Dark matter search in DEAP-3600: results and prospects

Dr. Michela Lai
on behalf of
DEAP-3600 Collaboration

UNIVERSITY OF CALIFORNIA LOS ANGELES - DARK MATTER 2023

DEAP Collaboration

UNIVERSITY OF ALBERTA

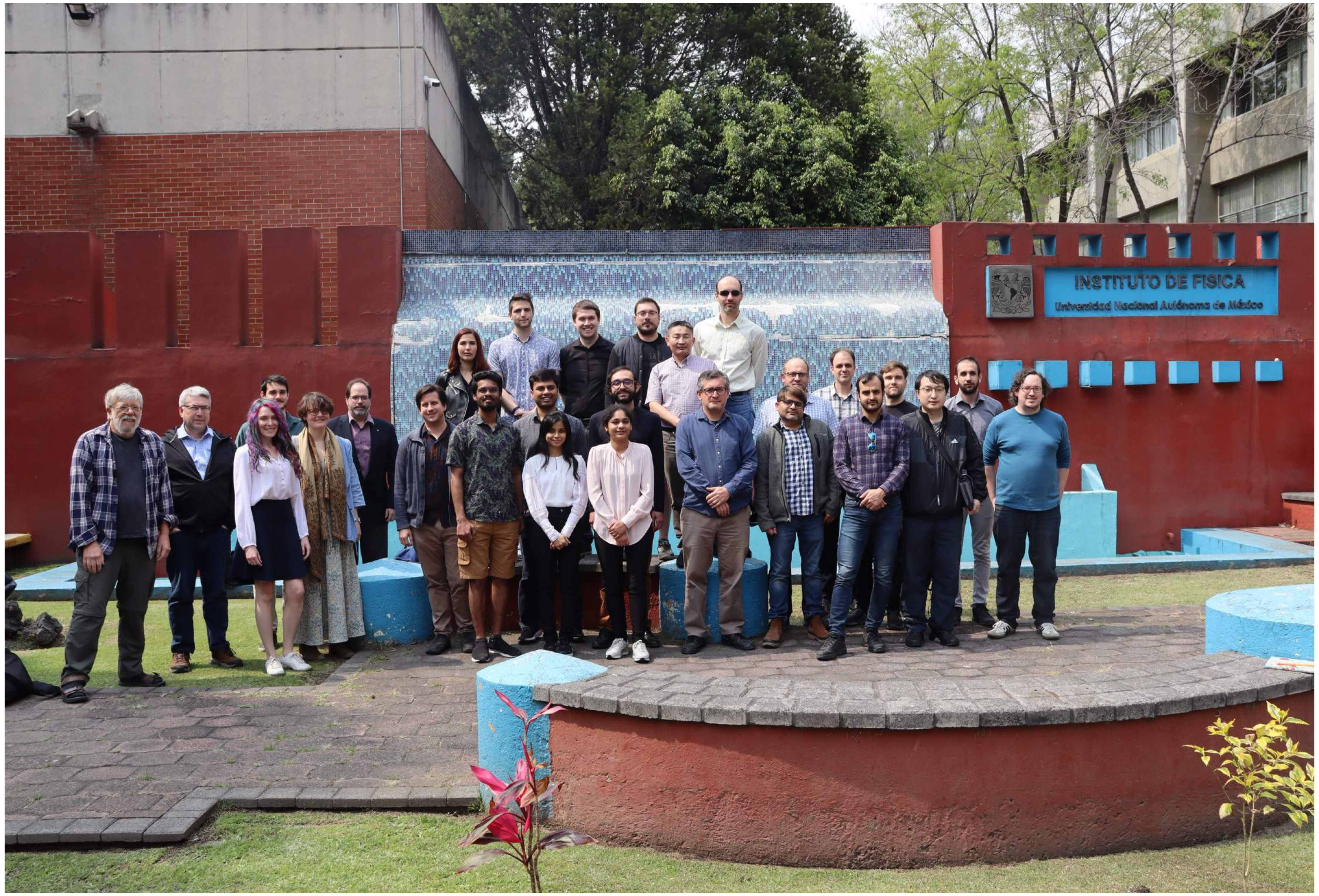
Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

ASTROCENT
Nicolaus Copernicus Astronomical Center
of the Polish Academy of Sciences

Carleton University

INFN
Istituto Nazionale di Fisica Nucleare

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U



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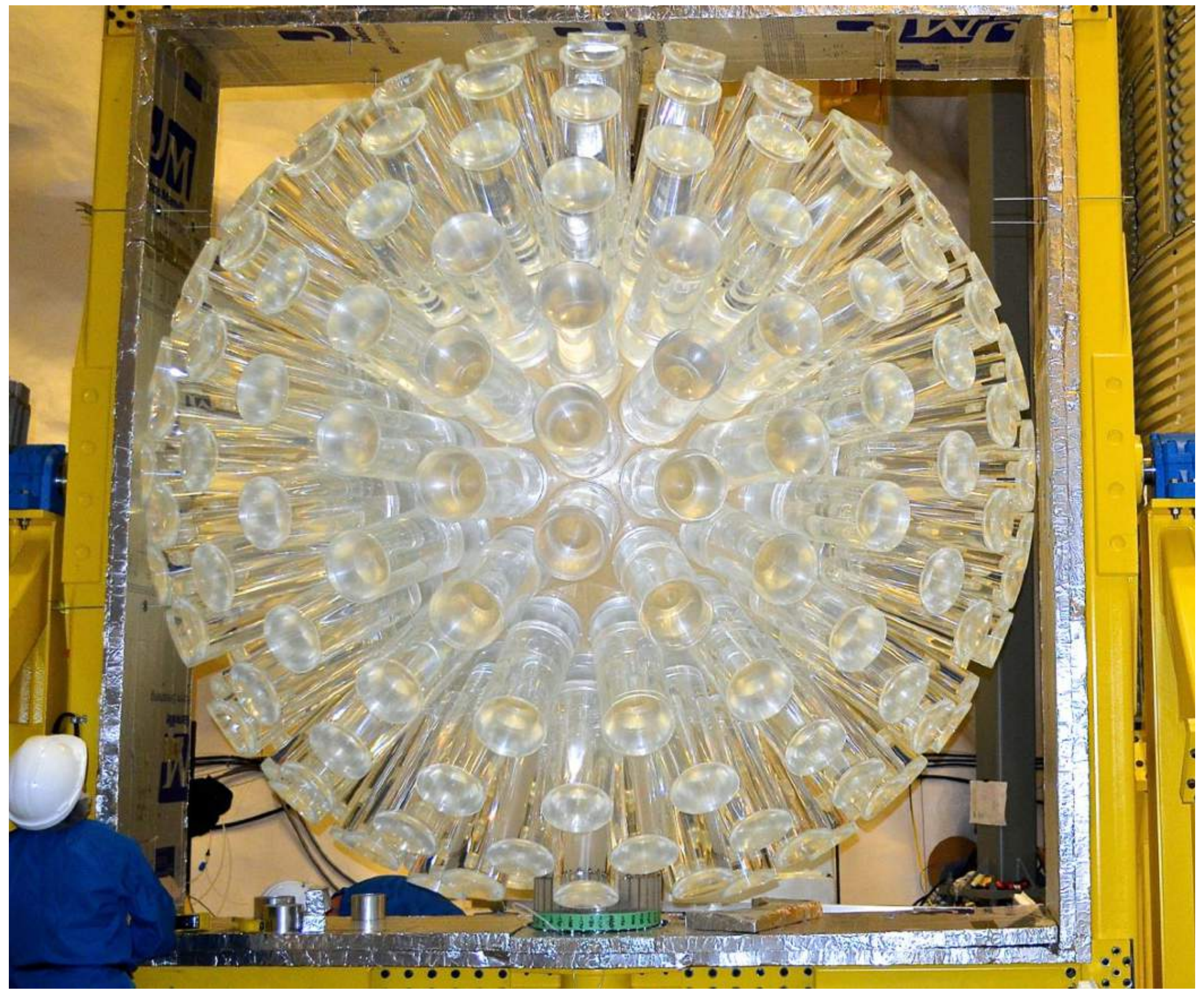
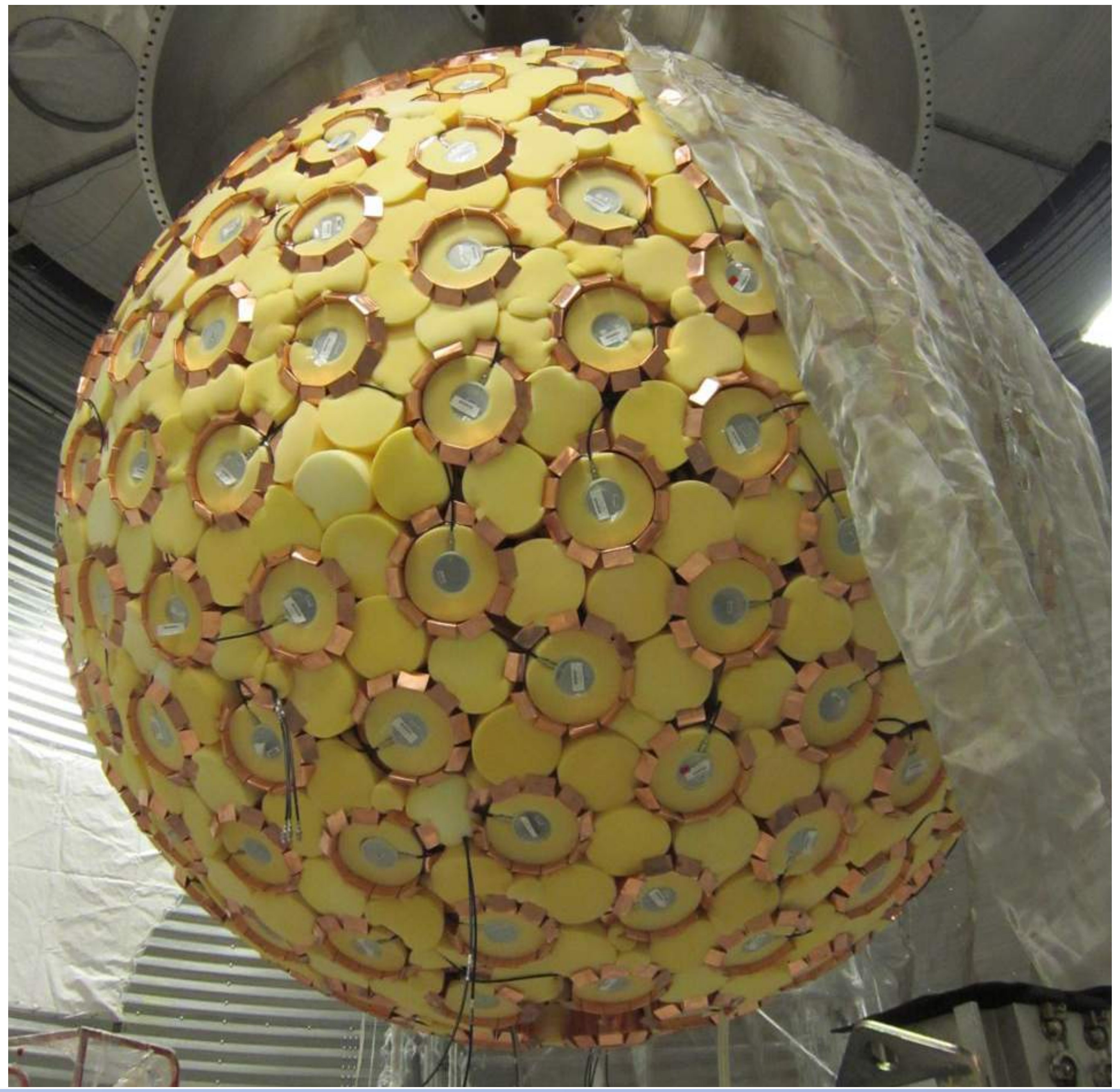
Particle Physics
Rutherford Appleton Laboratory

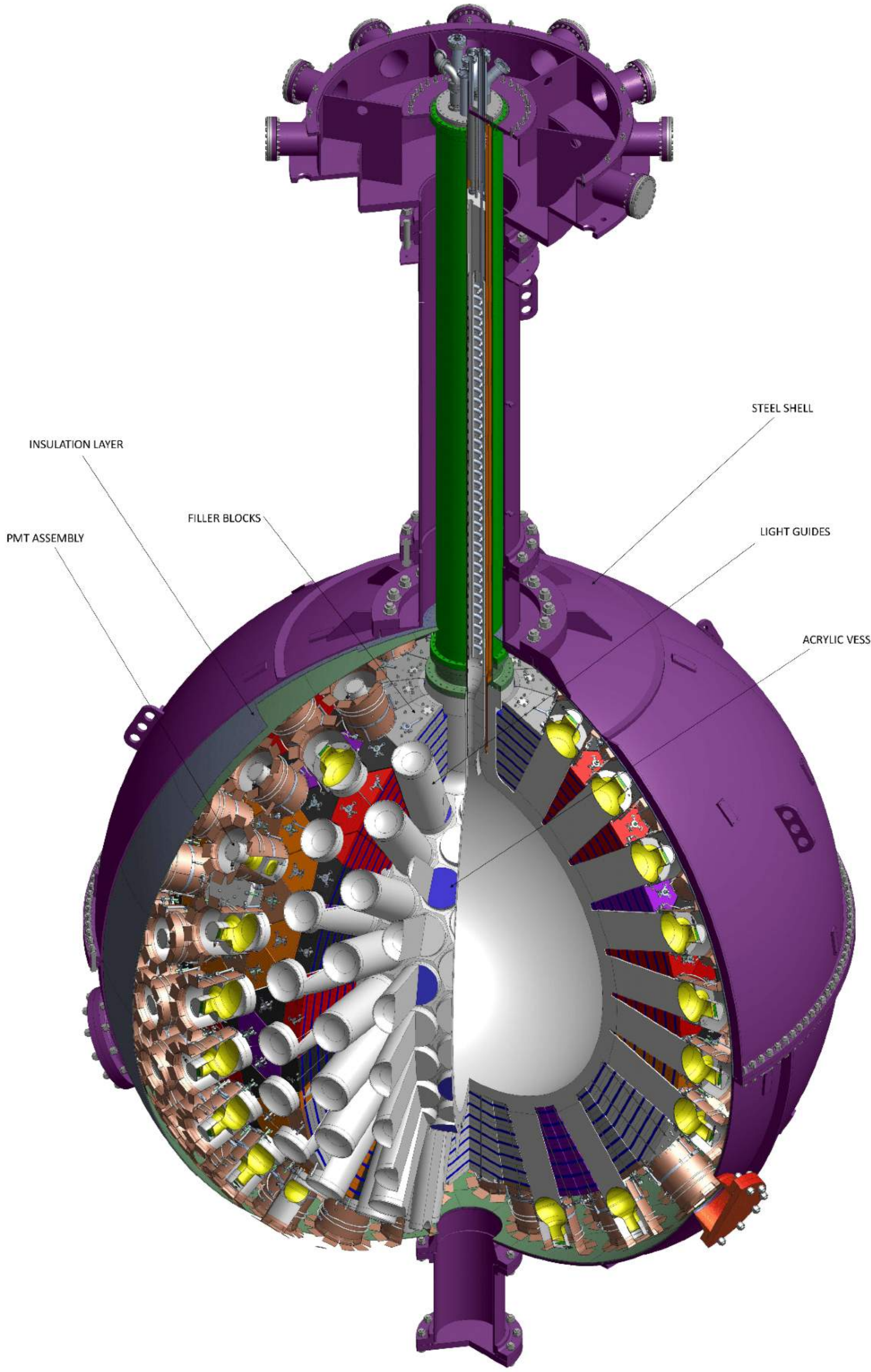
PRINCETON UNIVERSITY

US
University of Sussex

The detector

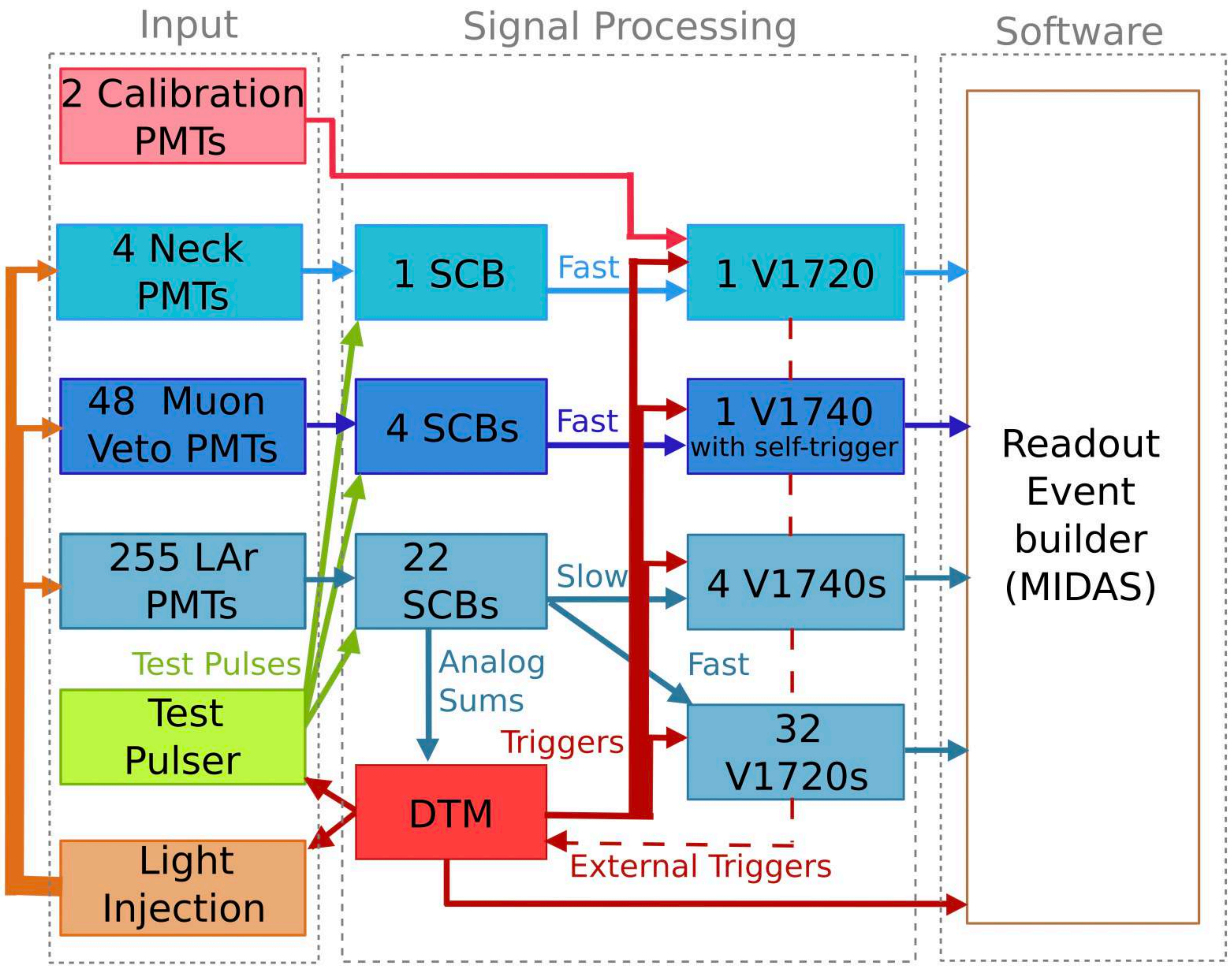






Astroparticle Physics 108 (2019) 1-23

Data Acquisition



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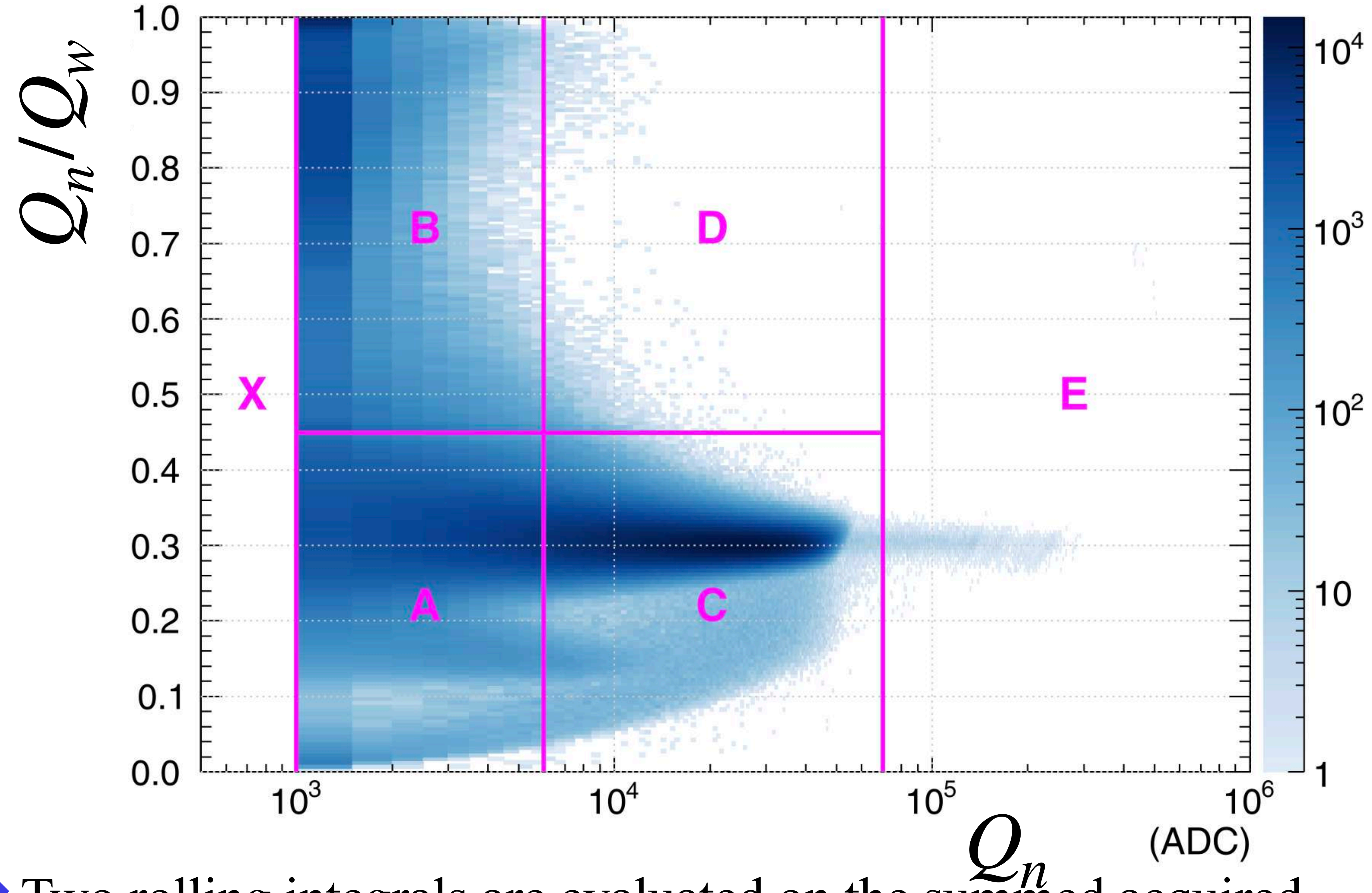


➡ Two rolling integrals are evaluated on the summed acquired and digitized waveform

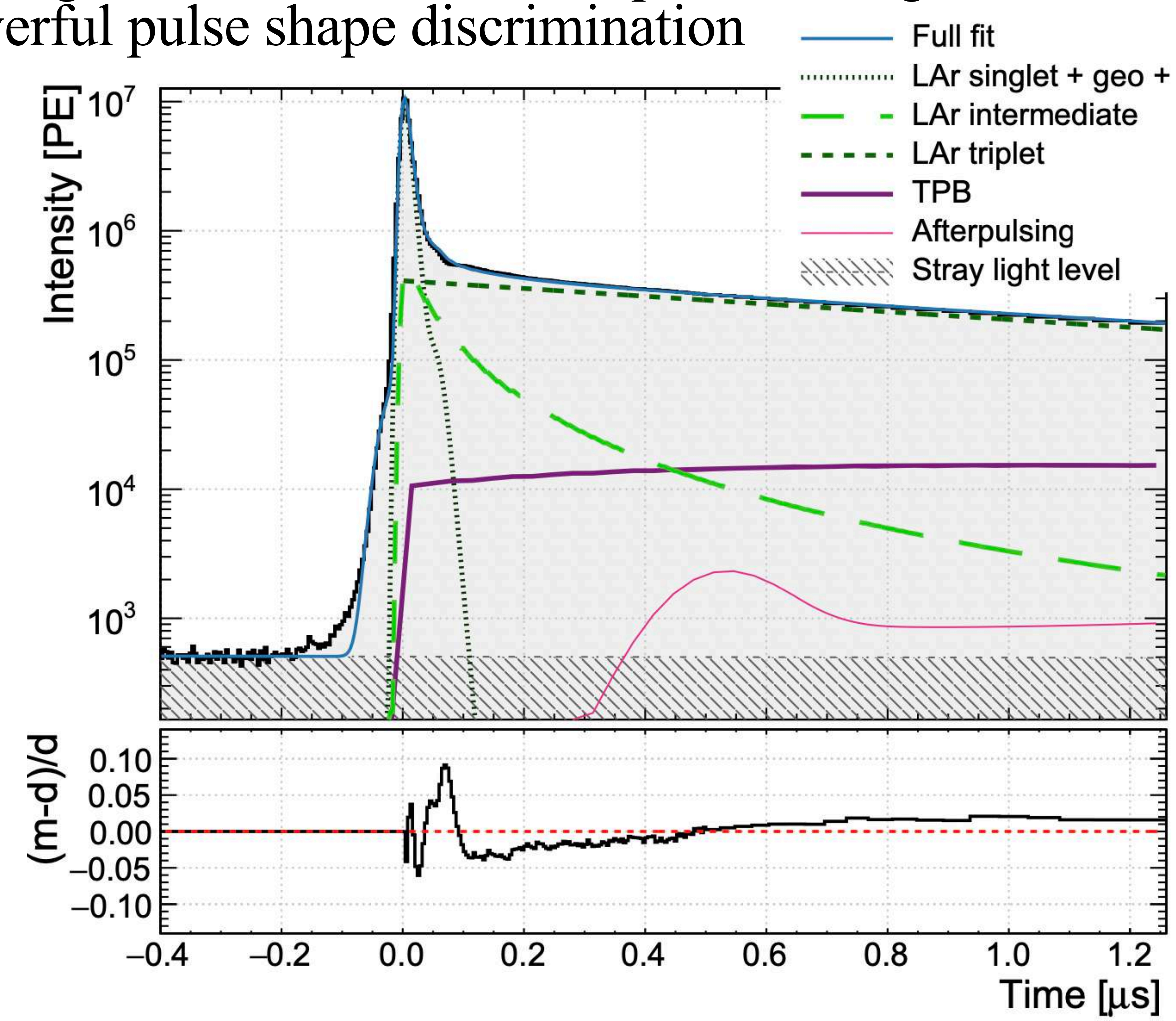
➡ Events in the region X are discarded

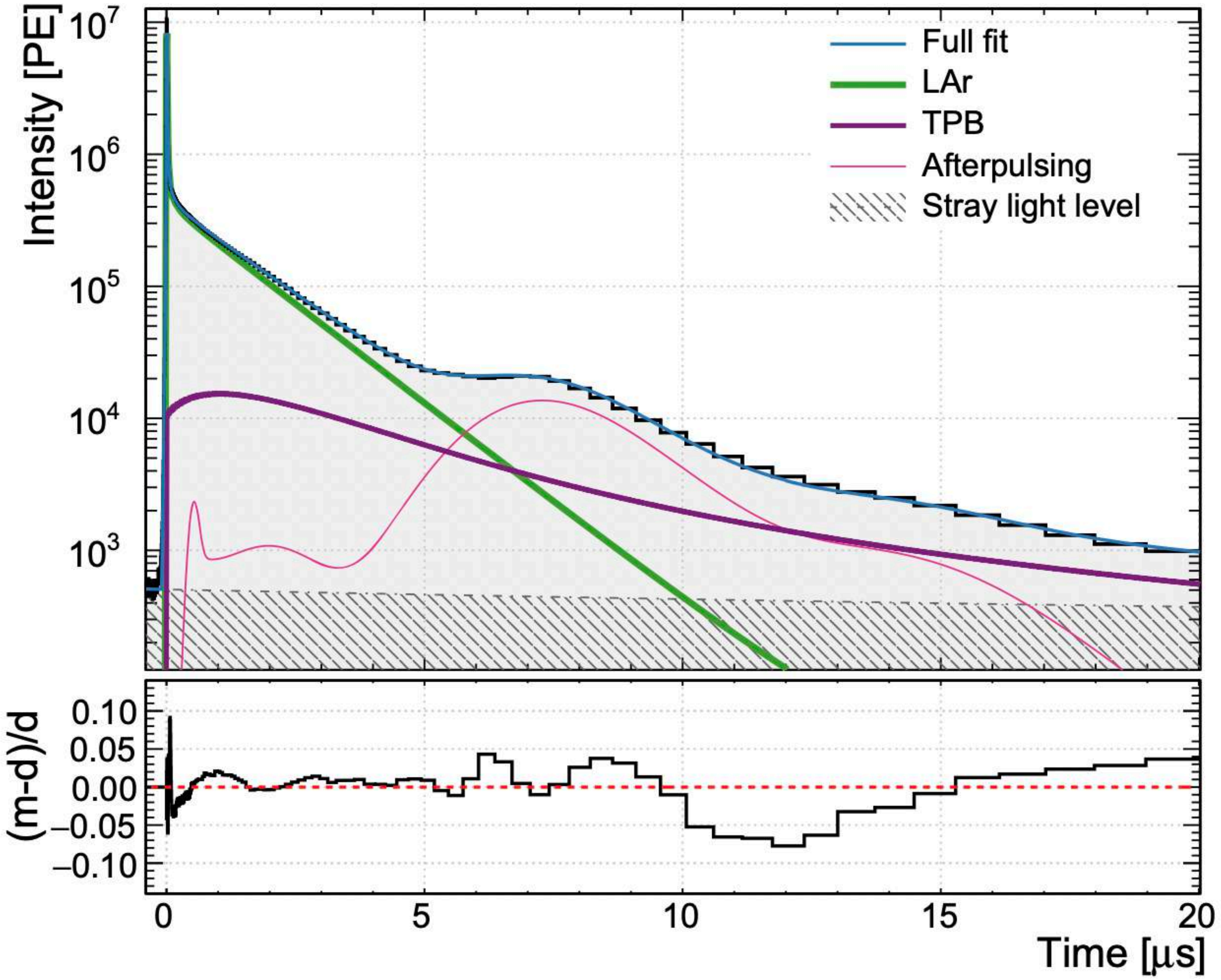
➡ Events in the region C are "prescaled" by the physics trigger, so only 1 events over 100 are stored, to reduce triggers from ^{39}Ar decays

$$Q_n = \int_0^{177ns} w(t)dt \qquad Q_w = \int_0^{3100ns} w(t)dt$$

Dark matter Experiment using Argon
Pulse-shape discrimination

- ➡ Modeled scintillation pulse shape due to ^{39}Ar β decays, convoluted with the detector response
- ➡ Included the LAr intermediate component and delayed TPB emission.
- ➡ The high difference between triplet and singlet state determines a powerful pulse shape discrimination





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

$\tau_t = 1445ns$

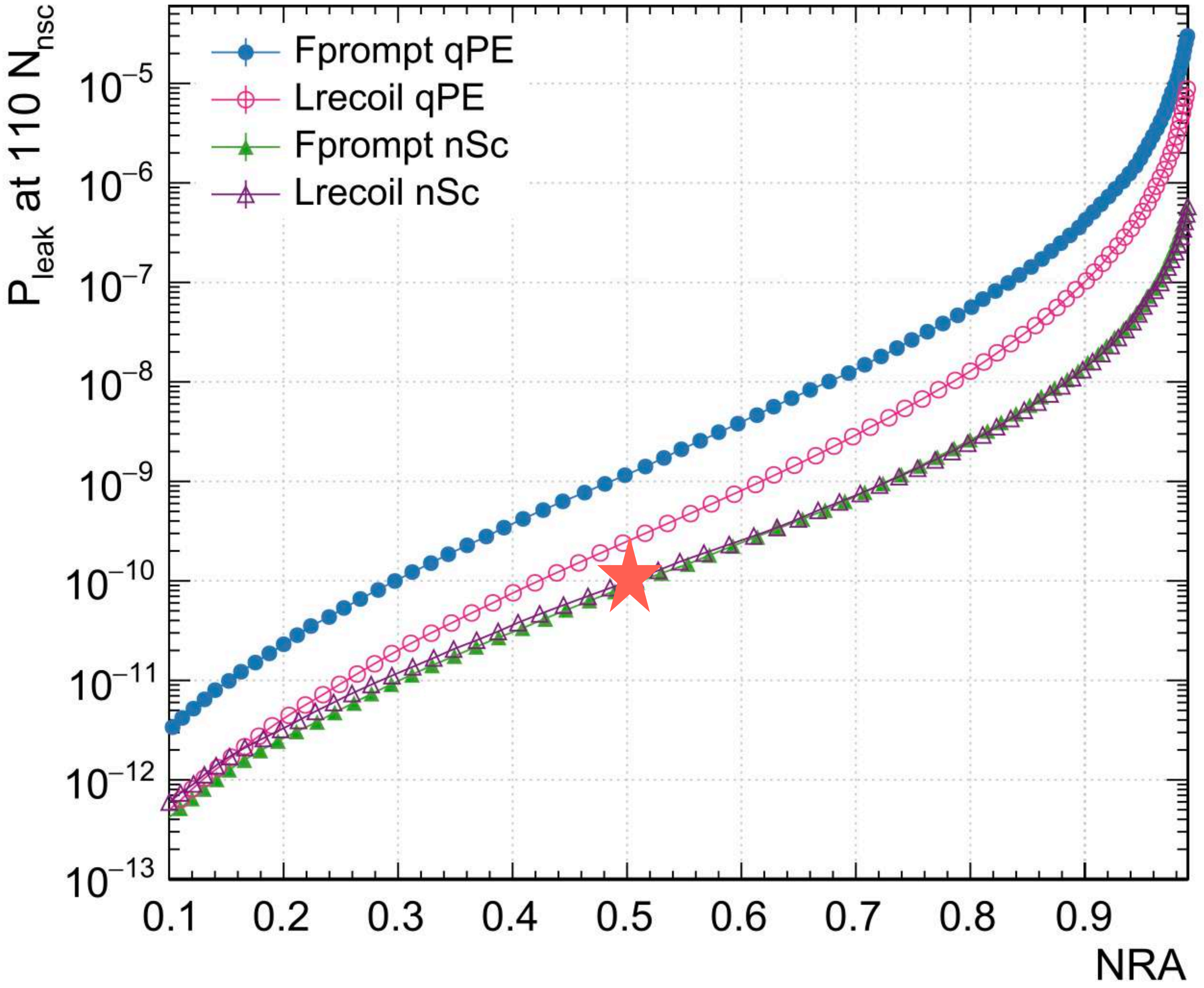
$\tau_s = 8.2ns$

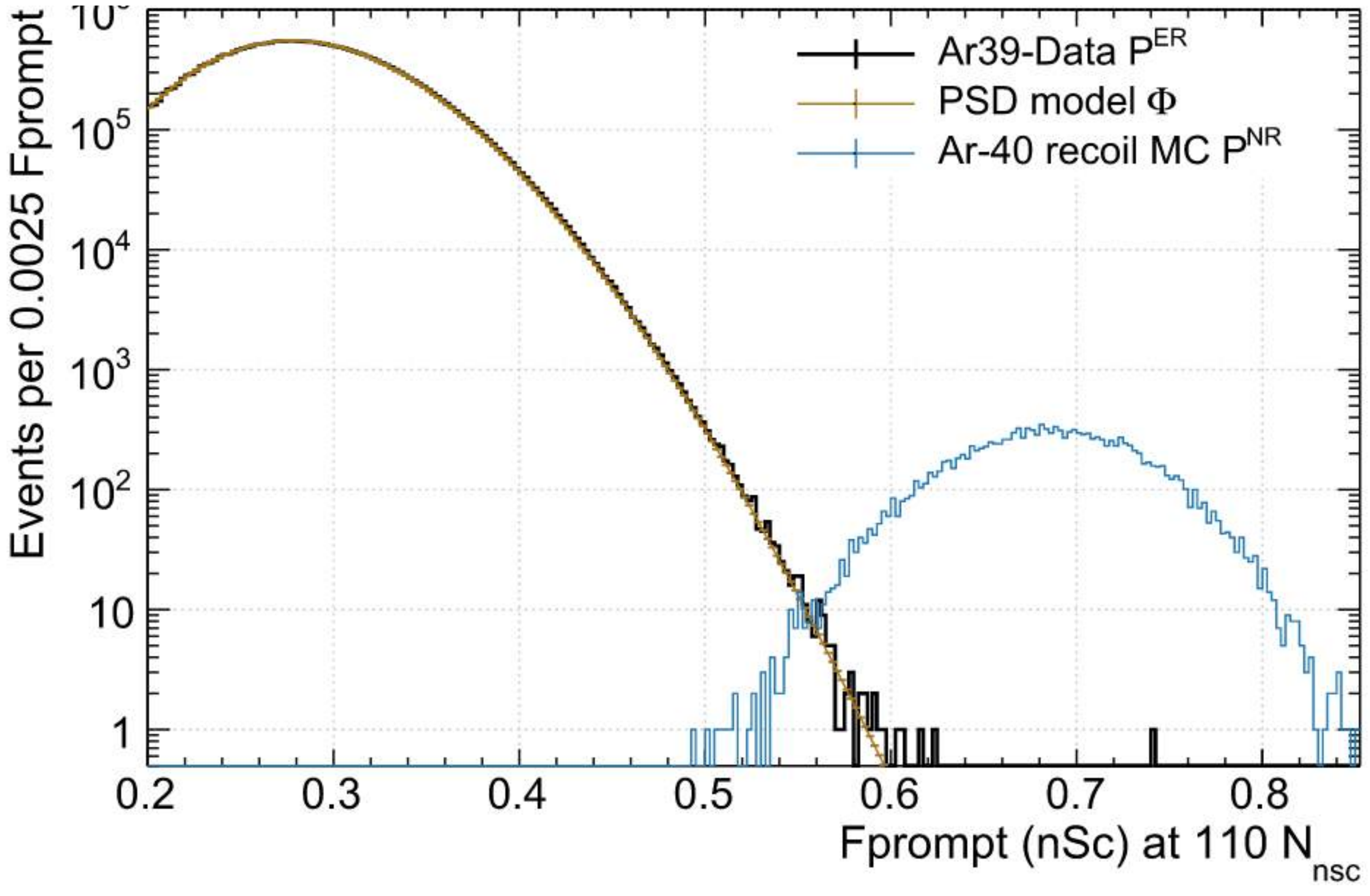
$\tau_{rec} = 175.5ns$

$R_t = 0.71$

$R_s = 0.23$

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





➡ Comparison in terms of the leakage probability performed between four different Pulse Shape Discriminators (PSD) estimators

Charge definitions

$$q_{PE} = \frac{Q}{Q_{SPE}}$$

$$P(n_{Sc} + n_{AP} = n_{PE}|Q) = \frac{p(Q|n_{PE})\,p(n_{Sc})\,p(n_{AP})}{p(Q)}$$

PSD algorithms

$$F_{prompt} = \frac{\int_{-28ns}^{150ns} PE(t)dt}{\int_{-28ns}^{1.6\mu s} PE(t)dt}$$

$$L_{recoil} = \frac{1}{2}\cdot\left(1 + \frac{\sum_{t>t_{start}}^{t<t_{total}} w(t)n(t)}{\sum_{t>t_{start}}^{t<t_{total}} n(t)}\right) \qquad w(t) = \log\frac{p(t)_{nr}}{p(t)_{er}}$$

➡ At about 18 keV_{ee} and a nuclear recoil acceptance of 50 % a **leakage probability** of about **10^{-10}** is reached with the nSc-based algorithm

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

^{39}Ar specific activity measurement

ArXiv: 2302.14639

➡Most precise measurement of the specific activity of atmospheric ^{39}Ar up to date

$$S_{^{39}Ar} = \frac{N_{single} + N_{pile-up}}{m_{LAr} T_{livetime}}$$

$$N_{pile-up} = N_{double} + N_{triple} + N_{ERB,39Ar} + N_{hFp,39Ar}$$

➡Updated value for the liquid argon mass

First

$$m_{LAr} = (3269 \pm 96)kg$$

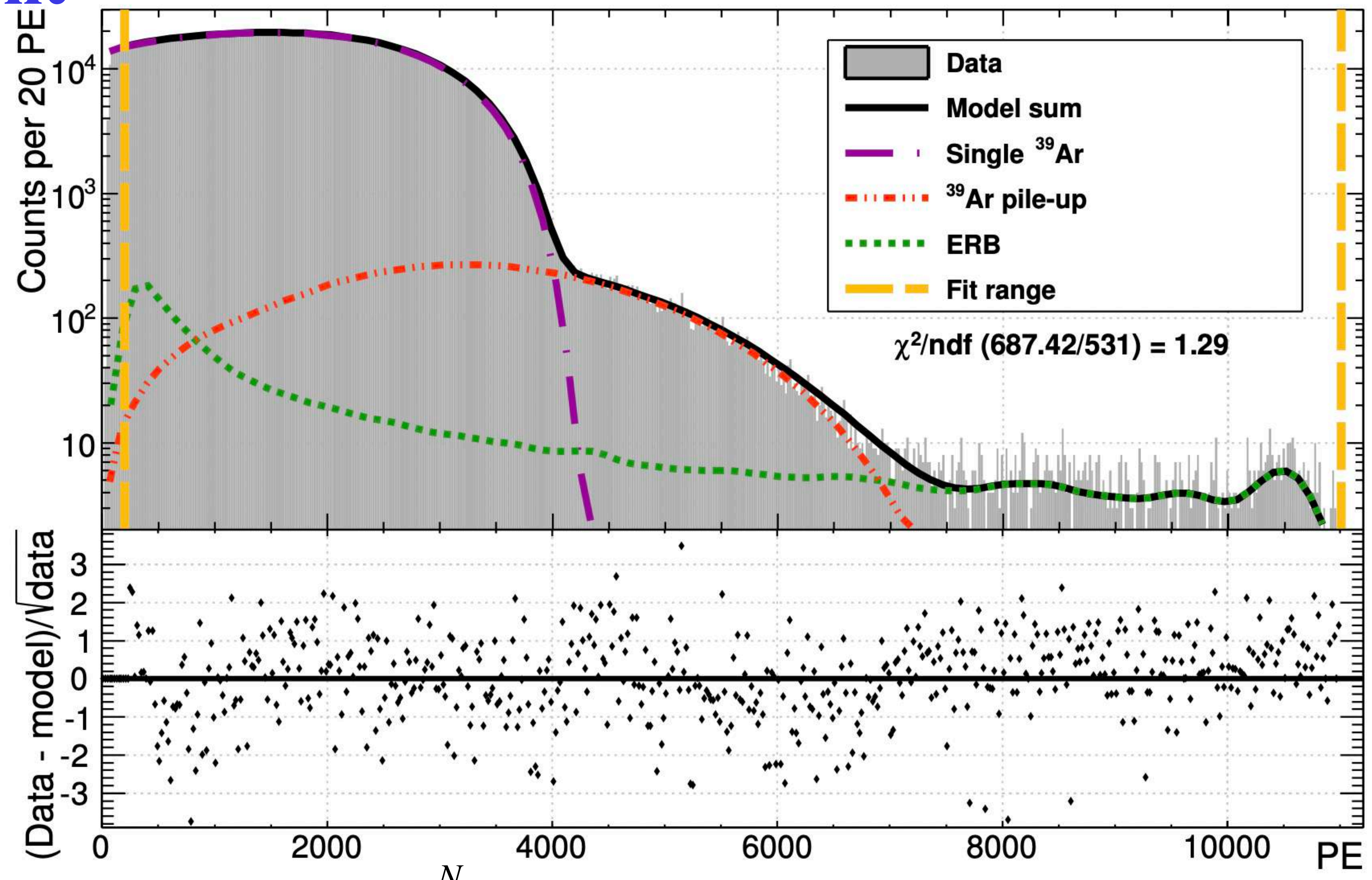
This work!

$$m_{LAr} = (3269 \pm 24)kg$$

➡Energy dependent detector resolution applied according to a Gaussian,

$$PE = p_0 + p_1 \cdot E + p_2 \cdot E^2$$

$$\sigma(PE) = \sqrt{p_3 \cdot PE + p_4 \cdot PE^2}$$



$$T_{livetime} = T_{run} - \sum_{i=1}^{N_{DCcut}} \delta t_i - N_{LLcut} \cdot \delta t_{cut} - N_{phys} \cdot (\delta t_{cut} - \delta t_{int})$$

$$\delta t_{cut} = 32\mu s \qquad \delta t_i \leq 32\mu s \qquad \delta t_{int} = 10\mu s$$

➡Analysis performed on $T_{livetime} = 167$ days

^{39}Ar specific activity measurement

➡Both Bayesian and Frequentist fit performed

➡Modeled the low F_{prompt} energy spectrum with the ^{39}Ar single and double pile-up events as well as the other electron recoil background sources

$$N_{single} = \frac{n_{fit,single} \cdot a_{presc}}{\epsilon_{fit,single} \cdot b} \qquad N_{double} = \frac{n_{fit,double} \cdot a_{presc}}{\epsilon_{fit,double} \cdot b}$$

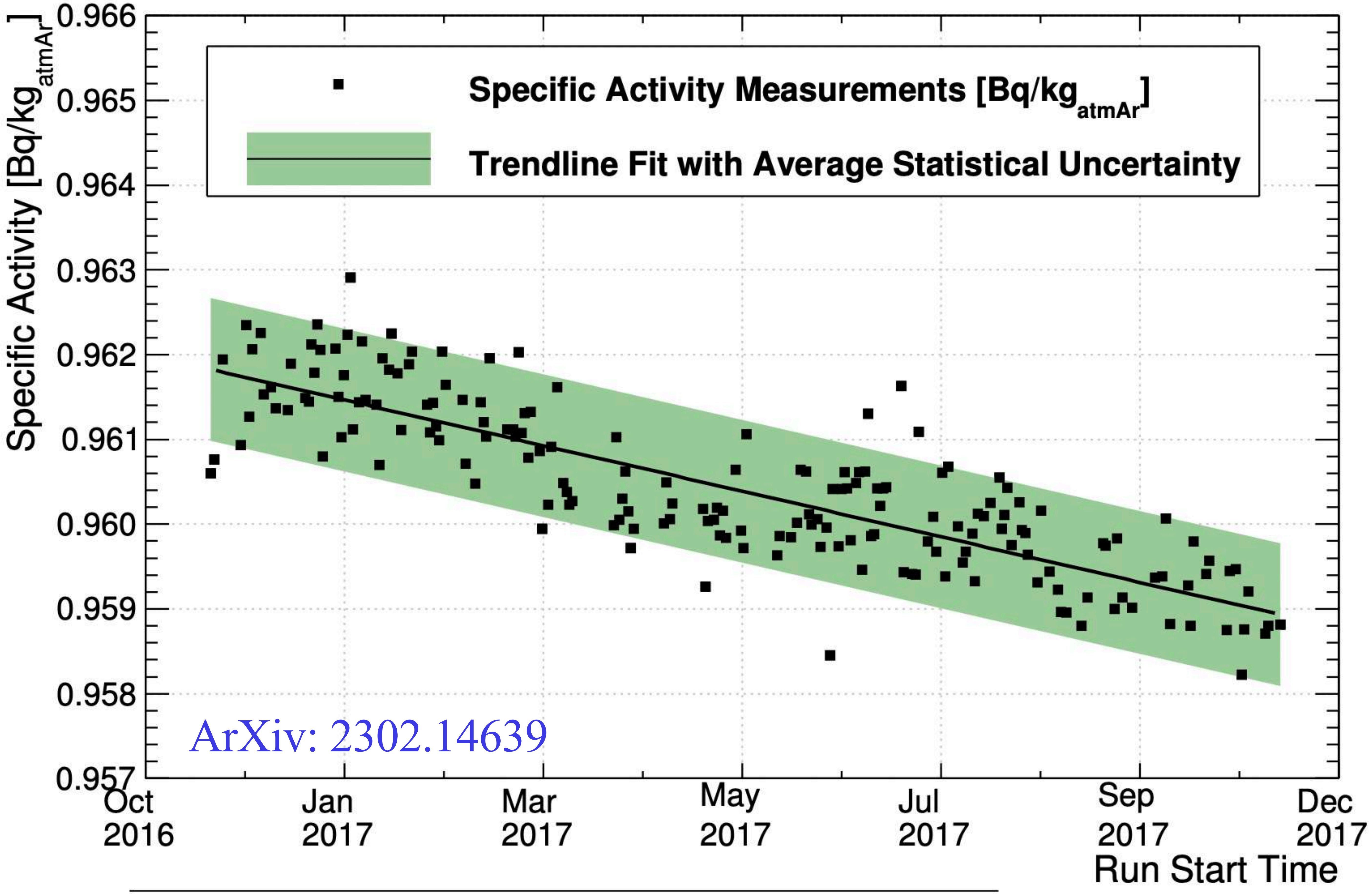
$a_{presc} = 100$ ➡Prescaling from DTM

$b = 20$ ➡Bin Width

$\epsilon_{fit,single}, \epsilon_{fit,double} =$ ➡Selection cut efficiencies

➡Other pile-up contribution evaluated assuming Poissonian statistics

$$S_{^{39}Ar} = (0.964 \pm 0.001(stat) \pm 0.024(syst))Bq/kg_{Ar}$$

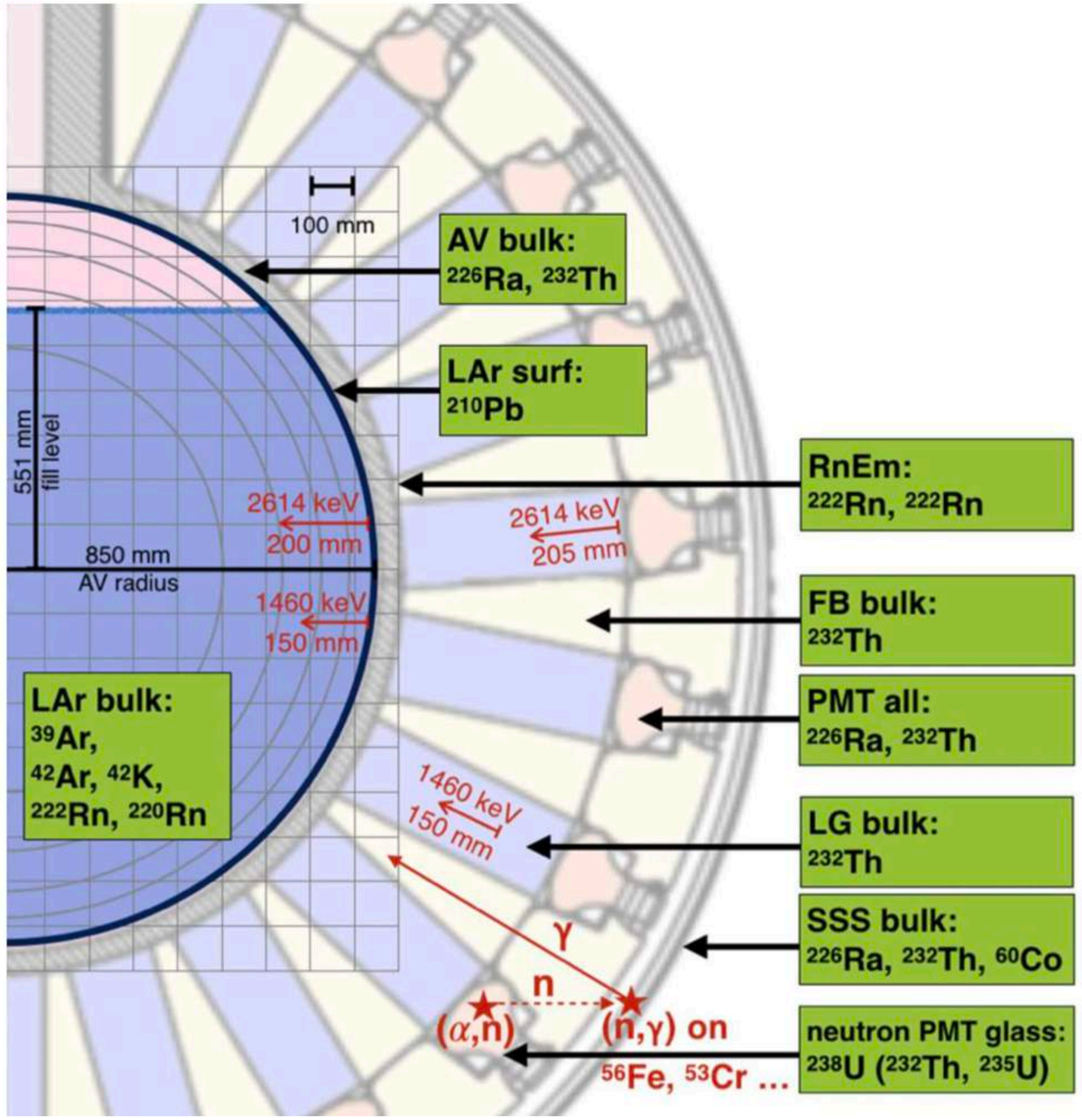


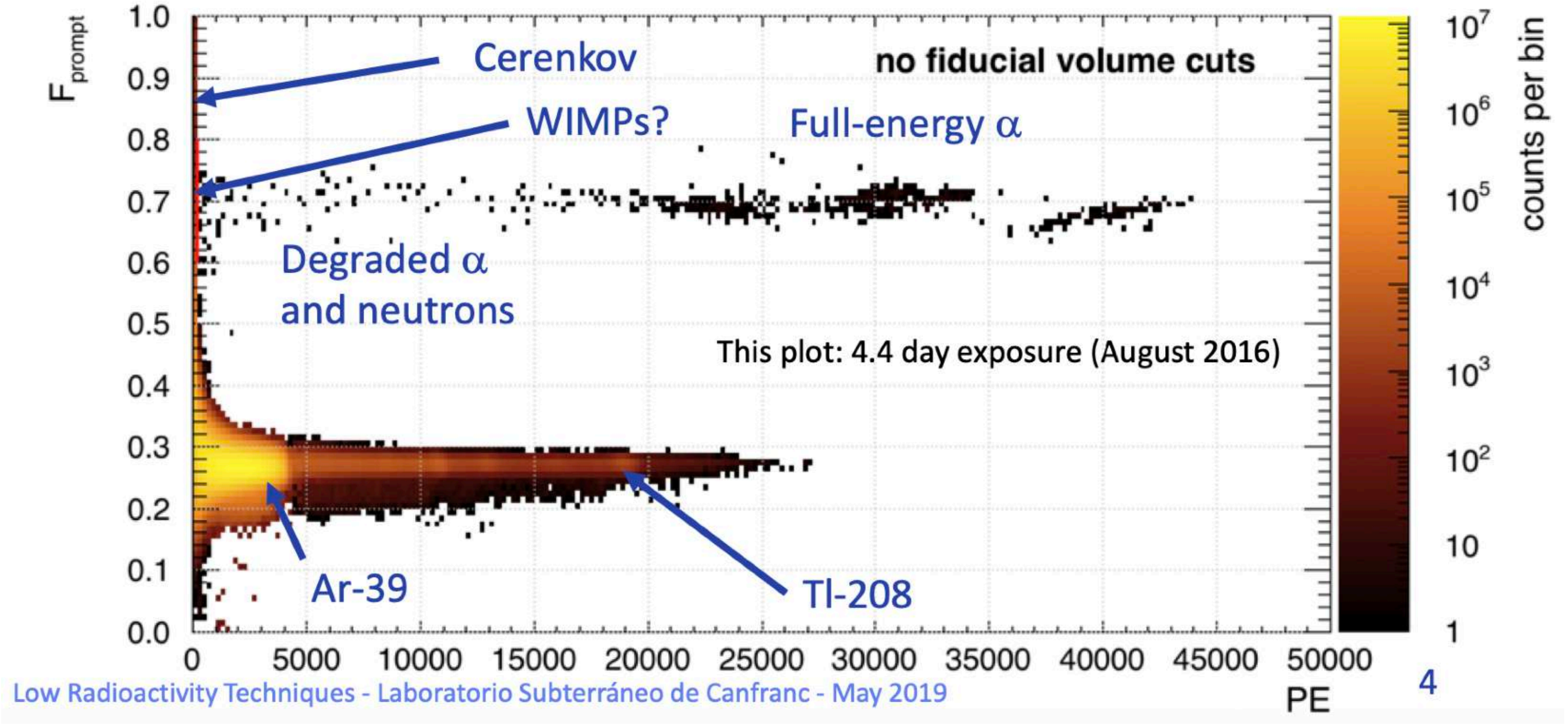
Measurement	Specific activity [Bq/kg_{atmAr}]
WARP [13]	1.01 ± 0.08
ArDM [14]	0.95 ± 0.05
DEAP-3600 (this work)	0.964 ± 0.024

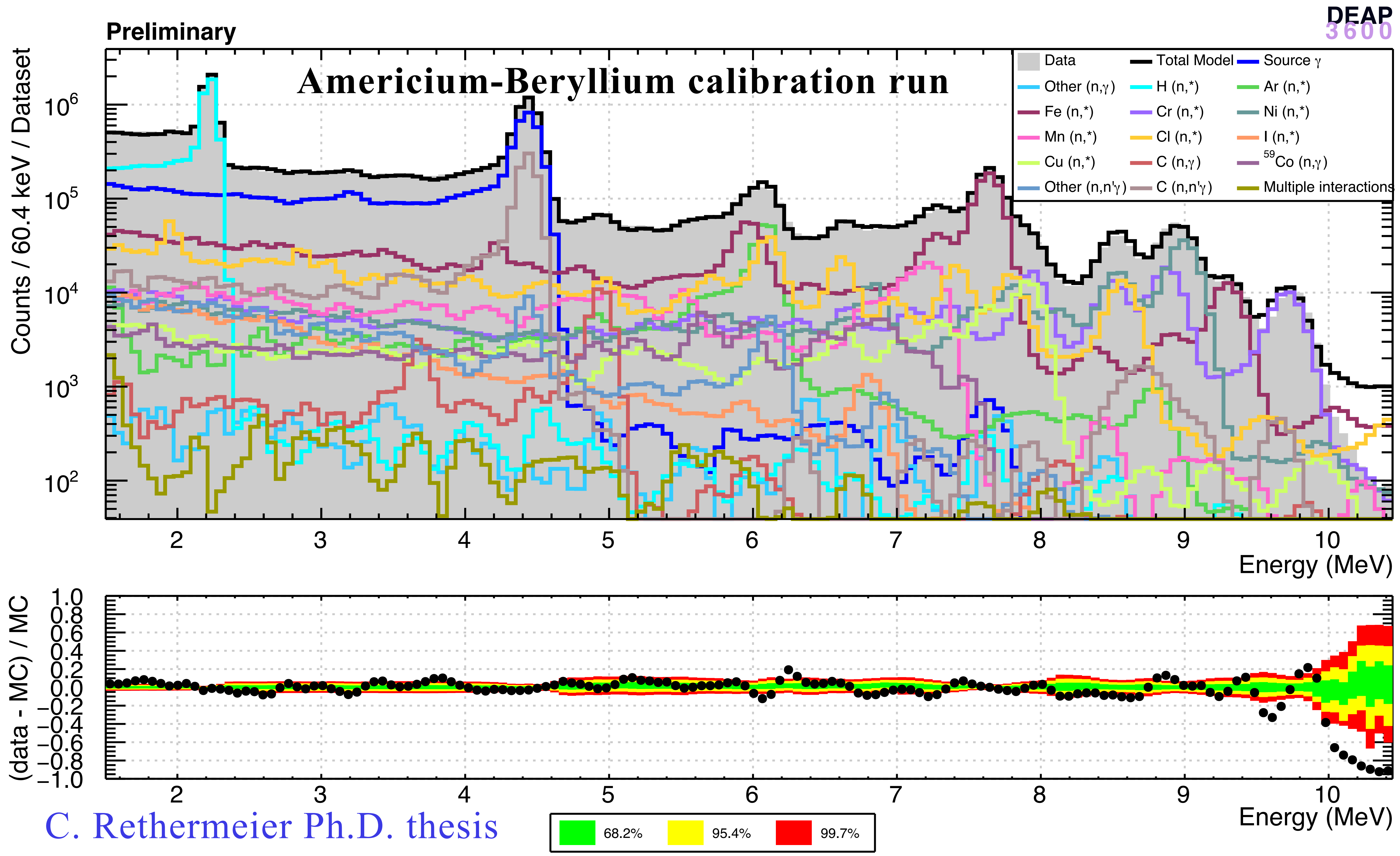
Backgrounds

- ➡ 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)



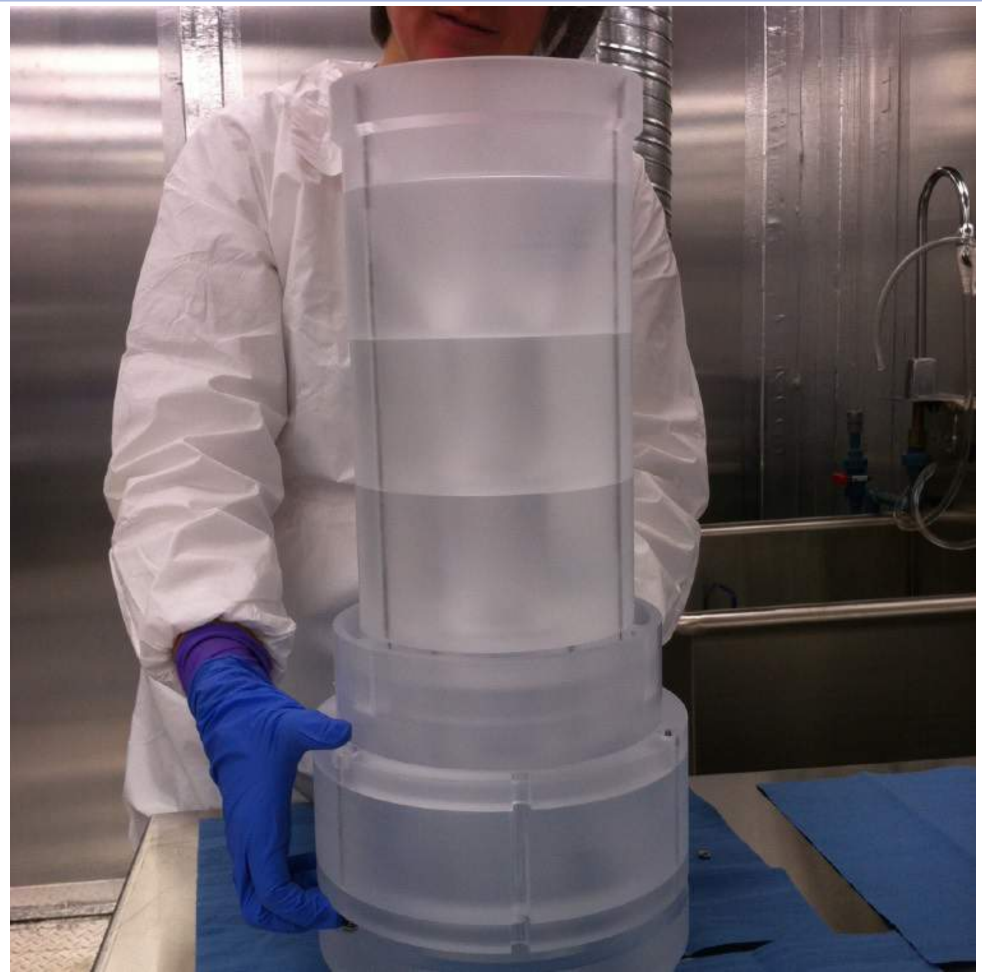


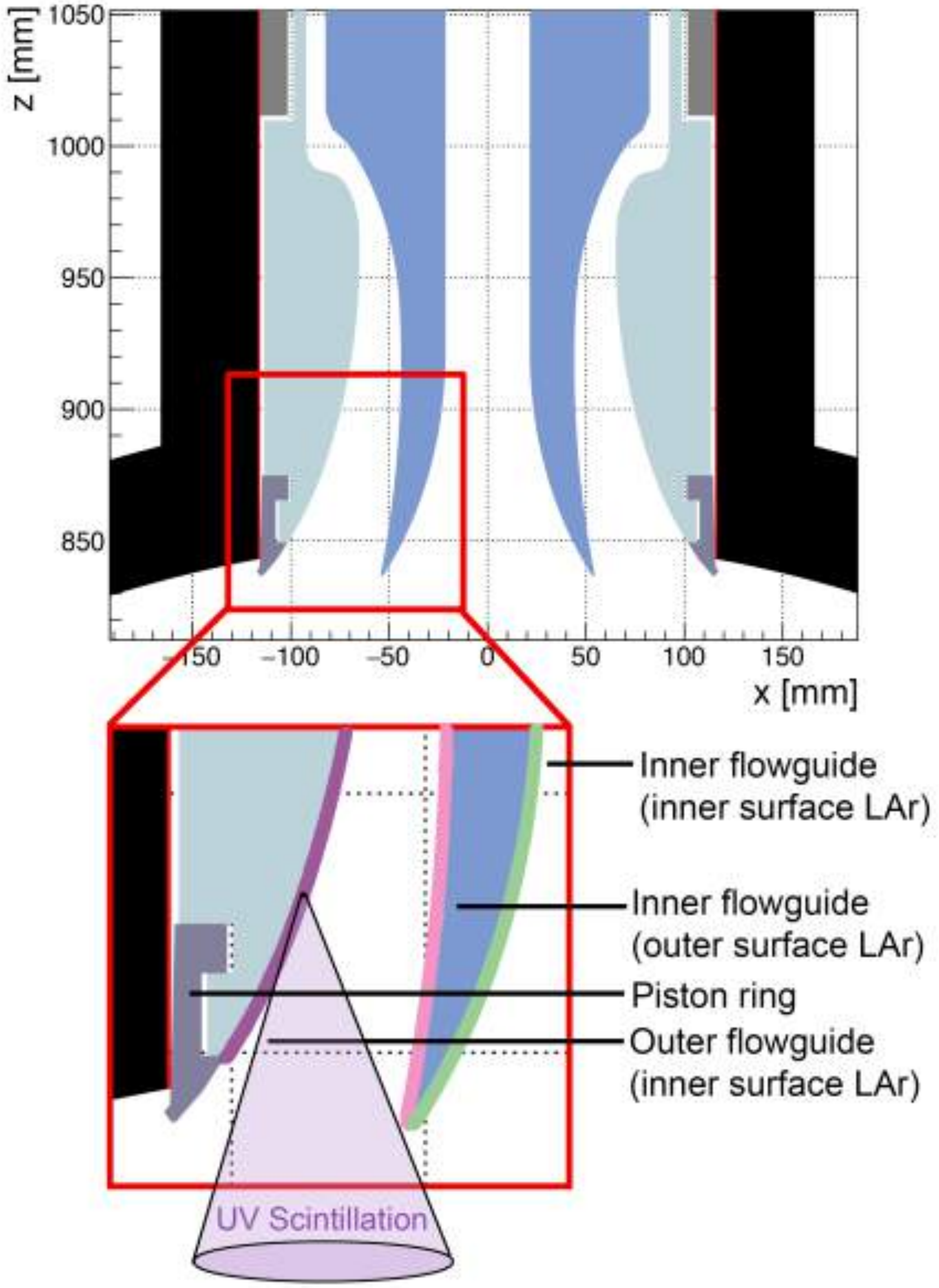


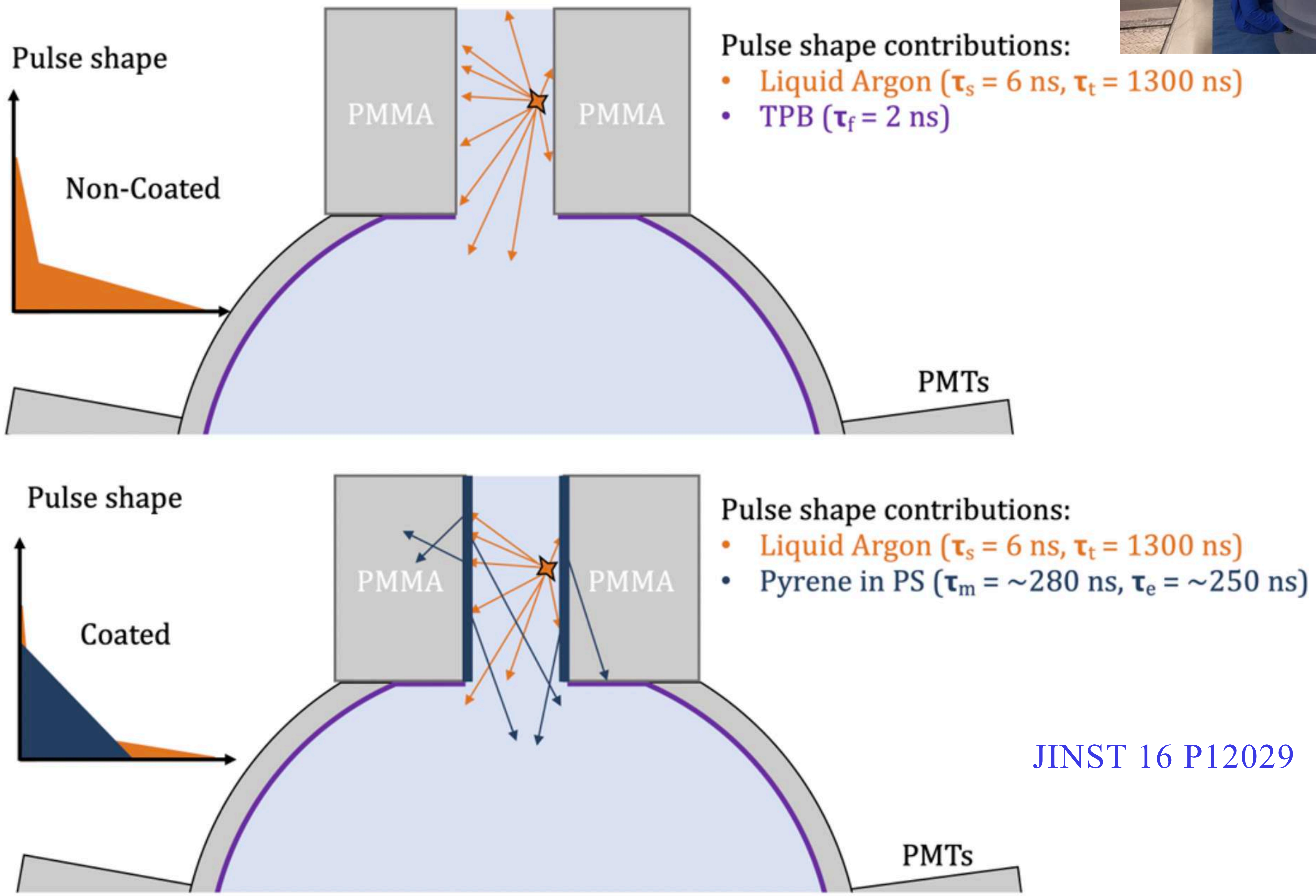
C. Rethermeier Ph.D. thesis

Hardware upgrades: pyrene coating

- Scintillation in condensed argon induced by alphas from ^{210}Po can be rejected thanks to new pyrene-coated flow guides
- Installation of external cooling system, to prevent argon condensation on flow guides



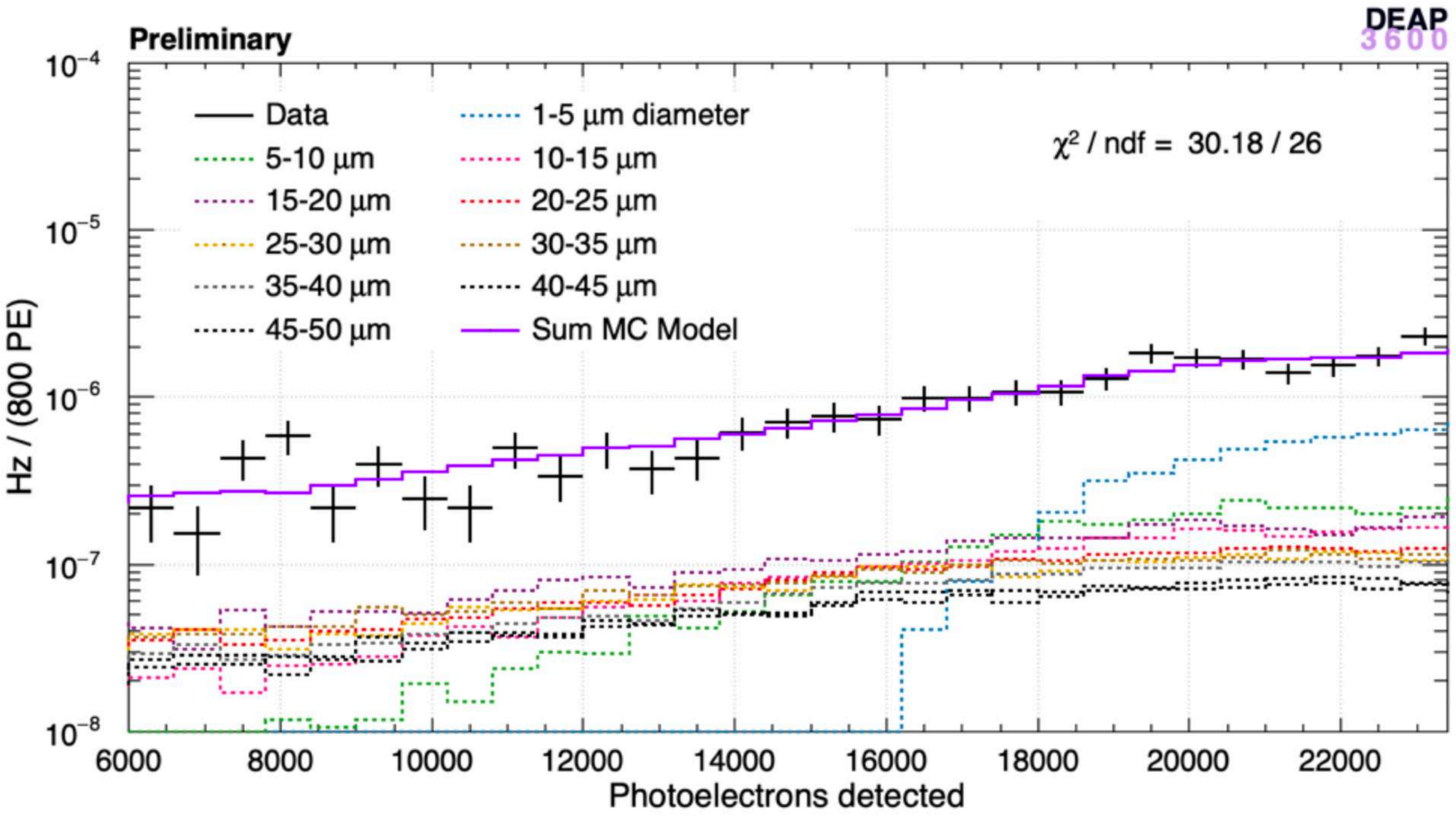


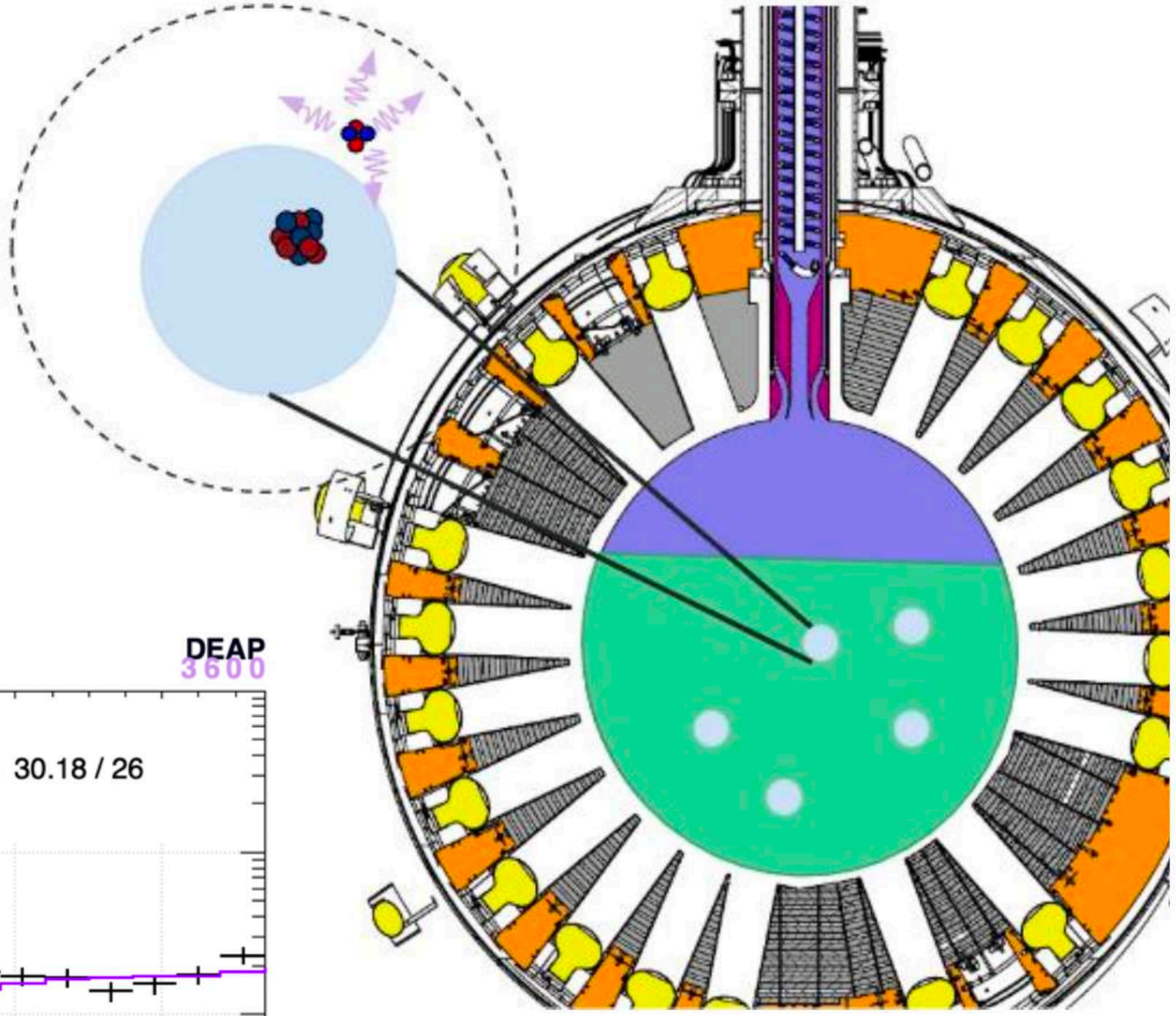


JINST 16 P12029

Hardware upgrades: pyrene coating

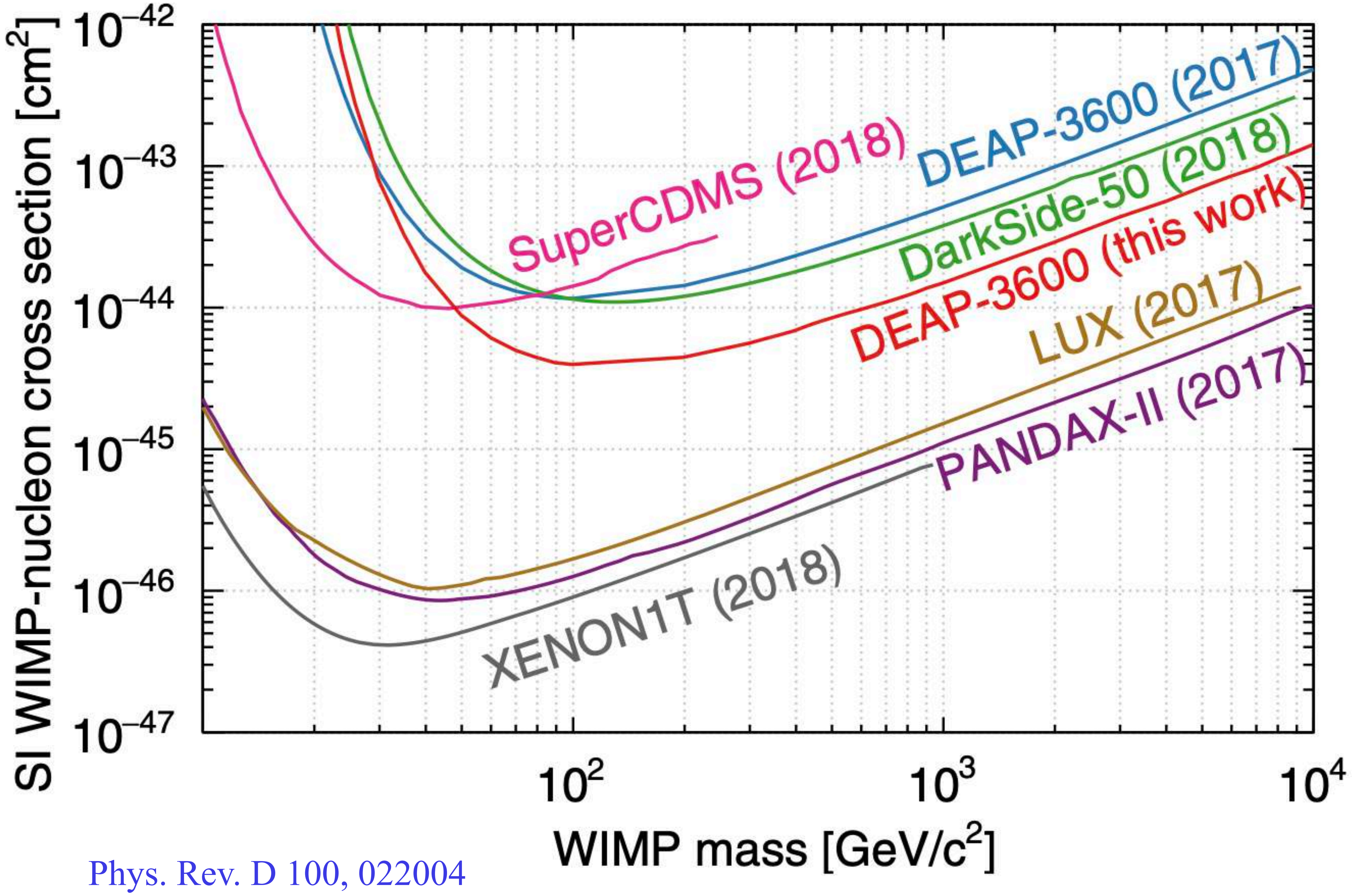
- ➡ Additional Alpha decays background consistent with metallic dust particulates ranging from 1 um - 50 um in diameter
- ➡ Could have entered the inner vessel during the purging with LN_2, after the resurfacing of the inner surface
- ➡ Reduction of dust background by **extraction and filtration of LAr**



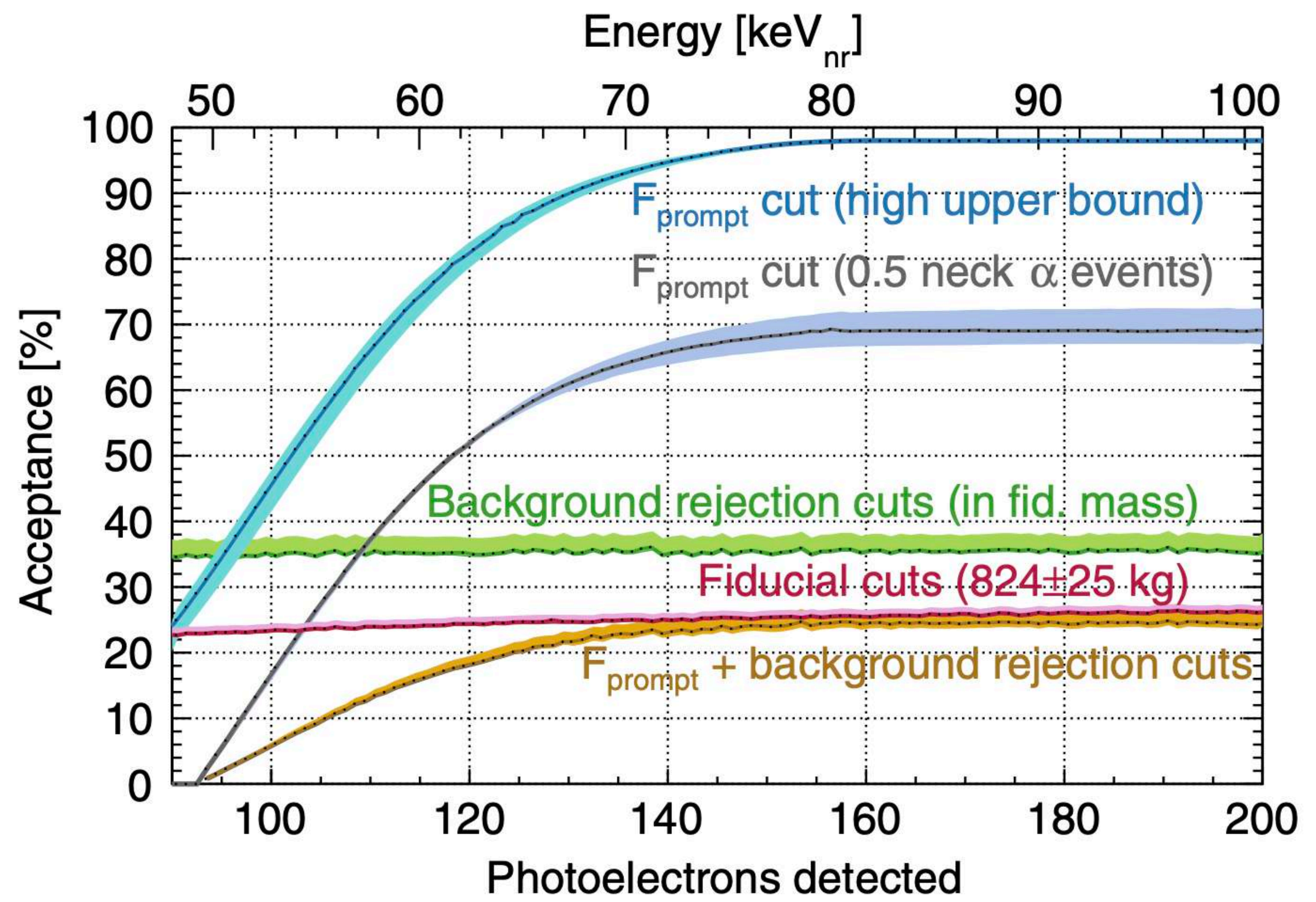


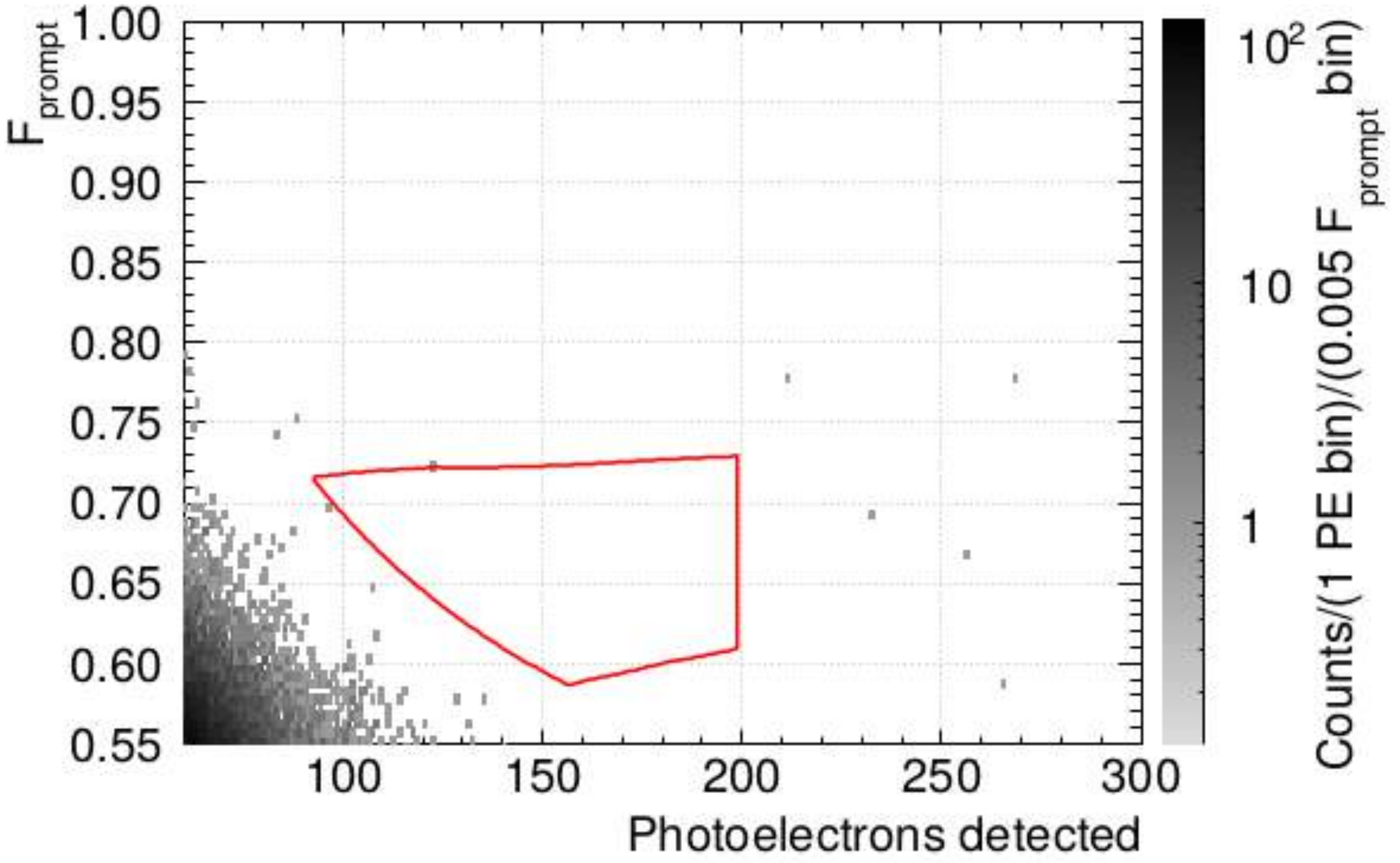
WIMP search

- Last WIMP search on 231 days live days
- Low background level in the ROI thanks to the fiducial cuts and the PSD
- Most stringent exclusion limit in argon above 20 GeV/c^2
- Upcoming reanalysis based on the Profile Likelihood Ratio, in order to gain back acceptance and sensitivity



Phys. Rev. D 100, 022004



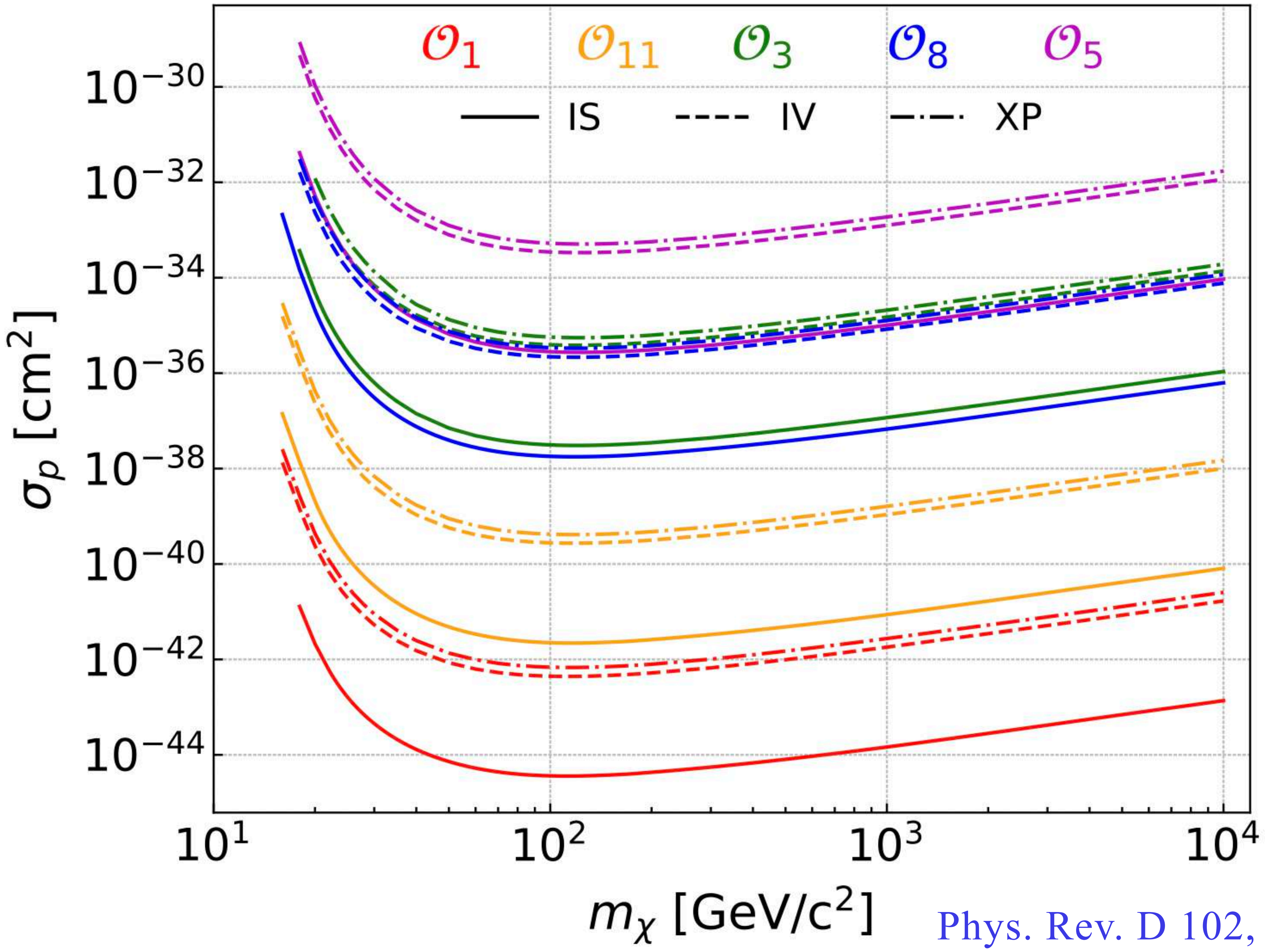


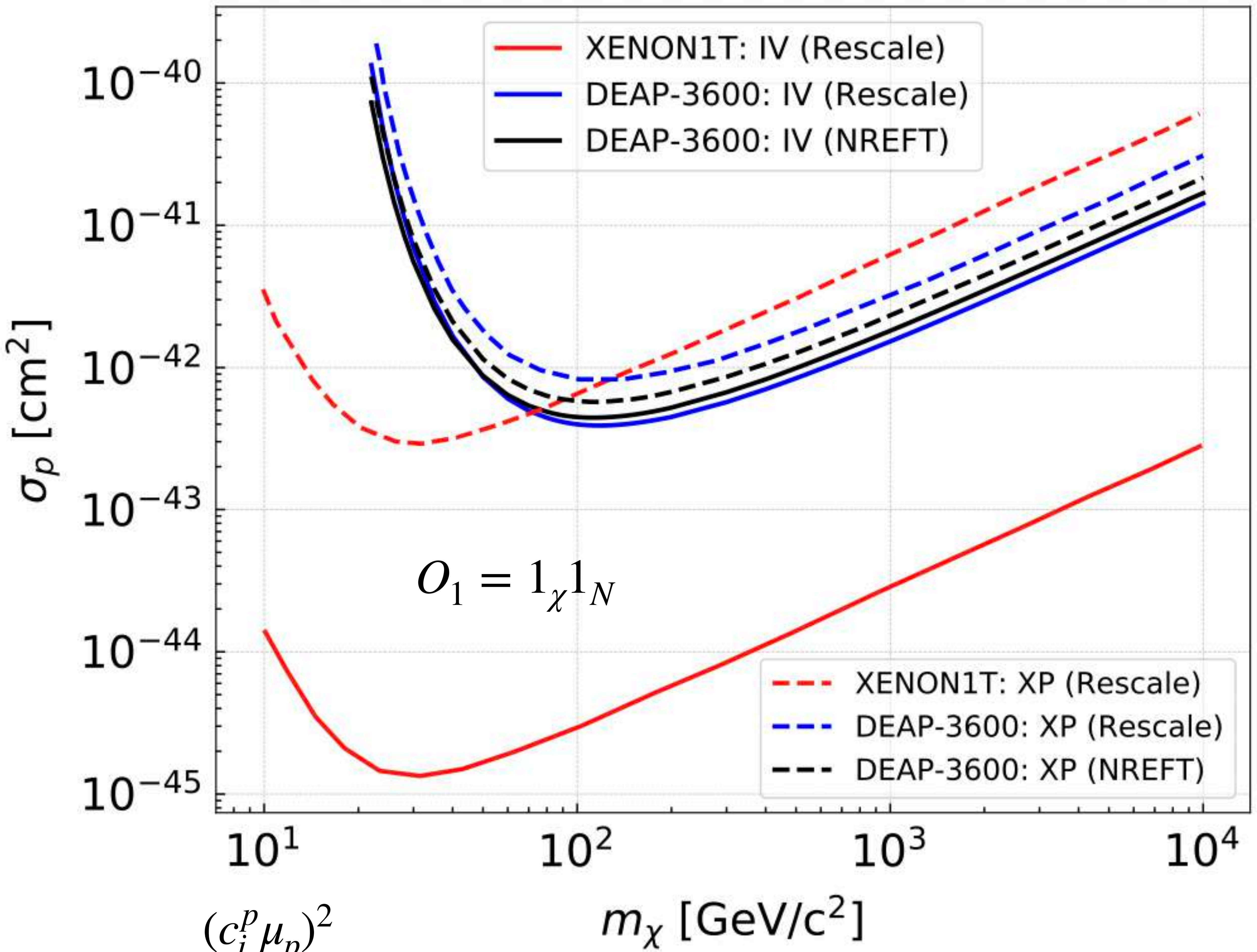
Constrains on NREFT interactions…

➡The results from 2019 analysis were reinterpreted in terms of a **Non relativistic effective field theory (NREFT)**

$$O_1 = 1_\chi 1_N \qquad O_5 = i\vec{S_\chi}\cdot\left(\frac{\vec{q}}{m_N}\times\vec{v_\perp}\right)$$

$$O_3 = i\,\vec{S_N}\cdot\left(\frac{\vec{q}}{m_N}\times\vec{v_\perp}\right) \qquad O_8 = \vec{S_\chi}\cdot\vec{v_\perp} \qquad O_{11} = i\vec{S_\chi}\cdot\frac{\vec{q}}{m_N}$$





$$\sigma^p = \frac{(c_i^p \mu_p)^2}{\pi}$$

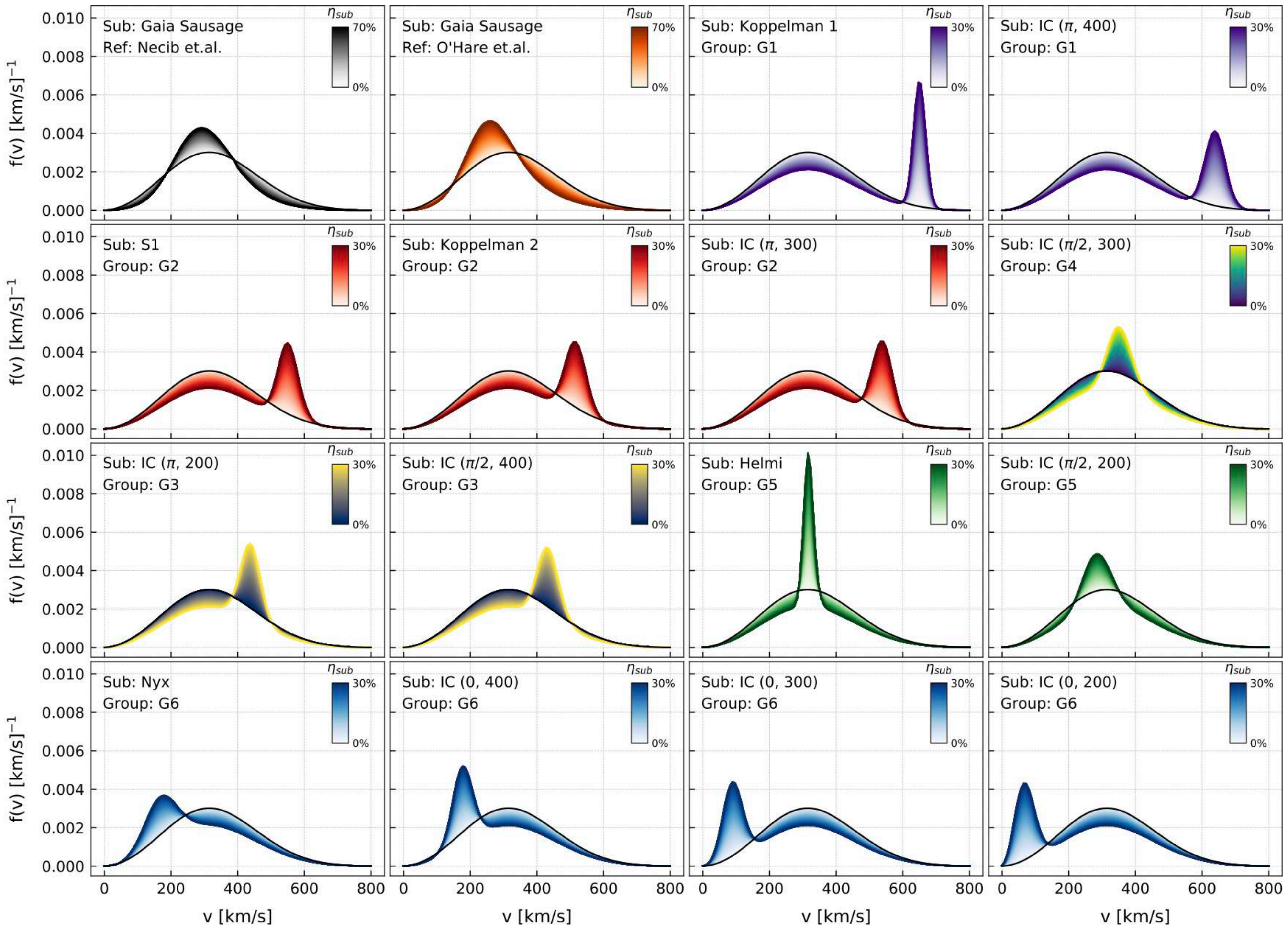
IS $\sigma_i^n = \sigma_i^p$ IV $\sigma_i^n = -\sigma_i^p$ XP $\sigma_i^n = -0.7\sigma_i^p$

Phys. Rev. D 102, 082001 (2020)

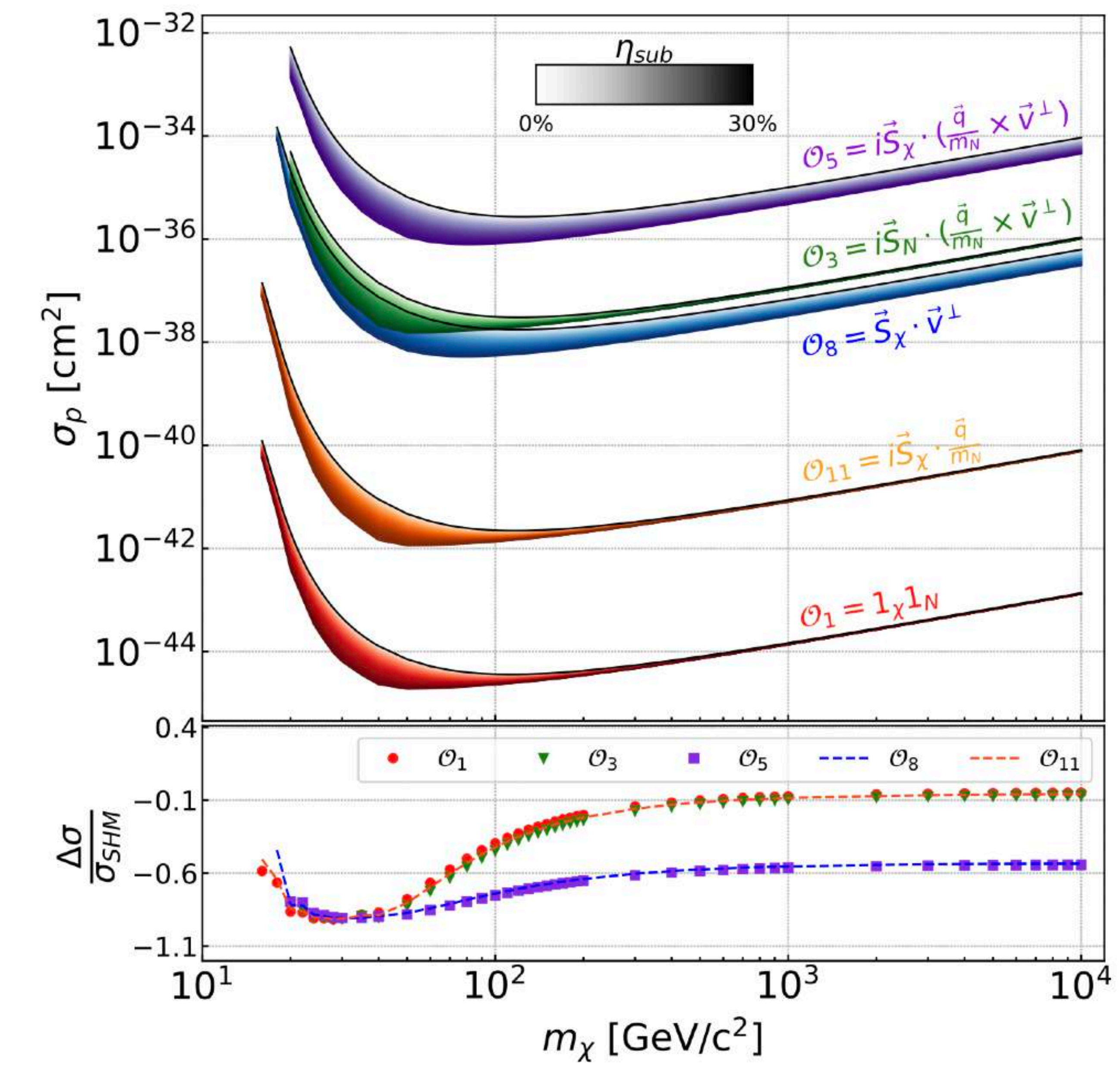
… and with non-standard halo

➡GAIA and Sloan Digital Sky Survey recently observed inflating clumps and streams around our Galaxy

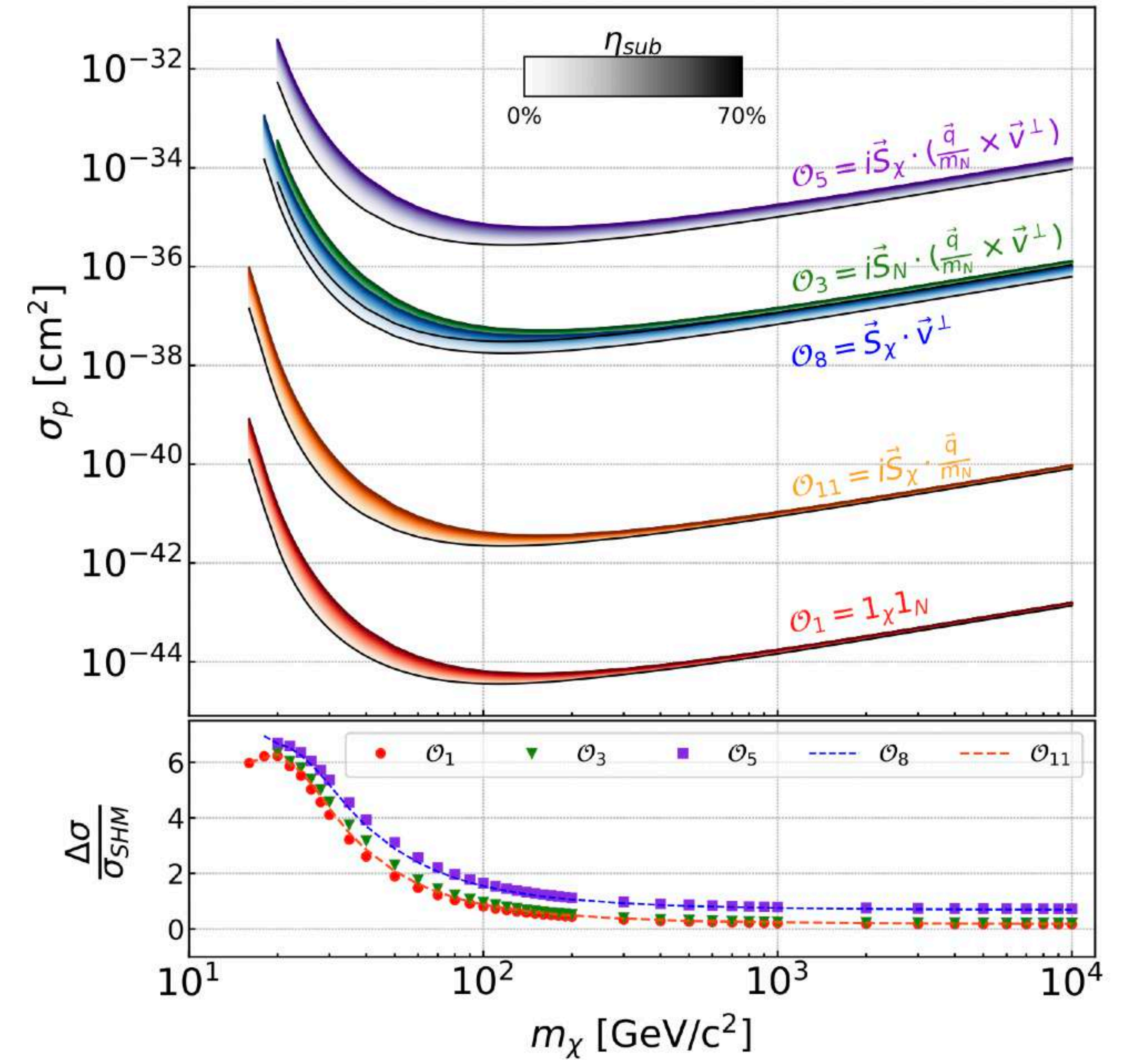
$$f_{DM}(\overrightarrow{v}) = (1-\eta_{sub})f^{gal}_{SHM}(\overrightarrow{v}) + \eta_{sub}f^{gal}_{sub}(\overrightarrow{v})$$



Phys. Rev. D 102, 082001 (2020)



G1 stream

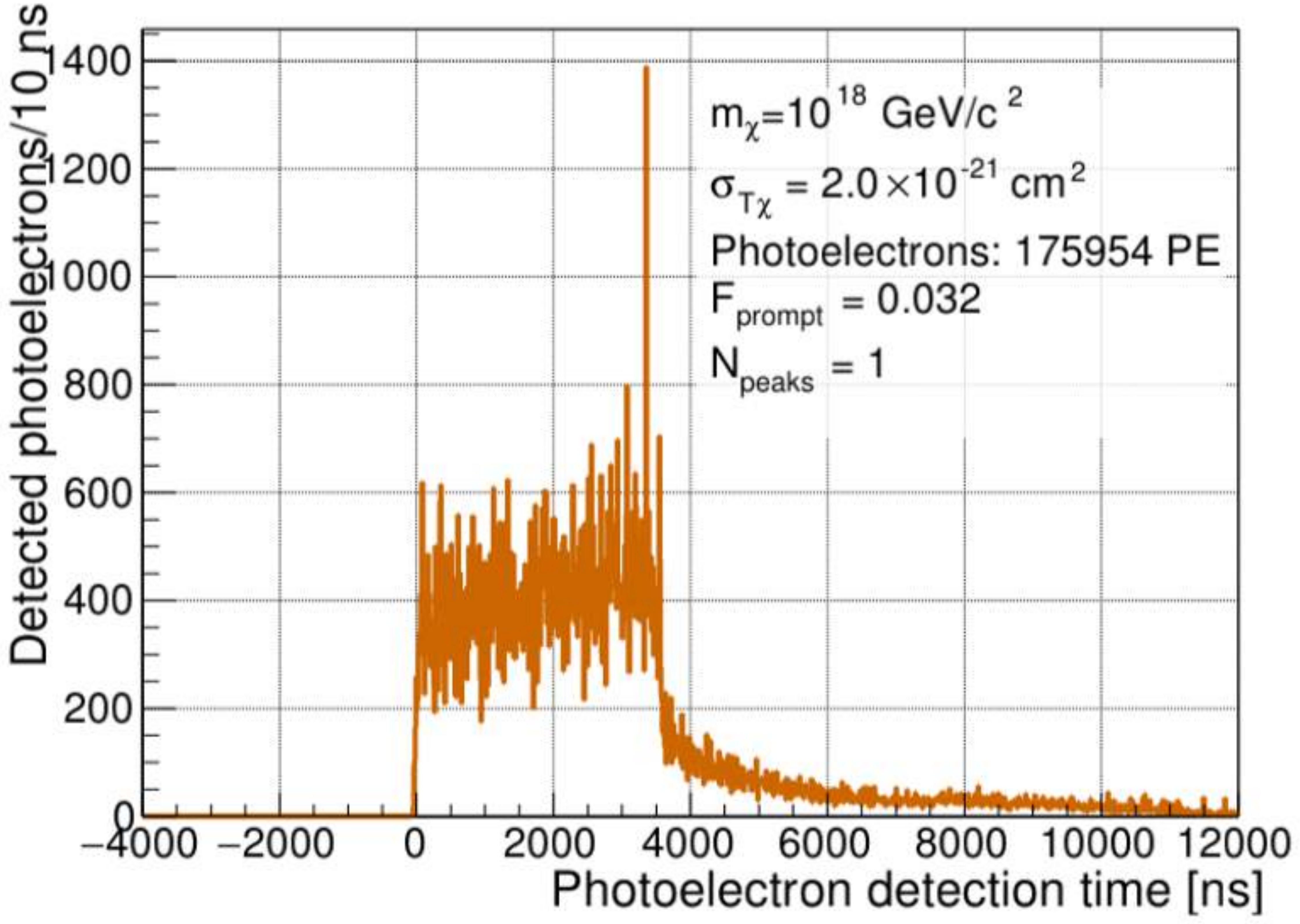


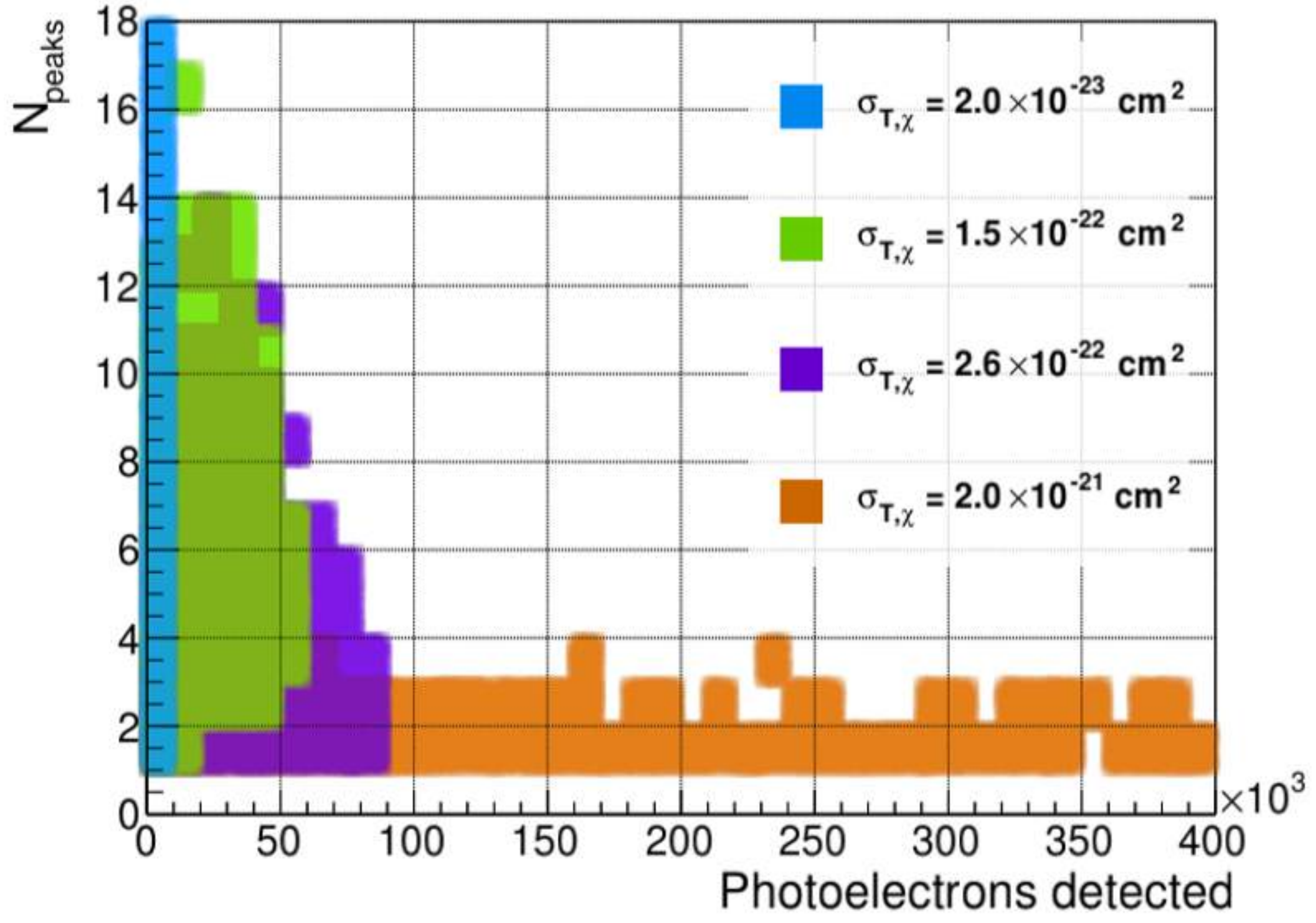
Gaia Sausage

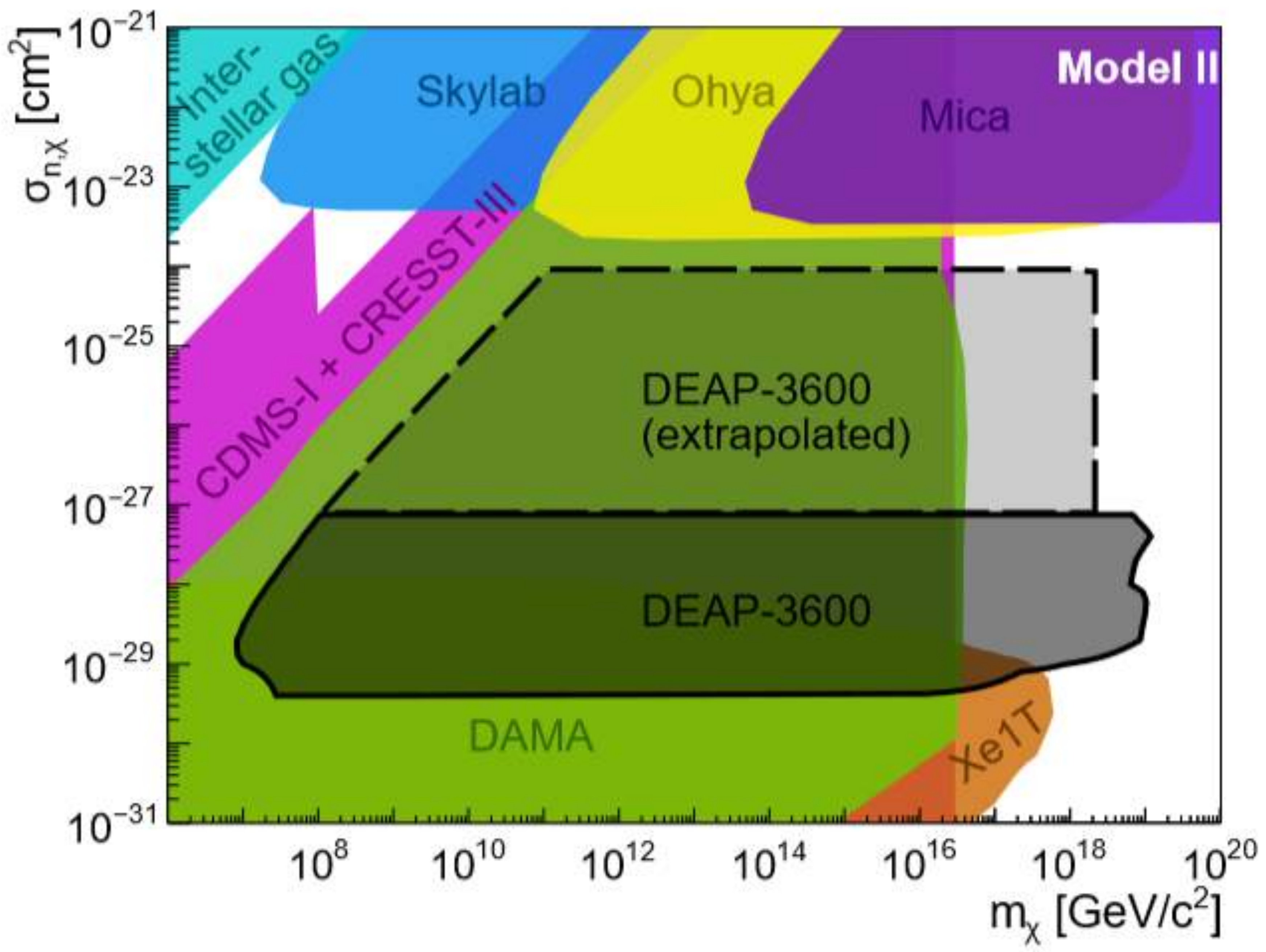
Multi-scatter search

- ➡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**
- ➡Expected multiple scatterings along a collinear track in DEAP inner vessel
- ➡Set exclusion limits within 90 % C.L. for Planck scale masses for two composite dark matter models

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







Take home

➡Most stringent exclusion limit for high mass WIMPs in liquid argon

➡World leading PSD!

➡Re-analysis of the WIMP results with NREFT and non-standard galactic halo

➡Unique sensitivity to heavy, multi-scattering dark matter candidates up to **Planck Scale masses**

➡**Precise measurements on the specific activity of atmospheric argon**

➡WIMP search on the open data with Profile likelihood ratio analysis: upcoming!

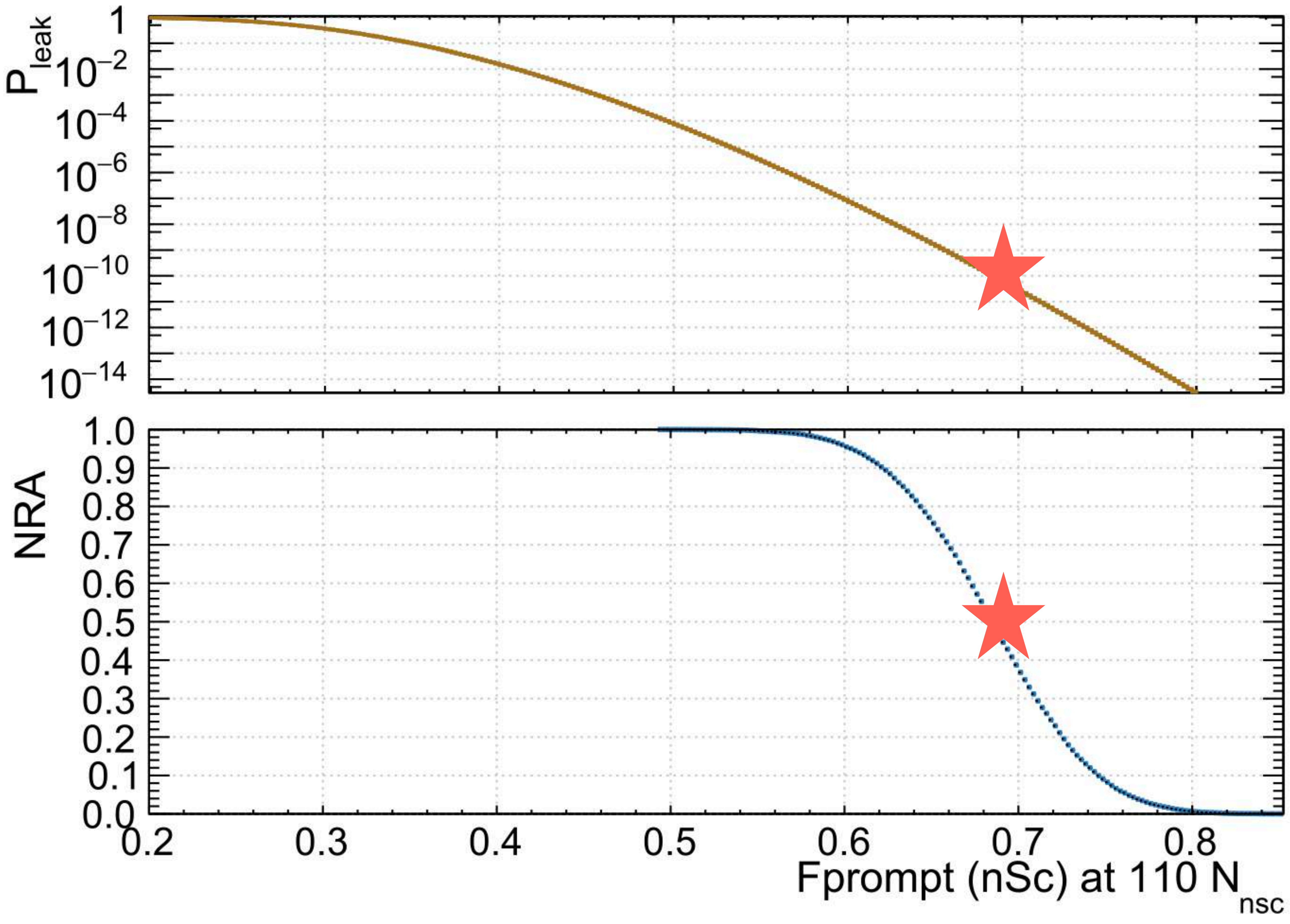
➡WIMP search on blind data: ongoing!

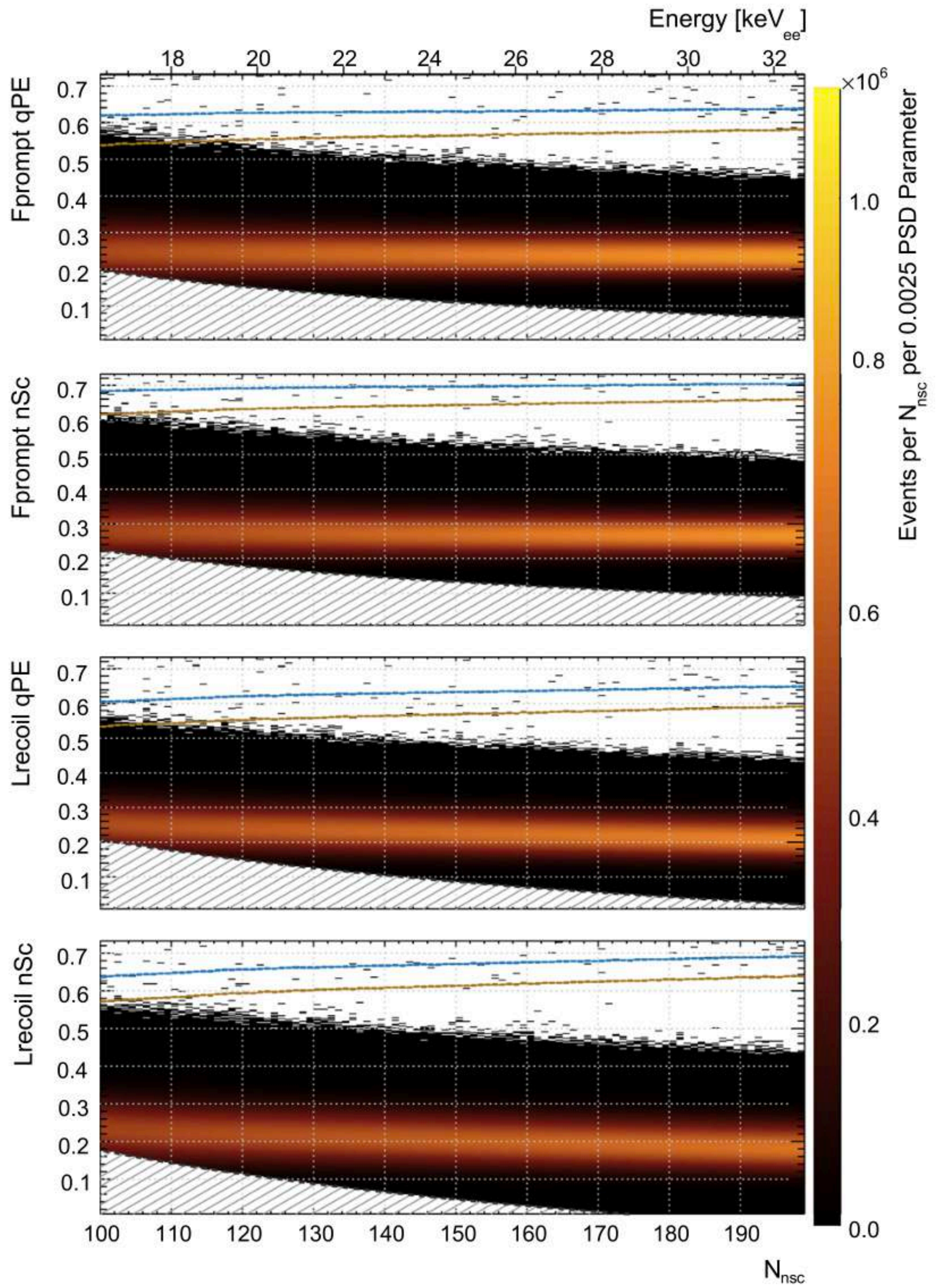
➡**Detector upgrades in progress, stay tuned!**

Back-up

Dr. Michela Lai
on behalf of
DEAP-3600 Collaboration

PSD algorithms





Precise measurement of the LAr target mass

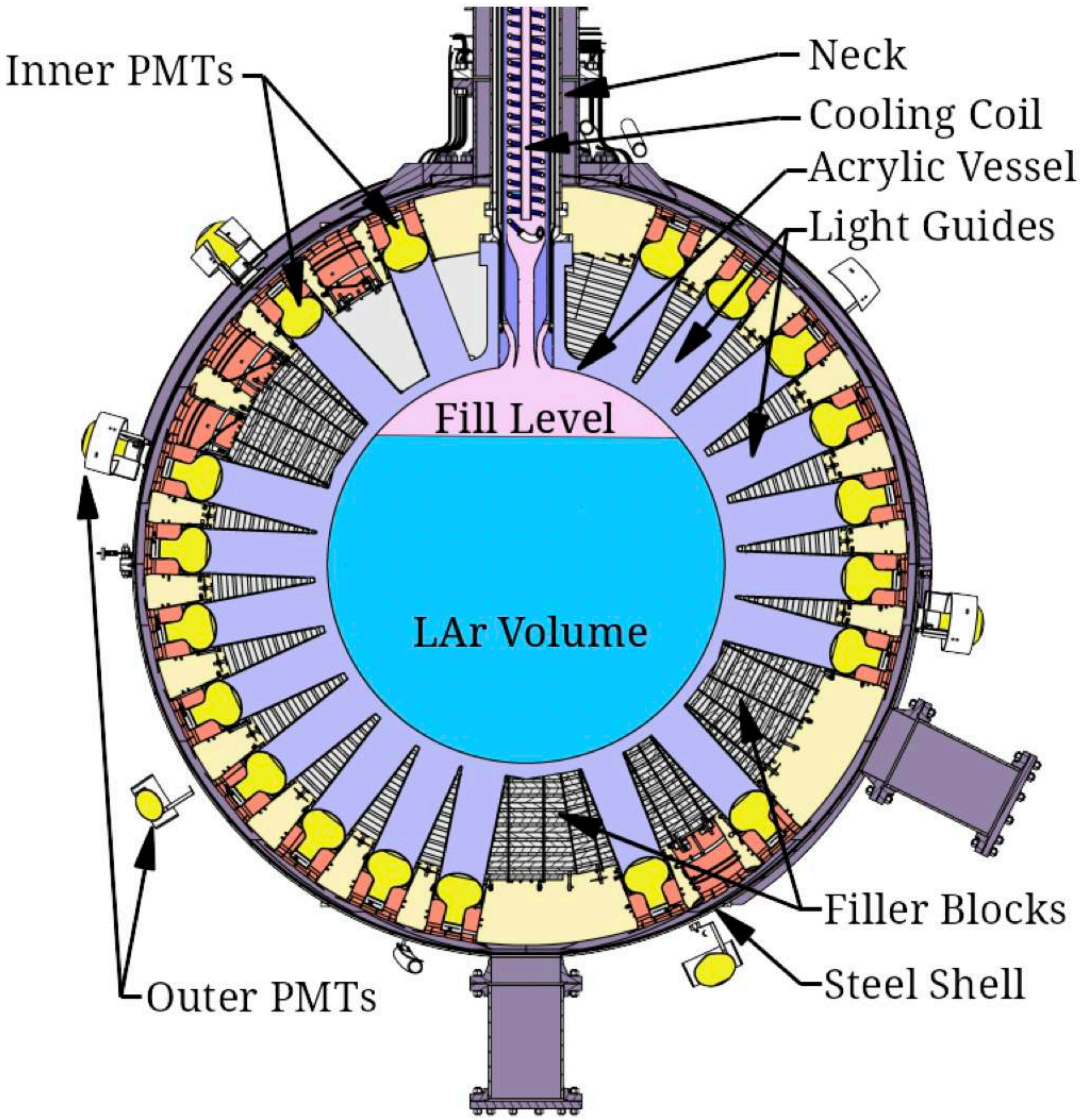
- LAr density known to 0.5%, thanks to the monitoring of the temperature and pressure
- Need to evaluate the inner vessel radius and height
- Radius measured before filling and then corrected for the inner vessel temperature dependent contraction after cool-down,

$$R_{LAr} = (845.6 \pm 0.9)mm$$

- Height evaluated according to the distribution of the light, considering
  - The reflection of UV light at the Gas-Liquid interface
  - The TPB coated surface fraction of the PMT immersed in the liquid phase
- Result validated by comparing data/simulation for different interface levels
- Cross-checked by comparing the reconstructed vertical positions of ^{39}Ar decays in data and simulations for different interface levels

$$H_{LAr} = (550 \pm 10)mm$$

- Need to consider the presence of bubbles
- Worst case scenario considered: if whole heat entering the vessel causes bubbles, 6.3 kg of argon goes in bubbles



Pile-up evaluation

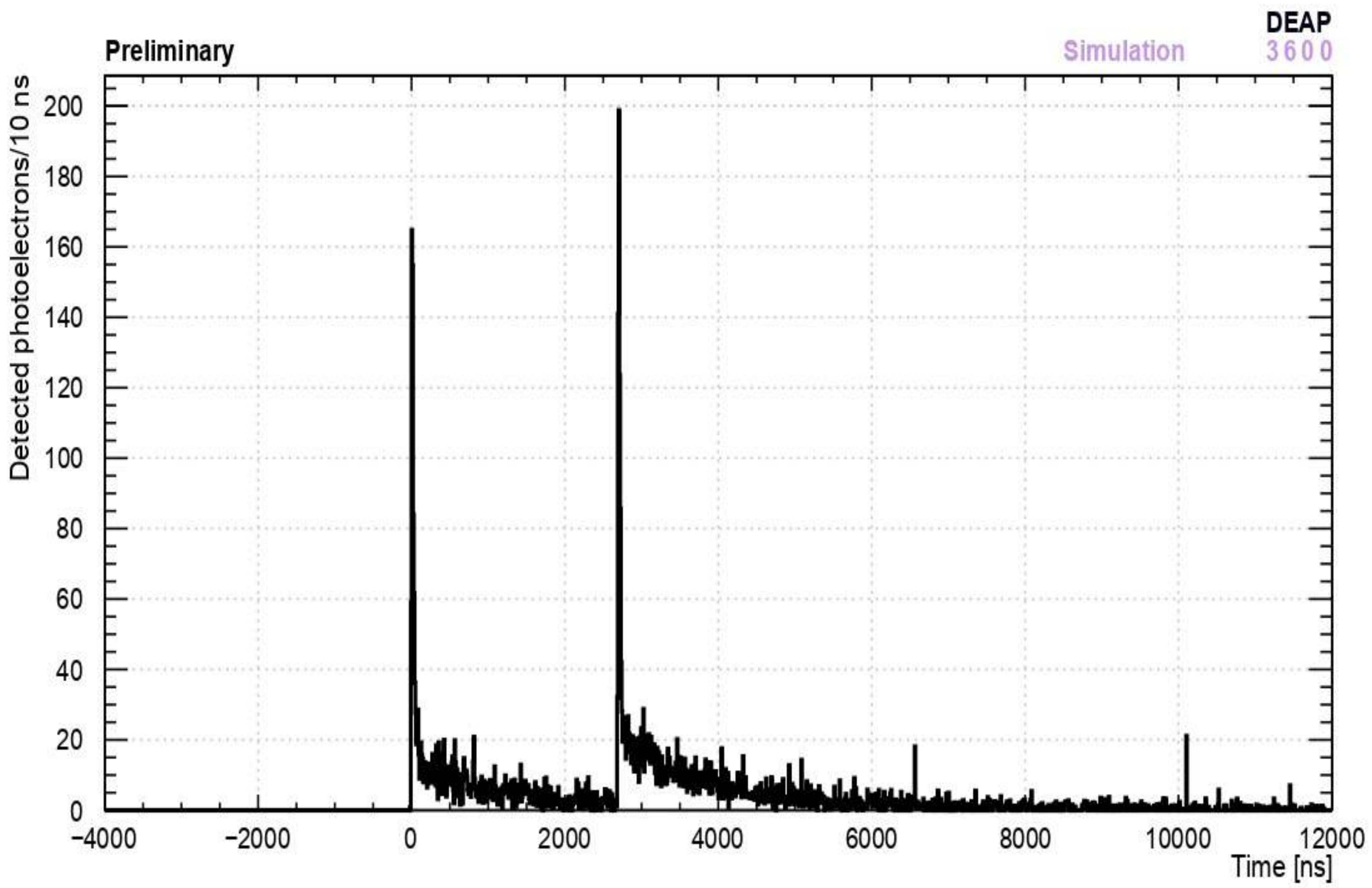
$$N_{pile-up} = N_{double} + N_{triple} + N_{ERB,39Ar} + N_{hFp,39Ar}$$

$$R_{39Ar} = \sqrt{\frac{N_{double}}{2T_{livetime}\delta t_{int}}}$$

$$N_{\mathrm{triple}} = 3 \cdot R^3_{\mathrm{Ar39}} \cdot \delta t^2_{\mathrm{int}} \cdot T_{\mathrm{live}}$$

$$N_{\mathrm{ERB,Ar39}} = R_{\mathrm{Ar39}} \cdot R_{\mathrm{ERB}} \cdot \delta t_{\mathrm{int}} \cdot T_{\mathrm{live}}$$

$$N_{\mathrm{hFp,Ar39}} = R_{\mathrm{Ar39}} \cdot R_{\mathrm{hFp}} \cdot \delta t_{\mathrm{int}} \cdot T_{\mathrm{live}}$$



$$R_{ERB} = (10.5 \pm 0.6)Hz$$

$$R_{hFp} = (270 \pm 3)Hz$$

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

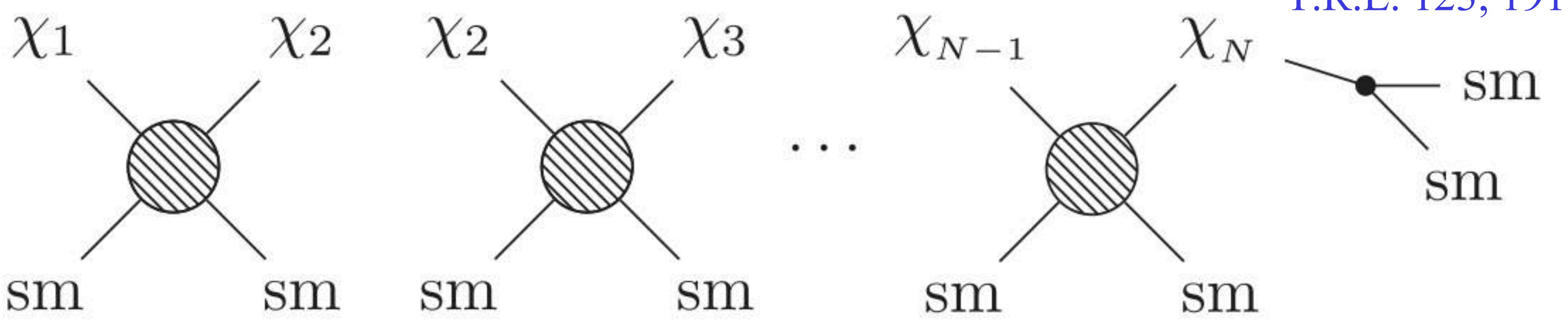
Phys. Rev. D 59, 123006 (1999).

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

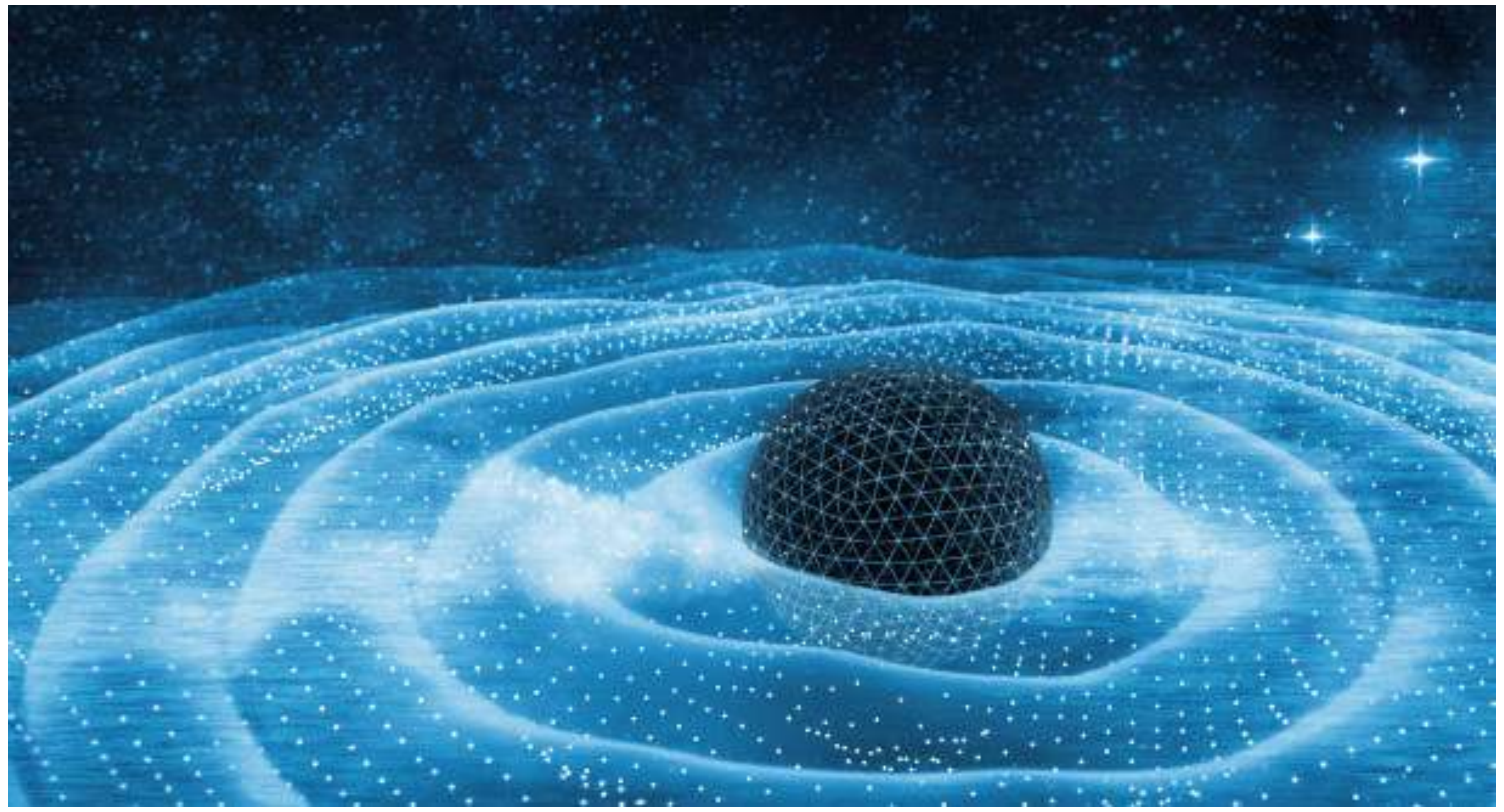
$$\chi_i + SM \leftrightarrow \chi_{i+1} + SM \qquad \chi_N \to SM + SM$$

These DM particles can reach Planck scale masses.

P.R.L. 123, 191801 (2019)

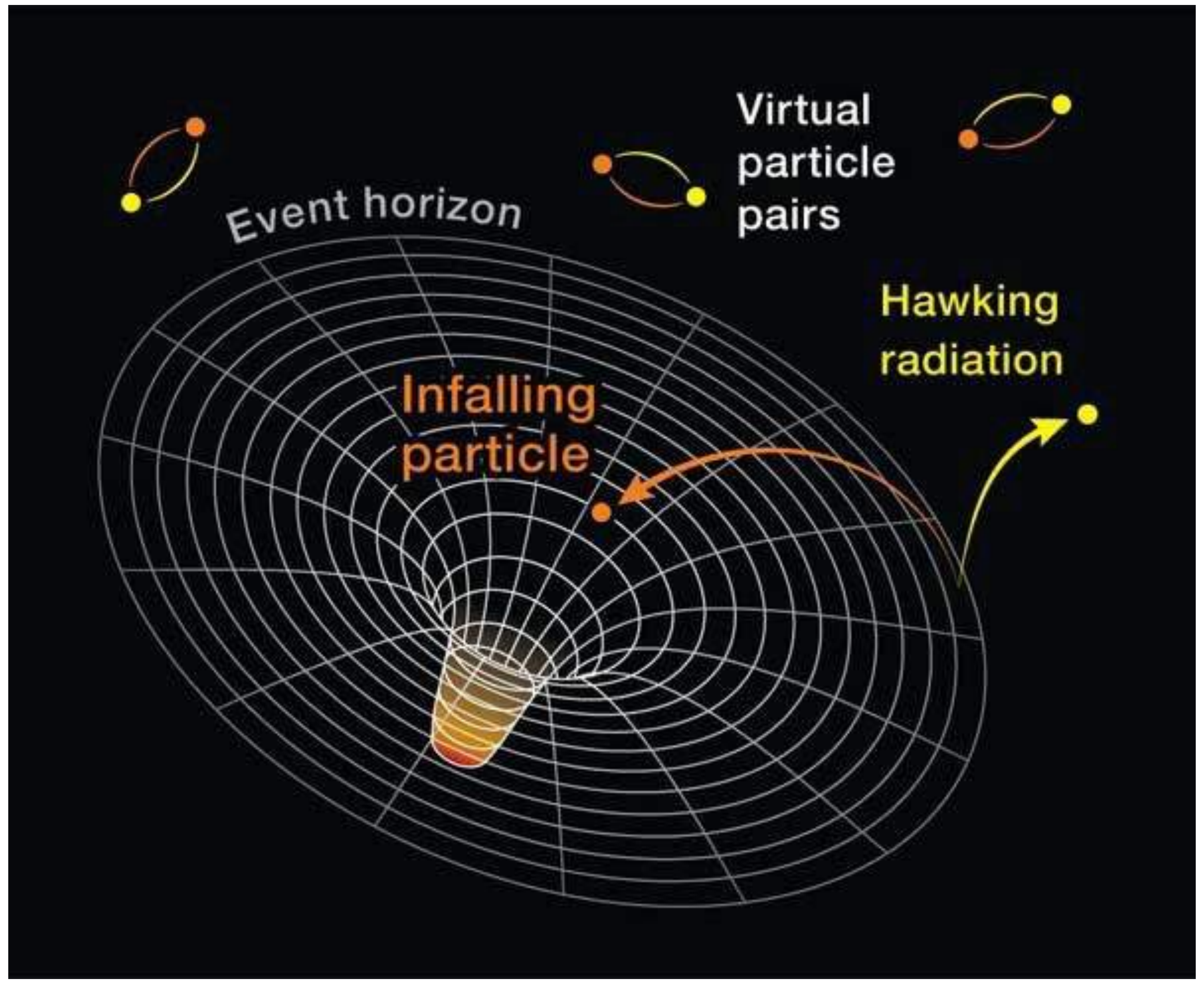


Inflational gravitational production, in quantum field theories in a curved spacetime, of dark matter up to Hubble inflation scale and beyond that, with higher spin dark matter.



arXiv:1808.08236

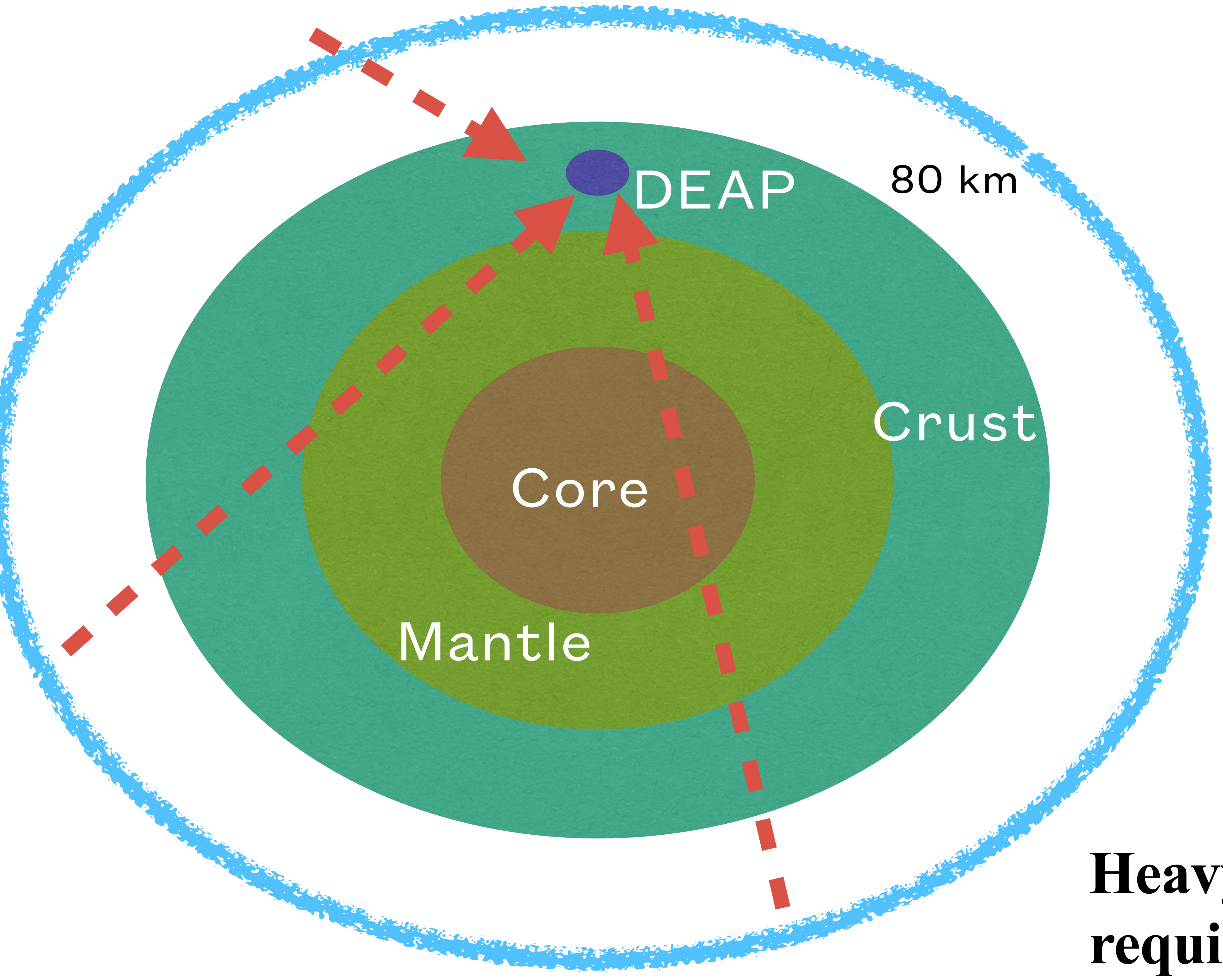
Primordial black holes ($M \lesssim 5 \times 10^8 g$) can produce heavy dark matter candidates ($m_{DM} \gtrsim 10^9 GeV$) by Hawking evaporation.

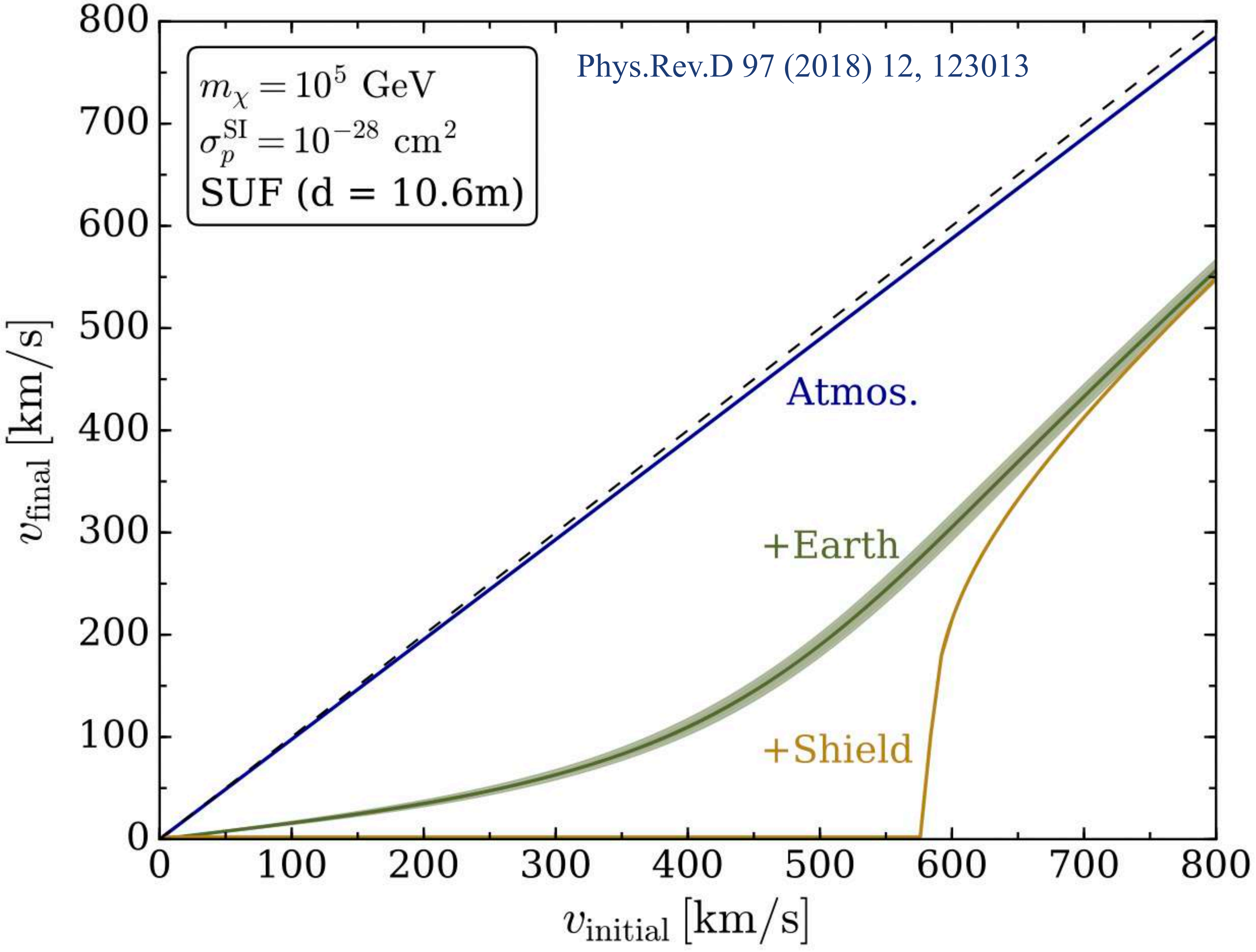


J. High Energ. Phys. 2019, 1 (2019).

Dark matter velocity distribution are affected by the scatterings **before reaching** the underground detector, depending on the scattering cross-section $\sigma_{i,\chi}$

$$\frac{d < E_\chi >}{dt} = -\sum_i n_i(\mathbf{r}) < E_{rec} >_i \sigma_{i,\chi}(v)v$$



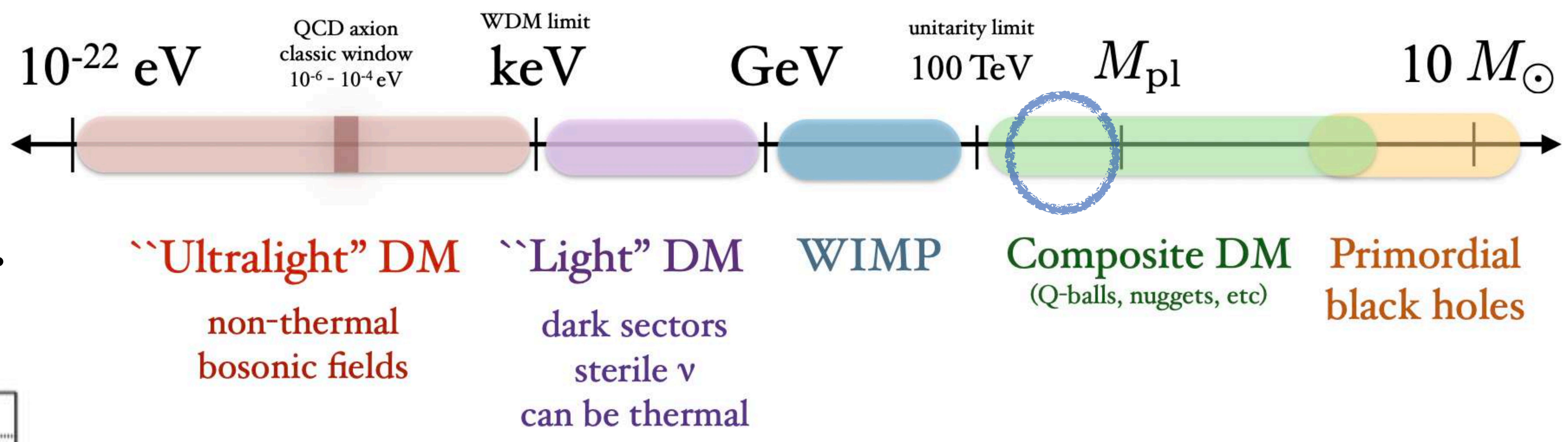


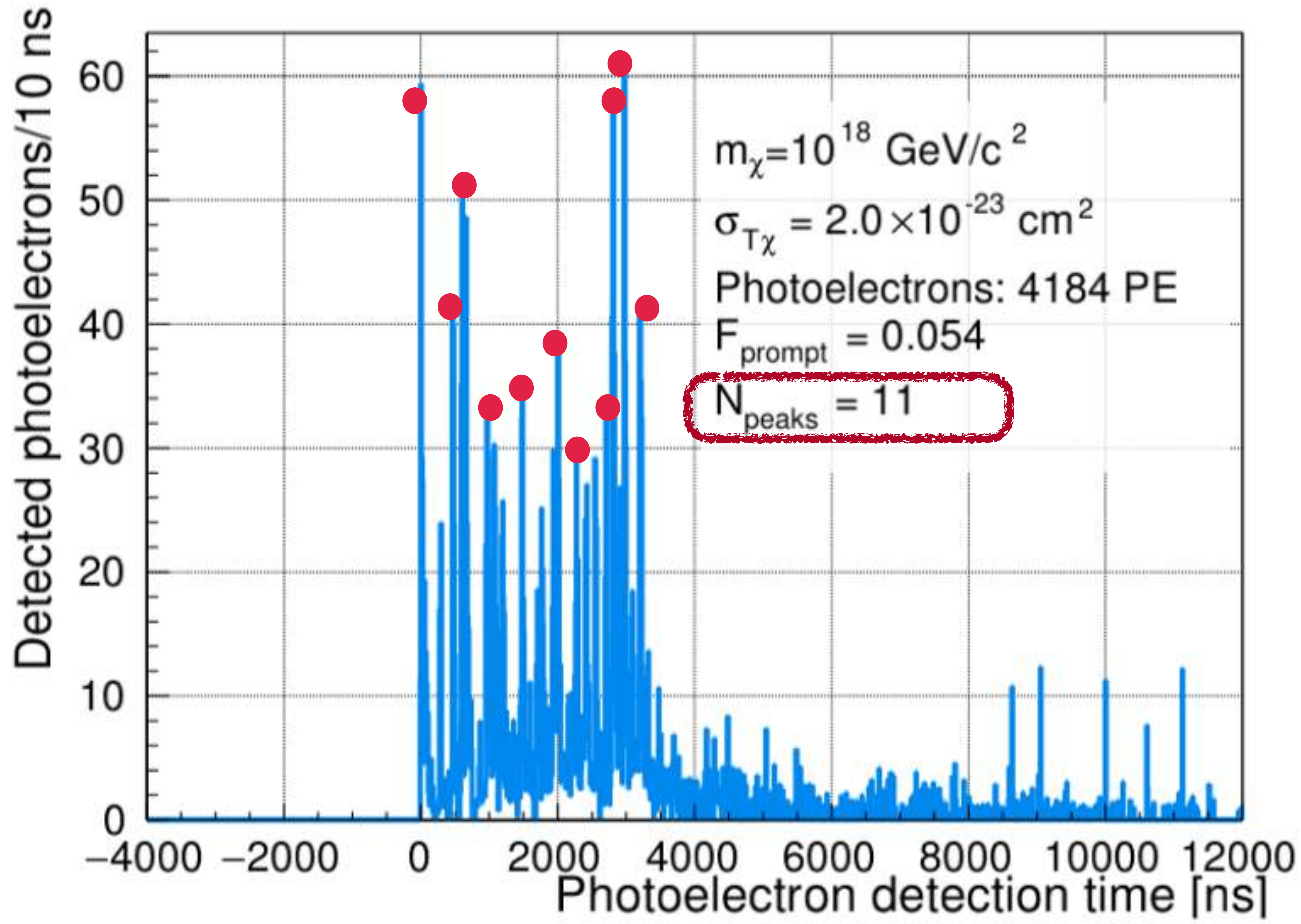
$$N_{scatt} = \sum_i n_i \sigma_{i,\chi} L_i$$

$$\alpha_{scatt} \approx \frac{m_i}{m_\chi}$$

Heavy candidates can reach underground detector. Still, a high cross-section is required to compensate for the low incoming flux

Dark matter (DM) candidates above $\sigma_{\chi\text{-}n} \cong 10^{-25}\,cm^2$ and $m_\chi \gtrsim 10^{12}$ GeV loose a negligible amount of energy in the scatterings with the Earth nuclei and **can reach underground detectors designed for WIMP searches.**





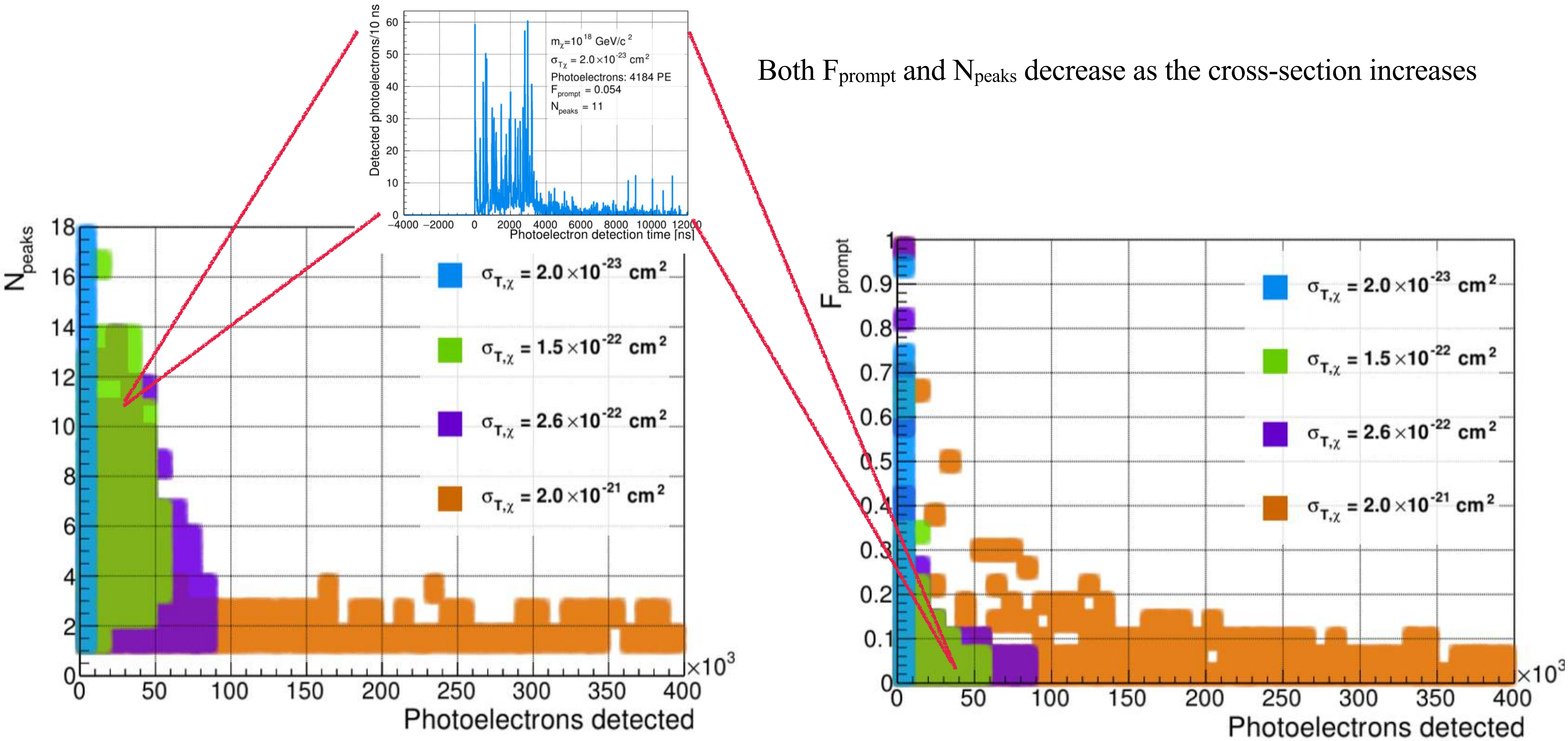
$$N_{scatt} = \sigma_{Ar,\chi} n_{LAr} R$$

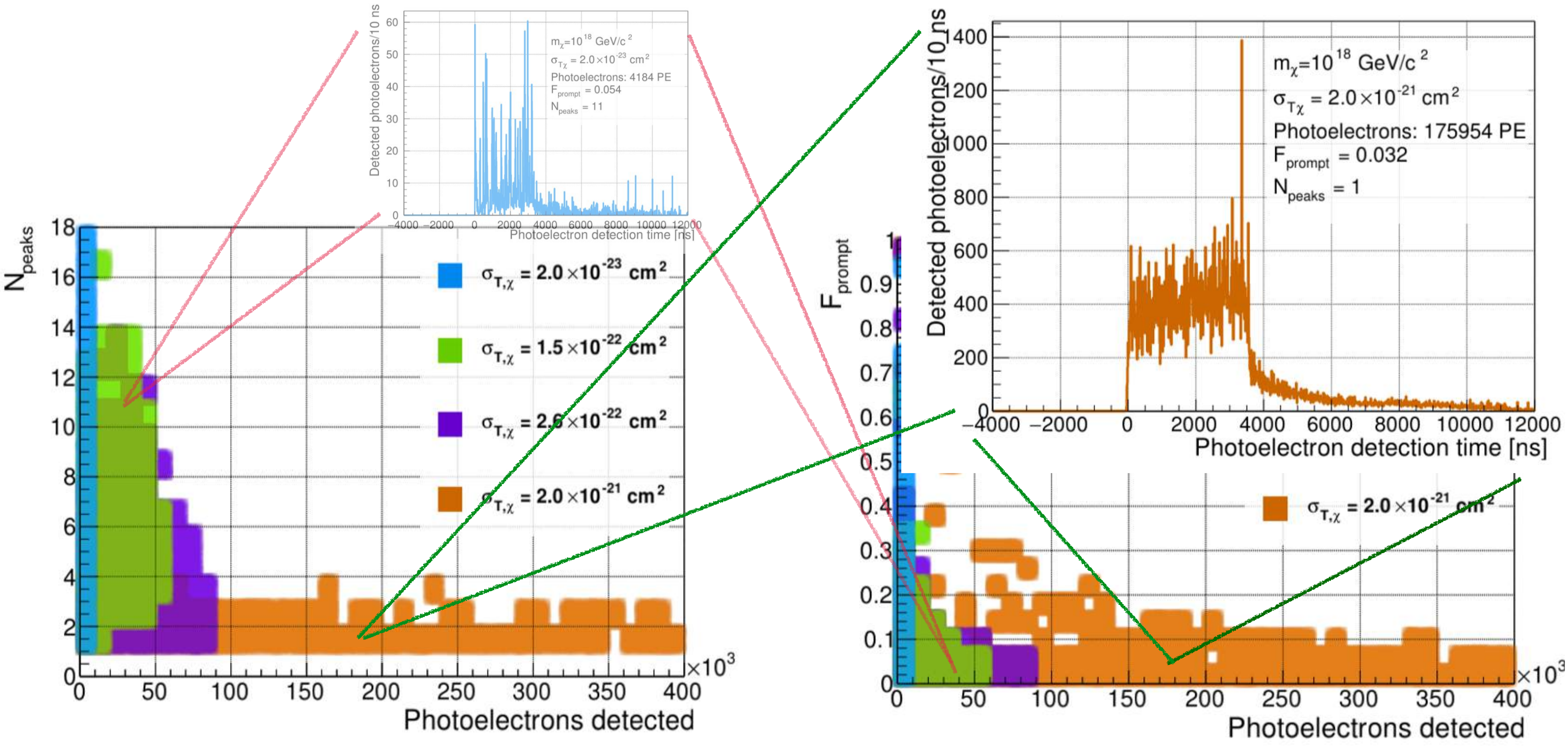
$$R = 85cm \qquad n_{LAr} = 2.1 \cdot 10^{22} cm^{-3}$$

$$N = \sigma_{\chi-T} \cdot 1.8 \cdot 10^{24} cm^{-2}$$

$$\alpha_{scatt} \approx \frac{40GeV}{10^{18}GeV}$$

Both F_{prompt} and N_{peaks} decrease as the cross-section increases

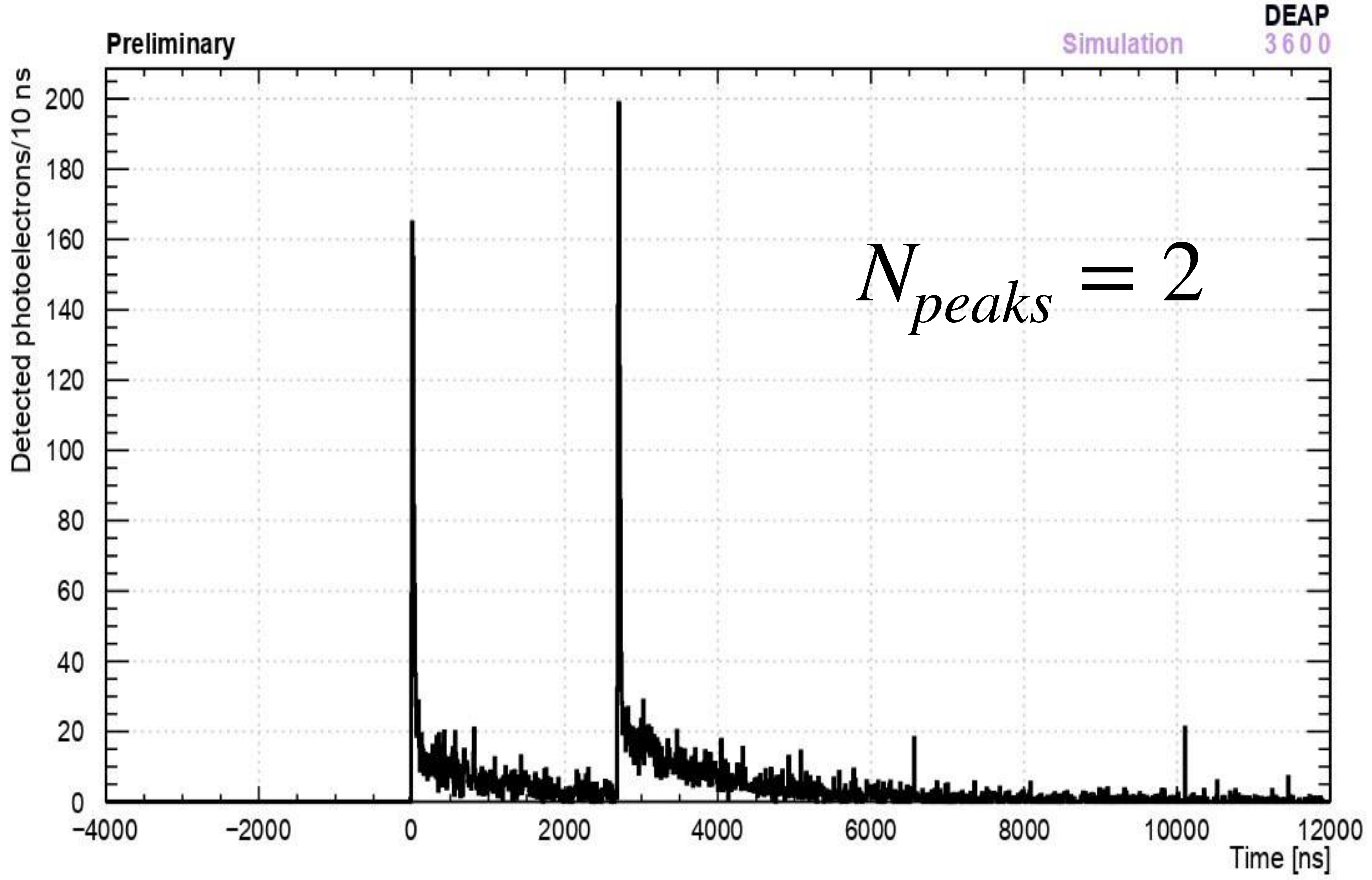


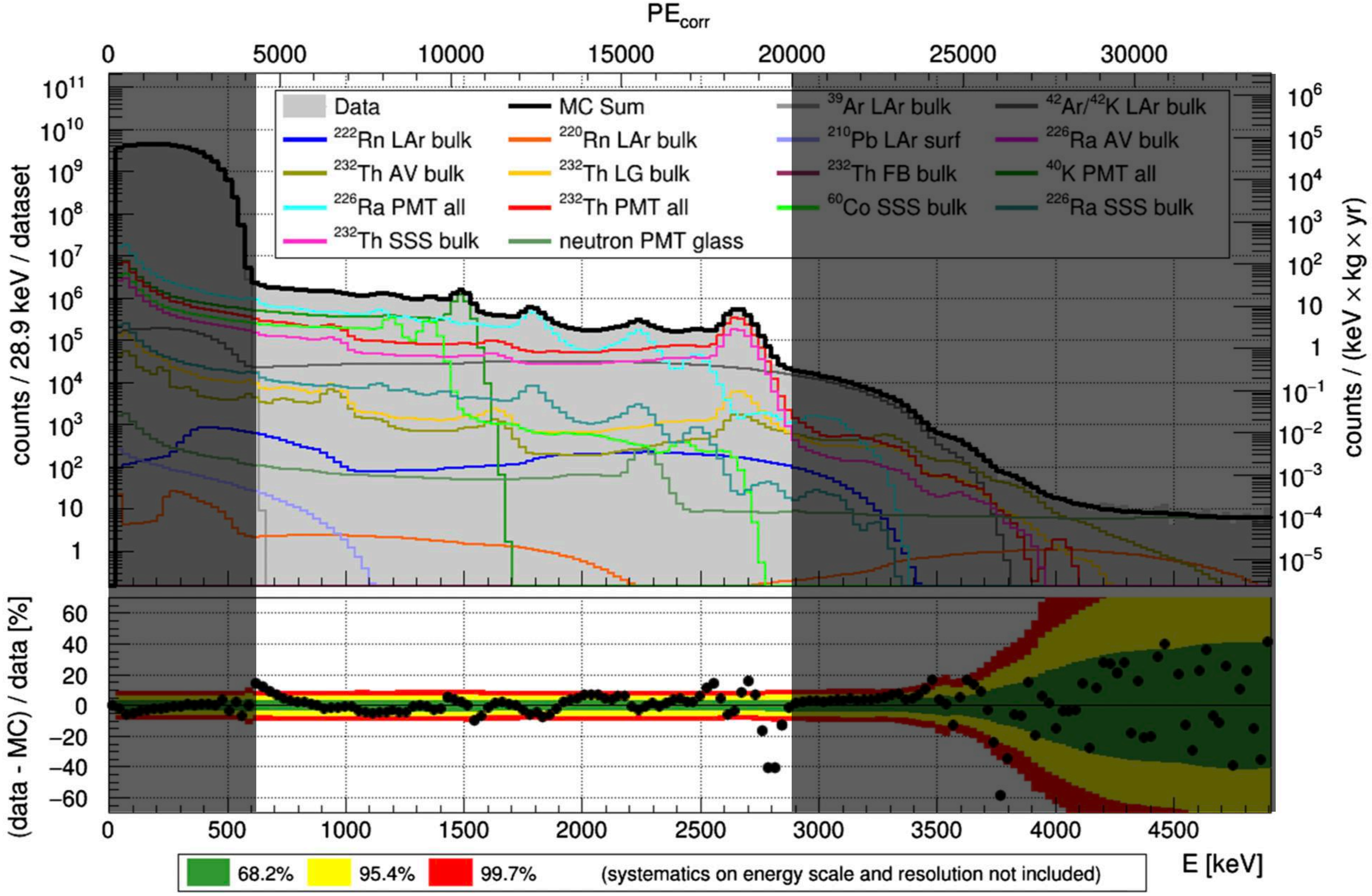


Selection cuts in N_{peaks} applied only up to 10 MeV, the highest observable energy at which the variable was validated

Below 10 MeV, any single scatter event is removed by asking $N_{peaks} > 1$

Still, more than one background event can happen in the same acquisition window: this is a **pile-up event**.





PE range	Energy [MeV]	N_{peaks}^{min}
4000–20 000	0.5–2.9	7

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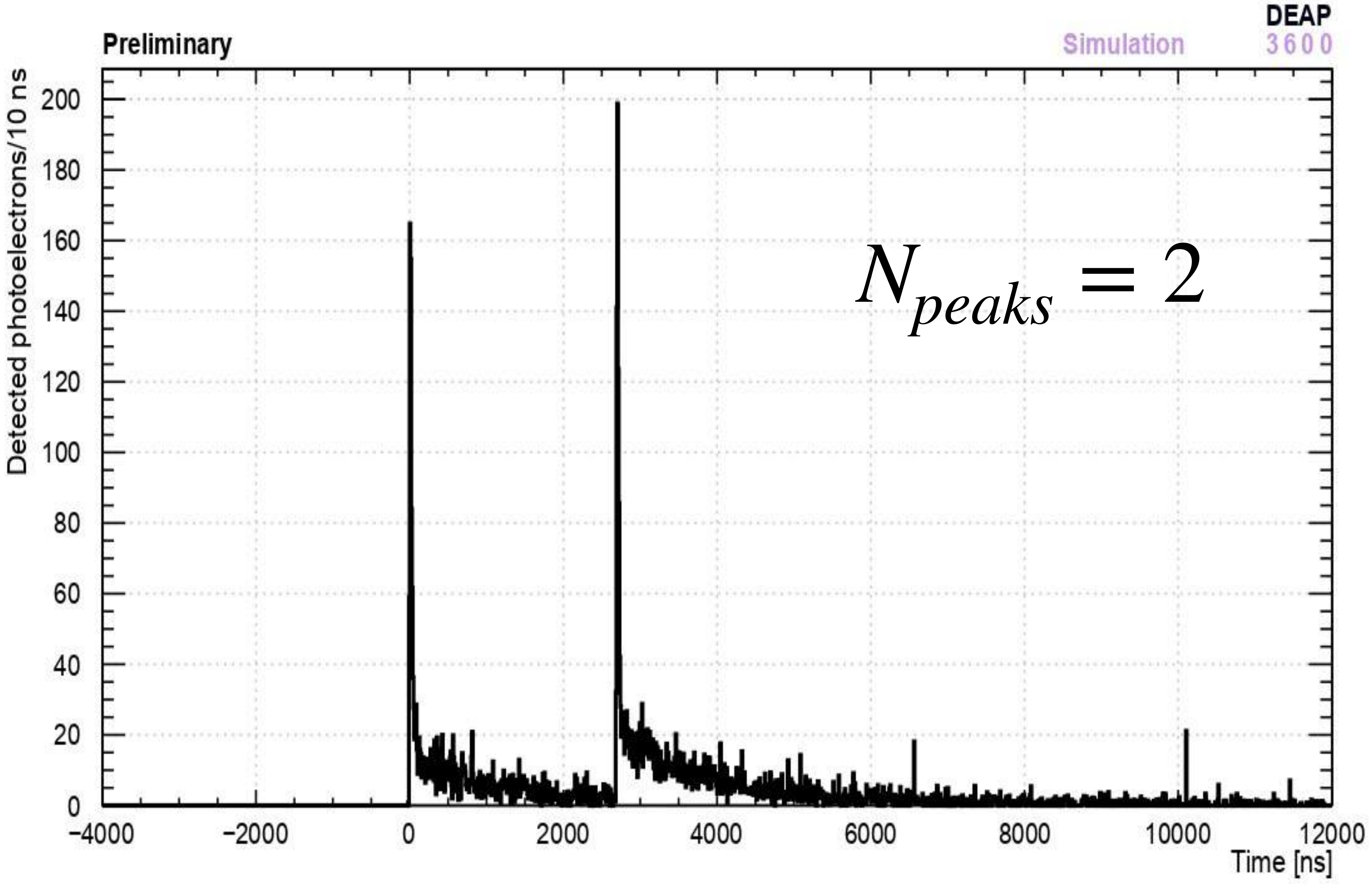
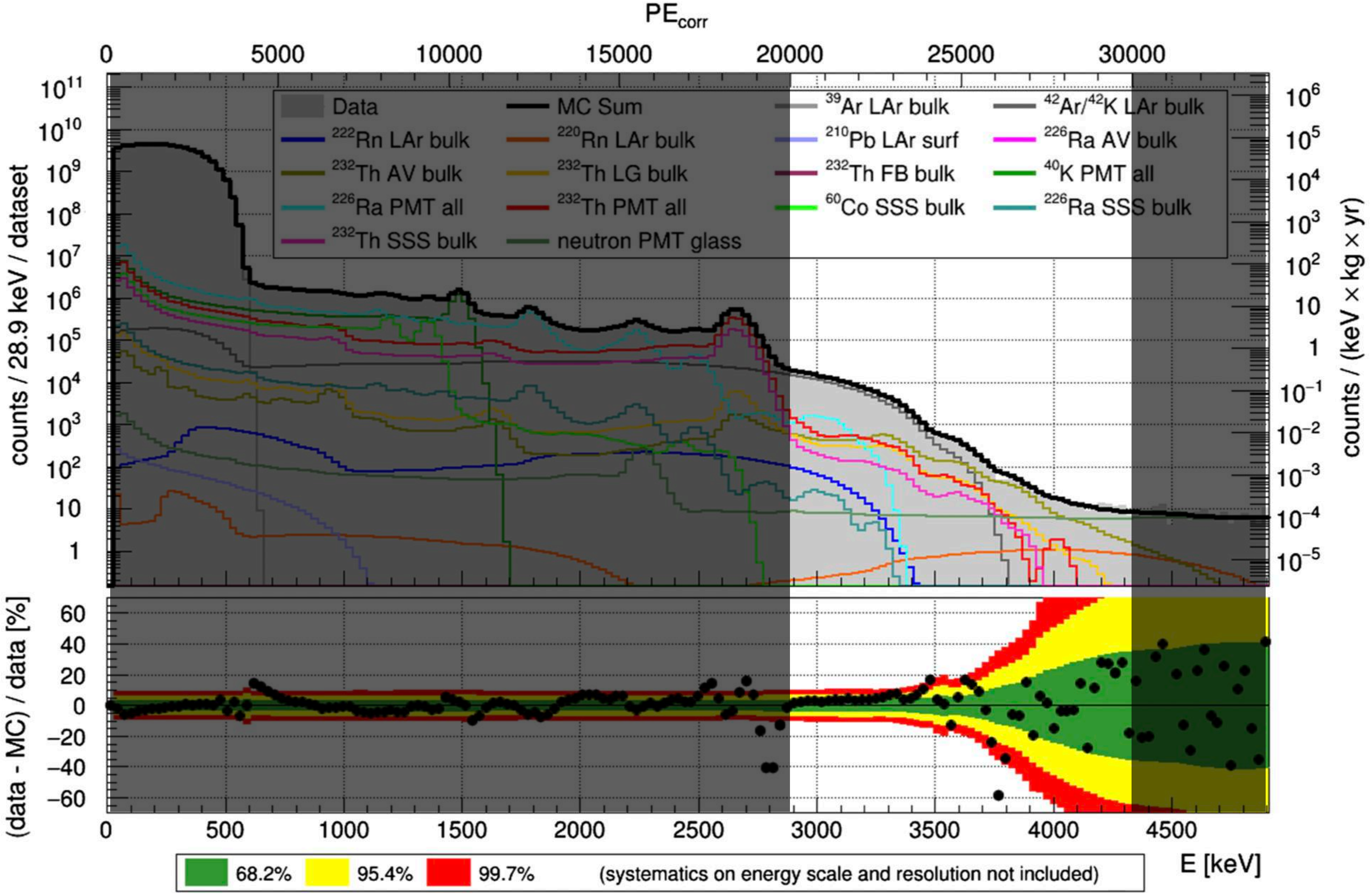


PE range	Energy [MeV]	N_{peaks}^{min}
4000–20 000	0.5–2.9	7
20 000–30 000	2.9–4.4	5



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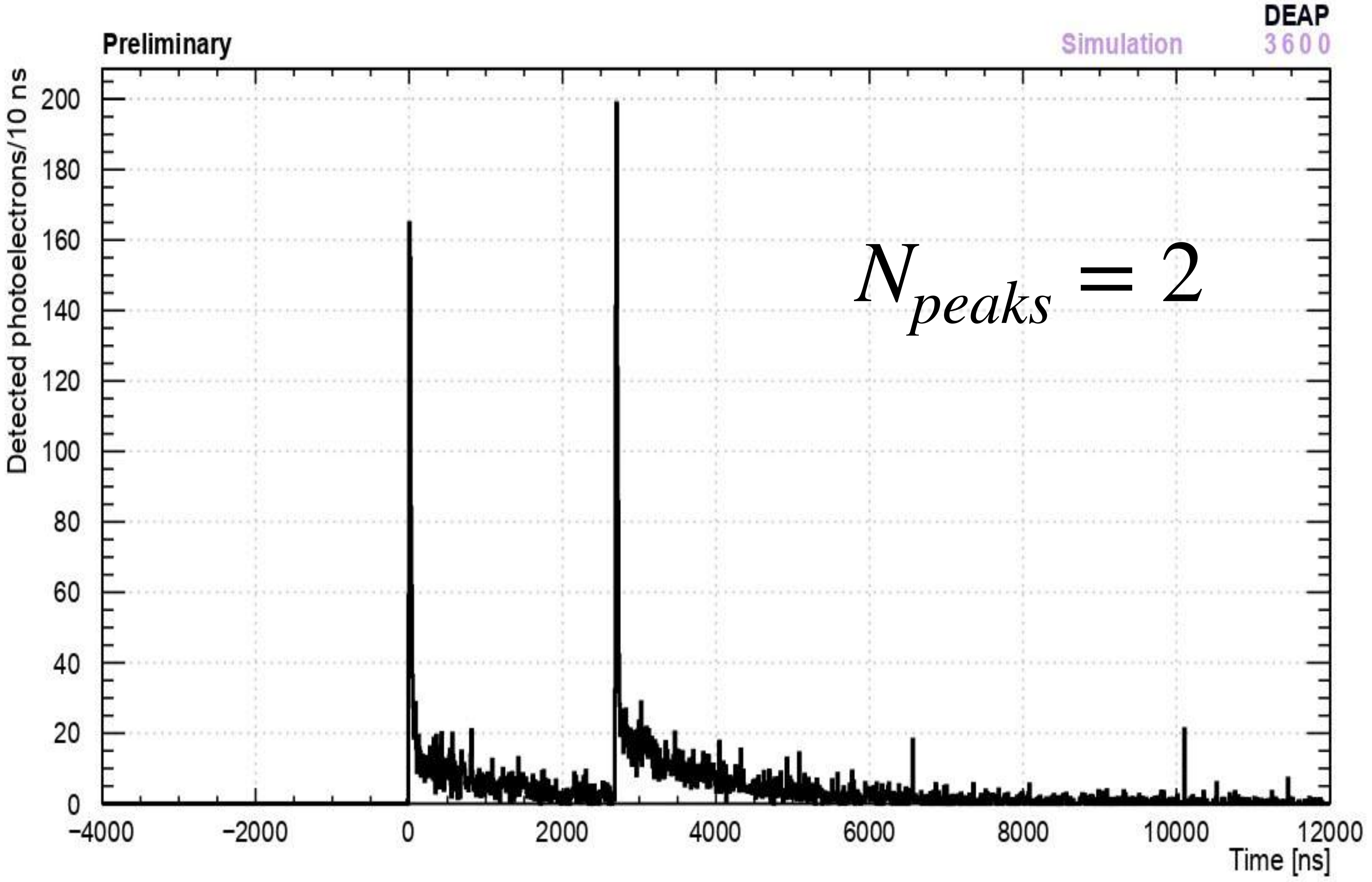
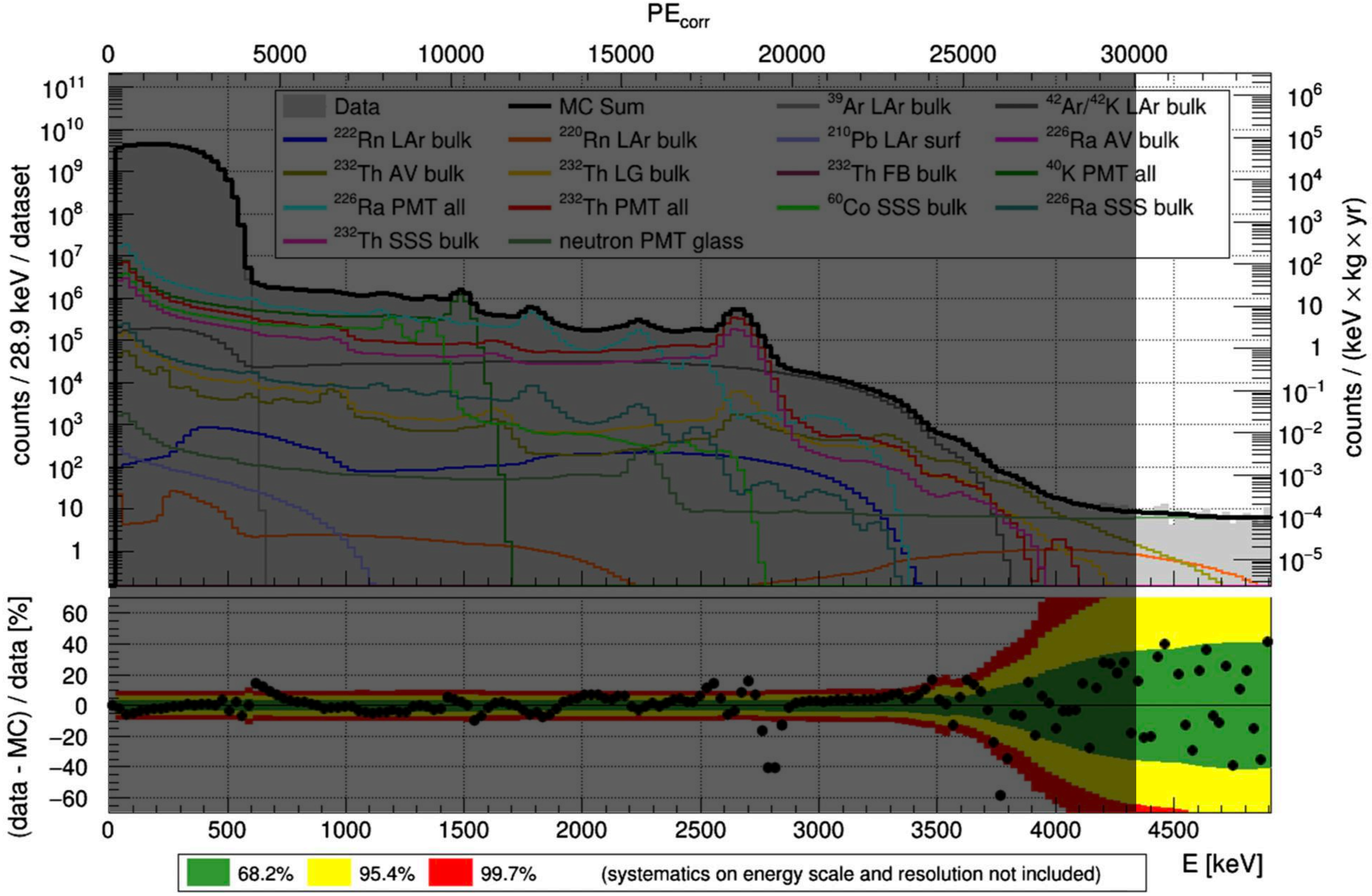
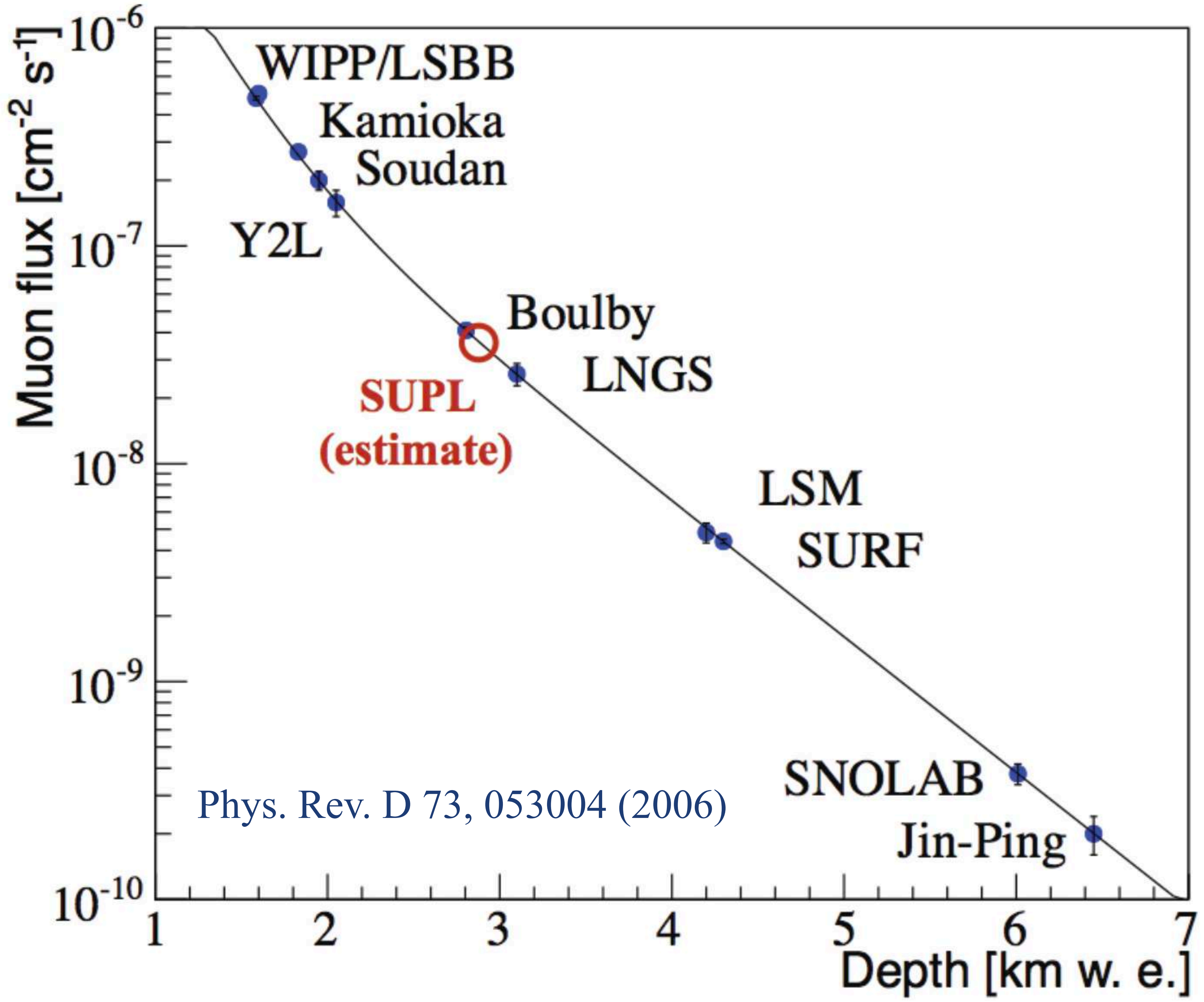


PE range	Energy [MeV]	N^{min}_{peaks}
4000–20 000	0.5–2.9	7
20 000–30 000	2.9–4.4	5
30 000–70 000	4.4–10.4	4



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

Above 10 MeV the number of pile-up is negligible, while the dominant background are **muon event** entering the inner vessel.

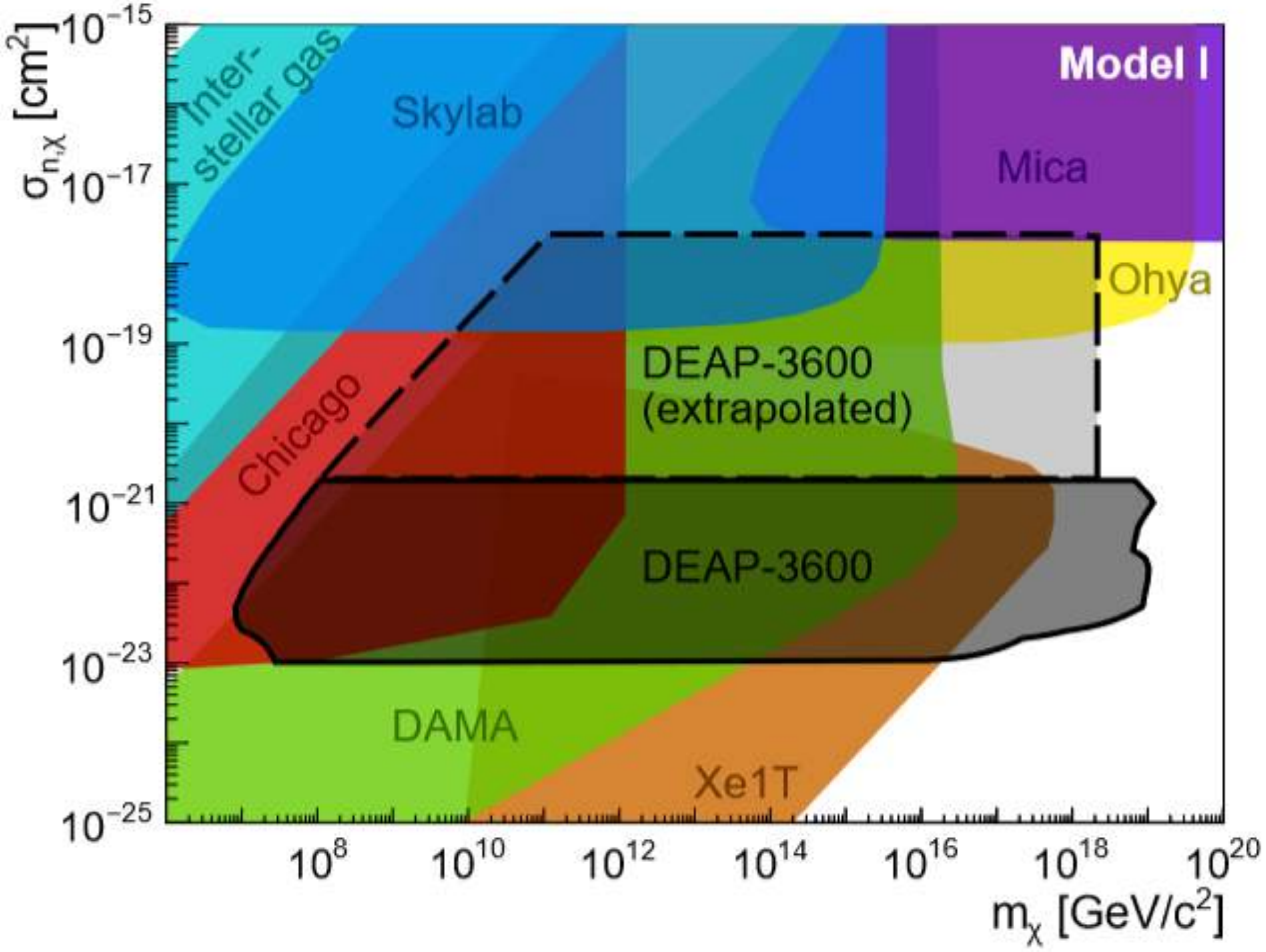


- Muon flux is about 17 muons per day, at SNOLAB
- Removal of **any event within [-10, 90]us** from the muon veto trigger

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

No event was found in all the ROIs!
Exclusion limits set within 90 % C.L. for two composite dark matter model

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



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Exclusion limits set within 90 % C.L. for two composite dark matter model

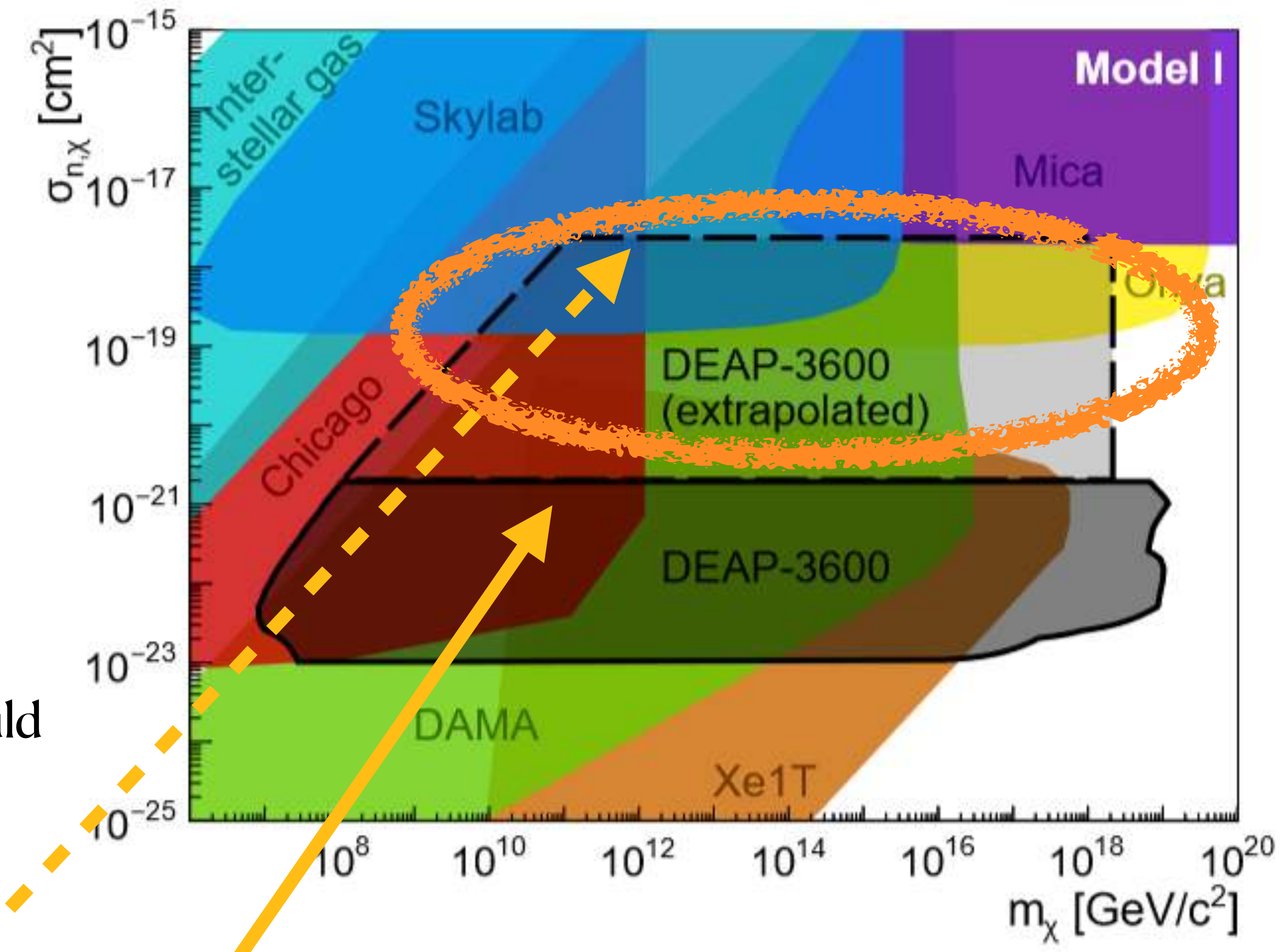
$$\mu_s = T \int d^3v \int dA \frac{\rho_\chi}{m_\chi} |v| f(\vec{v}) \epsilon(\vec{v}, \sigma_{T,\chi}, m_\chi)$$

Above 10 MeV:

- No calibration available
- simulations at very high cross-section candidates could not be performed due to computational limits.

Exclusion limit extrapolated assuming a conservative acceptance of 35 % in ROI4 , up to

$$\sigma_{n\chi}^{max} \times \left(\frac{PE_{Max}^{ROI4}}{PE_{90}^{sim}} \right)$$



$\sigma_{n\chi}^{max}$: highest cross-section which could be simulated

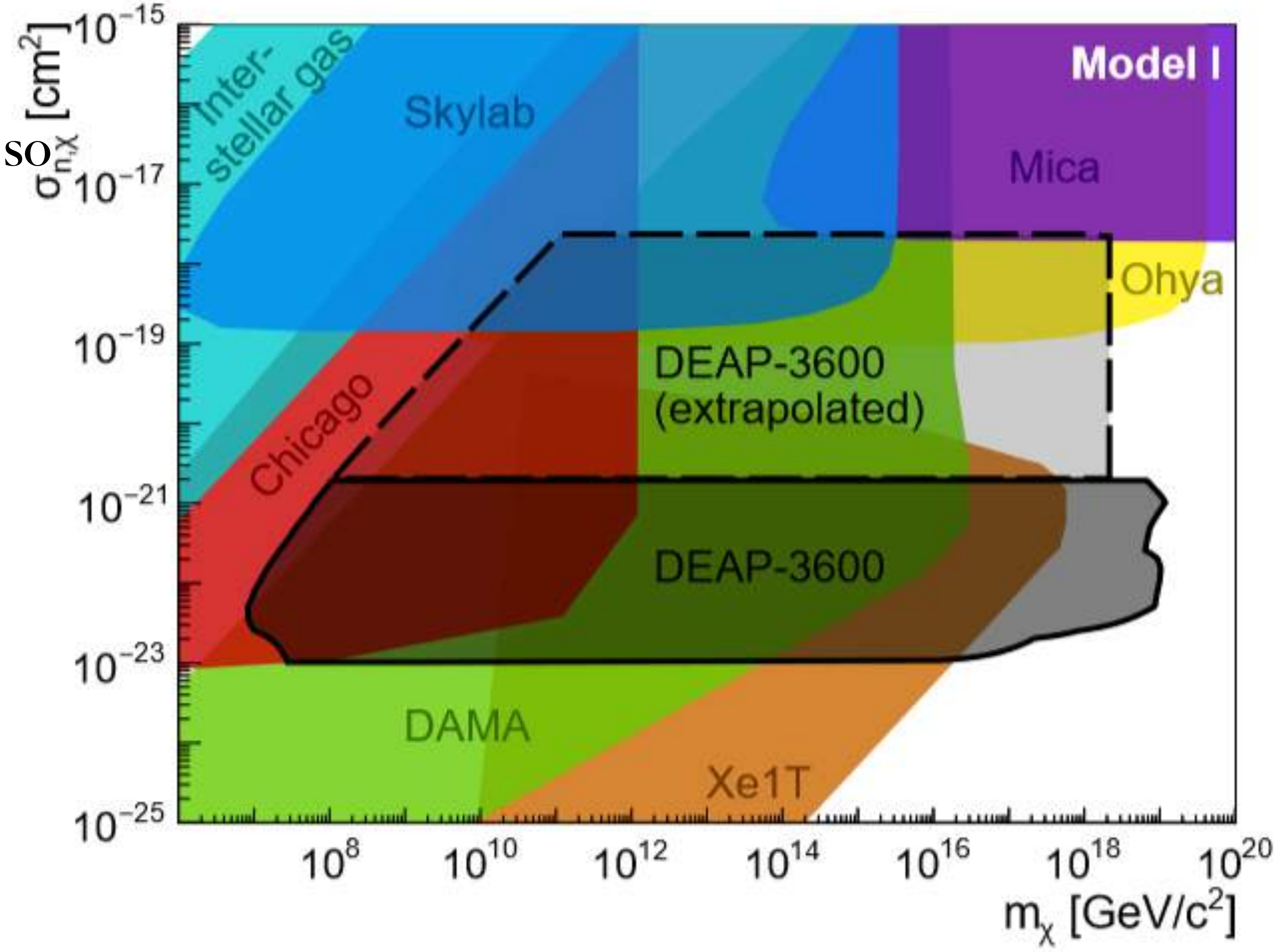
Results interpreted according to two theoretical models.

Model 1: dark matter candidate **opaque to the nucleus**, so the scattering cross-section at q=0 corresponds to the geometric size of the DM

This can be used to set **limits on strongly interacting, composite** dark matter candidates.

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

Interpolation on the flux scaling on the mass



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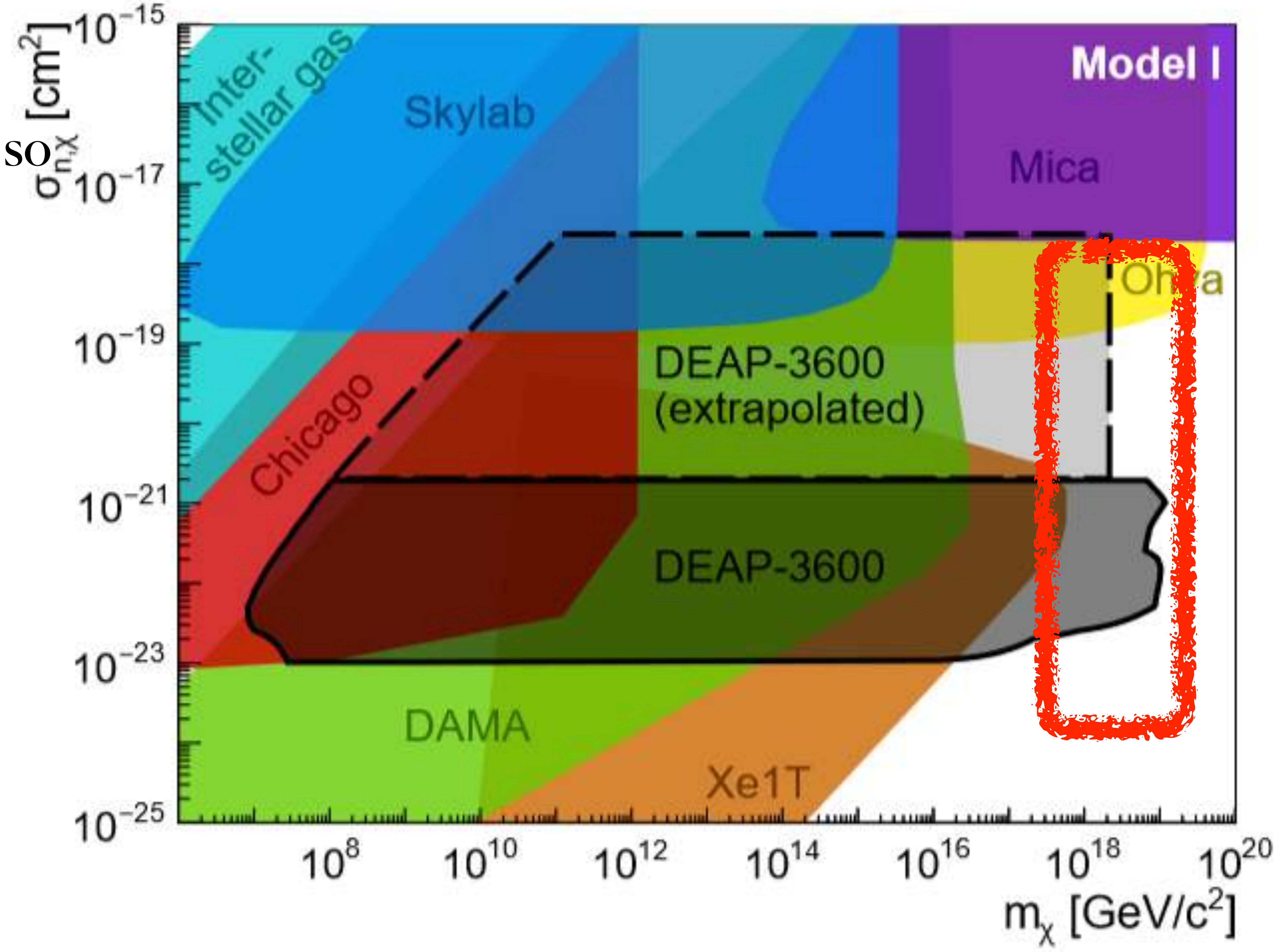

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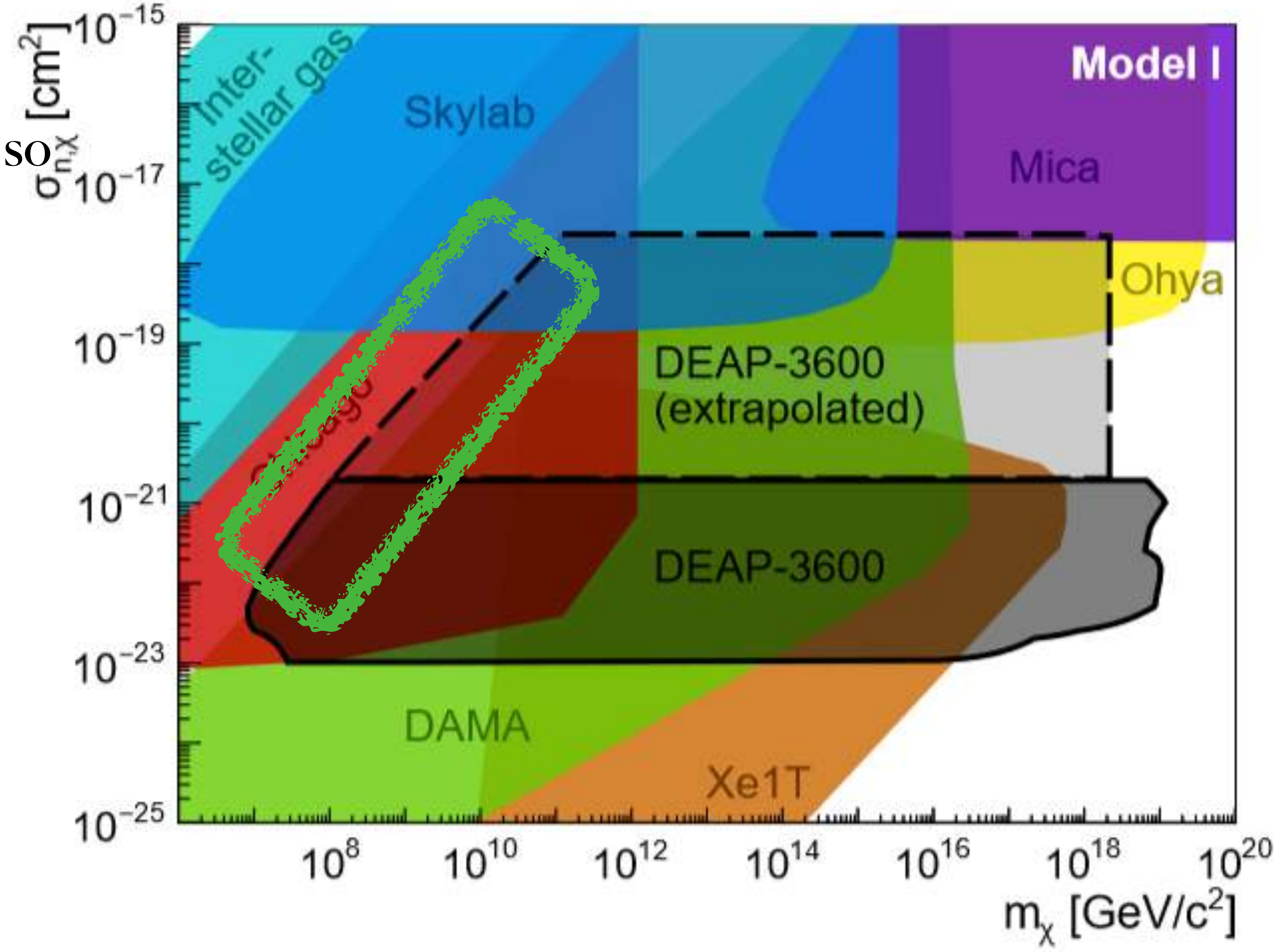
90 % of the expected DM signals falls below 1 MeV_{ee}



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This can be used to set **limits on strongly interacting, composite** dark matter candidates.

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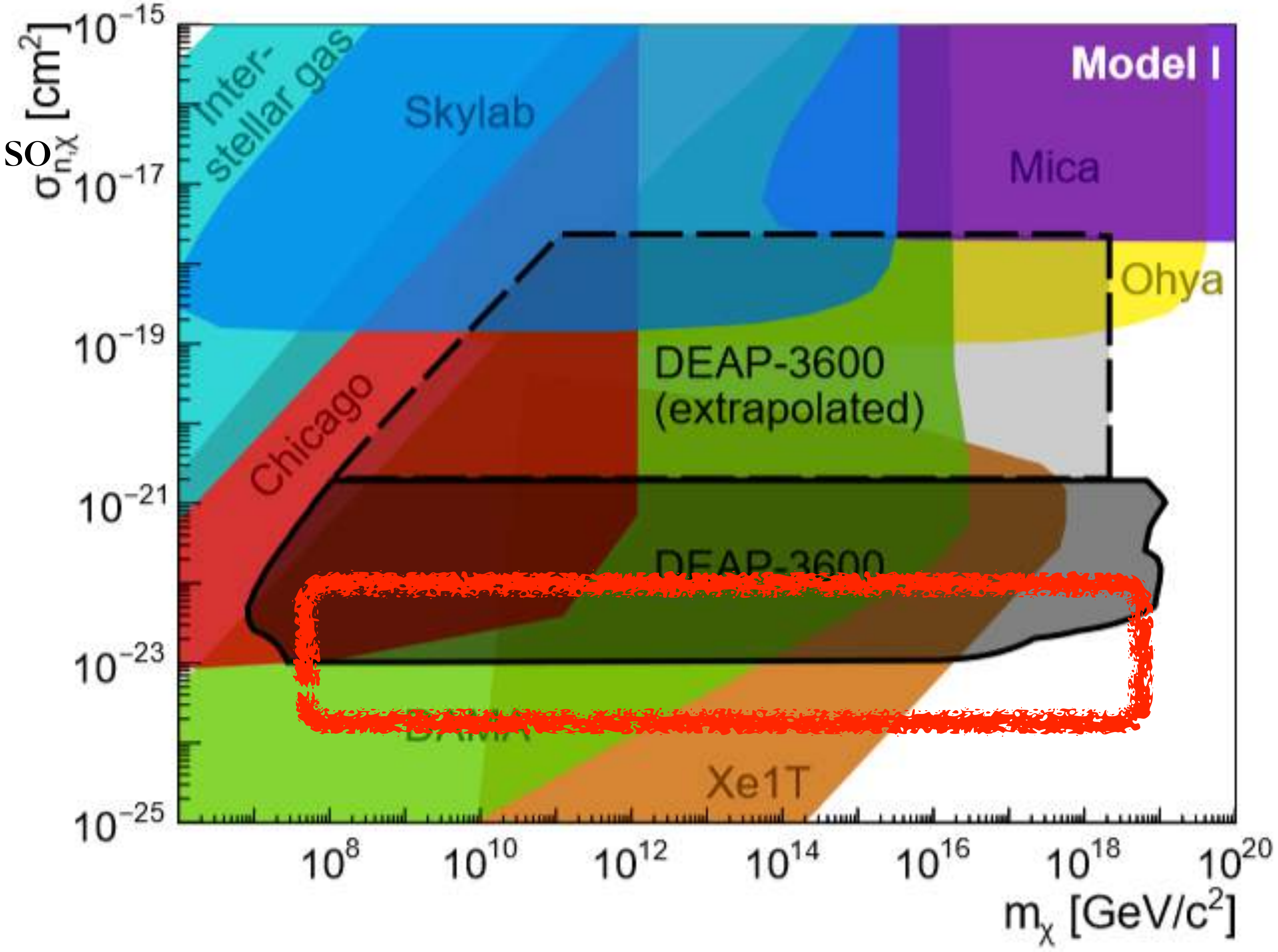


Lowest simulated cross-section that could be excluded

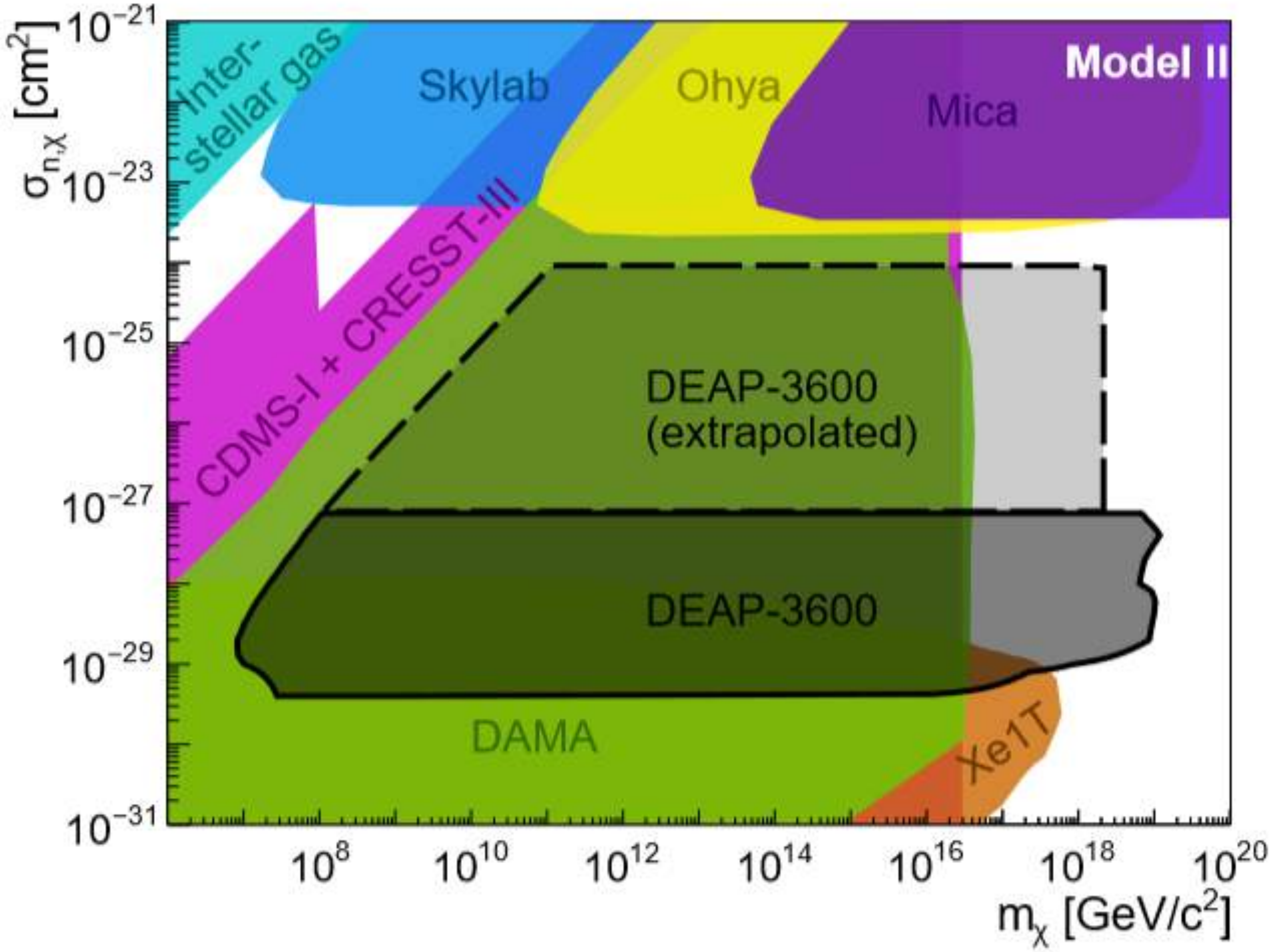
Model 2: at such high masses, this scaling is expected for **nuclear dark matter models**, with a N_D nucleons, each with mass m_D and radius r_D, resulting in a total mass $m_\chi = N_D m_D$ and radius $R_D = r_D N_D^{1/3}$.

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

Specifically, to keep the s-wave approximation, it must be

$$\sigma_{T\chi} < \sigma_{geo}$$

For dark nuclei R_D >> 1 fm we can find potentials resulting in $|F_\chi(q)|^2 \approx 1$,



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

The unblinding is performed for each single ROI.

The dataset in detail:

Start: November 4, 2016

End: March 8, 2020

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	$70\,000–4 \times 10^{8}$	10.4–60 000	0	0.05	$(10 \pm 3) \times 10^{-3}$

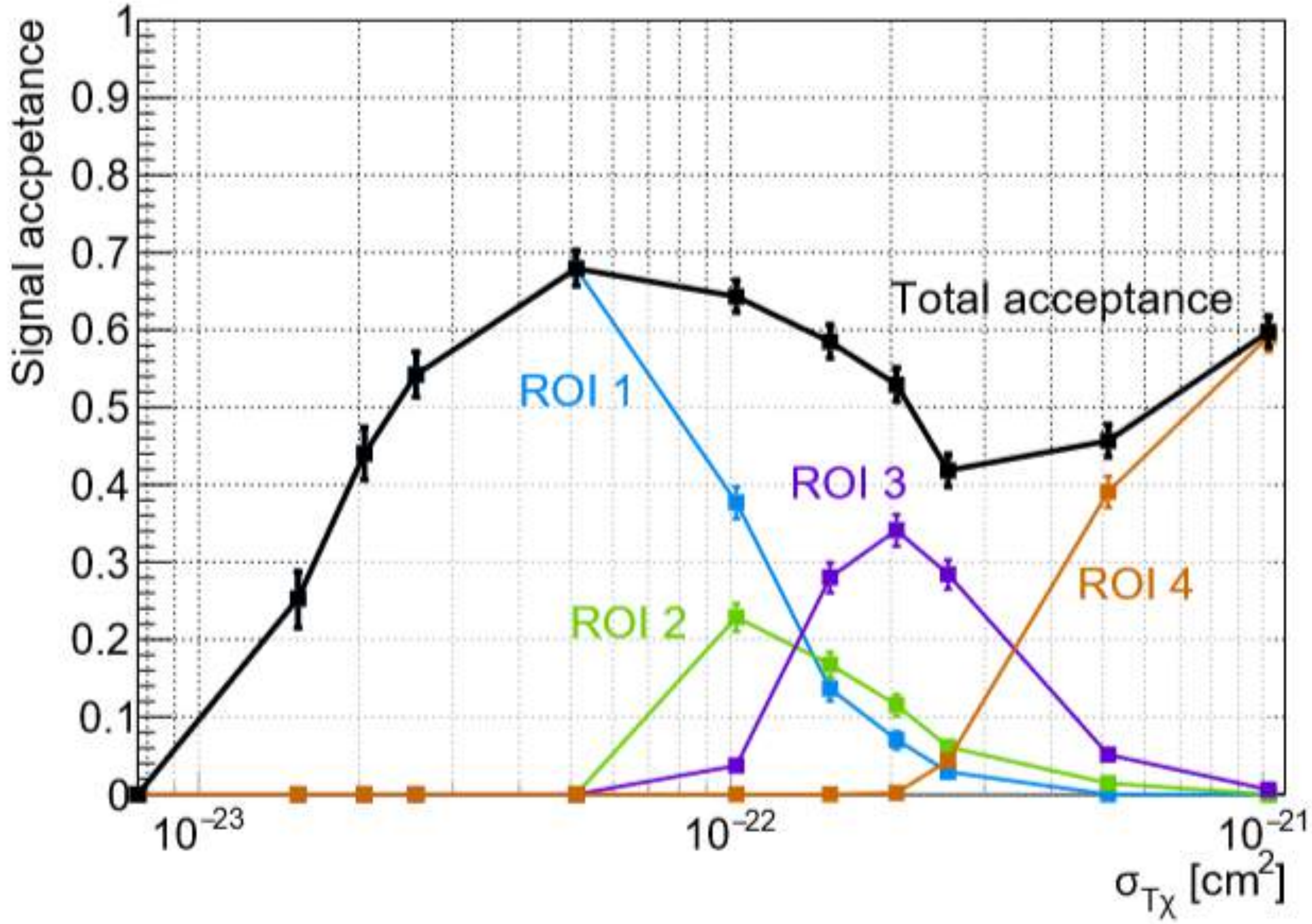
Excluded data:

(3 ± 3)us/trigger for signal falling in two events

9 days to test the selection cuts

6 days from the muon coincidence sideband

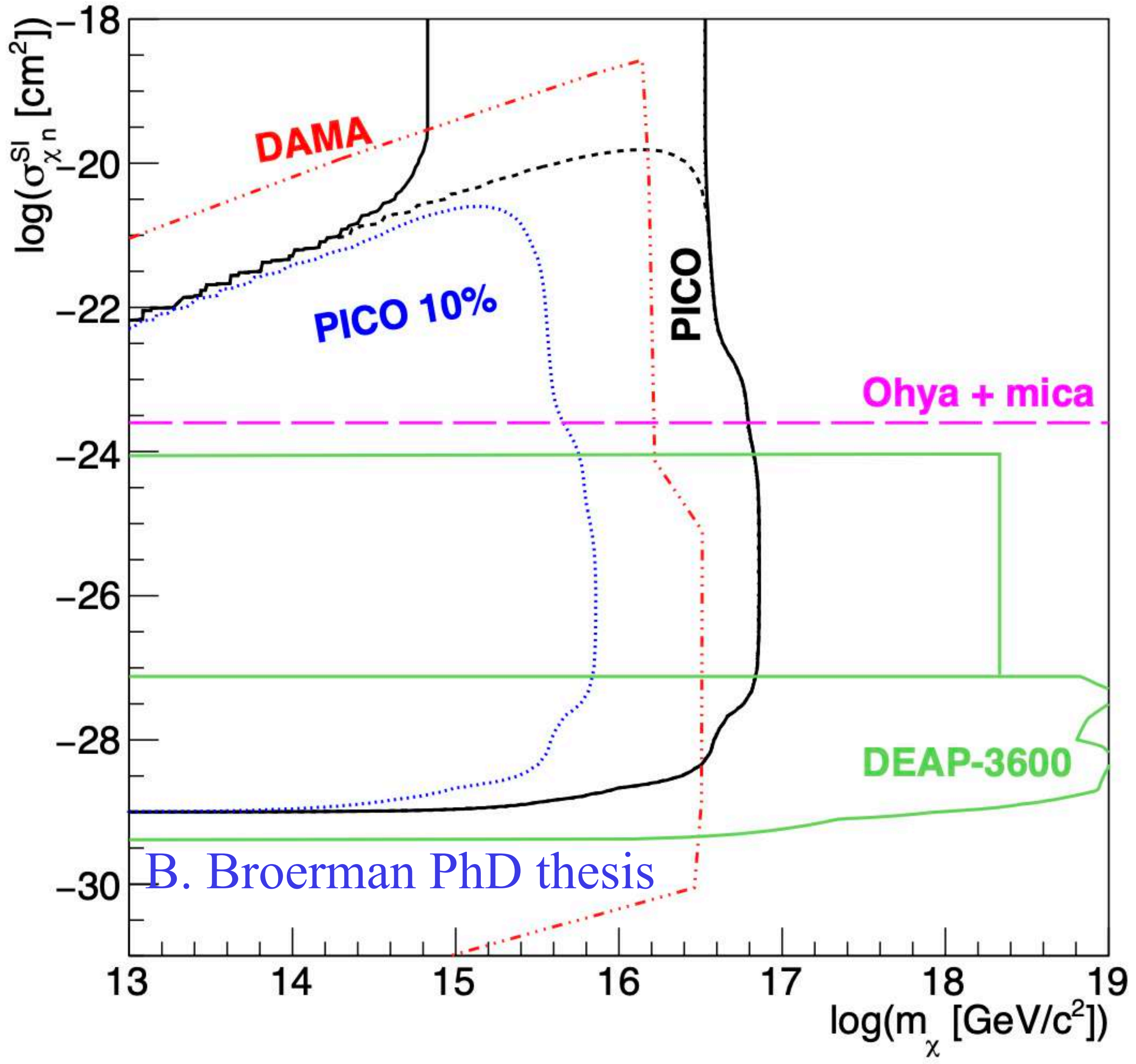
Total : (813 ± 8) days



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 %

In all the ROIs the background level is **0.05 ± 0.03**.



More ground-based experiments are now investigating their sensitivity to ultra-heavy dark matter candidates