ICHEP 2024
PRAGUE

Dark matter search in DEAP-3600: status and prospects

Dr. Michela Lai on behalf of

DEAP 3600

Carleton University

Queen's University

UC Riverside

INFN Istituto Nazionale di Fisica Nucleare

Particle Physics Rutherford Appleton Laboratory

Instituto de Física

AstroCeNT Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

Technical University of Munich TUM

US University of Sussex

SNOLAB

TRIUMF

Princeton University

Johannes Gutenberg Universität Mainz JGU

Royal Holloway University of London

National Research Center "Kurchatov Institute"

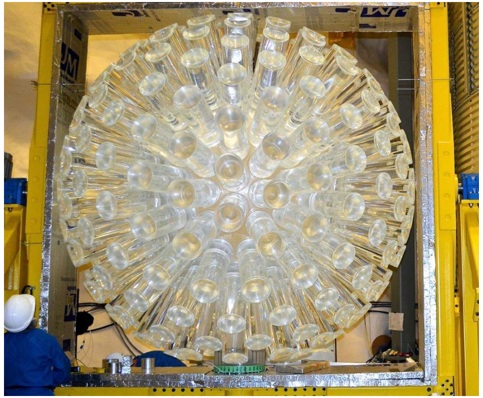
Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

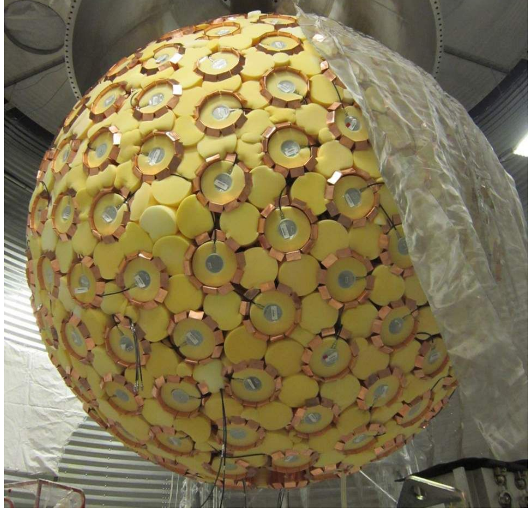
University of Alberta

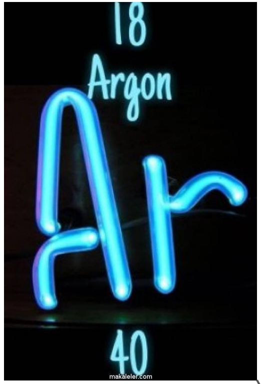
Gobierno de España
Ministerio de Ciencia, Innovación y Universidades
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

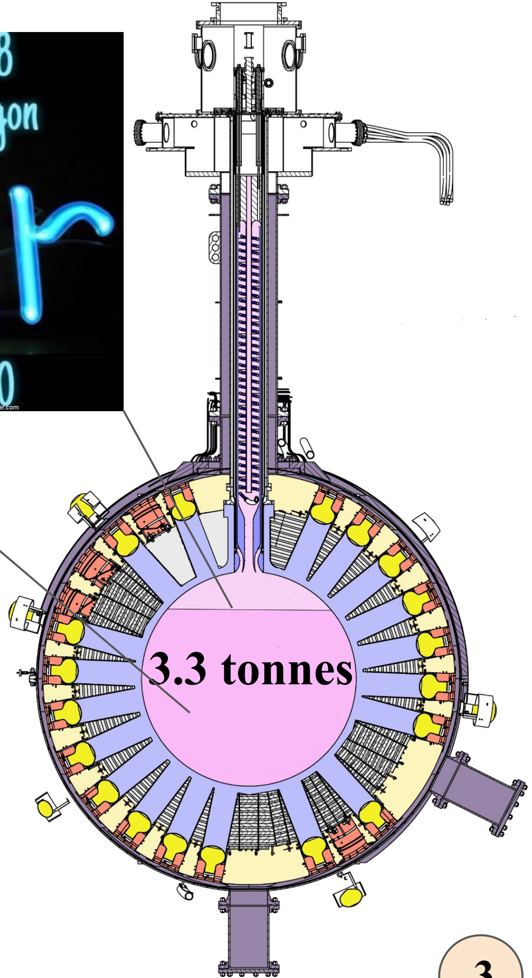
Laurentian University
Université Laurentienne

The detector





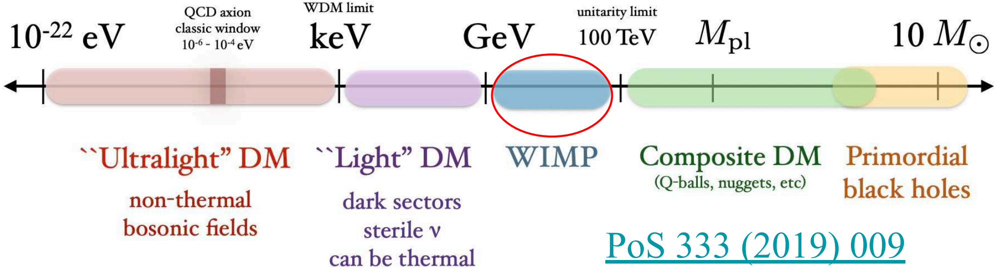




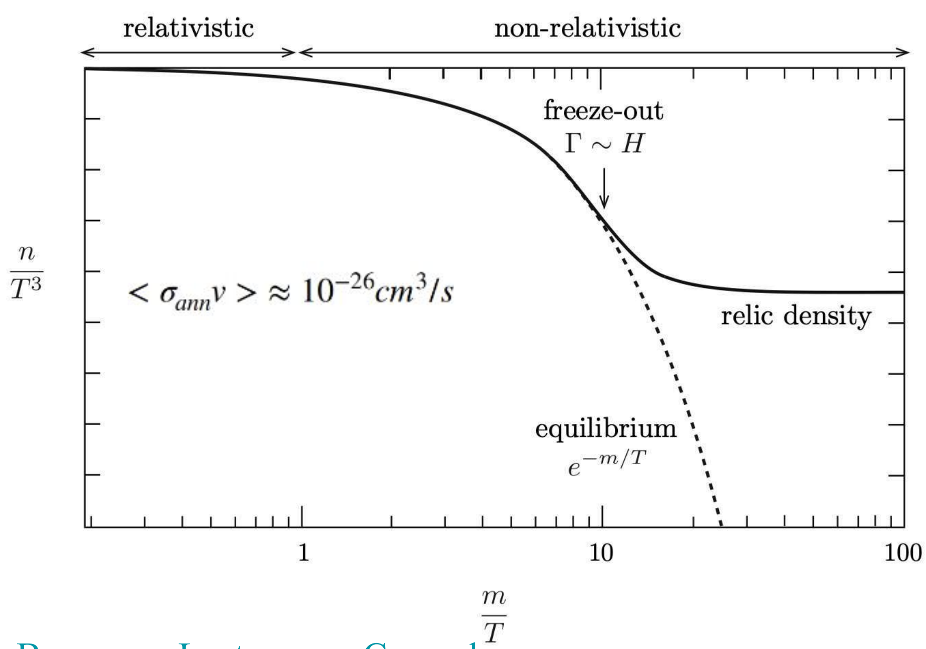
Astroparticle Physics 108 (2019) 1-23

WIMP Search

DEAP-3600 is the largest running experiment designed for the direct detection of Weakly Interacting Massive Particles

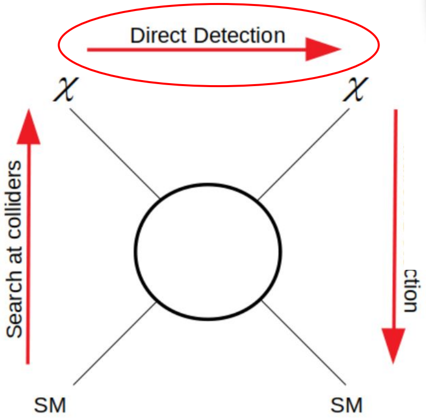


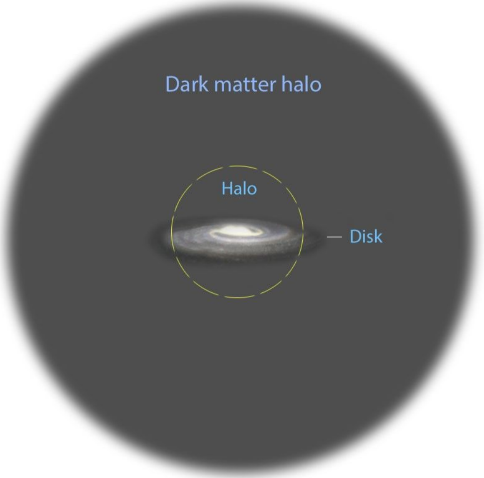
[PoS 333 (2019) 009](PoS 333 (2019) 009)



Baumann, Lectures on Cosmology

WIMP miracle: for dark matter candidates with masses of about 1 TeV, the coupling is equal to that of weak scale.



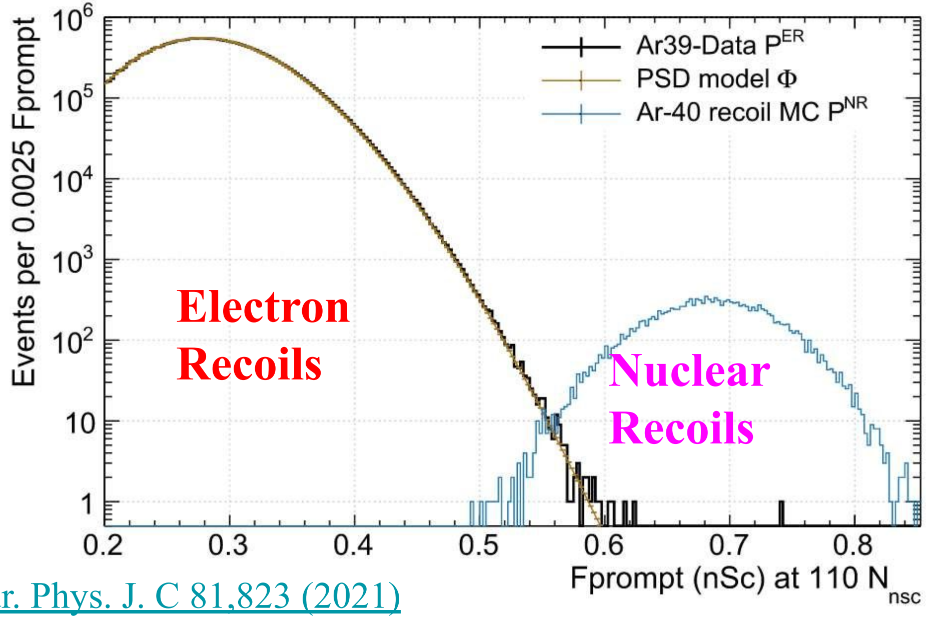


Milky Way model

Dark Matter **E**xperiment Using **A**rgon **P**ulse Shape Discrimination

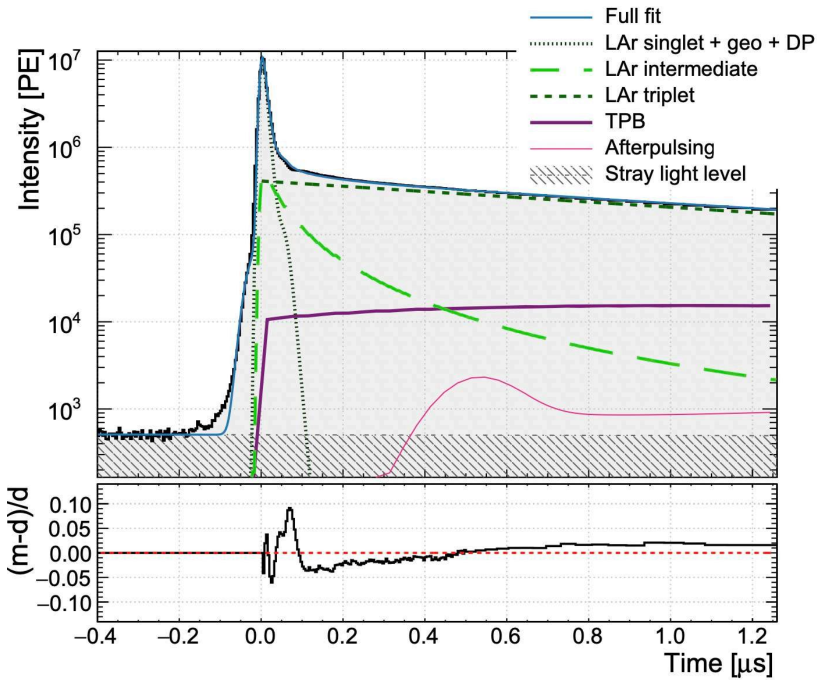
$$I_{LAr}(t) = \frac{R_s}{\tau_s} e^{-t/\tau_s} + \frac{1 - R_s - R_t}{\tau_{rec}(1 + t/\tau_{rec})^2} + \frac{R_t}{\tau_t} e^{-t/\tau_t}$$

$\tau_t = 1445ns$ $\quad \tau_s = 8.2ns$ $\quad \tau_{rec} = 175.5ns$ $\quad R_t = 0.71$ $\quad R_s = 0.23$



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

Pulse Shape for ^{39}Ar βs induced electron recoils



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

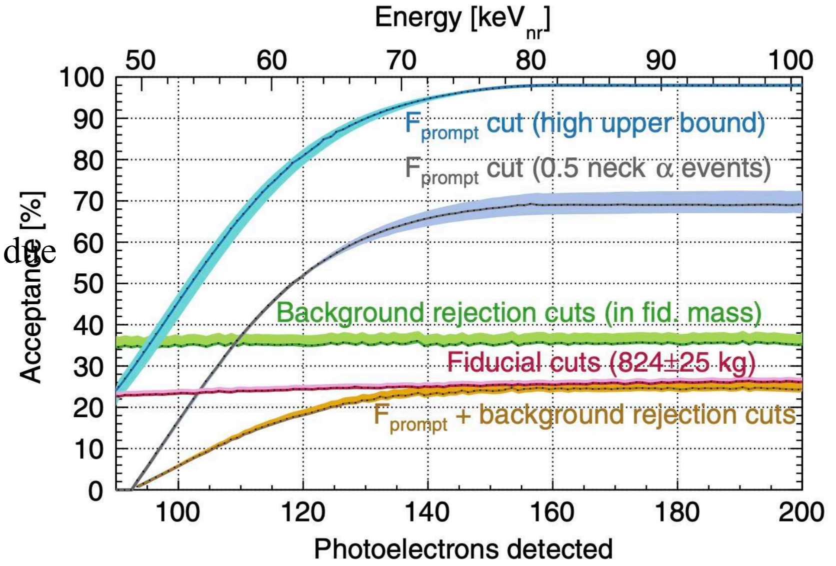
Eur. Phys. J. C 80, 303 (2020)

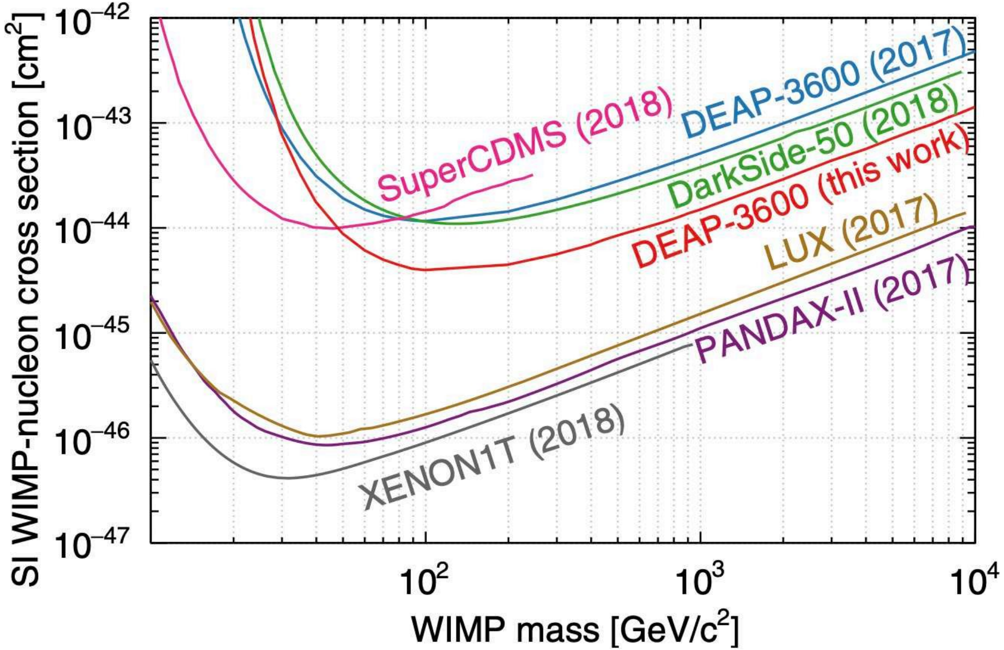
WIMP Search

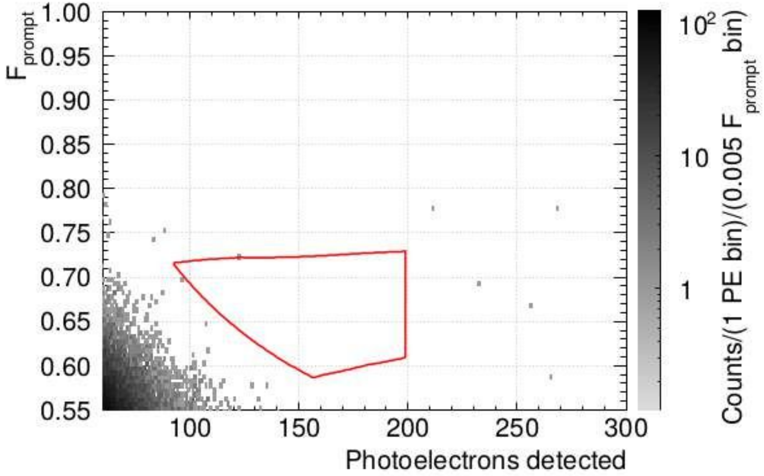
Phys. Rev. D 100, 022004

Last published WIMP Search in 2019

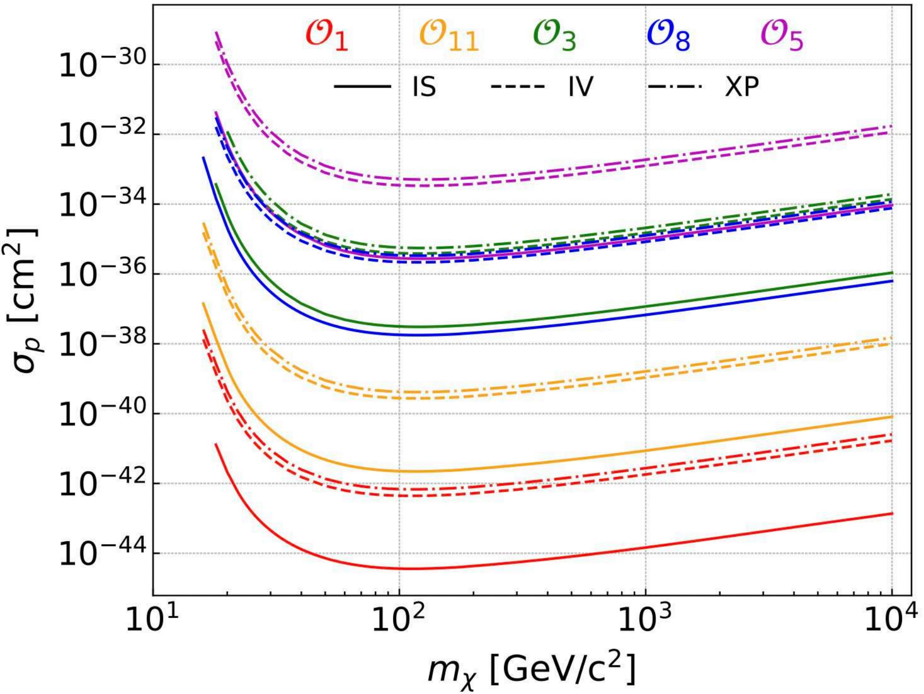
PSD + Fiducial cuts allowed for low background in the ROI, mainly due to neck alphas and dust alphas

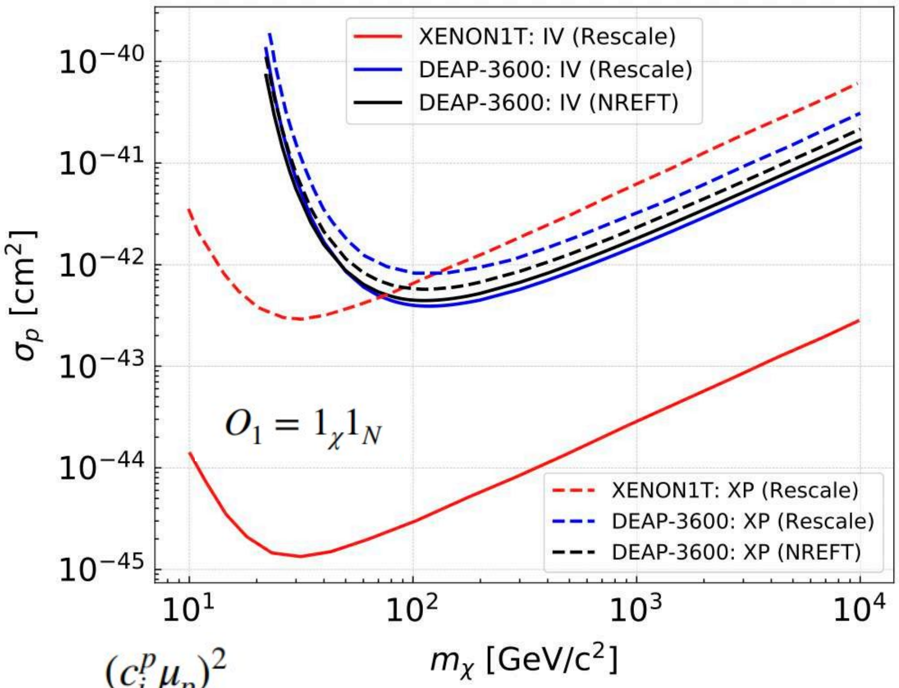






WIMP Search





$$\sigma^p = \frac{(c_i^p \mu_p)^2}{\pi}$$

IS $\sigma_i^n = \sigma_i^p$ IV $\sigma_i^n = -\sigma_i^p$ XP $\sigma_i^n = -0.7\sigma_i^p$

[Phys. Rev. D 102, 082001 (2020)]

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

$$O_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right) \qquad O_8 = \vec{S}_\chi \cdot \vec{v}_\perp \qquad O_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

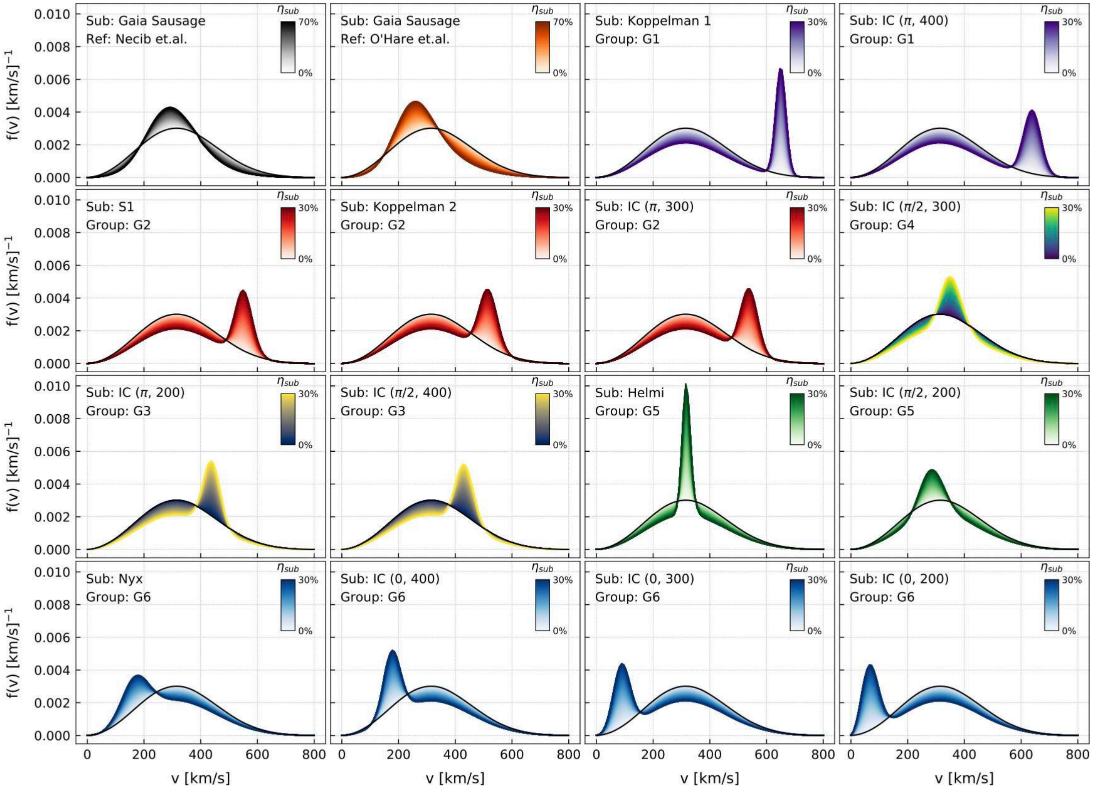
Evaluated exclusion limits within the
Non-Relativistic Effective Field Theory (NREFT)...

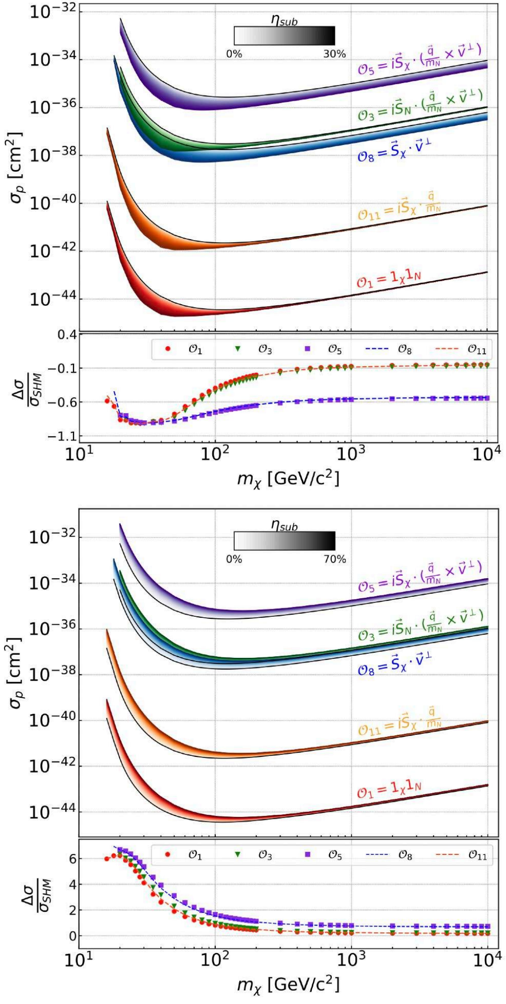
WIMP Search

[Phys. Rev. D 102, 082001 (2020)](https://doi.org/10.1103/PhysRevD.102.082001)

And non standard kinematic distribution of the dark matter halo

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



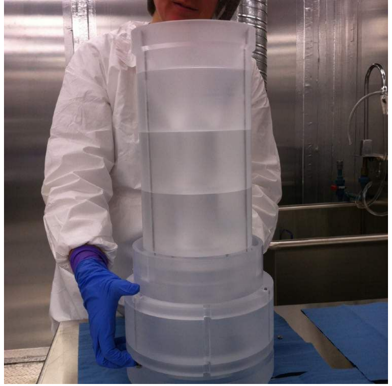


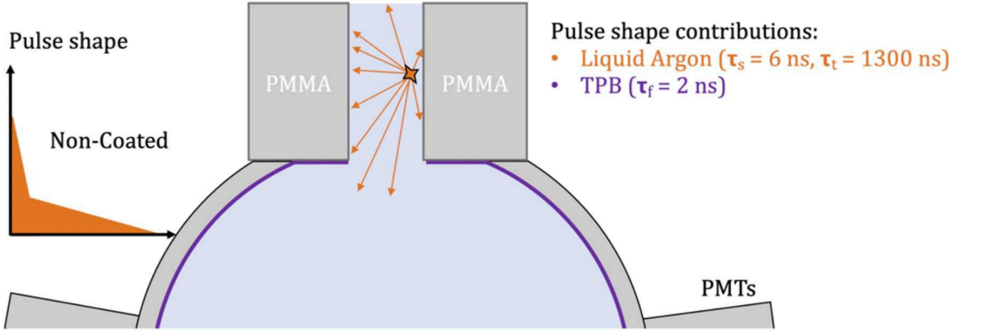
(a) *Gaia* Sausage (Necib)

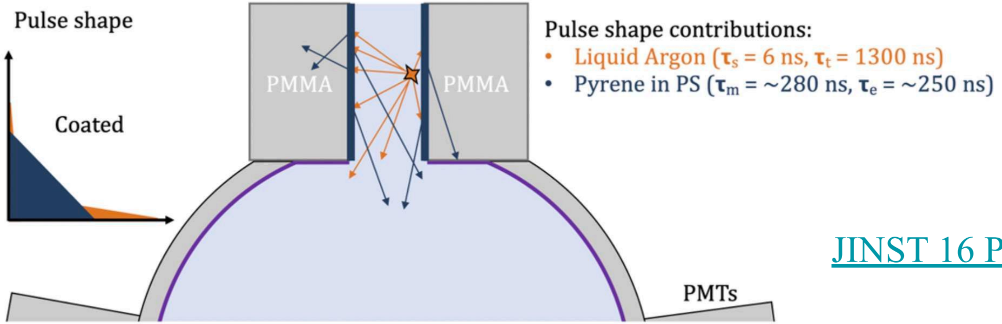
Detector upgrades vs neck alphas

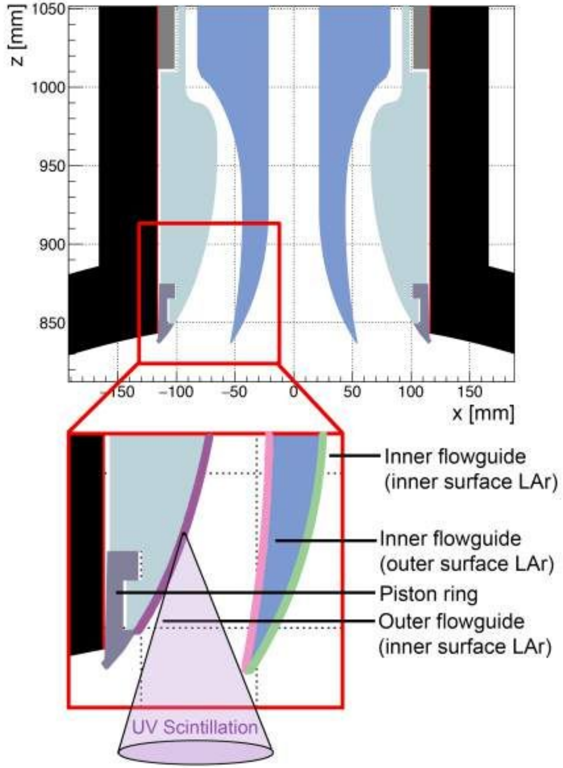
External cooling system to prevent gas argon condensation on the flowguides and consequent alphas scintillation

Installed pyrene-coated flowguides to improve PSD against neck alphas





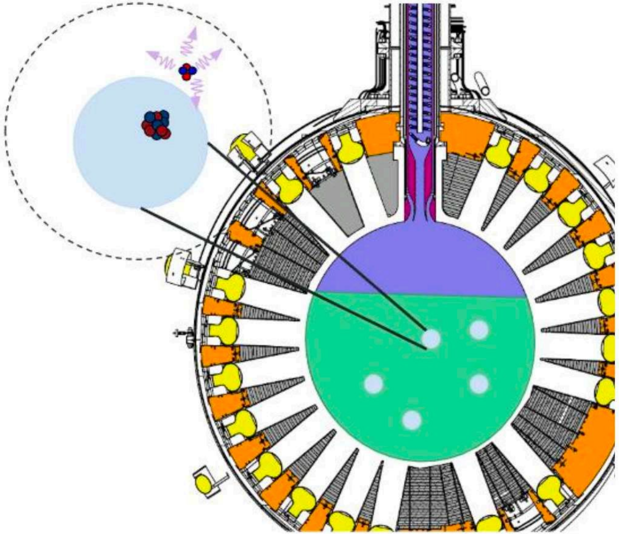




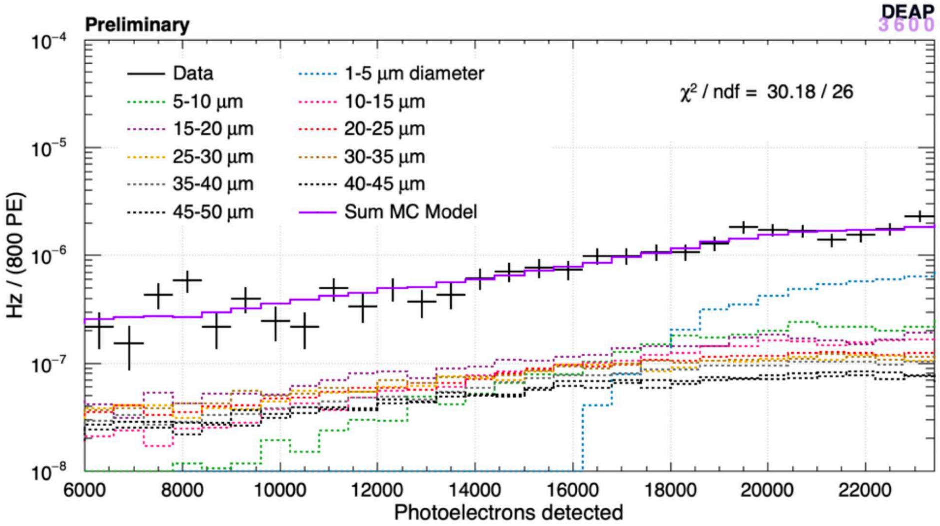
JINST 16 P12029

Detector upgrades vs dust alphas

Additional Alpha decays background consistent with metallic dust particulates ranging from 1 um - 50 um in diameter.
Could have entered the inner vessel during the purging with LN_2, after the resurfacing of the inner surface



Reduction of dust background by extraction
and filtration of LAr



^{39}Ar Specific activity

Most precise measurement of atmospheric ^{39}Ar specific activity up to date

$$S_{^{39}Ar} = \frac{N_{single} + N_{pile-up}}{m_{LAr} T_{livetime}}$$

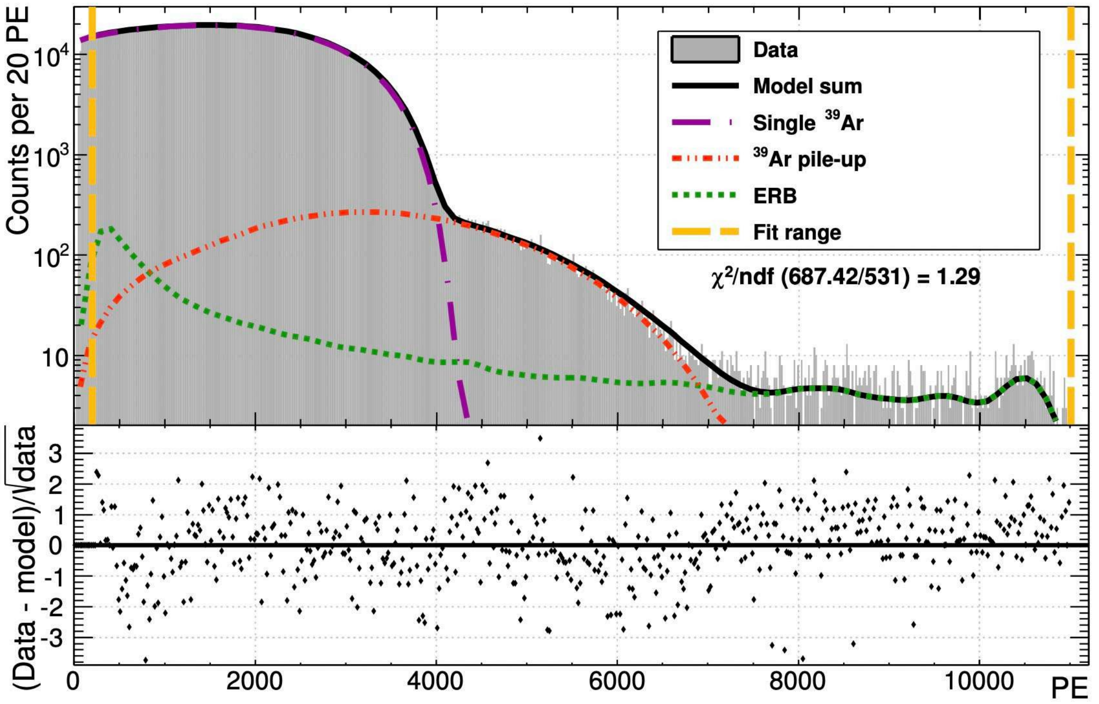
Updated measurement for the liquid argon target

First $\quad m_{LAr} = (3269 \pm 96)kg$

This work! $\quad m_{LAr} = (3269 \pm 24)kg$

Contribution from pile up from double and triple ^{39}Ar, other electron recoil + ^{39}Ar, Cherenkov + ^{39}Ar

$$N_{pile-up} = N_{double} + N_{triple} + N_{ERB,39Ar} + N_{hFp,39Ar}$$



$$T_{livetime} = T_{run} - \sum_{i=1}^{N_{DCcut}} \delta t_i - N_{LLcut} \cdot \delta t_{cut} - N_{phys} \cdot (\delta t_{cut} - \delta t_{int})$$

$$\delta t_{cut} = 32\mu s \qquad \delta t_i \leq 32\mu s \qquad \delta t_{int} = 10\mu s$$

Analysis performed on $T_{livetime}$ = 167 days

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

^{39}Ar Specific activity

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

Fit performed with both Bayesian and Frequentist approaches

Digital Trigger module prescaling = 100

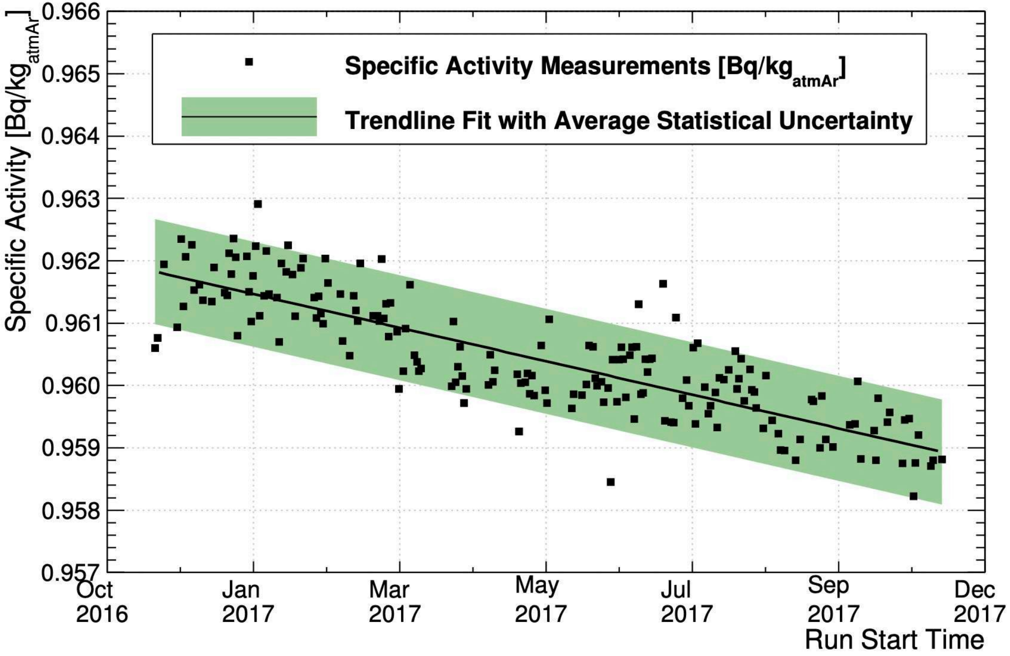
$$N_{single} = \frac{n_{fit,single} \cdot a_{presc}}{\epsilon_{fit,single} \cdot b} \qquad N_{double} = \frac{n_{fit,double} \cdot a_{presc}}{\epsilon_{fit,double} \cdot b}$$

Selection cuts efficiencies

Fit bin width = 20

$$S_{^{39}Ar} = \frac{N_{single} + N_{pile-up}}{m_{LAr} T_{livetime}}$$

$$S_{^{39}Ar} = (0.964 \pm 0.001(stat) \pm 0.024(syst)) Bq/kg_{Ar}$$



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

Alpha Quenching relative measurement

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

$$^{222}_{86}\mathrm{Rn} \xrightarrow{\alpha} {}^{218}_{84}\mathrm{Po} \xrightarrow{\alpha} {}^{214}_{82}\mathrm{Pb} \xrightarrow{\beta} {}^{214}_{83}\mathrm{Bi} \xrightarrow{\beta} {}^{214}_{84}\mathrm{Po} \xrightarrow{\alpha} {}^{210}_{82}\mathrm{Pb}$$

QF for ^{210}Po from Doke et al = 0.710 ± 0.028 (5.305MeV)

$$\mathrm{QF}_\alpha = \frac{\mathrm{PE}_\alpha}{Y \times E_{\alpha,\mathrm{dep}}}$$

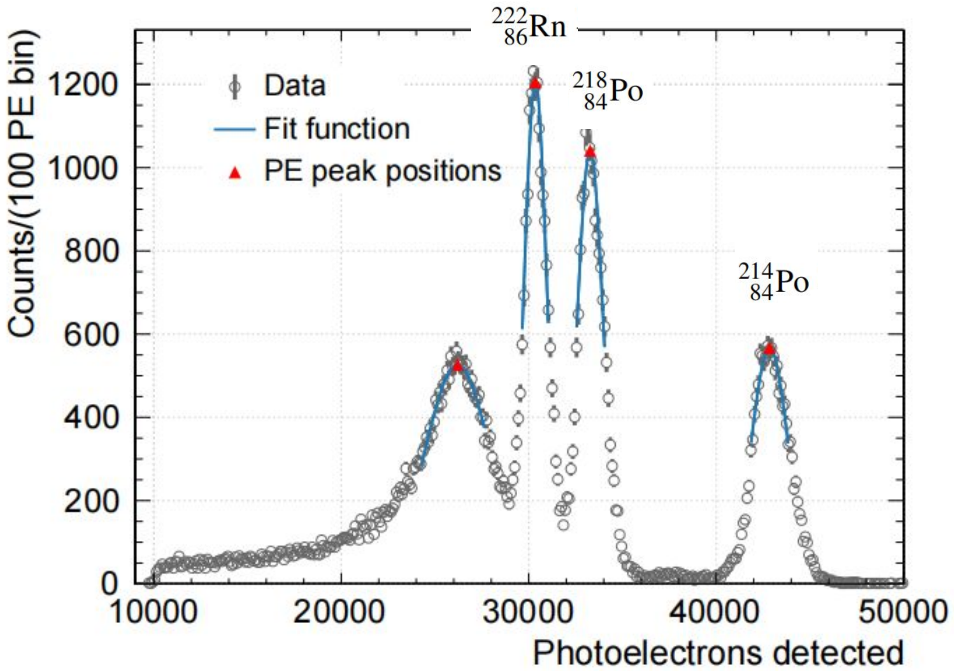
Two more data points from relative measurements to reduce the impact of non-linearity in the light detection efficiency

$$\frac{\mathrm{QF}_{\alpha,{}^{218}\mathrm{Po}}}{\mathrm{QF}_{\alpha,{}^{222}\mathrm{Rn}}} = \frac{\mathrm{PE}_{\alpha,{}^{218}\mathrm{Po}}}{\mathrm{PE}_{\alpha,{}^{222}\mathrm{Rn}}} \times \frac{E_{\alpha,{}^{222}\mathrm{Rn}}}{E_{\alpha,{}^{218}\mathrm{Po}}} \equiv R_2 \times \frac{E_{\alpha,1}}{E_{\alpha,2}},$$

$$\frac{\mathrm{QF}_{\alpha,{}^{214}\mathrm{Po}}}{\mathrm{QF}_{\alpha,{}^{222}\mathrm{Rn}}} = \frac{\mathrm{PE}_{\alpha,{}^{214}\mathrm{Po}}}{\mathrm{PE}_{\alpha,{}^{222}\mathrm{Rn}}} \times \frac{E_{\alpha,{}^{222}\mathrm{Rn}}}{E_{\alpha,{}^{214}\mathrm{Po}}} \equiv R_3 \times \frac{E_{\alpha,1}}{E_{\alpha,3}}.$$

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Relative Measurement and Extrapolation of the Scintillation Quenching Factor of α-Particles in Liquid Argon using DEAP-3600 Data

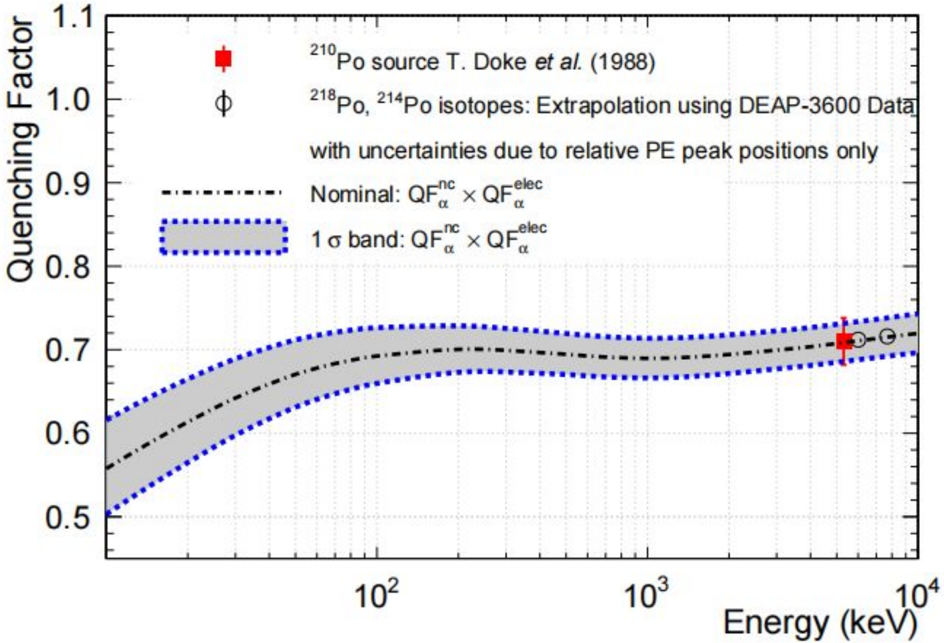


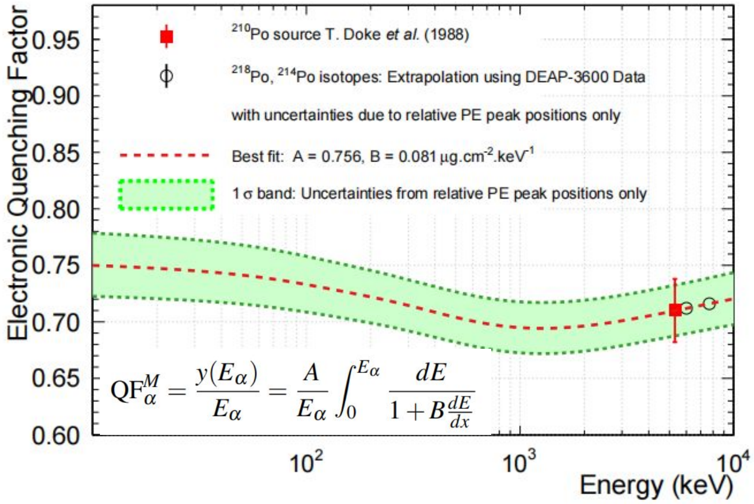
arXiv:2406.18597v1

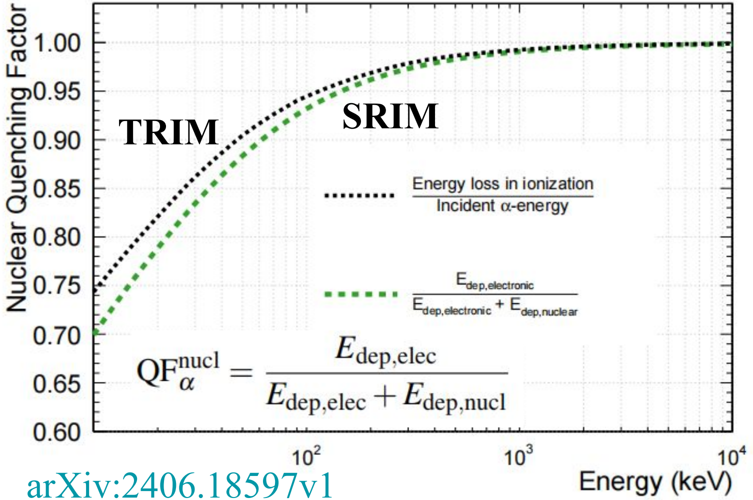
Alpha Quenching relative measurement

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

The energy-dependent QF product of the best-fit electronic QF curve and the nuclear QF curve from TRIM







arXiv:2406.18597v1

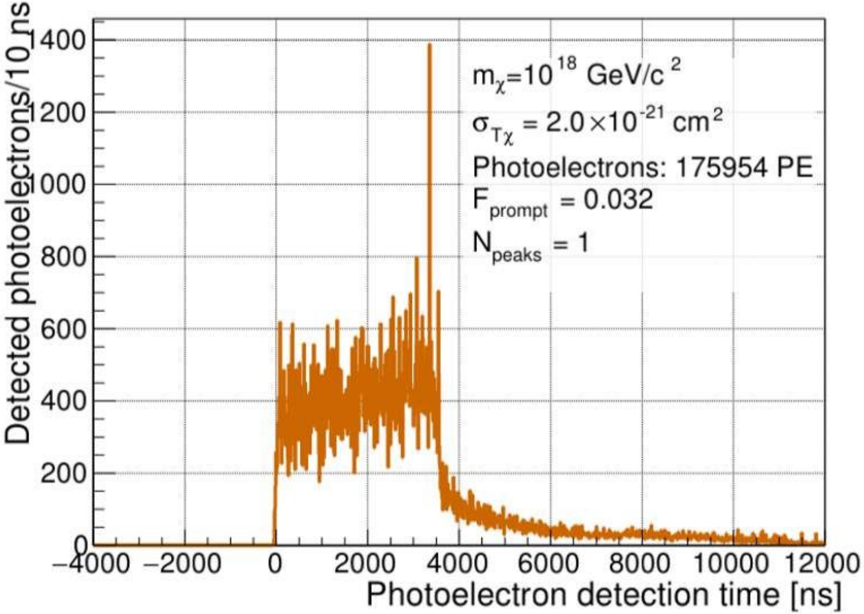
Multi-scattering, super-heavy dark matter search

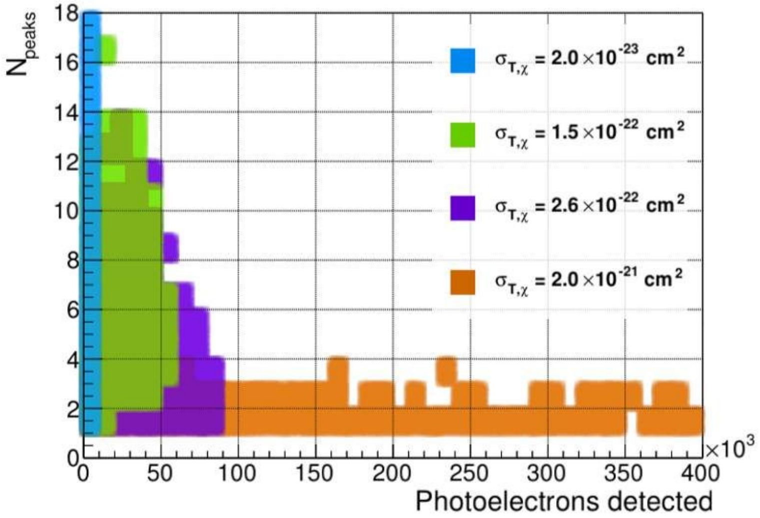
Phys. Rev. Lett. 128, 011801 (2022)

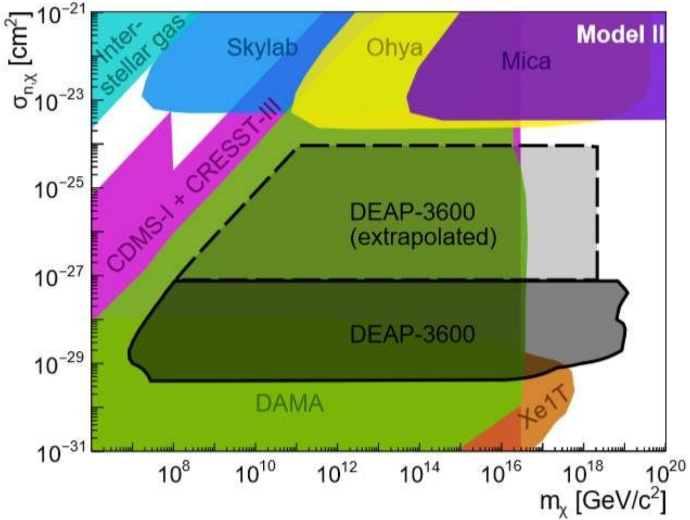
Extremely low number density in the halo, need for tonne-scale exposure and pretty high cross-section, hence multi-scattering in LAr!

Main backgrounds from ^{39}Ar + (n, γ) pile-ups

World-leading exclusion limits among direct detection experiments at Planck scale masses







Coming soon: First search for solar neutrino absorption in ^{40}Ar

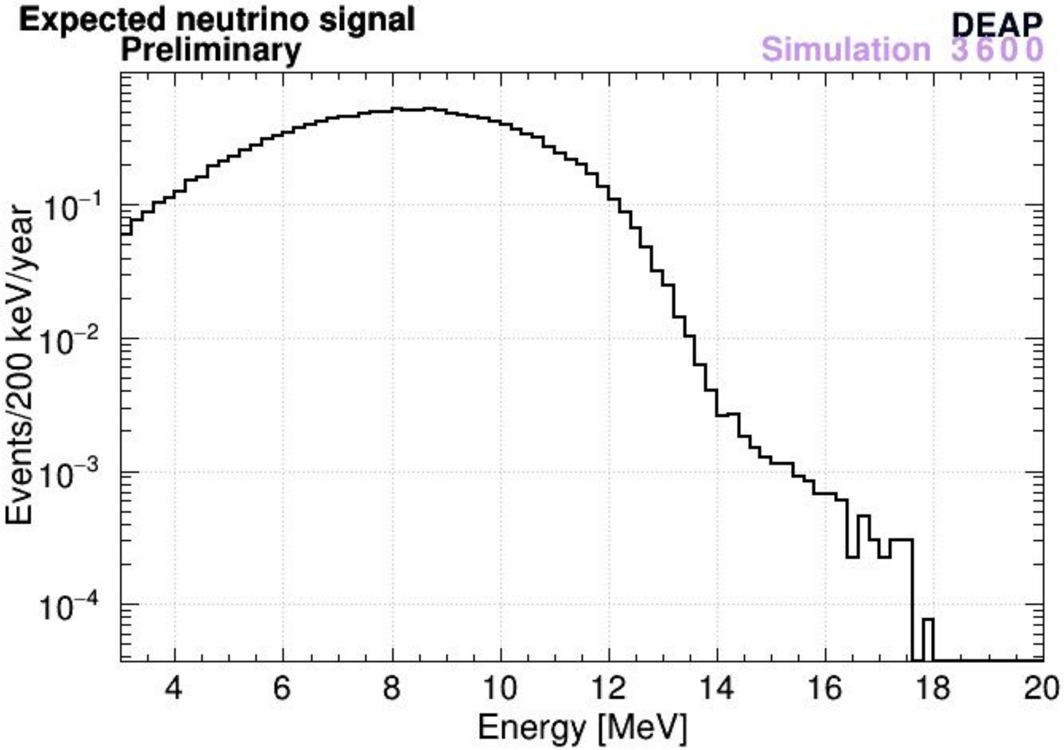
$$\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$$

Fundamental process for future multi-tonne dark matter and neutrino detectors!

R. S. Raghavan (1986): the process can be observed via the super-allowed 0+ → 0 + Fermi transition from the ground state of ^{40}Ar to an excited state of ^{40}K.

M. Bhattacharya et al. : measured Gamow-Teller (GT) strengths for transitions from ^{40}Ar to ^{40}K*

Energy threshold decreased from 5.885 MeV (Fermi) to 3.9 MeV (GT)



Main backgrounds: cosmogenics (above 10 MeV) and pile-ups (below 10 MeV)

- **DEAP-3600 is the largest running dark matter detector filled with liquid argon**
- **Set most stringent WIMP exclusion limits in argon above 20 GeV in 2019**
- **New WIMP search will be out this year**
- **Third fill after hardware upgrades starting this year**
- **Most precise measurement of ^{39}Ar activity**
- **New relative alpha quenching measurements in LAr**
- **World-leading exclusion limits for multi-scattering, Planck scale candidates**
- **Neutrino absorption in ^{40}Ar analysis coming soon**