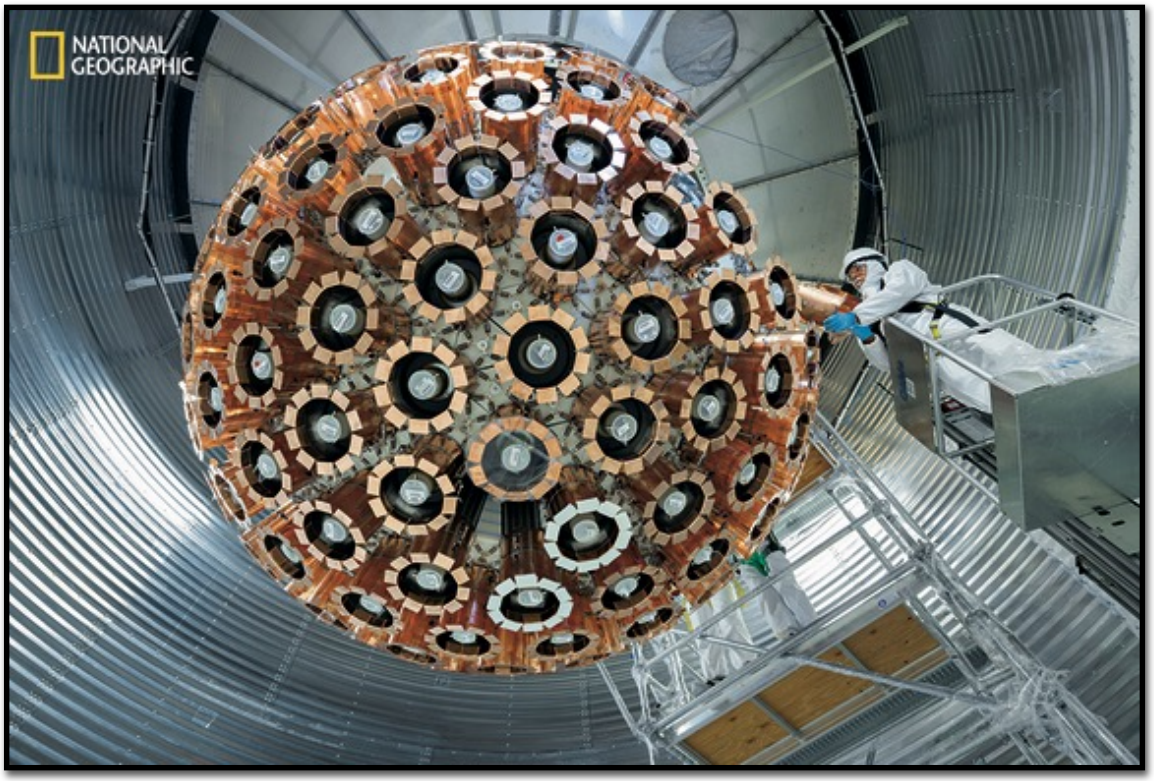
The Quest for Dark Matter with Liquid Argon Detectors

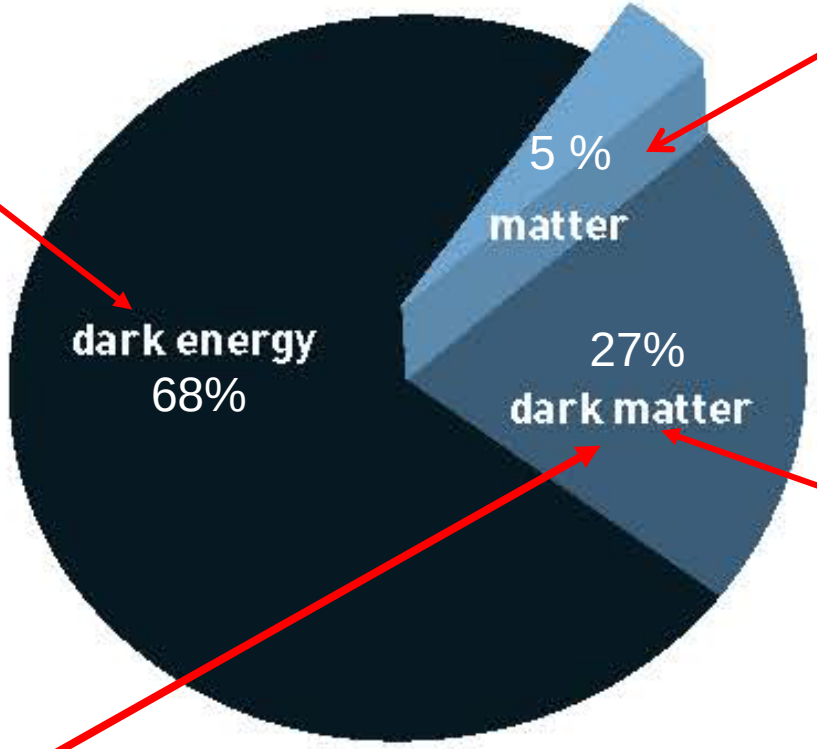


Art McDonald
Gray Chair in Particle Astrophysics Emeritus
Queen’s University, Kingston, Canada

Composition of the Universe as we understand it today

(Very different than 20 years ago thanks to very sensitive astronomical and astrophysical experiments such as measurements of the cosmic microwave background, large scale structure and distant supernovae.)

Responsible for accelerating the Universe's expansion

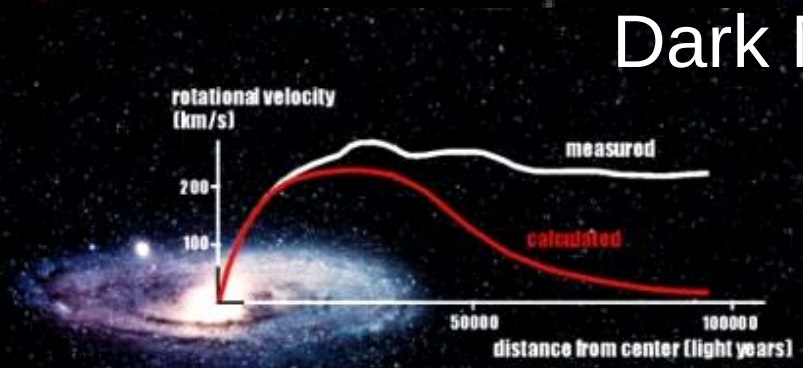


US!!!

Neutrinos Are only a few %

With underground labs we can look for Dark Matter particles left from the Big Bang, with ultra-low radioactive background.

Dark Matter

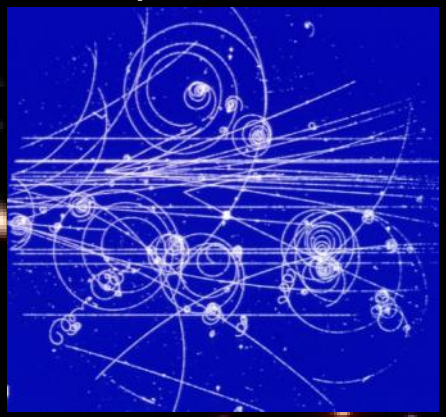


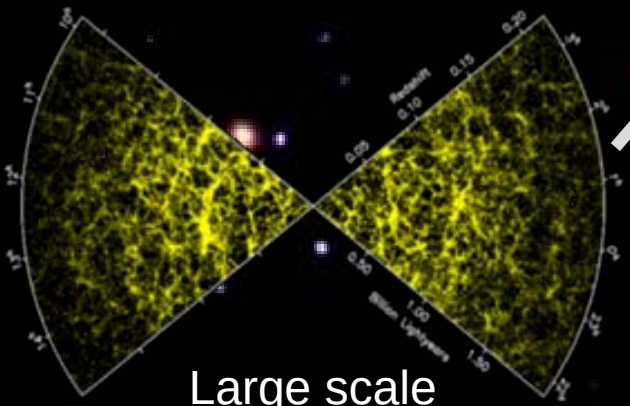
Here, but not yet observed directly in nature: **Weakly interacting**

WIMP

(Weakly Interacting Massive Particle)

Not observed in accelerator experiments:



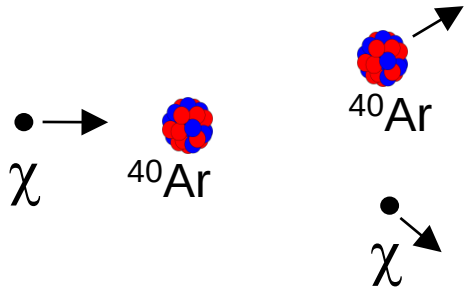


Large scale structure of the Universe:
Slowly moving ('cold')

Interaction with ordinary matter:
Nuclear Recoils
(most backgrounds: electron recoils)

Predicted by SUSY:
Neutralino
Universal extra dimensions:
Kaluza-Klein particles

Argon for Dark Matter Searches – Some Basics



Scattered nucleus (with 10's of keV) is detected in liquid argon.

Argon is inexpensive and relatively "easy" to purify to levels required for DM searches - true for O_2, N_2, etc. and **also for radon**

Singlet/triplet ratio and lifetimes in argon allow extremely good scintillation PSD (β/γ vs nuclear recoil rejection of 10^{10}) – low background single phase (scintillation-only) detector possible (DEAP-3600 = 3.6 tonnes)

TPC also exploiting charge collection (S1/S2) increases background rejection (β/γ vs recoil + position reconstruction) - DarkSide

^{39}Ar – approx. 1 Bq of β decays per kg of argon – must be reduced or rejected in analysis (can reject up to about 1 fiducial tonne with PSD)
Produced in atmosphere – underground sources low in 39 isotope

Scintillation (con't)

$$X_2^* \rightarrow X + X + photon$$

Singlet Triplet

LArgon scintillation	Singlet (~7ns)	Triplet (~1.6μs)
Electron	23%	67%
Nucleus	75%	25%

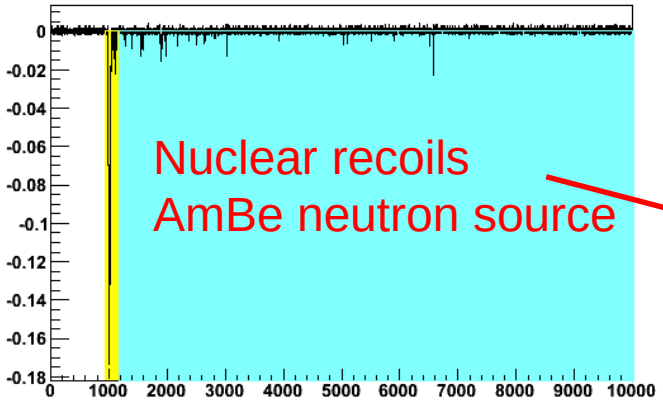
– Different lifetime

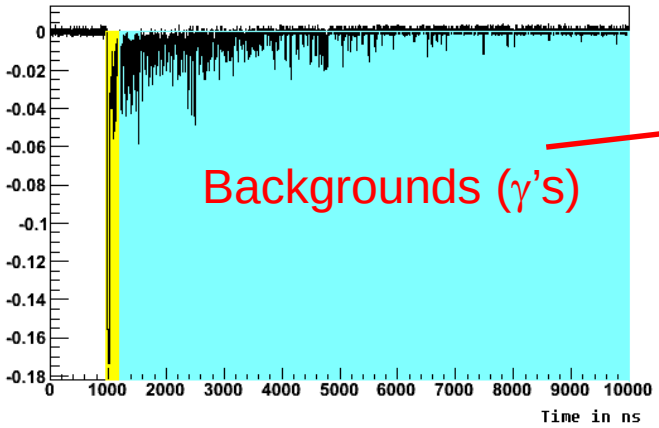
– Populated differently for electron/nucleus

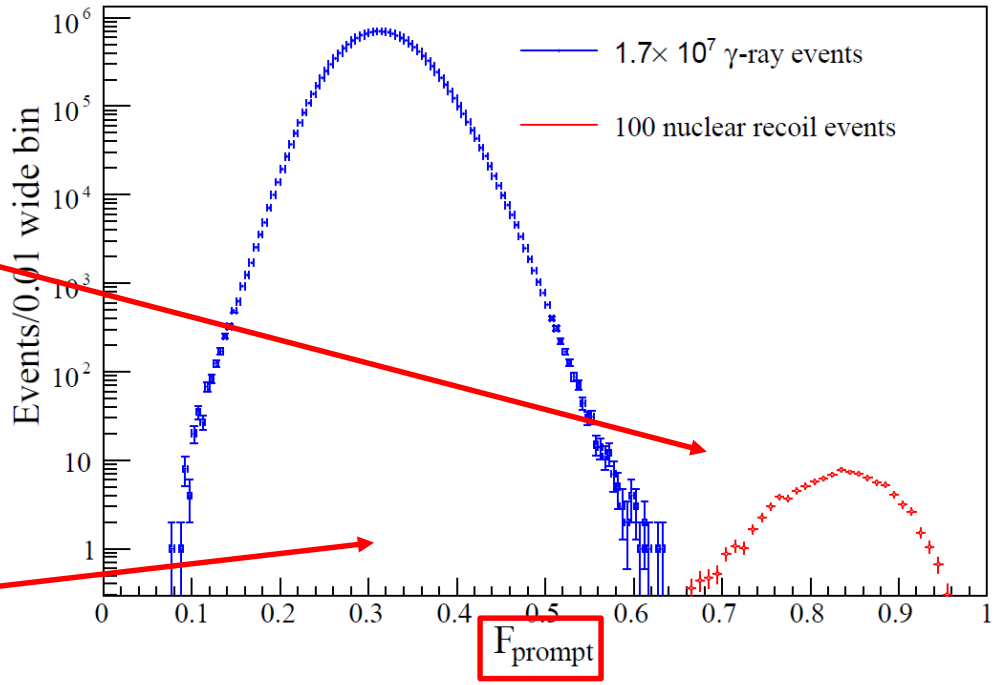
➢ Pulse shape discrimination (PSD)

- Argon Scintillator transparent at the emitted λ (128nm for Ar), TPB wavelength shifter on surface of acrylic converts UV to PMT wavelengths.

PSD in liquid argon with DEAP-1 (7 kg)

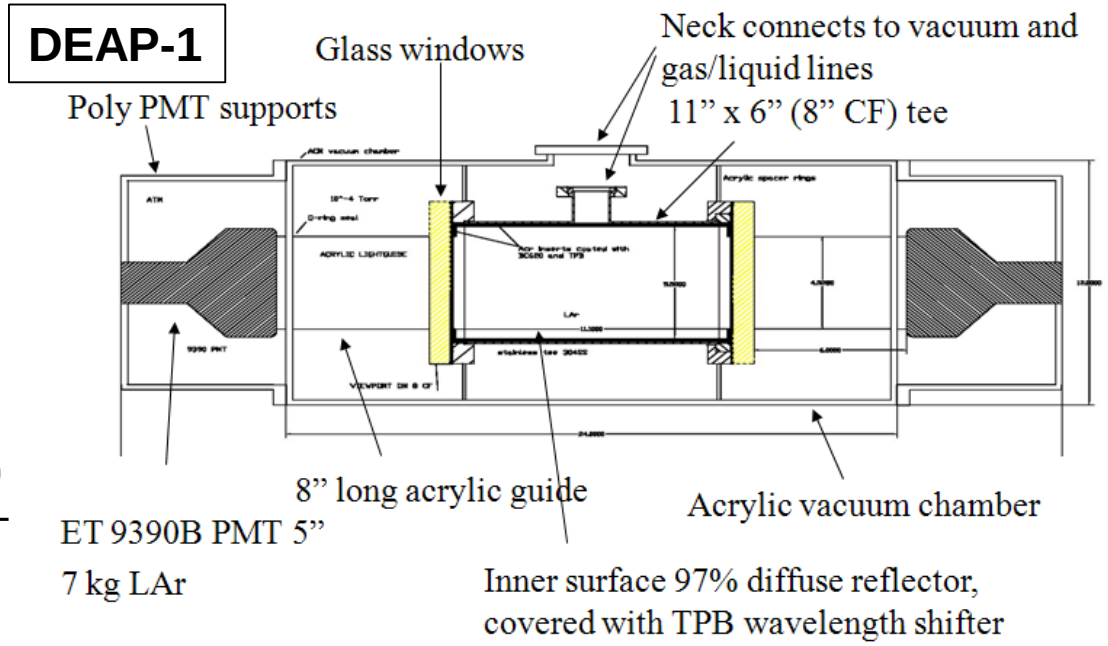


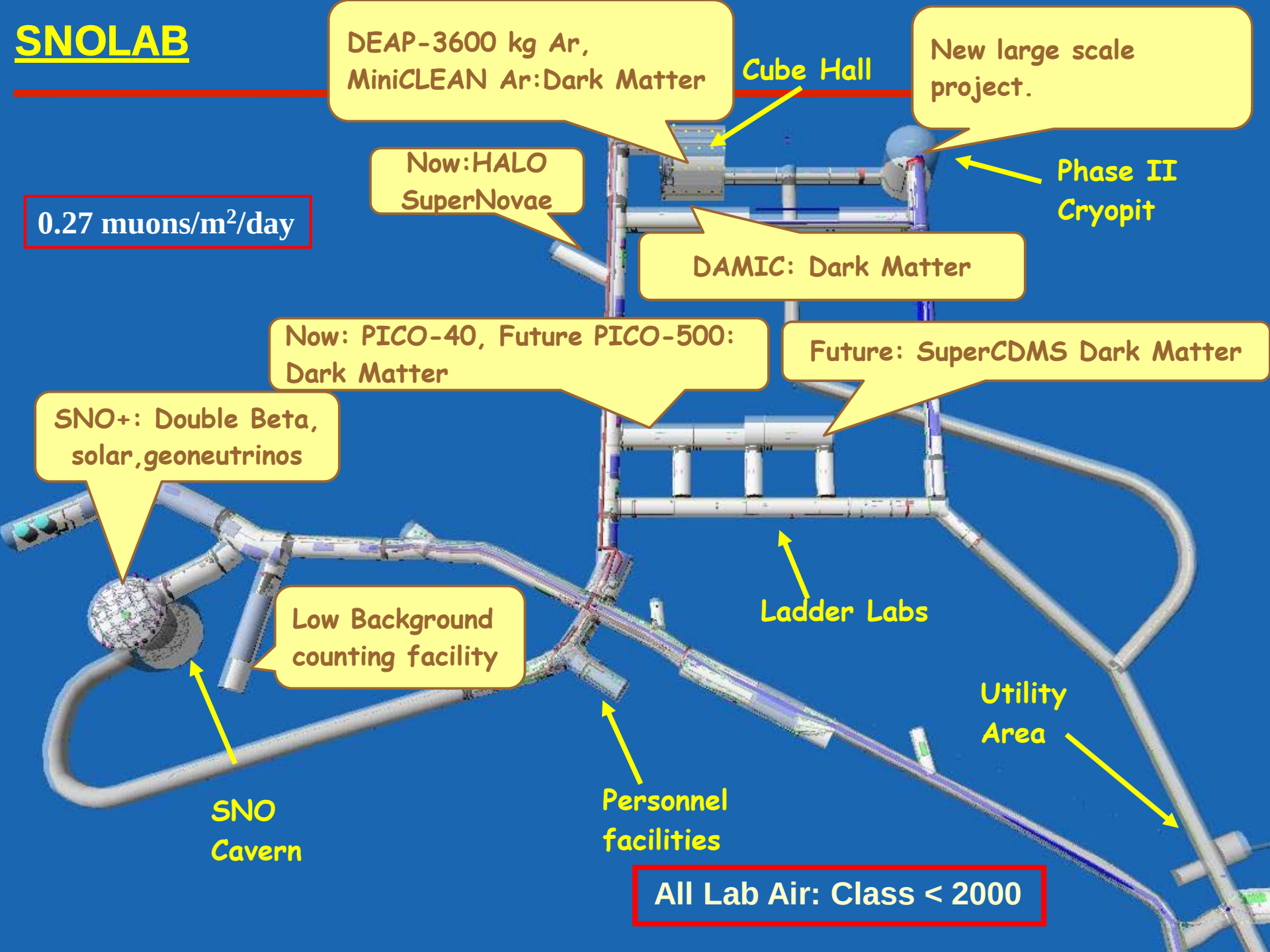




Yellow: Prompt light region
Blue: Late light region

$$F_{prompt} = \frac{PromptPE(150ns)}{TotalPE(9\mu s)}$$

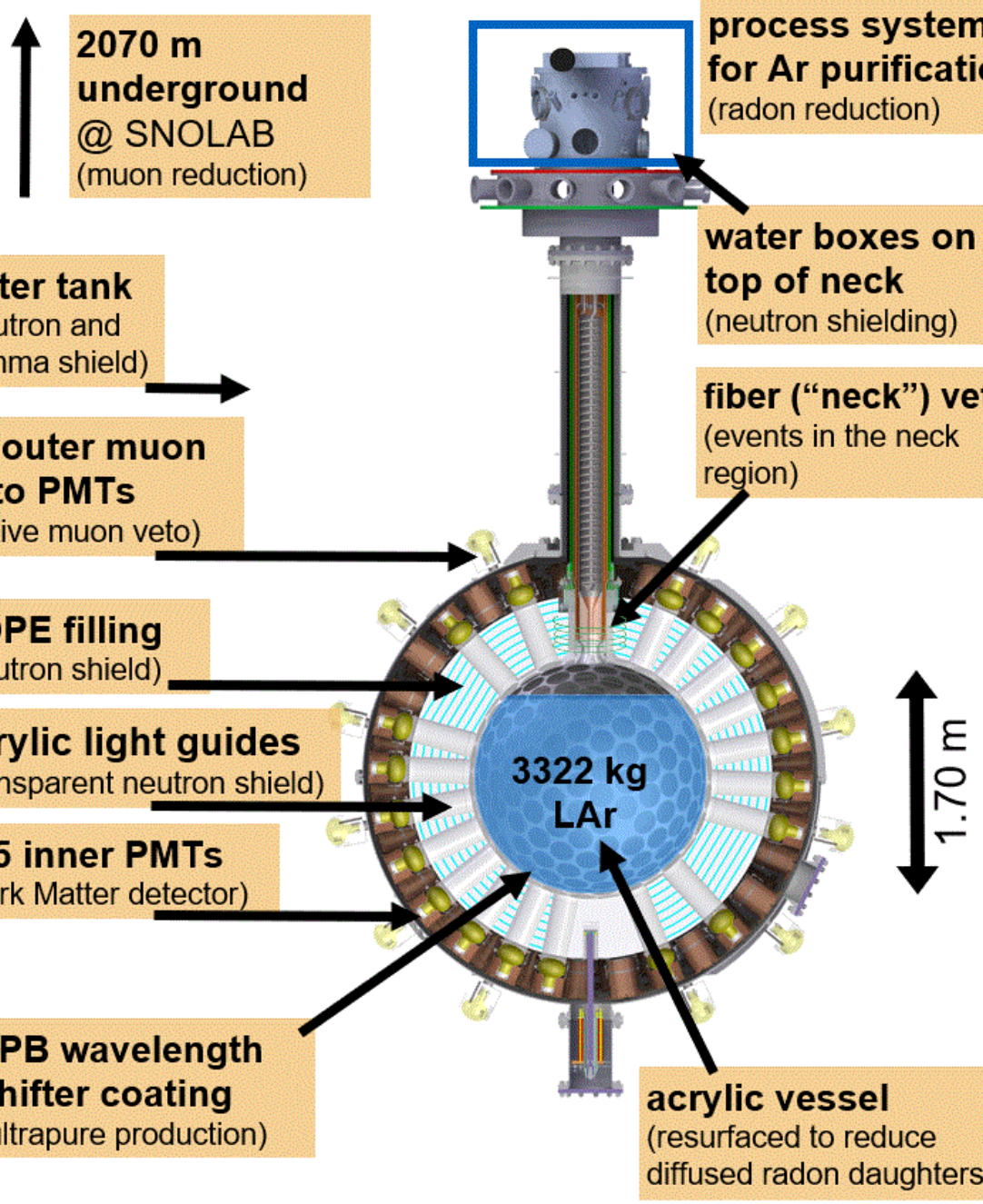



SNOLAB
DEAP-3600 kg Ar, MiniCLEAN Ar:Dark Matter
Cube Hall
New large scale project.
Now:HALO SuperNovae
Phase II Cryopit
0.27 muons/m²/day
DAMIC: Dark Matter
Now: PICO-40, Future PICO-500: Dark Matter
Future: SuperCDMS Dark Matter
SNO+: Double Beta, solar,geoneutrinos
Low Background counting facility
Ladder Labs
Utility Area
SNO Cavern
Personnel facilities
All Lab Air: Class < 2000


Personnel
Facility


Cube Hall

DEAP-3600



- **Single phase** liquid argon (**LAr**) target (new concept)
- Detection of **scintillation** light

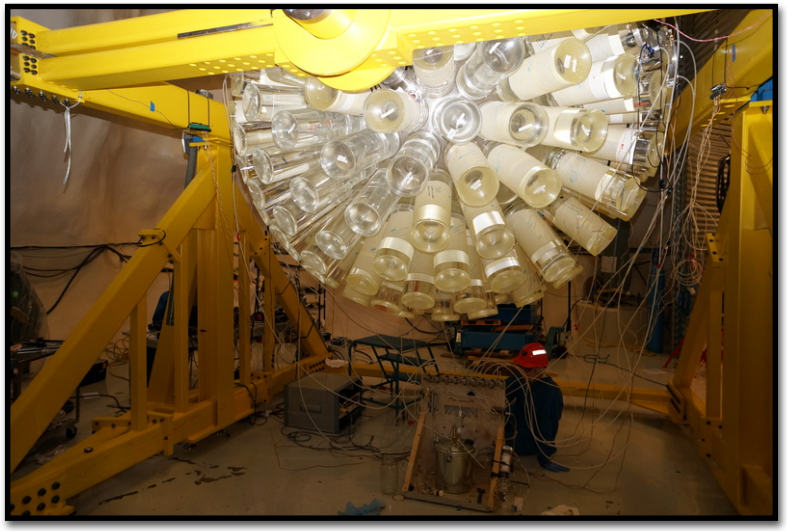
- Goal: **< 1 background event** in 3000 kg x yr fiducial exposure

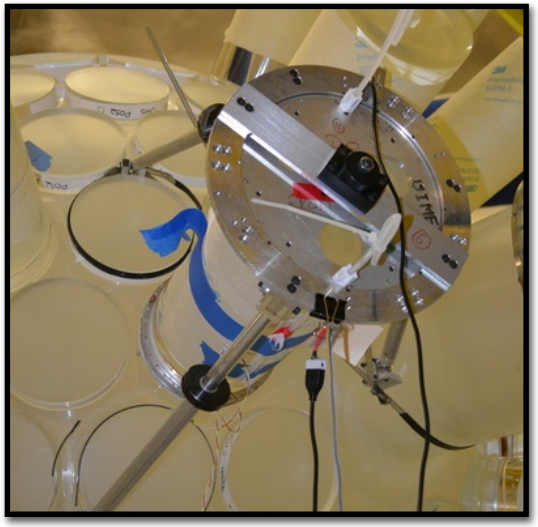
- Sensitivity for spin-independent WIMP-nucleon cross-selection: **10^{-46} cm^2 (@100 GeV)**

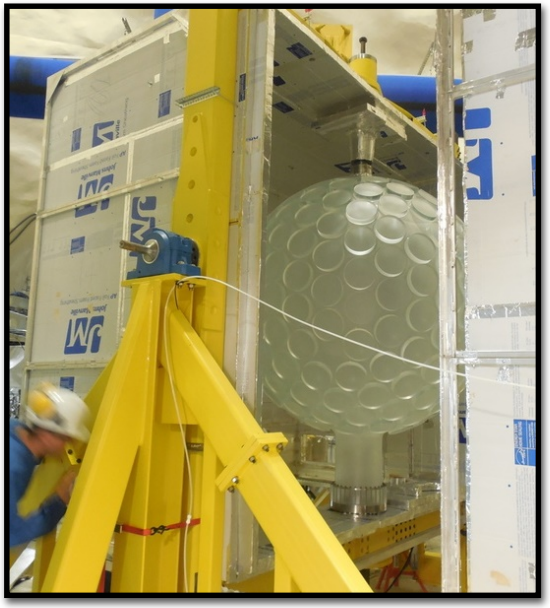
Hardware design concepts for background mitigation:

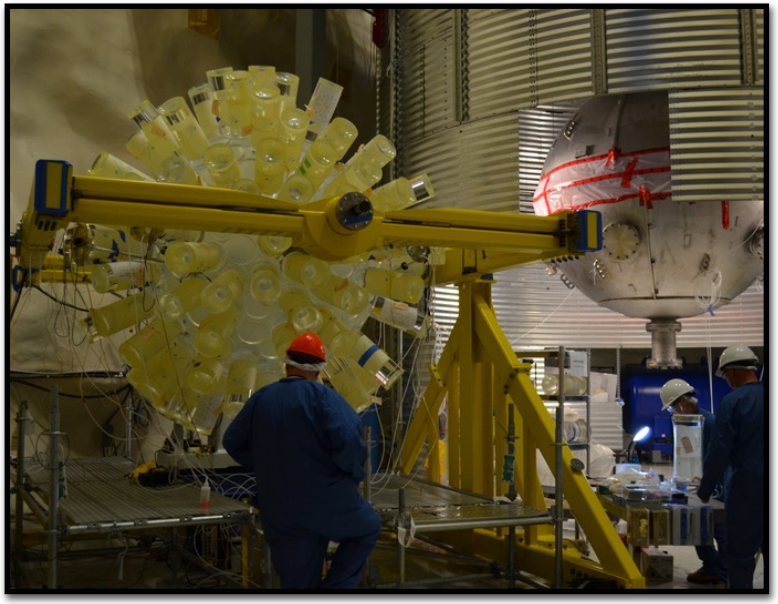
- Deep underground
- Active muon veto
- Onion-layer passive shielding
- Resurfacing of acrylic vessel to remove diffused radon
- Neutrons from PMTs shielded by long transparent acrylic light guides

255 Light Guides were bonded onto the acrylic vessel, which was then annealed in a Rn reduced air system.



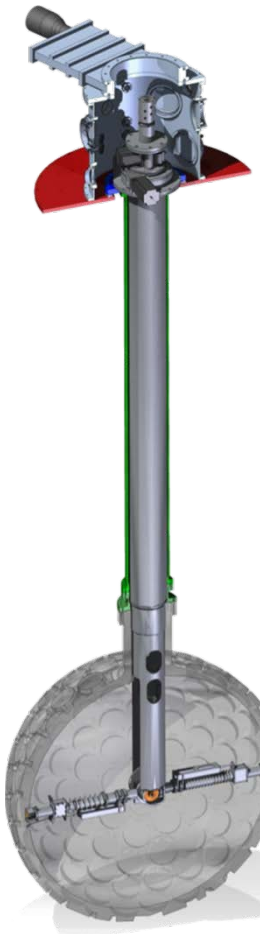


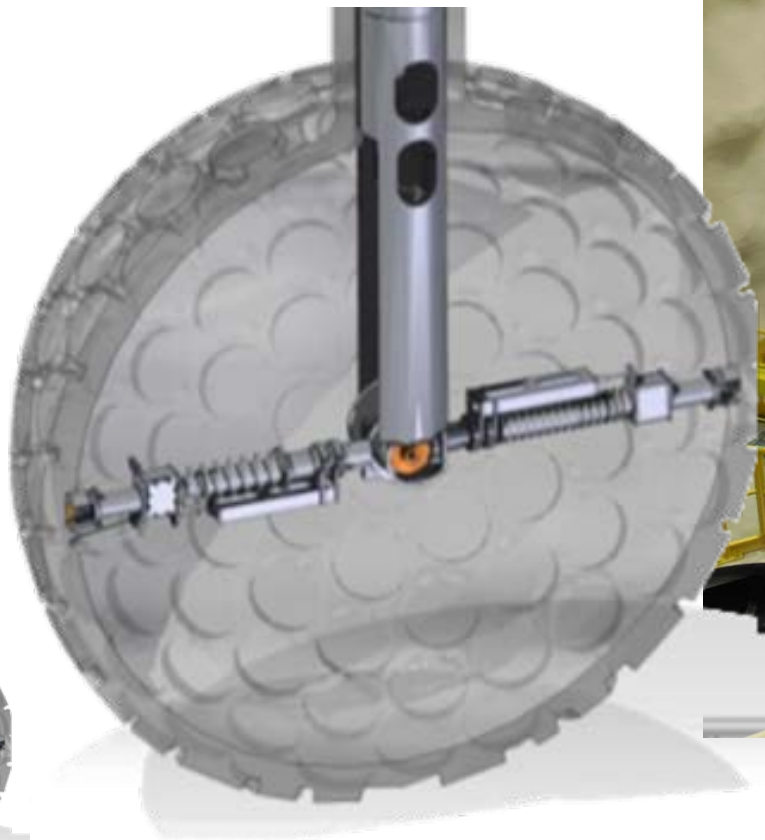


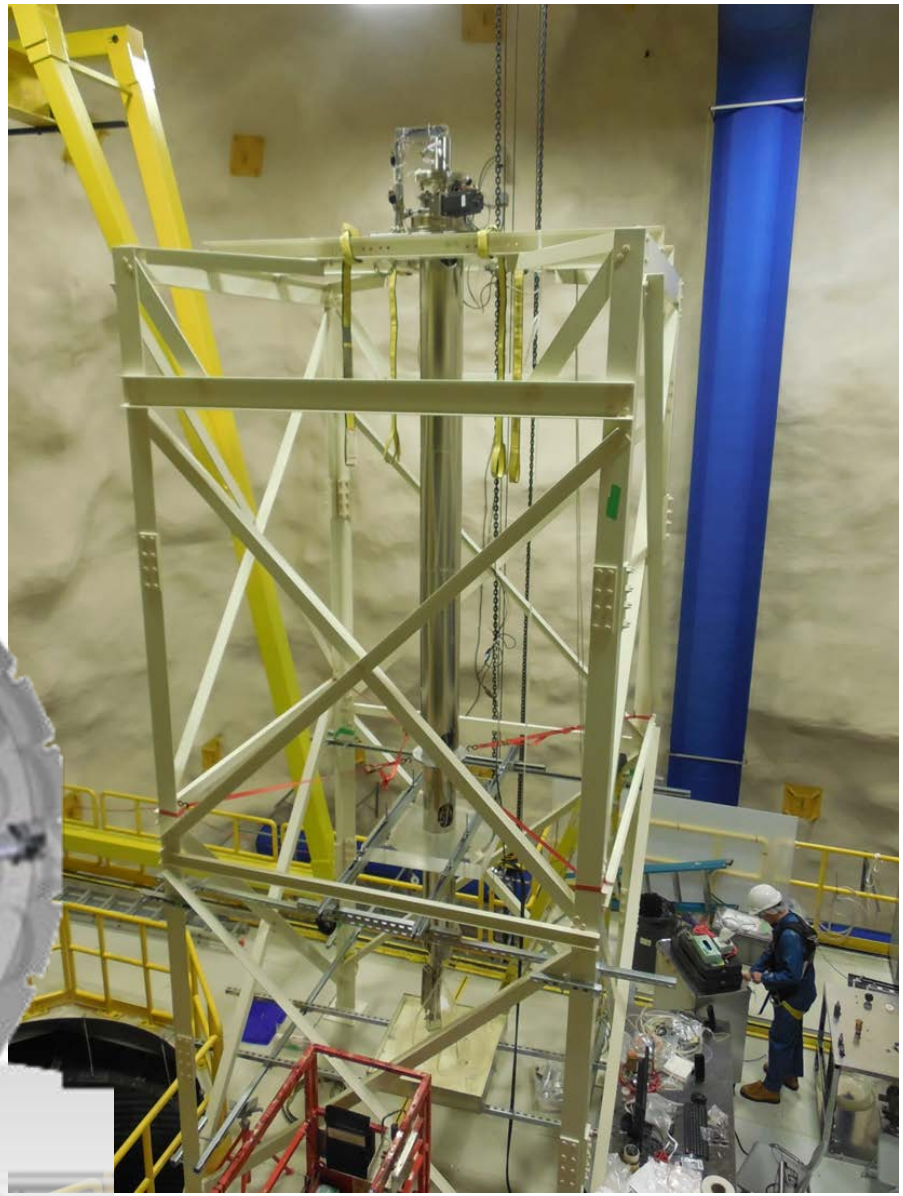


Acrylic Vessel Resurfacer

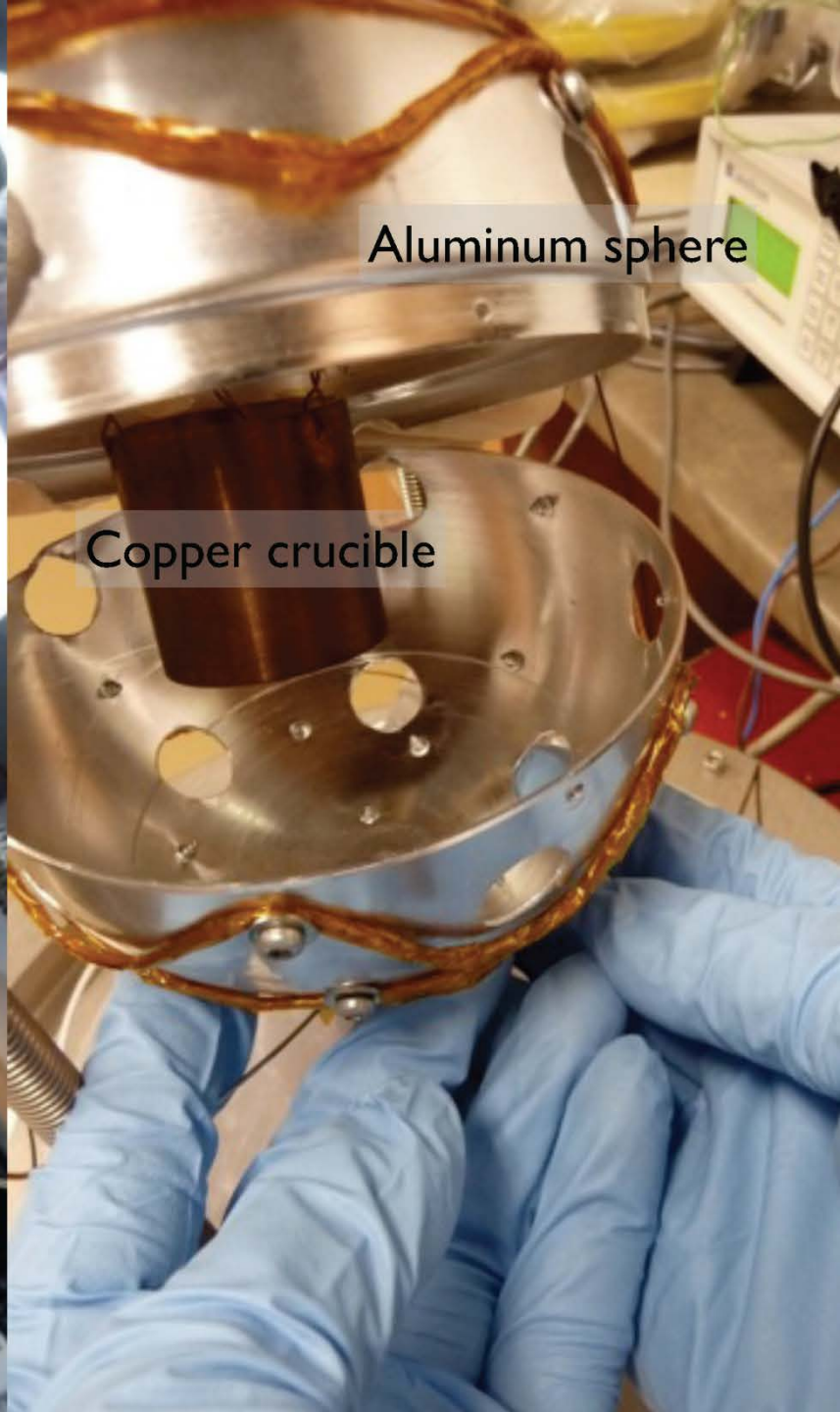
- Mechanical sander to clean inner surface
- Components selected for low radon emanation
- Remove 0.5-mm surface *in situ* with N2 purge
- Cleans surface to bulk-level impurities
  (order 100,000 cleaner than SNO vessel)





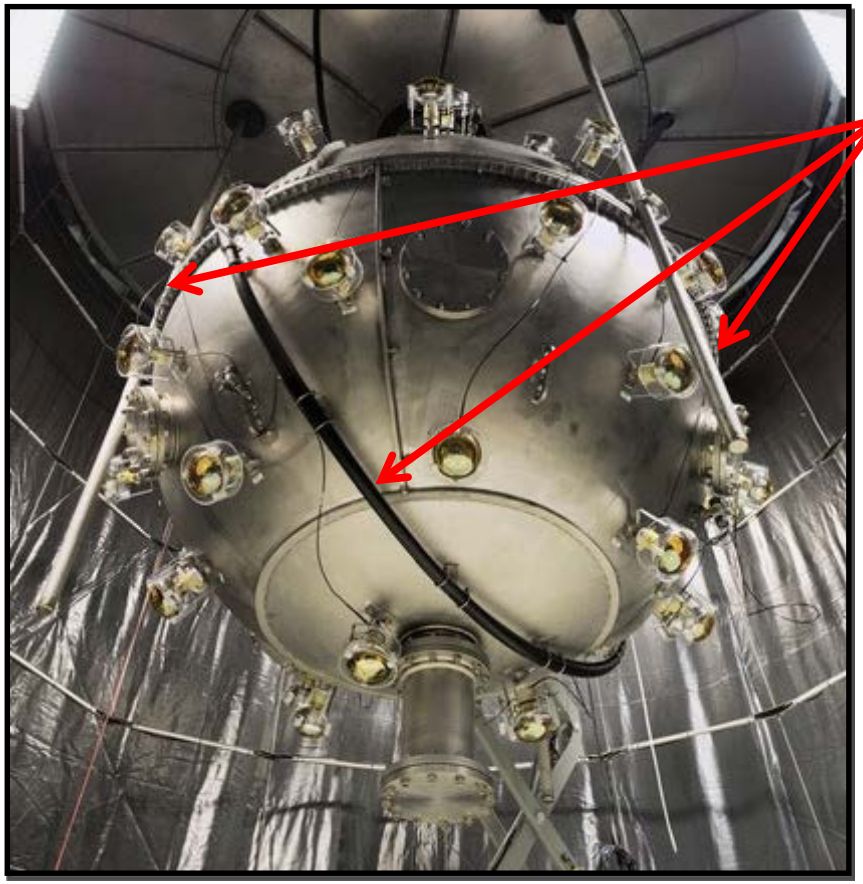


Deposition source for TPB



Demonstrated <15% deviation in thickness at distances similar to DEAP vessel.

Calibration sources



External tubes for calibration with radioactive sources:

- AmBe (neutrons)
- ^{22}Na (γ)
- ^{232}U (γ)

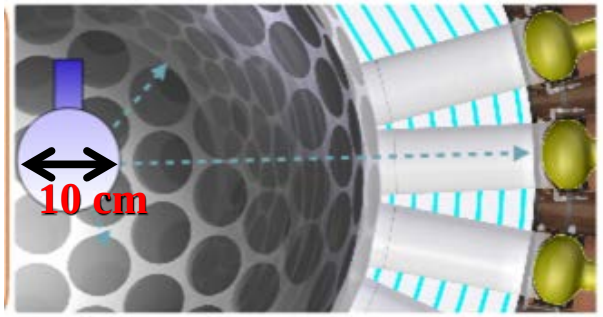
Energy calibration,
Position reconstruction

20 optical fibres attached to PMTs

- PMT gains
- Channel-to-channel relative efficiency variation
- Position reconstruction
- (optical model)

One-time calibration with an internal diffuse “laserball” source before the LAr fill.

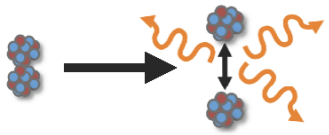
Channel-to-channel relative
- efficiency variation
- timing offsets
- Position reconstruction (optical model)



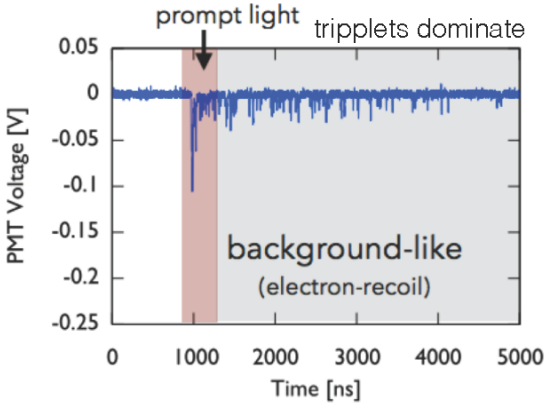
Experimental Signatures

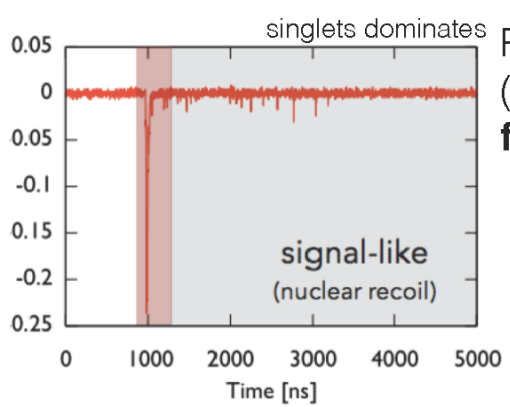
Ar scintillation:

- excimers are create



- singlet: 6 ns
- tripplet: 1500 ns
- wavelength: 128

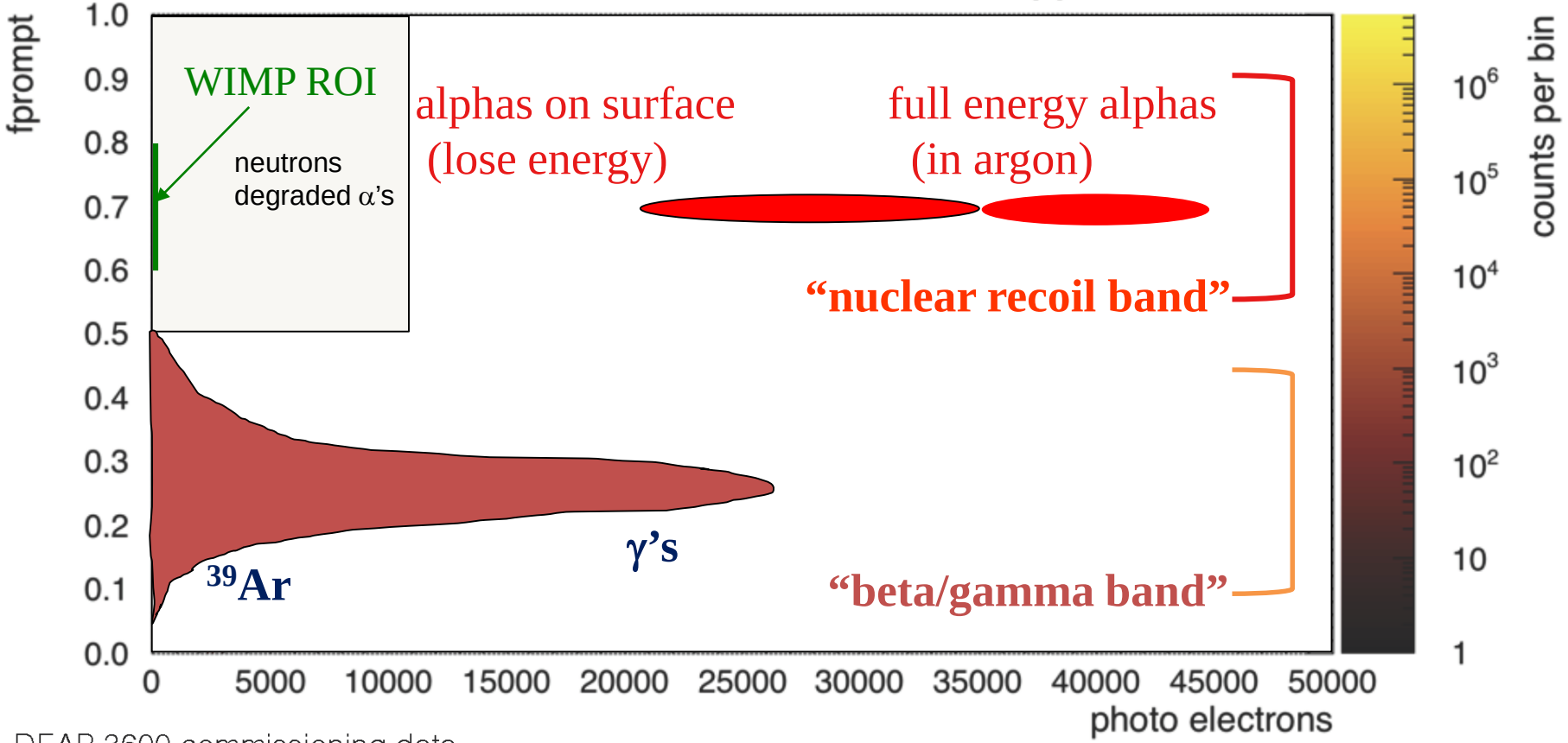




Pulse shape discrimination (PSD) parameter:

fprompt =

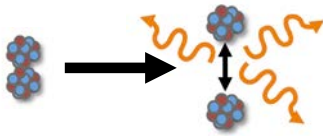
$$\frac{\text{prompt light (150 ns)}}{\text{total light (10000 ns)}}$$



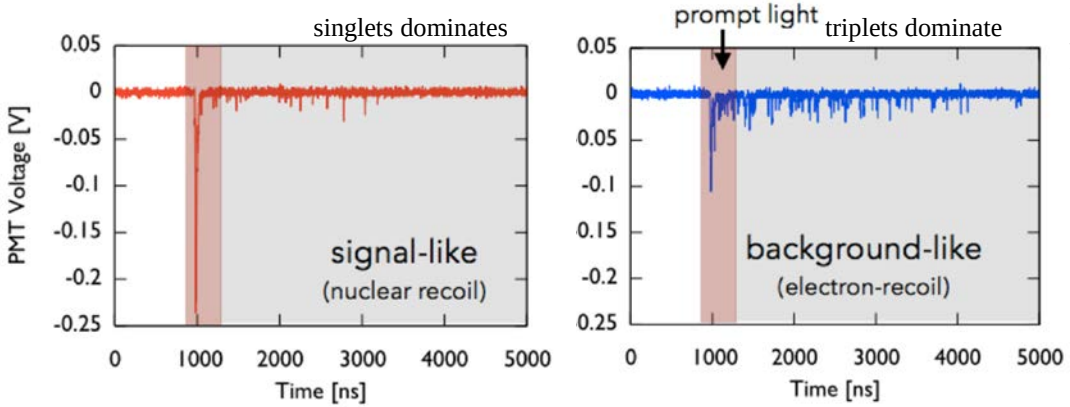
DEAP 3600 commissioning data

Experimental Signature: Pulse Shape Discrimination

Ar scintillation:
- excimers are created



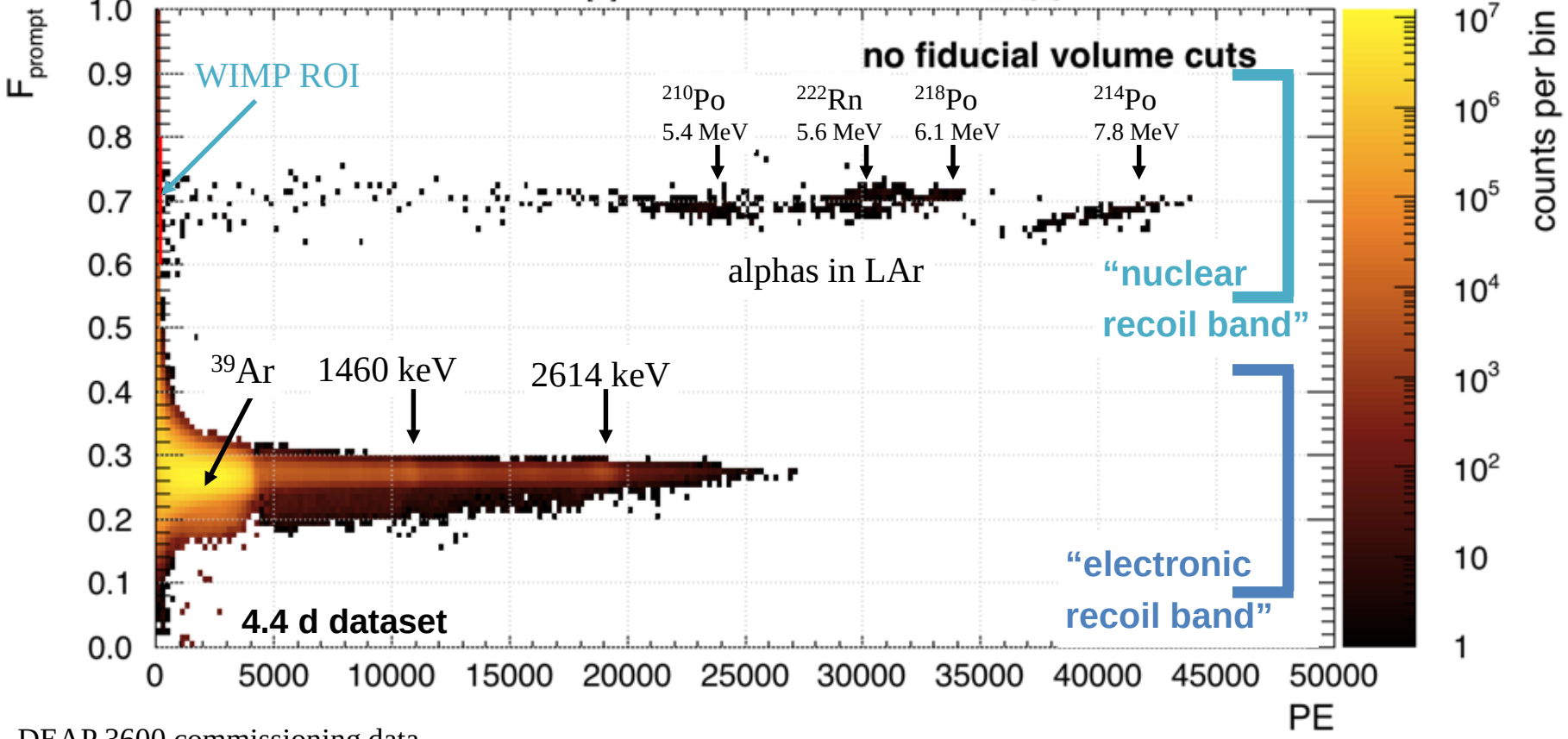
- singlet: 6 ns
- triplet: 1300 ns
- wavelength: 128 nm



Pulse shape discrimination (PSD) parameter:

$$F_{prompt} = \frac{\text{prompt light (150 ns)}}{\text{total light (10000 ns)}}$$

factor 10^{10} separation



DEAP 3600 commissioning data

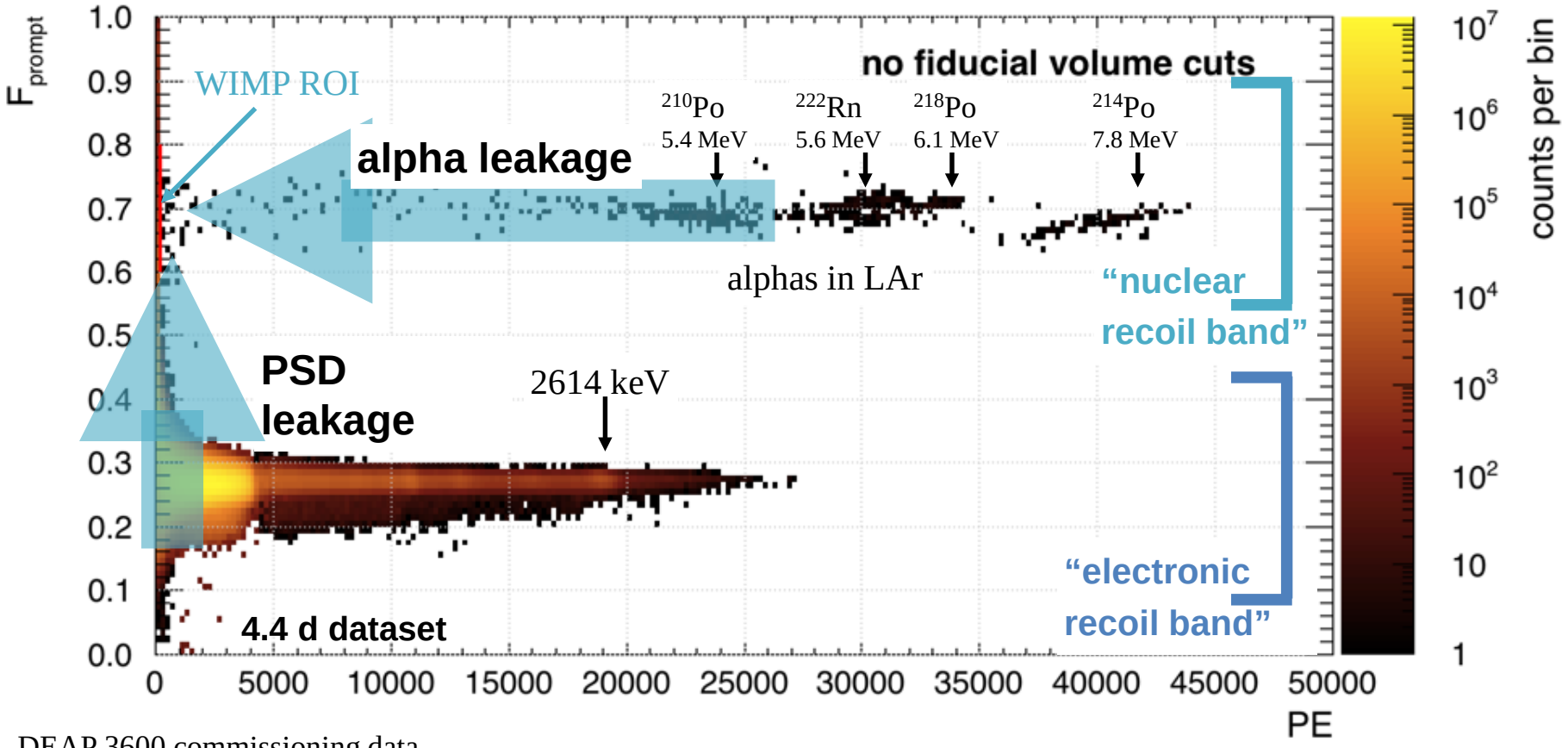
Major Expected Backgrounds in DEAP

Background sources for WIMP ROI:

- Alphas: Energy degraded or shadowed
- ^{39}Ar: PSD leakage from ER band
- Neutrons: Create Ar NR similar to WIMPs

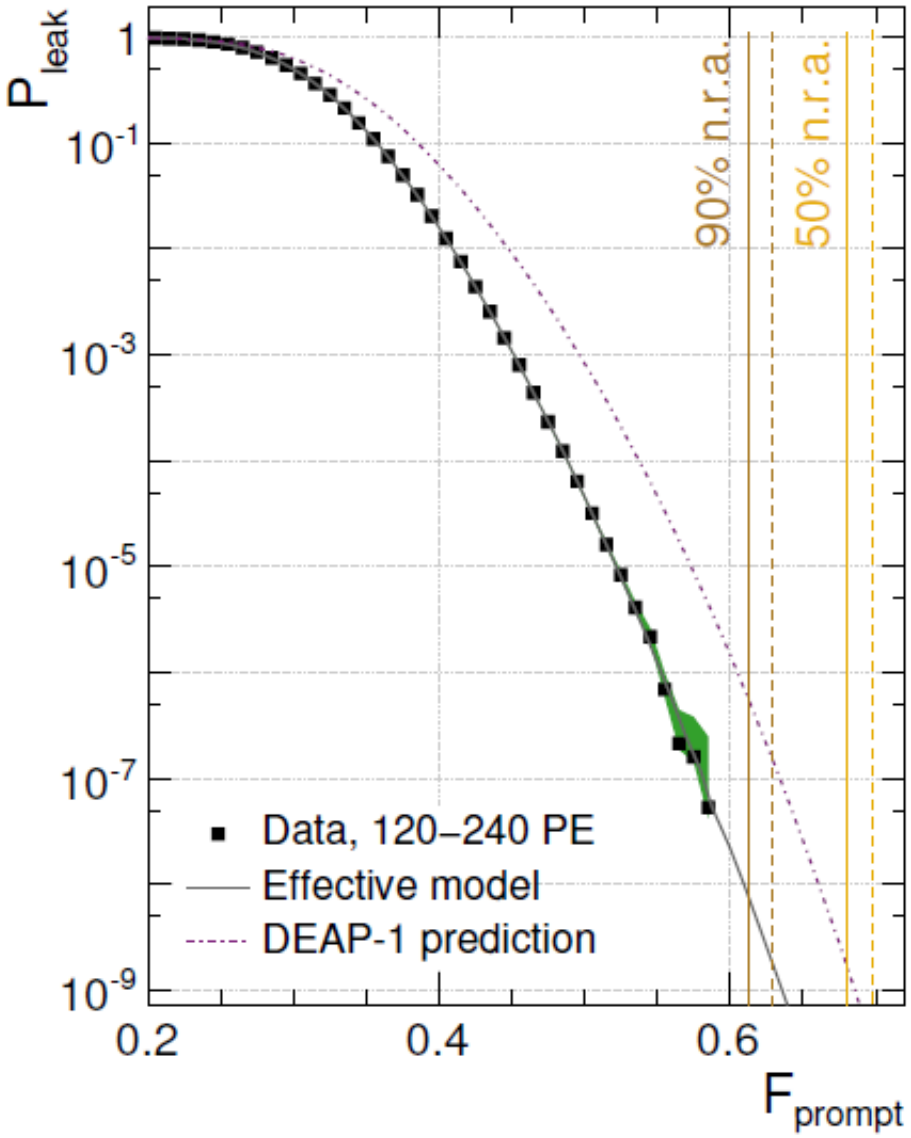
Design goals:

3000 kg x yr exposure	alphas	^{39}Ar	neutrons
events in ROI	< 0.2	< 0.2	< 0.2



DEAP 3600 commissioning data

Pulse-Shape Discrimination in DEAP-3600



We observe good PSD of beta events down to 11 keVee!

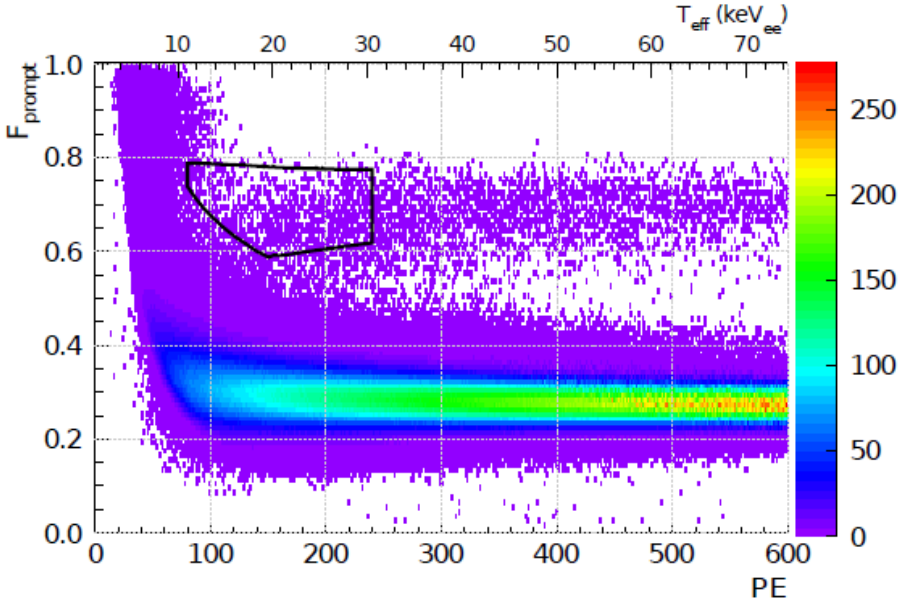
Best ever demonstrated at low energy, expect to meet design goal for full sensitivity run

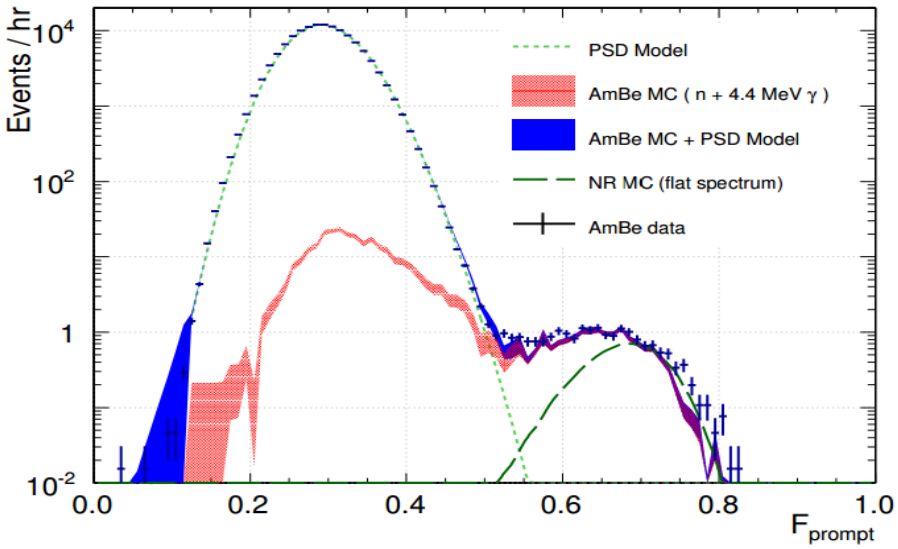
For larger detectors: Combine this with low-radioactivity argon (depleted in ^{39}Ar):

can use PSD for WIMP search with **several hundred tonnes** of depleted argon

Calibrated detector response

- AmBe neutrons (for nuclear recoil response Monte-Carlo validation)





- For F_{prompt} cut efficiency: on top of the literature physics parameters, simulation of the PMT/detector response is added

- MC/data agree within systematic uncertainties

- 1 year dataset analysis: larger calibration dataset, further improvements to the Monte Carlo model

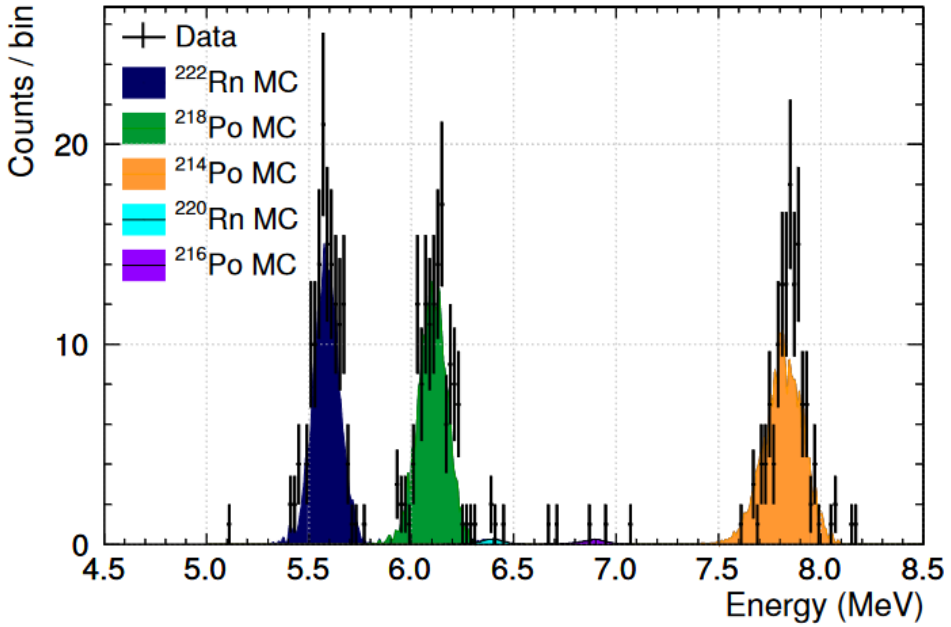
^{222}Rn in DEAP-3600

- Measuring the ^{222}Rn content in the bulk LAr shows the very competitive results
- Conclusion: ^{222}Rn induced background within expectations

^{222}Rn in Dark Matter experiments:

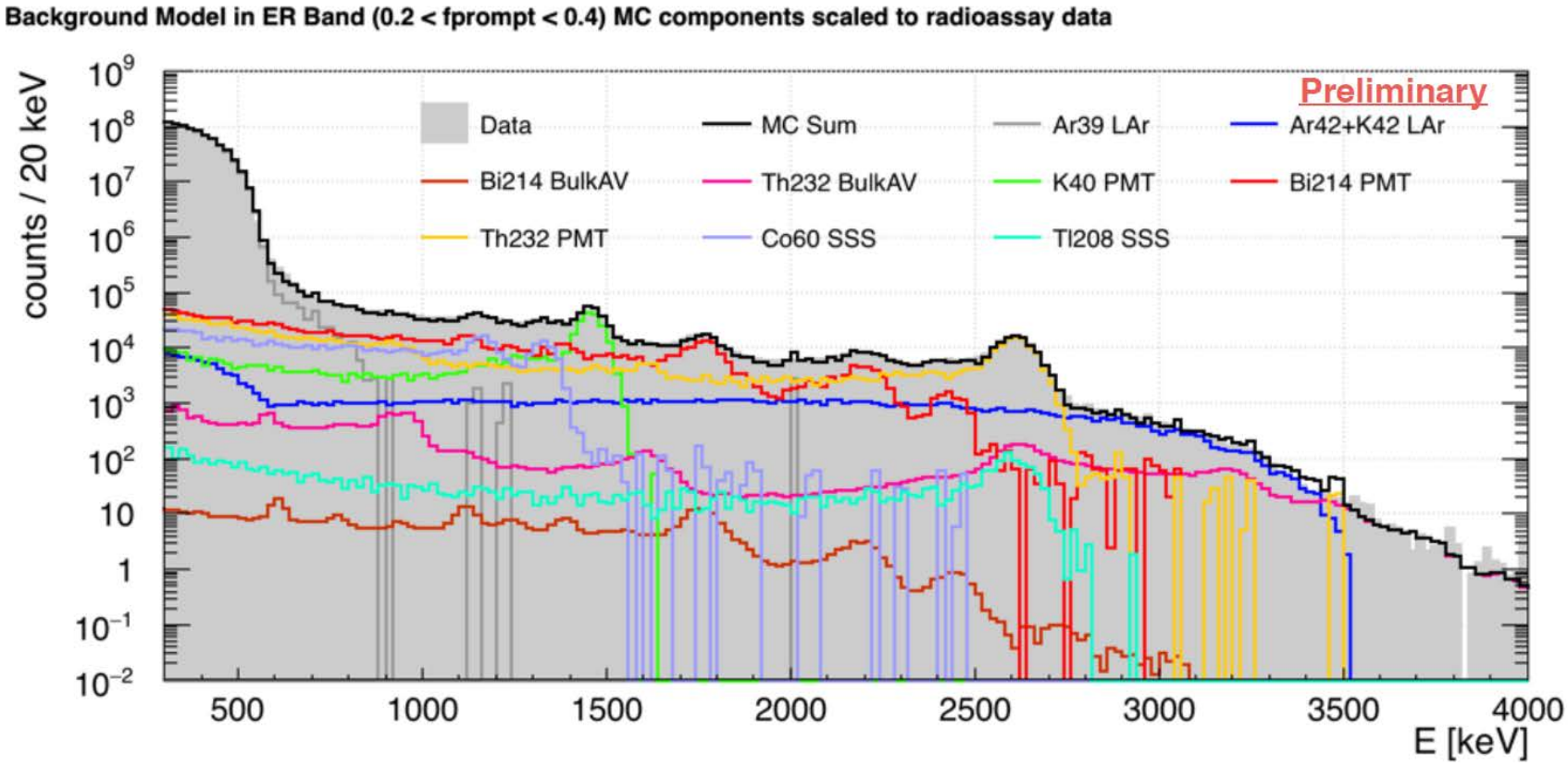
Experiment	Activity / rate	Target
DEAP-3600	≈0.2 μBq / kg	LAr
PandaX-II	6.6 μBq / kg	LXe
LUX	66 μHz / kg	LXe
XENON1T	10 μBq / kg	LXe

- PandaX-II: PHYSICAL REVIEW D 93, 122009 (2016)
- LUX: Physics Procedia 61 (2015) 658 – 665
- XENON1T: XeSAT 2017 talk [link]



30-300X lower radon levels than xenon DM experiments

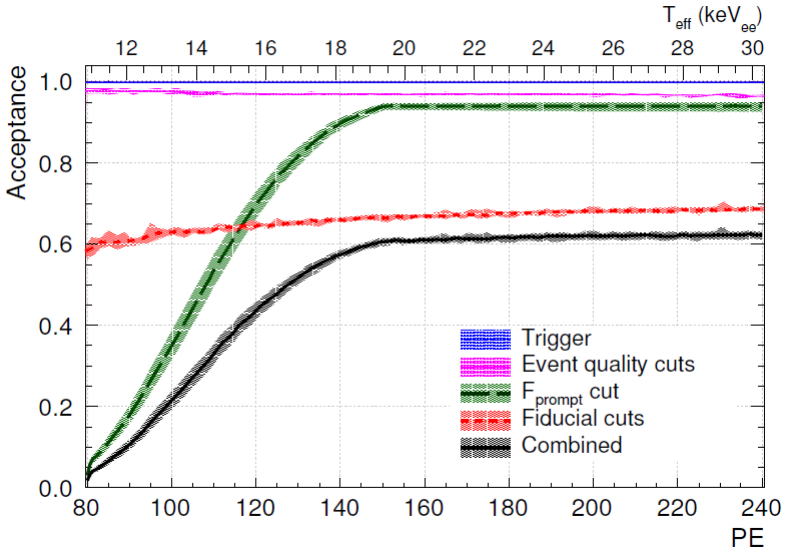
Gamma and Beta Background Model



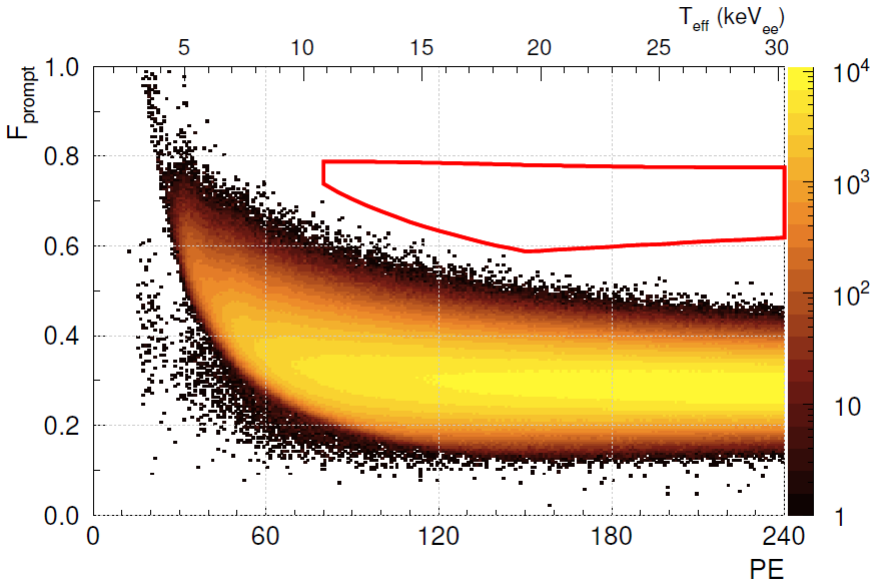
MC Simulations scaled by radioactivity screening results

These measurements set limits on radioactivity in PMT's and hence on neutrons in the detector that are well within dsign limits.

First Dark Matter Search with DEAP-3600 – 9,870 kg-days



	Cut	Livetime	Acceptance %		$\#^{\text{ROI}}_{\text{evt.}}$
run	Physics runs	8.55 d			
	Stable cryocooler	5.63 d			
	Stable PMT	4.72 d			
	Deadtime corrected	4.44 d			119181
low level	DAQ calibration				115782
	Pile-up				100700
	Event asymmetry				787
quality	Max charge fraction per PMT		99.58 ± 0.01		654
	Event time		99.85 ± 0.01		652
	Neck veto		$97.49^{+0.03}_{-0.05}$		23
fiducial	Max scintillation PE fraction per PMT			$75.08^{+0.09}_{-0.06}$	7
	Charge fraction in the top 2 PMT rings			$90.92^{+0.11}_{-0.10}$	0
	Total	4.44 d	96.94 ± 0.03	$66.91^{+0.20}_{-0.15}$	0



4.44 live days

Selected ROI for < 0.2 leakage from β's

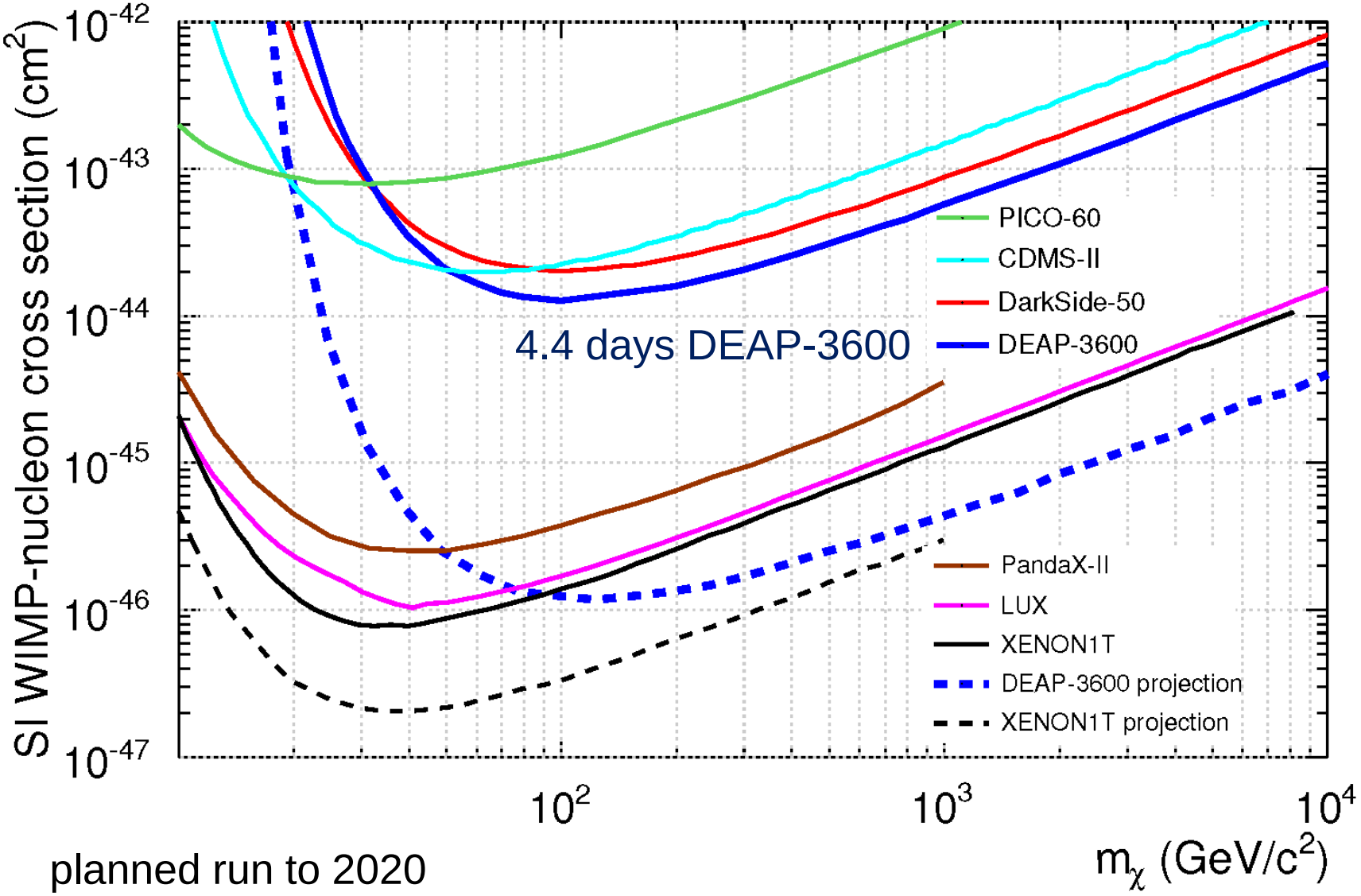
Developed prelim. cuts for instrumental and external-source events

2,223 kg fiducial mass

9,870 kg-day exposure

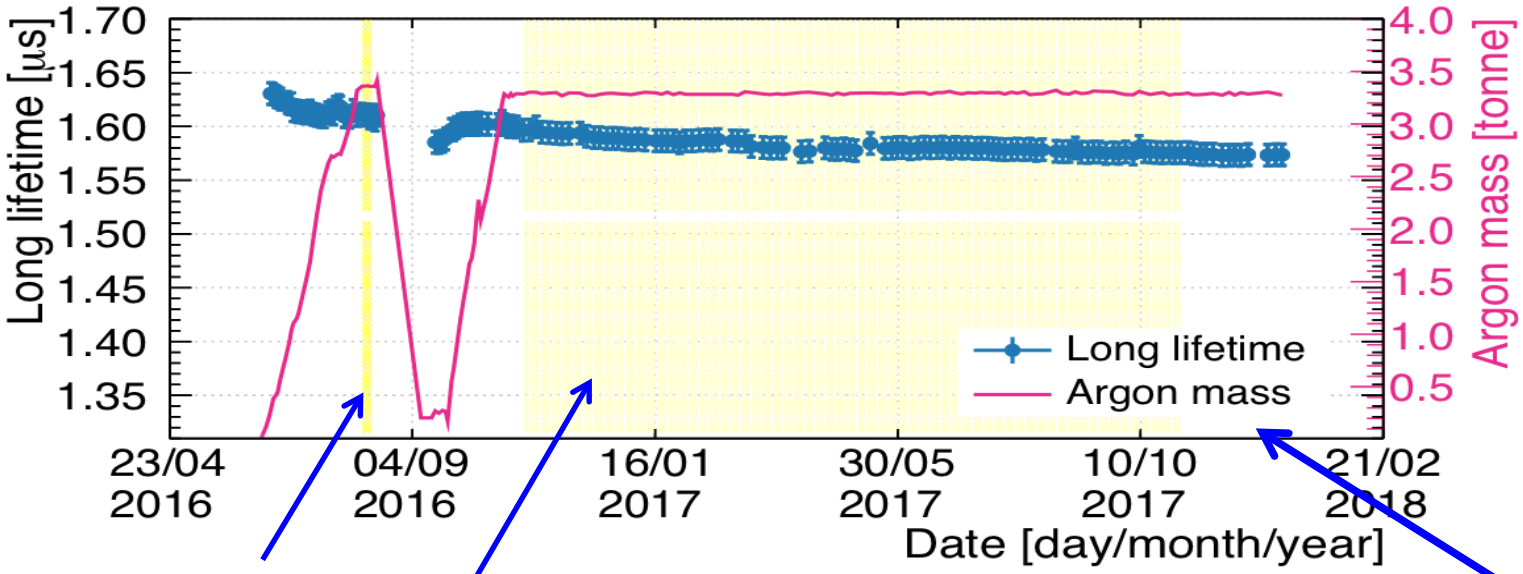
No events observed in ROI

WIMP exclusion with DEAP-3600 (July 2017 result)



planned run to 2020

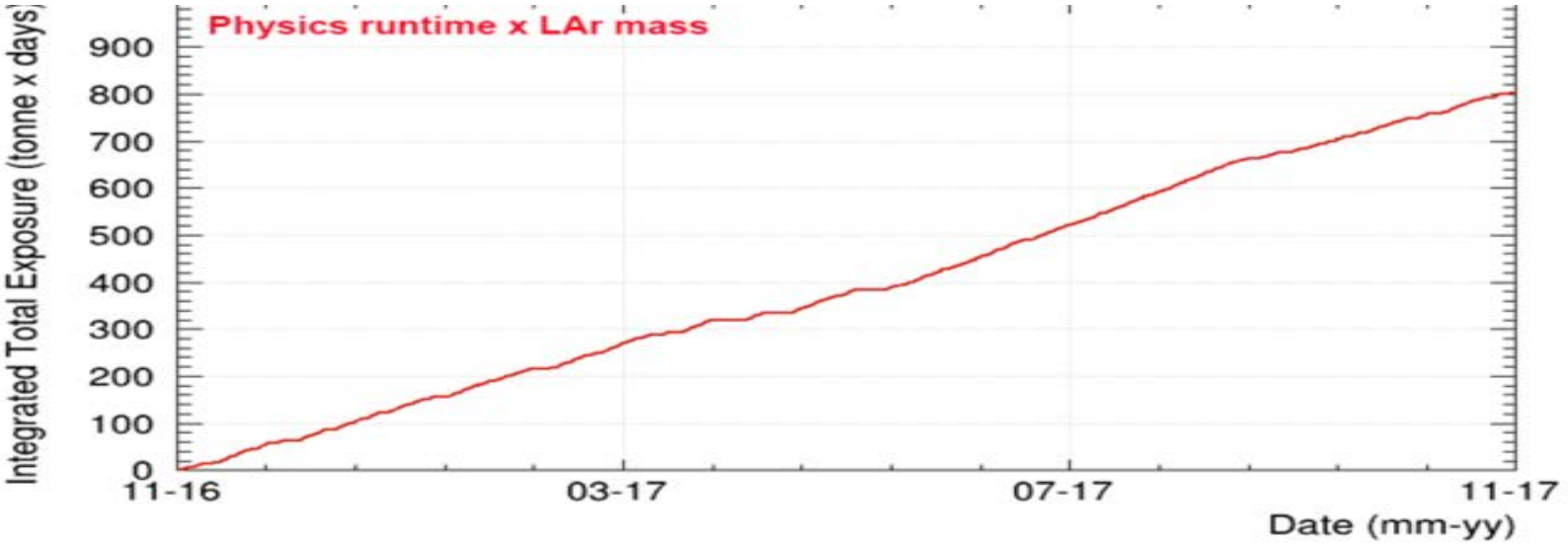
Analysis of 1 yr dataset



Published PRL 4.4d dataset

Open (non-blind) dataset for 2nd analysis: Nov 1 2016 – Dec 31, 2017

ROI and vicinity blinded since Jan 1, 2

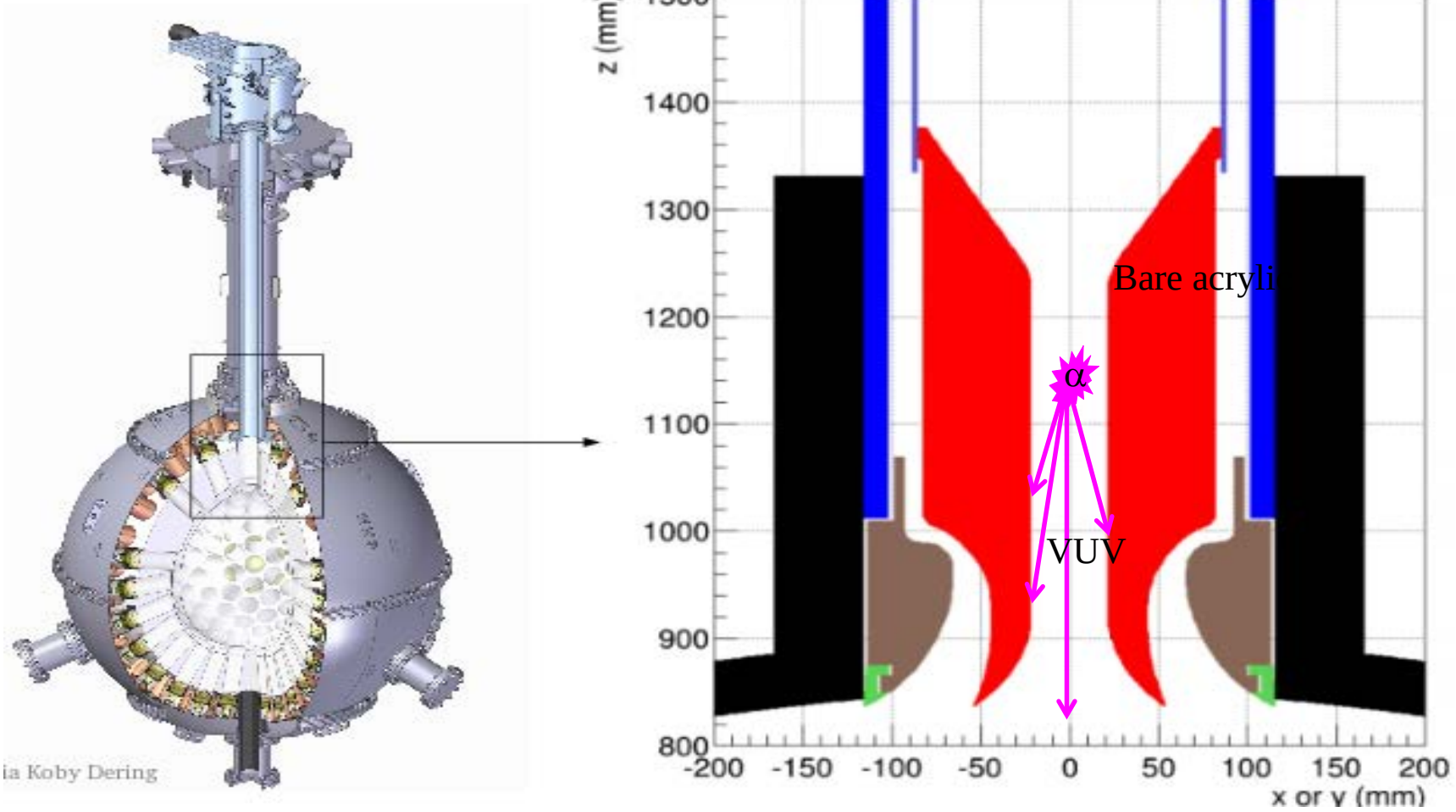


Projections for DEAP-3600 Backgrounds

Background	Target count for a 3tonne-year exposure	Mitigation
Neutron In 1t LAr	<0.2	Shielding: 6000 mwe (SNOLAB), Active water shield, light guides and filler blocks Material selection
β & γ In 1t LAr	<0.2	Pulse shape discrimination Material selection (for γ)
Radon In 1t LAr	negligible	Material selection, SAES getter, cold charcoal radon trap ** High energy events, not in ROI*
Surface α In 1t LAr	<0.2	Material selection (acrylic), sanding of AV (1mm removal), fiducialization.

So far, backgrounds appear to be close to target

“Geometric” backgrounds



Degraded light collection from high energy events shifts them to lower energies, where we look for WIMPs.

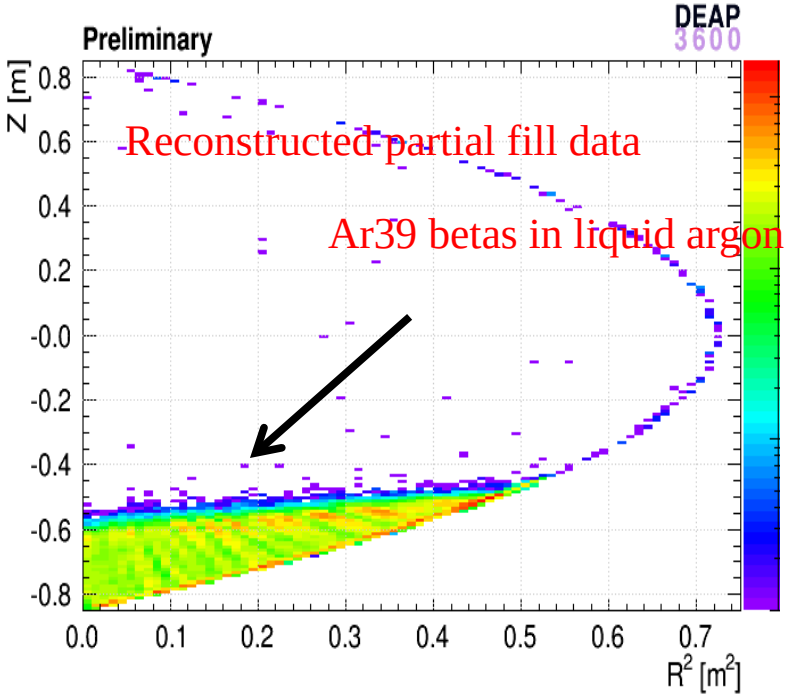
Position reconstruction

- Main measure against surface backgrounds

- Two independent maximum likelihood fitters based on charge tuned to Monte Carlo

- Surface event fiducial leakage probabilities of ~1.3e-3 into 1 tonne fiducial volume or better are expected with current algorithms (on MC)

- Spherical fiducial cut with an additional Z cut

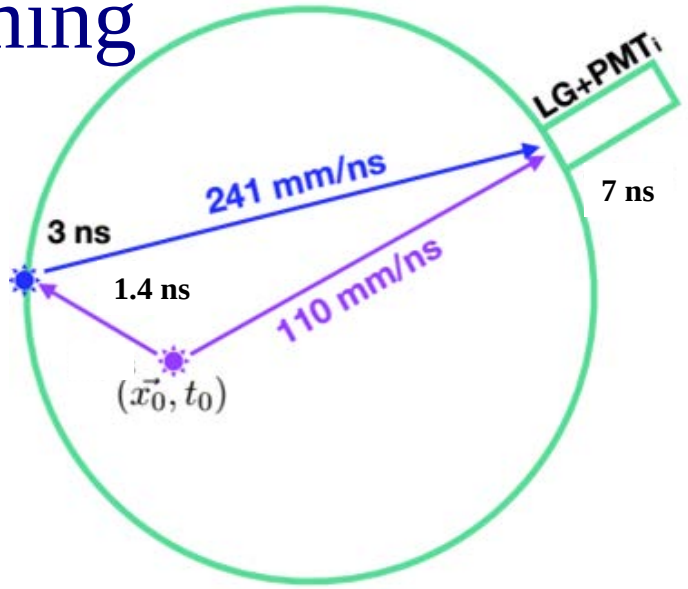


- Additional handle

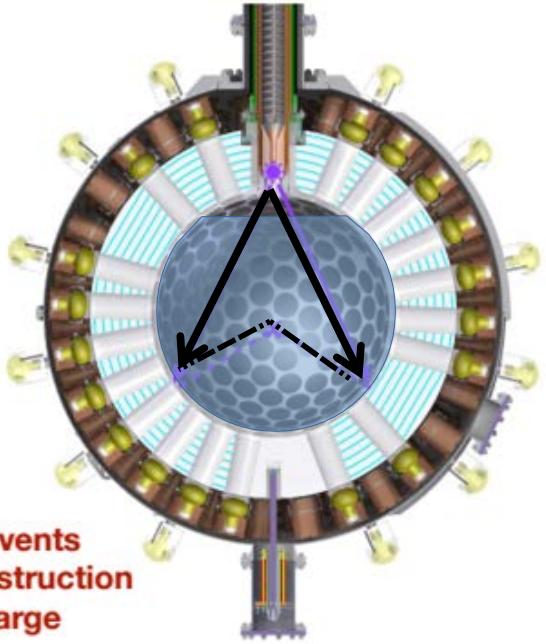
- alpha scintillation in TPB added to the argon scintillation, which makes those events easier to tag/remove with PSD

Fit with photon timing

- Fit with intensity and time of arrival for the first 40 ns of prompt light
- Group velocity of UV light = 110 mm/ns
- Group velocity of visible light = 241 mm/ns
- Construct PDFs for light emitted at vertex x0 and event time t_0 given PMT_i measures charge q_i
- Convolve singlet decay time (7 ns), TPB response time (3 ns), and PMT/LG, response time (1.4 ns)
- Consistency between Charge and Timing Fits
  - Both algorithms assume a single source of light.
  - For healthy, uniformly distributed events, such as ^{39}Ar or WIMPs, the positions reconstructed by charge and by timing should agree.
  - Not expect charge and timing fits to agree for
    - Events with substantial amount of afterpulsing
    - Light originates from multiple positions
    - **Events in the neck**

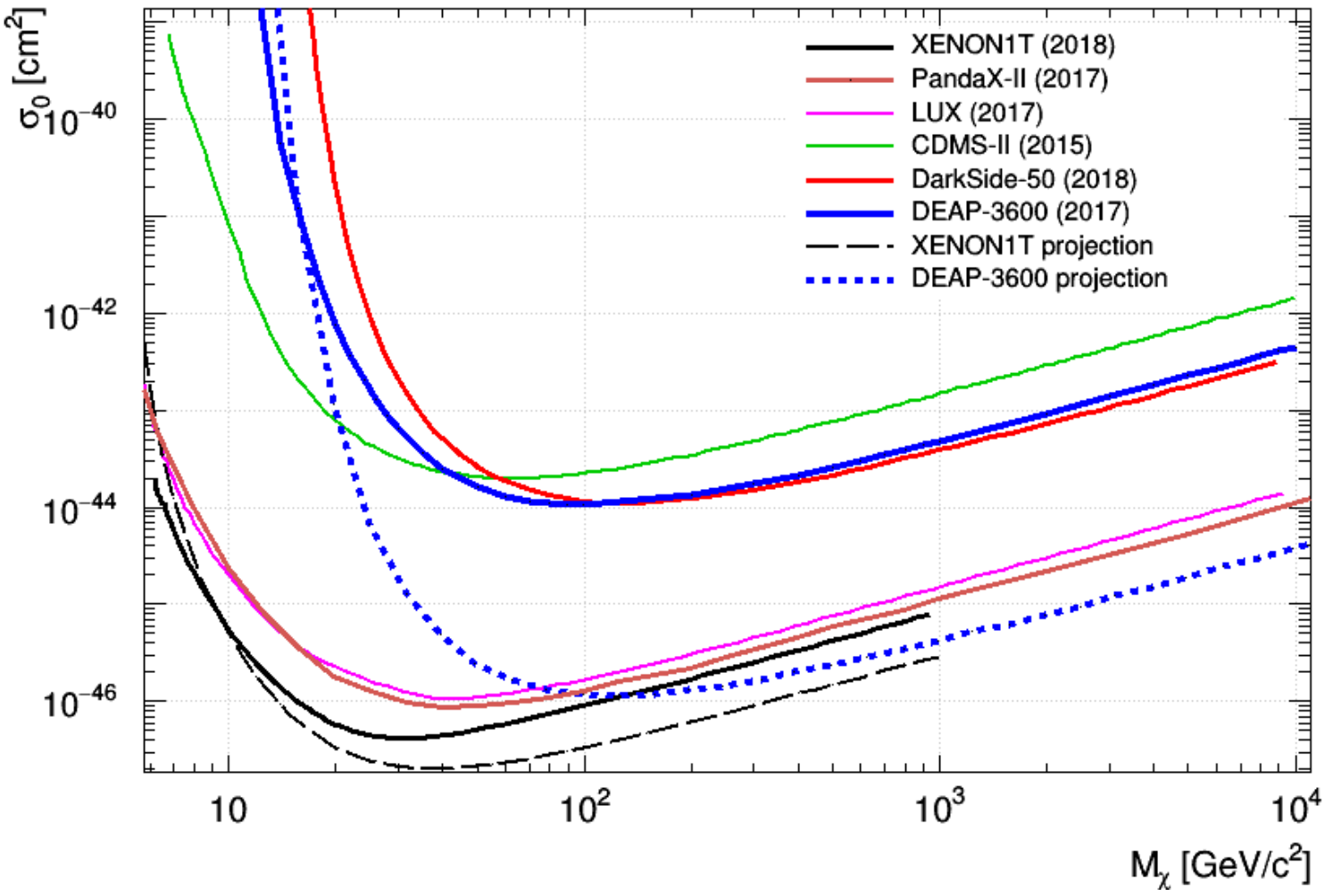


Scintillation hypothesis



Neck events
mis-reconstruction
by charge

Current landscape 2018



Paper on one year data set for DEAP-3600 planned for this fall

DEAP-3600 Collaboration

DEAP Collaboration: 75 researchers in Canada, UK, Mexico and Germany

University of Alberta
Carleton University
Laurentian University / Université Laurentienne
Technische Universität München
Queen's University
Royal Holloway University of London
Particle Physics, Rutherford Appleton Laboratory
SNOLAB — Mining for knowledge / Creuser pour trouver... l'excellence
University of Sussex
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
TRIUMF
Instituto de Física
Science & Technology Facilities Council

+ recent new DarkSide groups from Italy and US

Now I will hand over to Cristiano to speak about Darkside 50, 20k and the Global Argon Dark Matter Collaboration.