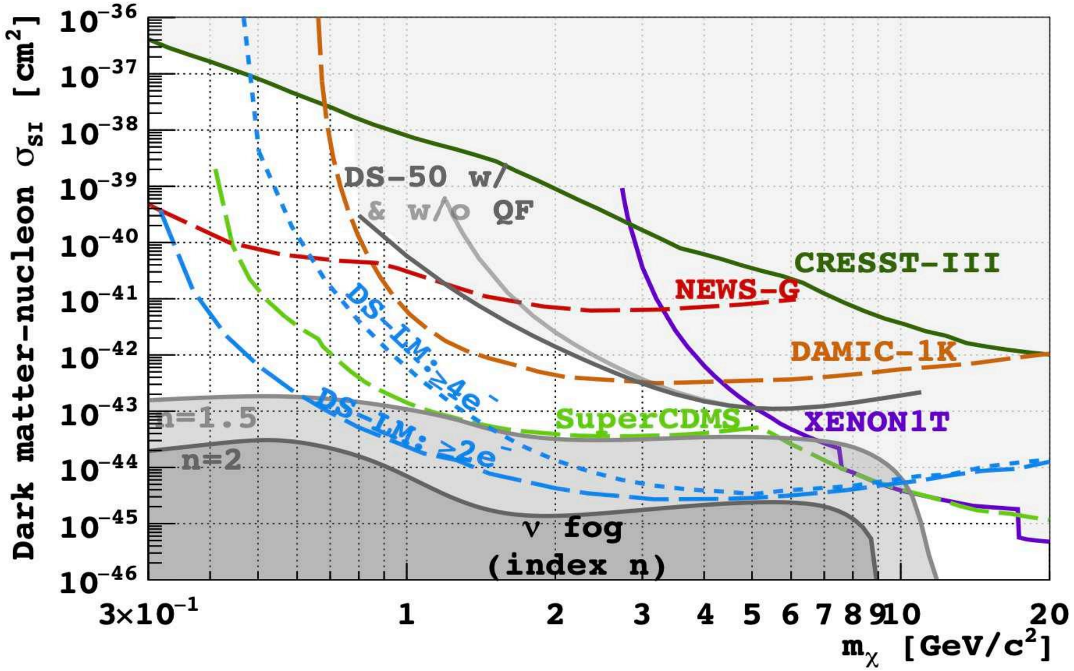
DarkSide-LowMass: Sensitivity projections for a Liquid Argon Detector optimized for GeV-Scale Dark Matter

Speaker:
Dr. **Michela Lai**,
University of California Riverside
on behalf of the
Global Argon Dark Matter Collaboration (GADMC)

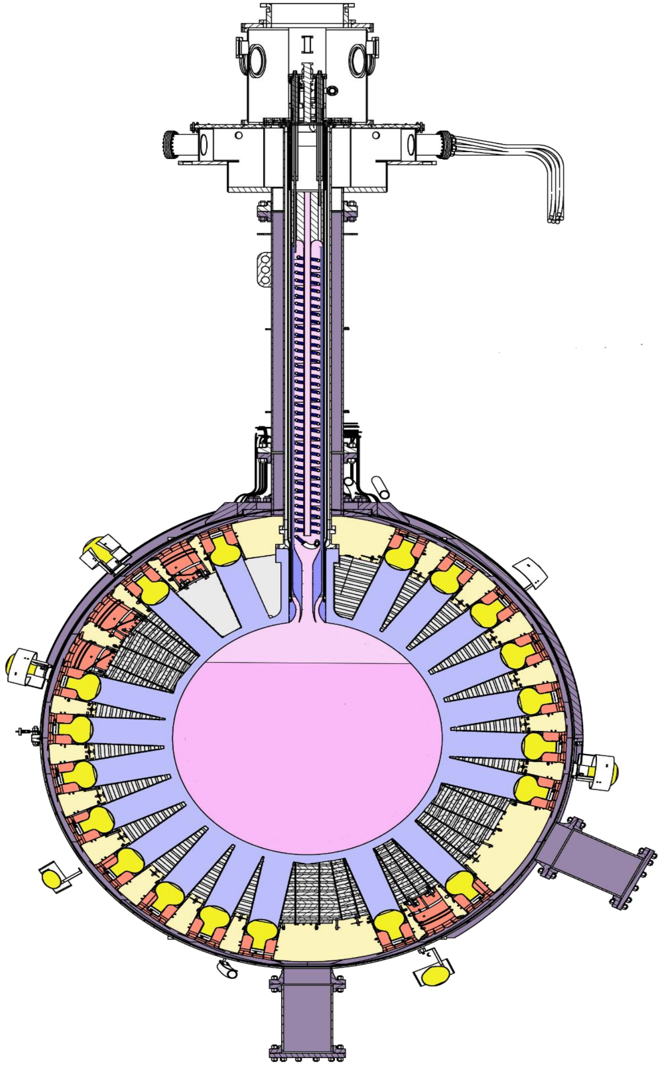
Future projects workshop

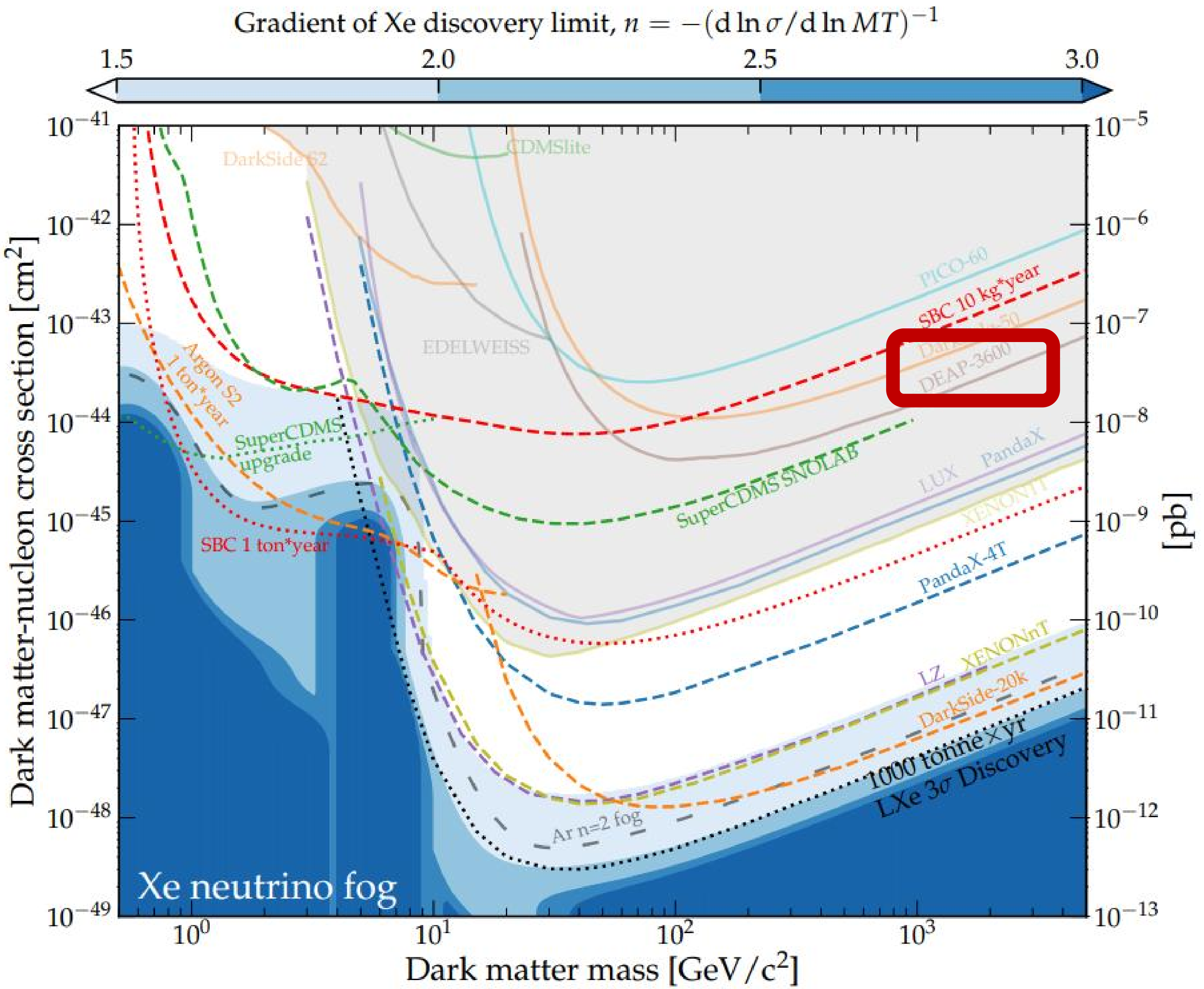
29th April 2025 - SNOLAB



[Phys. Rev. D 107, 112006 (2023)]

WIMP search in LAr





[ArXiv 2203.08084](https://arxiv.org/abs/2203.08084)

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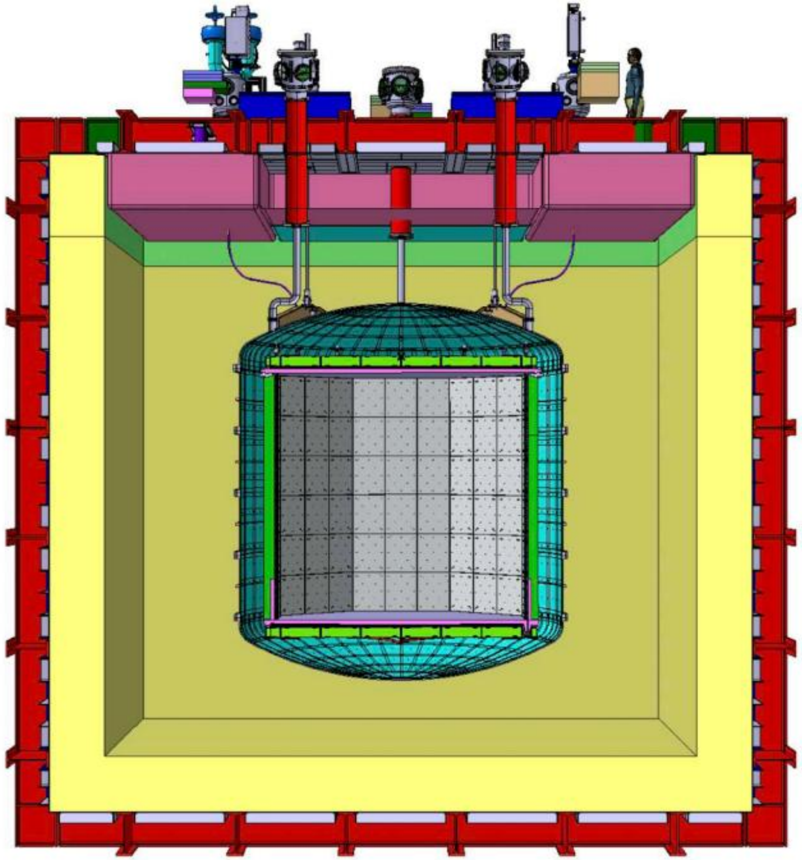

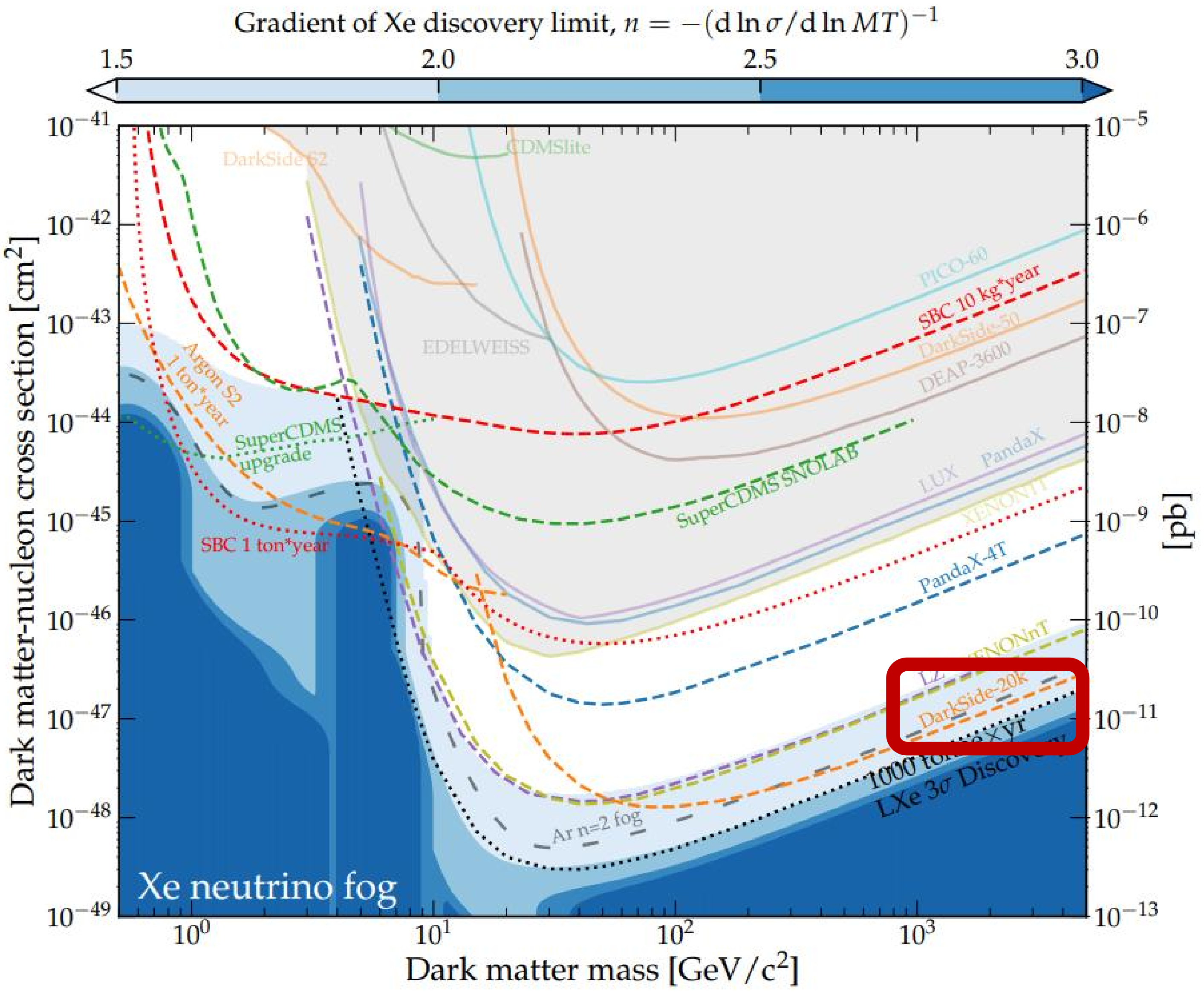

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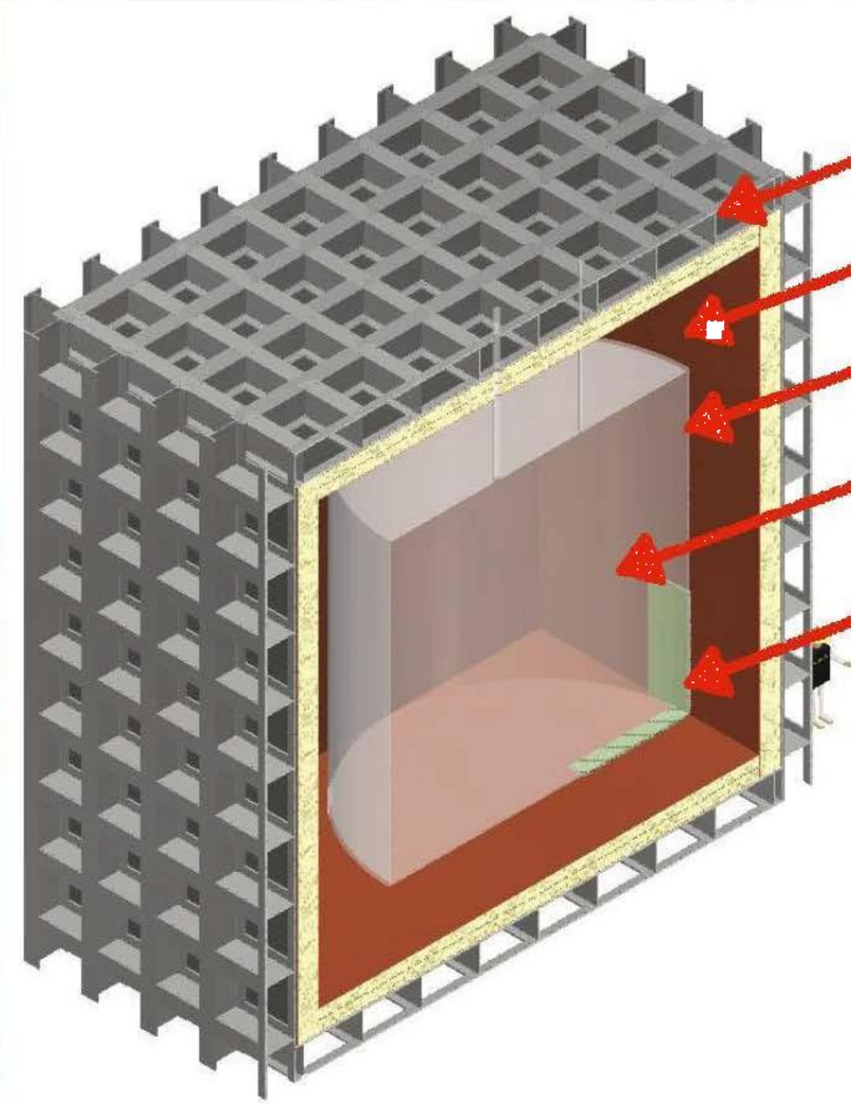

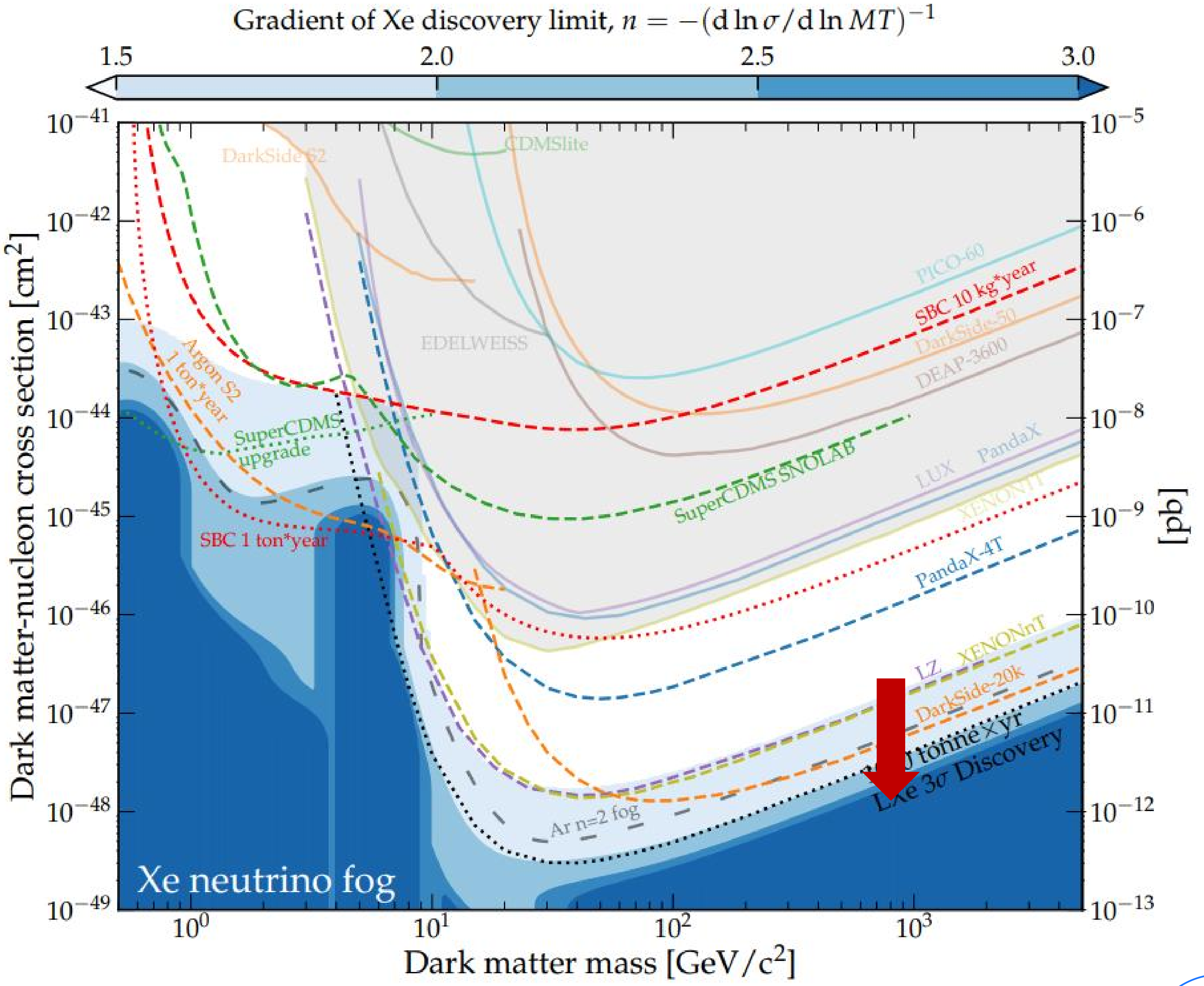

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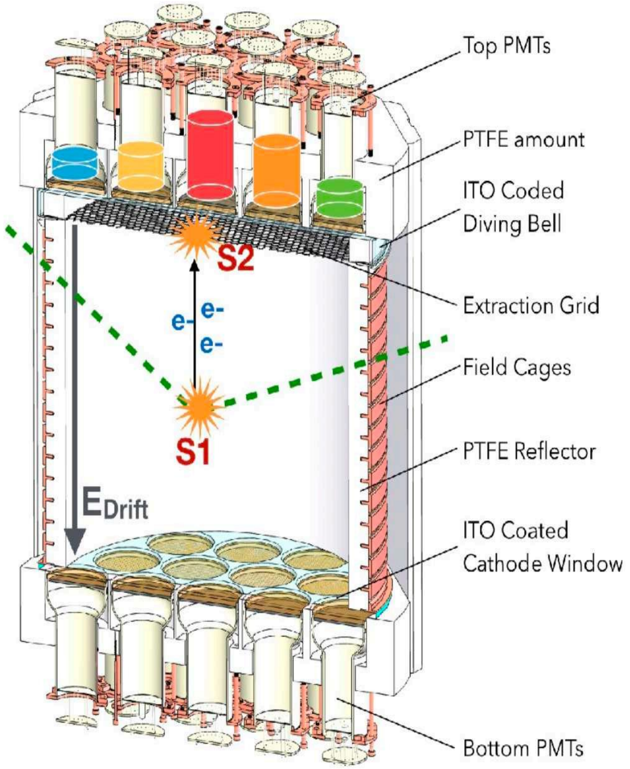
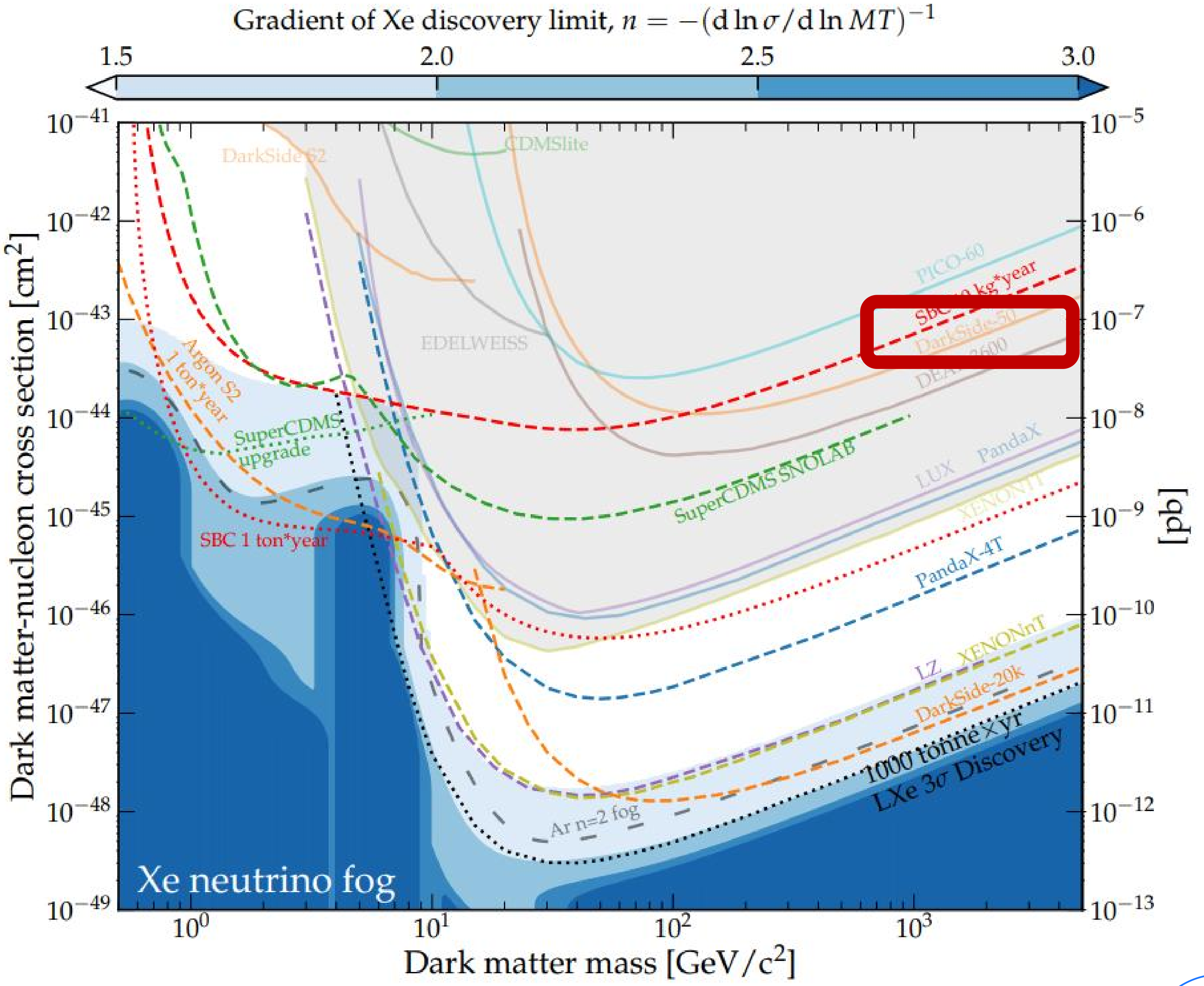


Drawing of DarkSide-50

- S1: PSD, Prompt signal, ~ 20 % photons detected
- S2: nearly 100 % electrons detected, multi-site event rejection, position reconstruction



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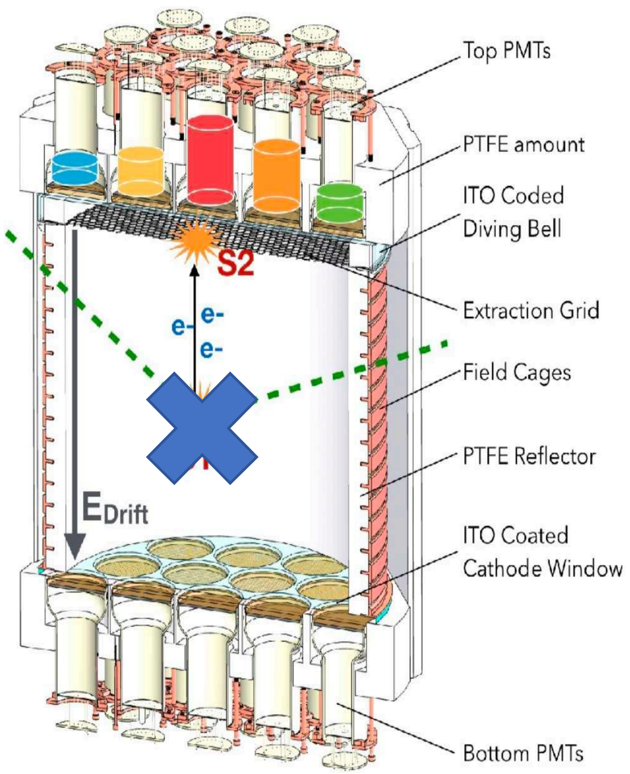
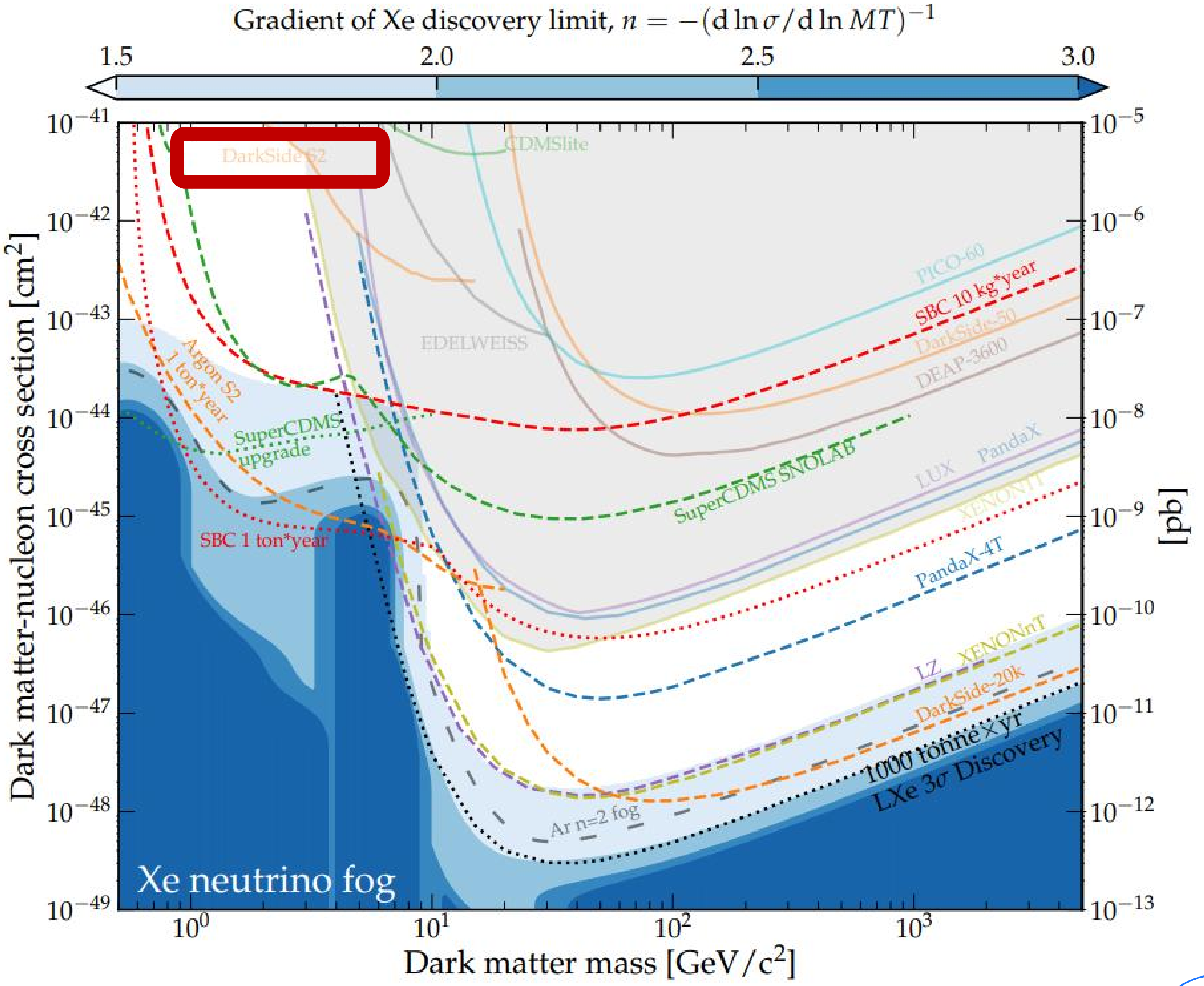
WIMP search in LAr



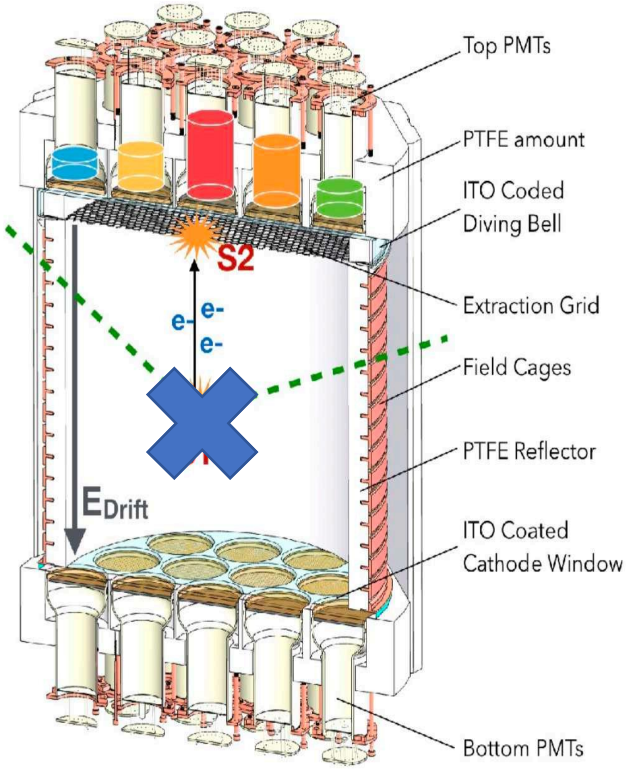
Drawing of DarkSide-50



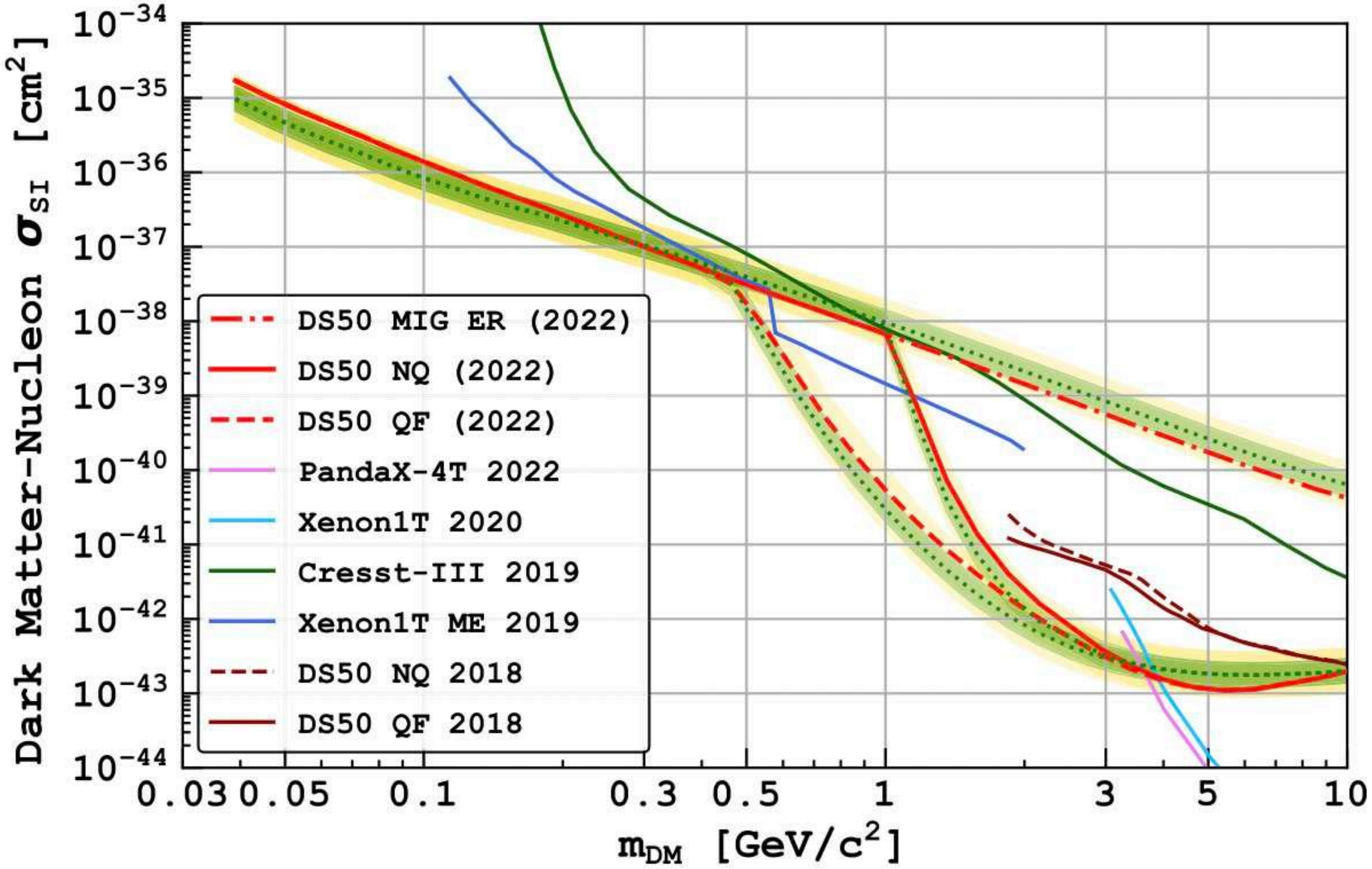
- Pro: Low threshold TPC via S2-only analysis
- Cons: No PSD, no z-fiducialization, time resolution limited by the drift time

ArXiv 2203.08084

Low-Mass search with DarkSide-50



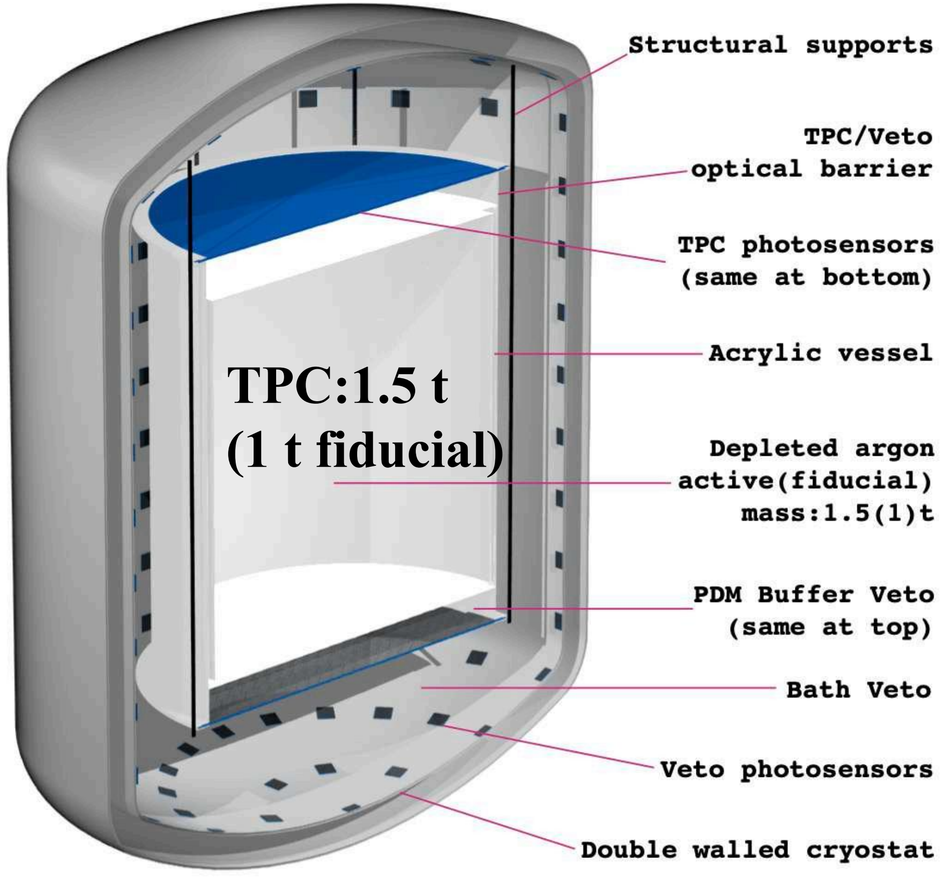
Drawing of DarkSide-50

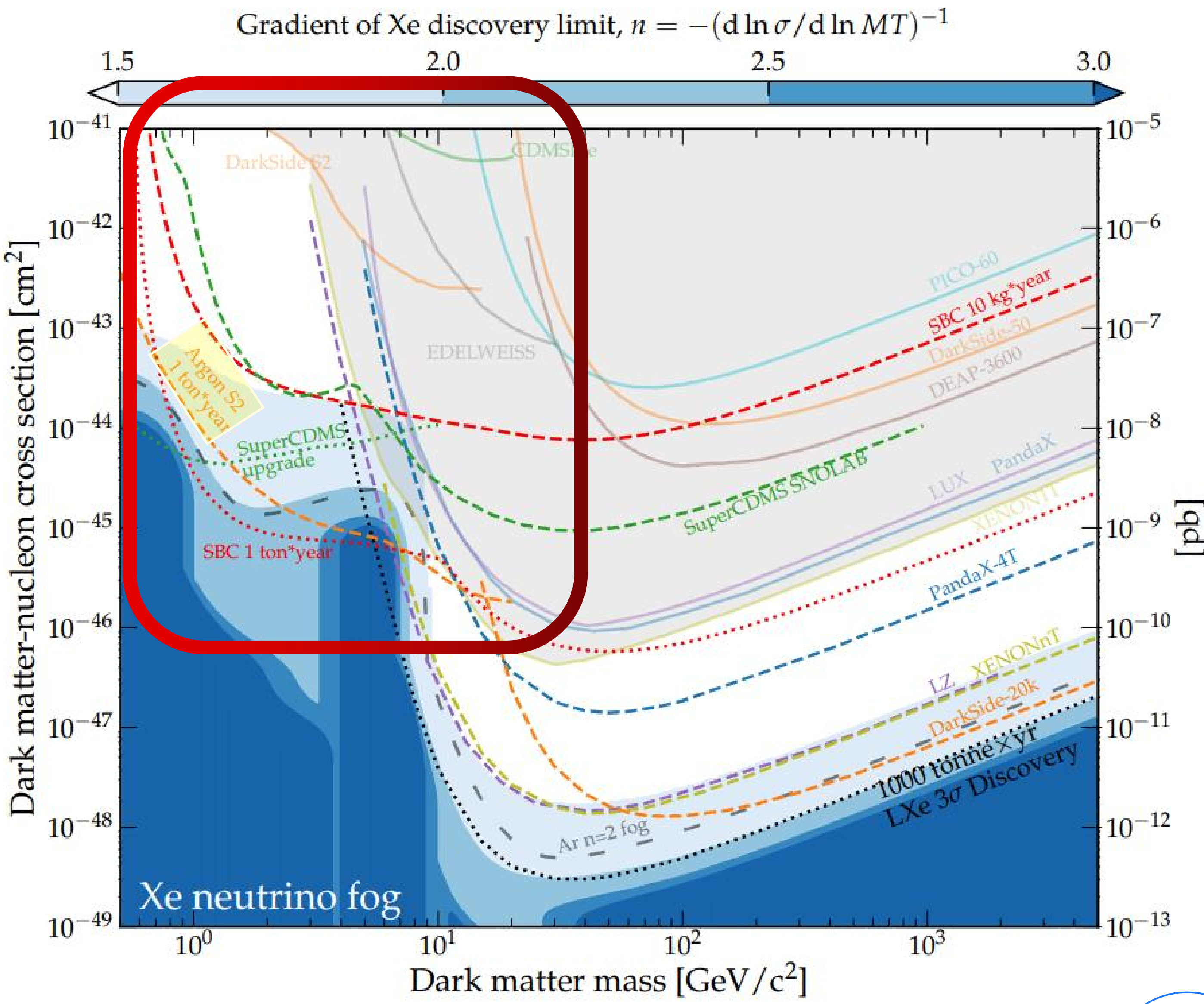


Set world-leading exclusion limits at sub-GeV candidates!

[Phys. Rev. Let. 130, 101001 (2023)]

DarkSide-LowMass!

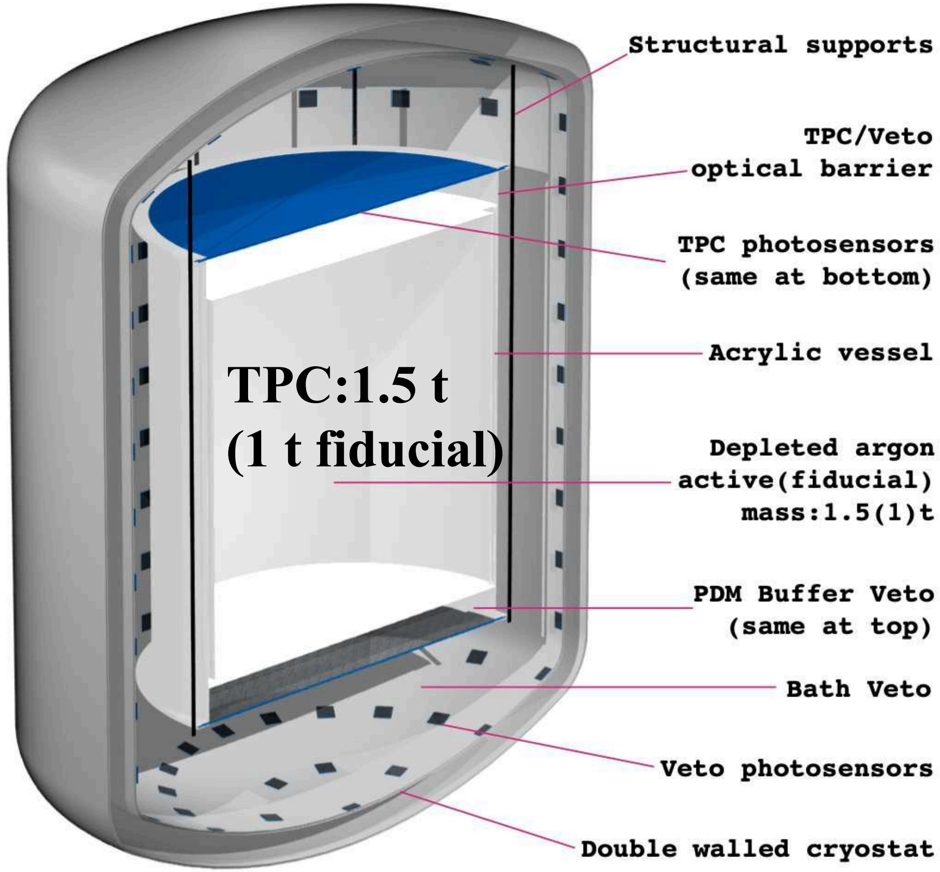


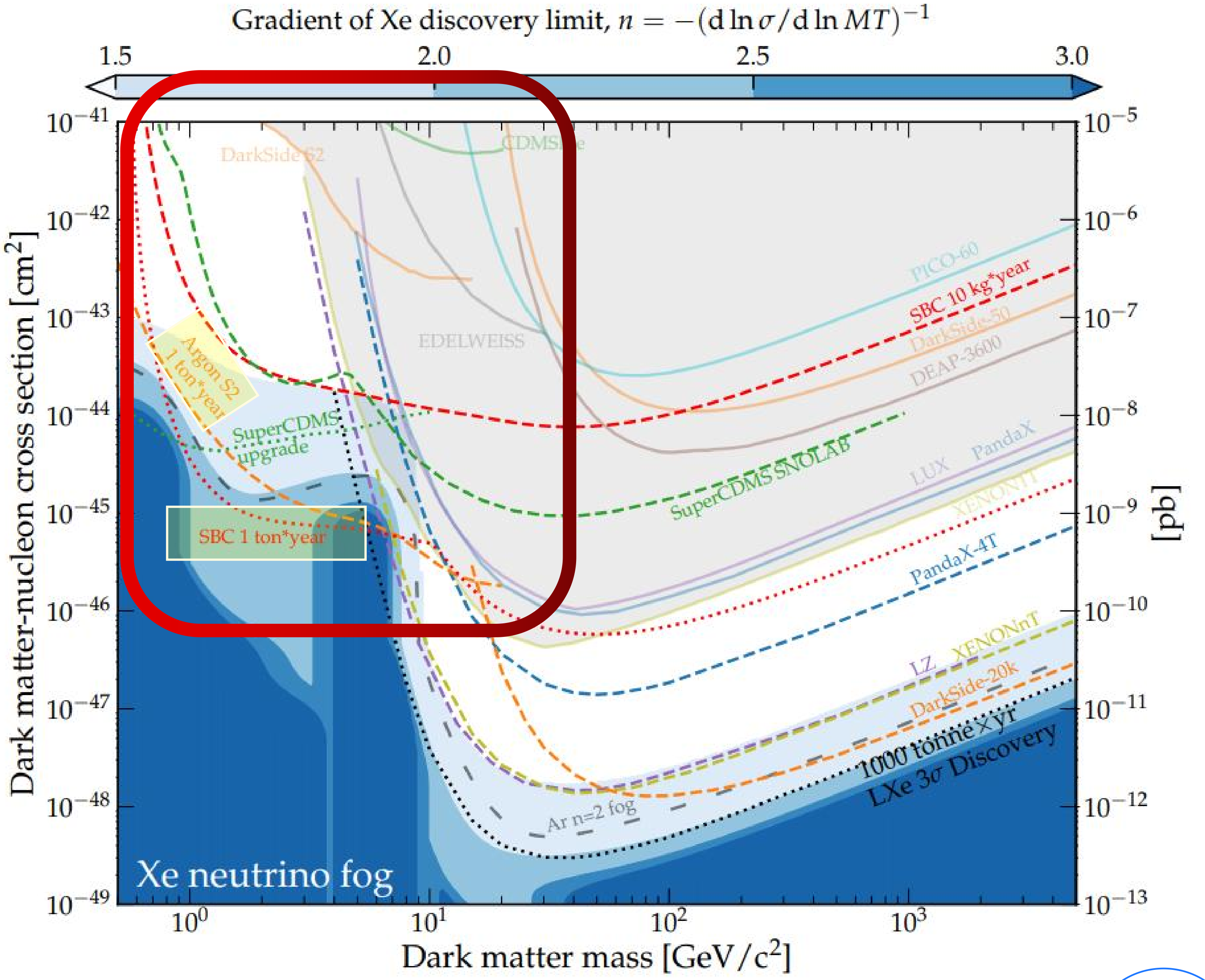


[Phys. Rev. D 107, 112006 (2023)]

[ArXiv 2203.08084]

DarkSide-LowMass!



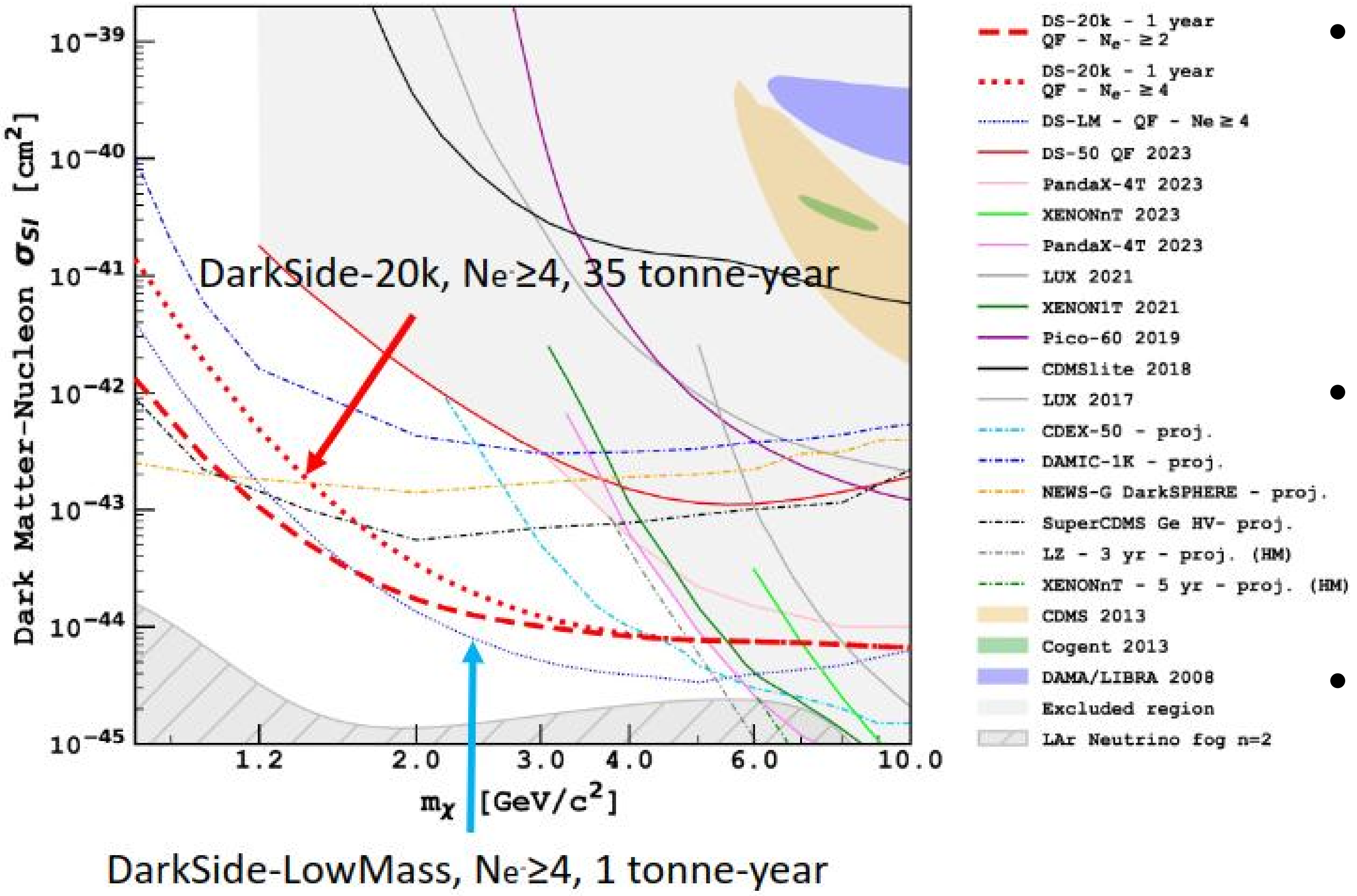


[Phys. Rev. D 107, 112006 (2023)]

- Unique complementaruty with the Scintillating Bubble Chamber!

[ArXiv 2203.08084]

Comparison with DS-20k's projected sensitivity



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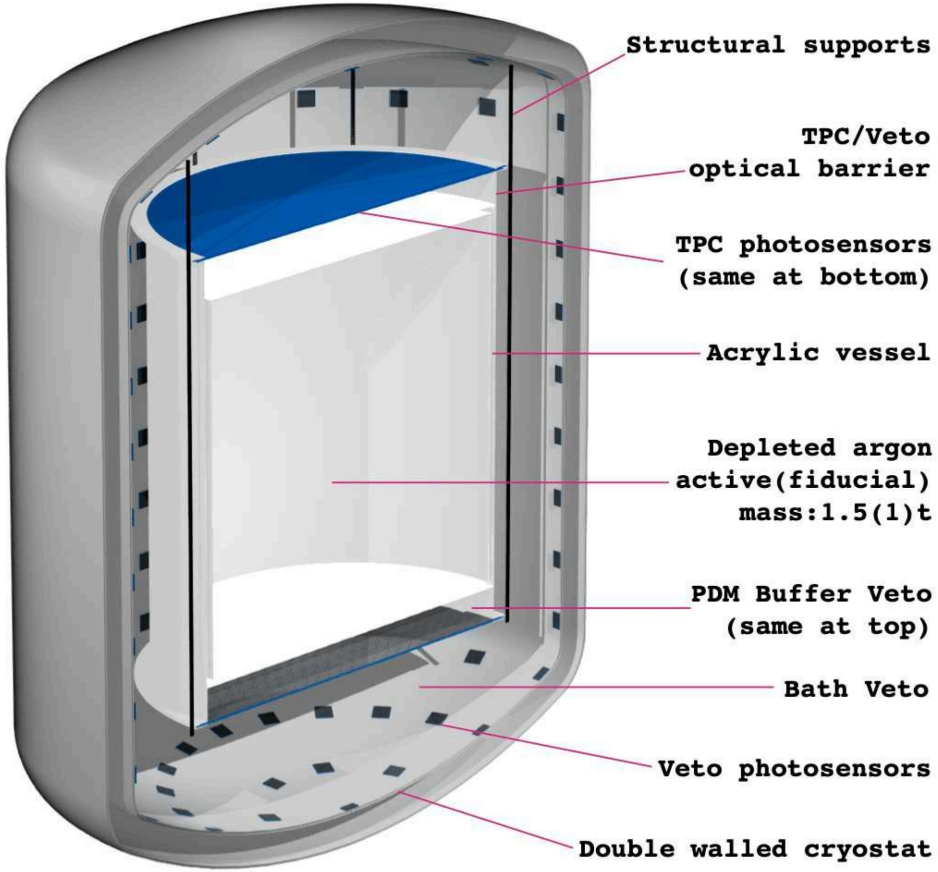
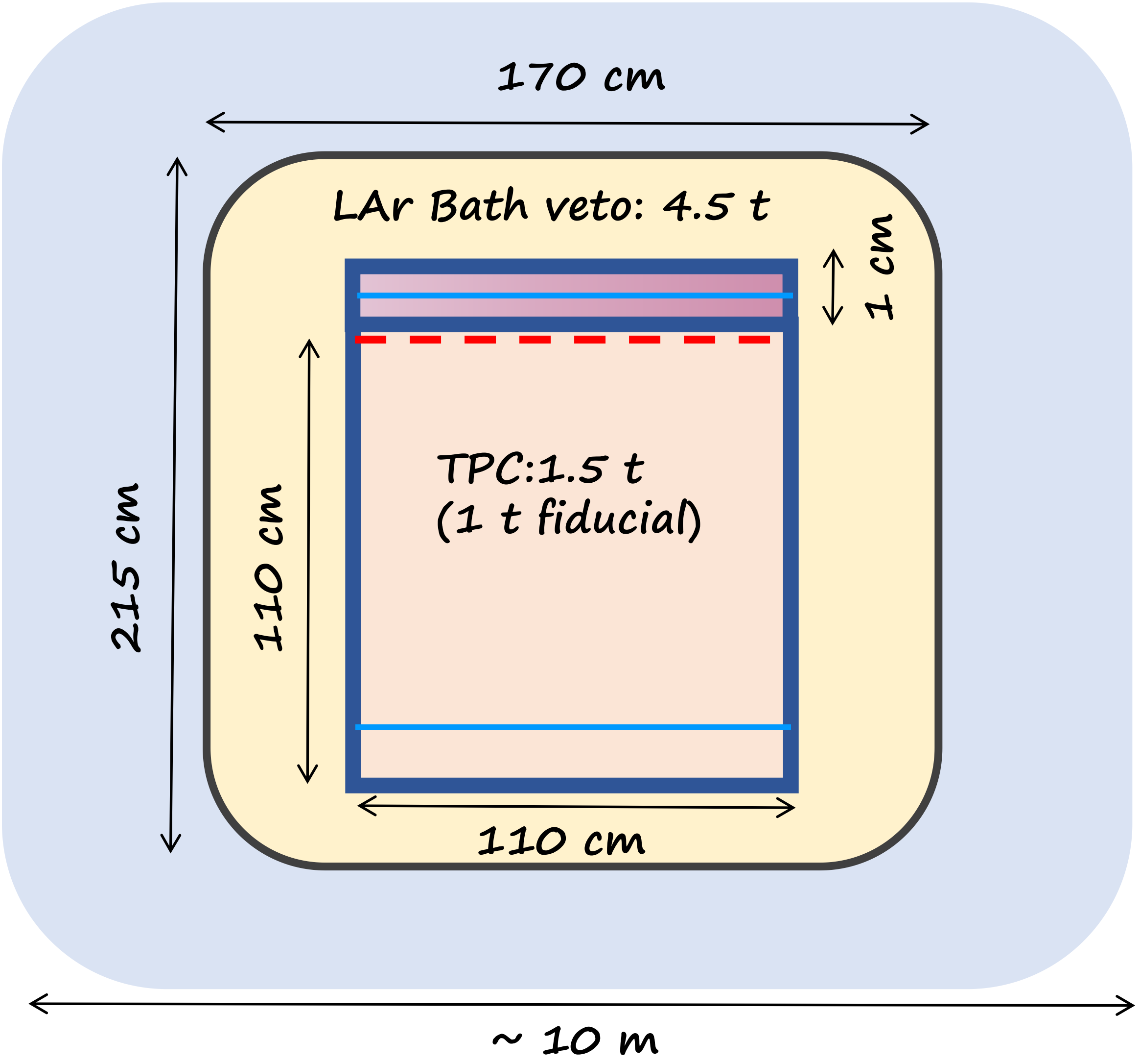
Commun.Phys. 7 (2024) 1, 422

- Assuming same energy threshold and already developed techonology, DarkSide-LowMass can prove lighter DM candidates
- Isotopic cryogenic distillation deliverable according to DS-LM time-scale (early-2030's)
- Additional ongoing R&D will further decrease the background & enhance the ionization yield, allowing for **even lower analysis threshold**

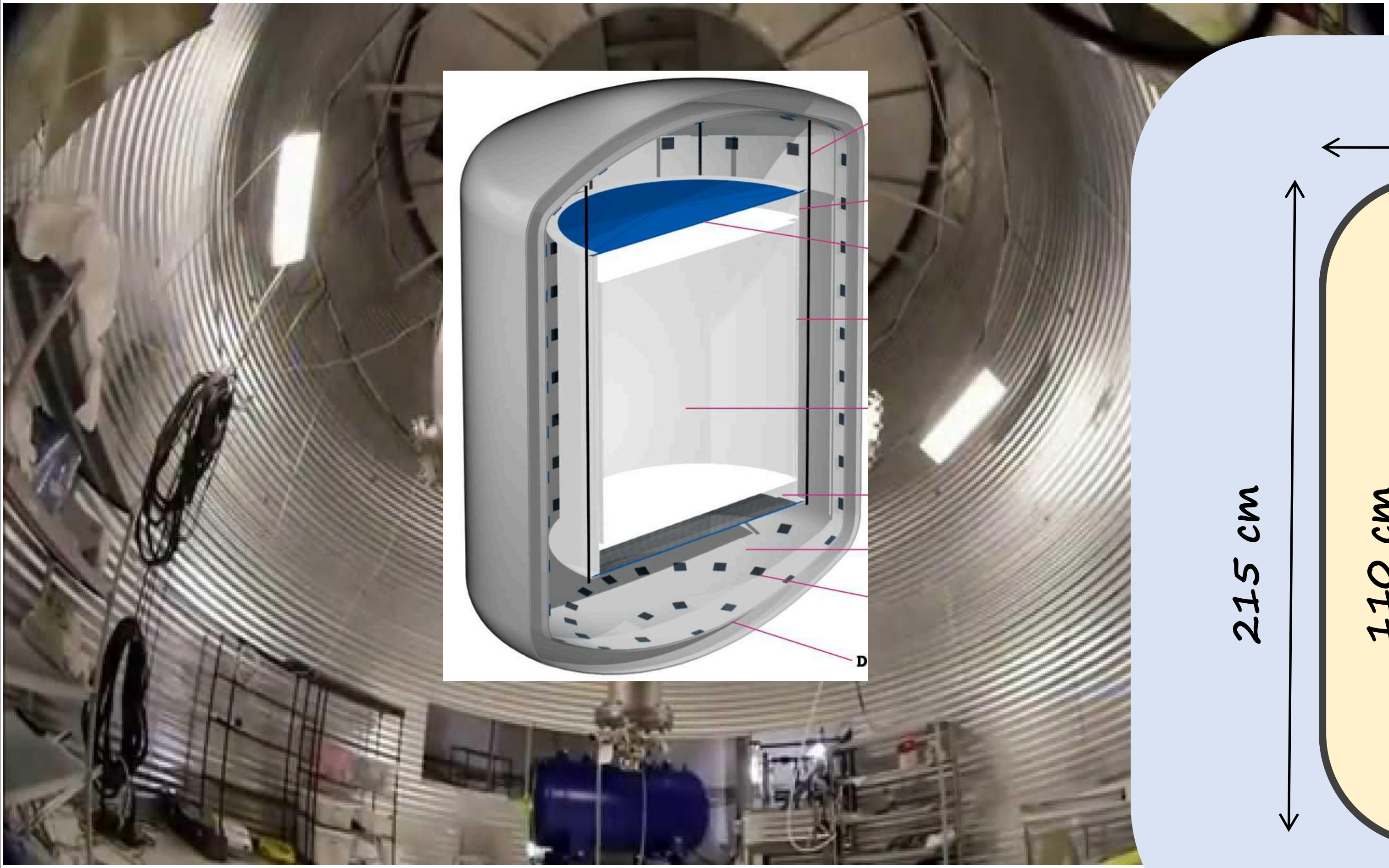
DS-Low-Mass: A first study design

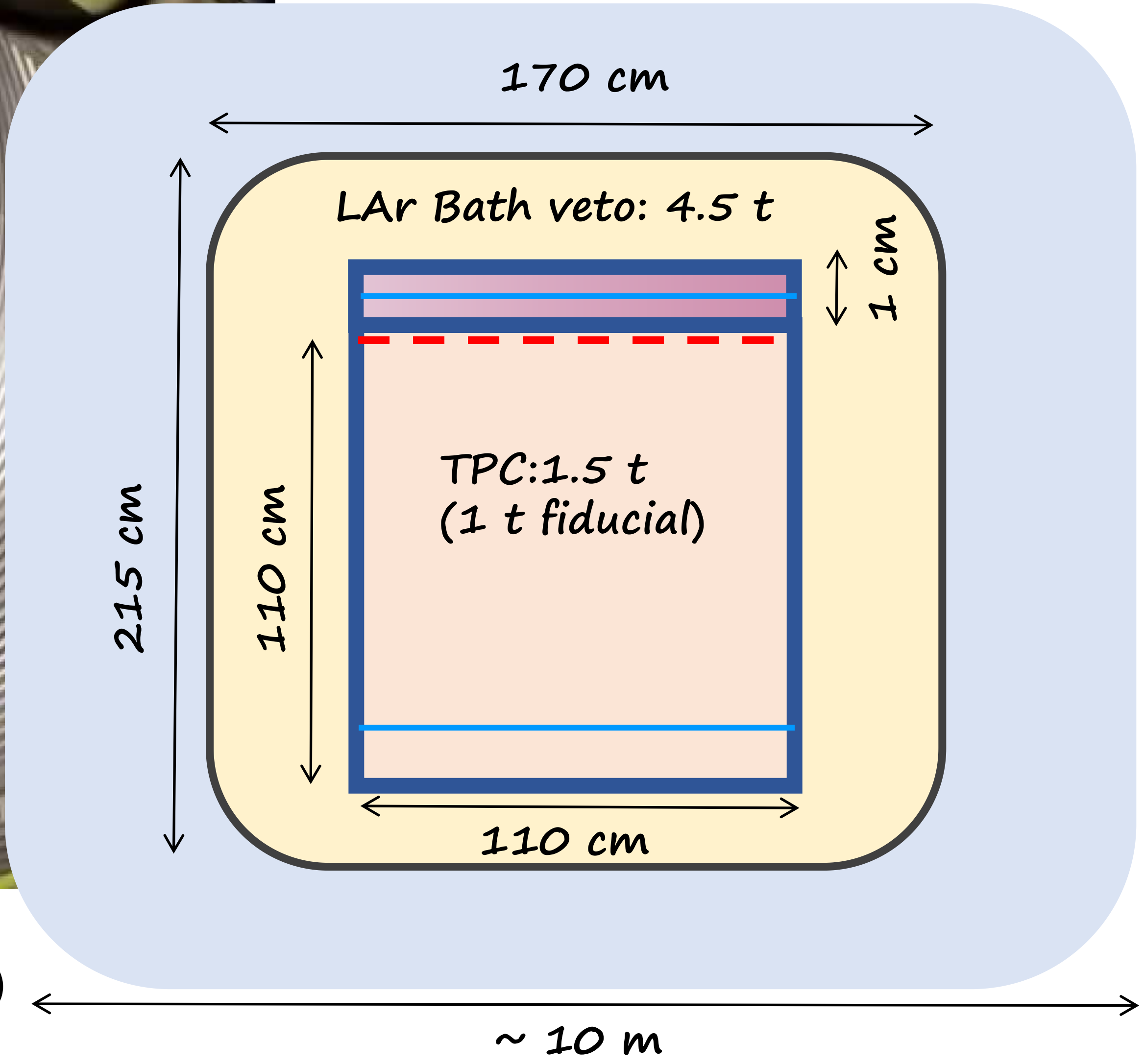




- Majority of the infrastructure requested within 2025 CFI IF application by GADMC-Canada (see M. Boulay talk)

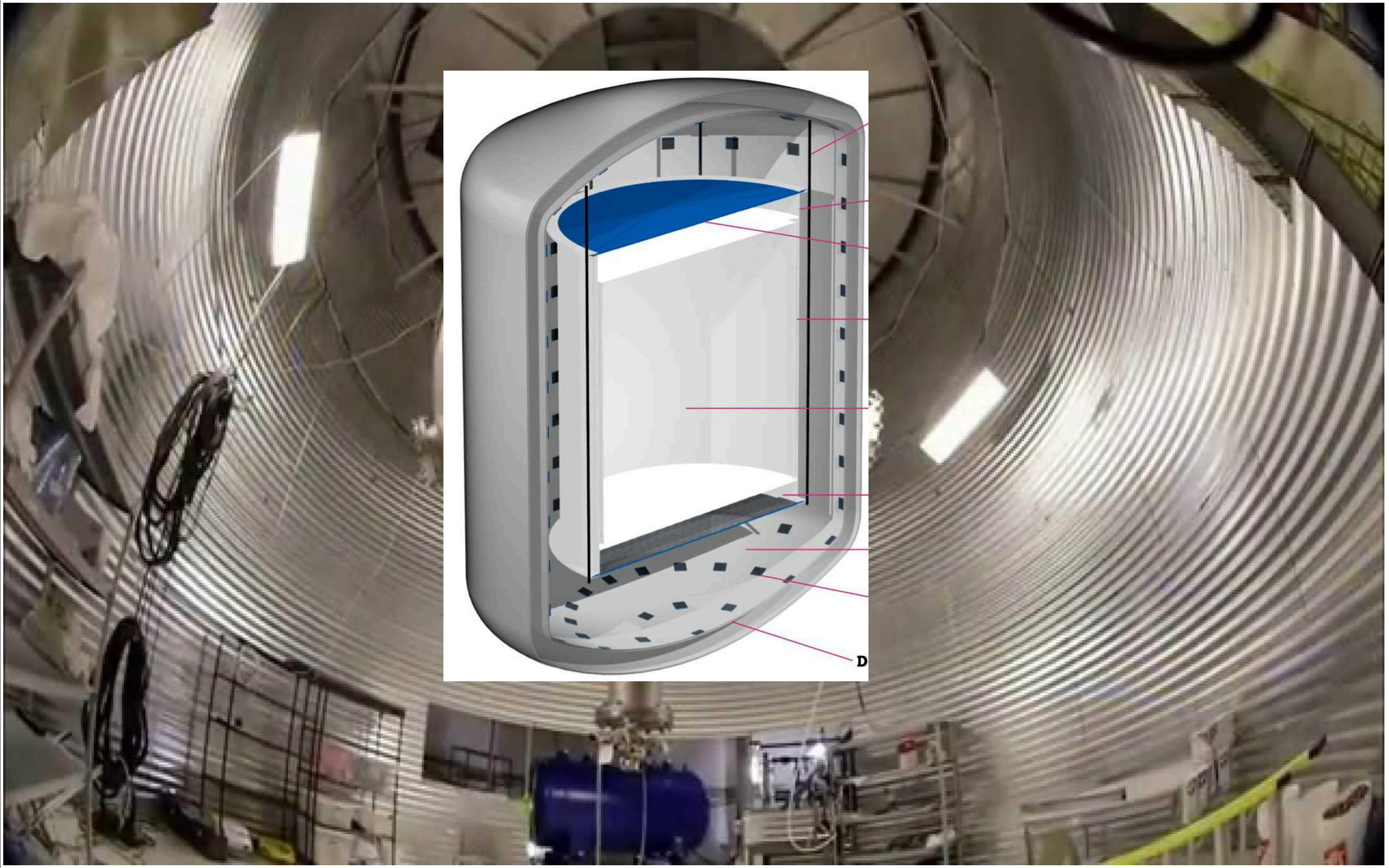
DS-Low-Mass: A first study design

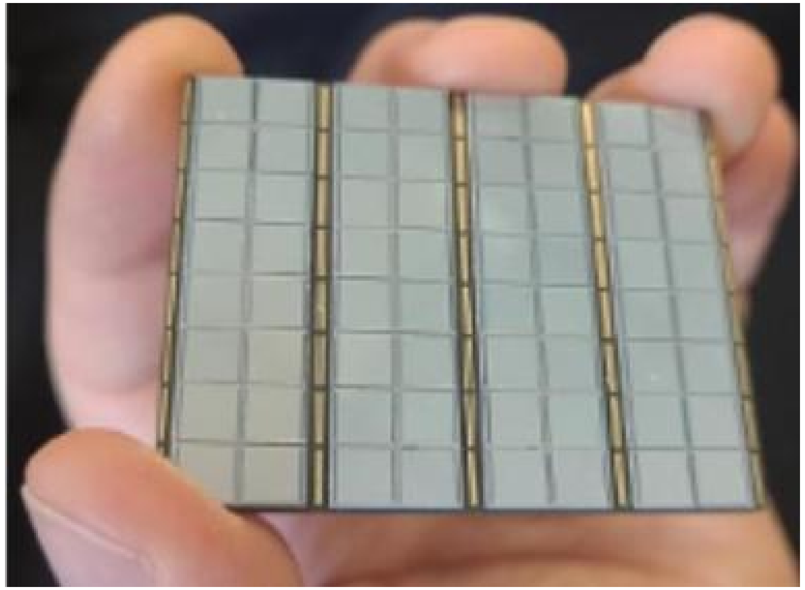


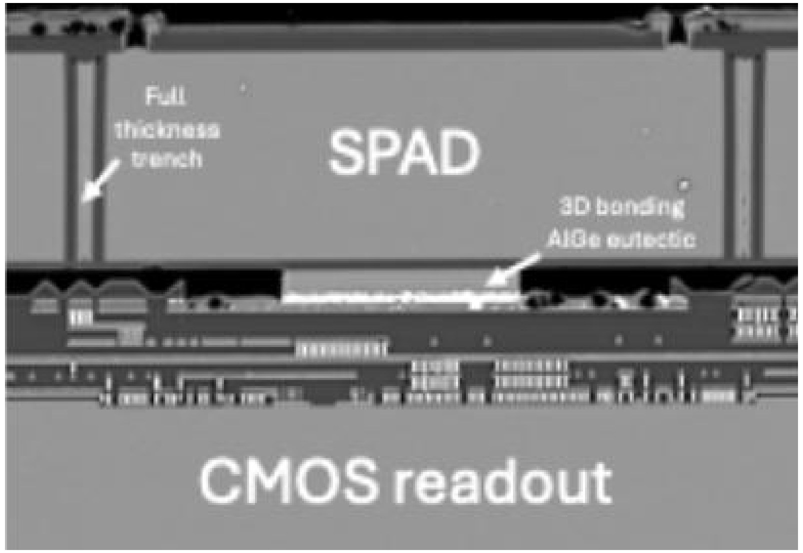


- Plan to use DEAP-3600 water tank (8.5 m) after development for ARGO is completed (expected 2031)

DS-Low-Mass: A first study design



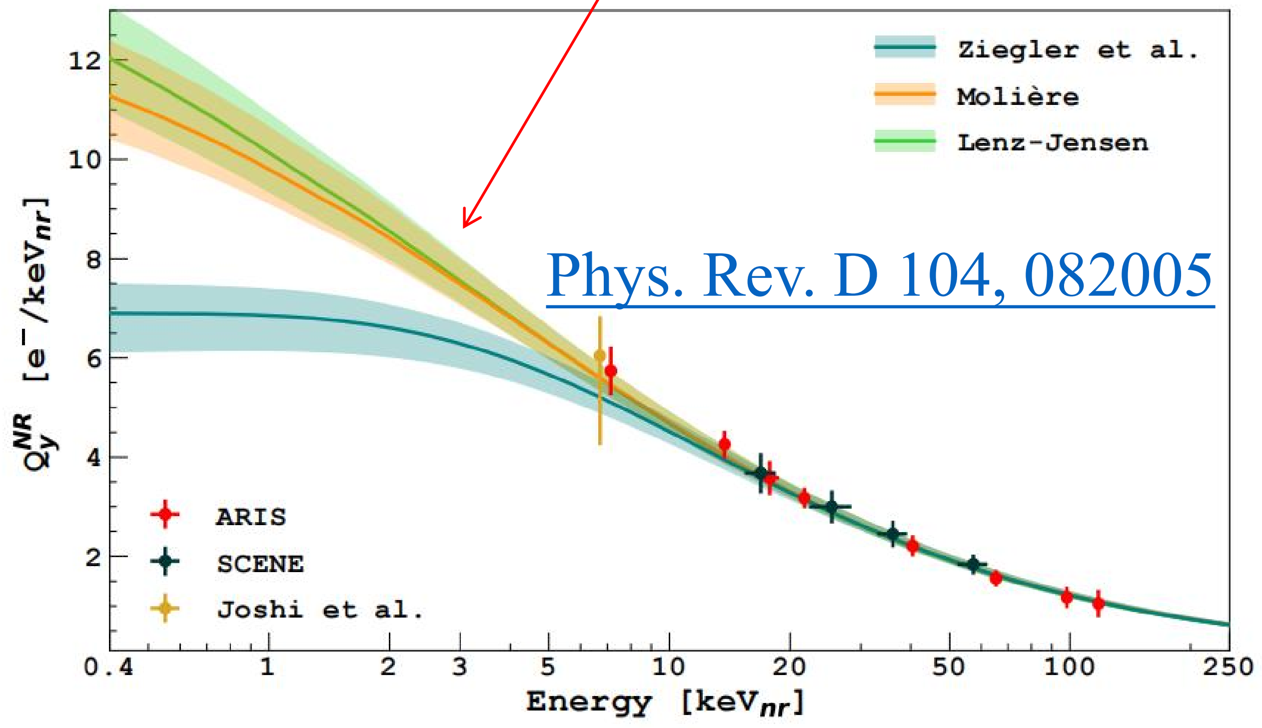




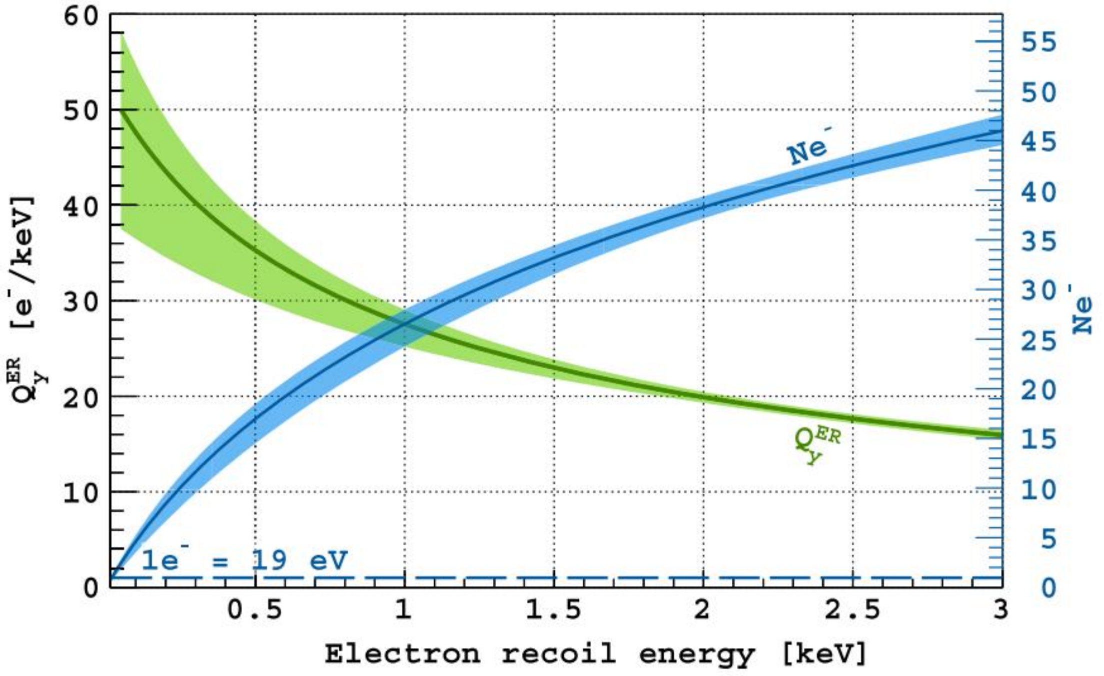
- **Pixelated digital SiPMs**:
  Electronic noise, Dark Noise reduction and afterpulse mitigation techinques: **lower energy threshold and higher energy resolution**

Low-energy calibrations

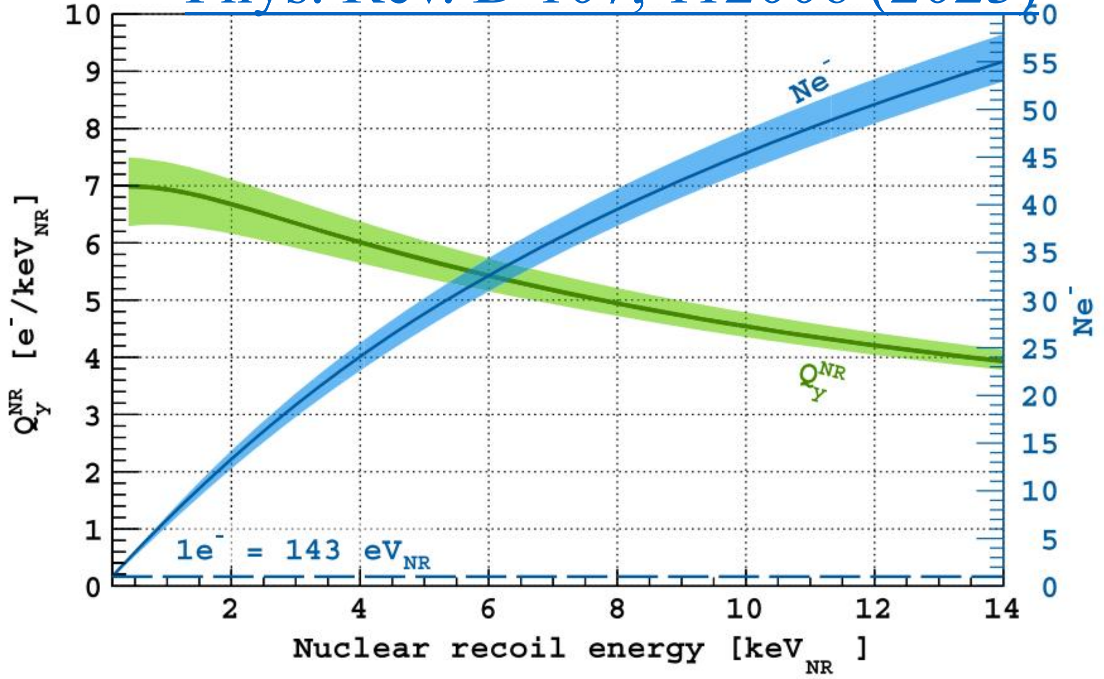
- Ionization yield for ER well-constrained by ^{37}Ar and ^{39}Ar
- Planned additional calibrations through 2025 CFI IF fundings!
- Assumed Ziegler et al. model for the present study



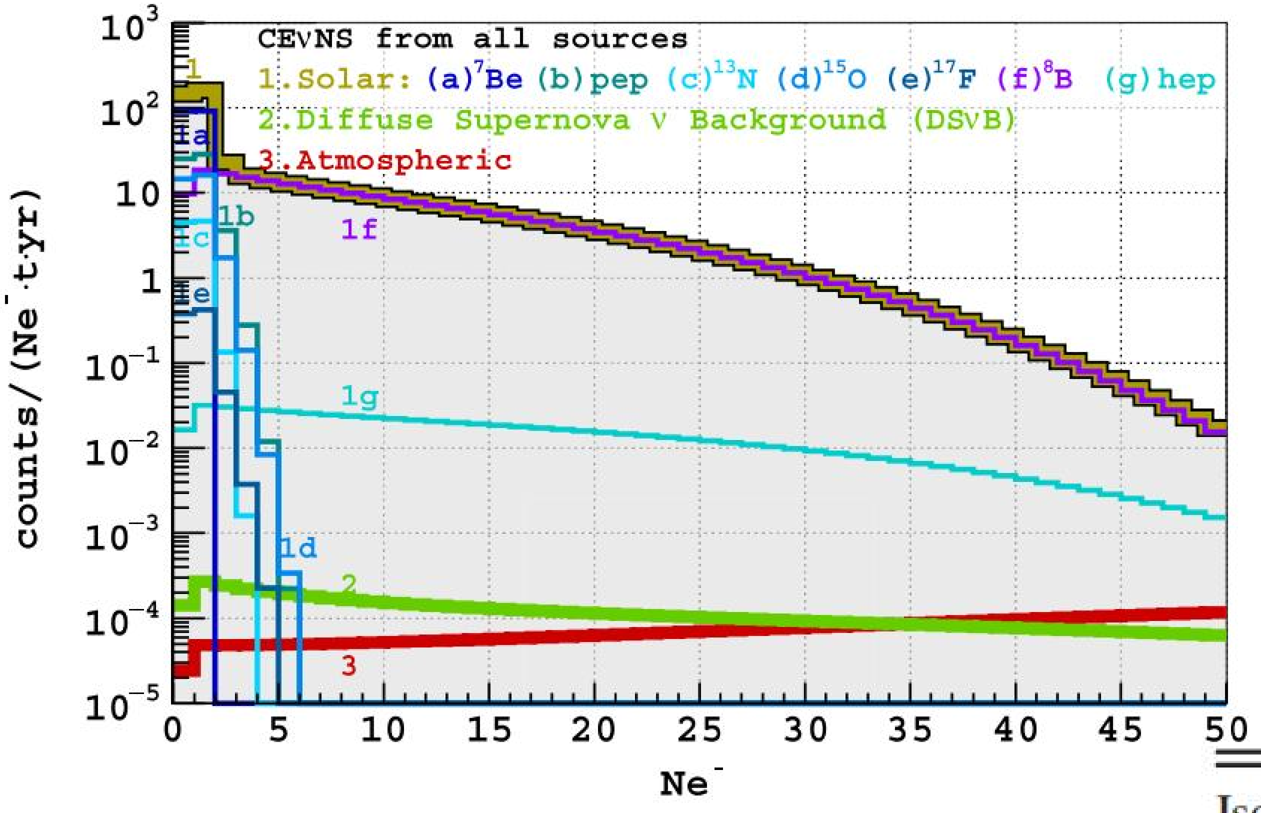
Phys. Rev. D 104, 082005



Phys. Rev. D 107, 112006 (2023)



Expected backgrounds



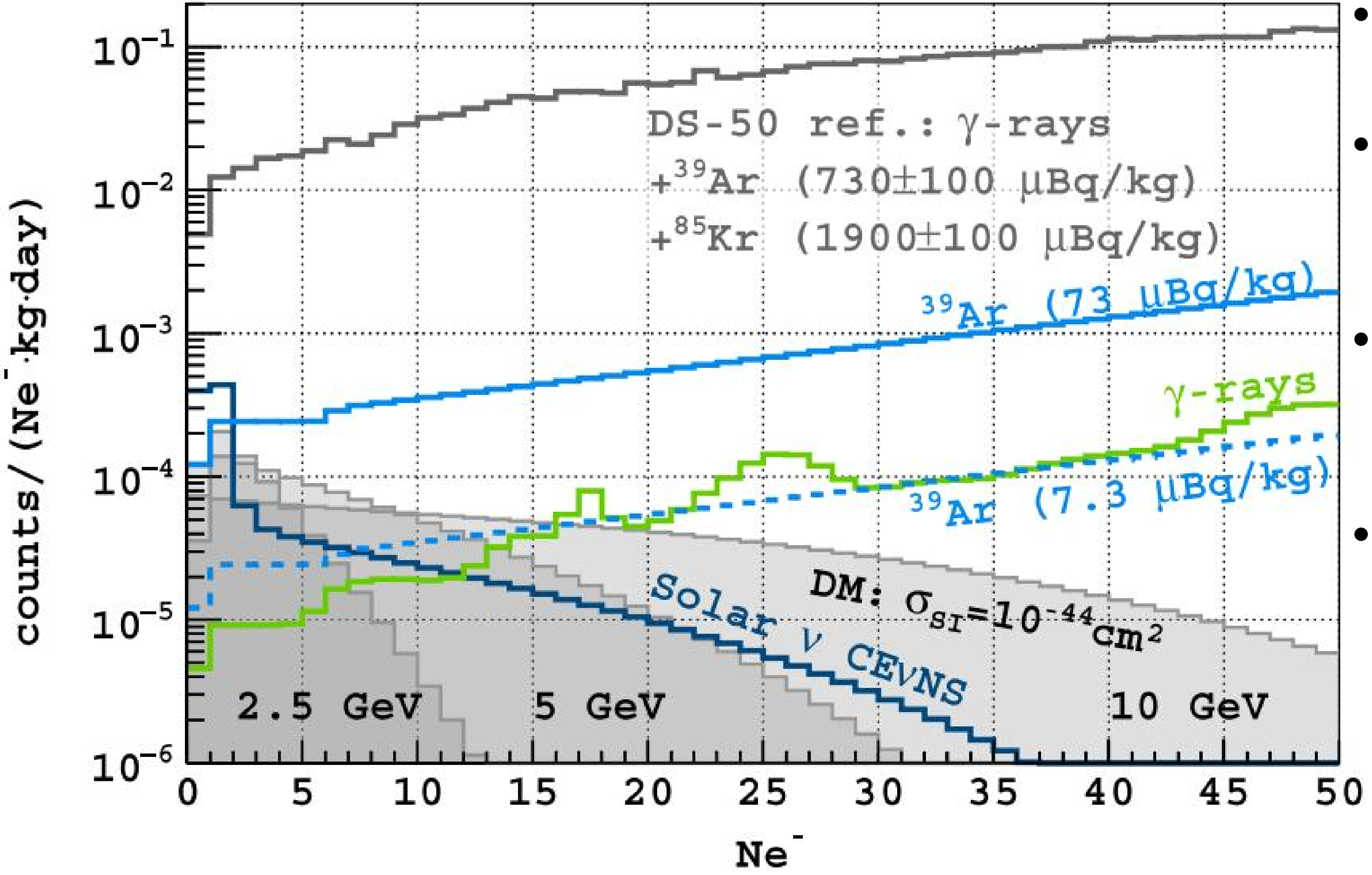
- Irreducible background: solar neutrinos performing CEvNS at O(1) ionization electron

- ^{222}Rn daughters isotopes removal with charcoal traps or molecular sieves
- Radon suppression & essay infrastructures requested on 2025 CFI-IF proposal
- Here assumed surface backgrounds contribute <10% of the γ-ray background rate from TPC components

Phys. Rev. D 107, 112006 (2023)

Isotope	$\mathcal{A}_{thr}$	DarkSide-50 [mBq/m^2]	DEAP-3600
^{222}Rn	6.01 ± 0.25	⋯	$<5 \times 10^{-3}$
^{210}Pb	2.21 ± 0.05	2.51 ± 0.01	0.26 ± 0.02

Expected backgrounds



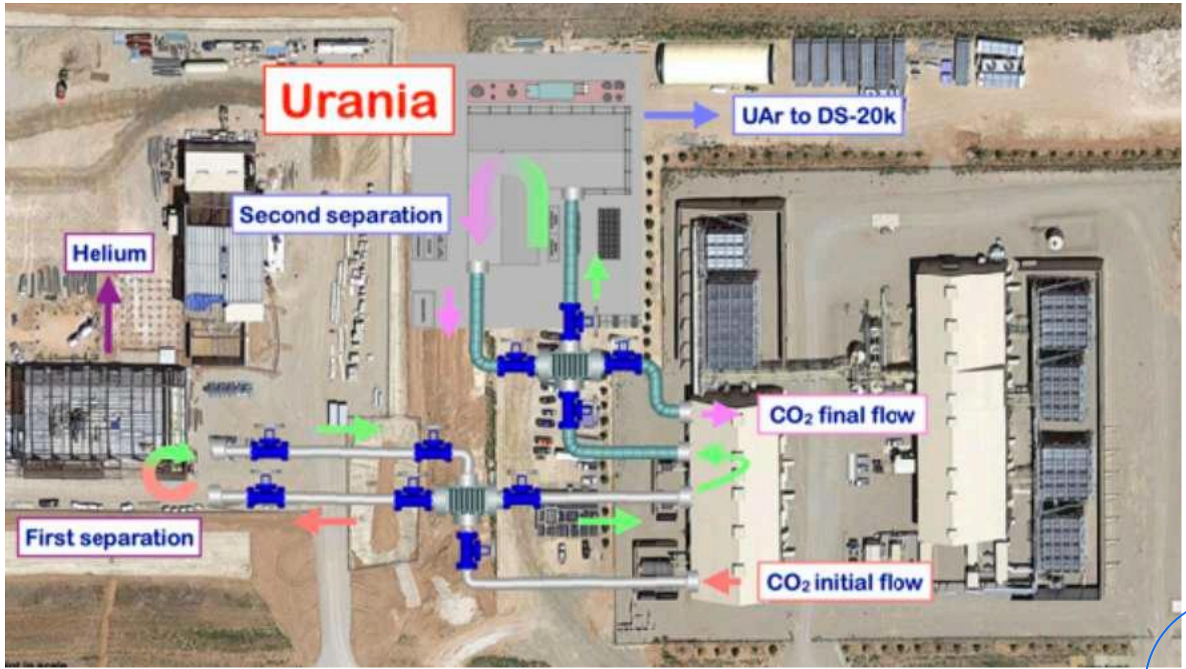
Phys. Rev. D 107, 112006 (2023)

- γ-rays rejection thanks to the **photosensor buffer veto**
- UAr from URANIA and Aria will bring the ^{39}Ar activity to **O(10) uBq/kg**
- ^{85}Kr expected to be negligible after improvements of the extraction process
- ^{42}Ar expected to be negligible in UAr - to be tested in ARGOLite (see M. Boulay talk)

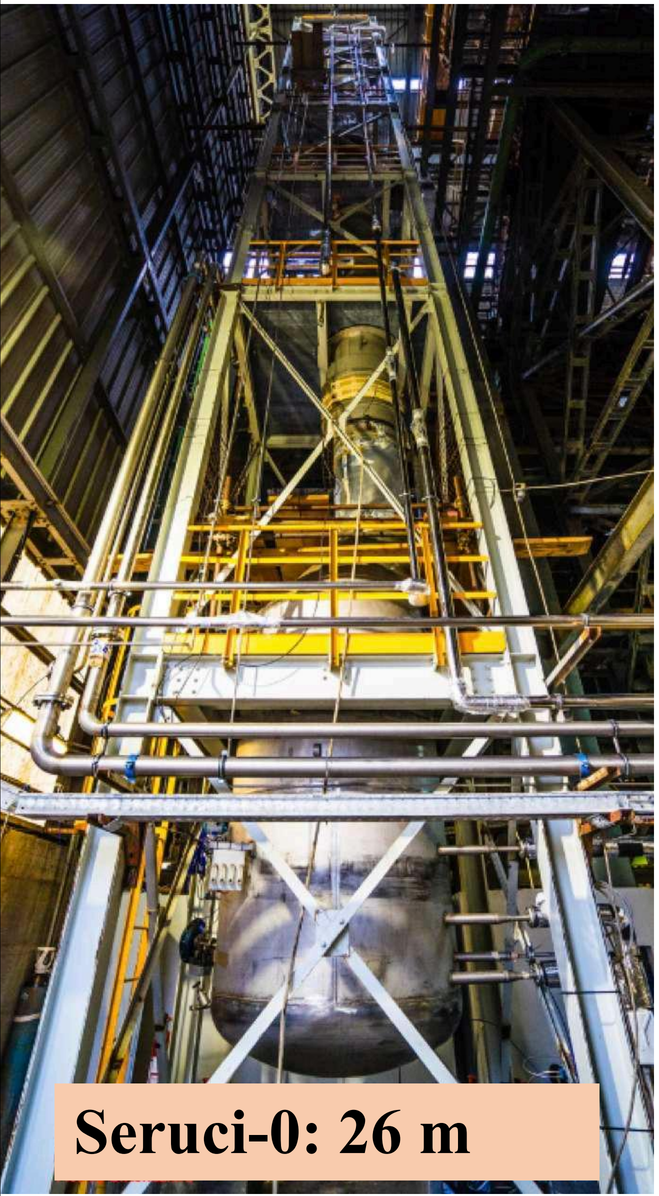
URANIA

- **UAr extraction performed at Urania, currently under construction**

- Low activity UAr found in 2009 at Southwest Colorado CO2 wells and purified at FNAL for DarkSide-50, with a rate 140 g/day
- Expected extraction rate **250 kg/day**
- Additional experiments interested in UAr from Urania: Argo, COHERENT, LEGEND
- Starting commissioning this spring/early summer

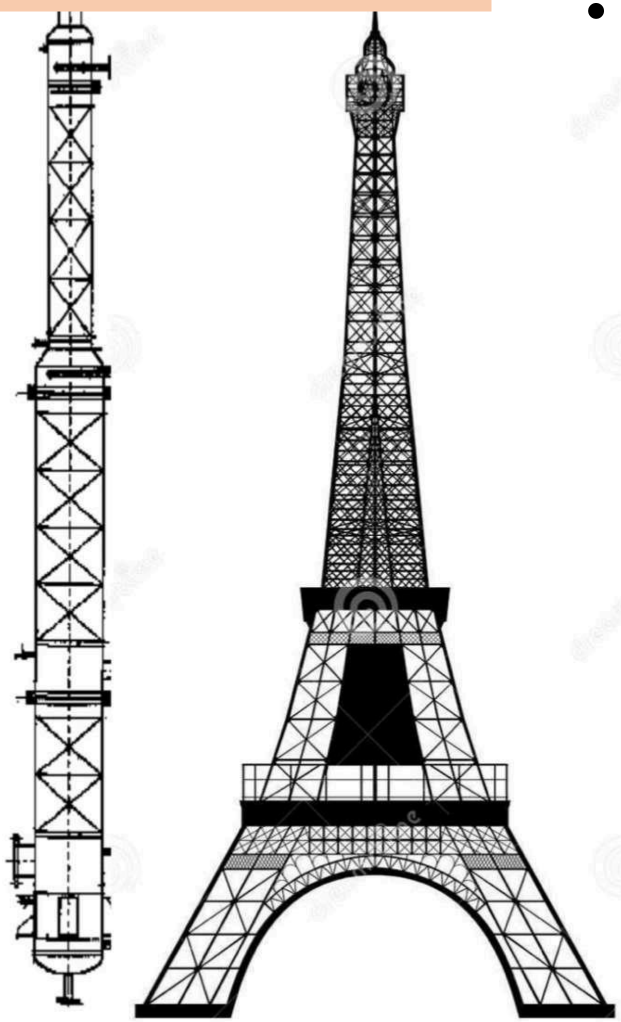


ARIA

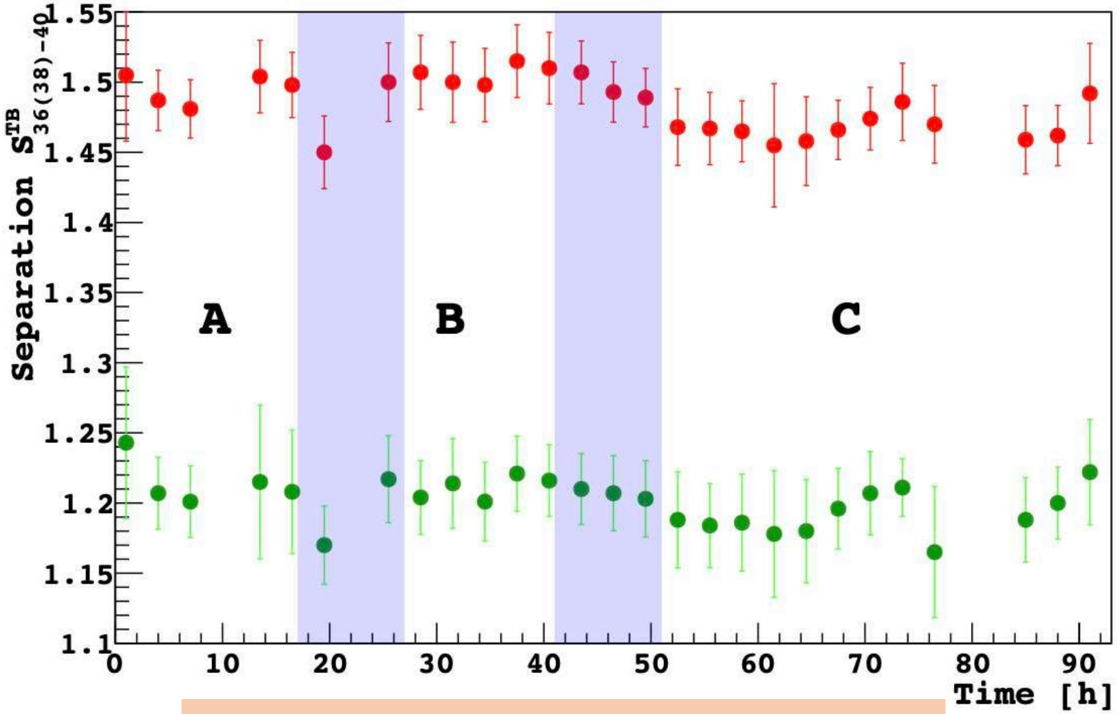


Seruci-0: 26 m

Seruci-1: 350 m



- First application of the isotopic distillation in DSLM, before ARGO
- Need to run Seruci-1 at **10 kg/day** throughput for isotopic ^{39}Ar depletion

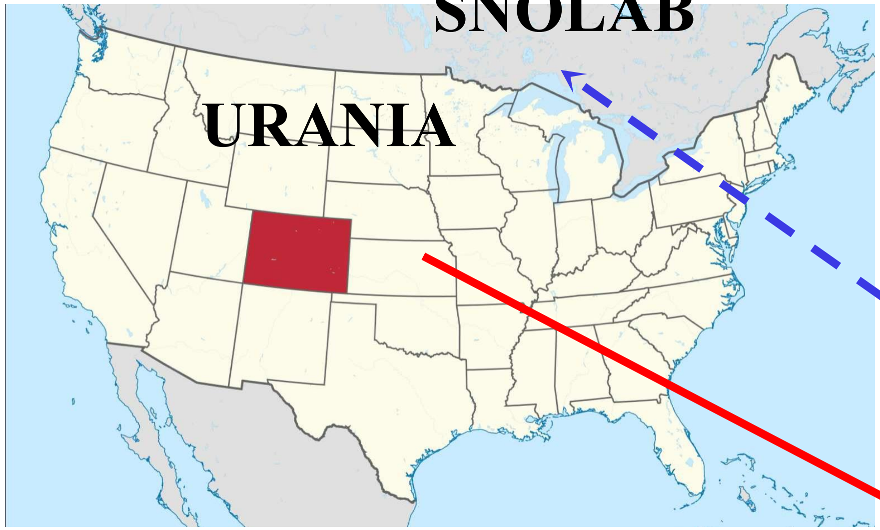


Seruci-0: ^{36}Ar - ^{40}Ar separation performances

Eur. Phys. J.C 81 (2021) 4, 359

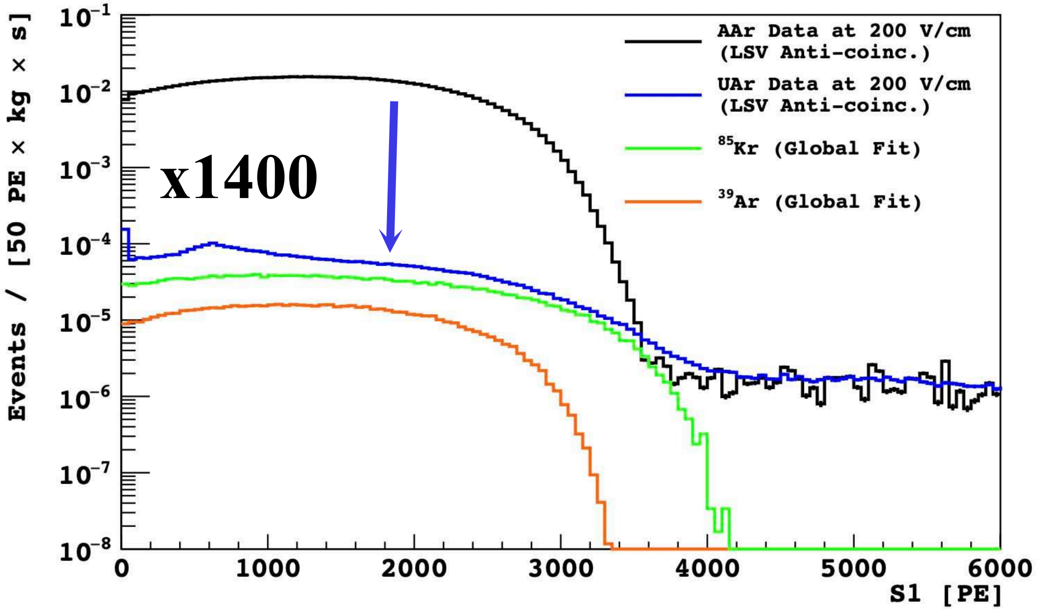
Eur. Phys. J.C 83 (2023) 5, 453

The UAr roadmap



	^{39}Ar	^{37}Ar [μBq/kg]	^{3}H
Urania → Aria	14.7 ± 1.3	806 ± 73	58 ± 12
Aria (1 mo, surface)	2.57 ± 0.33	294 ± 39	9.0 ± 2.8
Aria → LNGS	0.86 ± 0.11	118 ± 15	3.00 ± 0.95
Aria → N America	5.73 ± 0.73	483 ± 64	20.0 ± 6.3

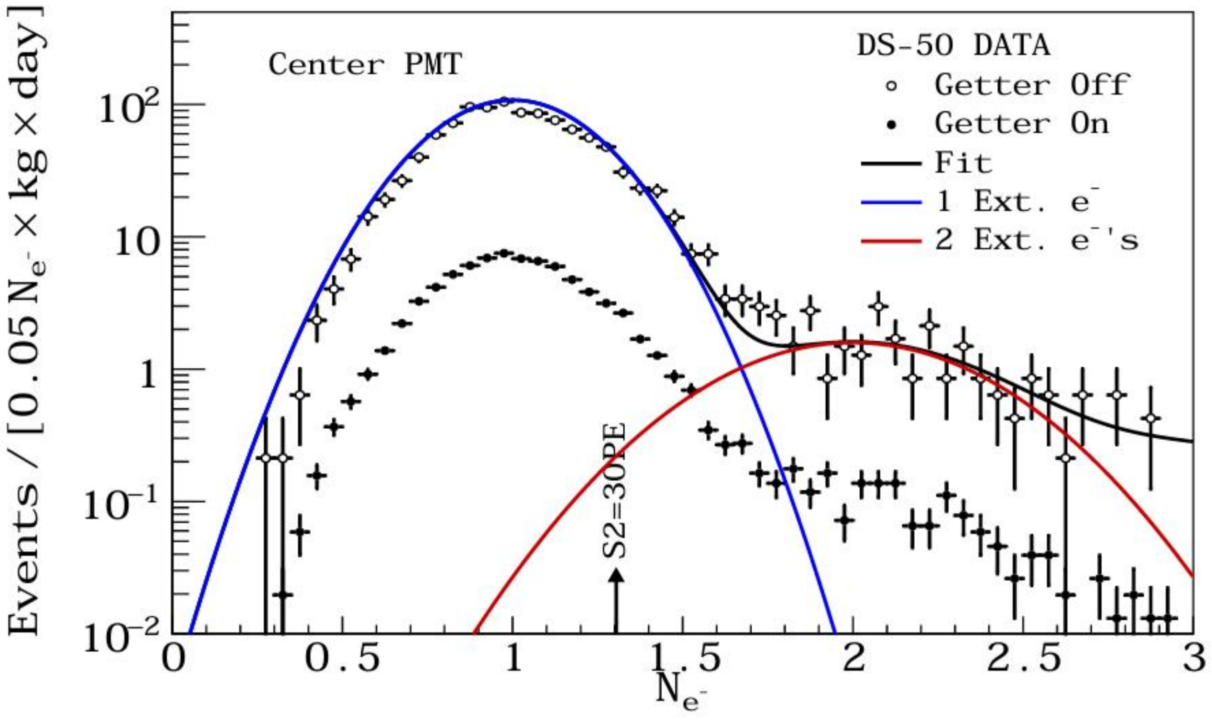
Phys. Rev. D 107, 112006 (2023)



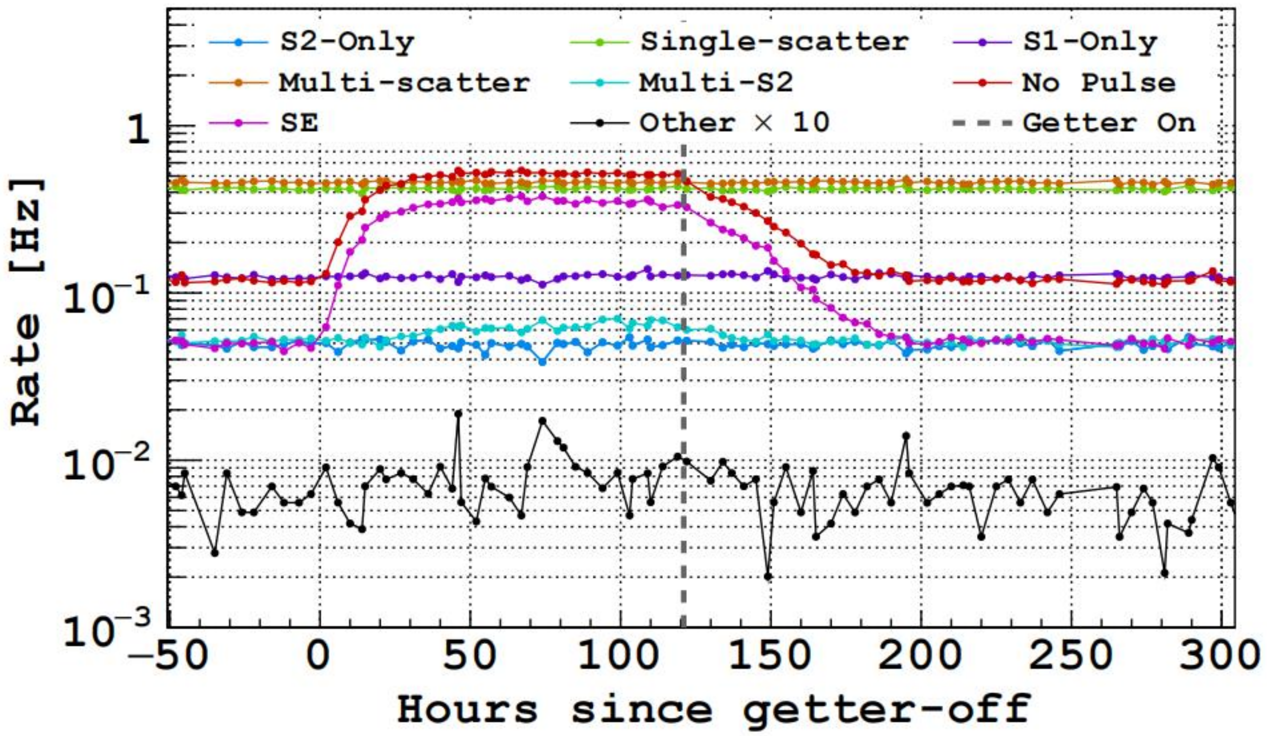
Phys.Lett.B 743 (2015) 456-466

Spurious electrons

- Unmodeled background at [1-4] Ne found in DarkSide-50 low-mass search
- Clear event rate increase when getter off
- Correlated to impurity in the detector

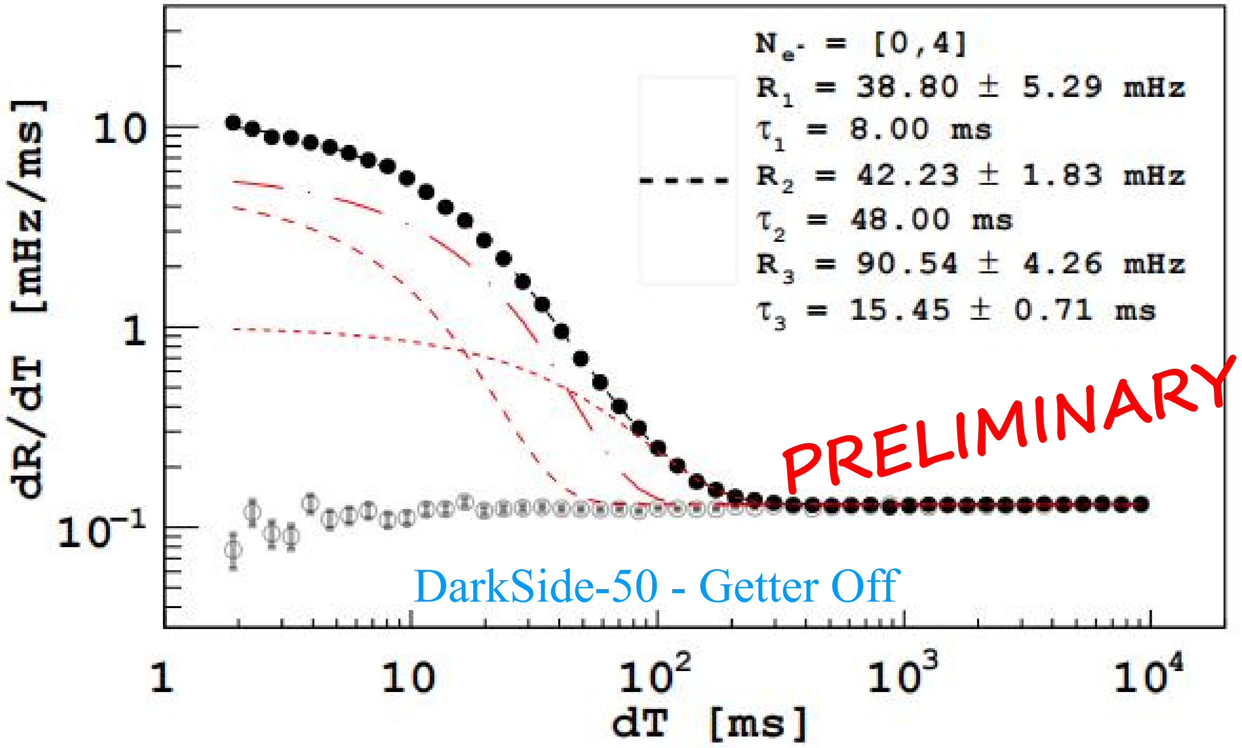


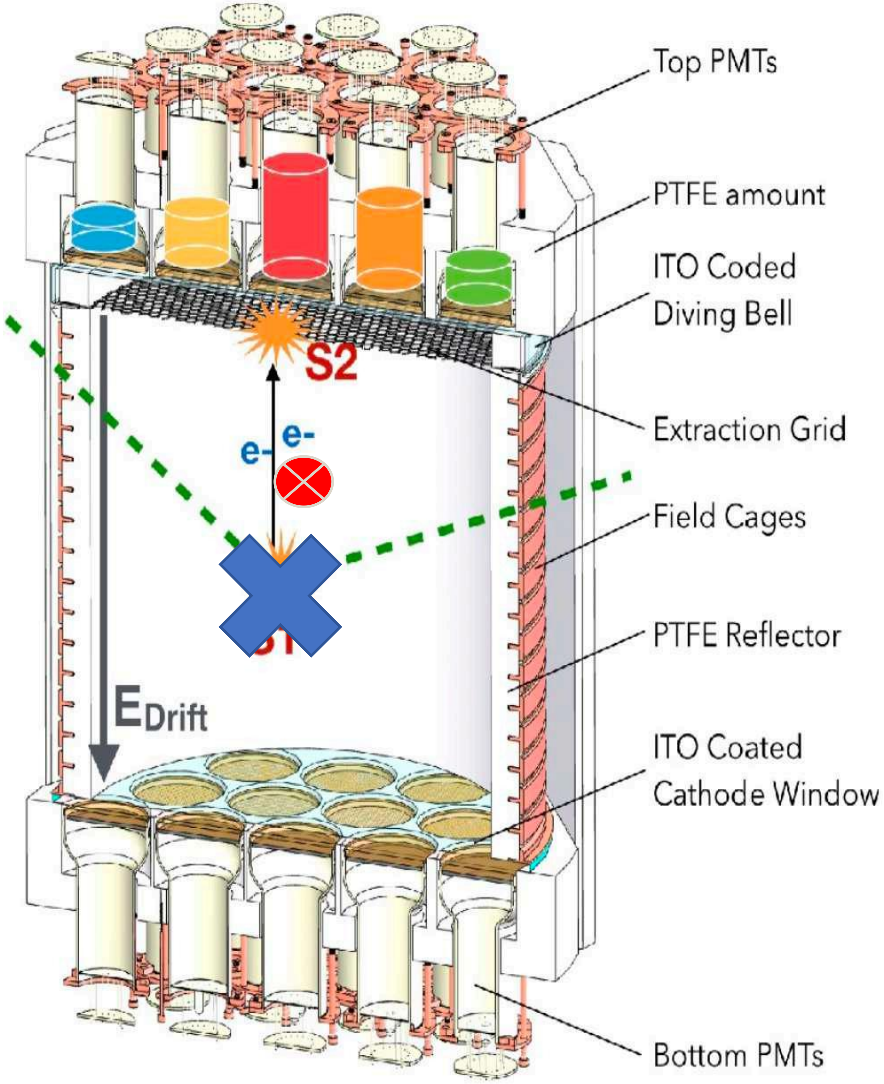
[Phys.Rev.Lett. 121 (2018) 8, 081307]()



- Ongoing R&Ds to tackle its source, dependency on the target purity, TPC electric fields, target ionization yield, inner detector materials ...

Addressing the spurious electrons



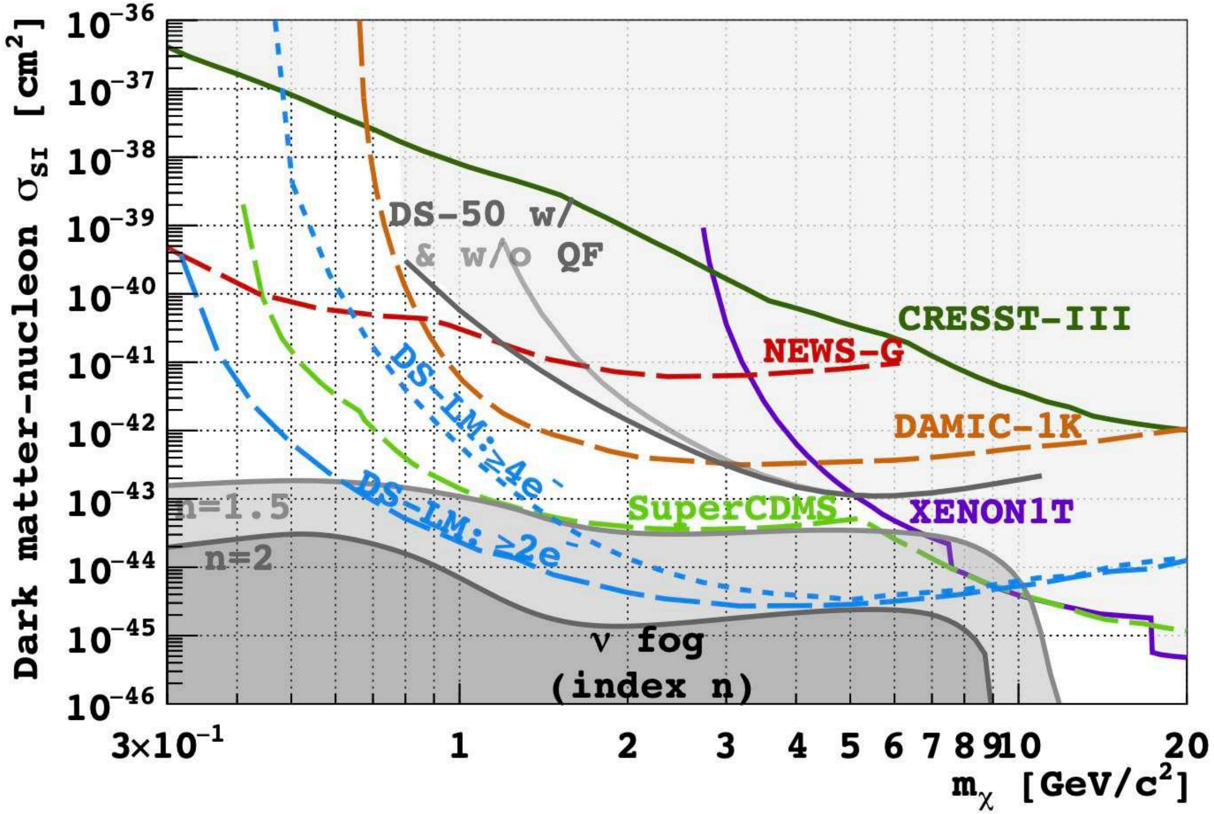


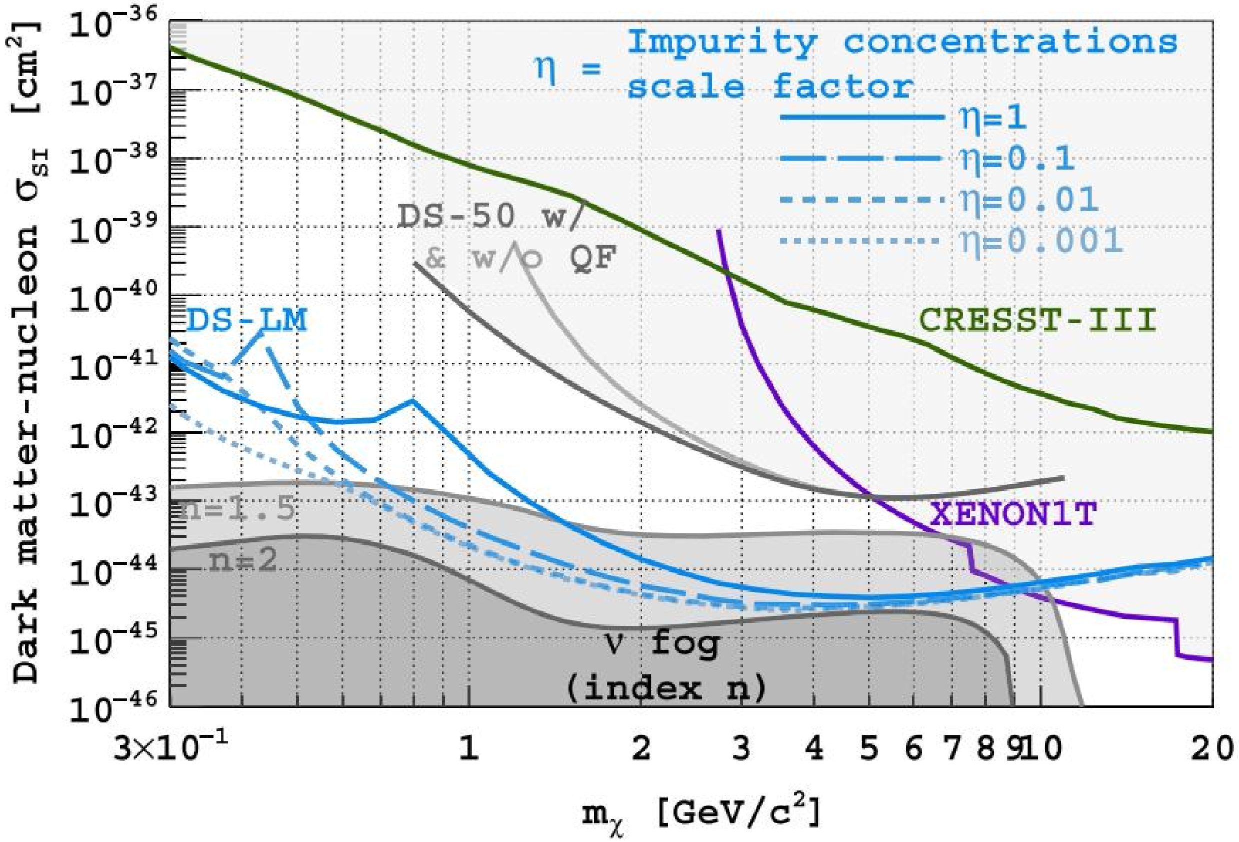
Drawing of DarkSide-50

- Promising theory: pile-ups from impurities trapping and then releasing ionization electrons
- R&Ds done by early-2030s, in time to be implemented in DS-LM

Sensitivity to WIMPs in 1 tonne-year

... for multiple analysis thresholds and impurity scaling from DarkSide-50 UAr run.

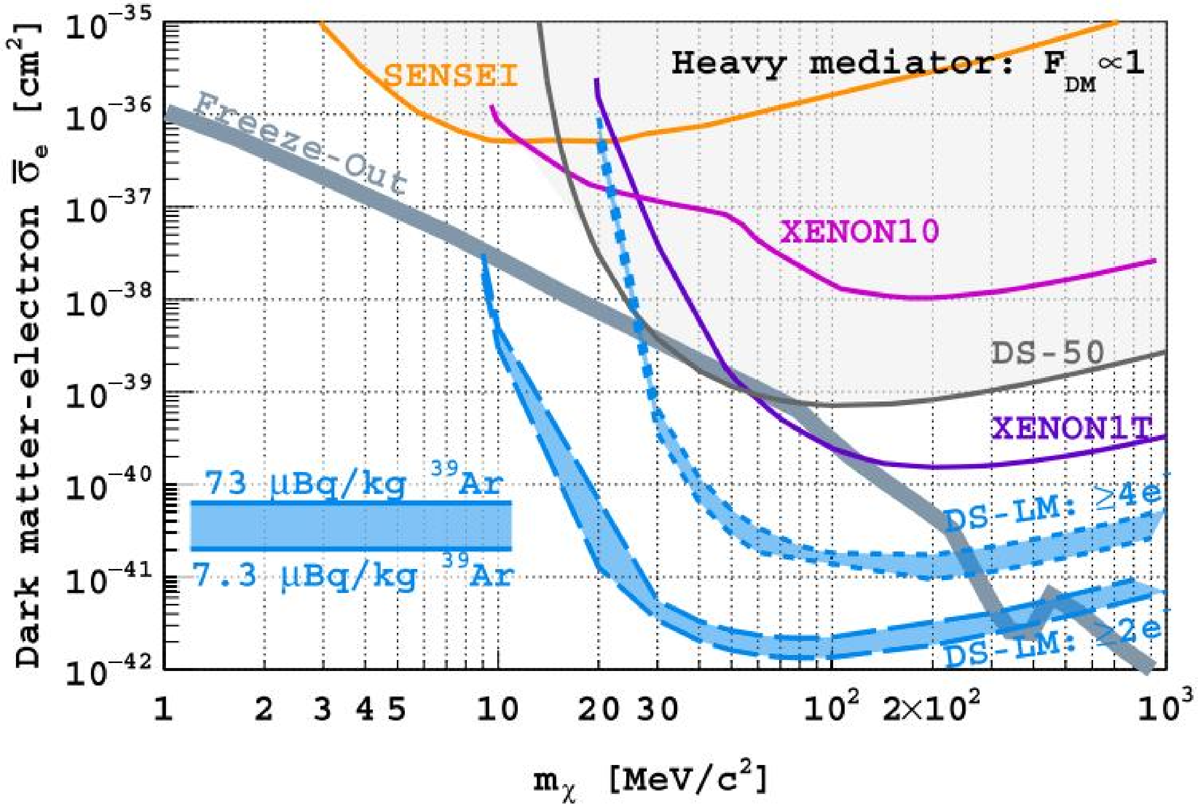


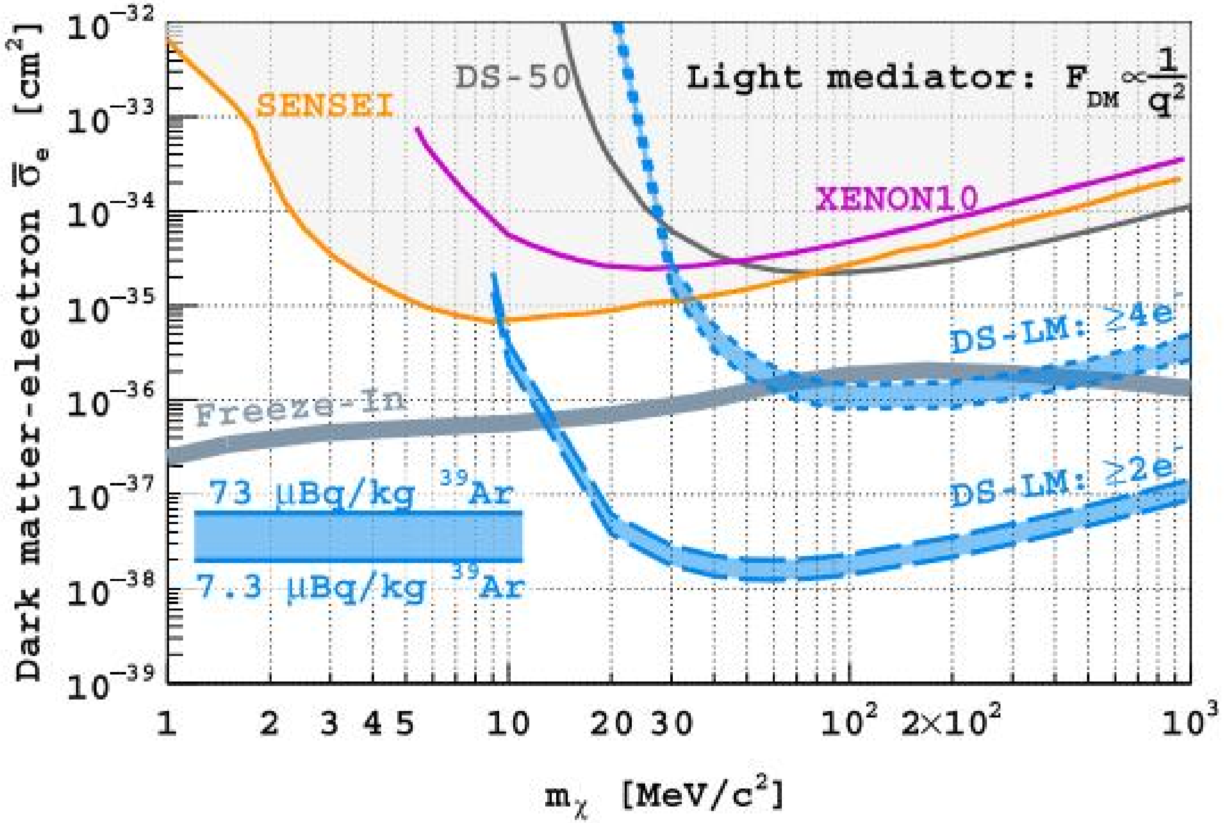


[Phys. Rev. D 107, 112006 (2023)]

Sensitivity to WIMPs in 1 tonne-year

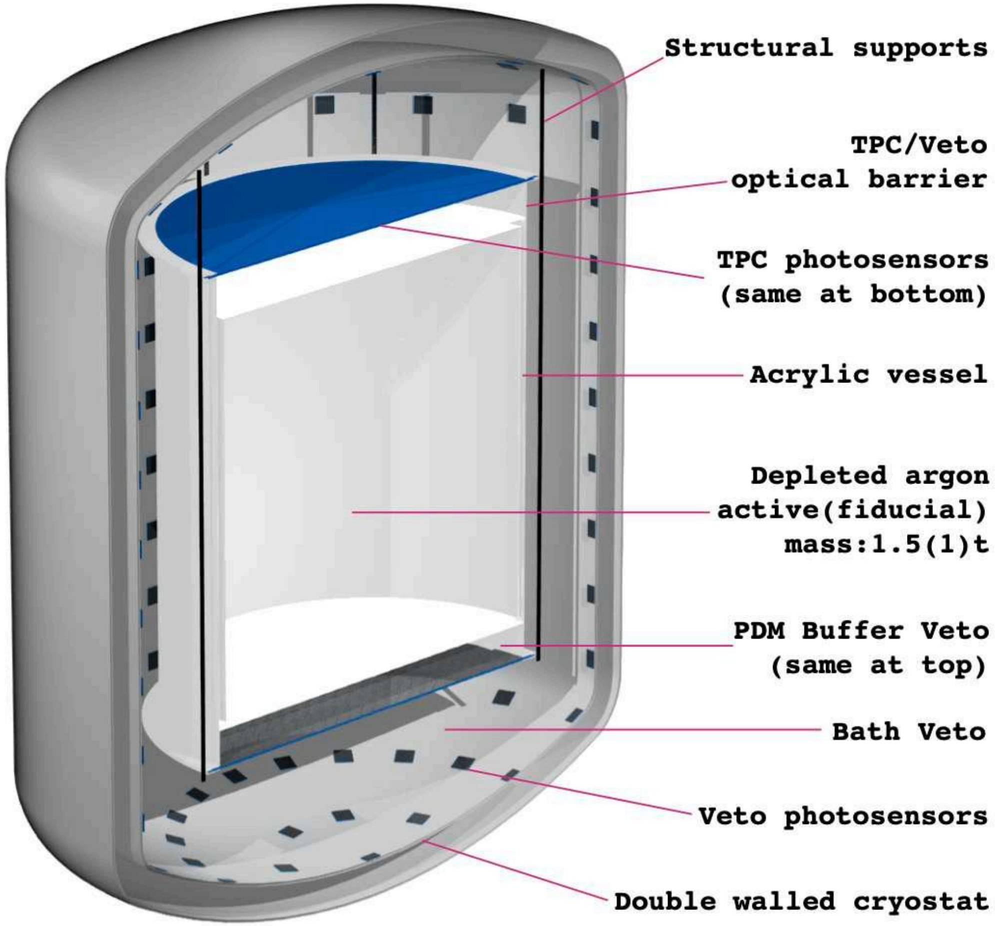
... as well as for DM-electron scattering

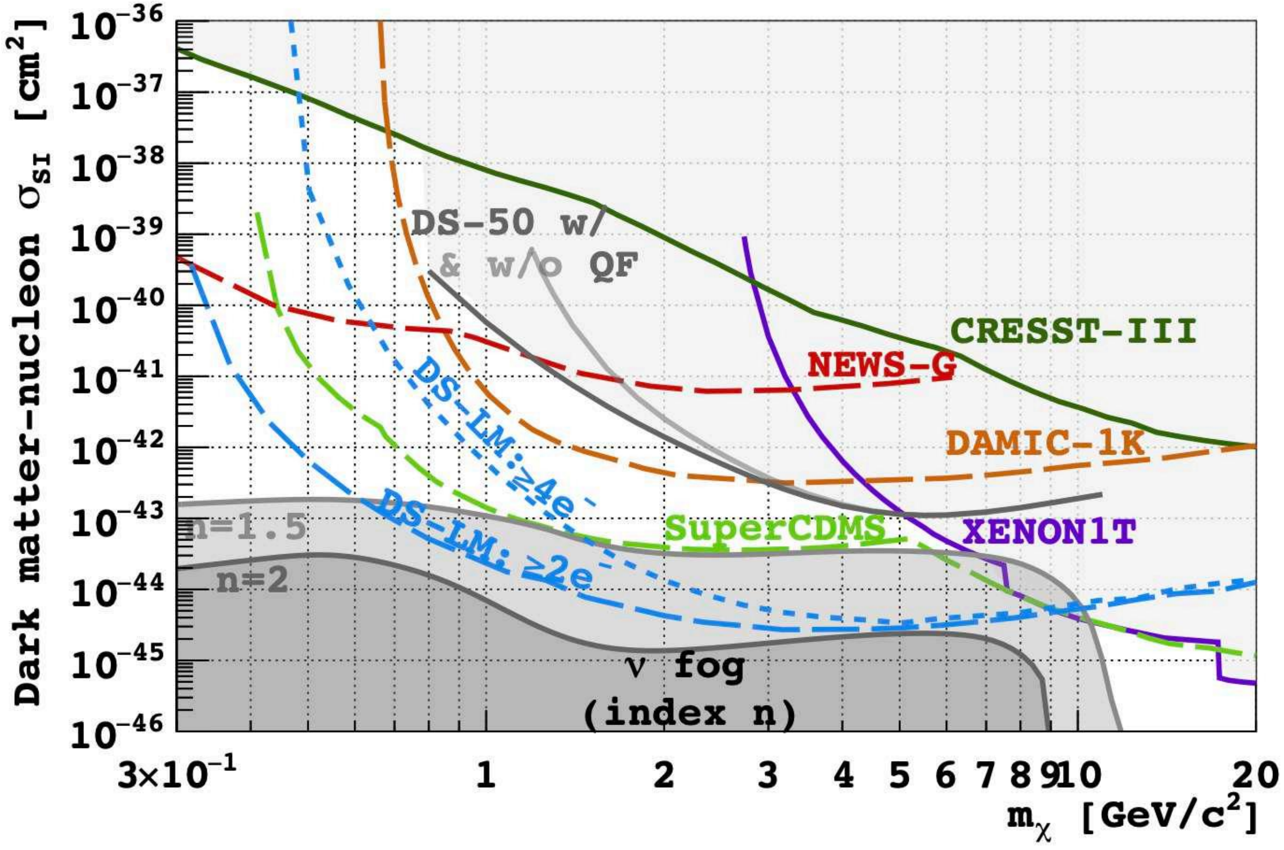




[Phys. Rev. D 107, 112006 (2023)]

Can we reach lower threshold?





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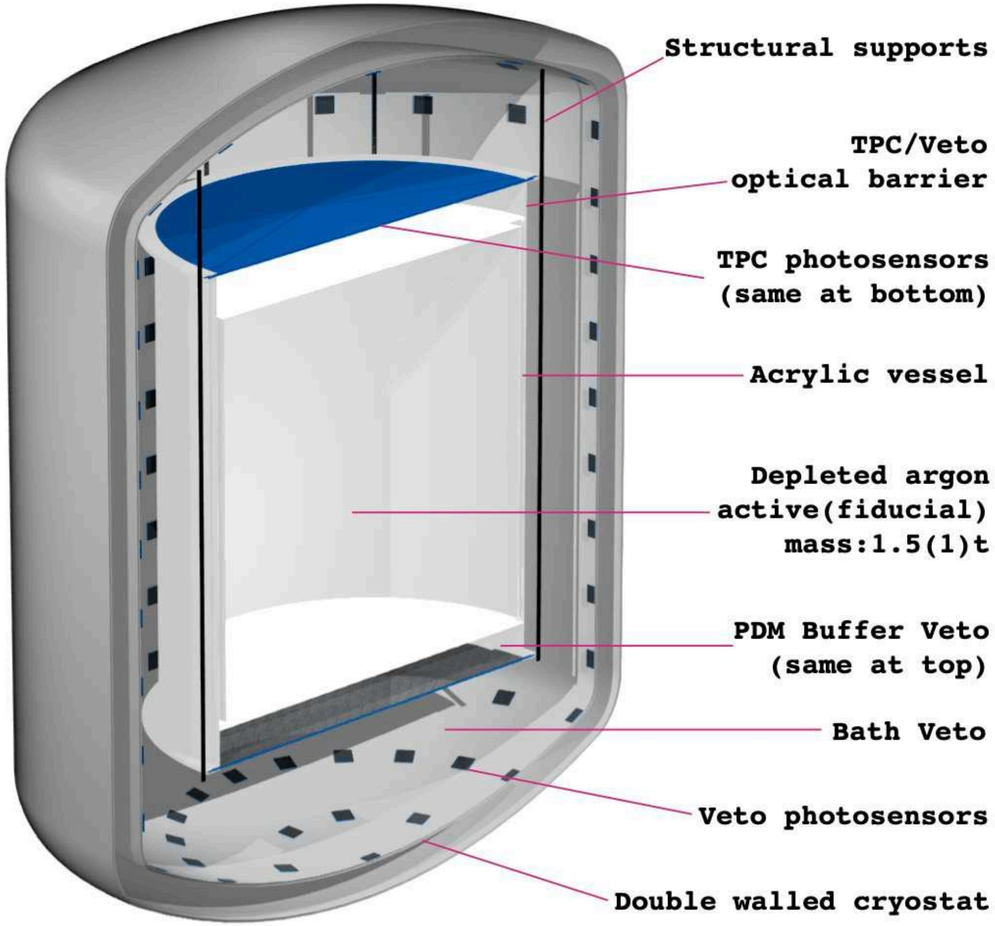

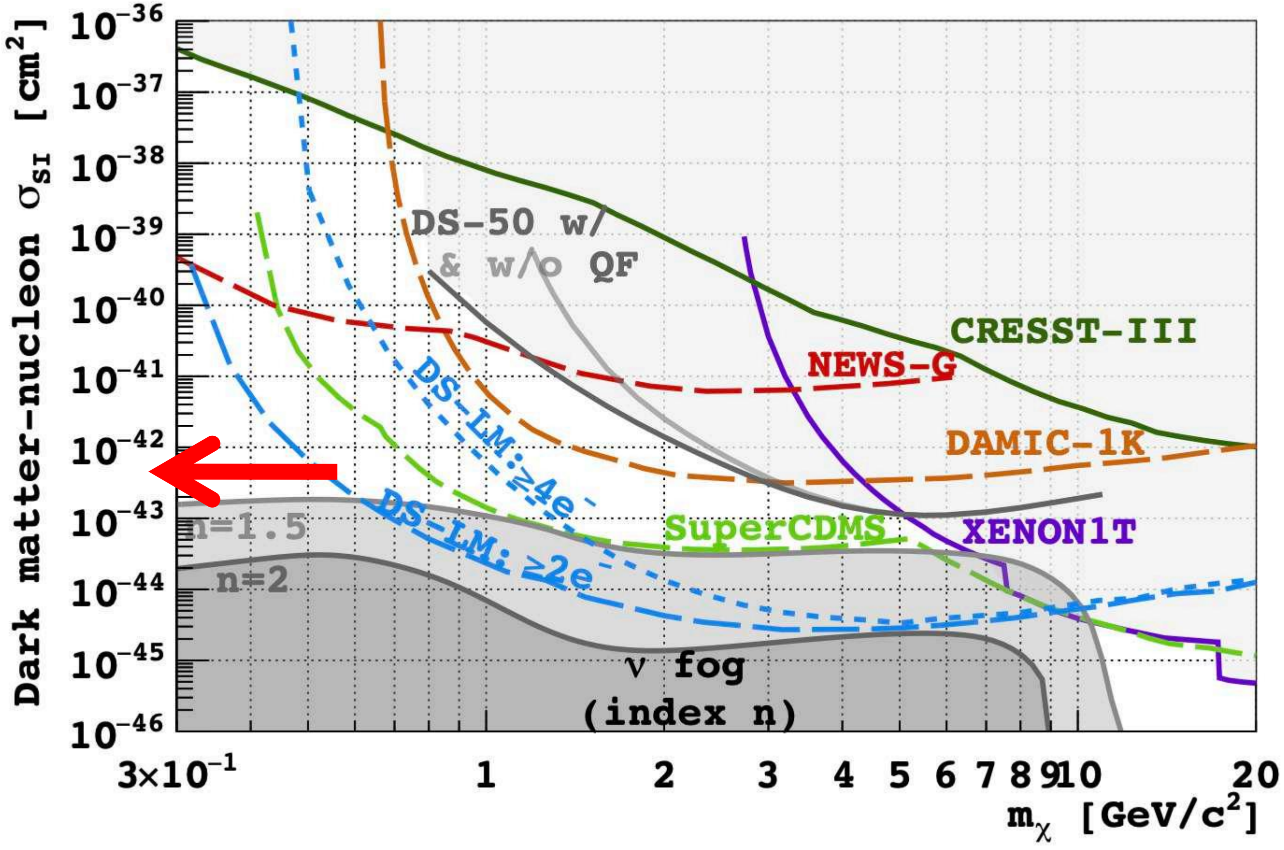

Phys. Rev. D 107, 112006 (2023)

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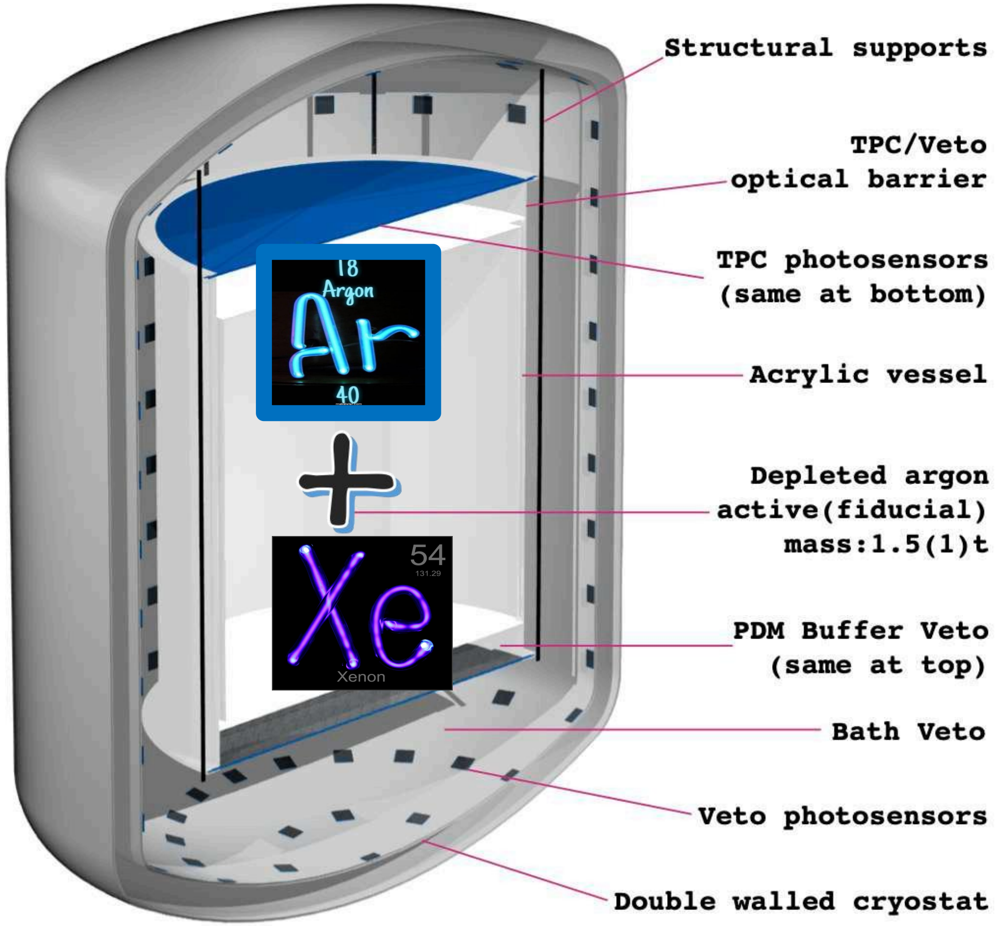
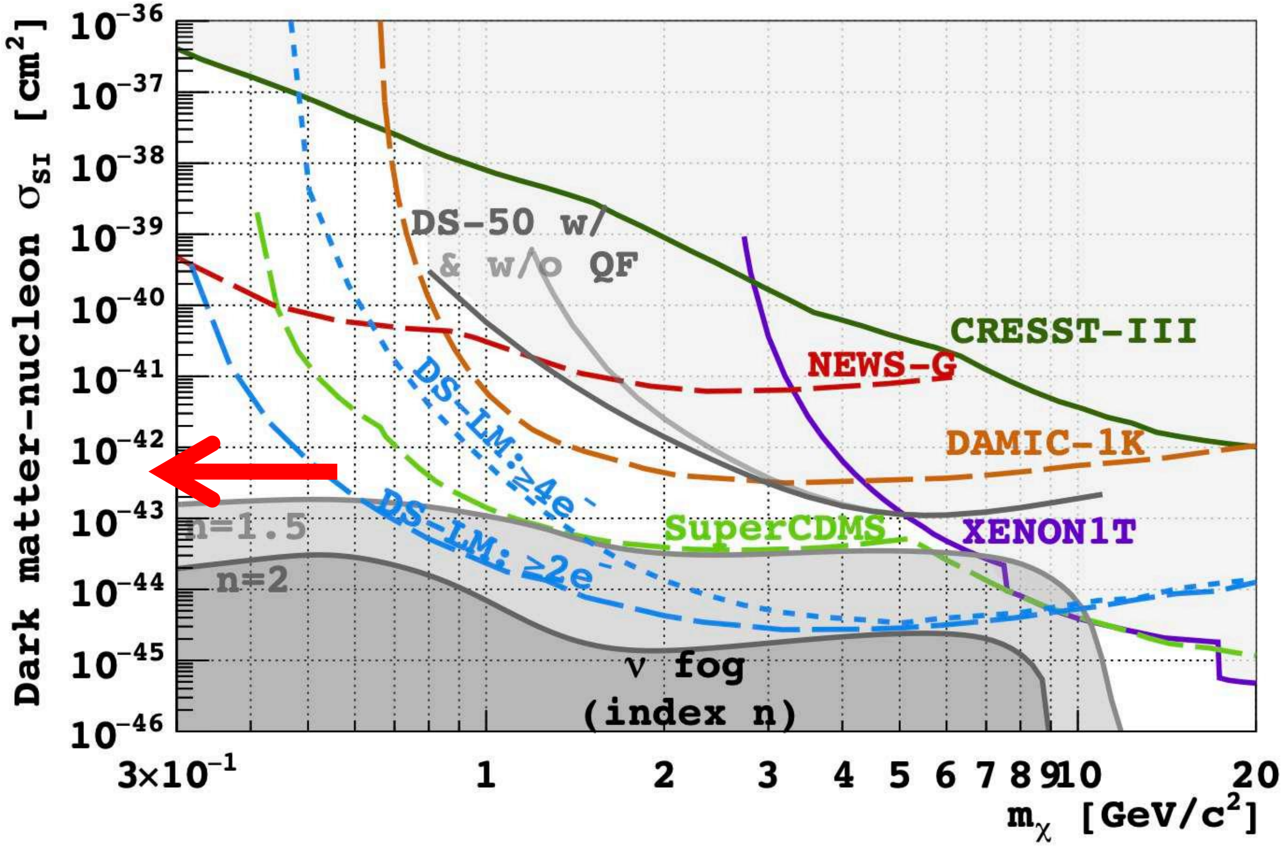
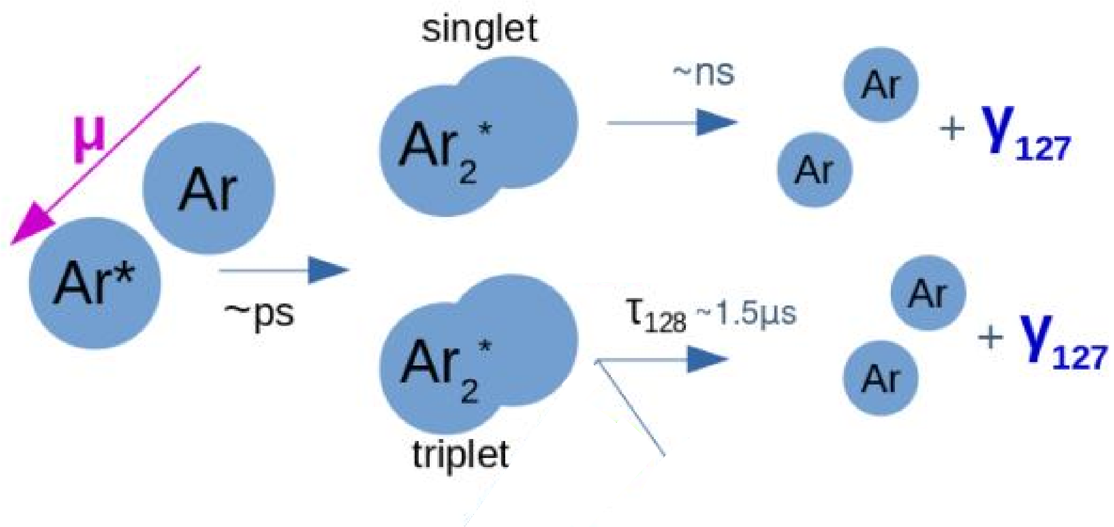
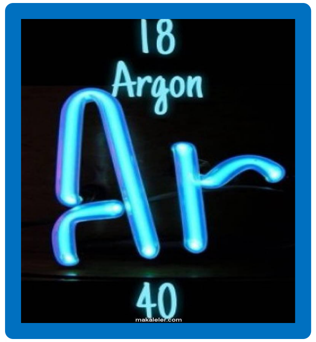




[Phys. Rev. D 107, 112006 (2023)]

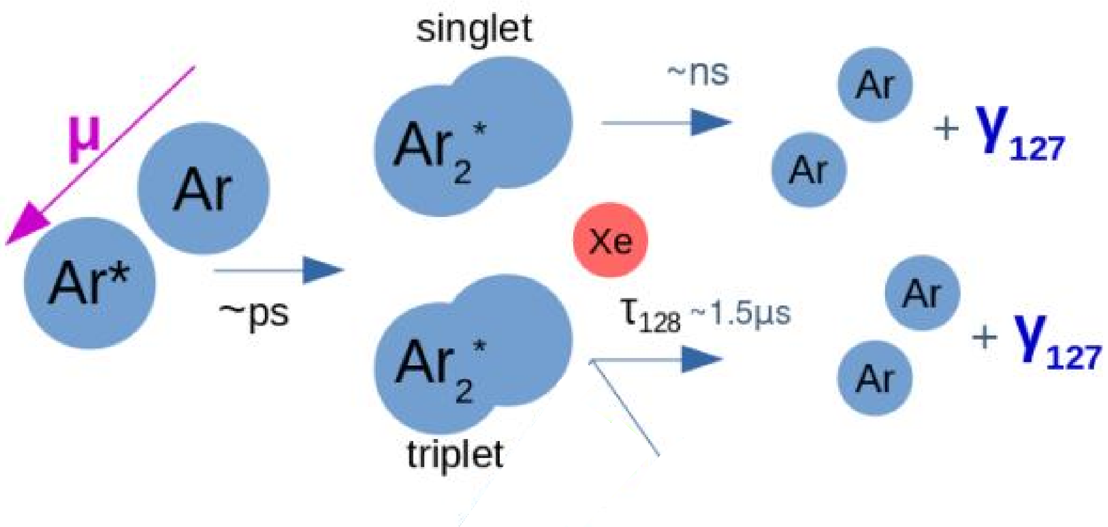
Xenon-doped Argon scintillation

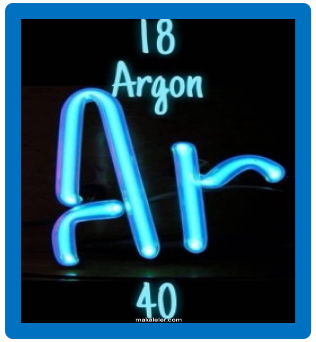




J. Phys.: Conf. Ser. 2374 012164

Xenon-doped Argon scintillation





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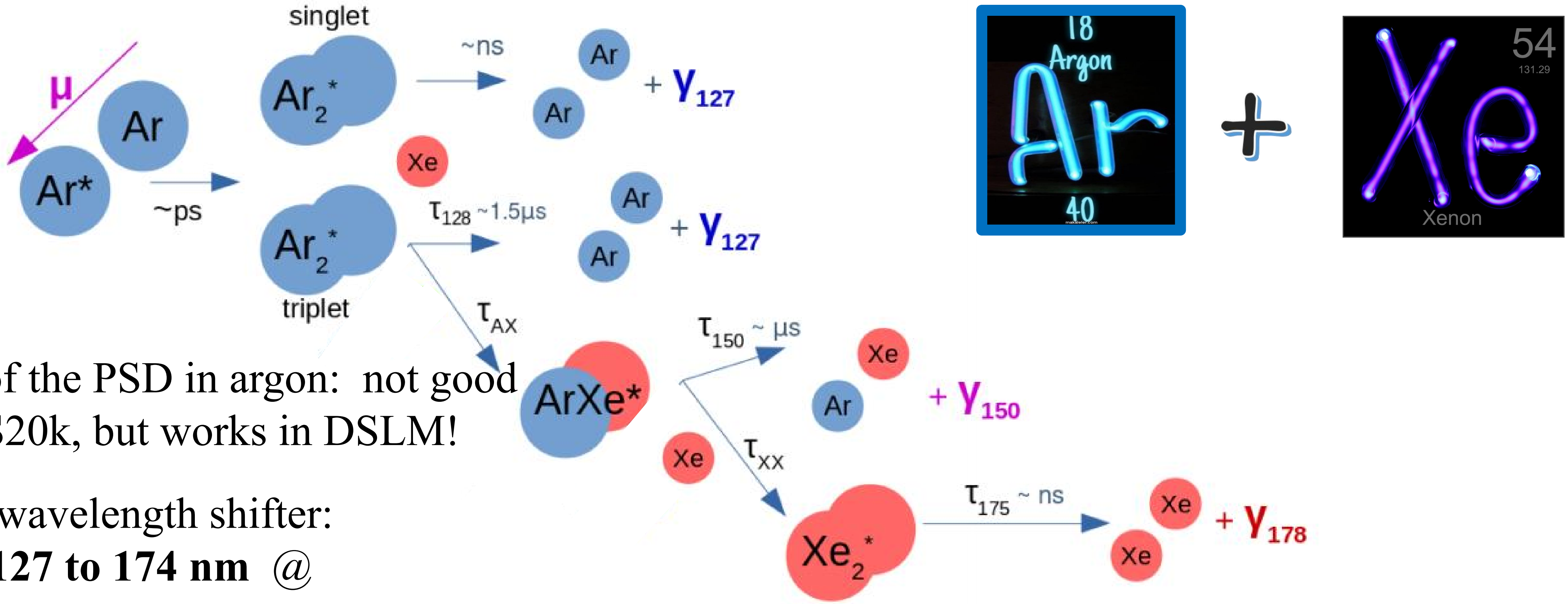
J. Phys.: Conf. Ser. 2374 012164

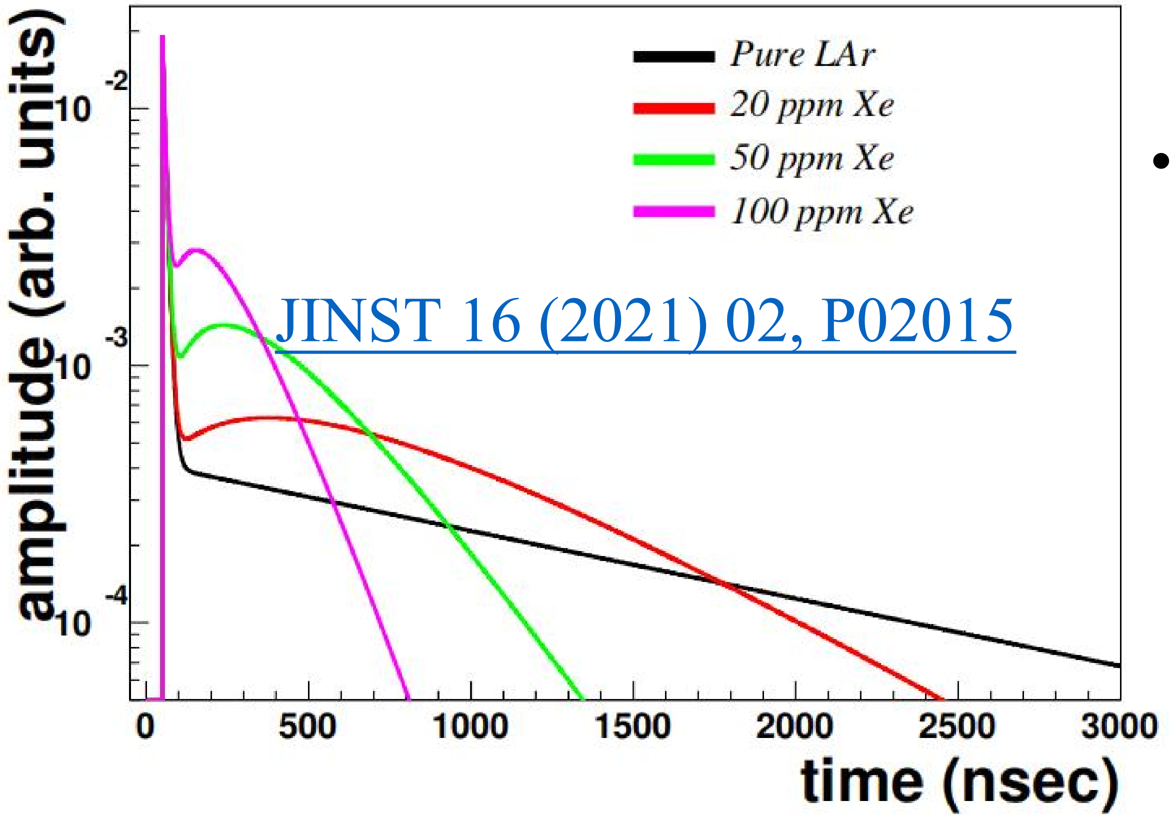
Xenon-doped Argon scintillation



- Loss of the PSD in argon: not good for DS20k, but works in DSLM!
- Local wavelength shifter: **from 127 to 174 nm** @ O(10) ppm Xe
- no TPB needed, possible decrease of spurious electron backgrounds

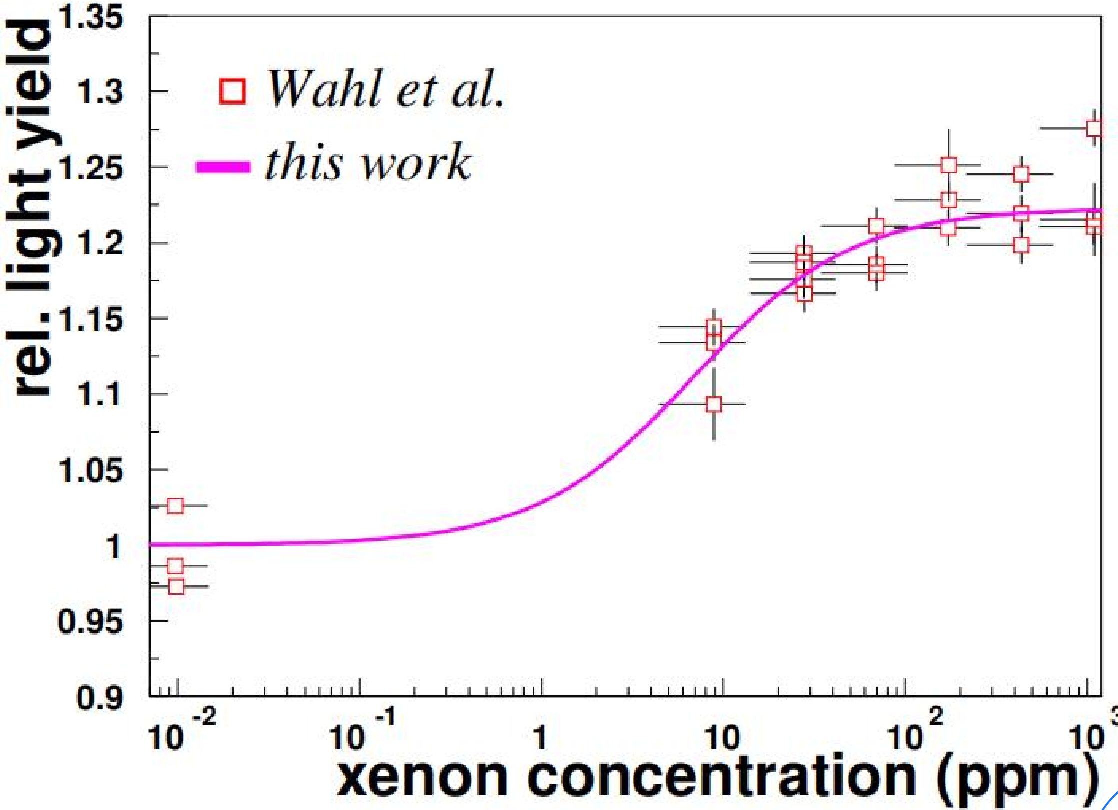
J. Phys.: Conf. Ser. 2374 012164

Xenon-doped Argon scintillation



JINST 16 (2021) 02, P02015

- Ongoing: evaluation on the ionization yield vs doping percentage (CHILLAX, LLNL, California)
- Additional synergies with DRD collaboration (Europe)

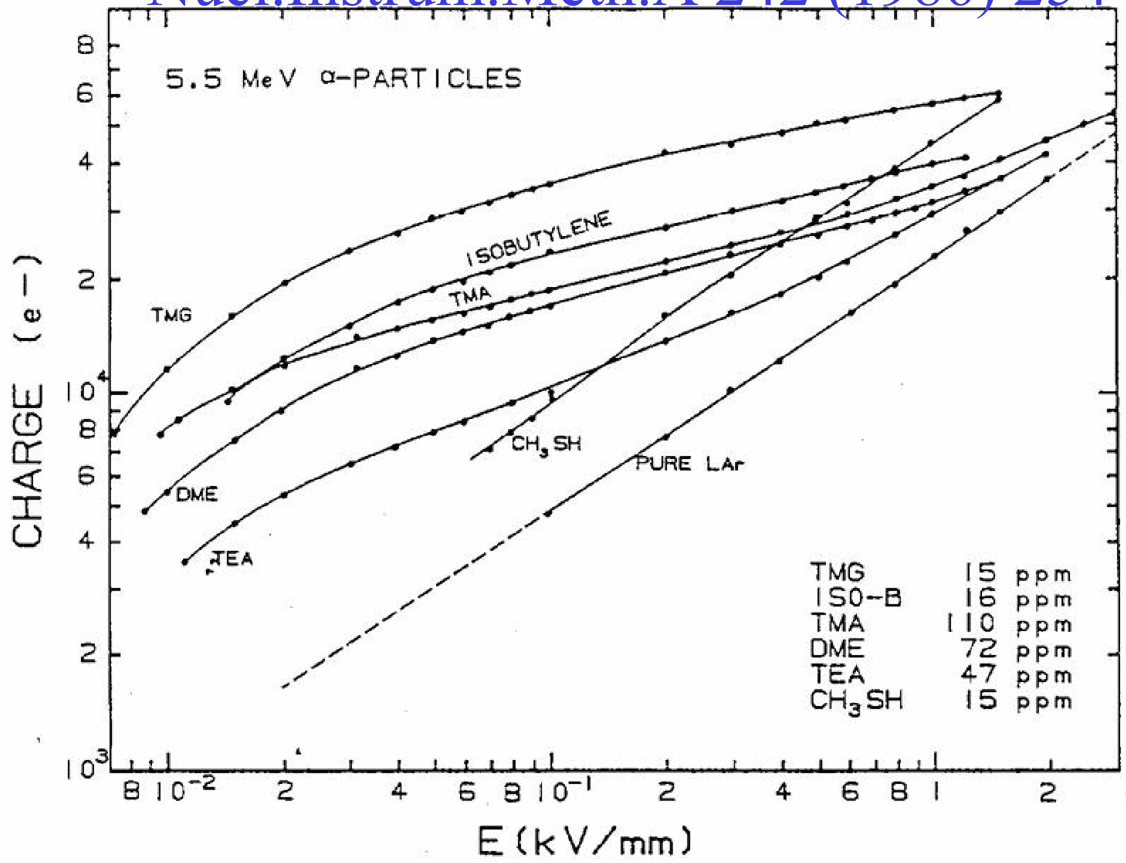


Phys.Rev.D 103 (2021) 4, 043001

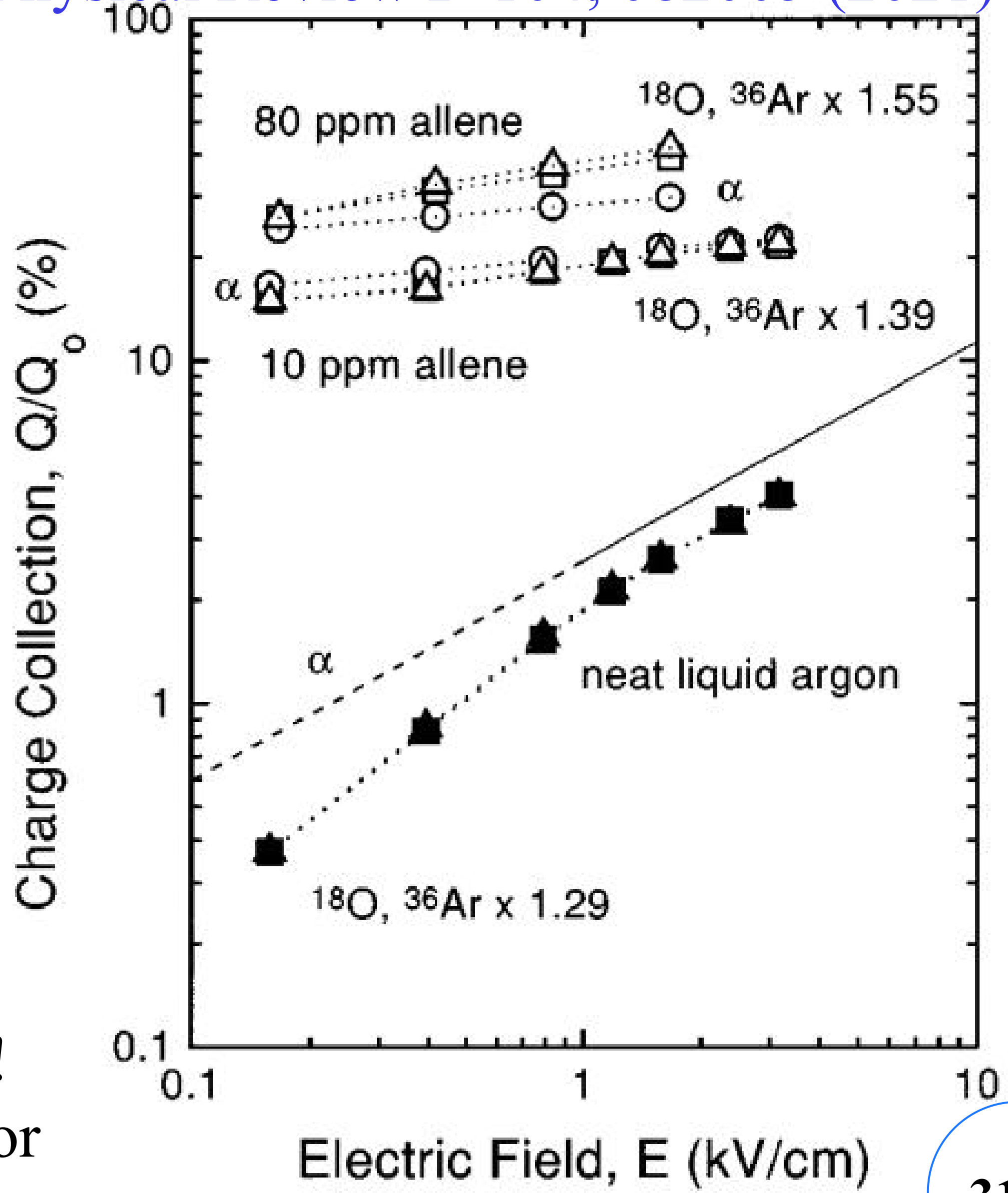
- Investigation of other photosensitive dopants starting soon at UC-Riverside
- **Starting 1 August 2025**: I will be starting an R&D for scalable double-phase TPC in doped Argon @ Queen's University

Beyond xenon!

Nucl.Instrum.Meth.A 242 (1986) 254



Physical Review D 104, 082005 (2021)

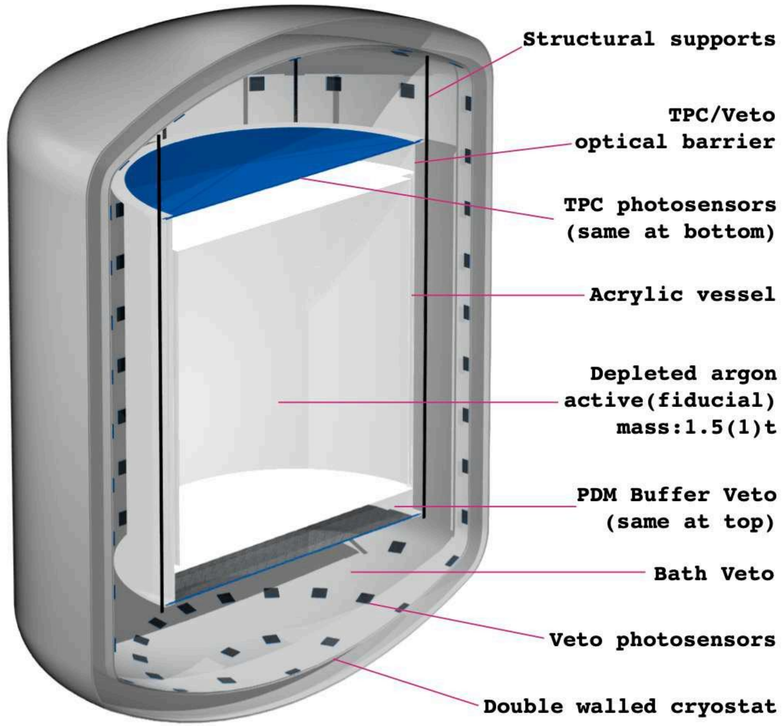


- **Addition of O(10) ppm Photosensitive dopants with 7.5–9.5 eV ionization energies enhances S2**!
- High-enough hydrogen in the dopants may allow for sensitivity to 40x lower WIMP masses

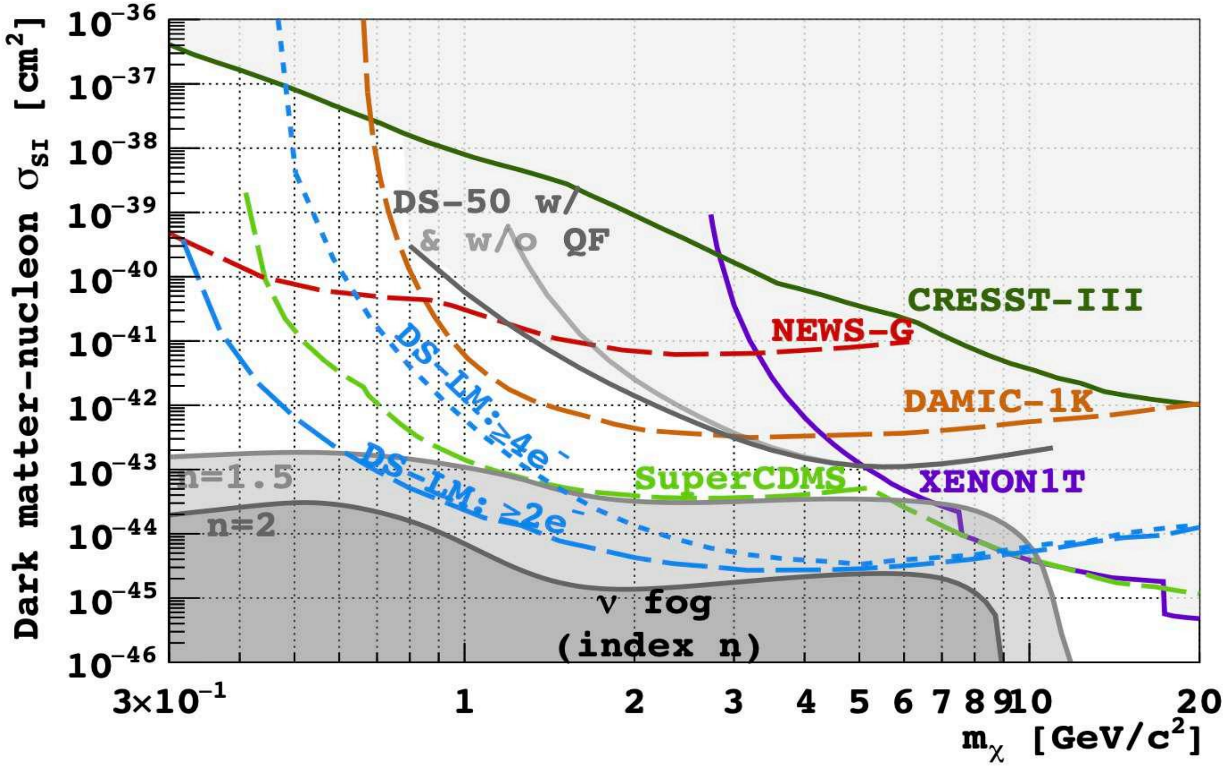
In a nutshell

- DSLM is the optimized tonne-scale detector for sub-GeV DM candidates in argon
- Using the analysis, hardware and UAr infrastructures already in place for DEAP, DS20k and ARGO
- Most of the infrastructure already requested within 2025 CFI-IF proposal by GADMC-Canada
- Ongoing and planned R&D to suppress and mitigate backgrounds as well as enhance the ionization yield and the energy resolution

Back up

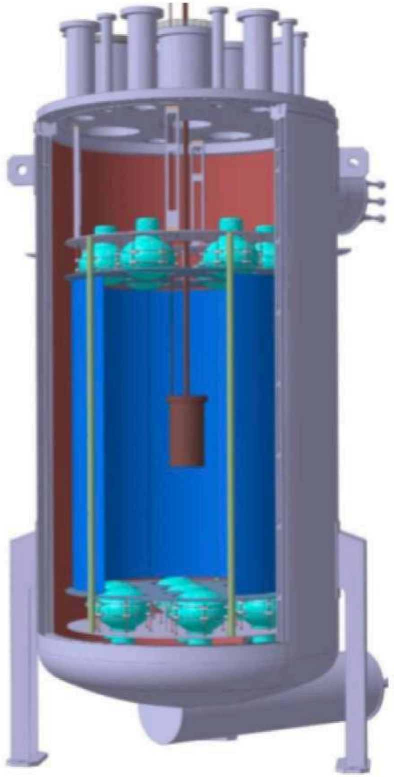


Structural supports
TPC/Veto optical barrier
TPC photosensors (same at bottom)
Acrylic vessel
Depleted argon active(fiducial) mass:1.5(1)t
PDM Buffer Veto (same at top)
Bath Veto
Veto photosensors
Double walled cryostat



Dark matter-nucleon σ_{SI} [cm^2]
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
3×10^{-1}
1
2
3
4
5
6
7
8
9
10
20
m_χ [GeV/c^2]
DS-50 w/ & w/o QF
CRESST-III
NEWS-G
DAMIC-1K
DS-LM: ≥4e
DS-LM: ≥2e
SuperCDMS
XENON1T
n=1.5
n=2
ν fog (index n)

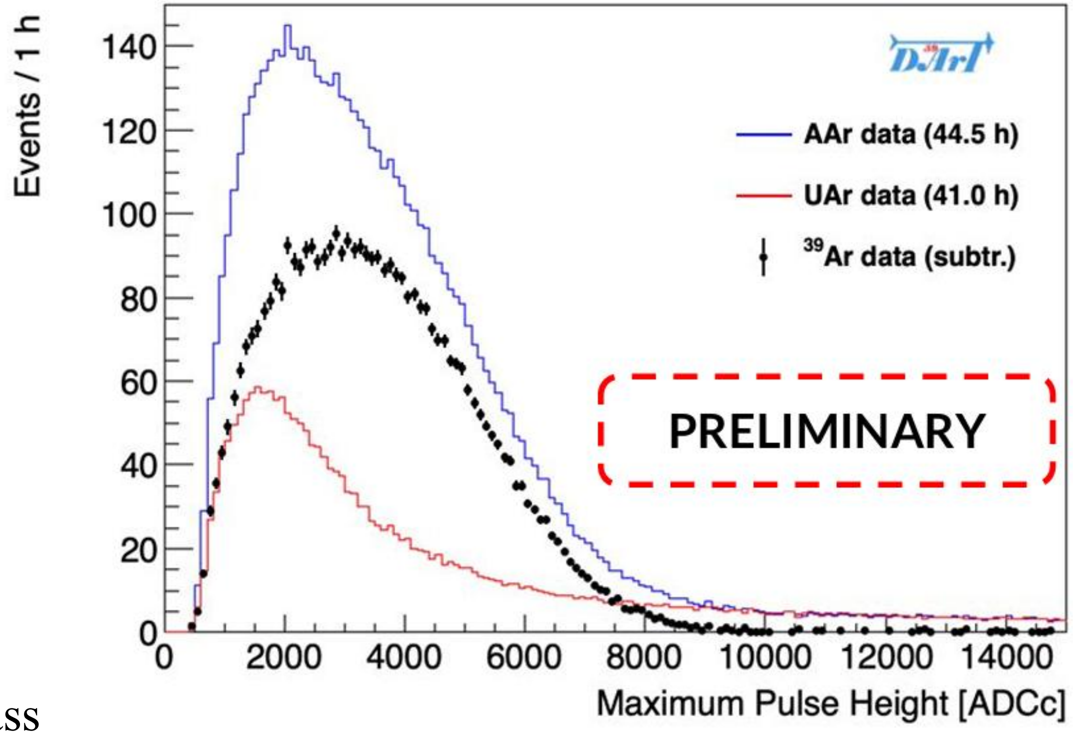
^{39}Ar essay in DArT with ArDM: small low-background detector located at Laboratorio Subterràneo de Canfranc (LSC, Spain), 1400 m.w.e undergound



ArDM: 850 kg AAr

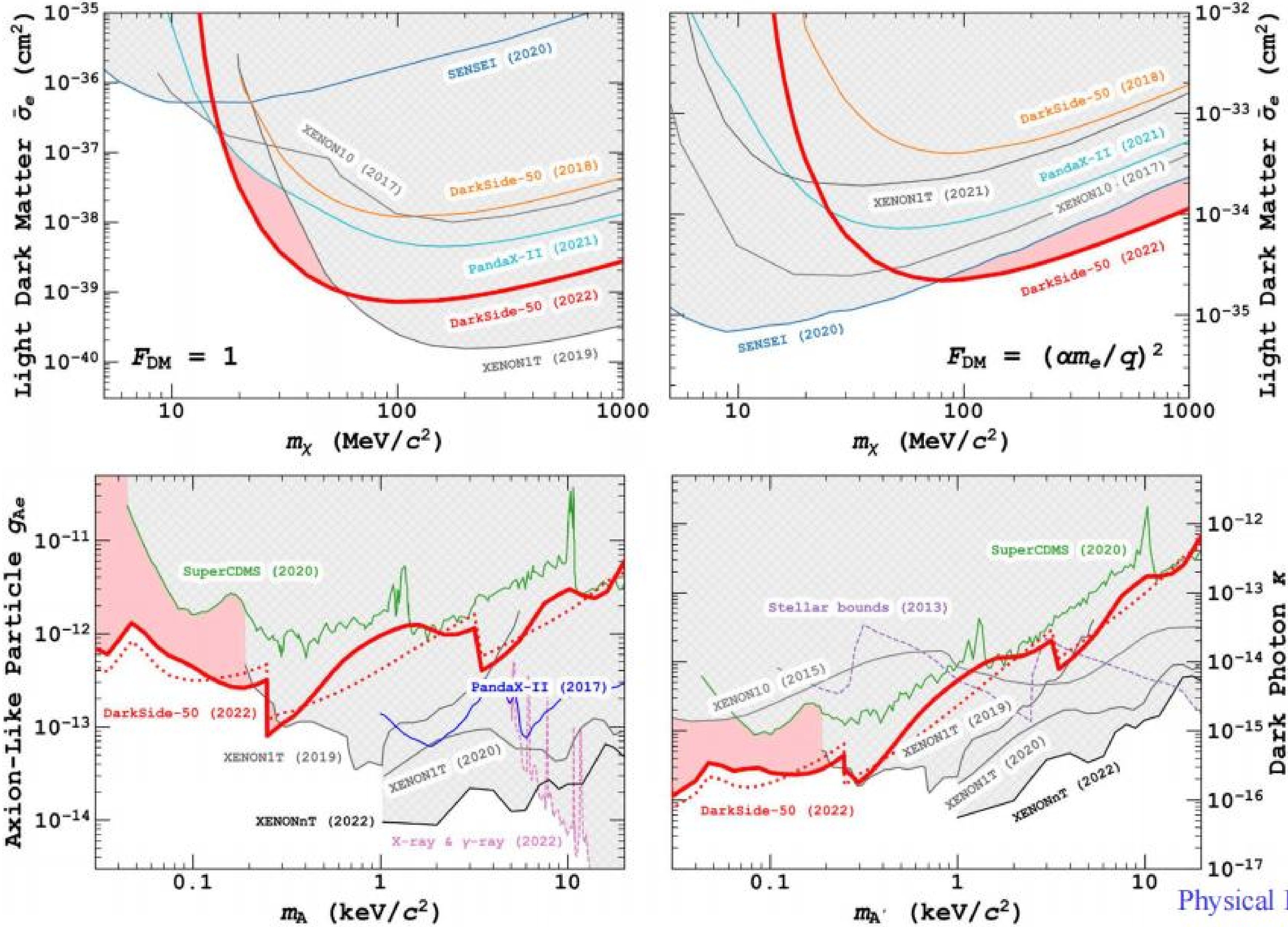
DArT: 1.35 kg active mass

Credits:
D. Gahan - ICHEP 2024



JINST 15 (2020) 02, C02044

Low mass searches



Anelastic scattering of fermion or bosons on Argon through light mediators

Absorption of ALPS by argon shell electrons

Physical Review Letters 130, 101002 (2023)

Dark matter Experiment using Argon
Pulse-shape discrimination

Triplet state

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

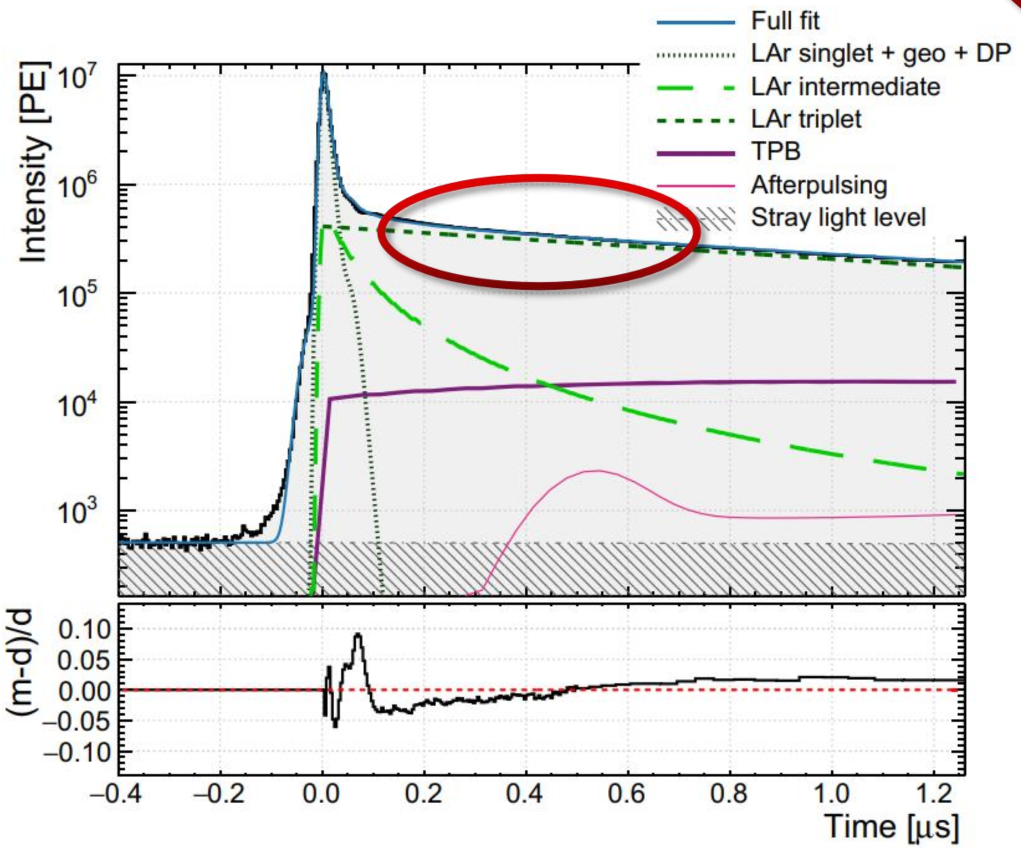
$\tau_s = 8.2ns$

$\tau_t = 1445ns$

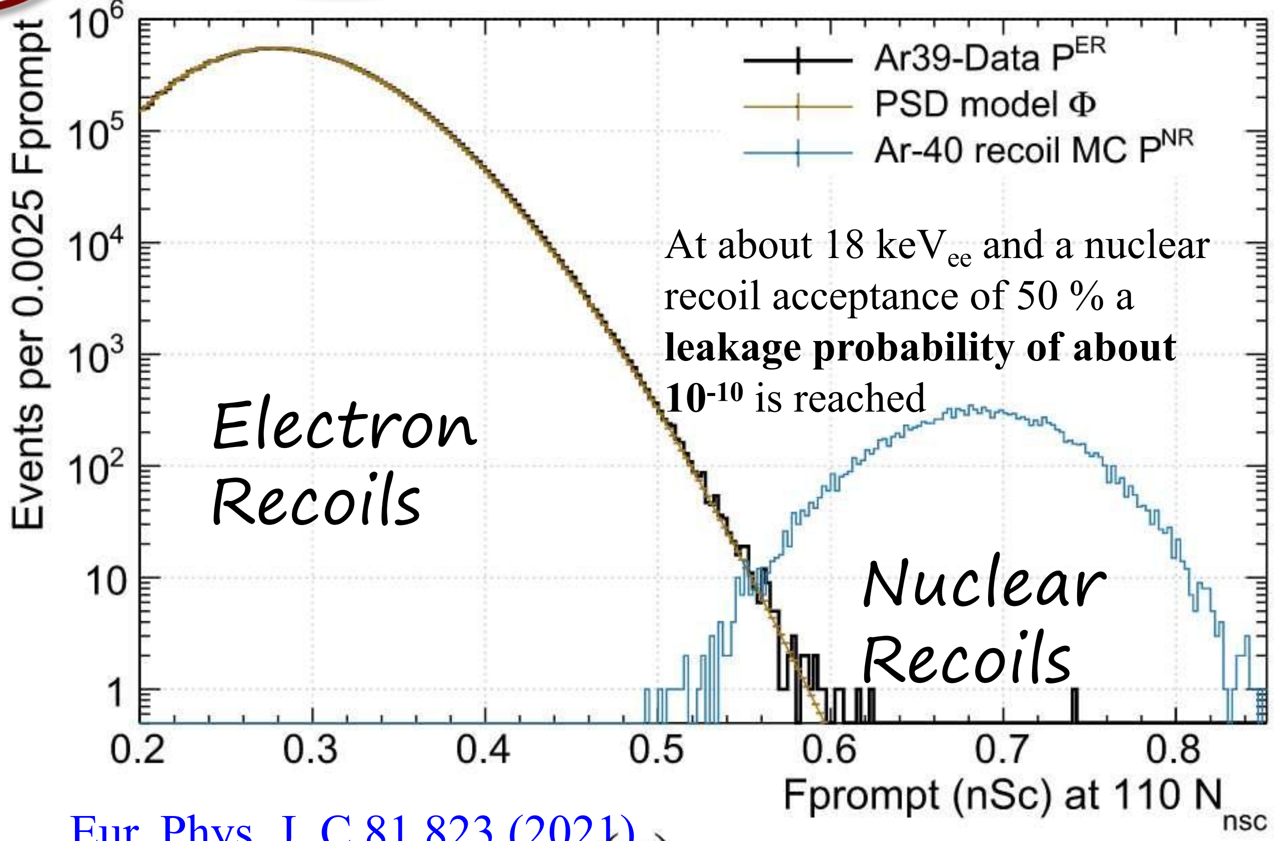
$\tau_{rec} = 175.5ns$

$R_s = 0.23$

$R_t = 0.71$



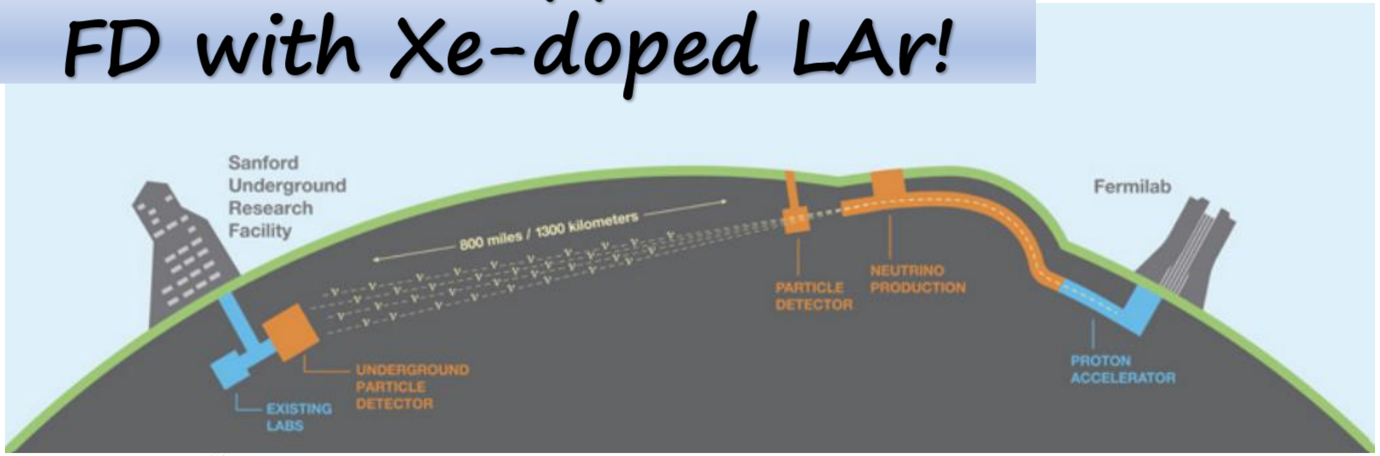
Eur. Phys. J. C 80,303 (2020)



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

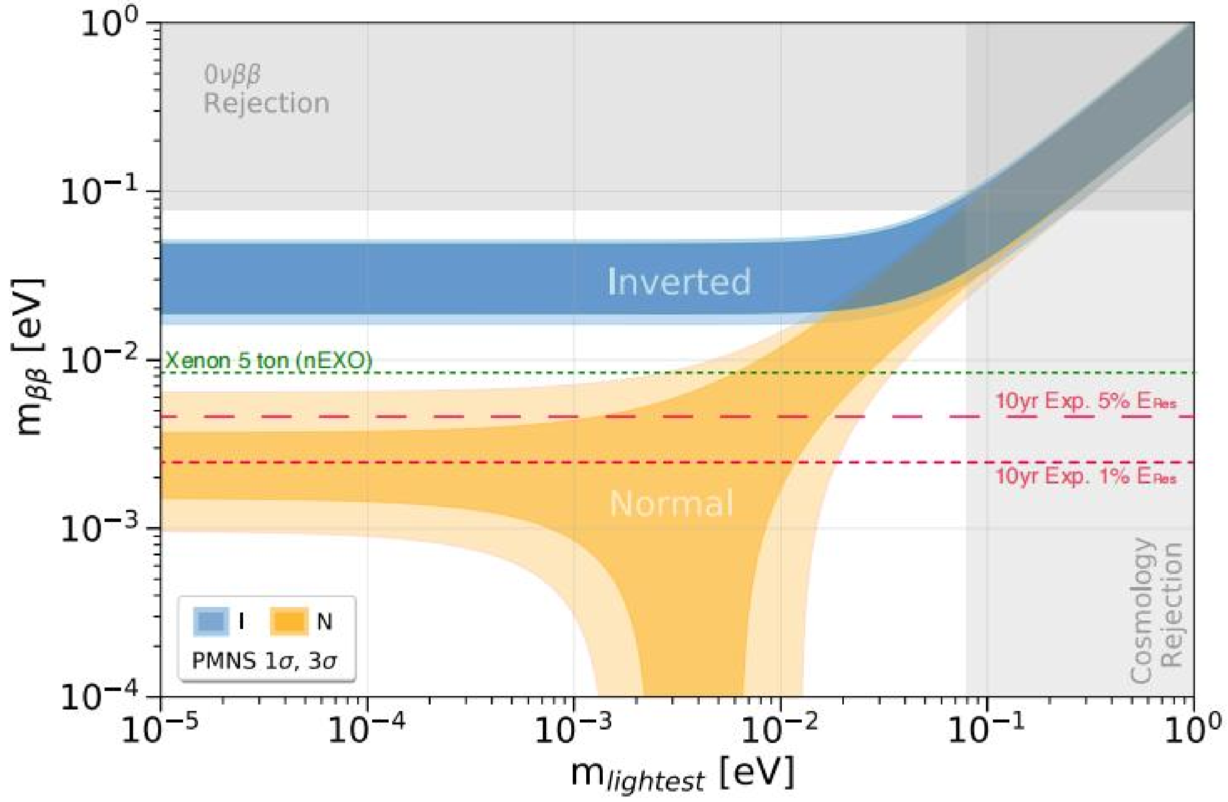
Eur. Phys. J. C 81,823 (2021)

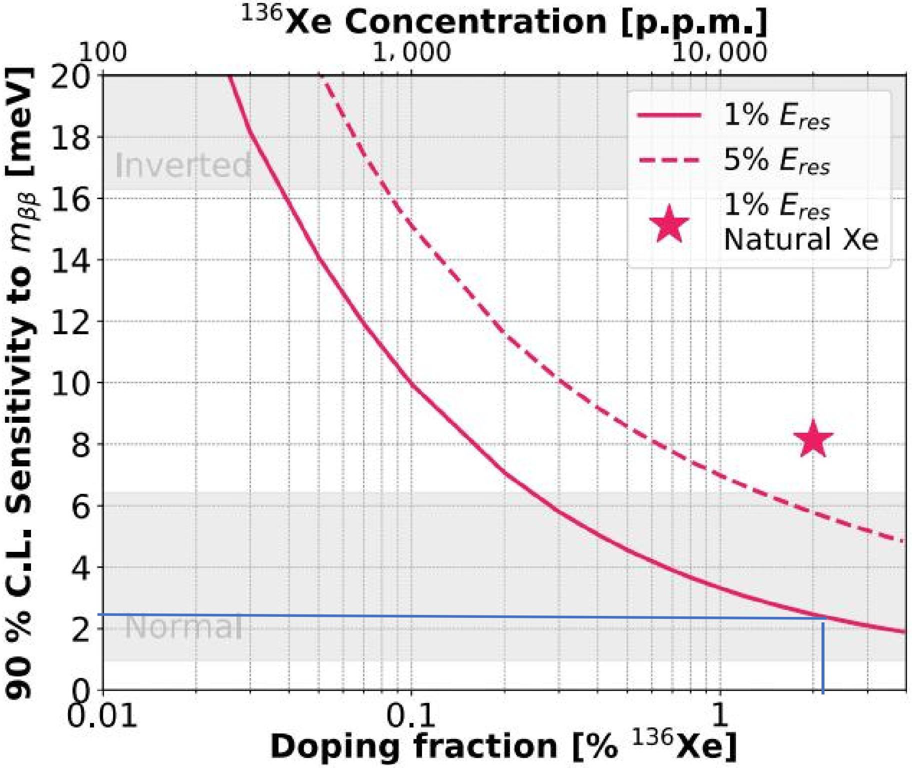
Search for 0νββ in DUNE FD with Xe-doped LAr!



- Is Neutrino its own antiparticle? How are neutrino masses ordered? We can get that with 2% of Xe-doping in DUNE FD (10 kton LArTPC)

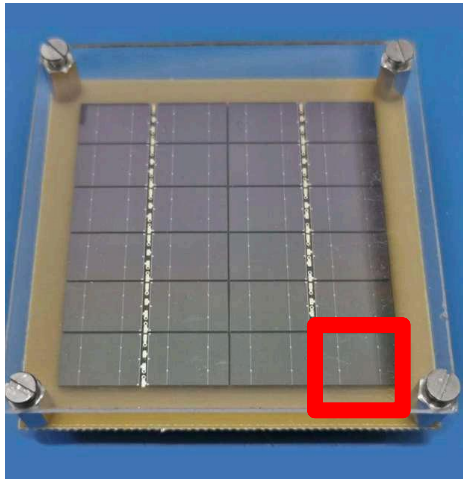
$m_{\beta\beta} = 2.46$ meV
$T_{1/2\ 0\nu} = 1.03 \times 10^{29}$ years

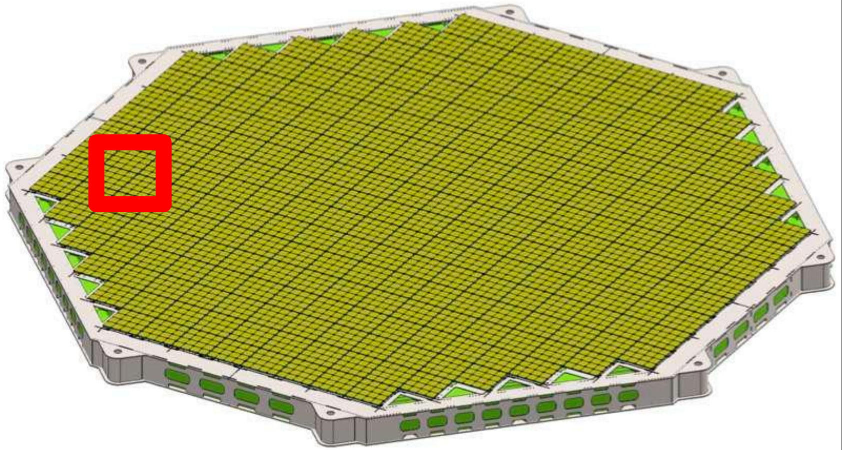




[Phys.Rev.D 106 (2022) 9, 092002](#)

Photosensors have being tested in NOA facility, Italy, while the read-out is developed at TRIUMF



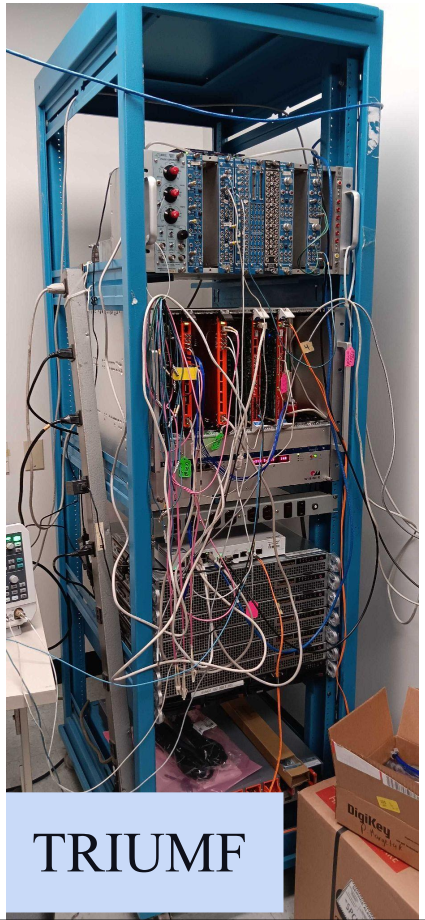


TPC: 525 PDU

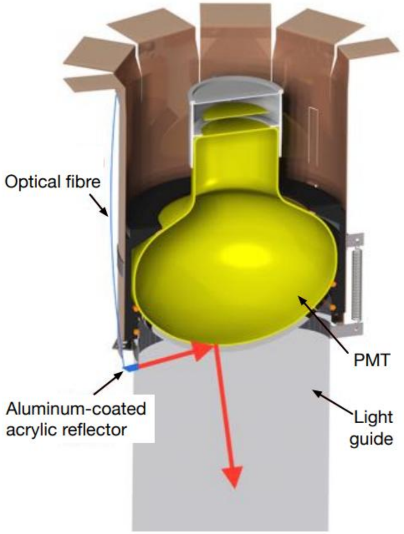
IV: 20 vPDU

OV: 32 vPDU

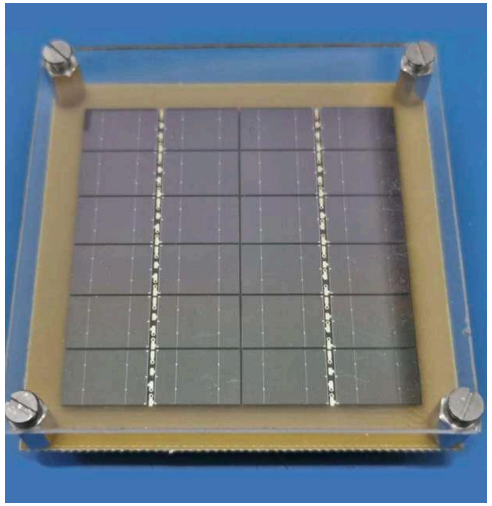
NOA facility

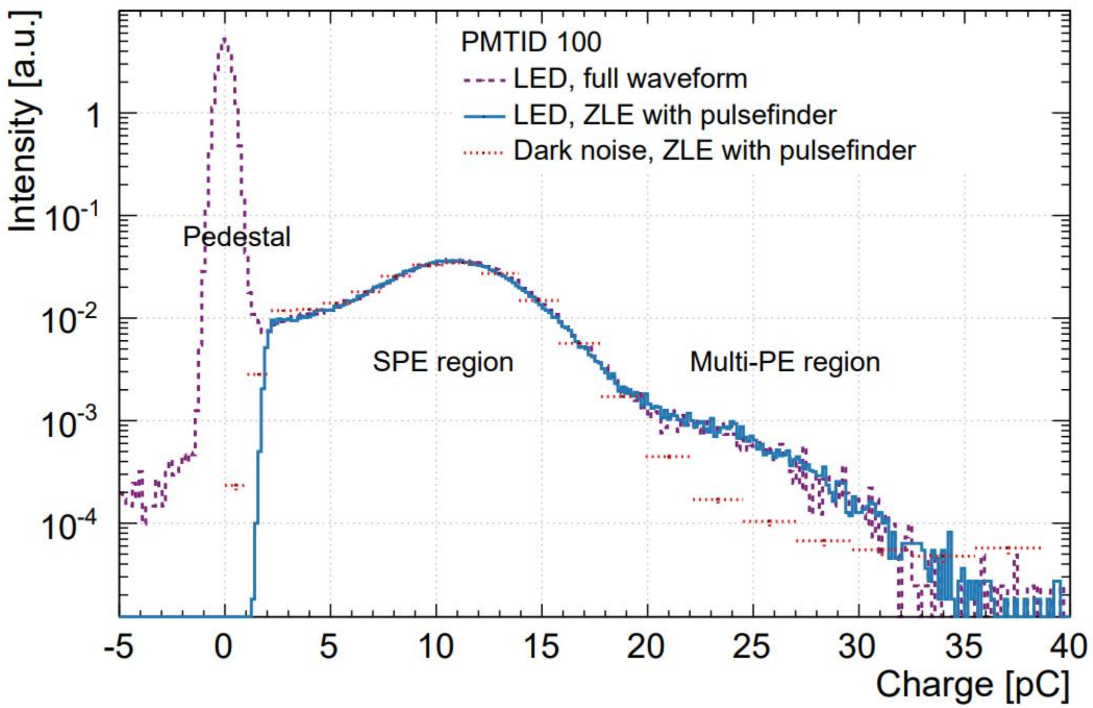


TRIUMF

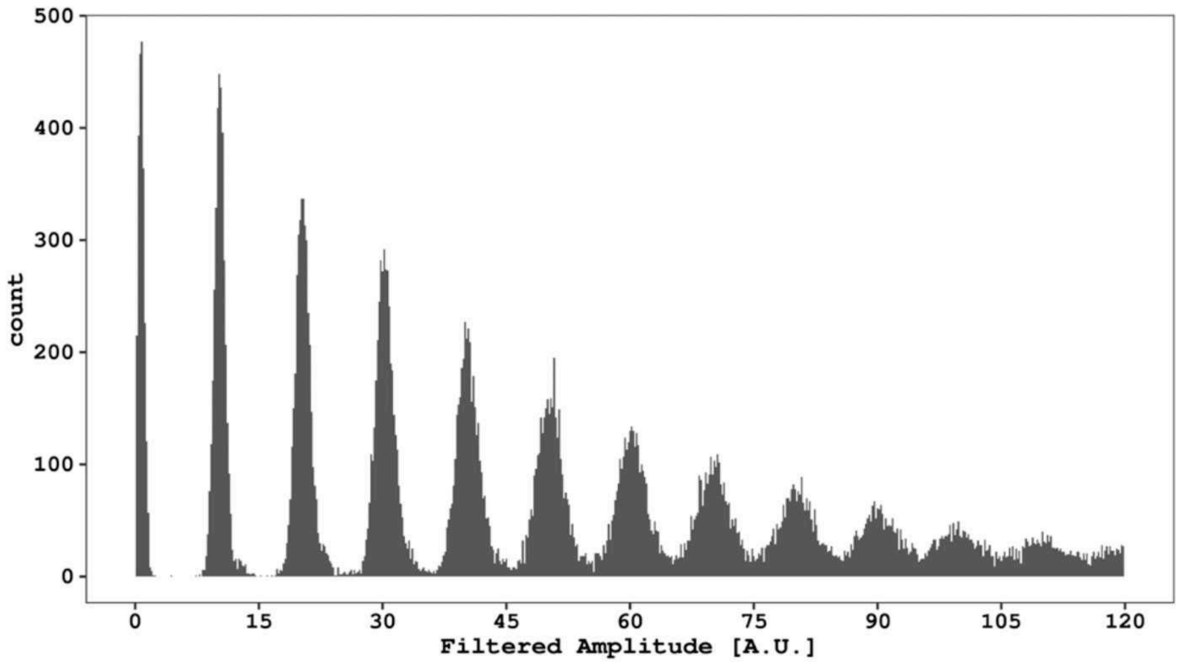


Photomultipliers tubes (PMTs) exchanged for Silicon Photomultipliers (SiPMs) customly developed by Fondazione Bruno Kessler



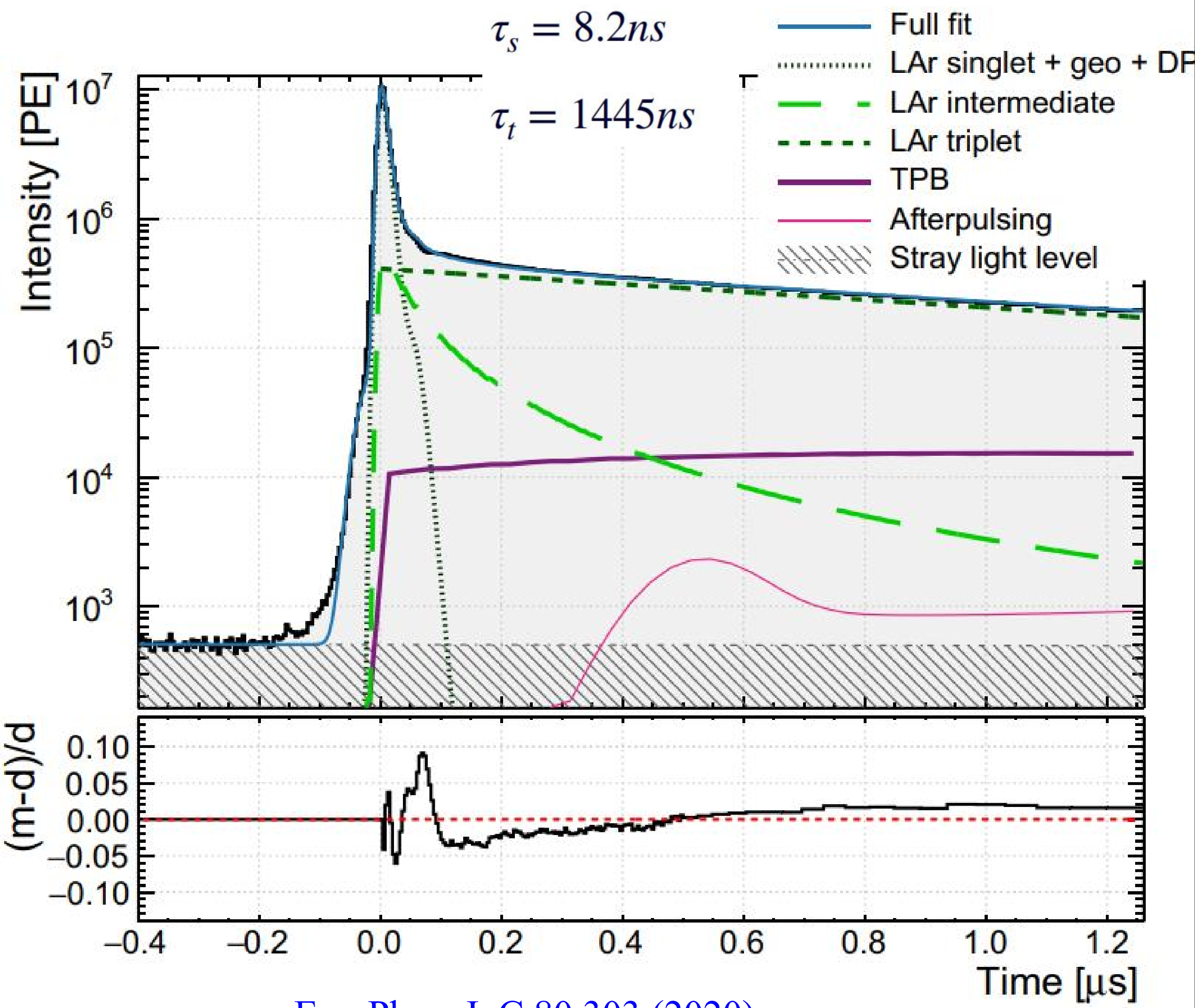


Nucl. Instr. Meth. A 922(2019) 373-384



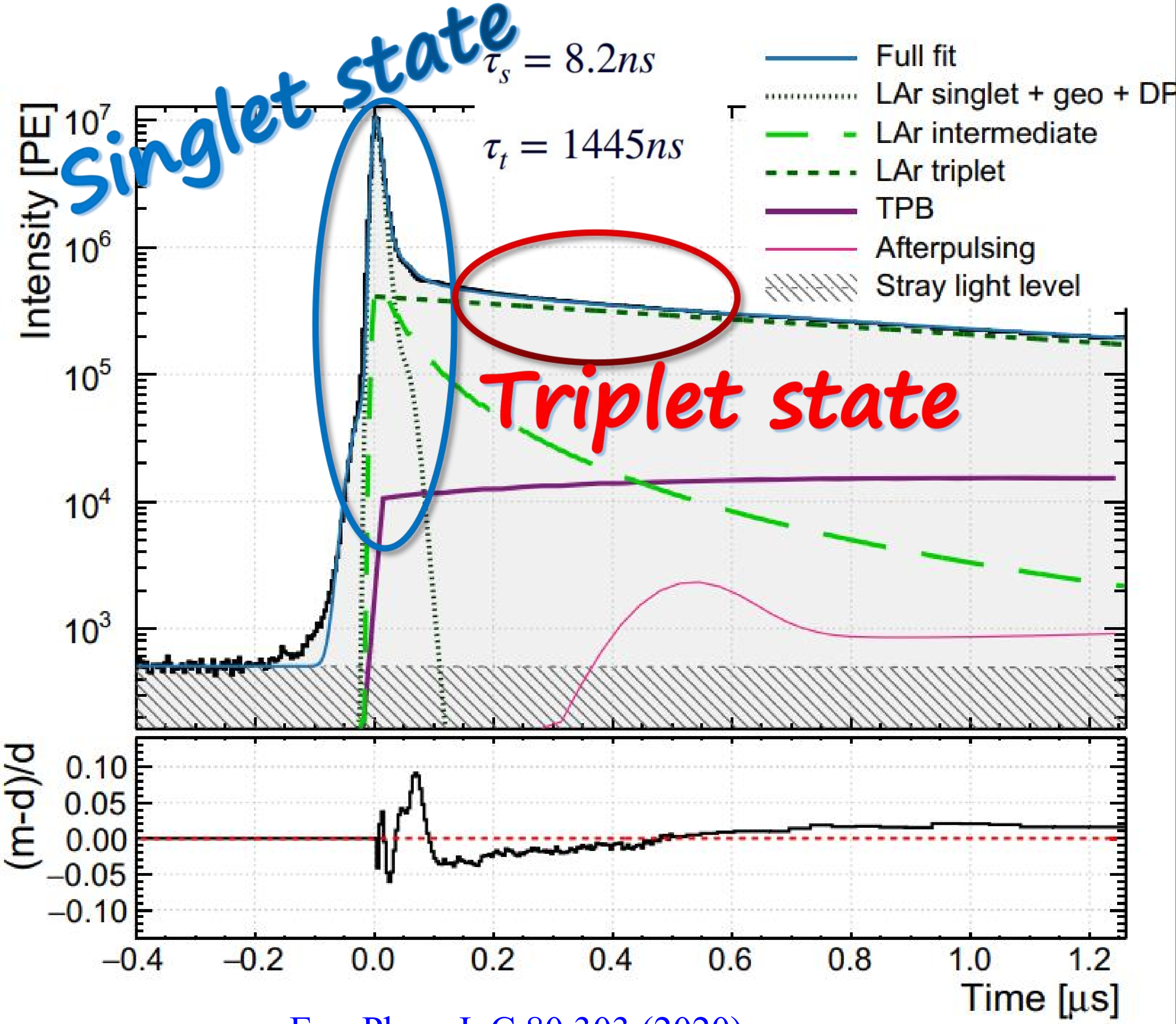
A. Gola et al. Sensors19(2), 308 (2019)

Dark matter Experiment using Argon Pulse-shape discrimination



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

Dark matter Experiment using Argon Pulse-shape discrimination

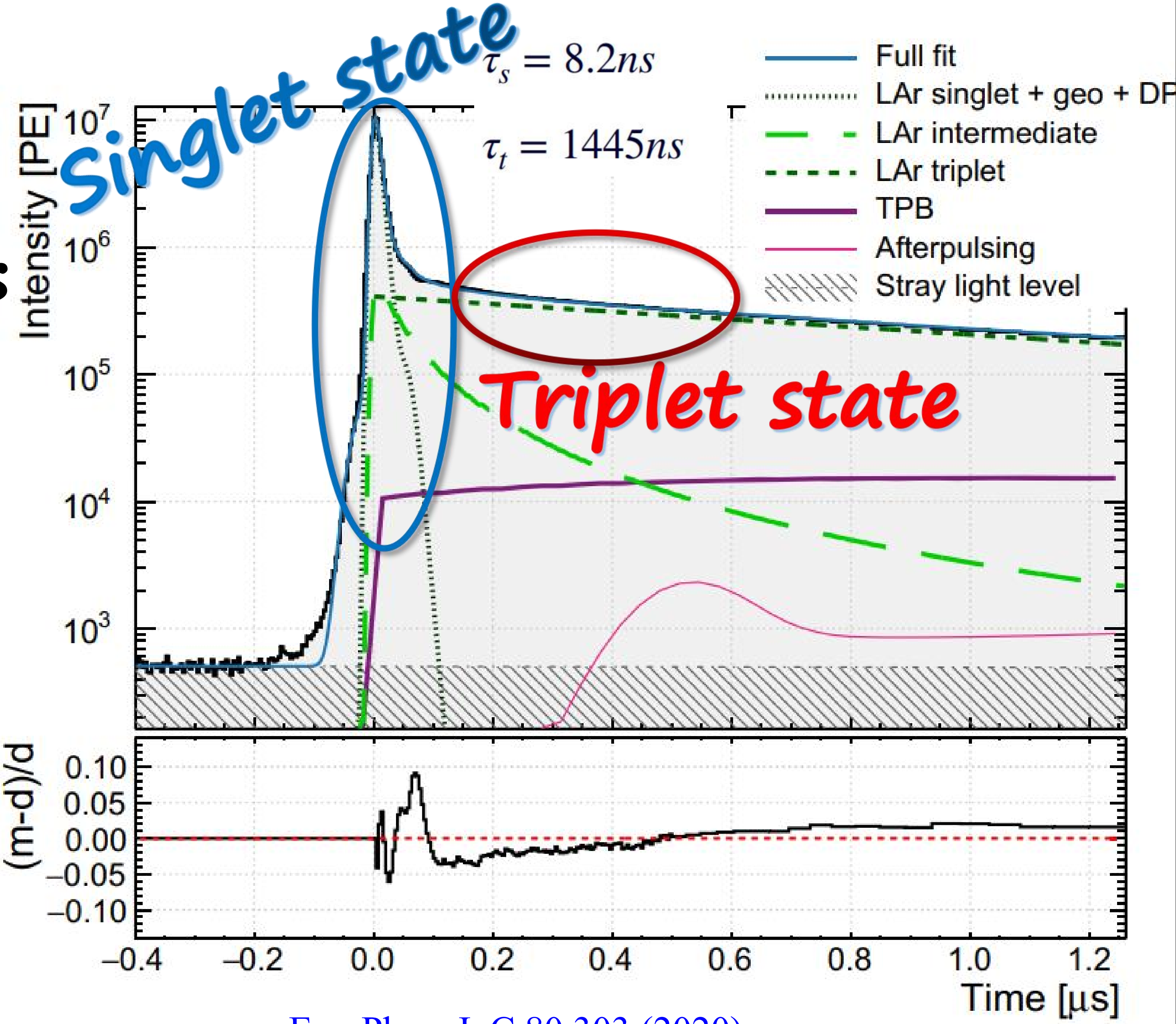


Eur. Phys. J. C 80,303 (2020)

Dark matter Experiment using Argon Pulse-shape discrimination

Nuclear recoils (DM, neutrons)

Electron recoils (e, gammas)



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

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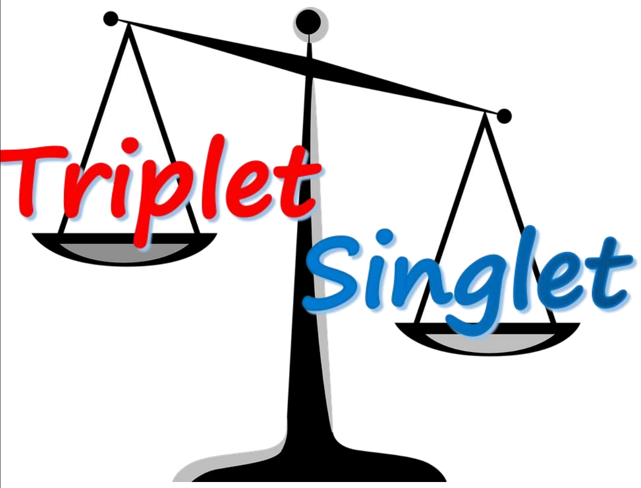
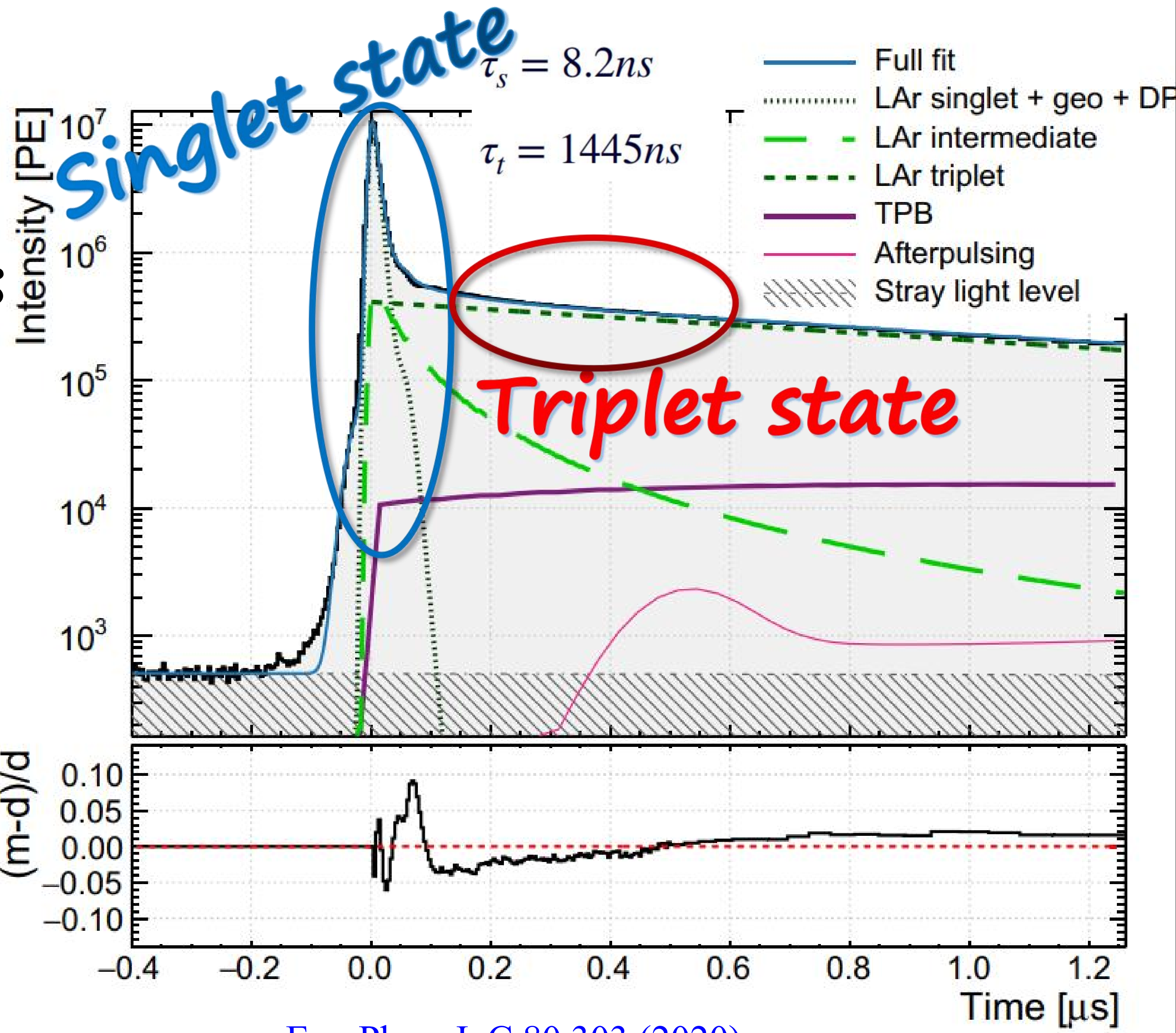


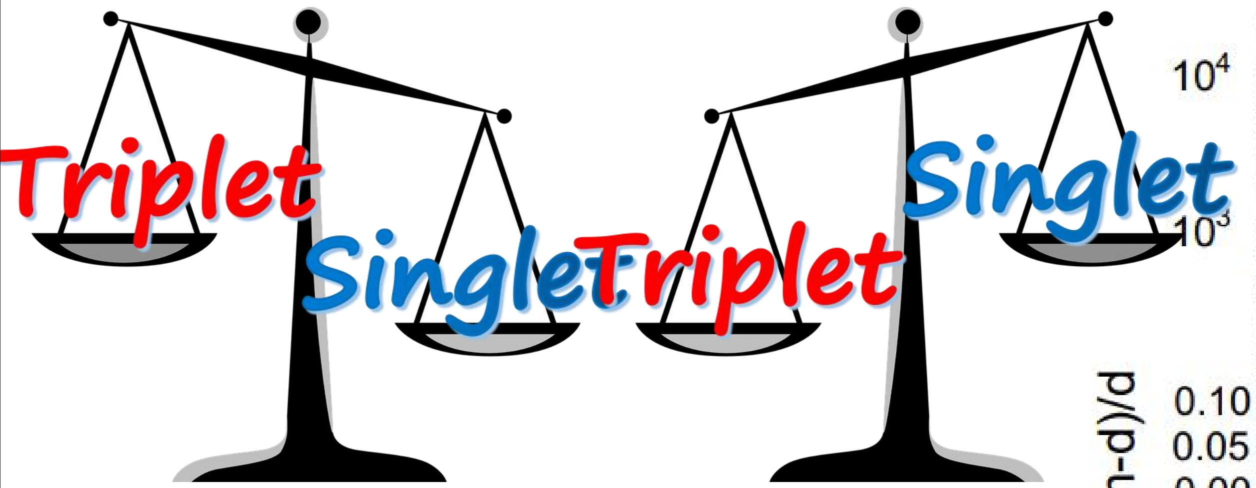


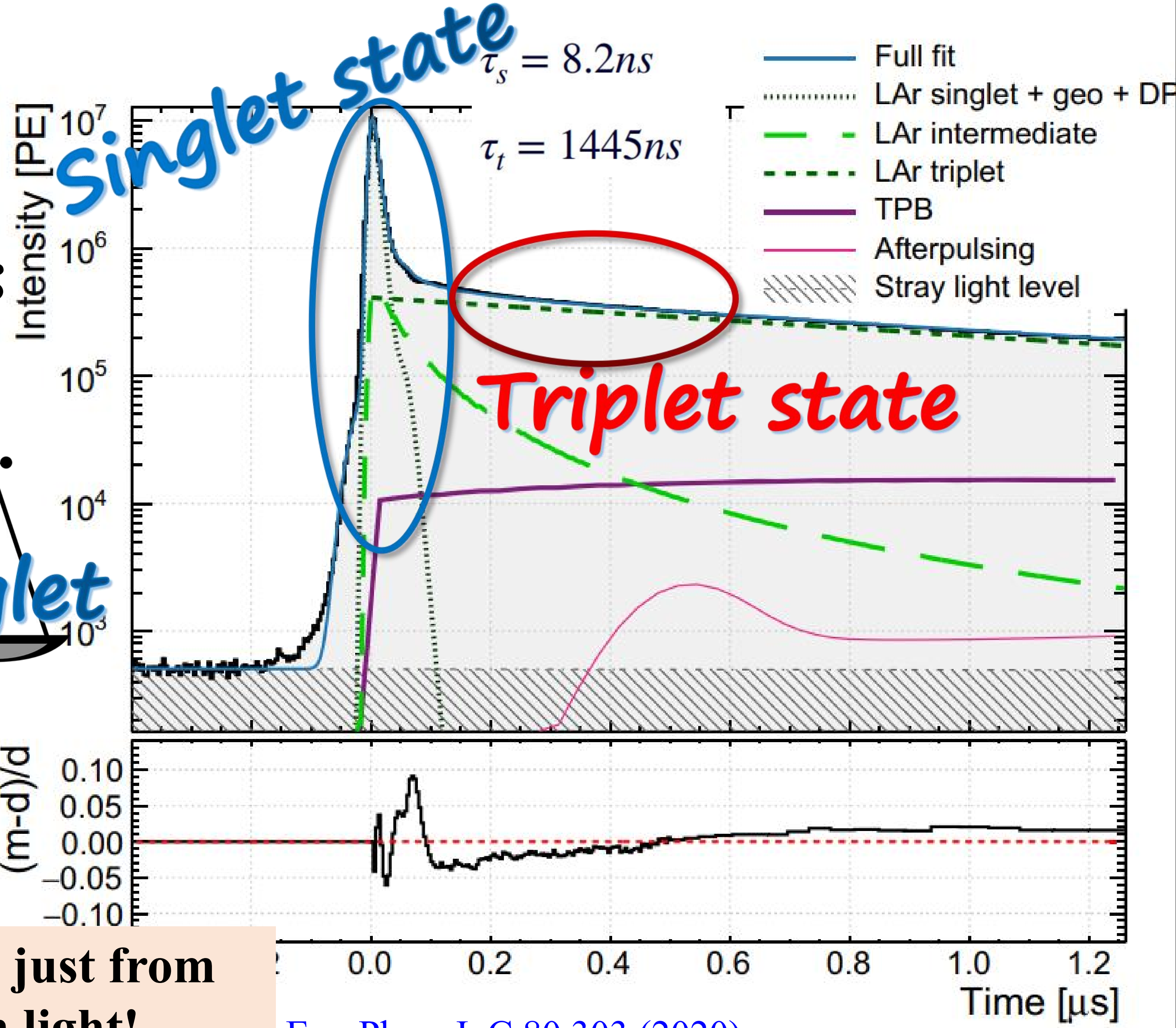
Eur. Phys. J. C 80,303 (2020)

Dark matter Experiment using Argon Pulse-shape discrimination

Nuclear recoils (DM, neutrons)

Electron recoils (e, gammas)



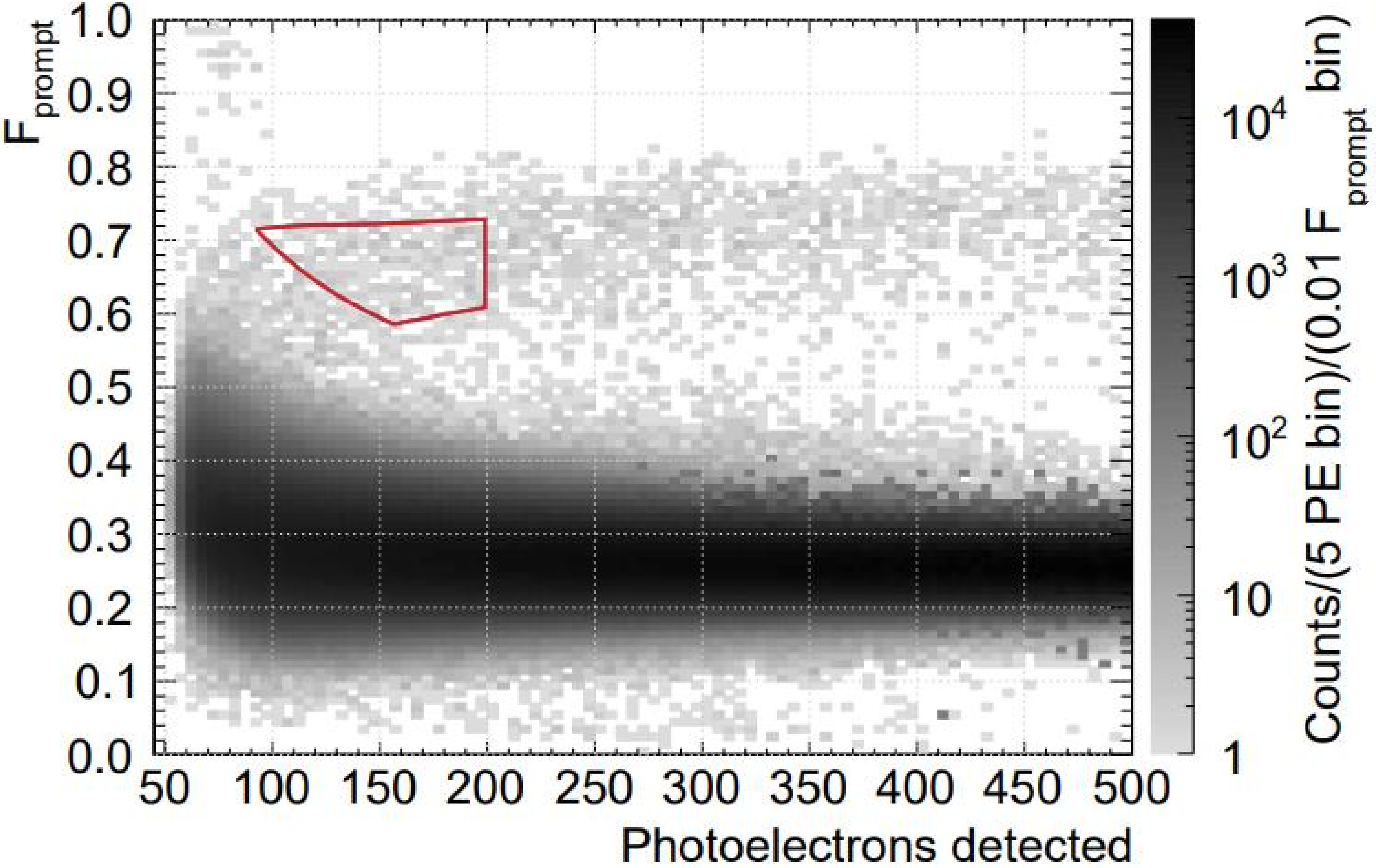


Eur. Phys. J. C 80,303 (2020)

In Argon we get Particle Identification just from the Fraction of the prompt scintillation light!

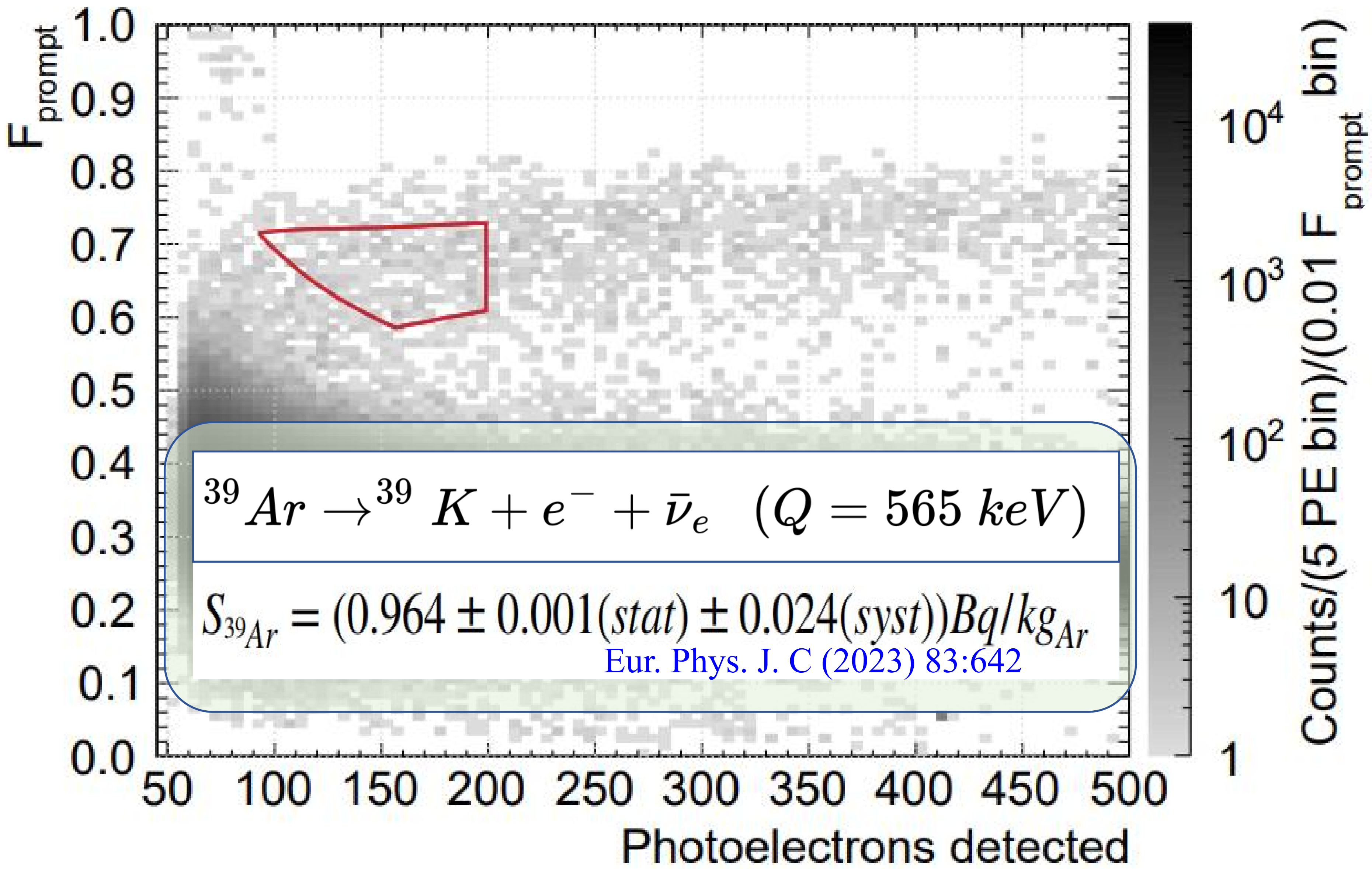
How does the data analysis look like?

Before selection cuts...



How does the data analysis look like?

Before selection cuts...



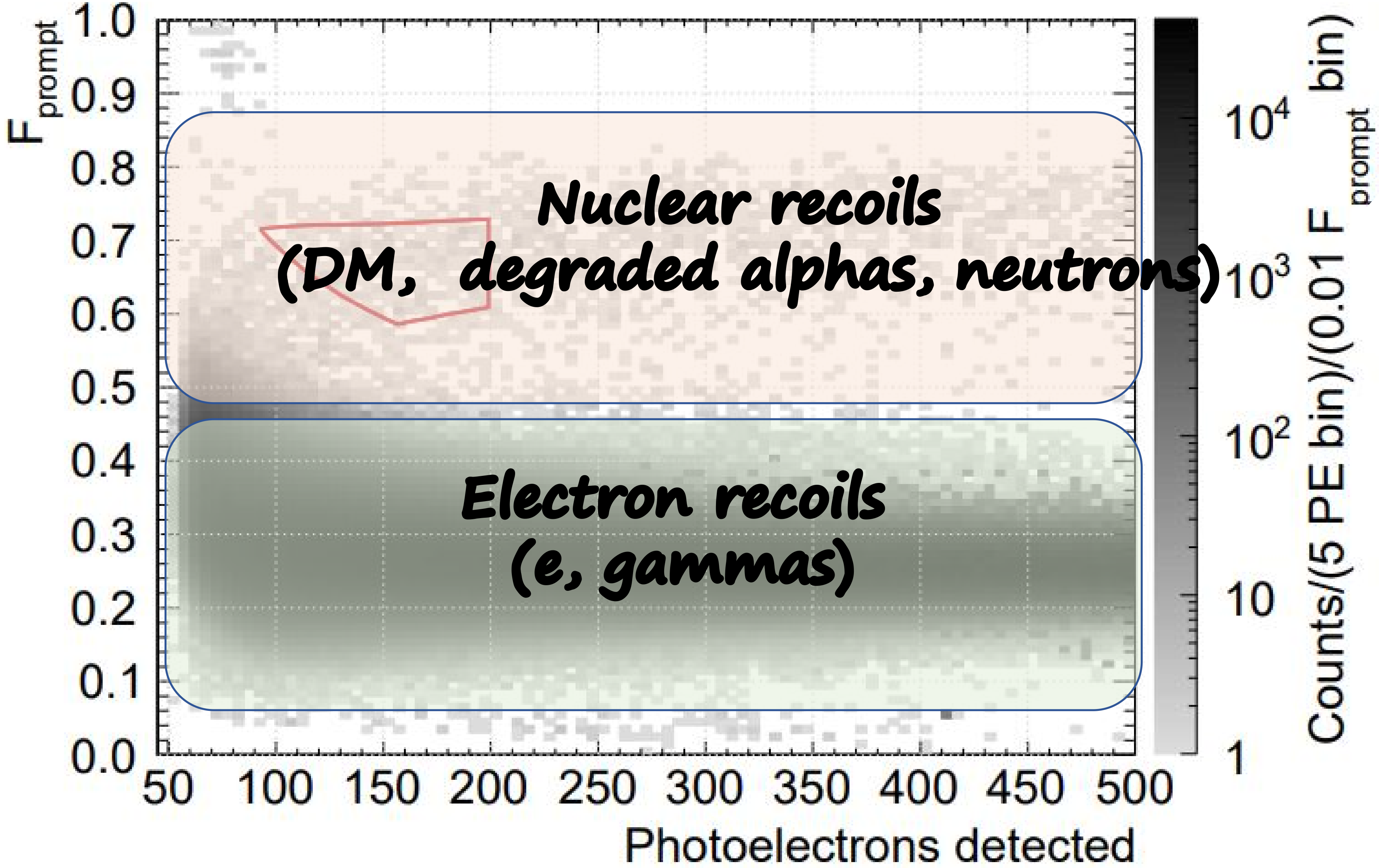
$$^{39}Ar \rightarrow ^{39}K + e^- + \bar{\nu}_e \quad (Q = 565\ keV)$$

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

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

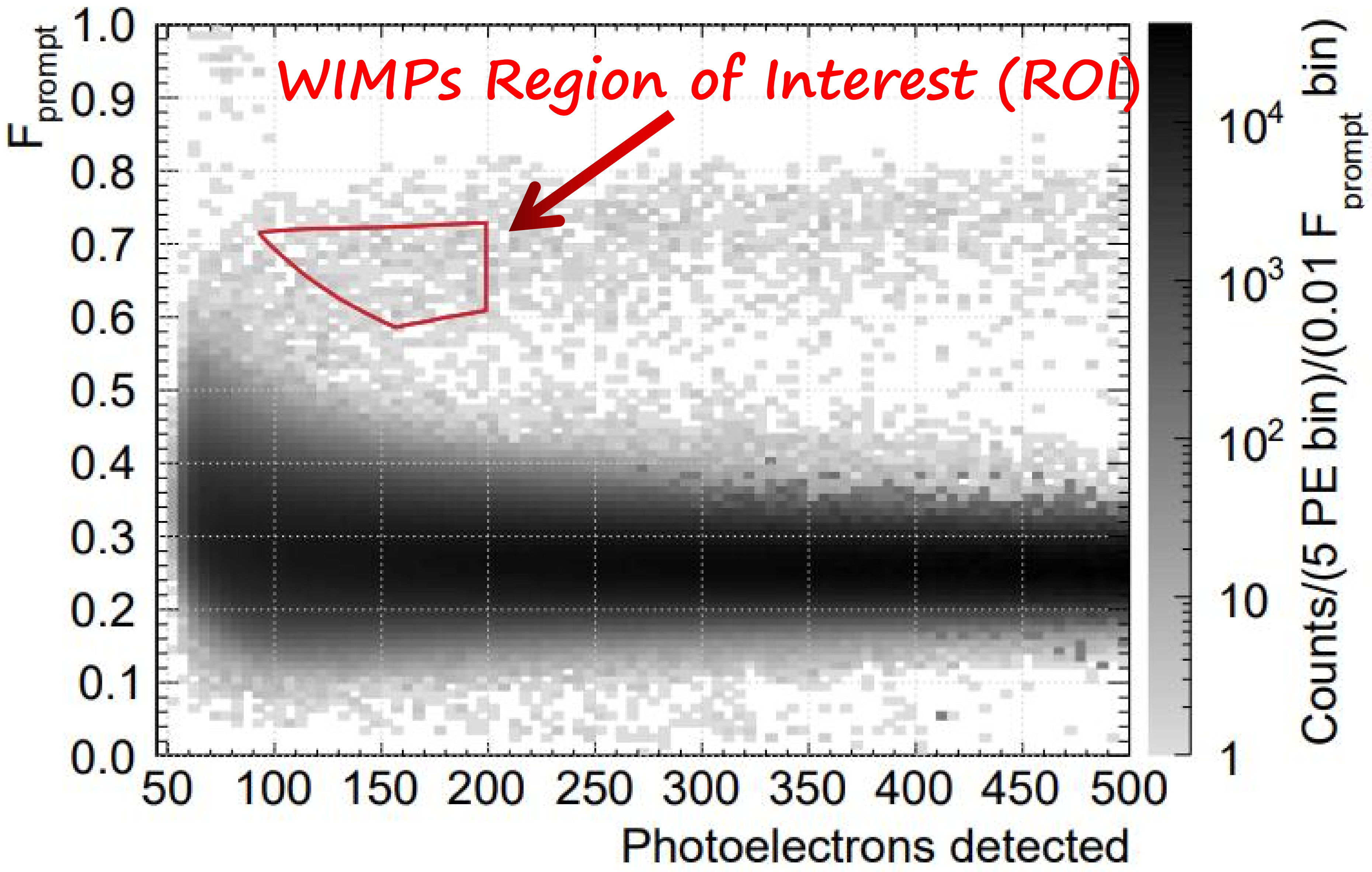
How does the data analysis look like?

Before selection cuts...

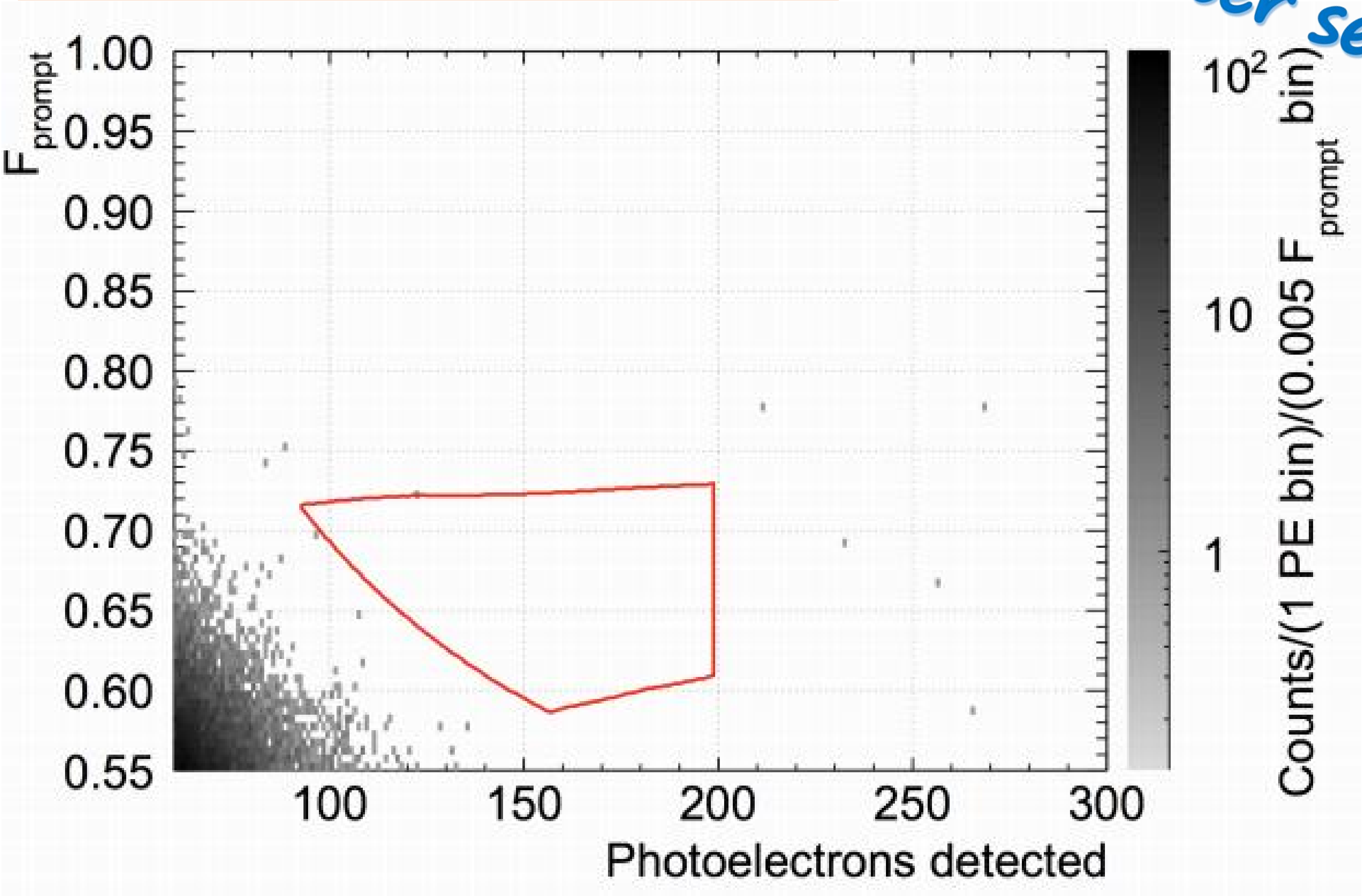


How does the data analysis look like?

Before selection cuts...

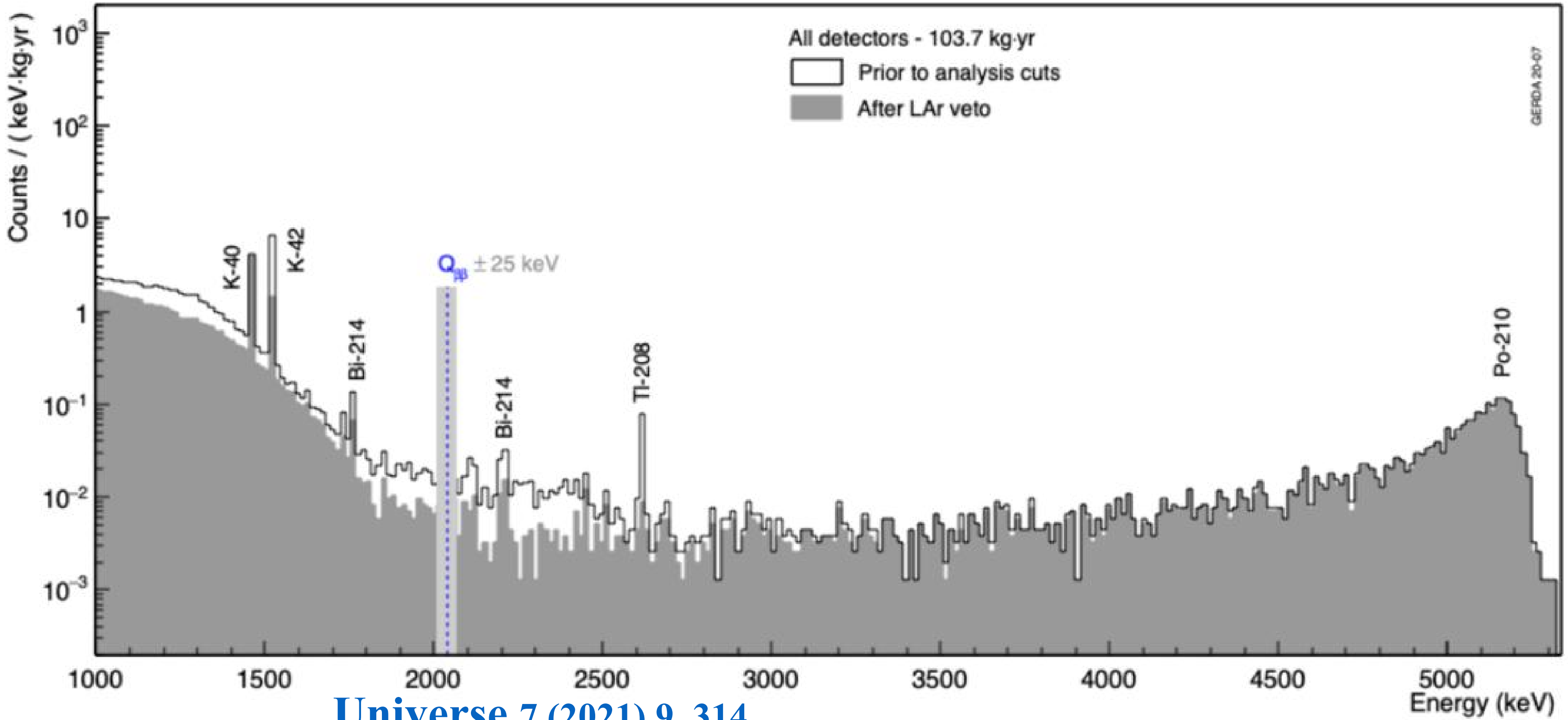


How does the data analysis look like?



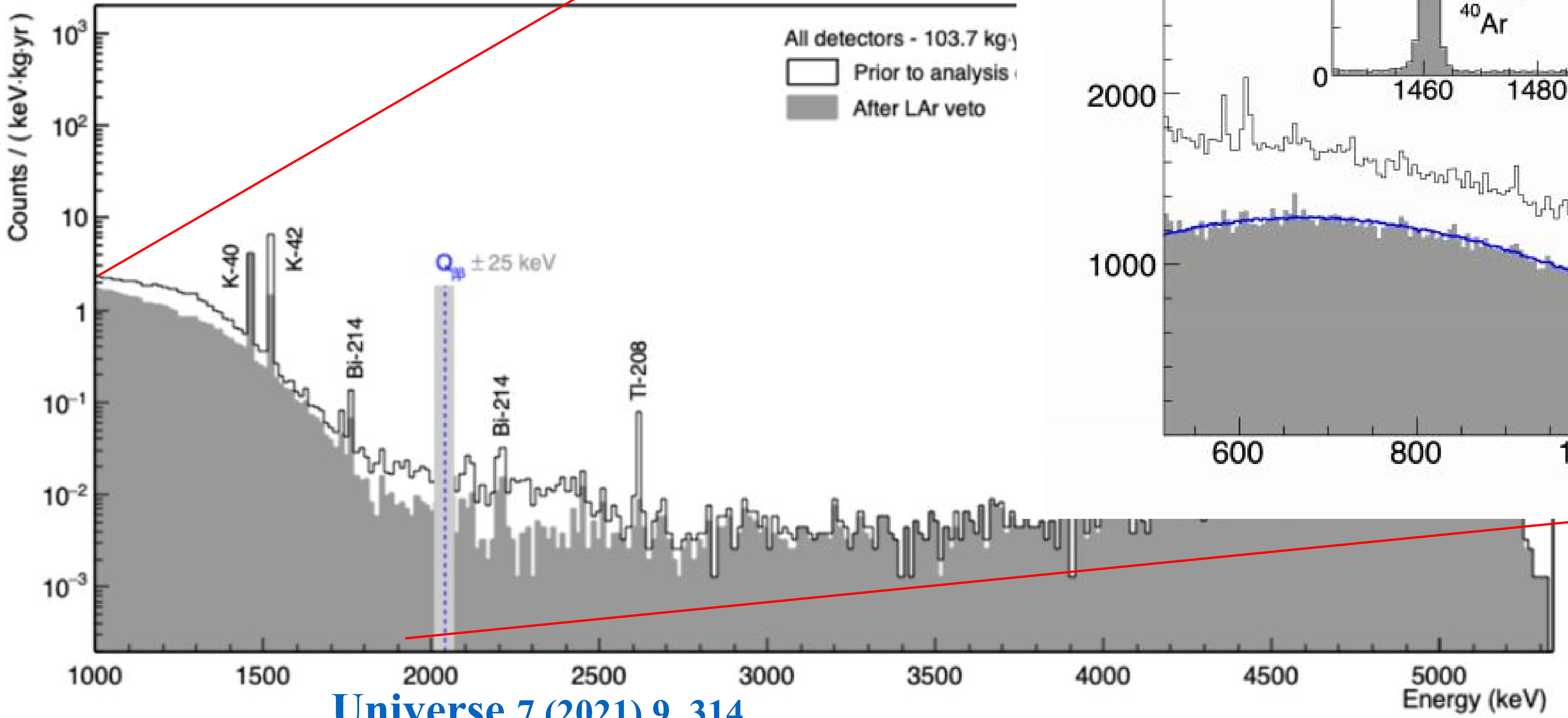
After selection cuts!

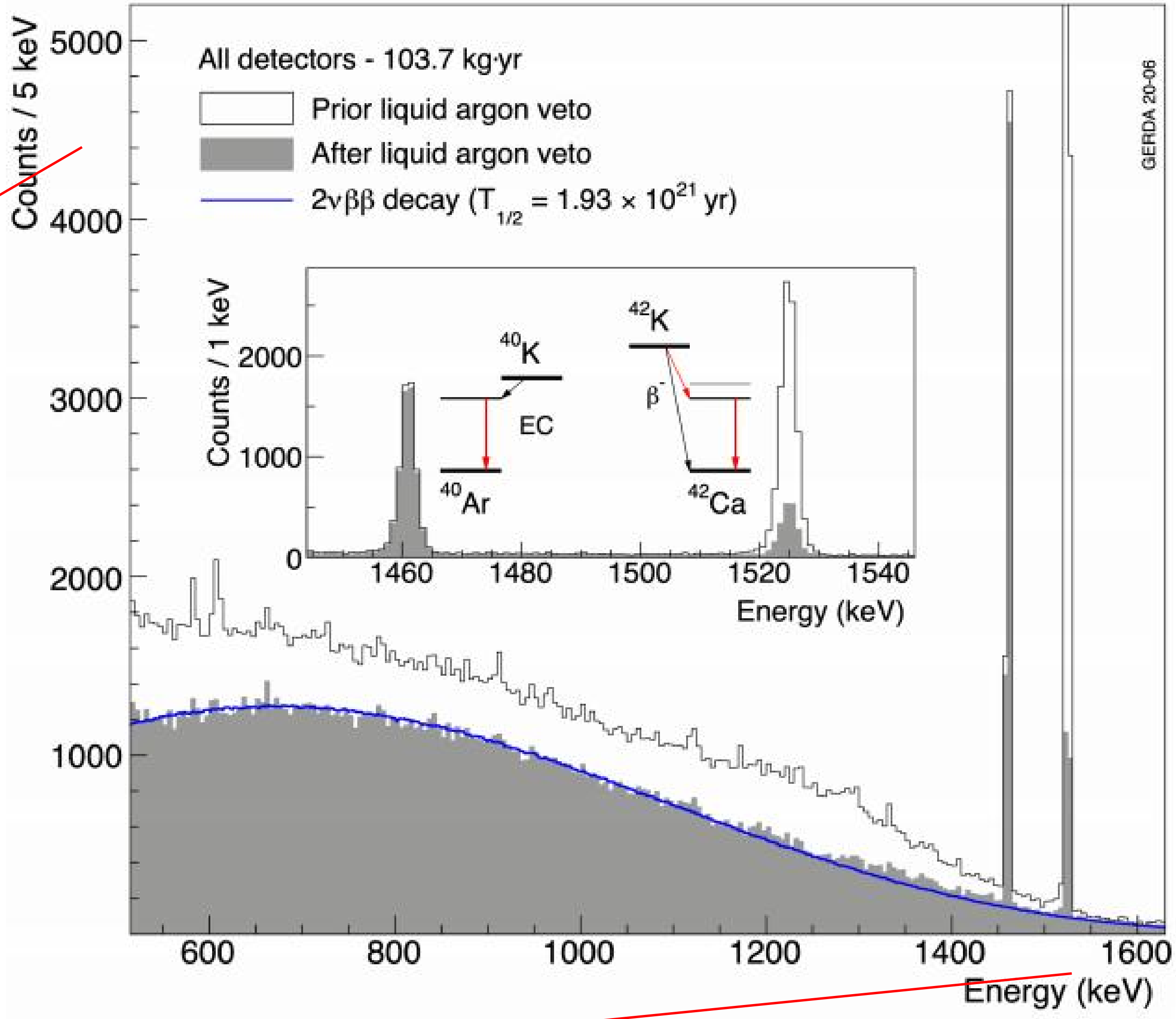
LAr as veto allows for the necessary background rejection in GERDA...



[Universe 7 (2021) 9, 314]

LAr as veto allows for the necessary background rejection in GERDA...



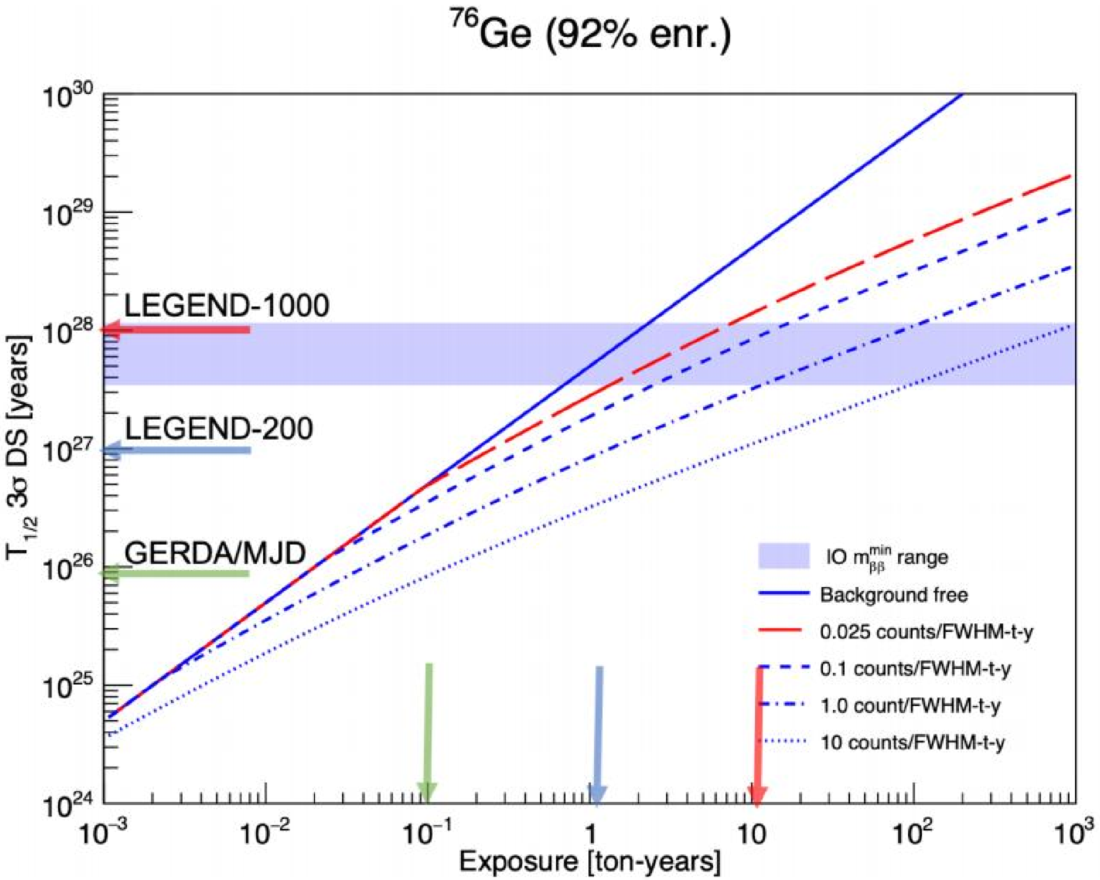


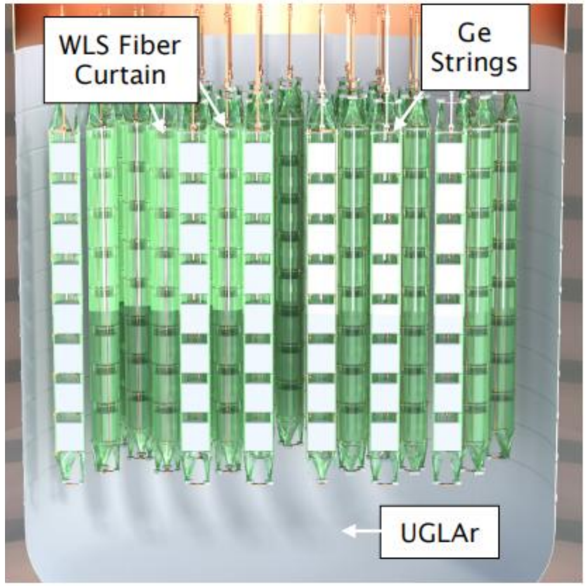
[Universe 7 (2021) 9, 314]

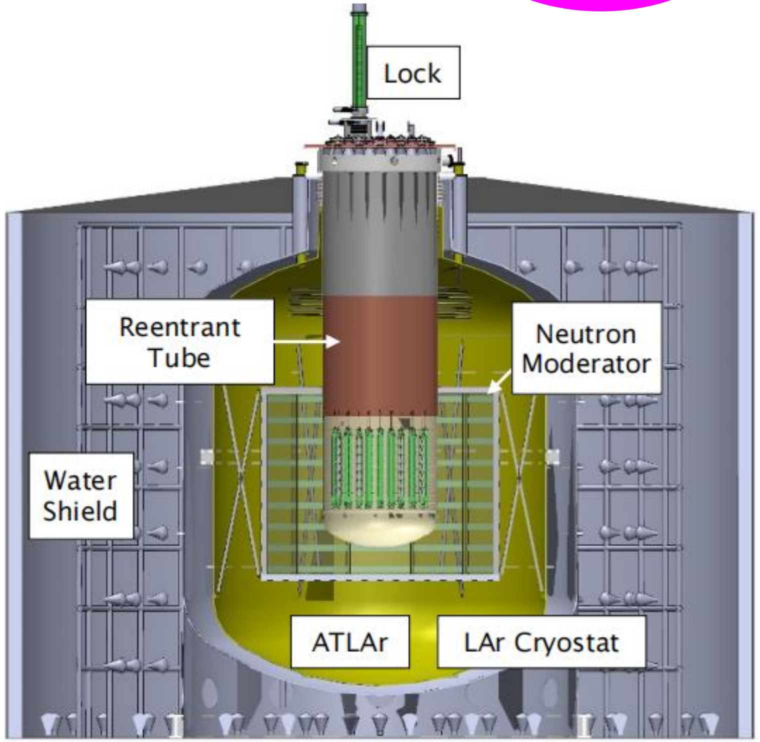
How to become LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

	GERDA	MJD	L-200	L-1000
Mass (kg)	44.2	40.4	200	1000
Exposure (kg·yr)	127.2	63.3	1000	10000
FWHM at $Q_{\beta\beta}$ (keV)	2.6 ± 0.2	2.53 ± 0.08	2.5	2.5
BI (counts/(keV·kg·yr))	$5.2^{+1.6}_{-1.3} \times 10^{-4}$	$6.2^{+0.6}_{-0.5} \times 10^{-3}$	2×10^{-4}	10^{-5}
$T^{0\nu}_{1/2}$ (yr)	$> 1.8 \cdot 10^{26}$	$> 8.3 \cdot 10^{25}$	10^{27}	1.3×10^{28}
$m_{\beta\beta}$ (meV)	$< 79 - 180$	$< 113 - 269$	$< 34 - 78$	$< 9.4 - 21.4$





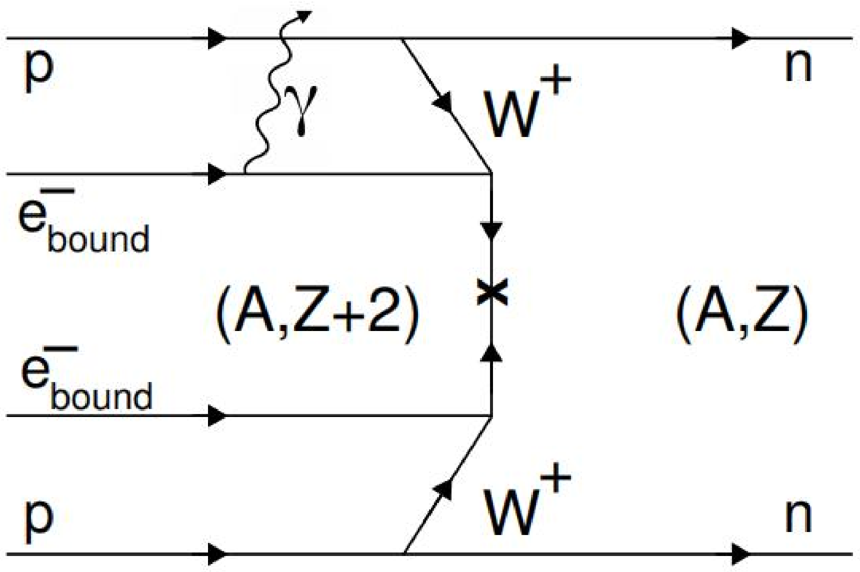


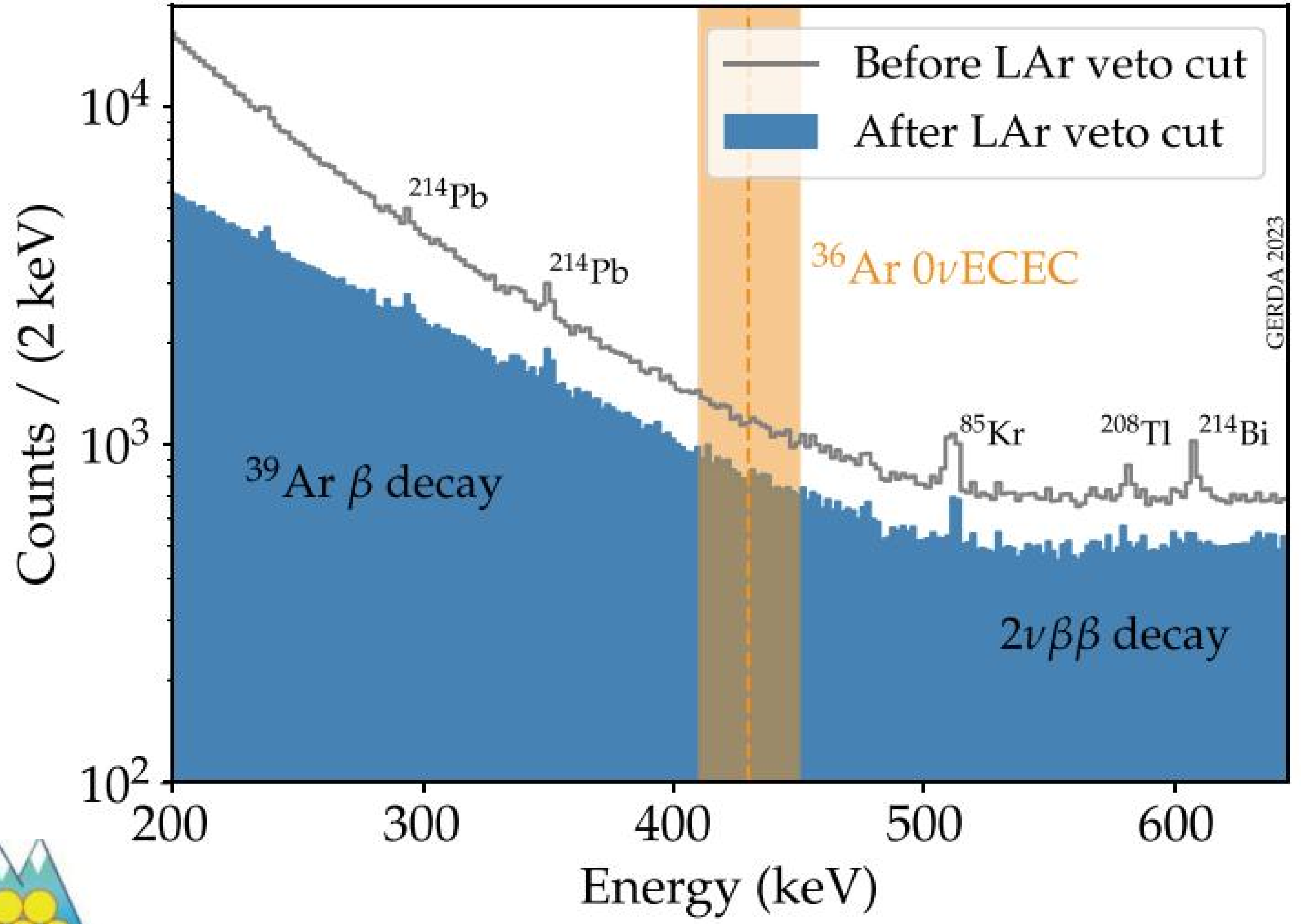
Nuovo Cim.C 47 (2024) 3, 69

... and for 0νECEC in ^{36}Ar!

$E_\gamma = Q_{ECEC} - E_K(2.47\ \mathrm{keV}) - E_L\ (0.23\ \mathrm{keV}) = (429.88 \pm 0.19)\ \mathrm{keV}$

$^{36}\mathrm{Ar} \rightarrow {}^{36}\mathrm{S} + \gamma\ + X_K\ + X_L$

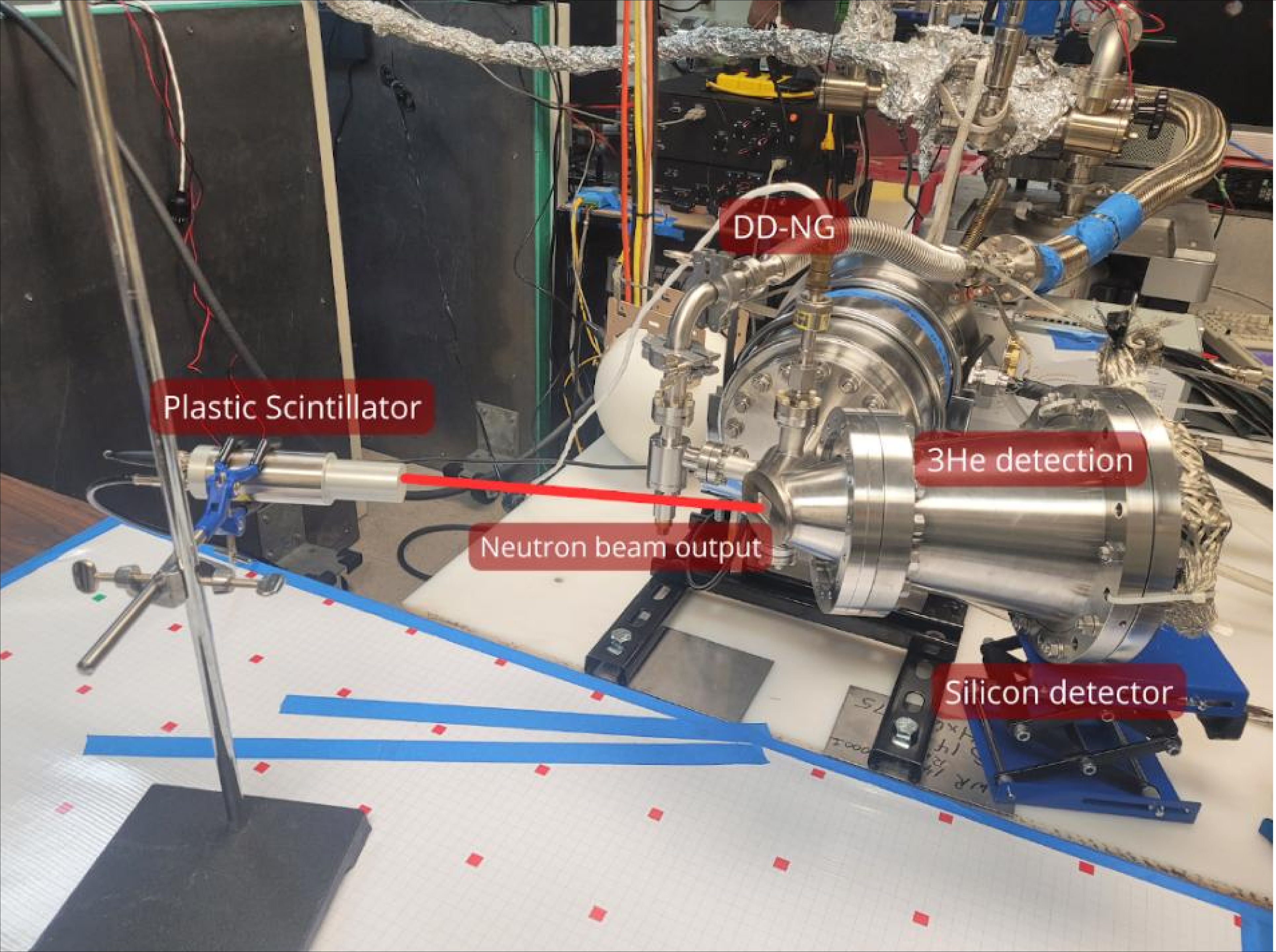


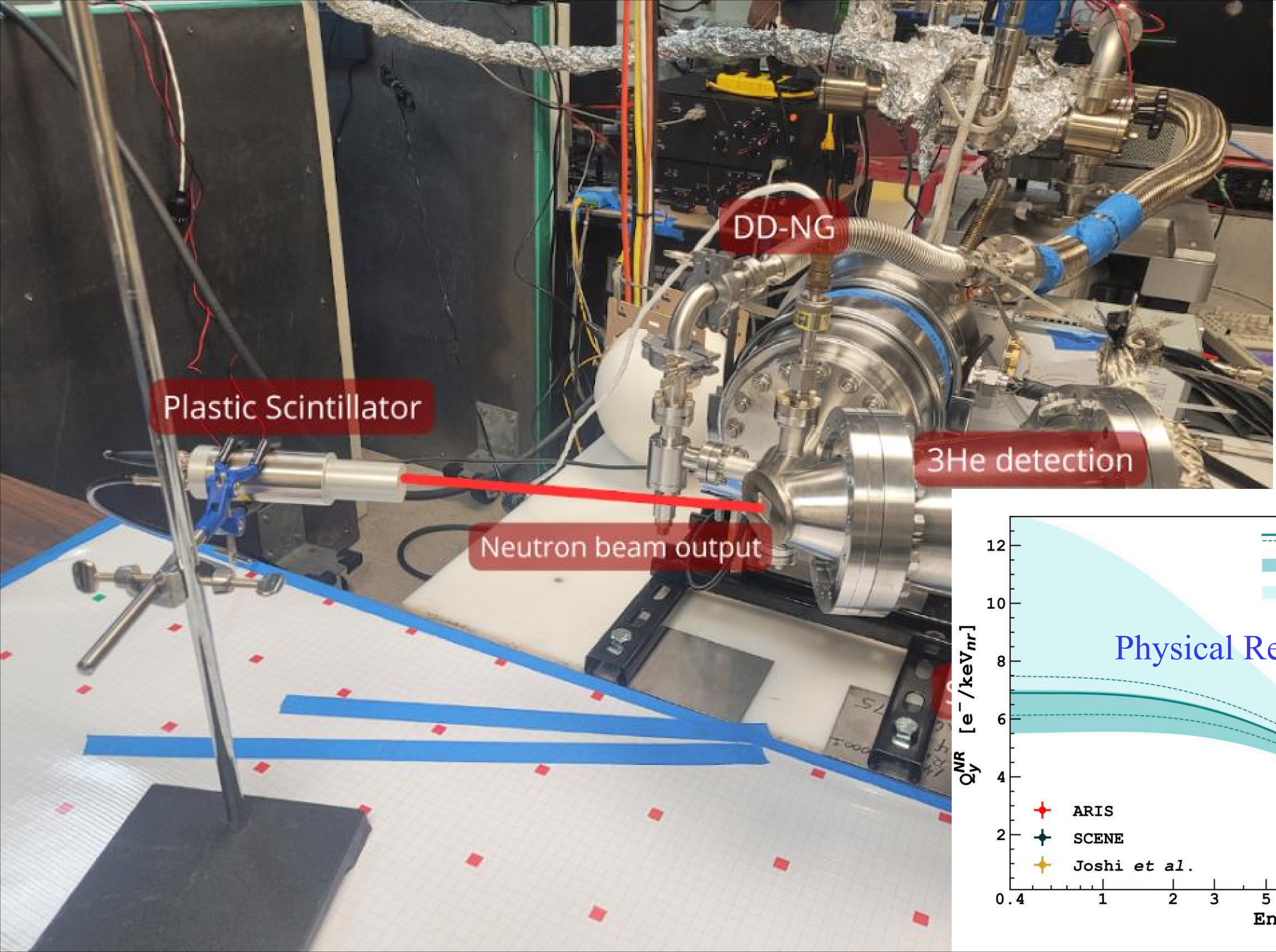


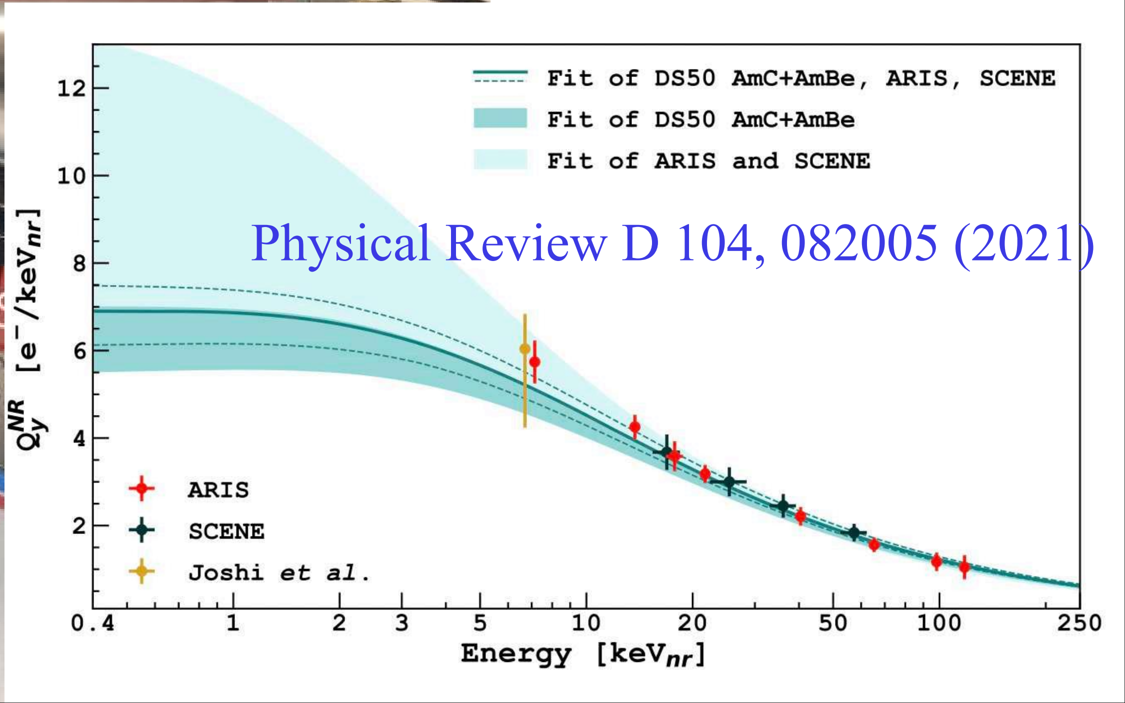
90% CL sensitivity: $T_{1/2} > 8.6 \cdot 10^{21}$ year
Observed lower limit $T_{1/2} > 1.5 \cdot 10^{22}$ year.

Eur. Phys. J. C **76**, 652 (2016)

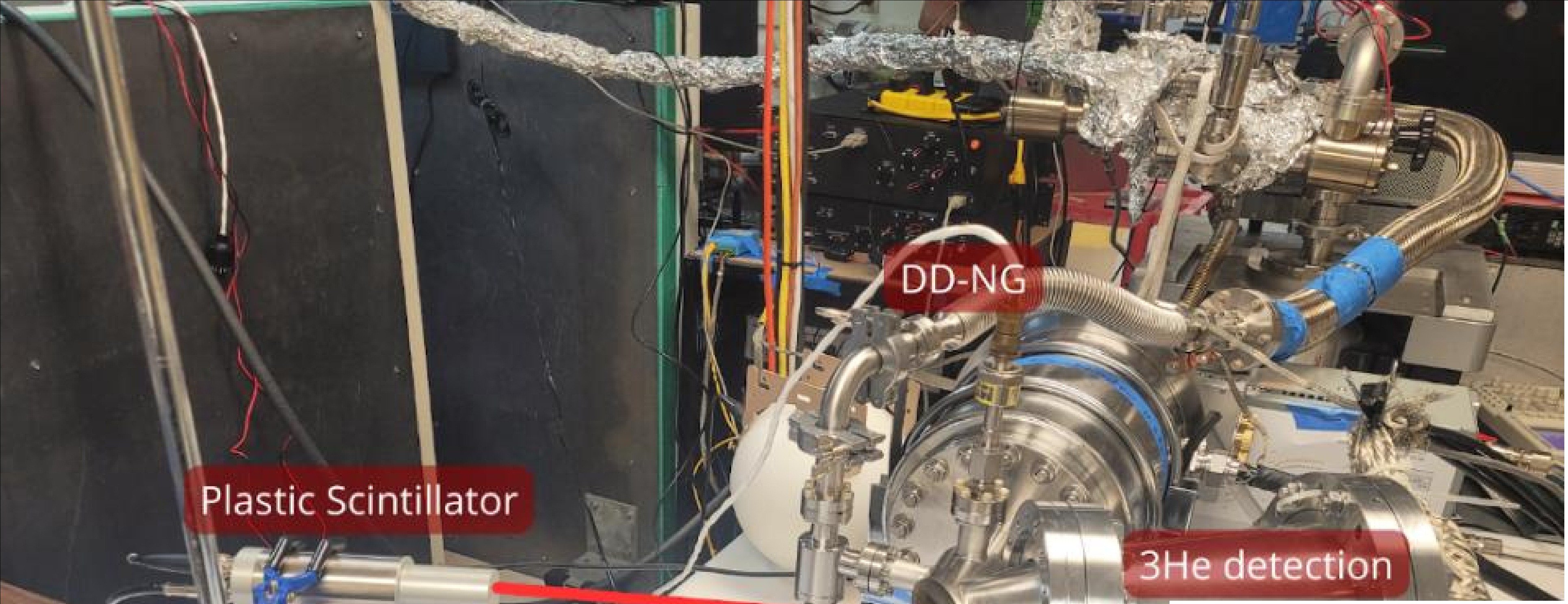
Eur. Phys. J. C **84**, 34 (2024)

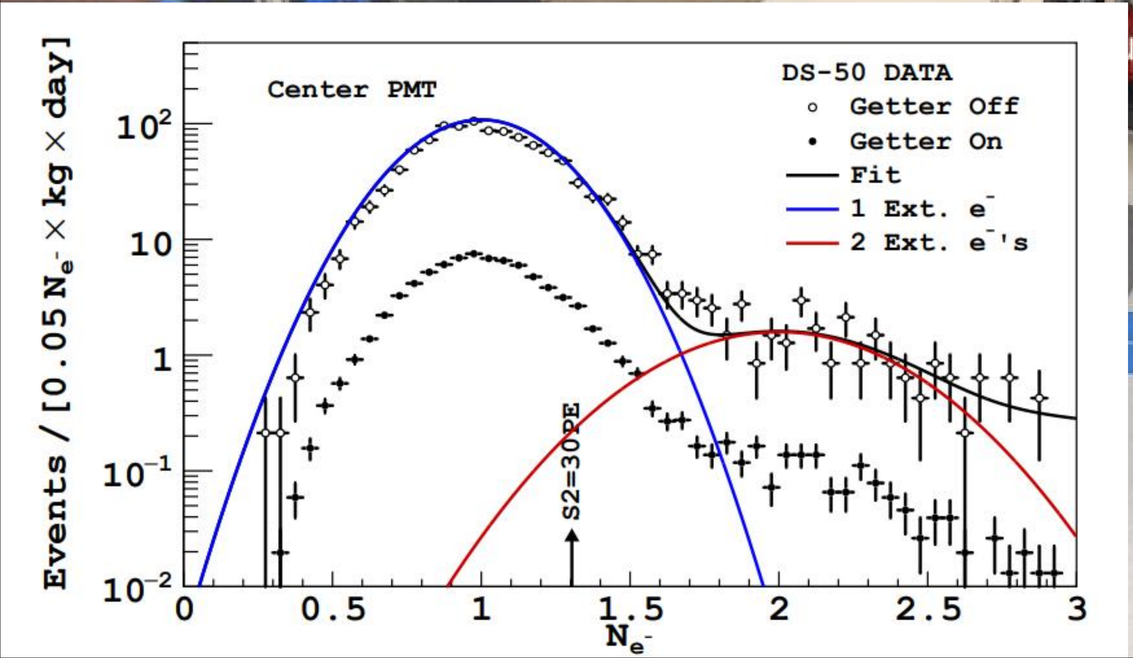

DD-NG
Plastic Scintillator
3He detection
Neutron beam output
Silicon detector

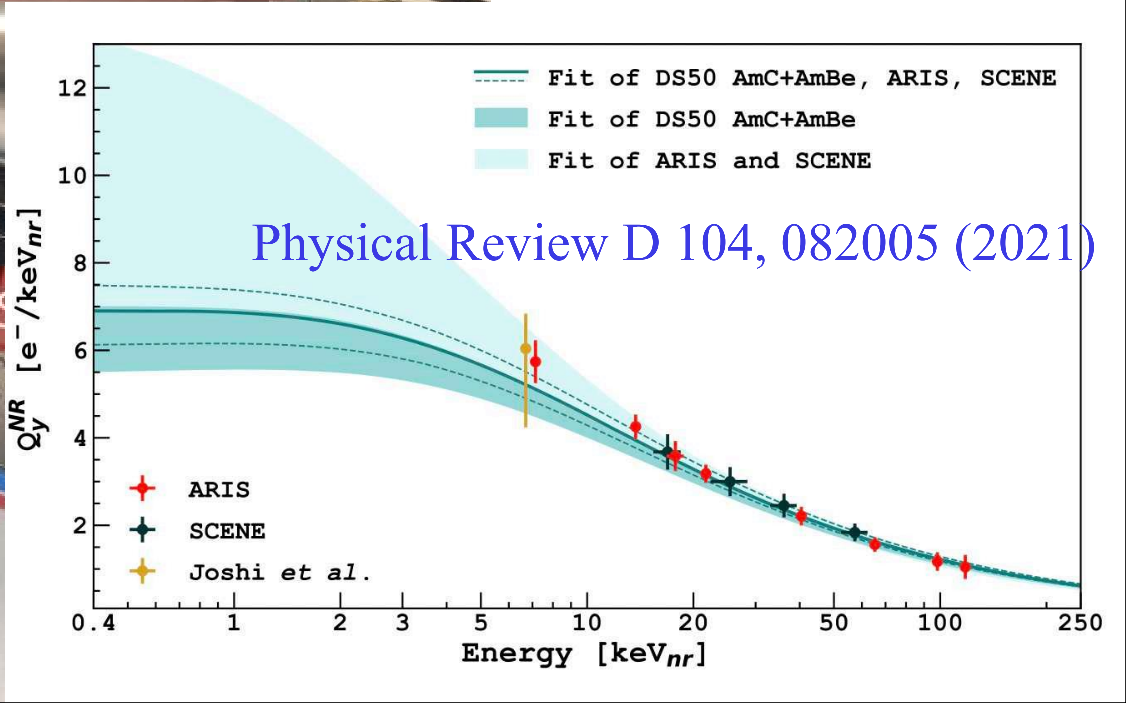




Physical Review D 104, 082005 (2021)

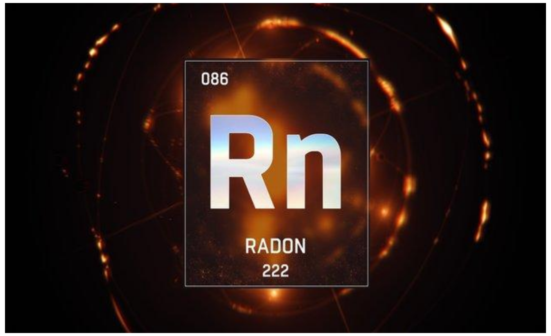


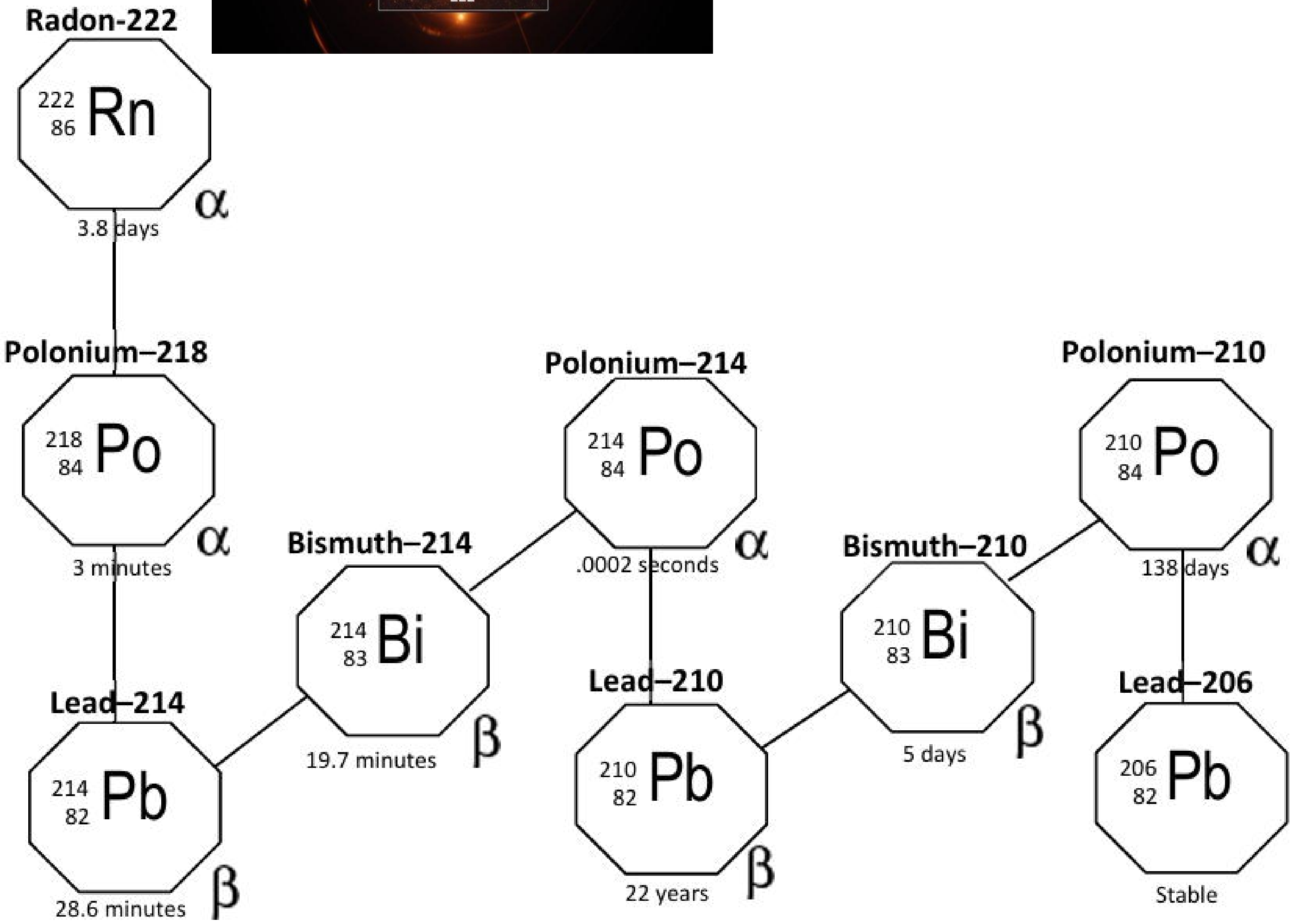


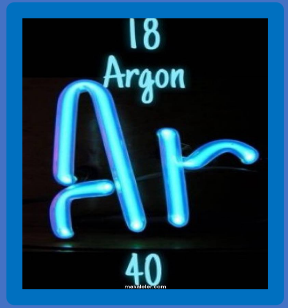


Physical Review D 104, 082005 (2021)

Main challenge: how to purge your new target?

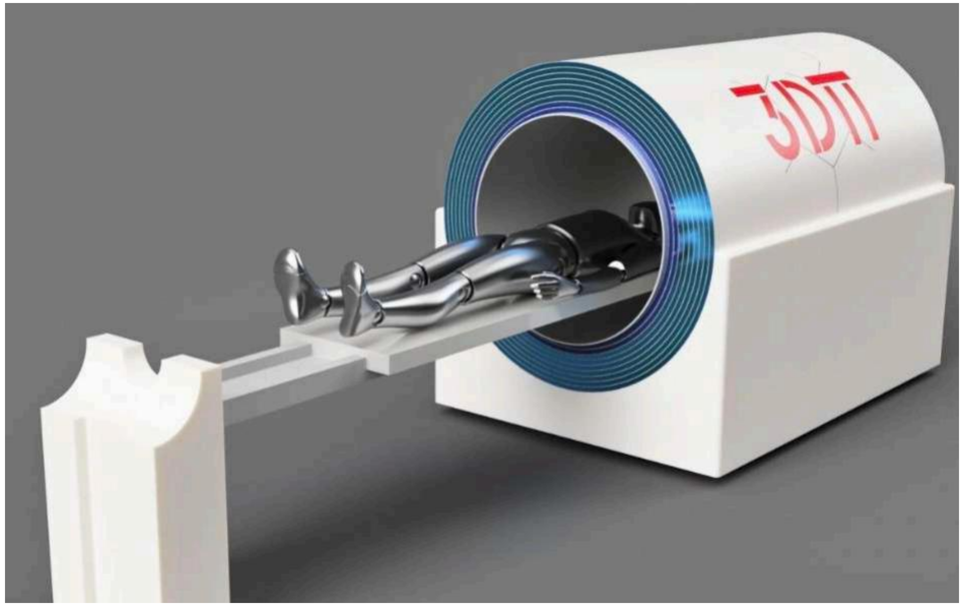


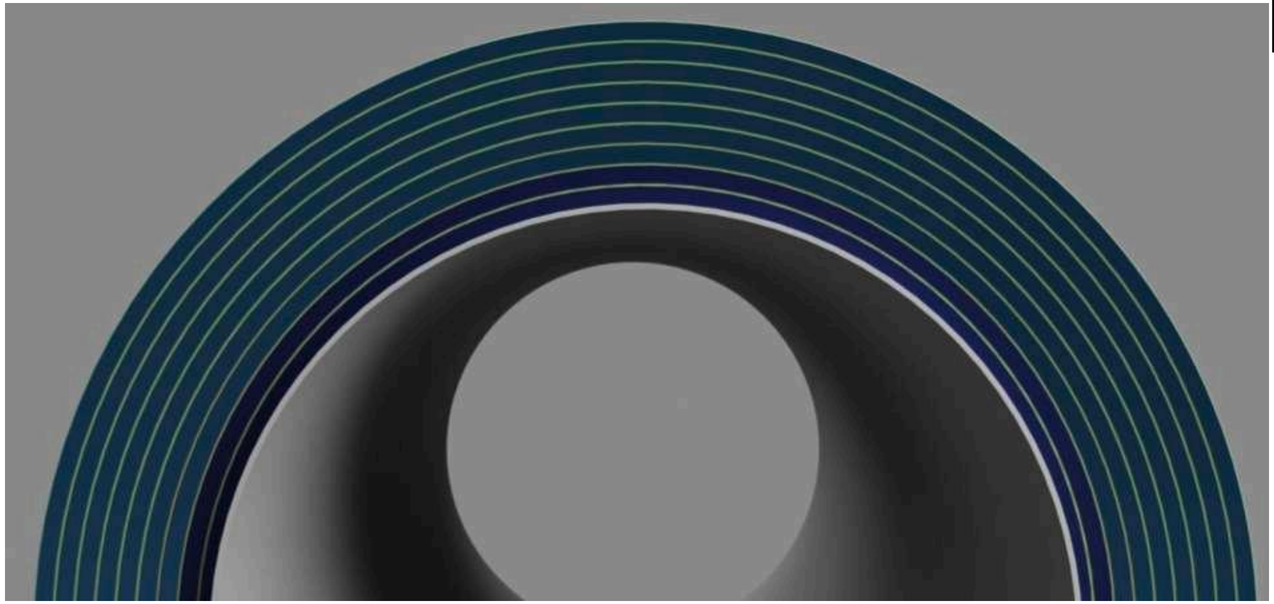




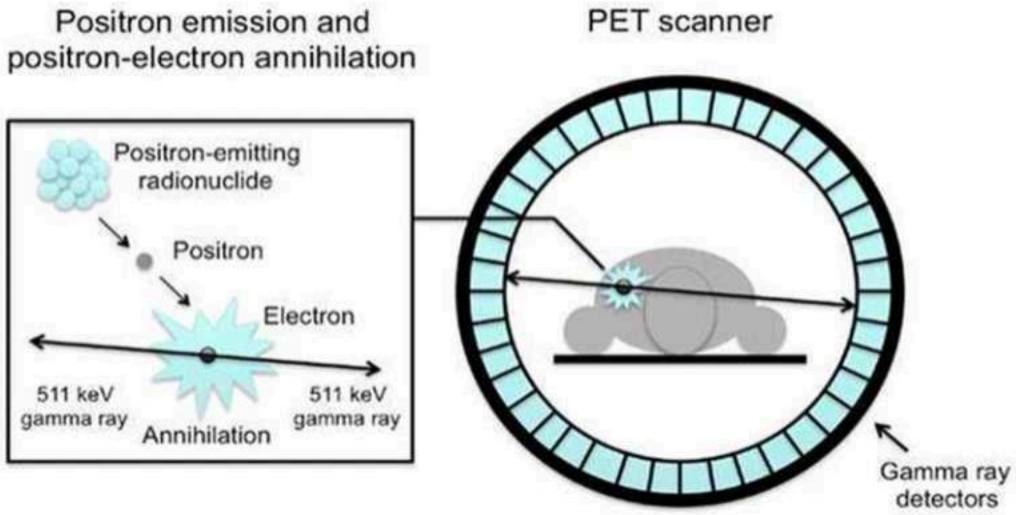
Xe-doped LAr for medical physics!

- Time-of-Flight PET scanner Total body
- Xenon-doped argon as scintillator medium observed by NUV-sensitive SIPMs
- Low dose or ultra-fast scanning time!



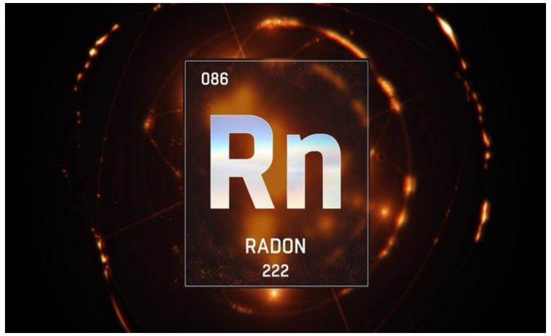


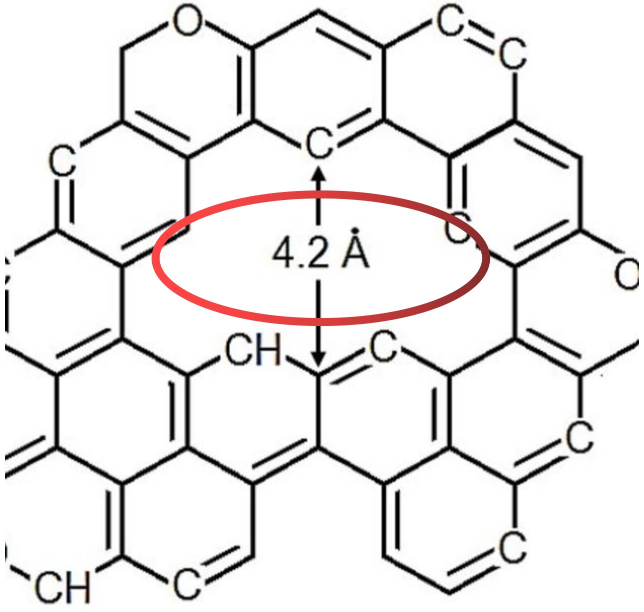
NSS/MIC 2021 and RTSD2021 Proceeding



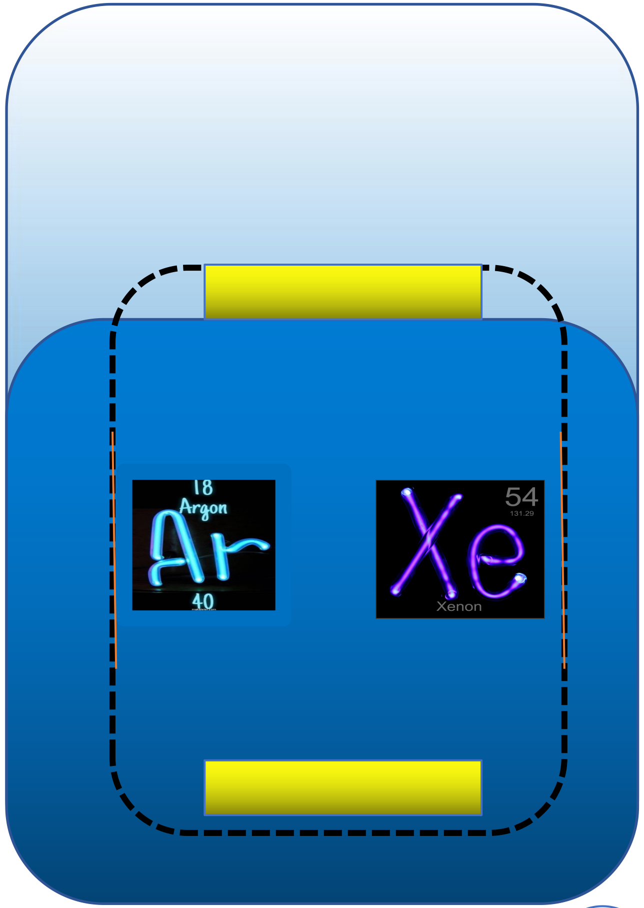
PoS EPS-HEP2021 (2022) 778

DArES Single-Phase





Atom	Van der Waal Atomic Diameter [A]
Ar	3.8
Rn	4.16
Xe	4.10



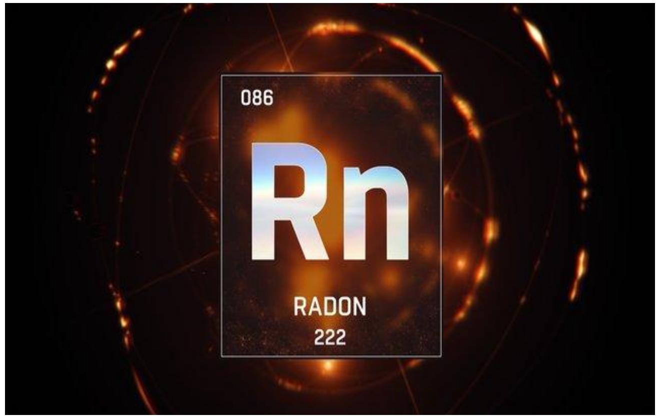
DArES Single-Phase

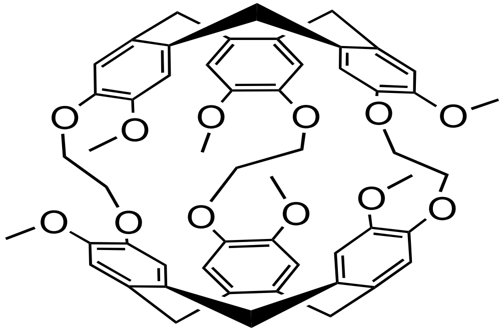
Both Cryptophane and zeolites have adjustable porous sizes!

Atomic Diameter

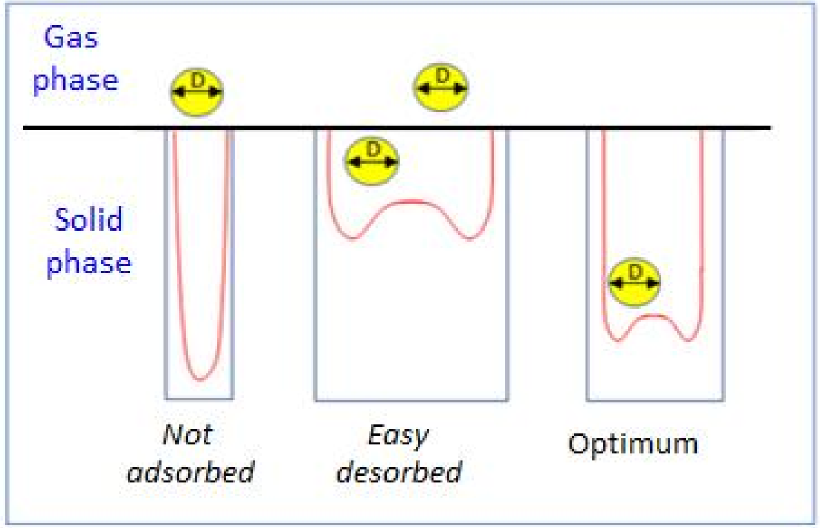
Gas	Van der Waals
Xe	4.10 Å
Rn	4.16 Å

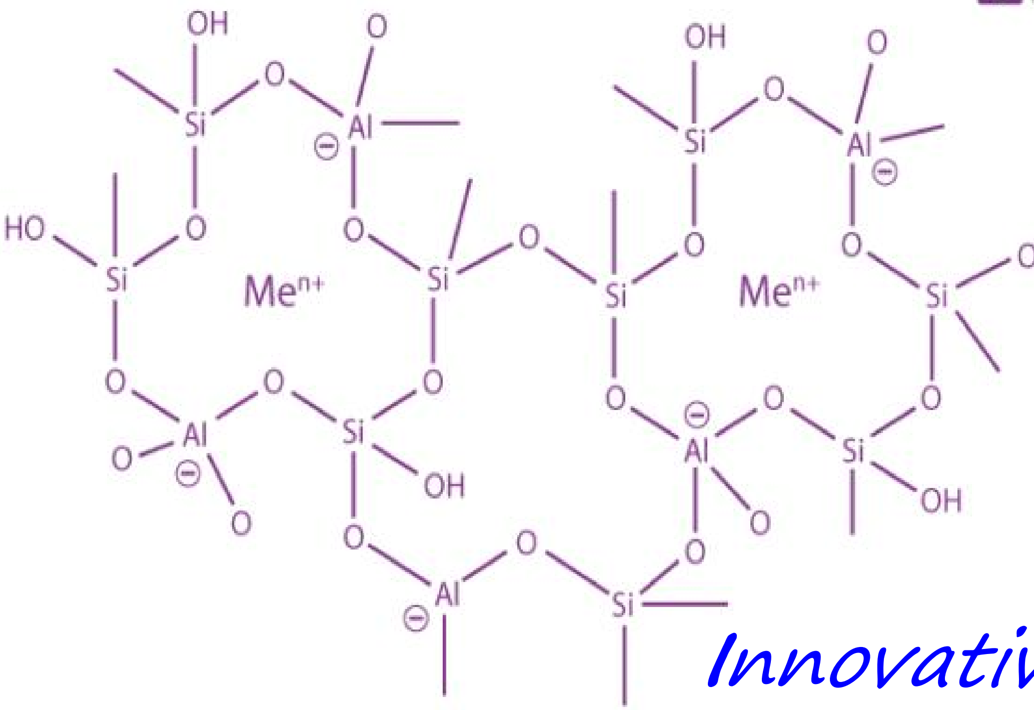
Xe/Rn competition





crptophane A
cryptophane 2,2,2





Innovative materials for Extreme rado capturE

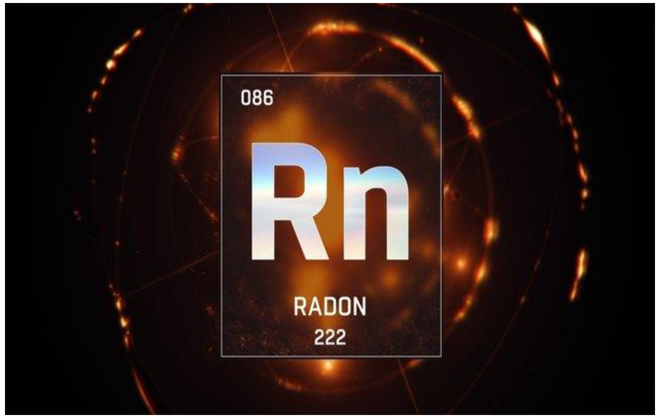
DArES Single-Phase

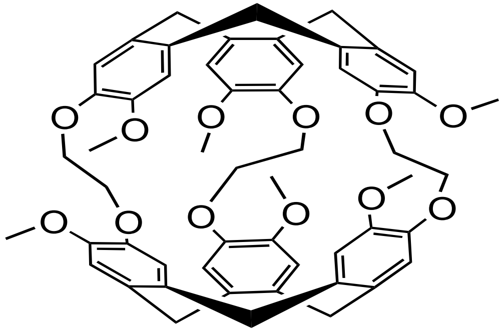
Both Cryptophane and zeolites have adjustable porous sizes!

Atomic Diameter

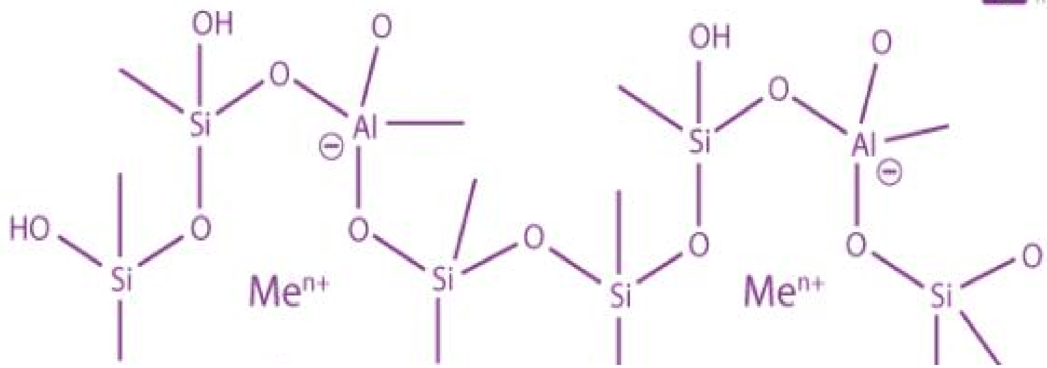
Gas	Van der Waals
Xe	4.10 Å
Rn	4.16 Å

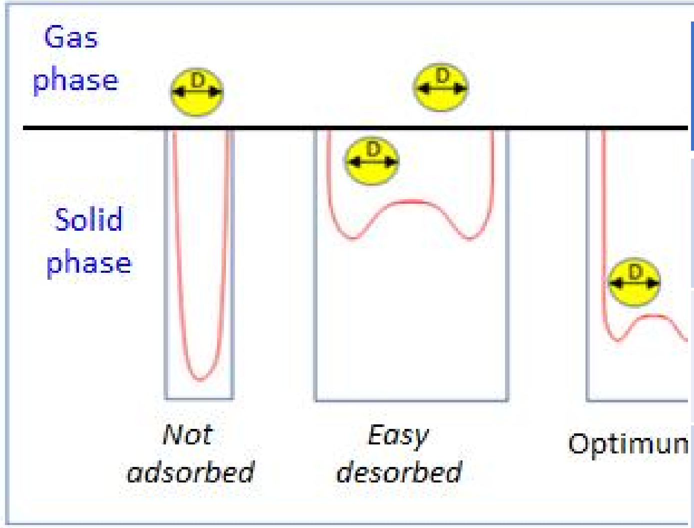
Xe/Rn competition





crptophane A





Adsorbent	K [m³ kg⁻¹] in N_2 @ 30 ℃	Notes
Chrypthophane	107	0.176 mmol/g adsorbed Xe
Activated charcoal Silcarbon K48	180	2.31 mmol/g adsorbed Xe
Ag-ETS-10 (Ag-Zeolite)	19940	0.988 Bq/Kg 226 Ra activity
Activated charcoal Carboact	182	0.0023 Bq/Kg 226 Ra activity

Other photosensitive dopants

Material [d)]		I_g [eV] [a)]	Dipole moment [debyes] [b)]	Estimated pressure 90 K [Torr] [b)]	Charge collected* [c)] (LAr ≡ 1)		Concentration [ppm]
					0.1 kv mm^{-1}	1.0 kV mm^{-1}	
TEA	$(C_2H_5)_3N$	7.50	0.66	–	2.2	1.3	47
TMA	$(Ch_3)_3N$	7.82	0.612	3×10^{-8}	3.4	1.6	110
TMT	$(CH_3)_4Sn$	8.25/8.76	–	4×10^{-12}	3.0	1.6	1.5
Cyclohexene	C_6H_{10}	8.95	–	–	2.1	1.3	3.6
1.3-butadiene	C_4H_6	9.06	0	4×10^{-7}	4.6	1.9	17
Cis & Trans 2 butene	C_4H_8	9.13	0 (trans)	5×10^{-8}	3.6	1.6	72
TMG	$(CH_3)_4Ge$	9.2/9.29	–	3×10^{-10}	7.4 (9.8)	2.6 (2.7)	15
Isobutylene	C_4H_8	9.23	0.5	5×10^{-7}	4.9	1.8	16
Methyl mercaptan	CH_3SH	9.44	1.52	2×10^{-8}	2.0	2.0	15
Pentene (technical)	C_5H_{10}	9.5	–	1×10^{-9}	3.1	1.5	7
Allene	C_3H_4	9.53	0	1×10^{-5}	6.5 (8.7)	2.5 (2.7)	14
TMS	$(CH_3)_4Si$	9.86	0.525	8×10^{-9}	4.6	1.8	5.8
DME	$(CH_3)_2O$	10.0	1.30	5×10^{-8}	3.6	1.4	14

D. F. Anderson, NIM. A 245, 361 (1986).