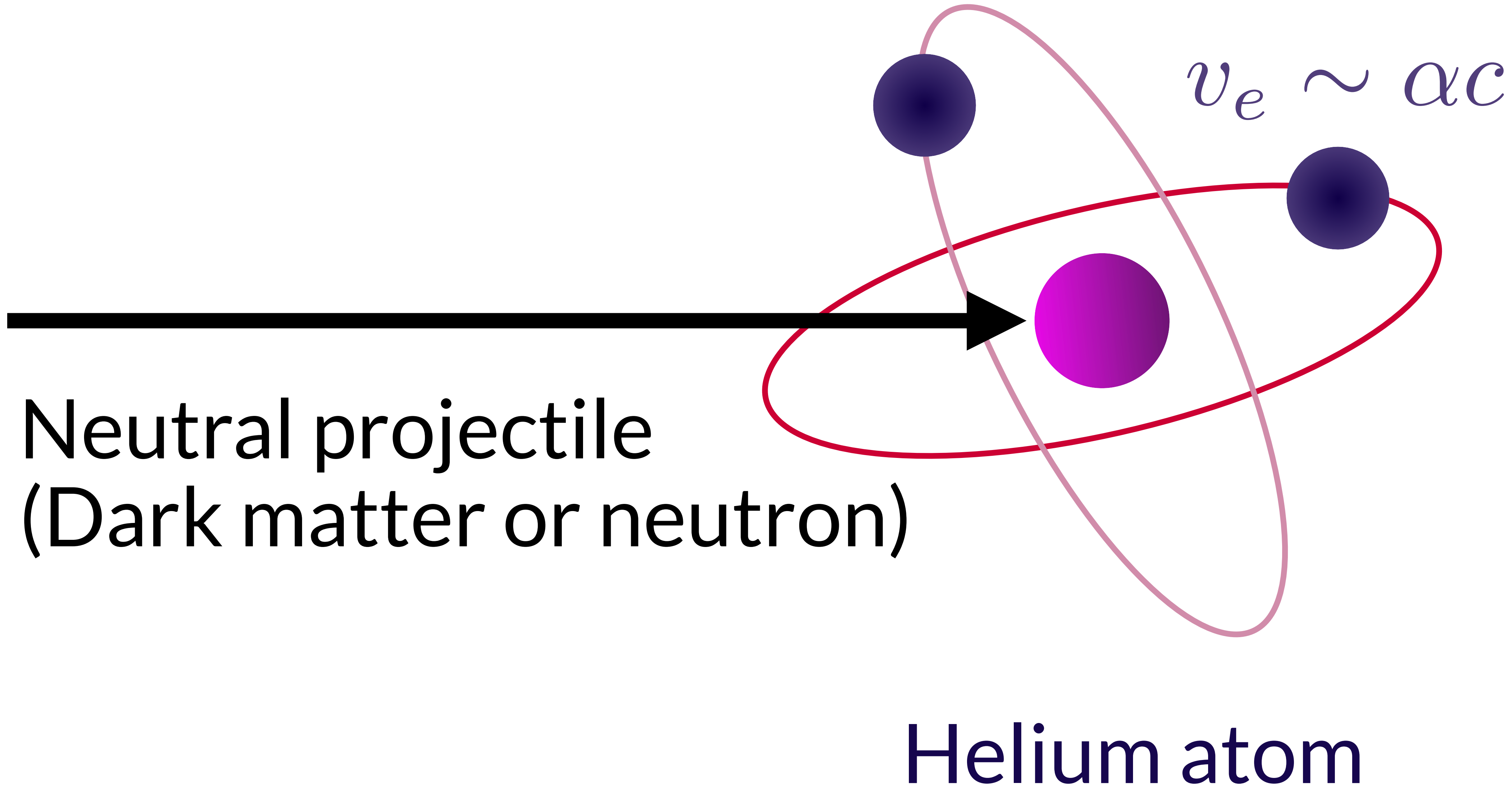
What is the Migdal effect?

Intuition: Neutral projectile scattering on helium



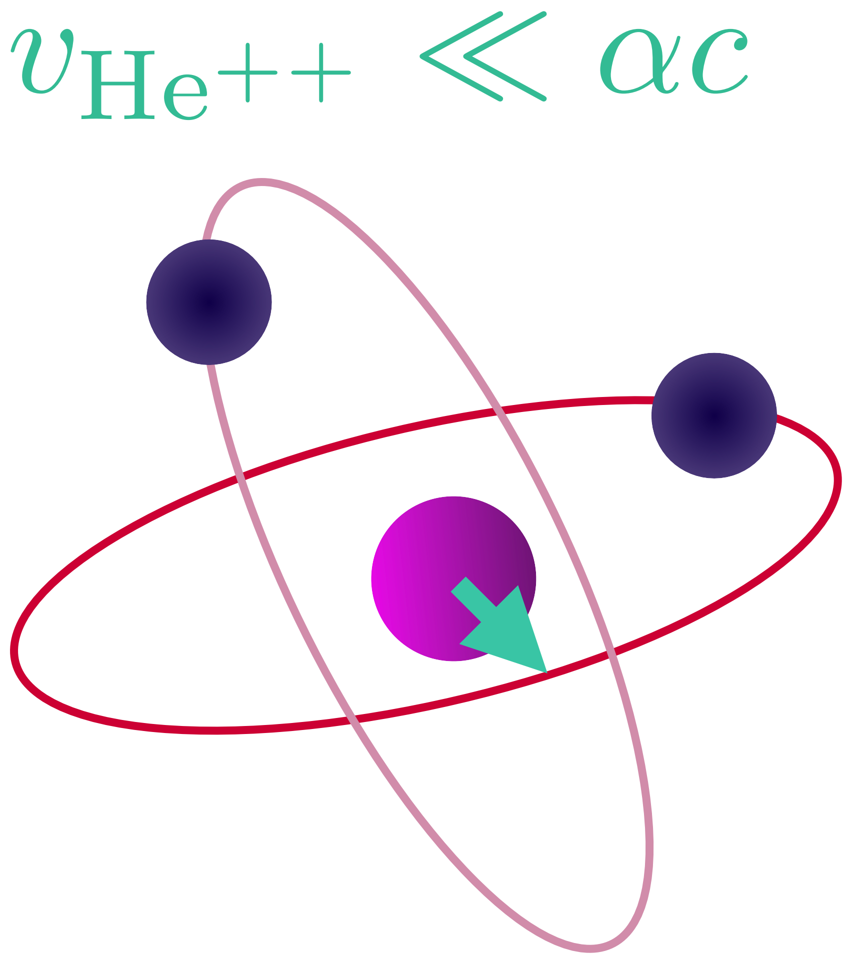
Fine-structure constant: $\alpha = 1/137$

Intuition: Neutral projectile scattering on helium

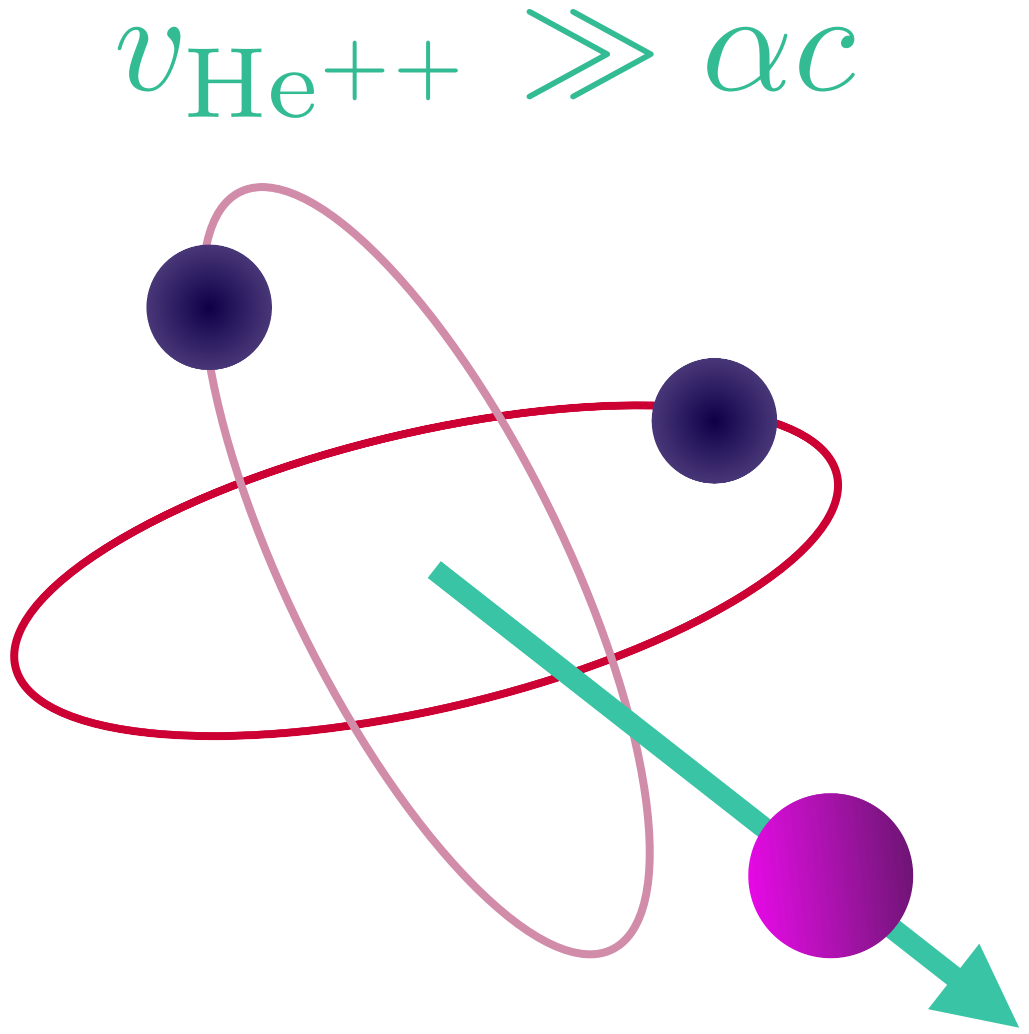


Fine-structure constant: $\alpha = 1/137$

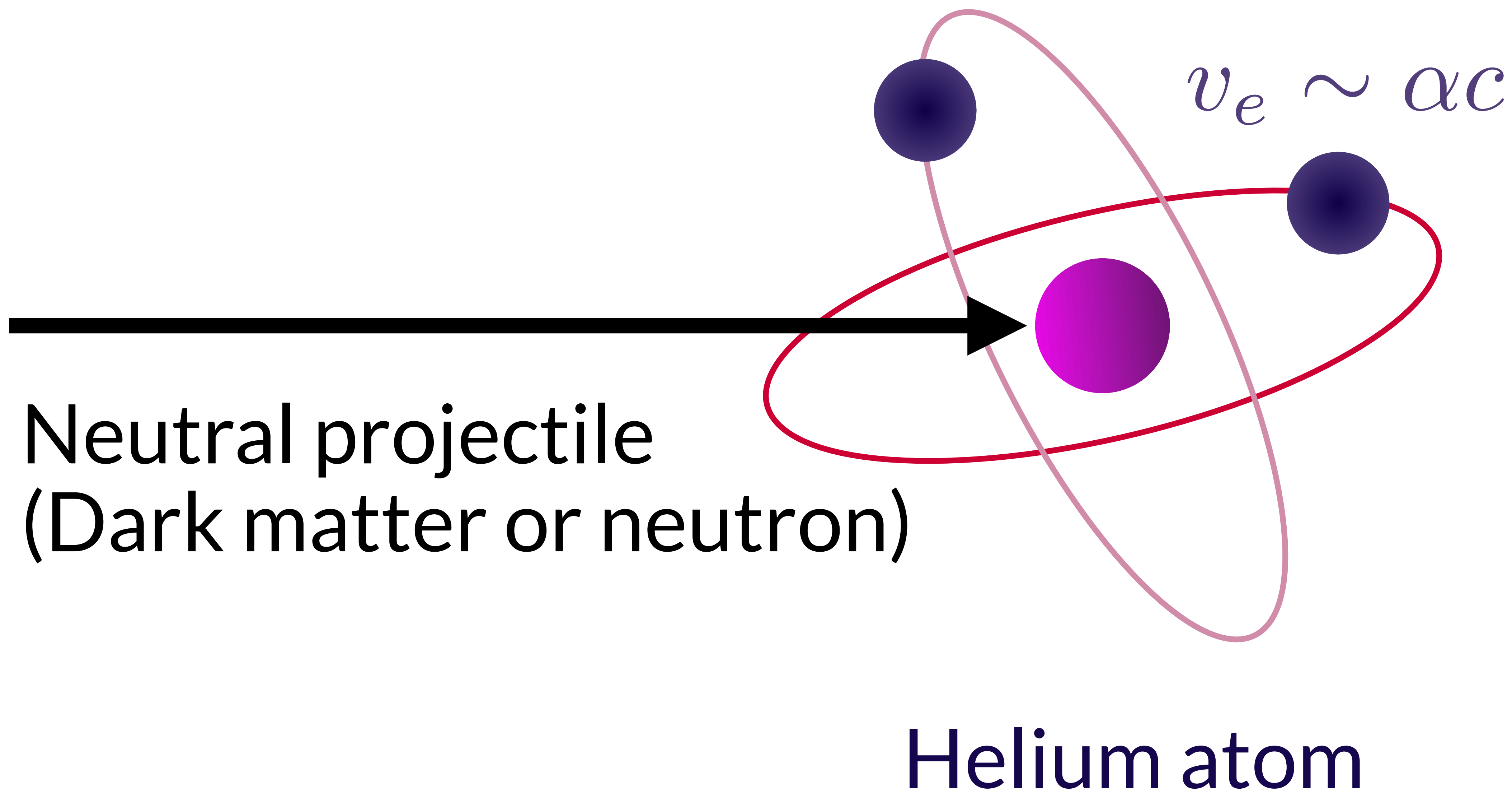
1. Low speed recoil:
   - *remain in ground state*



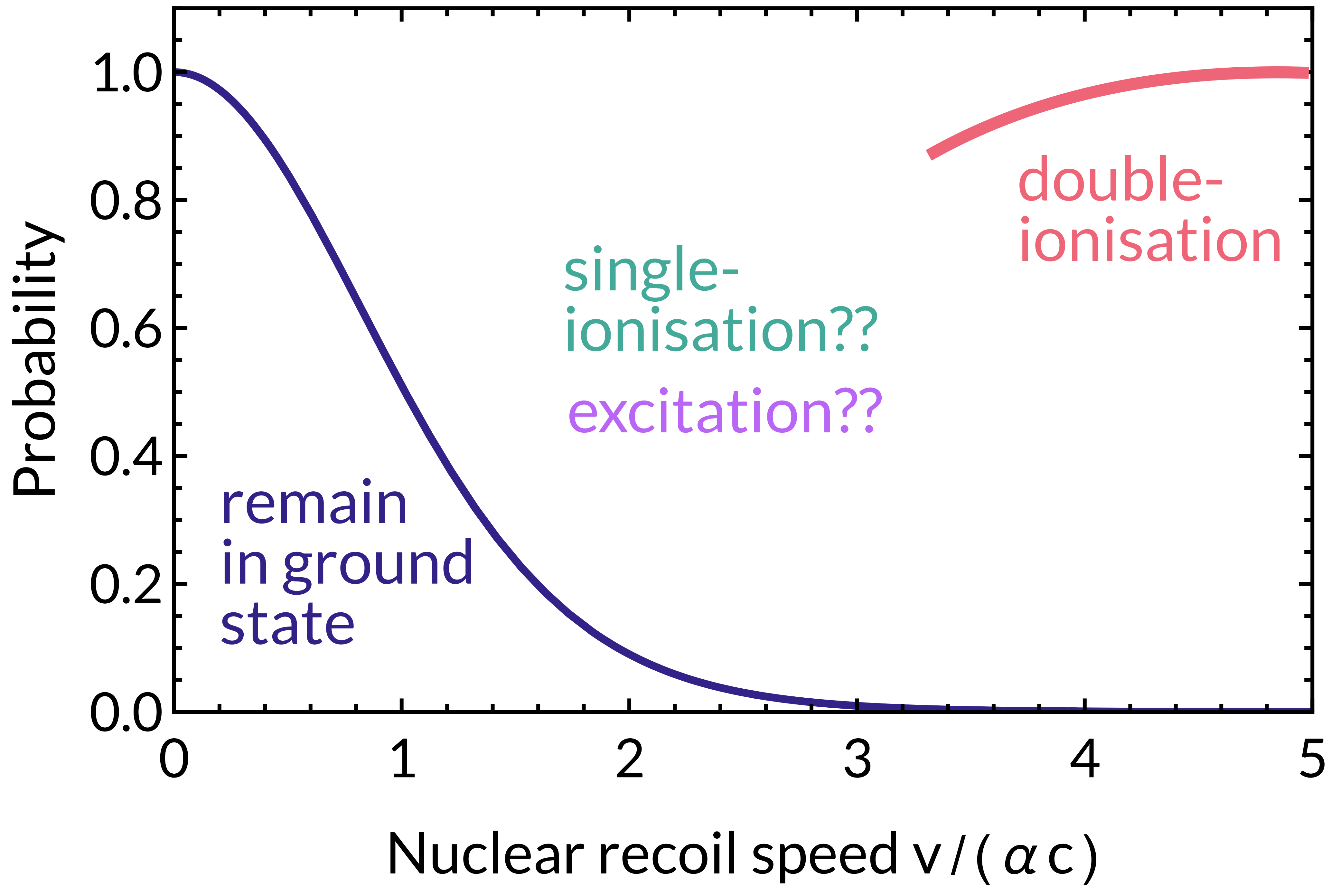
2. High speed recoil:
   - *double ionisation*
   (electrons 'left behind')



Intuition: Neutral projectile scattering on helium



Fine-structure constant: $\alpha = 1/137$

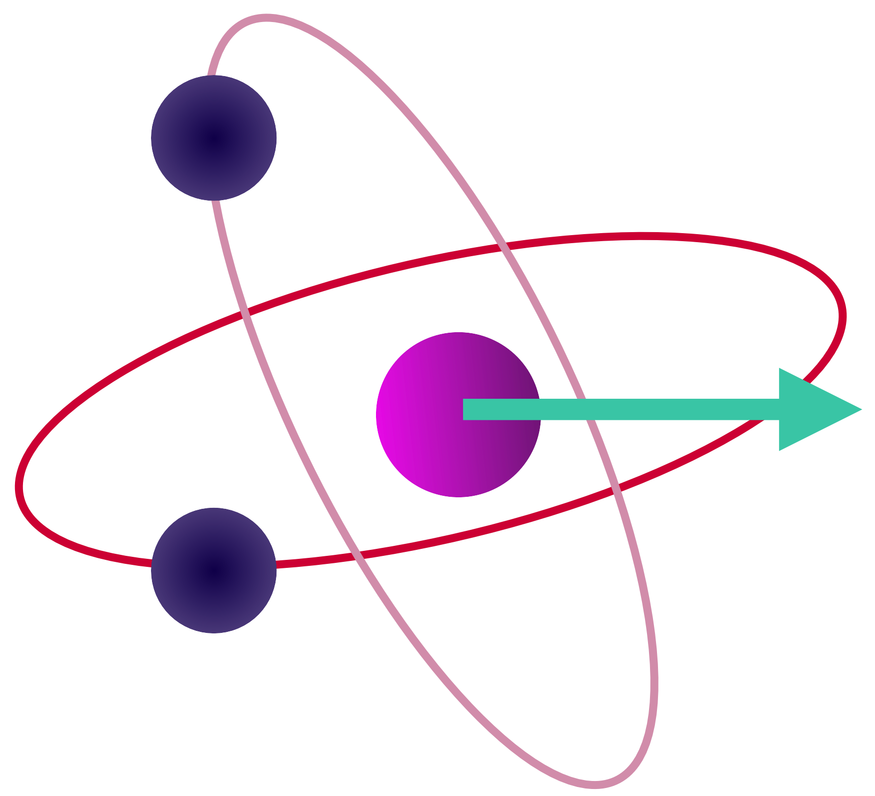


[**In the rest of this talk c=1*]

Migdal transition element

A. Migdal, J. Phys. Acad. Sci. USSR 4 (1941) 449–453
(See also E. L. Feinberg, J. Phys. Acad. Sci. USSR 4 (1941) 423)

$$\left\langle \Psi_f^{\{k\}} \middle| e^{i m_e \mathbf{v} \cdot \sum_a \mathbf{r}_a} \middle| \Psi_i^{\{j\}} \right\rangle$$



$|\Psi_i^{\{j\}}\rangle$ describes the bound atomic-electrons wavefunction

$e^{i m_e \mathbf{v} \cdot \sum_a \mathbf{r}_a}$ accounts for Galilean boost

$\mathbf{v} = \text{Nuclear recoil velocity}$

$|\Psi_f^{\{k\}}\rangle$ describes the final state wavefunction (excitation, ionisation, etc)

Migdal transition element

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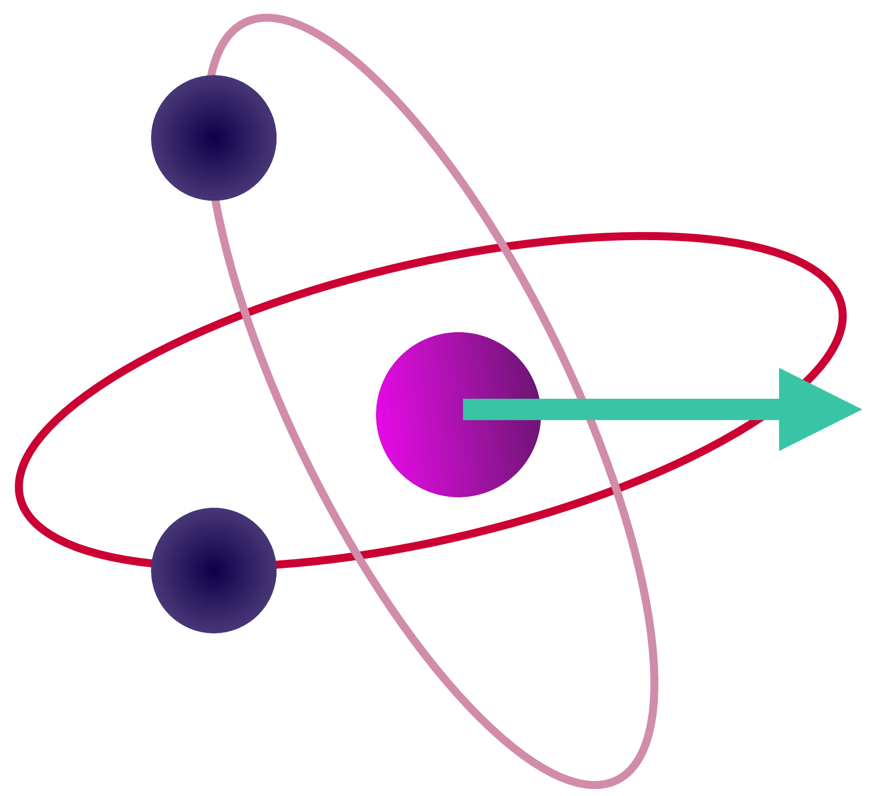
$$\left\langle \Psi_f^{\{k\}} \middle| e^{i m_e \mathbf{v} \cdot \sum_a \mathbf{r}_a} \middle| \Psi_i^{\{j\}} \right\rangle$$



Previous calculations utilise the 'dipole approximation':

$$\exp\left(i m_e \mathbf{v} \cdot \sum_{a=1}^{N} \mathbf{r}_a\right) \approx 1 + i m_e \mathbf{v} \cdot \sum_{a=1}^{N} \mathbf{r}_a$$

Dipole approximation good for:
(i) small **v** scattering processes and
(ii) single ionisation processes

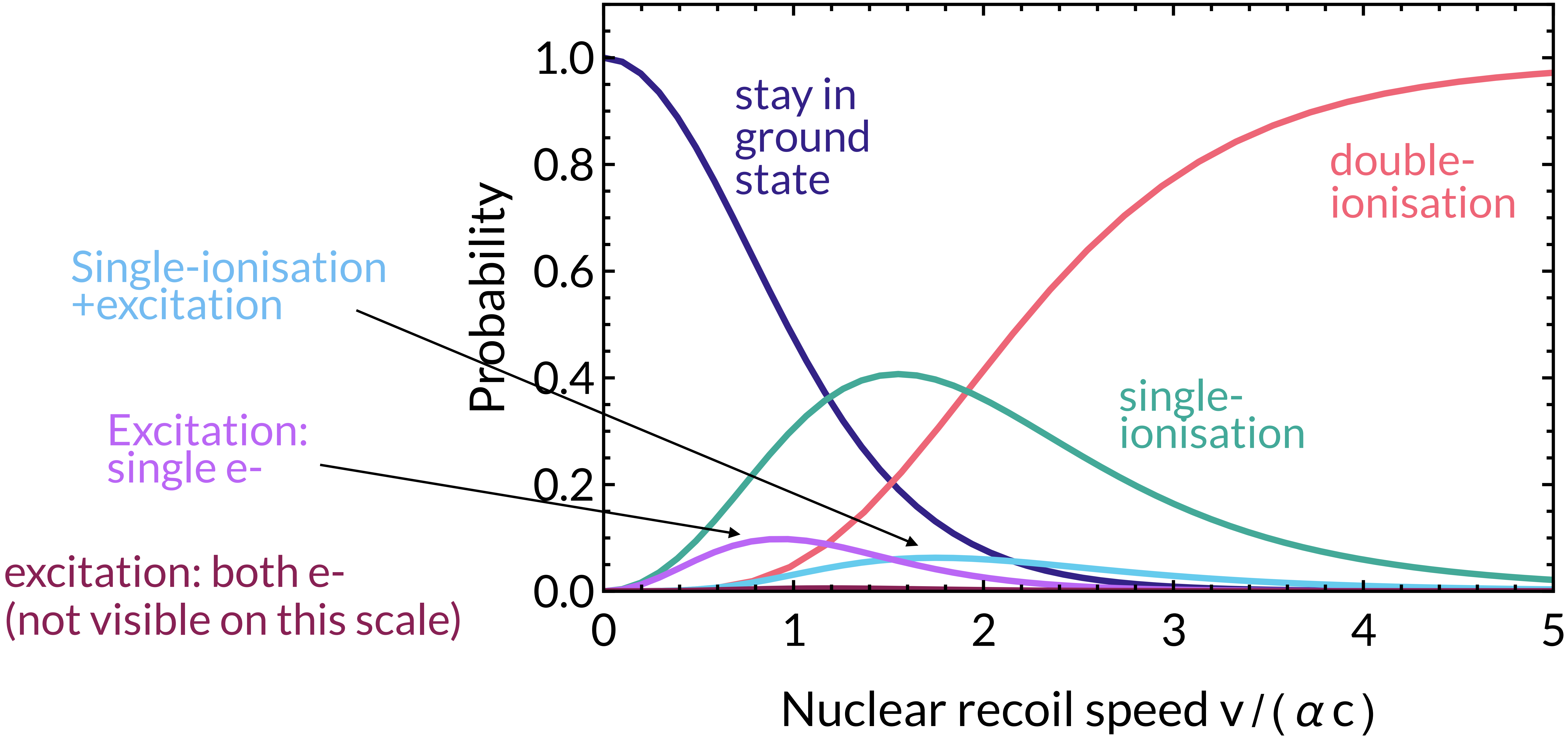
In our work, we keep the full exponential factor (sounds easy but lots of extra work!)

Cox, Dolan, CM, Quiney, arXiv:2208.12222, PRD

Intuition: Helium results

GRASP+RATIP

Cox, Dolan, CM, Quiney, arXiv:2208.12222, PRD



Previous calculations could only give the single-ionisation curve for $v/\alpha \ll 1$

Our results are valid for any v/α for He, C, F, Ne, Si, Ar, Ge, Kr, Xe

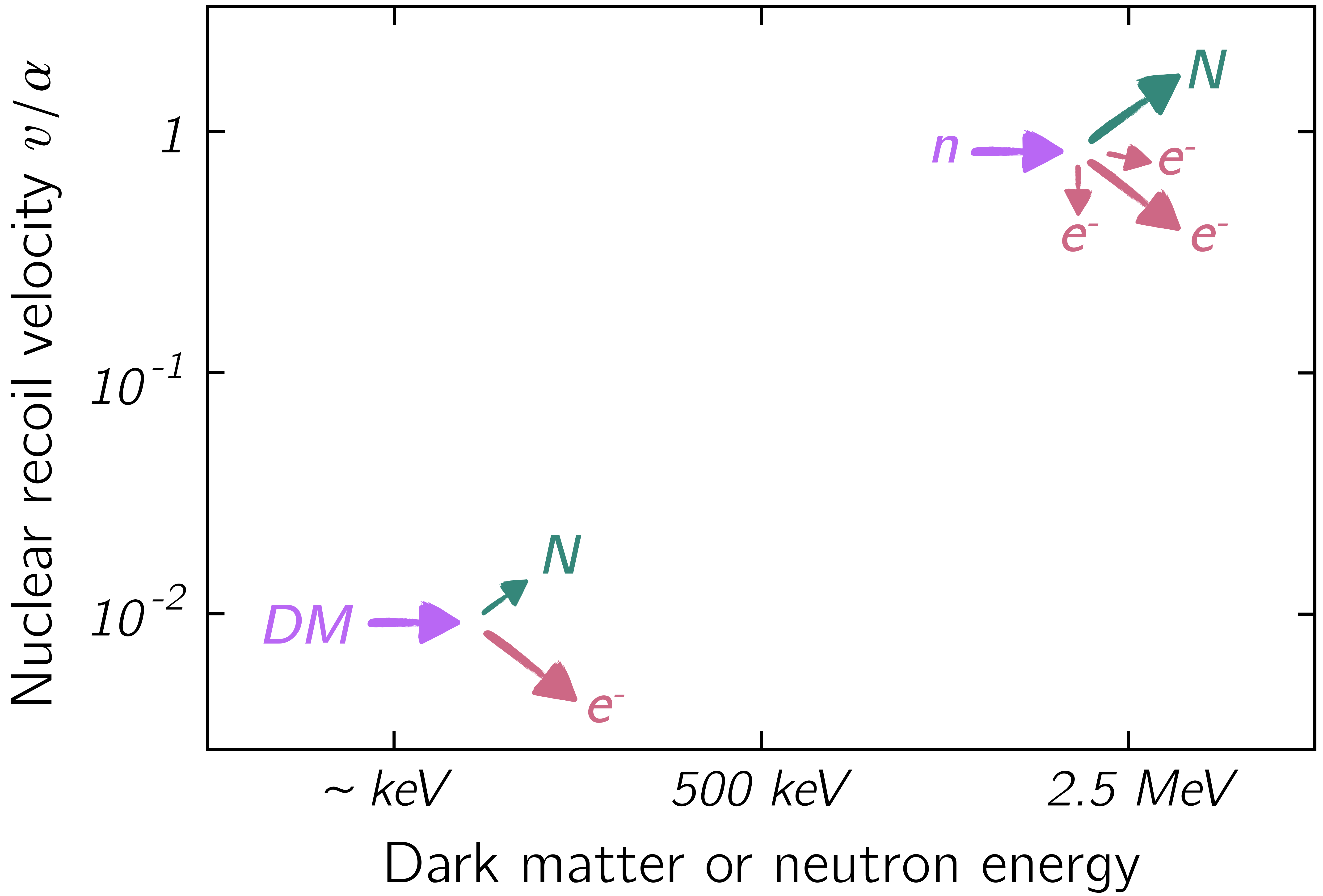
‘**Migdal effect**’

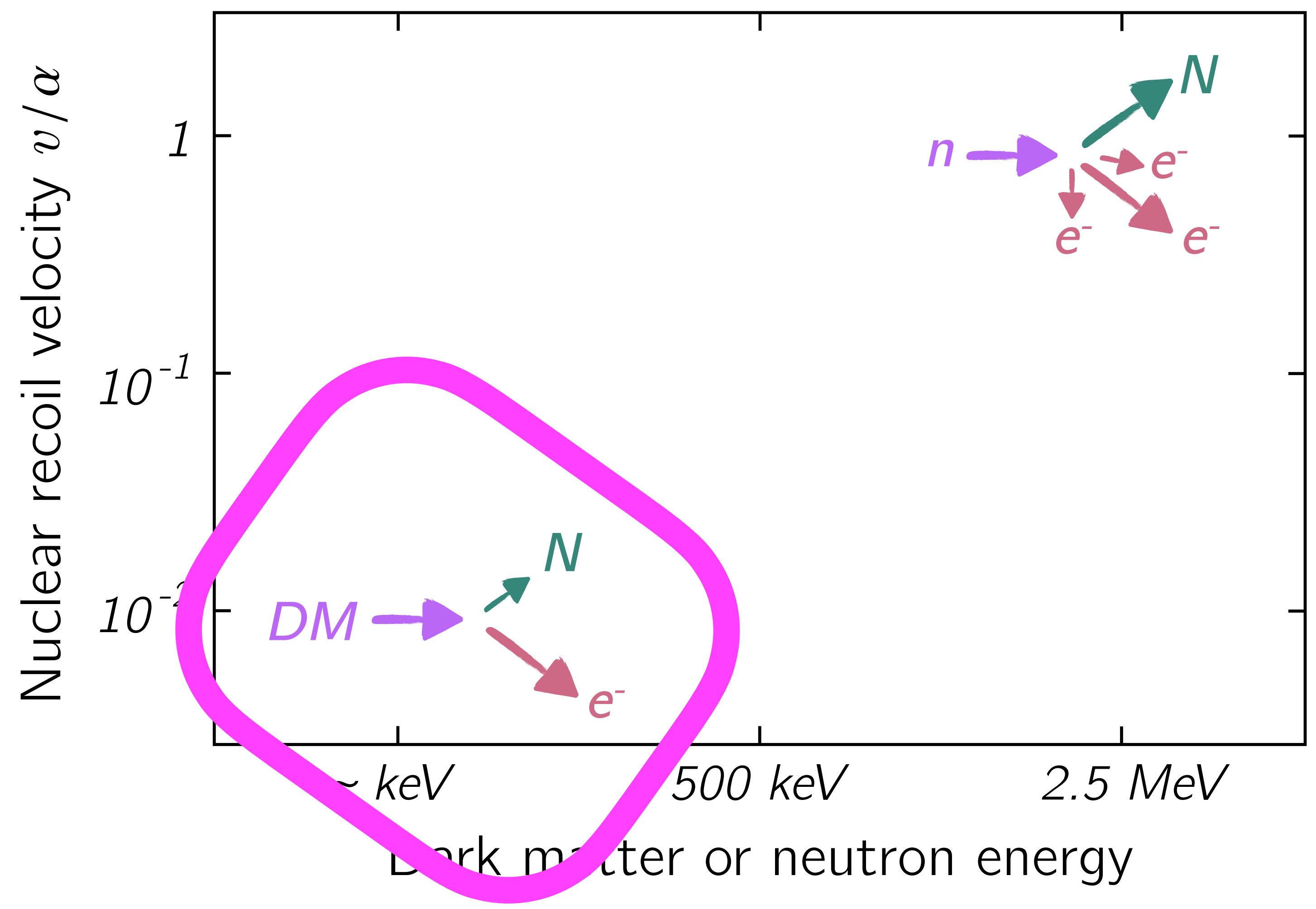
electrons and the nucleus are coupled in atomic systems:

perturbation of the nucleus can induce electronic transitions

Transition probability depends on the speed of the recoiling nucleus

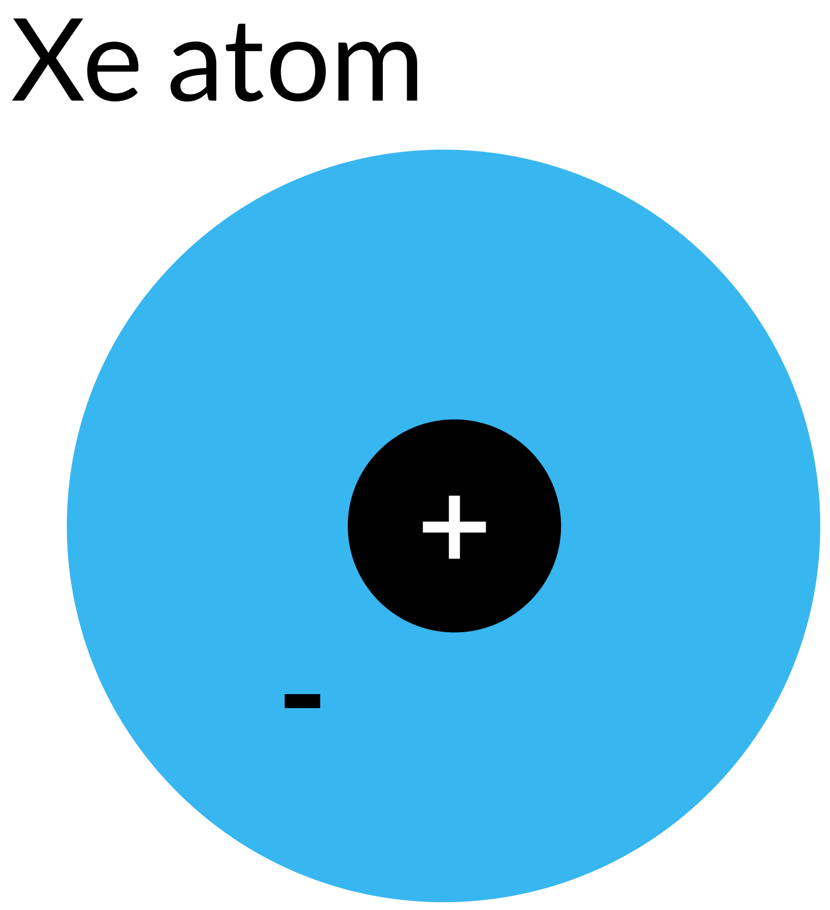
Migdal effect: regimes characterised by v/α

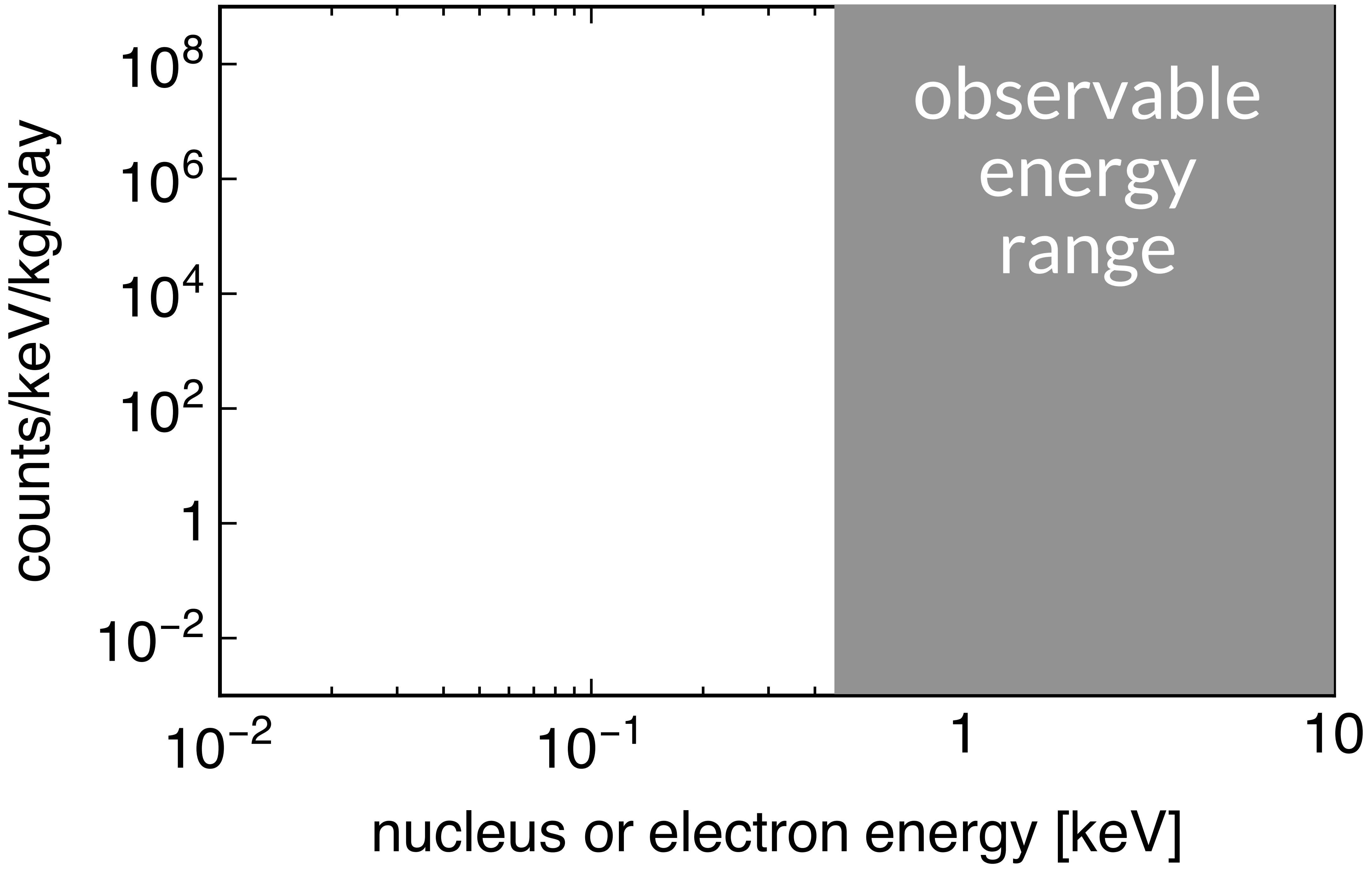




Small *v* regime: dark matter searches

Benefits: consider DM scattering with xenon





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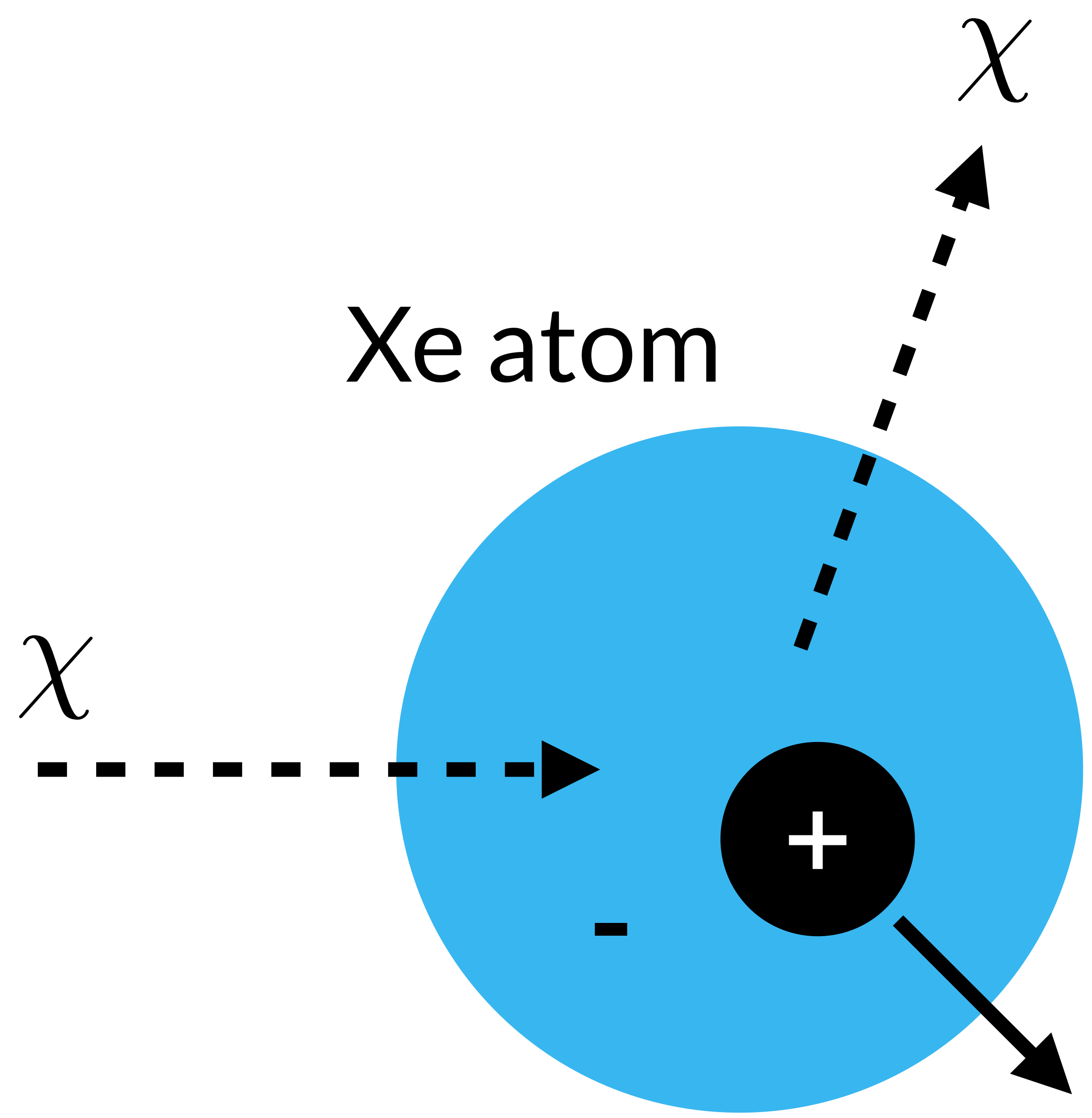
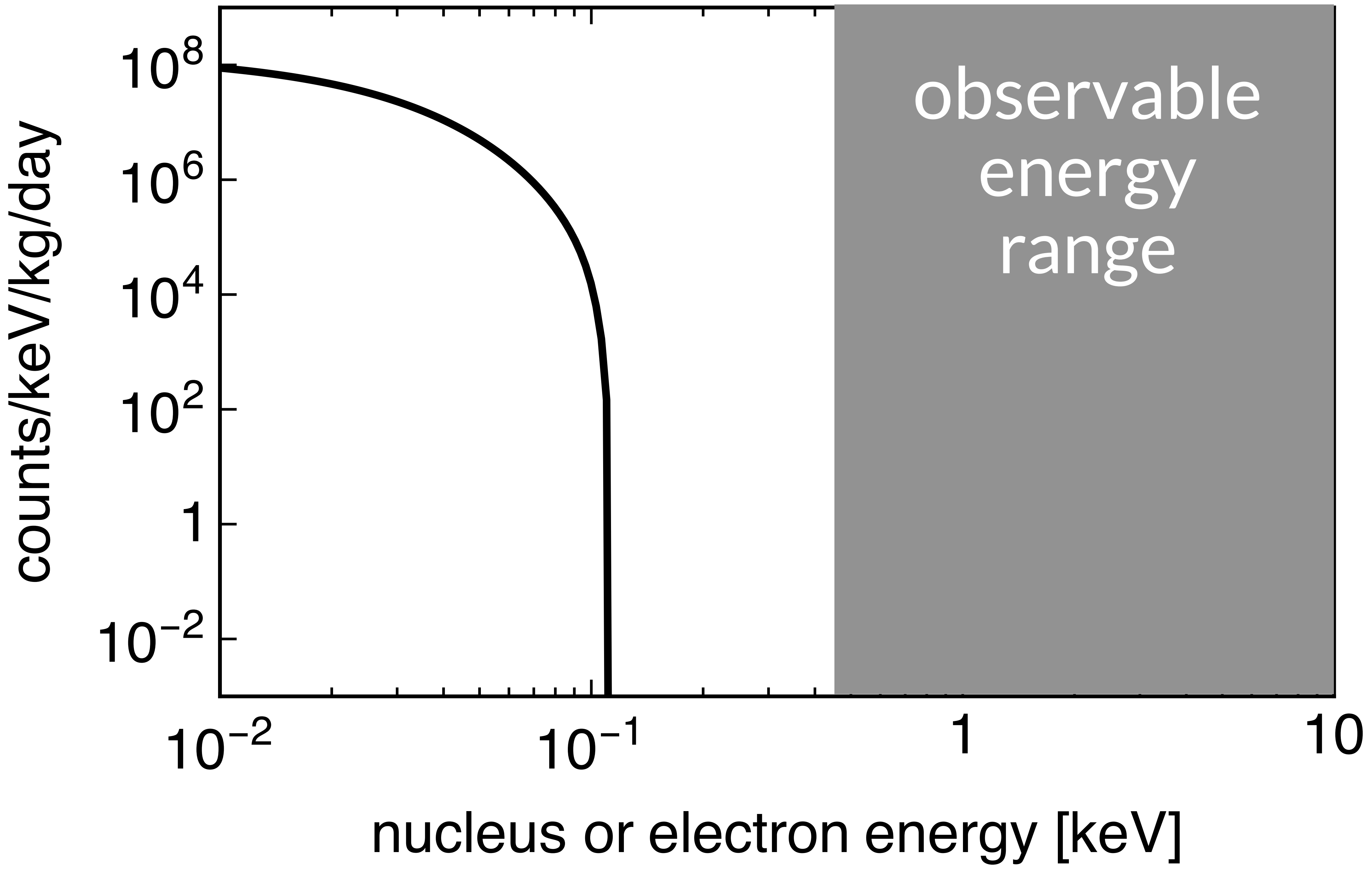


m_{DM} = 1 GeV
'Normal' nuclear scattering



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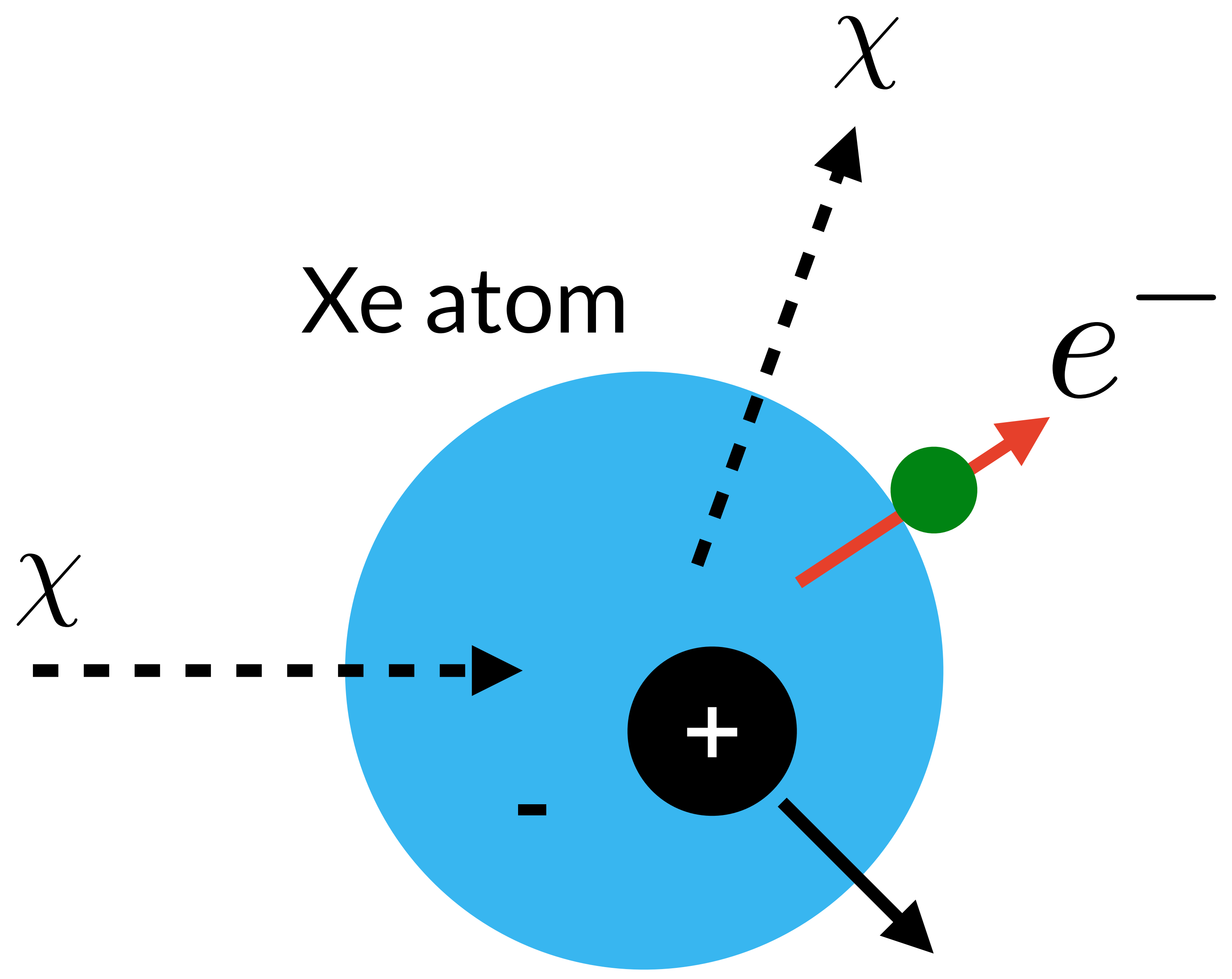
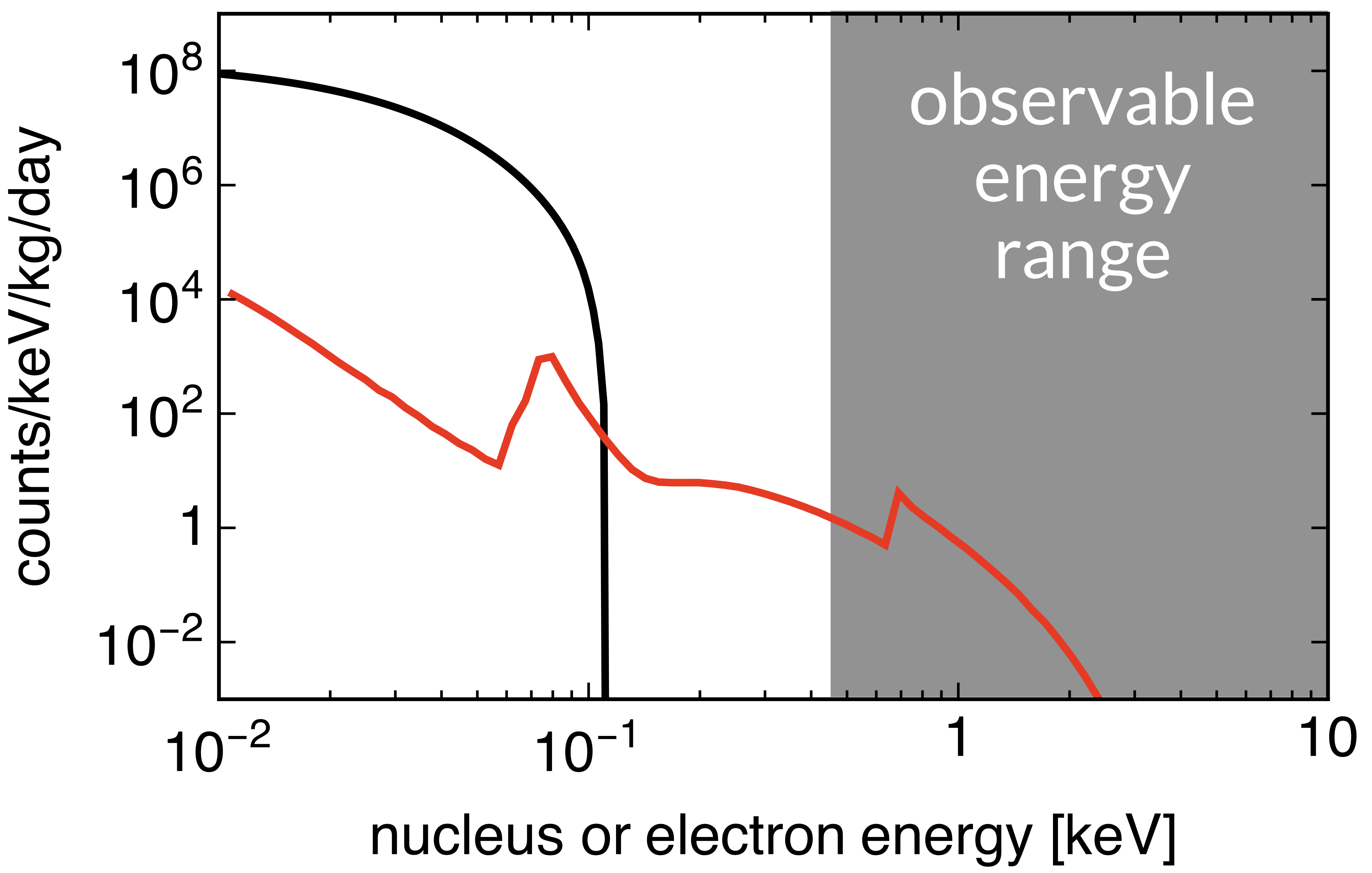
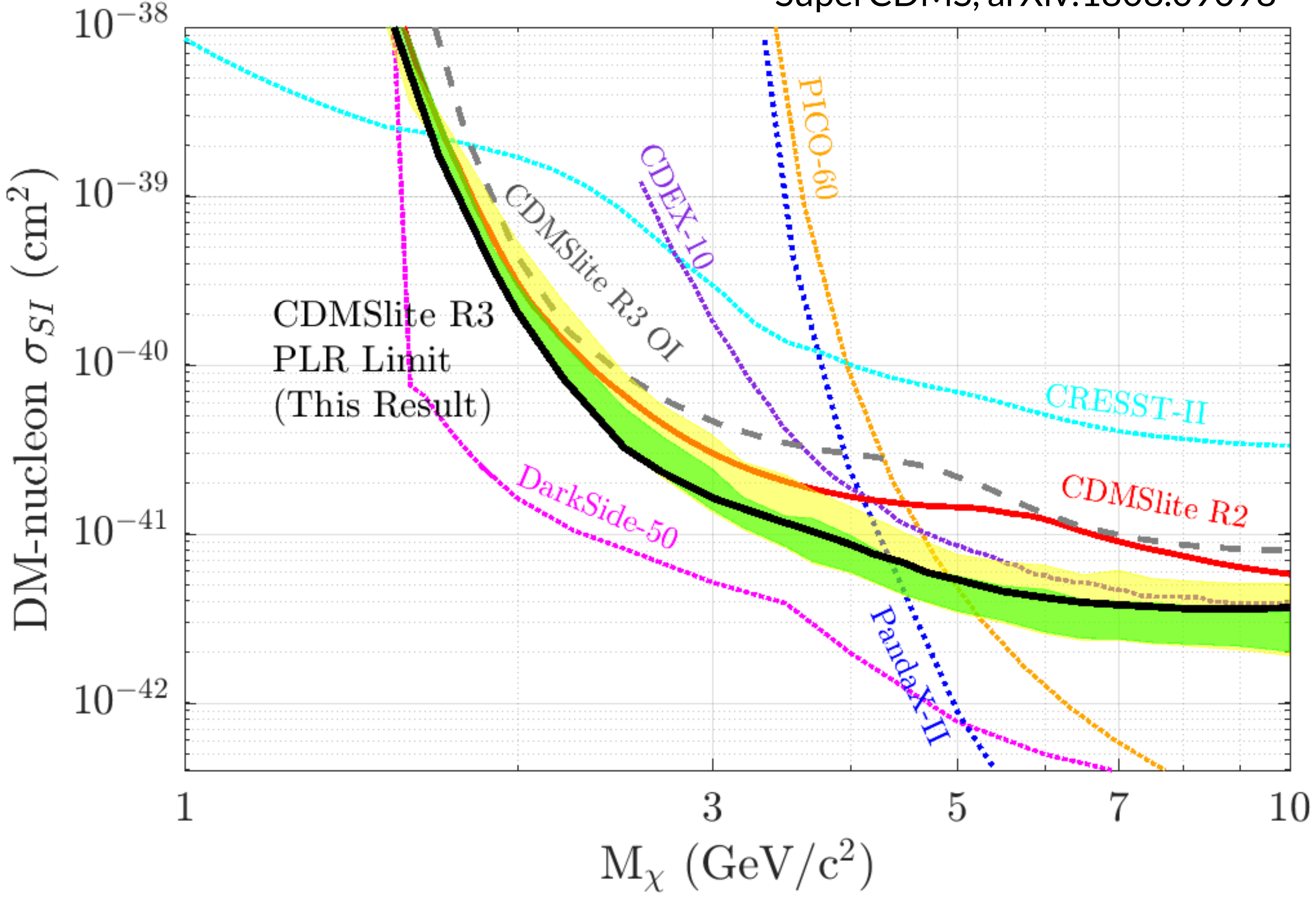


m_{DM} = 1 GeV
'Normal' nuclear scattering
+ Migdal effect (ionisation of 1 electron)

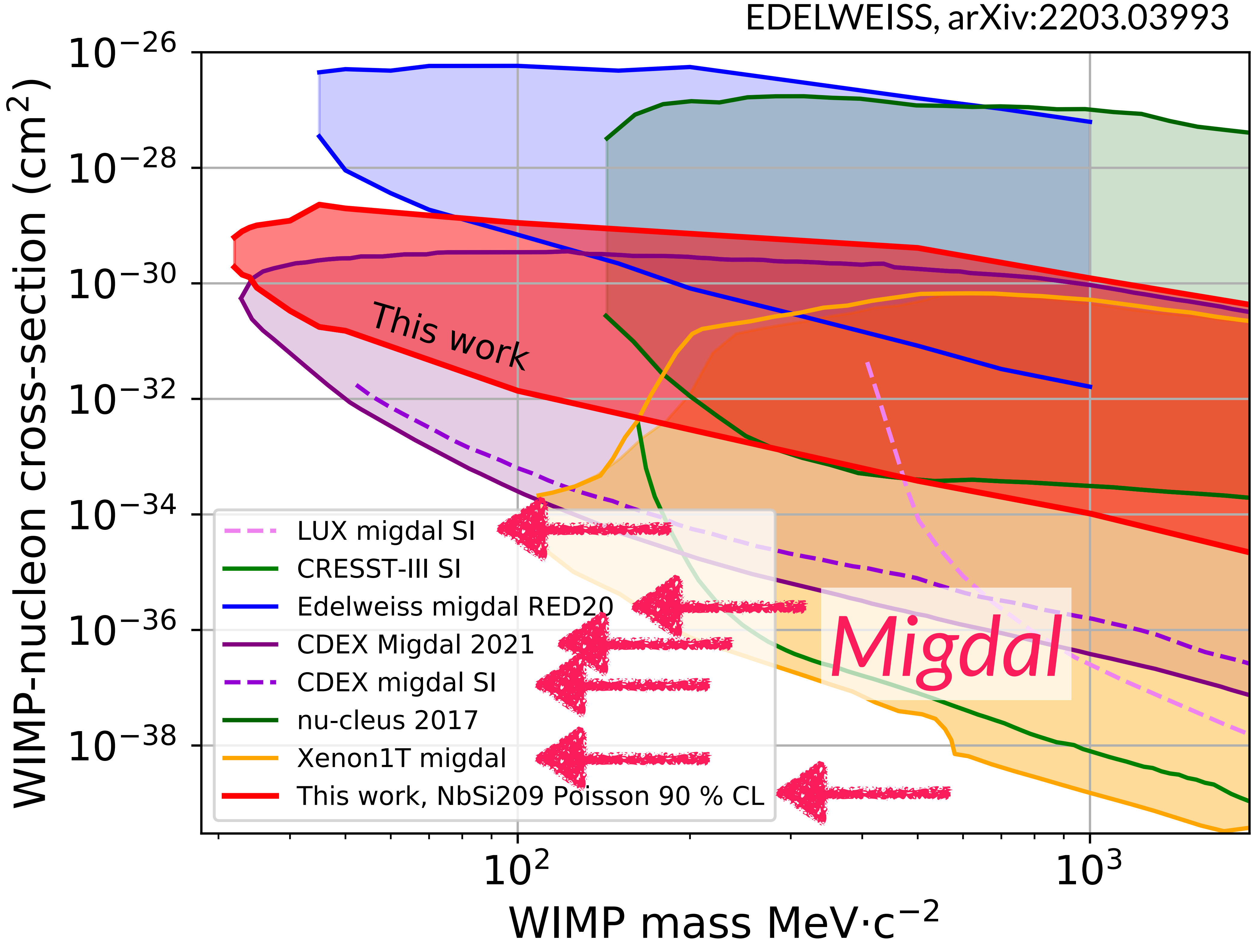


Sub-GeV searches increasingly dominated by Migdal

SuperCDMS, arXiv:1808.09098



EDELWEISS, arXiv:2203.03993



Pre-2018
No Migdal limits

Migdal effect in dark matter direct detection experiments, Ibe et al arXiv:1707.07258

Today
Dominated by Migdal

Is there evidence for the Migdal effect?

Evidence? Yes, but…

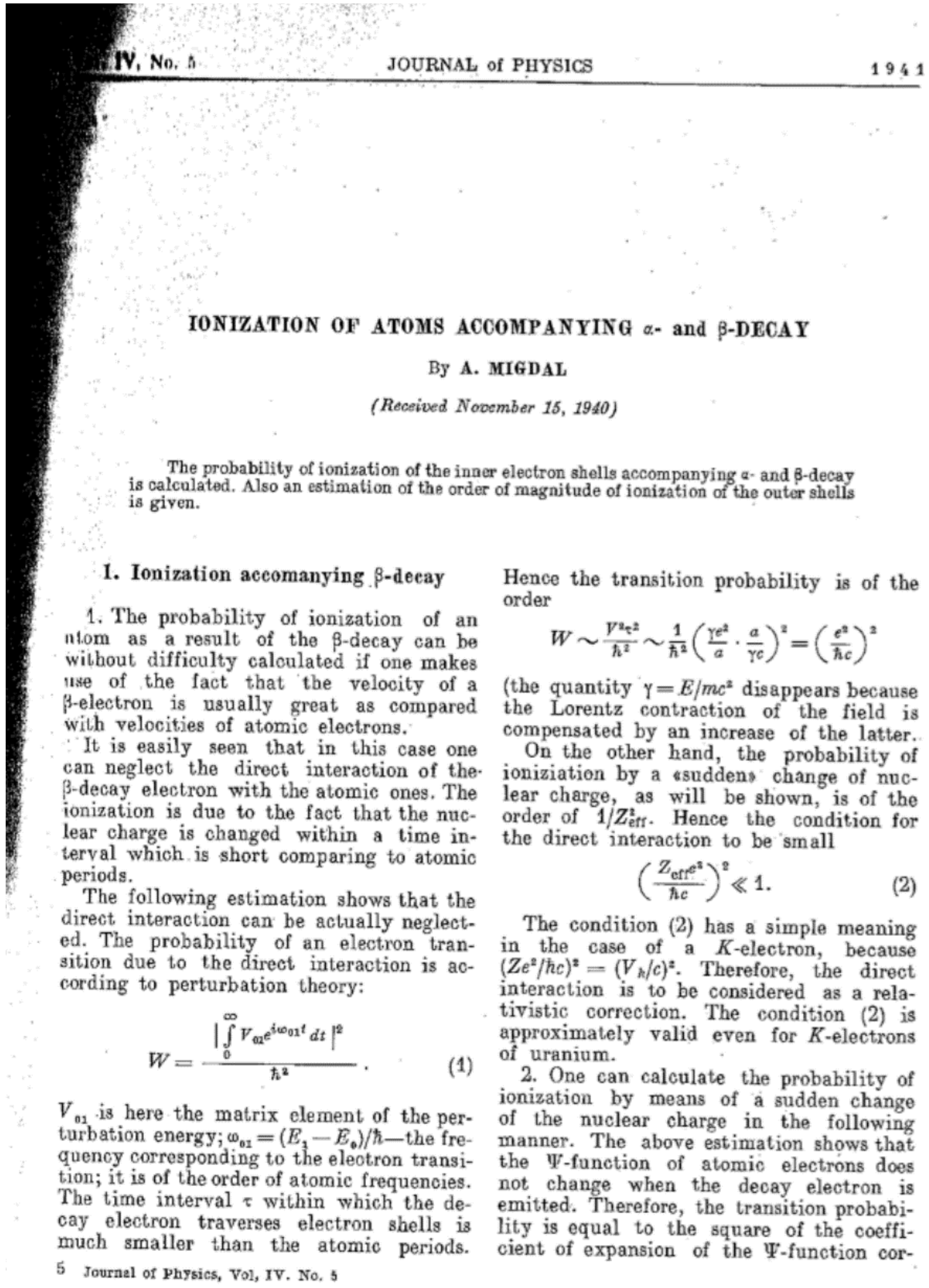
A.B. Migdal’s papers date back to the 1940s

Predicted effect in:
1. α, β decay
2. Neutral scattering

Effect ***has*** been observed in α and β decay

M.S. Rapaport, F. Asaro and I. Pearlman K-shell electron shake-off accompanying alpha decay, PRC 11, 1740-1745 (1975)
M.S. Rapaport, F. Asaro and I. Pearlman L- and M-shell electron shake-off accompanying alpha decay, PRC 11, 1746-1754 (1975)
C. Couratin et al. , First Measurement of Pure Electron Shakeoff in the β Decay of Trapped 6He+Ions, PRL 108, 243201 (2012)

Effect ***has not*** been observed with neutral projectiles



IV, No. 5 JOURNAL of PHYSICS 1941

IONIZATION OF ATOMS ACCOMPANYING α- and β-DECAY

By A. MIGDAL

(Received November 15, 1940)

The probability of ionization of the inner electron shells accompanying α- and β-decay is calculated. Also an estimation of the order of magnitude of ionization of the outer shells is given.

1. Ionization accomanying β-decay

1. The probability of ionization of an atom as a result of the β-decay can be without difficulty calculated if one makes use of the fact that the velocity of a β-electron is usually great as compared with velocities of atomic electrons.

It is easily seen that in this case one can neglect the direct interaction of the β-decay electron with the atomic ones. The ionization is due to the fact that the nuclear charge is changed within a time interval which is short comparing to atomic periods.

The following estimation shows that the direct interaction can be actually neglected. The probability of an electron transition due to the direct interaction is according to perturbation theory:

$$W = \frac{\left| \int_0^\infty V_{01} e^{i\omega_{01} t} dt \right|^2}{\hbar^2}. \quad (1)$$

V_{01} is here the matrix element of the perturbation energy; $\omega_{01} = (E_1 - E_0)/\hbar$—the frequency corresponding to the electron transition; it is of the order of atomic frequencies. The time interval τ within which the decay electron traverses electron shells is much smaller than the atomic periods.

Hence the transition probability is of the order

$$W \sim \frac{V^2 \tau^2}{\hbar^2} \sim \frac{1}{\hbar^2}\left(\frac{\gamma e^2}{a} \cdot \frac{a}{\gamma c}\right)^2 = \left(\frac{e^2}{\hbar c}\right)^2$$

(the quantity $\gamma = E/mc^2$ disappears because the Lorentz contraction of the field is compensated by an increase of the latter.

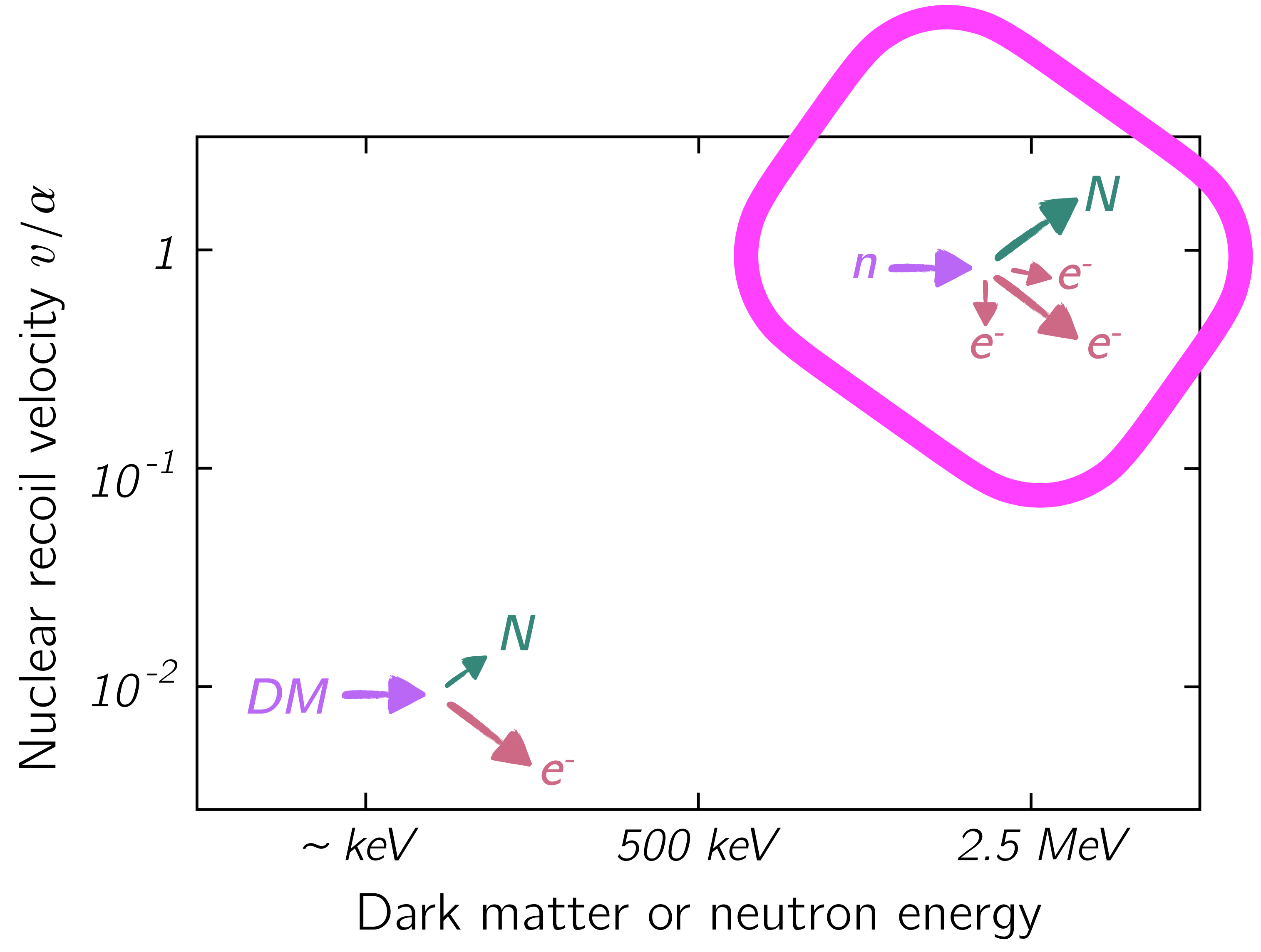
On the other hand, the probability of ioniziation by a «sudden» change of nuclear charge, as will be shown, is of the order of $1/Z^2_{eff}$. Hence the condition for the direct interaction to be small

$$\left(\frac{Z_{eff} e^2}{\hbar c}\right)^2 \ll 1. \quad (2)$$

The condition (2) has a simple meaning in the case of a K-electron, because $(Ze^2/\hbar c)^2 = (V_k/c)^2$. Therefore, the direct interaction is to be considered as a relativistic correction. The condition (2) is approximately valid even for K-electrons of uranium.

2. One can calculate the probability of ionization by means of a sudden change of the nuclear charge in the following manner. The above estimation shows that the Ψ-function of atomic electrons does not change when the decay electron is emitted. Therefore, the transition probability is equal to the square of the coefficient of expansion of the Ψ-function cor-

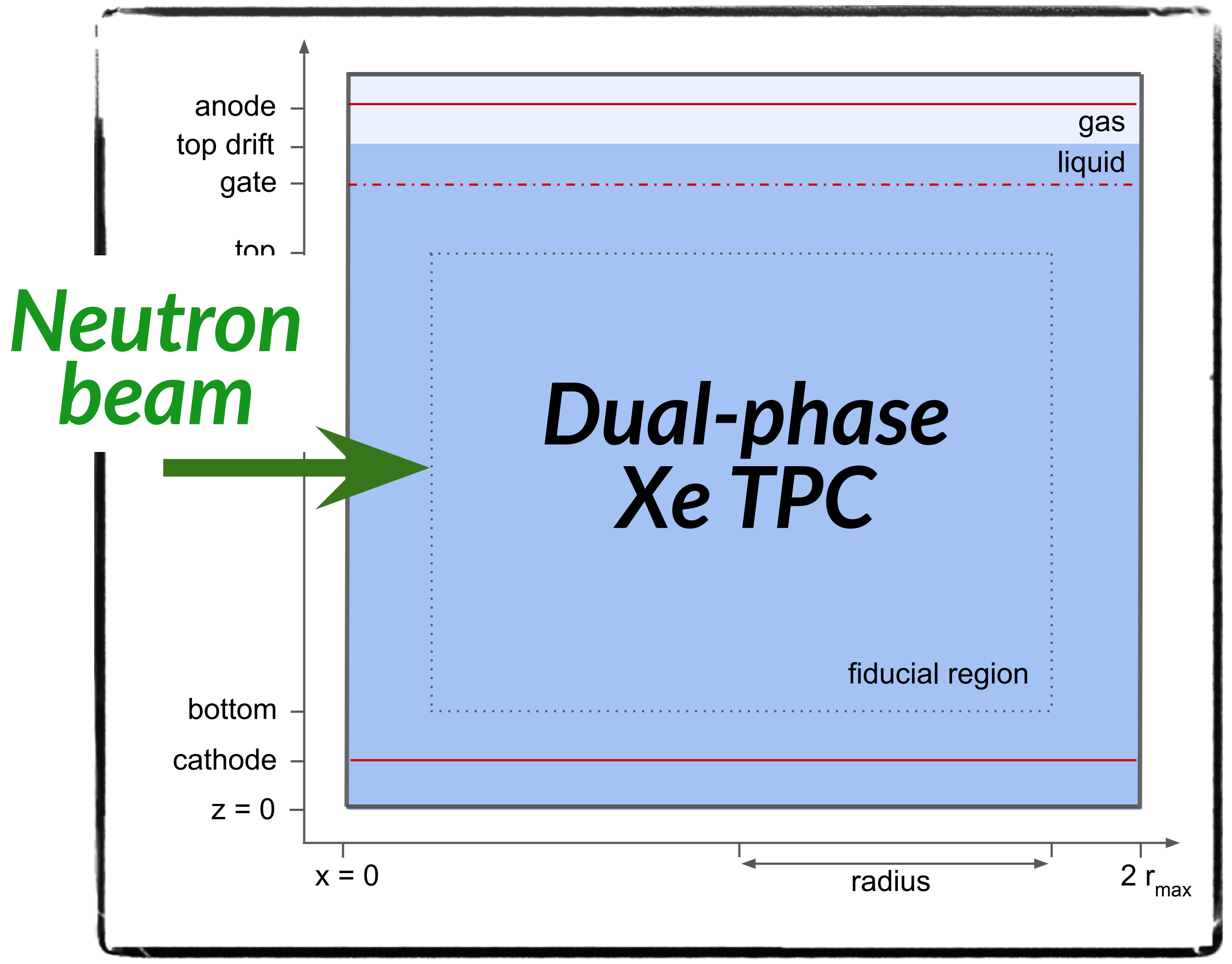
5 Journal of Physics, Vol, IV. No. 5



Large *v* regime: searches for the effect with neutrons

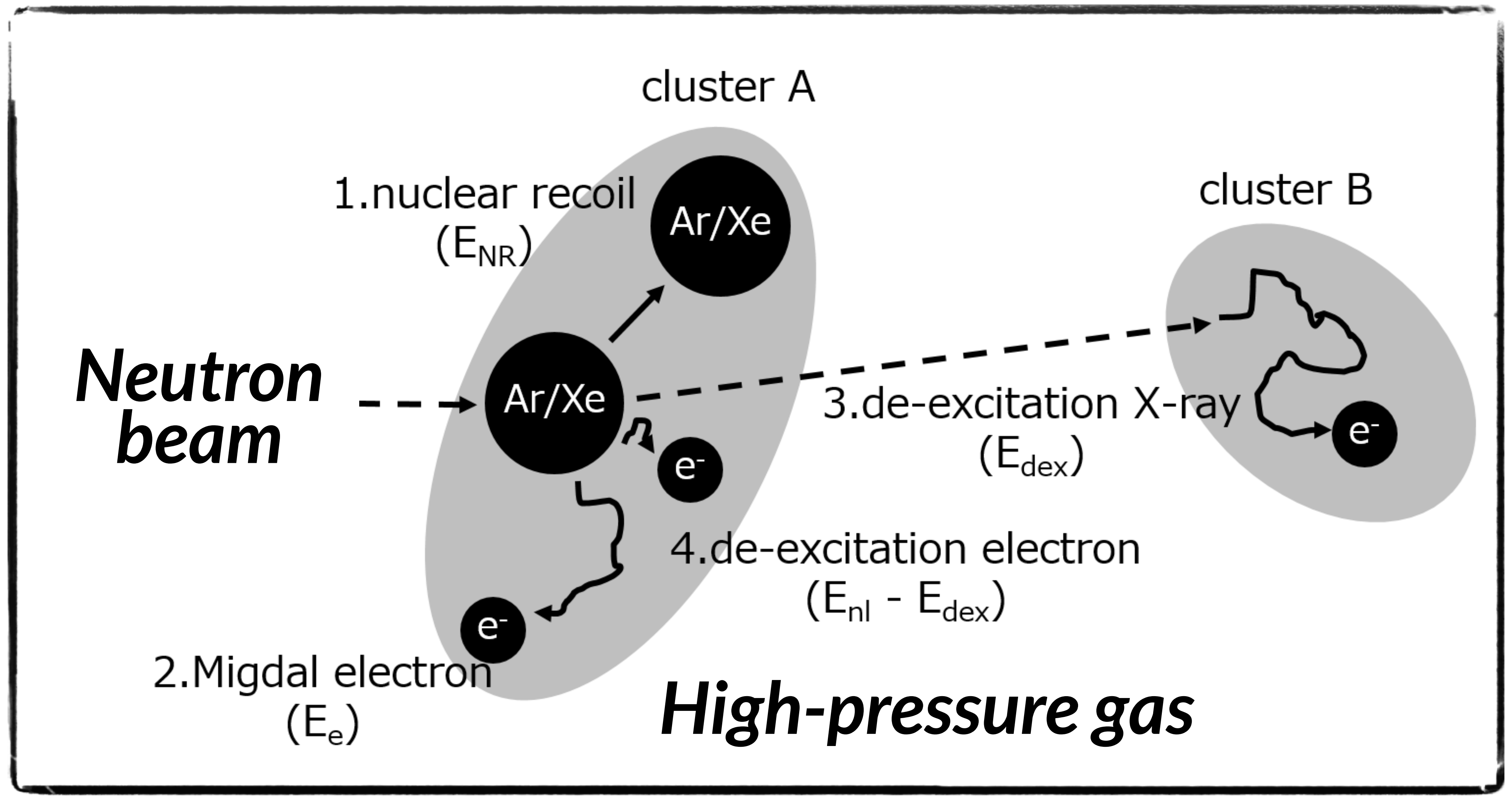
Finding evidence: Proposals with neutrons

Bell et al, arXiv:2112.08514
Xu et al, arXiv:2307.12952



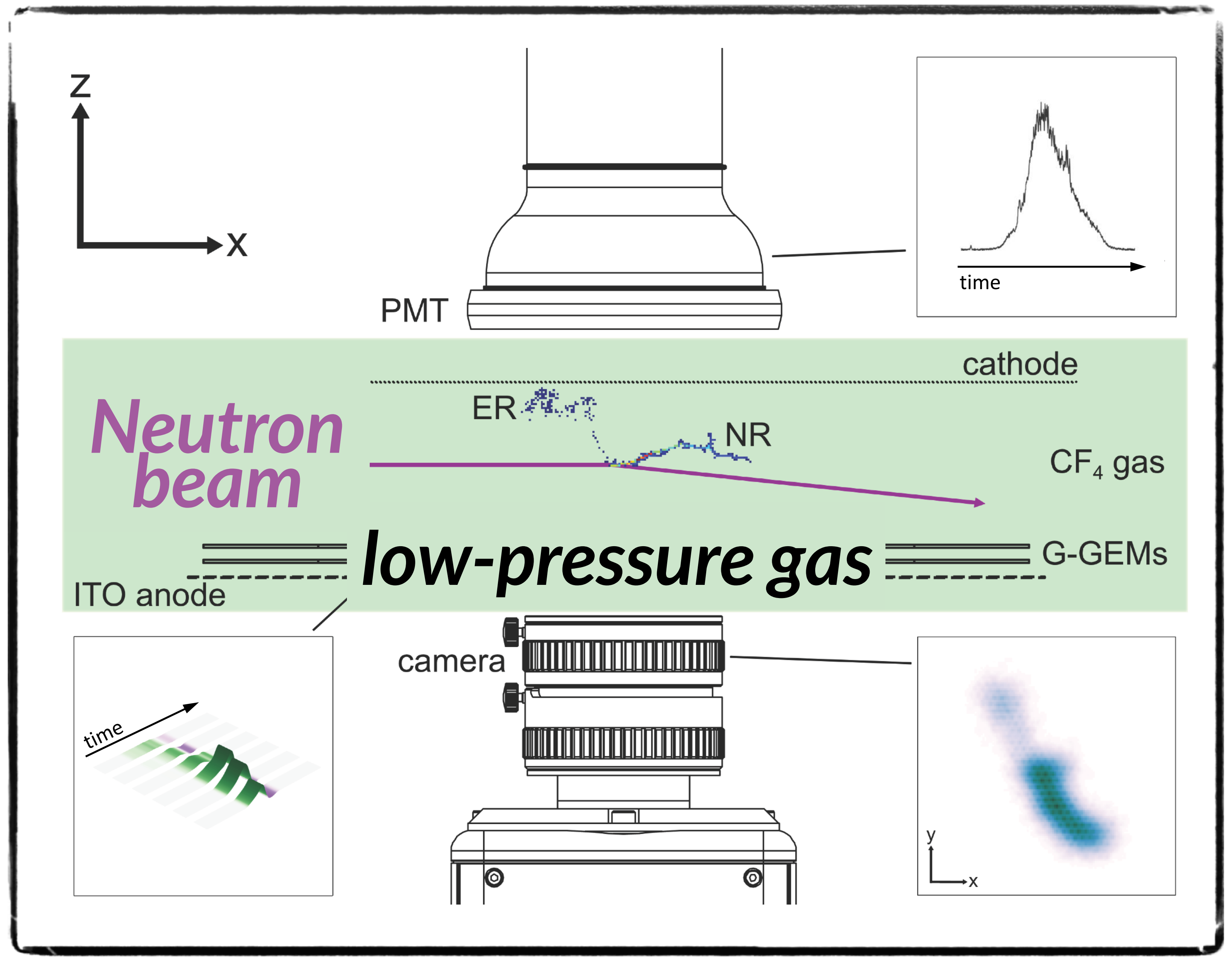
$E_{\text{neutron}} \sim 15 - 15000\ \text{keV}$

Nakamura et al, arXiv:2009.05939



$E_{\text{neutron}} \sim 500\ \text{keV}$

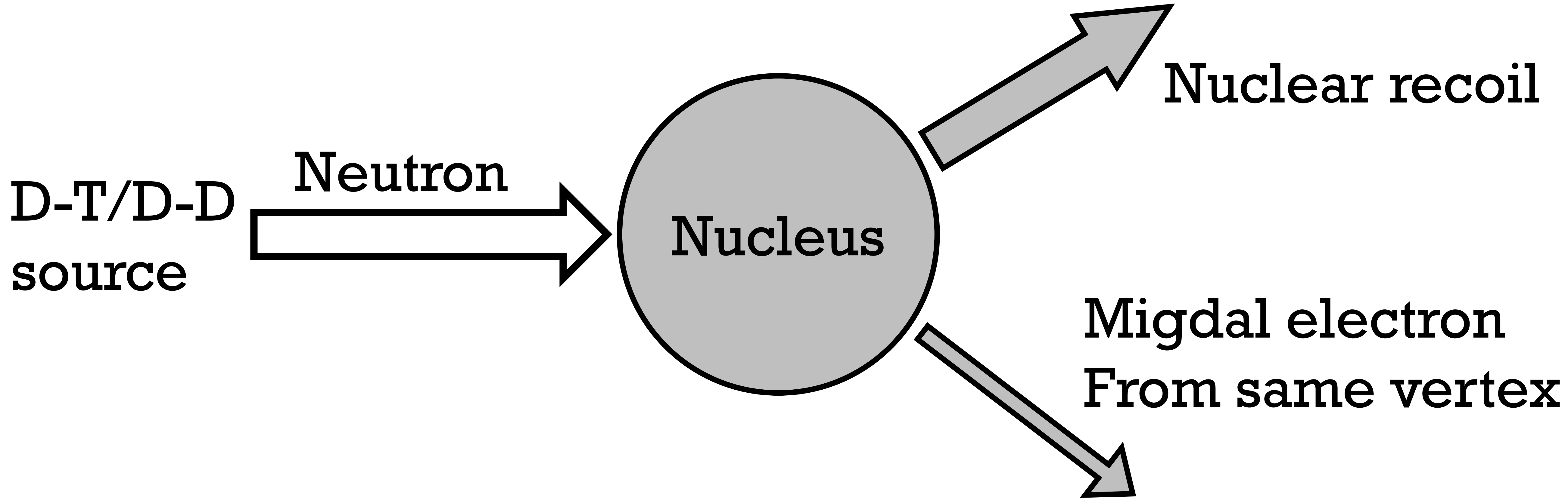
Araújo et al (MIGDAL), arXiv:2207.08284



$E_{\text{neutron}} \sim 2500 - 15000\ \text{keV}$

MIGDAL experiment: aims

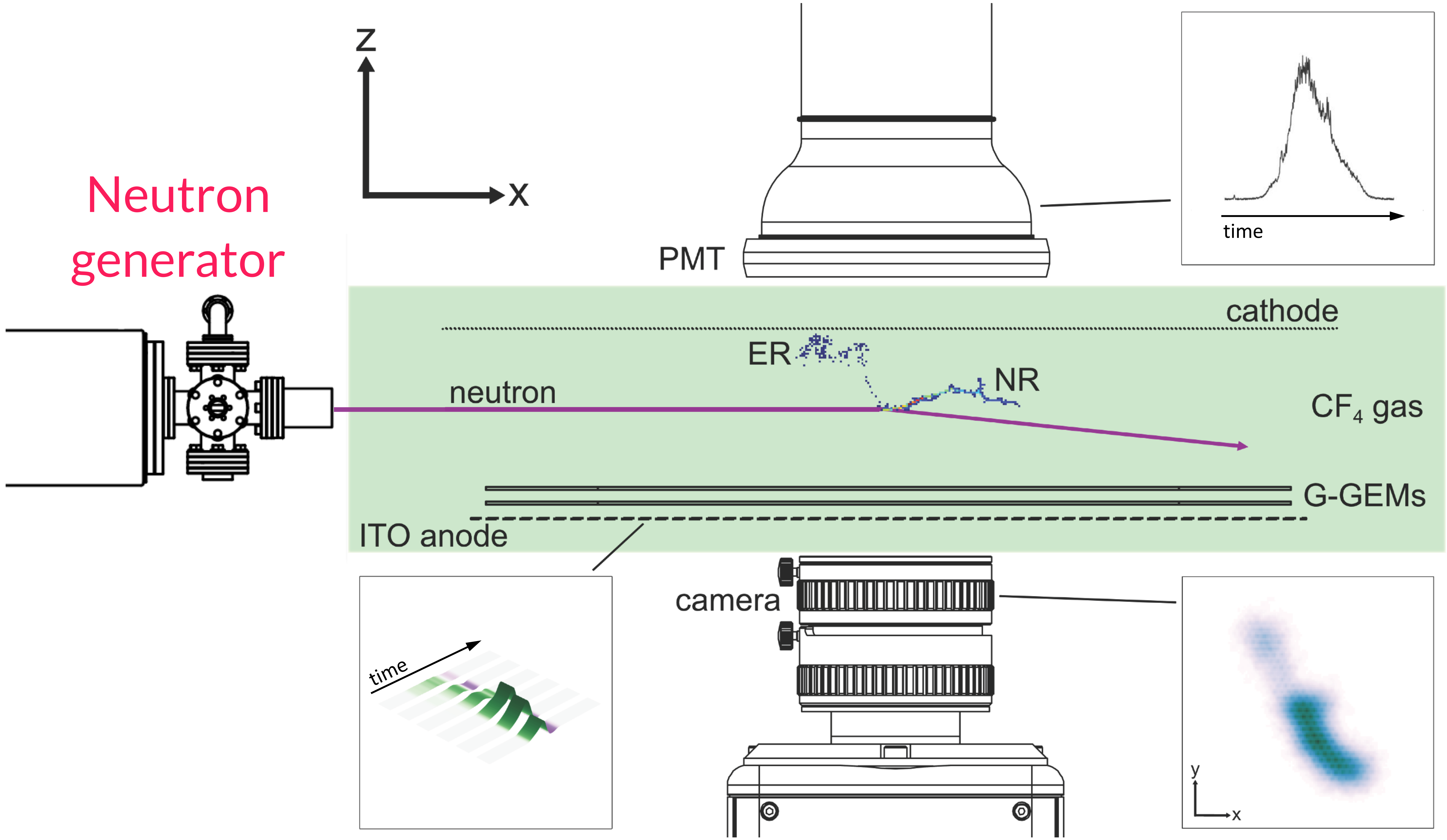
Create a dedicated experiment for the *unambiguous* observation of the Migdal effect in nuclear scattering:



We are the only experiment aiming to observe the nuclear and electron recoils emerging from a common vertex

- Phase 1: Observe the effect in CF4 in high energy recoils
- Phase 2: Observe the Migdal effect in CF4 + noble gases

MIGDAL experiment: schematic



Araújo, … ,CM, et al (MIGDAL) arXiv:2207.08284

Neutron collisions give recoils with energy:

$$E_r \simeq 100 - 3000 \text{ keV}$$

[higher than dark matter regime]

Optical Time Projection Chamber

Araújo, … ,CM, et al (MIGDAL) arXiv:2207.08284

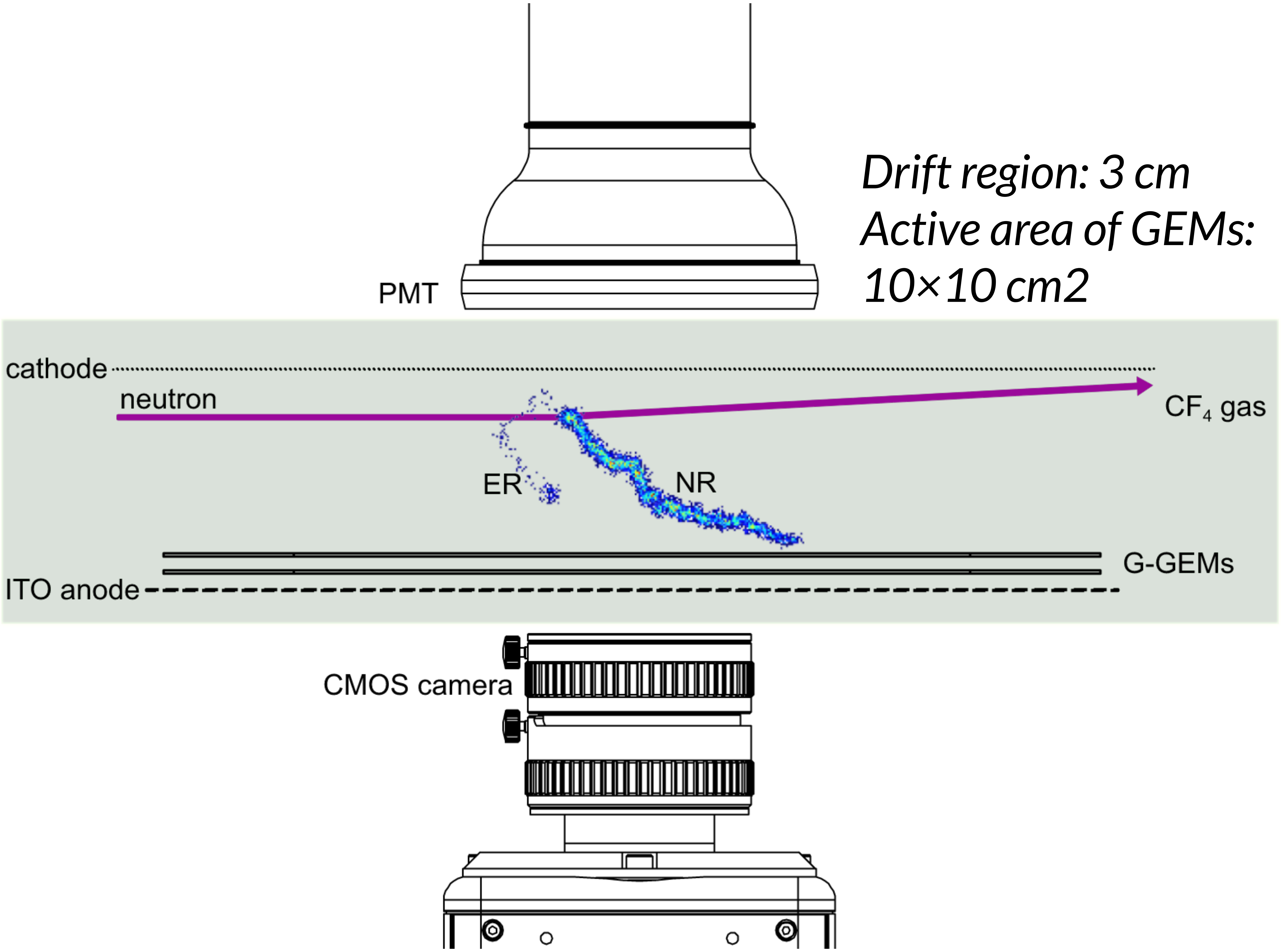
Camera: images GEM scintillation through viewport behind ITO anode.
Readout of (x,y) plane
O(10) ms timing resolution

ITO anode: collects charge.
Readout of (x,z) plane
O(1) ns timing resolution

PMT: Detects primary and secondary (GEM) scintillation
Readout of depth (z) coordinate

Setup allows for 3D track reconstruction

Drift region: 3 cm
Active area of GEMs: 10×10 cm2



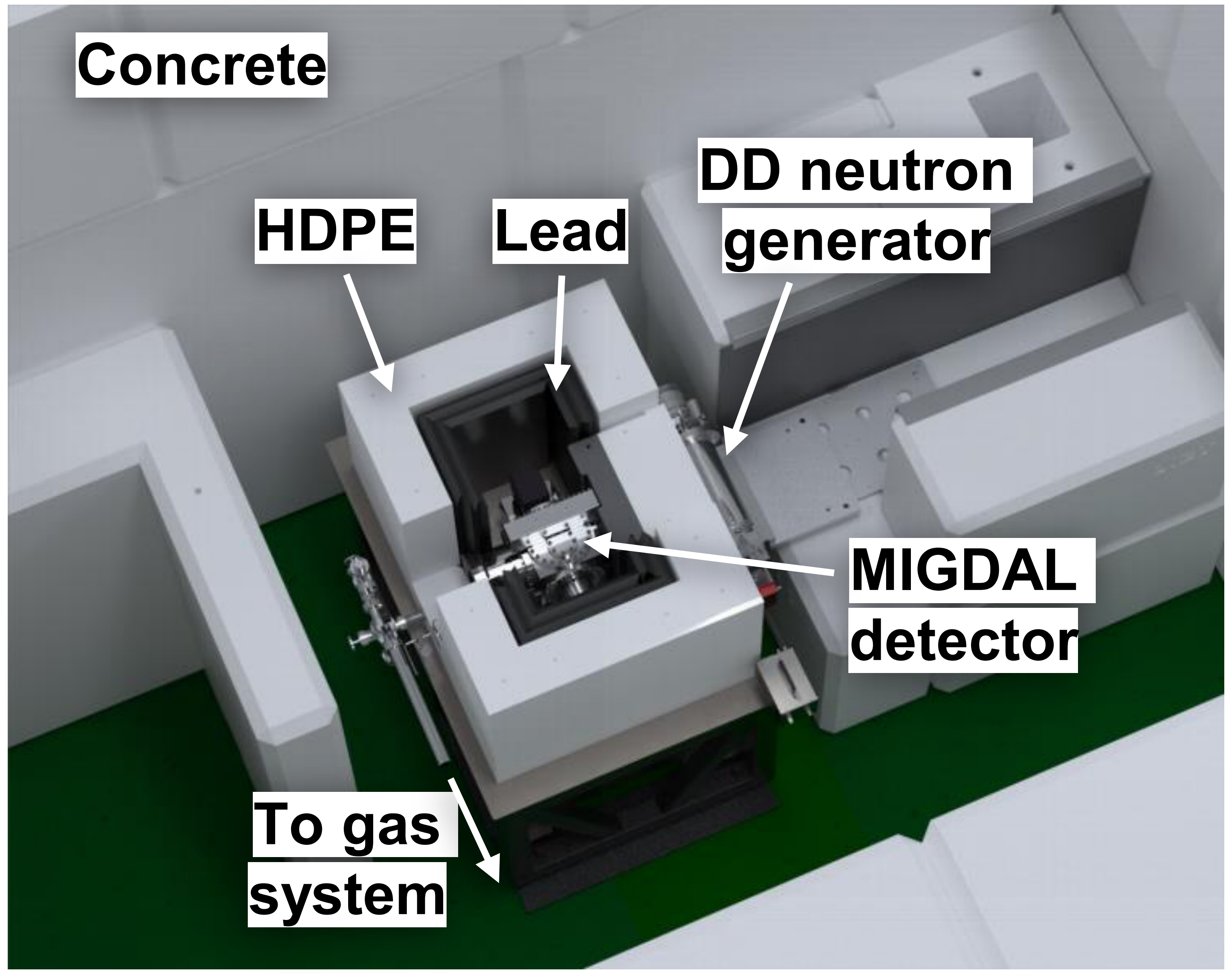
Simulated Migdal event with a 10 keV electron & 250 keV fluorine recoil. Scaled-up by a factor of 3.

Installed at NILE Facility, Rutherford Appleton Laboratory, UK

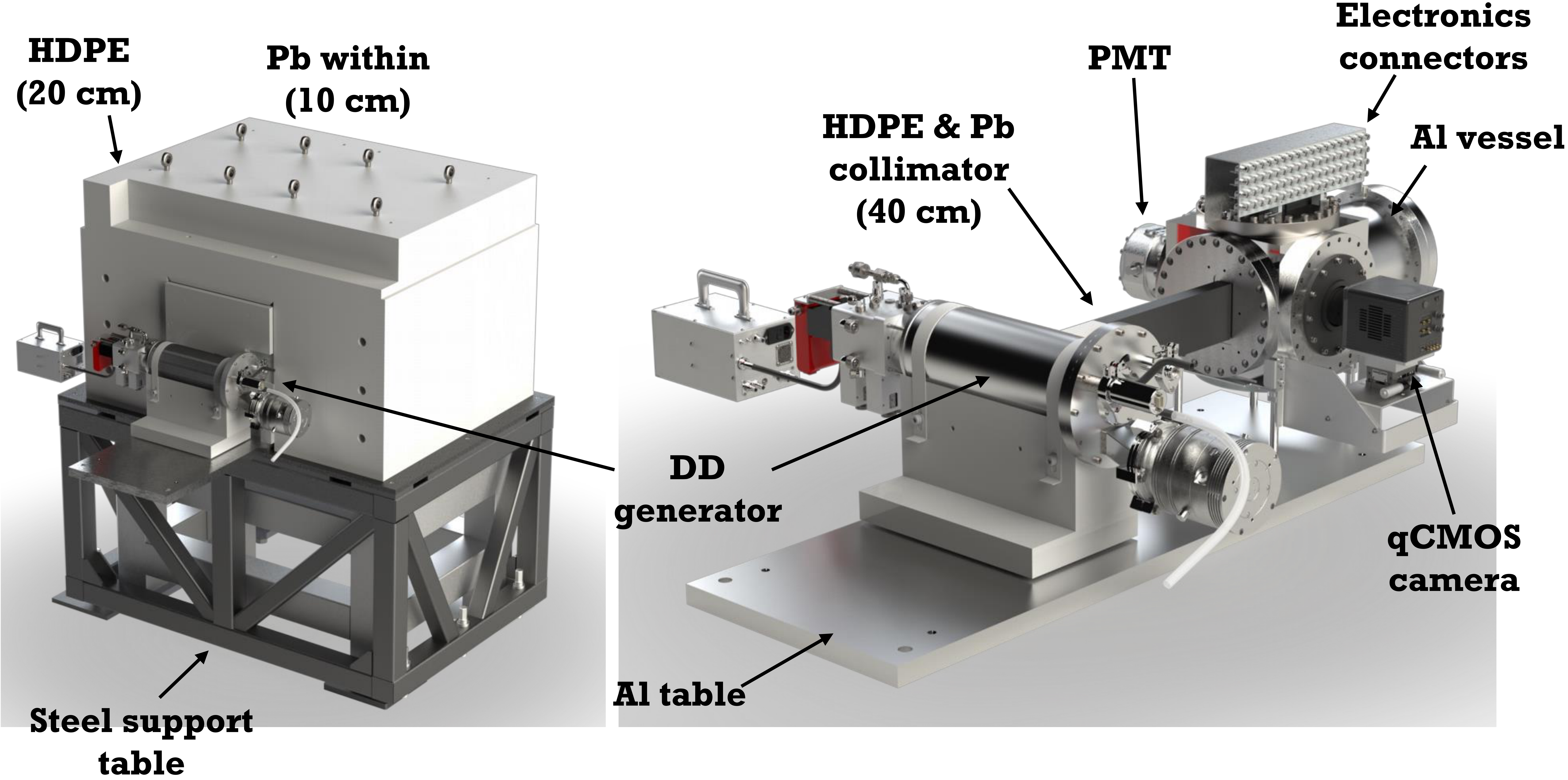
High-yield DD neutron generator
- 10^9 n/s @ 2.47 MeV

Bespoke DD neutron irradiation facility located within Target Station 2 at ISIS Neutron and Muon Source

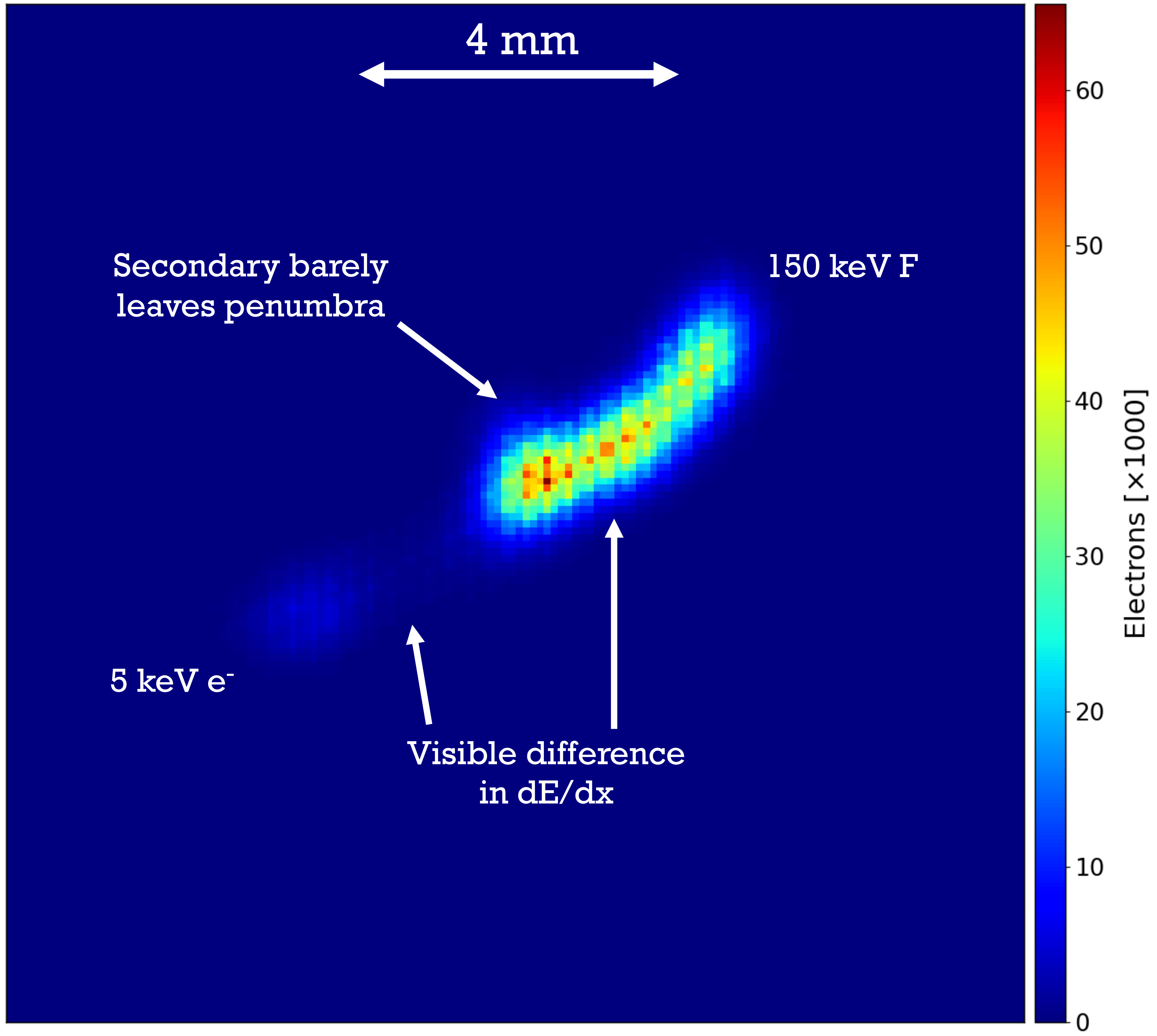
Concrete bunker with interlocked access
D-D generator installed in “shielding bunker”
MIGDAL detector in the centre of the bunker



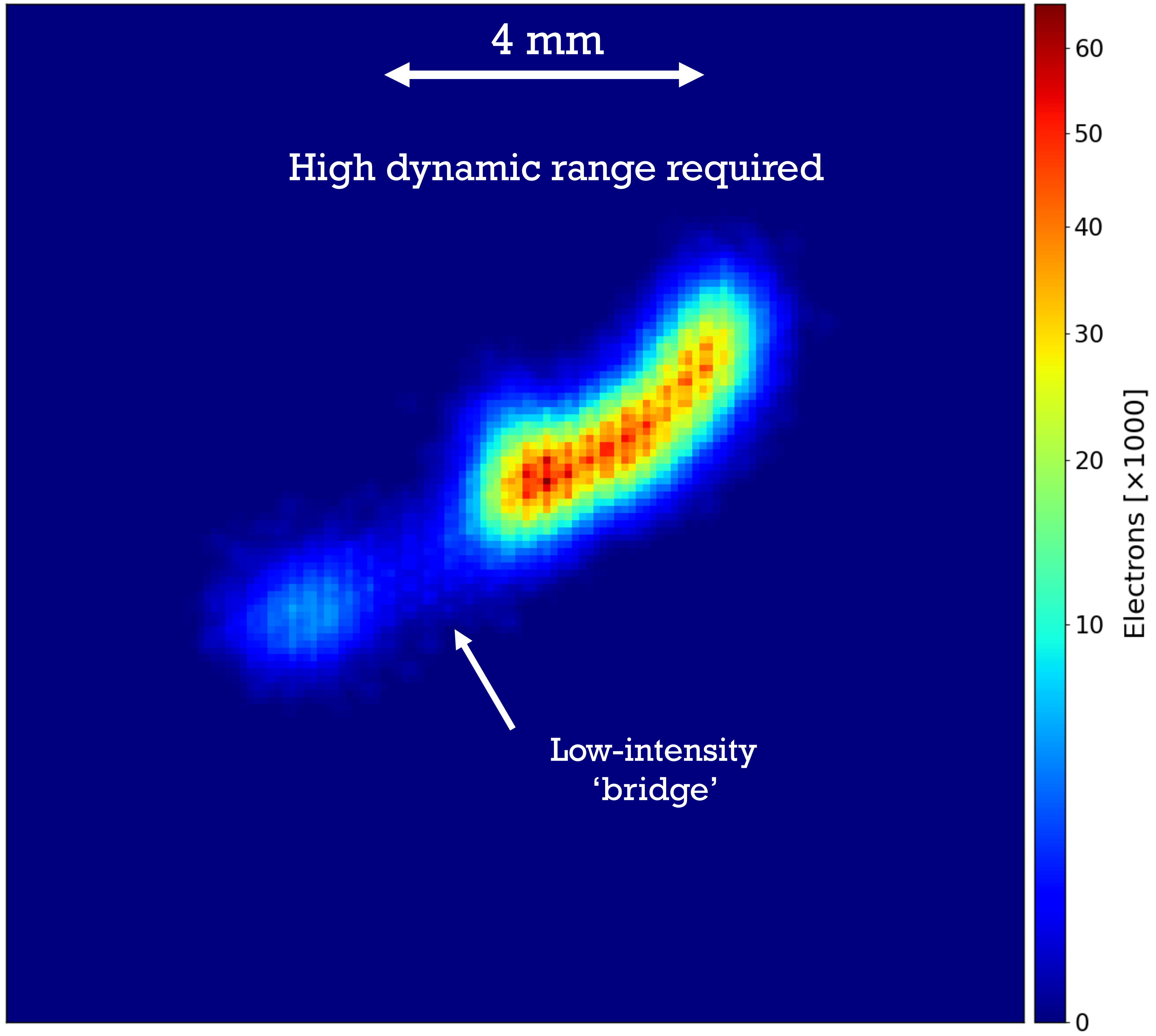
Shielded and Unshielded renders of the experiment



Simulated camera images of Migdal event

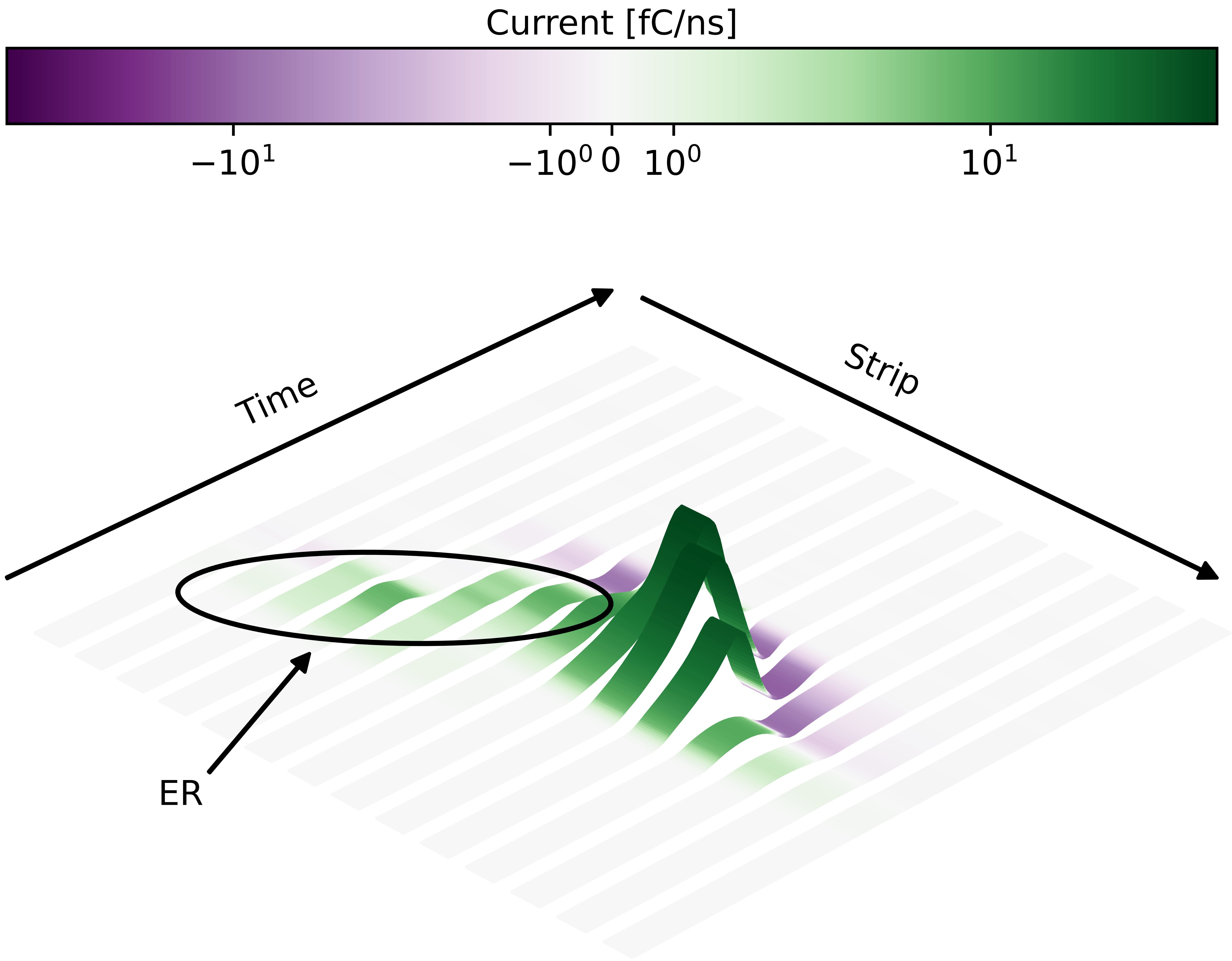


Linear-scale colour map



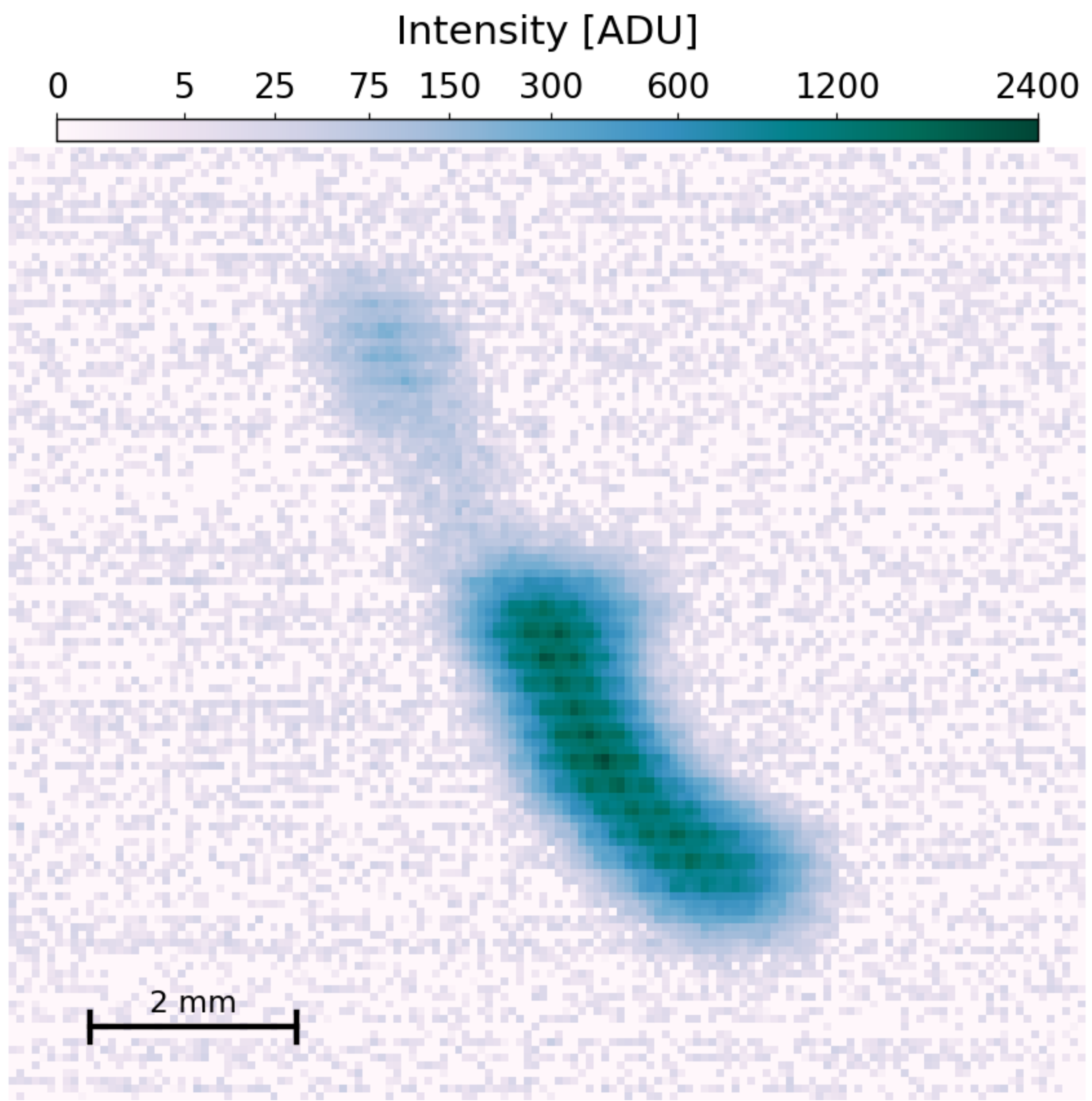
Log-scale colour map

Simulated ITO signals of Migdal event



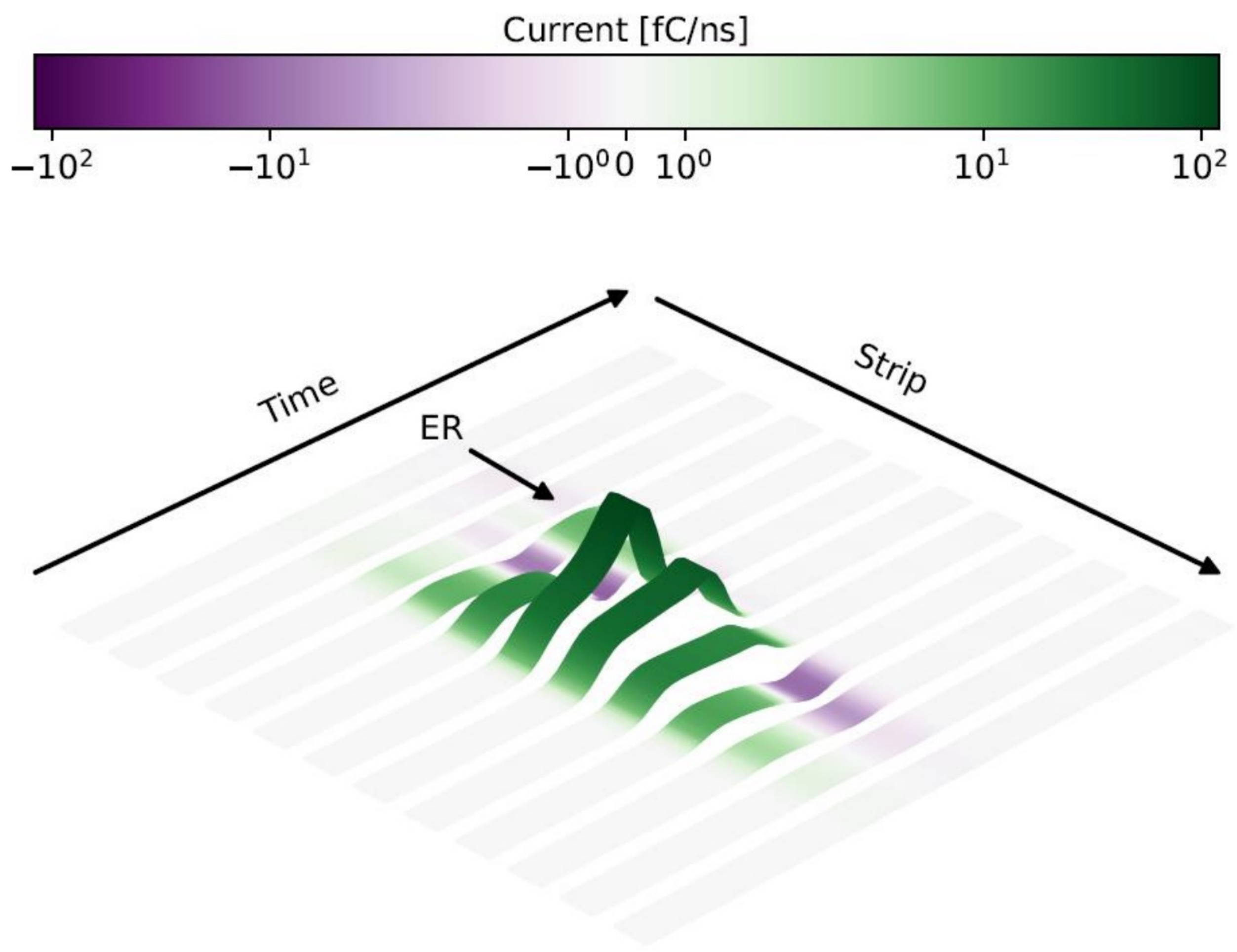
Track reconstruction

Camera readout
Diffusion + GEMs + noise



+

Anode strip readout
Induction/collection
(electronics deconvolved)



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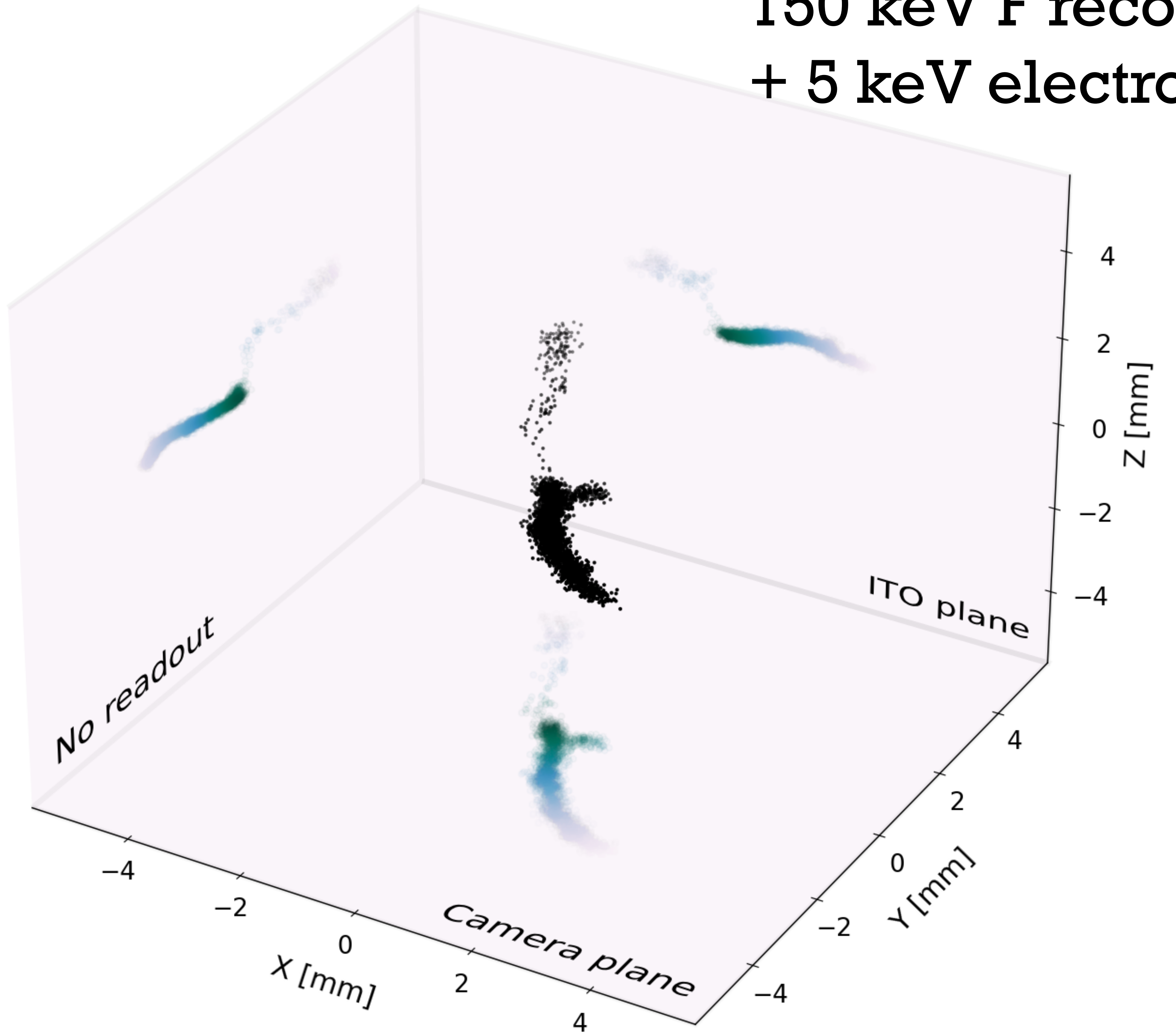
Migdal event
150 keV F recoil
+ 5 keV electron



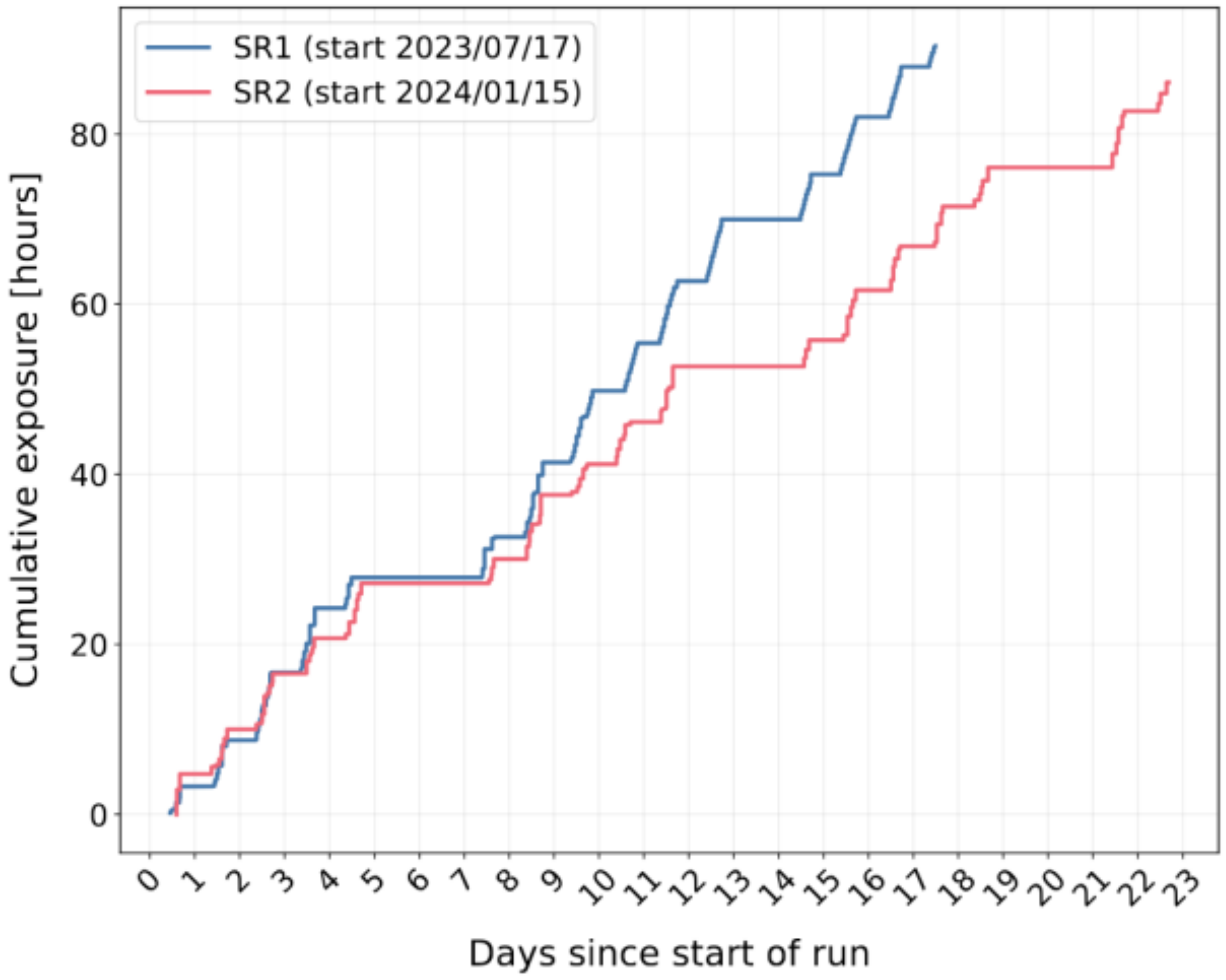
Science operations

- First Science Run: 17/07/23 - 03/08/23
- Second Science Run: 15/01/24 - 06/02/24

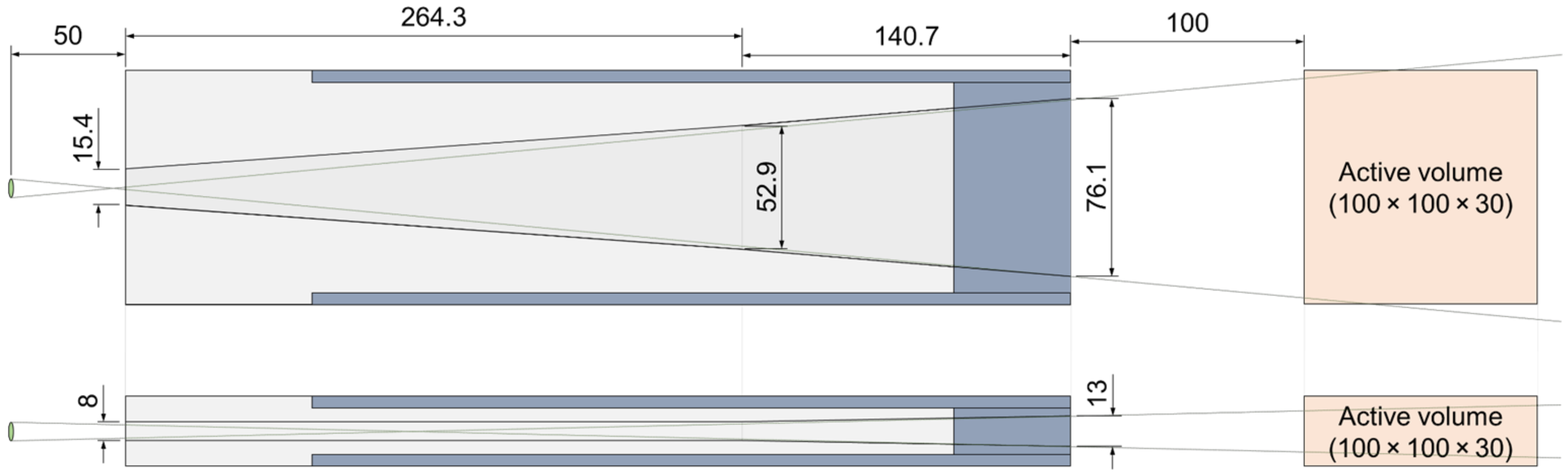
- Data taken using D-D neutron generator recorded continuously during 10-hour shifts

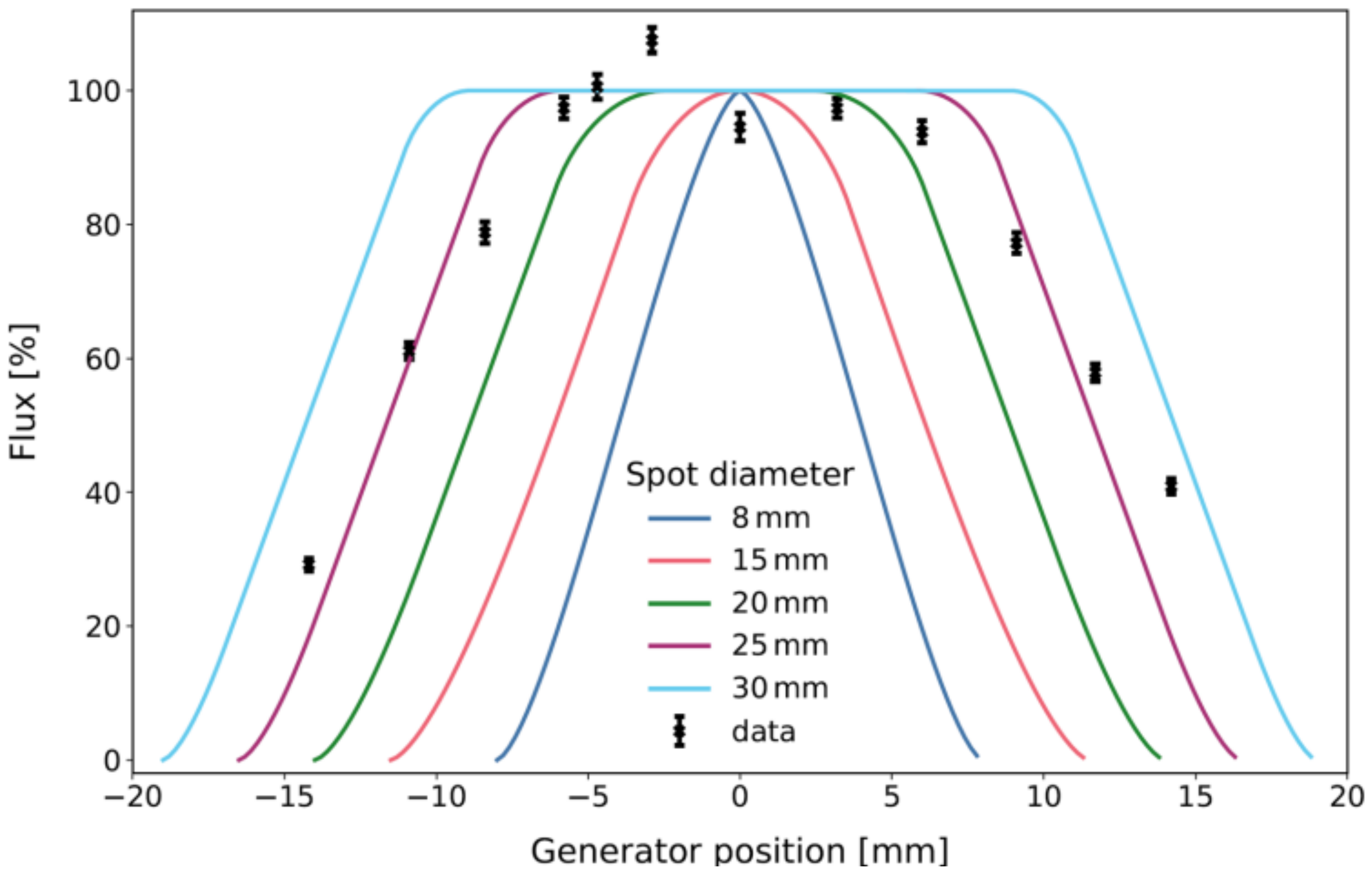
- 50% data remained blinded

- Approximately 500,000 NRs in total



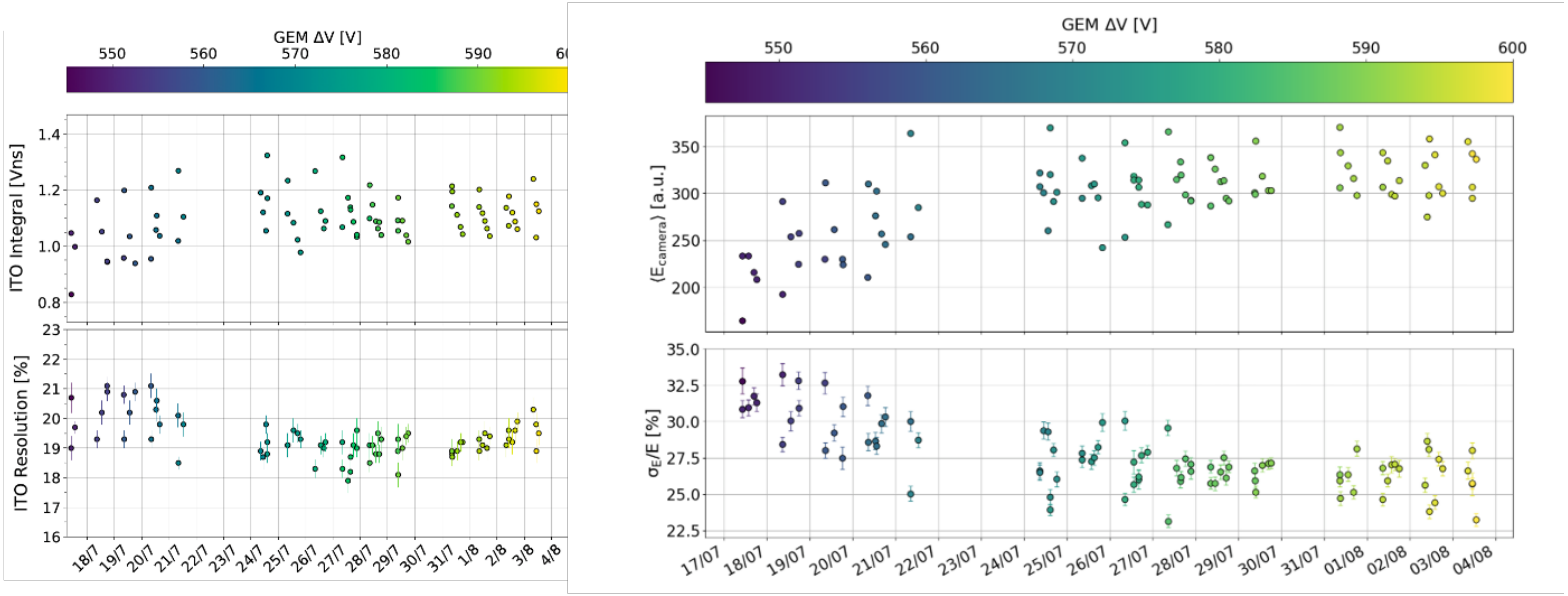
Science operations: neutron beam





- Expected 2.6×10^5 n/s entering the active volume, but measured 6×10^4 n/s.
- Collimator designed ~8 mm neutron production spot diameter within the DD generator: but measured diameter was ~25 mm.
  - This reduced the NR event rate in the active volume from ~15 Hz to ~5 Hz.
- The camera was pulled closer to the active volume to capture more light.
  - This further reduced the contained NR rate in the ROI to ~2 Hz, which we observe in the data.

Science operations: detector calibrations



- ^{55}Fe calibration performed several times per day
- Energy scale is consistent over the course of the science run with ~20% variation
- Resolution in ITO ~20% and in camera ~ 25 - 32 % camera readout depending on the gain

Backgrounds

Araújo, … ,CM, et al (MIGDAL) arXiv:2207.08284

Component	Topology	D-D neutrons		D-T neutrons	
		>0.5	5–15 keV	>0.5	5–15 keV
Recoil-induced δ-rays	Delta electron from NR track origin	≈0	0	541,000	0
Particle-Induced X-ray Emission (PIXE)					
X-ray emission	Photoelectron near NR track origin	1.8	0	365	0
Auger electrons	Auger electron from NR track origin	19.6	0	42,000	0
Bremsstrahlung processes†					
Quasi-Free Electron Br. (QFEB)	Photoelectron near NR track origin	112	≈0	288	≈0
Secondary Electron Br. (SEB)	Photoelectron near NR track origin	115	≈0	279	≈0
Atomic Br. (AB)	Photoelectron near NR track origin	70	≈0	171	≈0
Nuclear Br. (NB)	Photoelectron near NR track origin	≈0	≈0	0.013	≈0
Photon interactions					
Neutron inelastic γ-rays (gas)	Compton electron near NR track origin	1.6	0.47	0.86	0.25
Random track coincidences	Photo-/Compton electron near NR track	≈0	≈0	≈0	≈0
Gas radioactivity					
Trace contaminants	Electron from decay near NR track origin	0.2	0.01	0.03	≈0
Neutron activation	Electron from decay near NR track origin	0	0	≈0	≈0
Secondary nuclear recoil fork	NR track fork near track origin	–	≈1	–	≈1
Total background	Sum of the above components		1.5		1.3
Migdal signal	Migdal electron from NR track origin		32.6		84.2

† These processes were (conservatively) evaluated at the endpoint of the nuclear recoil spectra.

Backgrounds

Araújo, … ,CM, et al
(MIGDAL)
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Neutron activation	Electron from decay near NR track origin	0	0	≈0	≈0
Secondary nuclear recoil fork	NR track fork near track origin	–	≈1	–	≈1
Total background	Sum of the above components		1.5		1.3
Migdal signal	Migdal electron from NR track origin		32.6		84.2

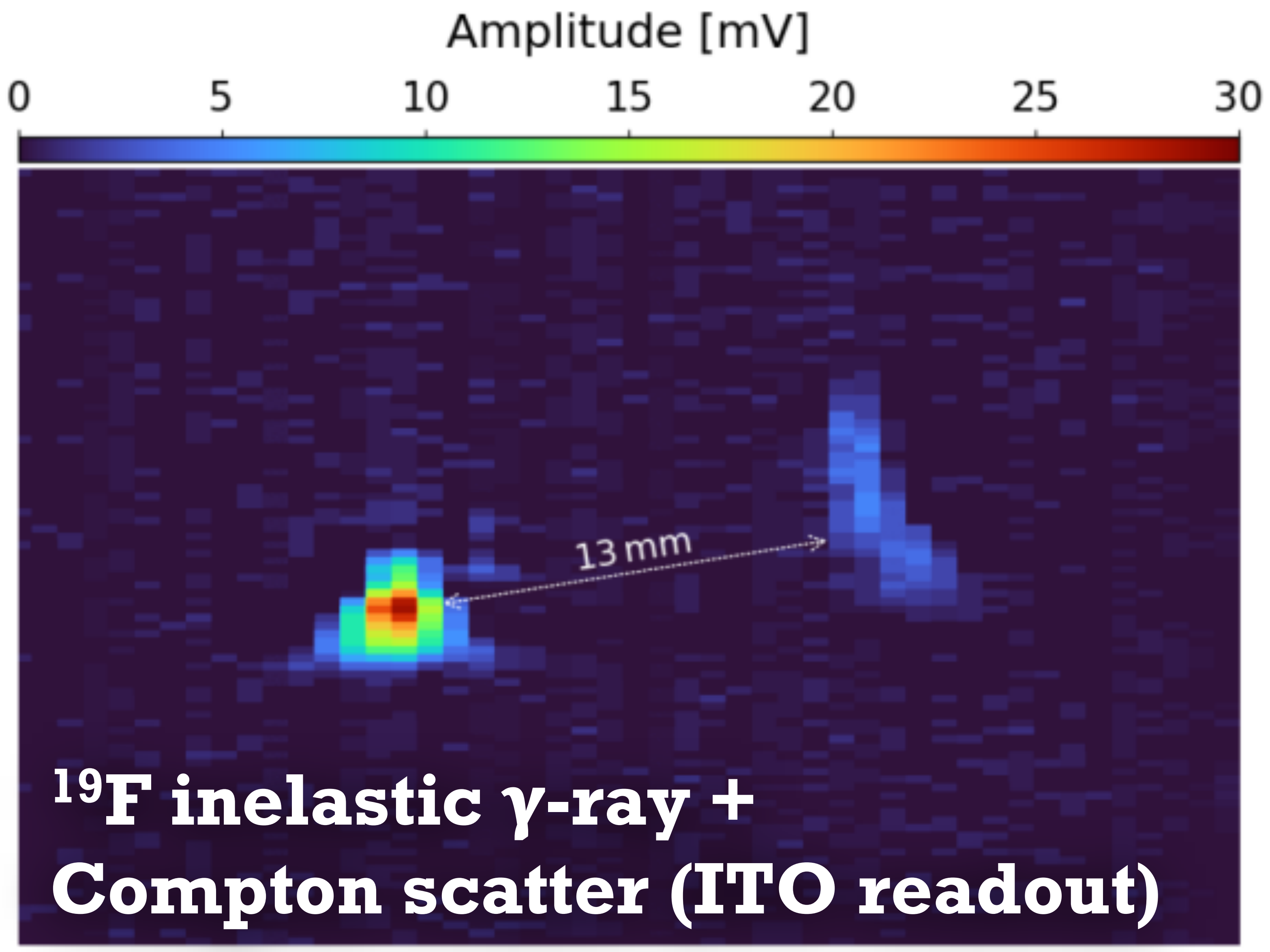
Eliminated by applying energy threshold

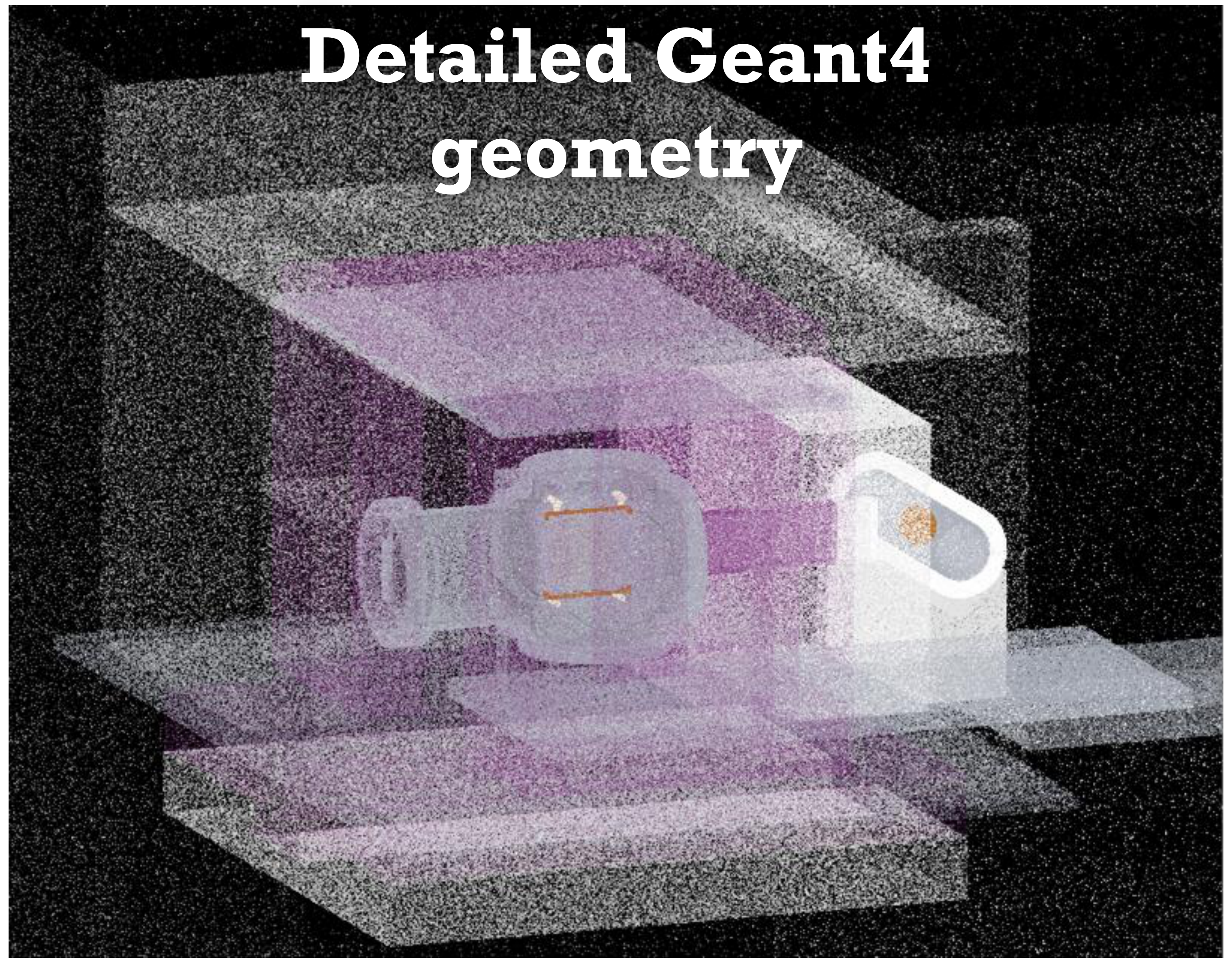
Eliminated by ITO timing resolution

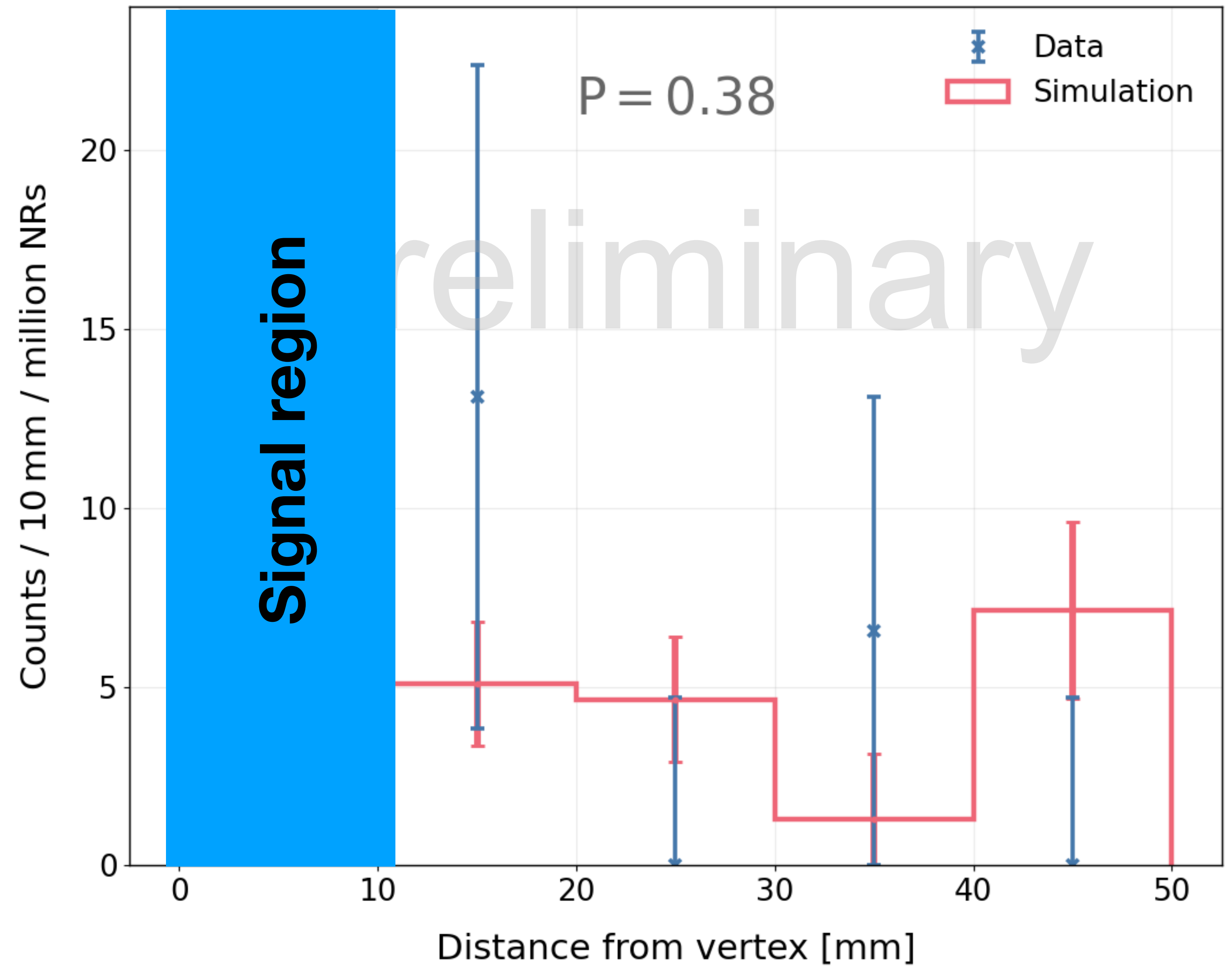
† These processes were (conservatively) evaluated at the endpoint of the nuclear recoil spectra.

Background simulations

- Constructed a GEANT4 detector geometry to calculate the expected number of γ-rays
- We find the simulated and measured NR + ER coincidences is consistent
- Expected (and measured) number of ERs produced within 3 mm of an NR vertex is very small (good news)



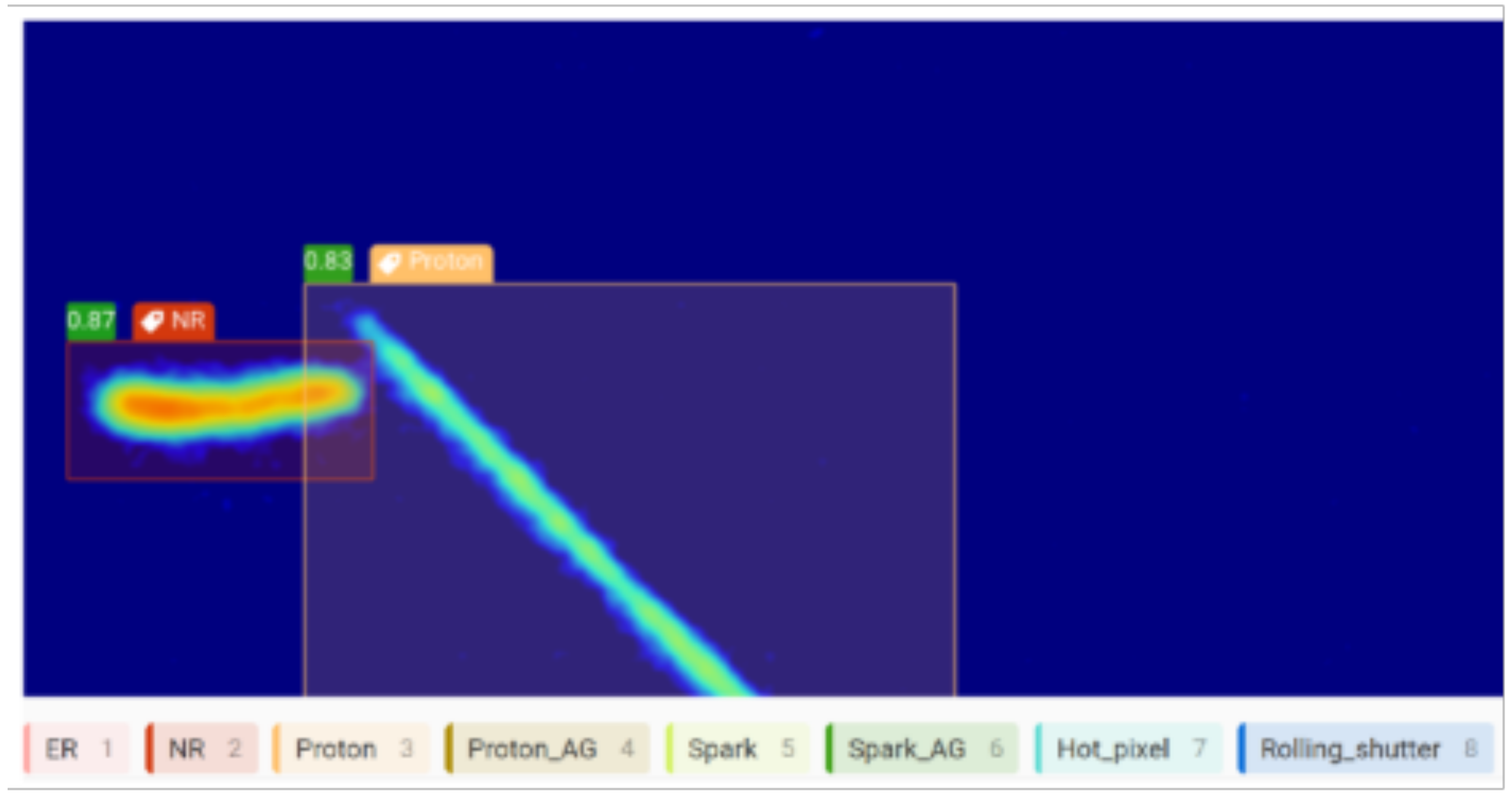


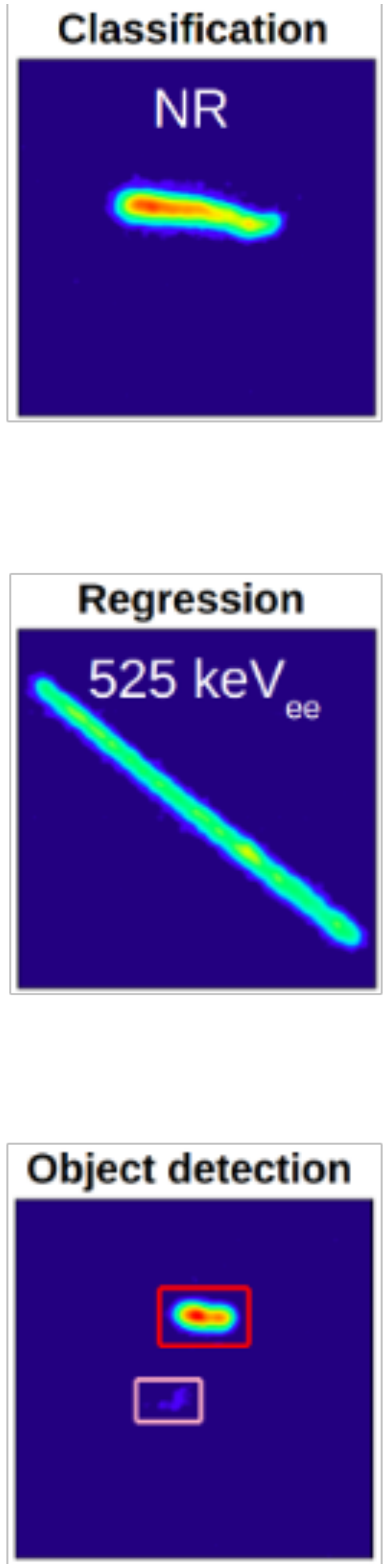


Search enhanced with object detection

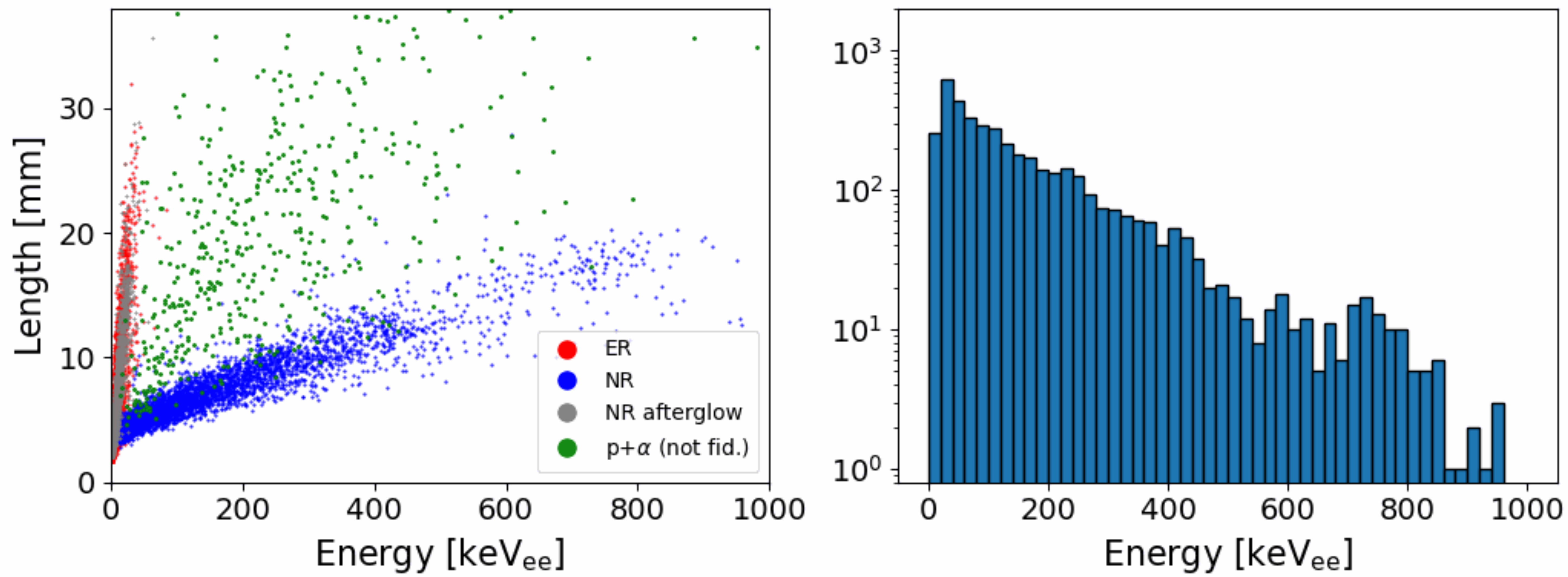
Schueler, … ,CM, et al (MIGDAL) arXiv:2406.07538

- Utilise YOLOv8: state-of-the-art object detection algorithm
- Simultaneously classifies and localises (with bounding boxes) any number of objects of interest in an image
- Provides online deliverables, including particle ID and NR energy spectra in real time

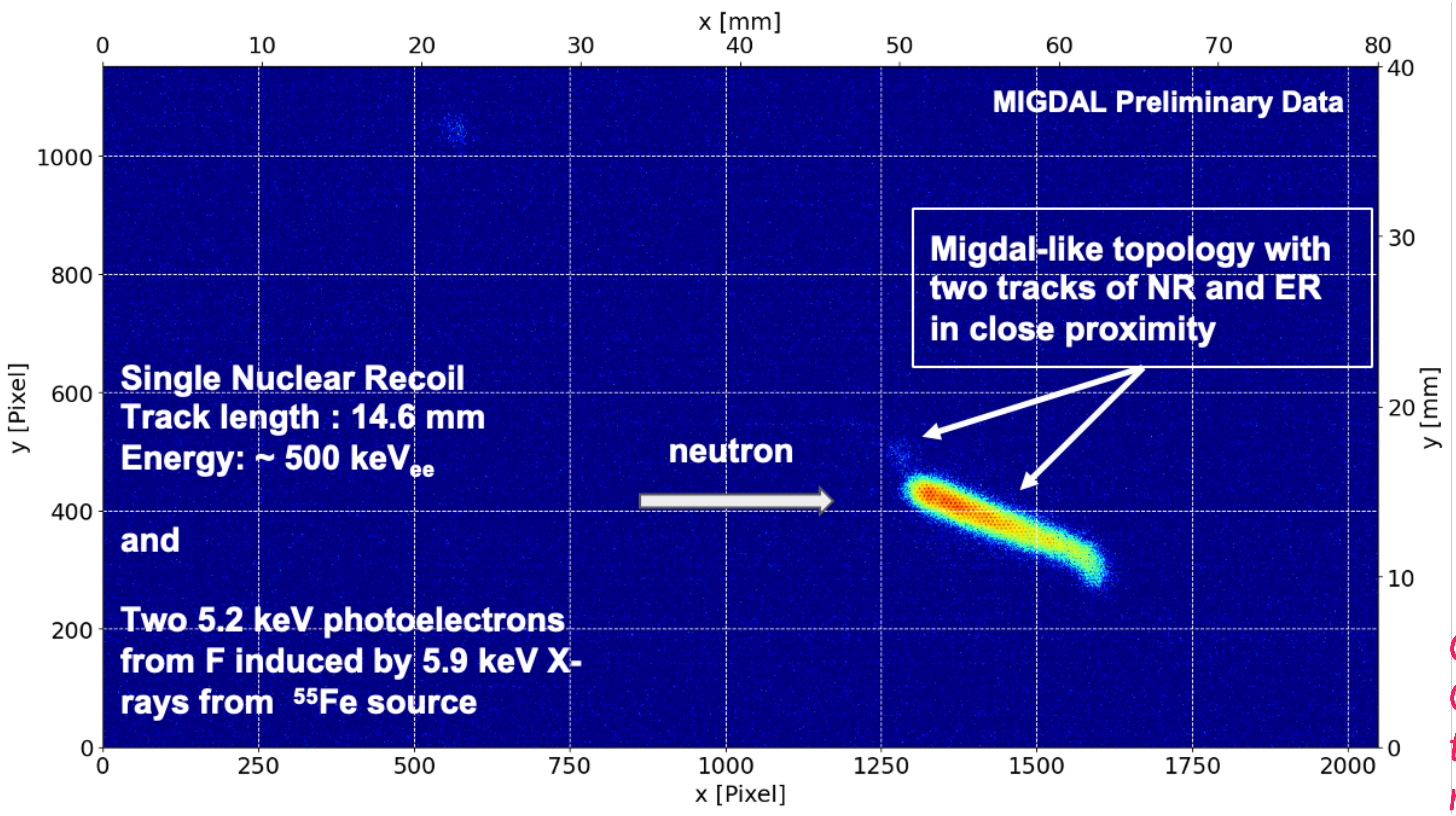




ER: 9180 NR: 4186 NR afterglow: 2958 p+α: 650 Spark: 220 Storm: 29 Candidate: 3

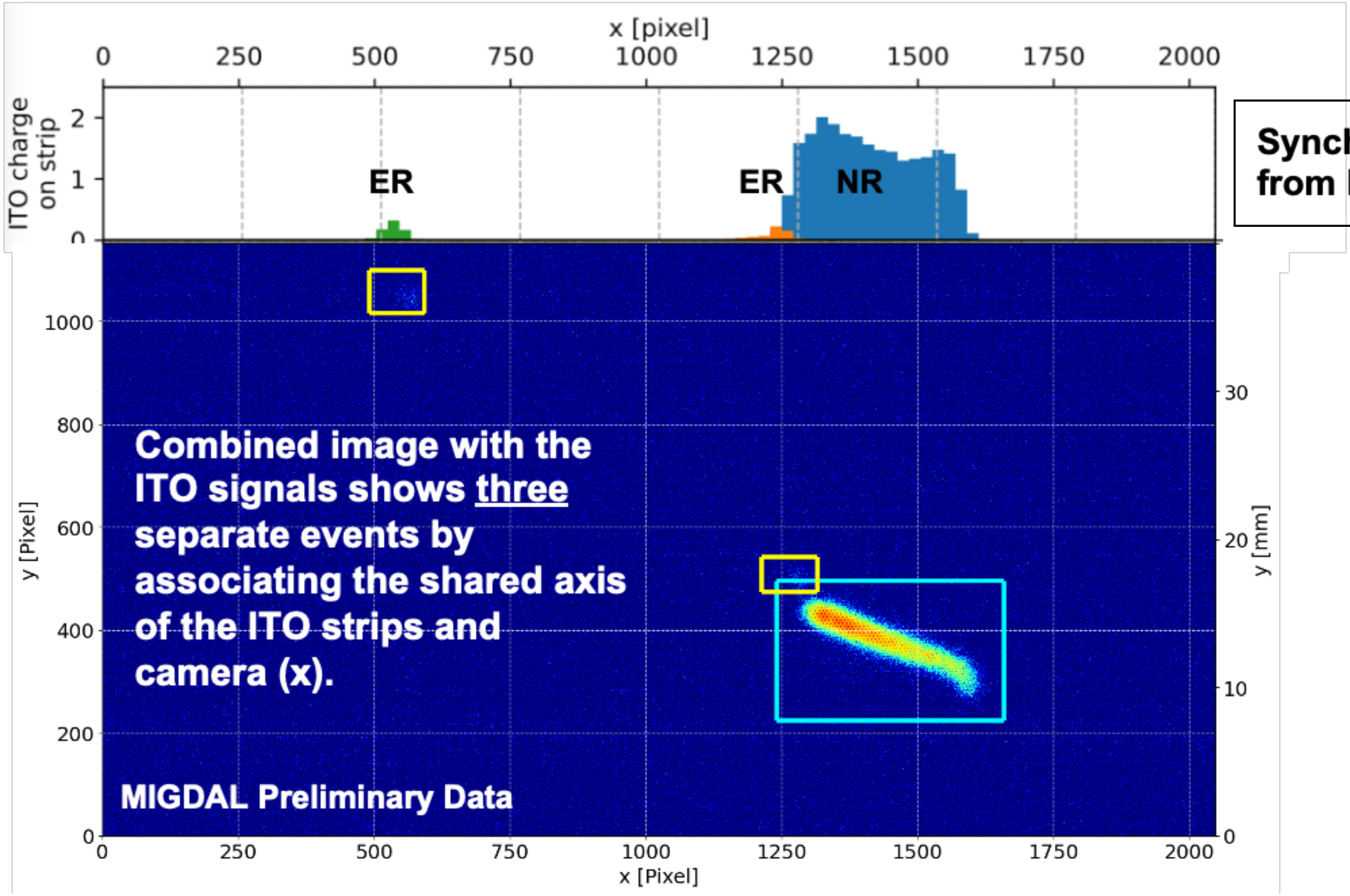


Example Migdal-topology event



Camera: O(10) ms timing resolution

Example Migdal-topology event

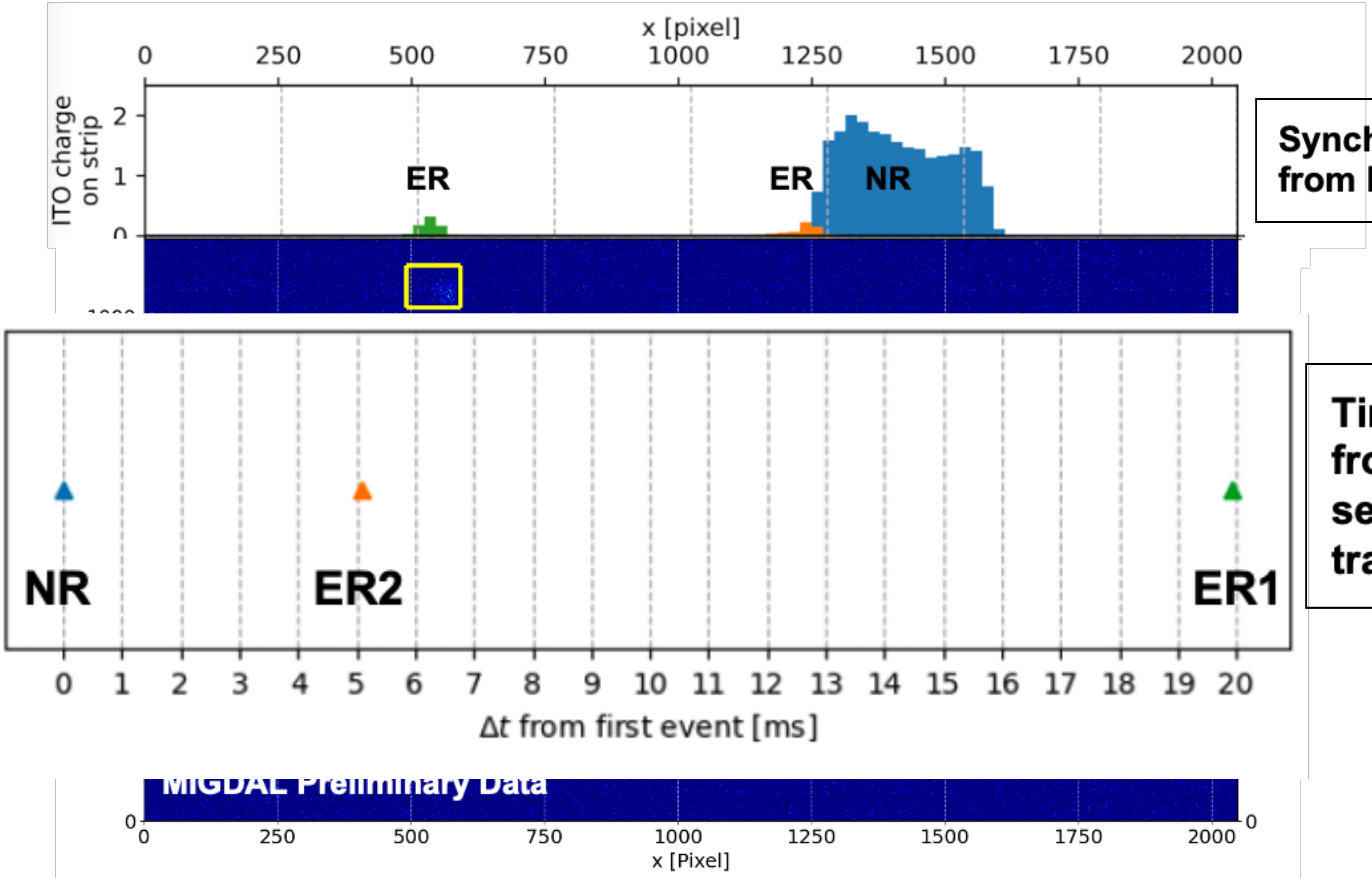


Synchronised signals from ITO strips.

ITO: O(1) ns timing resolution

Camera: O(10) ms timing resolution

Not a Migdal event: no temporal overlap!



Synchronised signals from ITO strips.

Timing information from ITO strips separates all 3 tracks.

Summary

The Migdal effect is an old effect (from 1940s) that is used for dark matter sub-GeV searches

On the theory side, we have extended previous calculations to the high nuclear-recoil speed regime & confirmed the accuracy of existing calculations (Ibe et al) for DM searches

In the UK…

- we are building a detection platform to characterise the effect in multiple elements

Summary & Next steps

The Migdal effect is an old effect (from 1940s) that is used for dark matter sub-GeV searches

On the theory side, we have extended previous calculations to the high nuclear-recoil speed regime & confirmed the accuracy of existing calculations (Ibe et al) for DM searches

In the UK…

- we are building a detection platform to characterise the effect in multiple elements

- Detector performed as designed during Science Runs 1 and 2
- We have several weeks of stable DD data: approximately 500,000 NRs in total
- Backgrounds appear to be as expected
- Data analysis of the two science runs is ongoing (stay tuned)

- Science Run 3 planned for this year with several improvements:
  - Higher resolution digitiser (CAEN V1730)
  - Increased spatial resolution in the ITO subsystem
  - Testing addition of a third GEM to provide additional amplification stage
  - Recommissioned DD generator with smaller spot size & redesigned collimator
  - Plans to run with CF4 + Ar mixture

Thank you

"Precise Predictions and New Insights for Atomic Ionisation from the Migdal Effect"
Peter Cox, Matthew Dolan Christopher McCabe and Harry Quiney
arXiv:2208.12222, PRD (2023)

Data files of probabilities available now: *https://petercox.github.io/Migdal/*

"*The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter*" H.M. Araújo et al (MIGDAL)

arXiv:2207.08284, Astroparticle Phys (2023)

"*Transforming a rare event search into a not-so-rare event search in real-time with deep learning-based object detection*" J. Schueler et al (MIGDAL)

arXiv:2406.07538, PRD (to appear)

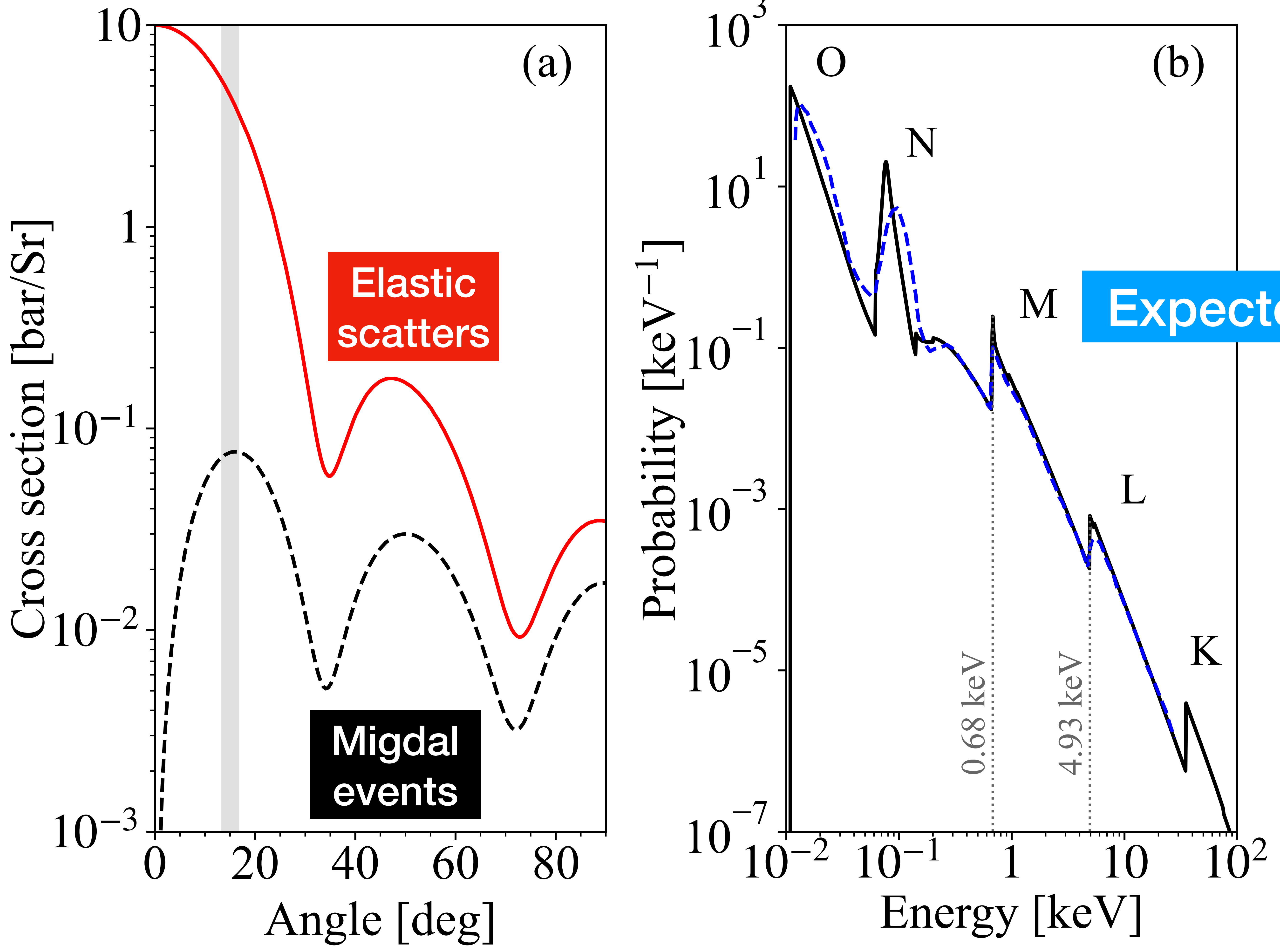
Backup

Other searches

Search in LXe with DT neutron generator

Search for neutrons scattered through narrow angle

Search for the Migdal effect in liquid xenon with keV-level nuclear recoils
Jingke Xu et al
arXiv: 2307.12952, PRD

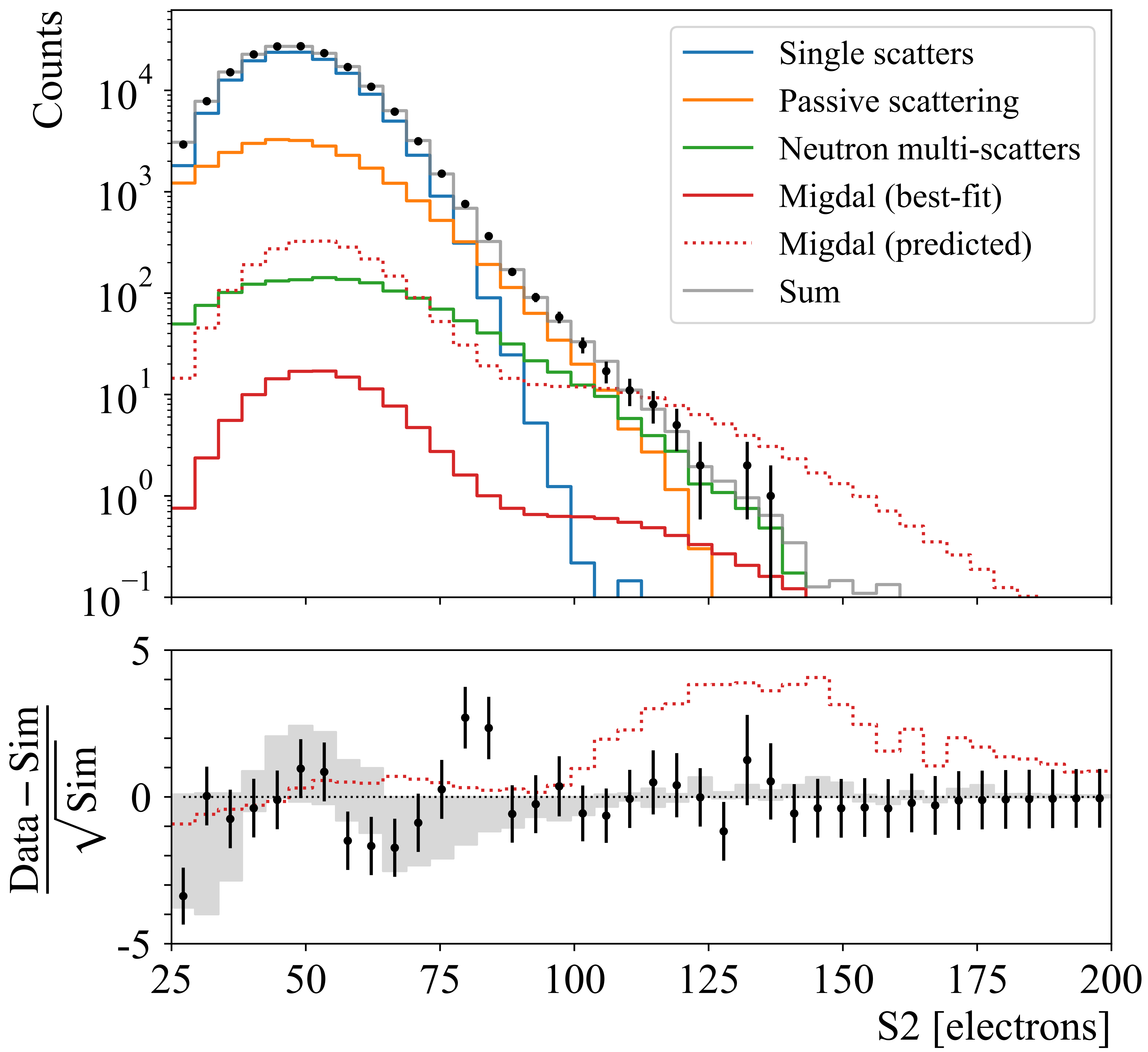


Expected 148.3 +- 16.3 events

Observed 16.3 + 21.7 (-16.3) events

Enhanced recombination in Liquid Xenon capturing Migdal electron after emission?

Search in LXe with DT neutron generator



Search for the Migdal effect in liquid xenon with keV-level nuclear recoils
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