Last results from DEAP-3600

Dr. Michela Lai
on behalf of
DEAP-3600 Collaboration

33 RENCONTRES DES BLOIS - 26 MAY 2022

DEAP Collaboration

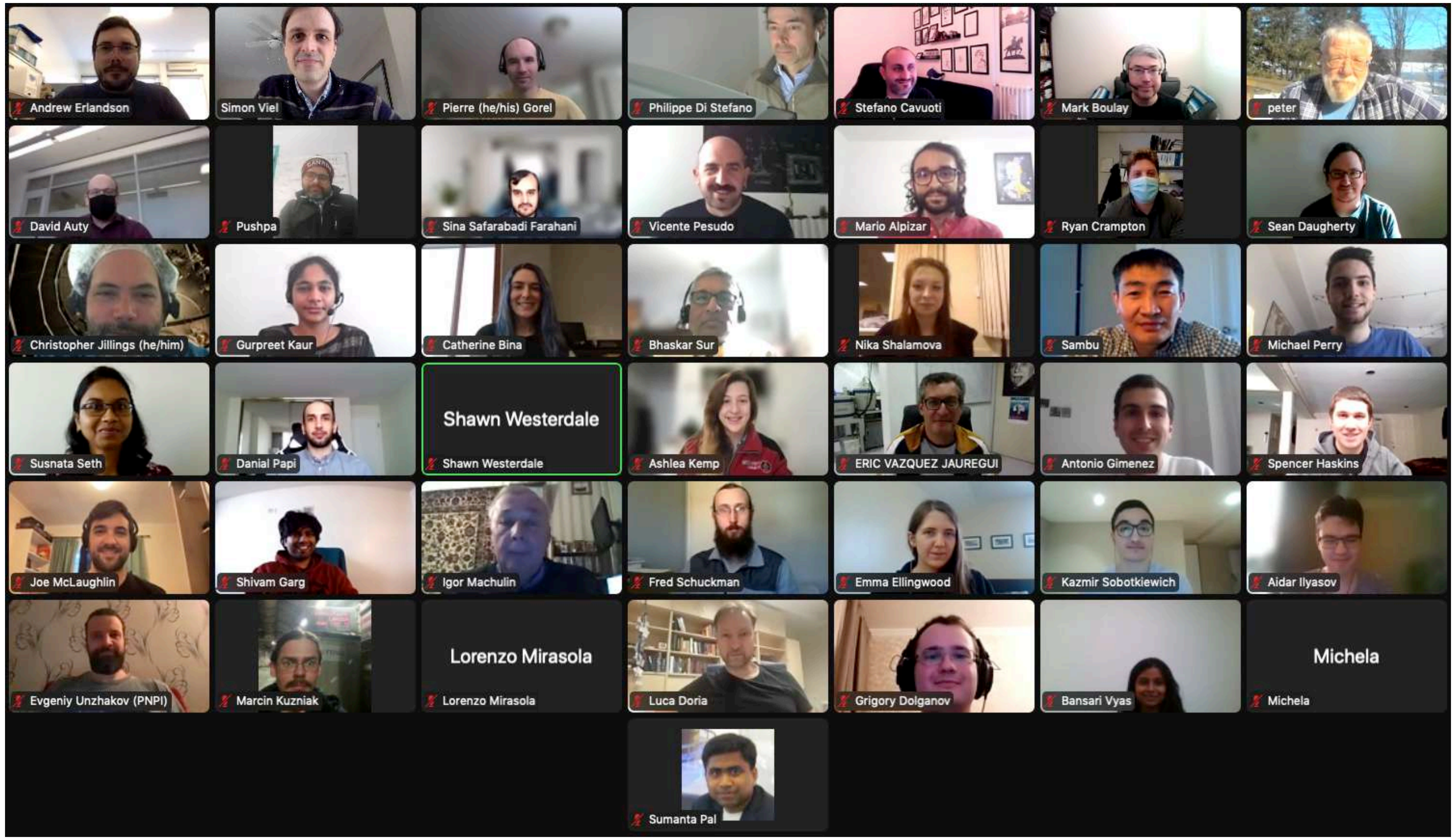
SNOLAB

TRIUMF

Technical University of Munich

TUM

US University of Sussex



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Princeton University

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National Research Center "Kurchatov Institute"

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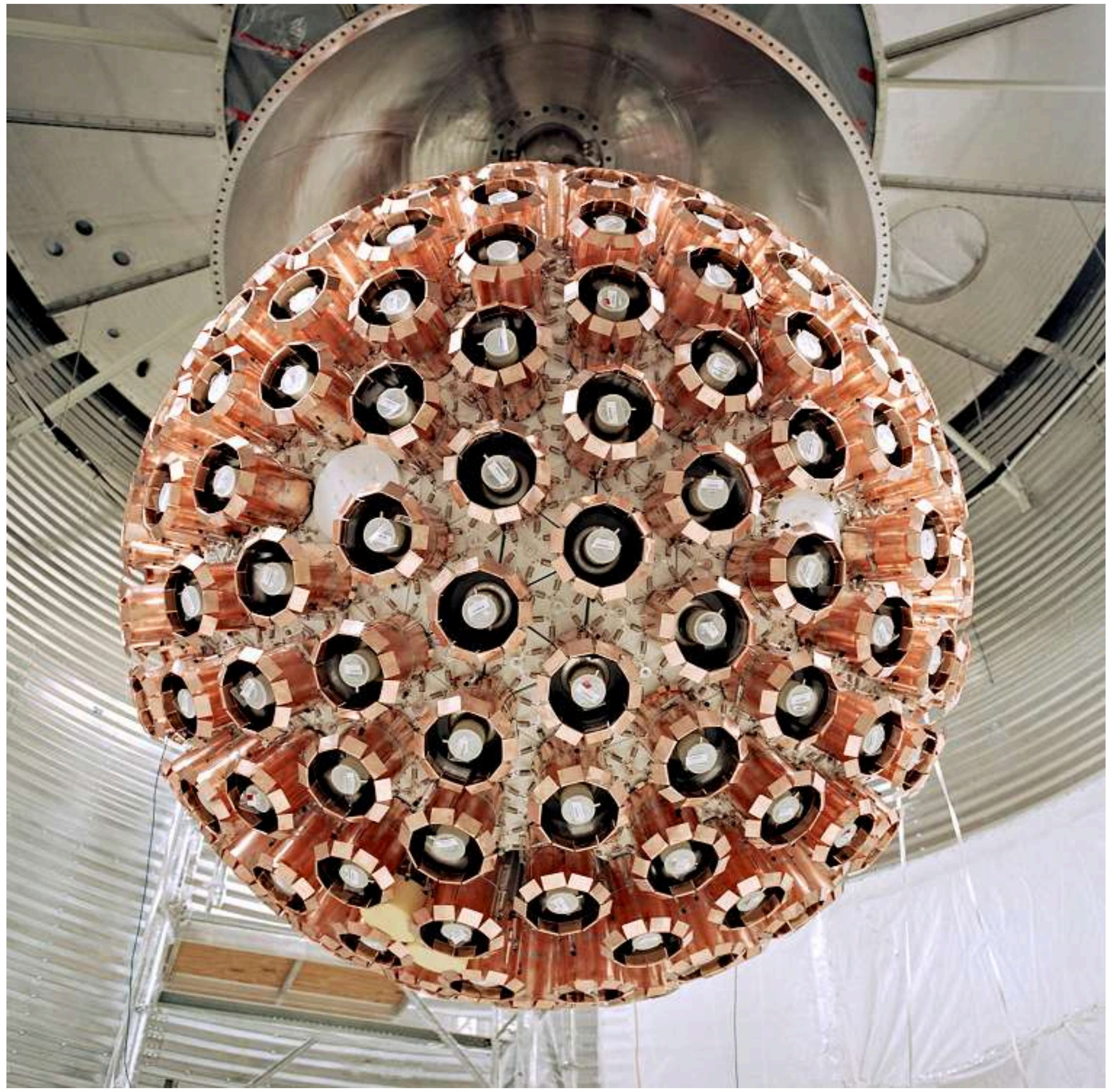
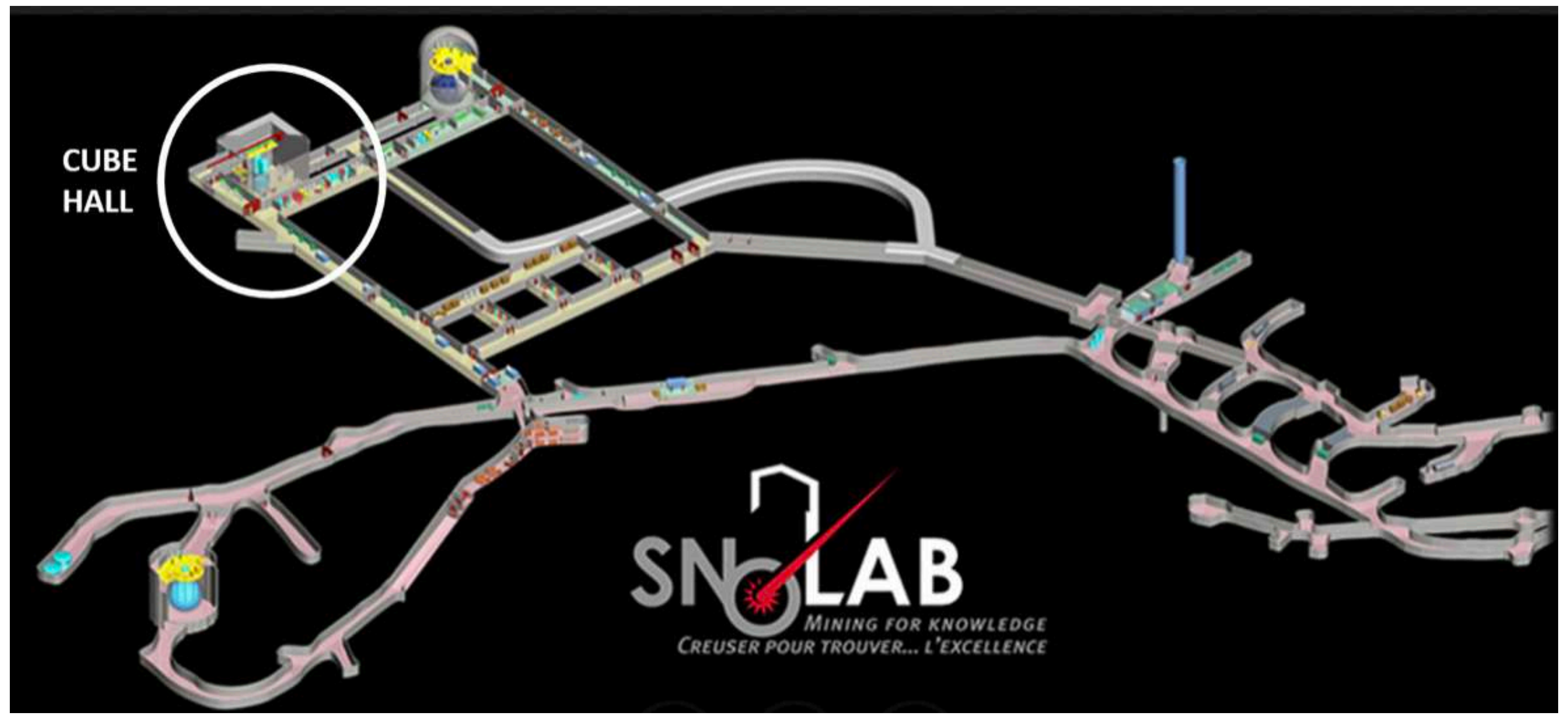
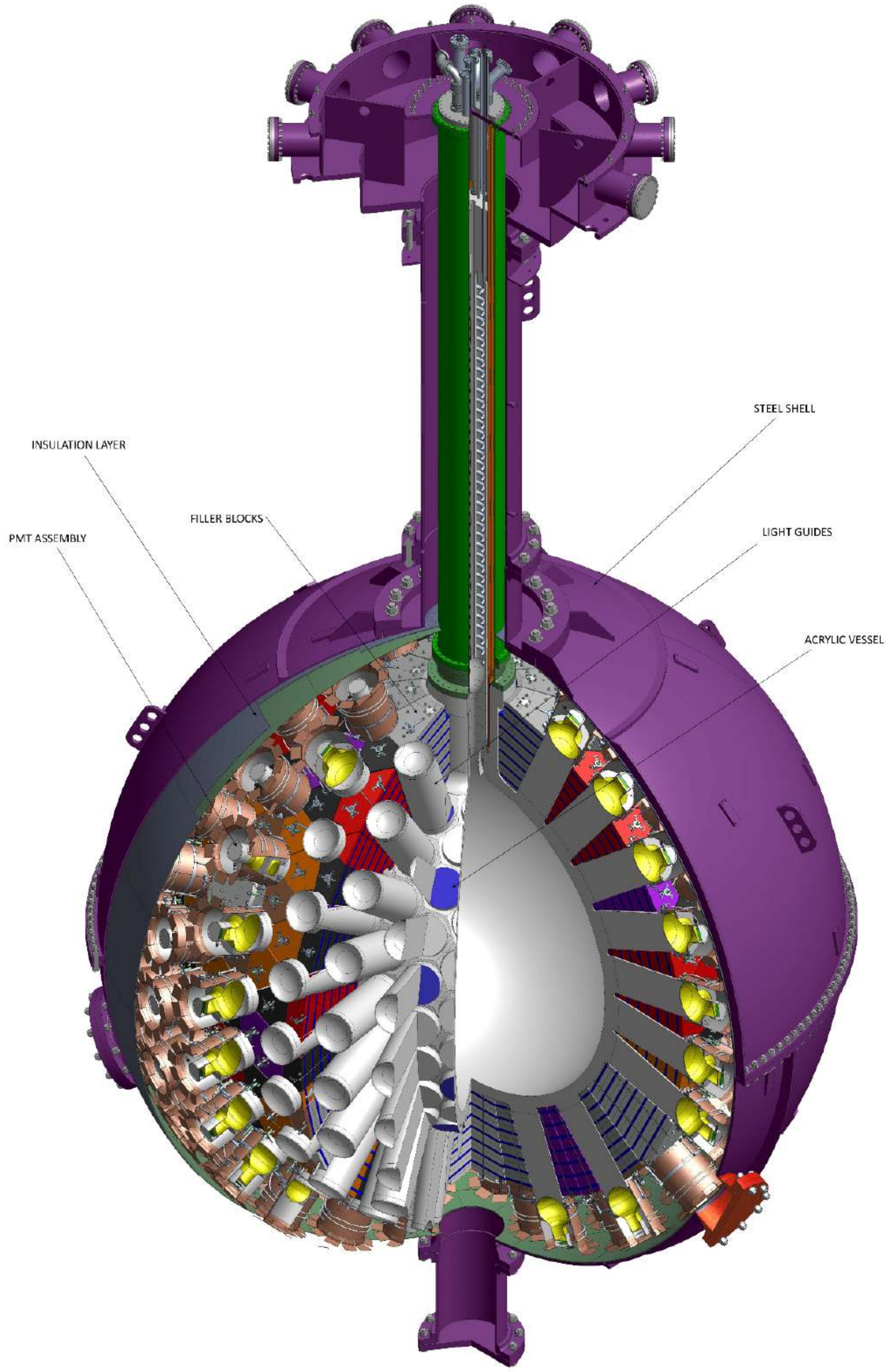
The detector

- 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$_{ee}$



Astroparticle Physics 108 (2019) 1-23

The target

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**

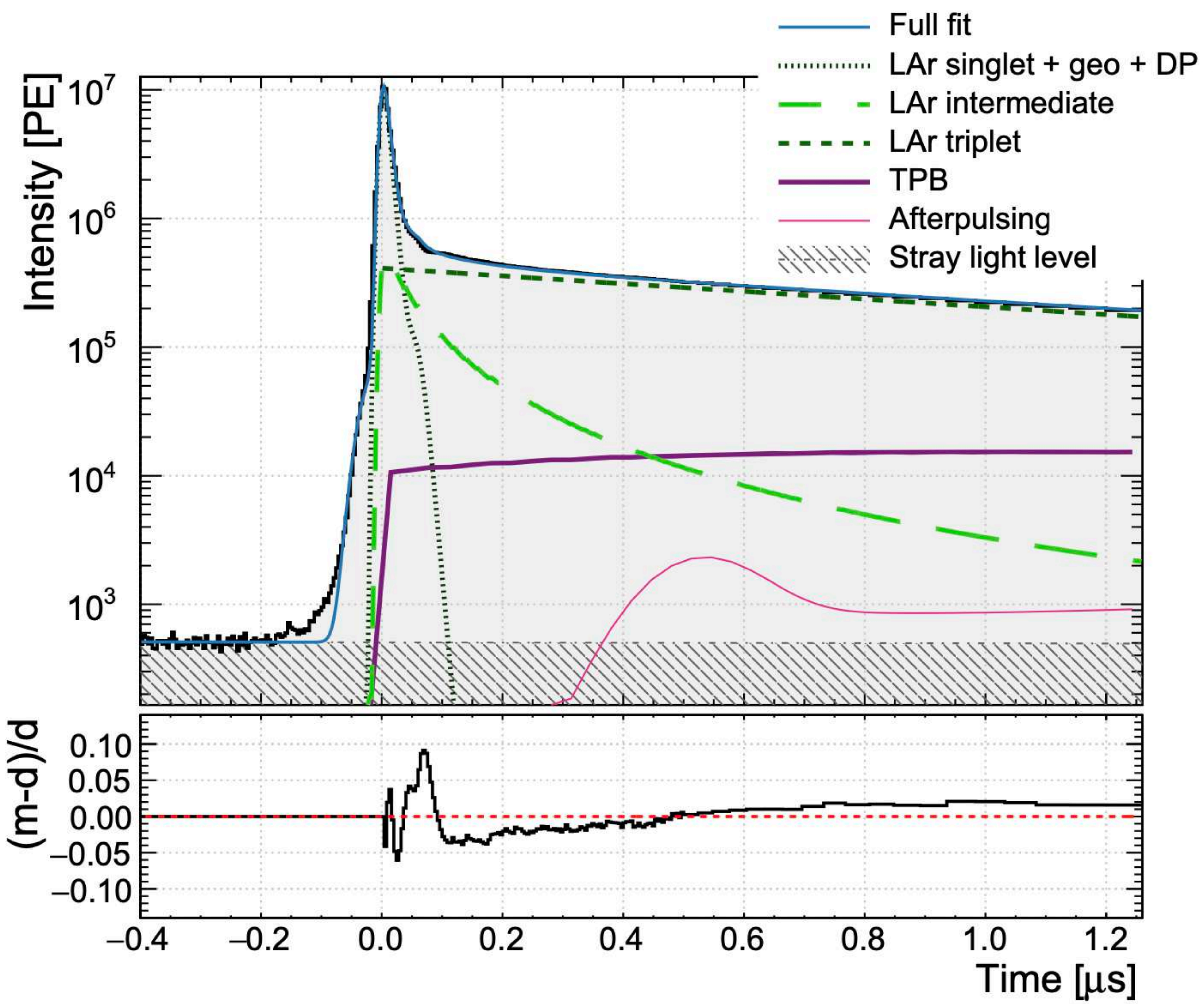
- ^{39}Ar beta decays allowed to model the pulse shape due to **scintillation and the detector response**

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

$\tau_s = 8.2ns$

$\tau_{rec} = 175.5ns$ $\quad R_t = 0.71$

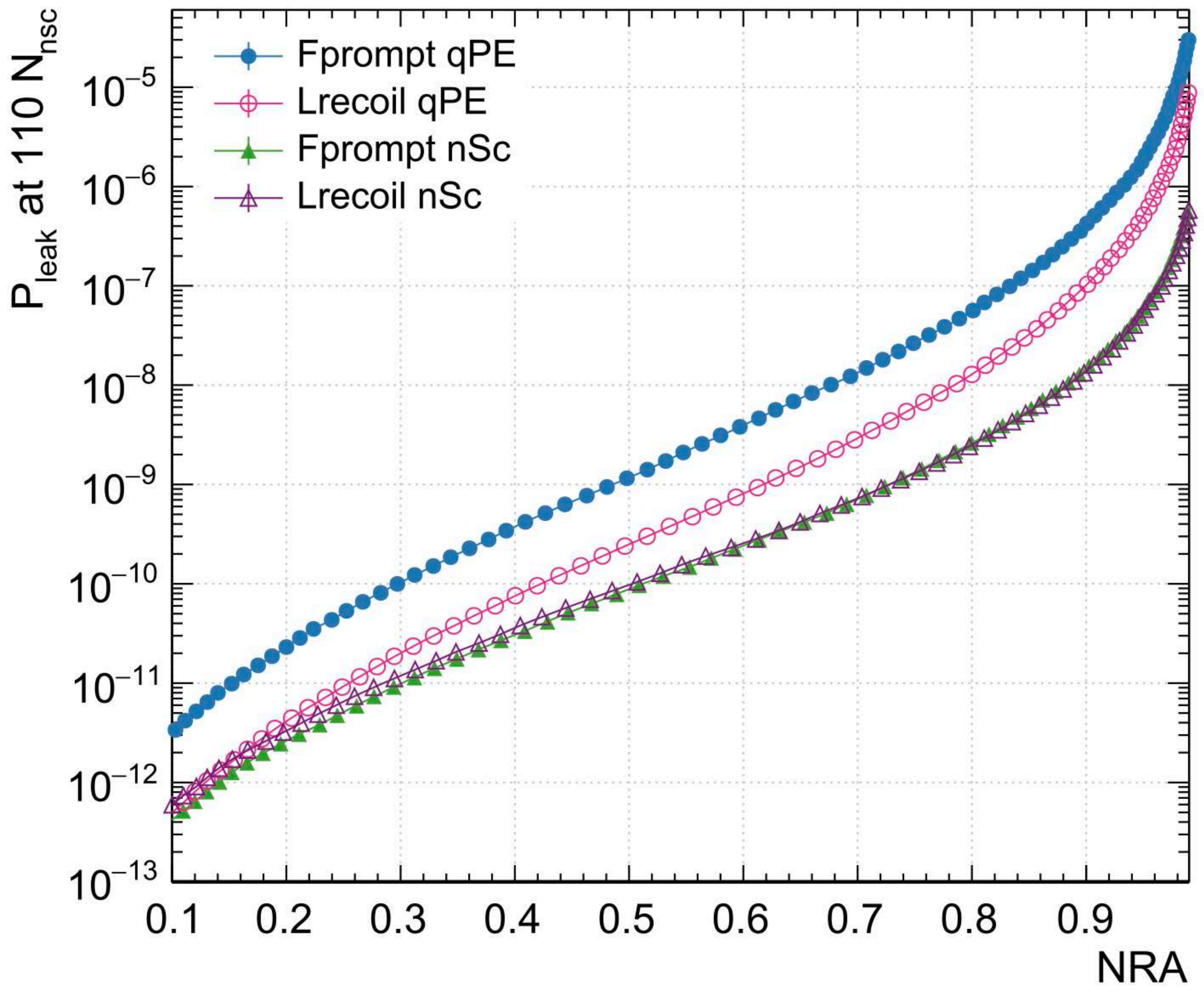
$\tau_t = 1445ns$ $\quad R_s = 0.23$



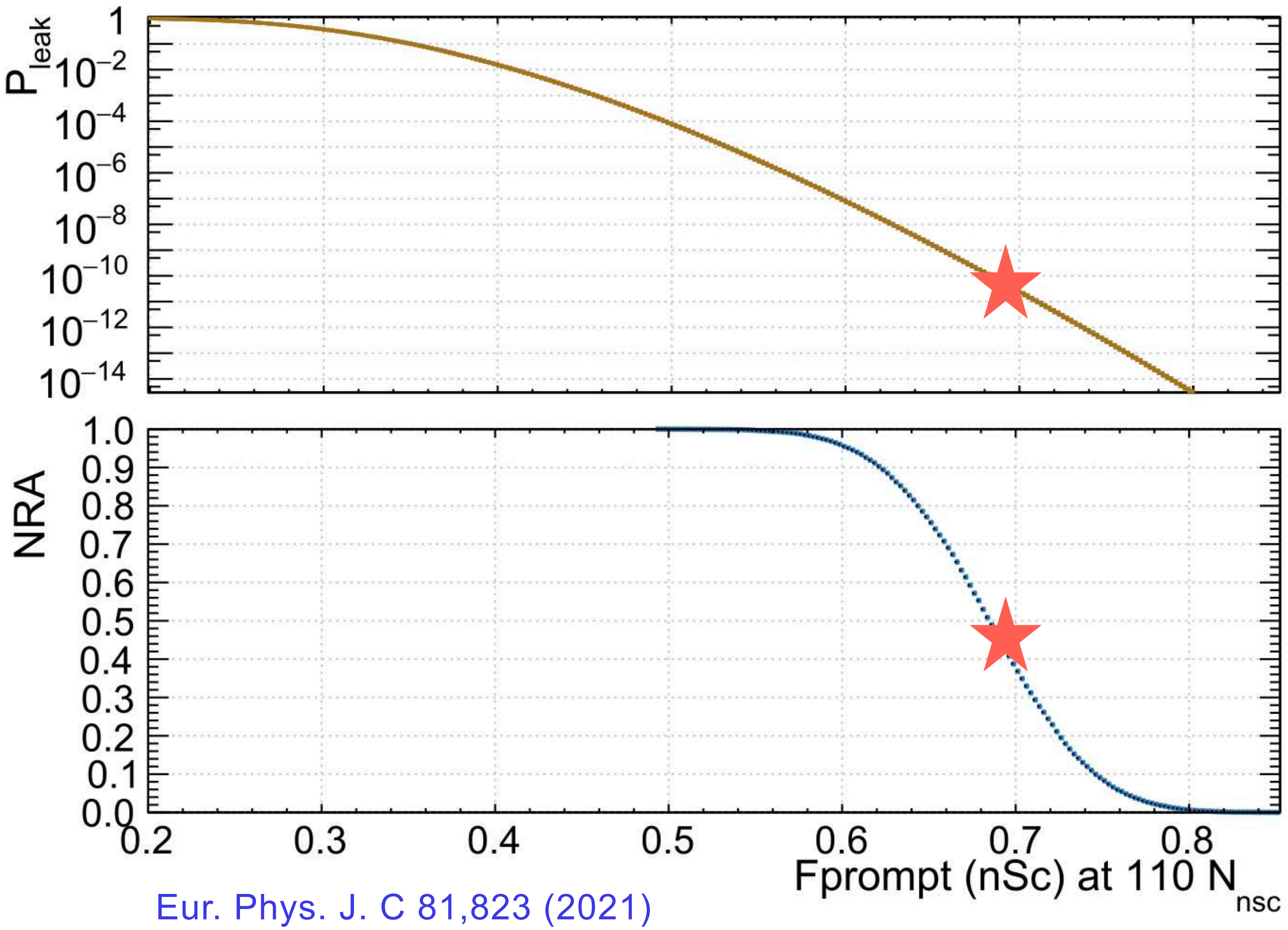
Eur. Phys. J. C 80, 303 (2020)

Pulse shape discrimination

- Four pulse shape discrimination parameters have been defined, based on different photon counting and test statistics



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

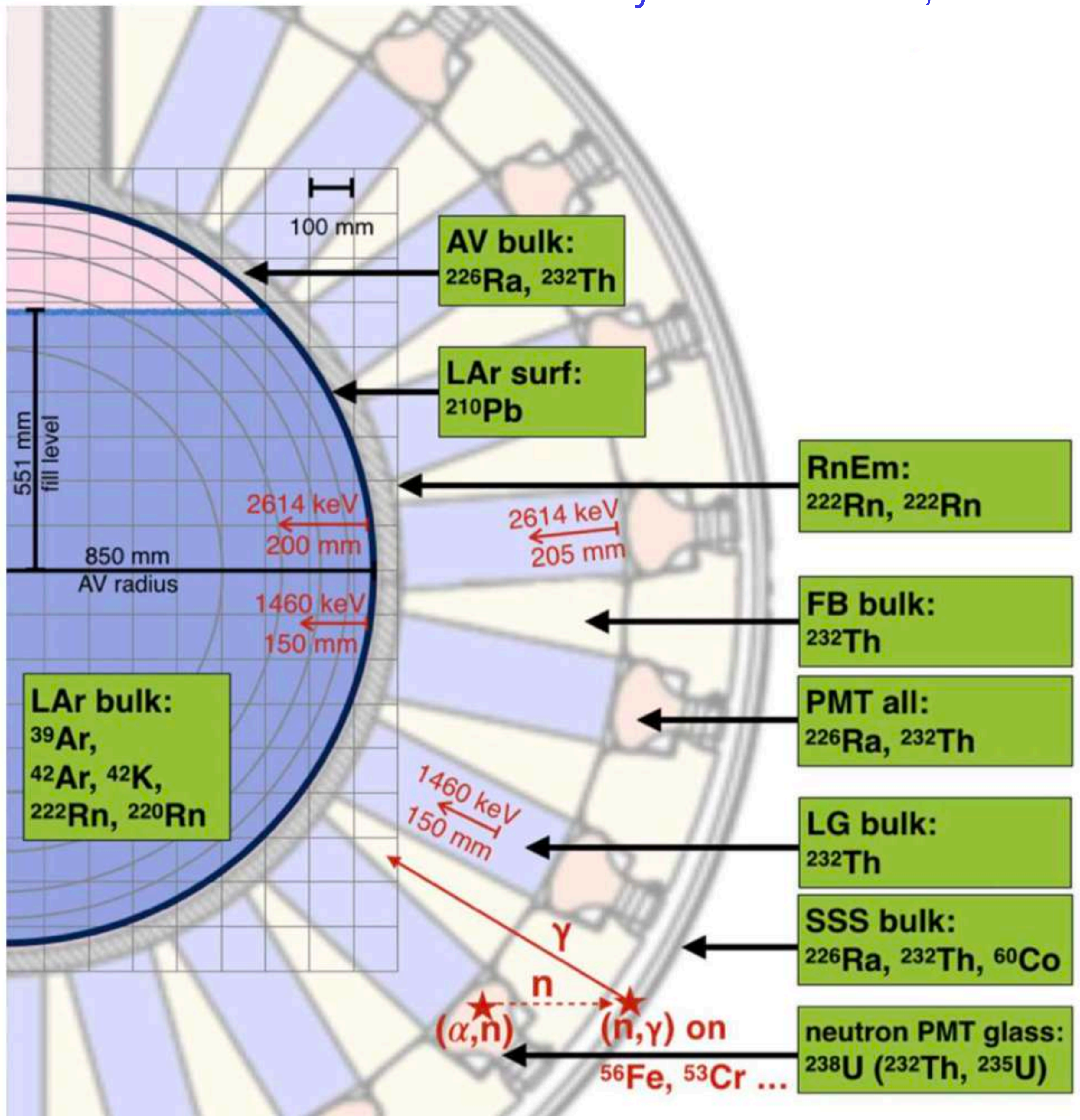


Eur. Phys. J. C 81,823 (2021)

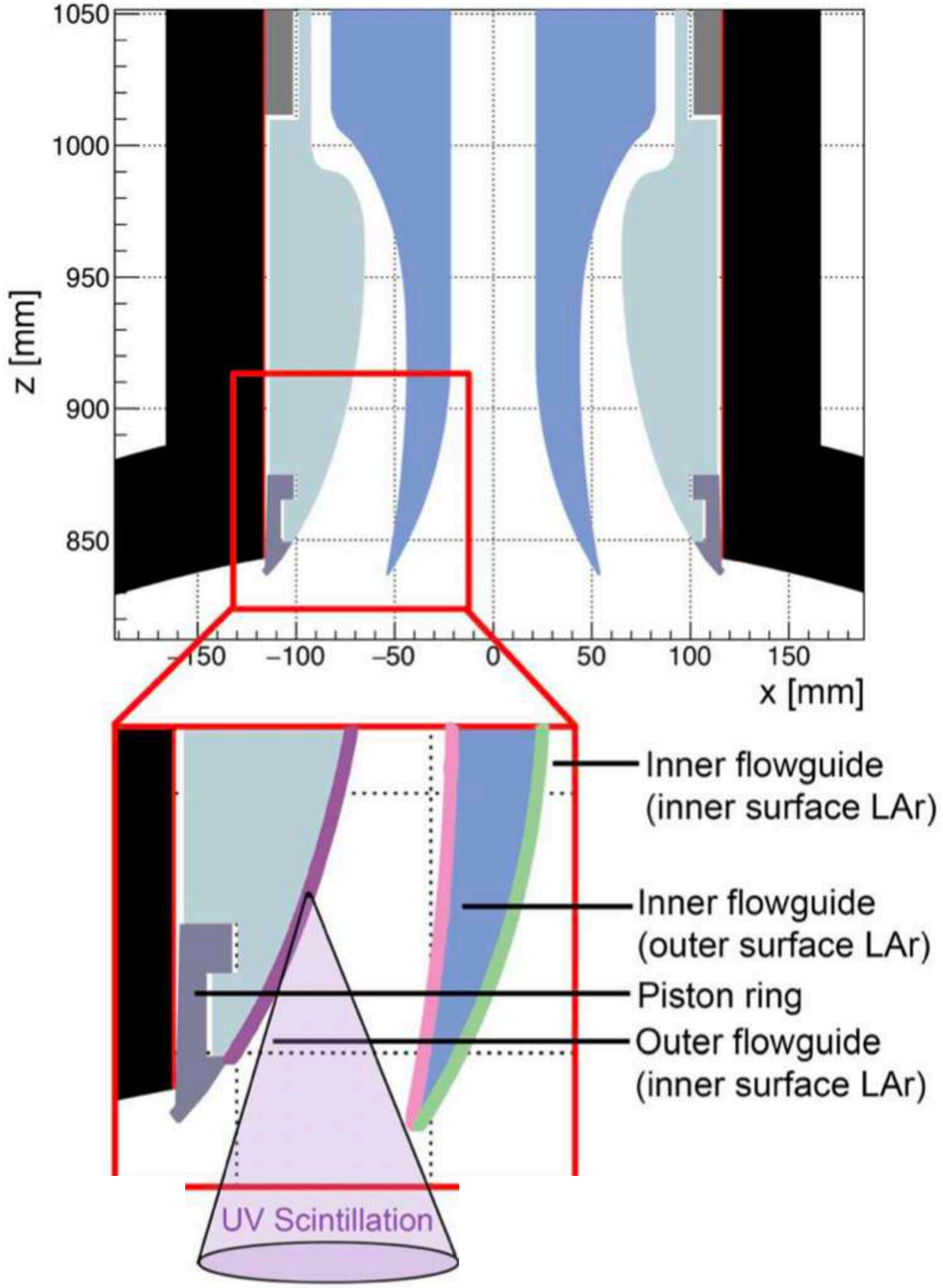
Backgrounds

- 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)

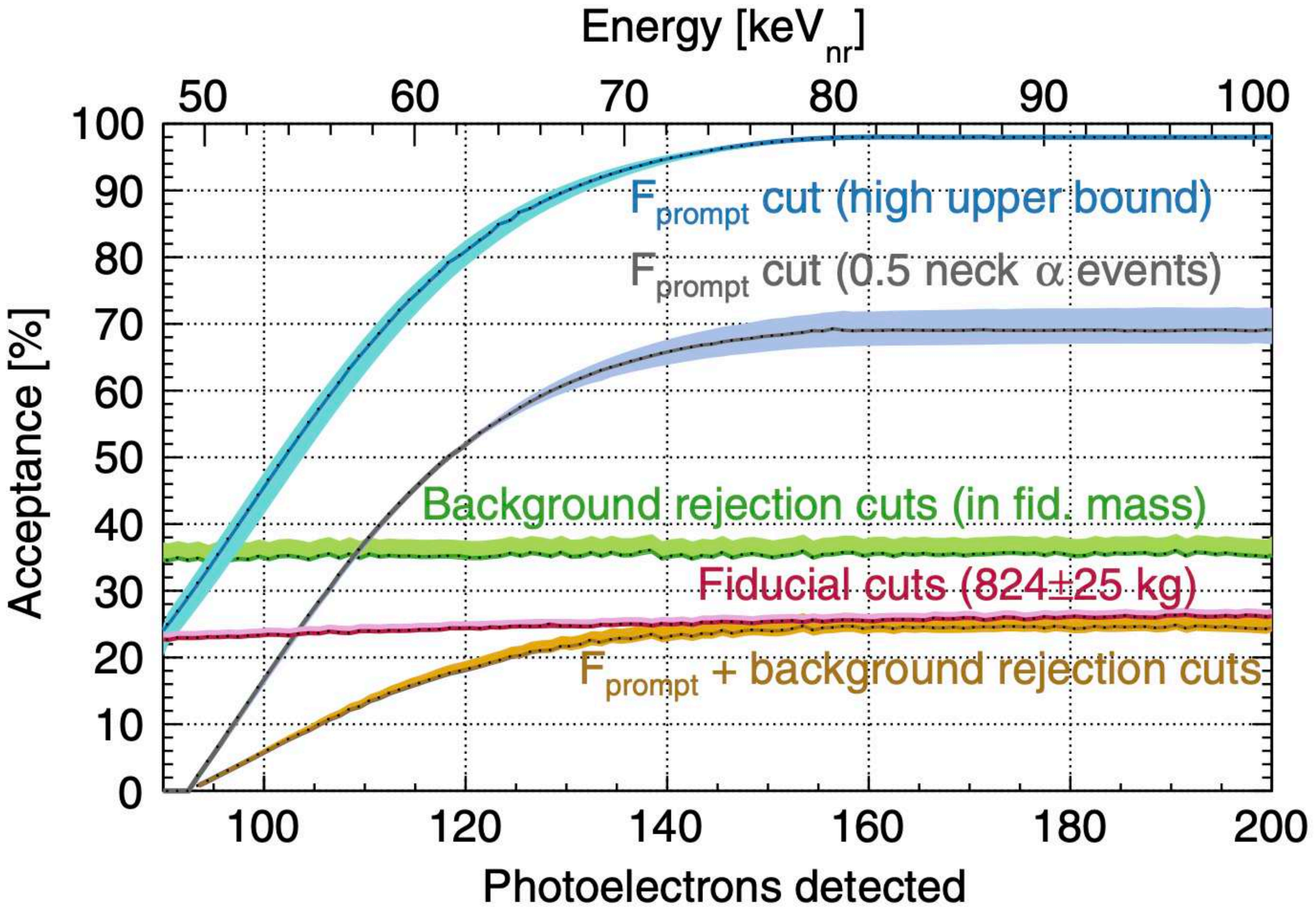


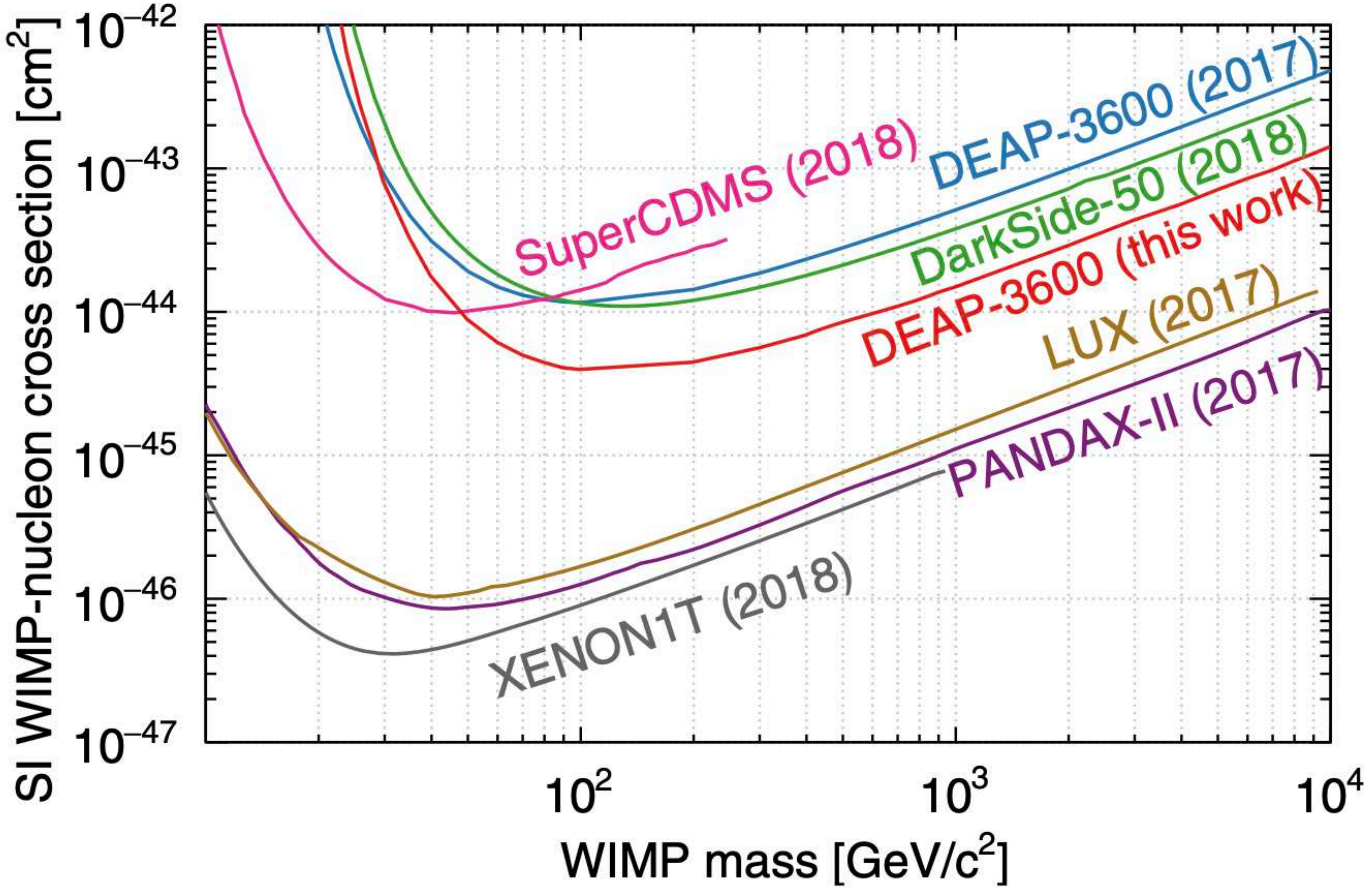
- Surface alphas removed with fiducial cuts, r < 630 mm
- Neck alphas removed with:
  - F_{prompt} upper cut
  - Early pulses in Gas Argon PMTs
  - Charge fraction in top 2 PMT rings
  - MVA selection cuts (ongoing)



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

Constrains on NREFT interactions…

- The results from previous analysis can be re-read in terms of **NREFT** operators

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

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

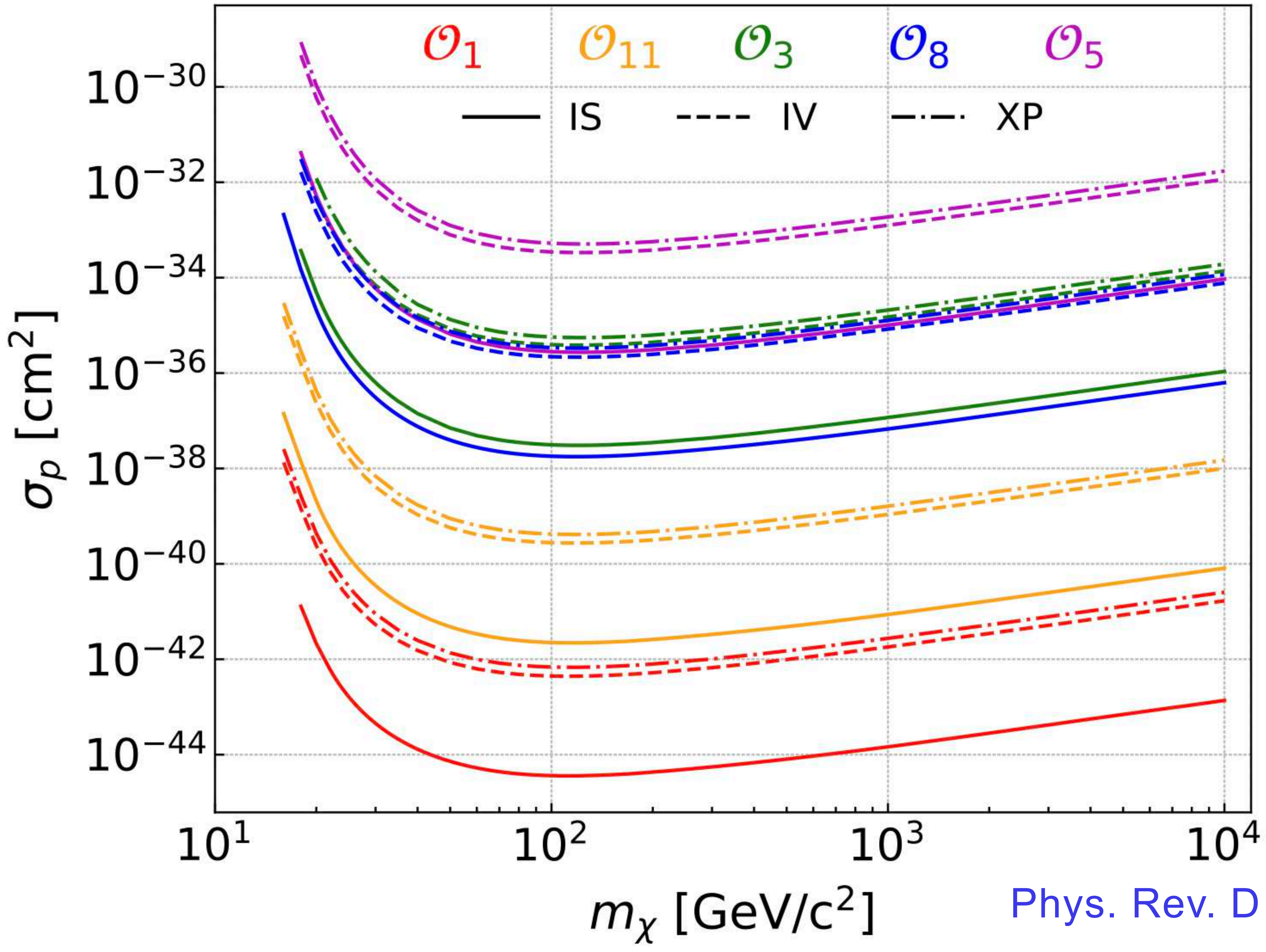
Effective DM-proton cross-section $\sigma^p = \frac{(c_i^p \mu_p)^2}{\pi}$

IS = Isospin coupling $\sigma_i^n = \sigma_i^p$

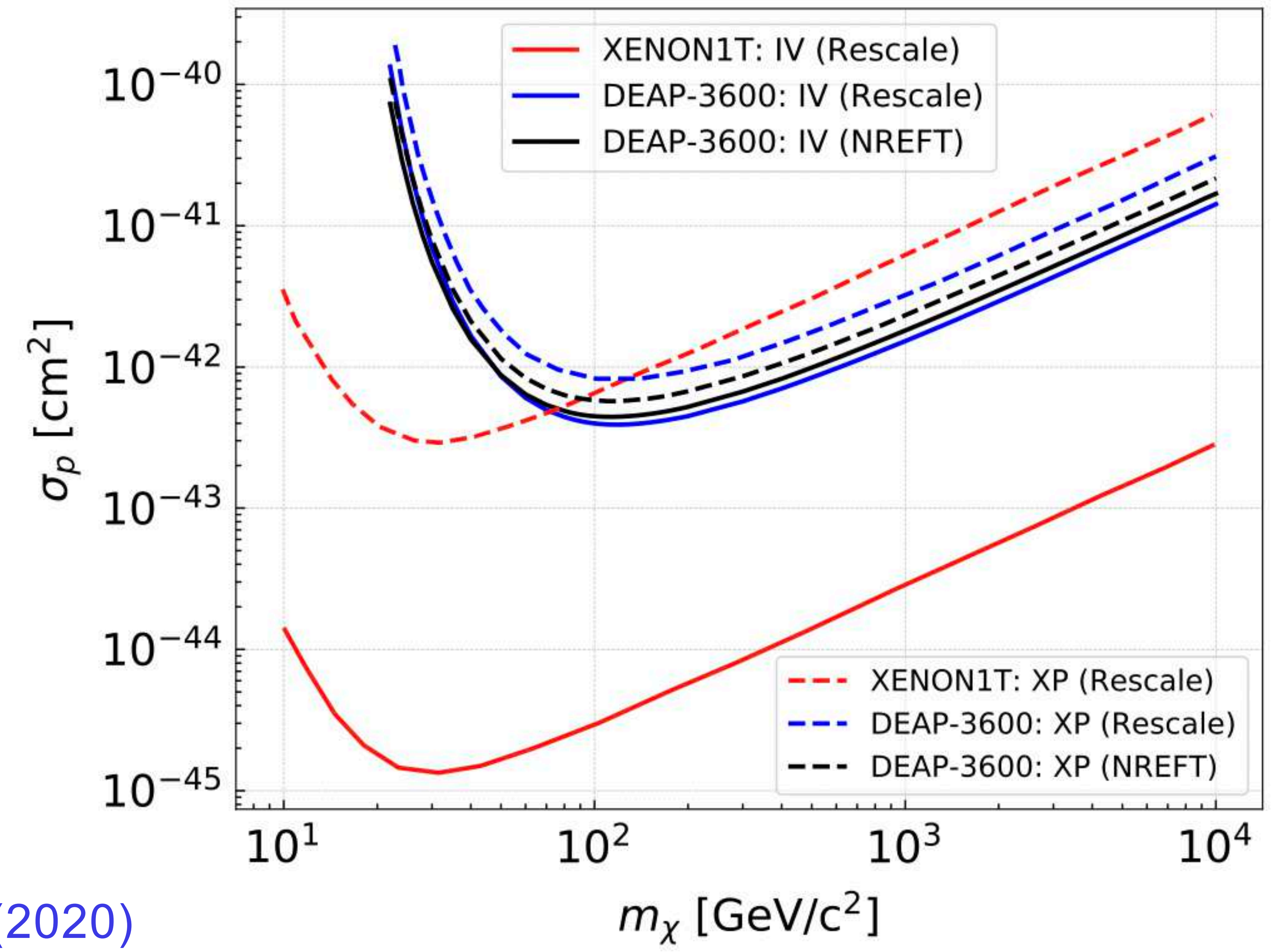
IV = Isovector coupling $\sigma_i^n = -\sigma_i^p$

XP =XenonPhobic coupling $\sigma_i^n = -0.7\sigma_i^p$

} **Isospin Violating Scenarios**



Phys. Rev. D 102, 082001 (2020)



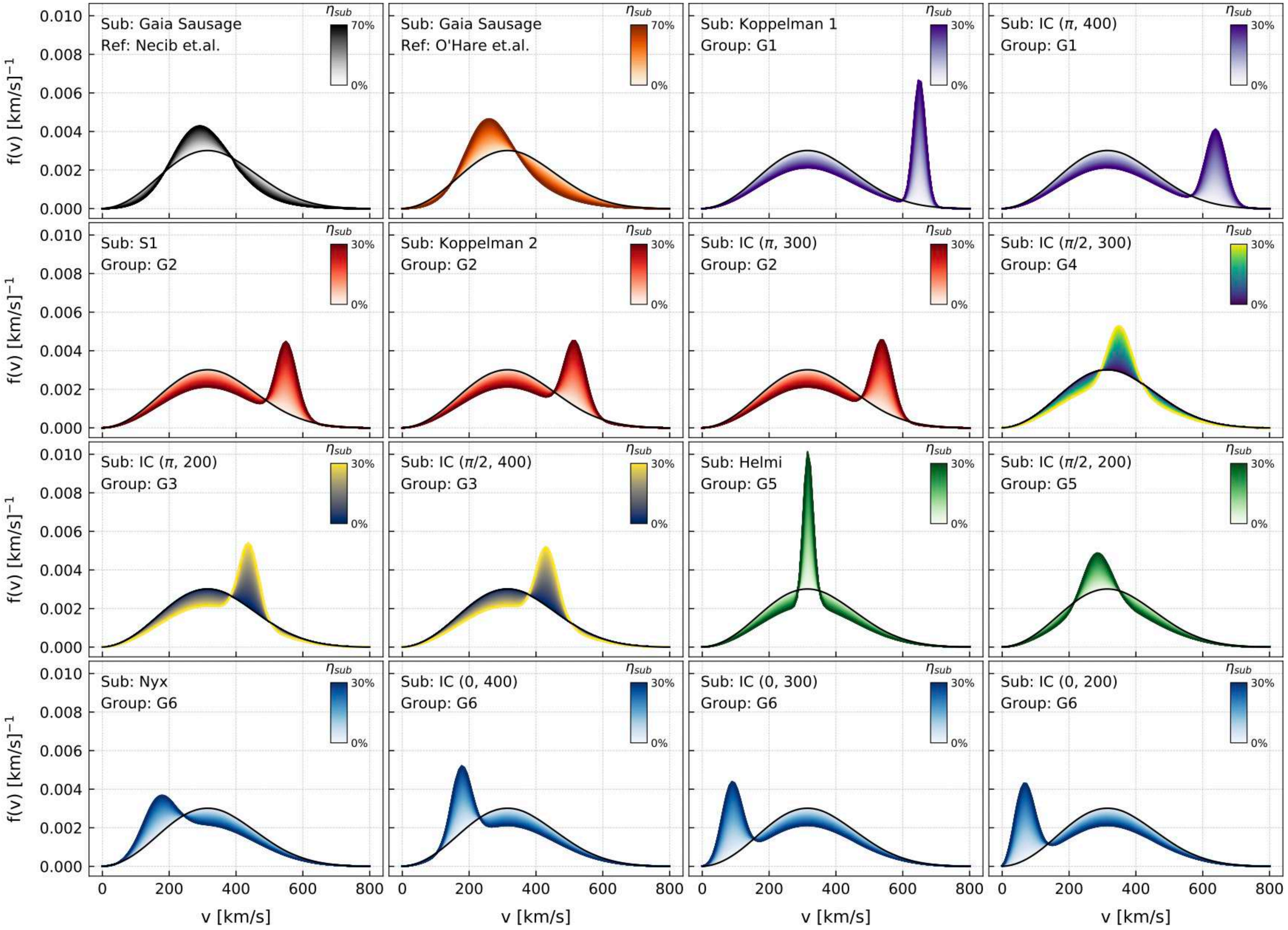
… with non-standard halo

- GAIA and Sloan Digital Sky Survey recently observed inflating clumps and streams around our Galaxy
- Some dark matter might be into these substructures

$$\frac{dR}{dt} = N_T \frac{\rho}{m_\chi} \int_{v>v_{min}} f(\mathbf{v} + \mathbf{v_E}(\mathbf{t})) \frac{d\sigma_T(E_R, v)}{dE_R} d^3v$$

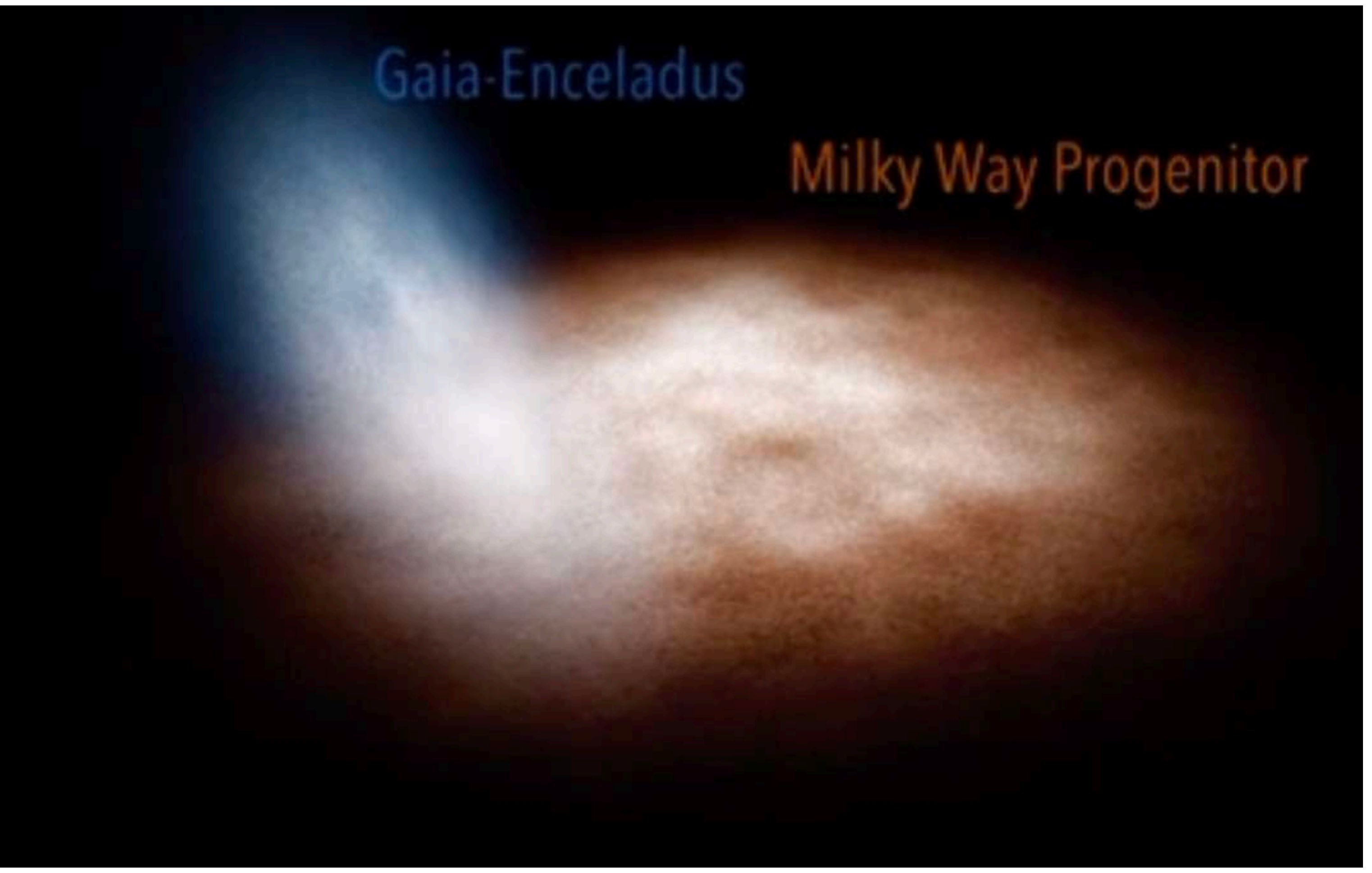
$$f_{SHM}(\vec{v}) = \frac{1}{\sqrt{2\pi\sigma}} exp\left(-\frac{v^2}{2\sigma^2}\right)$$

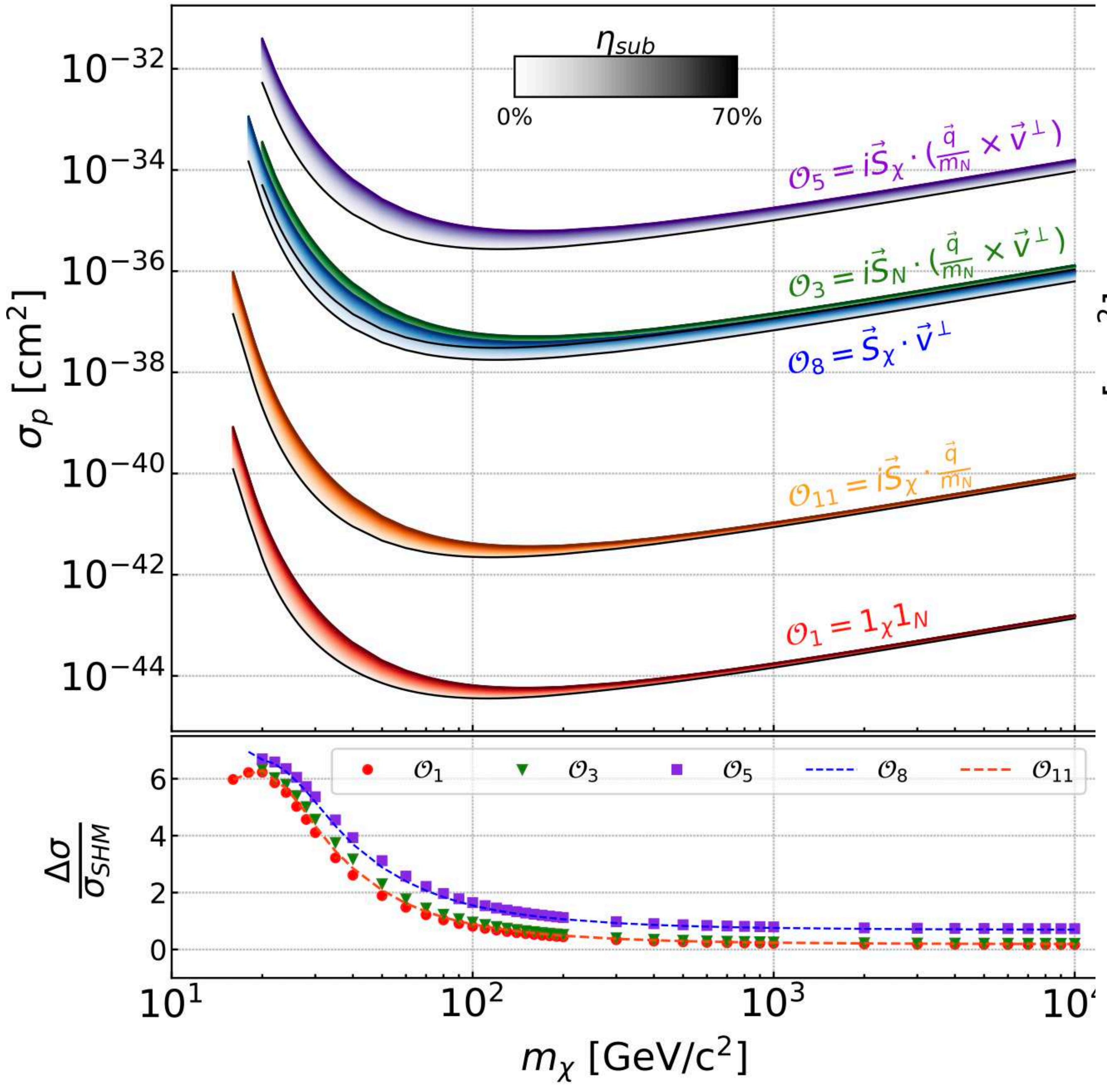
$$f_{DM}(\vec{v}) = (1-\eta_{sub}) f^{gal}_{SHM}(\vec{v}) + \eta_{sub} f^{gal}_{sub}(\vec{v})$$



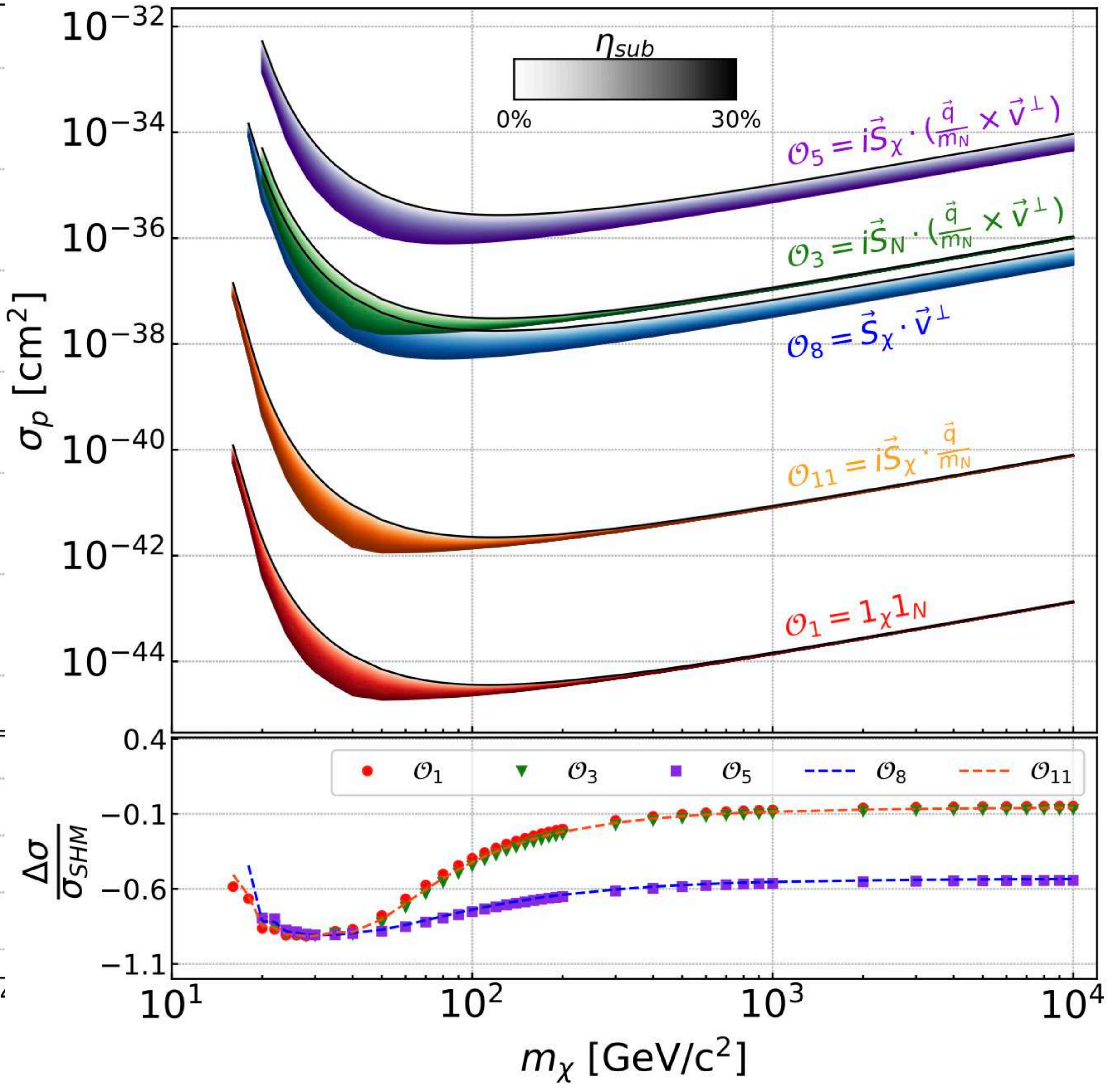
… with non-standard halo

- The **exclusion limits** are evaluated with these modified velocity distributions in the halo
- Streams and Infalling clumps (IC) are arranged in **groups**, according to their impact on the exclusion curves





Gaia Sausage (Necib)



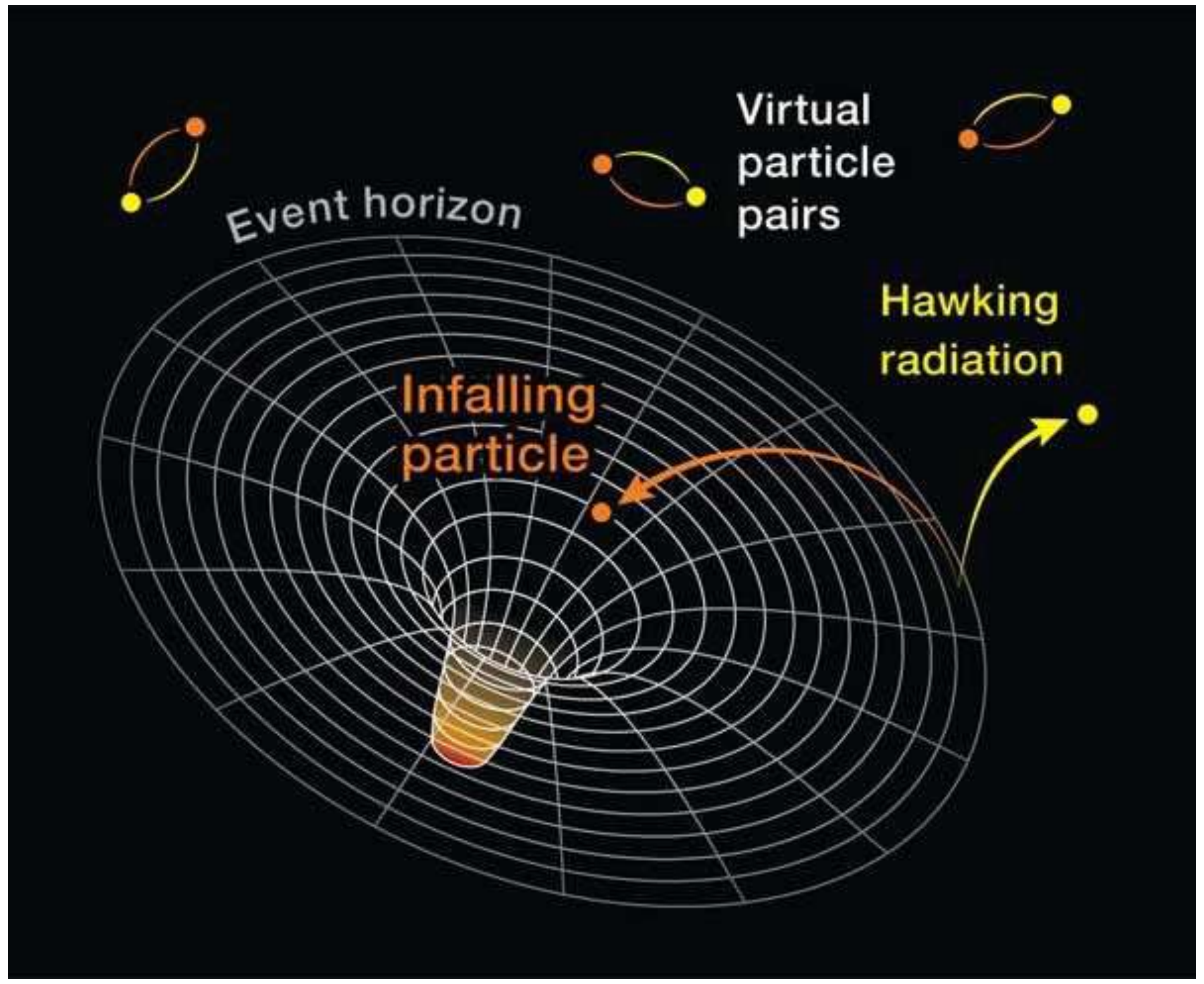
G1 stream

Phys. Rev. D 102, 082001 (2020)

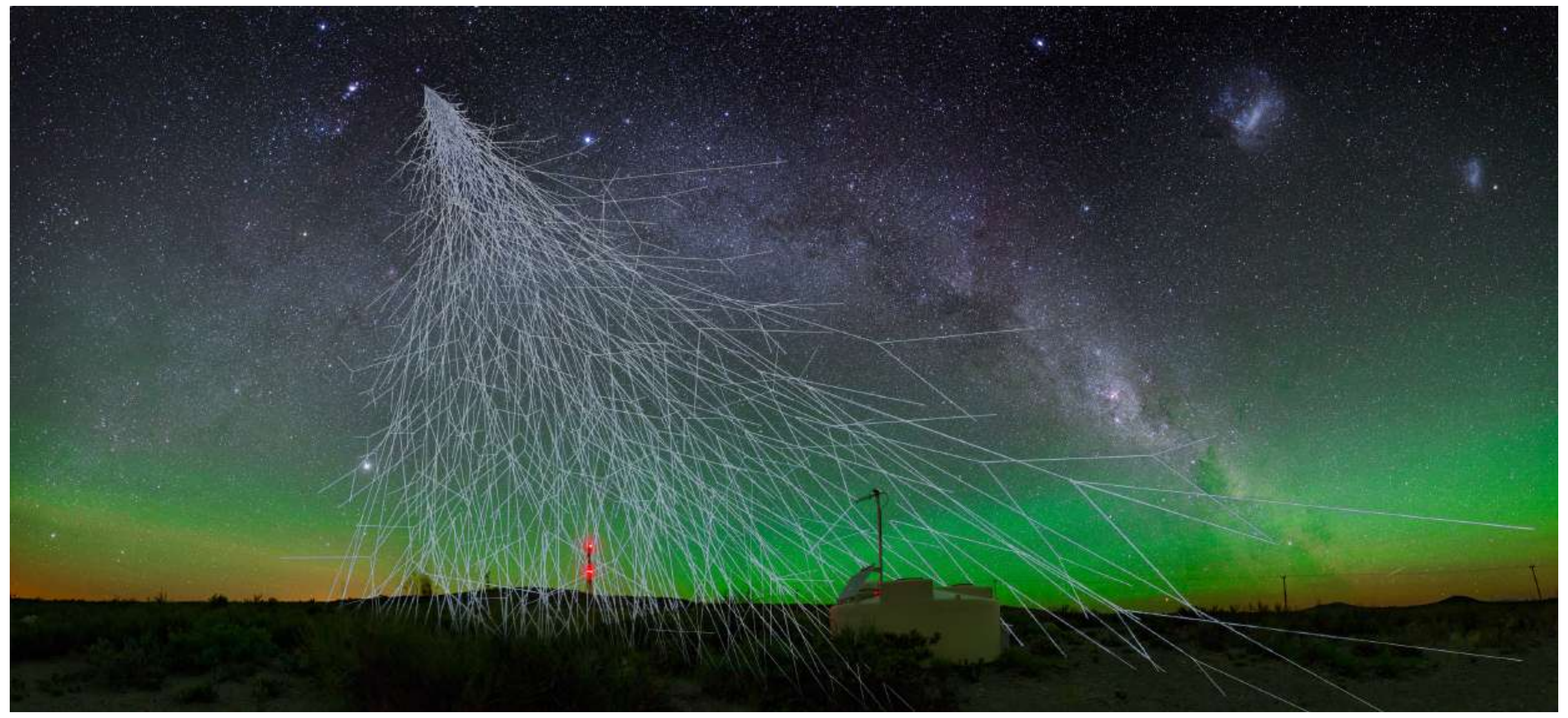
Heavy dark matter

Expected in GUTs but cannot be produced with WIMPs freeze out mechanism.

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).



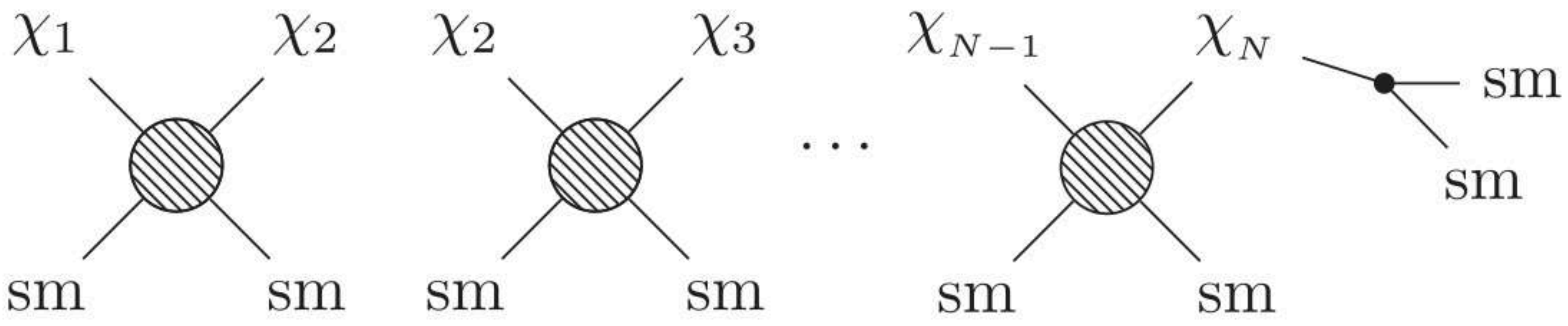
Phys. Rev. D 59, 123006 (1999).

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 ($m \approx 10^{13} GeV$).

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)

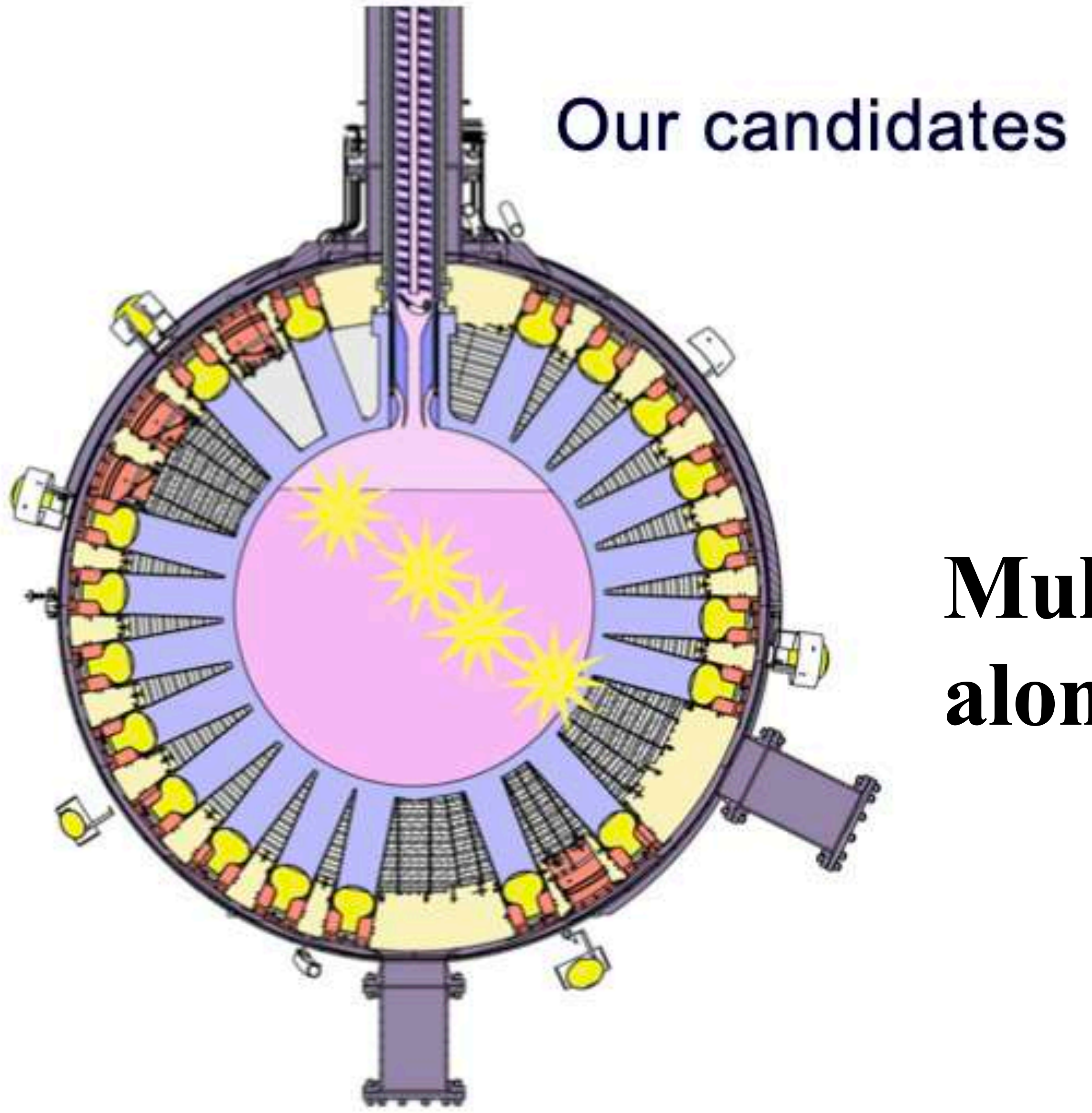
For more details: https://arxiv.org/abs/2203.06508

Multi-scattering search

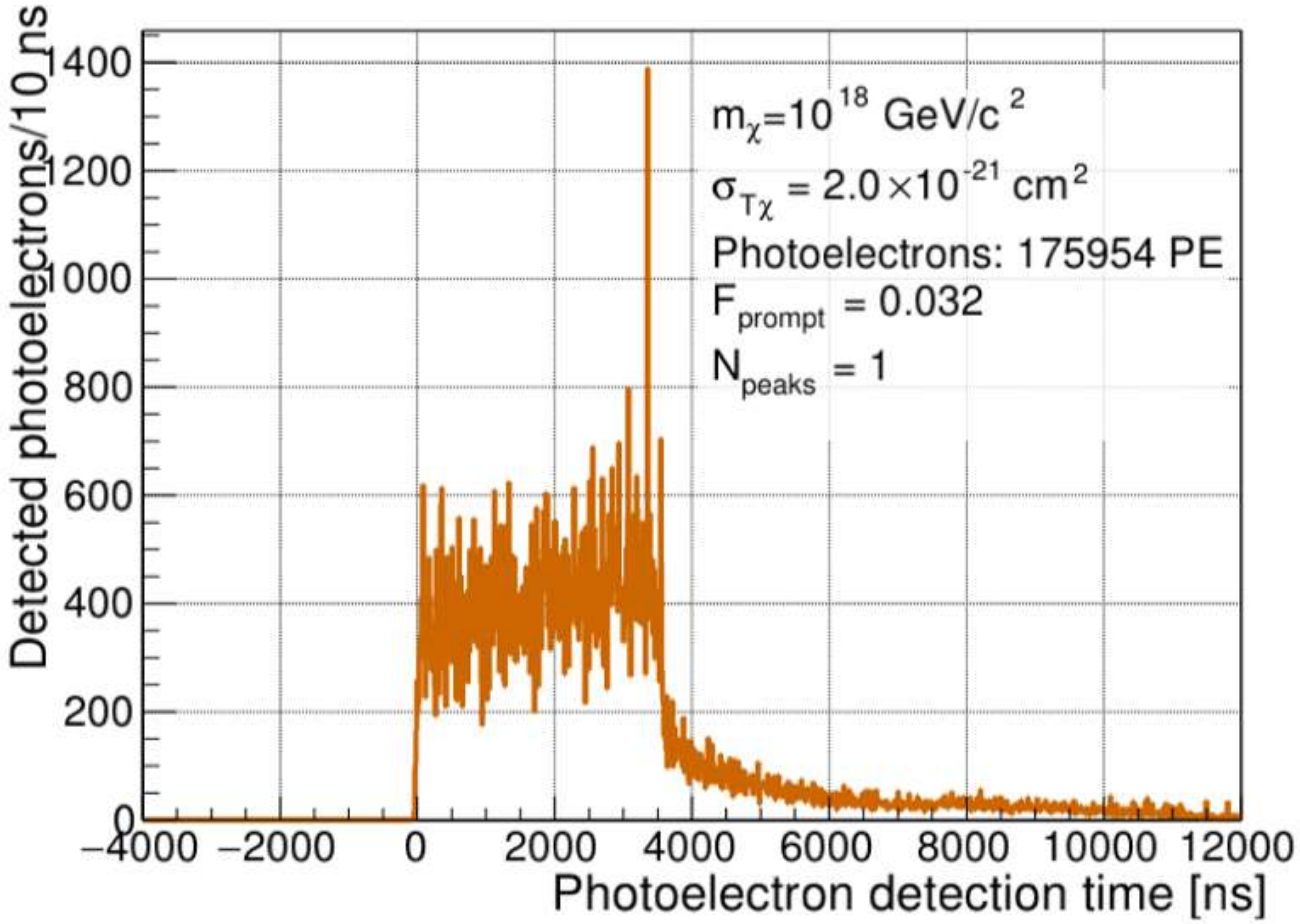
At such **high masses**, constrains are limited by the dark matter abundance rather than the cross-section, so a **large detector is needed**

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**



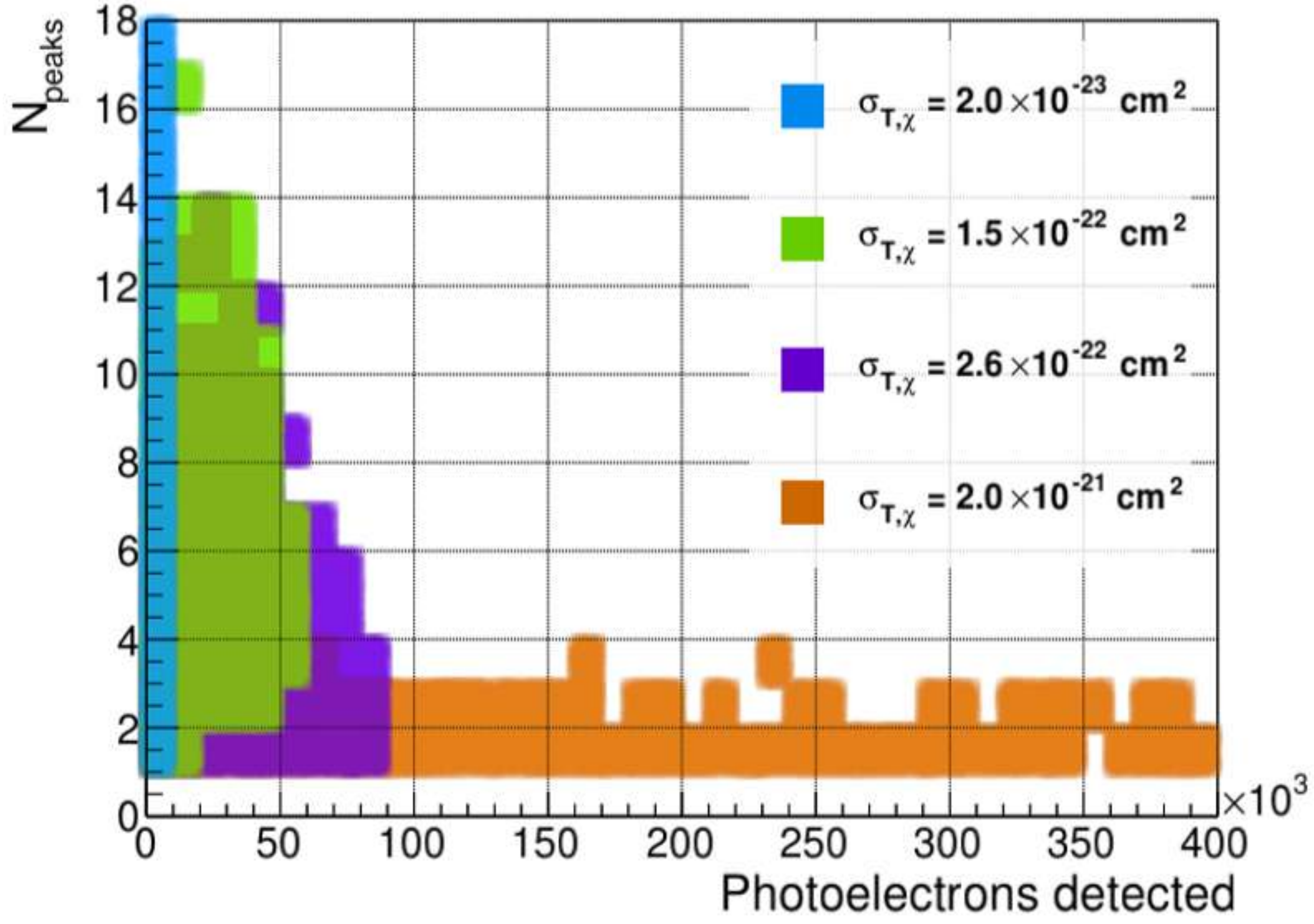
Multi-scattering particle along a collinear track

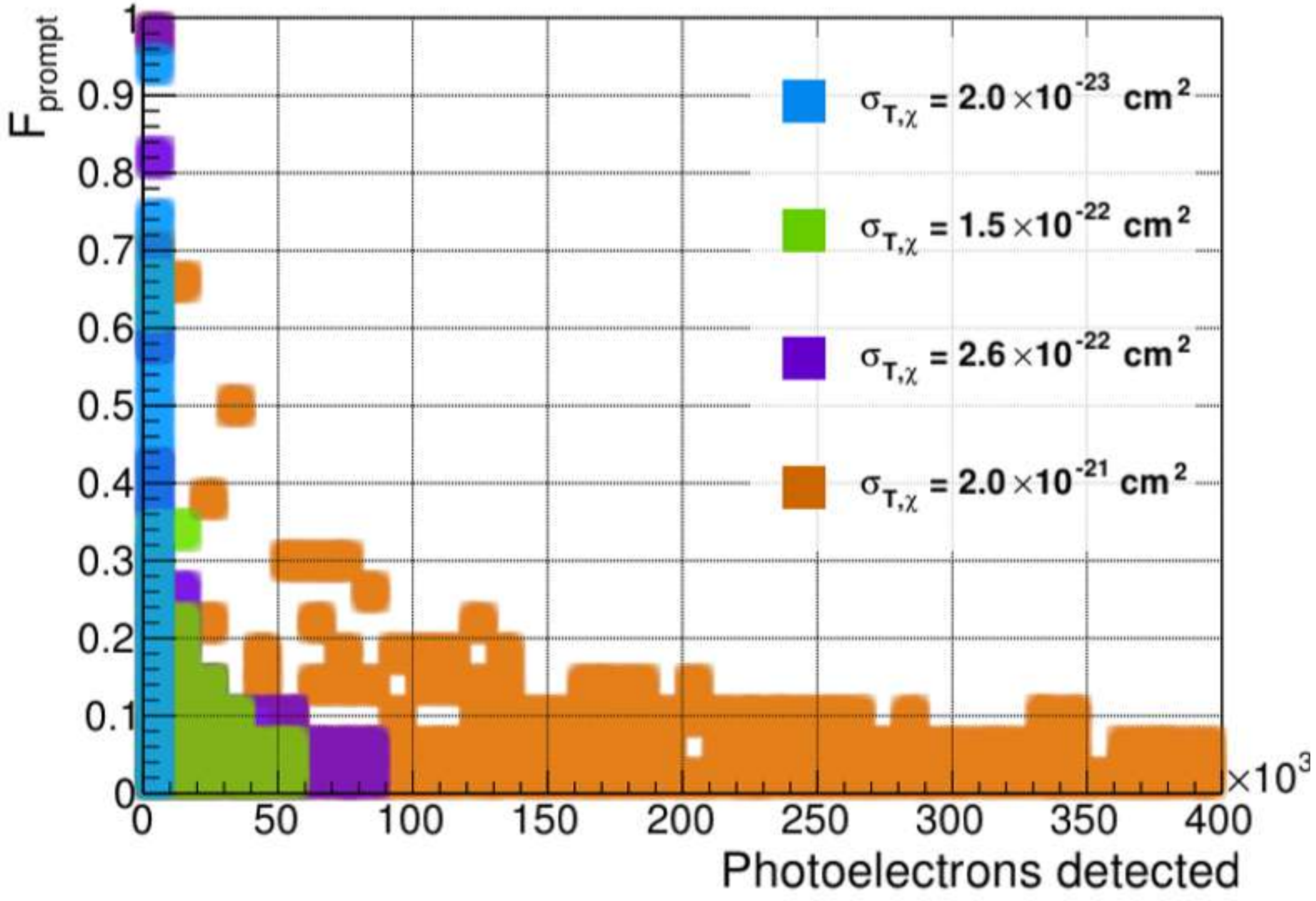


Simulation of the signal

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

N$_{peaks}$: number of significant peaks on the discrete derivative w'(t) of the binned summed waveform.

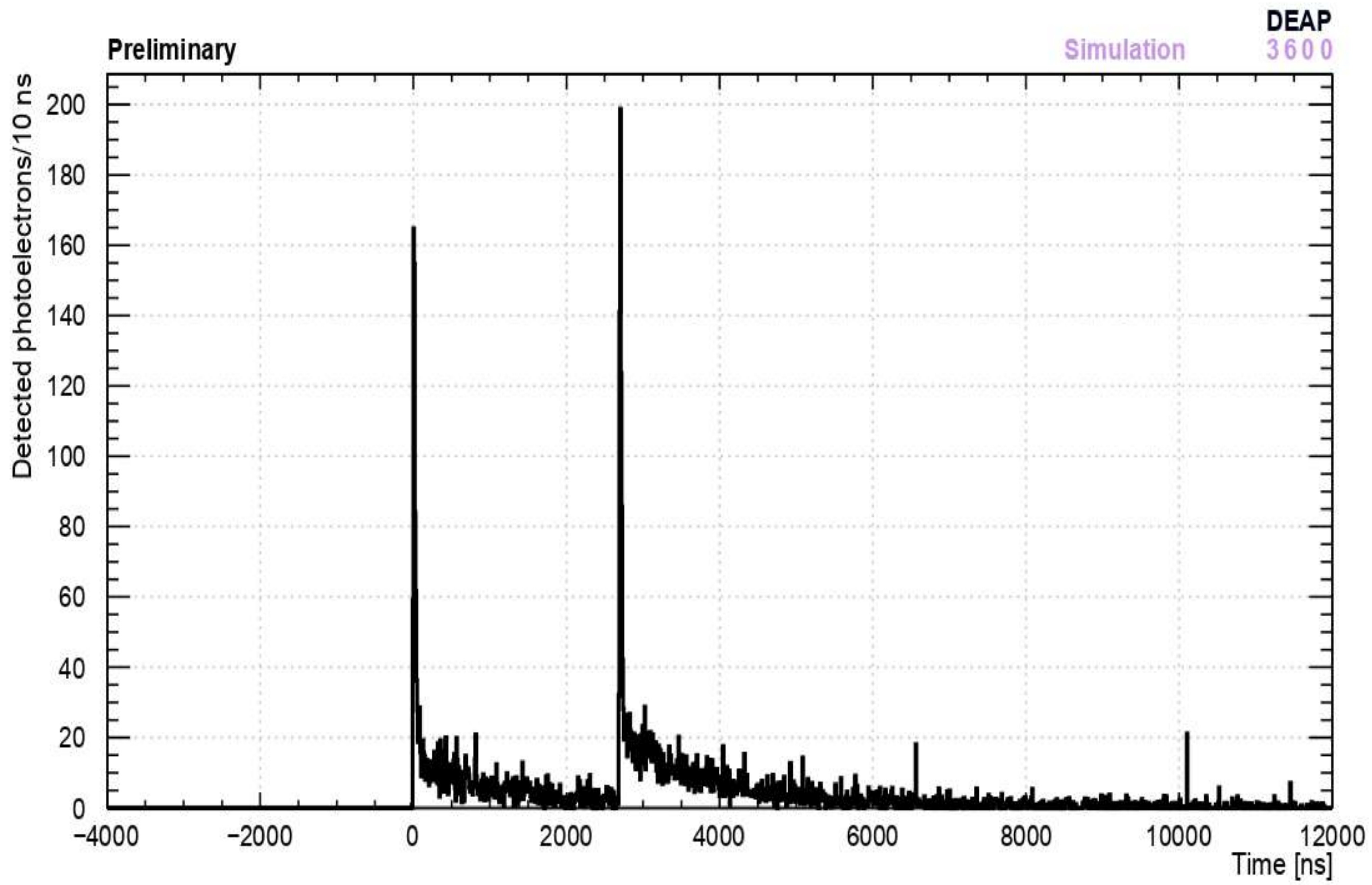




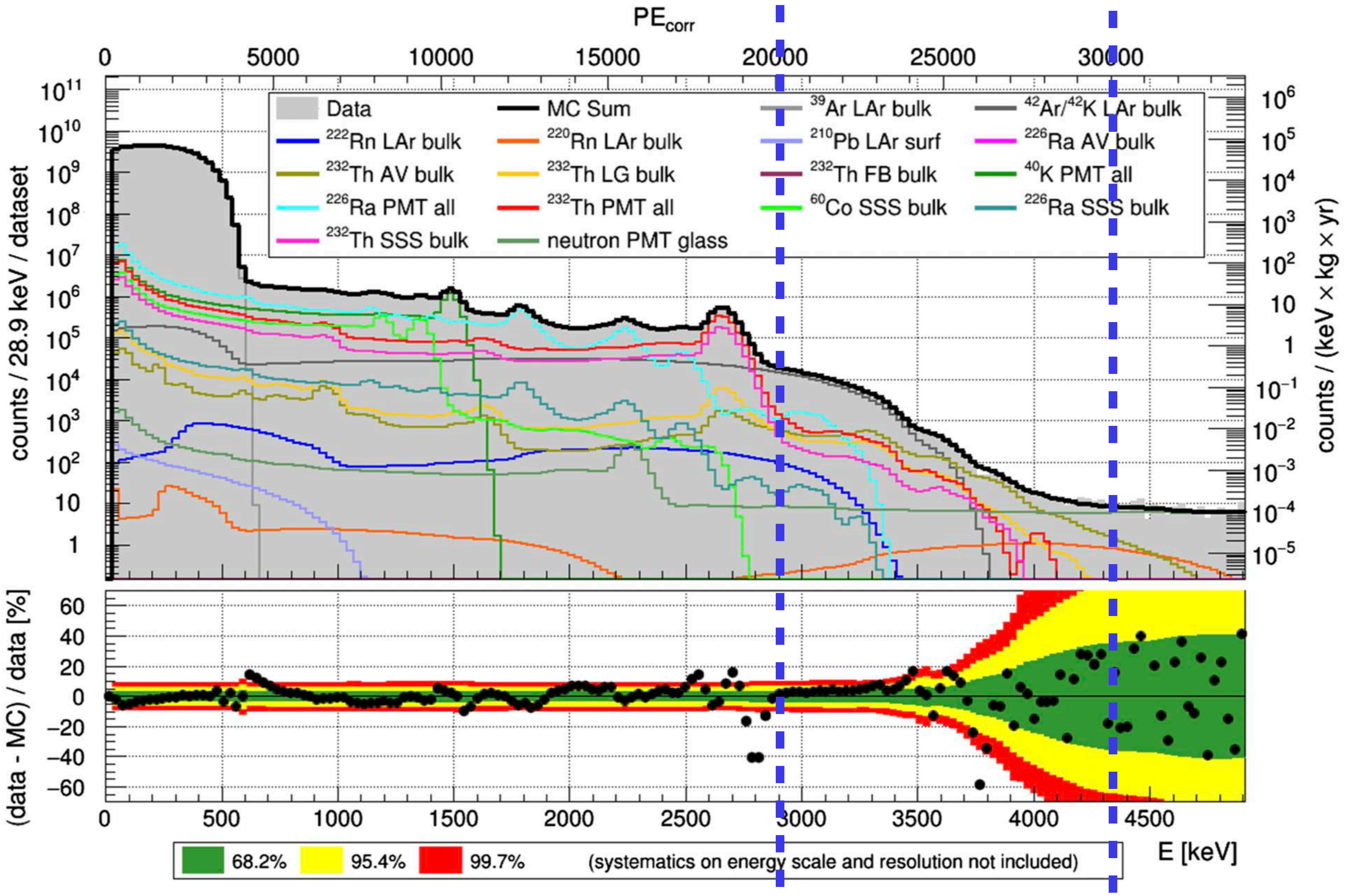
$$F_{prompt} = \frac{\int_{-28ns}^{150ns} PE(t)dt}{\int_{-28ns}^{10\mu s} PE(t)dt}$$

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}
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	$70\,000–4 \times 10^8$	10.4–60 000	0	0.05

Unblinding!

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

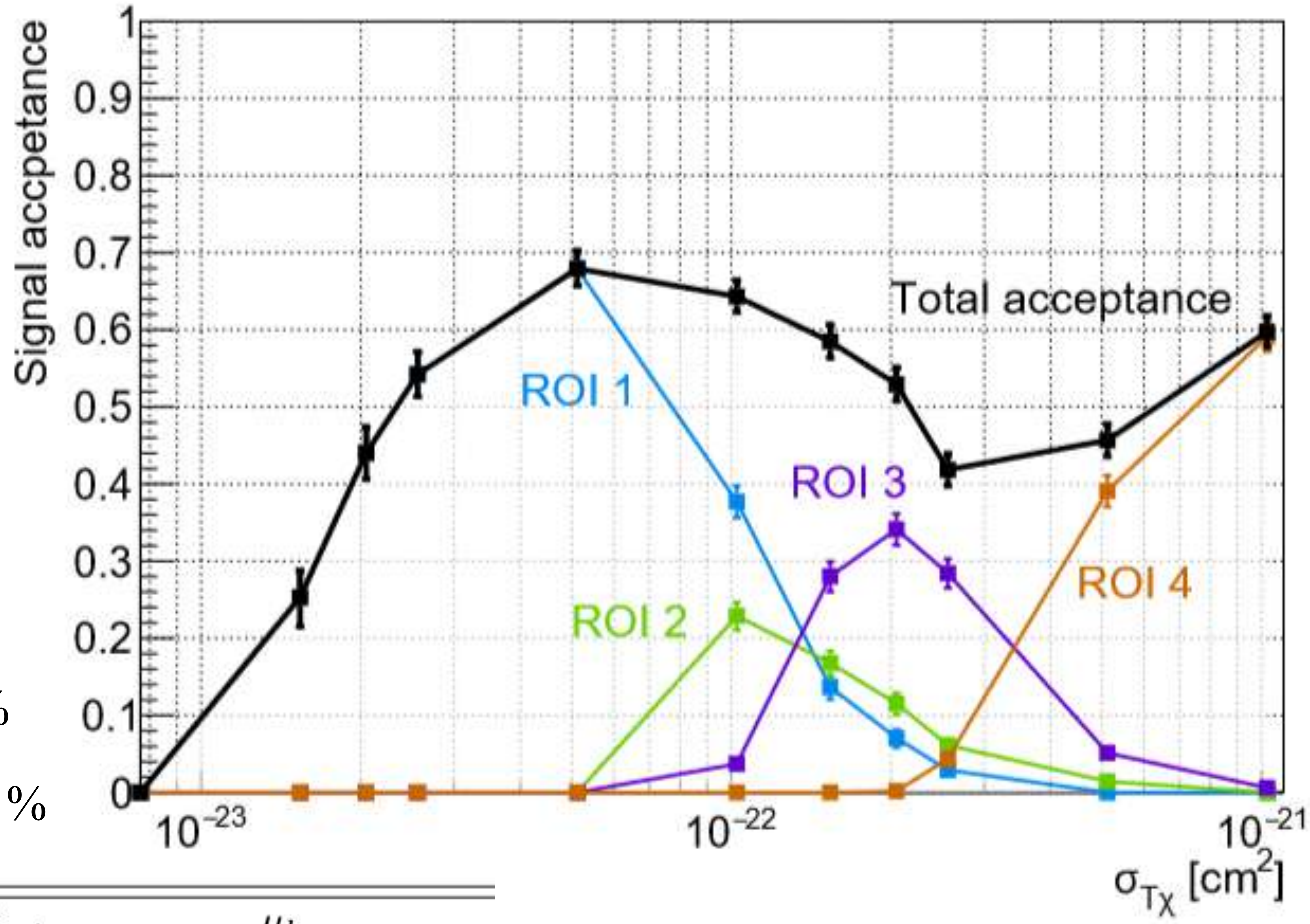
November 4, 2016 - March 8, 2020

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 %



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

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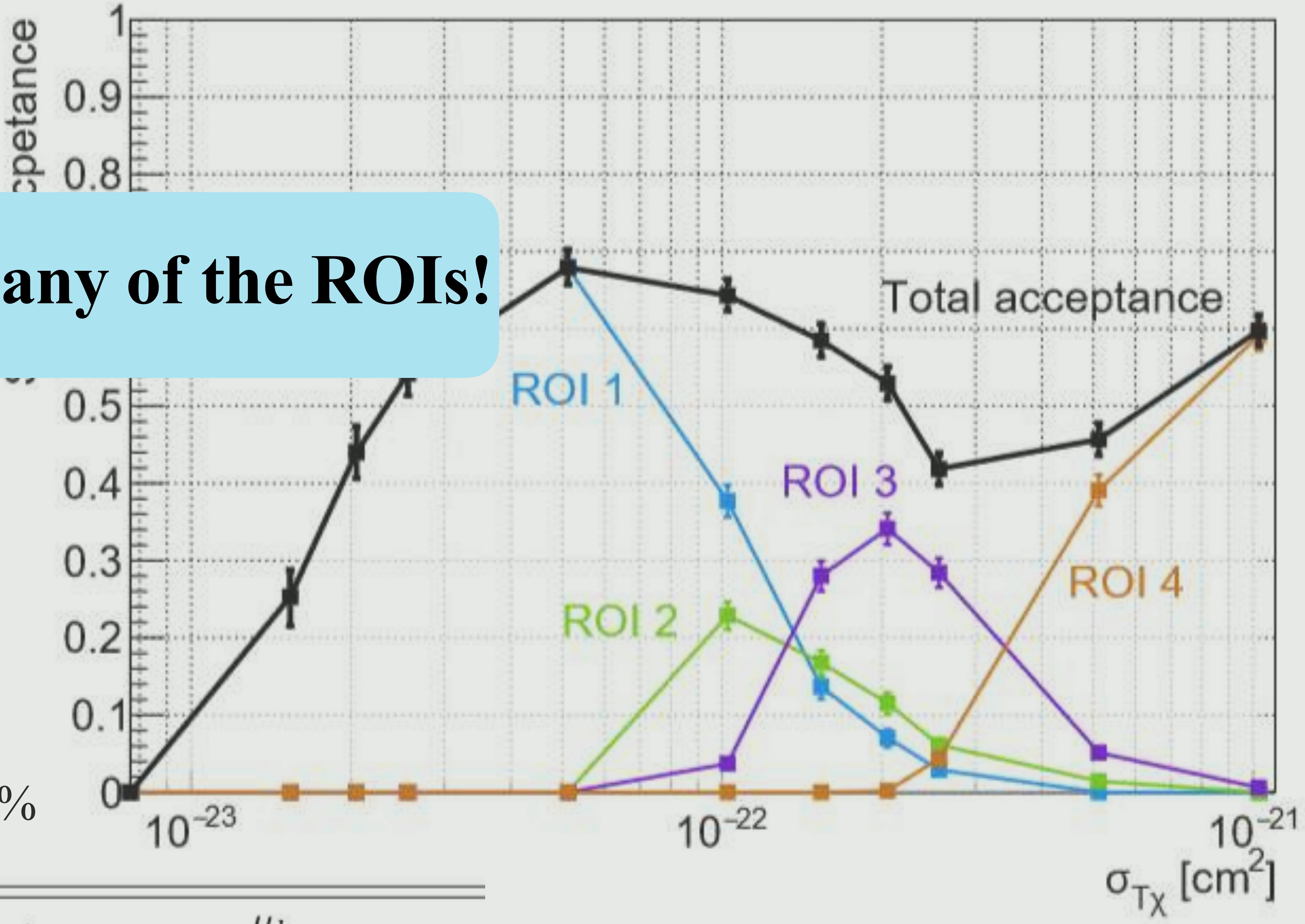

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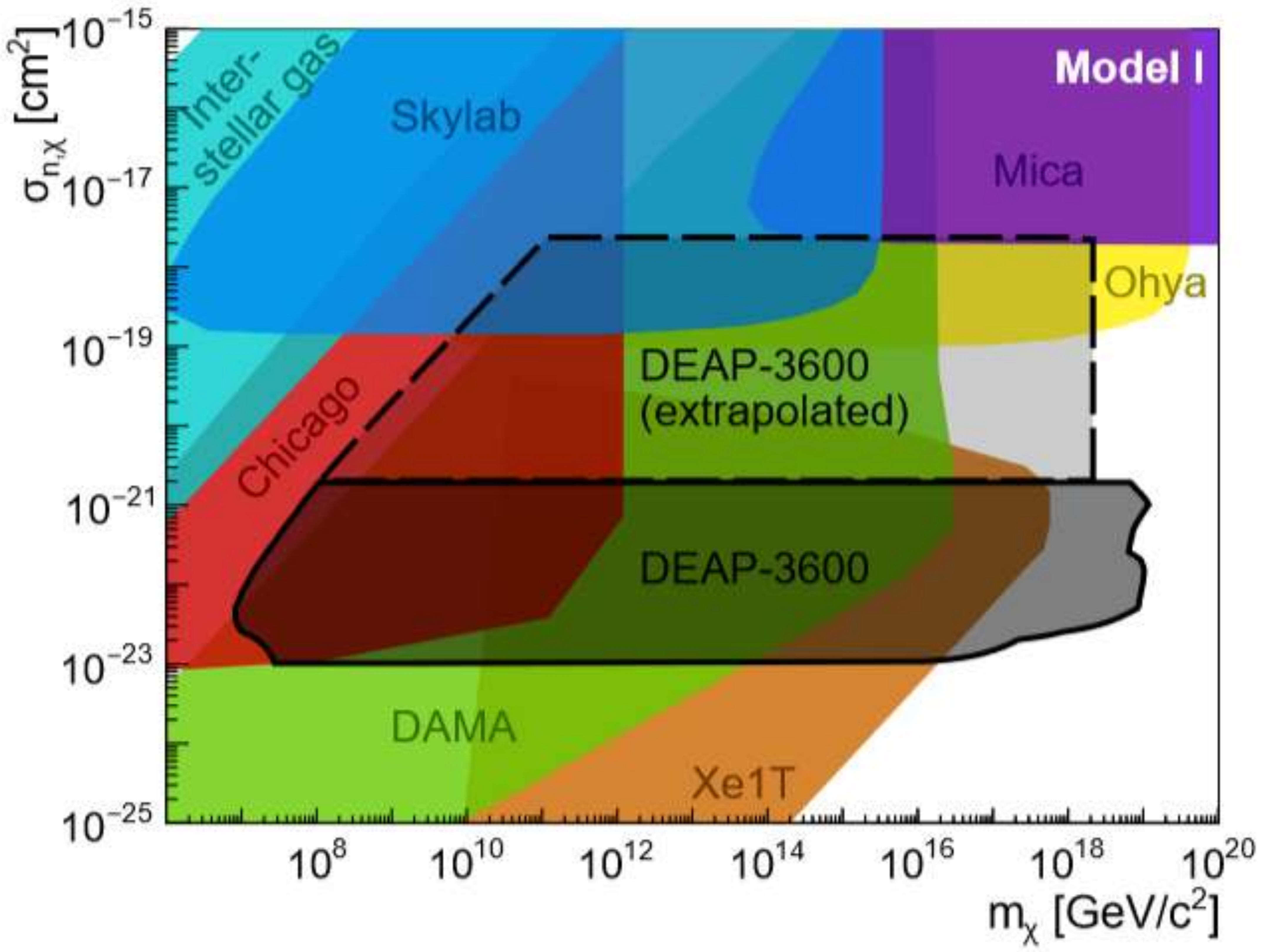

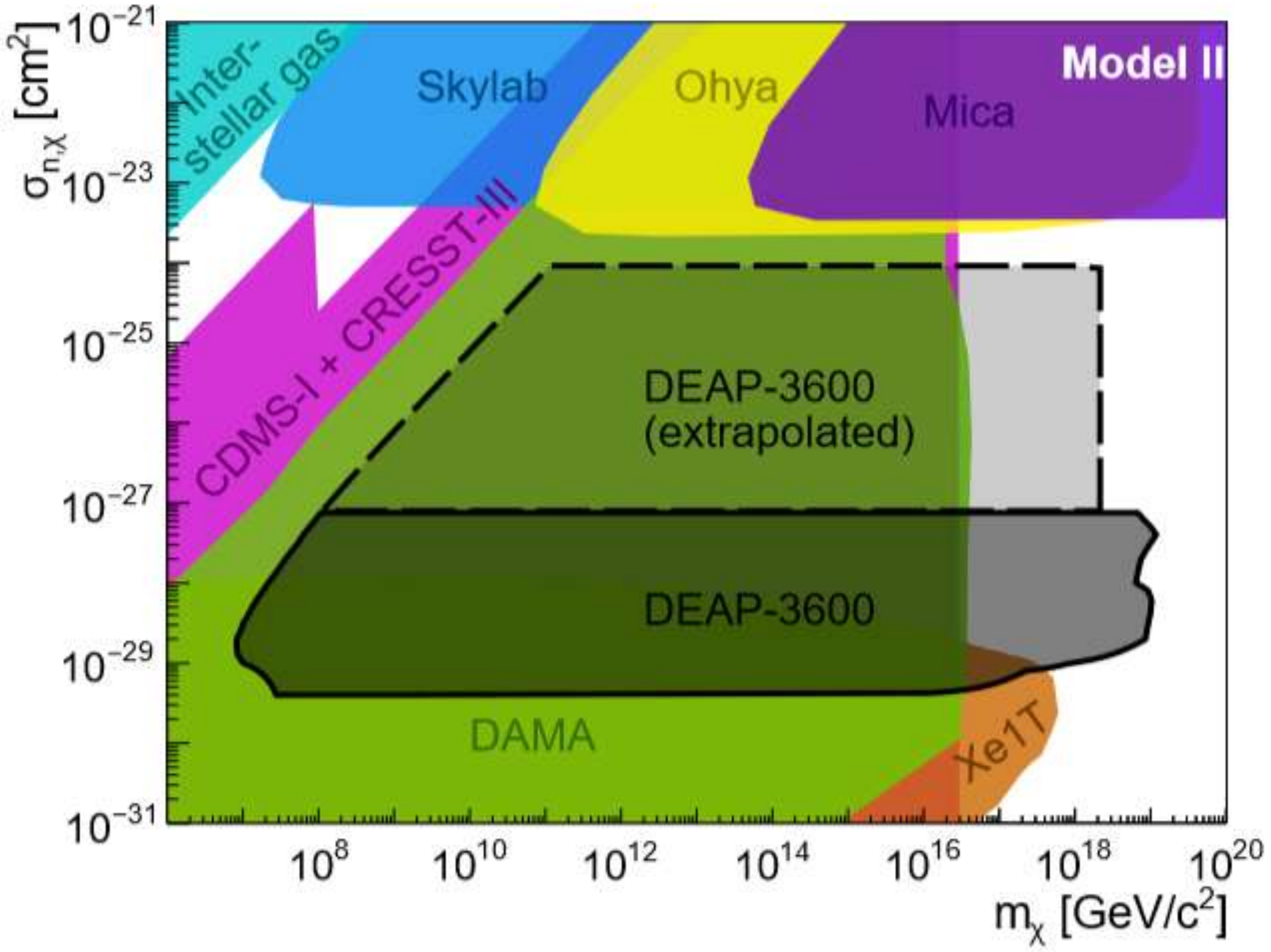

- **Model 1**: dark matter candidate **opaque to the nucleus**
- **Limits on strongly interacting, composite** dark matter candidates.

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

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

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

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

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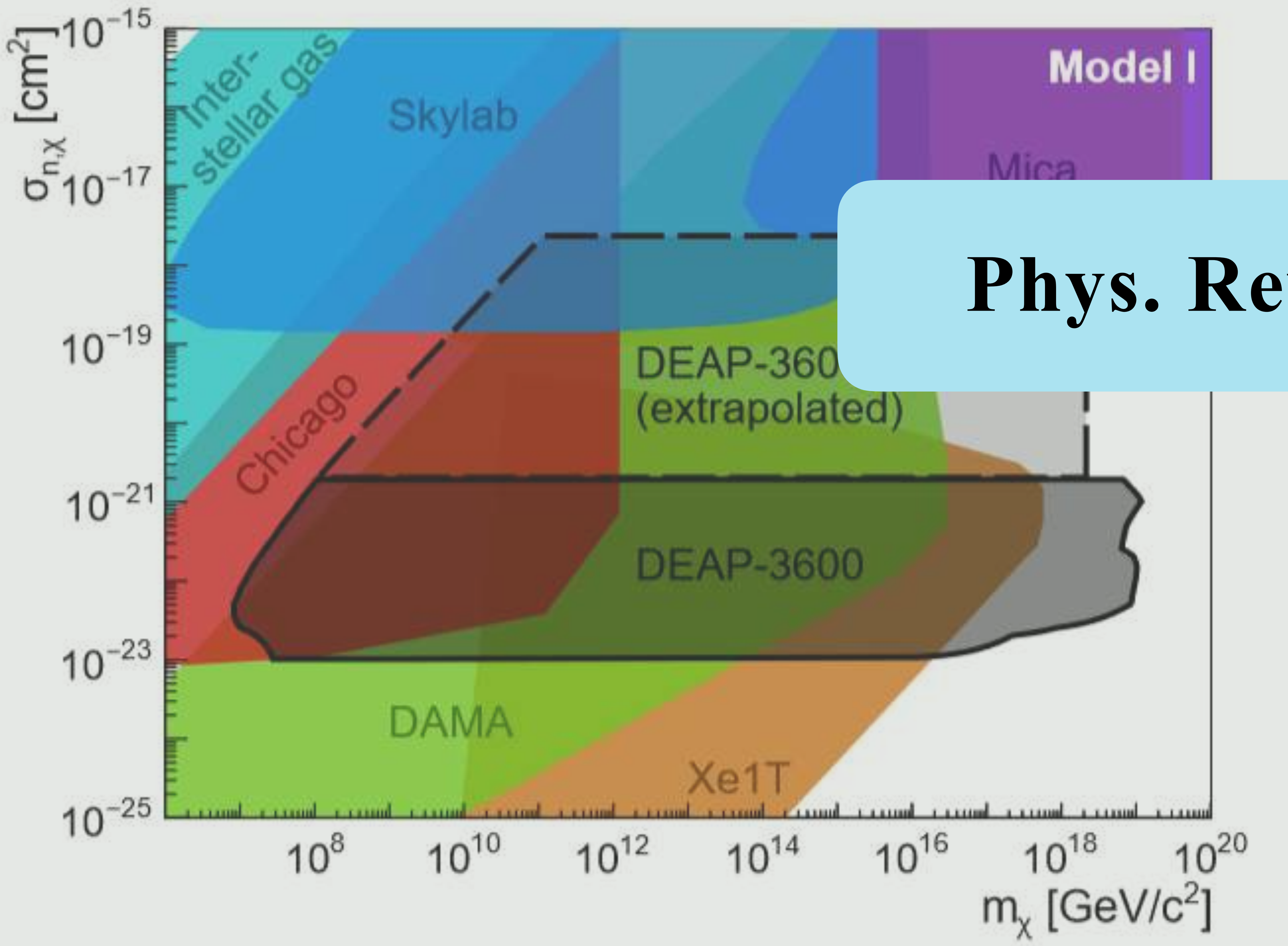
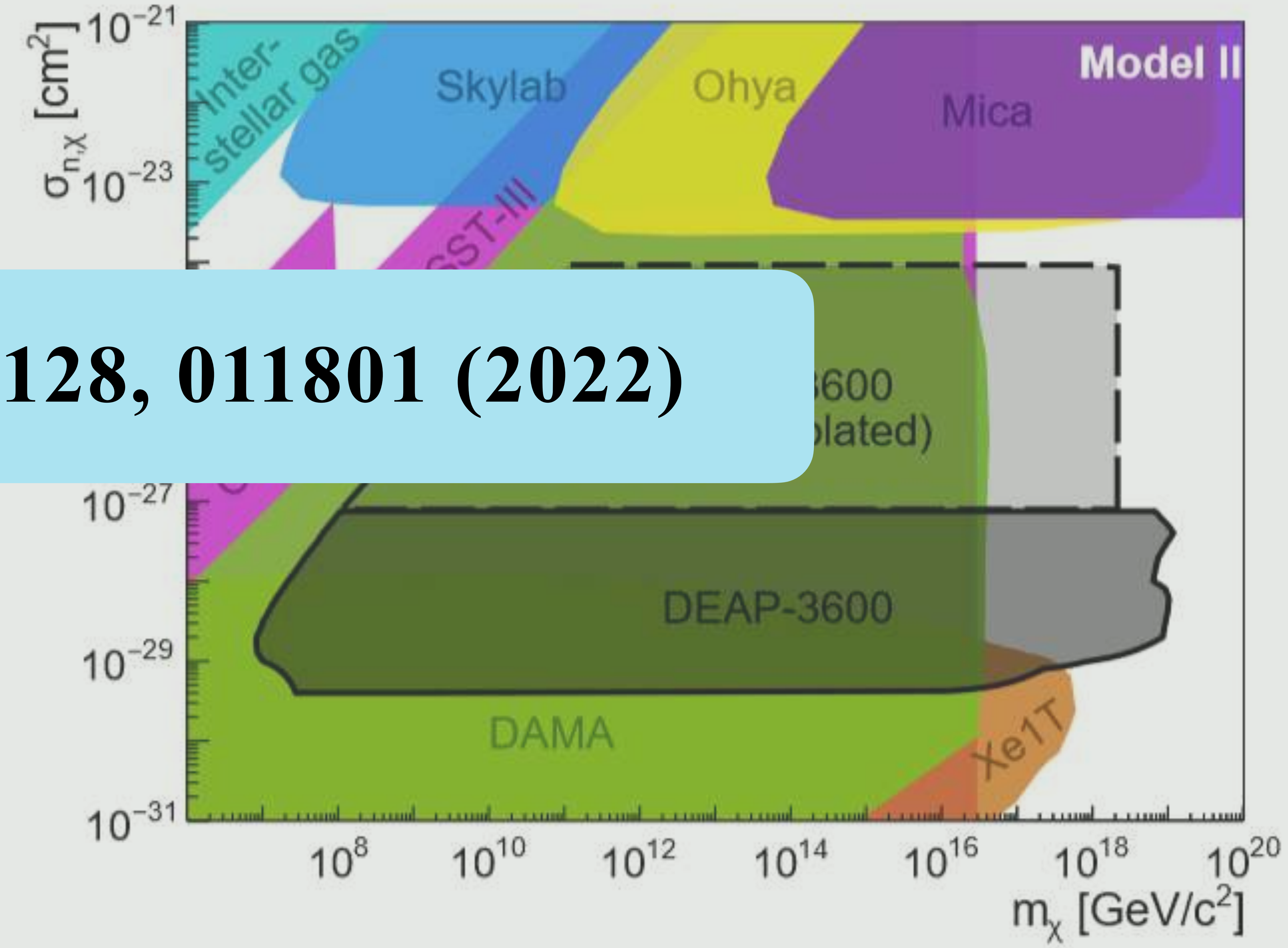


Phys. Rev. Lett. 128, 011801 (2022)



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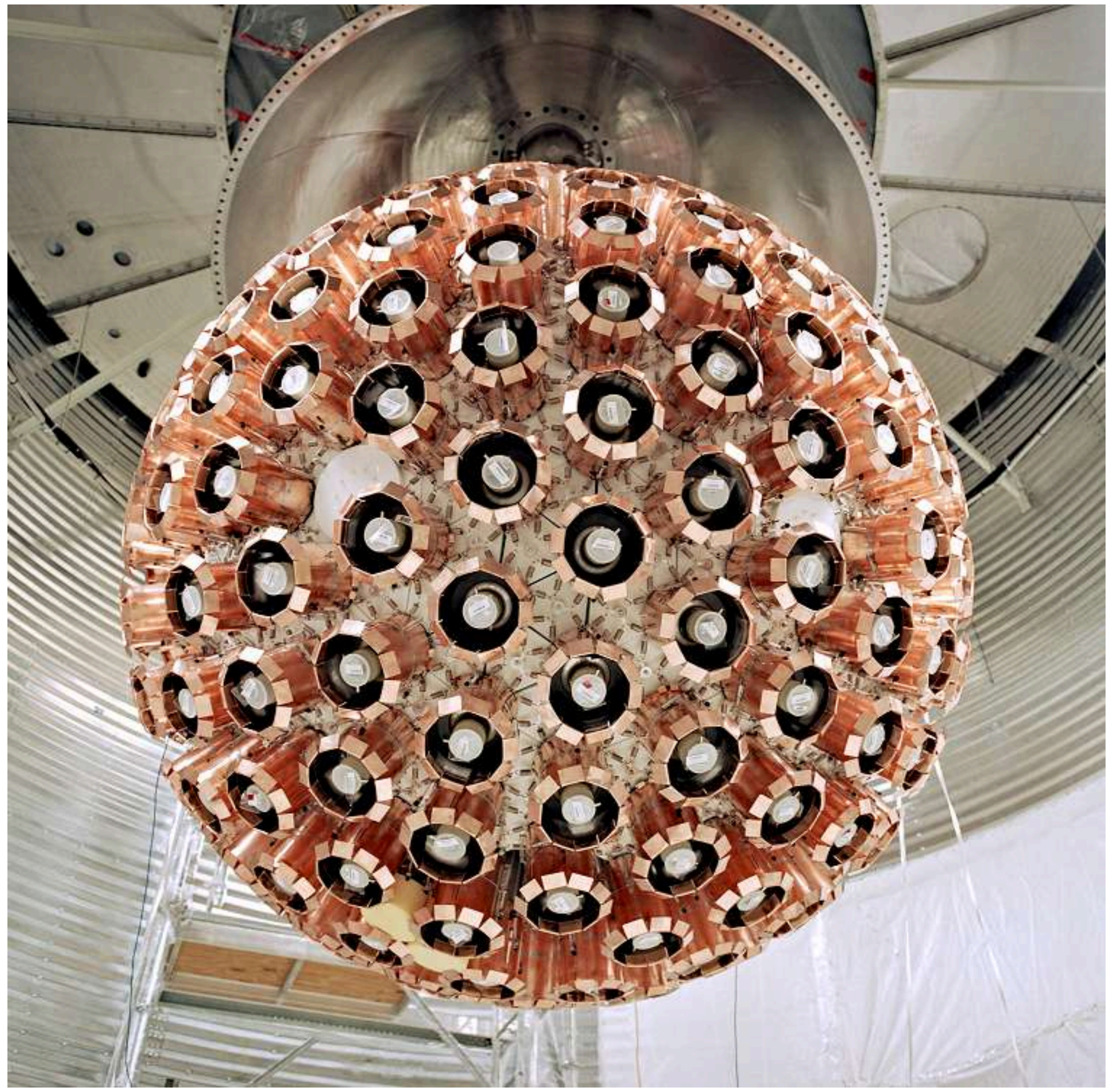
Next future

Most stringent exclusion limit to WIMPs at masses > 100 GeV in liquid argon



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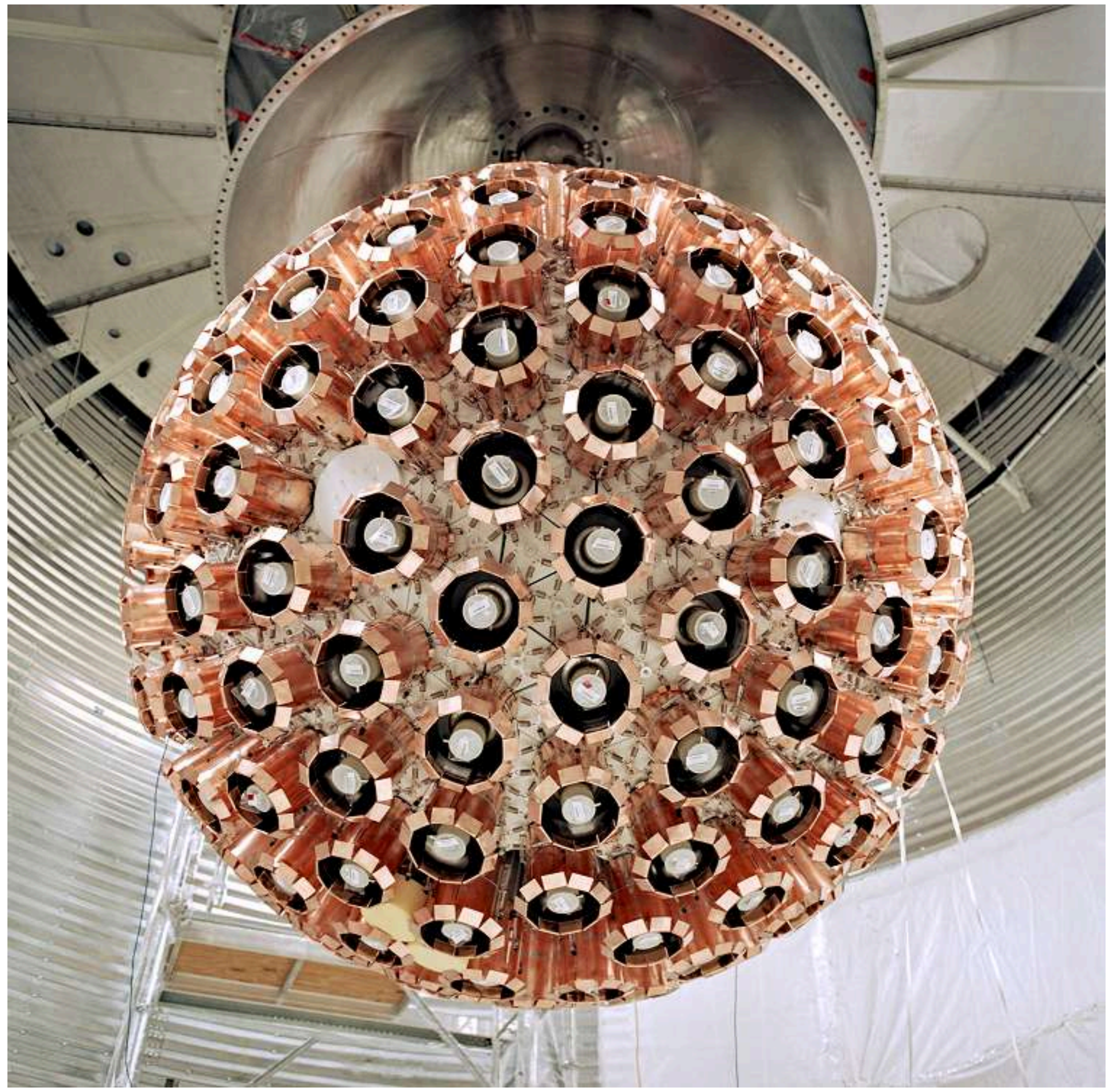

Pulse shape of the signal carefully modeled

Best PSD discrimination in liquid argon

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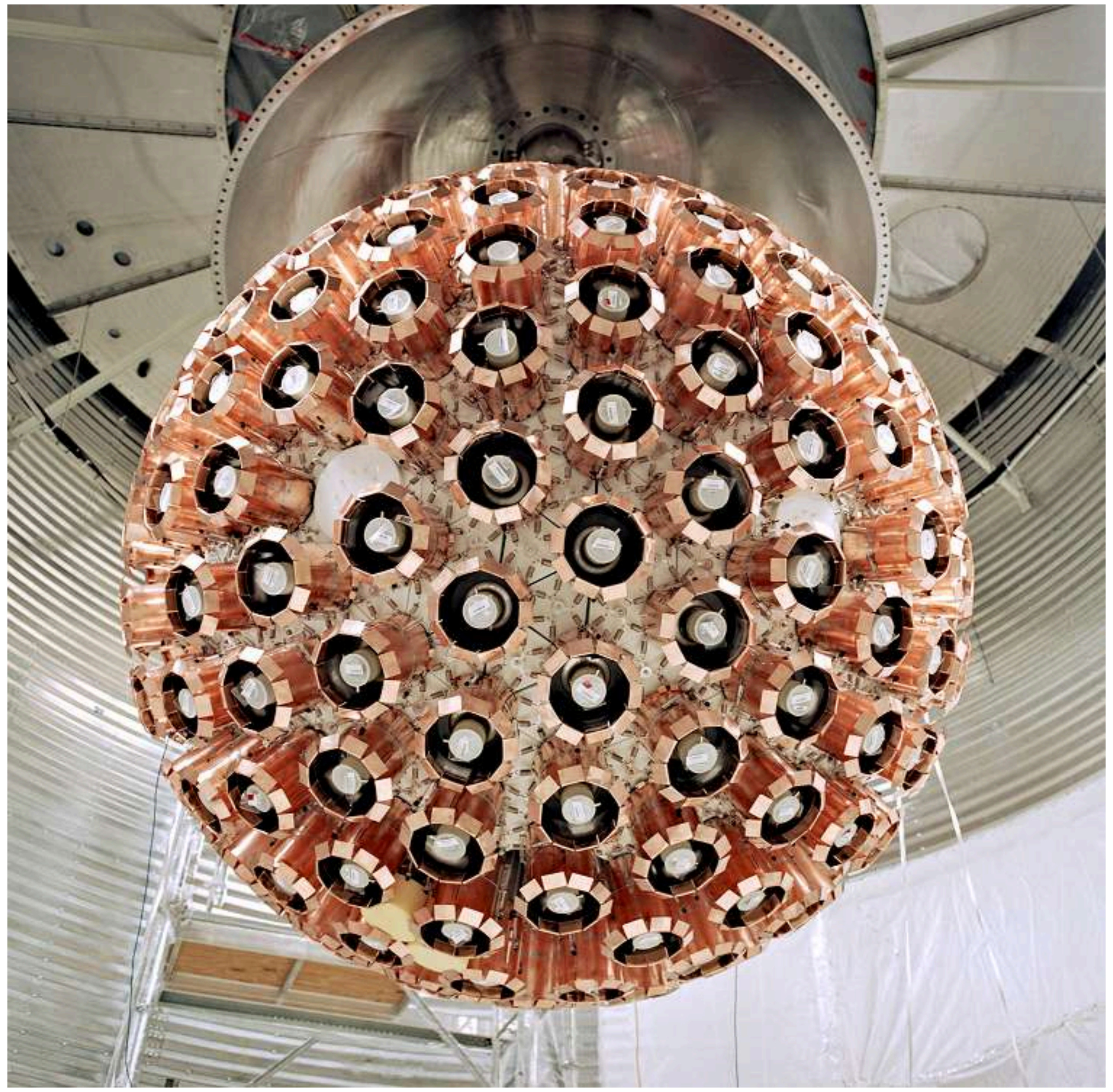
Re-analysis of the WIMP results with NREFT…

… and non-standard velocity distributions in the halo!

Best exclusion limit to xenon-phobic candidates



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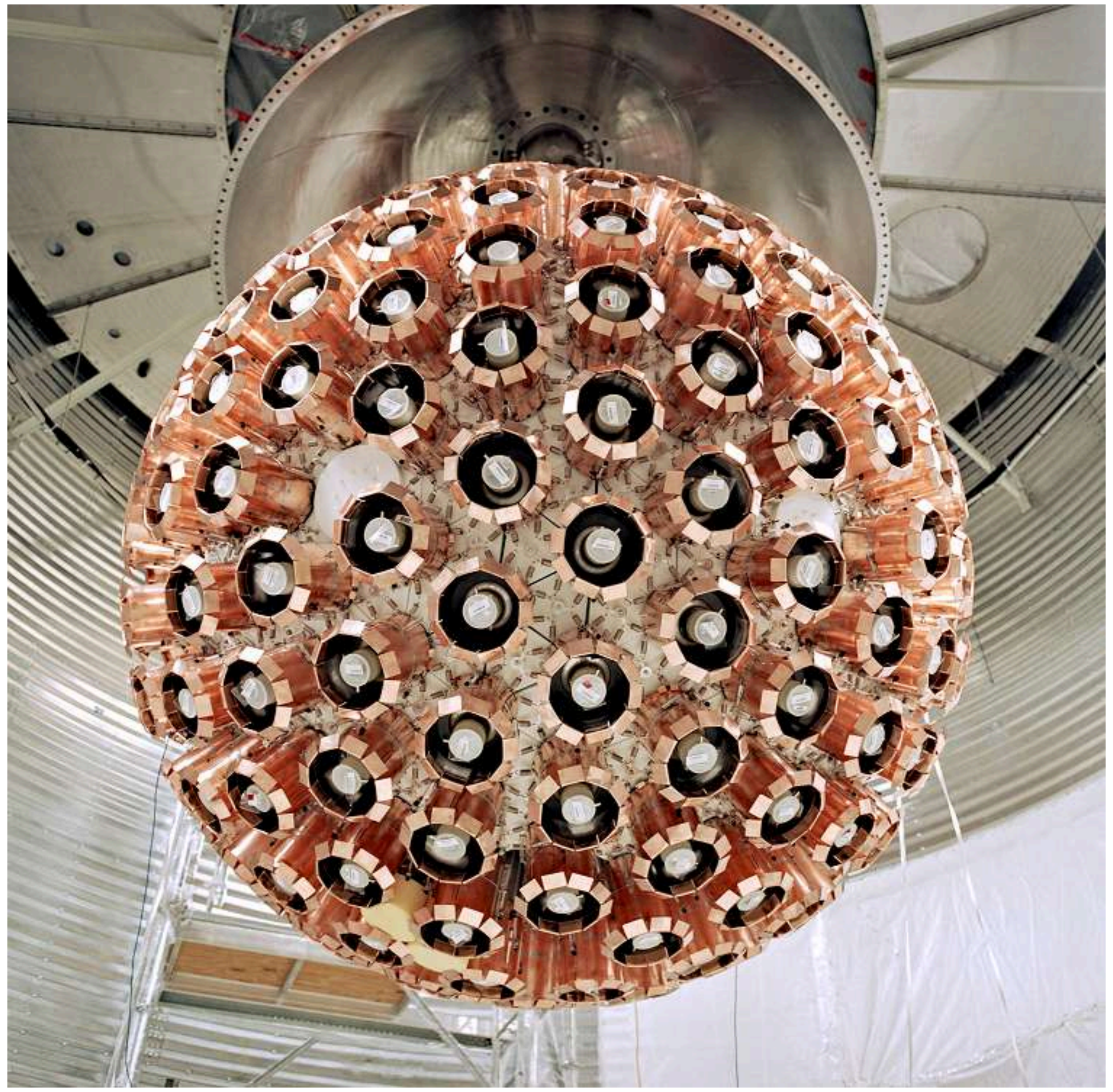

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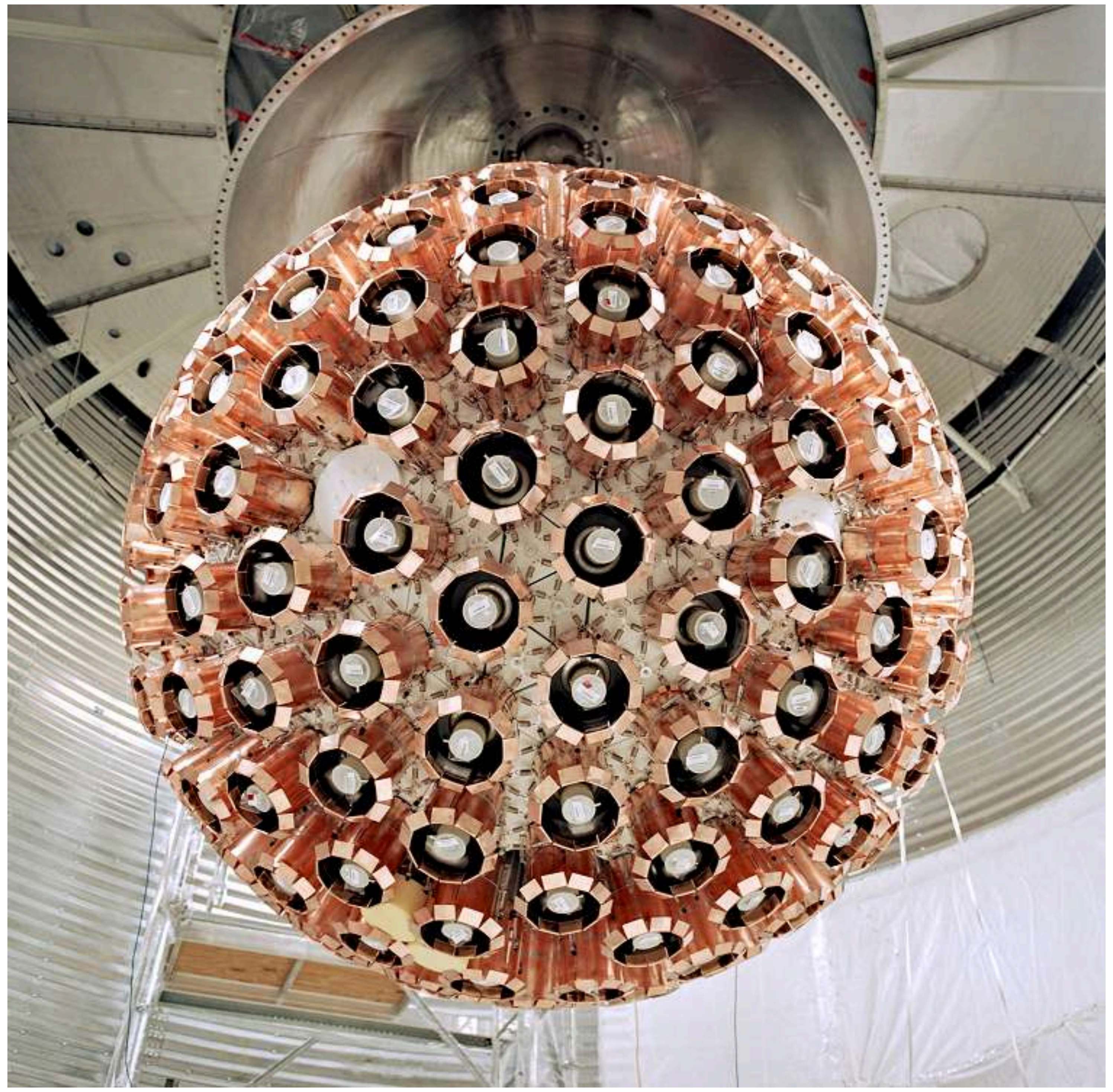

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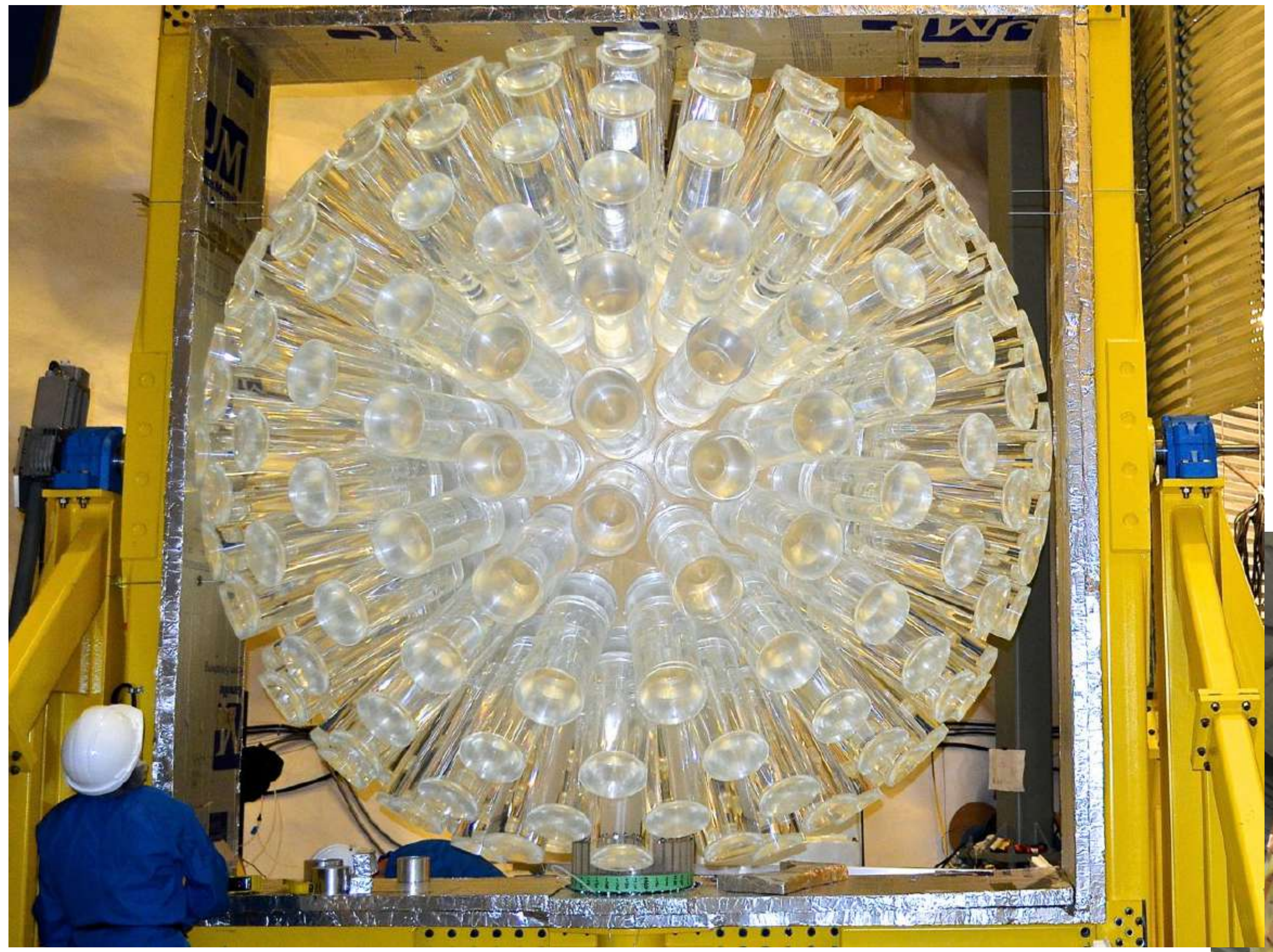
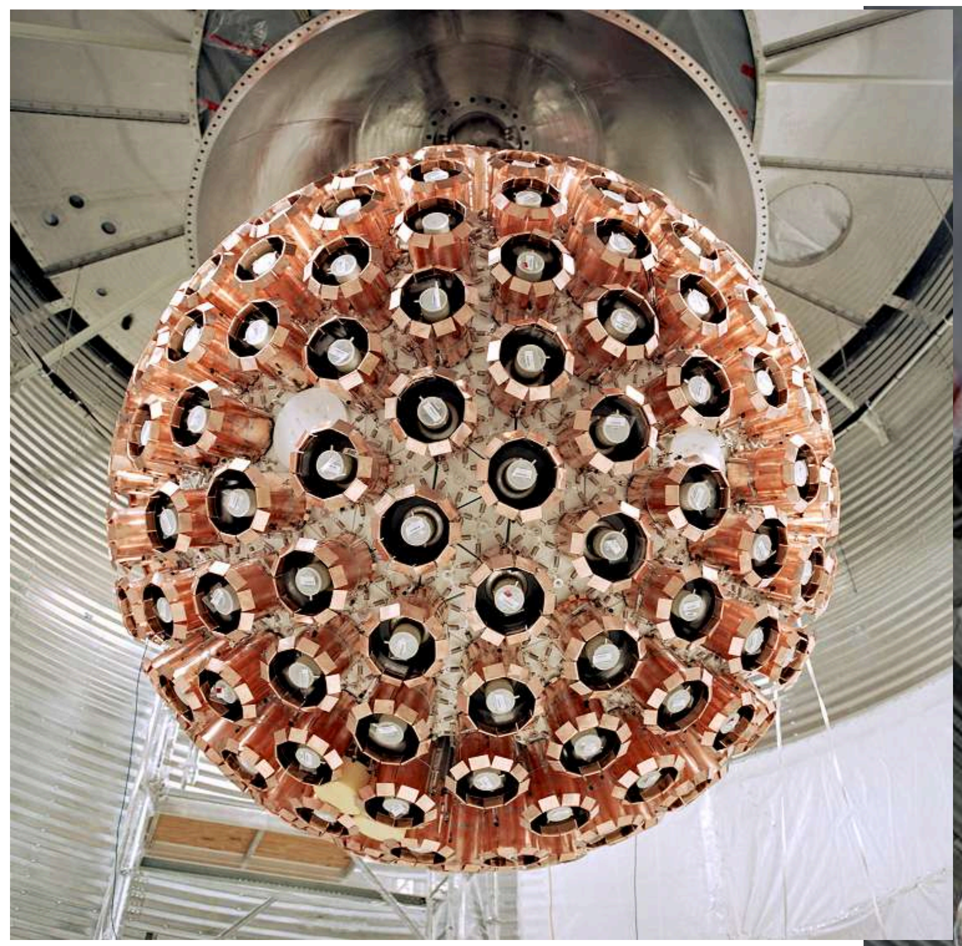
New WIMP search: coming soon!

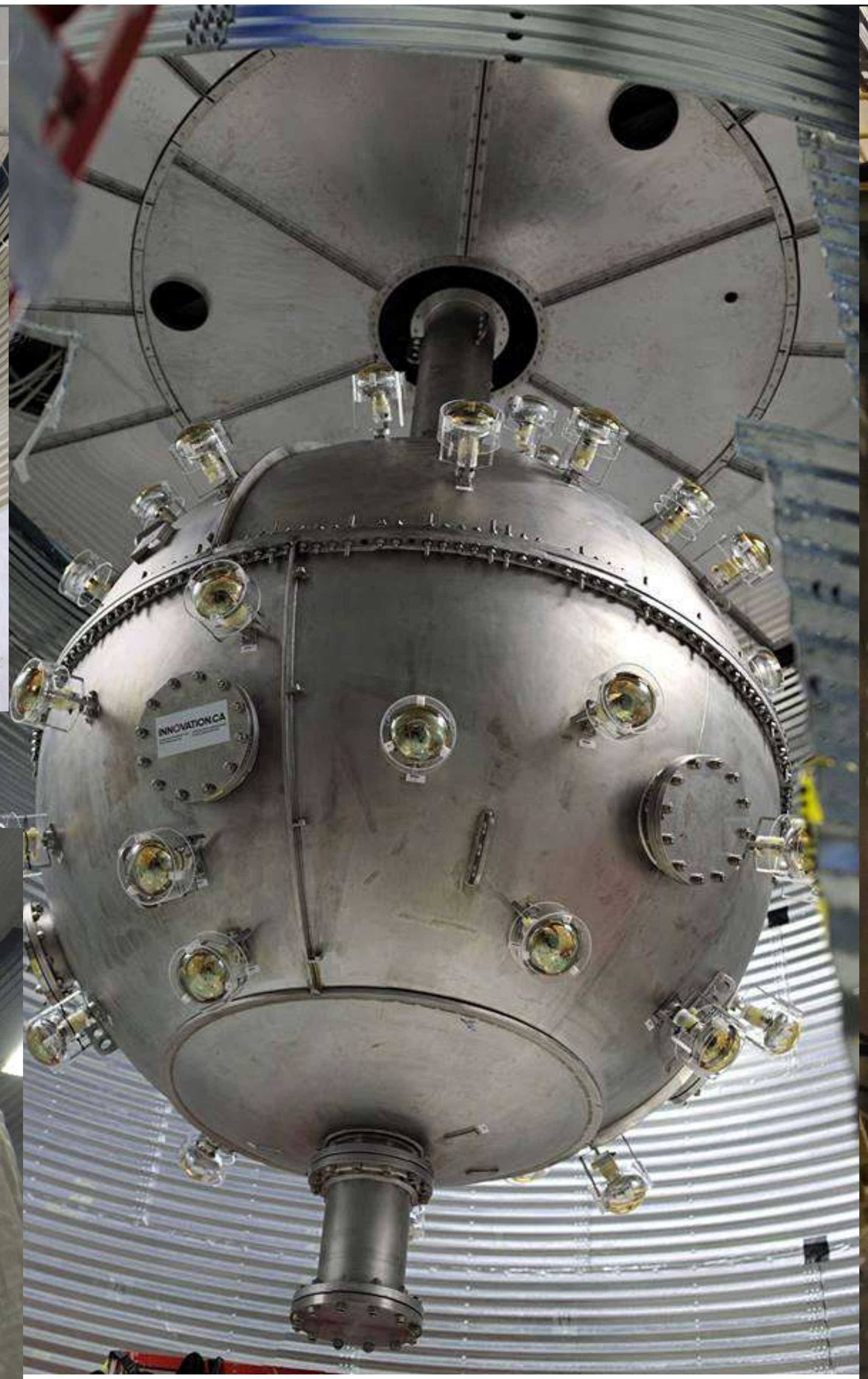
Back up

Dr. Michela Lai
on behalf of
DEAP-3600 Collaboration

The detector





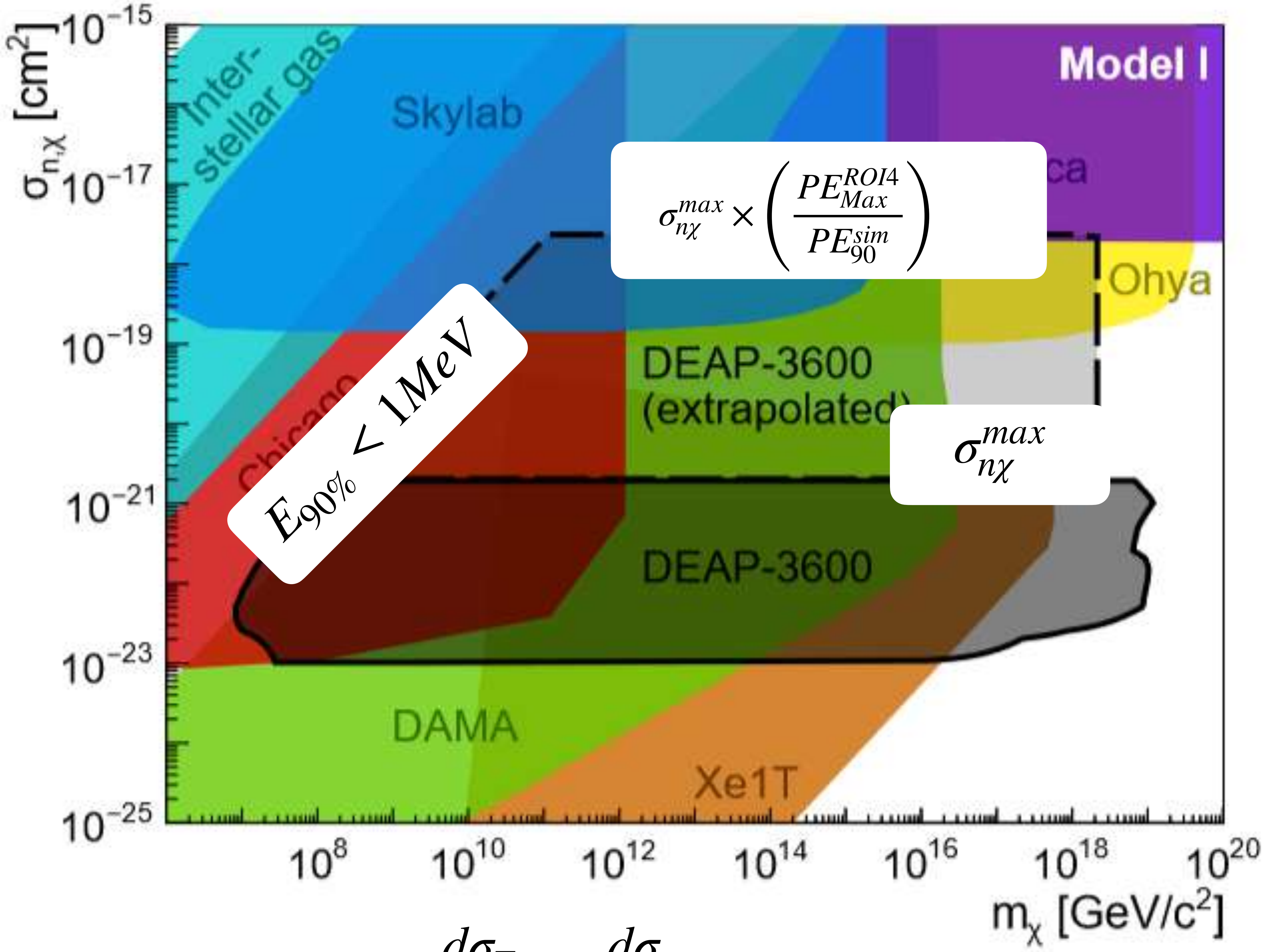


Results

- **0 events 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.



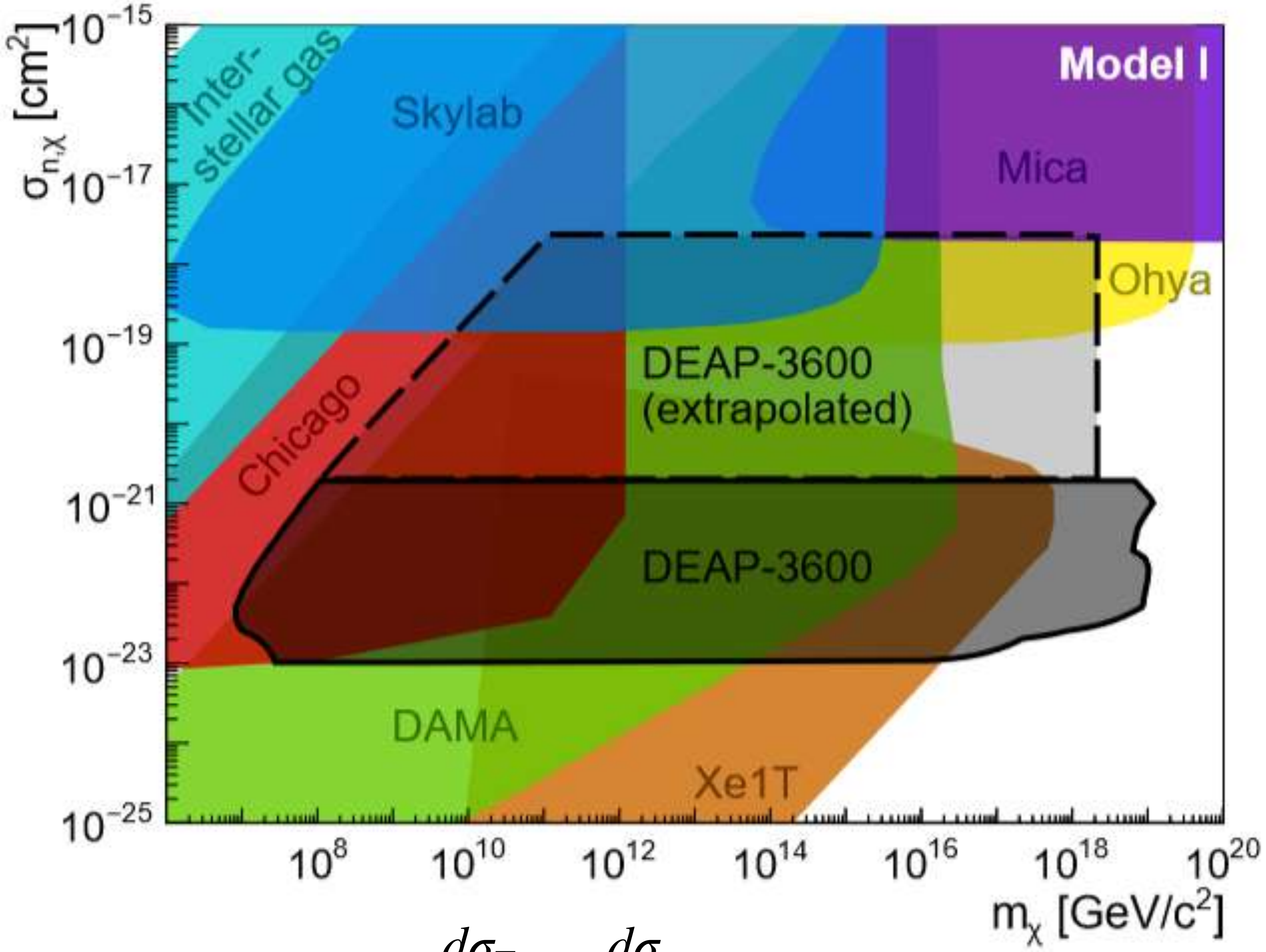
$$\frac{d\sigma_{T\chi}}{dE_R} = \frac{d\sigma_{n\chi}}{dE_R} |F_T(q)|^2$$

Results

- **0 events 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.



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

Results

- **No event** was found in all 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:

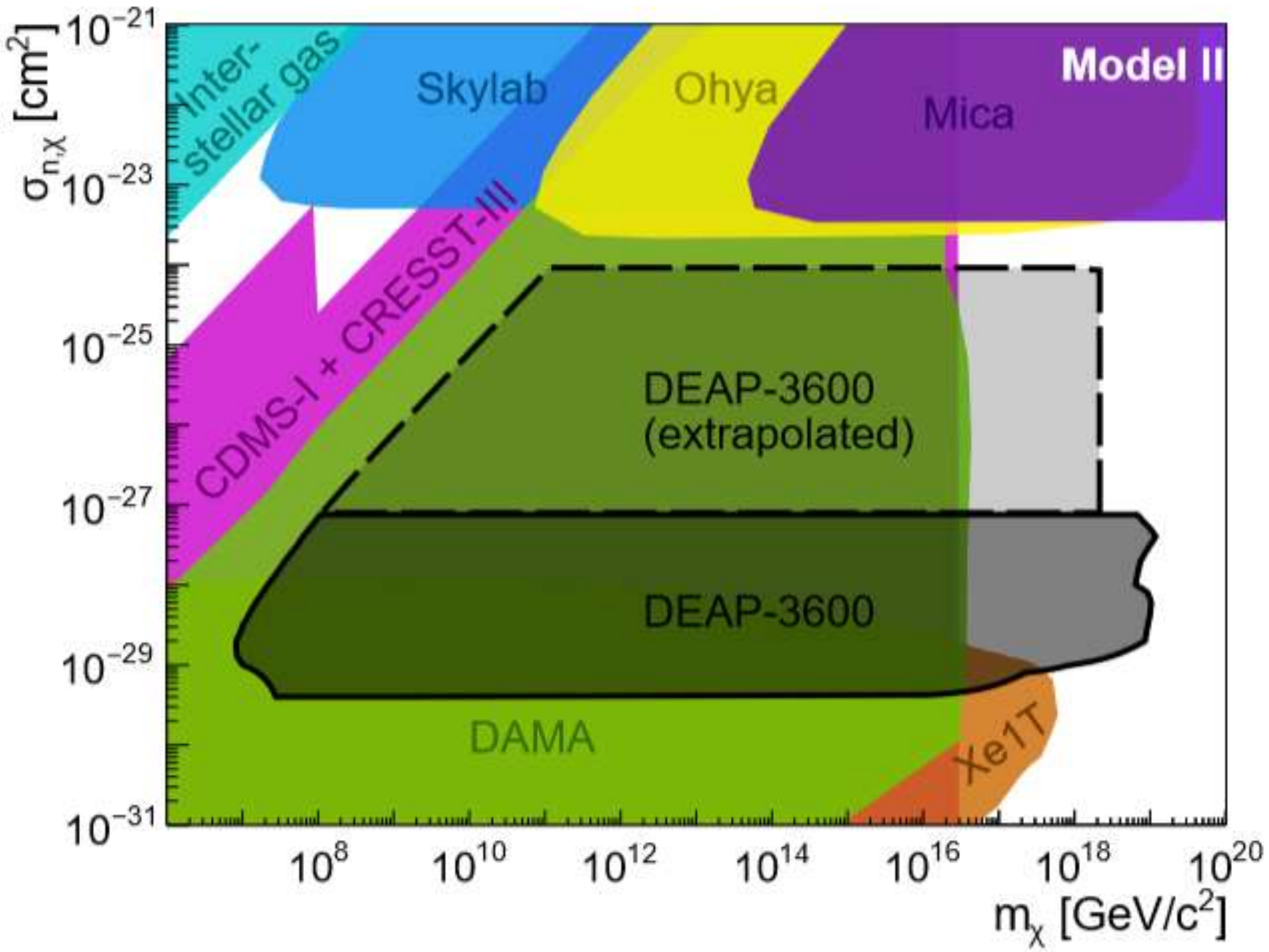
$$\mu_s = T\int d^3v \int dA \frac{\rho_\chi}{m_\chi} |v| f(\vec{v})\epsilon(\vec{v}, \sigma_{T,\chi}, m_\chi)$$

- **Model 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 $|F_\chi(q)|^2 \approx 1$

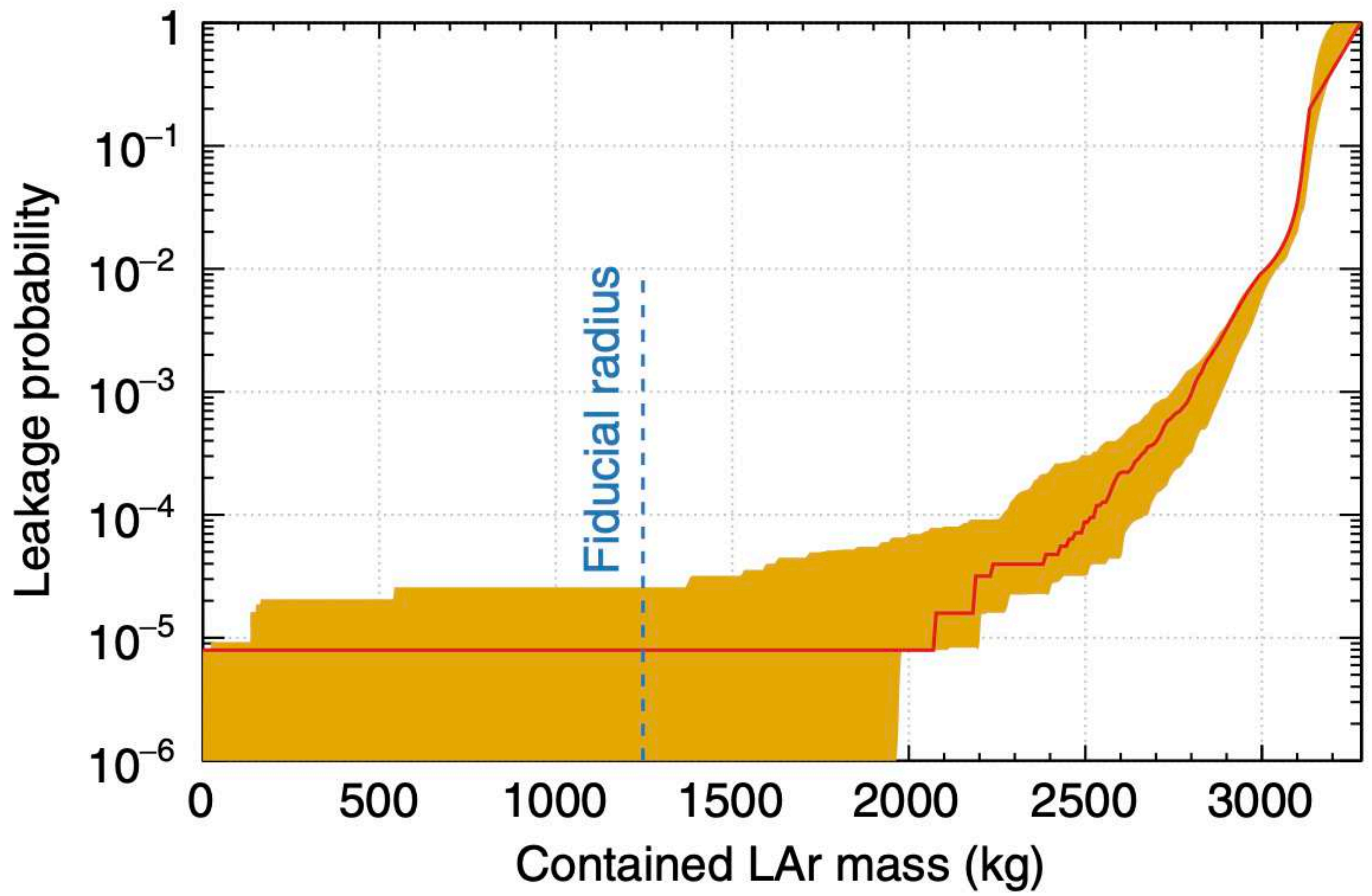
$$\frac{d\sigma_{T\chi}}{dE_R} = N_D^2 \frac{d\sigma_{nD}}{dE_R} |F_T(q)|^2 A^4$$

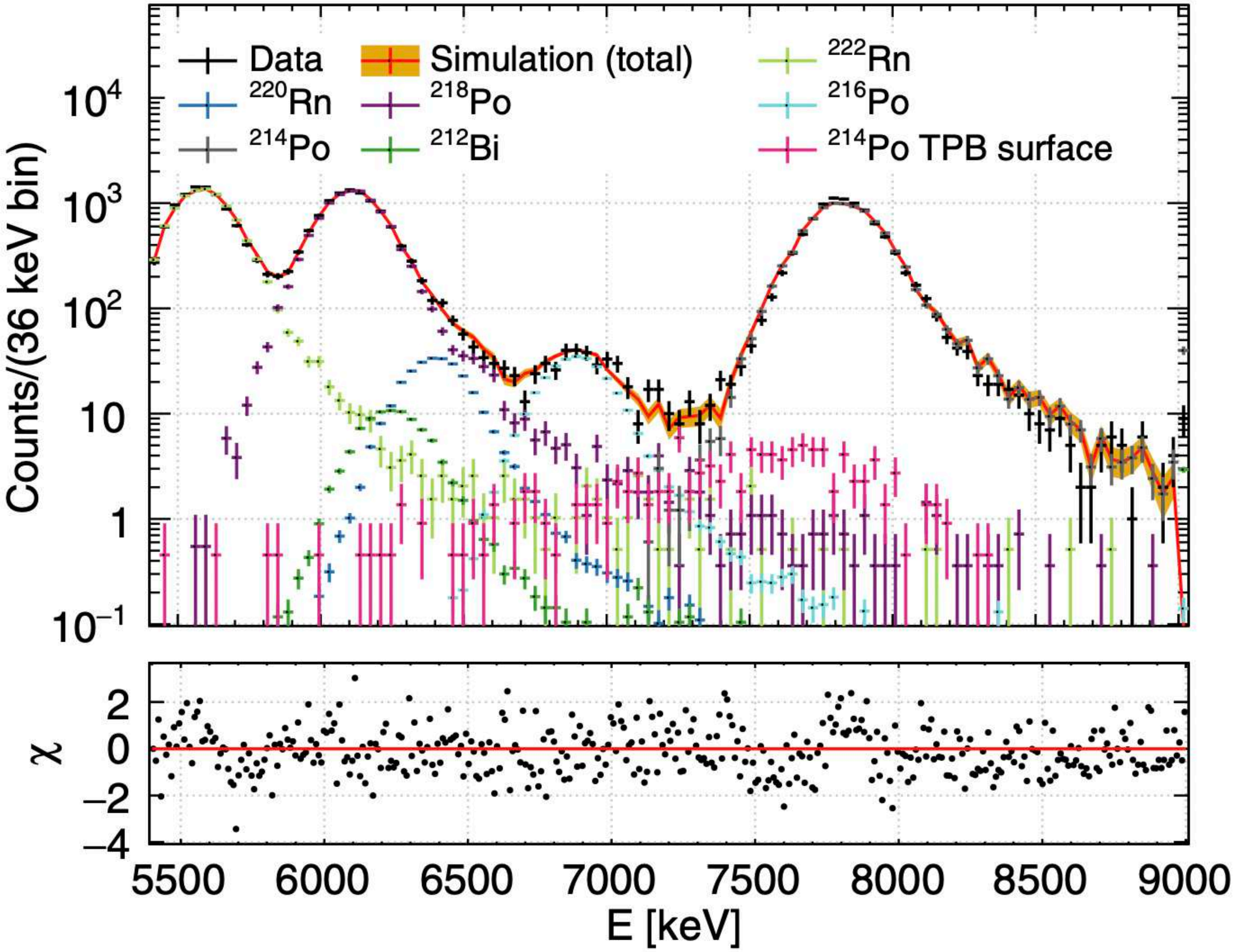


$$\frac{d\sigma_{T\chi}}{dE_R} = A^4 \frac{d\sigma_{n\chi}}{dE_R}$$

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





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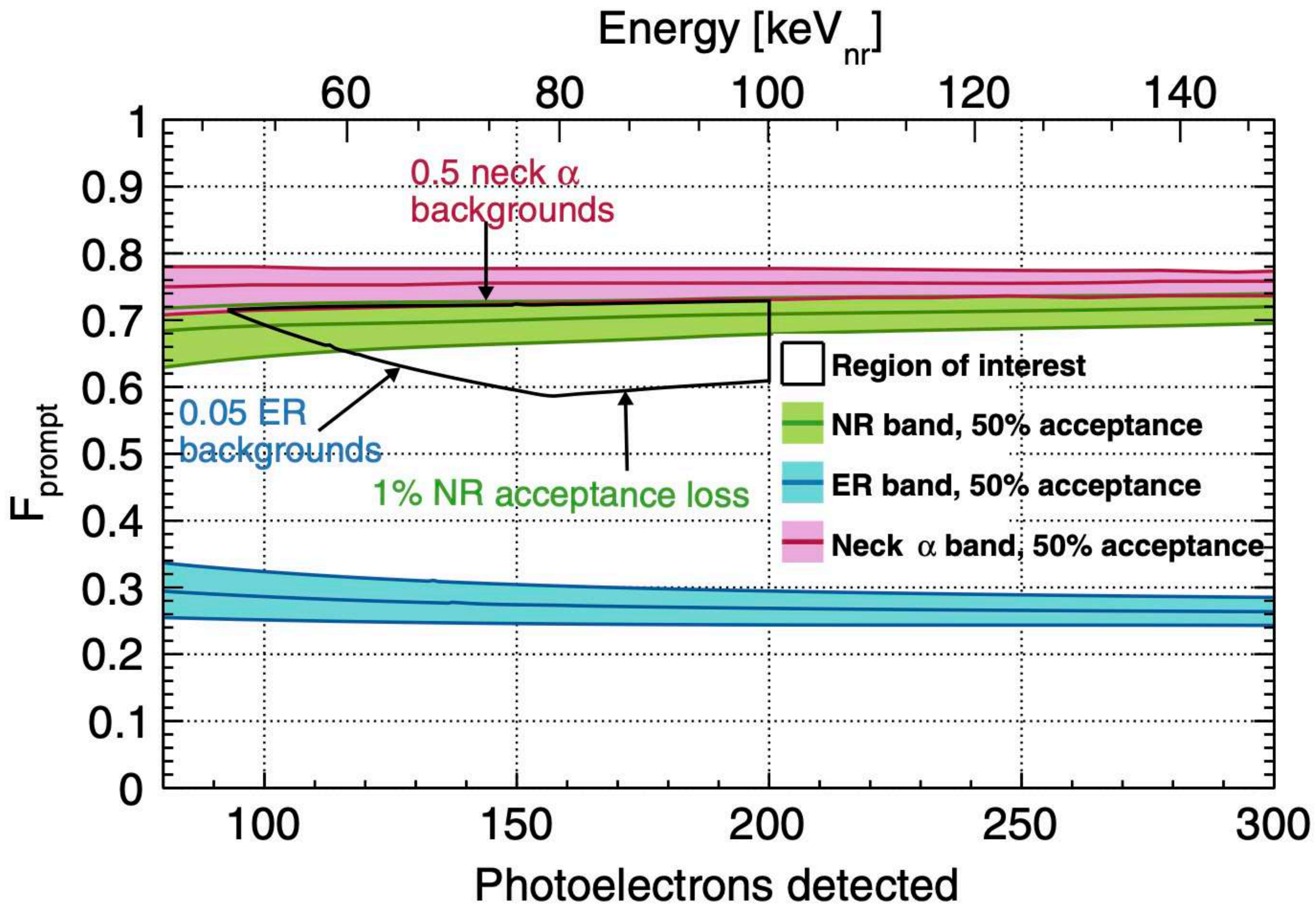
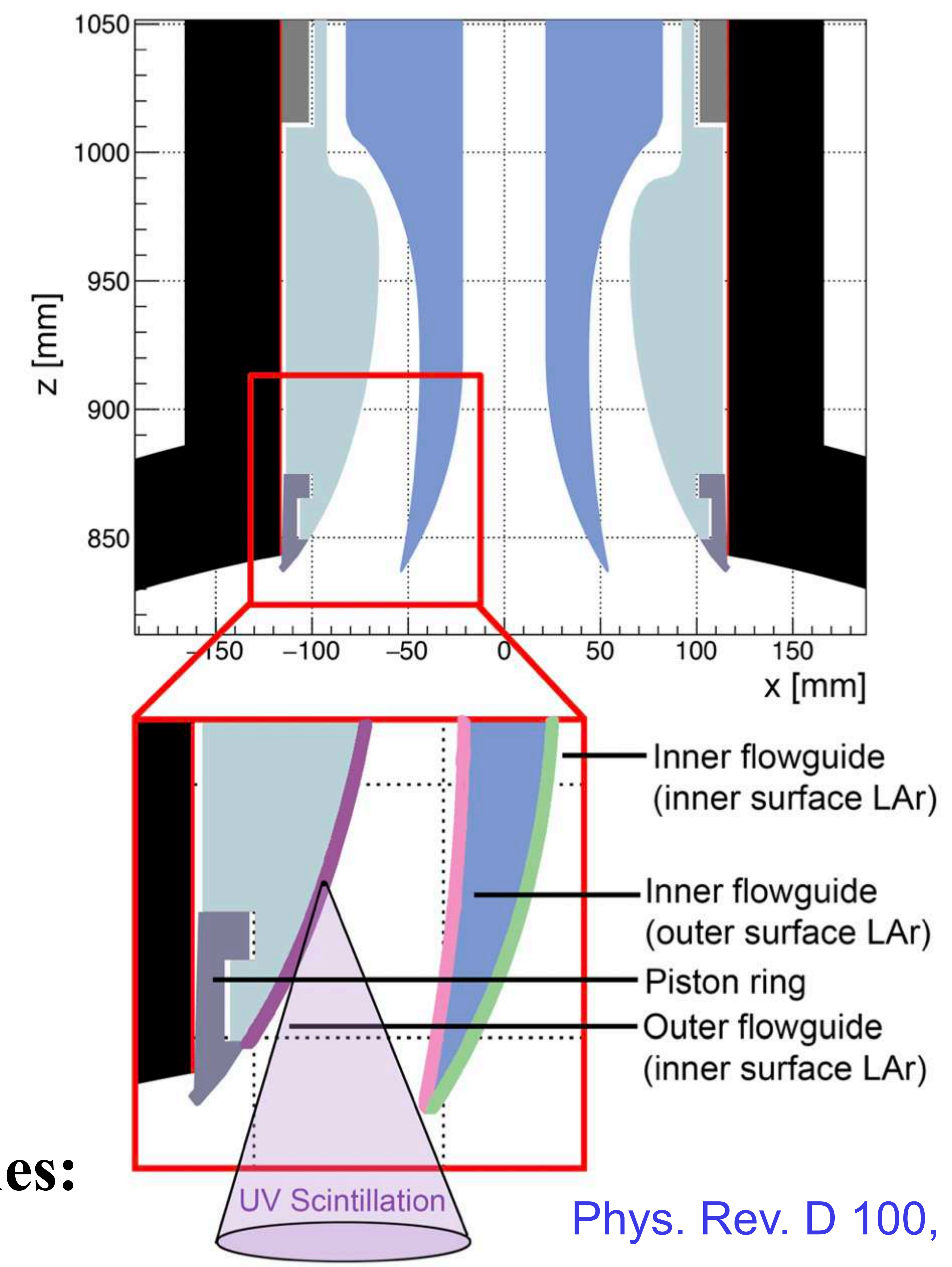
Background sources

- ^{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.





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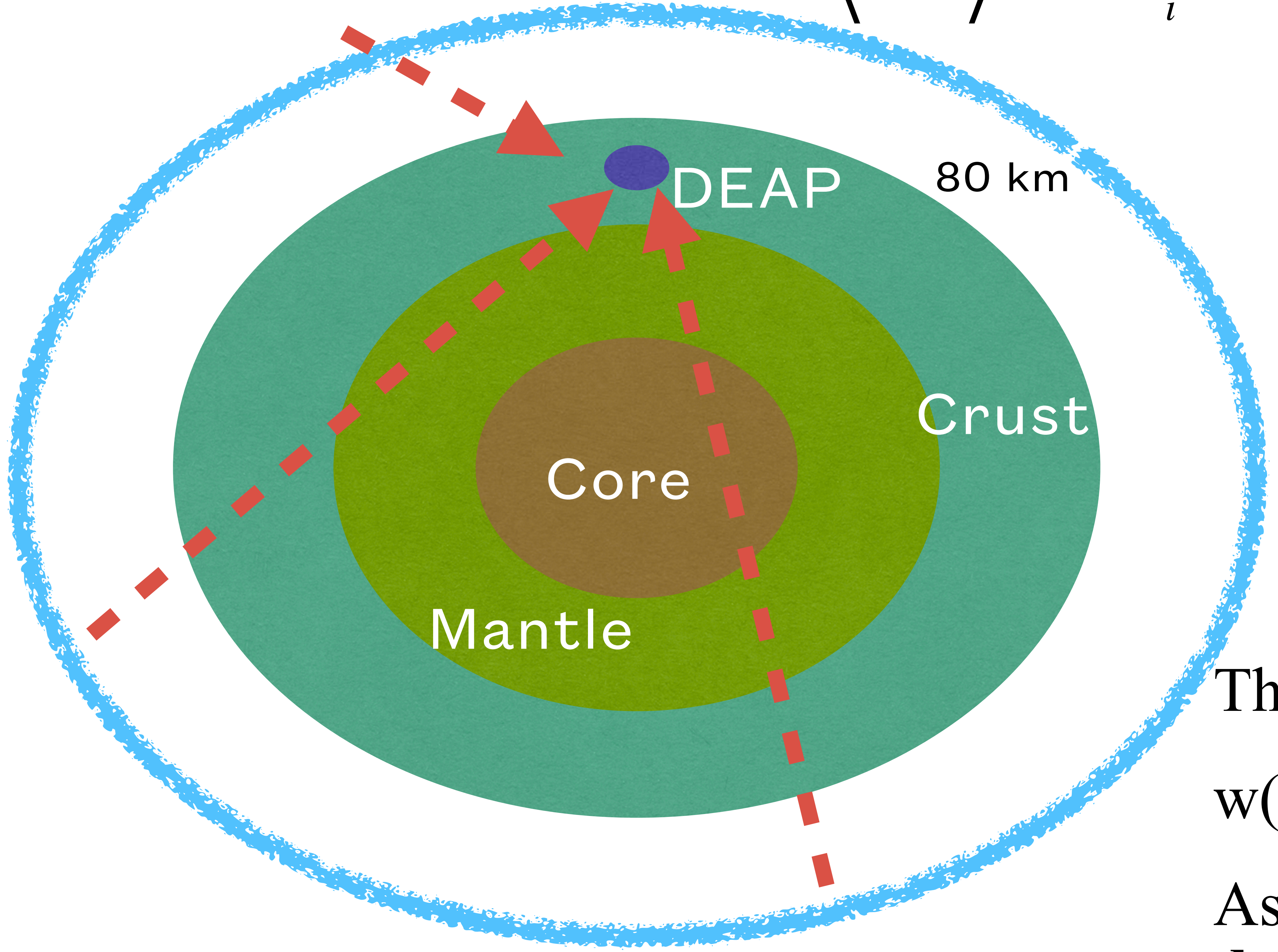
Rejection techniques:

- 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

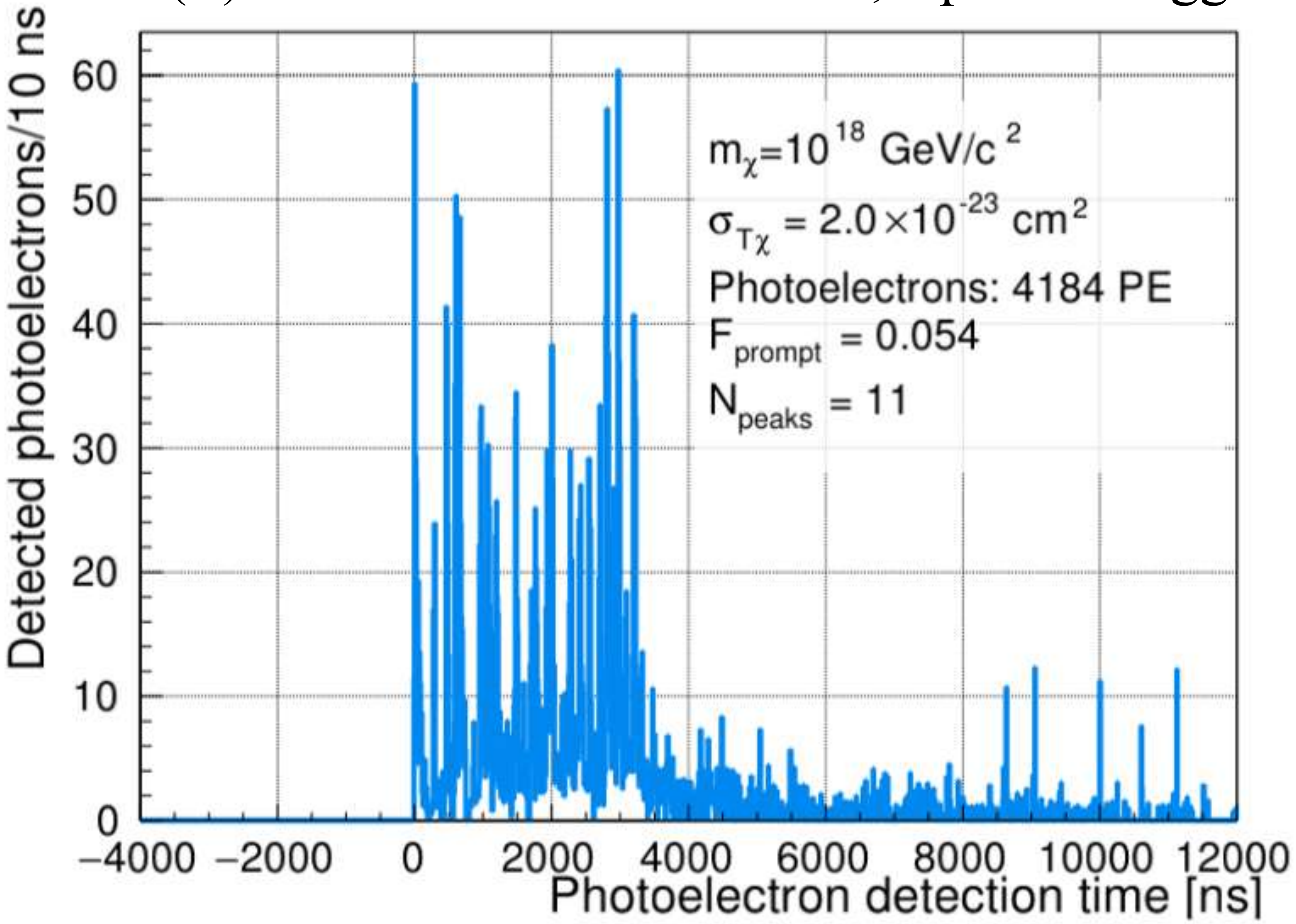
Simulation of the signal

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}.