Status and prospects of the DEAP-3600 experiment

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on behalf of the DEAP collaboration

TeVPA
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Outline

The DEAP-3600 experiment

Recovering WIMP sensitivity

More physics with DEAP-3600

The DEAP-3600 detector

First DM detector with a target > 1 tonne

Most stringent limits for standard WIMP SI interaction with a:

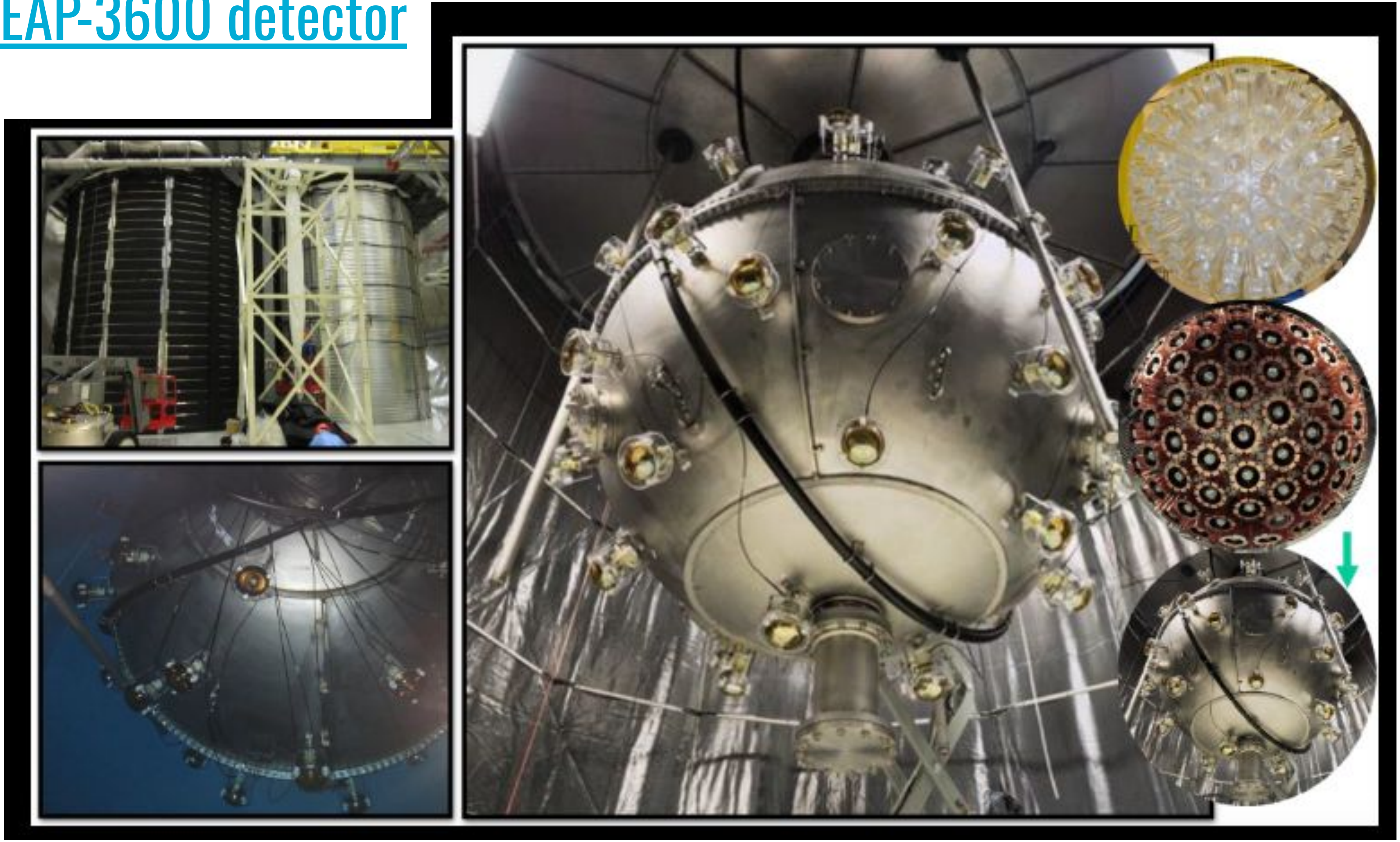
non-Xe target

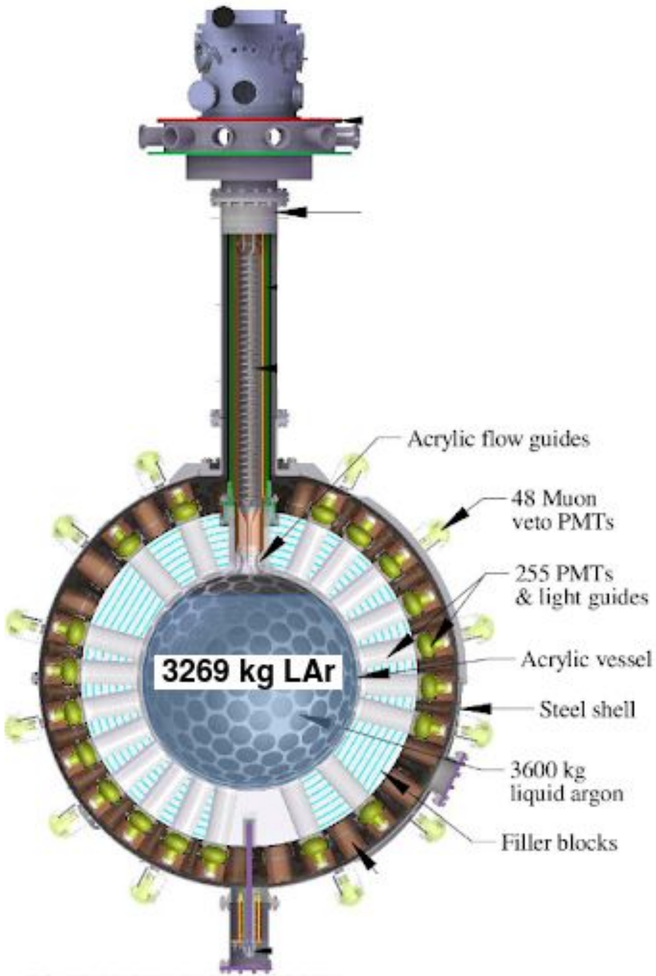
without a TPC

in single phase

Potential path for next generation

The DEAP-3600 detector



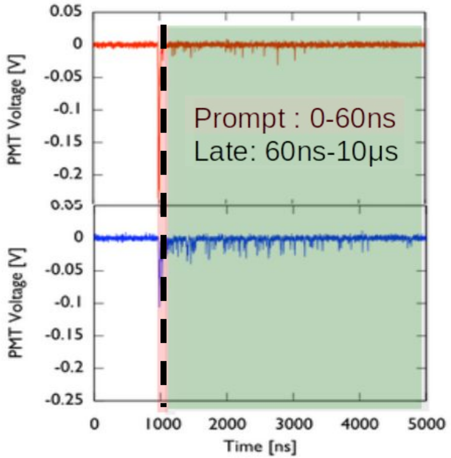


- 3.3 tonne LAr target in ultraclean acrylic vessel (R = 85 cm).
- In-situ vacuum evaporated TPB on inner 10 m^2 surface.
- Bonded 50-cm-long light guides: distance to PMTs
- 255 PMTs: Hamamatsu R5912 HQE. 8" - 32 % QE - 75% coverage.
- Immersed in water tank with PMTs to veto muons (Cherenkov light).
- Located 2 km underground @ SNOLAB: 6000 m.w.e -> 0.03 muon/m2/day

The DEAP-3600 detector: Ar scintillation

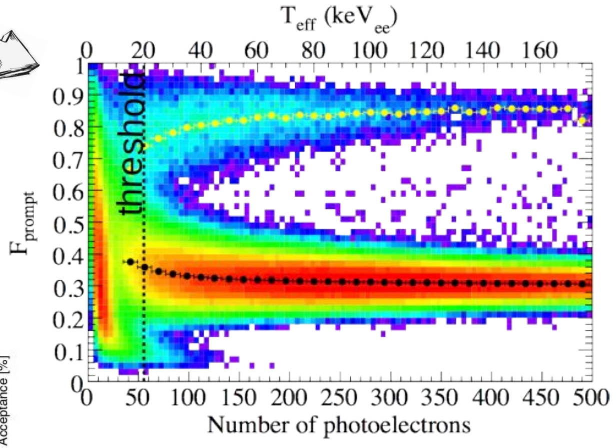
- Singlet state decays fast (8 ns) & dominantly populated by nuclear recoils
- Triplet state decays slowly (1.4 μs) & dominantly populated by electronic recoils

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



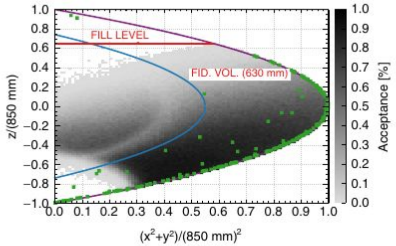
- **Pulse shape allows us to discriminate** against gamma and beta backgrounds.

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



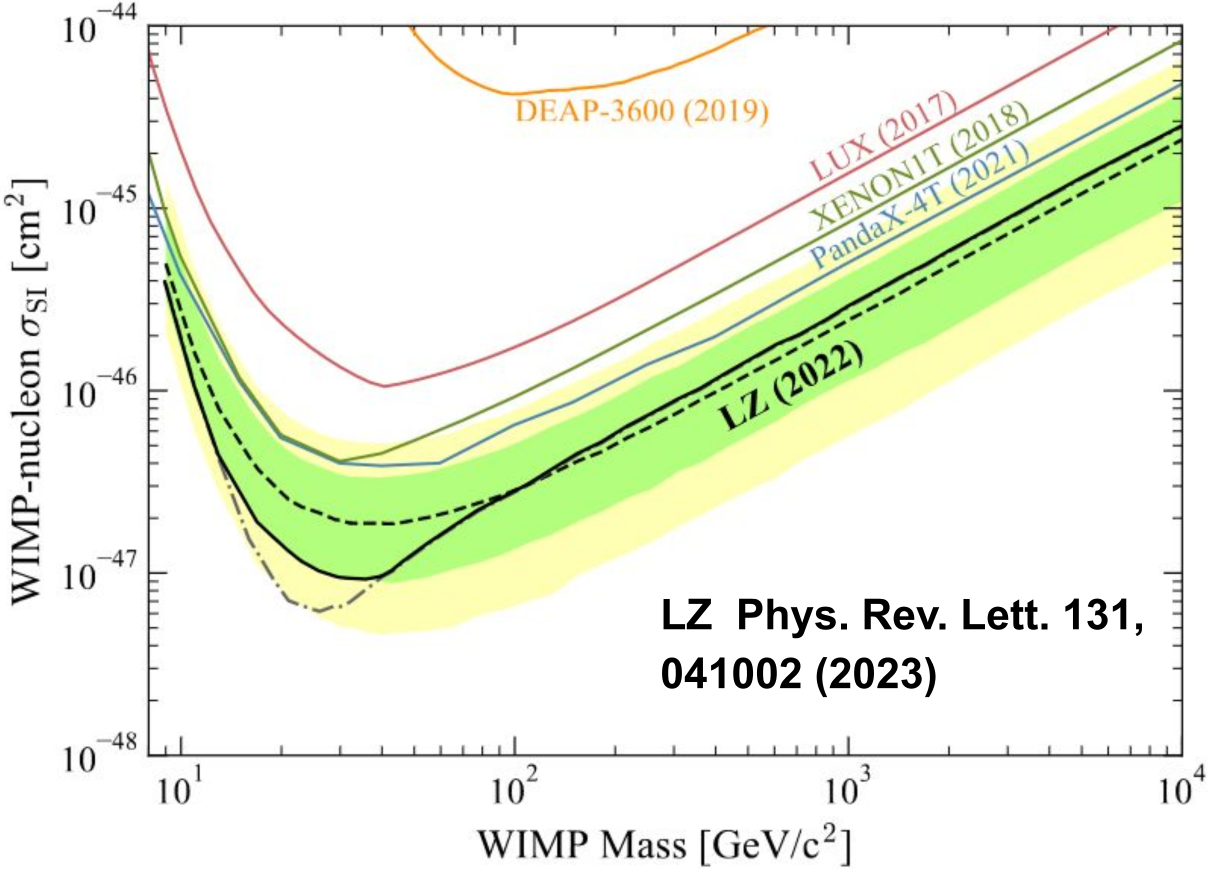
- Position reconstruction and fiducialization allow us to reduce surface and external backgrounds.

  JINST 20 P07012 (2025)



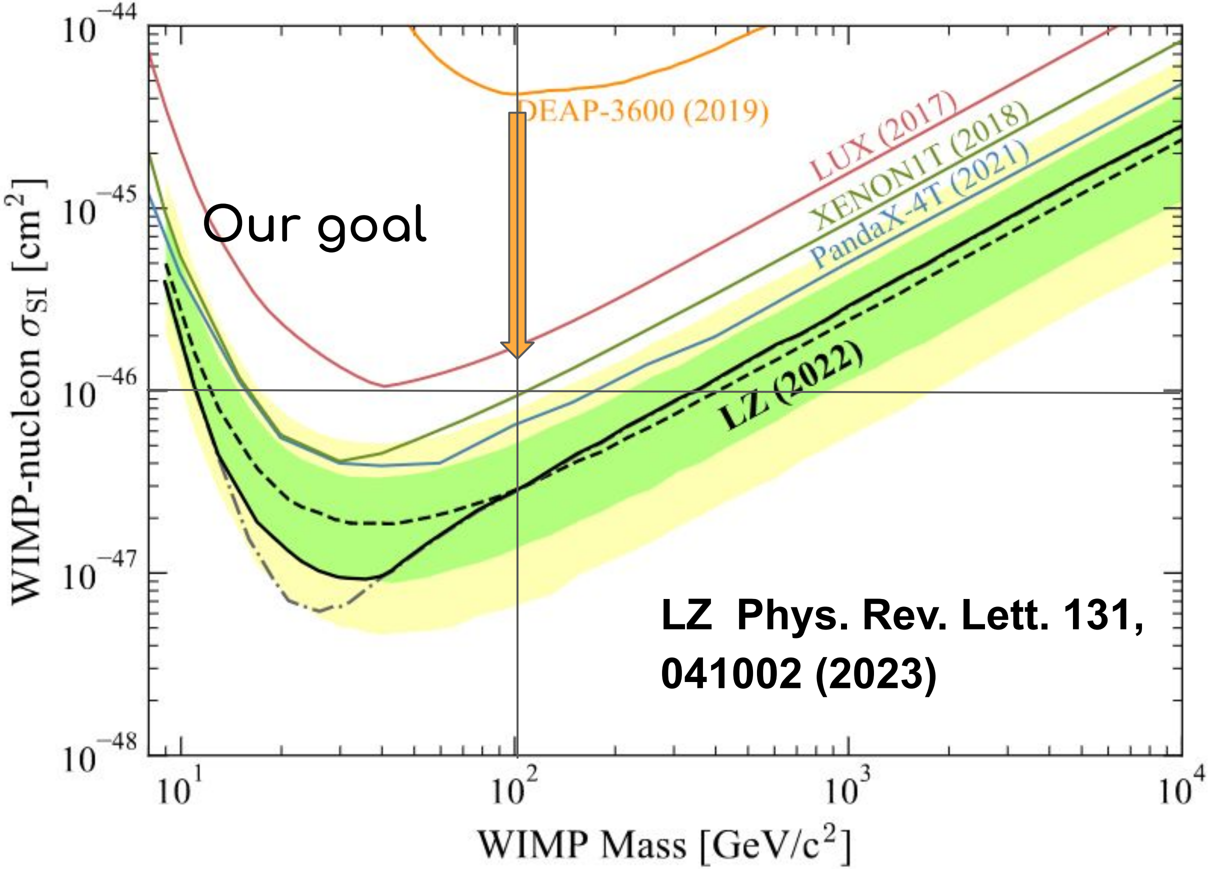
- No electric field

The DEAP-3600 detector



LZ Phys. Rev. Lett. 131, 041002 (2023)

The DEAP-3600 detector



The DEAP-3600 detector: goals

1. Tackling limiting factors to WIMP sensitivity (hardware upgrades)

2. **Finalize refined DM analyses** (better detector model + Profile likelihood + machine learning) **and unblind**

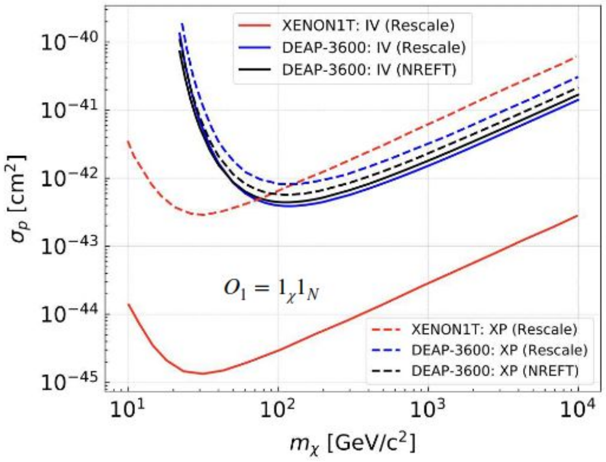
3. Learning for DarkSide-20k, ARGO and LAr detectors

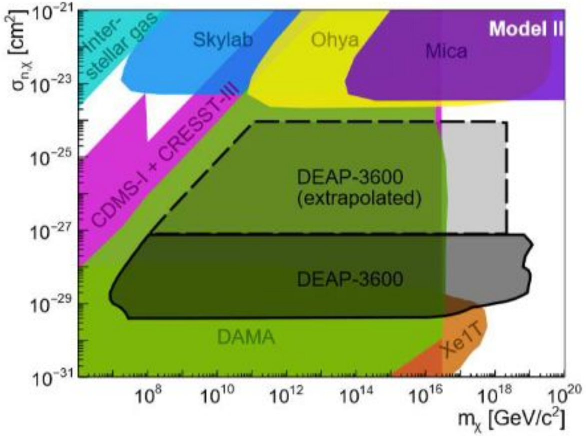
4. Exploit science cases: exotic DM candidates, solar neutrino, axions...

The DEAP-3600 detector: exotic DM searches

Particularly suited for some exotic DM scenarios:

- Best limits for xenon-phobic DM Phys. Rev. D 102, 082001 (2020).
- Prospection of unpopulated regions of the parameter space at Planck-scale masses (ultra heavy) Phys. Rev. D, 100, 072009 (2019).
- Ongoing analysis for inelastic boosted dark matter.

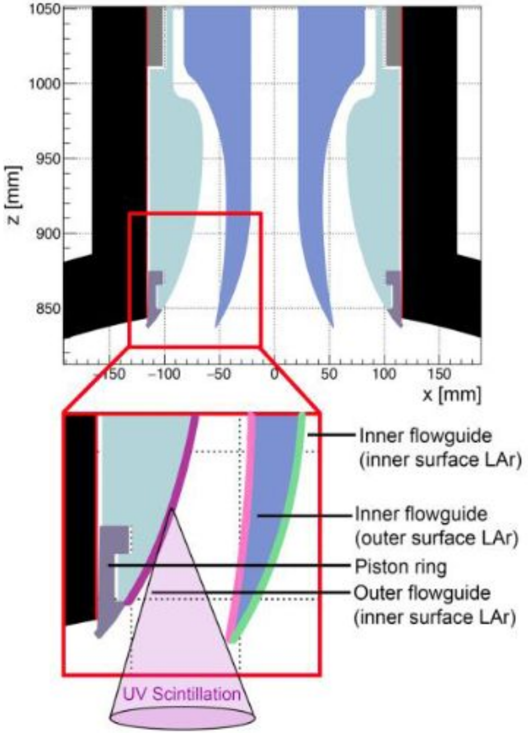


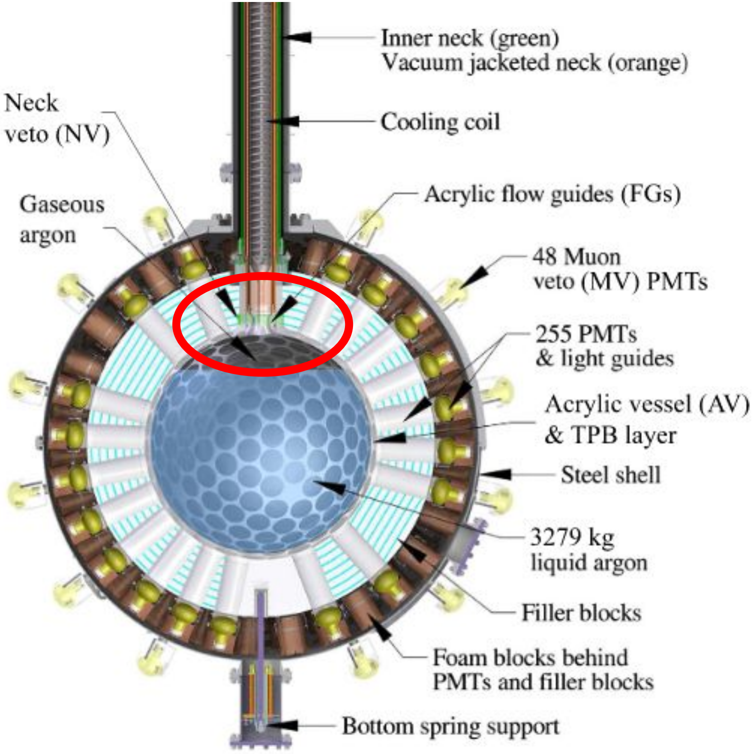


Recovering WIMP sensitivity

Bkg 1: surface

^{210}Po on the neck (above target)



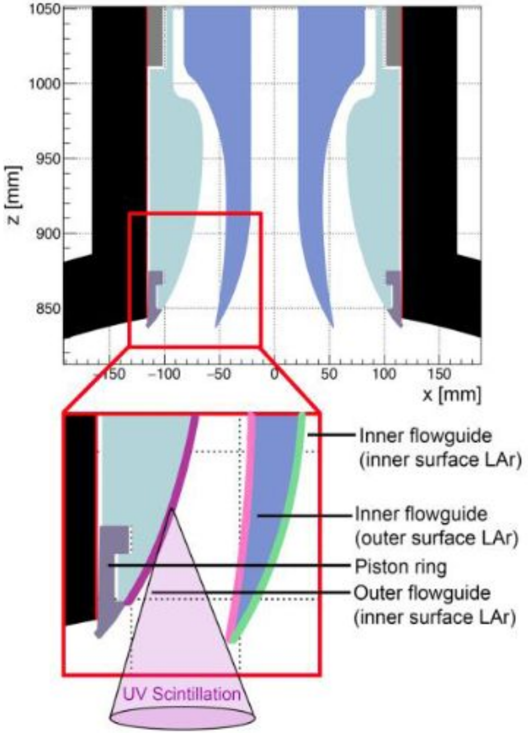


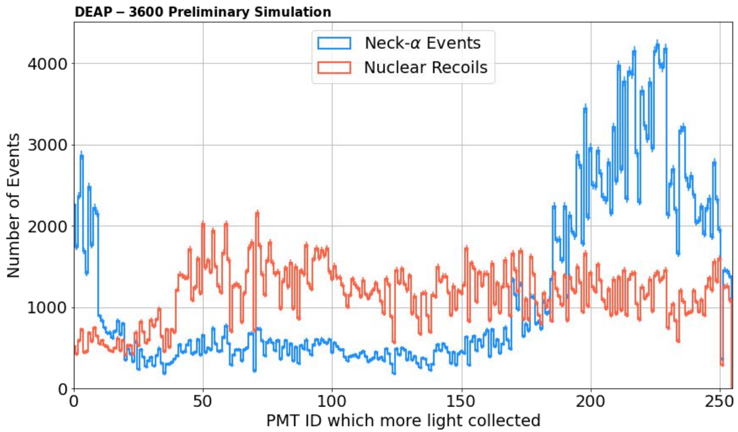
PRD, 100 (2019), p 022004

Recovering WIMP sensitivity

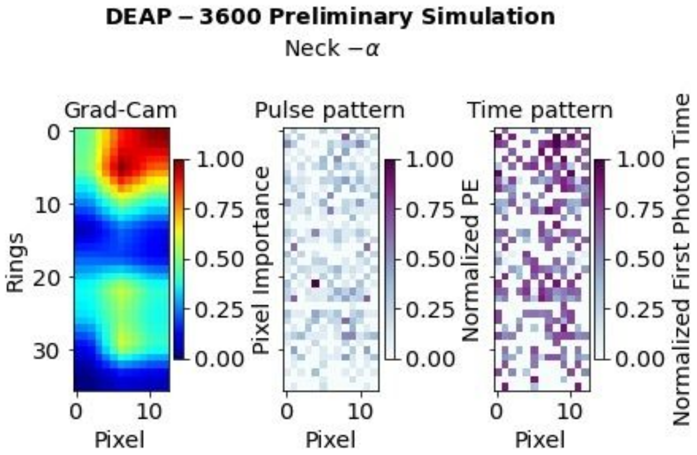
Bkg 1: surface

^{210}Po on the neck (above target)





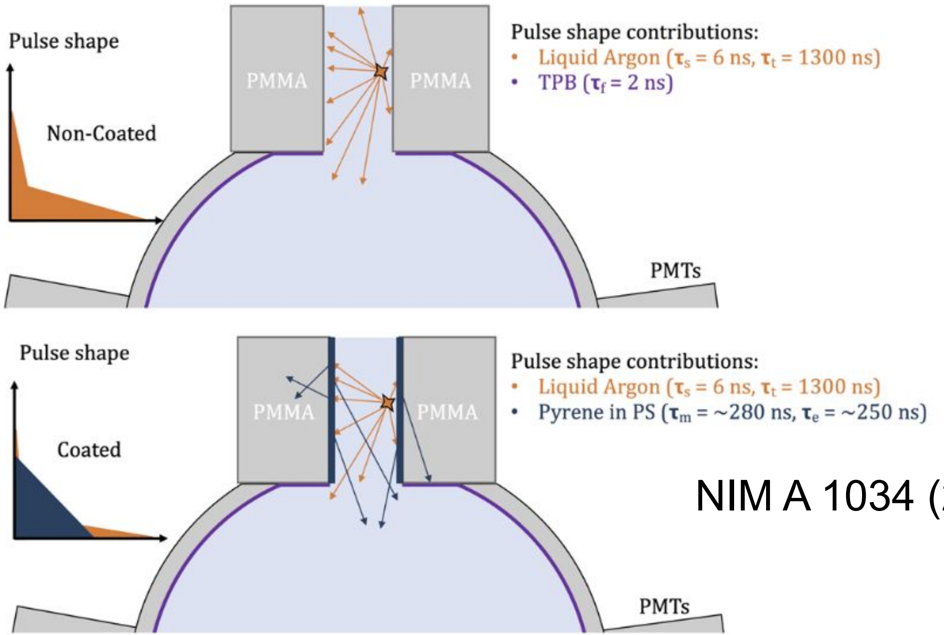
CNN trained against this bkg gives very good results!



Recovering WIMP sensitivity

Fix 1: WLS modifying the time profile of alpha scintillation

- Neck events will have a different time profile: distinct PSD pattern.
- More light collected.
- Out of the ROI.

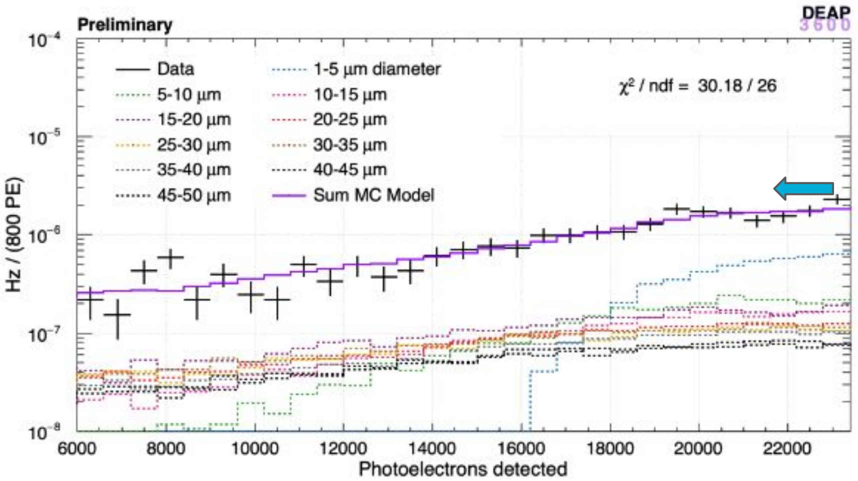


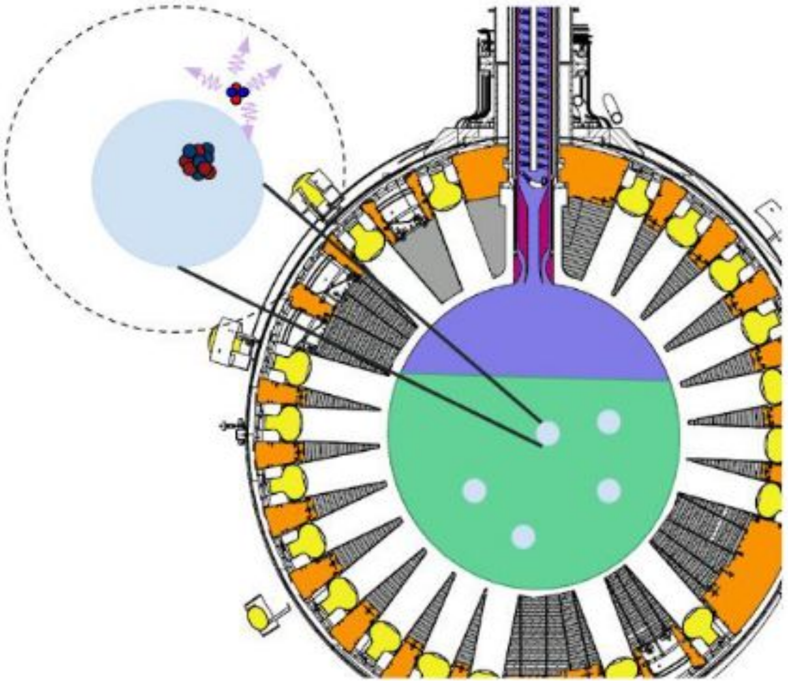
NIM A 1034 (2022) p 166683

Recovering WIMP sensitivity

Bkg 2: degraded alphas from dust particulates in suspension

DEAP operated with no recirculation or filtration



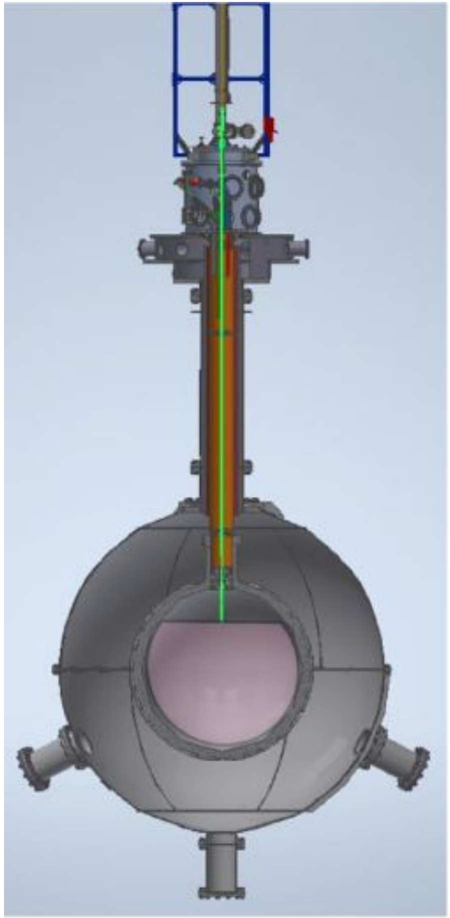


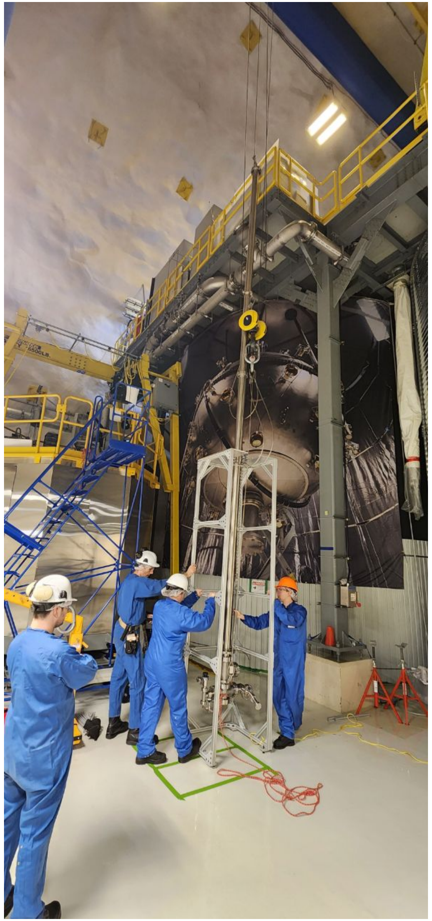
E lost in the dust itself does not produce photons.

Recovering WIMP sensitivity

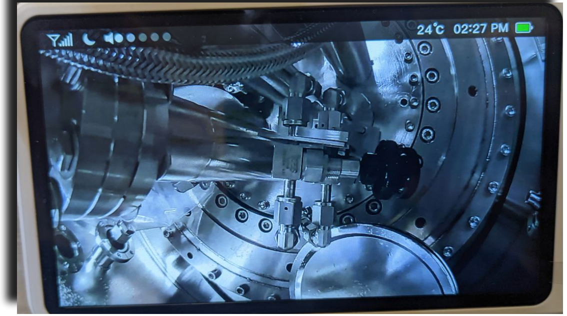
Fix 2: New recirculation+filtration system to remove dust from target

External cooling also prevents condensation in the neck!





Recovering WIMP sensitivity: hardware upgrades



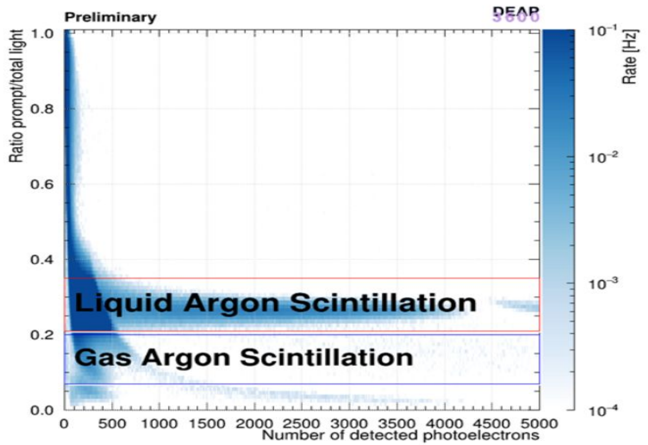
Current state and WIMP search prospects

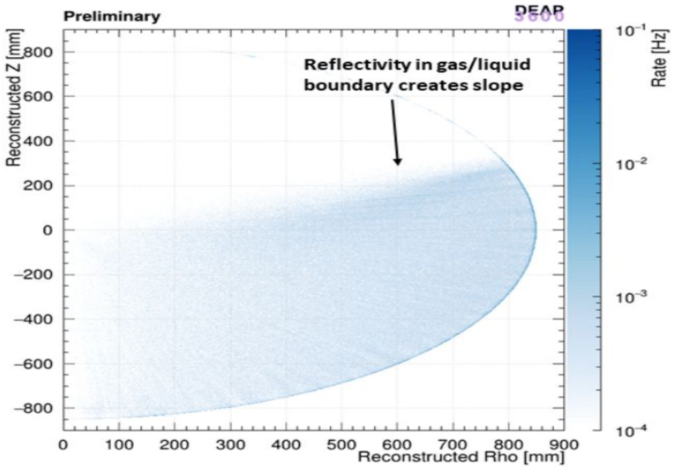
Neck upgrade finished

Detector cool down and Ar fill finalized on July

Data taking for ~2 more years (until DarkSide-20k is running)

Finalize refined analysis and unblind

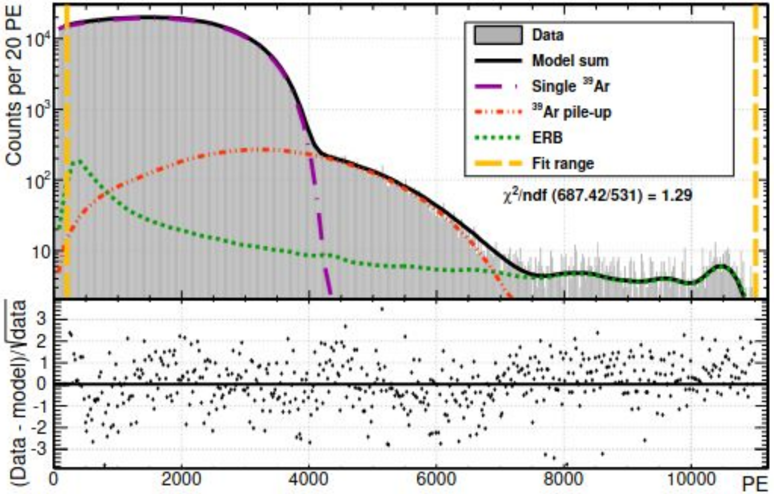


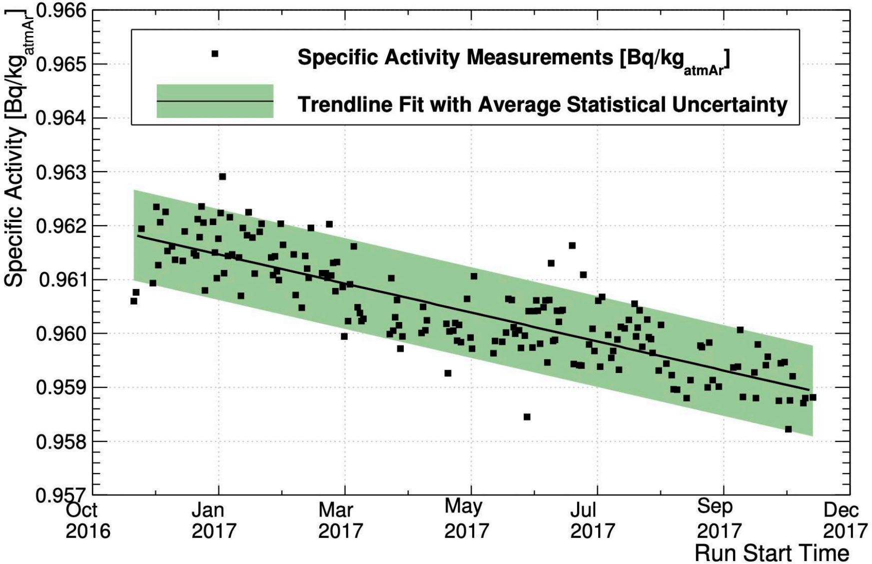


More physics with DEAP

39Ar specific activity in atmospheric Ar

Eur. Phys. J. C 83, 642 (2023)





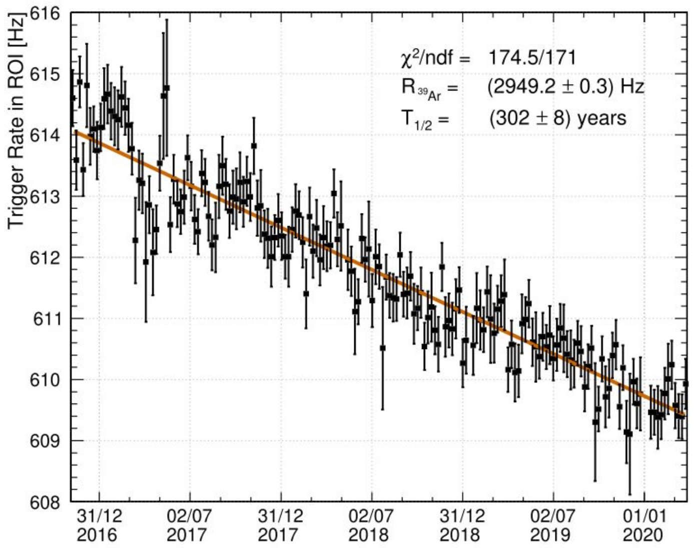
Measurement	Specific activity [Bq/kg$_{atmAr}$]
WARP [13]	1.01 ± 0.08
ArDM [14]	0.95 ± 0.05
DEAP-3600 (this work)	0.964 ± 0.024

Precision measurement of ^{39}Ar activity in atmospheric Ar:

$0.964 \pm 0.001_{stat} \pm 0.024_{sys}$ Bq/kg

39Ar lifetime

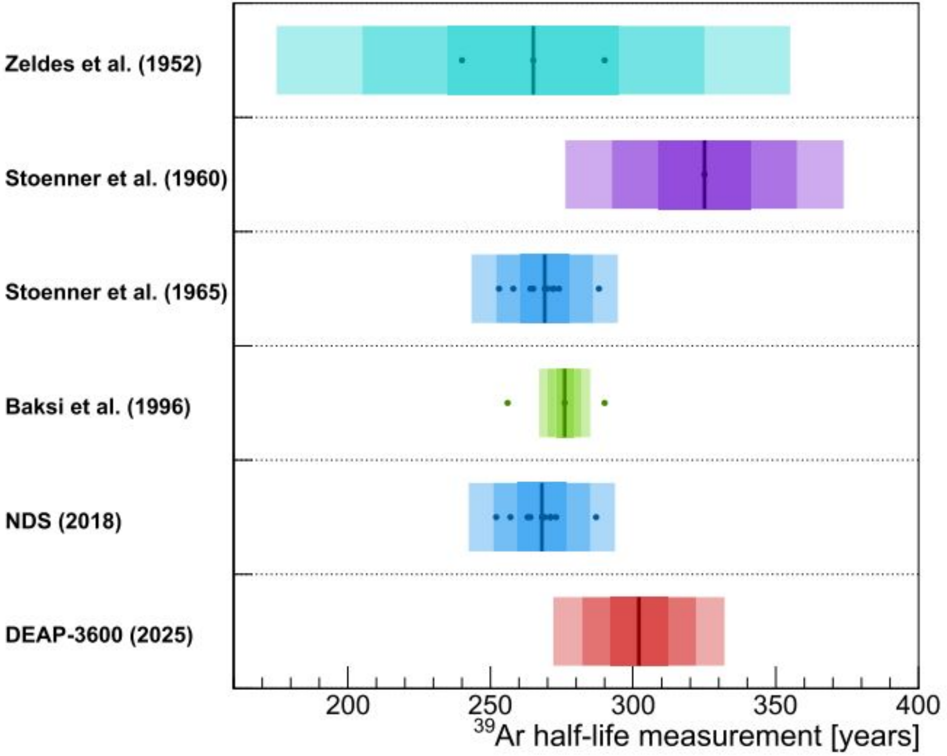
Eur.Phys.J.C 85 (2025) 7, 728



1st direct measurement of the ^{39}Ar half-life:

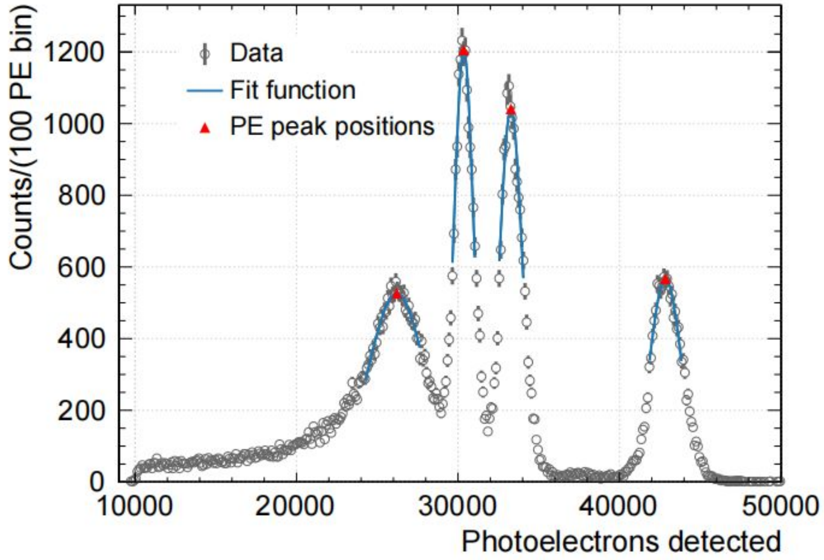
$T_{1/2} = (302 \pm 8_{stat} \pm 6_{sys})$ years

2.5 σ tension with NDS



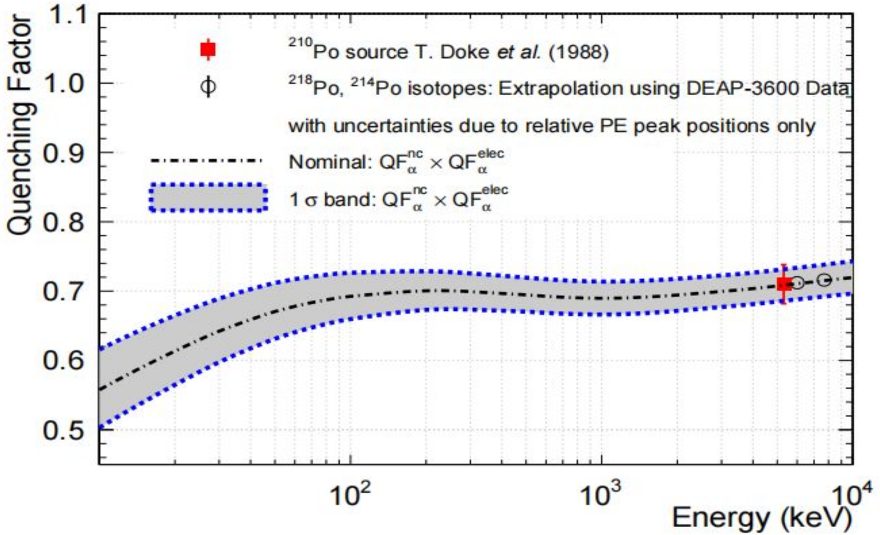
Alpha quenching in LAr

Eur.Phys.J.C 85 (2025) 1, 87



Three data points for the alpha Quenching Factor (QF) in the range (5.489 - 7.686) MeV.

Measurements relative to 210Po QF from Doke et al = 0.710 ± 0.028 (@ 5.305MeV)

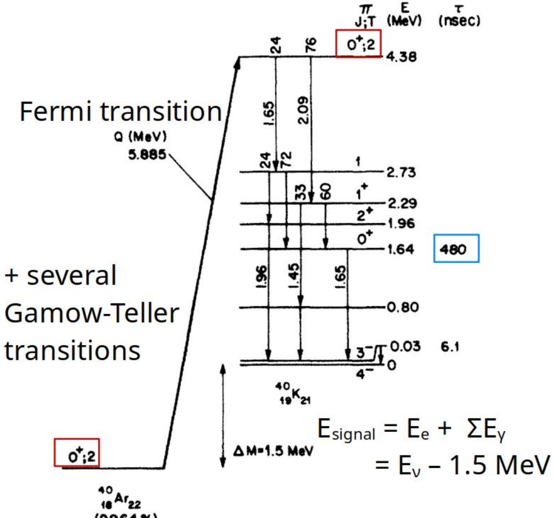


Extrapolation of the QF values into the low-energy region down to 10 keV

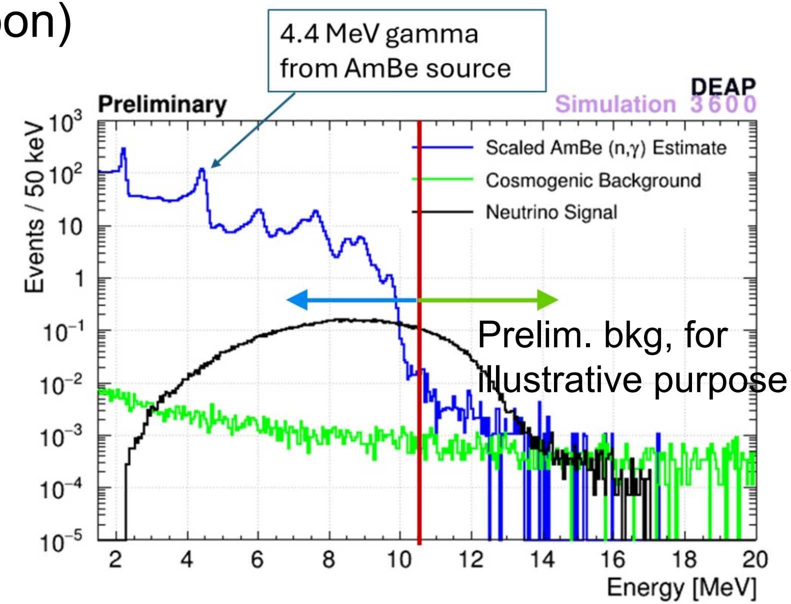
Detecting ^{8}B solar neutrinos (coming soon)

$$^{40}Ar + \nu_e \rightarrow {}^{40}K^* + e^-$$

Enhanced cross section for populating the isobaric analog state (although not directly measured!)



R.S. Raghavan (1986)



Two approaches towards radiogenic bkg estimation

Cosmogenic background from muon activation thoroughly studied

Even more physics in the oven

Solar axion search

Search for Inelastic Boosted DM

Muon flux and instrumentation

Neutrinoless double electron capture in ^{36}Ar

Search for neutrinos in coincidence with gravitational waves

Outlook

DEAP-3600: largest running LAr experiment designed for the WIMP search

World-leading sensitivity to WIMPs in LAr, as well as ν adsorption and ultra-heavy, multi-scattering DM

Hardware upgrades to strongly reduce the alpha-induced backgrounds in the WIMP ROIs

Main backgrounds within the WIMP ROI: dust-alphas and neck-alpha induced events, now included in the PLR WIMP search (coming soon)

Learning for DarkSide-20k, ARGO and other LAr experiments

Third-fill completed, more results on the way!

Moltes gràcies!

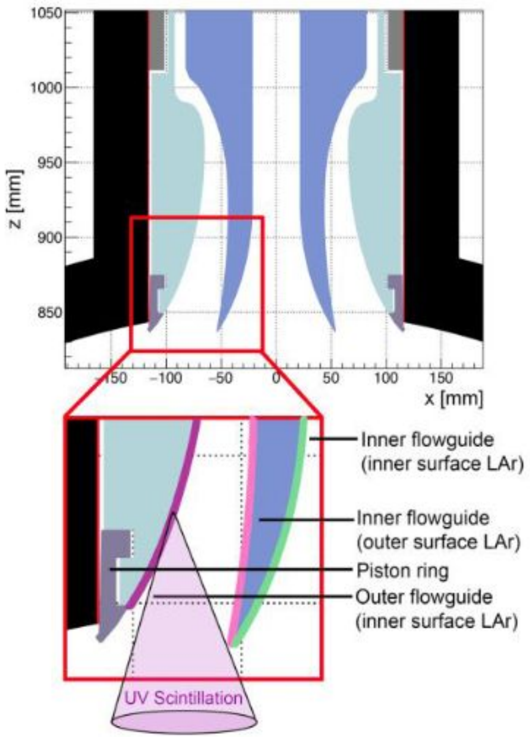
DEAP Collaboration:

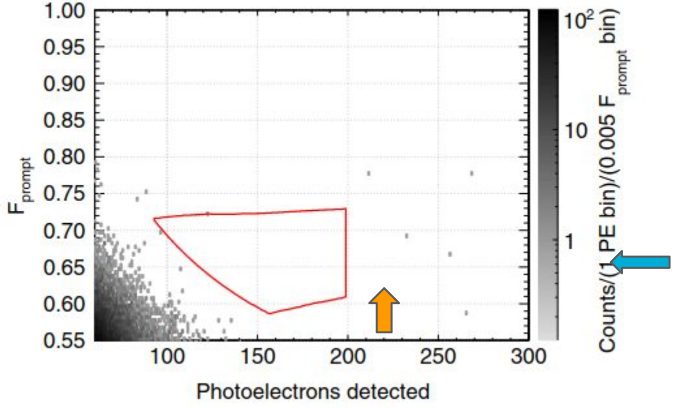
95 researchers in **Canada**, Germany, Italy, Mexico, Poland, Russia, Spain, UK, USA

Backup

Recovering WIMP sensitivity

Bkg 1: surface ^{210}Po on the neck (above target)

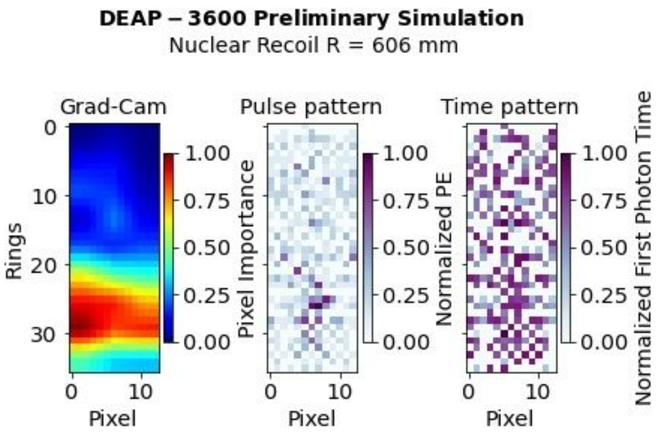


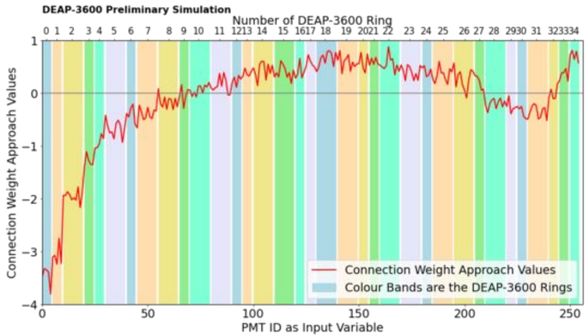


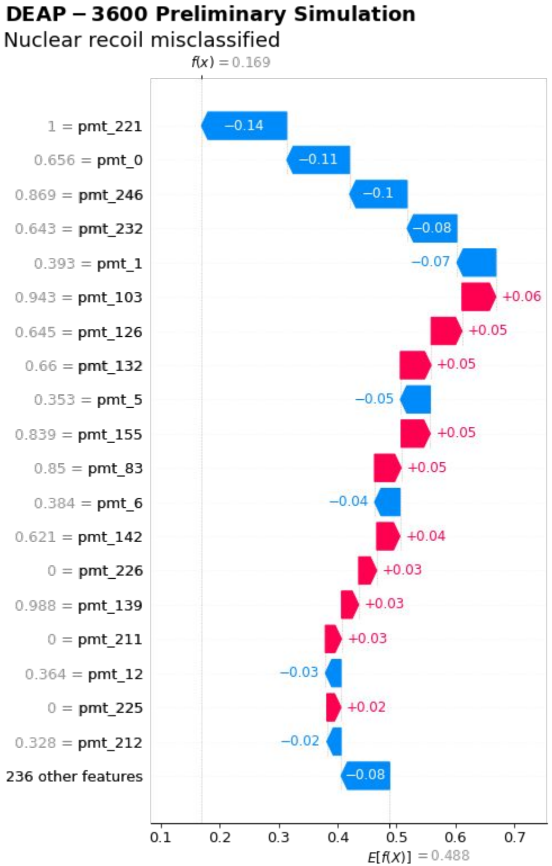
Unfortunate combination of:

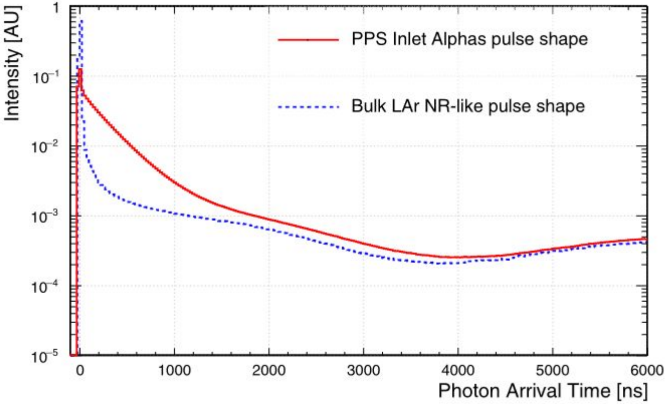
- Surface activity
- Condensation on neck surf.
- Many photons not detected
- Topologic pattern mimicking good NR events

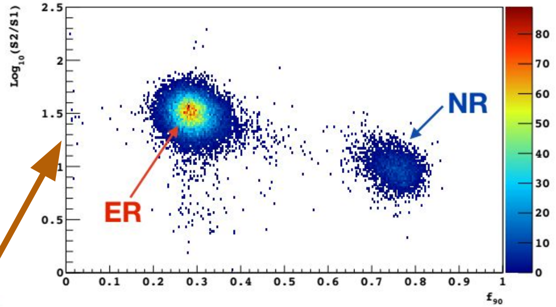
PRD, 100 (2019), p 022004


DEAP – 3600 Preliminary Simulation
Nuclear Recoil R = 606 mm
Grad-Cam
Pulse pattern
Time pattern
Rings
Pixel
Pixel Importance
Normalized PE
Normalized First Photon Time


DEAP-3600 Preliminary Simulation
Number of DEAP-3600 Ring
Connection Weight Approach Values
PMT ID as Input Variable
Connection Weight Approach Values
Colour Bands are the DEAP-3600 Rings


DEAP – 3600 Preliminary Simulation
Nuclear recoil misclassified
f(x) = 0.169
1 = pmt_221
0.656 = pmt_0
0.869 = pmt_246
0.643 = pmt_232
0.393 = pmt_1
0.943 = pmt_103
0.645 = pmt_126
0.66 = pmt_132
0.353 = pmt_5
0.839 = pmt_155
0.85 = pmt_83
0.384 = pmt_6
0.621 = pmt_142
0 = pmt_226
0.988 = pmt_139
0 = pmt_211
0.364 = pmt_12
0 = pmt_225
0.328 = pmt_212
236 other features
−0.14
−0.11
−0.1
−0.08
−0.07
+0.06
+0.05
+0.05
−0.05
+0.05
+0.05
−0.04
+0.04
+0.03
+0.03
+0.03
−0.03
+0.02
−0.02
−0.08
E[f(X)] = 0.488



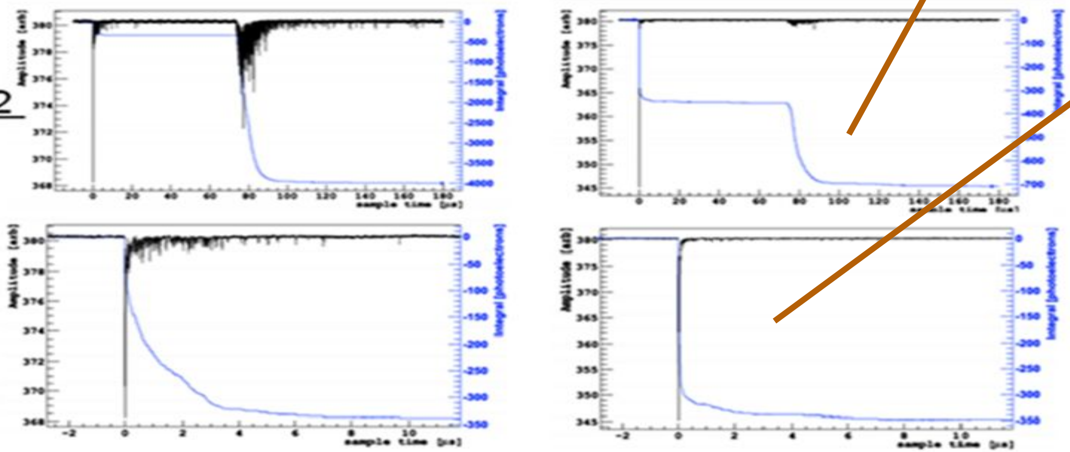


ER-like event

NR-like event

S1/S2

S1 only



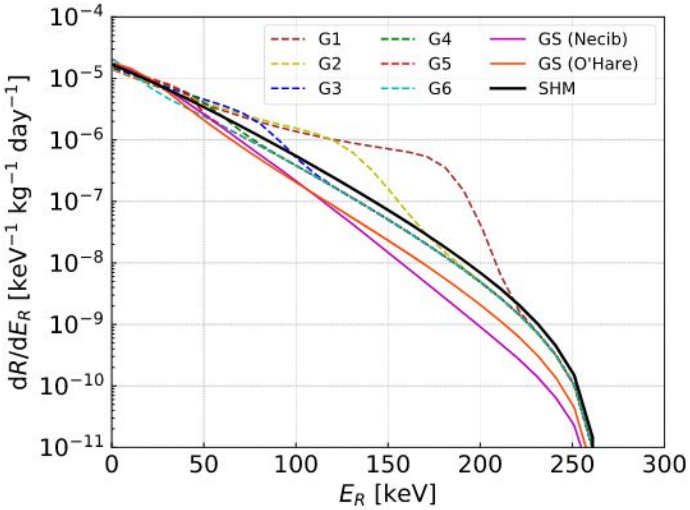
Exploring different scenarios

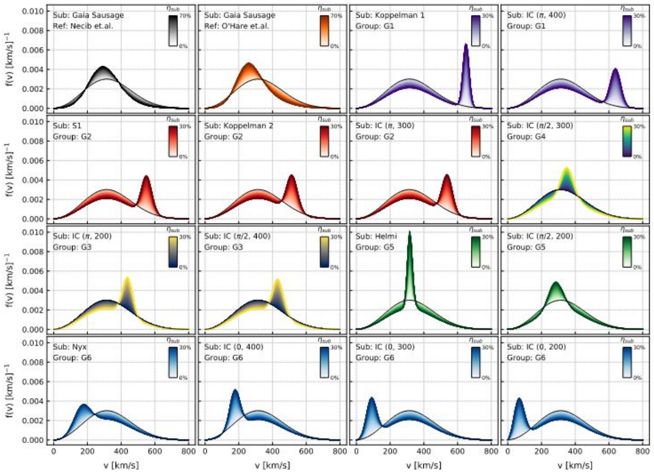
$$\frac{dR}{dE_R} = \frac{\rho_T}{m_T}\frac{\rho_\chi}{m_\chi}\varepsilon(E_R)\int_{v_{\min}}^{\infty} v f_\chi^{\oplus}(\vec{v})\frac{d\sigma}{dE_R}d^3\vec{v}$$

Recoil rate in Ar for

different WIMP distributions

	Substructure	Type	Reference
	Gaia Sausage (Necib *et al.*)	Debris flow	[60]
	Gaia Sausage (O'Hare *et al.*)	Debris flow	[17]
G1	Koppelman 1[a]	Stream	[19]
	IC (π, 400 km/s)	IC	...
G2	S1[a]	Stream	[17]
	Koppelman 2	Stream	[19]
	IC (π, 300 km/s)	IC	...
G3	IC (π, 200 km/s)[a]	IC	...
	IC ($\frac{\pi}{2}$, 400 km/s)	IC	...
G4	IC ($\frac{\pi}{2}$, 300 km/s)[a]	IC	...
G5	Helmi[a]	Stream	[19]
	IC ($\frac{\pi}{2}$, 200 km/s)	IC	...
G6	Nyx[a]	Stream	[18]
	IC (0, 400 km/s)	IC	...
	IC (0, 300 km/s)	IC	...
	IC (0, 200 km/s)	IC	...





Phys. Rev. D 102, 082001 – Published 22 October 2020; Erratum Phys. Rev. D 105, 029901 (2022)'

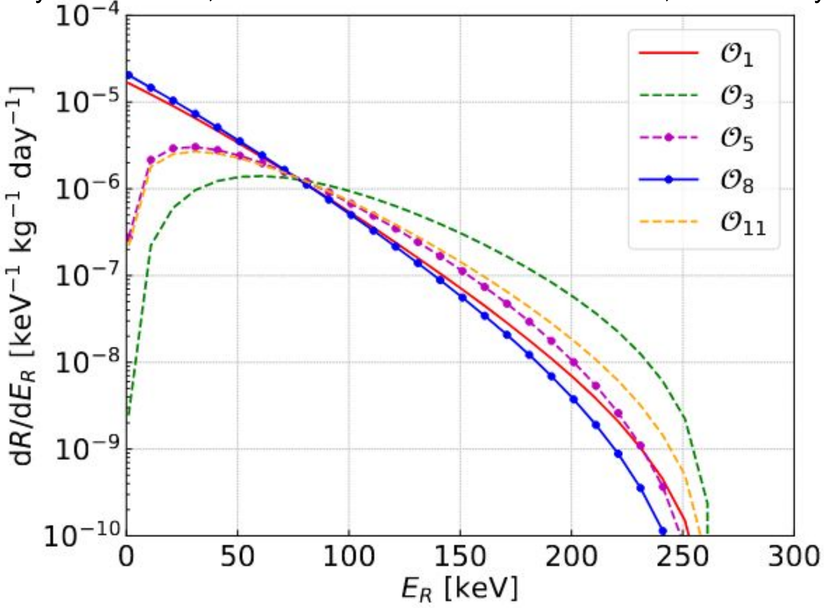
Exploring different scenarios

Recoil rate in Ar for

different non-relativistic effective operators

$$\mathcal{L}_{\text{int}} = \sum_{N=n,p} \sum_i c_i^{(N)} \mathcal{O}_i \chi^+ \chi^- N^+ N^-$$

Phys. Rev. D 102, 082001 – Published 22 October 2020; Erratum Phys. Rev. D 105, 029901 (2022)’



$$\mathcal{O}_1 = 1_\chi 1_N,$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right),$$

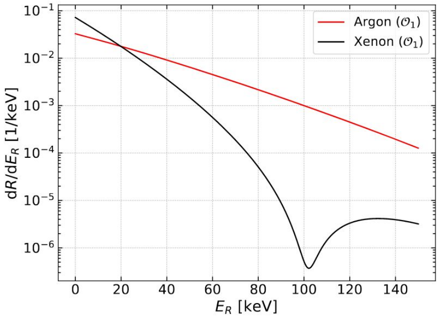
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right),$$

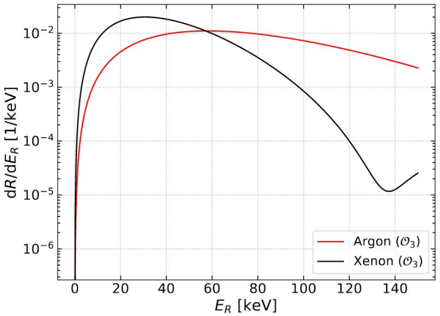
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}_\perp,$$

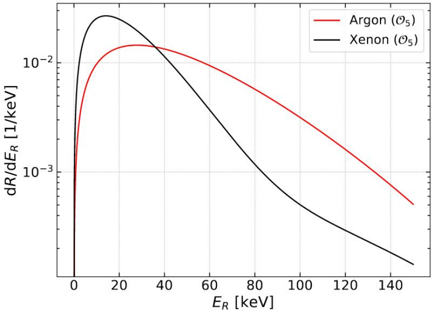
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N},$$

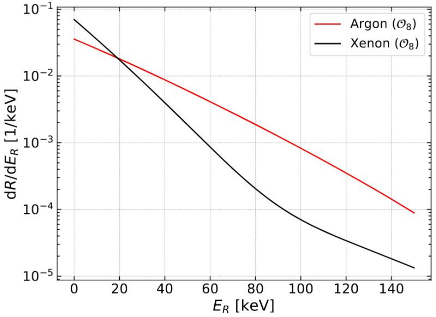
Exploring different scenarios

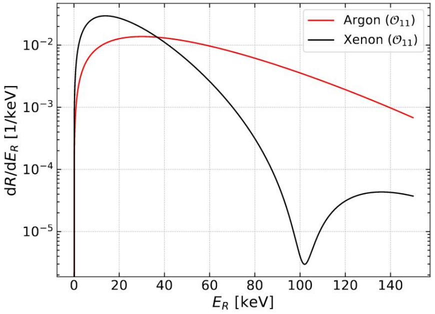
- Mχ = 100 GeV/c^2.
- Isoscalar coupling (cp = cn).
- Arbitrary cross section considered, just for comparison of shapes.









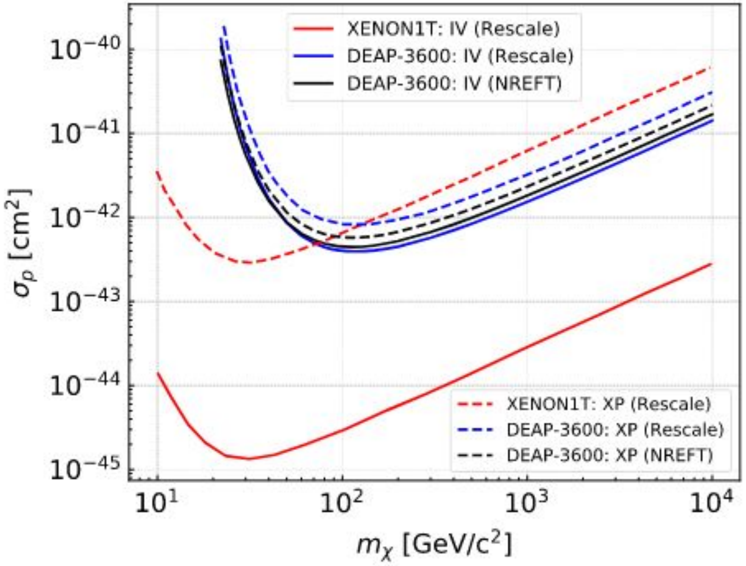


Exploring different scenarios

Recoil rate in Ar for

different c_i^0 / c_i^1 escenarios

Phys. Rev. D 102, 082001 – Published 22 October 2020; Erratum Phys. Rev. D 105, 029901 (2022)'



$$c_i^p \equiv (c_i^0 + c_i^1)/2$$
$$c_i^n \equiv (c_i^0 - c_i^1)/2$$

IS $\quad c_i^n = c_i^p$

IV $\quad c_i^n = -c_i^p$

XP $\quad c_i^n / c_i^p = -0.7$

Exploring different scenarios

[17] C. A. J. O'Hare, N. W. Evans, C. McCabe, G. C. Myeong, and V. Belokurov, Velocity substructure from *Gaia* and direct searches for dark matter, Phys. Rev. D **101**, 023006 (2020).

[18] L. Necib *et al.*, Evidence for a vast prograde stellar stream in the solar vicinity, arXiv:1907.07190.

[19] L. Necib *et al.*, Chasing accreted structures within Gaia DR2 using deep learning, arXiv:1907.07681.

[60] L. Necib, M. Lisanti, and V. Belokurov, Inferred evidence for Dark Matter Kinematic Substructure with SDSS–*Gaia*, Astrophys. J. **874**, 3 (2019).

	Substructure	Type	Reference	v_r (km/s)	v_θ (km/s)	v_ϕ (km/s)	$\lvert\sigma_{rr}\rvert$ (km/s)	$\lvert\sigma_{\theta\theta}\rvert$ (km/s)	$\lvert\sigma_{\phi\phi}\rvert$ (km/s)	η_{sub}
	Gaia Sausage (Necib *et al.*)	Debris flow	[60]	$\pm 147^{+7.2}_{-6.4}$	$-2.8^{+1.5}_{-1.6}$	$27.9^{+2.8}_{-2.9}$	$113.6^{+3.1}_{-3.0}$	$65.2^{+1.1}_{-1.2}$	$61.9^{+2.6}_{-2.9}$	0–0.70
	Gaia Sausage (O'Hare *et al.*)	Debris flow	[17]	−8.2	0.99	25.7	158.9	80.9	61.5	0–0.70
G1	Koppelman 1[a]	Stream	[19]	−169	−59	−375	11–37	3–16	6–28	0–0.30
	IC (π, 400 km/s)	IC	...	0	0	−400	35.4	35.4	30	0–0.30
G2	S1[a]	Stream	[17]	−29.6	−72.8	−297.4	82.6	58.5	26.9	0–0.30
	Koppelman 2	Stream	[19]	213	161	−226	52	18	29	0–0.30
	IC (π, 300 km/s)	IC	...	0	0	−300	35.4	35.4	30	0–0.30
G3	IC (π, 200 km/s)[a]	IC	...	0	0	200	35.4	35.4	30	0–0.30
	IC ($\frac{\pi}{2}$, 400 km/s)	IC	...	282.8	282.8	0	21.2	21.2	50	0–0.30
G4	IC ($\frac{\pi}{2}$, 300 km/s)[a]	IC	...	212.1	212.1	0	21.2	21.2	50	0–0.30
G5	Helmi[a]	Stream	[19]	29	−287	141	37–83	6–21	4–15	0–0.30
	IC ($\frac{\pi}{2}$, 200 km/s)	IC	...	141.4	141.4	0	21.2	21.2	50	
G6	Nyx[a]	Stream	[18]	$156.8^{+2.1}_{-2.2}$	$-1.4^{+3.1}_{-3.0}$	$141.0^{+2.5}_{-2.6}$	$46.9^{+1.7}_{-1.6}$	$70.9^{+2.4}_{-2.2}$	$52.5^{+1.8}_{-1.8}$	0–0.30
	IC (0, 400 km/s)	IC	...	0	0	−400	35.4	35.4	30	0–0.30
	IC (0, 300 km/s)	IC	...	0	0	−300	35.4	35.4	30	0–0.30
	IC (0, 200 km/s)	IC	...	0	0	−200	35.4	35.4	30	0–0.30

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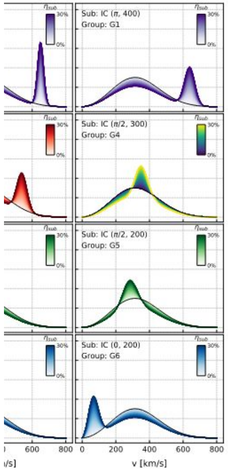
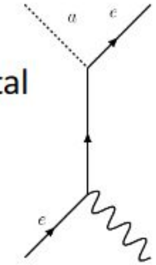


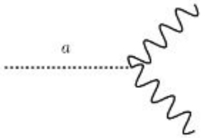
Axion interactions in DEAP-3600 produce EM events

- **Compton conversion**
  - Get 1 gamma and 1 electron, with 5.5 MeV total kinetic energy
- **Inverse Primakov**
  - Get 1 gamma with 5.5 MeV energy
- **Axio-electric effect**
  - Get 1 electron with 5.5 MeV kinetic energy
- **Axion decay into 2 gammas**
  - Get 2 gammas with 5.5 MeV total energy

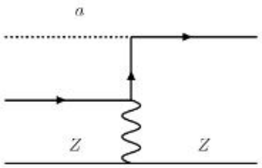
Compton Conversion



Decay to 2γ



Inverse Primakov



Axio-Electric Effect