



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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Particle Physics Seminar, Warwick University
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Outline

Intro to Dark Matter: Evidence & Candidates

The DEAP-3600 Detector

- ▶ Detector Overview
- ▶ Energy Calibration
- ▶ Pulse-Shape Discrimination
- ▶ Backgrounds
- ▶ Previous WIMP Search Results

Planck-Scale Dark Matter

- ▶ Introduction
- ▶ Characterisation and Exclusion Limit Contours
- ▶ Monte-Carlo Simulation in DEAP-3600
- ▶ Analysis and Search Results

Next Generation Experiments

Conclusions

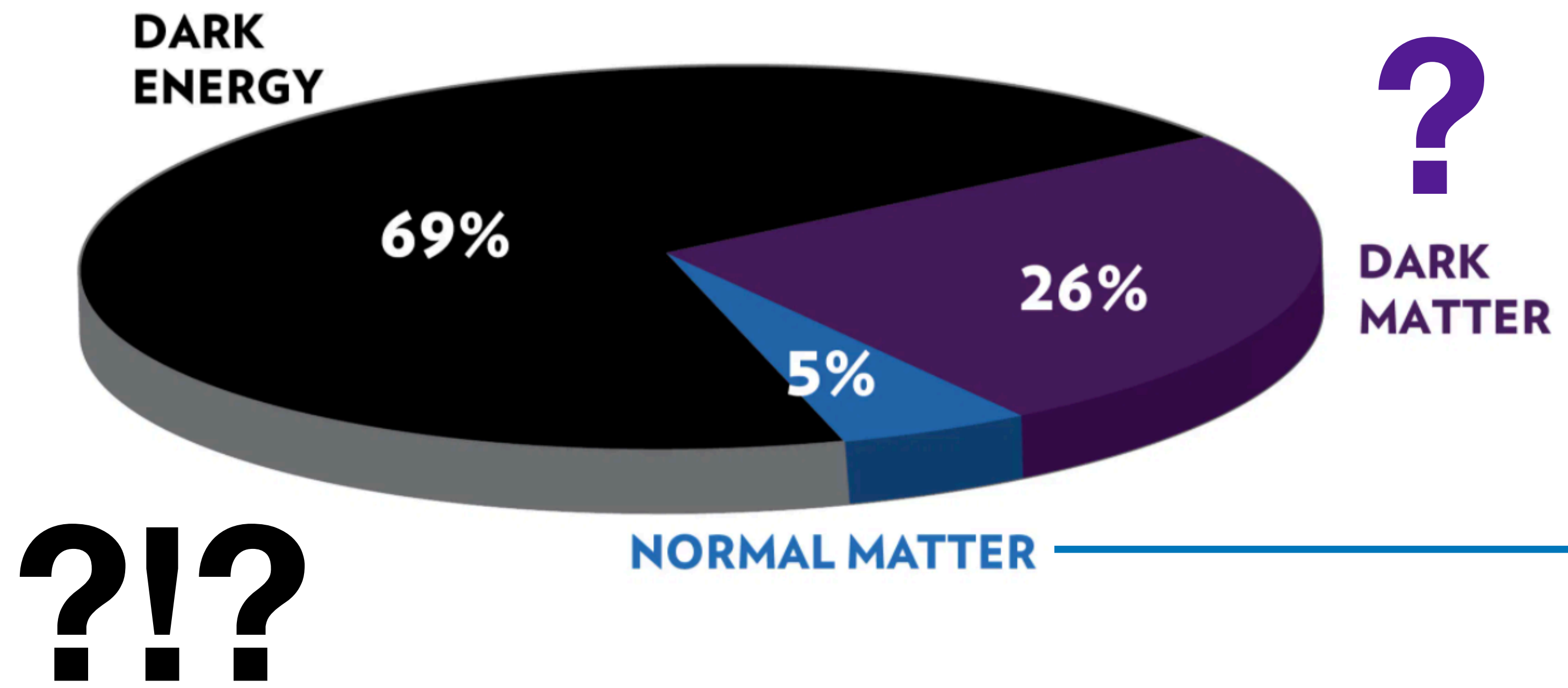


**“I’ve either discovered dark matter,
or I’ve left the lens cap on.”**

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



	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
QUARKS	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 γ photon	SCALAR BOSONS
	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau	0 1 Z Z boson	
LEPTONS	$< 1.0 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1 W W boson	
				Gauge Bosons Vector Bosons	

Evidence for Dark Matter

Clear evidence for DM on both galactic and cosmological scale

1933: Fritz Zwicky determined using the Virial Theorem that galaxies in Coma cluster were moving faster than could be explained by solely luminous components

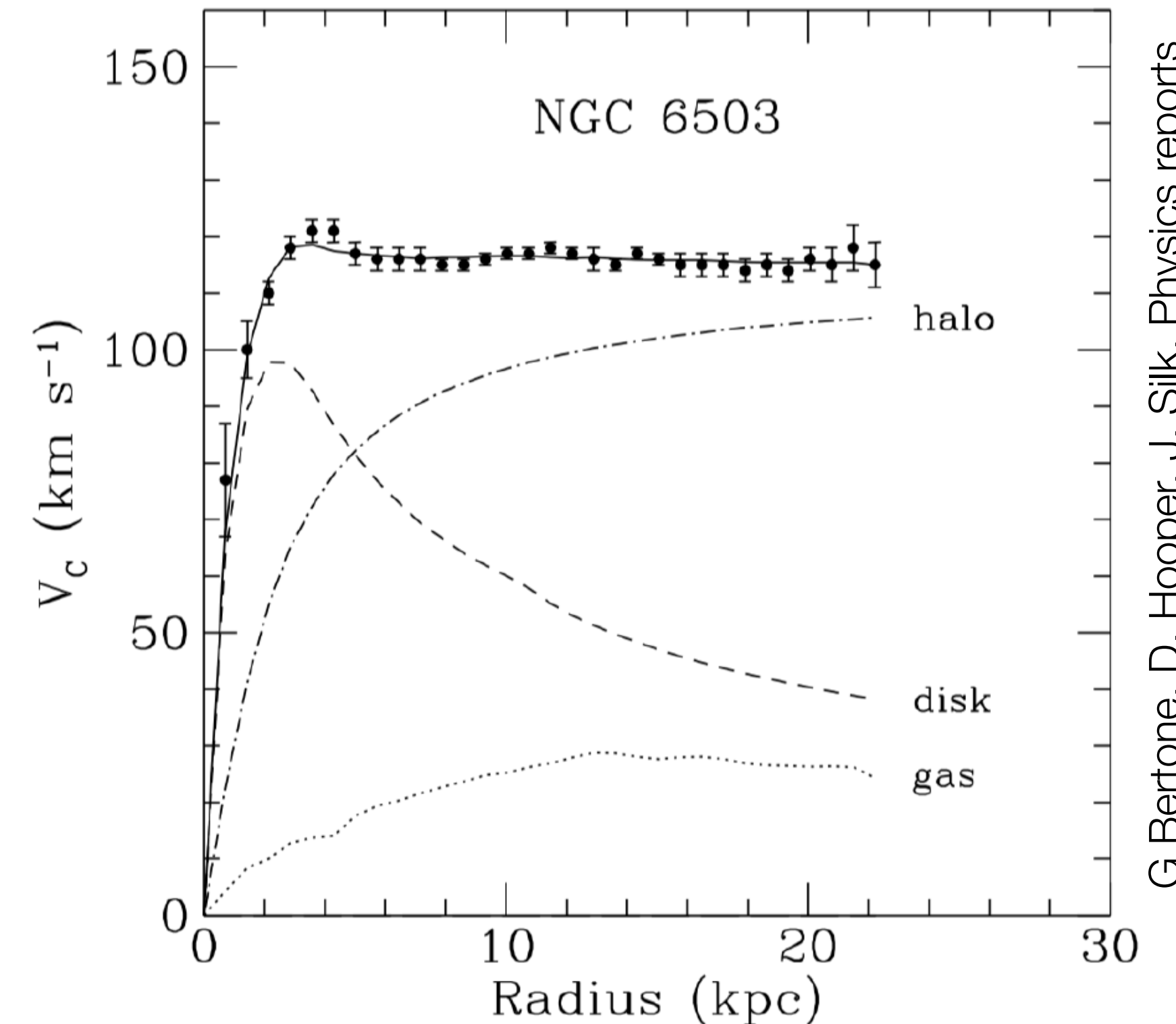
- ▶ Approximately x10 additional mass!

1970's: Kent Ford, Vera Rubin observed flat rotation curve for M31 (Andromeda) galaxy

- ▶ Circular velocity of star in galaxy expected to follow $v(r) = \sqrt{GM/r}$
- ▶ Flat rotation curve implies non-luminous DM halo of $M \propto r$ and $\rho \propto 1/r^2$



X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.



G Bertone, D. Hooper, J. Silk, Physics reports 405.5-6 (2005)

Bullet Cluster: two merging galaxy clusters ~ 100 Myr ago

- ▶ Distinct separation between DM and baryonic matter (hot gas) from galaxies; baryonic matter self-interacted in collision, DM did not, upper limit on the dark matter self-interaction cross section currently constrained to $\sigma/m < 0.47 \text{ cm}^2\text{g}^{-1}$ at 95% C.L
- ▶ Mass distribution inferred from weak gravitational lensing of BC from distant galaxies

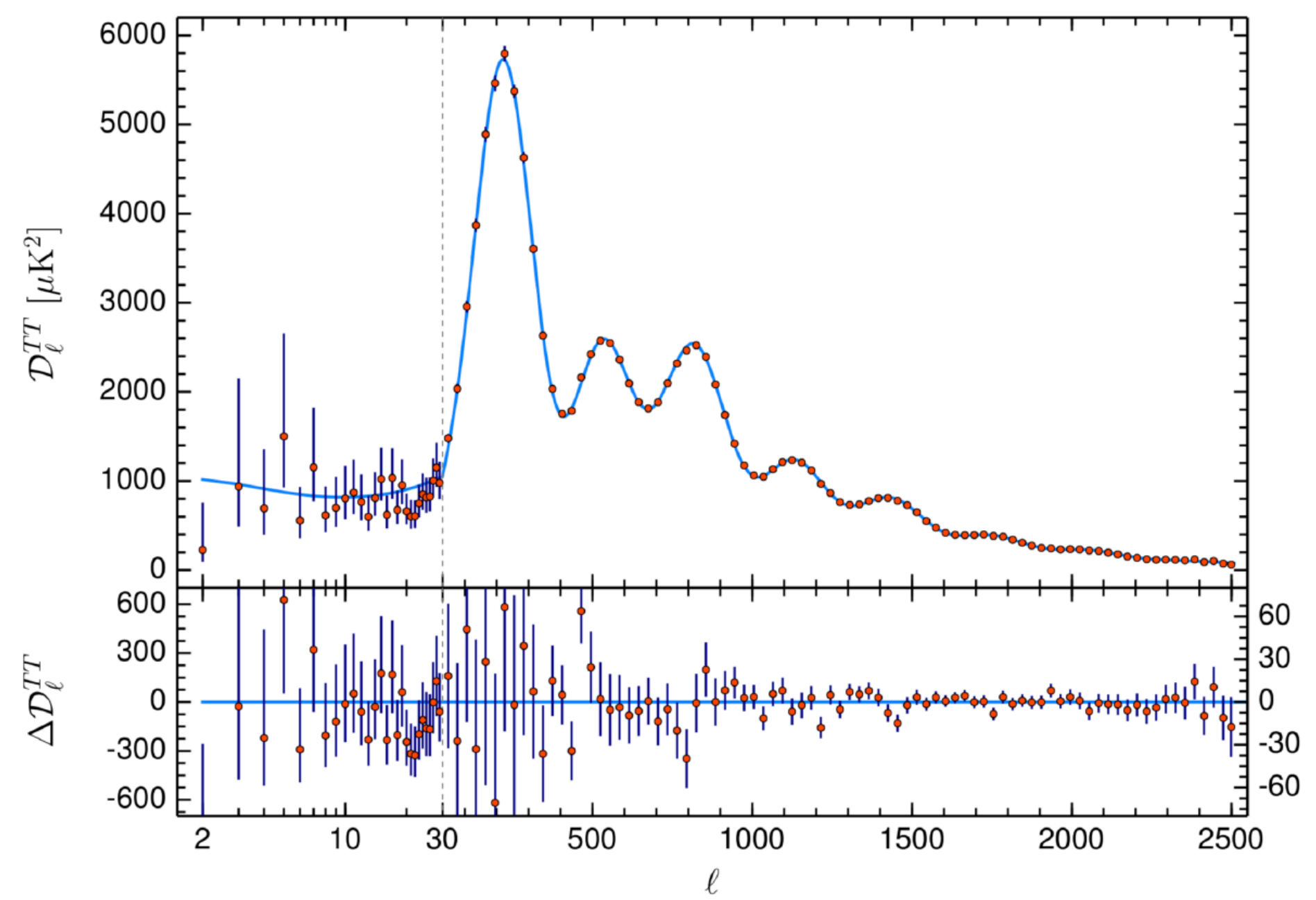
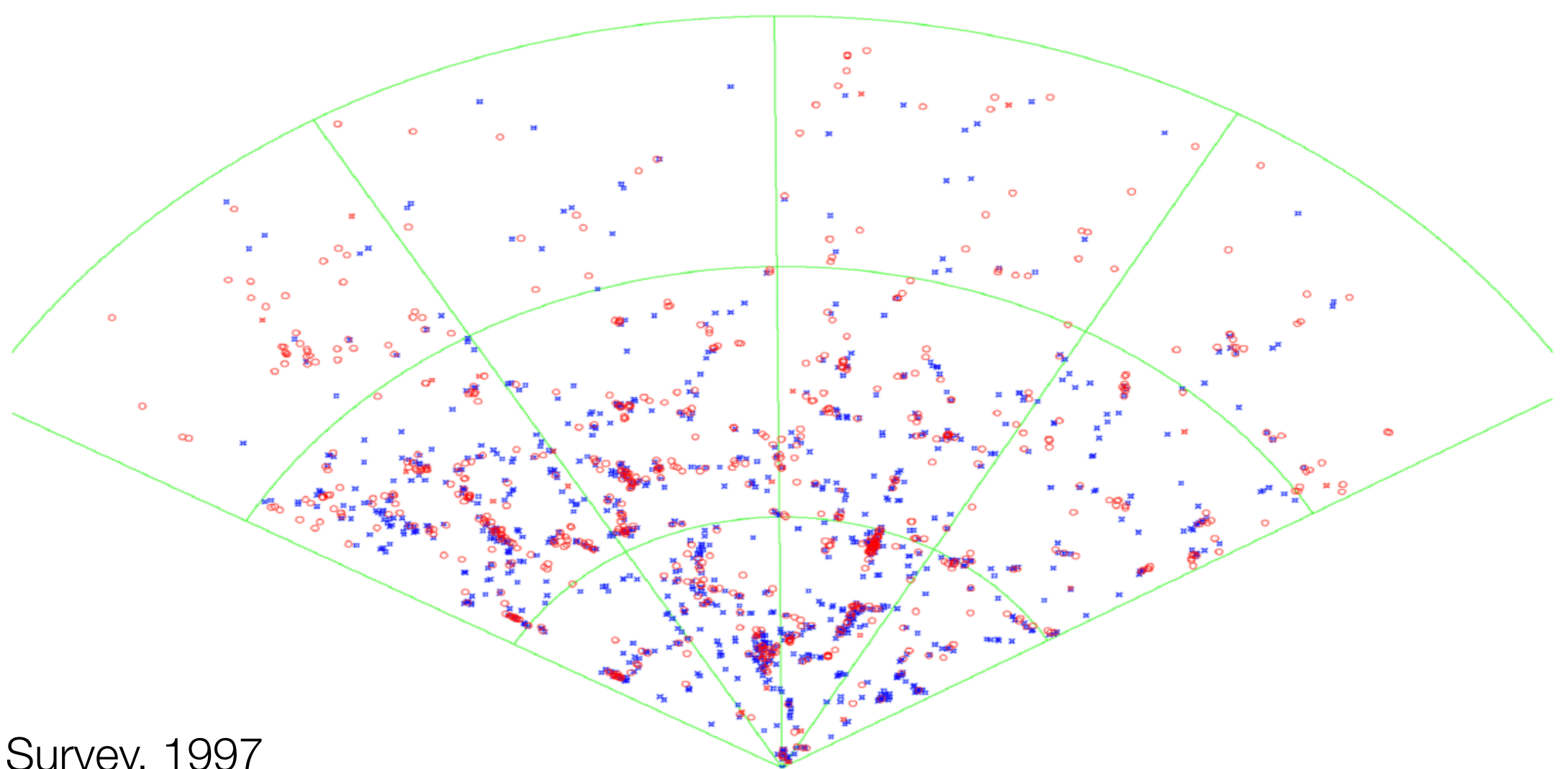
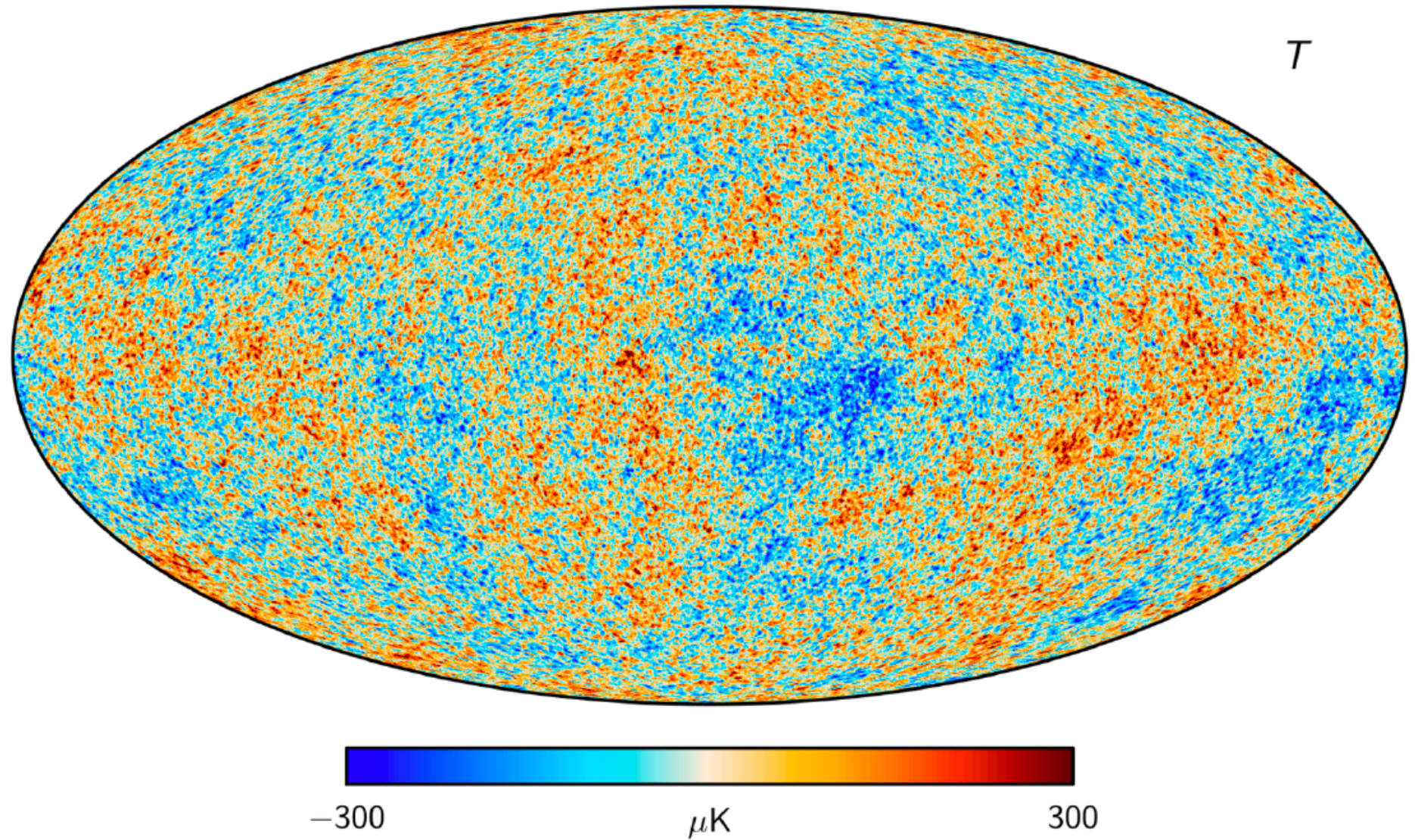
Evidence for Dark Matter

Cosmic Microwave Background (CMB): relic photons propagating through space since matter-radiation decoupling epoch ($t \sim 380,000$ yrs), decreasing in energy over time due to expansion of Universe

- ▶ $T_{\gamma,0} = 2.73$ K
- ▶ Observed T anisotropies of CMB on order of 10^{-5} ; can be used to deduce matter-energy content of Universe

Large-Scale Structure: primordial density fluctuations, first produced through quantum perturbations, seed the evolution of LSS

- ▶ Cold (non-relativistic) DM predicts that galaxies and galaxy clusters developed from the expansion of the universe over which time gravitational interactions produced hierarchical evolution; hot (relativistic) DM predicts inverse hierarchal evolution



Dark Matter Candidates

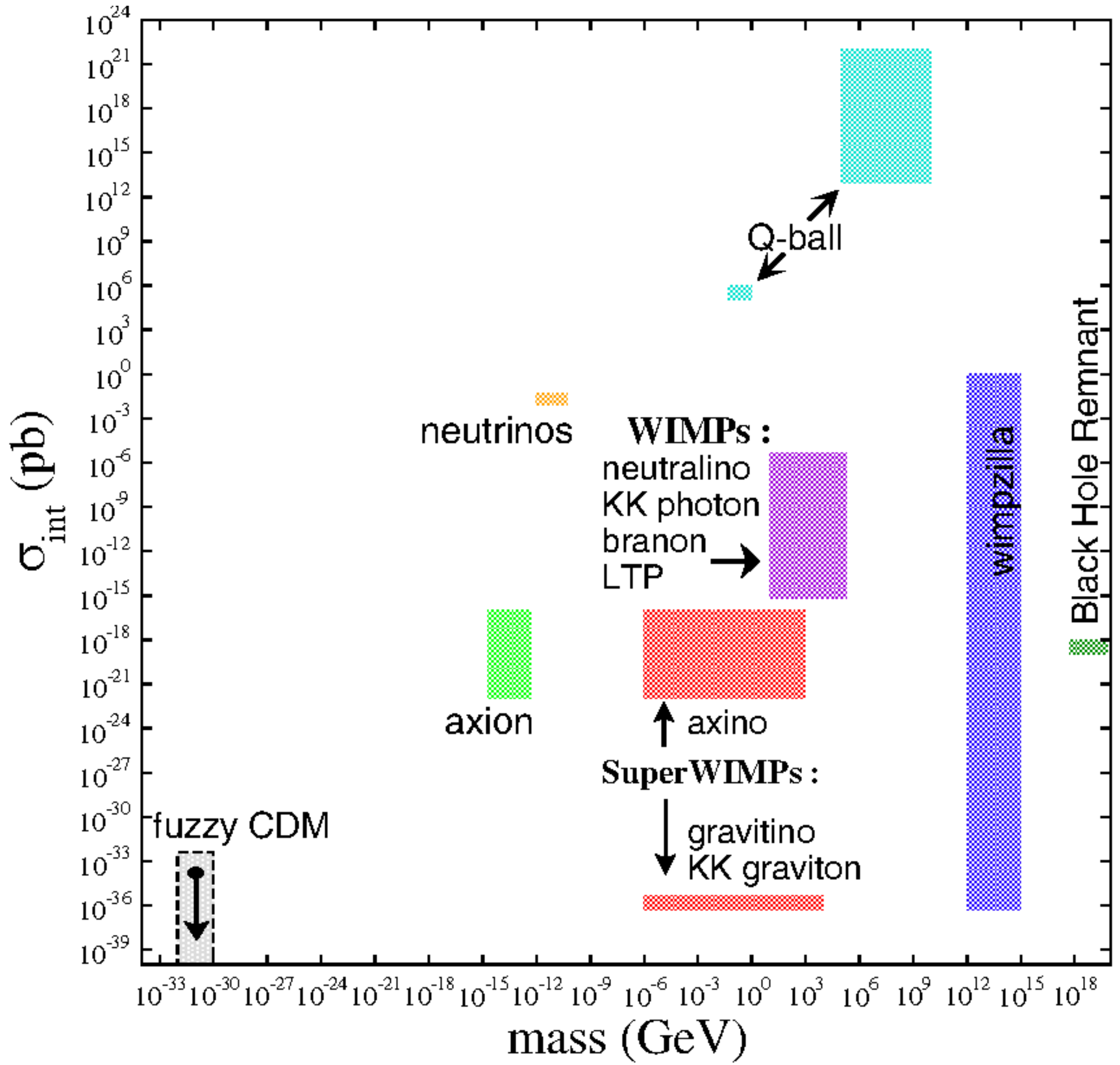
Many potential DM candidates spanning a wide range of interaction cross section-mass parameter space

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 $\sigma \sim 10^{-44} \text{ cm}^2$

Axions are becoming increasingly popular DM candidates

... Planck-Scale DM? (spoiler alert)

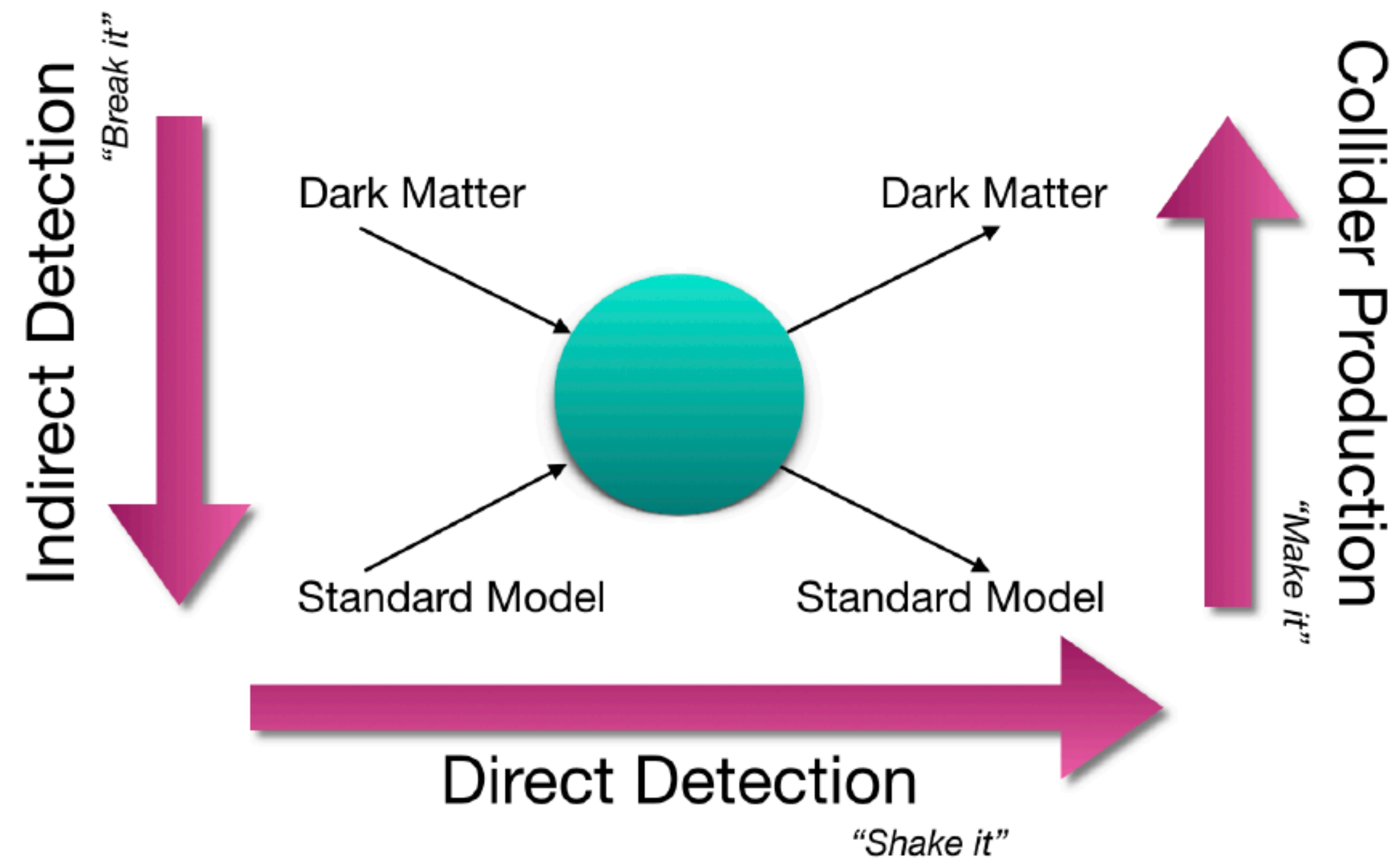


Prof J. Monroe Outreach Talk; HEPAP/AAAC DMSAG Subpanel (2007)

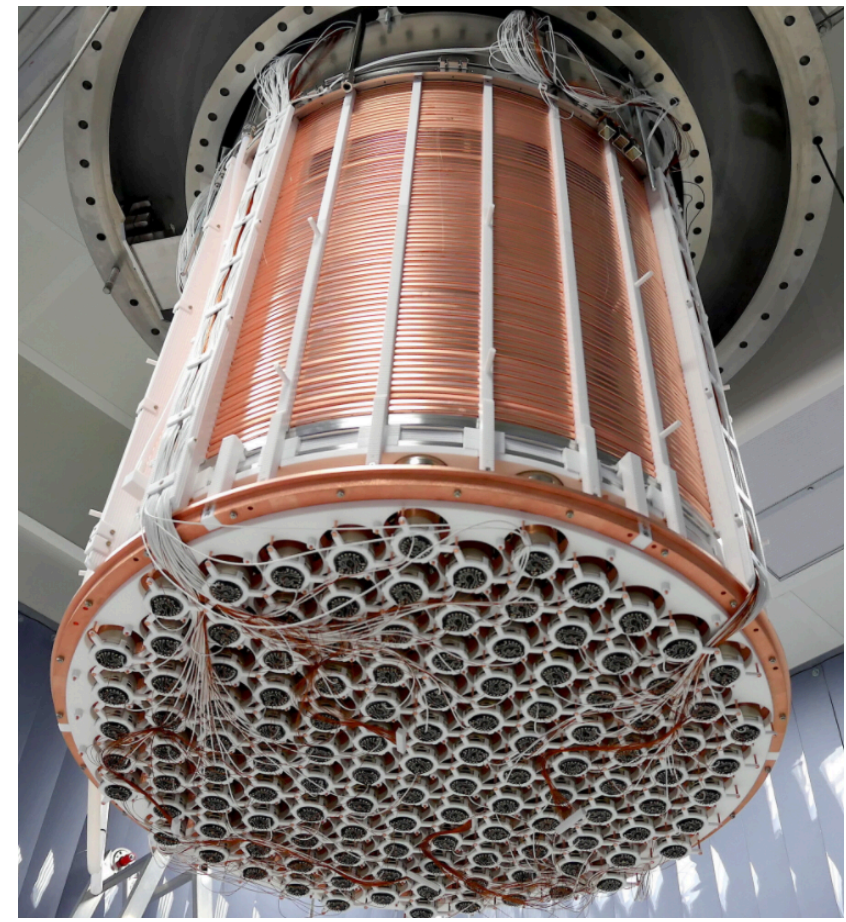
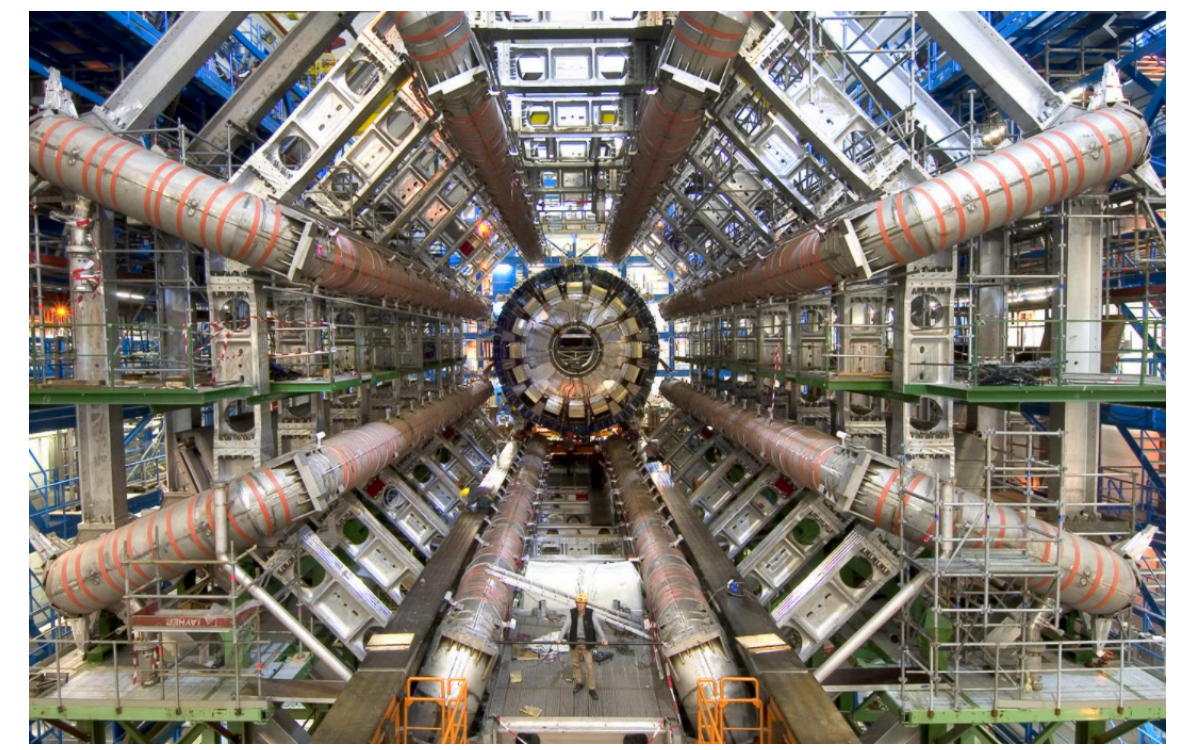
Experimental Channels For Dark Matter Detection

* Not comprehensive list

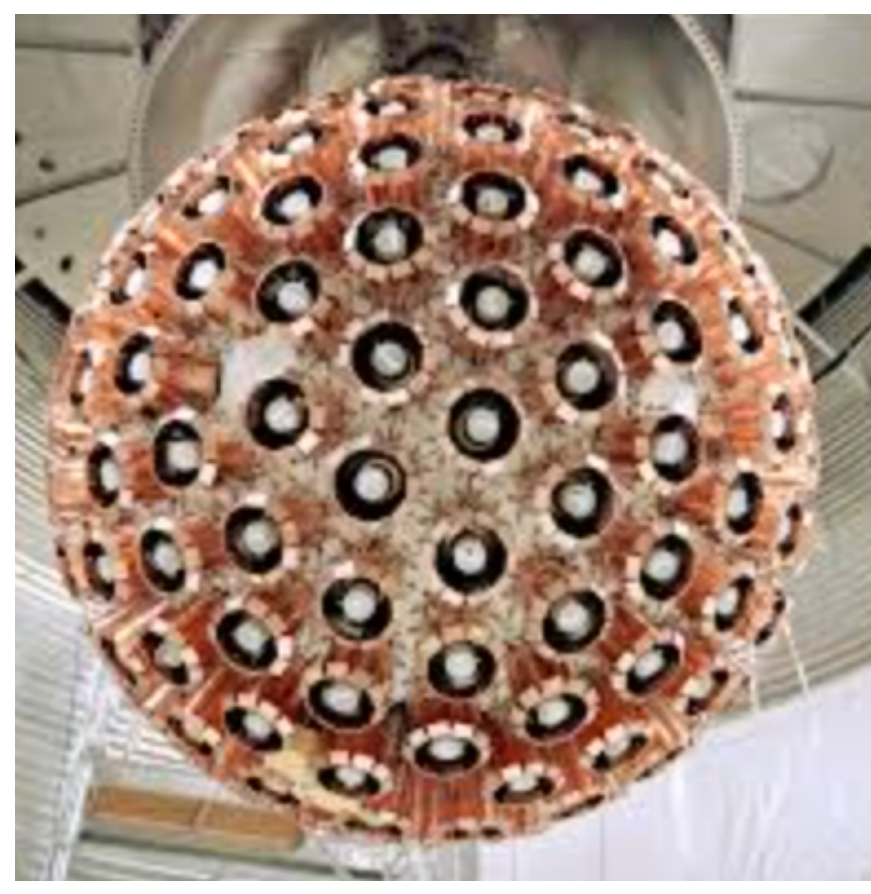
HESS PAMELA
AMS



ATLAS CMS



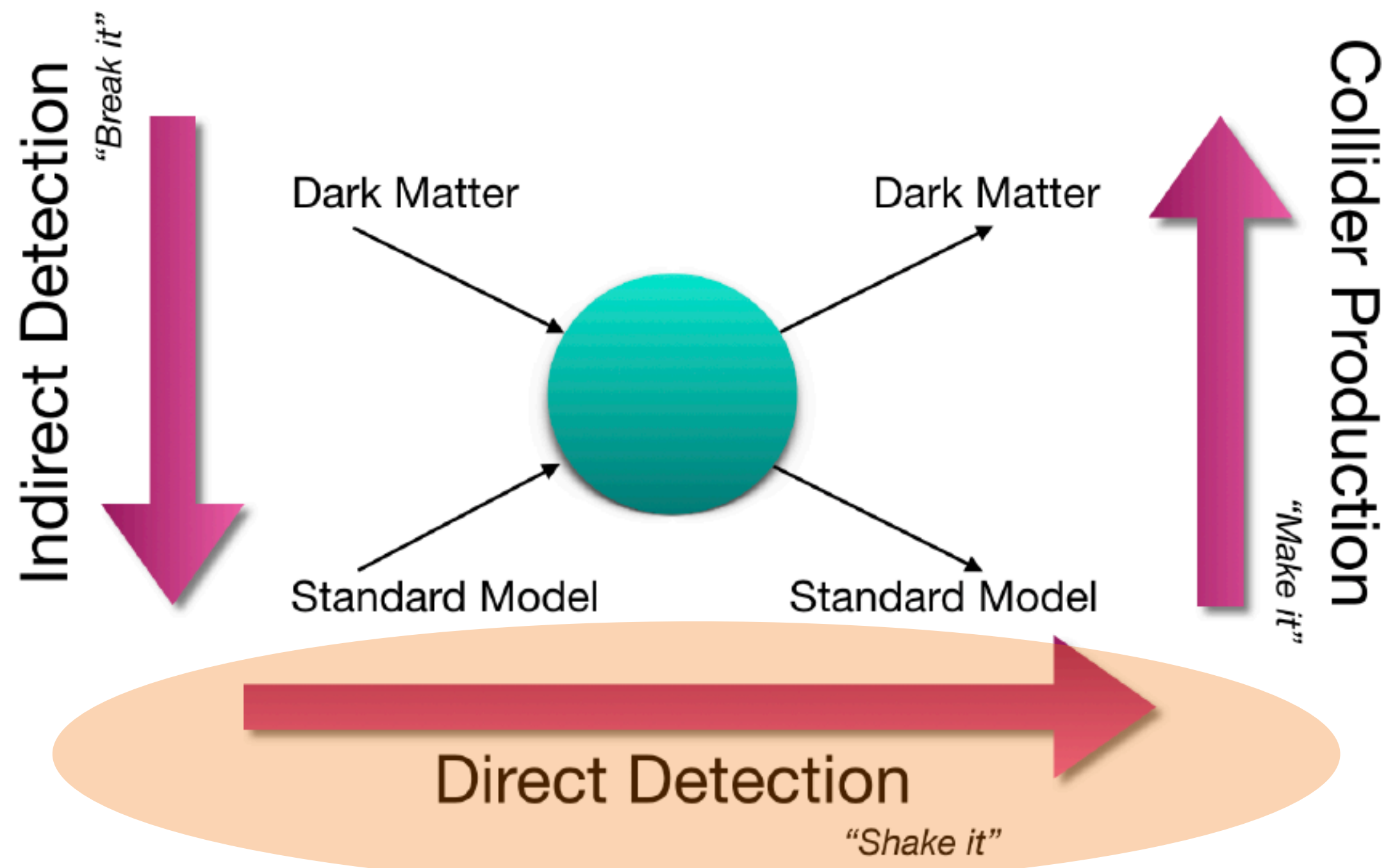
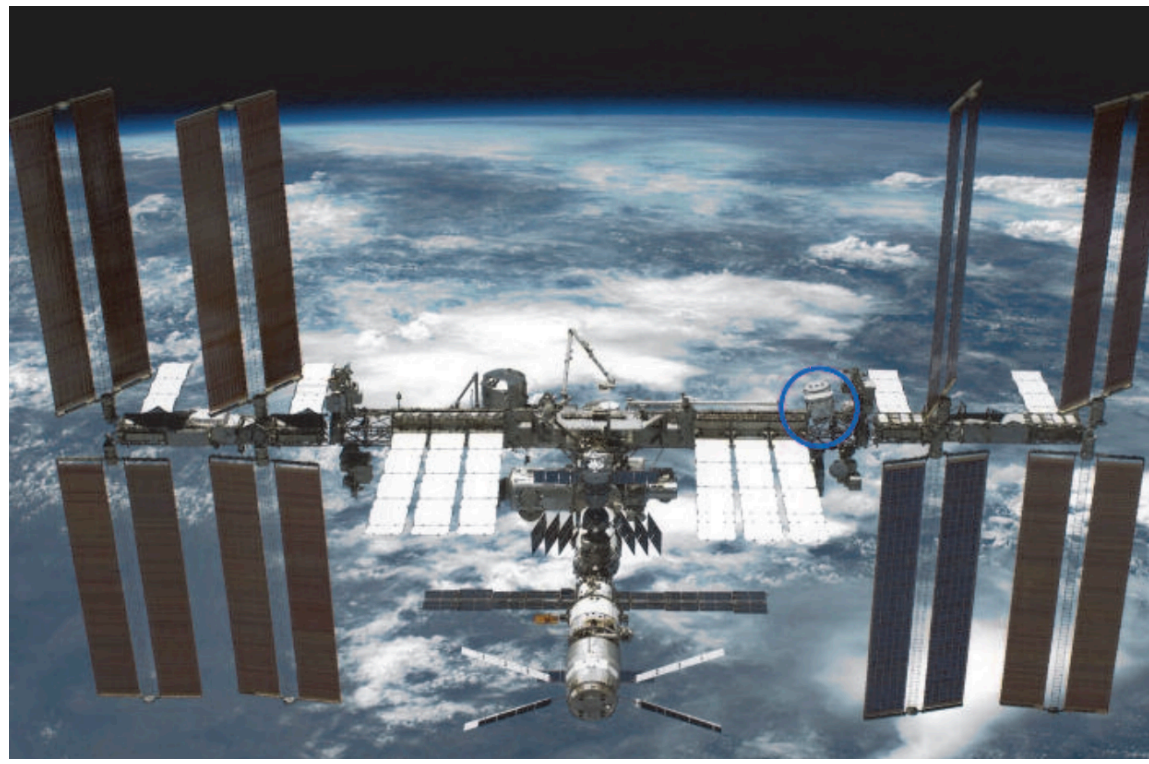
XENON100/1T DarkSide-50/20k DEAP-3600
LUX/LZ SuperCDMS



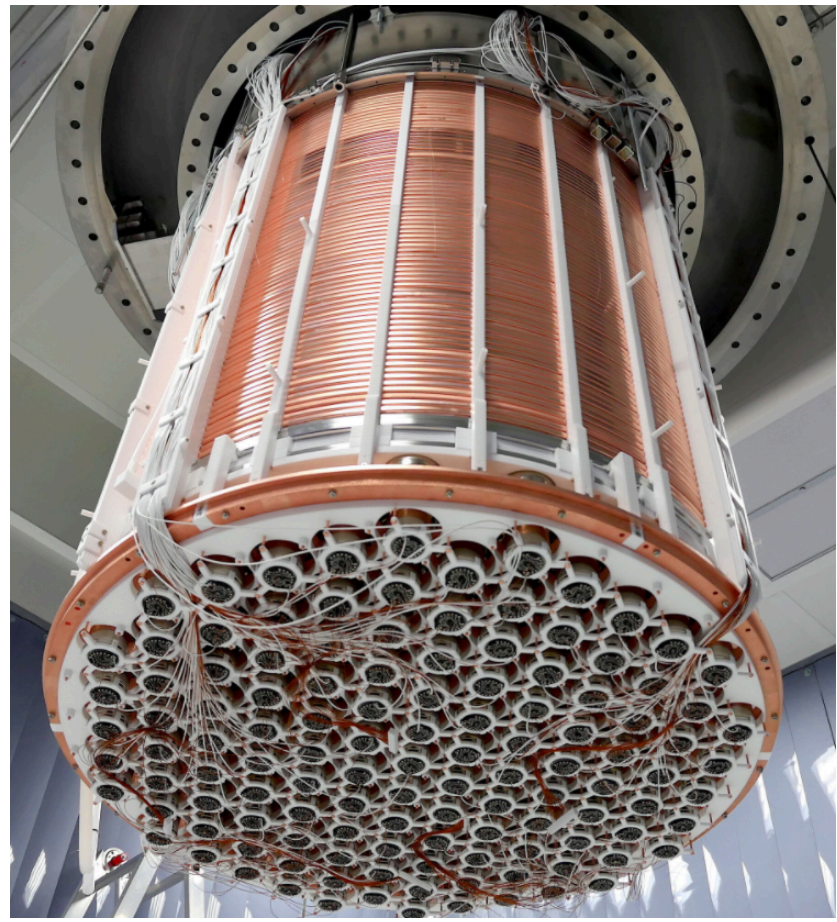
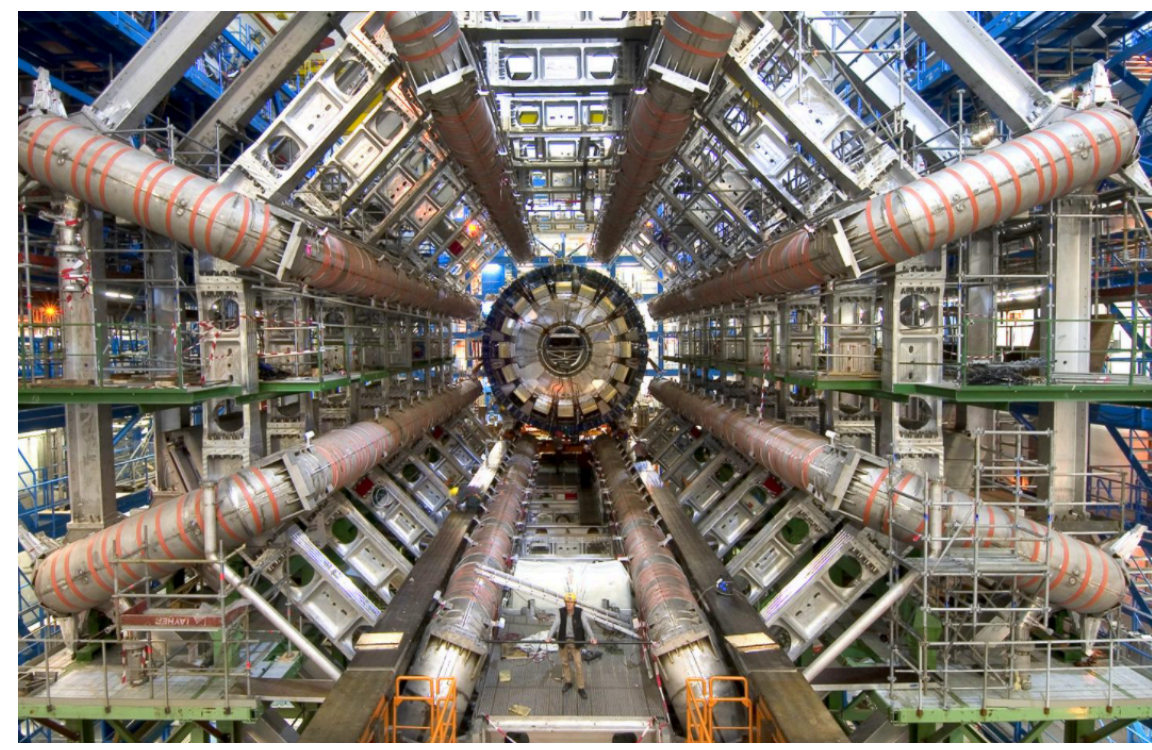
Experimental Channels For Dark Matter Detection

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HESS PAMELA
AMS



ATLAS CMS



XENON100/1T DarkSide-50/20k
LUX/LZ SuperCDMS DEAP-3600



Directly Detecting WIMPs

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

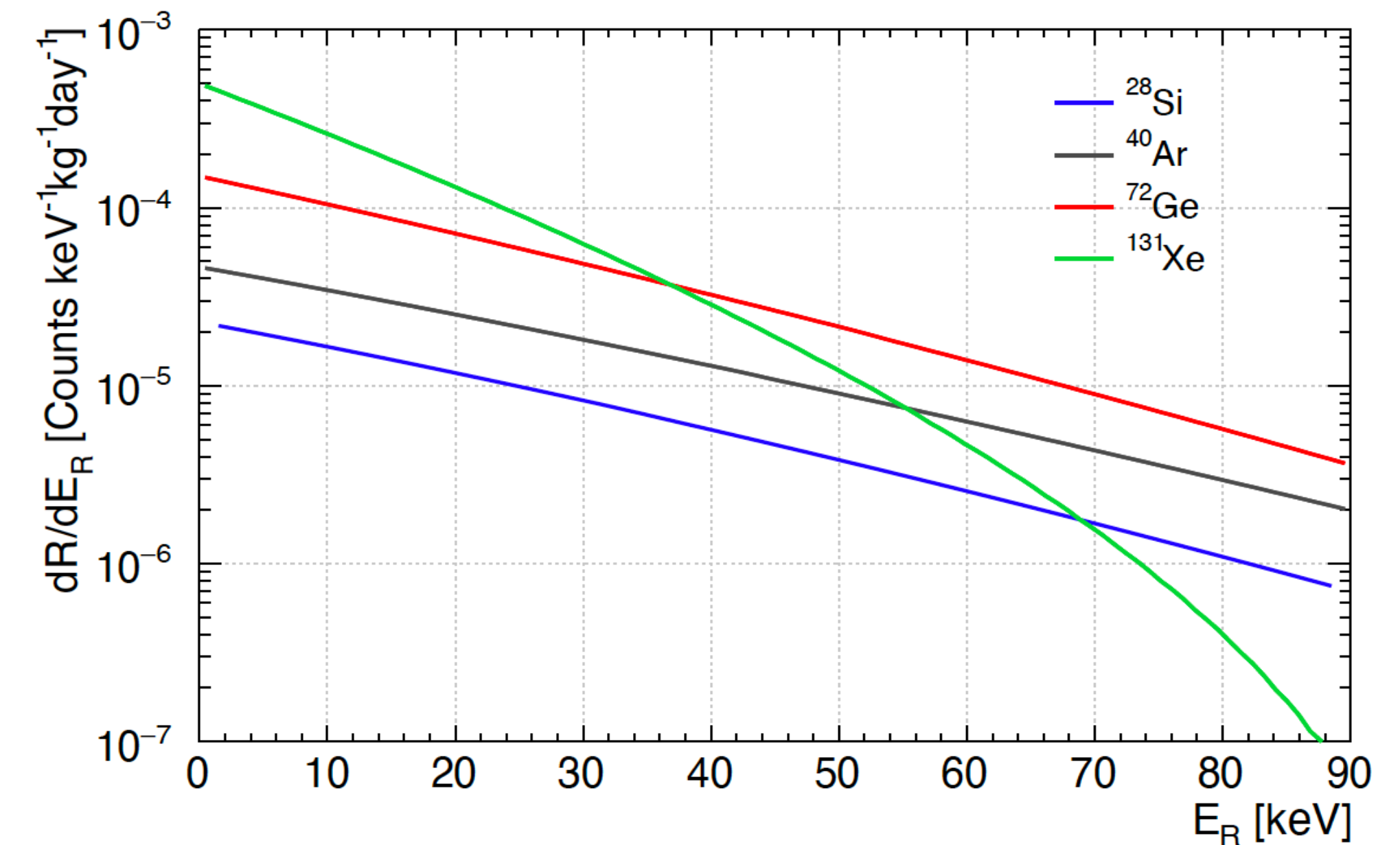
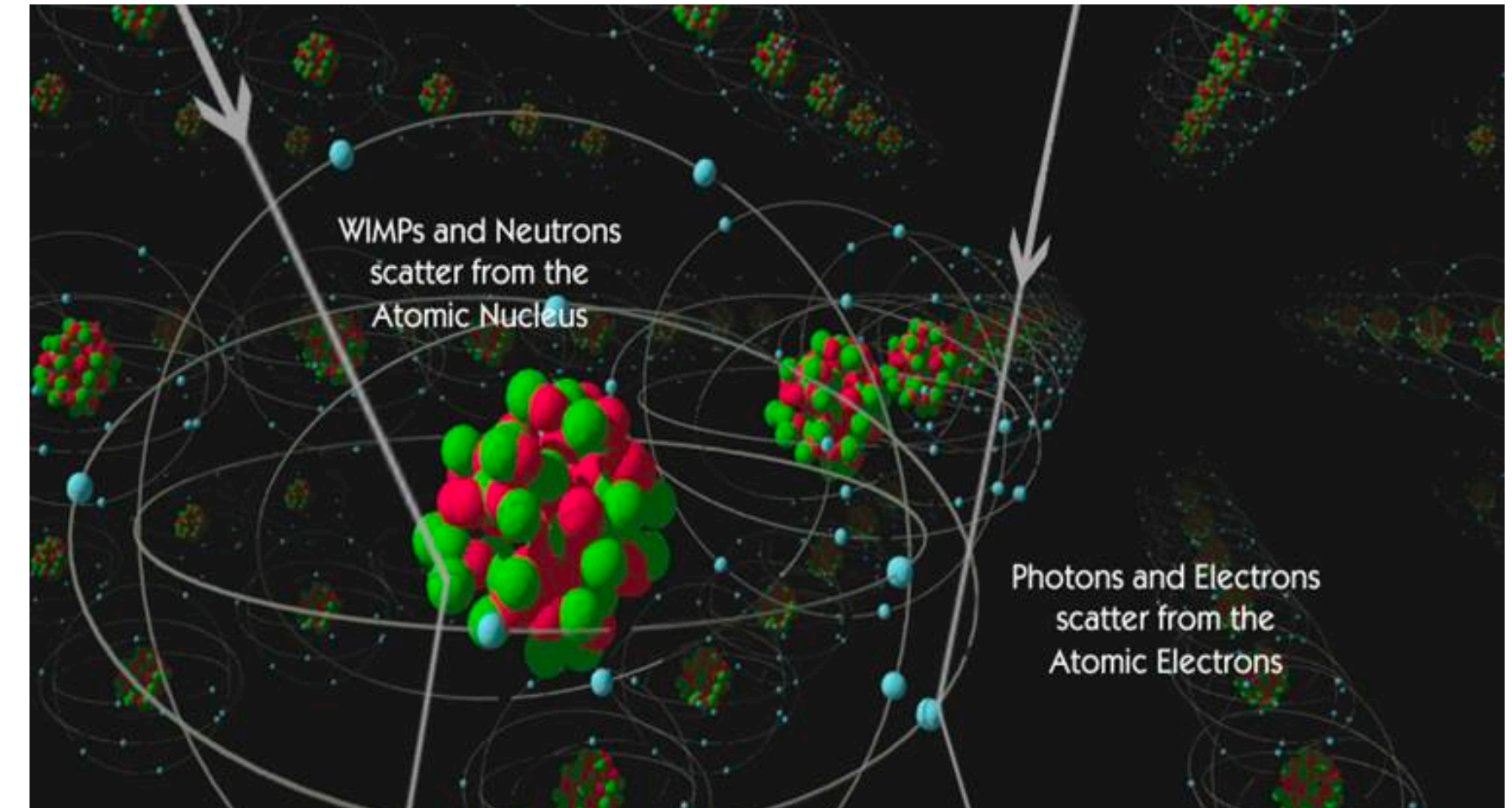
Detectors can measure the energy deposited by NRs in 3 ways: scintillation (light), ionisation (charge) and phonons (heat)

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



The DEAP-3600 Detector

Dark matter Experiment using Argon Pulse-shape discrimination

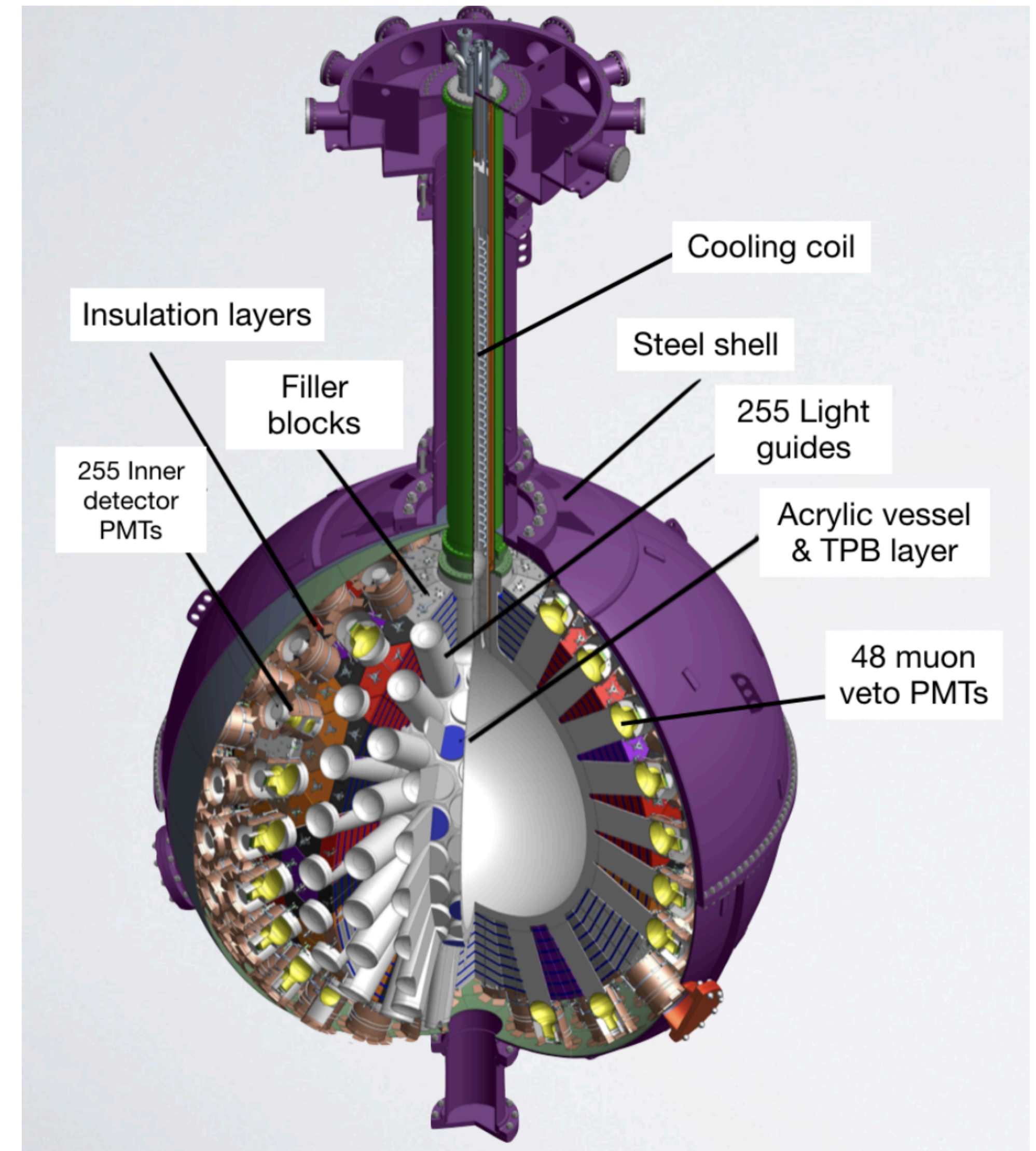
Single-phase liquid argon (LAr) scintillation light detector, holding 3279 kg target LAr inside spherical, radiopure acrylic vessel

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

VUV scintillation photons produced at $\lambda = 128 \text{ nm}$ 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 $\sim 75\%$ coverage of inner volume

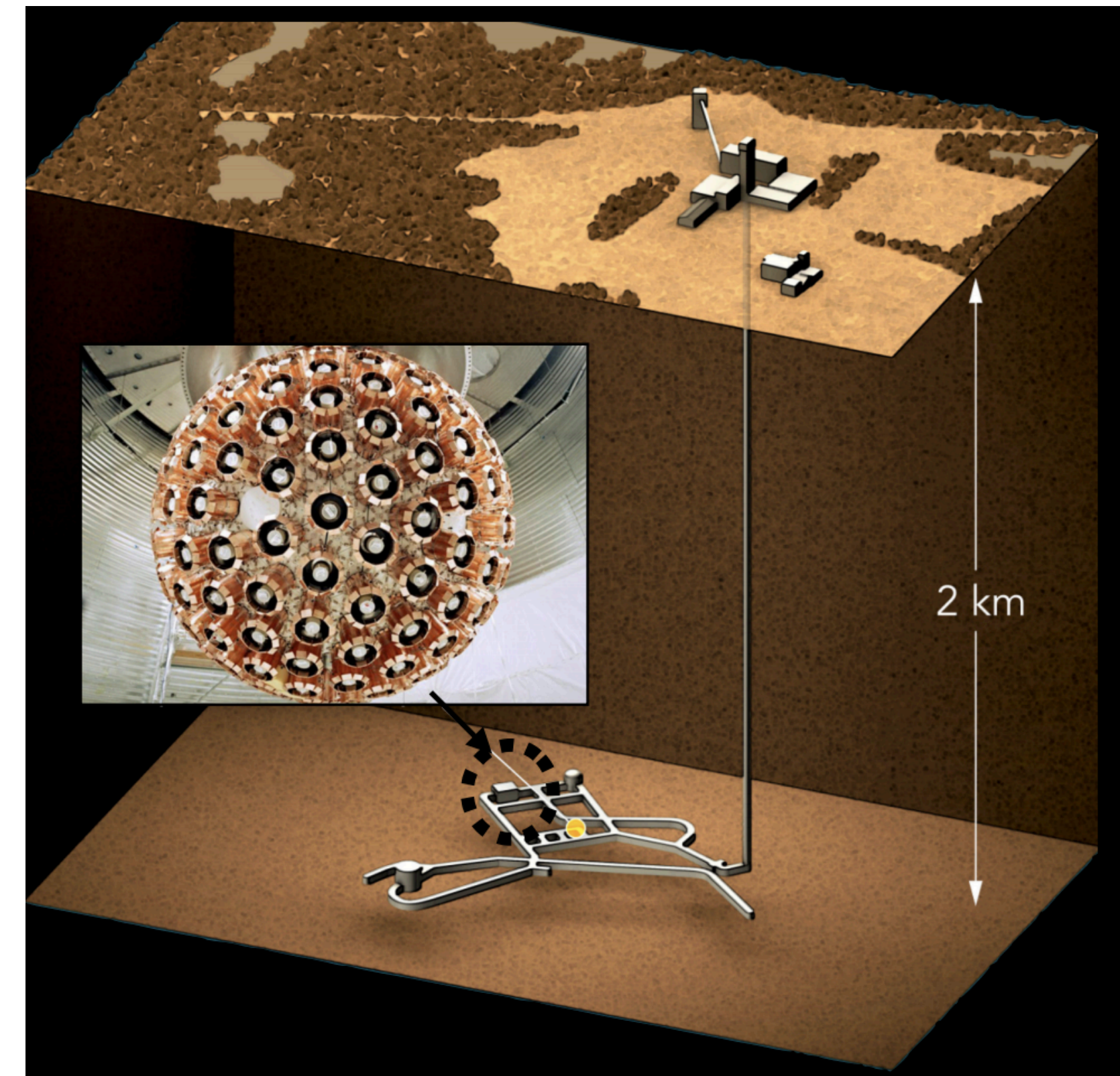
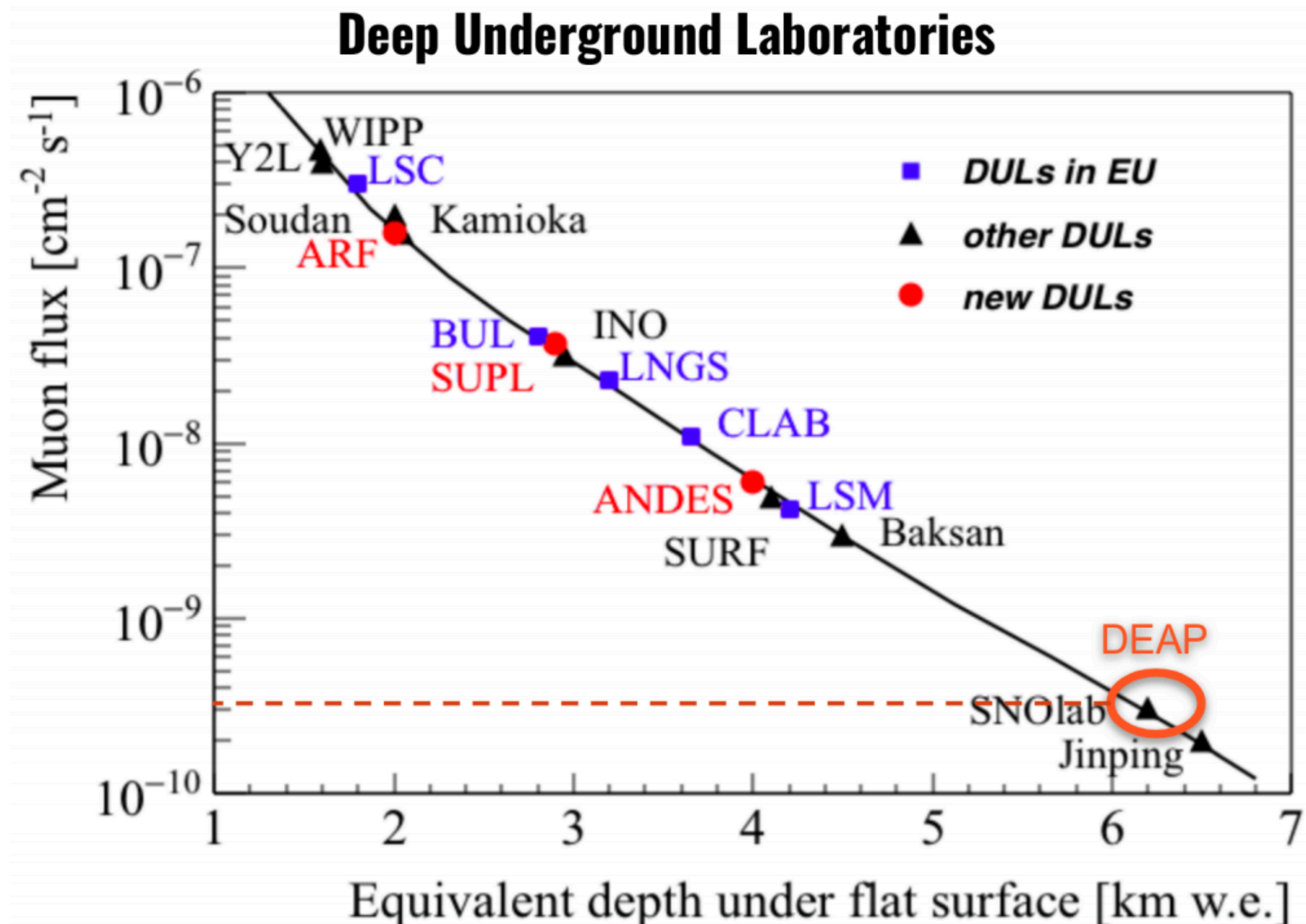
- ▶ “In-situ characterization of the Hamamatsu R5912-HQE photomultiplier tubes used in the DEAP-3600 experiment.” Nucl. Instrum. Meth. Phys. Res. A 922, 373 (2019)



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 $\sim 10^7$



Energy Calibration

Detector energy response is calibrated using ER events generated uniformly by the β -decays of the trace radioactive ^{39}Ar isotope in the LAr target

- ▶ Specific activity of $^{39}\text{Ar} = (0.95 \pm 0.05)$ Bq/kg, approx 3300 ER events/sec in DEAP-3600

Parameterisation of the ^{39}Ar spectrum to data described by response function relating the total energy deposited in the detector, E , to the number of detected photoelectrons (PEs) produced by PMTs

- ▶ Gaussian response with mean μ and variance σ :

$$\mu = \langle N_{\text{DN}} \rangle + Y_{\text{PE}} \cdot E,$$

$$\sigma^2 = \sigma_{\text{PE}}^2 \cdot \mu + \sigma_{\text{rel, LY}}^2 \cdot \mu^2$$

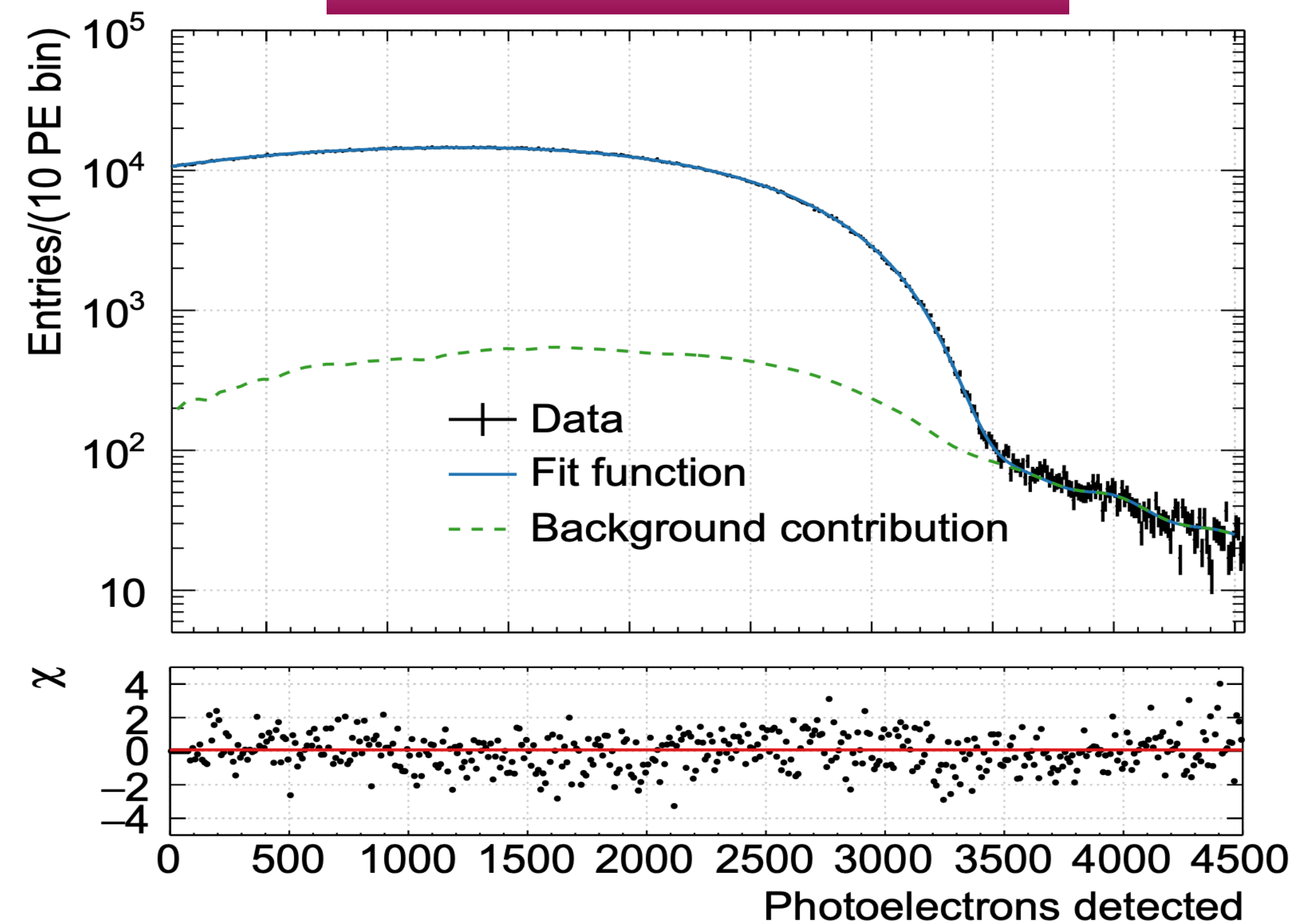
$\langle N_{\text{DN}} \rangle =$ Dark Noise PEs/ Uncorrelated Noise [PE]

$Y_{\text{PE}} =$ Light Yield [PE/keV]

$\sigma_{\text{PE}}^2 =$ Energy Resolution [PE]

$\sigma_{\text{rel, LY}}^2 =$ Accounts for variance of Y_{PE} relative to mean

$$Y_{\text{PE}} = (6.4 \pm 0.4) \text{ PE/keV}$$



Pulse-Shape Discrimination

Pulse-shape discrimination (PSD) is a powerful tool used in LAr experiments to reject electronic recoil (ER) backgrounds such as from β -particles and γ -rays

Particles recoiling in LAr deposit energy by ionising and exciting argon atoms, creating excitons Ar^* and ions Ar^+ , which create excited argon molecules (excimers) Ar_2^* that radiatively decay to generate 128 nm scintillation photons

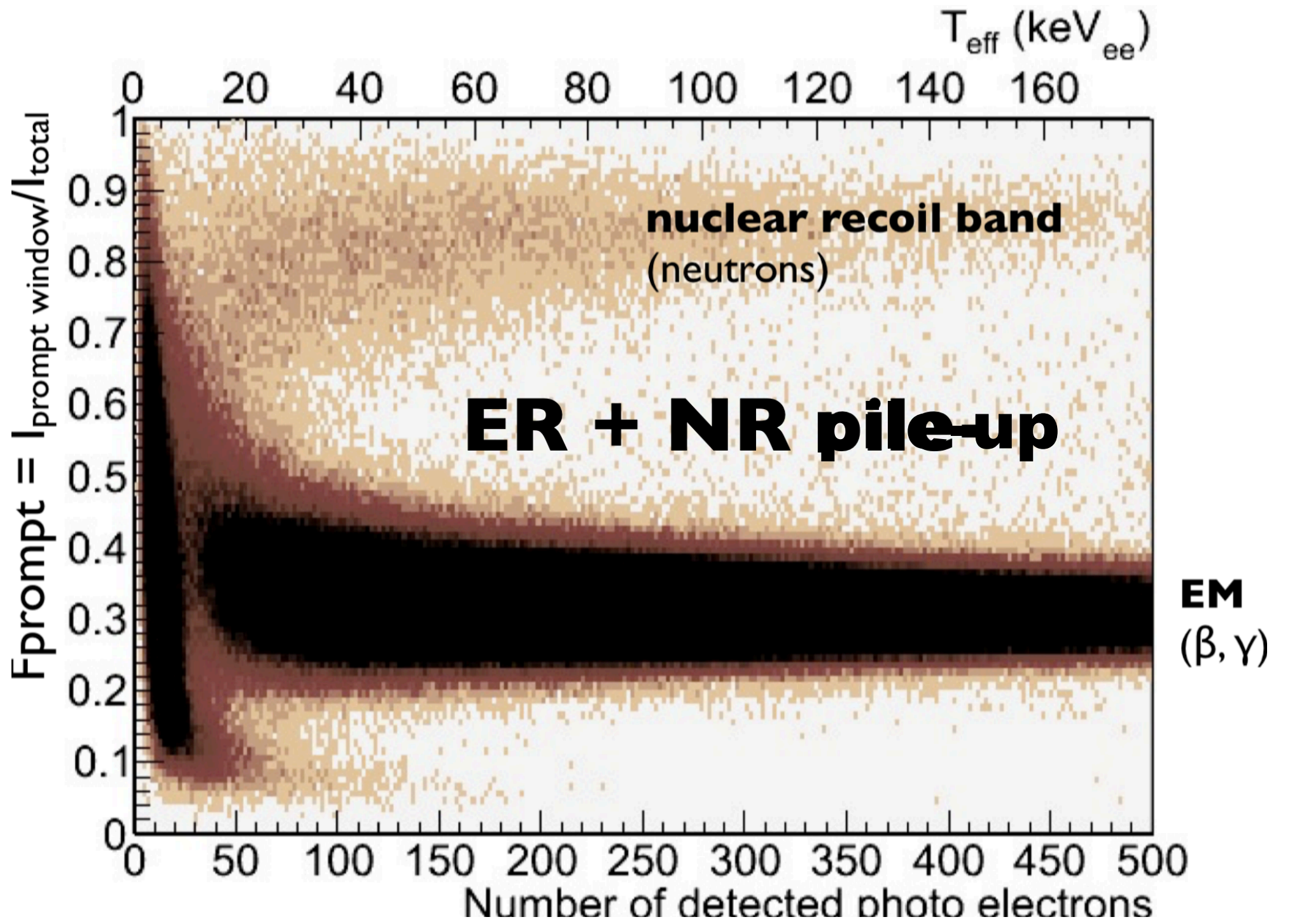
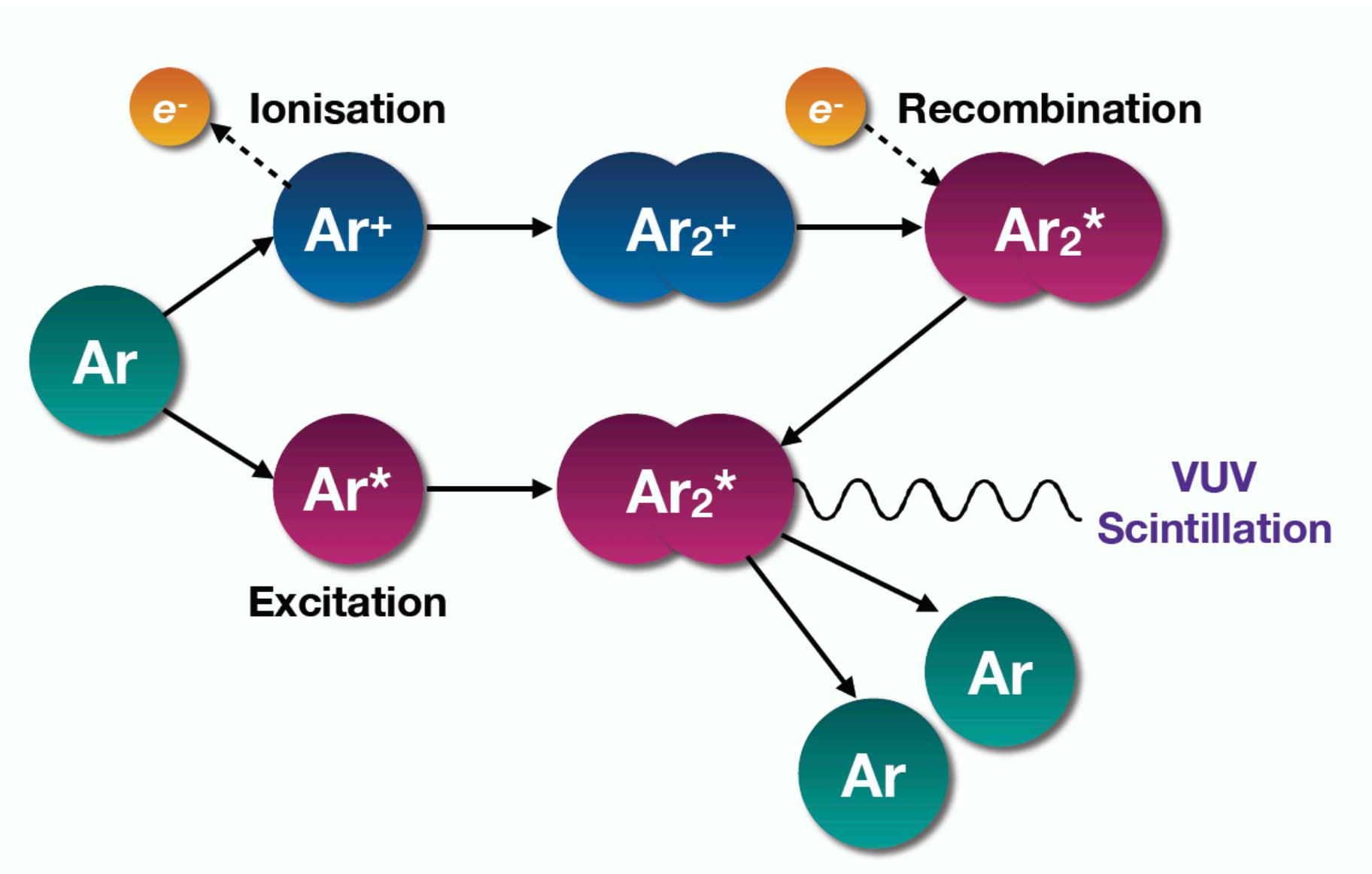
Number of excitons/ions produced dependent on particle interaction type

Excimers in LAr can be produced in singlet / triplet states with well-separated lifetimes (7 ns / 1445 ns) - this makes PSD effective. Details on the **pulse shape** and **PSD** published in Ref A and Ref B - see below!

Define a PSD variable known as F_{prompt} : fraction of prompt scintillation light

$$F_{prompt} = \frac{\sum_{t=-28ns}^{60ns} PE(t)}{\sum_{t=-28ns}^{10000ns} PE(t)}$$

Suppression factor of 10^{-10} determined by the DEAP-3600 collaboration at 90% NR acceptance (110 PE)



Data from AmBe (neutron emitter) run

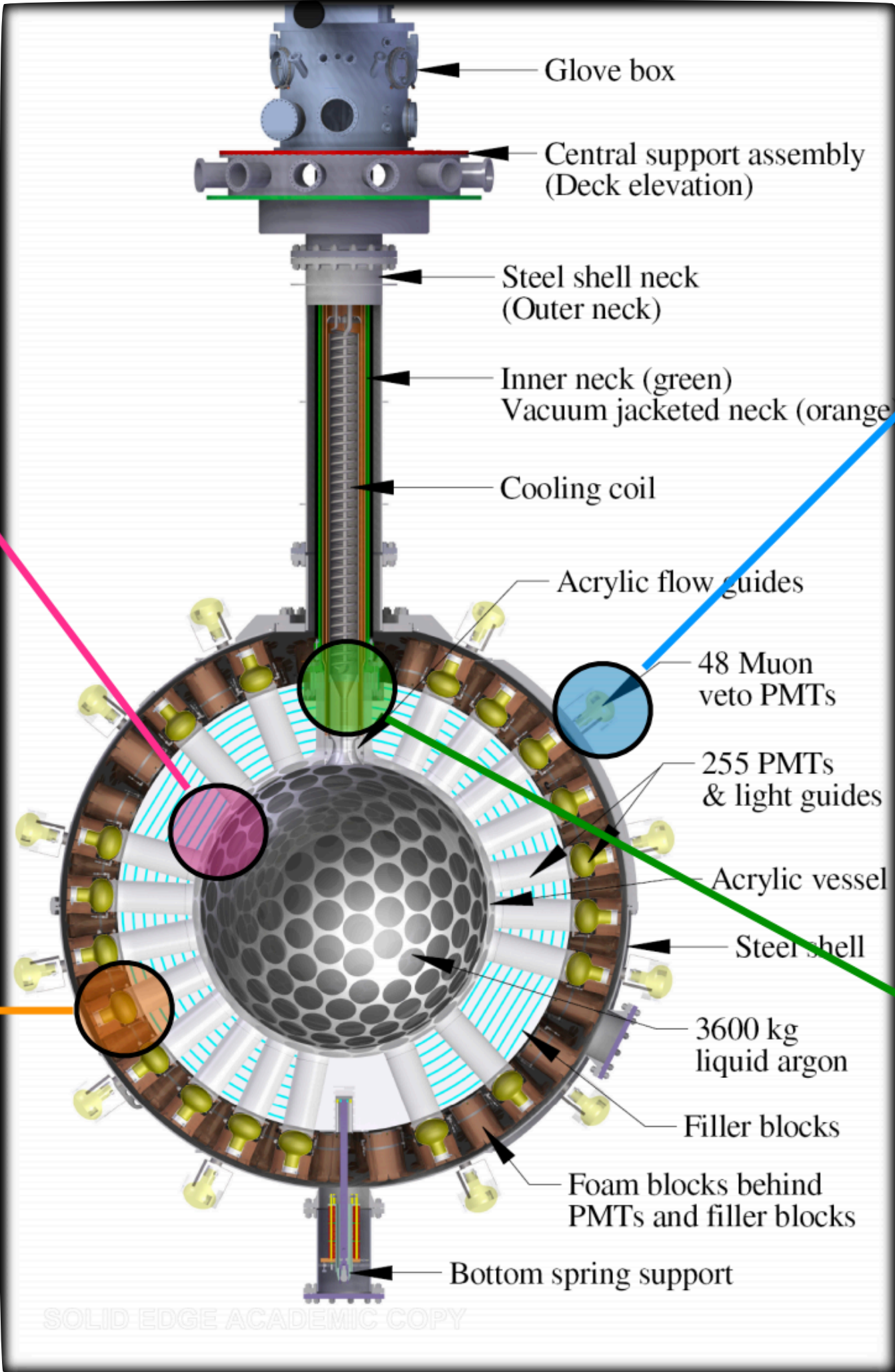
Ref A : <https://doi.org/10.1140/epjc/s10052-020-7789-x>

Ref B : <https://doi.org/10.1140/epjc/s10052-021-09514-w>

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

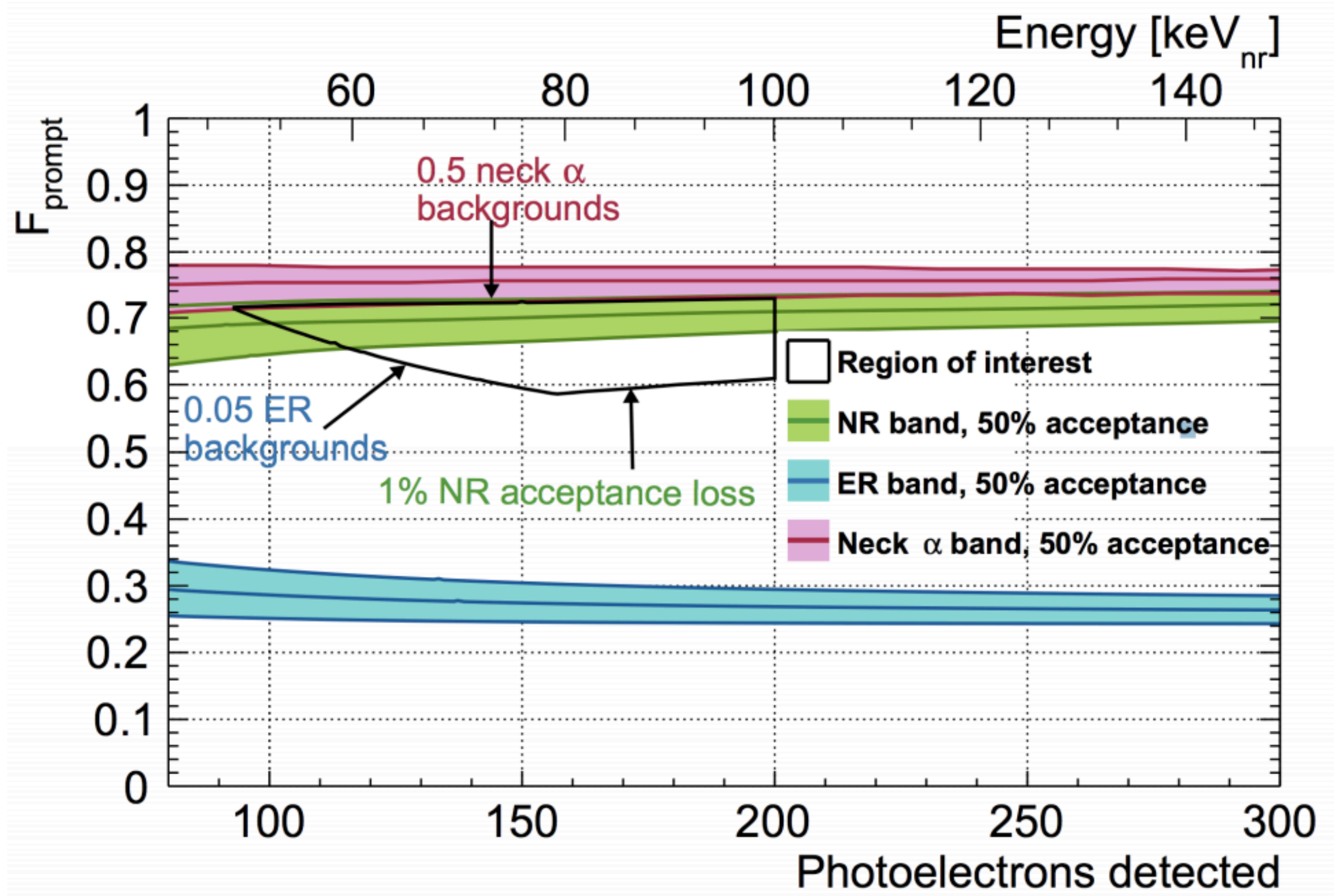
“Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB”. Phys. Rev. D 100, 022004 (2019)

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

2D ROI drawn in PE- F_{prompt} parameter space

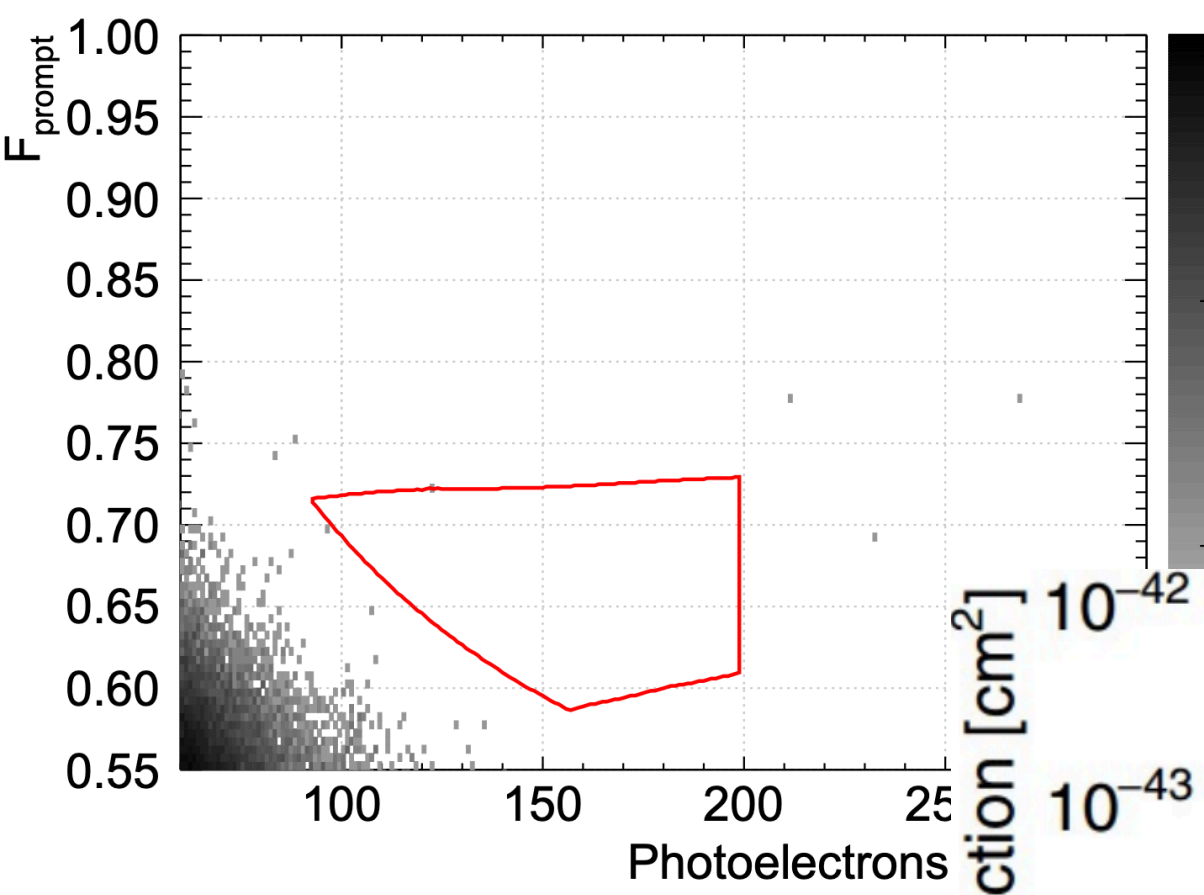
Designed to achieve background expectation < 1

	Source	N^{CR}	$N^{\text{ROI, LL}}$	N^{ROI}
β/γ 's	ERs	2.44×10^9	0.34 ± 0.11	0.03 ± 0.01
	Cherenkov	$< 3.3 \times 10^5$	< 3890	< 0.14
n 's	Radiogenic	6 ± 4	11_{-9}^{+8}	$0.10_{-0.09}^{+0.10}$
	Cosmogenic	< 0.2	< 0.2	< 0.11
α 's	AV surface	< 3600	< 3000	< 0.08
	AV Neck FG	28_{-10}^{+13}	28_{-10}^{+13}	$0.49_{-0.26}^{+0.27}$
Total		N/A	< 4910	$0.62_{-0.28}^{+0.31}$

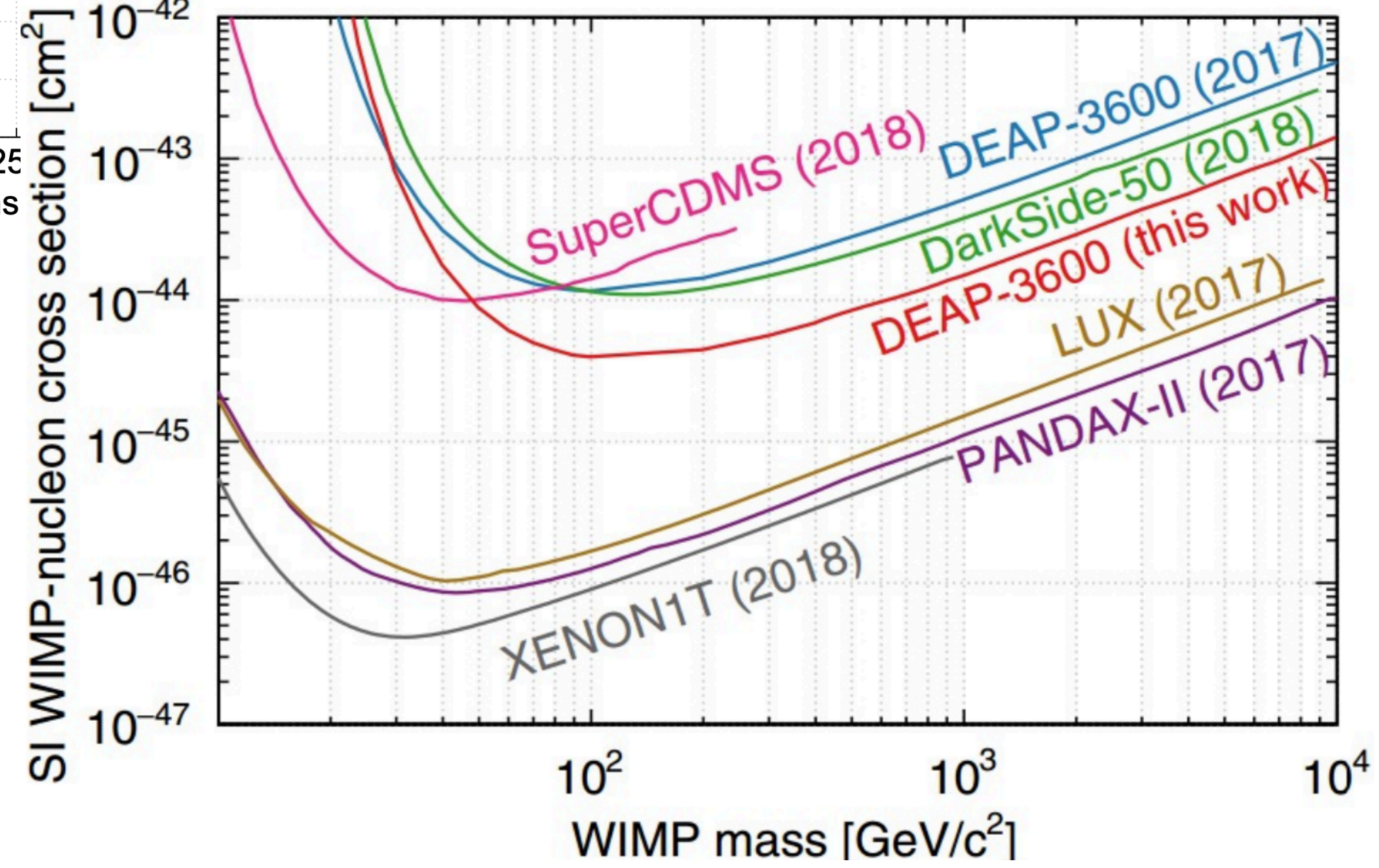


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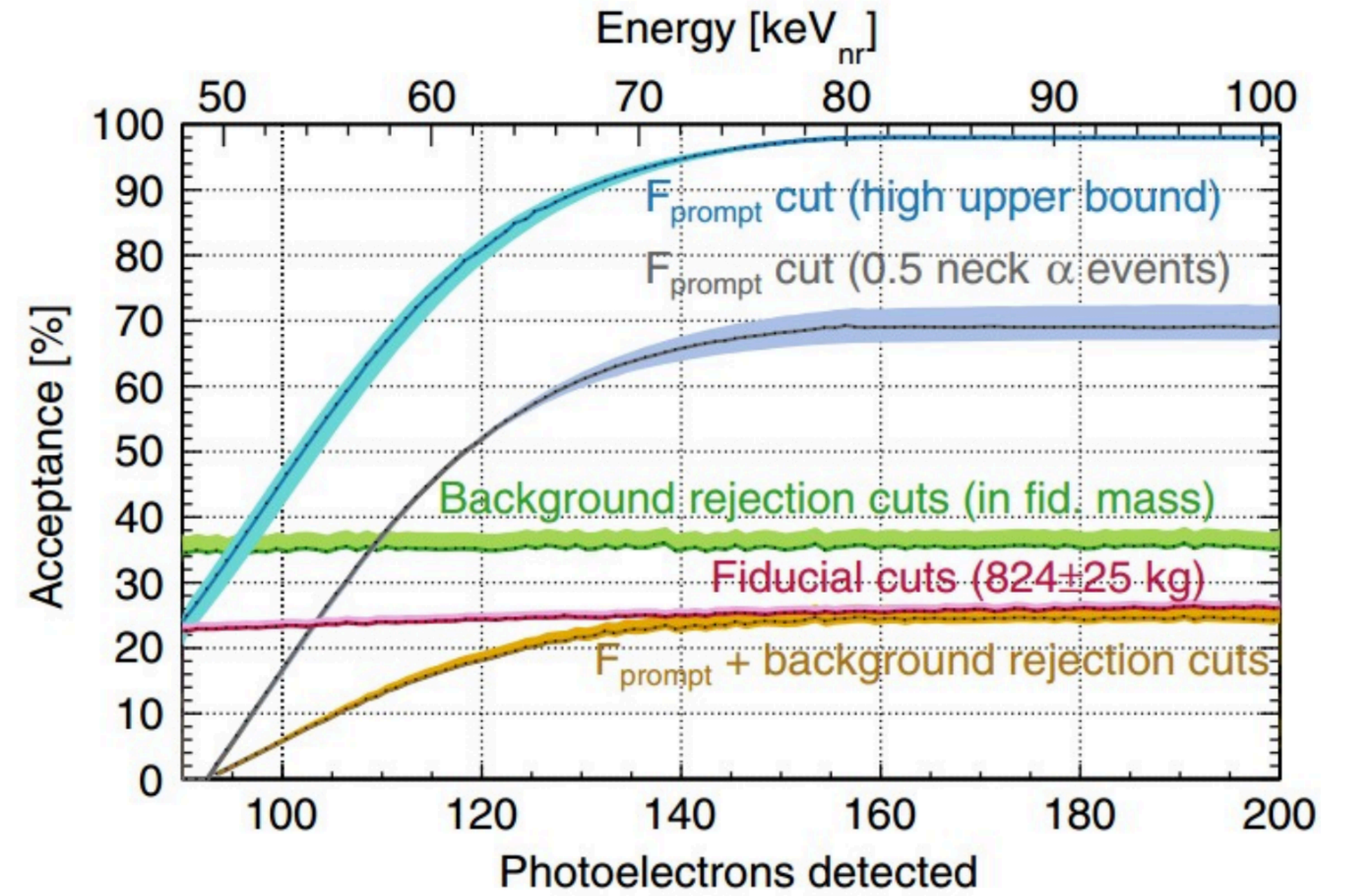
“Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB”. Phys. Rev. D 100, 022004 (2019)



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

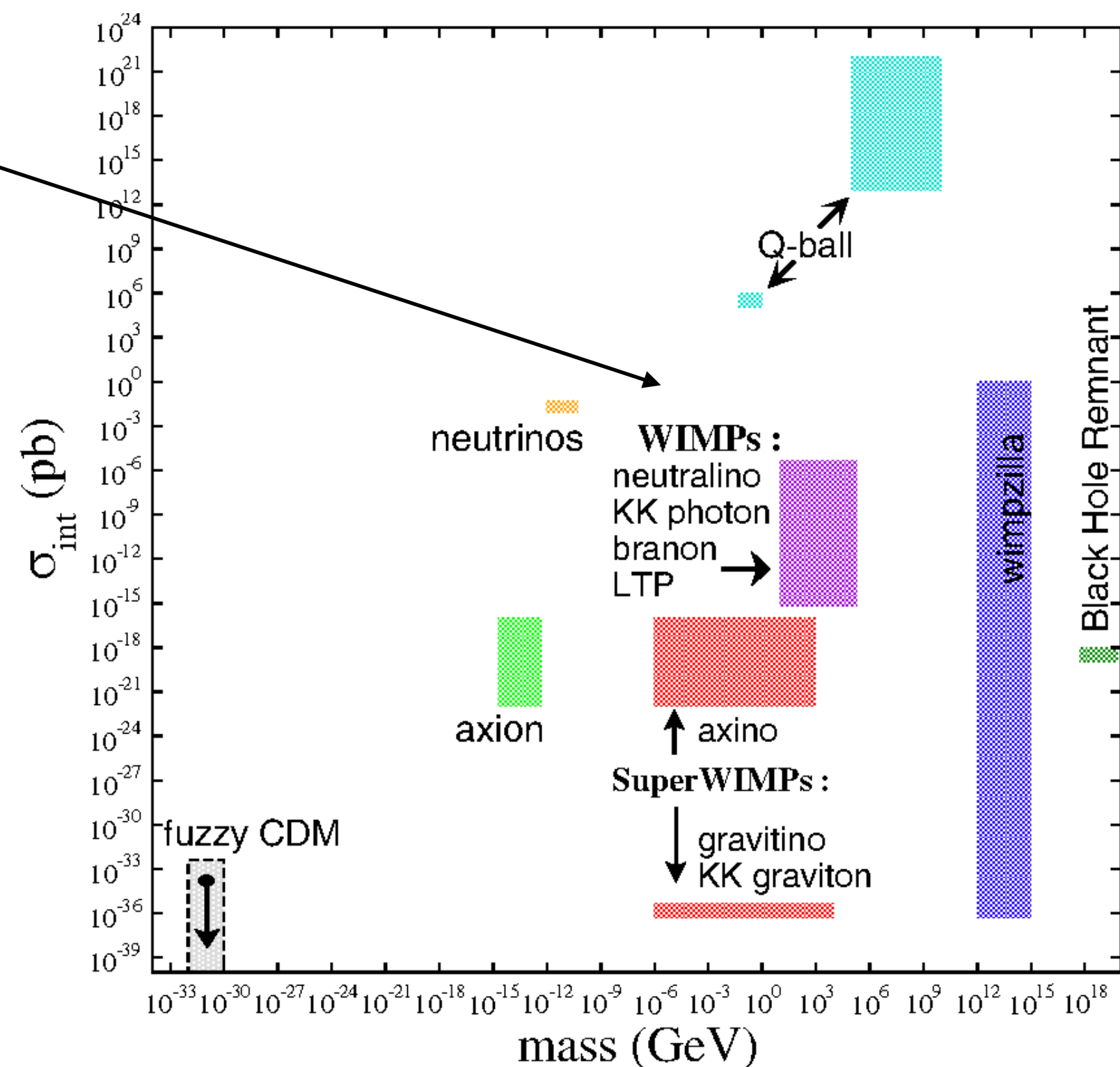
Re-analysis of 231 live-day dataset/ analysis of full open dataset (376 live-days) using Profile Likelihood Ratio PLR method in the works to attempt to gain back WIMP acceptance & sensitivity

► Watch this space!

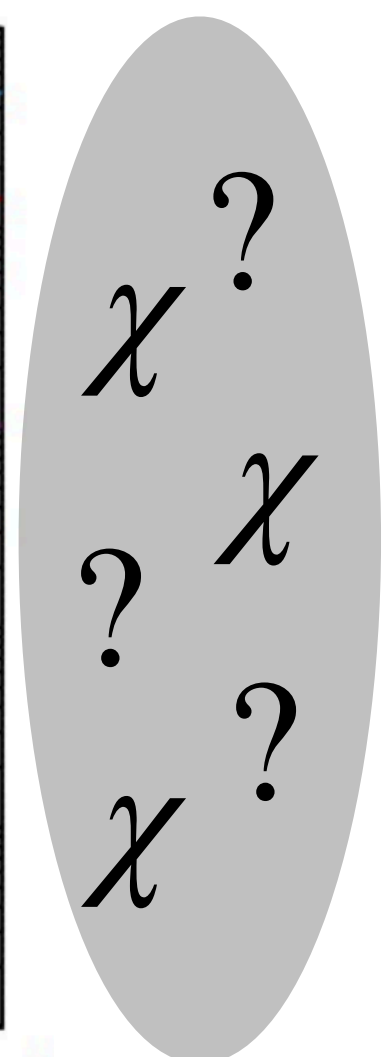
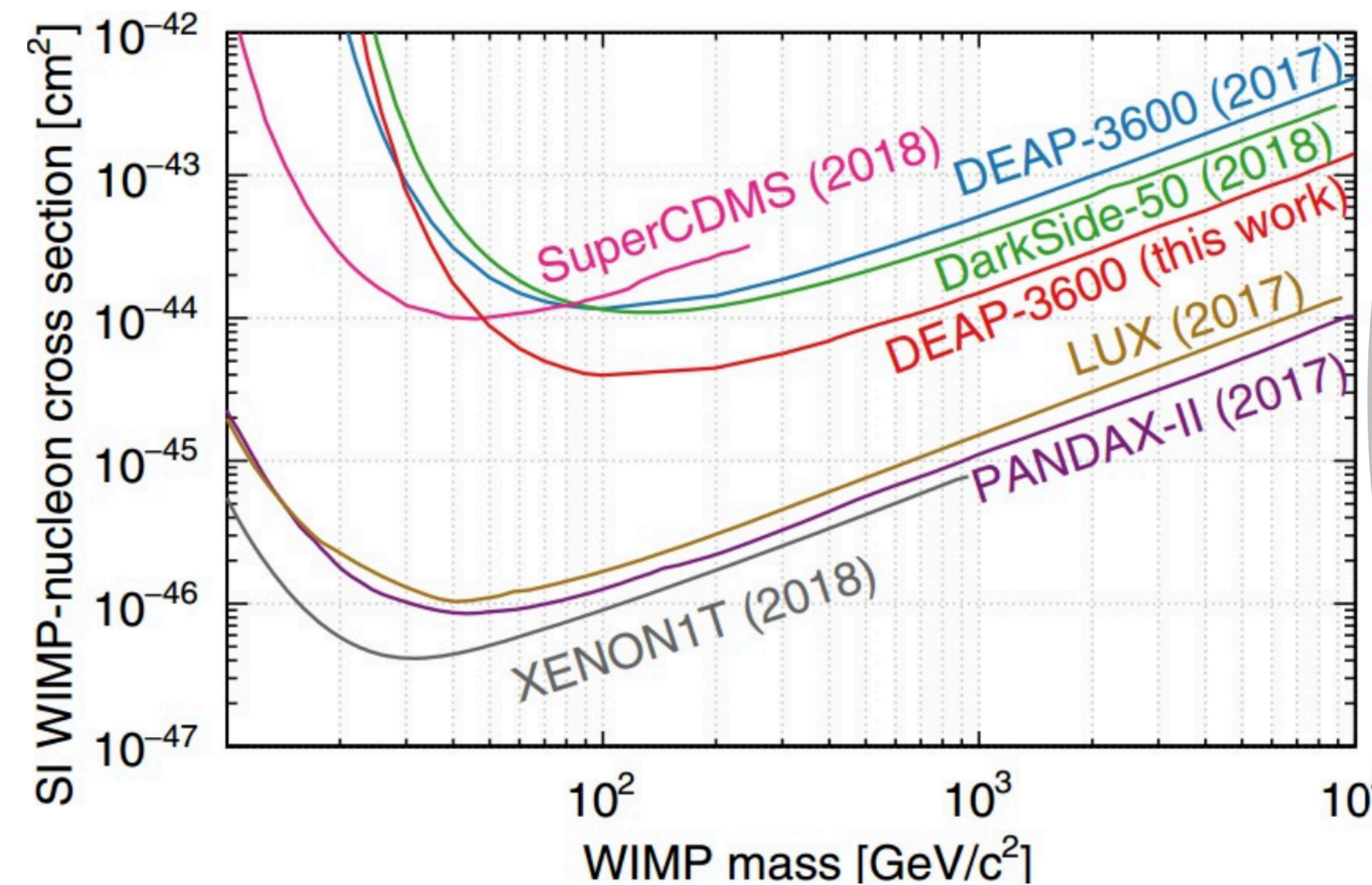
Also working on a blind analysis (802 live-days), using both PLR and machine learning techniques

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

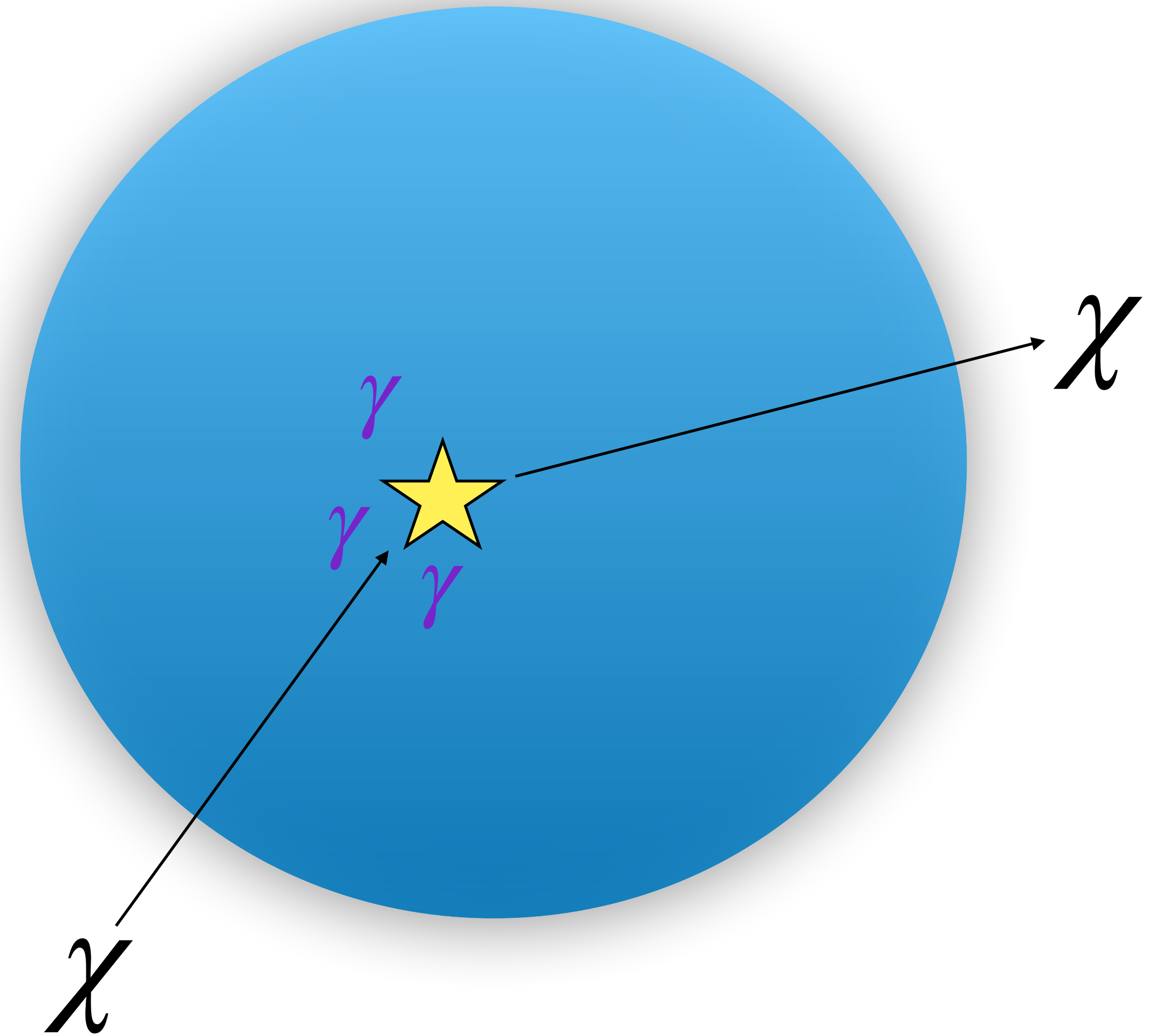
Another well-motivated DM candidate is super-heavy DM with Planck-scale mass

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

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



Planck-Scale Dark Matter

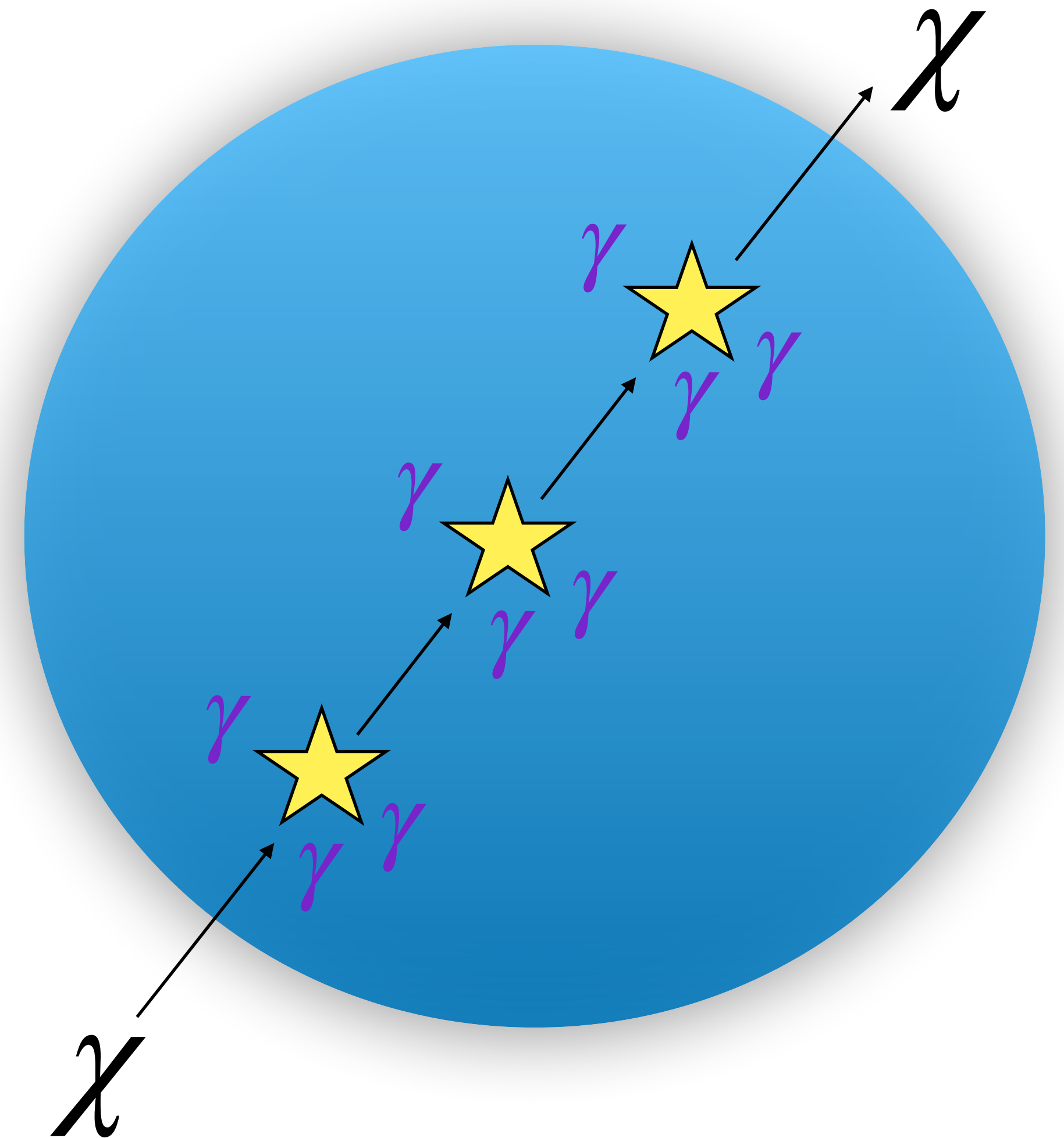
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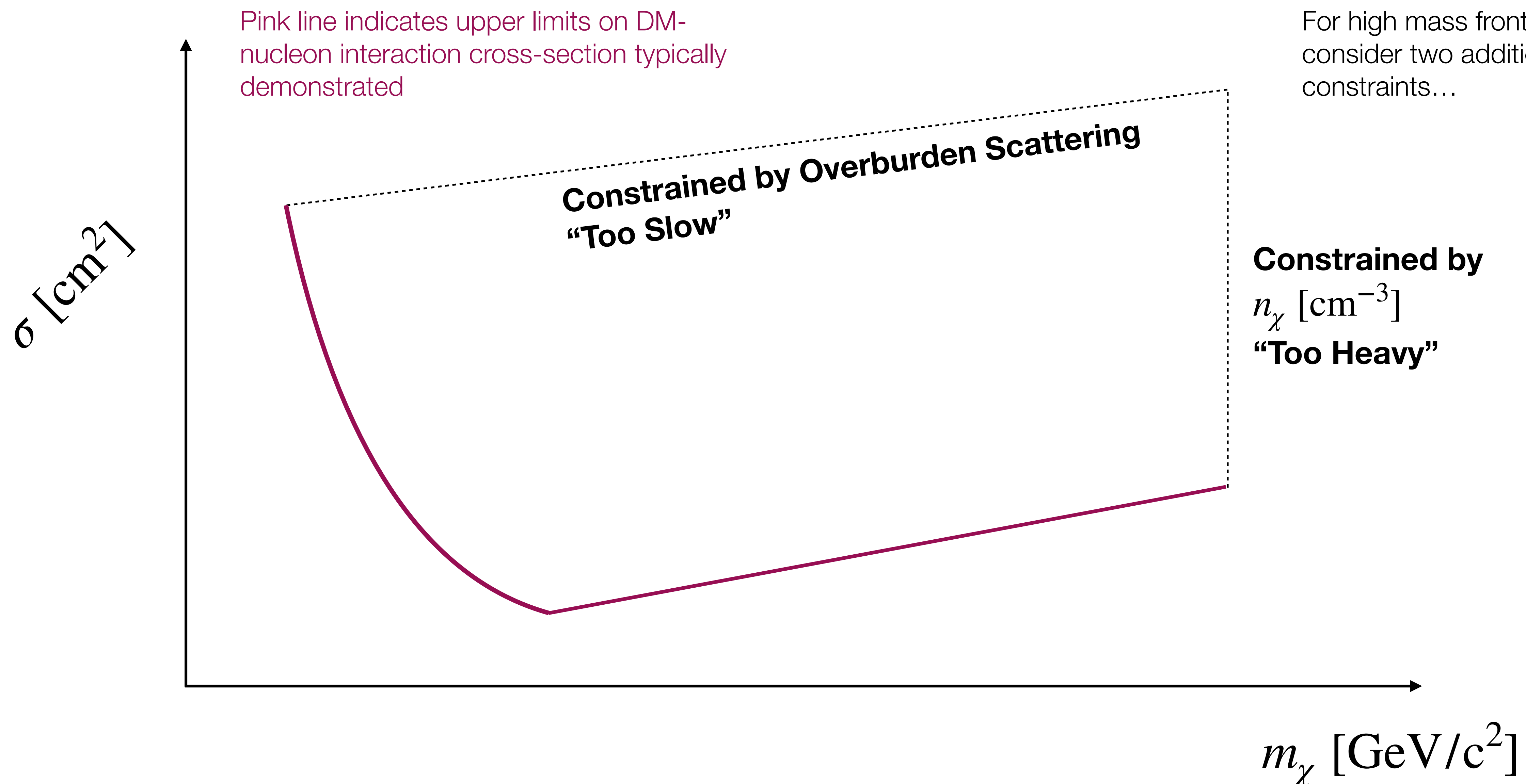
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Planck-Scale DM Multi-Scatter

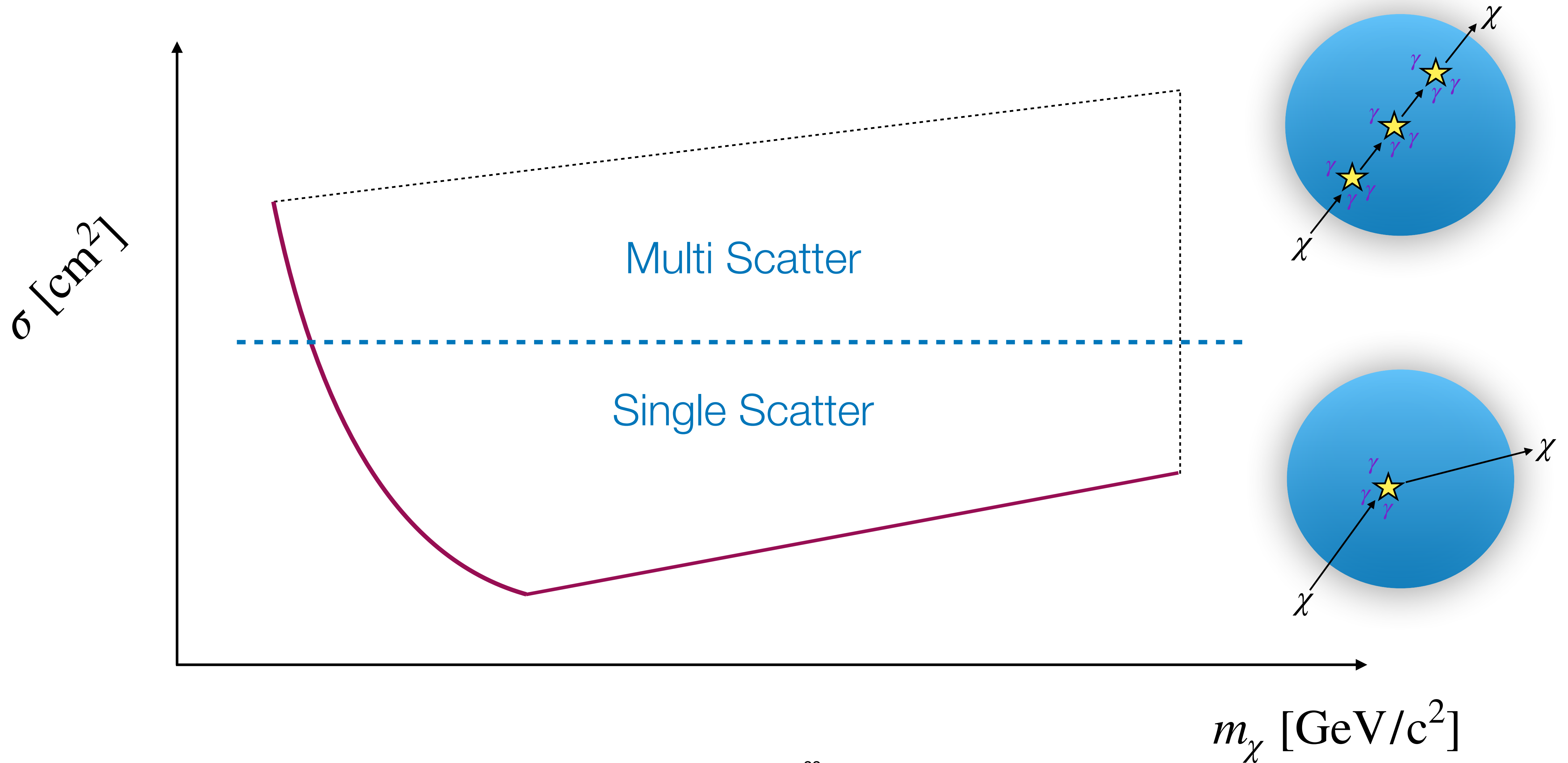


Characterising Planck-Scale DM

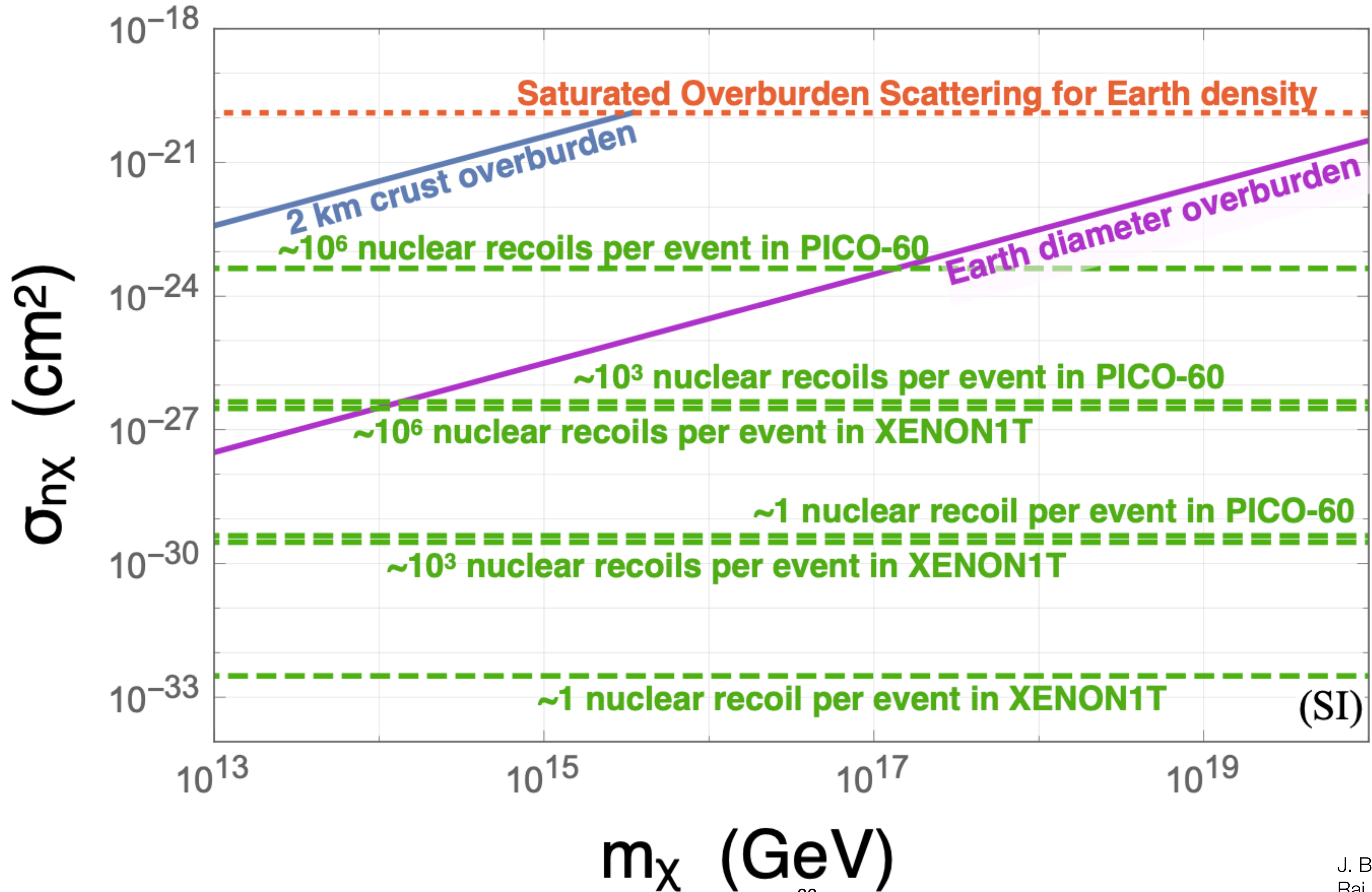


For high mass frontier, need to consider two additional constraints...

Characterising Planck-Scale DM



Characterising Planck-Scale DM



Characterising Planck-Scale DM

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

Φ = Integrated Flux

τ = Optical depth = $n_{\text{det}} \sigma L_{\text{det}}$

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,

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

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

And $n^{1/3} L_{\text{det}}$, 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/c², 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

Attenuation of DM at position \vec{r} calculated numerically as,

$$\left\langle \frac{dE_\chi}{dt} \right\rangle(\vec{r}) = - \sum n_i(\vec{r}) \sigma_{i,\chi} \langle E_R \rangle_i v \quad \text{DM Speed}$$

Nuclide Number Density DM-nucleus scattering Cross-Section

Average Recoil Energy

Atmospheric density profile: 79% N₂, 21% O₂

Earth's density profile and composition from [J. Lundberg and J. Edsjo, Phys. Rev. D 69, 123505 (2004)], [A. M. Dziewonski and D. L. Anderson, Phys. Earth Planet. Inter 25, 297 (1981).]

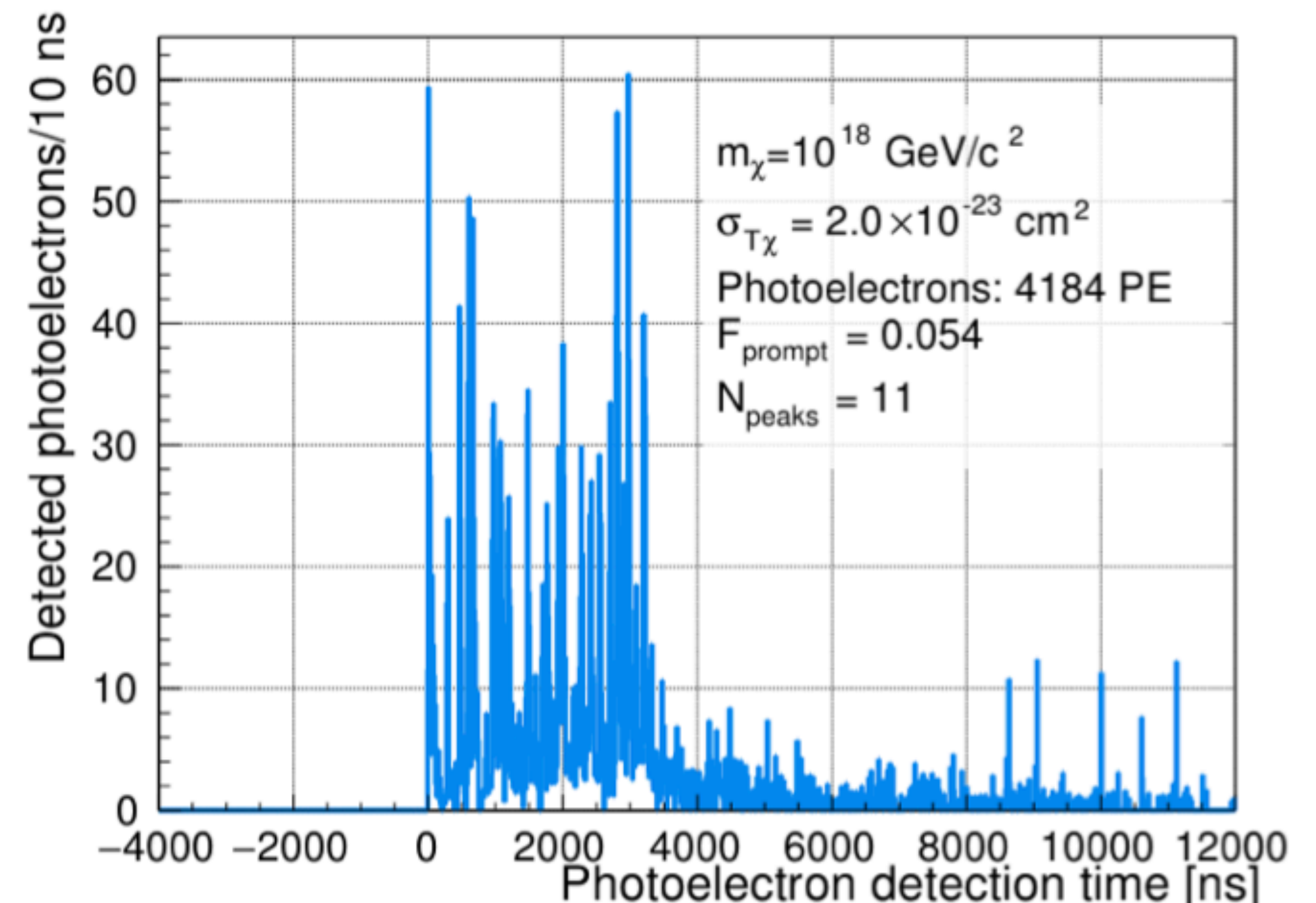
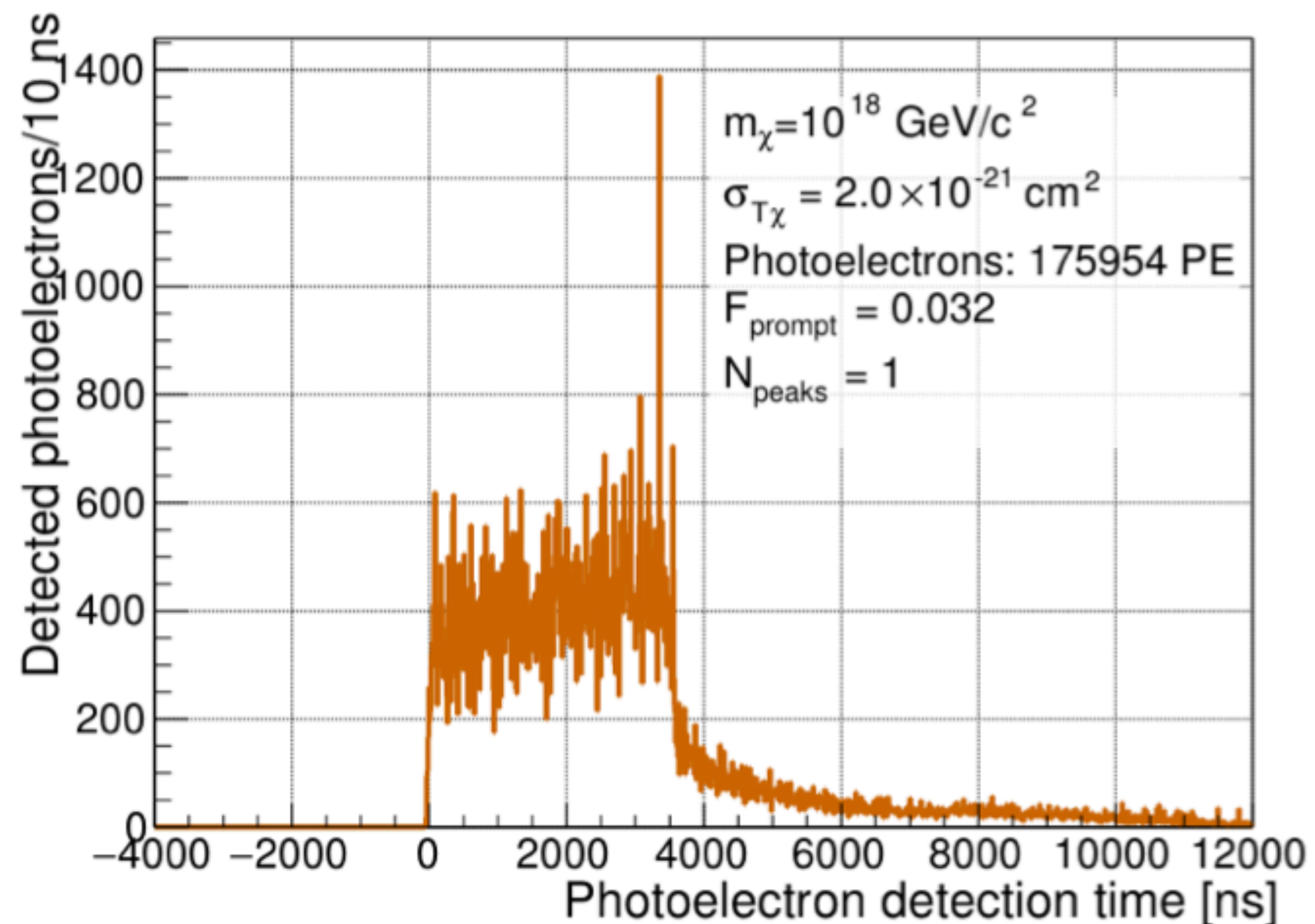
Uncertainties in Earth model found to have negligible effect

Planck-Scale DM: Simulation in DEAP-3600

DM that passes through the overburden is then propagated into the DEAP-3600 inner detector

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

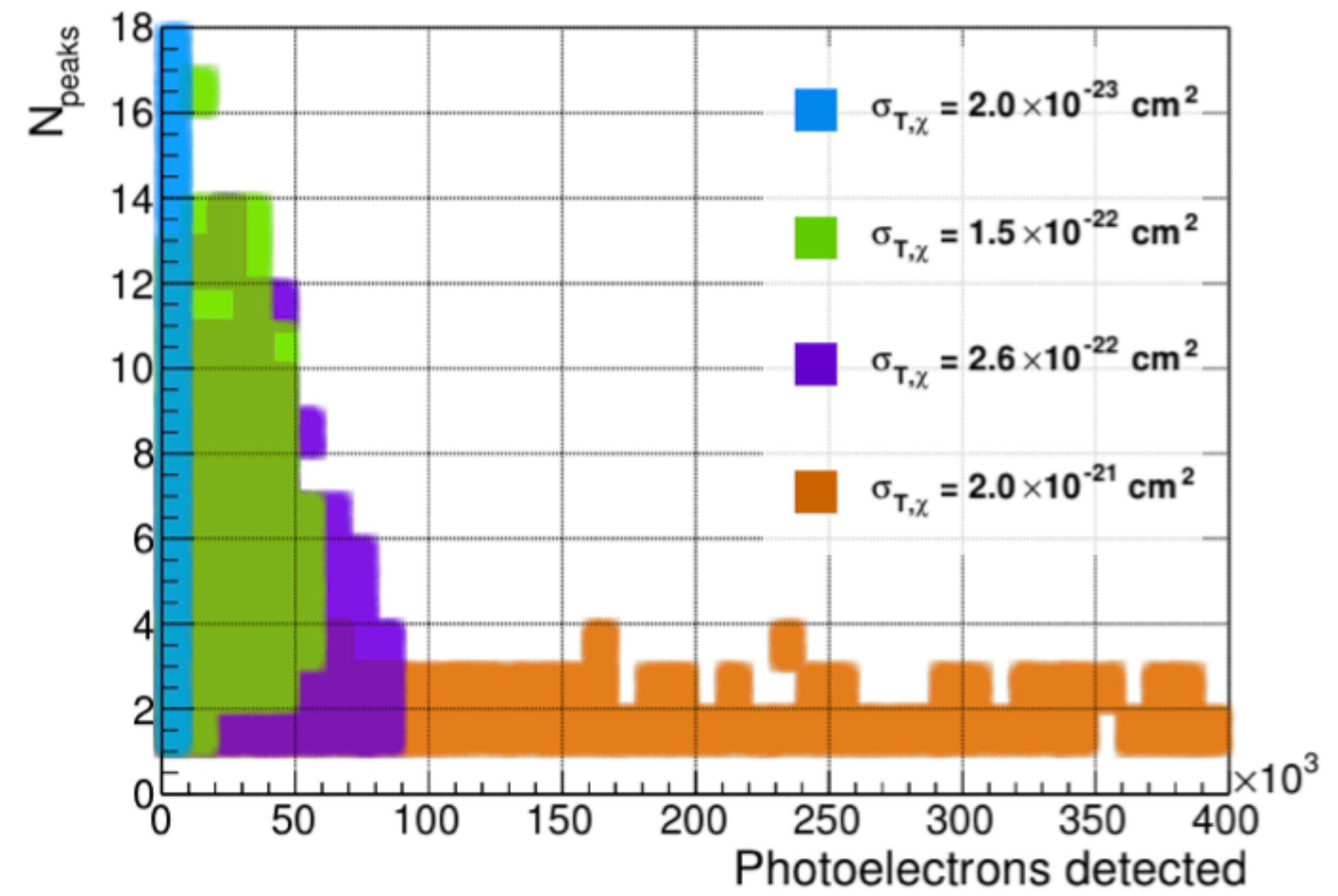
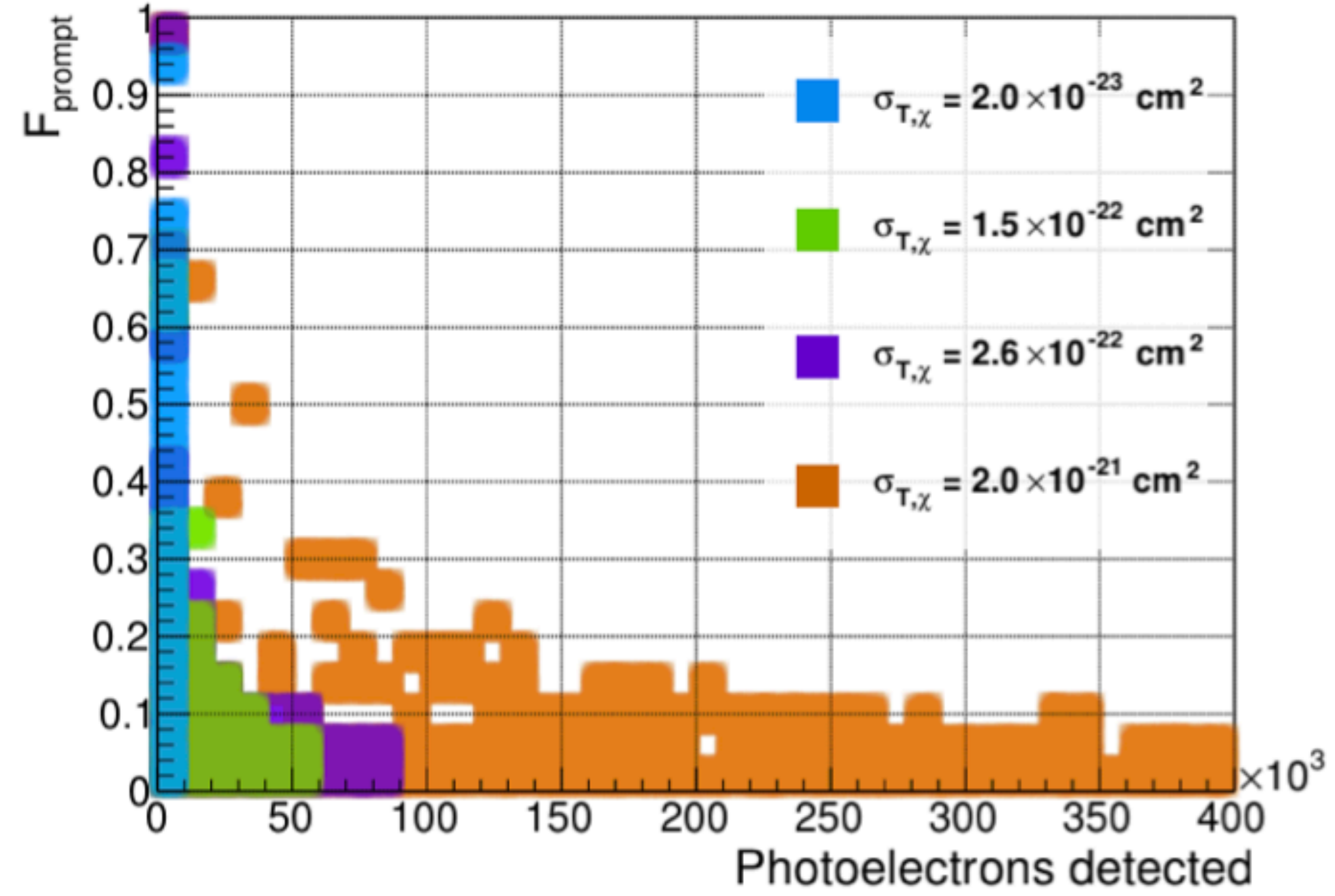
Simulated detected PE times for $m_\chi = 10^{18} \text{ GeV}/c^2$, for $\sigma_{T\chi} = 2 \times 10^{-21} \text{ cm}^2$ (left) and $\sigma_{T\chi} = 2 \times 10^{-23} \text{ cm}^2$ (right)



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 N_{peaks} variables loses accuracy



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

➔ 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

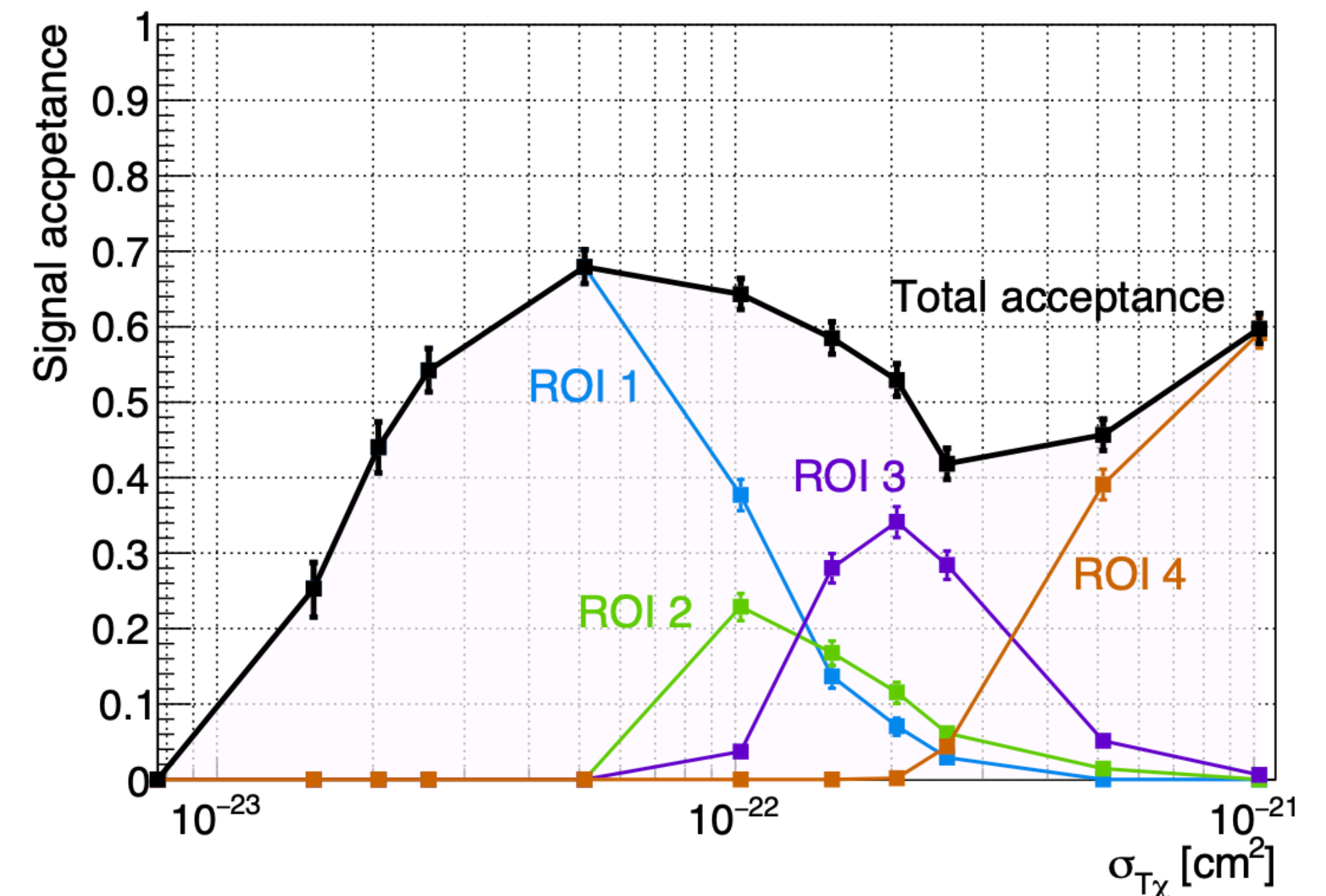
The ROIs are defined in different energy ranges, with varying cuts on N_{peaks} and F_{prompt}

ROI	PE range	Energy [MeV]	$N_{\text{peaks}}^{\text{min}}$	$F_{\text{prompt}}^{\text{max}}$	μ_b	$N_{\text{obs.}}$
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

Probability of Planck-scale DM
with $m_\chi = 10^{18}$ GeV/c²
populating each ROI and
surviving all cuts at varying $\sigma_{T\chi}$

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 $N_{\text{peaks}} > 2$ 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



Planck-Scale DM: Analysis and Search Results

DEAP-3600 blind dataset live time	$N_{\text{exp,total}}$	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:

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

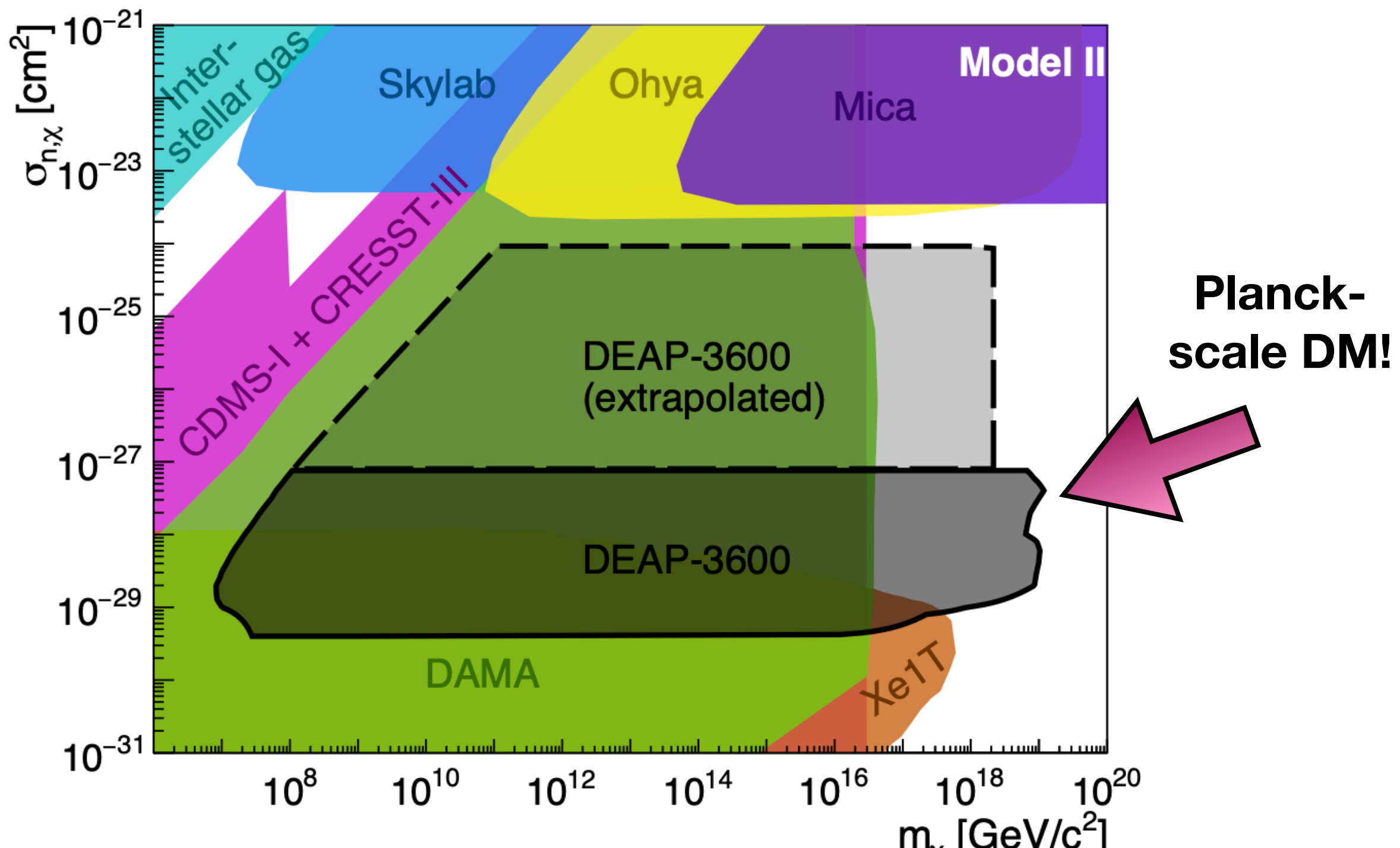
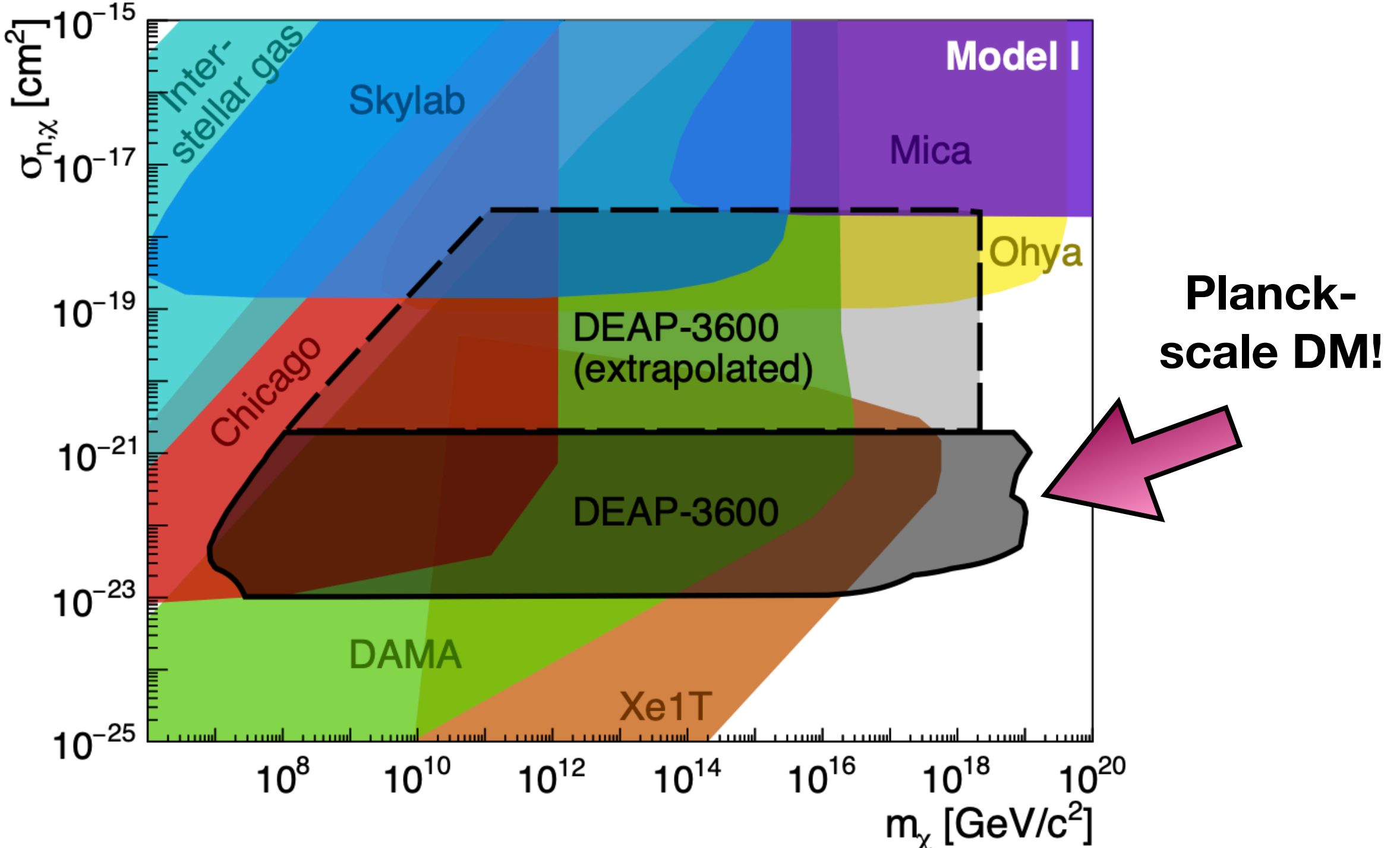
Most commonly used scaling; allows for direct comparison with other experiments as well as single scatter constraints

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_{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

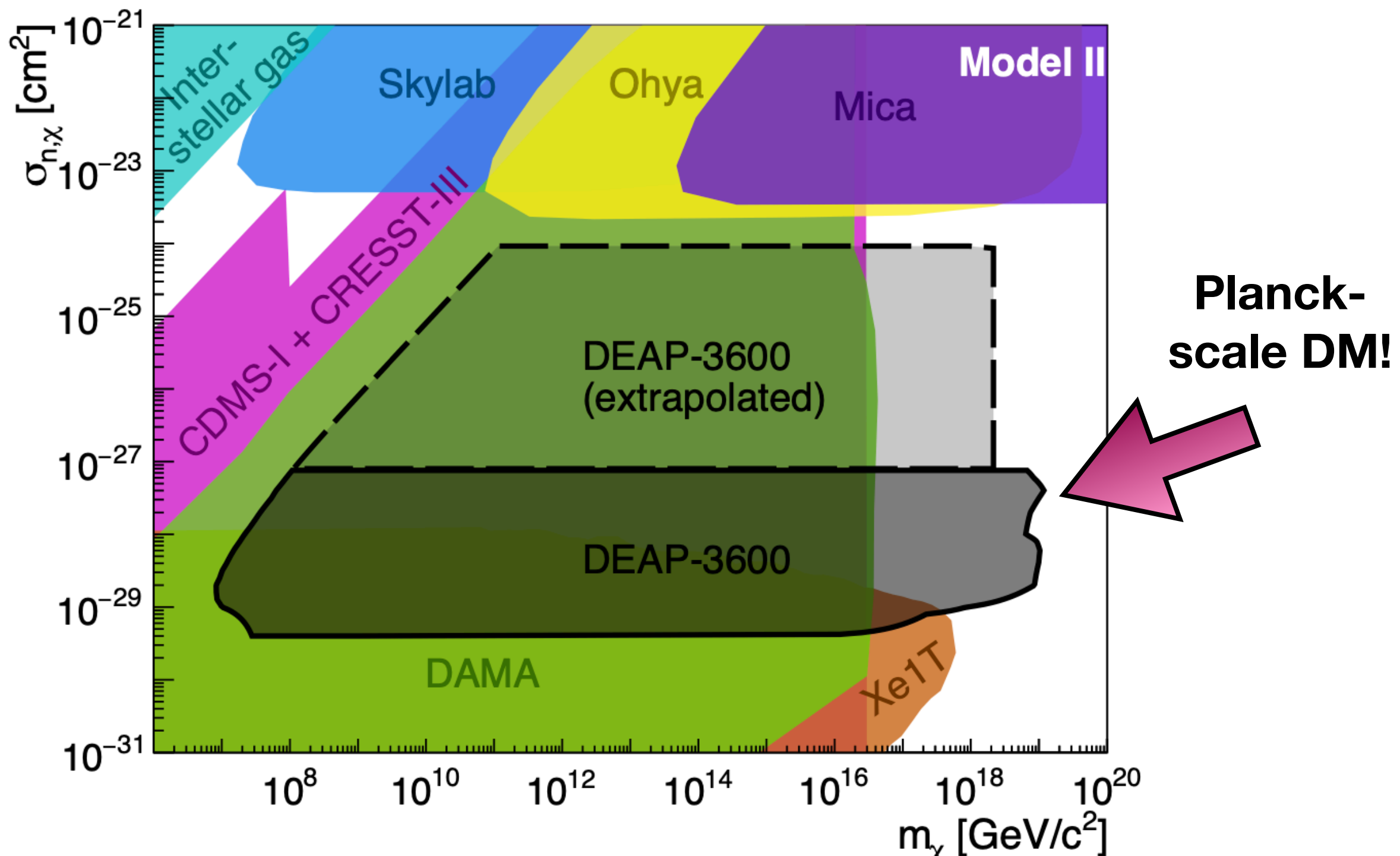
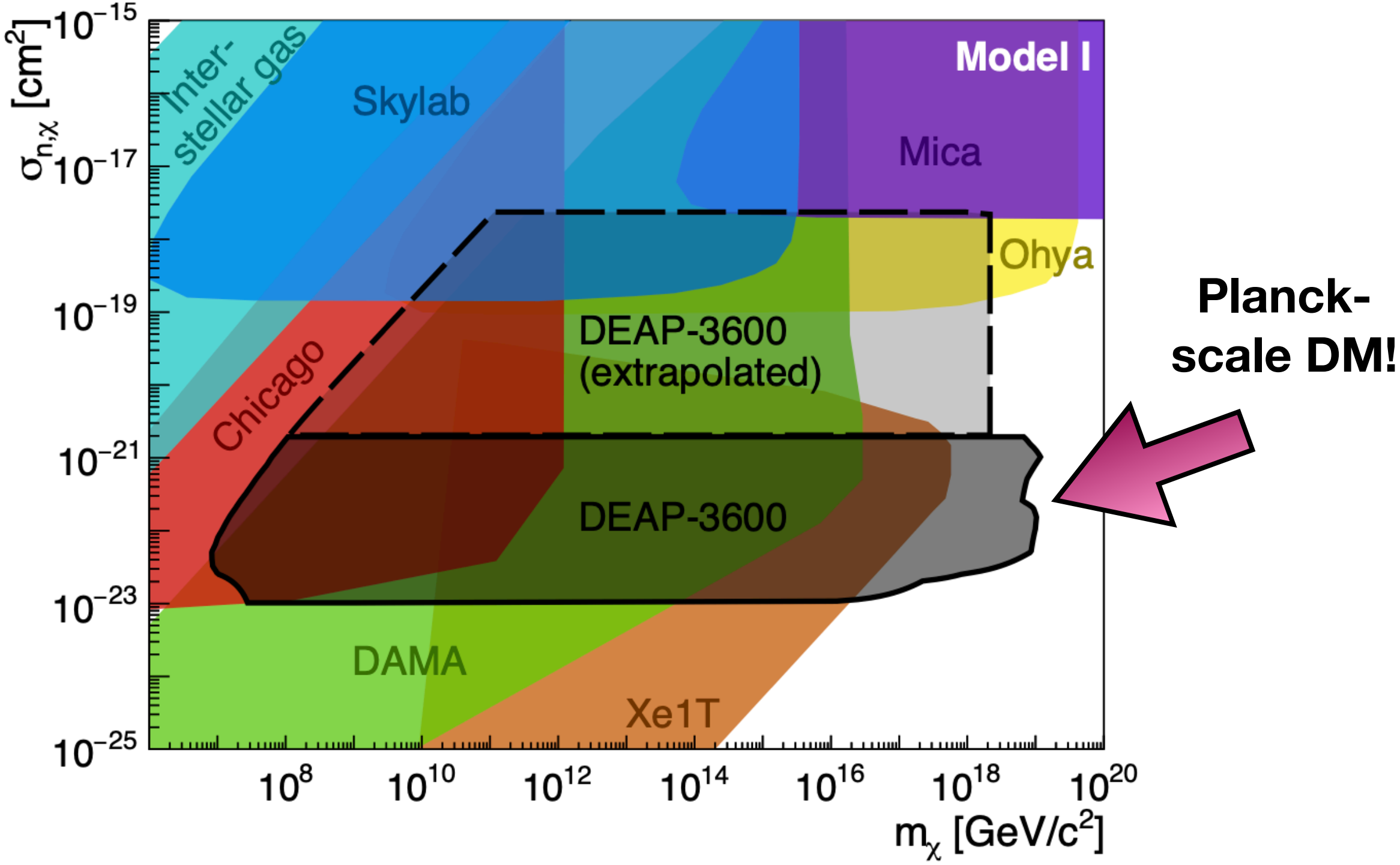


Planck-Scale DM: Analysis and Search Results

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



Next Generation Experiments

Much alike standard WIMP searches, better sensitivity to Planck-scale DM can be achieved with larger detectors, operating for a longer exposure

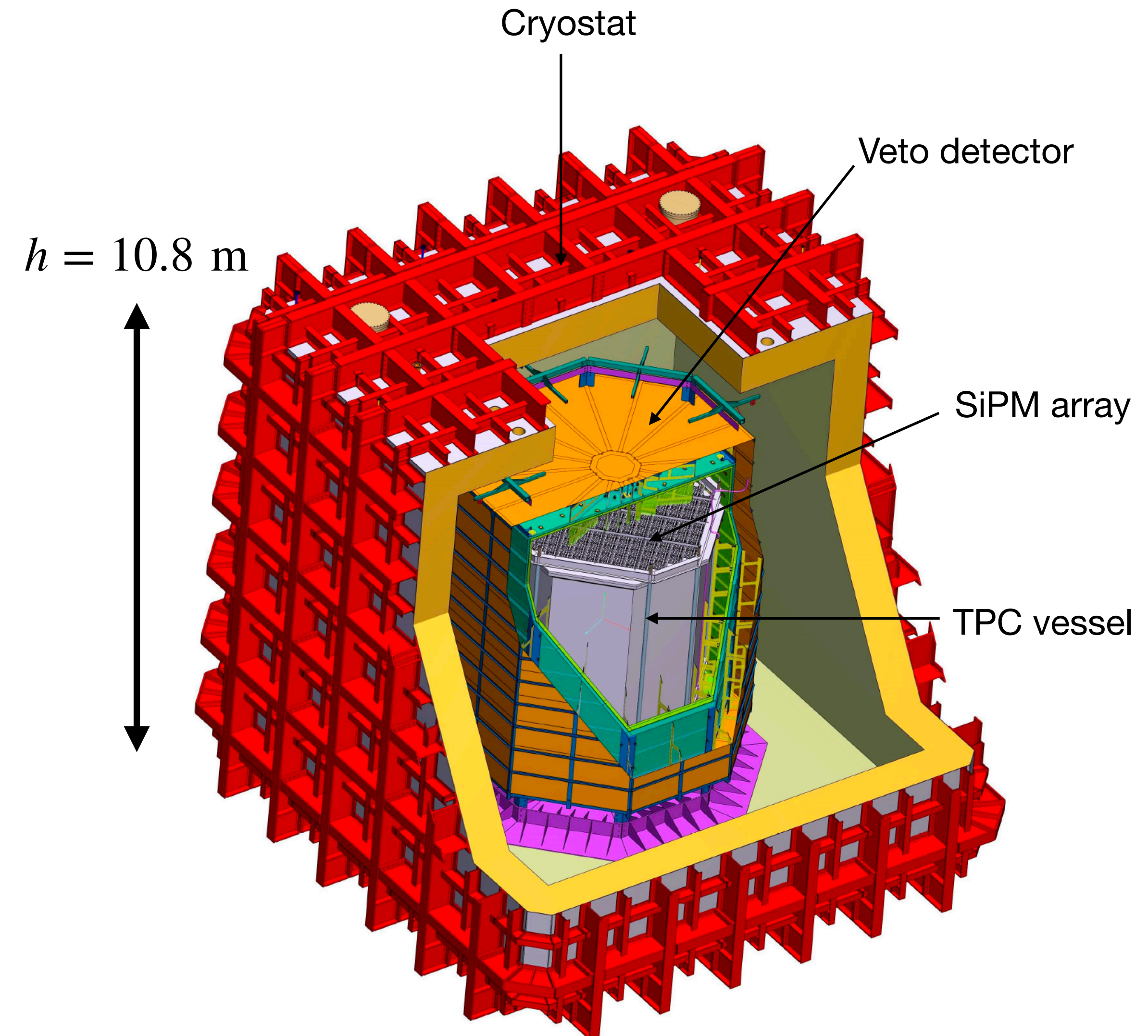
Next generation experiments, such as the DarkSide-20k experiment, may be well suited to set more stringent limits on Planck-scale DM

Dual-phase liquid argon time projection chamber (LAr TPC) containing 55 tonnes (20 t fiducial) of low-radioactivity underground argon (UAr)

- ➔ Particle interactions in Ar generate scintillation light via excitation and ionisation of argon atoms
- ➔ Scintillation light collected by Silicon Photomultiplier (SiPM) devices arranged on top/bottom of TPC vessel
- ➔ Scintillation “S1” signals used to discriminate between nuclear and electronic recoils using pulse-shape discrimination (PSD)
- ➔ Uniform electric field applied across TPC so that ionised electrons that do not recombine are drifted to top of TPC vessel towards gas pocket; in GAr phase extracted electrons produce secondary scintillation photons through electroluminescence generating a secondary “S2” signal
- ➔ S2 signal measured by the SiPM arrays Δt after S1 signal

TPC surrounded by veto detector

- ➔ Gadolinium-loaded plastic sheet for neutron captures



Next Generation Experiments

DarkSide-20k intends to use Silicon Photomultiplier (SiPM) technology instead of standard PMTs

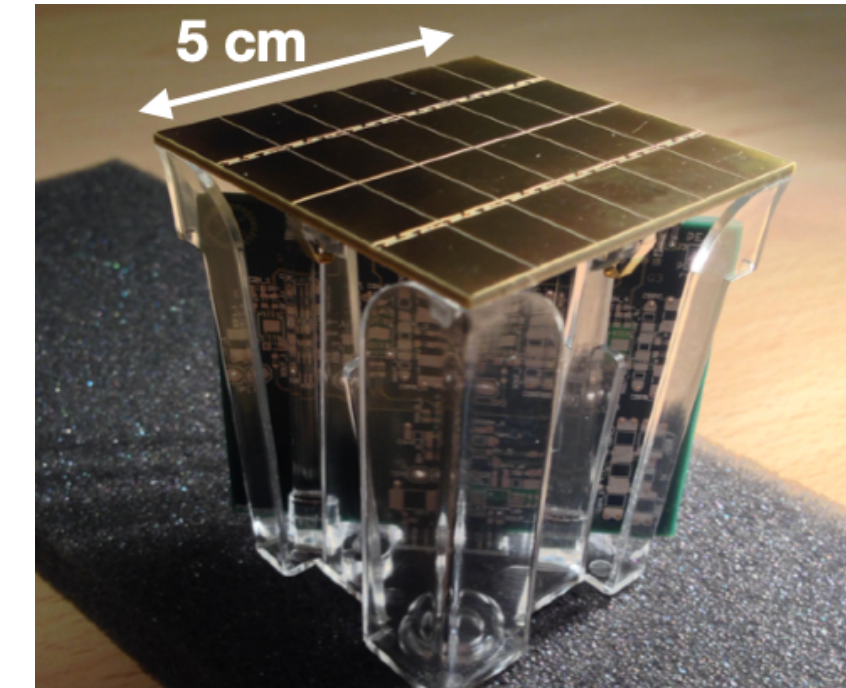
SiPMs are extremely sensitive, single-photon solid-state photodetectors, with potentially a lower radioactivity, a better single photon resolution and higher photon detection efficiency ($> 40\%$) compared to PMTs

Photodetector modules (PDMs) each comprised of 24 SiPMs

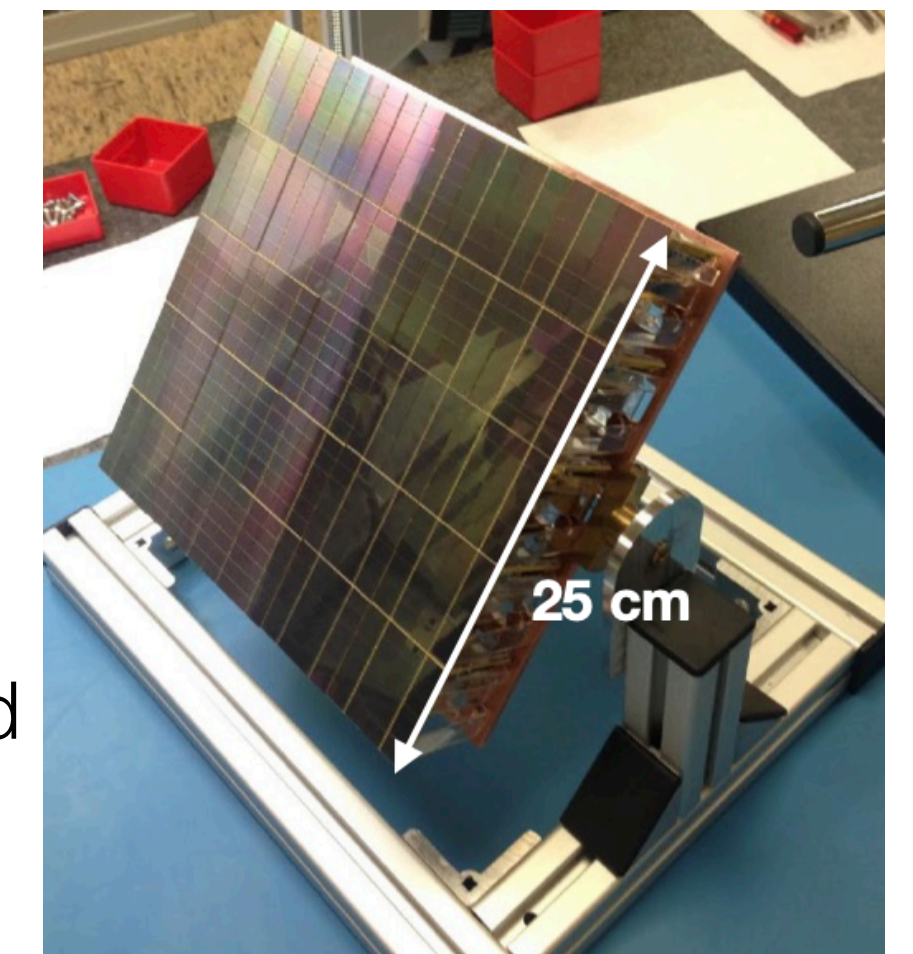
Each motherboard comprised of 25 PDMs

Extremely low dark count rate (DCR) of < 200 cps/PDM and high signal-to-noise ratio (~ 24 after filtering)

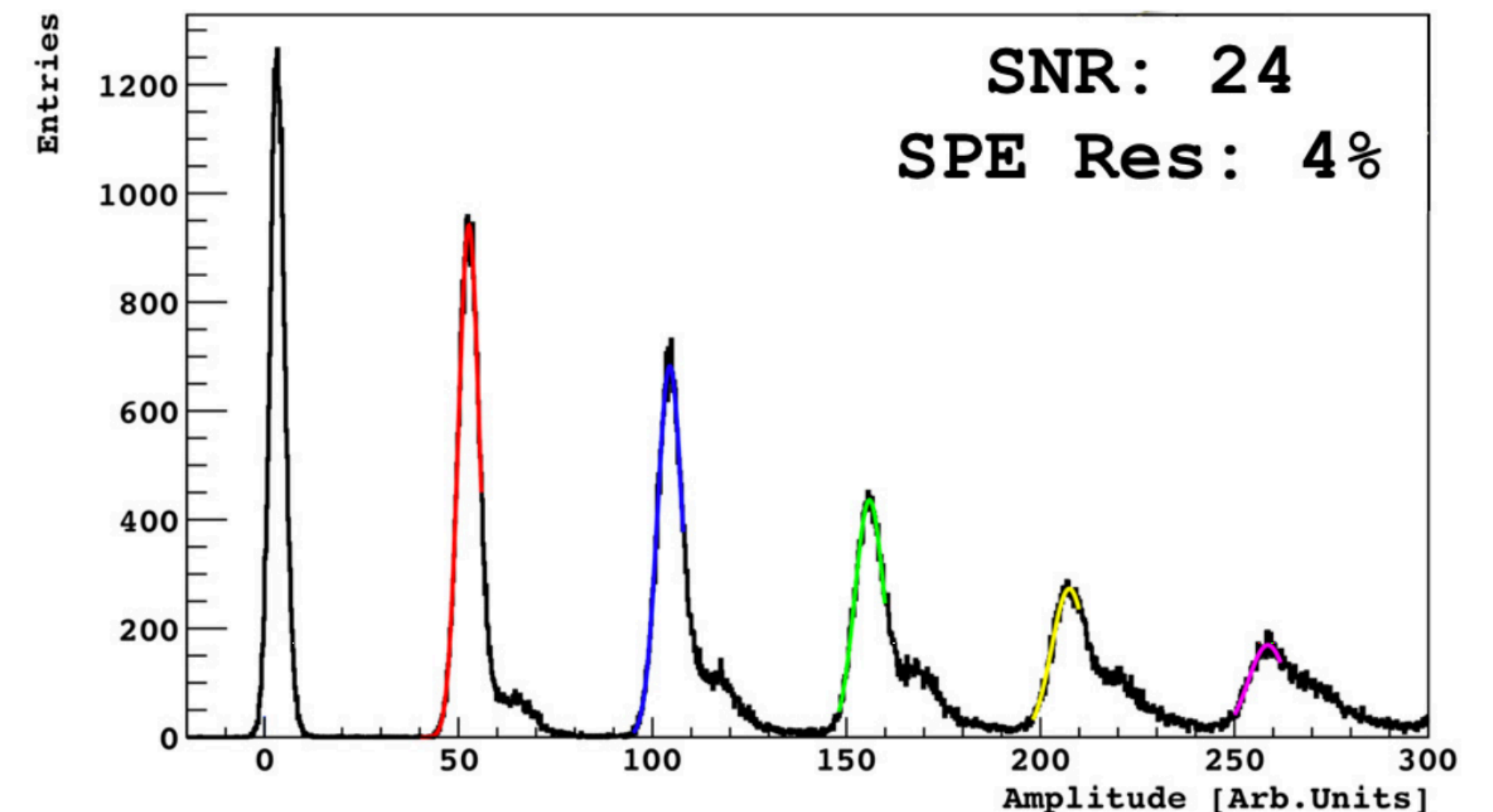
Full characterisation of the PDM technology for DarkSide-20k is currently ongoing!



24 SiPMs/PDM



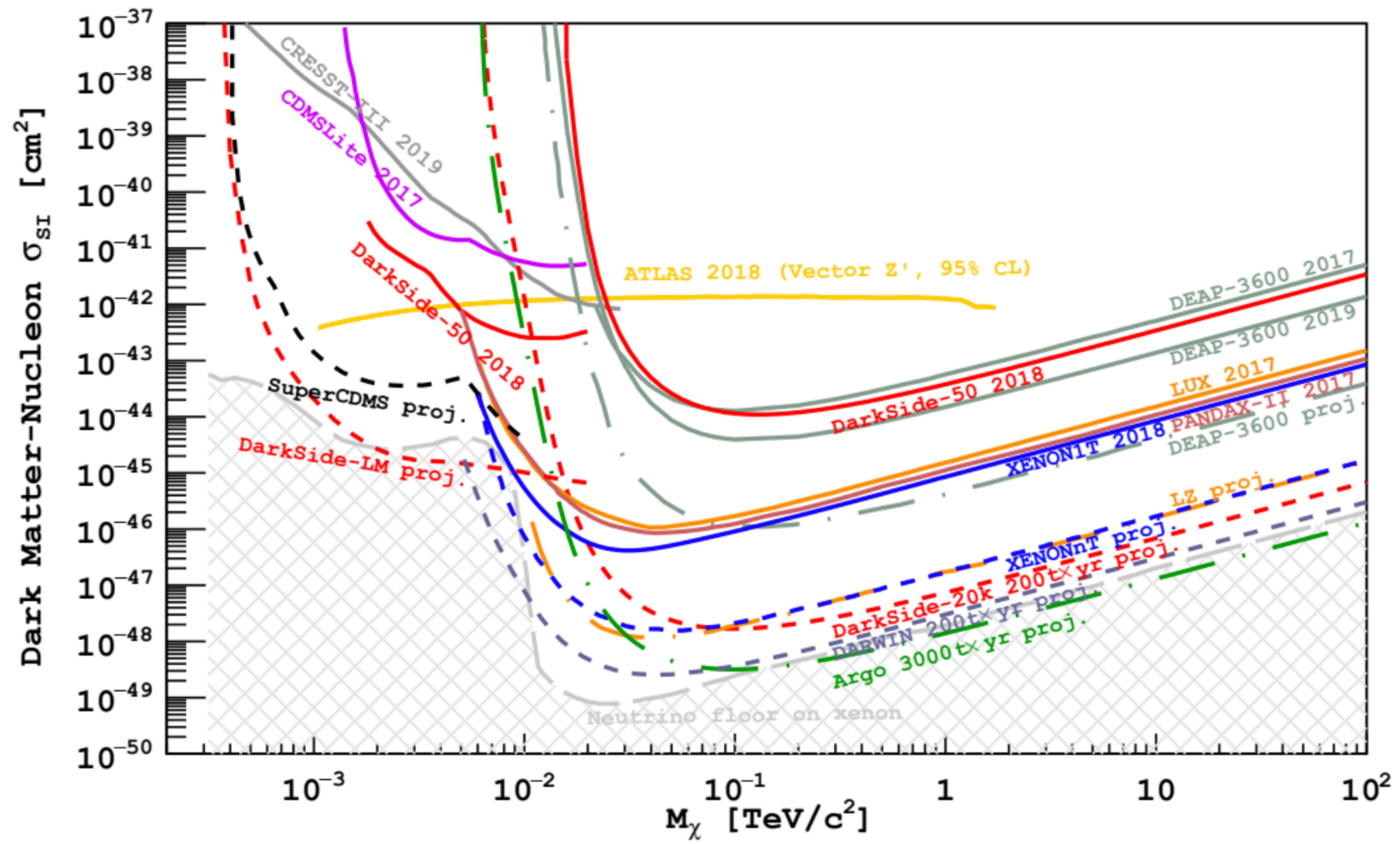
25 PDMs/
motherboard



Typical single channel energy response (superseded version of the FBK SiPM matrix): <http://www-kam2.icrr.u-tokyo.ac.jp/indico/event/3/session/40/contribution/60/material/slides/0.pdf>

Next Generation Experiments

Physics reach of DarkSide-20k:



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/c²

➡ 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 $8.3 \times 10^6 - 1.2 \times 10^{19}$ GeV/c², and cross-sections for scattering on argon nuclei between $1.0 \times 10^{-23} - 2.4 \times 10^{-18}$ cm²

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