Radiopurity of Atmospheric Argon

LEGEND

BERKELEY LAB

Björn Lehnert
Berkeley Lab

LRT Workshop, Jaca (Spain), May 22 2019

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See also underground argon talks:

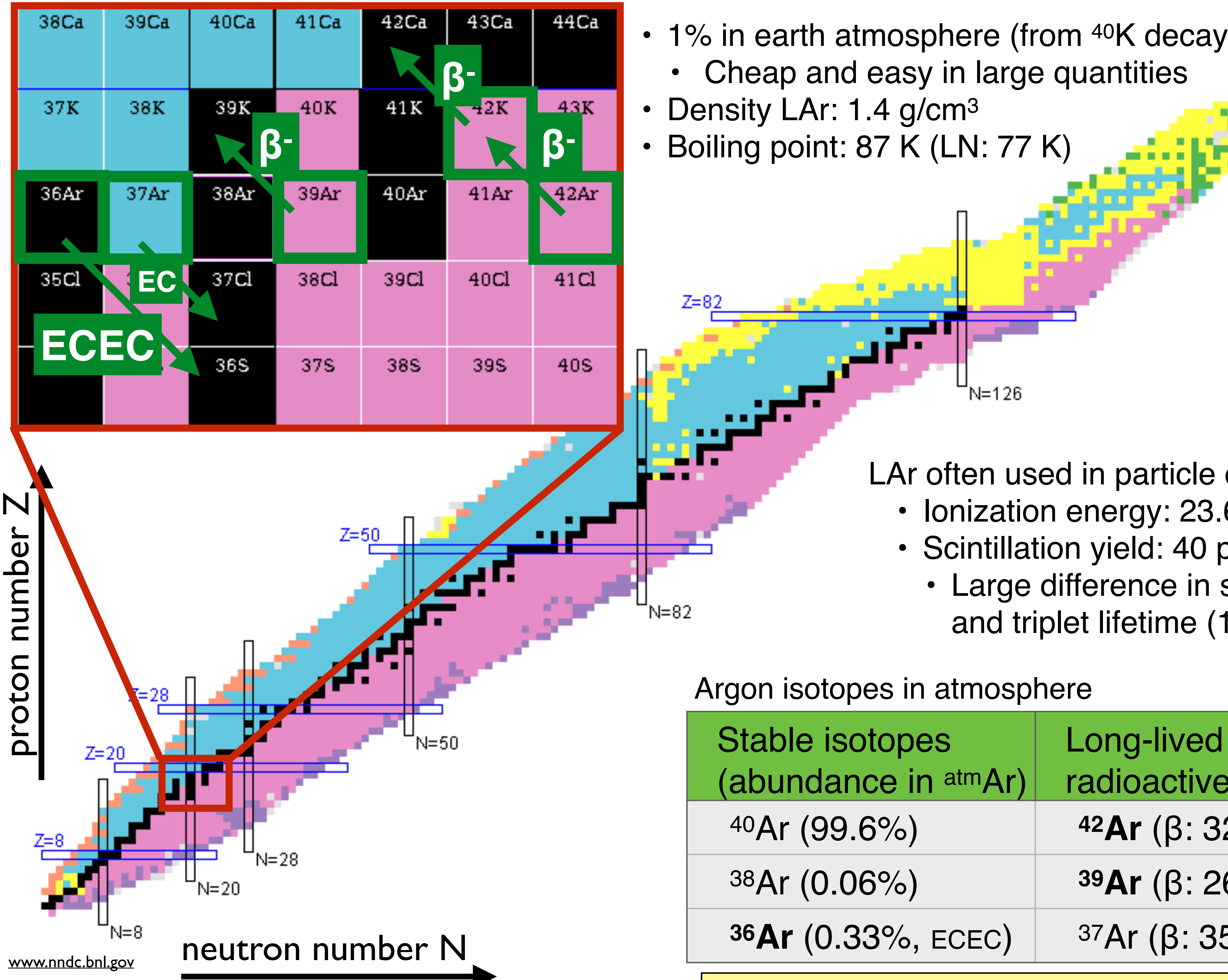
Henning Back:
Low-radioactivity argon for low-level radiation detectors: a global overview

Luciano Romero
Low-radioactivity argon for DarkSide 20k

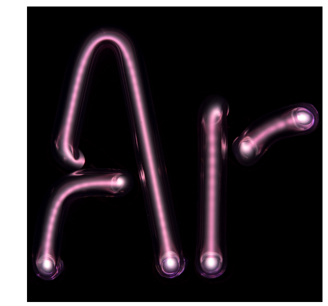
- **Intrinsic radioactive isotopes**
- **Challenges in low bg experiments**
- **Recent new measurements**
- **Physics one can do with argon isotopes**

LRT Workshop, Jaca (Spain), May 22 2019

Atmospheric Argon



- 1% in earth atmosphere (from ^{40}K decays)
  - Cheap and easy in large quantities
- Density LAr: 1.4 g/cm^3
- Boiling point: 87 K (LN: 77 K)



LAr often used in particle detectors

- Ionization energy: 23.6 eV
- Scintillation yield: 40 ph / keV
  - Large difference in singlet (6 ns) and triplet lifetime (1300 ns)

Argon isotopes in atmosphere

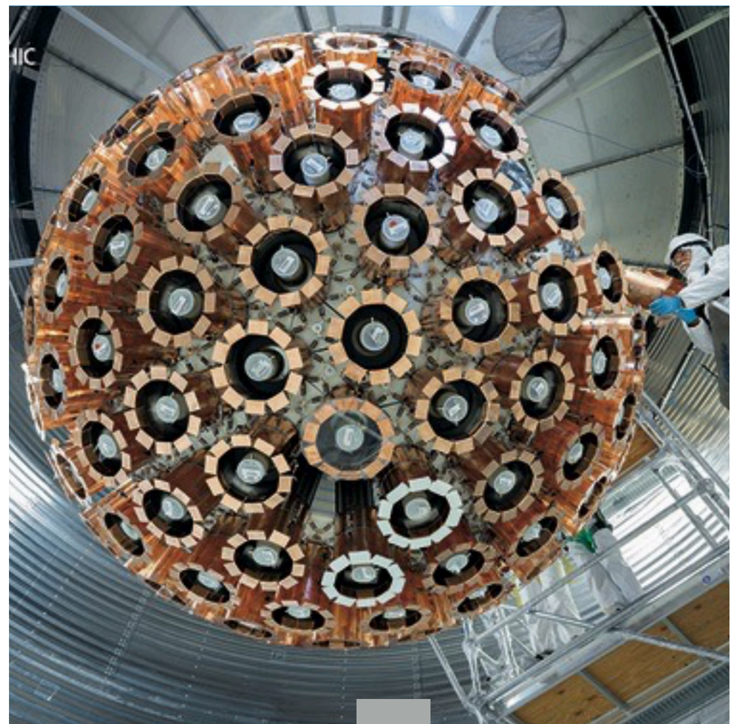
Stable isotopes (abundance in ^{atm}Ar)	Long-lived radioactive isotopes
^{40}Ar (99.6%)	**^{42}Ar** (β: 32.9±1.1 yr)
^{38}Ar (0.06%)	**^{39}Ar** (β: 269±3 yr)
^{36}Ar (0.33%, ECEC)	^{37}Ar (β: 35 d)

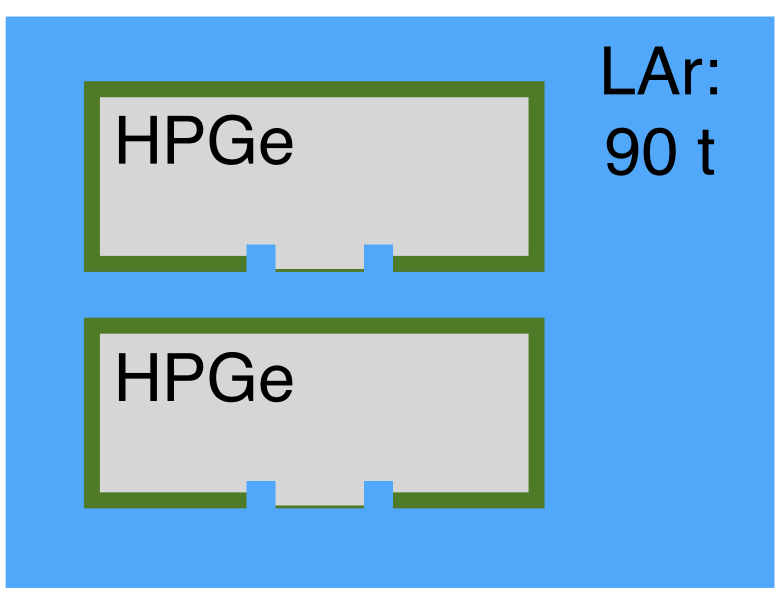
^{atm}LAr in Current/Future Low Background Experiments

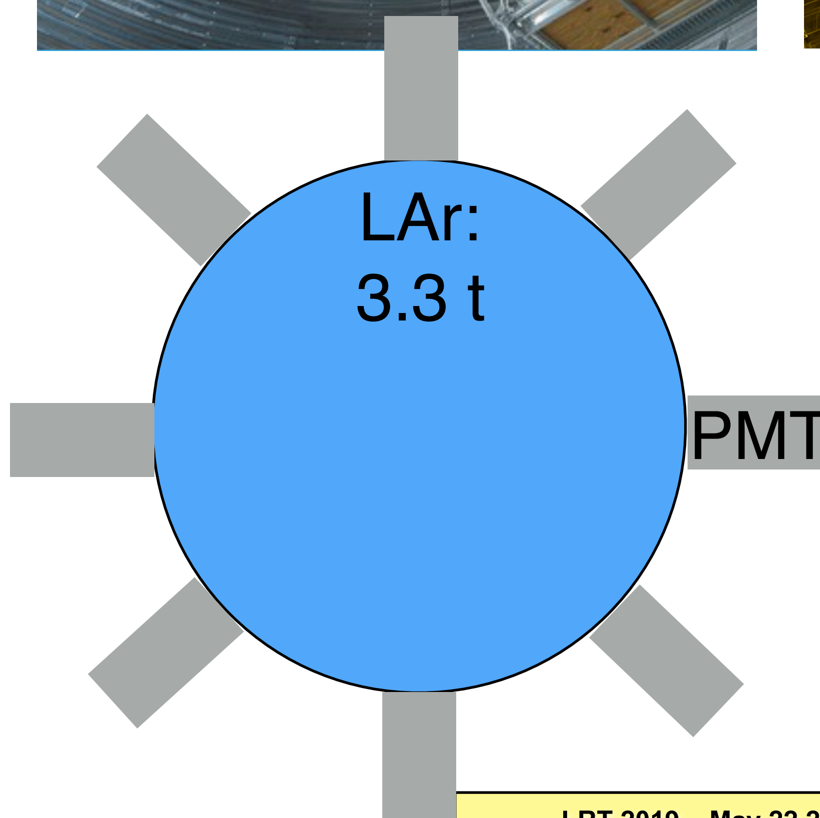
Double Beta Decay
GERDA (veto)
LEGEND-200 (veto)

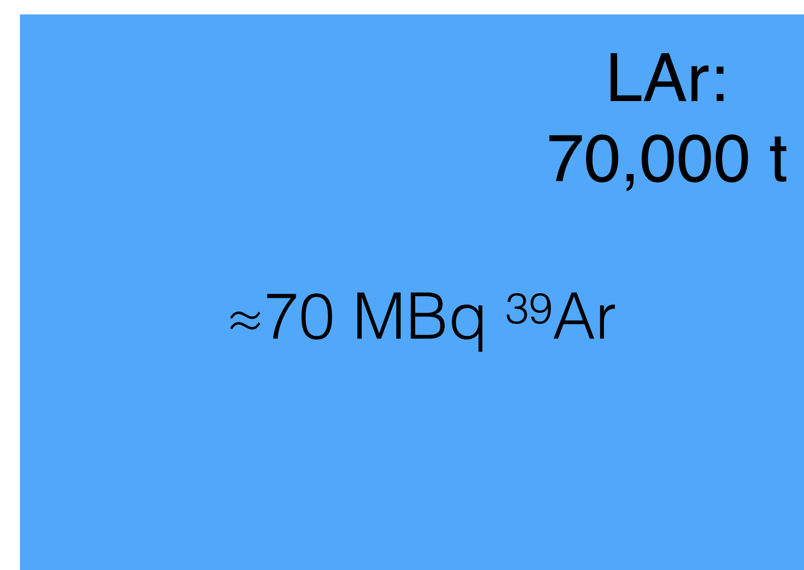
Dark Matter
DEAP-3600, ArDM (target)
DarkSide-20k (veto)

Neutrino Physics
DUNE, Icarus,
MicroBooNE, … (target)









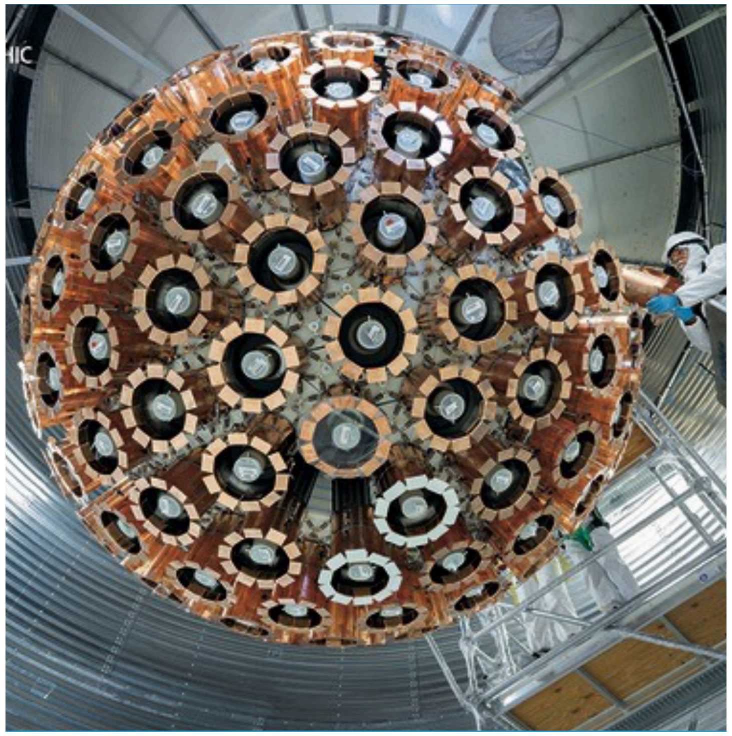
^{atm}LAr in Current/Future Low Background Experiments

Double Beta Decay
GERDA (veto)
LEGEND-200 (veto)

Talk: Mario Schwarz
Results of the background-free search for neutrinoless double beta decay with GERDA &challenges of the LEGEND experiment

Talk: Matthew Green
LEGEND: Next-Generation Neutrinoless Double-Beta Decay Search in Germanium-76

Dark Matter
DEAP-3600, ArDM (target)
DarkSide-20k (veto)



Talk: Chris Jillings
Results and the Background Model from DEAP-3600

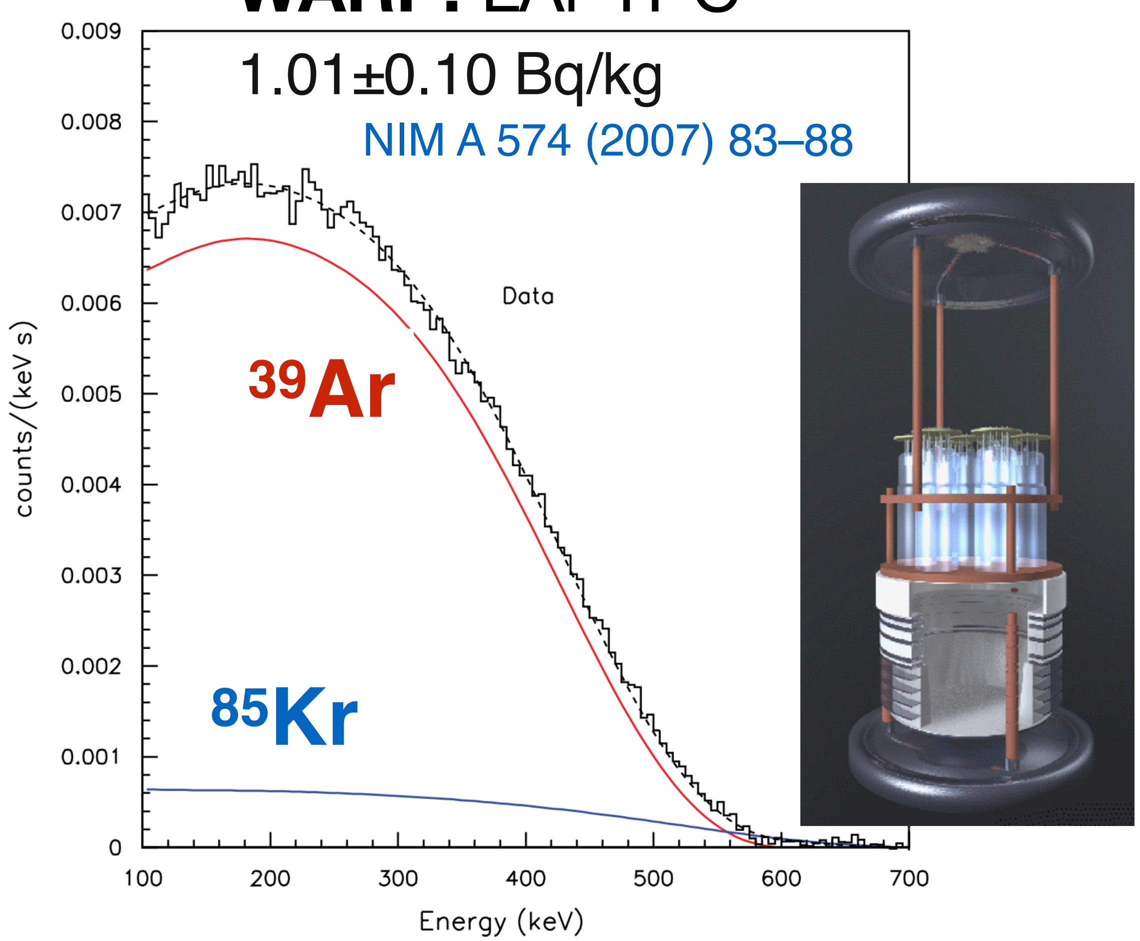
Neutrino Physics
DUNE, Icarus,
MicroBooNE, … (target)

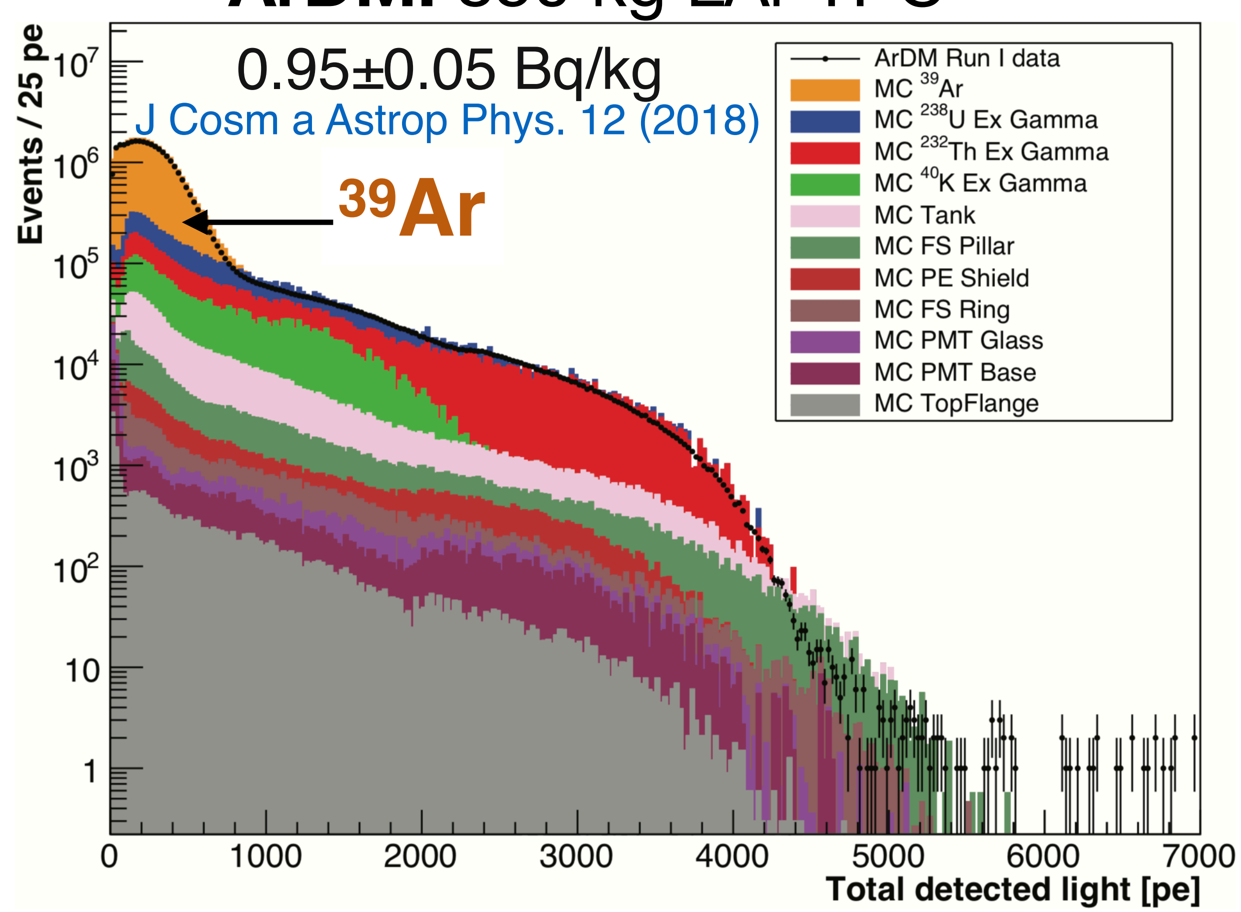
^{39}Ar in Atmospheric Argon

- ^{39}Ar is cosmogenically produced
- 1st forbidden unique β-decay:
  - $T_{1/2}$ = 269±3 yr
  - β endpoint: 565±5 keV
- Major background in LAr dark matter experiments
- Previously measured by WARP and ArDM

Reaction	Estimated ^{39}Ar Production rate [atoms/kg/day]	Fraction of total AAr [%]
^{40}Ar(n, 2n)^{39}Ar + ^{40}Ar(n, d)^{39}Cl	759 ± 122	72.3
^{40}Ar(μ, n)^{39}Cl	172 ± 19	16.4
^{40}Ar(γ, n)^{39}Ar	89 ± 19	8.5
^{40}Ar(γ, p)^{39}Cl	23.8 ± 8.7	2.3
^{40}Ar(p, 2p)^{39}Cl	<0.1	< 0.01
^{40}Ar(p, pn)^{39}Ar	3.6 ± 2.2	0.3
^{38}Ar(n, γ)^{39}Ar	≪0.1 (UAr) 1.1 ± 0.3 (AAr)	- 0.1
Total	1048 ± 126	100

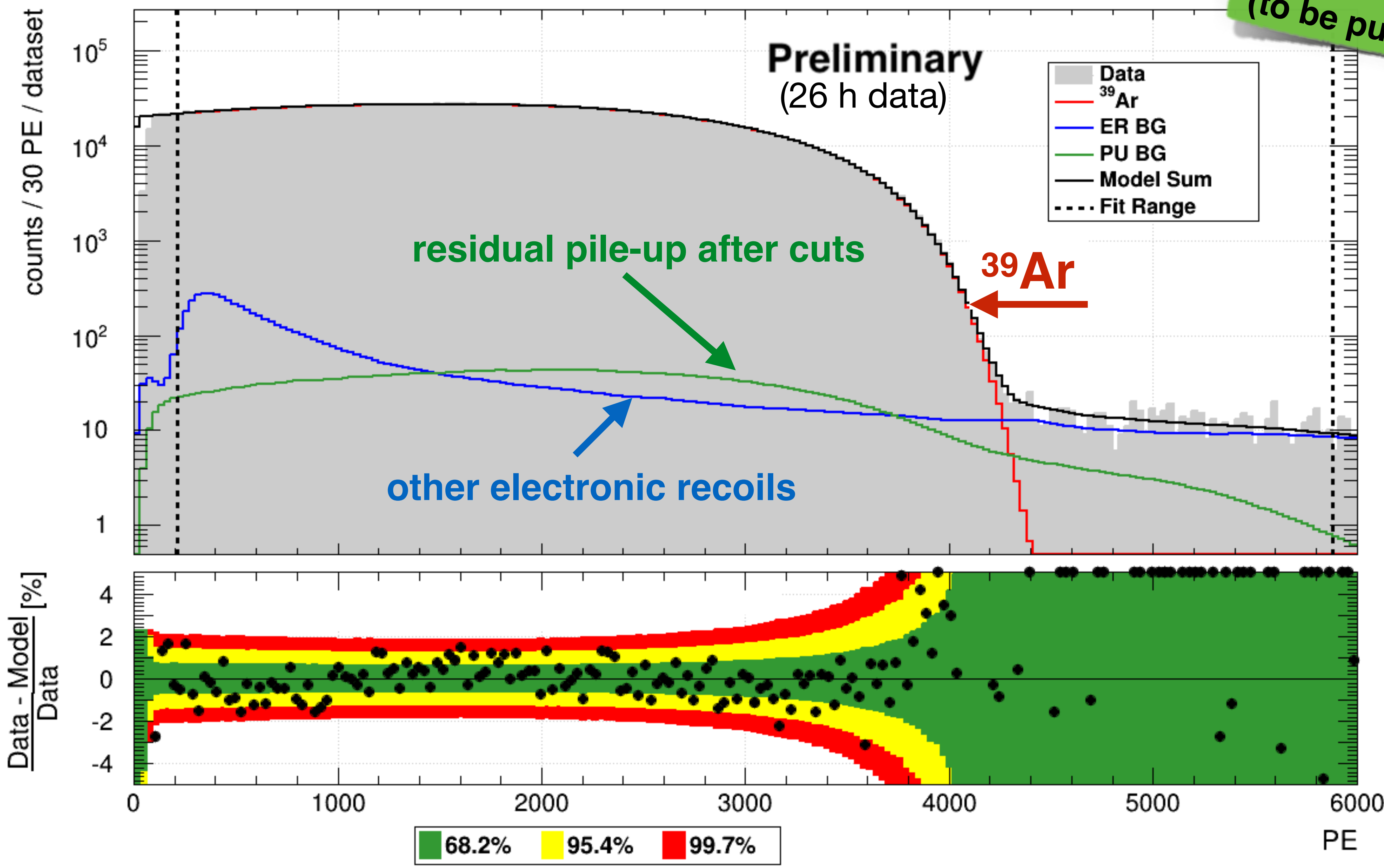
arXiv:1902.09072





^{39}Ar Measurement in DEAP-3600

PhD Thesis
M. Dunford 2018
(to be published)



Experiment	A [Bq/kg]	Reference
WARP	1.01 ±0.10	NIM A 574 (2007) 83–88
ArDM	0.95 ±0.05	J Cosm a Astrop Phys. 12 (2018)
DEAP-3600	**0.953 ±0.028**	**M. Dunford, PhD Thesis (2018)**

New

Precision Measurement of ^{39}Ar Shape

- 1st forbidden unique beta decay
- Weak sensitivity to g_A / g_V ratio appears in second order terms of shape factors

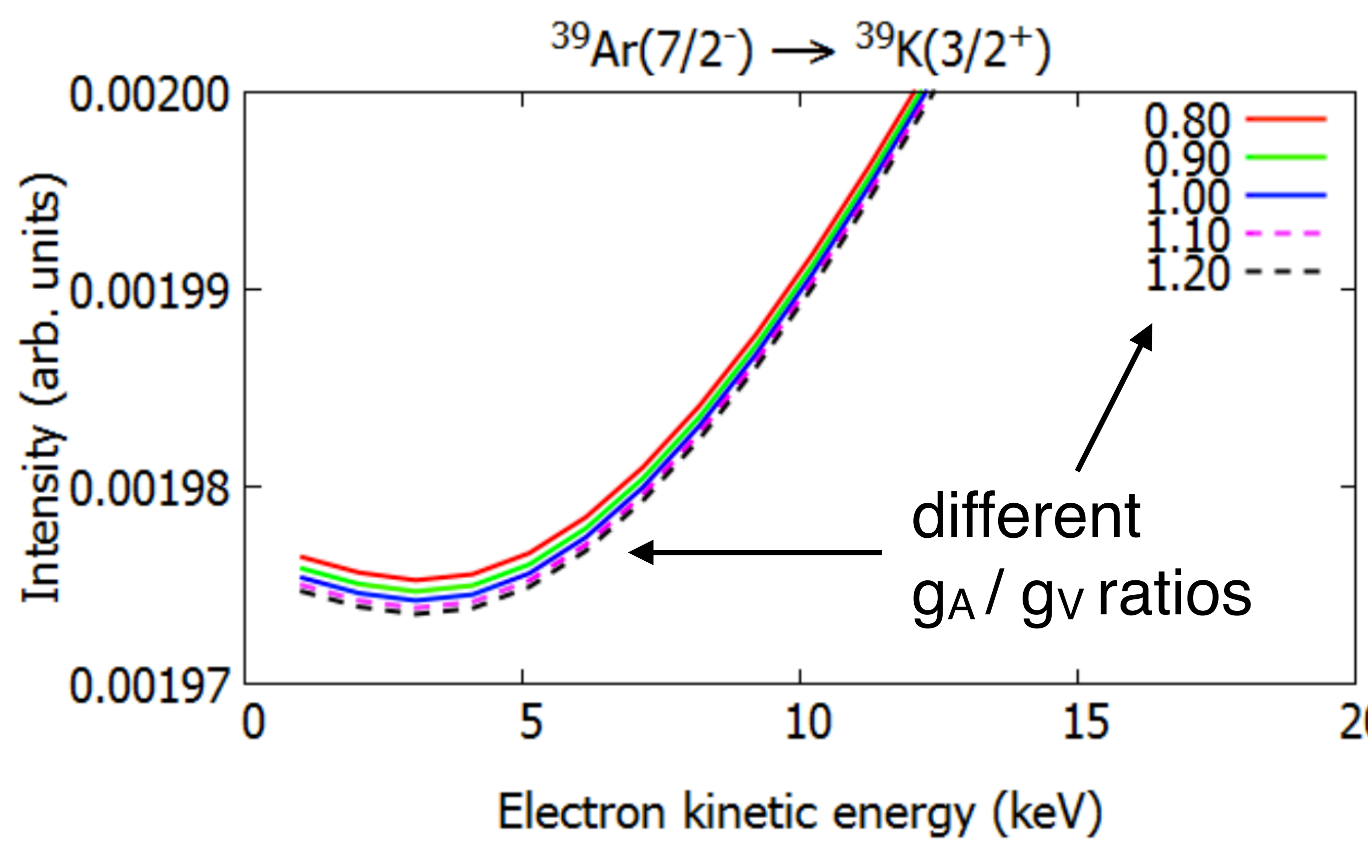
Spectral shapes of forbidden argon β decays as background component for rare-event searches

J. Kostensalo, J. Suhonen and K Zuber

arXiv:1705.05726v1

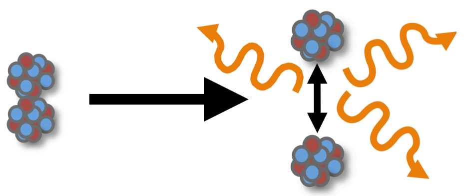
$$C(w_e) = g_V^2 C_V(w_e) + g_A^2 C_A(w_e) + g_V g_A C_{VA}(w_e)$$

- Sensitivity dominantly at low energies
- Can be explored by LAr dark matter experiments e.g. DEAP-3600
- Sensitivity is small (<0.1%) but DEAP-3600 will collect 3×10^{11} ^{39}Ar events in 3 yr
- Precision measurement with challenge to understand systematics of detector response

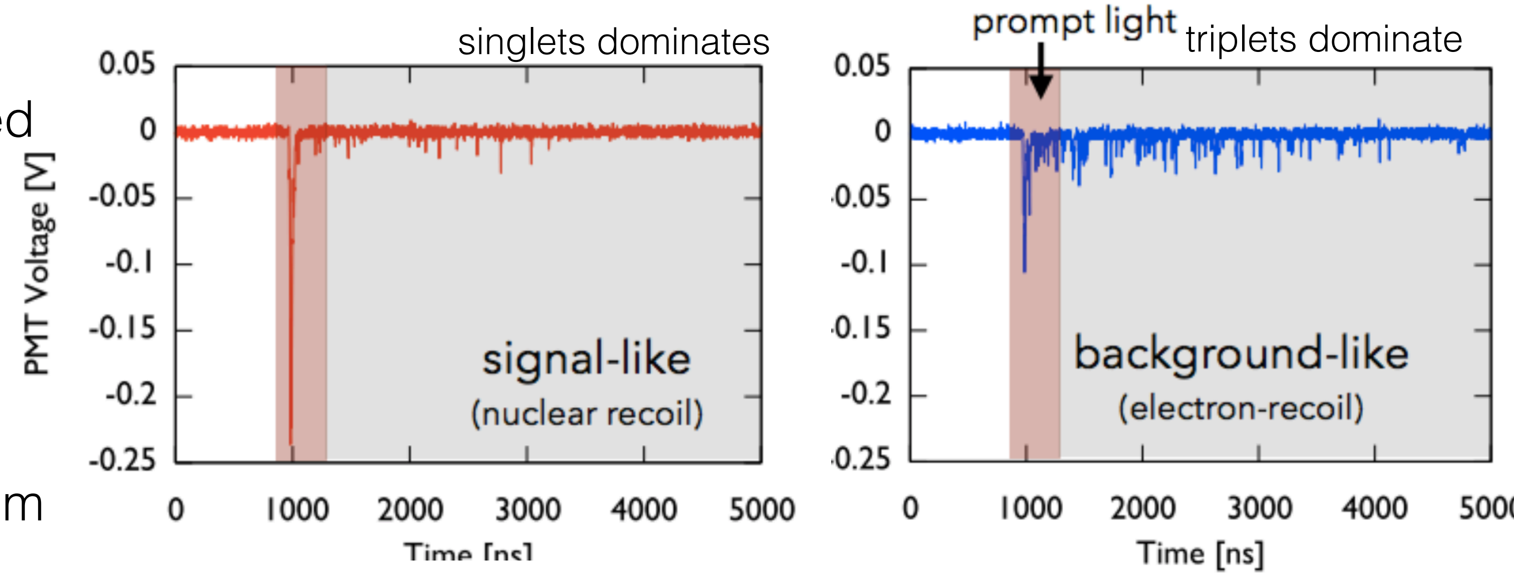


^{39}Ar Mitigation in DEAP-3600: Pulse Shape Analysis

Ar scintillation:
- excimers are created



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

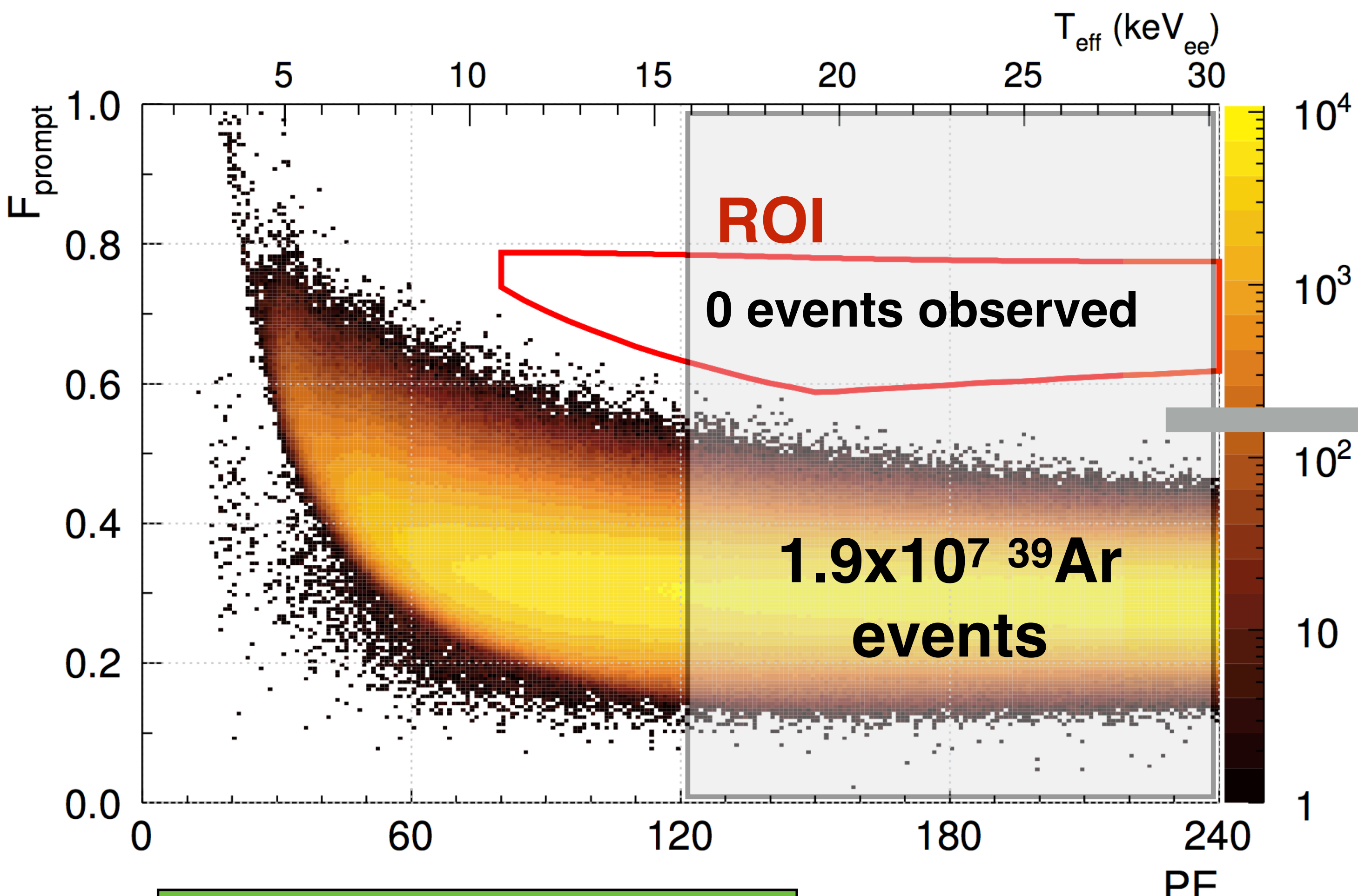


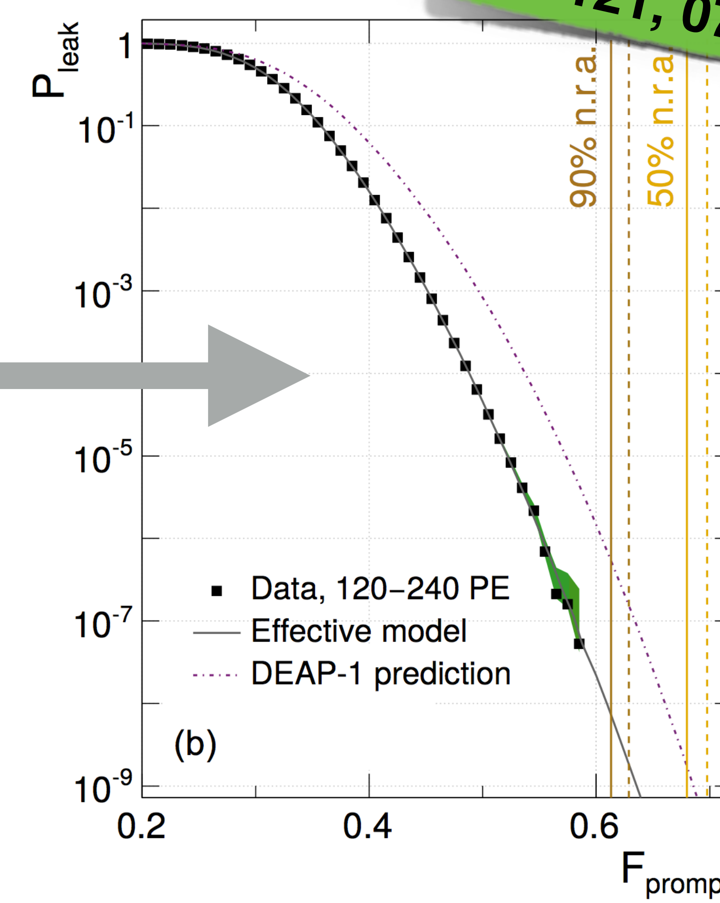
Pulse shape discrimination (PSD) parameter:

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

factor 10^{10} separation

First DEAP-3600 results, PRL 121, 071801 (2018)



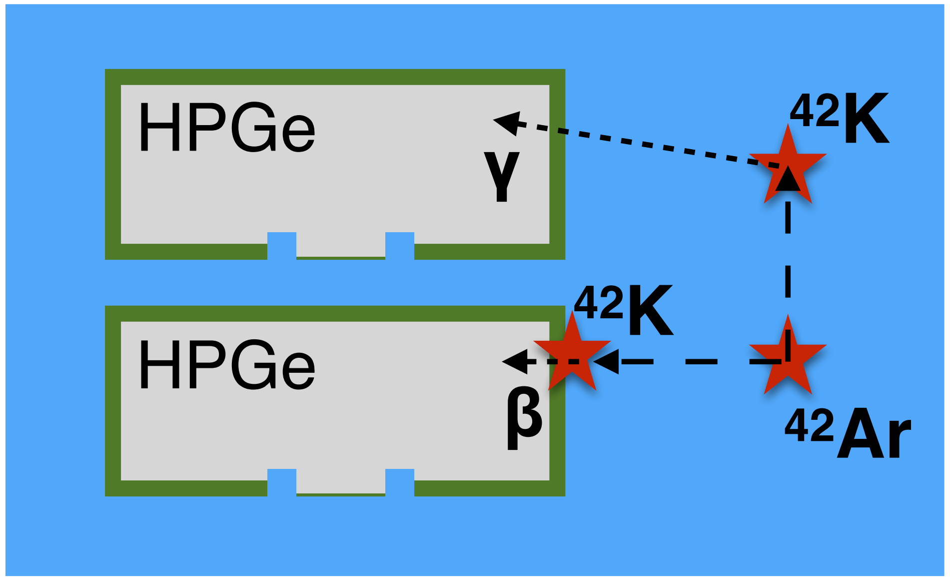


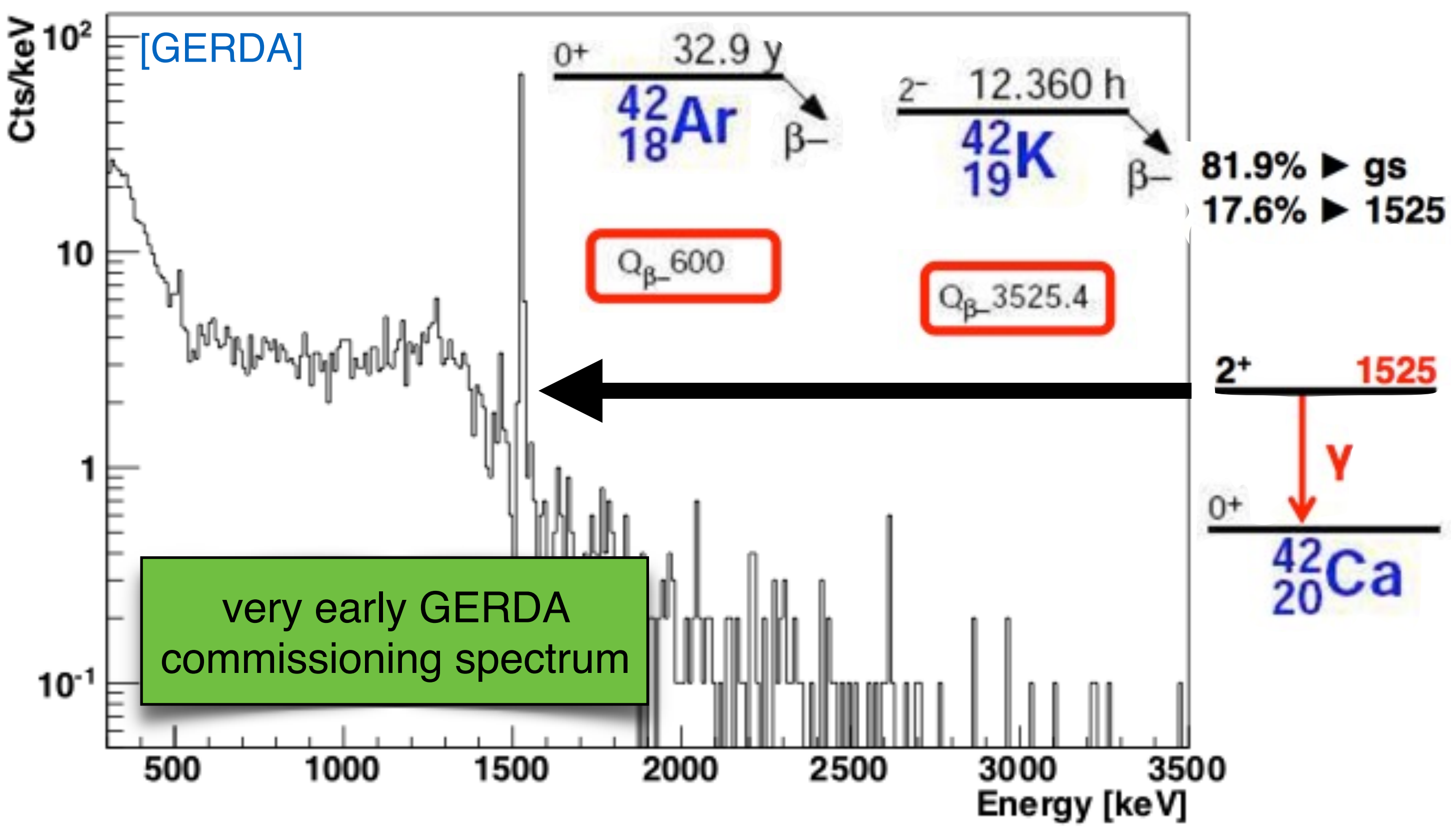
Recent results by Chris Jillings
Results and the Background Model from DEAP-3600

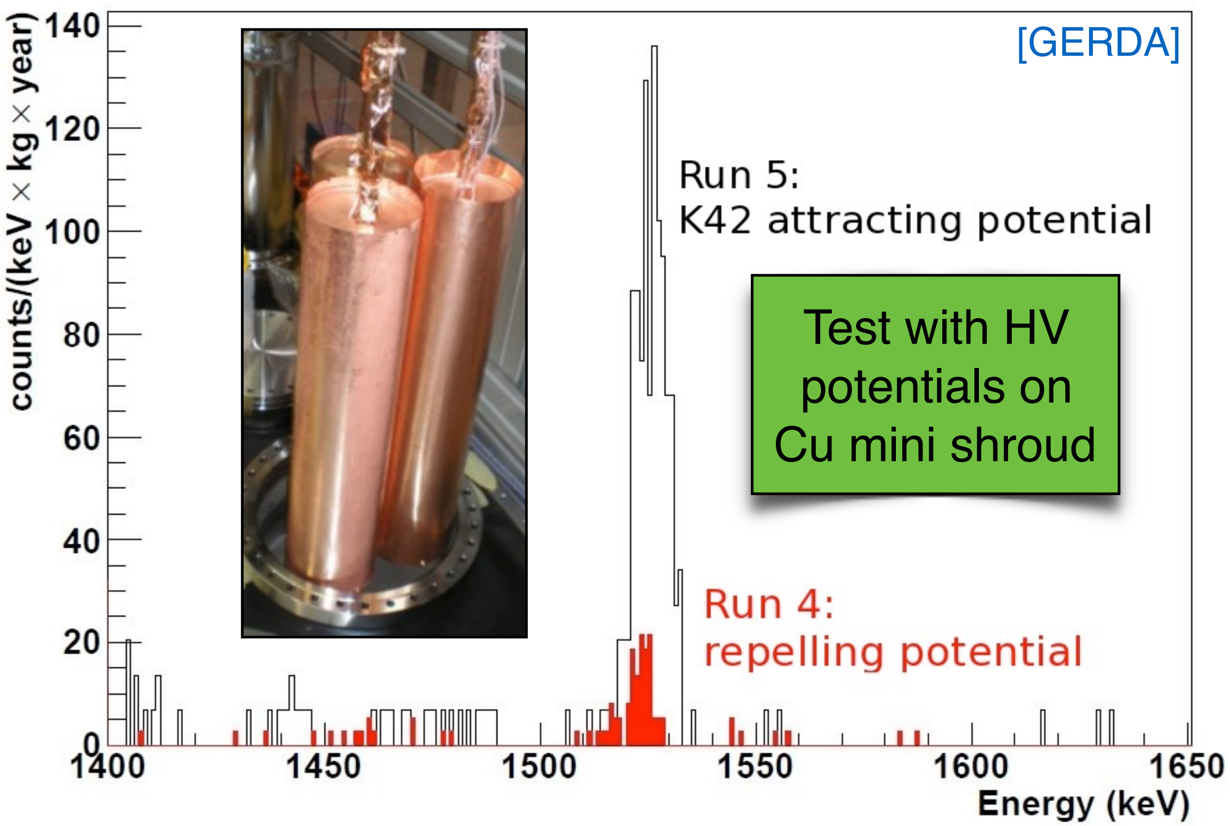
Best demonstrated PSD in LAr:
< 1.2x10^{-7} @ 90% NR acceptance

^{42}Ar / ^{42}K in Atmospheric Argon

- ^{42}Ar is produced in atmosphere via
  - ^{40}Ar(α,2p)^{42}Ar reactions (dominant)
  - ^{40}Ar(n,γ)^{41}Ar(n,γ)^{42}Ar (nuclear bombs)
- Decay chain
  - ^{42}Ar: 33 yr, β: 599 keV
  - ^{42}K: 12 h, β: 3525 keV (can be ion)
  - ^{42}Ca: stable
- Dominant background in GERDA / LEGEND-200







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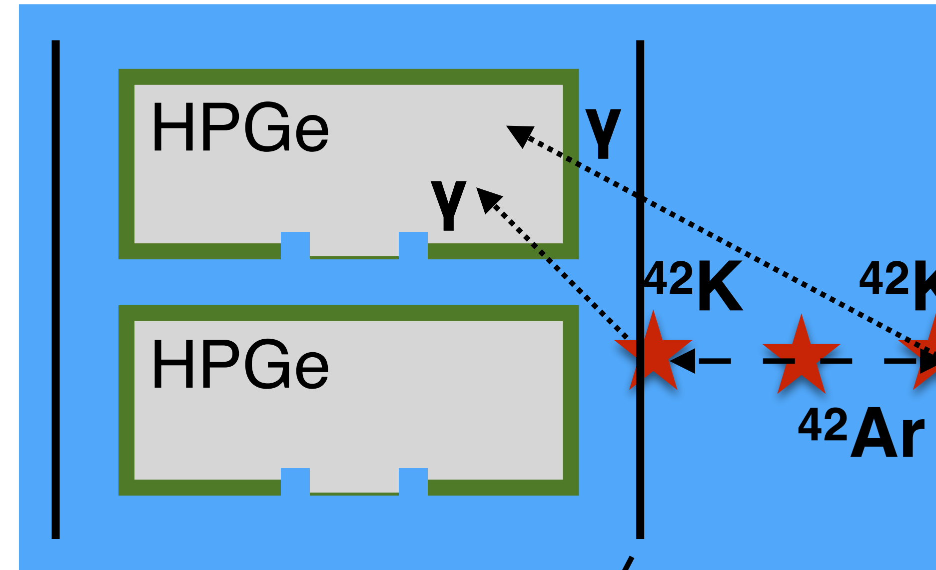
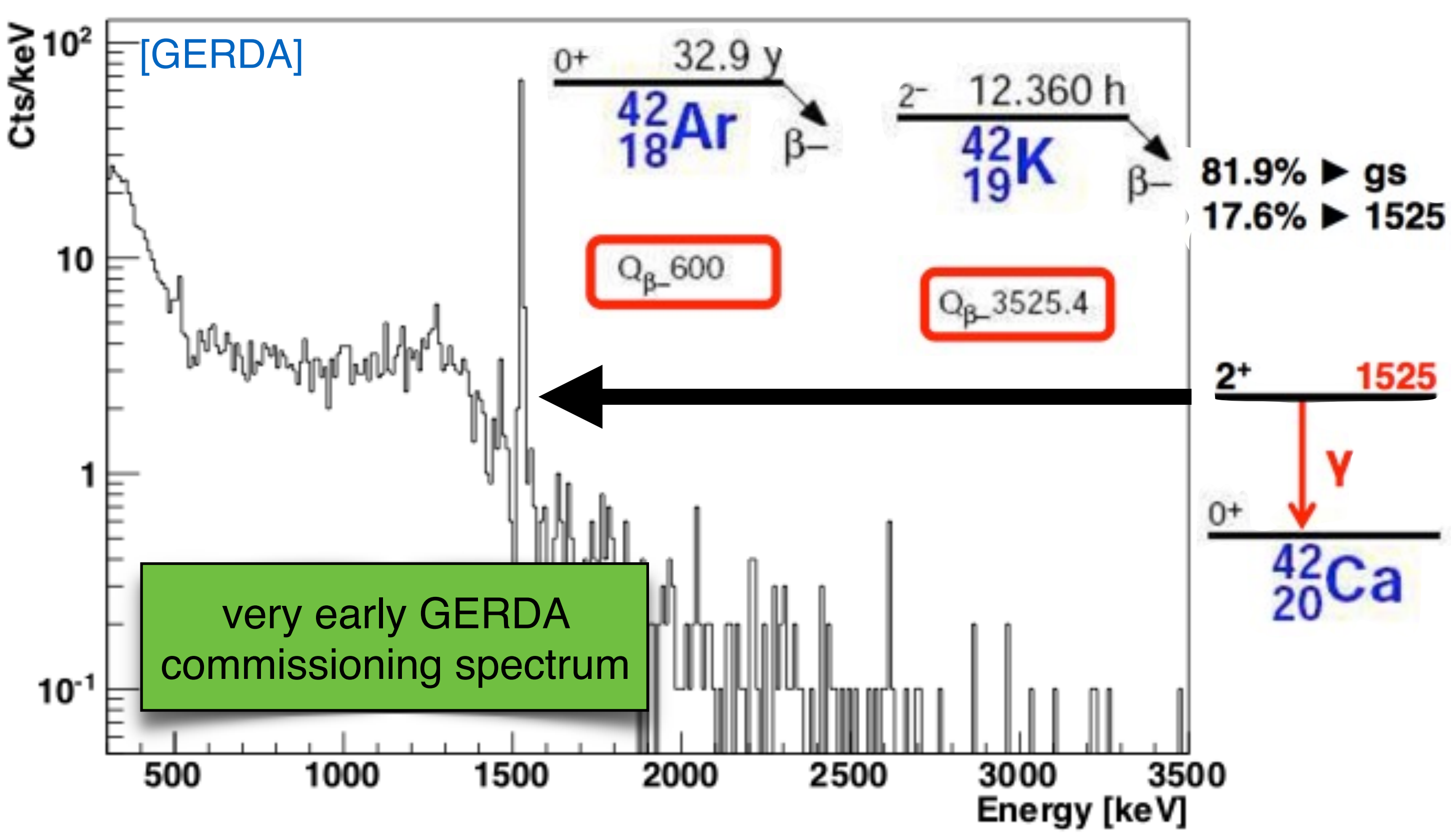
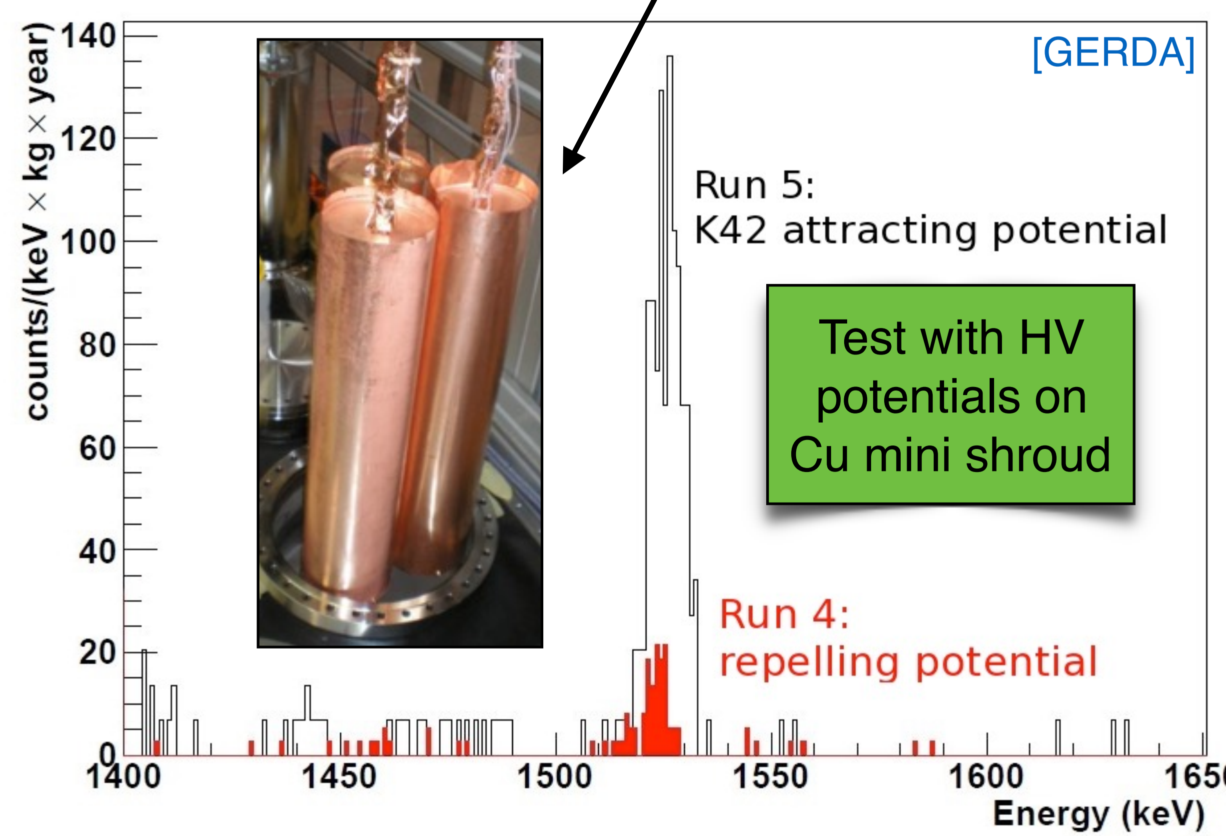


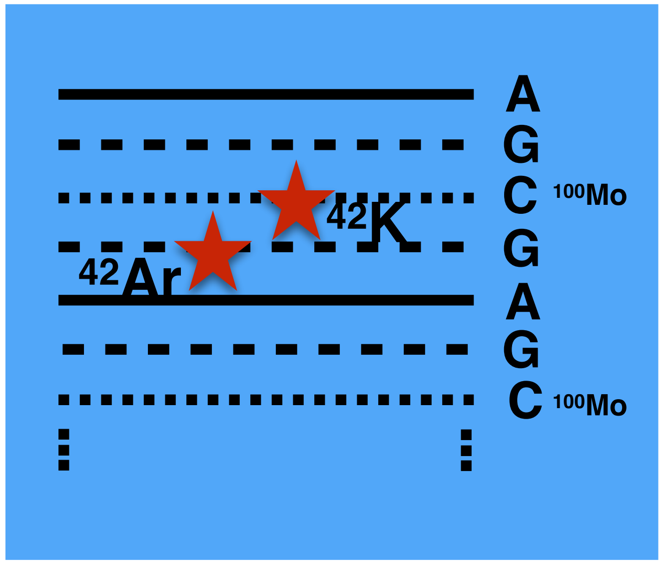




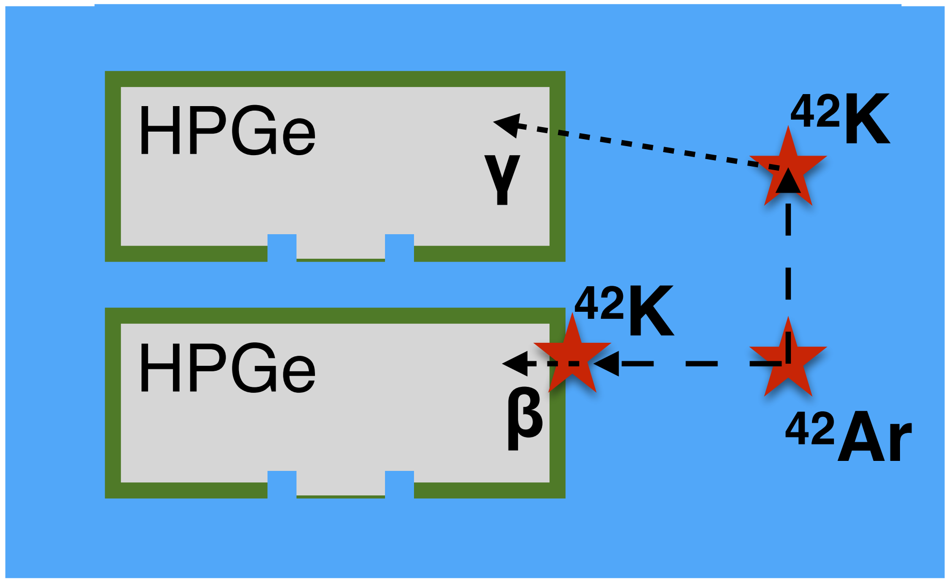
Previous ^{42}Ar Measurements

Experiment	Technique	Activity [μBq/kg]	Reference
DBA	LAr ion. det.	< 61.4 (90% CL)	NIM A 416:179 (1998)
DBA	LAr ion. det.	< 44.0 (90% CL)	Int.Ex.T. 46:153 (2003)
GERDA Phase I	HPGe γ-spec.	$= 91^{+8}_{-20}$ - 168^{+22}_{-18}	EPJ C 74:2764 (2014)
DBA	LAr ion. det.	$= 92^{+22}_{-46}$	J of P CS 718 062004 (2016)
DEAP-3600	**Scintillation**	**= 40.4 ± 5.9**	**arXiv:1905.05811 (2019)**

DBA ionization
main systematic:
background



GERDA γ-spec.
main systematic:
electric field

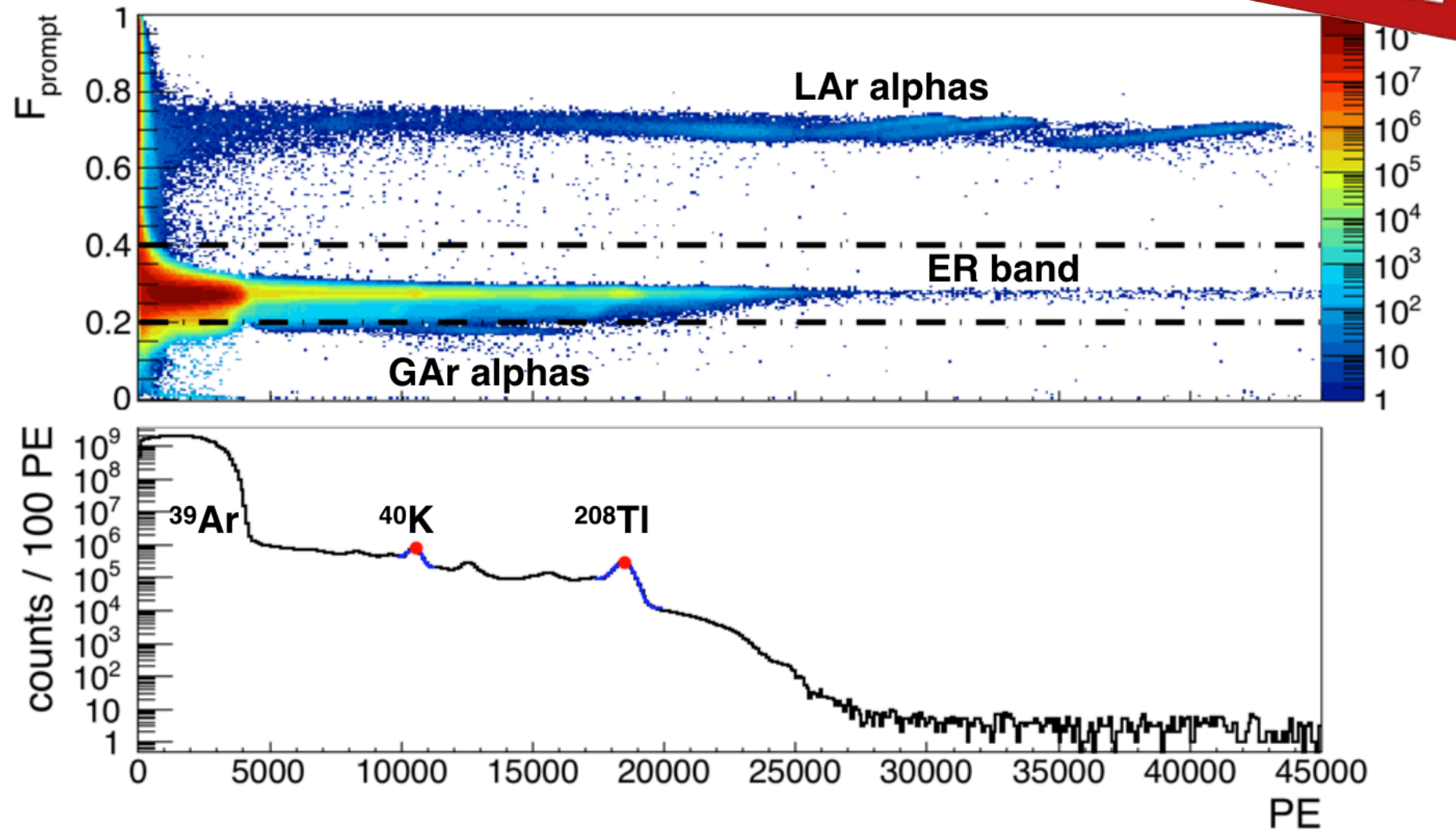


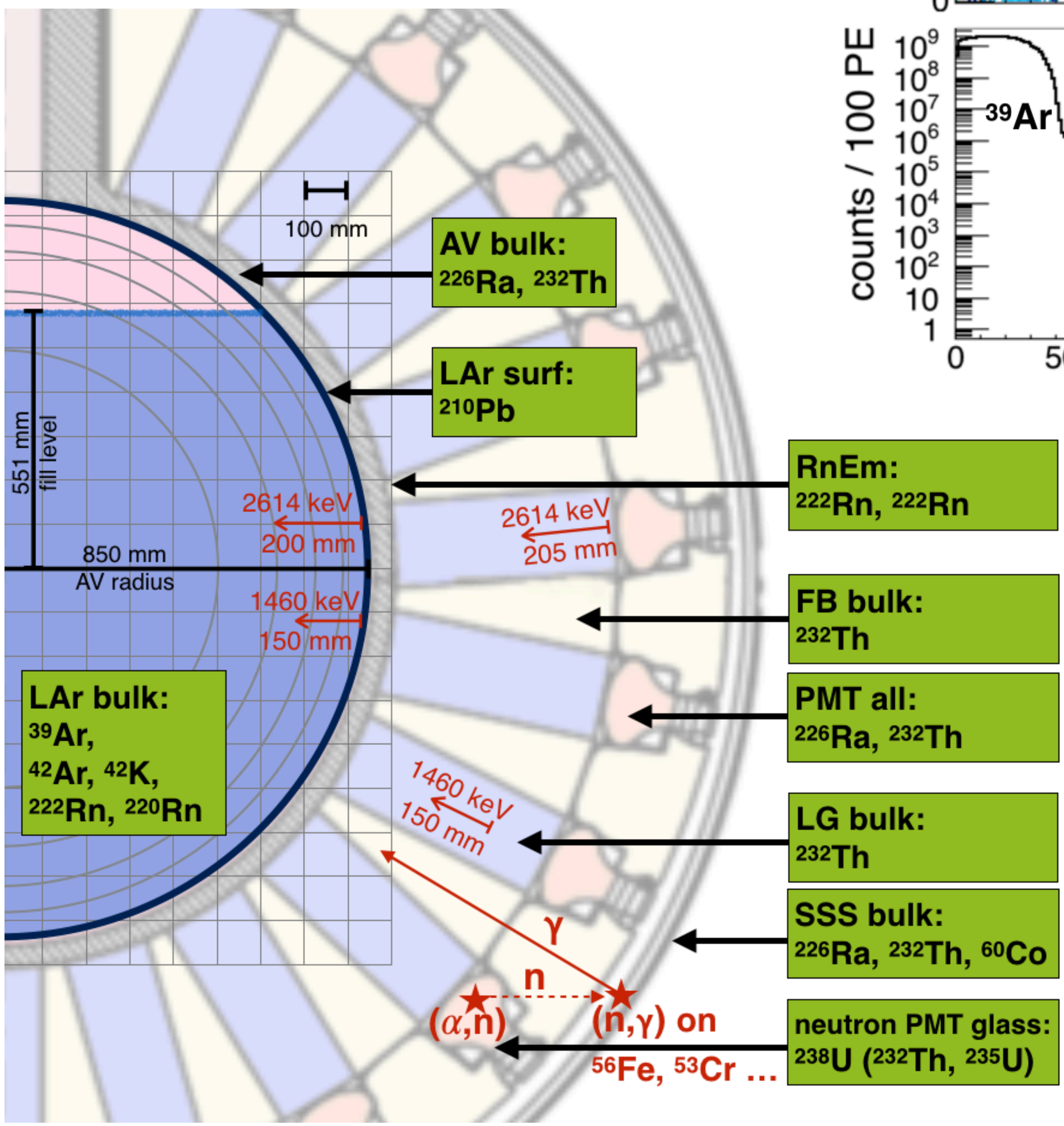
- **Recently: Measurement in DEAP-3600**

^{42}K Measurement in DEAP-3600

arXiv:1905.05811 (2019)

New





Dominant activities from screening or literature values (approximate)

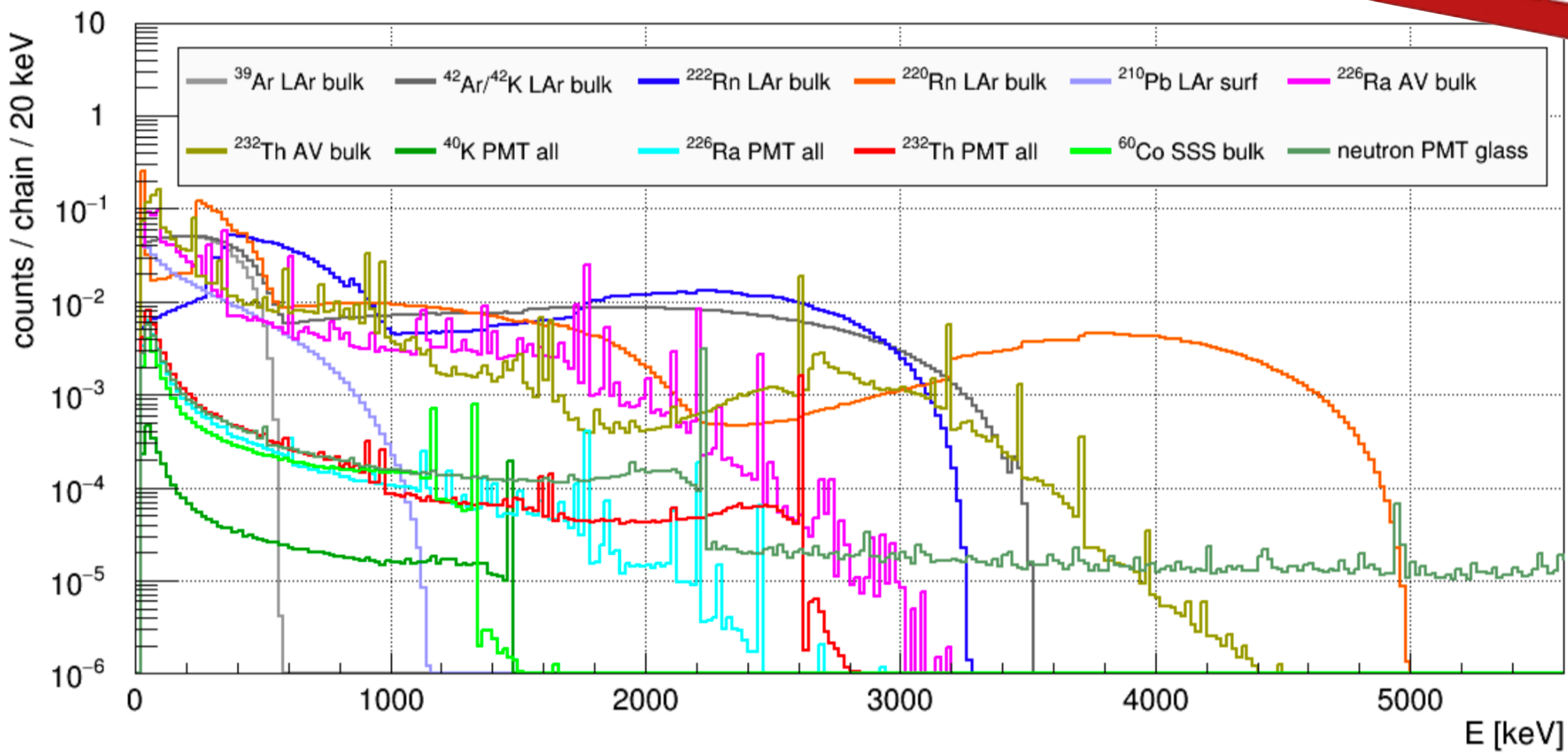
Isotope	Location	Activity [Bq]	specific activity [mBq/kg]	Concentration [ppb]
^{39}Ar	LAr	3300	1010	
^{232}Th	PMT glass	26	139	34
^{238}U	PMT glass	169	921	75
^{40}K	PMT glass	100	546	18

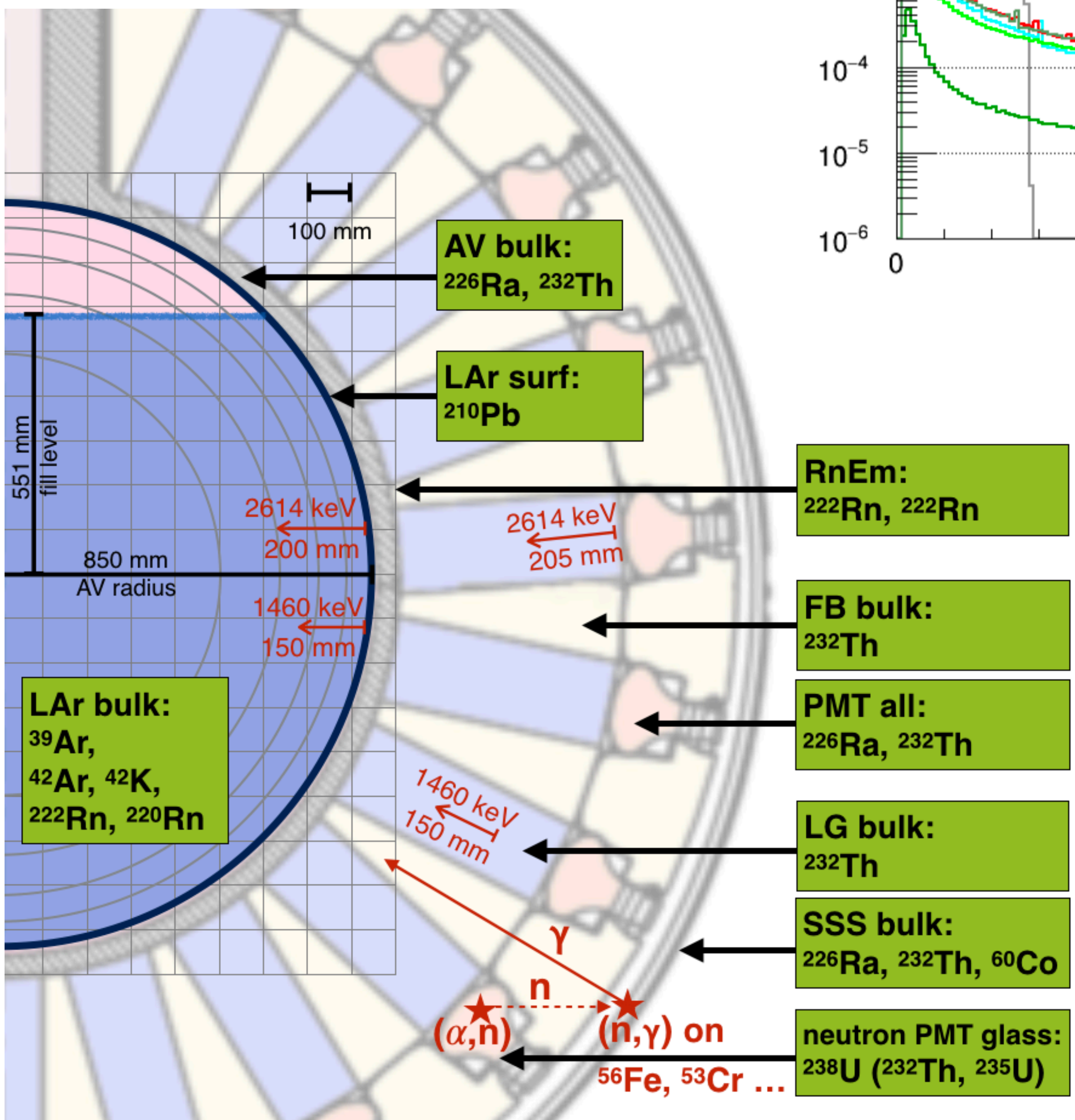
^{42}K Measurement in DEAP-3600

arXiv:1905.05811 (2019)

New

BAT
BAYESIAN ANALYSIS TOOLKIT
https://bat.mpp.mpg.de

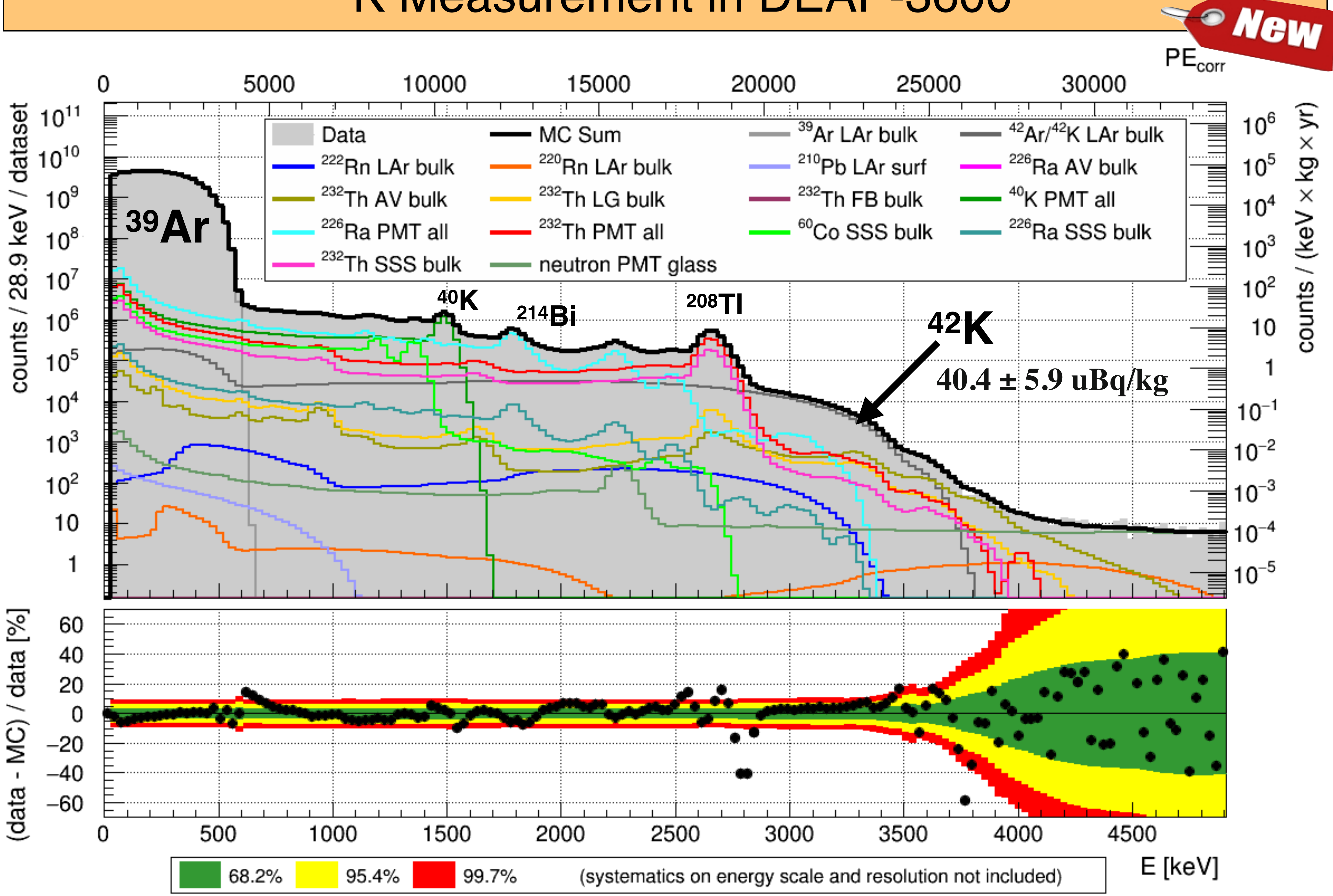




- MC simulations of all background components
- Full Bayesian posterior fit with BAT
- Activity priors based on
  - Material screening
  - Literature values
  - Dedicated in-situ analyses

^{42}K Measurement in DEAP-3600

arXiv:1905.05811 (2019)



^{42}Ar Summary

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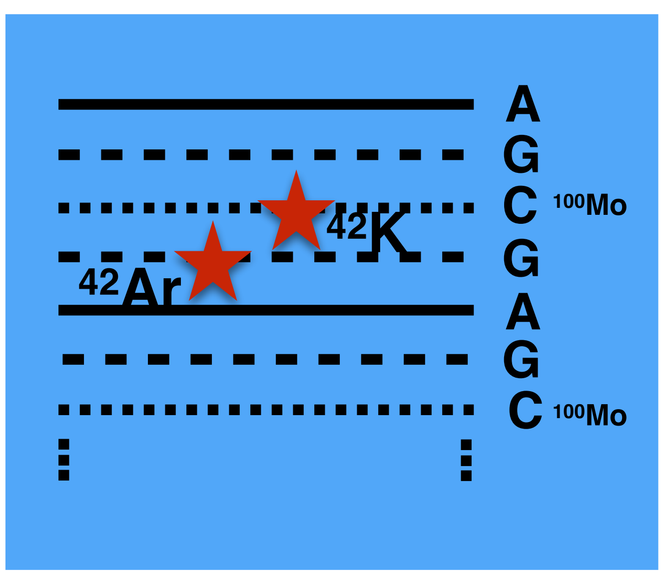
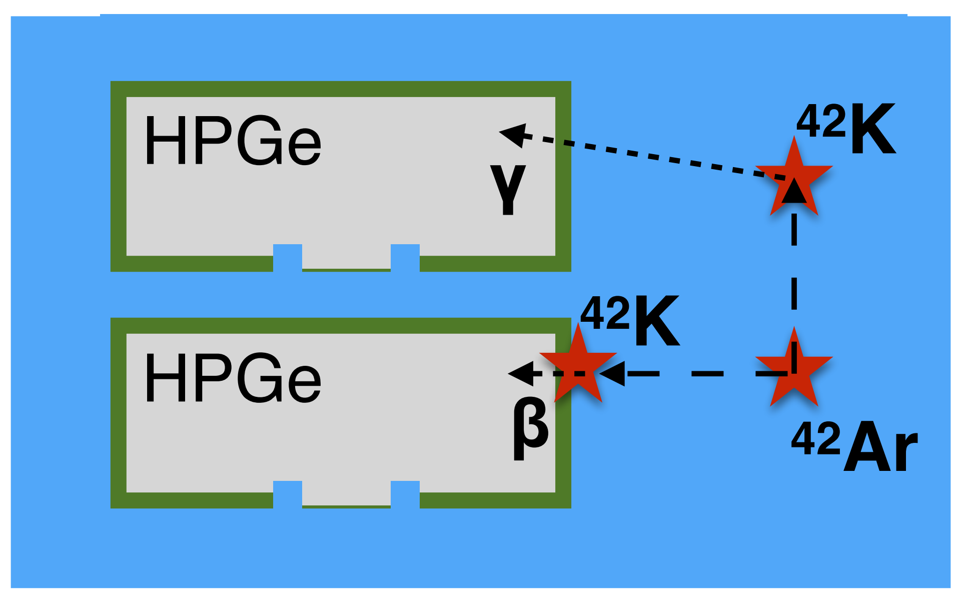
New

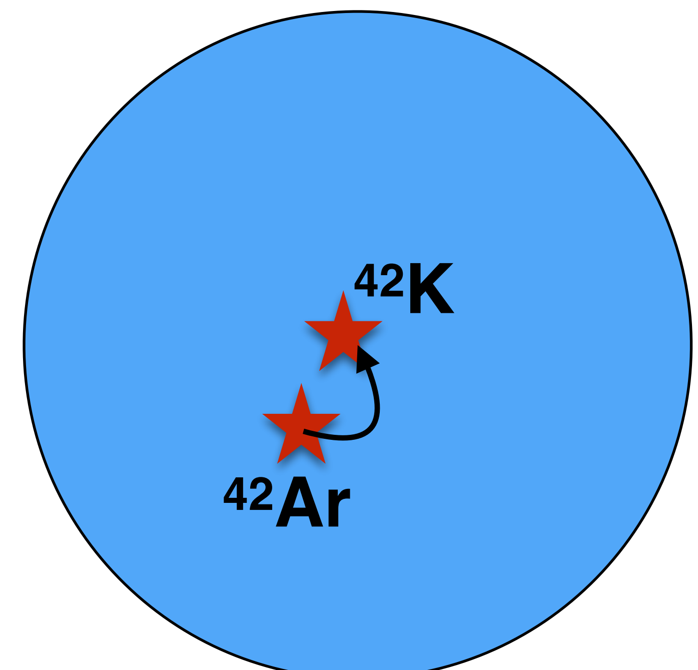
DBA ionization
main systematic:
background

GERDA γ-spec.
main systematic:
electric field

DEAP-3600 scintillation
main systematic:
energy scale

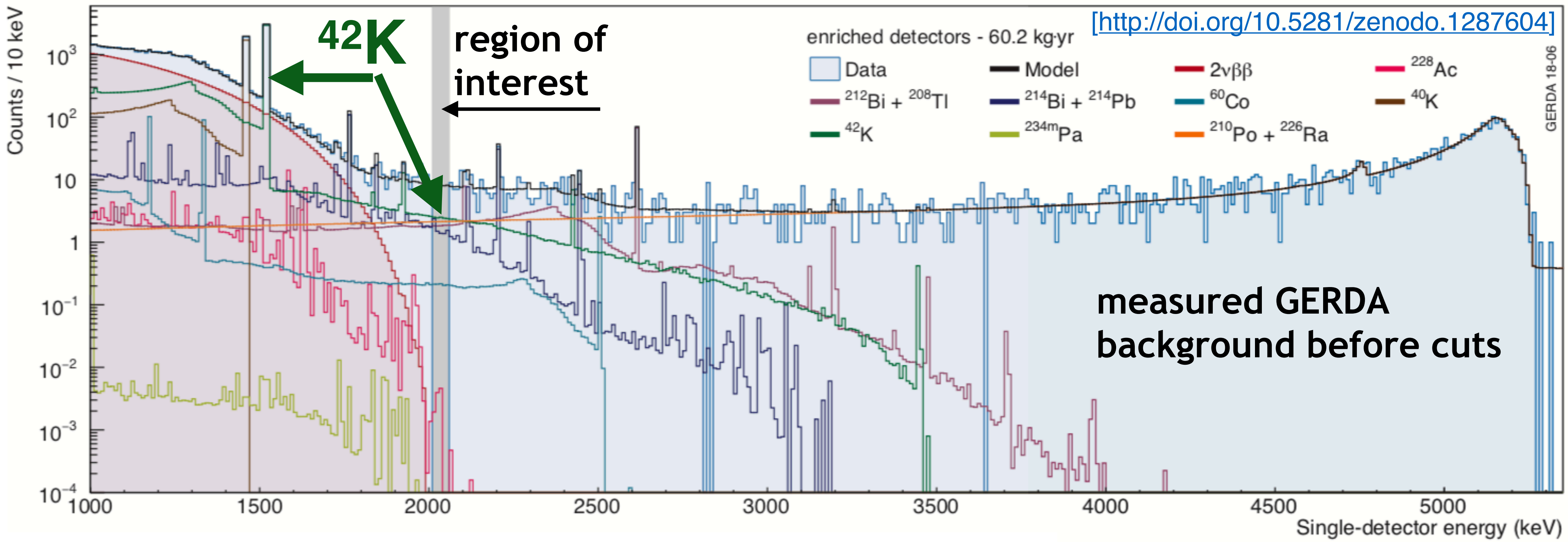


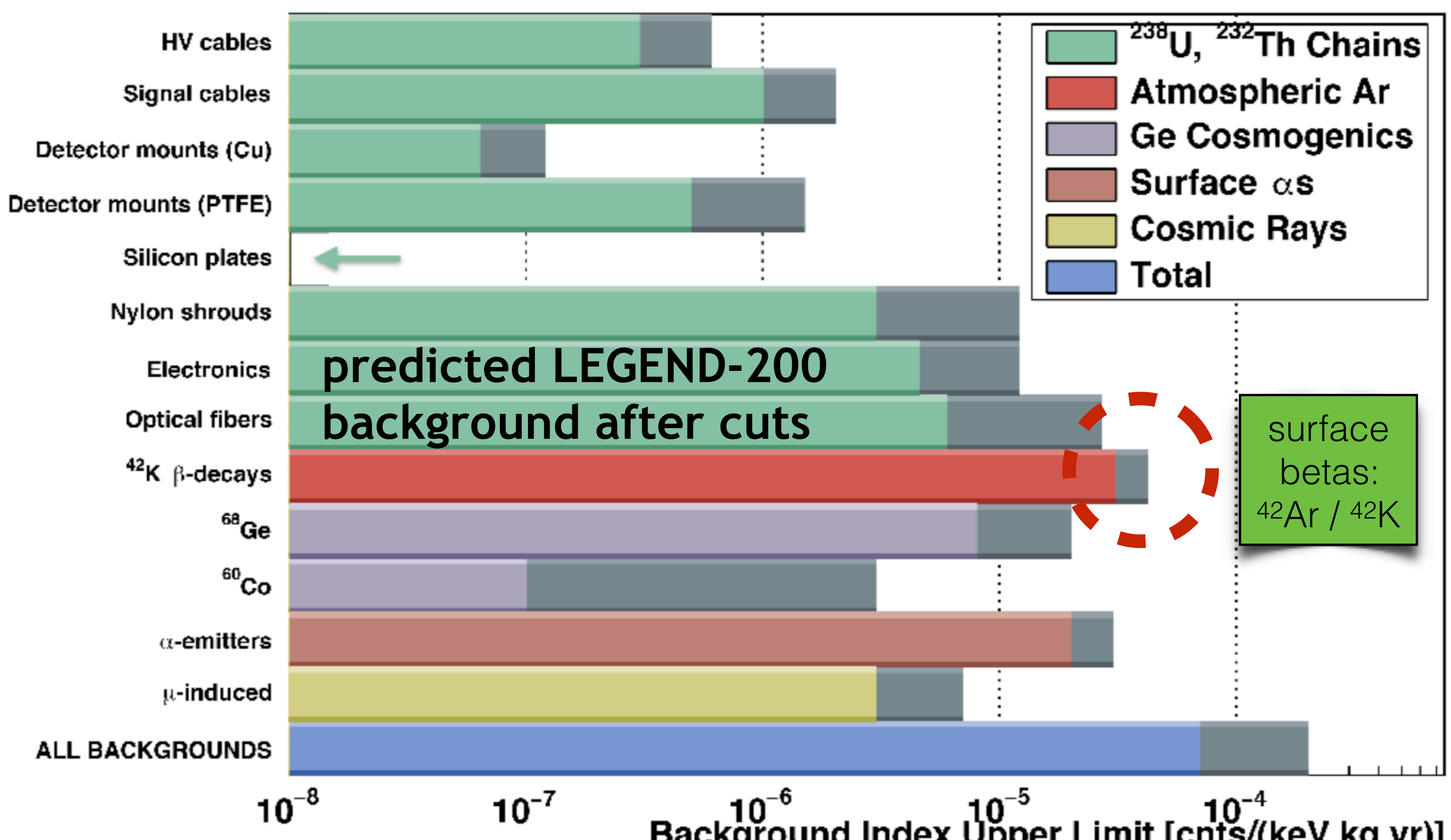




- **Three independent measurements of ^{42}Ar / ^{42}K activity in atmospheric LAr**
- **Different systematic uncertainties**
- **Dominant background for GERDA / LEGEND double beta decay search**

^{42}Ar / ^{42}K Background in GERDA + LEGEND-200





Talk: Mario Schwarz
Results of the background-free search for neutrinoless double beta decay with GERDA &challenges of the LEGEND experiment

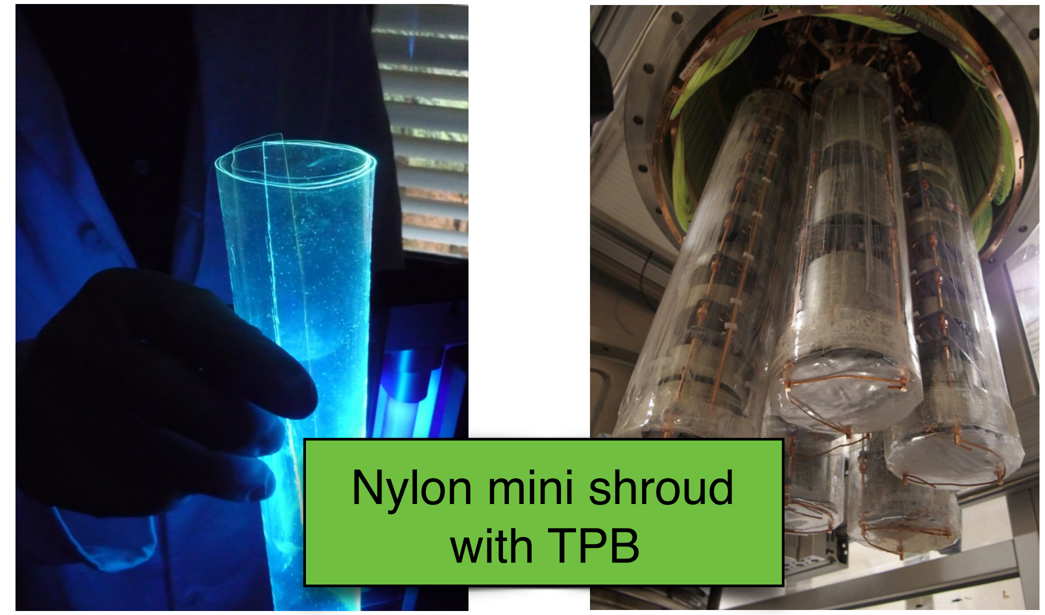
Talk: Matthew Green
LEGEND: Next-Generation Neutrinoless Double-Beta Decay Search in Germanium-76

^{42}K Background Mitigation: GERDA + LEGEND

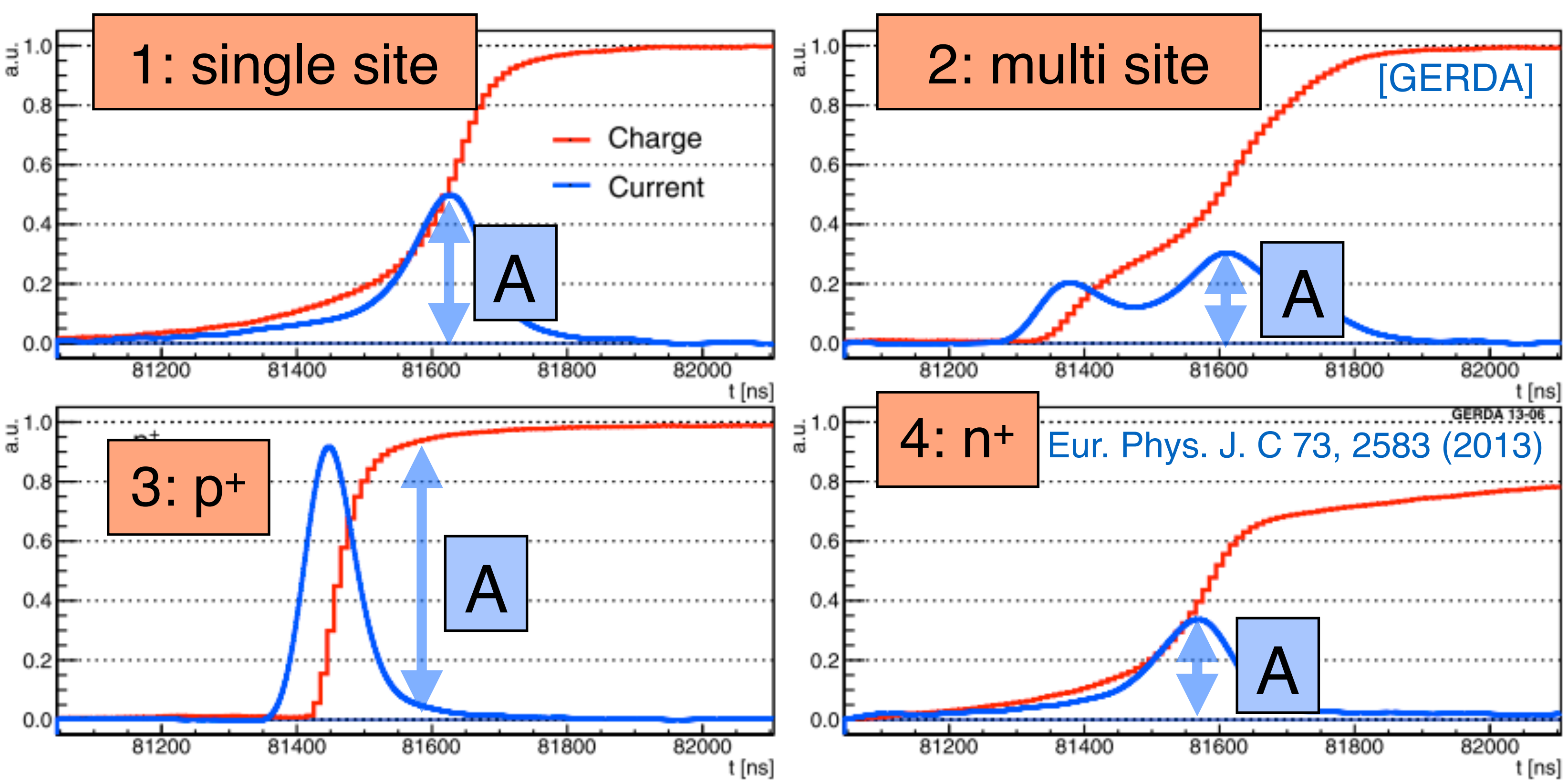
1. Avoid ^{42}K ion drift

- Deploy nylon mini-shroud around detector strings
- Transparent and TPB coated to shift 128 nm scintillation light

Eur. Phys. J. C (2018) 78:15



2. Pulse shape discrimination of surface events

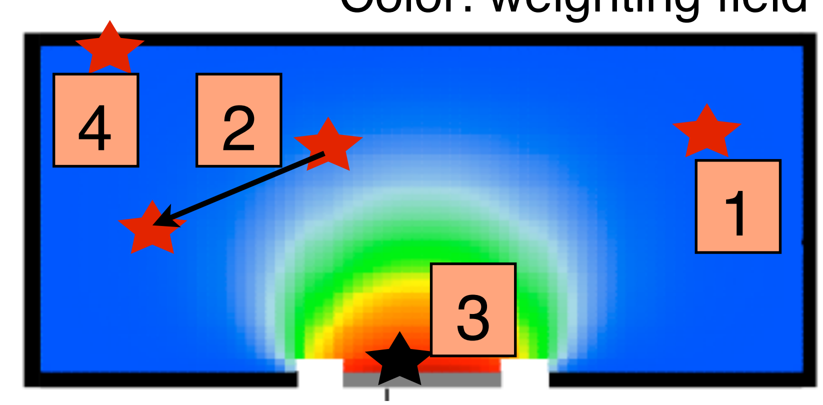


Pulse shape parameter: A/E

- Charge pulse (red) from FADC
- Current pulse (blue) yields amplitude
- Reconstructed energy independent of pulse shape

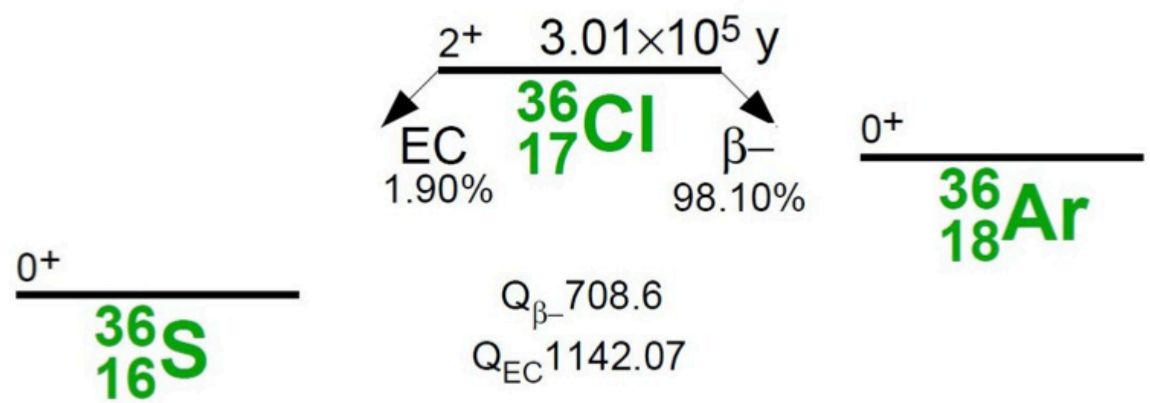
A
E

Color: weighting field



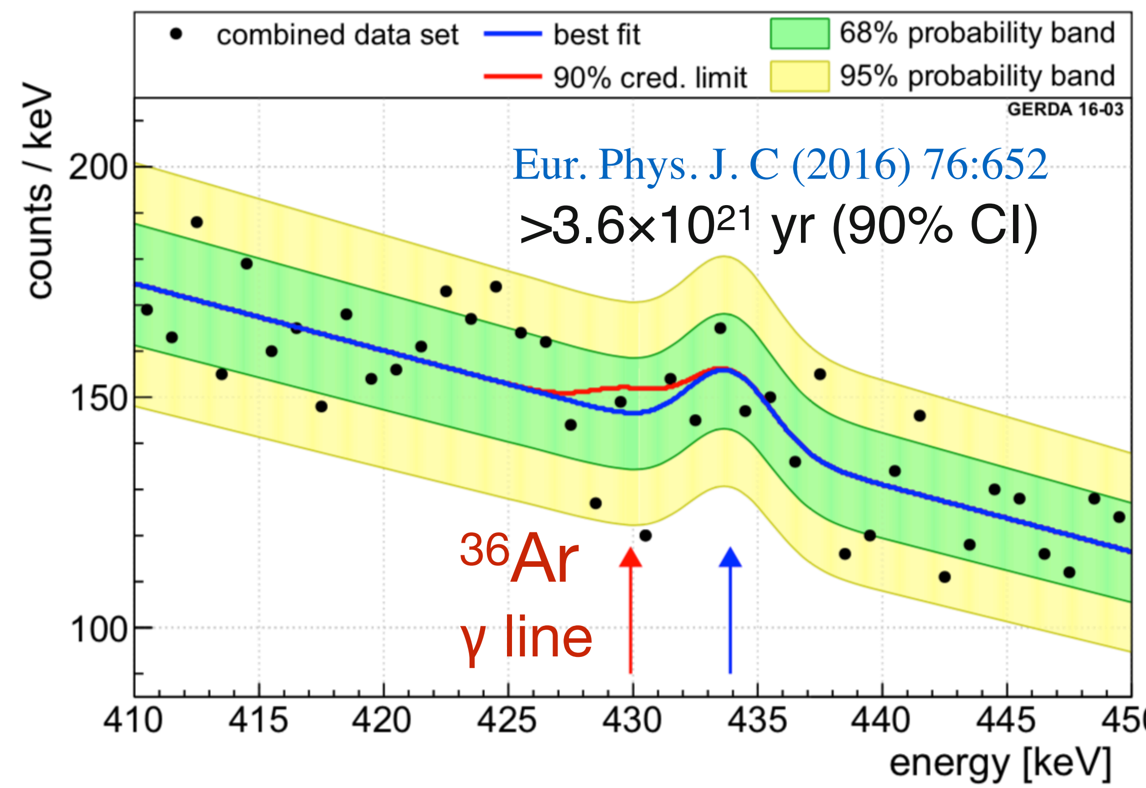
3. Future: Potentially use LAr from underground sources in LEGEND-1000

^{36}Ar - Neutrinoless Double Electron Capture



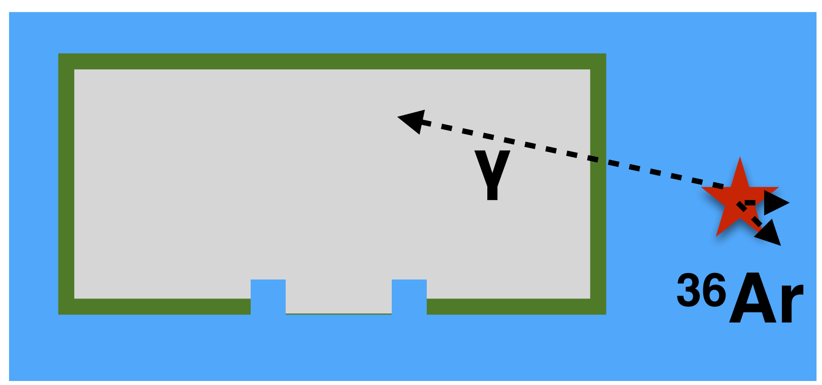
- Q-value = 432.58 ± 0.19 keV
- Lepton number violating process with 3 possible decay modes:
  - single γ emission (429.9 keV)
  - double γ emission
  - internal conversion e$^-$ emission

^{36}Ar + 2e$^-$ ---> ^{36}S + 2 X-ray + E



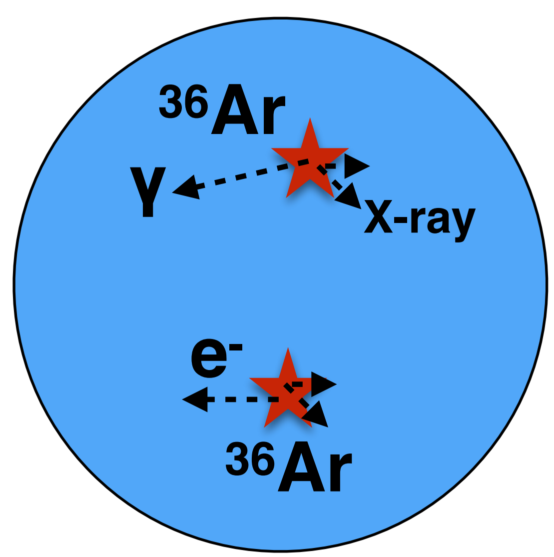
GERDA γ-spec:

- sensitive only to single γ emission
- low efficiency
- high resolution
- low background

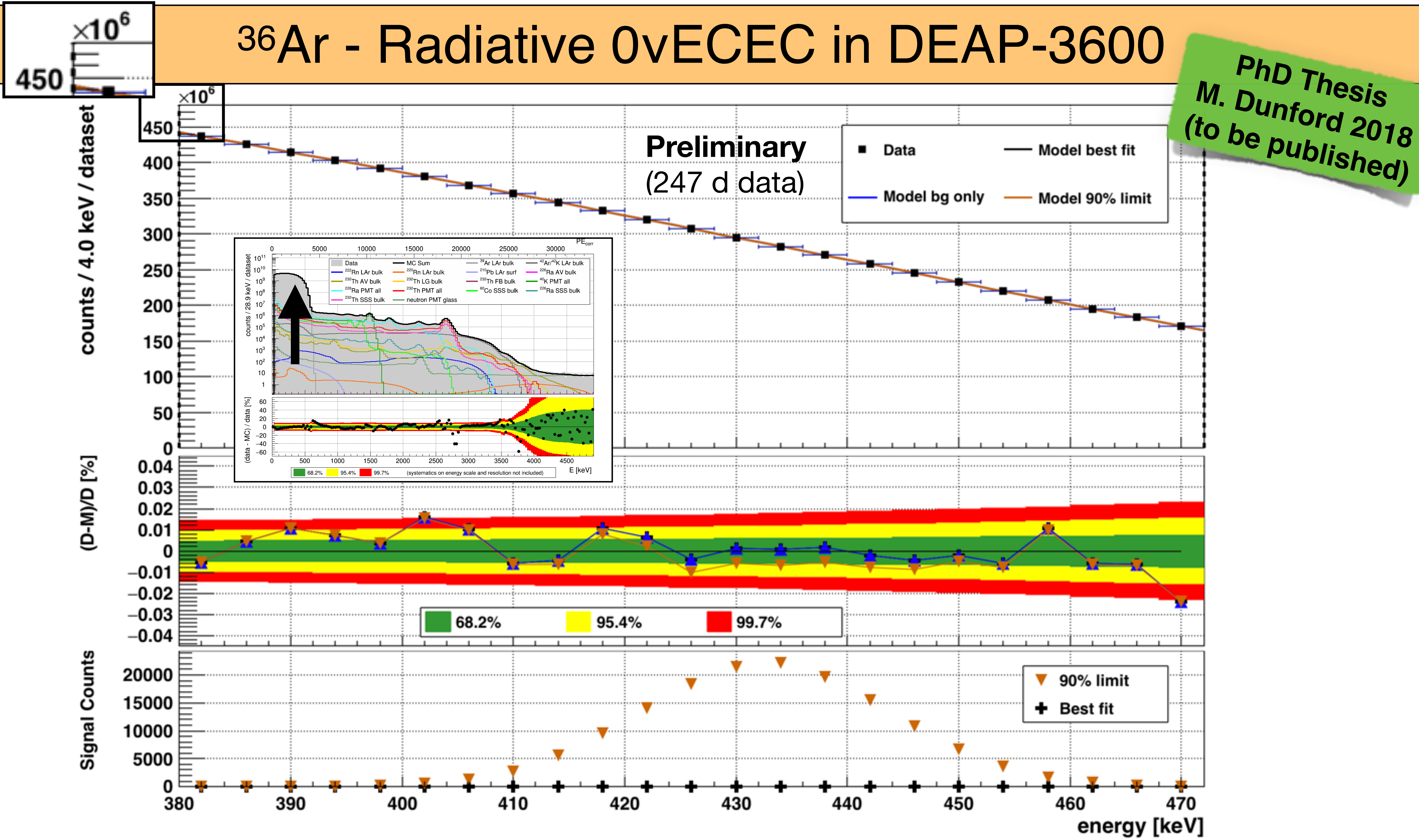


DEAP-3600 calorimetric:

- sensitive to all possible decay modes
- ≈100% efficiency
- poor resolution
- huge ^{39}Ar background



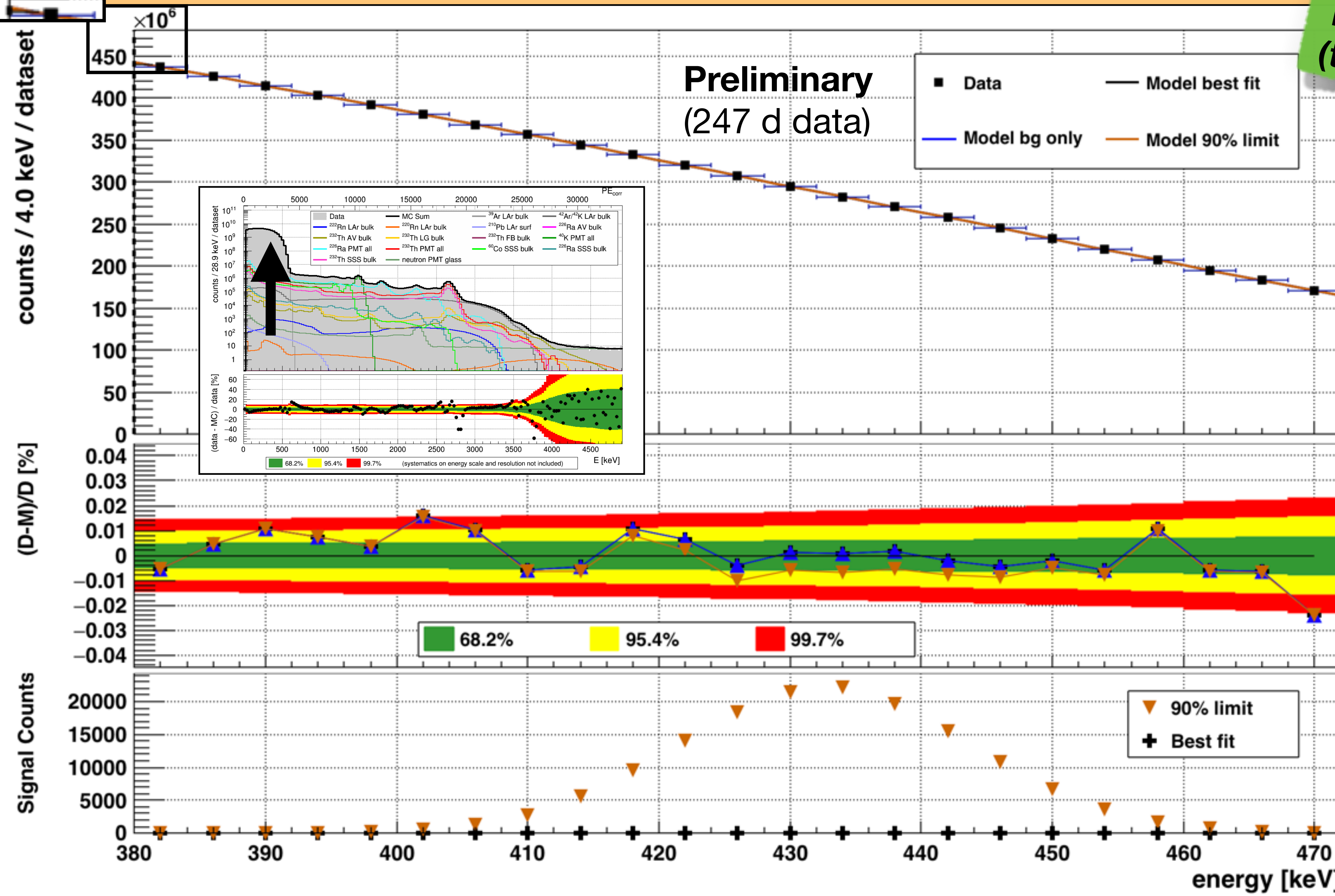
^{36}Ar - Radiative 0vECEC in DEAP-3600



- Peak search at 432.6 keV on large ^{39}Ar background
- The semi-empiric bg model describes the peak region with high precision $O(10^{-4})$
- Background in search window: 7.5×10^{7} cts/keV or 4×10^{4} cts/keV/kg/yr

^{36}Ar - Radiative 0νECEC in DEAP-3600

PhD Thesis
M. Dunford 2018
(to be published)



Experiment	Mode	Half-life	Reference
GERDA Phase I	ɣ	>3.6×10^{21} yr (90% CI)	EPJ C 76:652 (2016)
DEAP-3600	**ɣ, ɣɣ, IC**	**>4×10^{20} yr (90% CI)**	**M. Dunford, PhD Thesis (2018)**
Theory (QRPA)	all	10^{38} yr (@ m_ν = 1 eV)	A. Merle, PhD Thesis (2009)

New

Conclusions

- ^{39}Ar (≈1 mBq/kg)
  - Agreement in literature
  - Important background for DM exp.
  - Precision measurements interesting for nuclear structure (g_A)

Experiment	A [Bq/kg]	Reference
WARP	1.01 ±0.10	NIM A 574 (2007) 83–88
ArDM	0.95 ±0.05	J Cosm a Astrop Phys. 12 (2018)
DEAP-3600	**0.953 ±0.028**	**M. Dunford, PhD Thesis (2018)**

New

- ^{42}Ar (≈40-100 uBq/kg)
  - Three independent measurements: Tension between results
  - Dominant background for GERDA / LEGEND-200 double beta decay experiment

Experiment	Technique	Activity [μBq/kg]	Reference
GERDA Phase I	HPGe γ-spec.	$= 91^{+8}_{-20} - 168^{+22}_{-18}$	EPJ C 74:2764 (2014)
DBA	LAr ion. det.	$= 92^{+22}_{-46}$	J of P CS 718 062004 (2016)
DEAP-3600	**Scintillation**	**= 40.4 ± 5.9**	**arXiv:1905.05811 (2019)**

New

- ^{36}Ar (0.33%)
  - Double electron capture isotope
  - $T_{1/2} > 3.6\times10^{21}$ yr

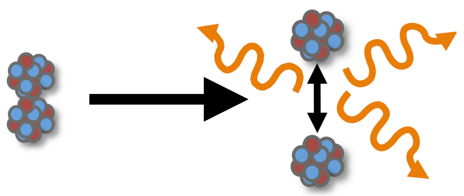
Experiment	Mode	Half-life	Reference
GERDA Phase I	γ	$>3.6\times10^{21}$ yr (90% CI)	EPJ C 76:652 (2016)
DEAP-3600	**γ, γγ, IC**	**$>4\times10^{20}$ yr (90% CI)**	**M. Dunford, PhD Thesis (2018)**
Theory (QRPA)	all	10^{38} yr (@ m_ν = 1 eV)	A. Merle, PhD Thesis (2009)

New

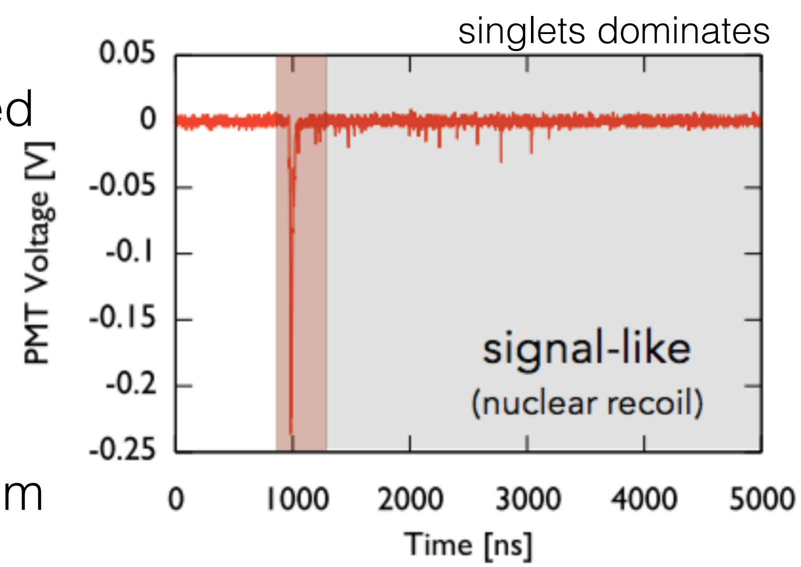
Backup

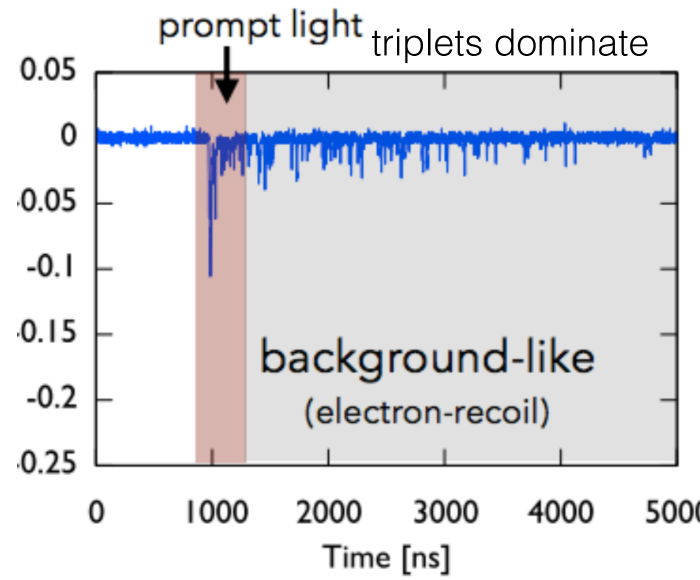
^{39}Ar Mitigation in DEAP-3600: Pulse Shape Analysis

Ar scintillation:
- excimers are created



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

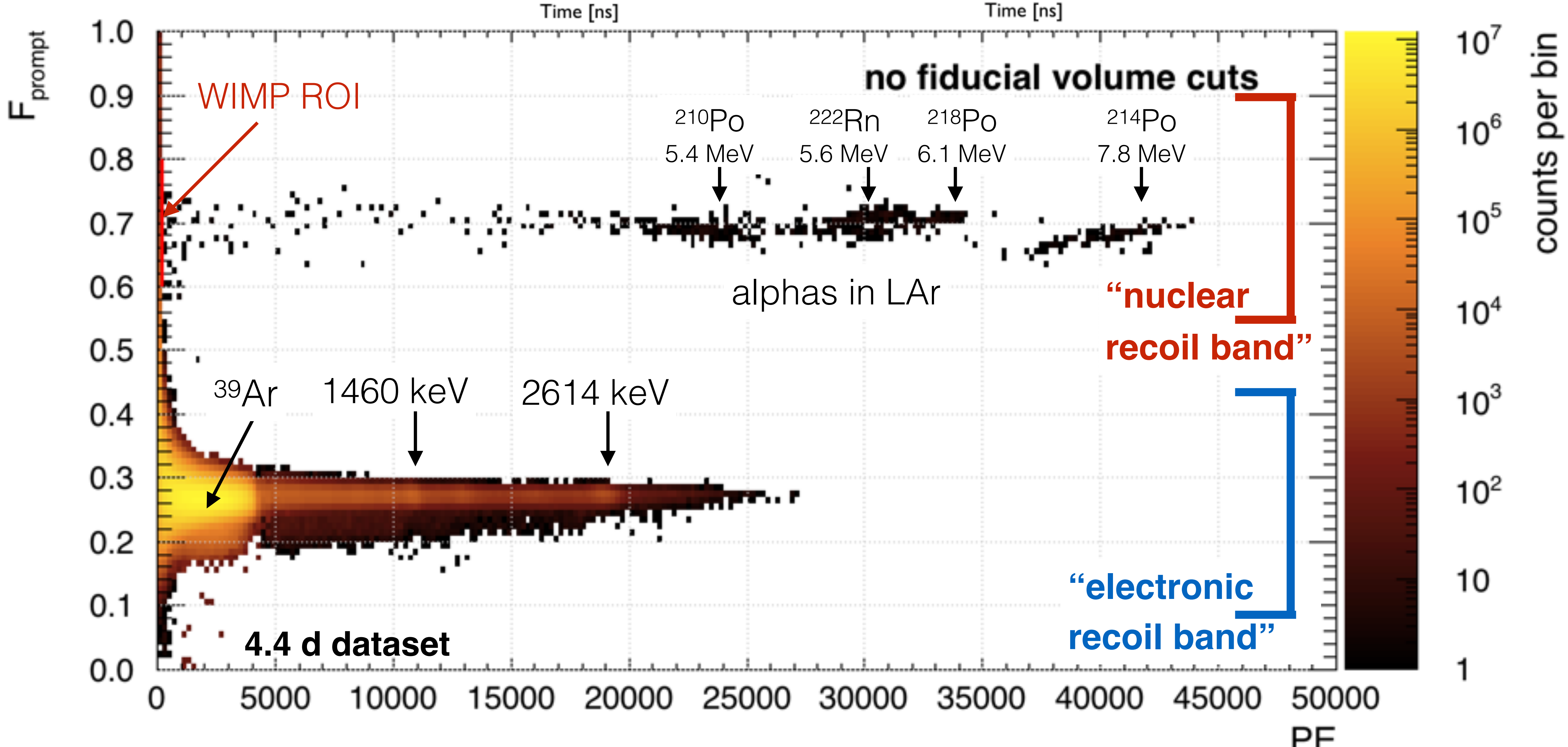




Pulse shape discrimination (PSD) parameter:

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

factor 10^{10} separation



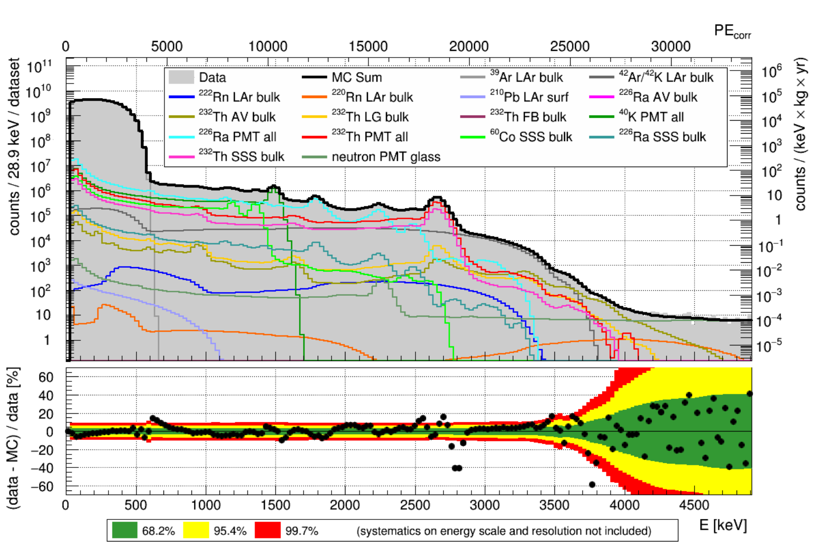
DEAP 3600 commissioning data

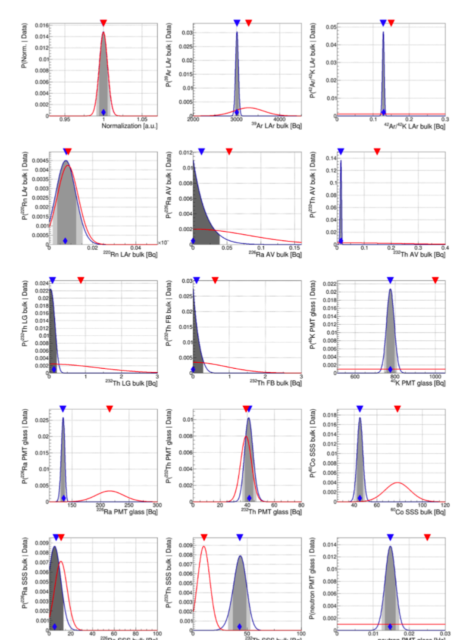
DEAP-3600 ER Component Activities

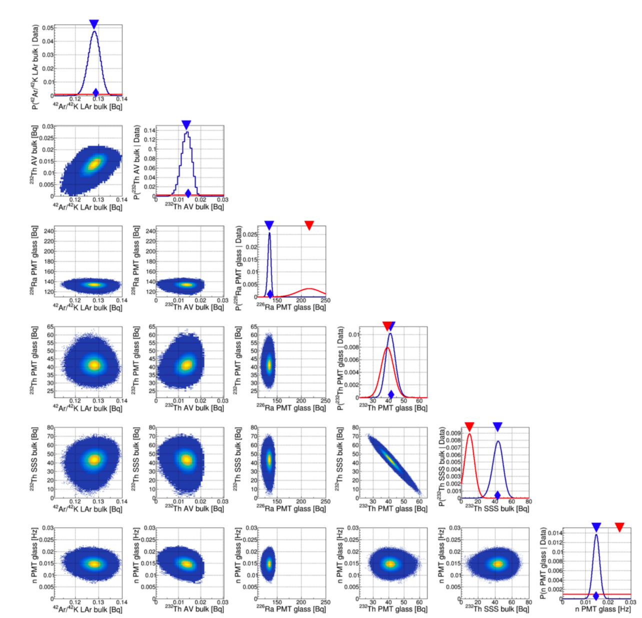
Component	Included in model?	Simulated isotopes	Total activity [Bq]	Reference
^{39}Ar LAr bulk	F	^{39}Ar	3282 ± 340	[11]
^{42}Ar/^{42}K LAr bulk	F	^{42}Ar , ^{42}K	—	—
^{222}Rn LAr bulk	C	^{214}Pb, ^{214}Bi	$(5.9 \pm 0.7) \times 10^{-4}$	[6]
^{220}Rn LAr bulk	F	^{212}Pb, ^{212}Bi, ^{208}Tl	$(8.5 \pm 4.9) \times 10^{-6}$	[6]
^{210}Pb LAr surf	C	^{210}Pb, ^{210}Bi	$(2.2 \pm 0.4) \times 10^{-3}$	[6]
^{226}Ra AV bulk	F	^{214}Pb, ^{214}Bi, ^{210}Pb, ^{210}Bi	< 0.08	[screening]
^{232}Th AV bulk	F	^{228}Ra, ^{228}Ac, ^{212}Pb, ^{212}Bi, ^{208}Tl	< 0.22	[screening]
^{40}K AV bulk	N	^{40}K	< 2.5	[screening]
^{222}Rn RnEm	D	^{214}Bi	< 1	[3]
^{220}Rn RnEm	D	^{208}Tl	< 1	[3]
^{226}Ra LG bulk	N	^{214}Pb, ^{214}Bi, ^{210}Bi	< 0.4	[screening]
^{232}Th LG bulk	F	^{228}Ac, ^{212}Pb, ^{212}Bi, ^{208}Tl	< 1.3	[screening]
^{40}K LG bulk	N	^{40}K	< 4.6	[screening]
^{226}Ra FB bulk	N	^{214}Pb, ^{214}Bi, ^{210}Bi	< 1.5	[screening]
^{232}Th FB bulk	F	^{228}Ac, ^{212}Pb, ^{212}Bi, ^{208}Tl	< 0.9	[screening]
^{40}K FB bulk	N	^{40}K	< 9.6	[screening]
^{226}Ra PMT all	F	^{214}Pb, ^{214}Bi, ^{210}Bi	216 ± 24	[screening]
^{232}Th PMT all	F	^{228}Ac, ^{212}Pb, ^{212}Bi, ^{208}Tl	39 ± 4	[screening]
^{40}K PMT all	F	^{40}K	454 ± 33	[screening]
neutron PMT glass	F	See caption	—	—
^{226}Ra SSS bulk	F	^{214}Bi	10.6 ± 5.8	[screening]
^{232}Th SSS bulk	F	^{228}Ac, ^{208}Tl	9.7 ± 5.6	[screening]
^{60}Co SSS bulk	F	^{60}Co	78 ± 11	[screening]

DEAP-3600 ER BG Model Priors + Posteriors

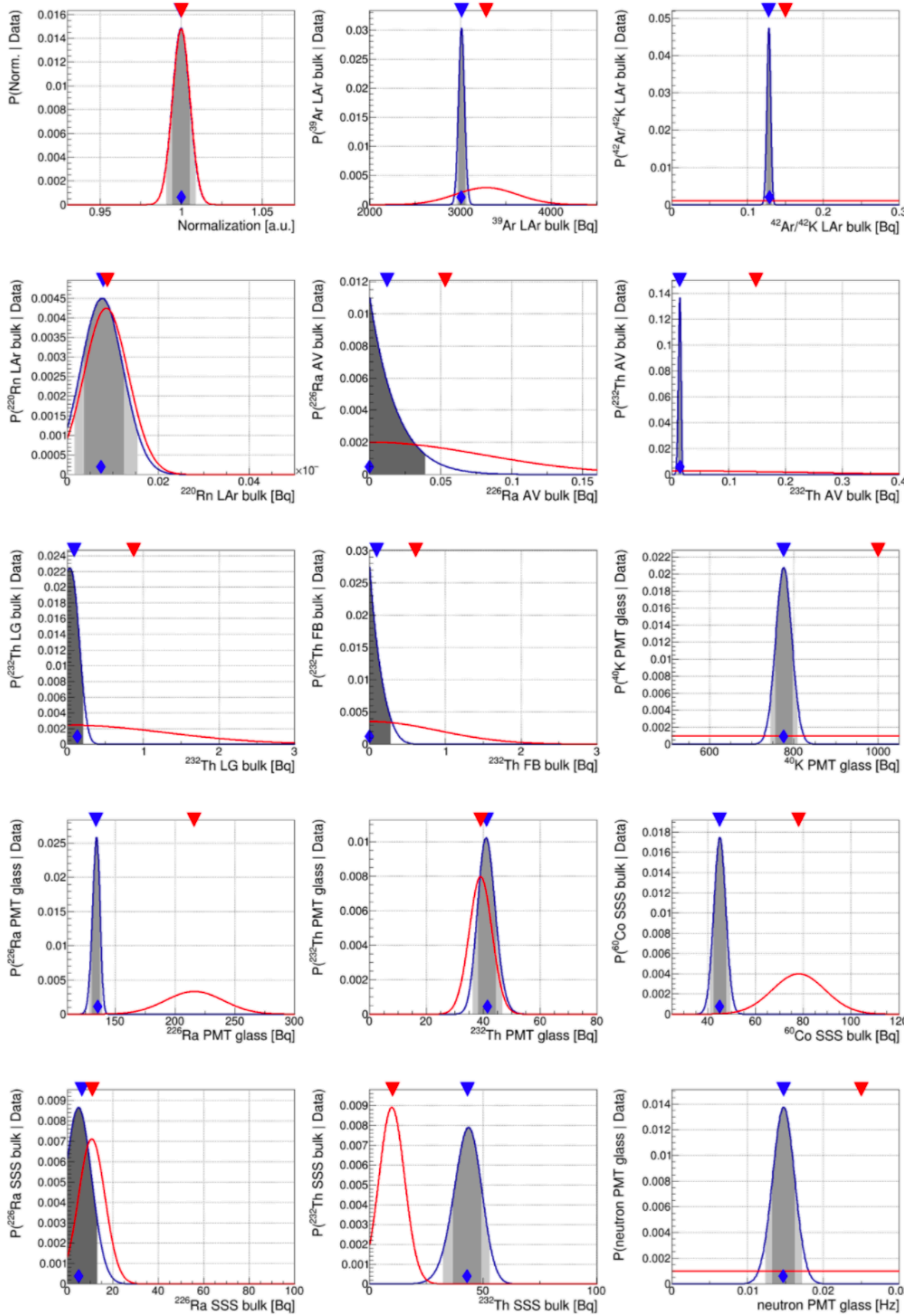
Component	Input prior [Bq]	Best fit [Bq]	Central 68% interval [Bq]
^{39}Ar LAr bulk	3282 ± 340	3009	[2977 – 3042]
^{42}Ar/^{42}K LAr bulk	[0 – 0.3]	0.129	[0.126 – 0.131]
^{222}Rn LAr bulk	$= 5.9 \times 10^{-4}$	-	-
^{220}Rn LAr bulk	$(8.5 \pm 4.9) \times 10^{-6}$	7.4×10^{-6}	$< 13.7 \times 10^{-6}$
^{210}Pb LAr surf	$= 2.0 \times 10^{-4}$	-	-
^{226}Ra AV bulk	$(0 \pm 8) \times 10^{-2}$	0	$< 3.9 \times 10^{-2}$ (90% CI)
^{232}Th AV bulk	$(0 \pm 22) \times 10^{-2}$	1.5×10^{-2}	$[1.1 - 1.6] \times 10^{-2}$
^{232}Th LG bulk	0 ± 1.3	0.13	< 0.2 (90% CI)
^{232}Th FB bulk	0 ± 0.9	0	< 0.27 (90% CI)
^{40}K PMT all	[500 – 1500]	776	[757 – 795]
^{226}Ra PMT all	216 ± 24	136	[131 – 137]
^{232}Th PMT all	39 ± 4	41.5	[38.1 – 44.4]
neutron PMT glass	$[0 - 5] \times 10^{-2}$	1.47×10^{-2}	$[1.33 - 1.62] \times 10^{-2}$
^{60}Co SSS bulk	78 ± 11	45.0	[42.5 – 47.5]
^{226}Ra SSS bulk	10.6 ± 5.8	4.9	< 12.9 (90% CI)
^{232}Th SSS bulk	9.7 ± 5.6	43.0	[36.9 – 49.0]

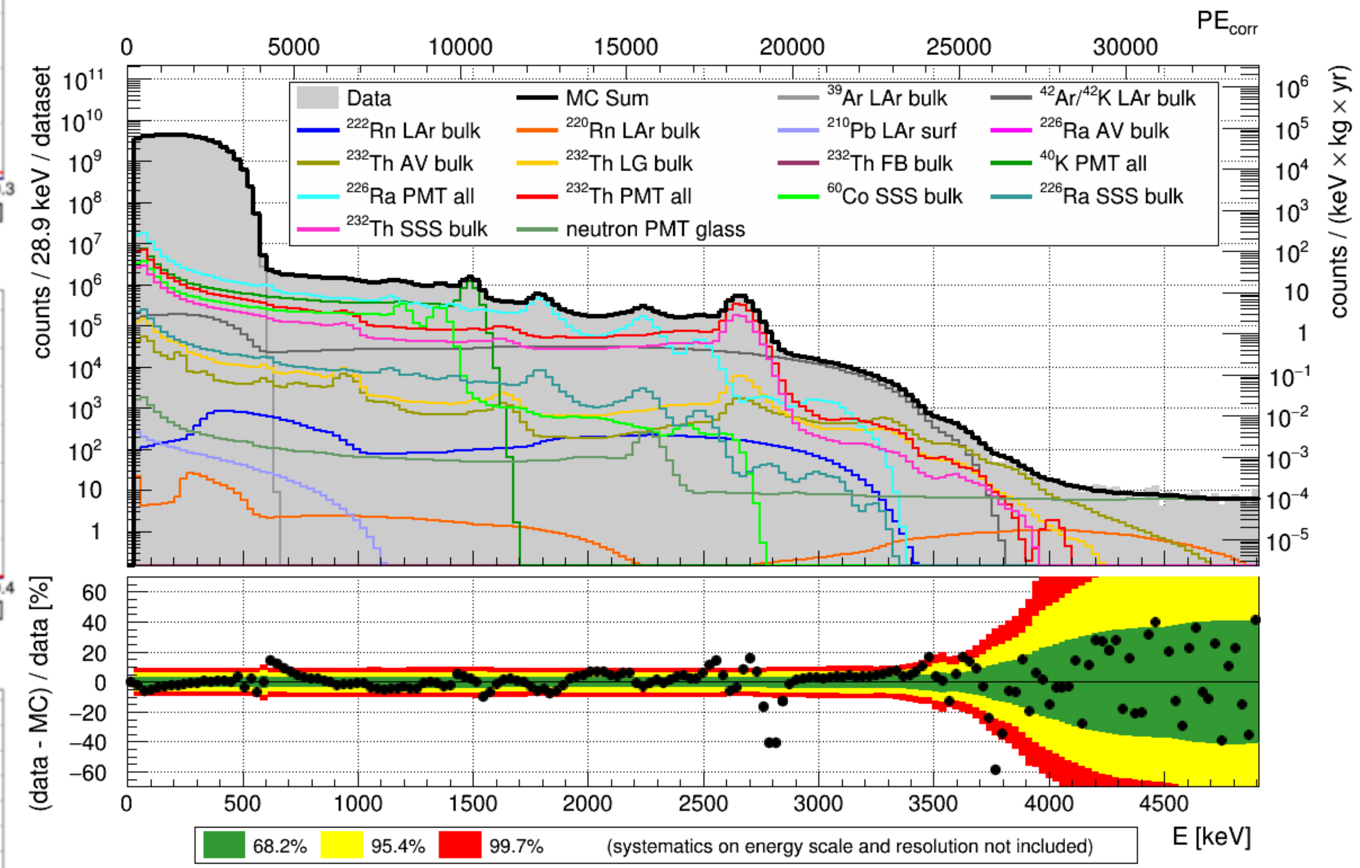


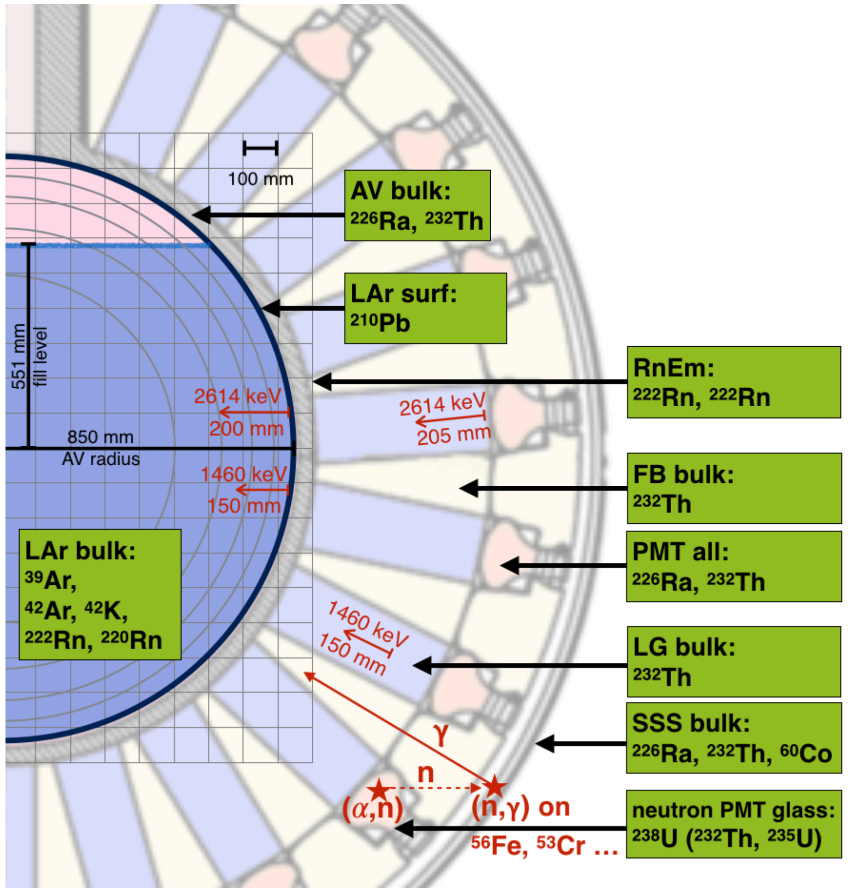




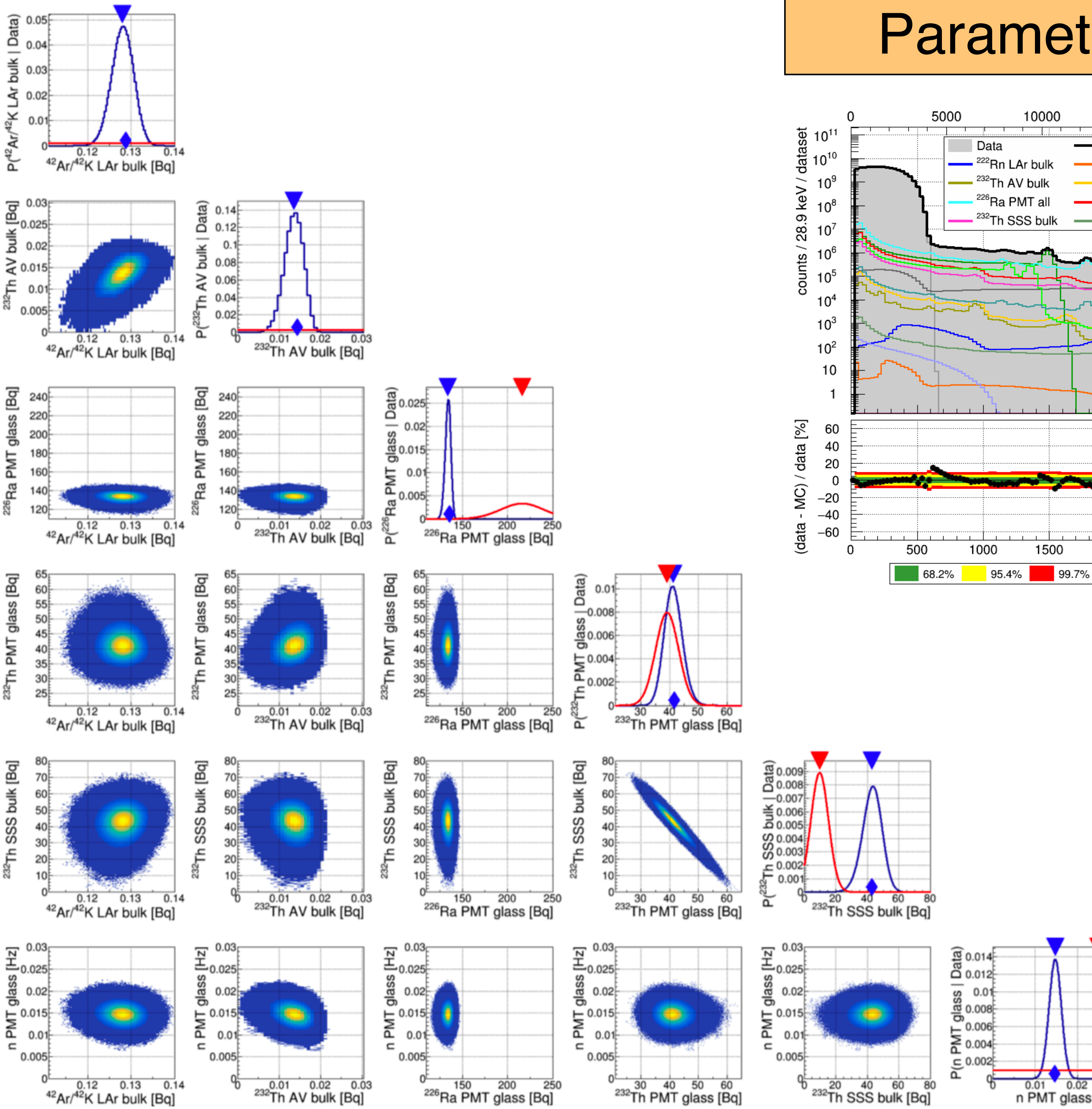
Priors + Posteriors

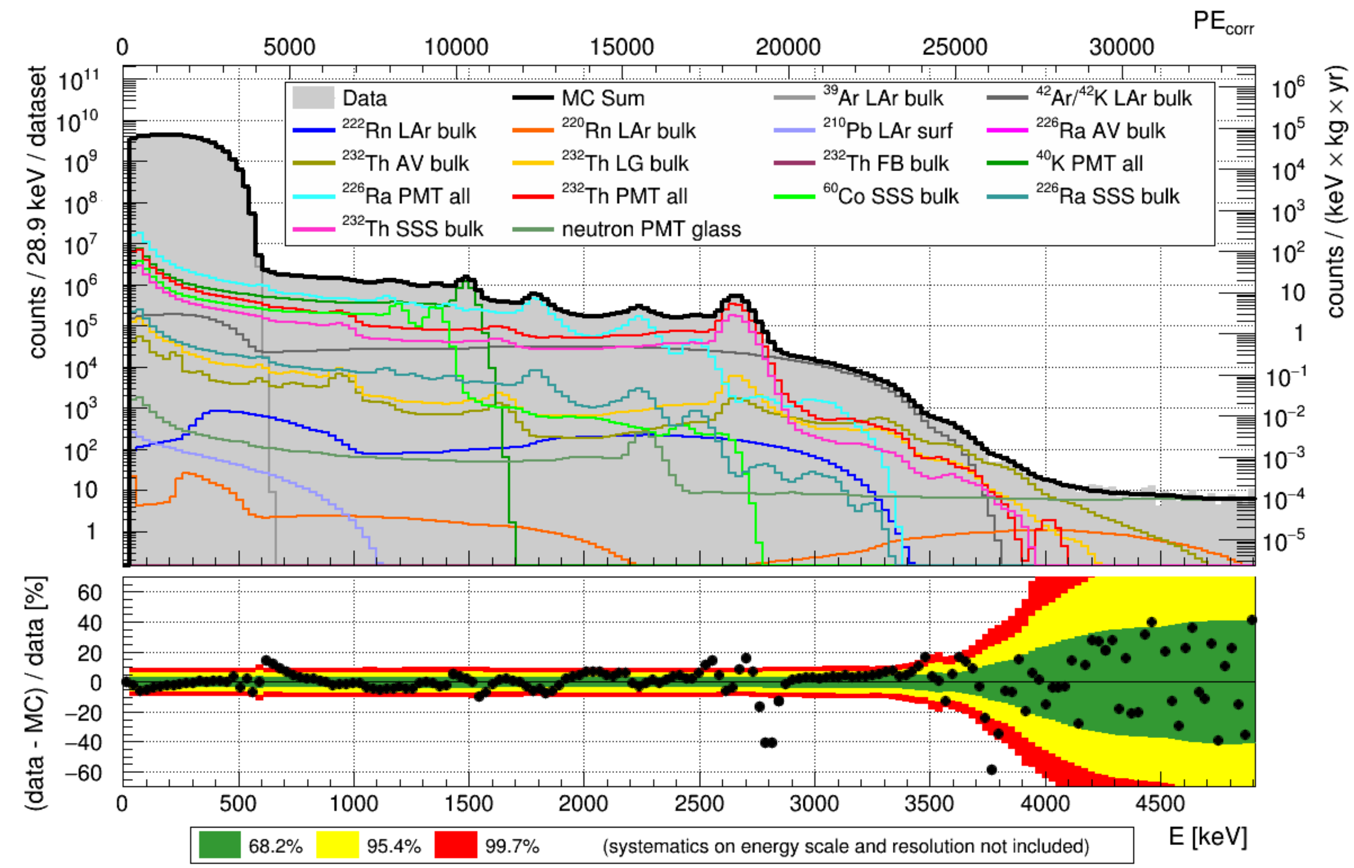


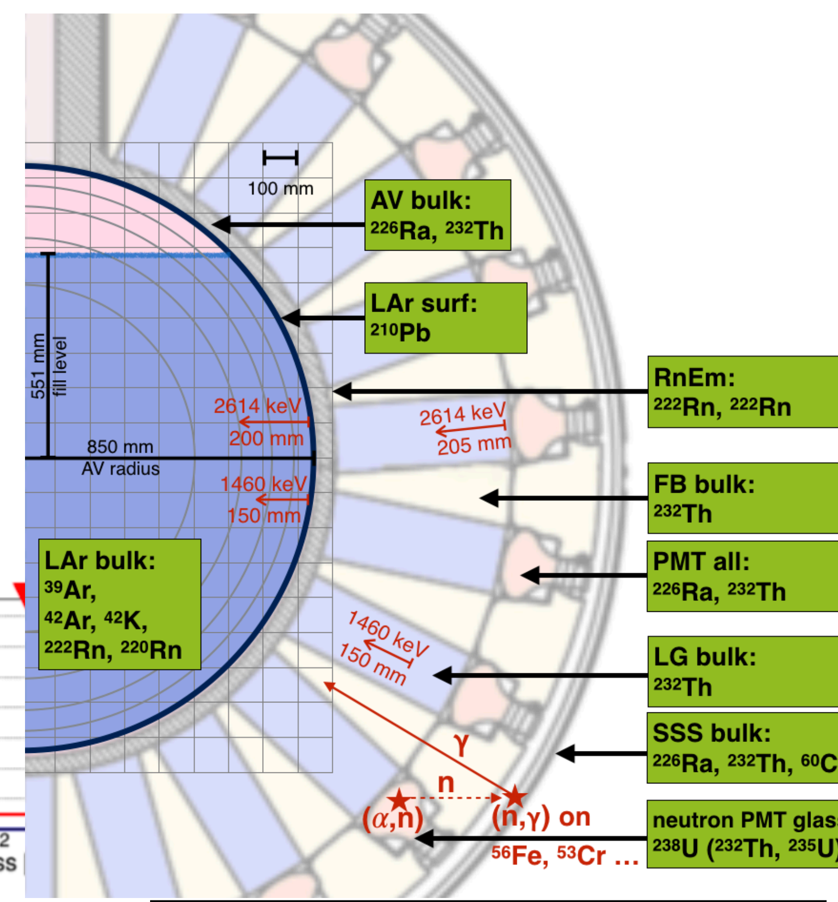




Parameter Correlations







Systematic Uncertainties ^{42}K Activity

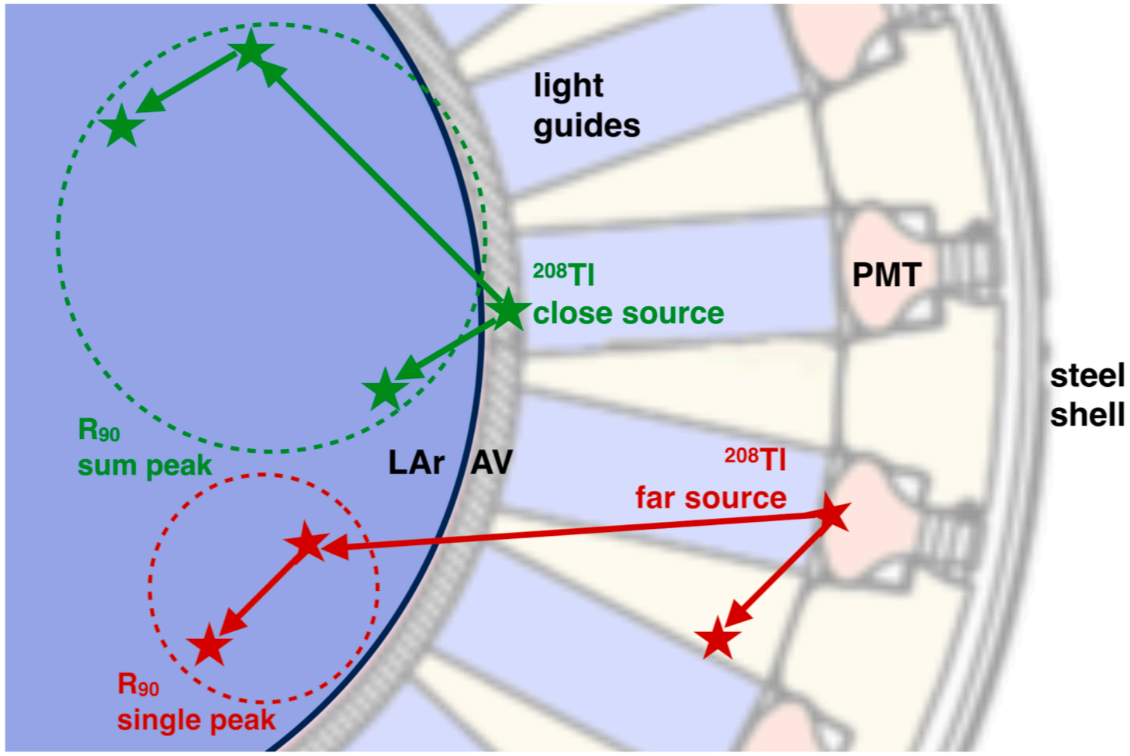


TABLE IV. Systematic uncertainties for ^{42}Ar/^{42}K activity measurement.

Systematics	Fraction of activity
Fit uncertainty	2%
MC simulation	3%
LAr mass	3.4%
Nuclear physics	4.7%
Energy scale	$< 0.8\%$
Topology correction	13%
Subtotal	14.7%
Age of LAr	1%