First direct detection constraints on Planck-scale mass dark matter with multiple-scatter signatures using the DEAP-3600 detector

On behalf of the DEAP-3600 Collaboration
See https://arxiv.org/pdf/2108.09405.pdf

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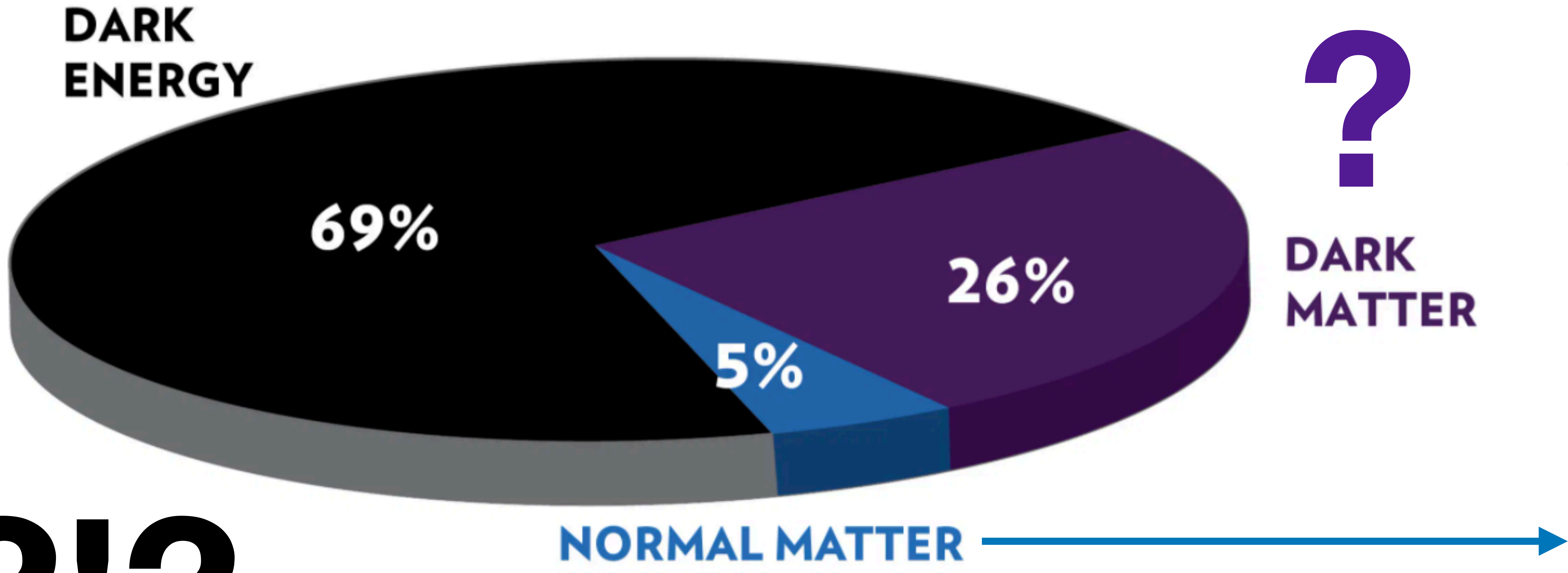
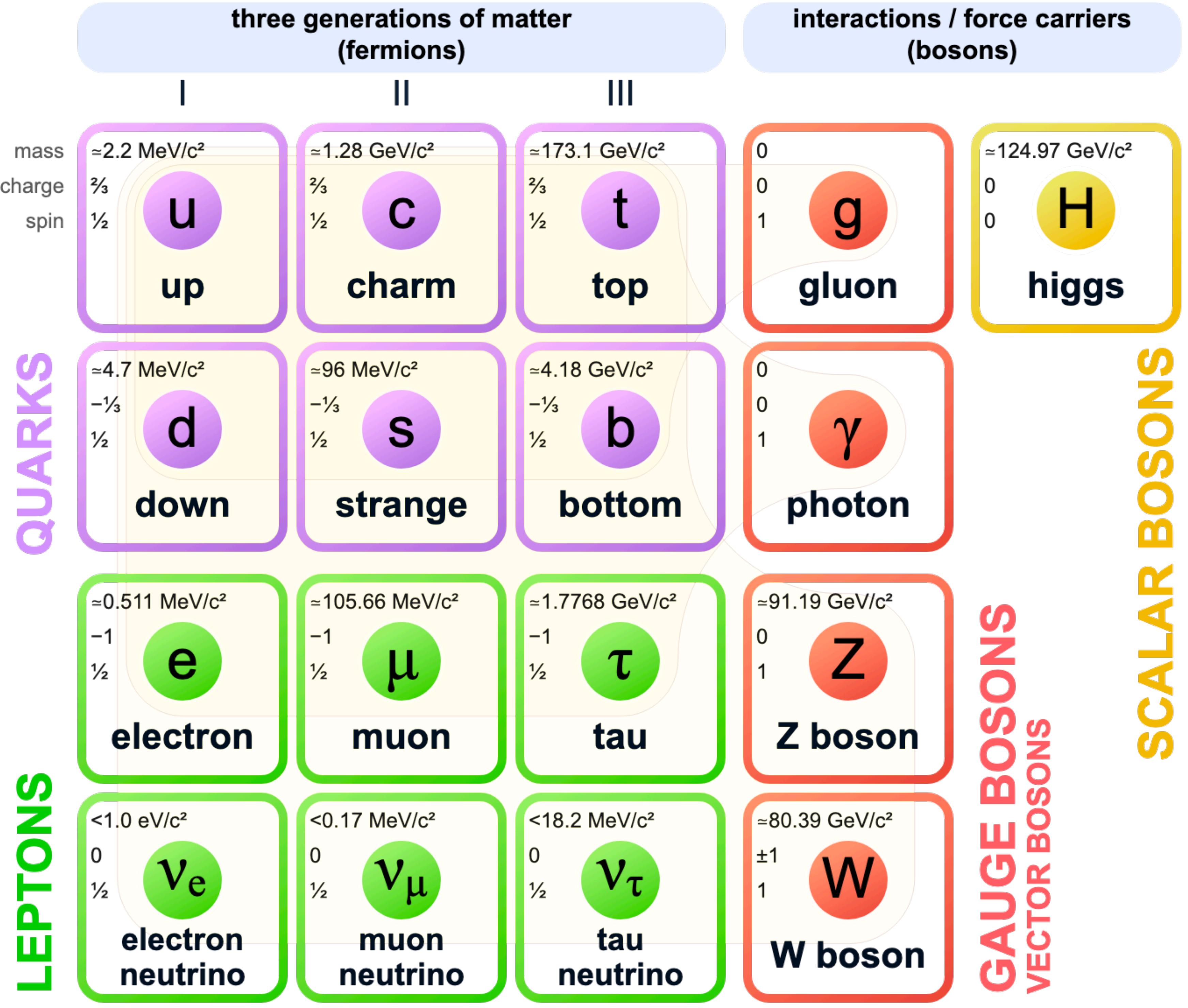
Composition of the Universe

The existence of a mysterious, non-luminous type of matter known as dark matter (DM), is well established

Astrophysical and cosmological observations show that DM makes up 27% of the total energy density of the Universe, and is approximately five times more abundant than the ordinary matter component comprised of Standard Model particles





?!?

What could Dark Matter be?

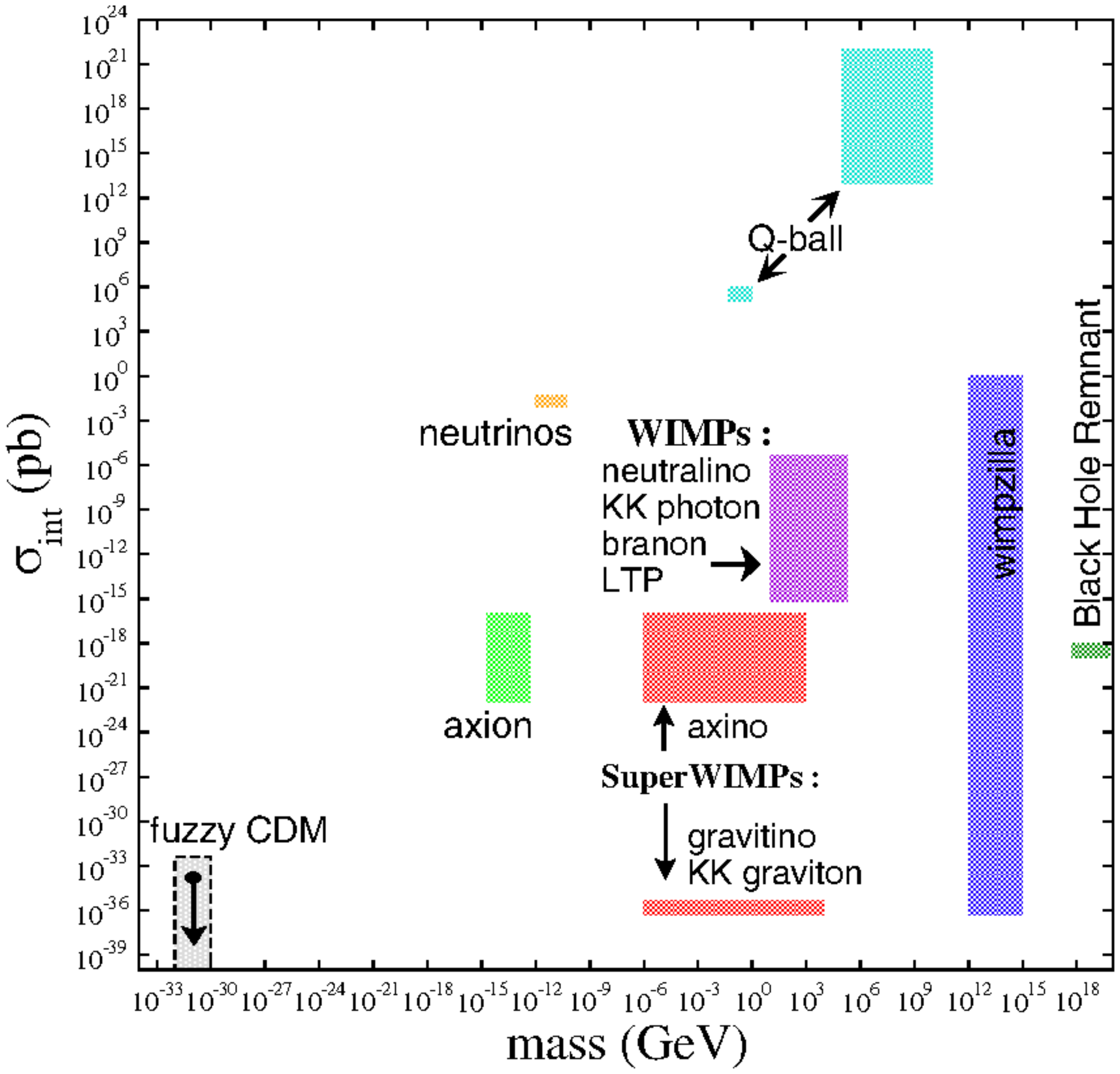
Many potential DM candidates spanning a wide range of interaction cross section-mass parameter space

Weakly-Interacting Massive Particles (WIMPs) are/remain a popular candidate:

- $\mathcal{O}(100)$ GeV long-lived, stable particle that interacts via the gravitational and weak forces would naturally predict the correct thermal relic density
- Predicted by SUSY; the Neutralino (LSP) would make an ideal WIMP candidate with $\sigma \sim 10^{-44}$ cm^2

Axions are becoming increasingly popular DM candidates

… Planck-Scale DM? (spoiler alert)

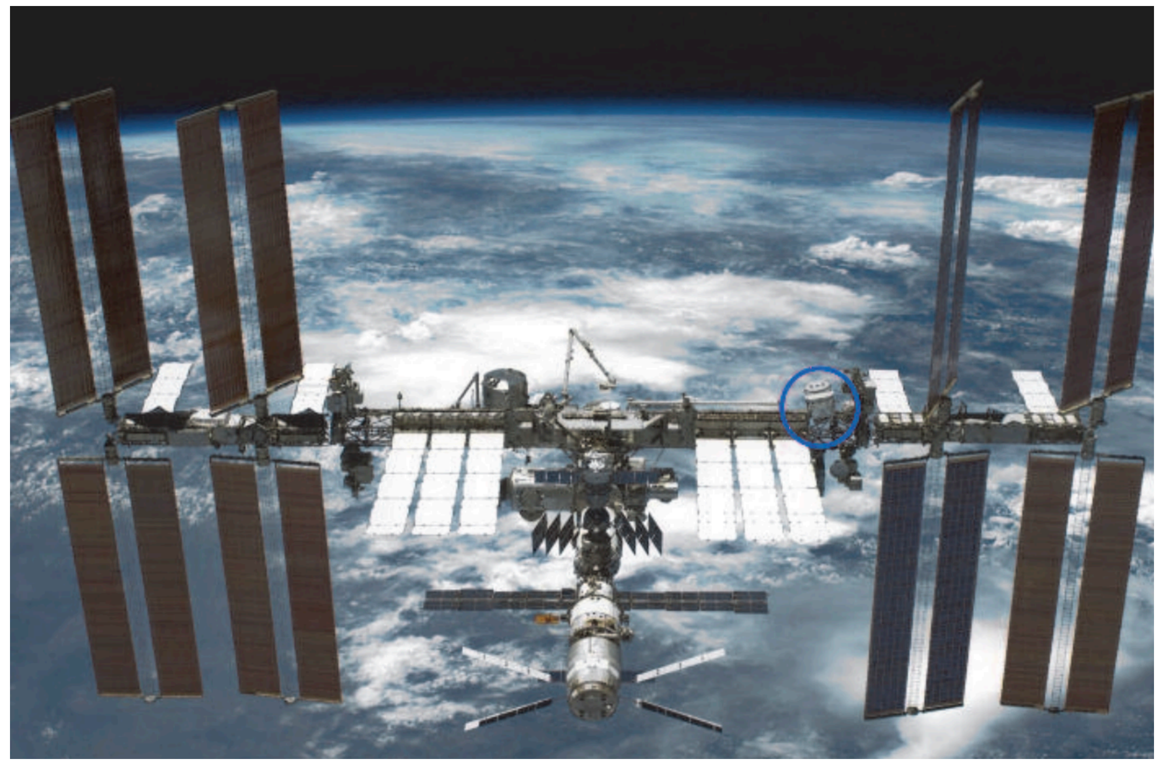


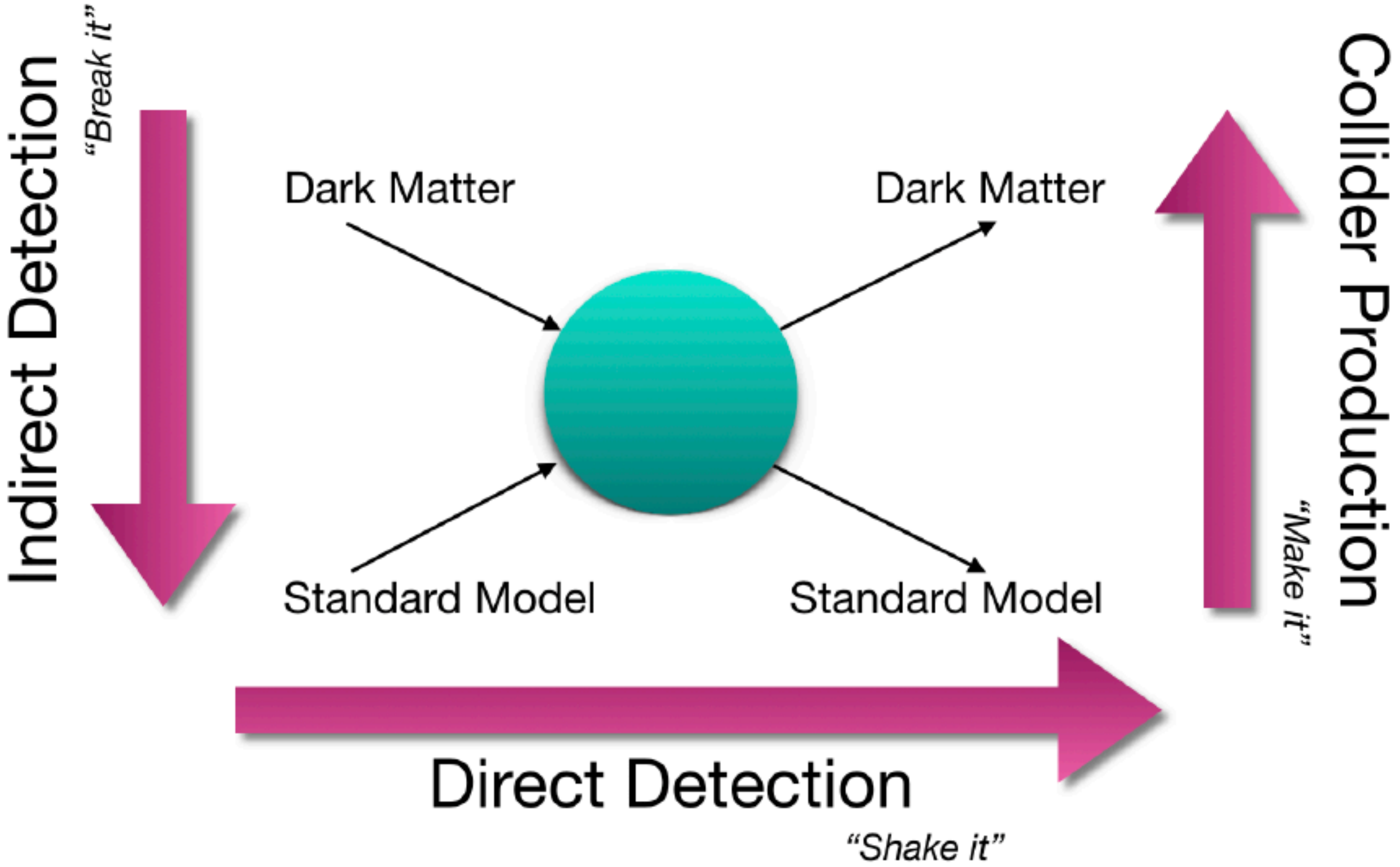
Prof J. Monroe Outreach Talk; HEPAP/AAAC DMSAG Subpanel (2007)

Experimental Channels For Dark Matter Detection

** Not comprehensive list*

HESS PAMELA AMS





Indirect Detection

“Break it”

Dark Matter

Dark Matter

Standard Model

Standard Model

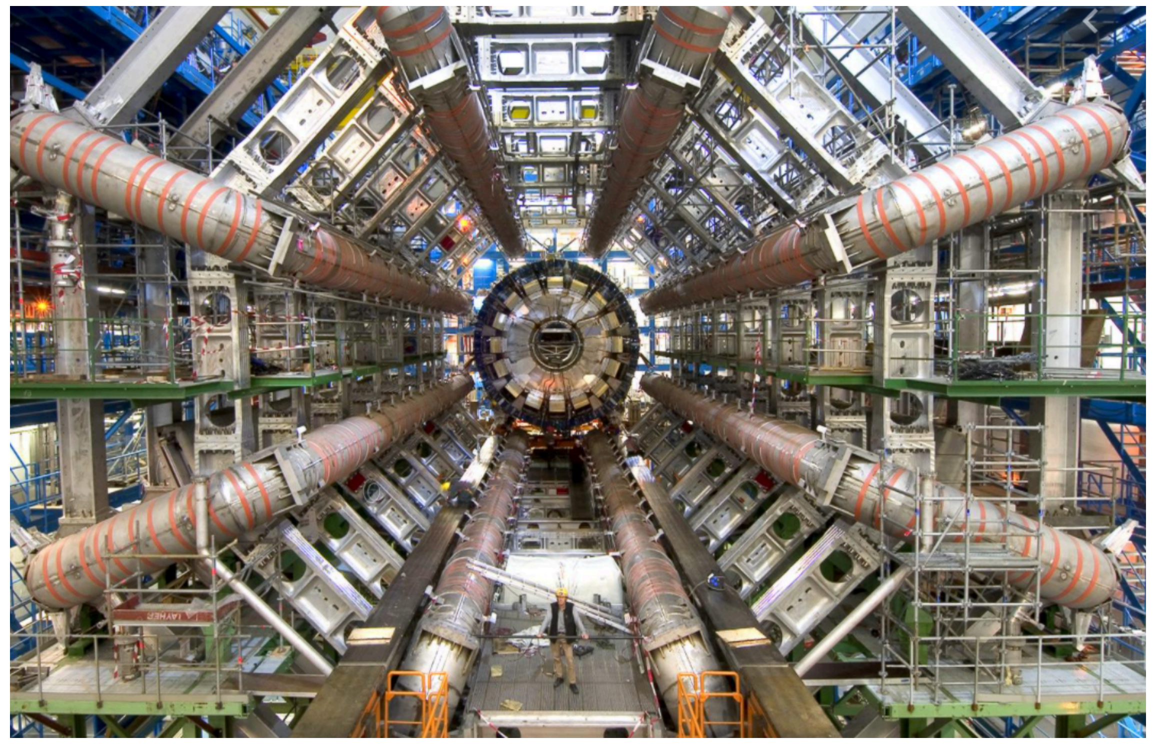
Collider Production

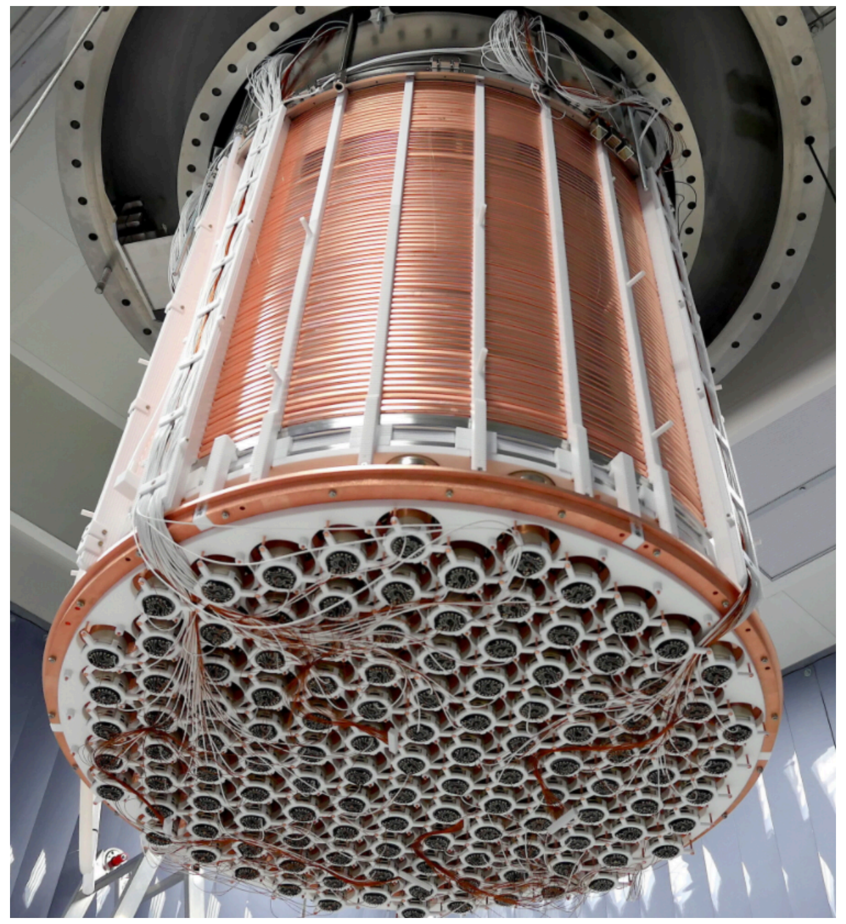
“Make it”

Direct Detection

“Shake it”

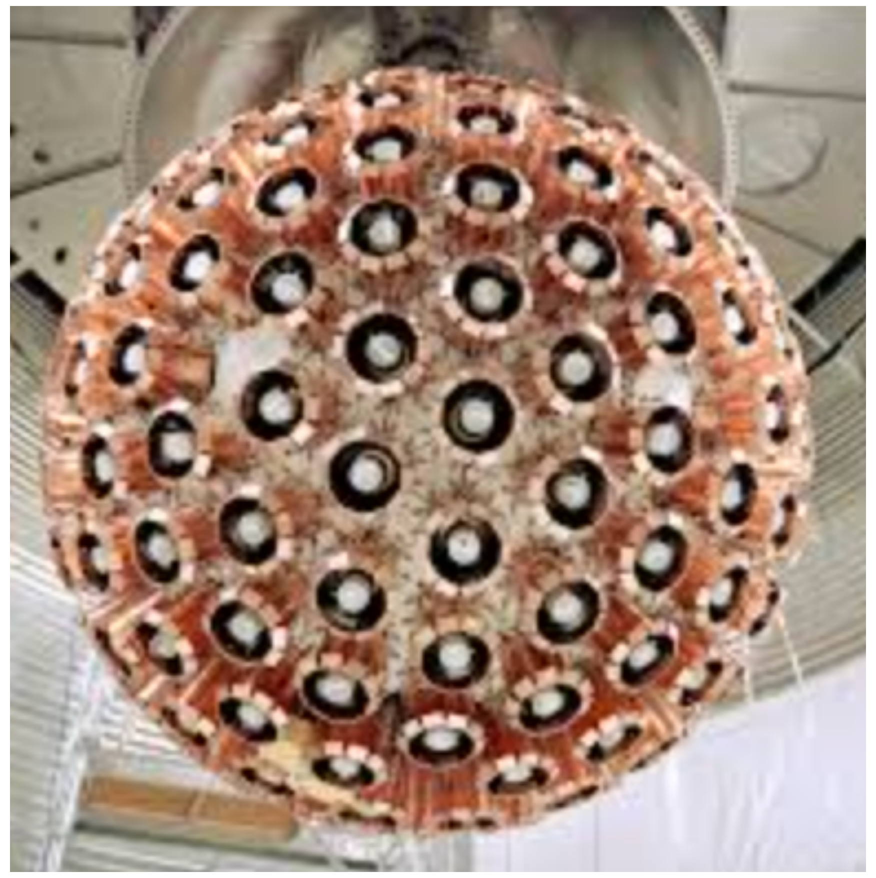
ATLAS CMS





XENON100/1T DarkSide-50/20k DEAP-3600

LUX/LZ SuperCDMS



Directly Detecting WIMPs

WIMP particles elastically scatter off of nuclei to generate nuclear recoils (NRs)

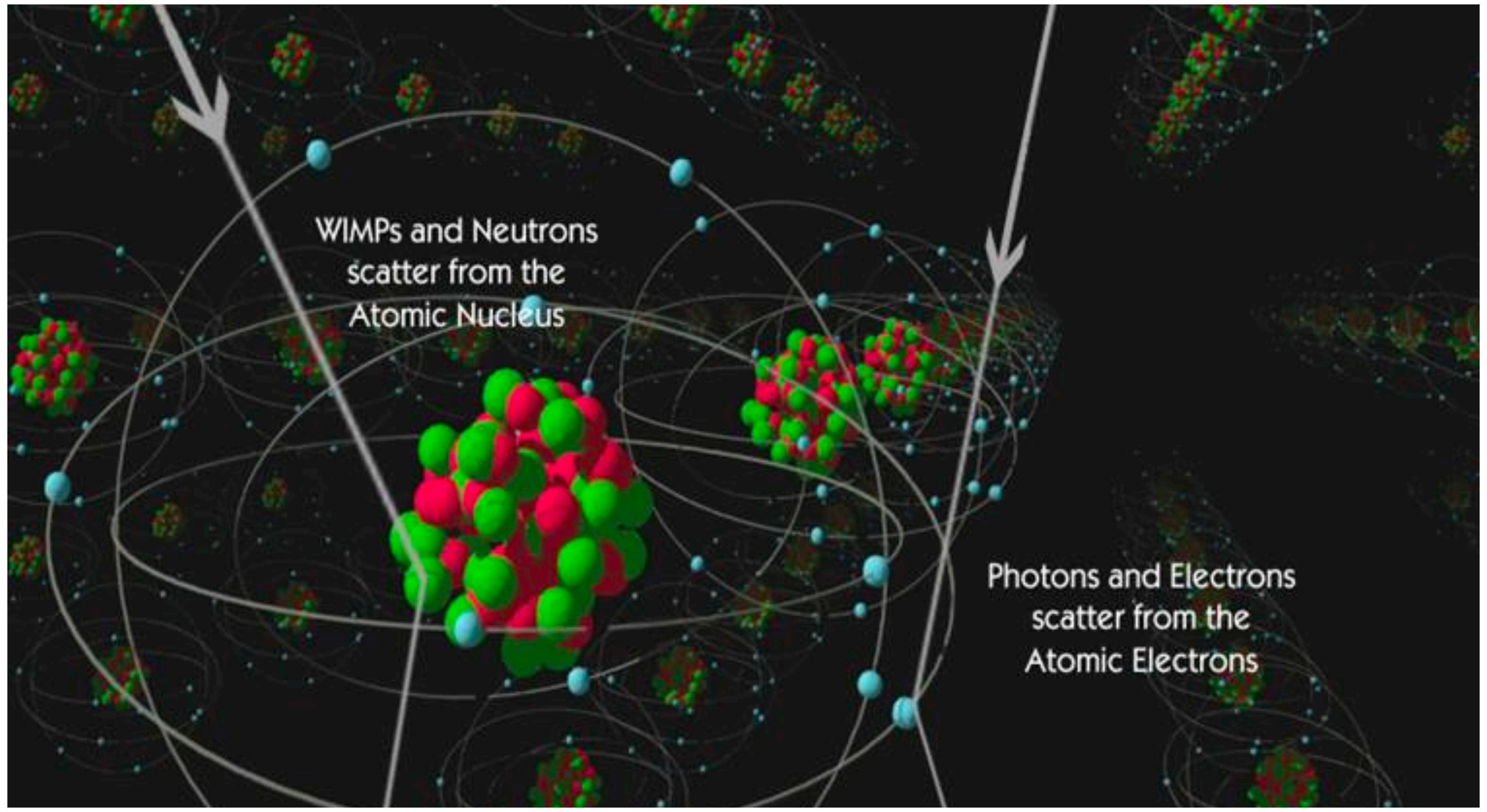
Detectors can measure the energy deposited by NRs in 3 ways: scintillation (light), ionisation (charge) and phonons (heat)

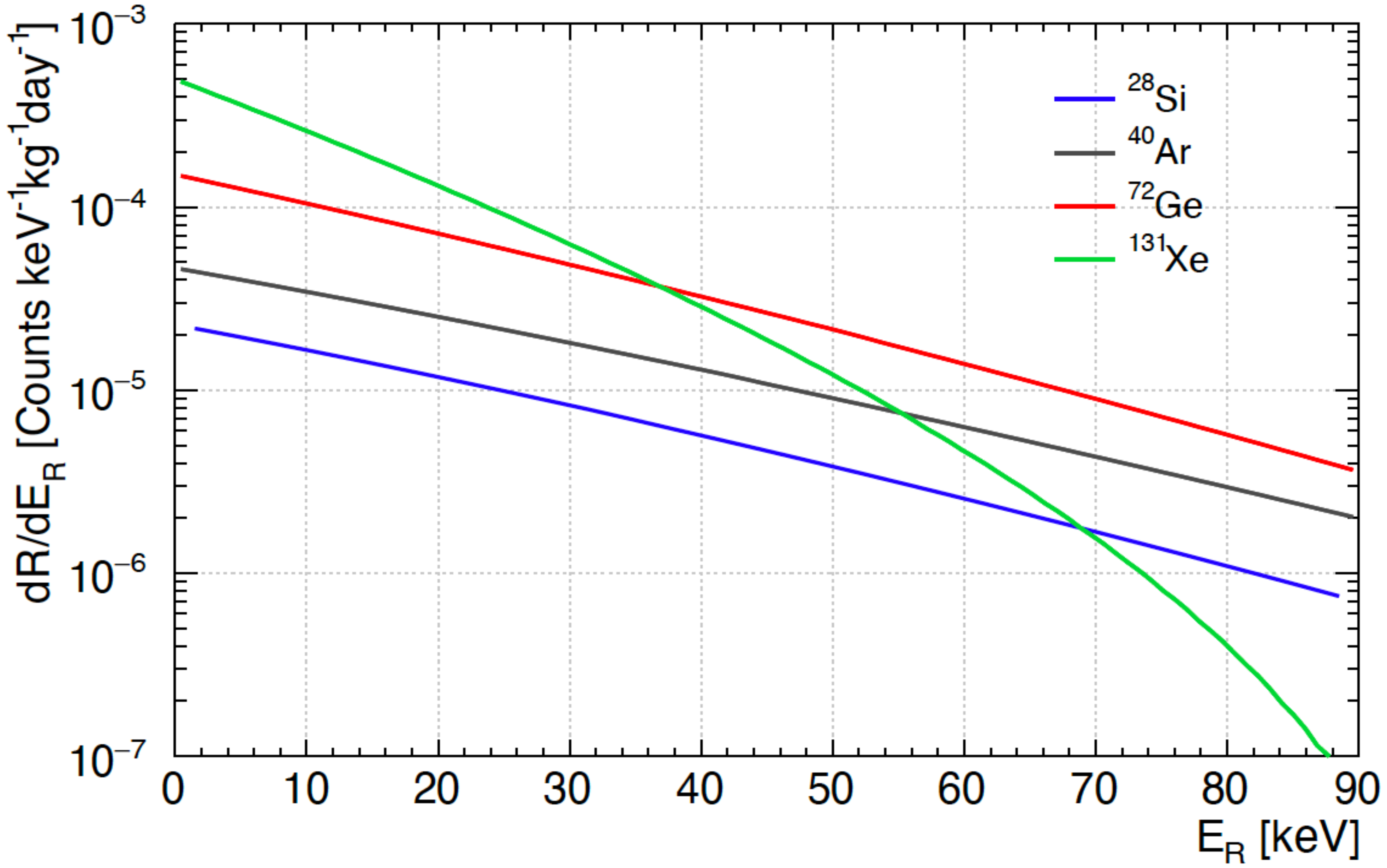
The choice of which technique(s) to use is based on the compromise between having the lowest possible energy threshold, the largest exposure and the most powerful background discrimination

The nature of the particle interaction can be inferred from the total energy deposited:

- Single-phase detectors such as DEAP-3600 measure scintillation light only
- Dual-phase detectors such as DarkSide, XENON, measure both scintillation and ionisation

WIMPs predicted to produce low-energy NRs at extremely low rate (few events/tonne-year)





DEAP-3600 Collaboration

Slide courtesy of S. Westerdale

The DEAP-3600 Detector

Dark matter Experiment using Argon Pulse-shape discrimination

Single-phase liquid argon (LAr) scintillation light detector, holding 3279 kg target LAr inside spherical, radiopure acrylic vessel

Optimised for collection of scintillation light from ^{40}Ar nuclear recoils (NRs) after scattering interaction with WIMP particle, χ

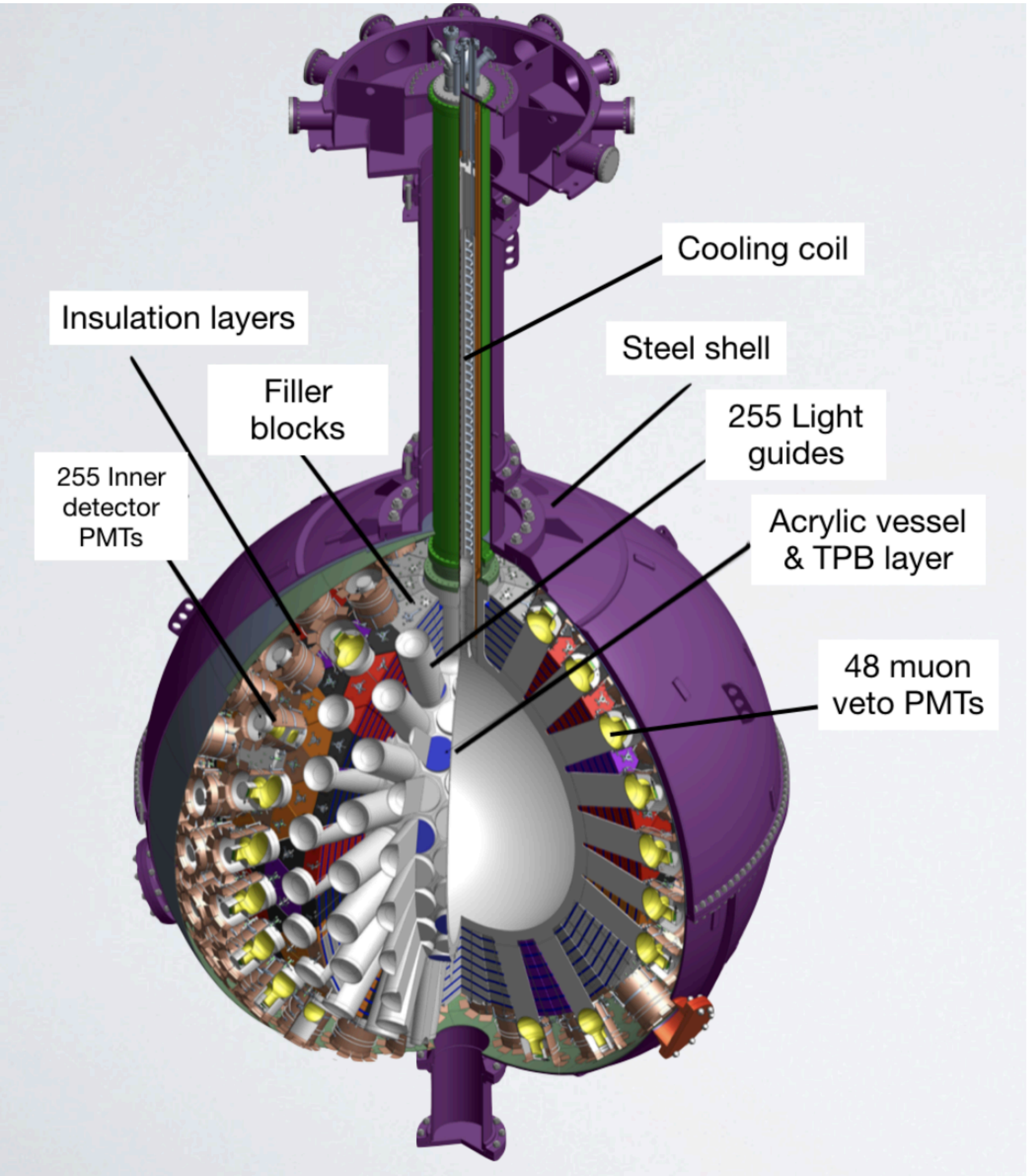
VUV scintillation photons produced at λ = 128 nm shifted to visible wavelengths via layer of tetraphenyl butadiene (TPB) wavelength shifter coated on inner acrylic vessel

Wavelength-shifted photons detected by 255 inward-facing, low radioactivity Hamamatsu photomultiplier tubes (PMTs) with ~ 75% coverage of inner volume

- "In-situ characterization of the Hamamatsu R5912-HQE photomultiplier tubes used in the DEAP-3600 experiment." Nucl. Instrum. Meth. Phys. Res. A 922, 373 (2019)

Total photoelectrons (PE) detected in an 'event' related to total energy deposited in detector from particle interaction

Pulse-shape discrimination: Fraction of 'prompt' light compared to total light used to distinguish electromagnetic ER recoils (β,γ-rays) from nuclear NR recoils (neutrons, WIMPs), see references below on PSD and LAr pulse shape



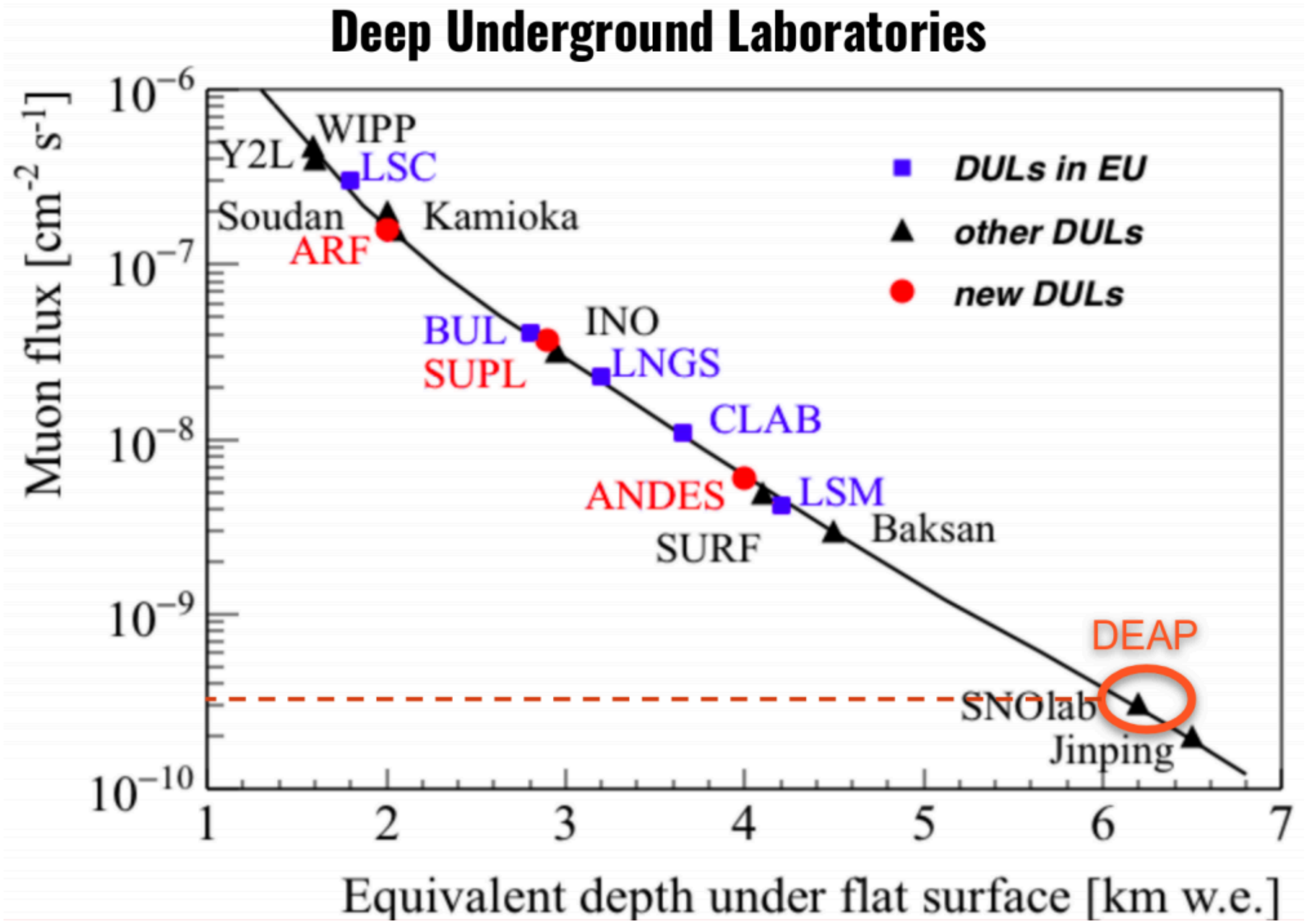
LAr pulse shape : https://doi.org/10.1140/epjc/s10052-020-7789-x

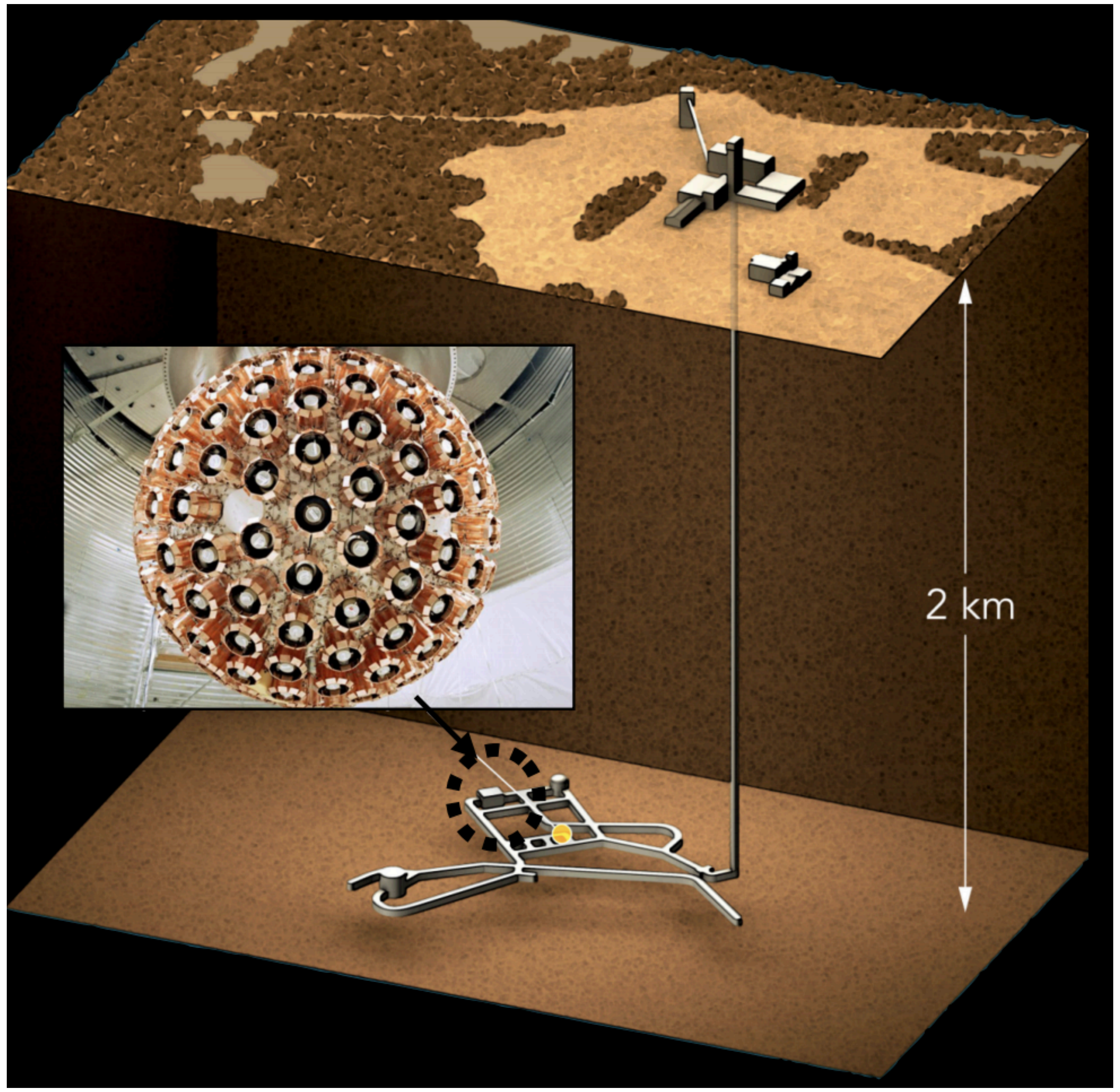
PSD : https://doi.org/10.1140/epjc/s10052-021-09514-w

SNOLAB

The DEAP-3600 detector is located 2 km underground @ SNOLAB, Sudbury, Ontario, Canada

- Excellent shielding from cosmogenic backgrounds
- Muons extremely problematic for DM searches; muons interacting with rock can produce neutrons which mimic WIMPs!
- Muon flux reduced by factor of ~ 10^7





https://phys.org/news/2018-05-world-sensitive-dark.html

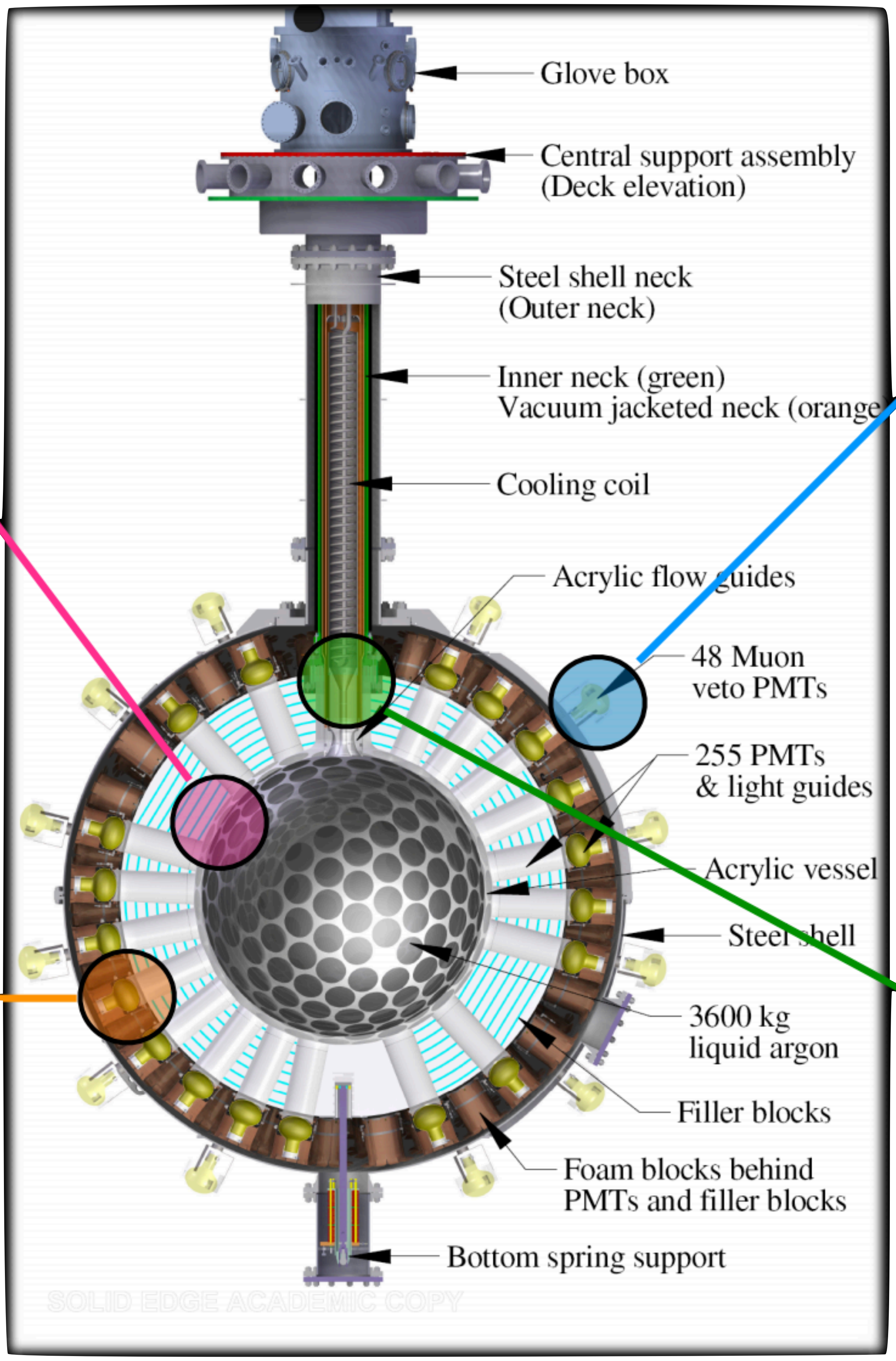
Backgrounds in DEAP-3600

LAr: Ar39 β decays, α decays from Rn222/ Rn220,

Acrylic Vessel (AV) surface: Po210 α decays.

PMTs & other detector components: Radiogenic neutrons, γ/β produced in glass…

➡ Cherenkov light produced in light guide acrylic.

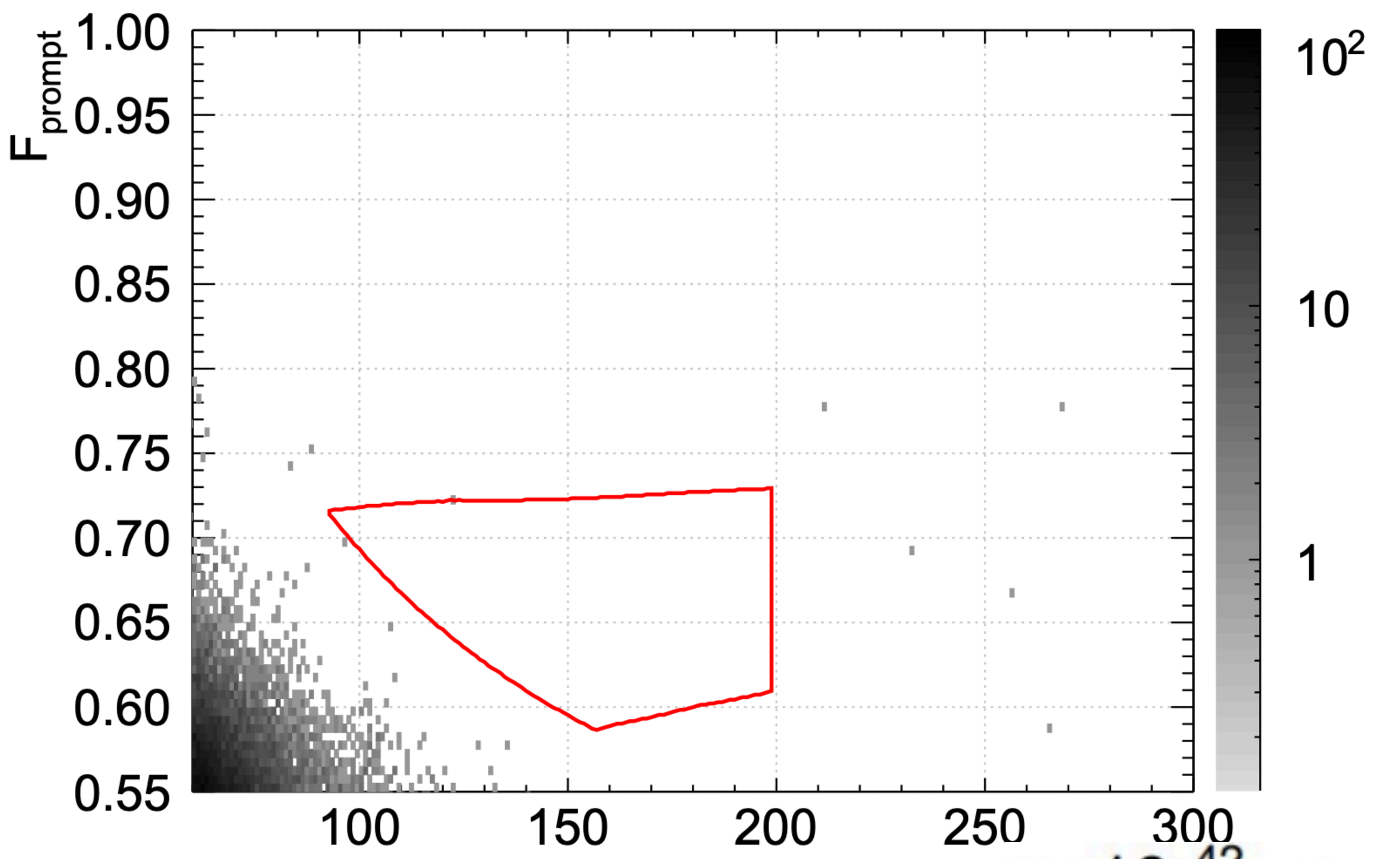


External: Cosmogenic-induced neutrons produced inside water tank/ rock.

Neck: Po210 α decays through LAr 'film' on surface of acrylic flowguides, originating from long-lived Pb210 (Rn222).

Results of WIMP Search from 231 Live-Days of Data

“Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB”. Phys. Rev. D 100, 022004 (2019)

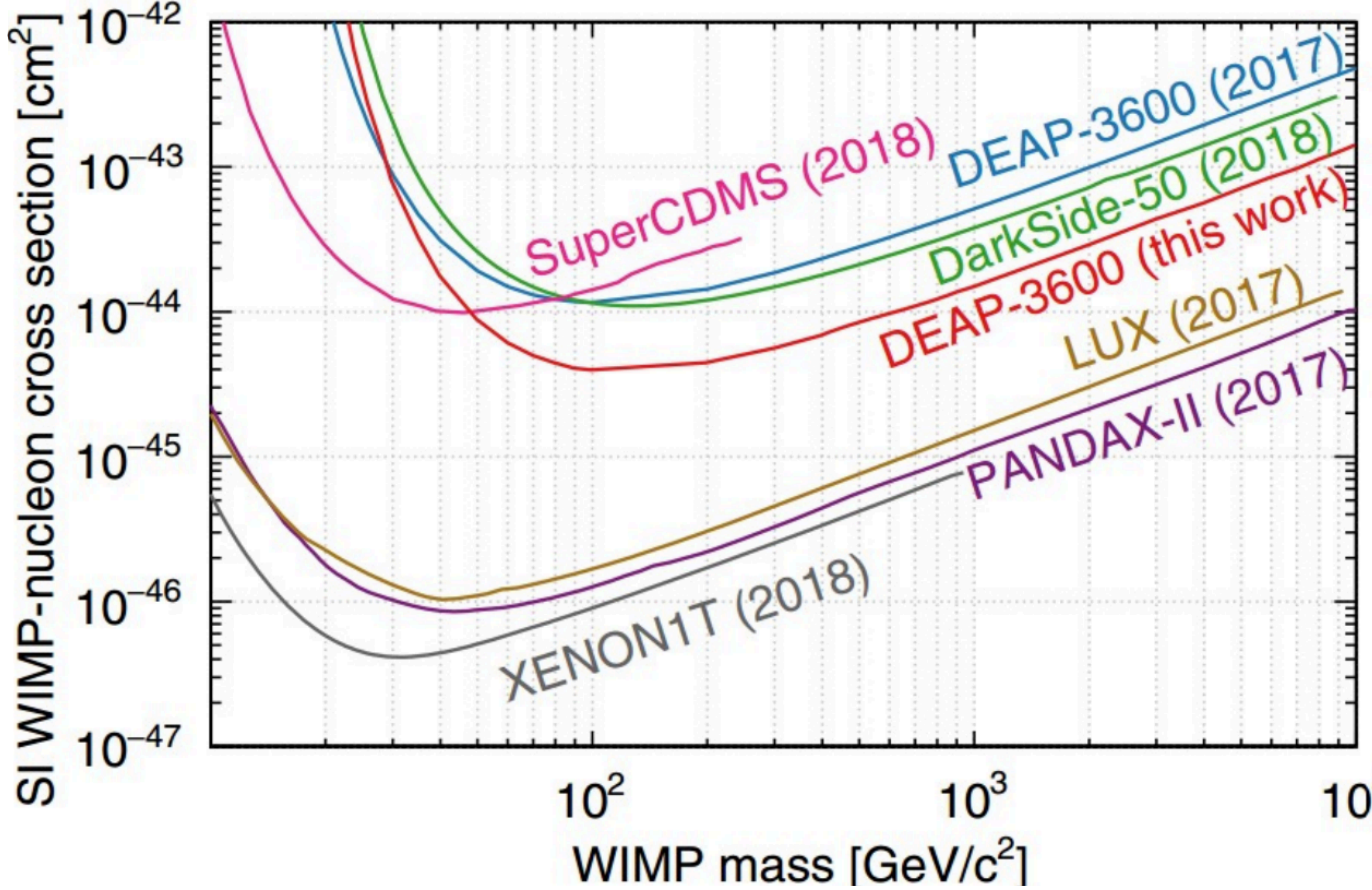


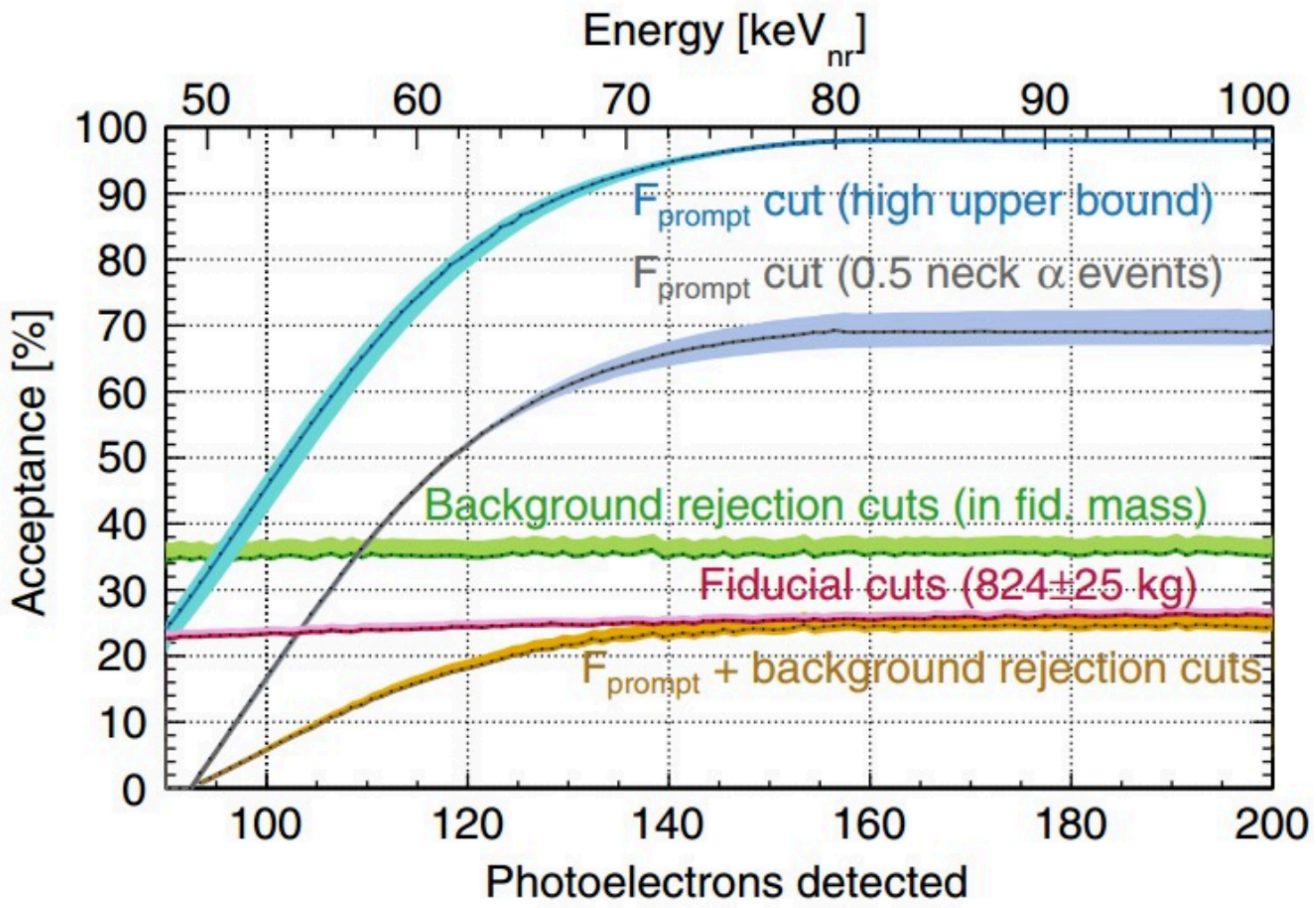
WIMP Region-of-Interest (ROI) driven by signal & background models

Designed to achieve background expectation < 1

After all background rejection and fiducial volume cuts, no WIMP-like events observed inside WIMP ROI

Most stringent limit on SI WIMP-nucleon cross section using Argon target





Loss in WIMP acceptance driven by harsh background rejection cuts

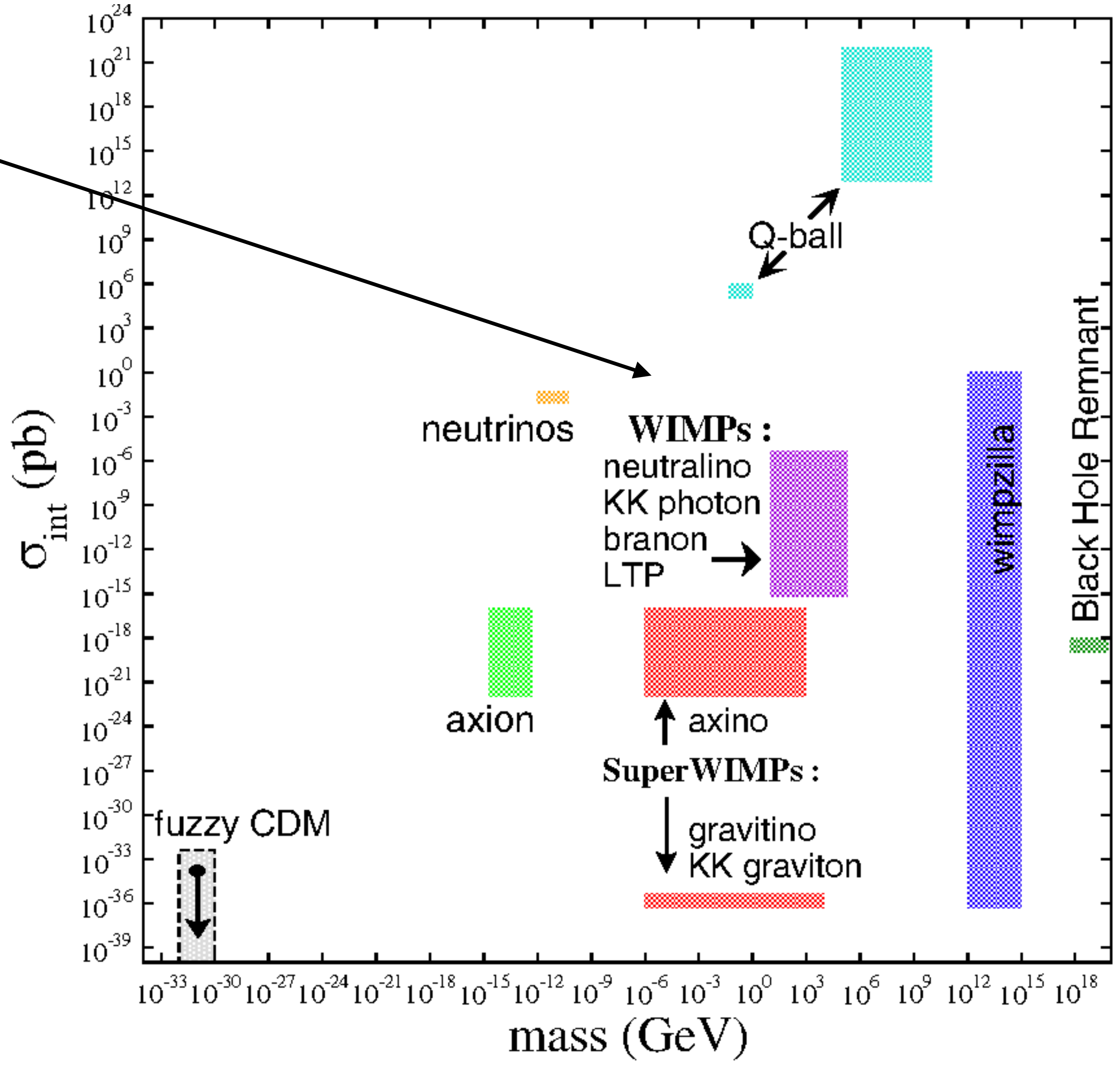
Upcoming publication: non-blind analysis using Profile Likelihood Ratio PLR method in order to attempt to gain back WIMP acceptance & sensitivity

- Watch this space!

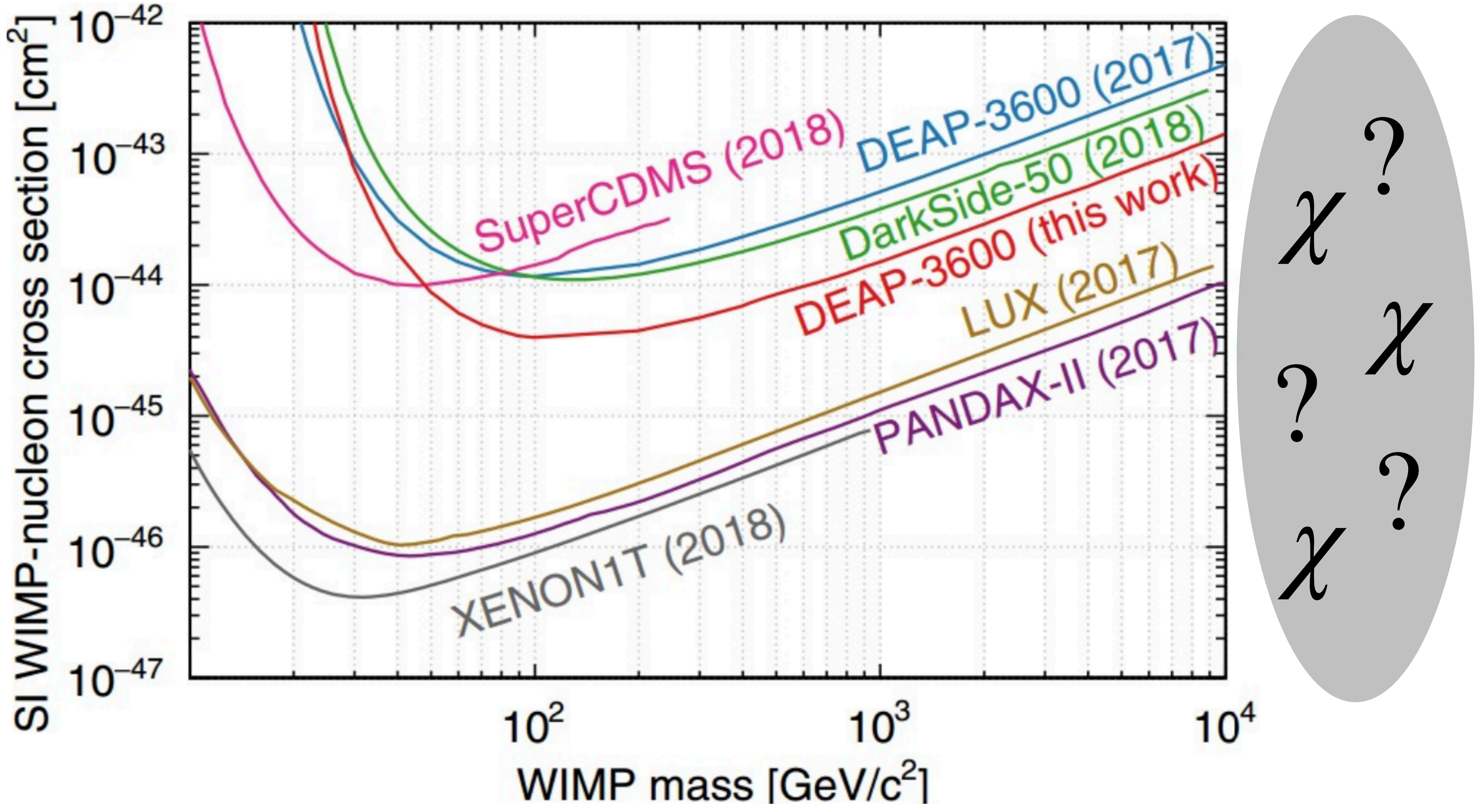
Also working on a blind analysis (802 live-days), using both PLR and machine learning techniques

An Alternative Theory….

So far we've focused on DM that resides here



But what about DM that resides beyond this scale?



➡ Planck-scale, super-heavy DM!

Planck-Scale Dark Matter

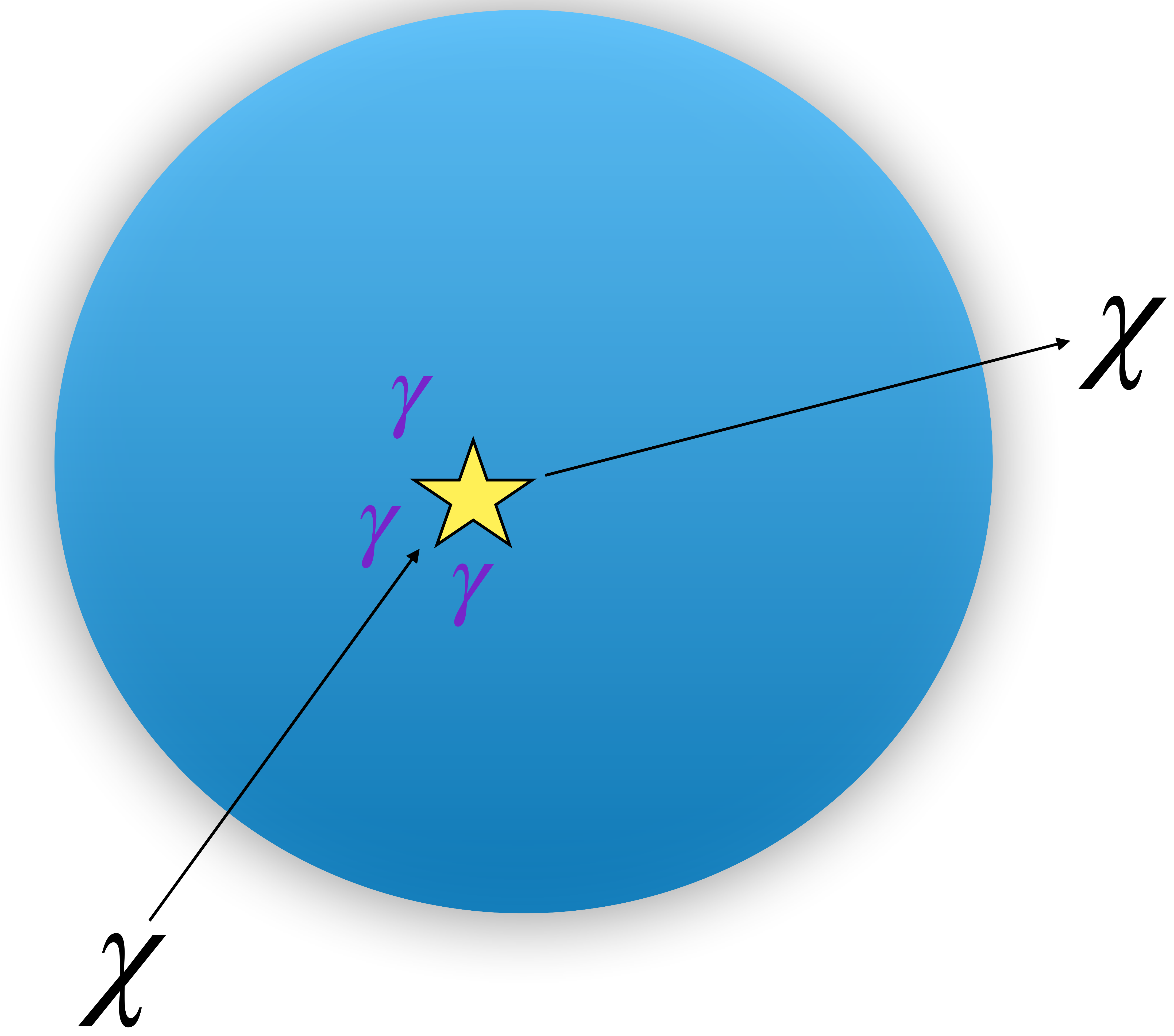
Another well-motivated DM candidate is super-heavy DM with Planck-scale mass

$m_\chi = 10^{19}\mathrm{GeV/c^2}$

Planck-scale DM may be produced non-thermally through GUTs, but other production mechanisms include primordial black hole radiation or extended thermal production in a dark sector

Unlike standard WIMPs, which scatter at most once in a detector, Planck-scale DM has a high enough mass to scatter multiple times as it traverses a detector…

Standard WIMP Scatter



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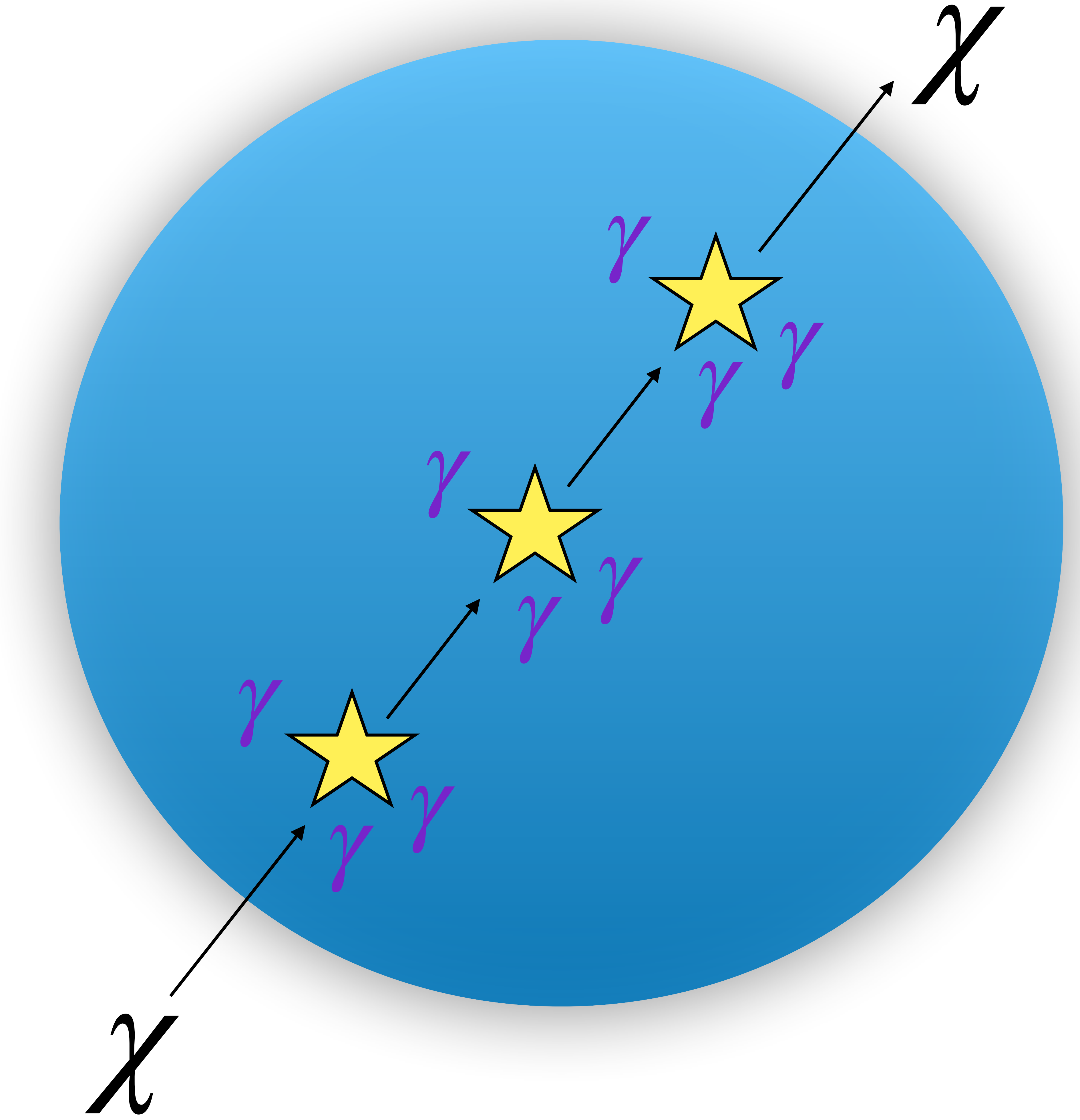
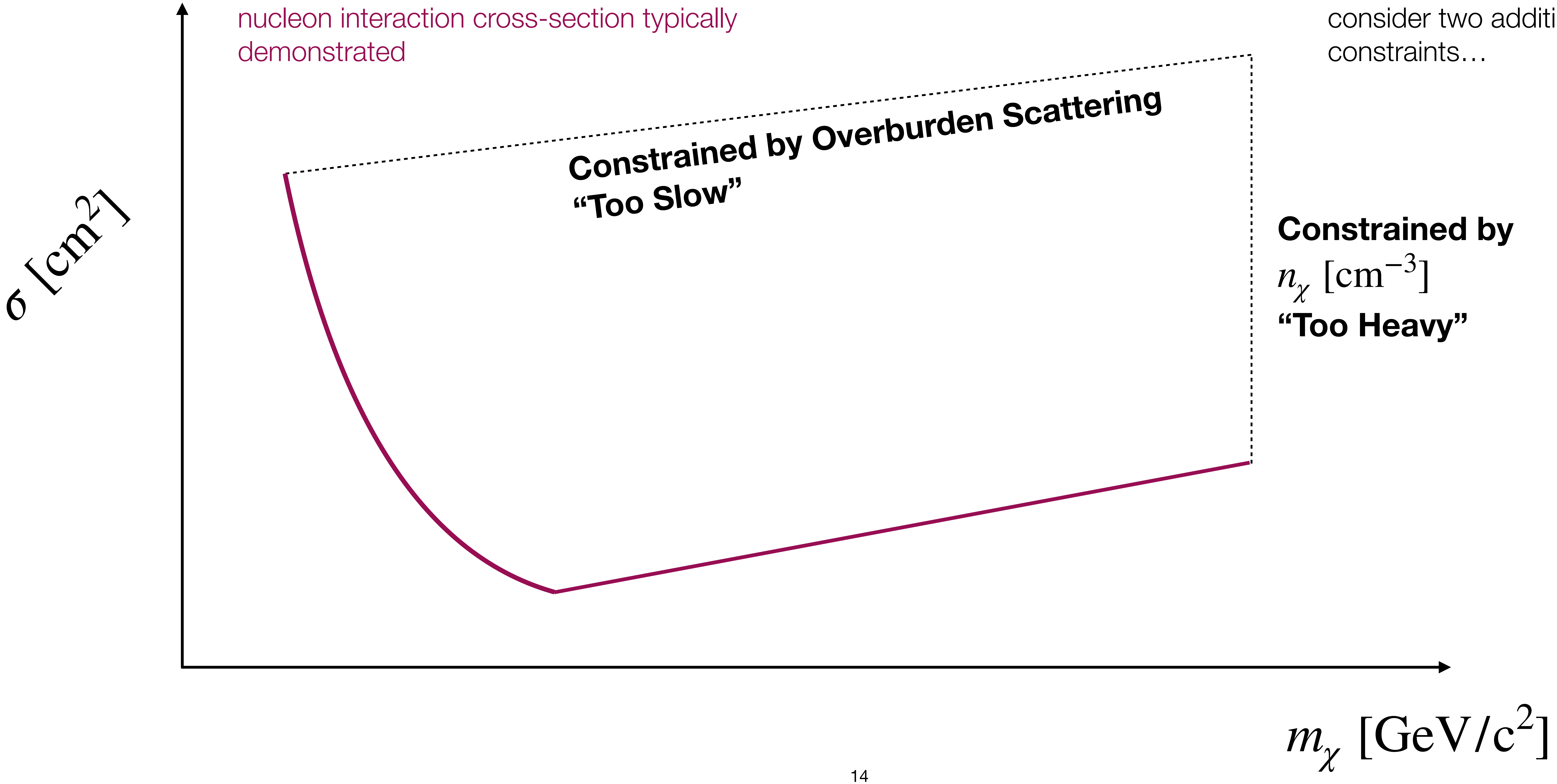
Planck-Scale DM Multi-Scatter



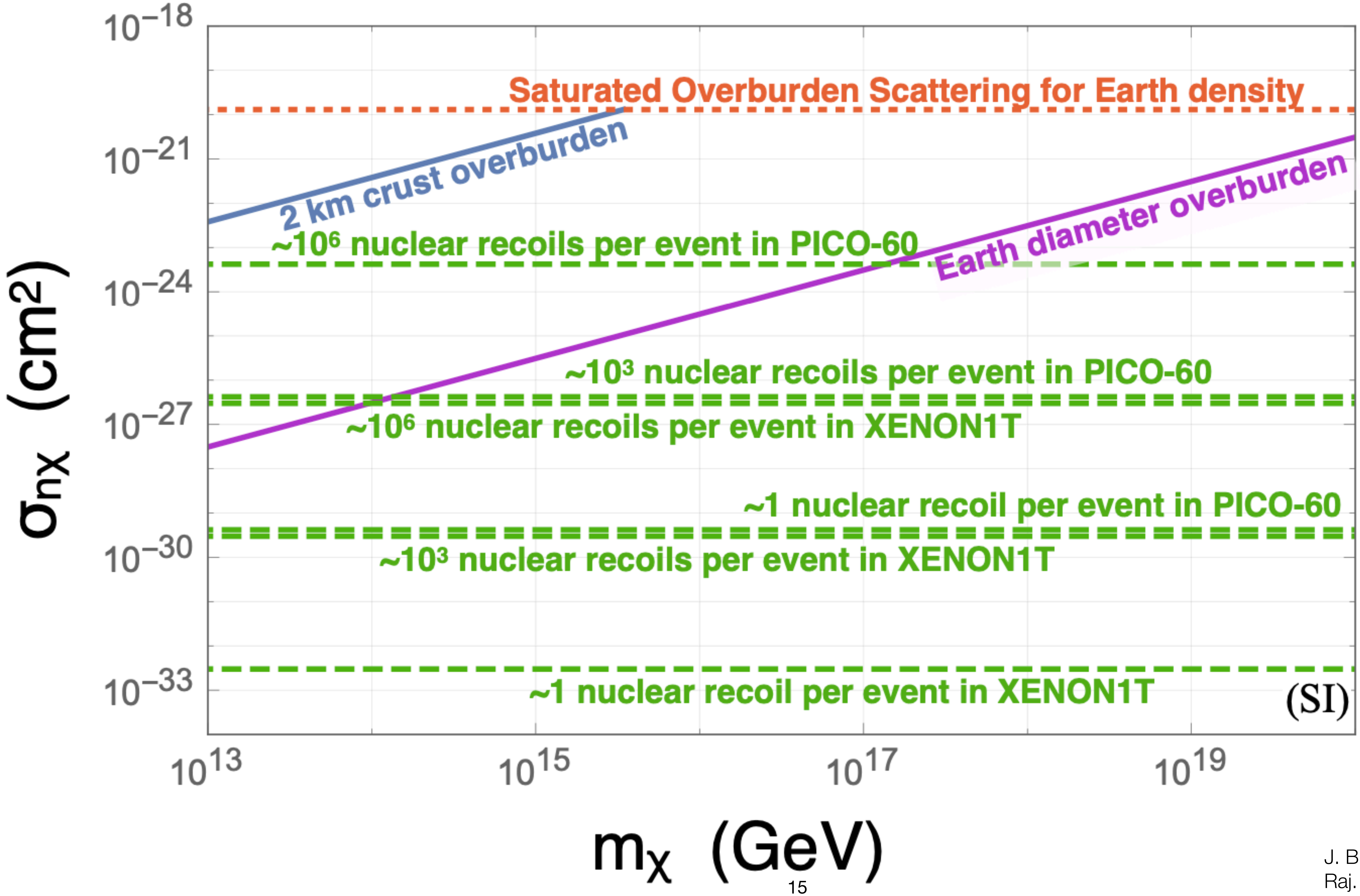
Characterising Planck-Scale DM

Pink line indicates upper limits on DM-nucleon interaction cross-section typically demonstrated

For high mass frontier, need to consider two additional constraints…



Characterising Planck-Scale DM



J. Bramante, B. Broerman, R. F. Lang, and N. Raj. Phys. Rev. D 98, 083516 (2018)

Characterising Planck-Scale DM

$$N_{\rm events} \sim \Phi \ \min[\tau, 1]$$

Φ = Integrated Flux
τ = Optical depth = $n_{\rm det}\sigma L_{\rm det}$

Single scatter limit: $\tau \ll 1$

Multi scatter limit: $\tau \gg 1$

➡ At the highest DM mass relevant parameter is detector area normal to the DM flux: number density of DM is limitation: if number density too low compared to detector area, no DM crosses the detector during the live-time

➡ In low cross-section limit, "thickness" of the detector is most important so we detect enough scatters to be reconstructed…

➡ At high mass AND low cross-section, detector area and thickness are both important…. a large spherical detector is ideal!

Important signature of Planck-scale DM: mostly collinear track of nuclear recoils through detector!

Maximum total deflection angle of DM particle in limit $m_\chi \gg m_N$ given by,

$$\Omega_{\rm max} \lesssim n^{1/3} L_{\rm det} \sin\alpha_{\rm max}$$

where $\sin\alpha_{\rm max} = m_T/m_\chi$, is the maximum detector-frame scattering angle)

And $n^{1/3}L_{\rm det}$, is the maximum number of recoils in the detector

Bottom line: NRs produced by transiting Planck-scale DM are typically collinear, although for $m_\chi < 10^{13}$ GeV/c^2, deflection on the order of ~degrees becomes feasible

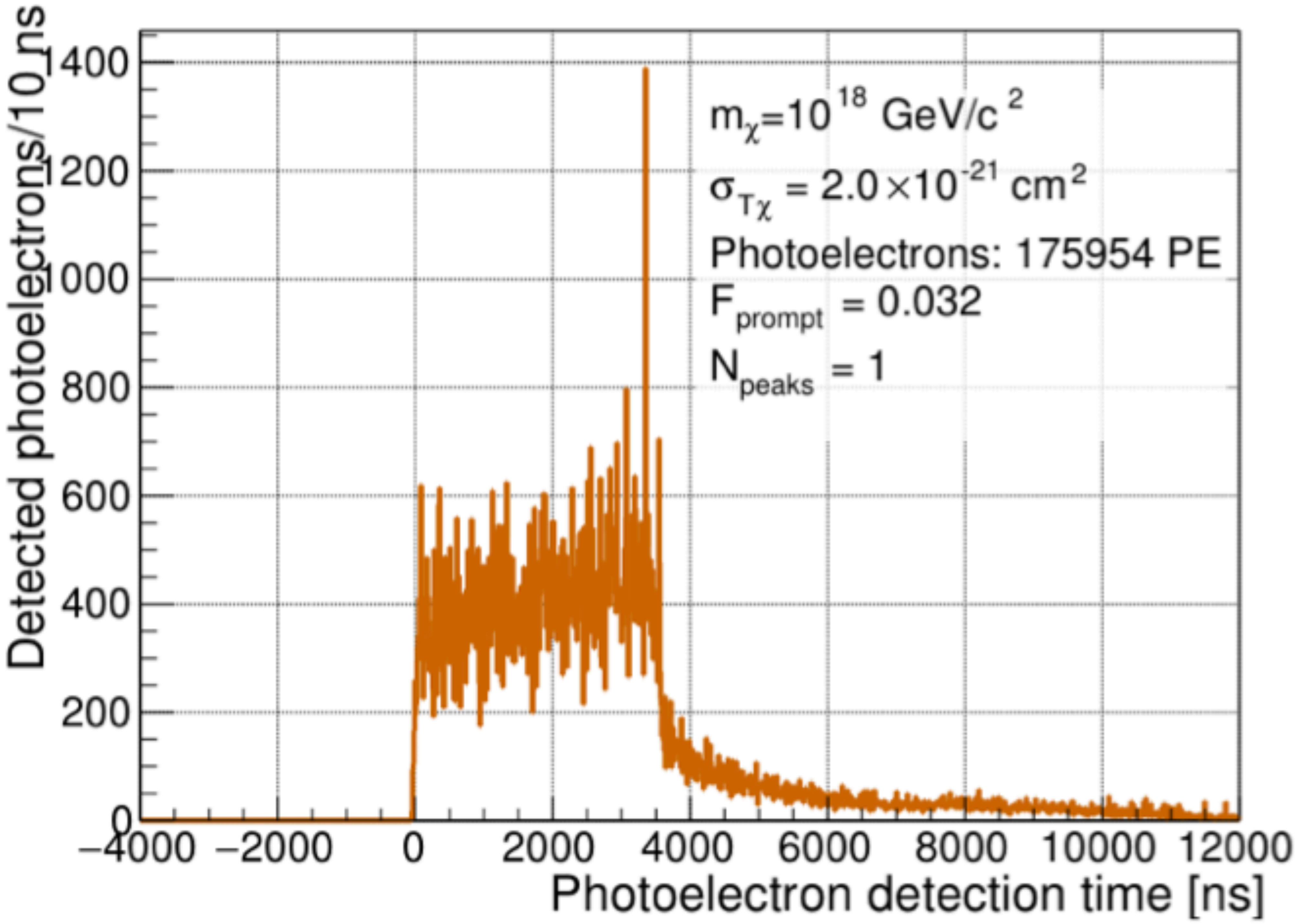
Planck-Scale DM: Simulation in DEAP-3600

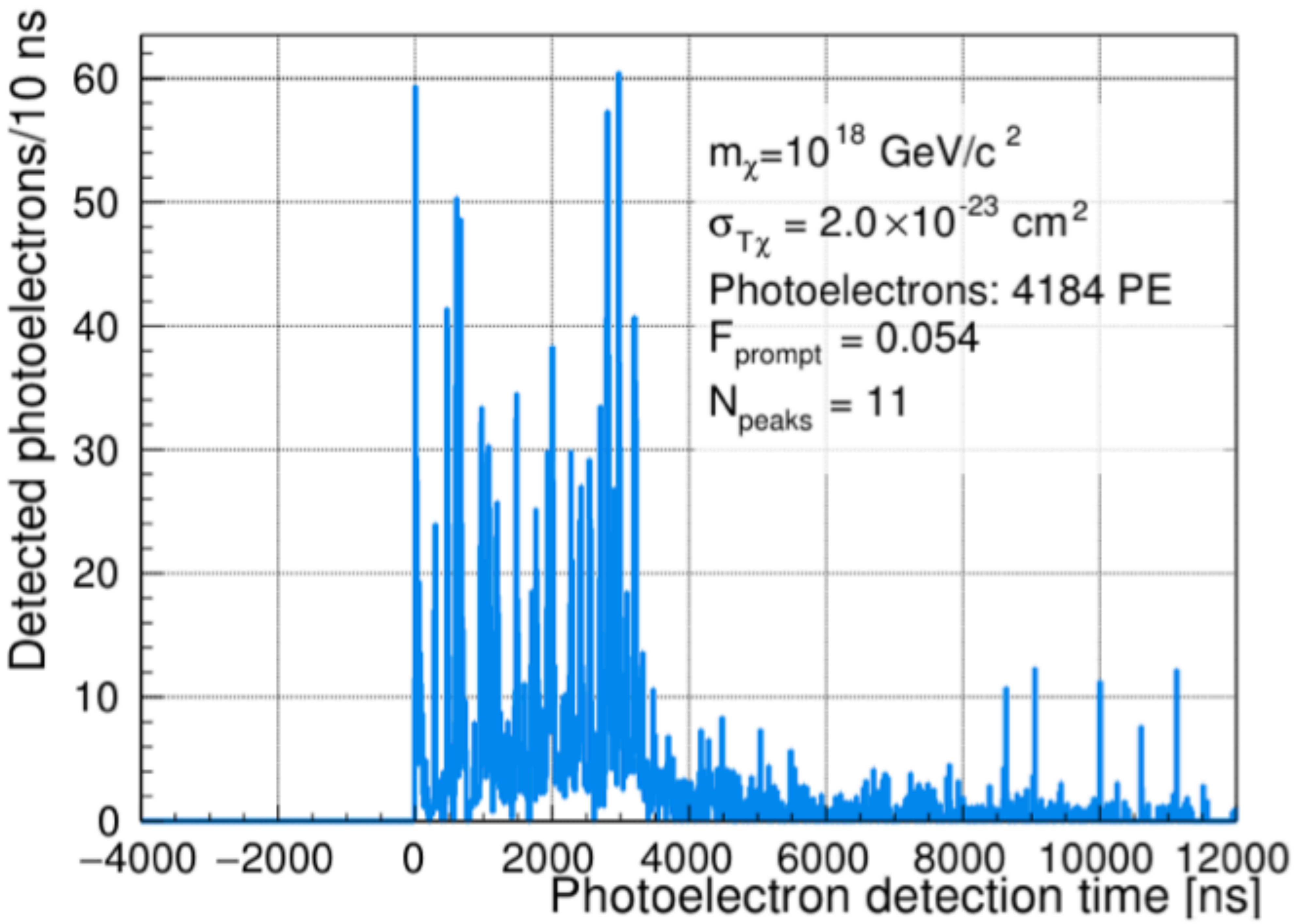
Planck-scale DM simulated in two steps in DEAP-3600:

1. DM is first attenuated in the overburden,
2. DM is then propagated in the detector, with simulation of optical and DAQ response

Light yield calibrated up to 10 MeV using Gaussian response function to (n,γ) lines from ^{241}AmBe neutron source

Simulated detected PE times for $m_\chi = 10^{18}$ GeV/c^2, for $\sigma_{T\chi} = 2\times10^{-21}$ cm^2 (left) and $\sigma_{T\chi} = 2\times10^{-23}$ cm^2 (right)

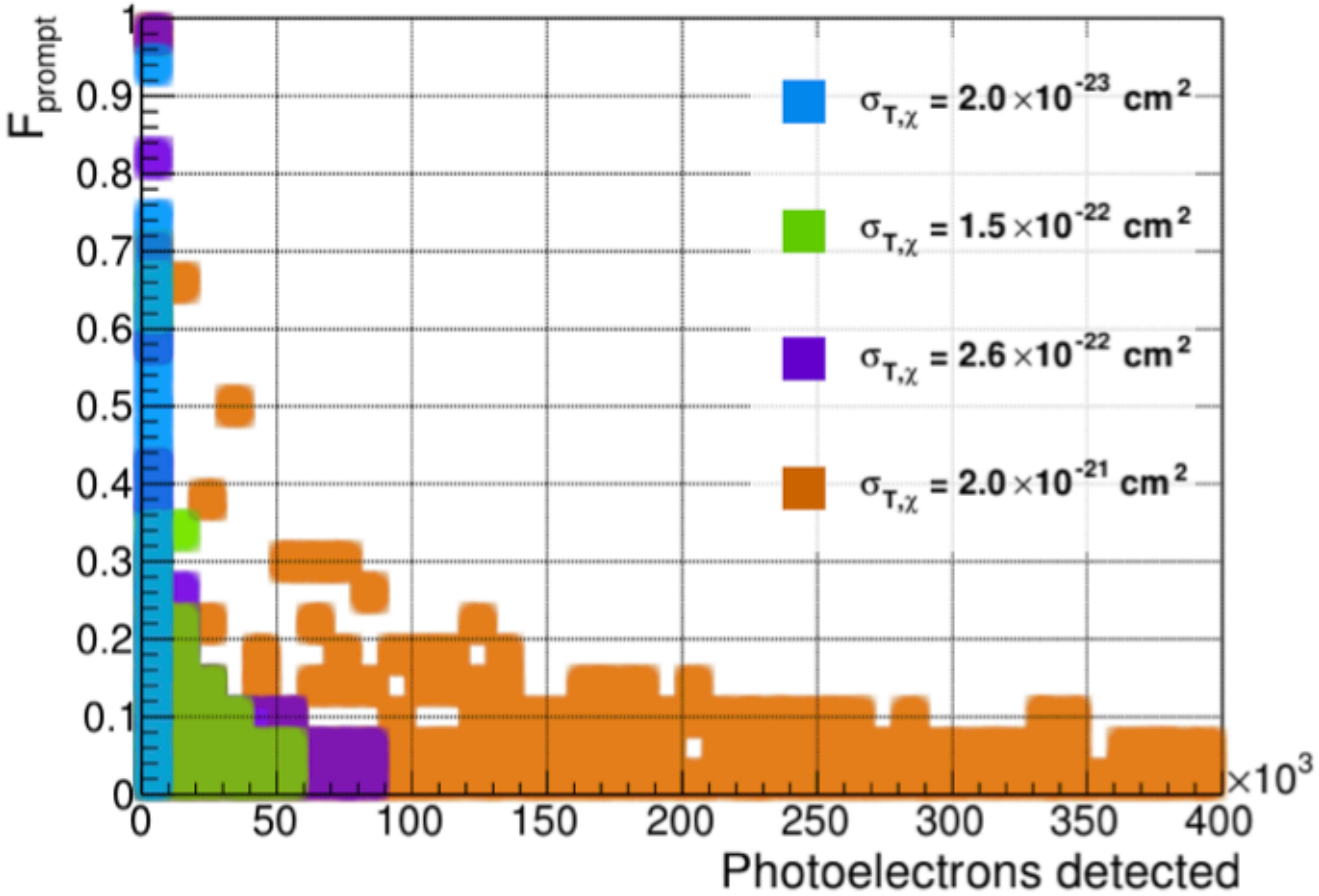


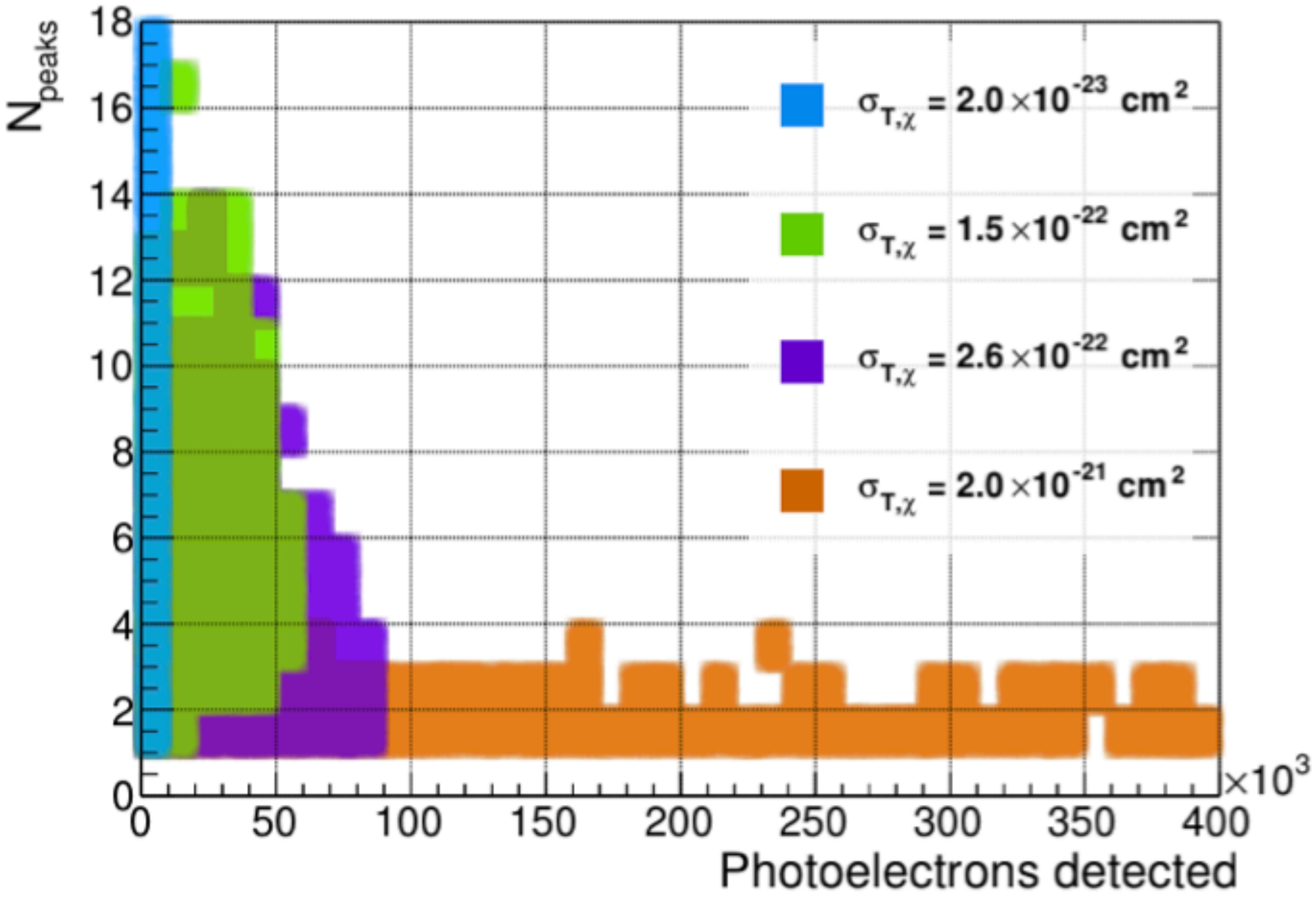


Planck-Scale DM: Simulation in DEAP-3600

At smaller $\sigma_{T\chi}$ values, the number of individual peaks identified per "event" is greater than for larger $\sigma_{T\chi}$ values

➡ If $\sigma_{T\chi}$ too high, PE times "merge" and $\mathrm{N_{peaks}}$ variables loses accuracy





As $\sigma_{T\chi}$ increases and $\mathrm{N_{peaks}}$ decreases, $\mathrm{F_{prompt}}$ decreases and narrows with the number of detected PE

➡ $\mathrm{F_{prompt}}$ = prompt light fraction in 150 ns about the trigger time

Planck-Scale DM: Analysis and Search Results

Four different region-of-interests (ROIs) are defined in order to search for Planck-scale DM

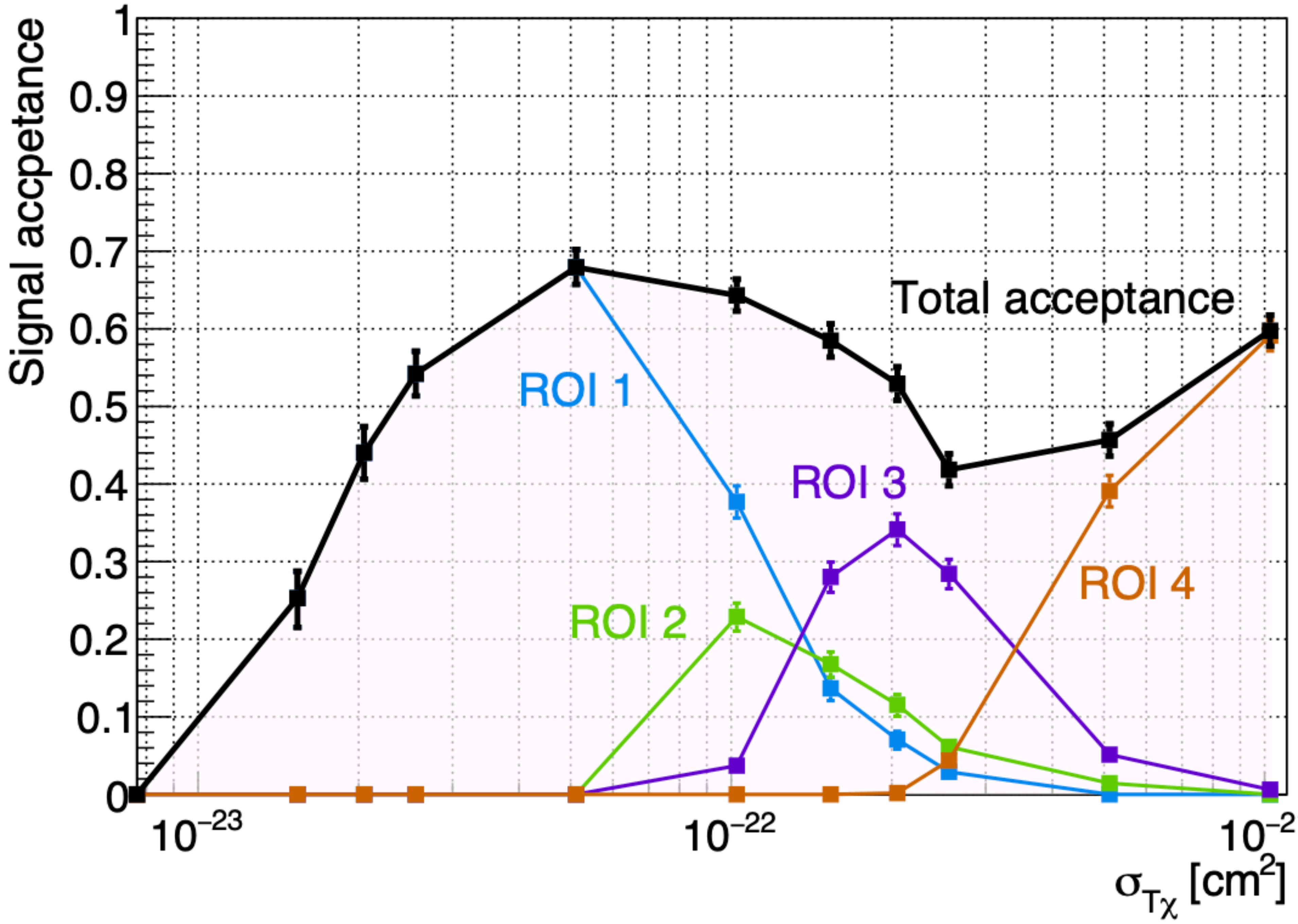
The ROIs are defined in different energy ranges, with varying cuts on N_{peaks} and F_{prompt}

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

Cuts on N_{peaks} and F_{prompt} in ROI's 1-3 are applied to mitigate background events coming from pile-up:

- ➡ Primary background contribution: uncorrelated pile-up of signals generated from intrinsic detector radioactivity
- ➡ Correlated pile-up, such as ^{212}Bi β-decays followed by ^{212}Po α-decays with $t_{1/2}$ = 300 ns, removed by requiring $N_{peaks} > 2$ over relevant energies
- ➡ Pile-up modelled with simulation, validated using AmBe neutron calibration source dataset and non-blind physics dataset; simulated N_{peaks} distribution agrees to within 5% in both datasets
- ➡ Pile-up backgrounds negligible in ROI 4, does not require N_{peak} cut - in this energy region, muons produce dominant background
- ➡ Candidate muons are tagged with the outer muon veto; untagged muons are rejected by F_{prompt} cut, tuned using muon-coincidence dataset
- ➡ Looser cuts on ROI 4 can be evaluated without full simulation; allows one to compute DM-nucleon cross sections that are computationally challenging to simulate

Probability of Planck-scale DM with $m_\chi = 10^{18}$ GeV/c^2 populating each ROI and surviving all cuts at varying $\sigma_{T\chi}$



Planck-Scale DM: Analysis and Search Results

DEAP-3600 blind dataset live time	**$N_{exp,total}$**	**N_{obs}**
813 days	0.05 ± 0.03	0

Poisson statistics: any DM model that predicts more than 2.3 events over all four ROIs can be excluded at 90% C.L

Two classes of composite DM models are considered:

Model 1

DM is opaque to nucleus; scattering cross-section at zero momentum transfer is geometric size of DM regardless of target nucleus

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

Model 2

Cross-section scales as:

$$\sigma_{T\chi} \simeq \sigma_{n\chi} A^4 |F_T(q)|^2$$

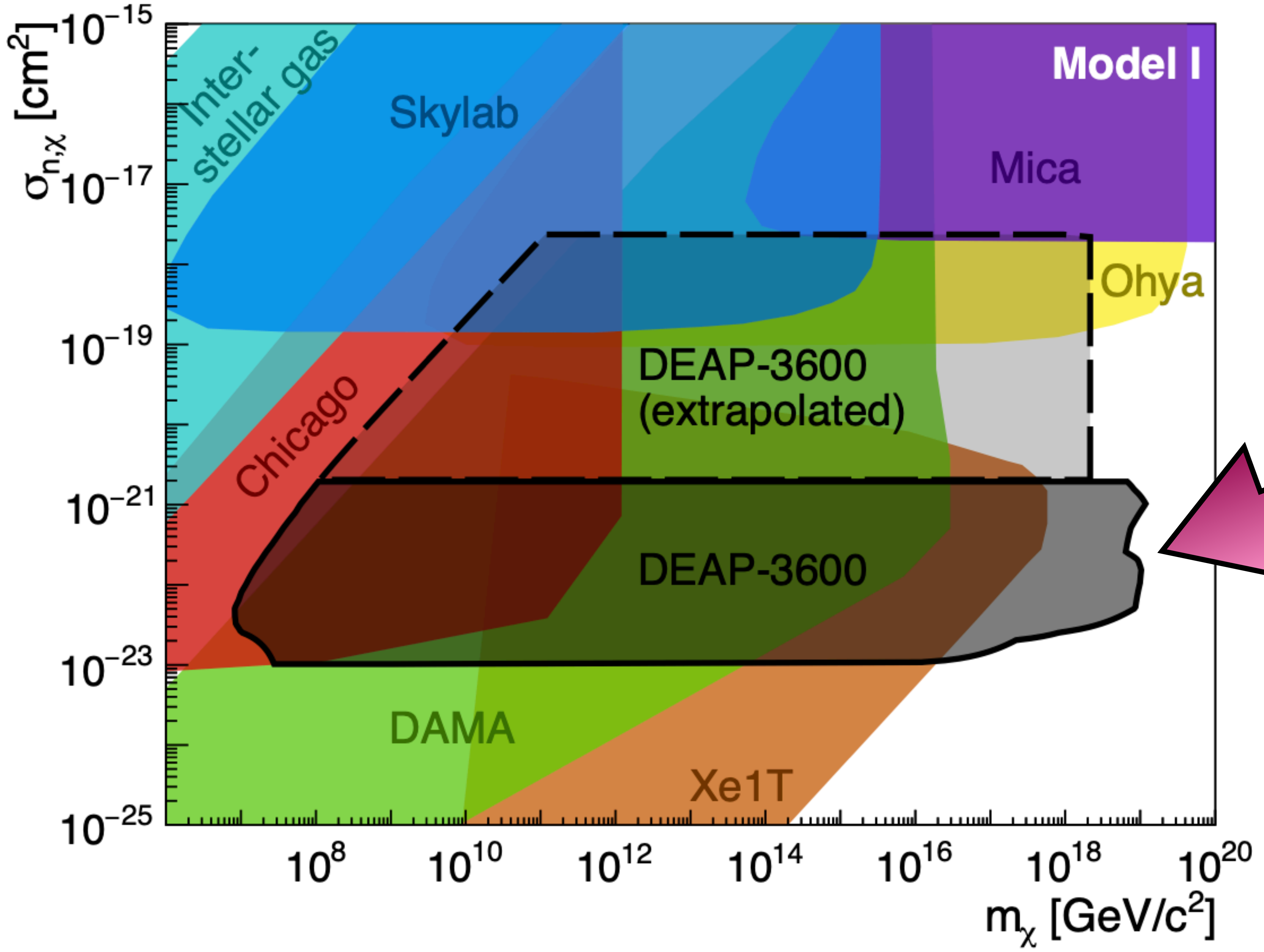
Most commonly used scaling; allows for direct comparison with other experiments as well as single scatter constraints

Planck-Scale DM: Analysis and Search Results

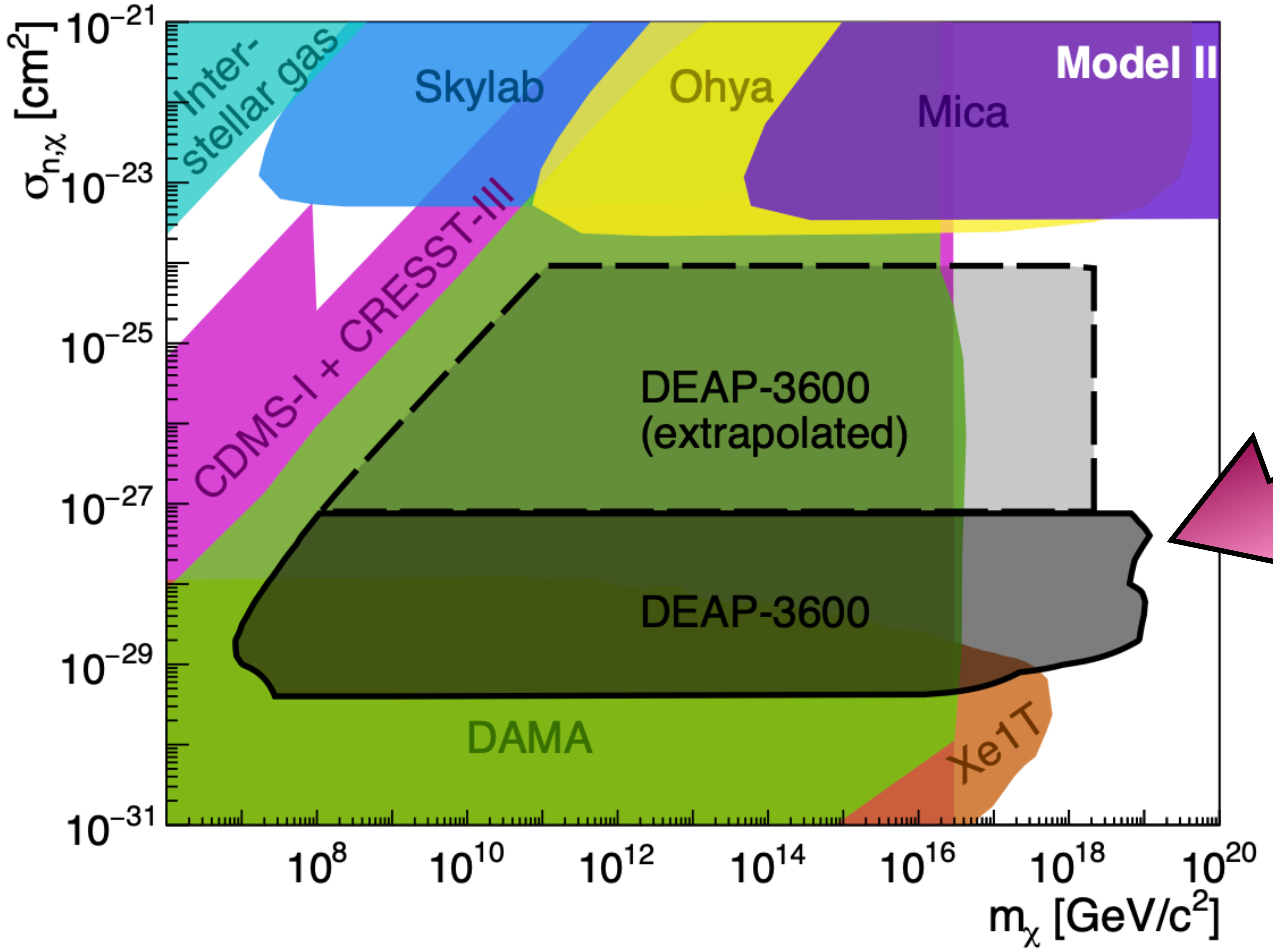
For each model, signal expectation μ_s is determined at various $m_\chi - \sigma_{n\chi}$ points, exclusion regions are constructed accounting for uncertainties using Highland and Cousins approach (R. D. Cousins and V. L. Highland, Nucl. Instrum. Methods Phys. Res. A 320, 331 (1992).)

Upper bounds on m_χ interpolated with ρ_χ/m_χ flux scale factor - Lower bounds on m_χ set to value at which 90% of expected signals, determined from overburden calculation, will be below 1 MeV$_{\text{ee}}$ after nuclear quenching

Upper bounds on $\sigma_{n\chi}$ limited by highest possible value of $\sigma_{n\chi}$ that could be simulated ($\sigma_{n\chi,\max}$) - Lower bounds on $\sigma_{n\chi}$ determined by lowest simulated values that can be excluded



Planck-scale DM!



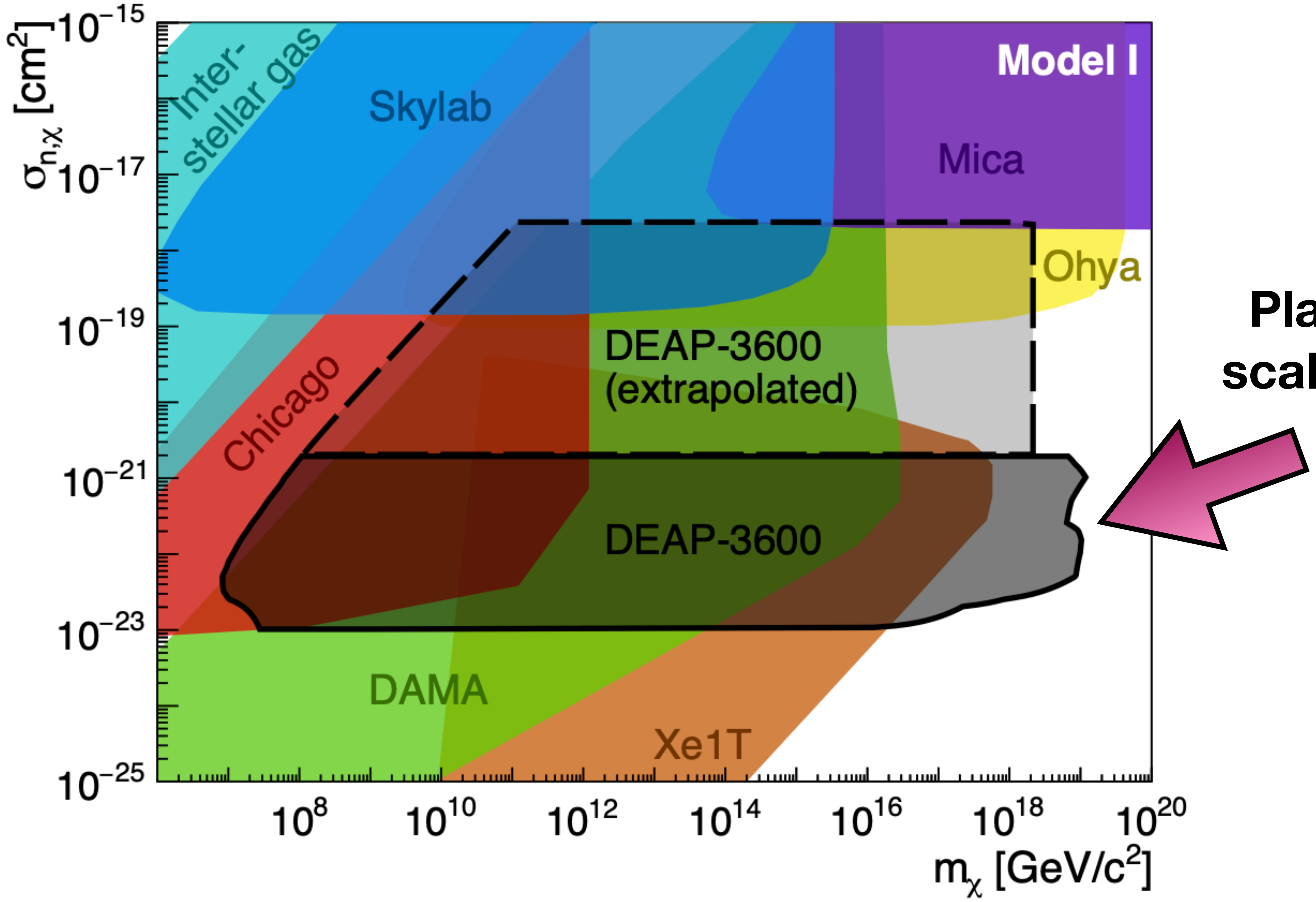
Planck-scale DM!

Planck-Scale DM: Analysis and Search Results

At higher $\sigma_{n\chi}$, the continuous scattering approximation and LAr time-of-flight implies a lower bound on the ROI 4 acceptance of 35%

Treating the probability of reconstructing in ROI 4 as constant above $\sigma_{n\chi,\max}$ and scaling the flux as ρ_χ / m_χ, exclusion regions are extrapolated to m_χ consistent with null results

➡ Conservative estimate



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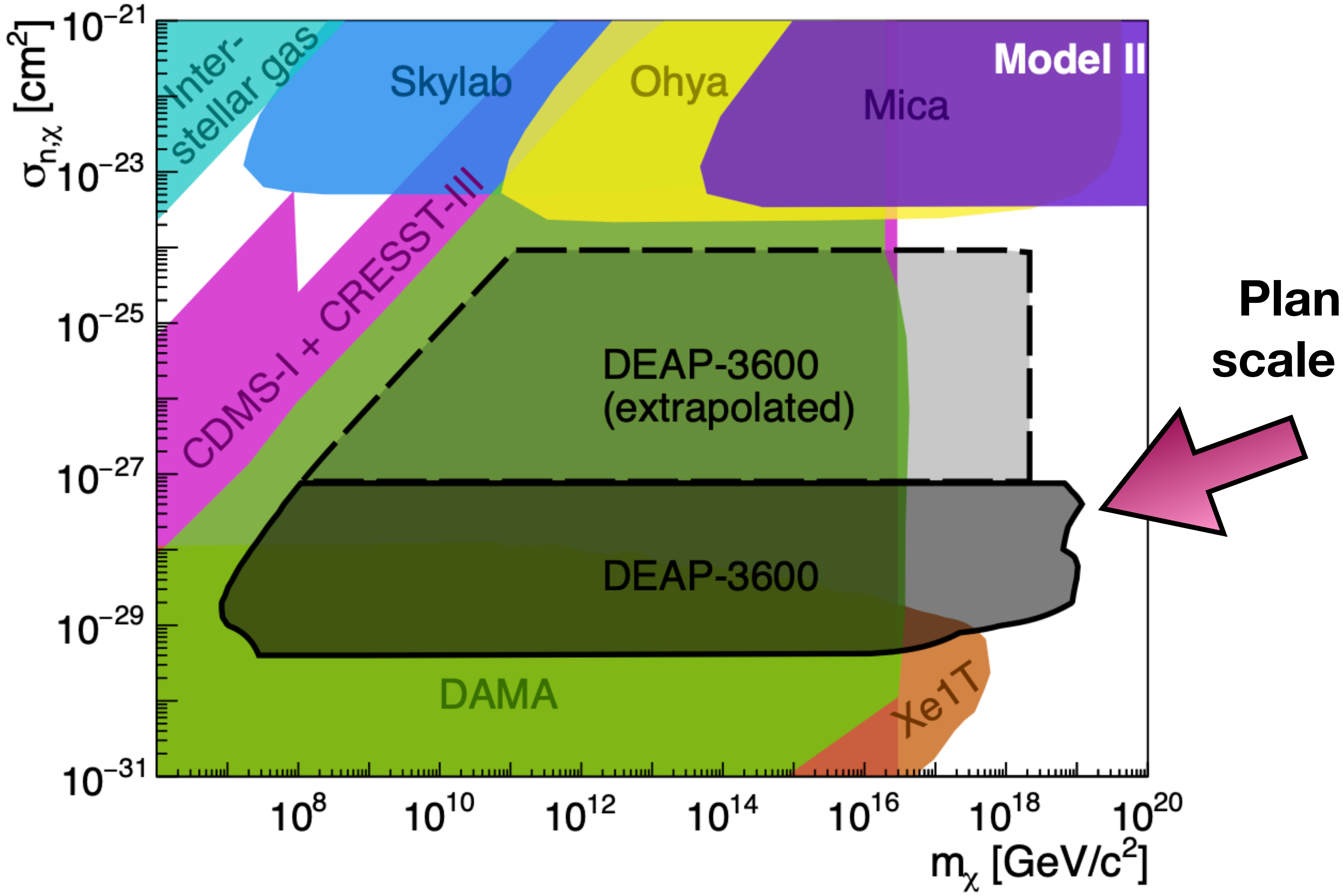

Planck-scale DM!

Summary and Outlook

DEAP-3600 is a single-phase LAr detector designed to directly detect WIMPs

No WIMP candidates observed after 1 year (231 live-days) of data, leading to the strongest upper bound on the WIMP-nucleon spin-independent, isoscalar cross section for an Argon target

Presented today are the results of a blind analysis using 813 live-days of DEAP-3600 detector to search for Planck-scale, super heavy DM with $m_\chi \sim 10^{19}$ GeV/c^2

➡ DEAP-3600 is the largest ever dark matter detector - this allows us reach Planck-scale DM!

Such candidates leave very different signatures in DEAP-3600 compared to standard WIMPs; Planck-scale DM will multi-scatter collinearly as it traverses the length of the detector

➡ Little to negligible background contributions in this region of parameter space with this type of signature

No candidate events were observed, producing the first direct detection constraints on Planck-scale DM!

Leading limits constrain Planck-scale DM for two composite models between 8.3 x 10^6 - 1.2 x 10^{19} GeV/c^2, and cross-sections for scattering on argon nuclei between 1.0 x 10^{-23} - 2.4 x 10^{-18} cm^2

This type of search could be extended to super-heavy DM depositing energy via alternative modes to elastic scattering, or repeated in larger, next generation experiments such as DarkSide-20k in order to improve sensitivity