Searching for WIMP and axion dark matter with DEAP-3600

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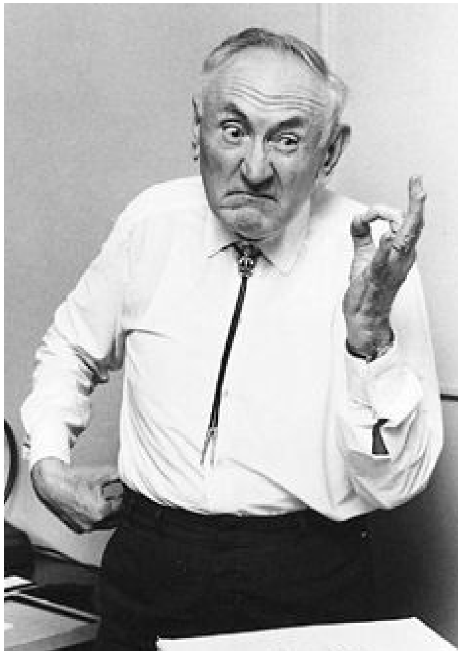
Outline

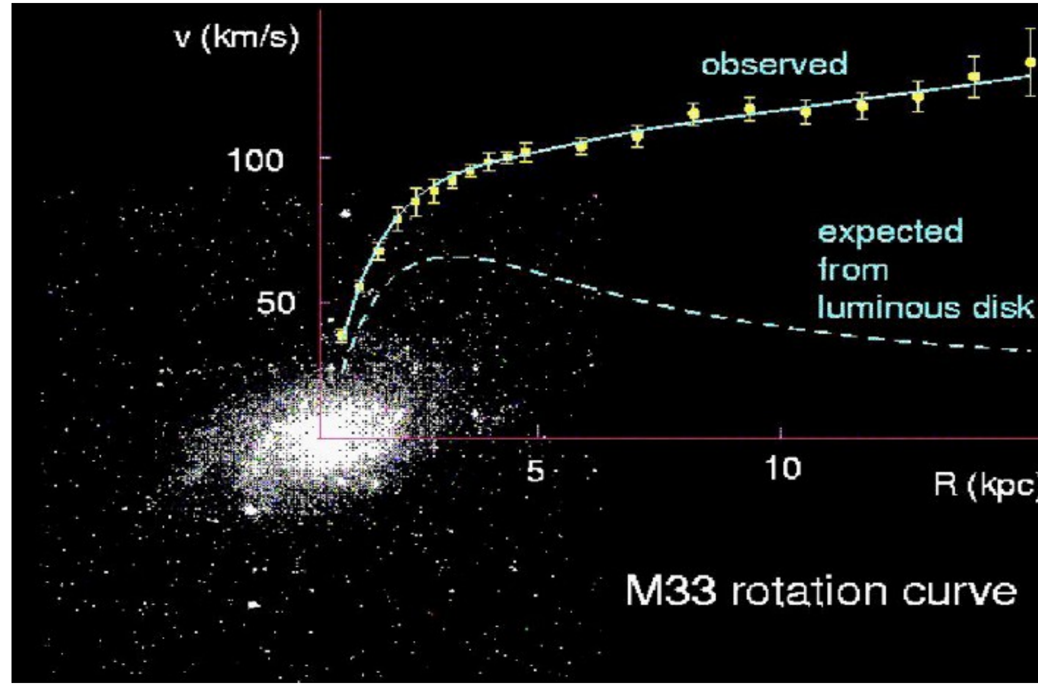
- Motivation
- Status and prospects of the WIMP search
- DEAP-3600 experiment
- DEAP-3600 status
  - WIMP search
  - Solar axion search
- Summary

Dark Matter: the missing mass

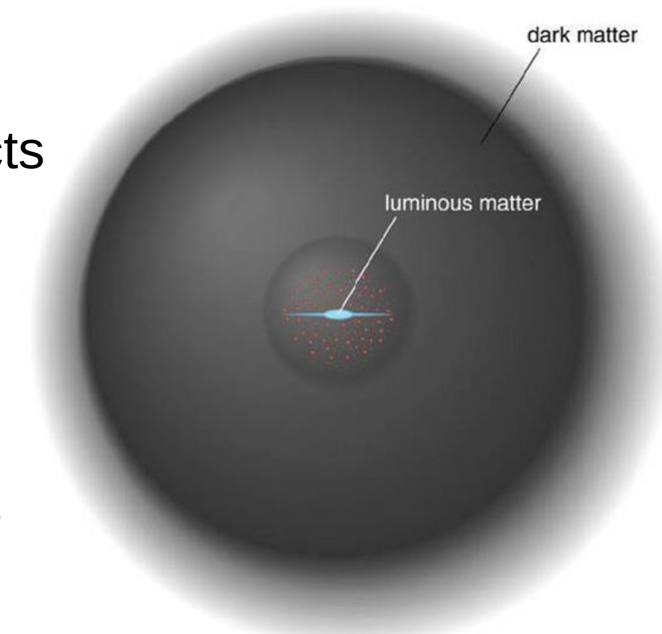


1933, Fritz Zwicky

1970, Vera Rubin

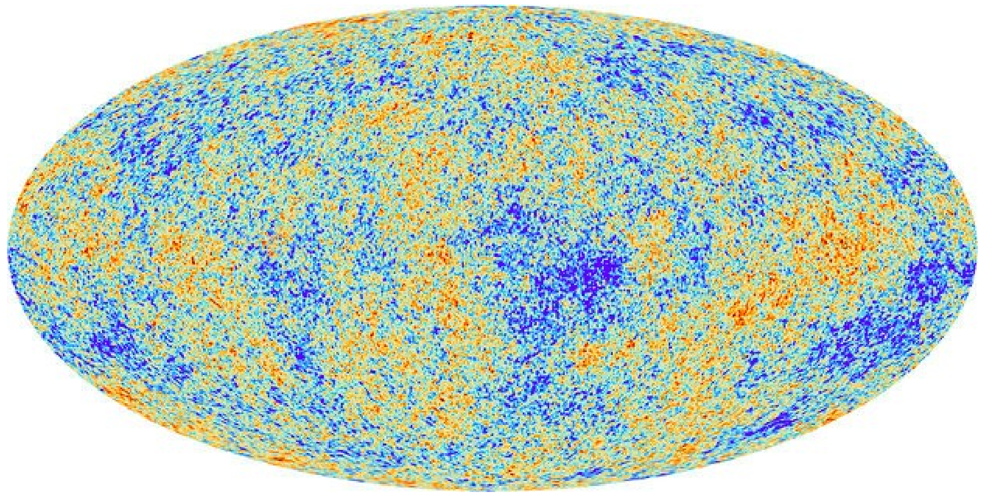


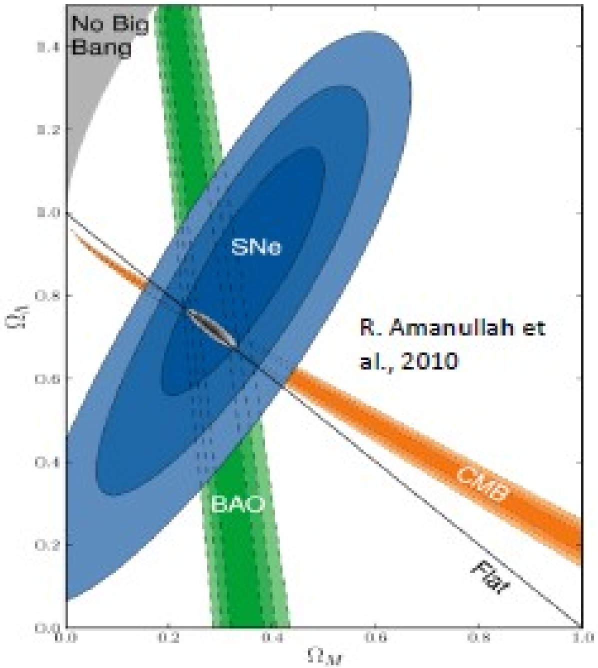
- Rotation curves measure the mass distribution
- Mass density distributed more broadly than visible objects
- Non-luminous halo required to describe rotation curves
- Found in 1933 by Zwicky from Coma Galaxy Cluster analysis
- Confirmed in 1970 by Vera Rubin for Andromeda
- Most of the matter is invisible (neither emits nor absorbs light)

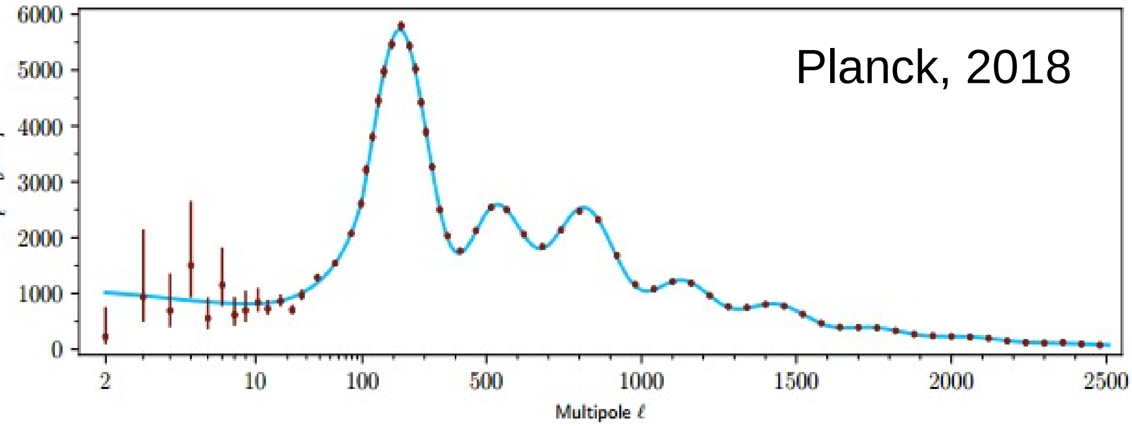


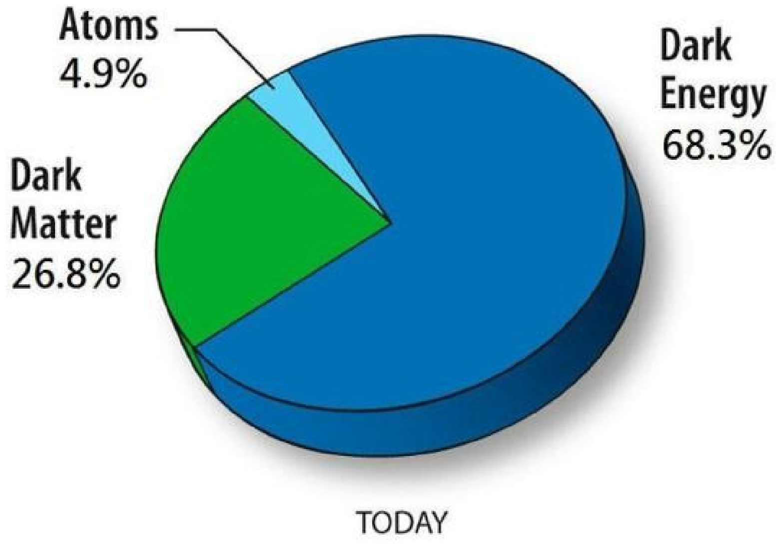
Evidence for Dark Matter

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



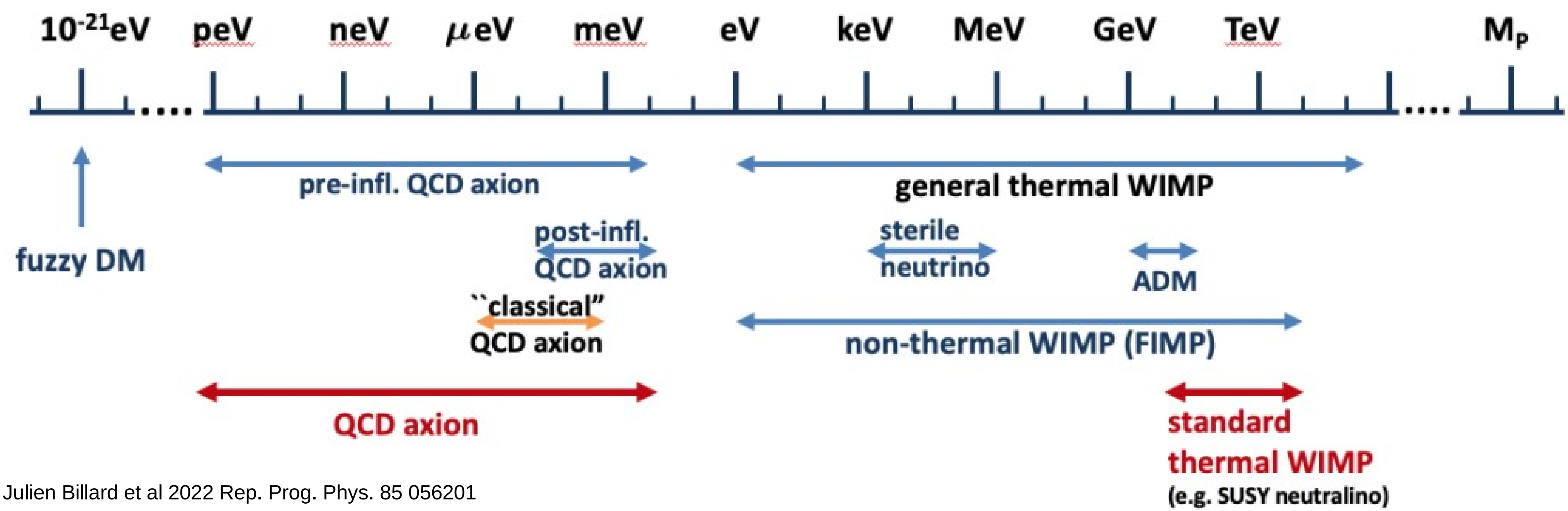






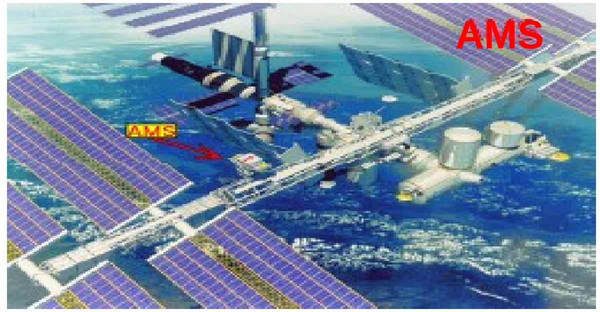
What is Dark Matter?

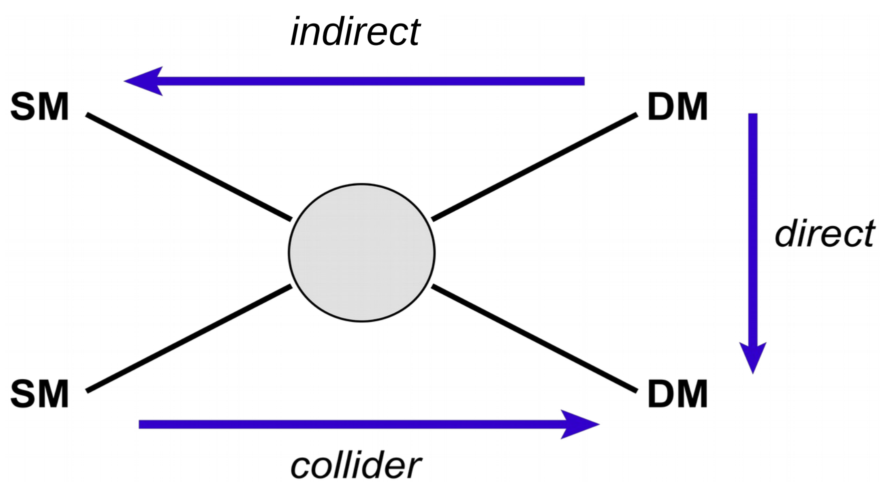
- A number of possibilities considered and excluded:
  - Modifications of the gravity law (MOND)
  - Massive compact halo objects (MACHOs)
- Primordial black holes
- New Particles
  - Weakly Interactive Massive Particles (WIMP)
  - Axions

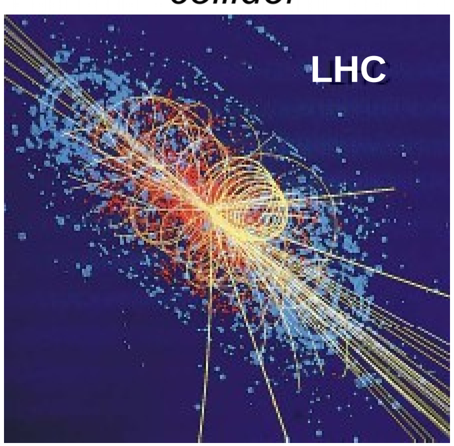


Julien Billard et al 2022 Rep. Prog. Phys. 85 056201

Ways to look for Dark Matter particles



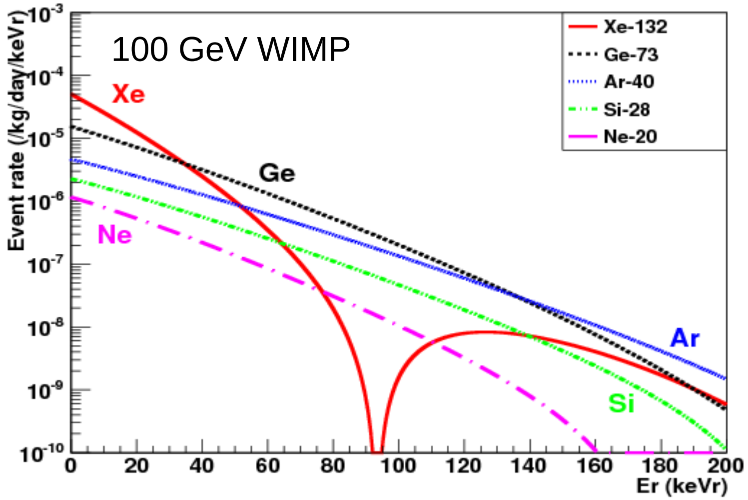




- Indirectly via their annihilation in Sun, Earth, Galaxy
  - Neutrinos (IceCube, Antares/KM3NeT)
  - Positrons, antiprotons (AMS)
  - γ-rays (Fermi-LAT, CTA)
- <u>**Direct detection**</u>
- By producing them at accelerators (LHC, beam dump experiments)

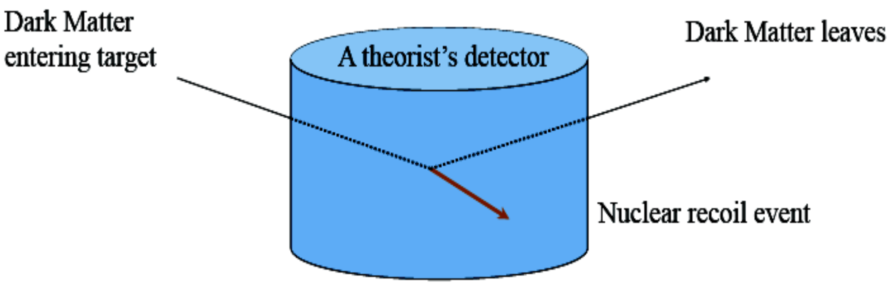
DM direct detection signature

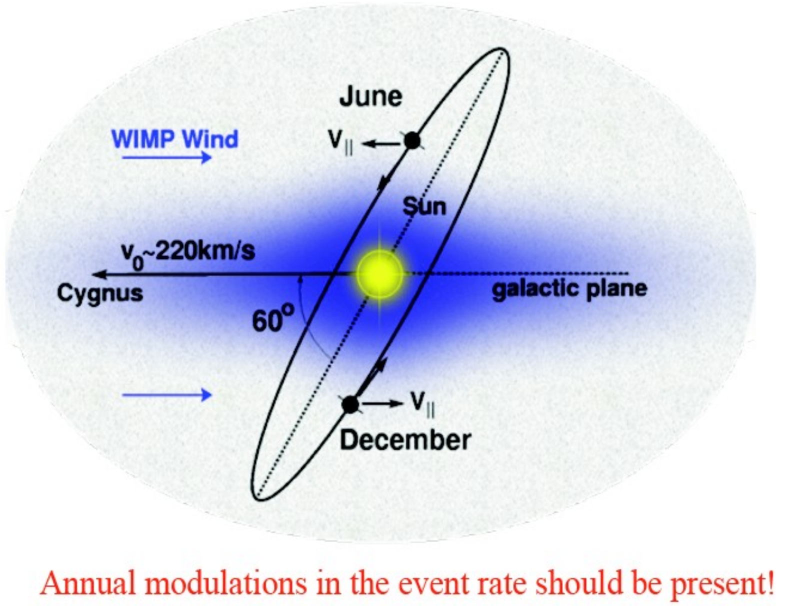
- Only through rare interactions with ordinary matter
- After the interaction, recoiling nucleus deposits energy in the detector, which is detectable (**heat, light, electric charge, ...**)



Nuclear recoil spectrum

- featureless, ~exponential
- lower threshold → more sensitivity
- natural radioactivity is a background





Directionality

→ annual modulation of the signal

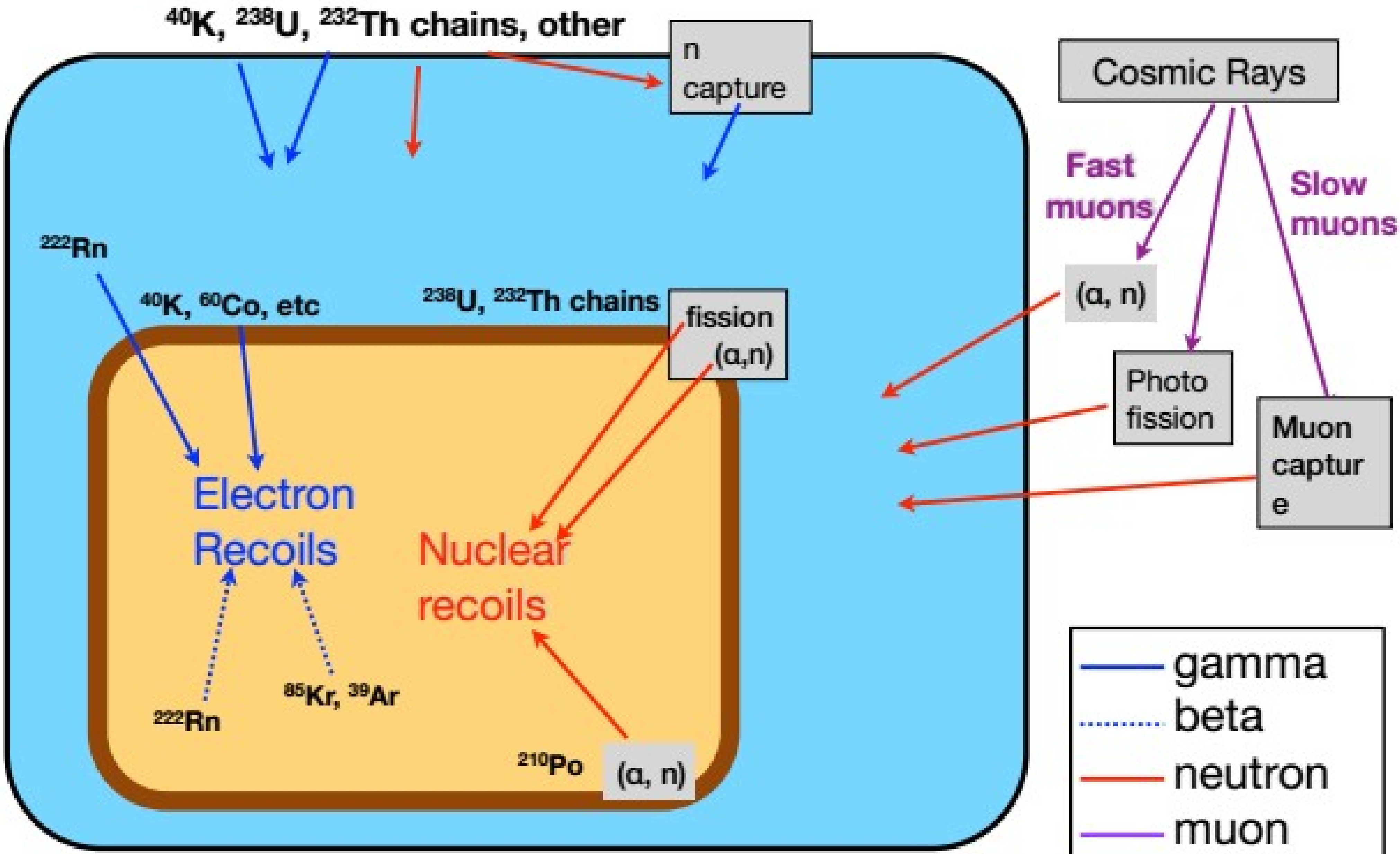
astrophysics

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

detector response

particle/nuclear physics

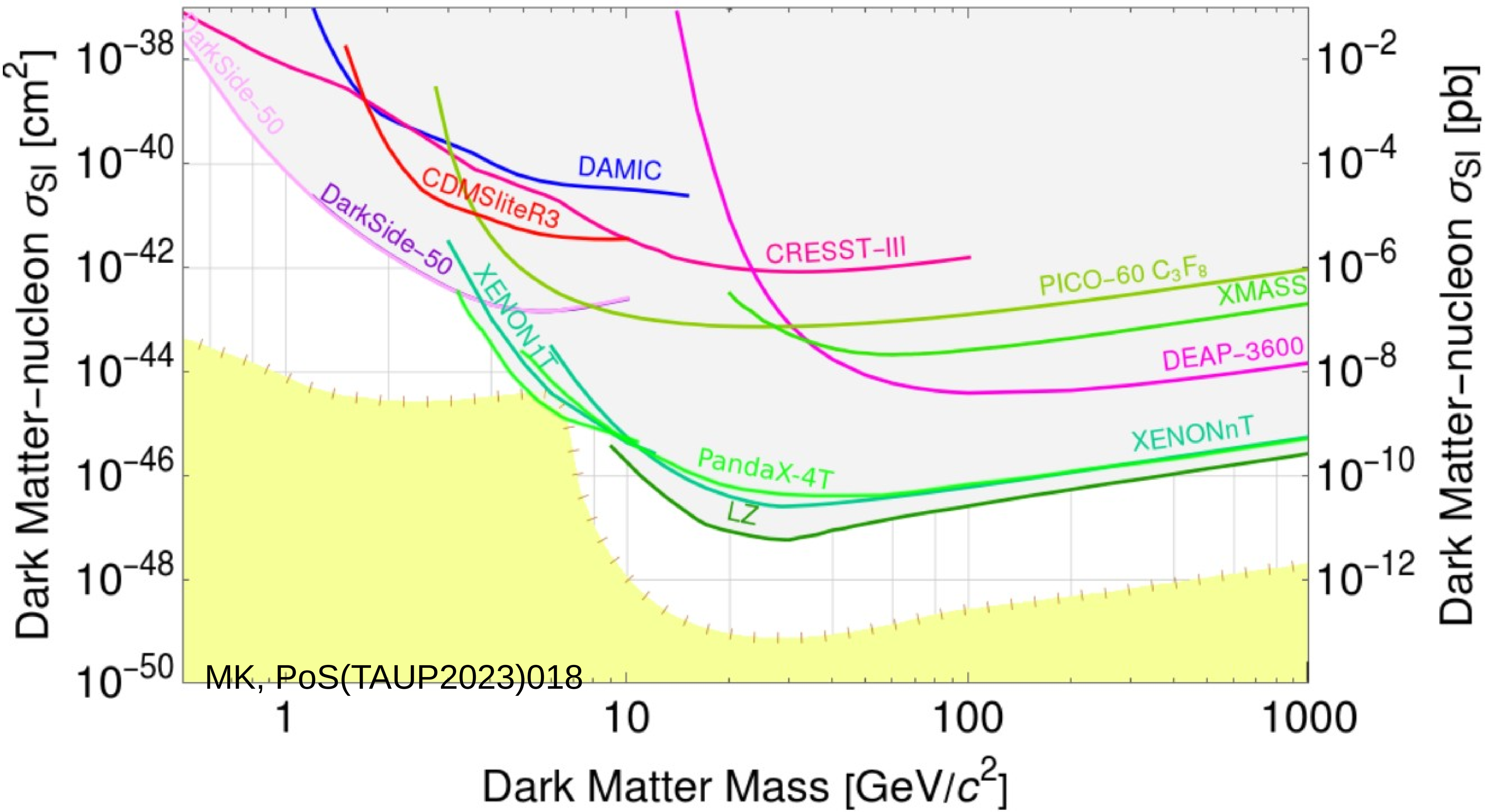
Backgrounds



Ambient backgrounds: 10^{11} time DM rate

T. Shutt -LIDINE, Sept 22, 2017

WIMP direct detection landscape (2023)



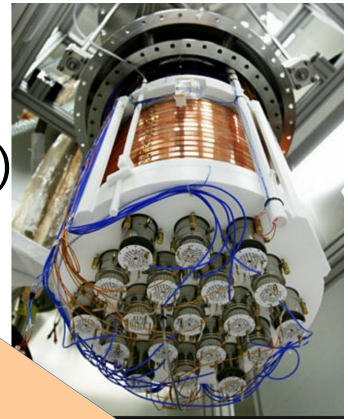
- Spin-independent, with the usual assumptions: Standard Halo Model, isospin parity
- **LAr and LXe dominate searches in the spin-independent sector >~2 GeV/c2**
- Continued search towards the neutrino floor still very well motivated

Liquid argon (LAr) detectors

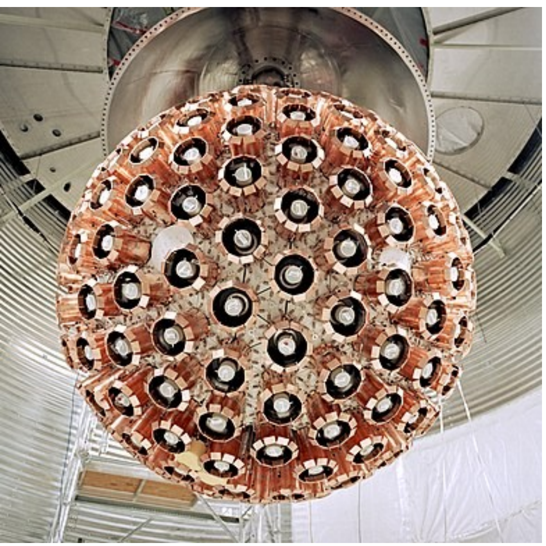
2010

10 kg

DarkSide-50
(50 kg, LNGS)



100 kg



ArDM (1t, LSC)

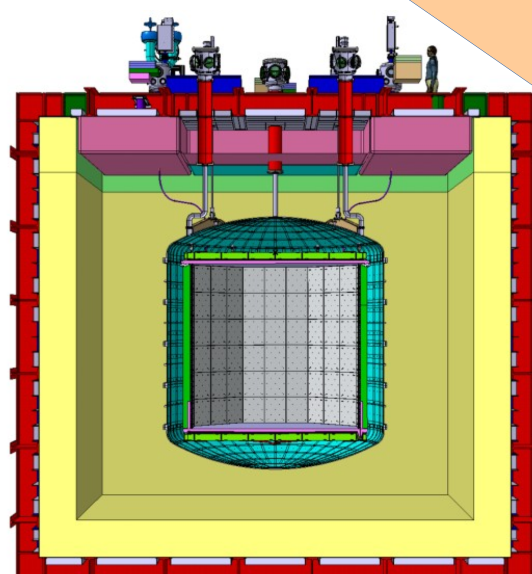
1000 kg

2015

DEAP-3600 (3.3t, SNOLAB)

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

Global Argon Dark Matter Collaboration formed



2020

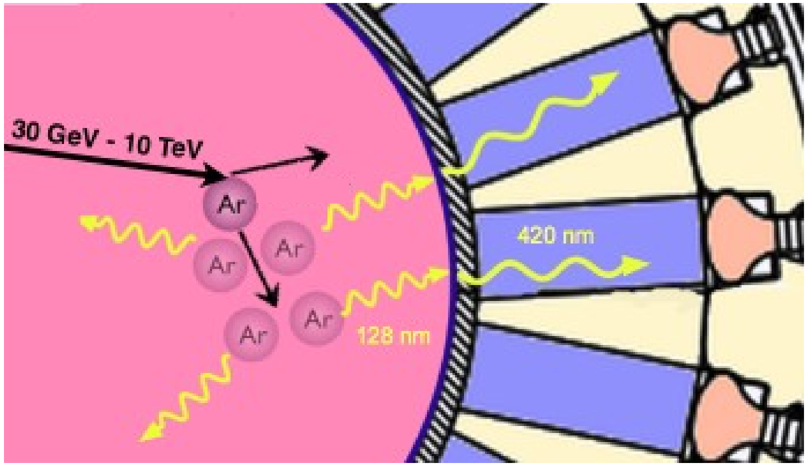
DarkSide-20k
(50t, LNGS)

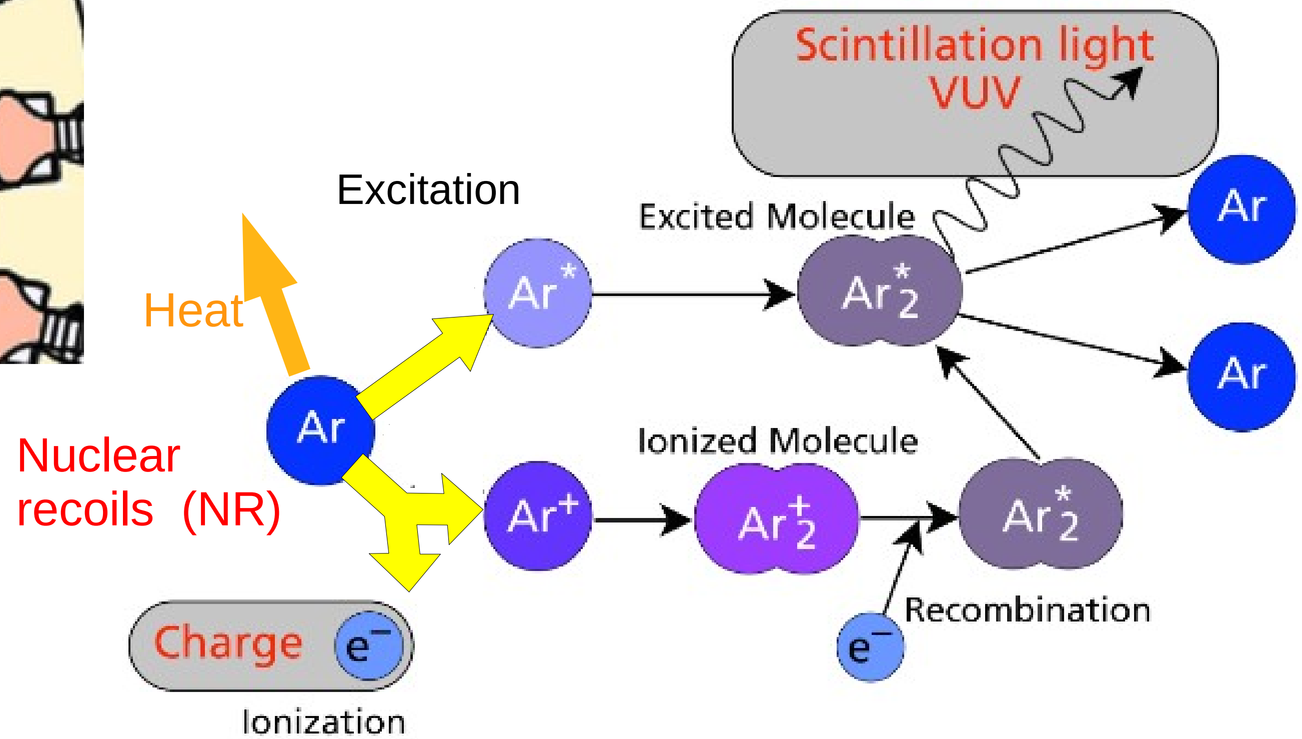
100000 kg

ARGO: 400 t

Slide courtesy J. Monroe

Liquid noble detectors





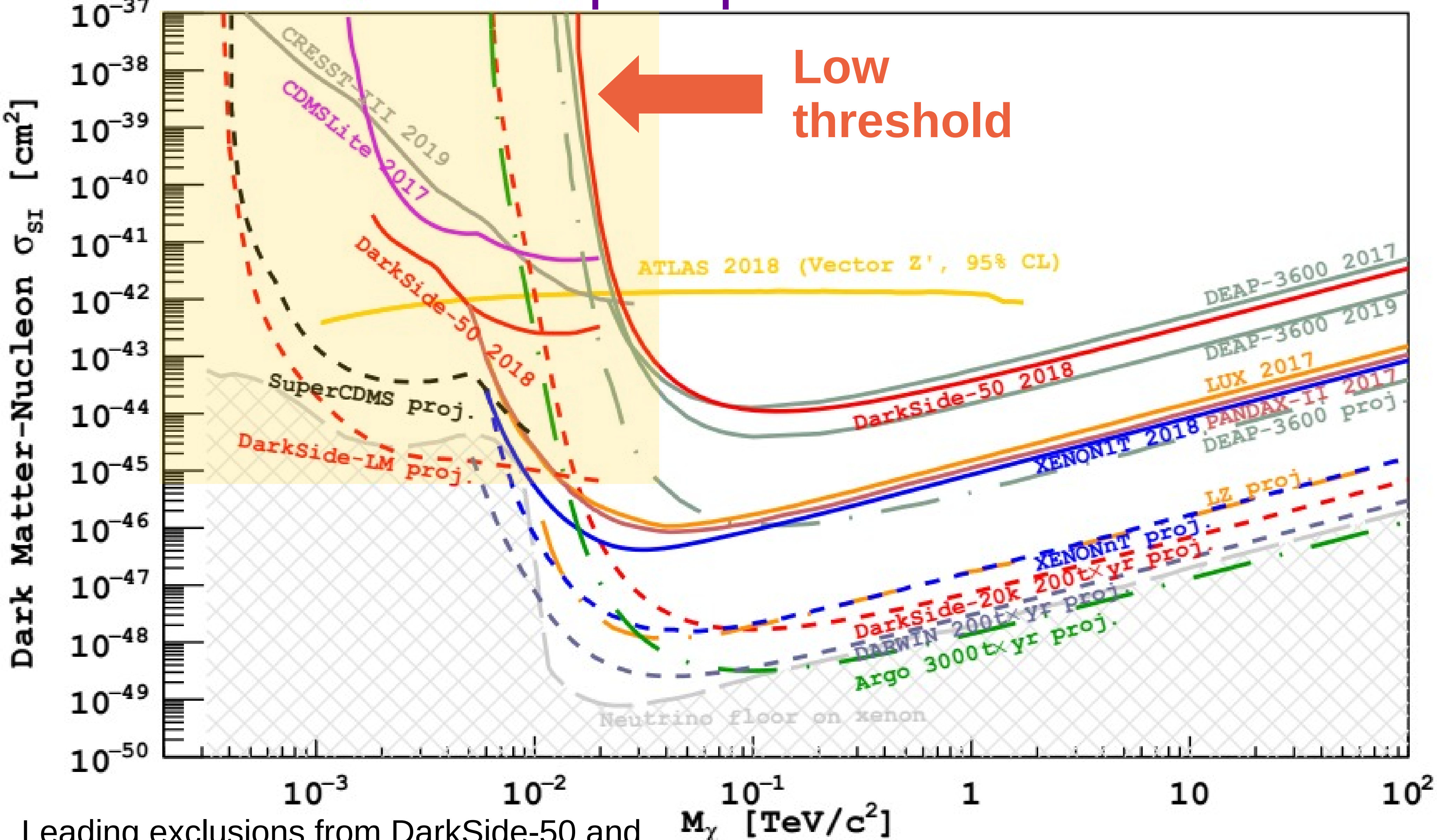
Ar and Xe are used for WIMP detection.

- Ar inexpensive and advantageous for purification and background rejection

Why noble elements?

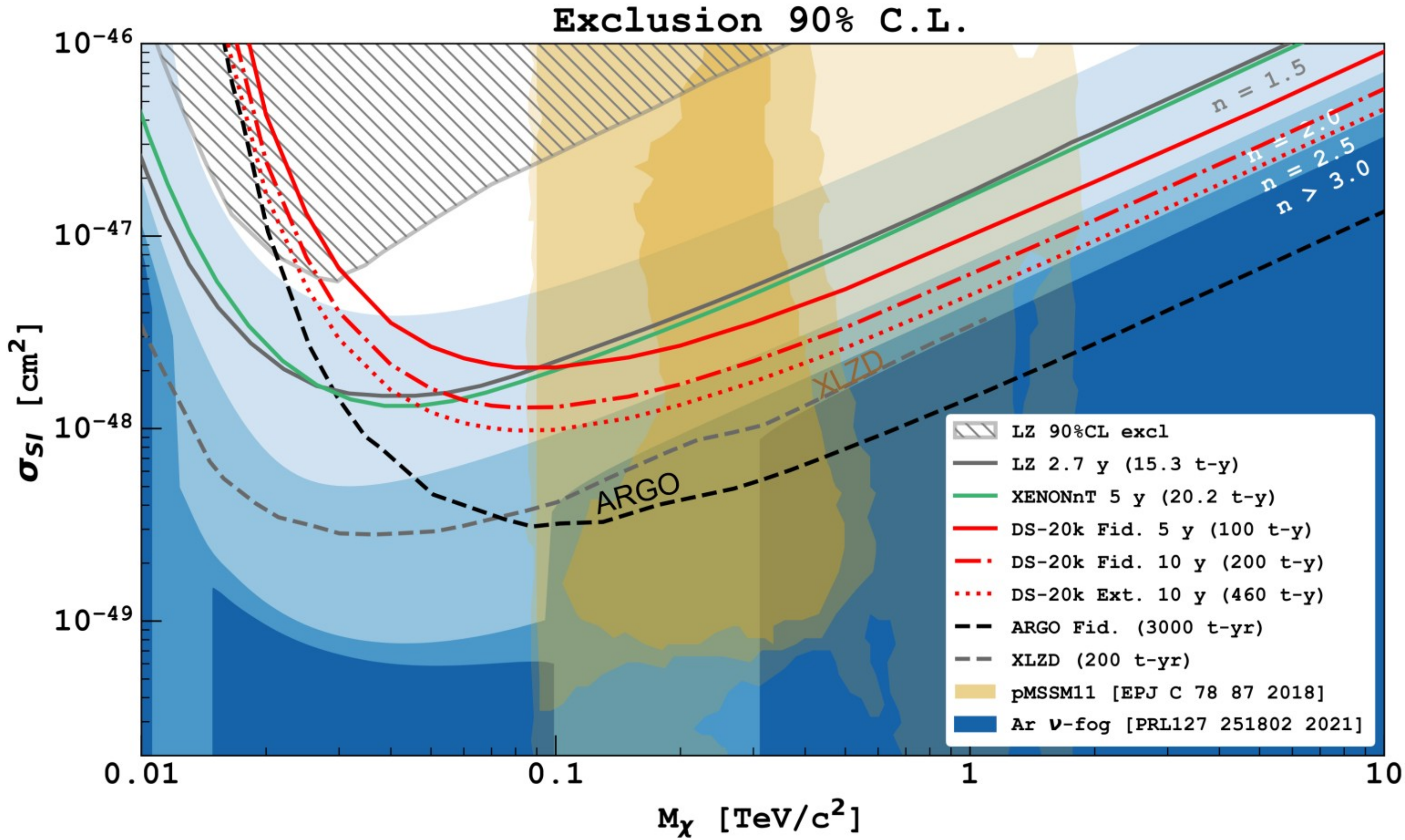
- High light yield, transparent to their own scintillation
- Easy to purify and scalable to very high masses
- (At least) two available detection channels: scintillation and ionization

Status and prospects: low mass



- Leading exclusions from DarkSide-50 and XENON1T (both S2-only)
- Multiple noble liquid-based and other technologies still in play in different parts of the mass spectrum (SuperCDMS, CRESST, NEWS-G, DAMIC)
- The neutrino floor soon within reach
- Still much work on low-energy calibration and backgrounds

Status and prospects: high mass

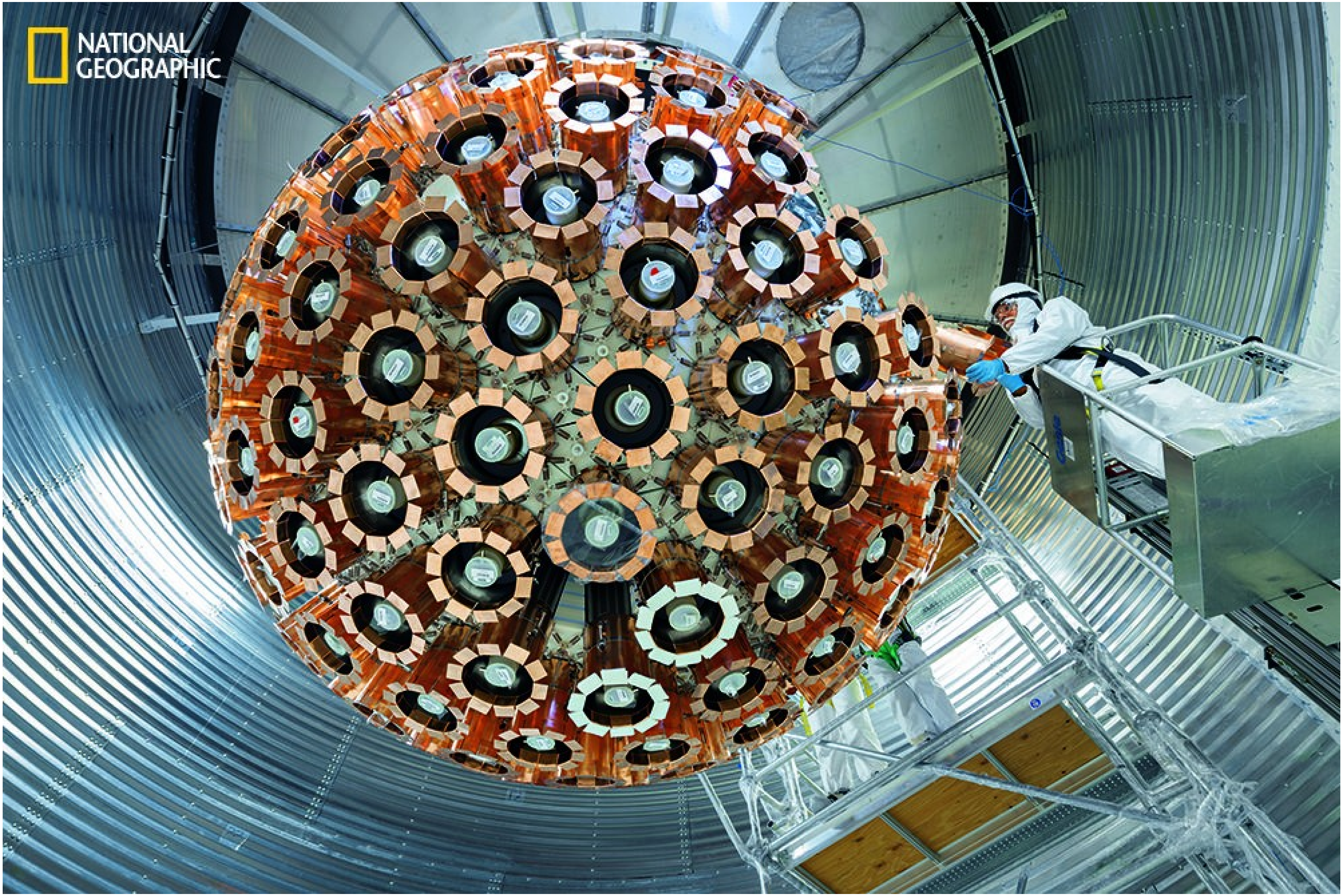


- Results from LZ, XENONnT and PandaX
- Multiple new results from LAr detectors, reducing the sensitivity gap

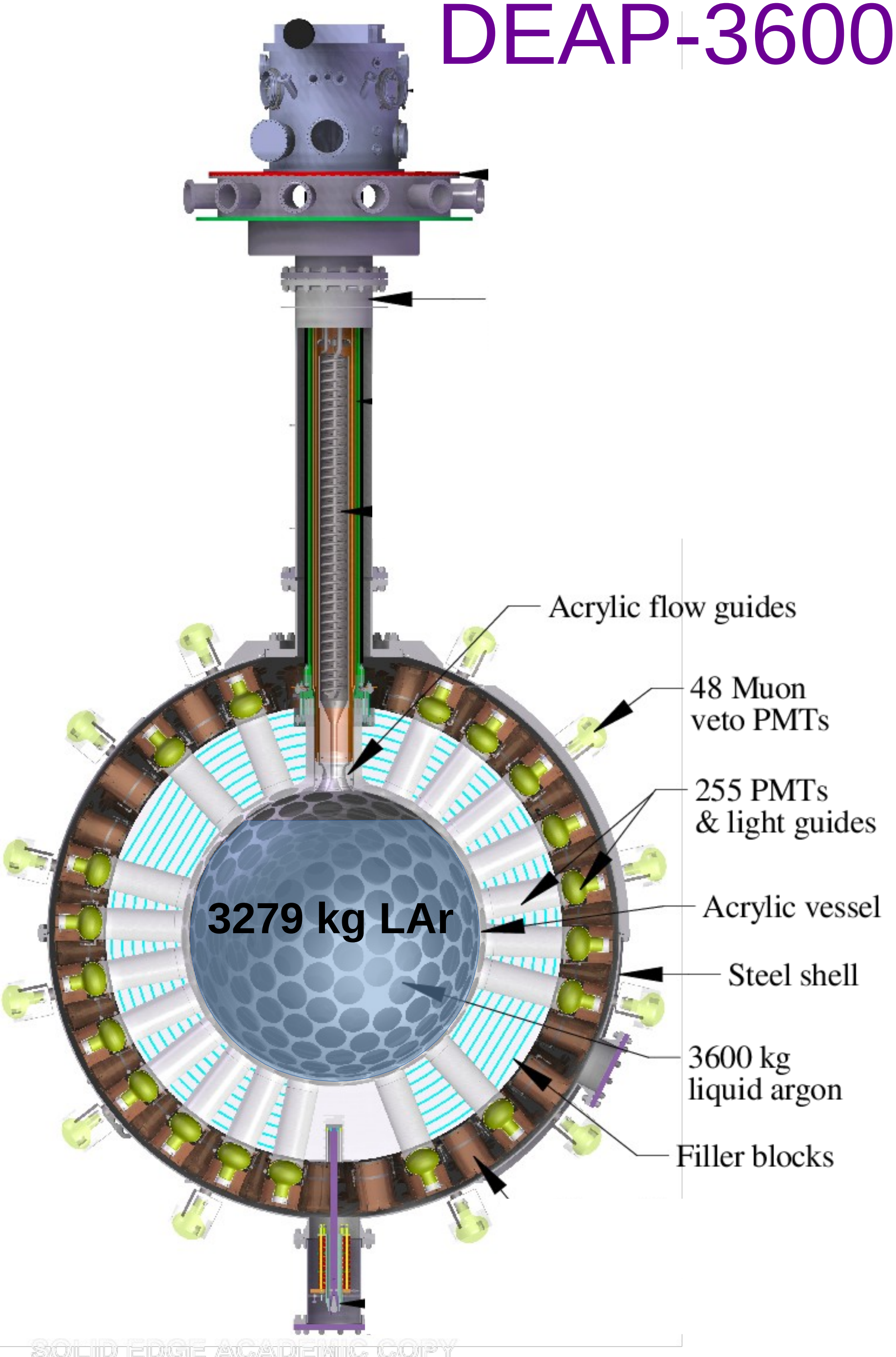
neutrino floor

- **Scale-up requires global consolidation of efforts and R&D**

DEAP-3600 detector



DEAP-3600 Dark Matter Search

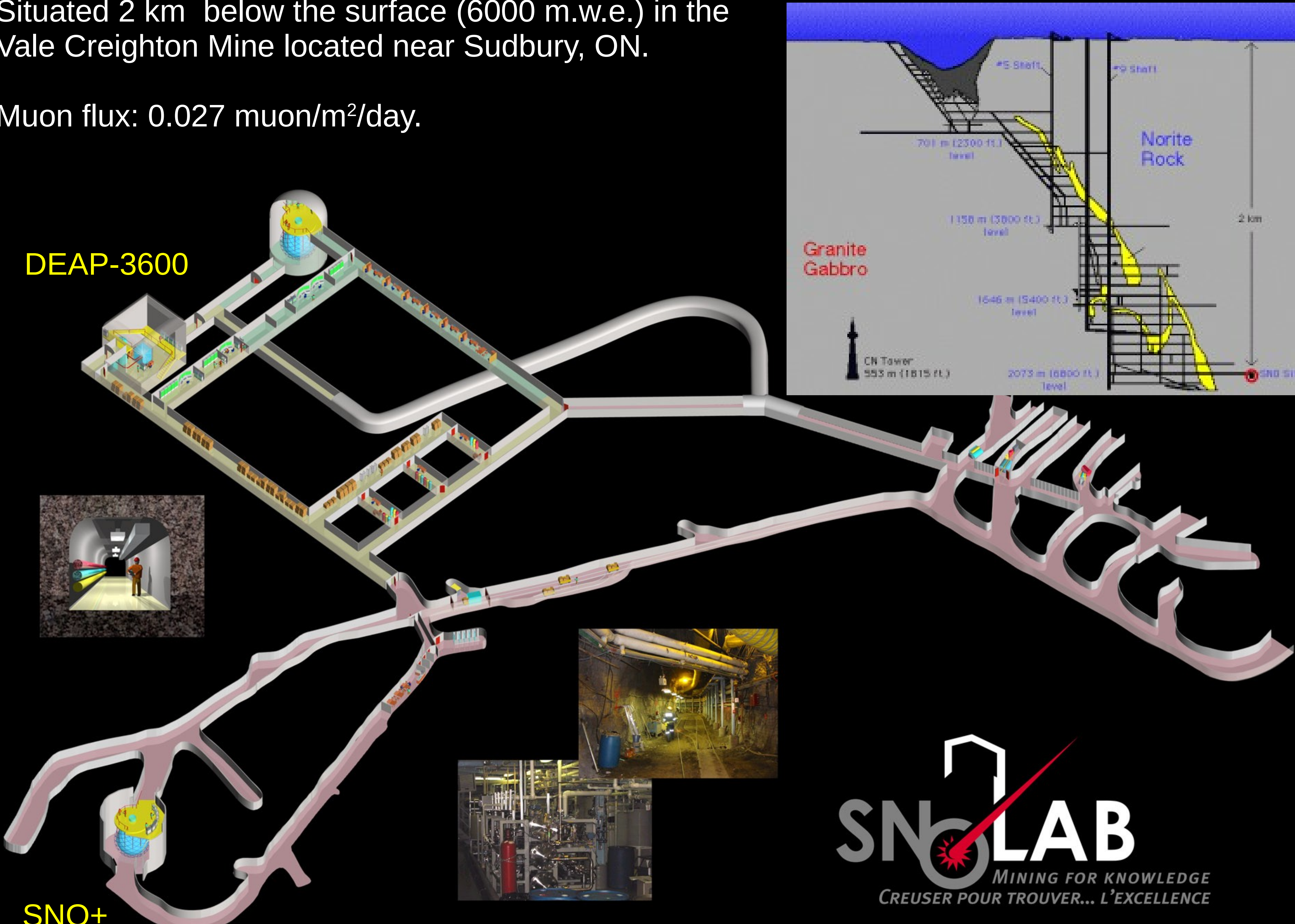


- 3.3 tonne liquid argon target (1000 kg fiducial) in sealed ultraclean Acrylic Vessel
- 128 nm scintillation from liquid argon is detected after converting it to visble
- In-situ vacuum evaporated TPB wavelength shifter (~10 m^2 surface)
- Bonded 50 cm long light guides + polyethylene shielding against 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
- Taking data since 2016

SNOLAB

Situated 2 km below the surface (6000 m.w.e.) in the Vale Creighton Mine located near Sudbury, ON.

Muon flux: 0.027 muon/m^2/day.



SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

Pulse shape discrimination (PSD)

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

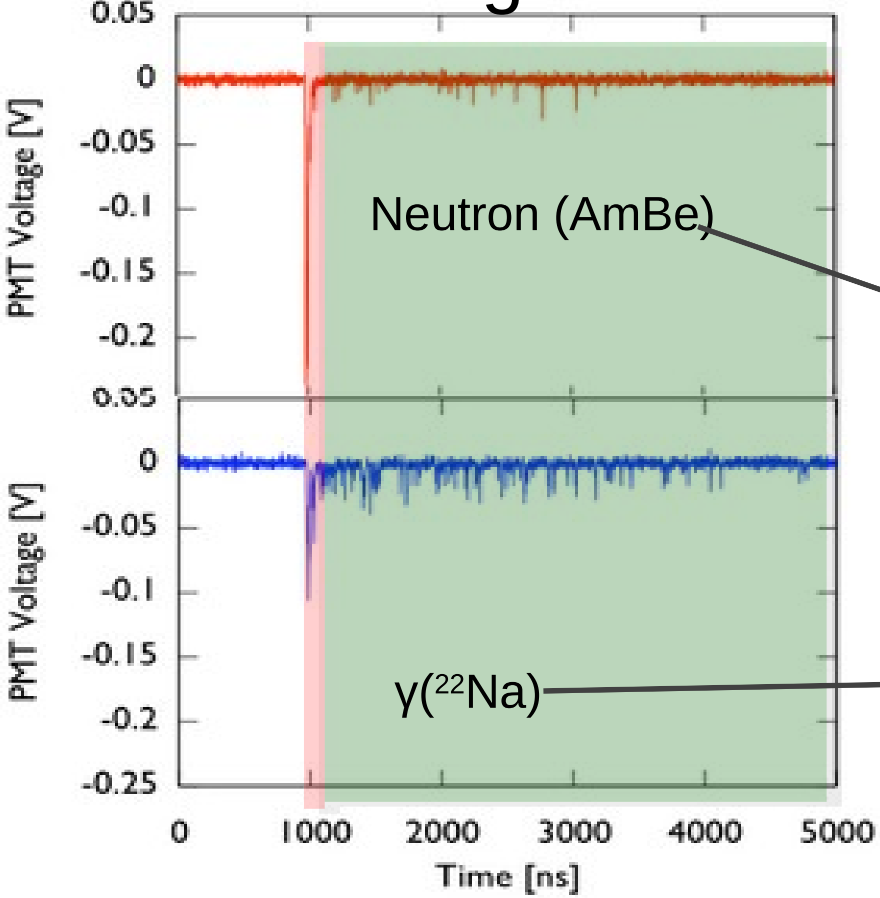
<u>**Single phase LAr:**</u>
scintillation channel is sufficient for β/γ rejection
no need for the ionization channel

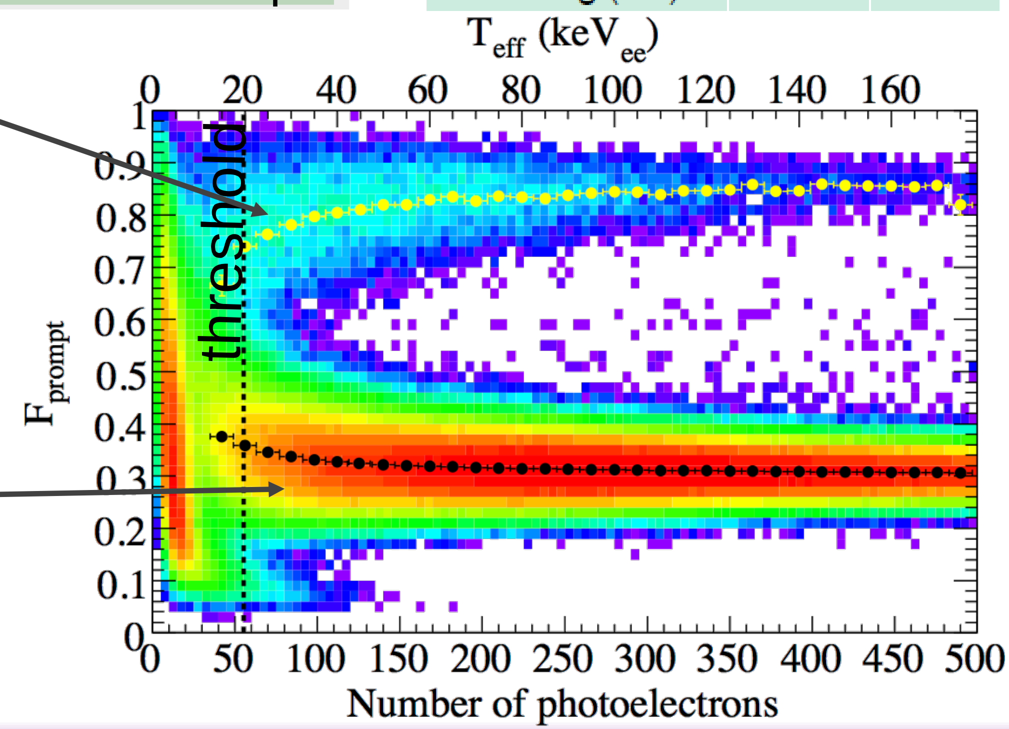
Parameter	Ar	Xe
Yield (x10^4 photons/MeV)	4	4.2
Prompt time constant τ_1	6 ns	2 ns
Late time constant τ_3	**1.5 μs**	21 ns
I_1/I_3 for electrons	0.3	0.3
I_1/I_3 for nuclear recoils	3	1.6
λ(peak) nm	128	174
Rayleigh scattering (cm)	90	30

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

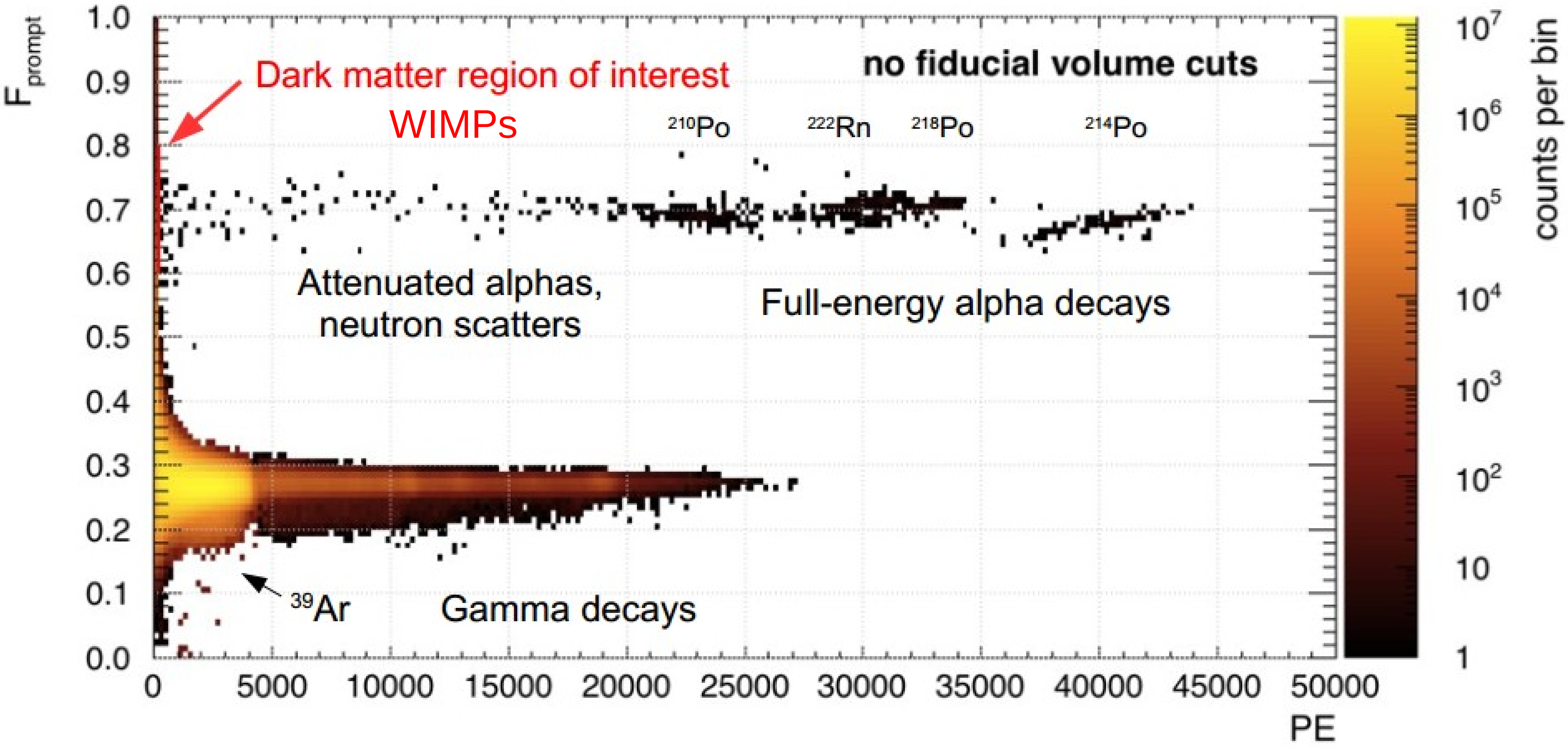
PMT signal:

Prompt : 0-60ns
Late: 60ns-10μs





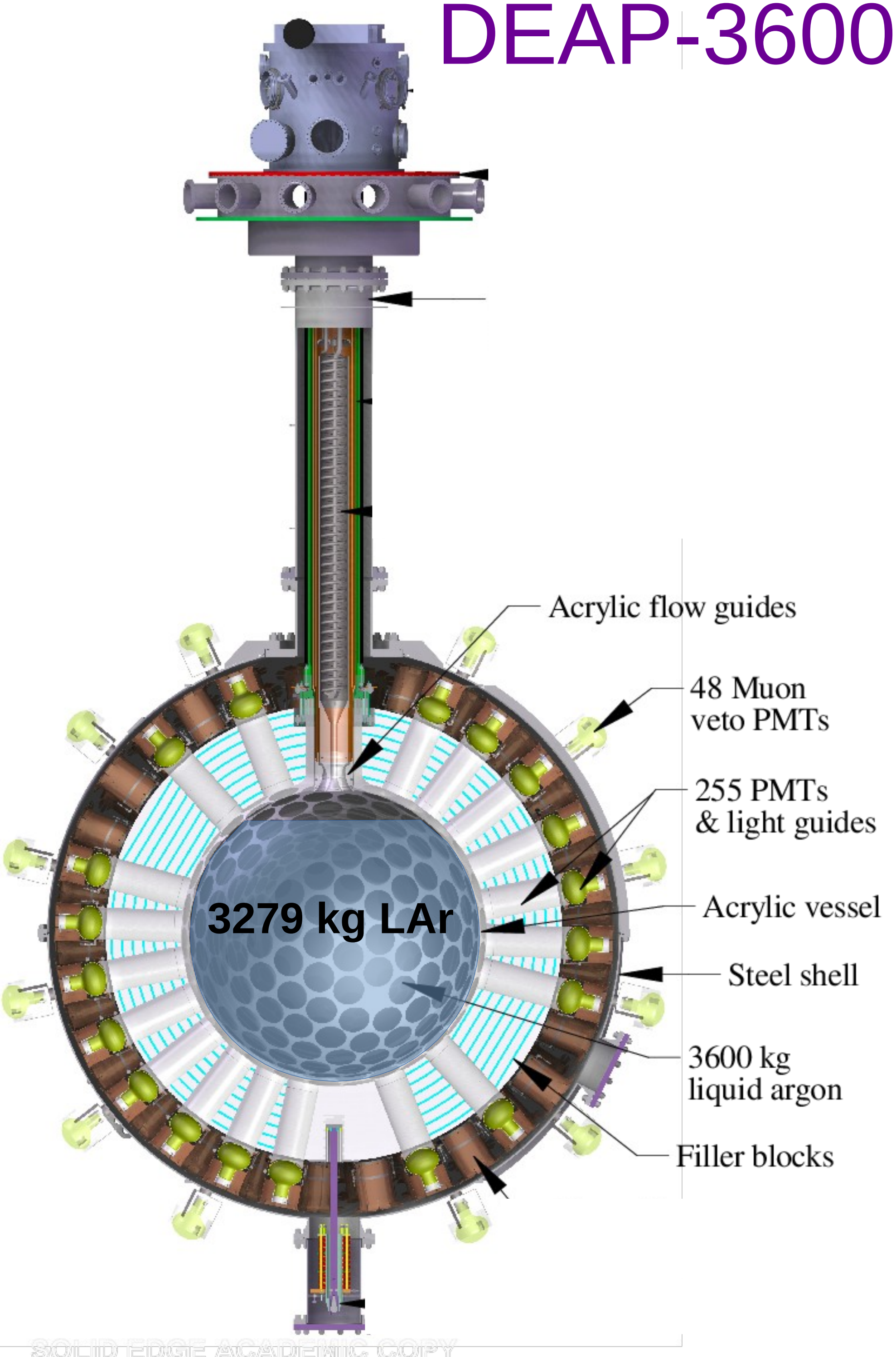
Event populations and their signatures



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

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

DEAP-3600 Dark Matter Search



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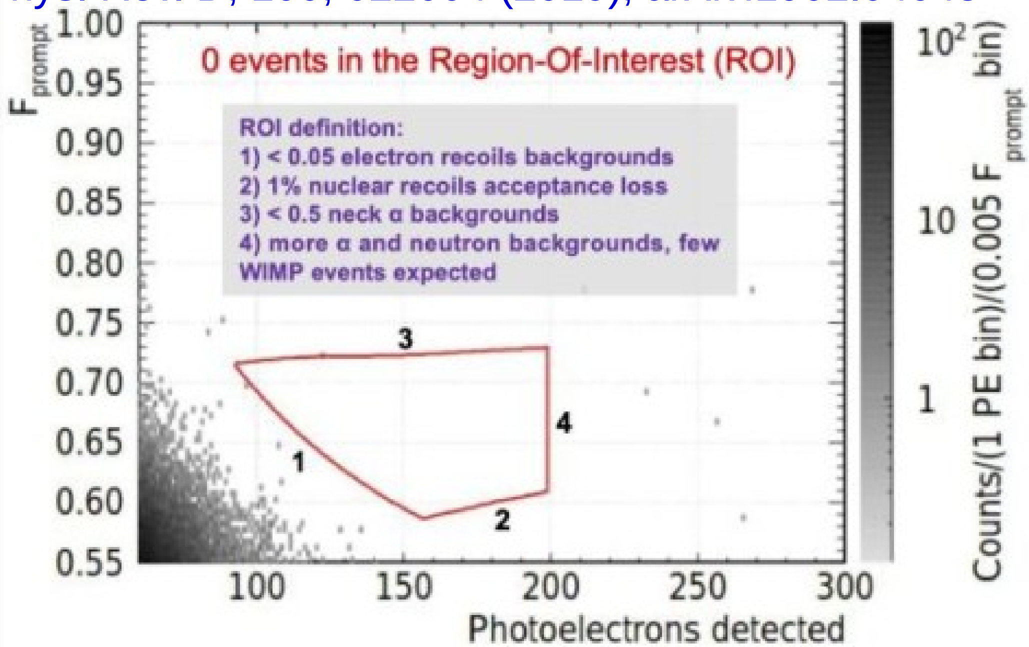
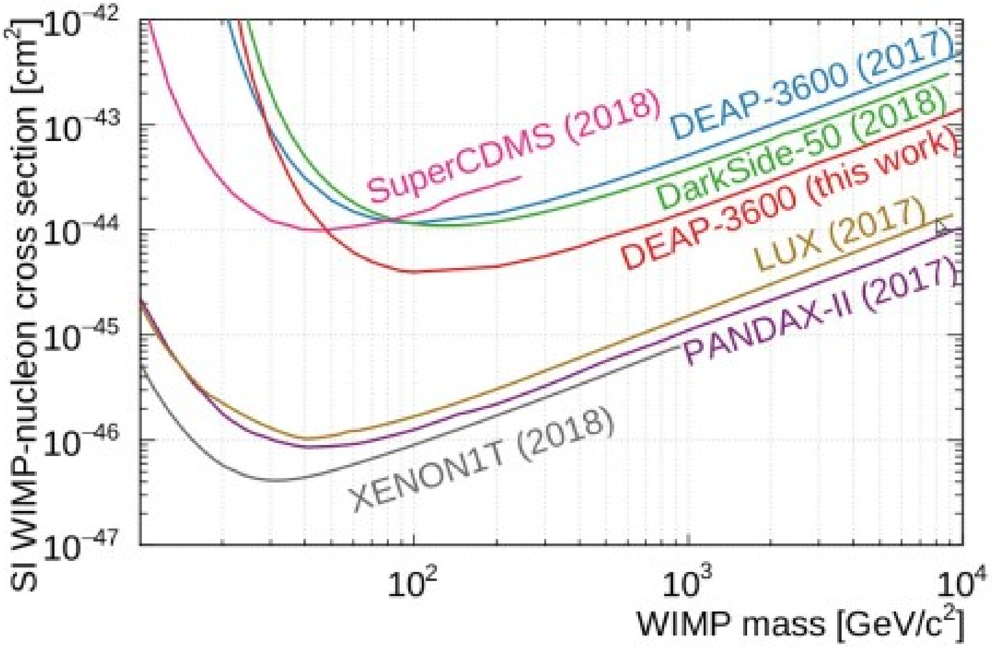
- Detector immersed in 8 m water shield, instrumented with PMTs to veto muons
- Located 2 km underground at SNOLAB
- Taking data since 2016

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

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



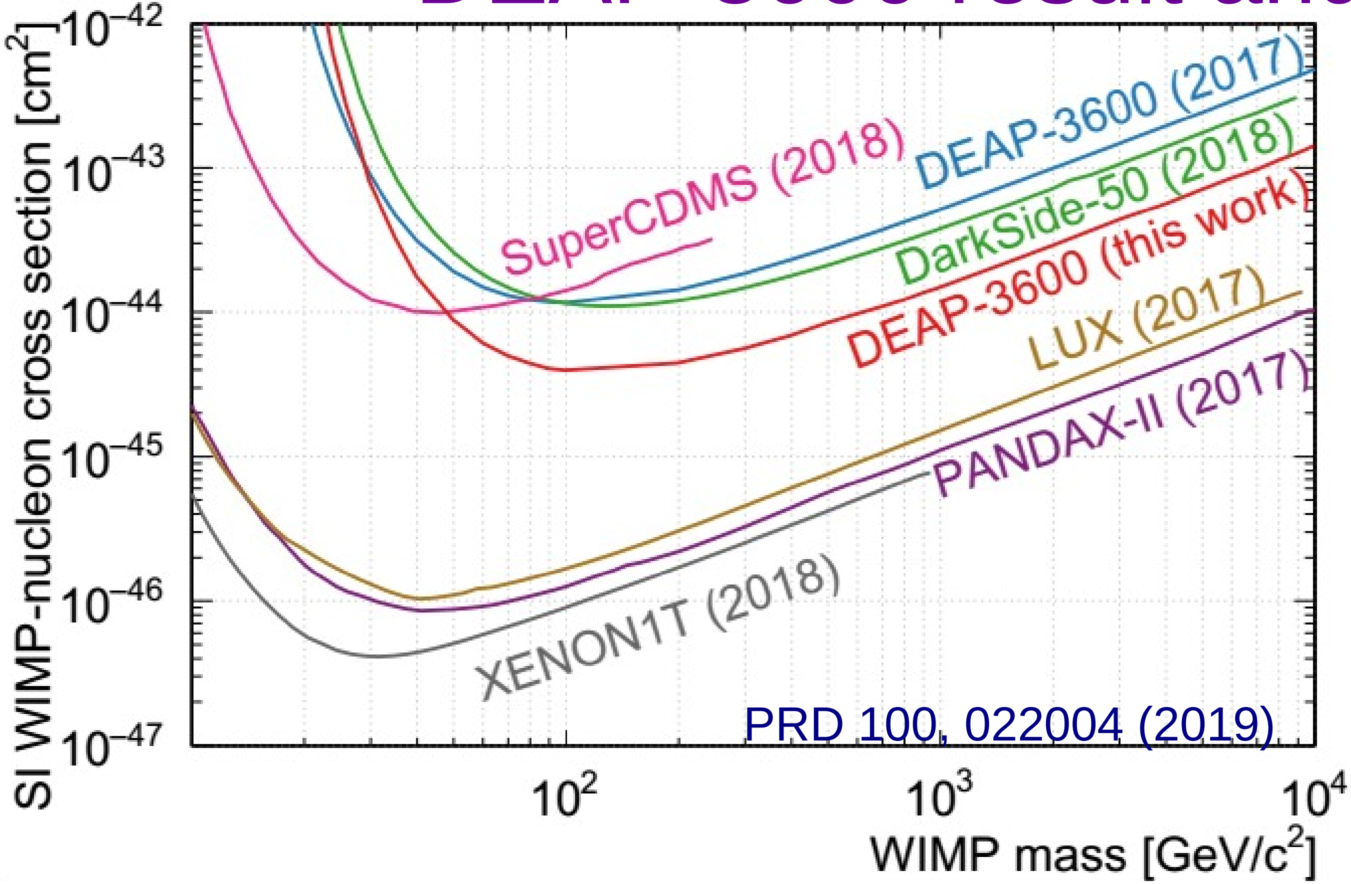


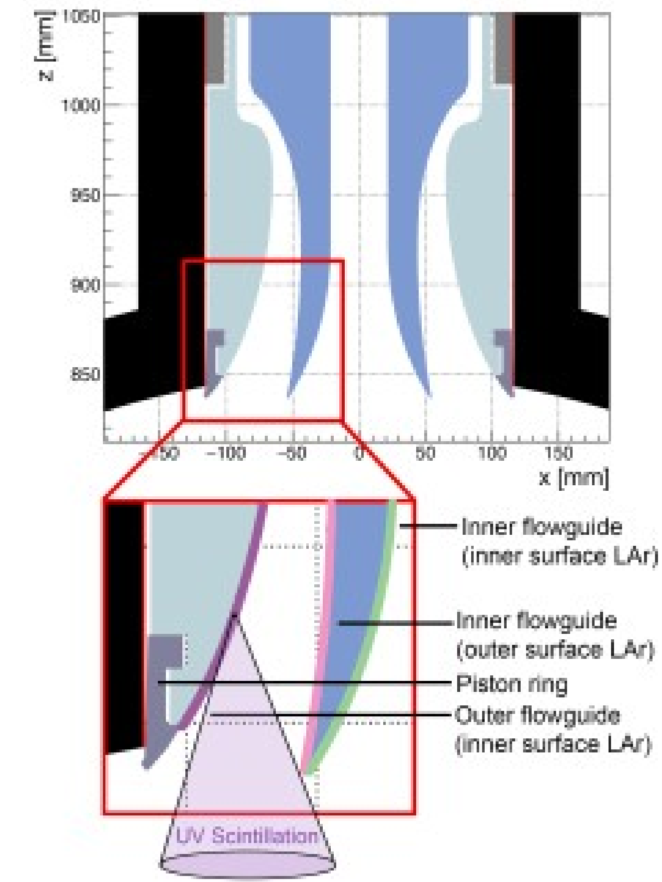
- Zero observed backgrounds, leading exclusion with LAr
- Excellent control over main background types, leading edge among other experiments
- Further sensitivity improvements **limited by backgrounds from alpha activity in the neck of the detector**
- Since then:
  - Stable data collection for DM search:
    - 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**

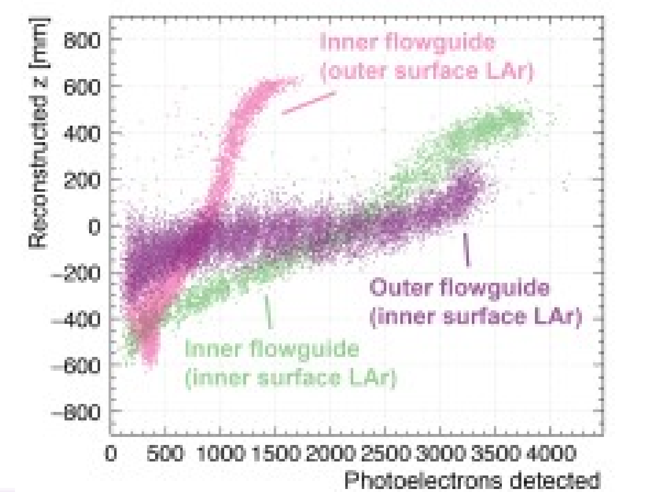
	Source	N^{CR}	N^{ROI}
β/γ's	ERs	2.44×10^9	0.03 ± 0.01
	Cherenkov	$< 3.3 \times 10^5$	< 0.14
n's	Radiogenic	6 ± 4	$0.10^{+0.10}_{-0.09}$
	Cosmogenic	<0.2	<0.11
α's	AV surface	<3600	< 0.08
	Neck FG	28^{+13}_{-10}	$0.49^{+0.27}_{-0.26}$
	Total	N/A	$0.62^{+0.31}_{-0.28}$

Backgrounds budget

DEAP-3600 result and plans





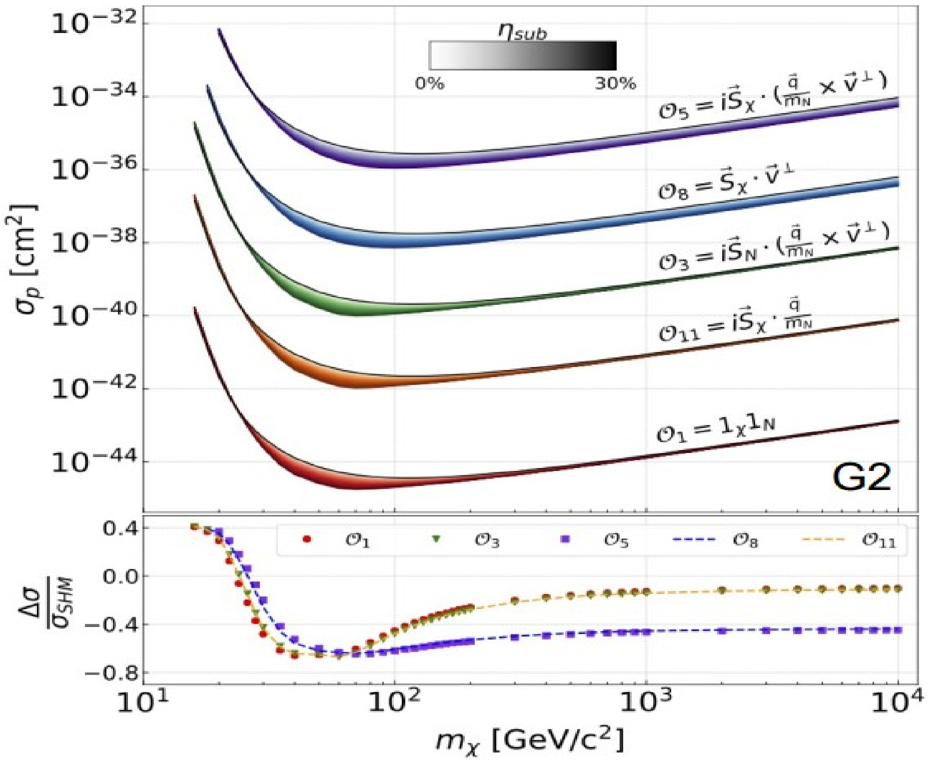


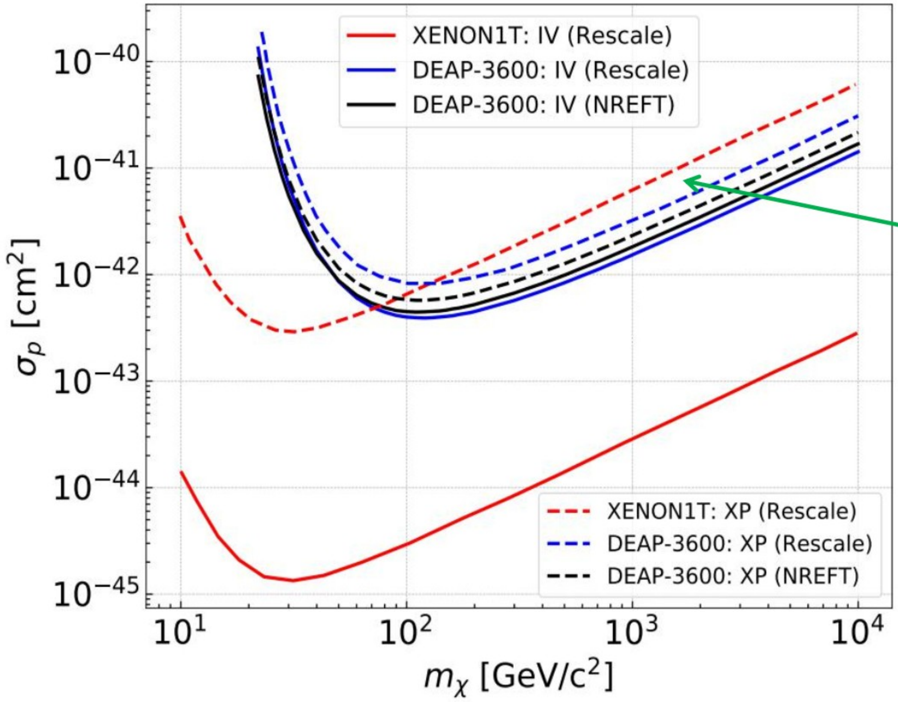
- Leading WIMP exclusion in Ar
- Acceptance reduced due to cuts against background events induced by alpha activity in the neck
  - New analysis expected to recover much of acceptance lost due to neck event cuts – nearly final
  - Hardware upgrade to fix the background problem
- Other physics papers in preparation: solar ^{8}B neutrino absorption observation, **solar axion search**, boosted DM search, ^{39}Ar: livetime, natural abundance and beta-decay spectrum measurements

Effective Field Theory, non-standard halo

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

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



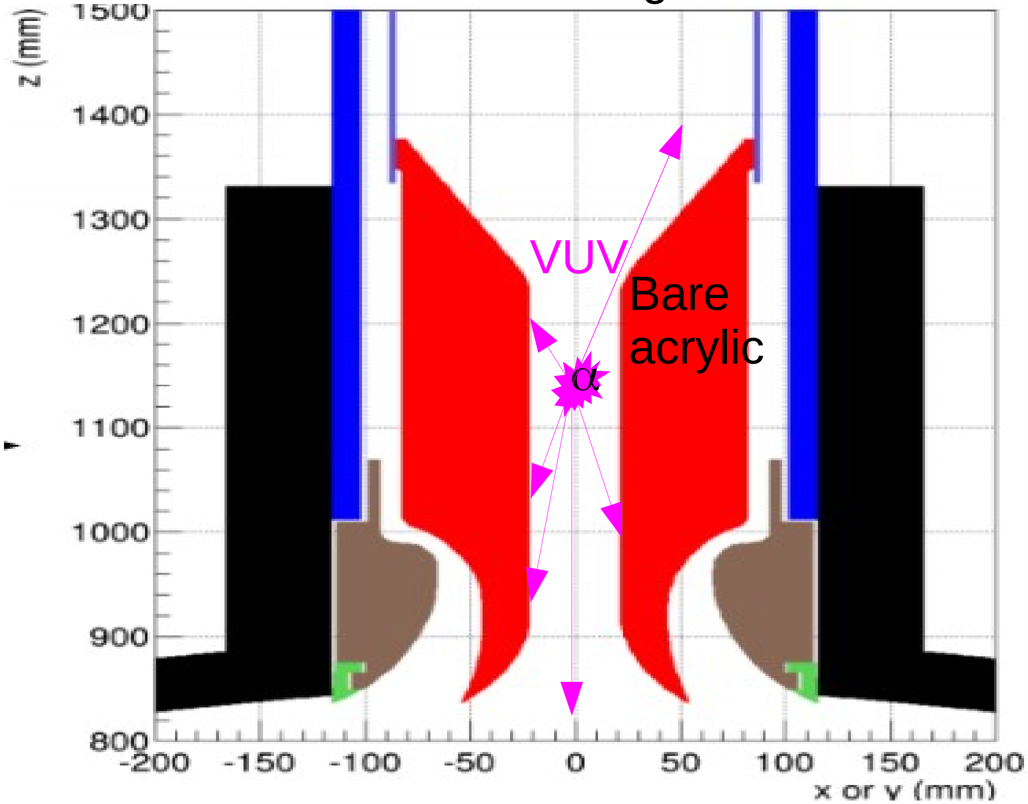


Region where DEAP-3600 sets stronger limits than XENON1T by considering the XP scenario.

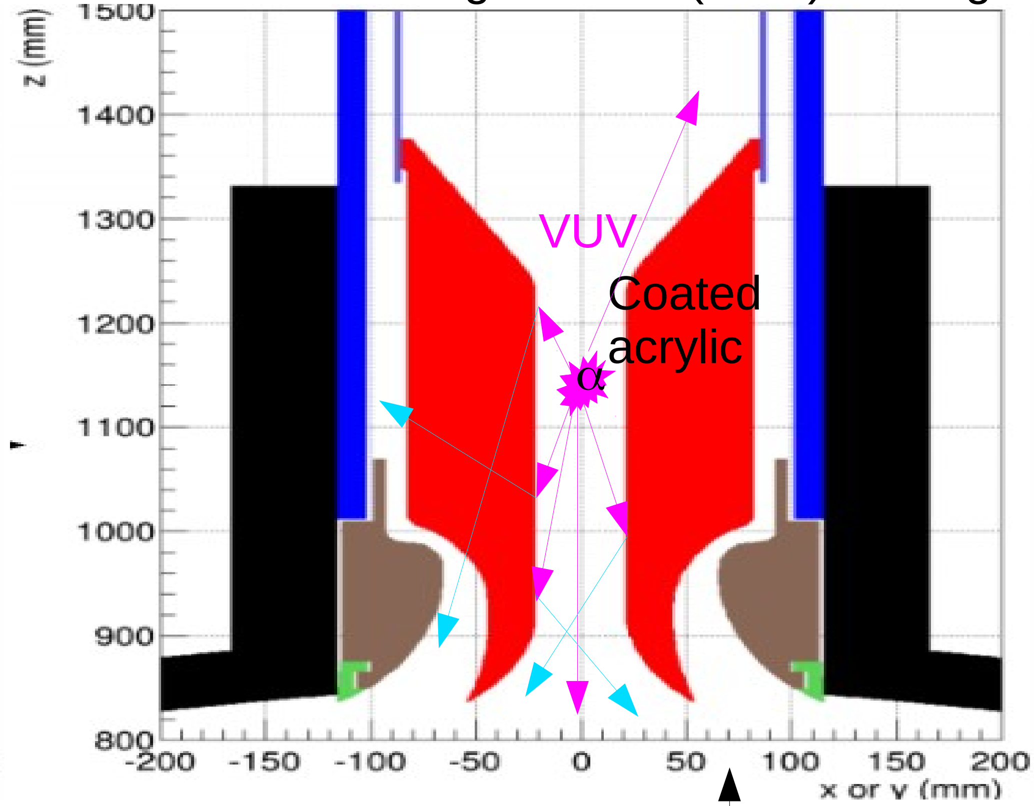
Using NREFT + XP (black dash line), the region increases. While the Helm form factor doesn't change assuming $c_n \neq c_p$, in the NREFT formalism the form factor does.

Hardware upgrade 1: neck events

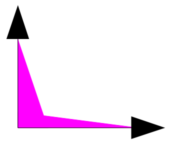
Current configuration



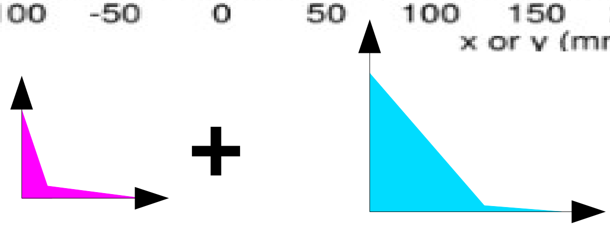
Slow wavelength shifter (WLS) coating



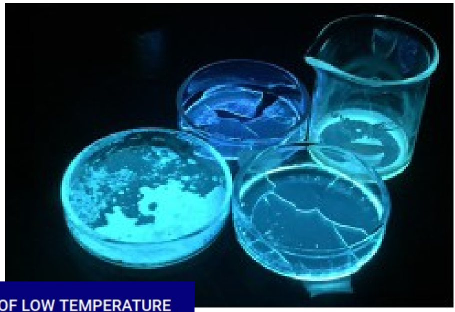
[NIM A 1034, 166683 (2021)]
[JINST 16, P12029 (2021)]



Resulting pulseshapes



- 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**
- Characterization of the final pyrene-PS coating at 87K and 128 nm excitation: AstroCeNT in collaboration with INTiBS PAN (Wrocław)
- New coated flowguides are already manufactured and ready for installation



INTIBS PAN WROCŁAW INSTITUTE OF LOW TEMPERATURE AND STRUCTURE RESEARCH Polish Academy of Sciences

Hardware upgrade 2: dust alpha backgrounds

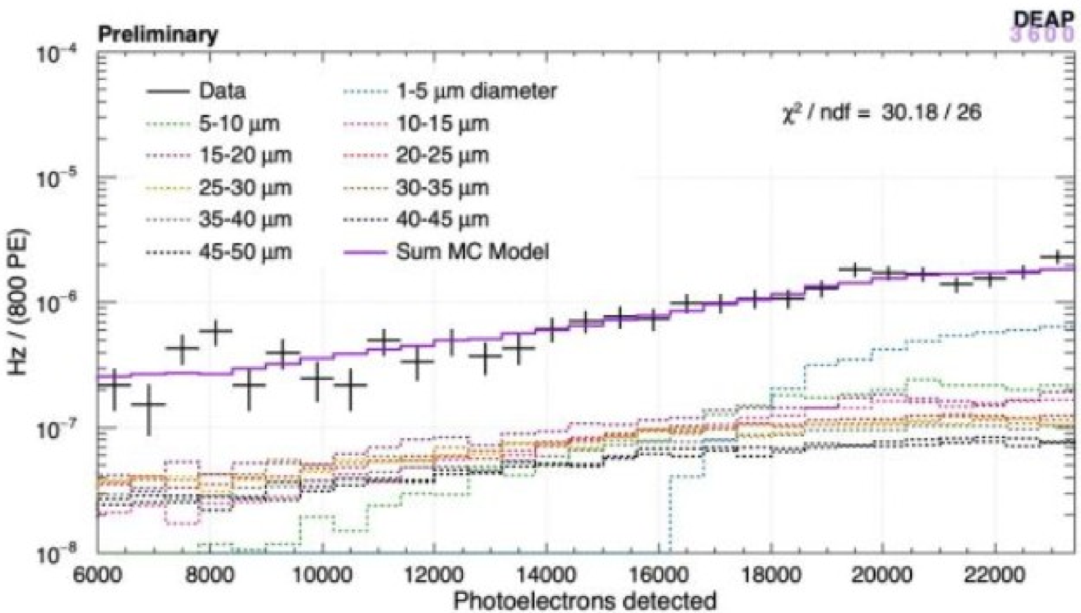
- Evidence for presence of dust particulates in LAr in the detector.
- Orginally installed LAr filtration loop could not be used for technical reasons

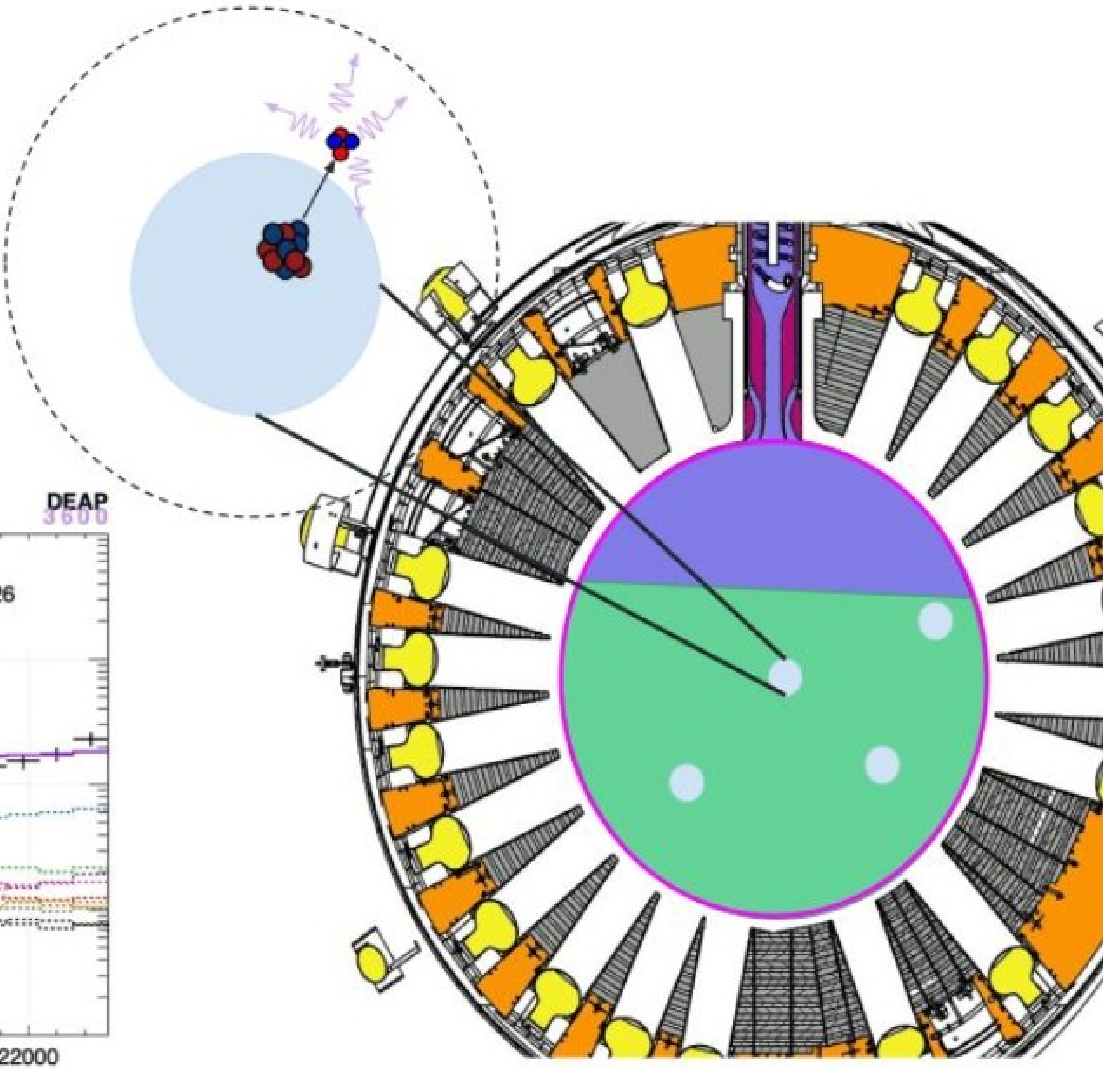
- Alpha decays embedded in dust particulates have reduced energy deposition in LAr

→ low-energy tail in the spectrum

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

- To be removed with dedicated filters





Axions and axion-like particles (ALPs)

- Strong CP problem

  Axion field has "vev" at $a = -\frac{f_a}{\zeta}\bar{\theta}$

  - $\mathcal{L}_{QCD} = \bar{\psi} i\gamma^\mu D_\mu \psi + \frac{1}{4} G^2 + \frac{g^2\bar{\theta}}{32\pi^2} G\tilde{G} - \frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{int}[\partial^\mu a / f_a ; \psi] + \zeta \frac{a}{f_a} \frac{g^2}{32\pi^2} G\tilde{G}$
  - From experiment: $\bar{\theta} < 1.98 \times 10^{-10}$ radians

  Peccei-Quinn (PQ) Theory

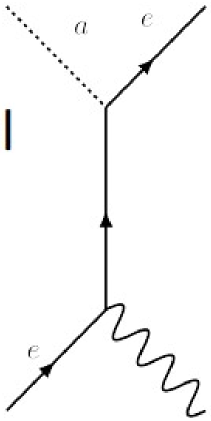
- Peccei-Quinn (PQ) theory cleans up the strong-CP Problem
  - Predicts a new particle, the axion
  - Axions are very light and interact very rarely
  - A compelling candidate for dark matter

- ALPs are like axions, except not 'required' to solve the strong CP problem

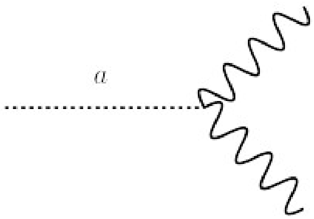
Axion interactions in DEAP-3600 produce electromagnetic events

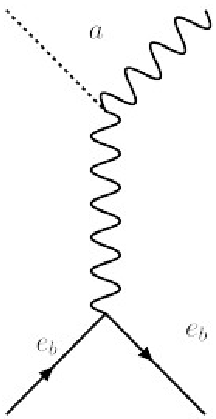
- Compton conversion
  - Get 1 gamma and 1 electron, with 5.5 MeV total kinetic energy
- Inverse Primakov
  - Get 1 gamma with 5.5 MeV energy
- Axio-electric effect
  - Get 1 electron with 5.5 MeV kinetic energy
- Axion decay into 2 gammas
  - Get 2 gammas with 5.5 MeV total energy

Compton Conversion

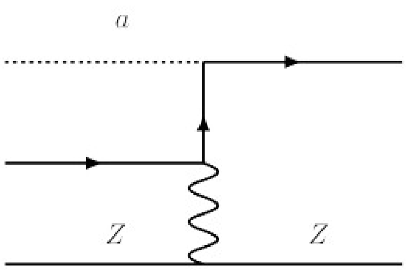


Decay to 2γ





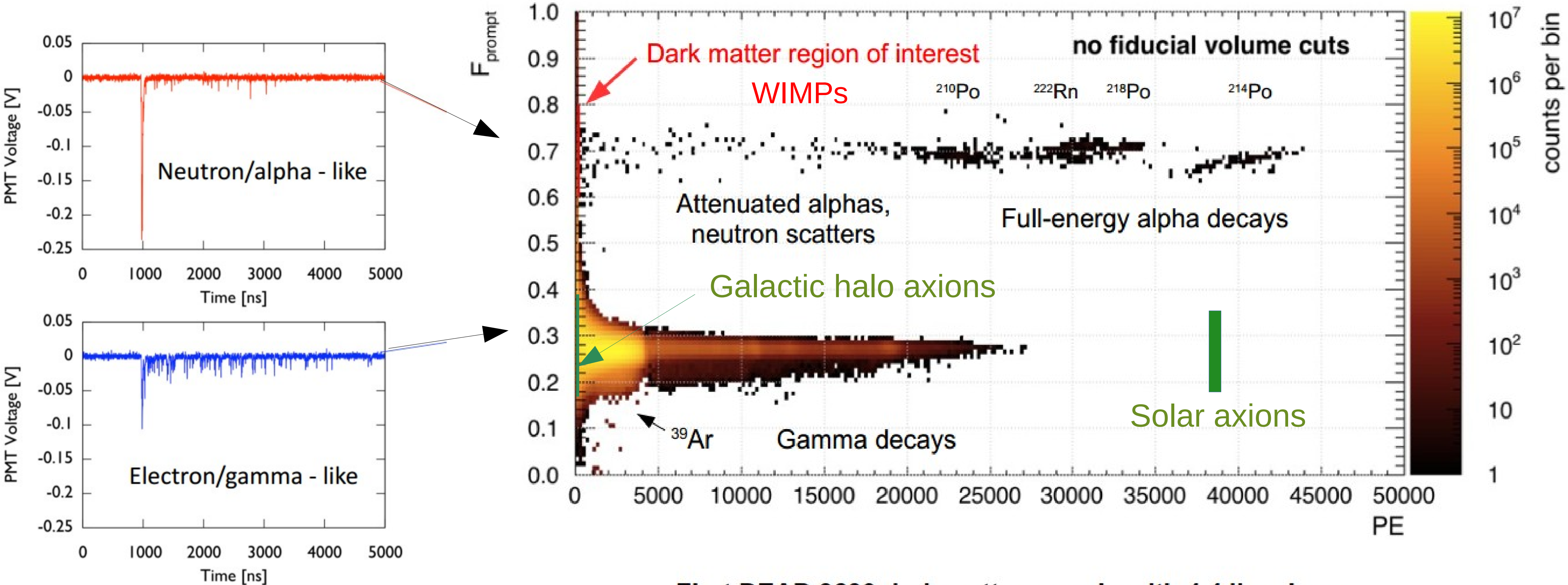
Inverse Primakov



Axio-Electric Effect

... and not nuclear recoil events as in the case of WIMPs

Event populations and their signatures

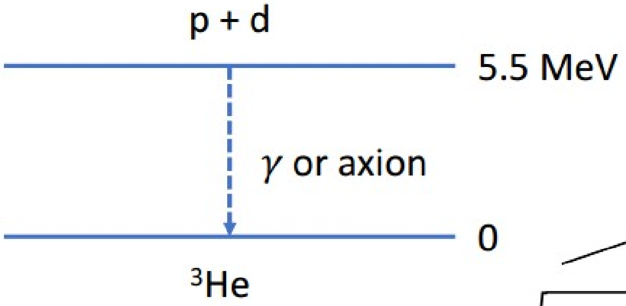


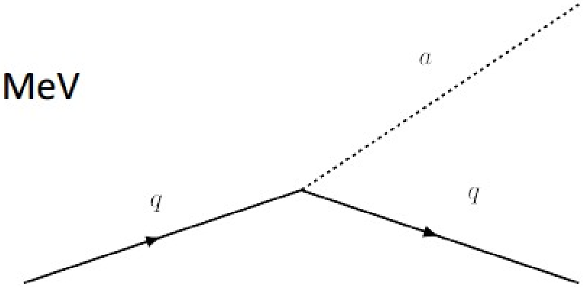
First DEAP-3600 dark matter search, with 4.4 live days

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

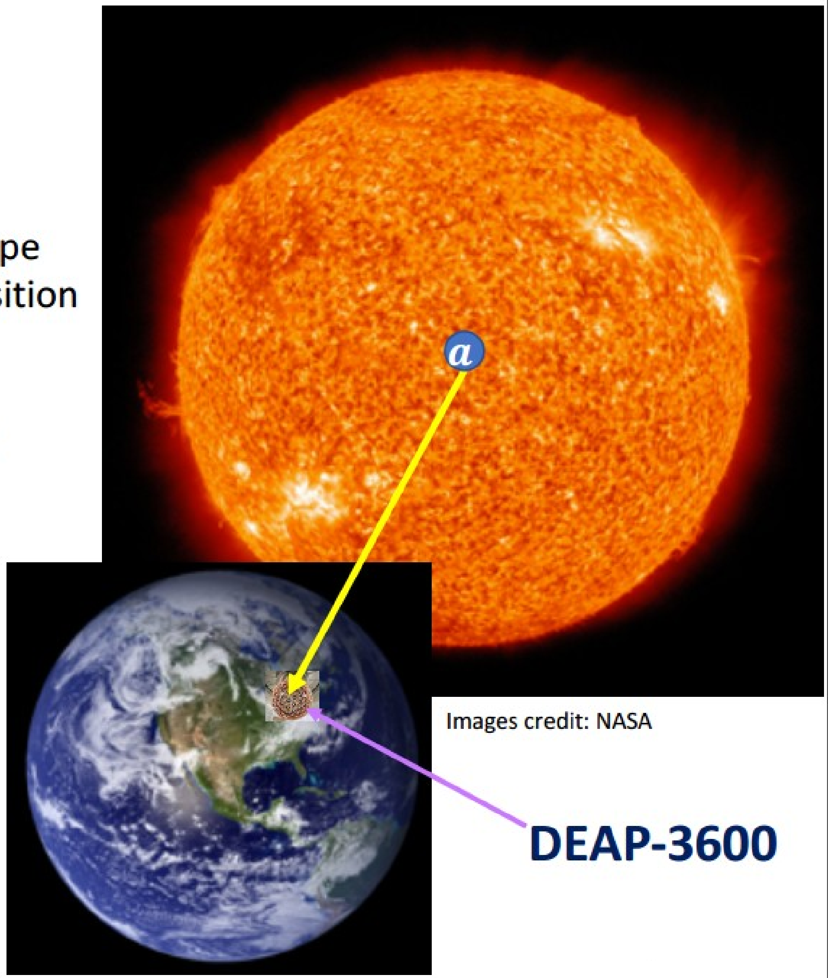
How are axions produced by the sun?

- One possibility in the proton-proton chain:
  - $p + p \rightarrow d + e^{+} + \nu_e$
  - $p + d \rightarrow {}^{3}He + \boldsymbol{\gamma}\ (\mathbf{5.5\ MeV})$ ← M-type transition
  - …
- Axion could be produced in place of photon:
  - $p + d \rightarrow {}^{3}He + \boldsymbol{a}\ (\mathbf{5.5\ MeV})$



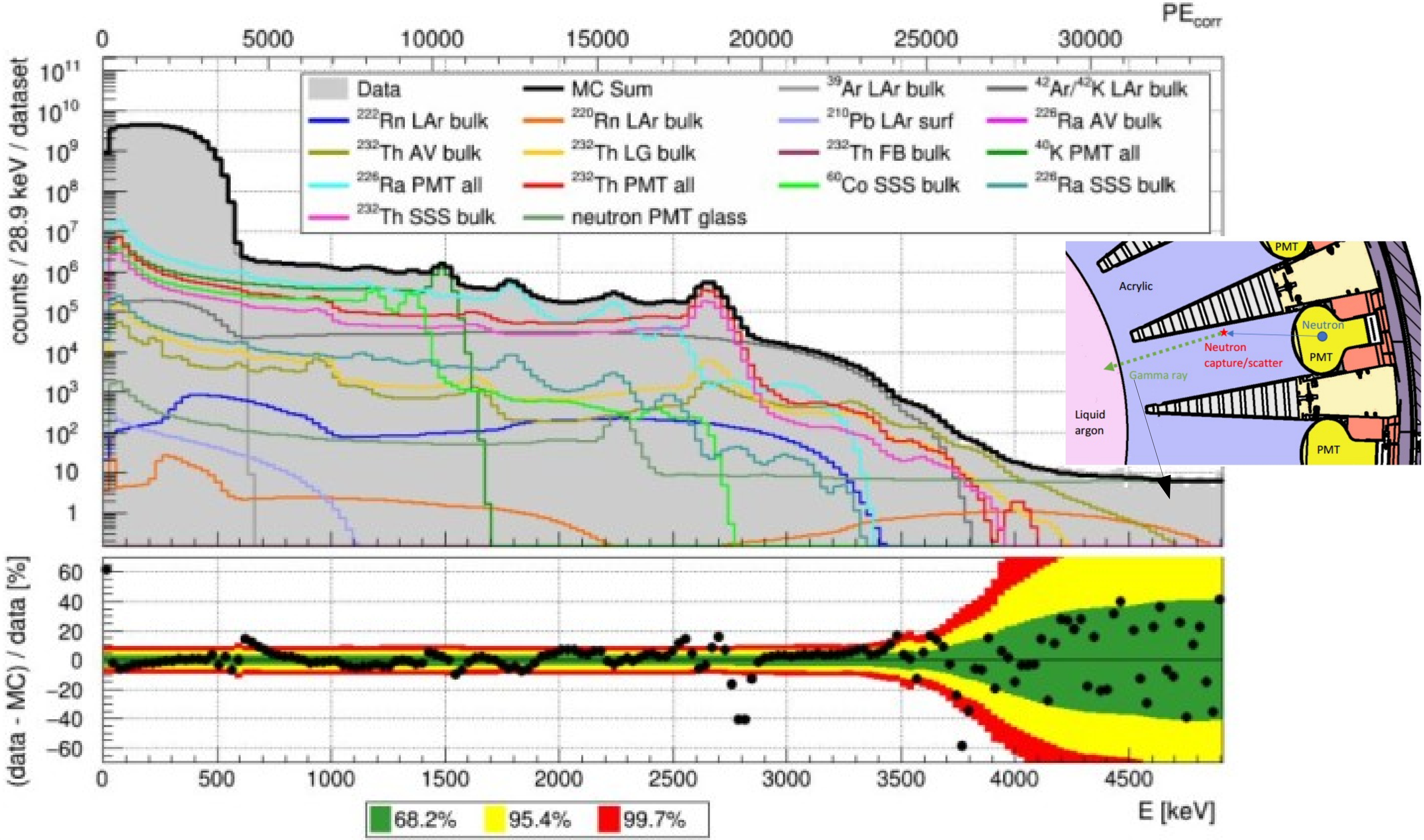


$$\sqrt{p_a^2 + m_a^2} = 5.5\ MeV$$



Images credit: NASA

Electromagnetic backgrounds

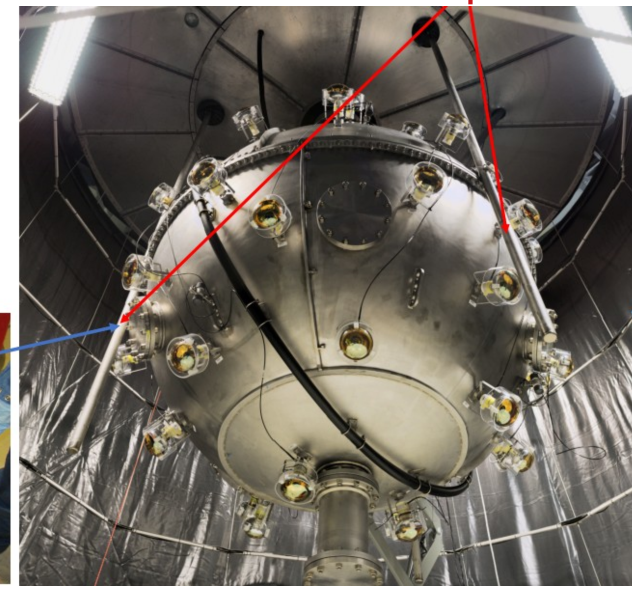


Phy. Rev. D, 100, 072009 (2019)

Model extended > 5 MeV

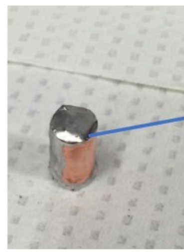
- Challenges:
  - Non-linear PMT response and energy scale
  - Uncertainties in Geant4 modelling of neutron capture and gamma cascades
  - Significant contribution from some isotopes present in small amounts in the detector
- Carl Rethmeier (Carleton University PhD thesis), and Mario Alpizar, now being prepared for publication

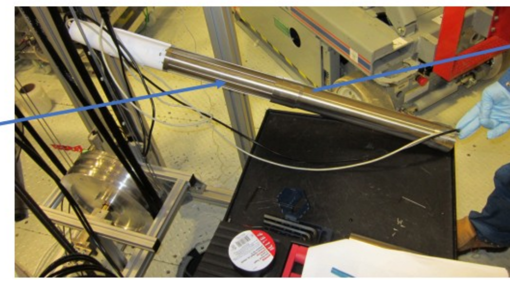
calibration ports

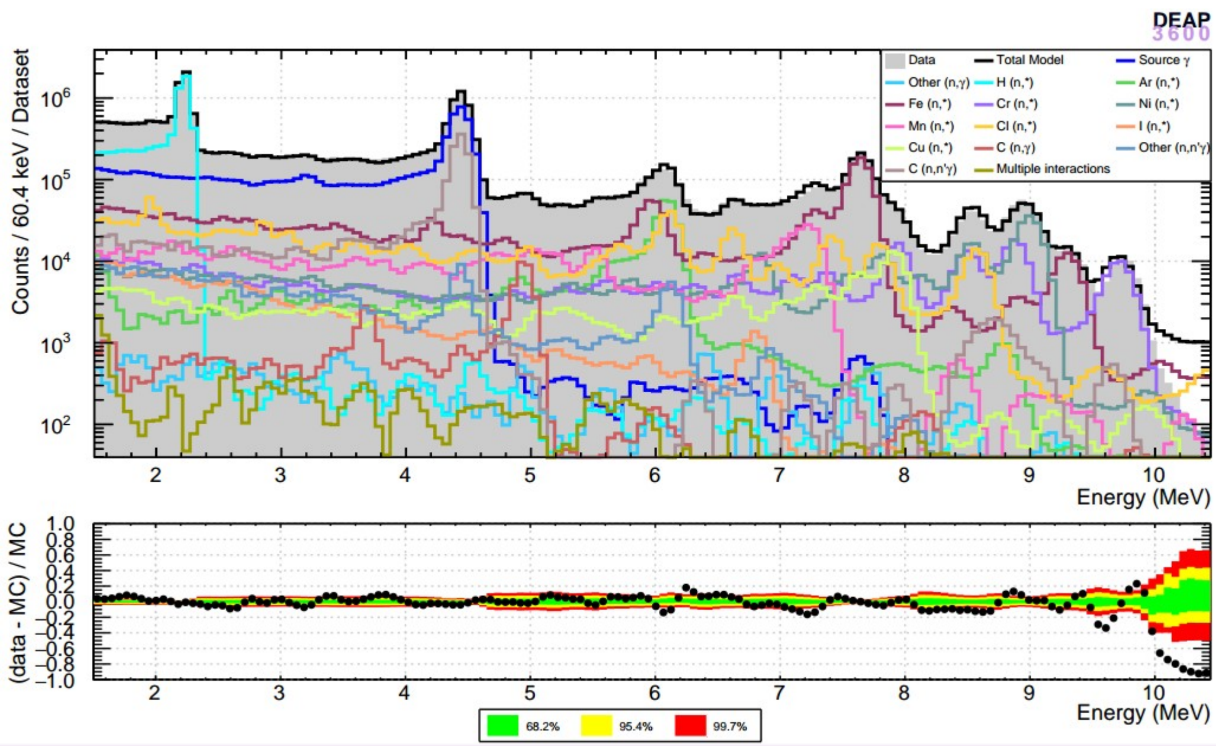


Source containing Am241 and Be9 (AmBe) generates neutrons and gammas

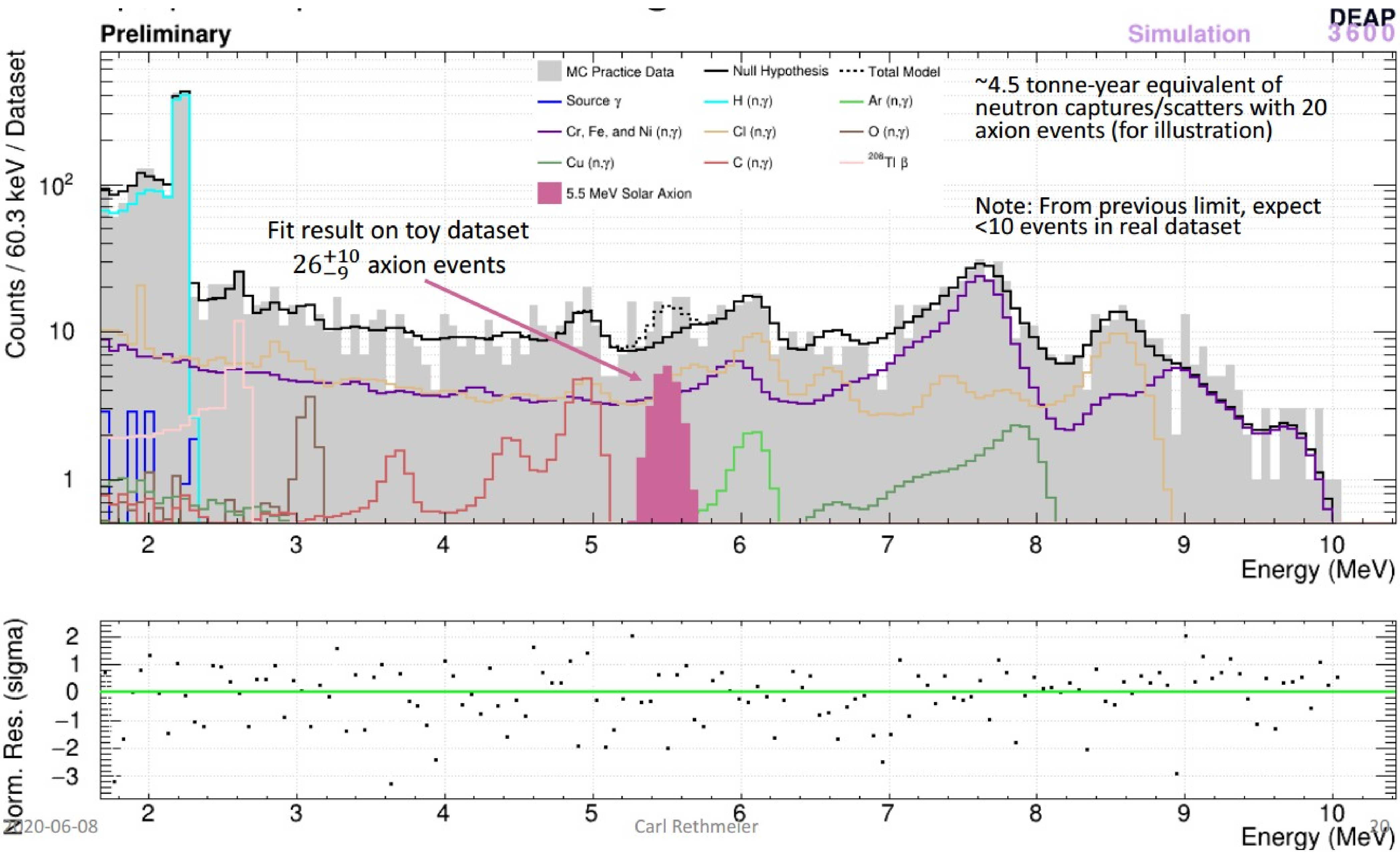
Complicated source geometry added to MC model







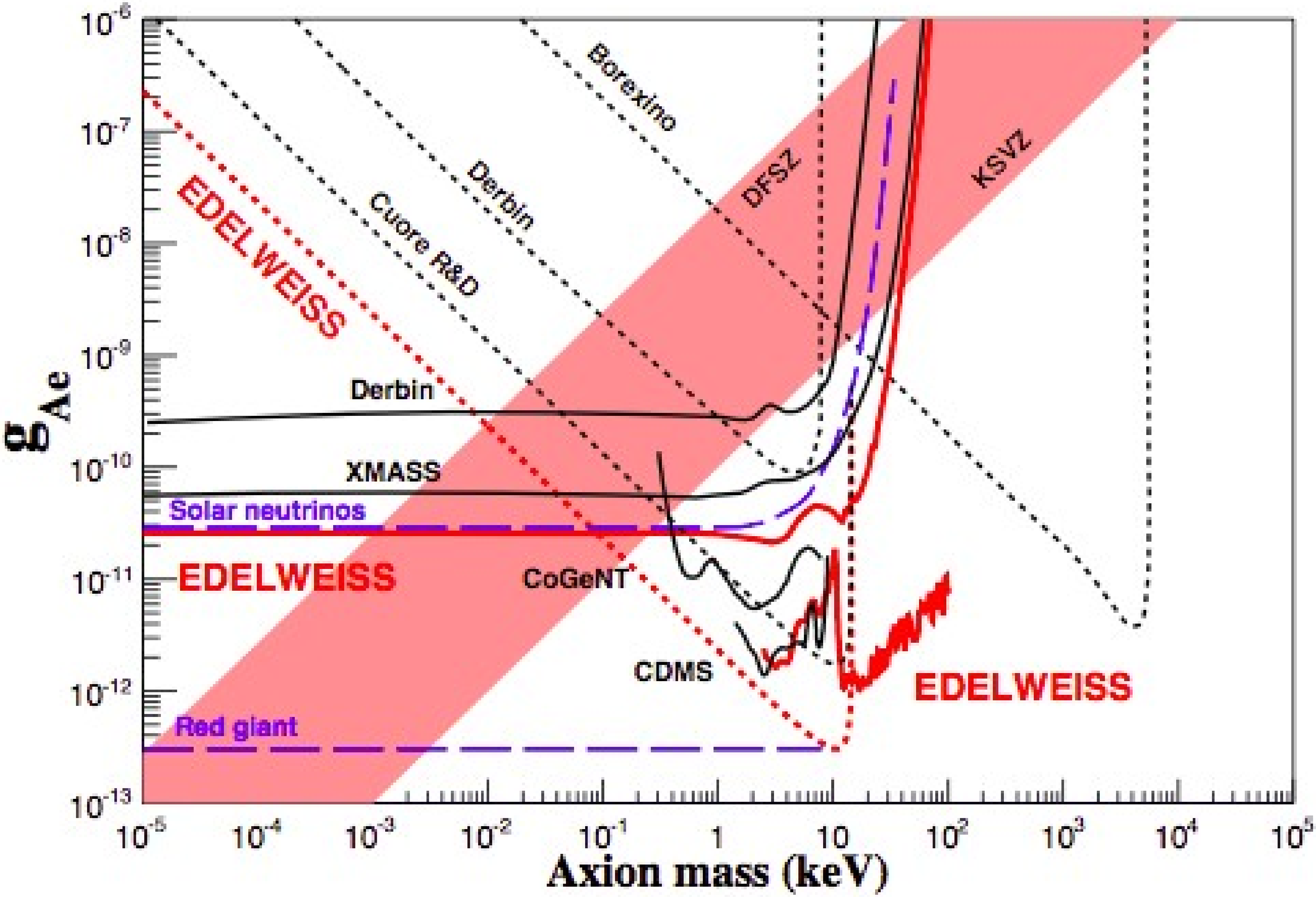
Fit of β/γ components to background simulation for axion search



Slide courtesy Carl Rethmeier

Expected sensitivity

With the collected data, expecting the sensitivity close to the Borexino exclusion.

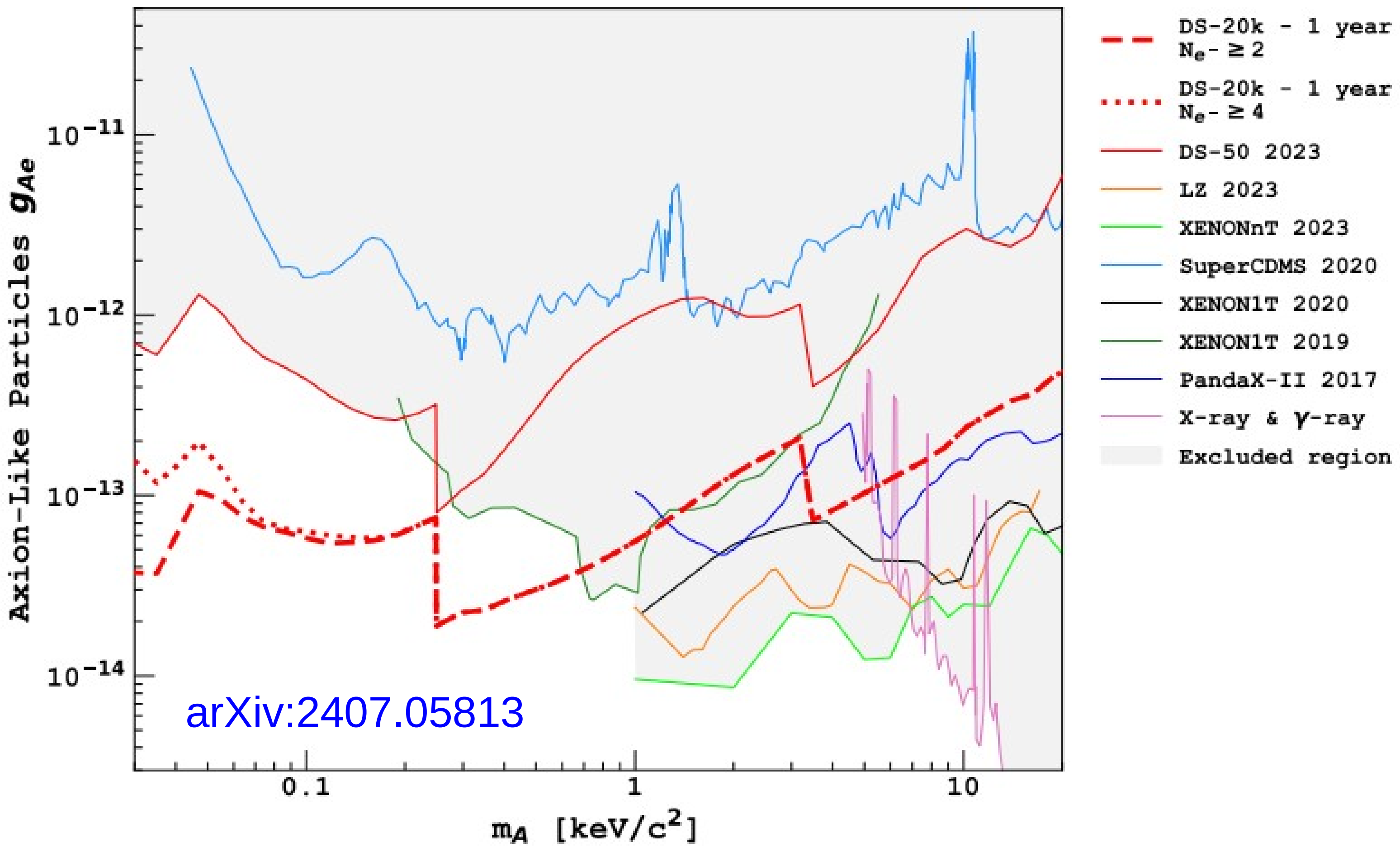


JCAP 1311 (2013) 067

Summary

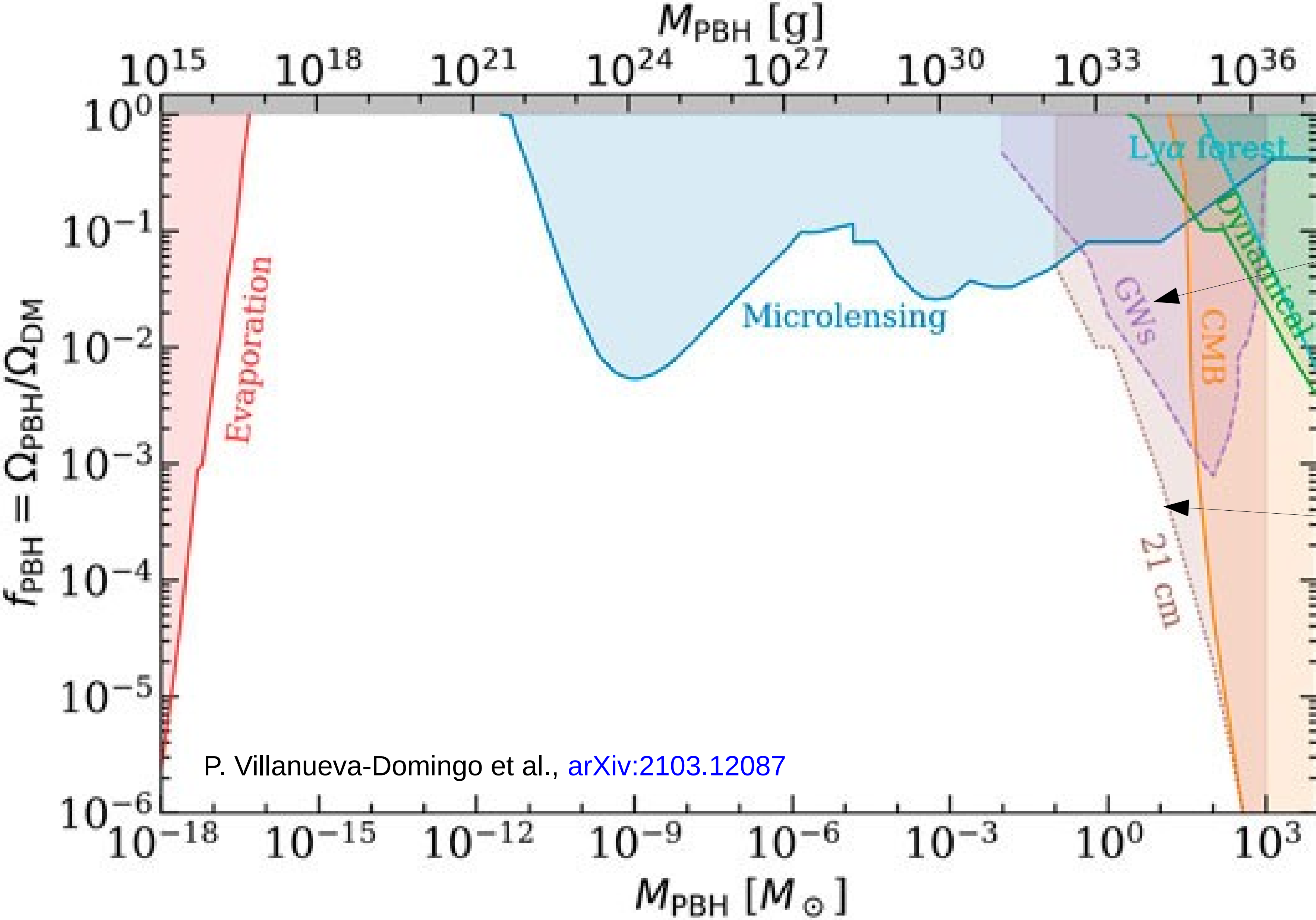
- Excellent control over ^{39}Ar, neutron, radon and surface alpha backgrounds
- Multiple improved or new physics searches on the already collected dataset
- Sensitivity to WIMPs currently limited by the neck and dust alpha backgrounds
  - Ongoing and nearly completed hardware upgrade
  - Will recover the design sensitivity with the upcoming physics run
- Solar axion search analysis is advanced and has competetive sensitivity
- Nature of dark matter is one of the most exciting mysteries in physics, with a real potential for groundbreaking discovery
- Liquid Argon based detectors well positioned in the global race for such discovery, with the ultimate sensitivity within reach in the next decade

Halo ALPs with liquid argon



- Extremely low background at low energies achieved with LAr from underground sources (depleted in Ar-39 by >1400 times), used in DarkSide detectors
- Leading sensitivity by DarkSide-50 (dual phase LAr TPC)
- Further improvements expected from DarkSide-20k

Primordial black holes



B. Kavanagh et al., Phys. Rev. D 98, 023536 (2021)

debated

C. Bœhm et al JCAP03(2021)078

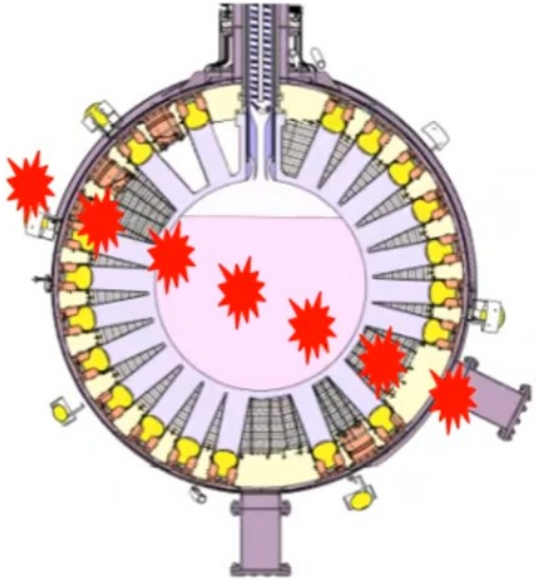
projected future sensitivity (SKA)

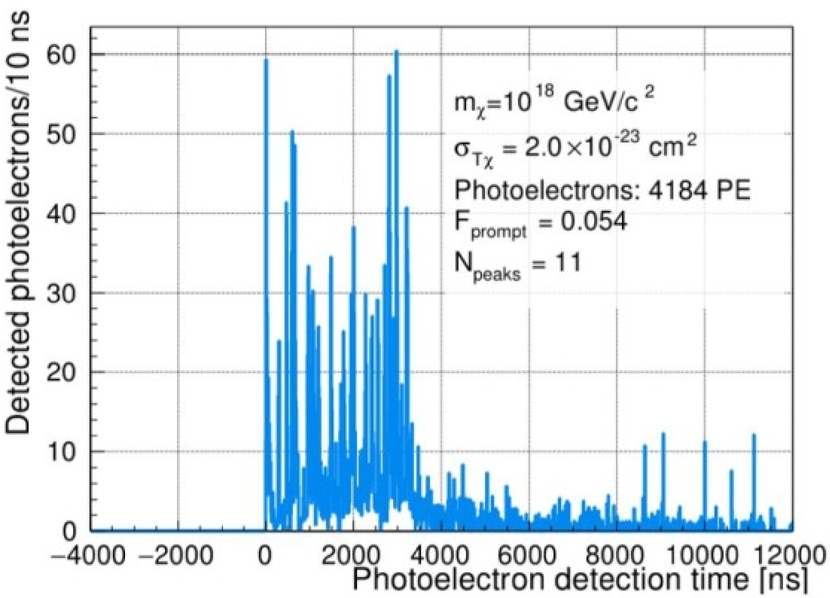
O. Mena et al., Phys. Rev. D 100, 043540 (2019)

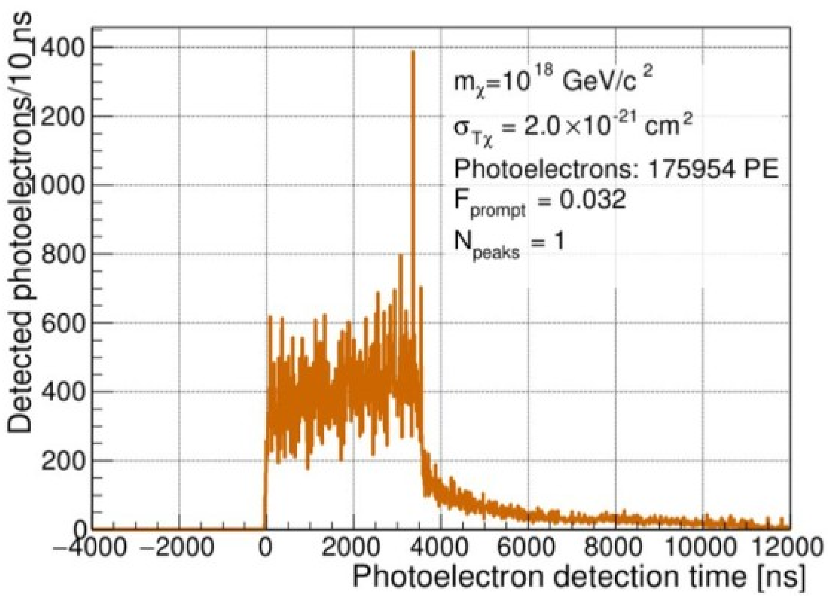
Heavily constrained as a primary DM component. But some room still exists...

Planck scale mass multi-scattering dark matter

- a.k.a multiply-interacting massive particles (MIMPs)
- DM candidates above $\sigma_{\chi\text{-}n} \cong 10^{-25}$ cm^2 and $m_\chi \gtrsim 10^{12}$ 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)



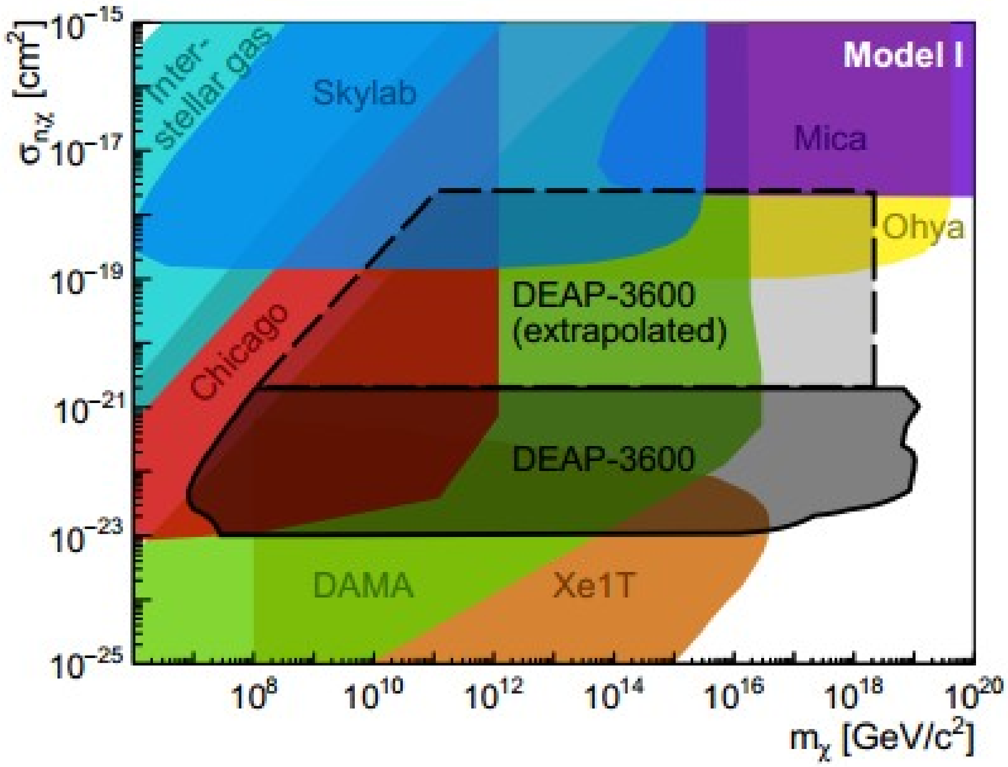


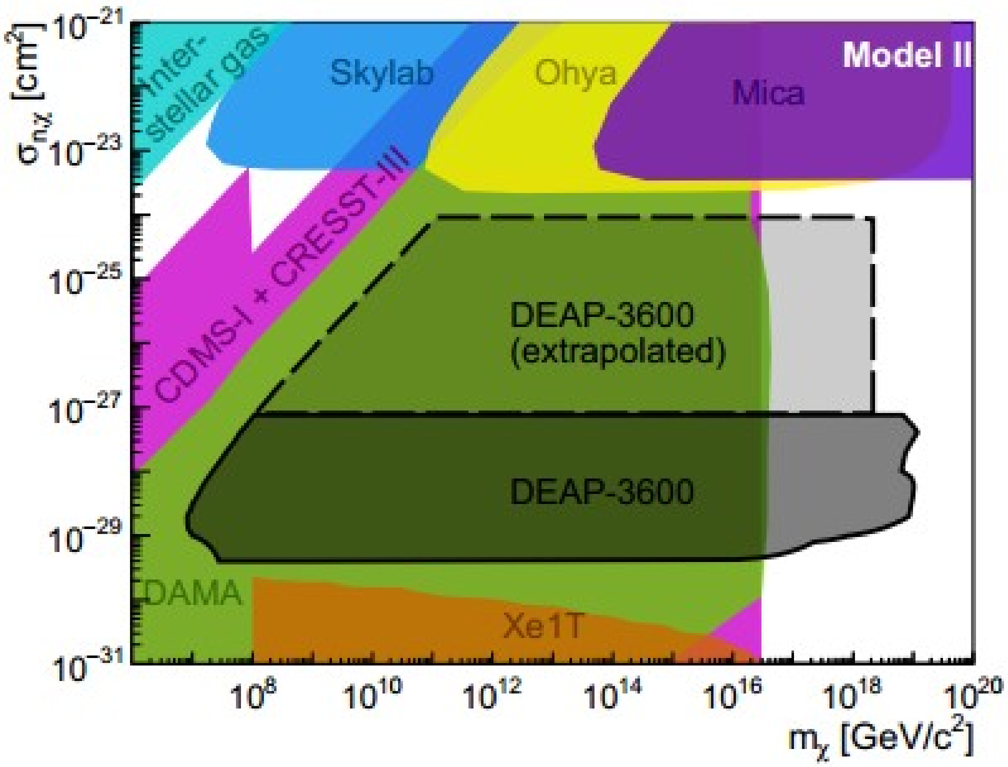


→ see Michela Lai's talk, Detection Of Heavy Dark Matter Particles In DEAP-3600

Planck-scale mass DM exclusion

- P. Adhikari et al. (DEAP Collaboration), Phys. Rev. Lett. 128, 011801 (2022)
- 813 live-days, blind analysis
- TAUP2021 exclusion for candidates at Planck-scale masses





$$\sigma_{T\chi} = \sigma_{n\chi}|F_T(q)|^2$$

(relevant for composite DM models)

$$\sigma_{T\chi} \simeq \sigma_{n\chi}A^4|F_T(q)|^2$$

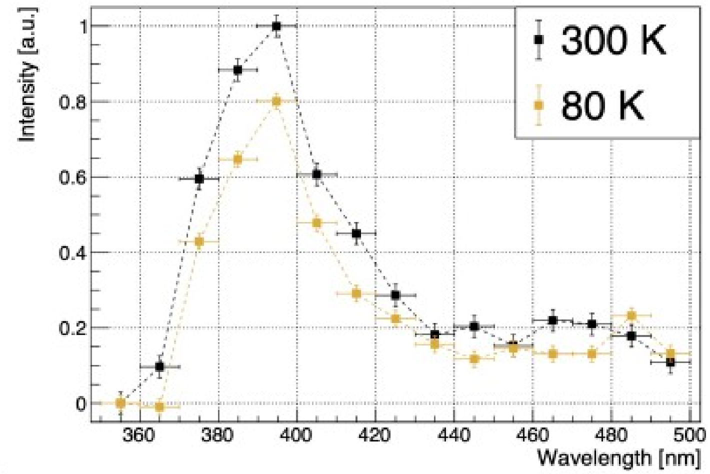
Have your cake and eat it too: Cryogenic 128 nm measurements

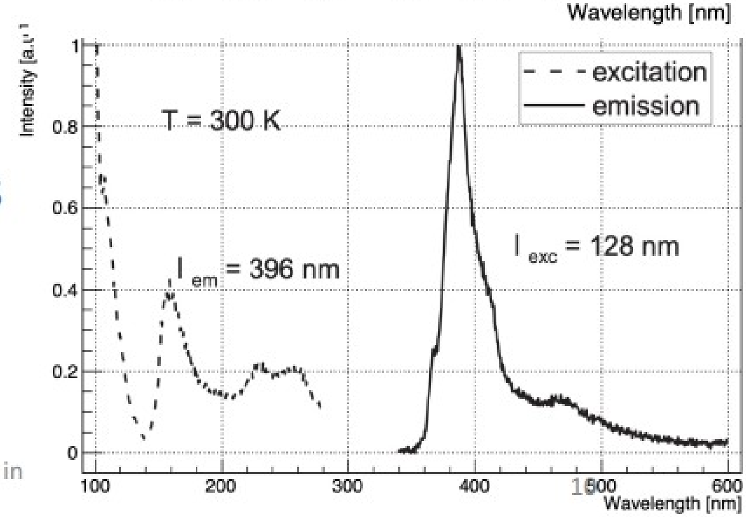
Measurements of WLS film properties at 128 nm (continuous light source) and 87 K performed at the Institute of Low Temperature and Structure Research (Poland)

Measured pyrene excitation(monomer) spectra at room temperature, and PLQY relative to TPB at RT and 80 K

Pyrene+PS film shows -23(11)% decrease in yield at 128 nm and 80 K relative to room temperature

Substantial yields demonstrated at LAr temps with LAr wavelengths -> Critical measurement for LAr applications

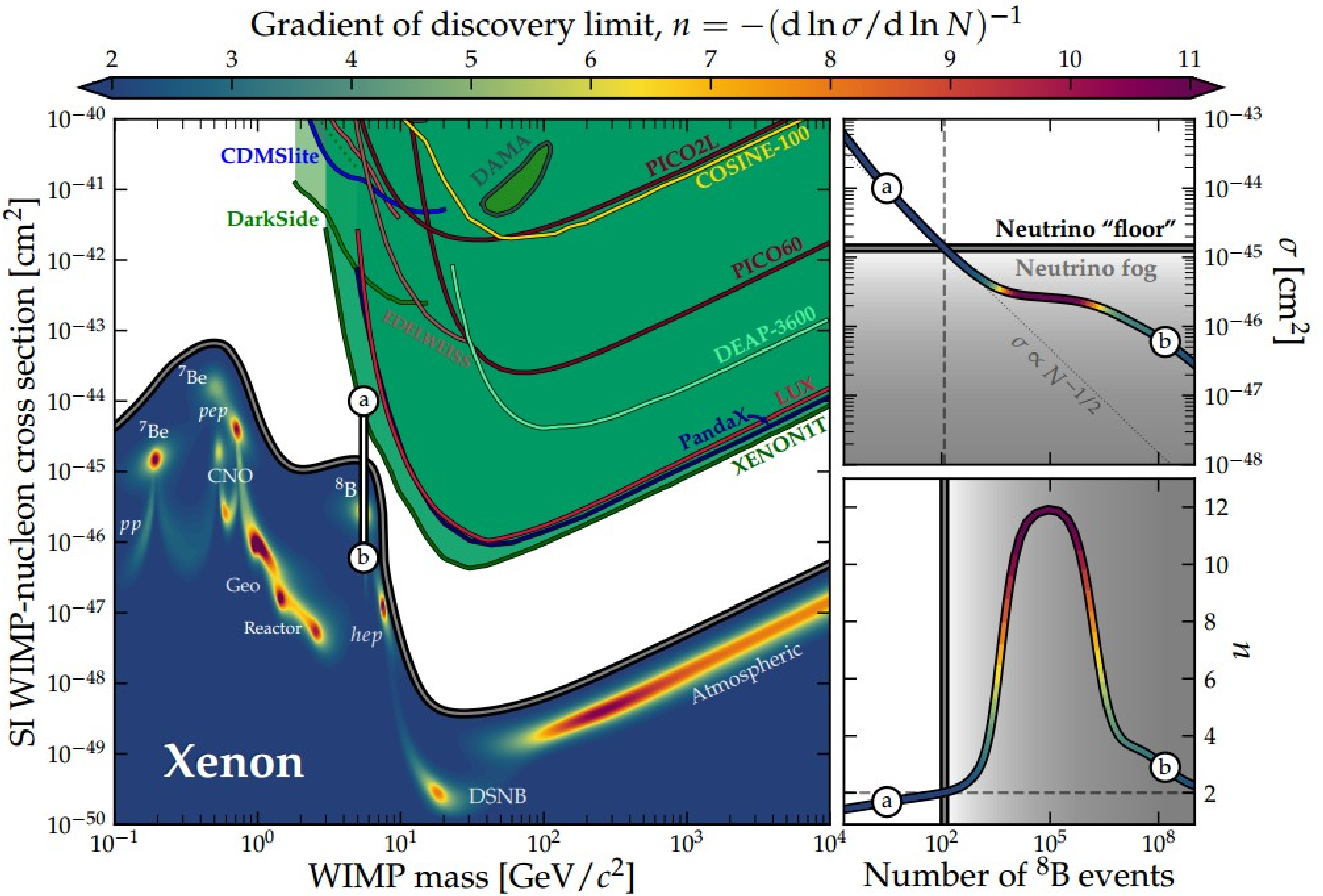




ASTROCENT

Institute of Low Temperature and Structure Research
Polish Academy of Sciences

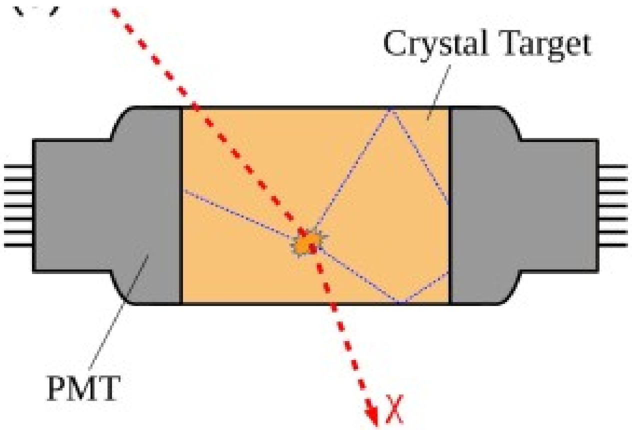
LIDINE 2021 - A Slow WLS coating for background rejection in LAr detectors



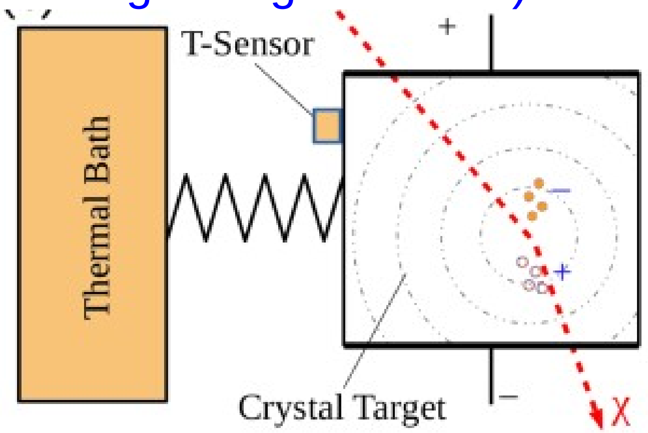
Phys. Rev. Lett. 127, 251802 (2021)

Main detection techniques

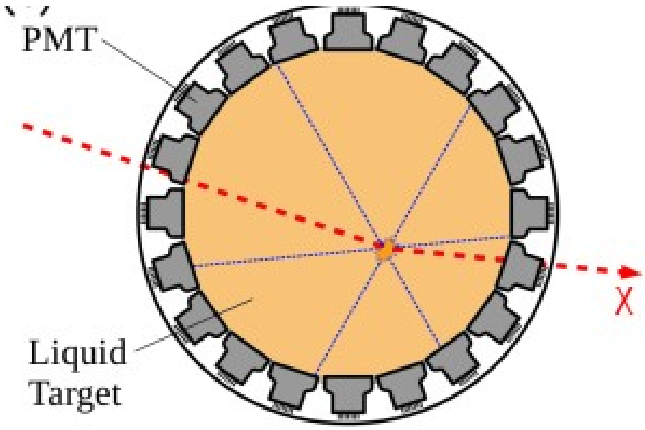
Scintillating crystal



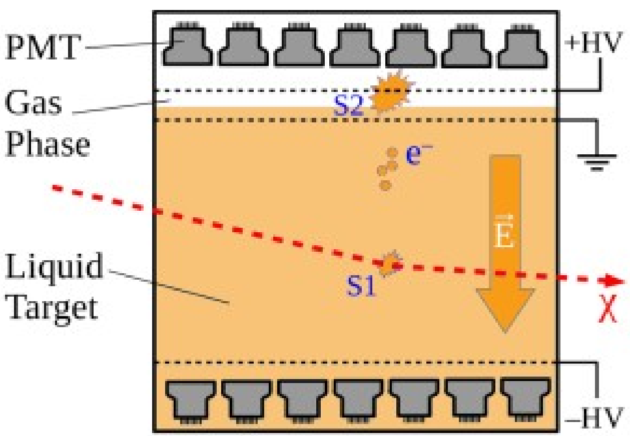
Cryogenic bolometer (with charge or light readout)



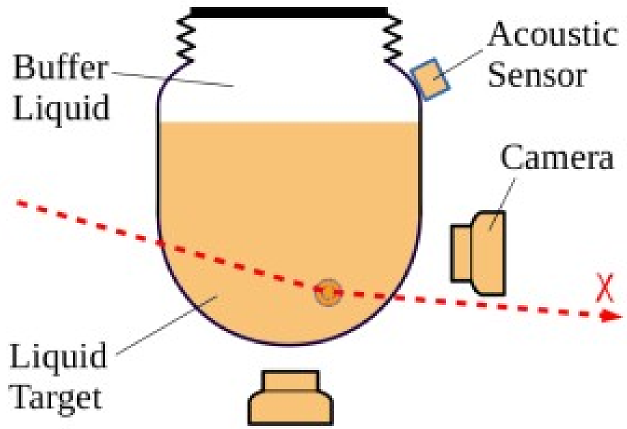
Single-phase noble liquid detector



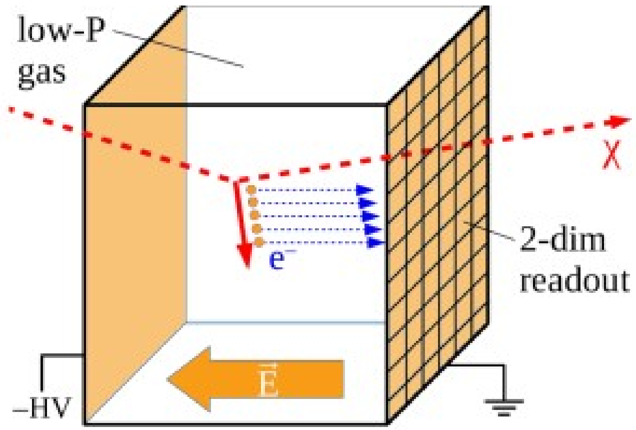
Dual-phase noble liquid detector



Bubble chamber (optionally scintillating)



Directional detector



Julien Billard et al 2022 Rep. Prog. Phys. 85 056201

- Bolometers and ionization detectors tend to provide lower energy threshold
- Not all techniques scalable to multi-tonne scales
- Sensitivity to multiple response channels helps to discriminate backgrounds