Migdal effect with neutral projectiles

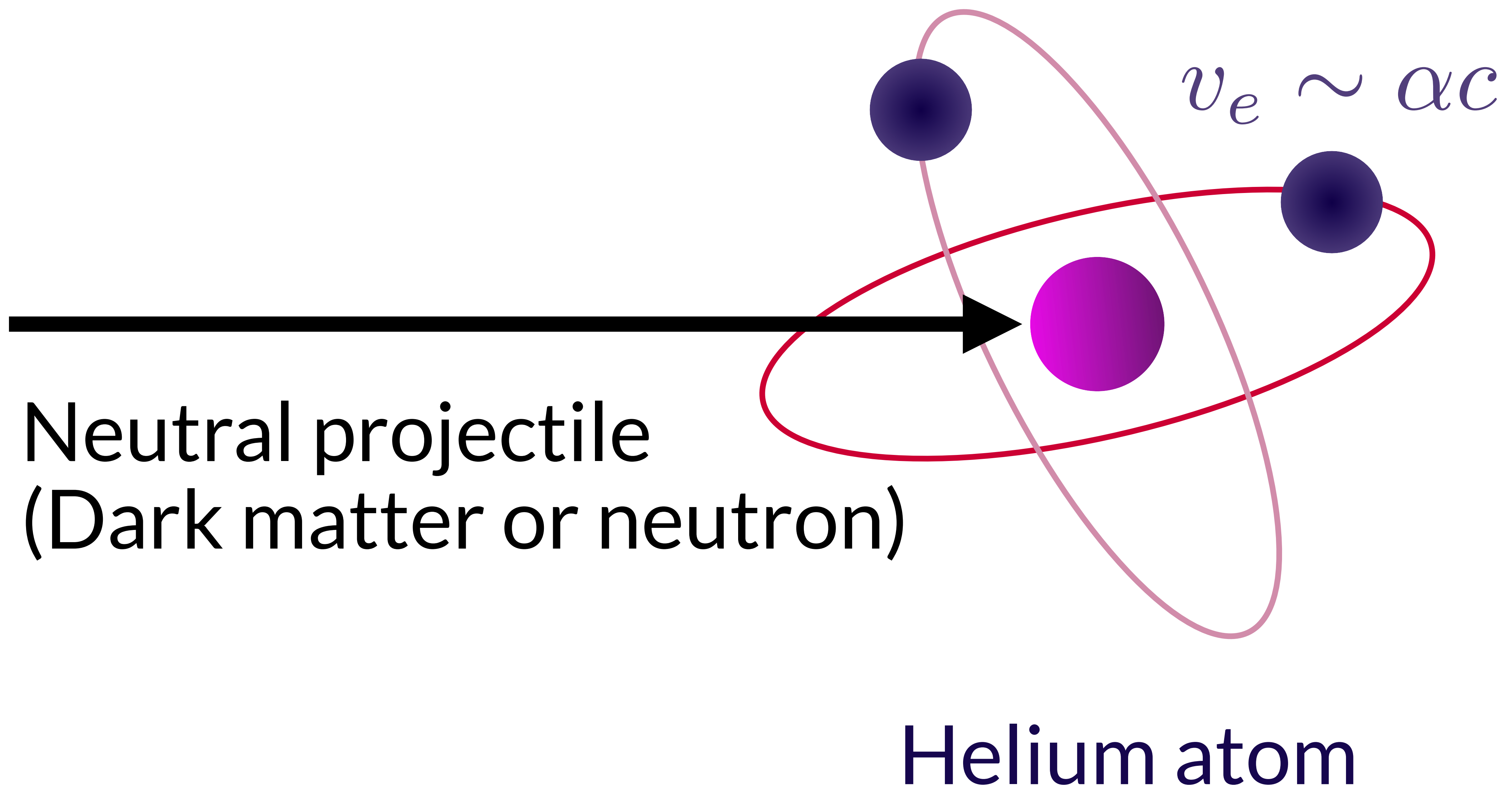
Christopher McCabe

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

Particle Avenues in the Dark Universe Arena (PADUA): Light dark sectors, 6 September 2023

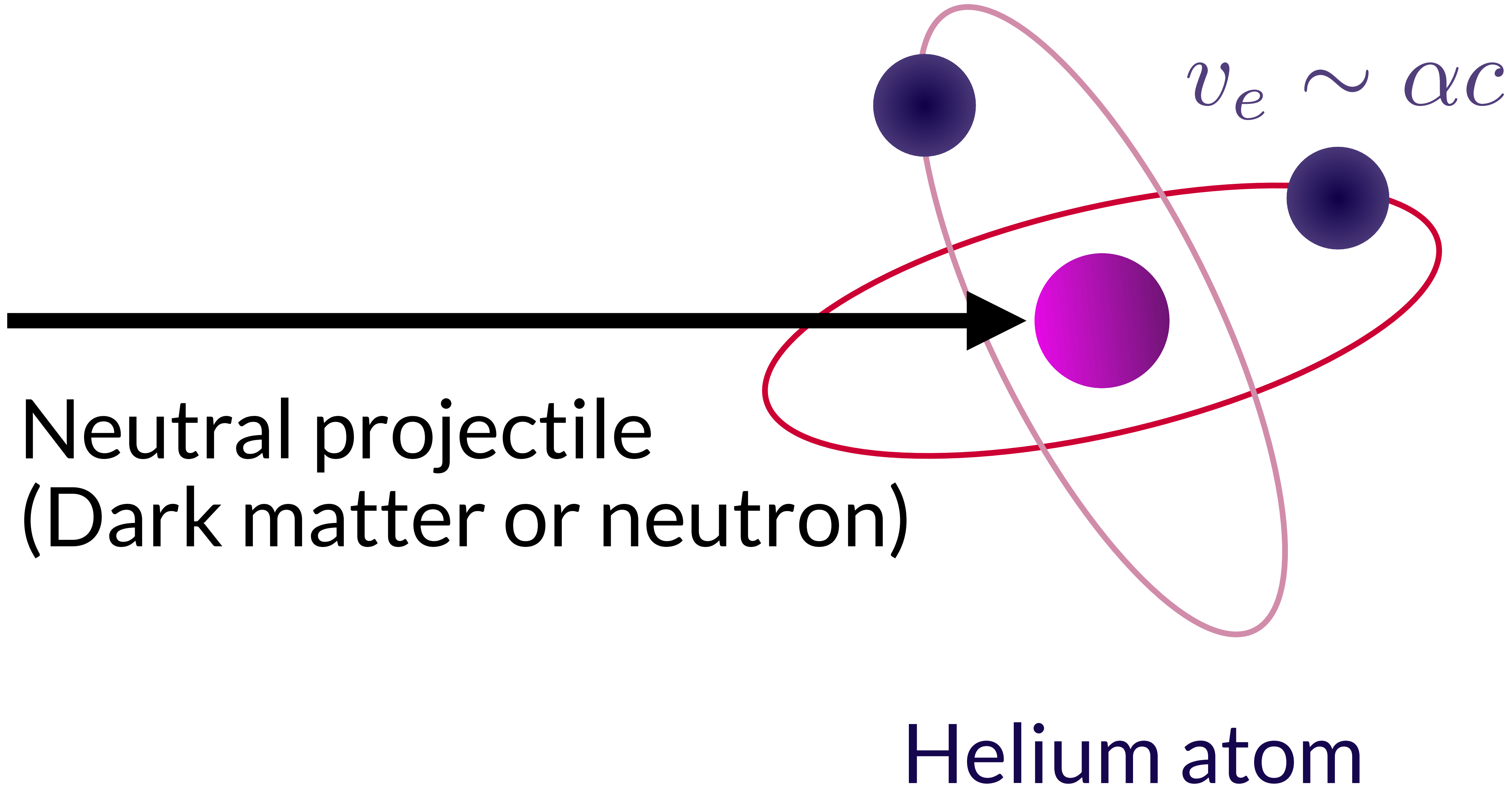
Motivation

Neutral projectile scattering on atoms



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

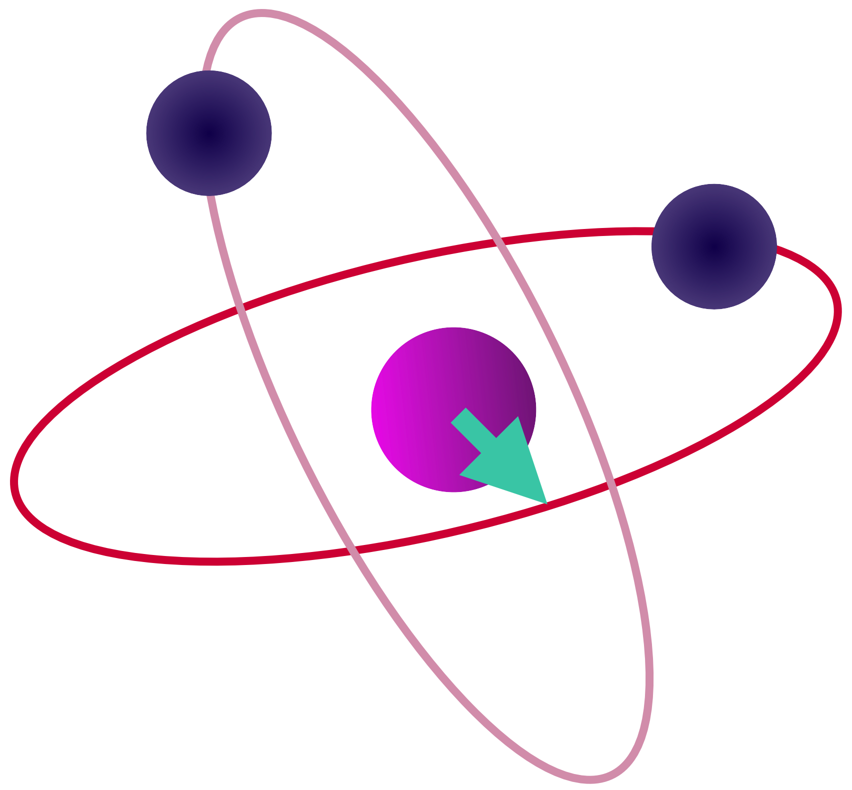
Neutral projectile scattering on atoms



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

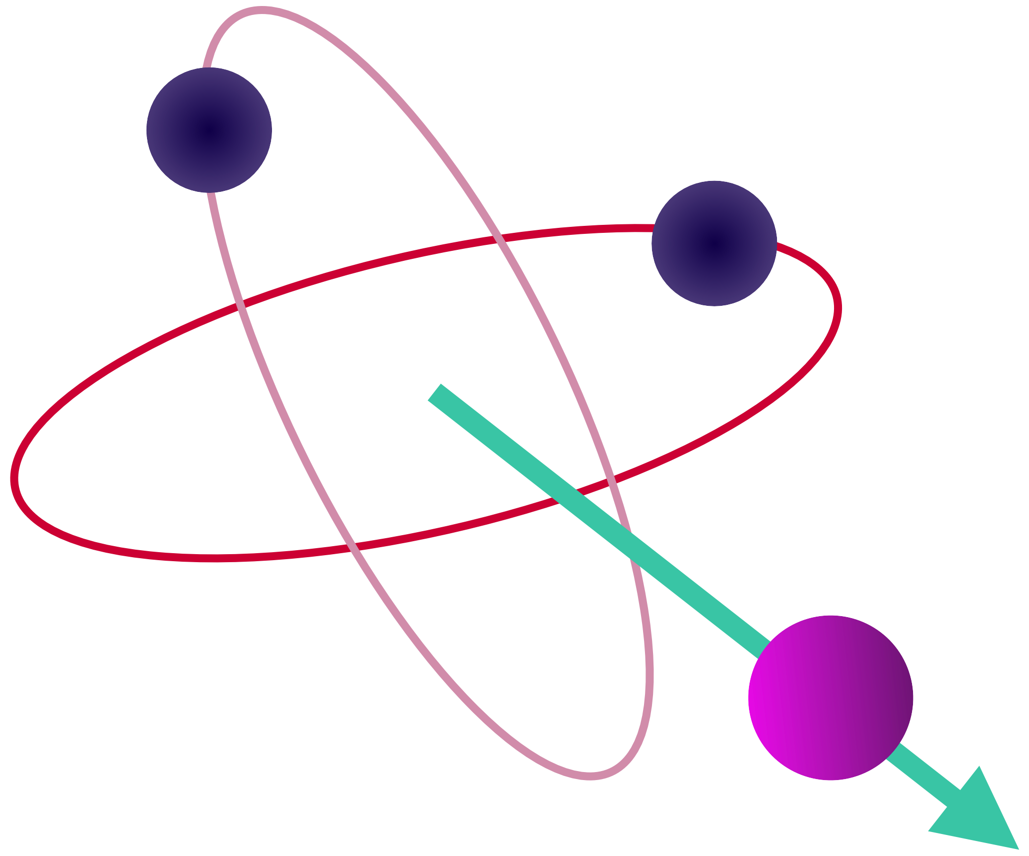
1. Low speed recoil:
   - *remain in ground state*

$v_{\mathrm{He}^{++}} \ll \alpha c$

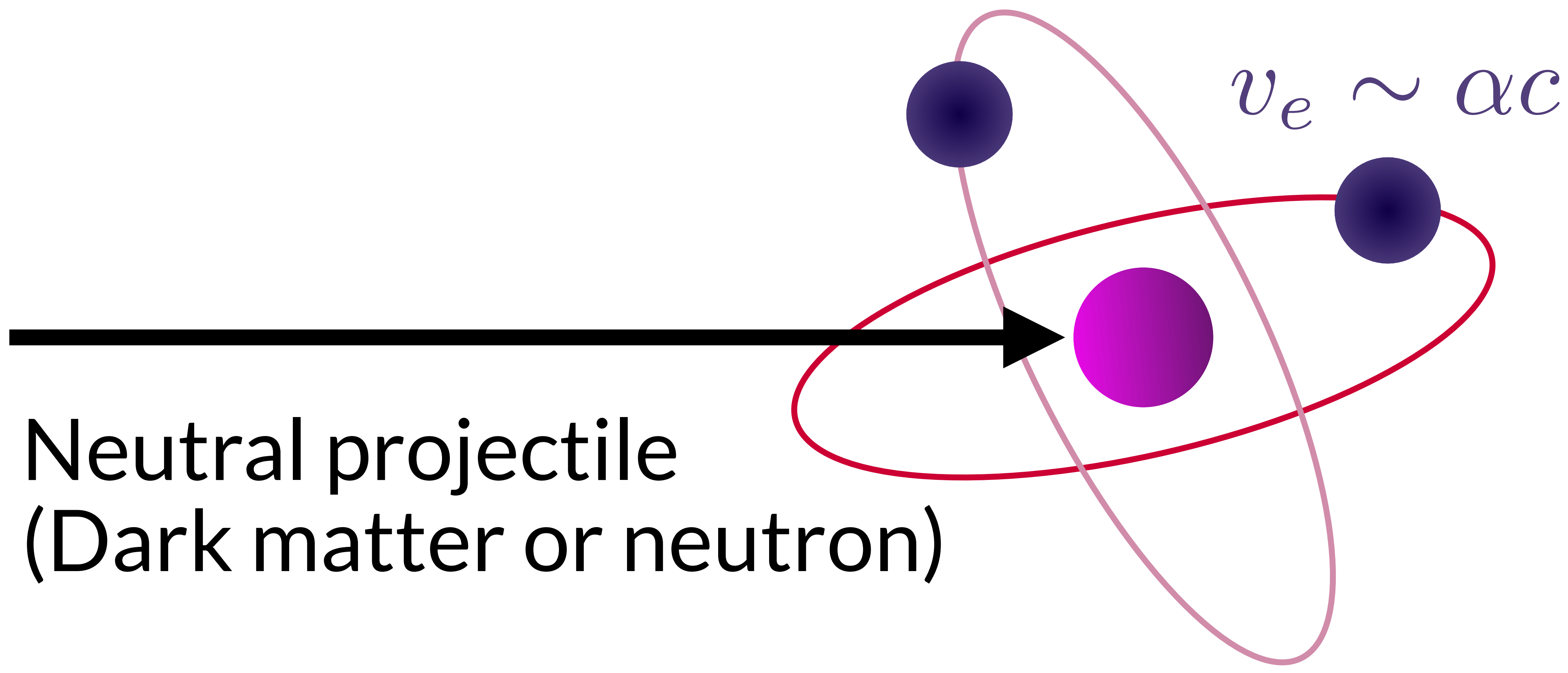


2. High speed recoil:
   - *double ionisation*
   (electrons 'left behind')

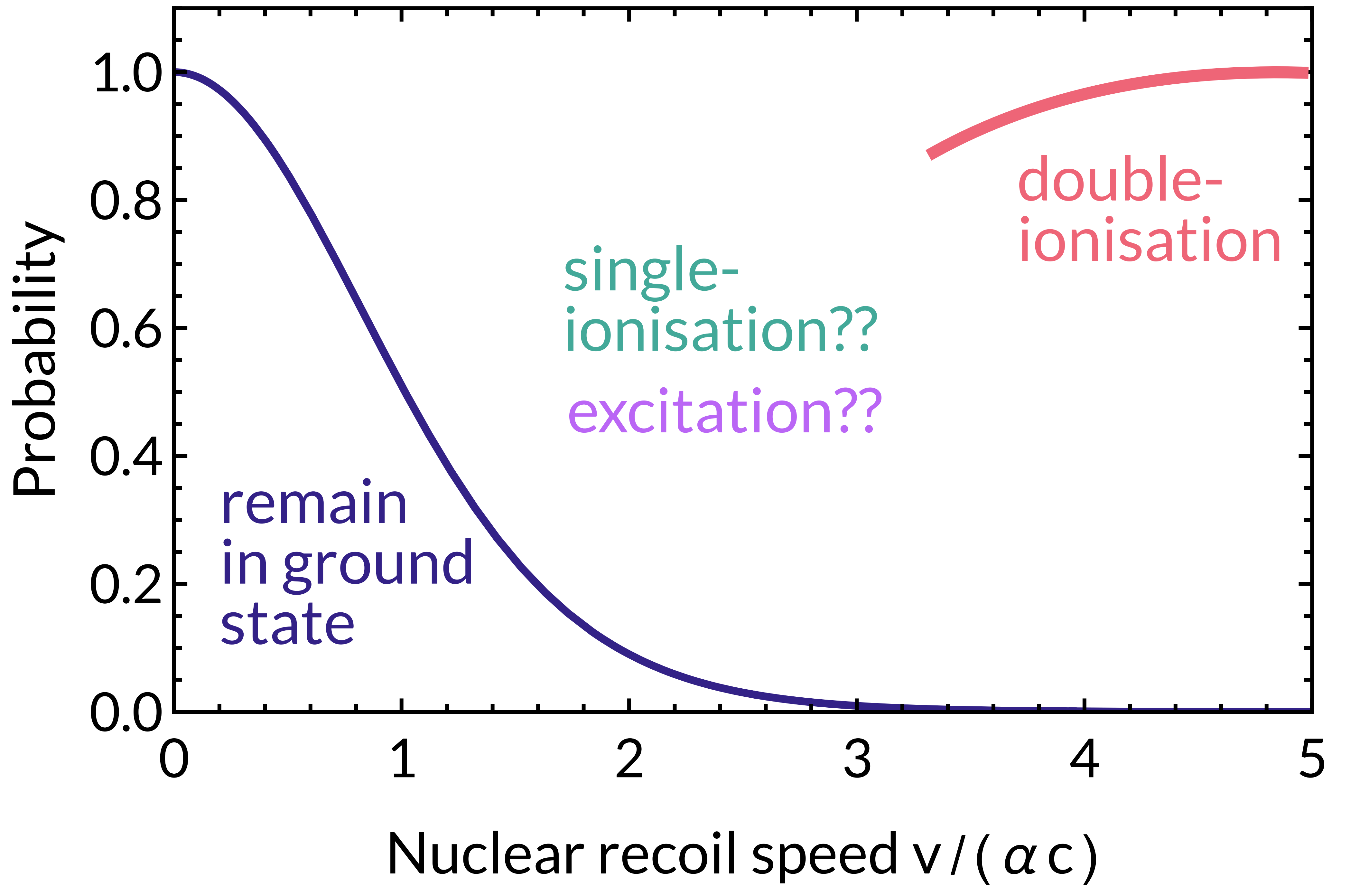
$v_{\mathrm{He}^{++}} \gg \alpha c$



Neutral projectile scattering on atoms



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



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

‘Migdal effect’

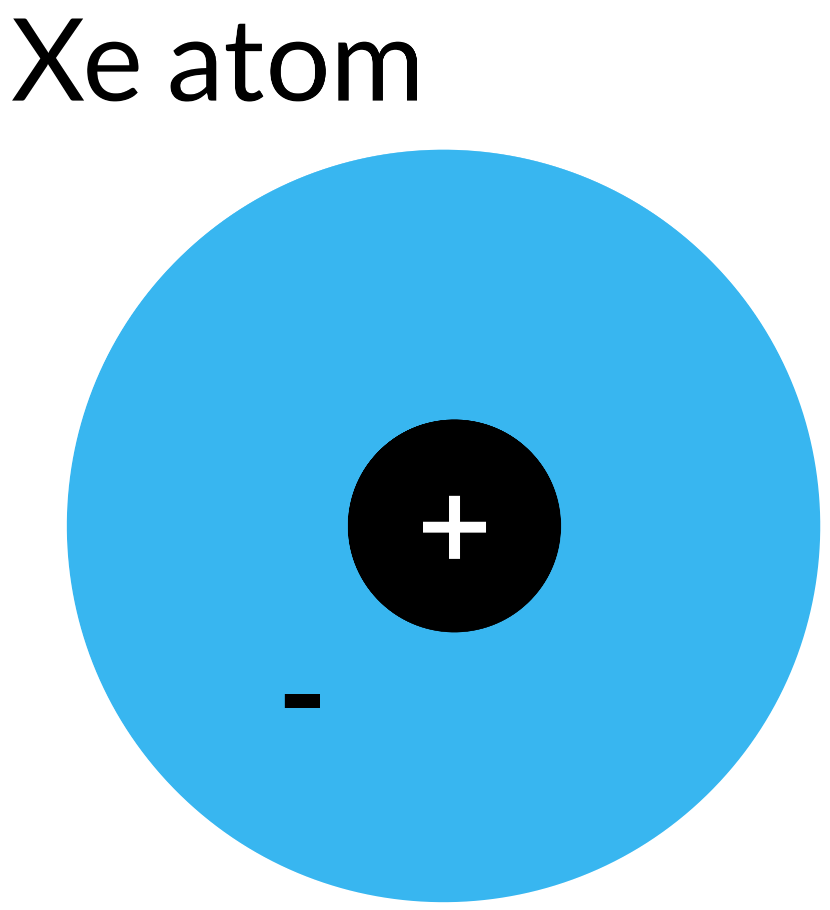
electrons and the nucleus are coupled in atoms so

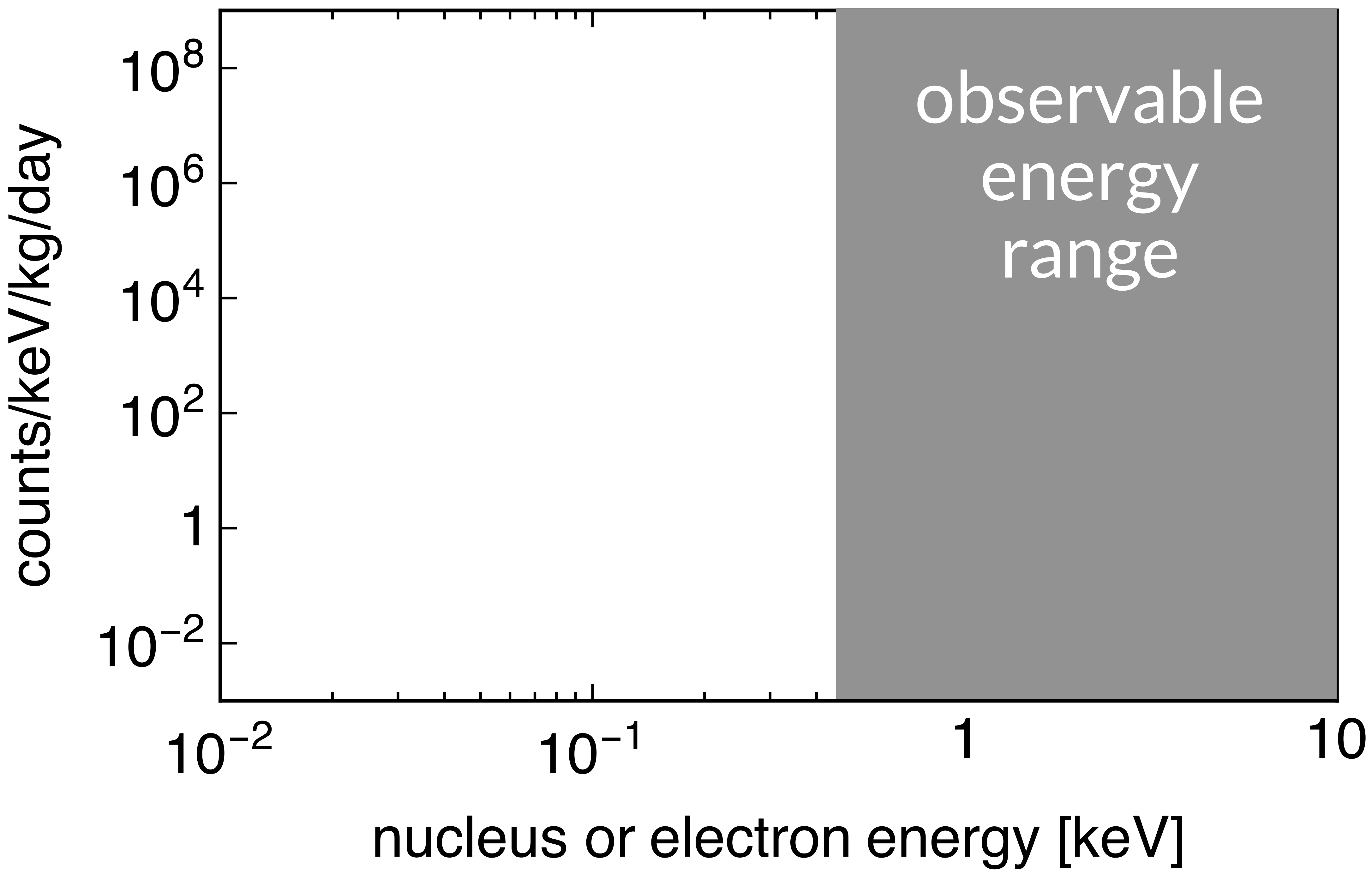
perturbations of the nucleus can induce electronic transitions

Transition probability depends on the speed of the recoiling nucleus

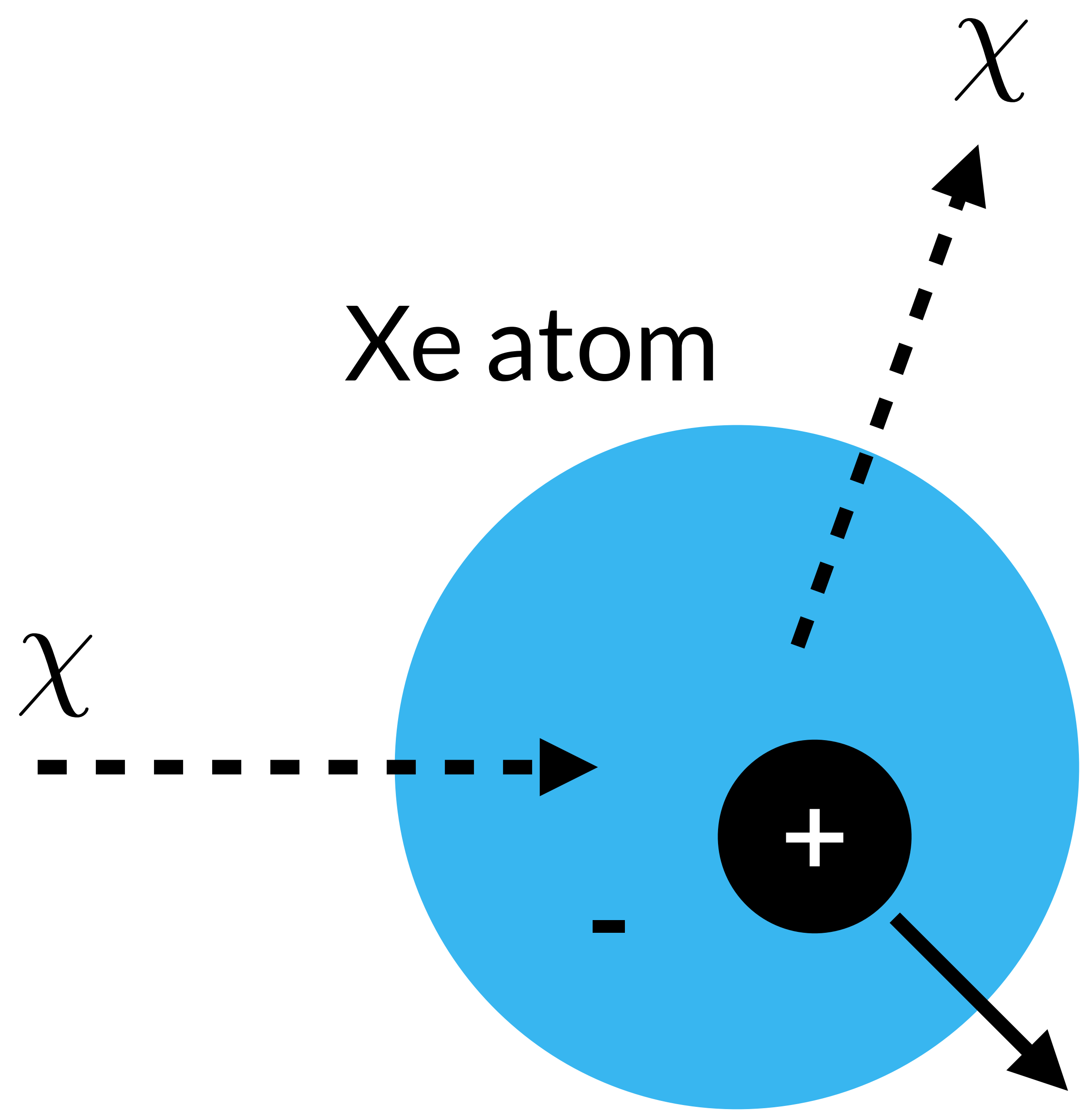
So what?

Consider DM scattering with xenon



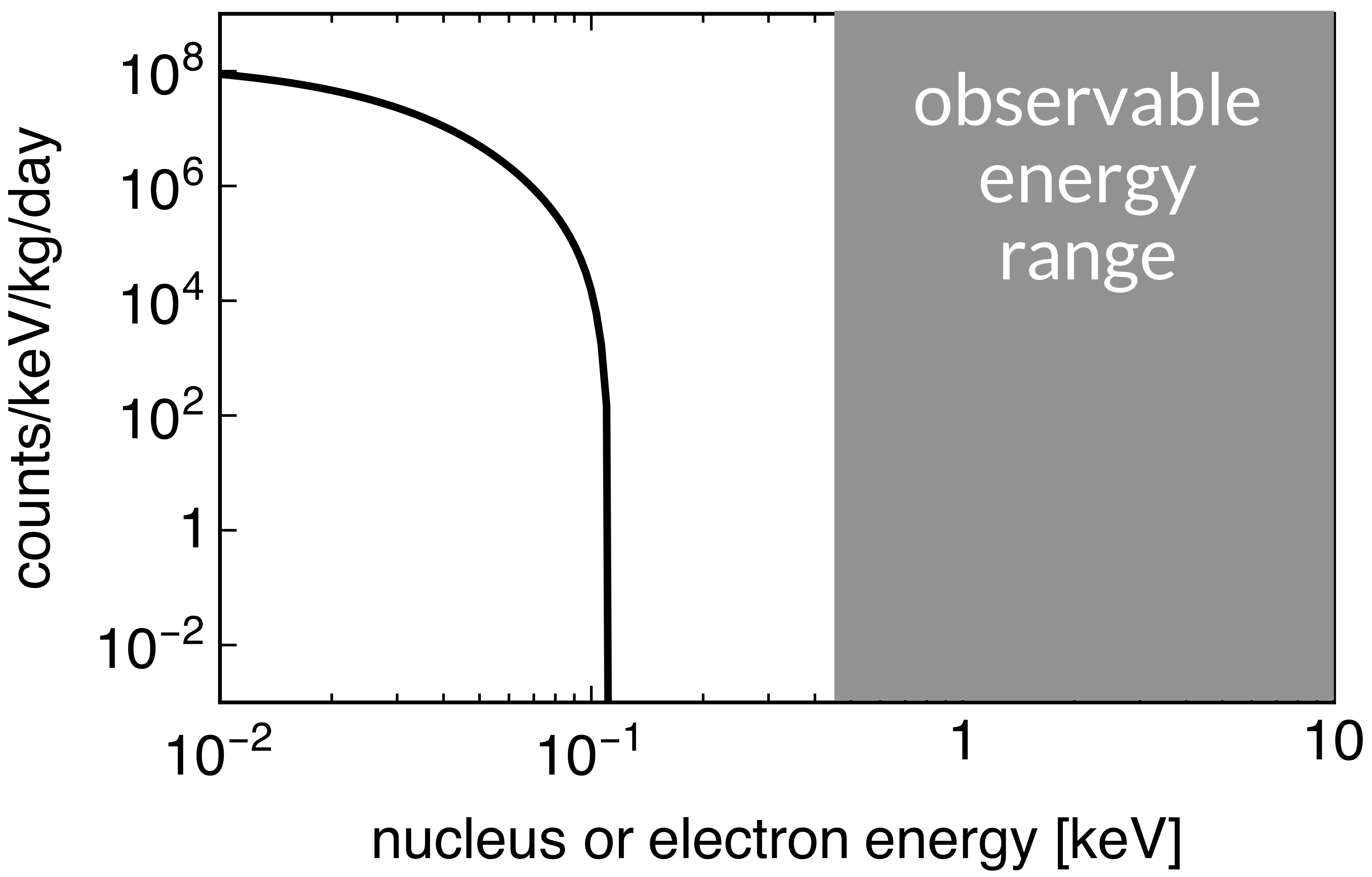


Consider DM scattering with xenon

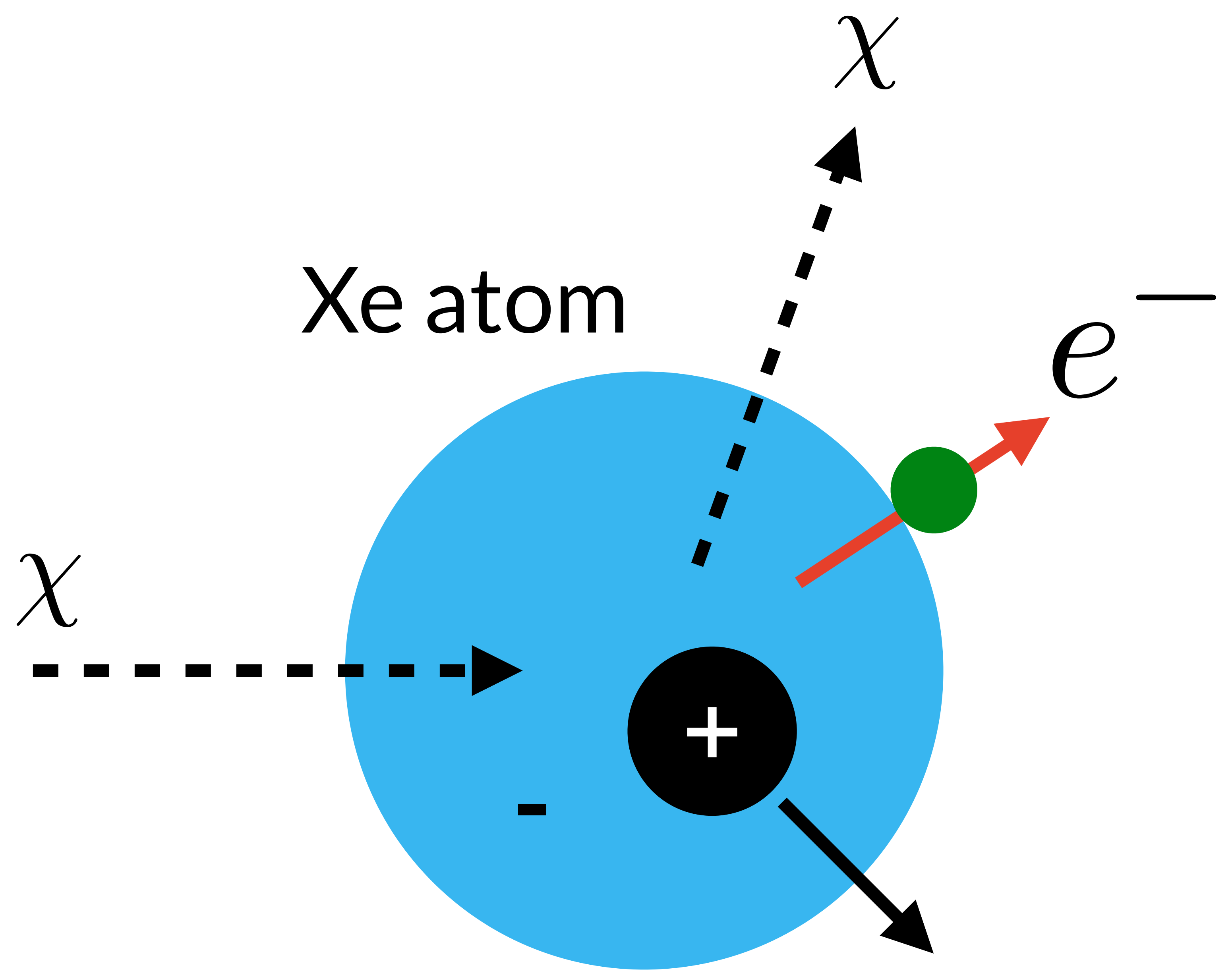


m_{DM} = 1 GeV

‘Normal’ nuclear scattering



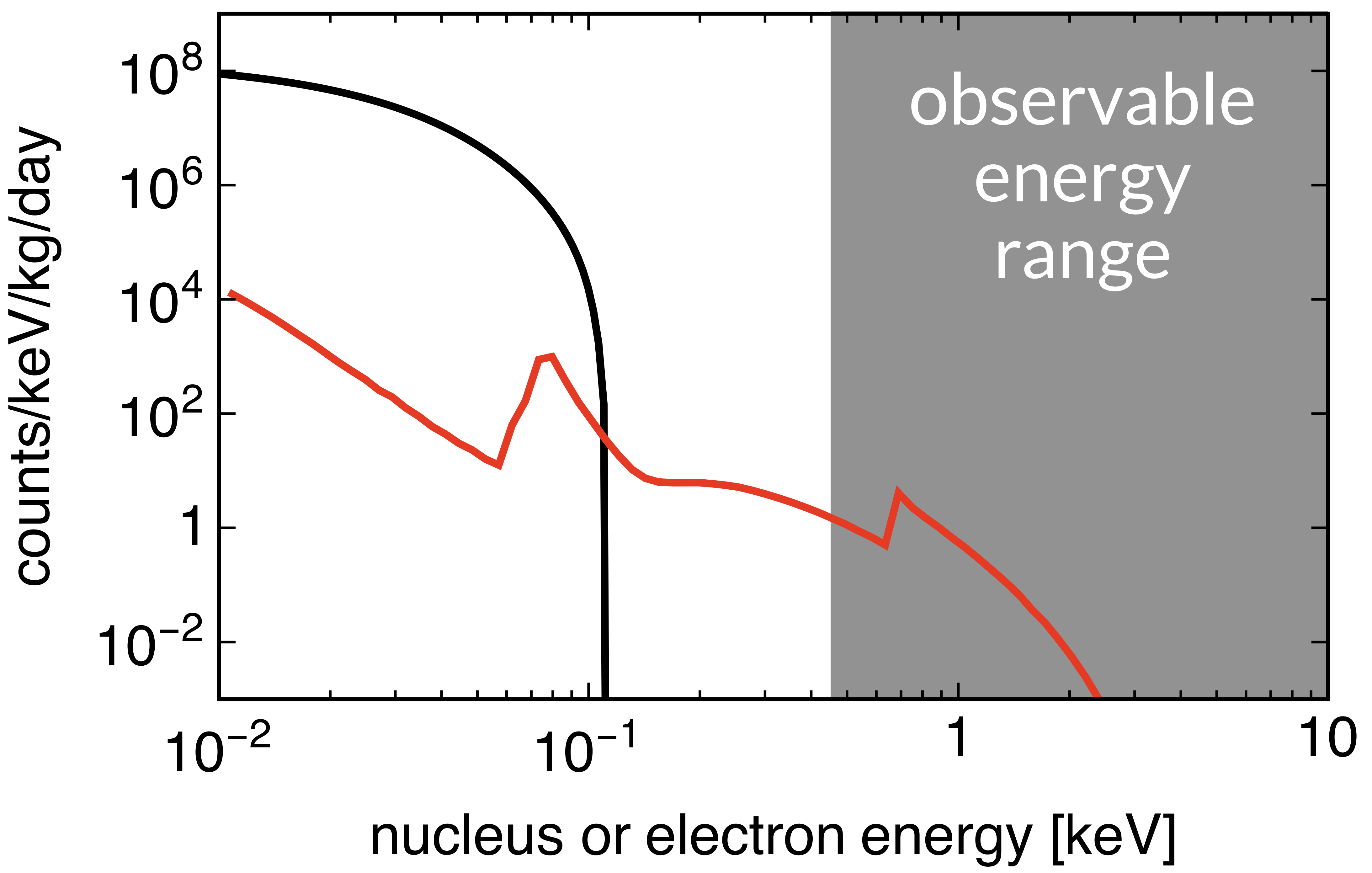
Consider DM scattering with xenon



m_{DM} = *1 GeV*

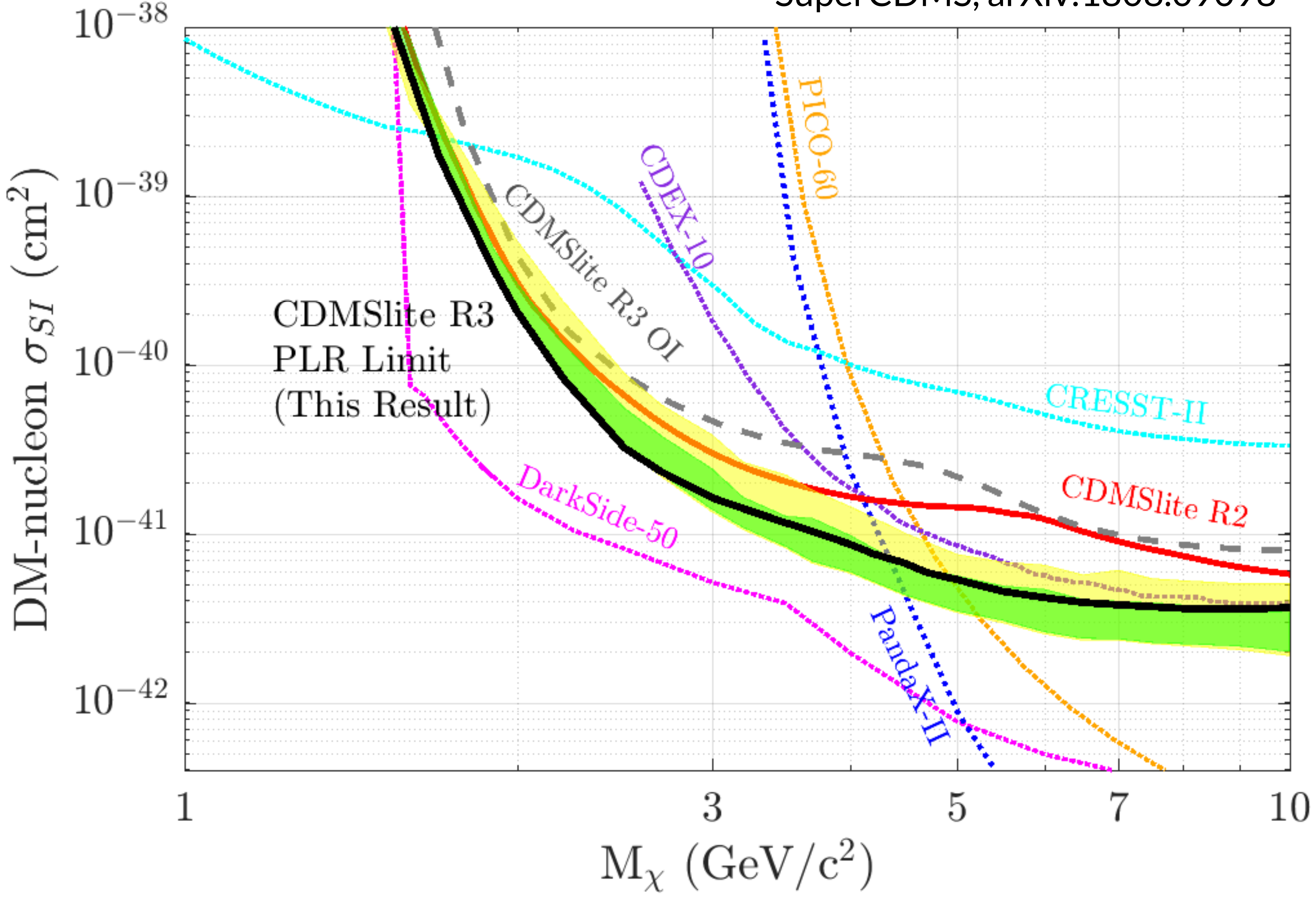
'Normal' nuclear scattering

+ Migdal effect (ionisation of 1 electron)

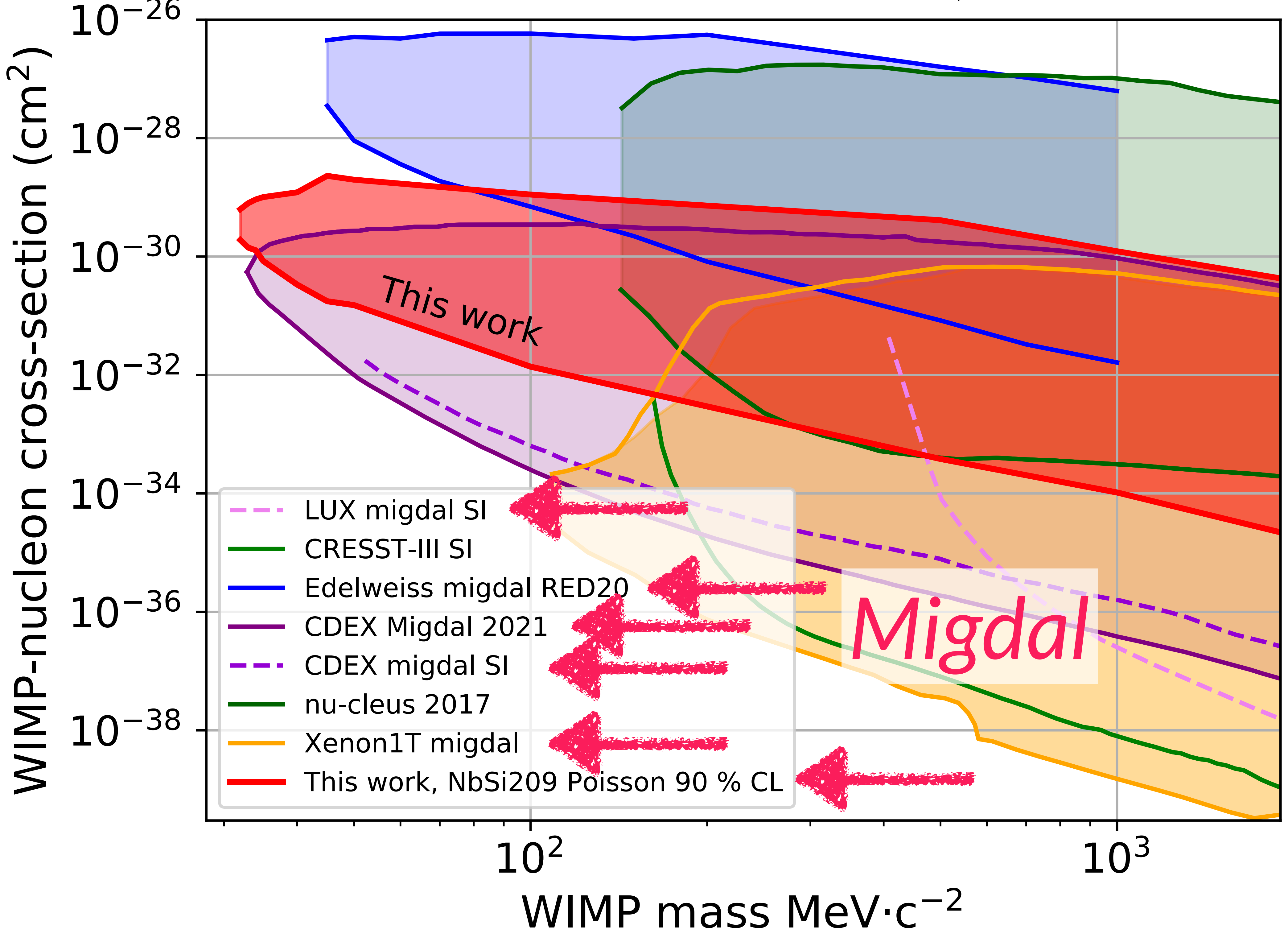


Sub-GeV searches increasingly dominated by Migdal

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

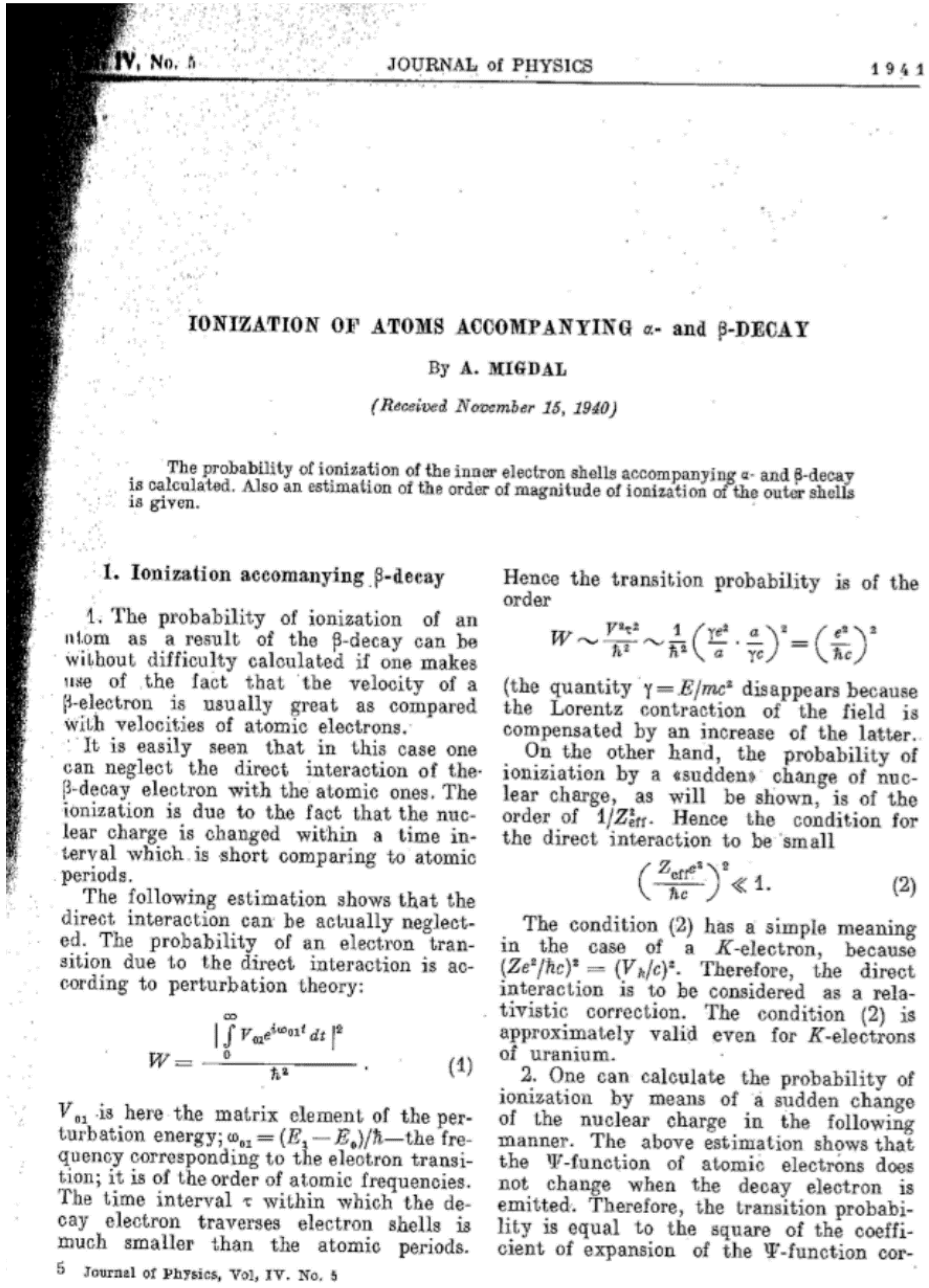
Predicted effect in:

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.

I. 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

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

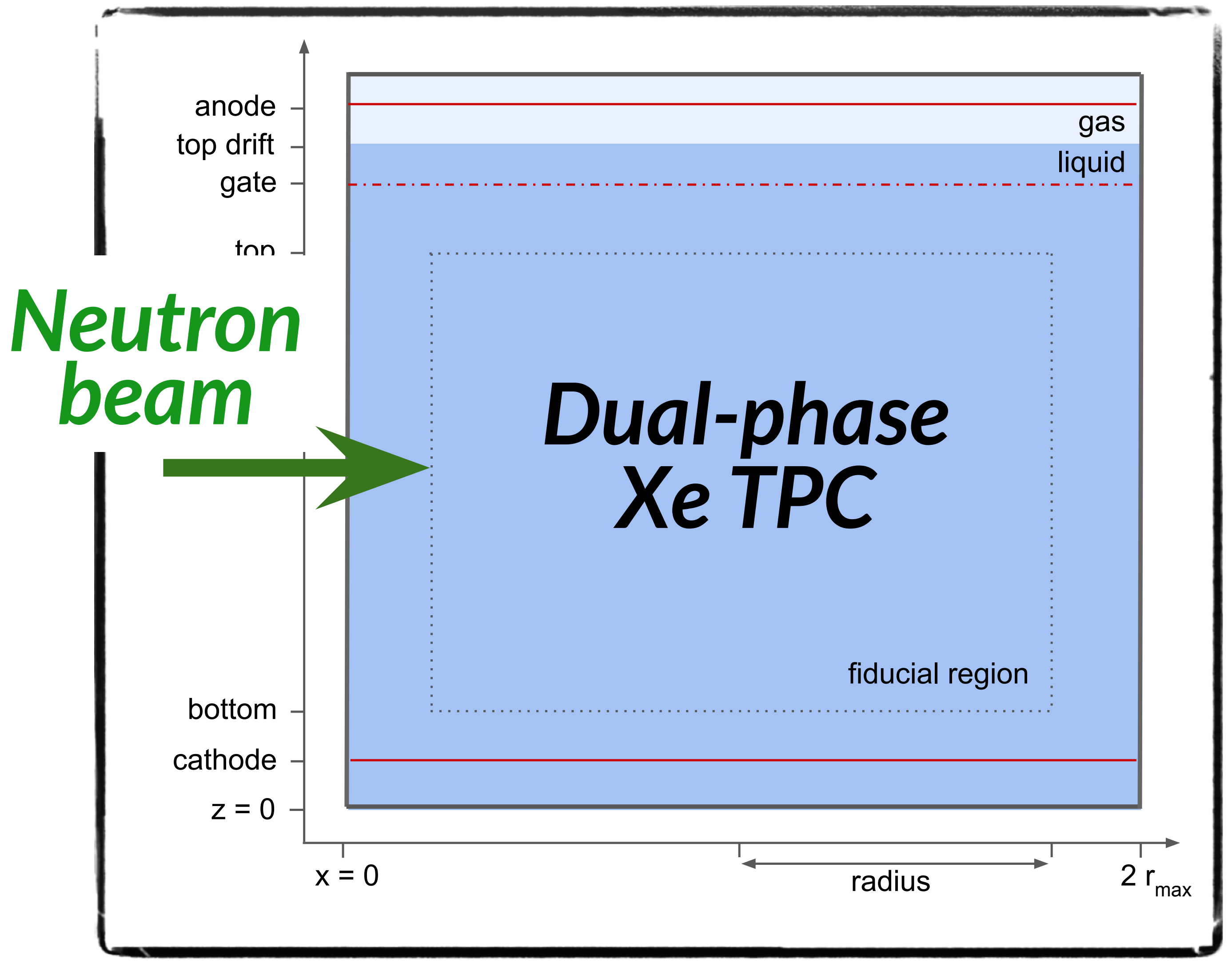
The condition (2) has a simple meaning in the case of a K-electron, because $(Ze^2/\hbar c)^2 = (V_k/c)^2$. Therefore, the direct interaction is to be considered as a relativistic correction. The condition (2) is approximately valid even for K-electrons of uranium.

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

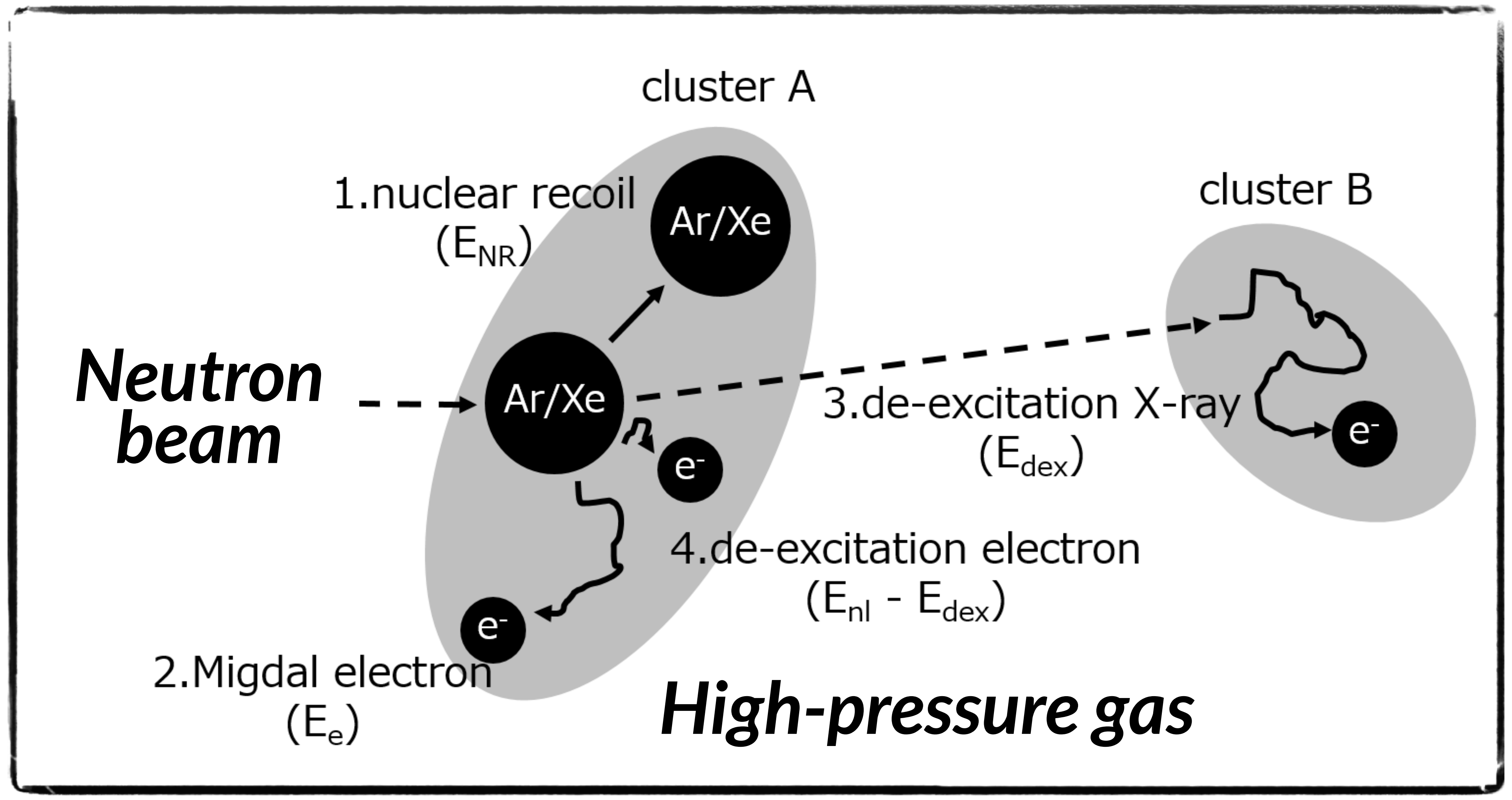
Finding evidence: Proposals with neutrons

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



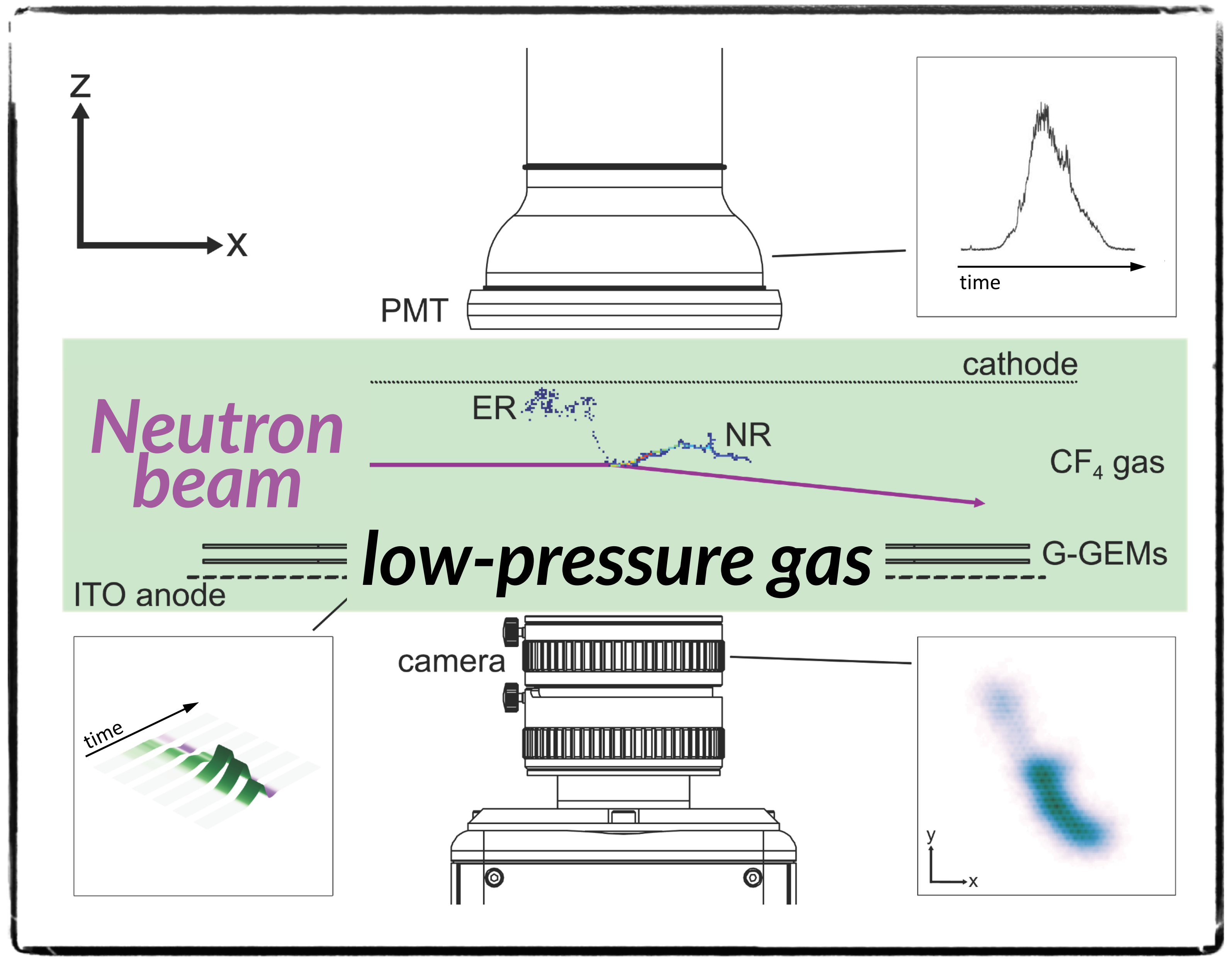
$E_{\mathrm{neutron}} \sim 15 - 15000~\mathrm{keV}$

Nakamura et al, arXiv:2009.05939



$E_{\mathrm{neutron}} \sim 500~\mathrm{keV}$

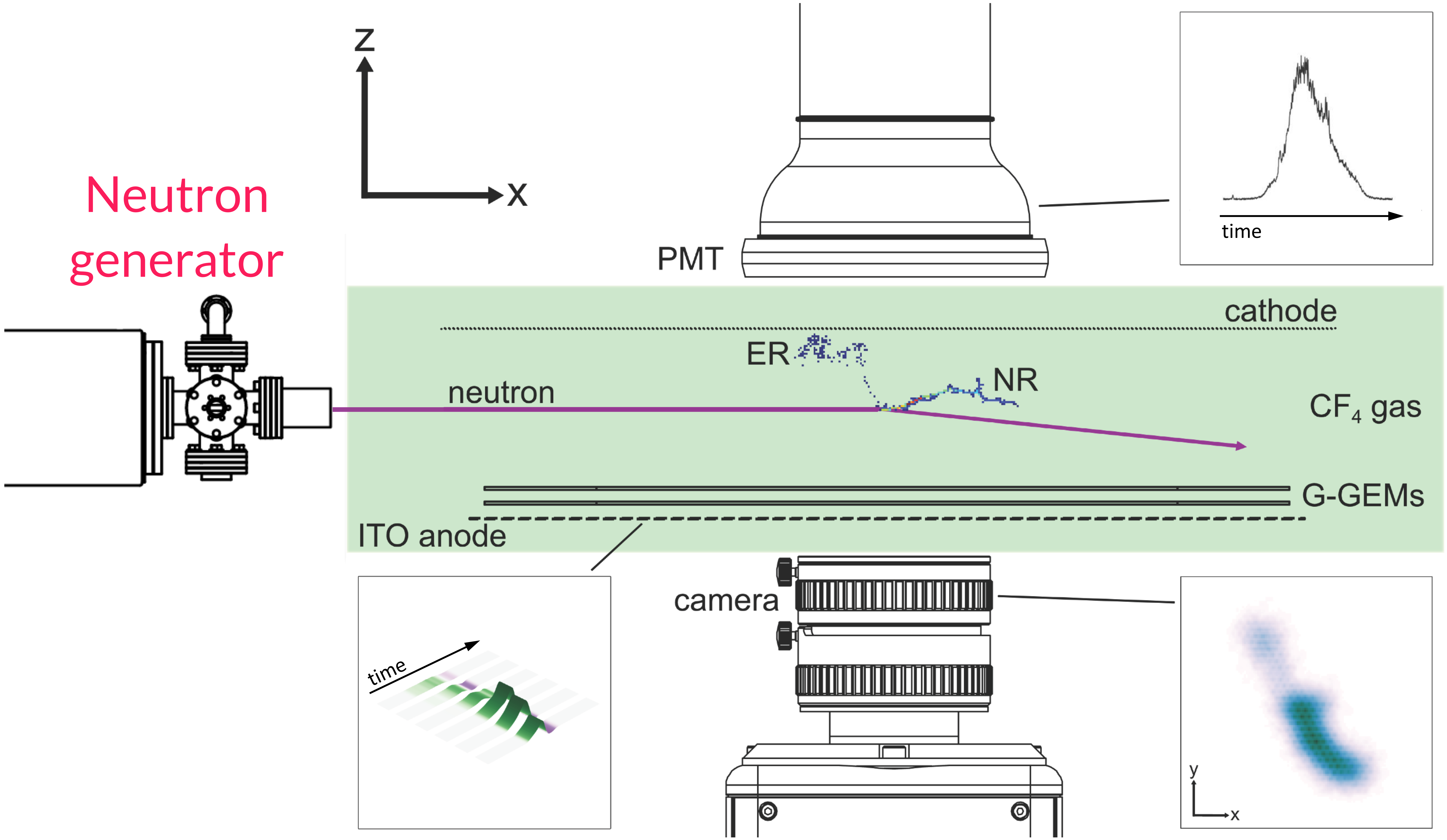
Araújo et al (MIGDAL), arXiv:2207.08284



$E_{\mathrm{neutron}} \sim 2500 - 15000~\mathrm{keV}$

In the UK: MIGDAL experiment

Neutron generator



MIGDAL

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

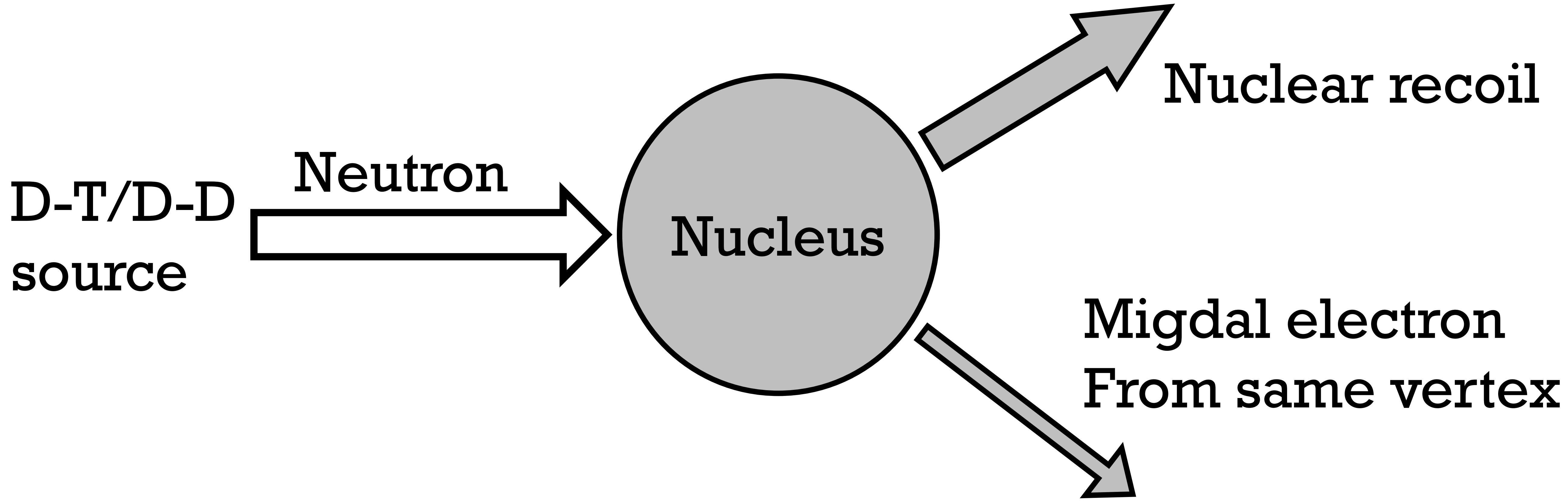
Neutron collisions give recoils with energy:

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

[higher than dark matter regime]

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 CF_4 in high energy recoils
- Phase 2: Observe the Migdal effect in CF_4 + noble gases

Schematic: Optical Time Projection Chamber

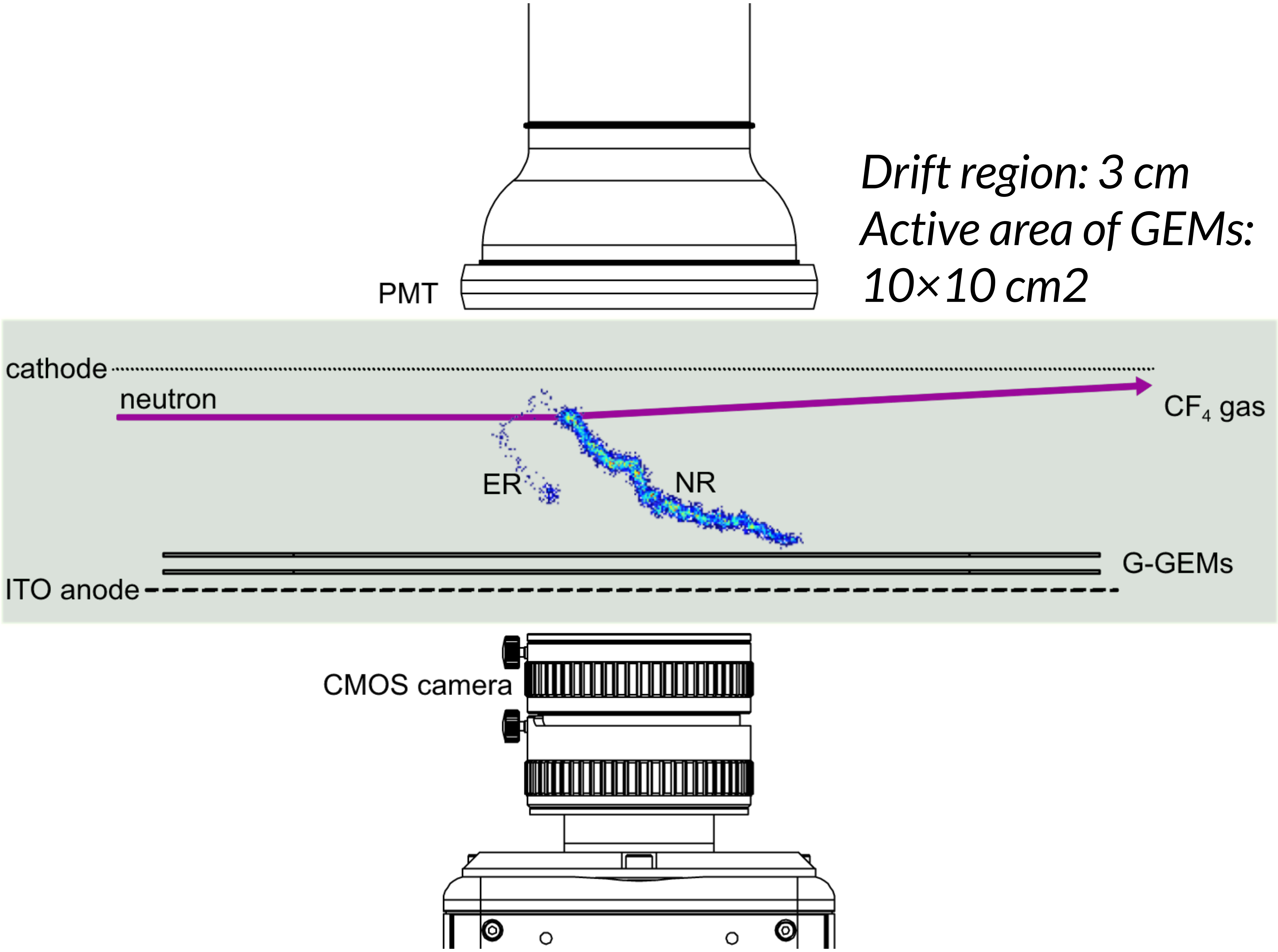
Camera: images GEM scintillation through viewport behind ITO anode. Readout of (x,y) plane

ITO anode: collects charge. Readout of (x,z) plane

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

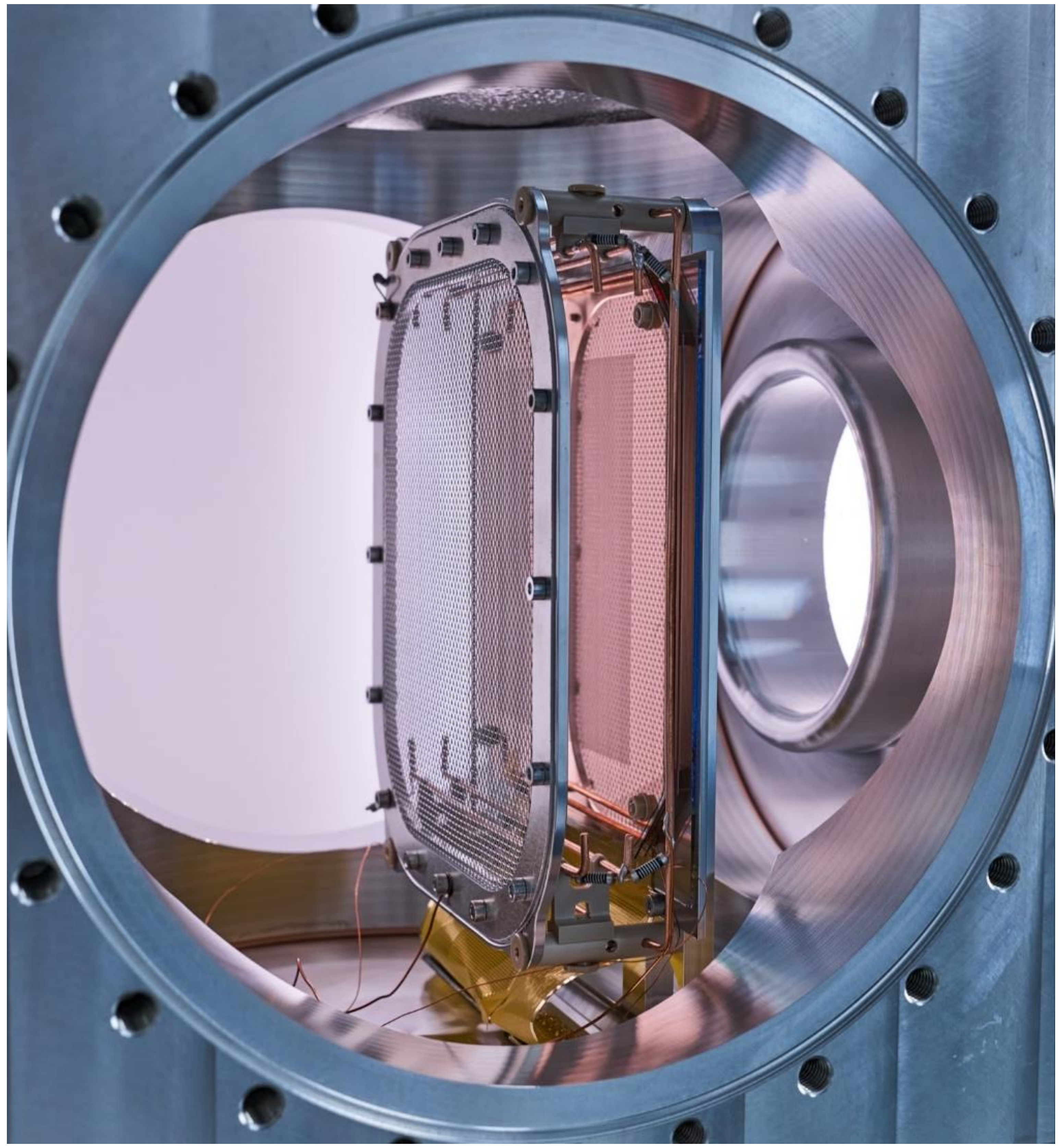
Setup allows for 3D track reconstruction

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.

Pictures: Optical Time Projection Chamber



Cathode

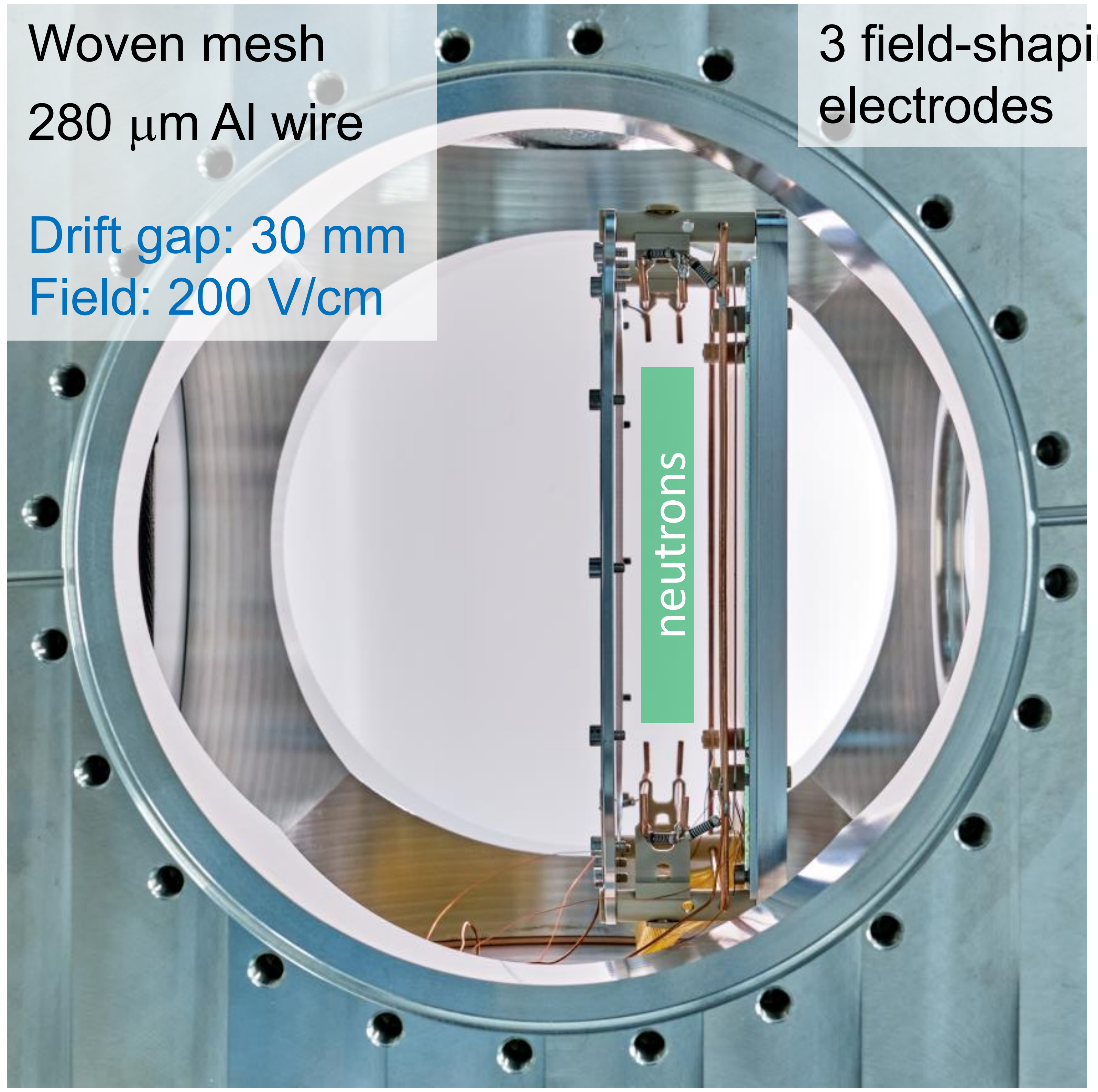
Woven mesh

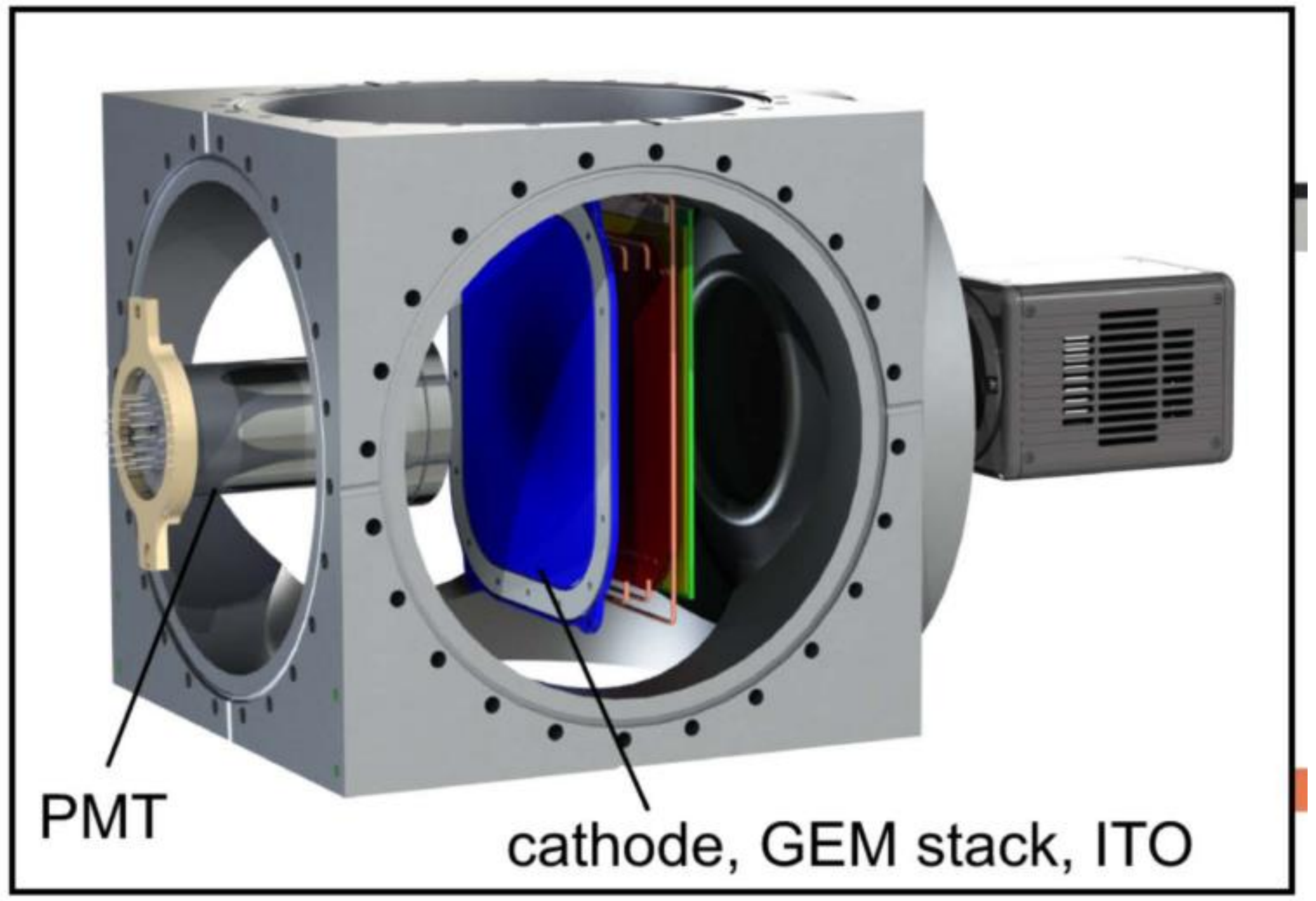
280 μm Al wire

Drift gap: 30 mm
Field: 200 V/cm

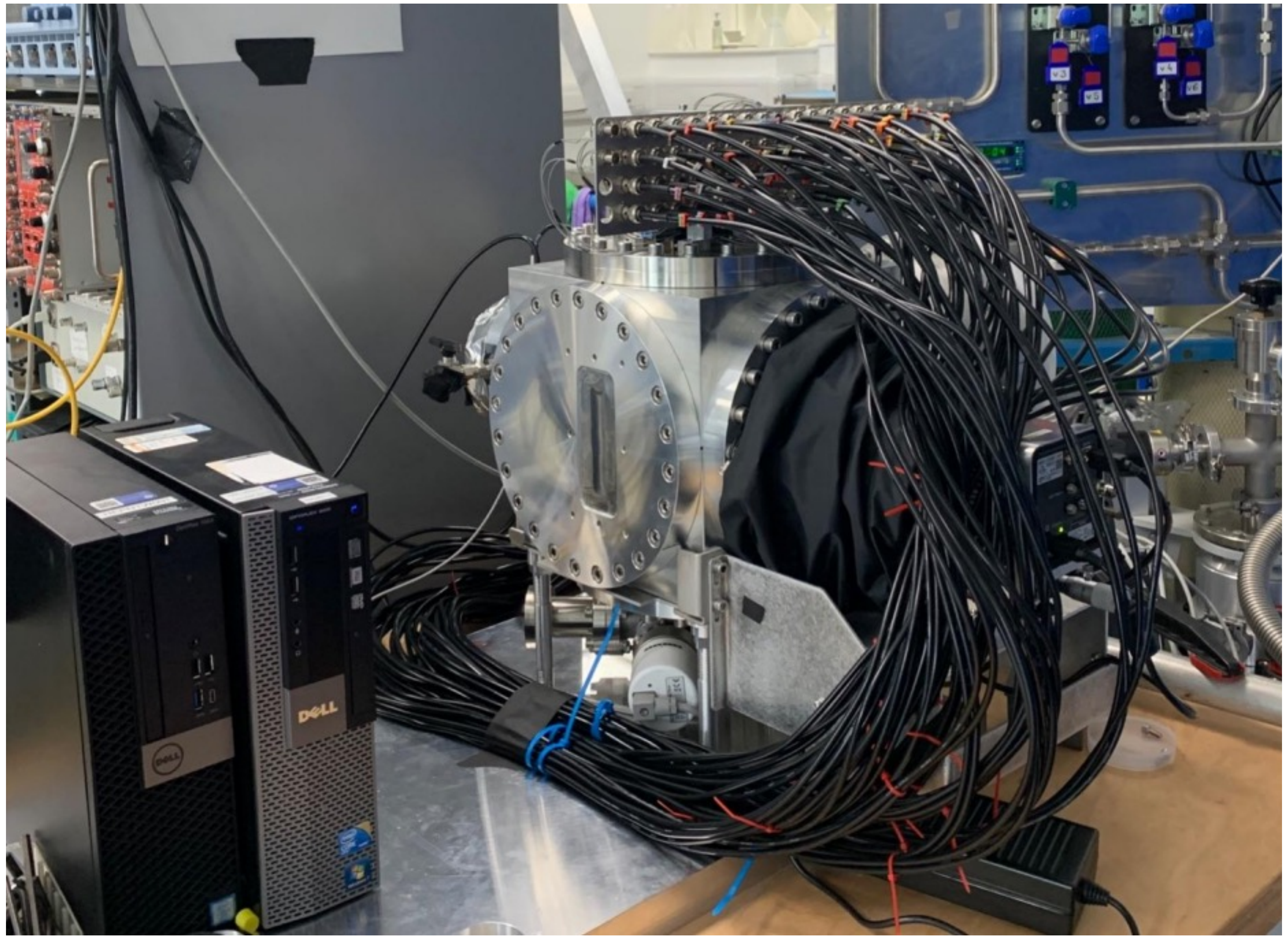
Fieldcage

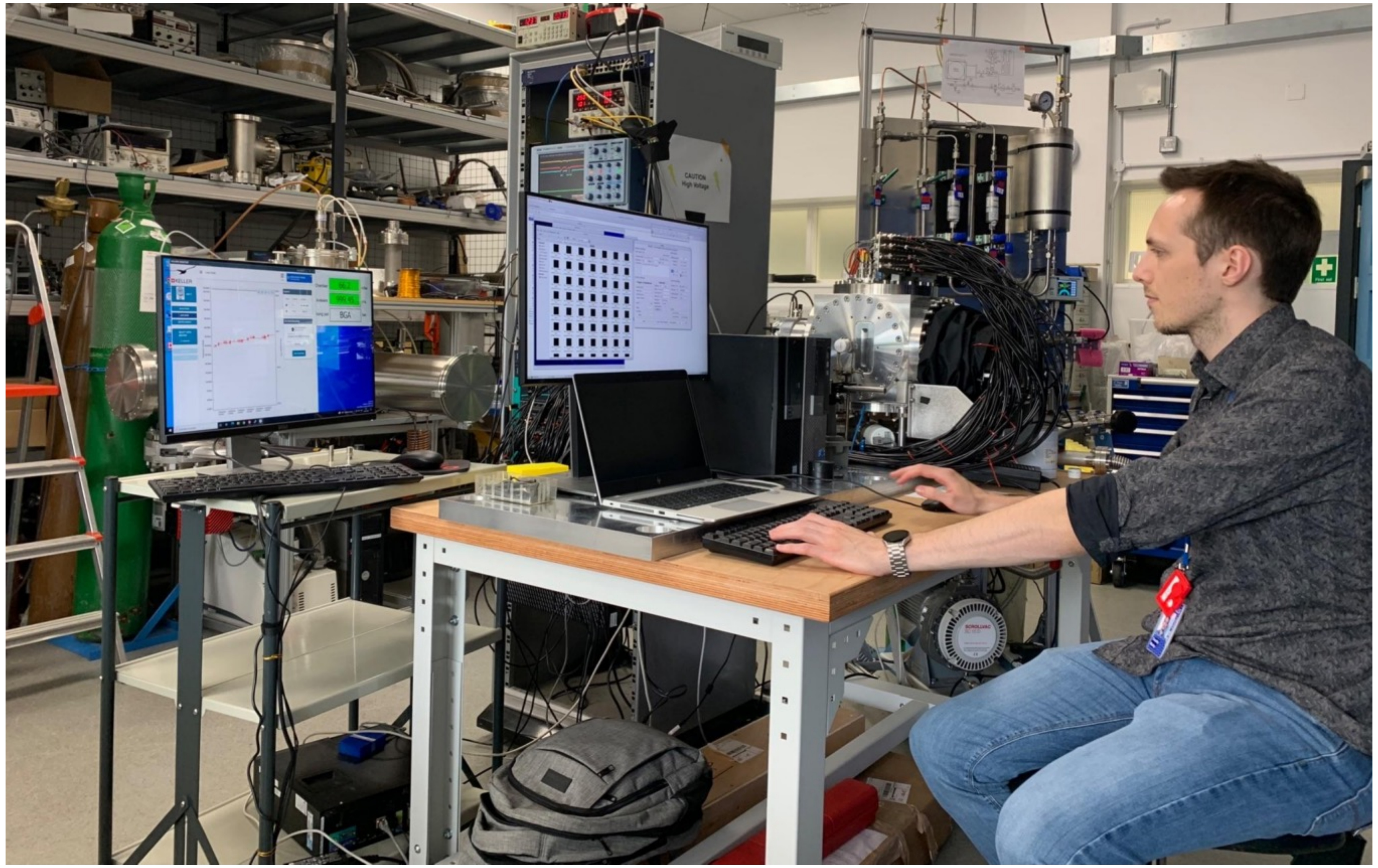
3 field-shaping electrodes





Pictures: Optical Time Projection Chamber



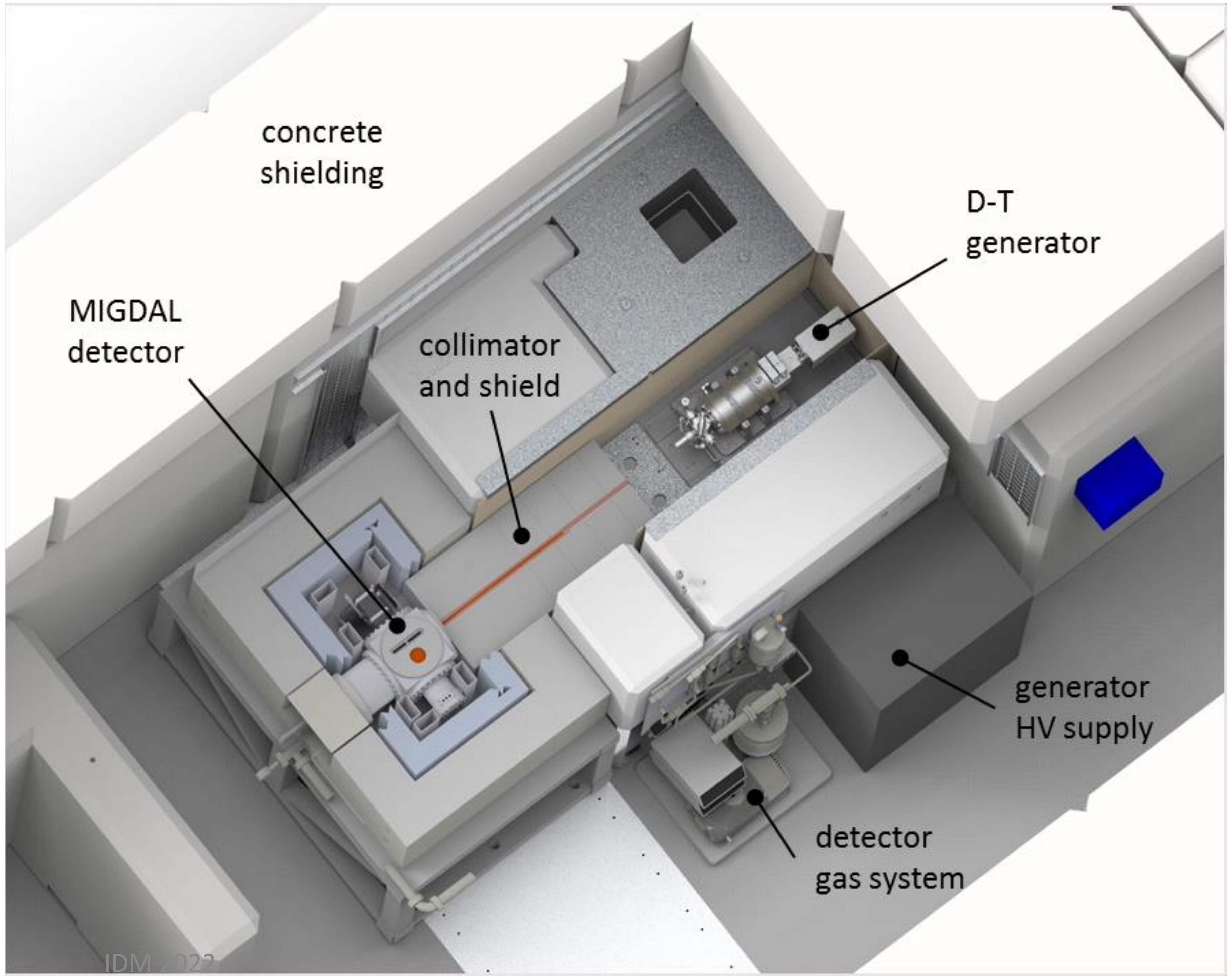


We also need some neutrons…

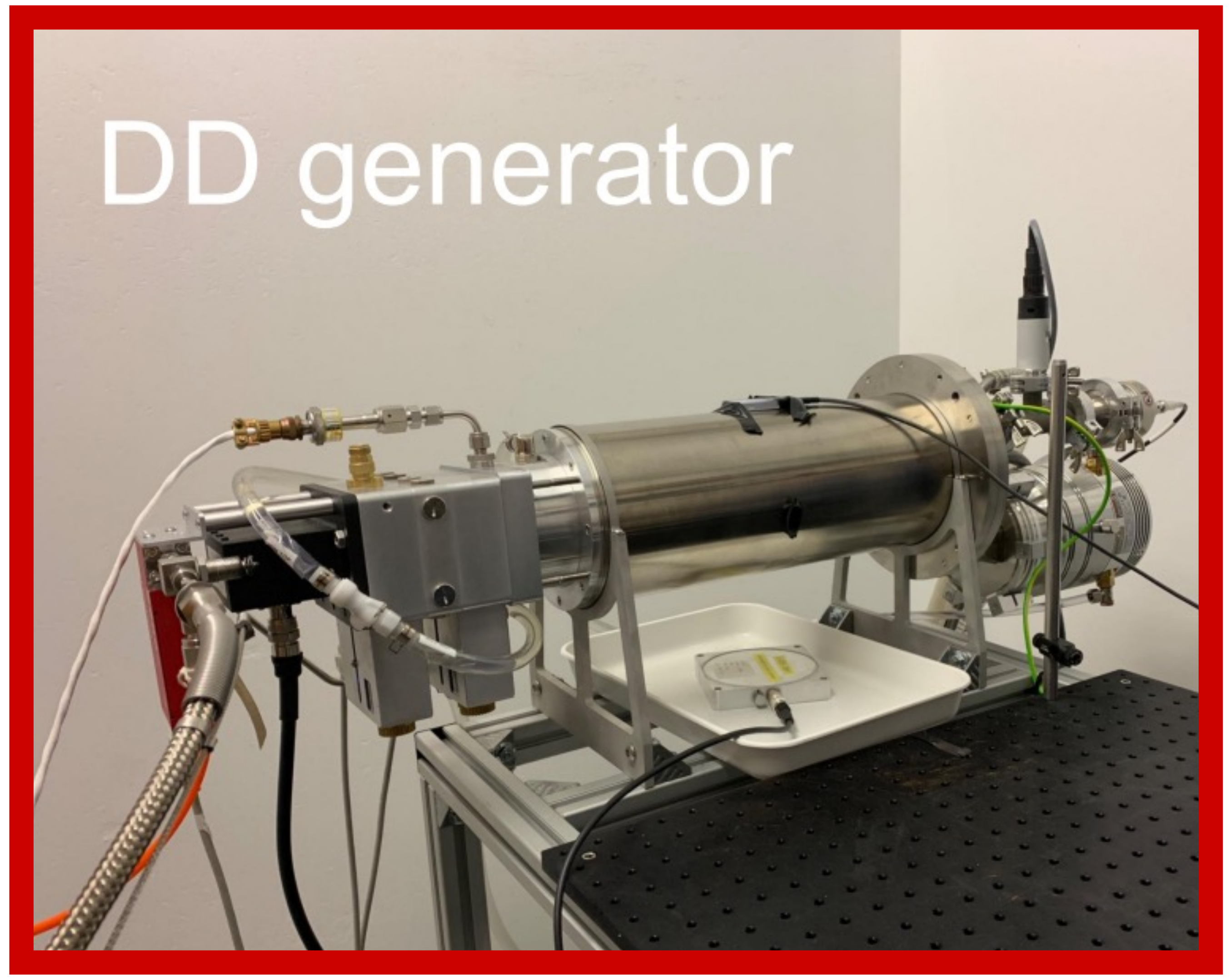
We operate at the NILE Facility at the Rutherford Appleton Laboratory, UK

D-D and D-T fusion generators installed in “shielding bunker”

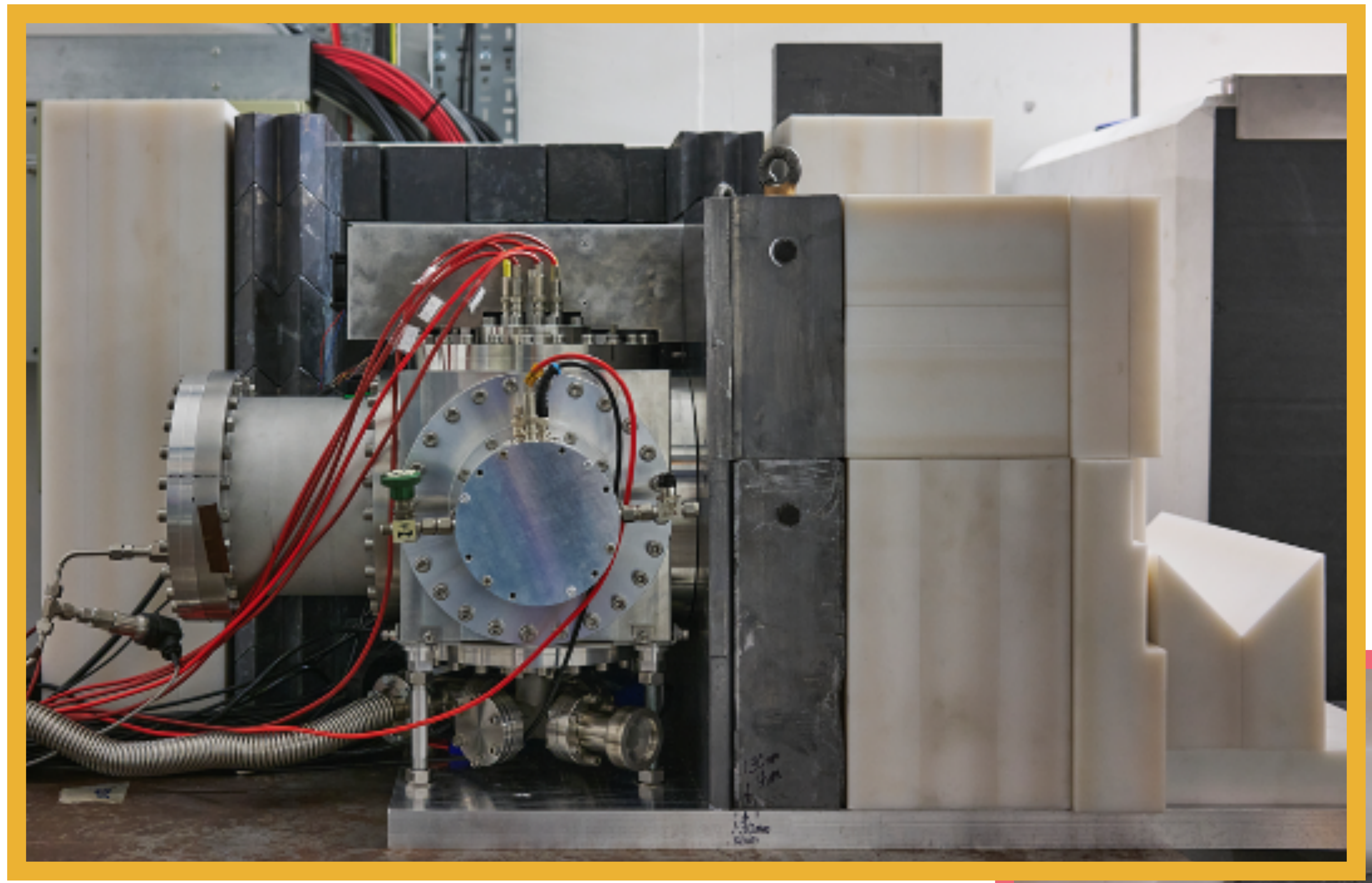
High-yield neutron generators
- D-D: 2.47 MeV (10^9 n/s)
- D-T: 14.7 MeV (10^{10} n/s)

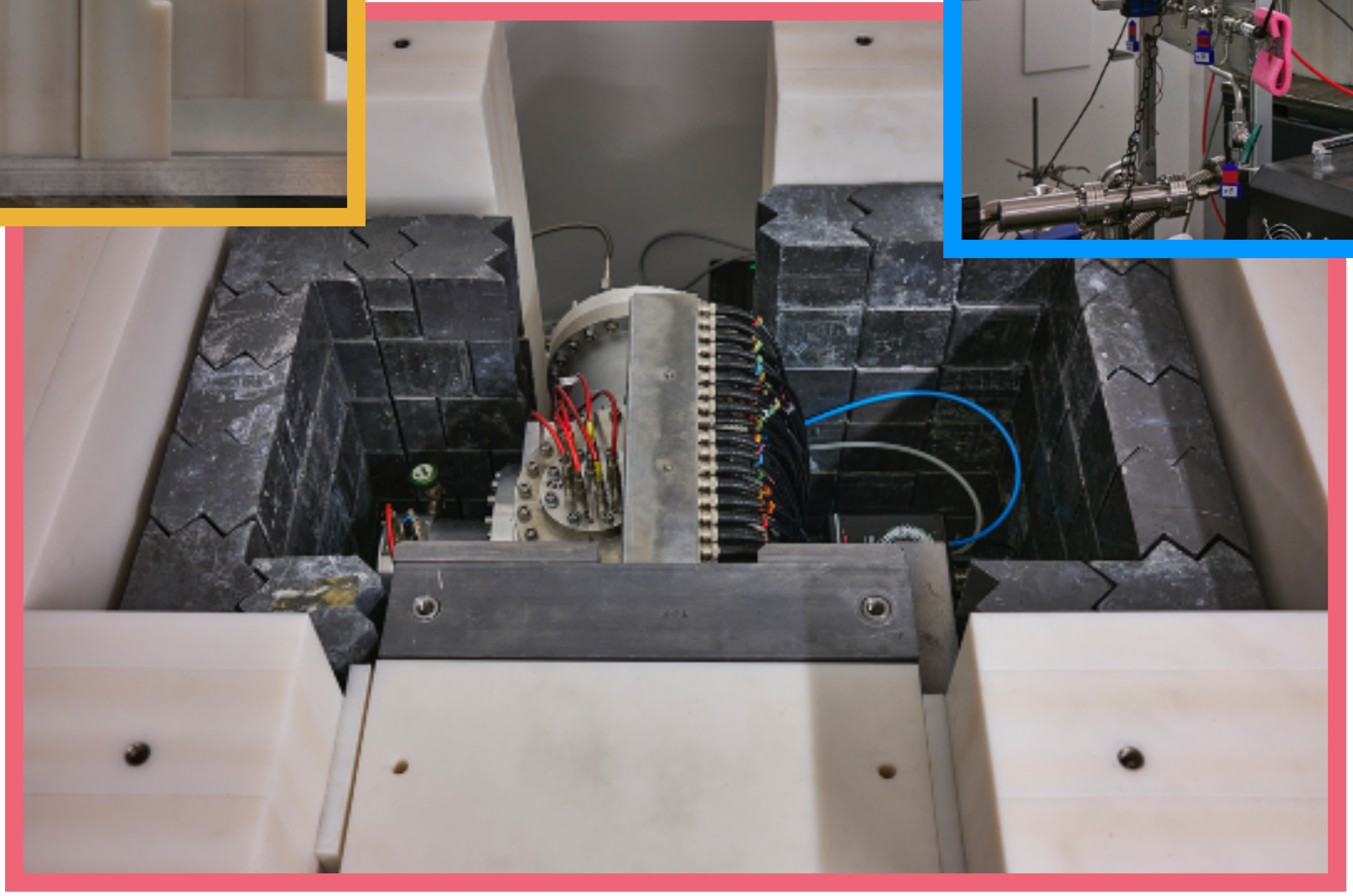


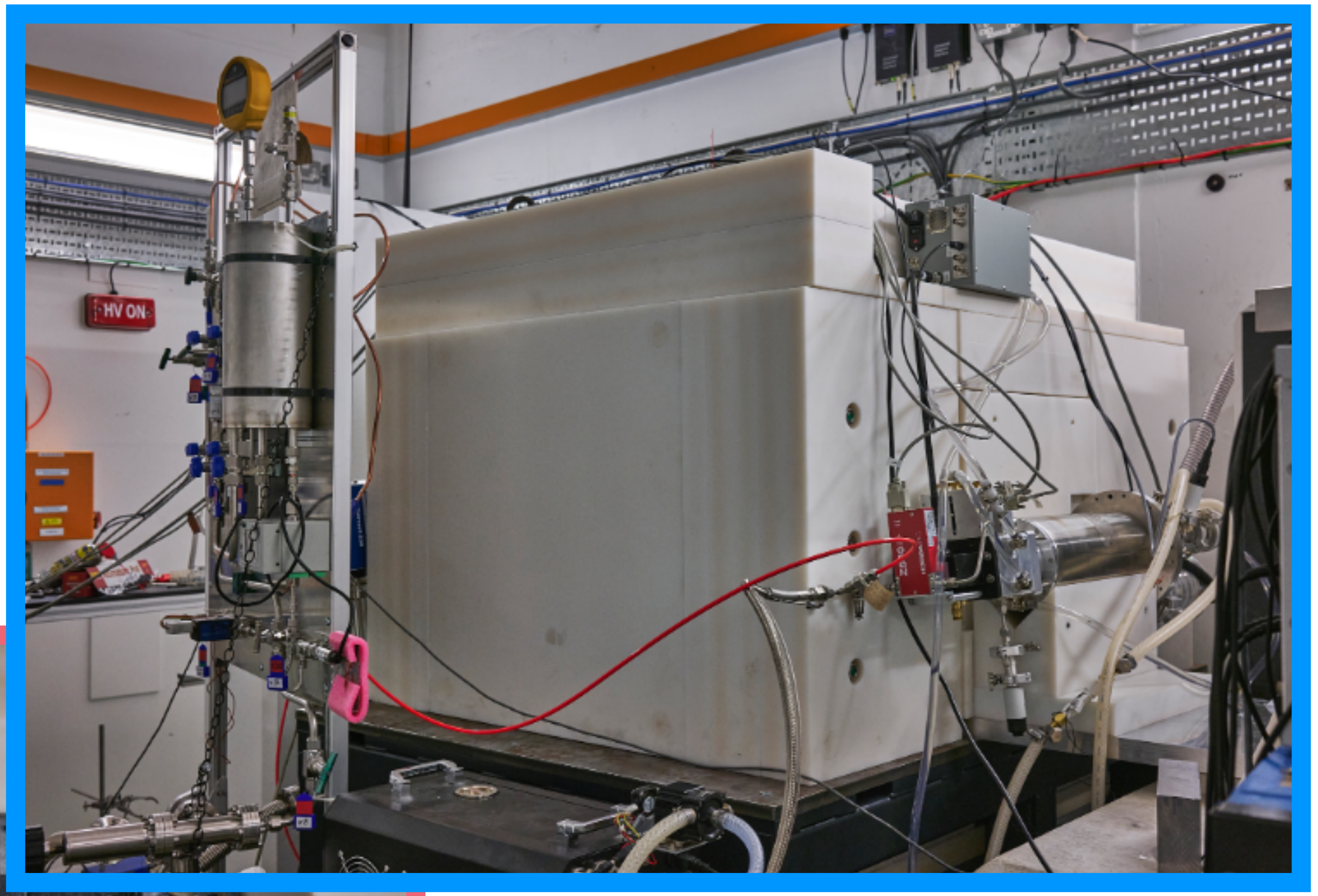
Photos of the construction phase



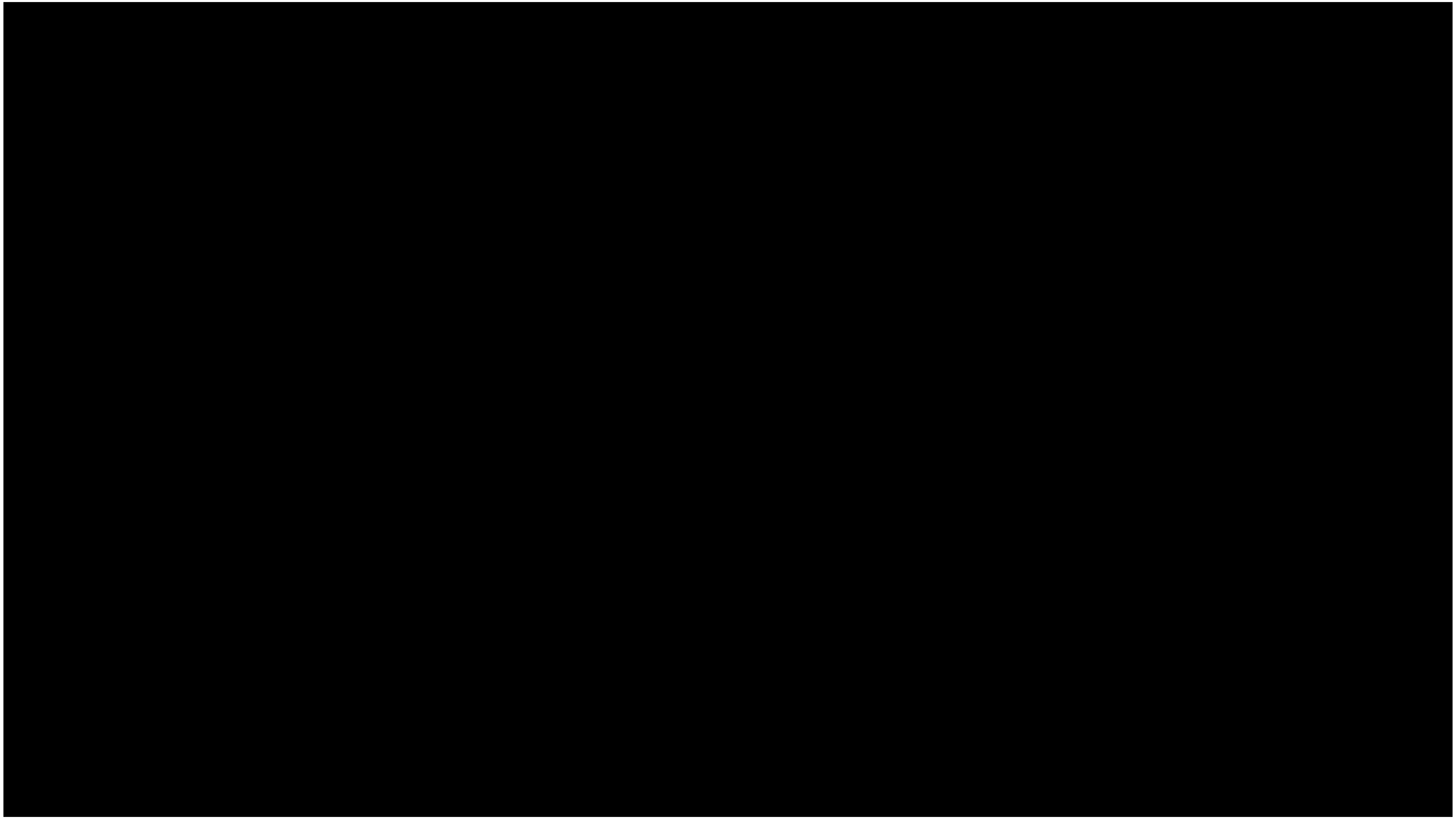
Installation in the NILE bunker



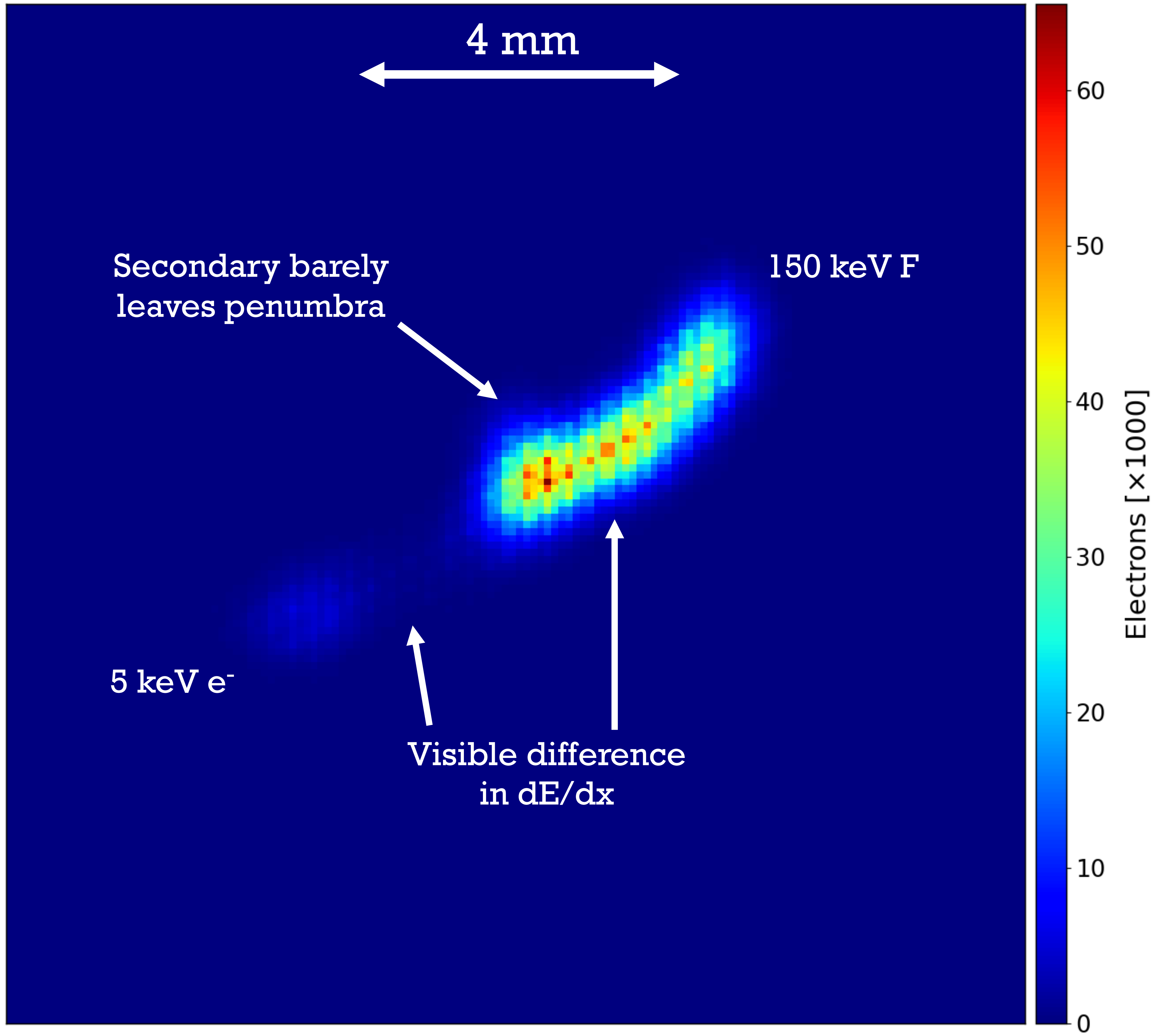




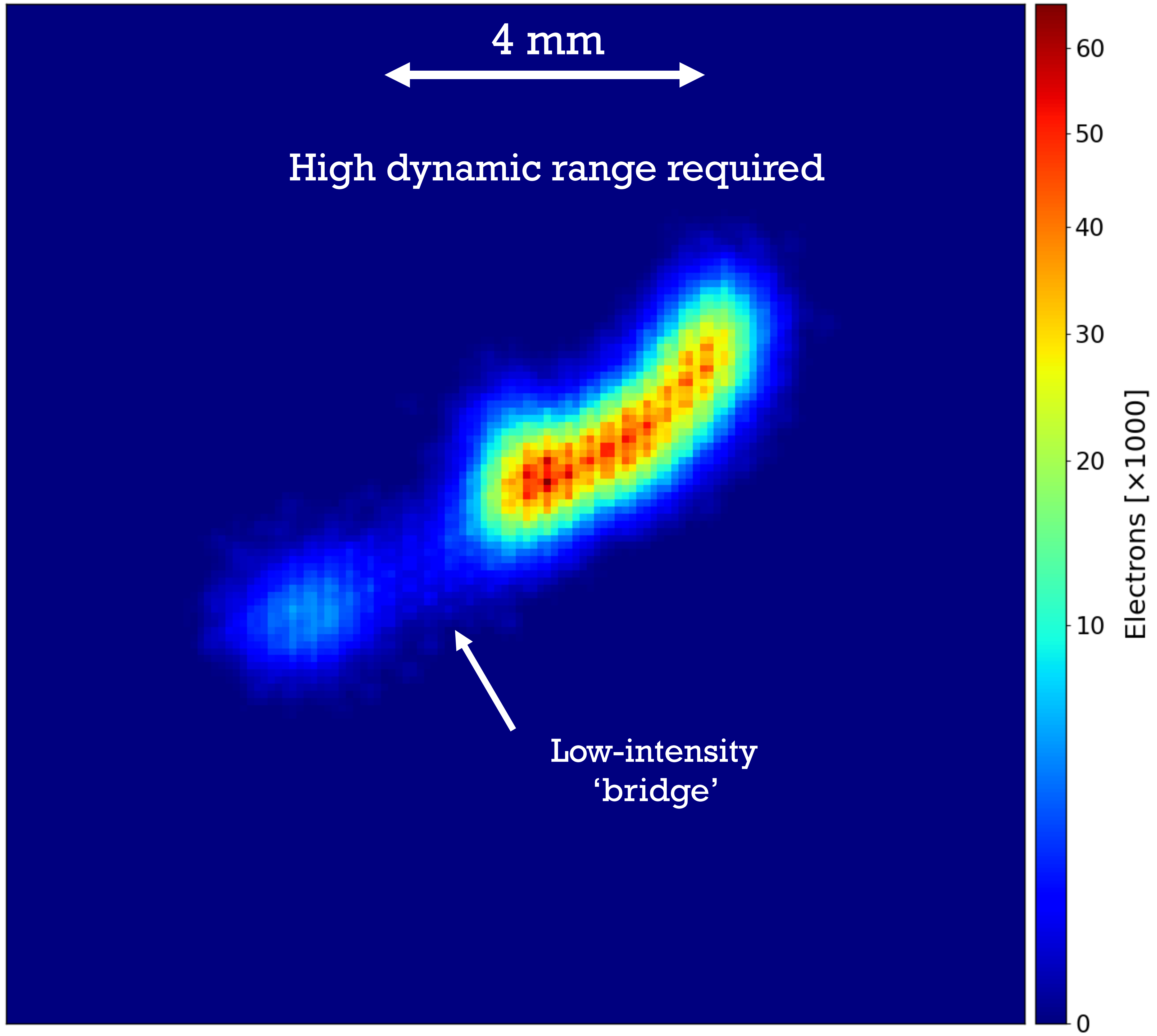
Neutrons plus OTPC gives…



Simulated camera images of Migdal event

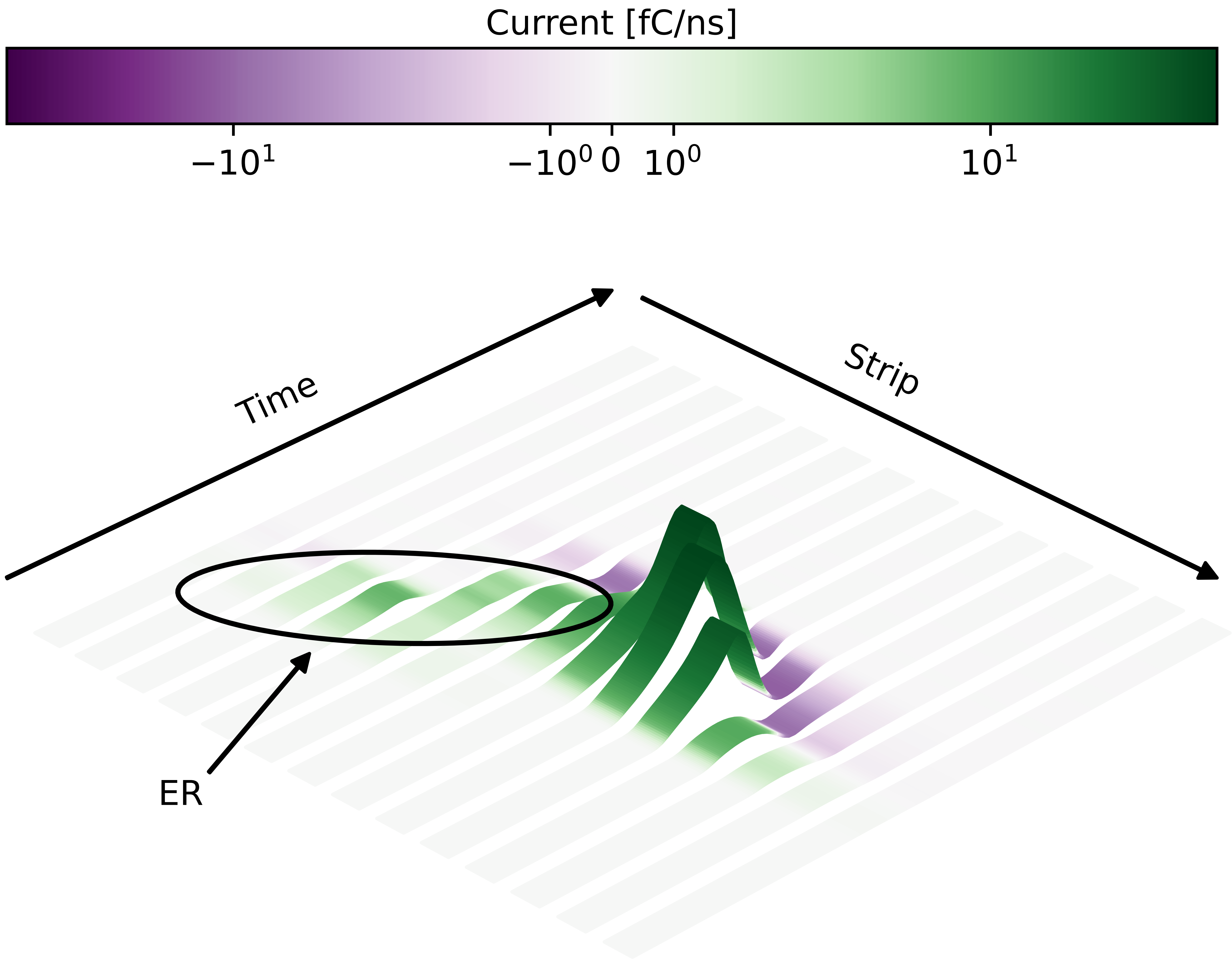


Linear-scale colour map



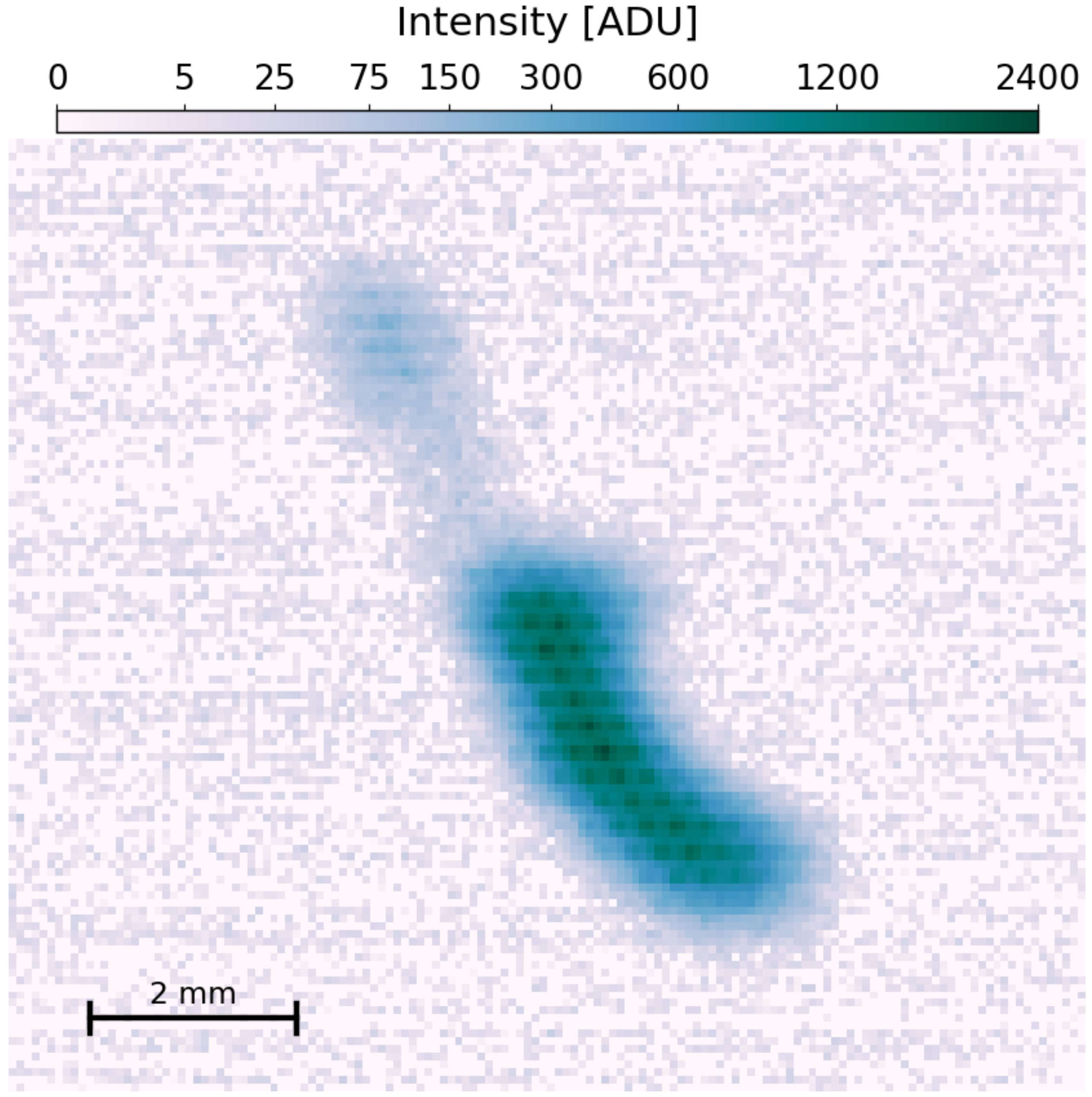
Log-scale colour map

Simulated ITO signals of Migdal event



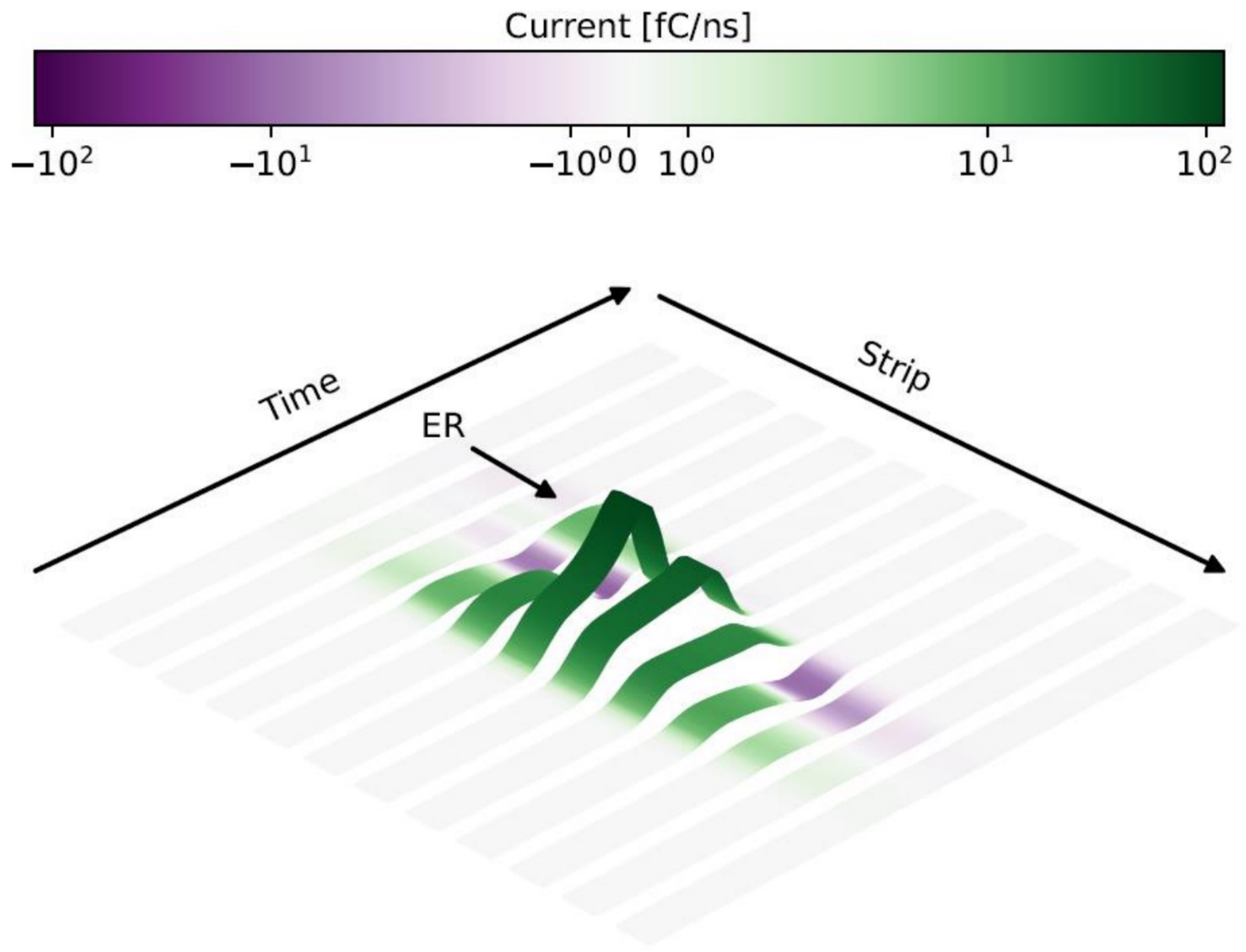
Track reconstruction: the idea

Camera readout
Diffusion + GEMs + noise



+

Anode strip readout
Induction/collection
(electronics deconvolved)



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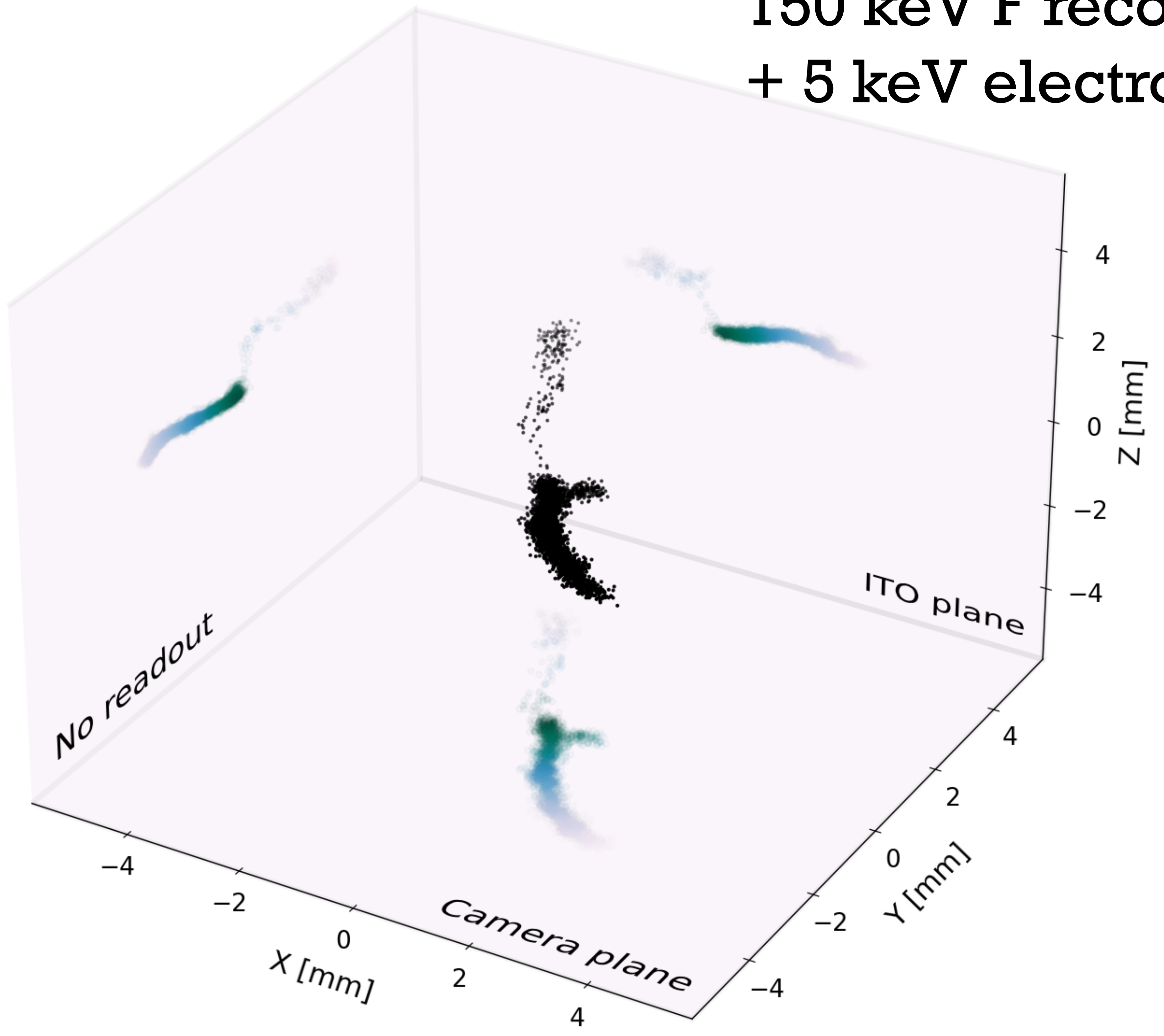
Migdal event
150 keV F recoil
+ 5 keV electron



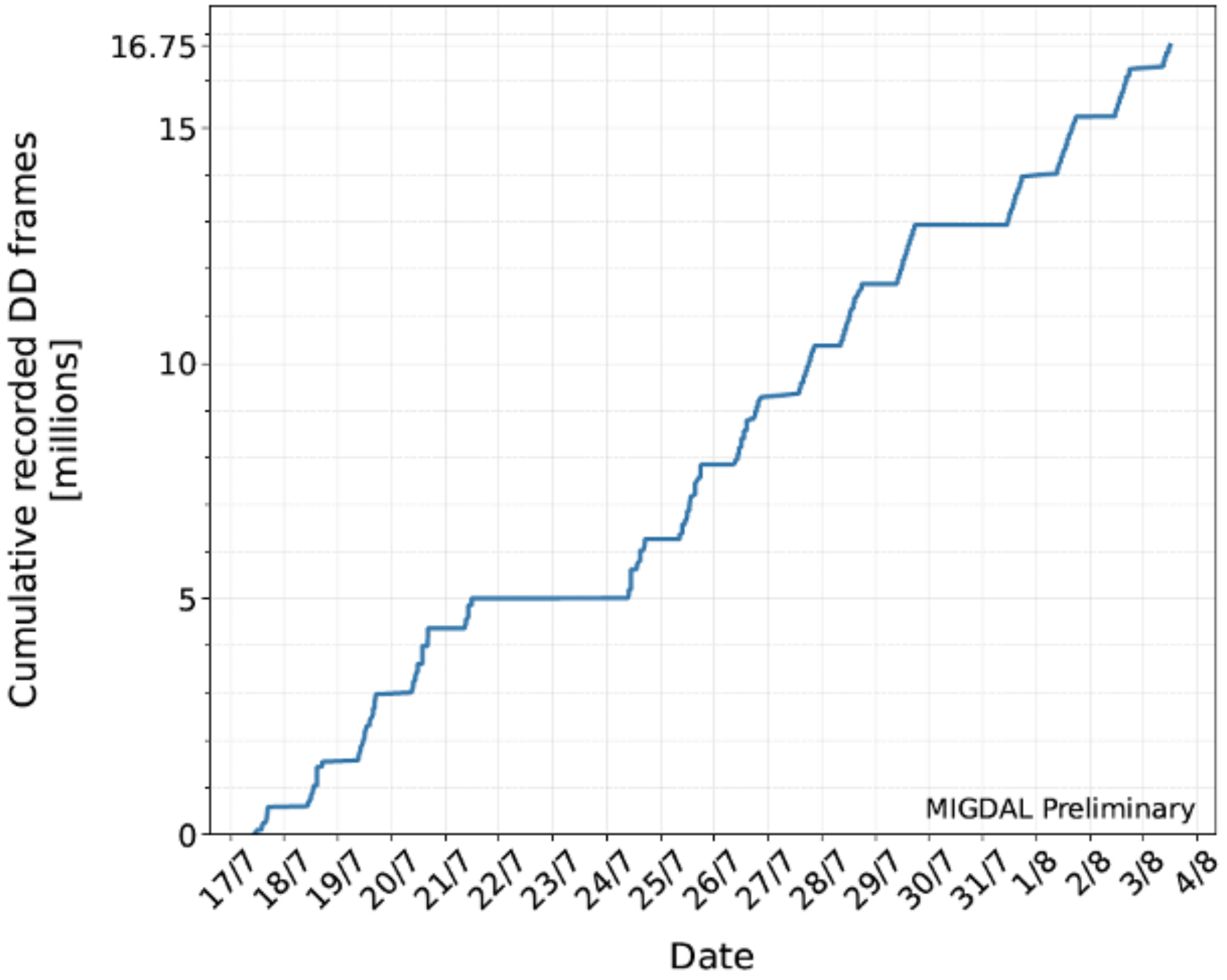
MIGDAL experiment: first science run

Summary of the run

- First Science run from 17July to 3 August, taken in 10 hour shifts/day

- Data taken using D-D neutron generator, with a lower NR rate than designed

- Frames taken with 20 ms exposure time, longer than planned due to problems with camera's Linux firmware



Summary of the run

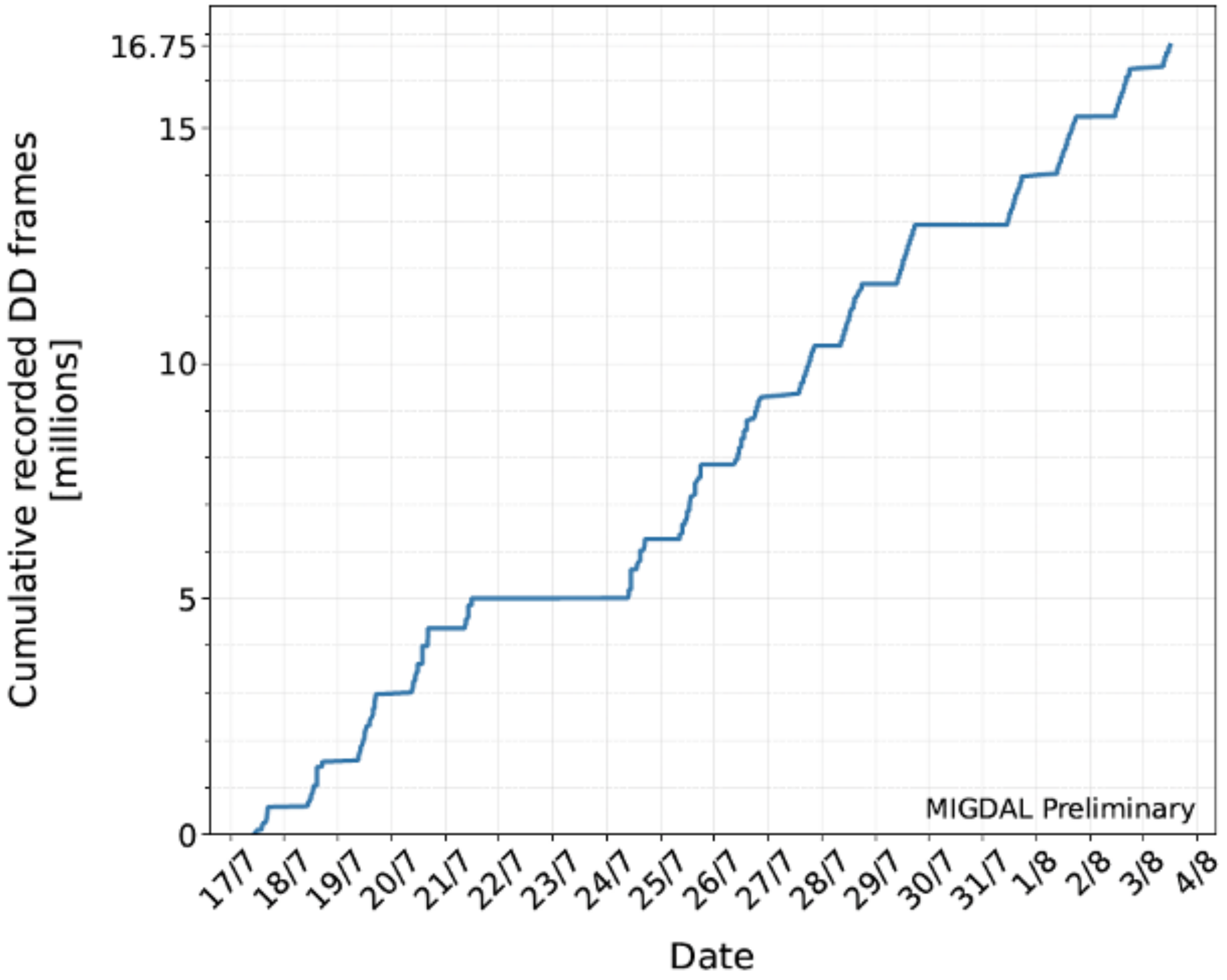
- Data taking interspersed with regular calibration runs (^{55}Fe) to monitor the gain of the detector

- Voltage across GEMs increased by a small amount each day to keep constant gain

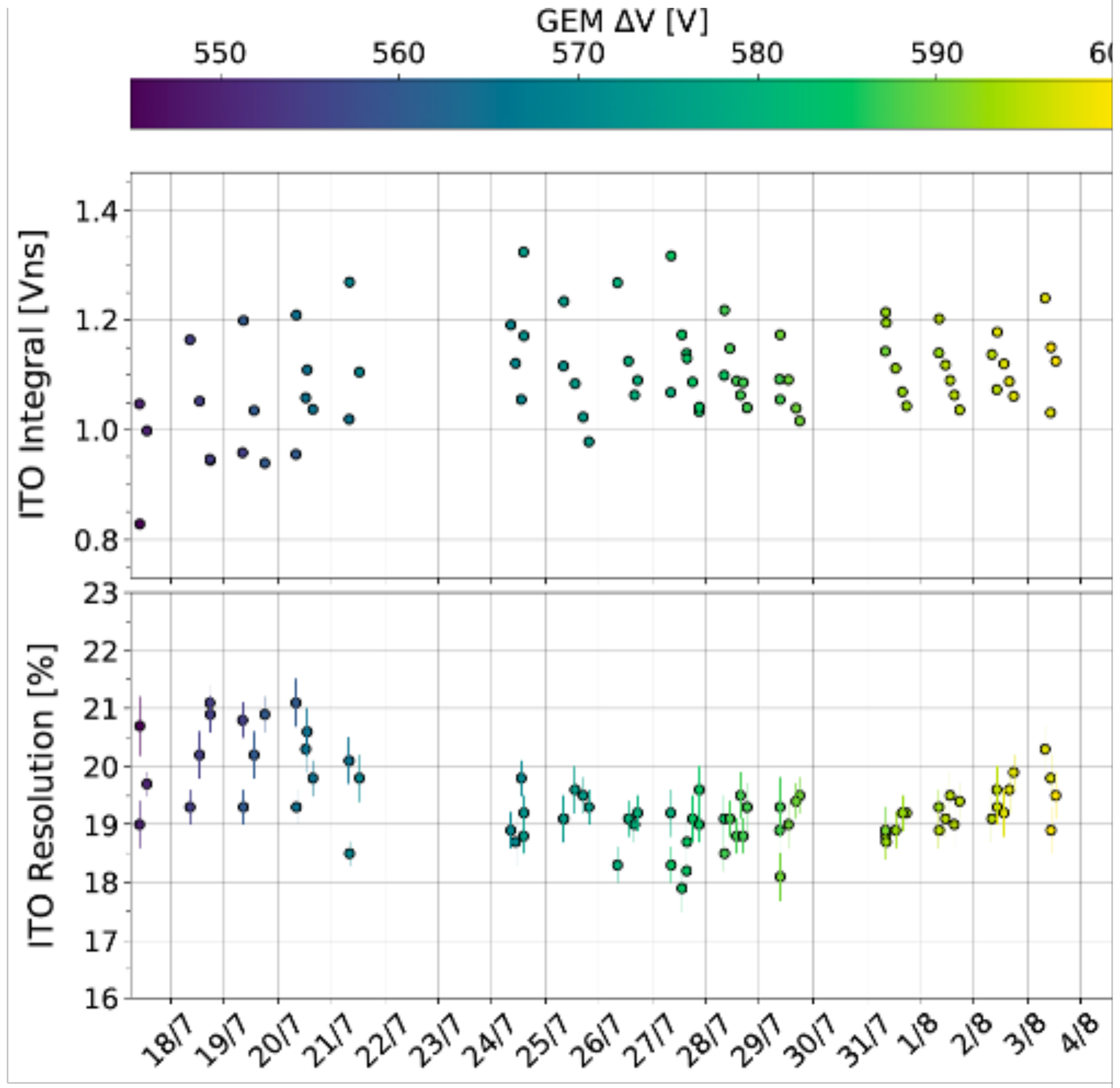
- Total gain in GEMs tuned to a threshold required to see fully resolved ^{55}Fe peak

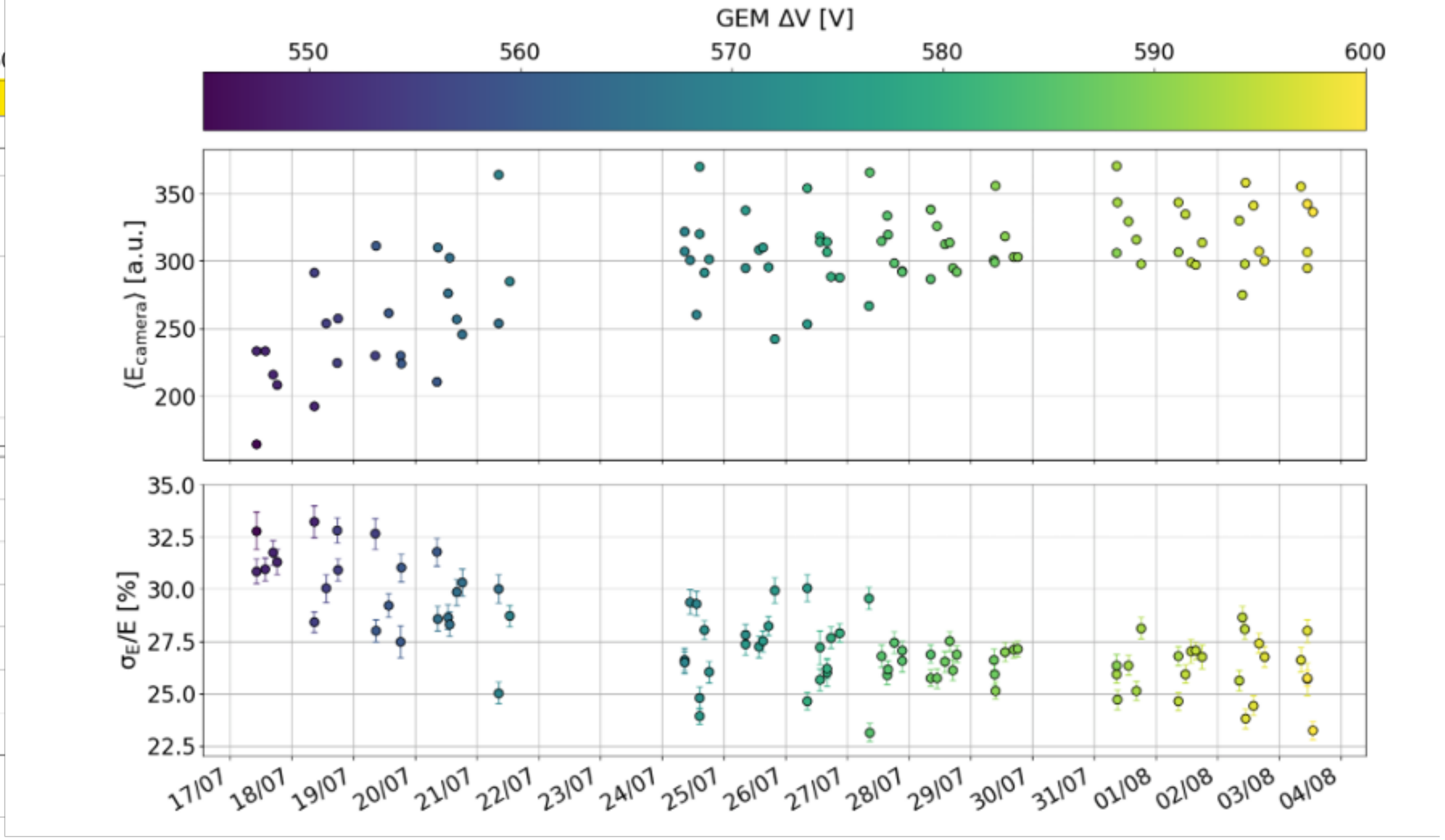
- Average spark rate ~ 7/min due to high dynamic range the detector operates at

- Half of the data is blinded



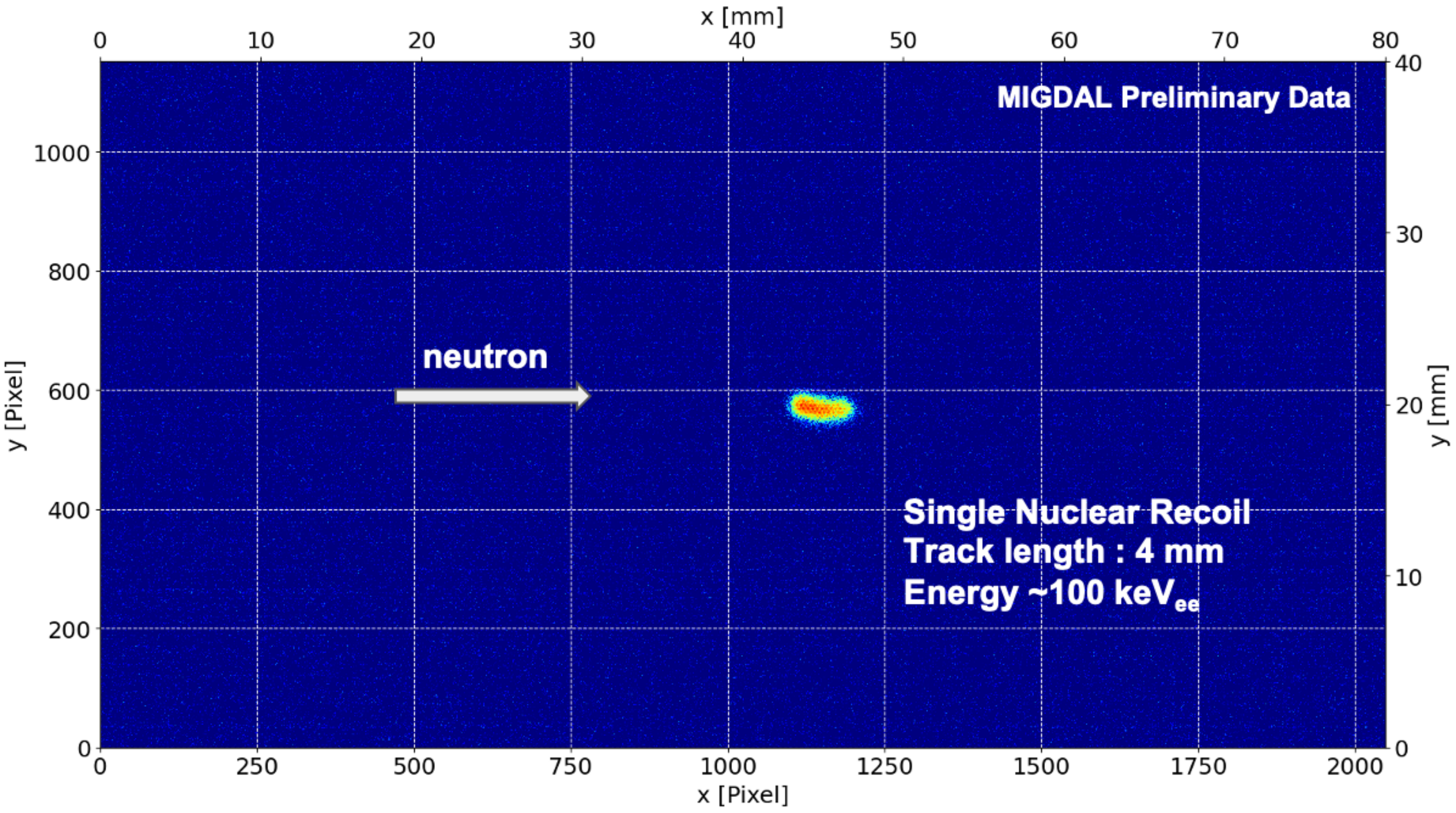
Detector calibration



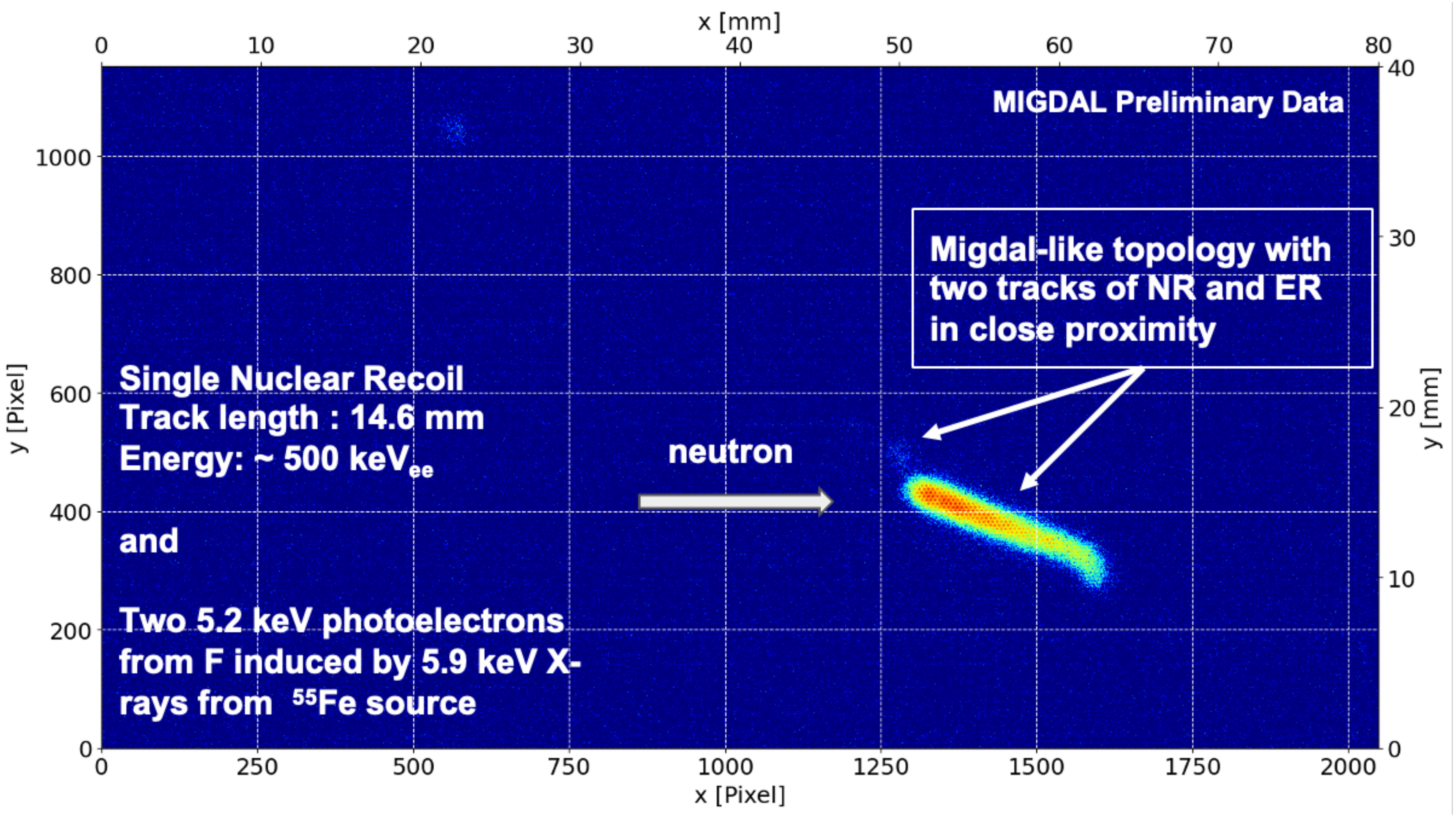


- ^{55}Fe calibration performed several times per day
- Energy scale is consistent over the course of the science run with ~20% variation
- Resolution in ITO ~20% and in camera ~ 25 - 32 % camera readout depending on the gain
- Further improvements are expected with better calibration methods

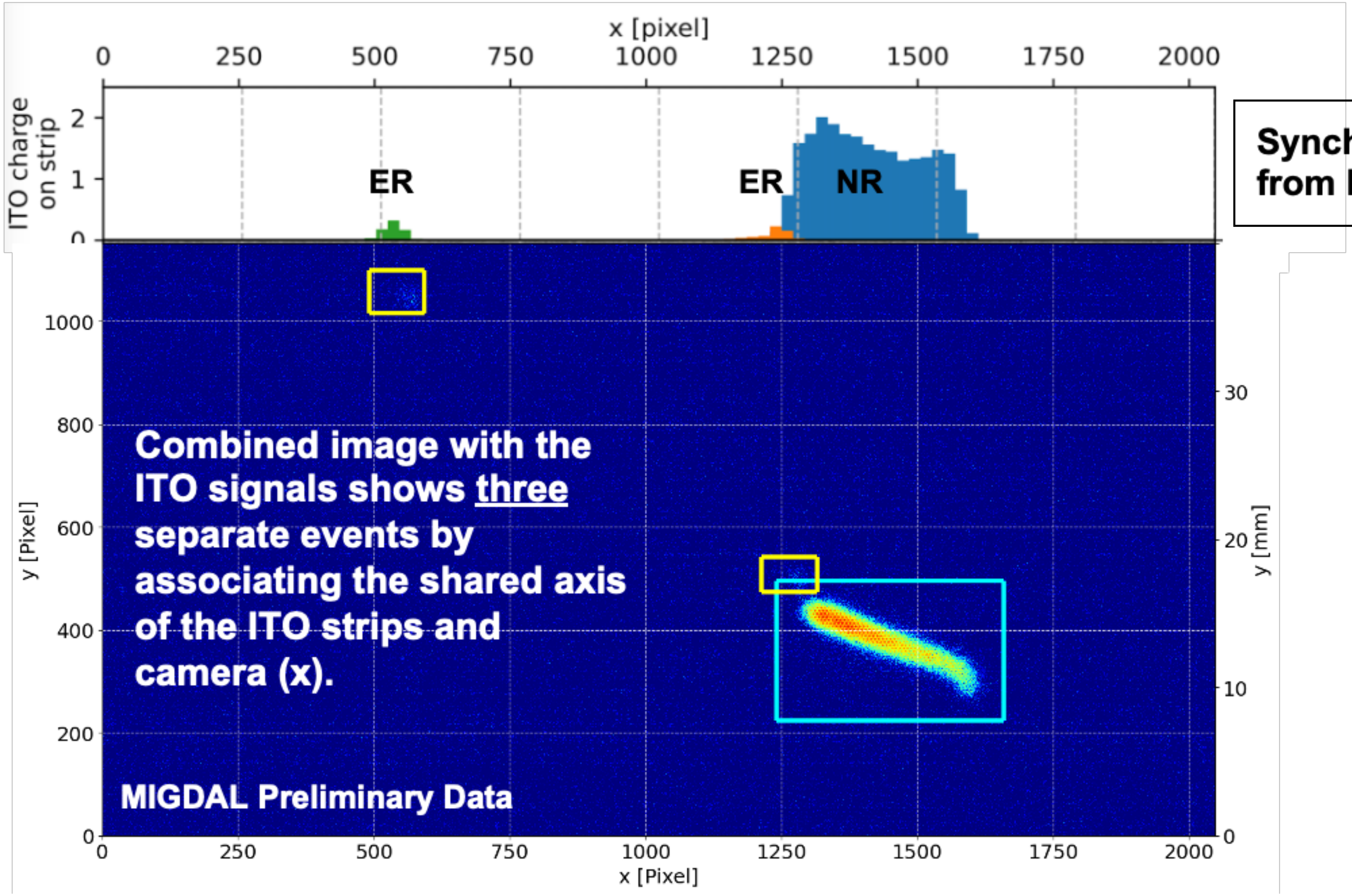
Examples of events: single nuclear recoil



Examples of events: Migdal topology

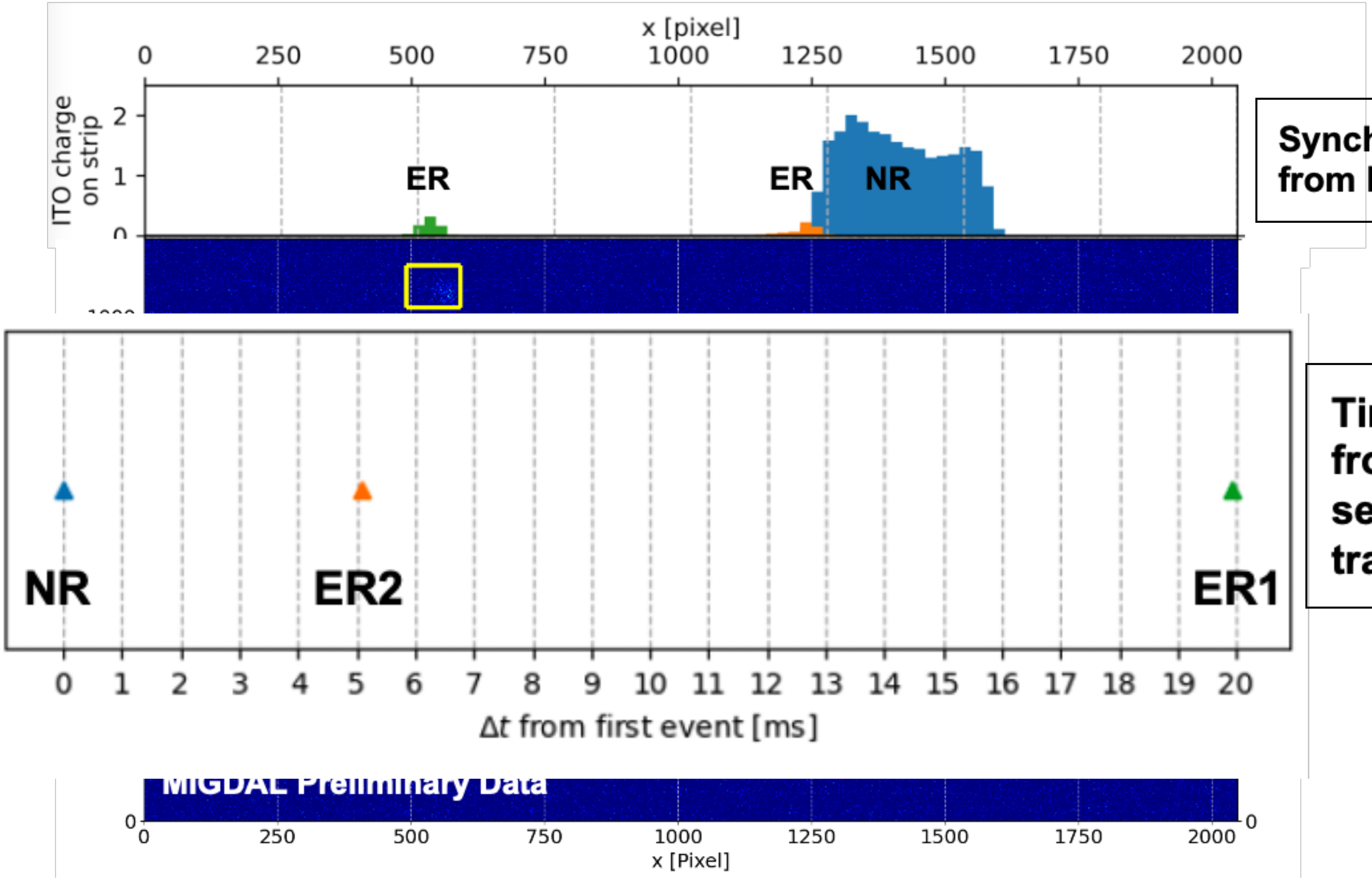


Examples of events: Migdal topology



Synchronised signals from ITO strips.

Migdal topology, *but not a Migdal event*



Synchronised signals from ITO strips.

Timing information from ITO strips separates all 3 tracks.

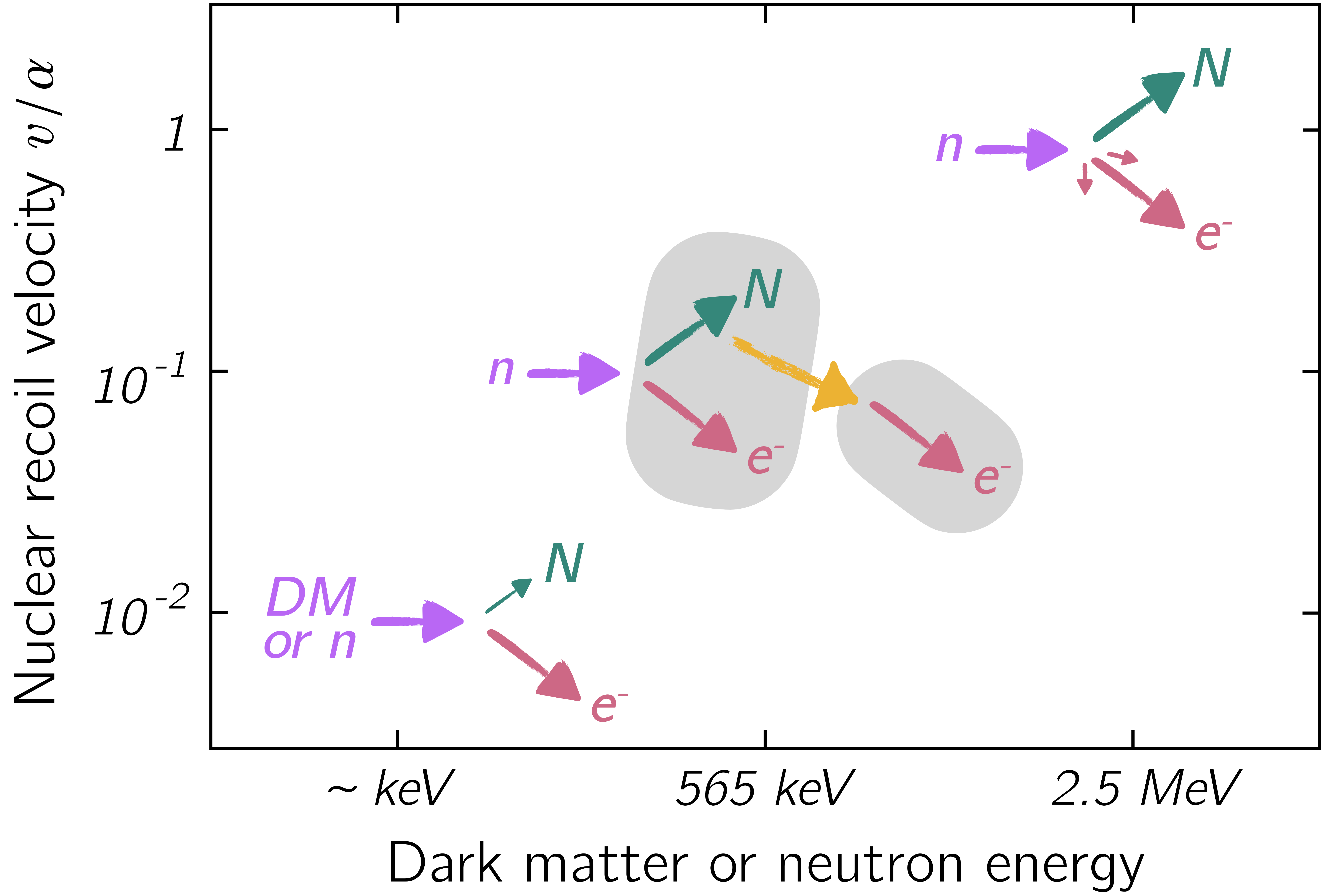
New theory work

"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

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

Proposals cover orders of magnitude in v/α

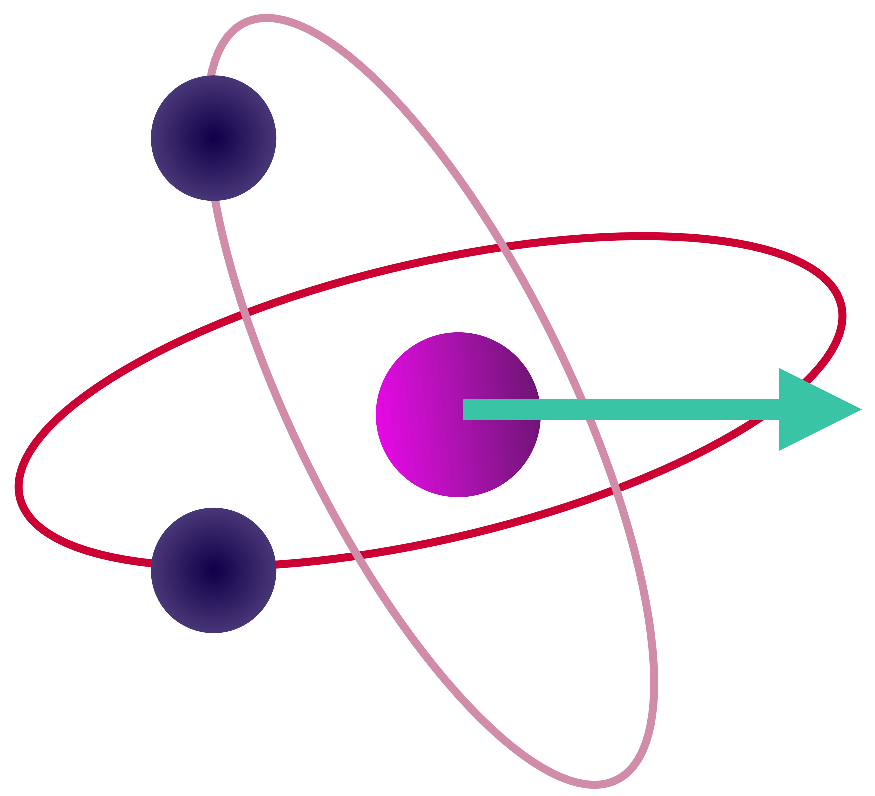


*[*In this talk c=1]*

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

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

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

Migdal transition element

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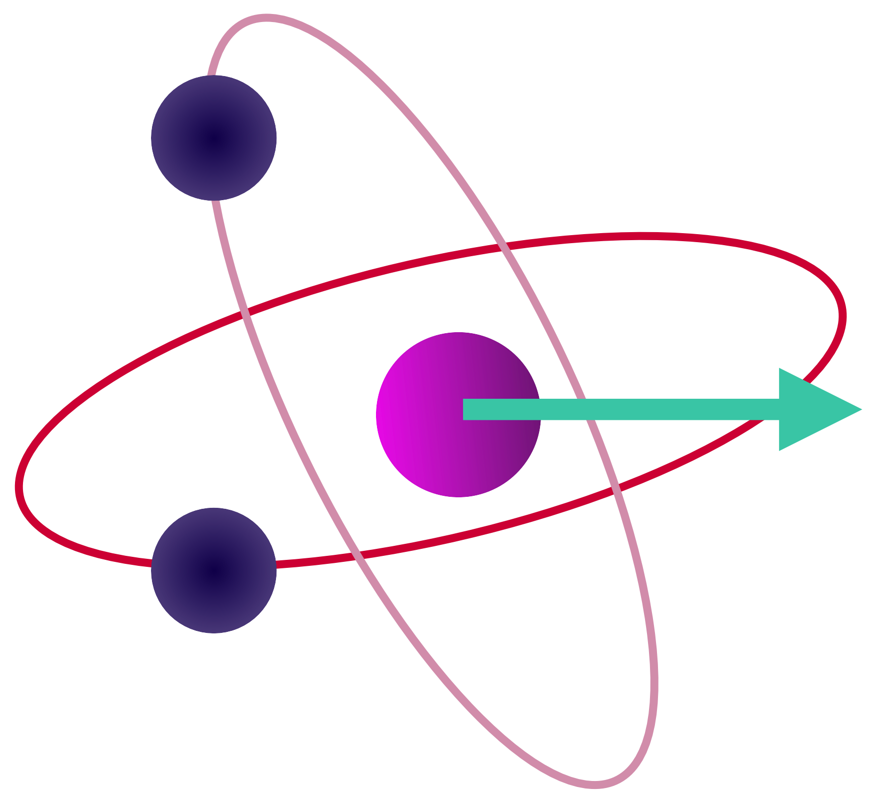
$$\left\langle \Psi_f^{\{k\}} \middle| e^{i m_e \mathbf{v}\cdot\sum_a \mathbf{r}_a} \middle| \Psi_i^{\{j\}} \right\rangle$$



Previous calculations made the 'dipole approximation':

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

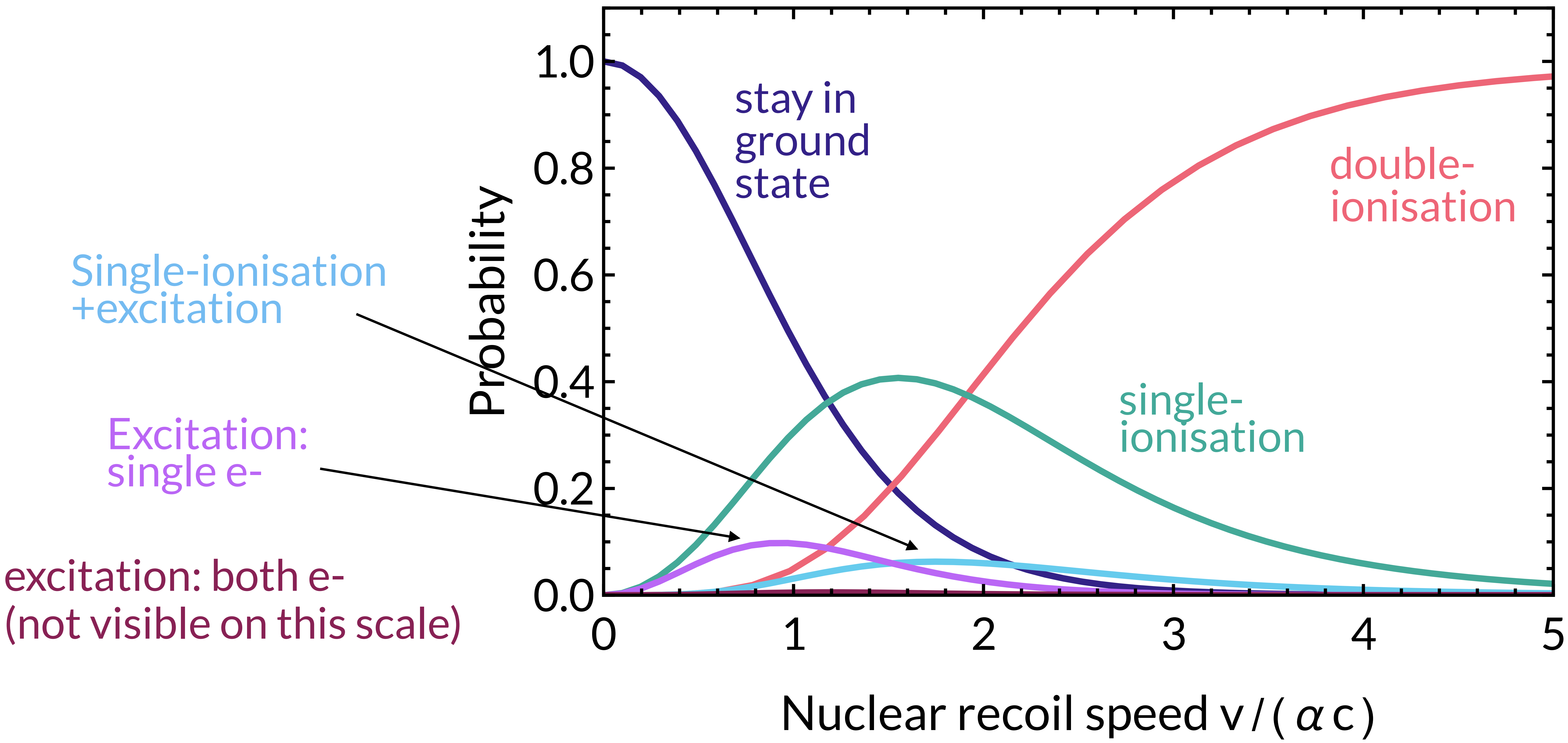
Unclear if dipole approximation holds for neutron scattering processes (high **v**) — and only allows for single ionisation processes to be accounted for

We keep the full exponential factor (sounds easy but lots of extra work!)

Cox, Dolan, CM, Quiney, arXiv:2208.12222

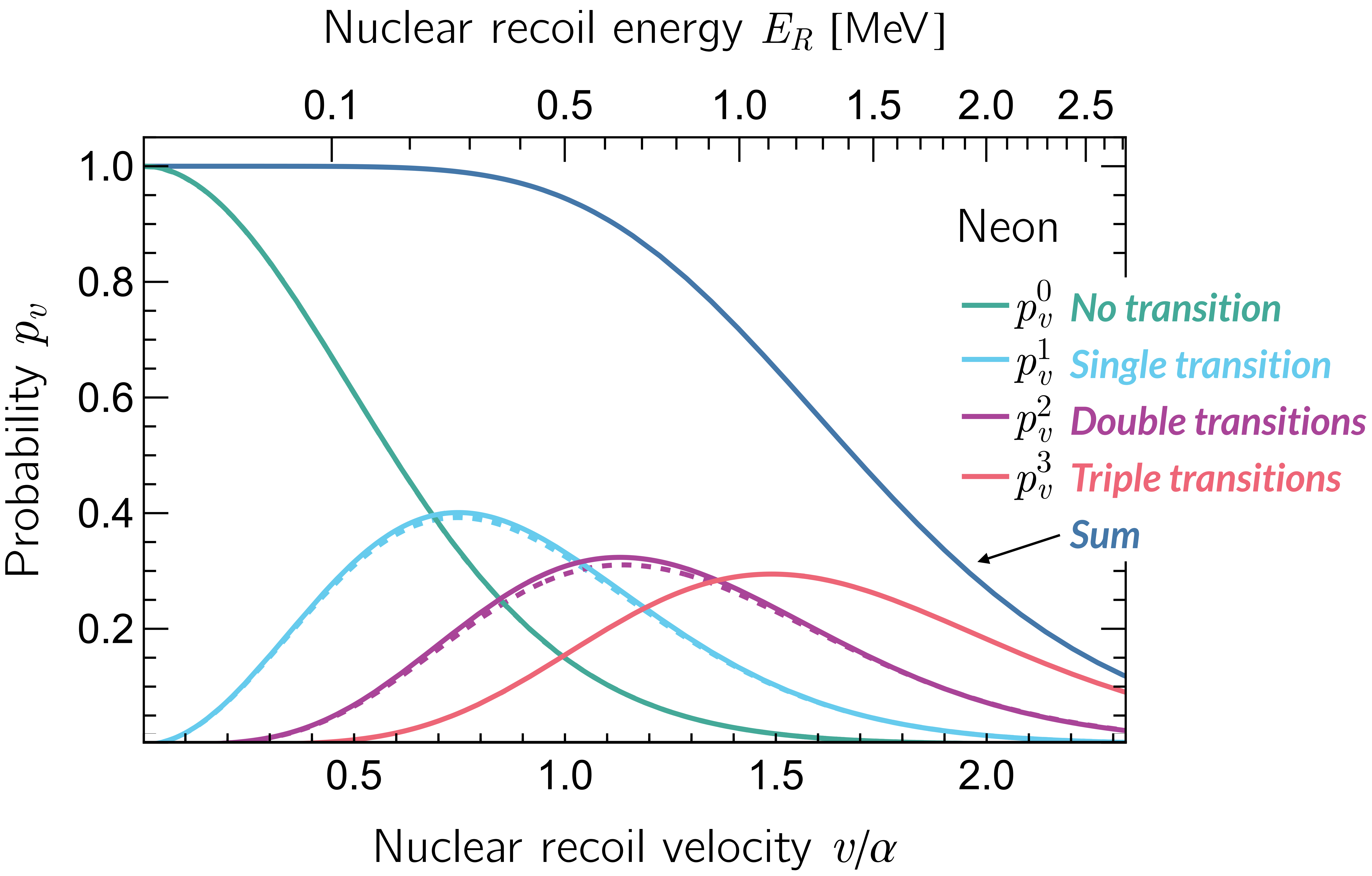
Total probability results
(with the exponential factor!)

Helium results (with GRASP+RATIP)



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

Extending to bigger atoms (neon)



Theory framework generalises straightforwardly to larger atoms…
…but there are more electrons

Probability sums to 1 to $v \simeq \alpha$ but clearly deviates beyond

At higher speeds, quads, quintics, … will contribute but VERY difficult to calculate

Without quads, quintics, …
will we have to give up on accurate predictions at higher NR speeds?

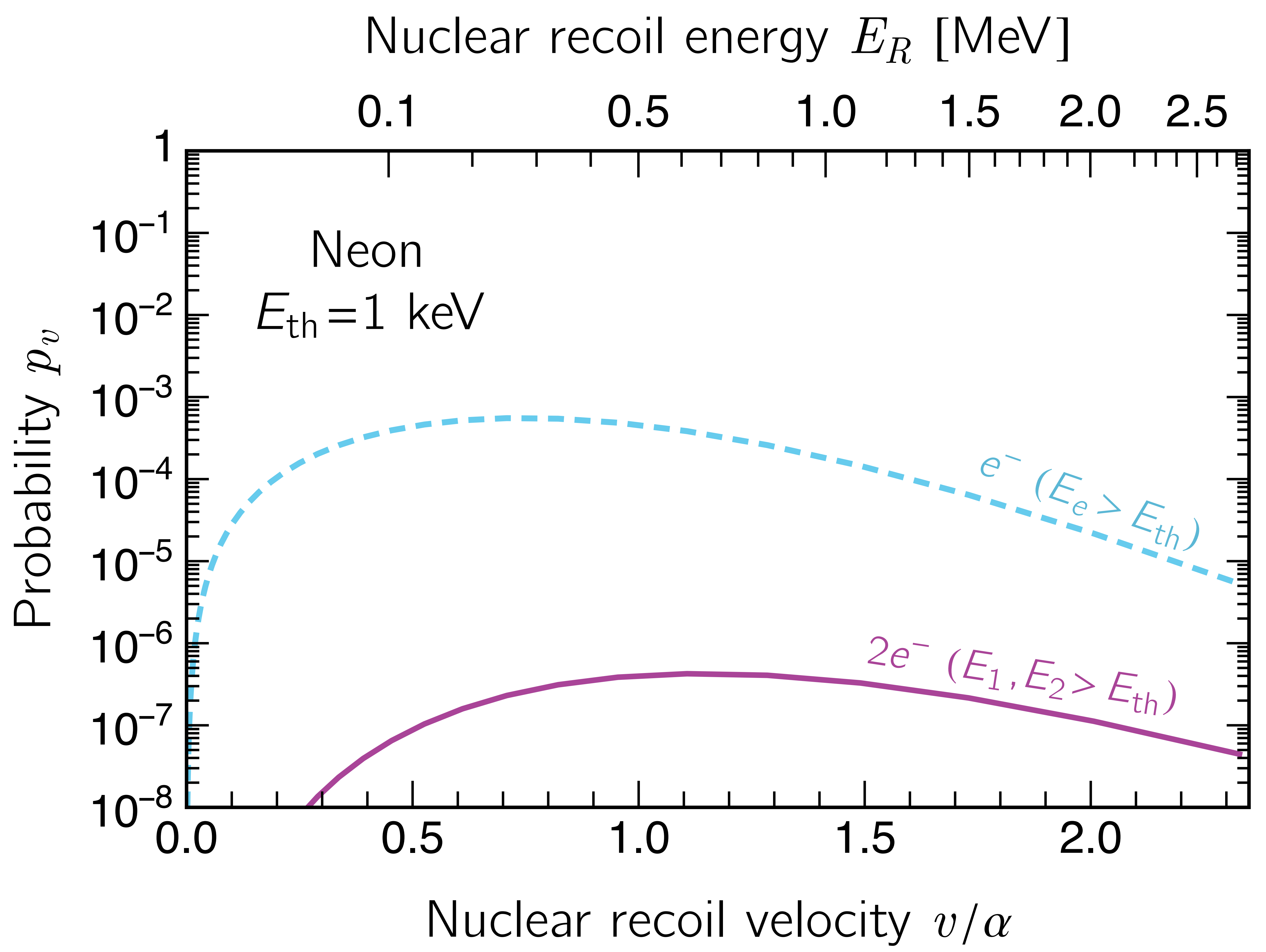
Without quads, quintics, …
will we have to give up on accurate predictions at higher NR speeds?

No! (for realistic experiments)

The impact of experimental thresholds

Realistic experiments have a **threshold** on the electron energy

Probability of two electrons above threshold is always suppressed, even at high NR speeds



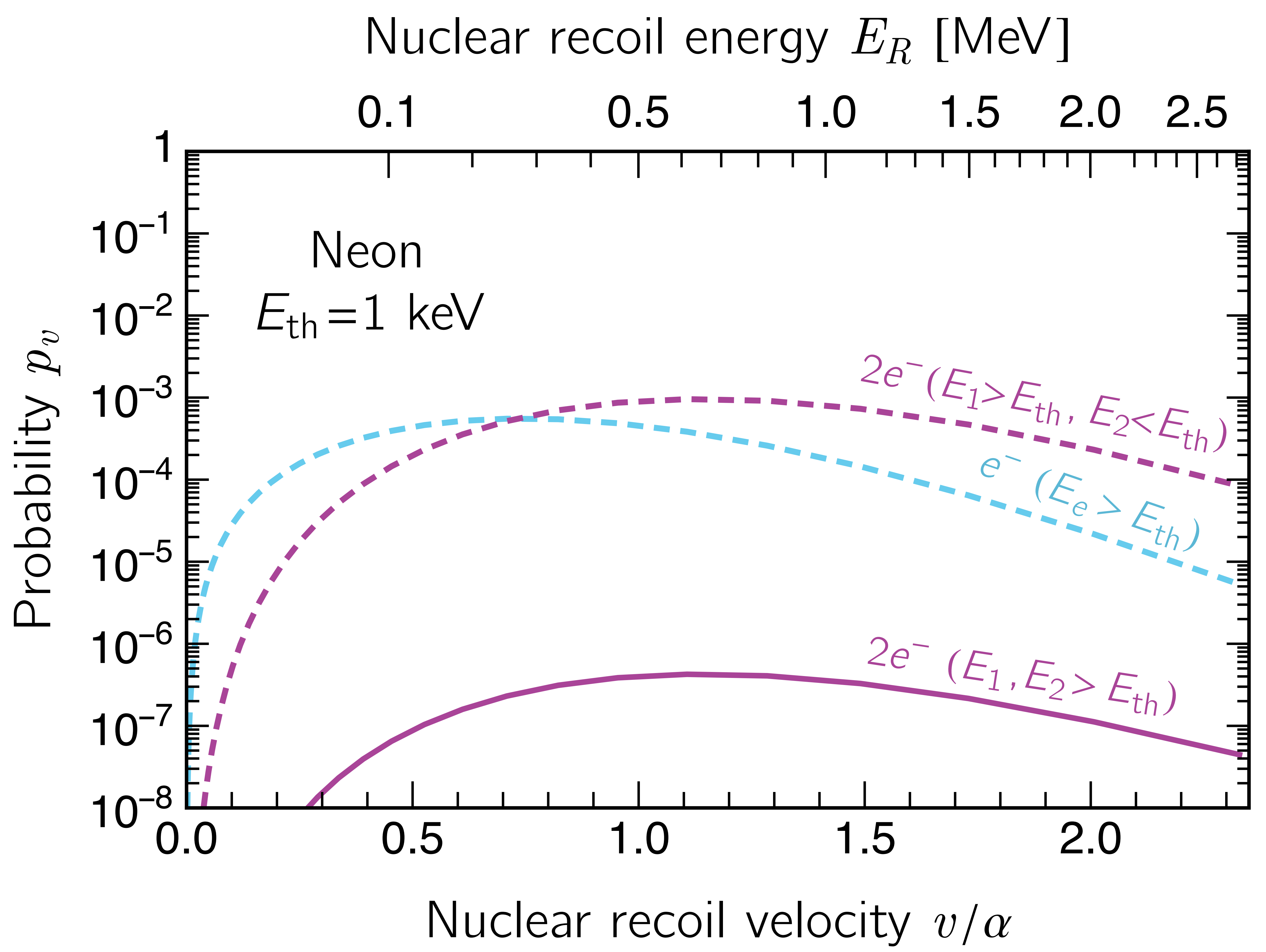
The impact of experimental thresholds

Realistic experiments have a **threshold** on the electron energy

Probability of two electrons above threshold is always suppressed, even at high NR speeds

…but what about 1 hard electron and 1 soft electron?
…Indeed, this is a large correction!

…the contributions from 1 hard, 2 soft; 1 hard 3 soft, …, will also be important



Summing over all soft electrons

Formally, the sum over all 1-hard + N soft-electrons is

$$p_v(|\Psi_i^{\{j\}}\rangle \to |\chi_{k_1} X_{\rm soft}\rangle) = \frac{1}{(N-1)!} \sum_{k_2,\ldots,k_N}^{E<E_{\rm th}} \left| \left\langle \Psi_f^{\{k\}} \middle| e^{i m_e \mathbf{v}\cdot \sum_a \mathbf{r}_a} \middle| \Psi_i^{\{j\}} \right\rangle \right|^2$$

To a good approximation*, this can be manipulated into the compact expression (which is straightforward to calculate numerically)

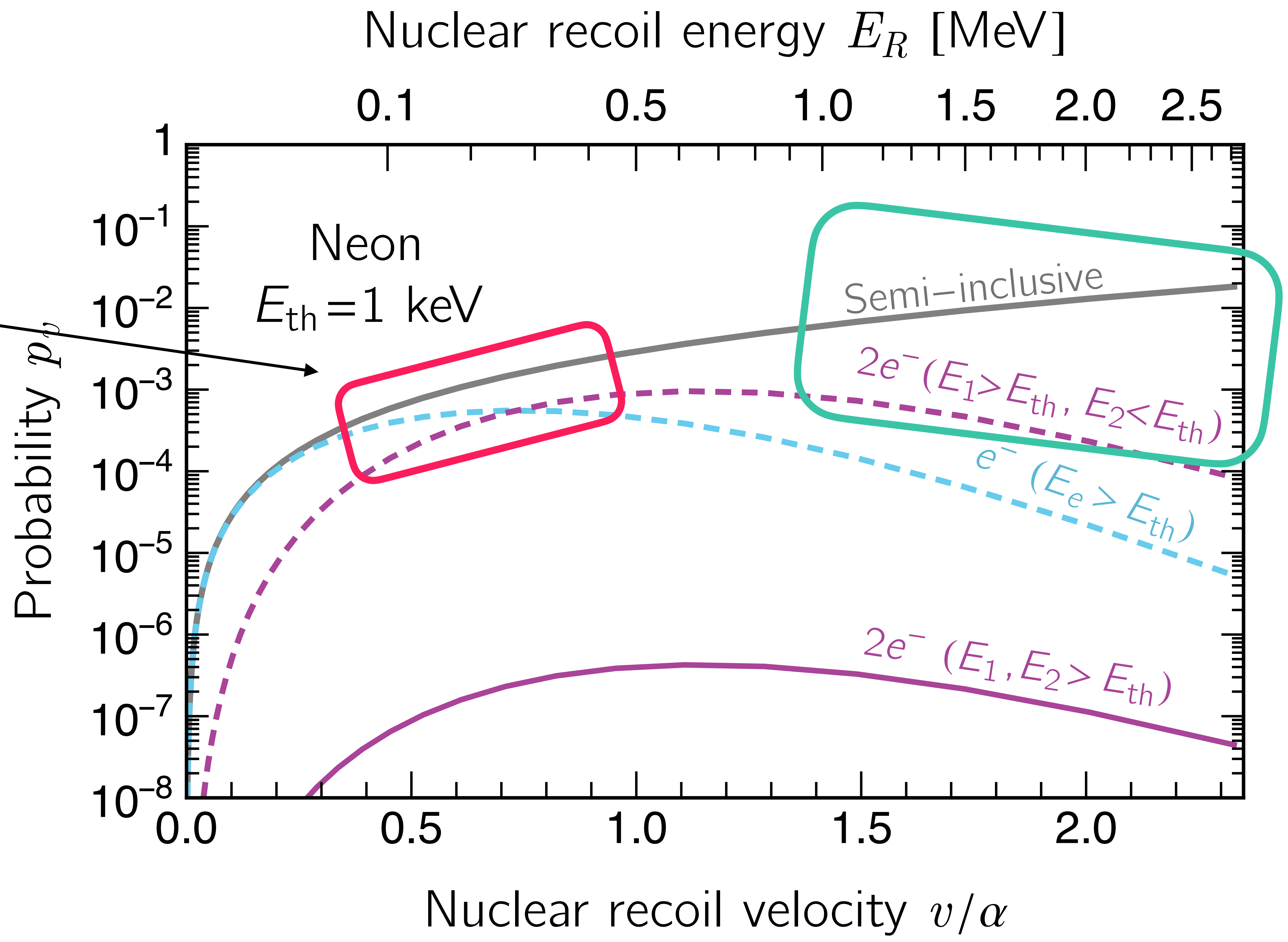
$$p_v(|\Psi_i^{\{j\}}\rangle \to |\chi_{k_1} X_{\rm soft}\rangle) = \sum_{\alpha=1}^{N} \left| \left\langle \chi_{k_1} \middle| e^{i m_e \mathbf{v}\cdot \mathbf{r}} \middle| \psi_{j_\alpha} \right\rangle \right|^2$$

We call this the 'semi-inclusive probability'

**Valid approximation if* $v/\alpha \lesssim 8.6\sqrt{(E_{\rm th}/1\ {\rm keV})}$

Semi-inclusive probability

Semi-inclusive includes contributions from ionisation + excitation

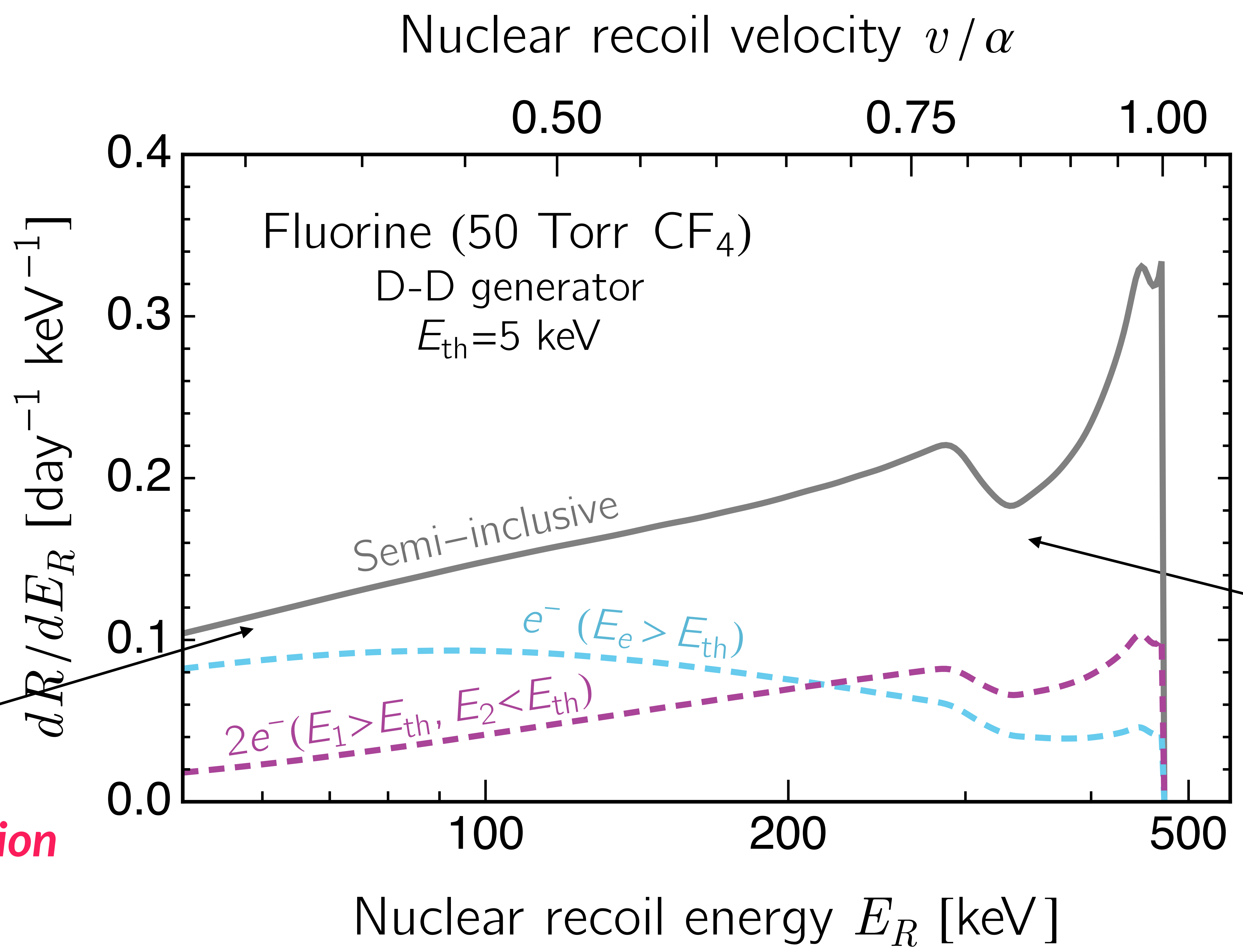


Semi-inclusive includes contributions from >2 e ionisation (+ excitation)

Semi-inclusive probability gives accurate rates even at high NR-speeds

Application to neutron scattering [high-NR speed]

Neutron scattering rates (DD = 2.47 MeV)



Semi-inclusive includes contributions from ionisation + excitation

Without semi-inclusive, would miss contributions from >2 e ionisation

**Peak from neutron cross-section*

Semi-inclusive rate is factor 1.6 higher than single+double ionisation

Background/Signal rates per million nuclear recoils

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.

Summary

The Migdal effect is…
- an old effect (from 1940s) that is used for dark matter sub-GeV searches and is an active target for near-future neutron-beam experiments

In the UK…
- we are building a detection platform to characterise the effect in multiple elements relevant to dark matter experiments

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

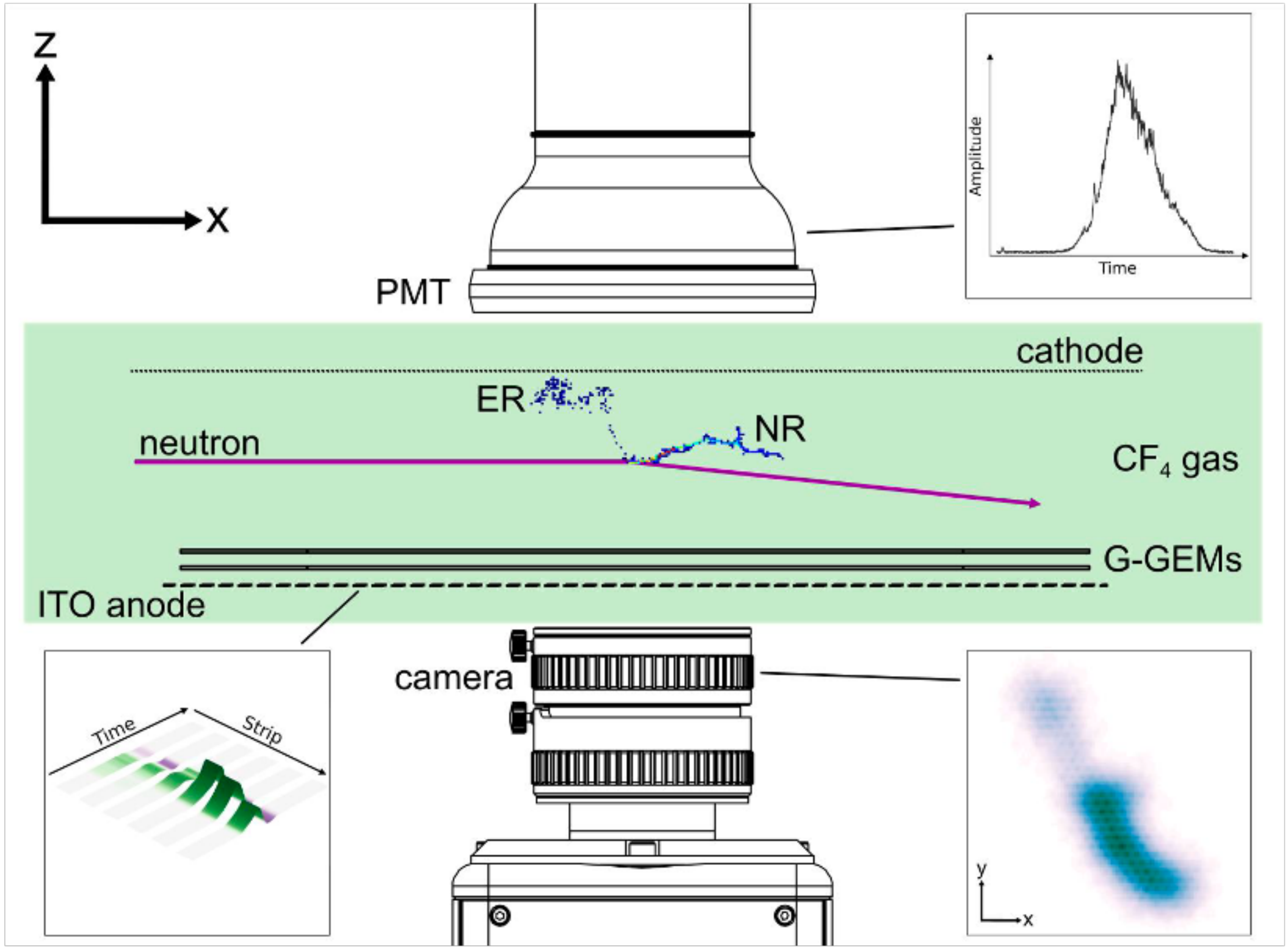
Thank you

“*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
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
arXiv:2207.08284, Astroparticle

Backup

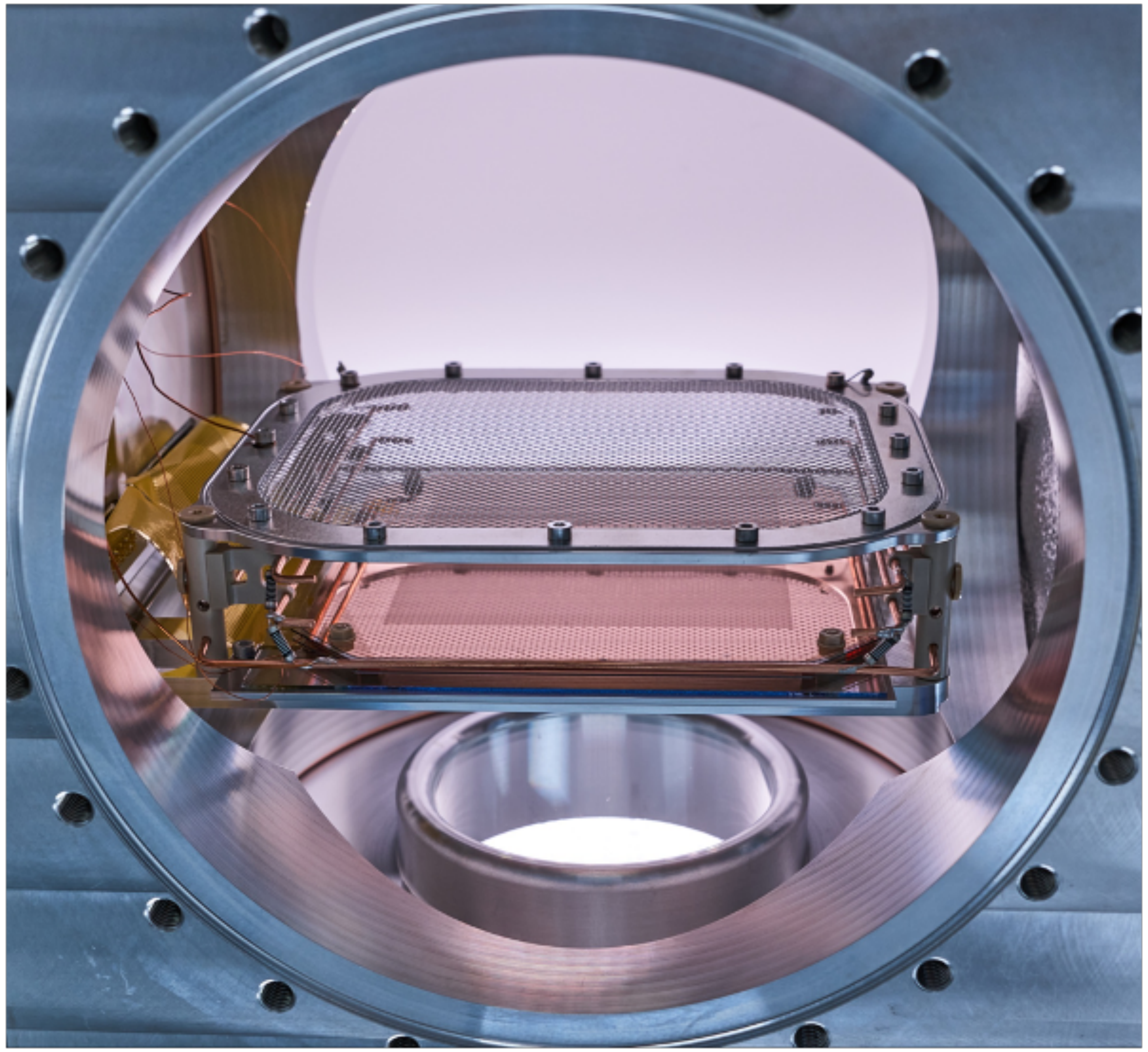
The MIGDAL experiment

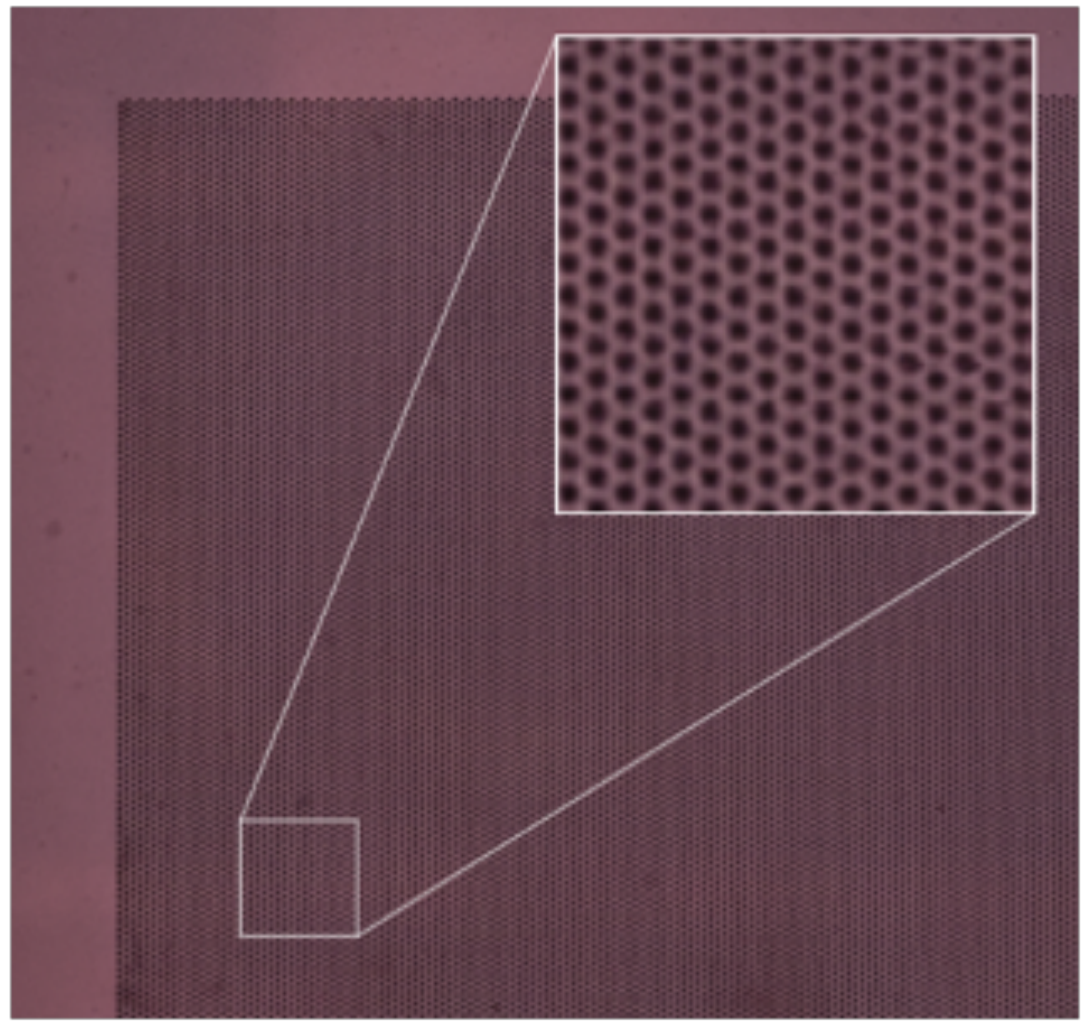


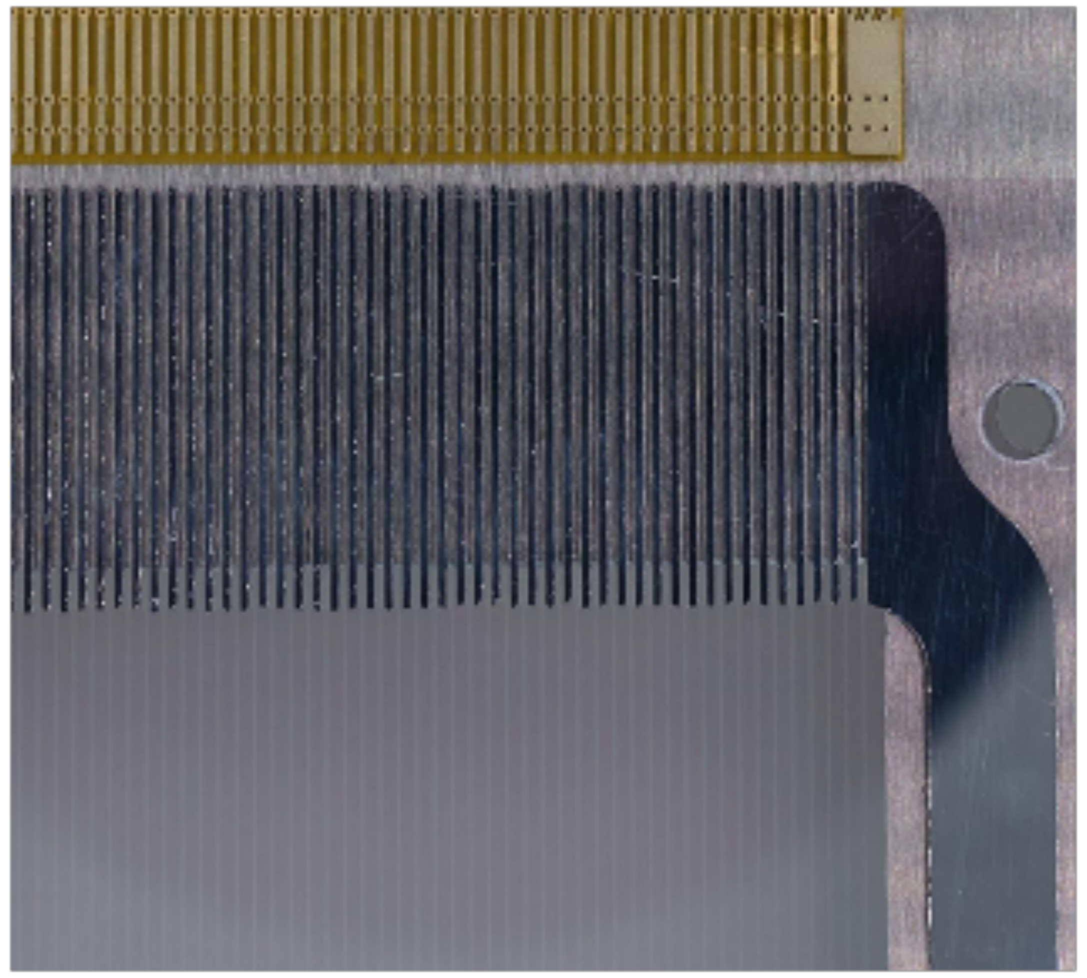
- Low-pressure gas: 50 Torr of CF_4
  - Extended particle tracks
  - Avoid gamma interactions
  - Can stably work with fraction of Ar
- TPC Signal amplification
  - 2 x glass-GEMs (Cu + Ni cladded)
- Readout :
  - Optical : Camera + photomultiplier tube
  - Charge: GEMs + 120 ITO anode strips
- High-yield neutron generator
  - D-D: 2.47 MeV (10^9n/s)
  - D-T: 14.7 MeV (10^{10}n/s)
  - Defined beam, “clear” through TPC
- Electron and nuclear recoil tracks
  - Migdal: NR+ER tracks, common vertex
  - NR and ER have very different dE/dx
  - 5 keV electron threshold

    5.9 keV X-rays from Fe-55 induce 5.2 keV photoelectrons from F for calibration at threshold.

The MIGDAL optical-TPC







Two glass GEMs one Cu- and one Ni-cladded :

- thickness: 550 μm

- OD /pitch: 170/280 μm

- active area: 10x10 cm^2

- total gain ~10^5

ITO strips wire bonded to readout

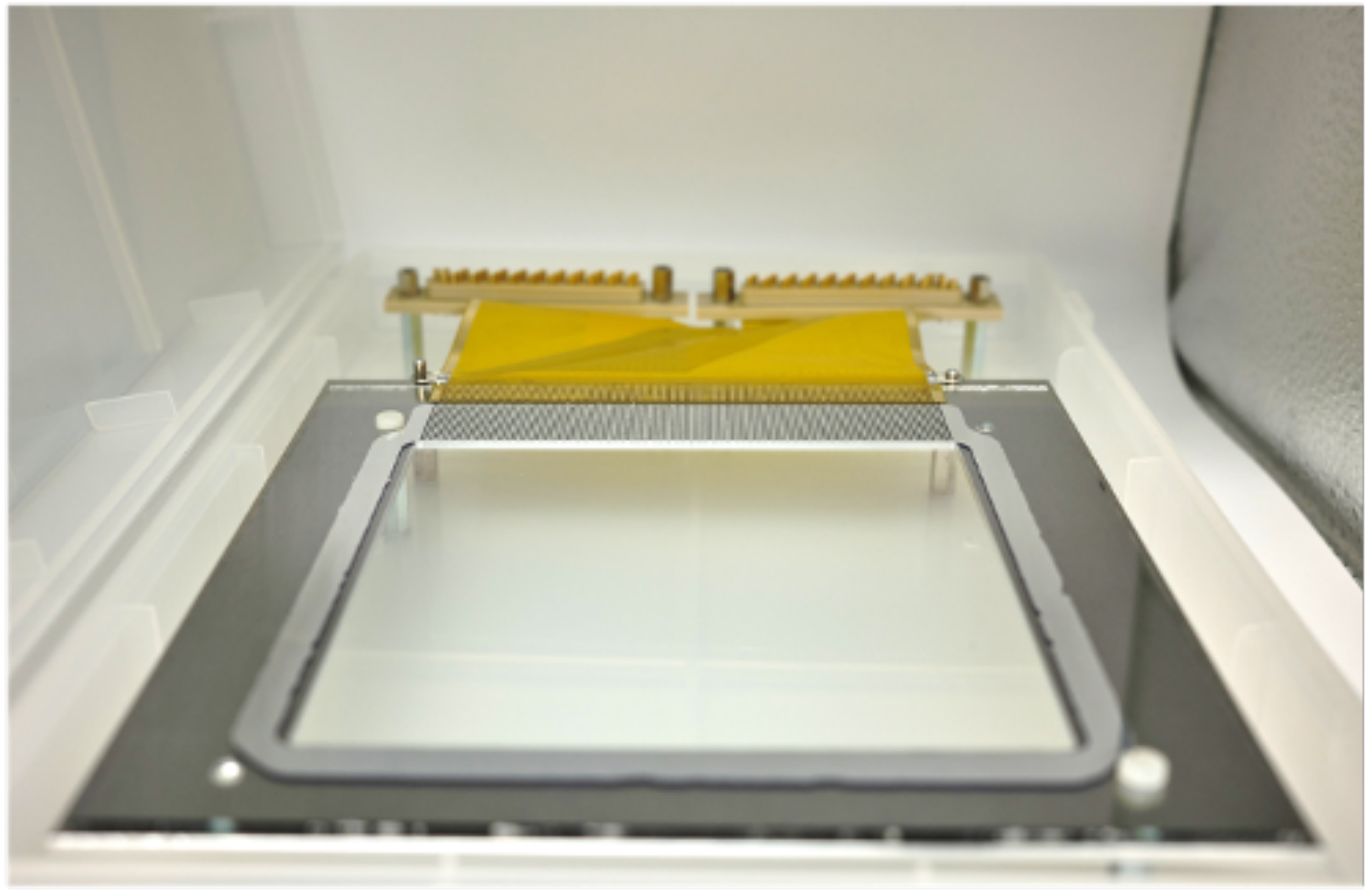
- 120 strips

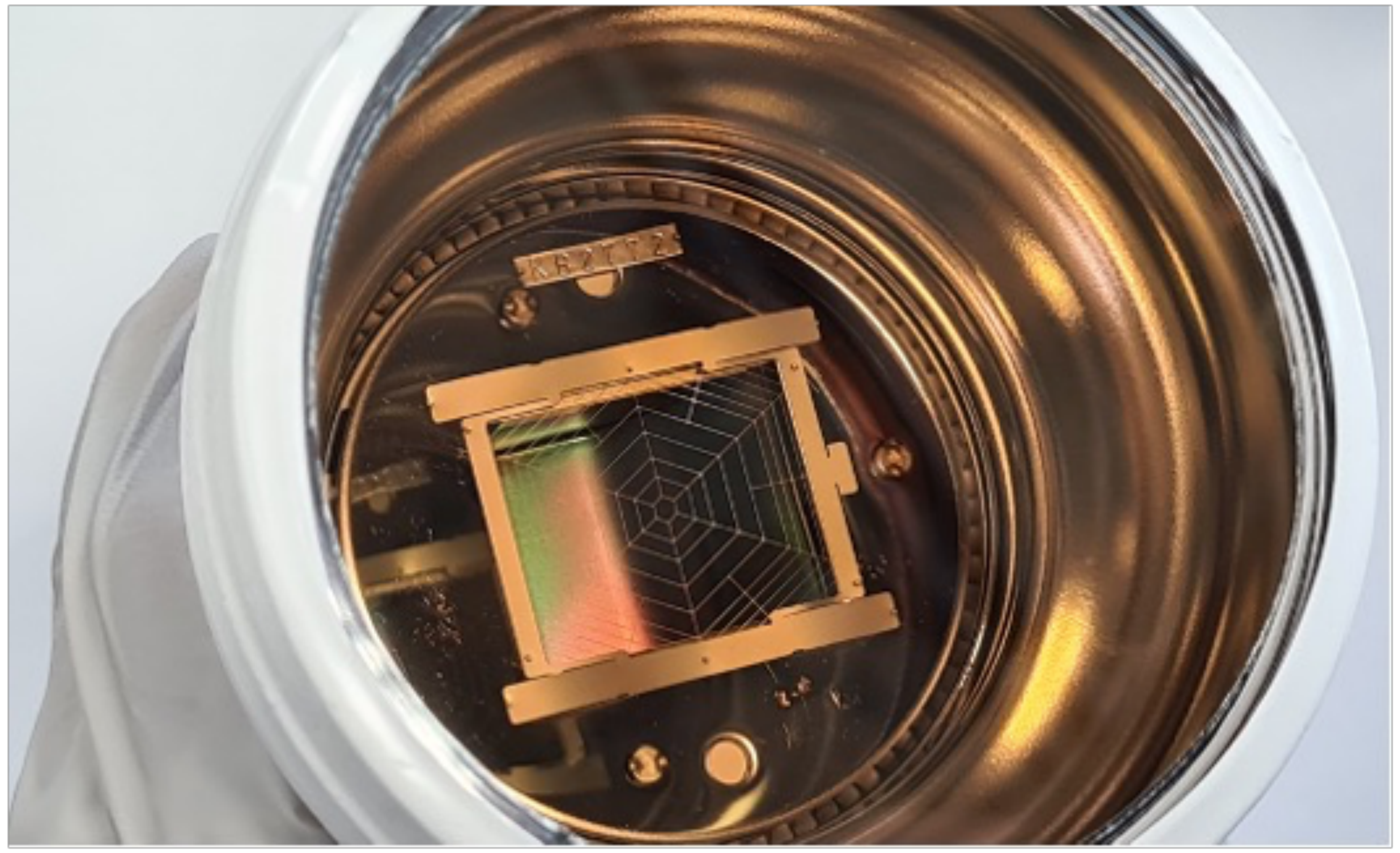
- width/pitch: 0.65/0.83 mm

Two field shaping copper wires

- TPC inside of the central aluminium cube
- Drift gap: 3 cm between woven mesh and cascade of two glass-GEMs (E_{DRIFT}=200 V/mm for minimum electron diffusion)
- Transfer and signal induction gaps : 2 mm
- Low outgassing materials; vacuum before fill $2*10^{-6}$ mbar; signal unchanged several days after fill

Light and charge readout





ITO anode strips
Post-GEM ionisation
Readout of (x,z) plane
Pitch: 833 µm
Digitised at 2 ns/sample
(Drift velocity: 130 µm/ns*)*

qCMOS camera
(Hamamatsu ORCA - QUEST)
Detects GEM scintillation through glass viewport behind ITO anode
Readout of (x,y) plane
Exposure: 8.33 ms/frame (continuous)
Px scale: 39 µm (2×2 binning)
Lens: EHD-25085-C; 25mm f/0.85

VUV PMT (Hamamatsu R11410)
Detects primary and secondary (GEM) scintillation
Absolute depth (z) coordinate
Digitised at 2 ns/sample [Trigger]

Migdal effect for neutral atoms

Transition matrix element first found by A. Migdal: $\left\langle \Psi_f^{\{k\}} \middle| e^{i m_e \mathbf{v} \cdot \sum_a \mathbf{r}_a} \middle| \Psi_i^{\{j\}} \right\rangle$

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

Key-point: When initial/final state wavefunctions expressed as anti-symmetric products of single-electron wavefunctions [e.g. as in Hartree-Fock], this can be expressed as:

$$\left\langle \Psi_f^{\{k\}} \middle| e^{i m_e \mathbf{v} \cdot \sum_a \mathbf{r}_a} \middle| \Psi_i^{\{j\}} \right\rangle = \det(M) \quad \text{where} \quad M_{ba} = \left\langle \chi_{k_b} \middle| \exp(i m_e \mathbf{v} \cdot \mathbf{r}) \middle| \psi_{j_a} \right\rangle$$

J. D. Talman and A. M. Frolov, Phys. Rev. A73, 032722 (2006)

Example: *Ground-state to ground-state transition in helium* $\psi_{\rm GS} = \psi_{1s}(\mathbf{r}_1, \mathbf{r}_2) \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2 \right)$

Approximate form (for illustration): $\psi_{1s}(\mathbf{r}_1, \mathbf{r}_2) = \psi_{1s}(\mathbf{r}_1)\psi_{1s}(\mathbf{r}_2) = \frac{Z_e^3}{\pi} e^{-Z_e(r_1 + r_2)}$, $Z_e = \frac{27}{16}$

$$\left.\begin{aligned} M_{12} &= M_{21} = 0 \\ M_{11} &= M_{22} = \left(1 + \frac{m_e^2 v^2}{4 Z_e^2}\right)^{-2} \end{aligned}\right\} \quad P_{\rm GS \to GS} = |\det(M)|^2 = \left[1 + (8 m_e v / 27)^2\right]^{-8}$$

Comparison of numerical methods

Our approach

Canonical Dirac-Hartree Fock method [Implemented in the GRASP+RATIP and BERTHA codes]

Ibe et al approach (arXiv:1707.07258)

Relativistic self-consistent mean-field [Implemented in the FAC code]

Impact: Model of atomic potential differs - expect ***small*** differences at low electron energies

We keep the full matrix element:

$$\det(M) = \left\langle \Psi_f^{\{k\}} \right| \exp\left(i m_e \mathbf{v} \cdot \sum_{a=1}^{N} \mathbf{r}_a \right) \left| \Psi_i^{\{j\}} \right\rangle$$

Makes the dipole approximation:

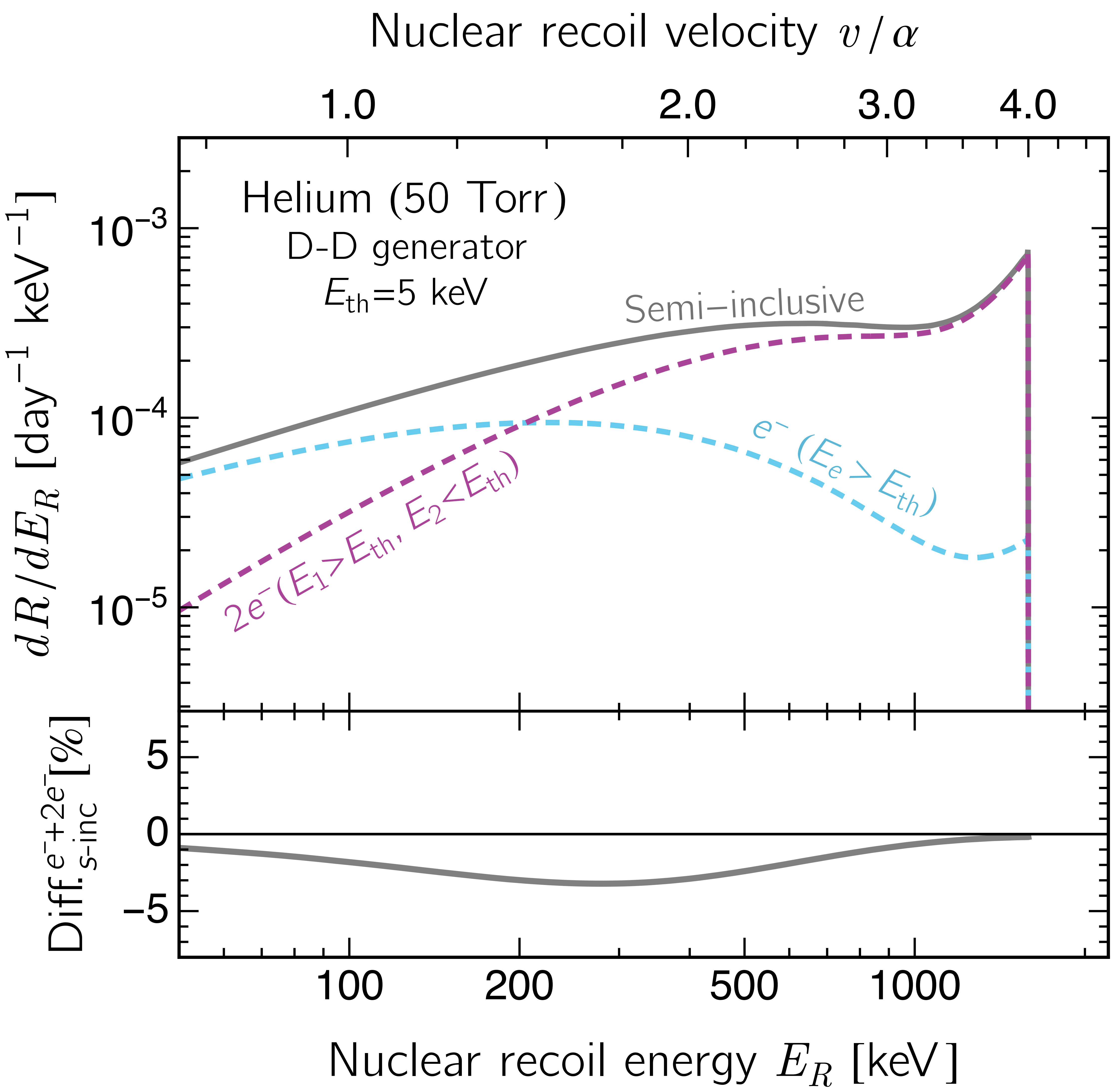
$$\exp\left(i m_e \mathbf{v} \cdot \sum_{a=1}^{N} \mathbf{r}_a \right) \approx 1 + i m_e \mathbf{v} \cdot \sum_{a=1}^{N} \mathbf{r}_a$$

Impact: Our calculation remains valid at large nuclear speed (NR energy);
and we can calculate single ionisation, double ionisation, single ionisation + excitation, …

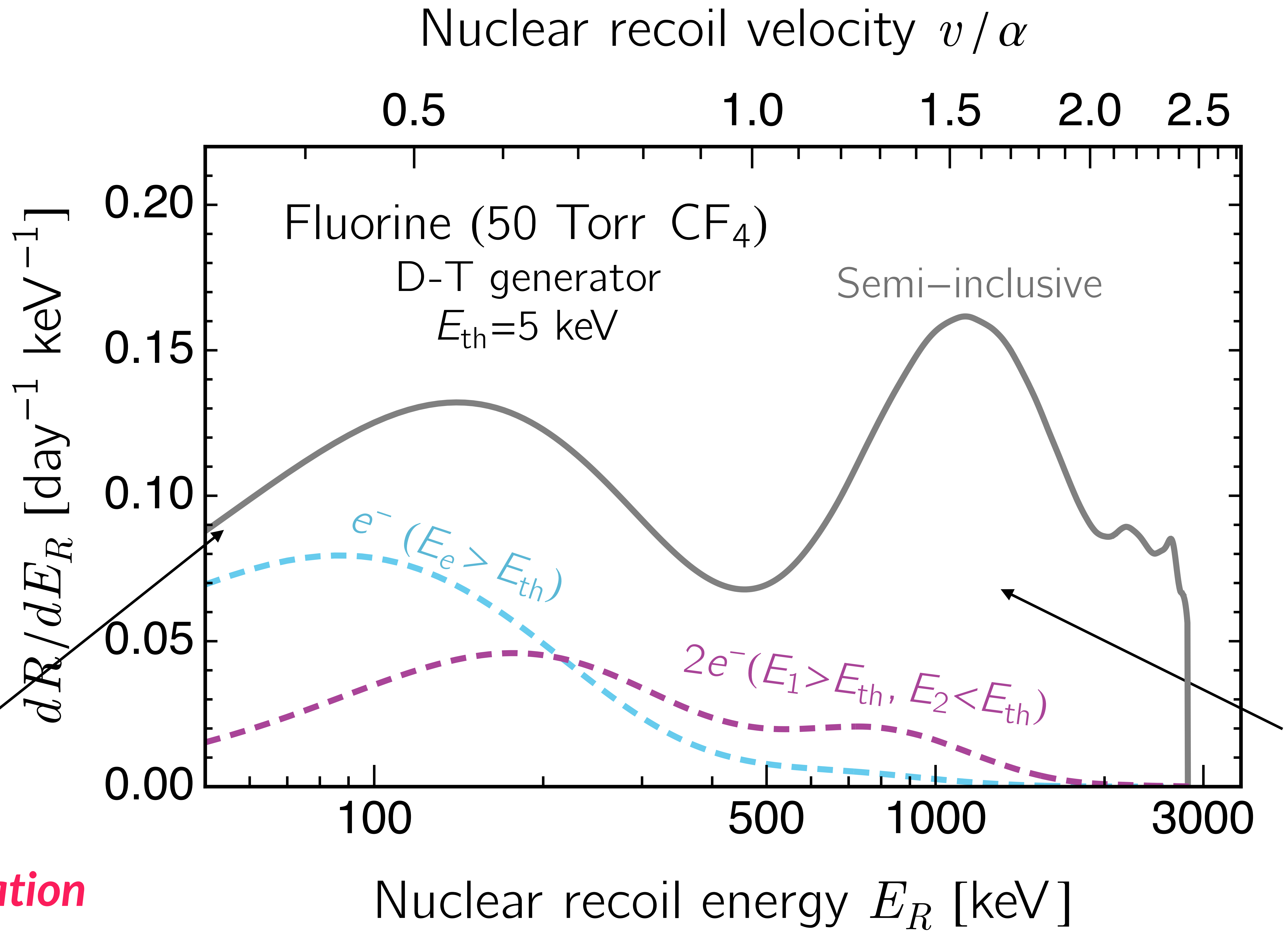
GRASP [Jonsson et al, Comput. Phys. Commun. 177, 597 (2007); Jonsson et al, Comput. Phys. Commun. 184, 2197 (2013); Froese Fischer et al, Comput. Phys. Commun. 237, 184 (2019)], RATIP [Fritzsche, Comput. Phys. Commun. 183, 1525 (2012)], BERTHA [Quiney et al, Adv. Quantum Chem. 32, 1 (1998)], FAC [Gu, Canadian Journal of Physics 86, 675 (2008)]

Helium neutron scattering rates (DD=2.47 MeV)

Helium provides a sanity check of semi-inclusive probability across all energies - it works!



Fluorine neutron scattering rates (DT=14.7 MeV)



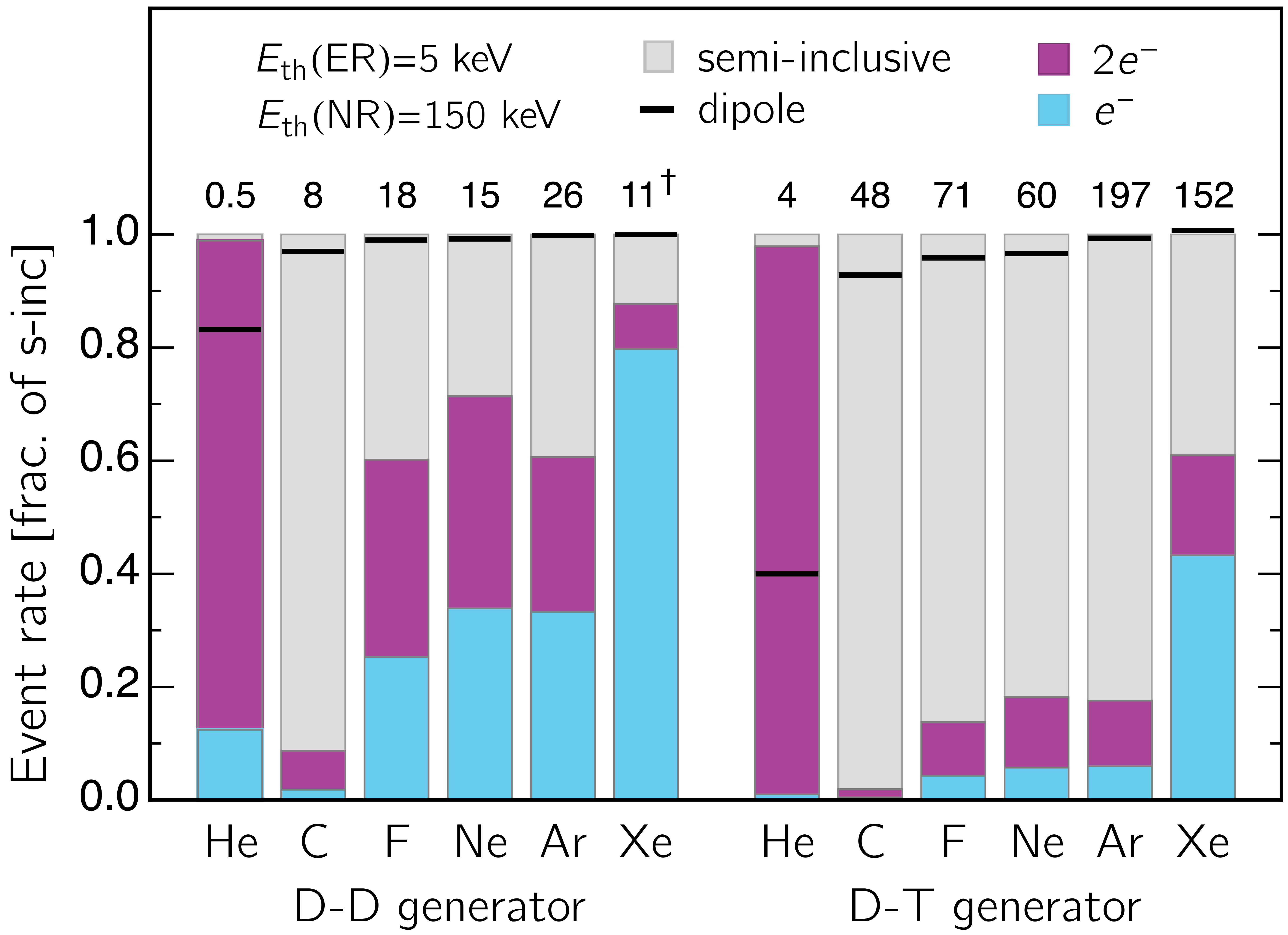
Peaks/troughs from neutron cross-section

Semi-inclusive includes contributions from ionisation + excitation

Completely miss triple+quad... contributions at high recoil energy without semi-ionisation

Semi-inclusive rate is factor 5.9 higher than single+double ionisation

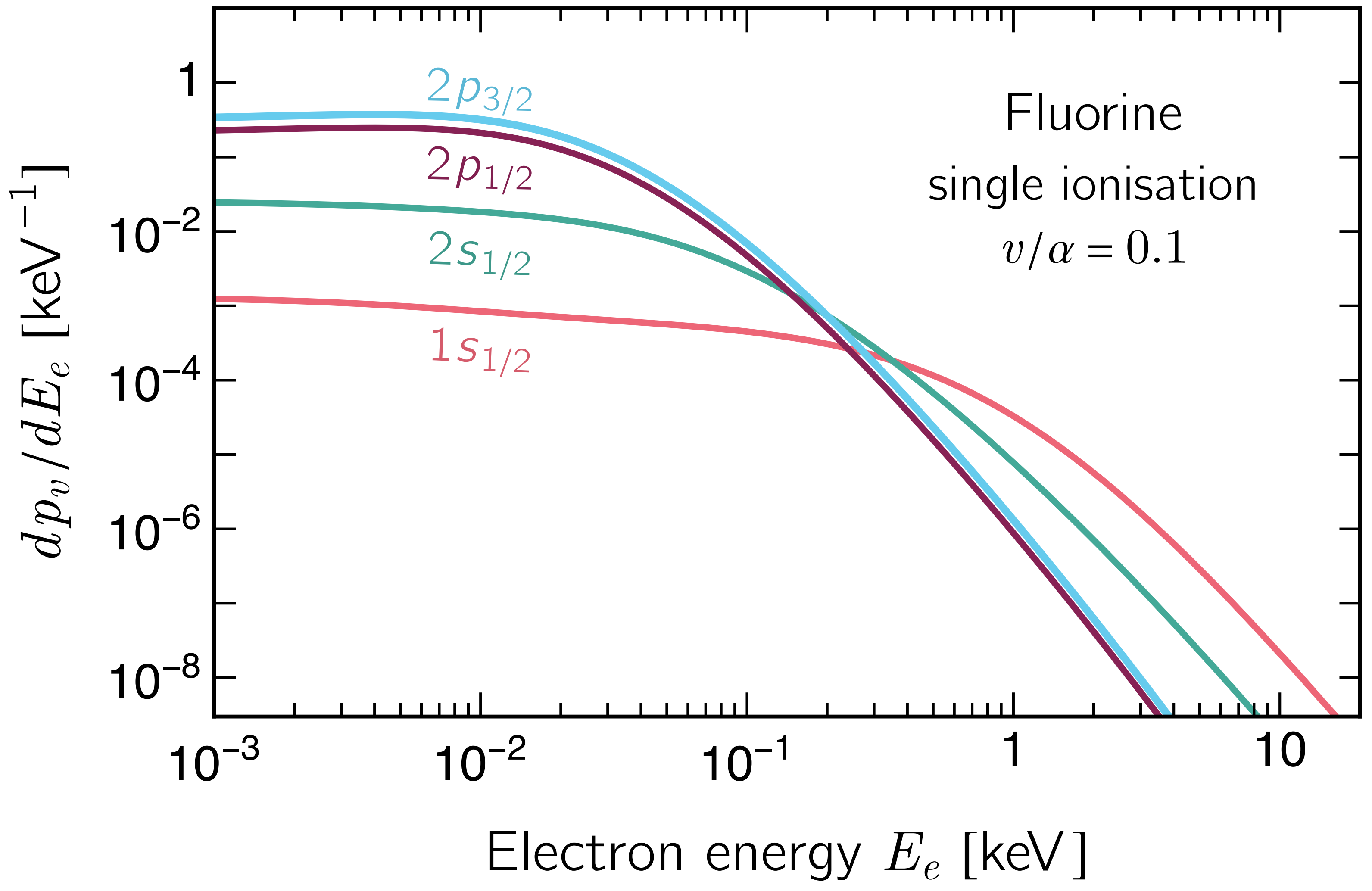
Integrated rates

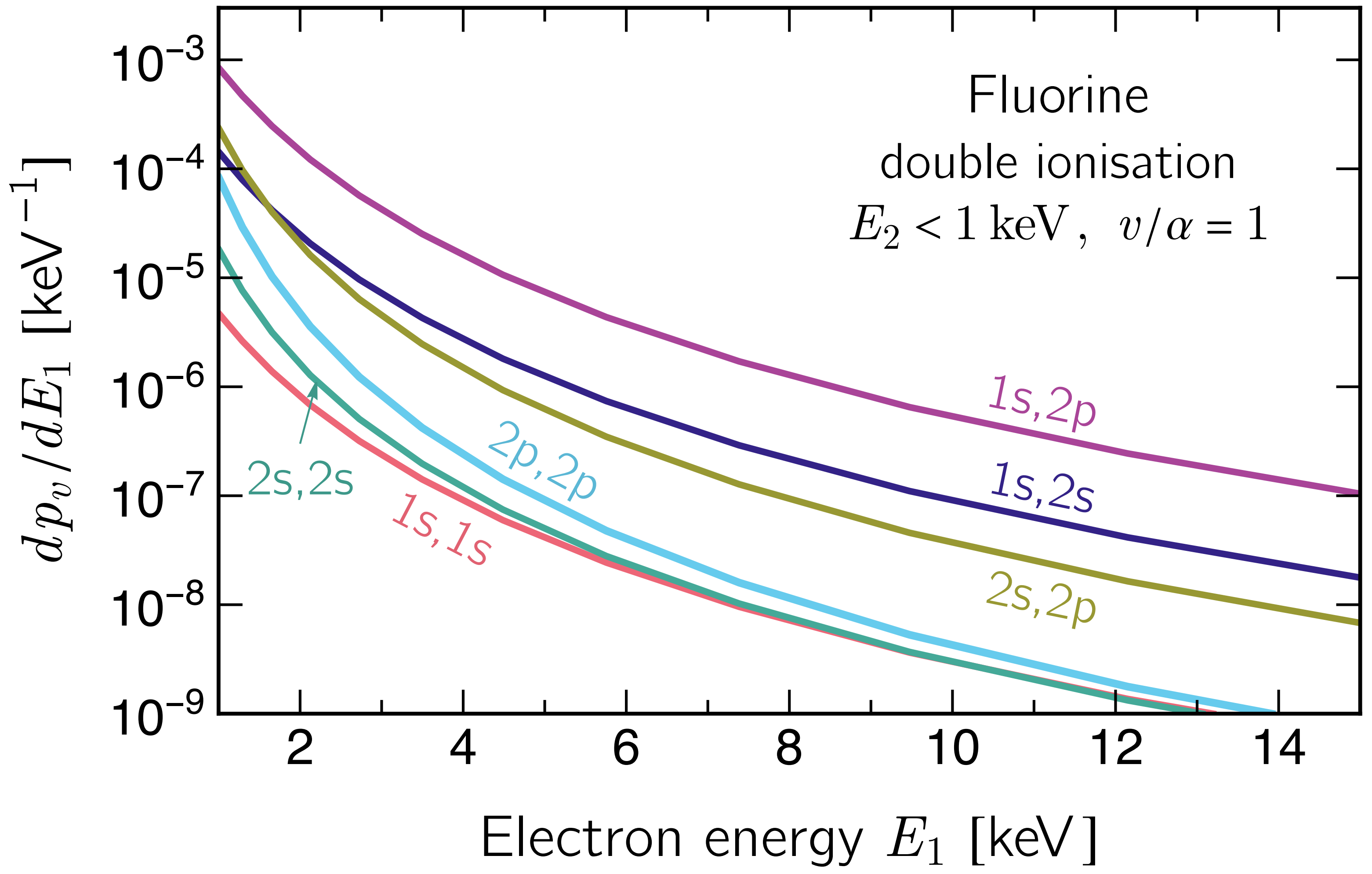


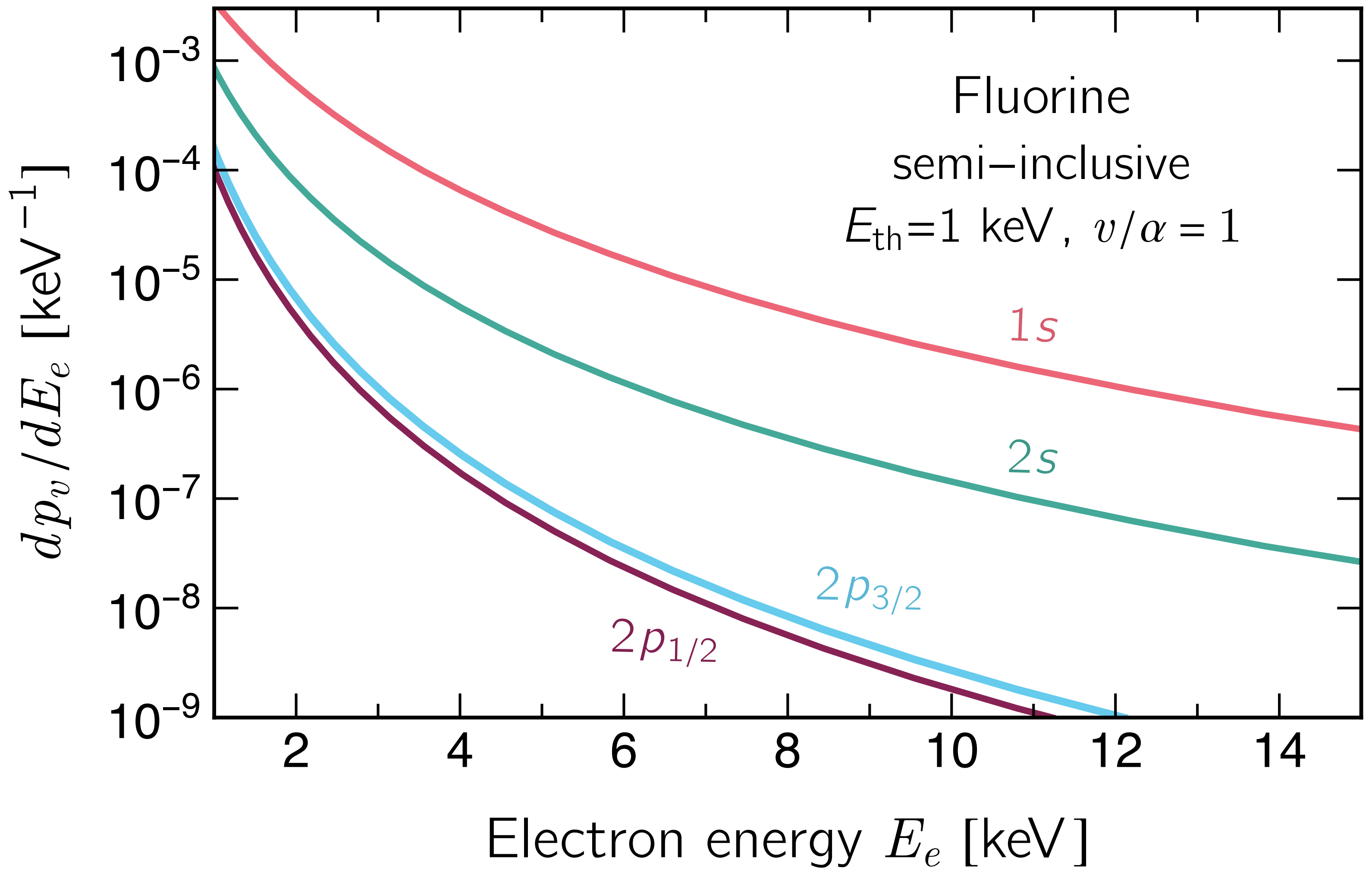
What shells are electrons ionised from?

Most likely configuration for single-ionisation:
Hard electron from inner-shell
Soft-electron from valence-shell

Most likely configuration for ionisation scenario with 1 hard- and soft-electrons:
Hard-electron from inner-shell with soft-electron from valence-shell



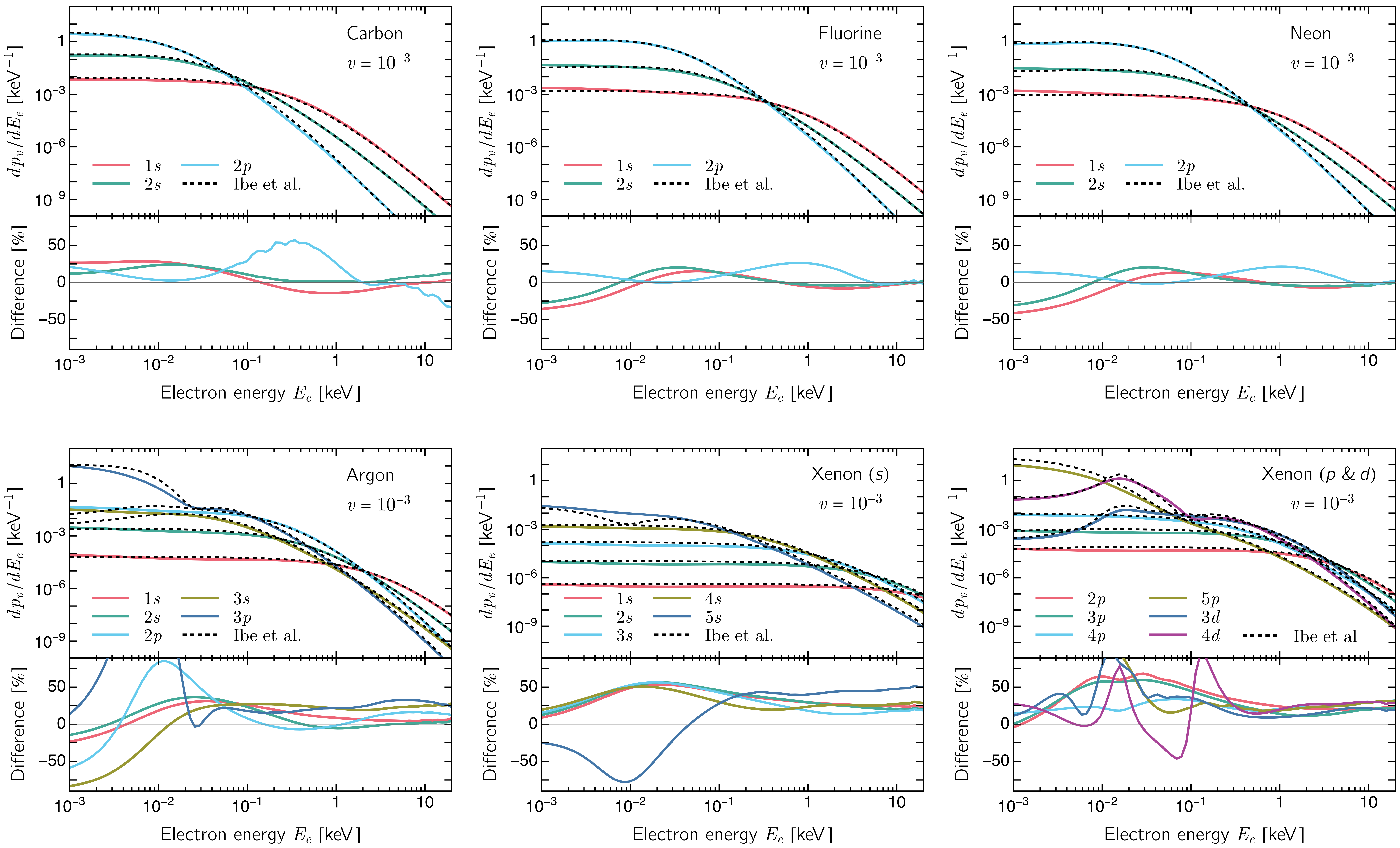




Comparison with Ibe et al

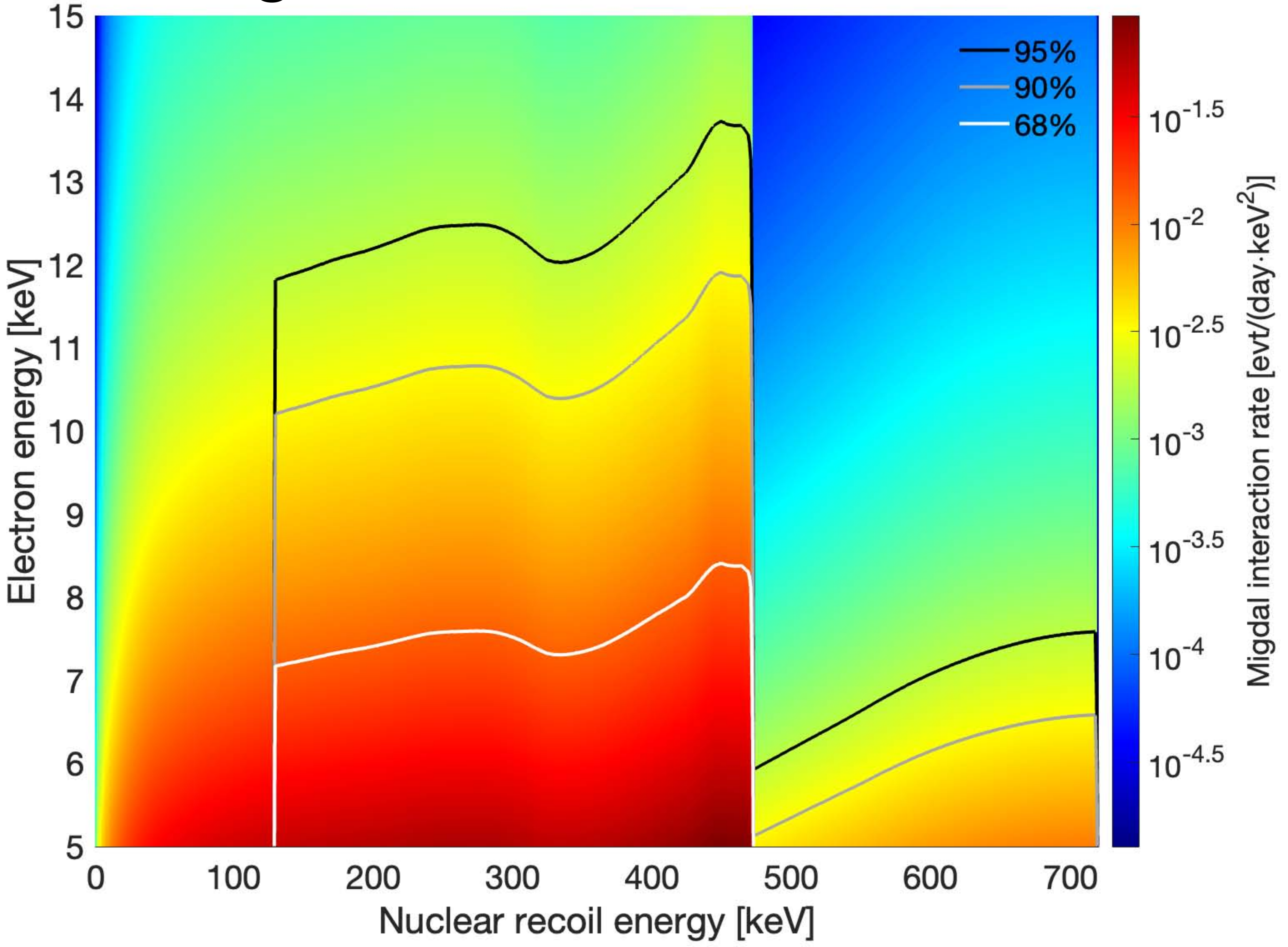
Comparison is at small v: when dipole approx is accurate

Agreement to ~25% in experimentally interesting parameter space

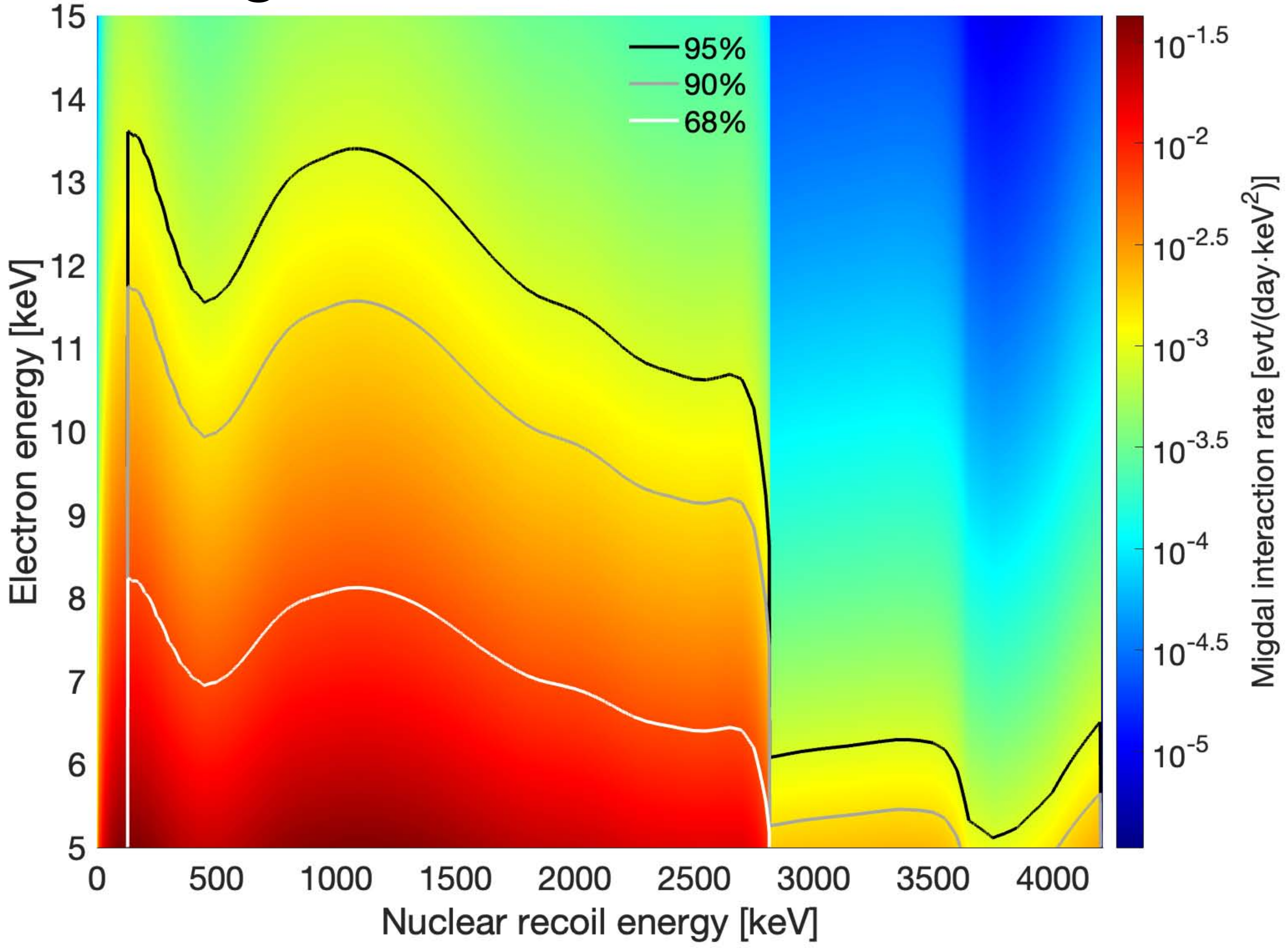


Event-rate map for MIGDAL experiment

D-D generator (CF4, 50 Torr)



D-T generator (CF4, 50 Torr)



Thresholds

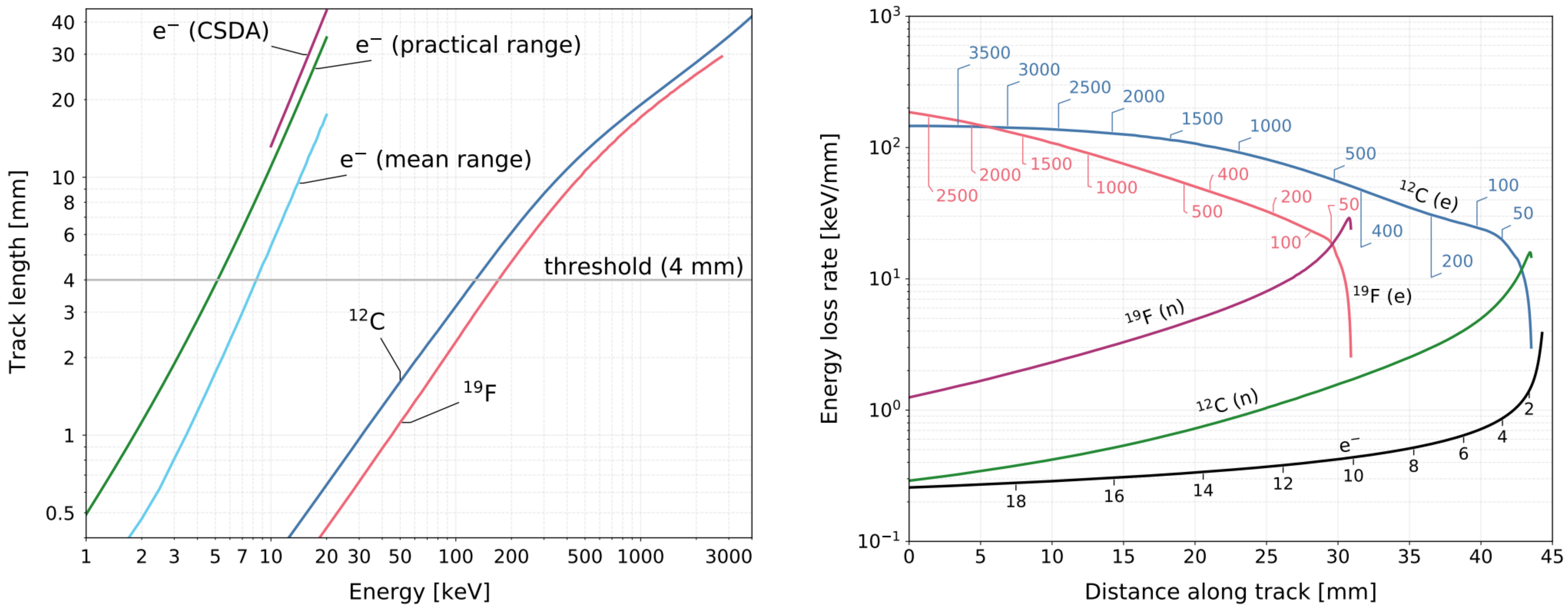


Figure 2: Left – Track length in CF_4 at 50 Torr for electrons (mean projected range calculated with Degrad [48], CSDA range with ESTAR [51], and the practical range formula from Ref. [52]), and mean projected range for carbon and fluorine ions from SRIM [49]). Right – Electronic and nuclear energy loss rates (CSDA) along carbon and fluorine ion tracks in CF_4 at 50 Torr, calculated with SRIM and electronic energy loss for 20 keV electrons obtained with ESTAR; called out values are interim particle energies (in keV) remaining at that point in the track.

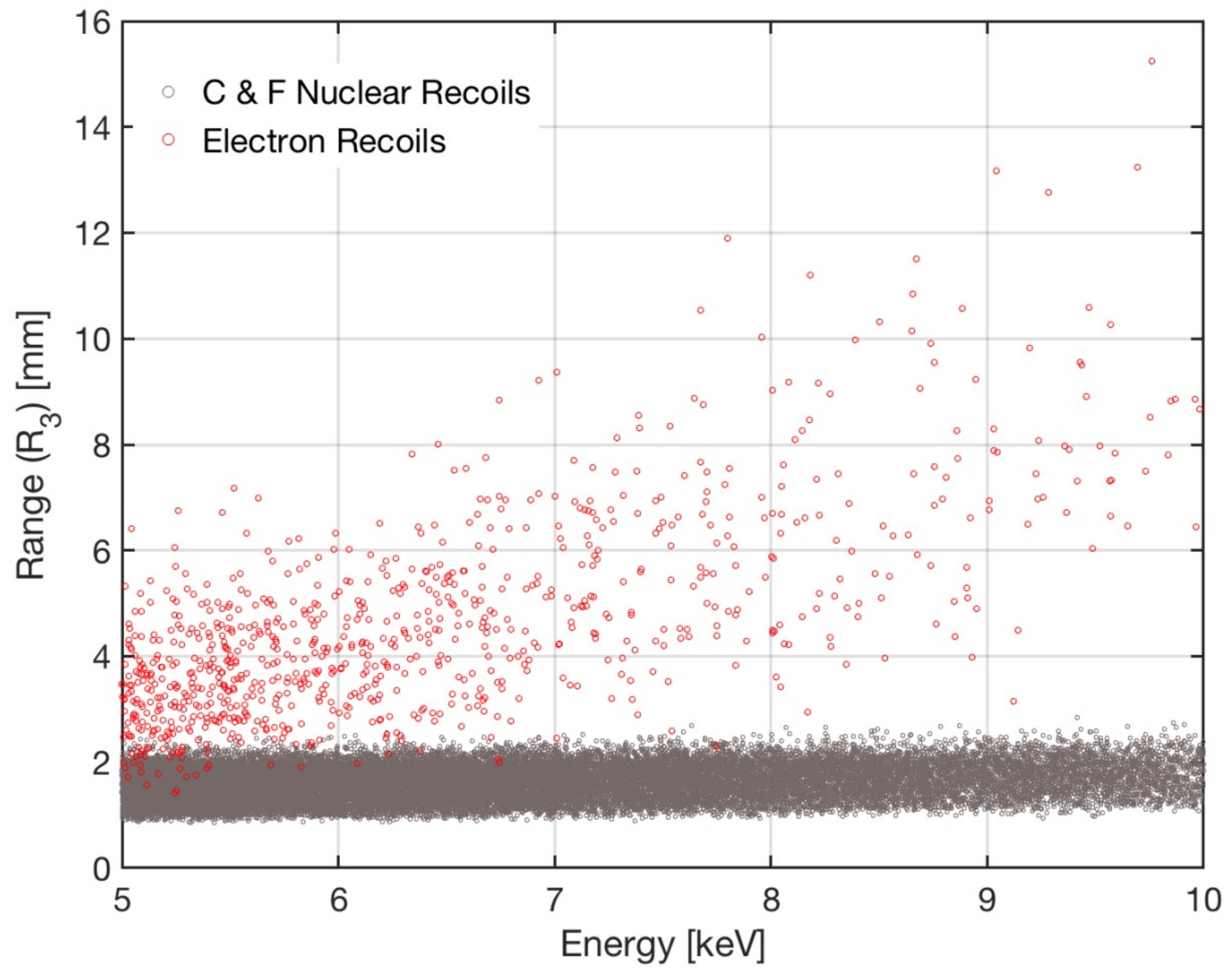
Backgrounds

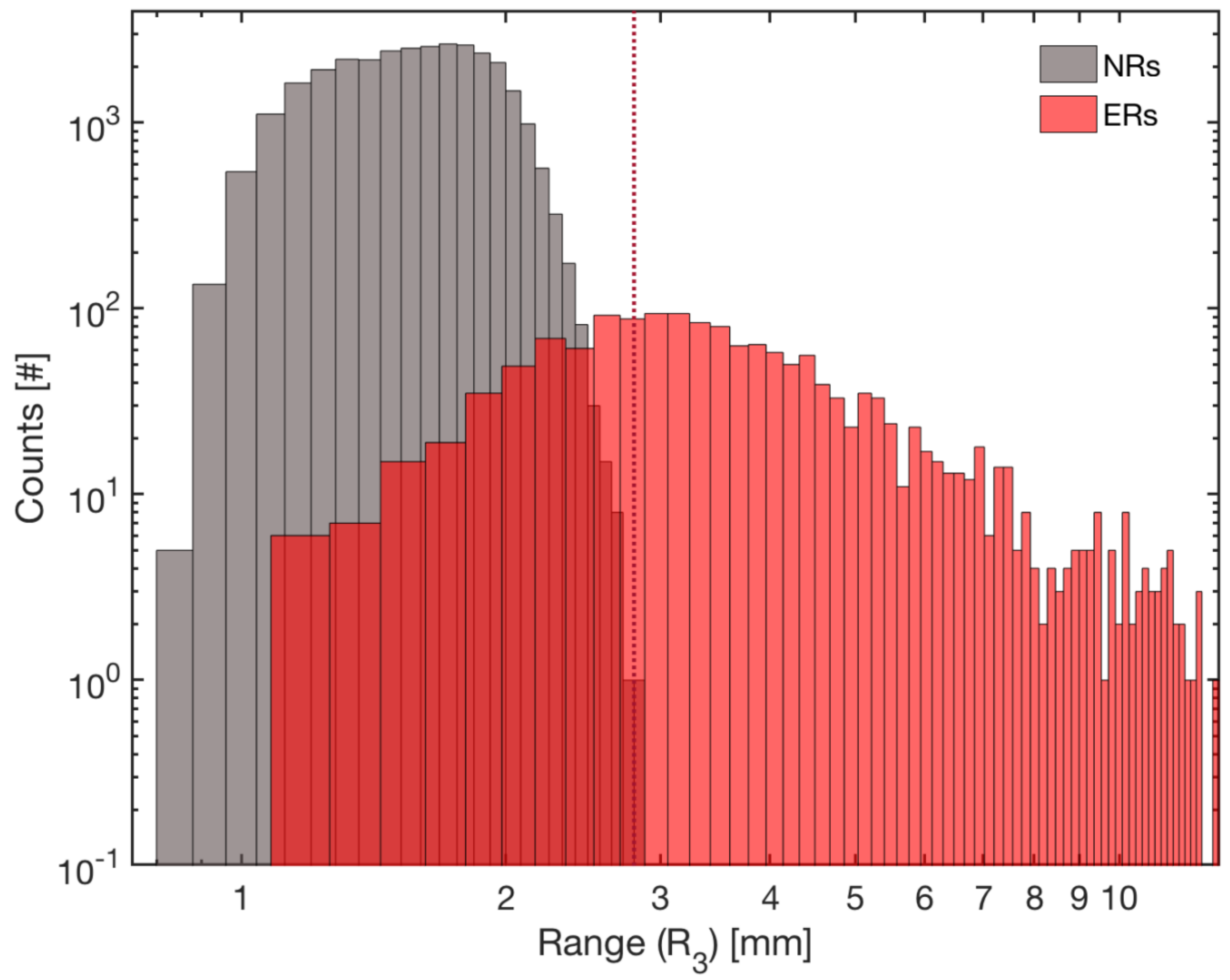
Secondary recoils per million primary ions (TRIM) created within 1 mm from the vertex in 50 Torr CF_4, when the "visible" energy of the secondary is 5–15 keVee.

Primary ion	Secondary ion	
Fluorine	Fluorine	Carbon
500 keV	22,310	4,800
400	26,840	5,930
300	36,640	7,640
200	56,130	1,263
170	67,040	1,418
Carbon	Fluorine	Carbon
500 keV	6,250	1,210
400	7,950	1,610
300	11,380	2,310
200	17,310	3,700
130	26,120	5,770

~70,000 per million (worst case)

How many of these look like 5-10 keV electrons? Simulate several thousand more tracks using full chain, analyse image and recover track lengths (R_3) Can cut down to ~1 per 70,000 secondaries, retaining 87% electron detection efficiency (i.e. ~1 per million primary recoils).





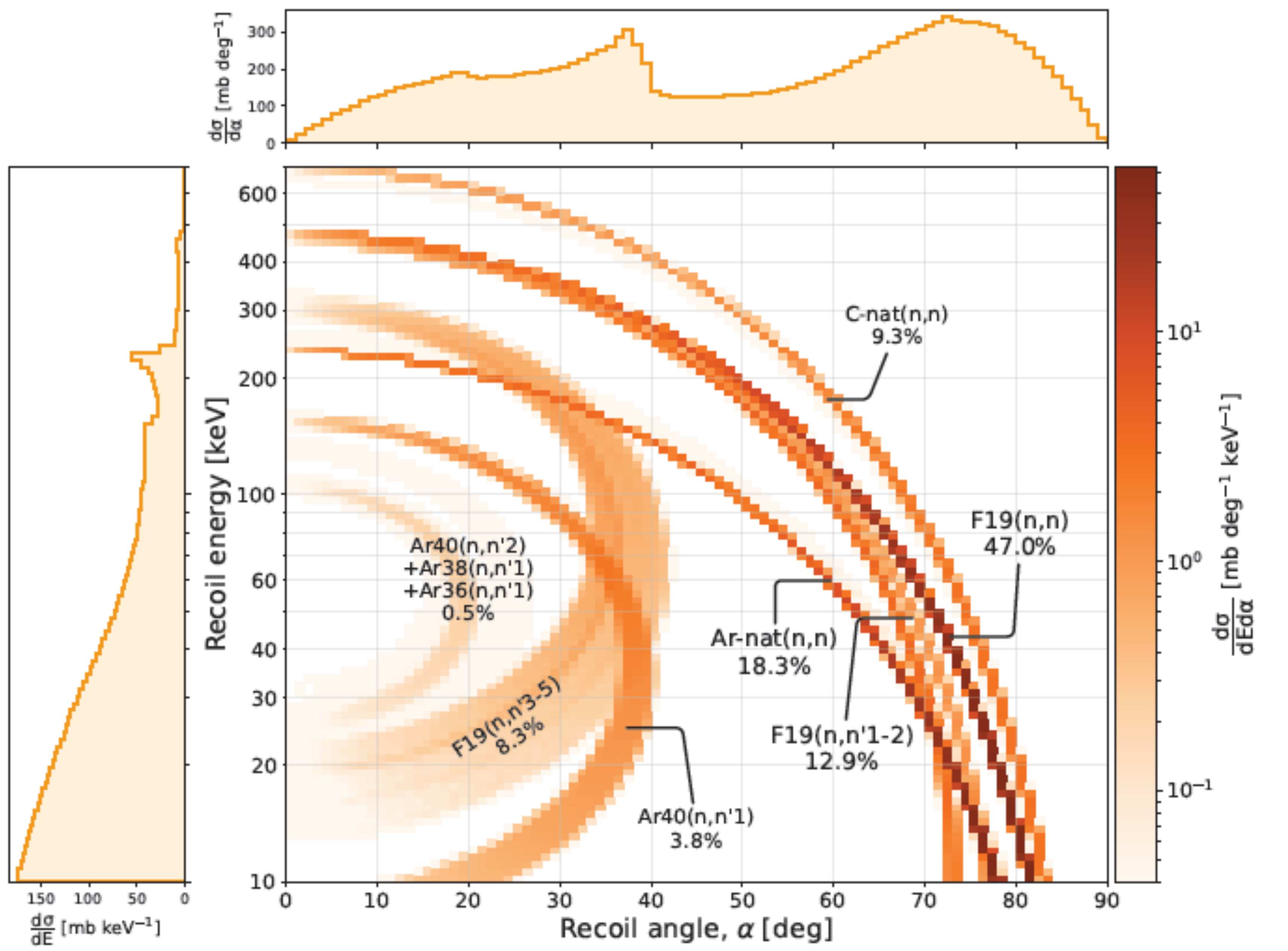
Migdal in other elements

Migdal probabilities in other elements of interest for DM searches which we aim to explore, mostly in mixtures with CF_4

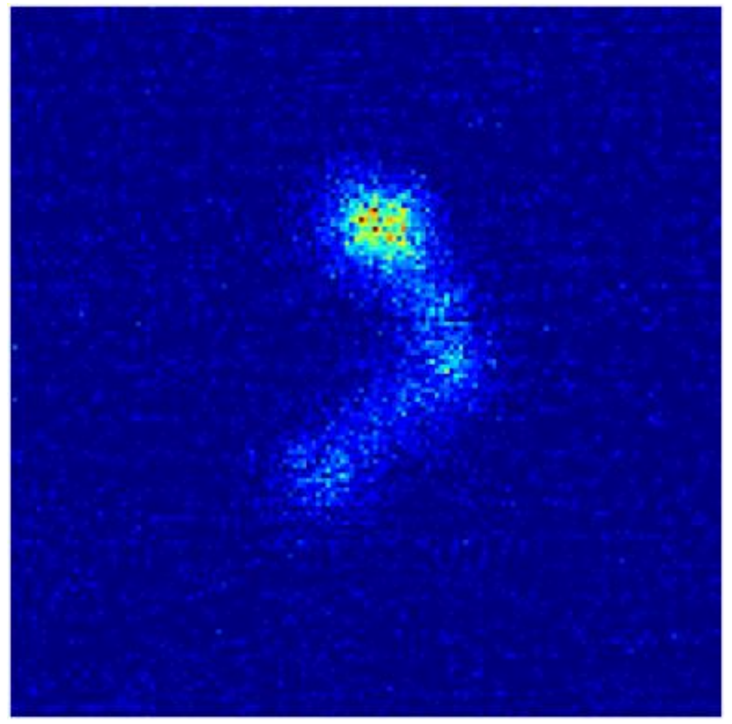
These probabilities are not too dissimilar (except for He)

Neutron scattering cross sections – total (σ_0) and bare-recoil processes (σ_s) plus Migdal probabilities for full neutron-induced NR spectrum, integrated down to zero NR threshold for electron thresholds of 0.5 keV and 5 keV (see C. McCabe's talk)

	2.47 MeV (D-D)				14.7 MeV (D-T)			
	σ_0, mb	σ_s, mb	P(>0.5 keV)	P(>5 keV)	σ_0, mb	σ_s, mb	P(>0.5 keV)	P(>5 keV)
^{4}He	3,239	3,239	2.98×10^{-3}	4.29×10^{-7}	1,017	1,017	9.01×10^{-2}	2.48×10^{-6}
^{12}C	1,613	1,613	6.01×10^{-3}	1.45×10^{-5}	1,379	1,321	2.15×10^{-2}	4.09×10^{-5}
^{19}F	3,038	3,038	2.81×10^{-3}	2.01×10^{-5}	1,786	1,272	9.95×10^{-3}	6.50×10^{-5}
^{nat}Ne	2,474	2,465	2.62×10^{-3}	2.32×10^{-5}	1,677	1,055	8.50×10^{-3}	6.89×10^{-5}
^{nat}Si	3,111	3,111	2.39×10^{-3}	2.87×10^{-5}	1,725	1,150	1.10×10^{-2}	1.25×10^{-4}
^{40}Ar	5,050	5,050	2.18×10^{-3}	2.92×10^{-5}	2,818	2,754	6.85×10^{-3}	8.94×10^{-5}
^{nat}Ge	3,401	3,401	1.64×10^{-3}	2.46×10^{-5}	3,227	3,130	5.47×10^{-3}	8.12×10^{-5}
^{nat}Kr	3,825	3,825	1.56×10^{-3}	2.37×10^{-5}	3,741	3,717	4.65×10^{-3}	7.03×10^{-5}
^{nat}Xe	5,760	5,760	7.31×10^{-4}	1.55×10^{-5}	4,871	4,861	2.80×10^{-3}	5.95×10^{-5}

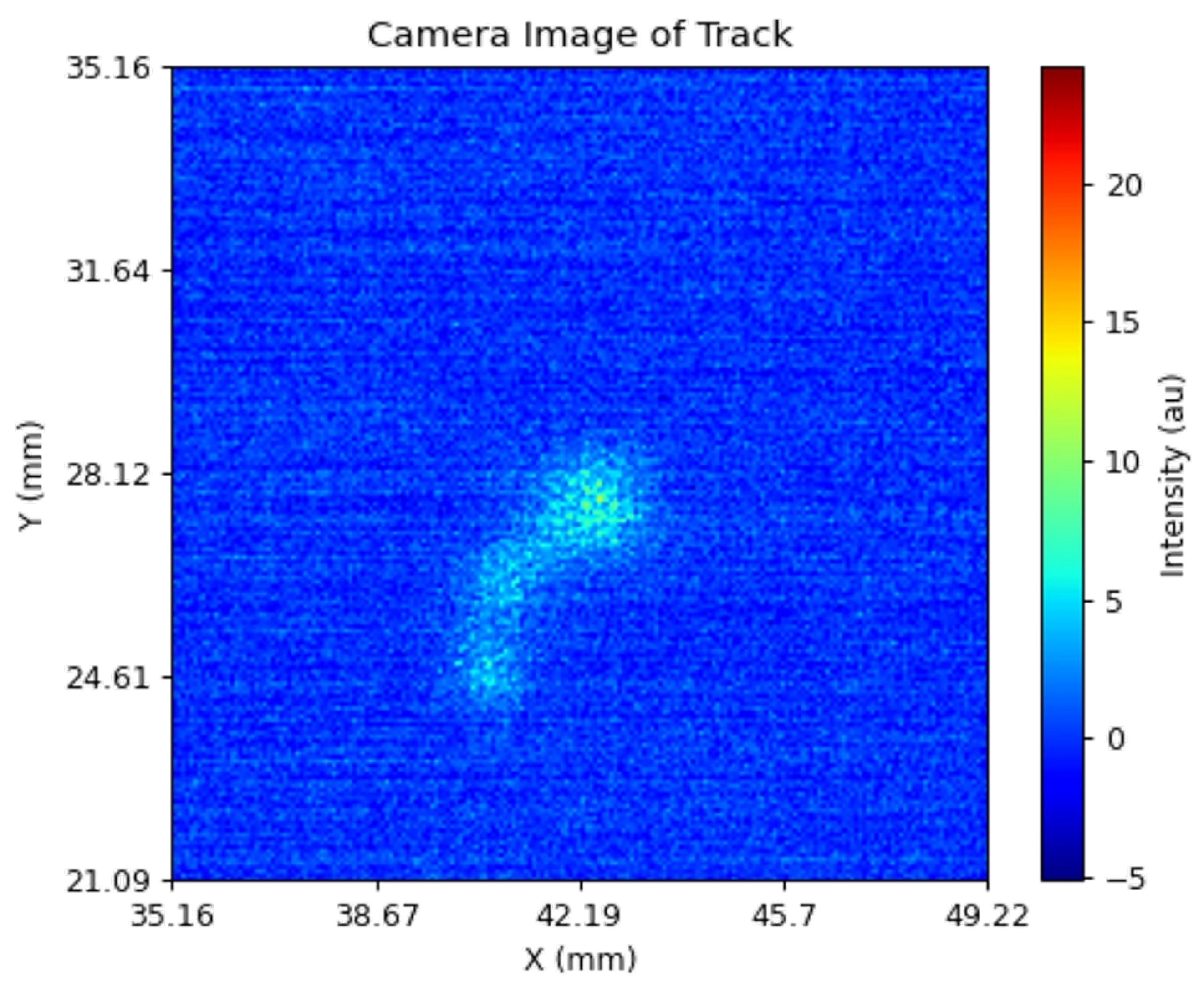


Energy-angle relations for D-D neutron scattering in 50% Ar/CF_4.

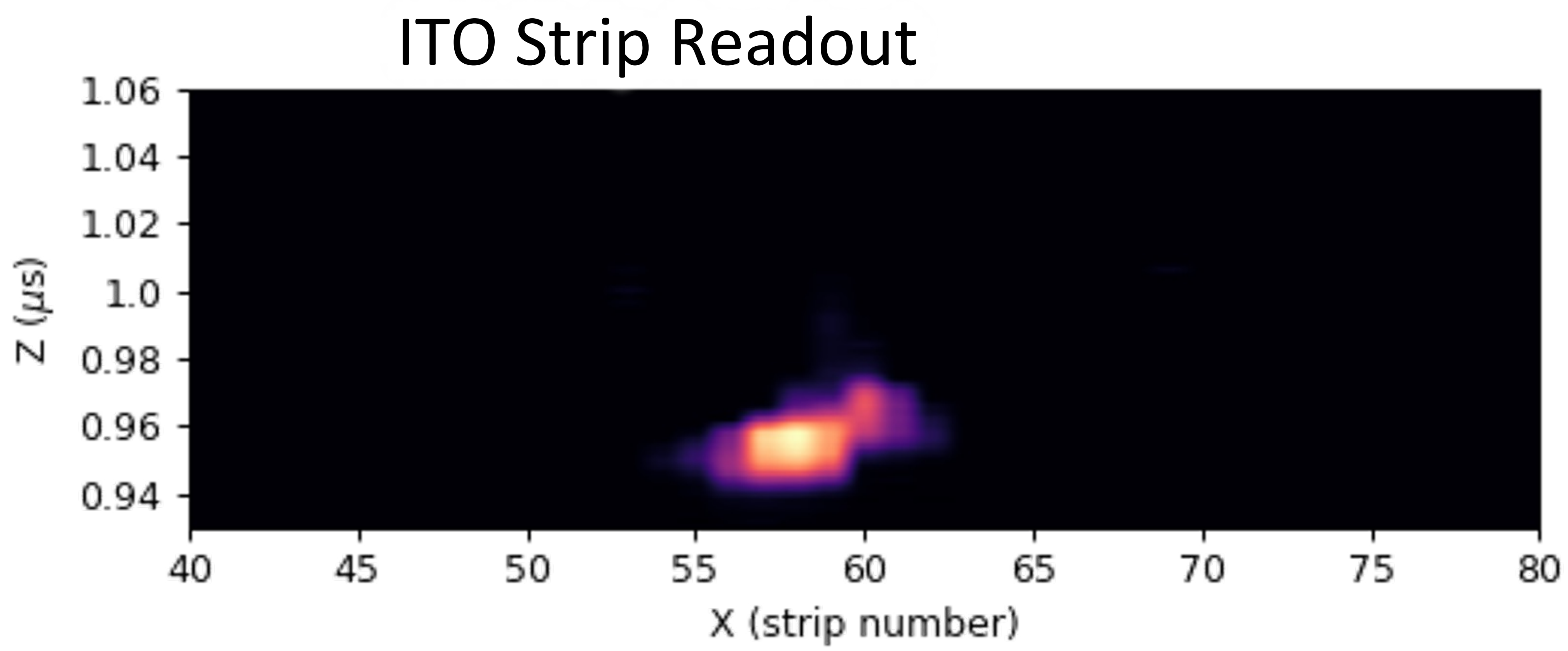


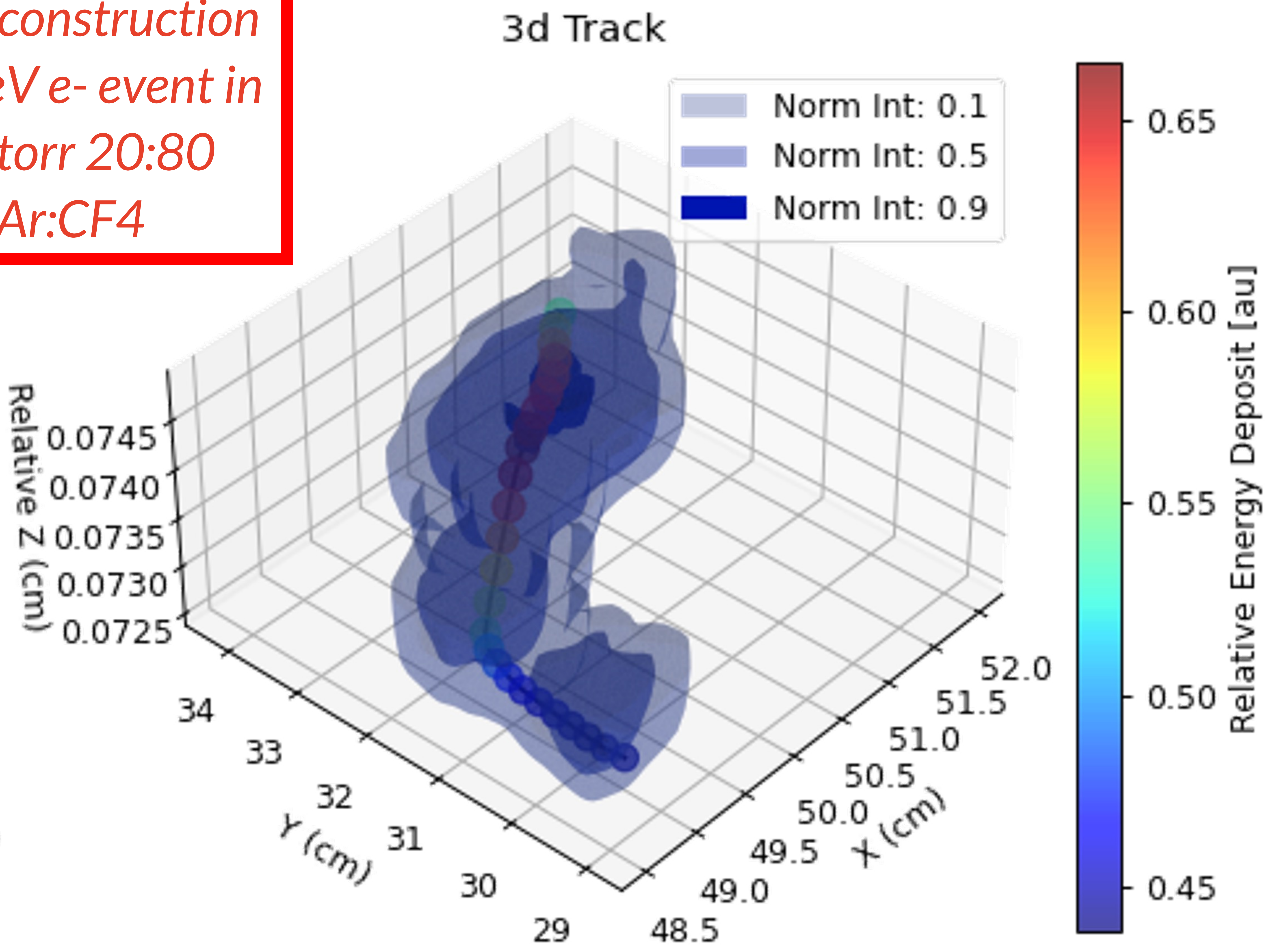
Blessing or curse? Auger emission in addition to Migdal electron

Track reconstruction with real data



3D reconstruction 5.9 keV e- event in 50 torr 20:80 Ar:CF4





Preliminary: still active area of development

Neutron cross sections