

Status and prospects of the DEAP-3600 experiment



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(CIEMAT)

on behalf of the DEAP collaboration

TeVPA

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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

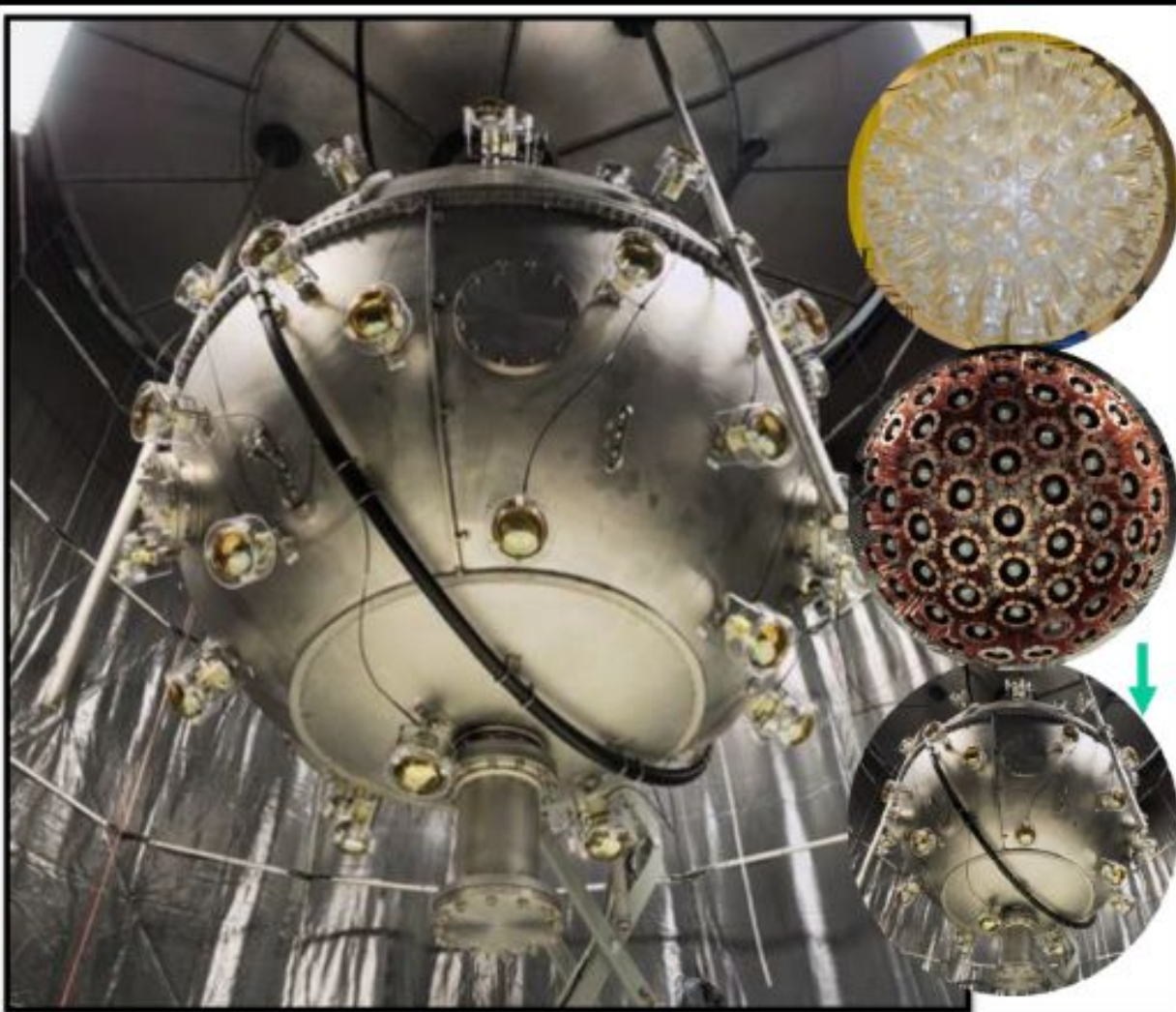
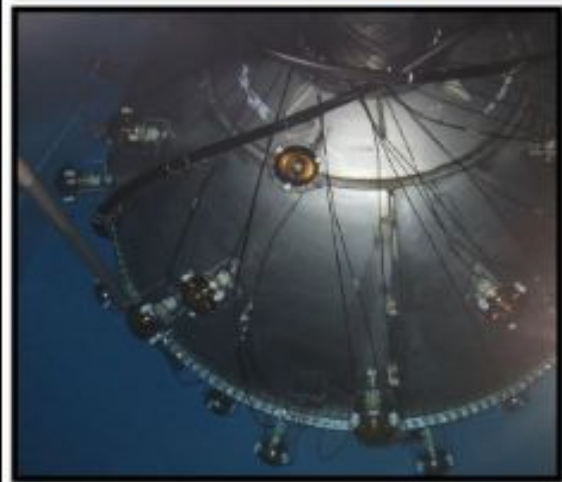
without a TPC

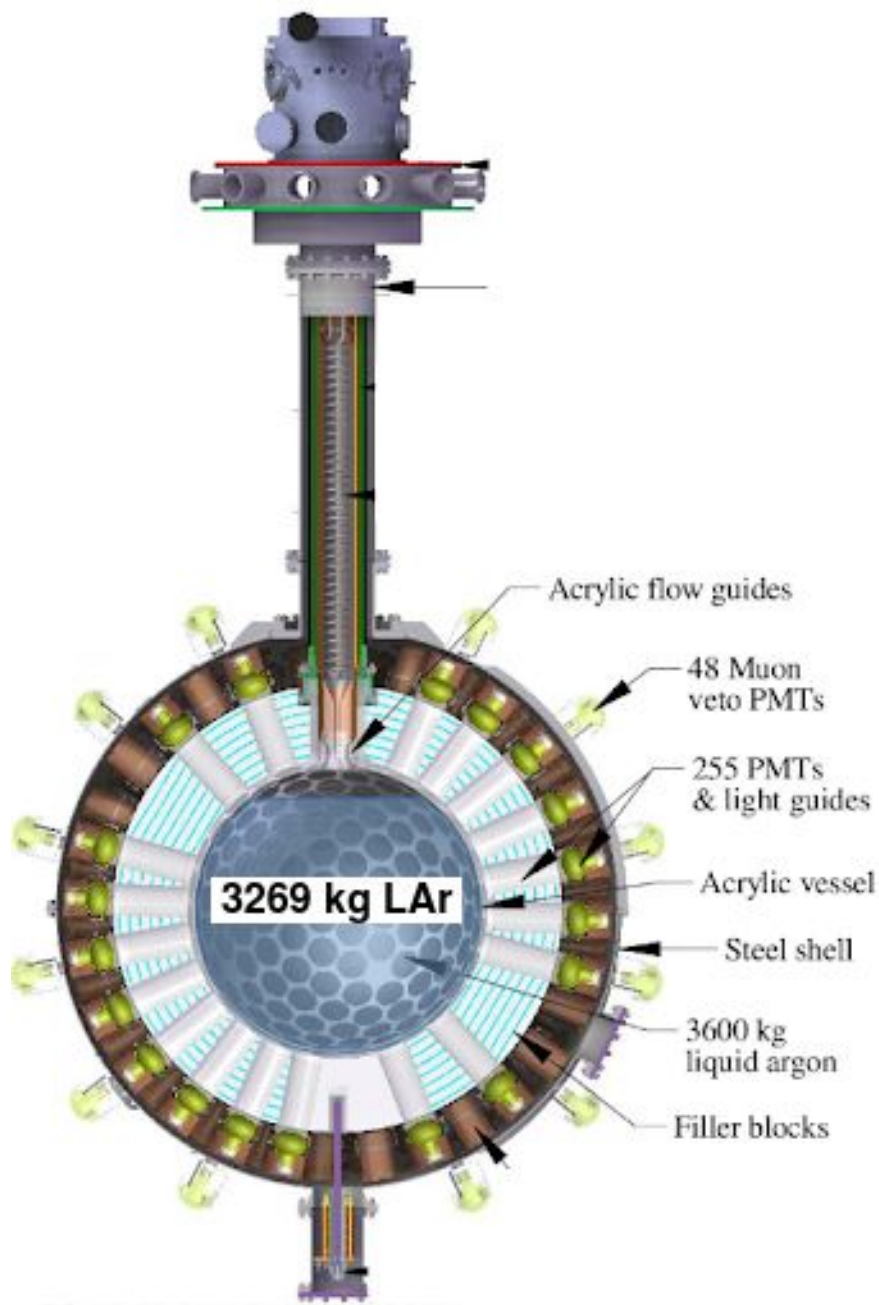
in single phase

Potential path for next generation

The DEAP-3600 detector

DEAP-3600 in Cube Hall
at SNOLAB

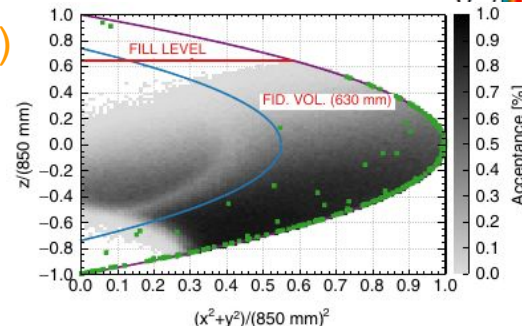
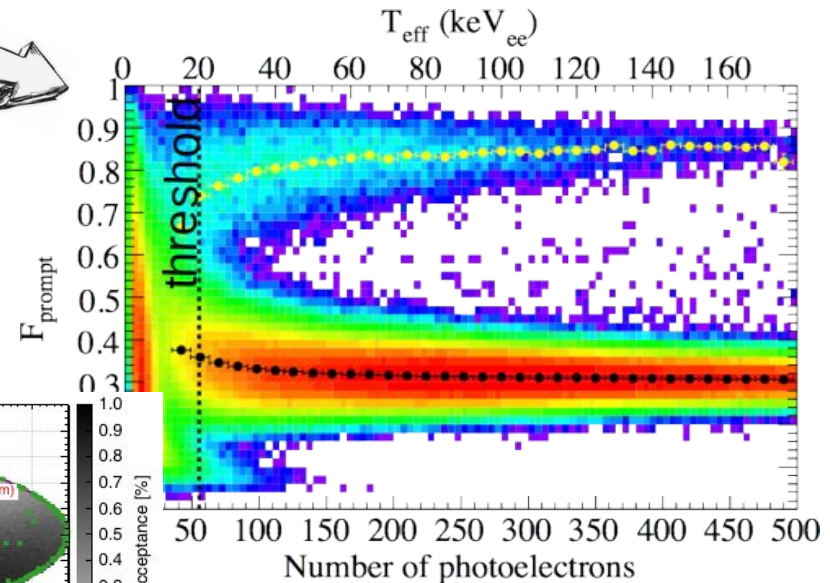
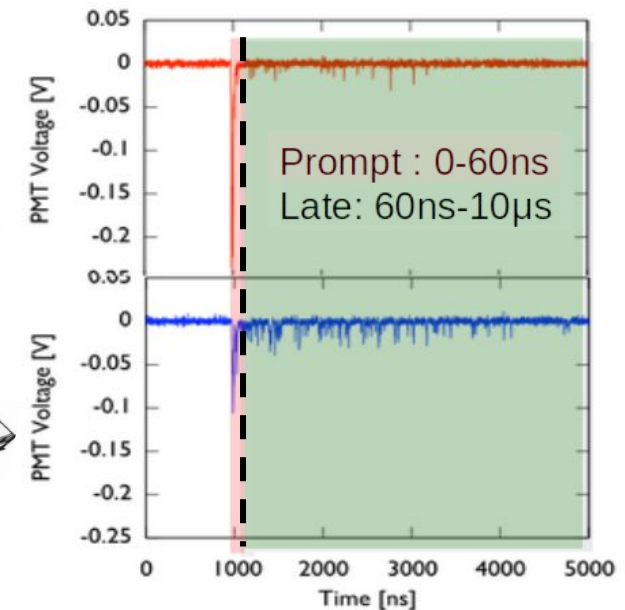
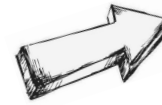




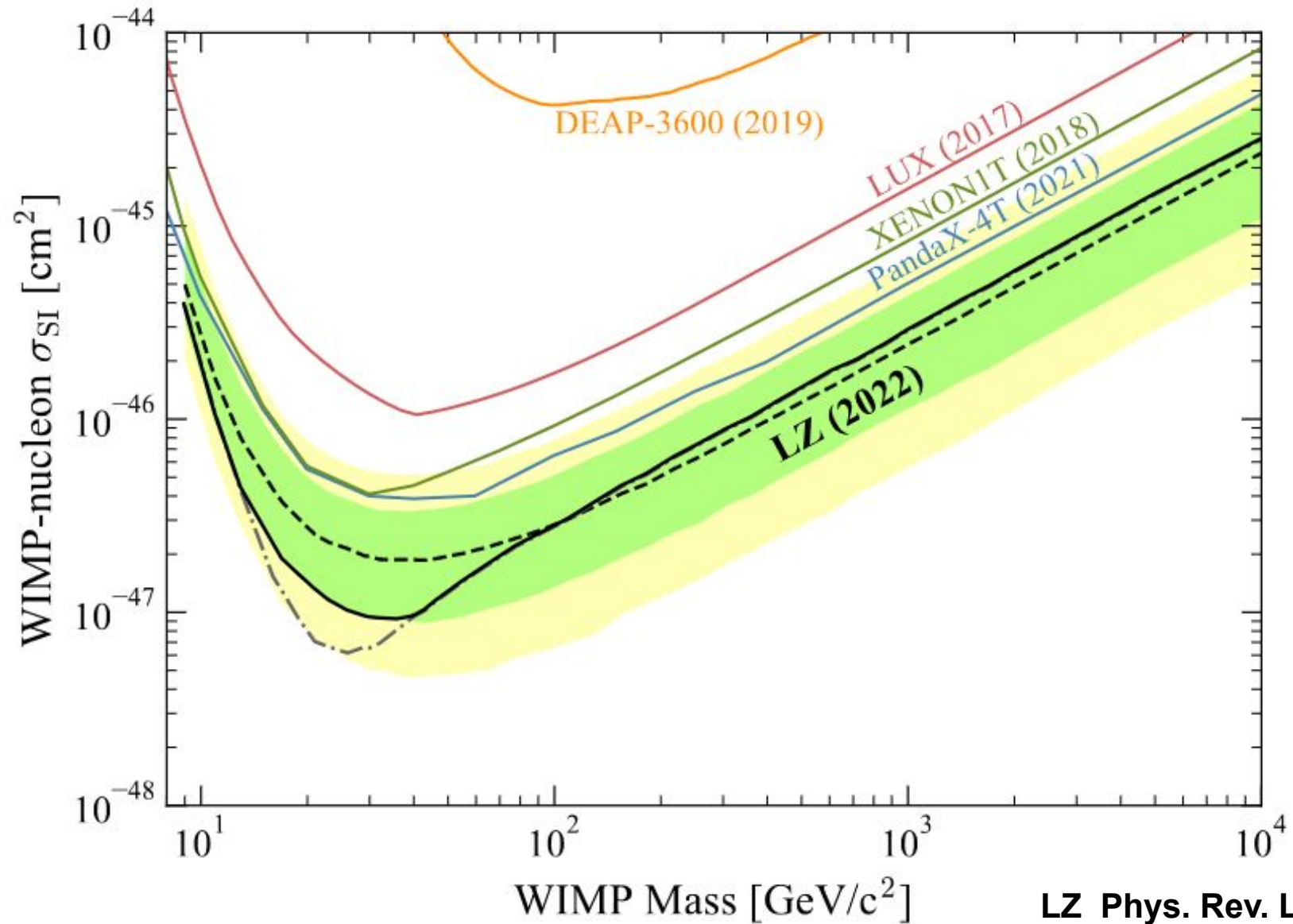
- 3.3 tonne LAr target in ultraclean acrylic vessel ($R = 85$ cm).
- In-situ vacuum evaporated TPB on inner 10 m^2 surface.
- Bonded 50-cm-long light guides: distance to PMTs
- 255 PMTs: Hamamatsu R5912 HQE. 8" - 32 % QE - 75% coverage.
- Immersed in water tank with PMTs to veto muons (Cherenkov light).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

The DEAP-3600 detector: Ar scintillation

- Singlet state decays fast (8 ns) & dominantly populated by nuclear recoils
- Triplet state decays slowly (1.4 μ s) & dominantly populated by electronic recoils
- Pulse shape allows us to discriminate against gamma and beta backgrounds.
- Position reconstruction and fiducialization allow us to reduce surface and external backgrounds.
- No electric field

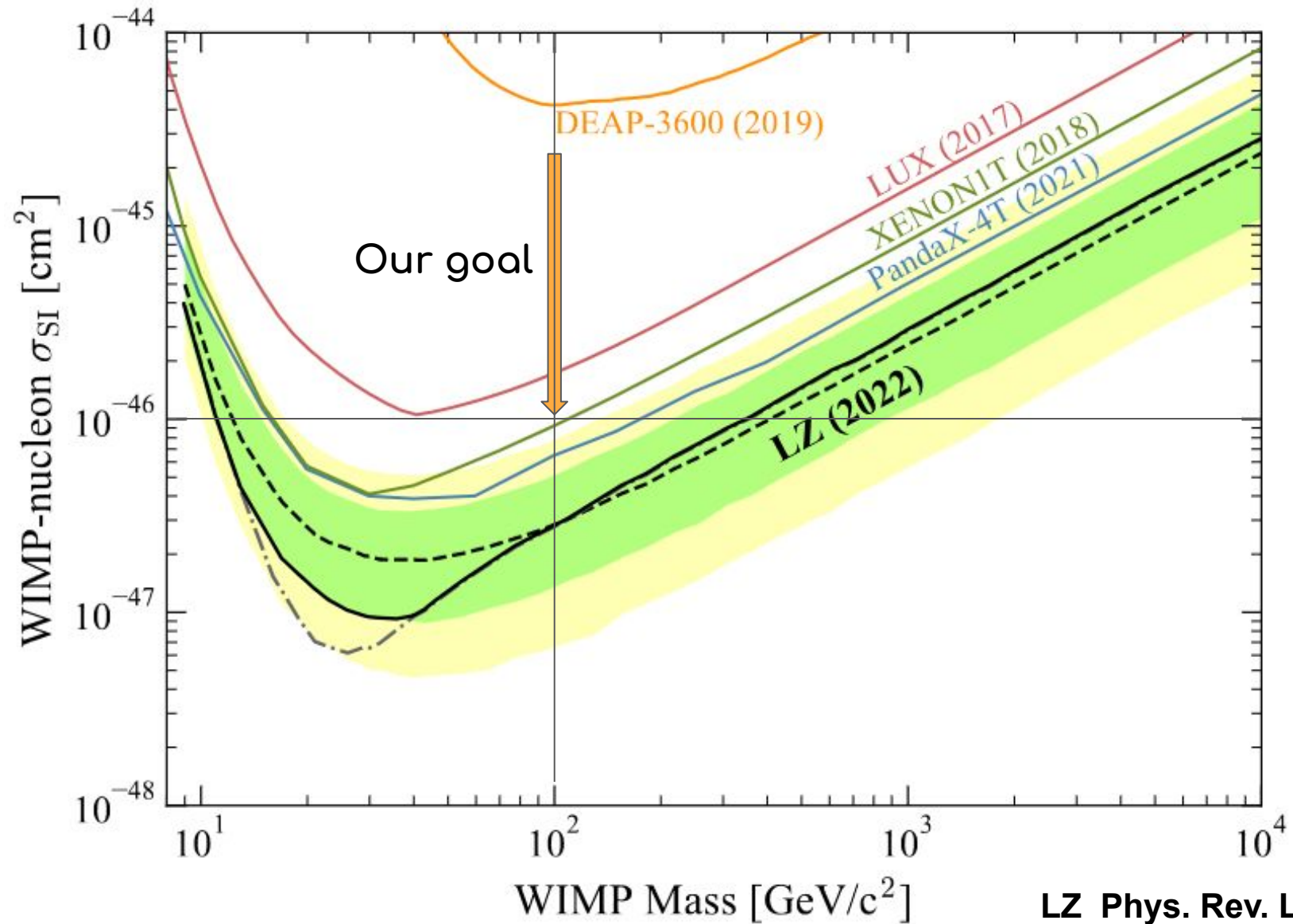


The DEAP-3600 detector



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

The DEAP-3600 detector



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

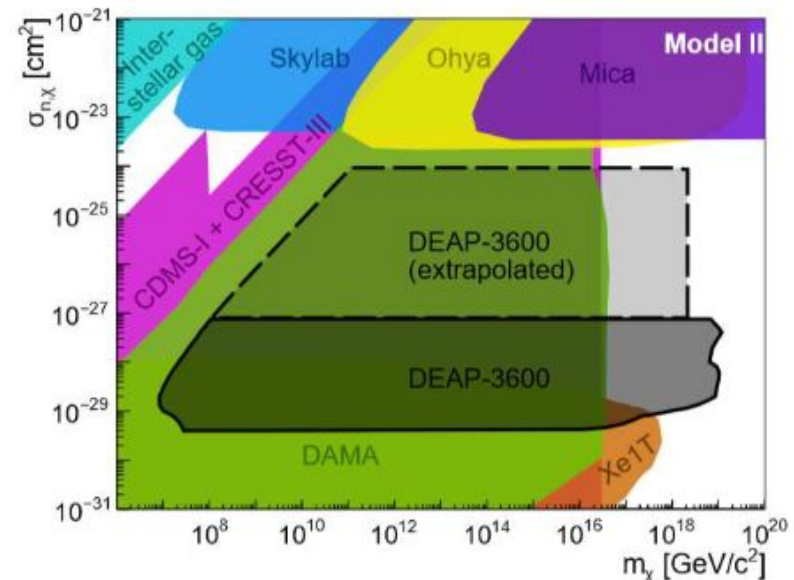
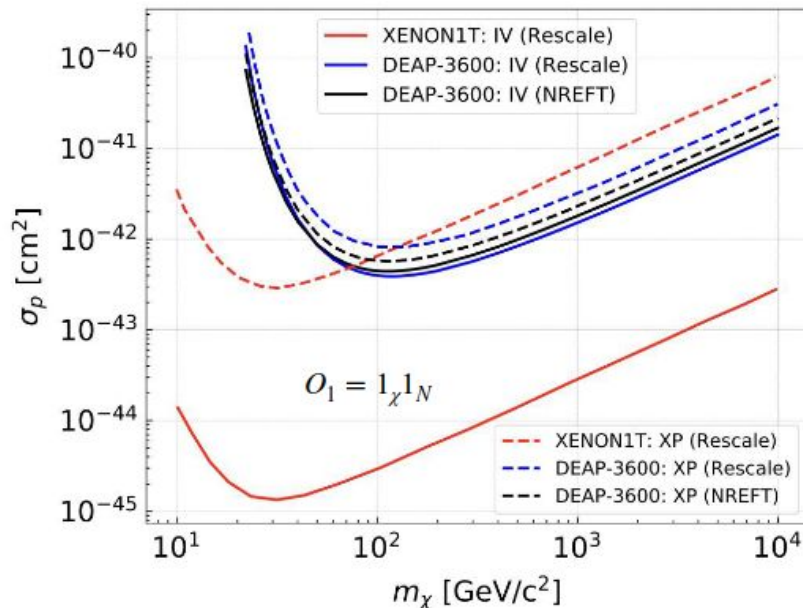
The DEAP-3600 detector: goals

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

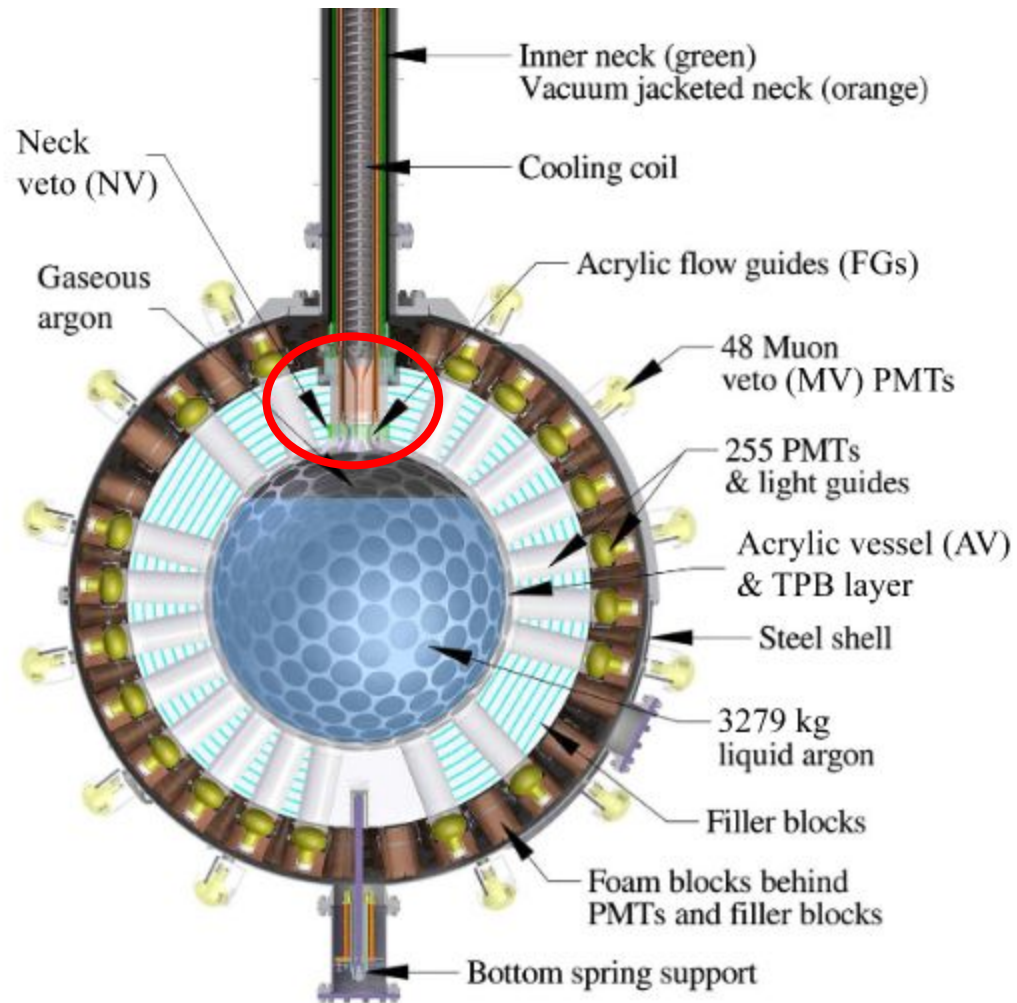
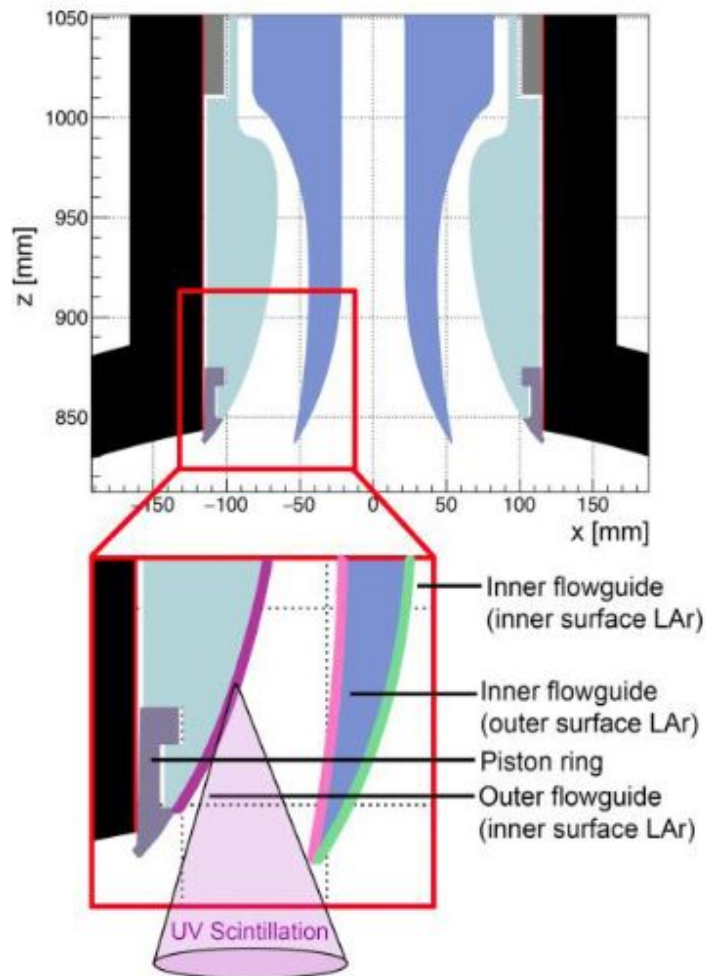
Particularly suited for some exotic DM scenarios:

- 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

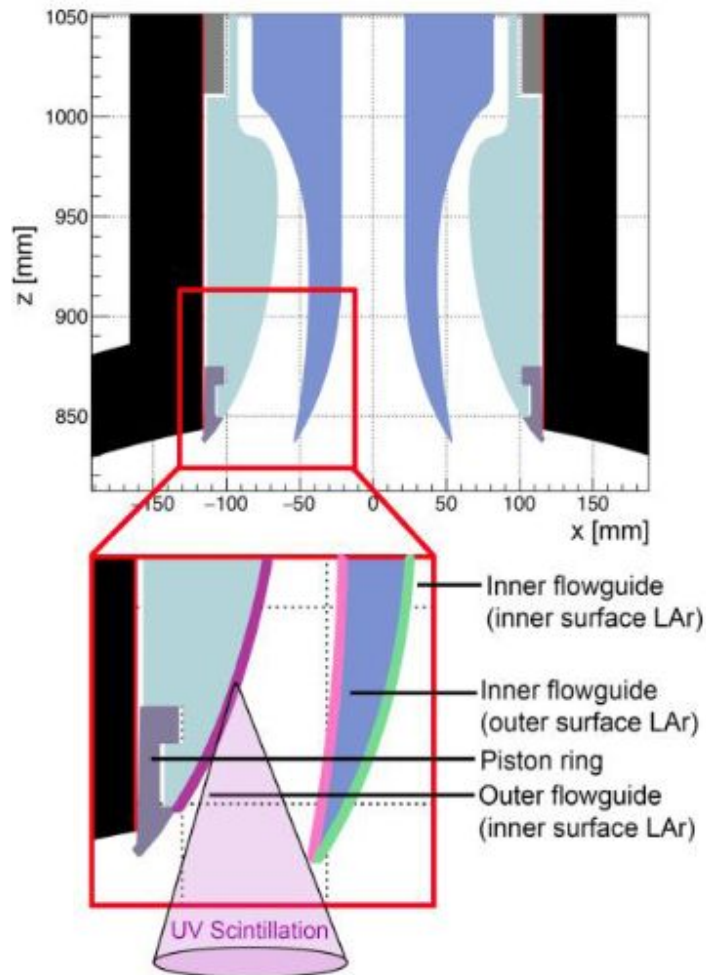
Bkg 1: surface ^{210}Po on the neck (above target)



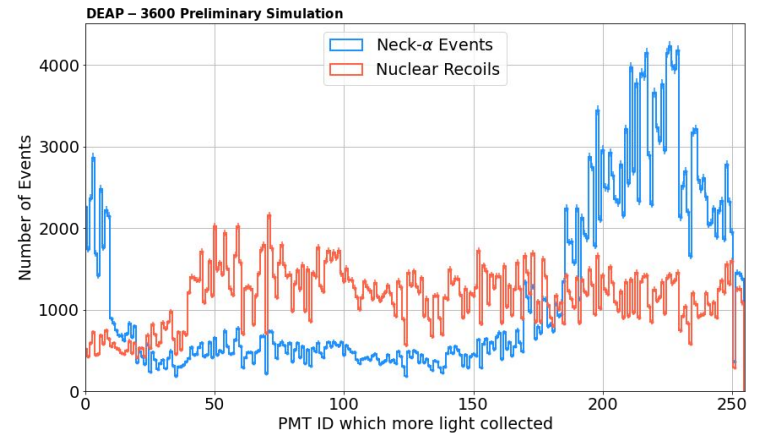
PRD, 100 (2019), p 022004

Recovering WIMP sensitivity

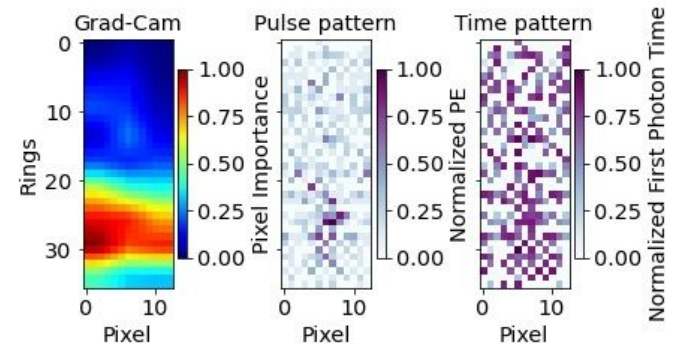
Bkg 1: surface ^{210}Po on the neck (above target)



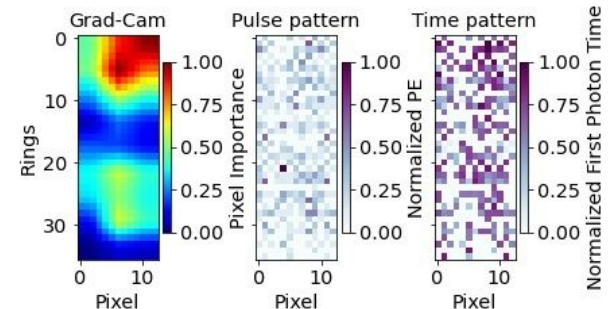
CNN trained against this bkg gives very good results!



DEAP - 3600 Preliminary Simulation
Nuclear Recoil R = 606 mm



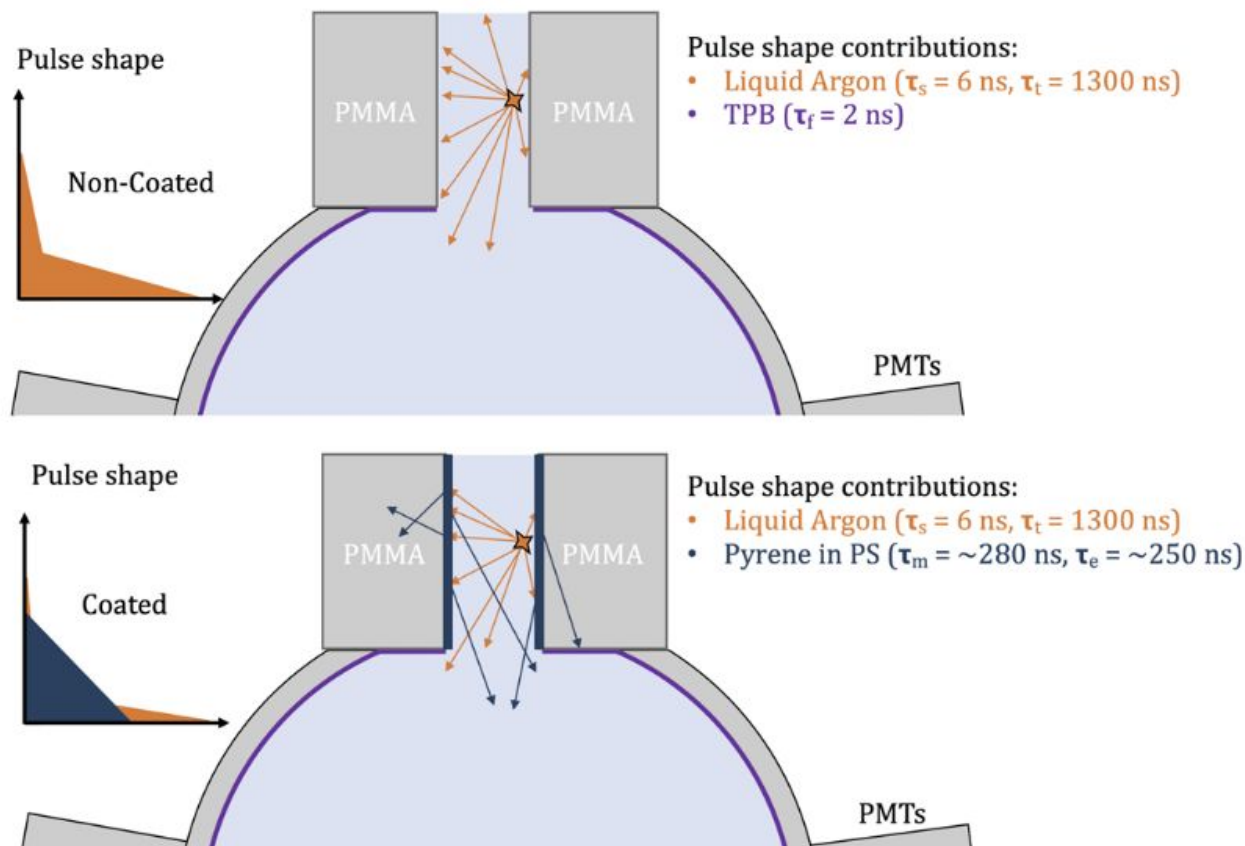
DEAP - 3600 Preliminary Simulation
Neck - α



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.

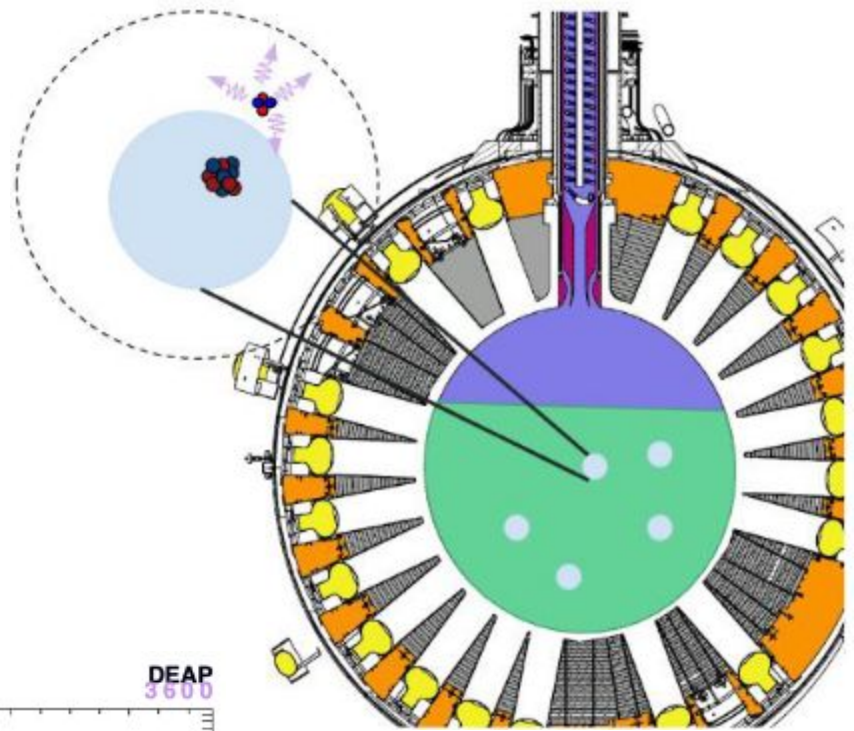
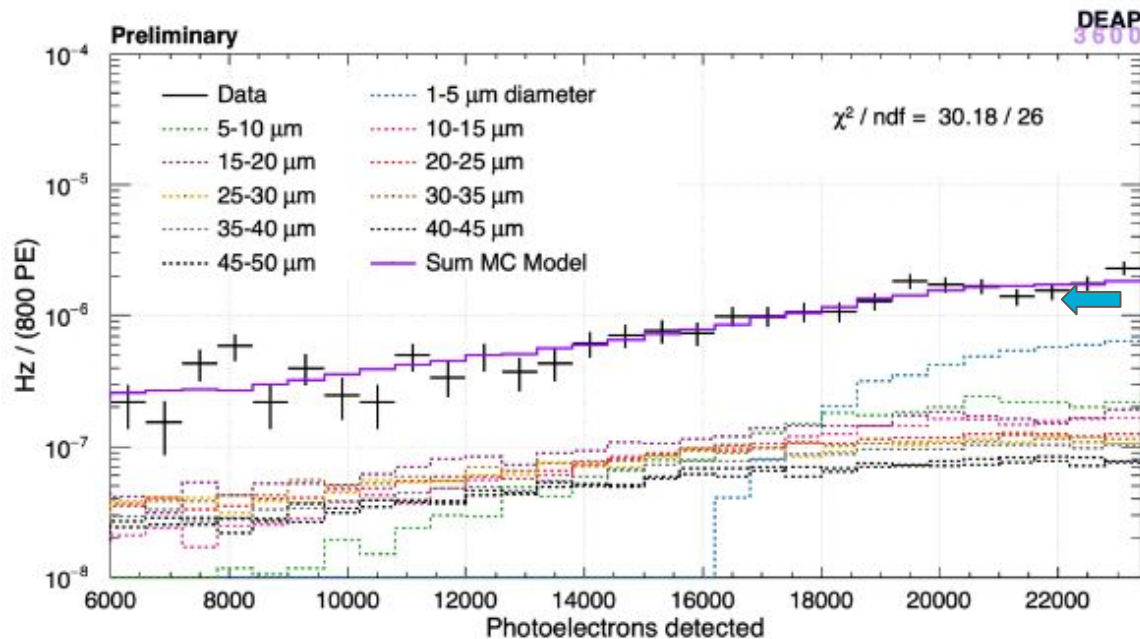


NIM A 1034 (2022) p 166683

Recovering WIMP sensitivity

Bkg 2: degraded alphas from dust particulates in suspension

DEAP operated with no recirculation or filtration

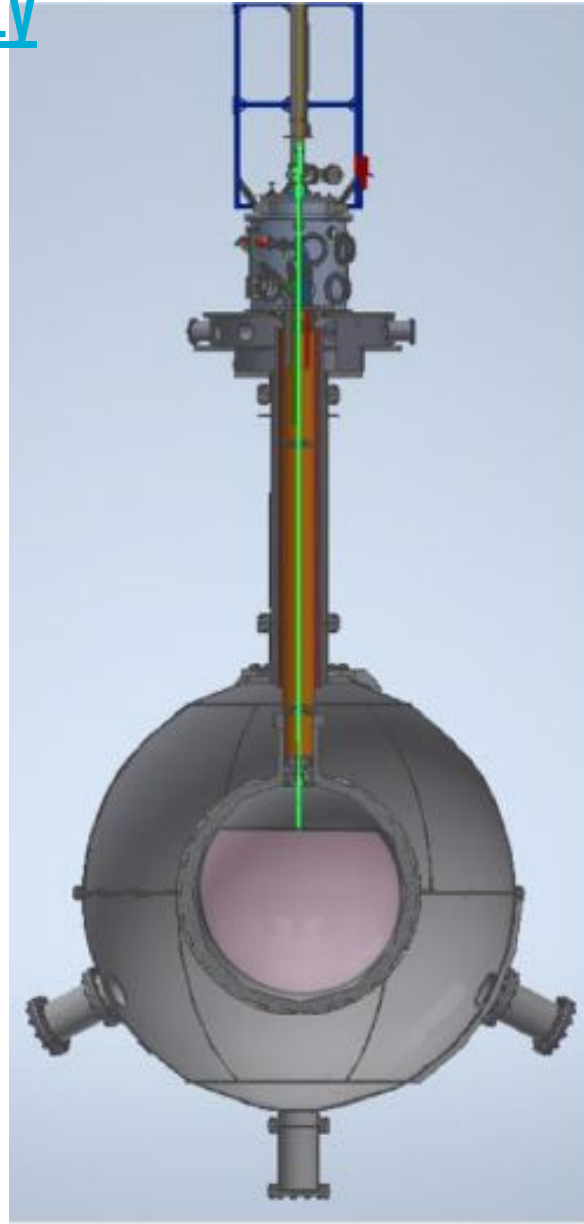


E lost in the dust
itself does not
produce photons.

Recovering WIMP sensitivity

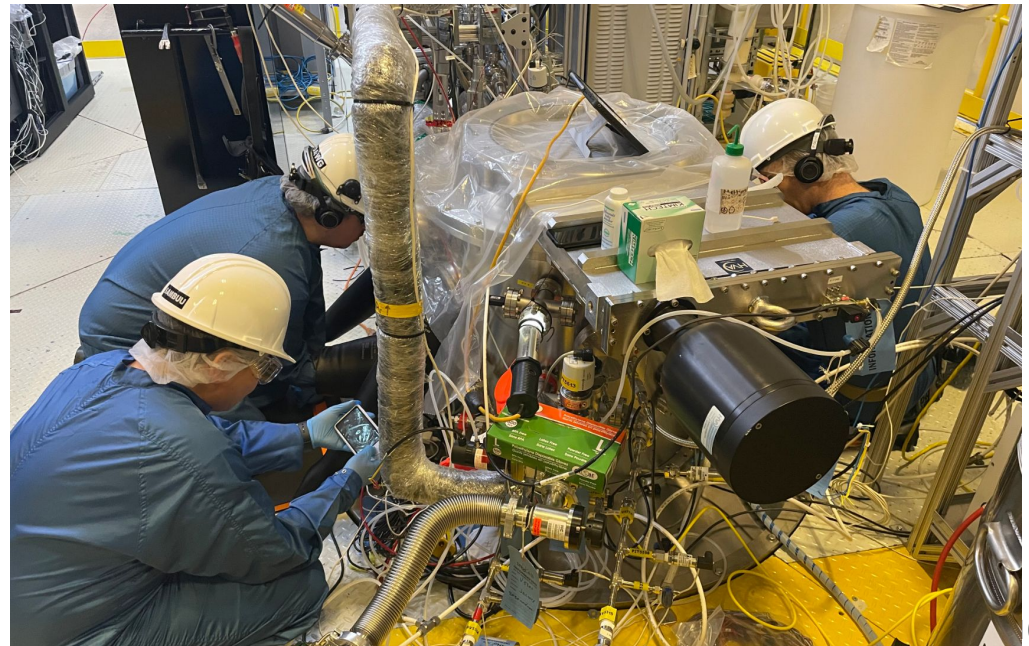
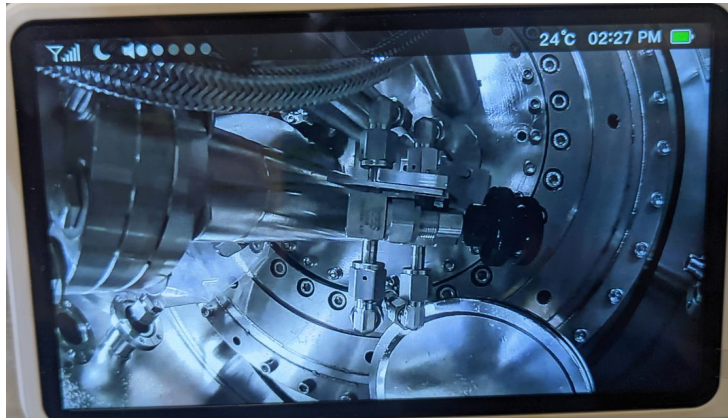
Fix 2: New
recirculation+filtration
system to remove dust
from target

External cooling
also prevents
condensation in
the neck!



Already @ SNOLAB

Recovering WIMP sensitivity: hardware upgrades



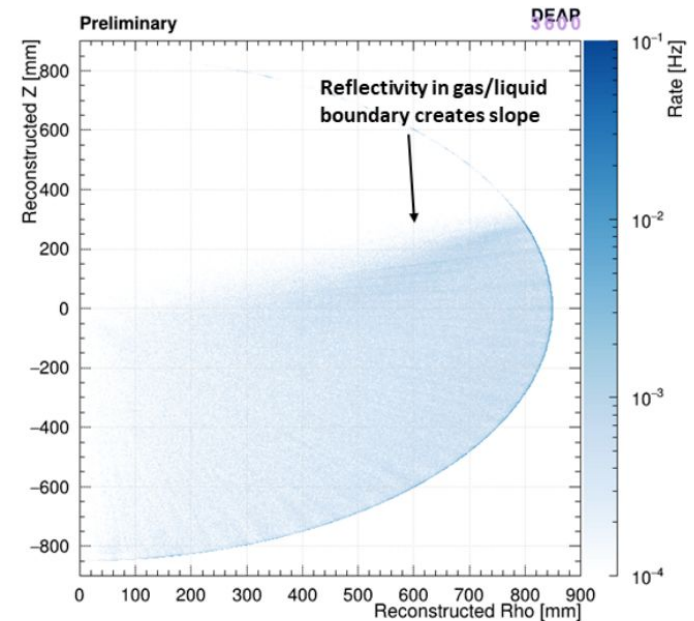
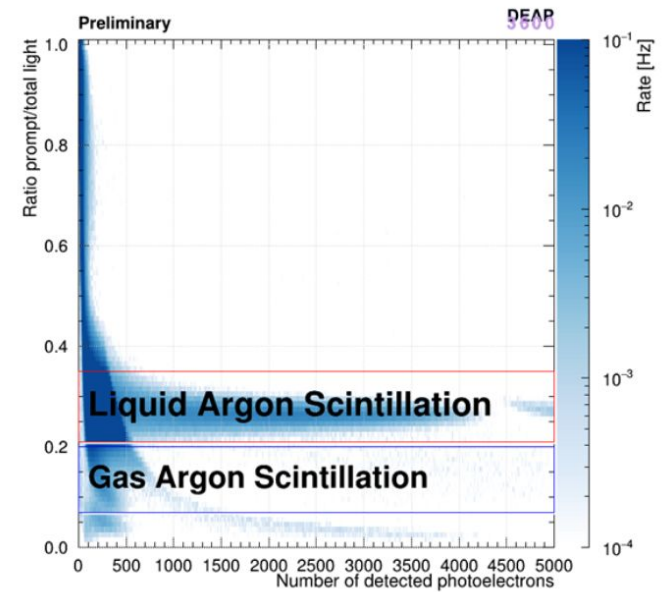
Current state and WIMP search prospects

Neck upgrade finished

Detector cool down and Ar fill
finalized on July

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

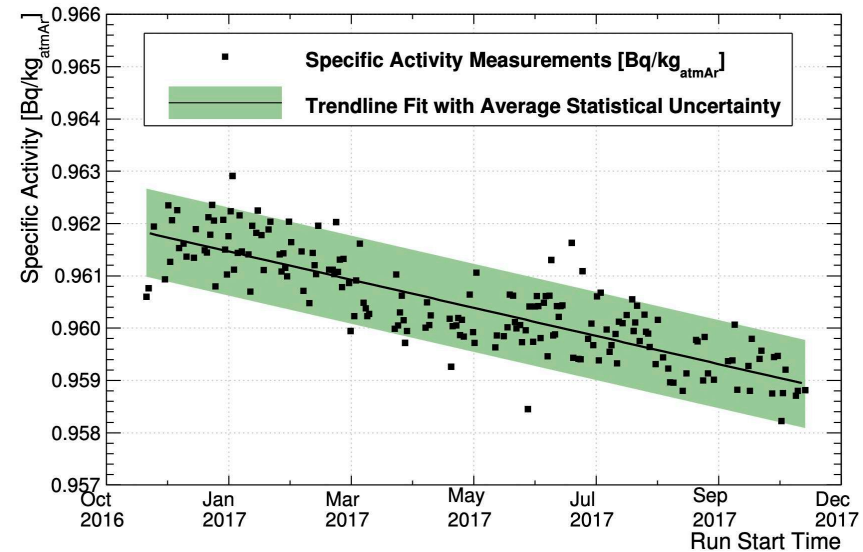
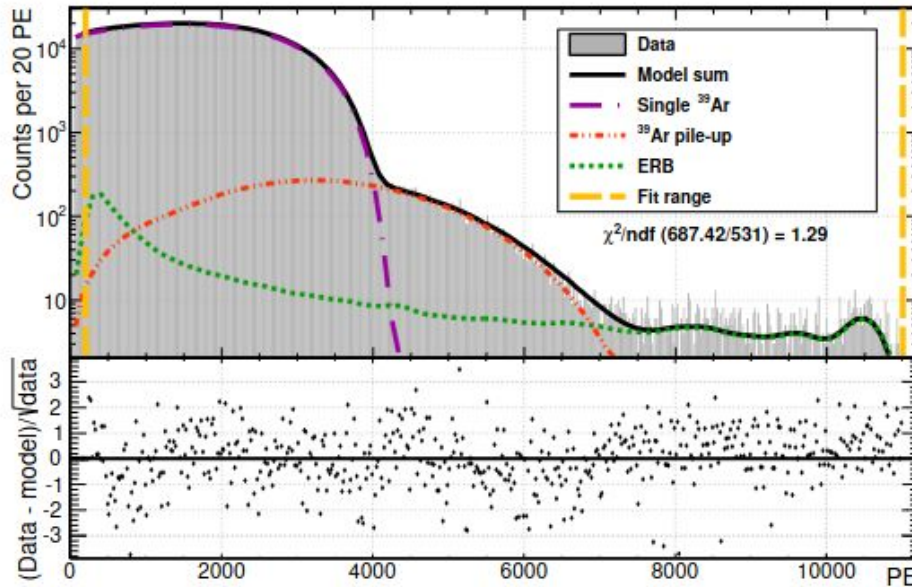
Finalize refined analysis
and unblind



More physics
with DEAP

^{39}Ar specific activity in atmospheric Ar

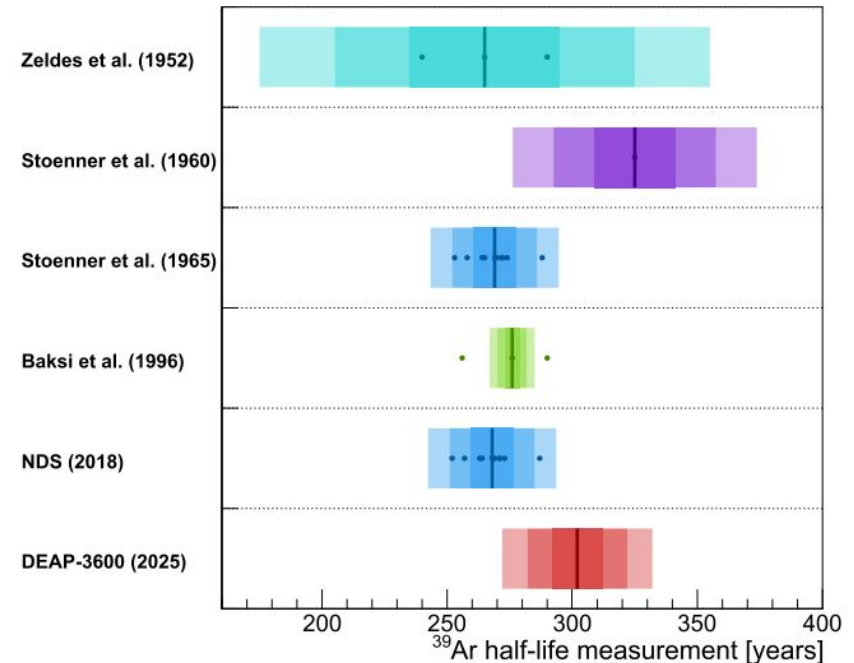
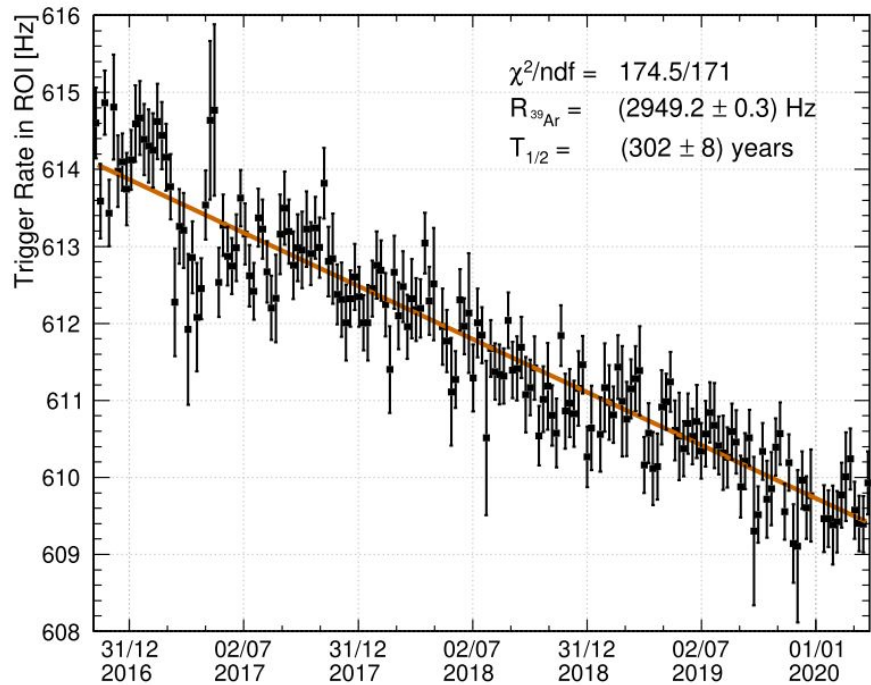
Eur. Phys. J. C 83, 642 (2023)



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:

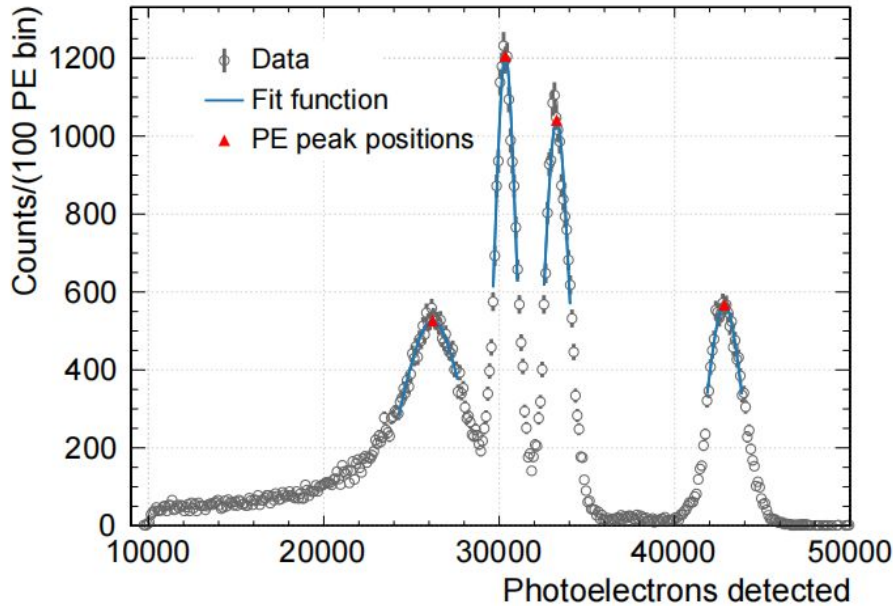
$$0.964 \pm 0.001_{\text{stat}} \pm 0.024_{\text{sys}} \text{ Bq/kg}$$



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

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

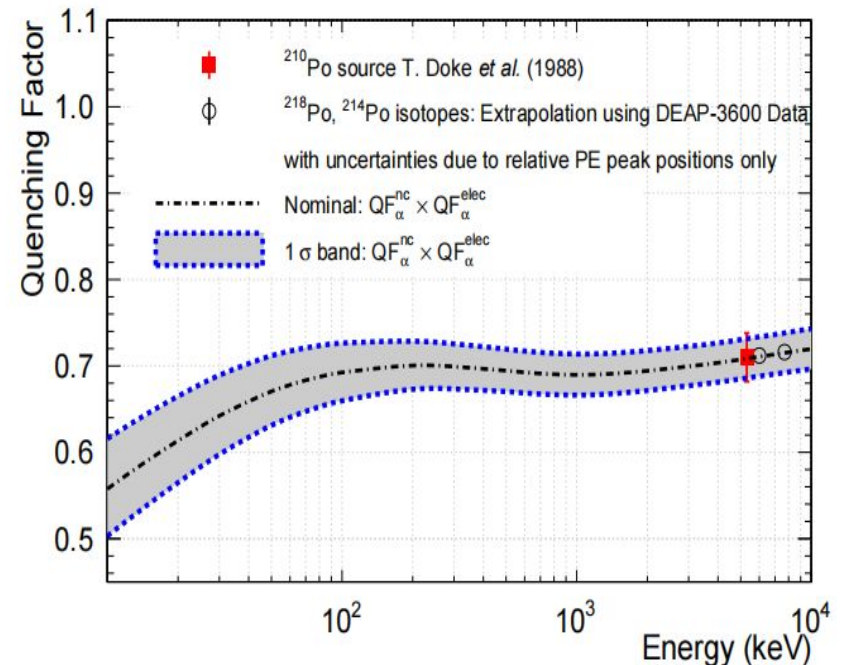
2.5 σ tension with Nuclear Data Sheets (NDS)



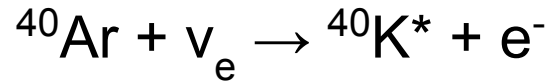
Extrapolation of the QF values into the low-energy region down to 10 keV

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

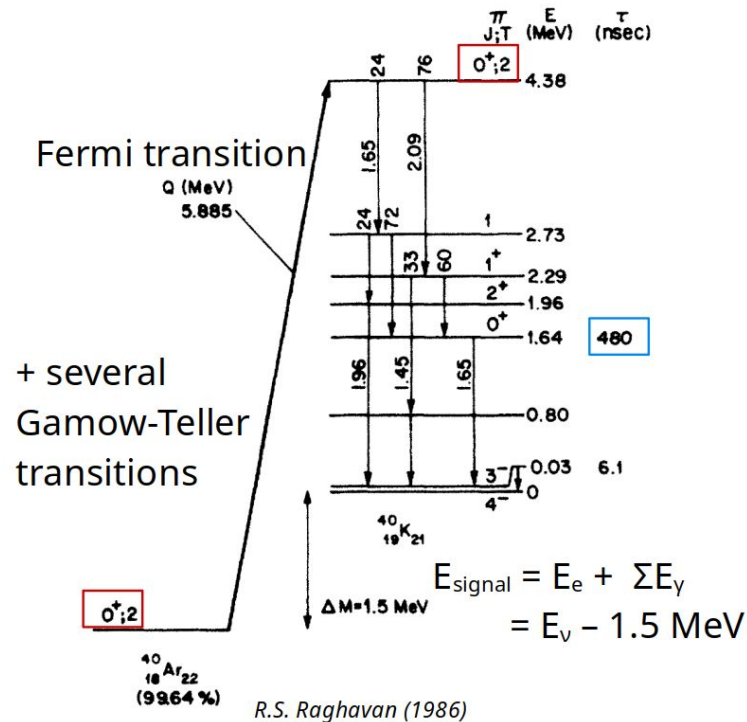
Measurements relative to ^{210}Po QF from Doke et al = 0.710 ± 0.028 (@ 5.305 MeV)



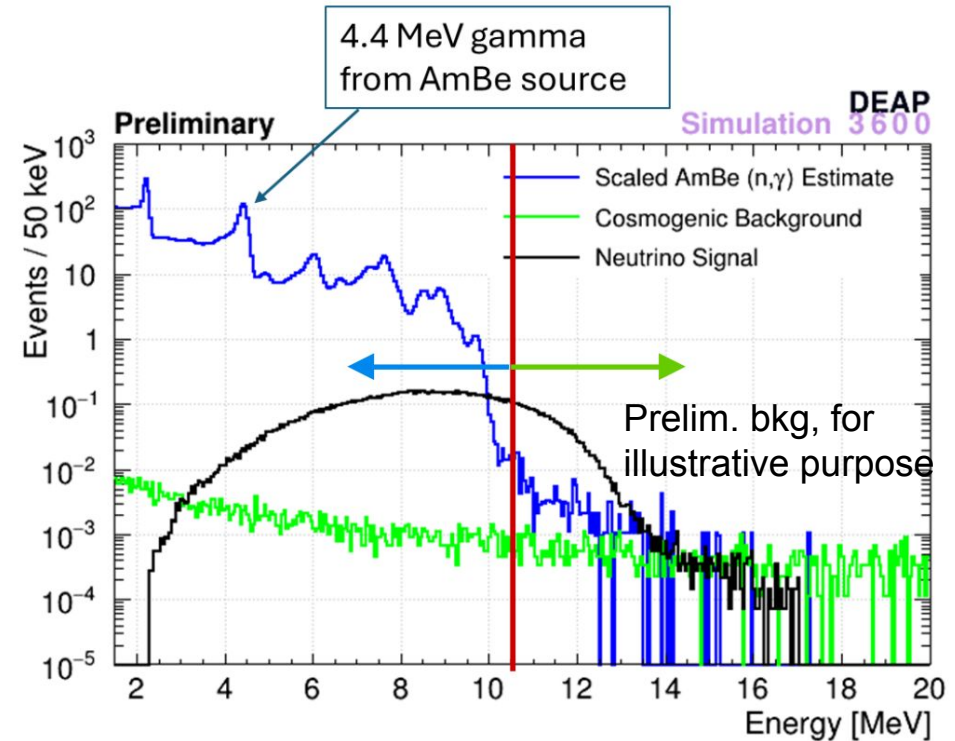
Detecting ^8B solar neutrinos



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



(coming soon)



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

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:

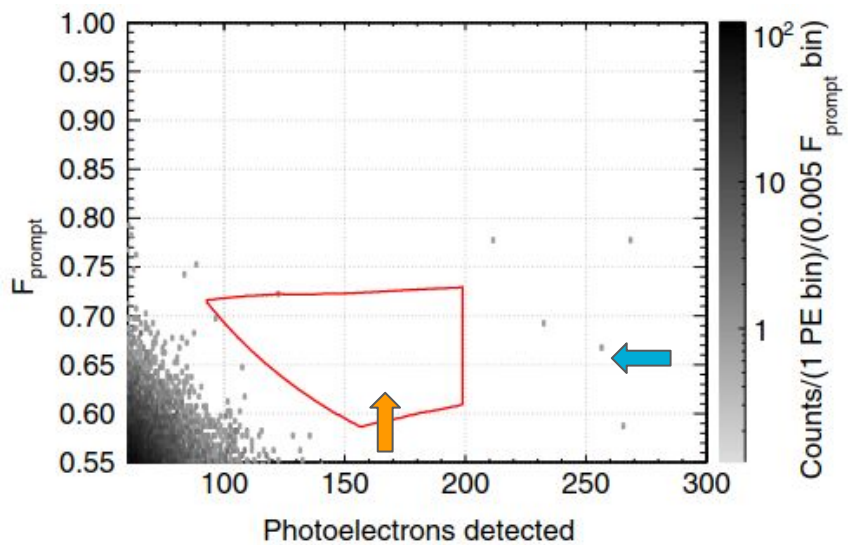
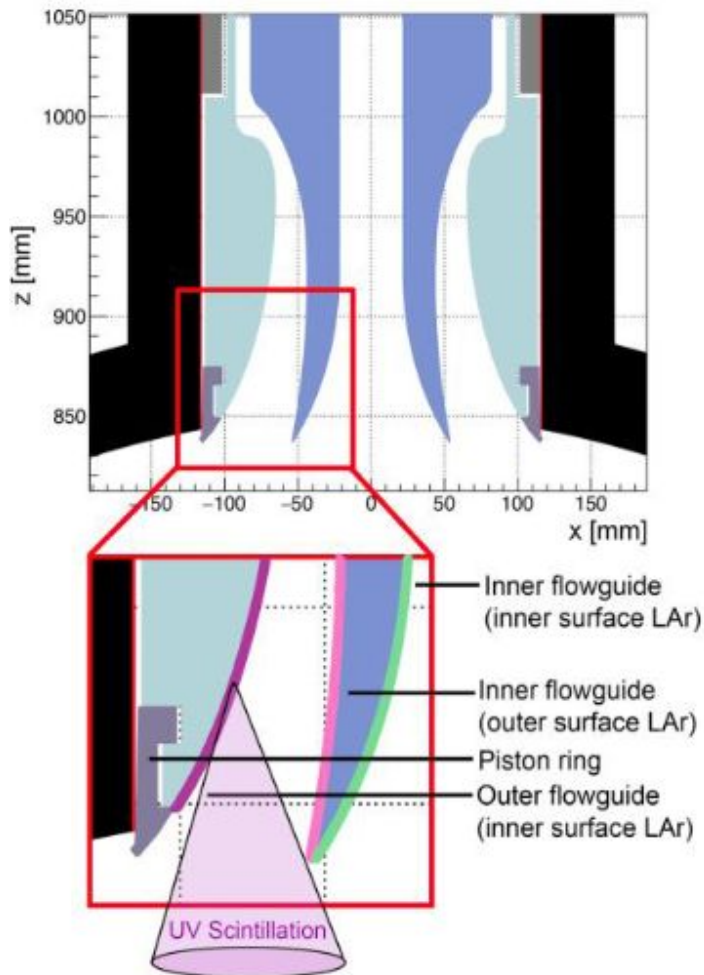
95 researchers in **Canada**, Germany, Italy, Mexico, Poland, Russia, Spain, UK, USA



Backup

Recovering WIMP sensitivity

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



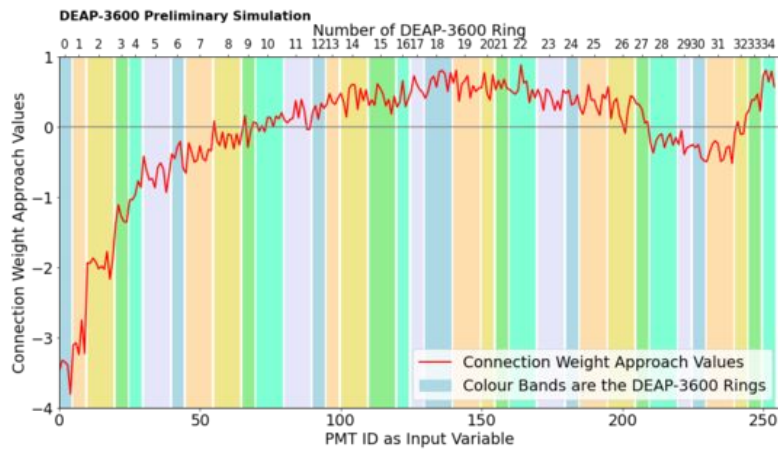
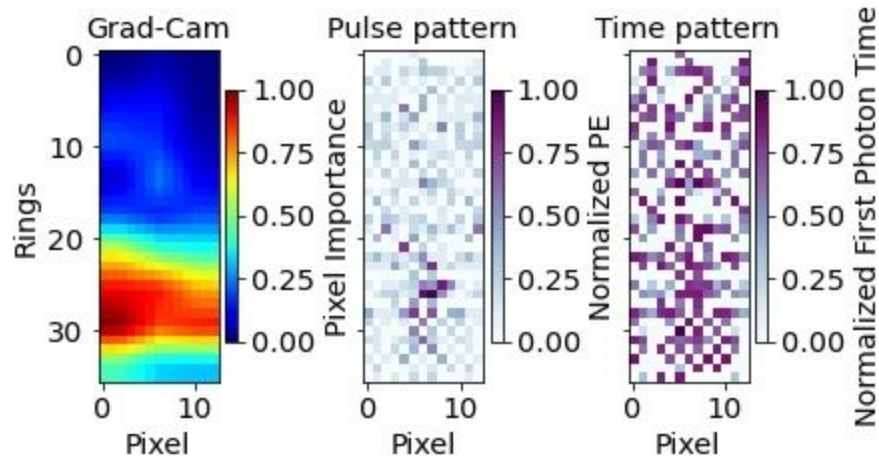
Unfortunate combination of:

- 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

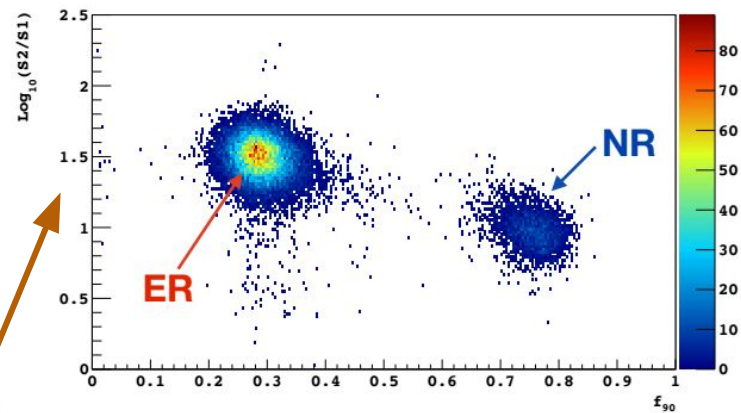
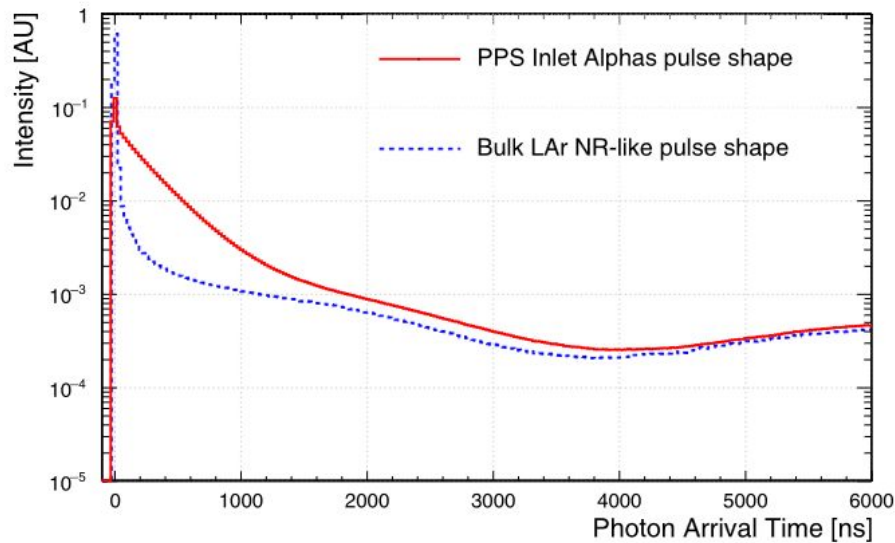
Nuclear Recoil R = 606 mm



DEAP – 3600 Preliminary Simulation

Nuclear recoil misclassified

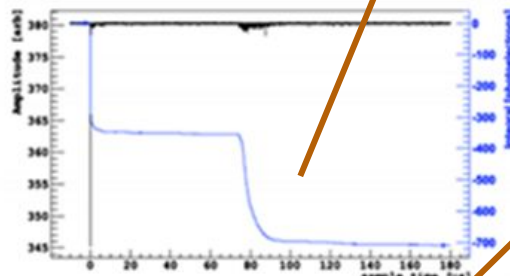
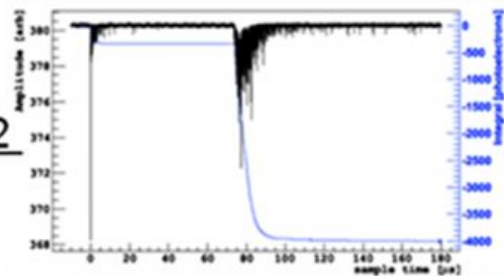




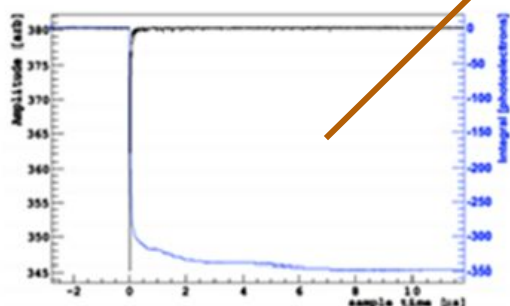
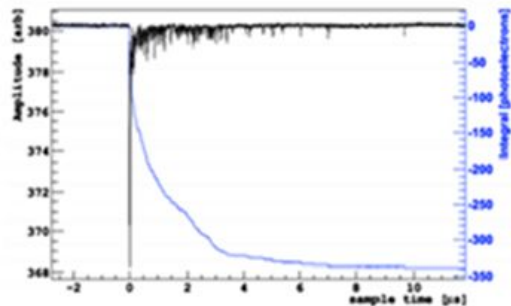
ER-like event

NR-like event

S1/S2



S1
only

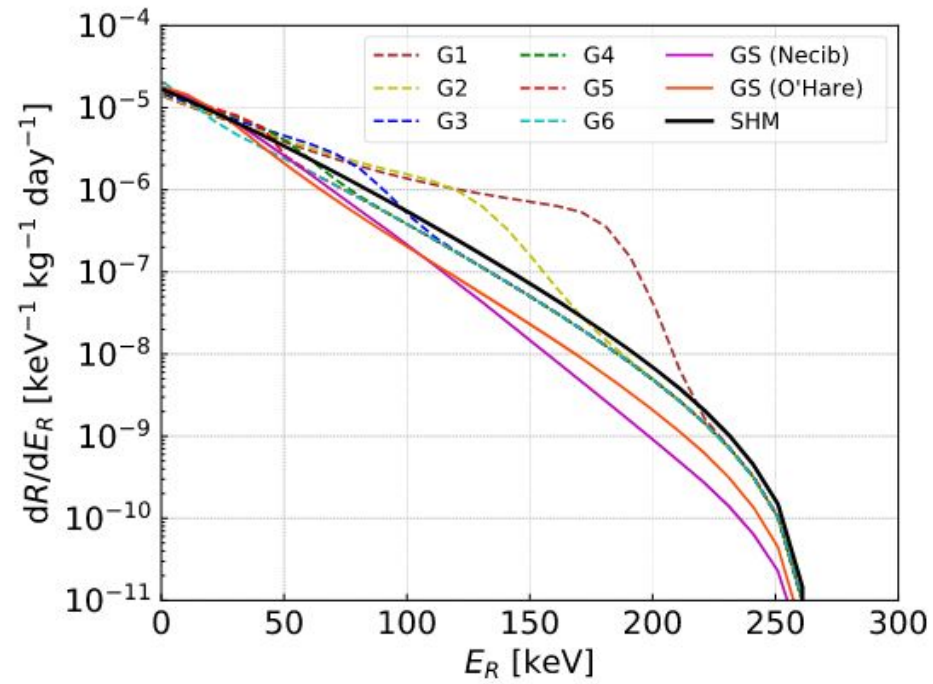


Exploring different scenarios

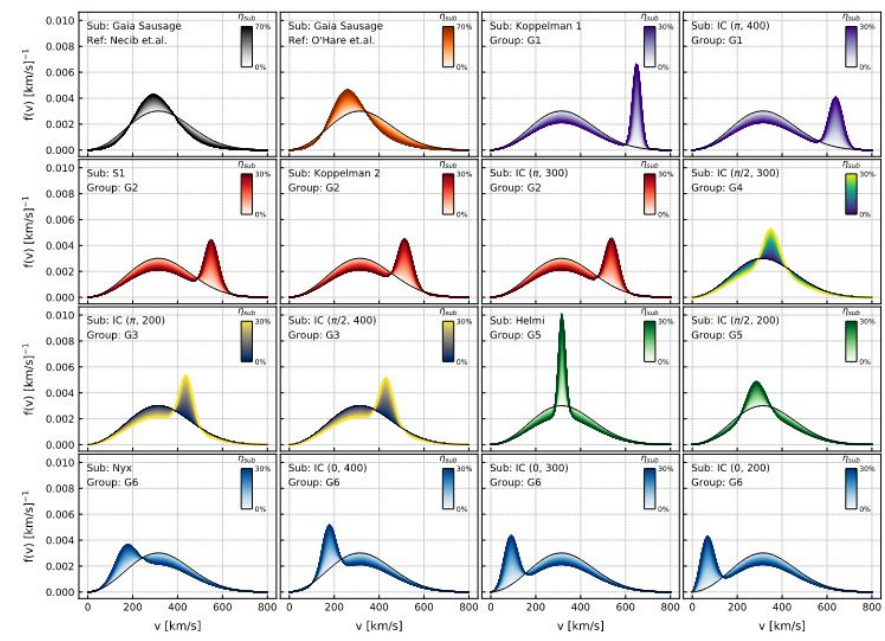
$$\frac{dR}{dE_R} = \frac{\rho_T}{m_T} \frac{\rho_\chi}{m_\chi} \varepsilon(E_R) \int_{v_{\min}}^\infty v f_\chi^\oplus(\vec{v}) \frac{d\sigma}{dE_R} d^3\vec{v}$$

Recoil rate in Ar for

different WIMP distributions



	Substructure	Type	Reference
	Gaia Sausage (Necib <i>et al.</i>)	Debris flow	[60]
	Gaia Sausage (O'Hare <i>et al.</i>)	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	...



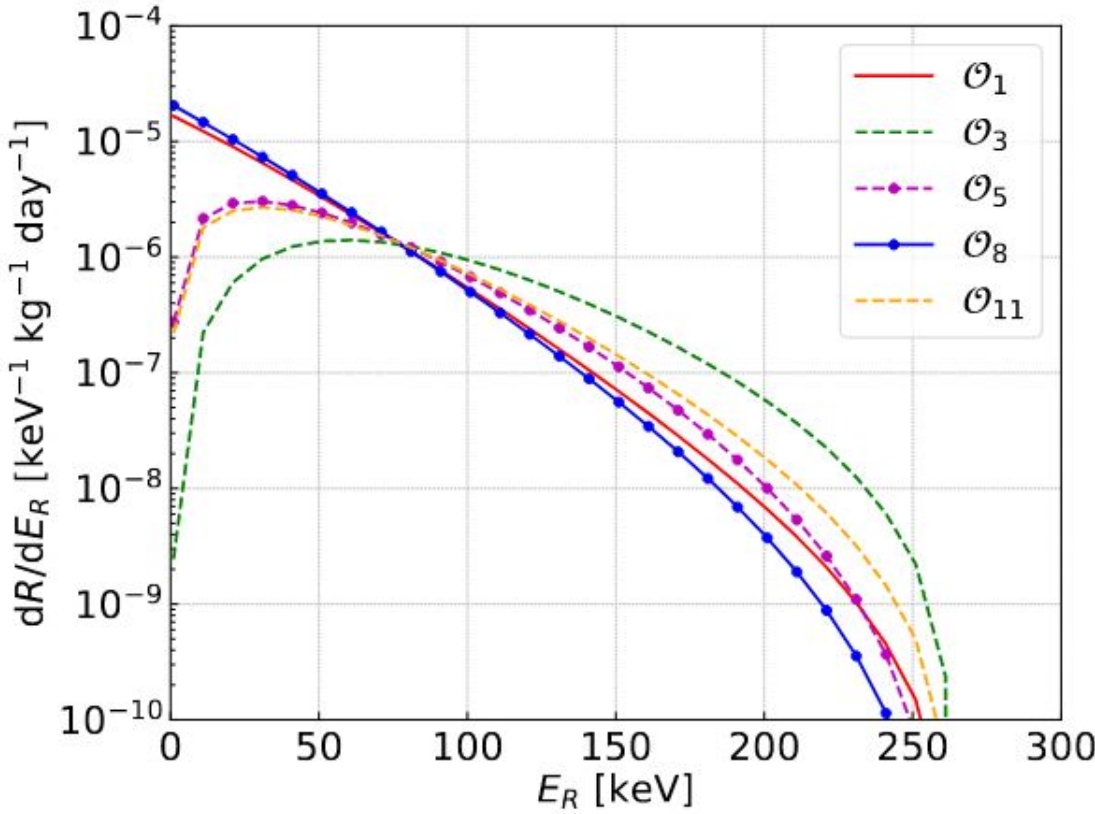
Exploring different scenarios

Recoil rate in Ar for

different non-relativistic
effective operators

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

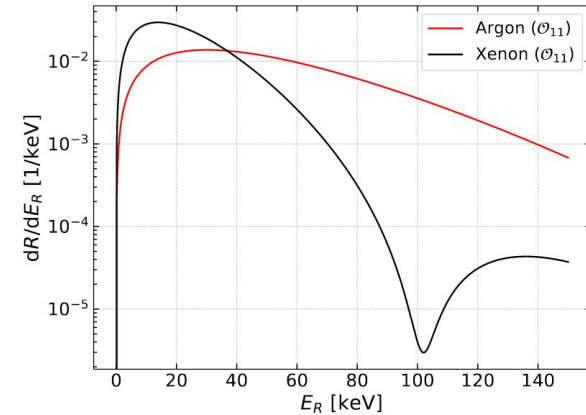
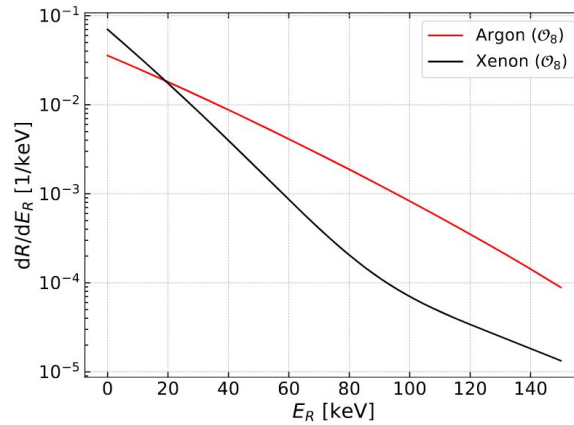
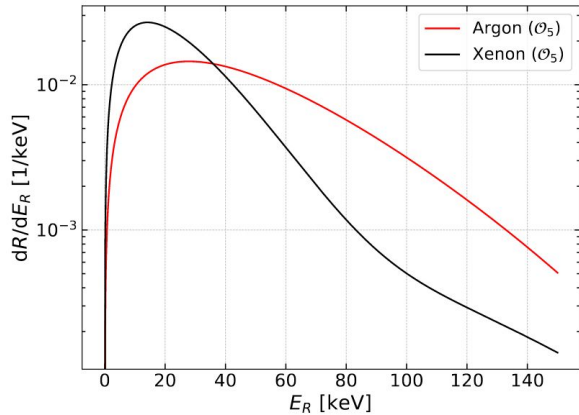
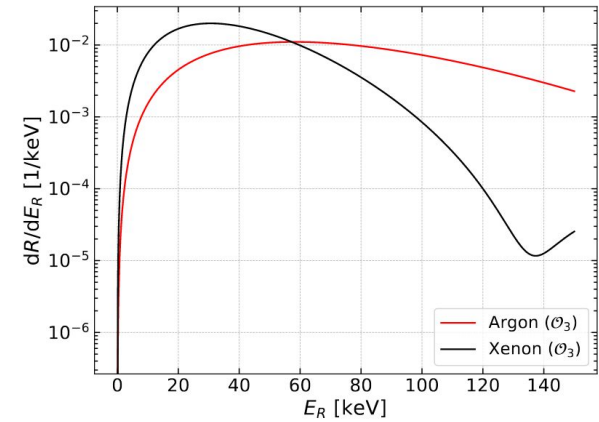
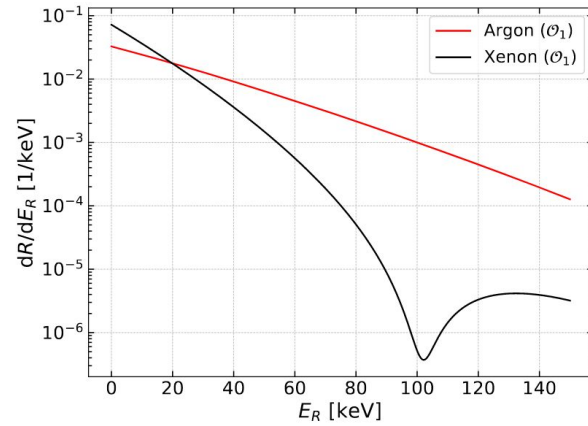
Phys. Rev. D 102, 082001 – Published 22 October 2020; Erratum Phys. Rev. D 105, 029901 (2022)



$$\begin{aligned} \mathcal{O}_1 &= 1_\chi 1_N, \\ \mathcal{O}_3 &= i \vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp \right), \\ \mathcal{O}_5 &= i \vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp \right), \\ \mathcal{O}_8 &= \vec{S}_\chi \cdot \vec{v}_\perp, \\ \mathcal{O}_{11} &= i \vec{S}_\chi \cdot \frac{\vec{q}}{m_N}, \end{aligned}$$

Exploring different scenarios

- $M_\chi = 100 \text{ GeV}/c^2$.
- Isoscalar coupling ($c_p = c_n$).
- Arbitrary cross section considered, just for comparison of shapes.

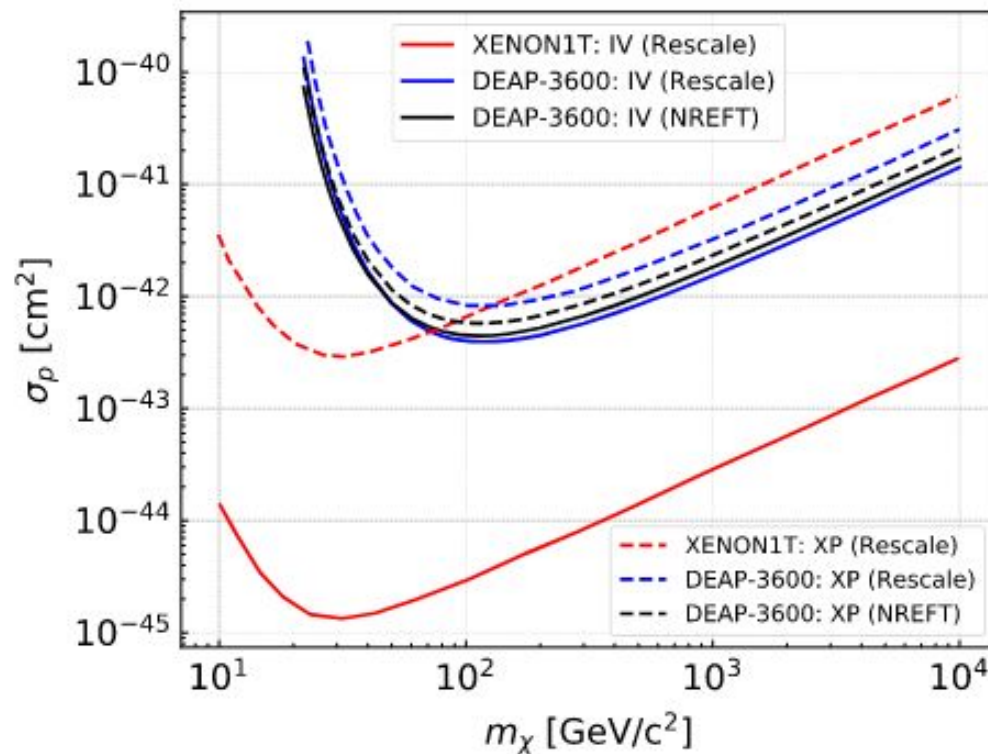


Exploring different scenarios

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)



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

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

$$\text{IS} \quad c_i^n = c_i^p$$

$$\text{IV} \quad c_i^n = -c_i^p$$

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

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	v_θ	v_ϕ	$ \sigma_{rr} $	$ \sigma_{\theta\theta} $	$ \sigma_{\phi\phi} $	η_{sub}
				(km/s)			(km/s)			
	<i>Gaia</i> Sausage (Necib <i>et al.</i>)	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
	<i>Gaia</i> Sausage (O’Hare <i>et al.</i>)	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

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

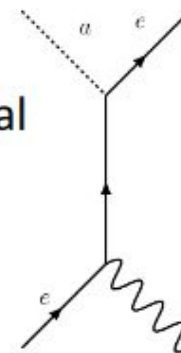
- **Axio-electric effect**

- Get 1 electron with 5.5 MeV kinetic energy

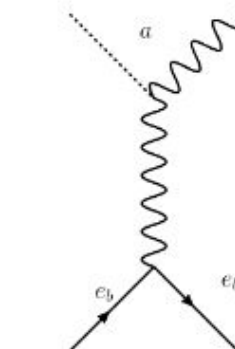
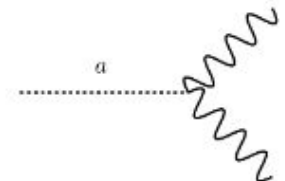
- **Axion decay into 2 gammas**

- Get 2 gammas with 5.5 MeV total energy

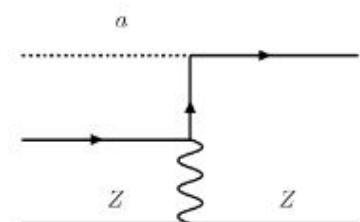
Compton Conversion



Decay to 2γ



Inverse Primakov



Axio-Electric Effect