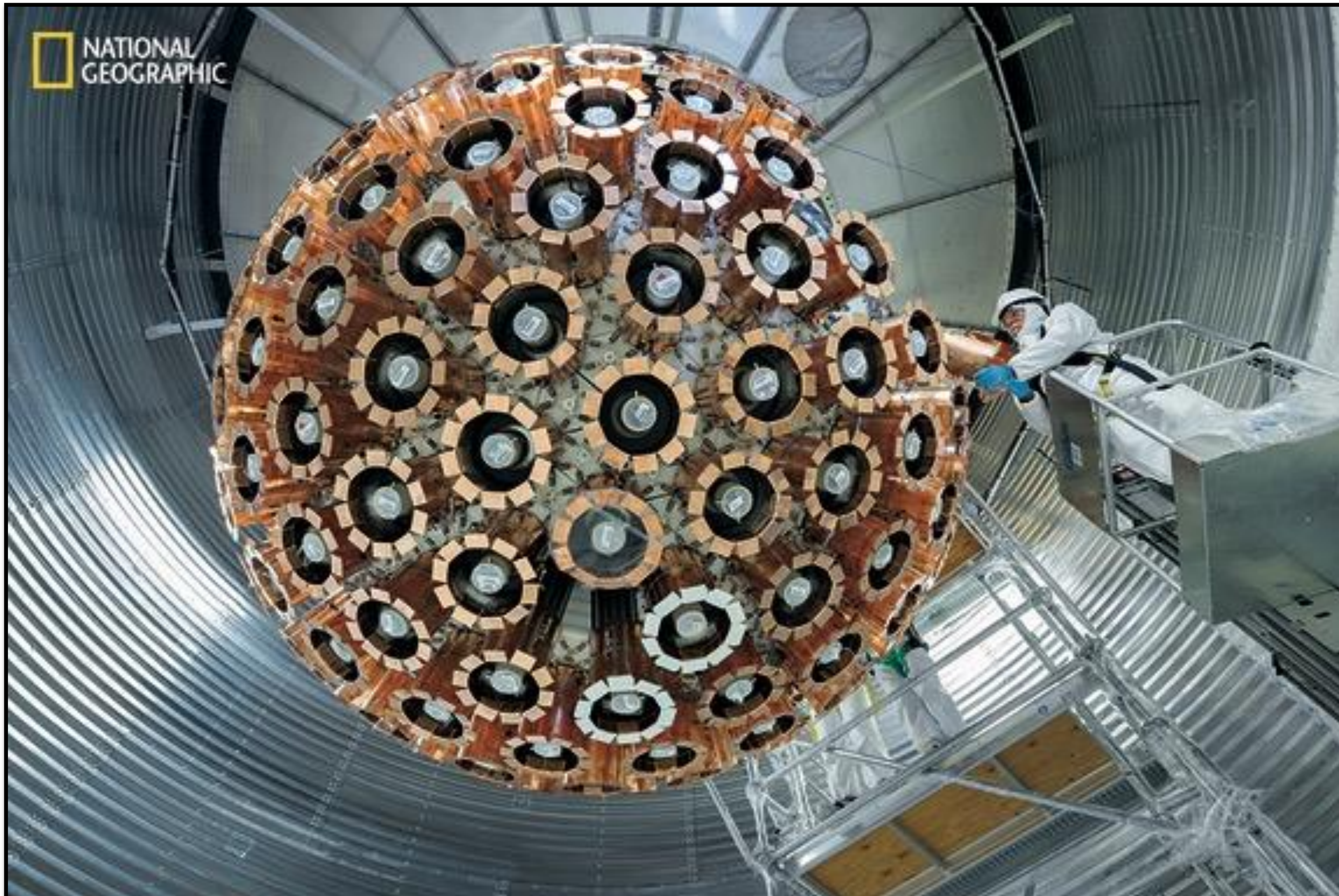
DEAP-3600 Dark Matter Search at SNOLAB

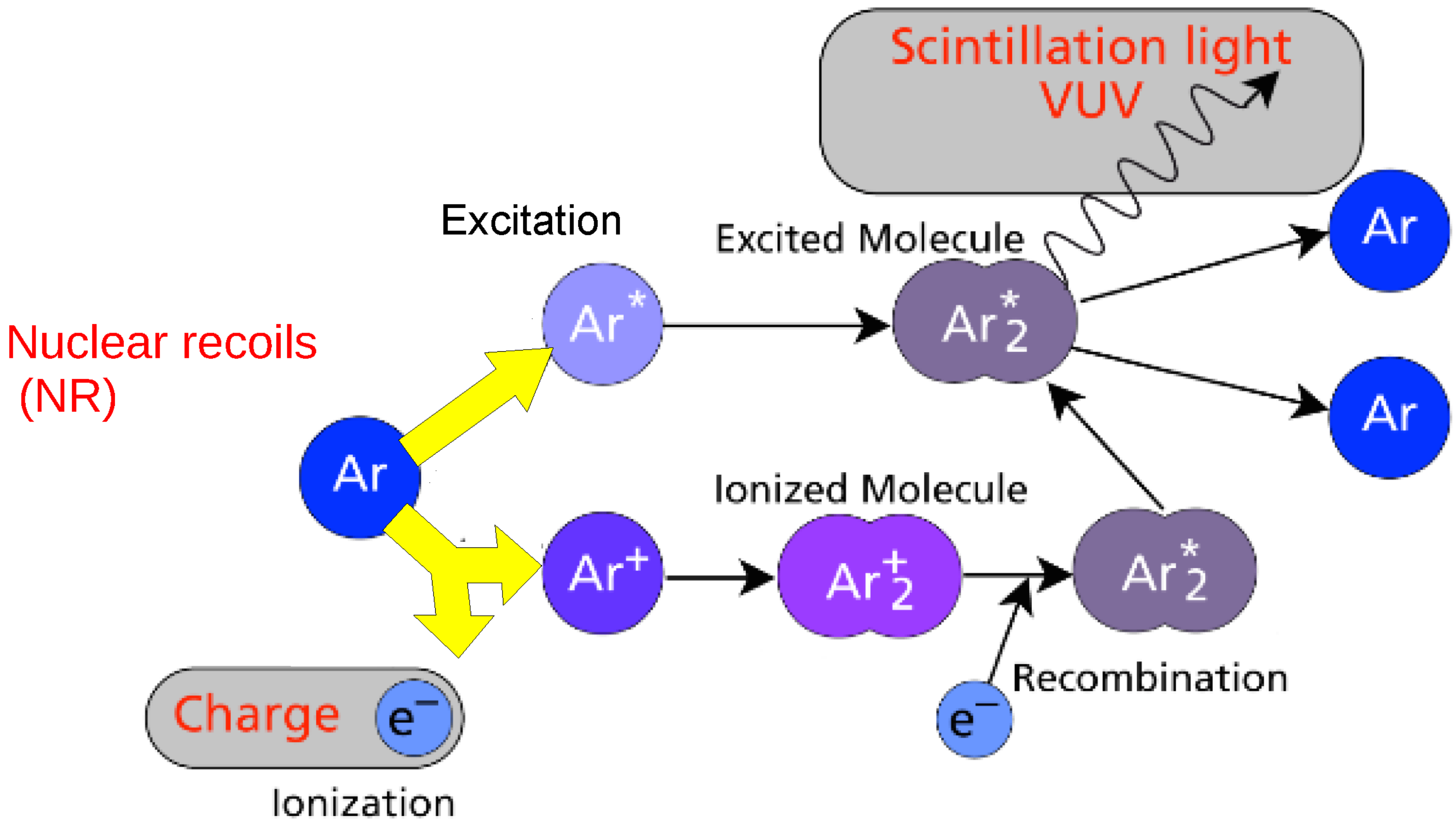


Mark Boulay
Carleton University

for the DEAP Collaboration

DBD 18
Waikoloa

Liquid noble gas detectors

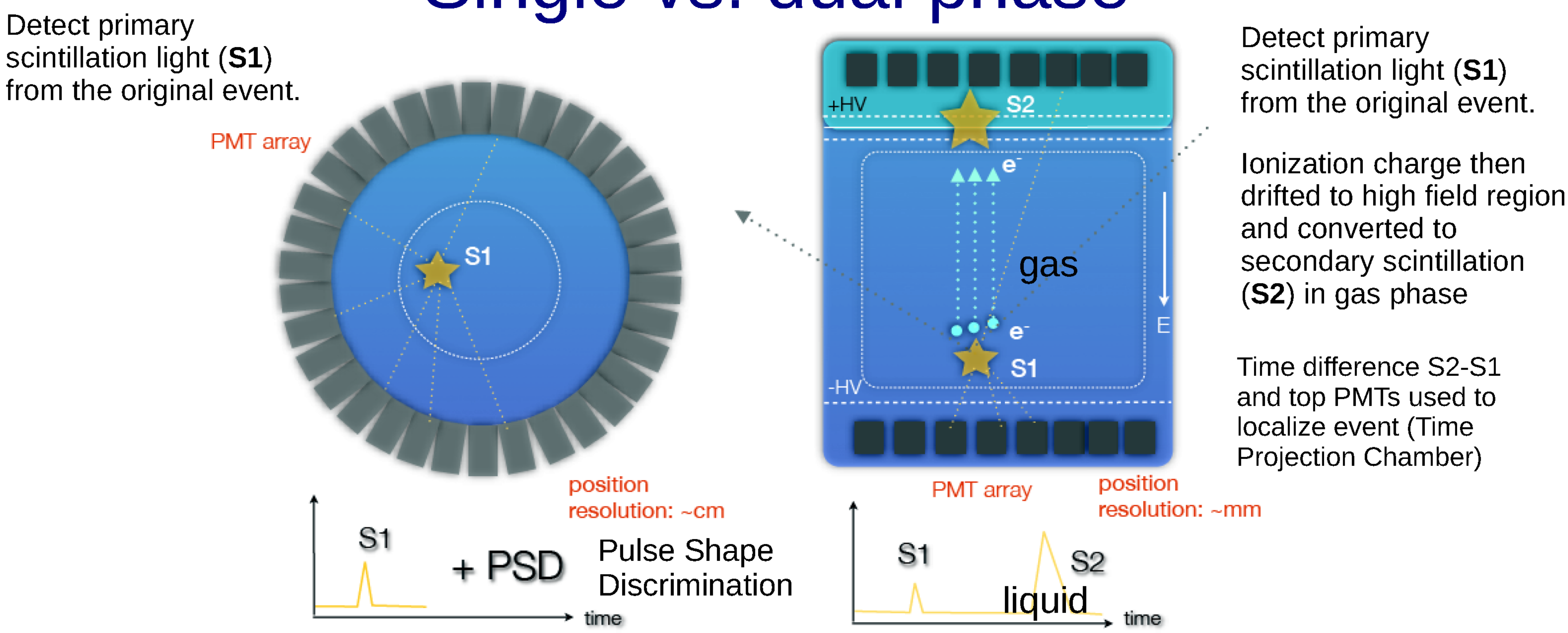


Why noble elements?

- (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

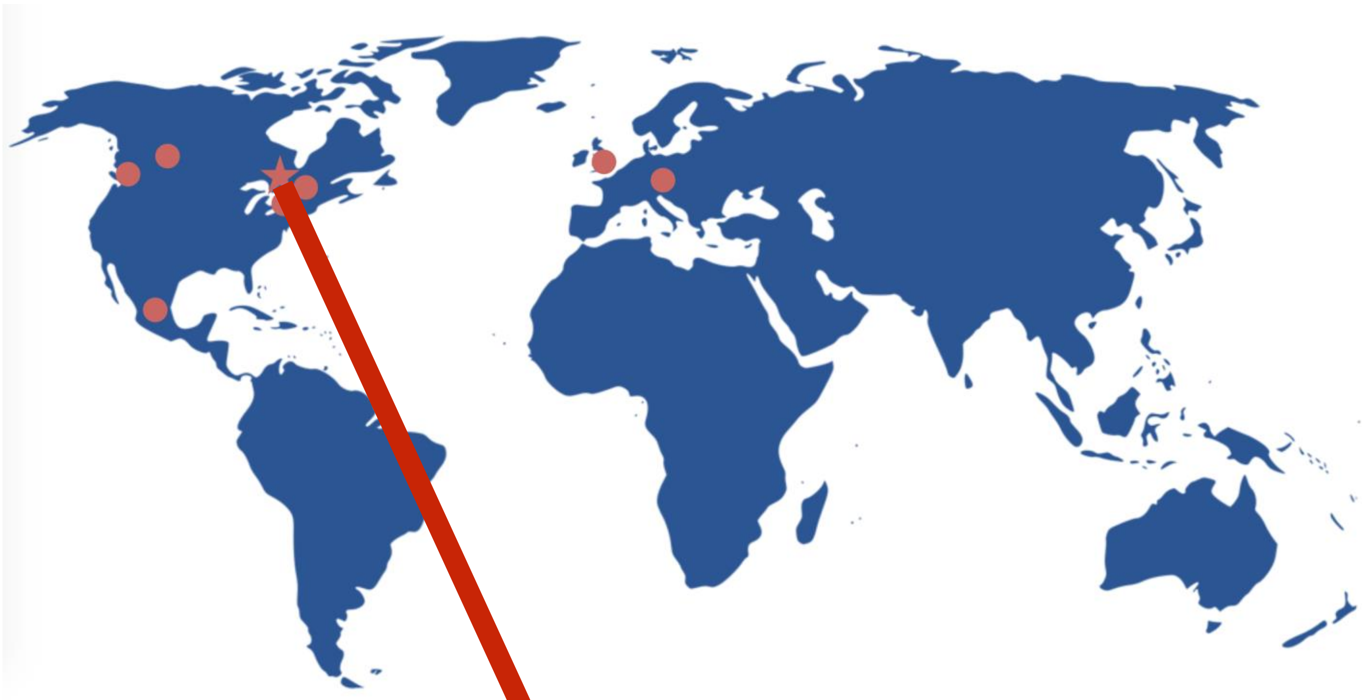
Single vs. dual phase

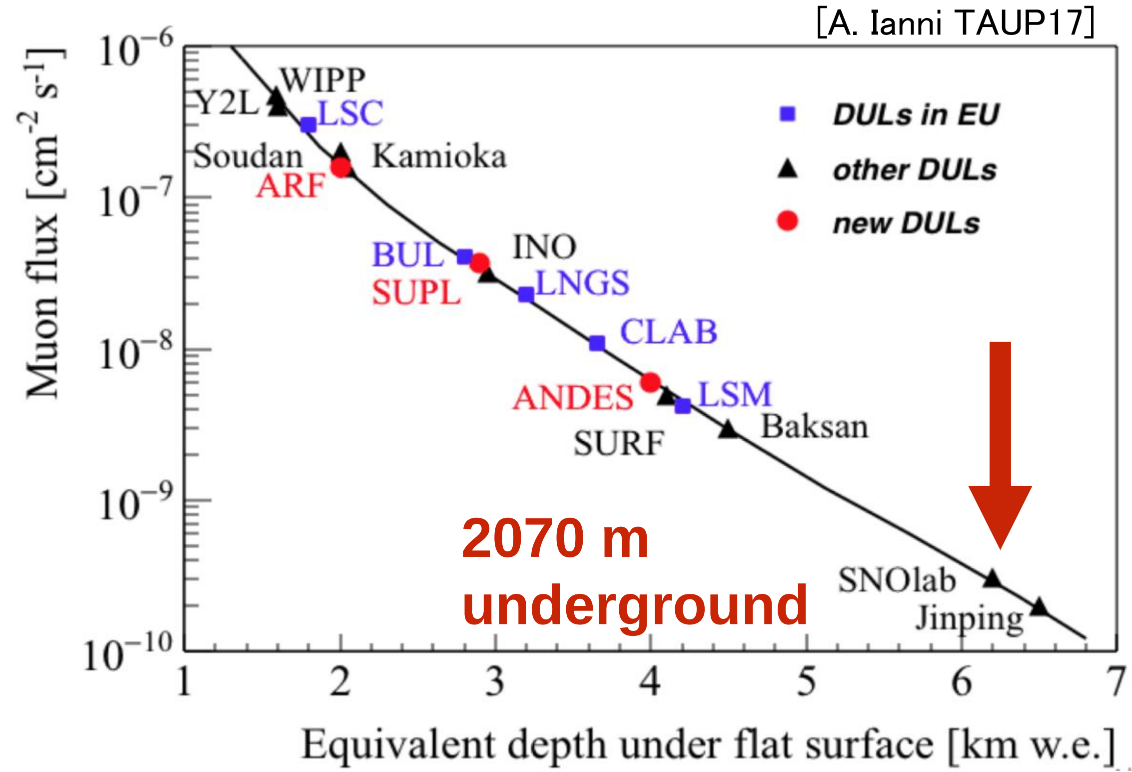


- Electronic recoil discrimination:
  - S2/S1 in Xe
  - PSD with S1 (scintillation only) in Ar; S2 signal used for position reconstruction

- 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 @ SNOLAB





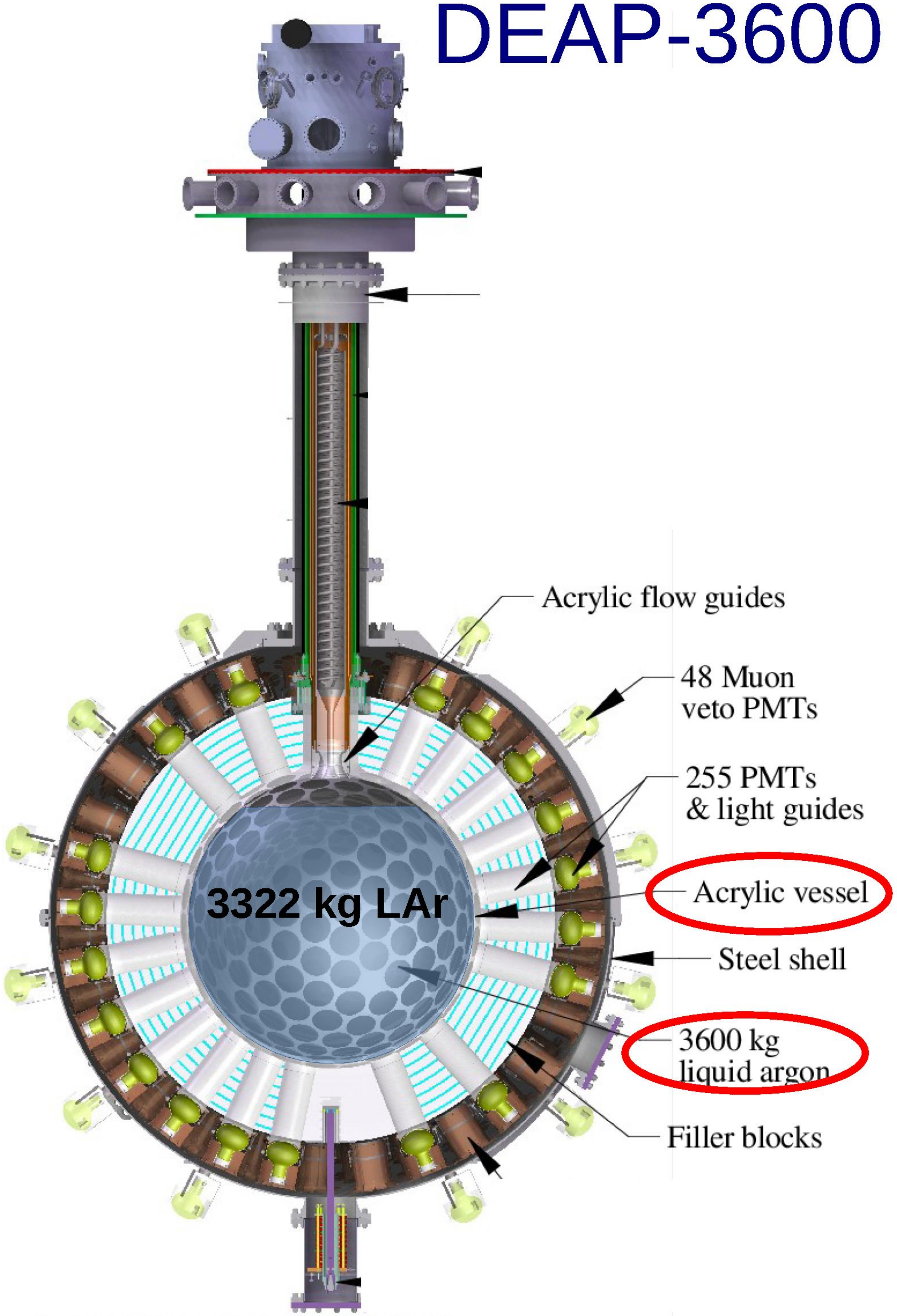
DEAP-3600 Collaboration

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
University of Massachusetts Amherst 1863
US University of Sussex
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
TRIUMF
IF Instituto de Física
Science & Technology Facilities Council
Ciemat

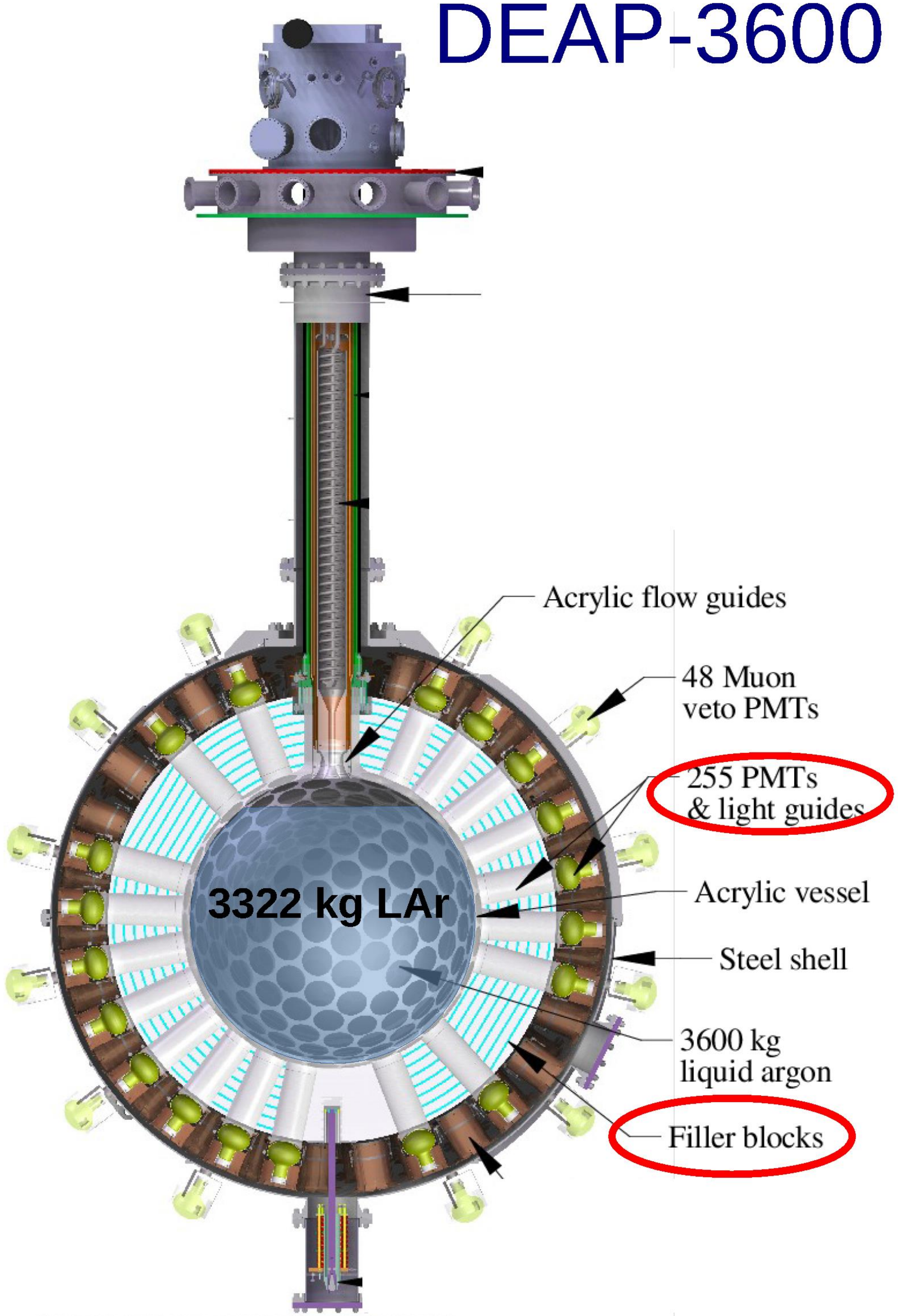
+ new DarkSide groups from Italy, US and Spain

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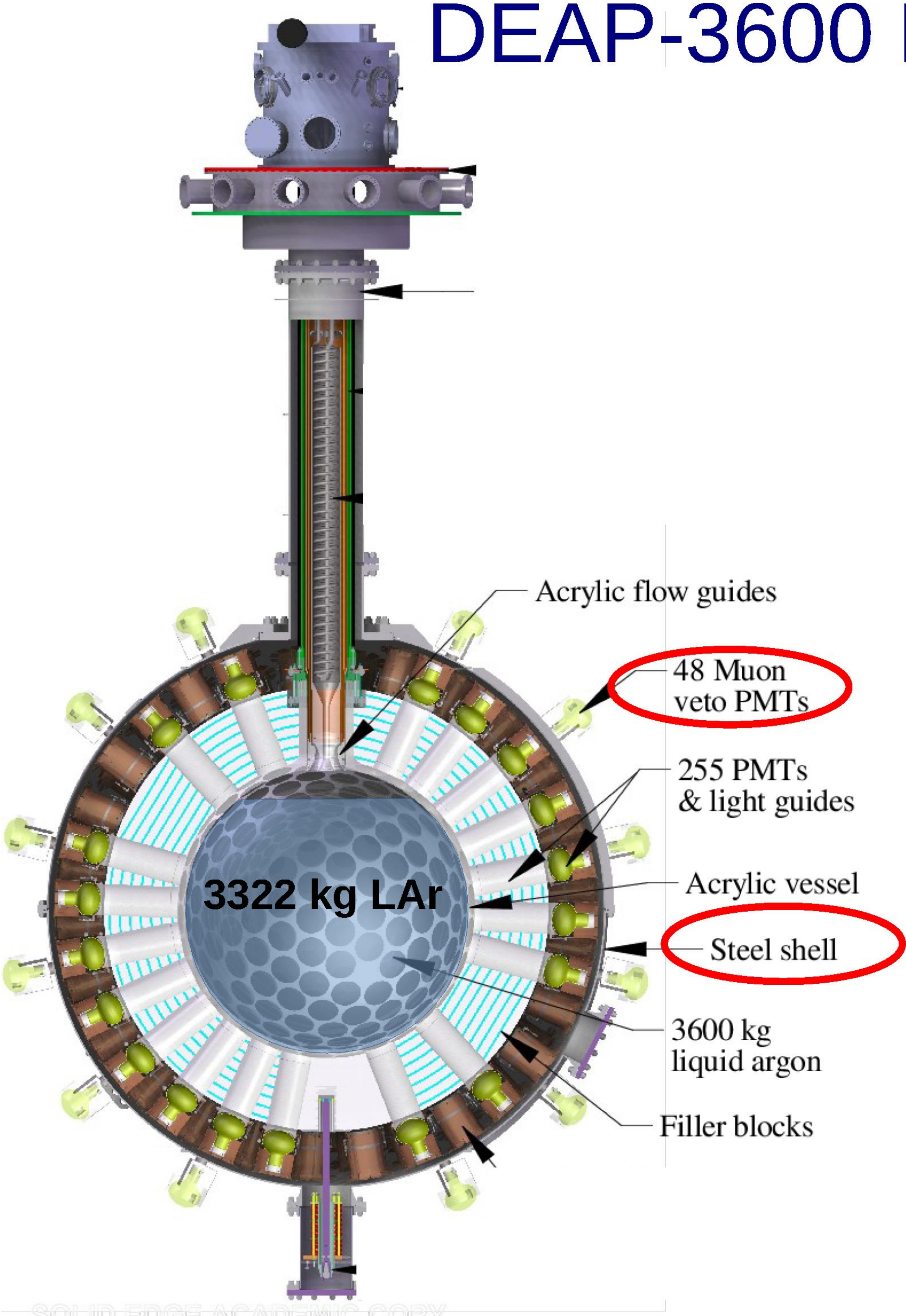
- In-situ vacuum evaporated TPB wavelength shifter (~10 m^2 surface)
- Bonded 50 cm long light guides + polyethylene shielding against neutrons
- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)

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

Background mitigation strategy

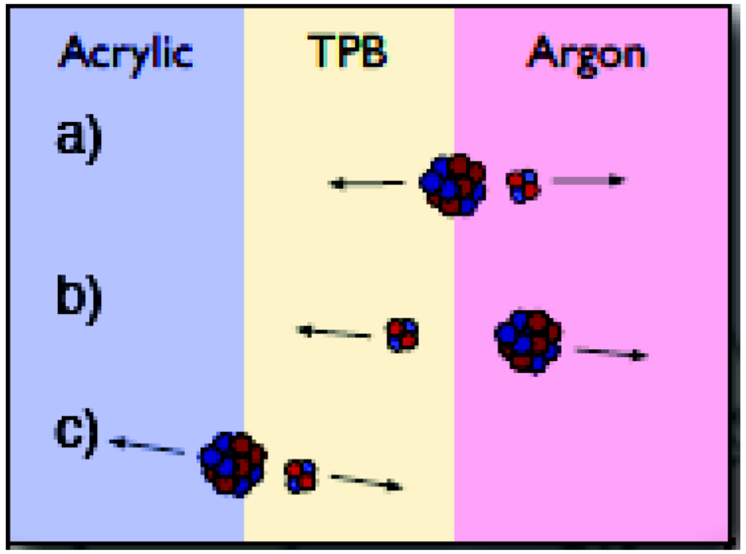
- **β/γ events:** dominated by ^{39}Ar beta decay rate, 1 Bq/kg
  - pulse shape discrimination is **very powerful in liquid argon** ~10^{-10}

- **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

Fabrication and Assay of DEAP Acrylic

- Fabrication from pure MMA monomer at RPTAsia (Thailand), strict control of radon exposure for all steps, to < 10^{-20} g/g ^{210}Pb (RPT was fabricator of the SNO Acrylic Vessel)

- Assay of production acrylic **< 2.2×10^{-19} g/g ^{210}Pb**
  (Corina Nantais M.Sc. Thesis 2014, <0.2 bkg events/3 years)

Monomer cast at RPT Asia, 2010

Thermoformed Panel at RPT Colorado

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DEAP Acrylic Vessel Fabrication

Reynolds Polymer (Colorado)

Underground at SNOLAB

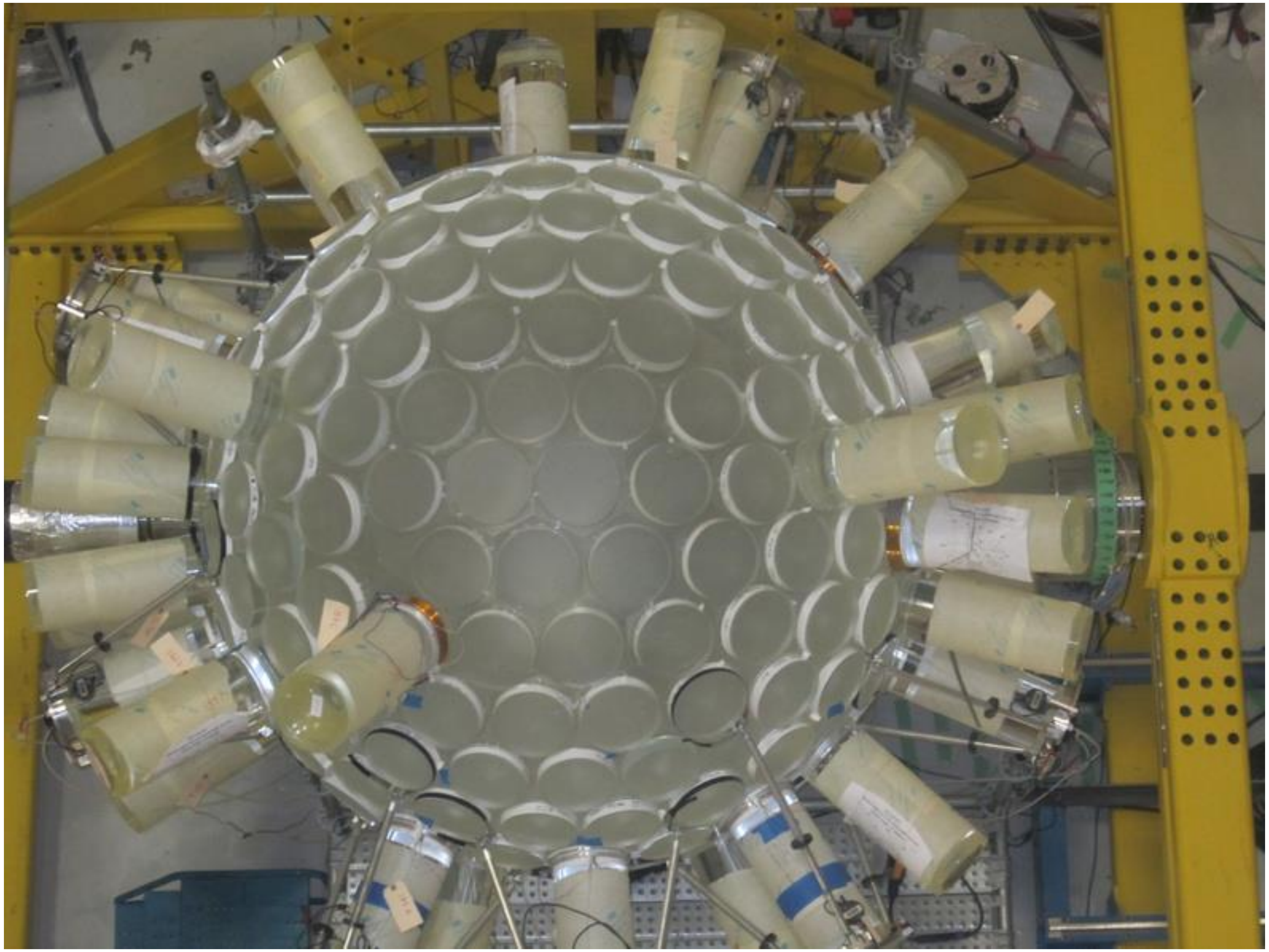
University of Alberta

Panels thermoformed and bonded into sphere
At RPT Colorado (2011)

Machined at U of A (2011, 2012)

Shipped to SNOLAB, neck and light guides
bonded (2012-2014)

Bonding light guides to the DEAP AV, underground at SNOLAB



Light guides bonded then annealed in radon-reduced air oven

>5 meter attenuation length in light guide acrylic!

DEAP AV in “The Rotator” at SNOLAB

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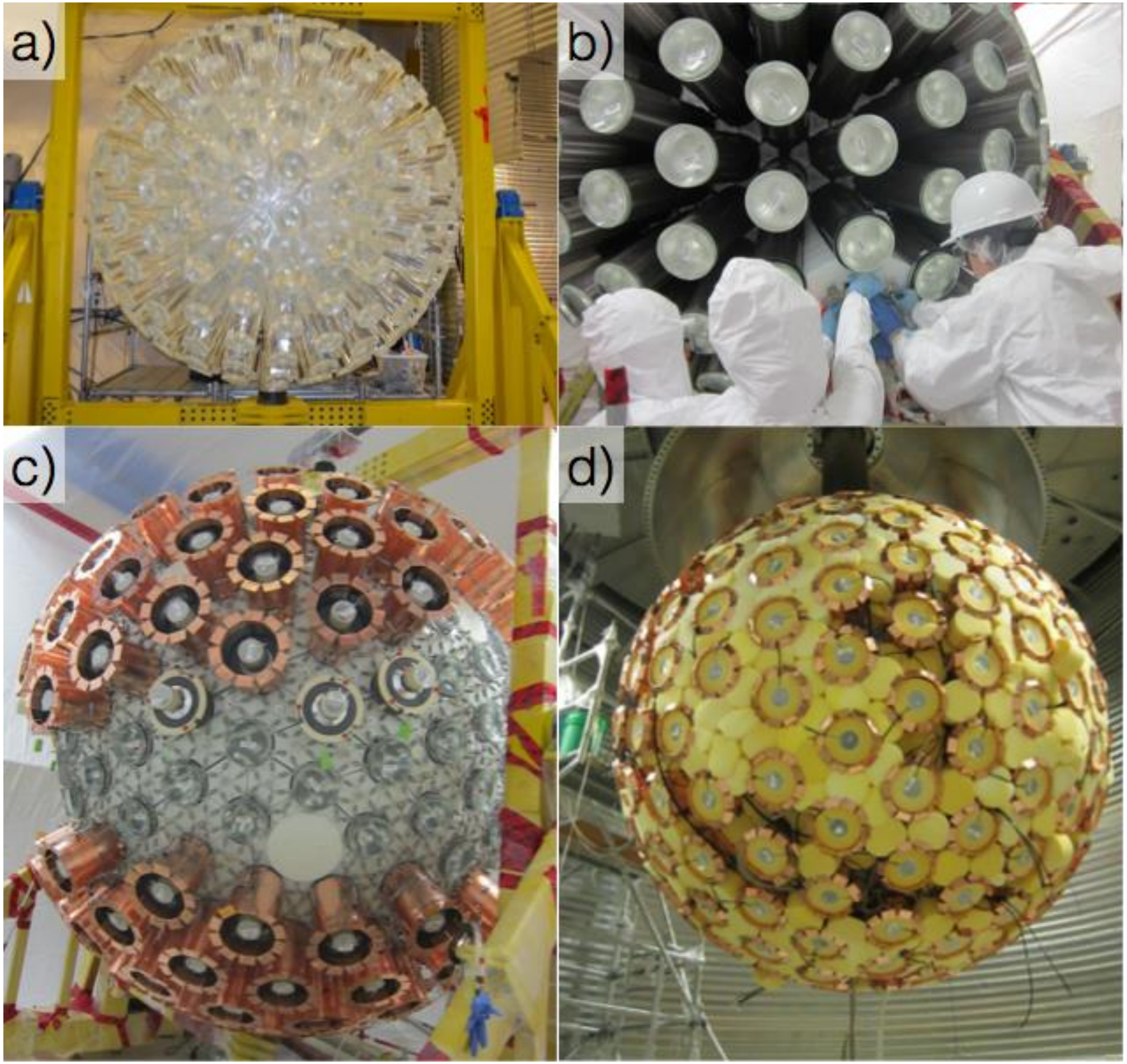
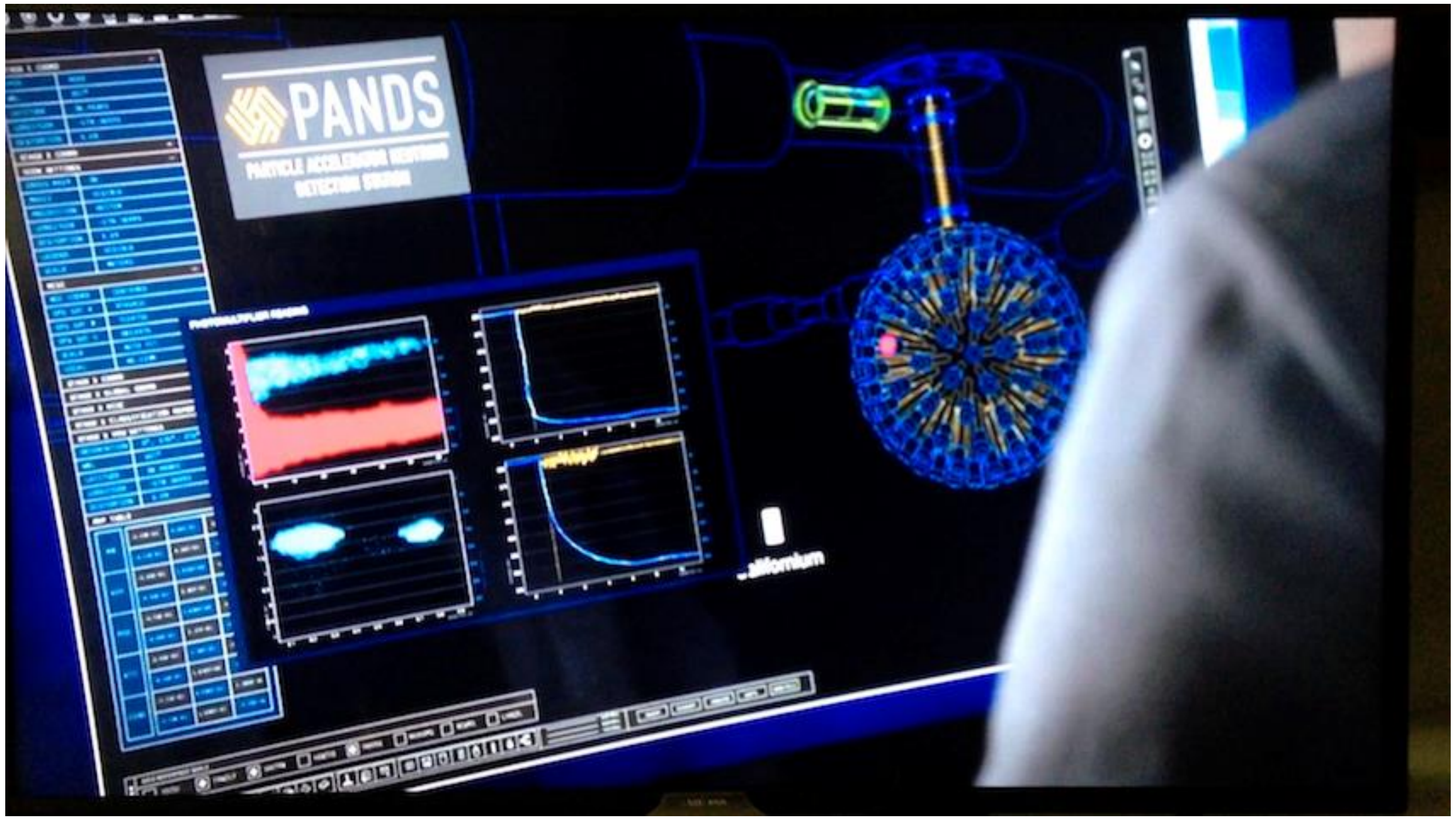
Light guides on AV

Reflectors on light guides



PMT and inner detector installation Oct 2014

Dark Matter in Hollywood



WIMP detector in
"Scorpion TV
series on CBS"

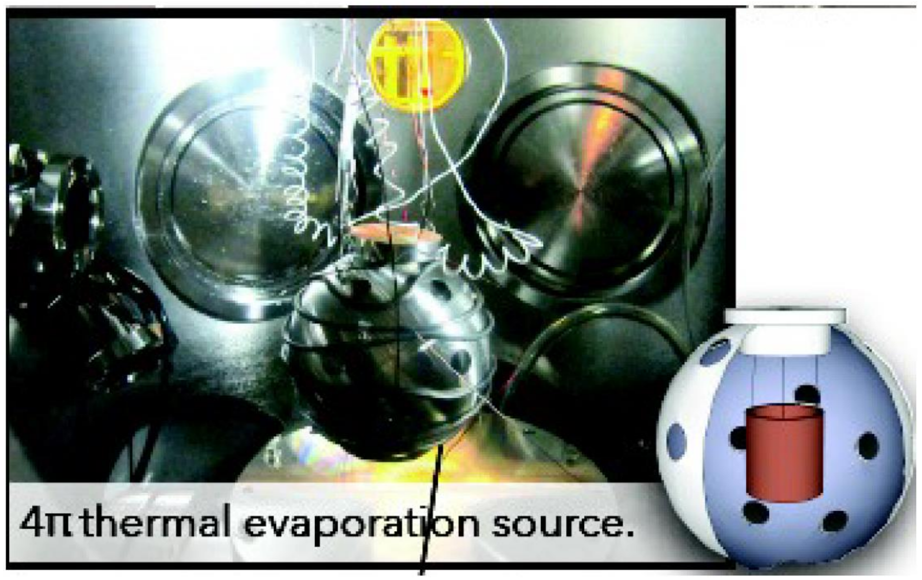
2018

An 18 foot tall sanding robot was deployed in the AV to remove inner surface layer of acrylic
"The Resurfacer"

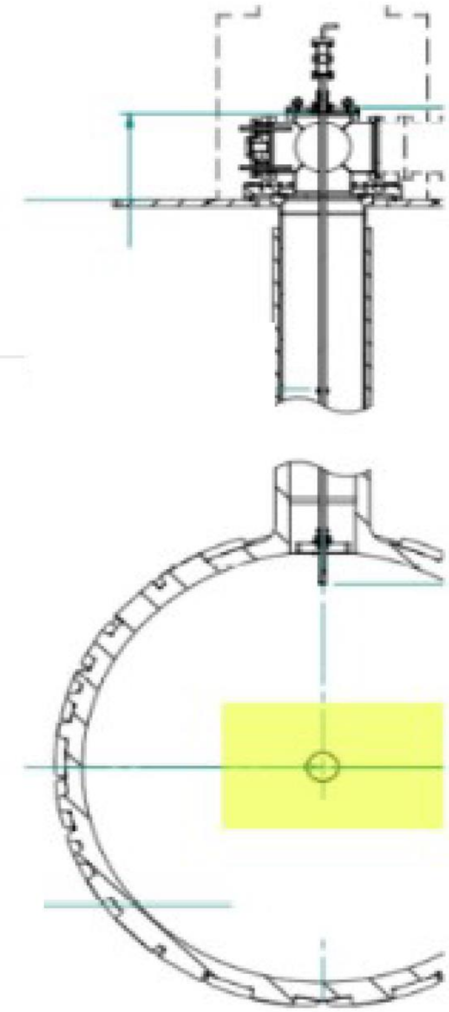
2016 J. Phys.: Conf. Ser. 718 042025

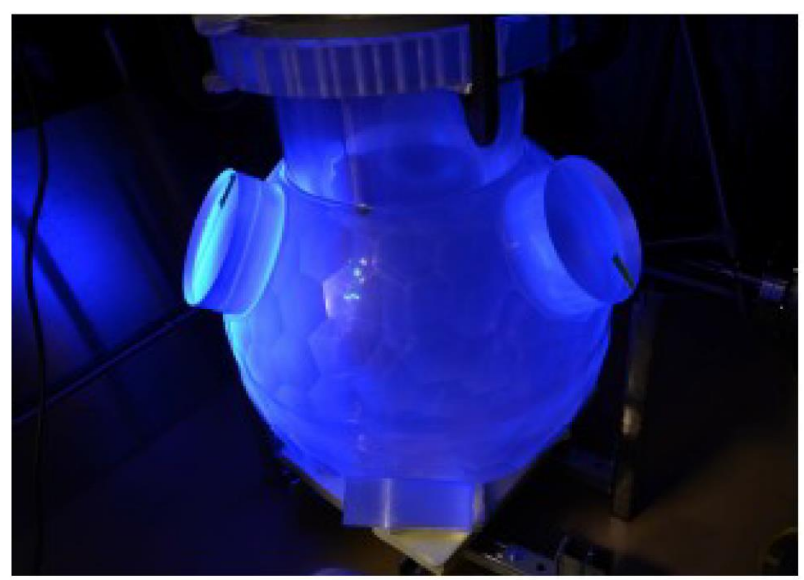
DEAP-3600 wavelength shifter (TPB) evaporation system

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



Evaporation source and deployment system

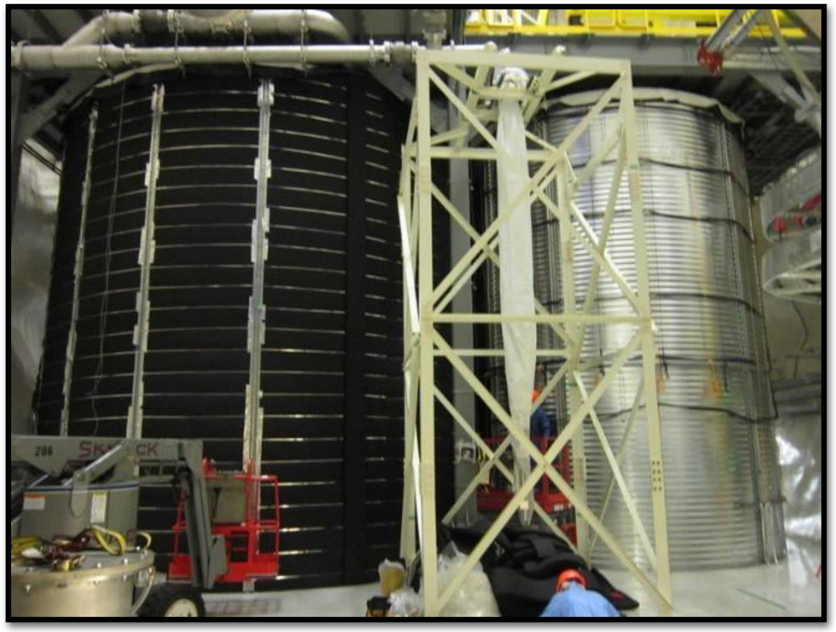


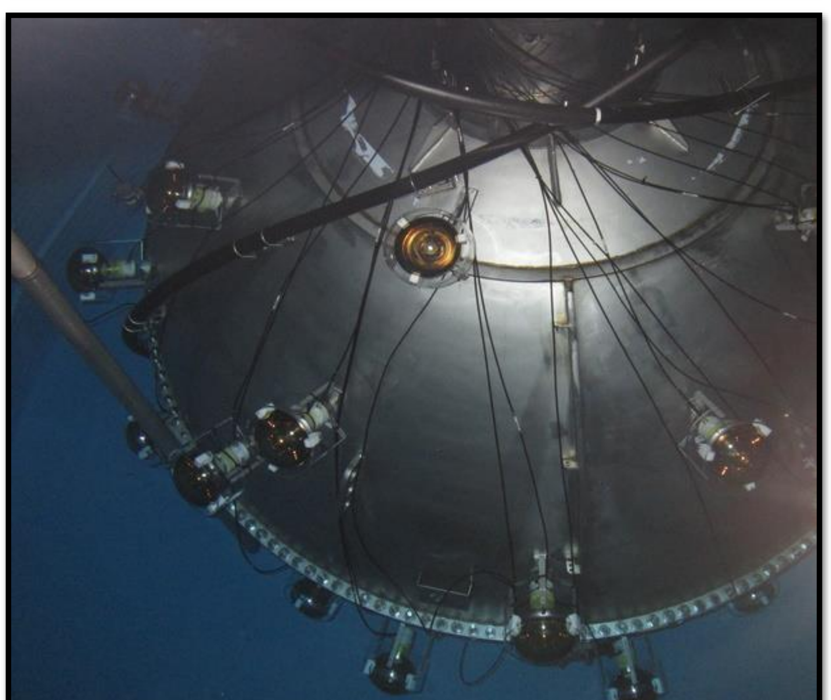


UV illuminated coating on a small test acrylic vessel (20” diameter).

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)

Construction of DEAP-3600 was completed in early 2016





Detector paper: 1712.01982, accepted Astroparticle Physics J.

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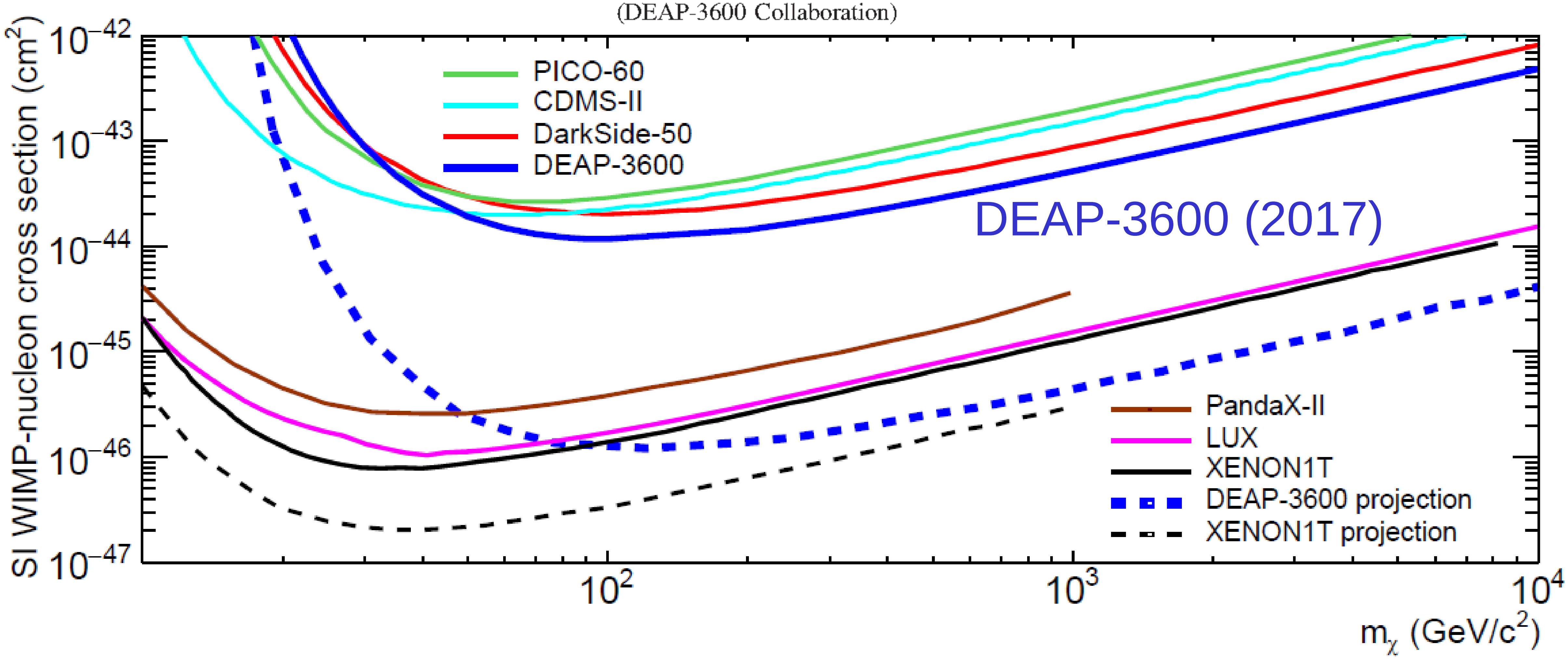
First Results from the DEAP-3600 Dark Matter Search with Argon at SNOLAB

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)



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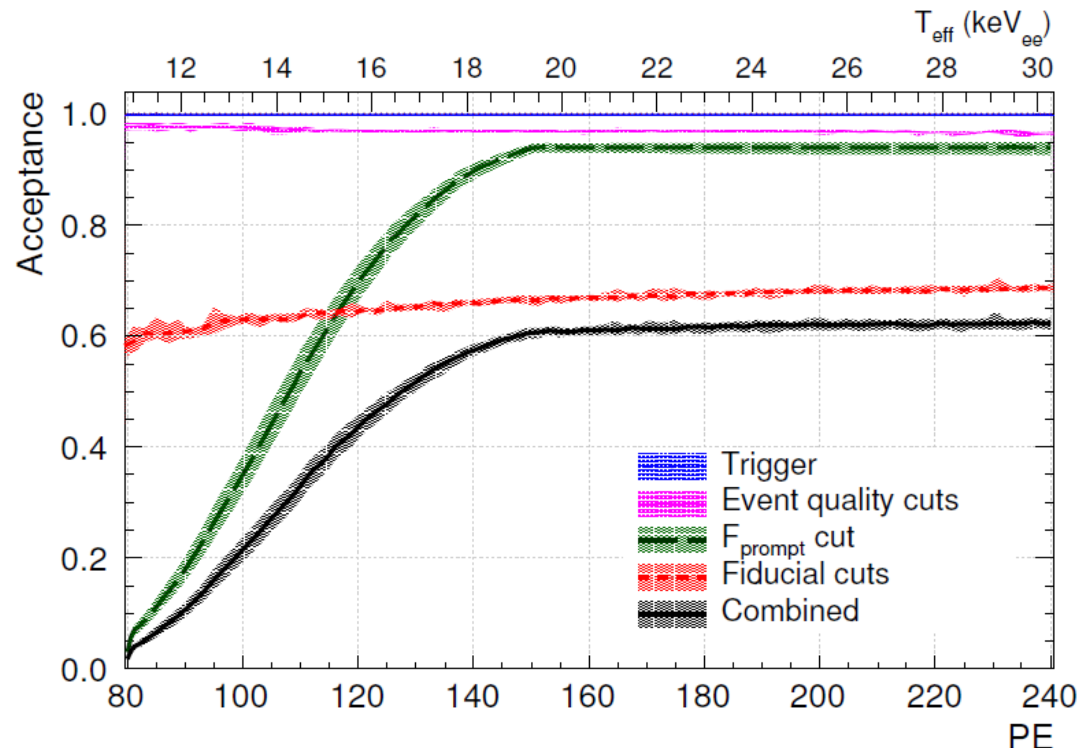
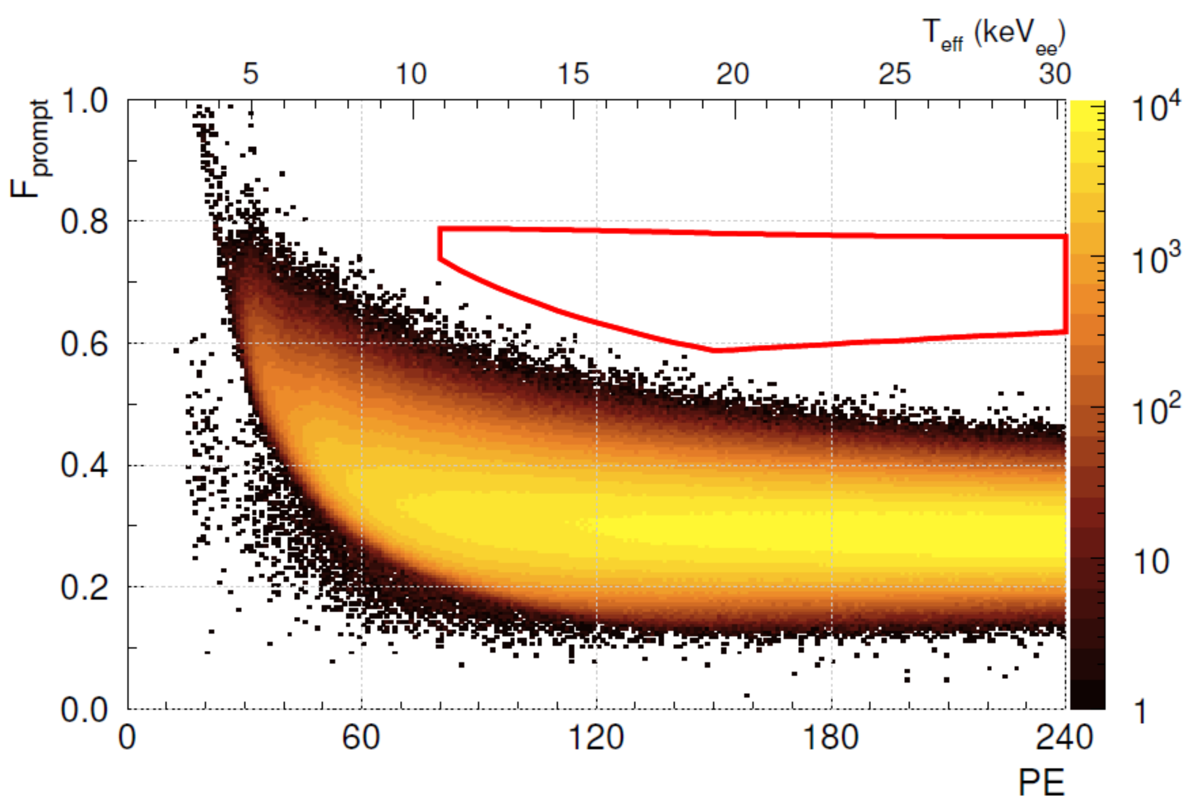
First Dark Matter Search with DEAP-3600 – July 2017





4.4 live days

Selected ROI for < 0.2 leakage from β's

Cuts for instrumental and external events

2223 kg fiducial mass

9,870 kg-day exposure

No events observed in ROI

Light yield consistent with expectation

LY = 7.80 ± 0.21 (fit syst.) ± 0.22 (SPE syst.) PE/keVee

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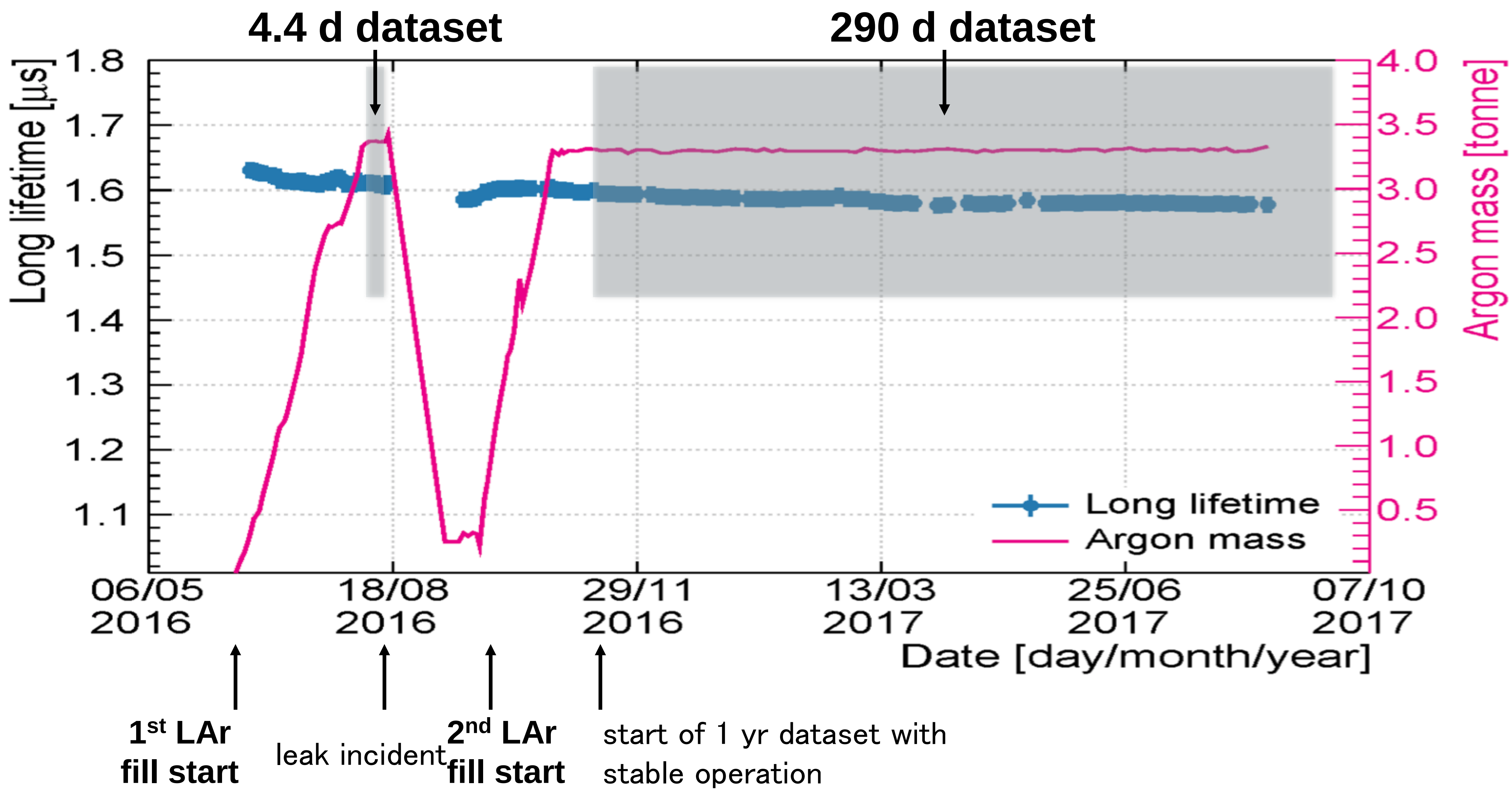
DEAP-3600 Timeline and Datasets



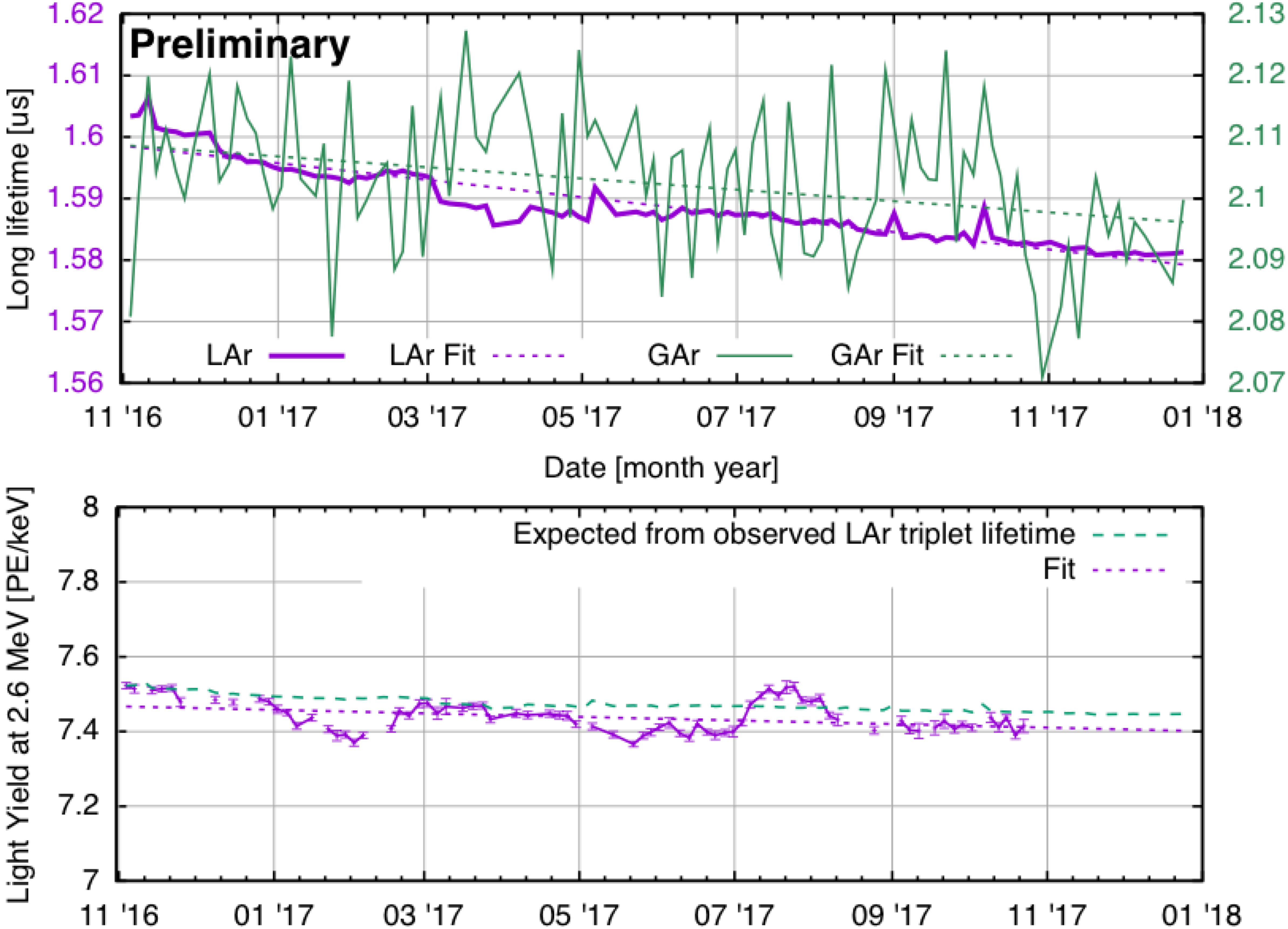
1st LAr fill: Jun - Aug 2016

- 10 day stable period selected as dataset
- 3322 kg of LAr in detector
- **4.4 live day dataset** (9.9 tonne-days fiducial exposure)
- Leak in neck region on August 17, 2016:
  - Contamination of LAr with ≈100 ppb N_2
  - Drain and re-fill LAr to slightly lower liquid level

2nd LAr fill: Sep - Oct 2016

- 1 yr dataset recorded (Nov 2016 - Nov 2017)
  - 3256 kg of LAr in detector
  - **247 live day dataset** (not blind)
  - Stable detector without LAr circulation
- Blinding scheme since Jan 2018 (20% of data visible)
- Plan to run until 2020

Detector stability



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Pulse shape discrimination (PSD)

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

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

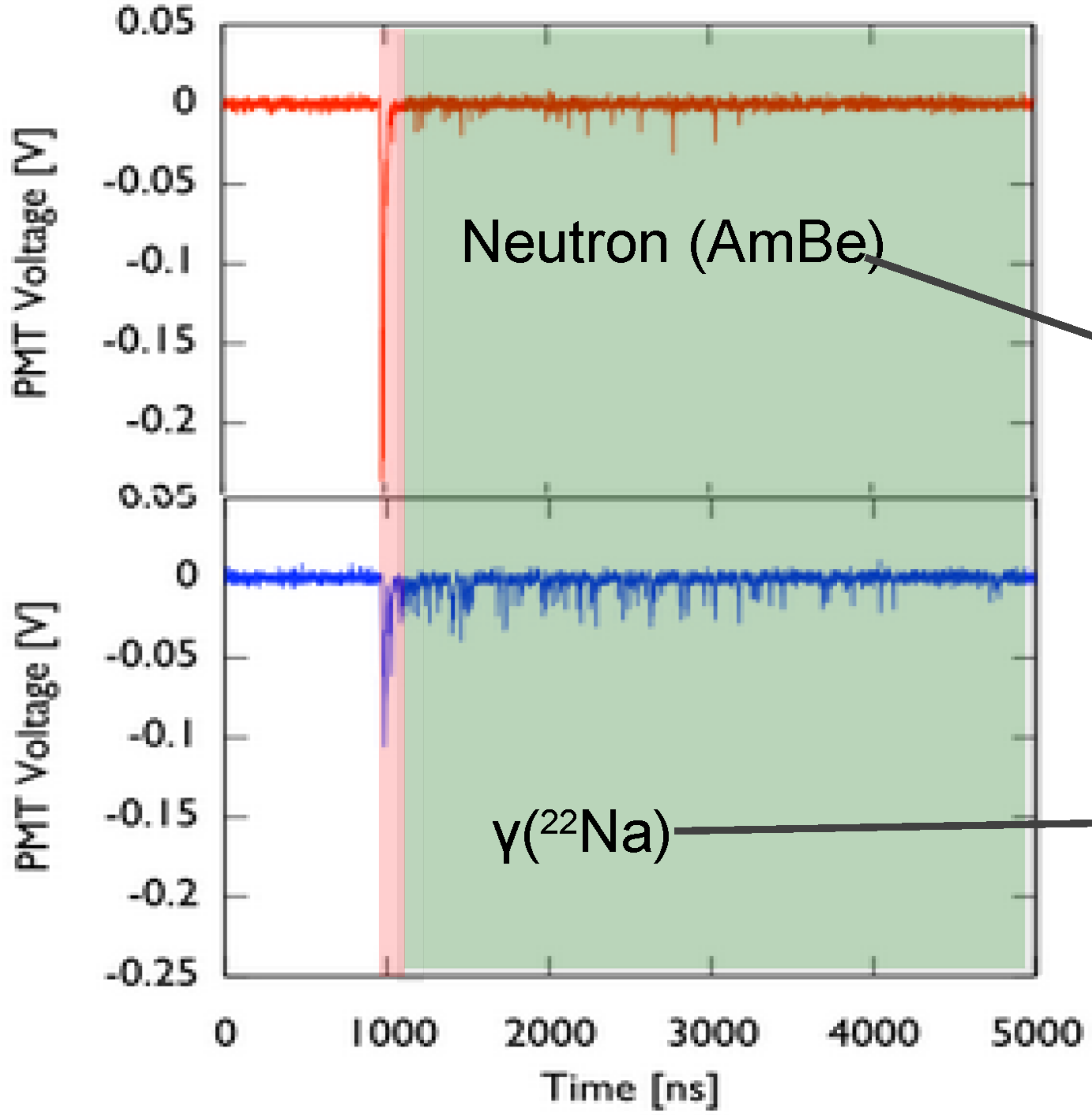
Single phase LAr:

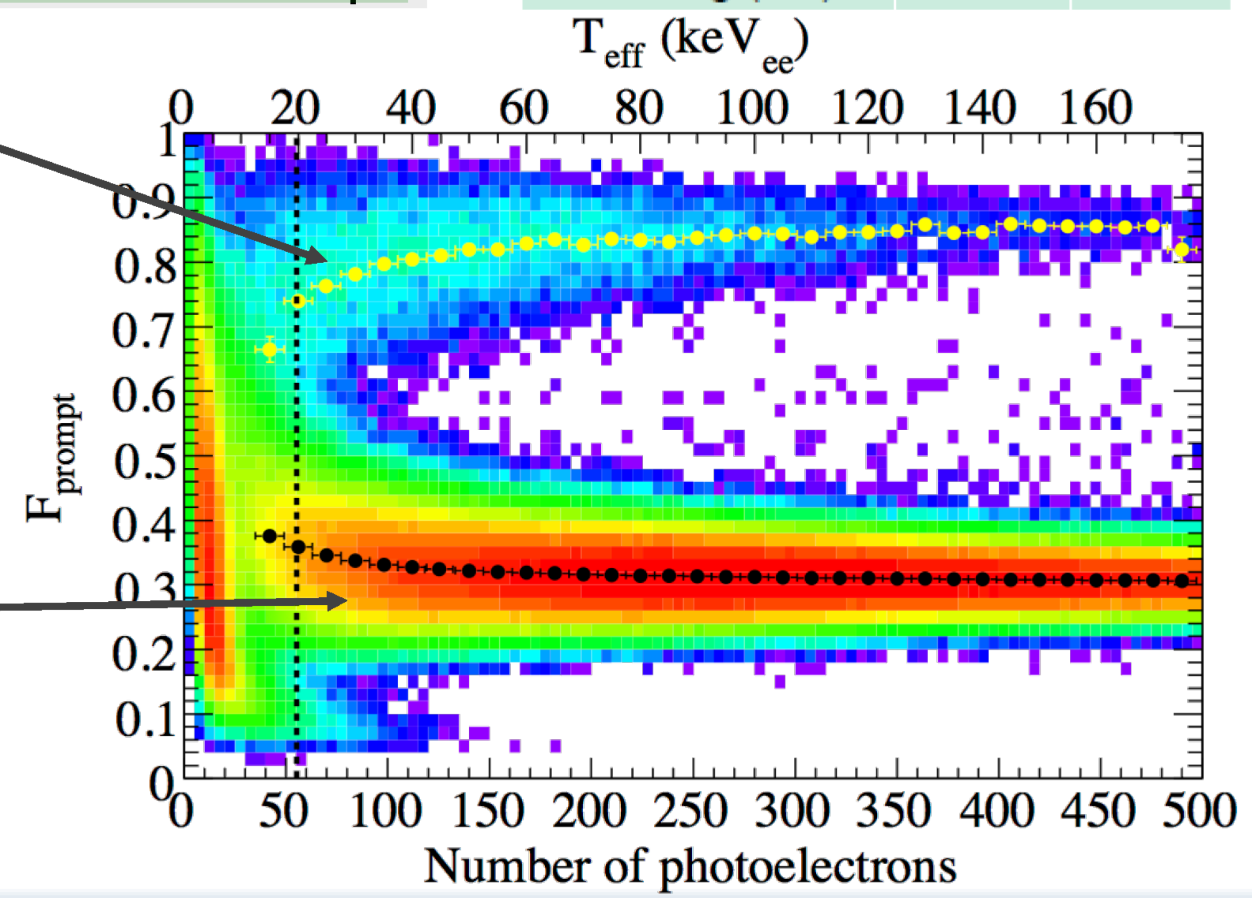
scintillation channel is sufficient for β/γ rejection
no need for the ionization channel

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

PMT signal:

Prompt : 0-150ns
Late: 150ns-10μs





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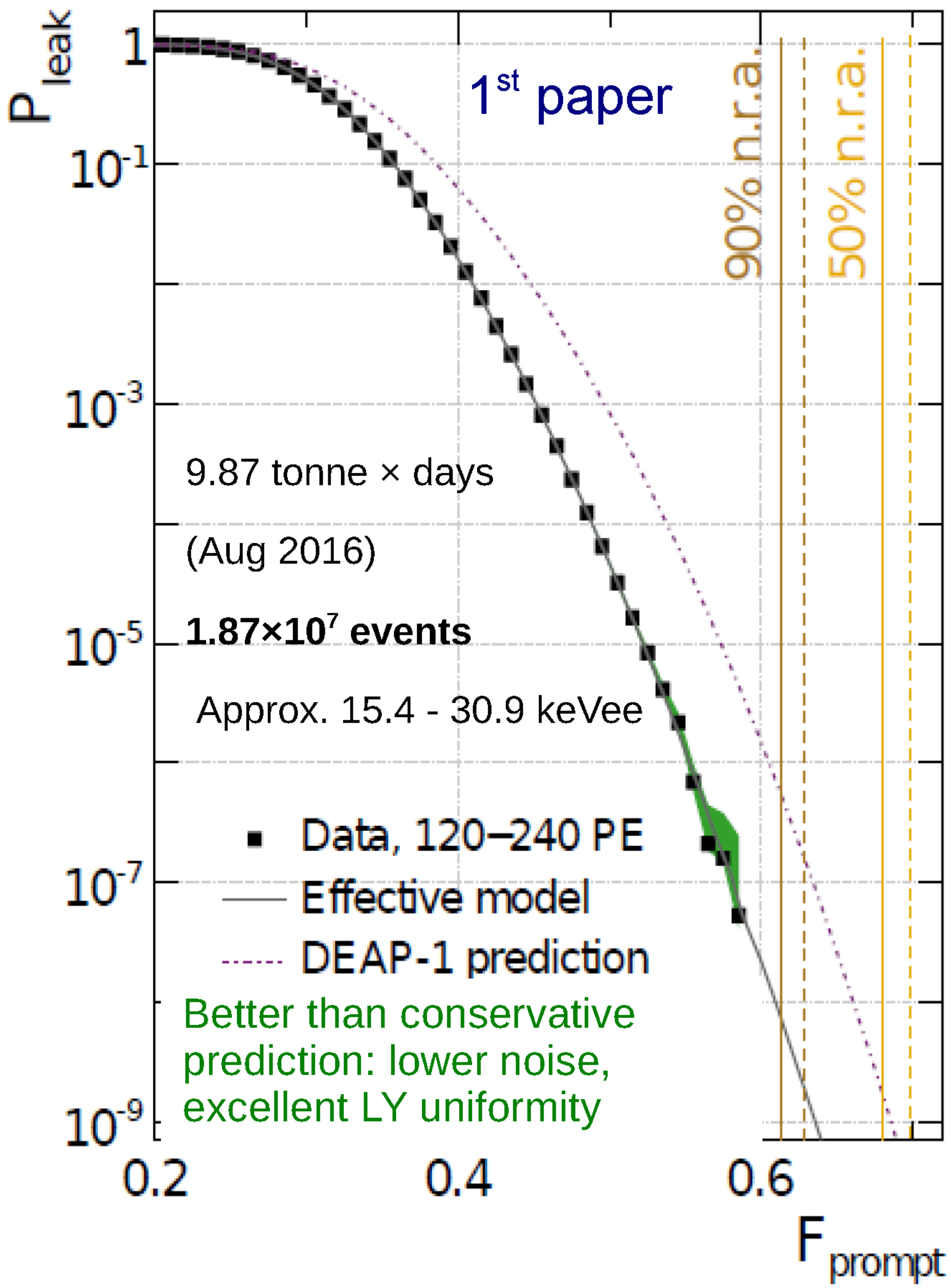
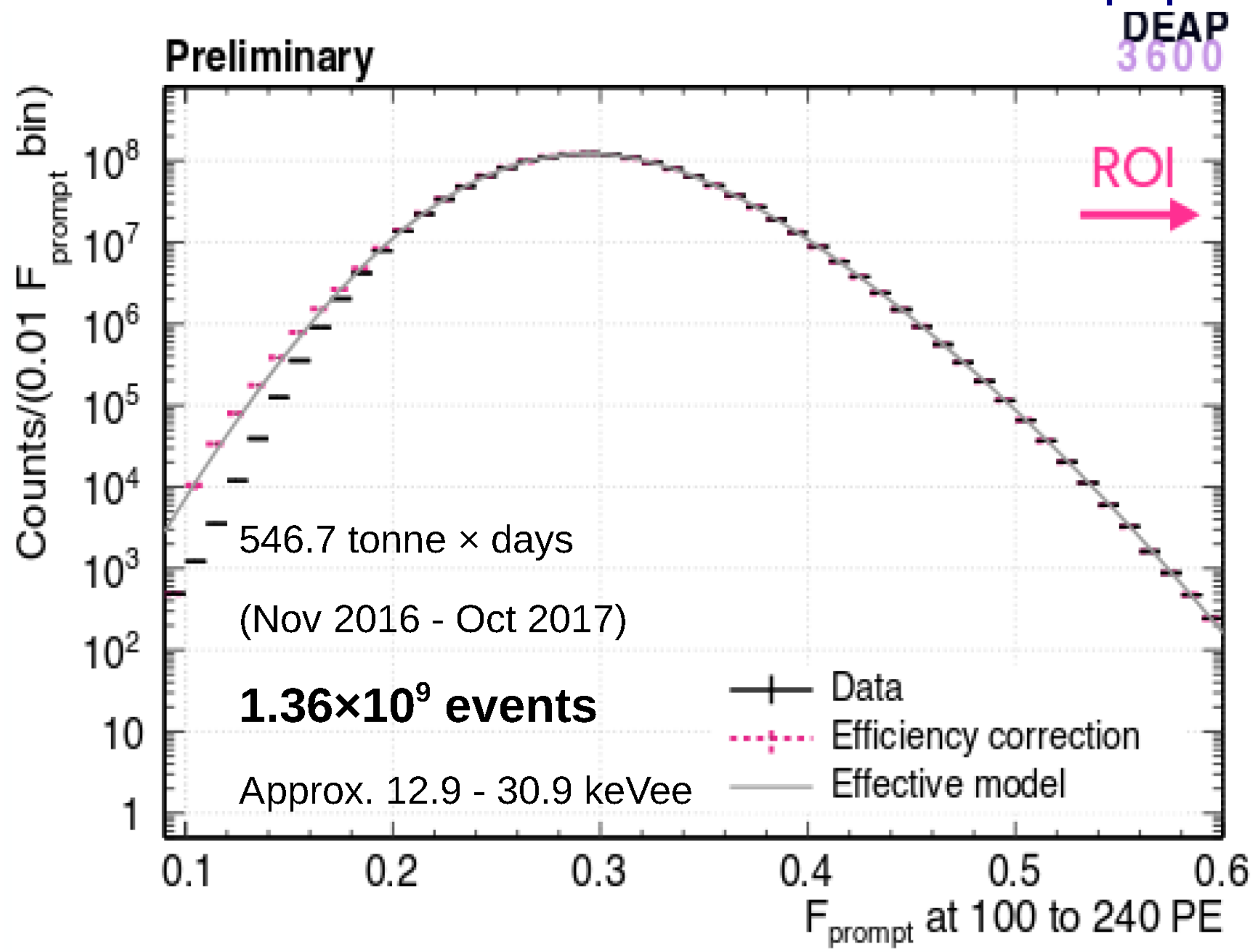
PSD in DEAP-3600



100-fold increase in statistics since the 1st paper



- 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

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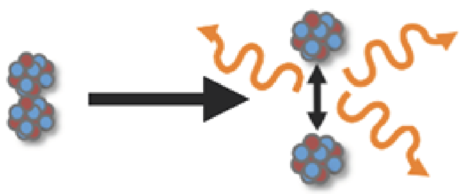
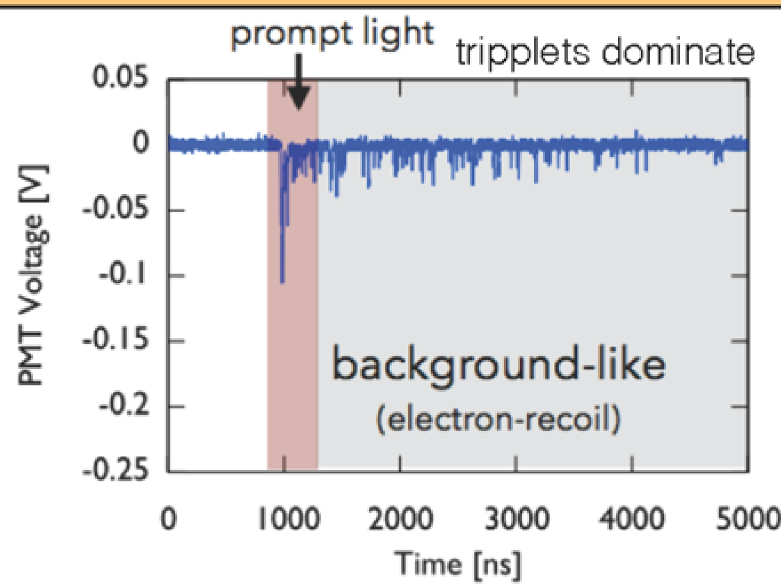
Experimental Signatures

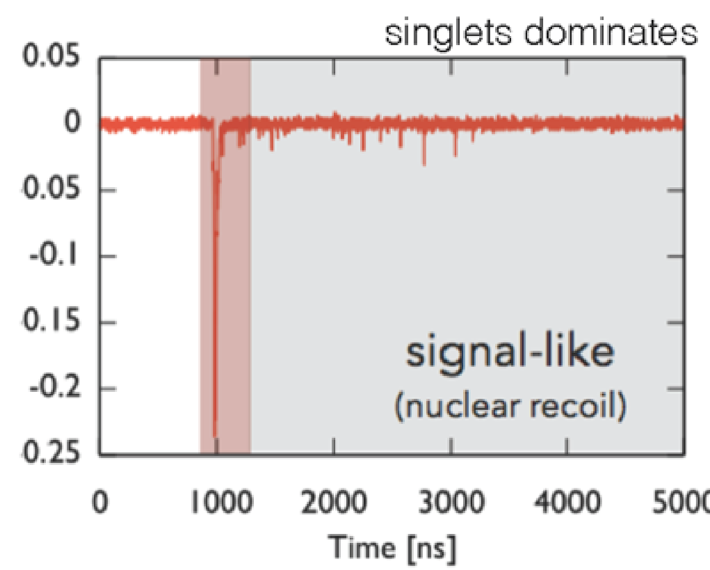
Ar scintillation:

- excimers are create



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

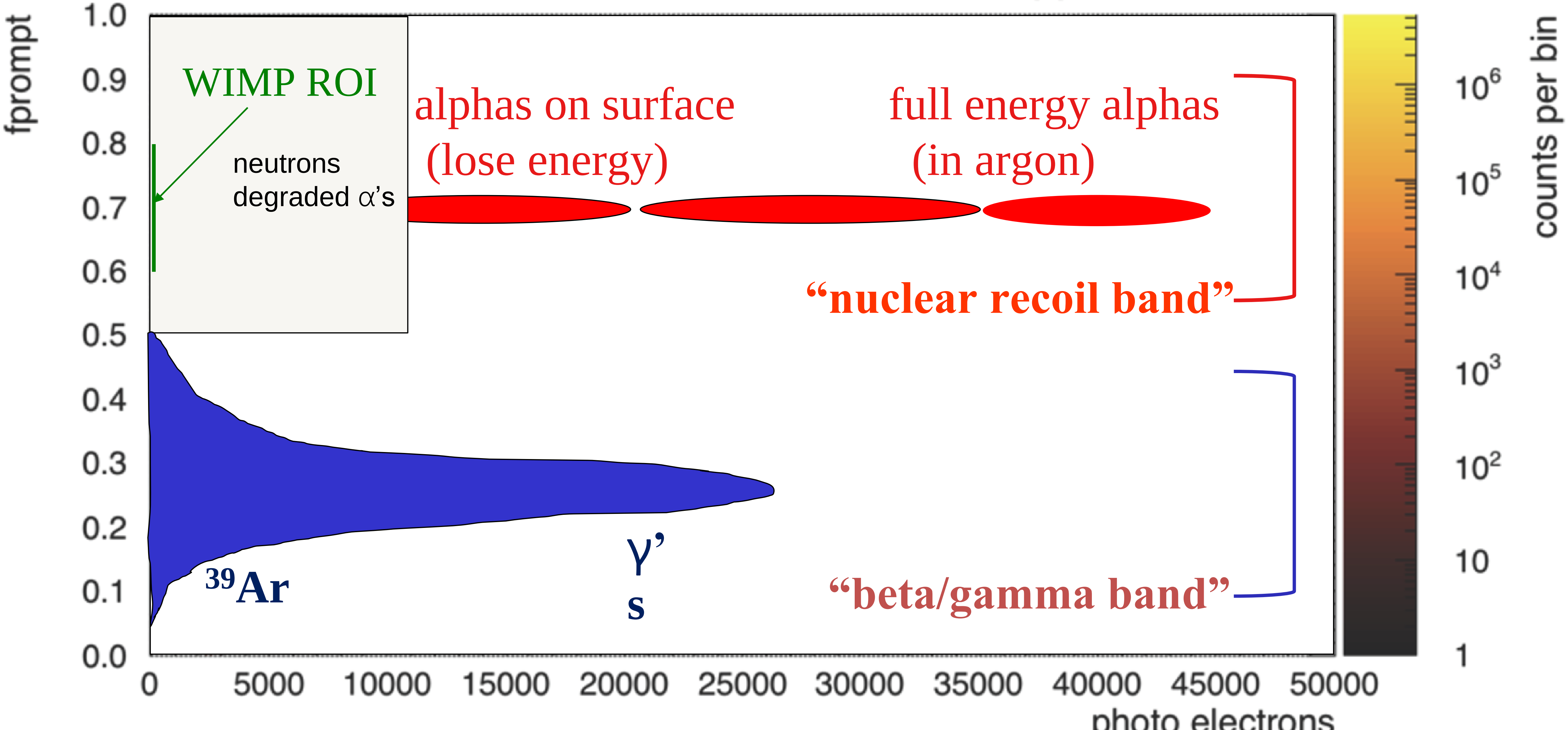




Pulse shape discrimination (PSD) parameter:

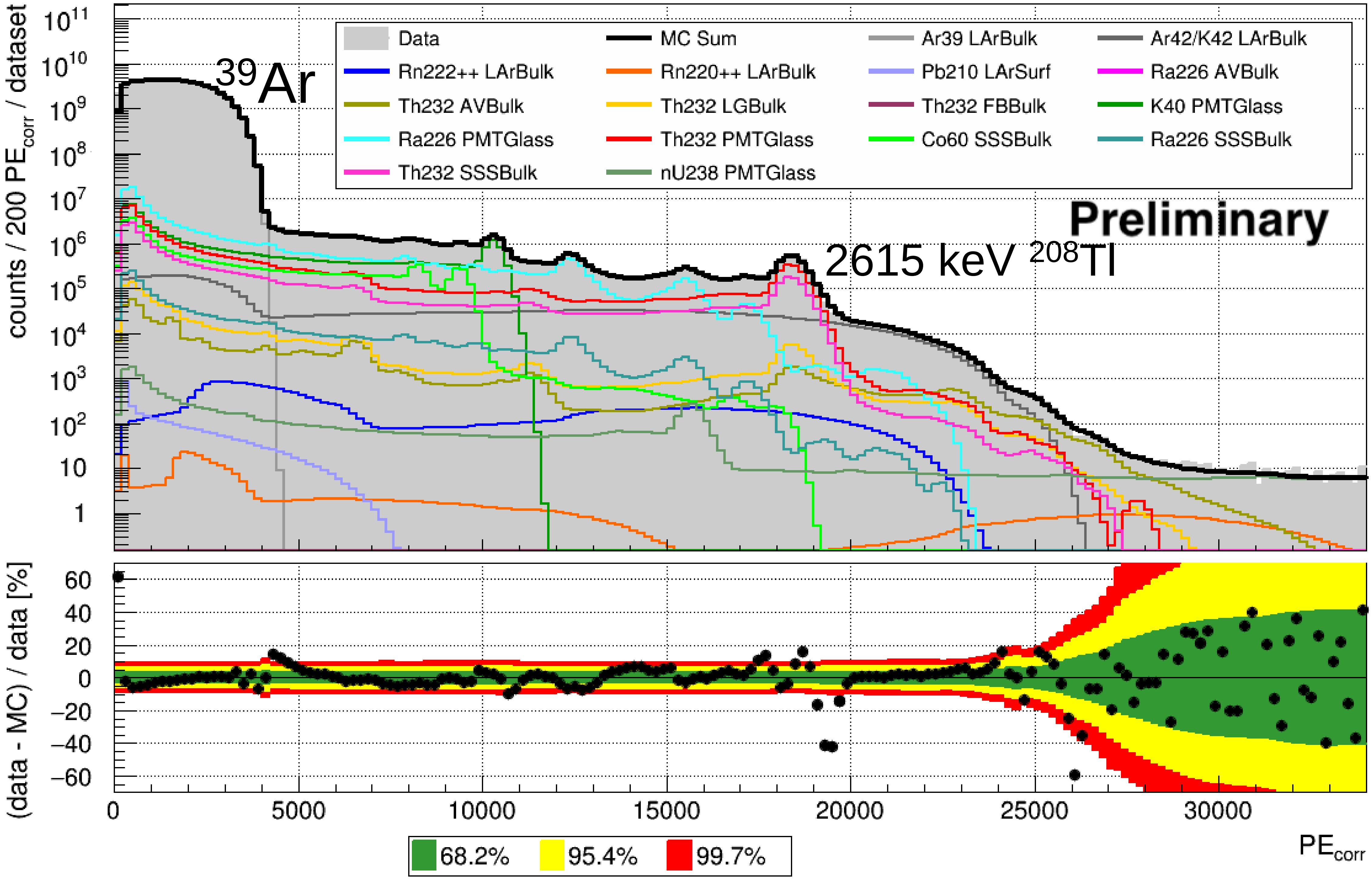
fprompt =

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



DEAP 3600 commissioning data

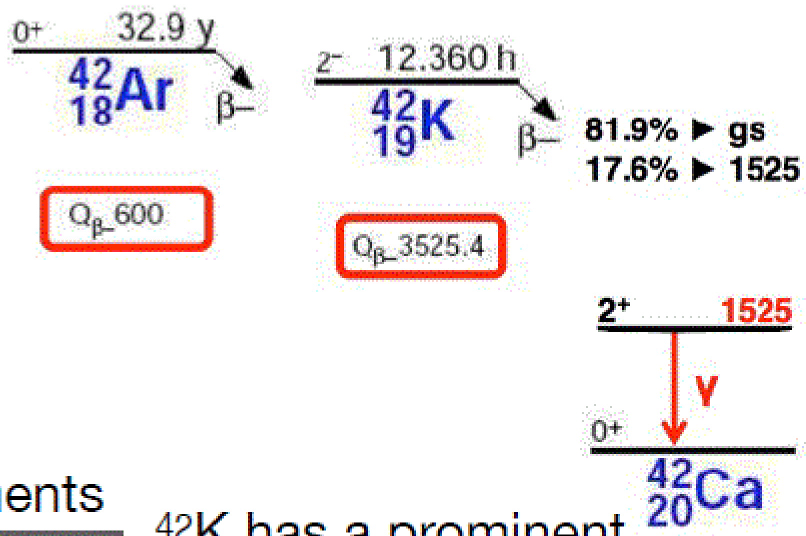
γ Backgrounds (see Bjoern's Lehnert's poster for this and other results)



Dominant internal background above ^{39}Ar is ^{42}Ar, which is produced through:

^{40}Ar(α,2p)^{42}Ar in upper atmosphere, maybe successive n captures on argon, so may be lower in underground argon

^{42}Ar / ^{42}K Specific Activity



- ^{42}Ar is mainly produced via (α,n) reactions on ^{40}Ar in the outer atmosphere.
- The decay chain with ^{42}Ar - ^{42}K is the dominant background in GERDA and LEGEND 0νββ experiments. The specific activity is debated in the literature *(table below)*

(below): other measurements

Experiment	Technique	Activity [µBq/kg]	Reference
DBA	LAr ion. det.	< 61.4 (90% CL)	Ashitkov et al. 1998
DBA	LAr ion. det.	< 44.0 (90% CL)	Ashitkov et al. 2003
GERDA Phase I	HPGe γ-spec.	$= 91^{+8}_{-20}$ - 168^{+22}_{-18}	GERDA 2016
DBA	LAr ion. det.	$= 92^{+22}_{-46}$	Barabash et al. 2016
DEAP-3600	**Scintillation**	**= 39.6 ± 5.8**	**unpublished preliminary**

^{42}K has a prominent signature in DEAP-3600 above 2.6 MeV *(BG model left).* Different systematics apply compared to GERDA and DBA. A significantly lower specific activity is measured

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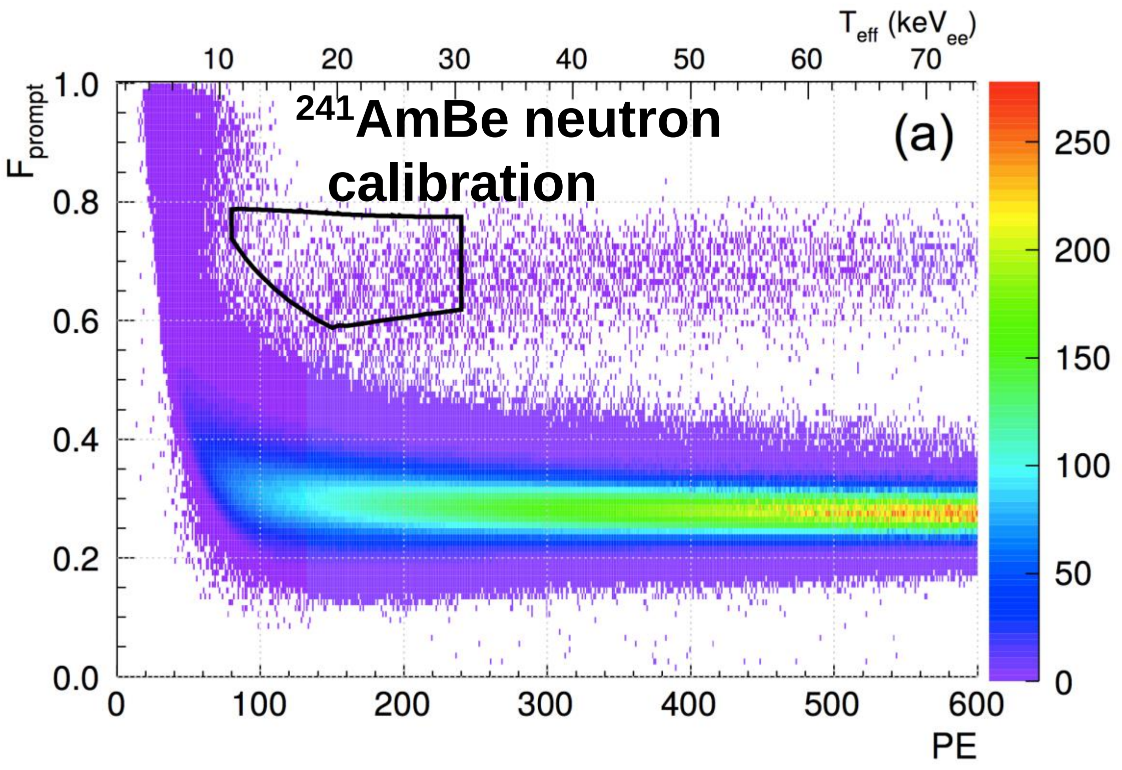
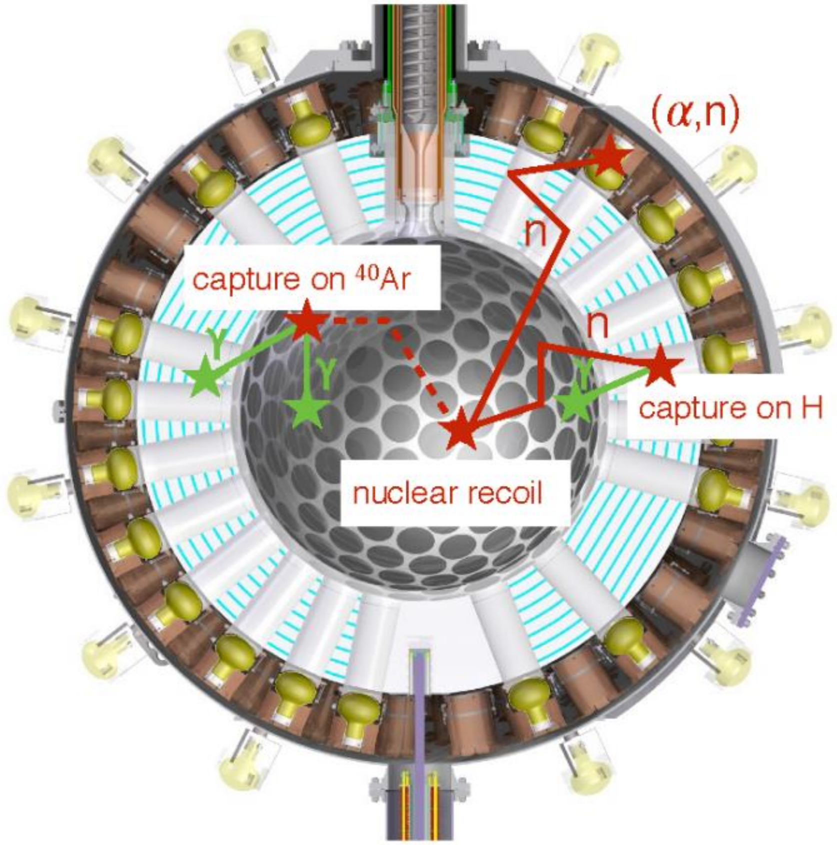
Neutron Backgrounds

- 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



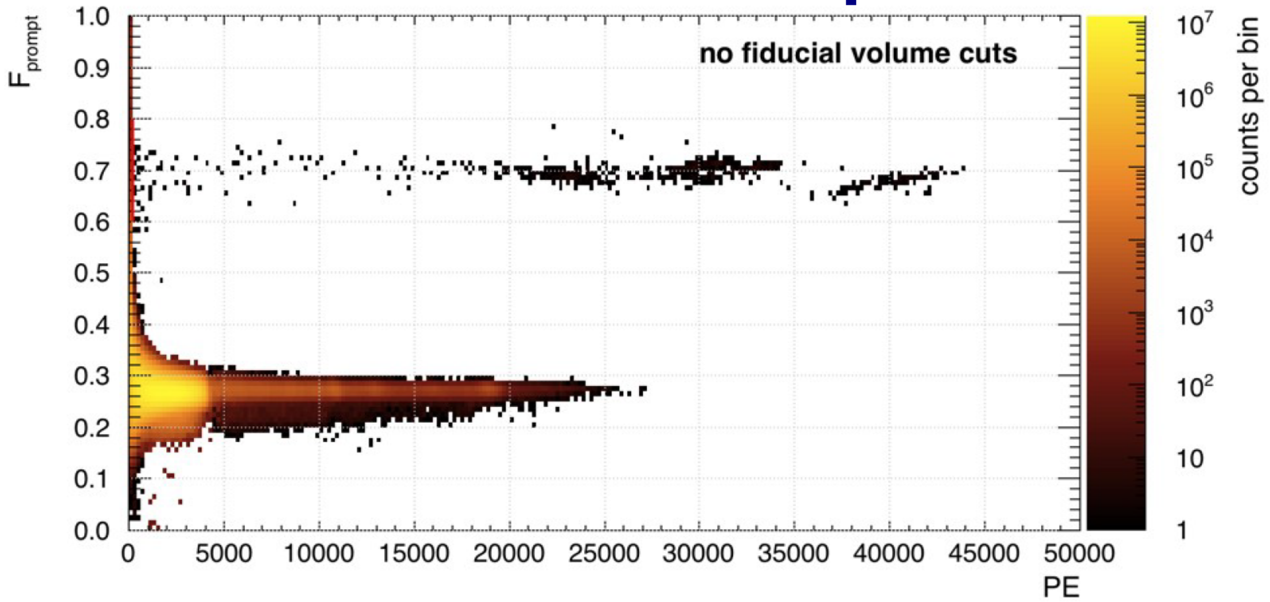


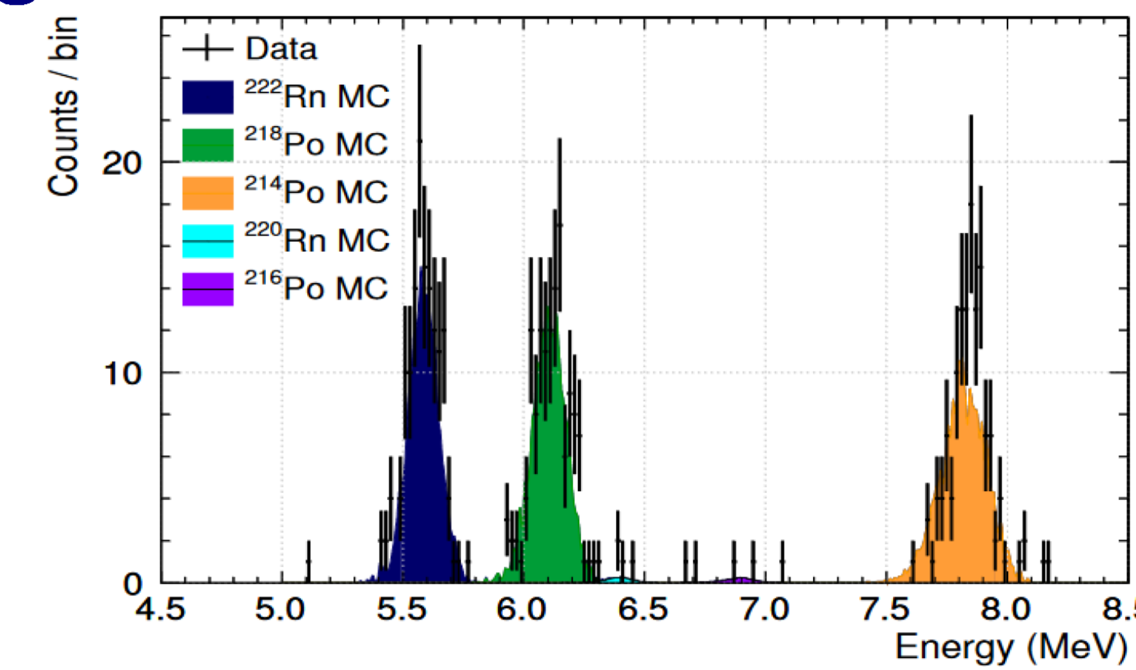
Data driven limit on neutron interactions:

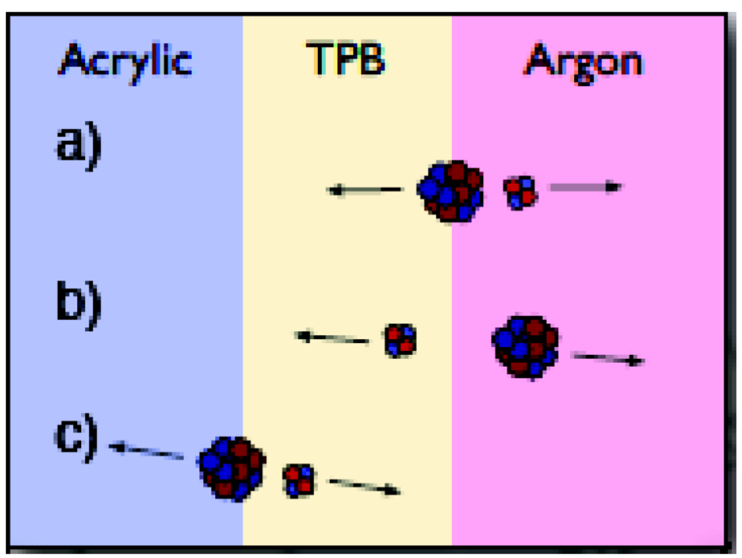
- **Tag with capture gammas:**
  - 2.2 MeV **γ** form ^{1}H in acrylic
  - 6.1 MeV **γ**-cascade from ^{40}Ar in LAr
  - Search for n - **γ** coincidences
- **Preliminary result:**
  - No coincidence found above expected random background In 4.4 day dataset (consistent with target value)

  - Measurement in 1-year dataset in upcoming publication (2018)

Alpha backgrounds







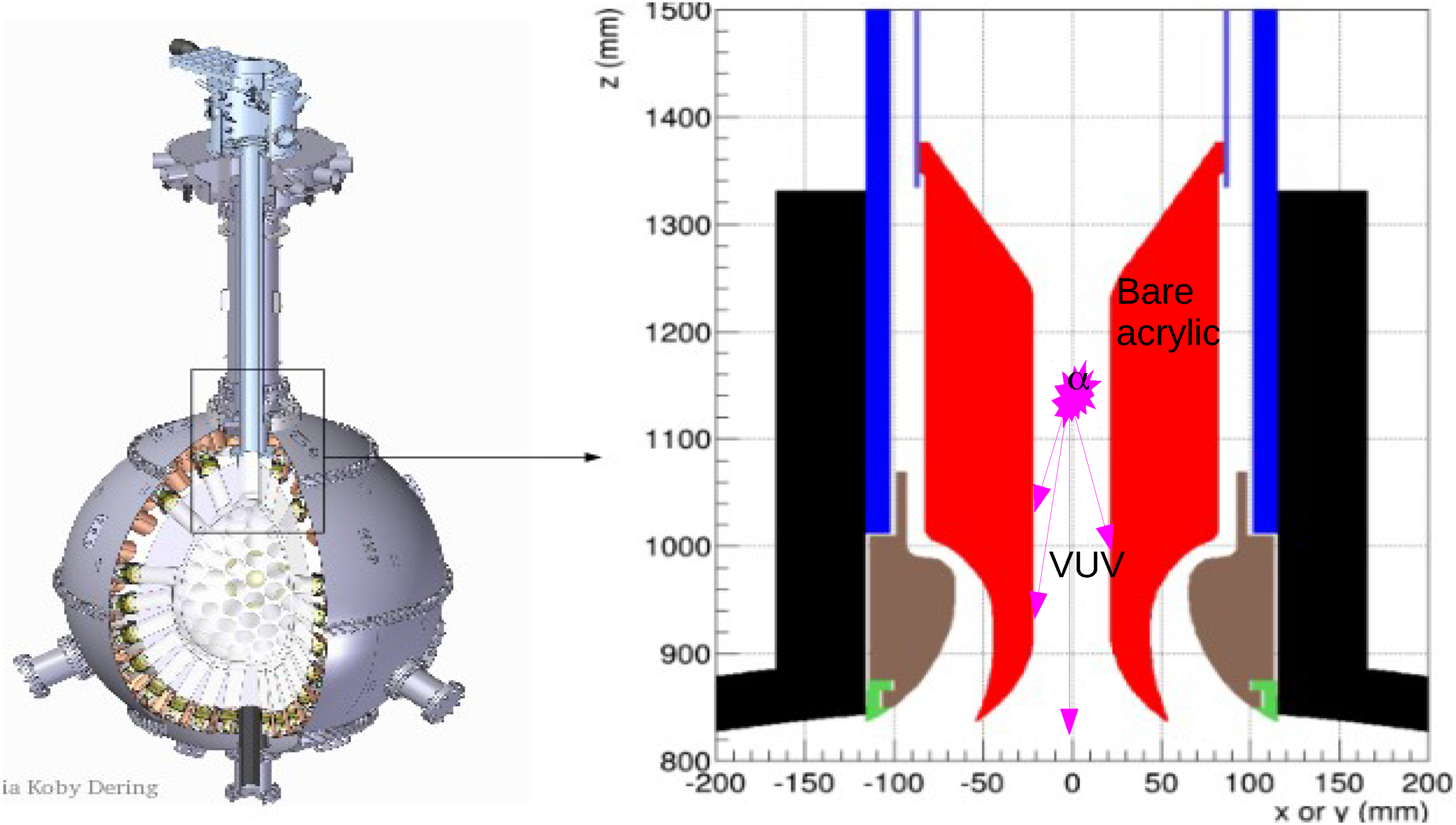
Component	Activity
^{222}Rn LAr	$(1.8\pm0.2)\times10^{-1}$ µBq/kg
^{214}Po LAr	$(2.0\pm0.2)\times10^{-1}$ µBq/kg
^{220}Rn LAr	$(2.6\pm1.5)\times10^{-3}$ µBq/kg
^{210}Po AV surface	0.22 ± 0.04 mBq/m^2
^{210}Po AV bulk	<3.3 mBq

- 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.

Additional cuts and position reconstruction to mitigate this background (details in upcoming paper)

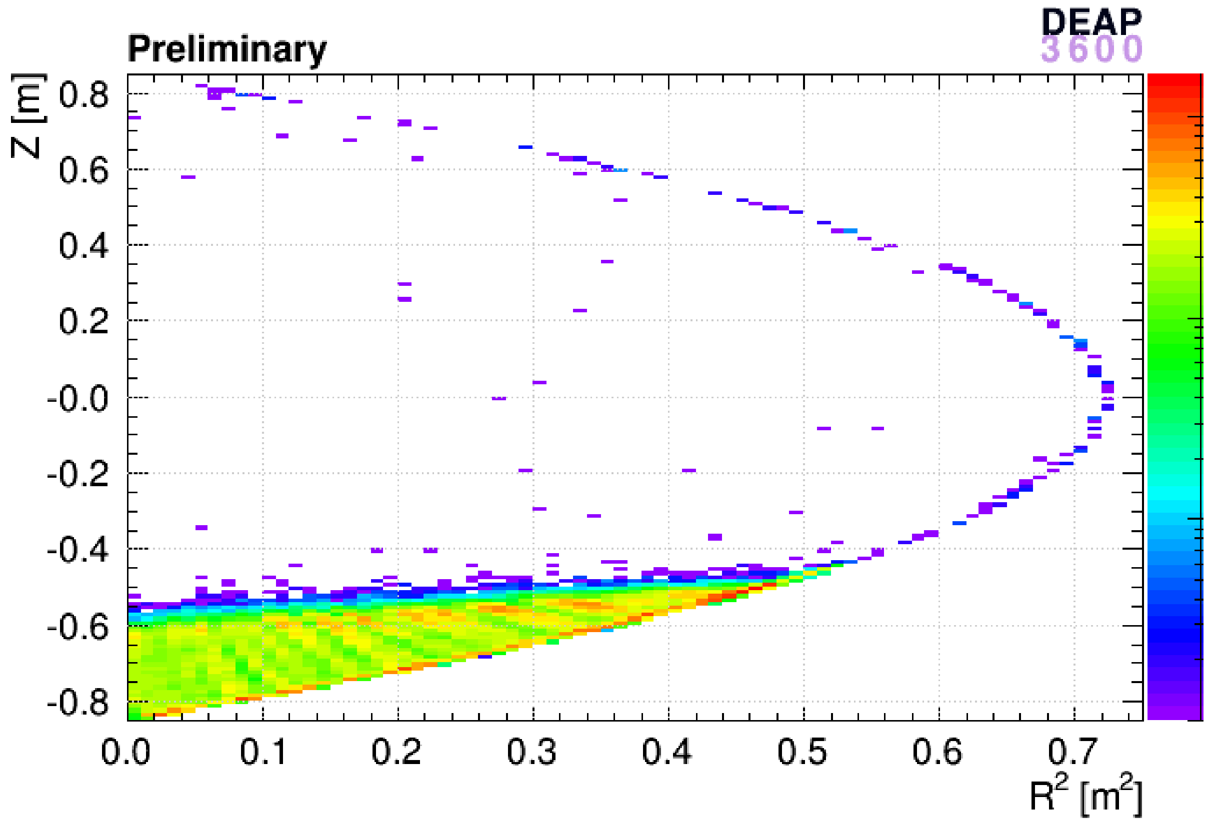
Position Reconstruction

Position reconstruction using spatial information (only) mitigates surface events

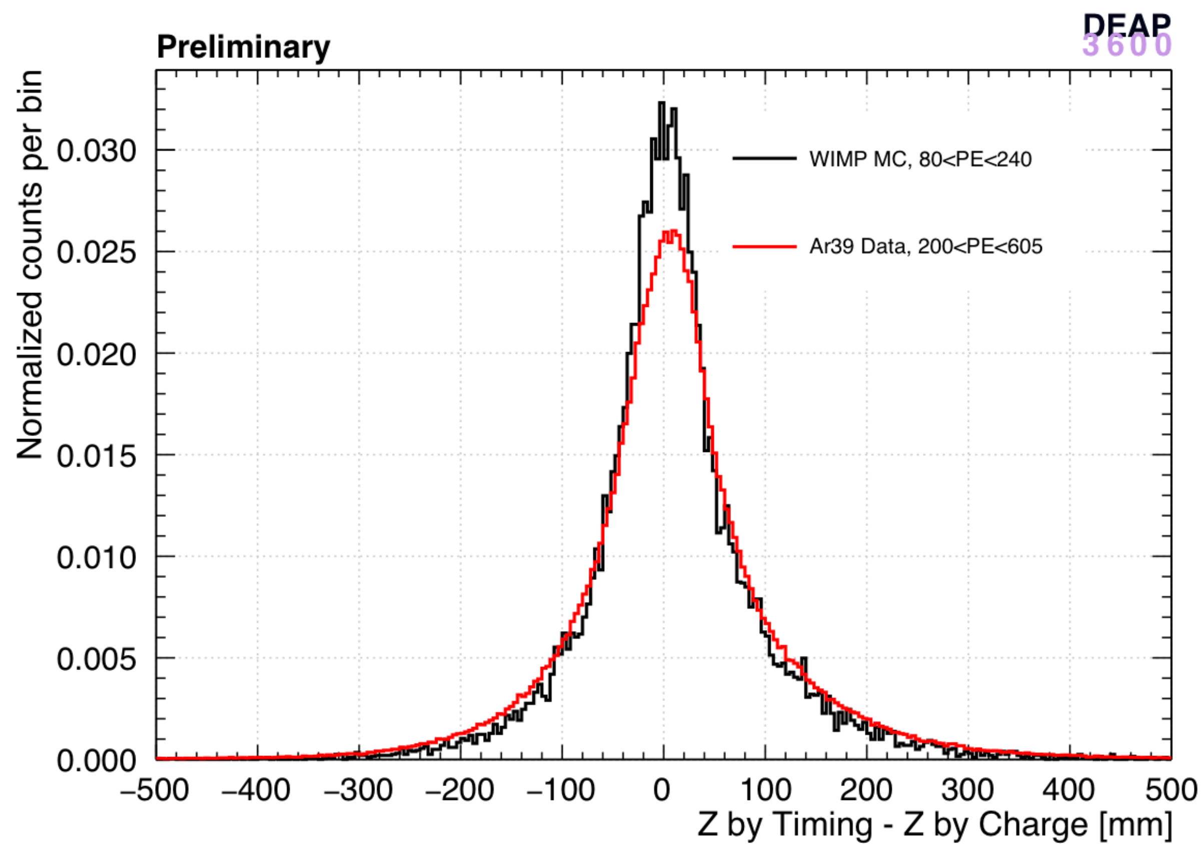
(design was for 10^{-3} leakage into fiducial volume, details in upcoming paper)

Also developed time-of-flight fitter, further reduces mis-reconstruction. Note that UV light speed is

11 cm/ns in LAr!



position reconstruction during fill



DEAP-3600 Current Status and Highlights

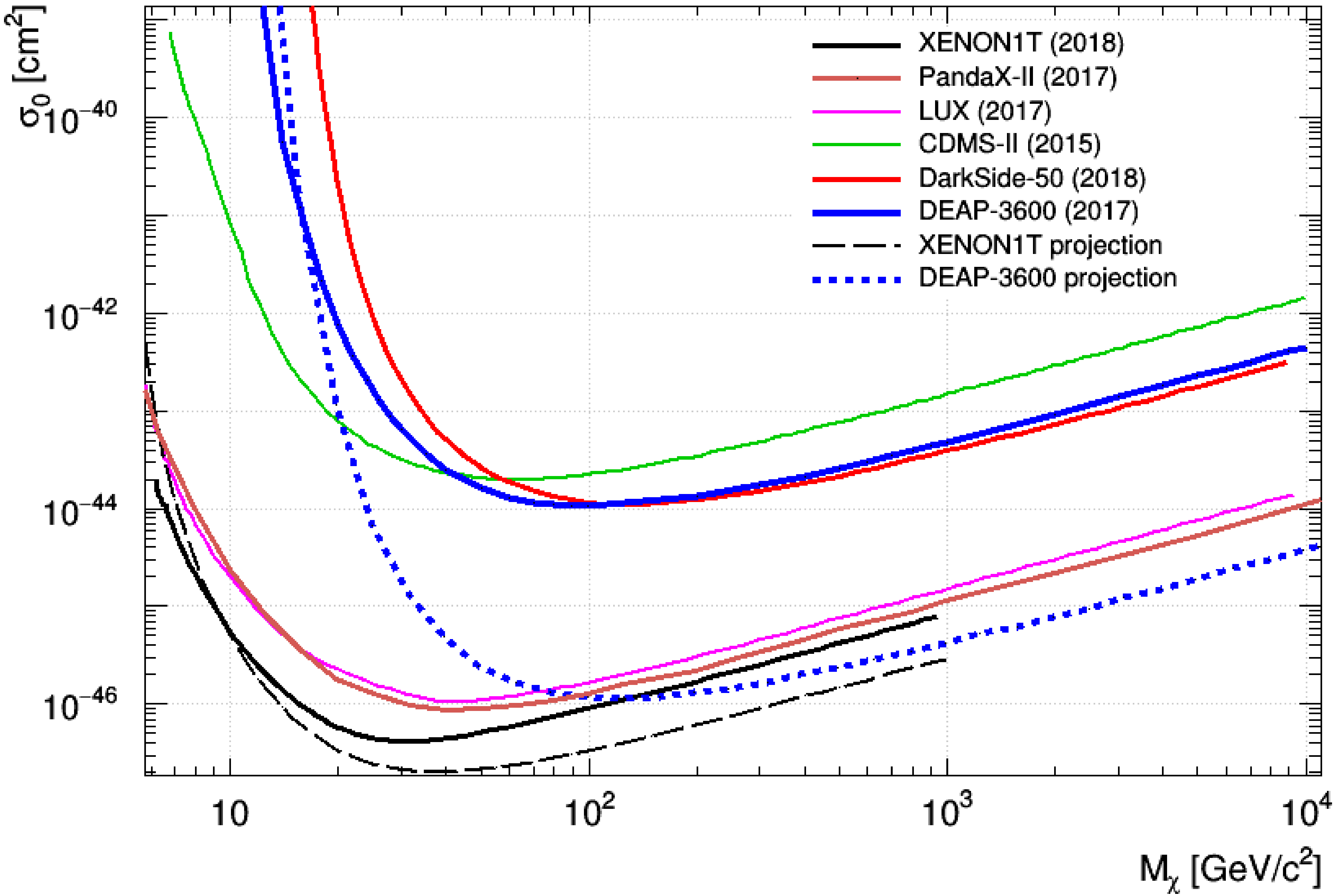
First results published (4.4) days data, low radon and neutron backgrounds.
PRL 121 171801 (2018)

Excellent pulse-shape discrimination of β/γ's from nuclear recoils, works as expected up to the scale of DEAP-3600 but require lower ^{39}Ar for larger detector. With underground argon (x1400 reduction), PSD is sufficient for ktonne-year exposure (ie to the neutrino floor with a 300-tonne detector).

Aside:
DEAP= "**D**ark matter **E**xperiment using **A**rgon **P**ulse-shape discrimination"

Currently completing analysis of one-year dataset, plan to submit by end of 2018. Improved optical calibration, position reconstruction, backgrounds model.

Blind running started Jan 1, 2018. Will collect data DM search data at least to 2020.



XENON1T (2018)
PandaX-II (2017)
LUX (2017)
CDMS-II (2015)
DarkSide-50 (2018)
DEAP-3600 (2017)
XENON1T projection
DEAP-3600 projection
σ_0 [cm^2]
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10
10^2
10^3
10^4
M_χ [GeV/c^2]

Global Argon Dark Matter Collaboration (Sep 2017)

Over 350 researchers from

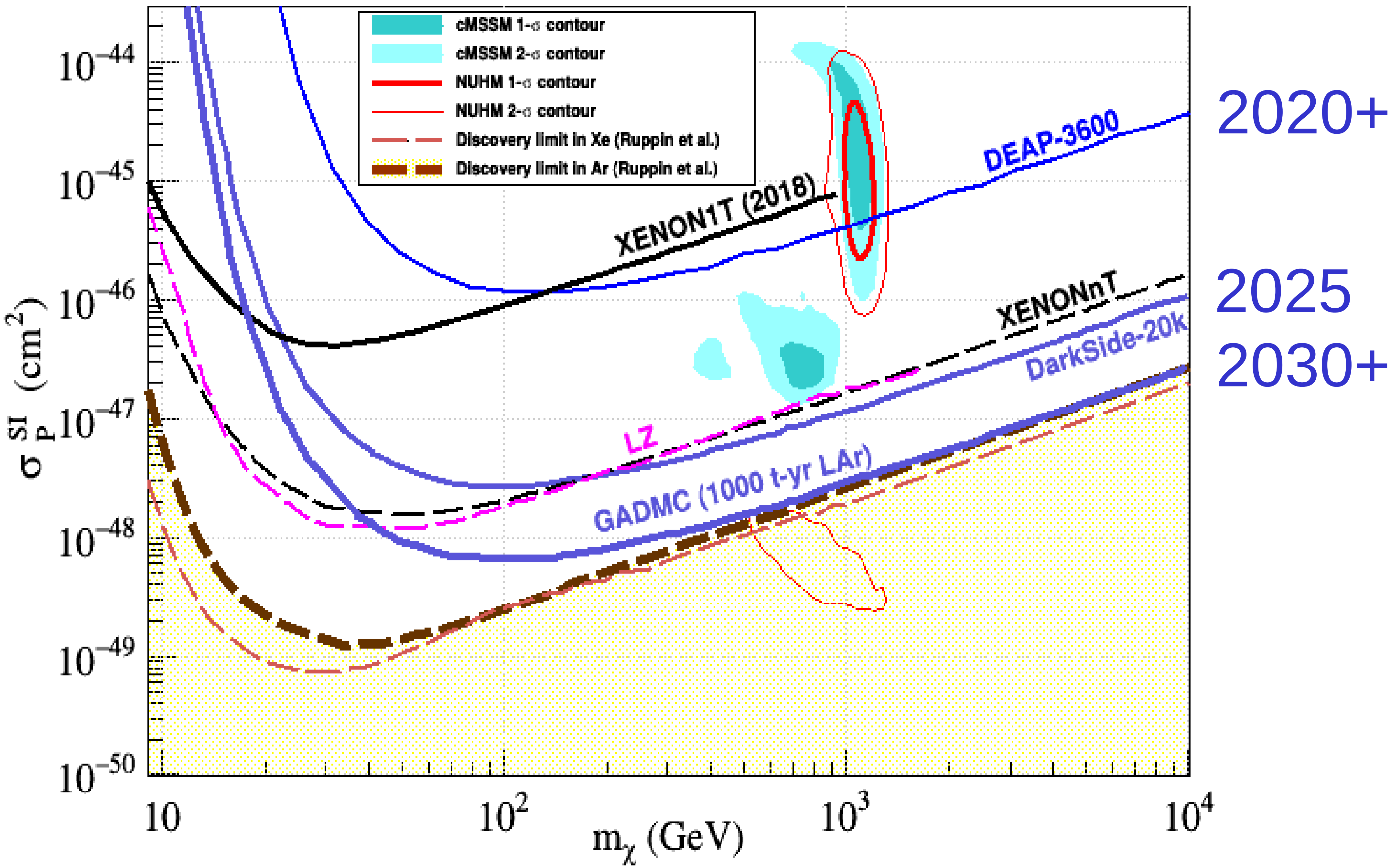
- DarkSide
- DEAP
- ArDM
- MiniCLEAN

DS-20K → multi-100-T

collaborating on future program:

- Completion of current science and R&D programs by each collaboration
- Joint collaboration on DS-20k at LNGS
  (DEAP groups formally joined around September 2017)
- Extraction of 50 tonnes of low ^{39}Ar underground argon for DS-20k, then ~400 tonnes for future detector (~5 years extraction)
- Joint collaboration on future multi-hundred-tonne LAr detector, site and detector technology TBD (mid-2020's)

Dark Matter Sensitivity

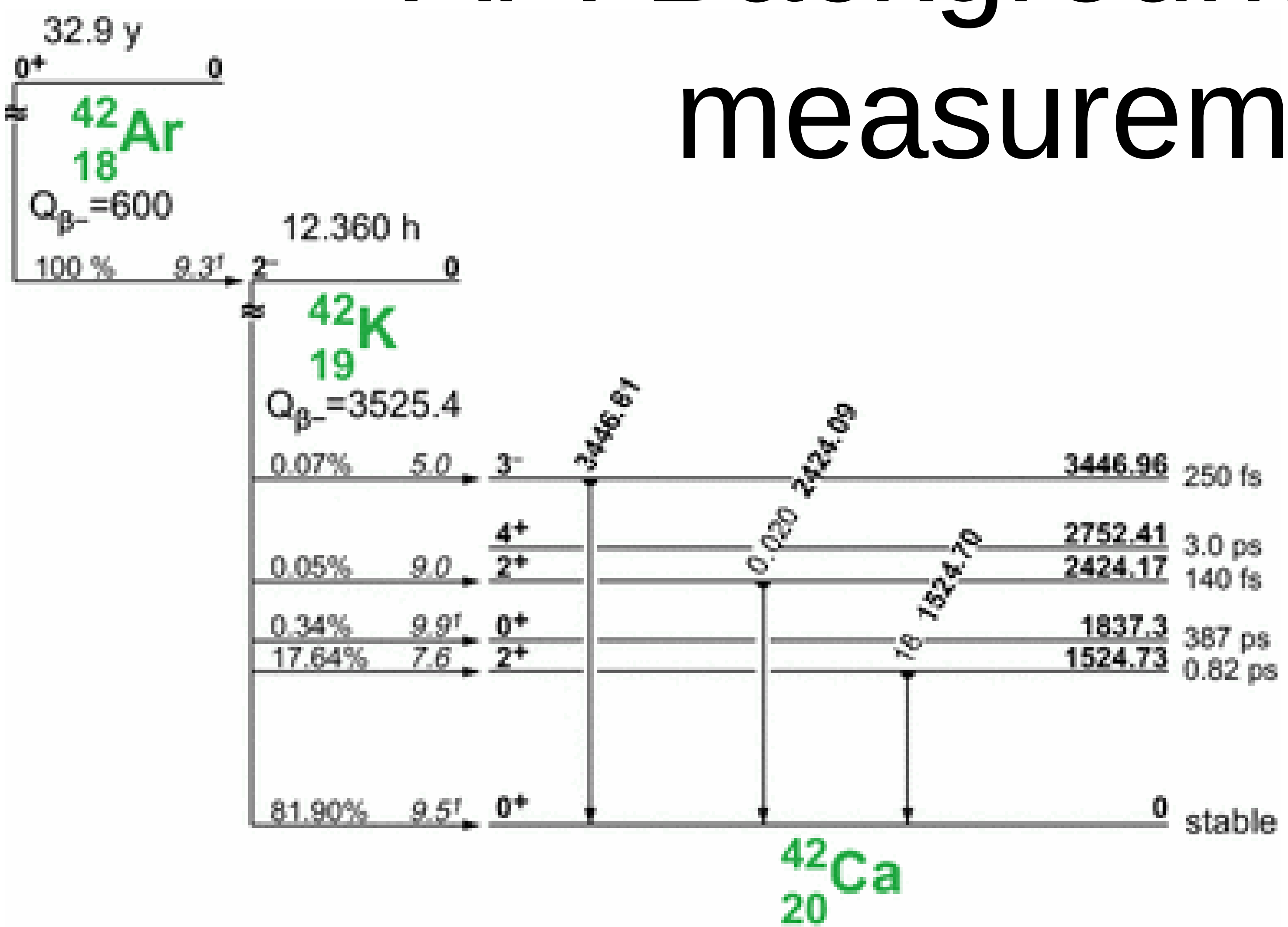


β/γ discrimination: solar pp neutrino ES and other ER backgrounds not a concern in argon due to PSD, ~100 events per tonne-year in xenon requires improved ER vs NR discrimination to reach "neutrino floor"

Mark Boulay

END

^{42}Ar : Background to solar ν measurements



Expect limit of 41 μBq/kg in atmospheric argon
(Inst. Exp. Tech. vol 46 issue 2, pp 153-160 March 2003),
perhaps reduced in underground argon

Require O(10 pBq/kg) for 10% background to
solar neutrino measurement; can we assay to that level?

DEAP-3600 Timeline

2006-2012	Design and component fabrication
2012-2015	Construction and assembly at SNOLAB
2015-2016	Commissioning and Cooldown
2016 Nov 1	Start of production data taking
2017 July	First result released PRL 121 071801 (2018)
2018 Jan 1	Start of blinded running
2018 Fall	2^{nd} result to be released (first year open dataset)
2020 March	Nominal 3 tonne-year dataset collected