First direct detection constraints on Planck-scale mass dark matter in DEAP-3600

Dr. Michela Lai

on behalf of
DEAP-3600 Collaboration

9TH WORKSHOP ON FLAVOR ASYMMETRIES - 28 JUNE 2022

DEAP Collaboration

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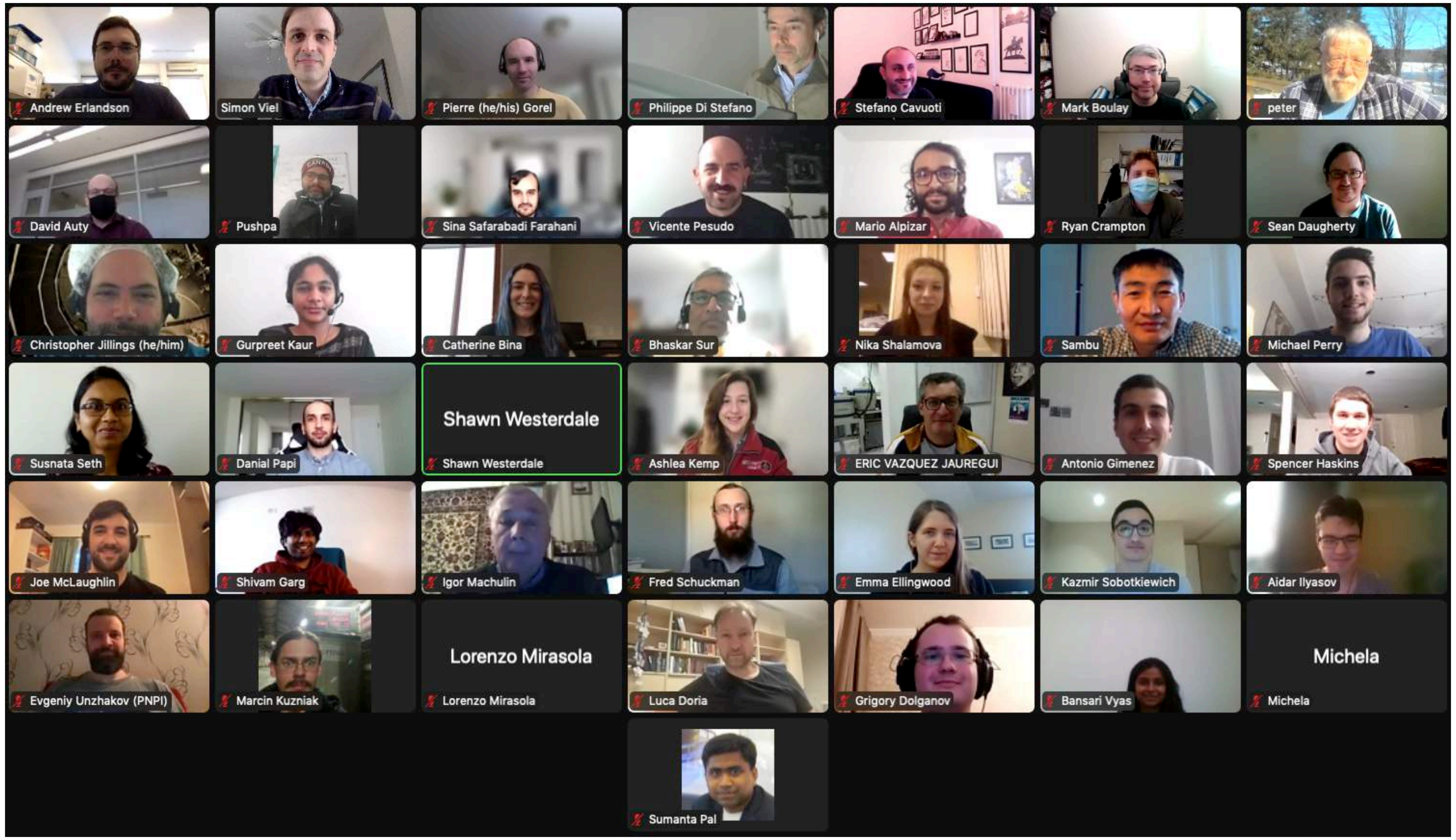

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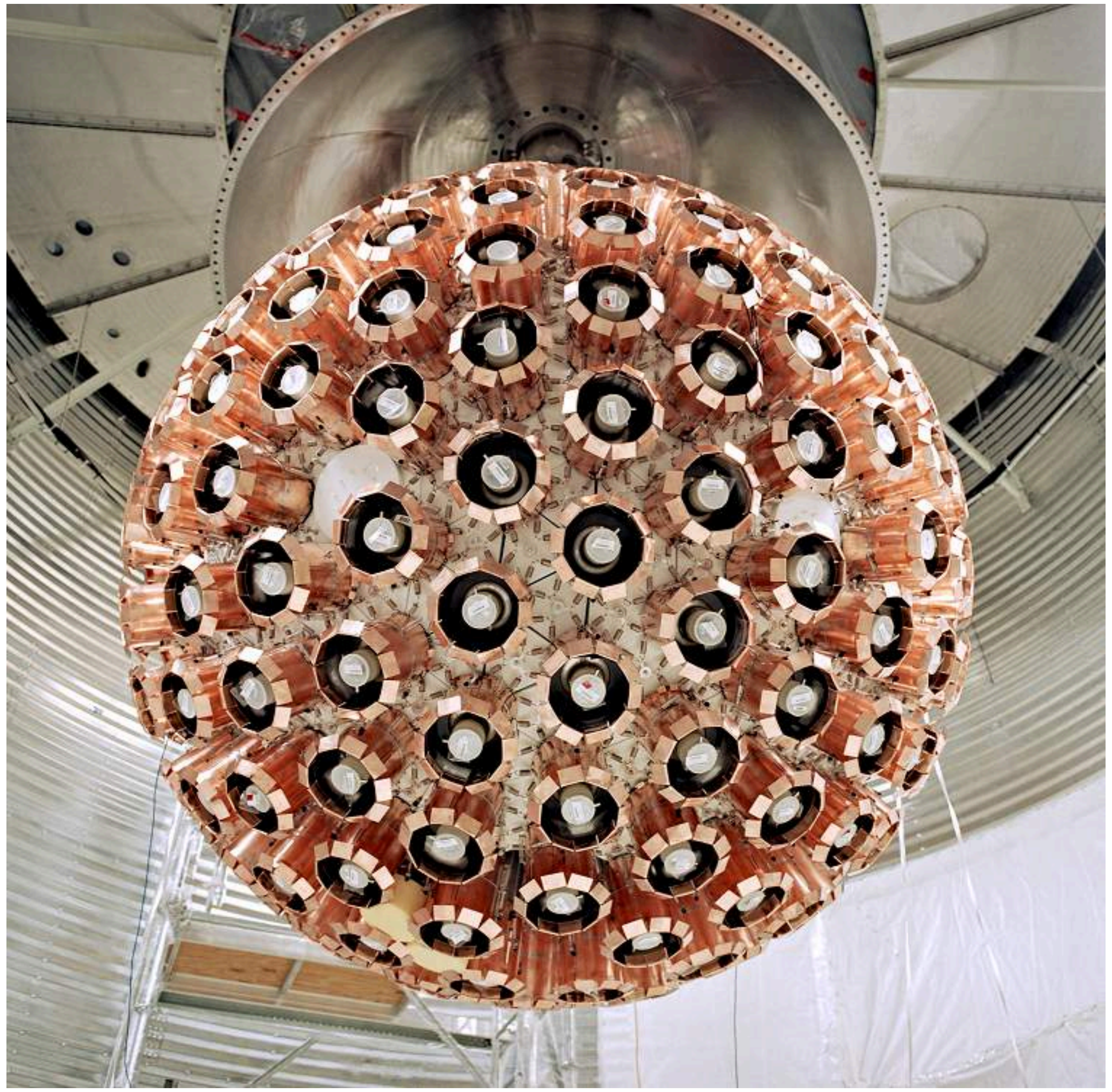
The detector

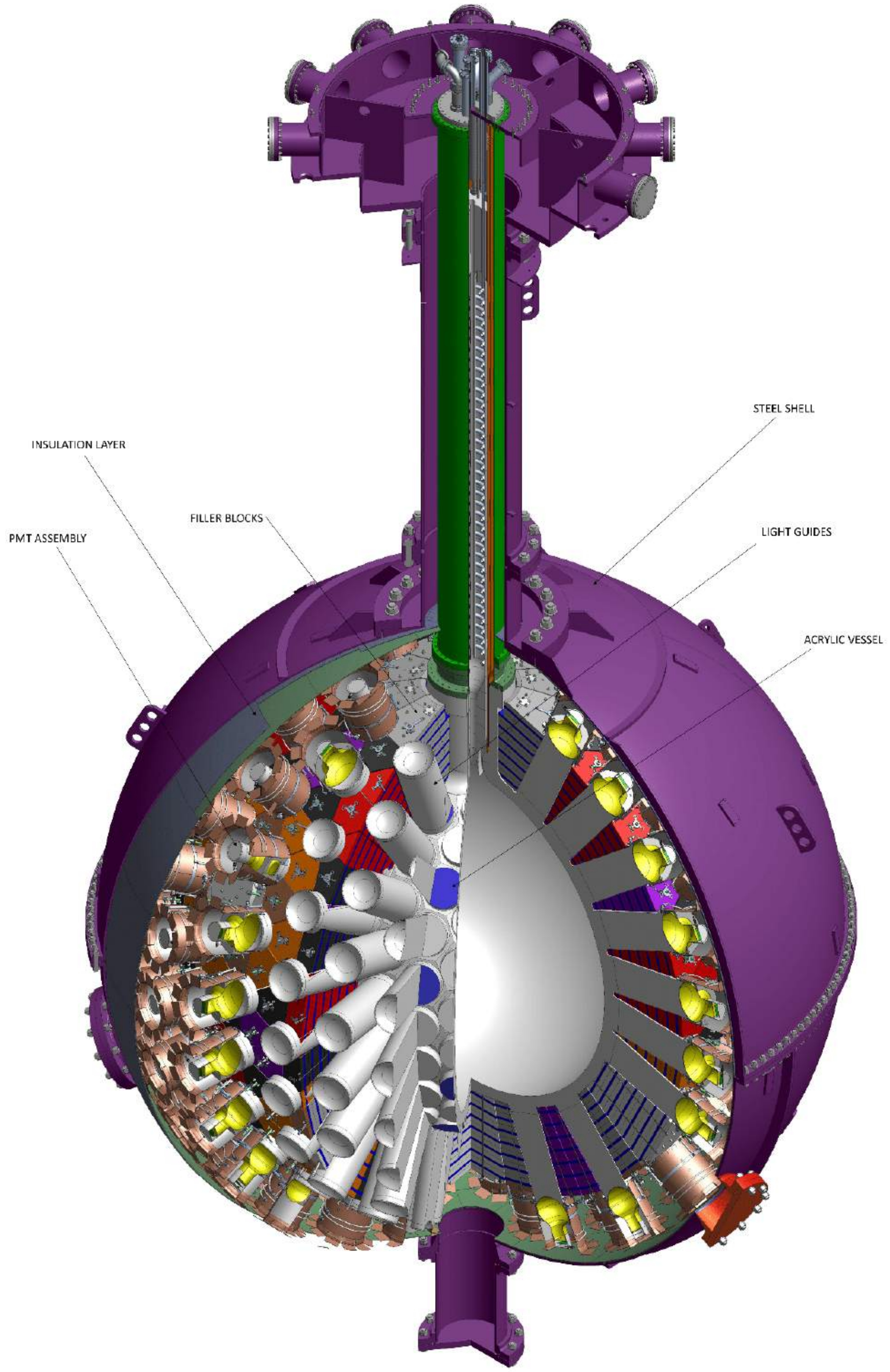
- DEAP-3600 is the largest running liquid argon detector designed for the dark matter search
- 3279 ± 96 kg of **Liquid Argon**



- Temperature: 86.8 K
- Pressure < 0.946 bar
- Density: 1.4 g/cm^3
- Scintillation light yield in DEAP: 7.1 photoelectrons (PE)/keV$_{ee}$

Advantages with Liquid argon

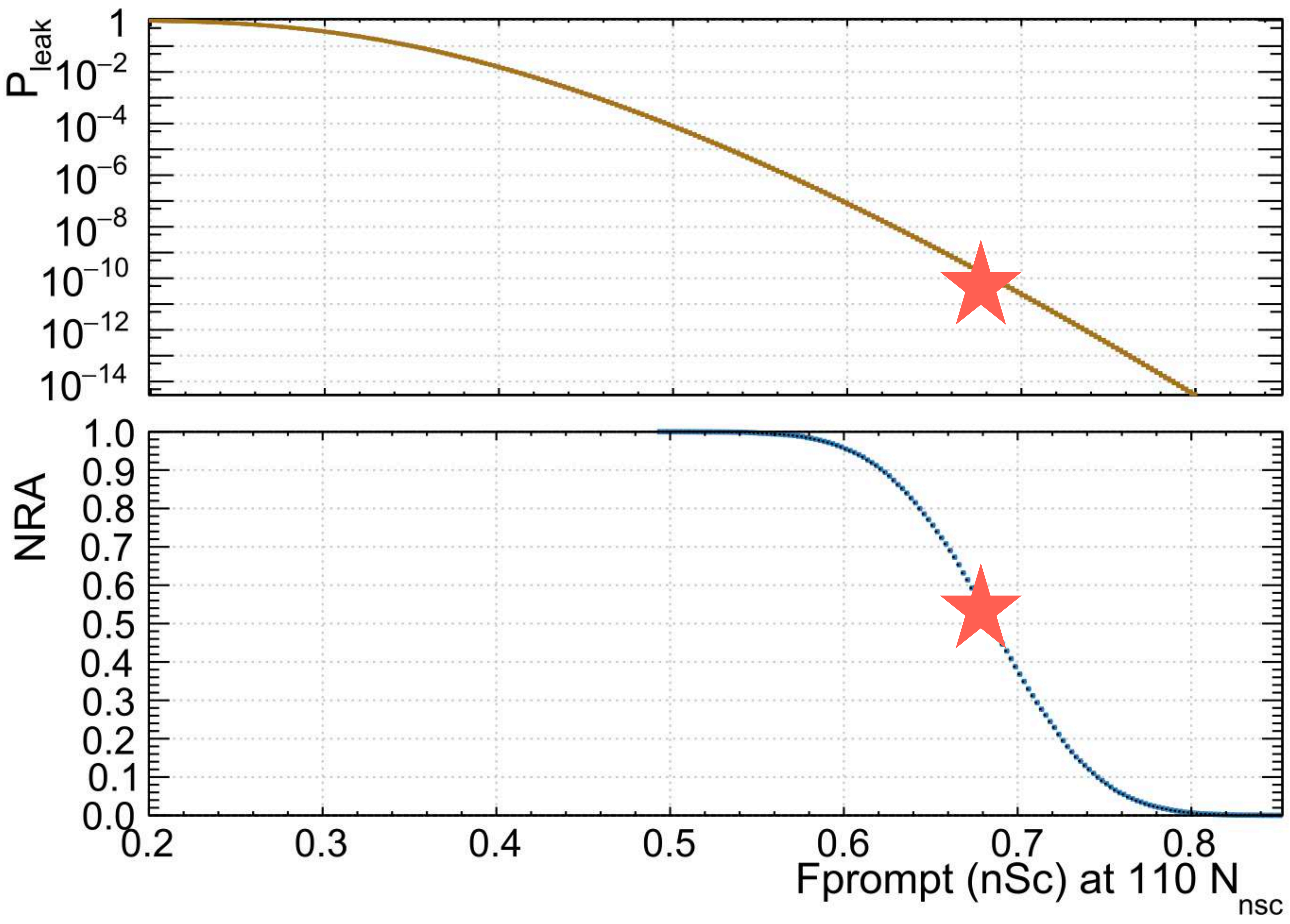
- High scintillation yield (40 ph/keV)
- Transparent to its own scintillation light
- Discrimination between nuclear recoils and electron recoils according to the **prompt scintillation light**



Astroparticle Physics 108 (2019) 1-23

The target

- At about 18 keV$_{ee}$ and a nuclear recoil acceptance of 50 % a **leakage probability** of about **10^{-10}** is reached



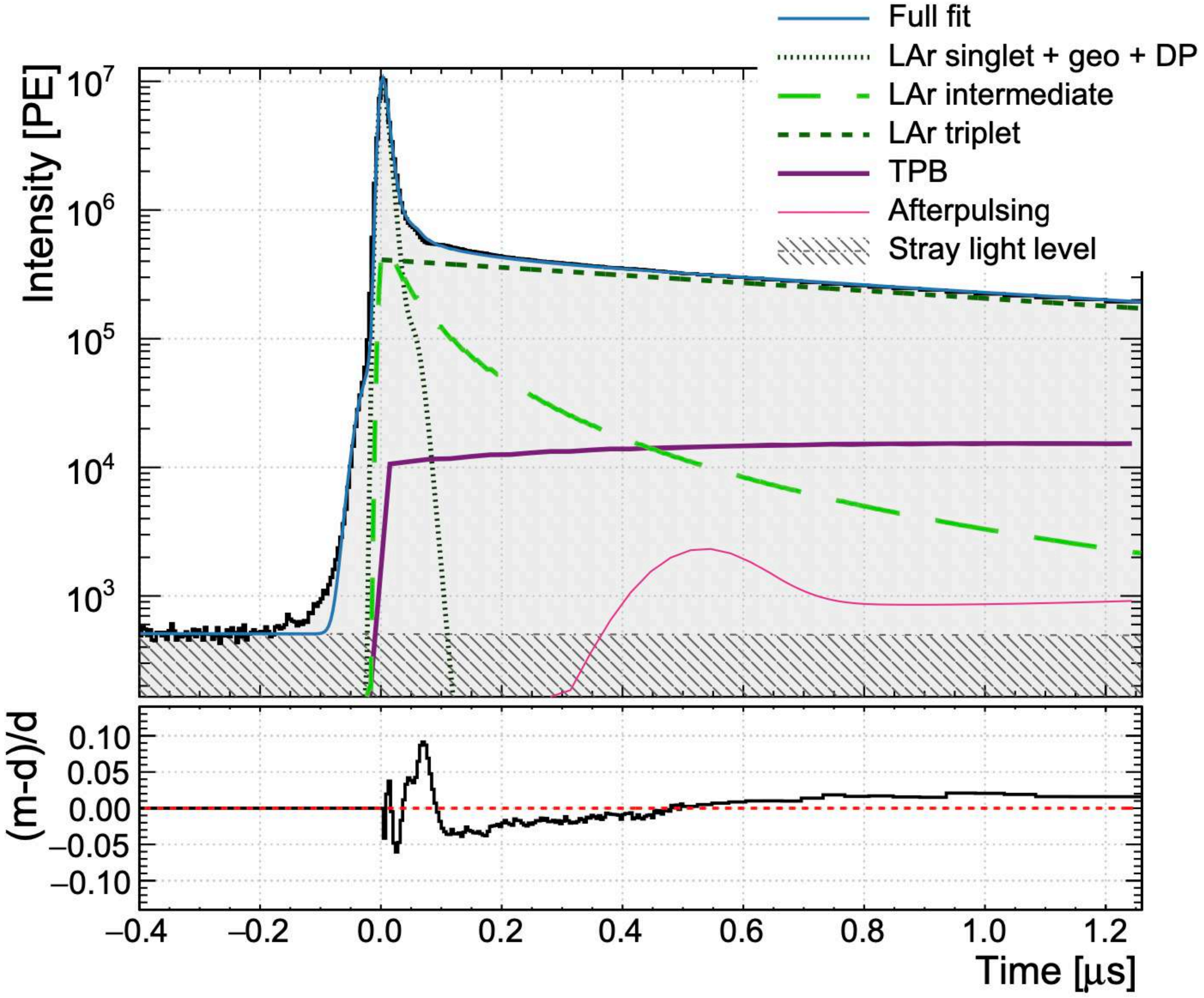
Eur. Phys. J. C 81,823 (2021)

$$I_{LAr}(t) = \frac{R_s}{\tau_s} e^{-t/\tau_s} + \frac{1 - R_s - R_t}{\tau_{rec}(1 + t/\tau_{rec})^2} + \frac{R_t}{\tau_t} e^{-t/\tau_t}$$

$R_t = 0.71$

$R_s = 0.23$

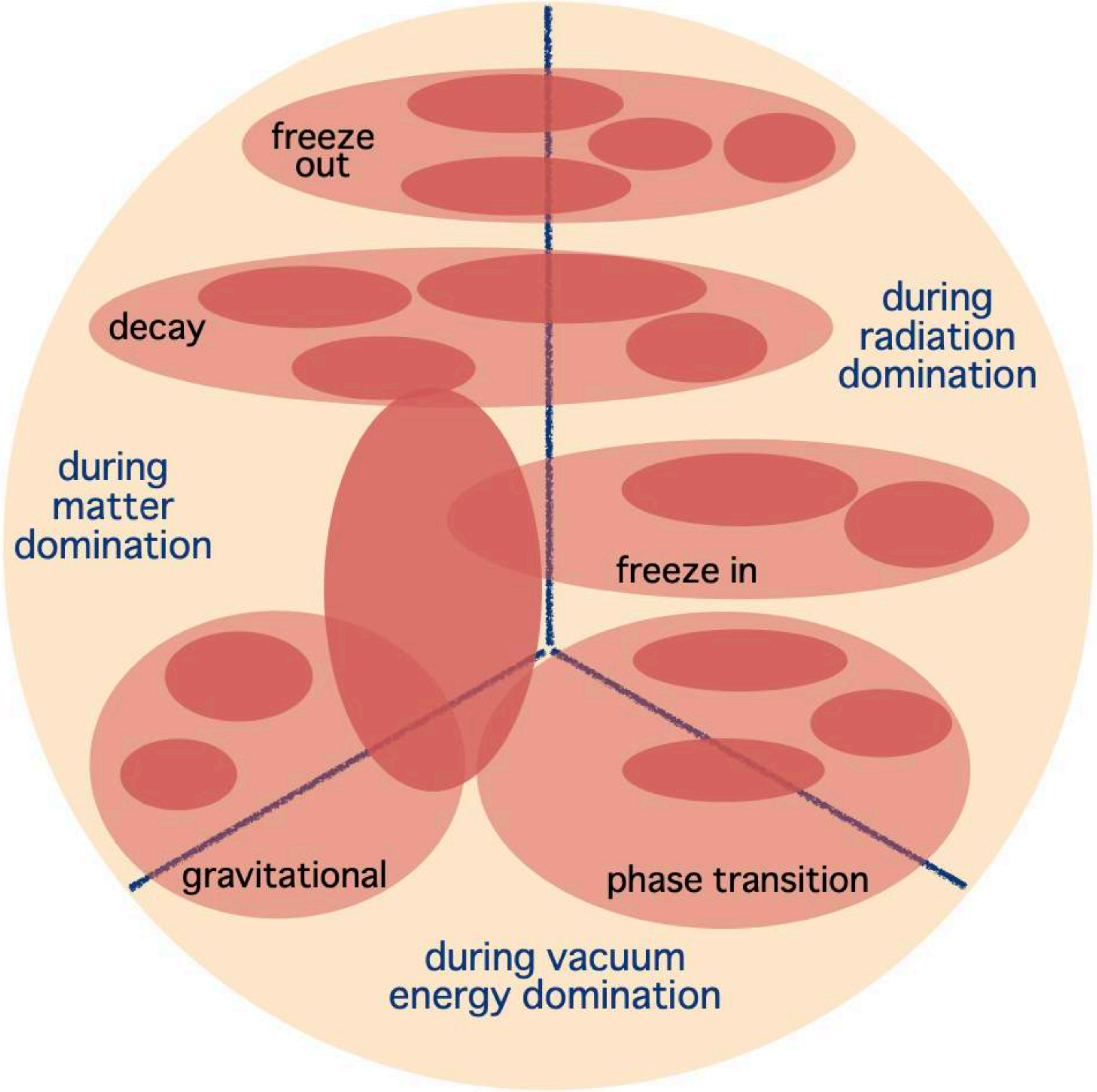
$\tau_s = 8.2ns \quad \tau_{rec} = 175.5ns \quad \tau_t = 1445ns$



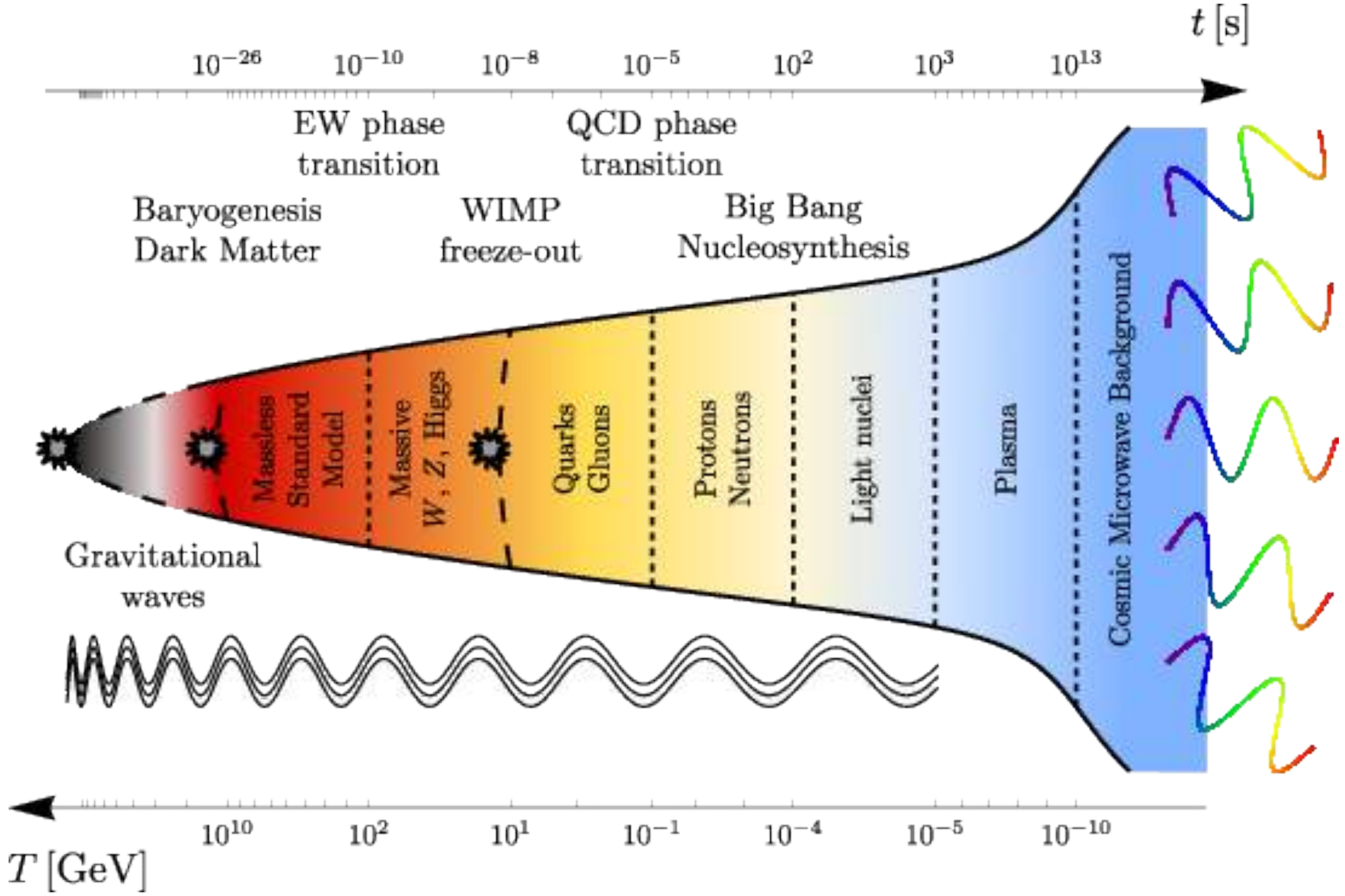
Eur. Phys. J. C 80, 303 (2020)

Dark matter production

- WIMPs: thermal relics coming from **freeze-out** in a radiation-dominated epoch before the Big Bang Nucleosynthesis
- Still, a **Early Matter Dominated Epoch** might have happened allowing for dark matter particles heavier than O(100) TeV



arXiv: 2203.06508



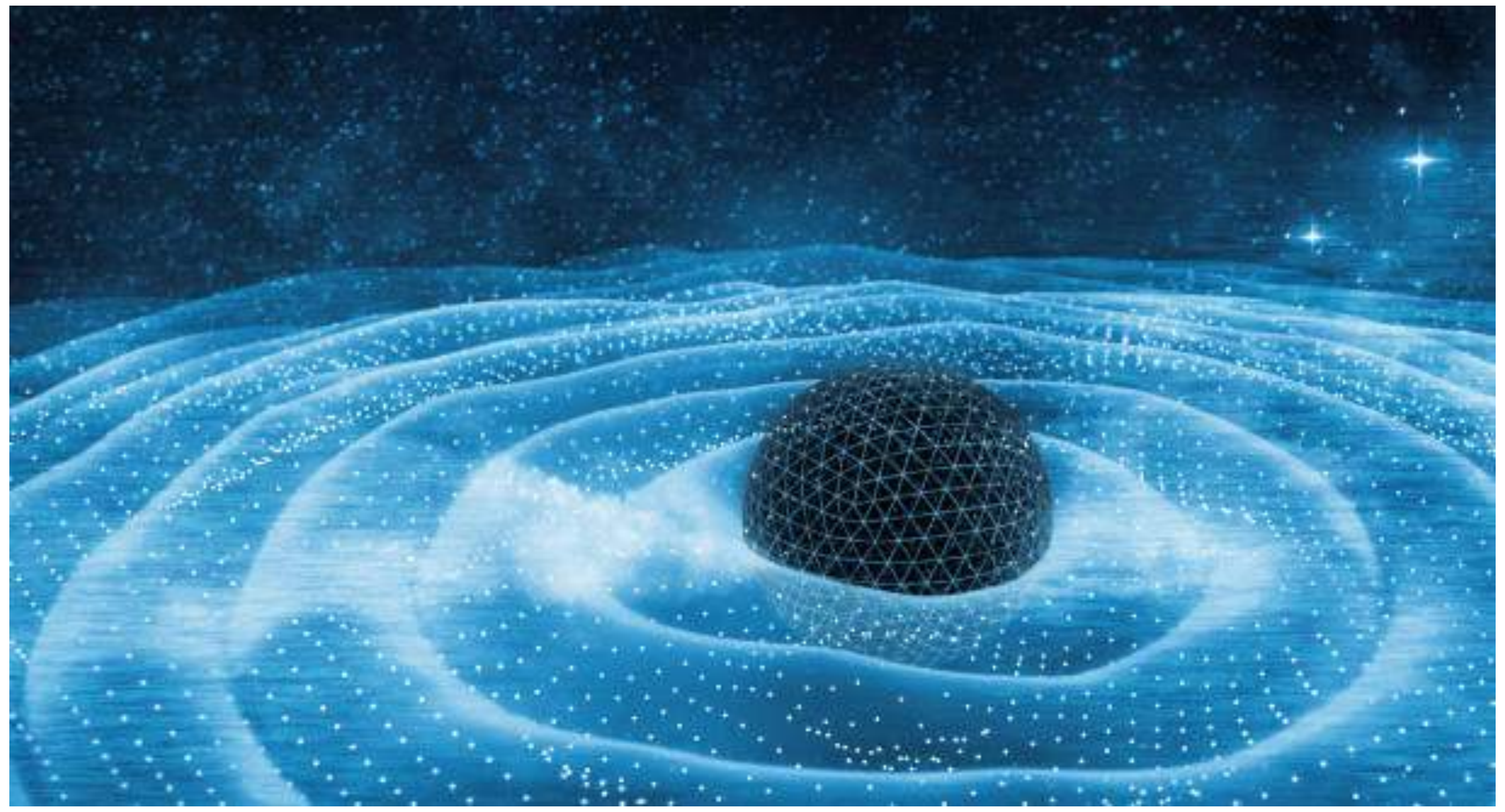
- A BSM field could indeed decouple, grow up and then decay, giving a second, late reheating before the BBN
- If **dark matter** particles are produced by these decay, they must compensate the time delay with a **much heavier mass**

Heavy dark matter production

Ultra High energy cosmic rays, above $E \approx 5 \times 10^{10} GeV$ can result from the **decay of very heavy dark matter particles**, produced by oscillations of the inflaton, a scalar massive field ($m \approx 10^{13} GeV$), or of moduli

Phys. Rev. D 59, 123006 (1999).

Inflational gravitational production, in quantum field theories in a curved spacetime, of dark matter up to Hubble inflation scale and beyond that, with higher spin dark matter.

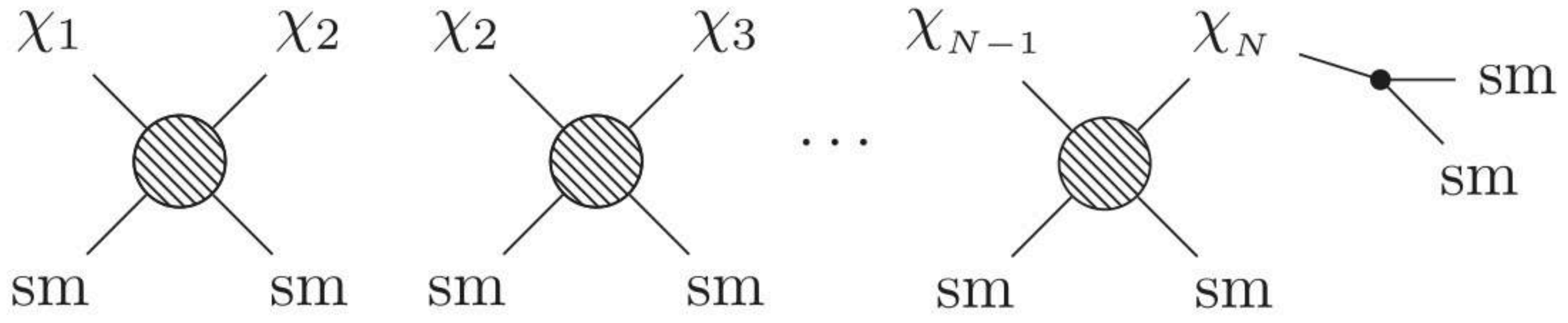


arXiv:1808.08236

Thermally produced in a **secluded sector,** where DM is a degenerate state of N particles,

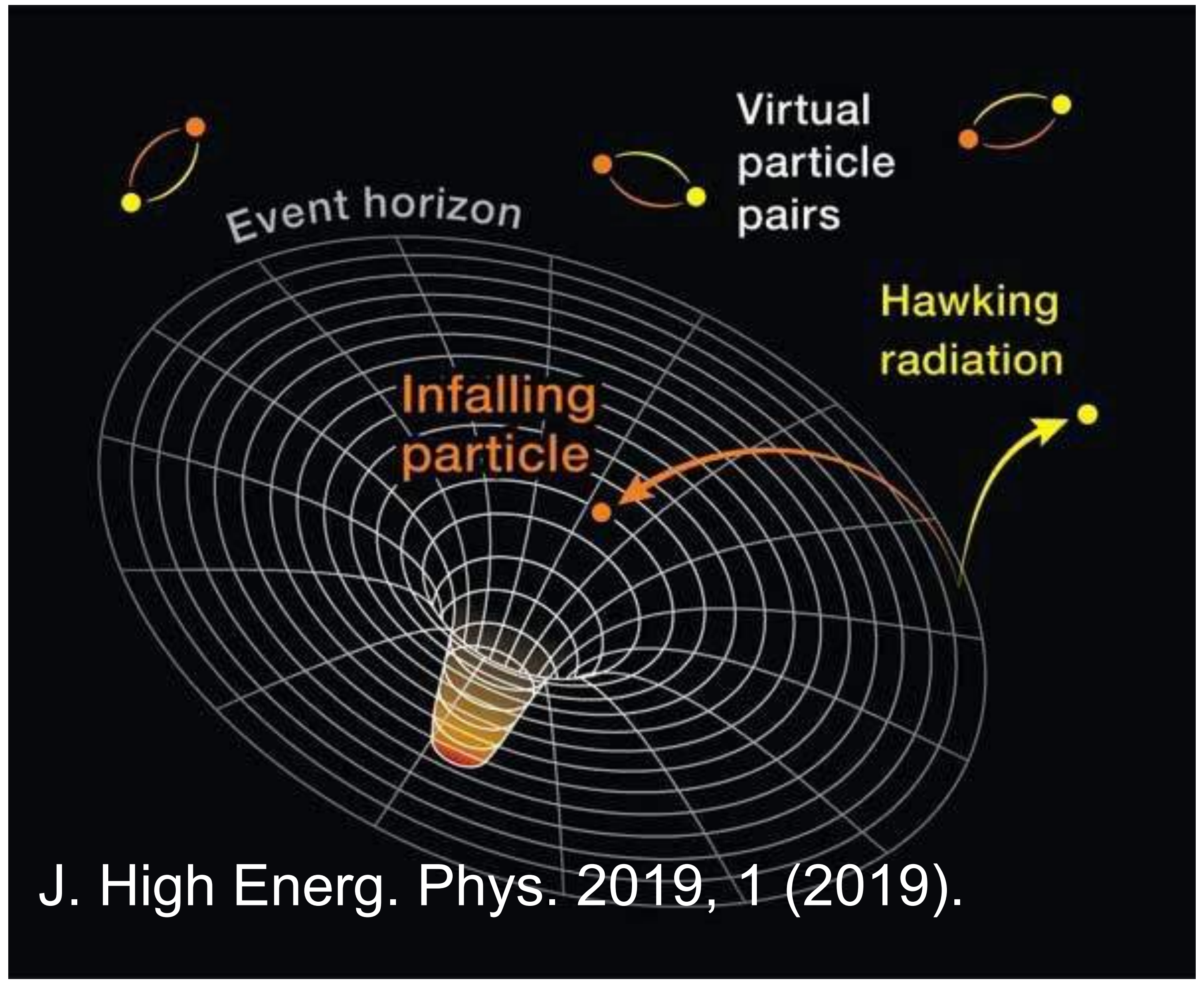
$$\chi_i + SM \leftrightarrow \chi_{i+1} + SM \qquad \chi_N \rightarrow SM + SM$$

These DM particles can reach Planck scale masses.



PRL 123, 191801 (2019)

Primordial black holes ($M \lesssim 5 \times 10^{8} g$) can produce heavy dark matter candidates ($m_{DM} \gtrsim 10^{9} GeV$) by Hawking evaporation.



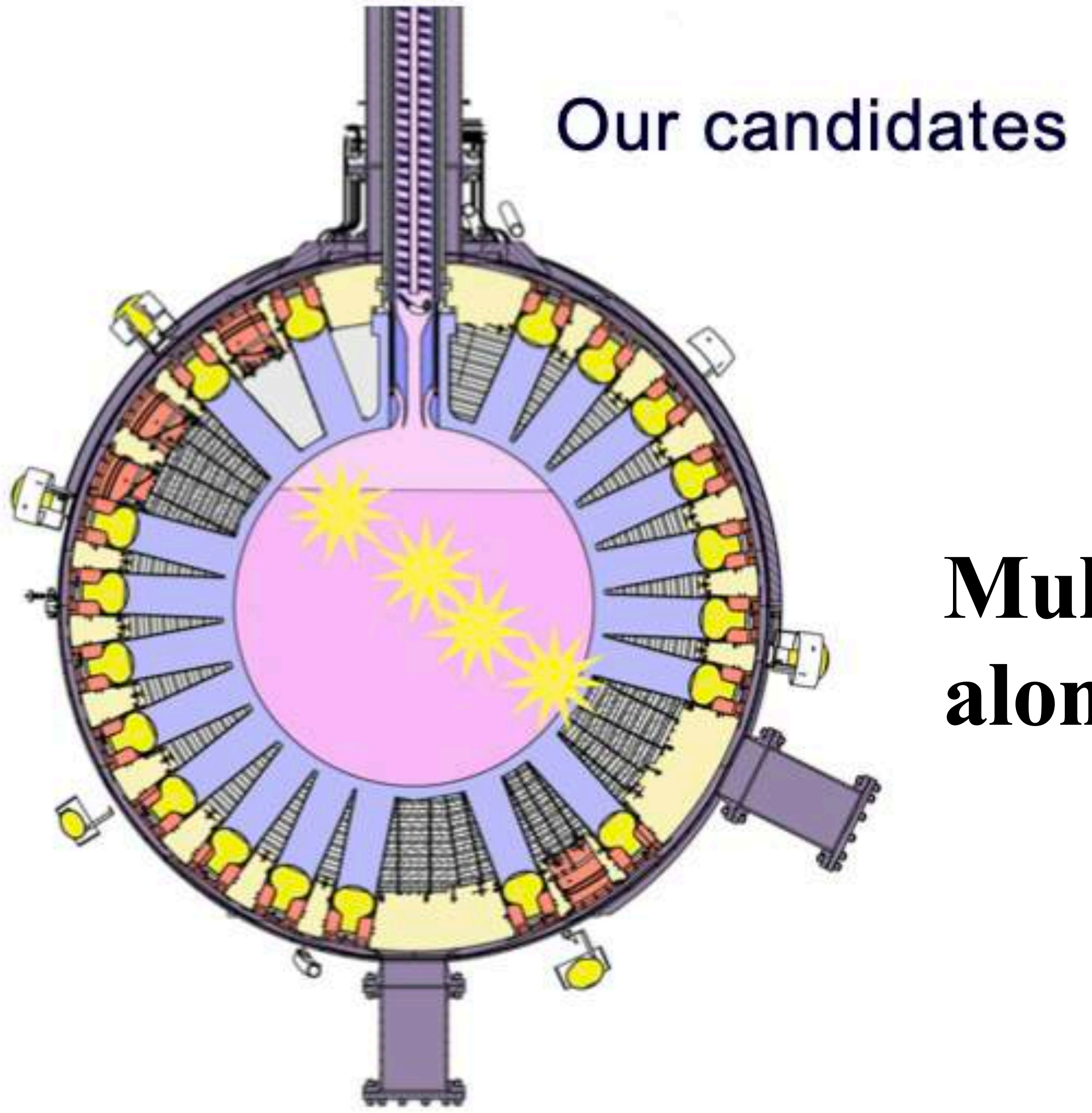
J. High Energ. Phys. 2019, 1 (2019).

Multi-scattering search

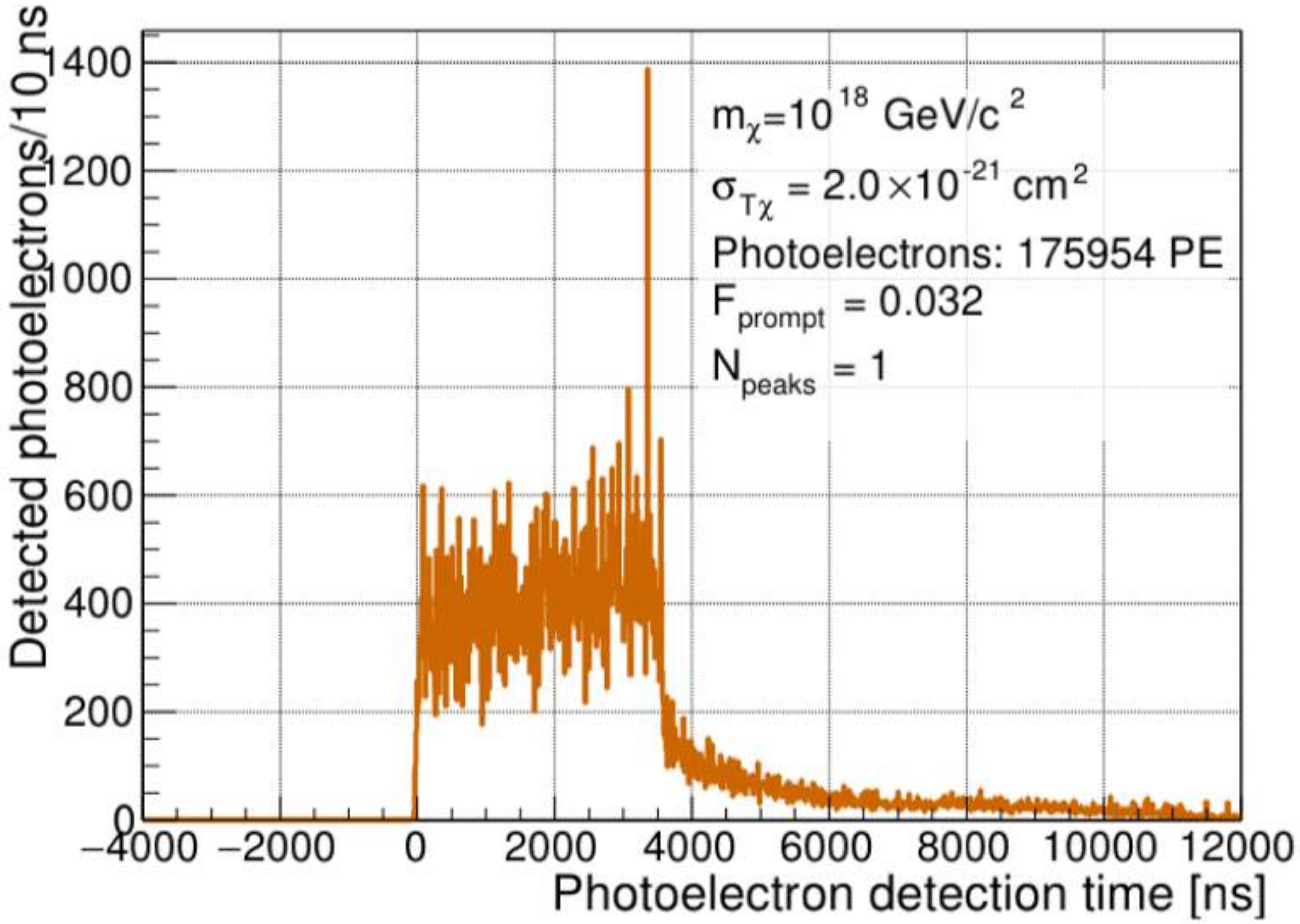
At such **high masses**, constrains are limited by the dark matter abundance rather than the cross-section, so a **large detector is needed**

Experimentally allowed cross-sections are high enough to produce **multiple scatters** in the detector

Dark matter (DM) candidates above $\sigma_{\chi\text{-n}} \cong 10^{-25}$ cm^2 and $m_\chi \gtrsim 10^{12}$ GeV **can reach underground detectors**



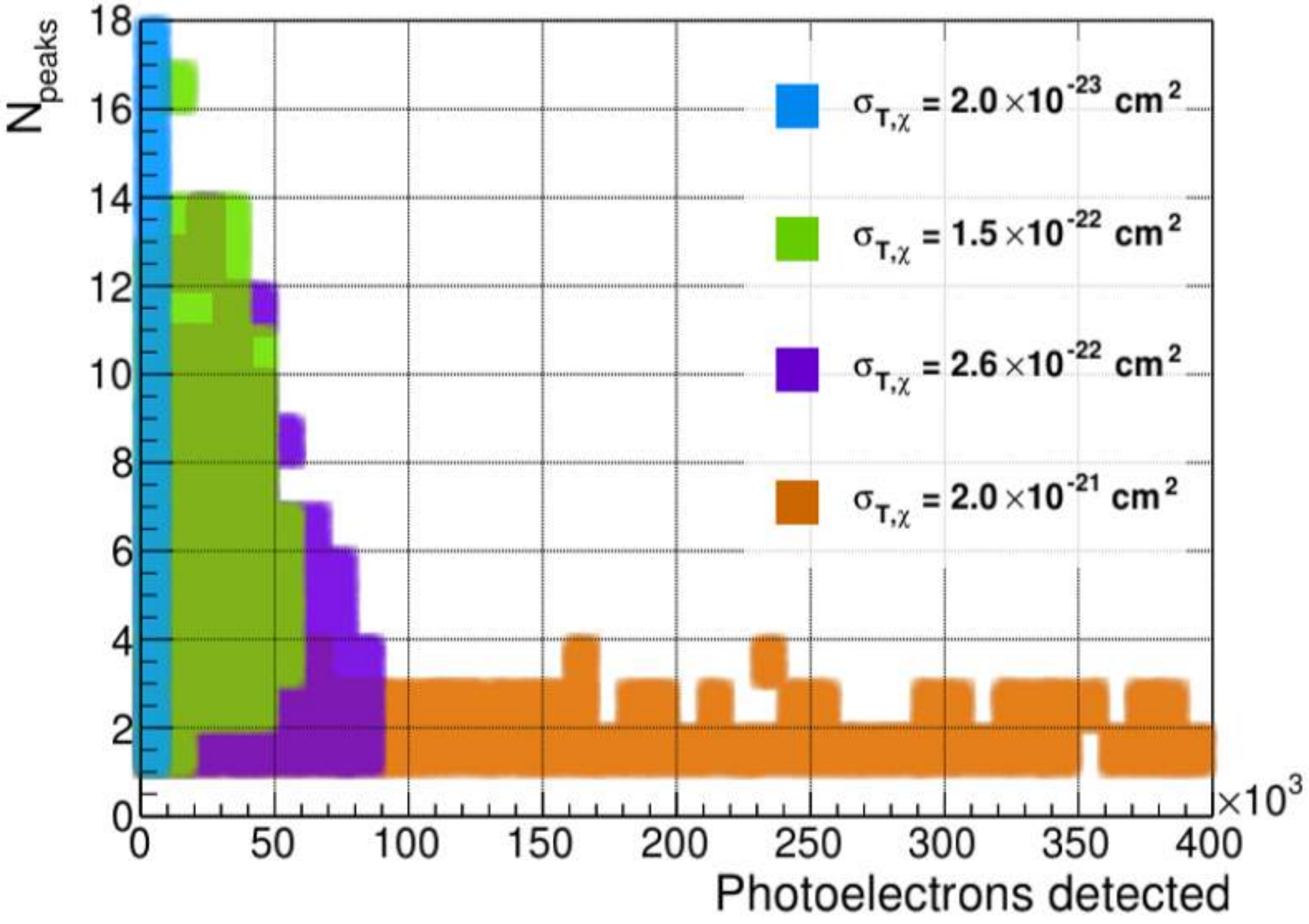
Multi-scattering particle along a collinear track

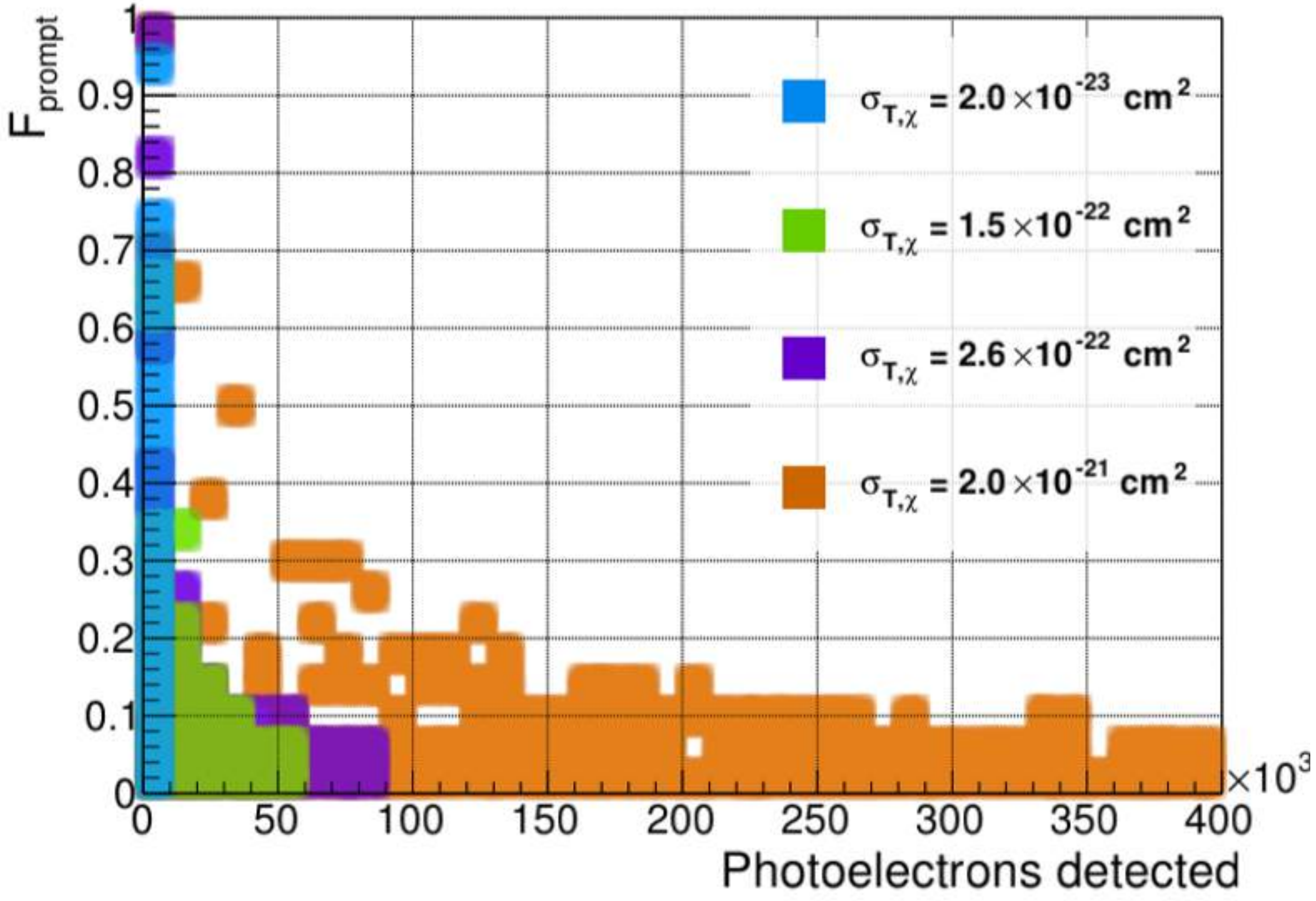


Simulation of the signal

- The detector response is calibrated with (n, γ) lines from ^{241}AmBe source at (4.6 ± 0.7) kHz up to 10 $\mathrm{MeV_{ee}}$.

$\mathbf{N_{peaks}}$**: number of significant peaks** on the discrete derivative w'(t) of the binned summed waveform.

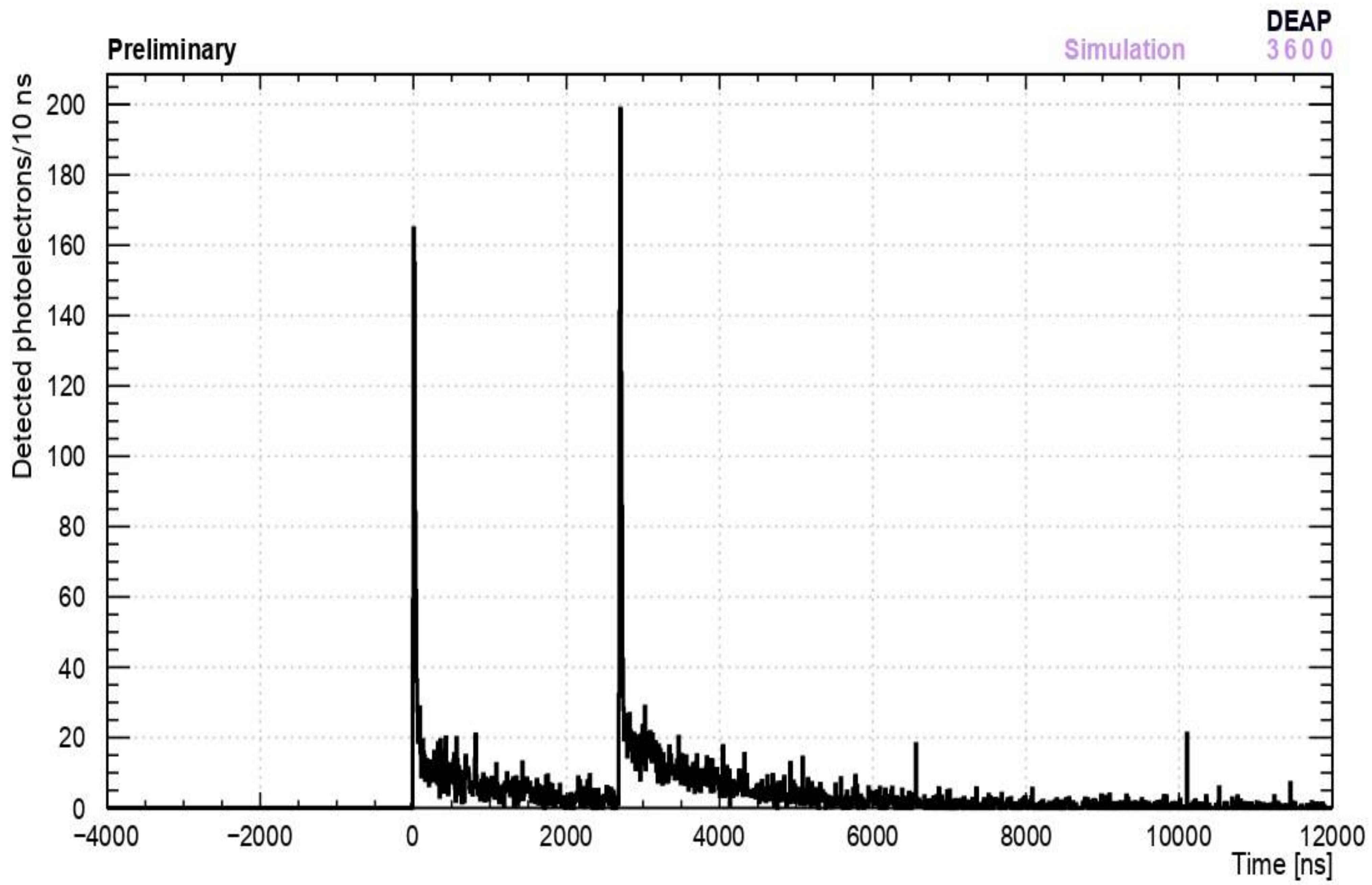




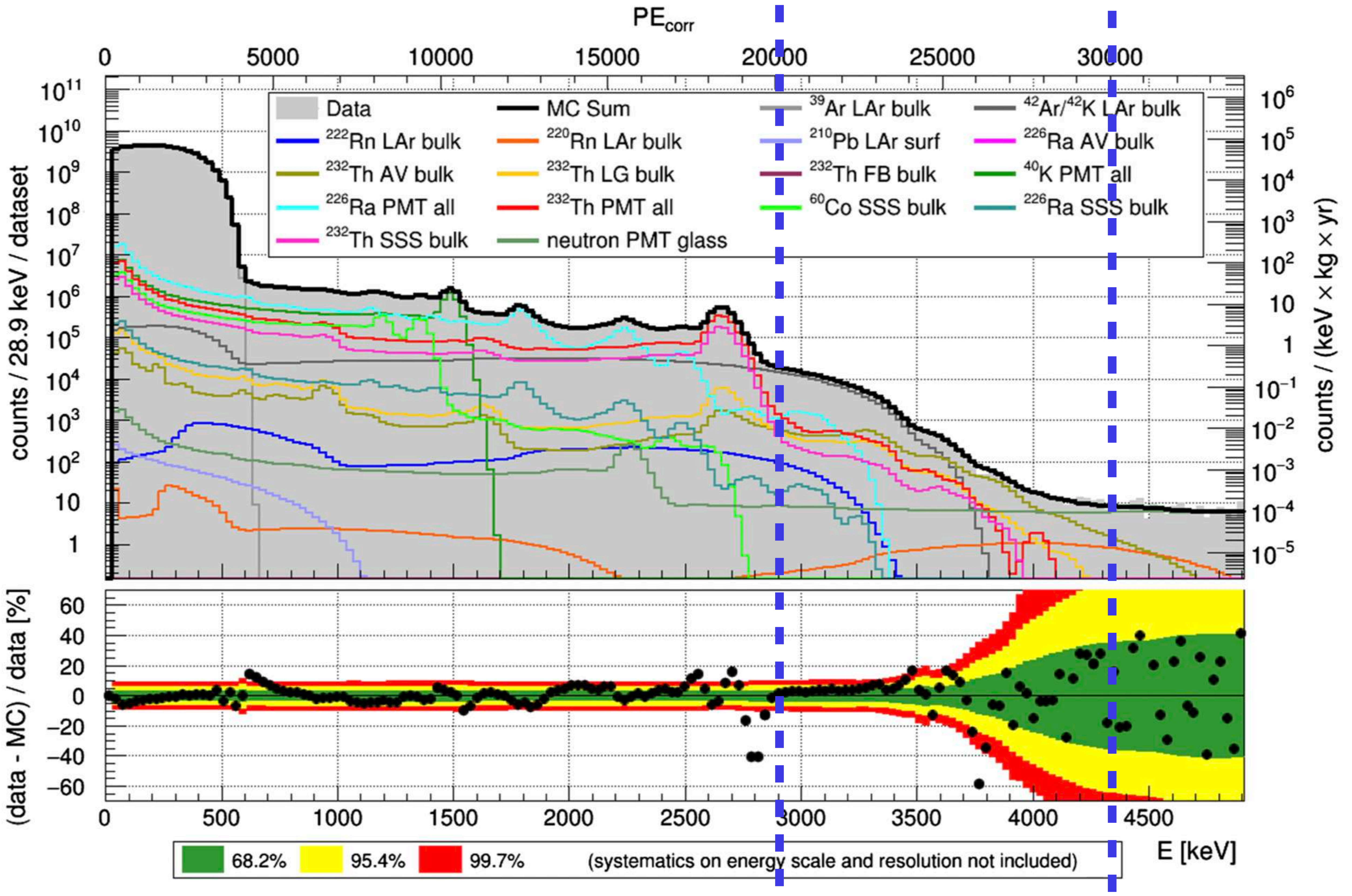
$$F_{prompt} = \frac{\int_{-28ns}^{150ns} PE(t)dt}{\int_{-28ns}^{10\mu s} PE(t)dt}$$

Background below 10 MeV

- Single scatter events removed by asking $N_{peaks} > 1$
- Left backgrounds: **pile-up events**
- The number of pulses in a pile-up is given by N_{peaks}.



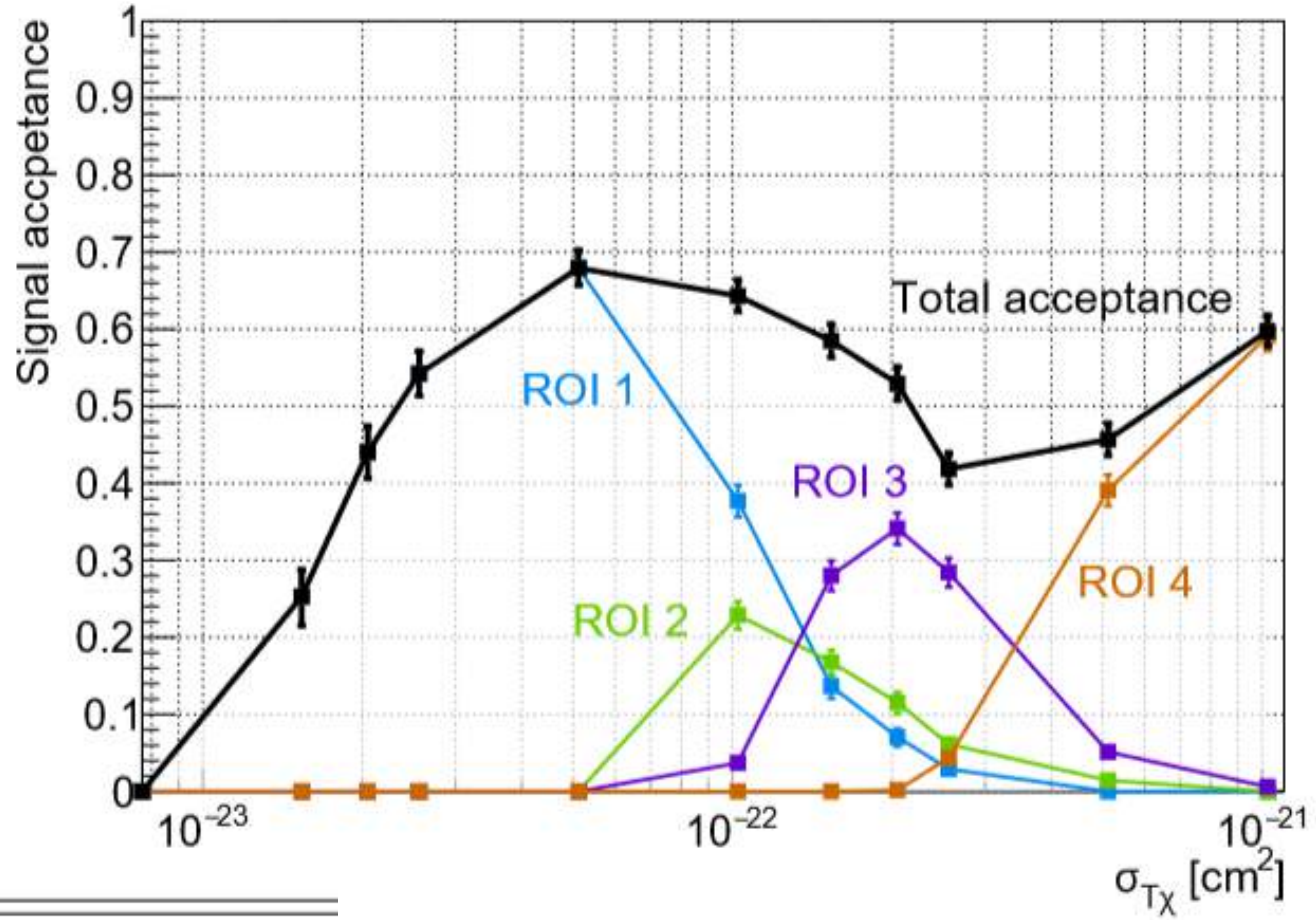
PE range	Energy [MeV]	N^{min}_{peaks}
4000–20 000	0.5–2.9	7
20 000–30 000	2.9–4.4	5
30 000–70 000	4.4–10.4	4



- Single scatter background already modeled
- Assumed Poissonian statistics for the number of pulses in a pile-up
- Agreement between data and simulation within 5 % in two test dataset
- For each **energy range** it follows the **selection cut in N_{peaks}**

Background above 10 MeV

- No calibration available
- simulations at very high cross-section candidates could not be performed due to computational limits.
- A conservative **acceptance of 35 %** assumed according to the time-of-flight across the inner vessel
- 17 muons per day in the water tank
- Removal of any event within **[-10, 90]us** from the muon veto trigger
- Upper selection cut at $\mathbf{F_{prompt} < 0.05}$ from the muon coincidence sideband



ROI	PE range	Energy [MeV]	N_{peaks}^{min}	F_{prompt}^{max}	μ_b
1	4000–20 000	0.5–2.9	7	0.10	$(4 \pm 3) \times 10^{-2}$
2	20 000–30 000	2.9–4.4	5	0.10	$(6 \pm 1) \times 10^{-4}$
3	30 000–70 000	4.4–10.4	4	0.10	$(6 \pm 2) \times 10^{-4}$
4	70 000–4×10^8	10.4–60 000	0	0.05	$(10 \pm 3) \times 10^{-3}$

Total lifetime (813 ± 8) days

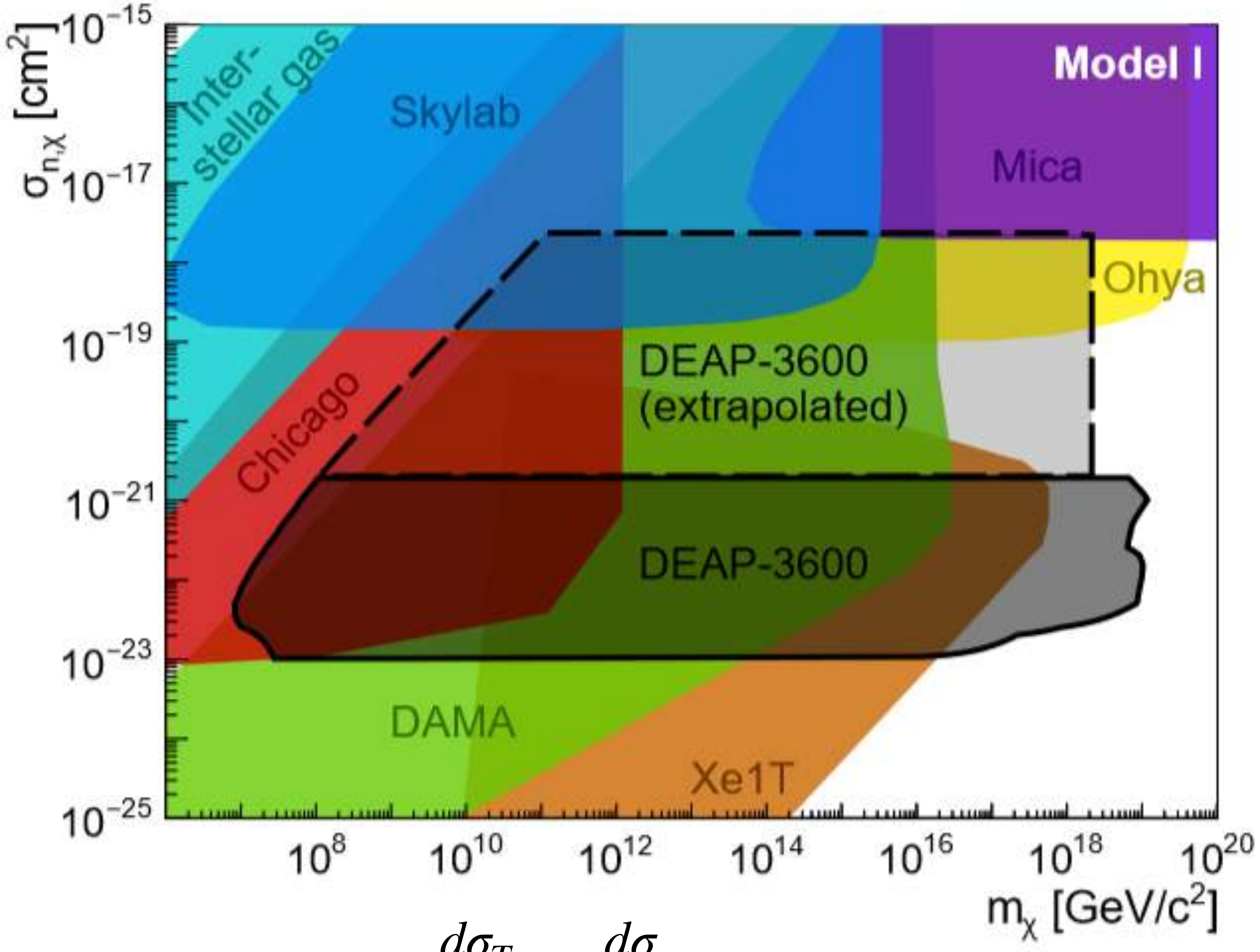
Total background level = 0.05 ± 0.03

Results

- **No event found in any of the ROIs**!
- Exclusion limits at 90 % C.L. set for any DM model predicting at least 2.3 events across all the ROIs.
- Expected number of event:

$$\mu_s = T \int d^3v \int dA \frac{\rho_\chi}{m_\chi} |v| f(\vec{v}) \epsilon(\vec{v}, \sigma_{T,\chi}, m_\chi)$$

- **Model 1**: dark matter candidate **opaque to the nucleus**
- Scattering cross-section at q=0 corresponds to the geometric size of the DM
- **Limits on strongly interacting, composite** dark matter candidates.



$$\frac{d\sigma_{T\chi}}{dE_R} = \frac{d\sigma_{n\chi}}{dE_R} |F_T(q)|^2$$

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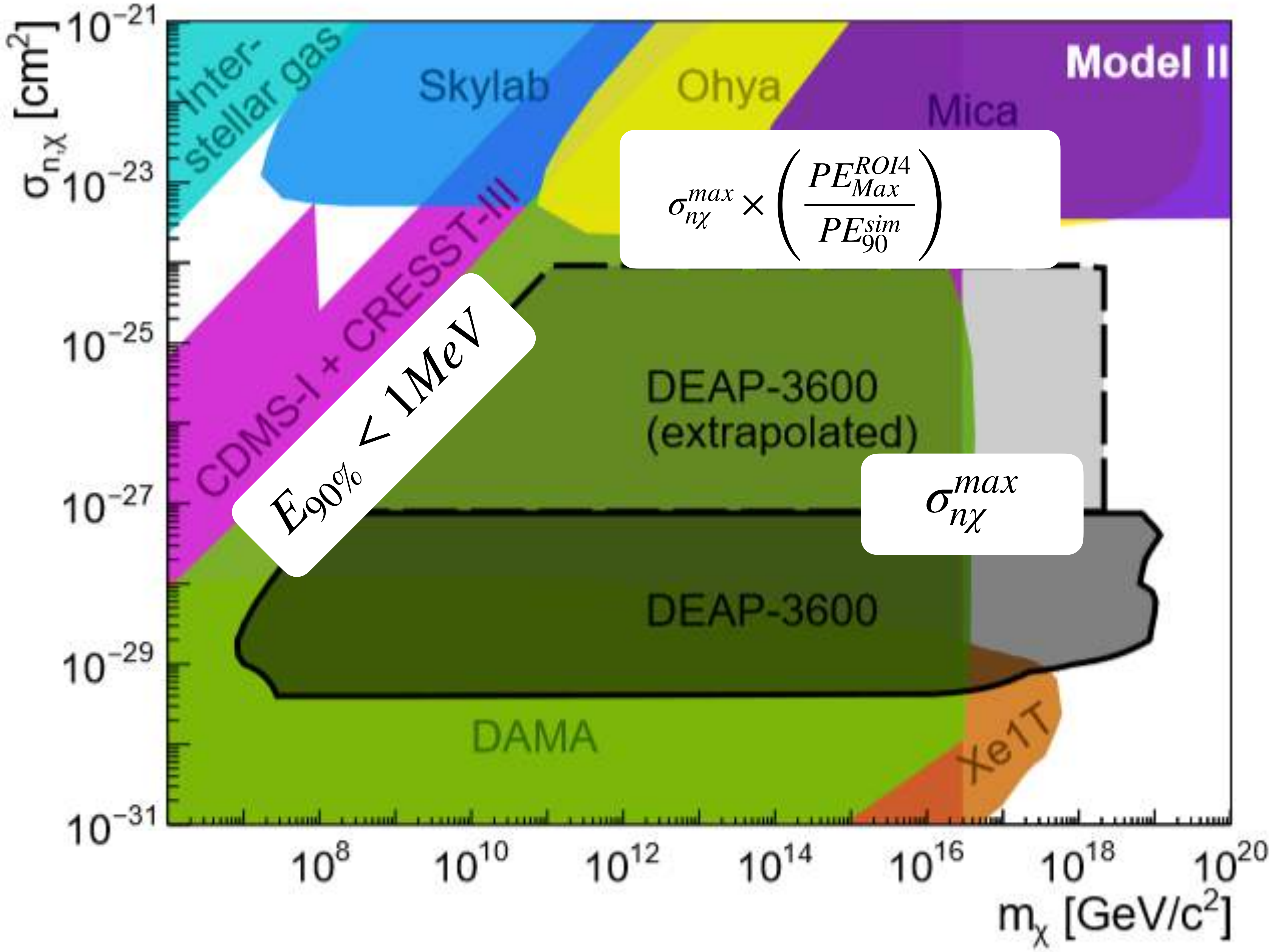
$$\mu_s = T\int d^3v \int dA \frac{\rho_\chi}{m_\chi} |v| f(\vec{v})\epsilon(\vec{v}, \sigma_{T,\chi}, m_\chi)$$

- **Model 2**: **nuclear dark matter models**, with N_D nucleons, each with mass m_D and radius r_D,

$$\frac{d\sigma_{T\chi}}{dE_R} = N_D^2 \frac{d\sigma_{nD}}{dE_R} |F_T(q)|^2 A^4 |F_\chi(q)|^2$$

- To keep s-wave approximation ($\sigma_{T\chi} < \sigma_{geo}$) , for dark nuclei $R_D >> 1$ fm we can find potentials resulting in $|F_\chi(q)|^2 \approx 1$

$$\frac{d\sigma_{T\chi}}{dE_R} = N_D^2 \frac{d\sigma_{nD}}{dE_R} |F_T(q)|^2 A^4$$



$$\frac{d\sigma_{T\chi}}{dE_R} = A^4 \frac{d\sigma_{n\chi}}{dE_R}$$

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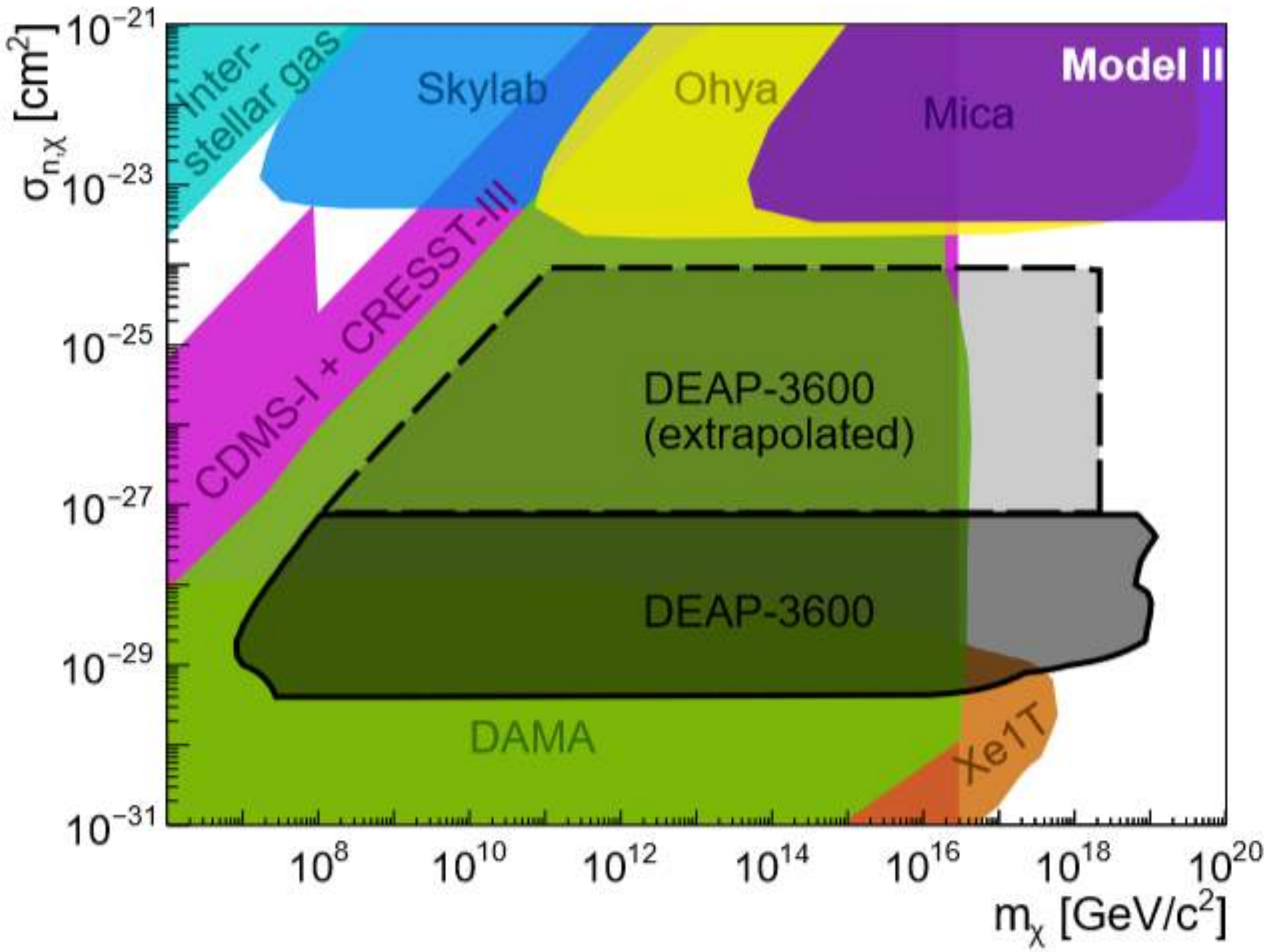
Phys. Rev. Lett. 128, 011801 (2022)



$$\frac{d\sigma_{T\chi}}{dE_R} = A^4 \frac{d\sigma_{n\chi}}{dE_R}$$

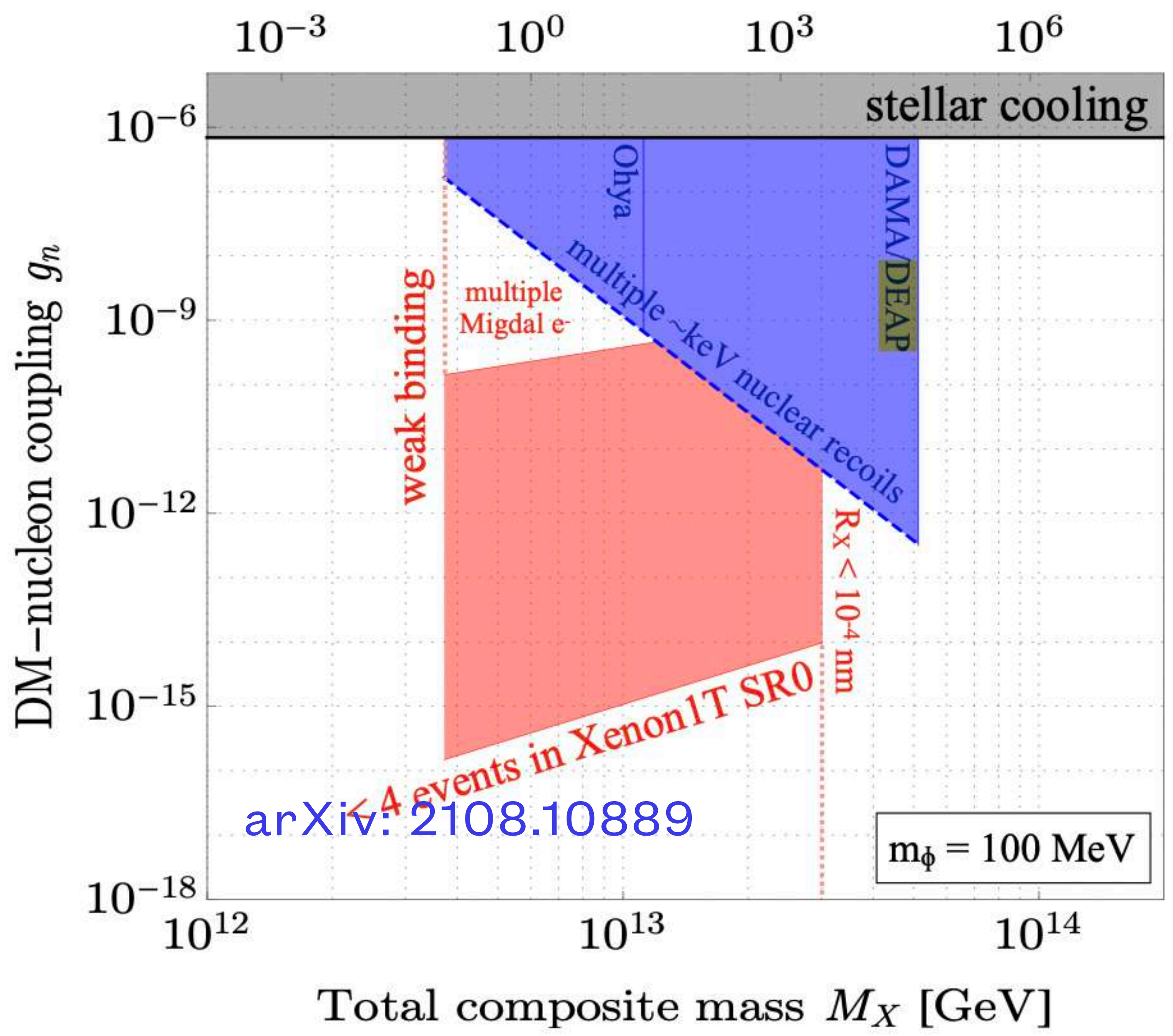
Impact of the research

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

arXiv: 2203.06508v1

Snowmass2021 Cosmic Frontier White Paper:
Ultraheavy particle dark matter

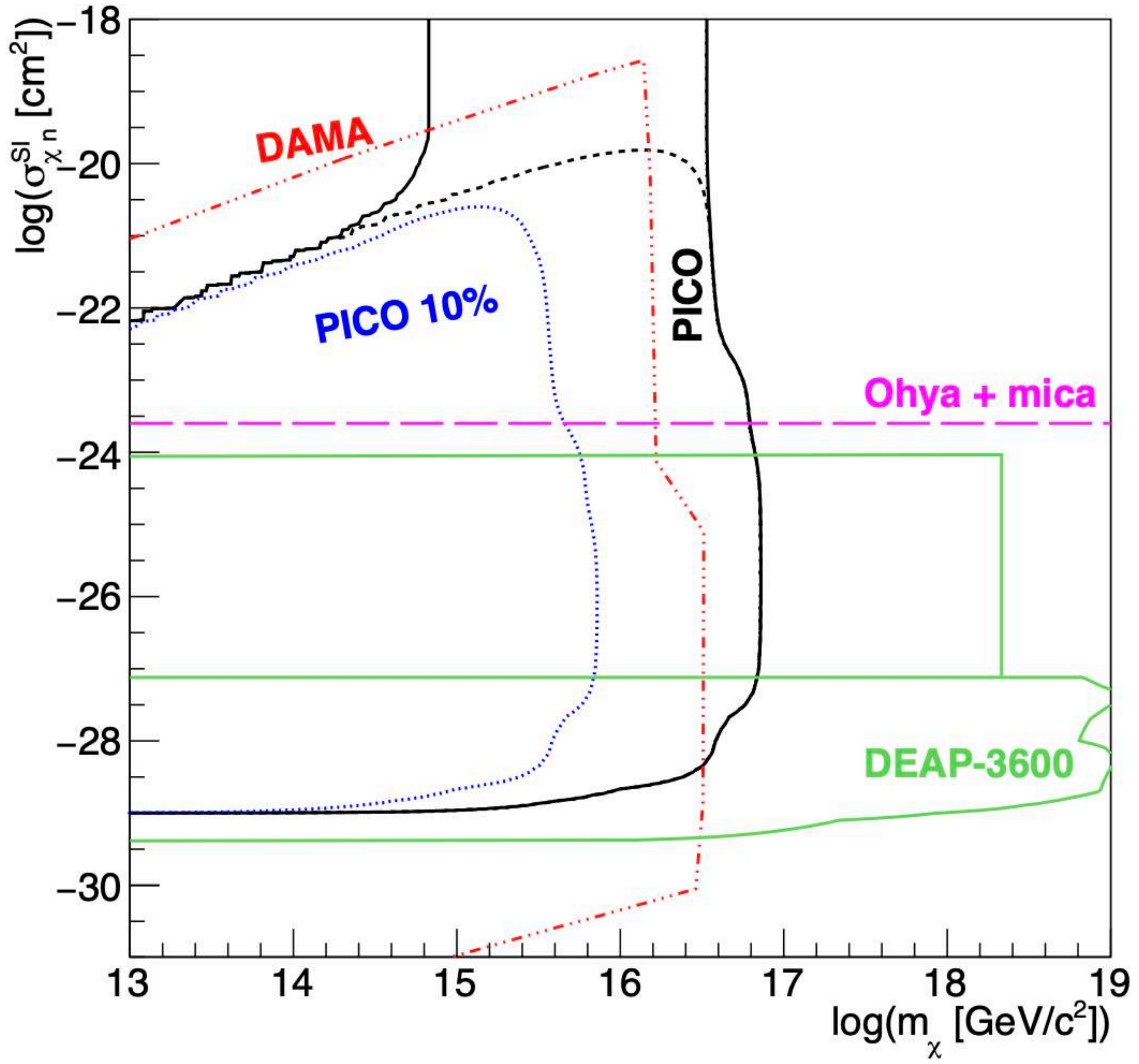
Re-analysis of single-scatter in XENON1T for composite dark matter candidates with Midgal electrons



arXiv: 2108.10889

Limits for q-monopole balls having internal electroweak symmetry

JHEP 01 (2022) 109



B. Broerman PhD thesis

Outline

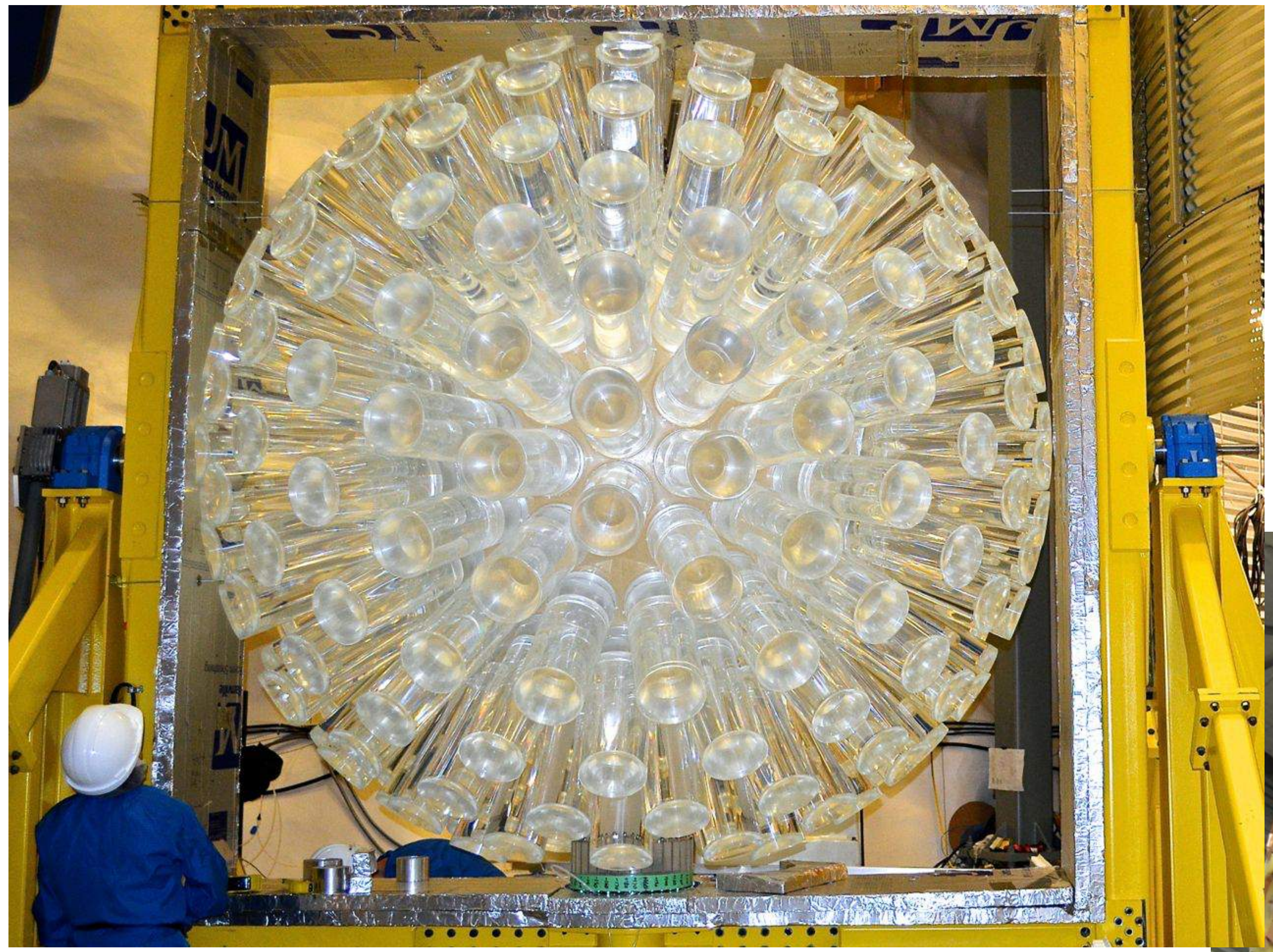
- Dark matter particles are expected even at Planck scale masses
- Underground detectors designed for the WIMP search are also sensitive to them
- Due to the large cross-sectional area of DEAP-3600 these candidates give a multi-scatter signature
- A custom developed analysis brought to 4 ROIs with a background level << 1
- No event was found after the unblinding of three years of data
- World-leading exclusion limits were set for two different models of composite dark matter

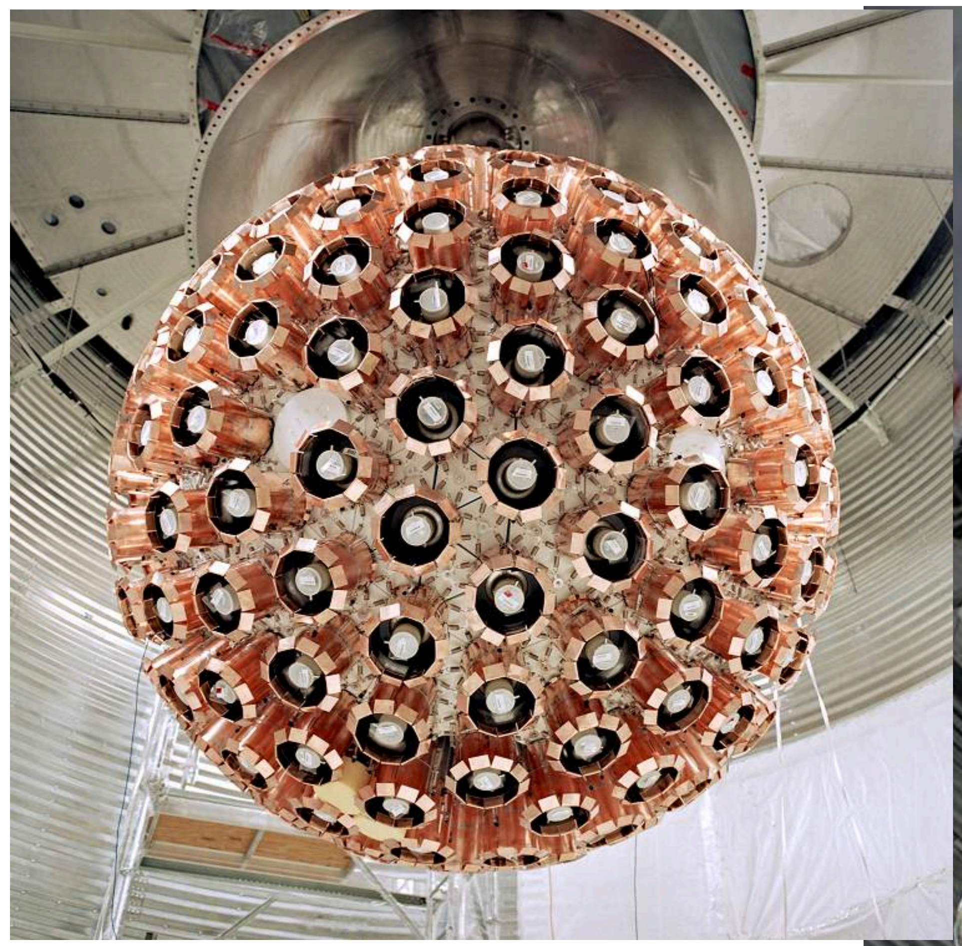
Back up

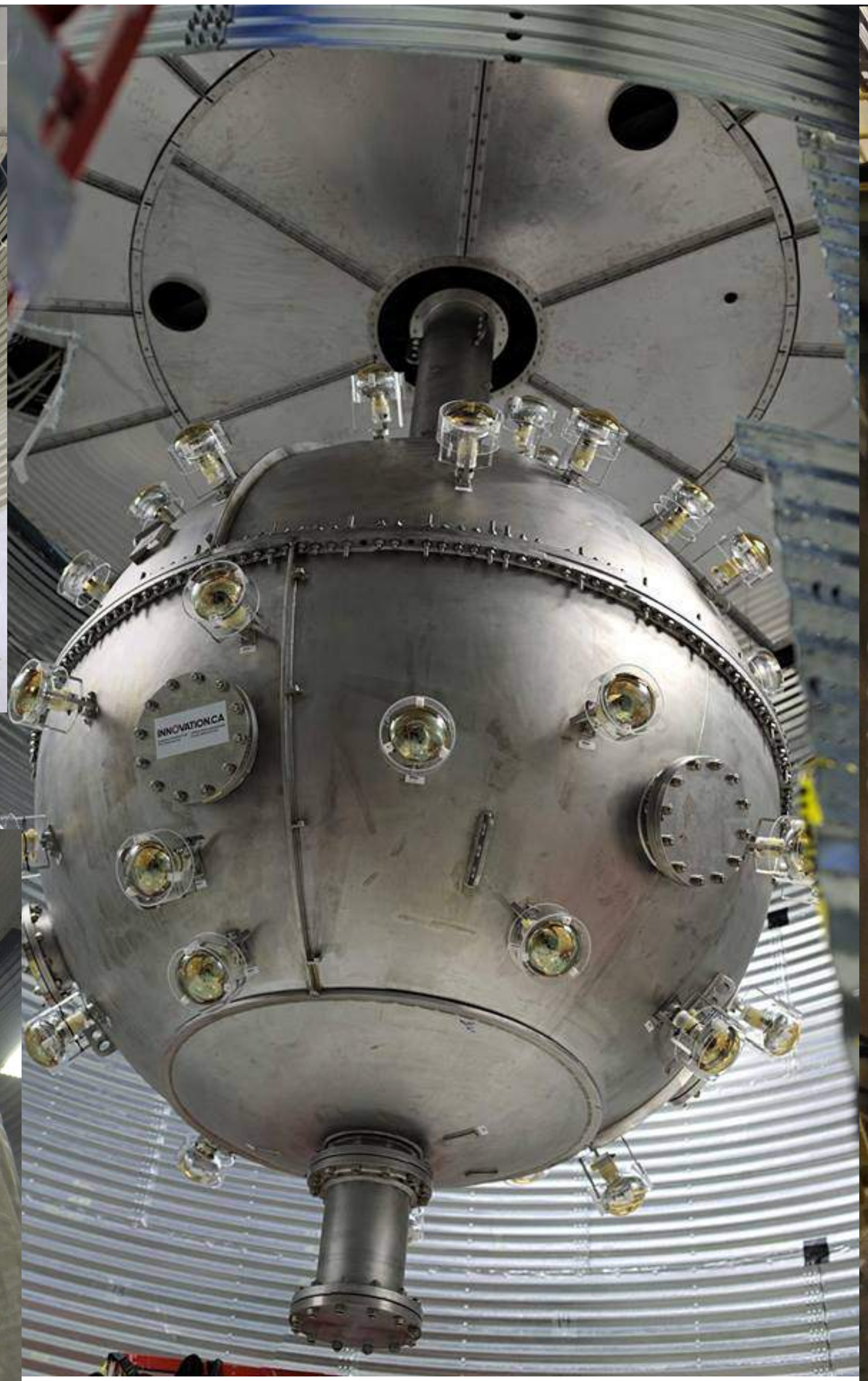
Dr. Michela Lai

on behalf of
DEAP-3600 Collaboration

The detector



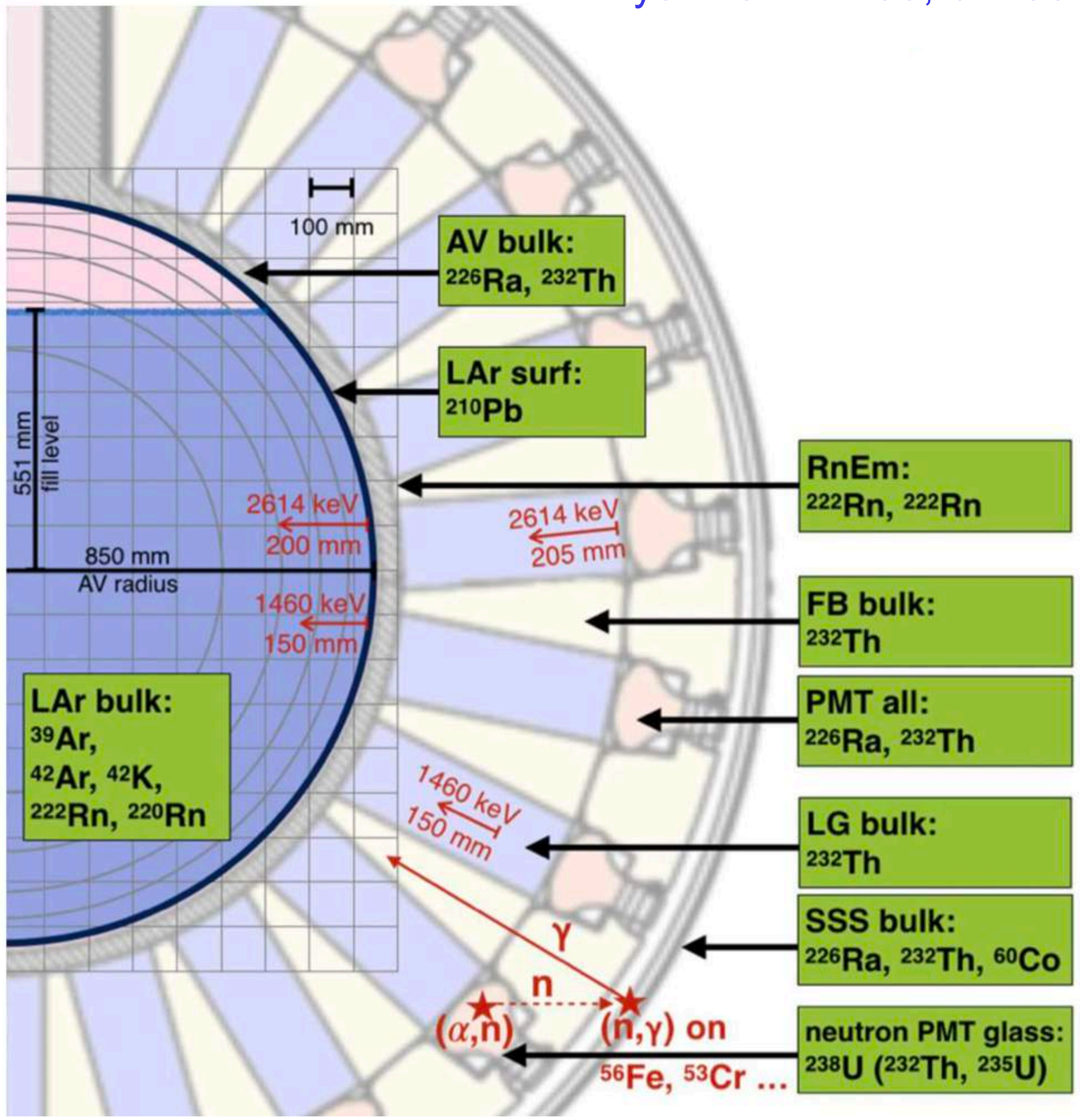




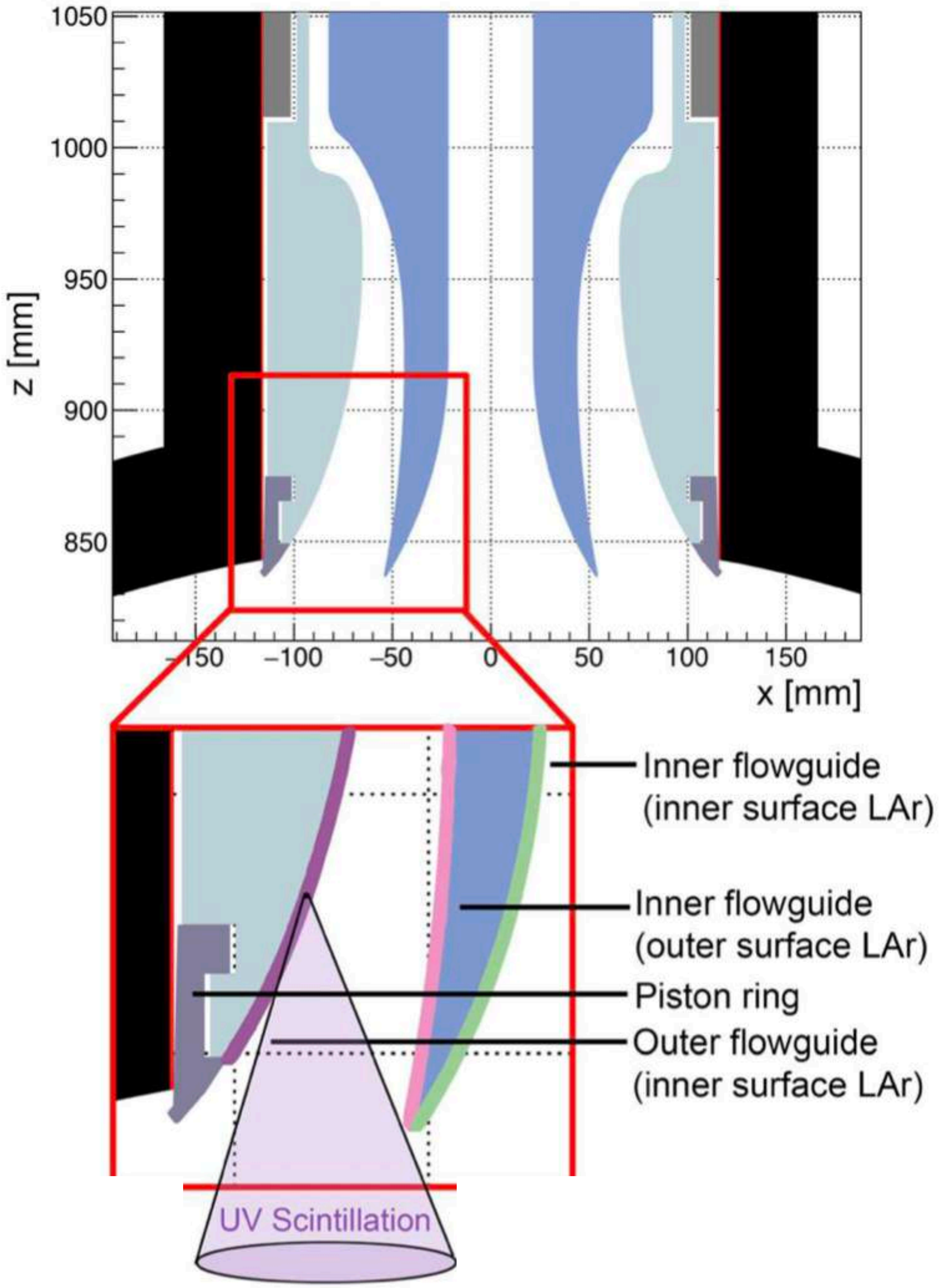
Backgrounds

- Electron recoil background fully modeled up to 10 MeV
- Measured $^{42}Ar/^{42}K$ activity = 40.4 ± 5.9μBq/kg

Phys. Rev. D **100**, 072009 (2019)

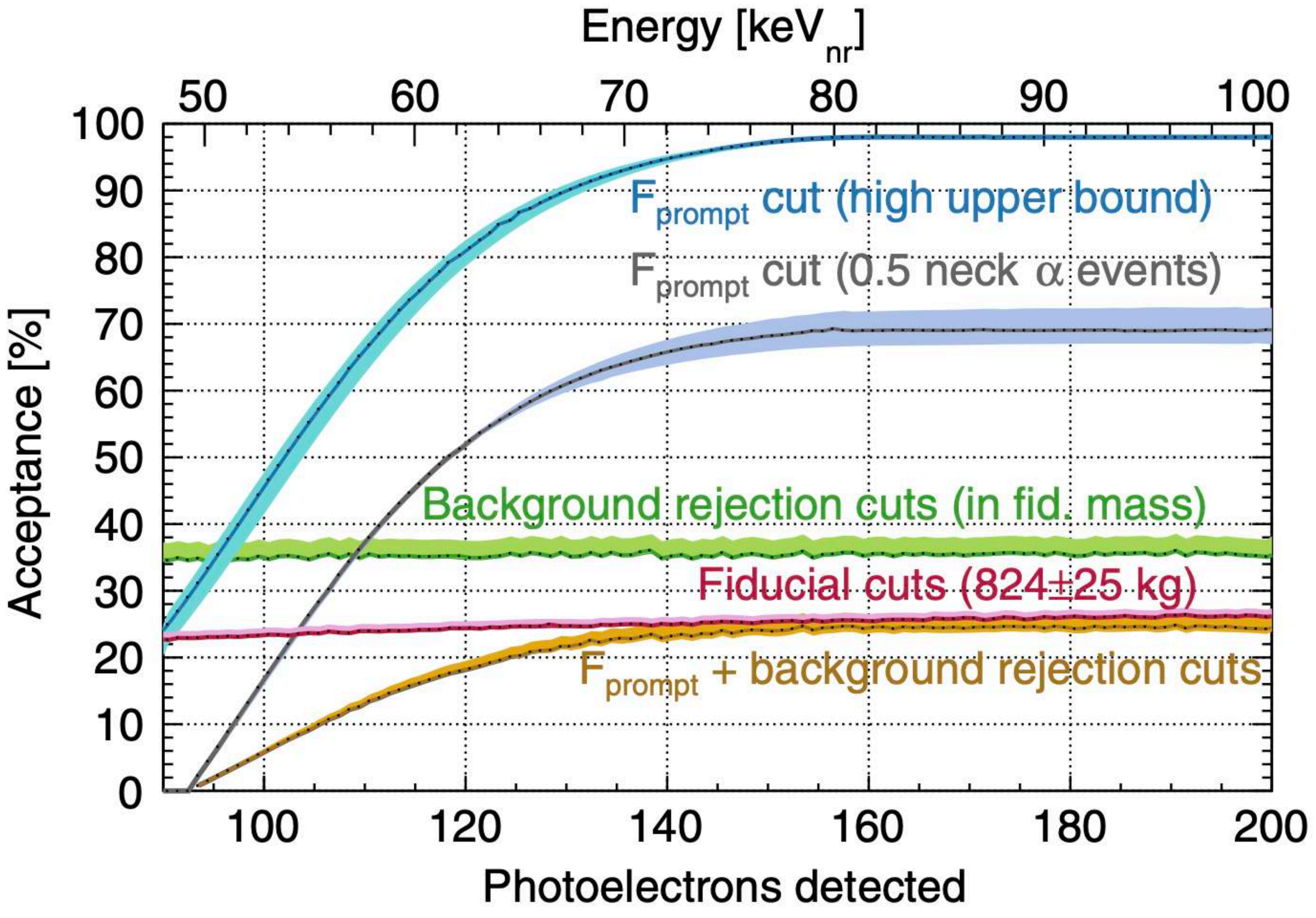


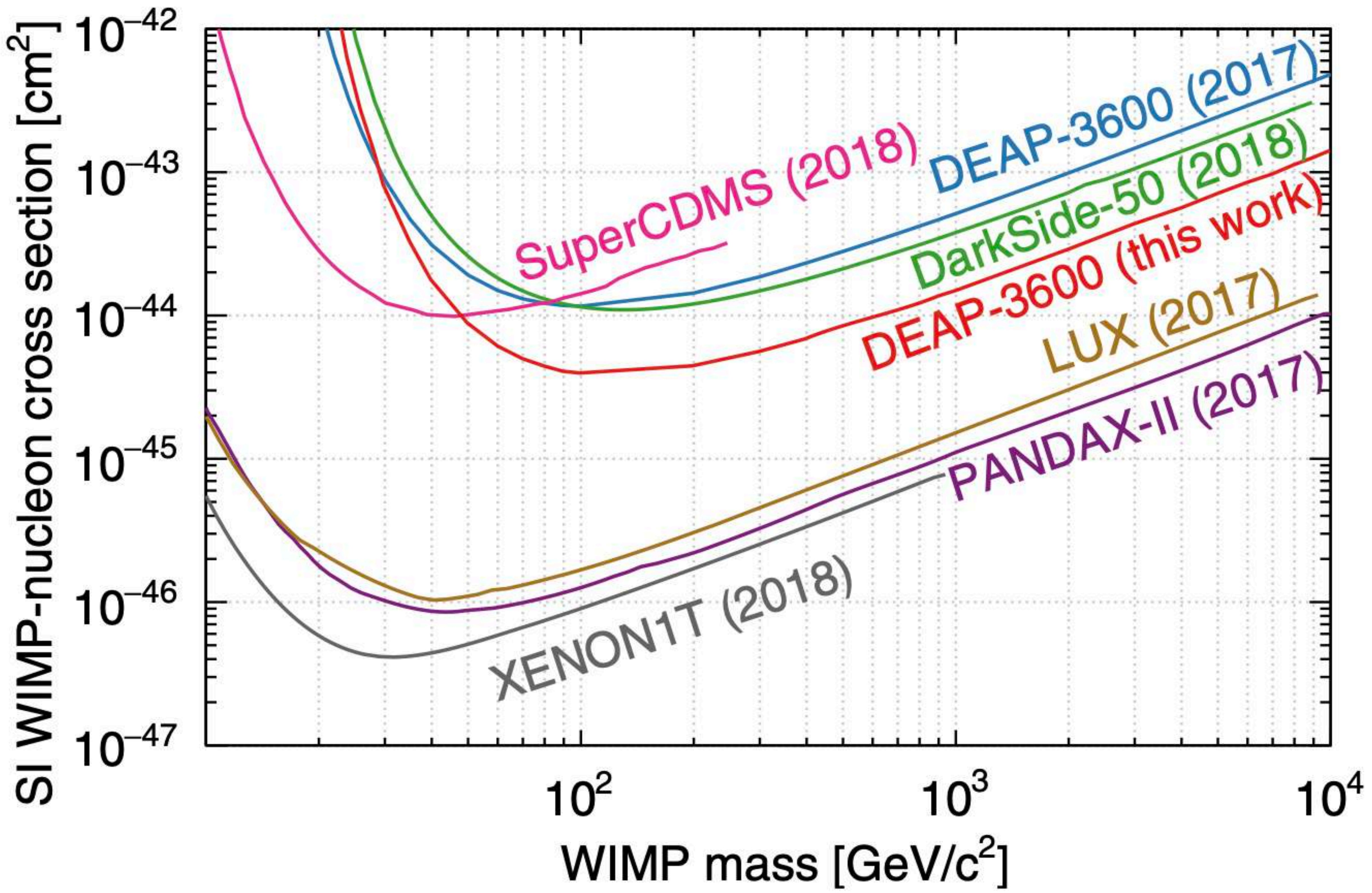
- Surface alphas removed with fiducial cuts, r < 630 mm
- Neck alphas removed with:
  - F_{prompt} upper cut
  - Early pulses in Gas Argon PMTs
  - Charge fraction in top 2 PMT rings
  - MVA selection cuts (ongoing)



Exclusion limits

- Stringent **exclusion limits** for the WIMP spin-independent interaction are set.
- The next WIMP search, with about three more years of data taking and improved selection cuts, **will scan lower cross-sections.**





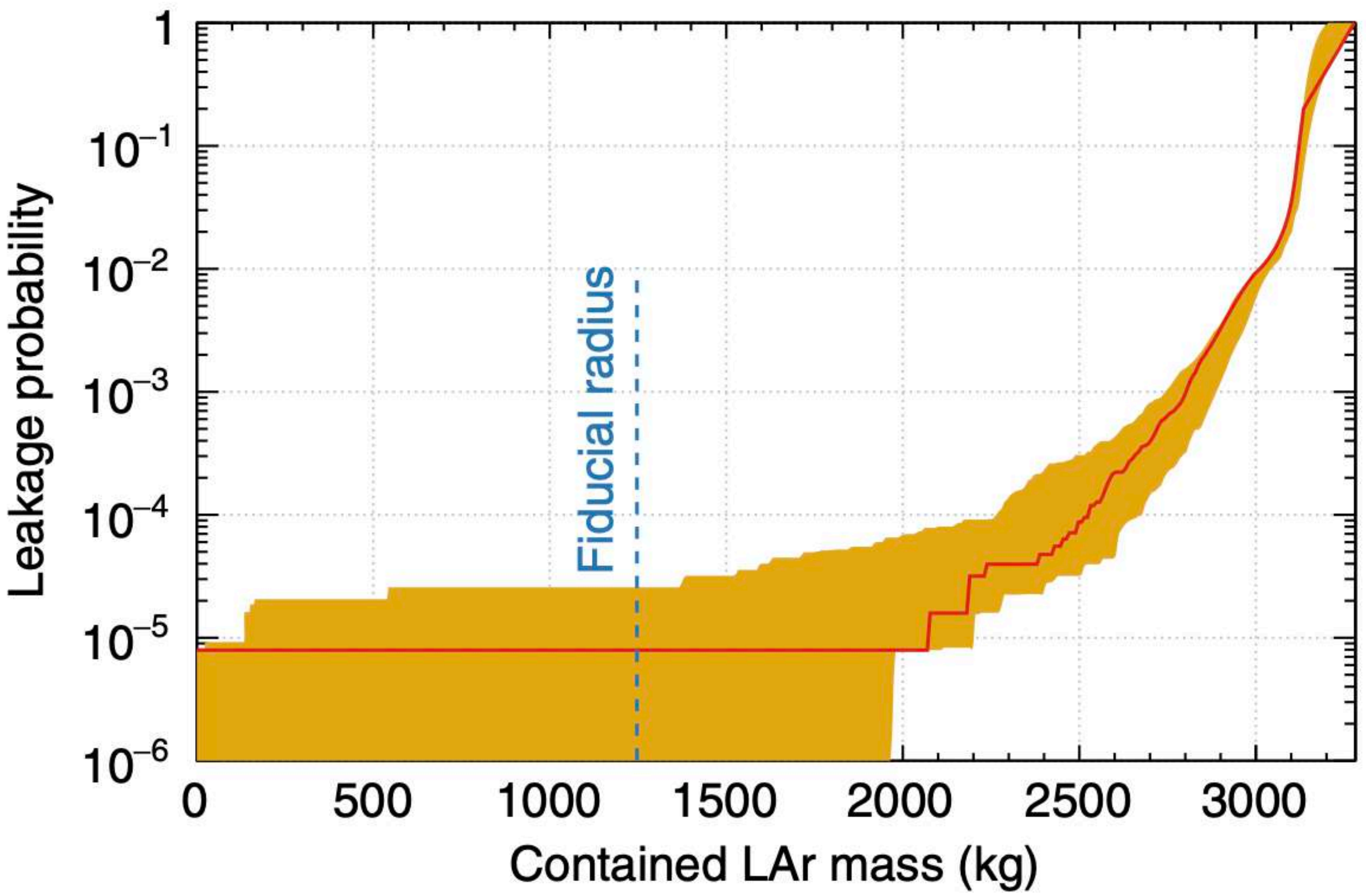
$$\frac{d\sigma}{dE} = \frac{m_A}{2\mu_A^2 v} \cdot (\sigma_0^{SI} F_{SI}^2(E) + \sigma_0^{SD} F_{SD}^2(E))$$

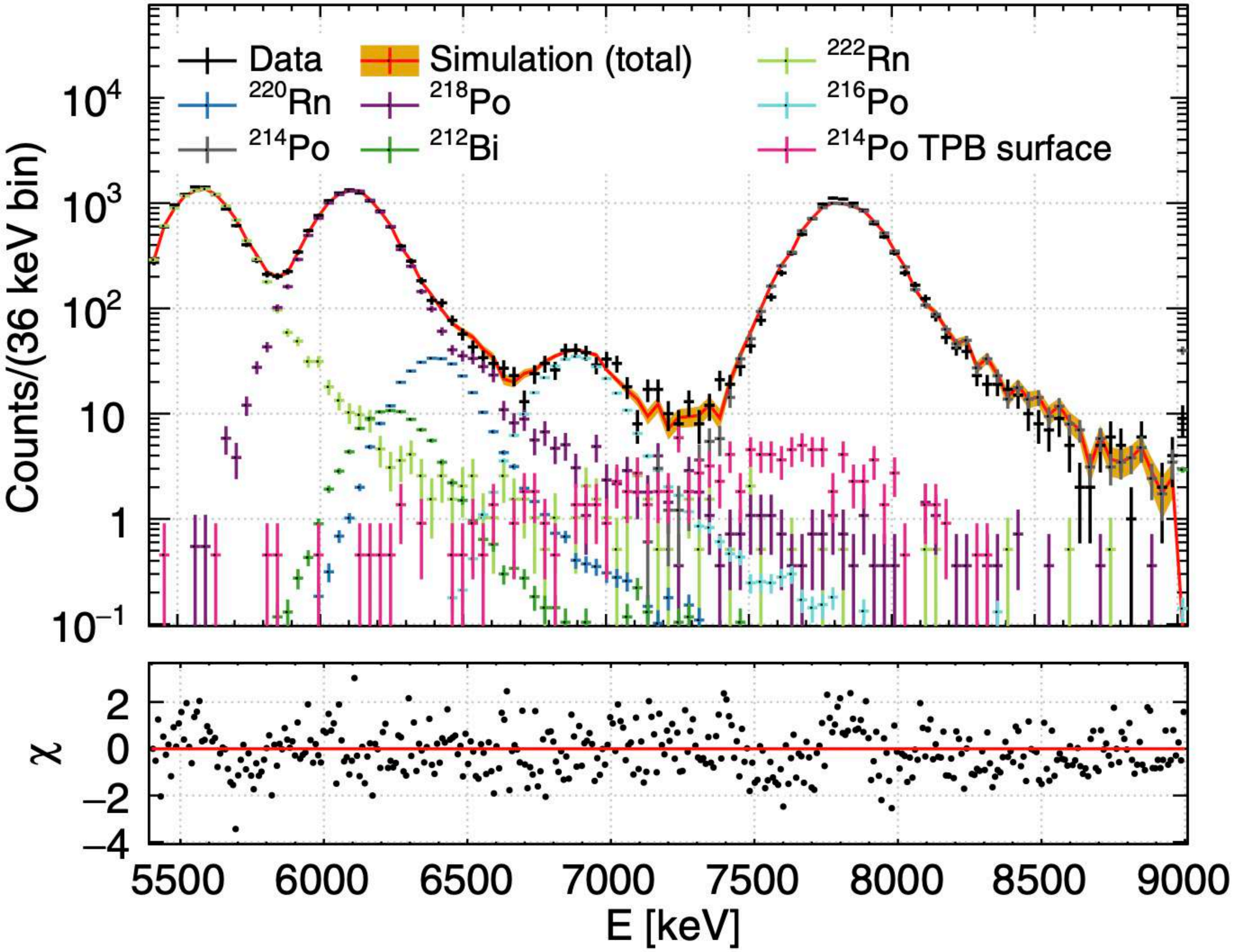
$$\sigma_0^{SI} = \sigma_p \frac{\mu_A^2}{\mu_p^2}[Zf^p + (A-Z)f^n]^2$$

Phys. Rev. D 100, 022004

Background sources

- **Bulk alphas**: energy fully deposited in LAr, much above WIMP ROI
- Surface alphas: most of the energy lost in TPB and/or acylic, giving a lower energy deposit in LAr. Might fall in WIMP ROI.
- **Fiducialization** volume cut at r < 630 mm

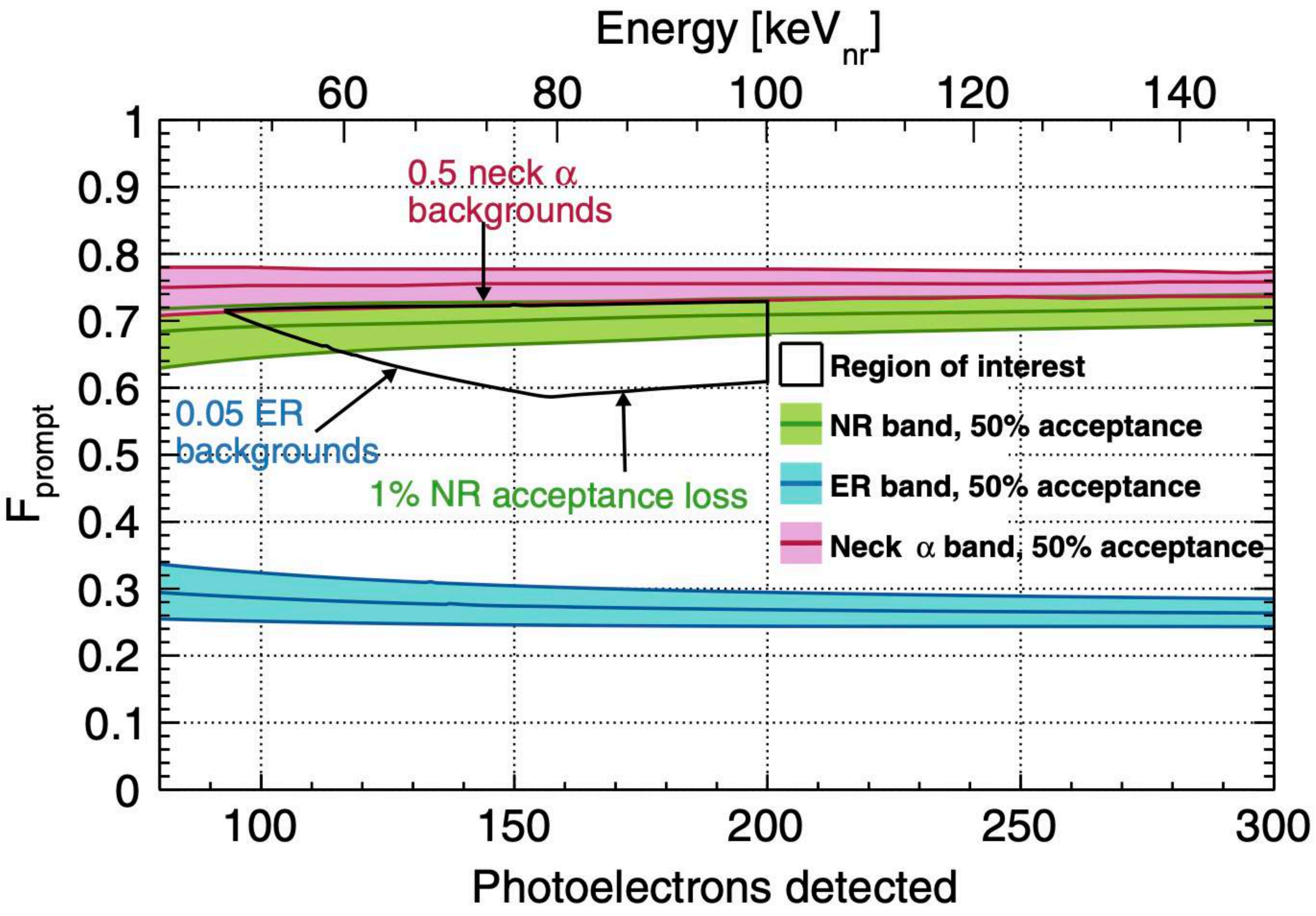


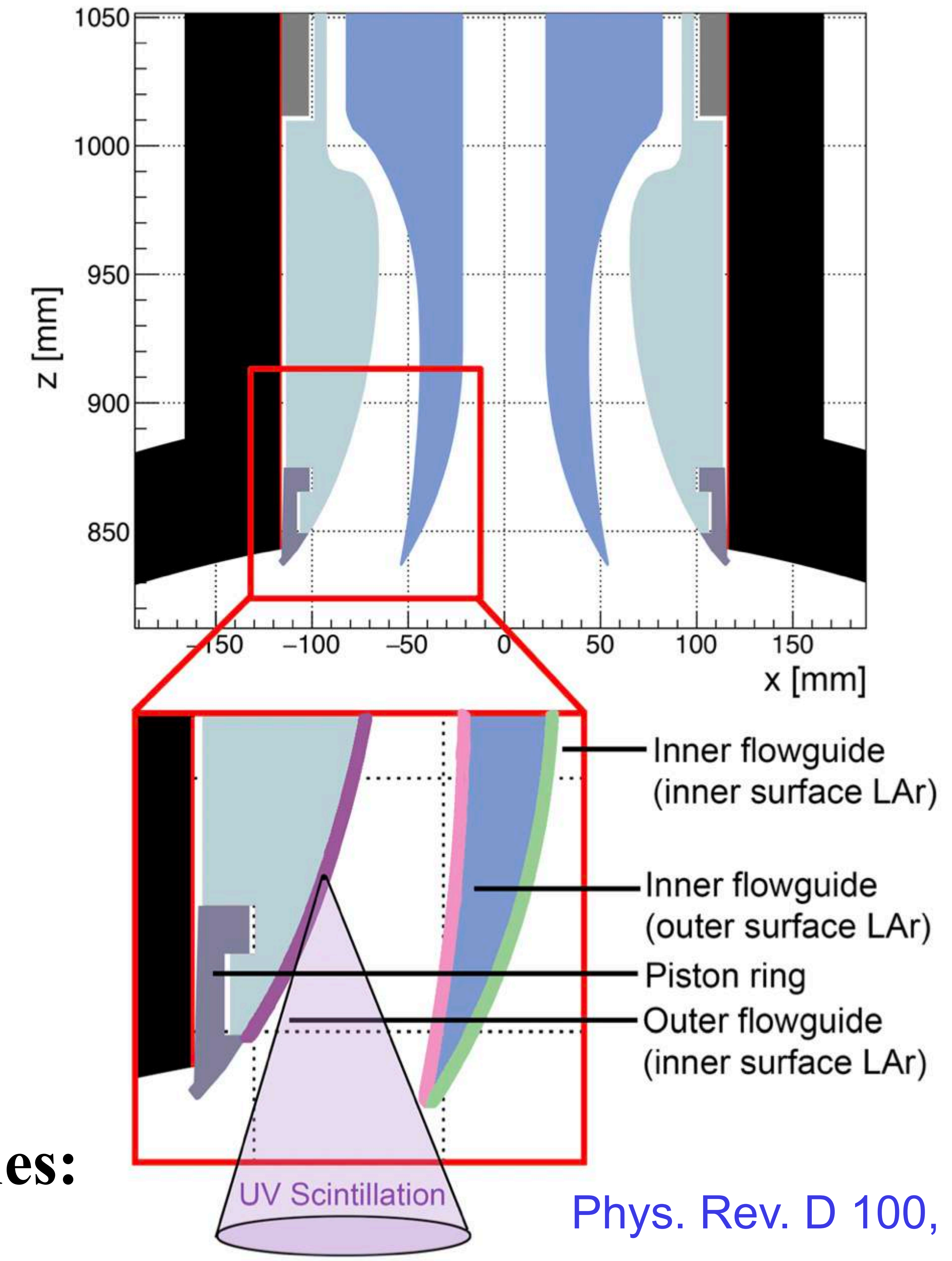


Phys. Rev. D 100, 022004

Background sources

- ^{210}Po releases alphas in the acrylic of the flowguides
- Alphas scintillate in the LAr film on the flowguides
- Their light is **shadowed** by the flowguide geometry and might enter the WIMP ROI.





Phys. Rev. D 100, 022004

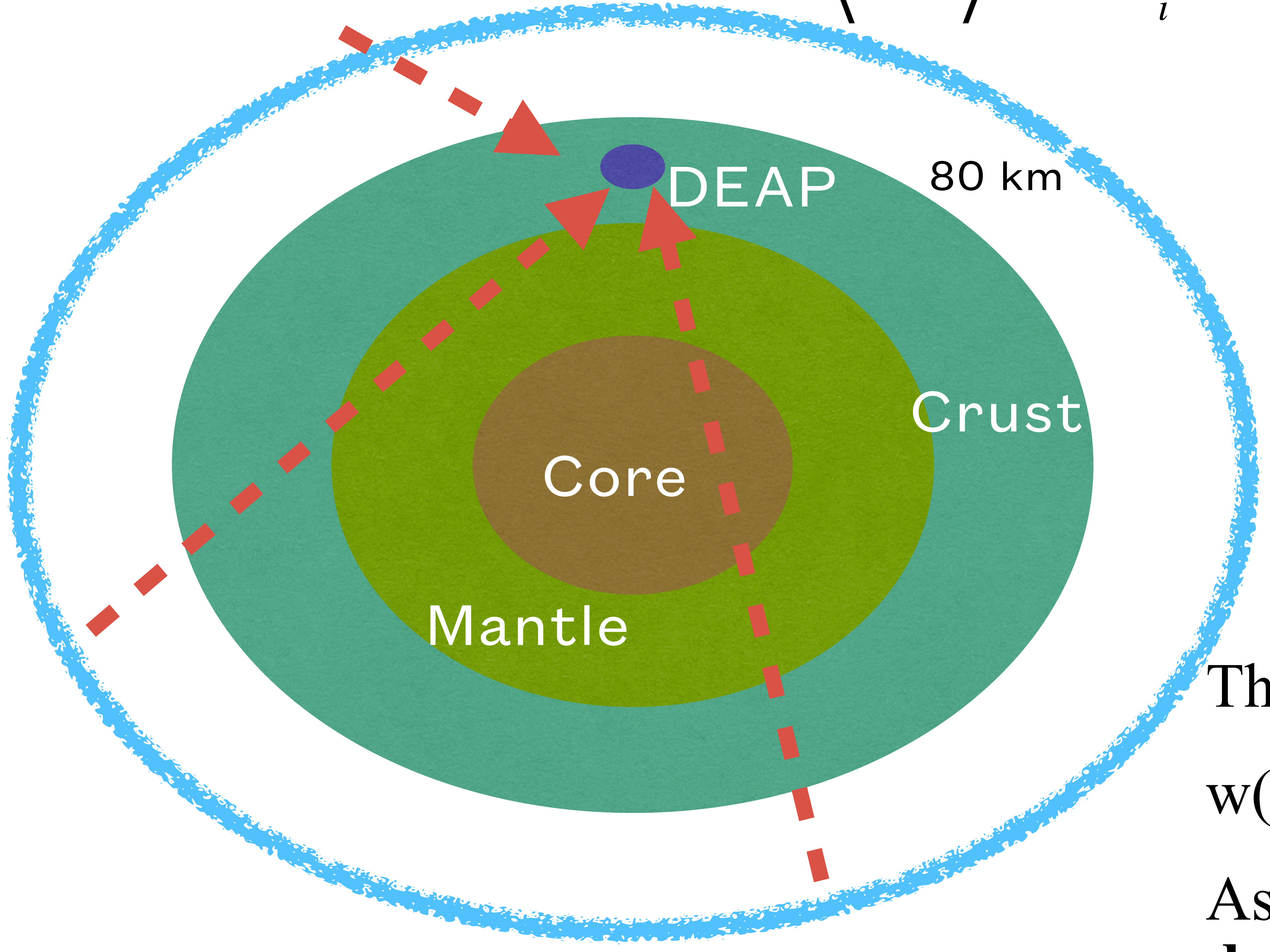
Rejection techniques:

- F_{prompt} upper cut
- Early pulses in Gas Argon PMTs
- Charge fraction in top 2 PMT rings
- Near future: **multivariate analysis** with high efficiency in vetoing neck alphas

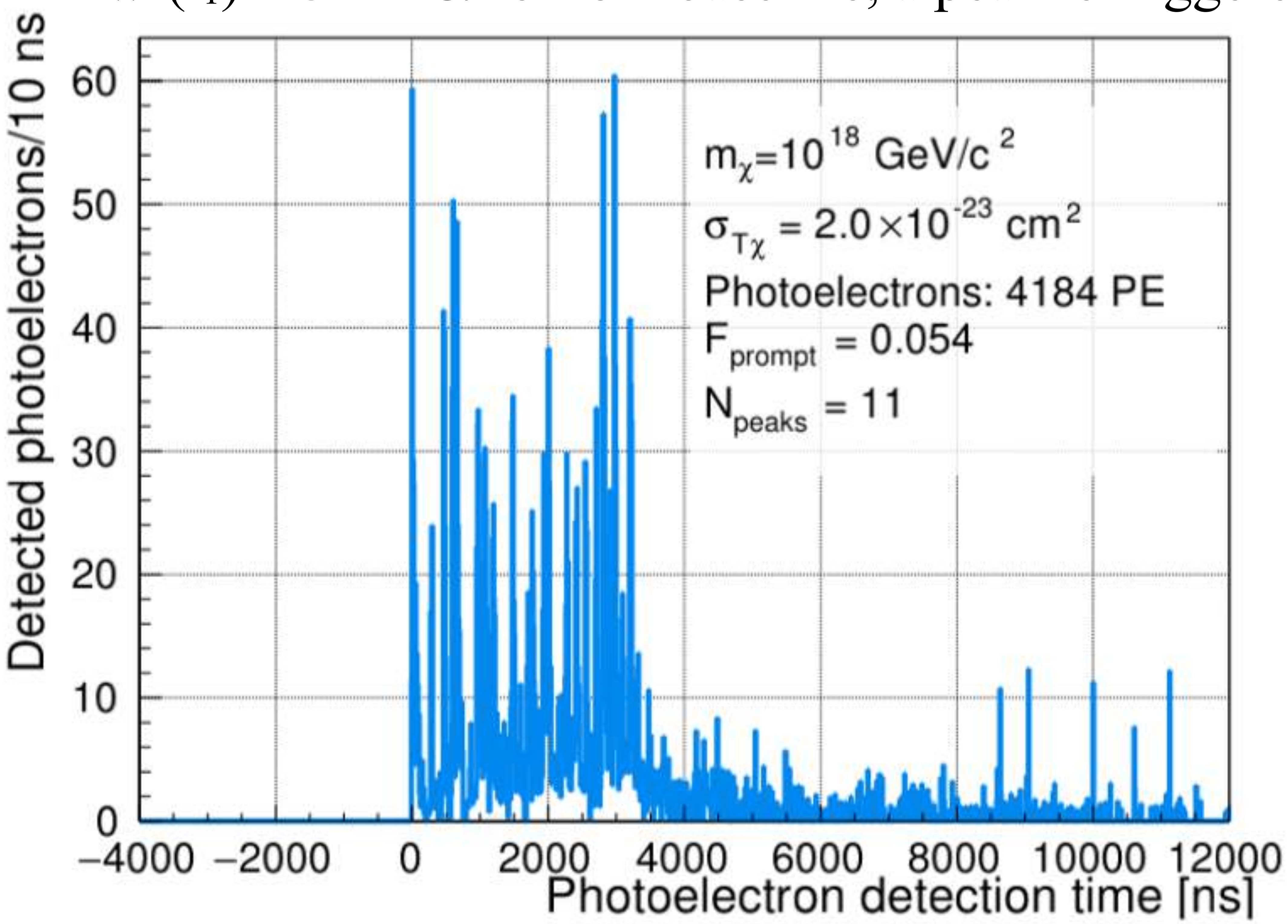
Simulation of the signal

The dark matter particle is generated at 80 km from Earth Surface. It is propagated via Monte Carlo method through the overburden. Then, if it enters the detector, its response to this signal is simulated in **Geant4 .**

$$\left\langle \frac{dE_\chi}{dt} \right\rangle = -\sum_i n_i(r)\sigma_{i,\chi} < E_R >_i v$$



If w'(t_1) > 3 ADC/ns from baseline, a peak is triggered.



The next peak is triggered only if "significant", so if

w(t_3) > 5 ADC + w(t_1)

As the cross-section increases, **the significance of the peaks along the waveform decreases**, bringing to a decrease of N_{peaks}.

Unblinding!

The unblinding was performed for **each single ROI**.

November 4, 2016 - March 8, 2020

Excluded data:

- (3 ± 3)us/trigger for signal falling in two events
- 9 days to test the selection cuts
- 6 days from the muon coincidence sideband

Two low level cuts applied

- < 5 % PE must be in the brightest channel, acceptance of 87 %
- < 5% PE must be in PMTs in gaseous argon, acceptance of 99 %