Search for Dark Matter with liquid argon detectors

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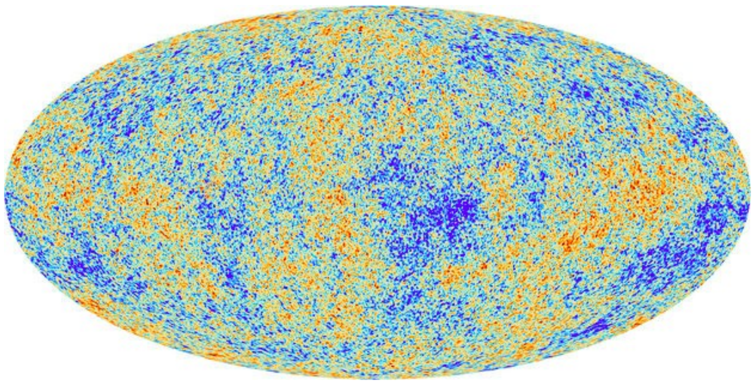
Dark Wave

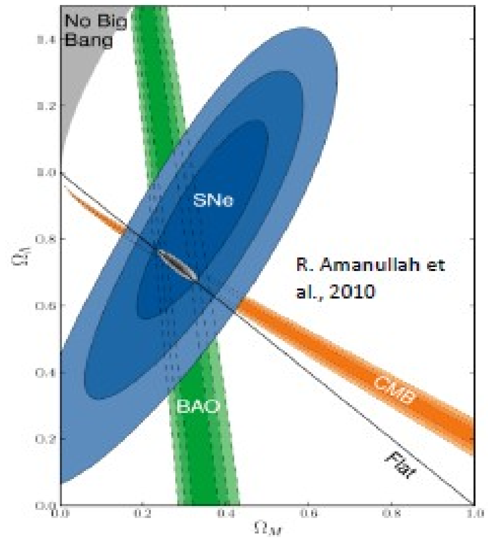
Outline

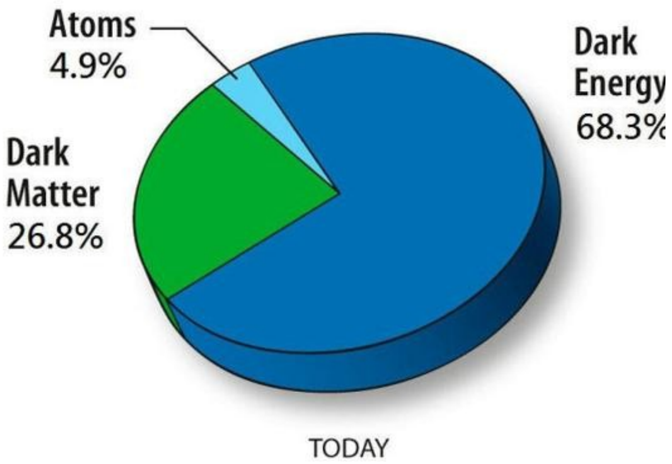
- Evidence and candidates for dark matter
- Direct detection of dark matter
- Advantages of noble liquid detectors
- DEAP-3600 experiment
- Latest results DarkSide-50, XENON1T and LZ
- Under construction: DarkSide-20k
- Future: ARGO, DarkSide-LM
- Summary

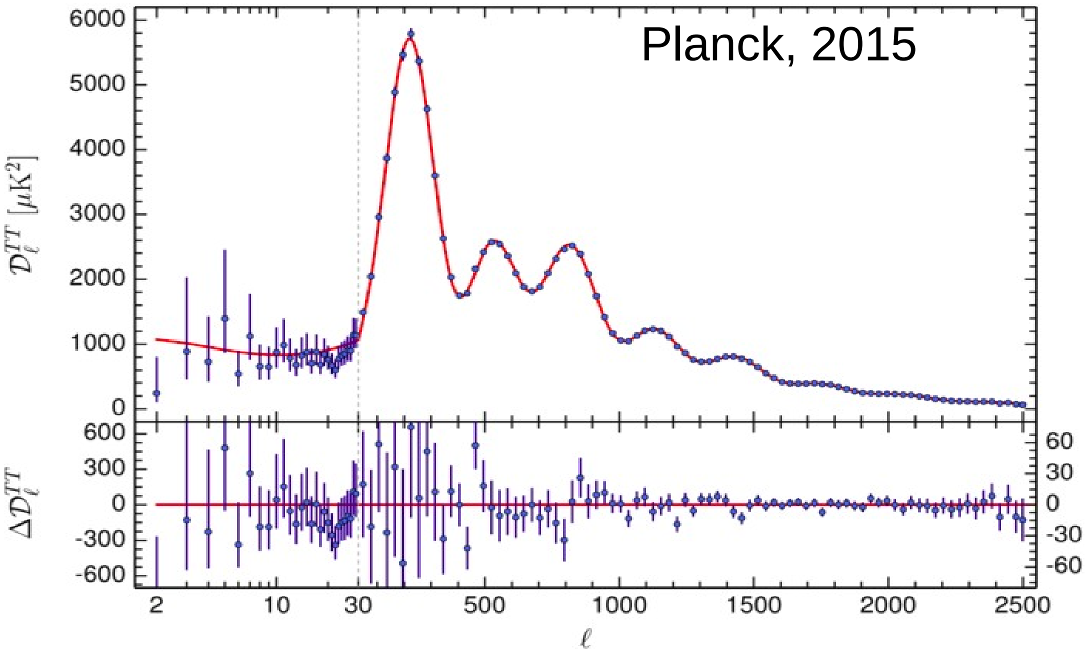
Evidence for Dark Matter

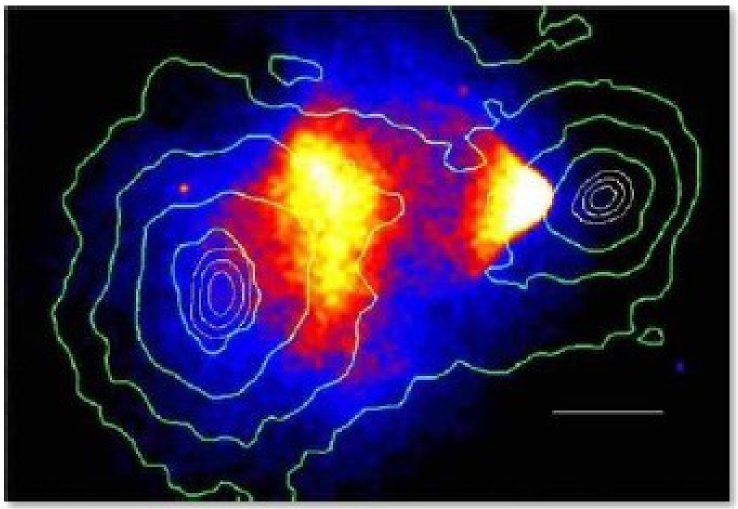
- Cosmic microwave background (CMB) observations, resulting in precise estimates (WMAP, Planck) supporting ΛCDM model







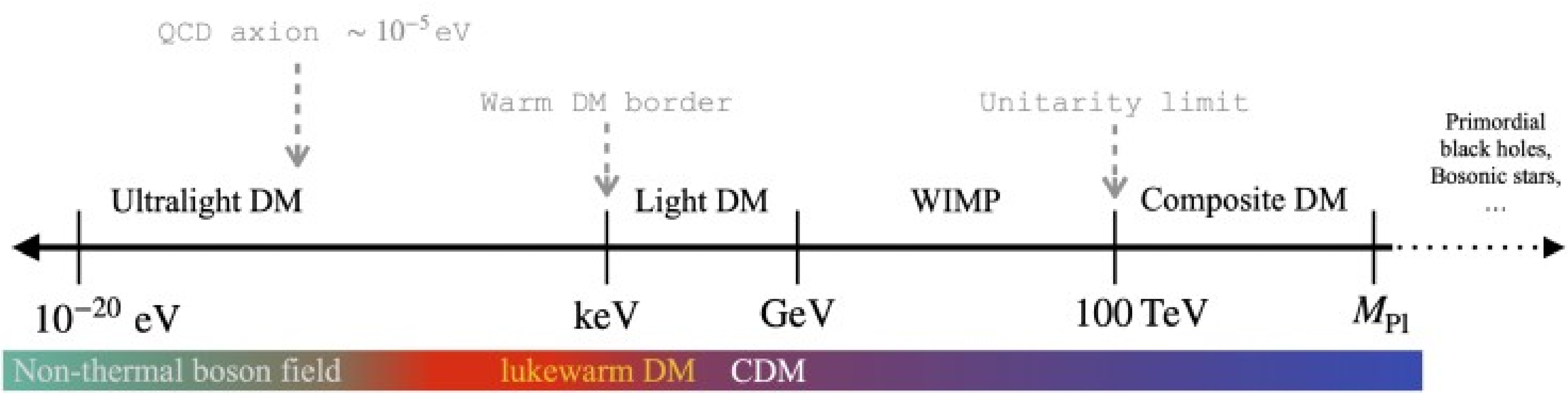




The bullet cluster, D. Clowe et al., 2006

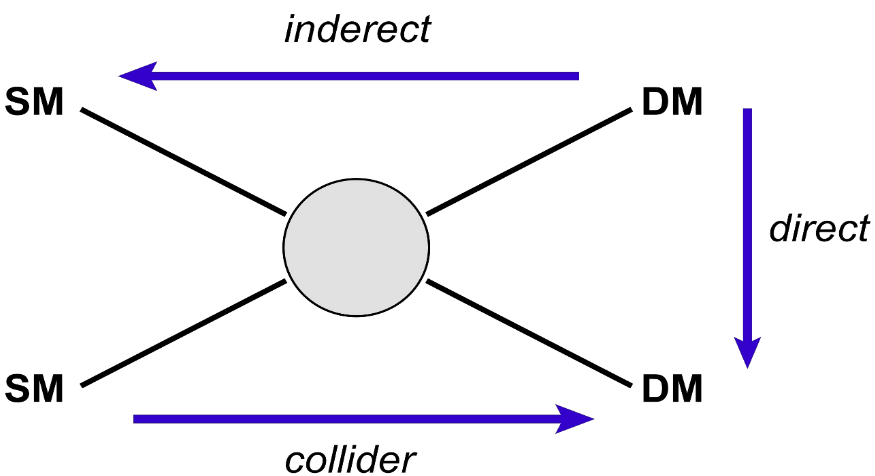
What is Dark Matter?

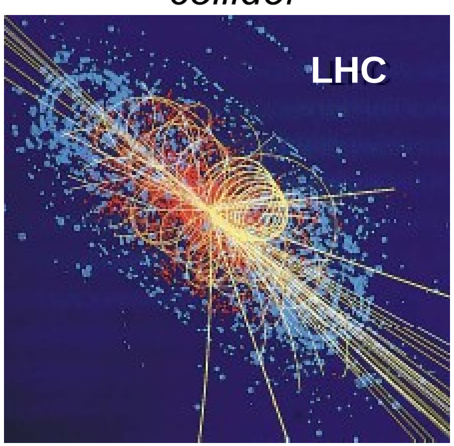
- A number of possibilities considered and excluded:
  - Modifications of the gravity law (MOND)
  - Massive compact halo objects (MACHOs)
- Primordial black holes
- New Particles. Options include:
  - Axions
  - **Weakly Interacting Massive Particles (WIMPs)**
  - ...



K. Tuominen, Symmetry 2021, 13, 1945

Ways to look for Dark Matter particles

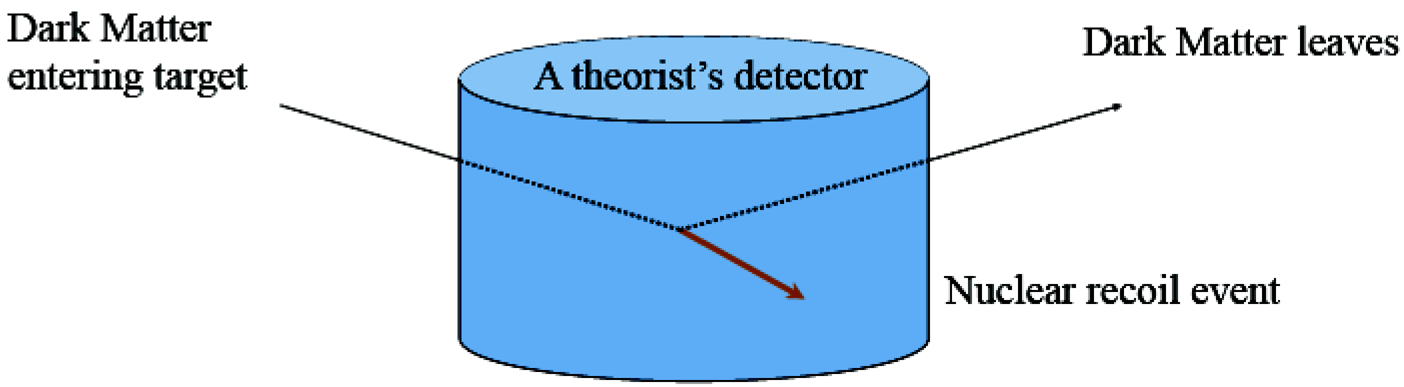




- Indirectly via their annihilation in Sun, Earth, Galaxy
  - Neutrinos (IceCube, Antares)
  - Positrons, antiprotons (AMS)
  - γ-rays (Fermi-LAT, CTA)
- **<u>Direct detection</u>**
- By producing them at accelerators (LHC)

WIMP direct detection

(for **WIMPs** - **W**eakly **I**nteracting **M**assive **P**articles)



- Only through rare interactions with ordinary matter
- After the interaction, recoiling nucleus deposits energy in the detector: **heat, light, electric charge, ...**

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

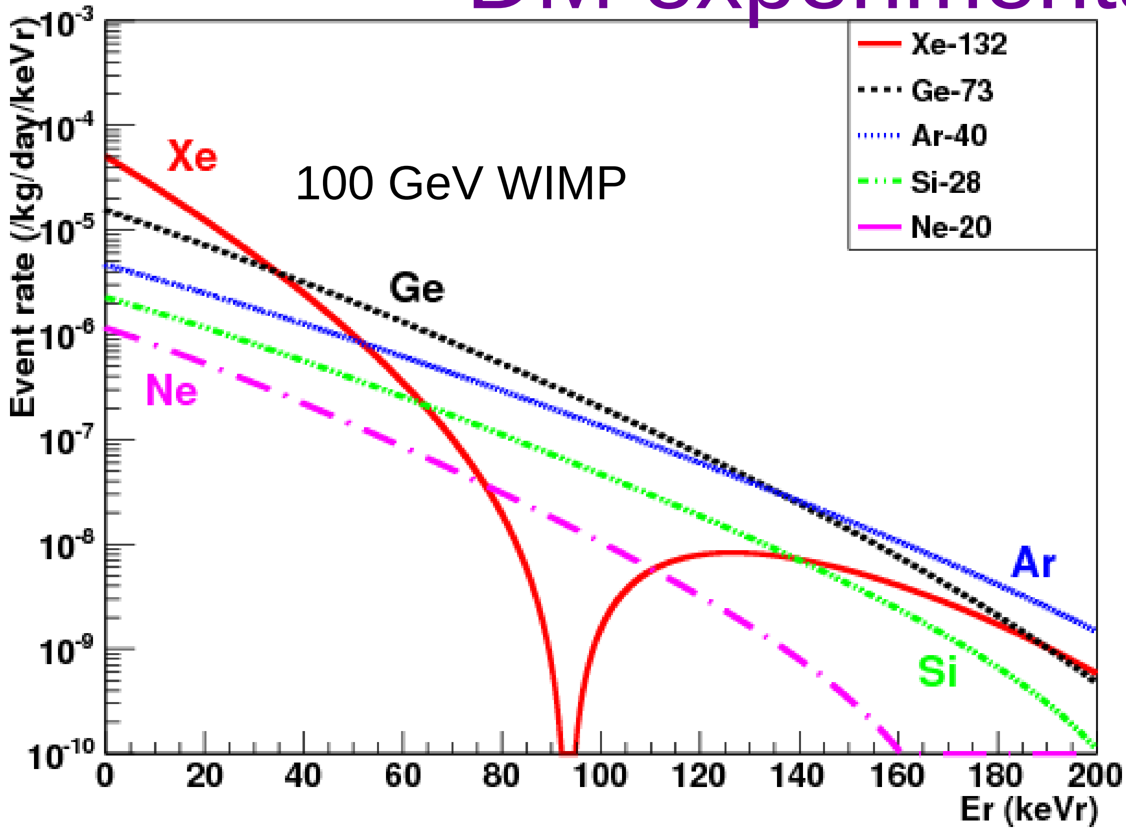
Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany

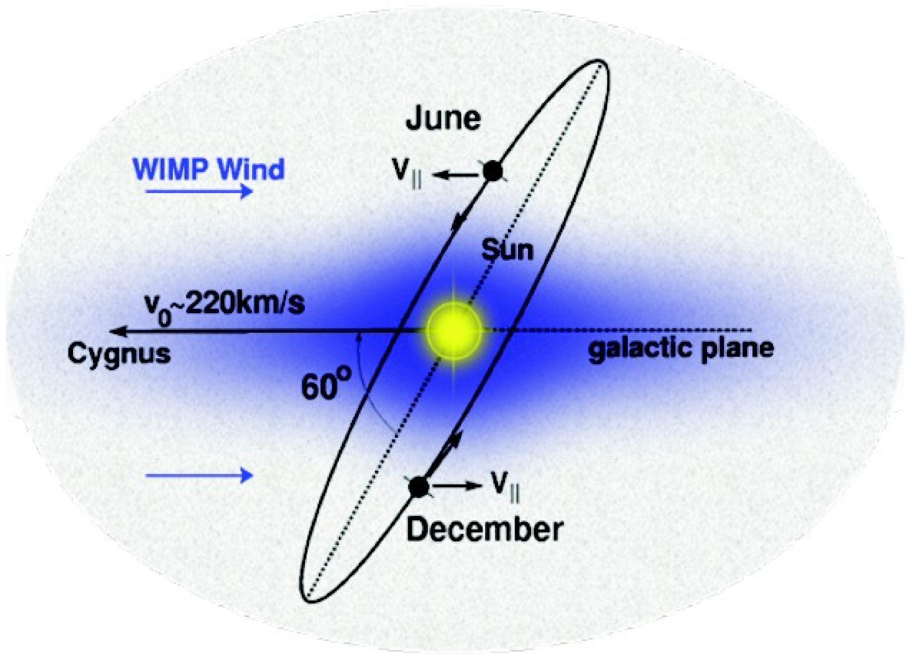
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

DM experimental signature



Nuclear recoil spectrum
- featureless, ~exponential
- lower threshold => more sensitivity
- natural radioactivity is background



Directionality
=> annual modulation of the signal

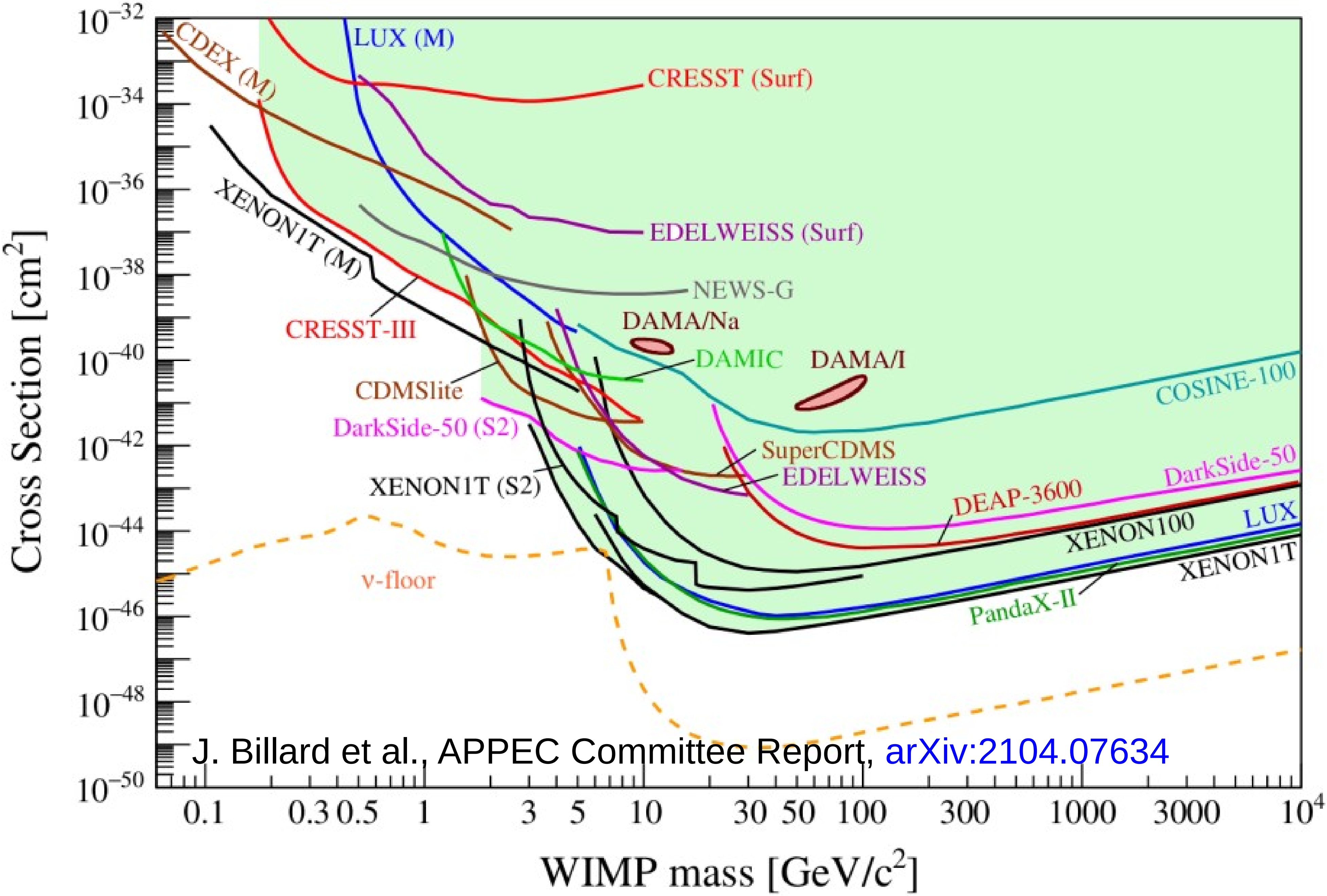
astrophysics

$$\frac{dR}{dE_R} = N_T \int_{v_{min}}^{\infty} dv\, v\, \Phi(v,v_E)\, \frac{d\sigma}{dE_R}\, \varepsilon(E_R)$$

detector response

particle/nuclear physics

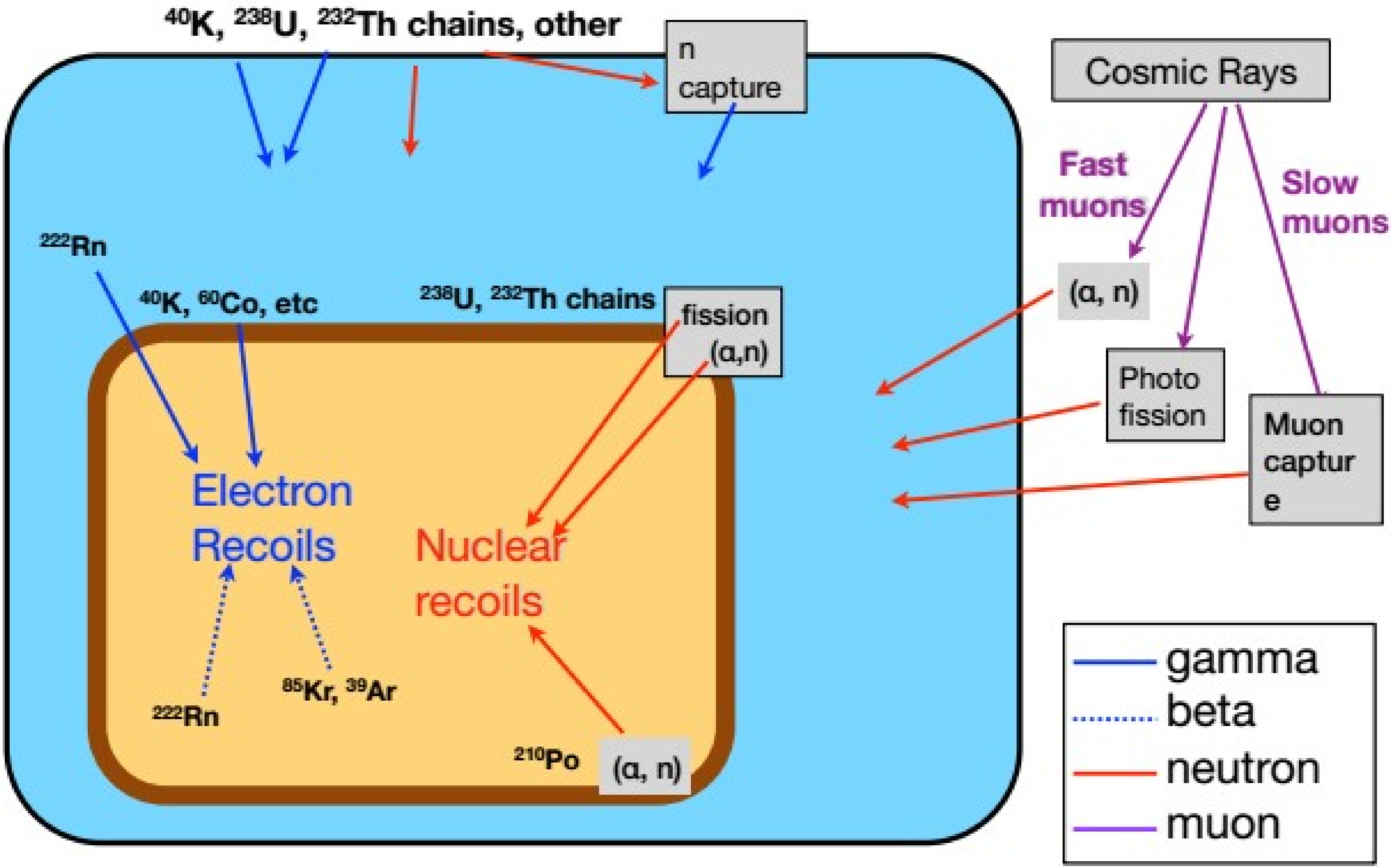
Direct detection: current landscape



J. Billard et al., APPEC Committee Report, arXiv:2104.07634

Spin-independent, with the usual assumptions: Standard Halo Model, isospin parity

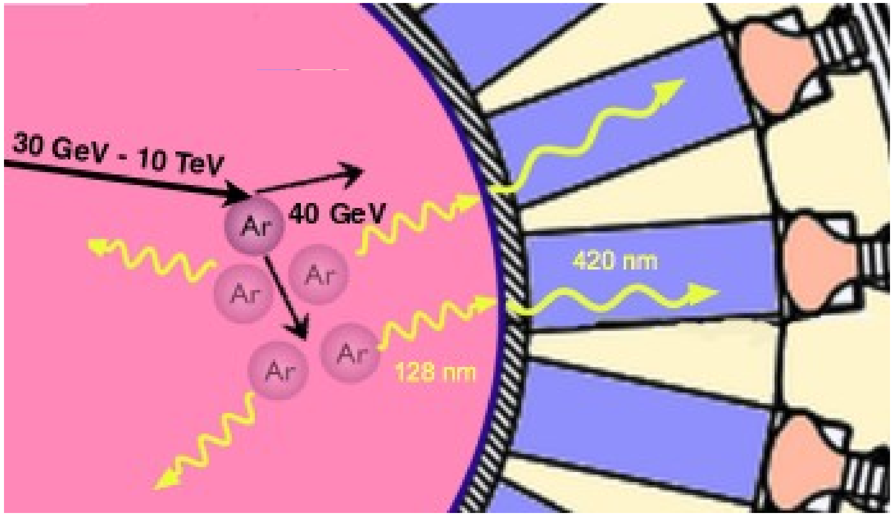
Backgrounds

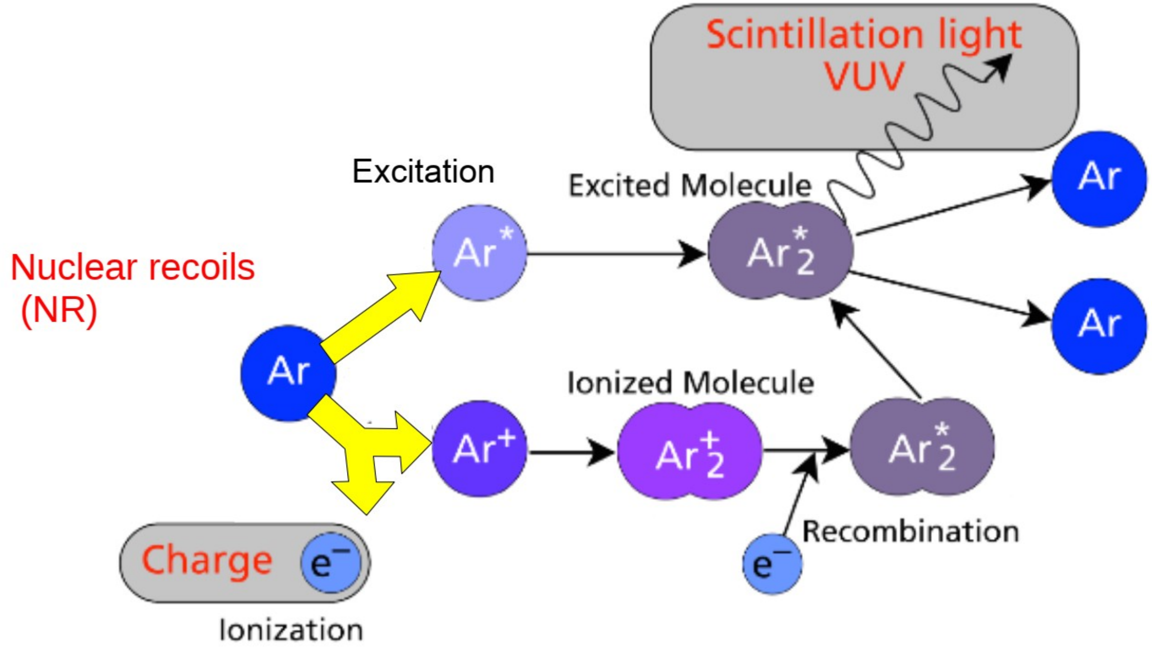


Ambient backgrounds: 10^{11} time DM rate

T. Shutt -LIDINE, Sept 22, 2017

Liquid noble detectors





Ar and Xe are used for WIMP detection.

- Ar inexpensive and advantageous for purification and background rejection

Why noble elements?

- High light yield, transparent to their own scintillation
- Easy to purify and scalable to very high masses
- (At least) two available detection channels: scintillation and ionization

Pulse shape discrimination (PSD)

Ar singlet and triplet excited states have well separated lifetimes (6ns vs. ~1.5us)

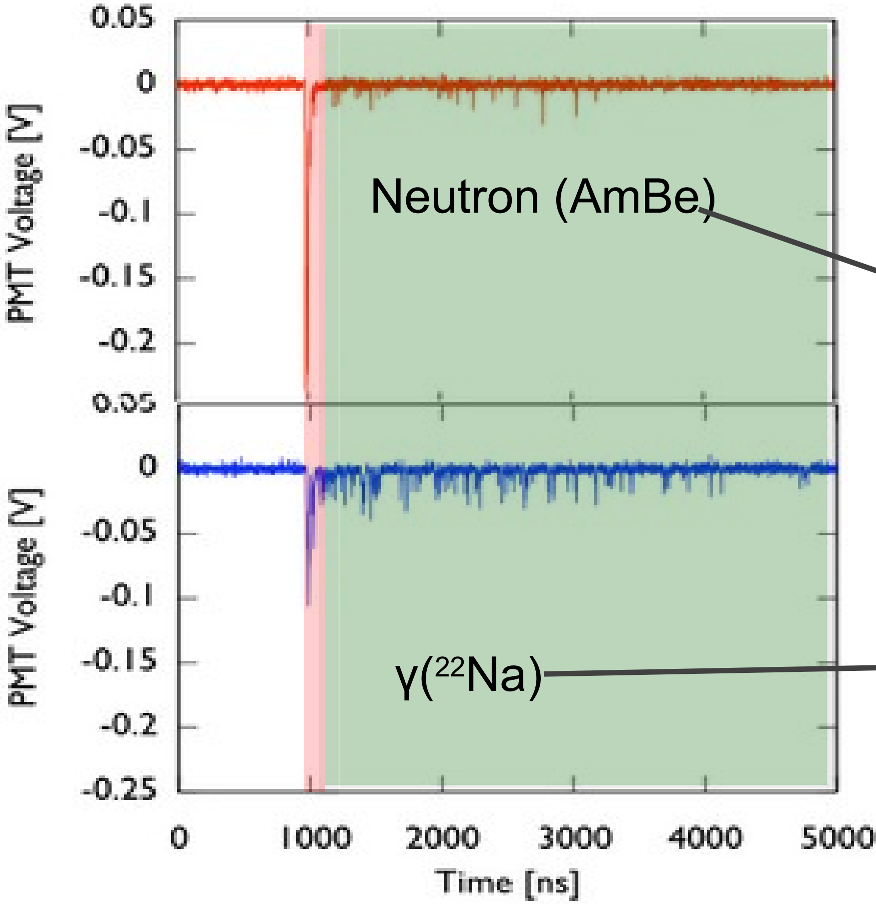
Single phase LAr:
scintillation channel is sufficient for β/γ rejection
no need for the ionization channel

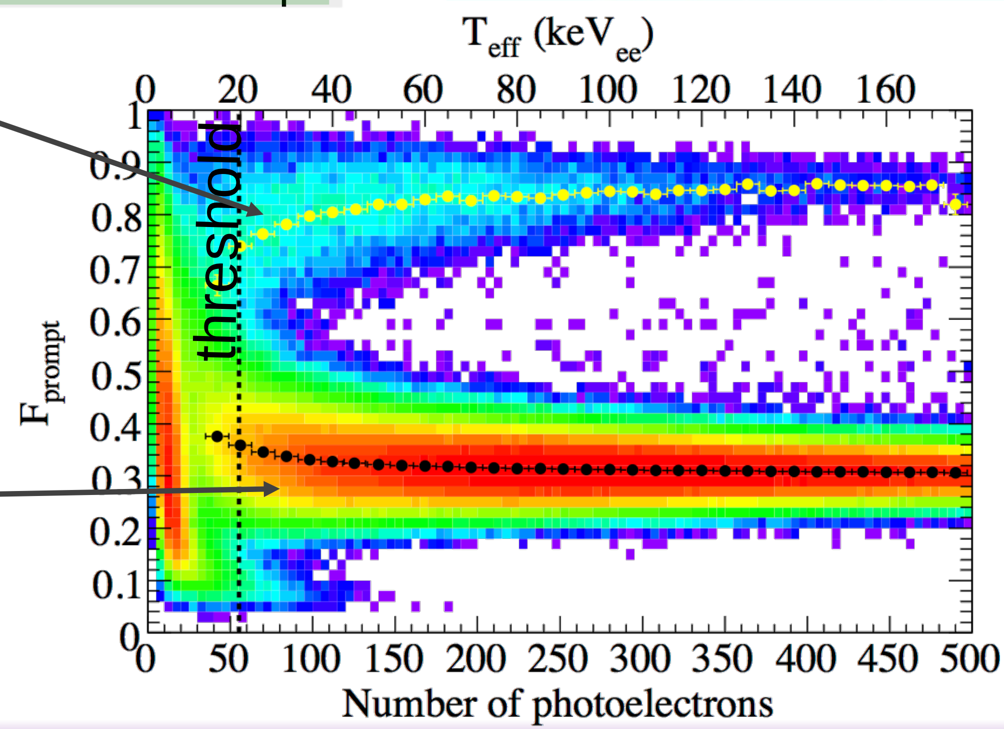
Parameter	Ar	Xe
Yield (x10^4 photons/MeV)	4	4.2
Prompt time constant τ_1	6 ns	2 ns
Late time constant τ_3	**1.5 μs**	21 ns
I_1/I_3 for electrons	0.3	0.3
I_1/I_3 for nuclear recoils	3	1.6
λ(peak) nm	128	174
Rayleigh scattering (cm)	90	30

$$\mathrm{FPrompt} = \frac{N_{prompt}}{N_{prompt} + N_{Late}}$$

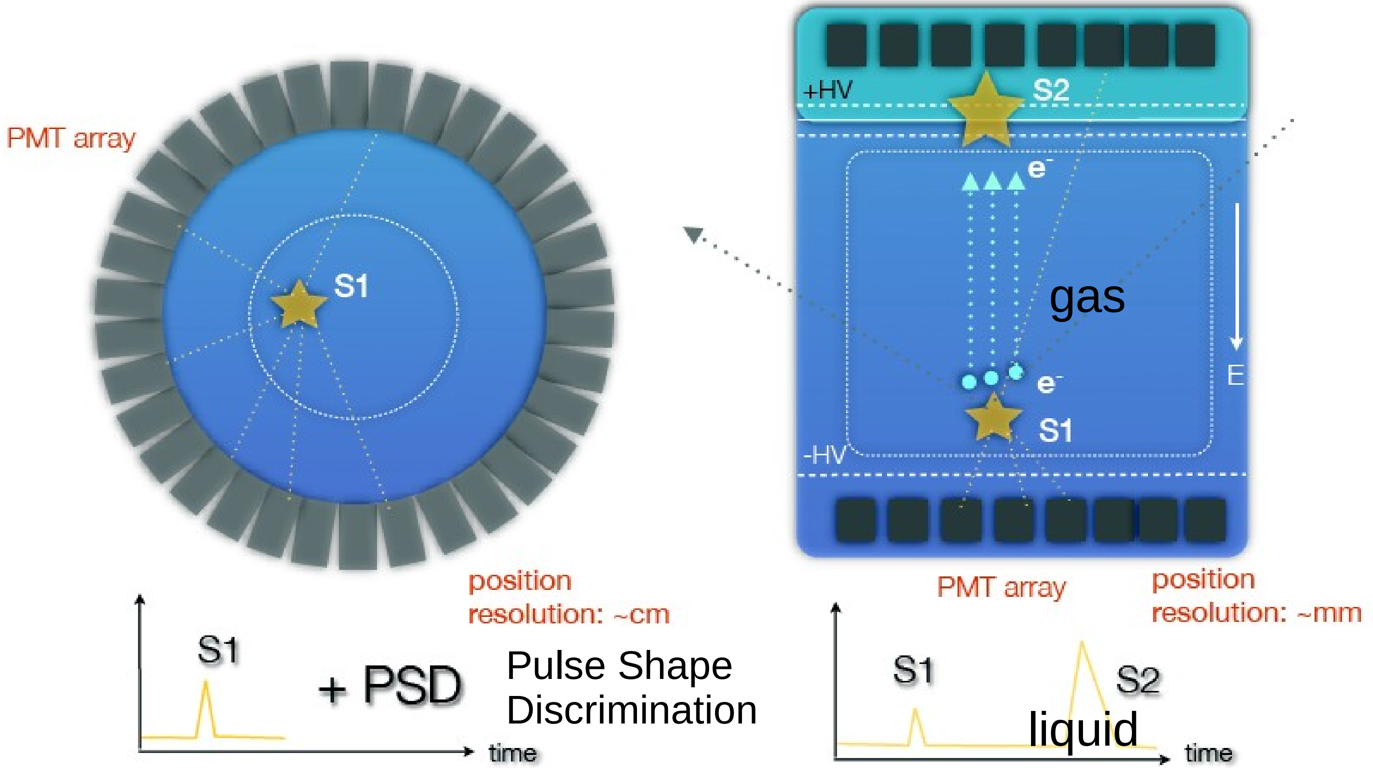
PMT signal:

Prompt : 0-150ns
Late: 150ns-10μs





Single vs. dual phase



- Detect primary scintillation light (S1) from the original event. Ionization charge then drifted to high field region and converted to secondary scintillation (S2) in gas phase
- Time difference S2-S1 and top PMTs used to localize event (time projection chamber)
- Electronic recoil discrimination:
  - S2/S1 in Xe
  - In Ar PSD on S1 only is superior (S2 still used for position reconstruction)
- Dual phase
  - has better position resolution
  - low thresholds available with S2-only analysis (if low background)
- **Single phase is more scalable.**

LXe detectors

2010

XENON10 (LNGS)

ZEPLIN II (Boulby)

ZEPLIN III (Boulby)

10 kg

100 kg

XENON100 (LNGS)

LUX (250 kg, **SURF)**

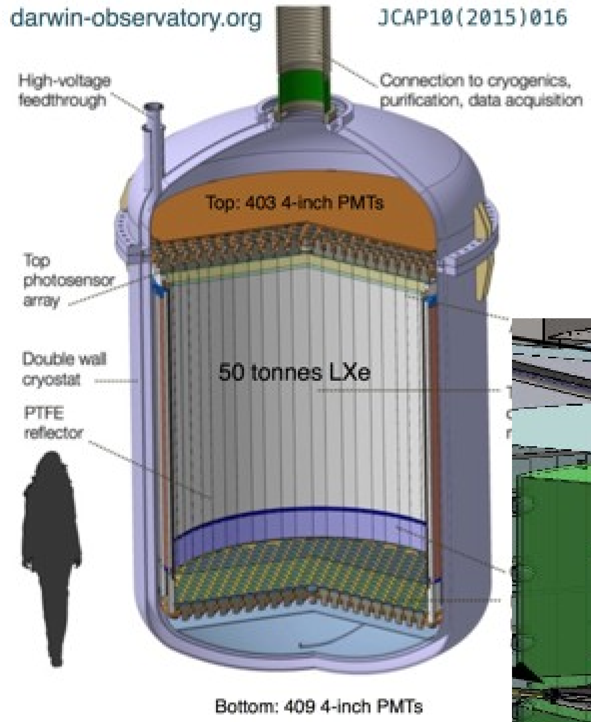
PandaX
(500 kg, CJPL)

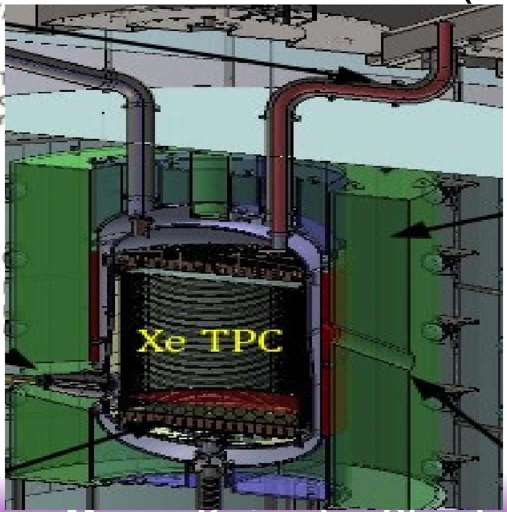
2015

XMASS
(0.8t, Kamioka)

1000 kg

XENON1T
(1t, LNGS)





PandaX-4 (4t, CJPL)

2020

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

10000 kg

DARWIN? XLZD?: ~50 t

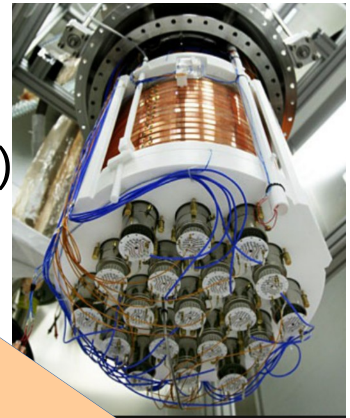
Slide courtesy J. Monroe

LAr detectors

2010

10 kg

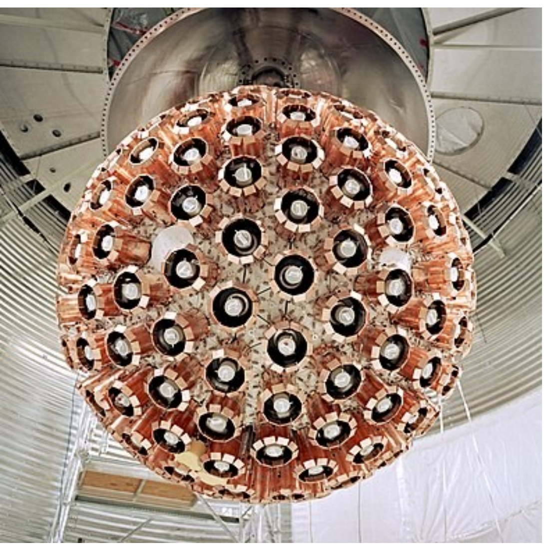
DarkSide-50
(50 kg, LNGS)



100 kg

ArDM (1t, LSC)

- More than 300 scientists from 15 countries and 60 institutions
- Officially supported by underground labs: LNGS, LSC, and SNOLAB

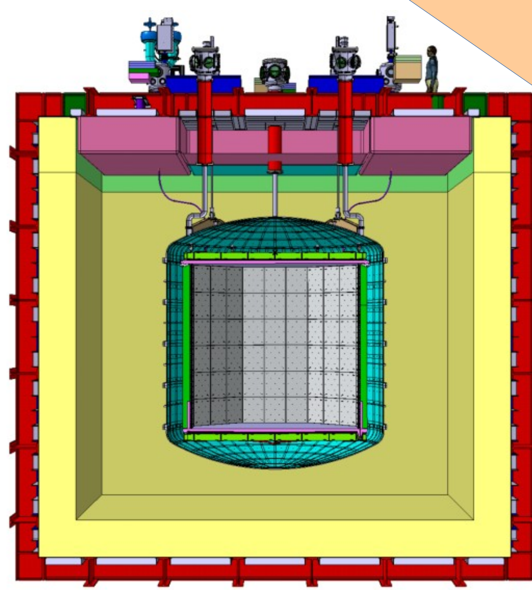


1000 kg

2015

DEAP-3600 (3.3t, SNOLAB)

Global Argon Dark Matter Collaboration formed



2020

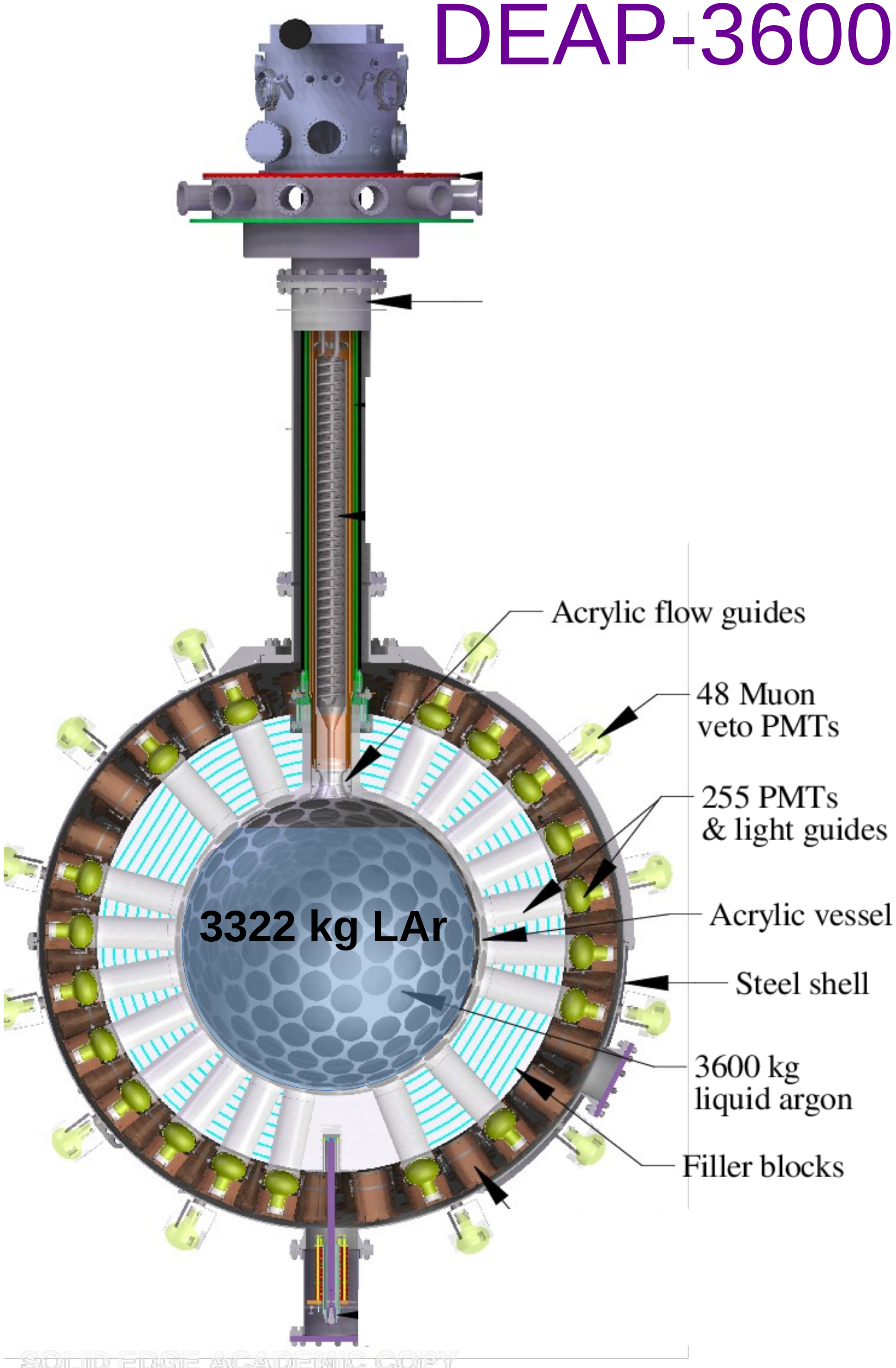
DarkSide-20k
(50t, LNGS)

100000 kg

Argo: 400 t

Slide courtesy J. Monroe

DEAP-3600 Dark Matter Search



- 3.3 tonne liquid argon target (1000 kg fiducial) in sealed ultraclean Acrylic Vessel
- 128 nm scintillation from liquid argon is detected after converting it to visble

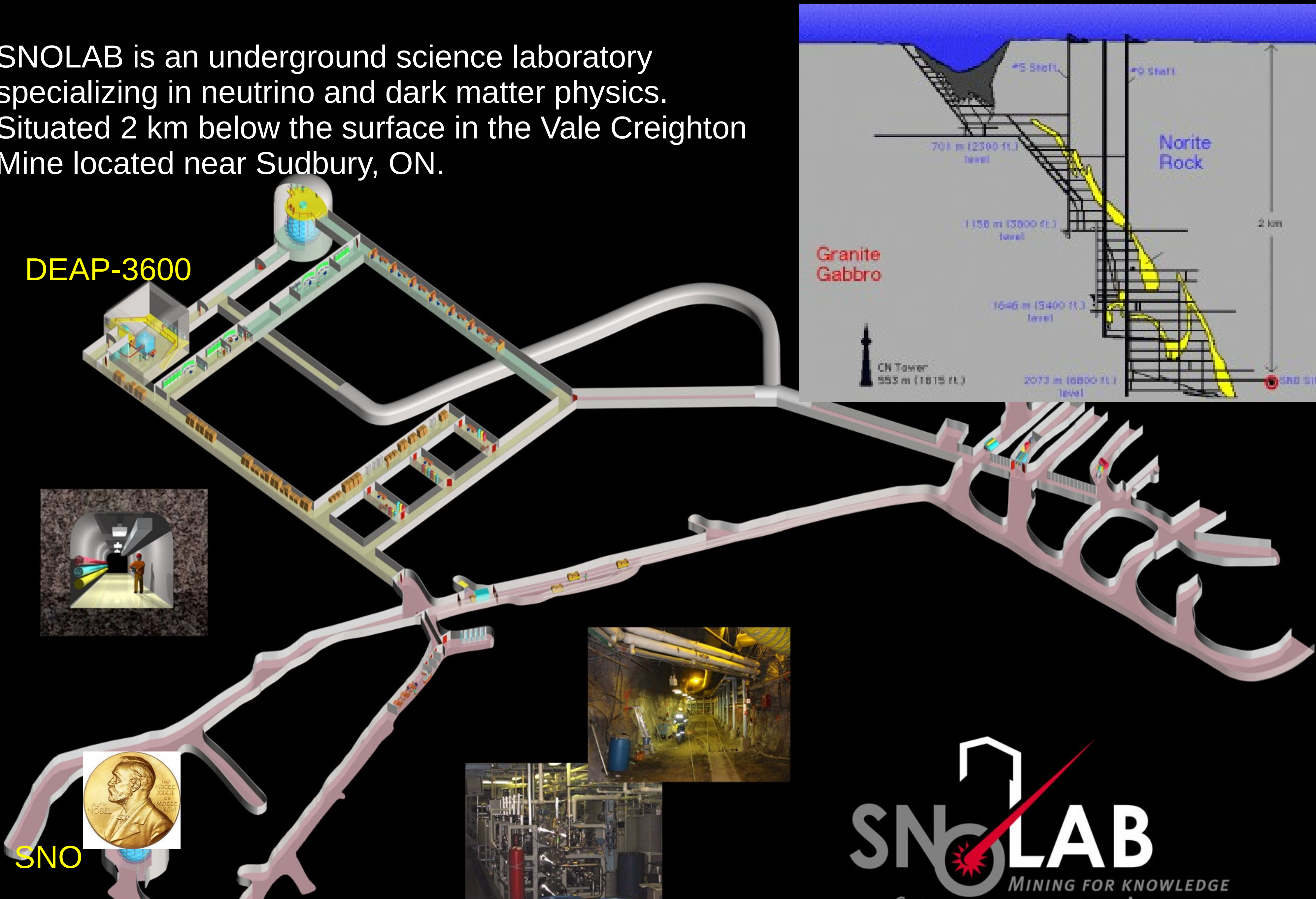
)

- In-situ vacuum evaporated TPB wavelength shifter (~10 m^2 surface)
- Bonded 50 cm long light guides + polyethylene shielding against neutrons
- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)
- Detector immersed in 8 m water shield, instrumented with PMTs to veto muons
- Located 2 km underground at SNOLAB
- ~100 scientists from Canada, UK, Mexico, Germany, US, Italy, Spain, Russia, Poland

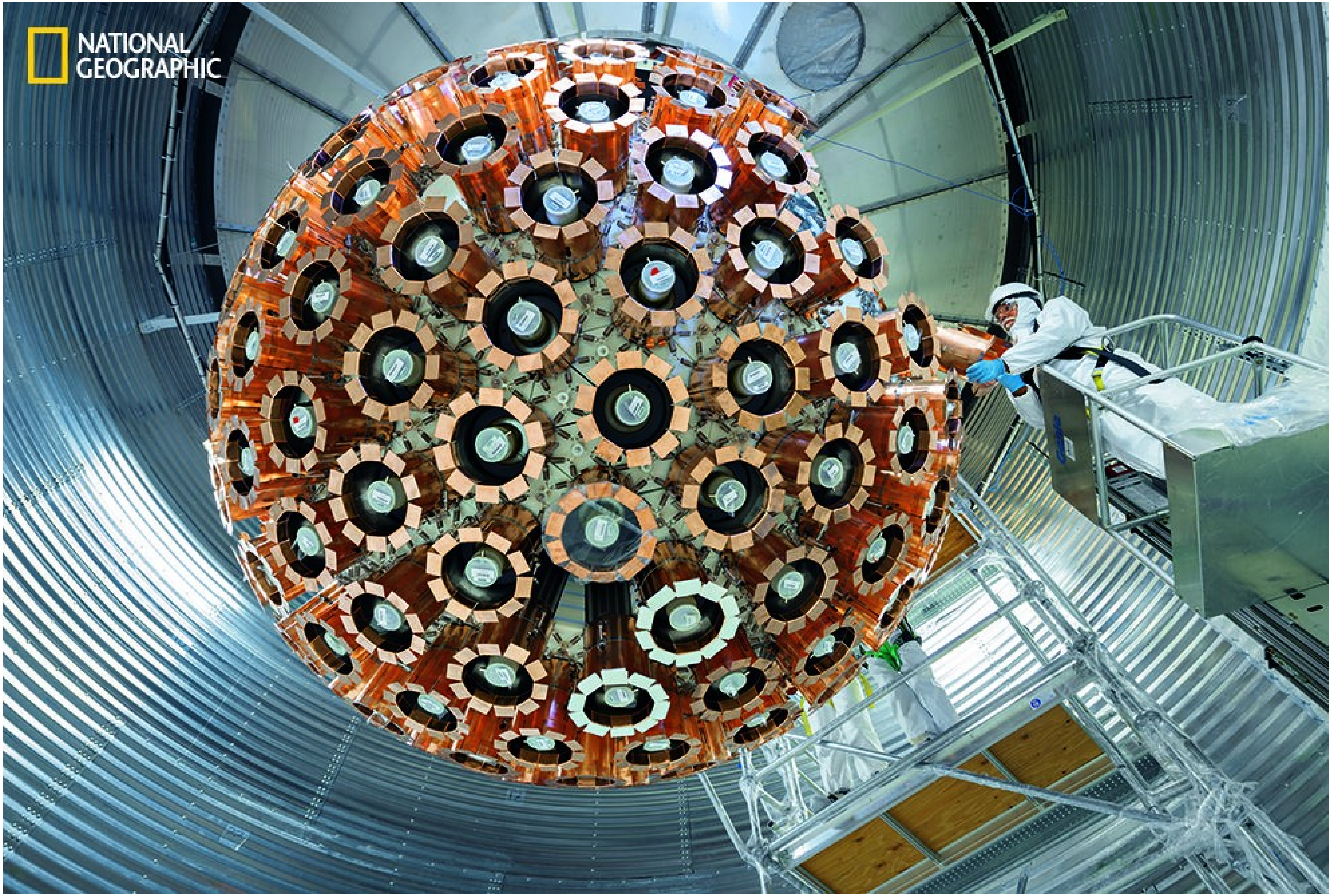
DEAP-3600 construction

SNOLAB

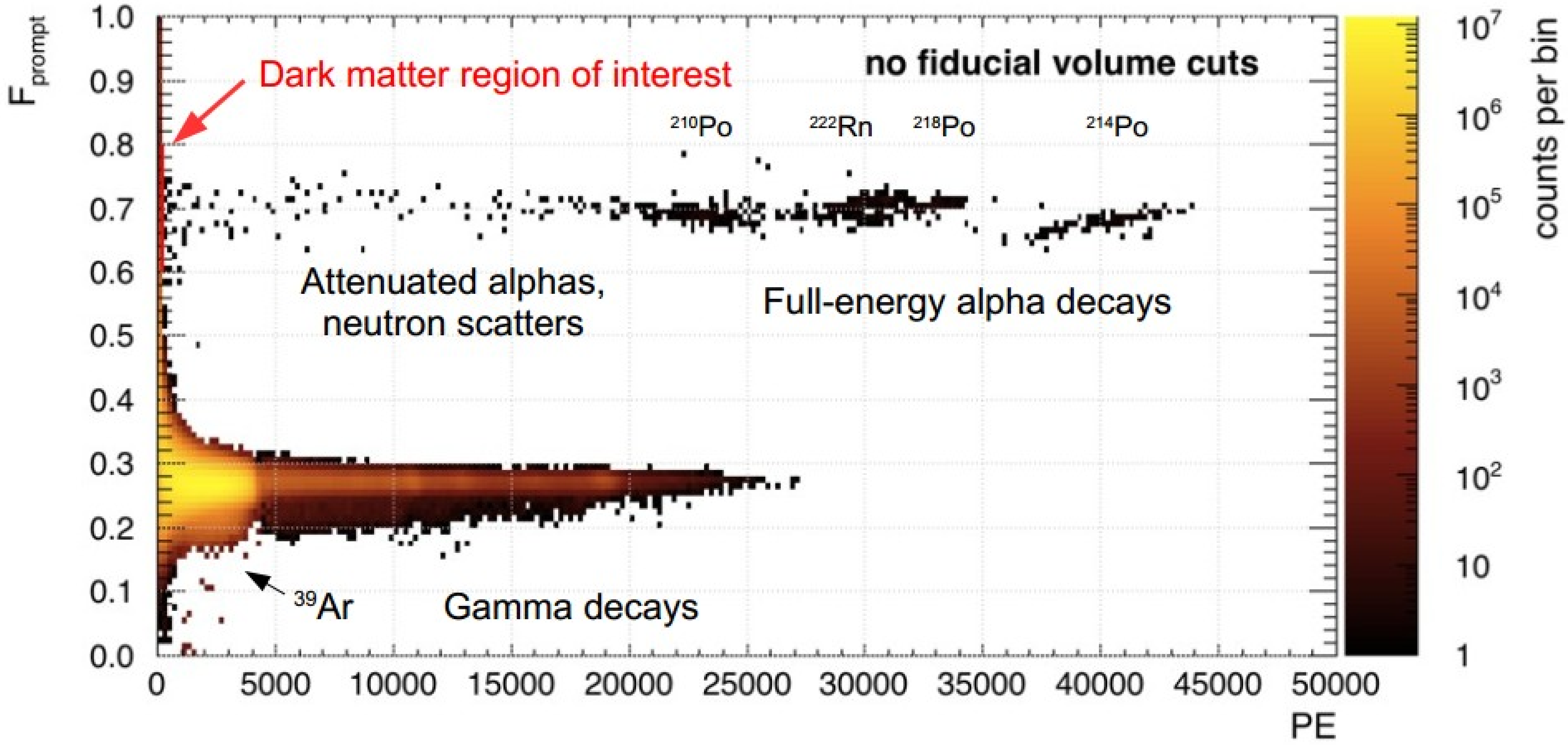
SNOLAB is an underground science laboratory specializing in neutrino and dark matter physics. Situated 2 km below the surface in the Vale Creighton Mine located near Sudbury, ON.



DEAP-3600 construction highlights



Event populations and their signatures

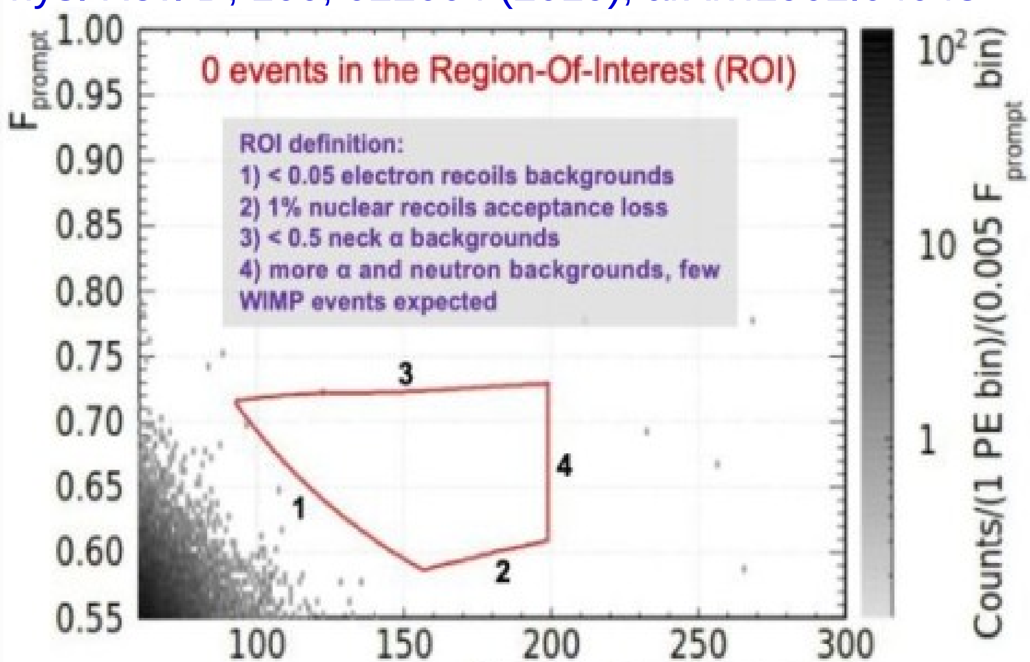


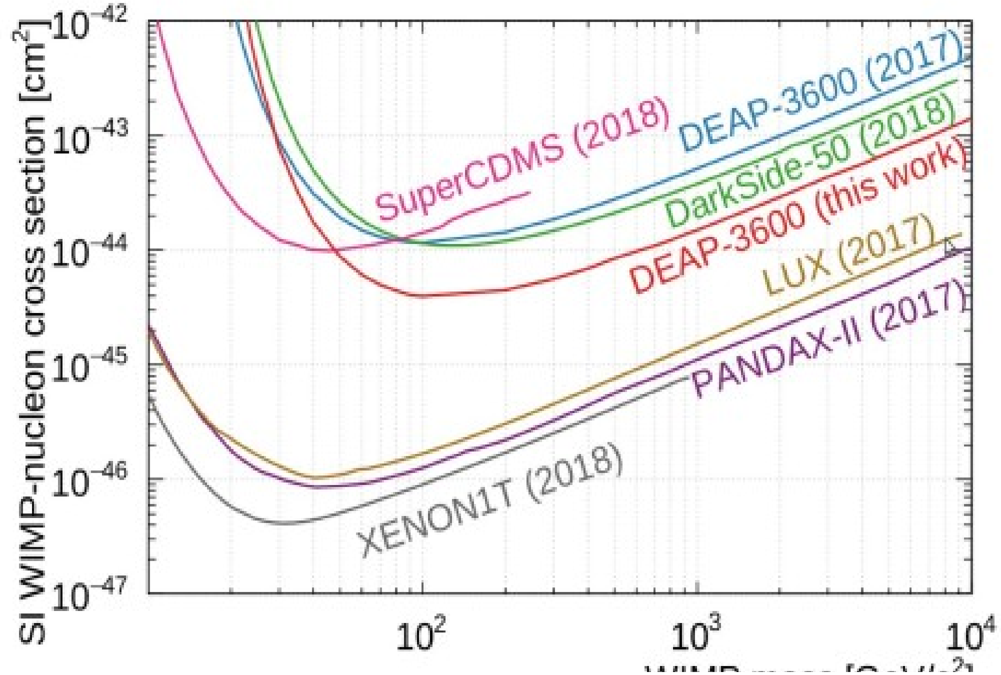
First DEAP-3600 dark matter search, with 4.4 live days

Phys. Rev. Lett. 121, 071801 (2018) arXiv:1707.08042

231 live-days dataset (Nov ‘16 – Oct ‘17)

Phys. Rev. D, 100, 022004 (2019), arXiv:1902.04048





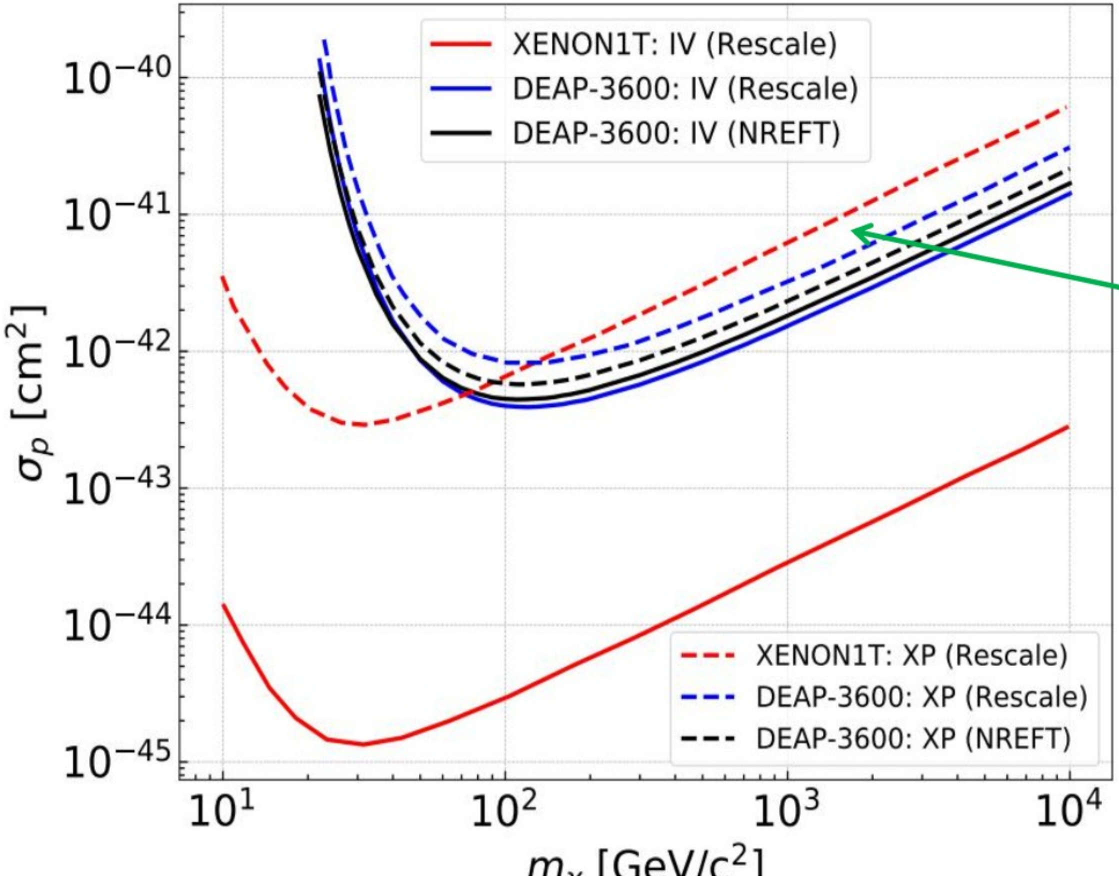
- Zero observed backgrounds, leading exclusion with LAr
- Excellent control over main background types, leading edge among other experiments
- Further sensitivity improvements **limited by backgrounds from alpha activity in the neck of the detector**
- Since then:
  - Stable data collection for DM search:
    - 802 live days (Nov 2016 – March 2020)
    - 80% blind since Jan 2018
  - Ongoing MVA/machine learning analysis, with improved signal acceptance and lower backgrounds
  - **Work on a hardware fix to the alpha backgrounds problem**
  - **Other DM searches and physics analyses**

	Source	N^{CR}	N^{ROI}
β/γ's	ERs	2.44×10^9	0.03 ± 0.01
	Cherenkov	$< 3.3 \times 10^5$	< 0.14
n's	Radiogenic	6 ± 4	$0.10^{+0.10}_{-0.09}$
	Cosmogenic	<0.2	<0.11
α's	AV surface	<3600	< 0.08
	Neck FG	28^{+13}_{-10}	$\boxed{0.49^{+0.27}_{-0.26}}$
	Total	N/A	$0.62^{+0.31}_{-0.28}$

Backgrounds budget

Effects of isospin parity breaking

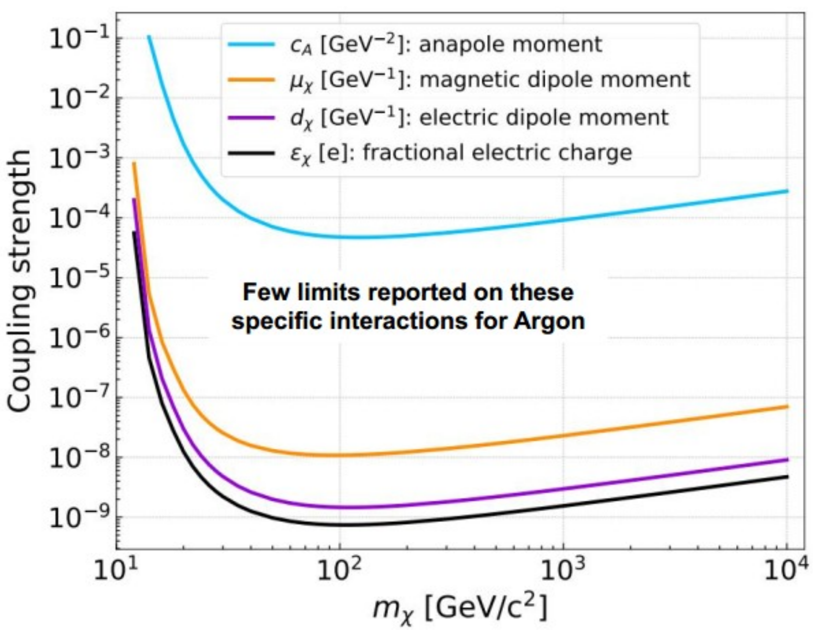
231 live-days results are reinterpreted with a more general non-relativistic EFT framework, and exploring how possible substructures in DM halo affect these constraints



Region where DEAP-3600 sets stronger limits than XENON1T by considering the XP scenario.

Using NREFT + XP (black dash line), the region increases. While the Helm form factor doesn't change assuming $c_n \neq c_p$, in the NREFT formalism the form factor does.

Limits on specific interactions



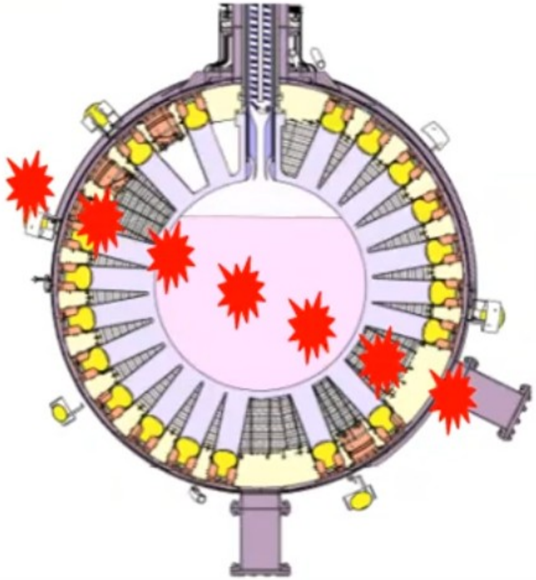
P. Adhikari et al. (DEAP-3600 Collaboration), Phys. Rev. D **102**, 082001 (2020)

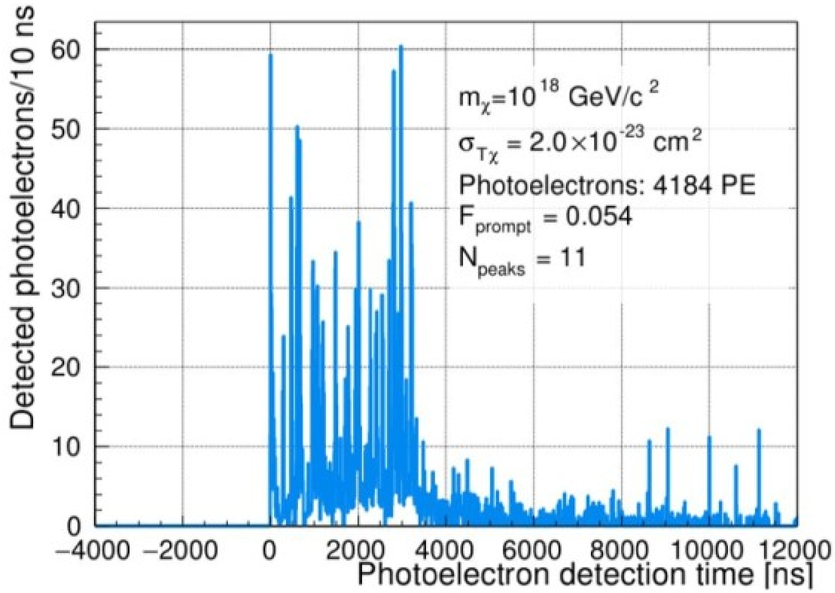
Planck scale mass multi-scattering dark matter

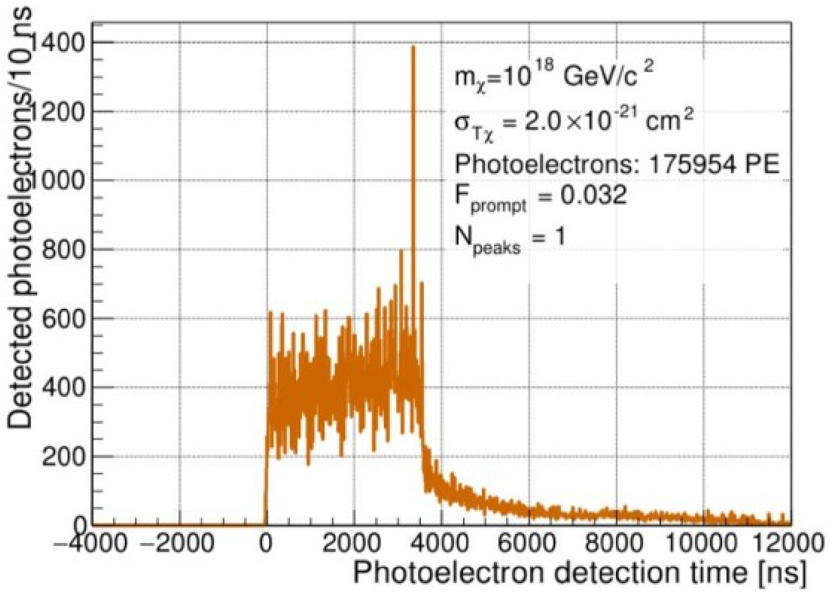
- a.k.a multiply-interacting massive particles (MIMPs)

- DM candidates above σ-n≅ 10^{-25} cm^2 and m ≳ 10^{12} GeV lose a negligible amount of energy in the scatterings with the Earth nuclei and can reach underground detectors designed for WIMP search.

- Event signature:
  - Contains multiple nuclear recoil scatters
  - Apparent low Fprompt (electronic recoil-like event)

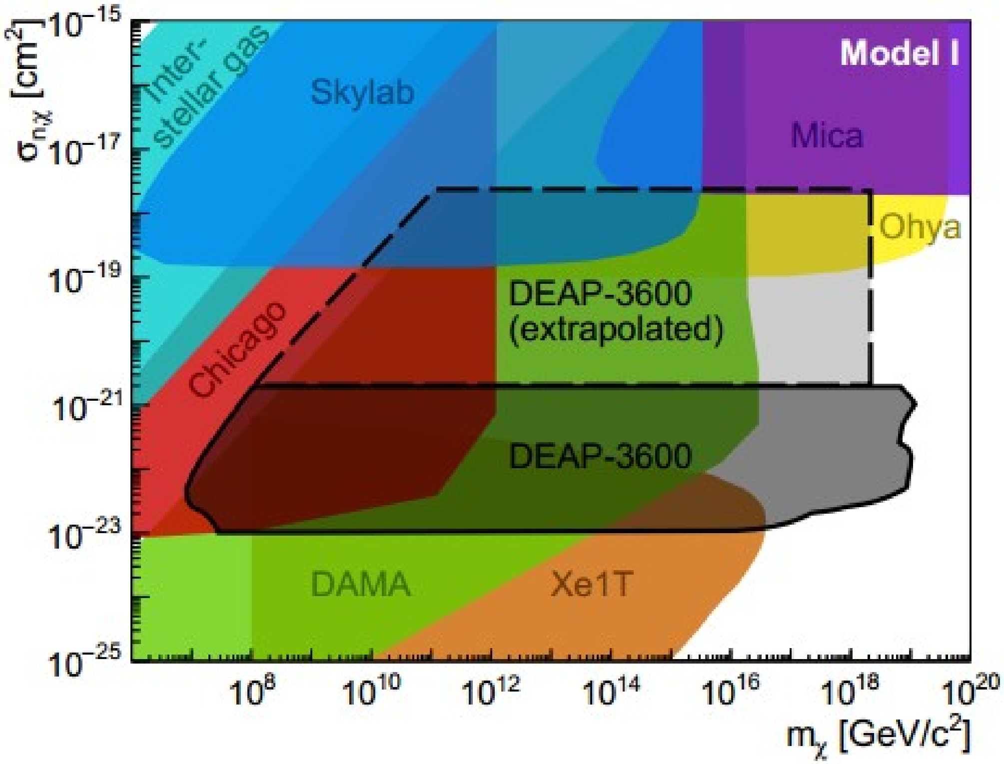


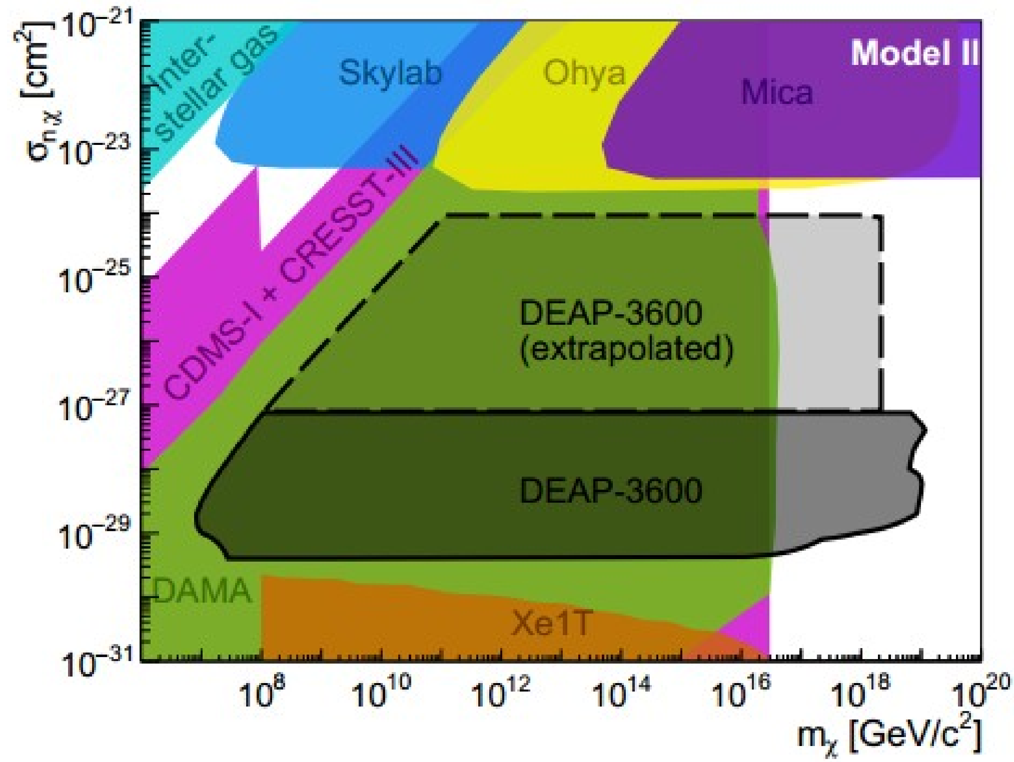




MIMP exclusion limits

- Phys. Rev. Lett. 128, 011801 (2022)
- 813 live-days, blind analysis
- New exclusion for candidates at Planck scale masses





(relevant for composite DM models)

Low-mass WIMPs: new DarkSide-50 result

Masato Kimura | LIDINE - 21 Sept '22

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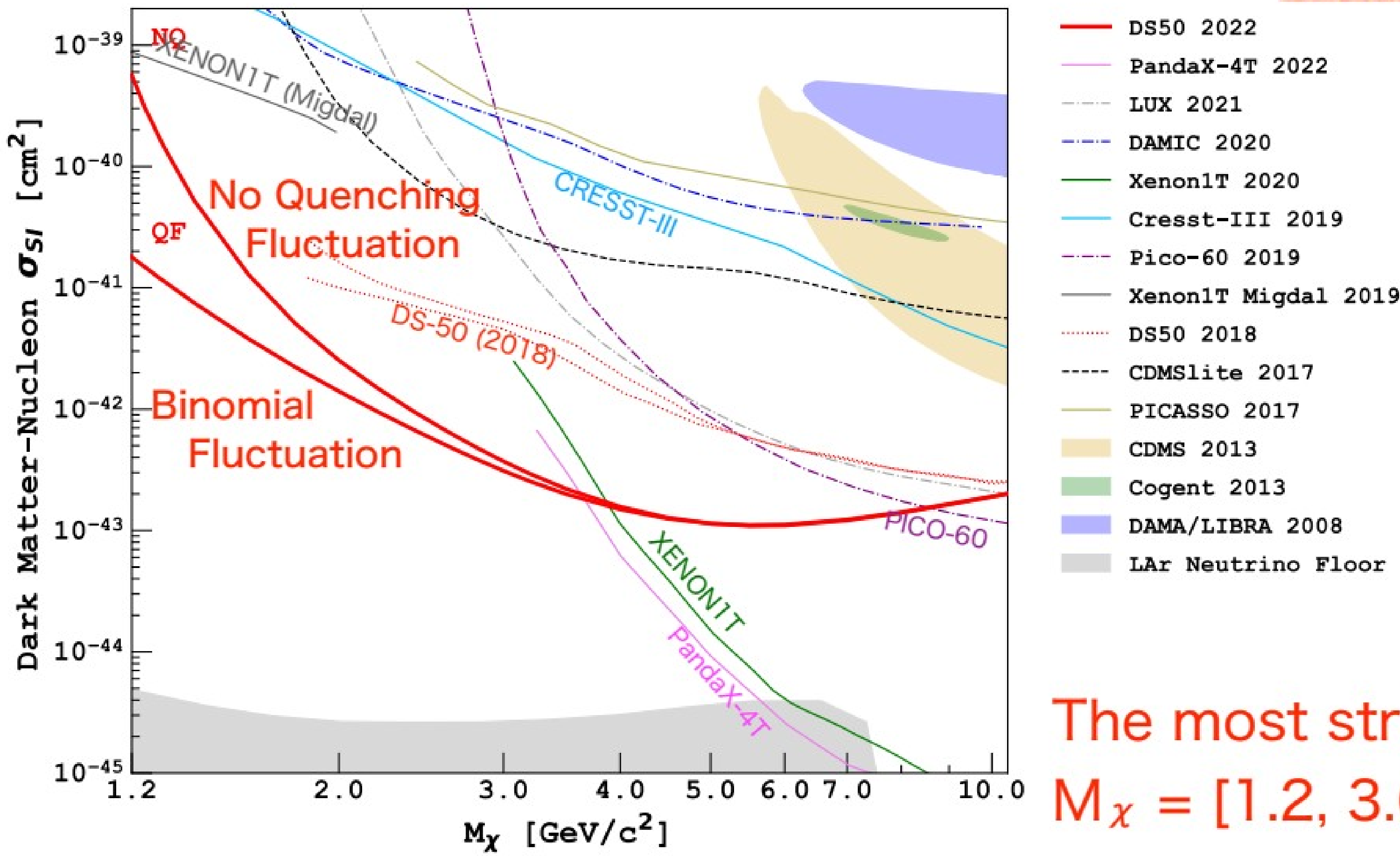
WIMP Exclusion Result

arXiv:2207.11966



The most stringent limit at M_χ = [1.2, 3.6] GeV/c^2

DarkSide-50: other new results

Masato Kimura | LIDINE - 21 Sept '22

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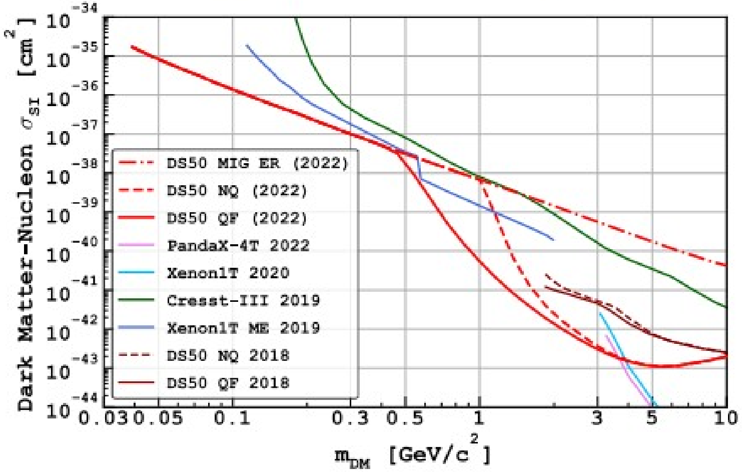
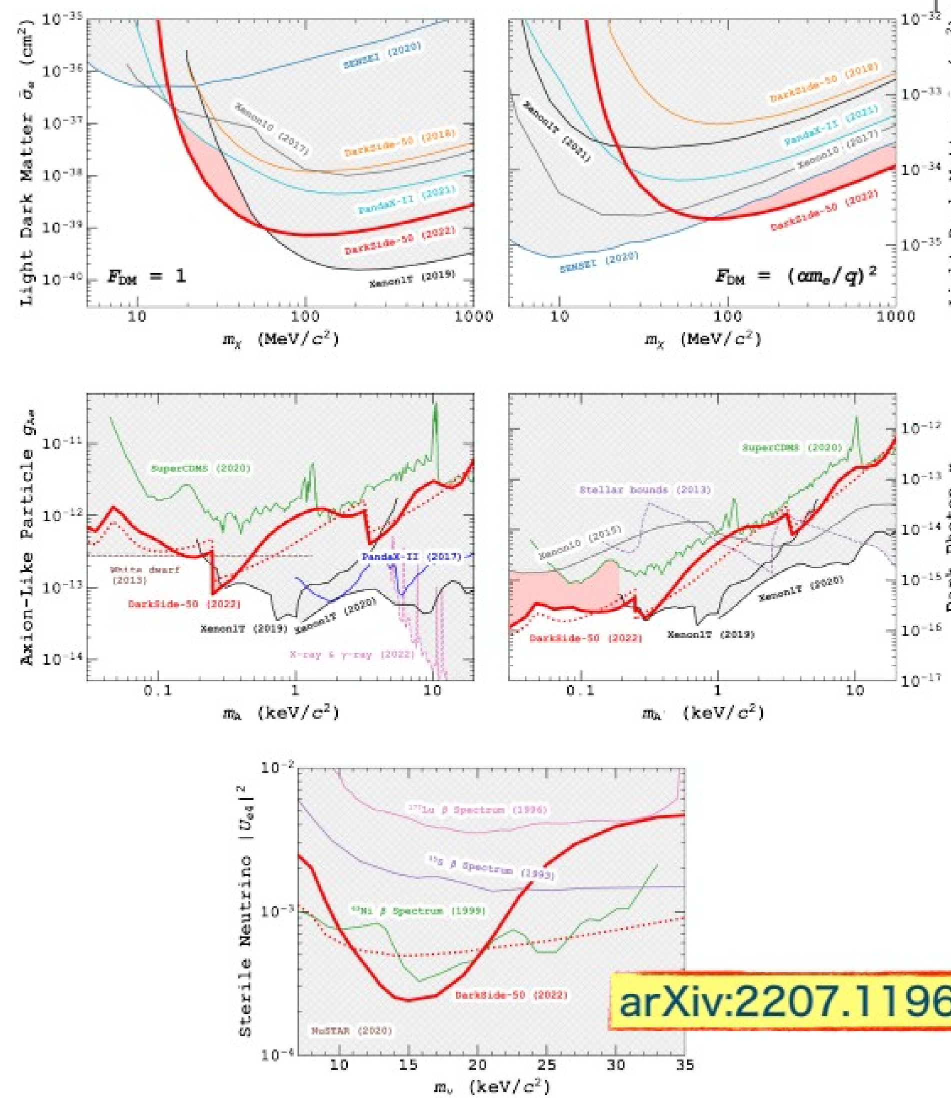
WIMP with Migdal Effect



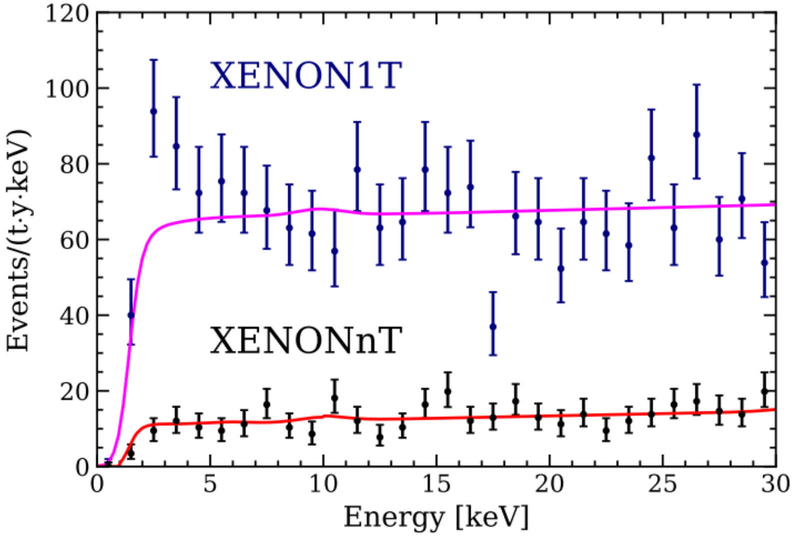
arXiv:2207.11967

Electron Coupling Channel



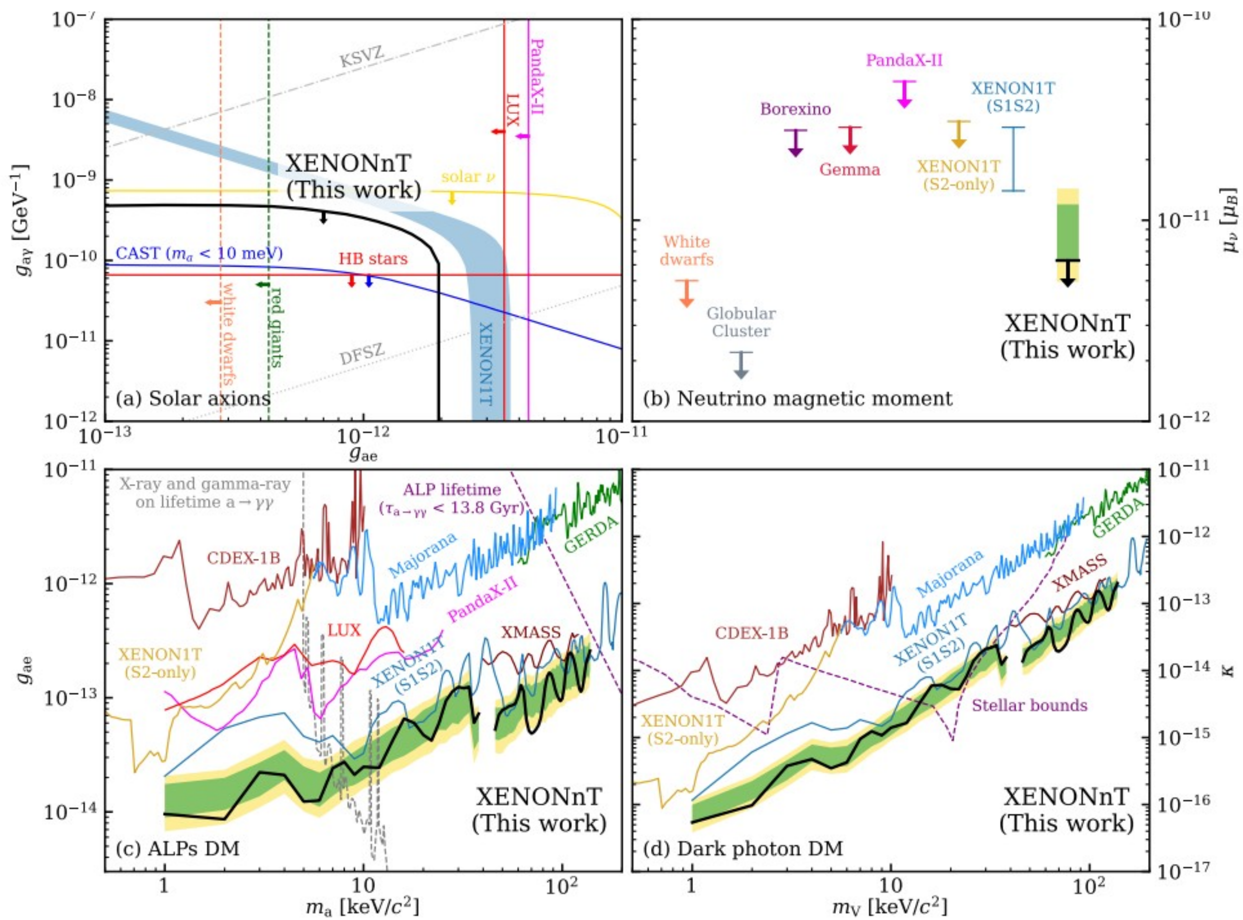
arXiv:2207.11968

New results from XENONnT



arXiv:2207.11330

- First science run results from XENONnT
- 97.1 days livetime, 4.37 tonne fiducial volume
- **No sign of low-energy excess reported by XENON1T**



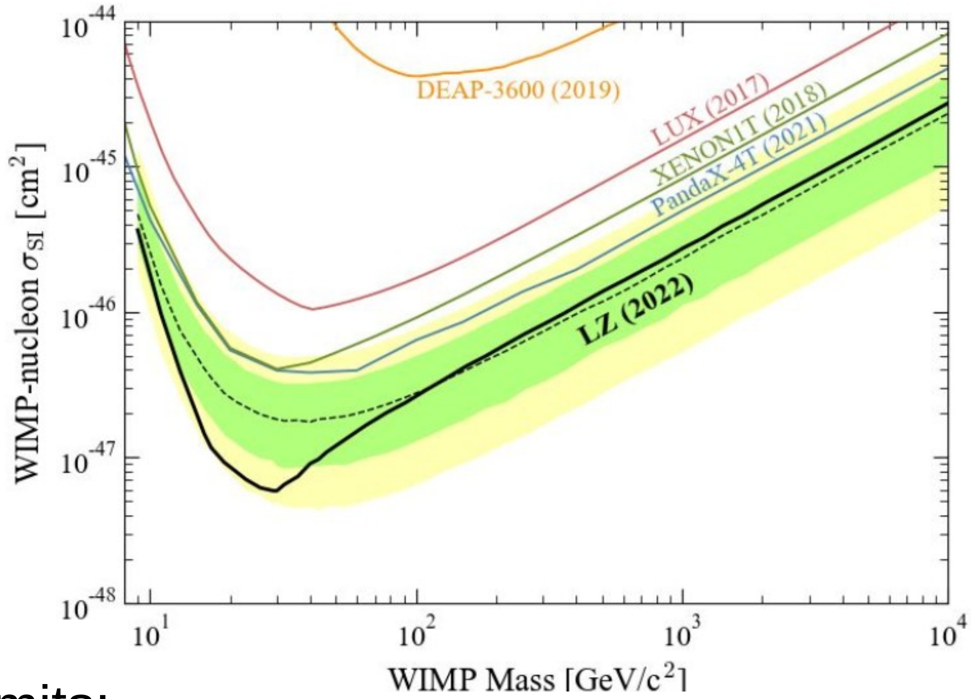
- New leading constraints on BSM physics
- Complementary to DarkSide-50

New results from LZ

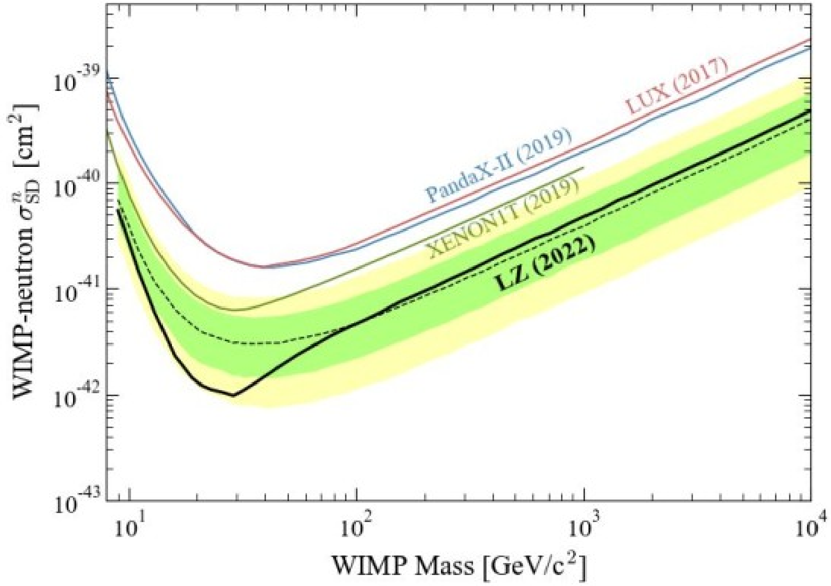
arXiv:2207.03764

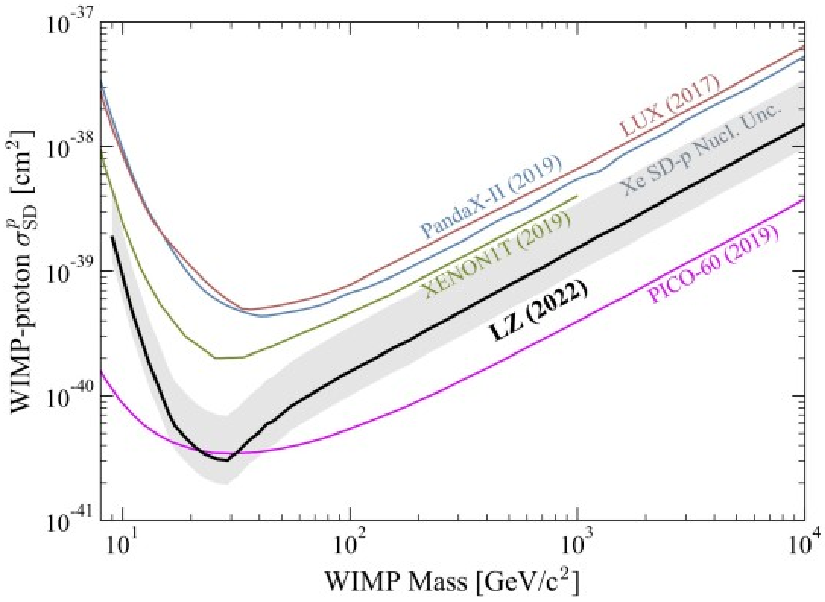
90% CL upper limit on WIMP-nucleon σ_{SI} is 5.9 x 10^{-48} cm^2 at 30 GeV/c^2 WIMP mass

- Limit constructed using frequentist profile likelihood ratio (PLR)
- Two sided
- Signal rate constrained to be positive only

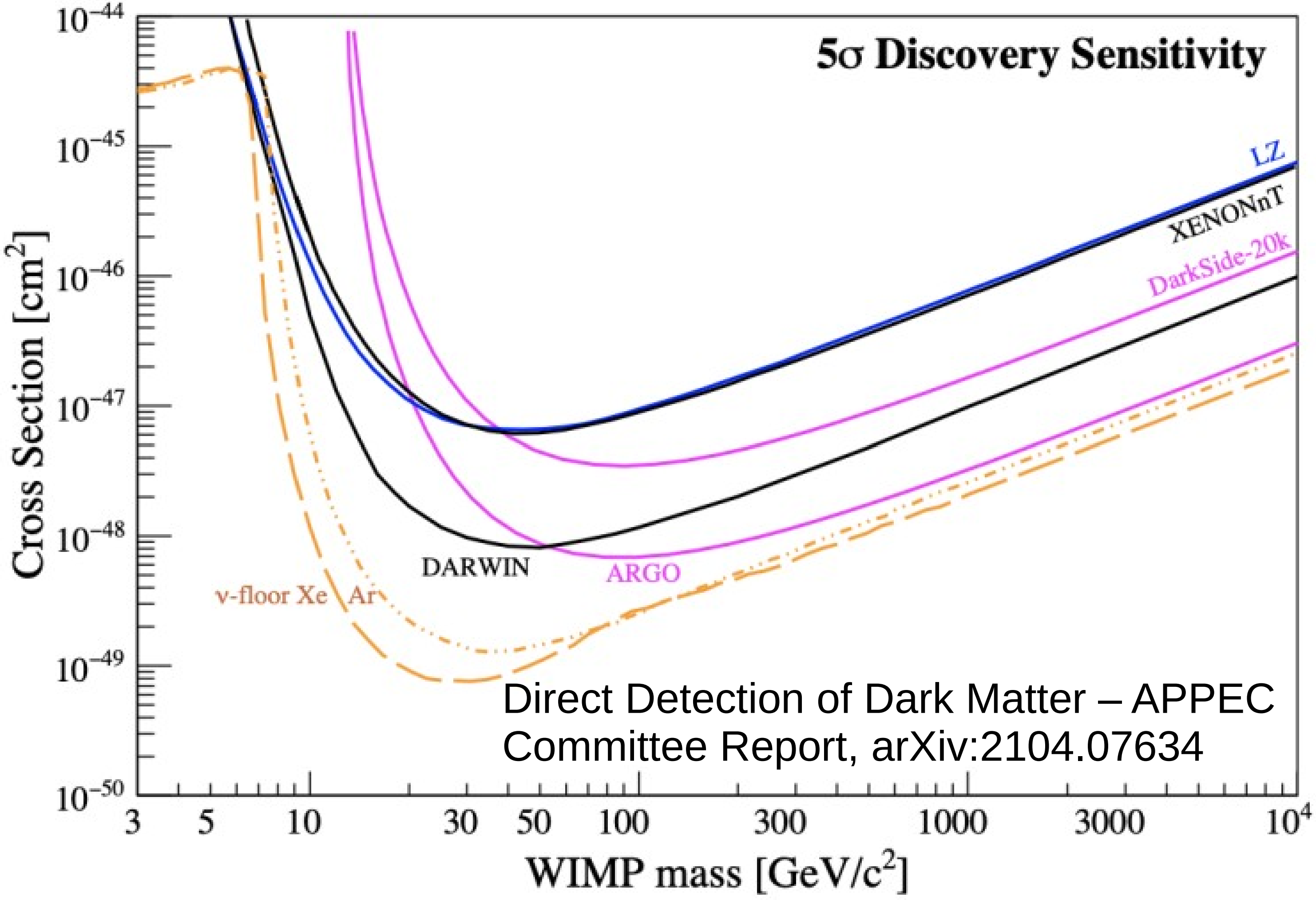


...also new leading spin-dependent limits:





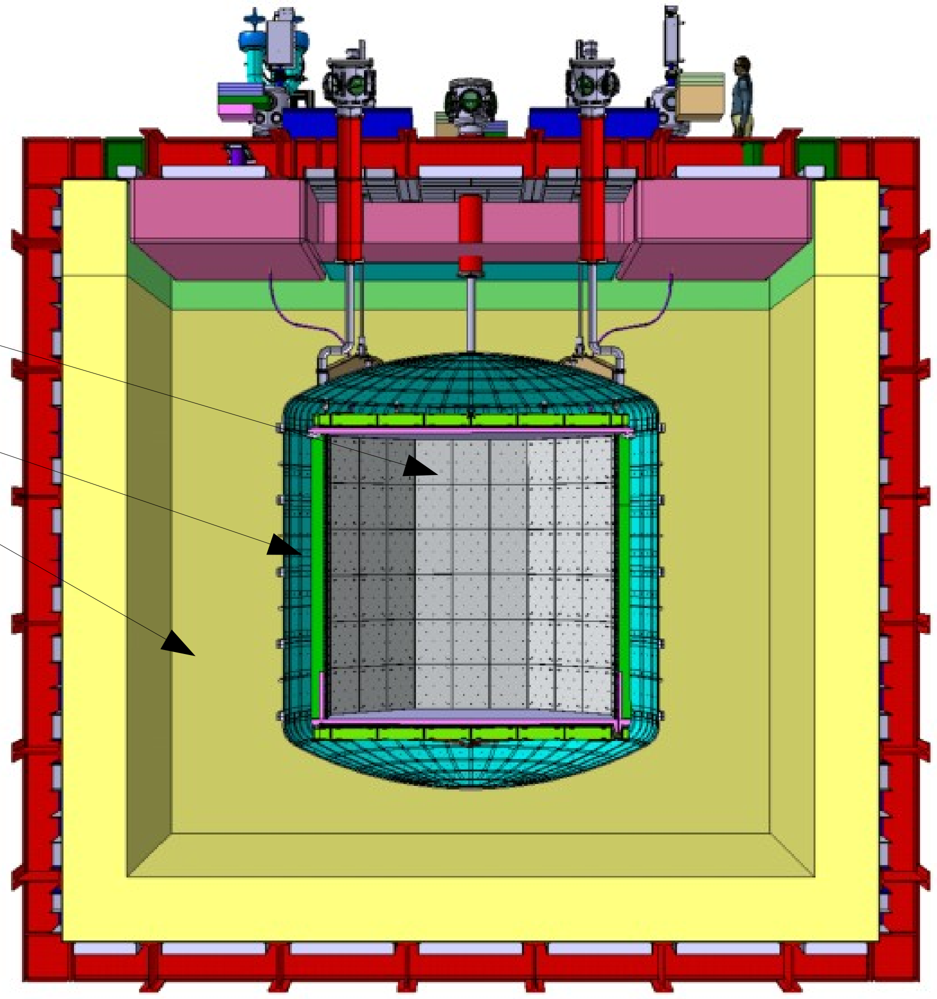
Discovery potential



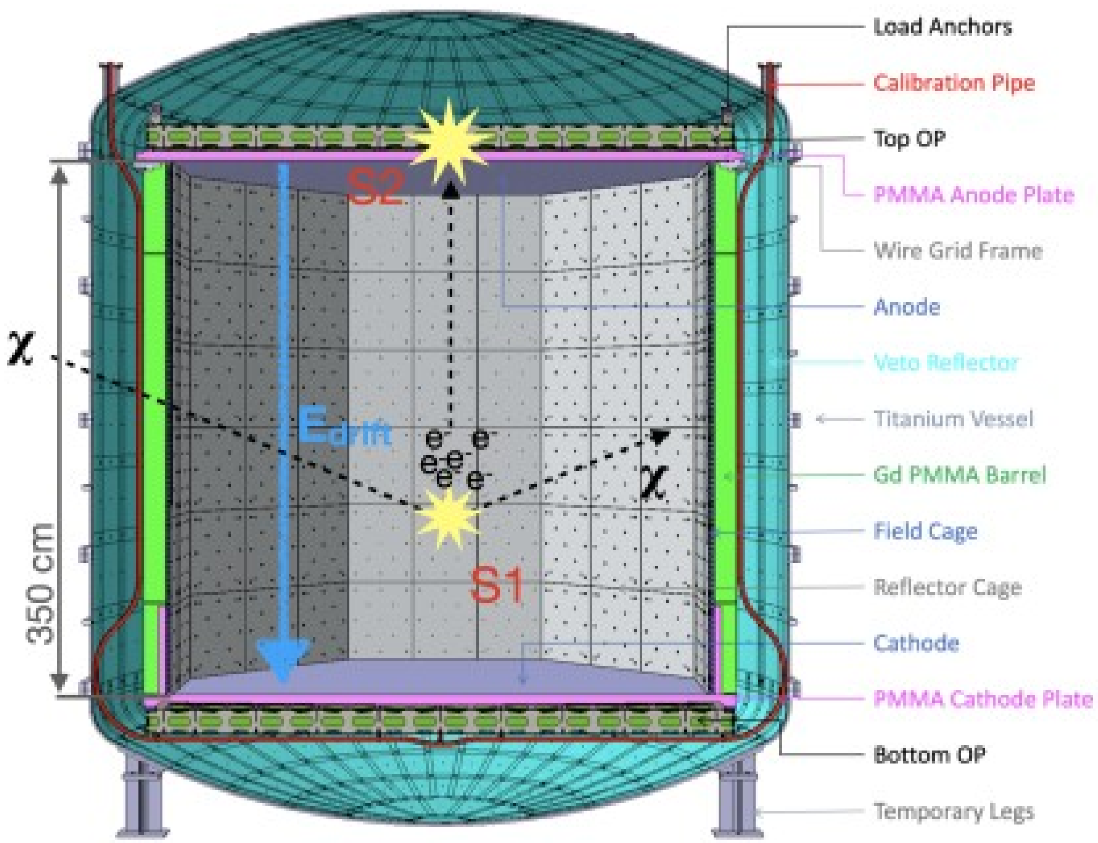
- Superior ER rejection in LAr (with PSD) allows to suppress background from elastic scattering of solar neutrinos on electrons
- Zero background paradigm results translates to better 5-sigma discovery sensitivity
- **Need for both programs recognized by APPEC, P5, and under consideration for the European Long Range strategy**

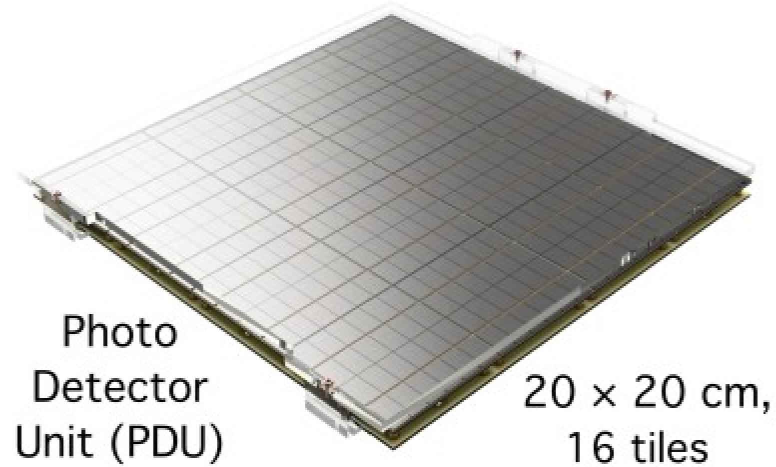
DarkSide-20k

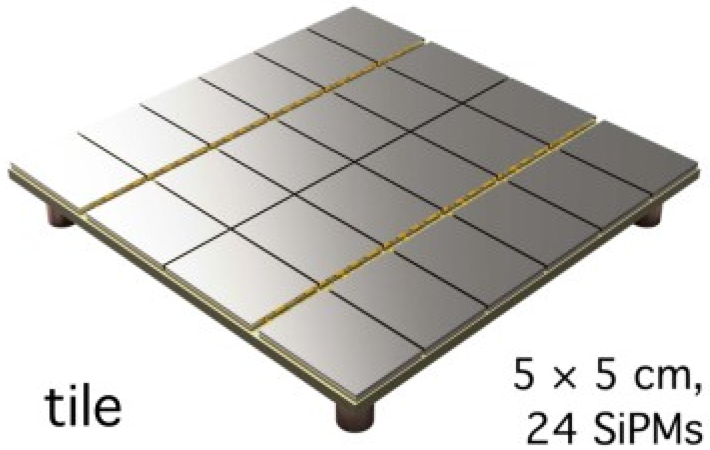
- ~300 physicists, 60 institutions, 11 countries
- Under costruction at Gran Sasso (Italy)
- Concept:
  - Inner LAr tank (~50 tons) instrumented with **SiPMs**
  - Enclosed in an active LAr veto
  - Enclosed in a passive LAr shield tank
- Our responsibilities at Astrocent:
  - **Relectors and wavelength shifter for the active LAr veto (~300 m^2 surface)**
  - **Veto SiPM system: analysis, testing and development**
- After DarkSide-20k:
  - In 10 years?
  - ARGO: 400 tonnes of LAr



DS-20k Time Projection Chamber (TPC)





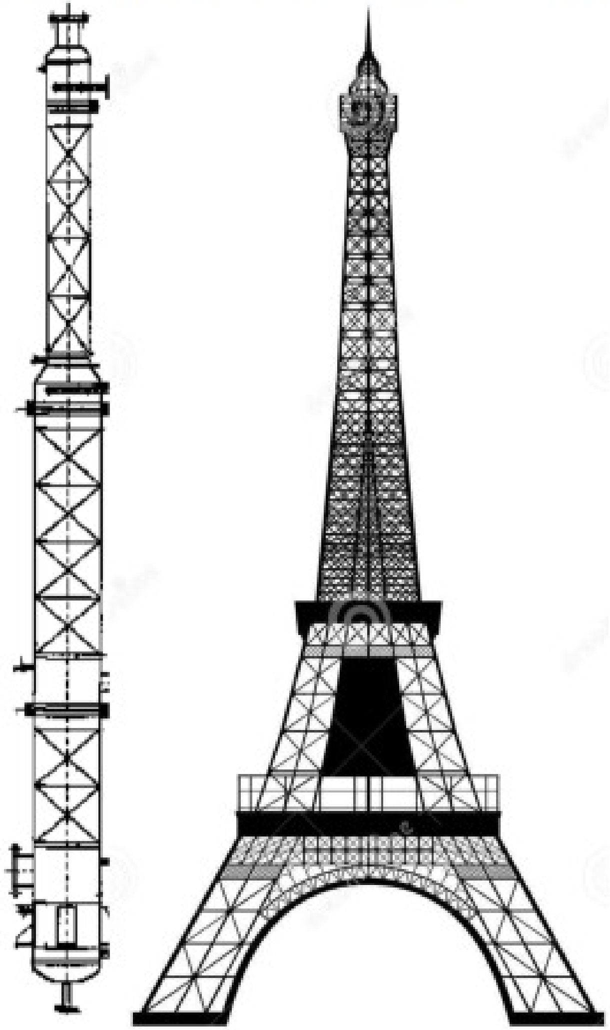


- S1: energy and pulse shape discrimination (PSD)
- S2: energy information and the 3D position measurement of the event
- Resolution: 10 mm horizontal,1 mm vertical

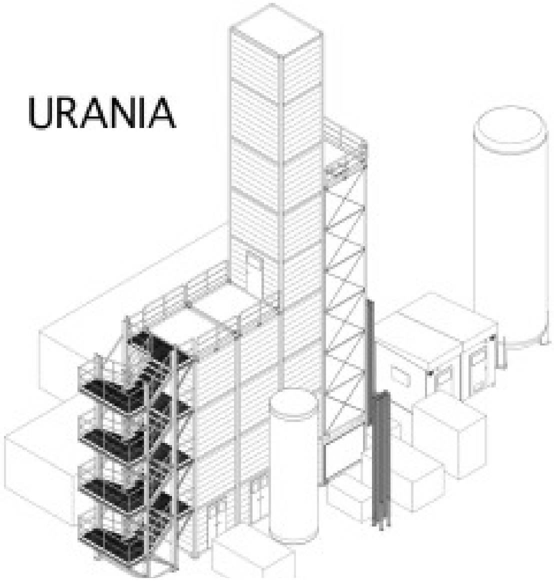
- Custom silicon photomultipliers (SiPM)
- Photon detection efficiency: 45%
- Timing resolution: 10 ns
- Dark-count rate < 20 cps
- 26 m^2 for the TPC and veto

Low radioactivity argon

ARIA, Seruci mine in Sardinia



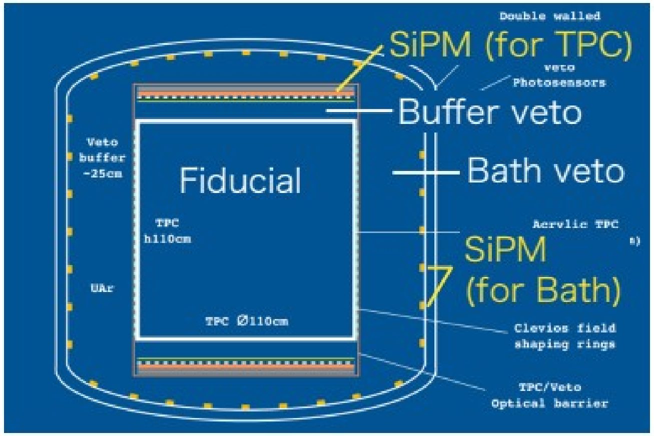
- URANIA: Colorado, capacity of 330 kg/day of Underground Ar
- ARIA: 350 m tall column - separation of isotopes: a factor 10 reduction of ^{39}Ar per pass. Assembly of the column in the well this year [Eur. Phys. J. C 81, 359 (2021)]
- **^{39}Ar reduction factor of at least 1400**(to be measured by DArT [JINST 15, P02024 (2020)])

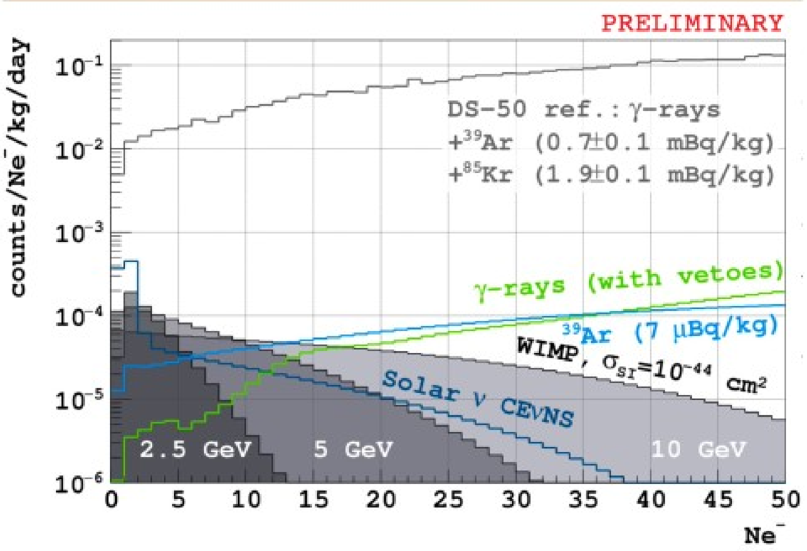


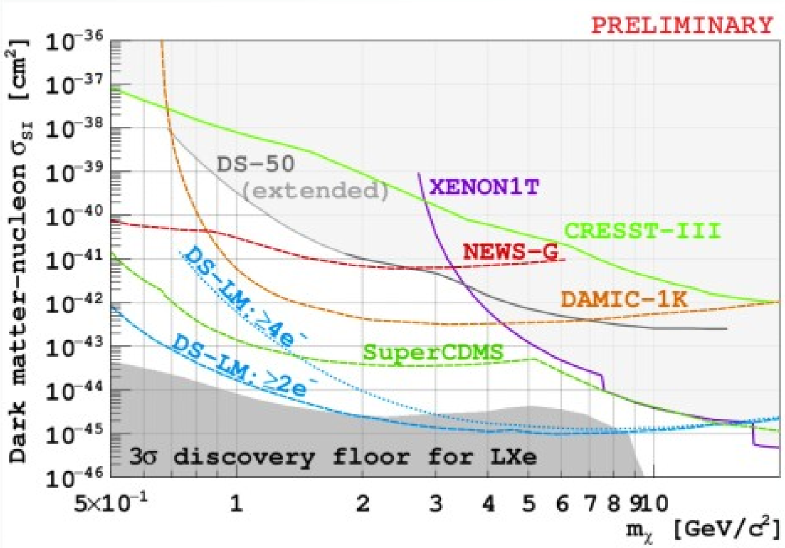
DarkSide-LowMass

arXiv:2209.01177

- S2-only dedicated detector
  - Smaller and lower ER-background rate by depleted-UAr, low-γ materials, and veto-buffers
- Expected to reach **ν-floor** above 1 GeV/c² with 1 year exposure







Summary

- Nature of dark matter is one of the most exciting mysteries in physics, with a real potential for groundbreaking discovery
- First leading results from the new generation of LXe experiments
- Liquid Argon based detectors well positioned in the global race for such discovery, with the ultimate sensitivity within reach in the next decade
  - Leading low-mass exclusion from DarkSide-50
  - DEAP-3600 to reach its target sensitivity after the upgrade and fully demonstrate the single phase approach
  - DarkSide-20k under construction
  - Plans for ARGO and DarkSide-LowMass
- Increasing number of BSM channels/scenarios probed by dark matter detectors

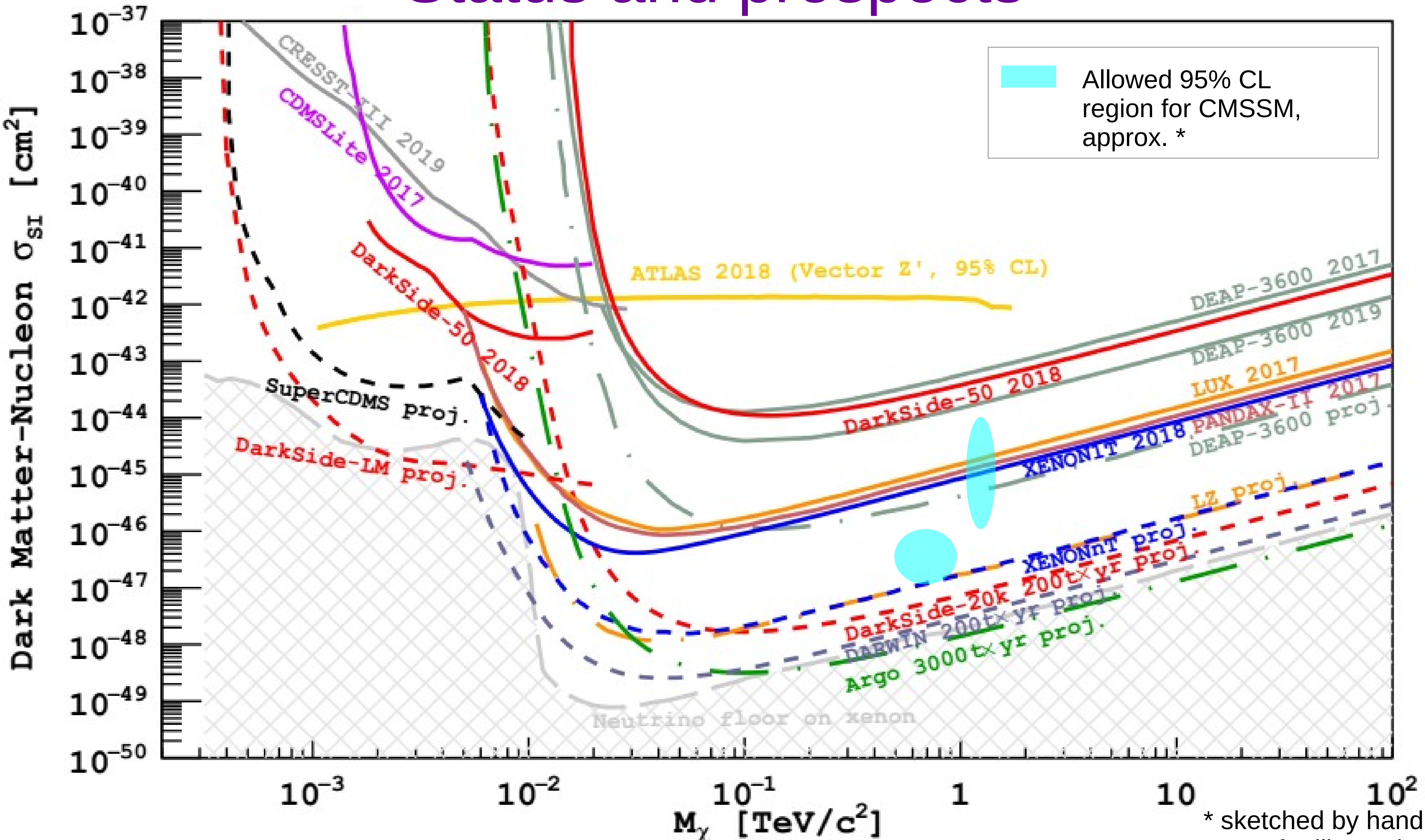
Backup

Activities at Astrocent

- R&D
  - Proposed (with success!) novel materials for light collection in large LAr detectors (WLS, reflectors)
  - SiPM testing and development (dedicated cryostat under construction)
  - LAr low-energy response calibration (dedicated system under construction)
- Data analysis
  - Leading boosted DM search (DEAP-3600)
  - Leading PSD analysis (DEAP-3600)
  - SiPM data analysis development (DarkSide-20k, ReD)
  - Background rejection with methods of machine learning
- Simulation
  - Light collection in LAr detectors
  - Design optimization for DarkSide-20k, DarkSide-LowMass, LAr-based TOF-PET
- Long and short term exchange with our partners (APC Paris, INFN, Gran Sasso Science Inst., TUM) supported by the Horizon 2020 project DarkWave
  - Training
  - Participation in detector installation and operation
- Hosting the LIDINE 2022 (LIght Detection in Noble Liquids) conference in Sept. 2022
- Currently looking for new postdocs!

https://astrocent.camk.edu.pl
https://darkwave.astrocent.pl

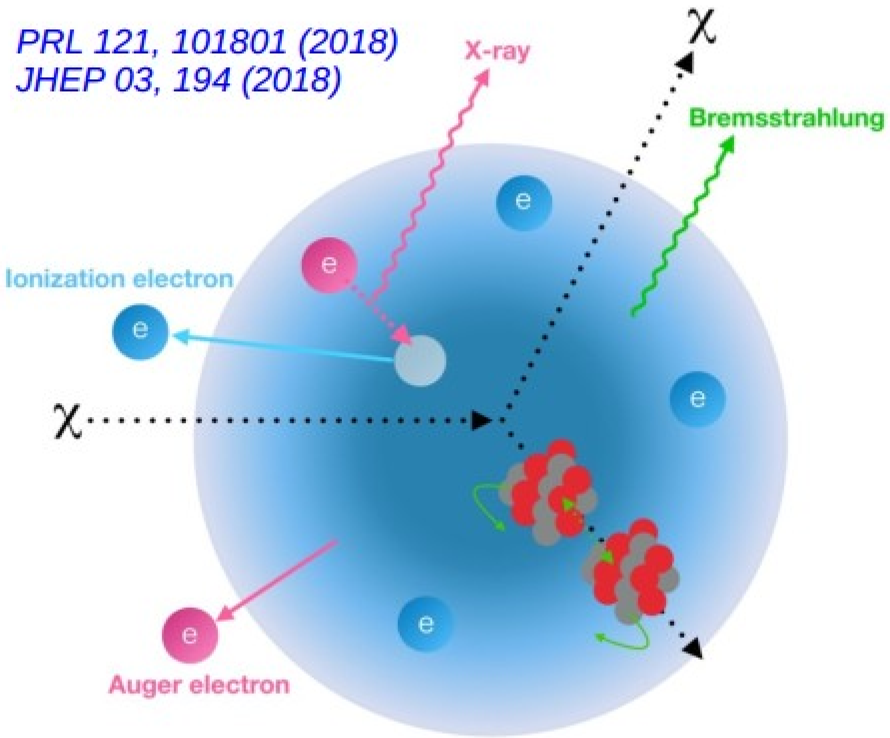
Status and prospects



- No new WIMP detection claims
- LAr and LXe dominate searches in the spin-independent sector >~2 GeV/c2
- Continued search towards the neutrino floor still very well motivated
  - see e.g. Roszkowski et al., Rept.Prog.Phys. 81 (2018), 066201

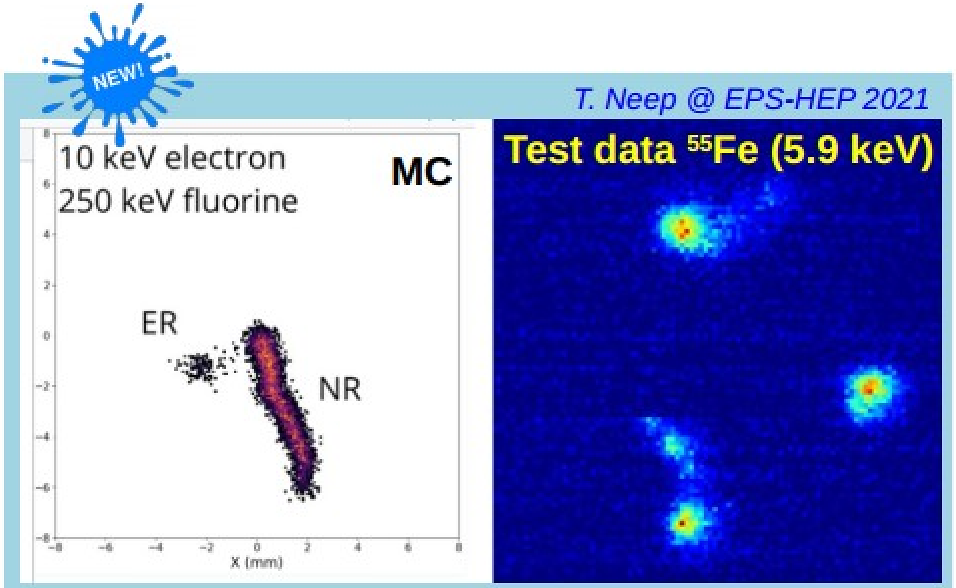
Migdal Effect

PRL 121, 101801 (2018)
JHEP 03, 194 (2018)



– exploit expected effects after nuclear recoil
→ very low threshold

– caveat: effect not yet observed in calibration



Experiments to detect Migdal effect from n-scattering are being prepared, e.g., **MIGDAL collaboration** (UK)
– optical TPC filled with gas
– initially CF_4, later mixed with Xe and Ar
– track details for signal/background discr.

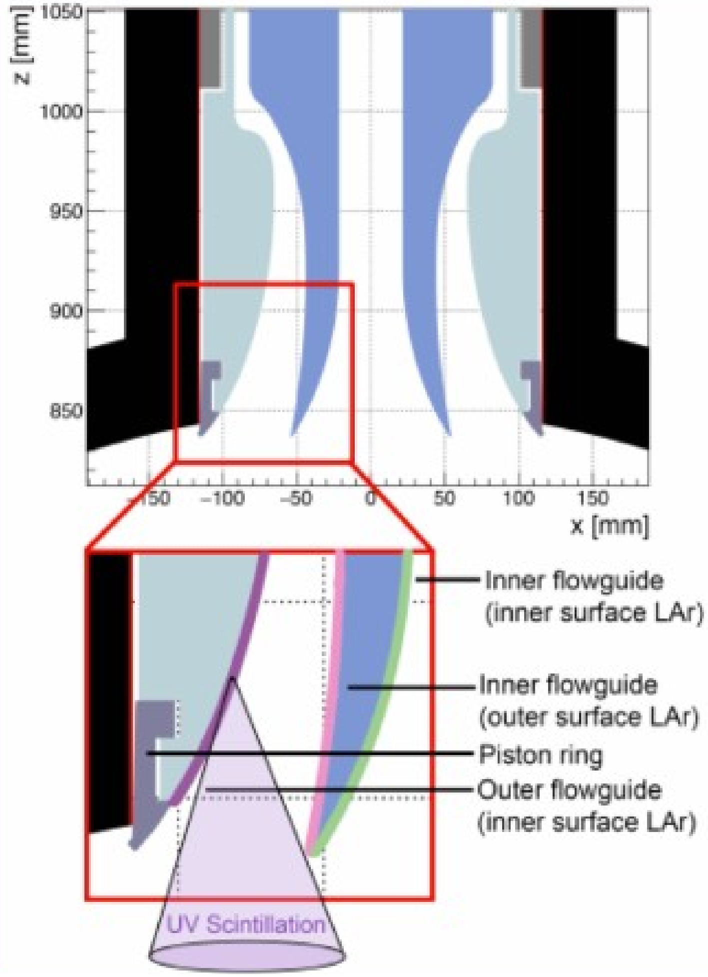
M. Schumann (Freiburg): Direct Detection – Experiments 13

(TAUP2021)

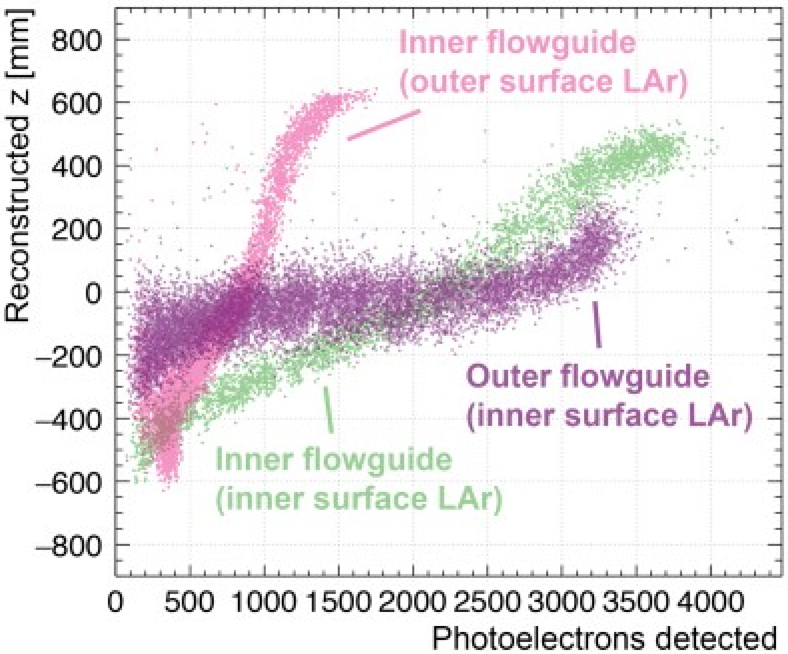
Neck alpha backgrounds

- Alpha scintillation in LAr film/mist covering the flowguides
- Shadowing effect from the flowguides limiting the solid angle

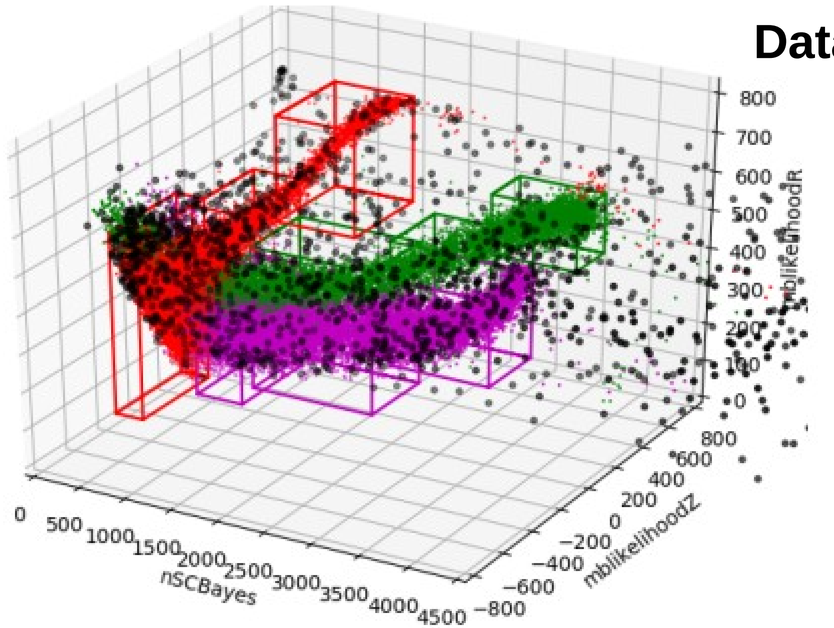
→ Apparent low-energy nuclear recoil events



Monte Carlo

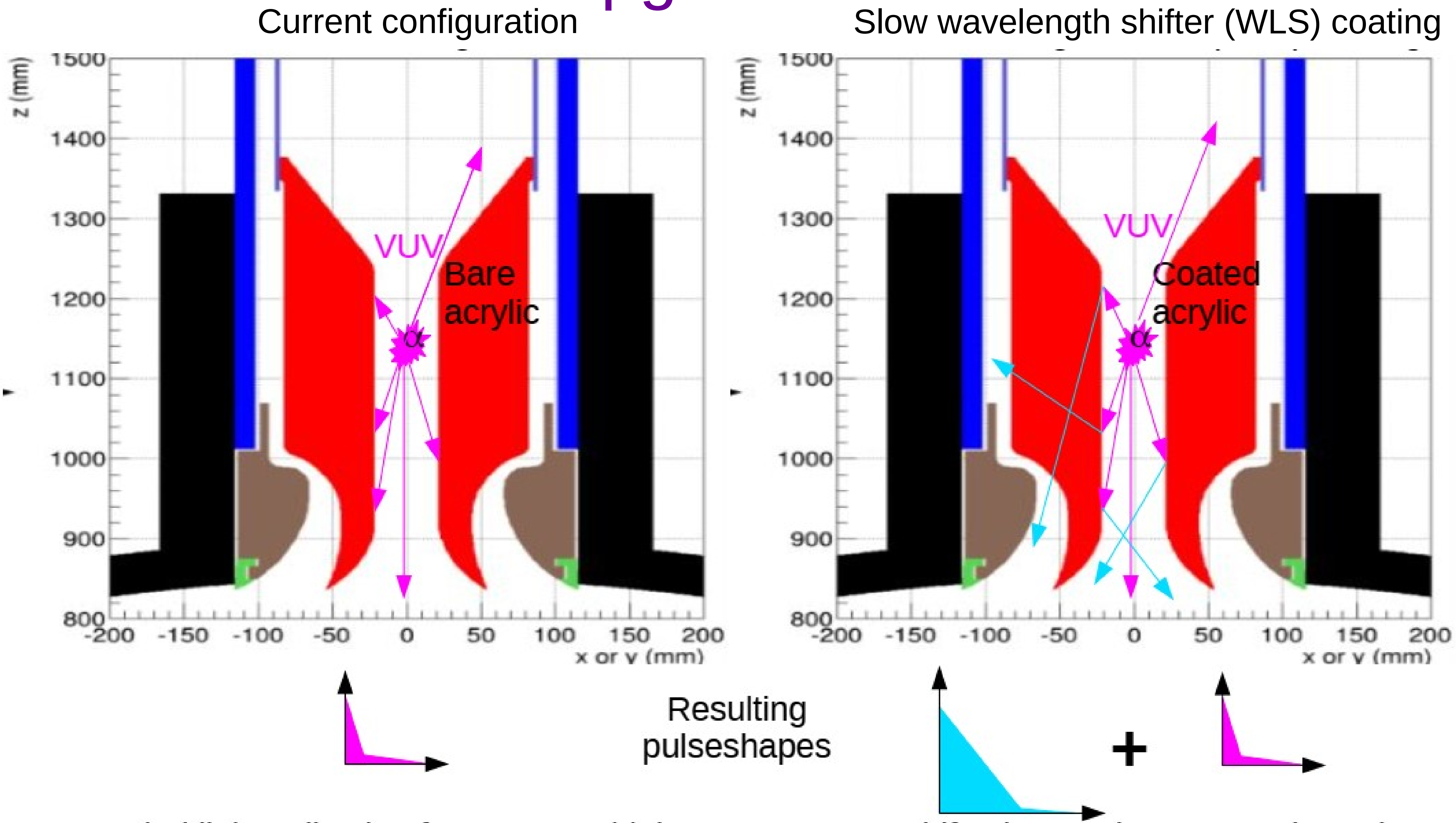


Data



The optical model in good agreement with data

Hardware upgrade: neck events



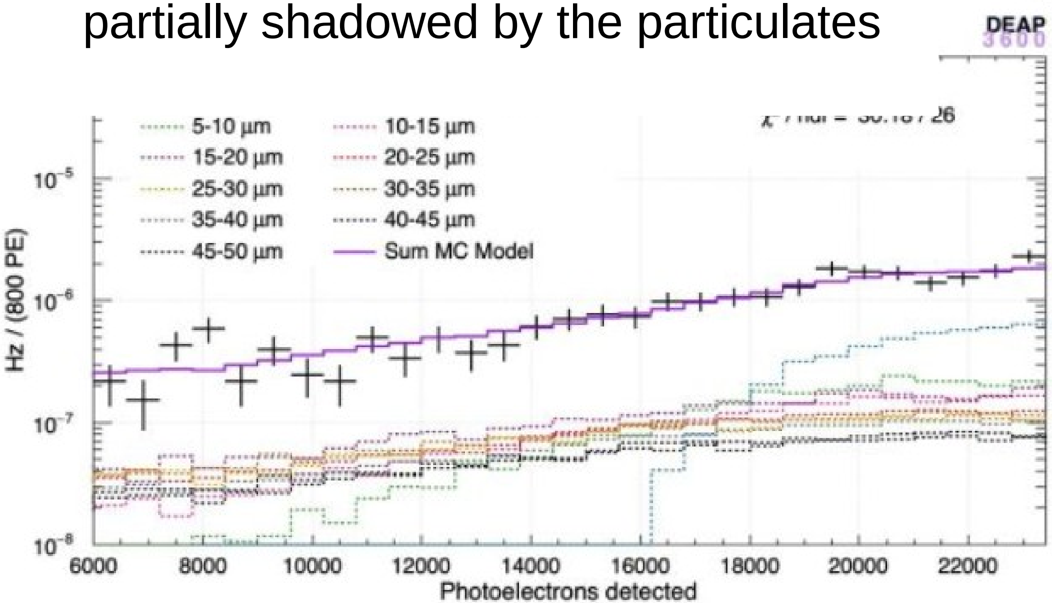
- Degraded light collection from prompt high energy events shifts them to lower energies, where we look for WIMPs
- **Solution: WLS with long time constant deposited in the problematic part of the detector**
- New coated flowguides are already manufactured and ready for installation

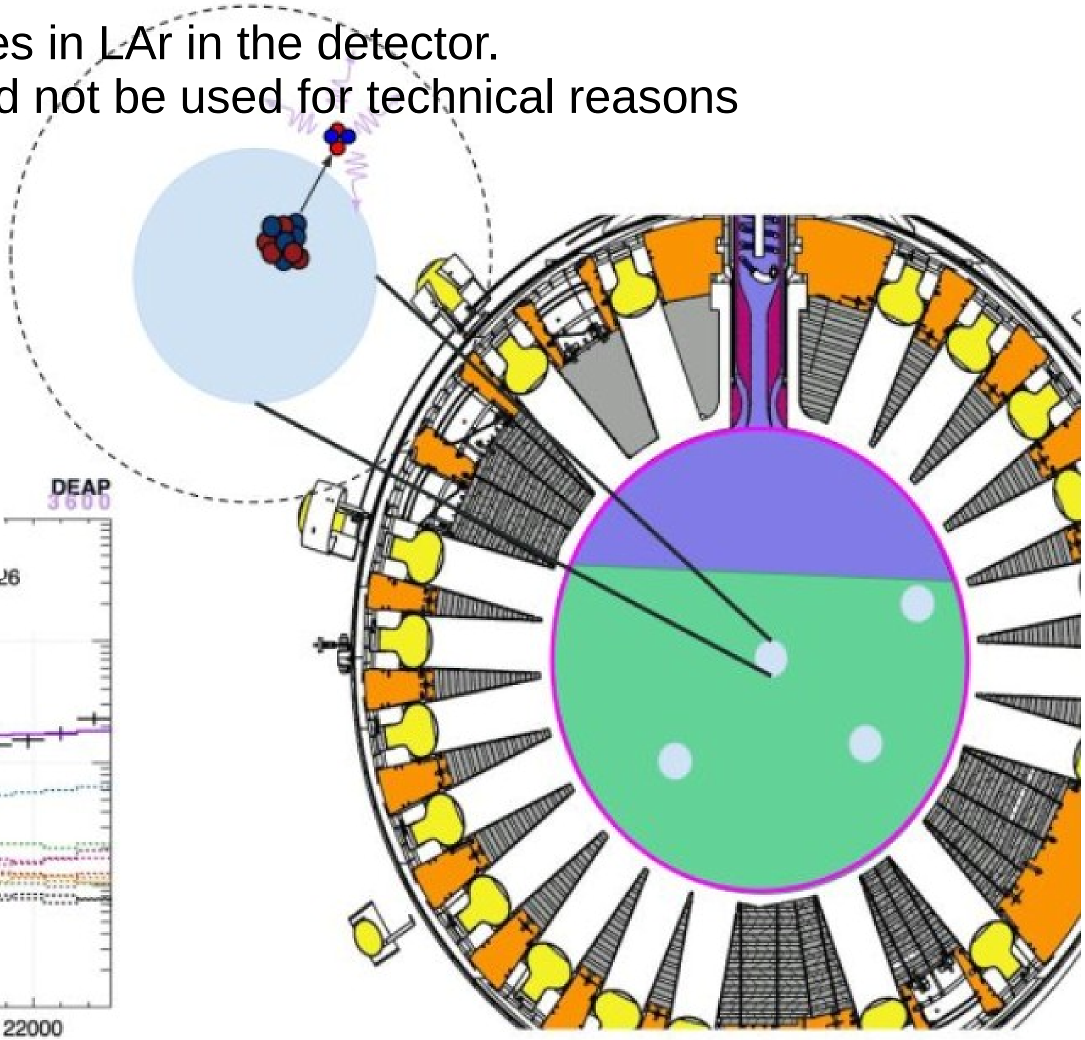
Hardware upgrade: dust alpha backgrounds

- Evidence for presence of dust particulates in LAr in the detector.
- Orginally installed LAr filtration loop could not be used for technical reasons
- Alpha decays embedded in dust particulates have reduced energy deposition in LAr

→ low-energy tail in the spectrum

- Scintillation from such events can be partially shadowed by the particulates





Remedy: deploy stainless steel vacuum jacketed pipe to remove LAr and allow for filtration