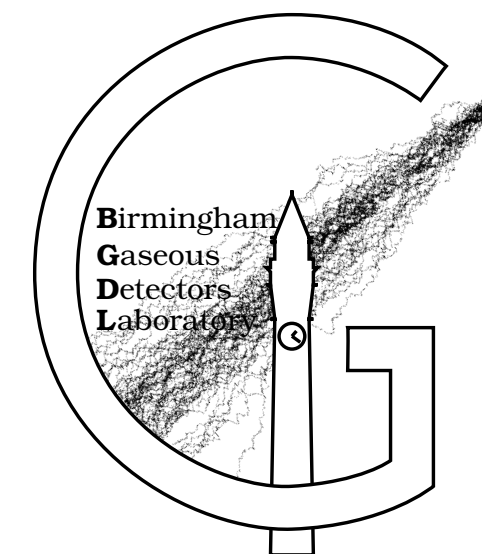




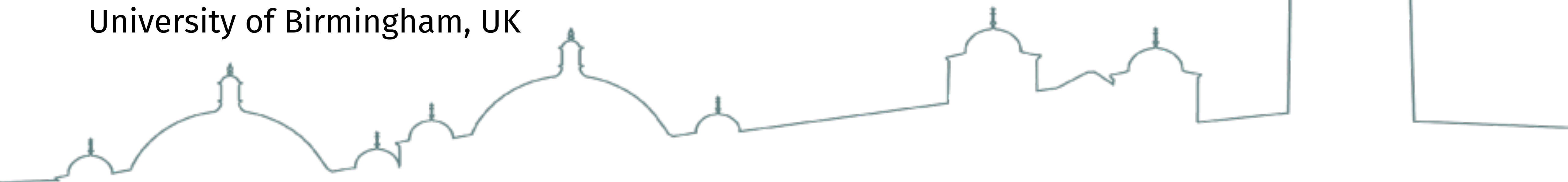
UNIVERSITY OF
BIRMINGHAM



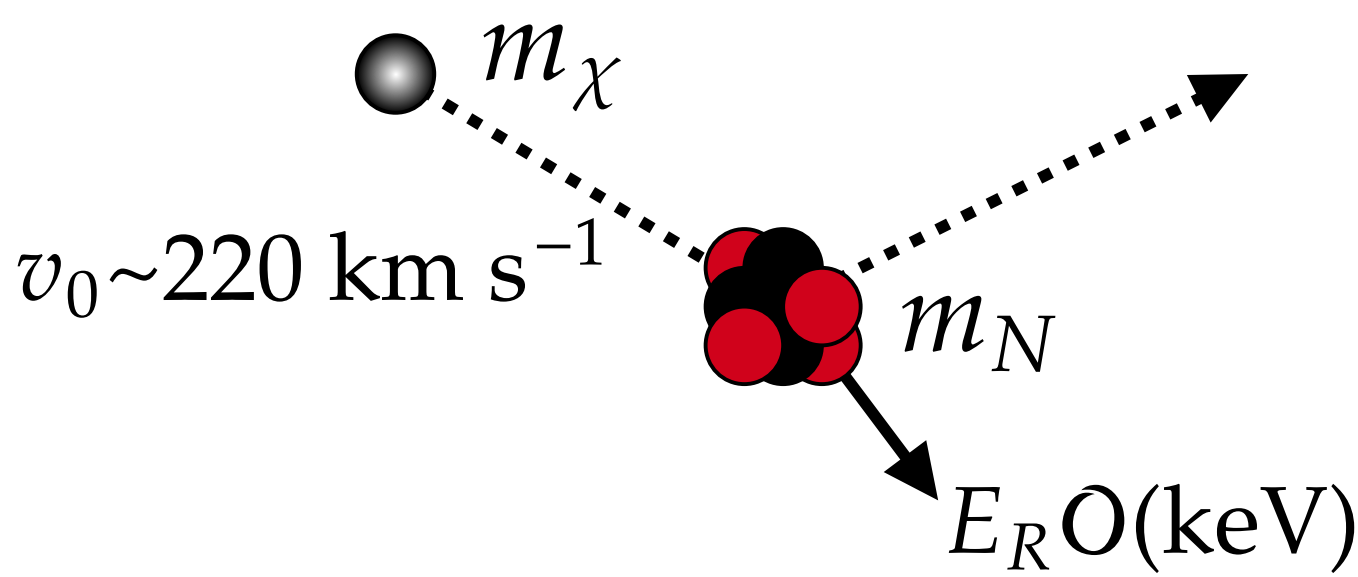
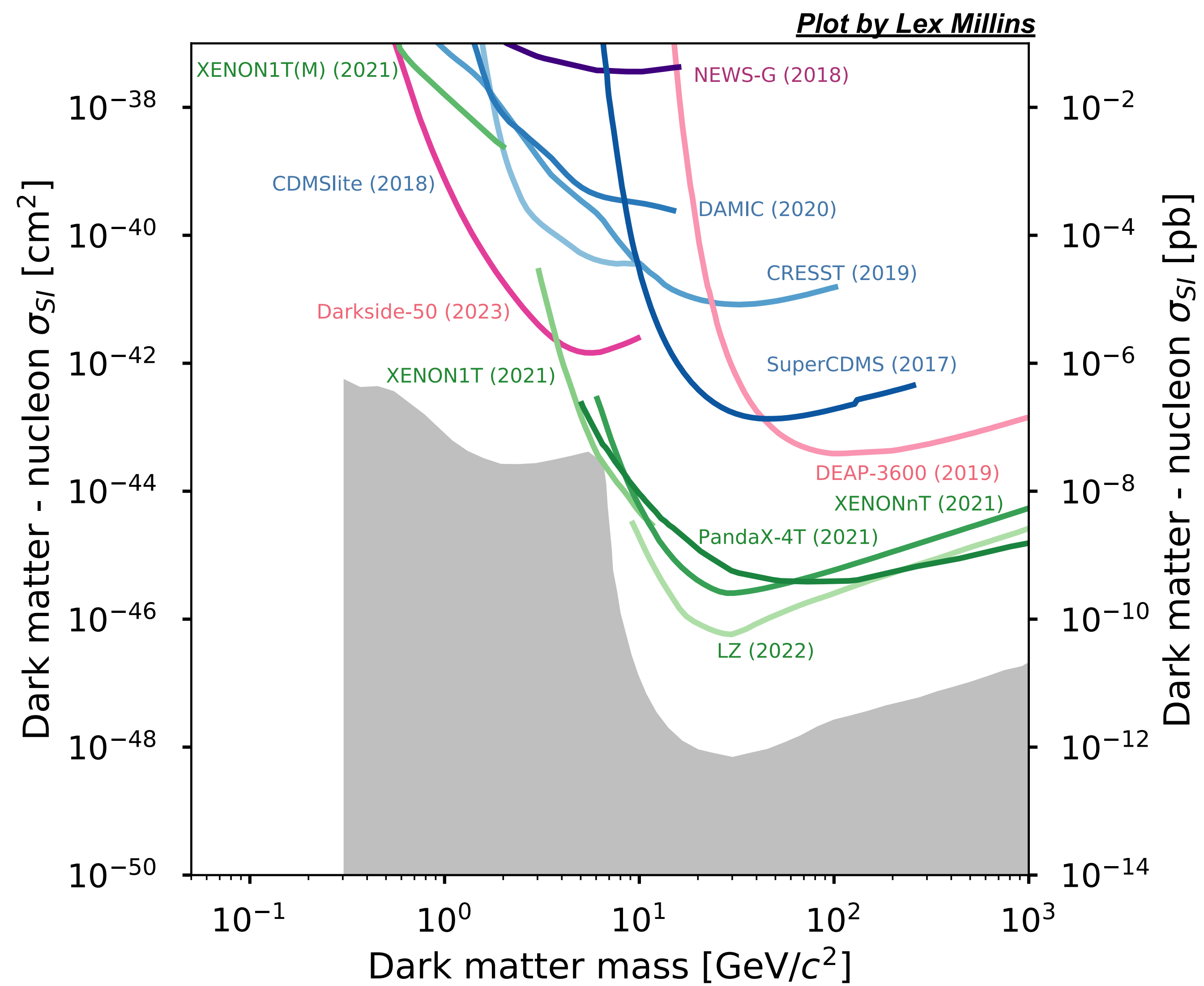
Light Dark Matter Searches with Spherical Proportional Counters

Patrick Knights

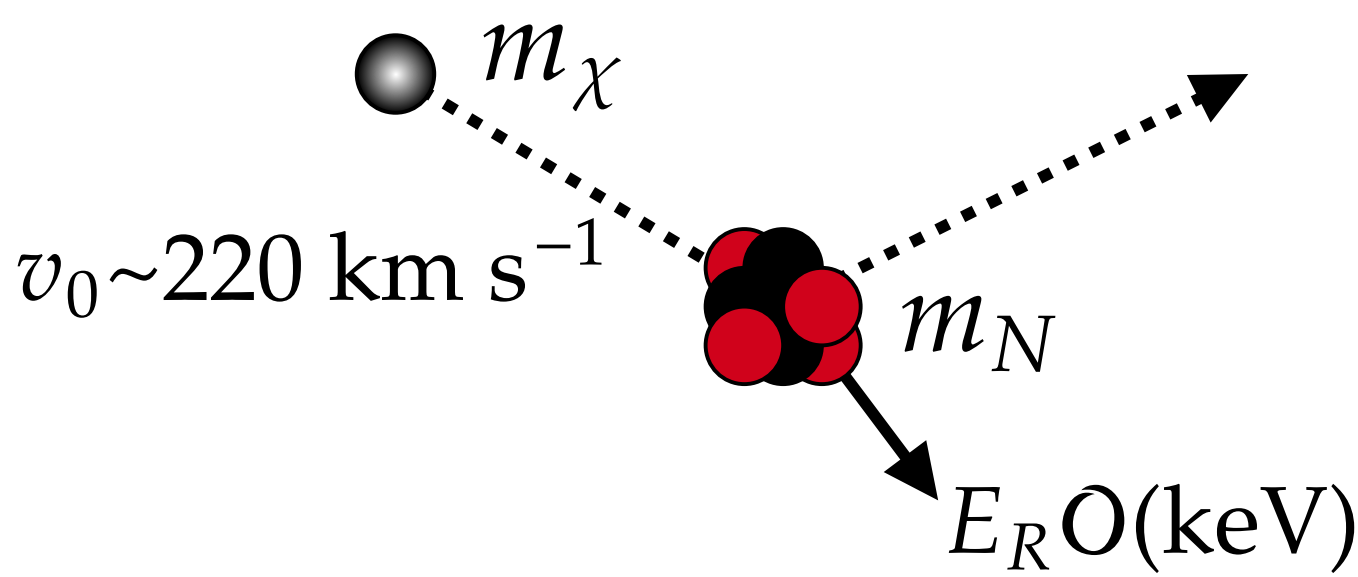
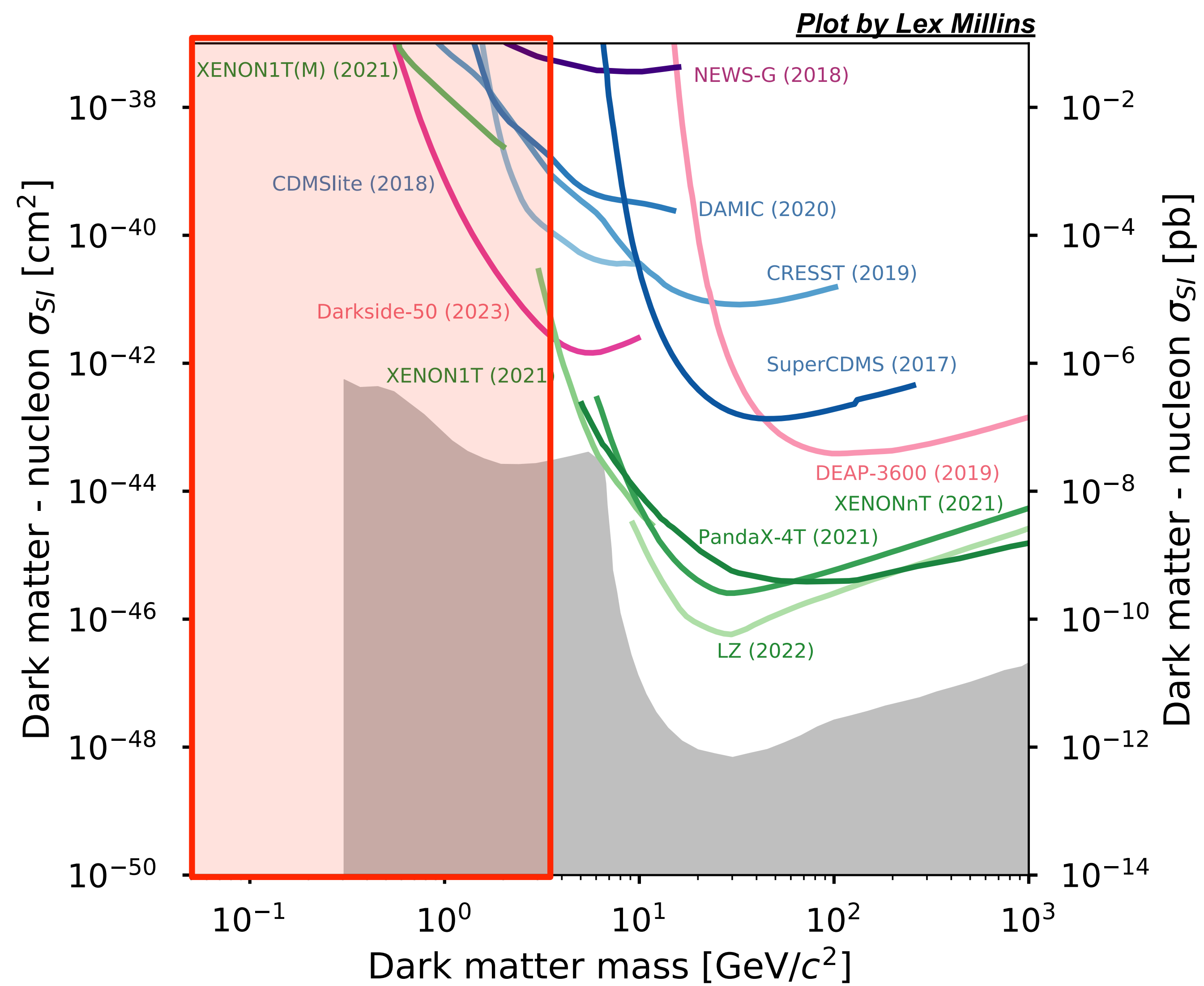
University of Birmingham, UK



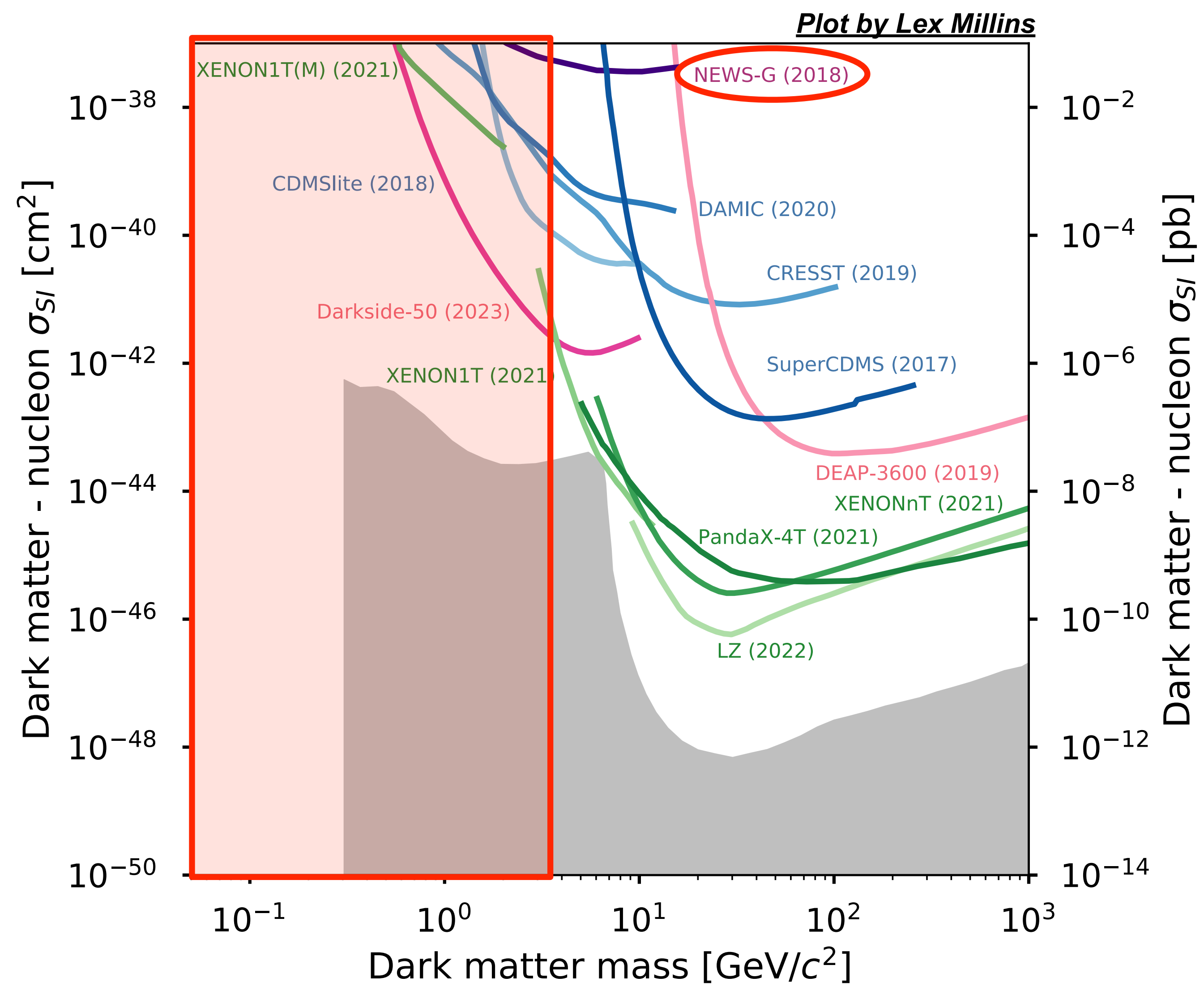
Particle Dark Matter Parameter Space



Particle Dark Matter Parameter Space

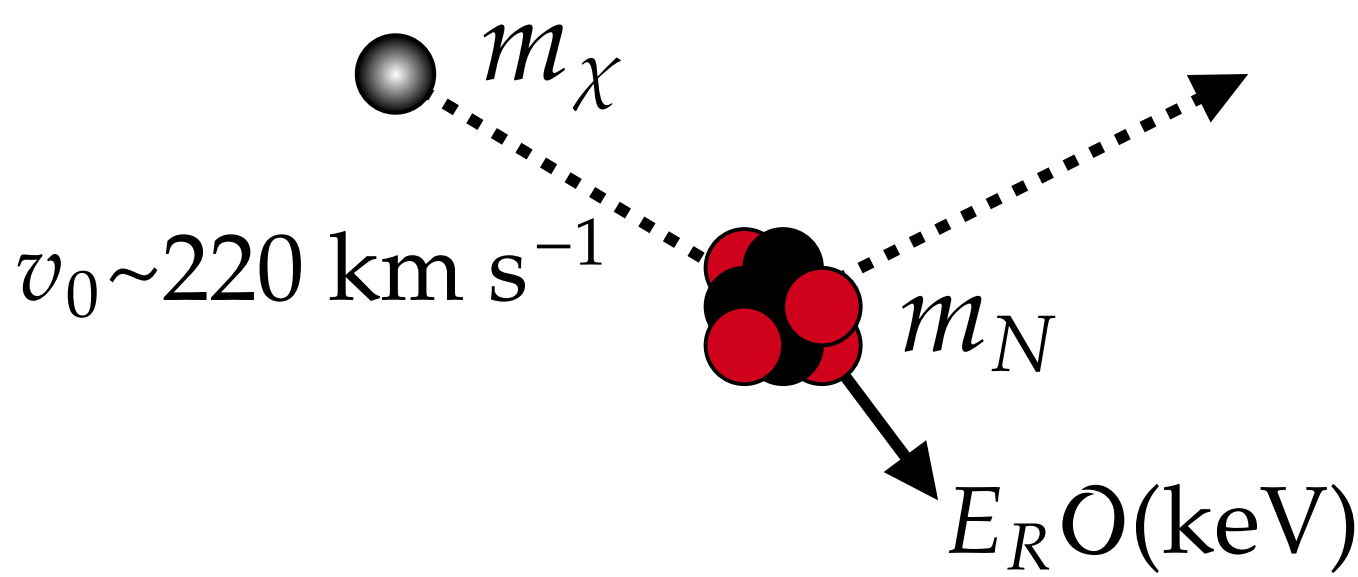


Particle Dark Matter Parameter Space

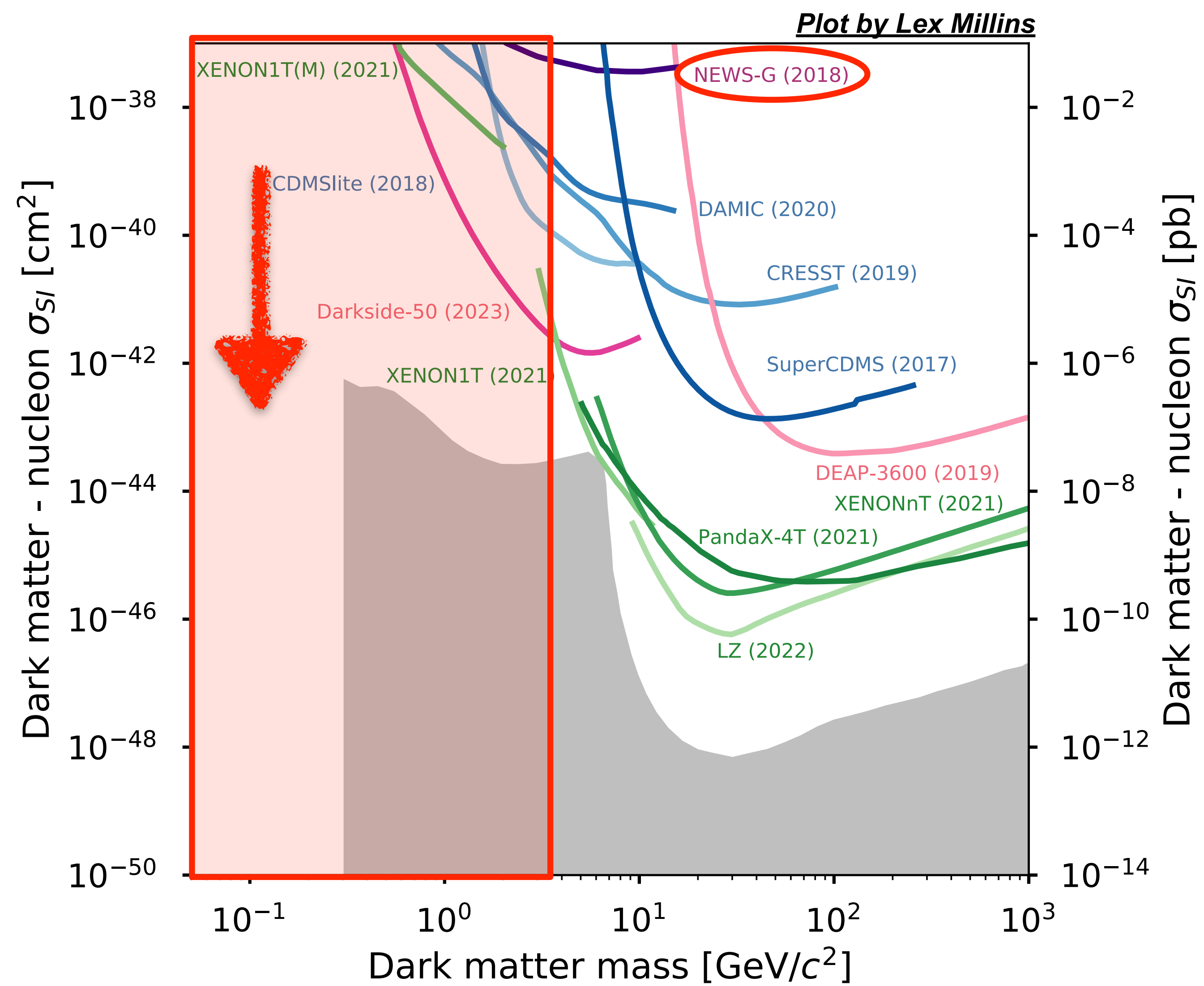


SEDINE, LSM

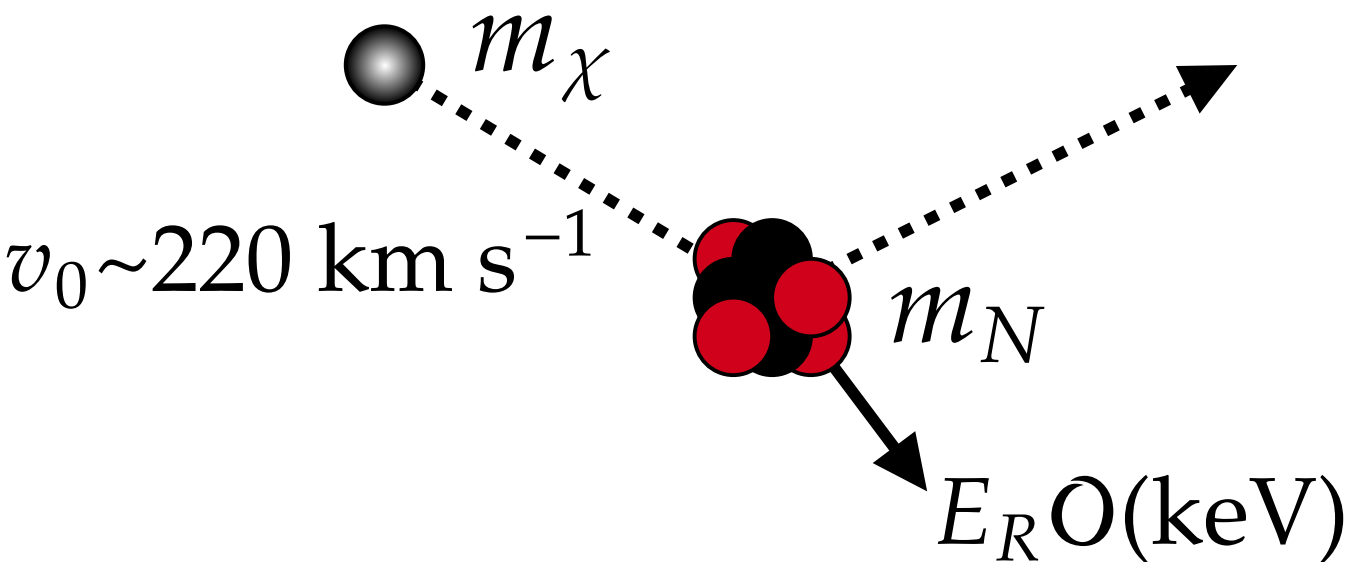
Astropart.Phys. 97 (2018) 54-62



Particle Dark Matter Parameter Space



SEDINE, LSM
Astropart.Phys. 97 (2018) 54-62



NEWS-G

Light DM searches with a novel gaseous detector, the spherical proportional counter



Boulby Underground Laboratory



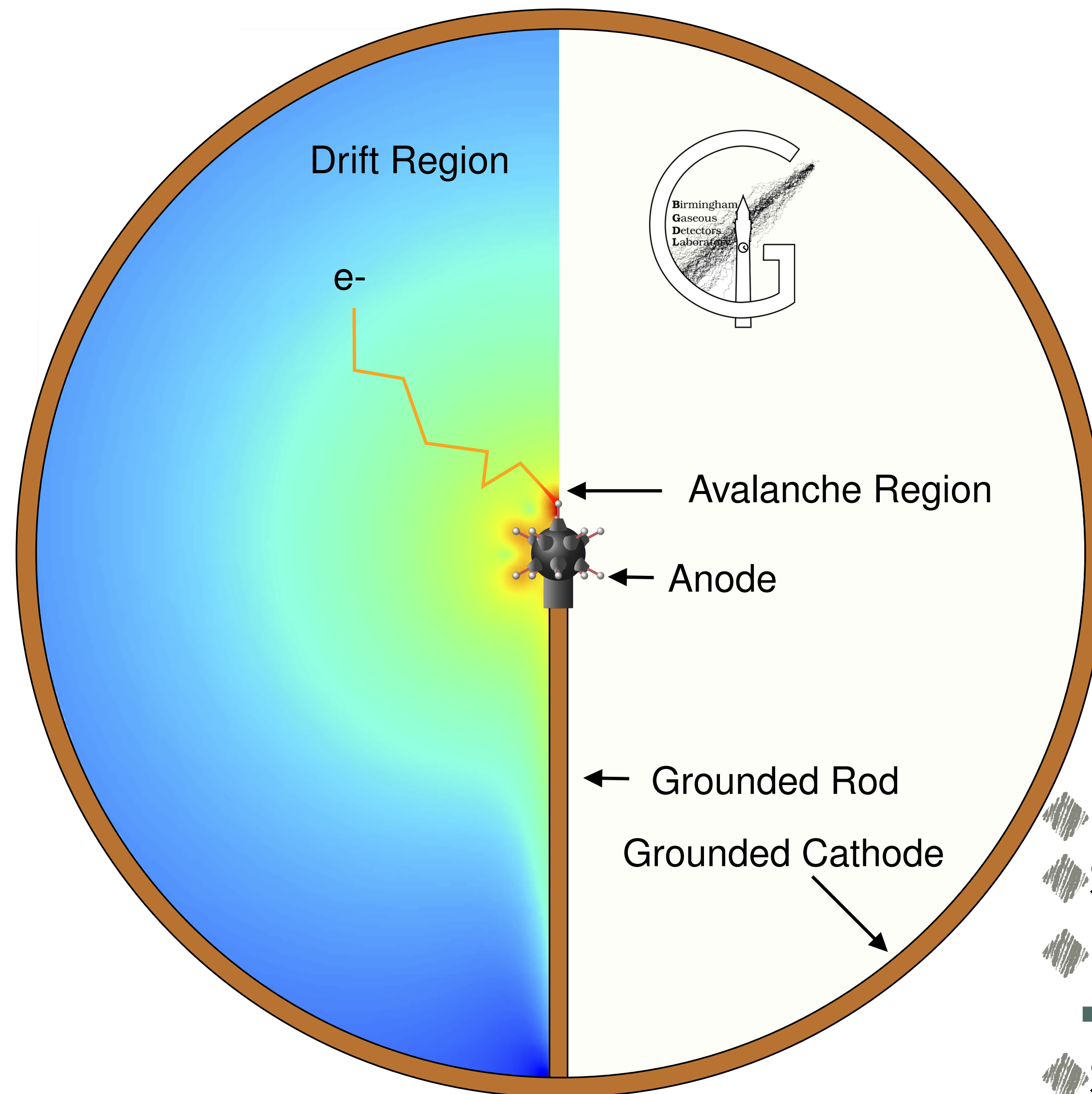
UNIVERSITY OF BIRMINGHAM



Universität Hamburg

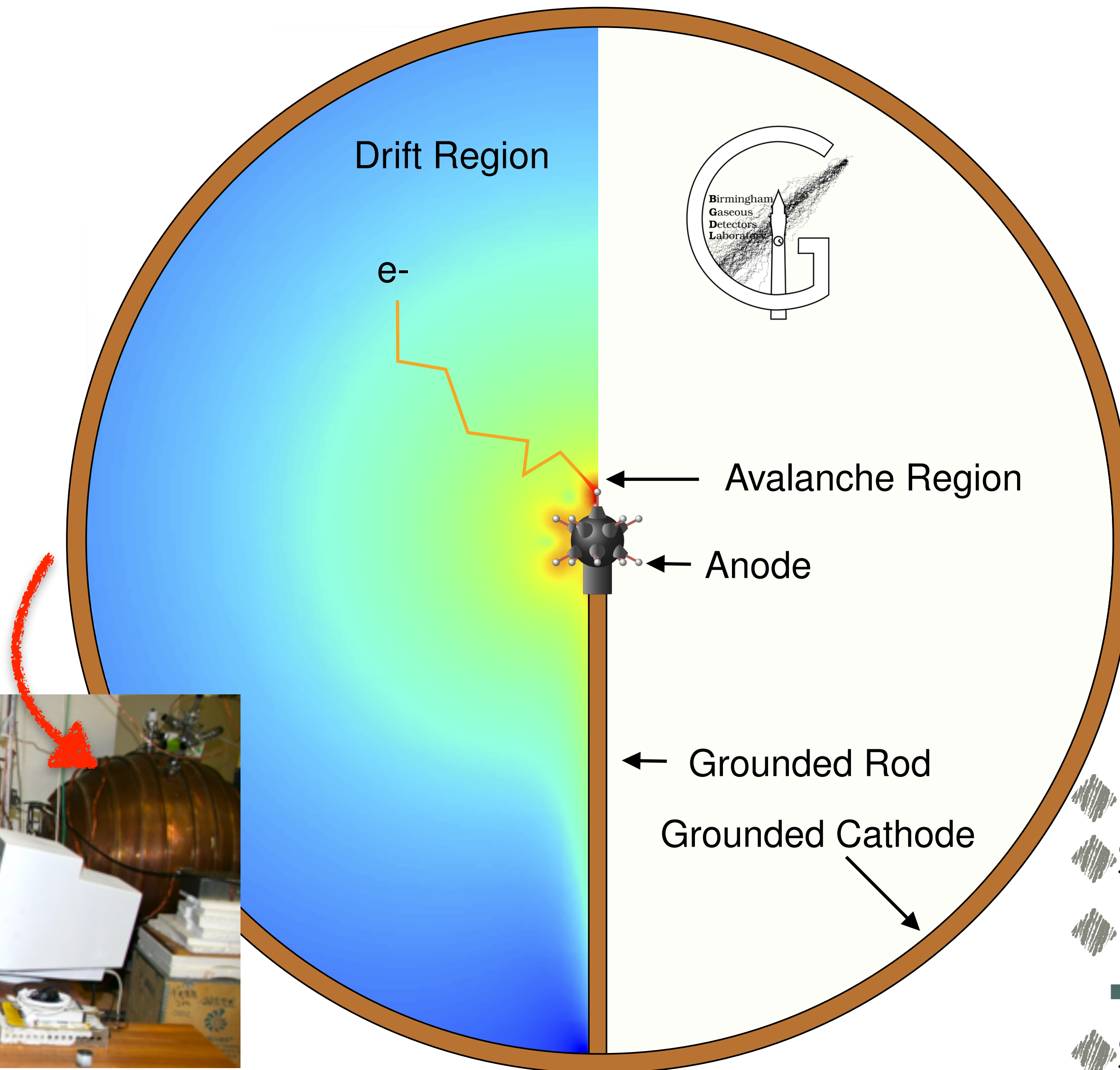
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Spherical Proportional Counter



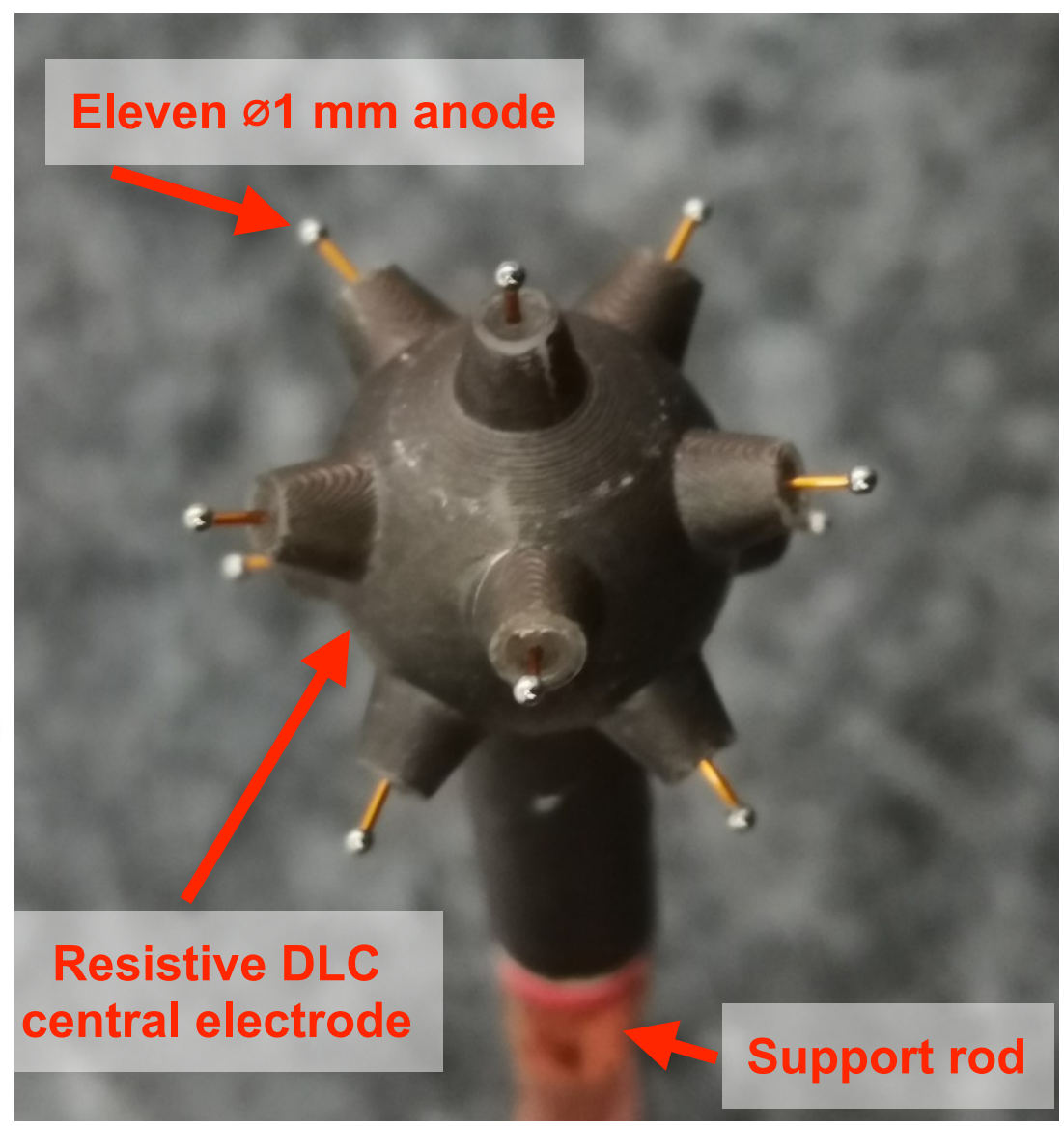
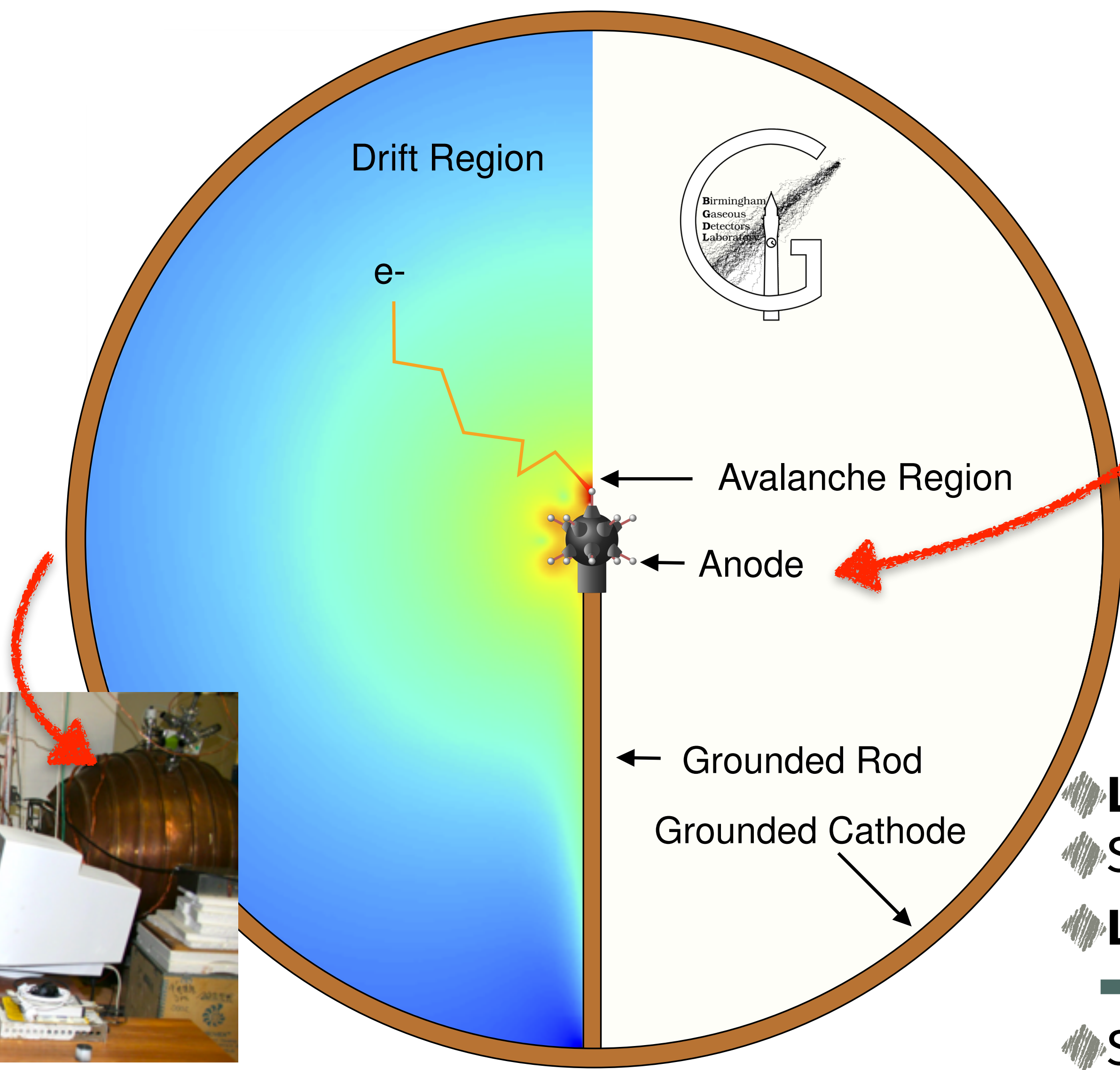
- ◆ **Low capacitance**, single-e detection
- ◆ Smallest surface area to volume ratio
- ◆ **Low-mass target nuclei**
 - ➡ H and C (in CH_4 , i- C_4H_{10}), He, Ne, etc.
- ◆ Simple, radiopure construction

Spherical Proportional Counter



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Spherical Proportional Counter



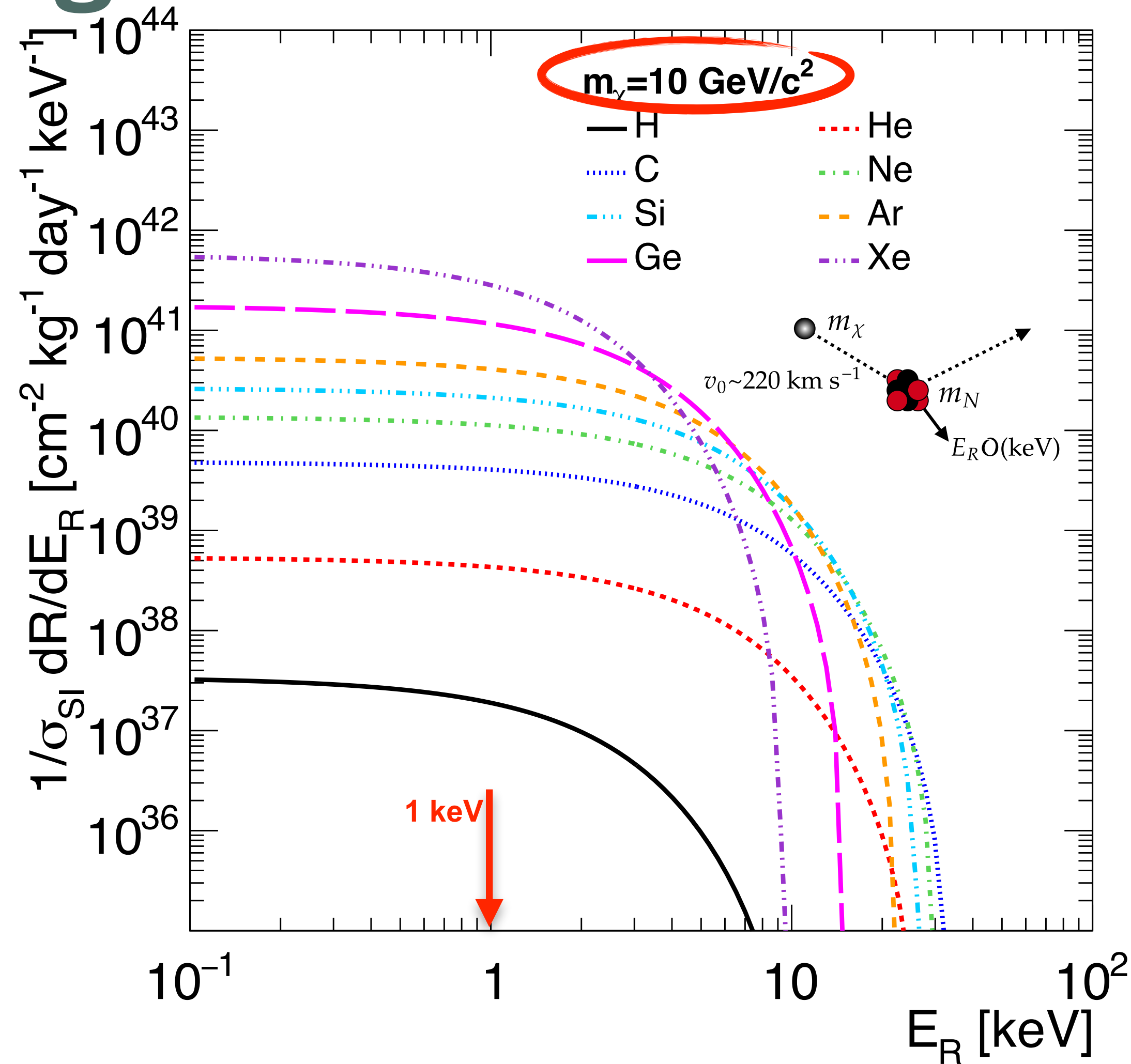
JINST 15 (2020) 11, 11

JINST 19 (2024) 01, P01018



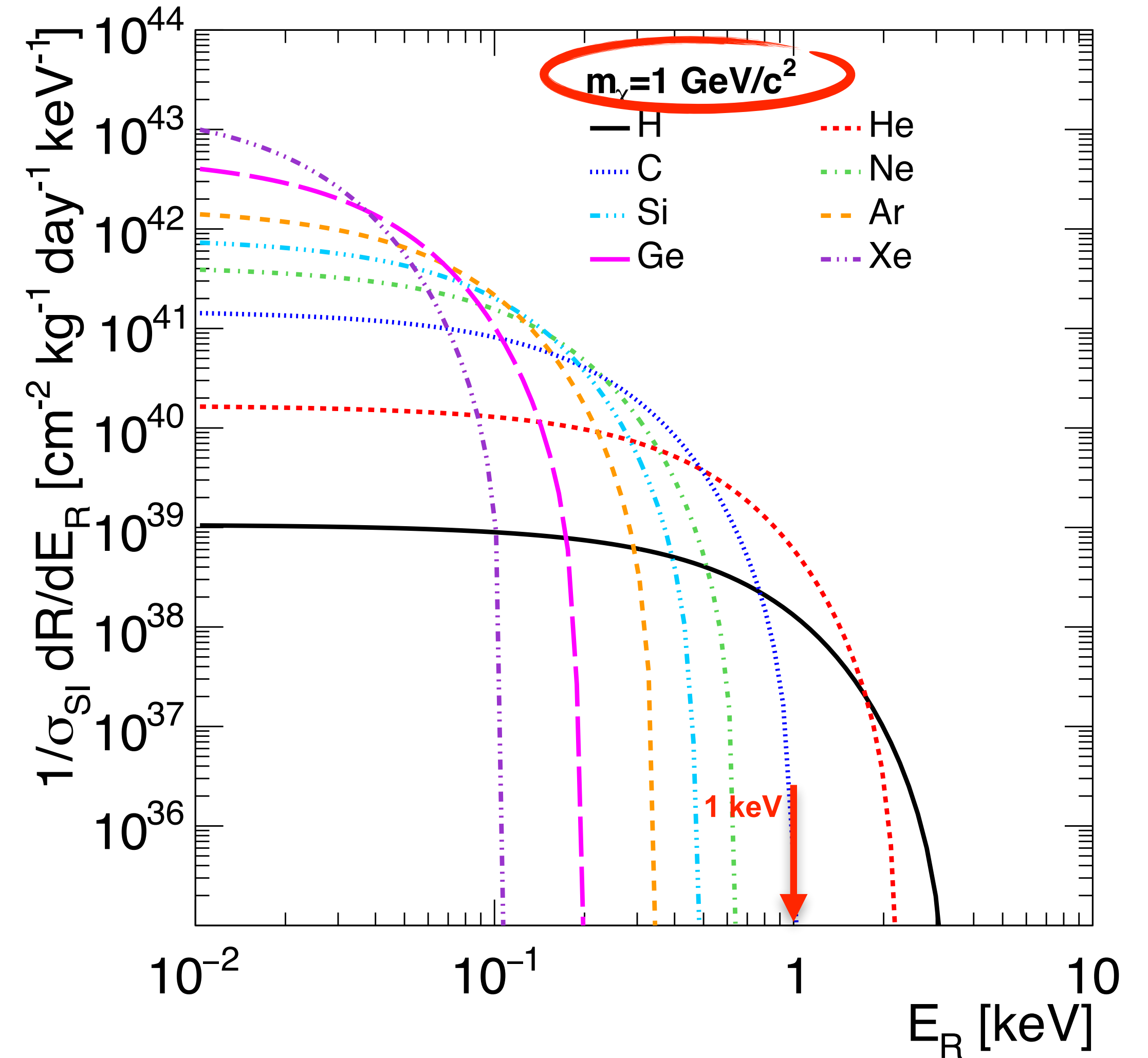
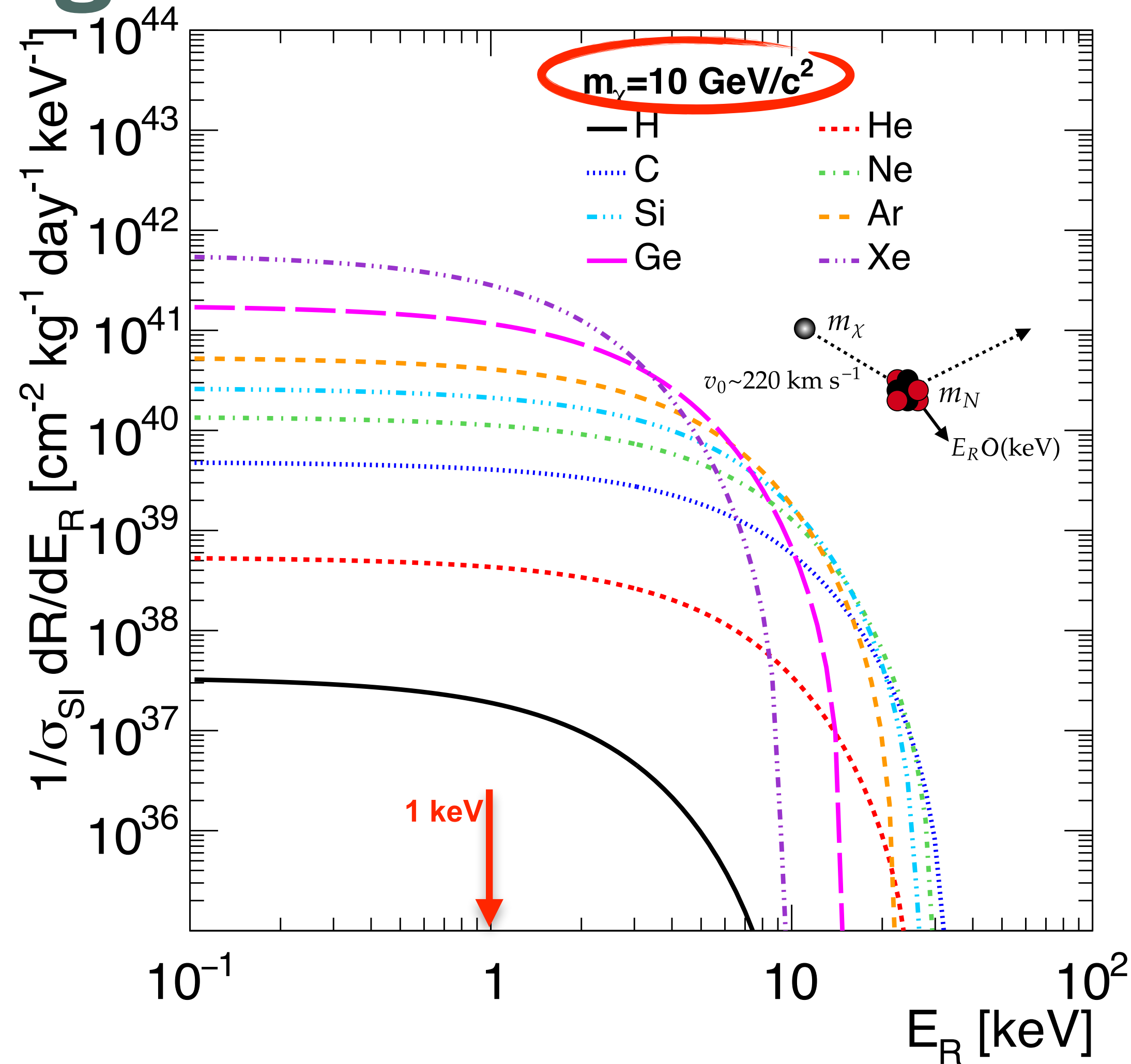
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Light Dark Matter Detection - Kinematics



- Light targets give enhance sensitivity to light particle DM elastic scattering
- Requirement of low energy threshold

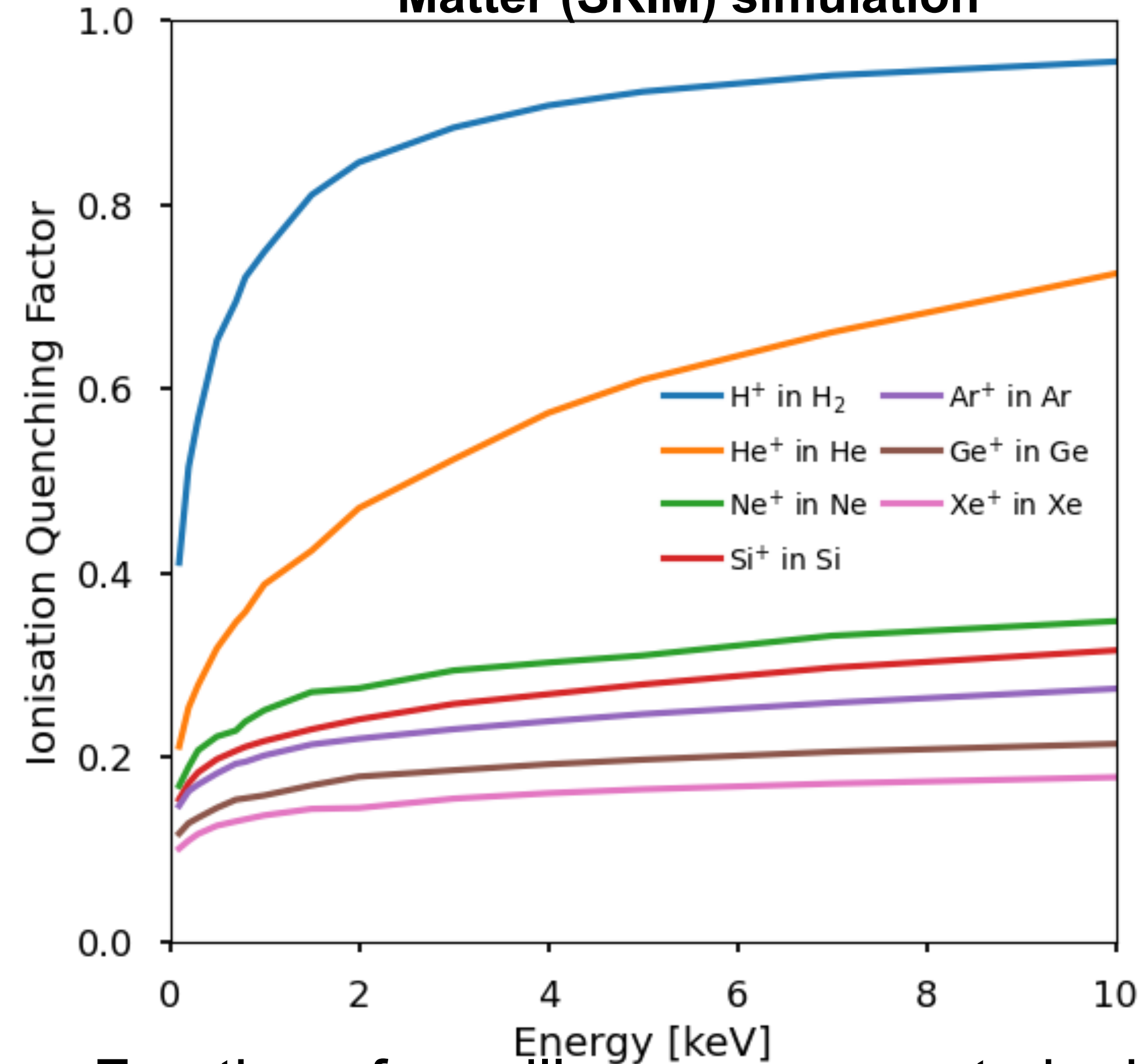
Light Dark Matter Detection - Kinematics



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Ionisation Quenching Factor

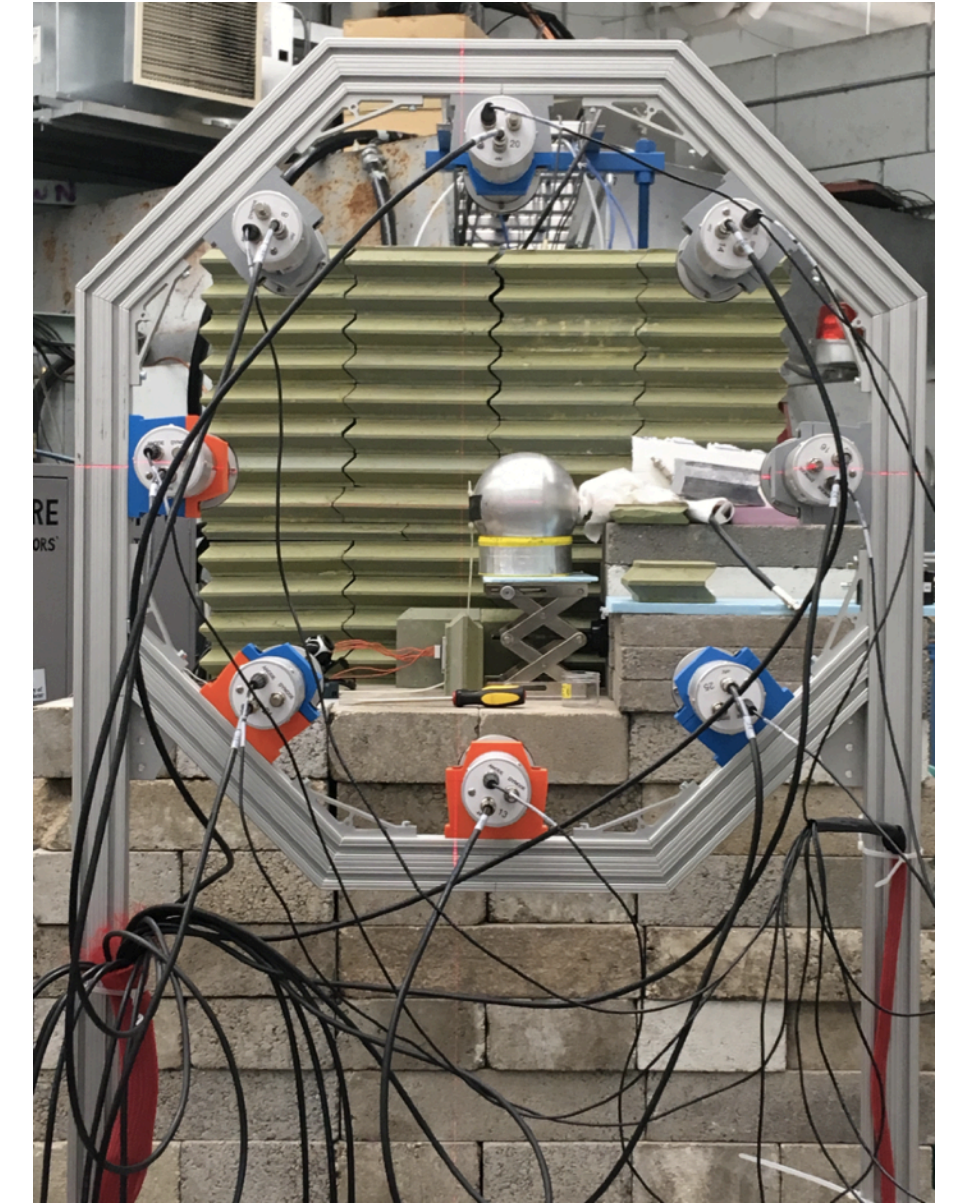
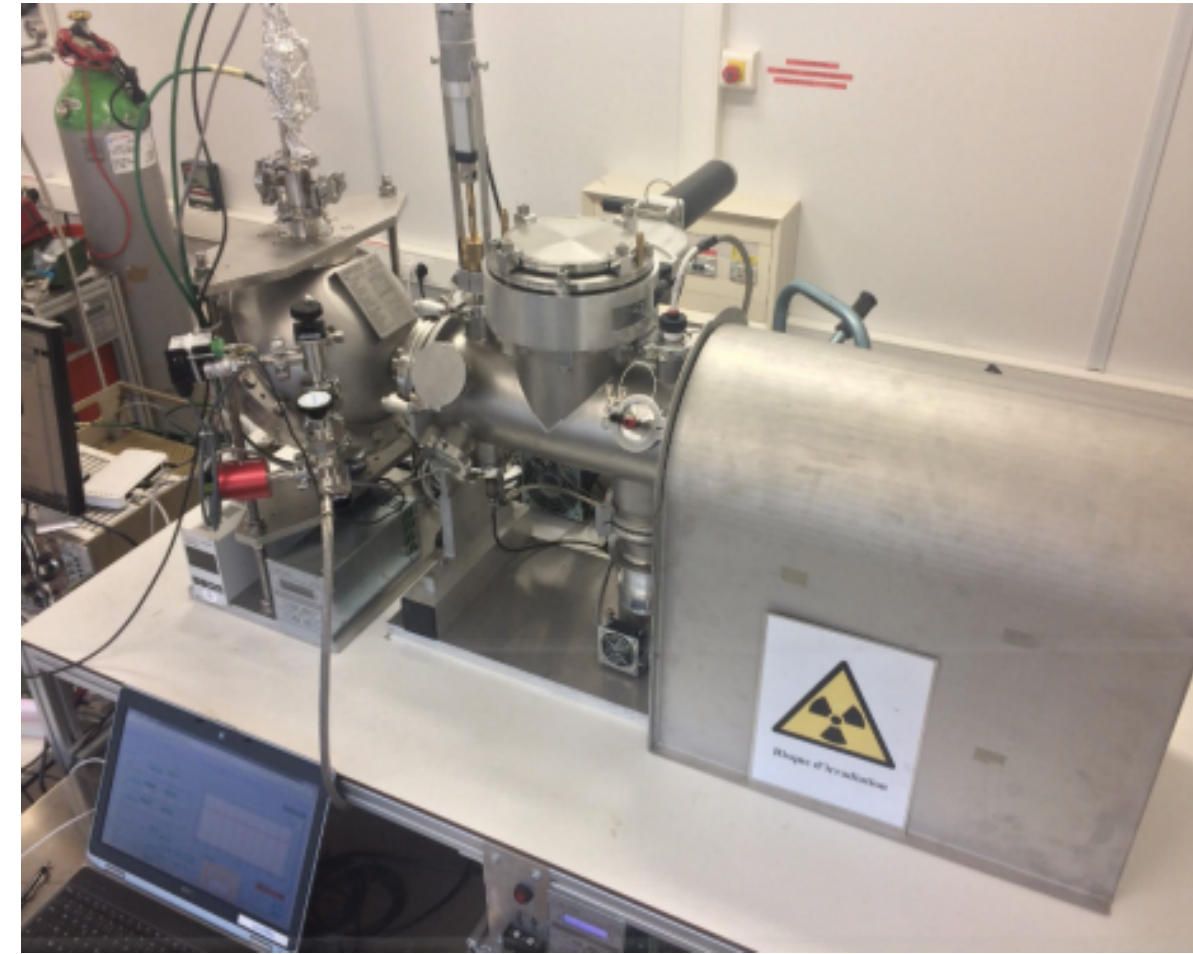
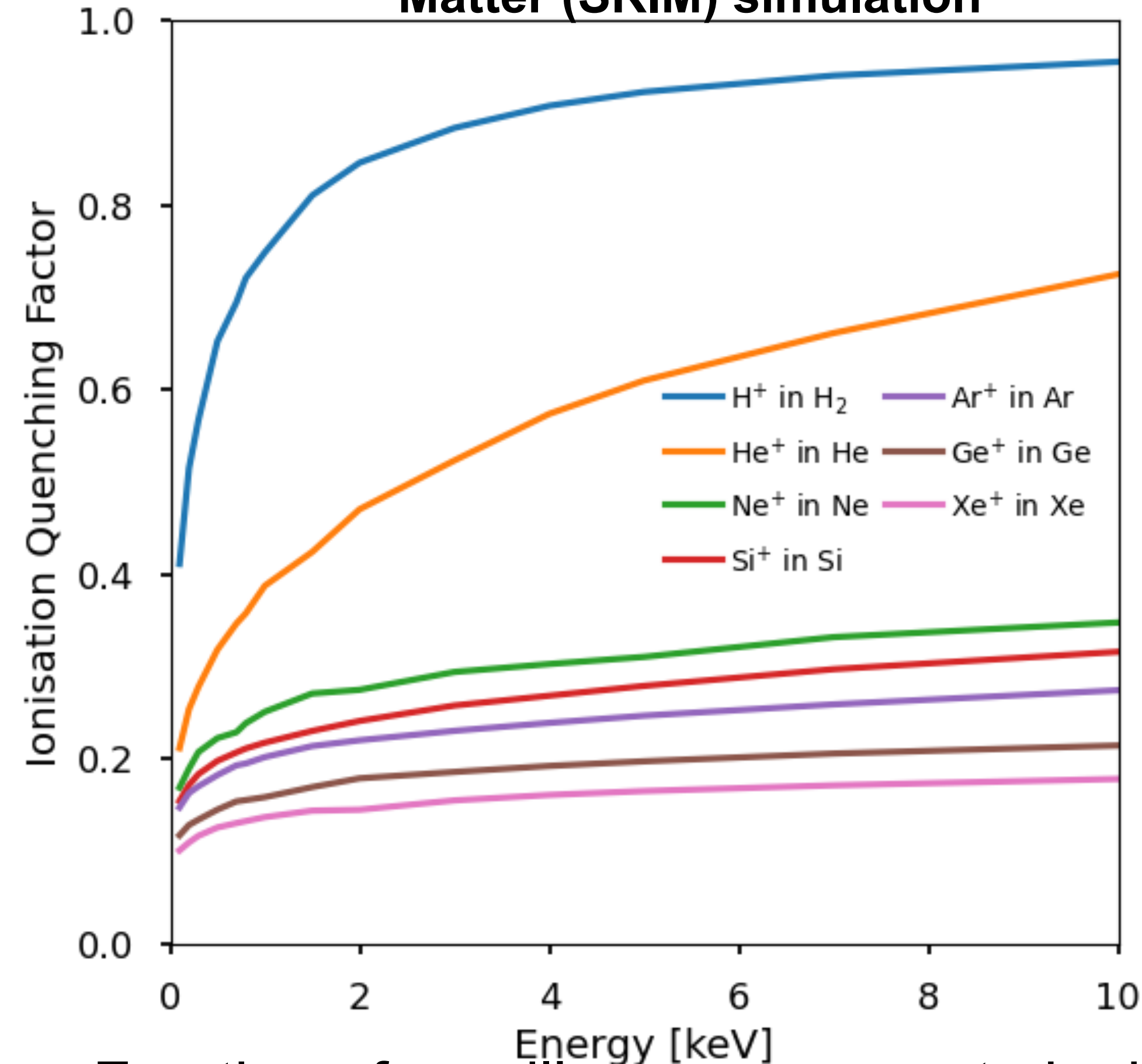
Stopping and Range of Ions in Matter (SRIM) simulation



- Fraction of recoil's energy goes to ionisation - Ionisation quenching factor
- Must be measured to infer recoil's energy from measured signal
- Further measurements planned in near future

Ionisation Quenching Factor

Stopping and Range of Ions in Matter (SRIM) simulation



2 measurement approaches in NEWS-G

➔ Neutron scattering at TUNL

Phys.Rev.D 105 (2022) 5, 052004

➔ Electron/Ion beam, COMIMAC, Grenoble

Eur.Phys.J.C 82 (2022) 12, 1114

Innovative approach using literature measurements

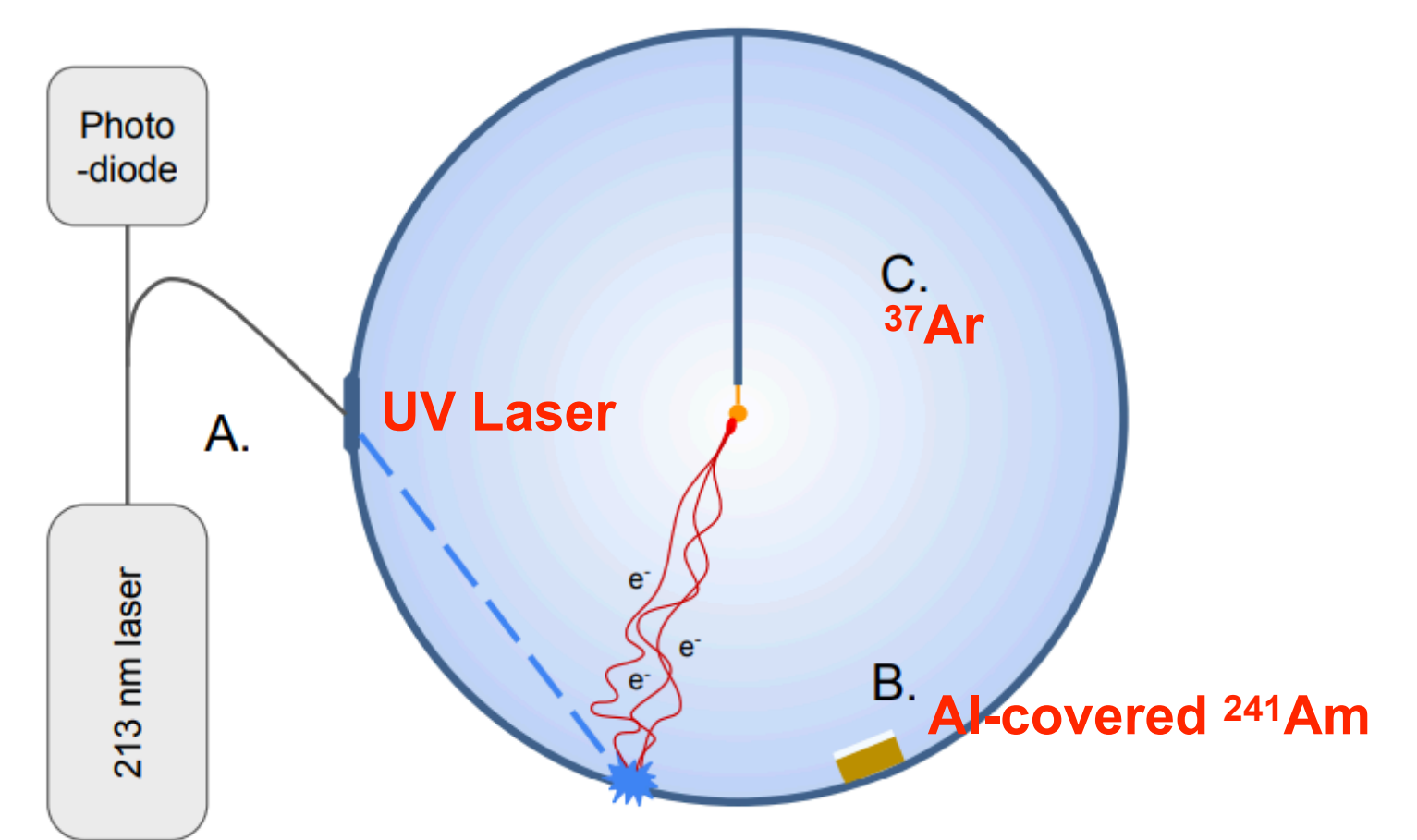
Astropart.Phys. 141 (2022) 102707

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Ionisation Yield Measurements

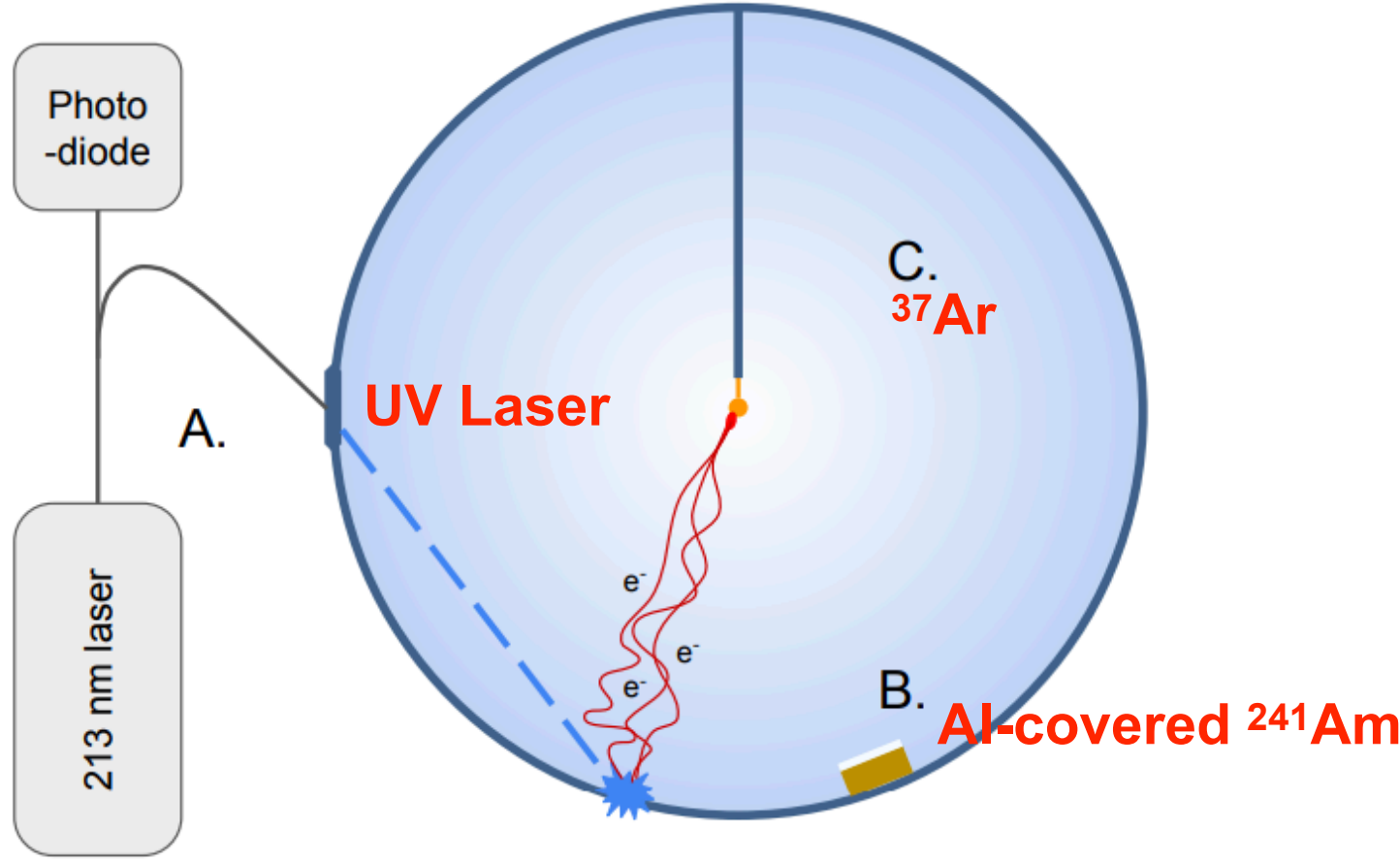
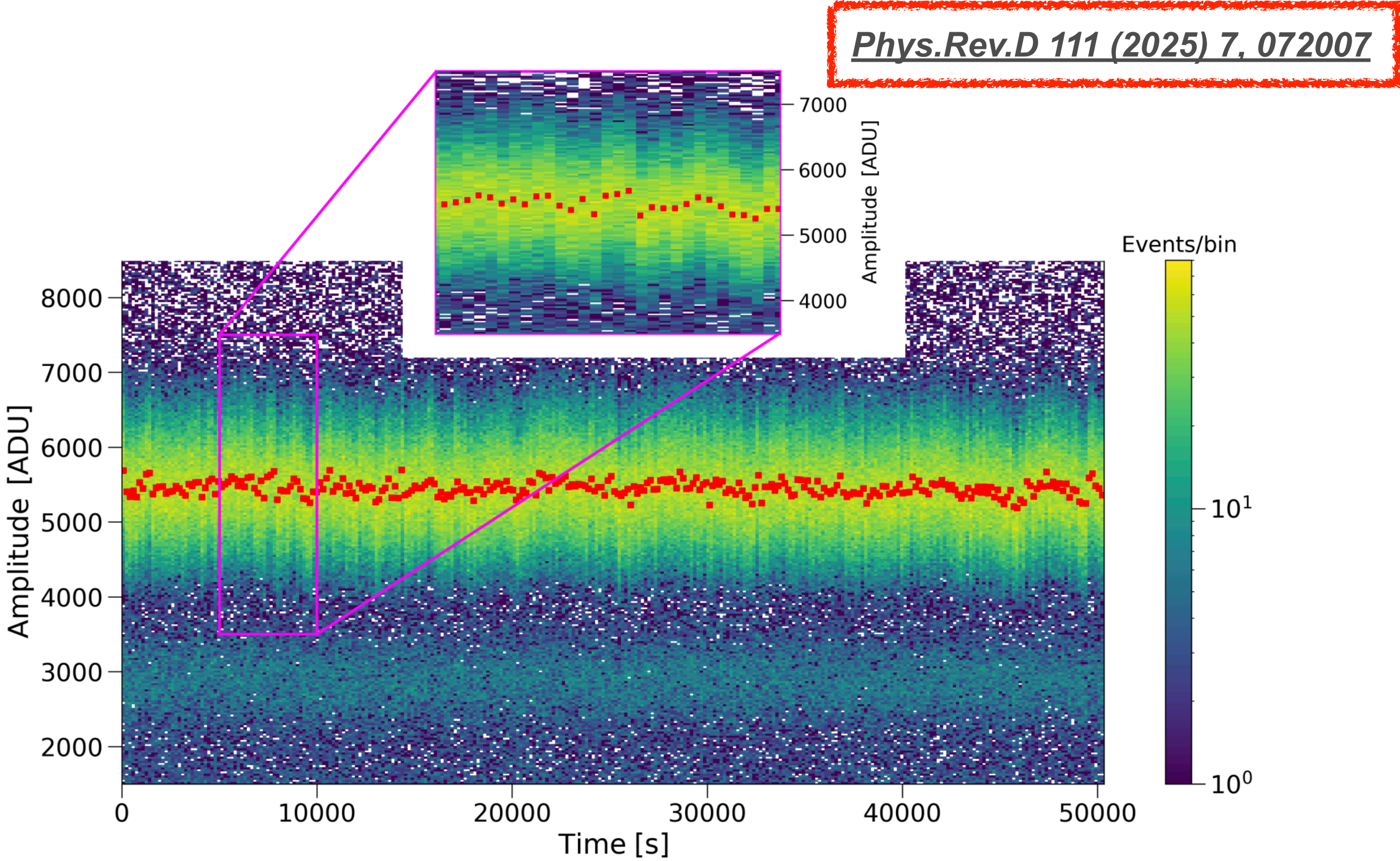
- Direct measurement of ionisation yield in SPC
 - Ø30 cm used, with laser calibrations
- Ionisation yield measured at various voltages at Al fluorescence and ^{37}Ar energies
 - Gain independent and consistent with literature to ~5%

Phys.Rev.D 111 (2025) 7, 072007



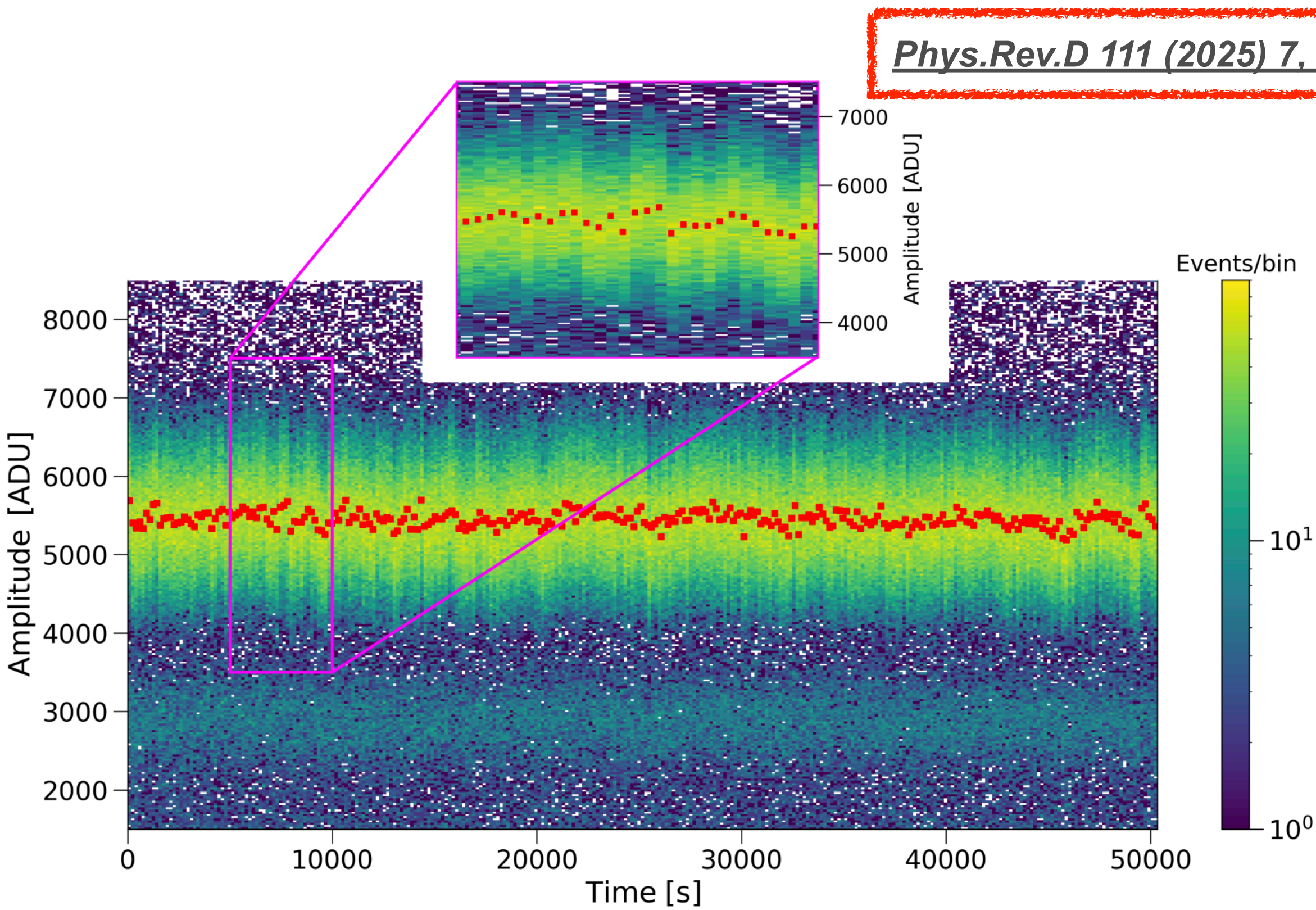
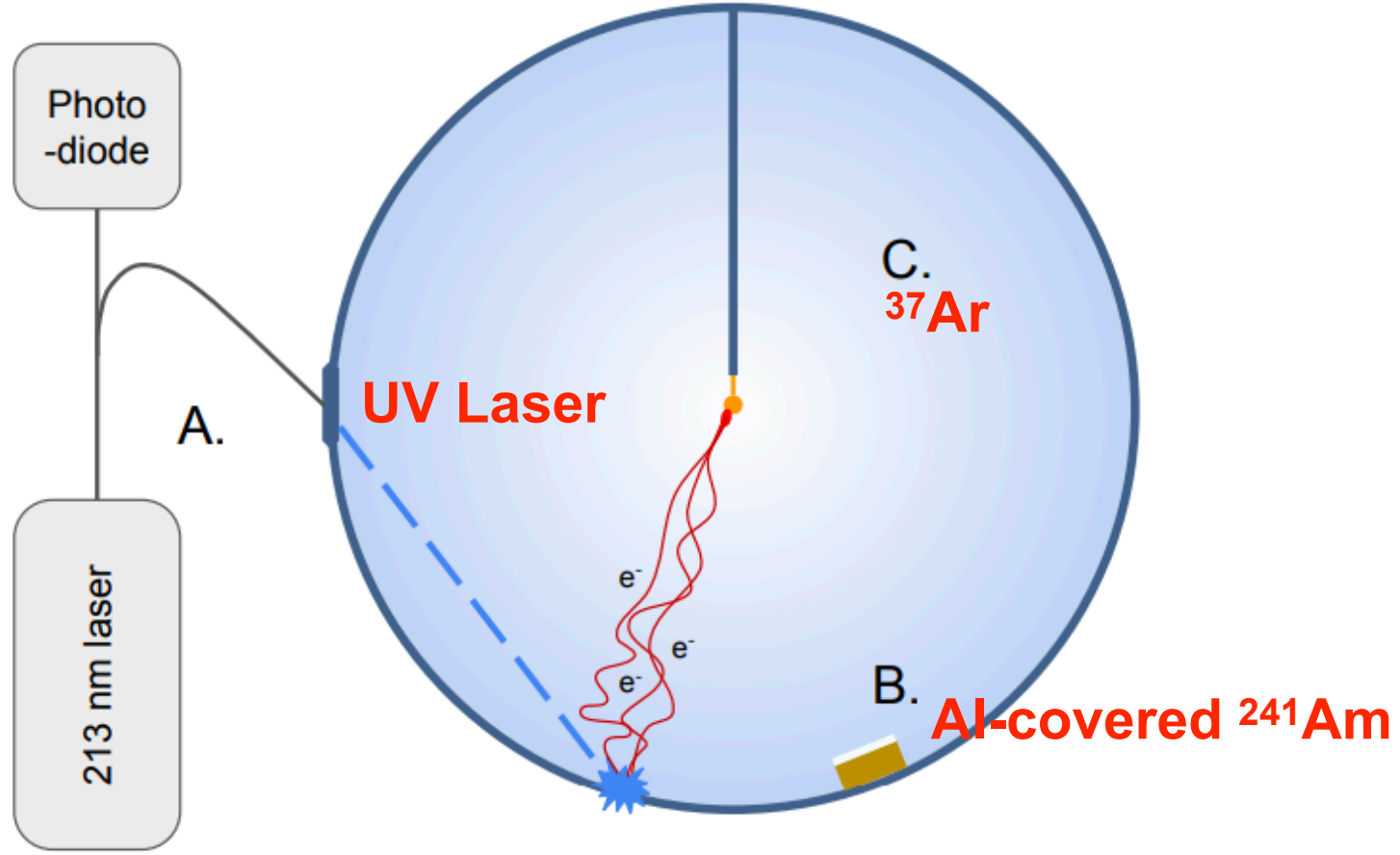
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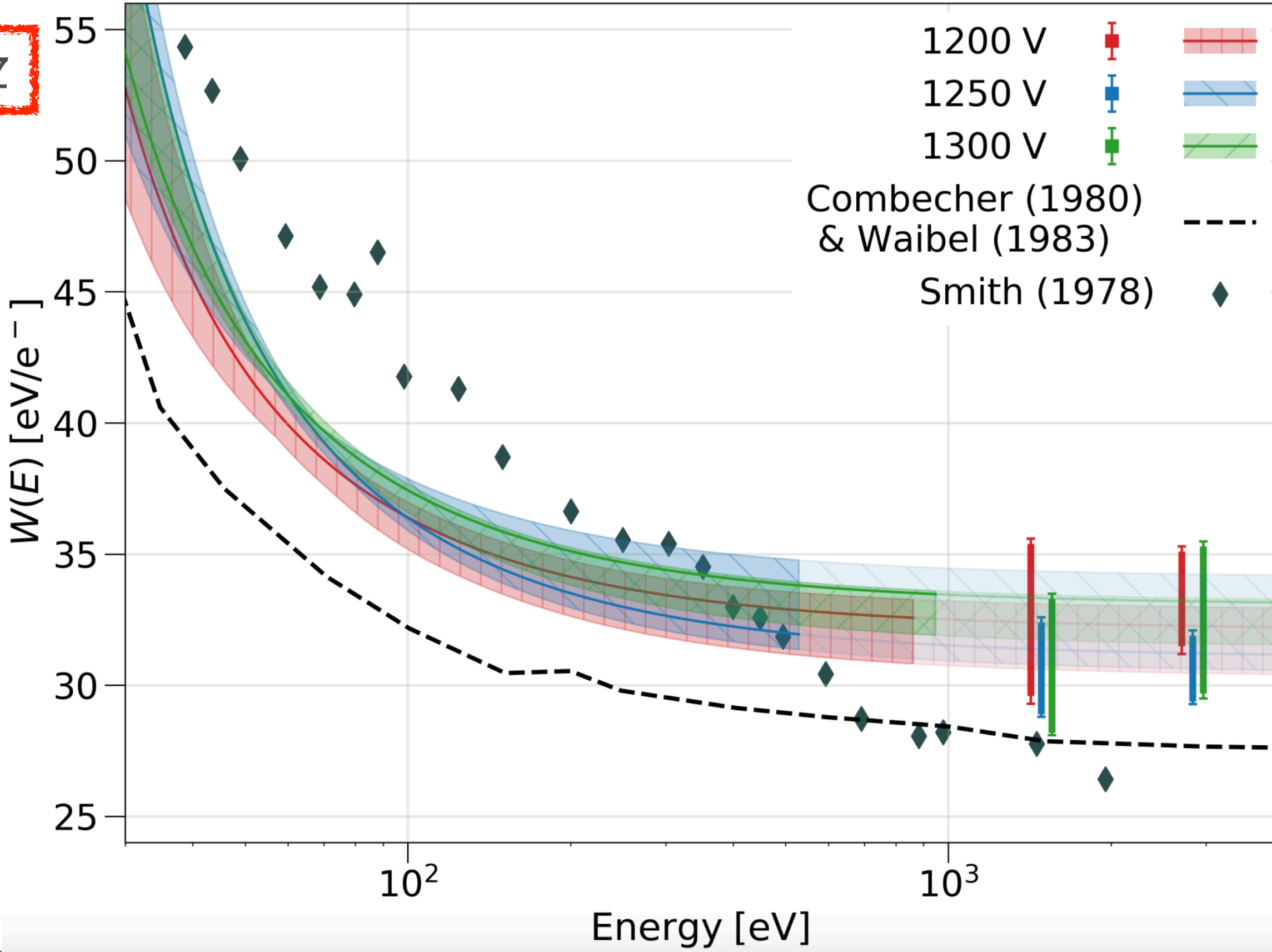


Ionisation Yield Measurements

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 - $\varnothing 30$ cm used, with laser calibrations
- Ionisation yield measured at various voltages at Al fluorescence and ^{37}Ar energies
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Phys.Rev.D 111 (2025) 7, 072007



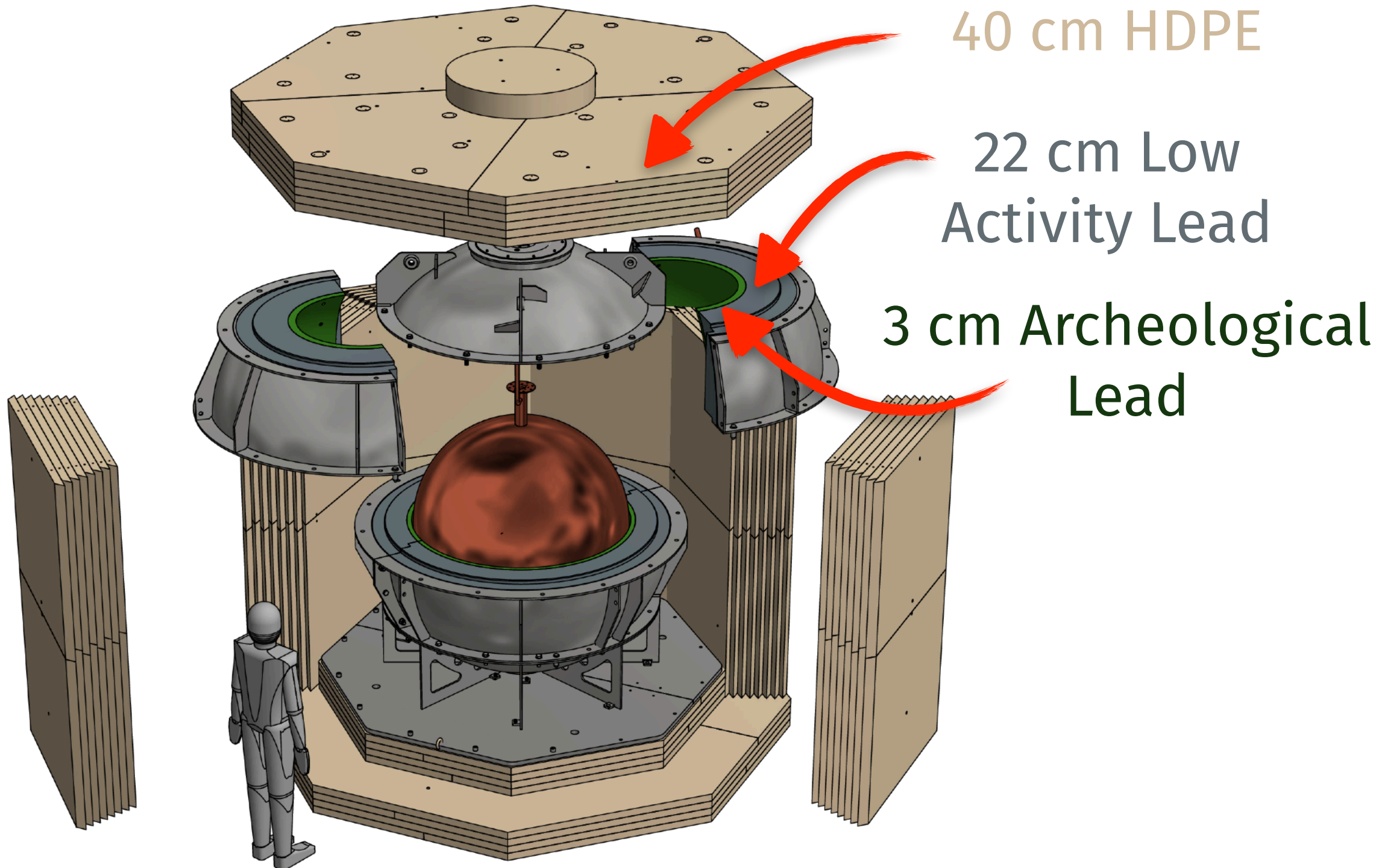
S140 Detector

✦ S140 detector: $\varnothing 140$ cm detector

➡ 99.99% pure Cu with 0.5mm *electroplated*
ultra-pure Cu internal layer

Nucl.Instrum.Meth.A 988 (2021) 164844

JINST 18 (2023) 02, T02005



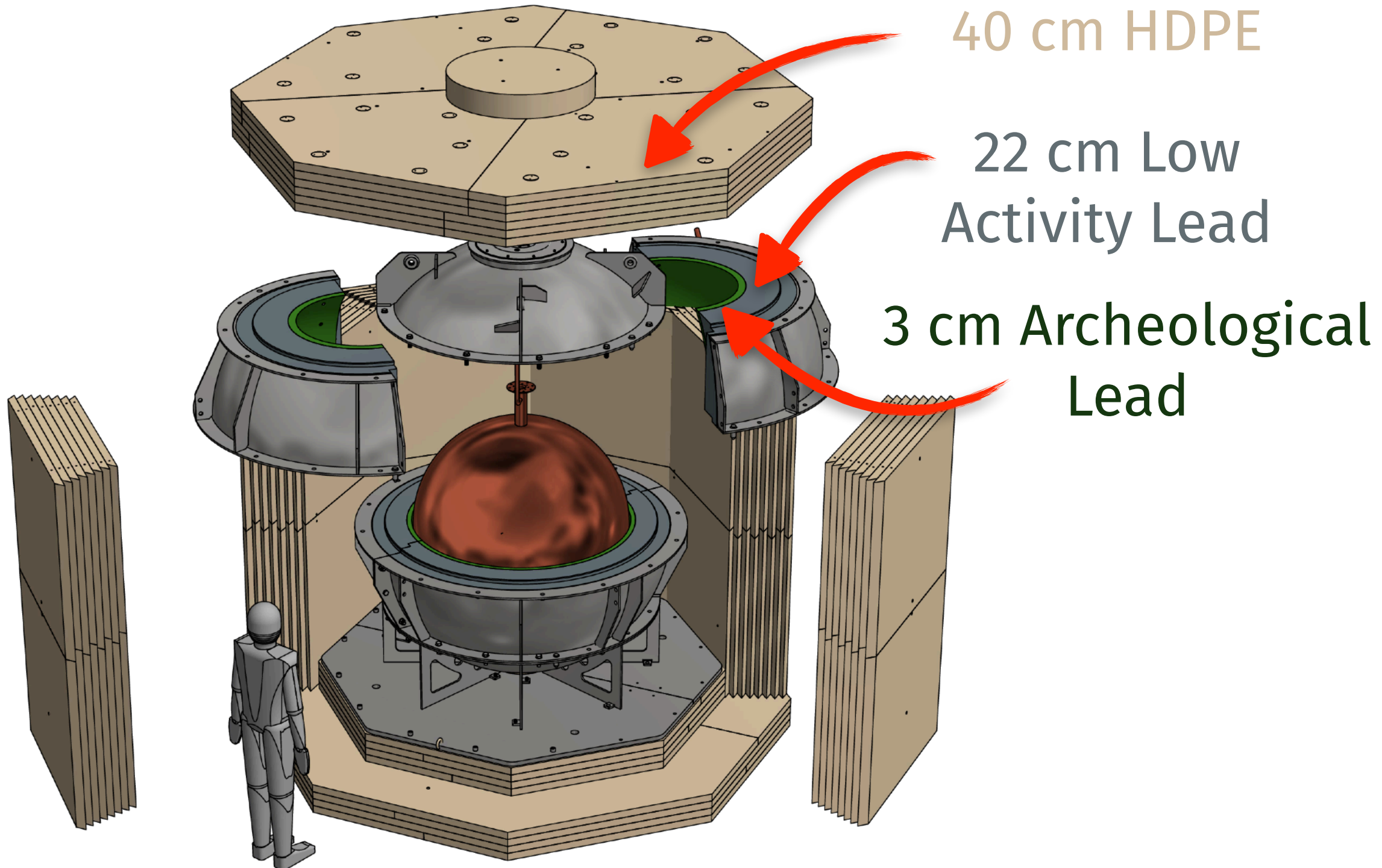
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Nucl.Instrum.Meth.A 988 (2021) 164844

JINST 18 (2023) 02, T02005



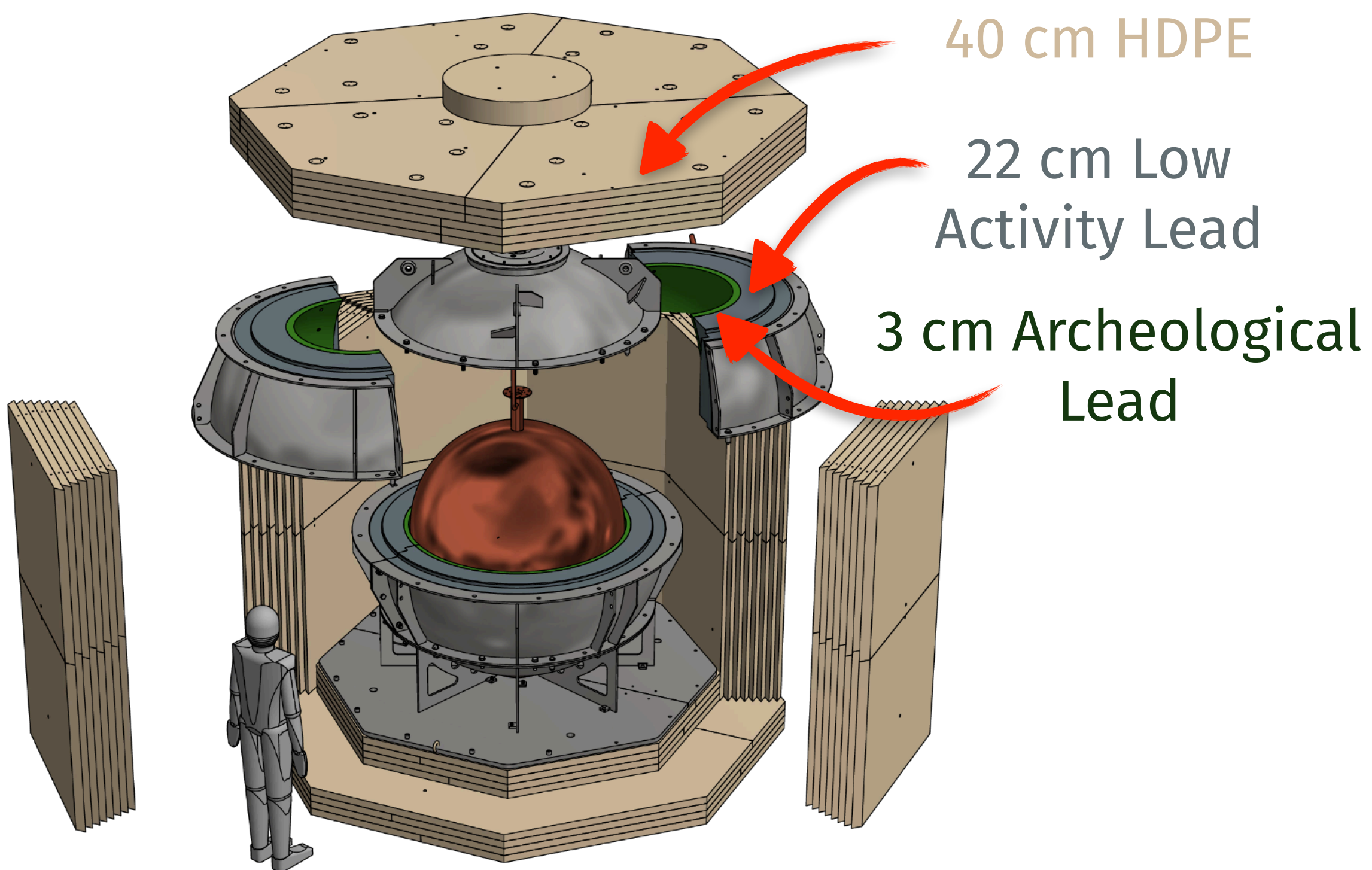
S140 Detector

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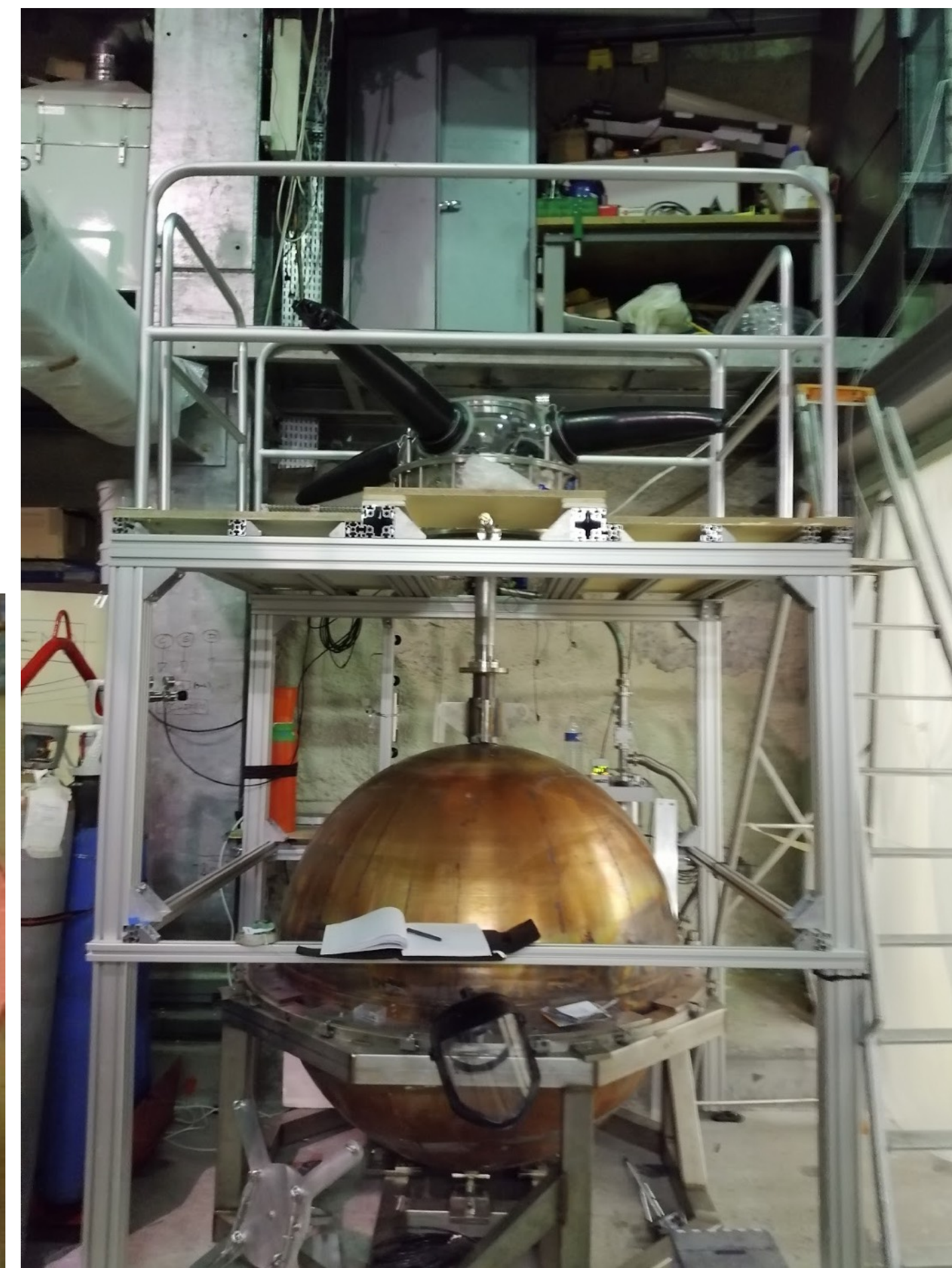
➡ 99.99% pure Cu with 0.5mm *electroplated*
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Nucl.Instrum.Meth.A 988 (2021) 164844

JINST 18 (2023) 02, T02005

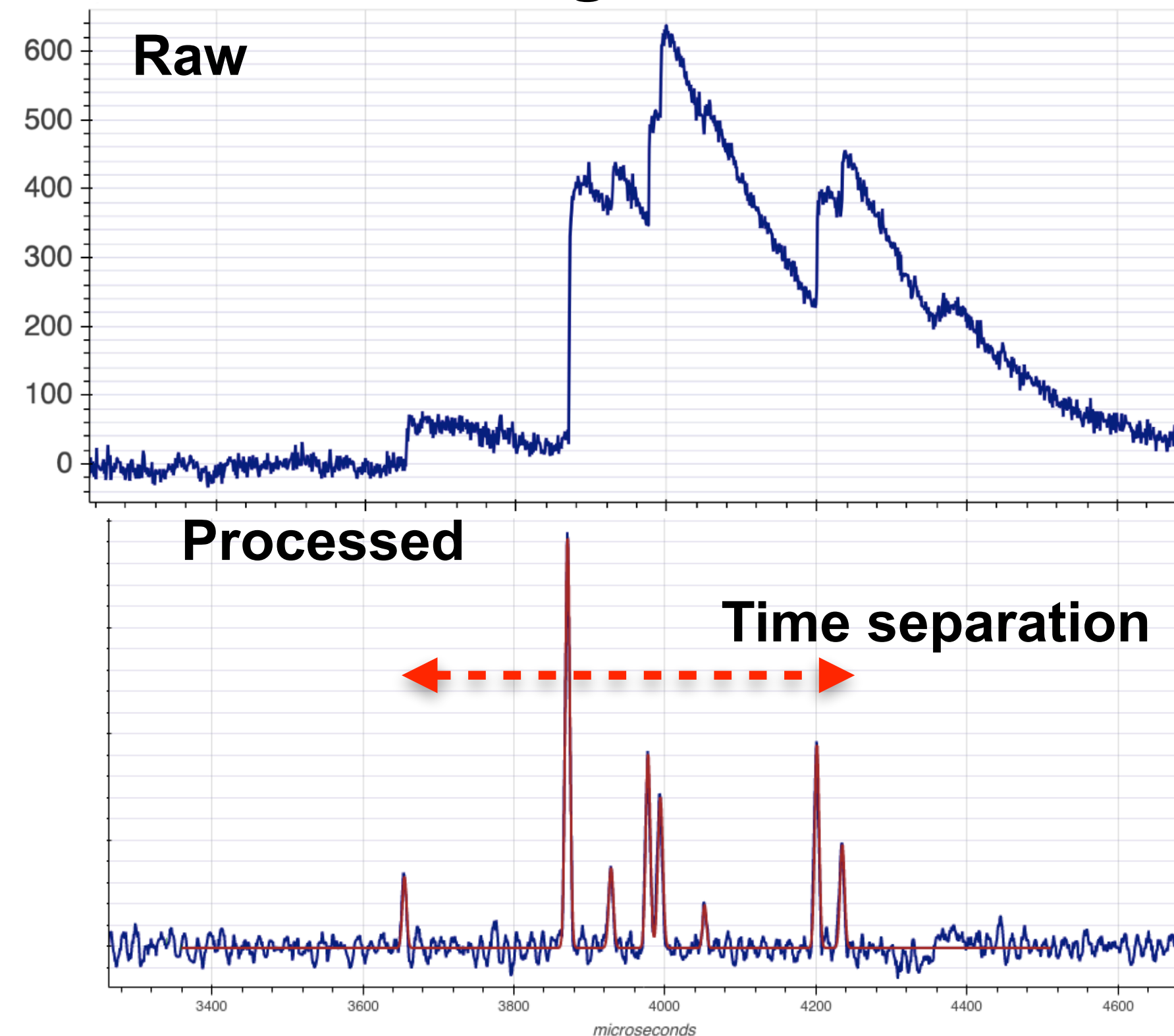


S140 in LSM



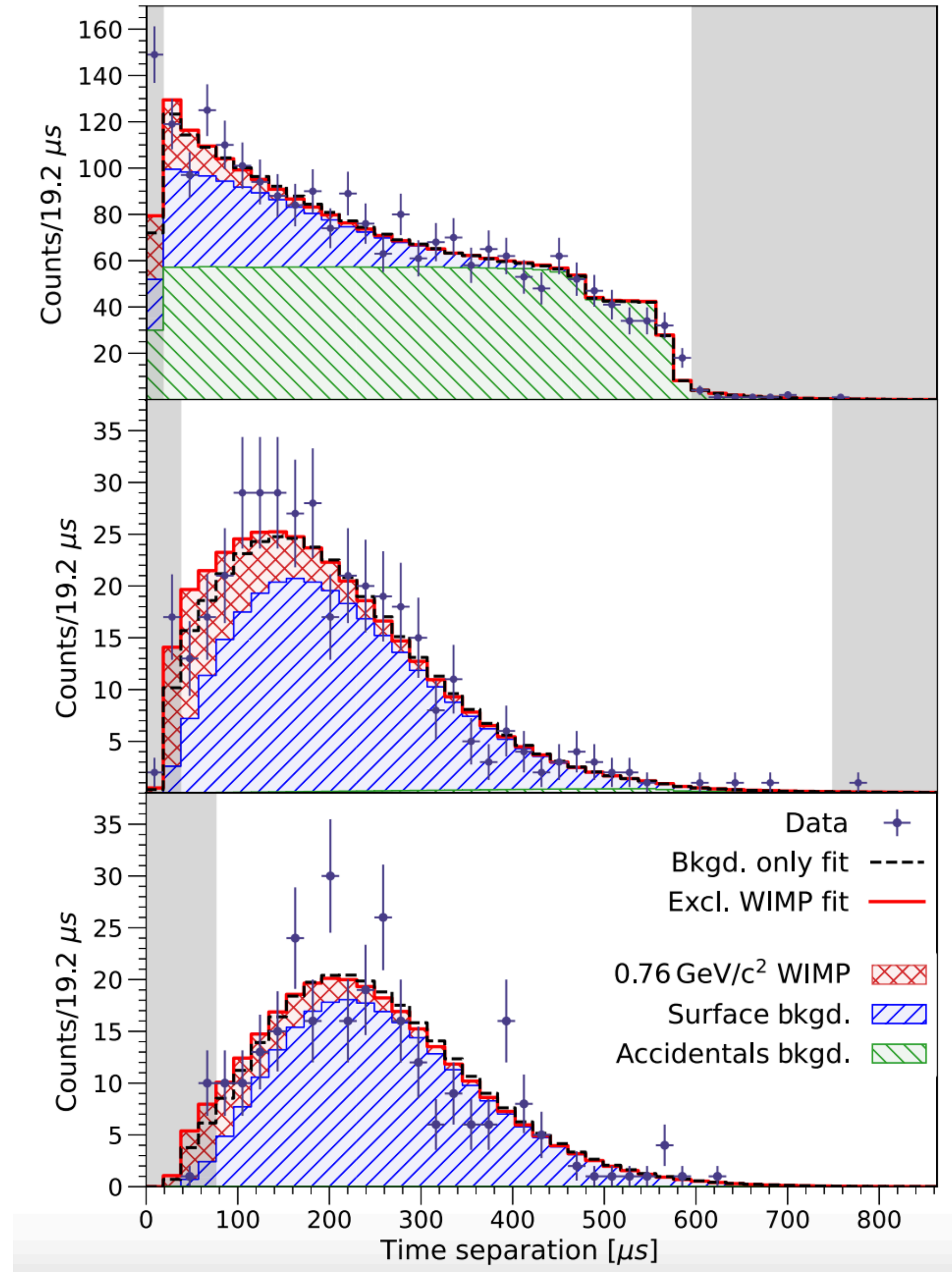
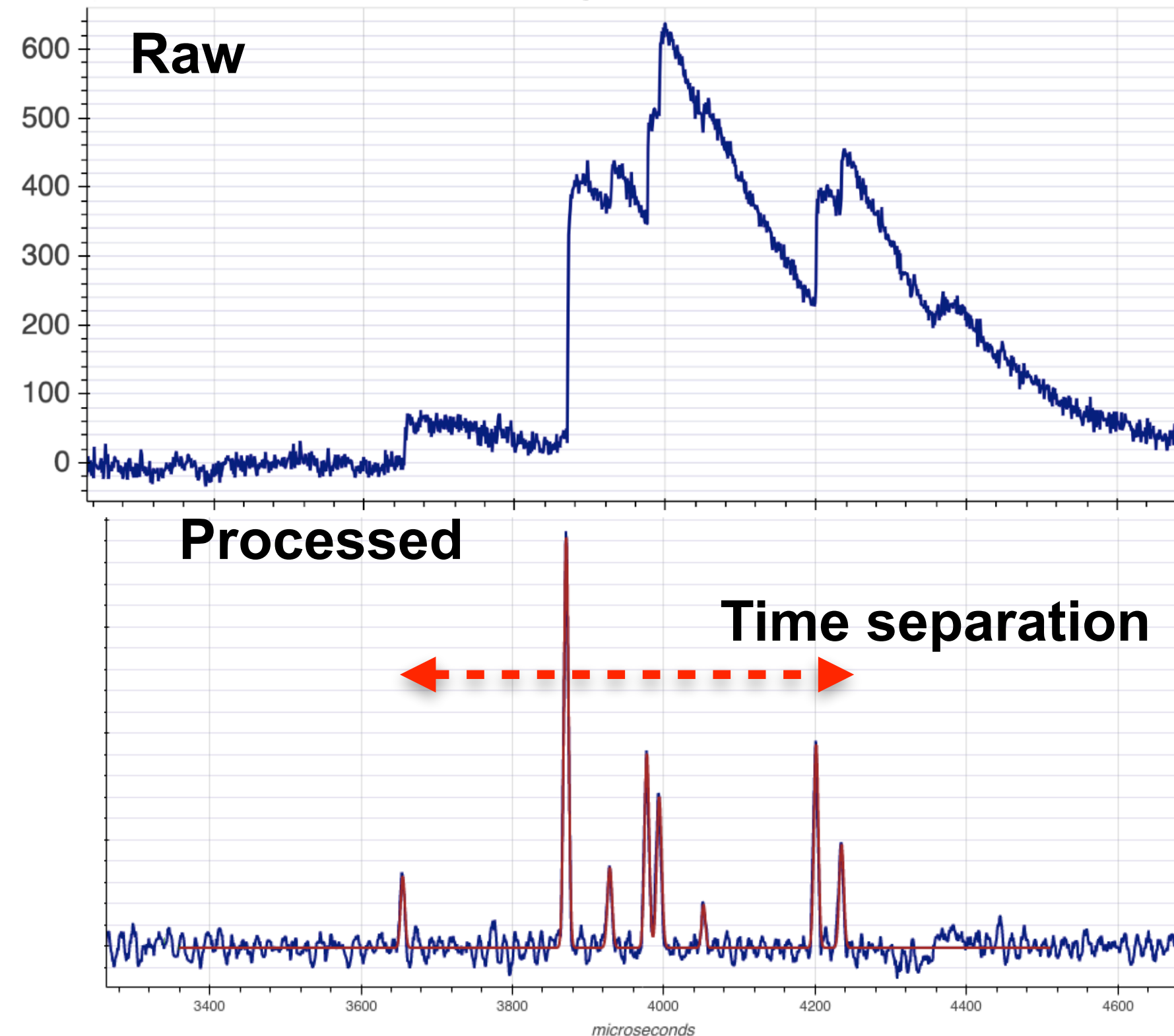
S140 in LSM

- ◆ Built and tested in LSM
 - ➔ First physics from commissioning data
 - ➔ 135 mbar (114 g) CH₄ for 10 days
- ◆ Detector calibrated with UV-Laser and ³⁷Ar source
- ◆ Electron counting performed with time separation used as discriminating variable



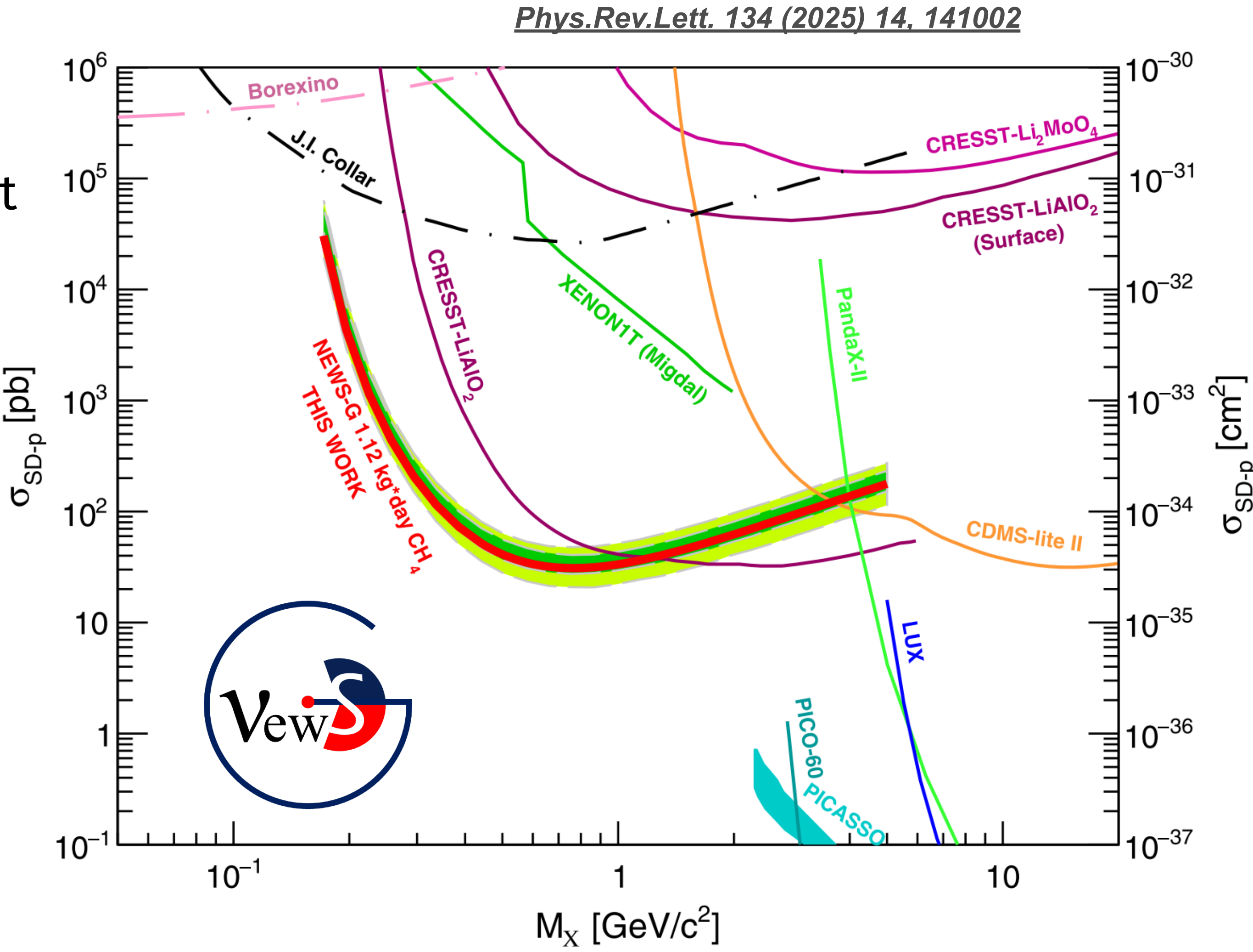
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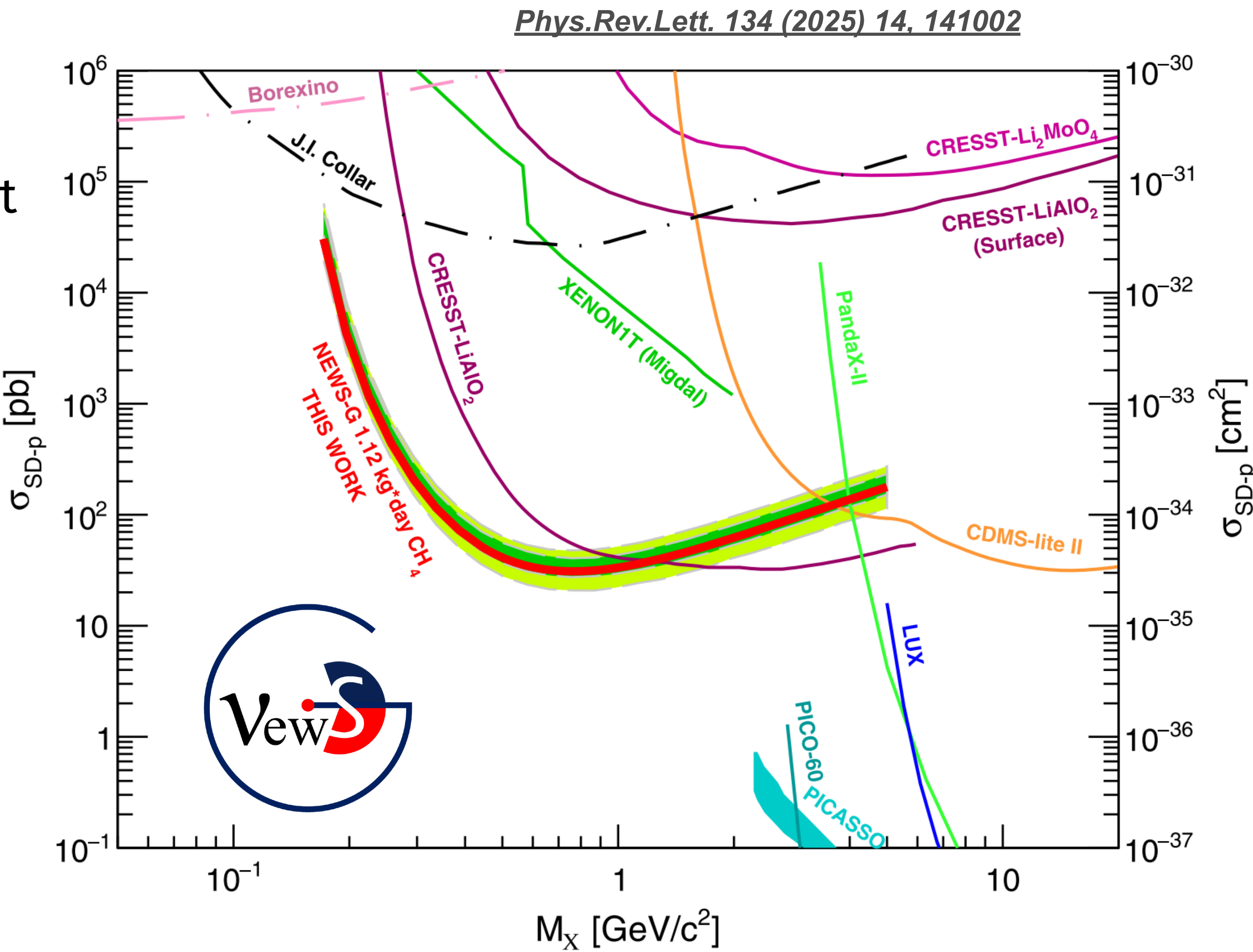
Recent NEWS-G Results

- After cuts, 0.599 kg·day exposure
- World-leading constraints on spin-dependent proton interaction for m_χ 0.2-1 GeV
- Detector moved to SNOLAB in 2022 and data taking underway



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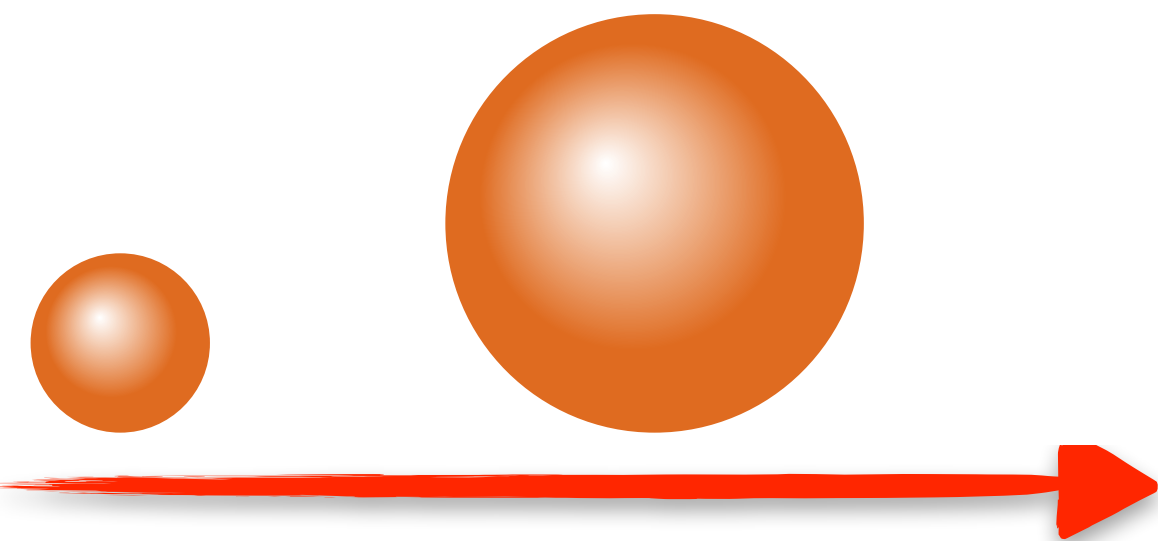


DarkSPHERE

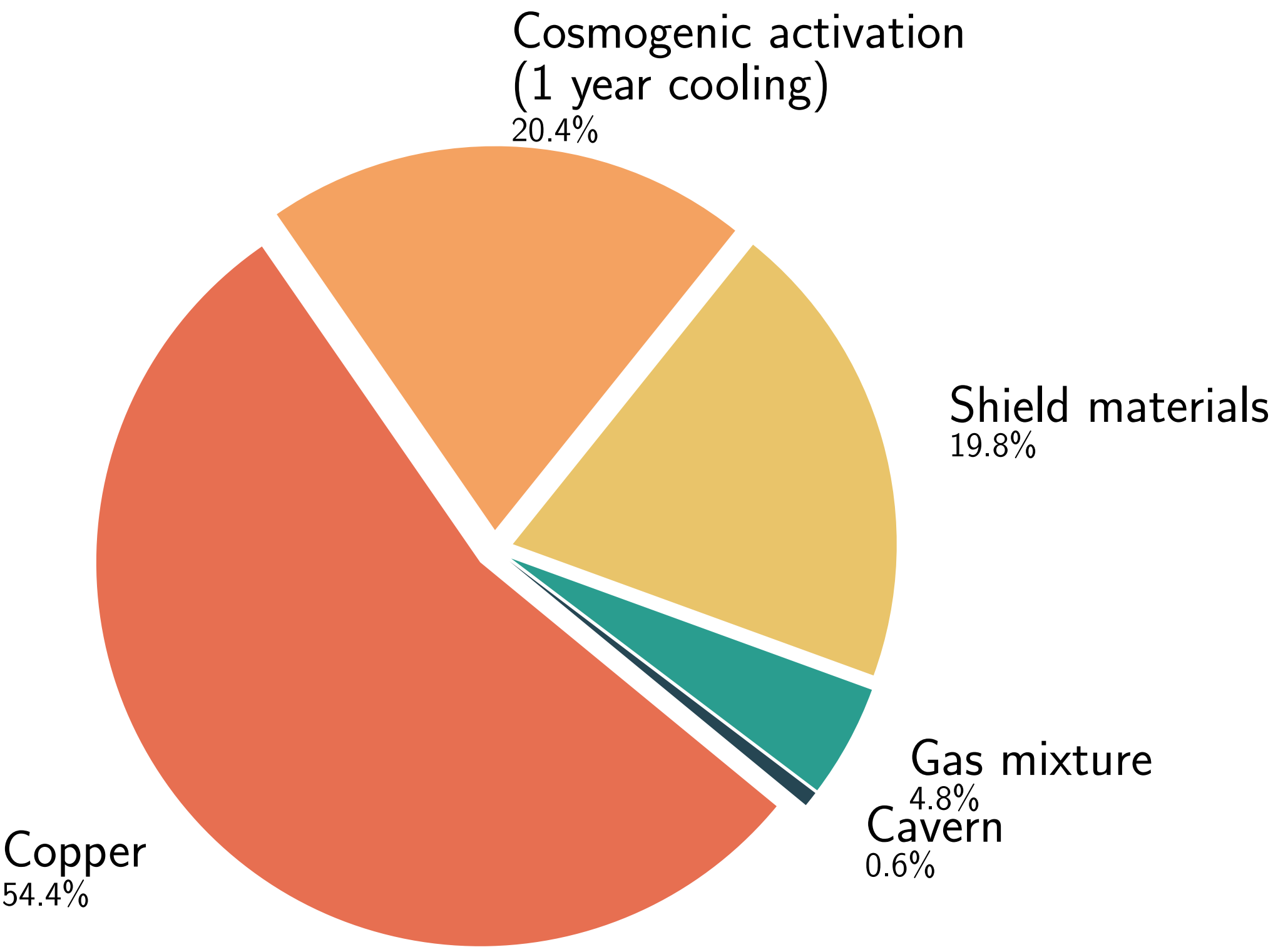
Simulated backgrounds in S140

SEDINE SNOGLOBE

Ø60 cm Ø140 cm
NOSV Cu 99.99% Cu
500 µm EFCu Layer

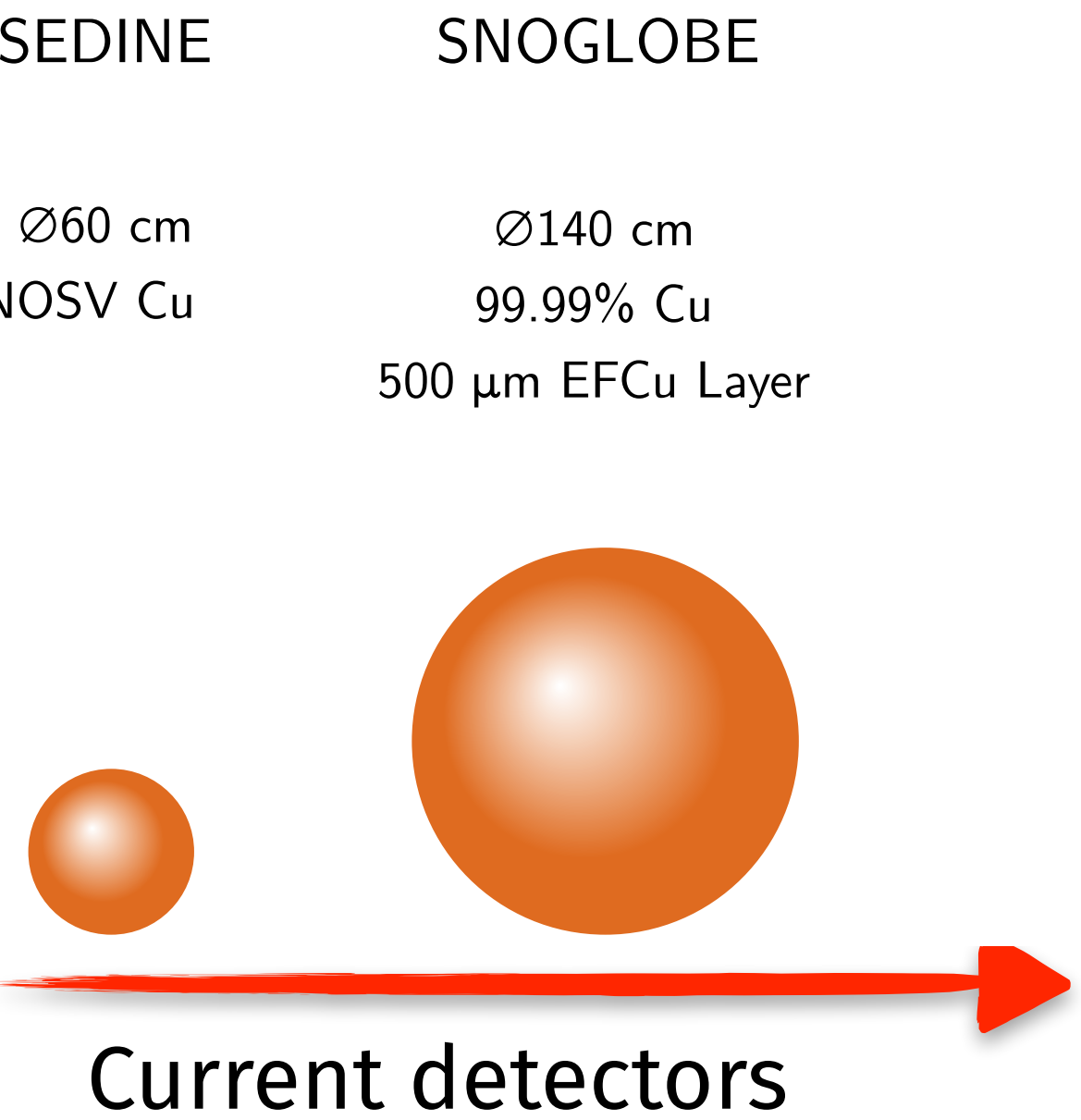


Current detectors



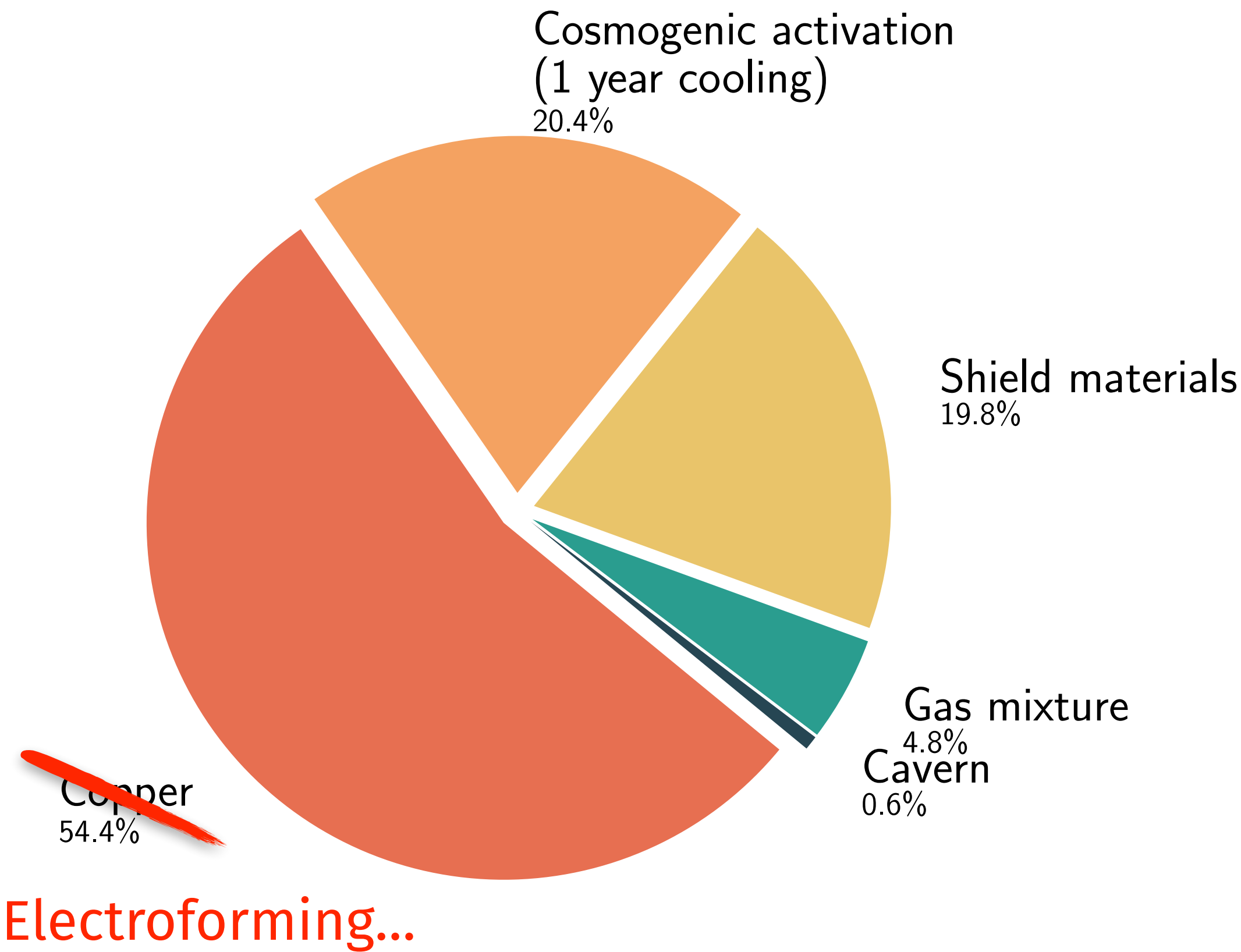
Phys.Rev.D 108 (2023) 11, 112006

DarkSPHERE



Phys.Rev.D 108 (2023) 11, 112006

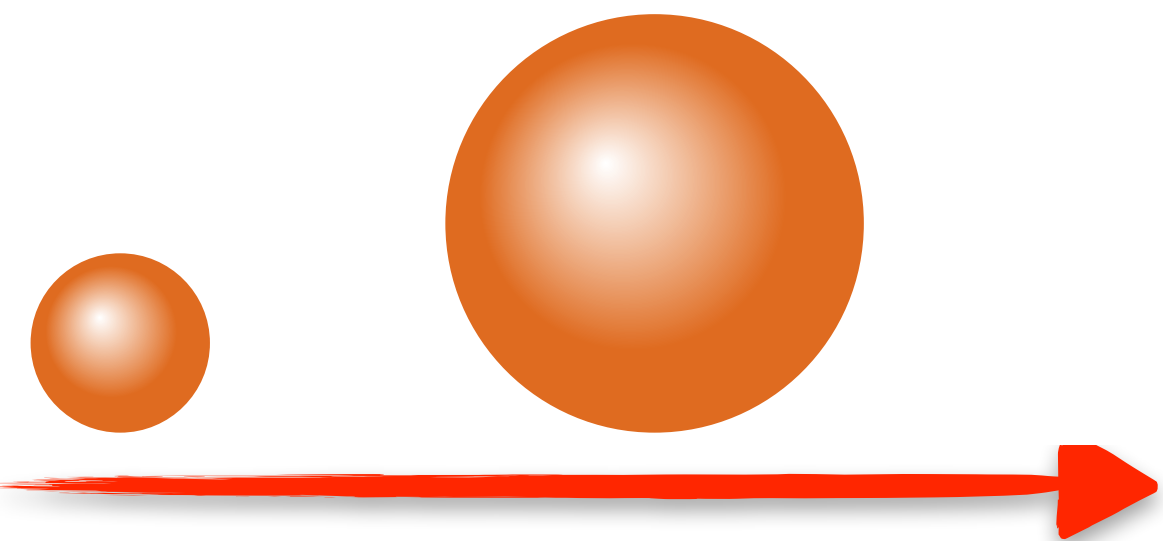
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DarkSPHERE

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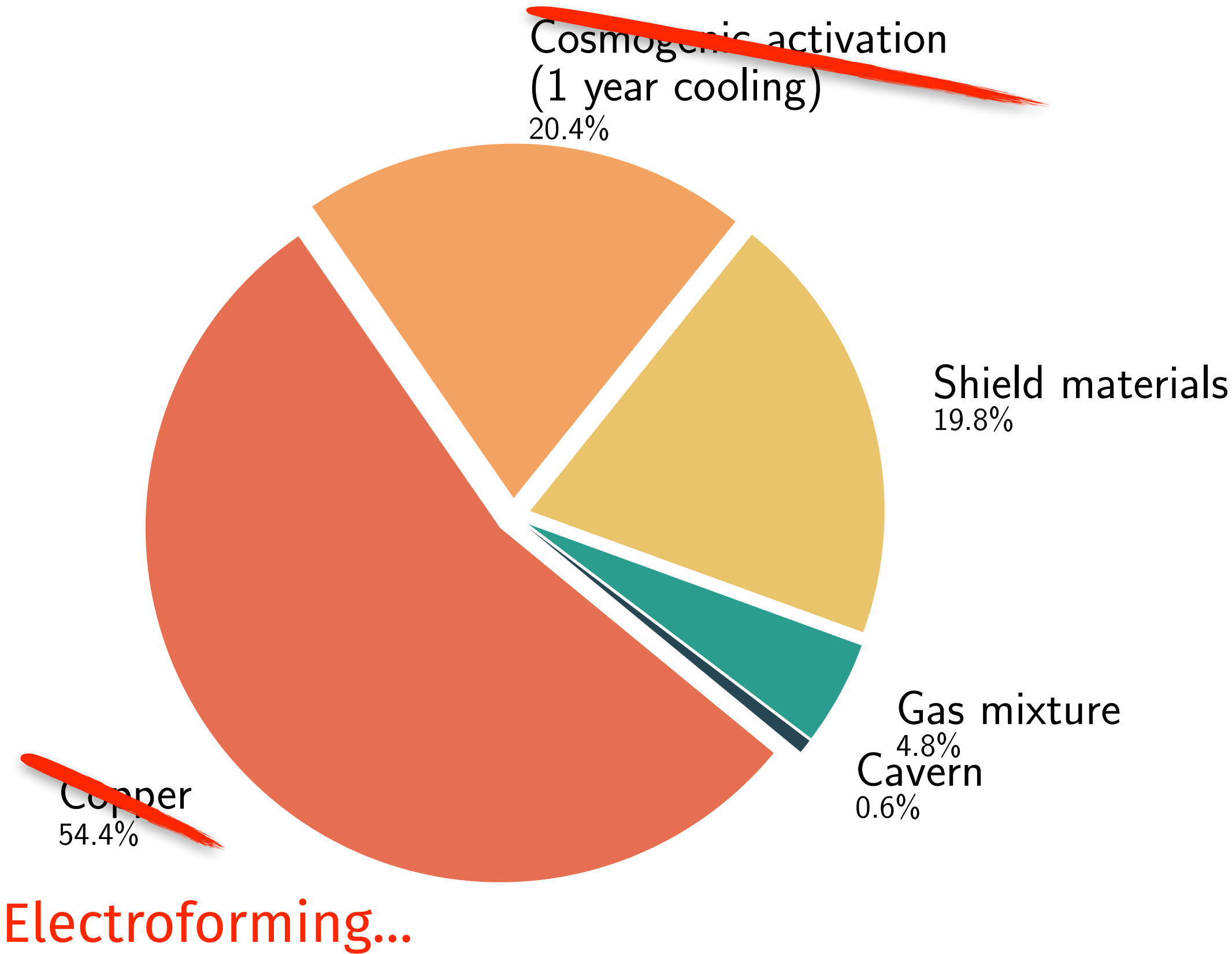
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Phys.Rev.D 108 (2023) 11, 112006

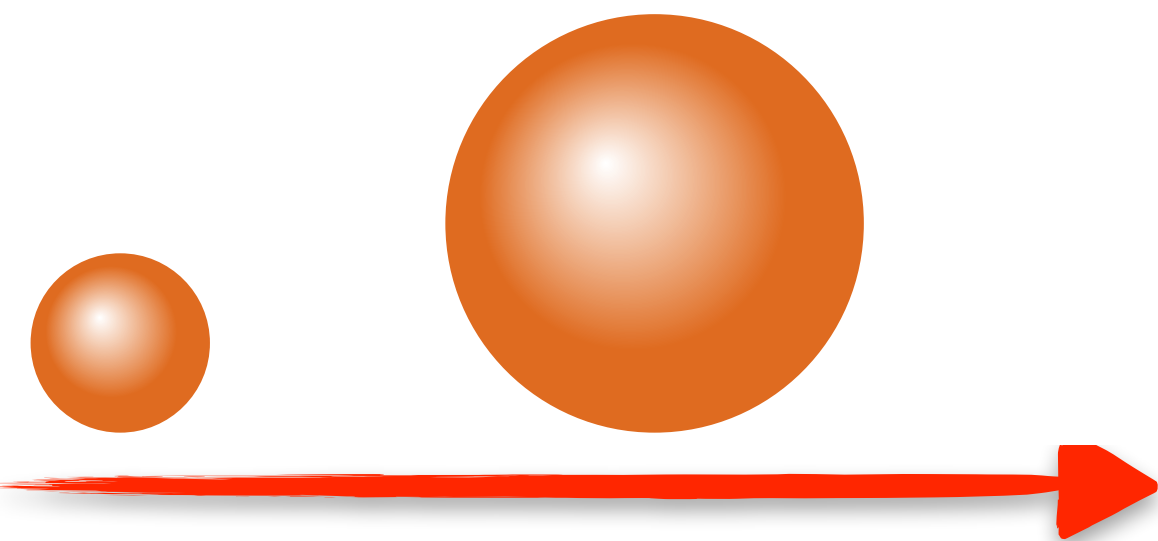
Simulated backgrounds in S140 ...underground



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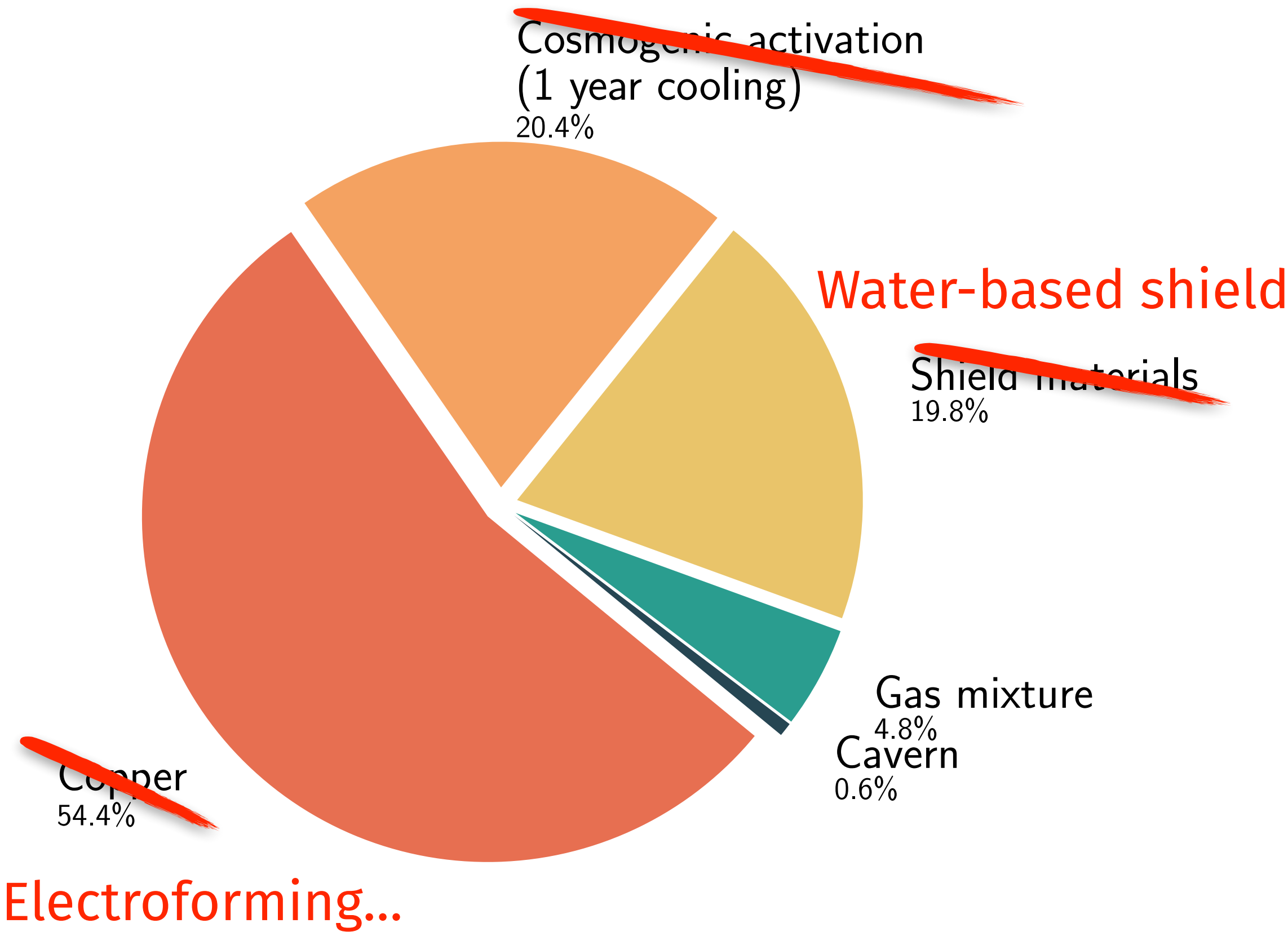


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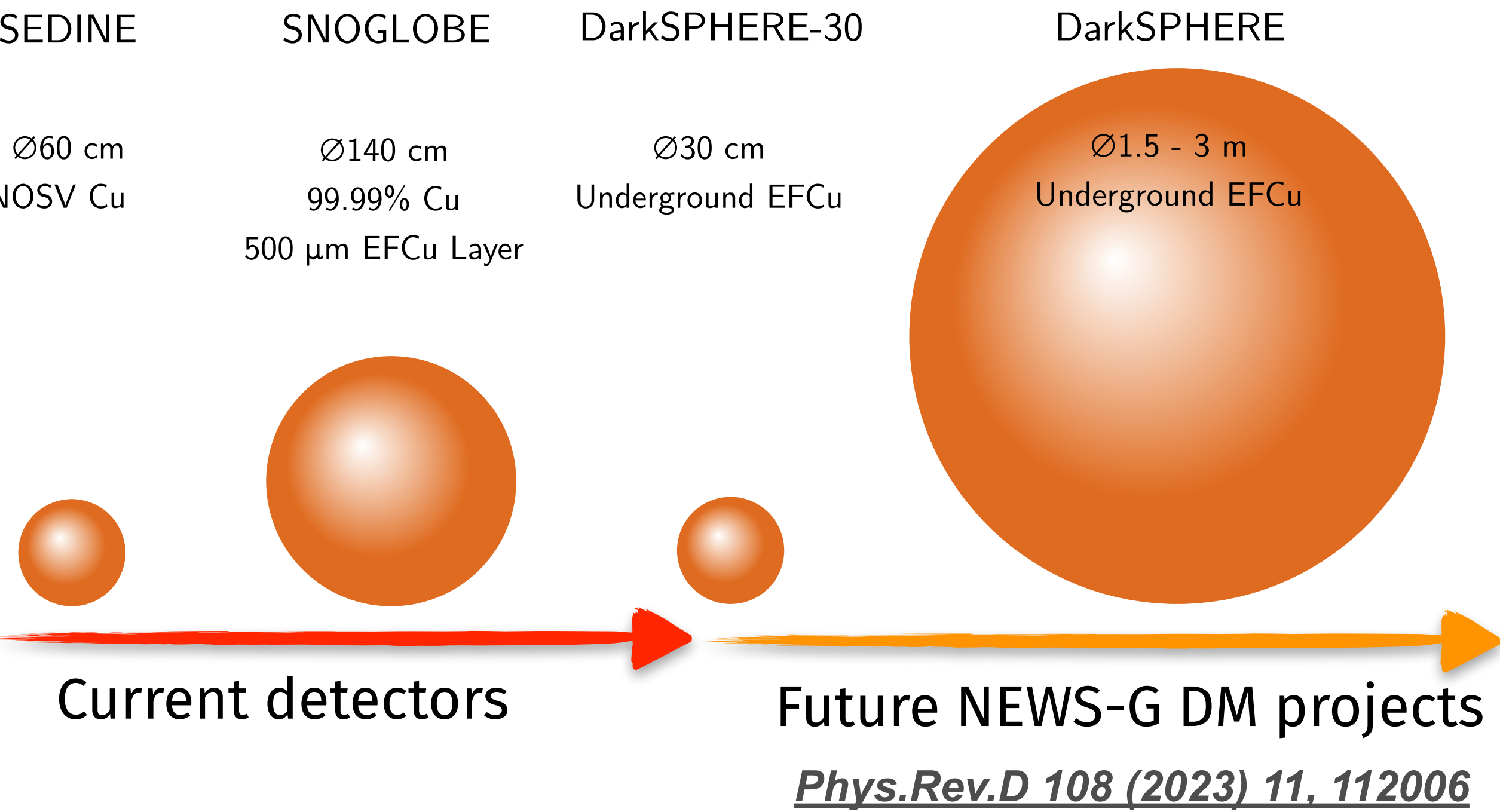
Phys.Rev.D 108 (2023) 11, 112006

Simulated backgrounds in S140

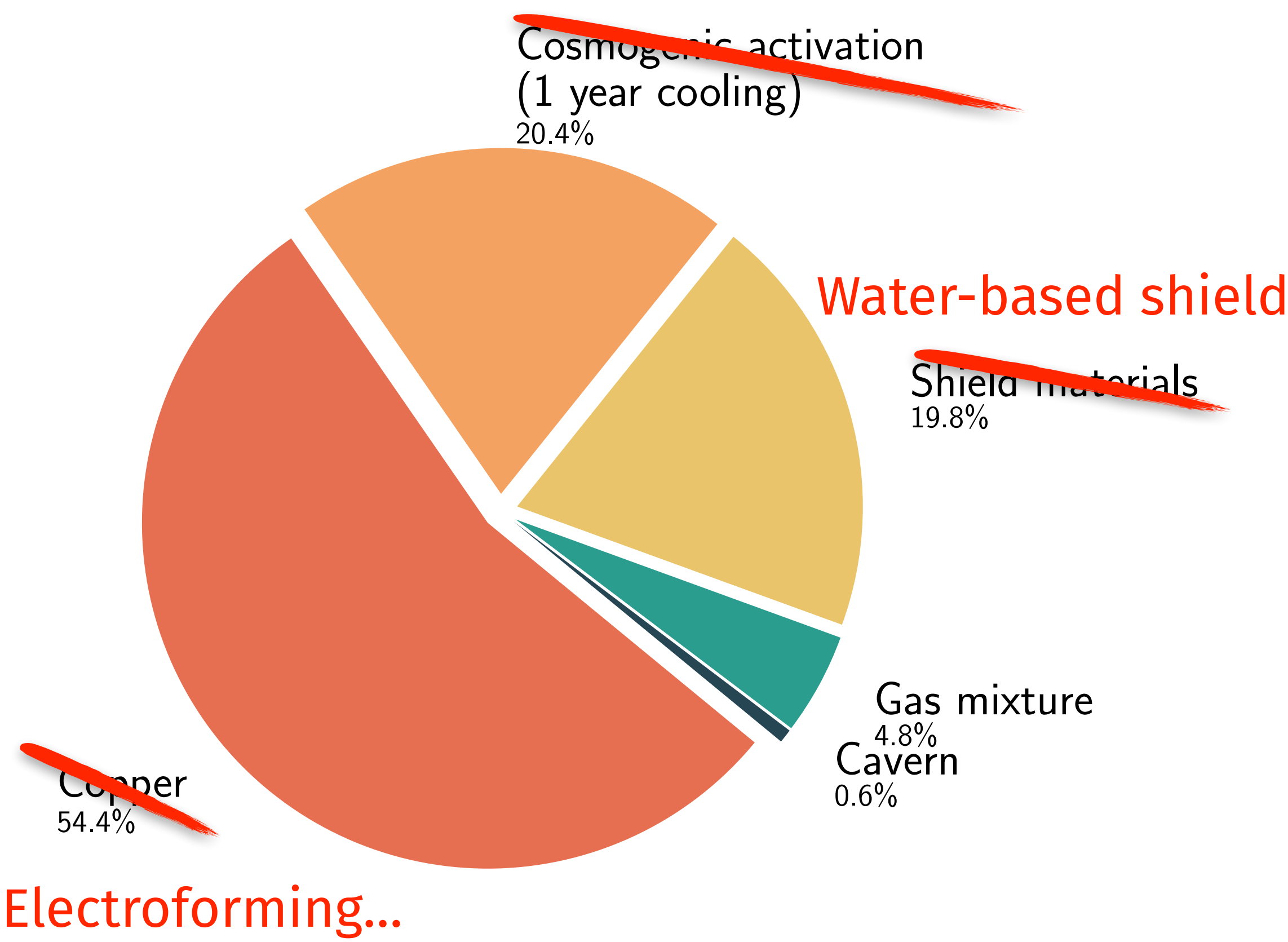
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DarkSPHERE

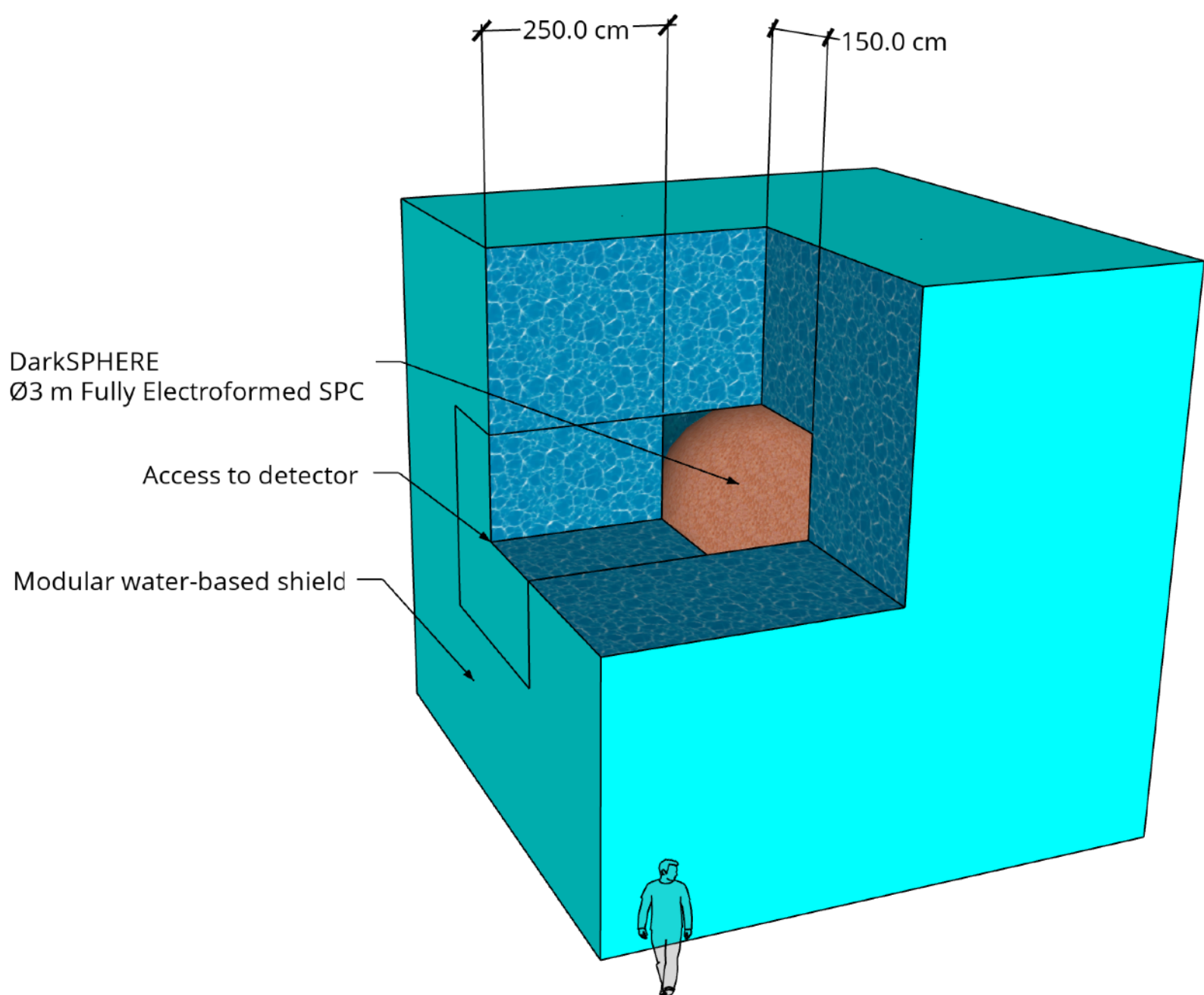


Simulated backgrounds in S140
...underground

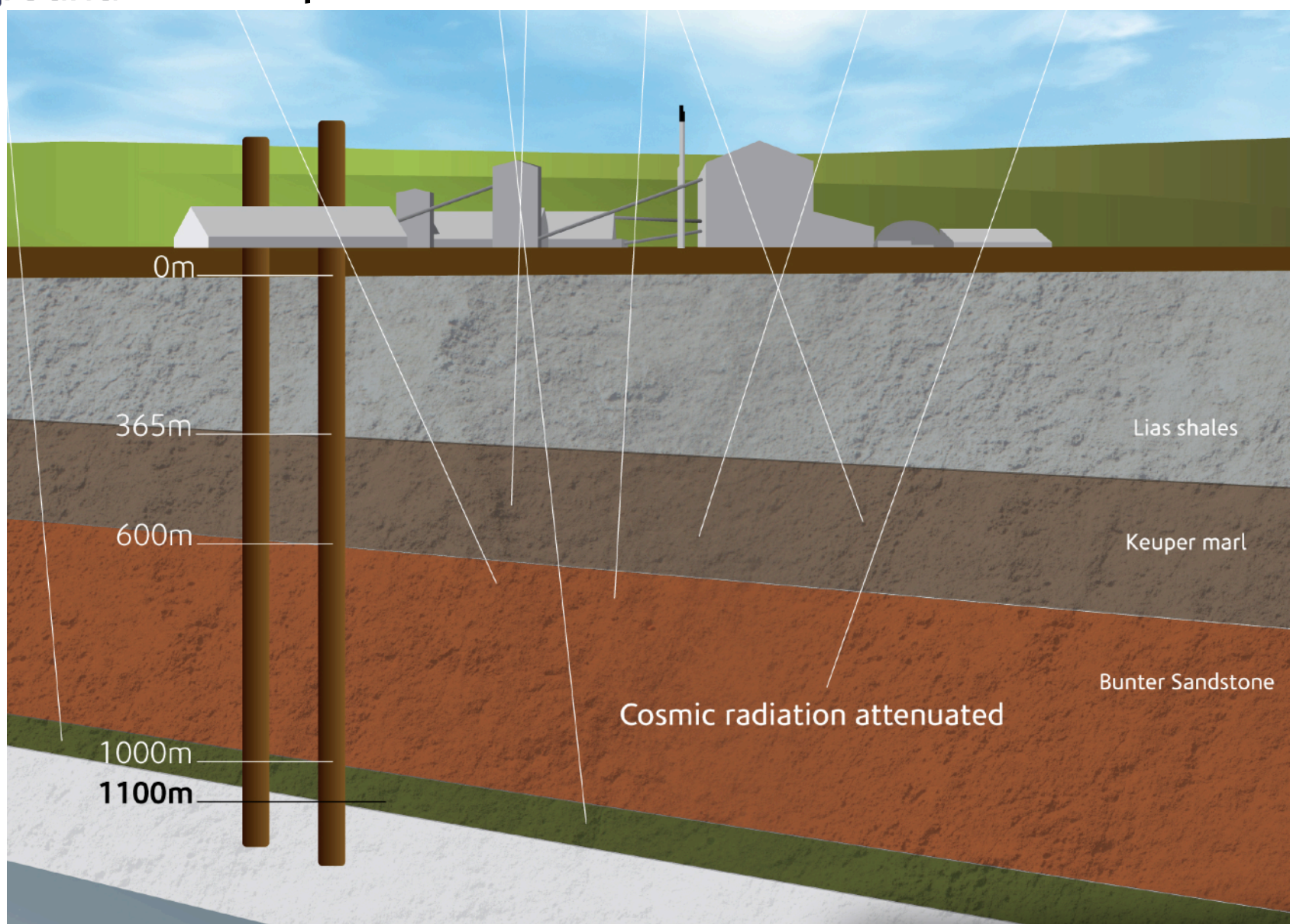


DarkSPHERE in Boulby

- DarkSPHERE will use a modular water-based shield
- A pure water shield is sufficient for background goal of **0.01 event/keV/kg/day** in ROI
- Conceptual design fits in available space in Boulby's LEC



Shielding configuration	Environmental background rate ≤ 1 keV [dru]			
	Photon-induced	Neutron-induced		Muon-induced
	Photon	Neutron	Photon	
2.5 m water	4.2×10^{-3} (0.3)	9×10^{-5} (5)	1.3×10^{-4} (0.4)	5×10^{-3} (4)



EFCu in Boulby

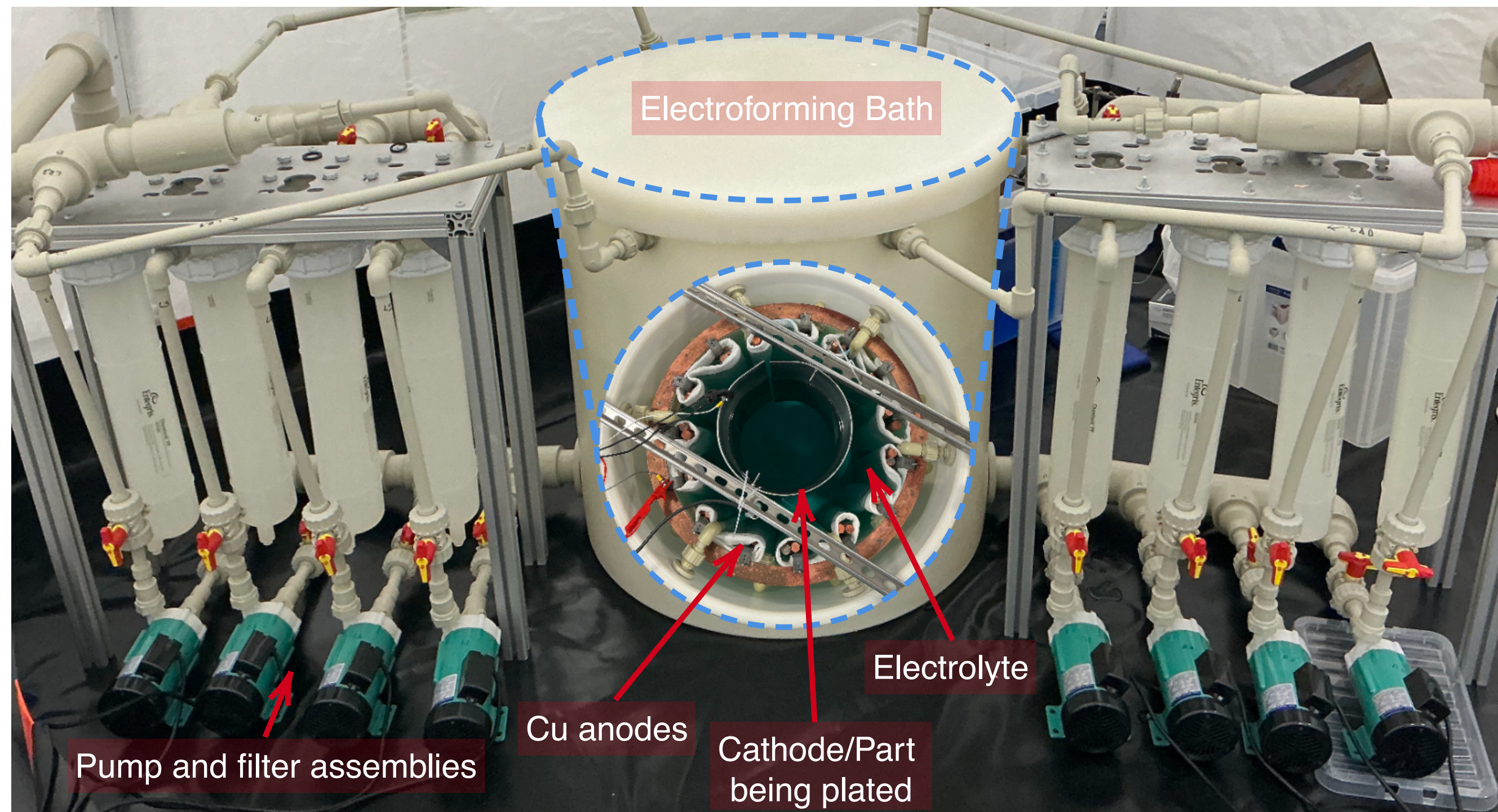
- ◆ ECuME project: **R&D completed** for Ø140cm detector + scale model
- ◆ Established EFCu facility underground in Boulby
 - ➡ Currently being commissioned
 - ➡ First Cu produced and being assayed
- ◆ Also exploring plating materials to reduce Rn emanation and high-purity alloys [arXiv: 2507.00799](#)
[arXiv: 2506.23231](#)

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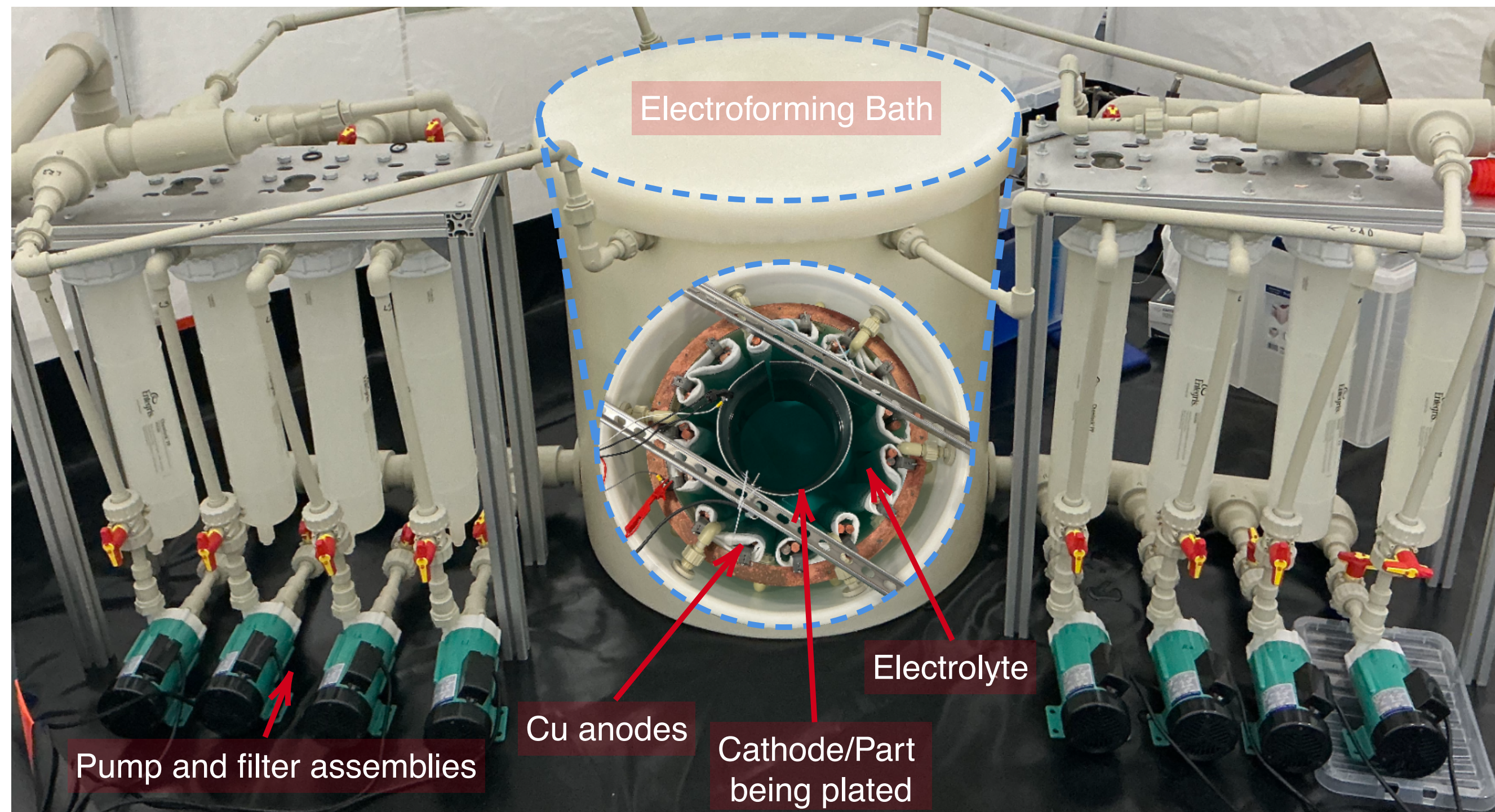
Commissioning of bath underway

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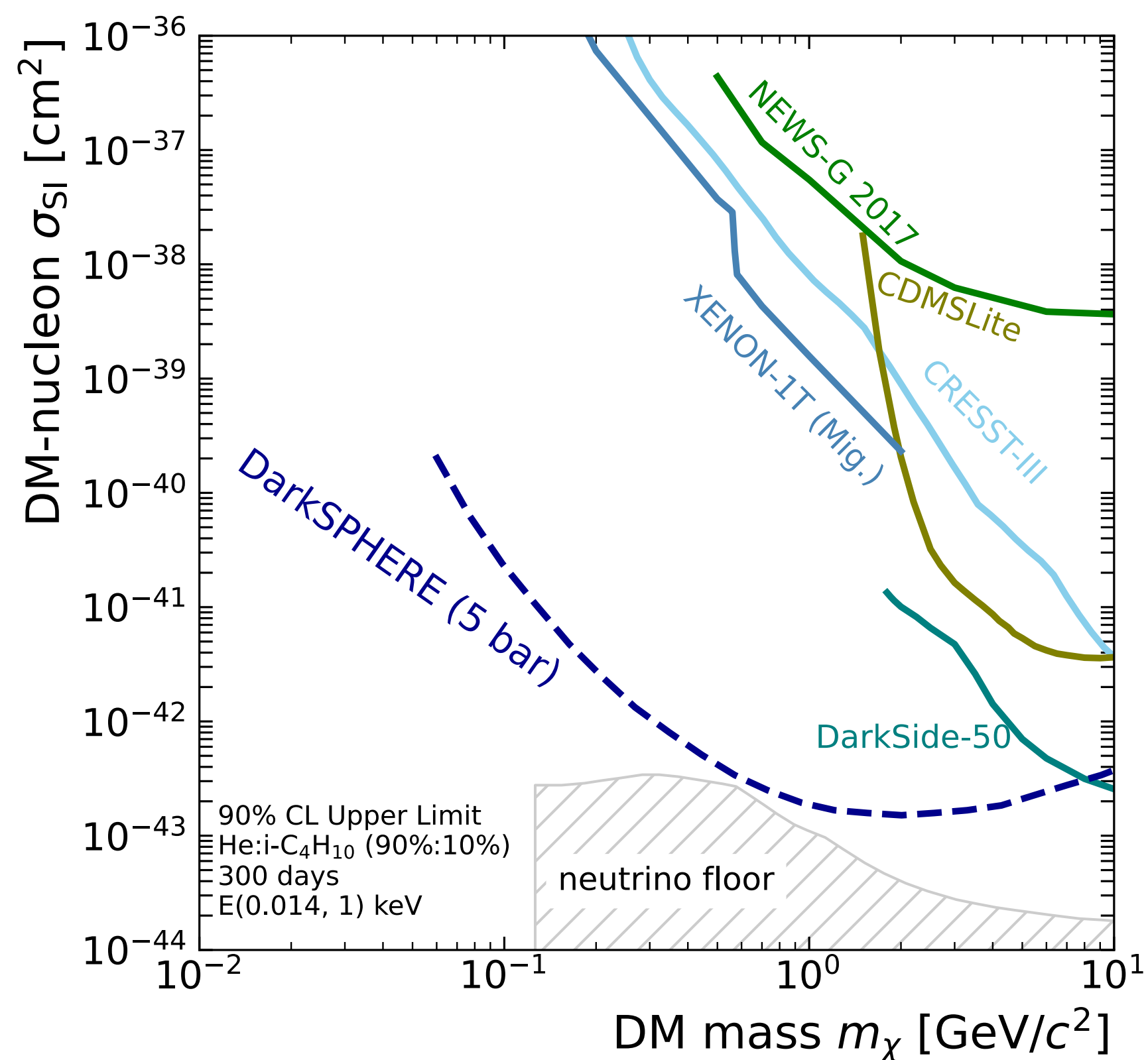


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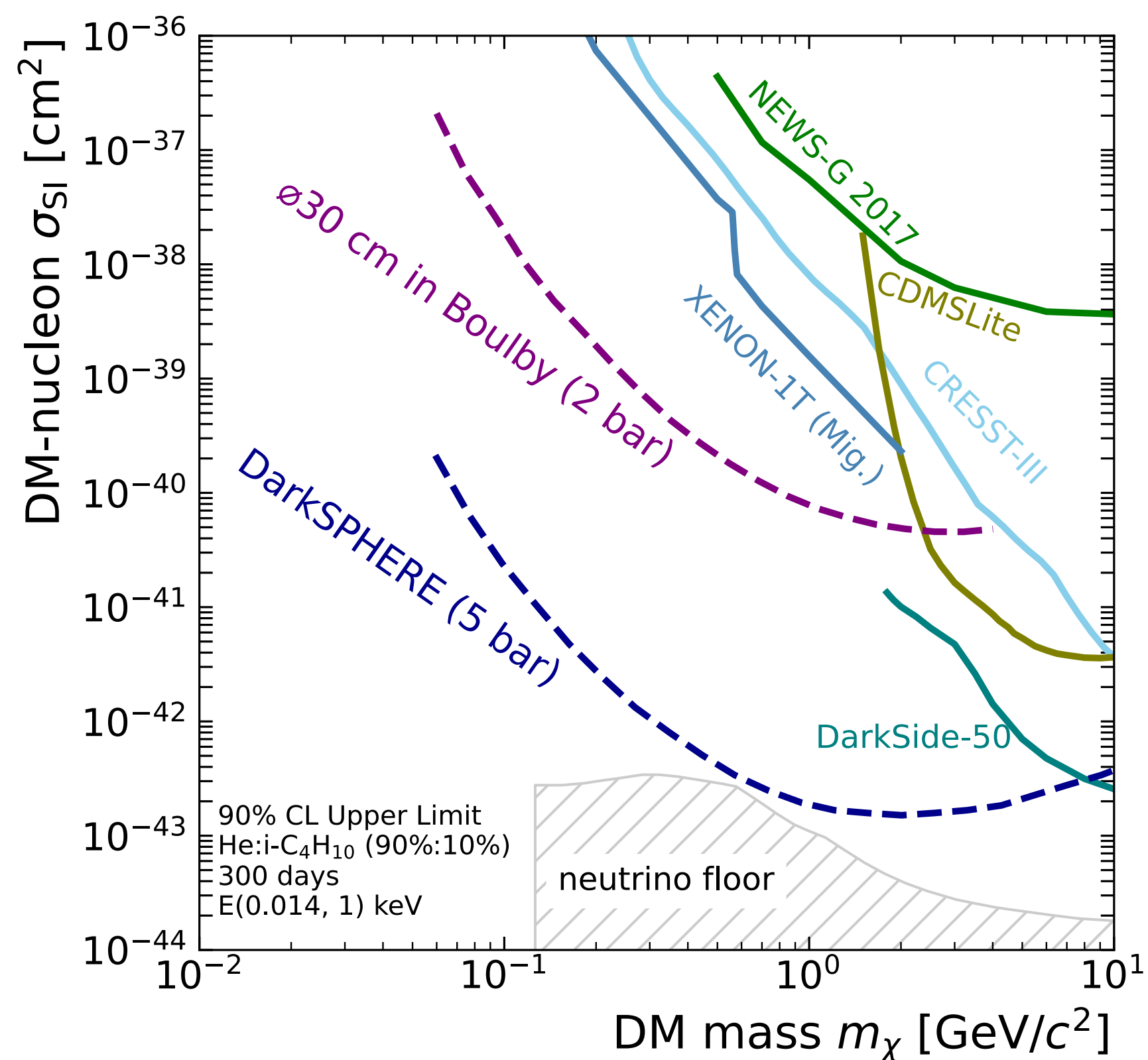
First EFCu Underground in Boulby

DarkSPHERE (ø3m) Physics Potential



- ◆ **‘Neutrino-floor’ reaching potential** in DM-nucleon SI interactions
- ◆ **World-leading** potential in SD interactions through natural-abundance H and C isotopes
- ◆ ø30cm prototype in Boulby in a DarkSPHERE-like shield will have world-leading sensitivity

DarkSPHERE (ø3m) Physics Potential

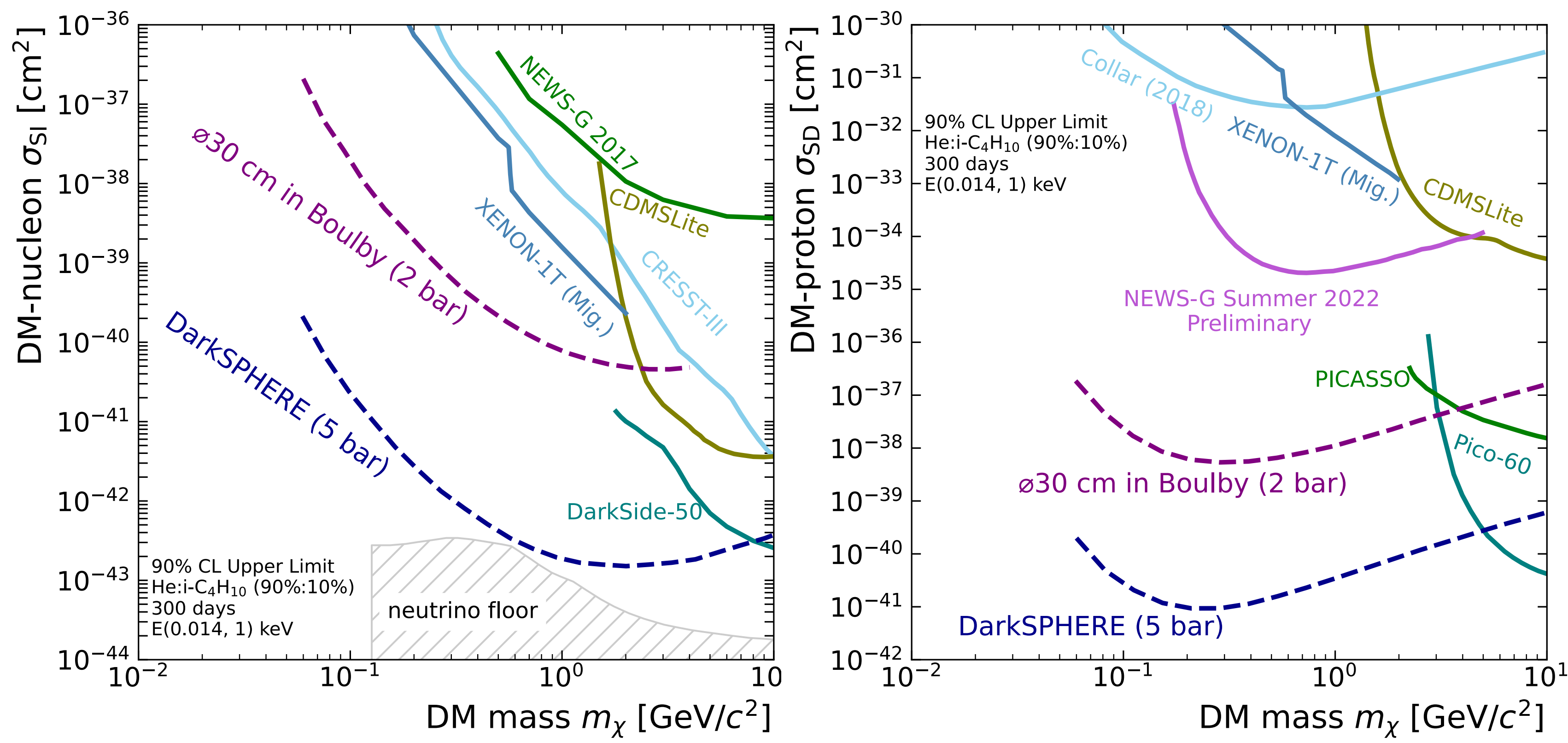


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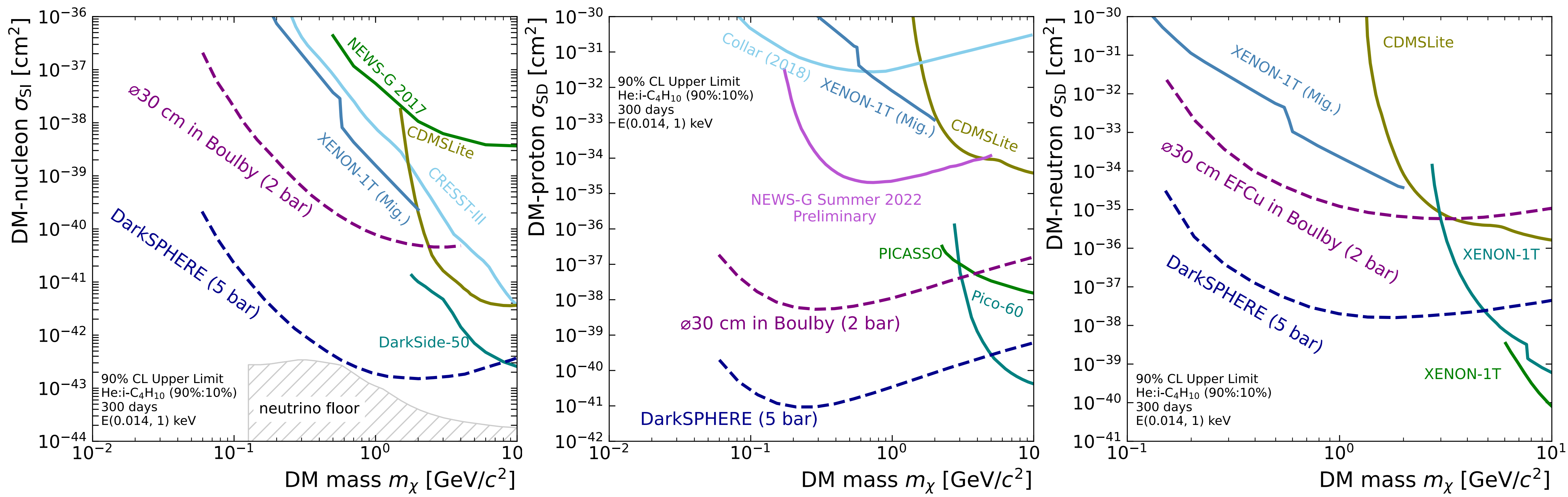
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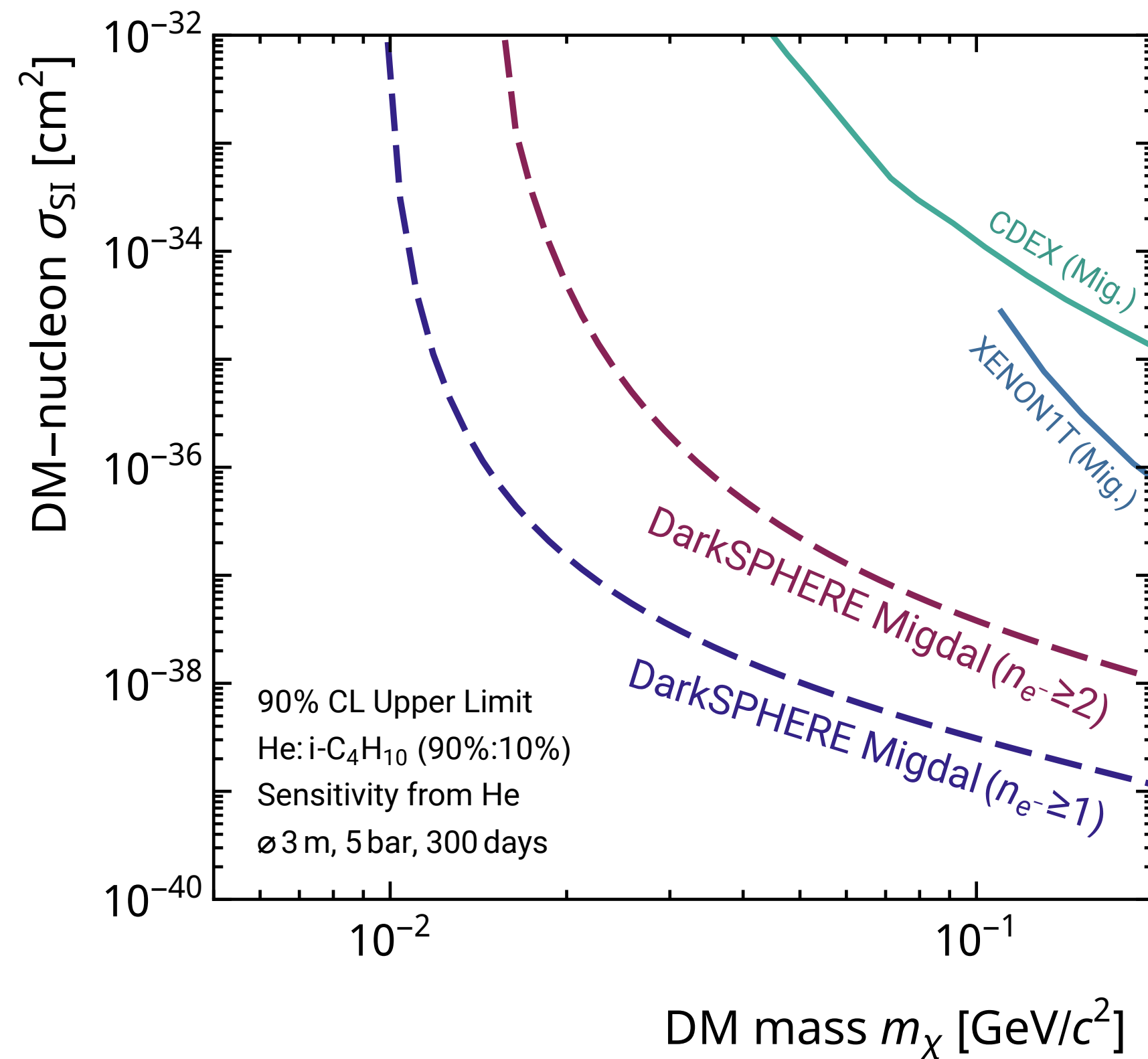
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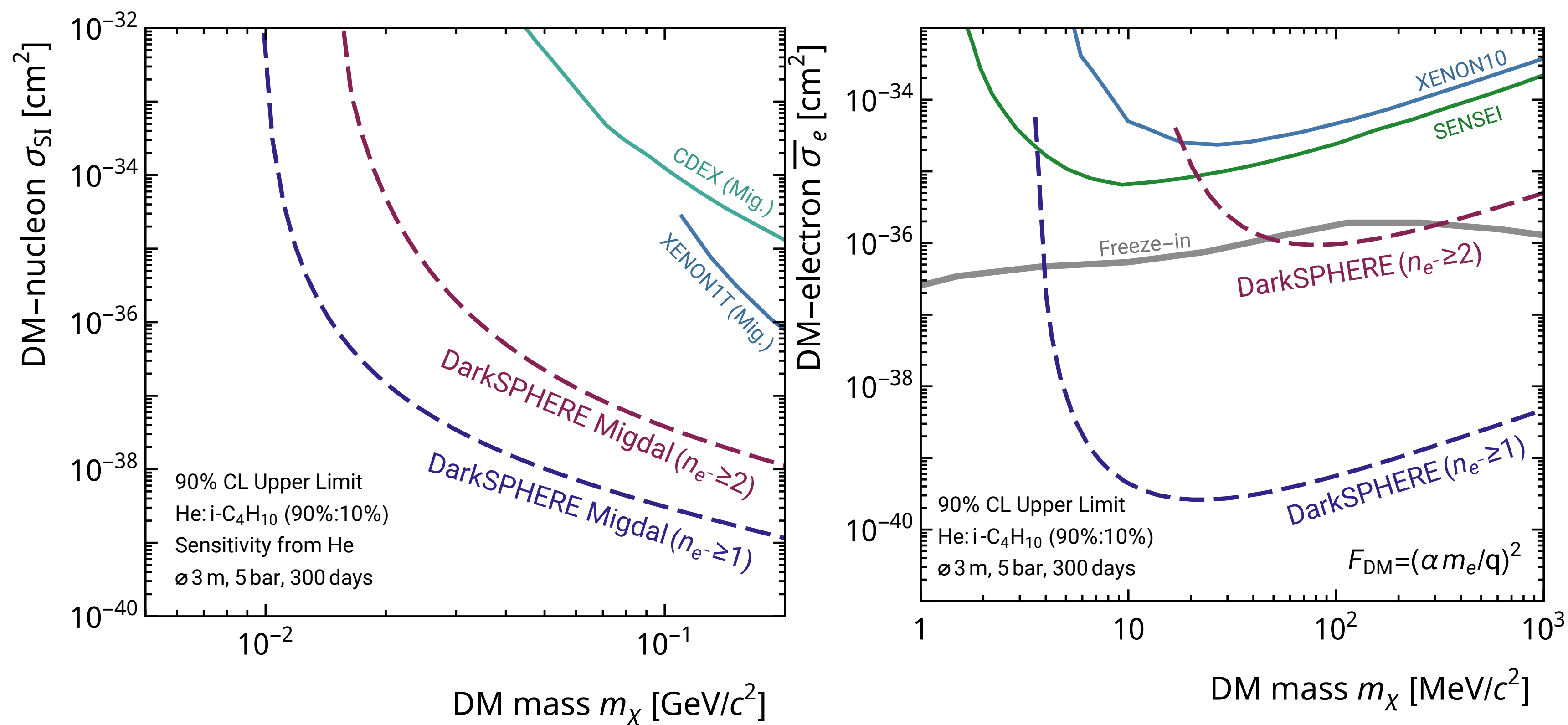
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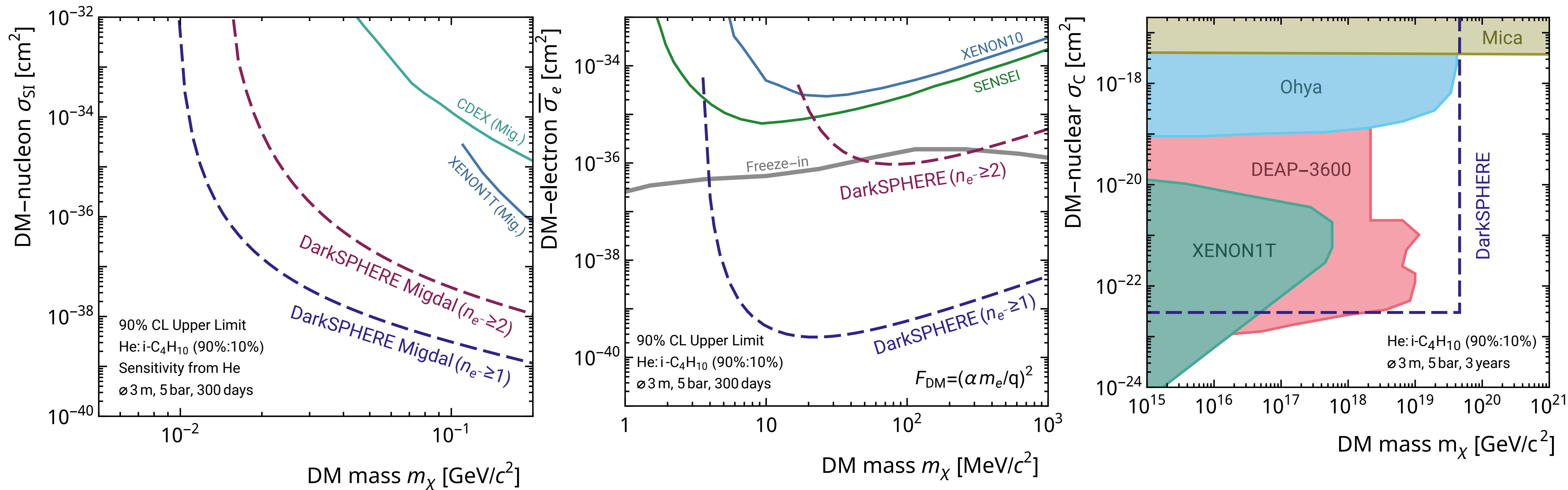
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- Sensitivity to electron scattering through low threshold
- Large sphere is also ideal shape to study more **exotic candidates**

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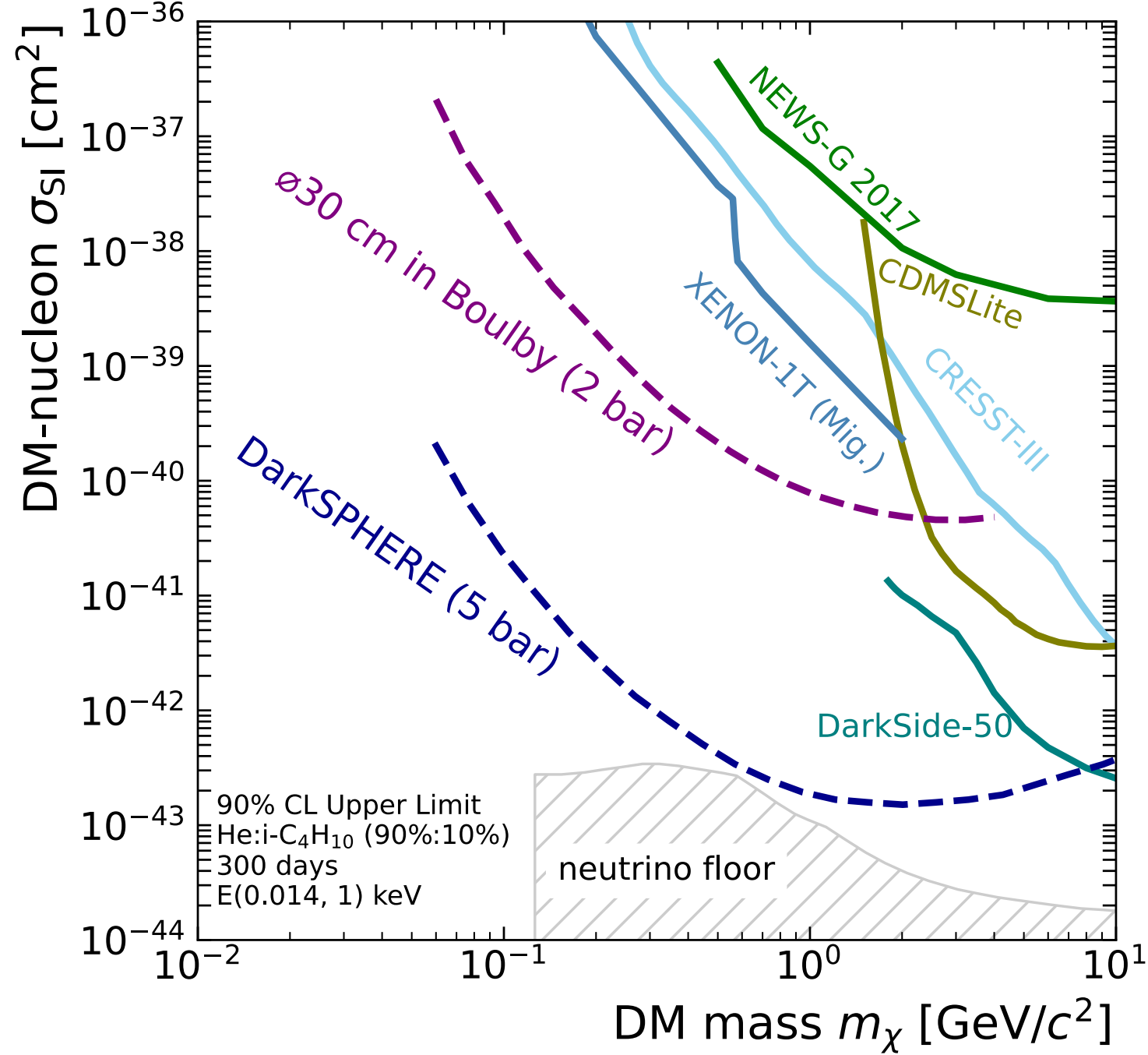
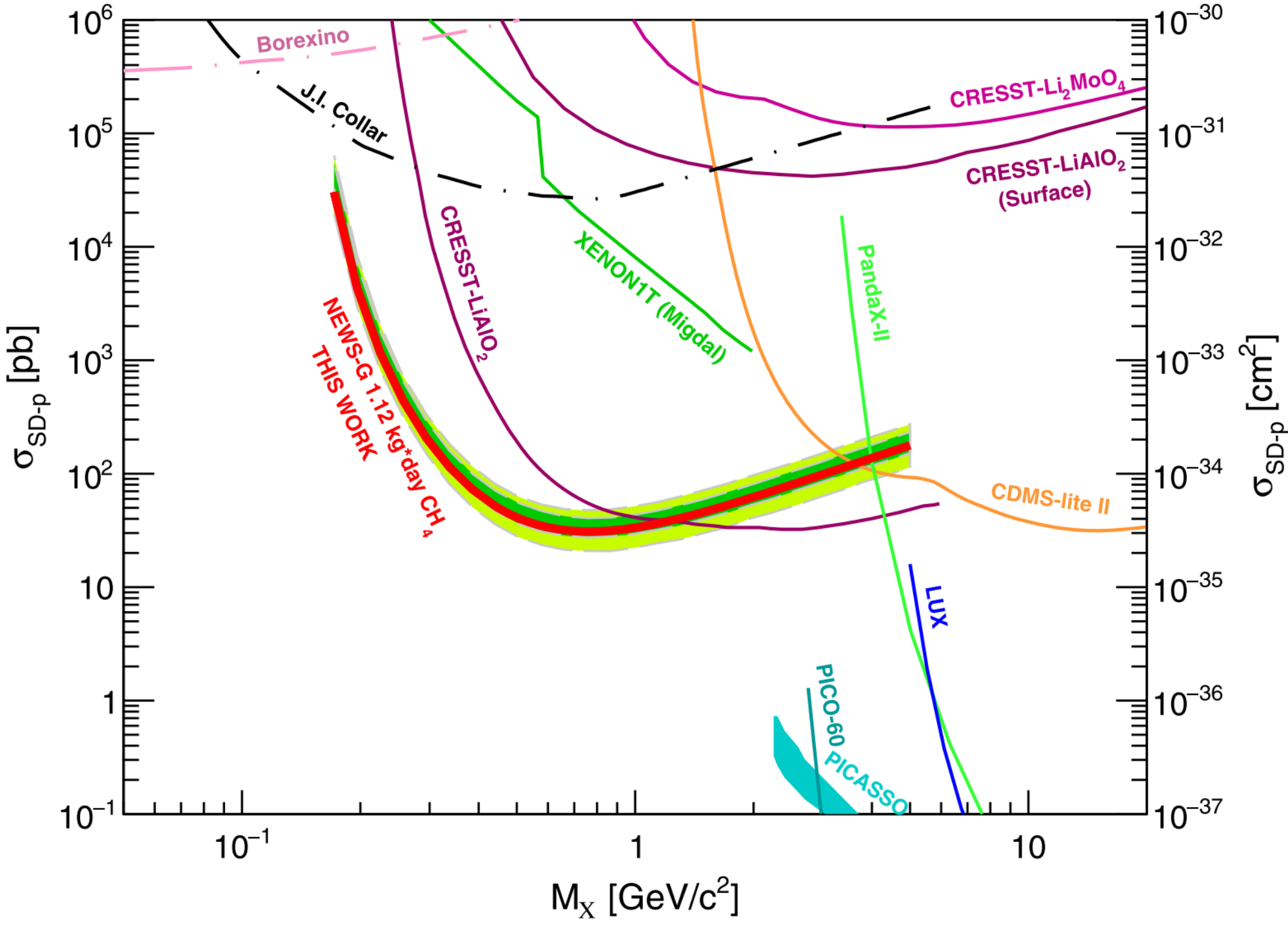
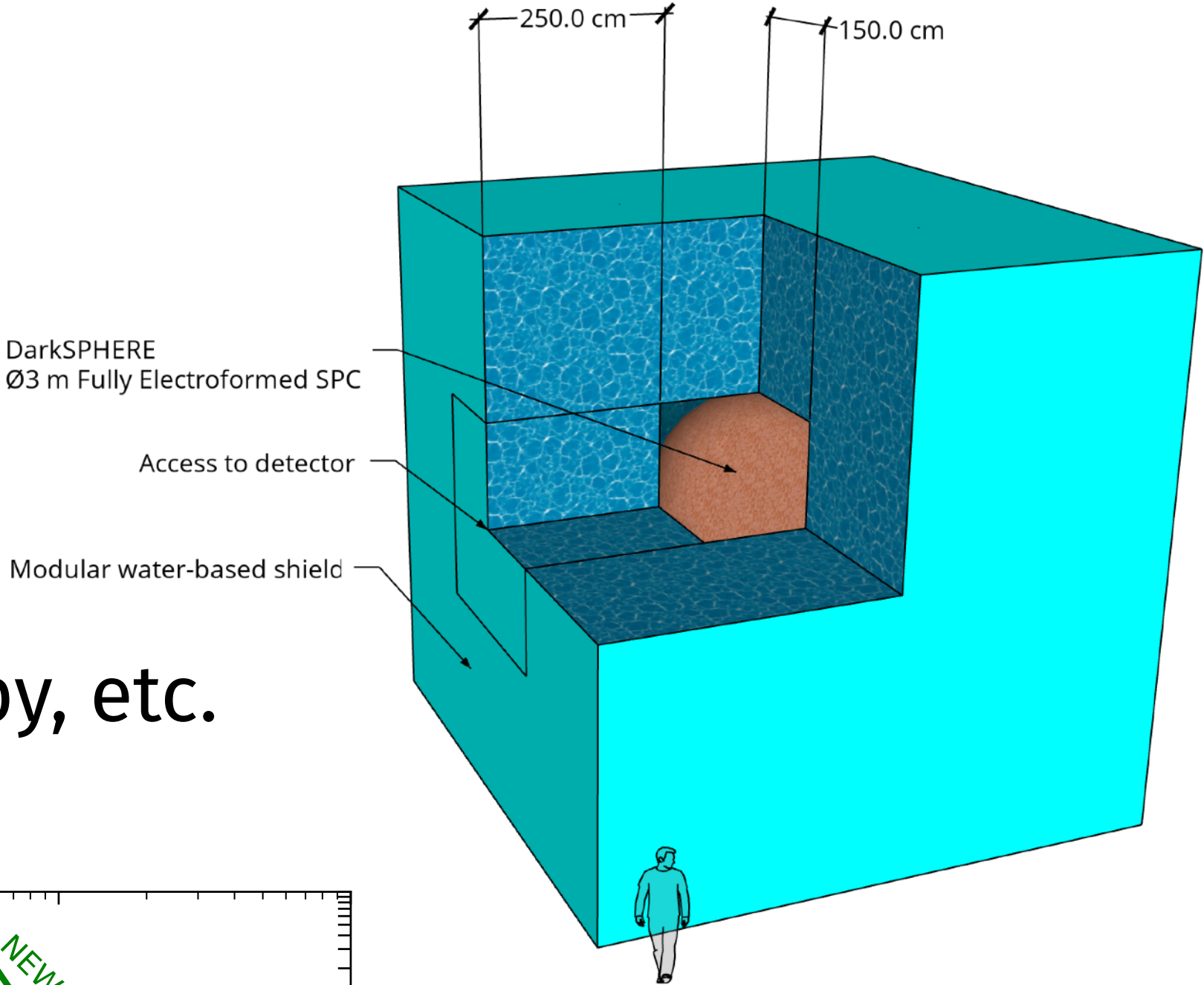
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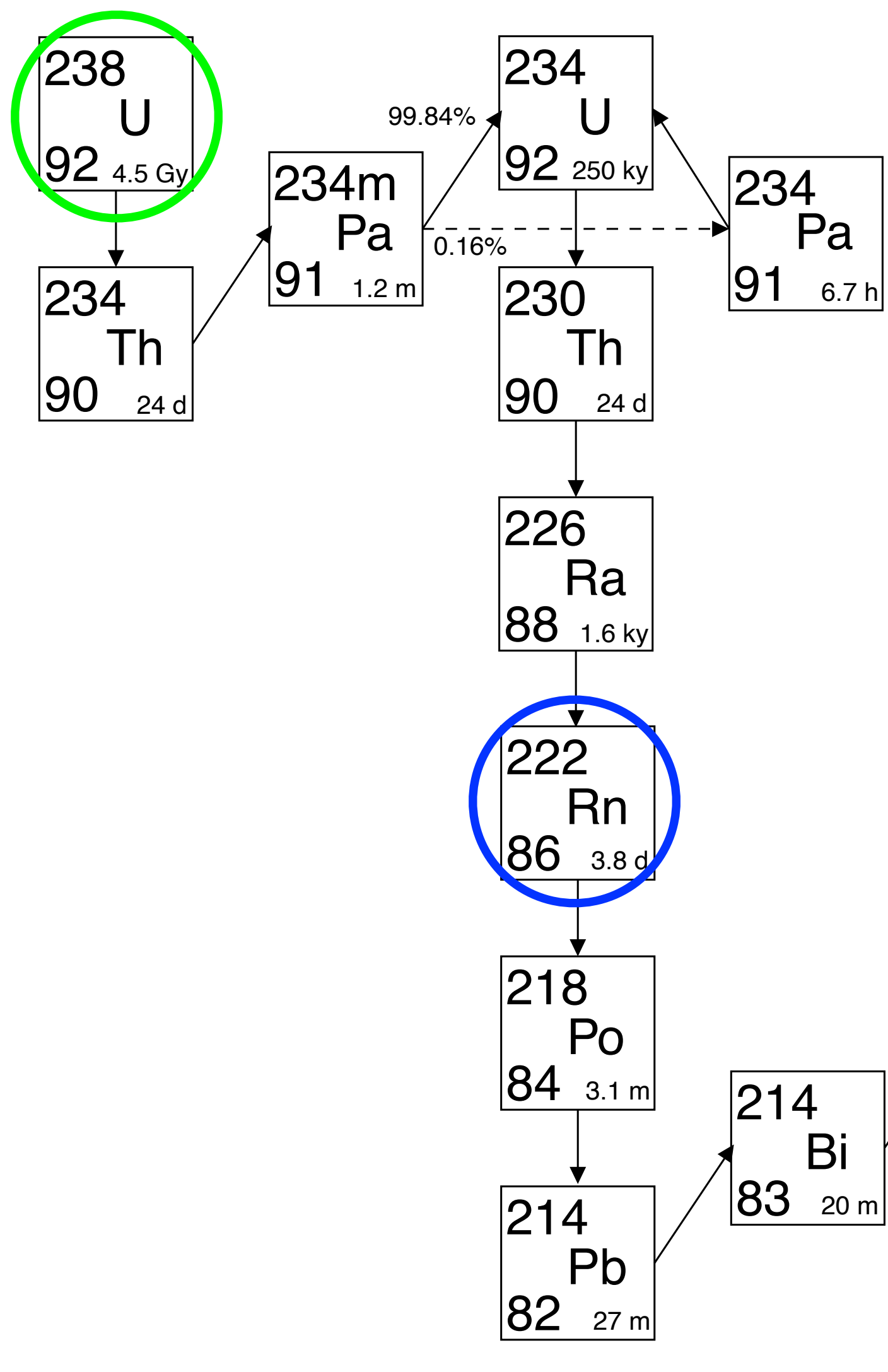
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Summary

- Spherical proportional counters employed for light-DM searches
- Full detector electroformation will overcome main BG
- DarkSPHERE** proposed for Boulby's existing space
 - World-leading physics potential in multiple interactions
- Other exciting physics potential: $0\nu\beta\beta$, CEvENs, neutron spectroscopy, etc.



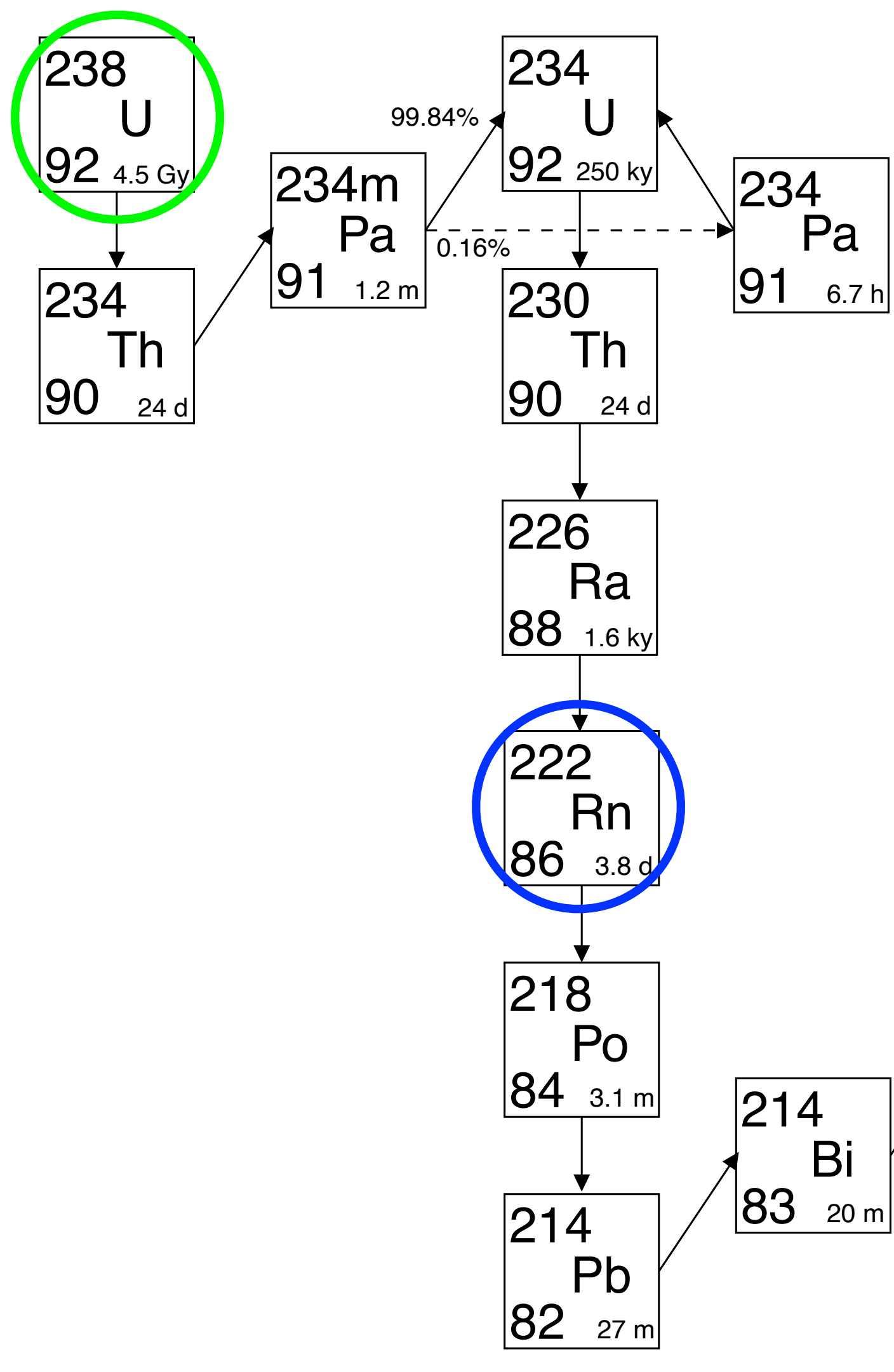
Ultra-Pure Cu Electroforming



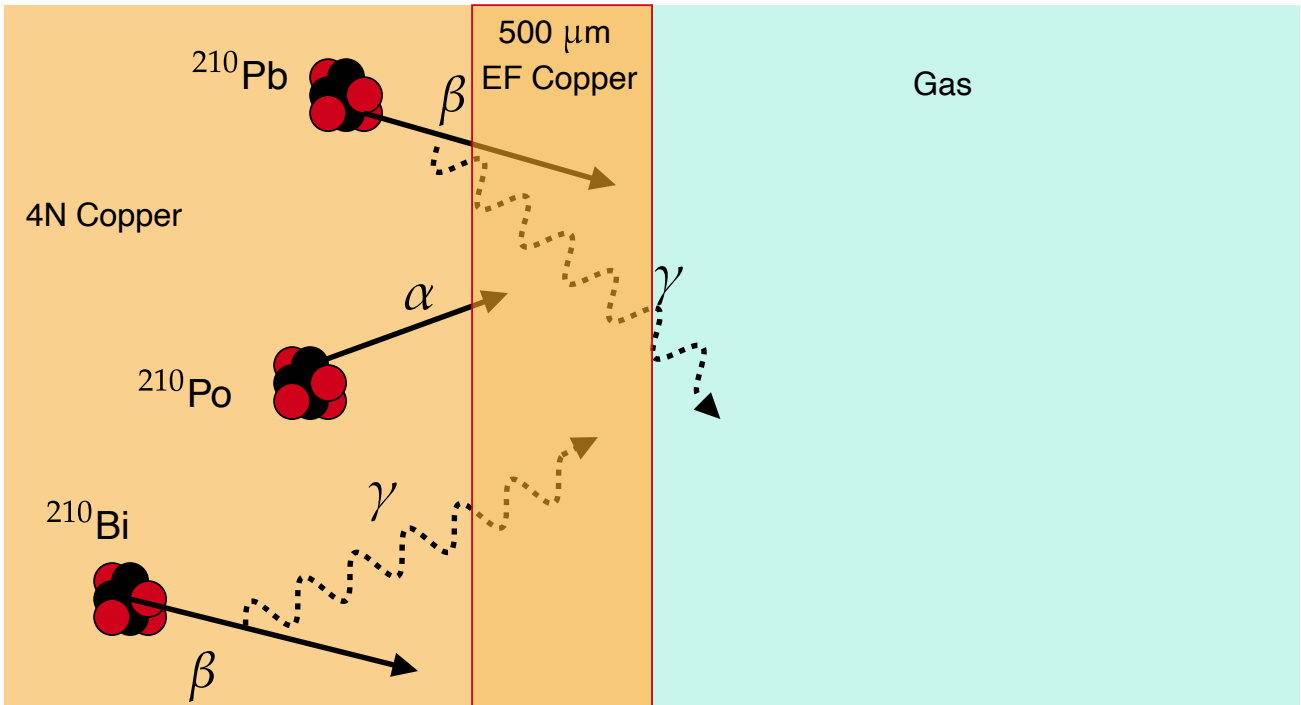
- Main background source Cu detector
- Favourable electrochemical properties of copper → Possible to produce copper with reduced contaminants (e.g. U, Th, K, etc.)
- Performing this underground → suppressed cosmogenic activation
- Used by several experiments, e.g. NEWS-G

Nucl.Instrum.Meth.A 988 (2021) 164844

Ultra-Pure Cu Electroforming

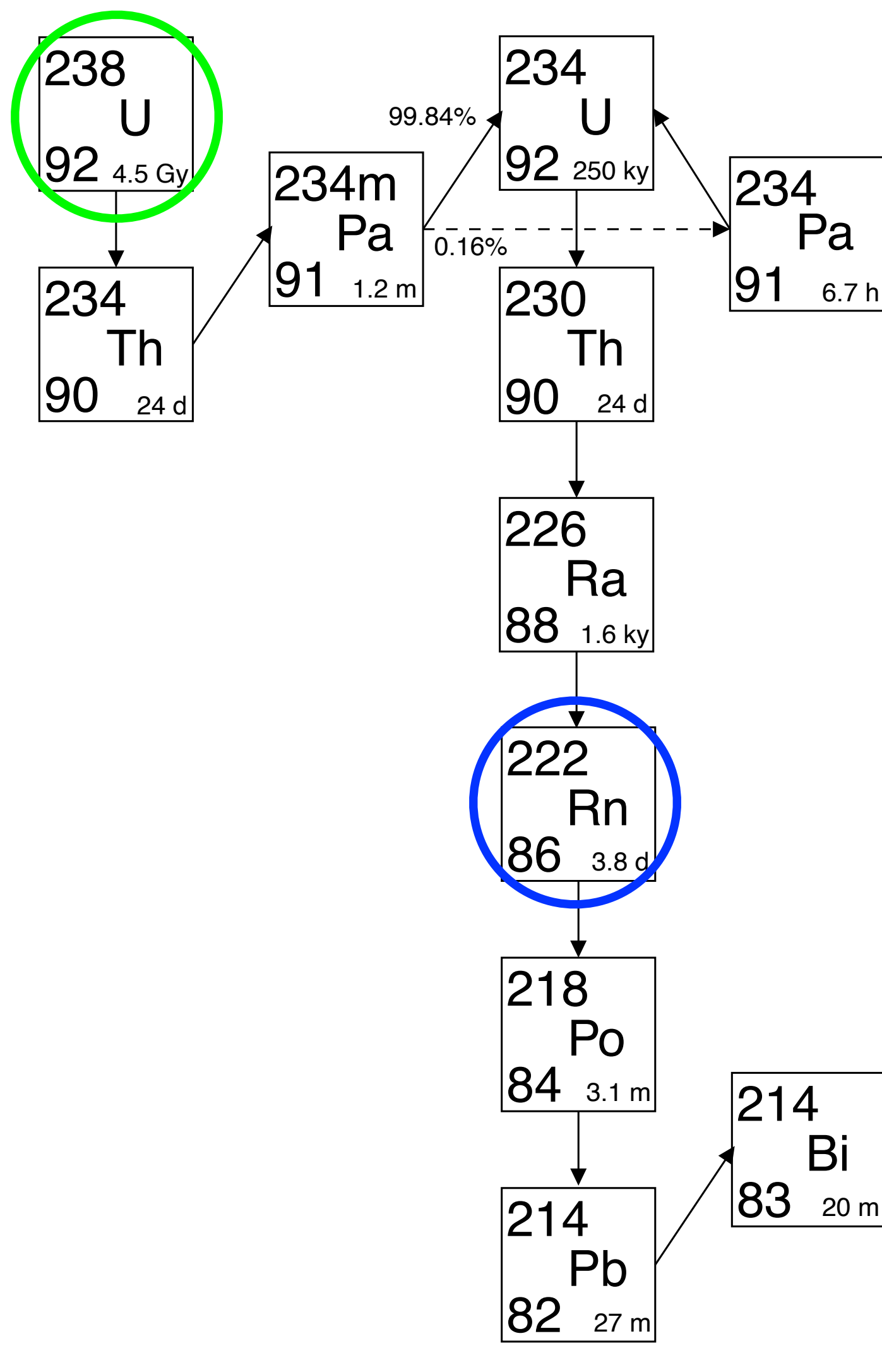


- Main background source Cu detector
- Favourable electrochemical properties of copper → Possible to produce copper with reduced contaminants (e.g. U, Th, K, etc.)
- Performing this underground → suppressed cosmogenic activation
- Used by several experiments, e.g. NEWS-G

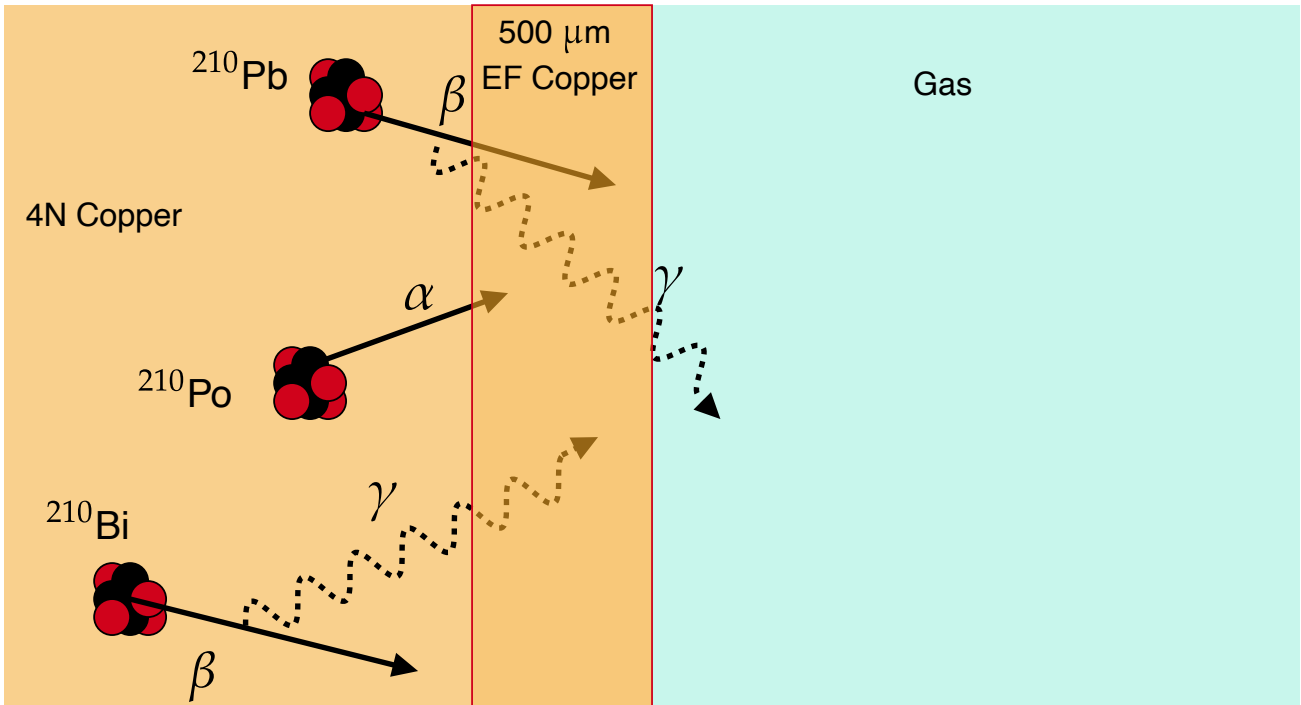


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ICP-MS Assay

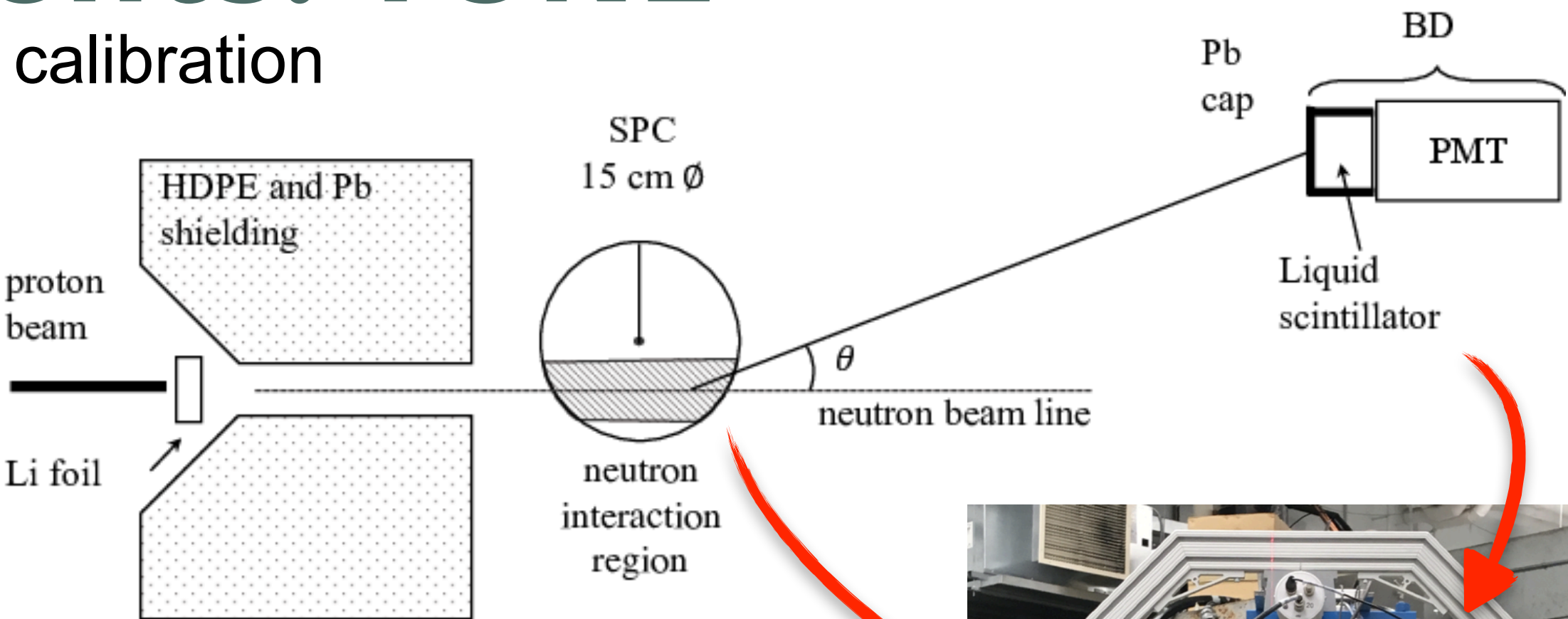
Sample	Weight [g]	^{232}Th [$\mu\text{Bq kg}^{-1}$]	^{238}U [$\mu\text{Bq kg}^{-1}$]
C10100 Cu (Machined)	-	8.7 ± 1.6	27.9 ± 1.9
Cu Electroformed	-	<0.119	<0.099
Hemisphere 1	0.256	<0.58	<0.26
Hemisphere 2	0.614	<0.24	<0.11

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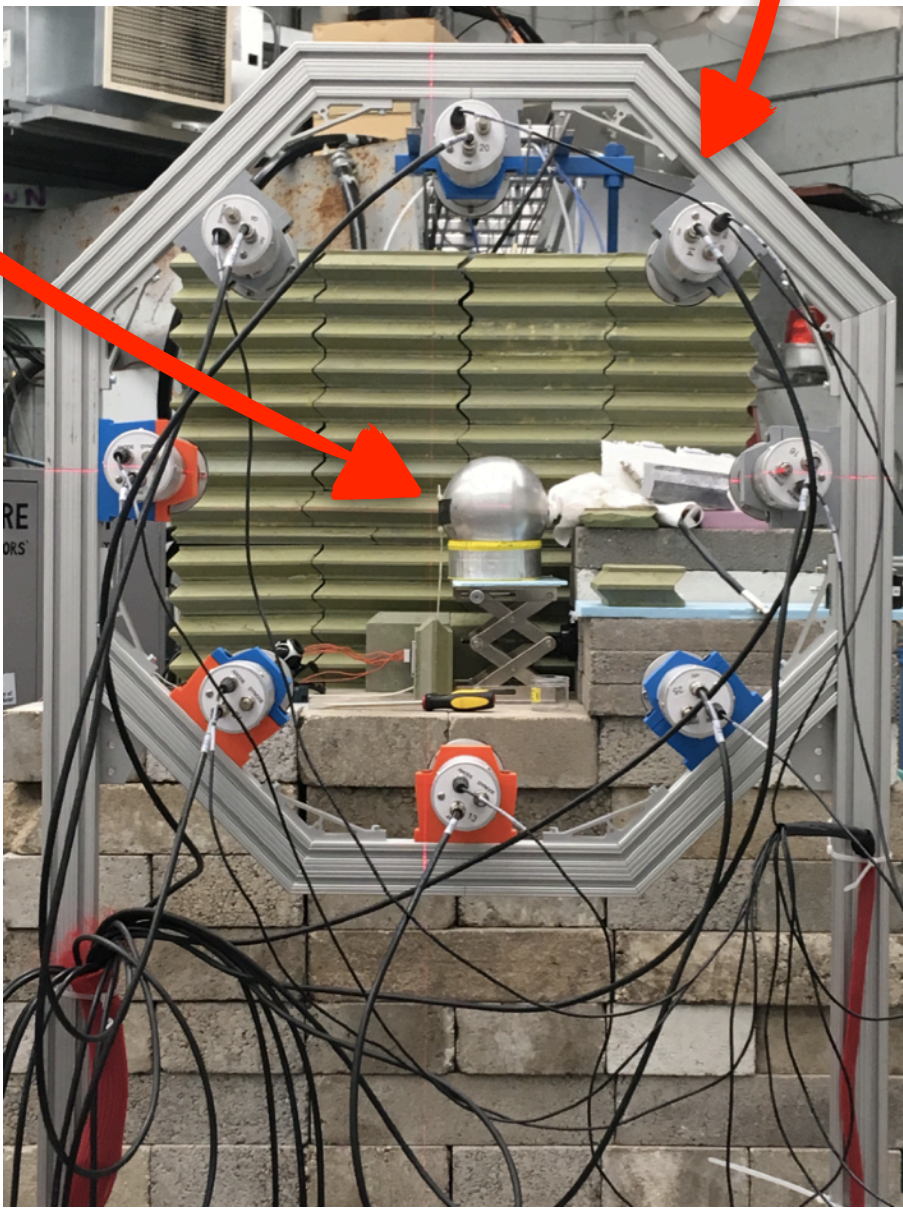


Quenching Factor Measurements: TUNL

Neutron scattering-induced nuclear recoils in SPC → compare to calibration

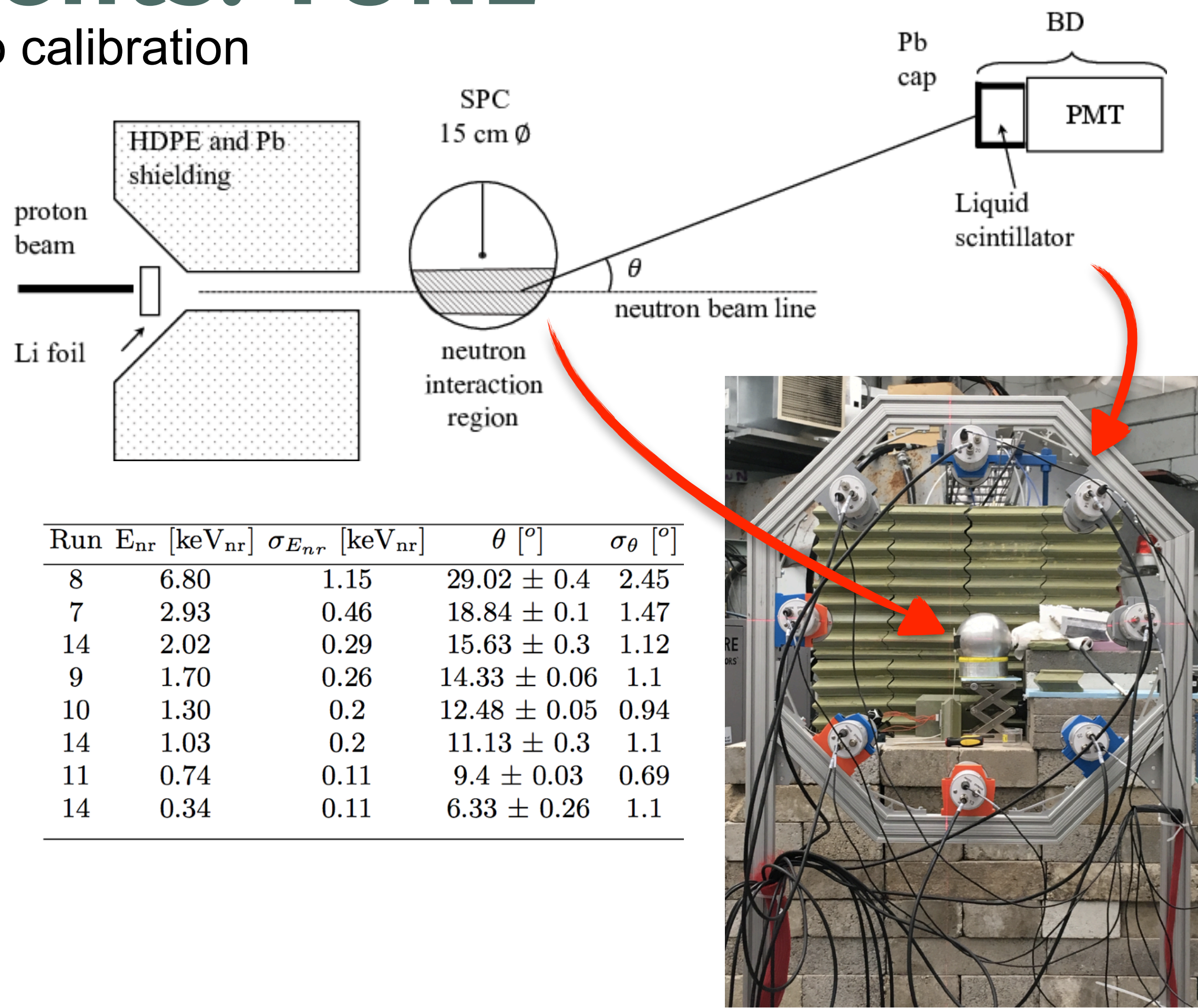
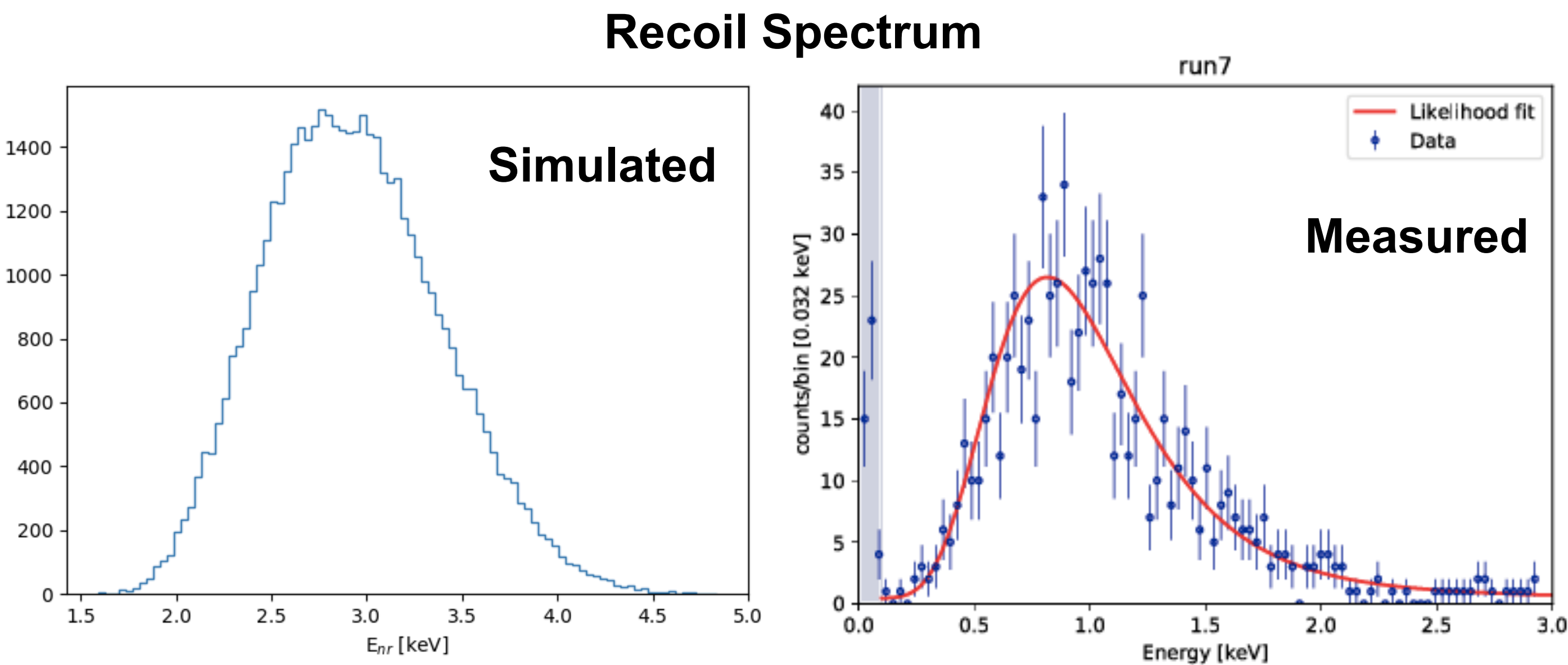


Run	E_{nr} [keV _{nr}]	$\sigma_{E_{nr}}$ [keV _{nr}]	θ [°]	σ_{θ} [°]
8	6.80	1.15	29.02 ± 0.4	2.45
7	2.93	0.46	18.84 ± 0.1	1.47
14	2.02	0.29	15.63 ± 0.3	1.12
9	1.70	0.26	14.33 ± 0.06	1.1
10	1.30	0.2	12.48 ± 0.05	0.94
14	1.03	0.2	11.13 ± 0.3	1.1
11	0.74	0.11	9.4 ± 0.03	0.69
14	0.34	0.11	6.33 ± 0.26	1.1



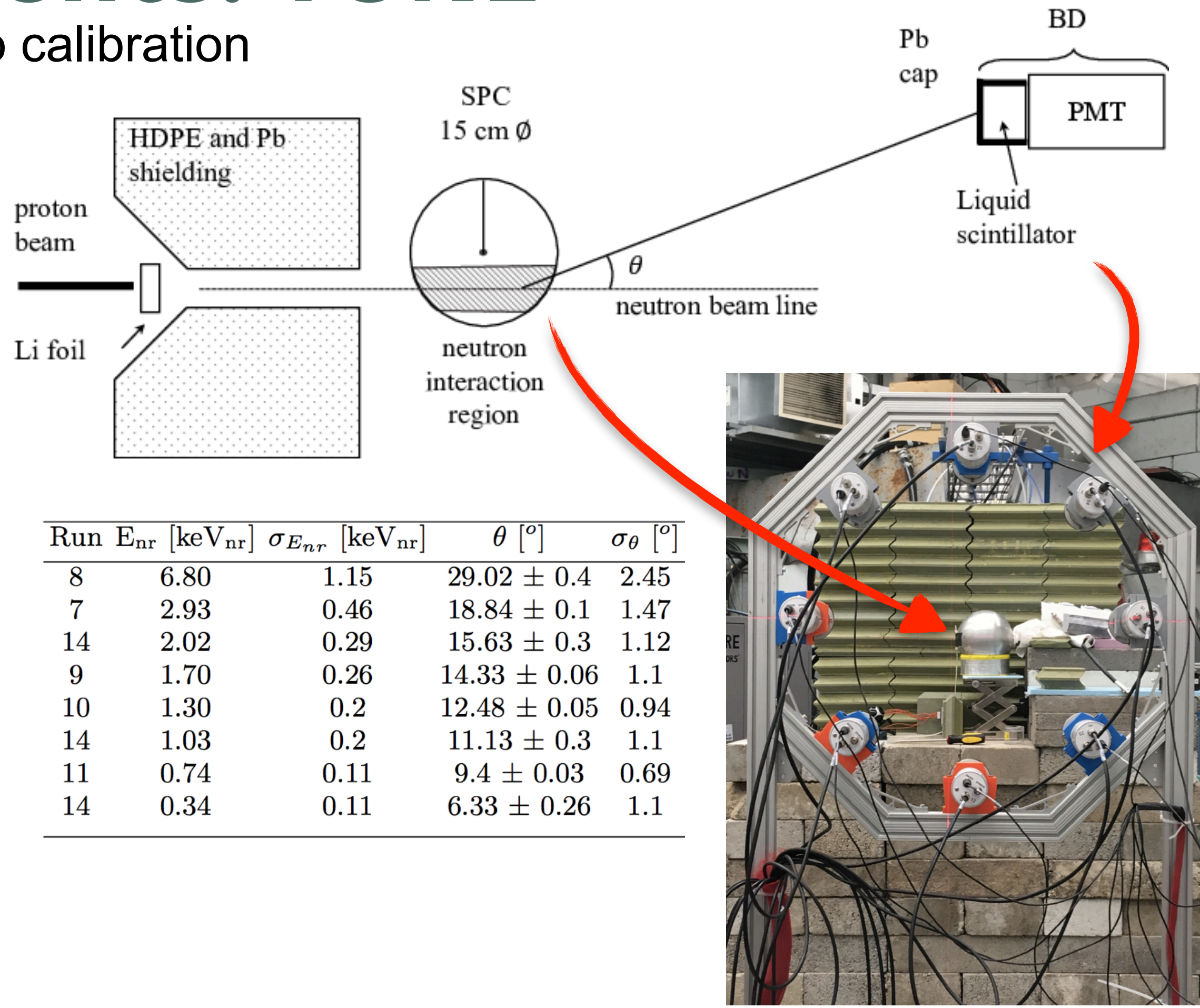
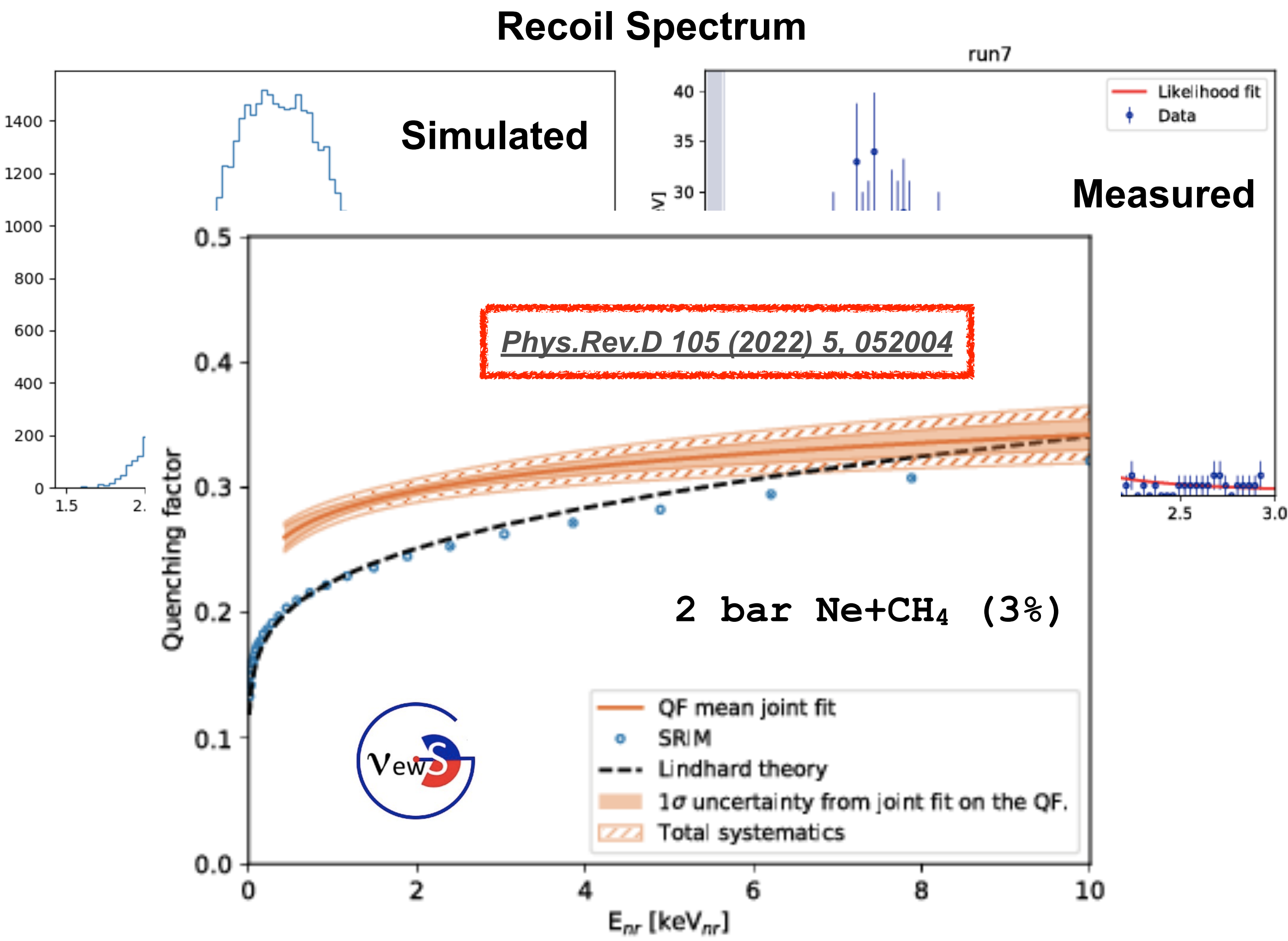
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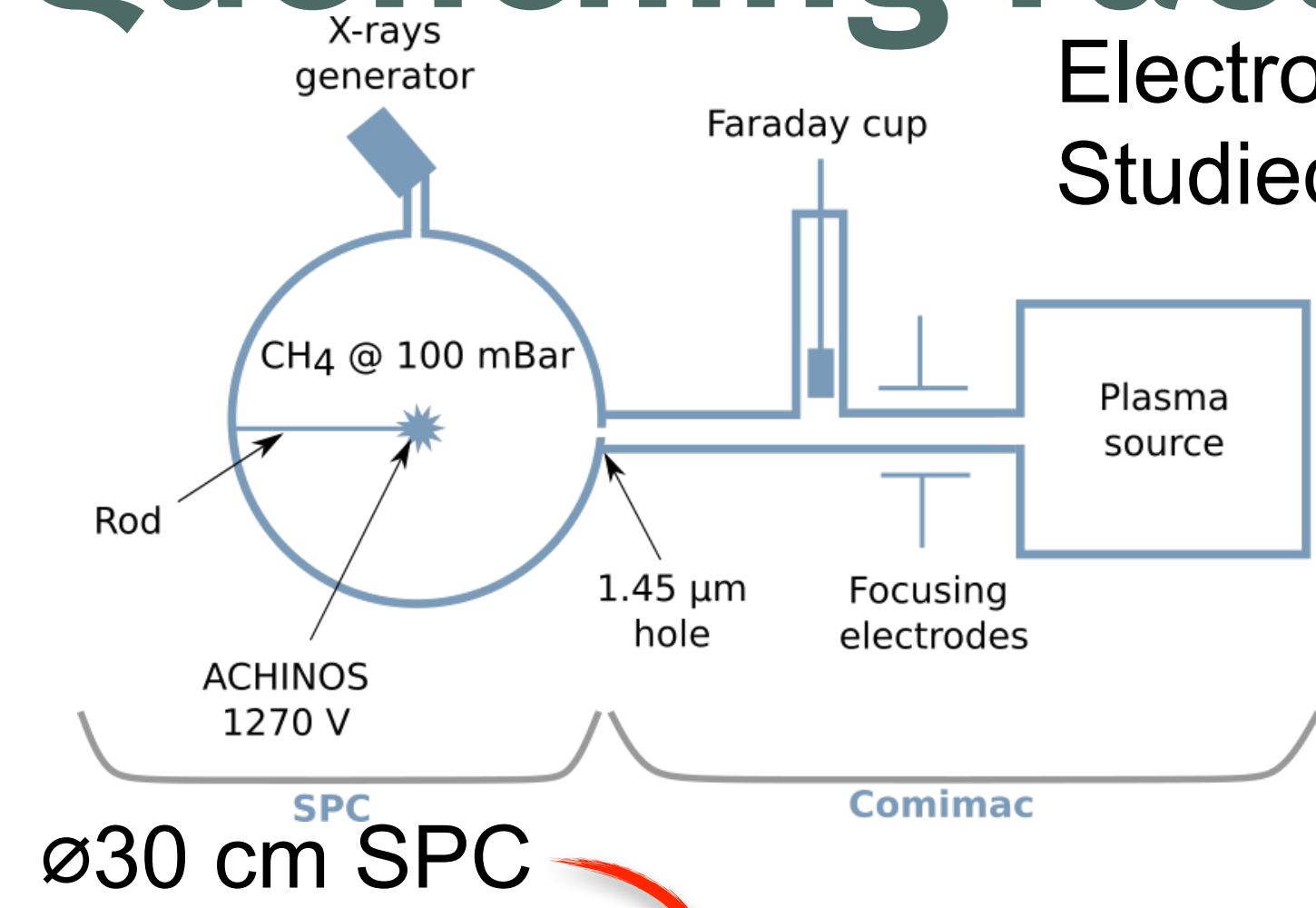
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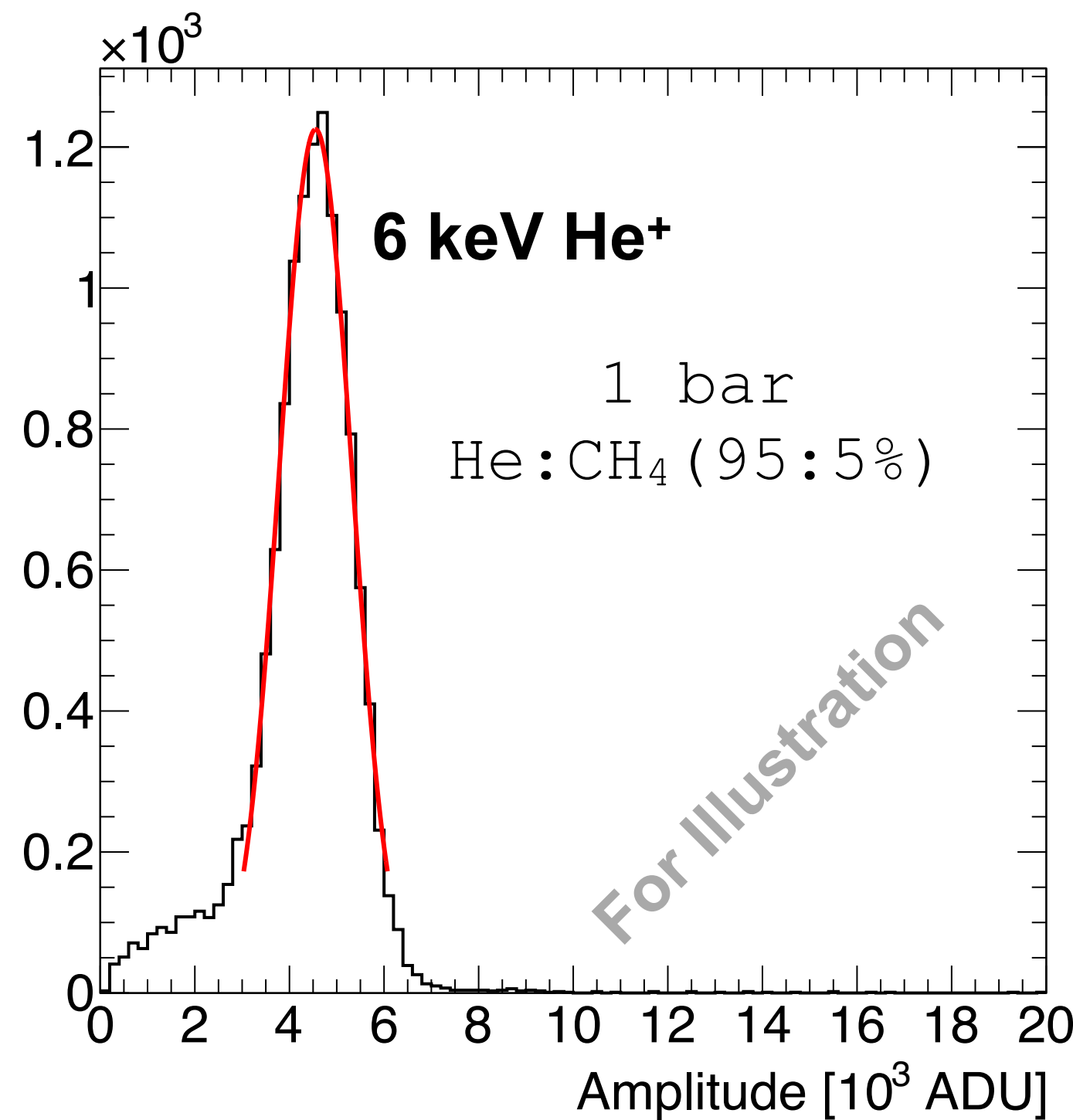
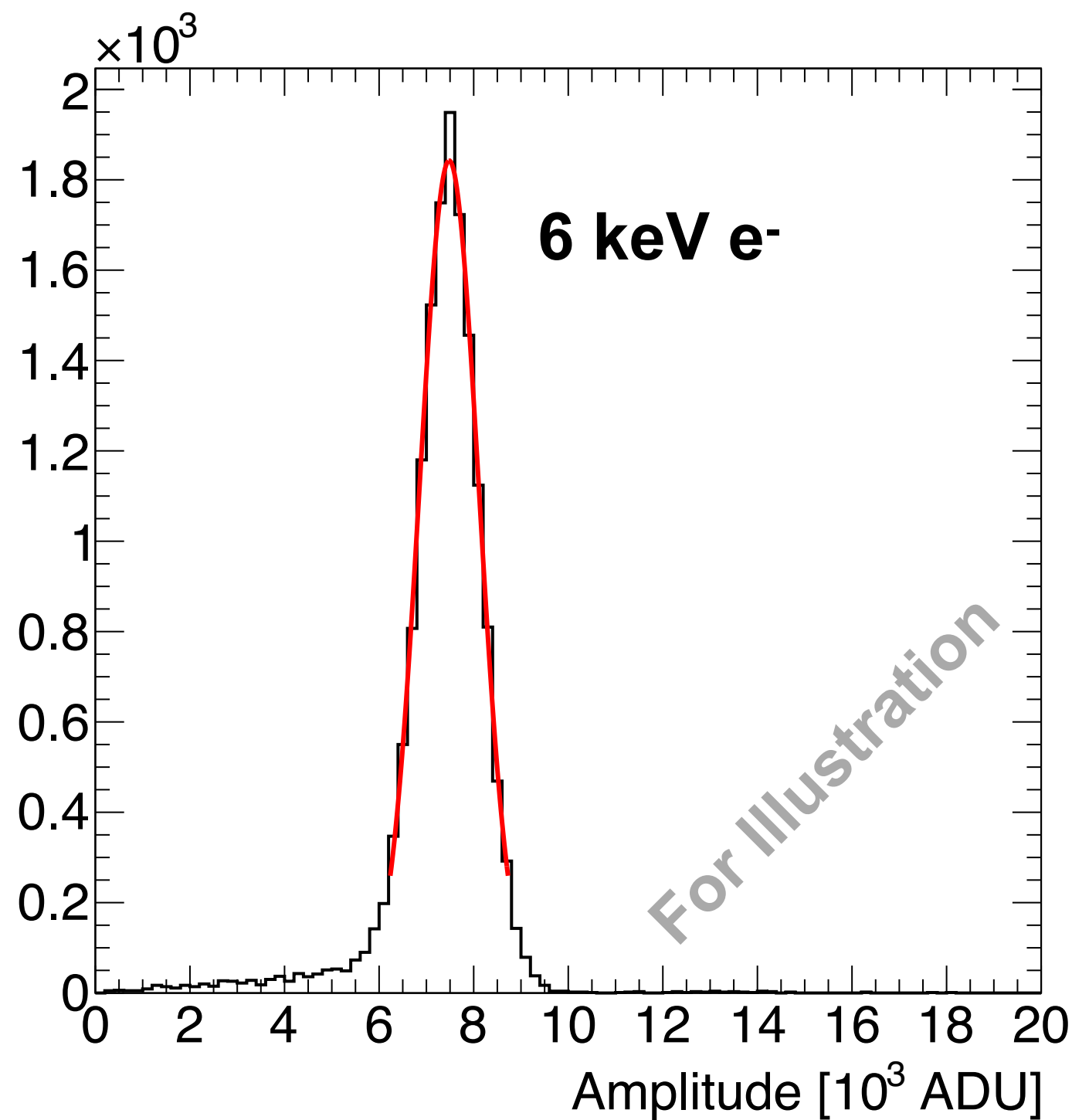
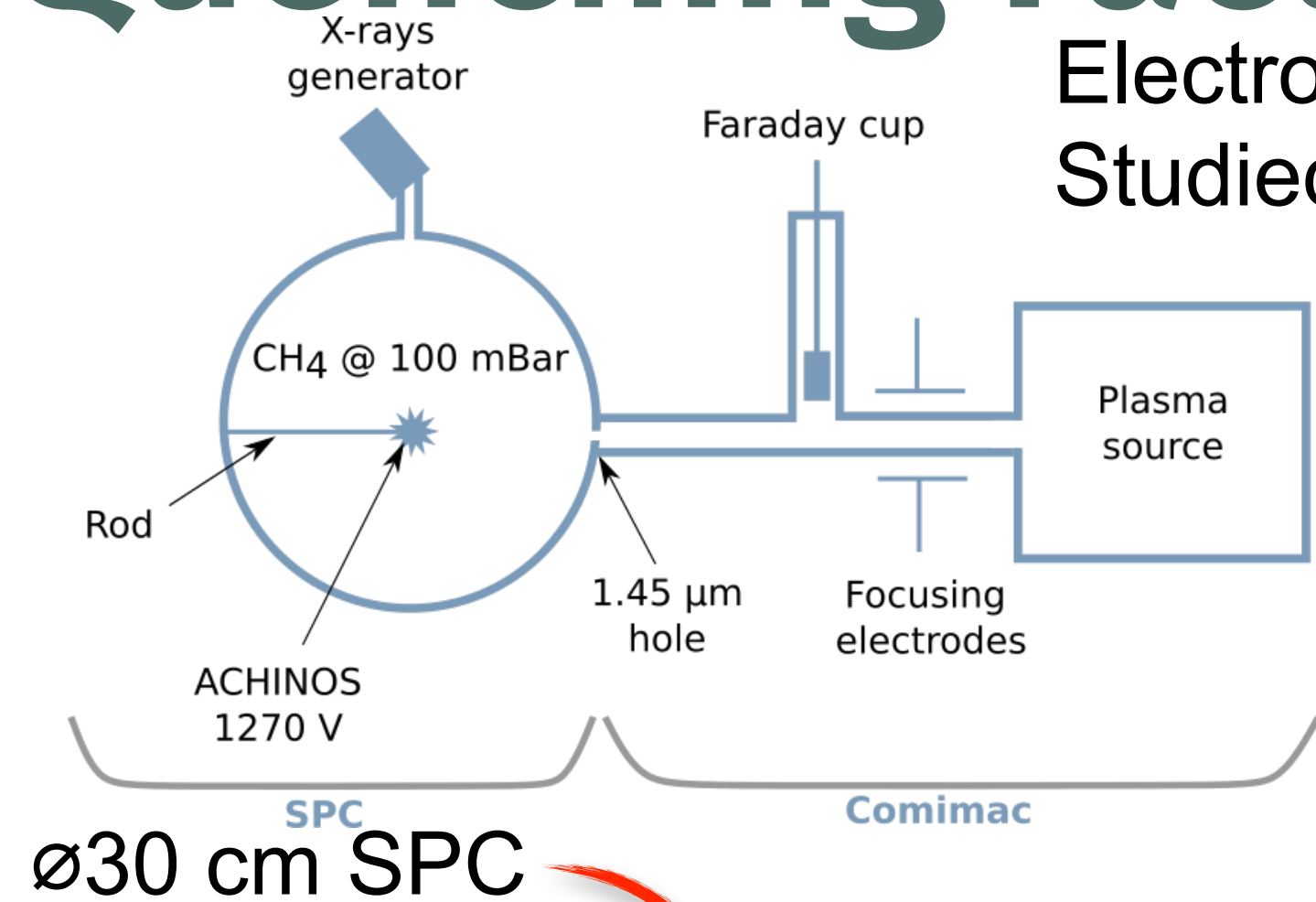
Quenching Factor Measurements: COMIMAC

Electrons and ions directed into SPC → compare response
Studied ions 2 - 13 keV, calibrated with e⁻ 1.5 - 13 keV



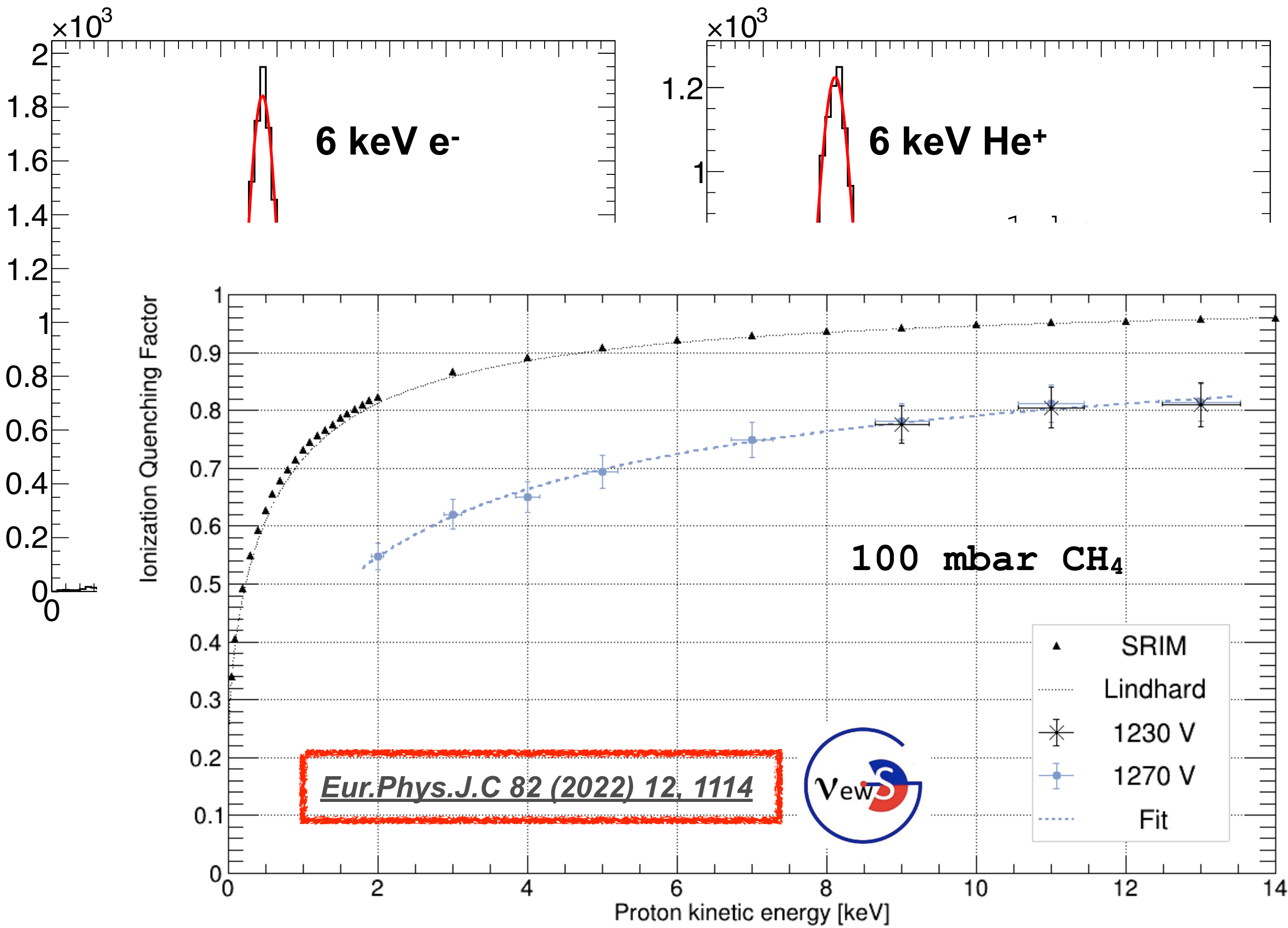
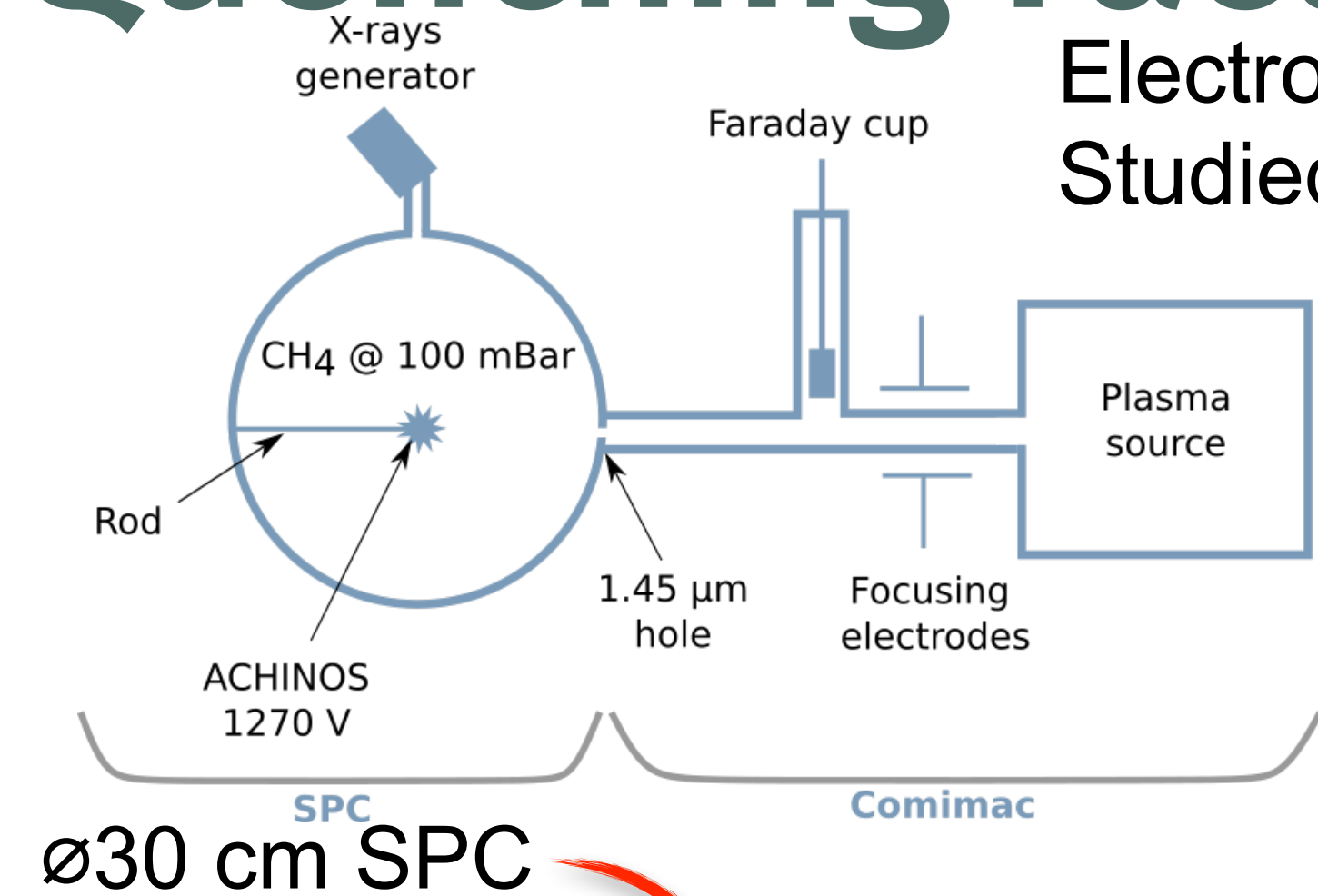
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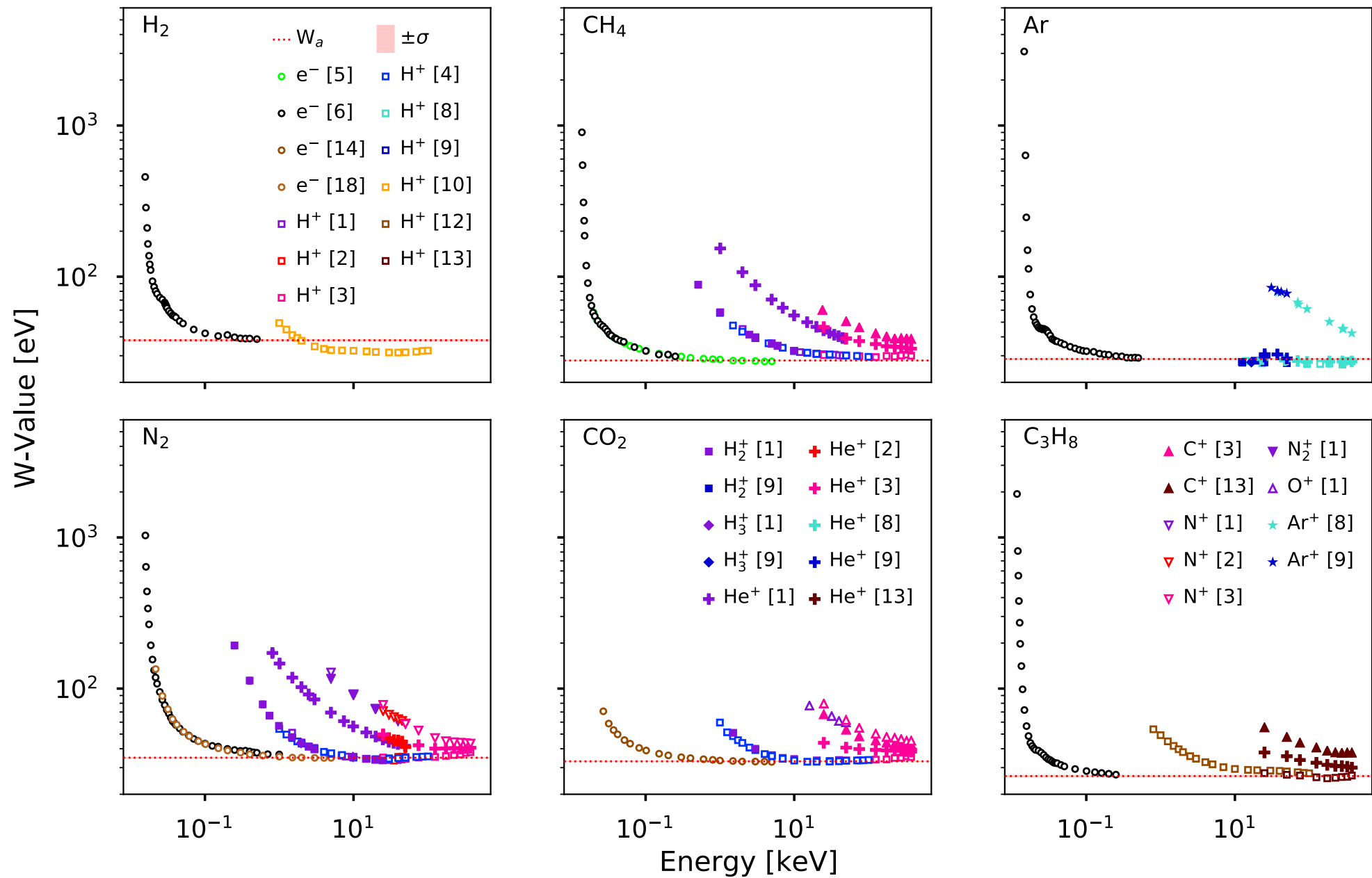
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Quenching Factor Estimates: W-Values

- W-value: **Average energy** required to produce **electron-ion pair**
- W different for electrons and ions, and varies with energy
 - Difference is quantified by QF
- W of electrons and ions in gases prev. studied for dosimetry
 - Comparing asymptotic electron W-value and W(E) for ions, get QF

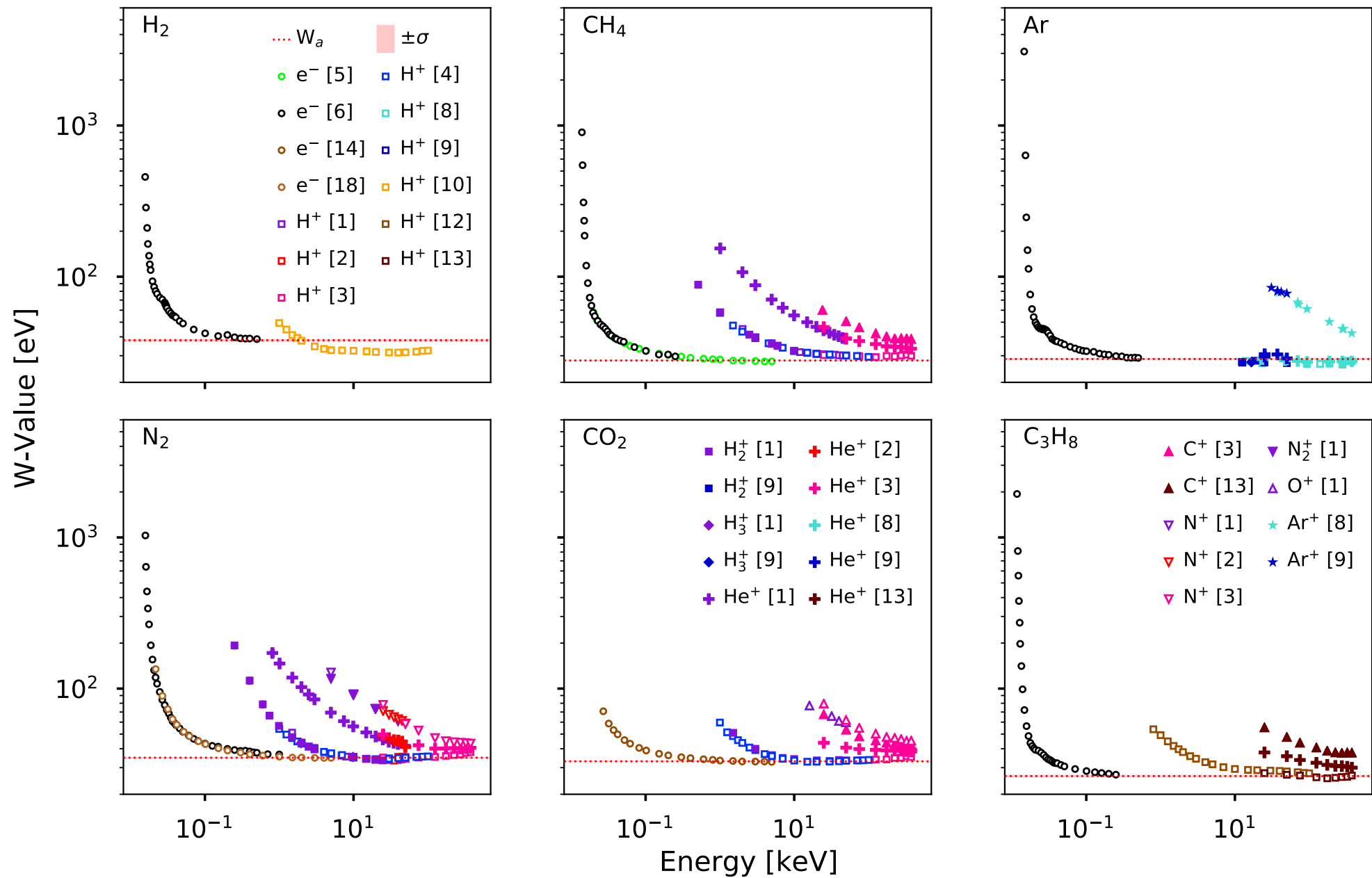


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	ICRU	Asymptotic
H ₂	36.5±0.7	38.0±0.8
CH ₄	27.3±0.6	27.90± 0.01
N ₂	34.8±0.7	34.91±0.17
Ar	26.4±0.5	28.5±0.6
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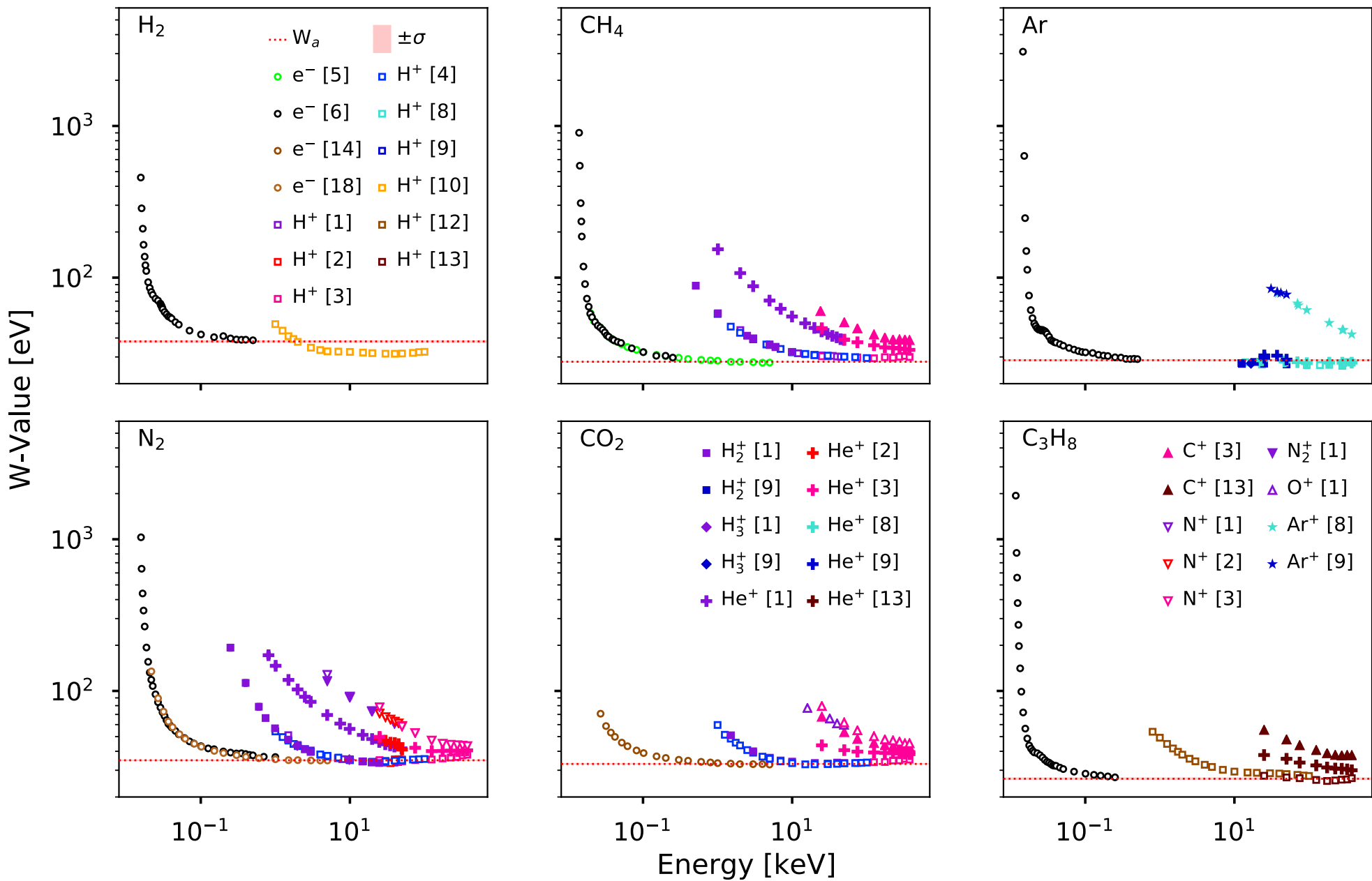


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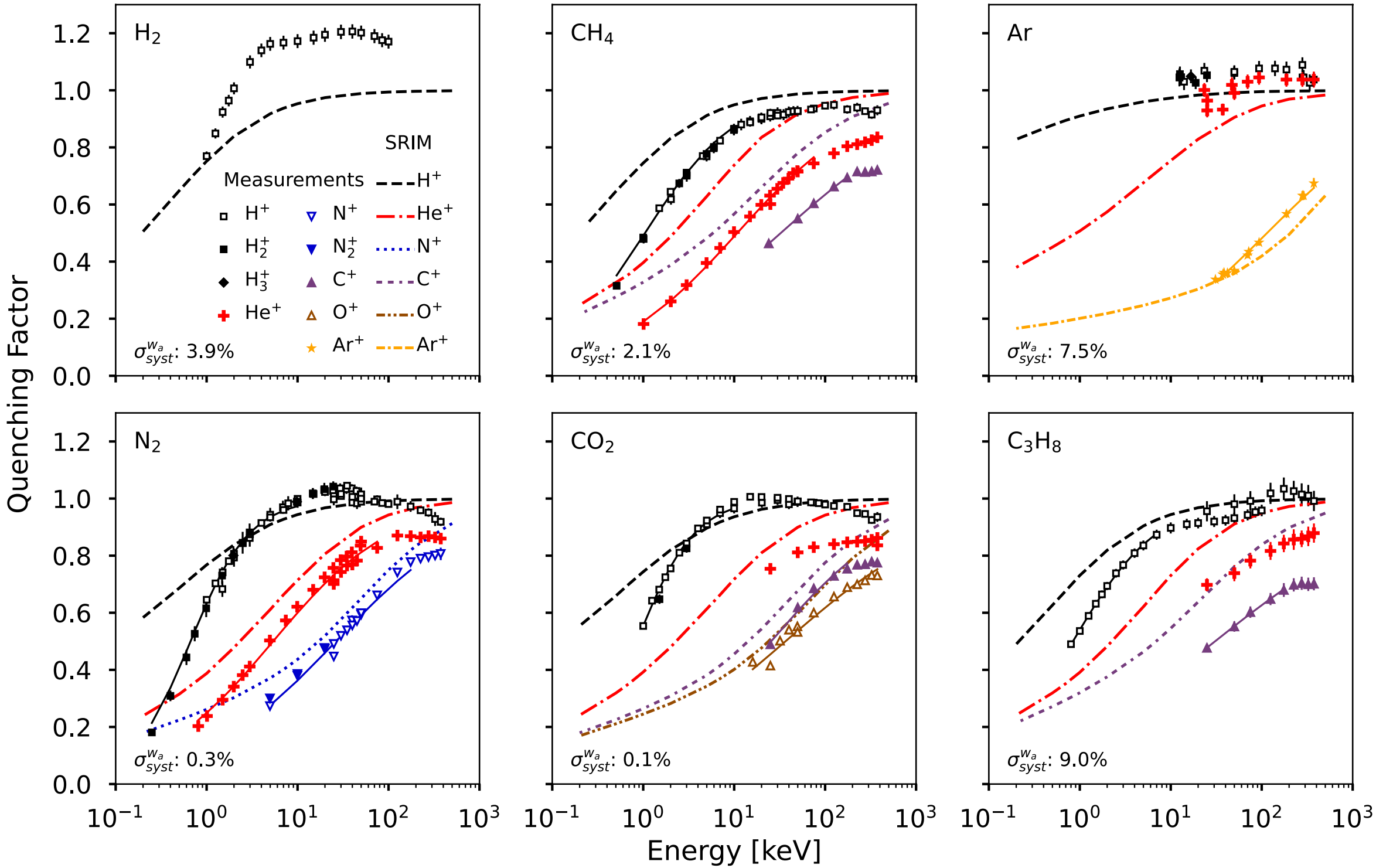
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Extends QF knowledge in NEWS-G gases beyond current measurements!

SPC Applications: Neutron Spectroscopy

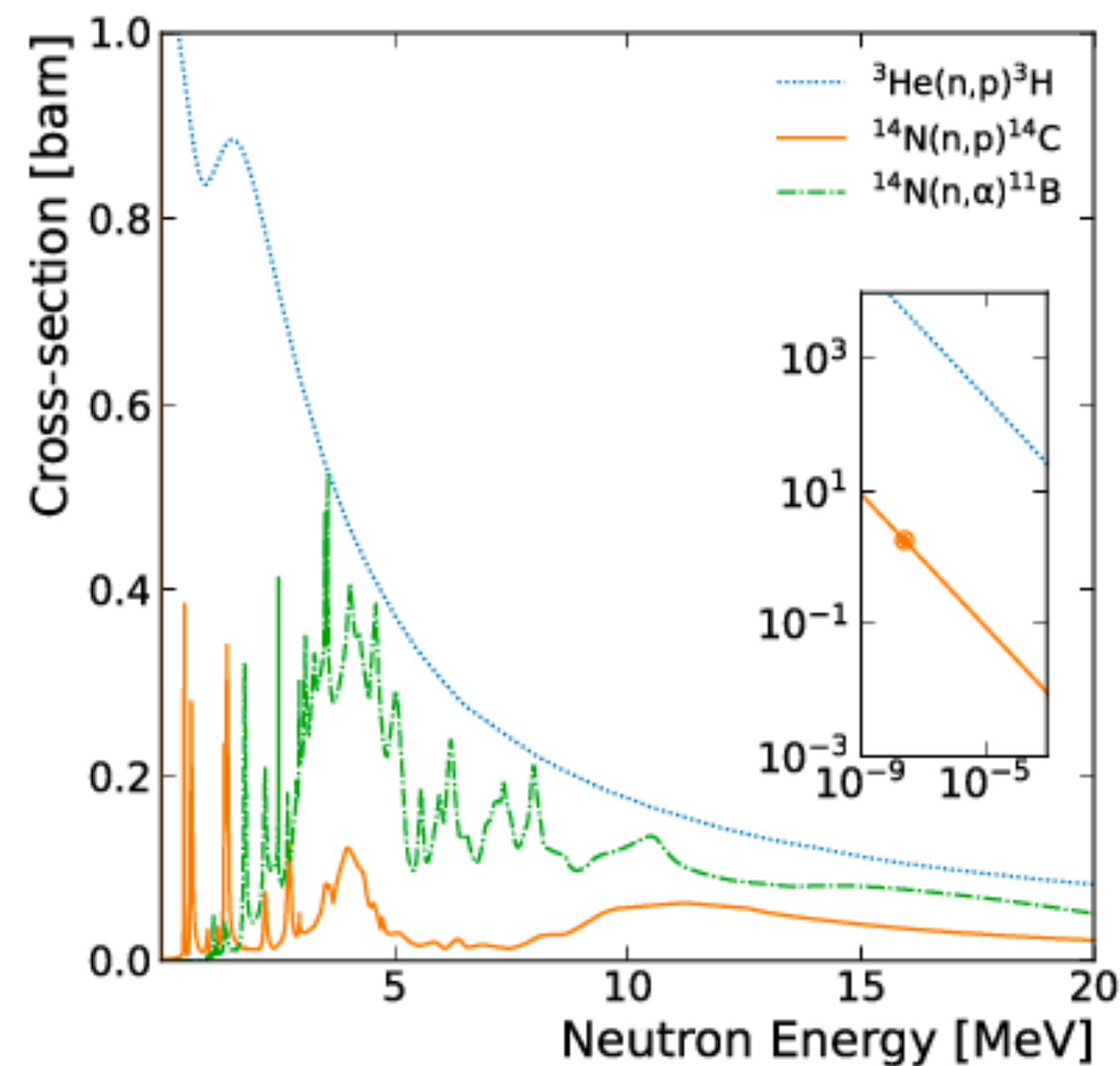
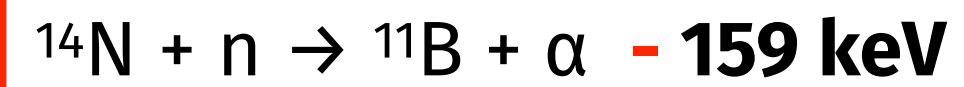
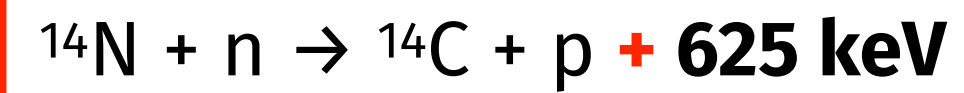
- ◆ Background measurements for rare-event searches
- ◆ Medical and industrial applications

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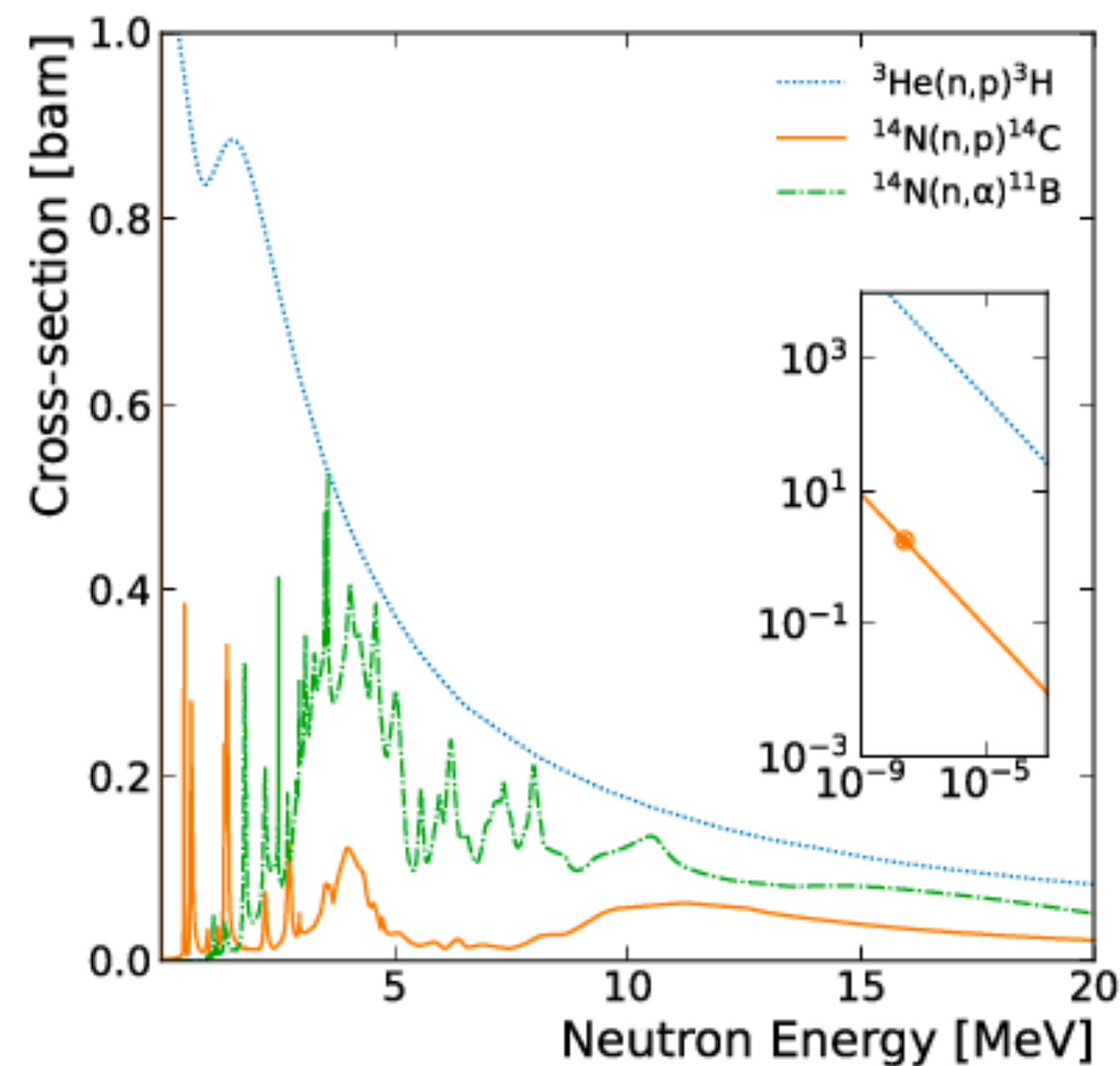
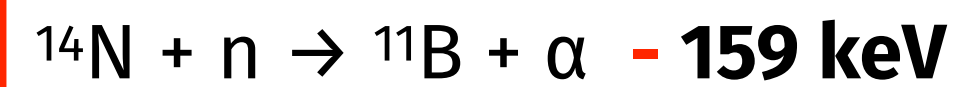
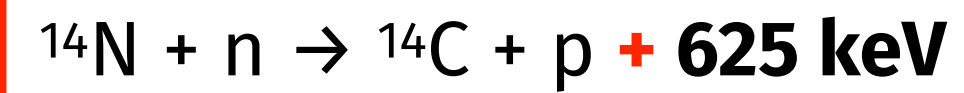
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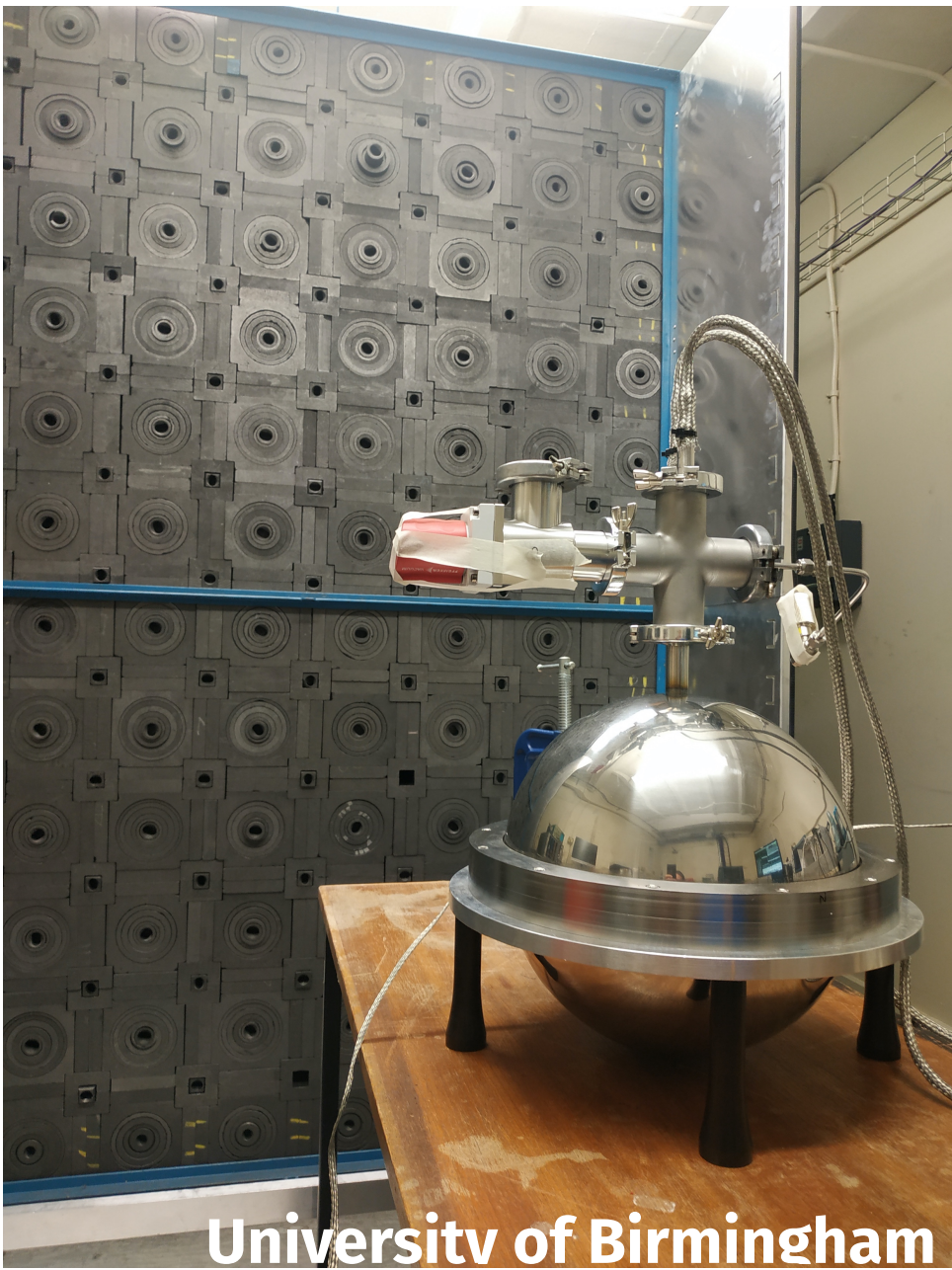
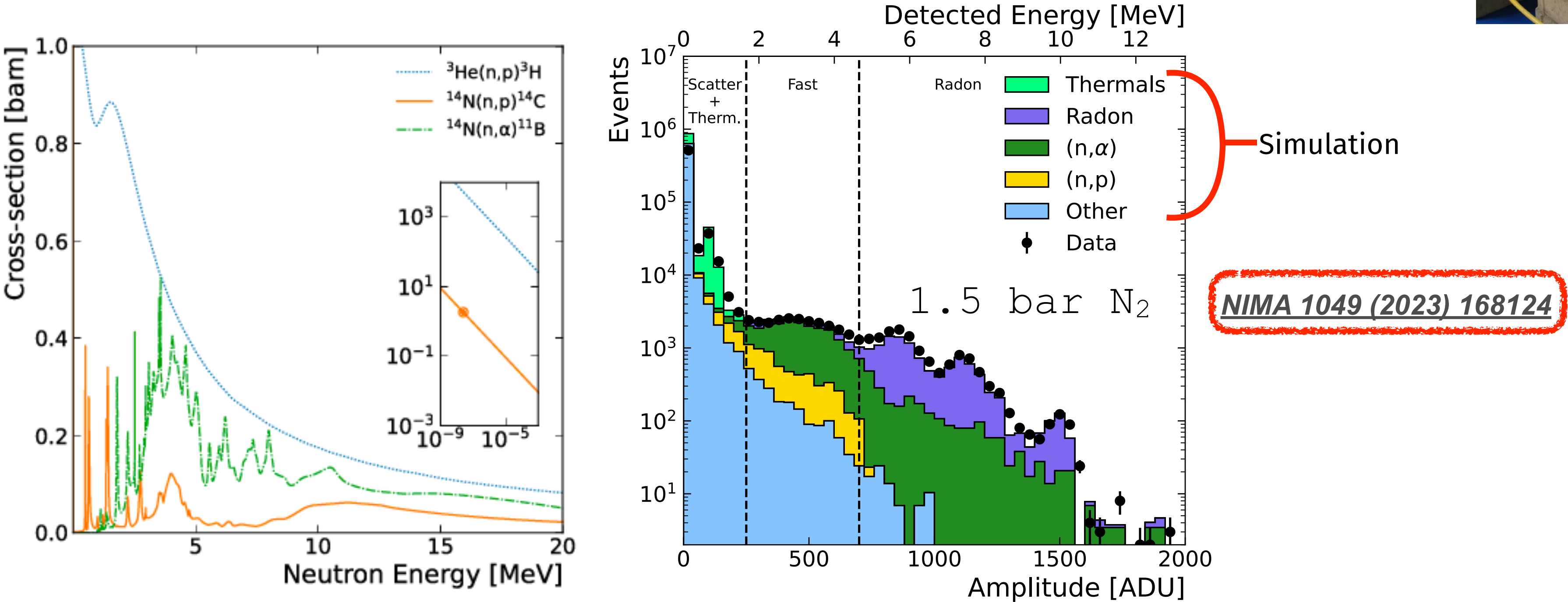
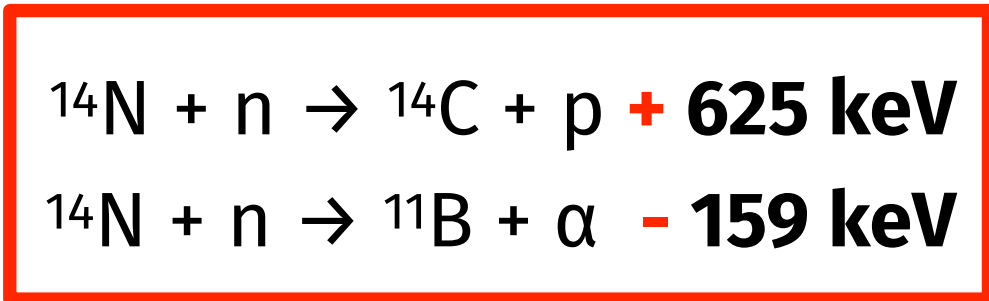
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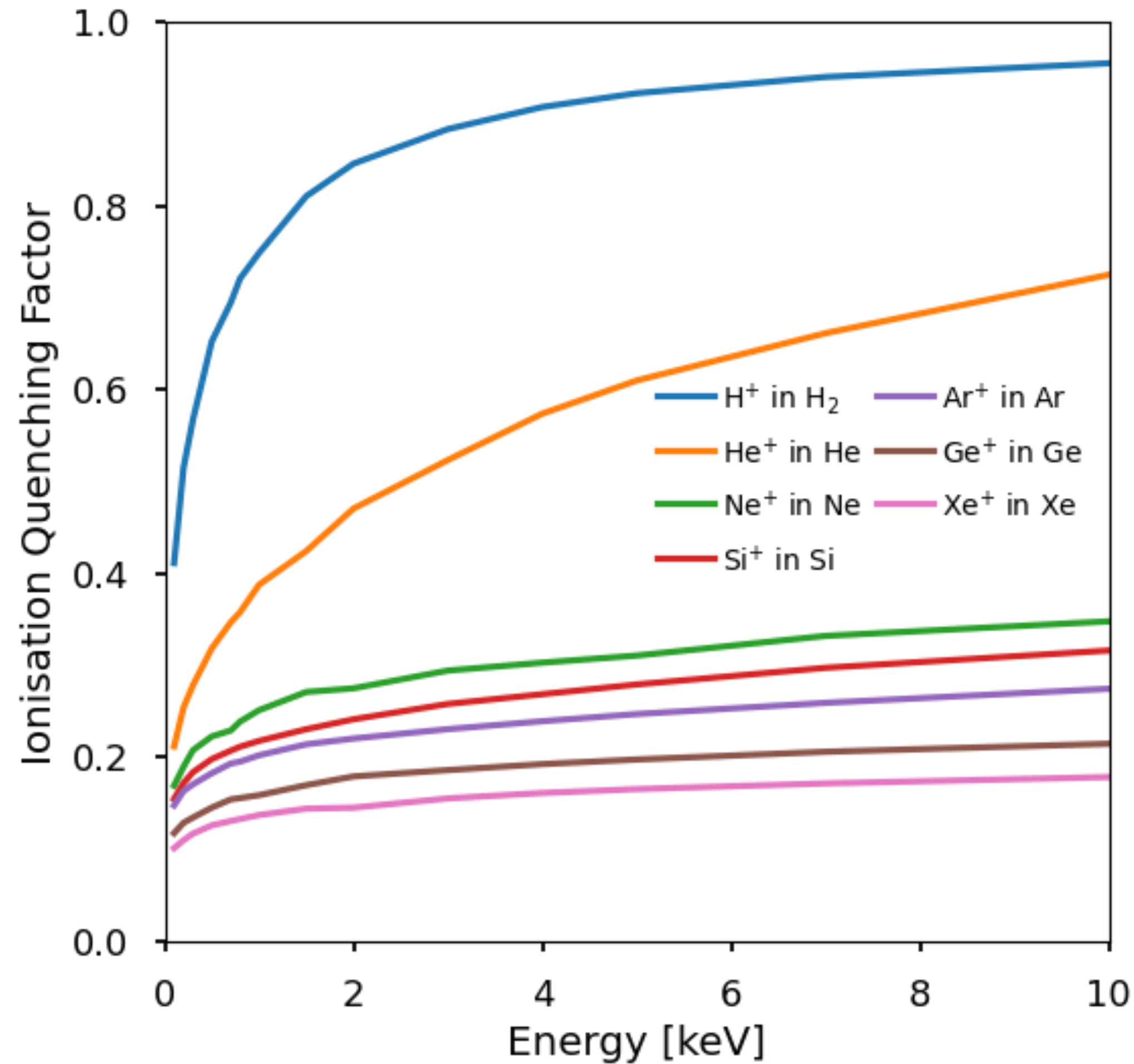


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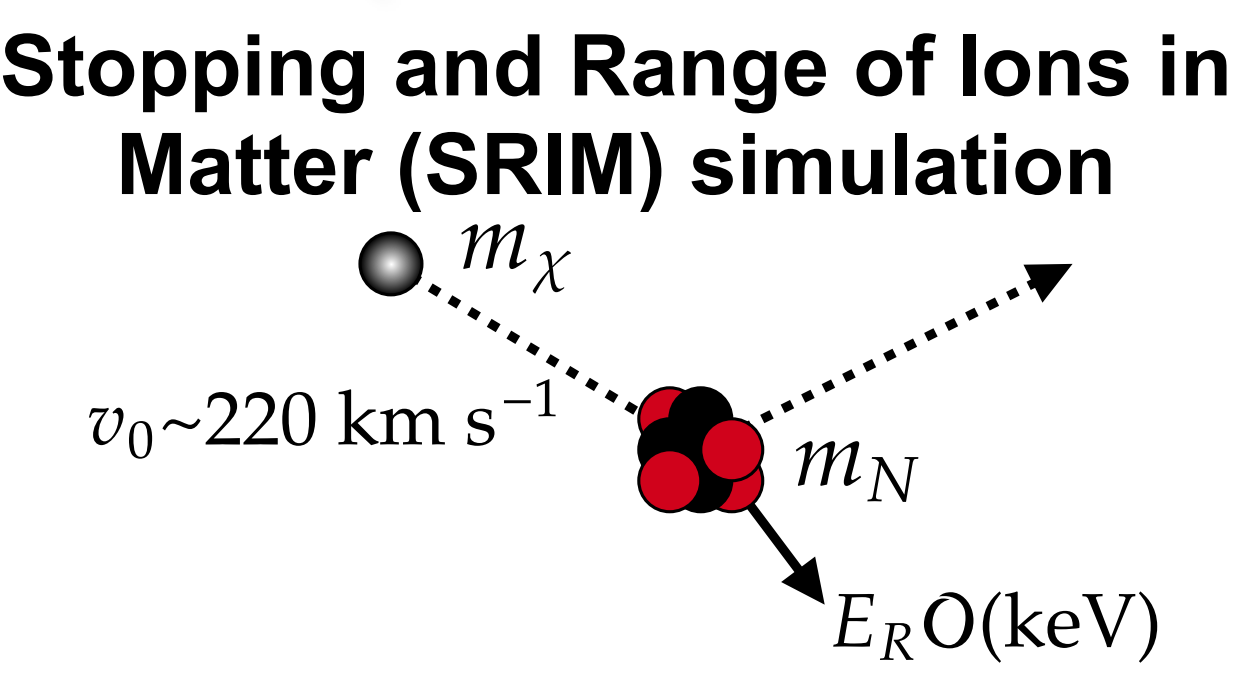
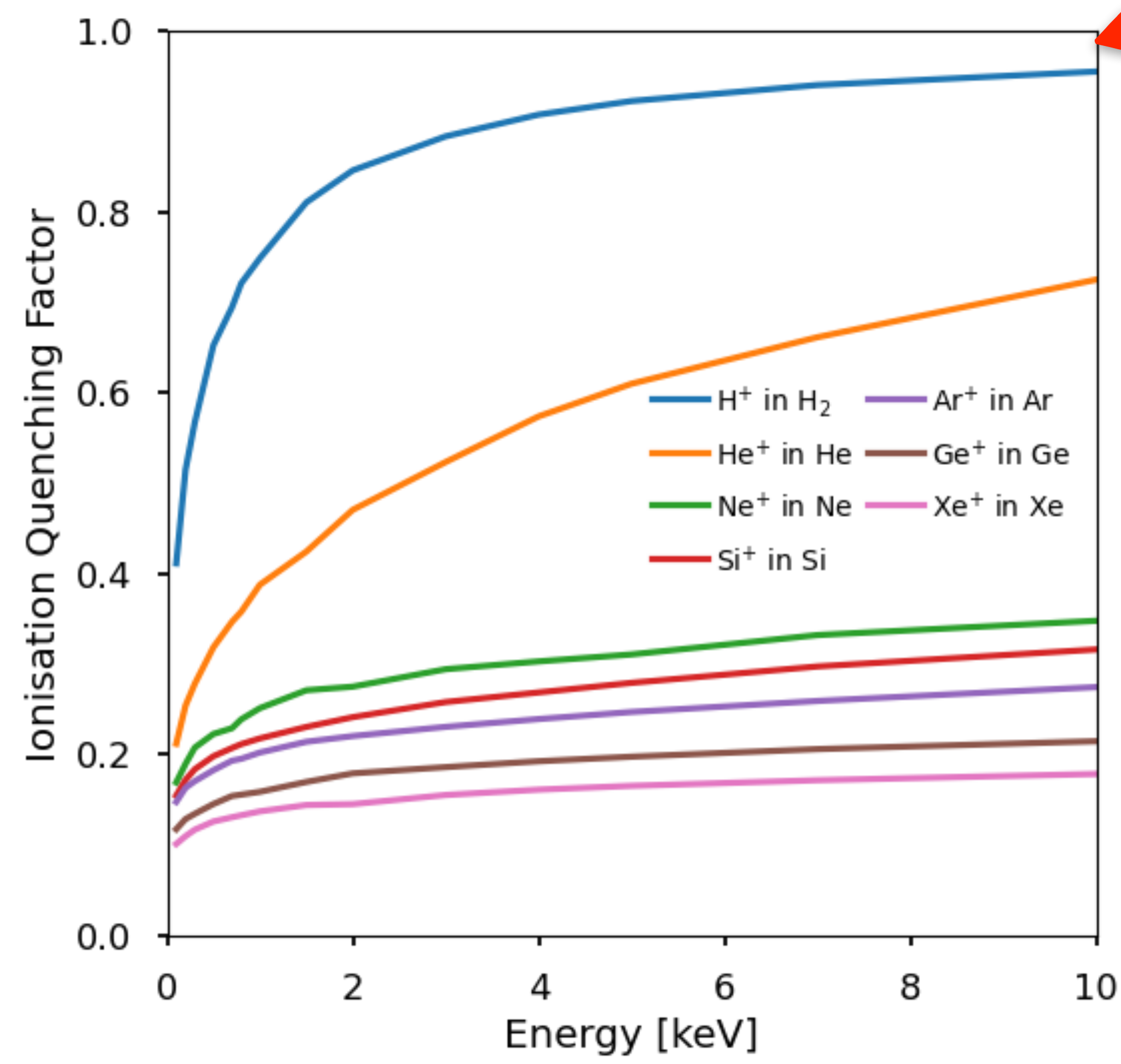


Ionisation Quenching Factor



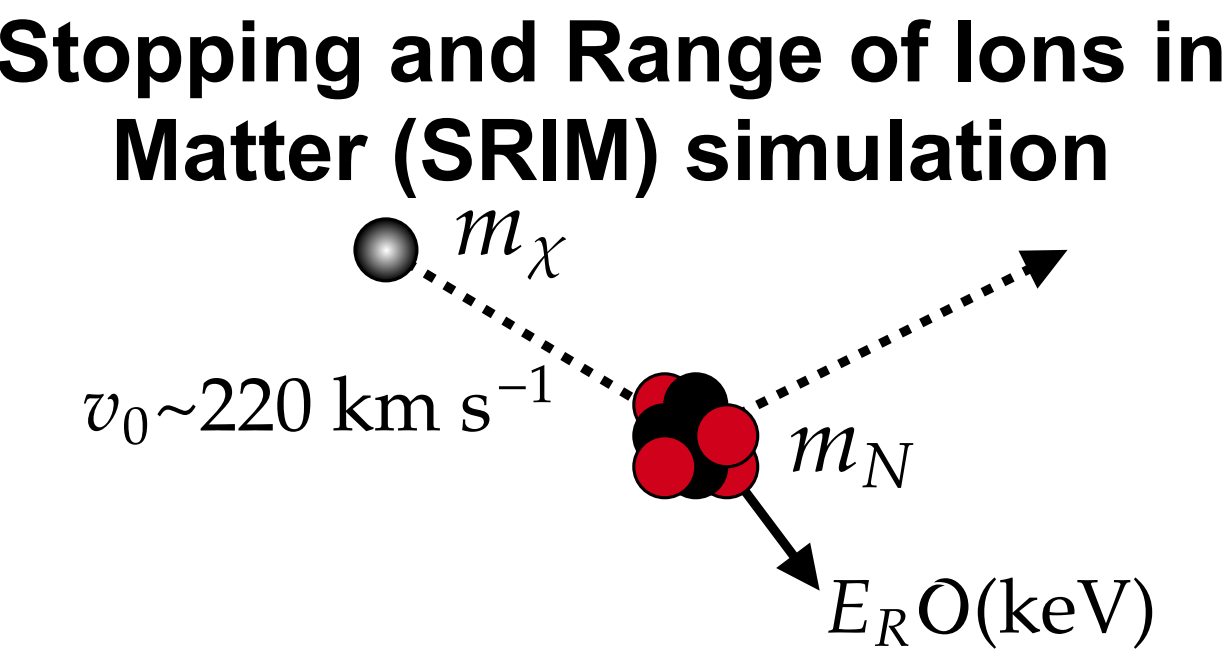
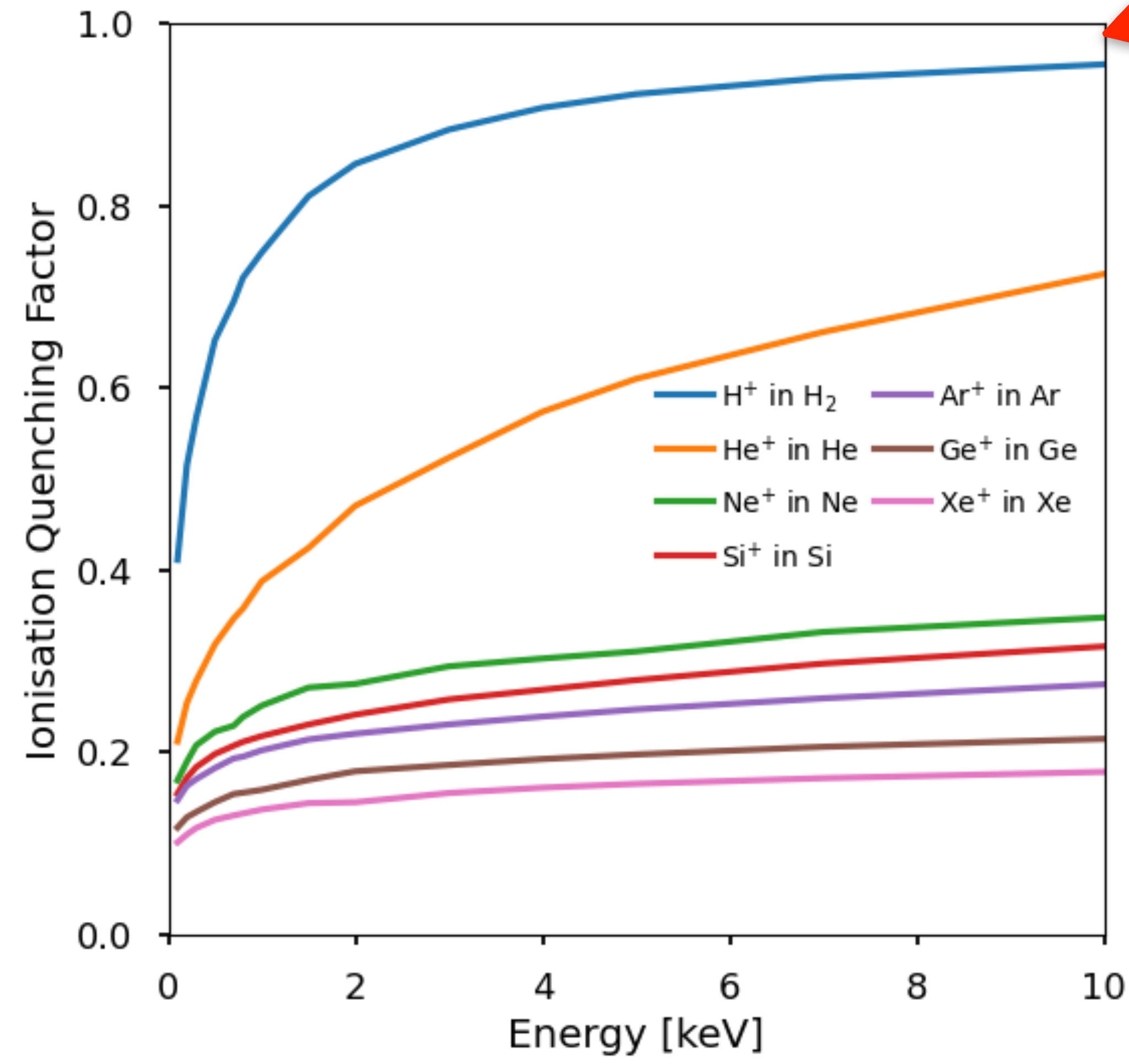
- ❖ **Kinematic matching: low-mass targets are favourable for light-DM** detection by nuclear recoils
- ❖ **Light targets have favourable quenching factors**

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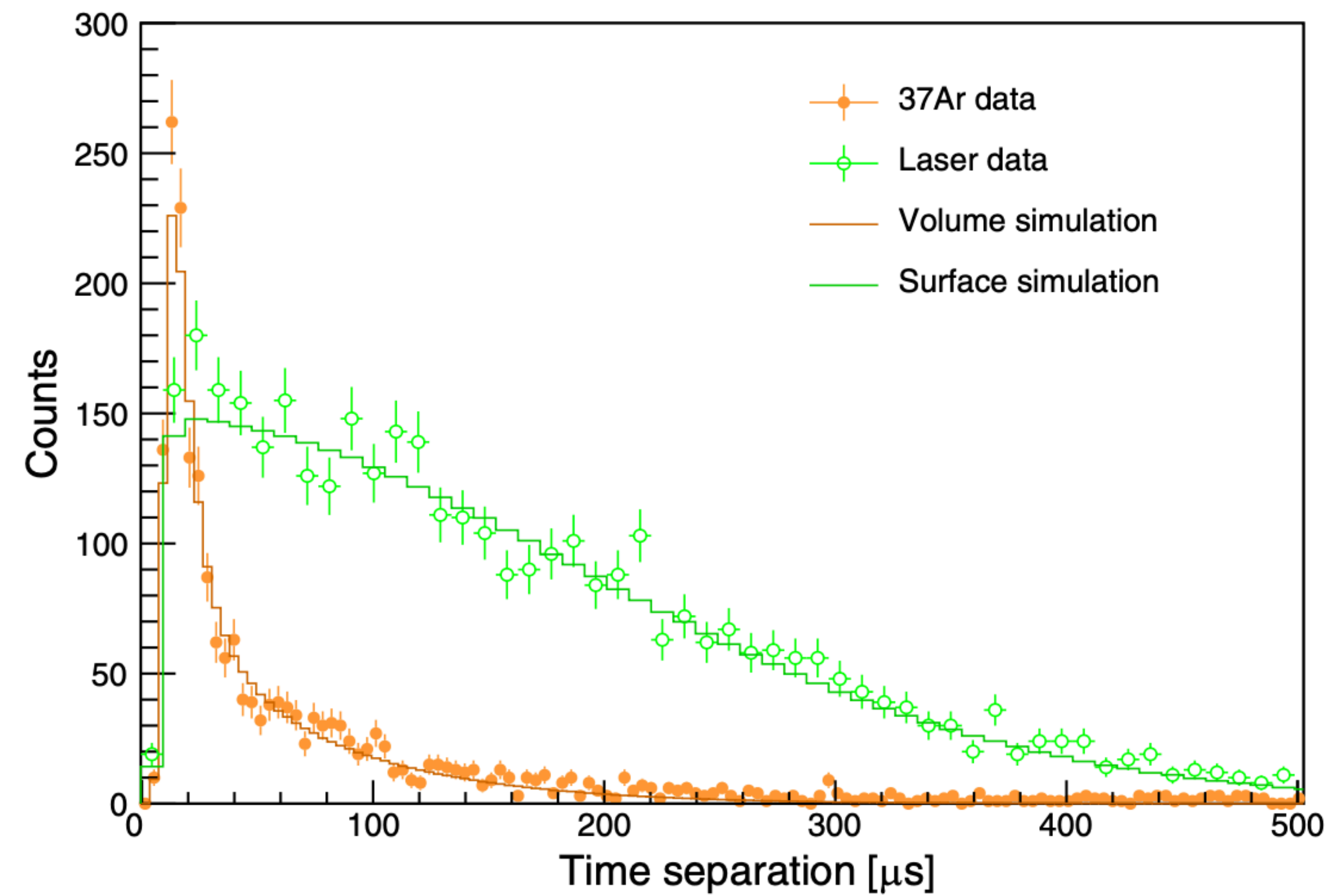


- 2 measurement approaches in NEWS-G
 - Neutron scattering at TUNL [*Phys.Rev.D 105 \(2022\) 5, 052004*](#)
 - Electron/Ion beam, COMIMAC, Grenoble [*Eur.Phys.J.C 82 \(2022\) 12, 1114*](#)
- Innovative approach using literature measurements [*Astropart.Phys. 141 \(2022\) 102707*](#)

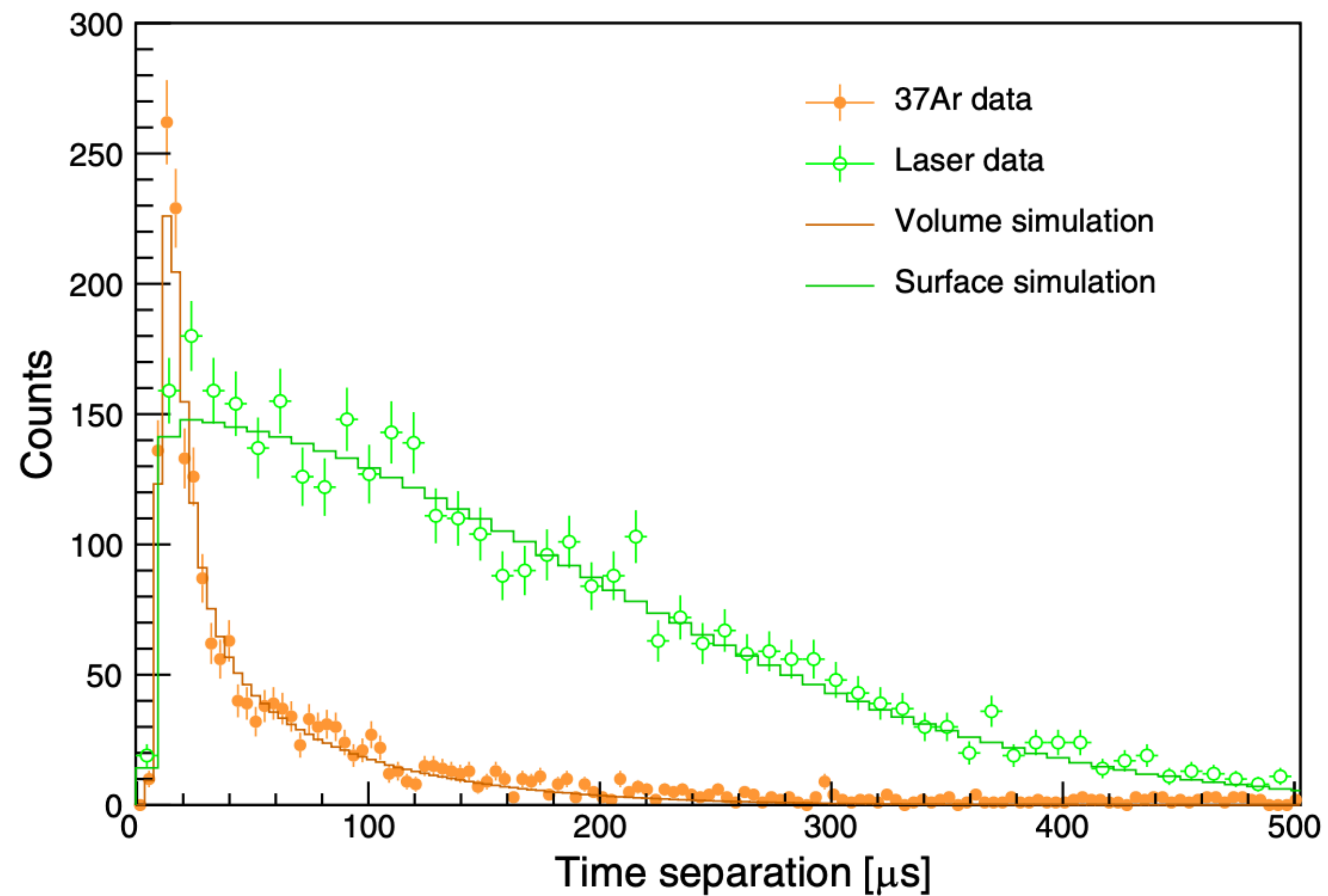
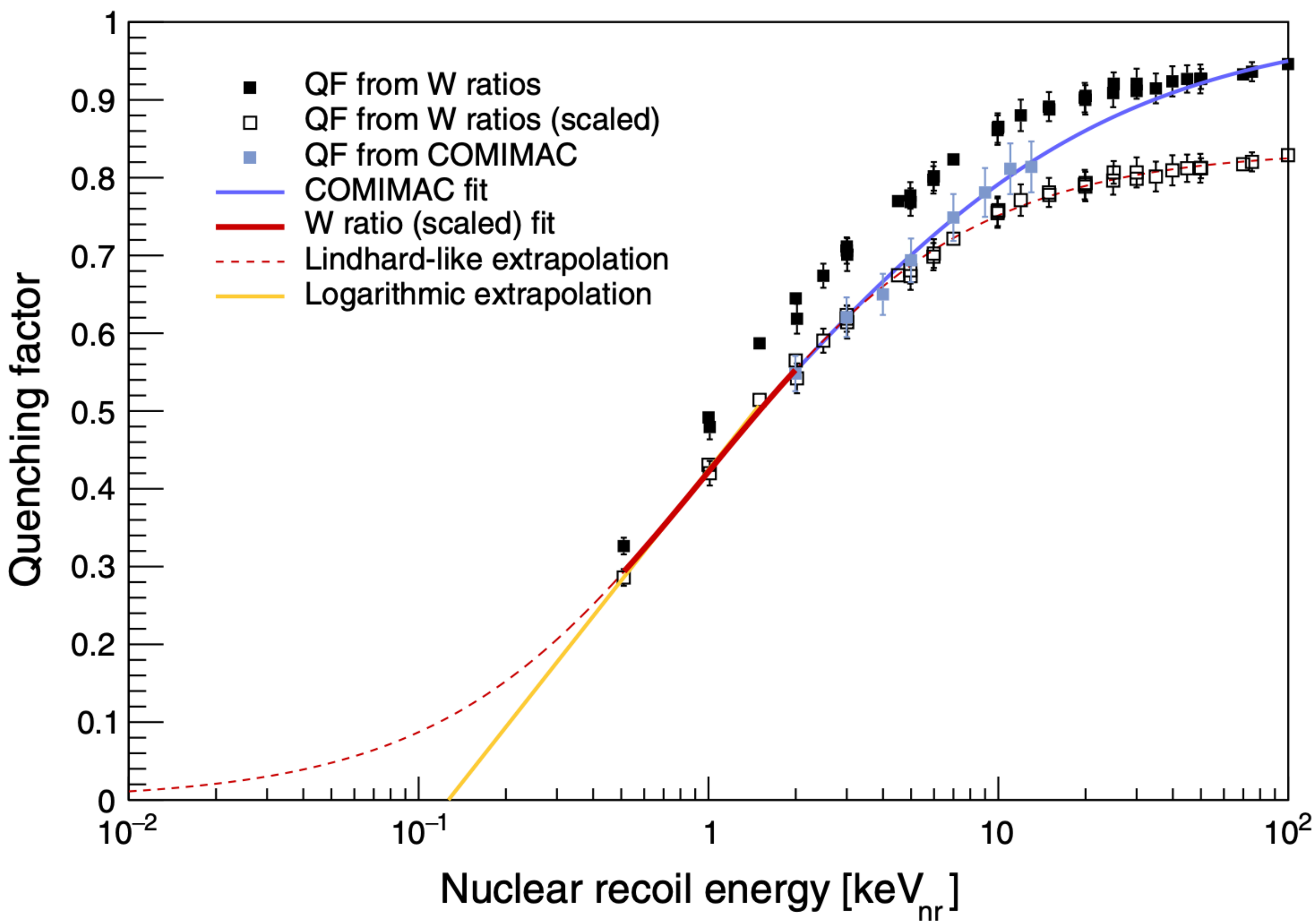
Kinematic matching: low-mass targets are favourable for light-DM detection by nuclear recoils

Light targets have favourable quenching factors

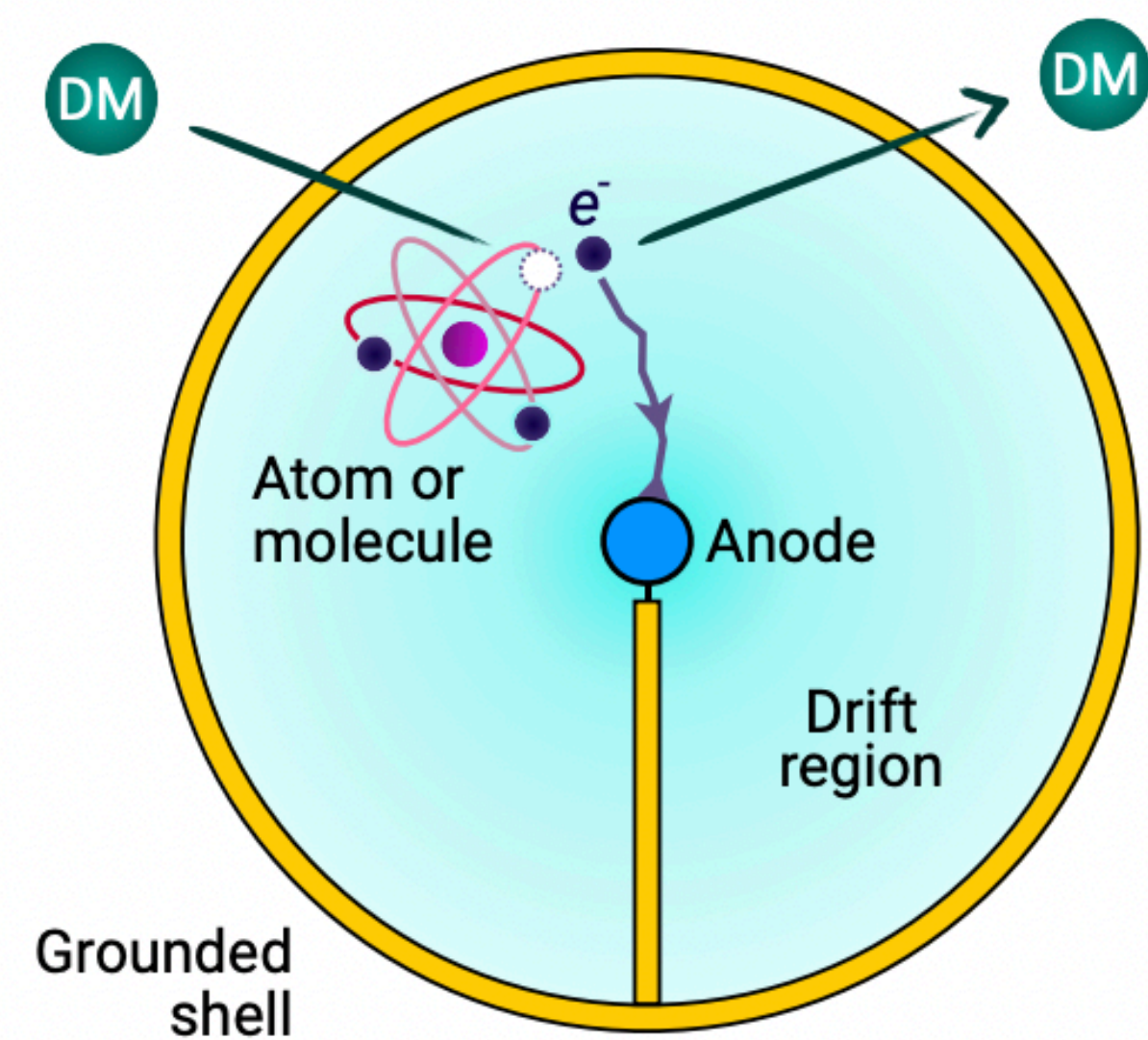
NEWS-G Results



NEWS-G Results



DM-Electron Scatte



L Hamaide and C McCabe Phys.Rev.D 107 (2023) 6, 063002

Helium (He)			Neon (Ne)			Methane (CH ₄)		
Basis: aug-cc-pV5Z			Basis: aug-cc-pV5Z			Basis: 6-31G(d,p)		
Tot. energy [au] [†] : −2.8616			Tot. energy [au] [†] : −128.5467			Tot. energy [au] [†] : −40.2016		
Orbital	<i>I</i> _{HF} [eV]	<i>I</i> _{exp} [eV]	Orbital	<i>I</i> _{HF} [eV]	<i>I</i> _{exp} [eV]	Orbital	<i>I</i> _{HF} [eV]	<i>I</i> _{exp} [eV]
1s ²	24.98	24.6	2p ⁶	23.14	21.7	1t ₂ ⁶	14.80	13.6
			2s ²	52.53	48.5	2a ₁ ²	25.66	22.9
			1s ²	891.79	870.2	1a ₁ ²	304.96	290.8

Isobutane (C ₄ H ₁₀)			Xenon (Xe)		
Basis: 6-31G(d,p)			Basis: Jorge-QZP		
Tot. energy [au] [†] : −157.3123			Tot. energy [au] [†] : −7229.7195		
Orbital	<i>I</i> _{HF} [eV]	<i>I</i> _{exp} [eV]	Orbital	<i>I</i> _{HF} [eV]	<i>I</i> _{exp} [eV]
6a ₁ ²	12.34	11.13	5p ⁶	12.45	12.7
5e ⁴	12.44	11.75	5s ²	25.54	23.3
1a ₂ ²	13.86	12.85	4d ¹⁰	75.72	68.5
4e ⁴	14.54	13.71	4p ⁶	163.56	146.1
3e ⁴	16.04	15.03	4s ²	212.69	213.2
5a ₁ ²	17.15	15.91	3d ¹⁰	711.26	682.7
4a ₁ ²	20.62	18.58	3p ⁶	958.02	971.4
2e ⁴	25.17	21.83	3s ²	1087.7	1149
3a ₁ ²	29.44	24.83	2p ⁶	4839.8	4947
2a ₁ ²	305.01	—	2s ²	5132.0	5453
1e ⁴	305.01	—	1s ²	33321	34561
1a ₁ ²	305.30	—			

TABLE I. A summary of the most pertinent details from our PySCF calculations. In the second and third rows, we give the basis-set used and the total converged energy in atomic units (au) for each atomic or molecule species. The values *I*_{HF} and *I*_{exp} give the ionisation energy in eV from the PySCF Hartree-Fock calculation and the experimental value from refs. [105–108], respectively. The superscript in the orbital name gives the number of electrons in that orbital. For isobutane, we do not have a reference for the ionisation energies of the inner core orbitals (denoted by —). Following ref. [107], we group the isobutane orbitals into three categories: the outer valence orbitals (6a₁, 5e, 1a₂, 4e, 3e, 5a₁), the inner valence orbitals (4a₁, 2e, 3a₁), and the core orbitals (2a₁, 1e, 1a₁). The large number of orbitals (and therefore number of electrons) in isobutane with ionisation energies less than 30 eV is much higher than in the other species.

[†] To provide for a more straightforward comparison of the total energy with other computational approaches, we quote the total energy in atomic units, where 1 au = 27.211 eV.