Rare event searches with Argon detectors

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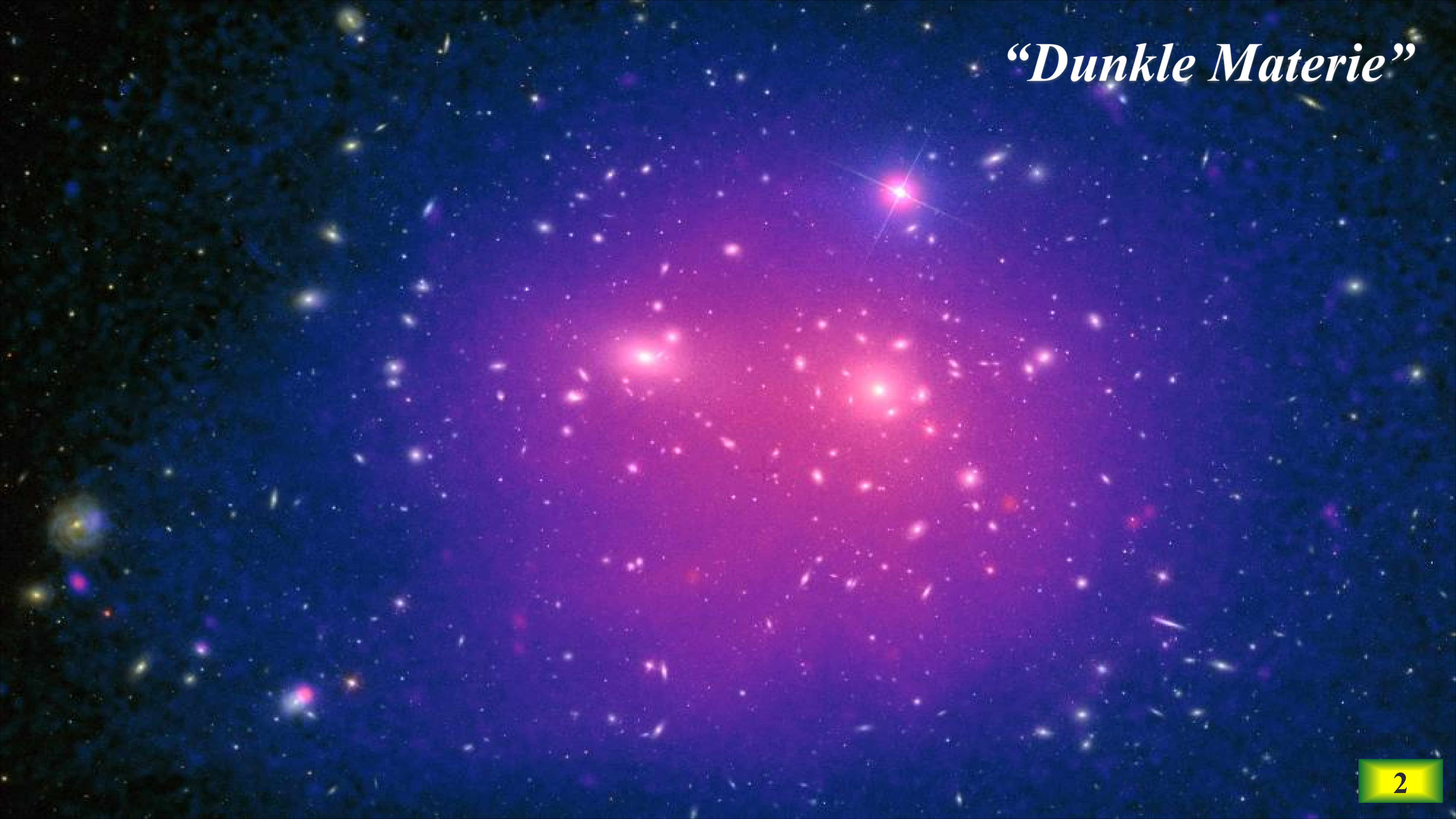
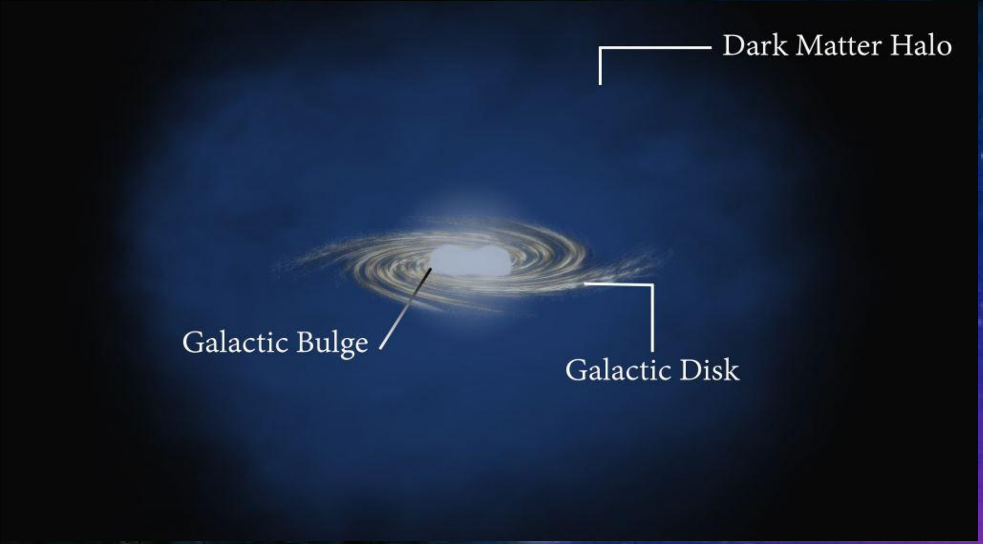
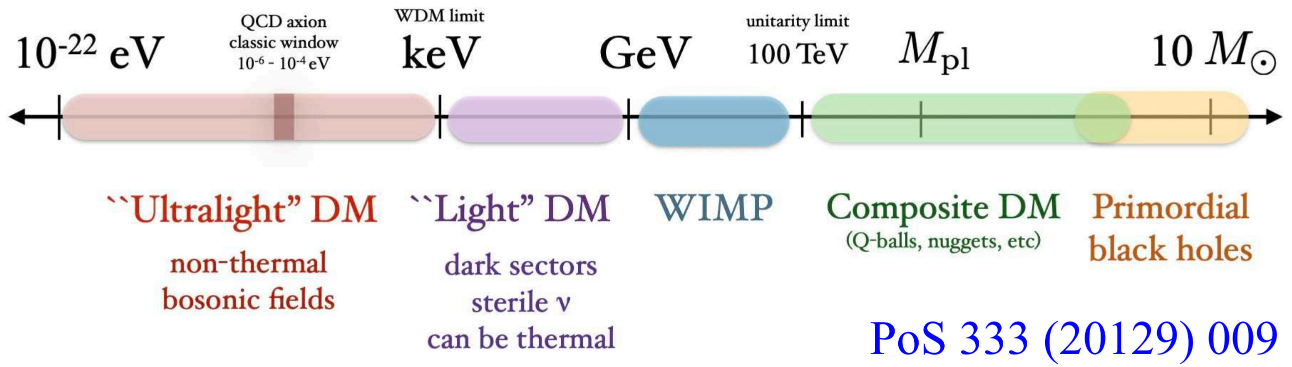
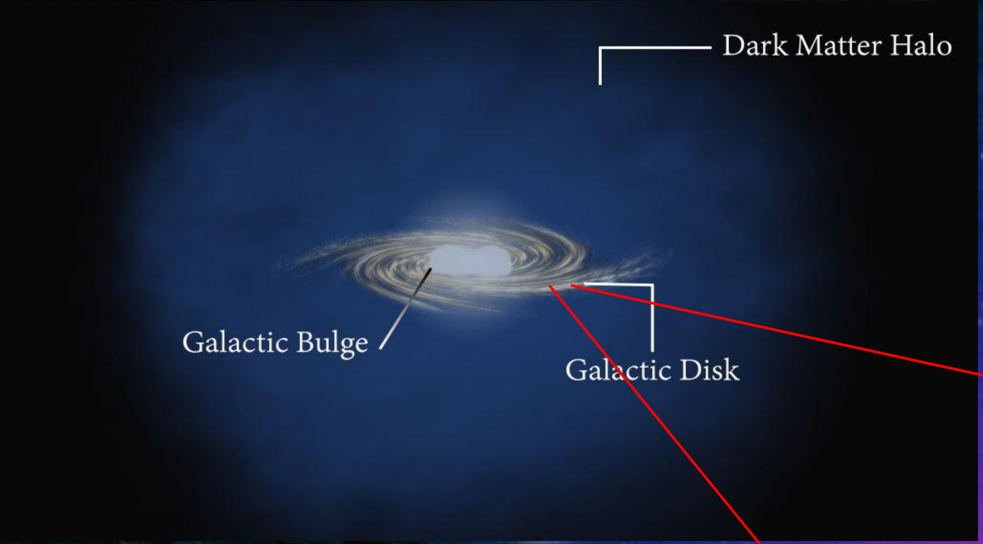
"Dunkle Materie"

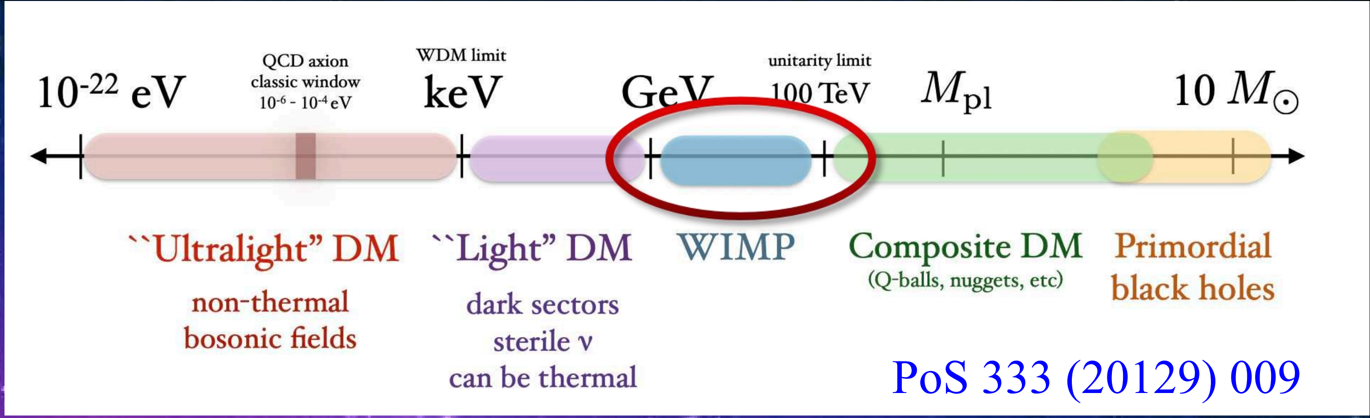


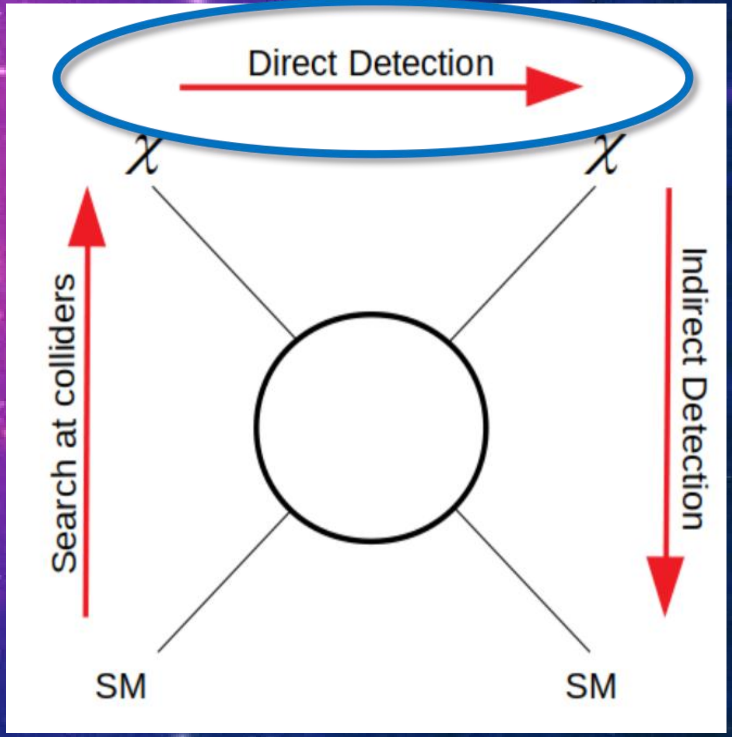


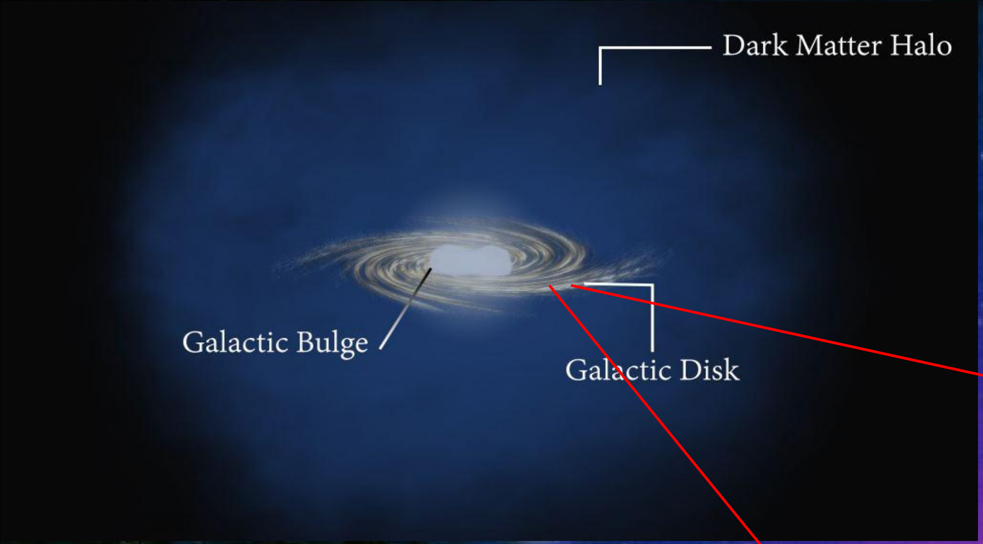


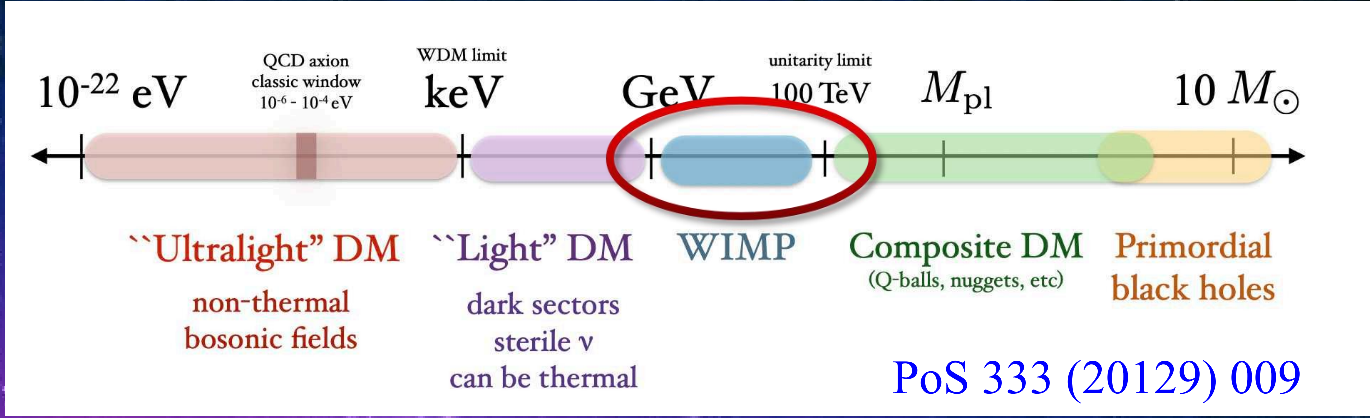
PoS 333 (20129) 009

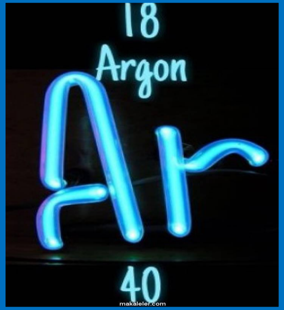

Dark Matter Halo
Galactic Bulge
Galactic Disk

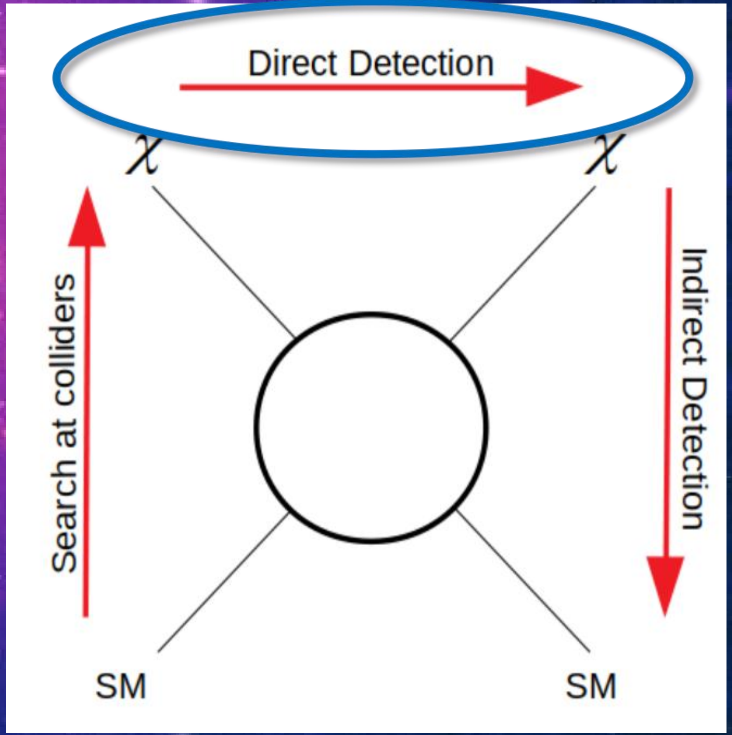

10-22 eV
QCD axion
classic window
10-6 - 10-4 eV
WDM limit
keV
GeV
unitarity limit
100 TeV
Mpl
10 M⊙
``Ultralight” DM
non-thermal
bosonic fields
``Light” DM
dark sectors
sterile ν
can be thermal
WIMP
Composite DM
(Q-balls, nuggets, etc)
Primordial
black holes
PoS 333 (20129) 009


Direct Detection
χ
χ
Search at colliders
Indirect Detection
SM
SM









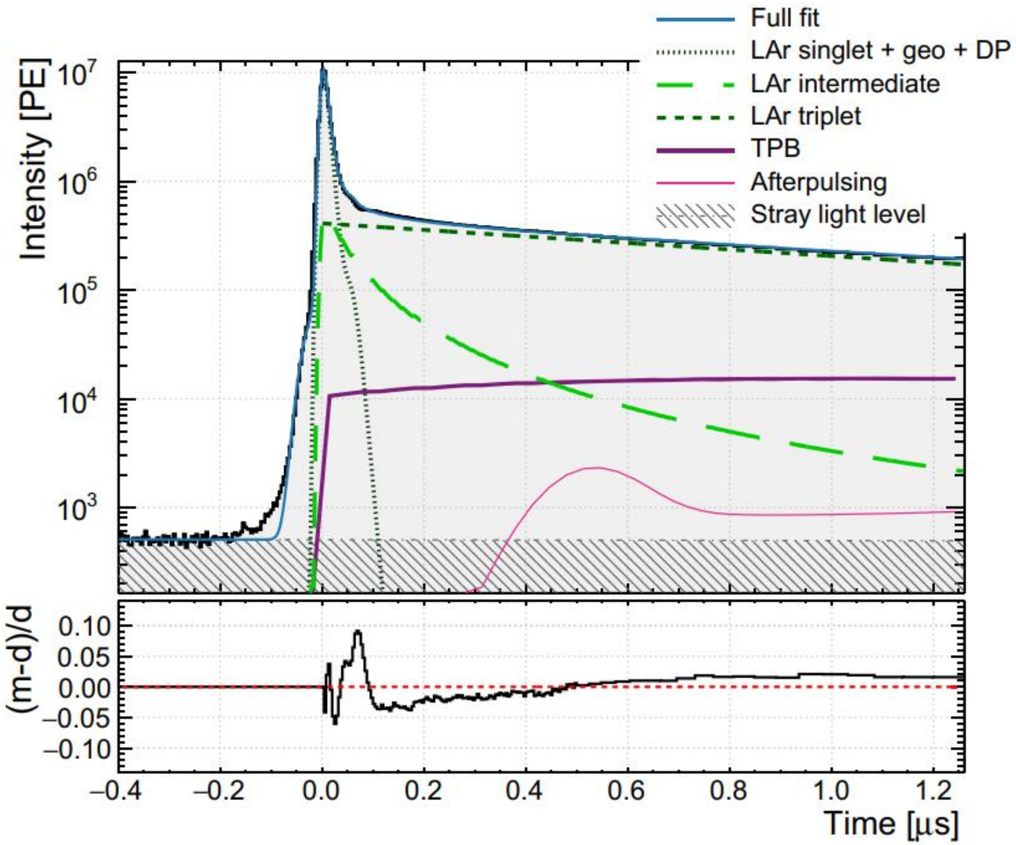
- Noble element
- Liquid at ~ 87 K (P ~ bar)
- Relatively light nucleus
- Efficient scintillator (~ 40k photons/MeV)
- Transparent to its own scintillation light (128 nm)
- Relatively cheap and easy to purge
- Activity mainly set by the ^{39}Ar abundance (Q = 565 keV)
- **Unique Pulse-shape Discrimination power**

Pulse Shape Discrimination in Argon: Either singlet or triplet argon excimer states, with ratios depending on the kind of recoil.

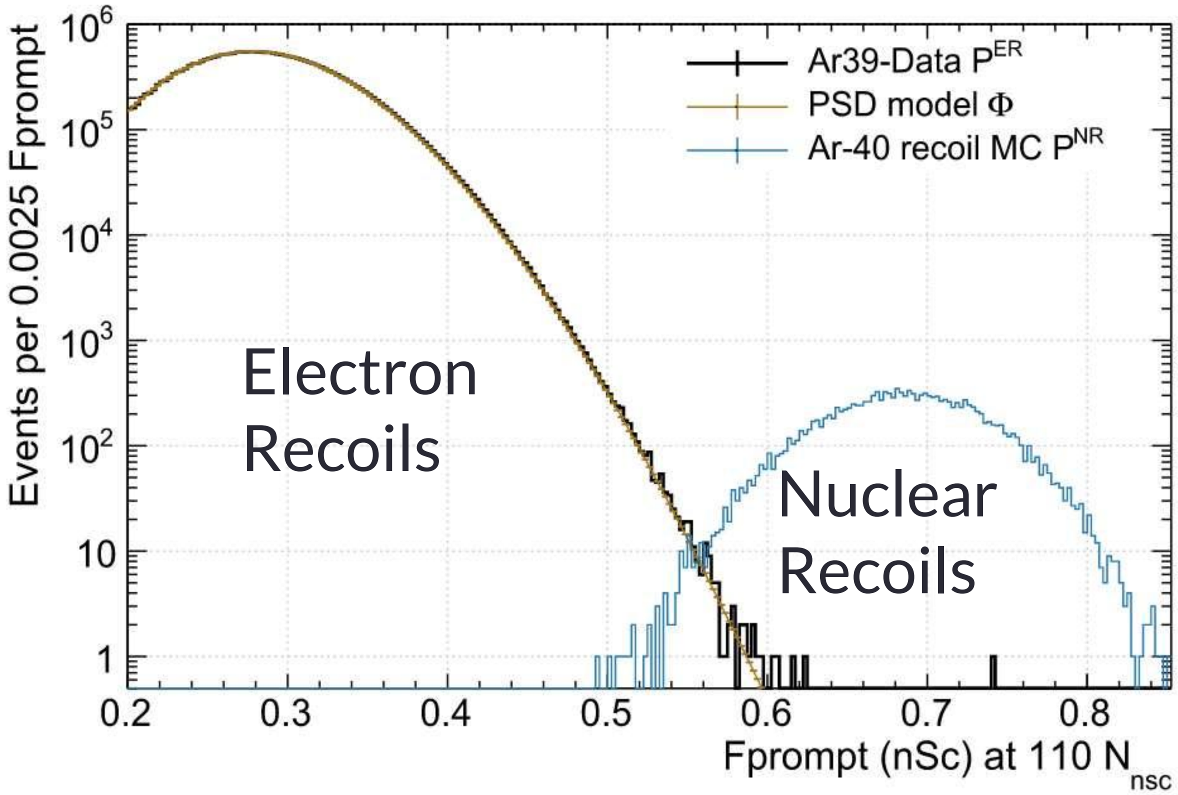
$$I_{LAr}(t) = \frac{R_s}{\tau_s} e^{-t/\tau_s} + \frac{1 - R_s - R_t}{\tau_{rec}(1 + t/\tau_{rec})^2} + \frac{R_t}{\tau_t} e^{-t/\tau_t}$$

$\tau_s = 8.2ns$ $\tau_{rec} = 175.5ns$ $R_s = 0.23$

$\tau_t = 1445ns$ $R_t = 0.71$

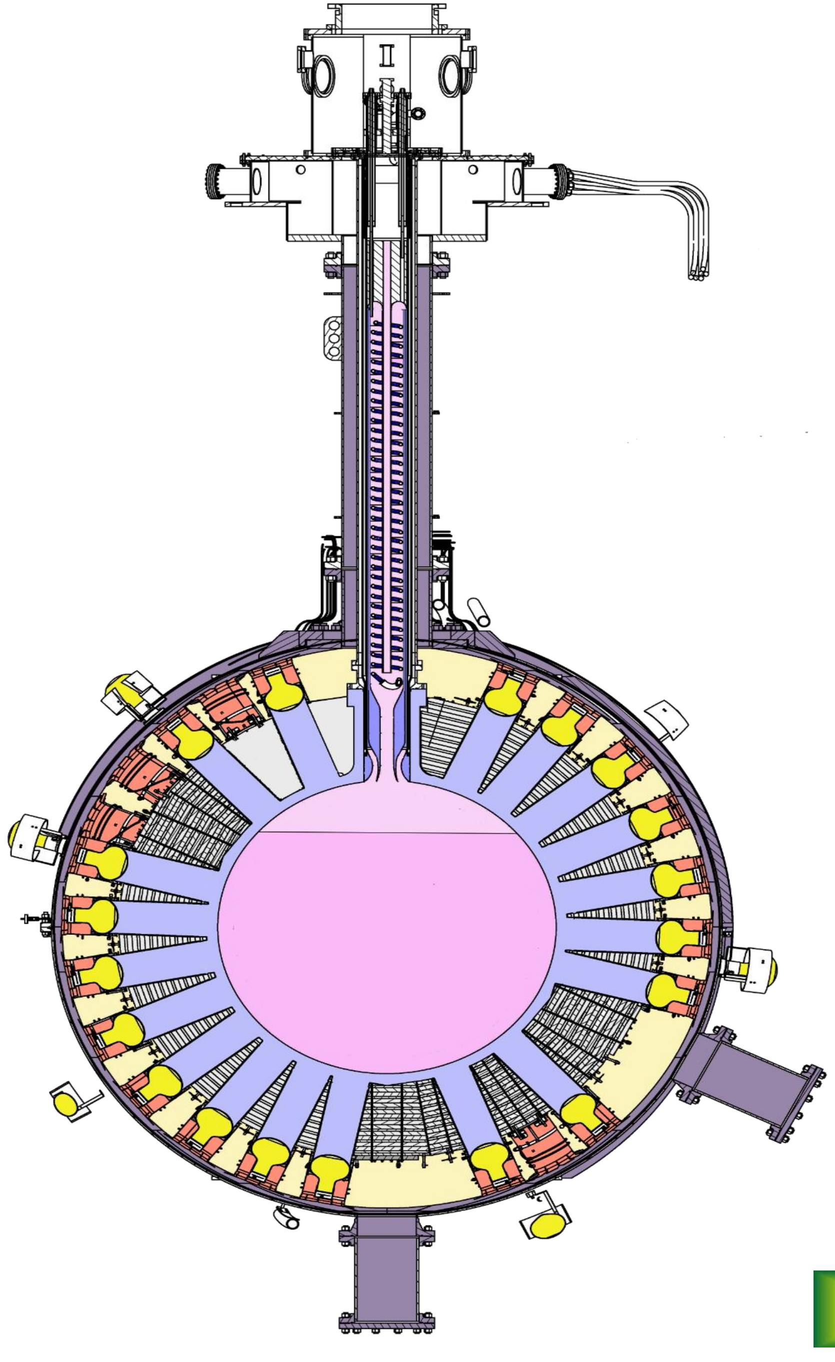


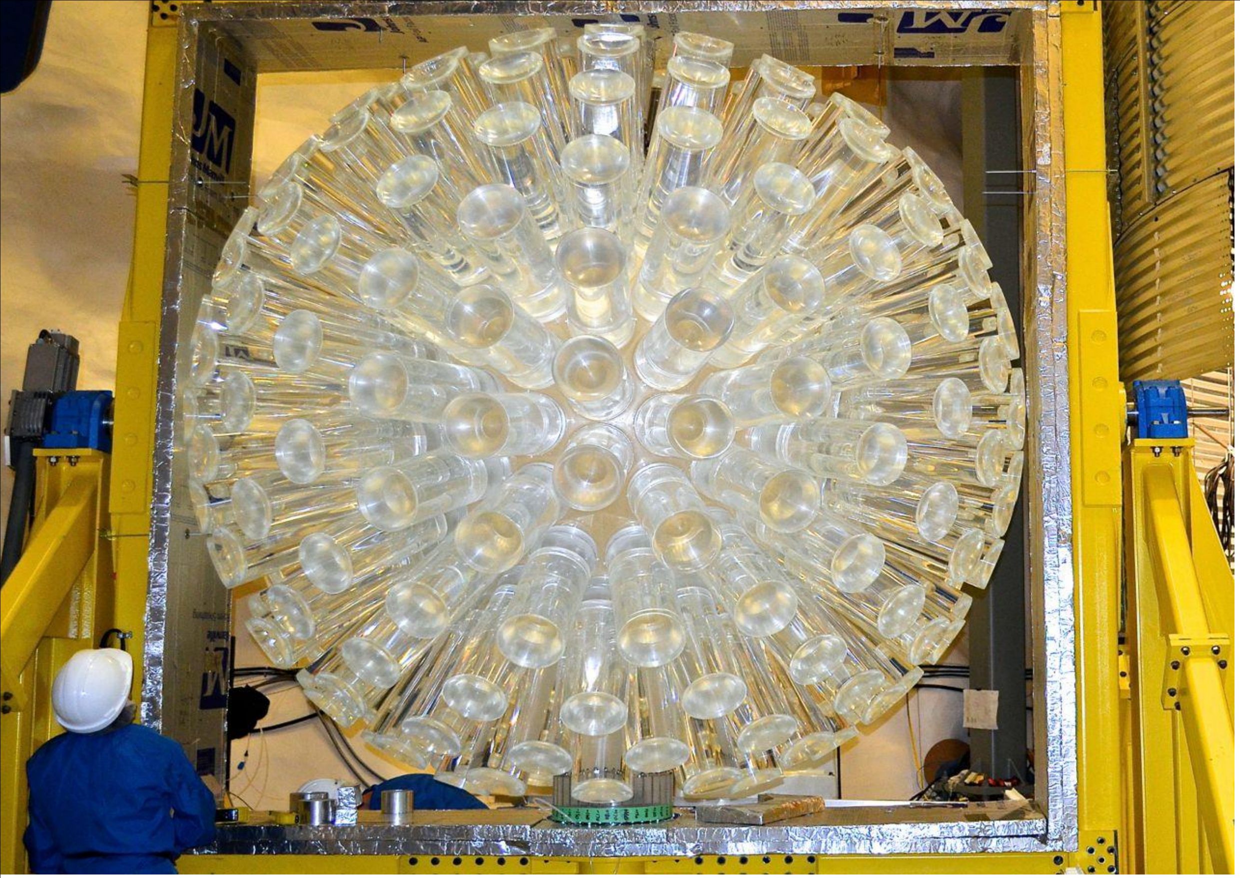
Eur. Phys. J. C 80,303 (2020)



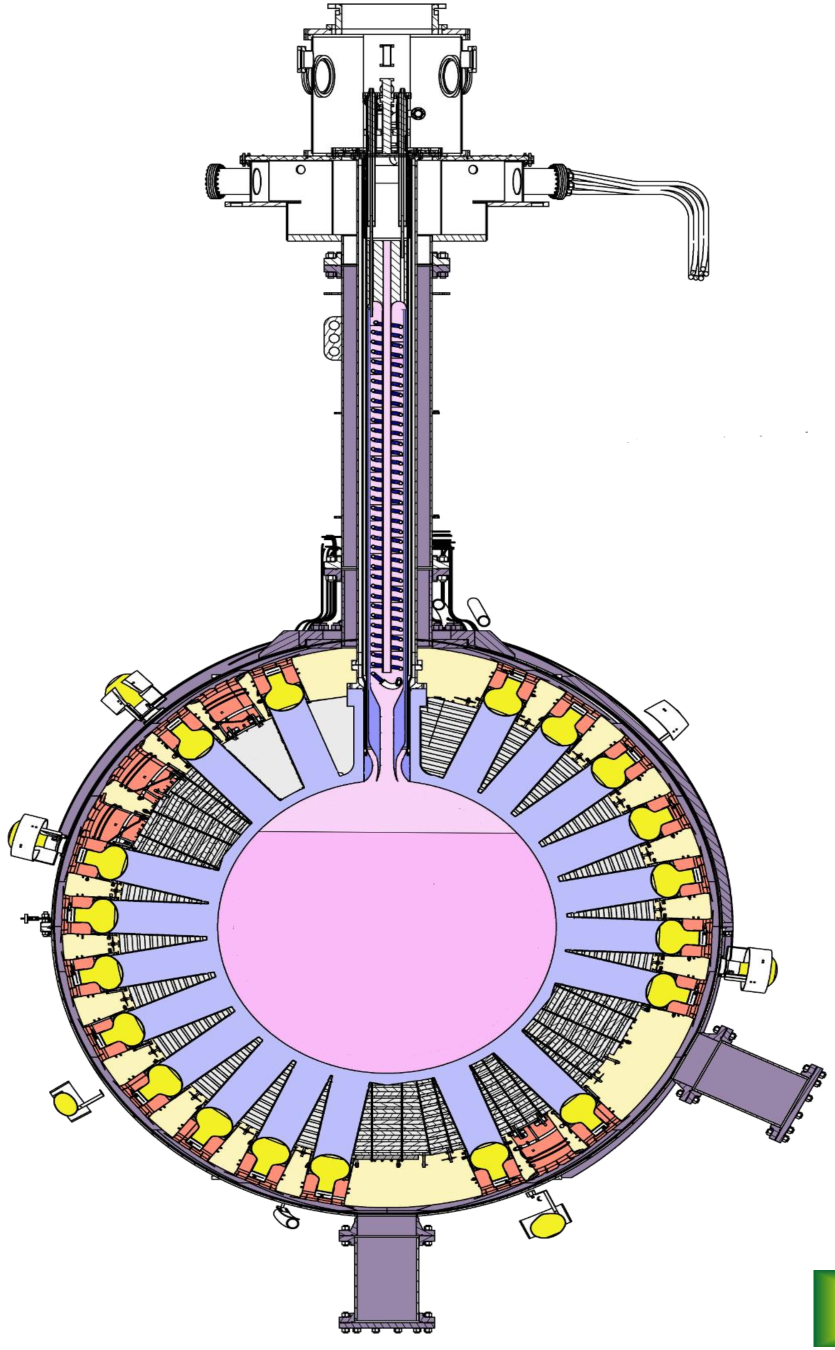
Eur. Phys. J. C 81,823 (2021)

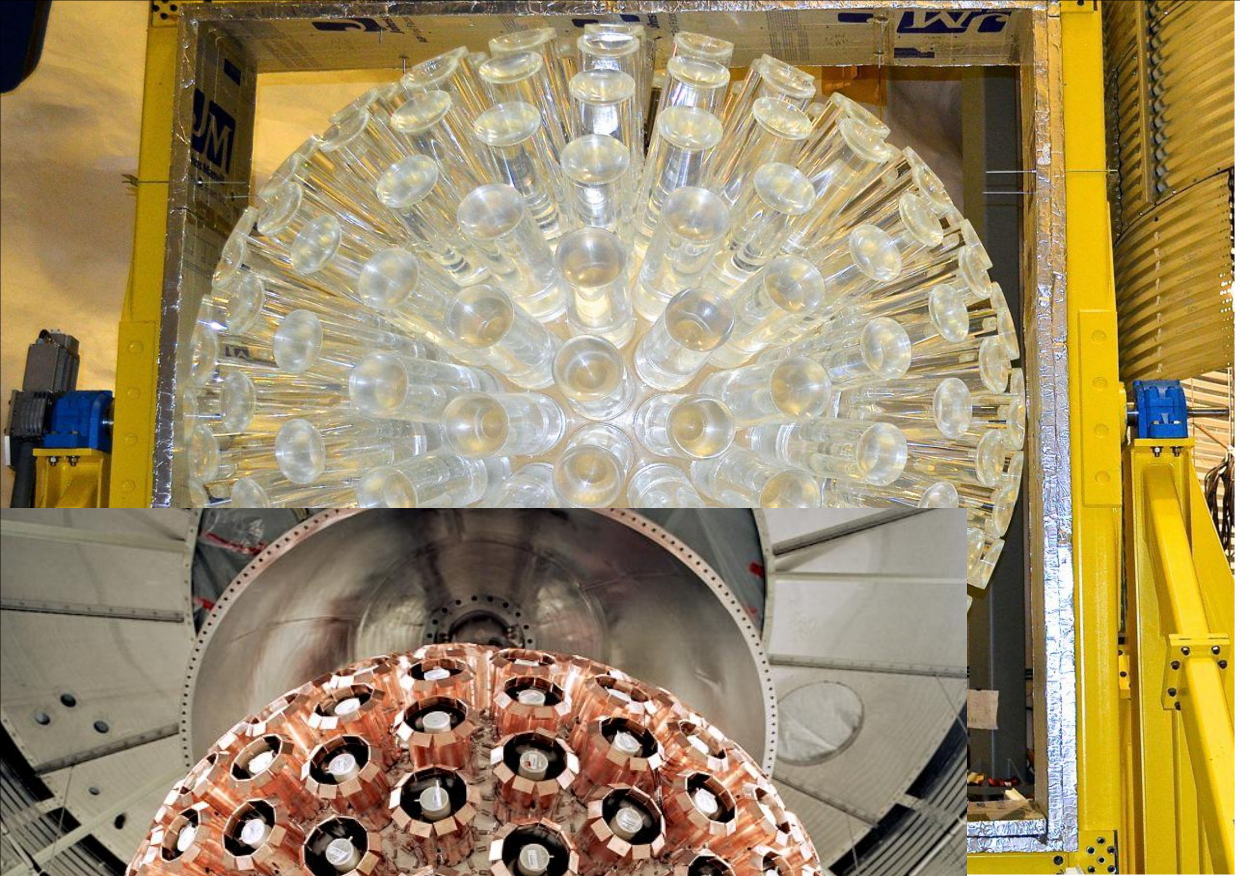
DEAP 3600

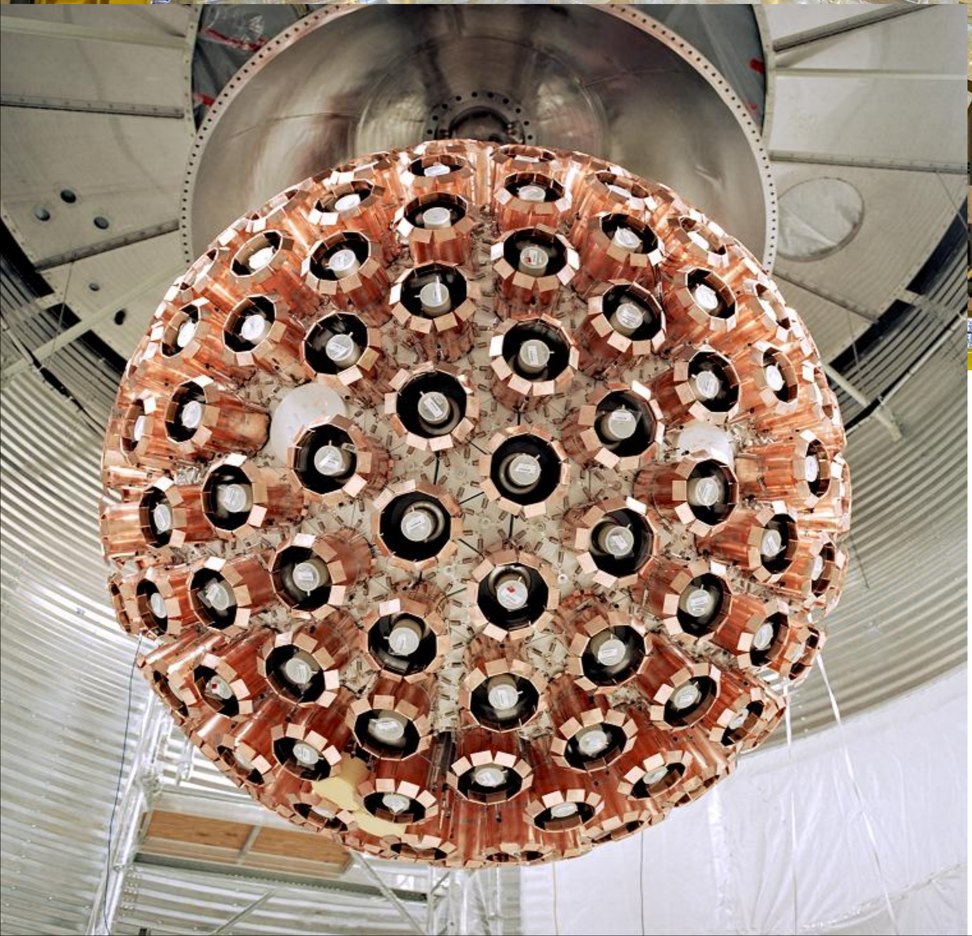




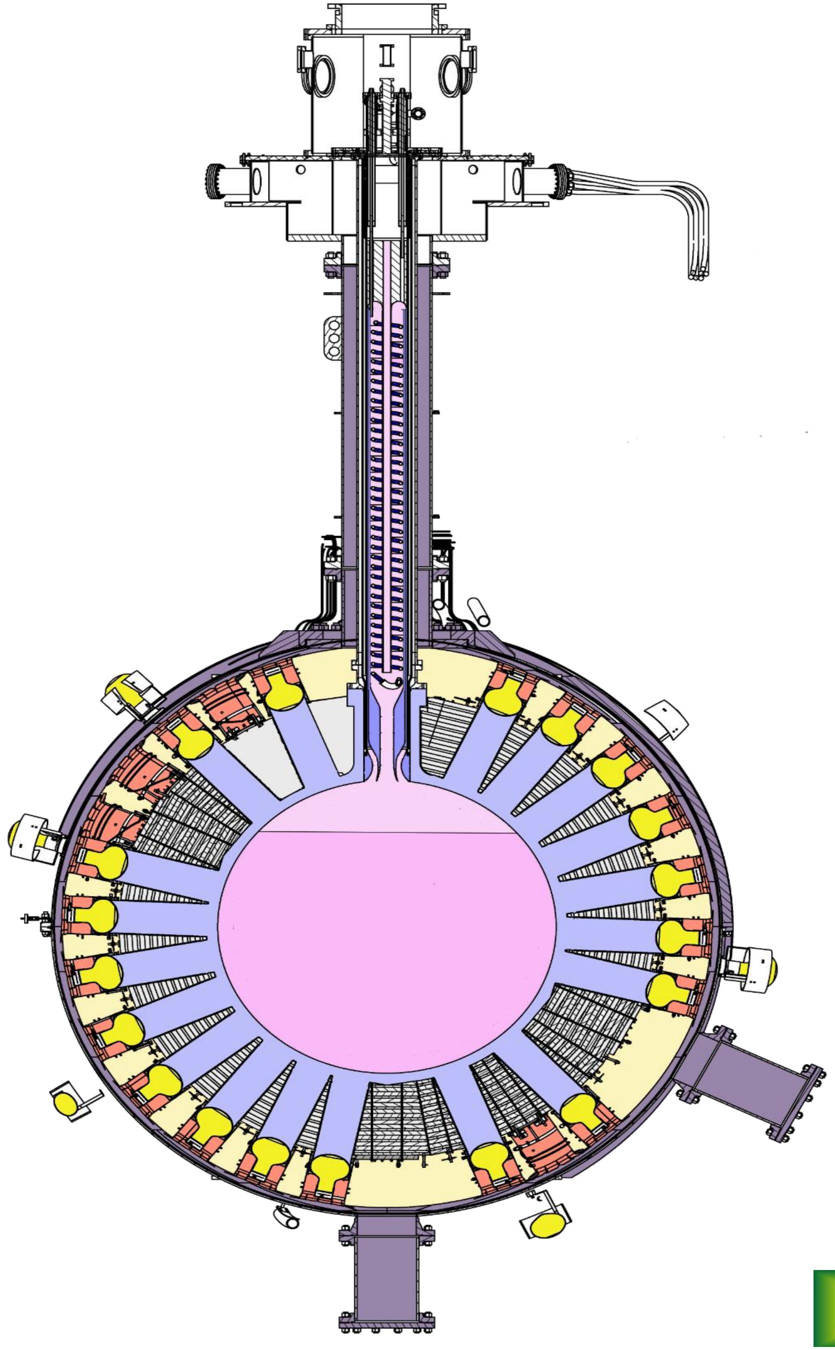
DEAP 3600

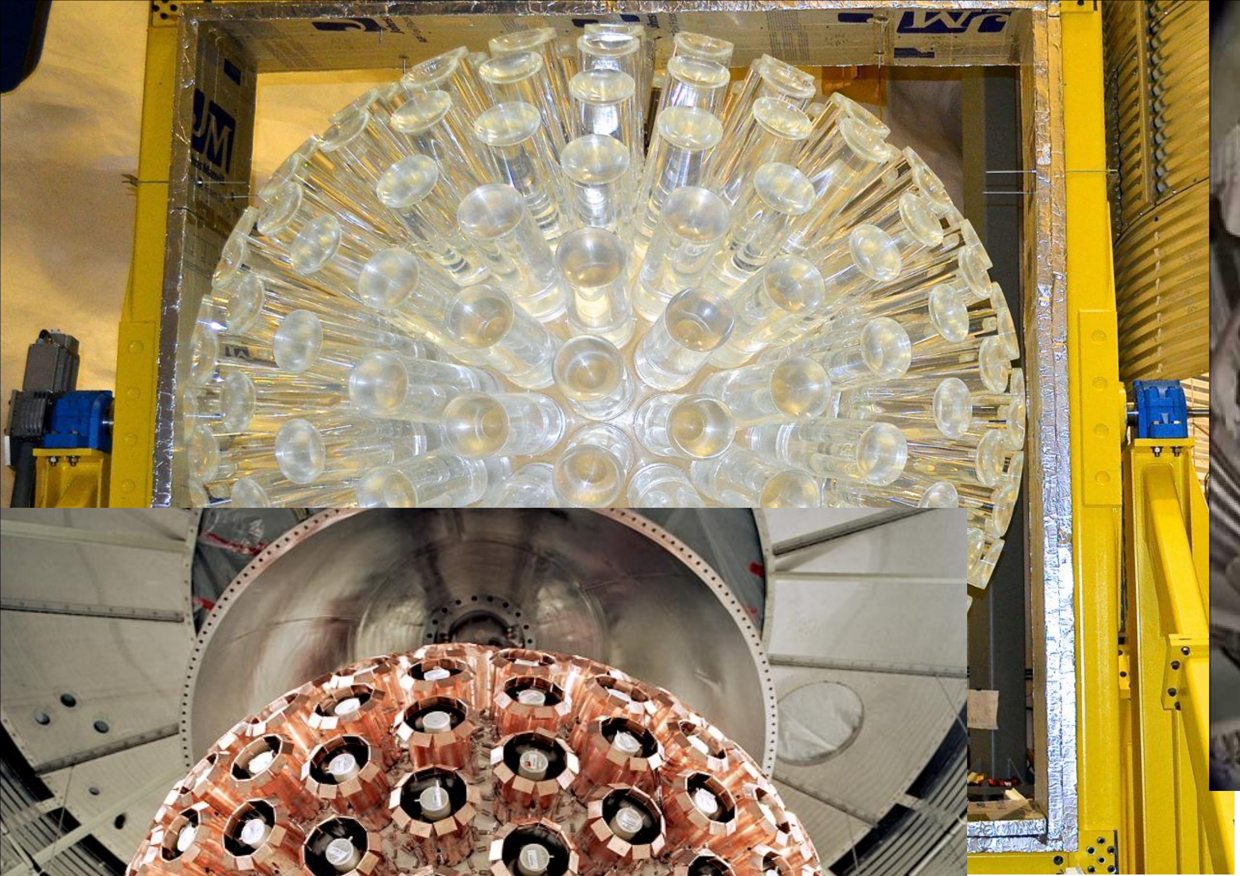


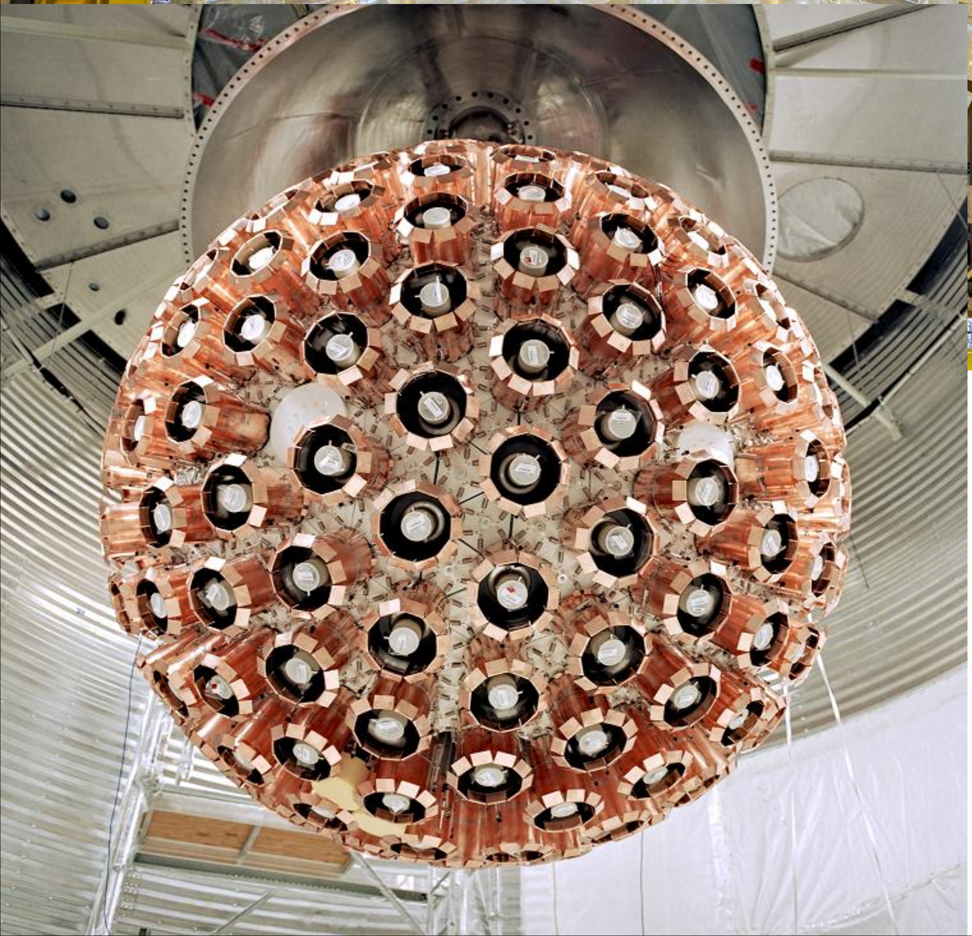




DEAP 3600







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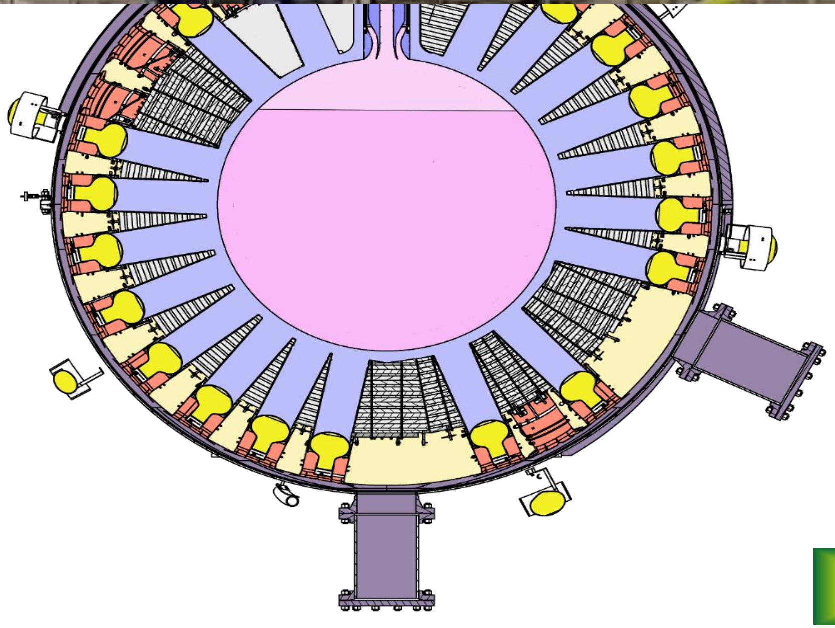
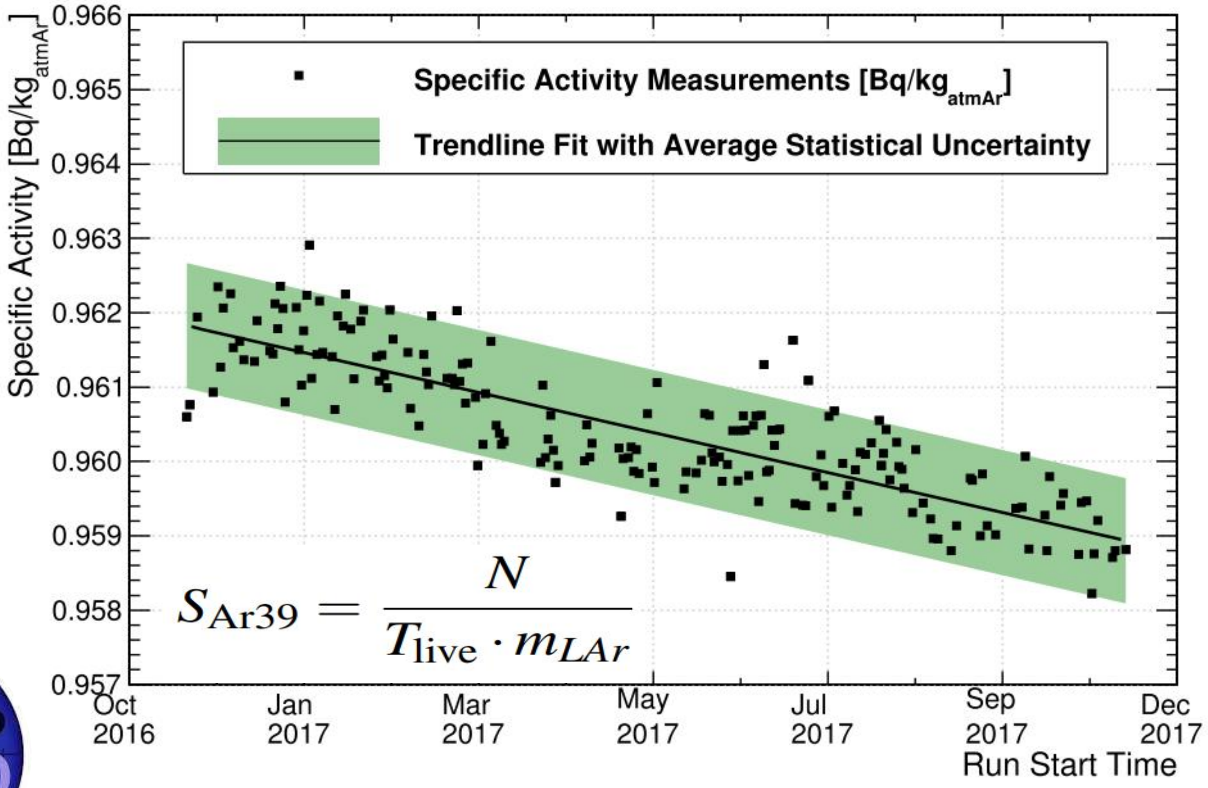


All that you can do with a tonne-scale LAr detector...

Most precise measurement of the ^{39}Ar specific activity in Atmospheric Argon



$$S_{Ar39} = \frac{N}{T_{live} \cdot m_{LAr}}$$

Eur.Phys.J.C 83 (2023) 7, 642

Measurement	Specific activity [Bq/kg$_{atmAr}$]
WARP [15]	$1.01 \pm 0.02_{stat} \pm 0.08_{sys}$
ArDM [16]	0.95 ± 0.05
DEAP-3600 (this work)	$0.964 \pm 0.001_{stat} \pm 0.024_{sys}$

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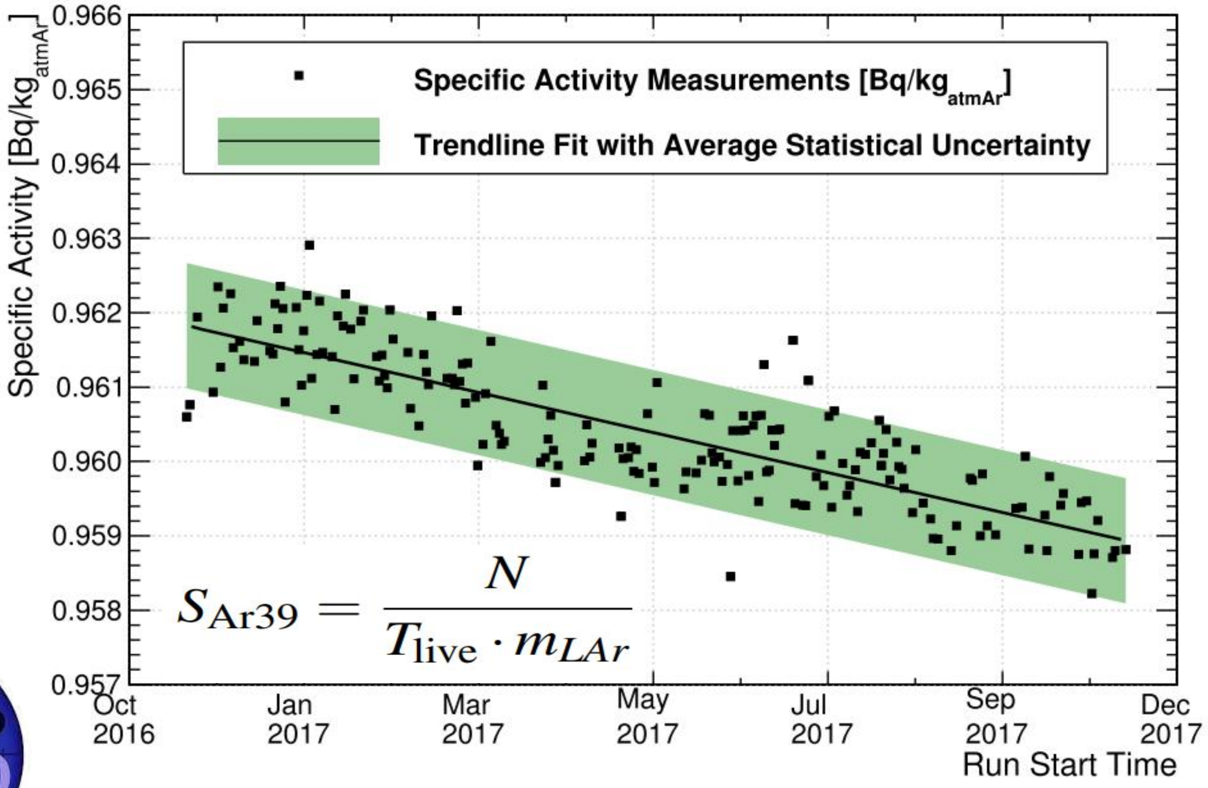

Eur.Phys.J.C 83 (2023) 7, 642

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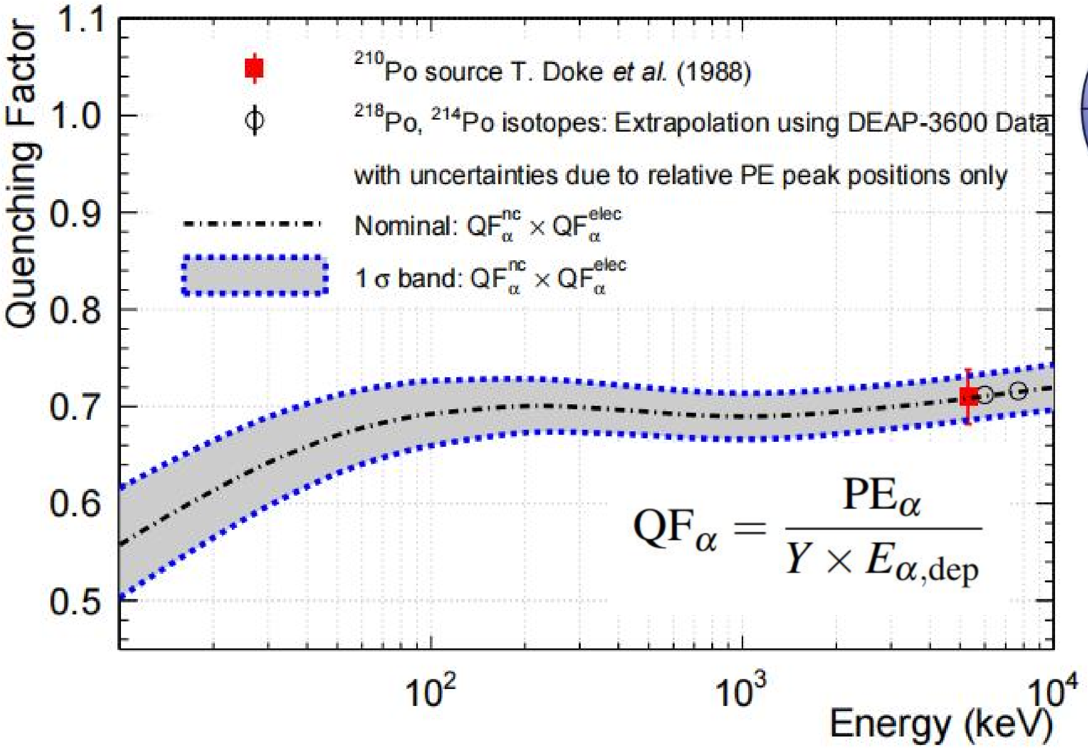
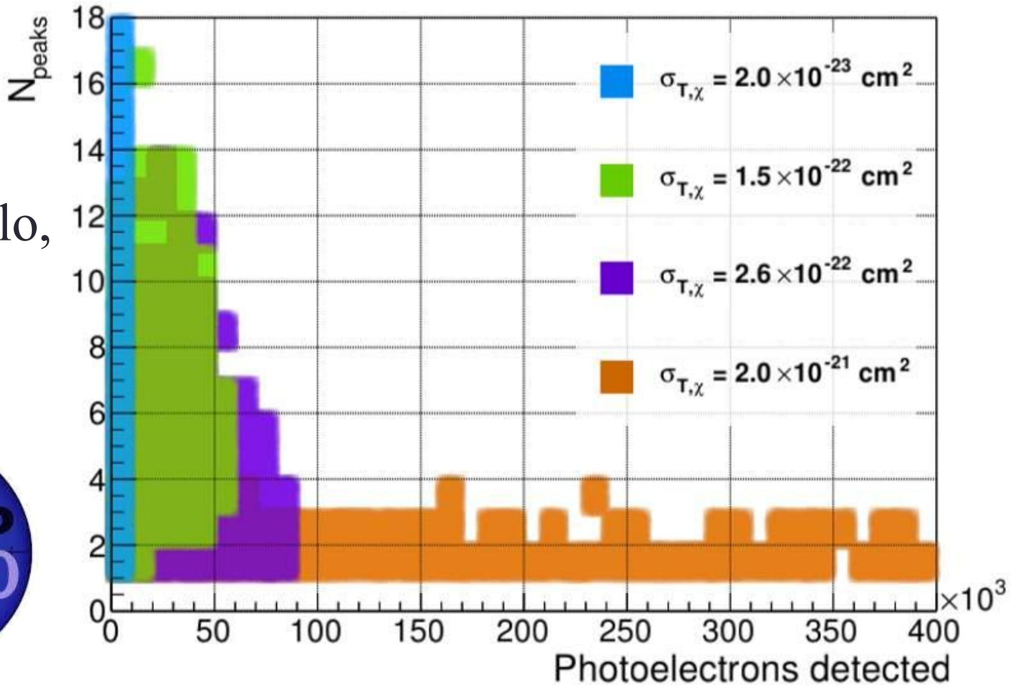
Extrapolation of the QF values into the low-energy region down to 10 keV

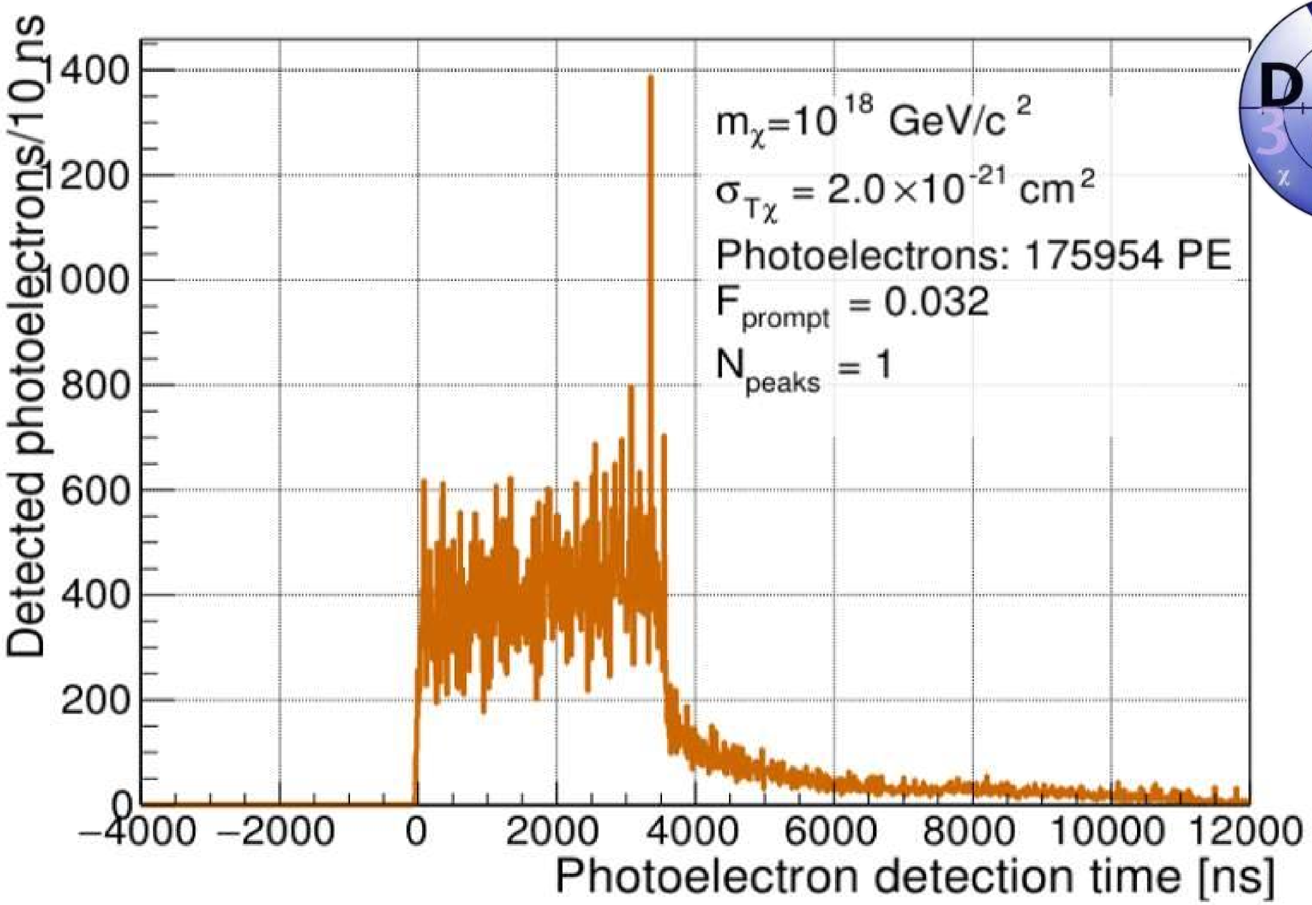
arXiv: 2406.18597v1



All that you can do with a tonne-scale LAr detector...

Ultra-heavy DM candidates: extremely low number density in the halo, need for tonne-scale exposure and pretty high cross-section, hence **multi-scattering in LAr**!





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

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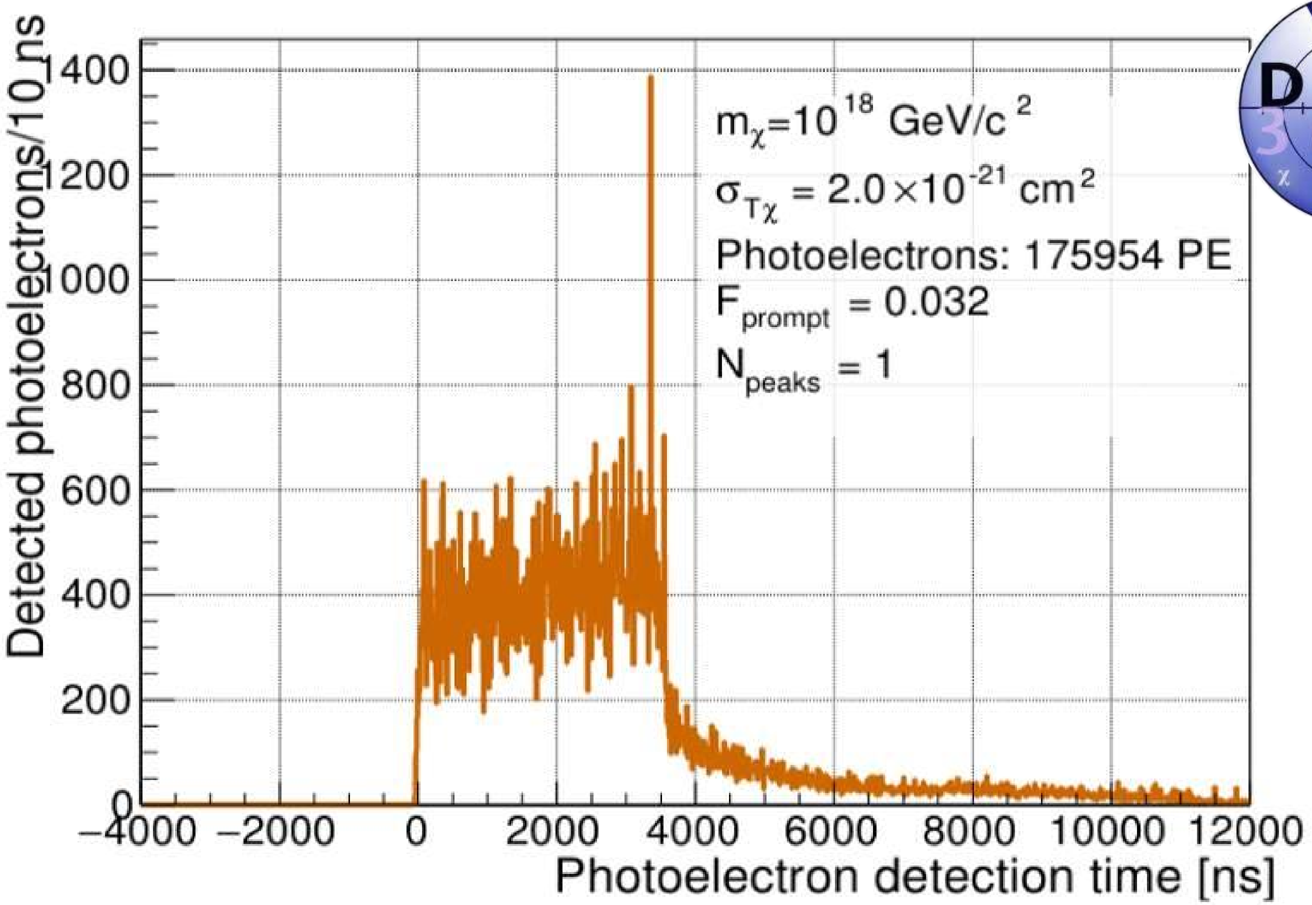
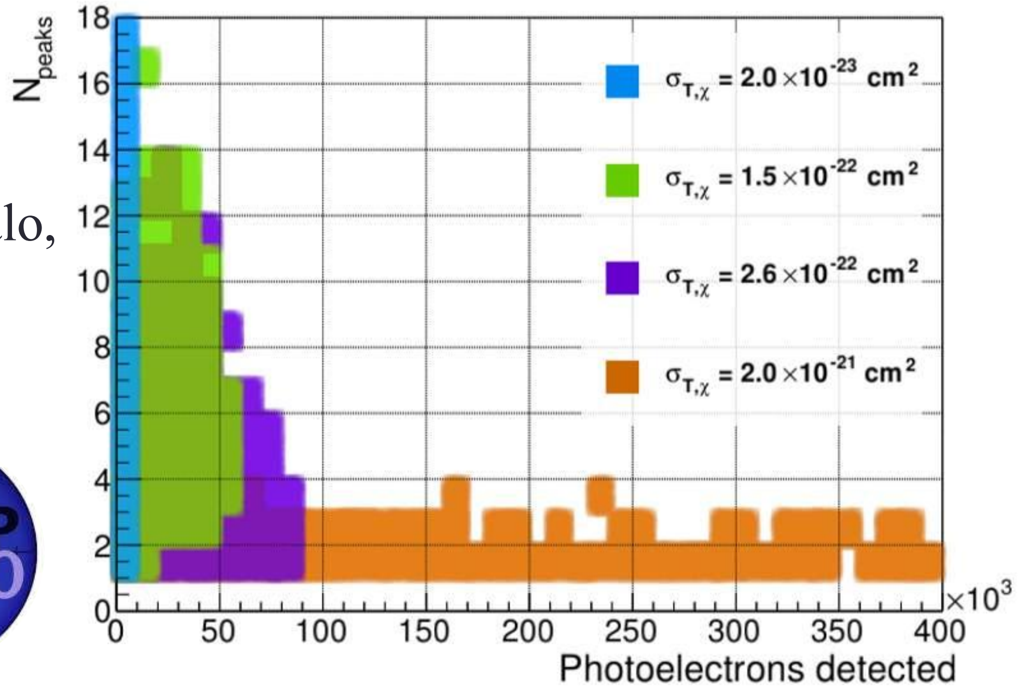
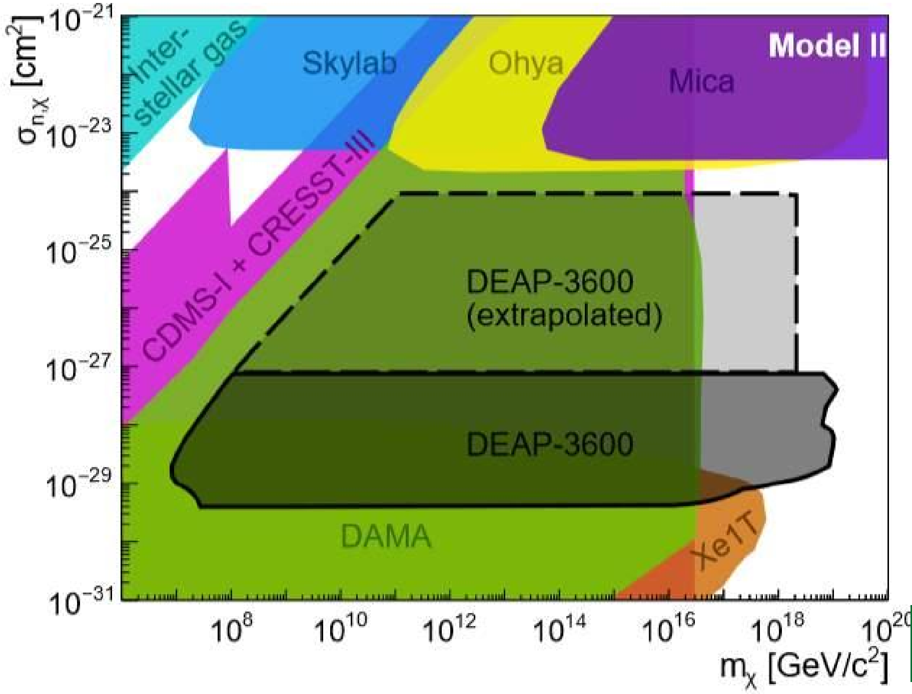




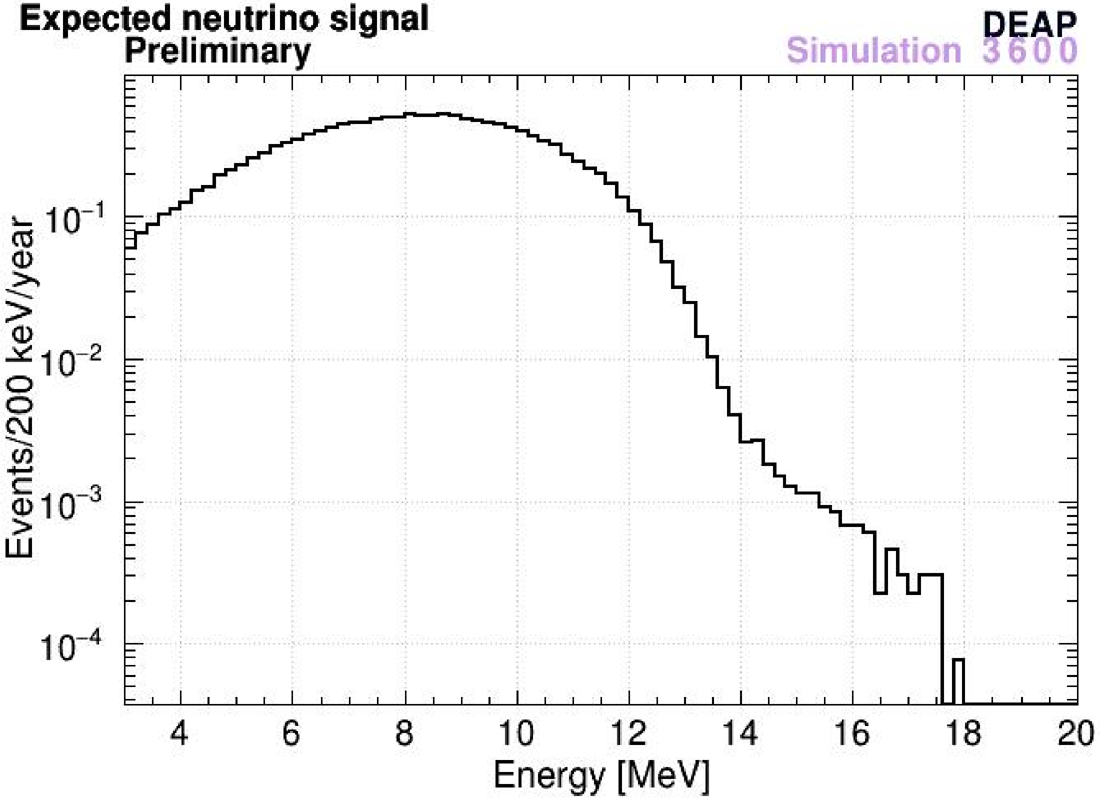


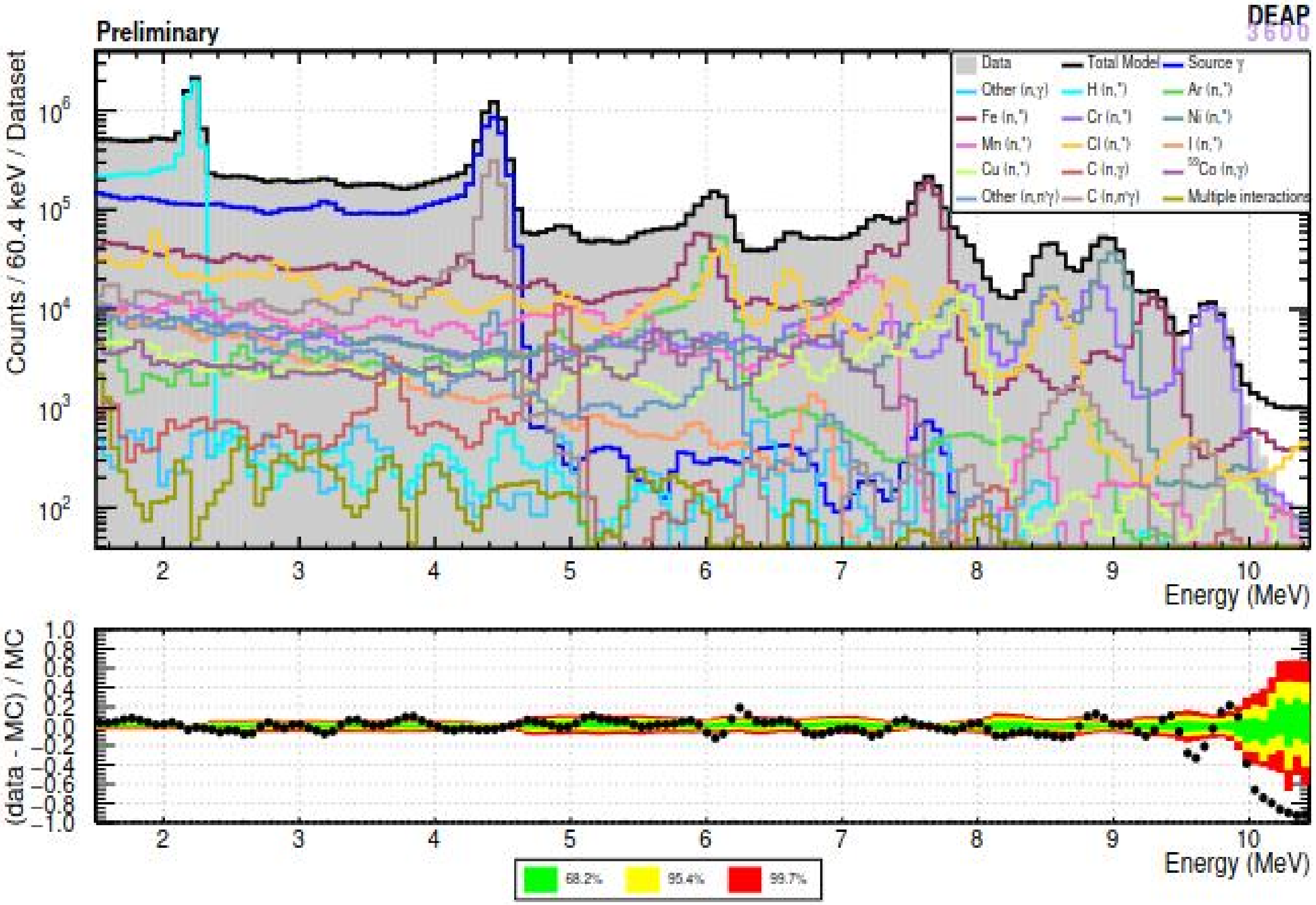
Phys. Rev. Lett. 128, 011801 (2022)

All that you can do with a tonne-scale LAr detector...

Coming soon from DEAP-3600: First search for solar neutrino absorption in ^{40}Ar

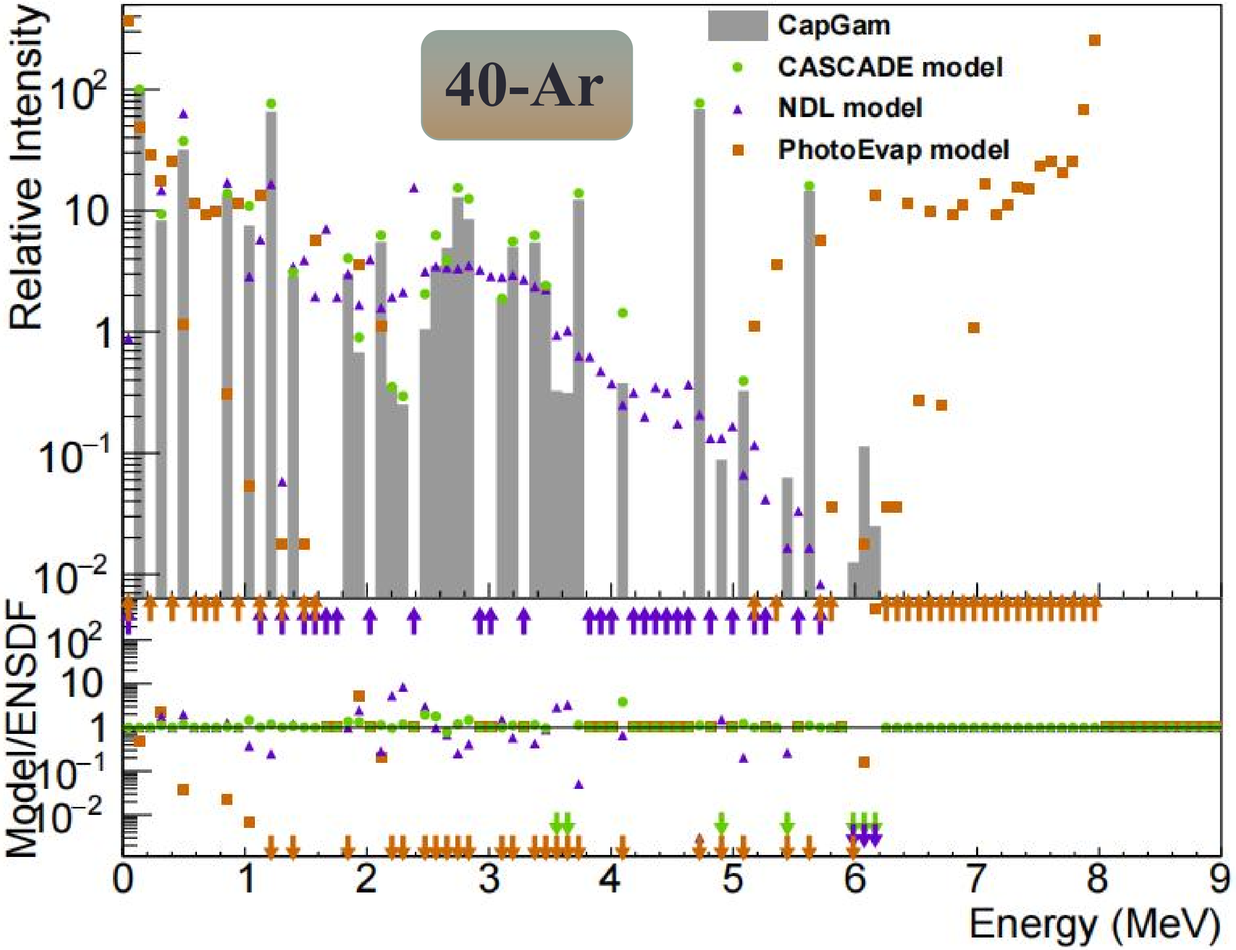
$$\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$$

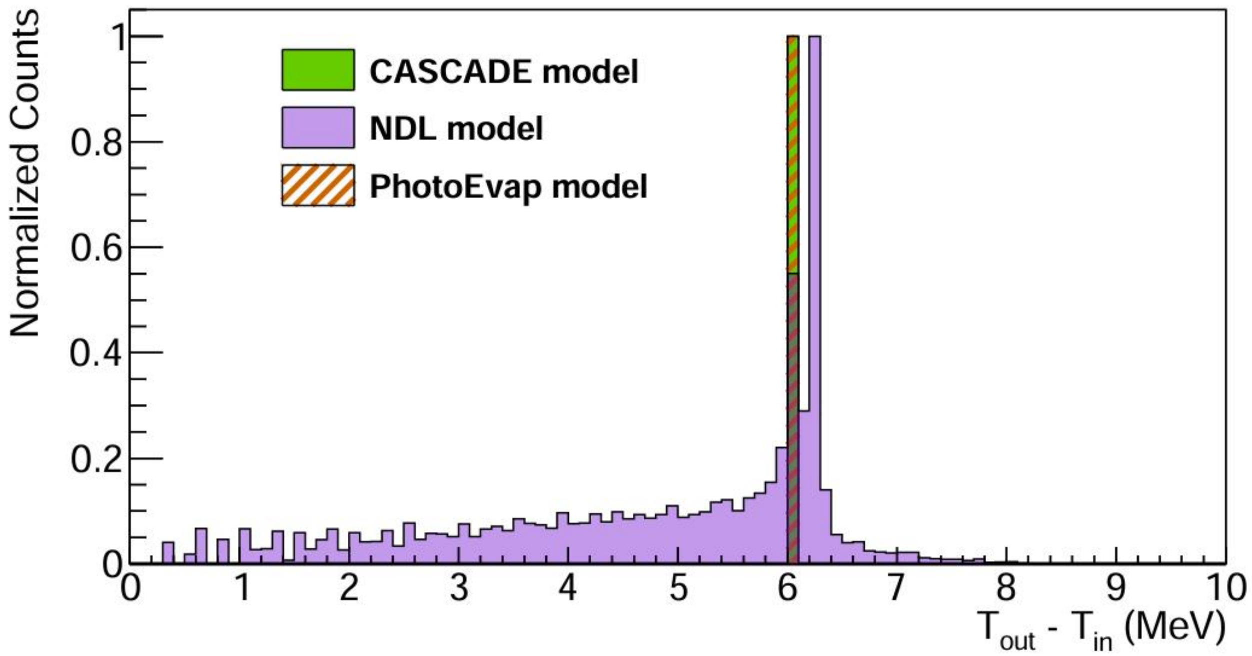


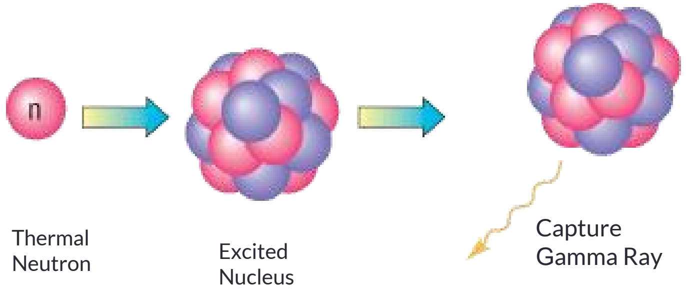


- Energy threshold decreased from 5.885 MeV (Fermi) to 3.9 MeV (GT)
- Dominant backgrounds:pile-up (< 10 MeV) and comosmogenics (> 10 MeV)

- **CASCADE: Geant4 Code for Allowing Simulation of n-Capture and De-excitation with ENSDFgamma**
- It simulates de-excitation by moving down the level structure according to branching ratios



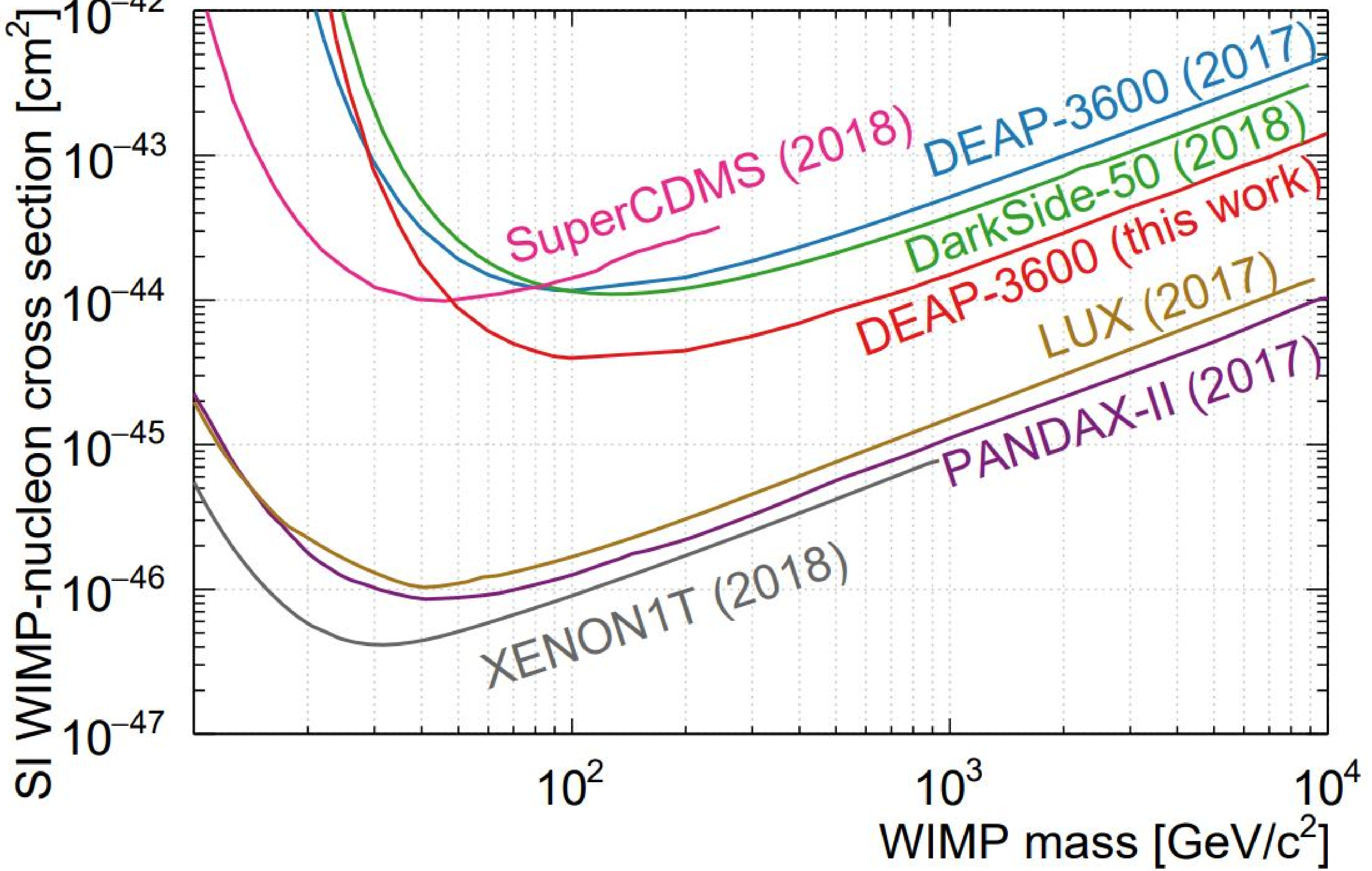




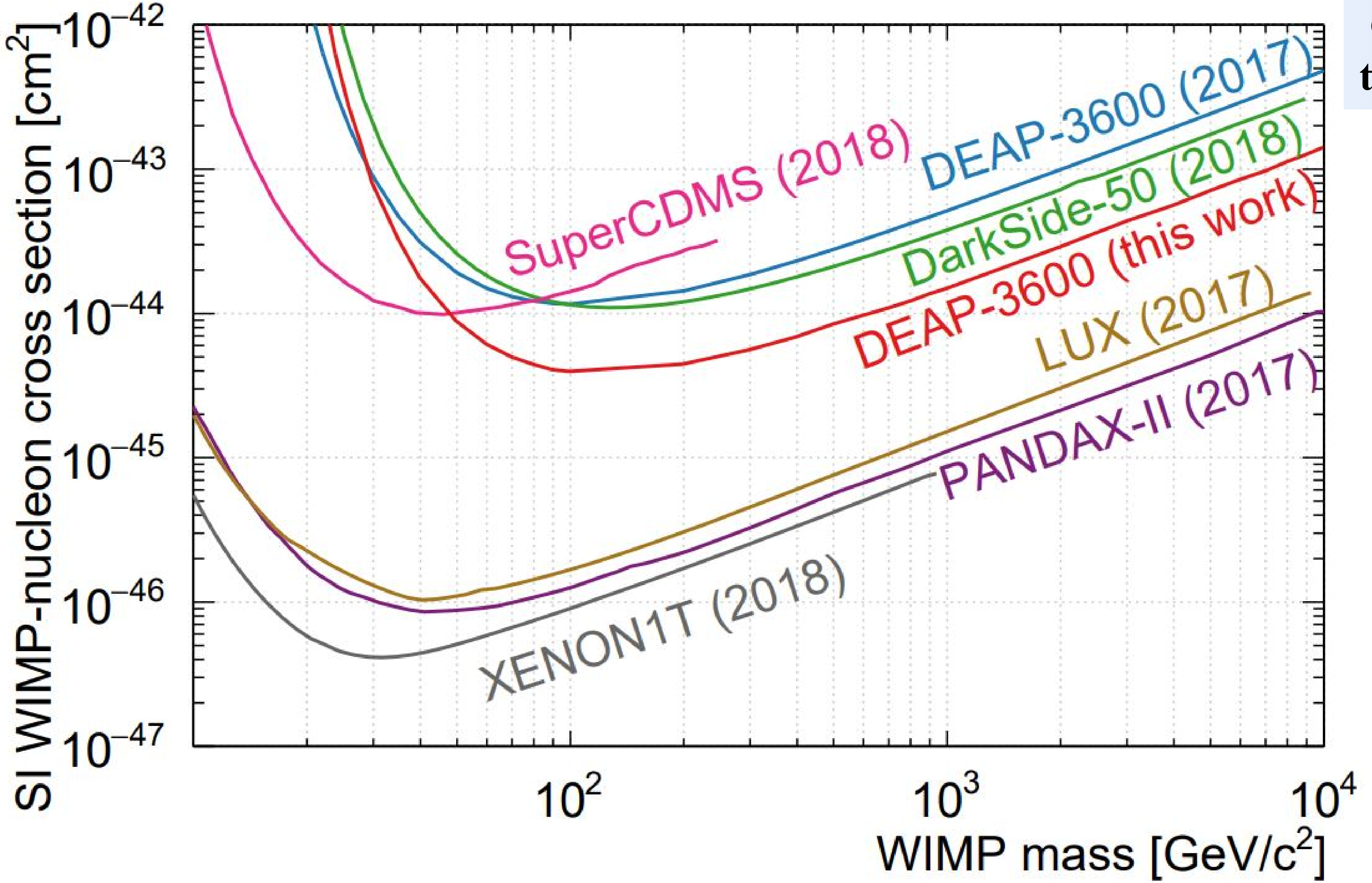
- Data-driven (and data-limited), clear improvement of the background modeling in DEAP-3600
- Already available for Geant4.10 at

https://github.com/UCRDarkMatter/CASCADE

ArXiv:2408.02774

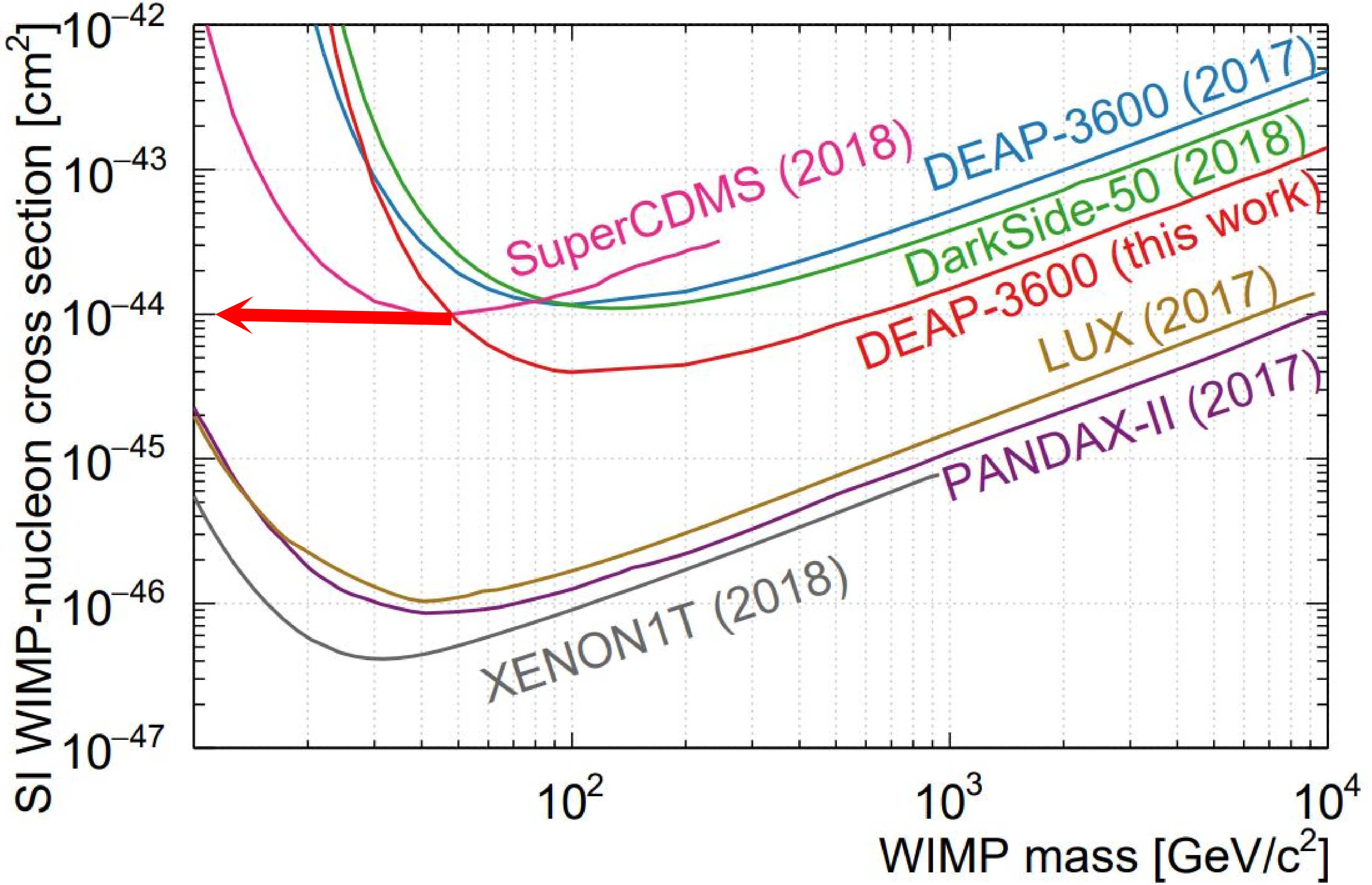


Phys. Rev. D. 100, 022004 (2019)



Chris Jillings poster on the hardware upgrades!

Phys. Rev. D. 100, 022004 (2019)



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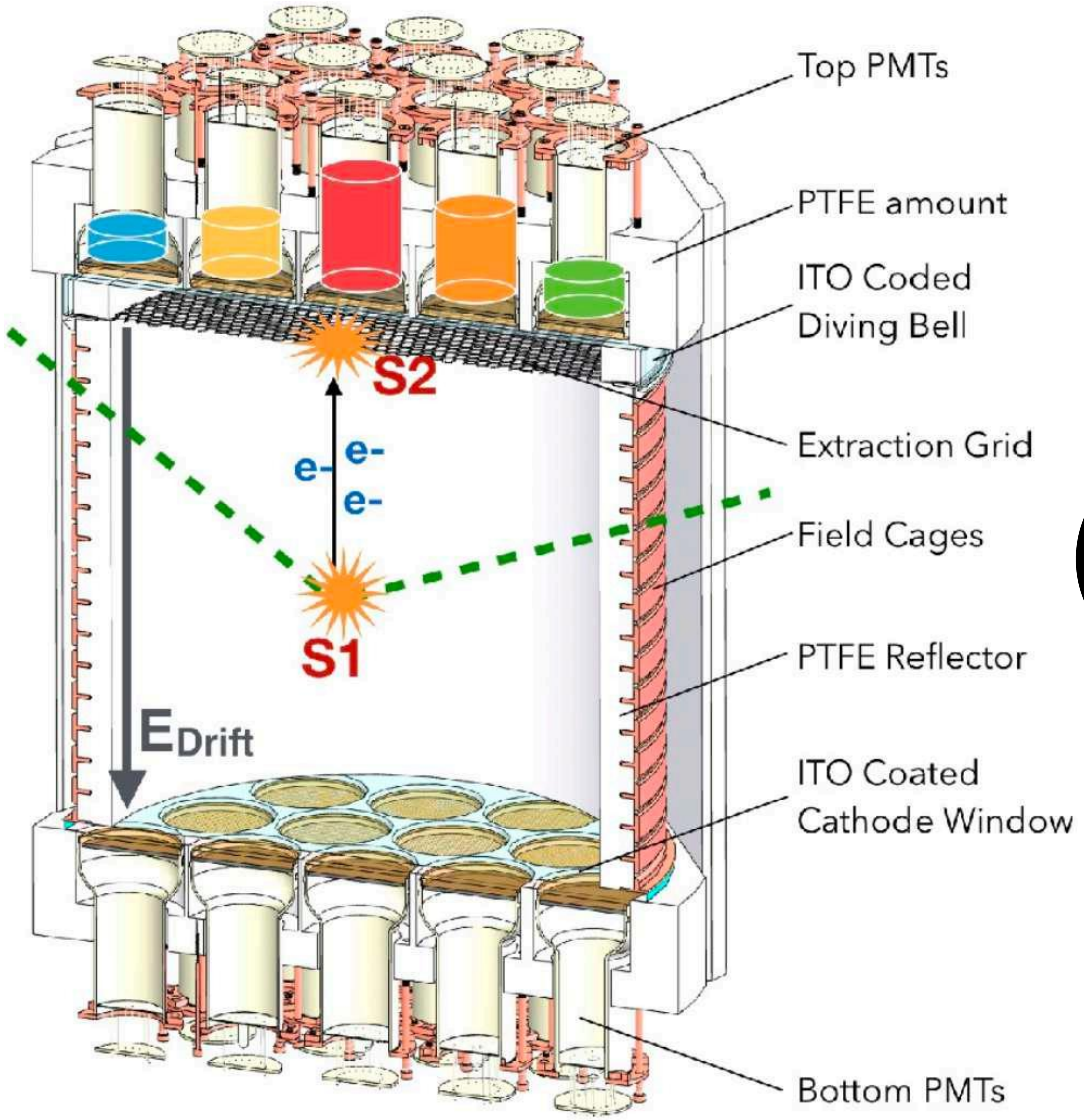
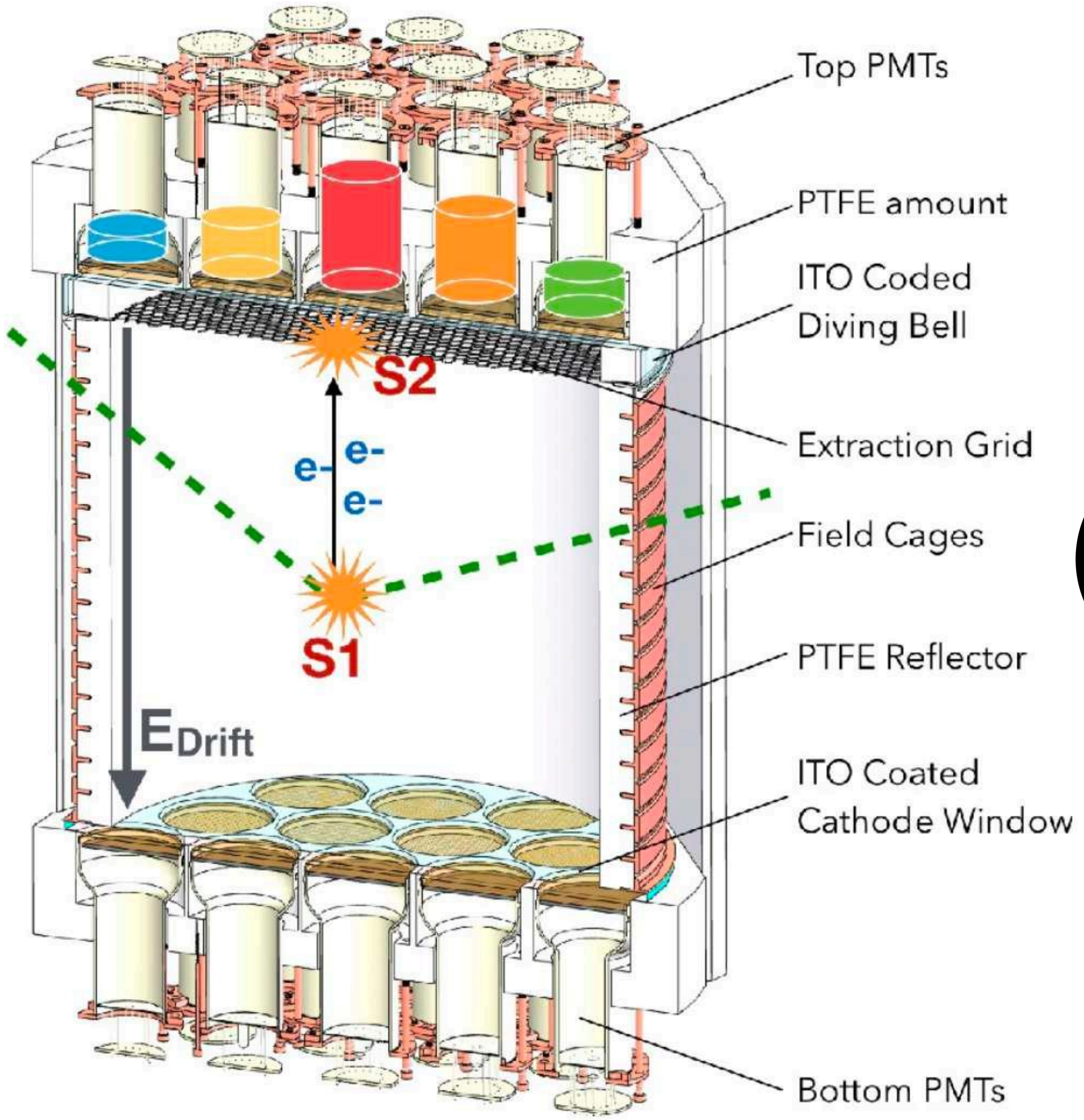
Phys. Rev. D. 100, 022004 (2019)

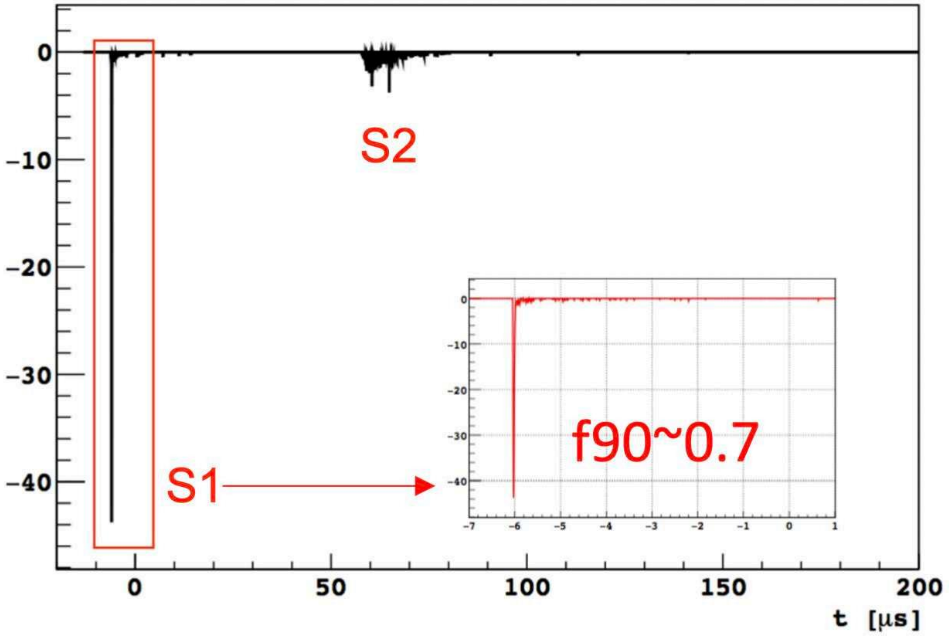


Drawing of DarkSide-50

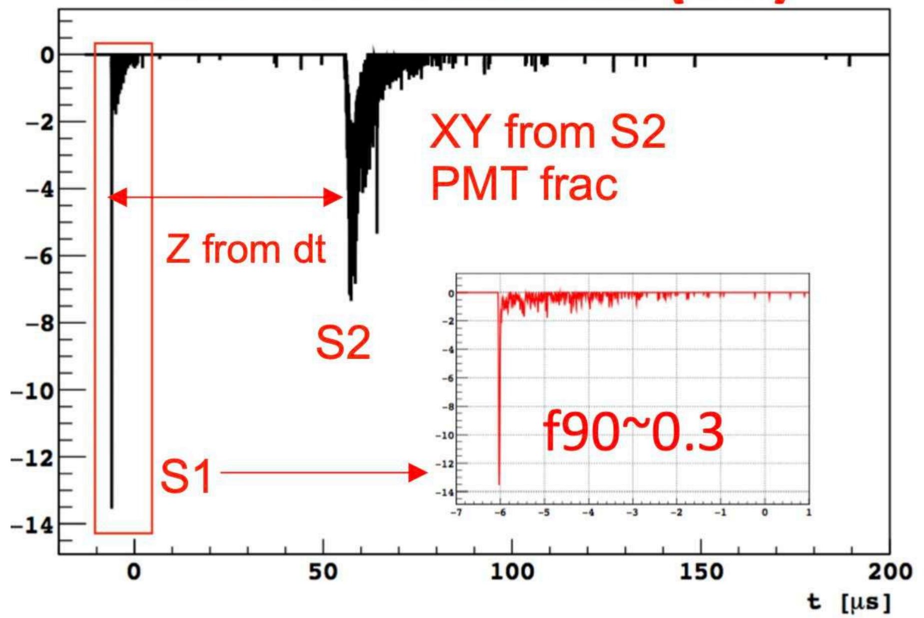


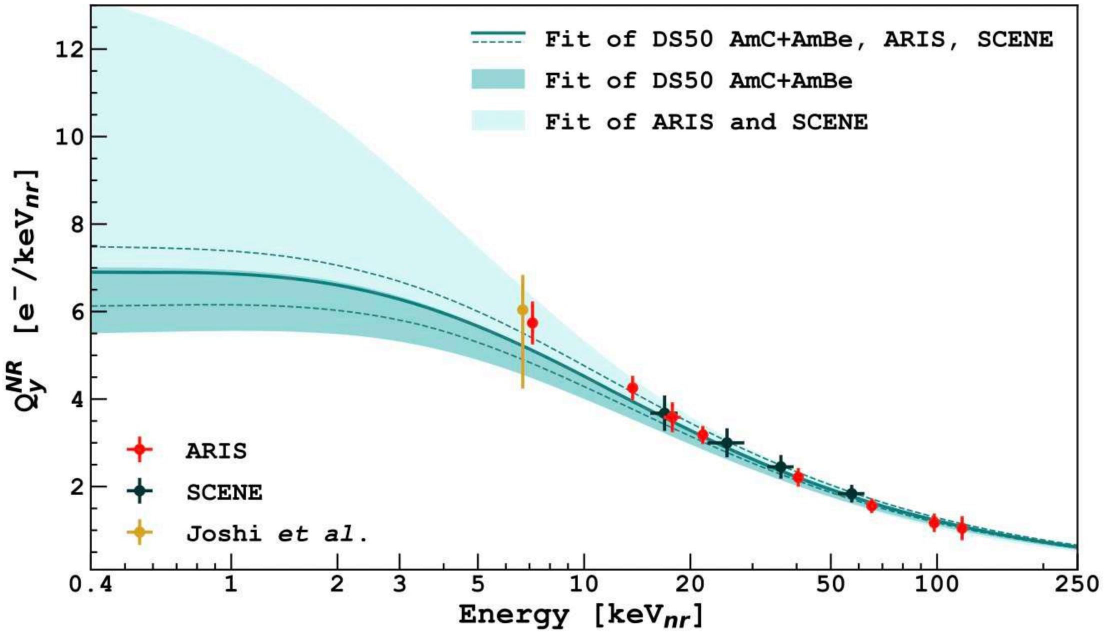
Drawing of DarkSide-50

Nuclear Recoil (NR)

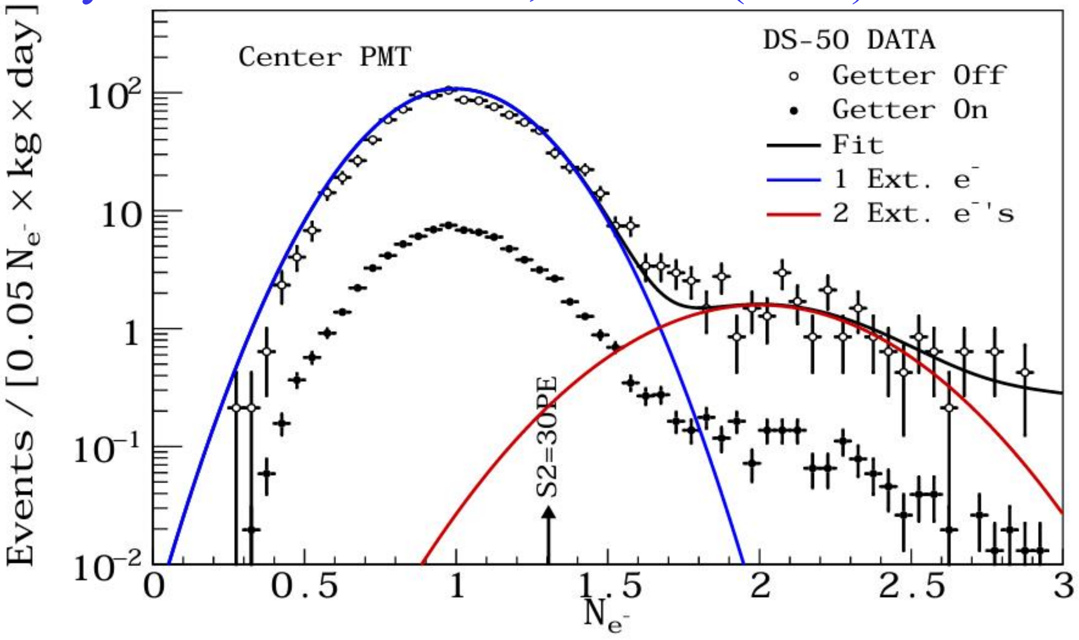


Electron Recoil (ER)





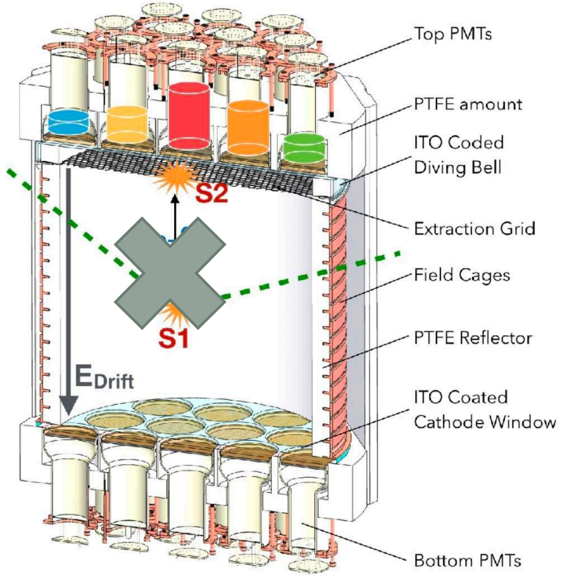
Physical Review D 104, 082005 (2021)



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

Additional research program: sensitivity to sub-GeV mass candidates with S2-only

DARKSIDE



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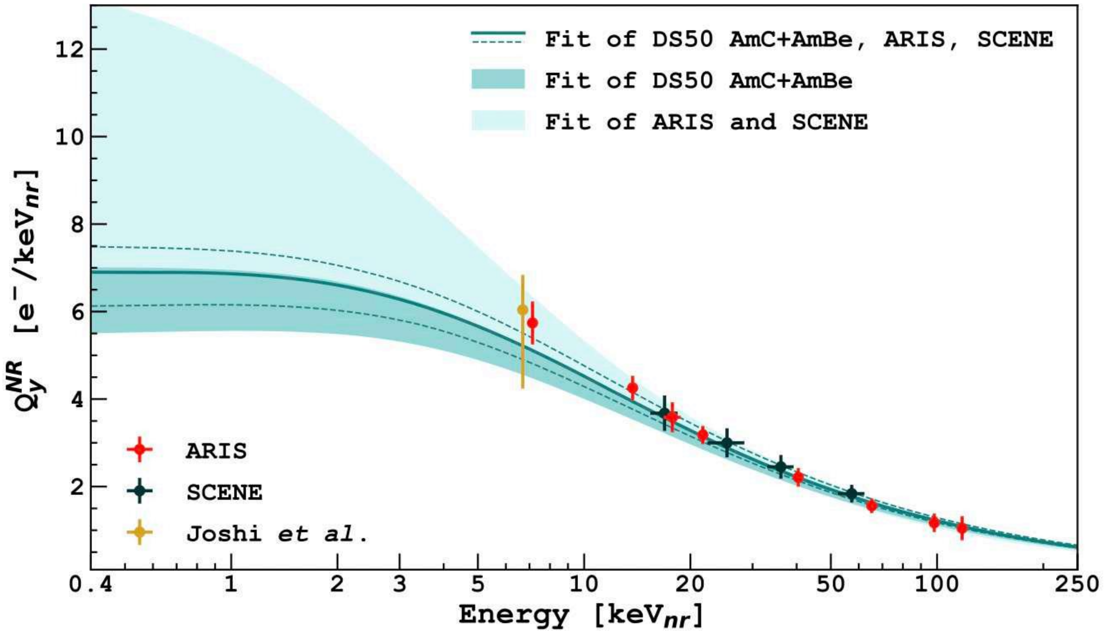

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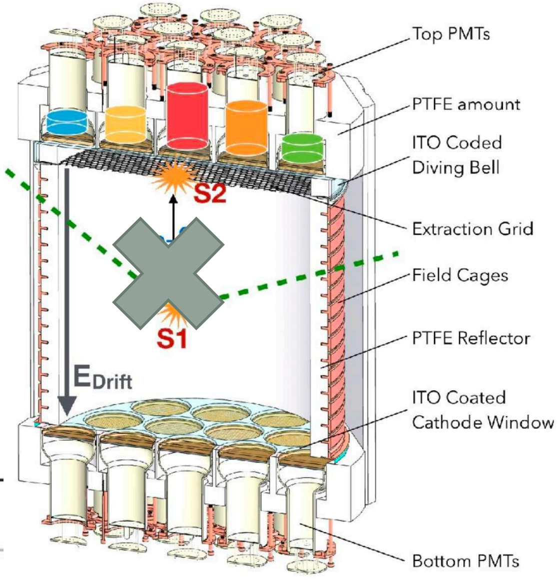

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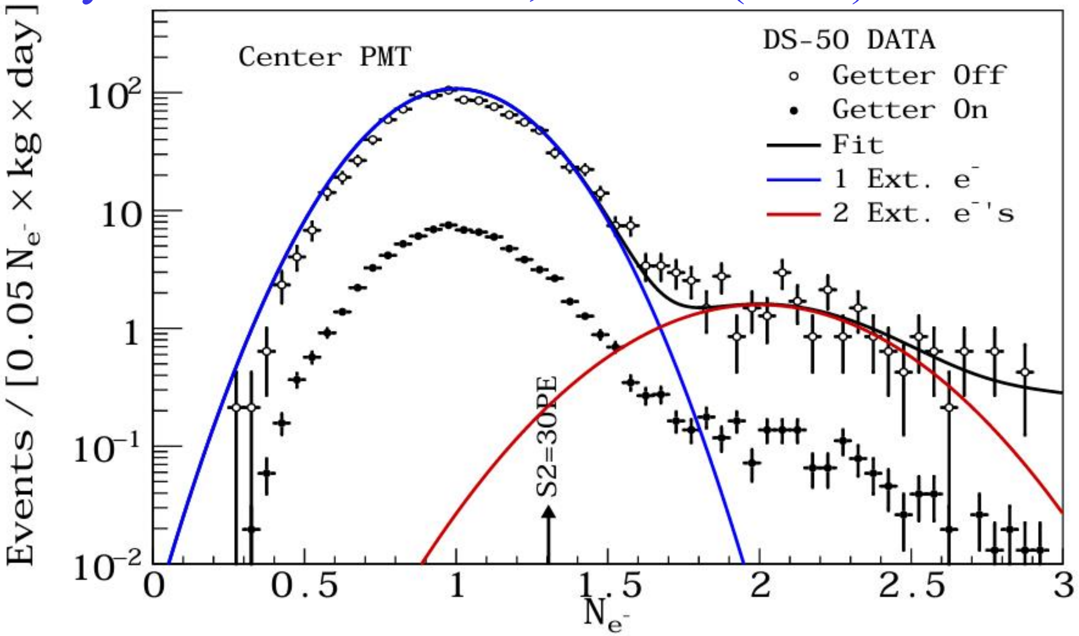

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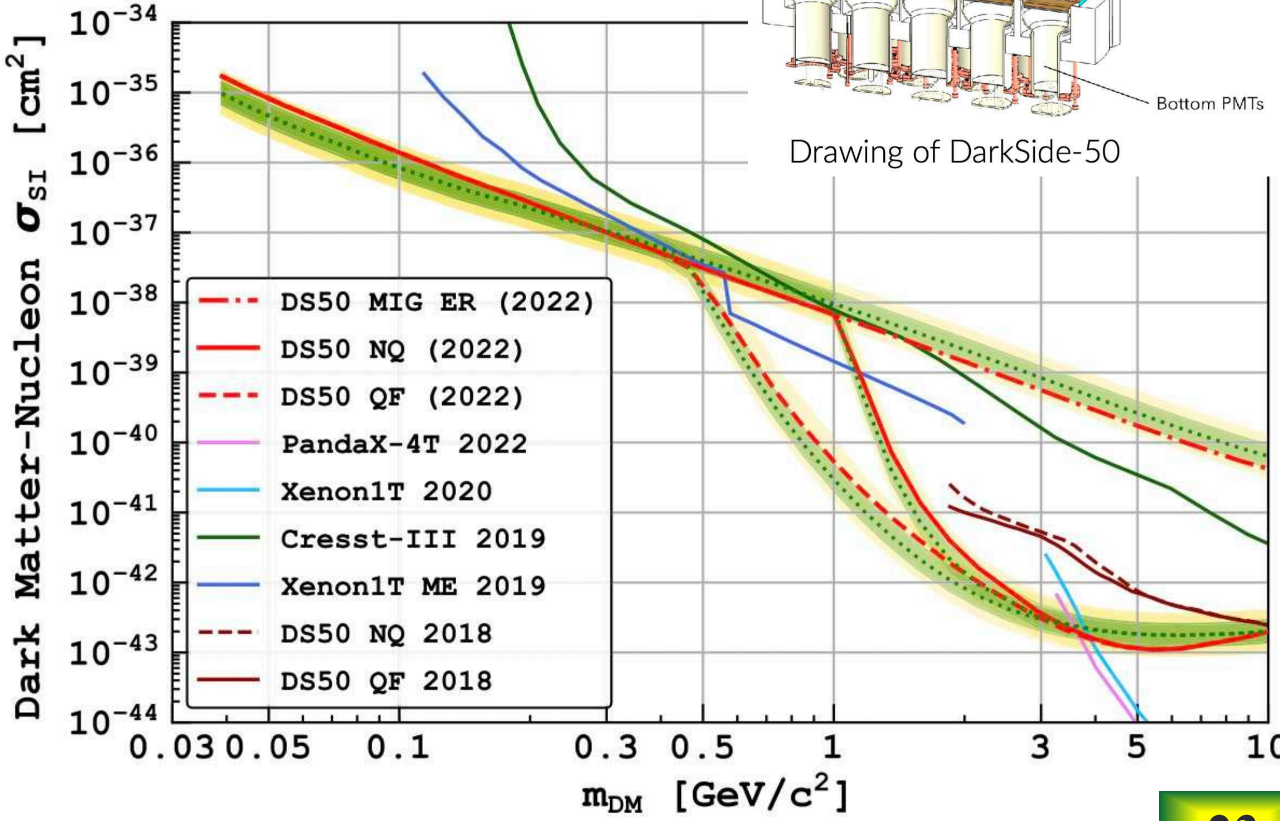
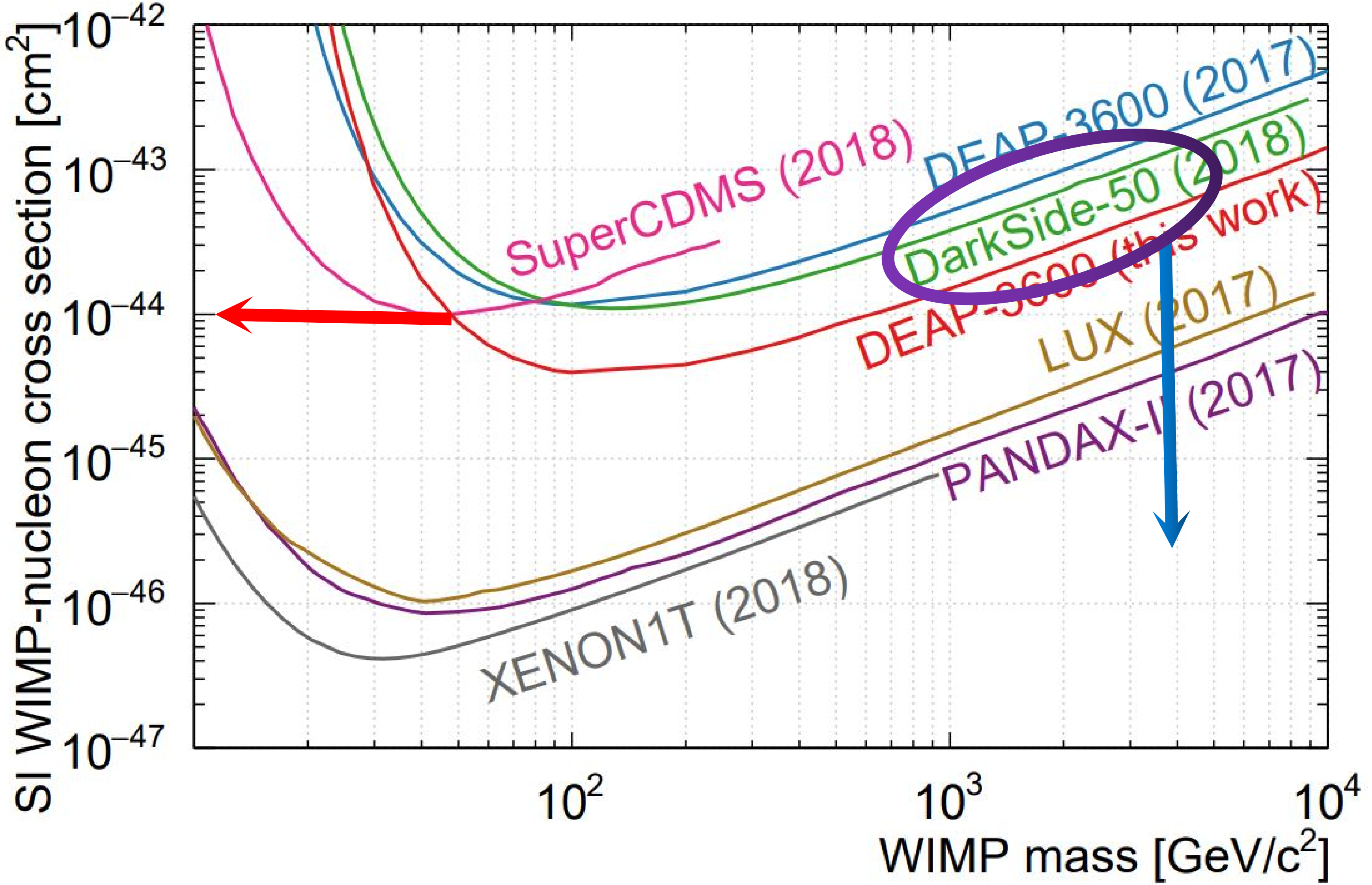


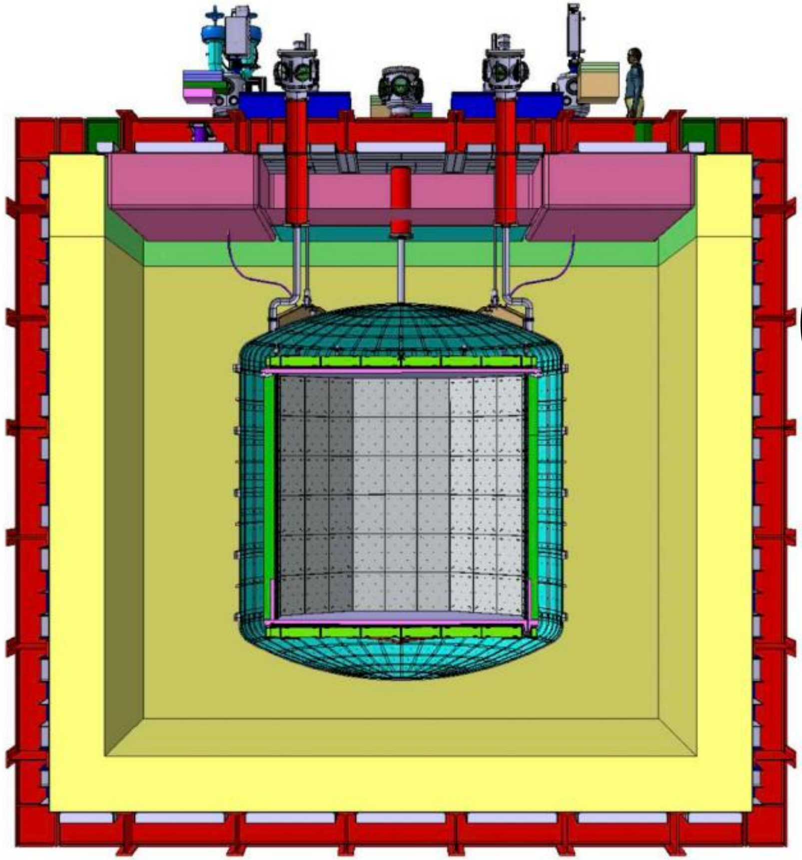
Physical Review Letters 130, 101001 (2023)

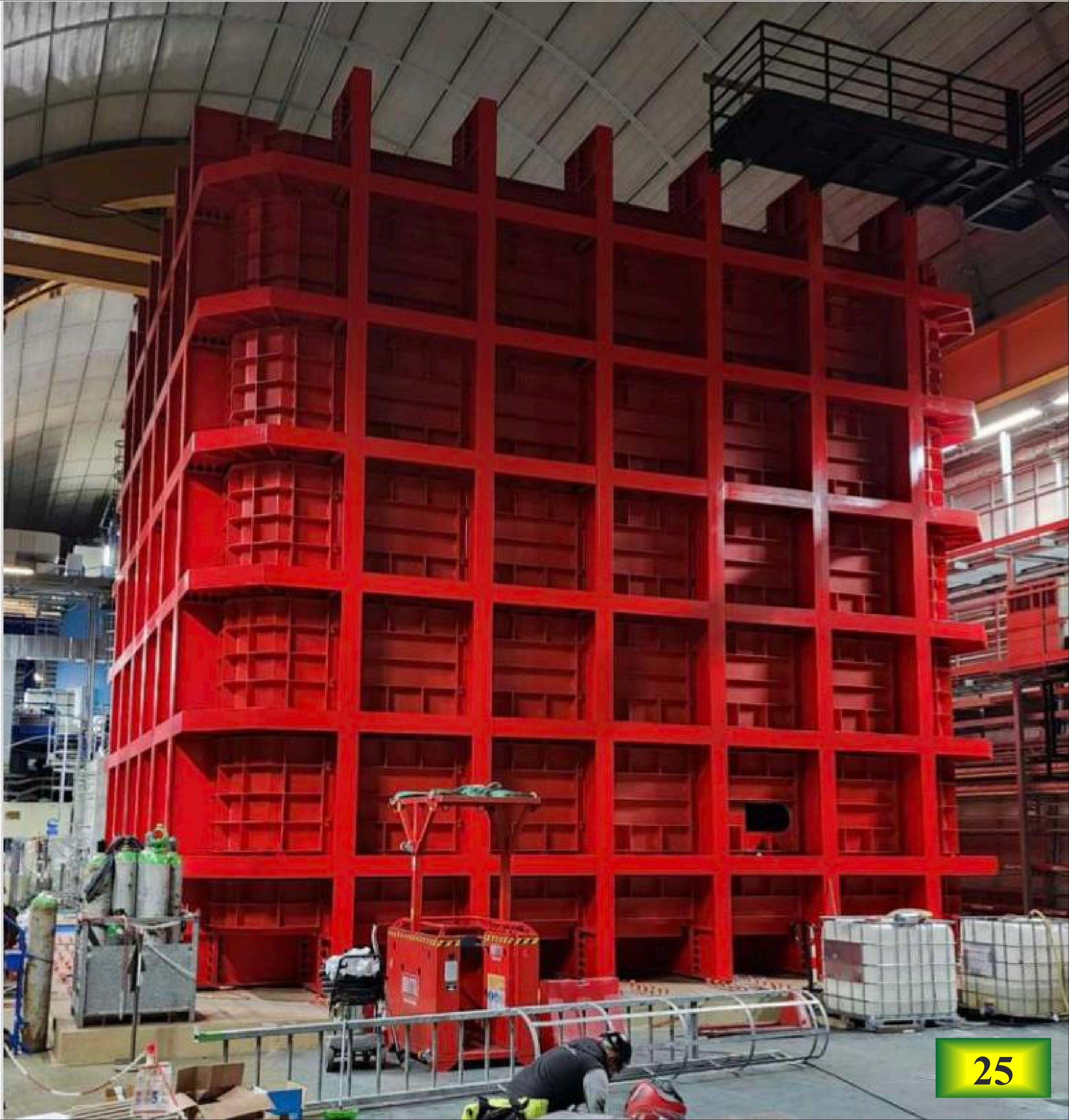


Phys. Rev. D. 100, 022004 (2019)

Next step: DarkSide-20k experiment!

Three nested detectors designed for being instrumental background free in 10 years of data taking





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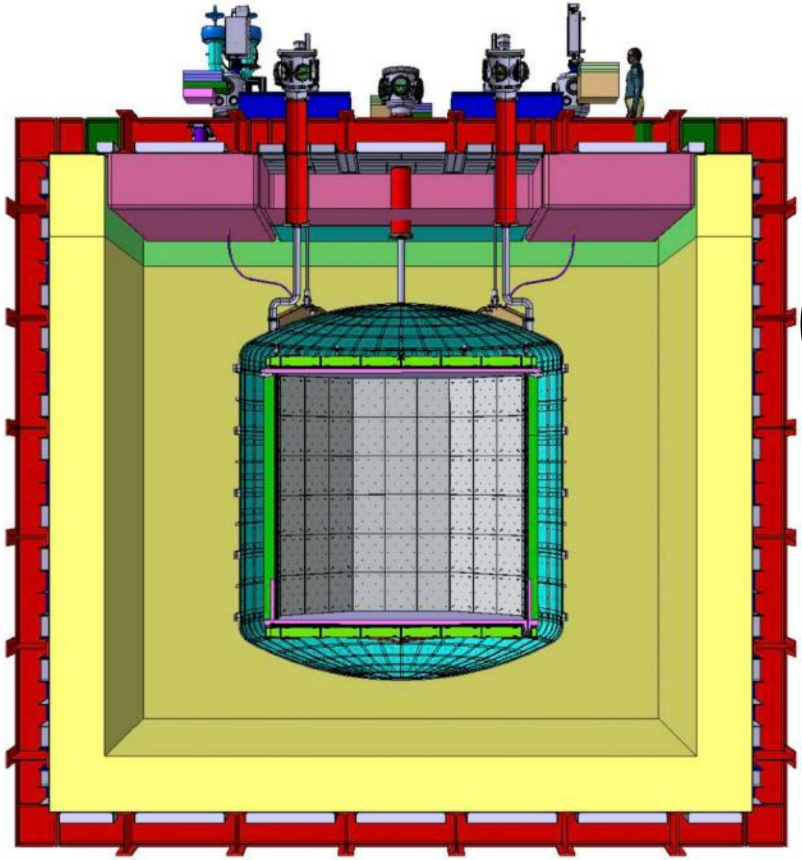
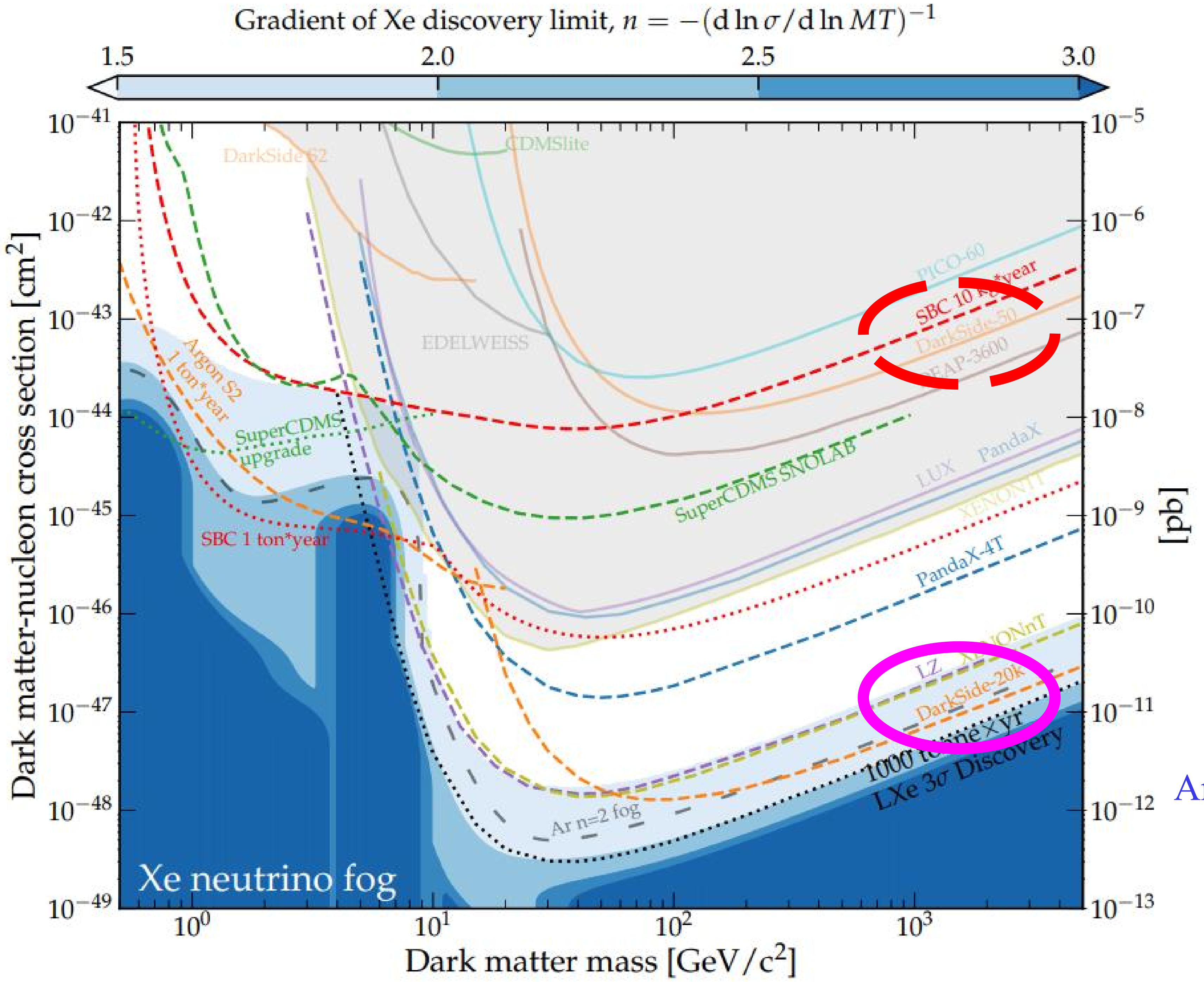


Andrea Maransciulli's talk!



DarkSide-20k will be the first argon detector actually entering the neutrino fog!

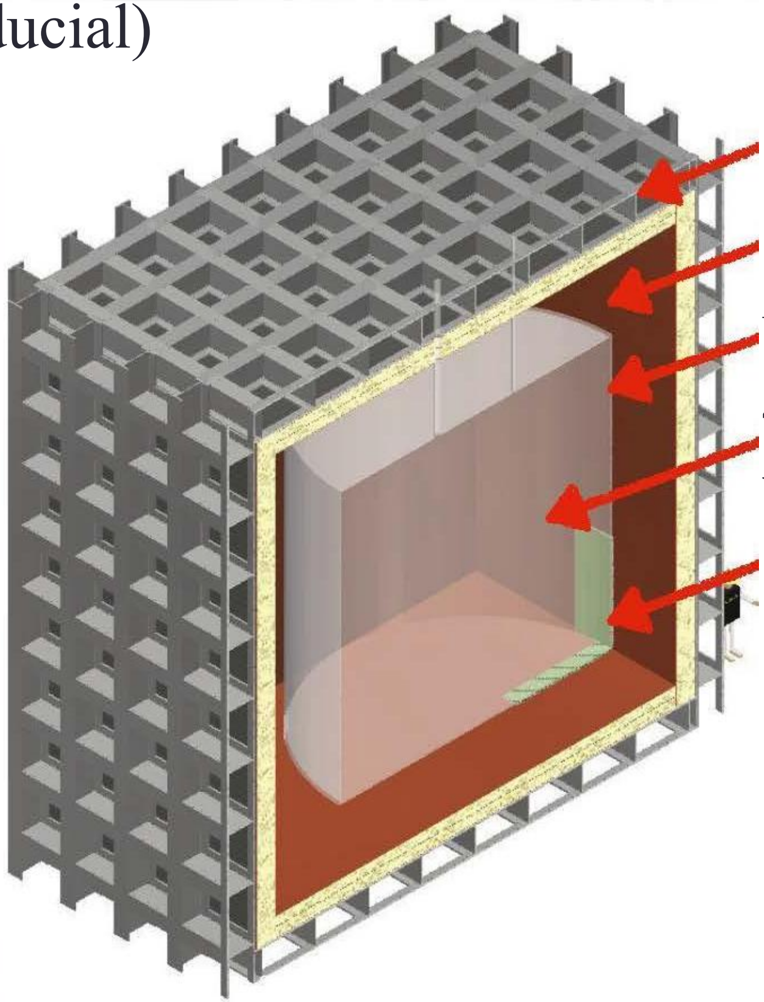
With 20 tonnes x 10 years:

- Instrumental background: < 0.1 neutrons in RoI (30~200 keV_{NR})
- 90% C.L. exclusion: 6.3×10^{-48} cm^2 at 1 TeV/c^2

ArXiv 2203.08084

ARGO will be the ultimate experiment from GADMC

- UAr Mass target: 400 tonnes (300 fiducial)
- SiPMs arranged as photon-to-digital converters (PDCs)
- 5 x 10^3 PE/m^2 x s during operations
- 1 x 10^5 PE/^{2} x s during calibrations

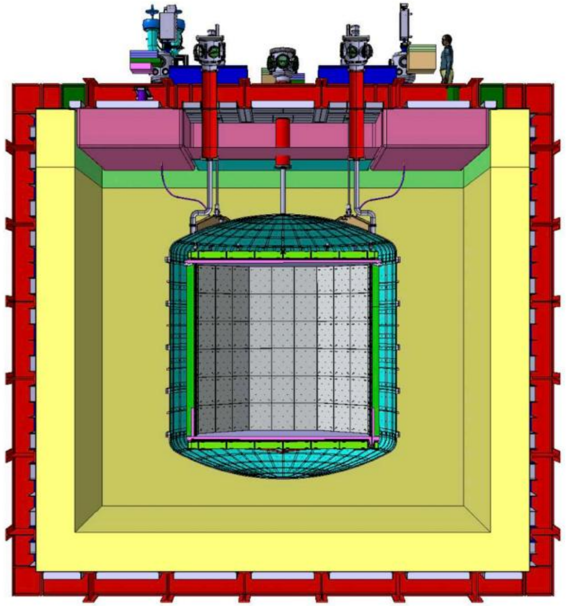


Currently performing detailed background calculations to refine concept.

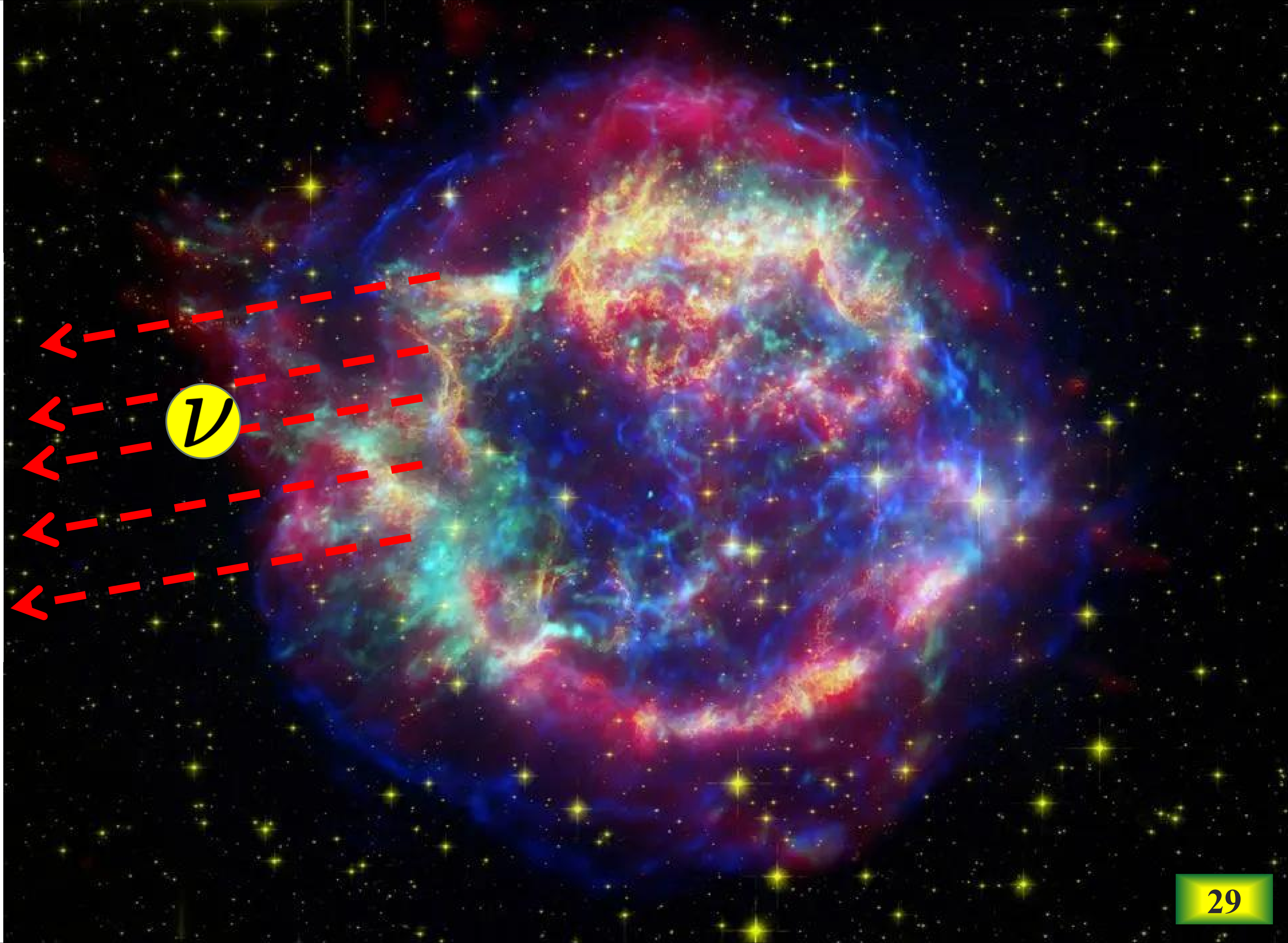
Need to determine if SNOLAB Cube Hall would allow adequate shielding

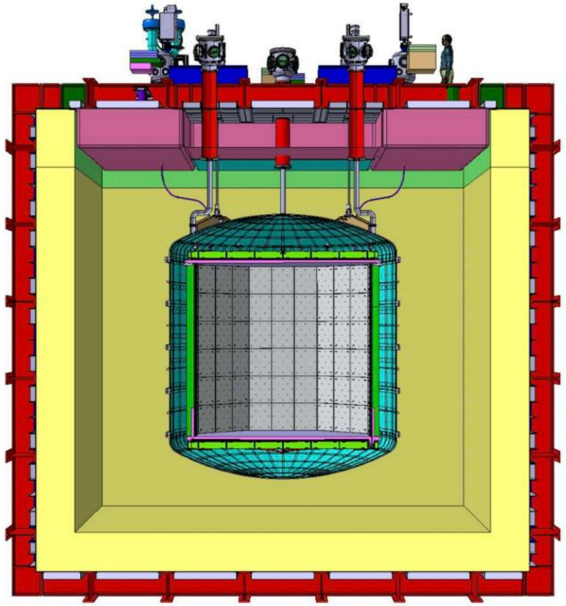
Aiming to complete the key features of its design in the early 2030's.

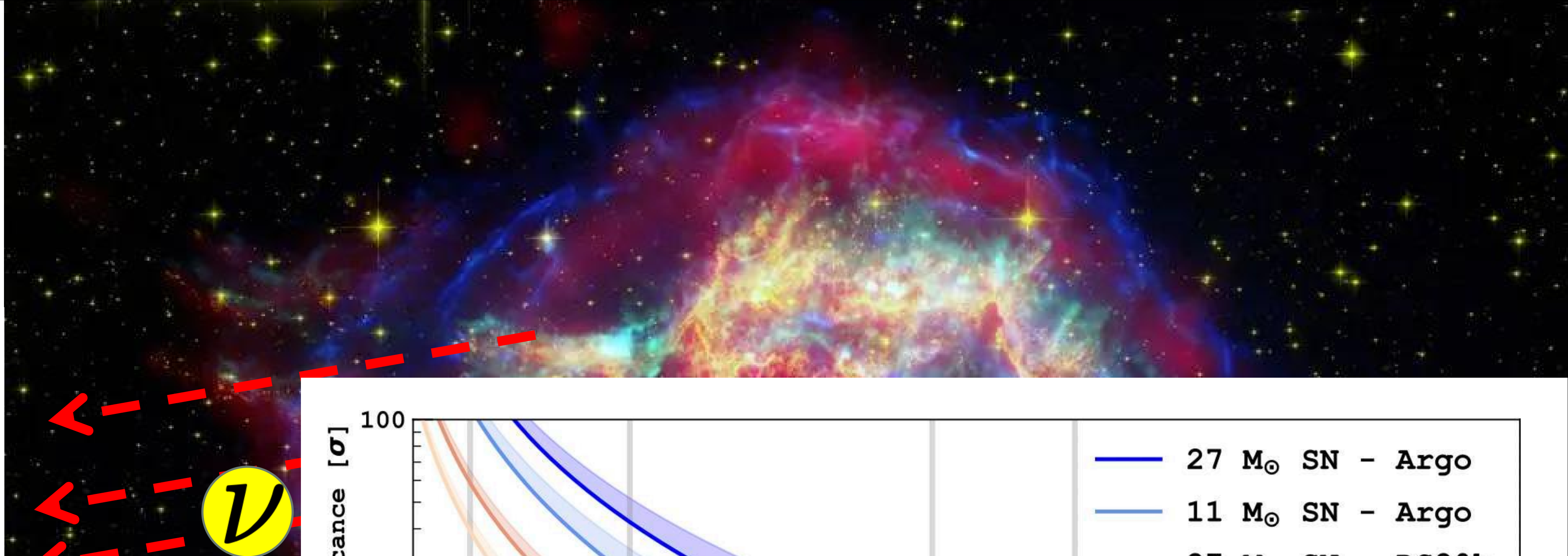
DARKSIDE

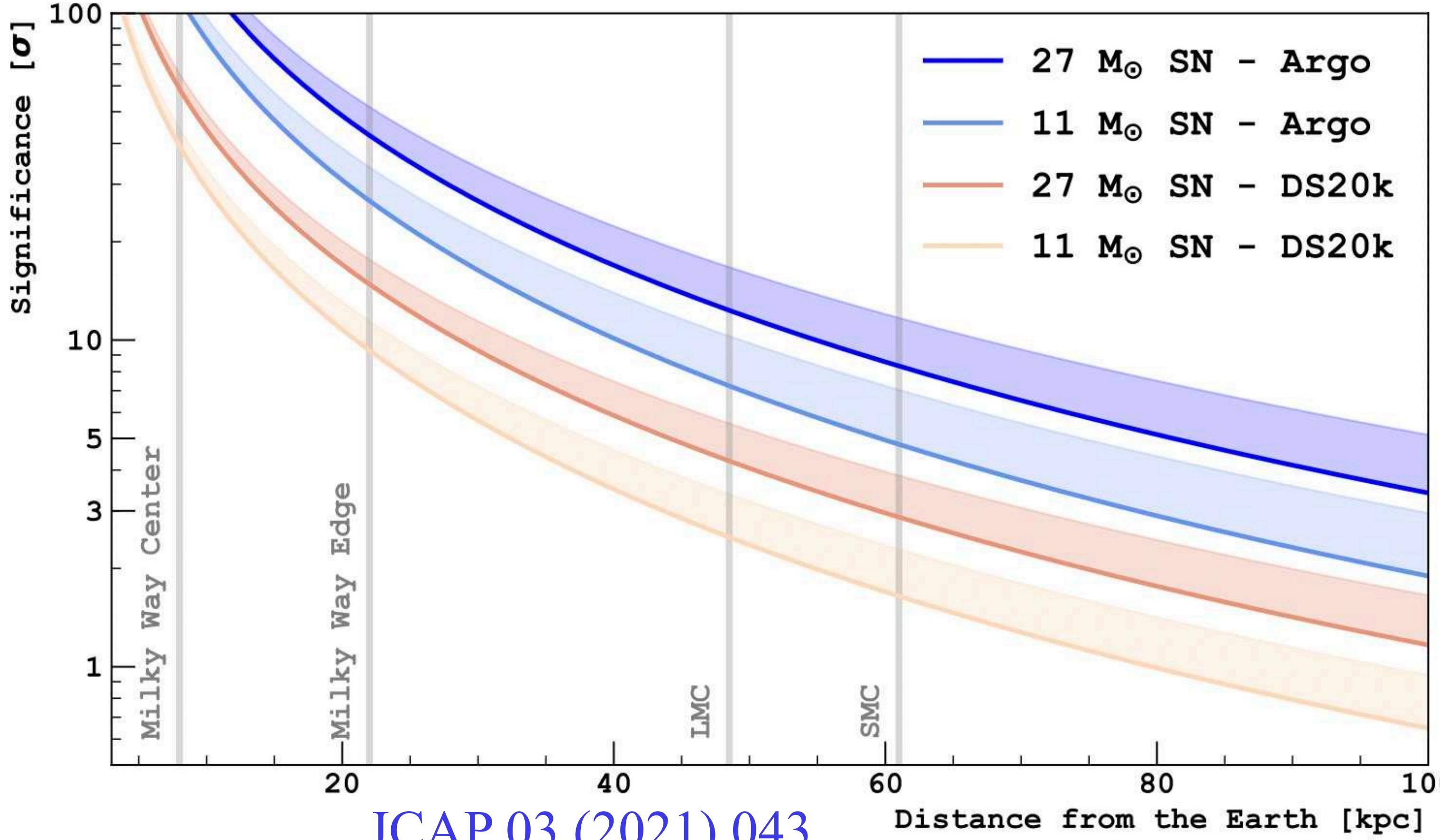


Sensitivity to core-collapse supernova neutrinos...



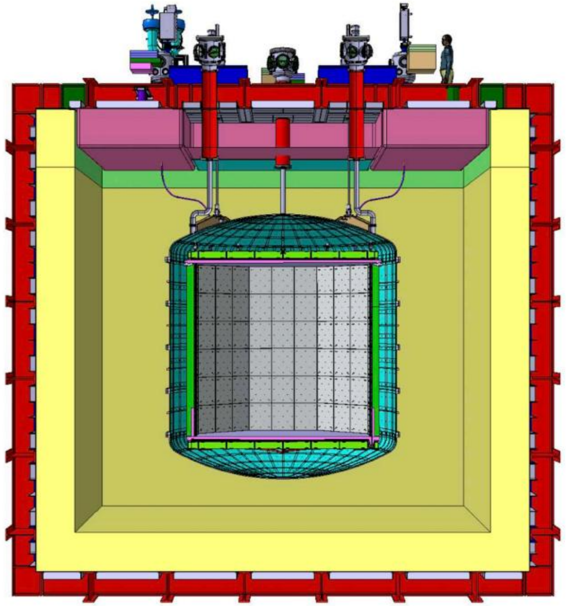




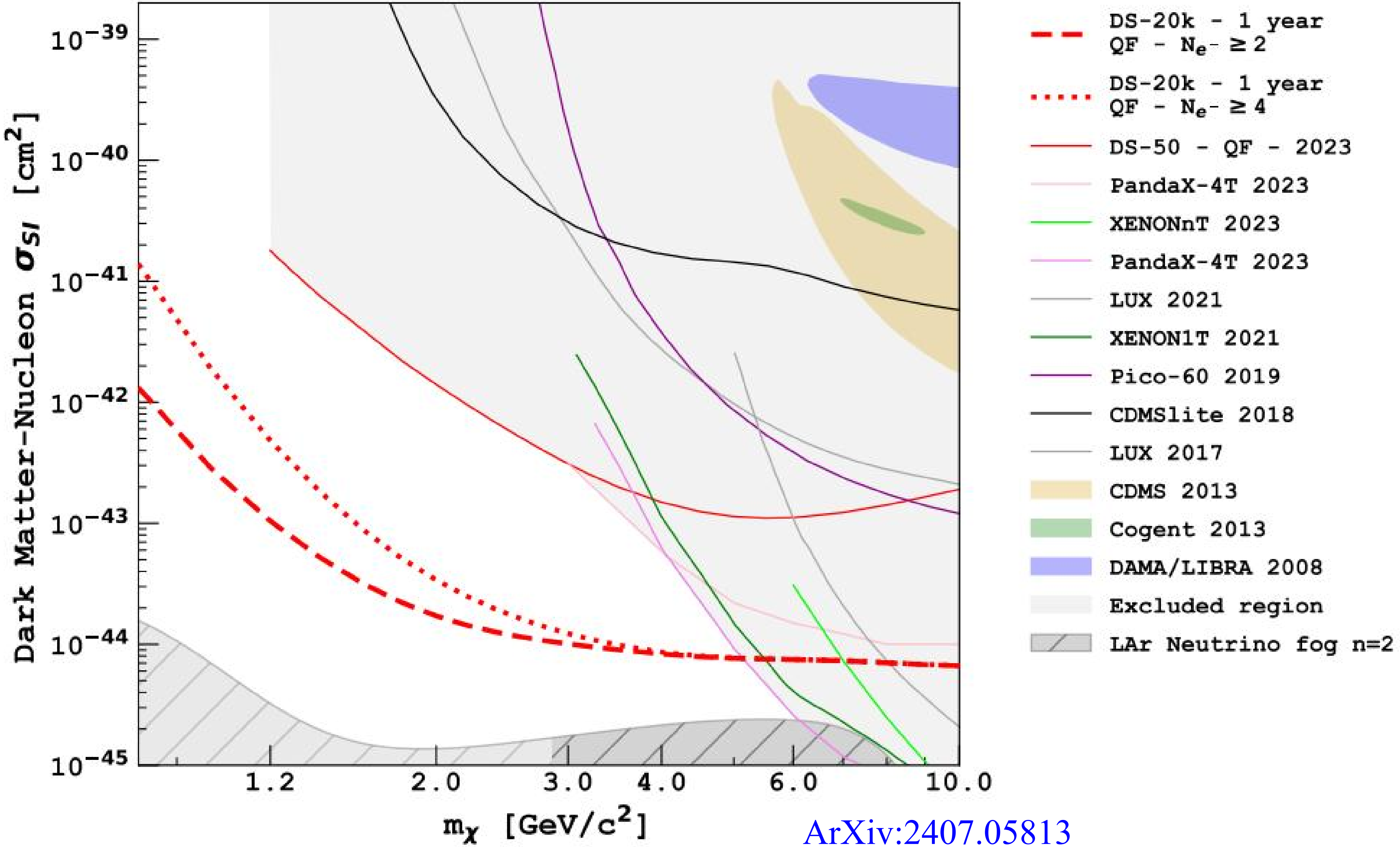


JCAP 03 (2021) 043

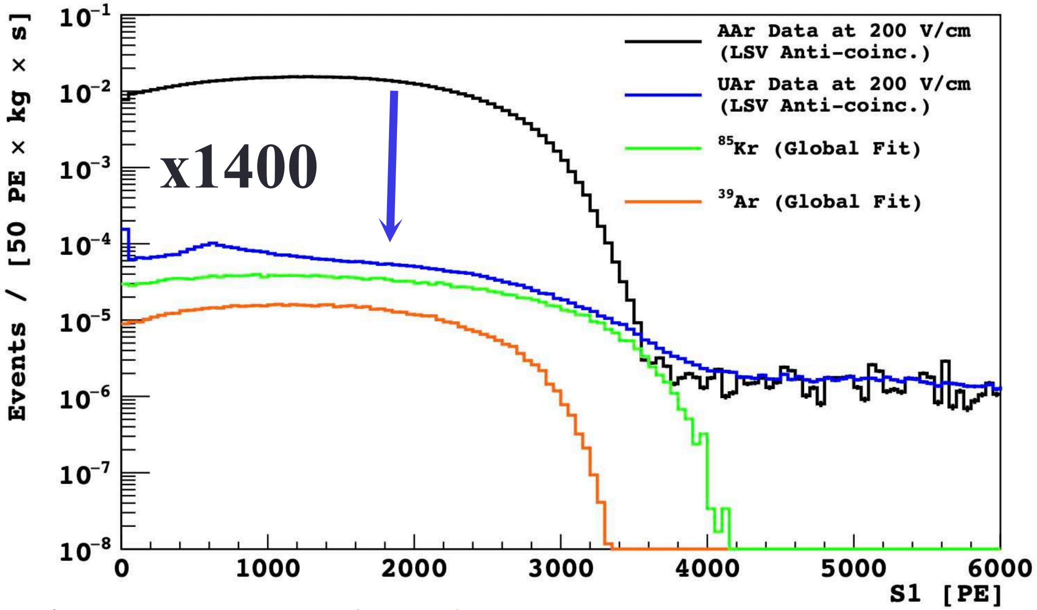
... up to the Large Magellanic Cloud...



... thanks to the Low-Mass dark matter search!

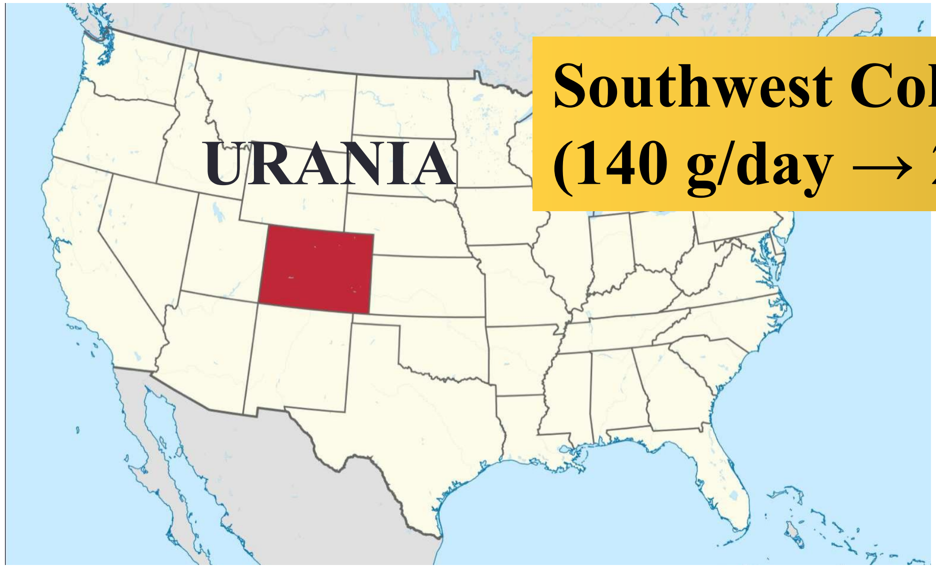


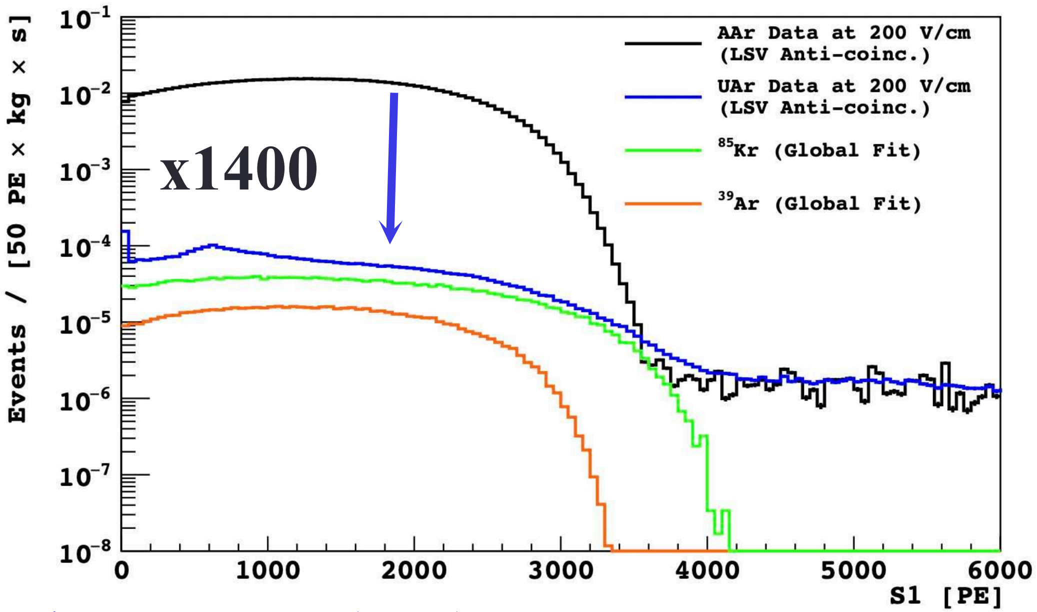
ArXiv:2407.05813



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

Southwest Colorado CO_2 wells (140 g/day → 250 kg/day)





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

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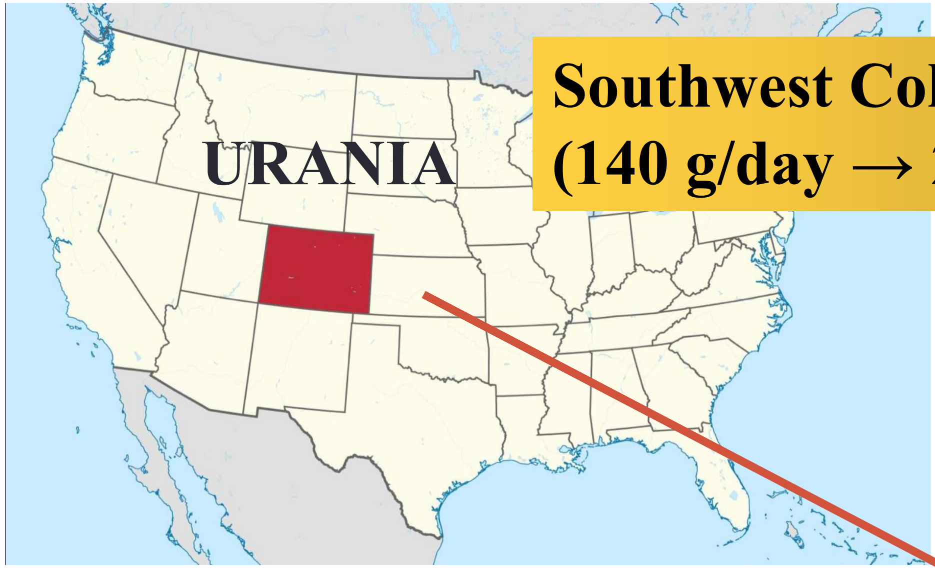

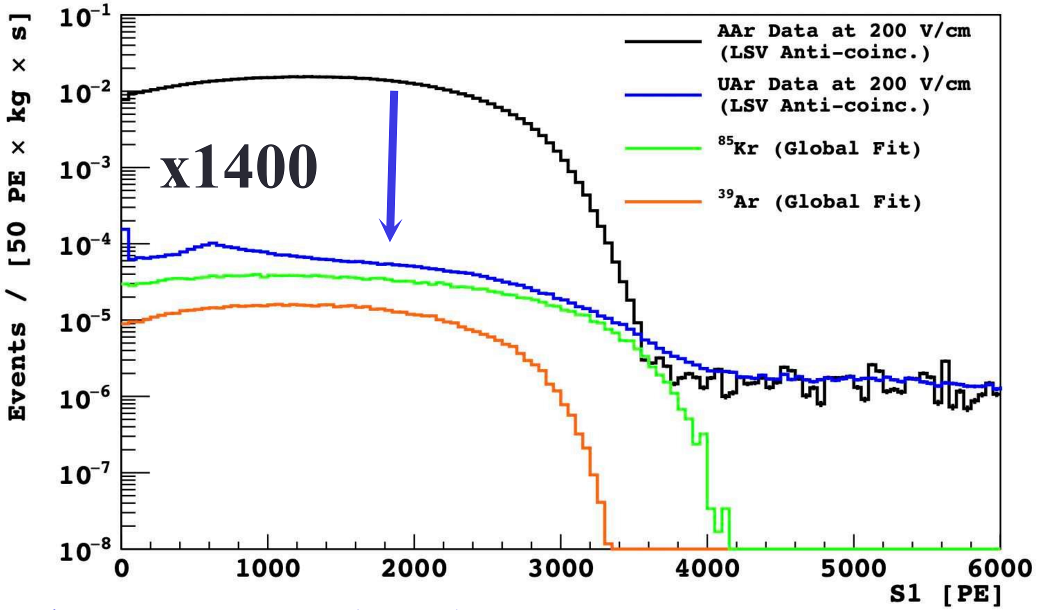

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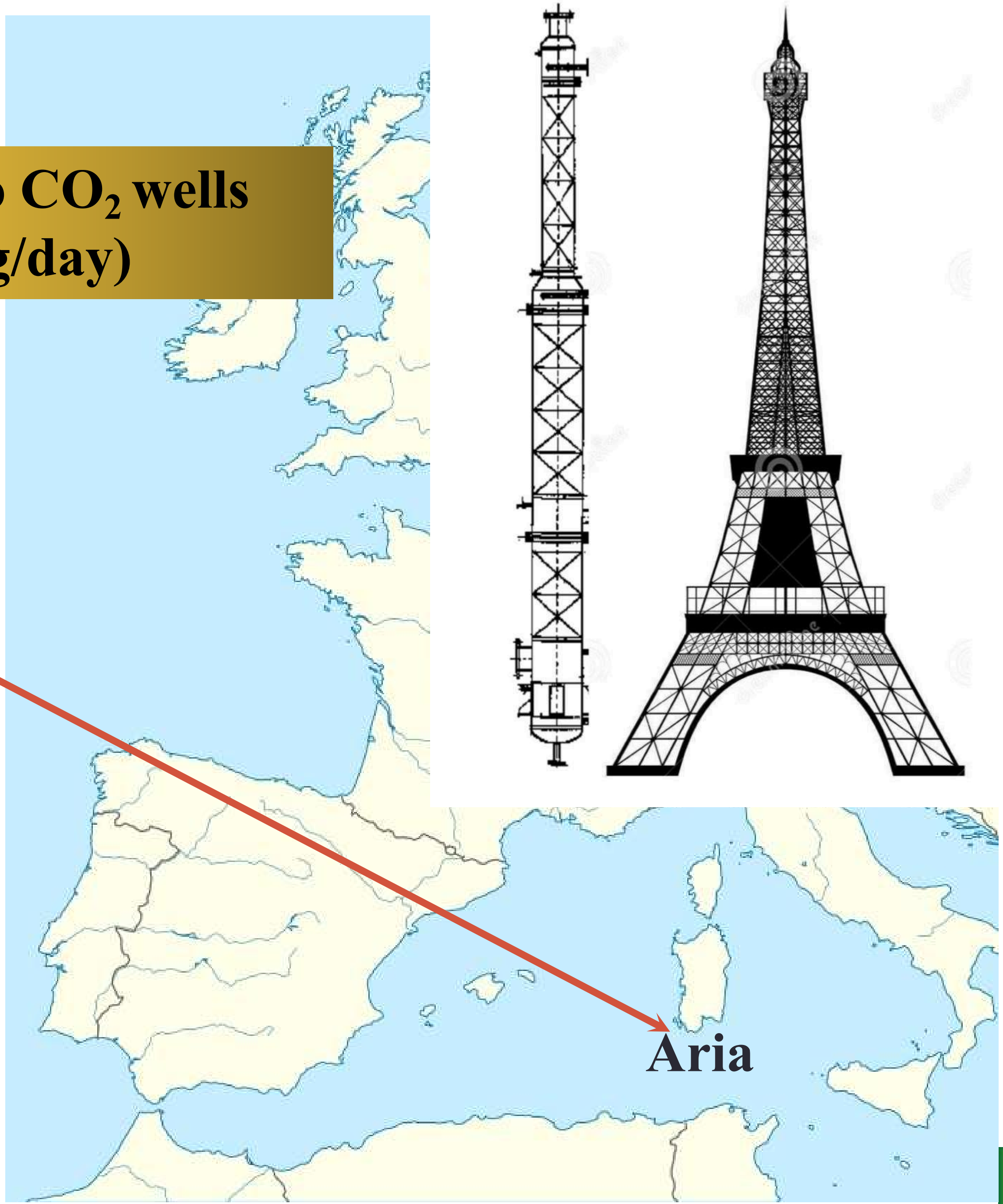

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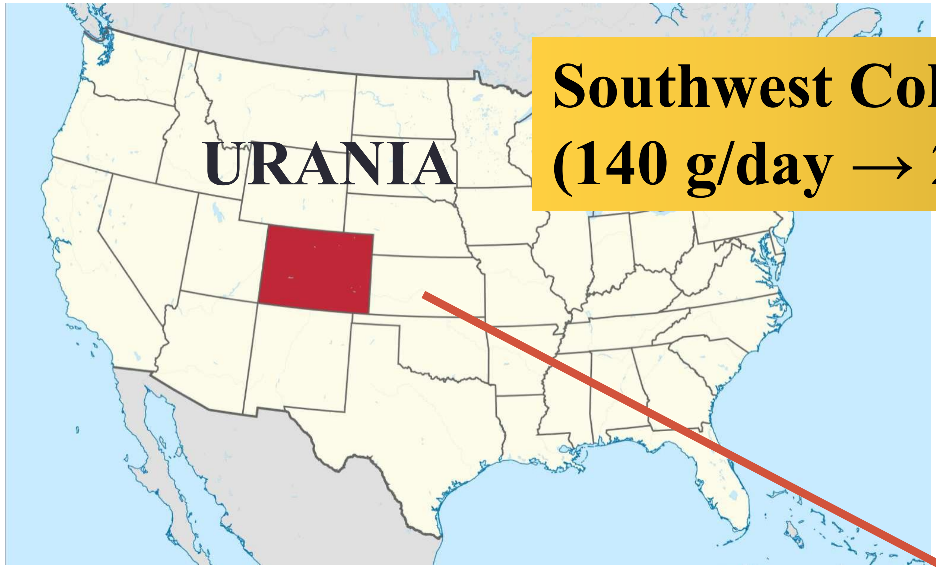

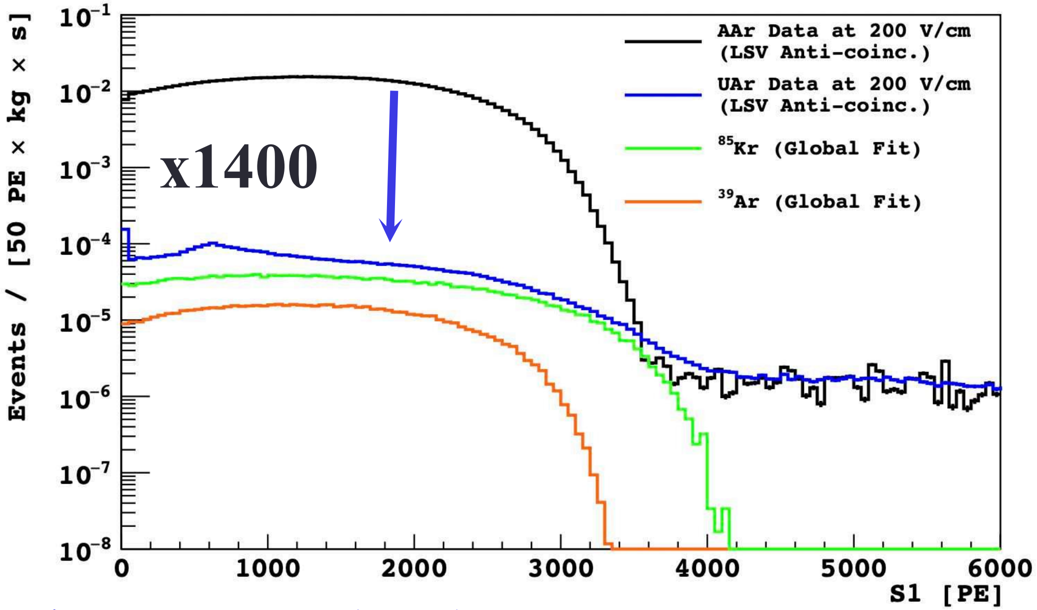

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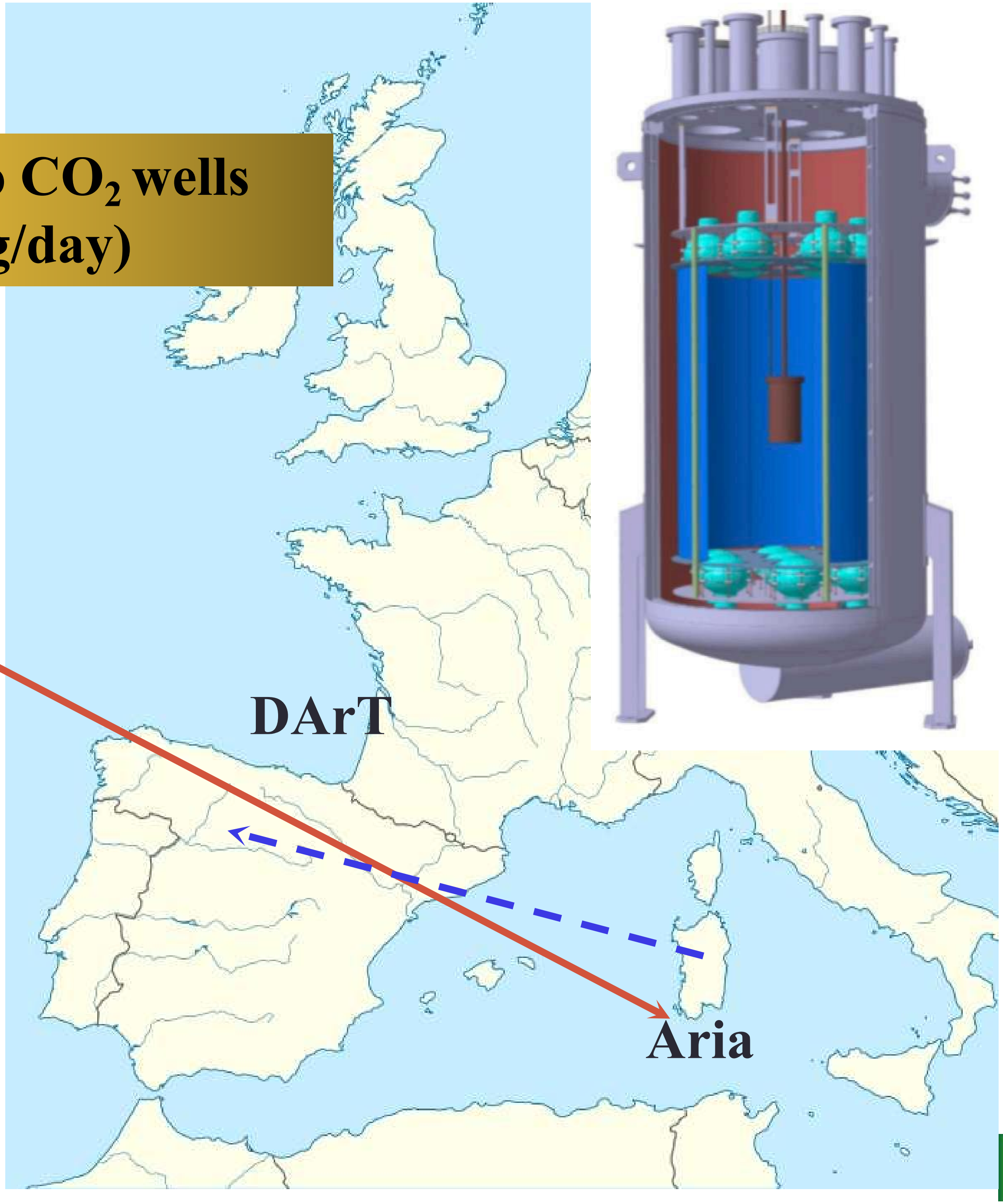

Vicente Pesudo’s talk!

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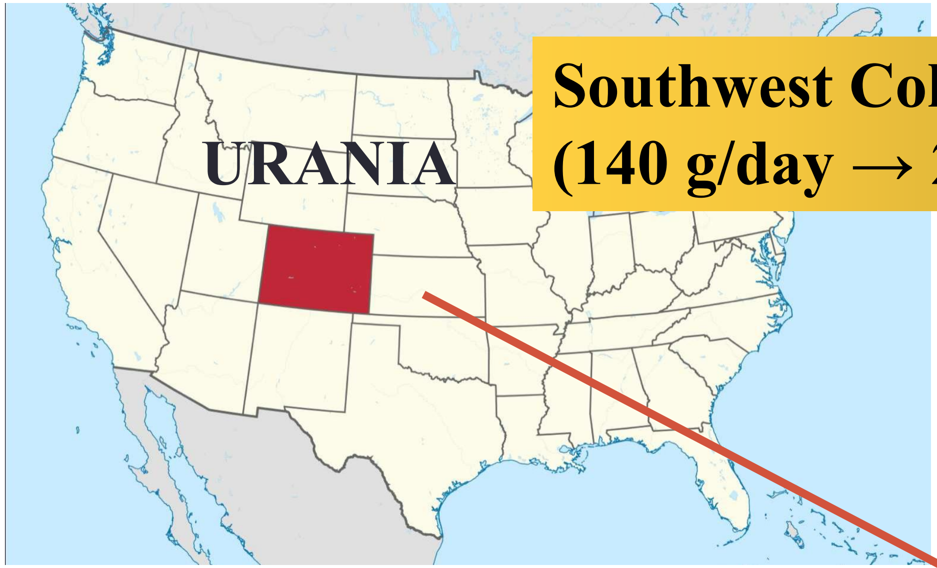

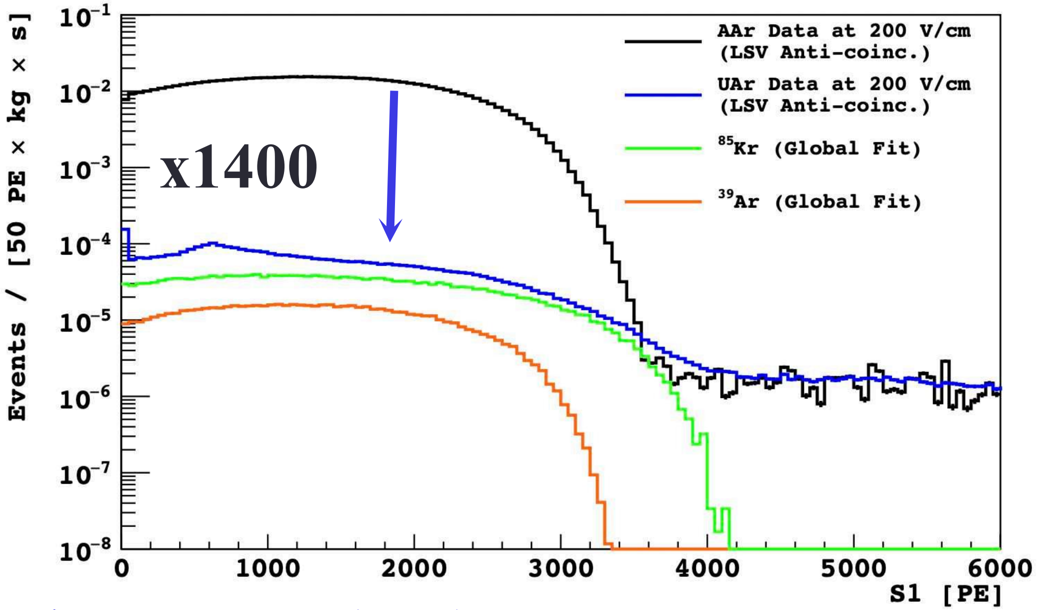

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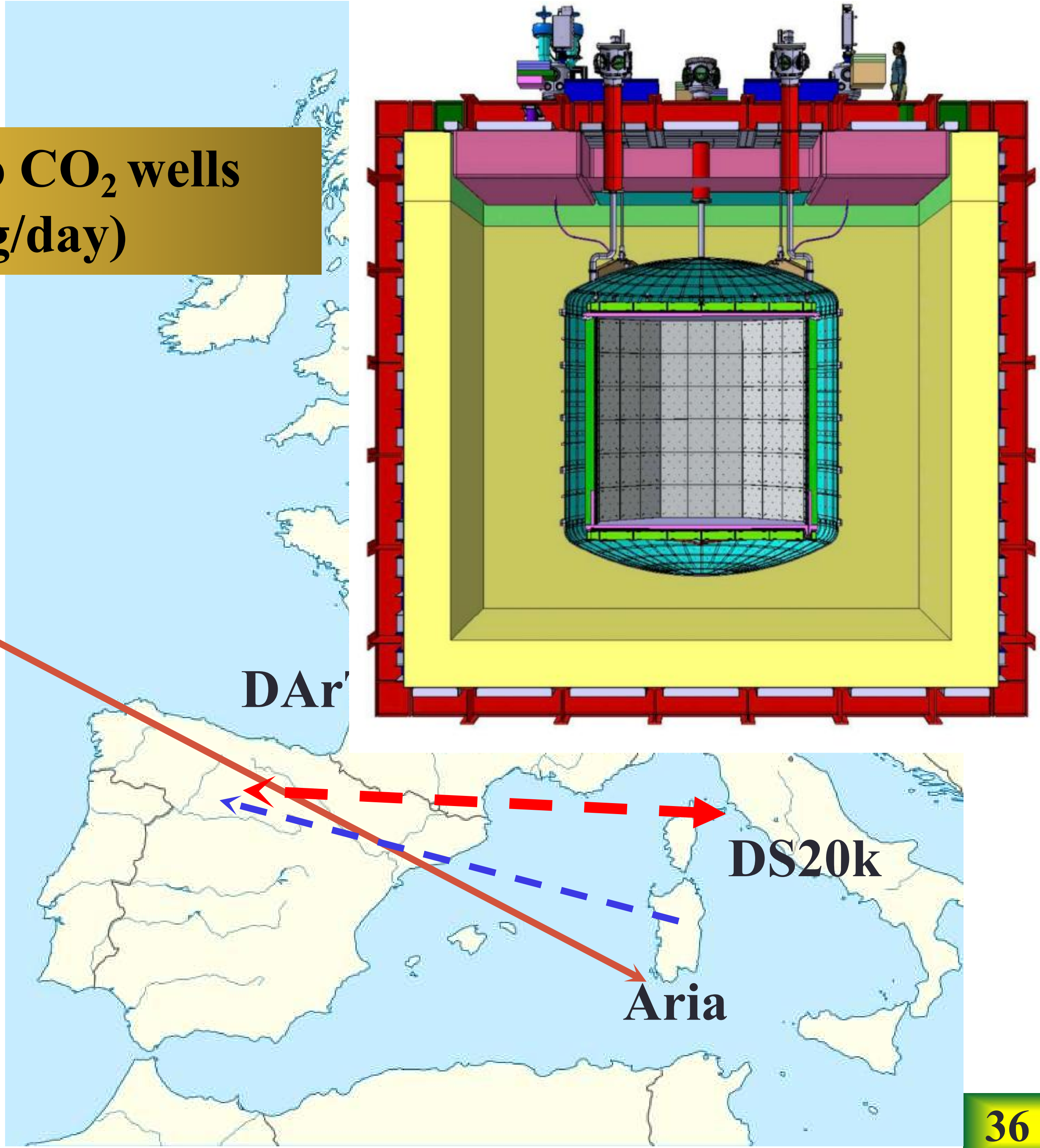

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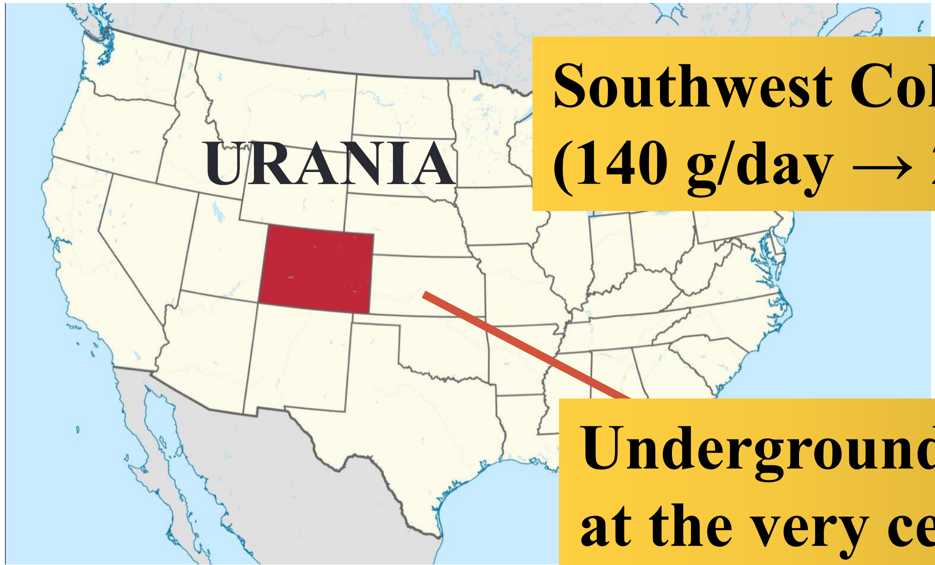

Southwest Colorado CO_2 wells
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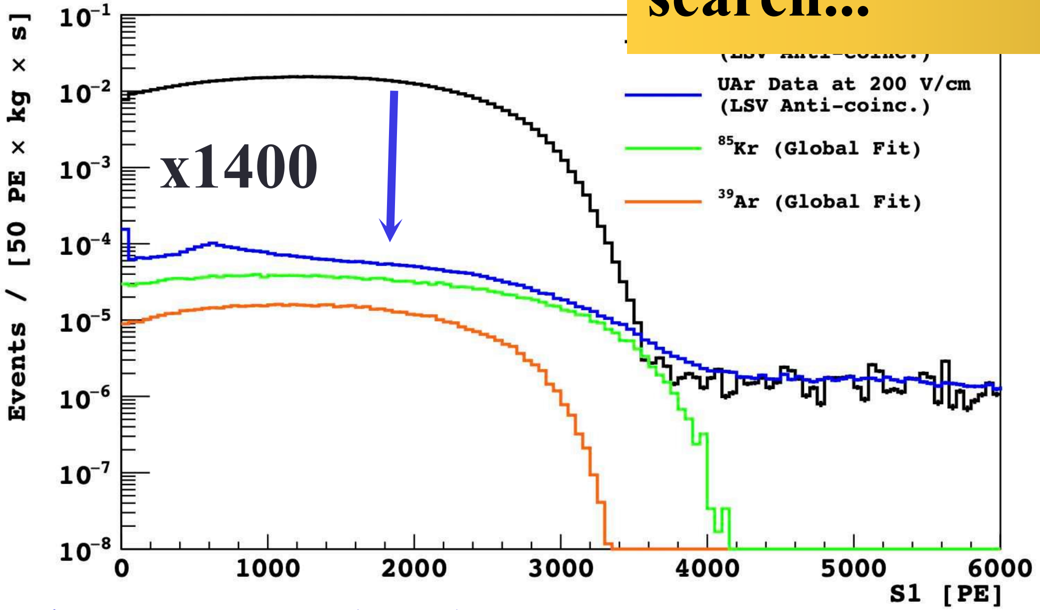
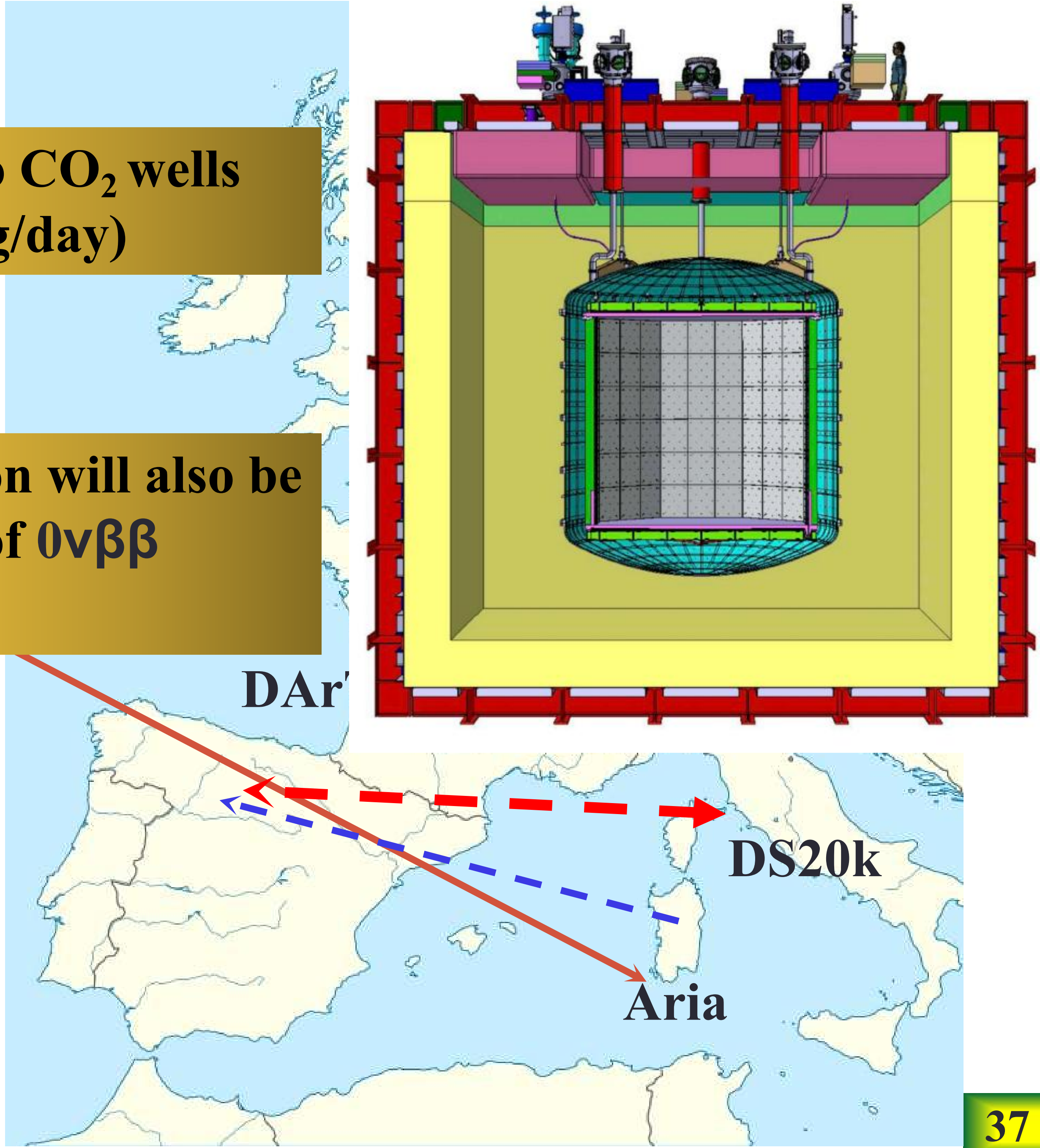
Underground Argon will also be at the very center of 0νββ search...



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



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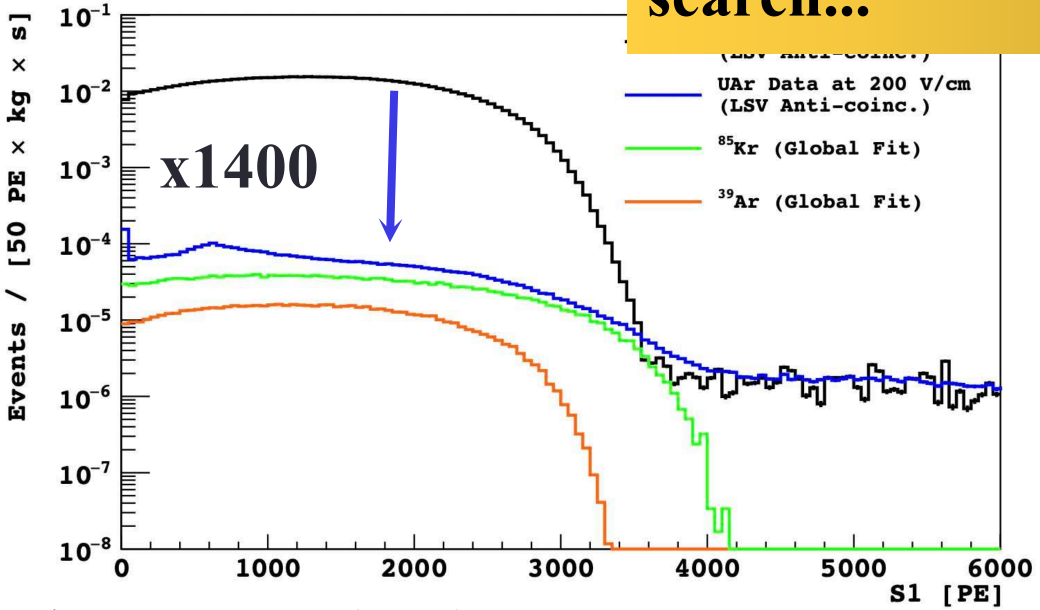

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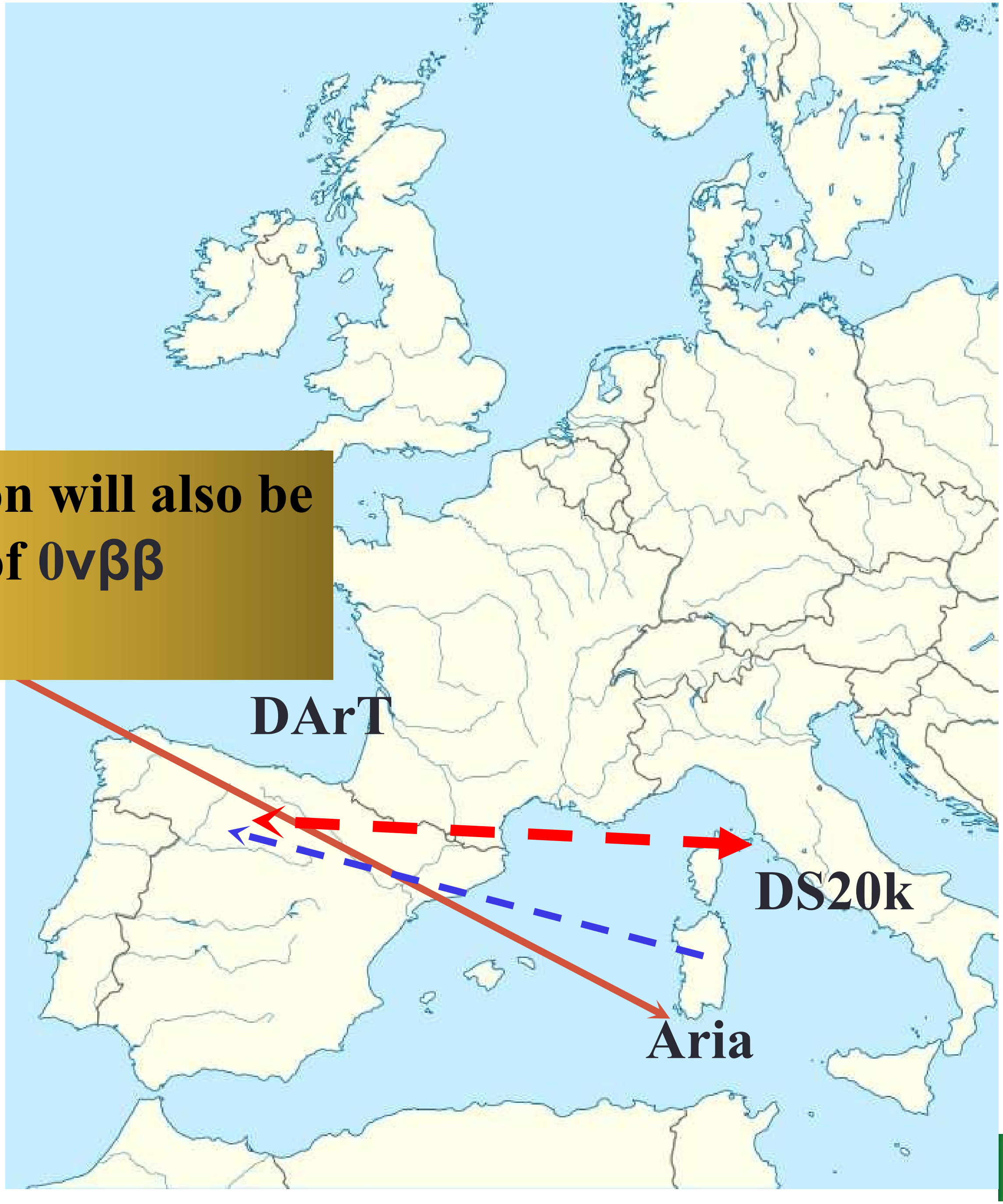

Majorana neutrino mass

Matter-antimatter asymmetry

$$(Z, A) \rightarrow (Z+2, A) + 2e + 2\bar{\nu} + Q_{\beta\beta}$$

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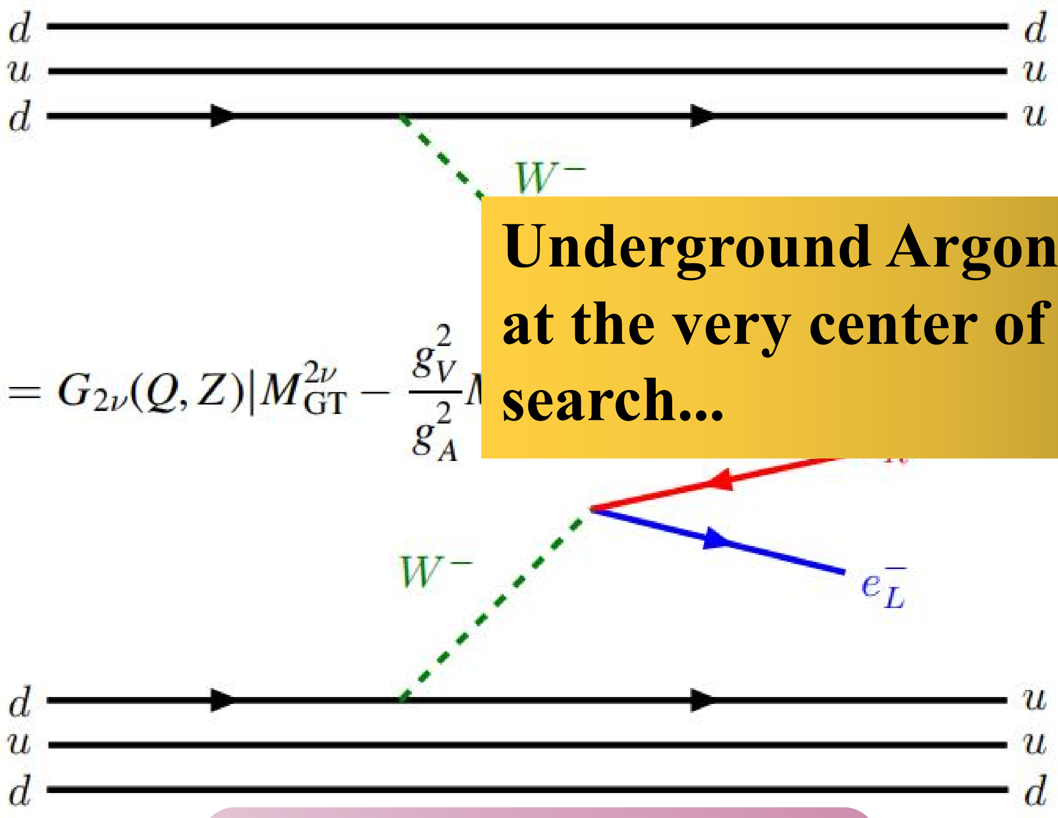

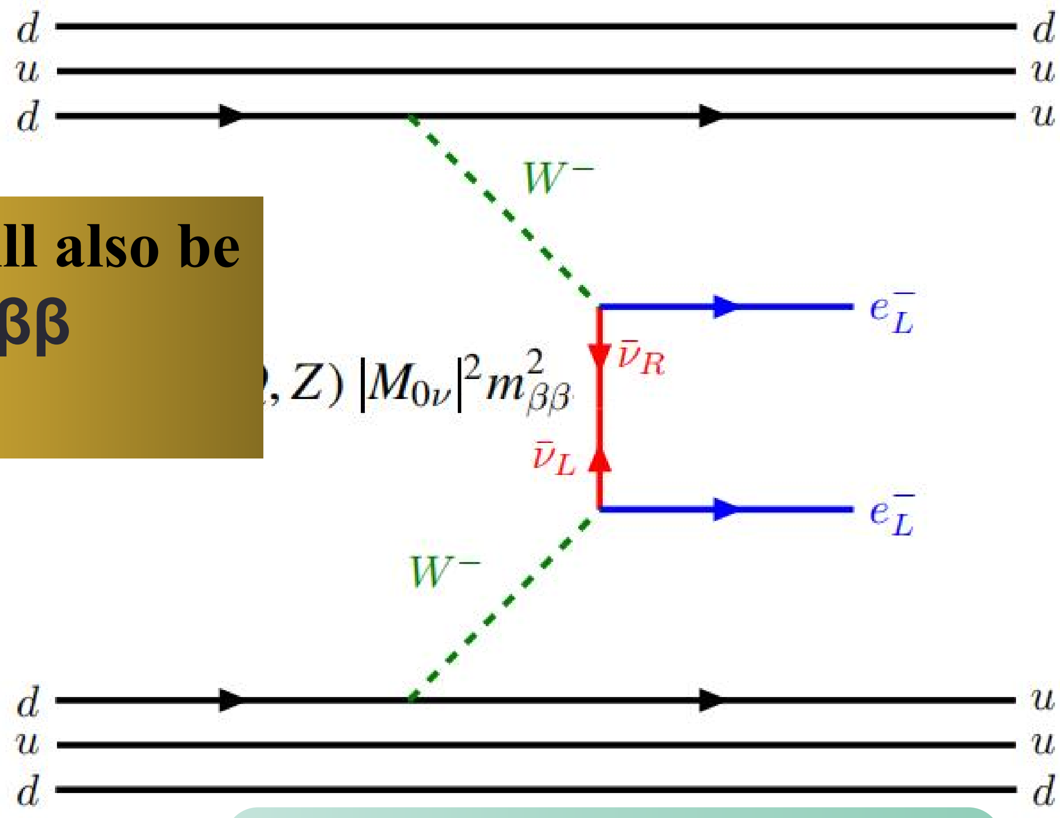

$$[T^{2\nu}_{1/2}]^{-1} = G_{2\nu}(Q,Z)|M^{2\nu}_{GT} - \frac{g_V^2}{g_A^2} M$$

$$, Z)\,|M_{0\nu}|^2 m^2_{\beta\beta}$$

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First observation $\Delta L \neq 0$

Neutrino Mass ordering

Majorana neutrino mass

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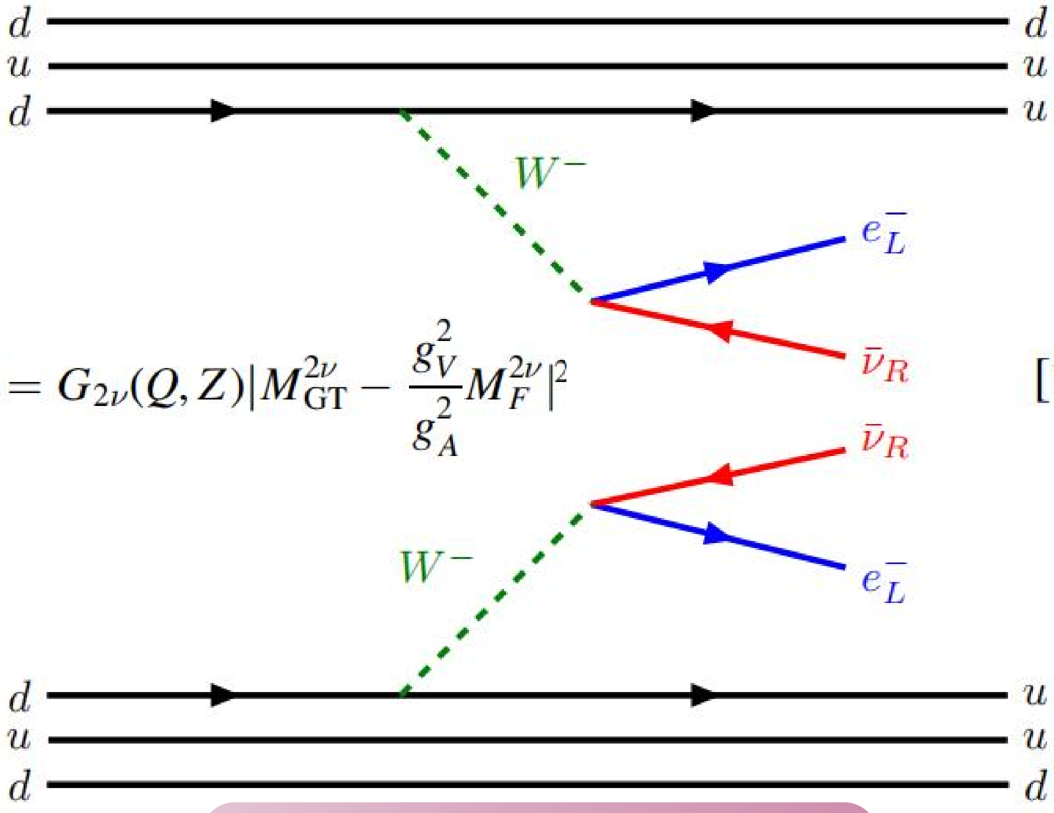
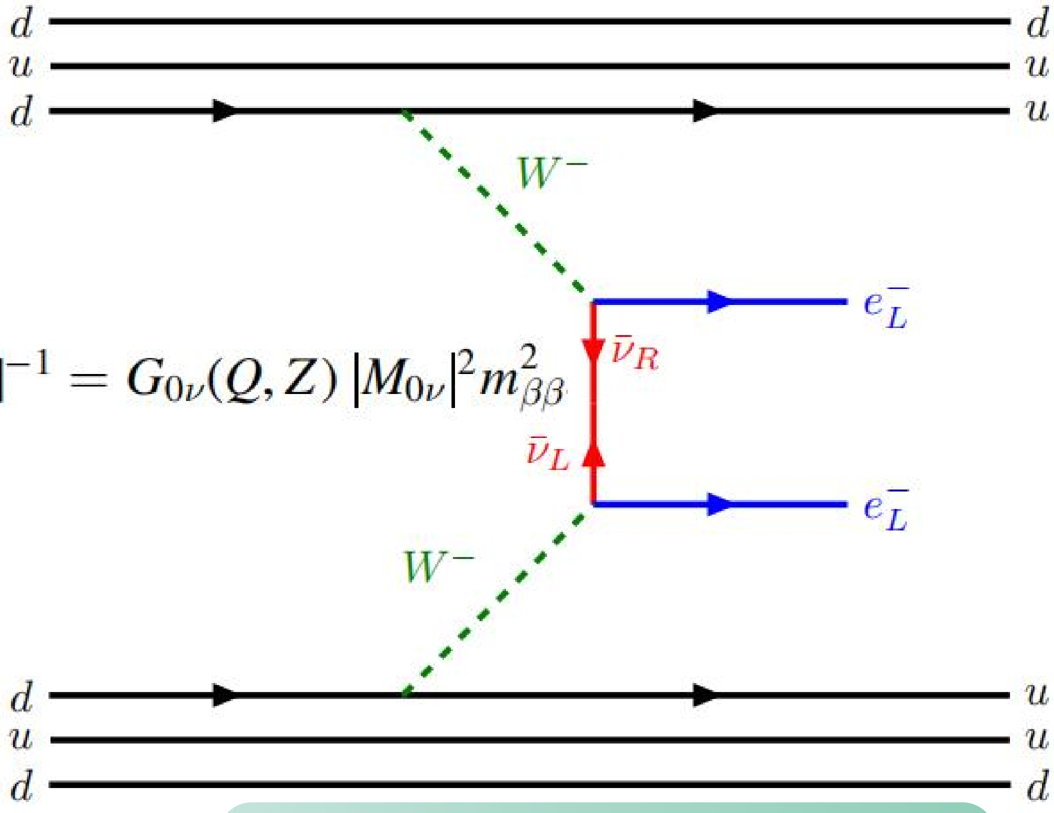


$$[T_{1/2}^{2\nu}]^{-1} = G_{2\nu}(Q, Z)|M_{GT}^{2\nu} - \frac{g_V^2}{g_A^2} M_F^{2\nu}|^2$$



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Neutrino Mass ordering

^{76}Ge is one of the most appealing isotopes for the 0νββ

Isotope	Natural Abundance (%)	$Q_{\beta\beta}$ (MeV)	$T_{1/2}^{2\nu}$ (yr)
^{48}Ca	0.187	4.263	$5.3^{+1.2}_{-0.8} \times 10^{19}$
^{76}Ge	7.8	2.039	$(1.88 \pm 0.08) \times 10^{21}$
^{82}Se	9.2	2.998	$0.87^{+0.02}_{-0.01} \times 10^{20}$
^{96}Zr	2.8	3.348	$(2.3 \pm 0.2) \times 10^{19}$
^{100}Mo	9.6.	3.035	$7.06^{+0.15}_{-0.13} \times 10^{18}$
^{116}Cd	7.6	2.813	$(2.69 \pm 0.09) \times 10^{19}$
^{130}Te	34.08	2.527	$(7.91 \pm 0.21) \times 10^{20}$
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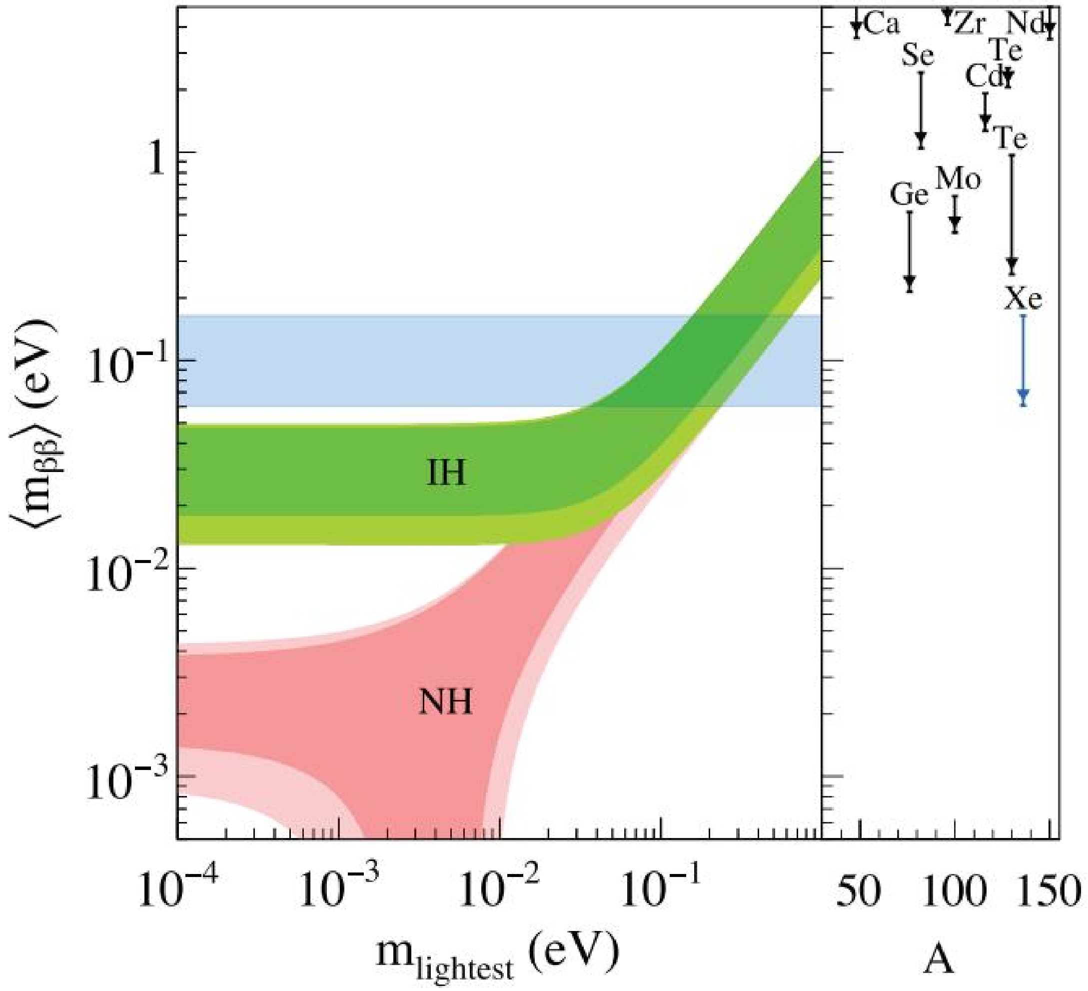

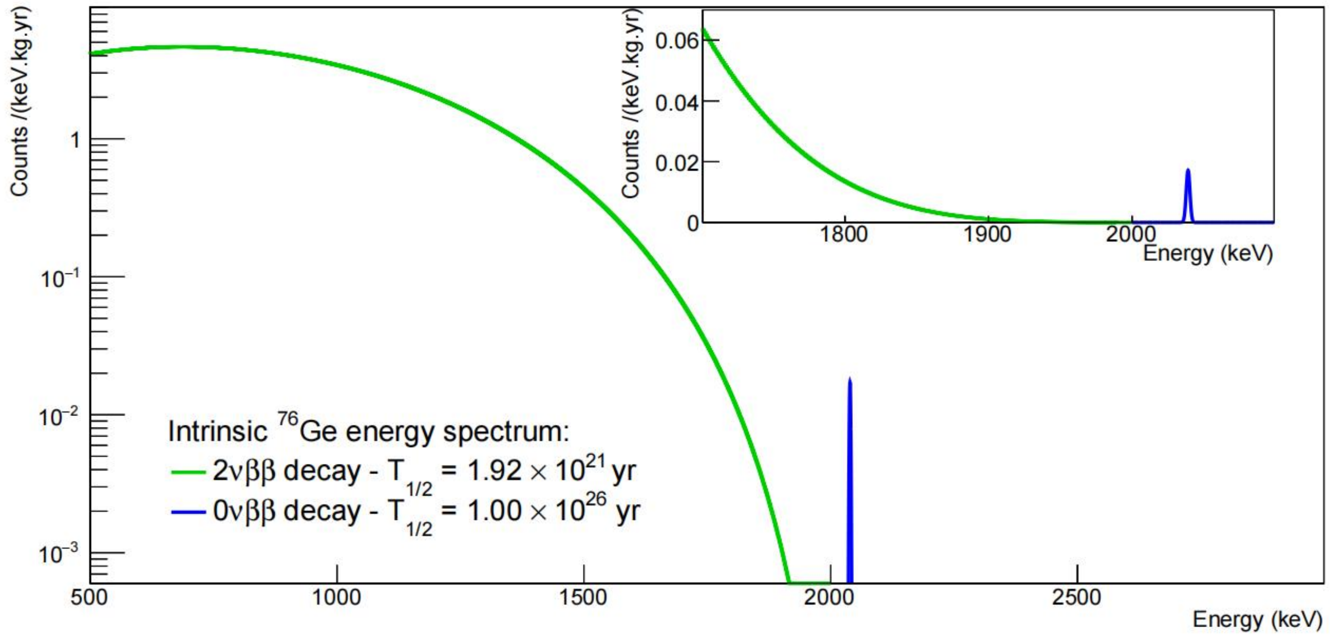

[Rep. Prog. Phys. **80** 046301 (2017)]

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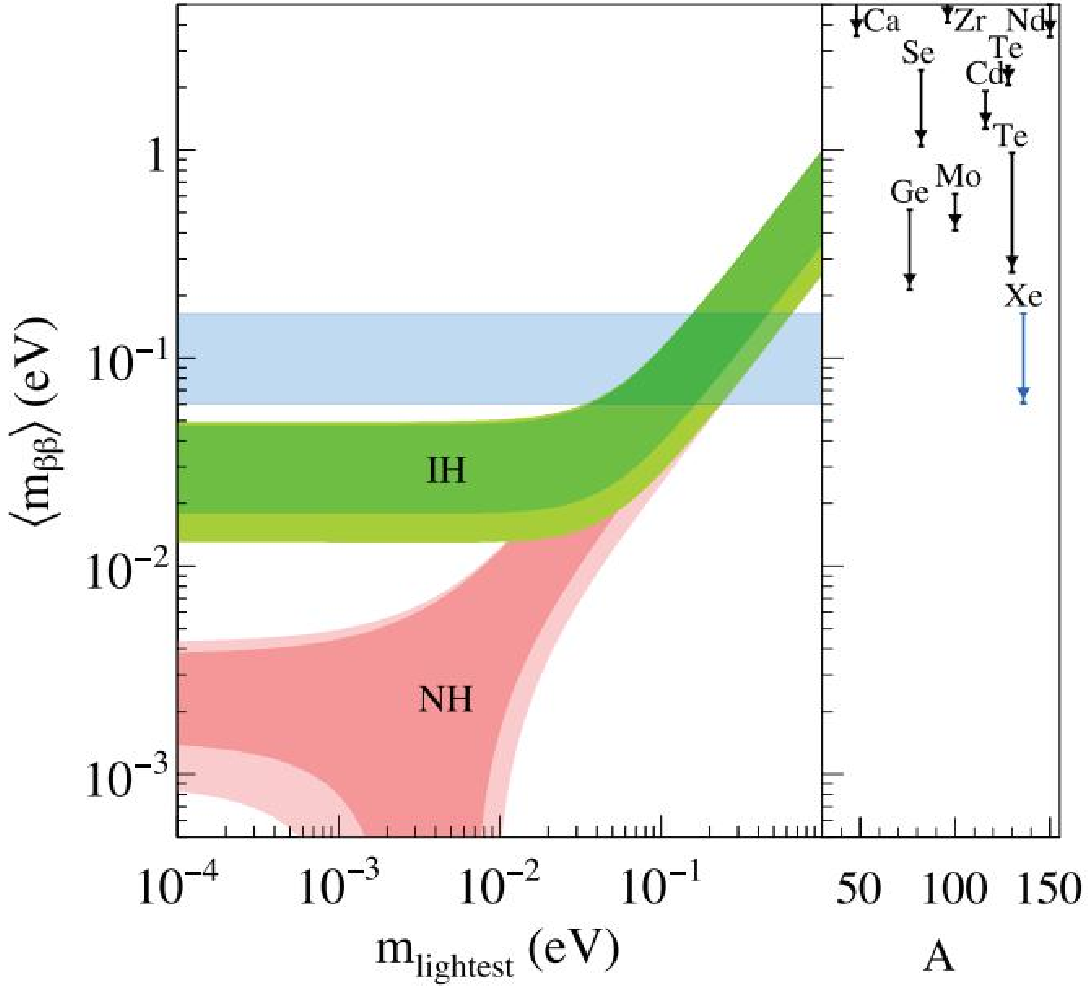

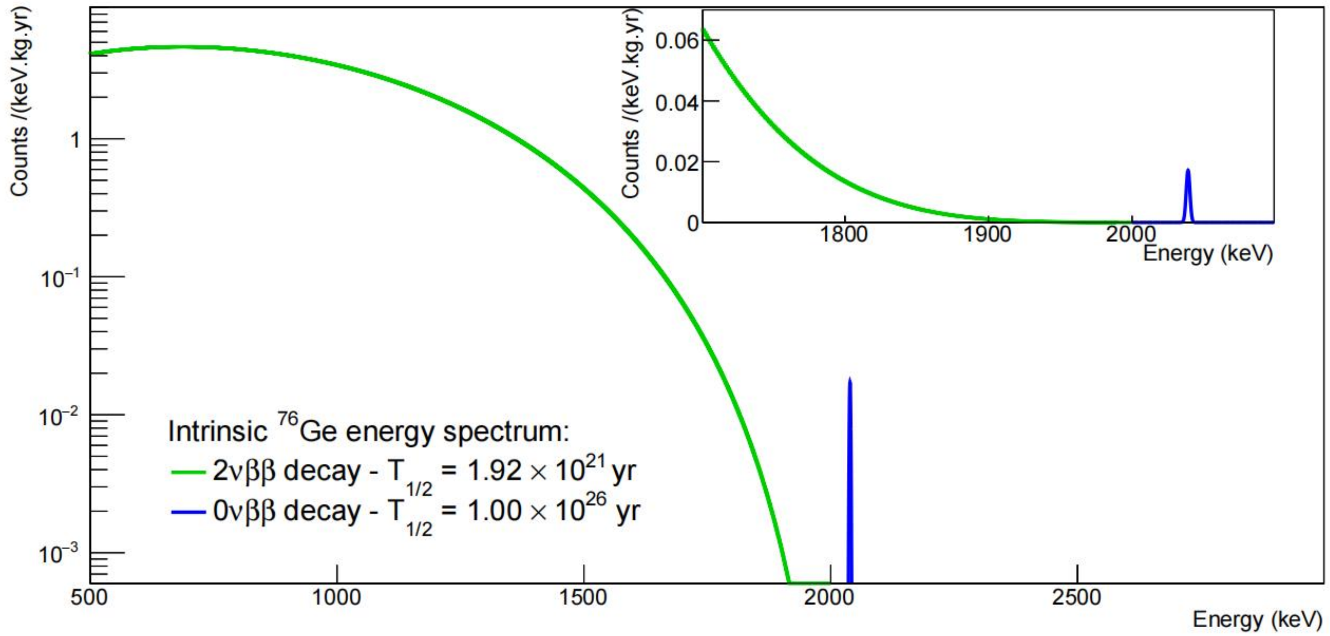

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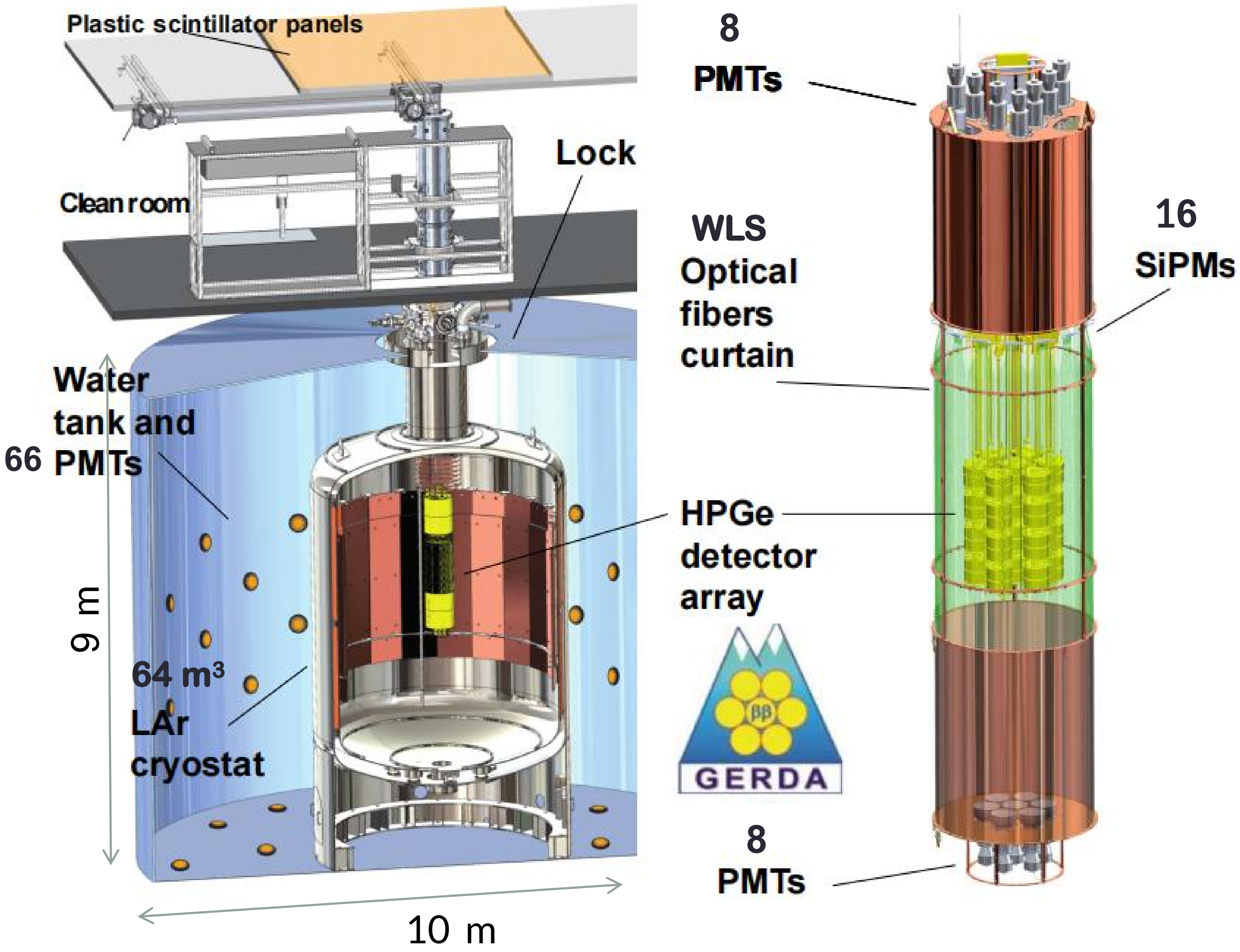
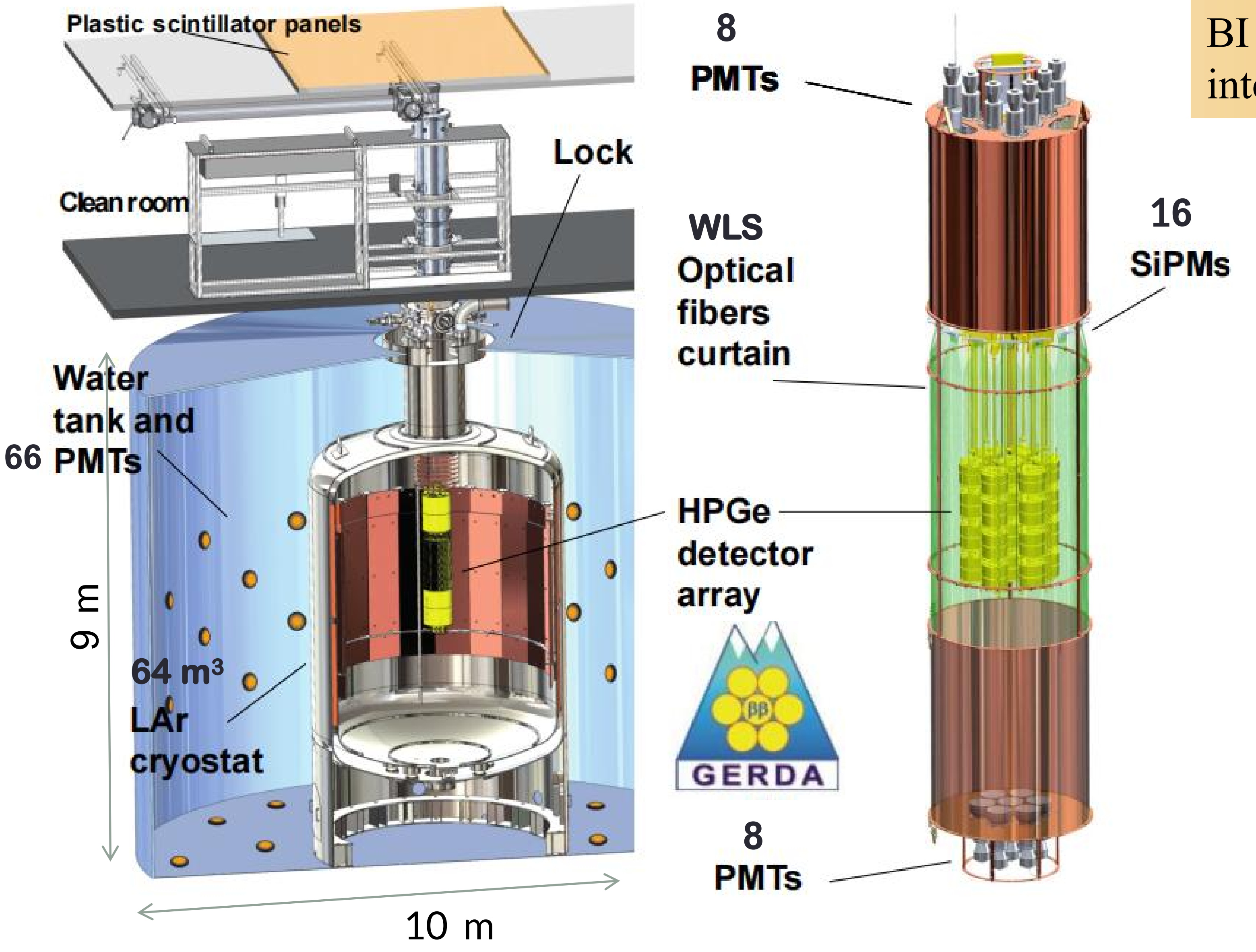


HPGe detectors enriched in ^{76}Ge enriched up to ~ 87%, set at LNGS

Universe 7 (2021) 9, 314



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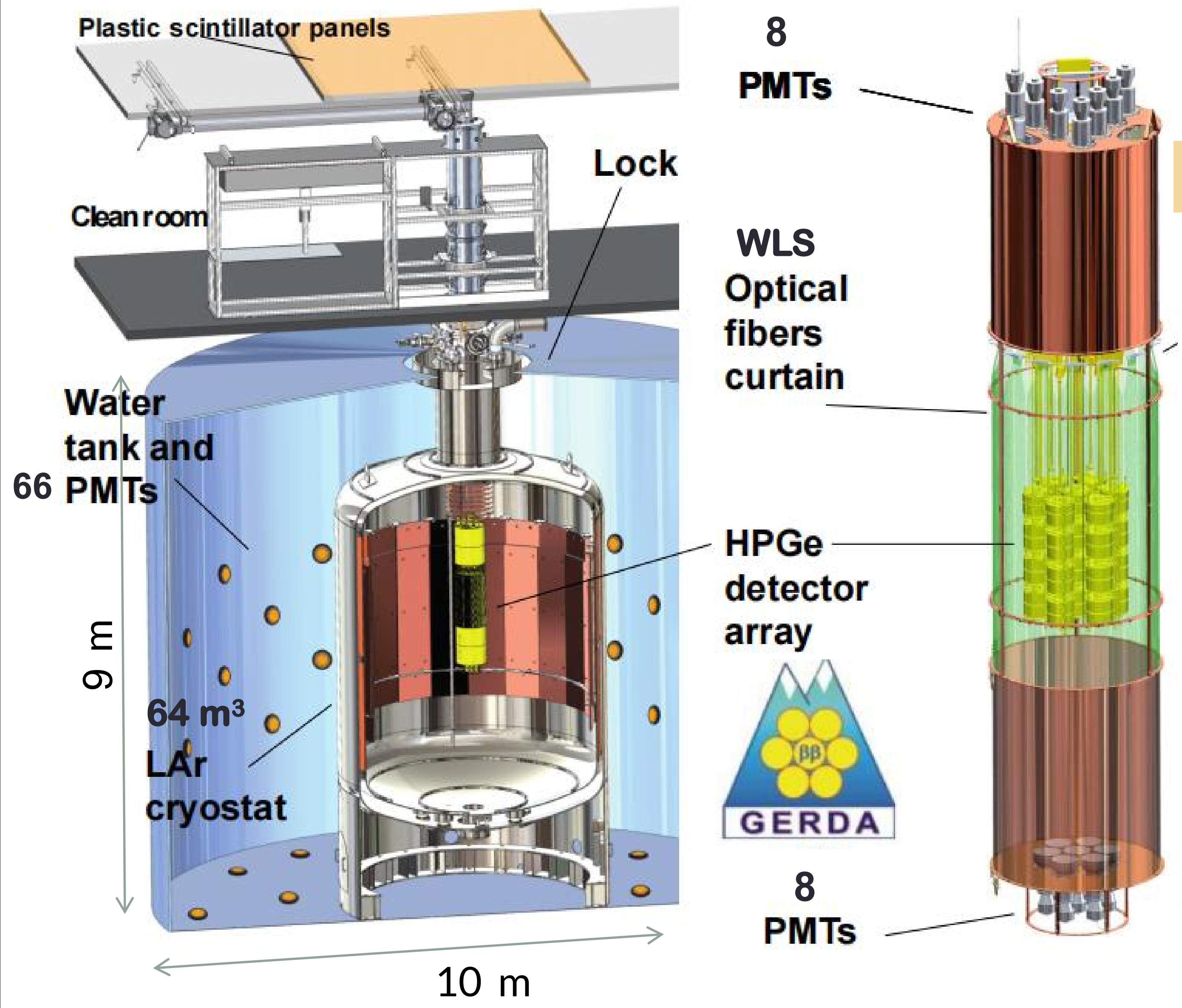

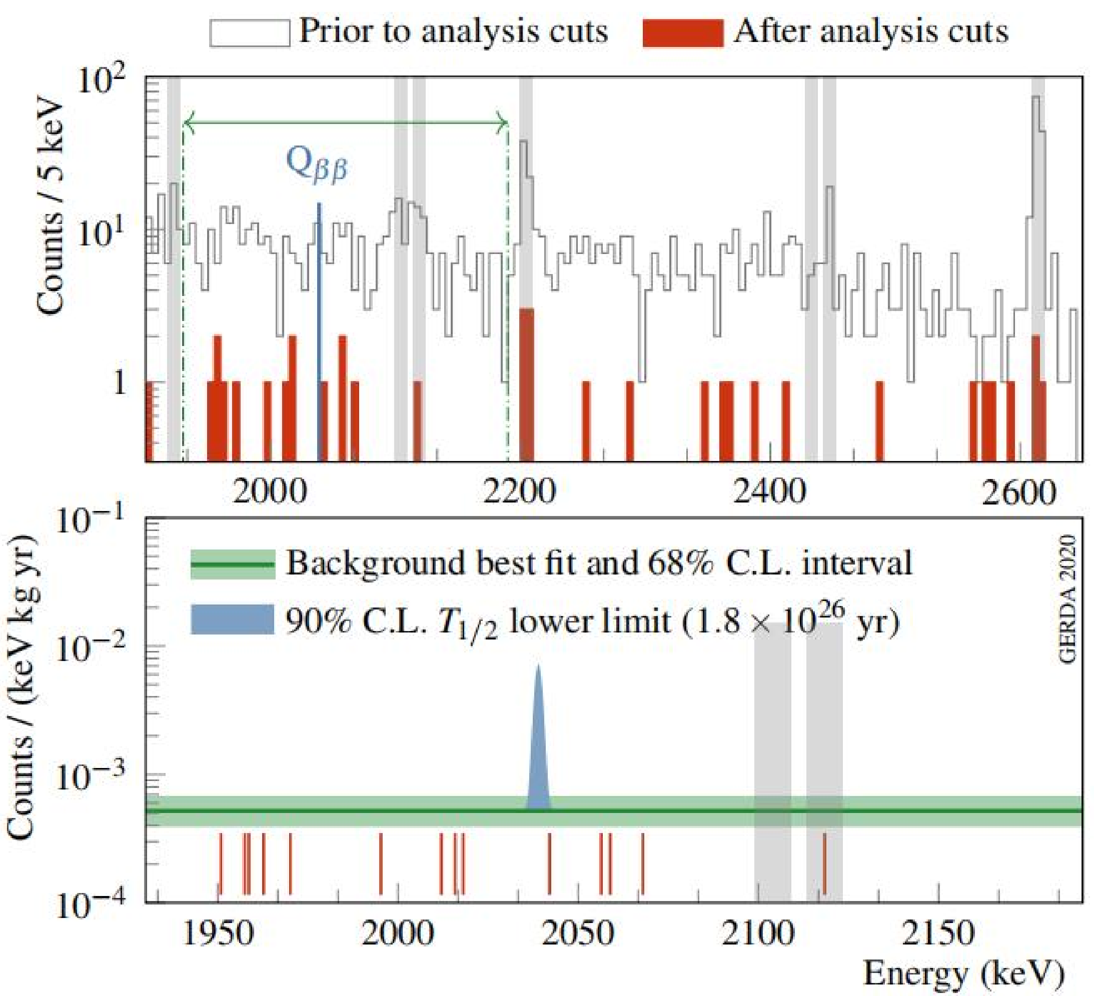

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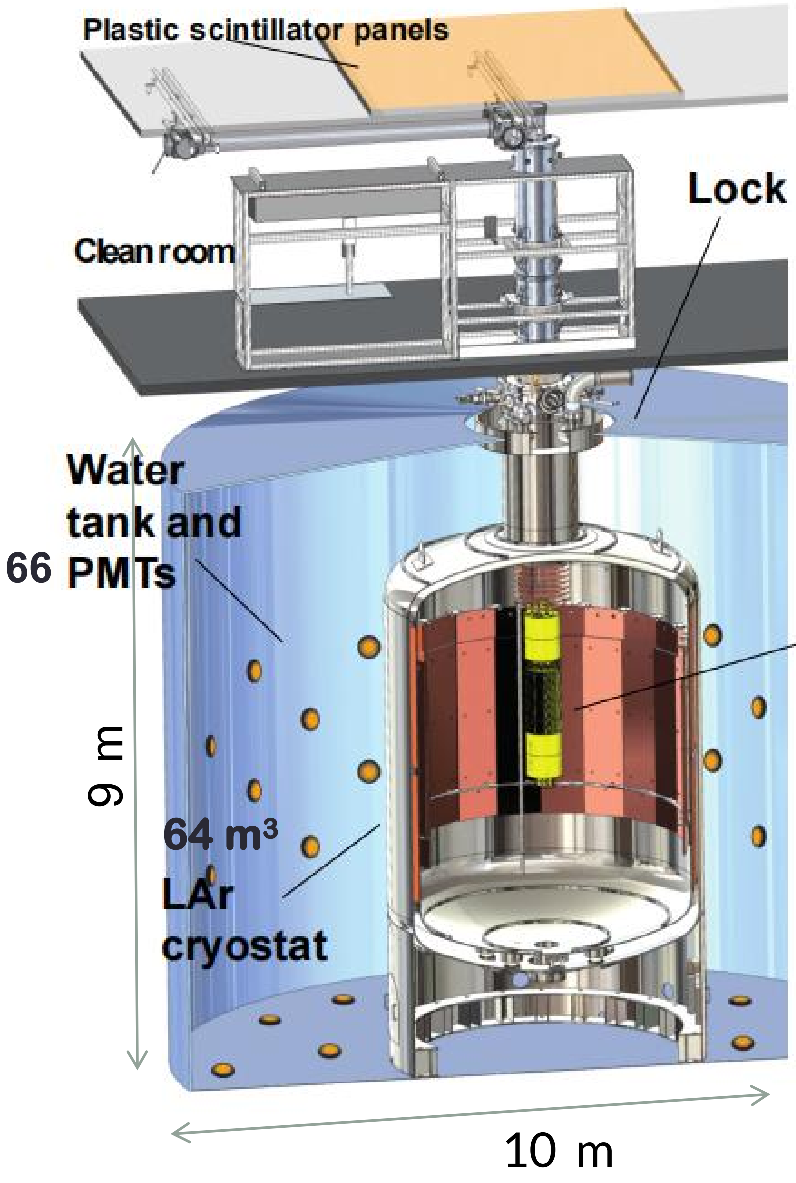
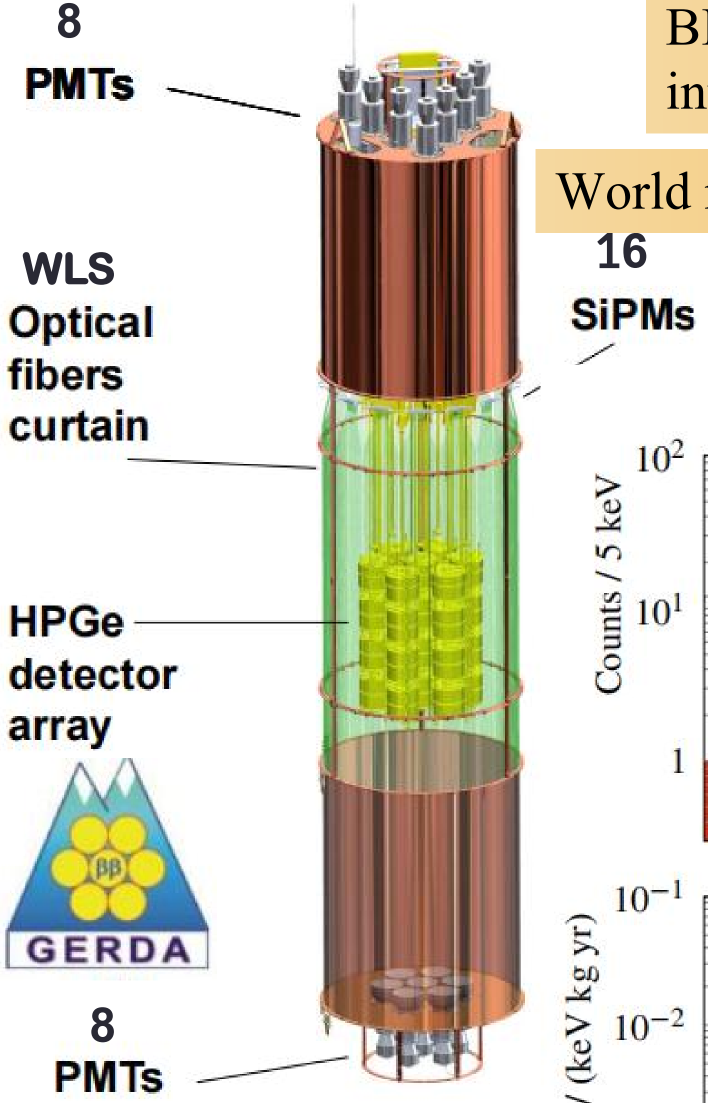
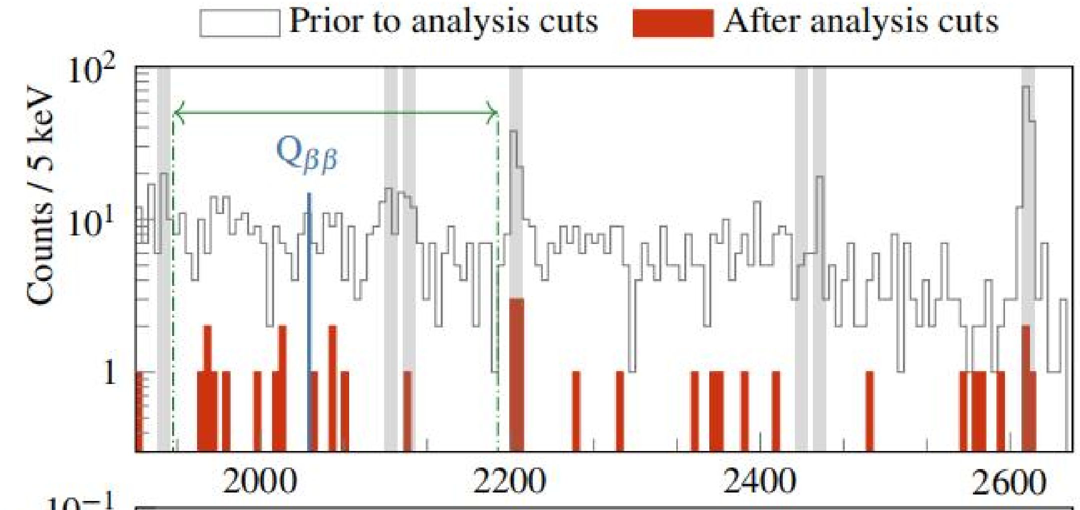
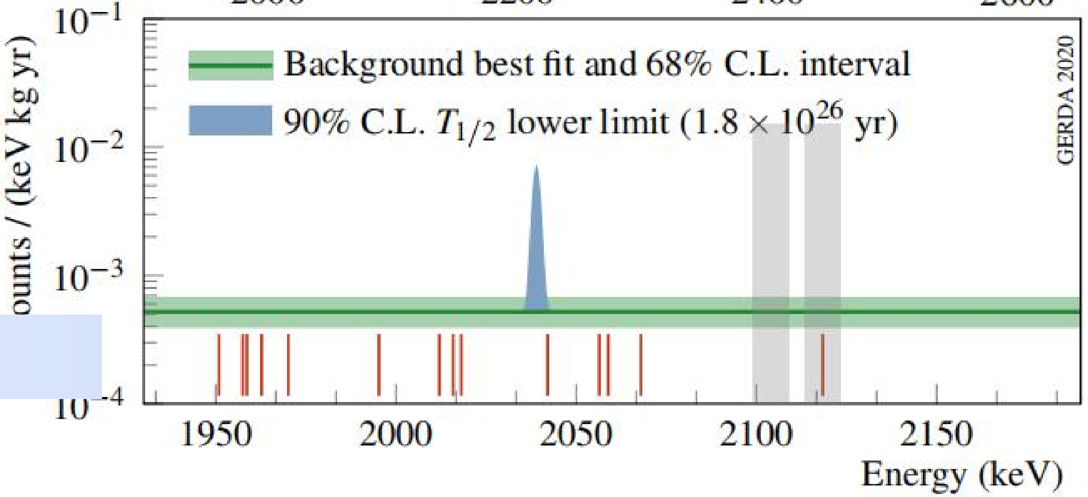
$m_{\beta\beta} < (79 - 180)$ meV at $g_A = 1.27$







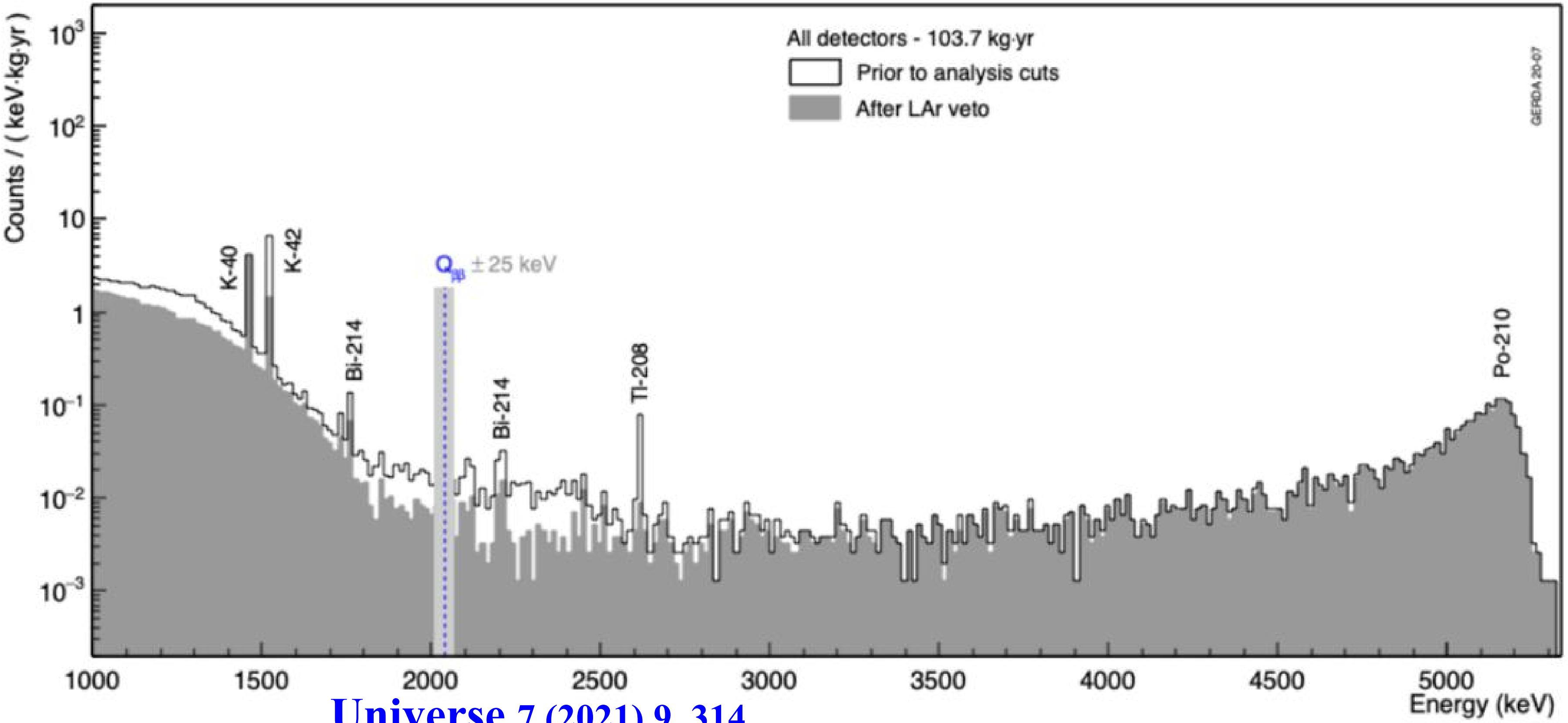


HPGe detectors enriched in ... enriched up to ~ 87%, set at LNGS

Luigi Pertoldi’s talk!

[Universe 7 (2021) 9, 314]

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



Universe 7 (2021) 9, 314

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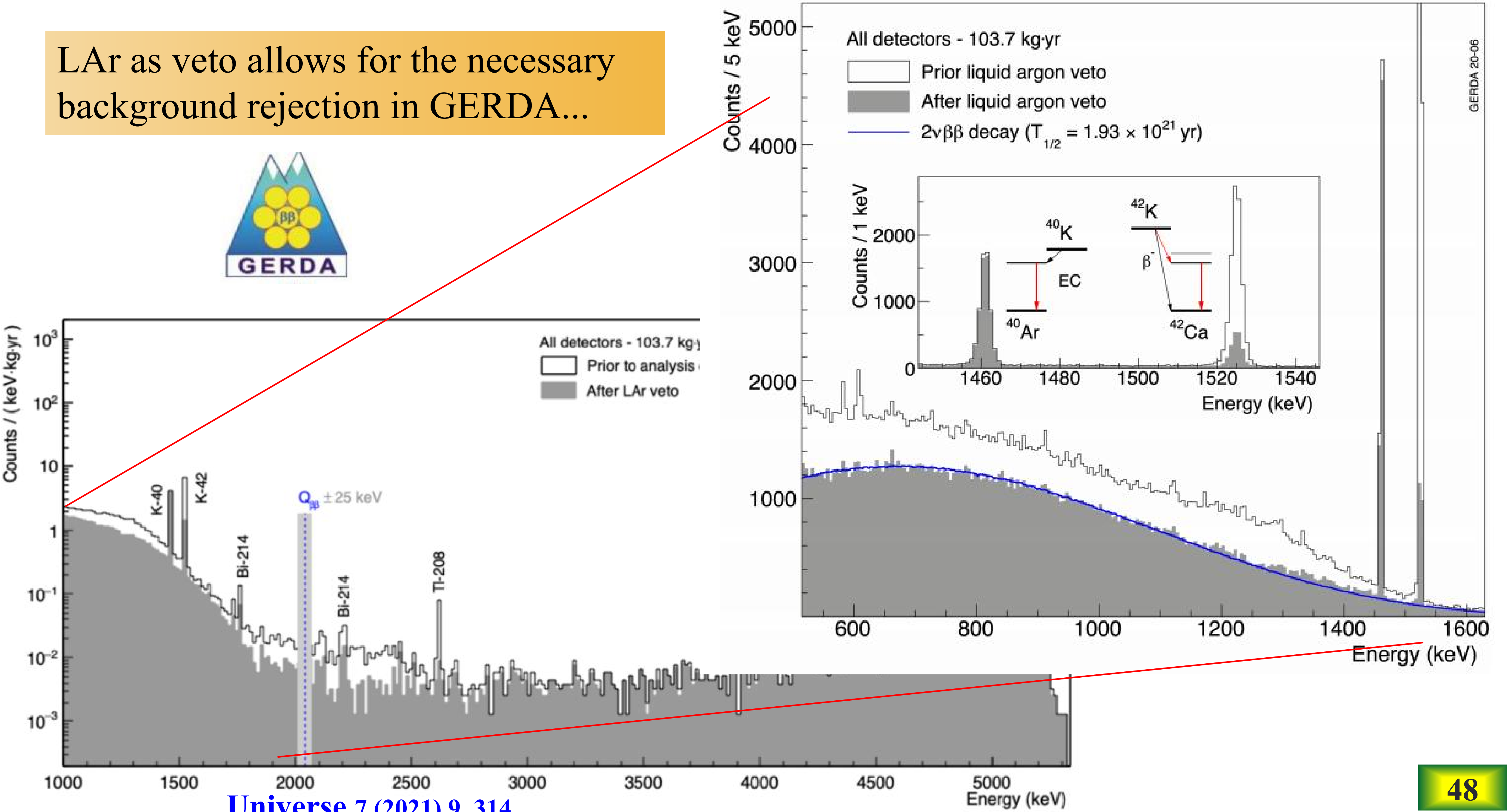
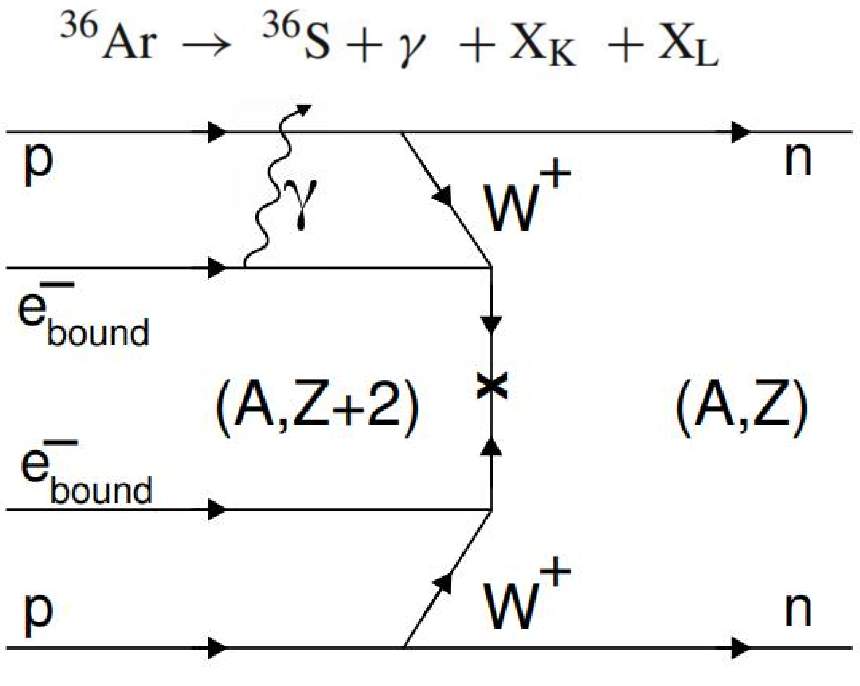
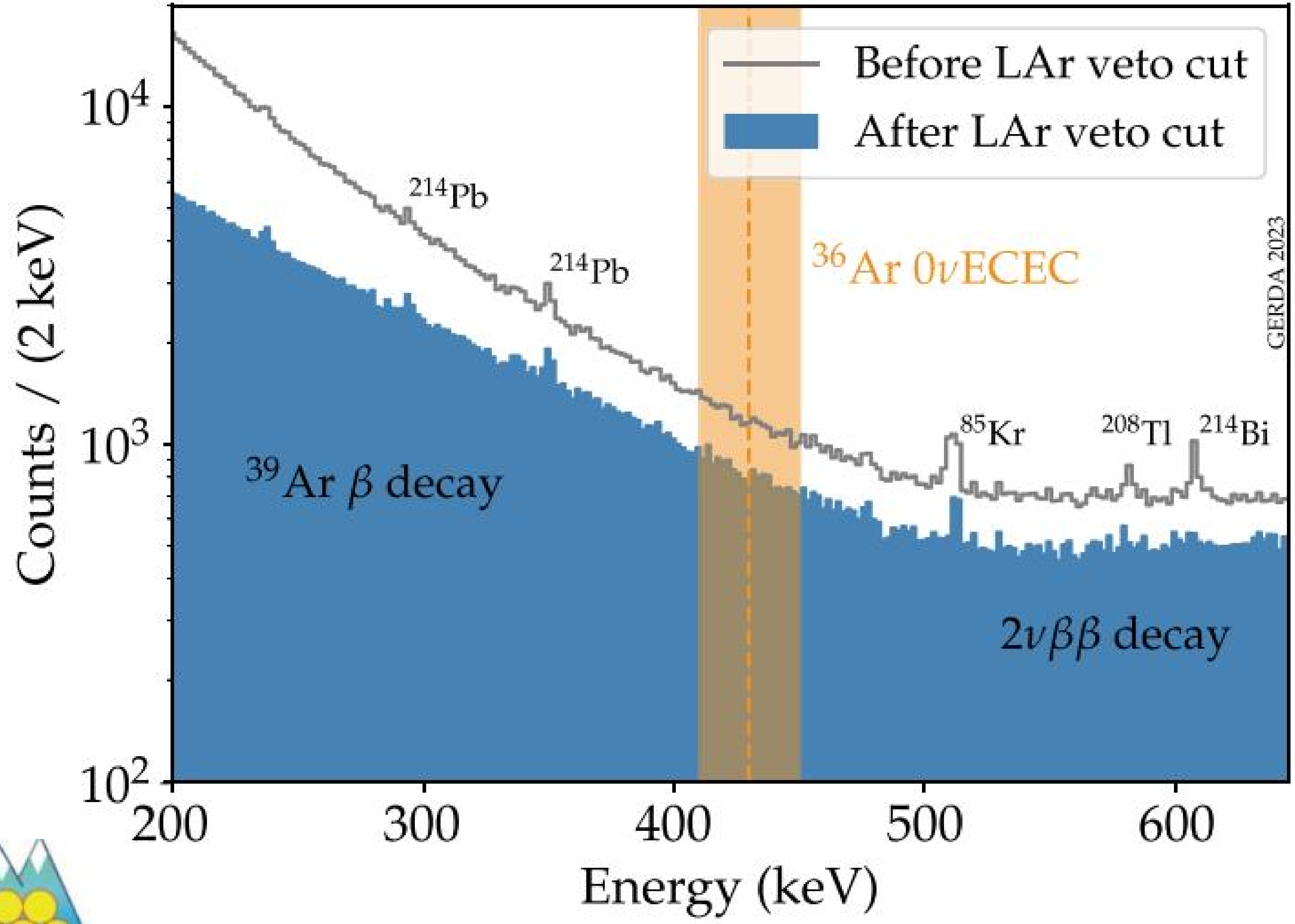


[Universe 7 (2021) 9, 314](#)

... and for 0vECEC in ^{36}Ar!

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





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)

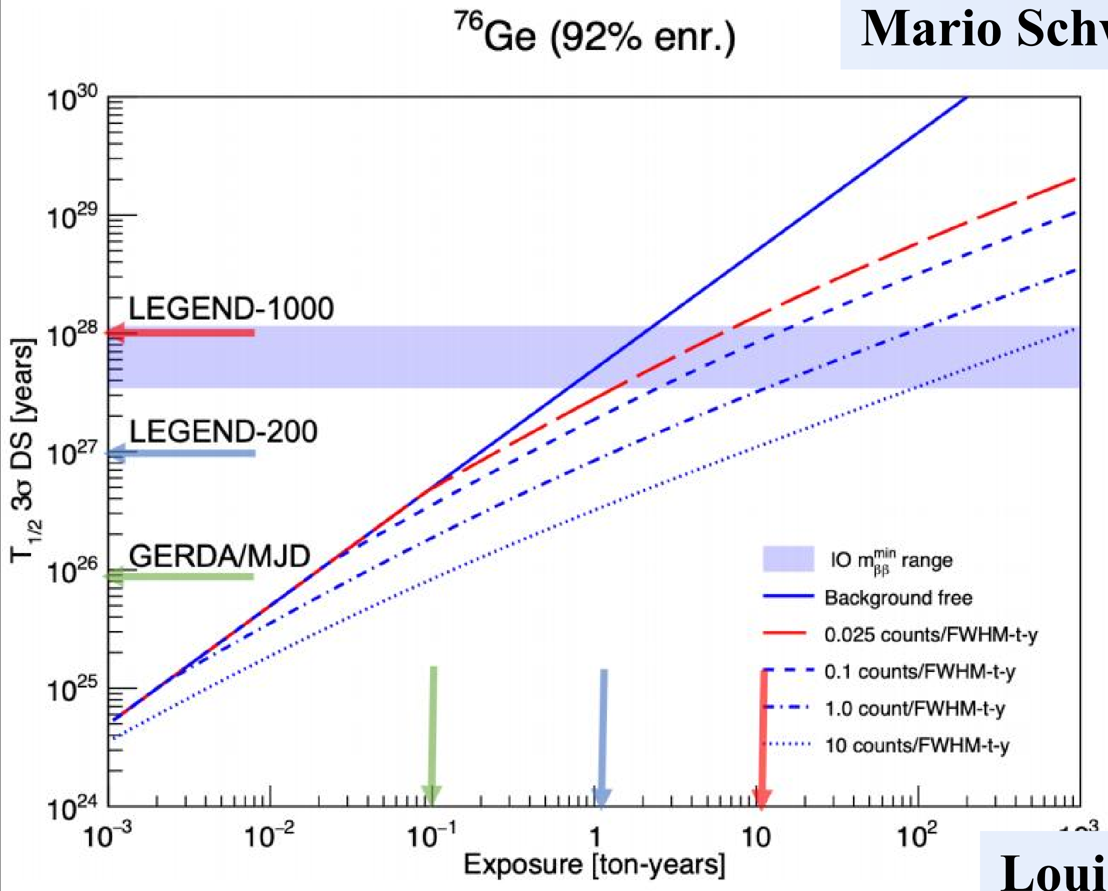
GERDA

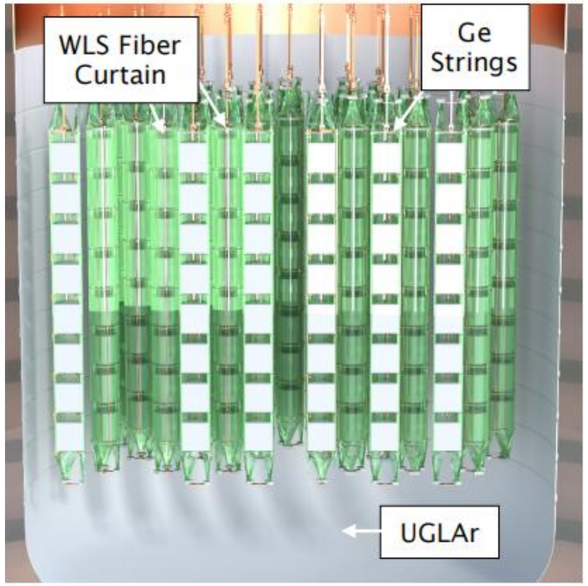
How to become LEGEND

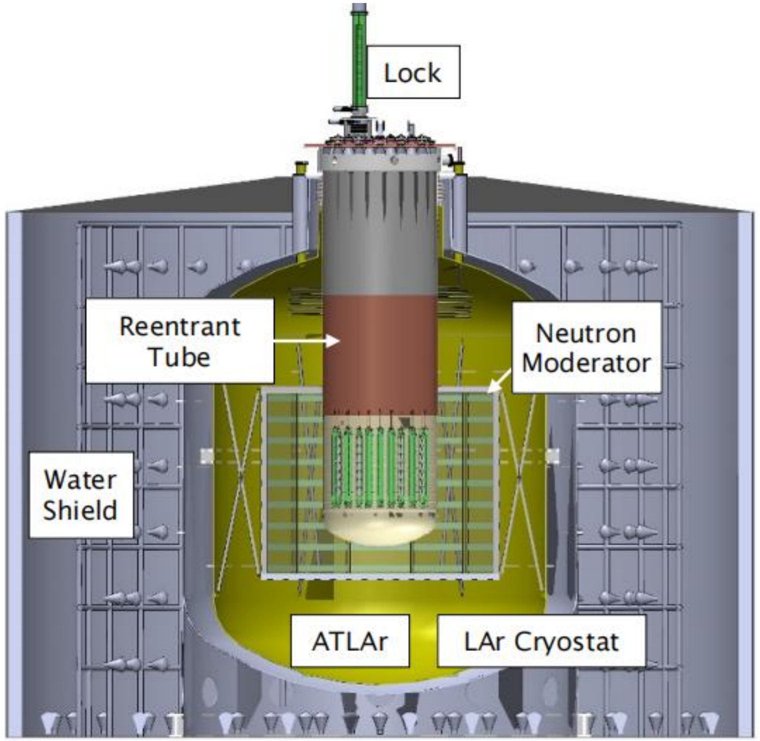
LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

	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)	$< 79 - 180$	$< 113 - 269$	$< 34 - 78$	$< 9.4 - 21.4$

Mario Schwarz's & Niko Lay's talk!







Nuovo Cim.C 47 (2024) 3, 69

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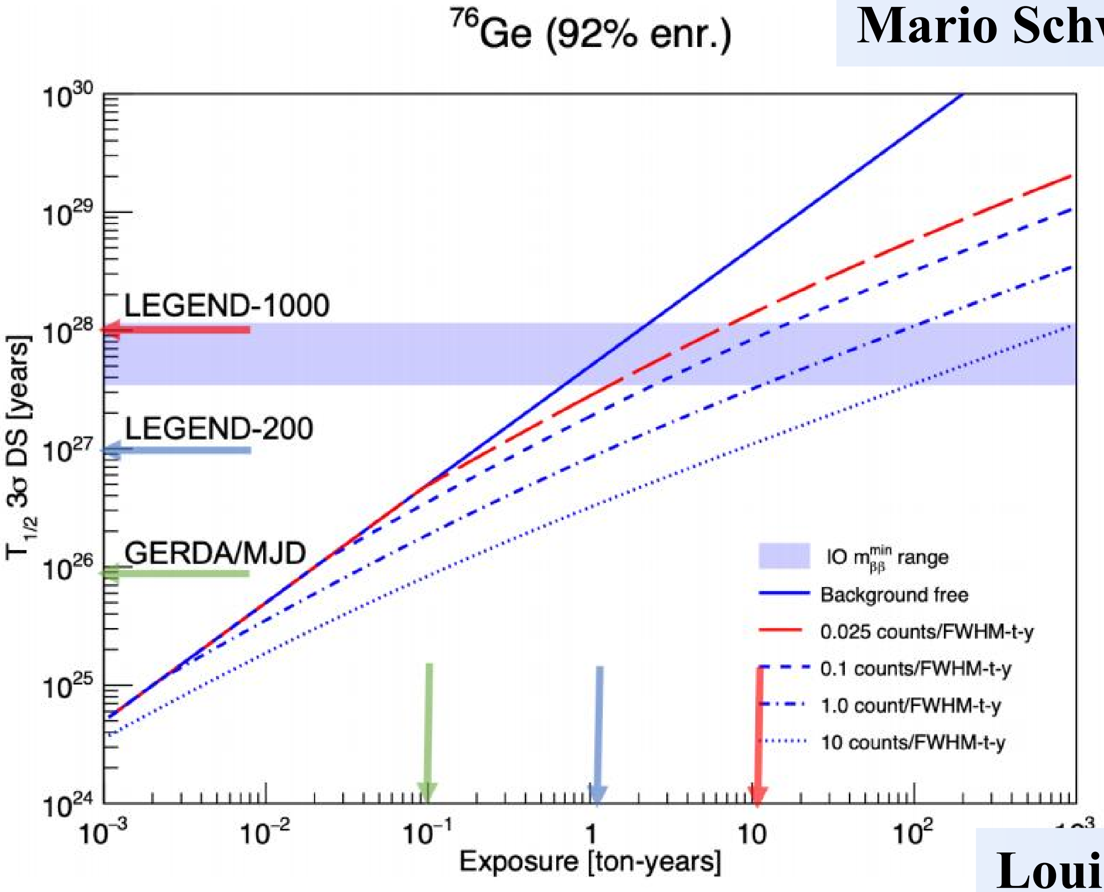

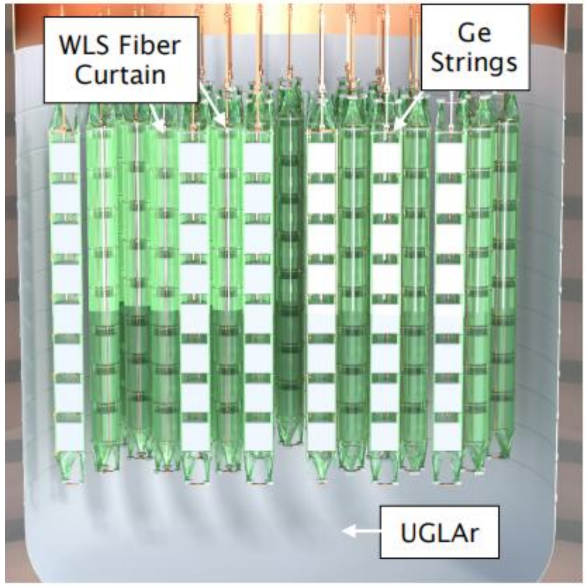

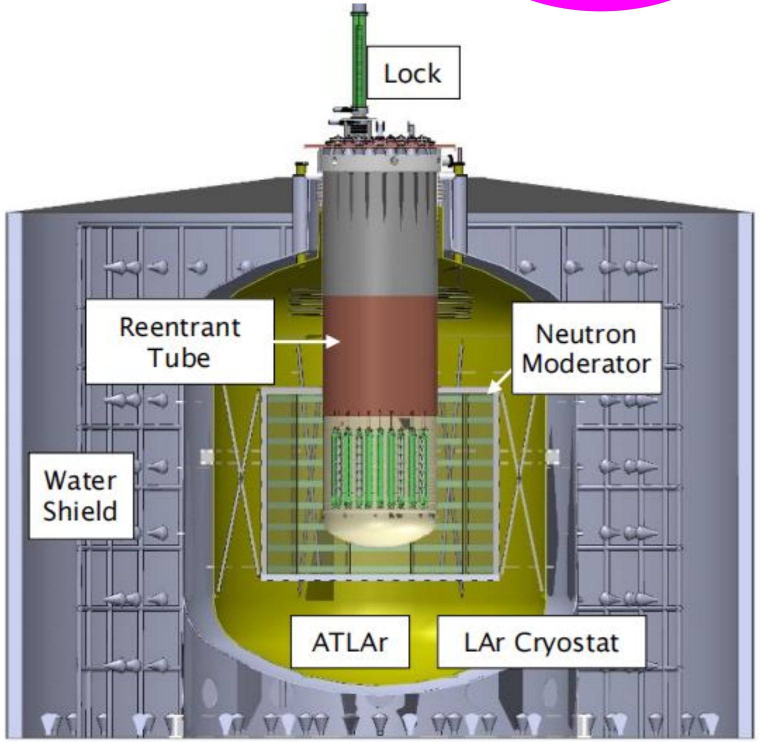

Nuovo Cim.C 47 (2024) 3, 69

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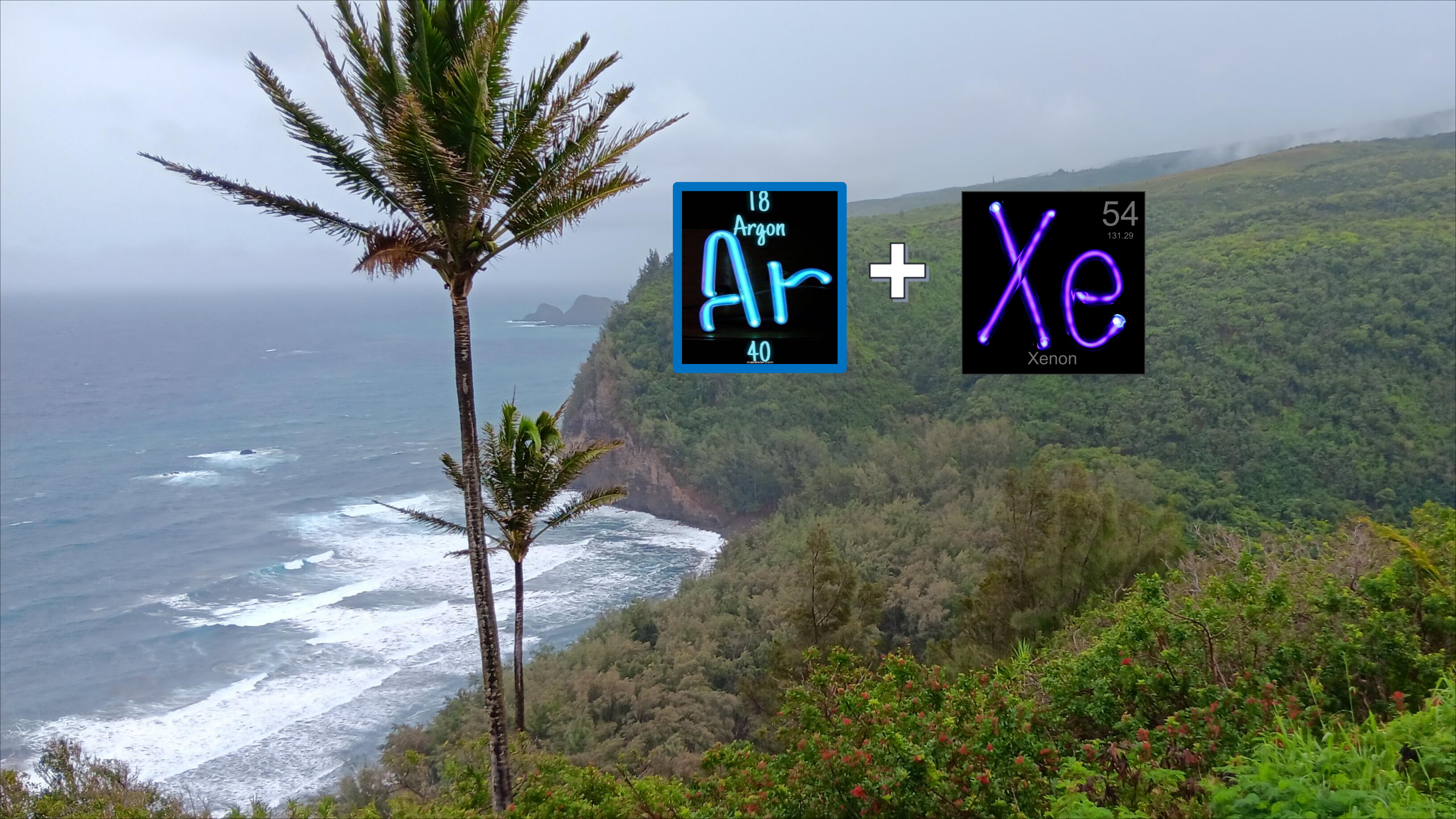
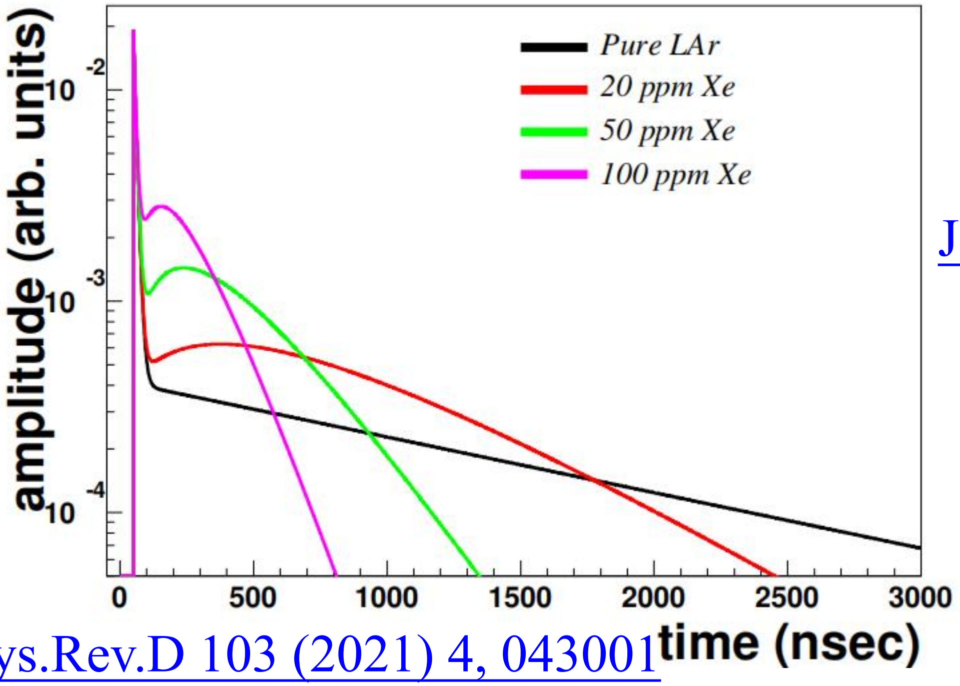
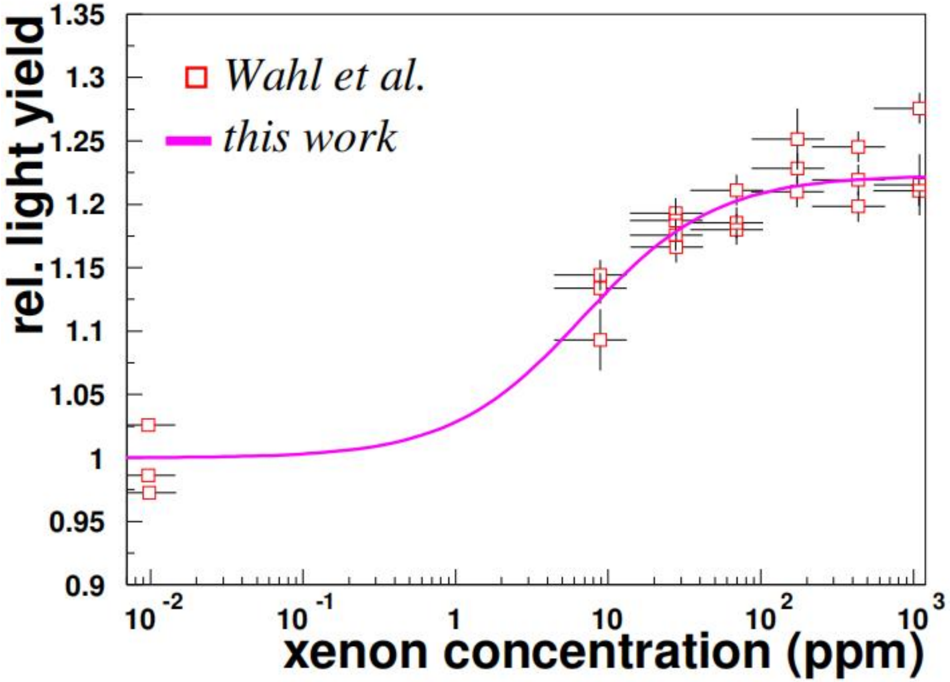

18
Argon
Ar
40
+
Xe
54
131.29
Xenon

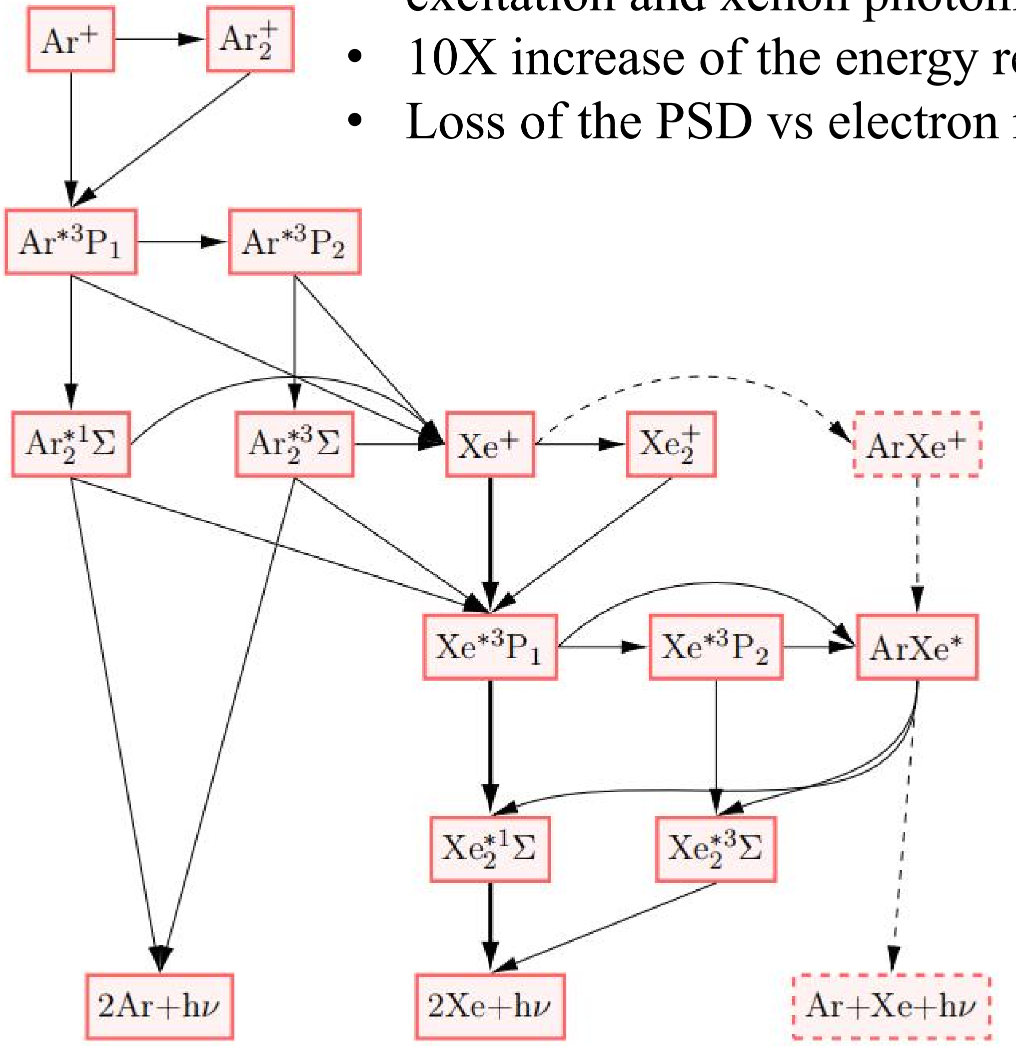
- Shift of the slow scintillation component 127 nm -> 174 nm @ O(10) ppm Xe
- increase of the number of detected scintillation photons with increasing xenon concentration through Penning de-excitation and xenon photonionization
- 10X increase of the energy resolution
- Loss of the PSD vs electron recoils



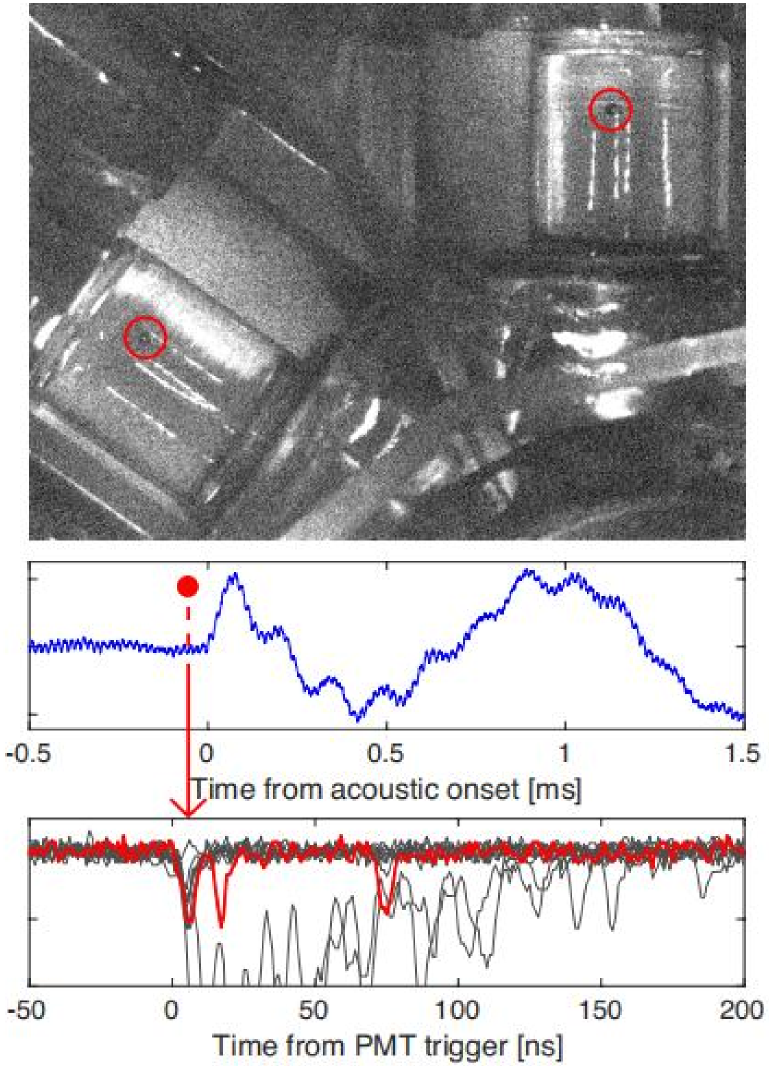
Phys.Rev.D 103 (2021) 4, 043001



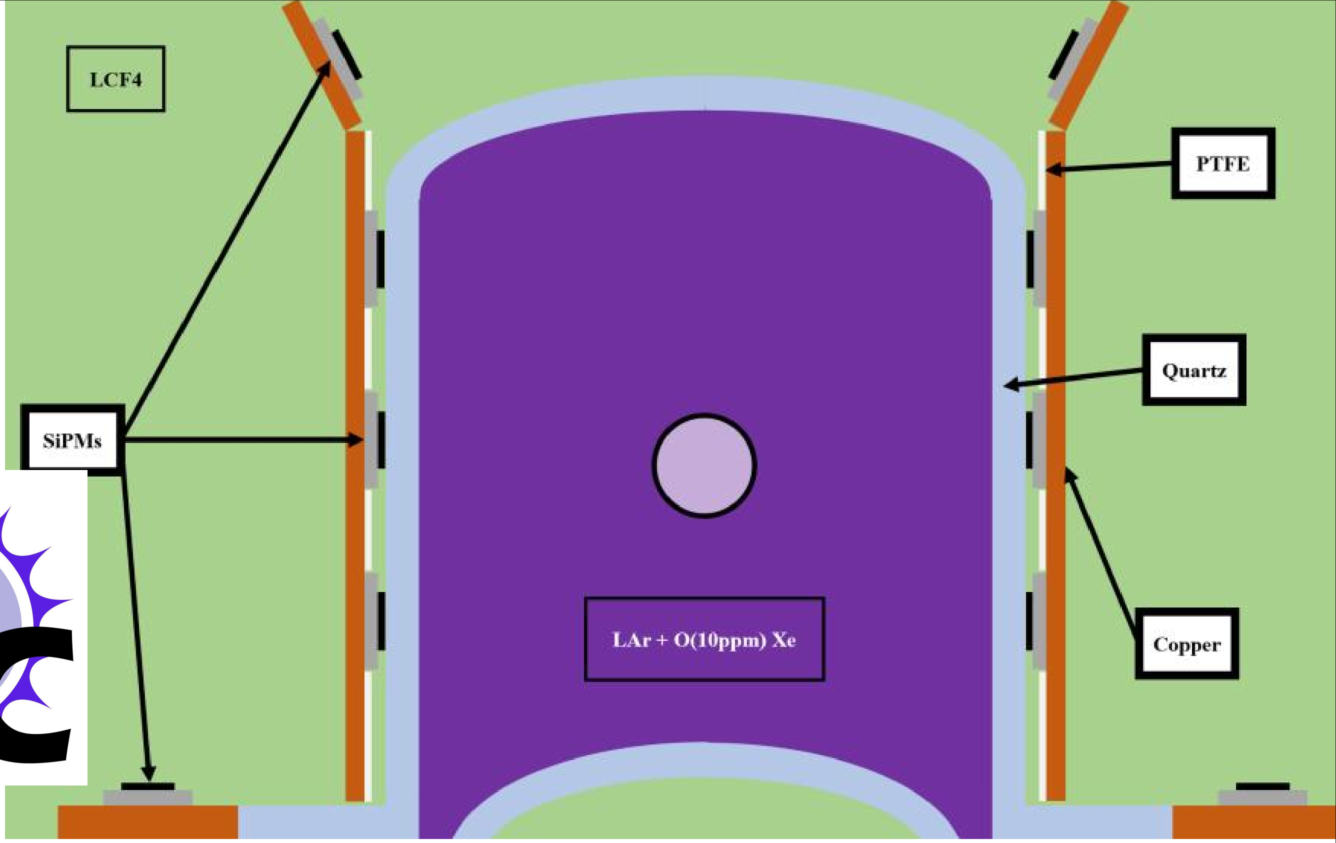
JINST 16 (2021) 02, P02015



Search for 1-10 GeV/c^2 dark matter with the Scintillating Bubble Chamber in Xe-doped Argon!



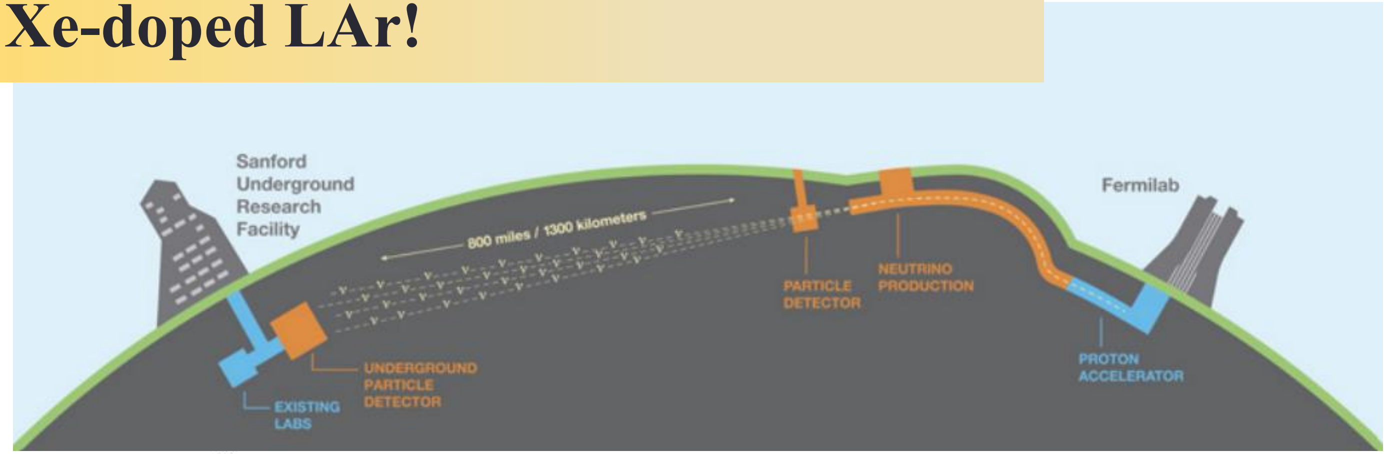
Universe 9 (2023) 8, 346



JINST 19 (2024) 01, C01023

Target fluid	Xe-doped Ar, with options for pure Ar, Xe, N_2, or CF_4
Fiducial volume	10 L (10 kg LAr at 130 K)
Thermodynamic regulation	±0.5 K, ±0.1 bar (±5 eV Seitz threshold)
Seitz threshold	Down to 40 eV (LAr at 1.4 bara, 130 K)
Scintillation detection	1 photon per 5 keV NR in Xe-doped argon
Bubble imaging	stereoscopic at 100 fps with mm-resolution
Acoustic reconstruction	Time-of-nucleation reconstructed to ±25 μs resolution

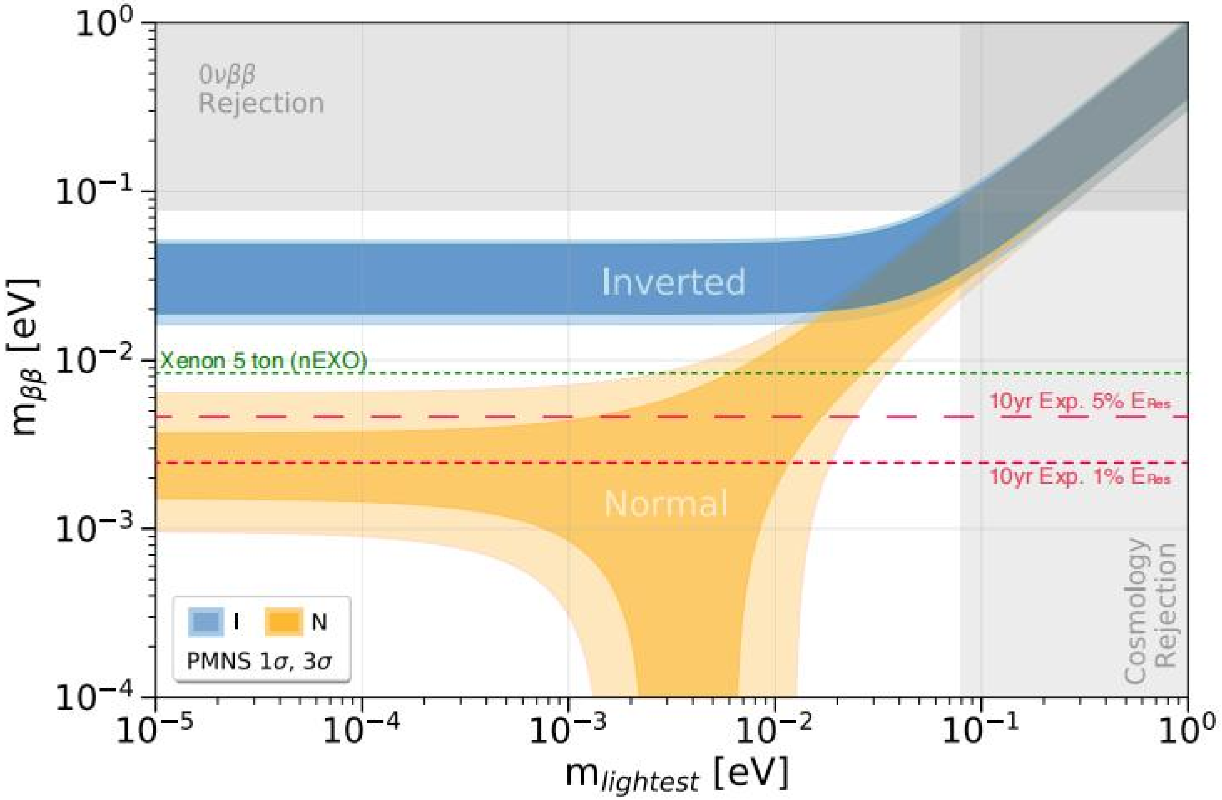
Search for 0νββ in DUNE FD by with Xe-doped LAr!

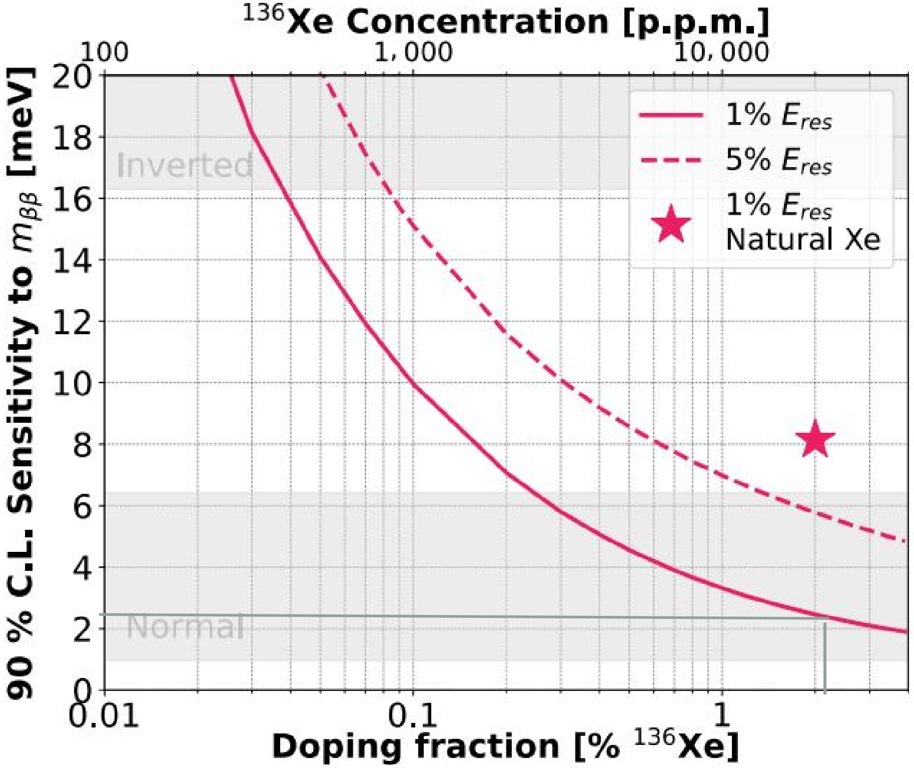


- 10 x charge yield increase at O(ppm) Xe-doping increas levels of photosensitive dopant would imply a 1% @ 1MeV in DUNE FD (10 kton LArTPC)
- UAr would suppress the ^{42}K decay background $Q = 3.53$ MeV

$m_{\beta\beta} = 2.46$ meV

$T_{1/2\ 0\nu} = 1.03\times10^{29}$ years

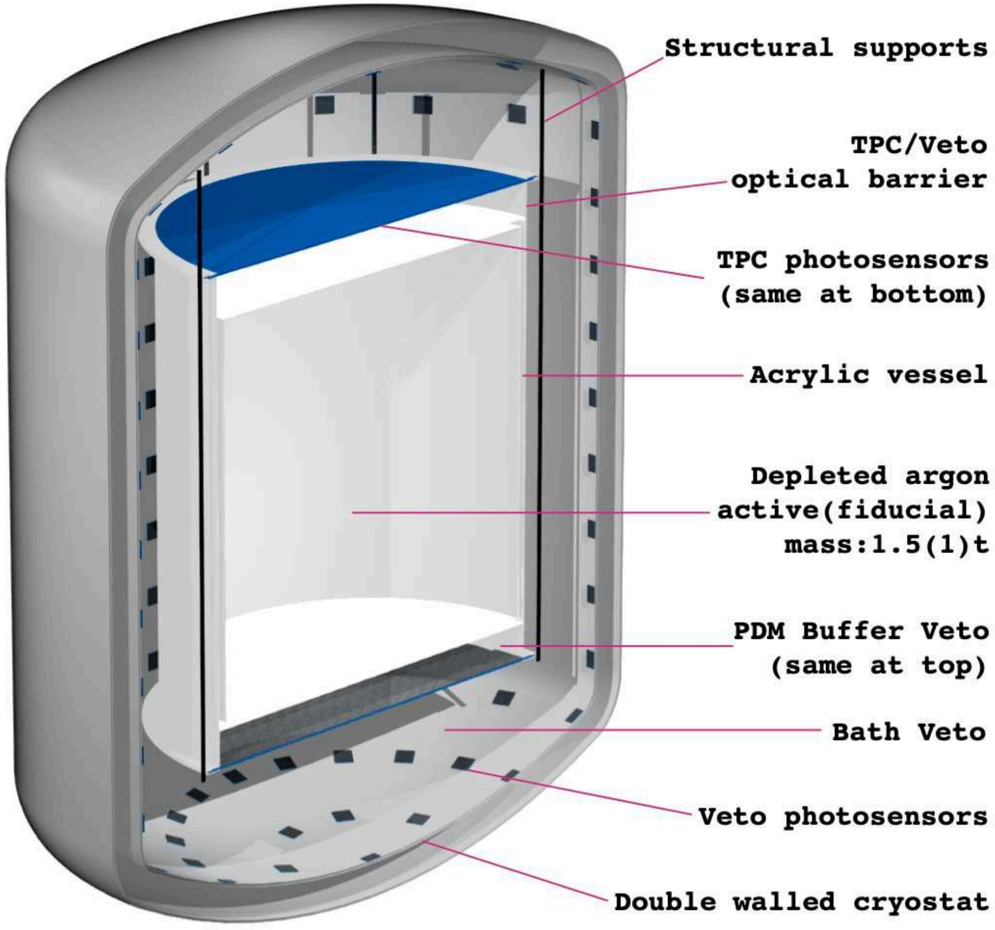


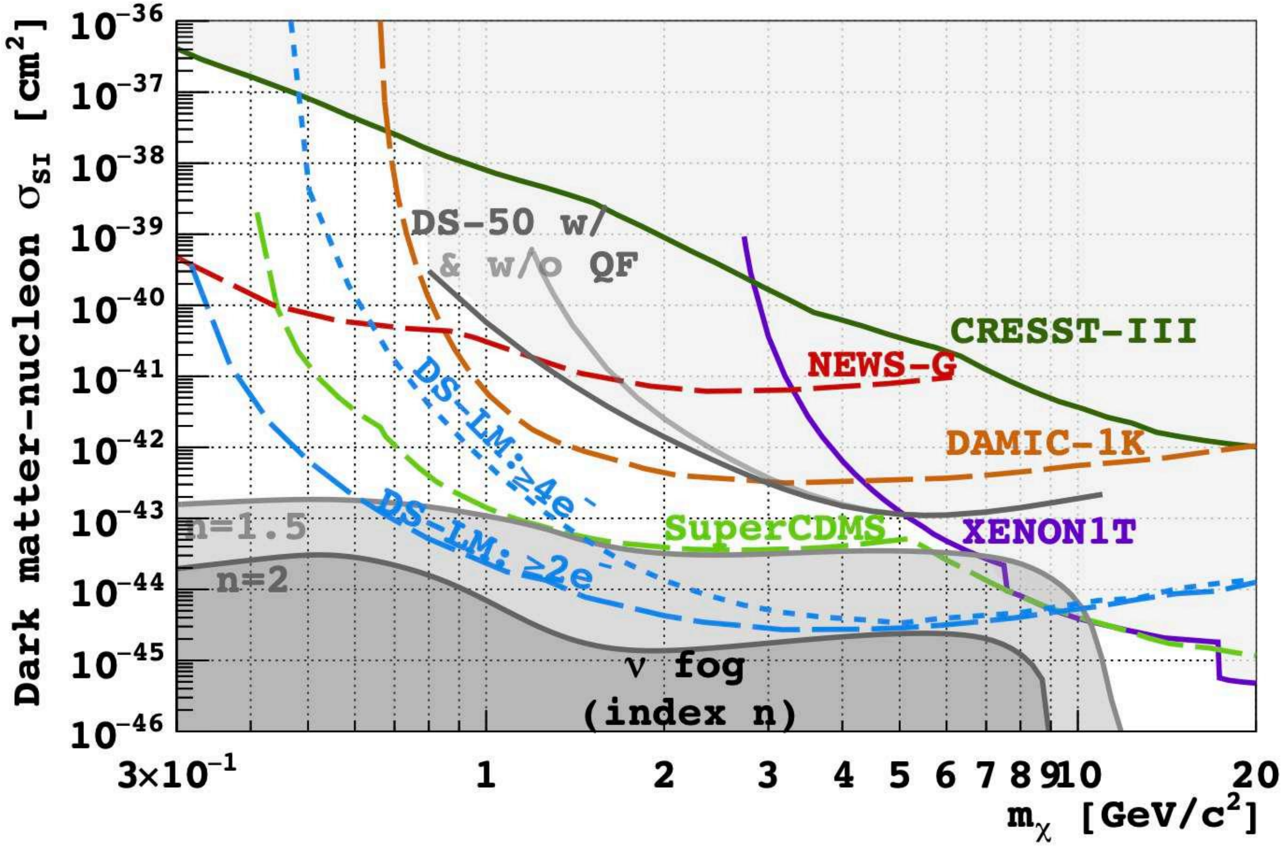


[Phys.Rev.D 106 (2022) 9, 092002](https://doi.org/)

DarkSide-Low Mass could also be filled with Xe-doped Ar

- 1 tonnes of active UAr volume
- Optimized for the S2-only analysis
- Sensitive to the neutrino fog with 1 tonne year exposure

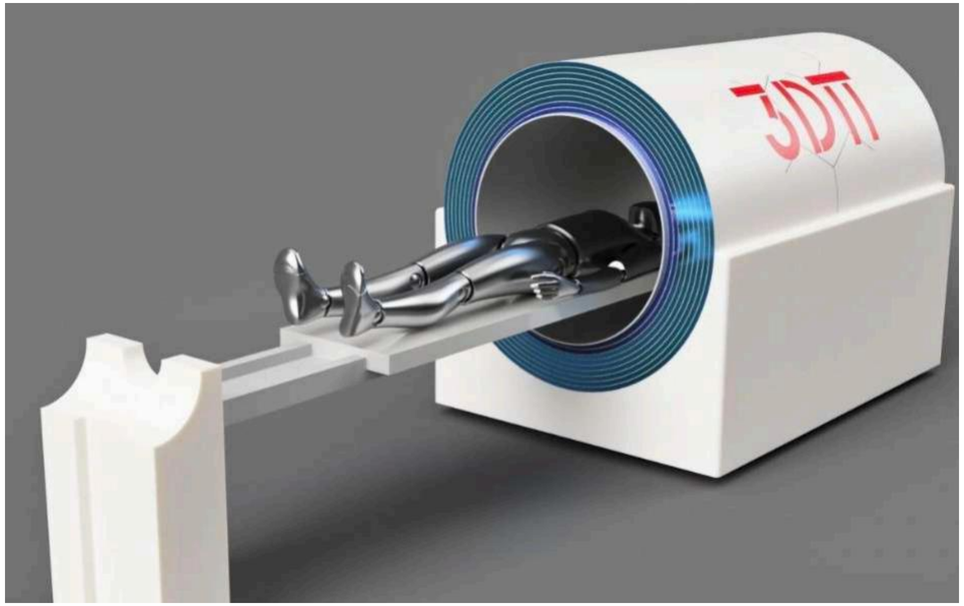


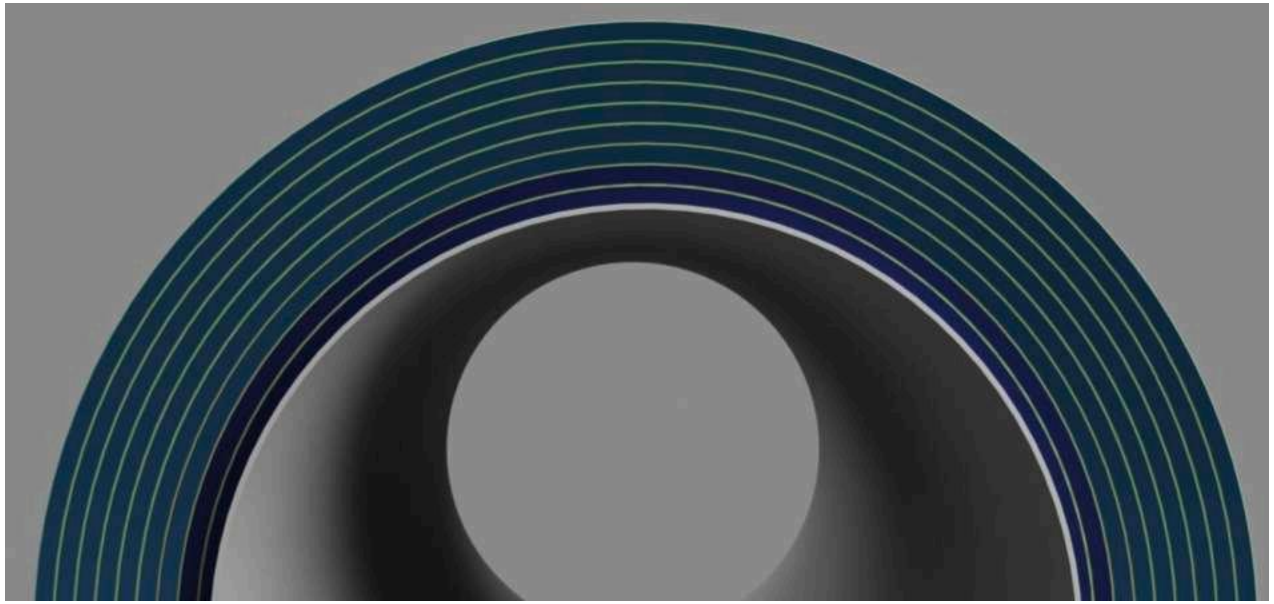


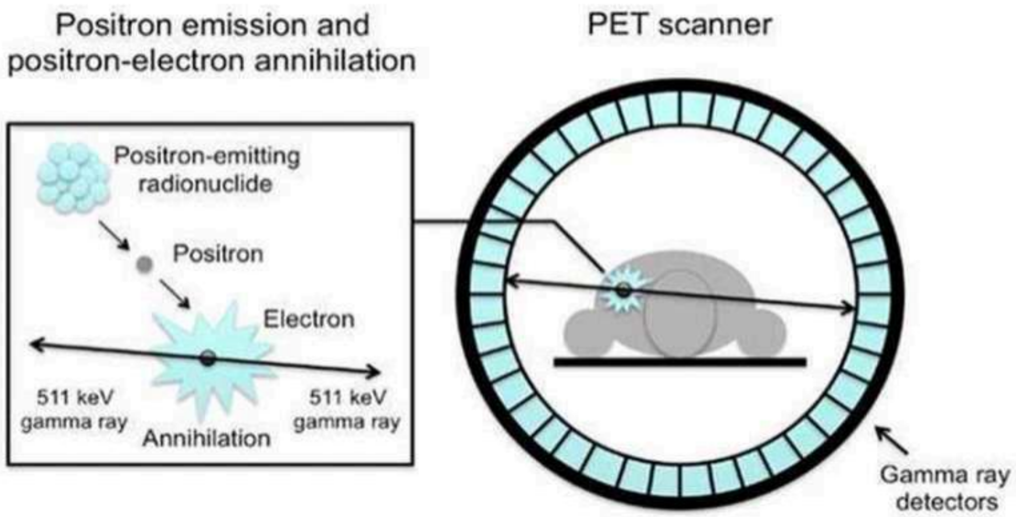
Phys. Rev. D 107, 112006 (2023)

...As well as the 3DΠ scanner!

- 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!





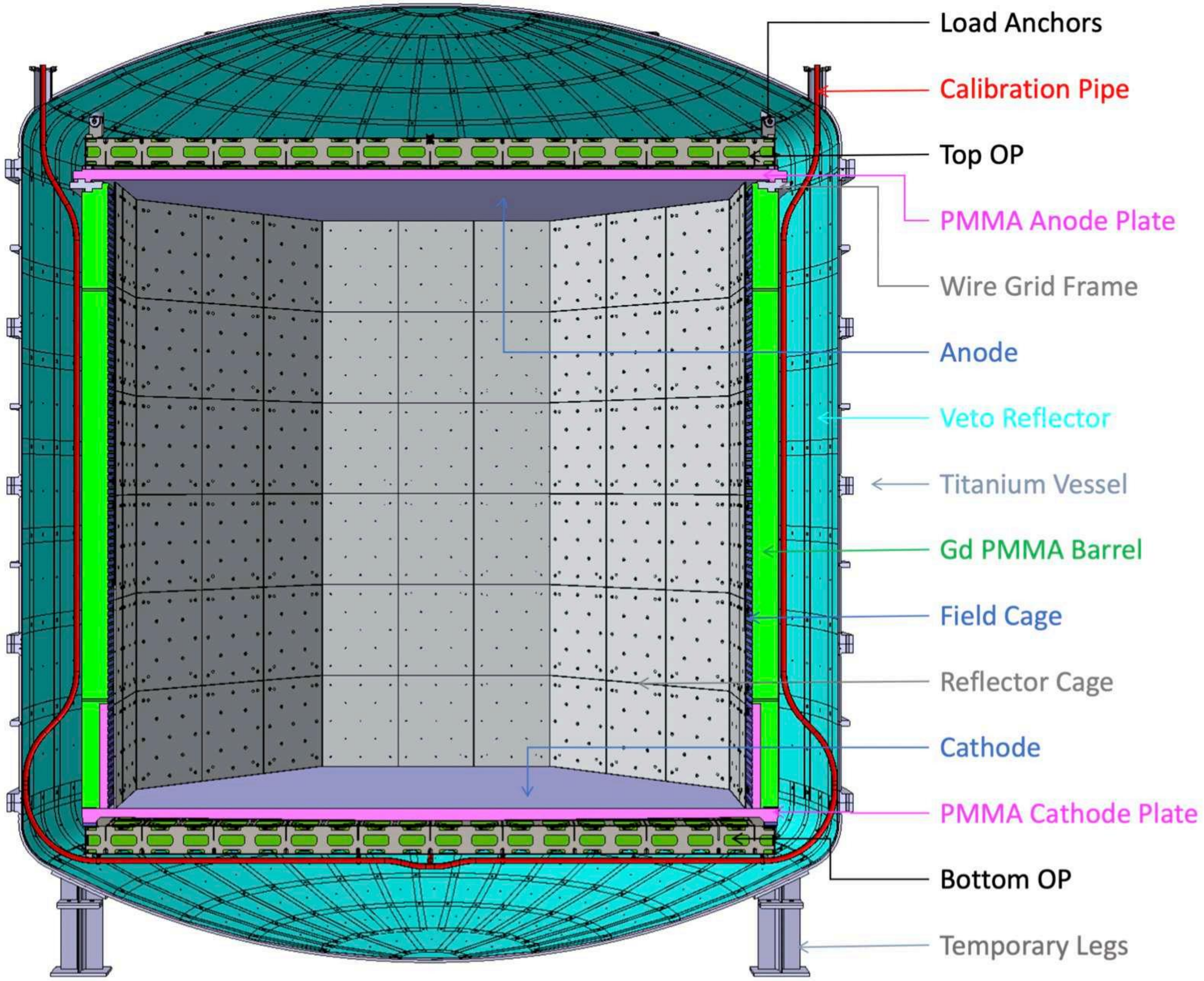


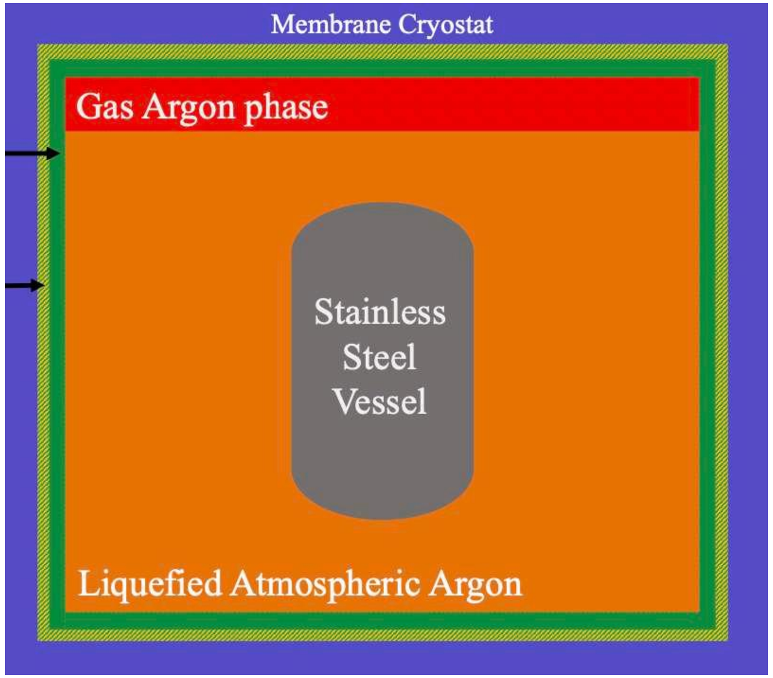
NSS/MIC 2021 and RTSD2021 Proceeding

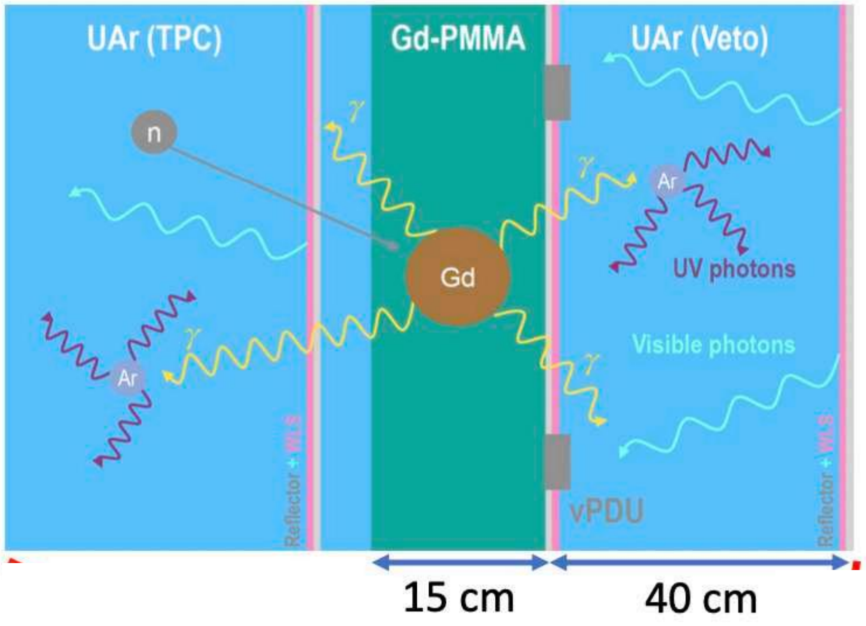
PoS EPS-HEP2021 (2022) 778

Thank you!

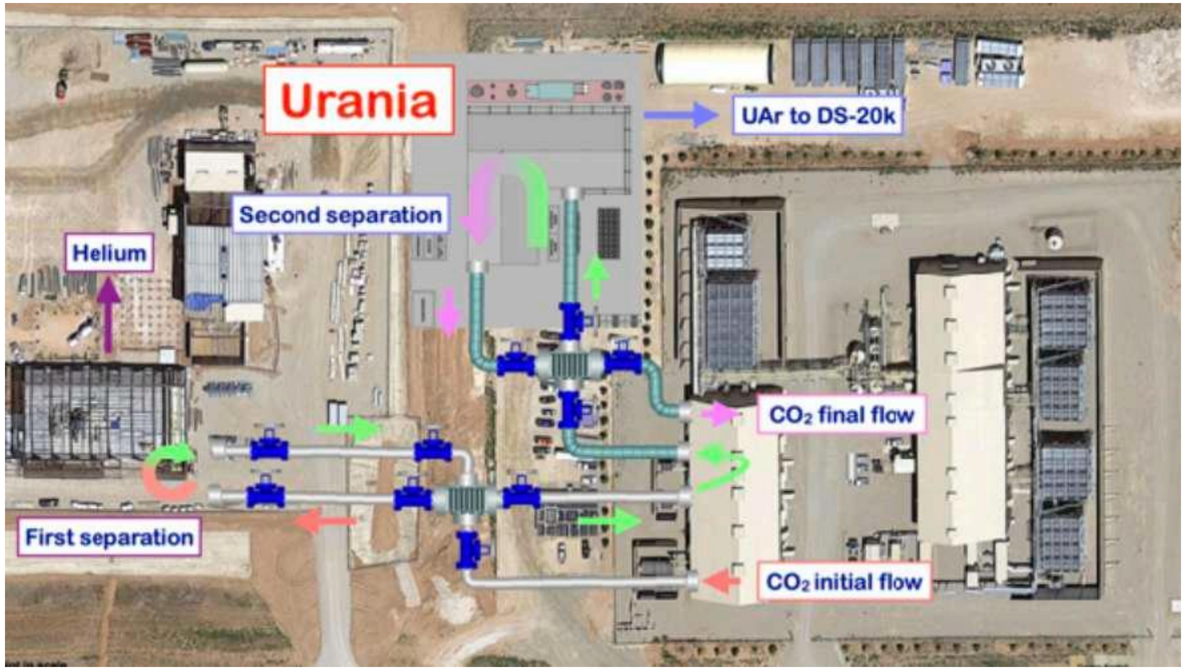
50 tonnes (TPC) of UAr + 27 tonnes of UAr (Inner Veto) + 650 tonnes of AAr (Outer Veto)





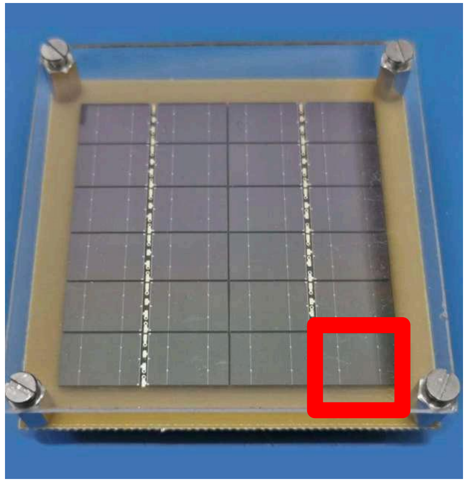


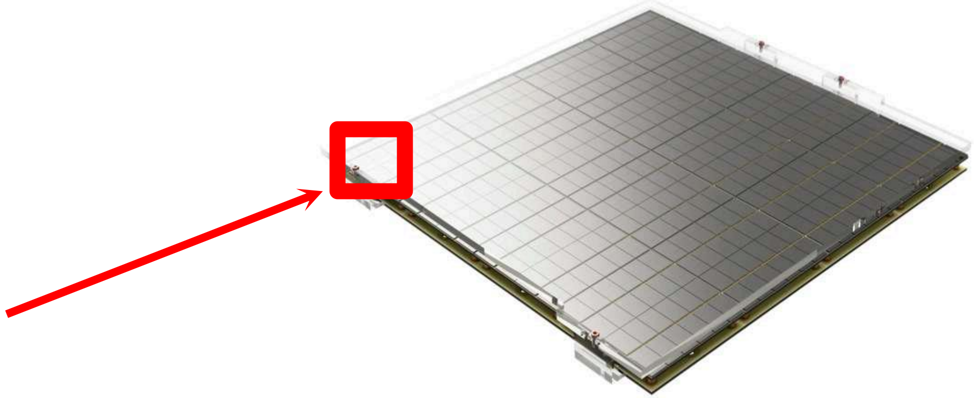
UAr extraction performed at Urania, currently under construction

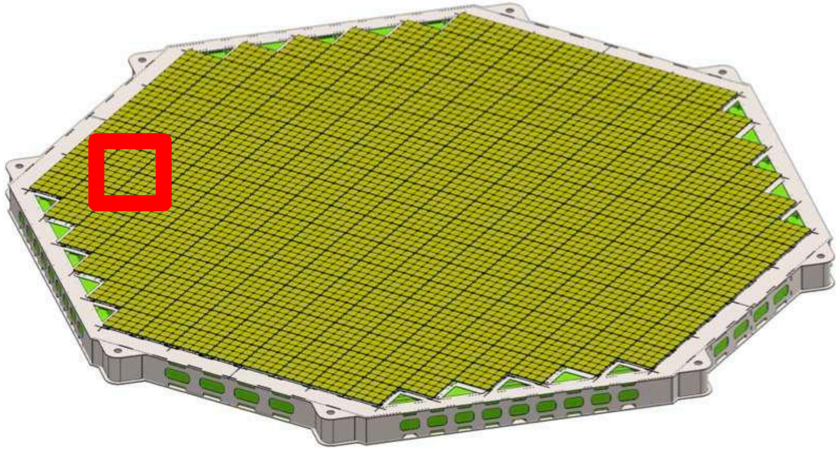


- Low activity UAr found in 2009 at Southwest Colorado CO_2 wells and purified at FNAL for DarkSide-50, with a rate 140 g/day
- Urania will be built next to the previous site by Polaris S.p.A.
- Expected extraction rate 250 kg/day
- Additional experiments interested in UAr from Urania: Argo, COHERENT, LEGEND

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





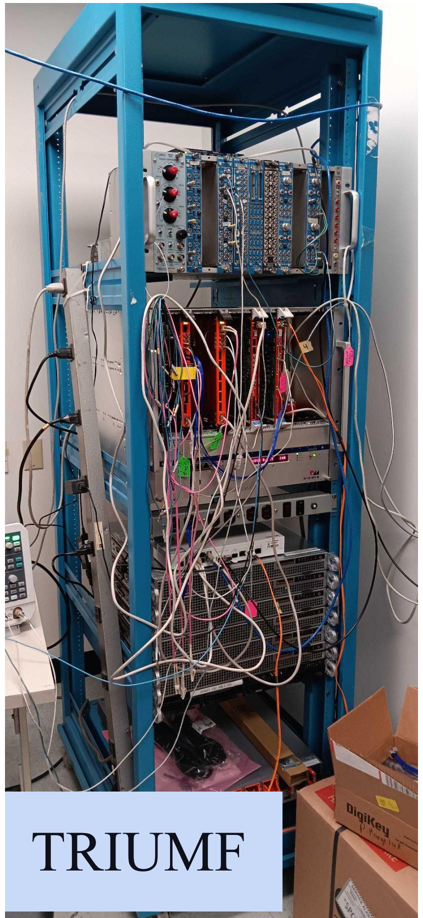


TPC: 525 PDU

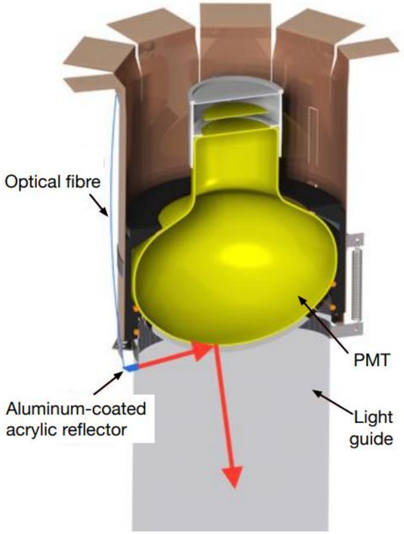
IV: 20 vPDU

OV: 32 vPDU

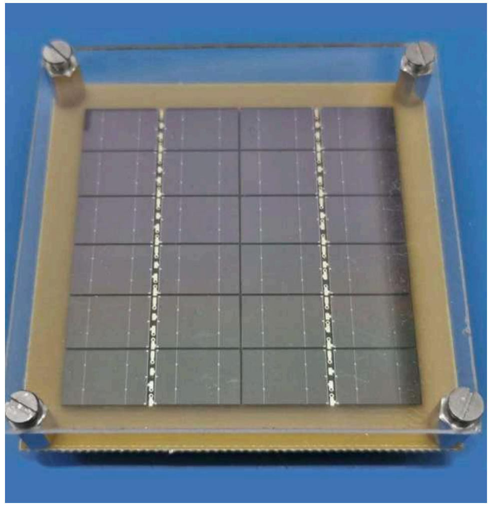
NOA facility

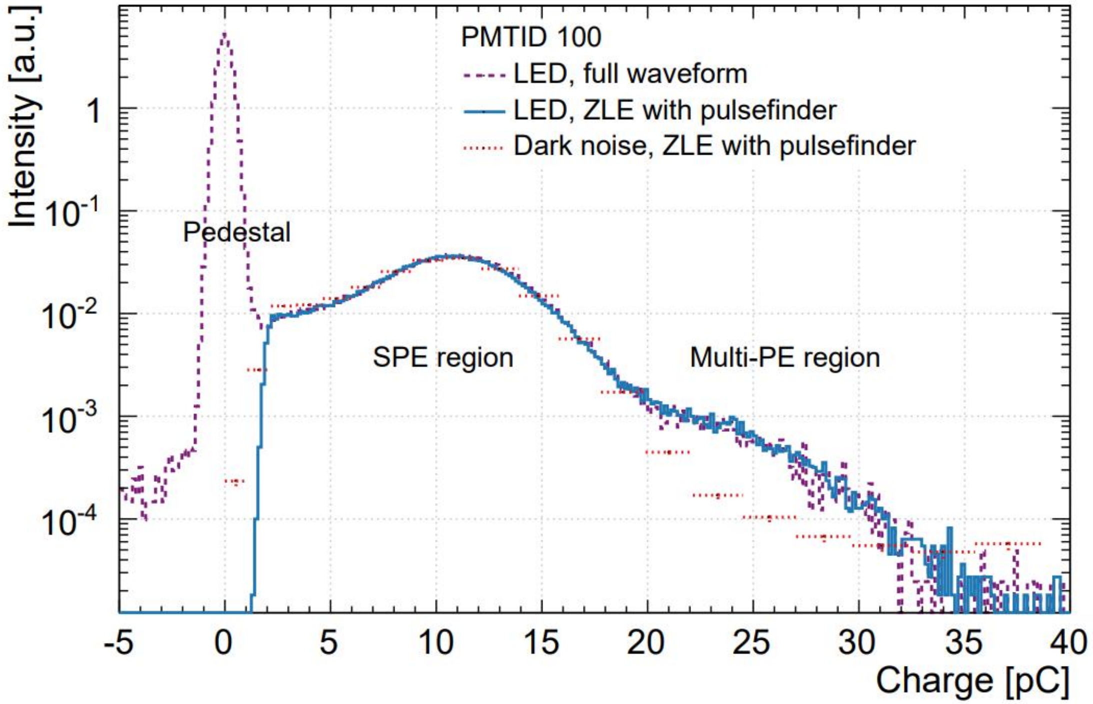


TRIUMF

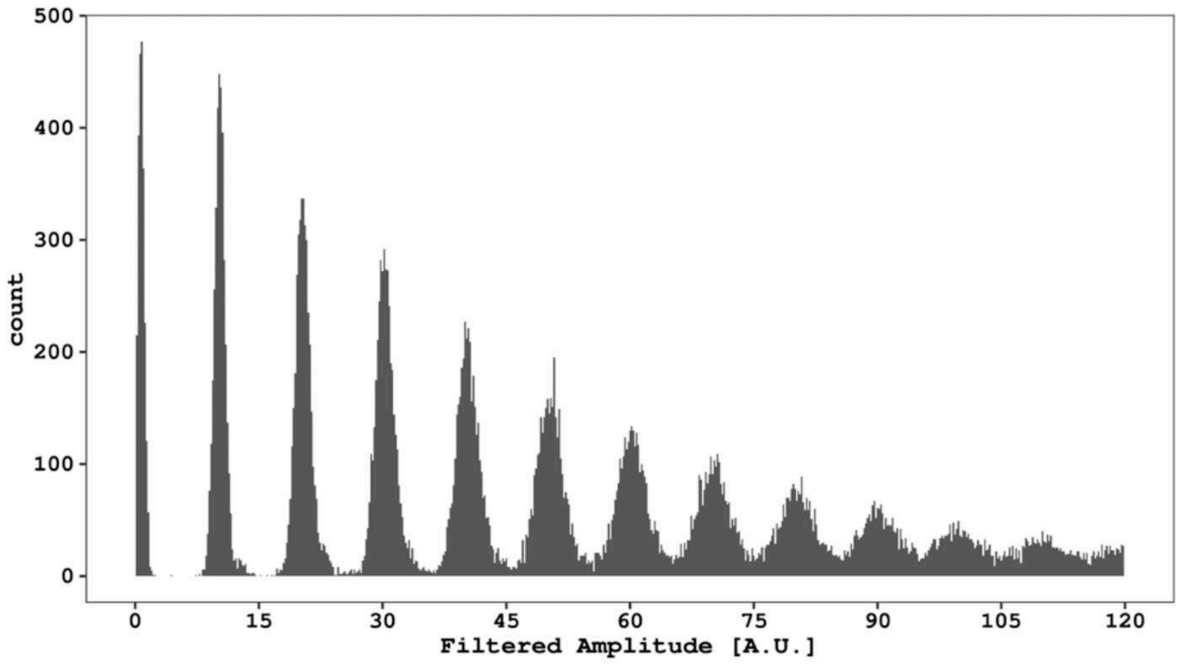


Photomultipliers tubes (PMTs) exchanged for Silicon Photomultipliers (SiPMs) customly developed by Fondazione Bruno Kessler



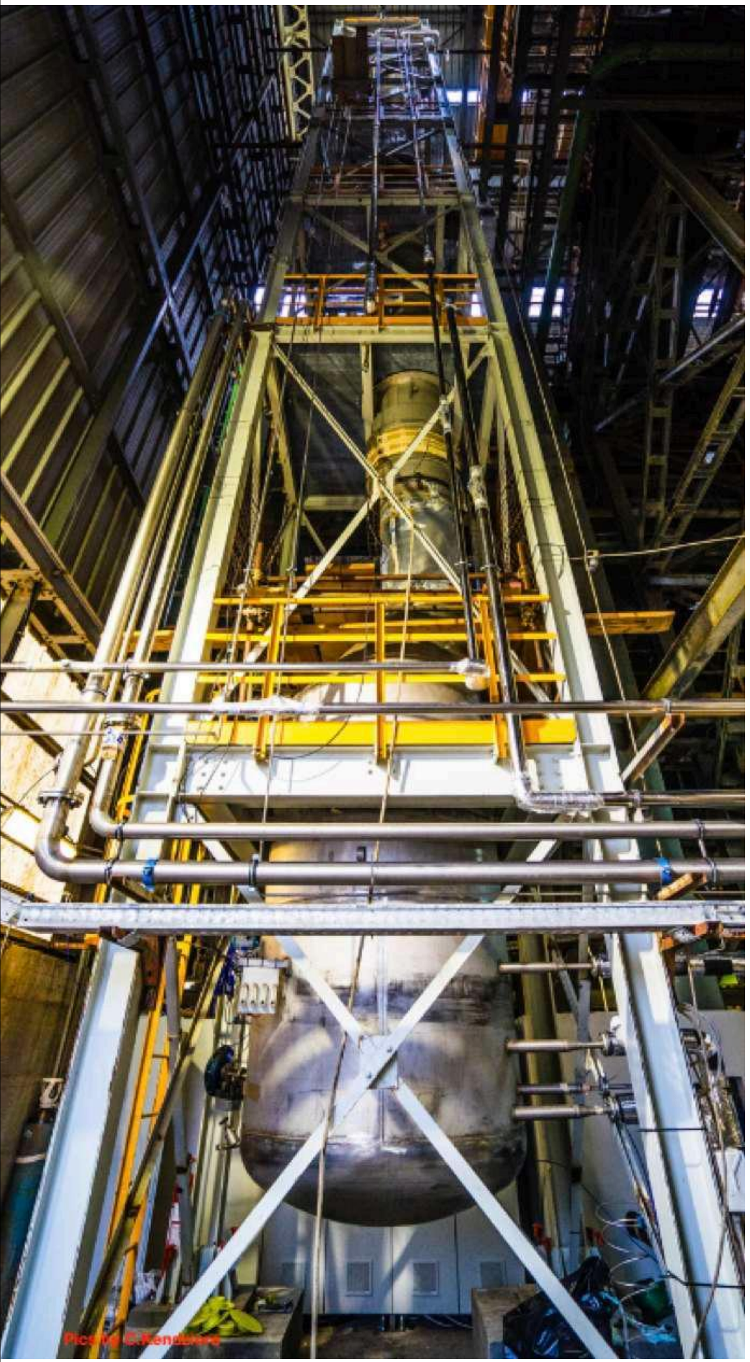


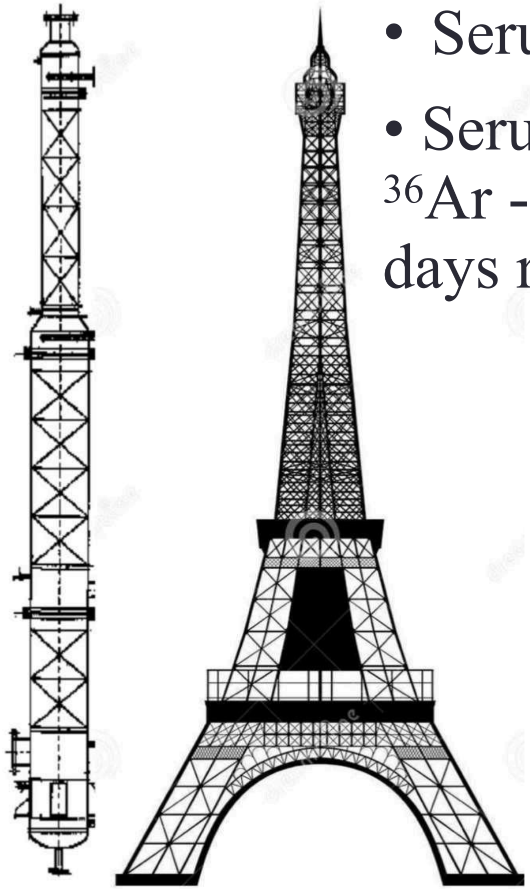
Nucl. Instr. Meth. A 922(2019) 373-384



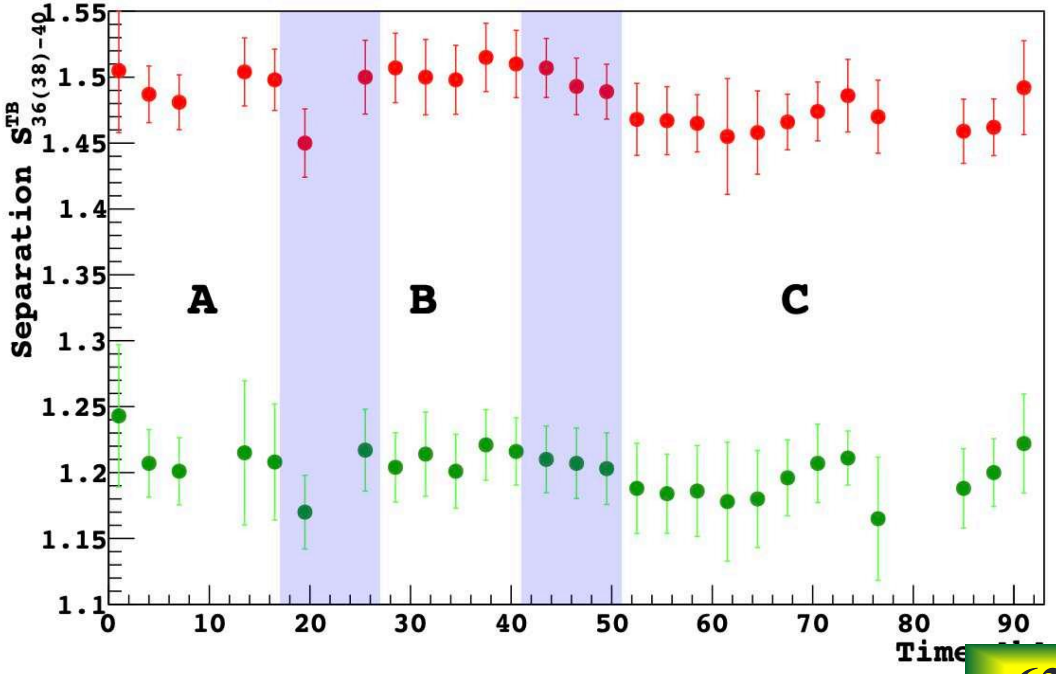
A. Gola et al. Sensors19(2), 308 (2019)

- Expected purity from URANIA: 99.9 %
- At least two more orders of magnitude needed for DarkSide-20k
- **Aria: argon cryogenic distillation plant**
- Seruci-1: 350 m tall distillation column
- Seruci-0: 26 m tall already demonstrated ^{36}Ar - ^{40}Ar separation performances in a few days run



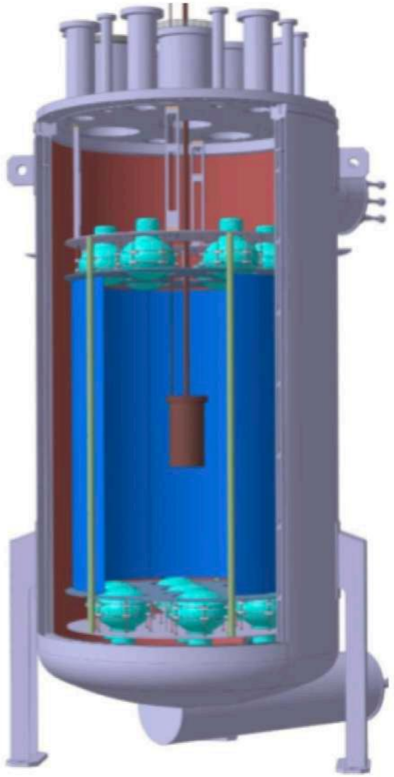


Eur. Phys. J.C 81 (2021) 4, 359



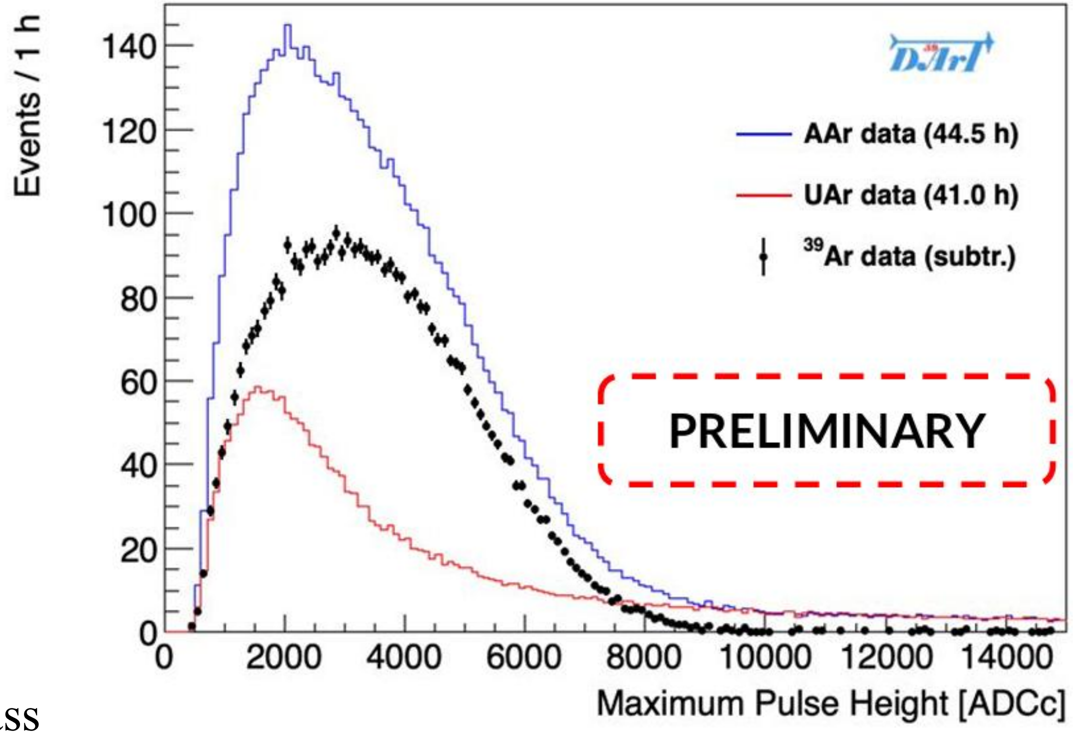
Eur. Phys. J.C 83 (2023) 5, 453

^{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

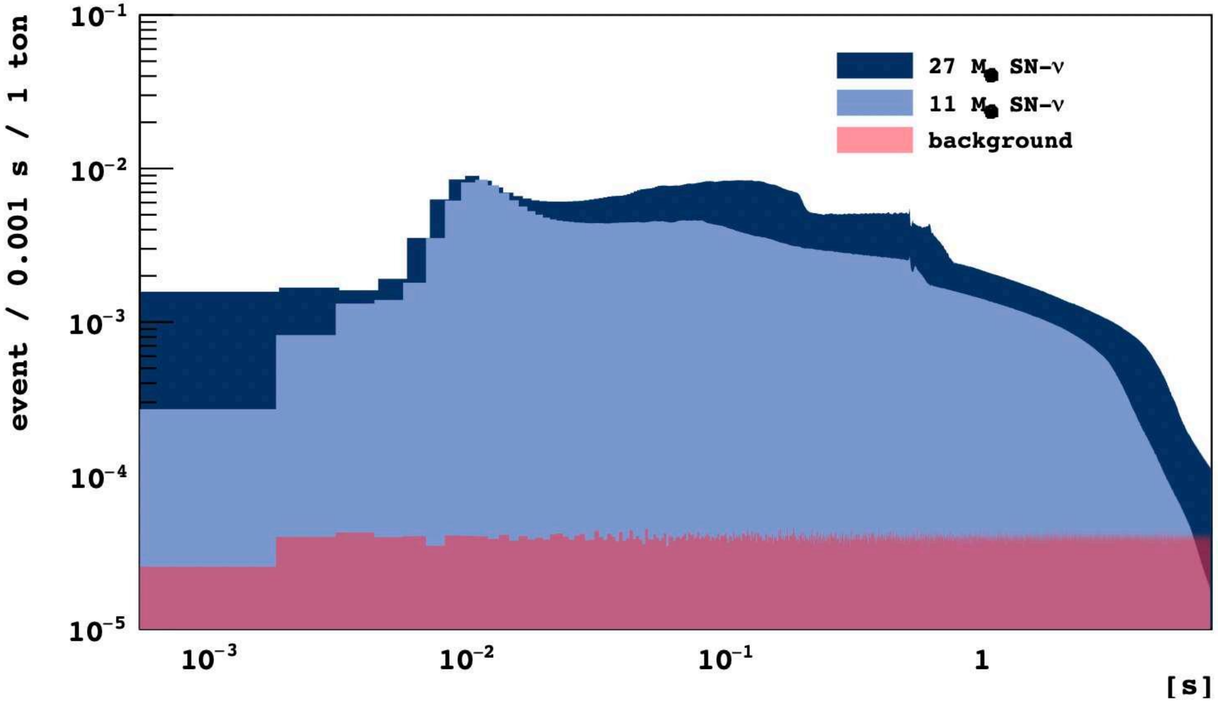
DArT: 1.35 kg active mass



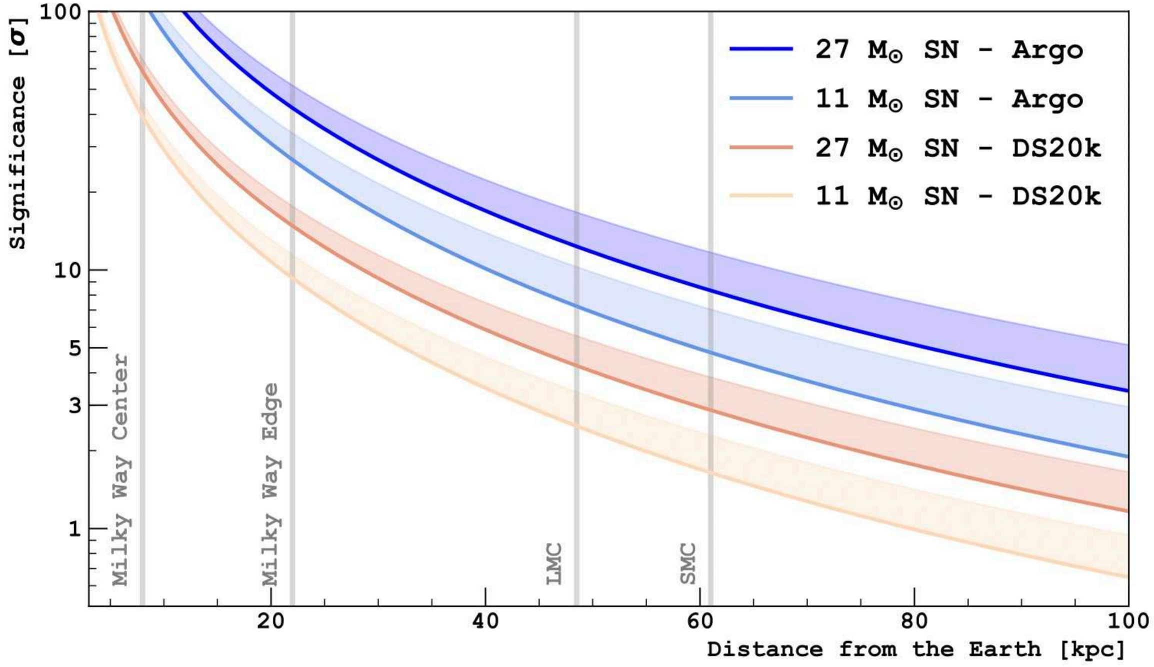
Credits:
D. Gahan - ICHEP 2024

JINST 15 (2020) 02, C02044

Competitive sensitivity to galactic supernova neutrinos performing Coherent Elastic Neutrino Nucleus scattering in the TPC



	DarkSide-20k	Argo
11-$M_\odot$ SN-νs	181.4	1396.6
27-$M_\odot$ SN-νs	336.5	2591.6
^{39}Ar	4.3	33.8
external background	1.8	8.8
single-electrons	0.7	5.1



JCAP 03 (2021) 043

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

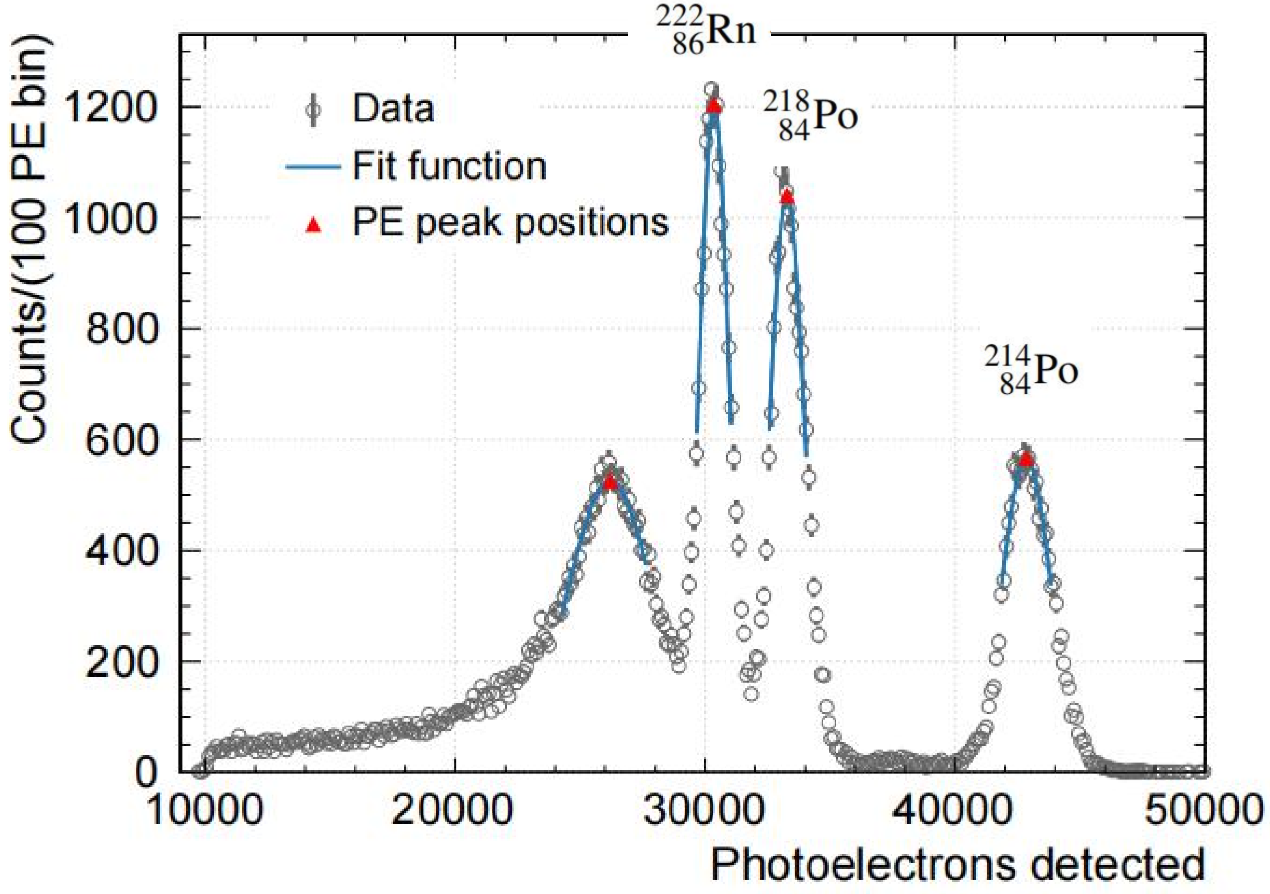
Three data points for the alpha Quenching Factor (QF) in the range (5.489 - 7.686) MeV

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

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

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

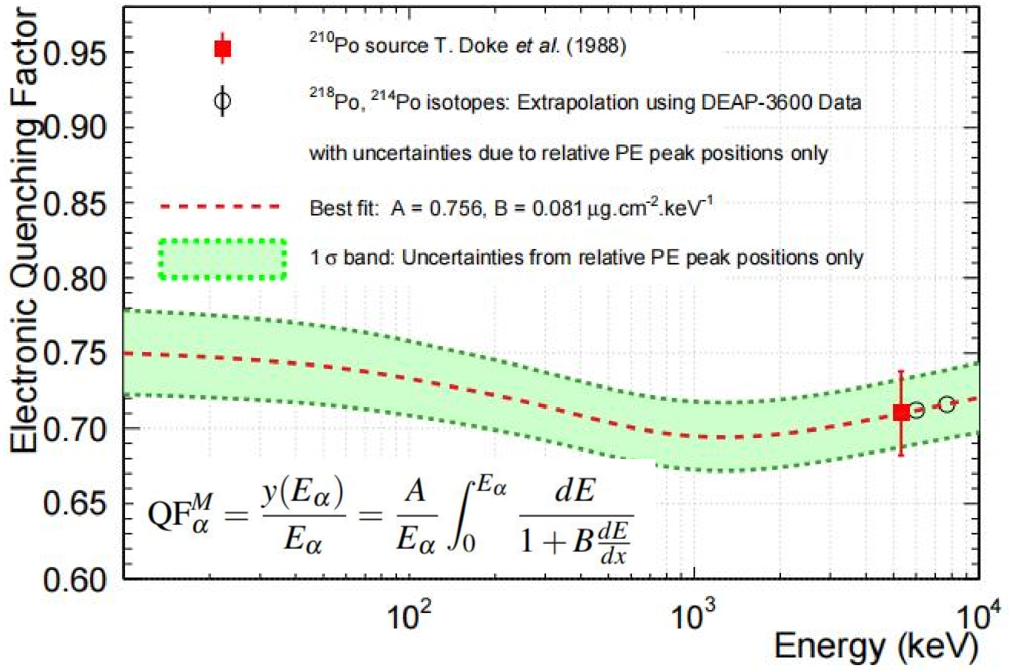
$$\frac{\mathrm{QF}_{\alpha,{}^{214}\mathrm{Po}}}{\mathrm{QF}_{\alpha,{}^{222}\mathrm{Rn}}} = \frac{\mathrm{PE}_{\alpha,{}^{214}\mathrm{Po}}}{\mathrm{PE}_{\alpha,{}^{222}\mathrm{Rn}}} \times \frac{E_{\alpha,{}^{222}\mathrm{Rn}}}{E_{\alpha,{}^{214}\mathrm{Po}}} \equiv R_3 \times \frac{E_{\alpha,1}}{E_{\alpha,3}}.$$

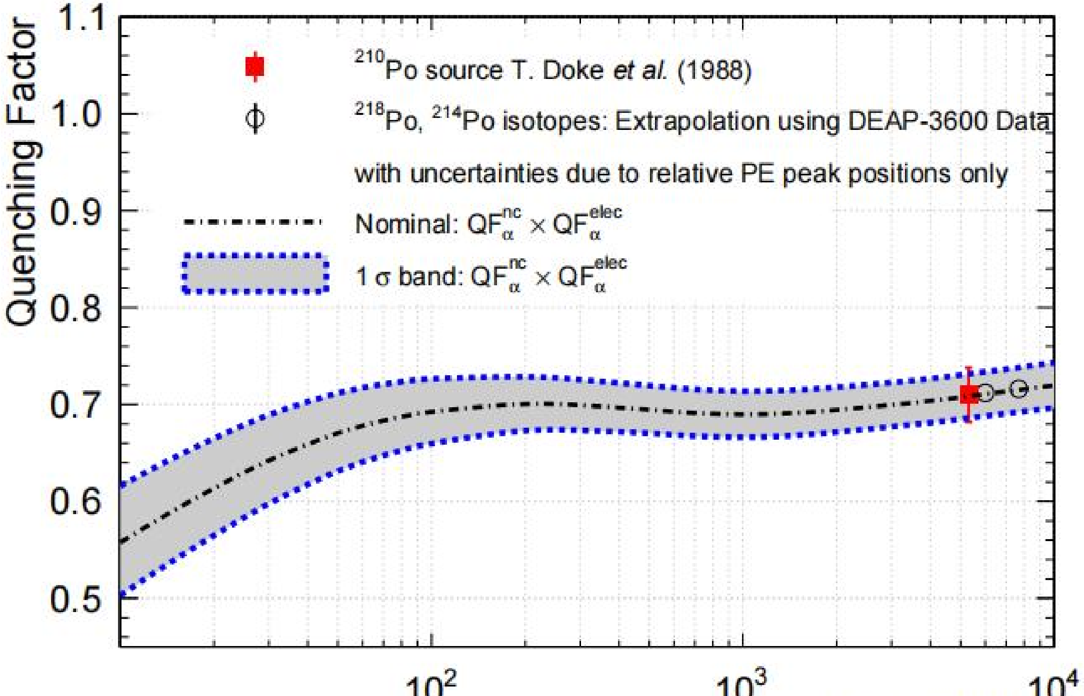


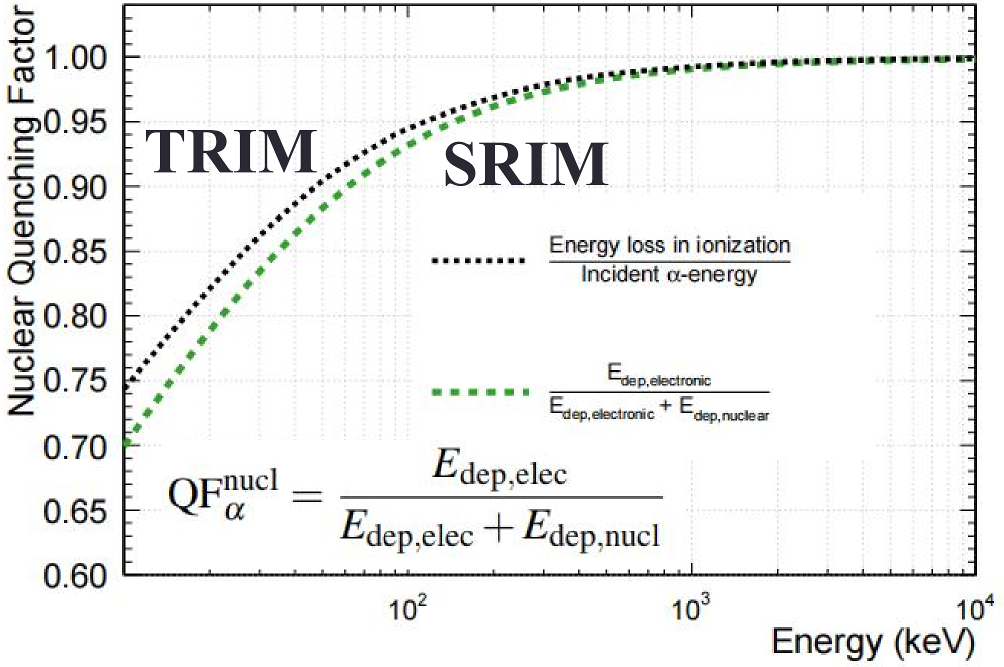
arXiv: 2406.18597v1

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

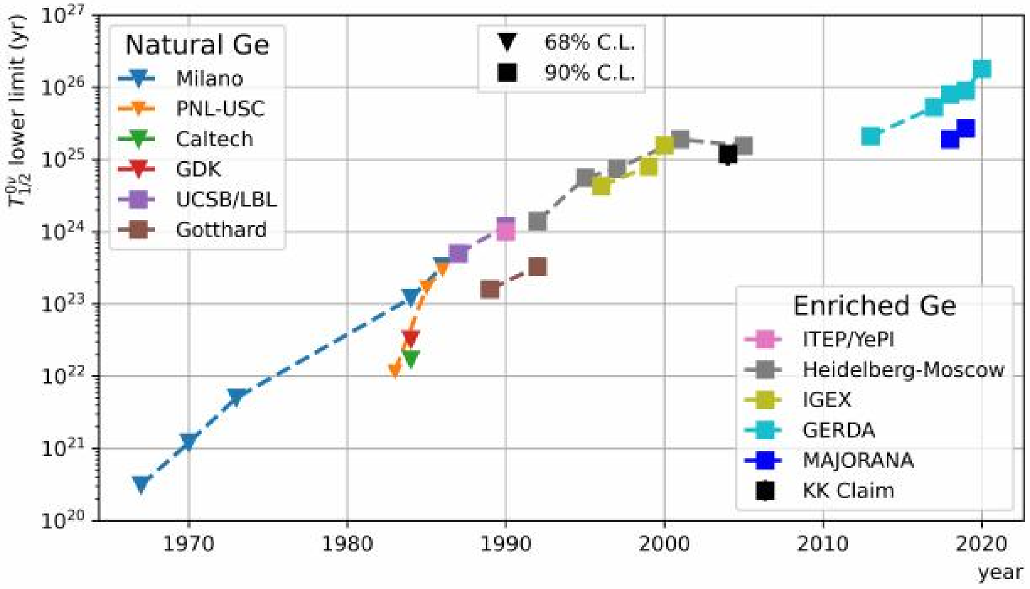
The energy-dependent QF product of the best-fit electronic QF curve and the nuclear QF curve from TRIM

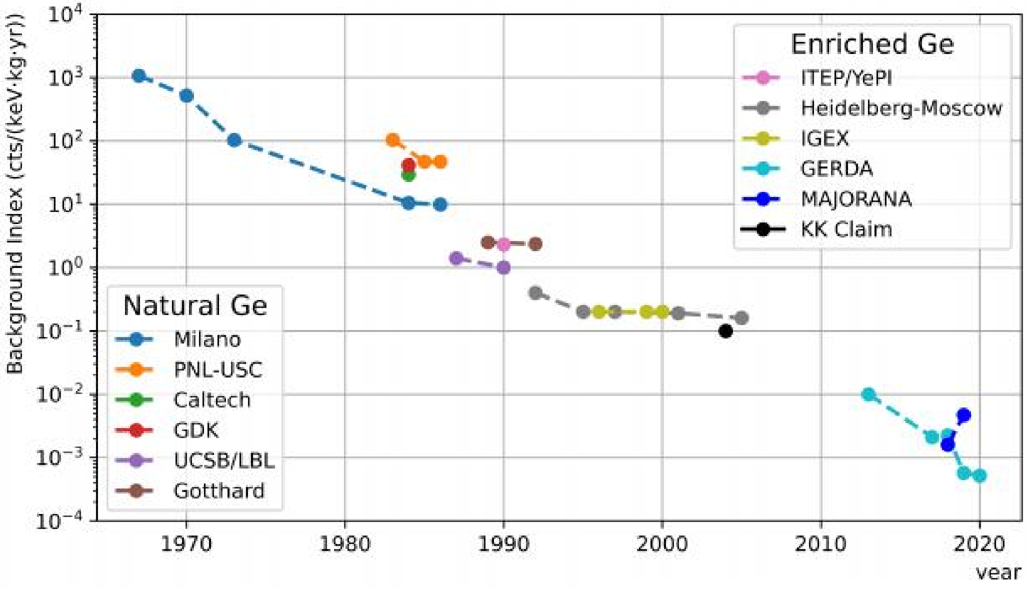


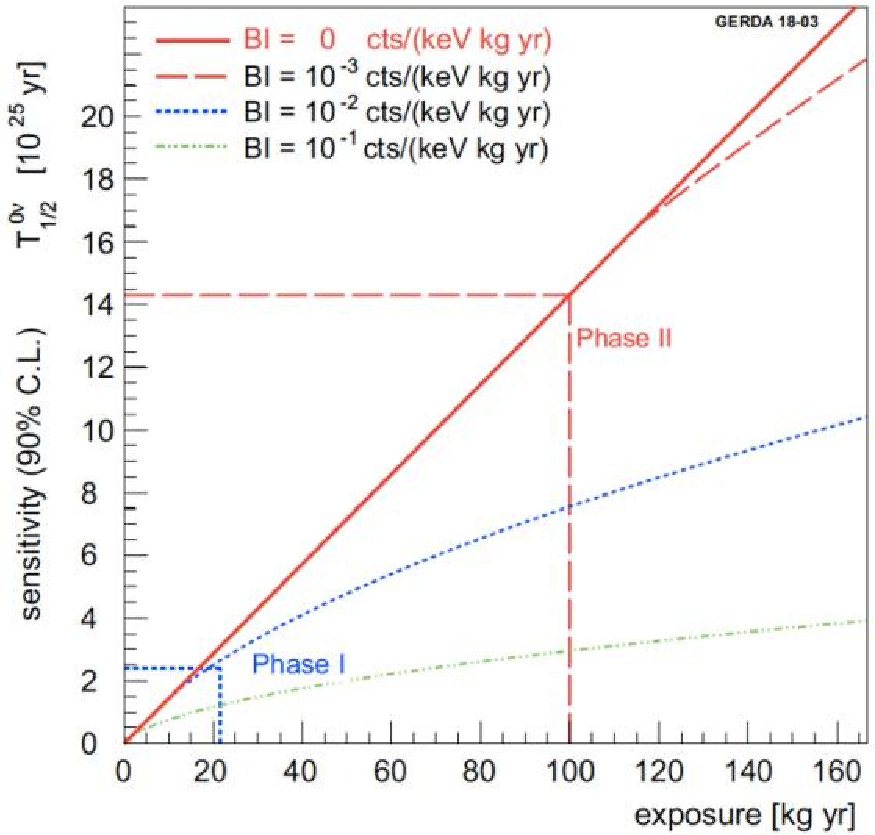




arXiv: 2406.18597v1







$$S^{0\nu} = \ln(2)\ \frac{N_A}{m_A}\left(\frac{\varepsilon\, a}{n_\sigma}\right)\sqrt{\frac{M\ T}{\mathrm{BI}\ \Delta E}}$$