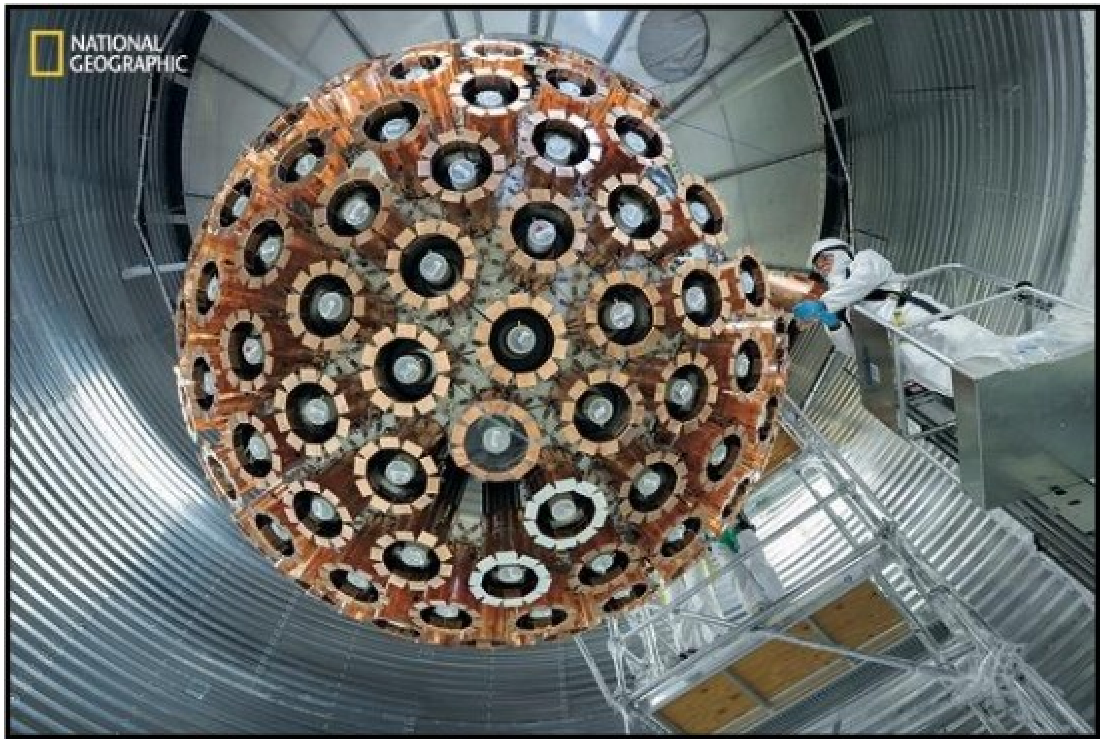
Status of the DEAP-3600 dark matter search

Marcin Kuźniak
Carleton University, Ottawa



DEAP-3600 Collaboration

75 researchers in Canada, UK, Mexico and Germany

UNIVERSITY OF ALBERTA
Carleton UNIVERSITY
Laurentian University Université Laurentienne
TUM TECHNISCHE UNIVERSITÄT MÜNCHEN
INFN Istituto Nazionale di Fisica Nucleare
Queen's UNIVERSITY
ROYAL HOLLOWAY UNIVERSITY OF LONDON
Particle Physics Rutherford Appleton Laboratory
SNOLAB MINING FOR KNOWLEDGE CREUSER POUR TROUVER... L'EXCELLENCE
US University of Sussex
Canadian Nuclear Laboratories Laboratoires Nucléaires Canadiens
TRIUMF
IF Instituto de Física
Ciemat
Science & Technology Facilities Council

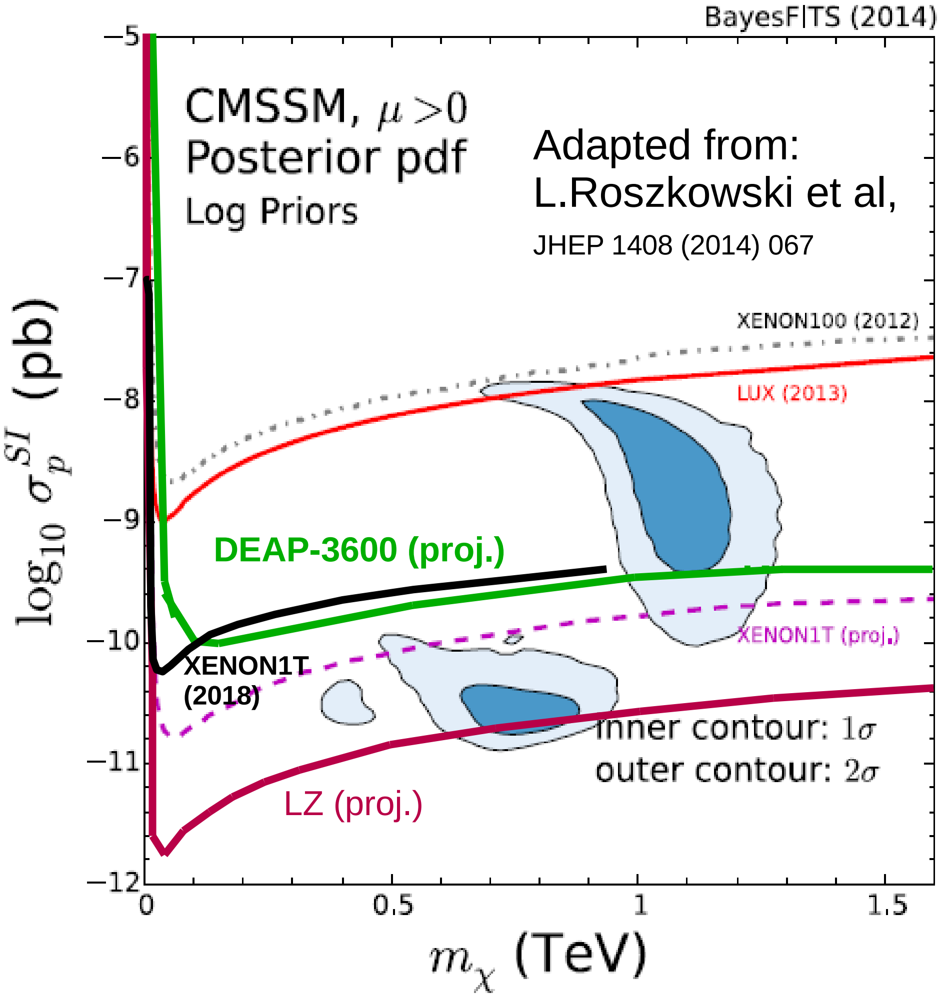
+ new DarkSide groups from Italy, US and Spain

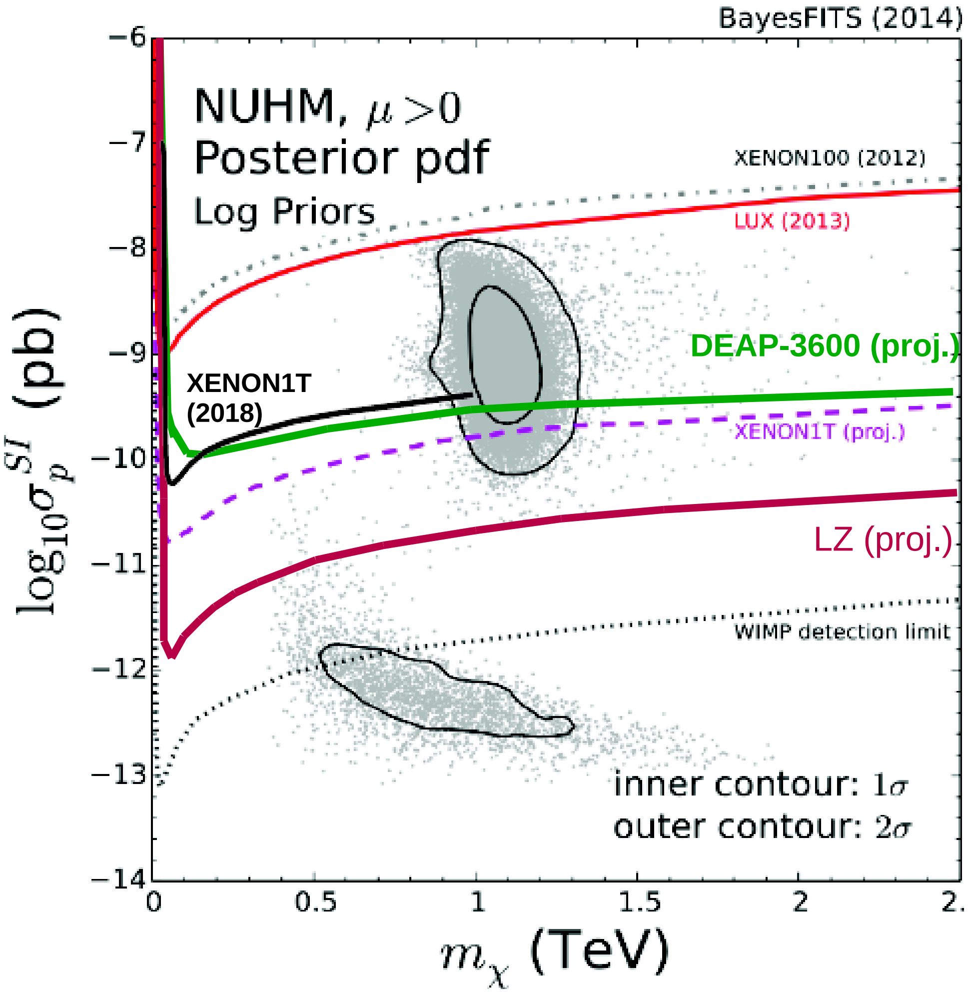
Outline

- Physics reach
- Liquid argon as a target for WIMP detection
- DEAP-3600:
  - Detector design, background mitigation strategy and construction
  - First results
  - Overview of analysis improvements towards the 2nd analysis
    - Pulse shape discrimination
    - Energy calibration
    - Position reconstruction
- Future LAr program

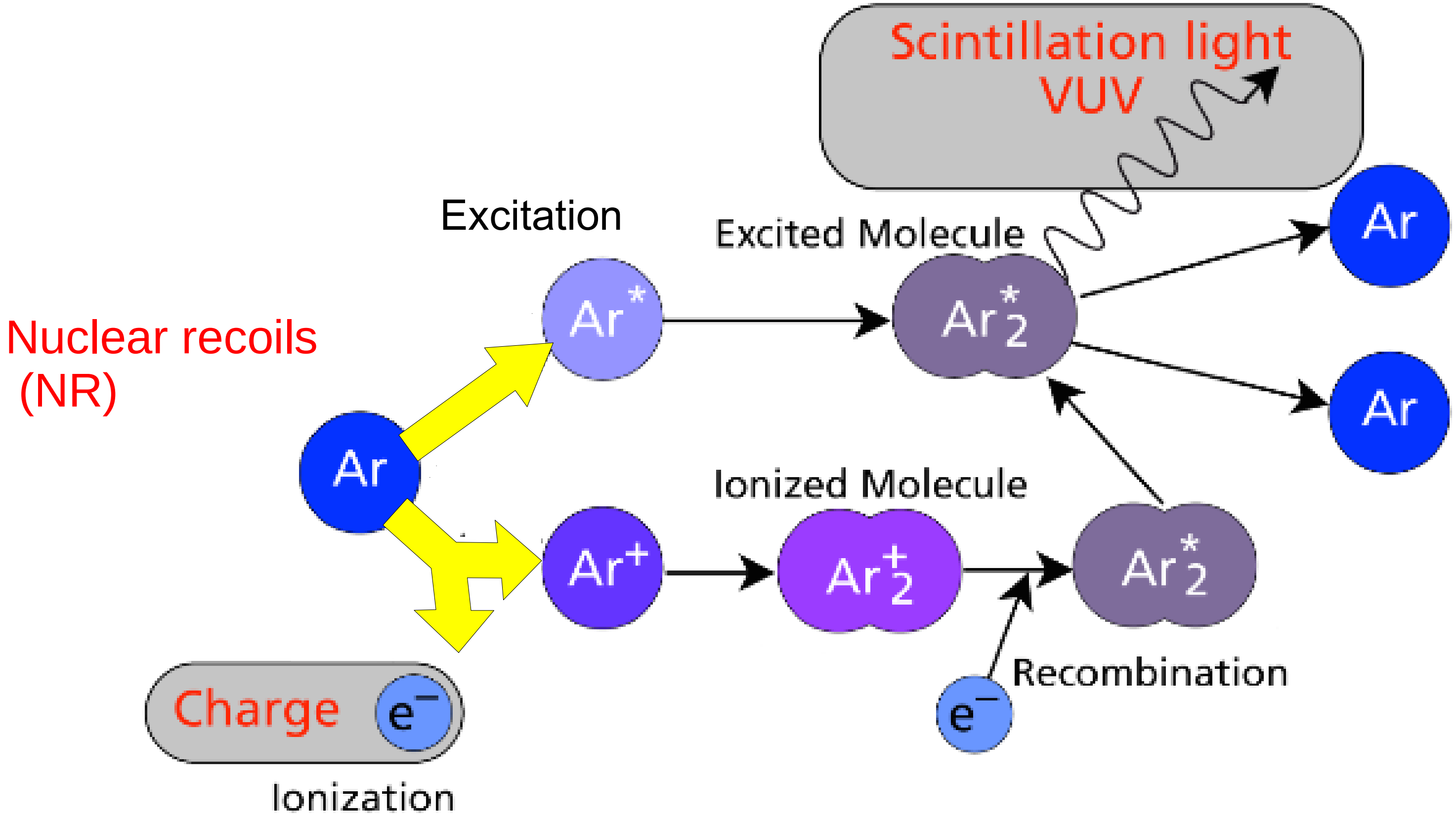
Physics reach for 1-tonne WIMP detectors

- All available experimental data combined (LHC, LUX, Planck) are still consistent with even the simplest versions of SUSY (cMSSM, NUHM)
- Remaining parameter space is probed by direct WIMP searches with tonne scale detectors: DEAP-3600, XENON1T, LZ
- Complementarity with LHC (cMSSM/NUHM are mostly out of reach of the 14 TeV run!)





Liquid noble gas detectors



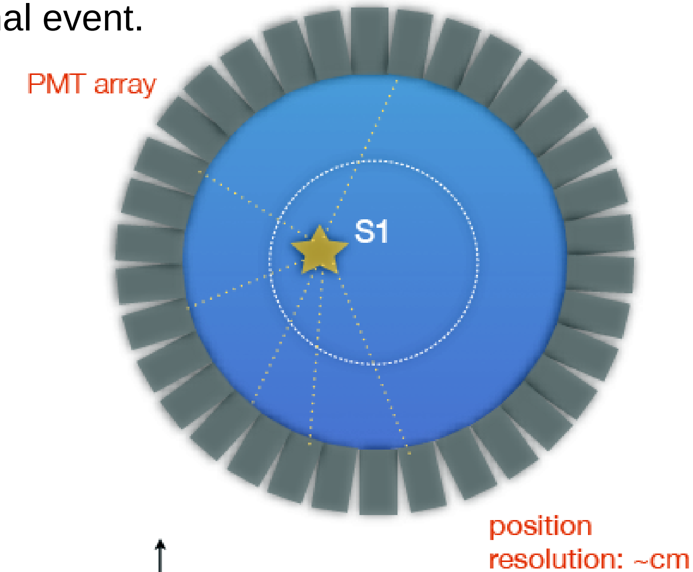
Why noble elements?

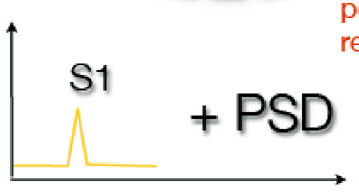
- (At least) two available detection channels: scintillation and ionization
  - Avenue to reject electron recoil backgrounds (from γ / β activity)
- High light yield, transparent to their own scintillation
- Easy to purify and scalable to very high masses

Ar and Xe are used for WIMP detection

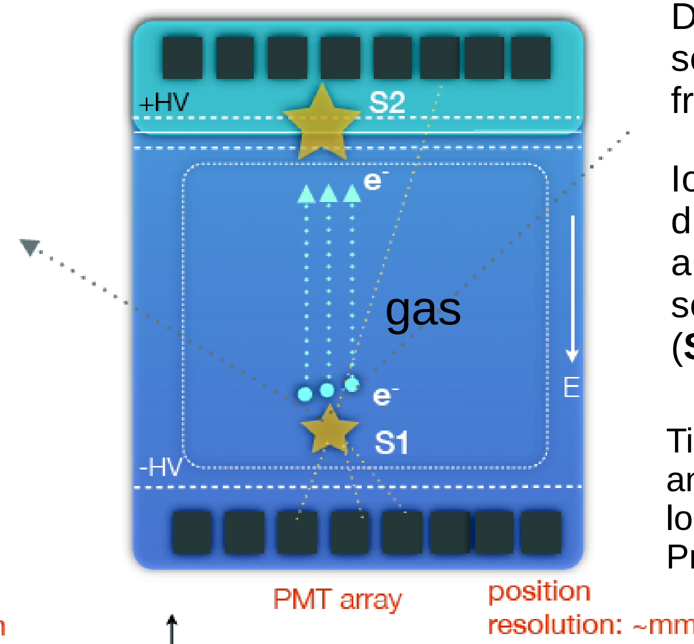
Single vs. dual phase

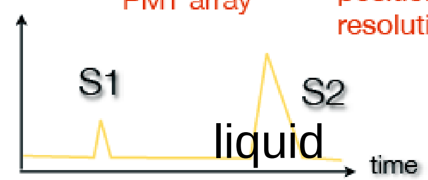
Detect primary scintillation light (**S1**) from the original event.





Pulse Shape Discrimination





Detect primary scintillation light (**S1**) from the original event.

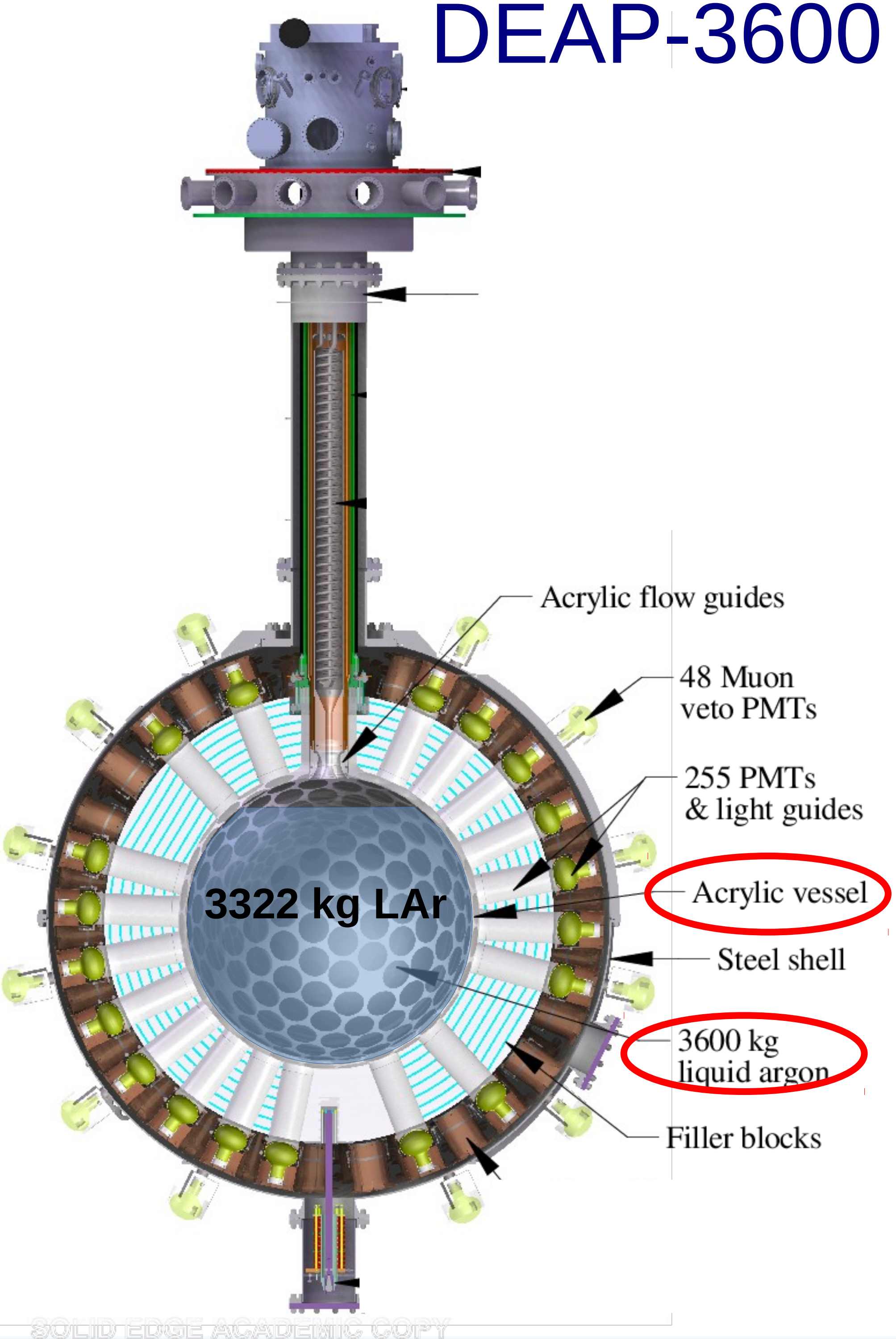
Ionization charge then drifted to high field region and converted to secondary scintillation (**S2**) in gas phase

Time difference S2-S1 and top PMTs used to localize event (Time Projection Chamber)

- Electronic recoil discrimination:
  - S2/S1 in Xe
  - PSD with S1 (scintillation only) in Ar; S2 signal used for position reconstruction

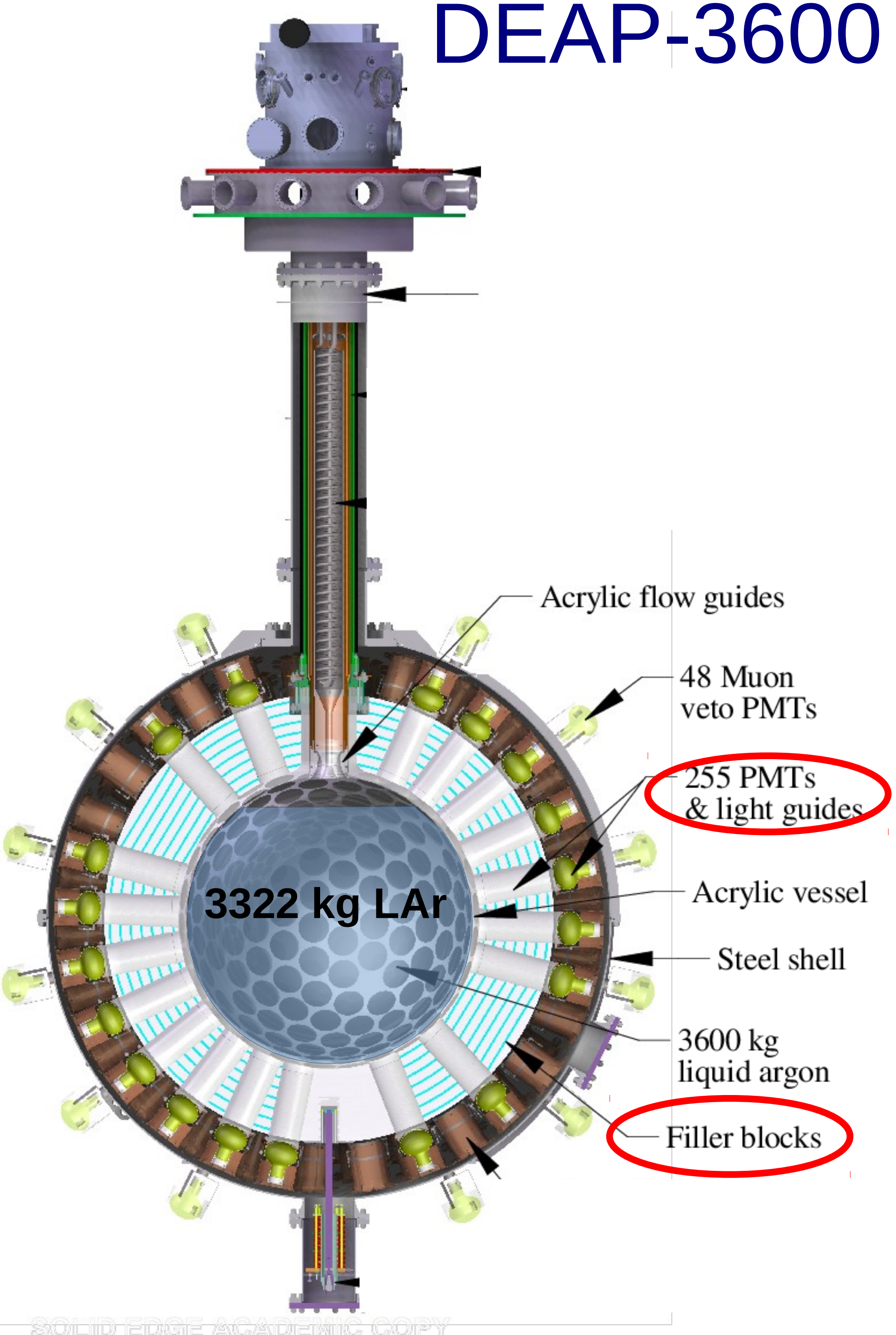
- A single phase detector of several hundred tonnes could be realized
  - PSD with currently-demonstrated low-radioactivity underground Ar mitigates electron recoil backgrounds;
  - position reconstruction mitigates external-source events

DEAP-3600 Dark Matter Search



- **Single phase liquid argon** approach: simple, scalable, inexpensive
- 3.3 tonne target (1000 kg fiducial) in sealed ultraclean Acrylic Vessel
- Vessel is “resurfaced” in-situ to remove deposited Rn daughters after construction

DEAP-3600 Dark Matter Search



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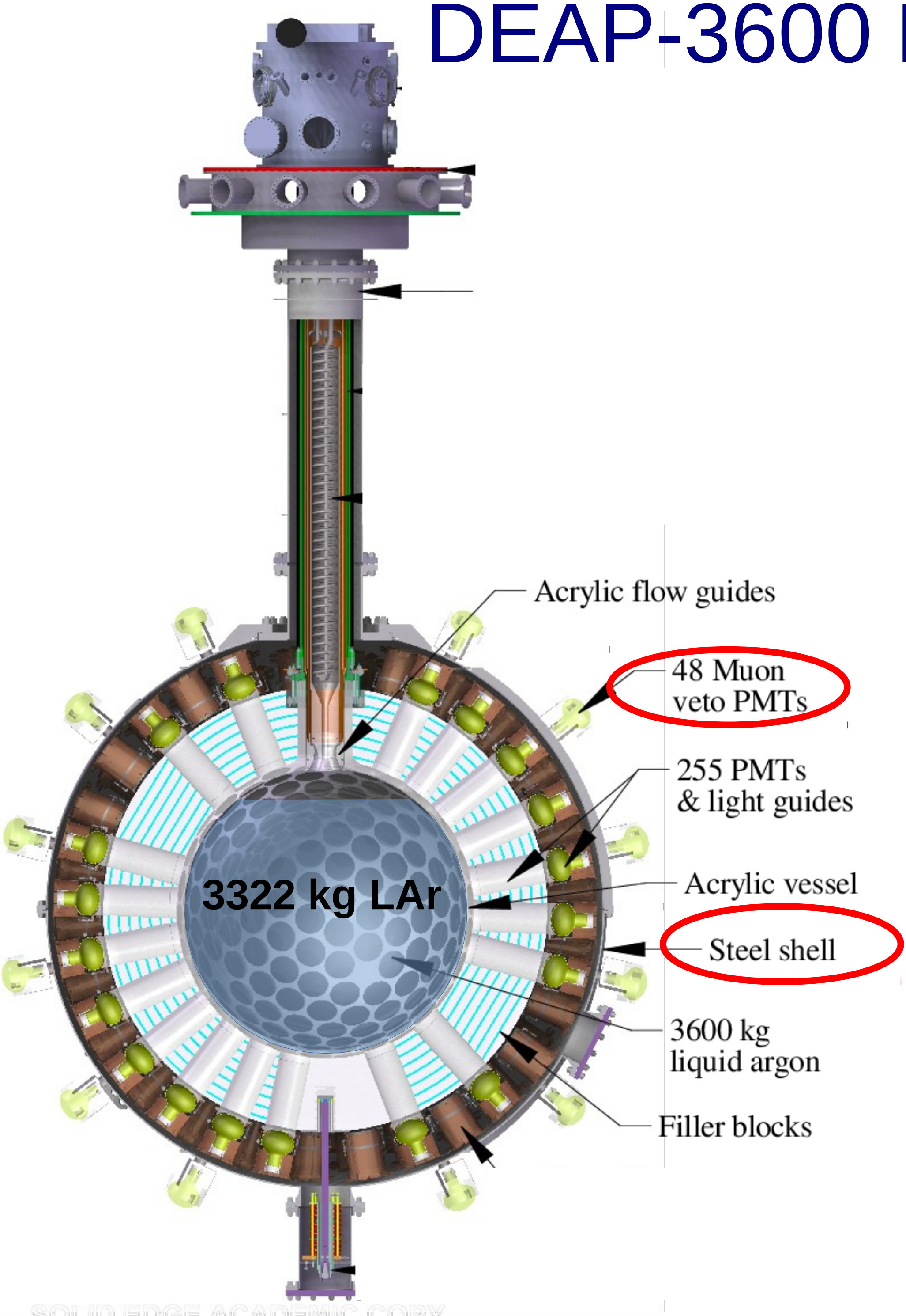
- In-situ vacuum evaporated TPB wavelength shifter (~10 m^2 surface)
- Bonded 50 cm long light guides + polyethylene shielding against neutrons
- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)

DEAP-3600 Dark Matter Search



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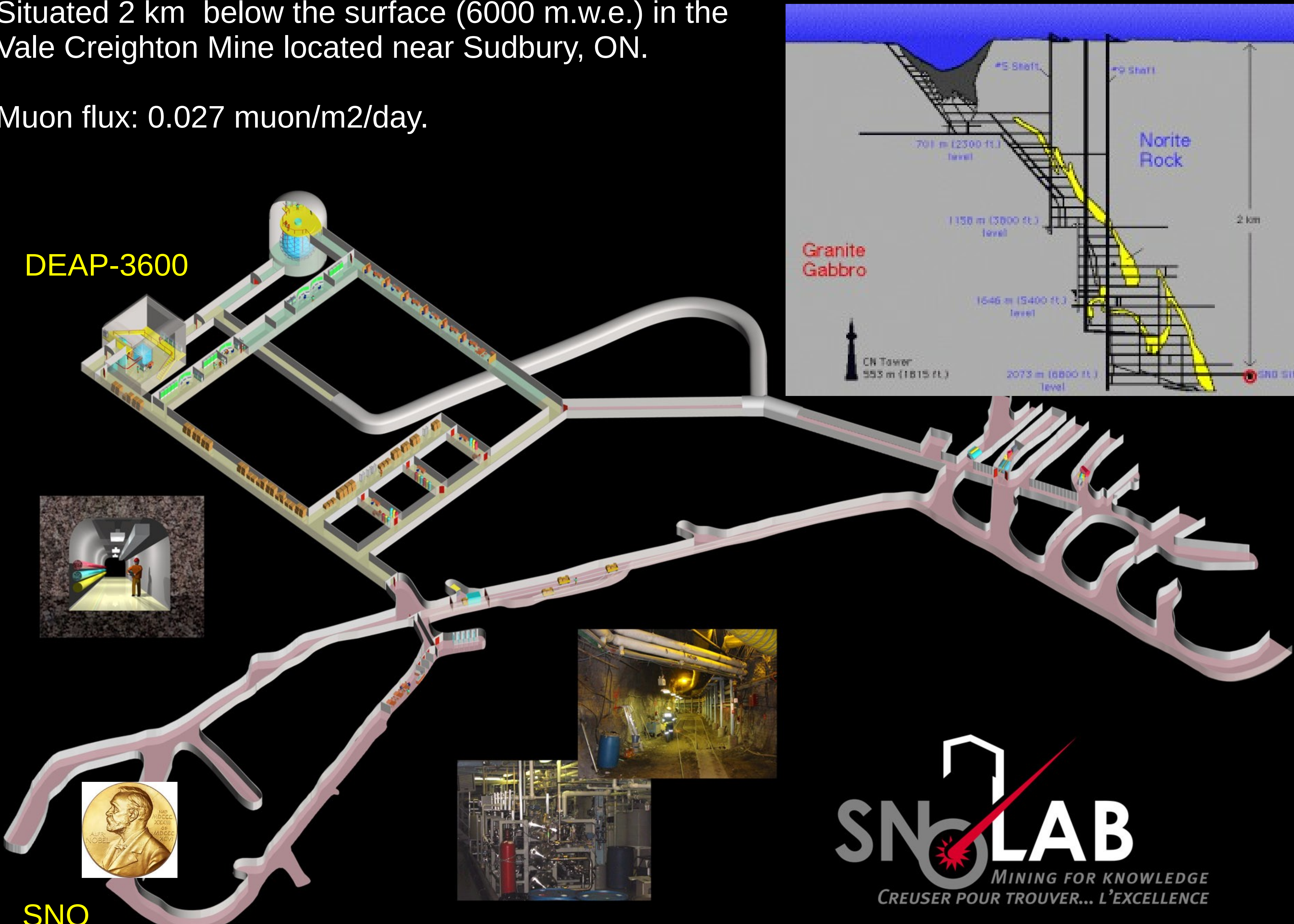
- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)
- Detector immersed in 8 m water shield, instrumented with PMTs to veto muons
- Located 2 km underground at SNOLAB

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/m2/day.



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

Background mitigation strategy

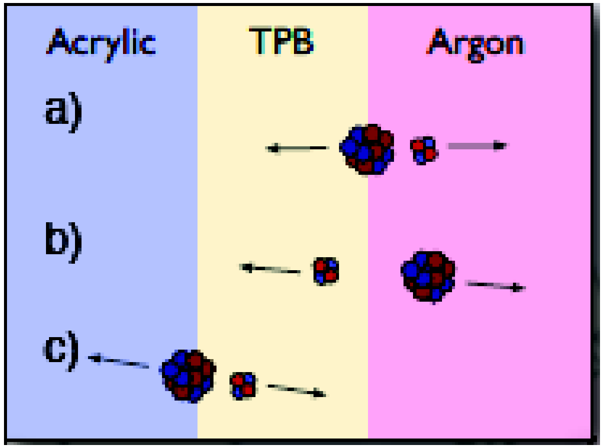
- **β/γ events:** dominated by ^{39}Ar beta decay rate, 1 Bq/kg
  - pulse shape discrimination is **very powerful in liquid argon** ~10^{-10}

- **surface events:** Rn daughters and other surface contamination
  - procured ultrapure materials (screening, quality assurance, co-operation with suppliers)
  - surfaces sanded in-situ
  - limited exposure to radon
  - position reconstruction & fiducialization
  - other analysis techniques

<u>rejection factor:</u>

position reconstruction & fiducialization: **~10^{-3}**

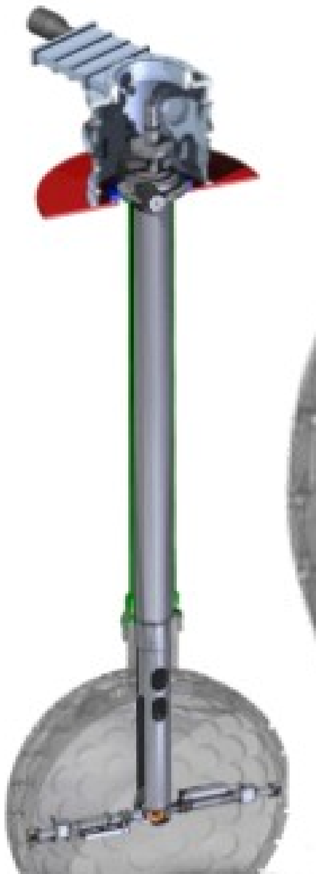
other analysis techniques: ~10

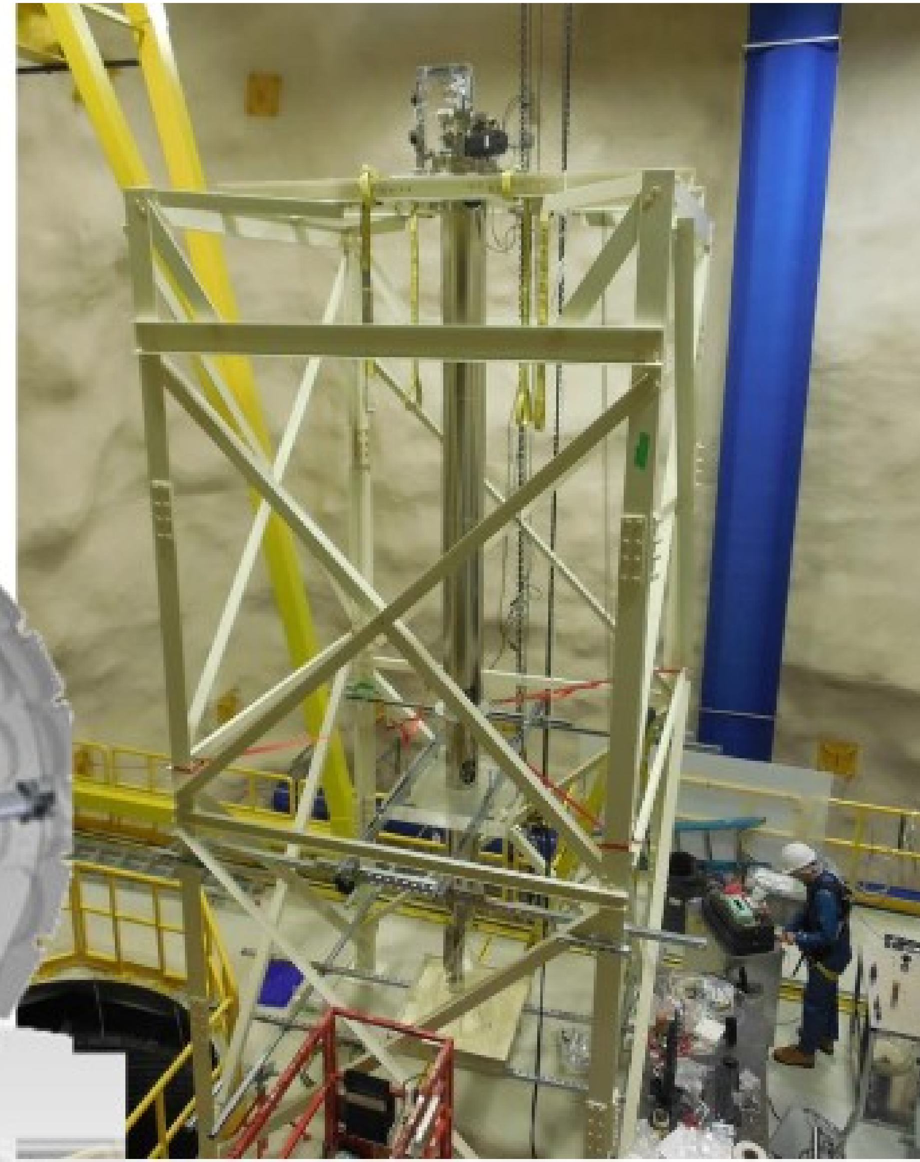


- **neutron recoils:** (α,n)+fission, cosmogenic μ-induced
  - SNOLAB depth + water Cerenkov muon veto
  - clean detector materials (material assay, quality assurance)
  - shielding

Acrylic vessel resurfacer

- Mechanical sander to clean inner surface
- Components selected for low radon emanation
- Remove 0.5-mm surface *in situ* with N_2 purge
- Cleans surface to bulk-level impurities
  (order 100,000 cleaner than SNO vessel)





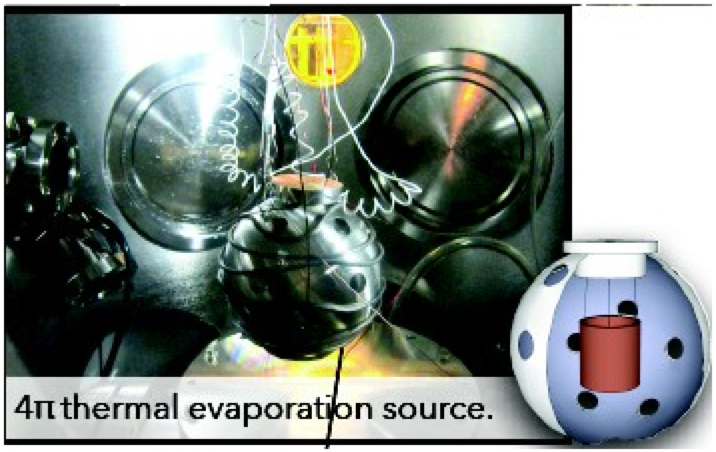
P. Giampa (DEAP), J. Phys.: Conf. Ser. 718 (2016) 042025

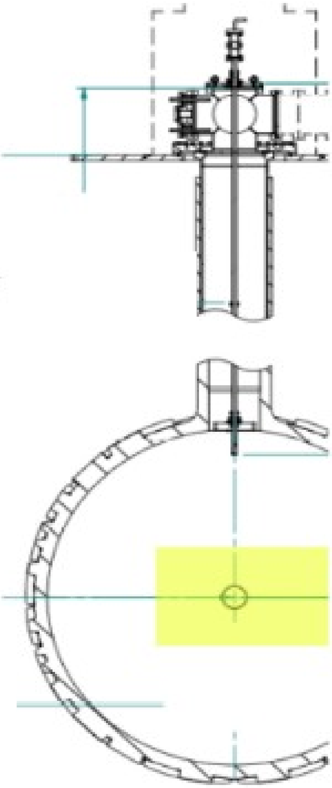
(Ultrapure acrylic coatings were considered in the past as an alternative and used in DEAP-1:
MK, AIP Conf. Proc. 1338, 101 (2010).

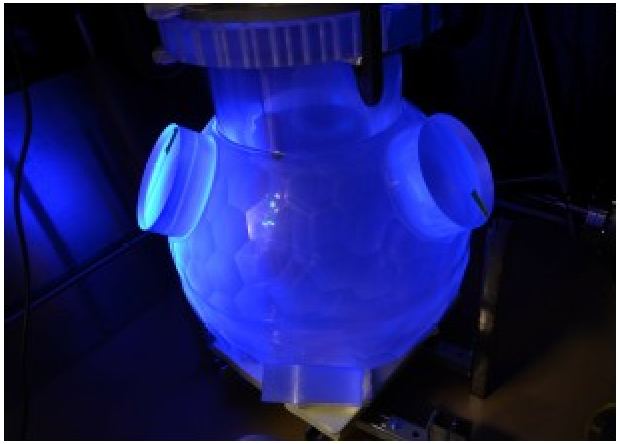
DEAP-3600 wavelength shifter (TPB) evaporation system

Evaporator source installation in a Rn-free atmosphere, through a glovebox.

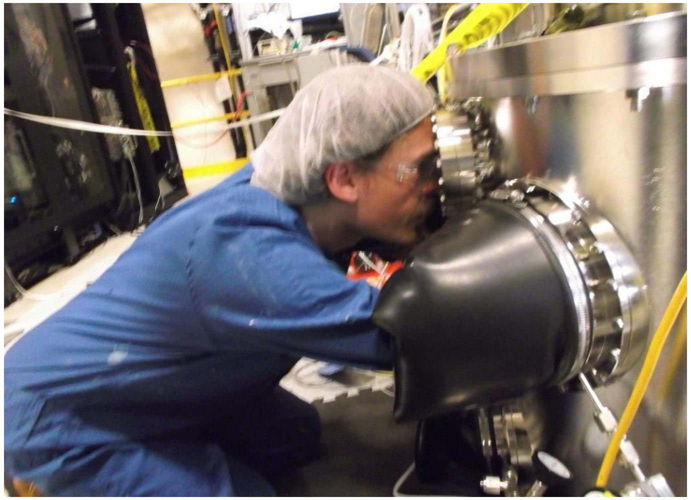
Evaporation source and deployment system





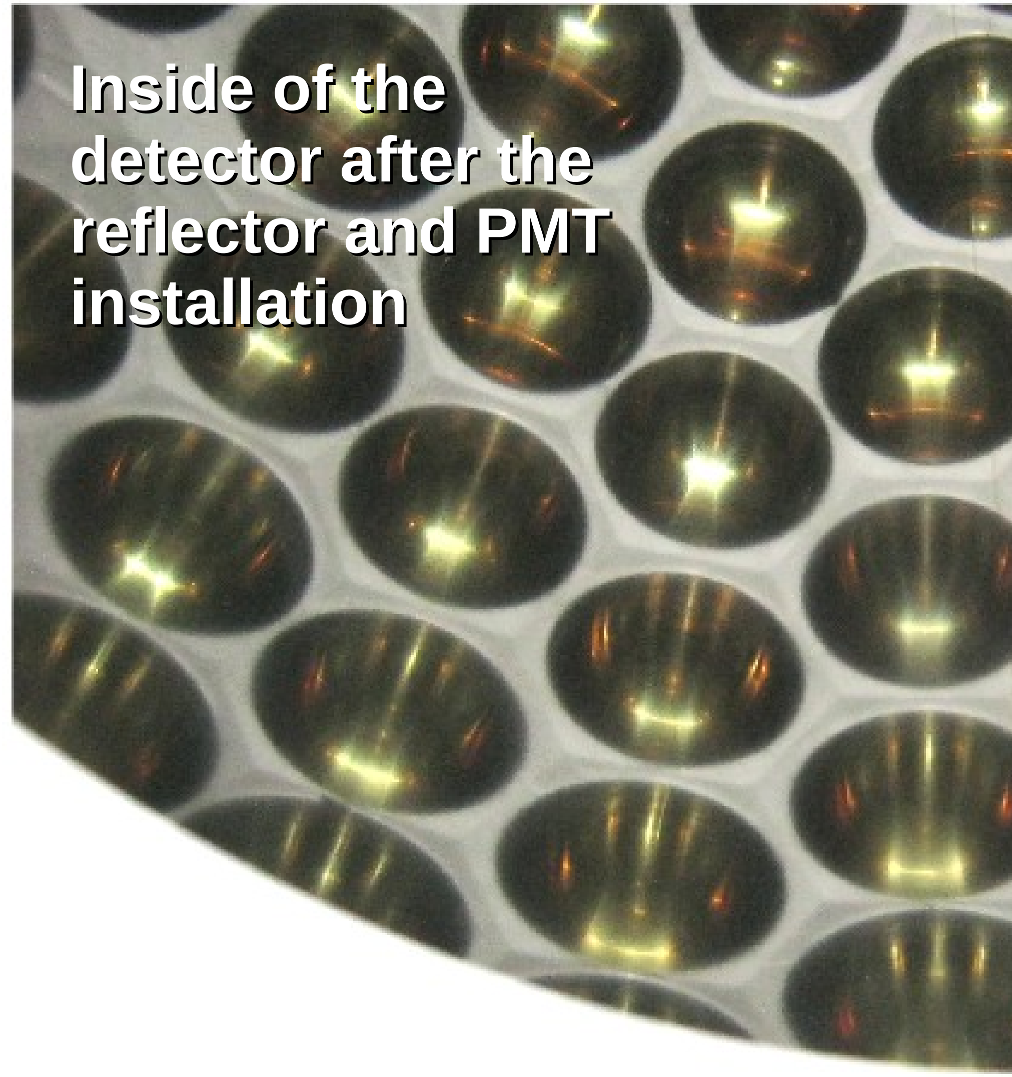


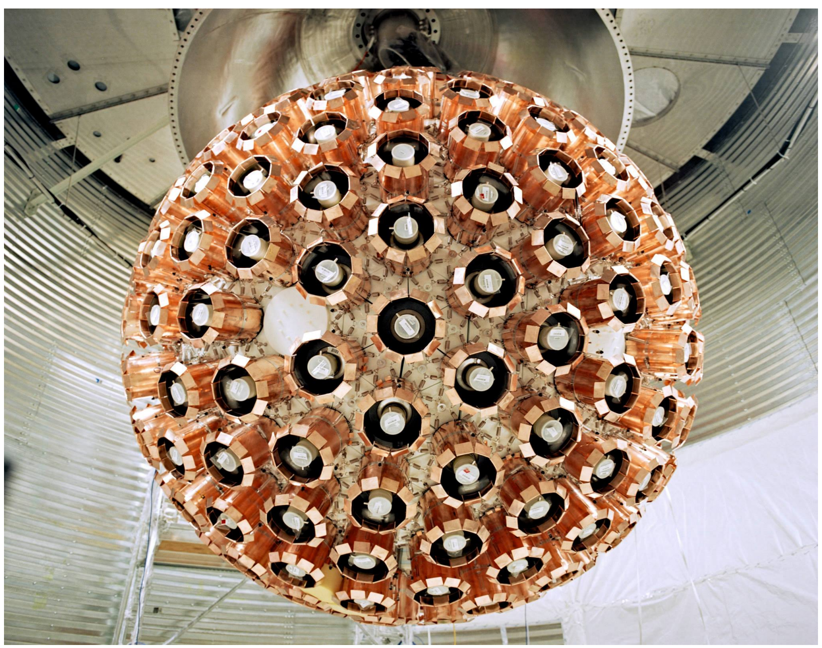
UV illuminated coating on a small test acrylic vessel (20” diameter).



B. Broerman, M. Kuzniak et al., *Application of the TPB Wavelength Shifter to the DEAP-3600 Spherical Acrylic Vessel Inner Surface*, JINST 12 P04017 (2017)

Reflector & PMT installation



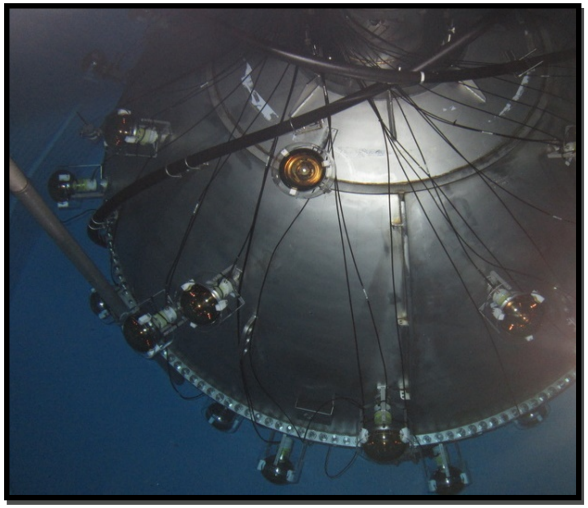


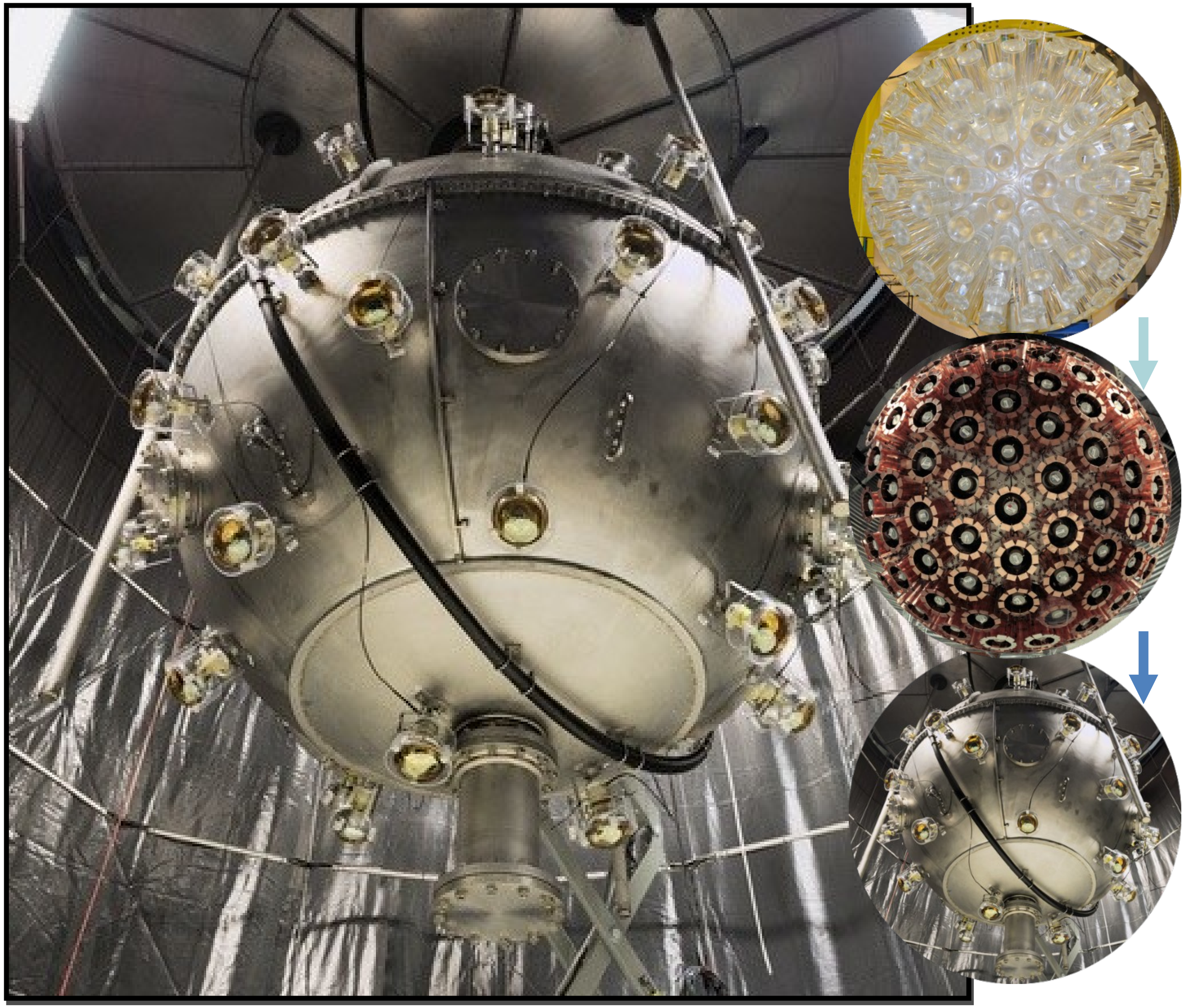
Installation of the instrumented acrylic vessel in the steel shell

Completed detector and shield tank

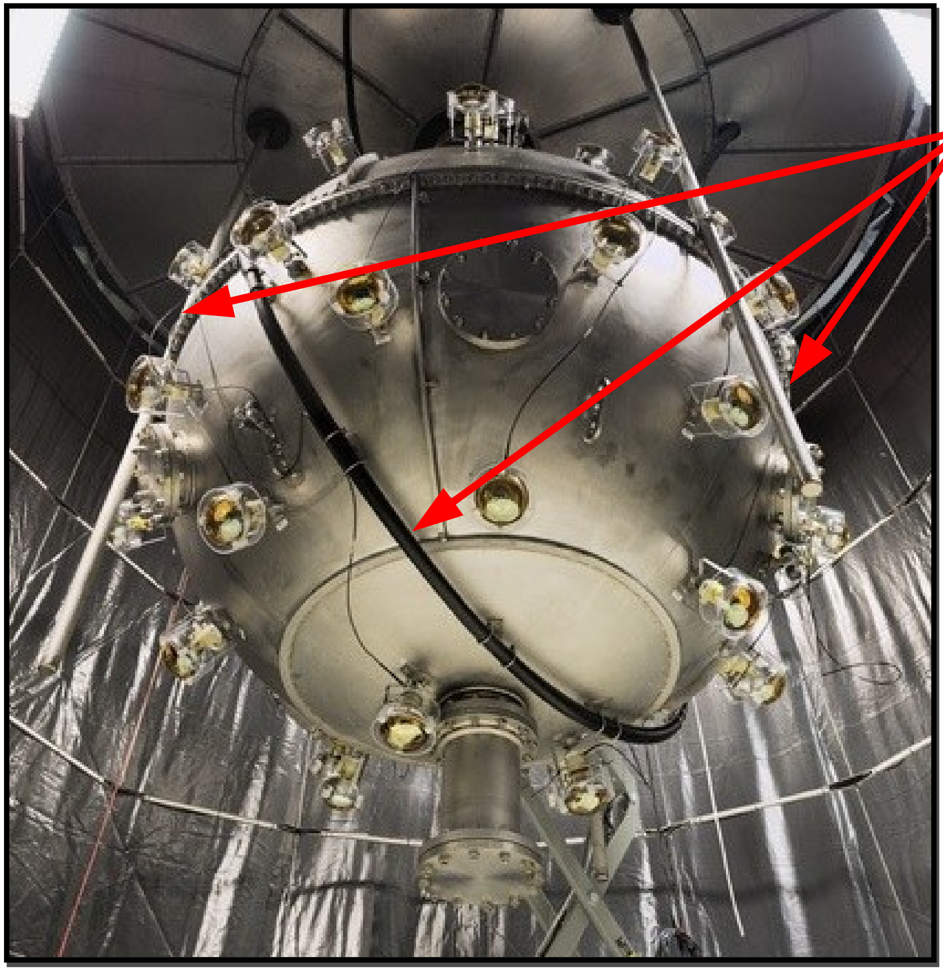
Detailed instrumentation paper submitted to Astroparticle Physics:

https://arxiv.org/abs/1712.01982





Calibration sources



External tubes for calibration with radioactive sources:

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

Energy calibration,
Position reconstruction

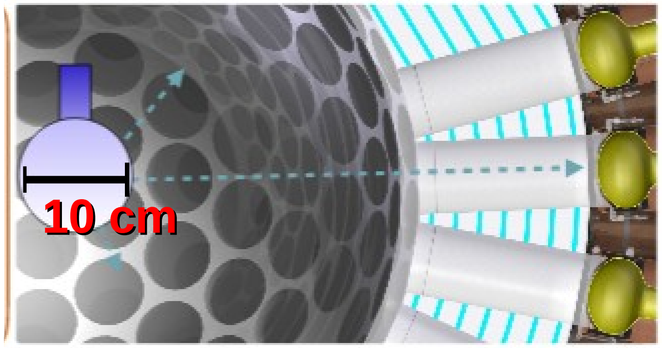
20 optical fibres attached to PMTs

- 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.

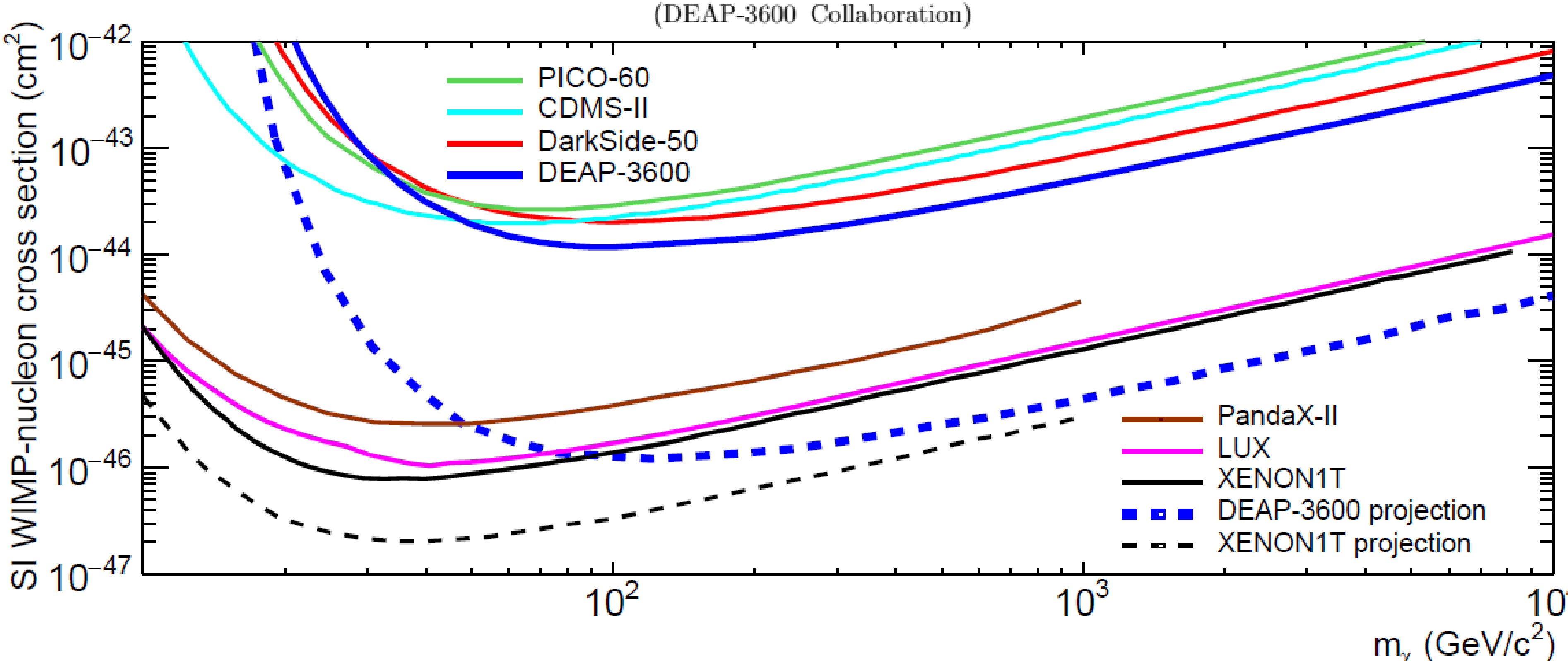
Channel-to-channel relative

- efficiency variation
- timing offsets
- Position reconstruction (optical model)



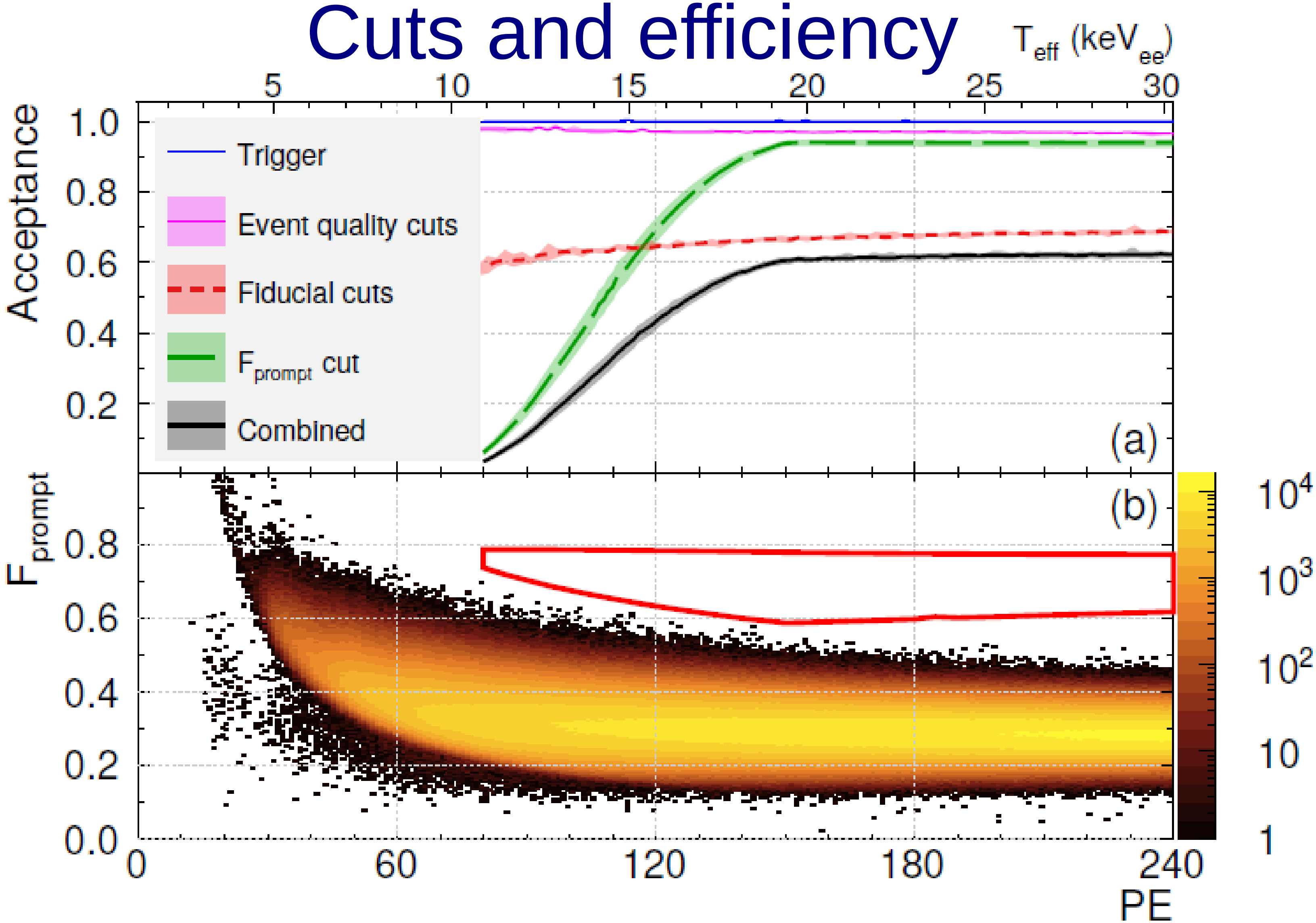
First results from the DEAP-3600 dark matter search with argon at SNOLAB

P.-A. Amaudruz,[1] M. Baldwin,[2] M. Batygov,[3] B. Beltran,[4] C.E. Bina,[4] D. Bishop,[1] J. Bonatt,[5] G. Boorman,[6] M. G. Boulay,[7,5] B. Broerman,[5] T. Bromwich,[8] J.F. Bueno,[4] P.M. Burghardt,[9] A. Butcher,[6] B. Cai,[5] S. Chan,[1] M. Chen,[5] R. Chouinard,[4] B.T. Cleveland,[10,3] D. Cranshaw,[5] K. Dering,[5] J. DiGioseffo,[5] S. Dittmeier,[1] F.A. Duncan,[10,3,†] M. Dunford,[7] A. Erlandson,[7,11] N. Fatemighomi,[6] S. Florian,[5] A. Flower,[7,5] R.J. Ford,[10,3] R. Gagnon,[5] P. Giampa,[5] V.V. Golovko,[11,5] P. Gorel,[4,10,3] R. Gornea,[7] E. Grace,[6] K. Graham,[7] E. Gulyev,[1] R. Hakobyan,[4] A. Hall,[6] A.L. Hallin,[4] M. Hamstra,[7,5] P.J. Harvey,[5] C. Hearns,[5] C.J. Jillings,[10,3] O. Kamaev,[11] A. Kemp,[6] M. Kuźniak,[7,5,*] S. Langrock,[3] F. La Zia,[6] B. Lehnert,[7] J.J. Lidgard,[5] C. Lim,[1] T. Lindner,[1] Y. Linn,[1] S. Liu,[4] P. Majewski,[2] R. Mathew,[5] A.B. McDonald,[5] T. McElroy,[4] T. McGinn,[7,5,†] J.B. McLaughlin,[5] S. Mead,[1] R. Mehdiyev,[7] C. Mielnichuk,[4] J. Monroe,[6] A. Muir,[1] P. Nadeau,[10,5] C. Nantais,[5] C. Ng,[4] A.J. Noble,[5] E. O'Dwyer,[5] C. Ohlmann,[1] K. Olchanski,[1] K.S. Olsen,[4] C. Ouellet,[7] P. Pasuthip,[5] S.J.M. Peeters,[8] T.R. Pollmann,[9,3,5] E.T. Rand,[11] W. Rau,[5] C. Rethmeier,[7] F. Retière,[1] N. Seeburn,[6] B. Shaw,[1] K. Singhrao,[1,4] P. Skensved,[5] B. Smith,[1] N.J.T. Smith,[10,3] T. Sonley,[10,5] J. Soukup,[4] R. Stainforth,[7] C. Stone,[5] V. Strickland,[1,7] B. Sur,[11] J. Tang,[4] J. Taylor,[6] L. Veloce,[5] E. Vázquez-Jáuregui,[12,10,3] J. Walding,[6] M. Ward,[5] S. Westerdale,[7] E. Woolsey,[4] and J. Zielinski[1]
(DEAP-3600 Collaboration)



https://arxiv.org/abs/1707.08042 - **Accepted** for publication in Physical Review Letters

Cuts and efficiency

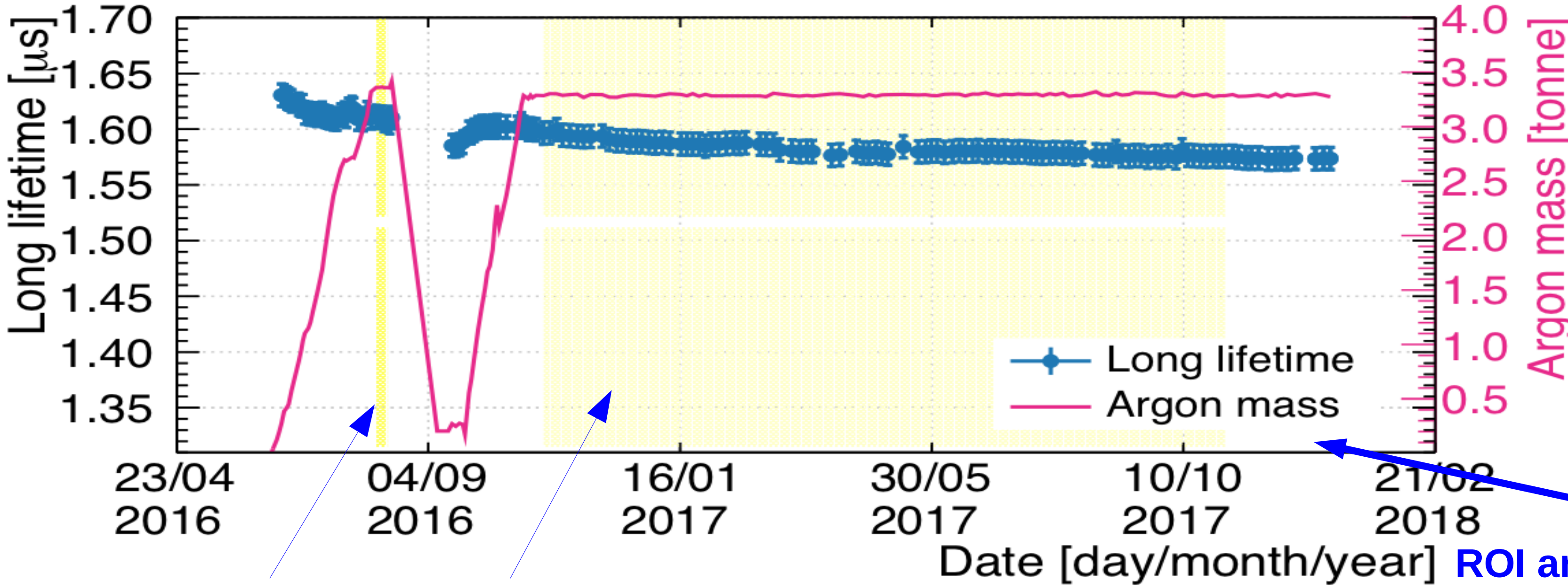


- 4.44 live days
- Selected ROI for < 0.2 leakage from β's
- Cuts for instrumental and external-source events
- 2,223 kg fiducial mass
- 9,870 kg-day exposure
- No events observed in ROI

- Light yield consistent with expectations:

LY= $7.80 \pm 0.21(\text{fit syst.}) \pm 0.22(\text{SPE syst.})\ \text{PE/keV}_{ee}$

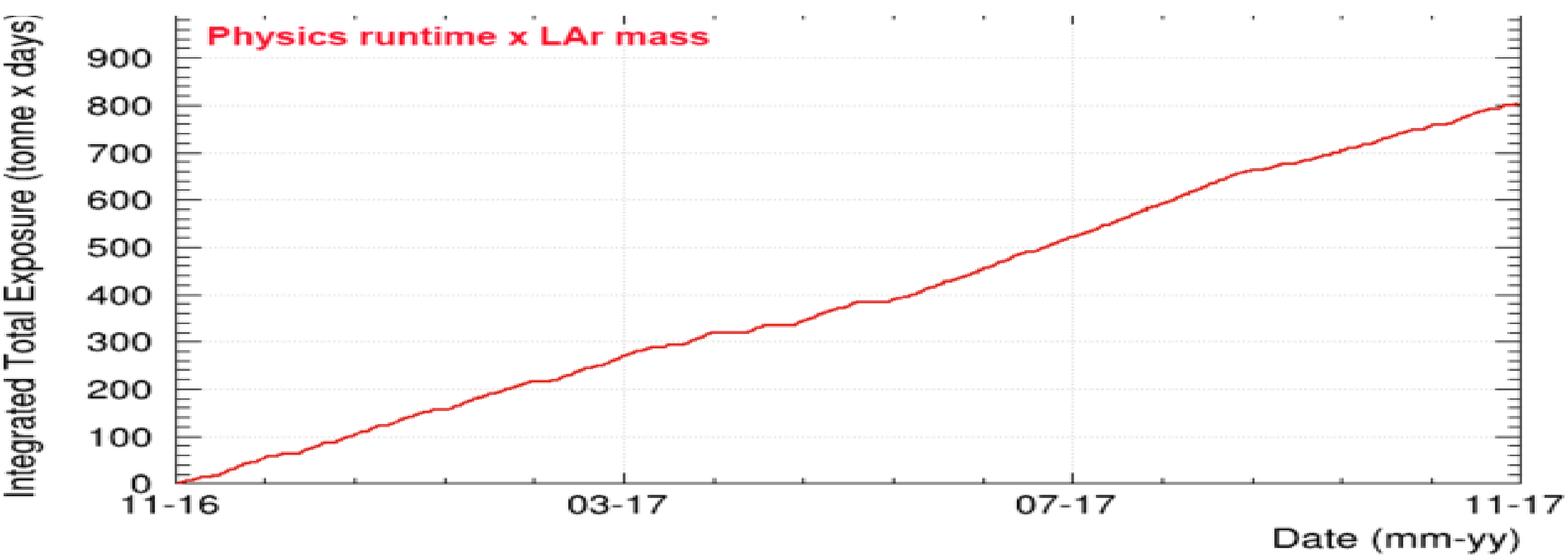
Analysis of 1 yr dataset



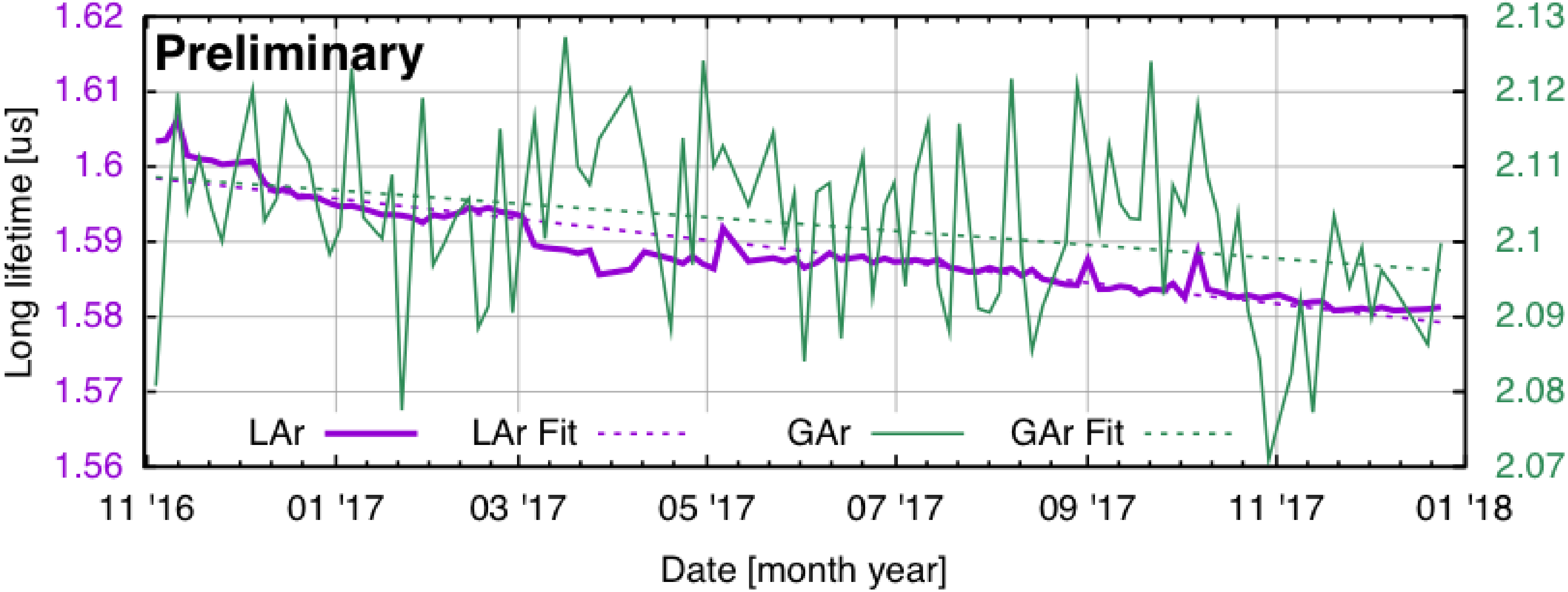
Published PRL 4.4d dataset

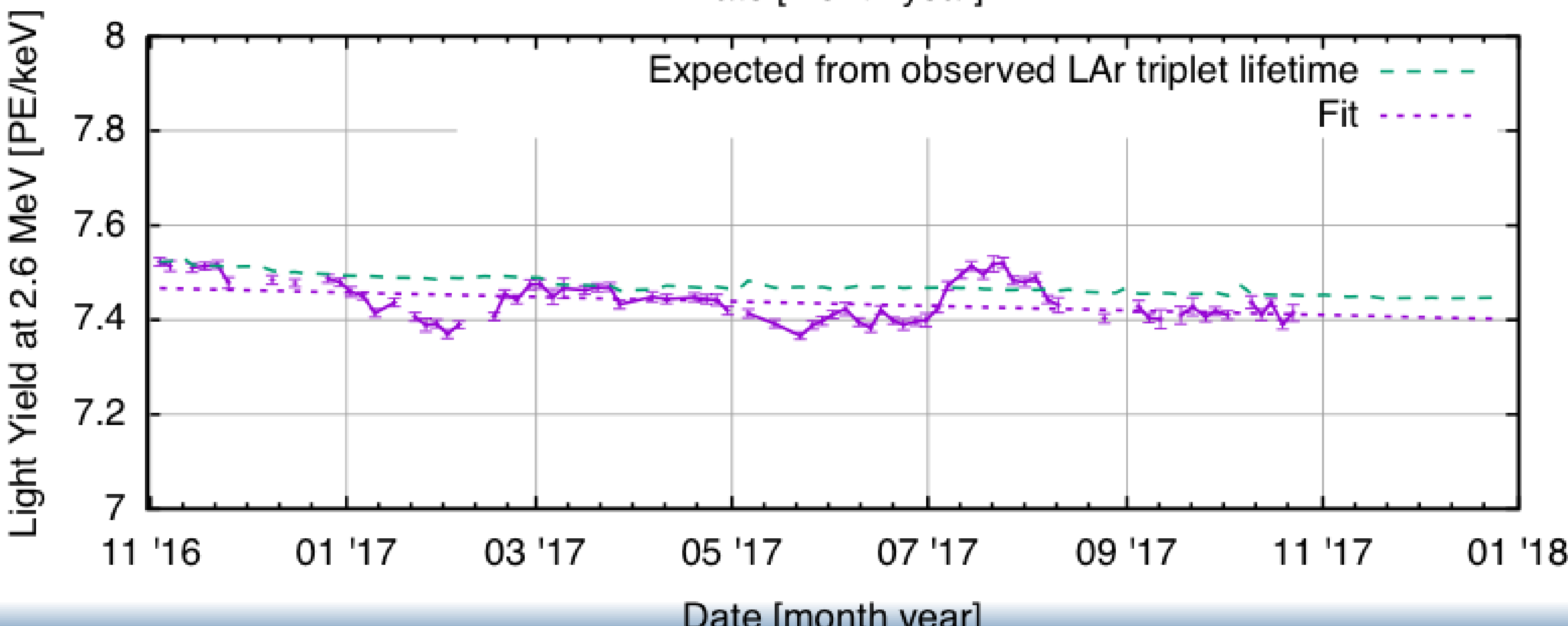
Open (non-blind) dataset for 2nd analysis: Nov 1 2016 – Dec 31, 2017

ROI and vicinity blinded since Jan 1, 2018



Detector stability





Pulse shape discrimination (PSD)

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

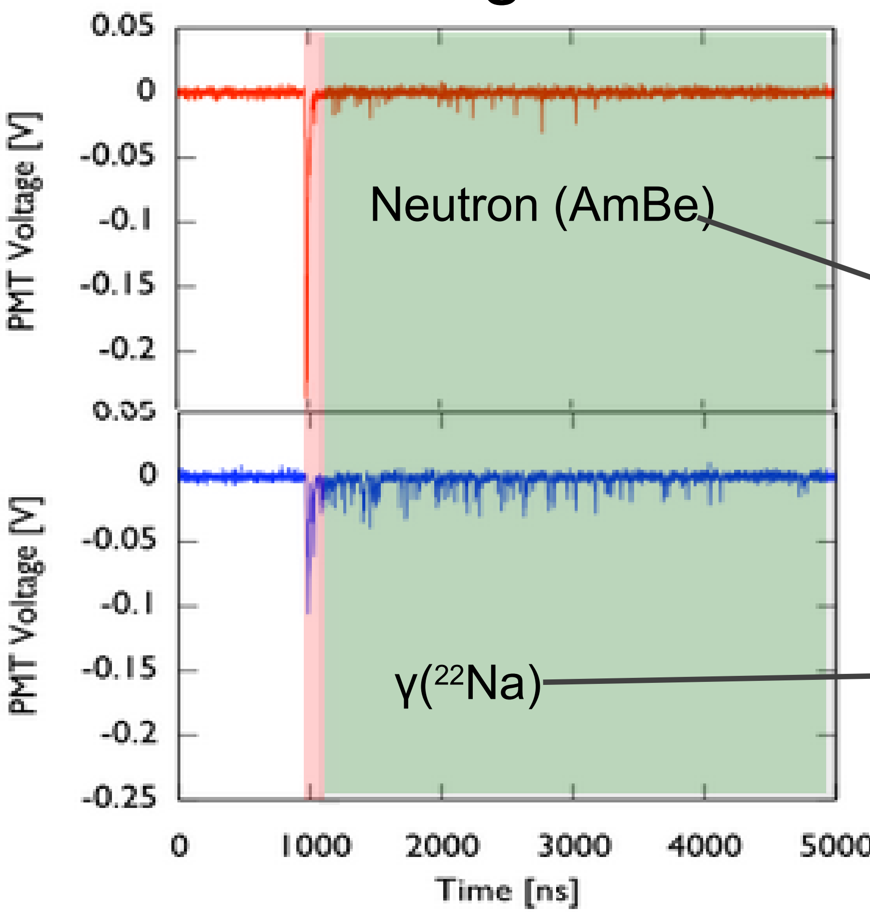
<u>**Single phase LAr:**</u>
scintillation channel is sufficient for β/γ rejection
no need for the ionization channel

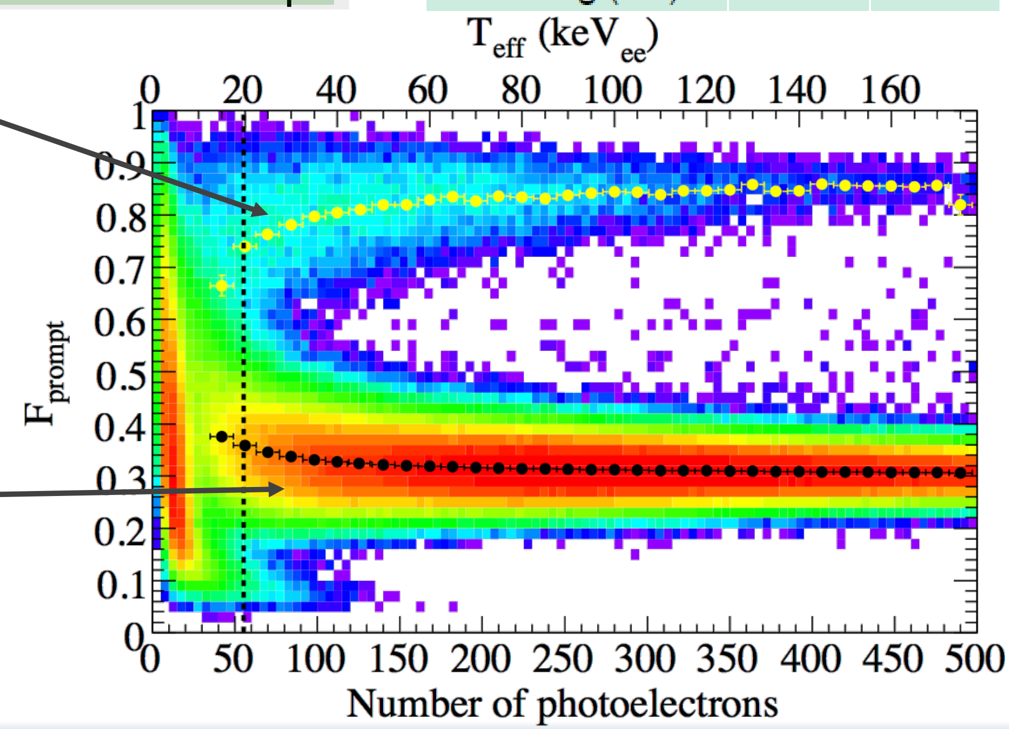
Parameter	Ar	Xe
Yield ($\times 10^4$ photons/MeV)	4	4.2
Prompt time constant τ_1	6 ns	2 ns
Late time constant τ_3	**1.5 μs**	21 ns
I_1/I_3 for electrons	0.3	0.3
I_1/I_3 for nuclear recoils	3	1.6
λ(peak) nm	128	174
Rayleigh scattering (cm)	90	30

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

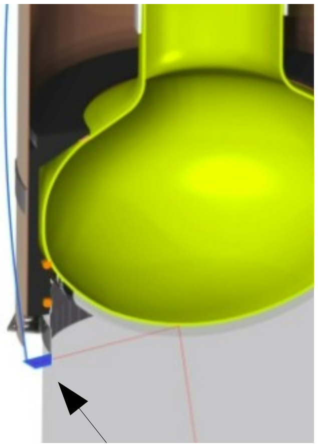
Prompt : 0-150ns
Late: 150ns-10μs

PMT signal:



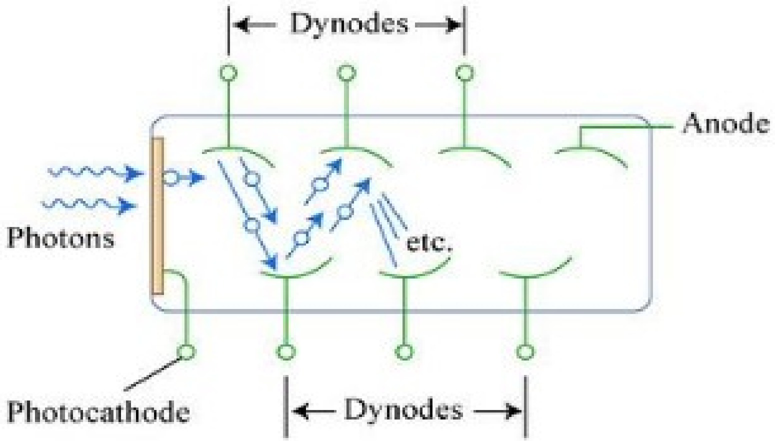


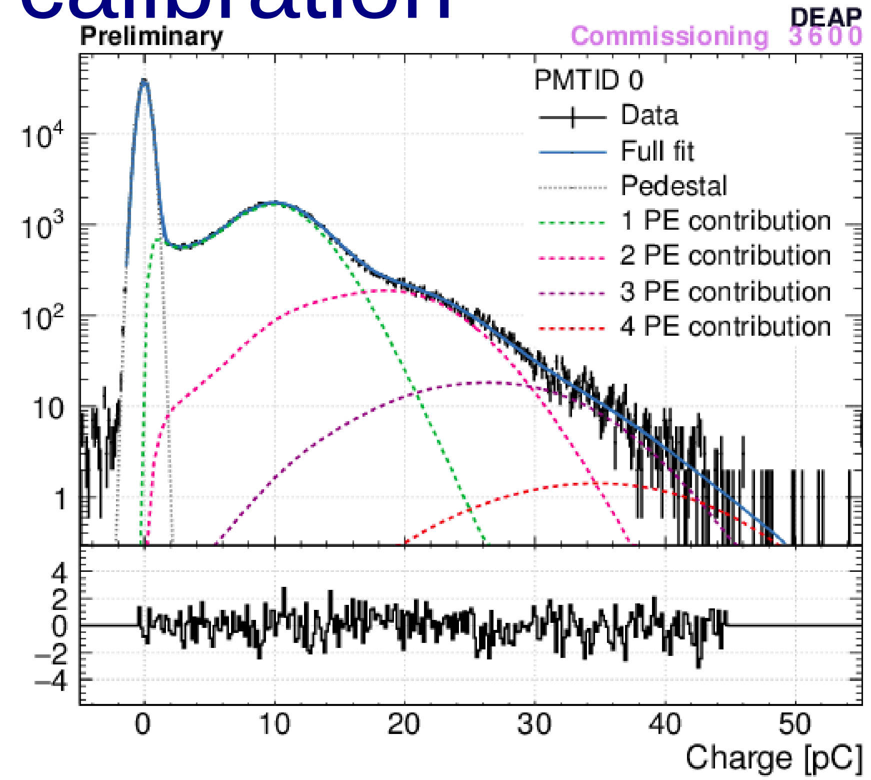
DEAP-3600 PMT calibration



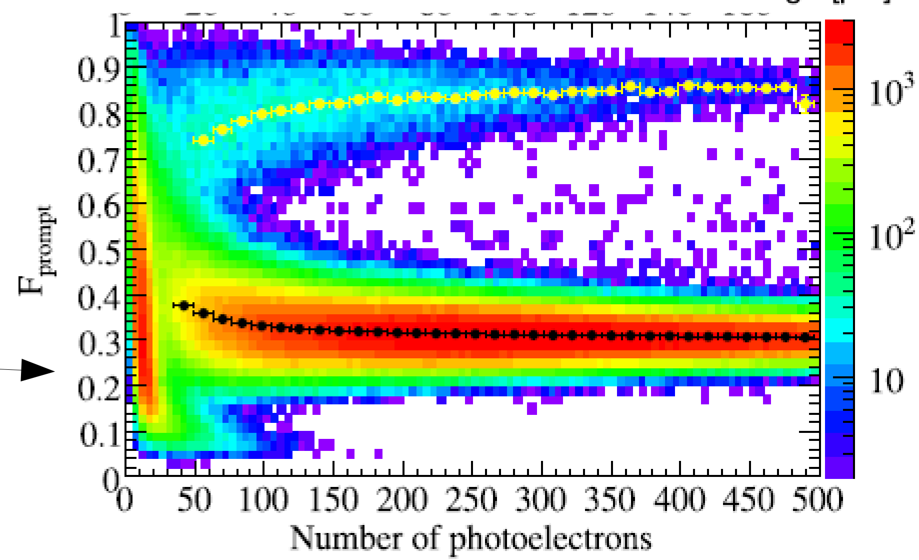
LED driven light injection calibration system

charge multiplication in PMT



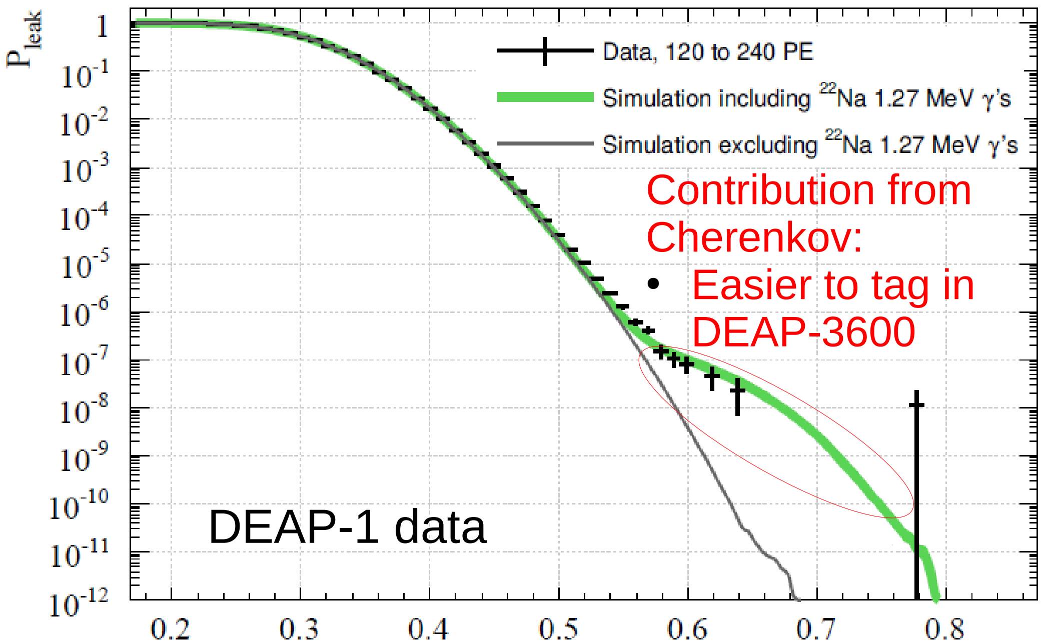


- Provides:
  - mean single PE charge for simple charge division calibration
  - functional form of the SPE distribution used by more advanced SPE counting algorithms
  - input for DAQ simulation
  - “PMT noise” contribution to PSD

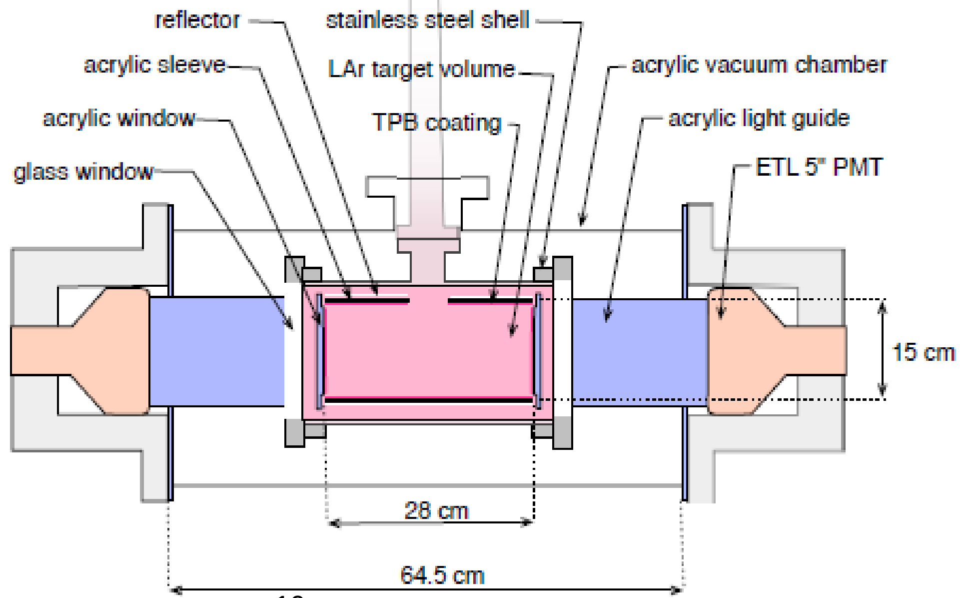


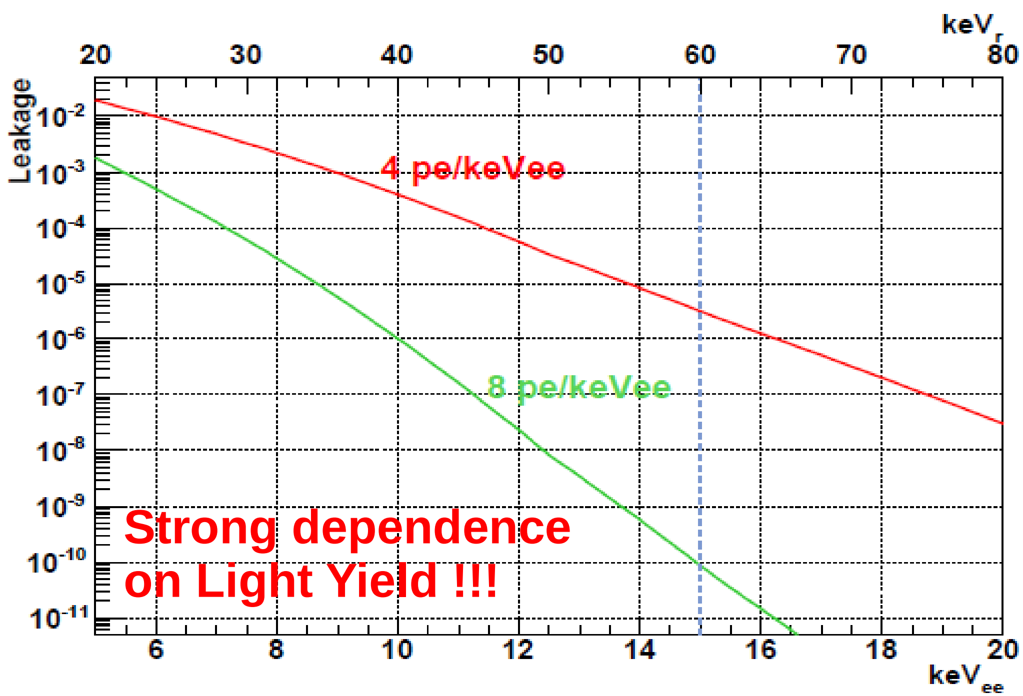
Submitted to NIM: https://arxiv.org/abs/1705.10183

DEAP-1 and the PSD model



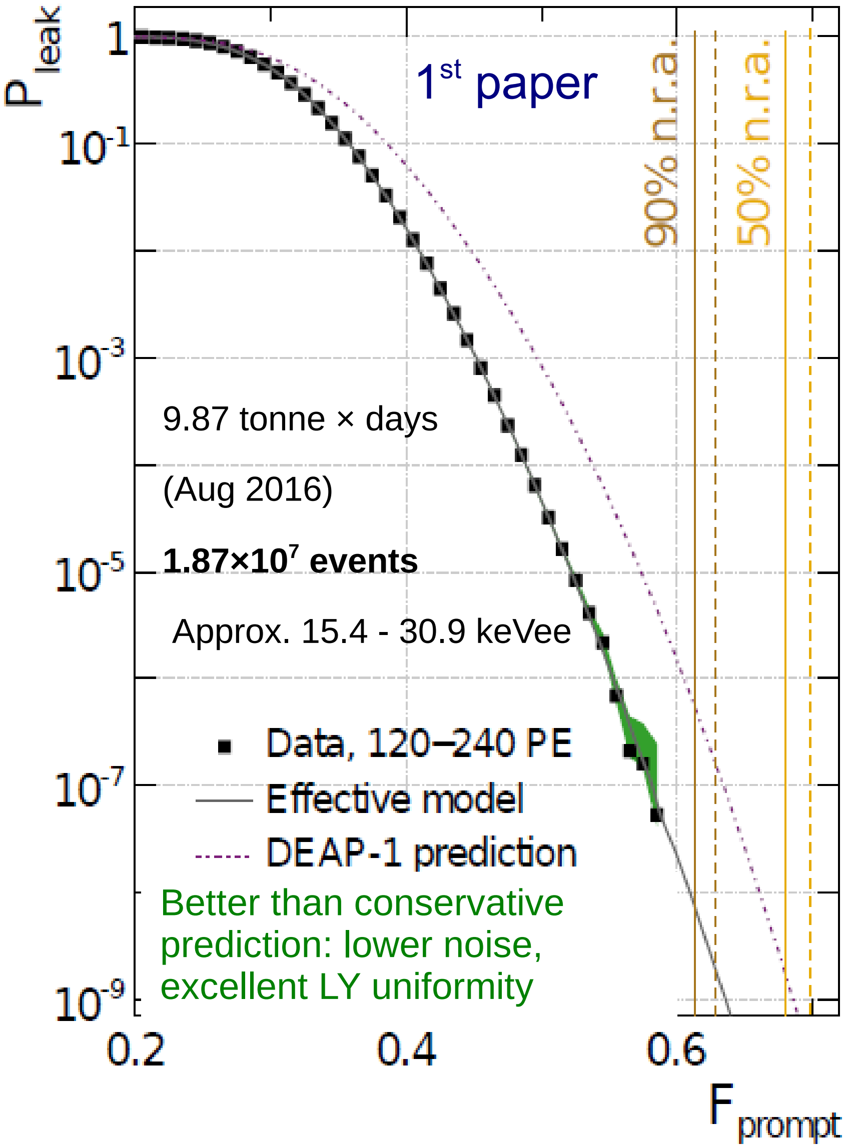
Astropart. Phys. 85 (2016) 1

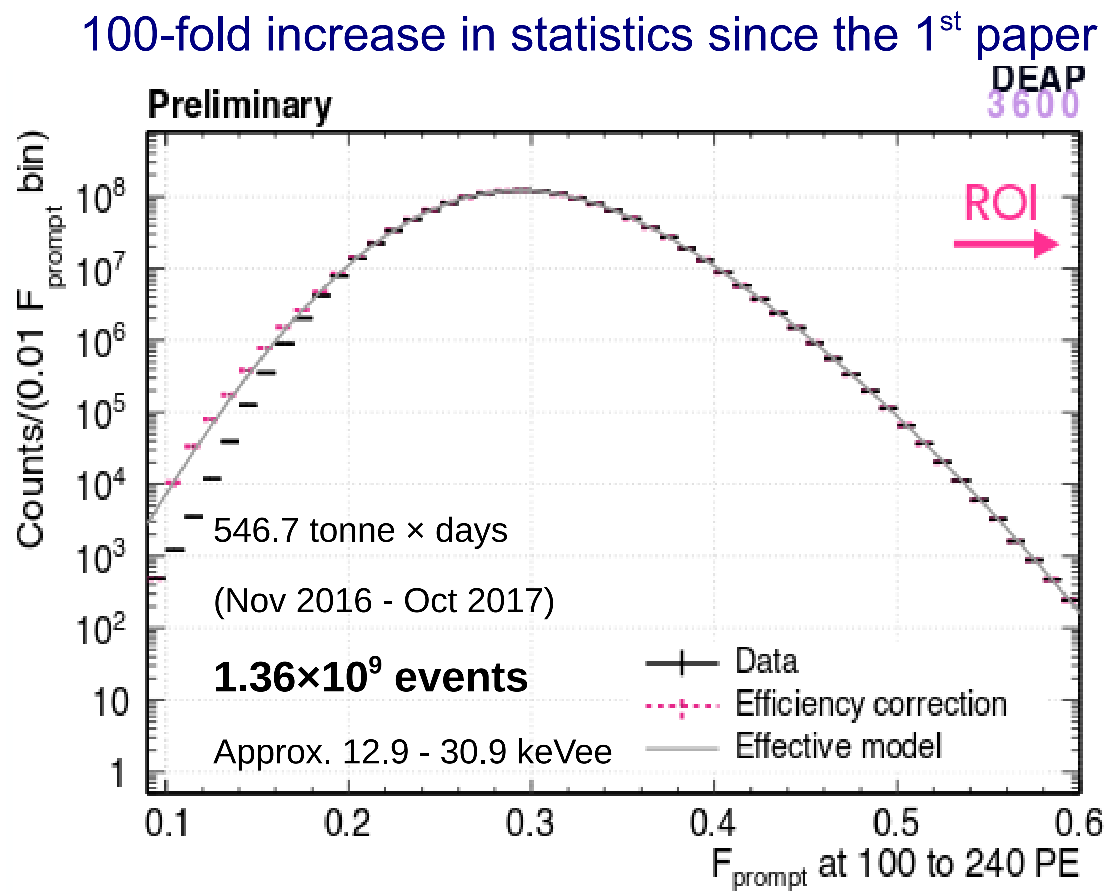




- PSD of ~10^{-10} required in DEAP-3600 to beat down backgrounds from ^{39}Ar (beta emitter) present at 1 Bq/kg rate.
- Measured with a tagged Na-22 gamma source using DEAP-1 at SNOLAB.
- Collected 1.23e+8 events.
  Leakage <2.7e-8 (90% C.L.)
- Data well described with analytic model and toy simulation. Dependence of PSD on **absolute LY**, **LY uniformity** and **noise.**
- Projection for DEAP-3600 indicates PSD of 10^{-10}

PSD in DEAP-3600





- Good PSD of β events down to 11 keVee!
- Best ever demonstrated at low energy, expect to meet design goal for the full sensitivity run
- Combined with low-radioactivity argon (depleted in ^{39}Ar by a factor of >1500):

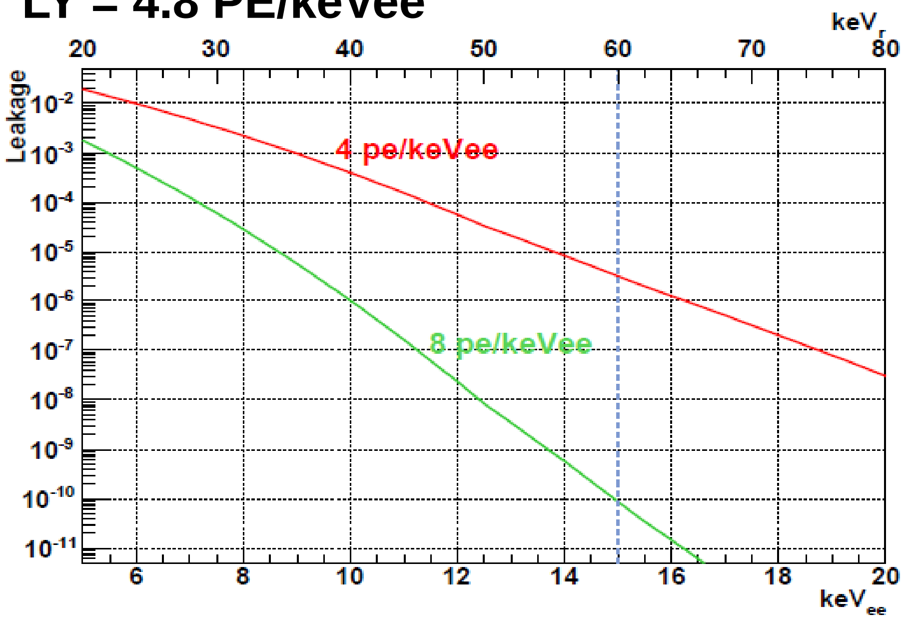
Can use PSD for WIMP search with **several hundred tonnes** of argon

Relative to Xenon

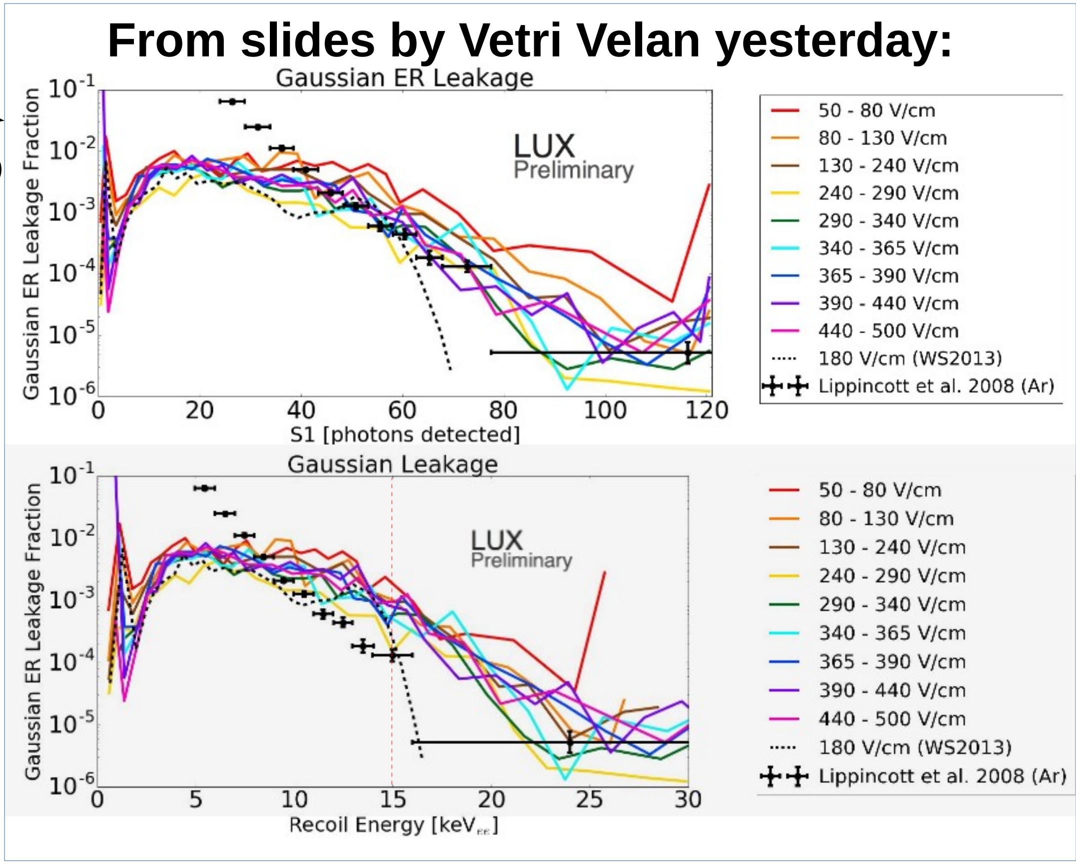
Congratulations for this very nice results for Xe!

However, much progress happened with Ar PSD over the last decade:

- Lippincott et al (2008) measured leakage with **LY = 4.8 PE/keVee**



- Current detectors routinely operate with LY = **7-8 PE/keVee**, which alone brings **>2 orders of magnitude improvement** over the 2008 results at fixed energy
- (10 PE/keVee or better expected with SiPMs in the next generation detectors...)



- Additional improvements brought by using low-noise DAQ and much better detector response uniformity: **1 order of magnitude**
- Window optimization, single photoelectron counting, afterpulsing removal: **1 order of magnitude**

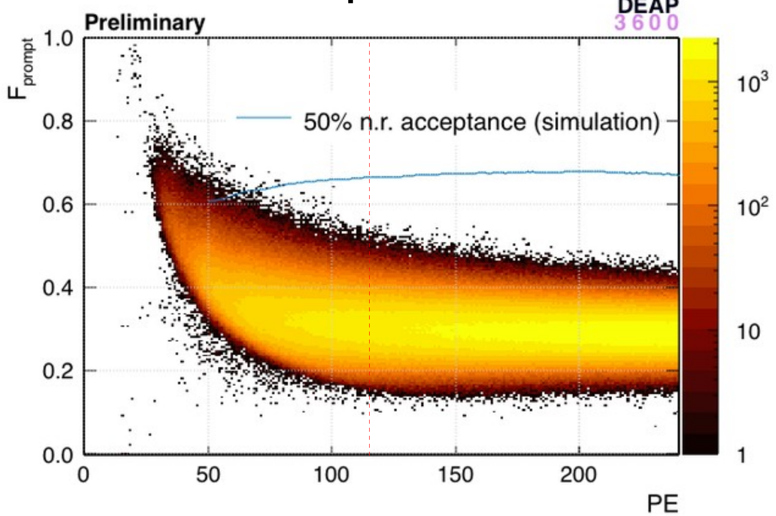
- **Apples-to-apples comparison gives >10^4 lower leakage in LAr**

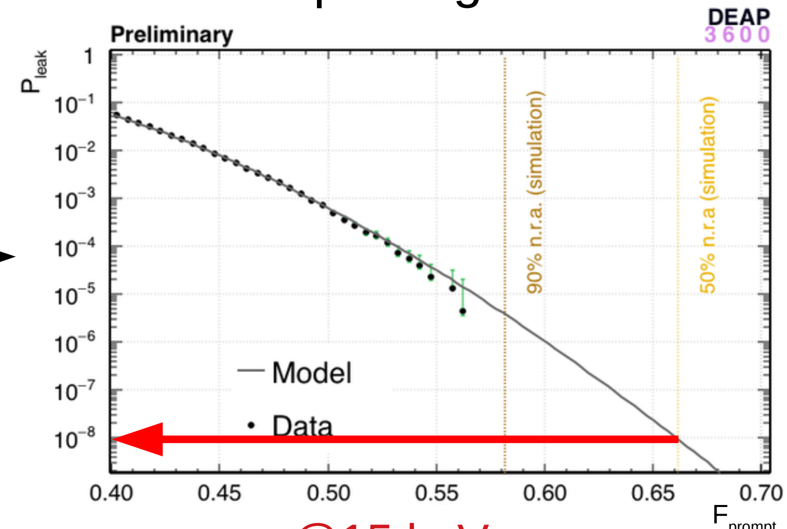
Further improvements to PSD

- Optimized prompt window size

Astropart. Phys. 65, 40 (2015)

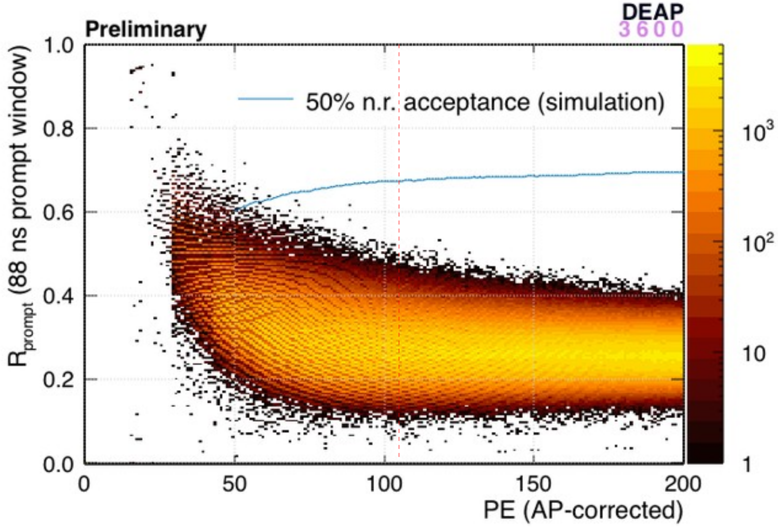
- Introducing Bayesian Single Photoelectron Counting technique
  - Suppresses the PMT charge resolution effect on PSD
  - Technique extended to correct for PMT afterpulsing

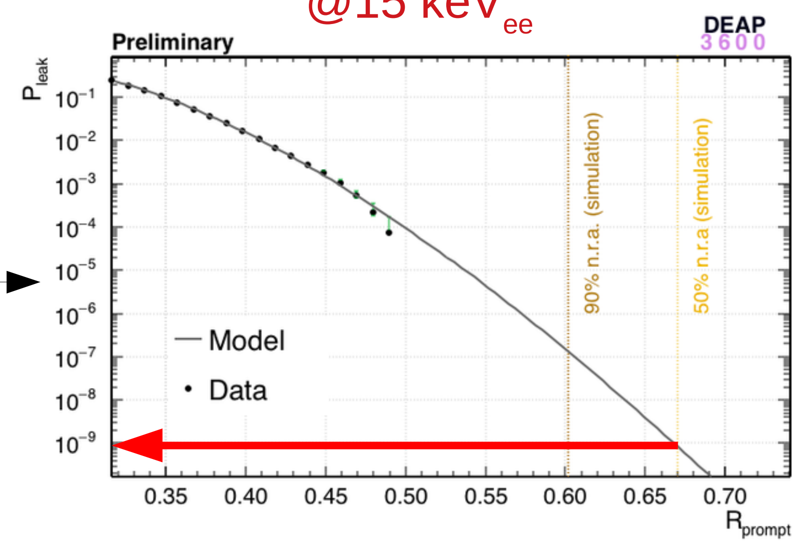




@15 keV$_{ee}$

Will allow for low analysis threshold in 1-yr dataset analysis!



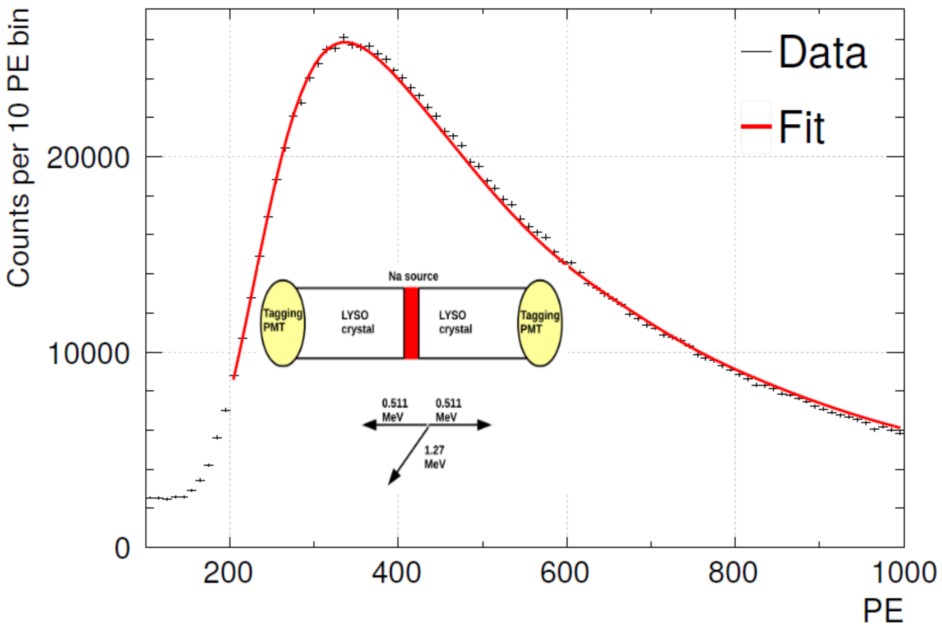


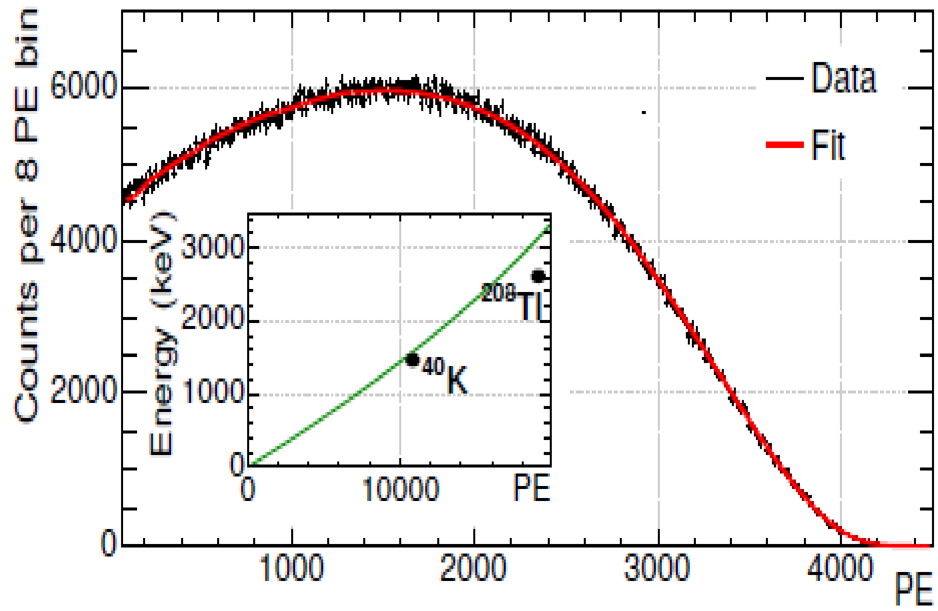
P.M. Burghardt MSc thesis, TUM, 2018

Dedicated PSD paper in preparation.

Calibrated detector response

- 1st paper analysis:
  - ^{22}Na gammas and ^{39}Ar betas (for energy calibration)

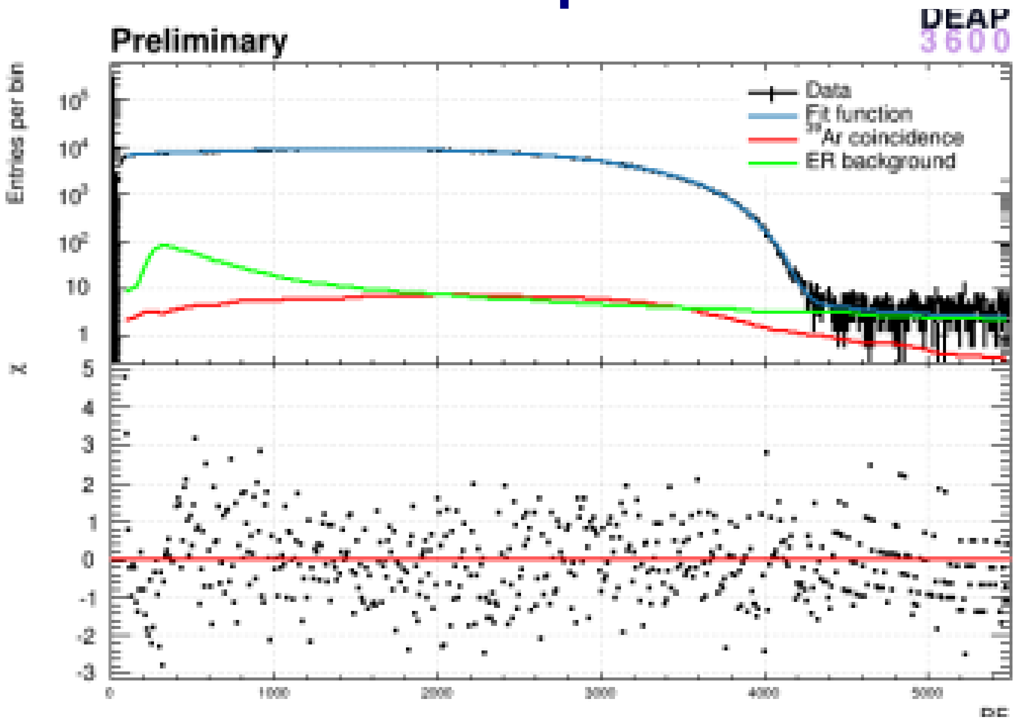




LY= $7.80\pm0.21(\text{fit syst.})\pm0.22(\text{SPE syst.})\ \text{PE/keV}_{ee}$

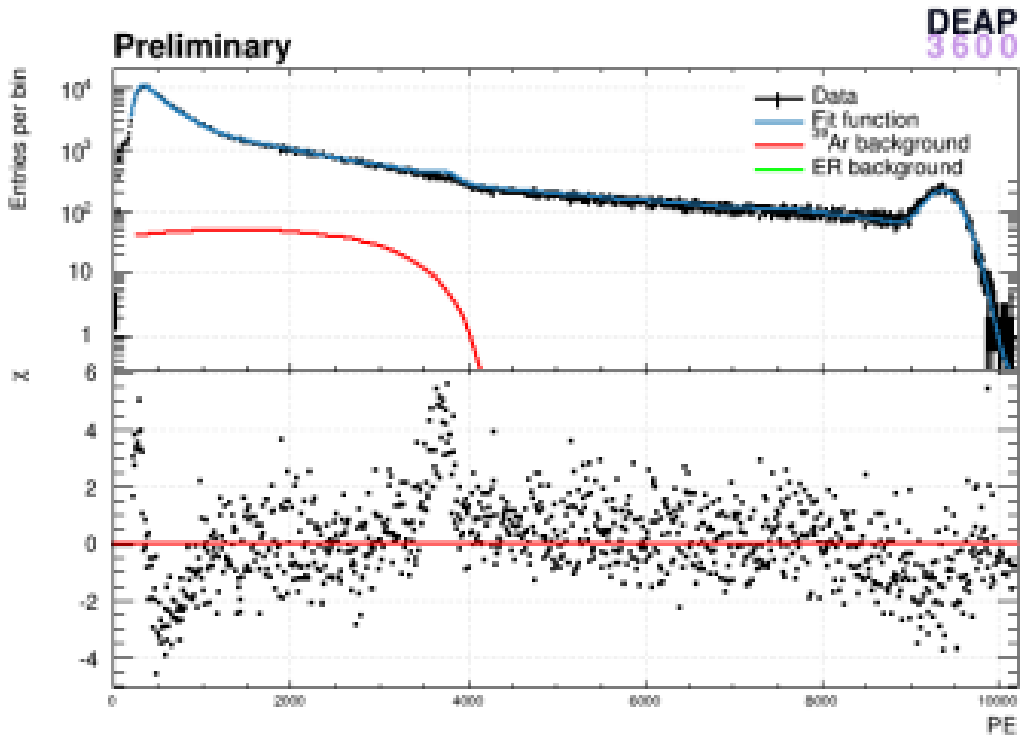
- ^{39}Ar beta events are uniformly distributed in the detector - powerful calibration!
- With the exception of F_{prompt} (pulse shape) ^{39}Ar events are a good proxy for WIMPs
- Signal efficiency of all cuts except F_{prompt} are evaluated on the ^{39}Ar population

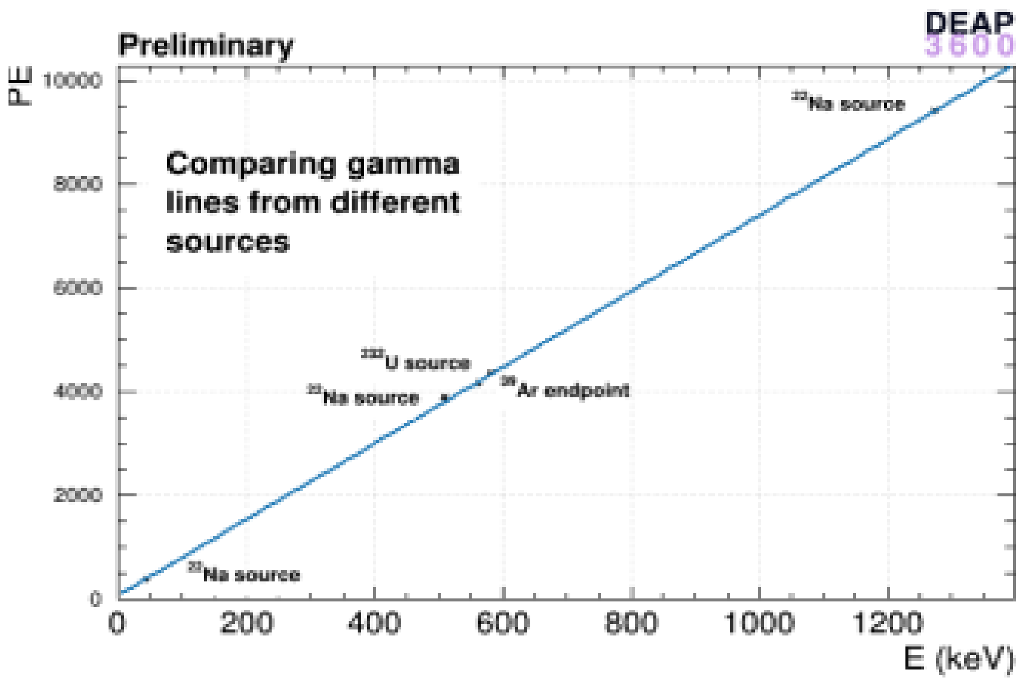
Improved energy calibration



Development of a combined energy response function fit:

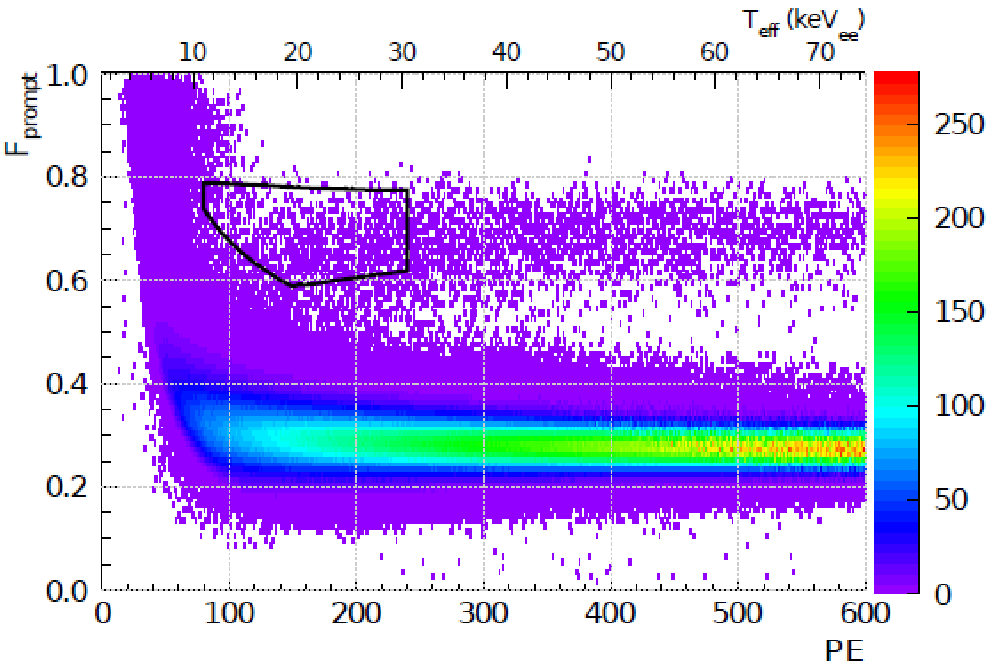
- taking into account available spectral features in calibration and physics datasets
- including the dominant backgrounds
- corrected for DAQ/PMT effects

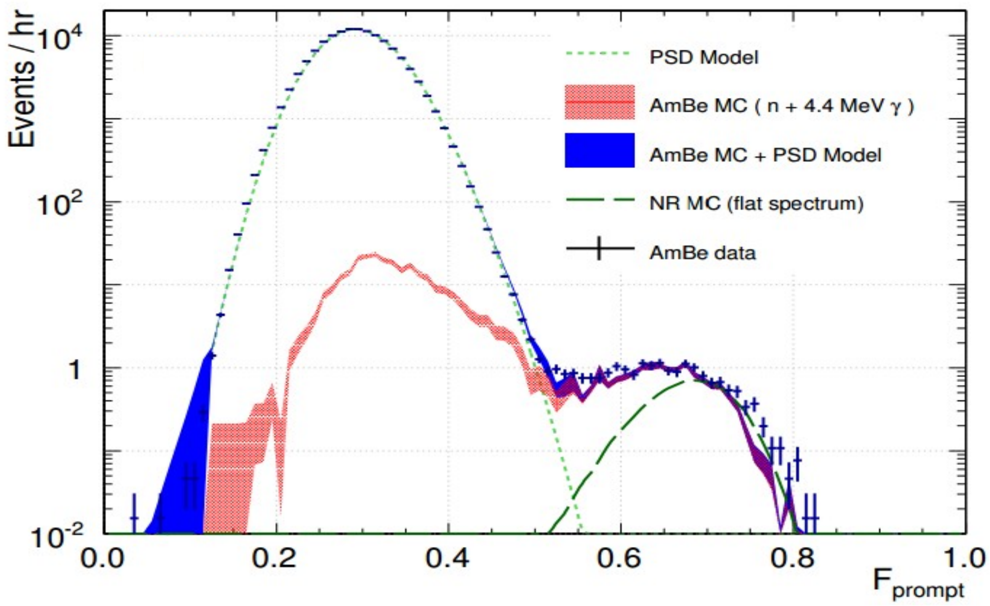




Calibrated detector response

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

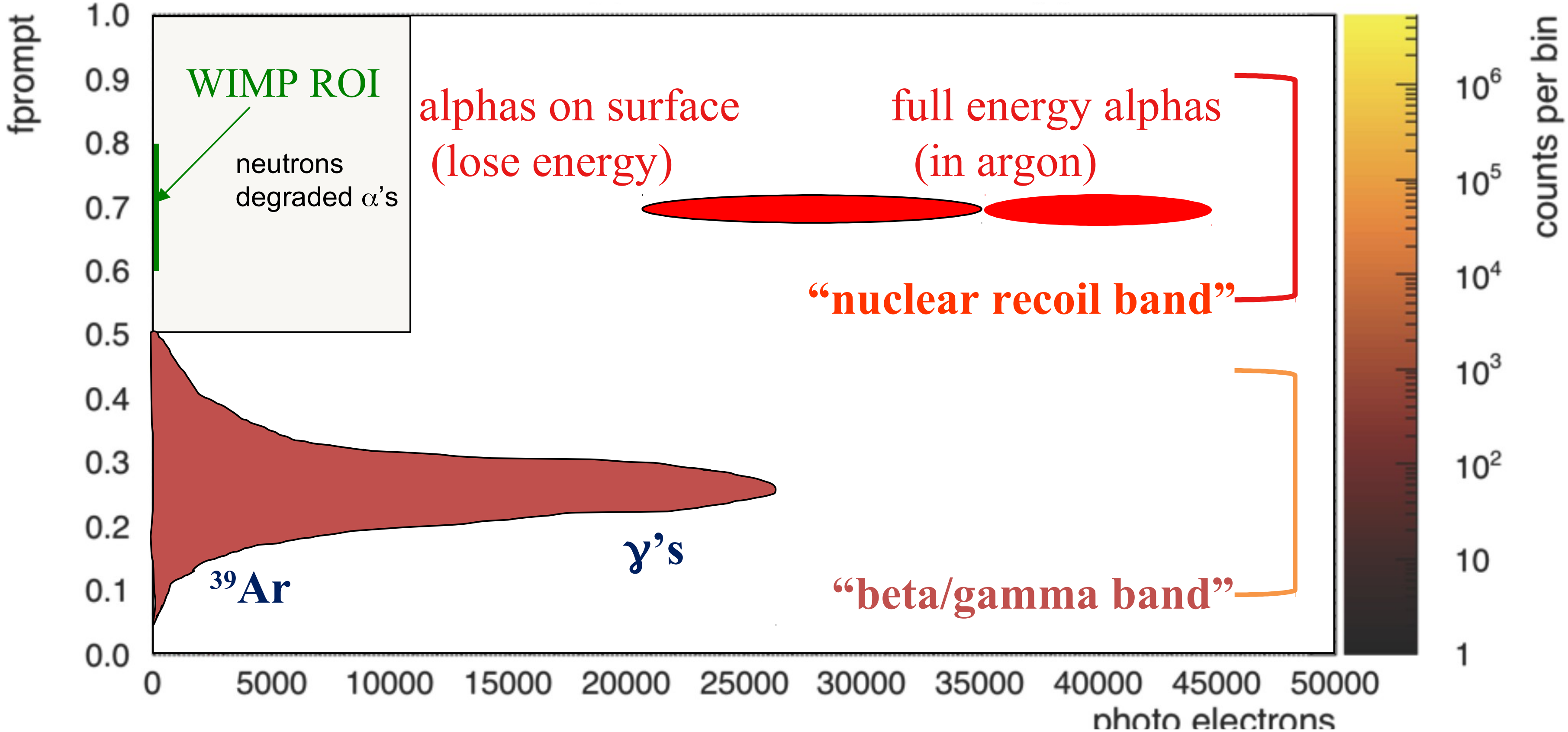




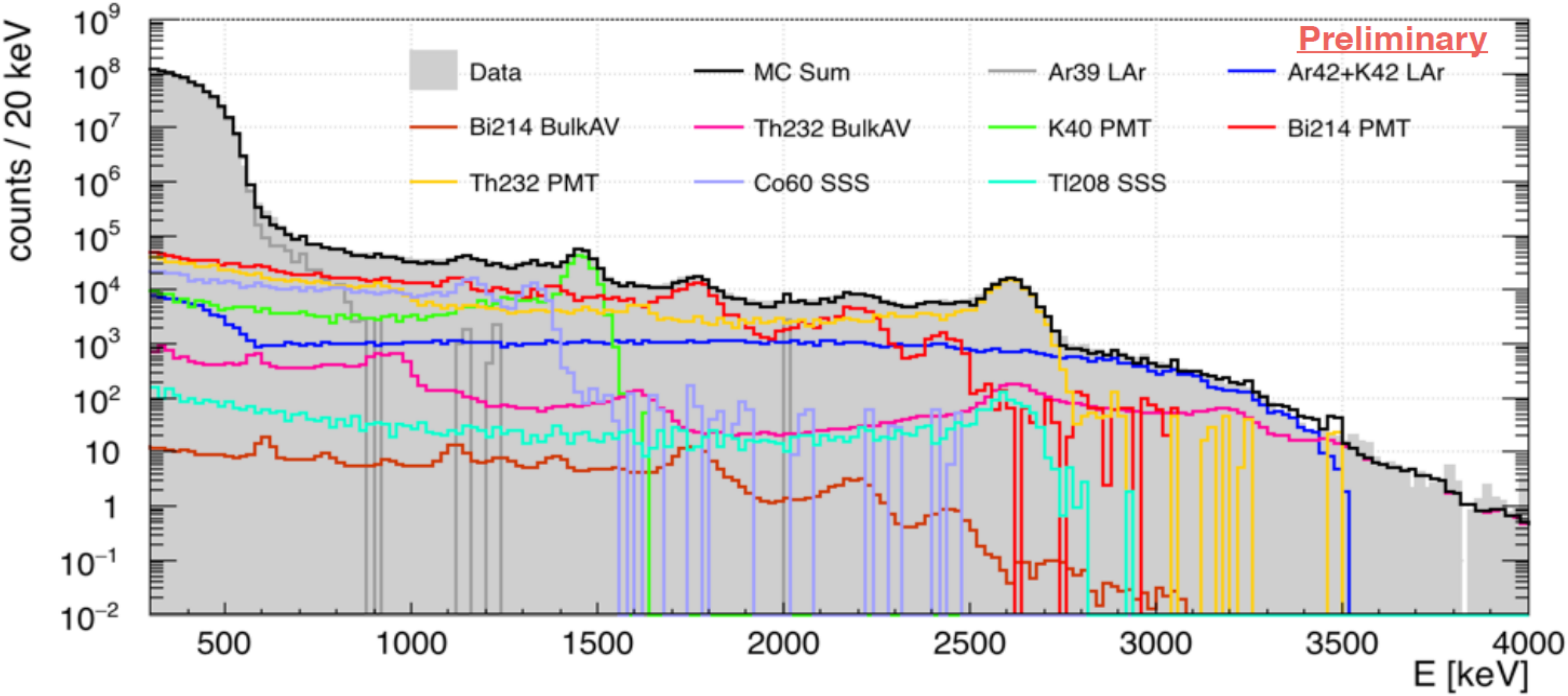
- For F_{prompt} cut efficiency: on top of the literature physics parameters, simulation of the PMT/detector response is added
- MC/data agree within systematic uncertainties

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

Experimental signatures



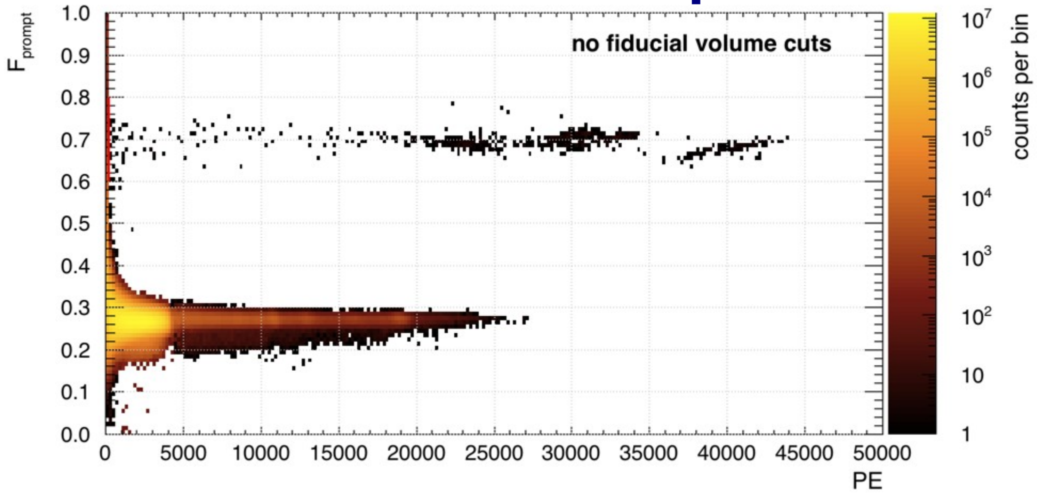
Gamma backgrounds

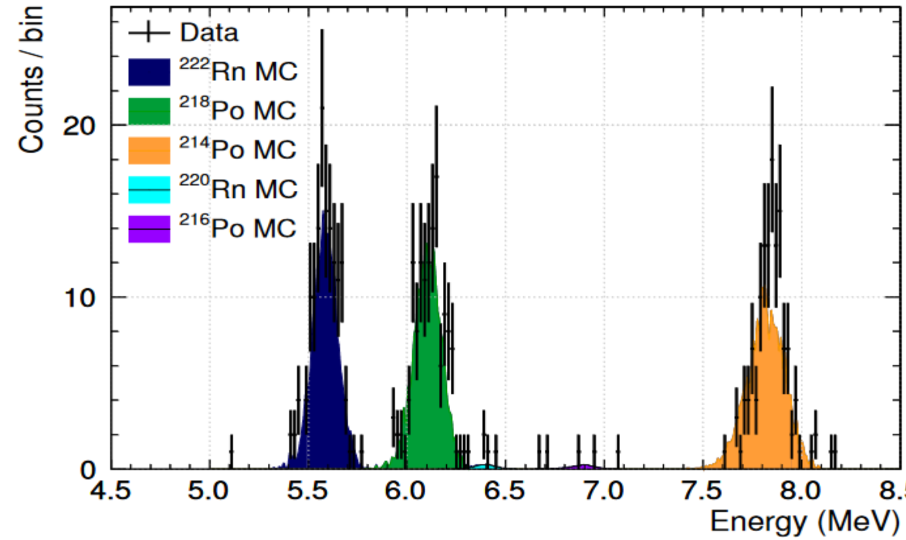


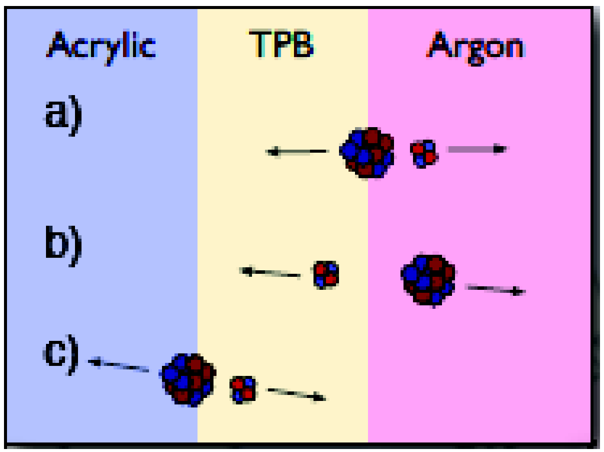
- MC Simulations scaled by radioactivity screening results
- Dominant contributions to the spectrum from ^{39}Ar and ^{42}Ar

Dedicated paper in preparation.

Alpha backgrounds







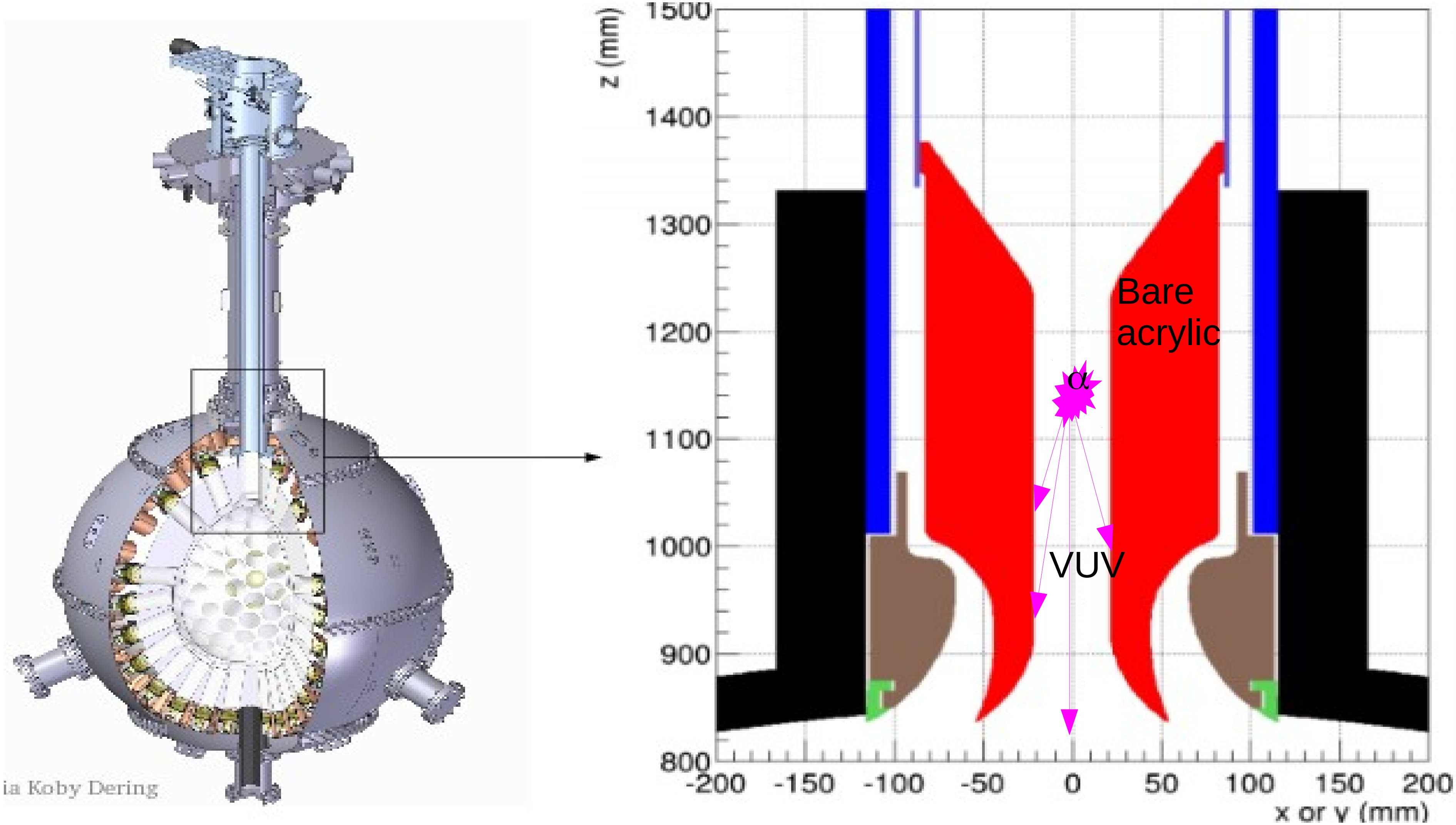
Component	Activity
^{222}Rn LAr	$(1.8\pm0.2)\times10^{-1}$ µBq/kg
^{214}Po LAr	$(2.0\pm0.2)\times10^{-1}$ µBq/kg
^{220}Rn LAr	$(2.6\pm1.5)\times10^{-3}$ µBq/kg
^{210}Po AV surface	0.22 ± 0.04 mBq/m^2
^{210}Po AV bulk	<3.3 mBq

- Stable throughout 1 yr data taking

30 – 300 times lower Rn levels than in Xenon-based experiments (LUX, XENON, PandaX)!

Experiment	Activity/Rate	Target	Reference
DEAP-3600	0.2 µBq/kg	LAr	
DarkSide-50	1.74 µBq/kg	LAr	C. J. Stanford, Ph.D. thesis, Princeton University (2017)
PandaX-II	6.6 µBq/kg	LXe	Phys. Rev. D 93, 122009 (2016)
LUX	66 µHz/kg	LXe	Physics Procedia 61 (2015) 658 – 665
XENON-1T	10 µBq/kg	LXe	XeSat2017 talk [link]

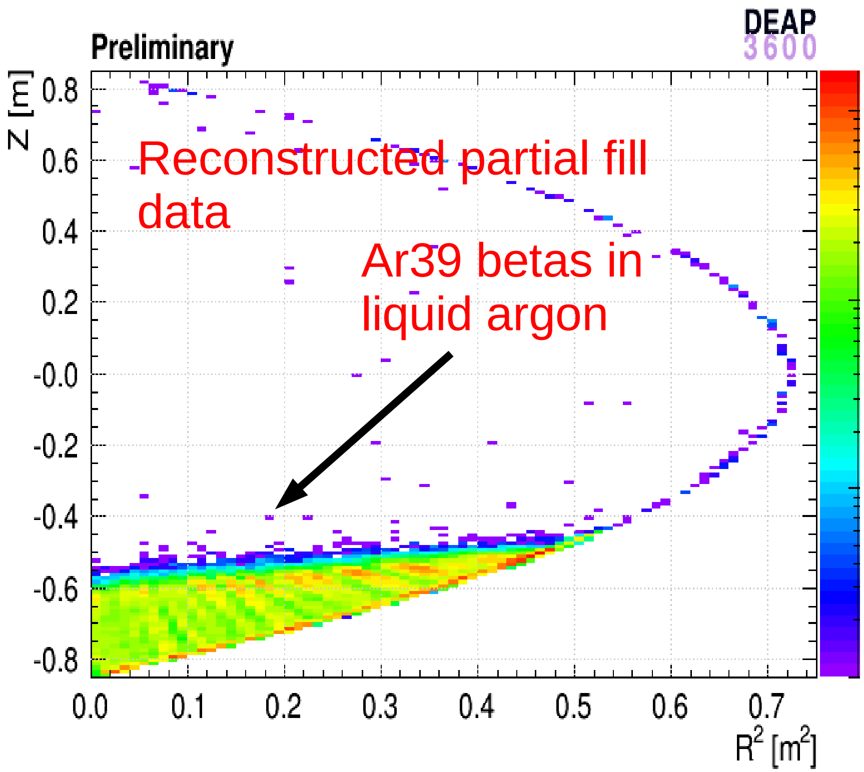
"Geometric" backgrounds



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 – need a reliable optical model
  - Surface event fiducial leakage probabilities of ~1.3e-3 into 1 tonne fiducial volume (specification target) or better are expected with current algorithms (on MC)
- Spherical fiducial cut with an additional Z cut

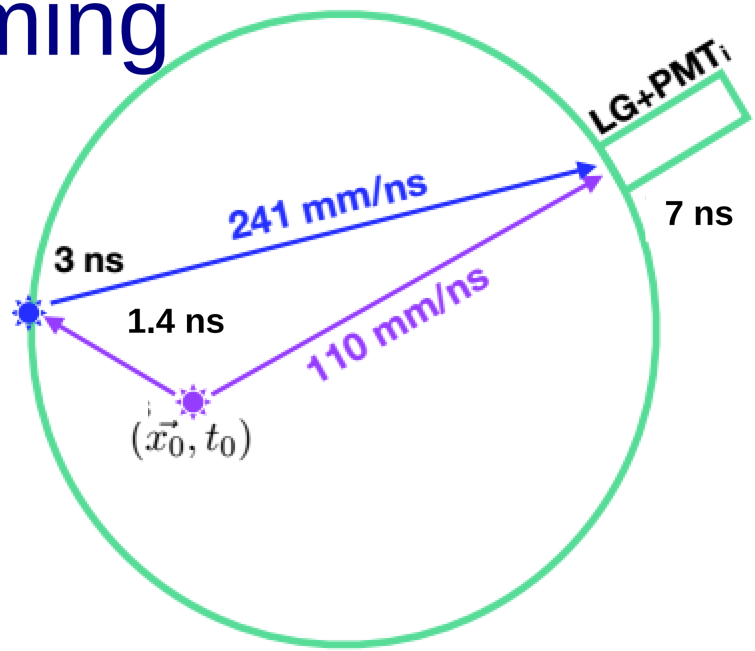


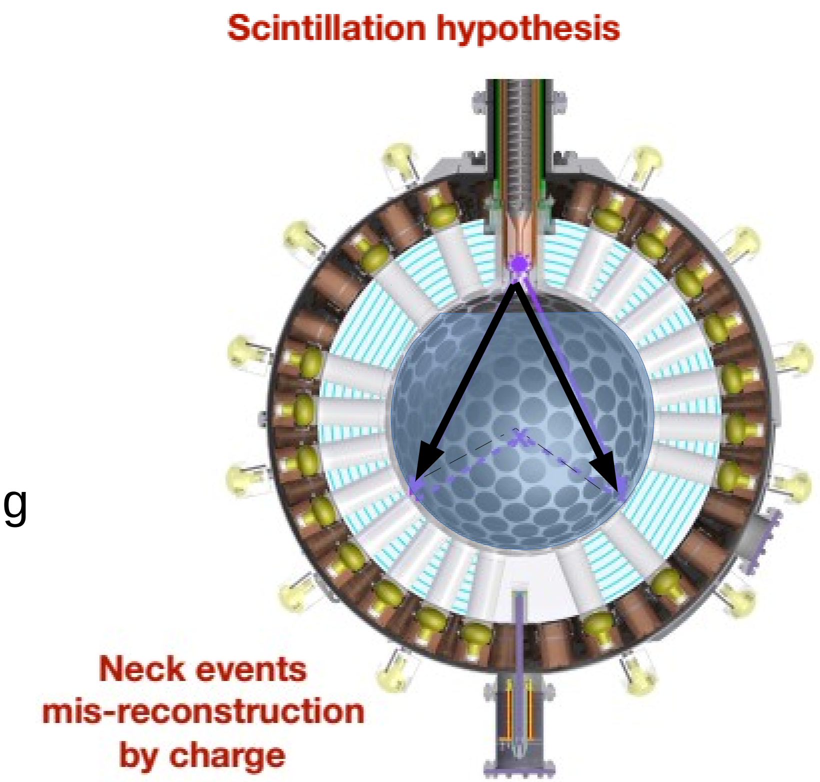
- Optical model improved and fine tuned over the last months
- Additional handle
  - alpha scintillation in TPB added to the argon scintillation, which makes those events easier to tag/remove with PSD

1st paper: fitters used only as a cross-check...

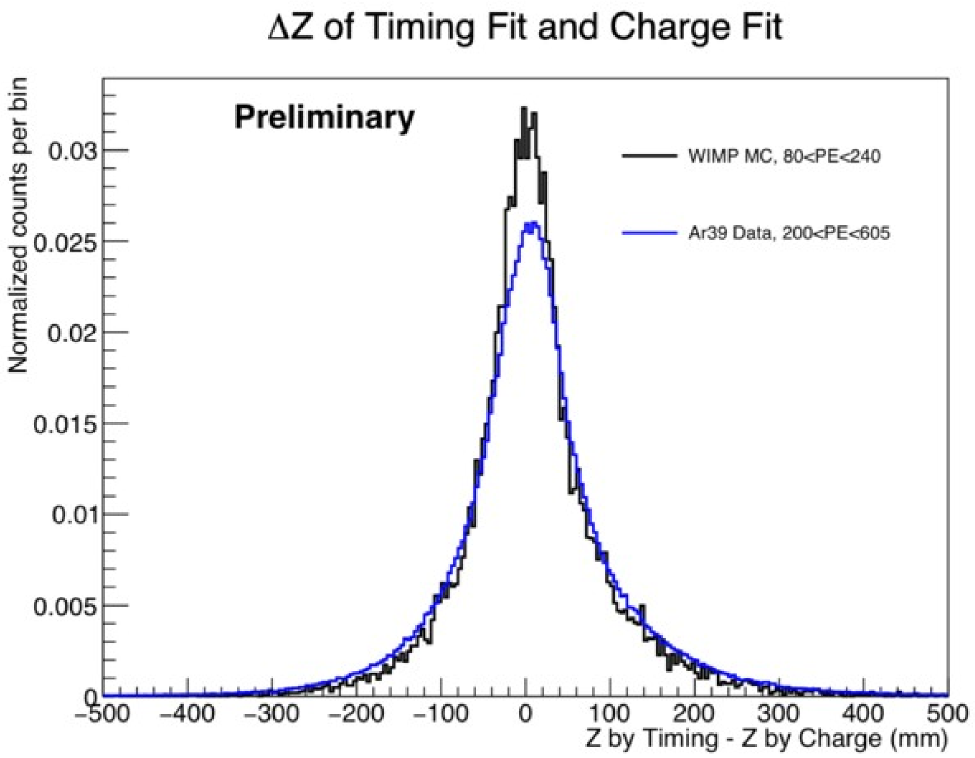
Fit with photon timing

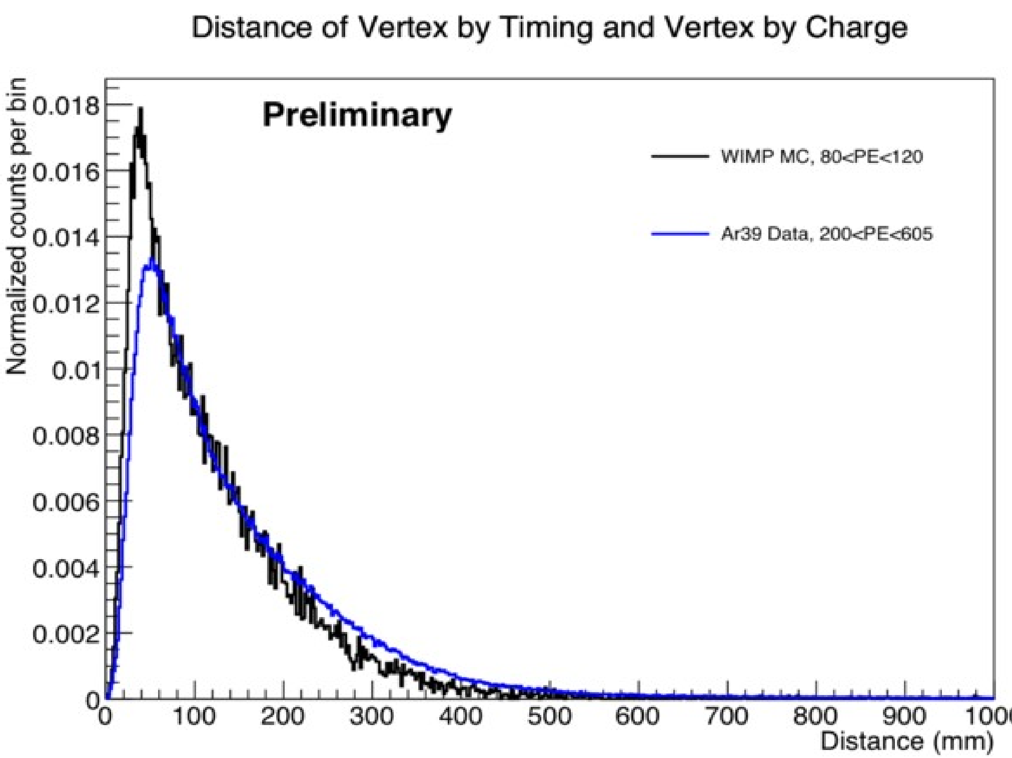
- Fit with intensity and time of arrival for the first 40 ns of prompt light
- Group velocity of UV light = 110 mm/ns
- Group velocity of visible light = 241 mm/ns
- Construct PDFs for light emitted at vertex x0 and event time t_0 given PMT_i measures charge q_i
- Convolve singlet decay time (7 ns), 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**





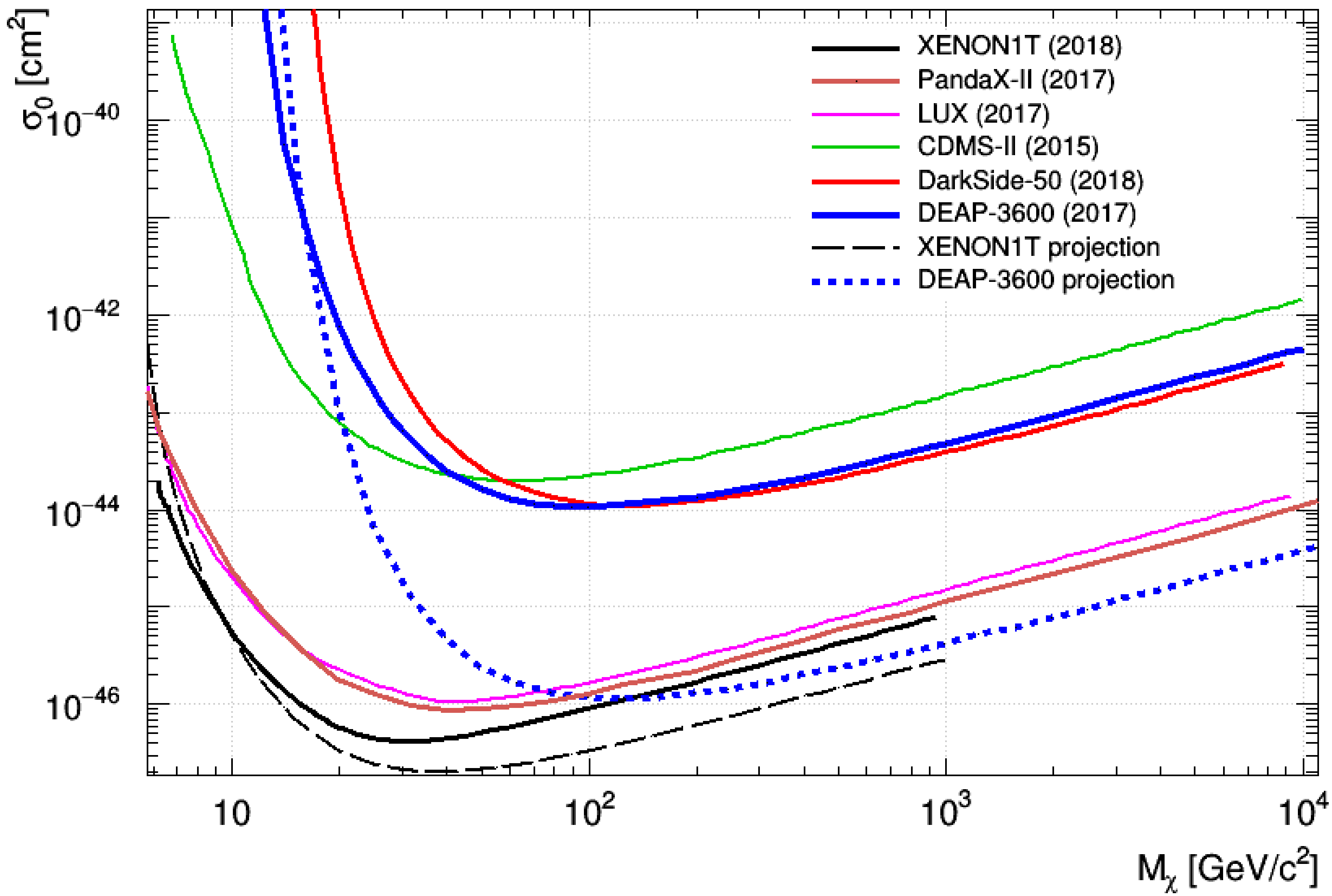
Consistency between charge and time fitters





Agreement between data driven Monte Carlo and data (Ar-39 used as a proxy for WIMPs)

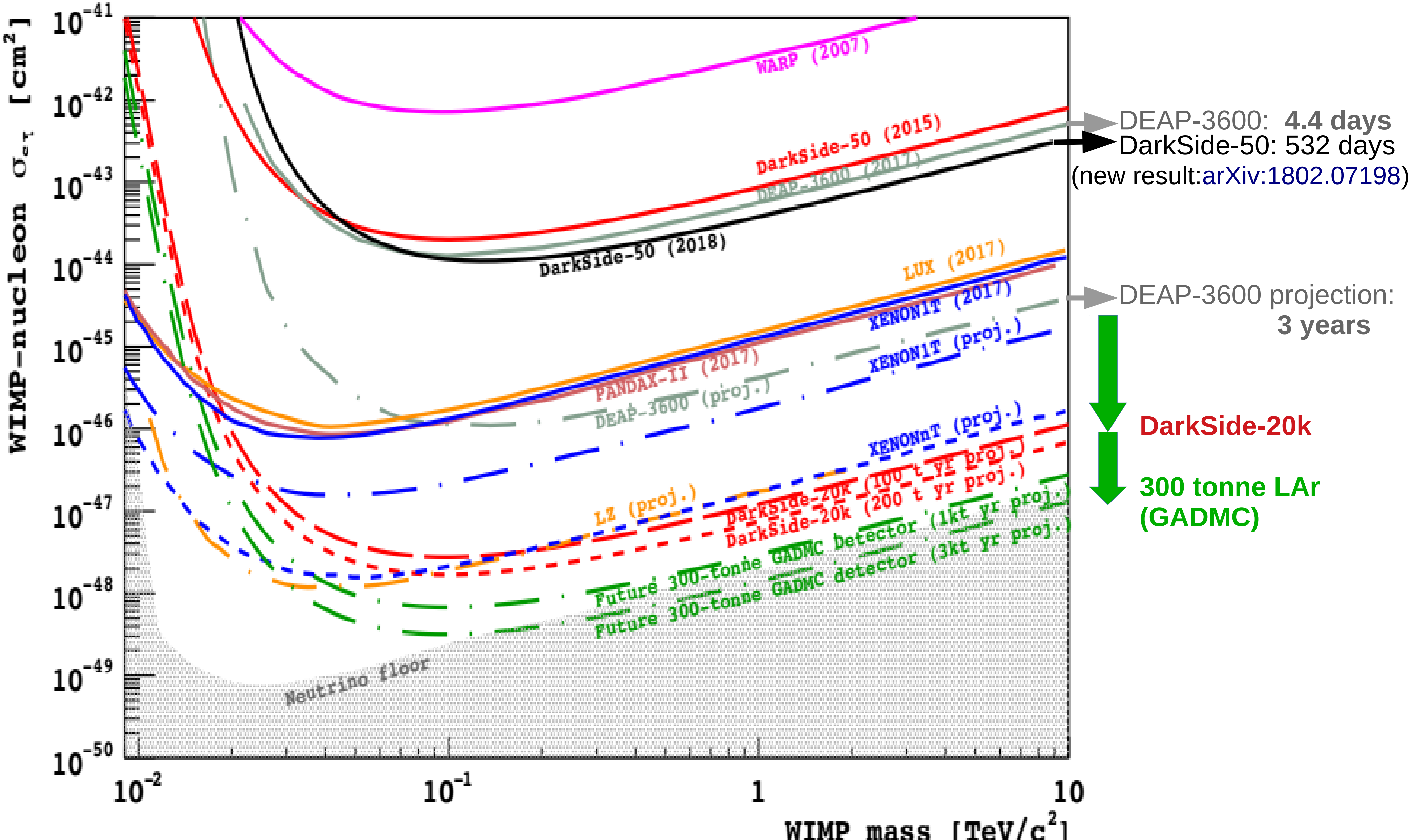
Current landscape



DEAP-3600 status

- Detector filled and collecting DM search data since Nov 1, 2016
- Stable performance, good light yield, excellent PSD
- Record-low rates of Rn alphas
- World's best result in LAr
- Continued physics and calibration data taking
- Work on higher sensitivity 1 year dataset analysis in progress:
  - Improved PSD using optimized integration windows and extended single photoelectron counting technique
  - Constraining the systematic uncertainty of energy calibration
  - Realistic and detailed simulation essential for the background model. Particularly challenging for surface and neck backgrounds: non-trivial geometry, physics and optics!
  - Using position reconstruction fitters in the 1 year analysis
  - New powerful position reconstruction fitter using time
  - Finalizing the systematic uncertainty on background expectations
- Planning to collect 3 live-years of data to reach our full sensitivity

Bright future



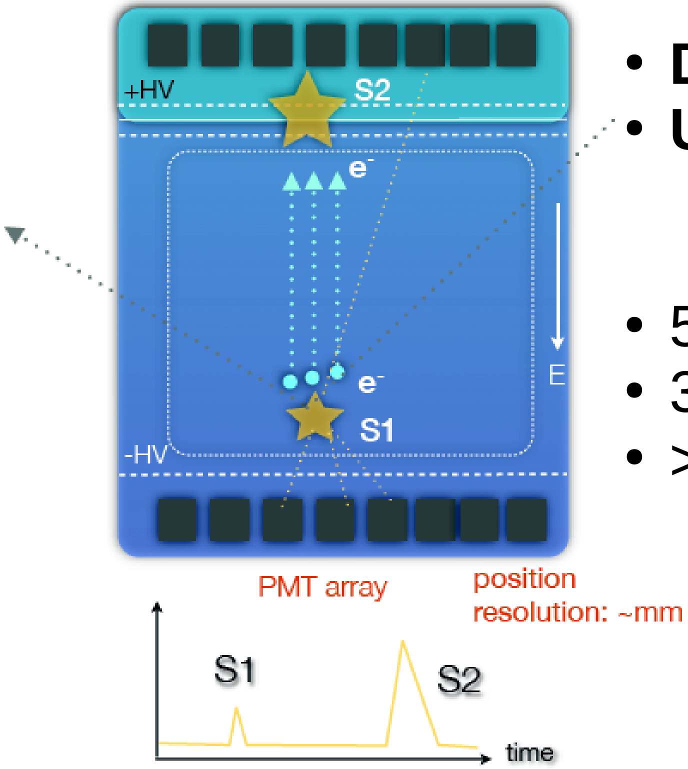
Global Argon Dark Matter Collaboration

Recent formal announcement of the Letter of Intent at the Canadian Embassy in Rome
350+ researchers from DarkSide, DEAP, ArDM and MiniCLEAN.

Supported by the Underground Labs: LNGS, LSC and SNOLAB.

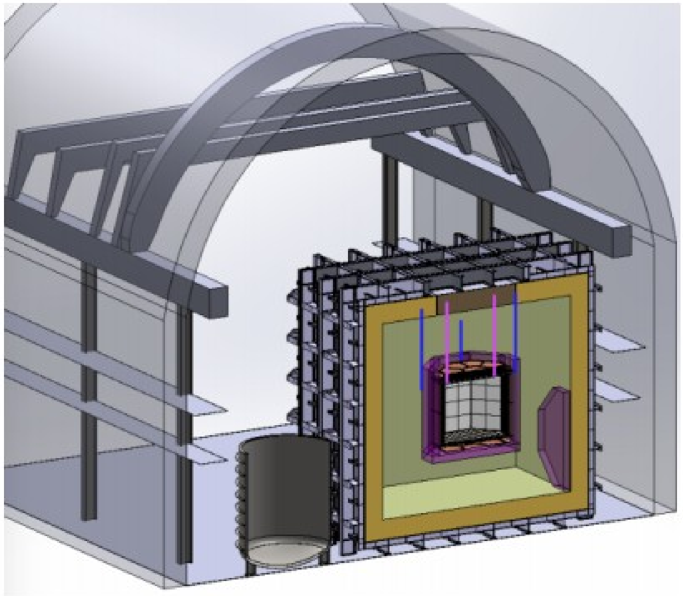
Next steps:
- Completion of the DarkSide-50 and DEAP-3600 science programs
- Joint collaboration on DarkSide-20k at LNGS (2021 –)
- 300 tonnes fiducial mass detector (2026 – , location TBD)

DarkSide-20k



- **Dual-phase detector**
- **Uses low radioactivity Ar**

- 50 tonnes total mass
- 30 tonnes fiducial mass
- >20 m^2 of SiPM coverage



C. Aasleth et al. (DarkSide-20k), arXiv:1707.08145

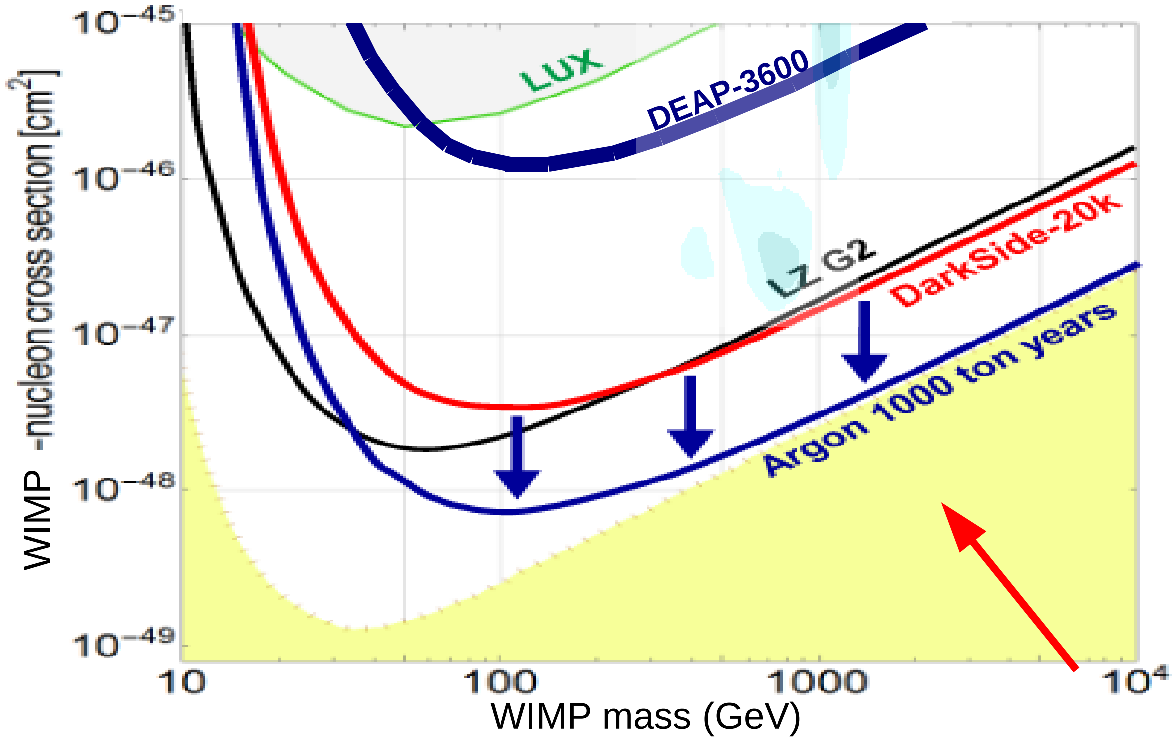
- To be located at LNGS (Gran Sasso, Italy)
- Officially supported by underground labs: LNGS, LSC, and SNOLAB

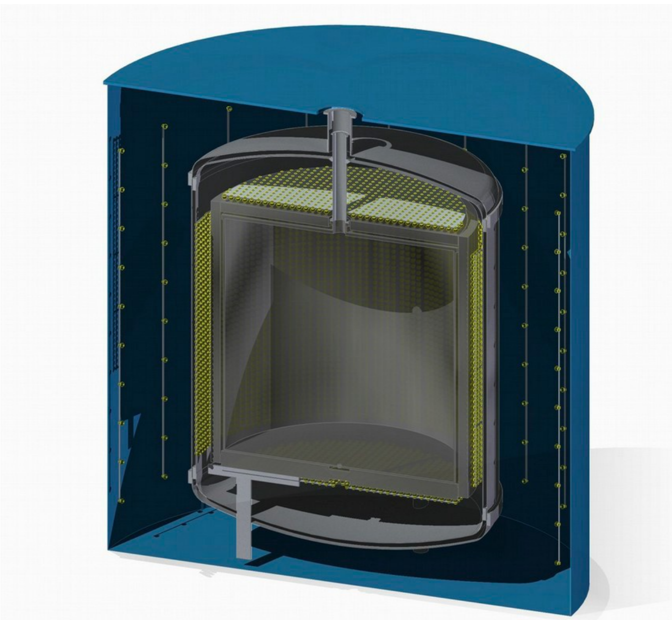
- Planned start in 2022
- Projected LY = 10 PE/keV (highly efficient SiPMs)

- Approved by INFN and LNGS in April 2017 and by NSF in Oct 2017

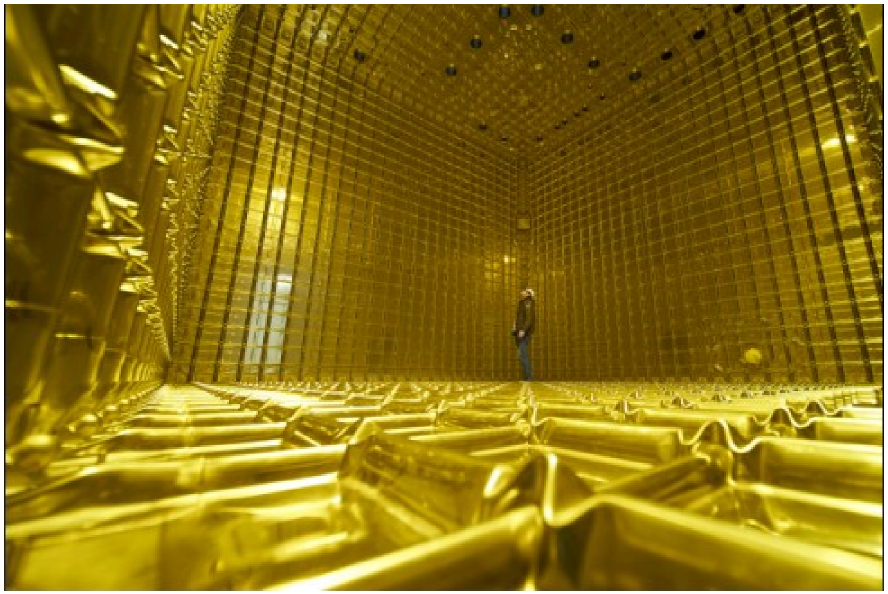
Beyond DarkSide-20k

- In pre-conceptual phase currently, design (single vs dual phase) and name TBD
- 300 tonnes fiducial for ktonne-yr exposure:
  (**10^{-48} cm^2** sensitivity @ 1 TeV)
- Large detector will require low radioactivity Argon
- **LAr capable of exploring parameter space down to the neutrino floor!**





Very likely do adopt some of the (Proto)DUNE-like solutions following new ideas for DarkSide-20k

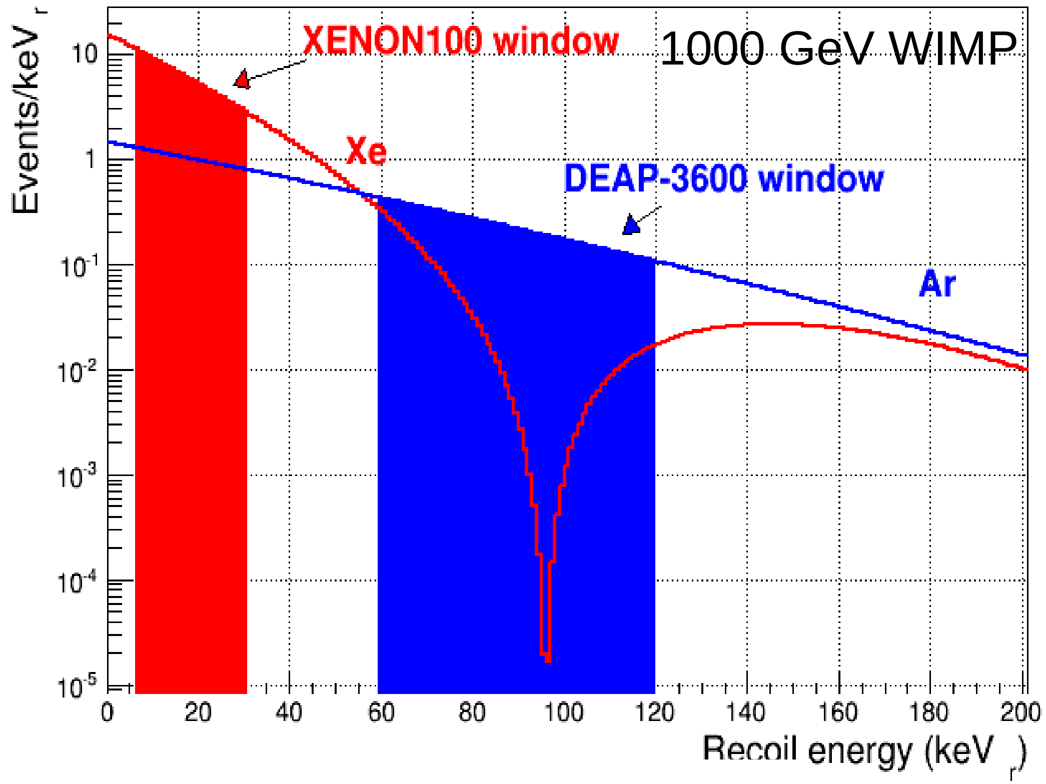


Summary

- Strong discovery potential for the upcoming generation of experiments
- DEAP-3600 analysis ongoing 1 year analysis results will come soon!
- Success of DEAP-3600 and DS-20k will motivate the ultimate detector
- A global LAr collaboration has formed, with a goal of reaching the neutrino floor within a decade
  - 350+ scientists
  - Strong physics case for using complementary targets (LAr in addition to LXe) and exploring the remaining parameter space
  - LAr appears to have the best potential at ~1 TeV WIMP masses, due to lack of neutrino induced electronic recoils

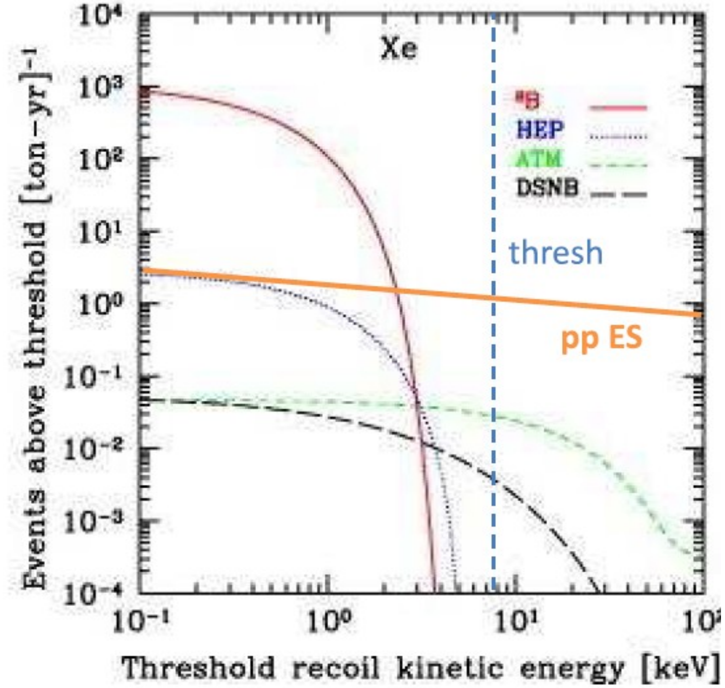
Backup

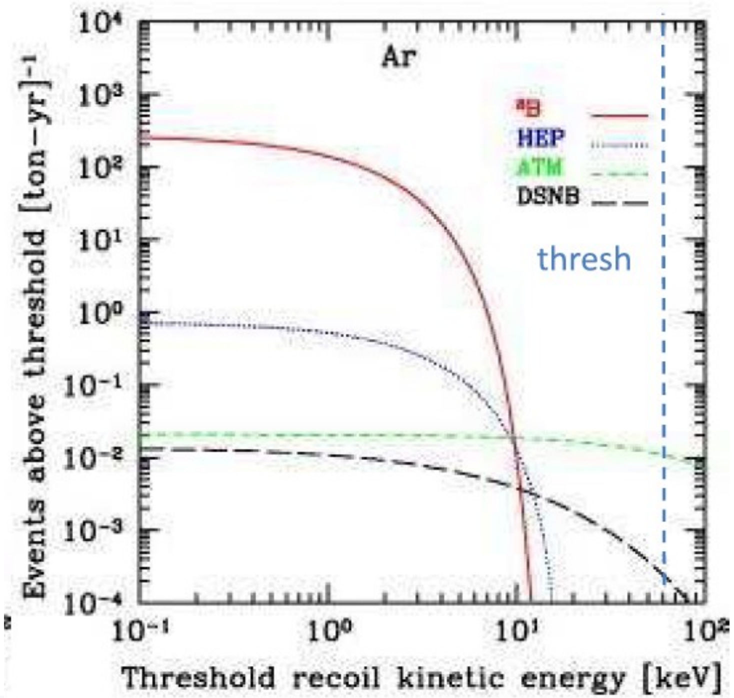
Xe and Ar for direct WIMP scattering



$$\sigma_{0\mathrm{WN,SI}} \approx \frac{4\mu_A^2}{\pi} f_n^2 A^2$$

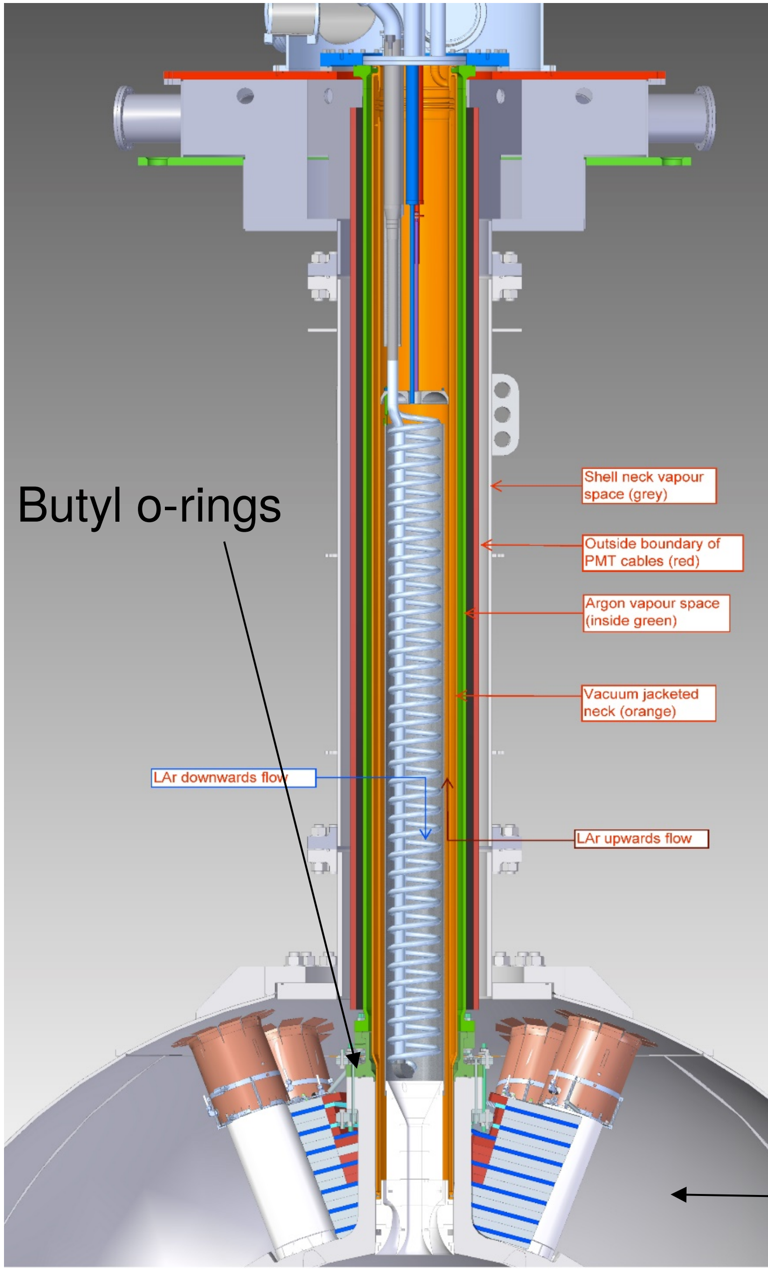
- Potential for very large and very sensitive searches
- Complementarity:
  - For high WIMP masses Ar is very competitive with Xe
  - Due to superior PSD, Ar insensitive to *pp* neutrino backgrounds





L.E. Strigari, New J. Phys. 11 (2009) 105011

August 17, 2016 Incident



Leak developed between Butyl o-rings and Steel Shell region

~100 ppb N_2 into LAr

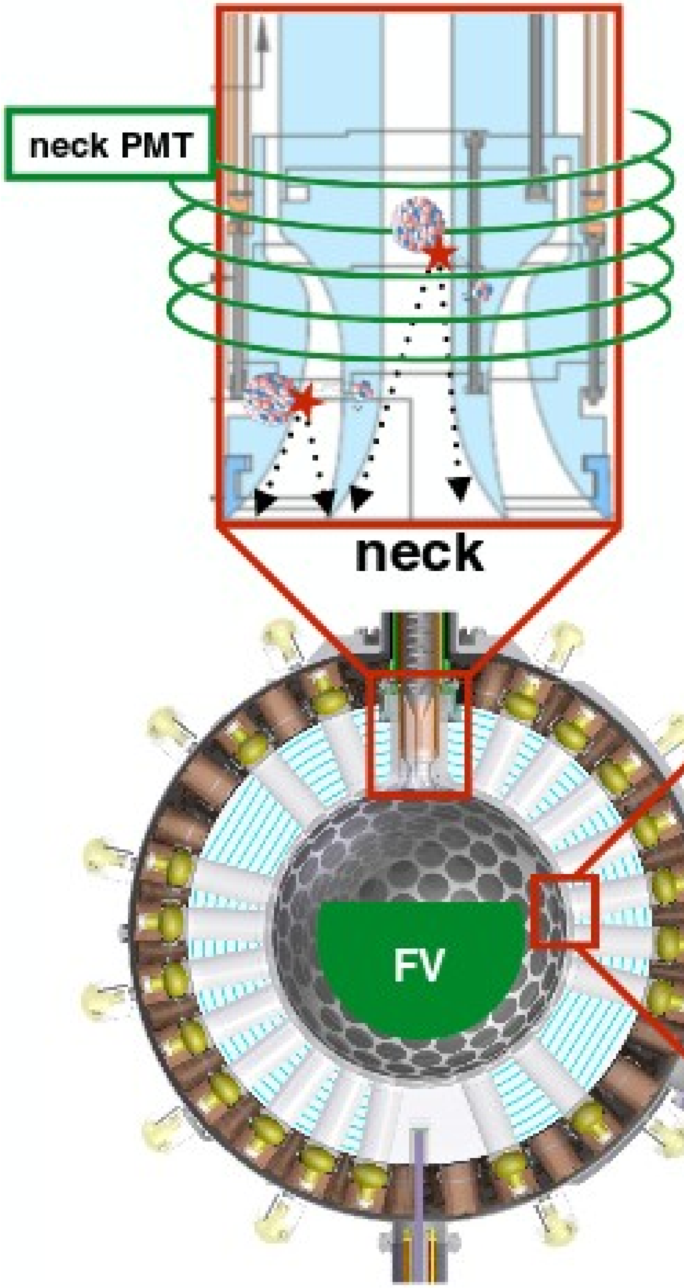
Drained and refilled to slightly lower LAr level by October 2016

Continued collecting data at new level since Nov 1, 2016 – 3322 kg

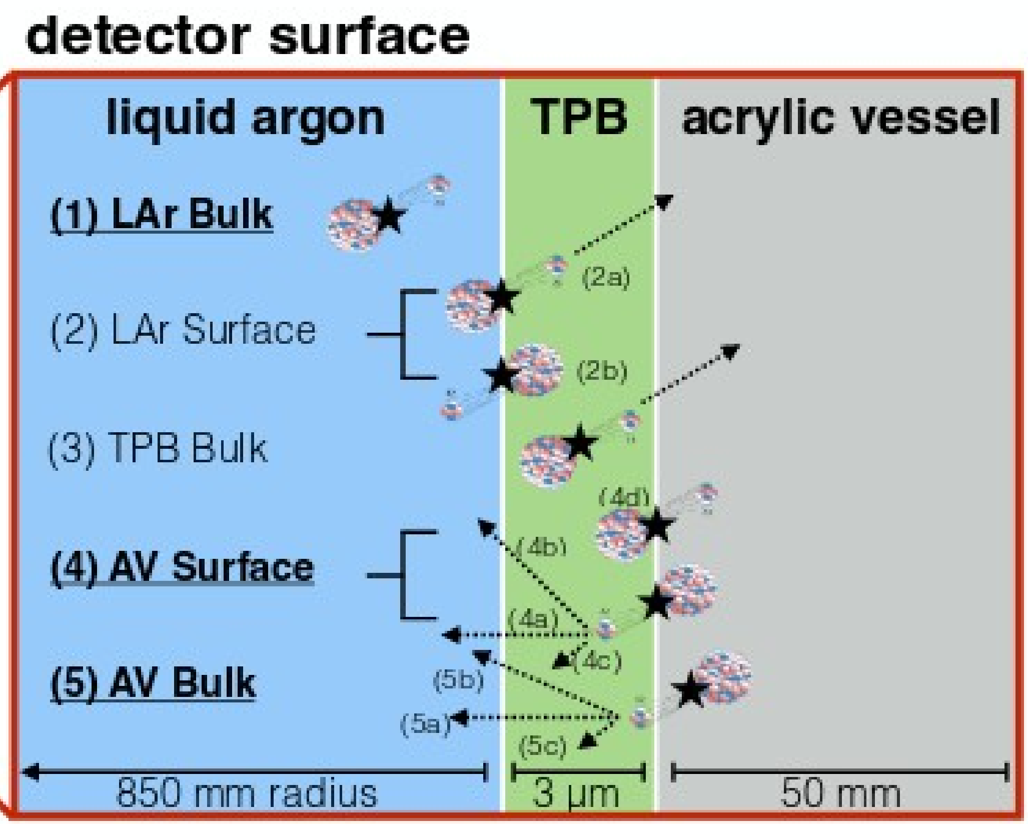
Current plan to continue running in this configuration for full data collection

Rn-scrubbed N2 gas in Steel Shell

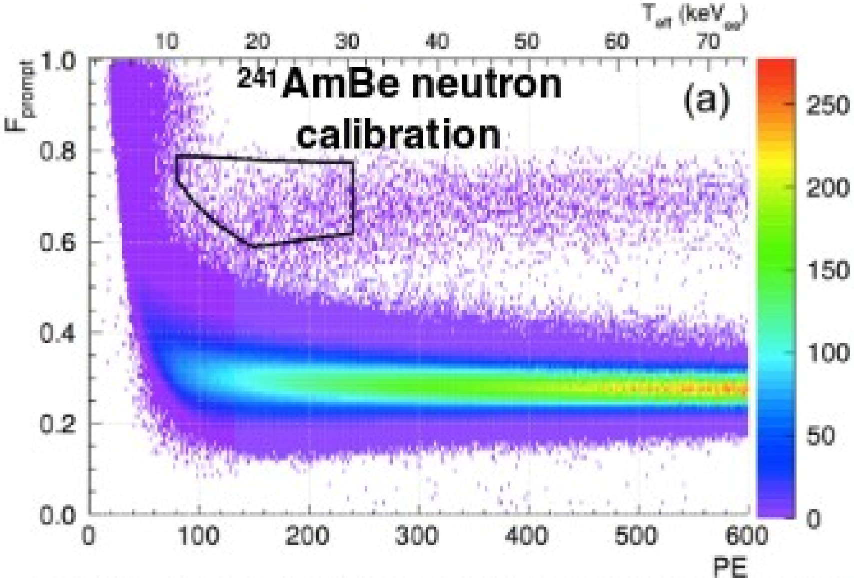
Alpha background topologies



- Alphas result in a low energy detector response if:
  - Part of energy is deposited in a dead surface (e.g. acrylic)
  - Energy is deposited in medium with less scintillation (TPB)
  - Scintillation light is lost due to shadowing
- Mitigation in analysis:
  - Fiber ("neck") veto
  - Fiducial volume (FV) cut



Constraints on neutron backgrounds



Neutrons recoil ^{40}Ar similar to WIMPs

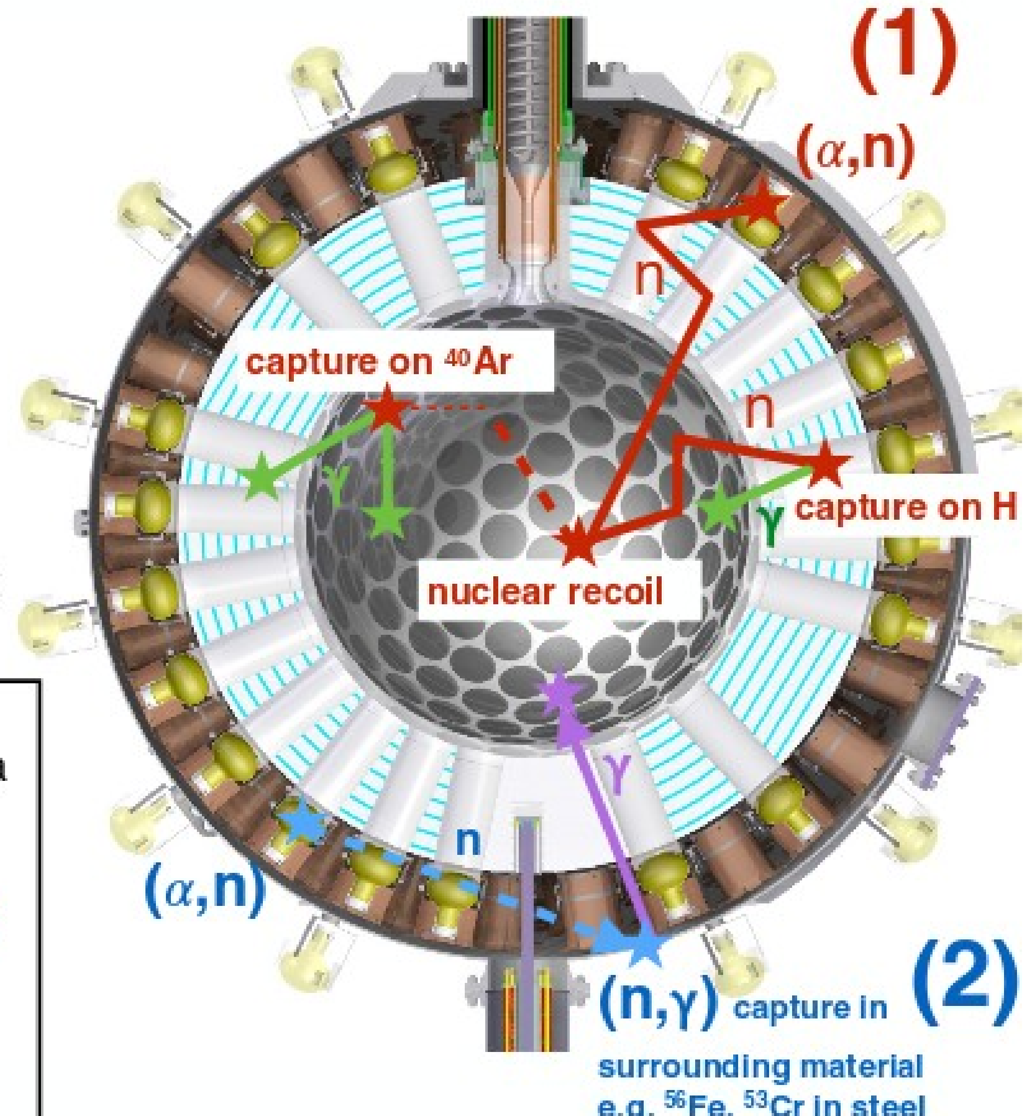
Neutrons produced by (α,n) reactions, fission or muons

Extensive neutron MC campaign using radio-purity assays and (α,n) yields from SOURCES-4C

- Dominant source is (α,n) in PMT glass (≈70%)
- Well constrained from γ-background and consistent with target values

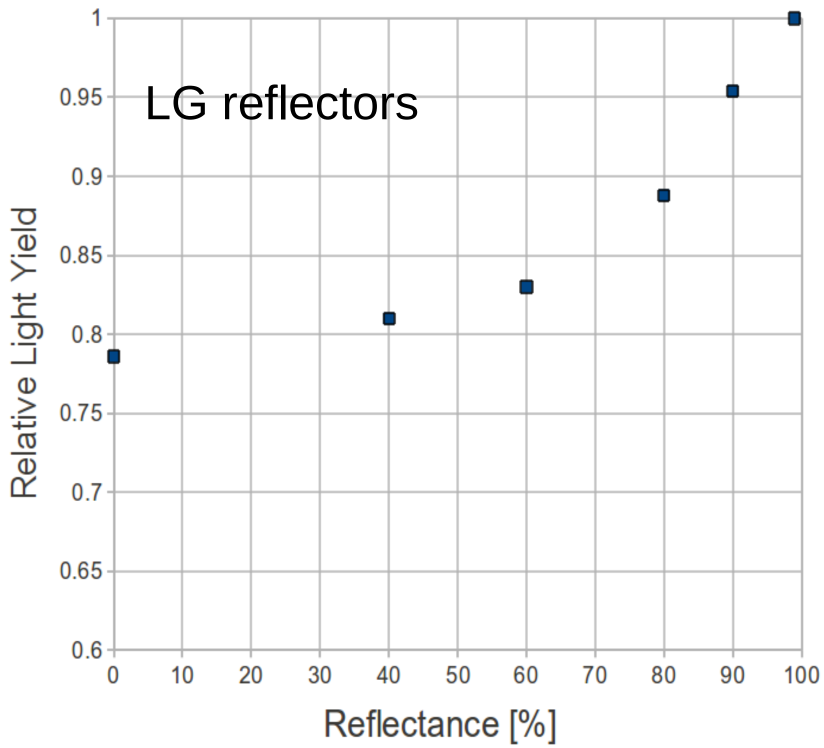
Two data driven limits on neutrons:

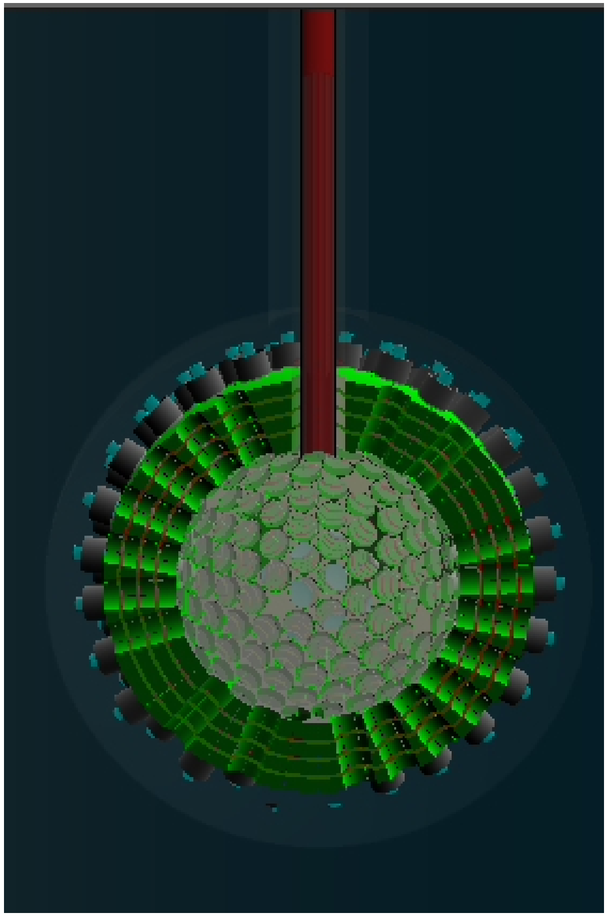
- **Idea:** Eventually all neutrons capture and leave gamma signature
- **(1) n enters LAr and captures in LAr or acrylic**
  - 2.2 MeV γ from ^{1}H or 6.1 MeV γ-cascade from ^{40}Ar
  - Search for n - γ coincidences
- **(2) n captures in surrounding material**
  - Variety of high energy γ's
  - γ's > 5 MeV can be easily distinguished from BG



DEAP-3600 Optics

PMTs the only choice at the time the detector was designed.
PMT glass is the main neutron source in the detector => a lot of acrylic required for shielding.





- Factors affecting LY:
  - Acrylic attenuation (>10% loss)
  - LG reflectors (1 – 20% loss)
  - AV reflector (0 – 5% loss)
  - Magnetic fields (1 – 20% loss)
  - LG/PMT coupling (5 -- 10% loss)

- Prediction from Monte-Carlo tuned to DEAP-1 data:
  ~8 PE/keV

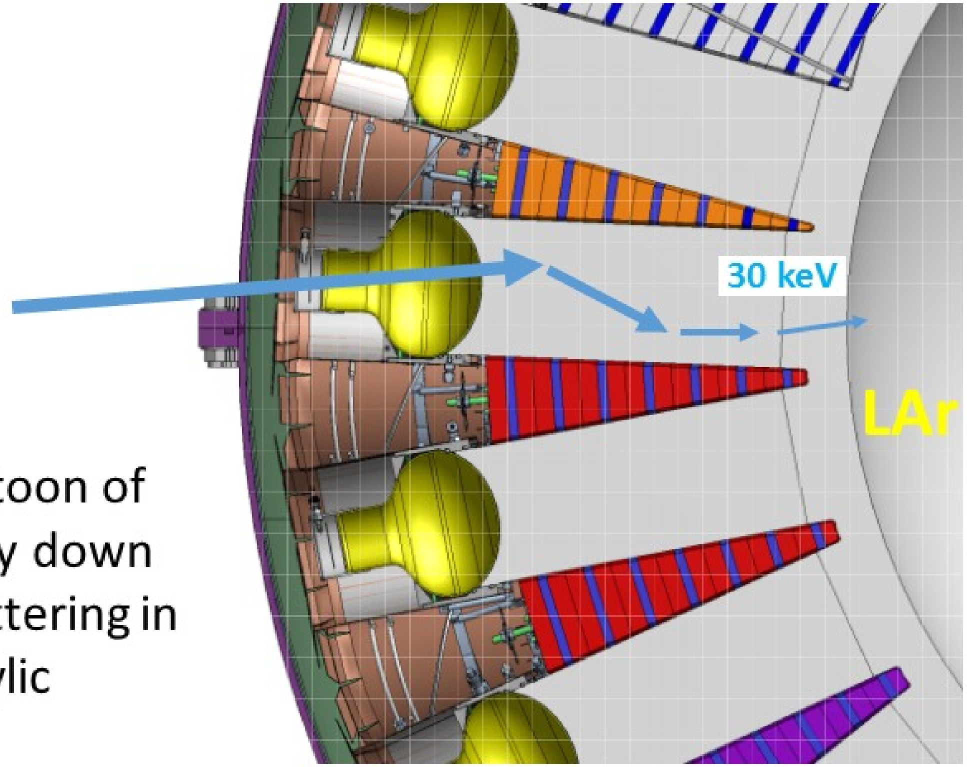
Acrylic fabrication and assay

- Fabrication from pure MMA monomer at RPT Asia (Thailand), strict control of radon exposure for all steps, to **< 1e-20 g/g Pb-210** (RPT was fabricator of the SNO Acrylic Vessel)
- Assay of production acrylic < 2.2e-19 g/g Pb-210 (Corina Nantais M.Sc. Thesis 2014, <0.2 bkg events/3 years)

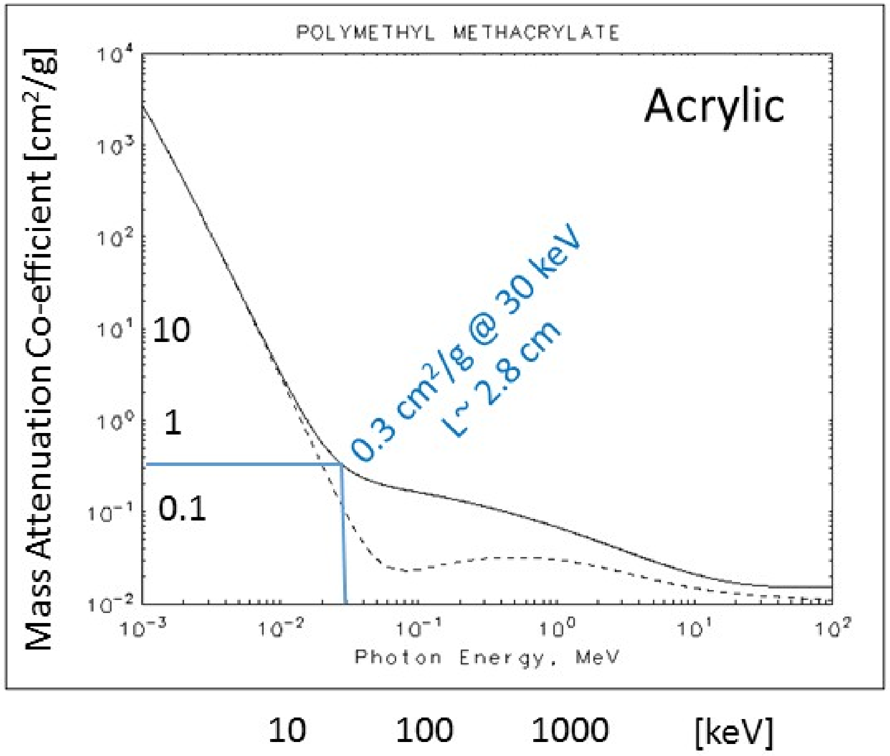
Monomer cast at RPT Asia, 2010

Thermoformed Panel at RPT Colorado

^{22}Na calibration: low energy feature

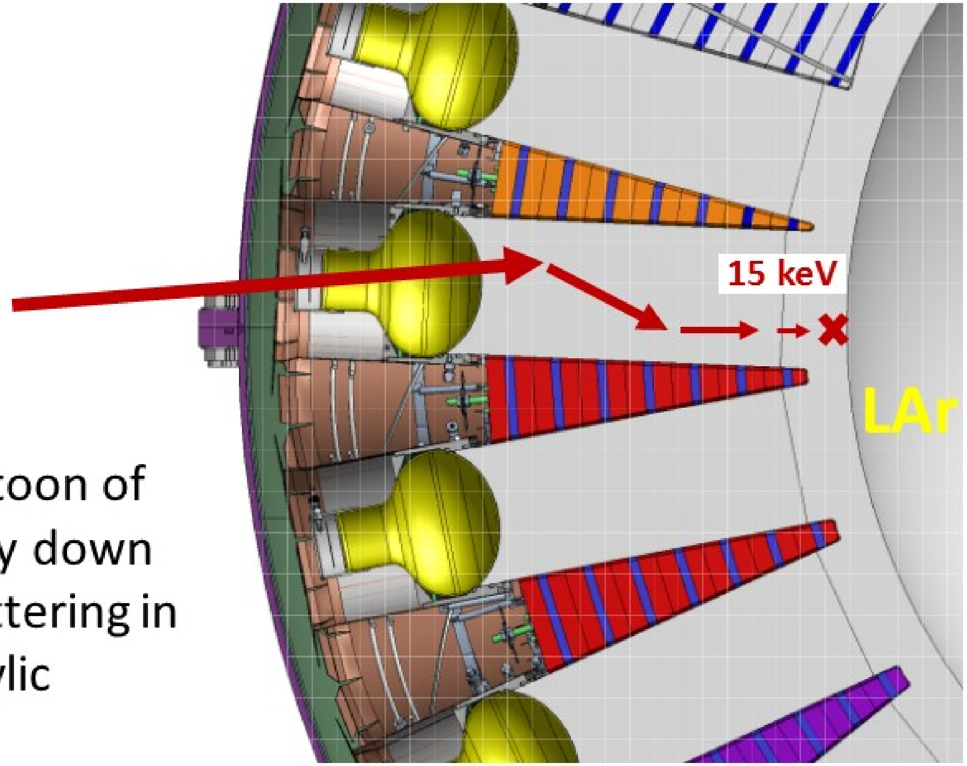


Cartoon of γ-ray down scattering in acrylic

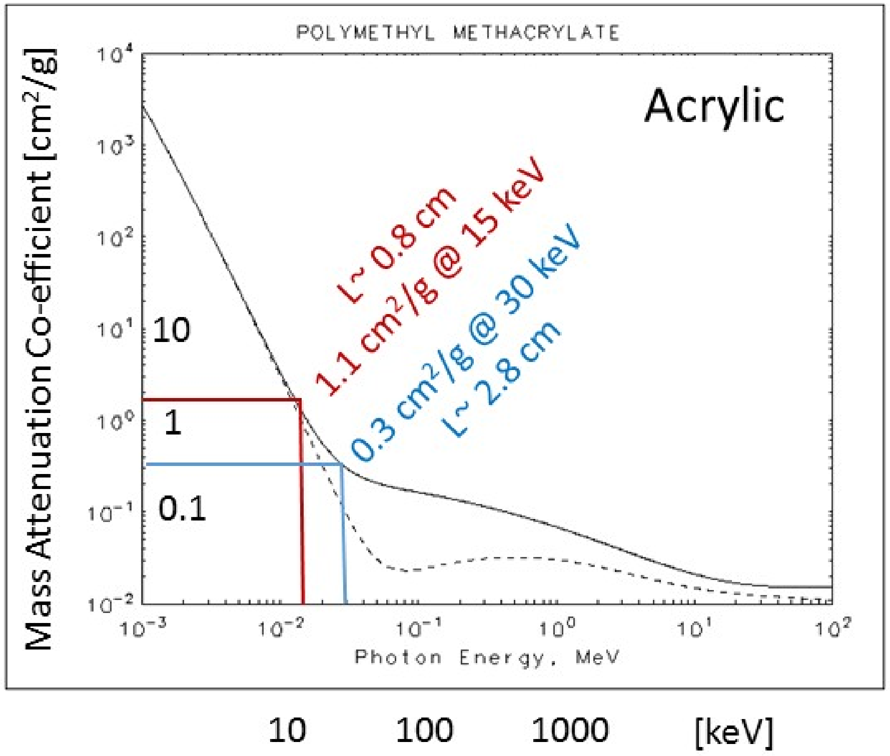


Plot and data from NIST.gov
X-ray mass attenuation coefficients

^{22}Na calibration: low energy feature



Cartoon of γ-ray down scattering in acrylic

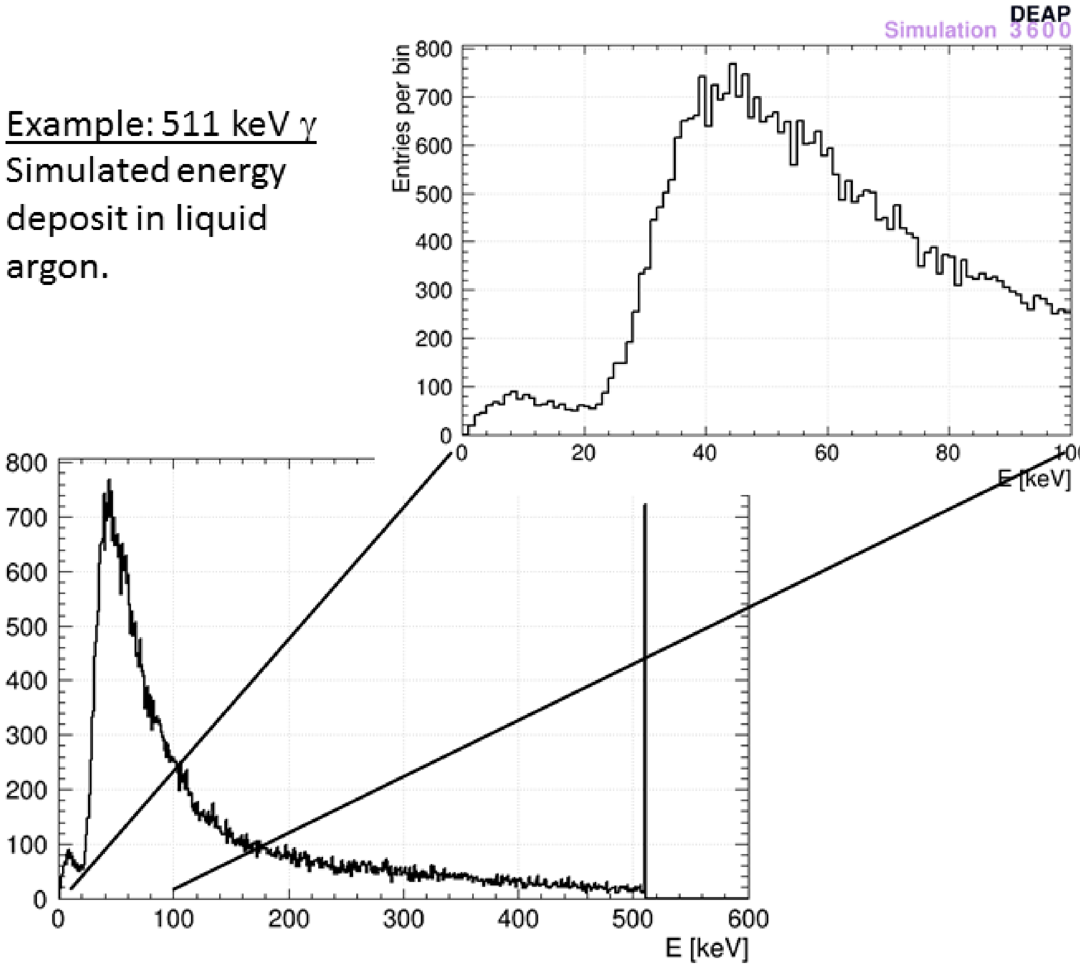


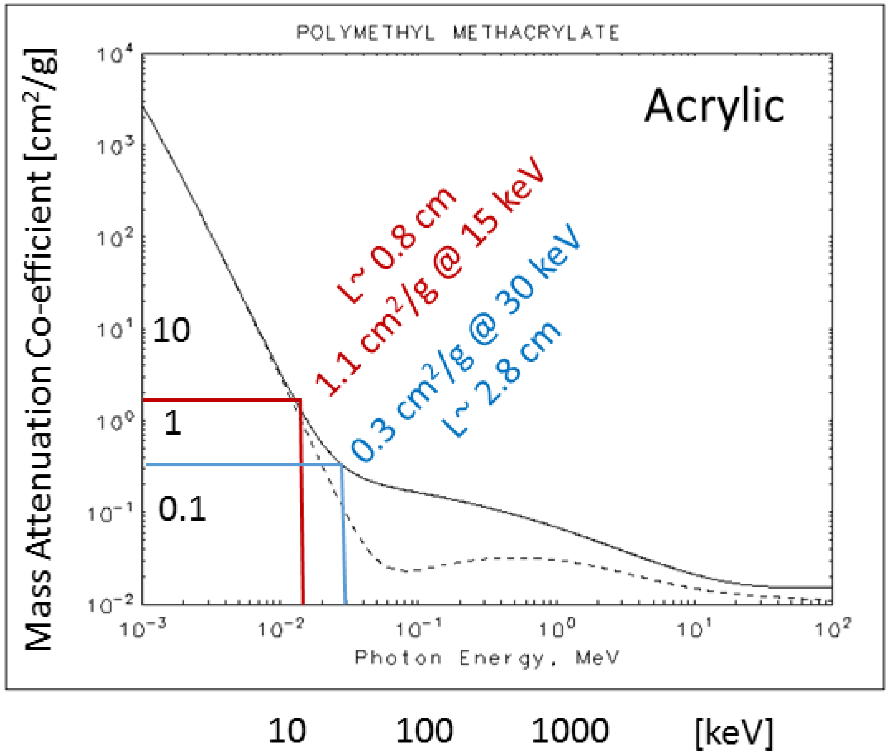
Plot and data from NIST.gov
X-ray mass attenuation coefficients

^{22}Na calibration: low energy feature

Both the Rising and Falling Edge in Distribution Energy Deposit Arise from Electromagnetic Physics

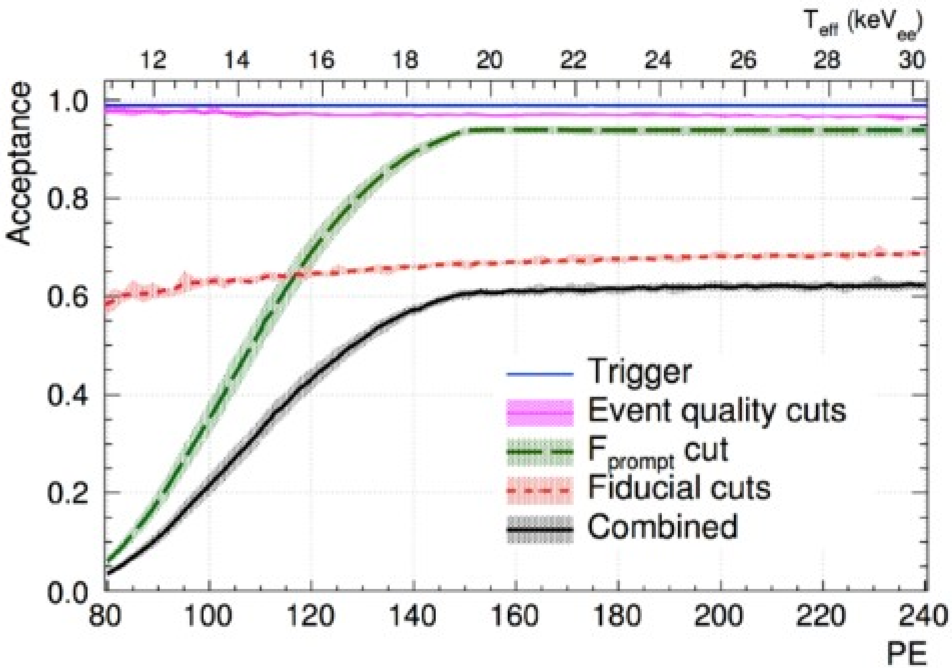
Example: 511 keV γ
Simulated energy deposit in liquid argon.





Plot and data from NIST.gov
X-ray mass attenuation coefficients

1st paper cuts and efficiencies



	Cut	Livetime	Acceptance %		$\#^{\mathrm{ROI}}_{\mathrm{evt.}}$
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