Searching for low-mass WIMPs: Dark matter from the tabletop

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5 Aug 2010

Outline

- The MAJORANA neutrinoless double-beta decay experiment and P-type Point Contact (P-PC) germanium detectors
- R&D detectors in Soudan, MN
  - Pacific Northwest National Lab P-PC
  - University of Chicago BEGe

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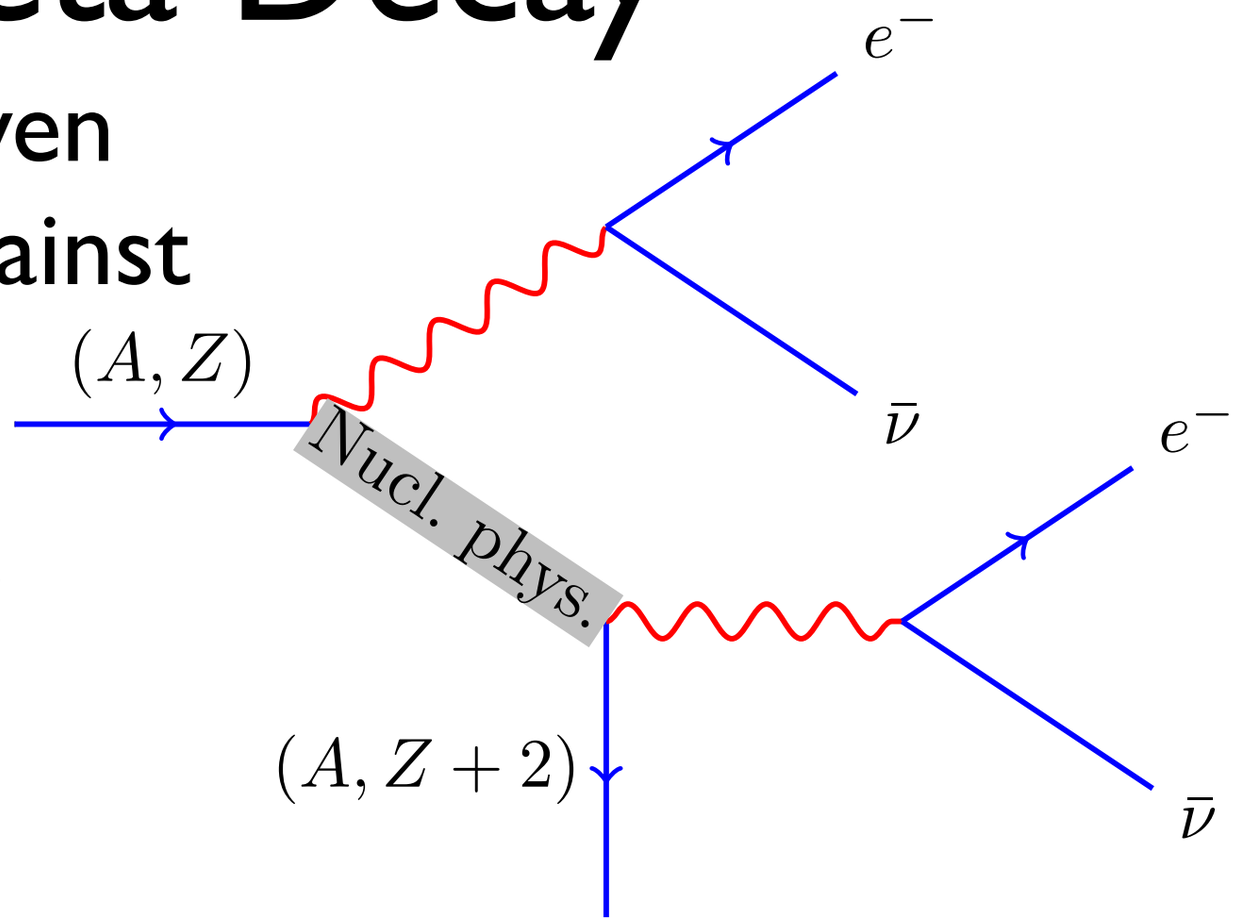
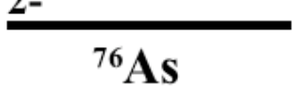
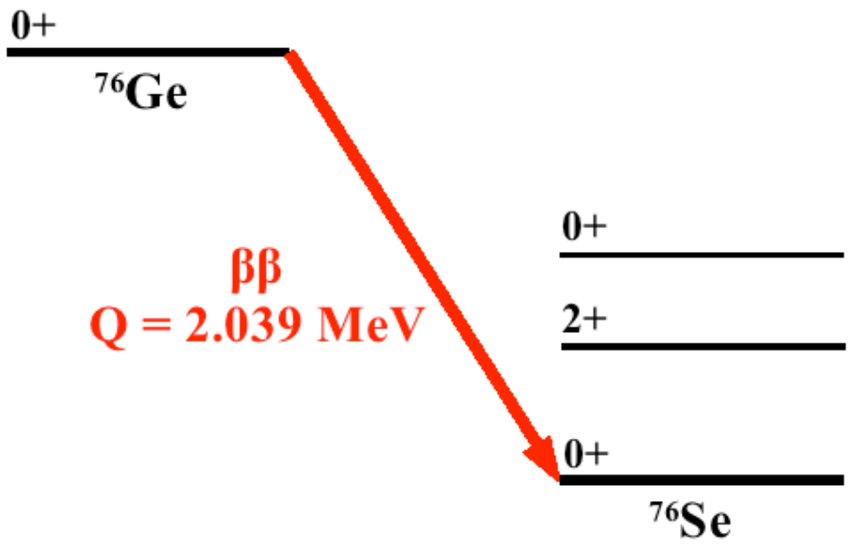
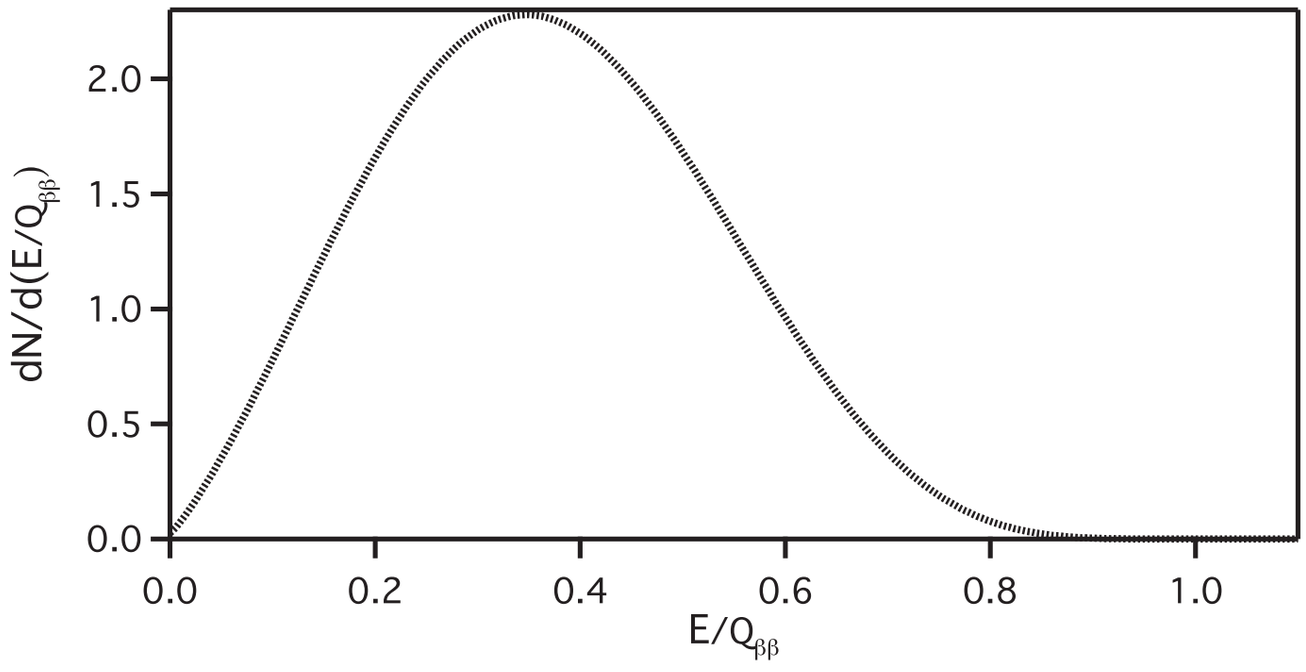
Double-Beta Decay

- Allowed for some even-even nuclei otherwise stable against β-decay.
- Observed, $T^{2\nu}_{1/2} \sim 10^{20}$ yrs.



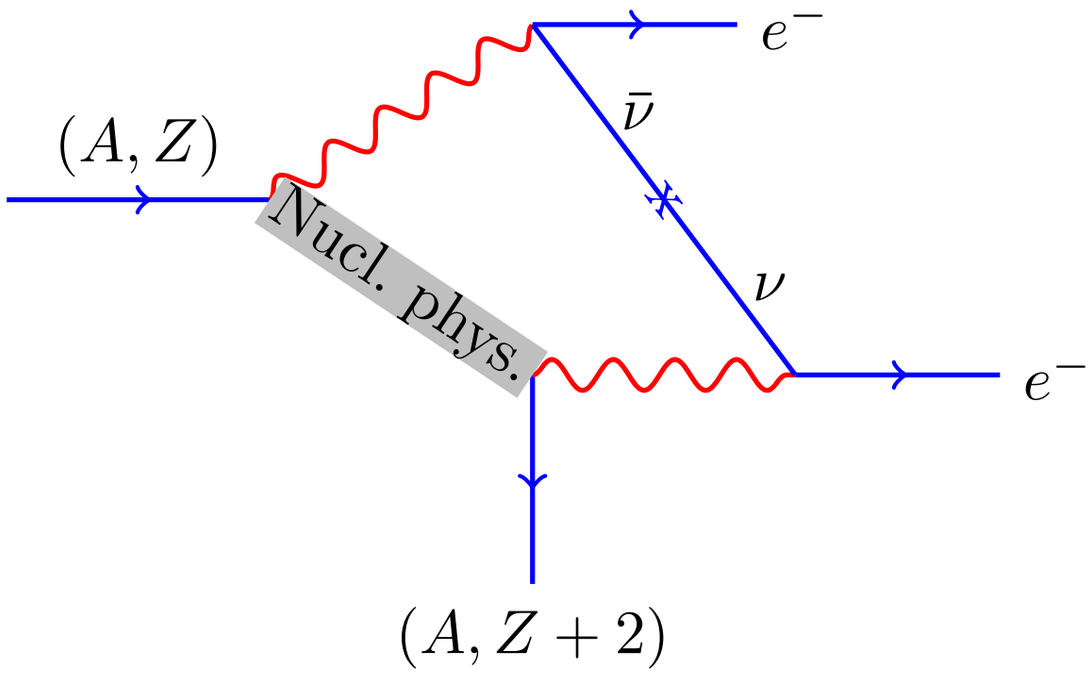


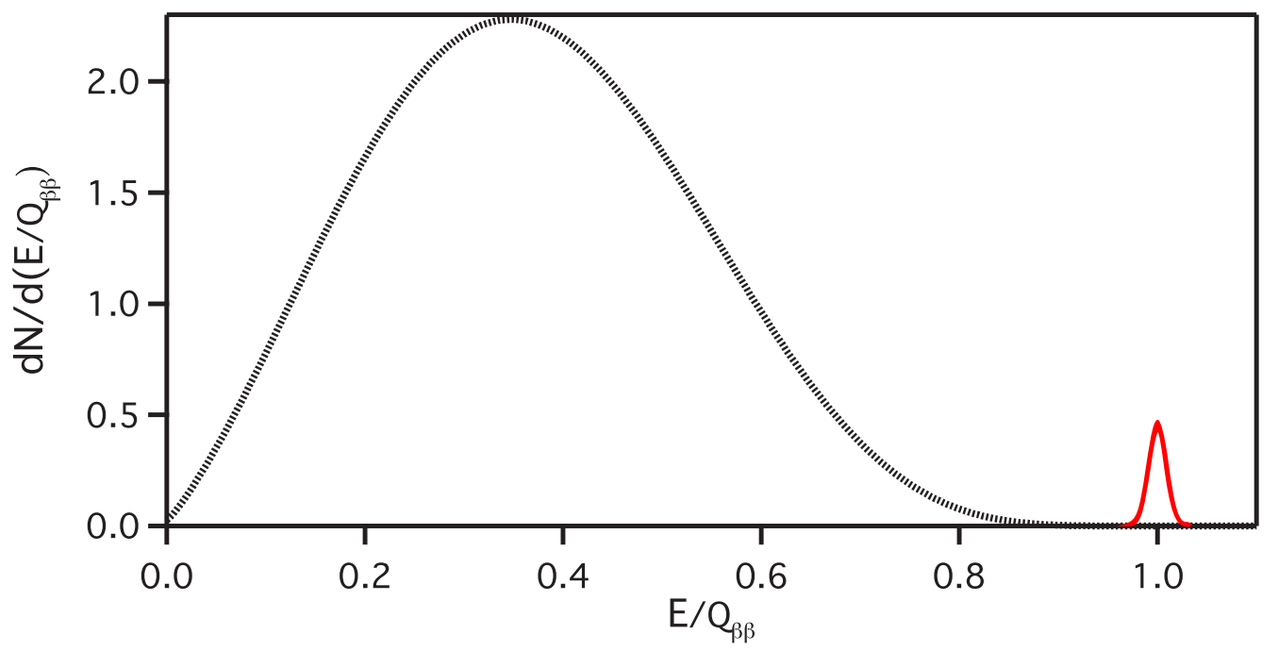




Neutrinoless Double-Beta Decay (0νββ)

- If seen:
  - Lepton-number violation
  - ν-mass measurement
- How to find it?
  - Find an isotope (e.g. ^{76}Ge, Q-value 2039 keV)
  - Make a detector out of it.
  - Reduce backgrounds.
  - Wait.





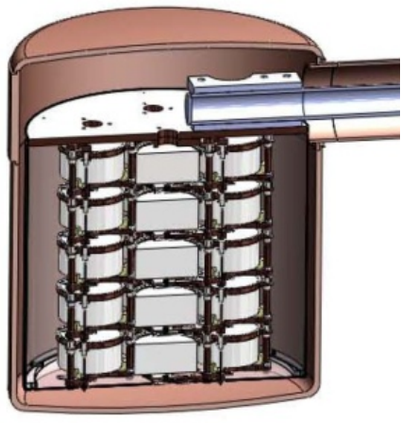
The MAJORANA Collaboration Goals

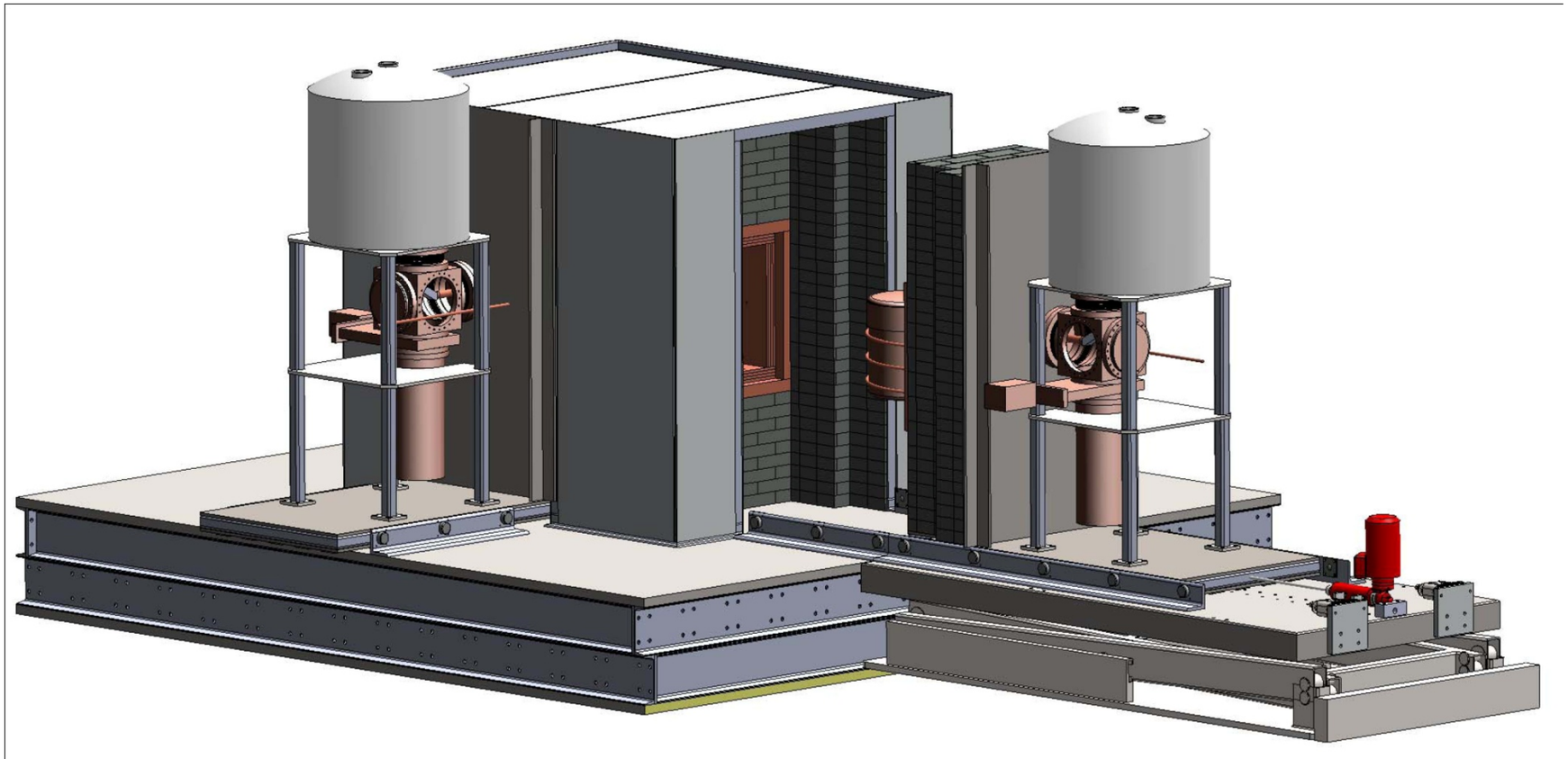
Actively pursuing R&D aimed at a ~1 tonne scale ^{76}Ge $0\nu\beta\beta$-decay experiment

- Technical Goal: Demonstrate backgrounds low enough to justify building a tonne-scale experiment
- Science Goal: Build a prototype module to test the recent claim of an observation of $0\nu\beta\beta$
- Opportunistic Science: Explore physics enabled by choice of detector technology
- Cooperation: Partner with GERDA, sharing resources (e.g. analysis tools, simulation), eventual technology down-select

Towards the goals:
MAJORANA DEMONSTRATOR Module

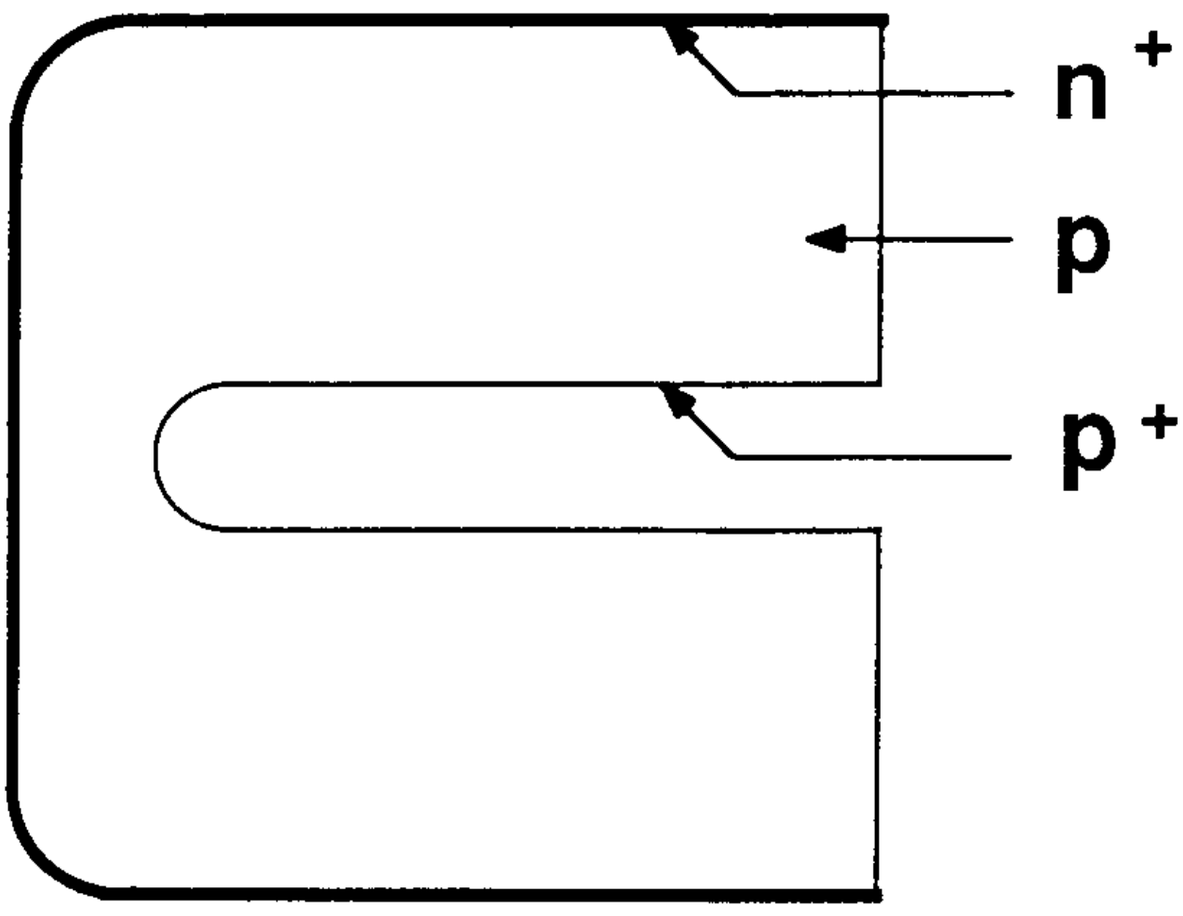
- 35-40 kg of detectors, focusing on p-type point-contact detectors (PPCs)
- Low-background cryostats: ultra-clean, electroformed Cu
- Compact low-background passive Cu and Pb shield with active muon veto
- Located underground, 4850' level of Sanford Lab / DUSEL.

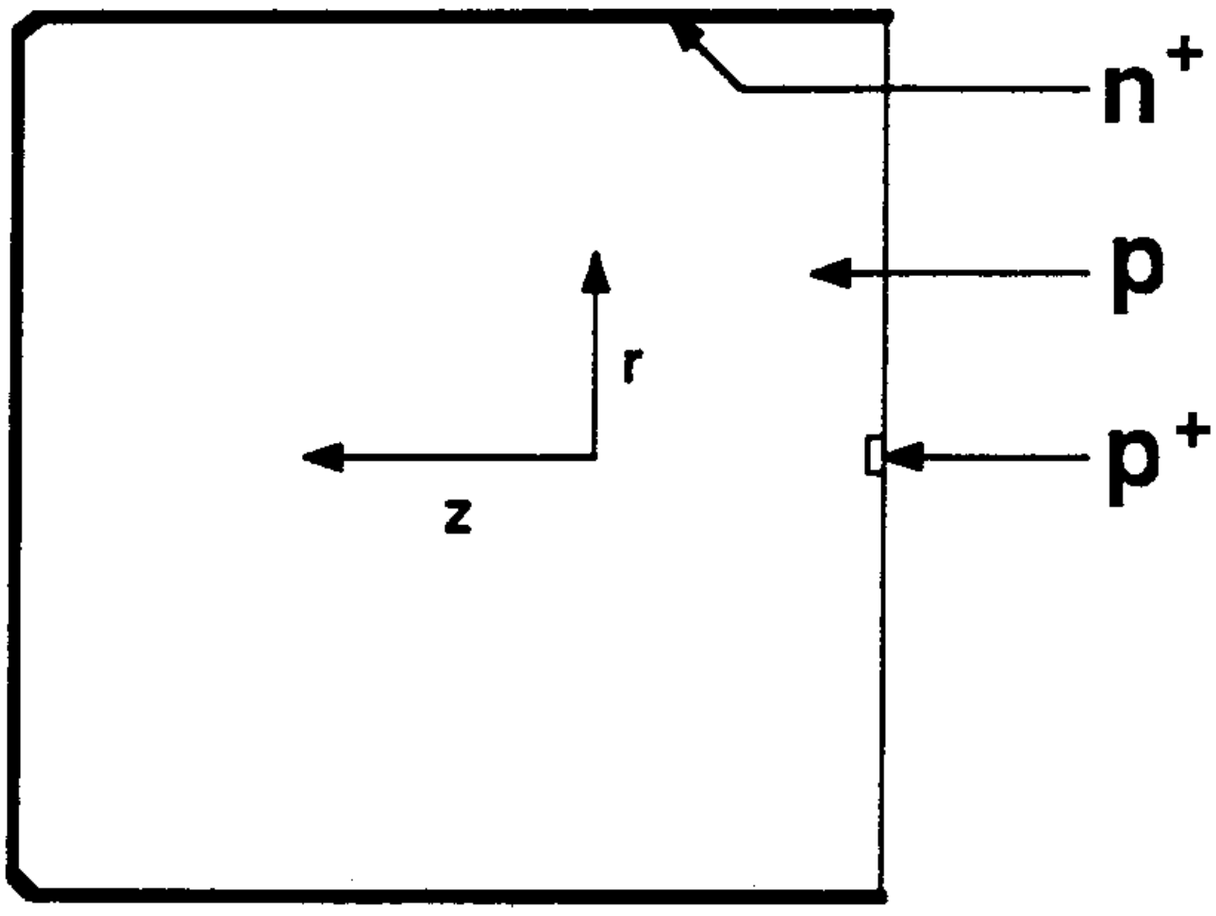




Point-Contact Detectors

- P-type Point-Contact (P-PC)
- Geometry: low-capacitance, noise; long-charge drift times





Luke et al., IEEE trans. Nucl. Sci. 36 , 926(1989).

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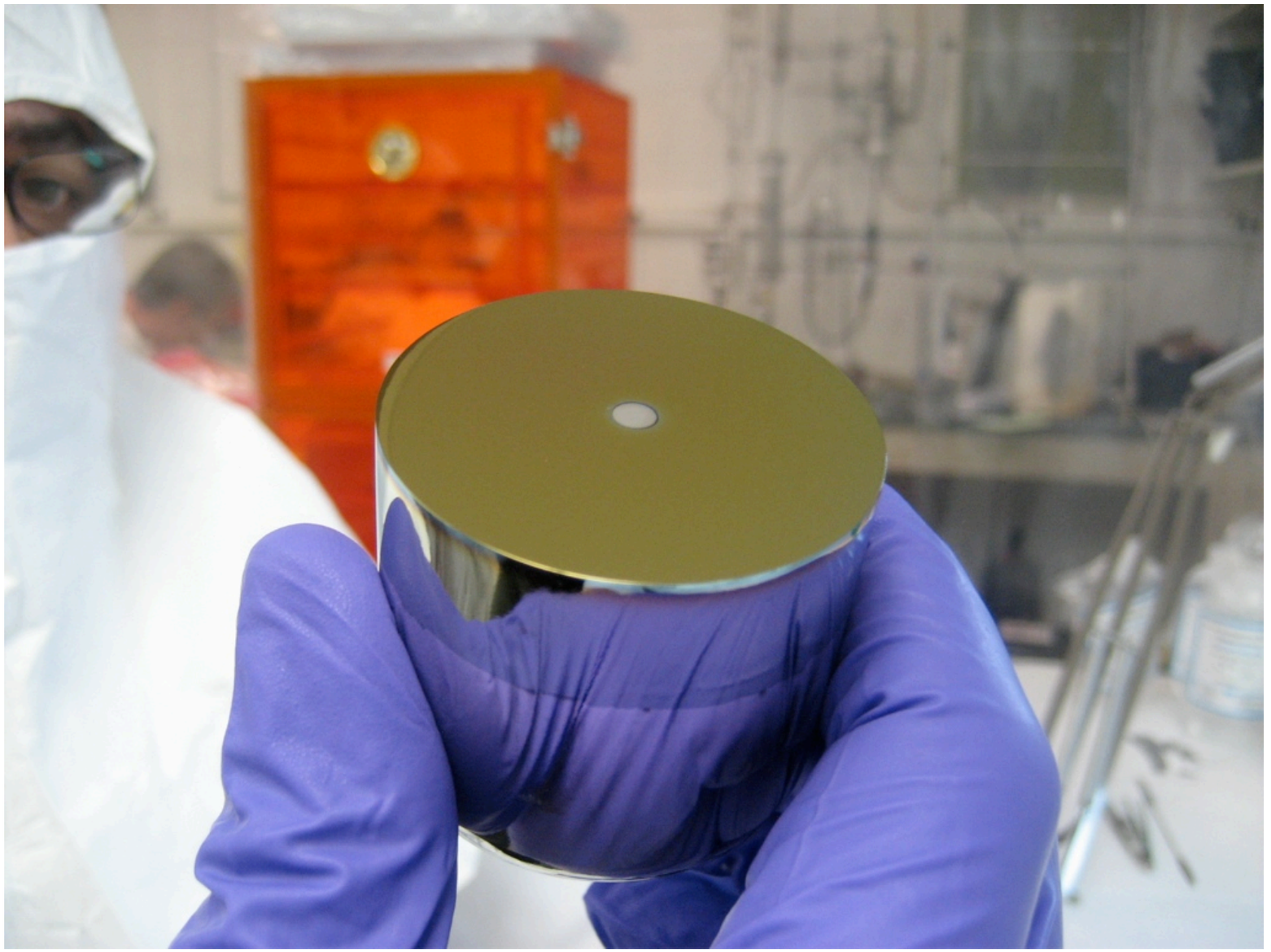
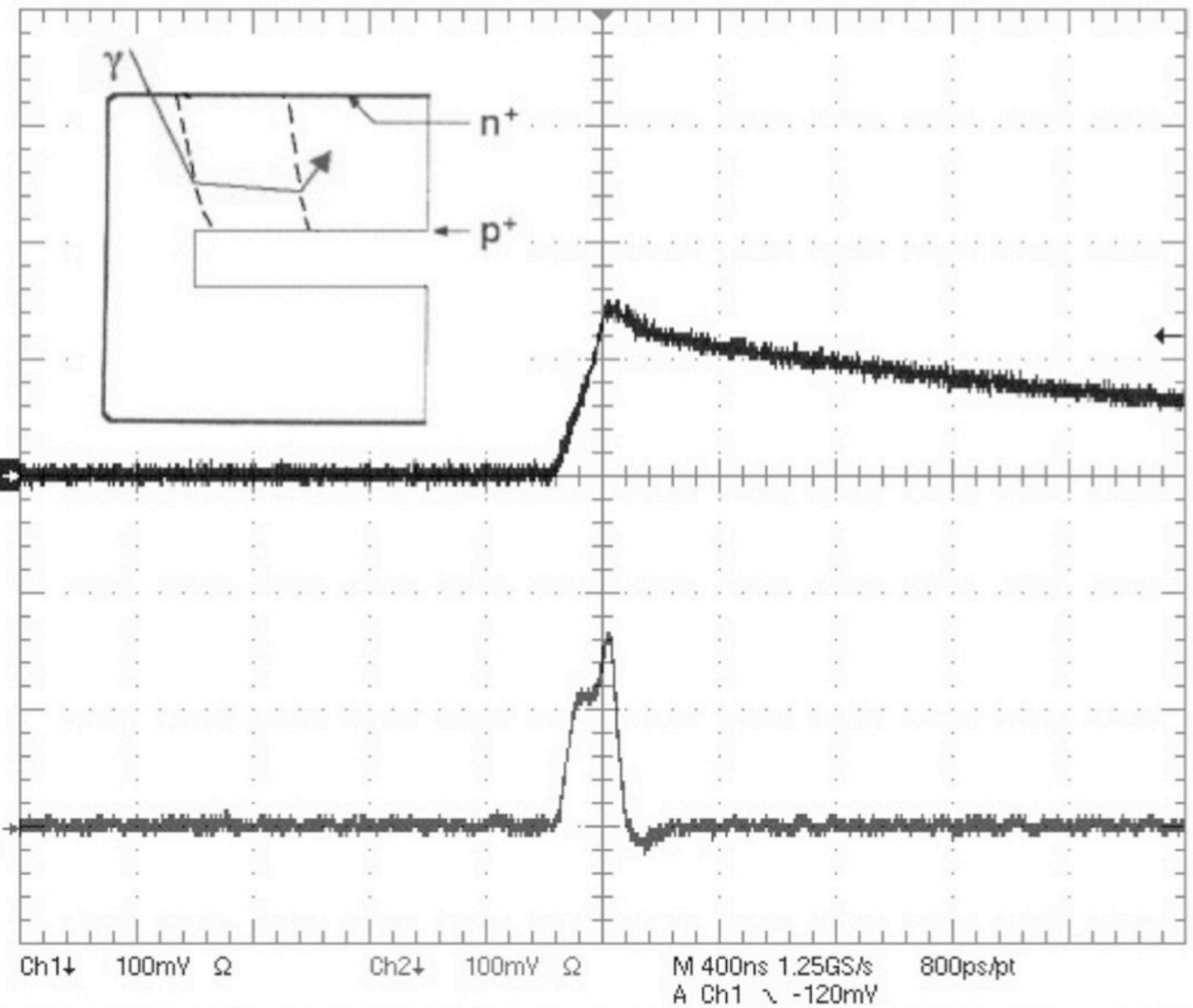
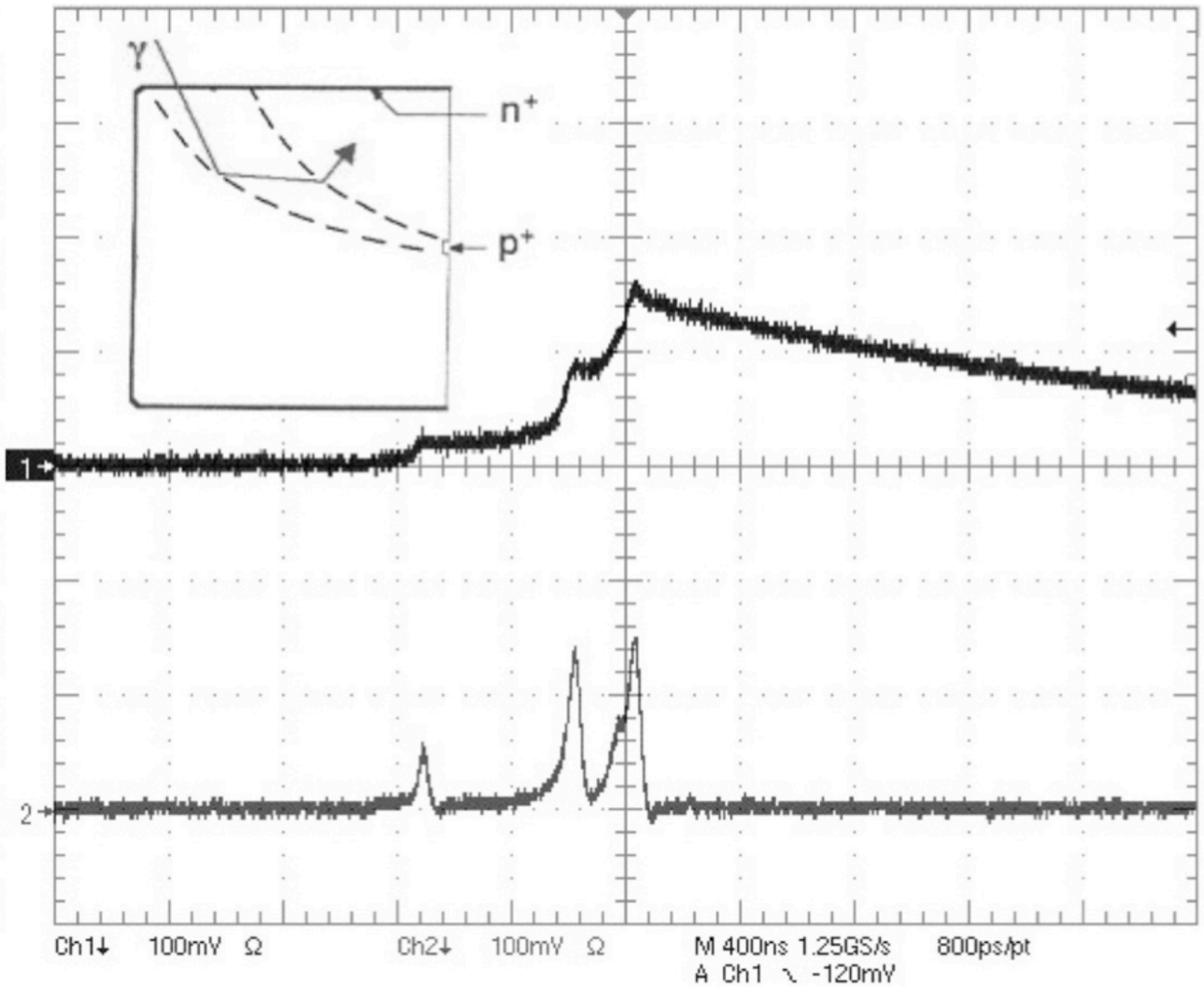


Background reduction

- Long drift times: multi-site rejection, 0νββ single-site interaction





Barbeau, et al. JCAP09 (2007) 009

Background reduction

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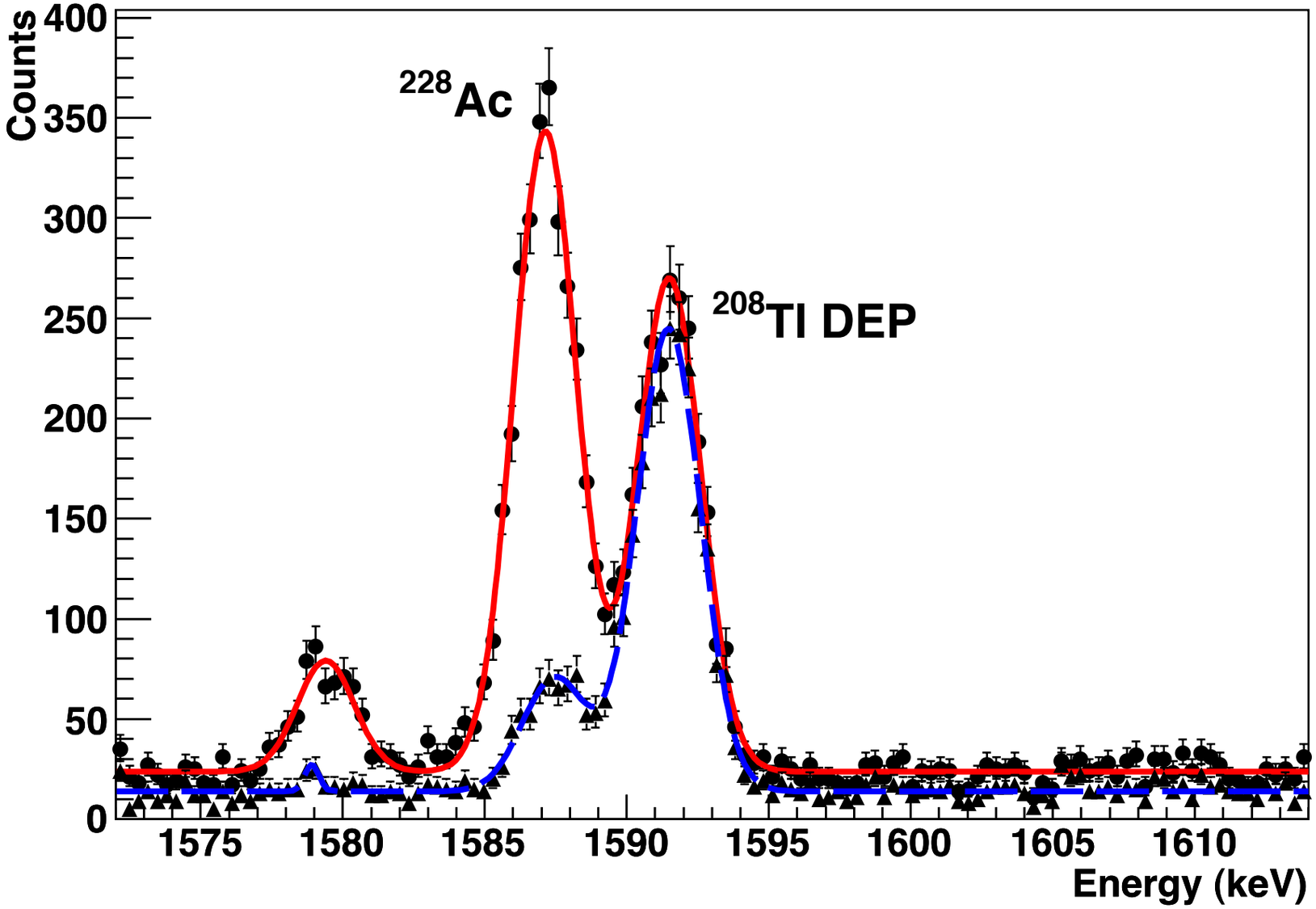
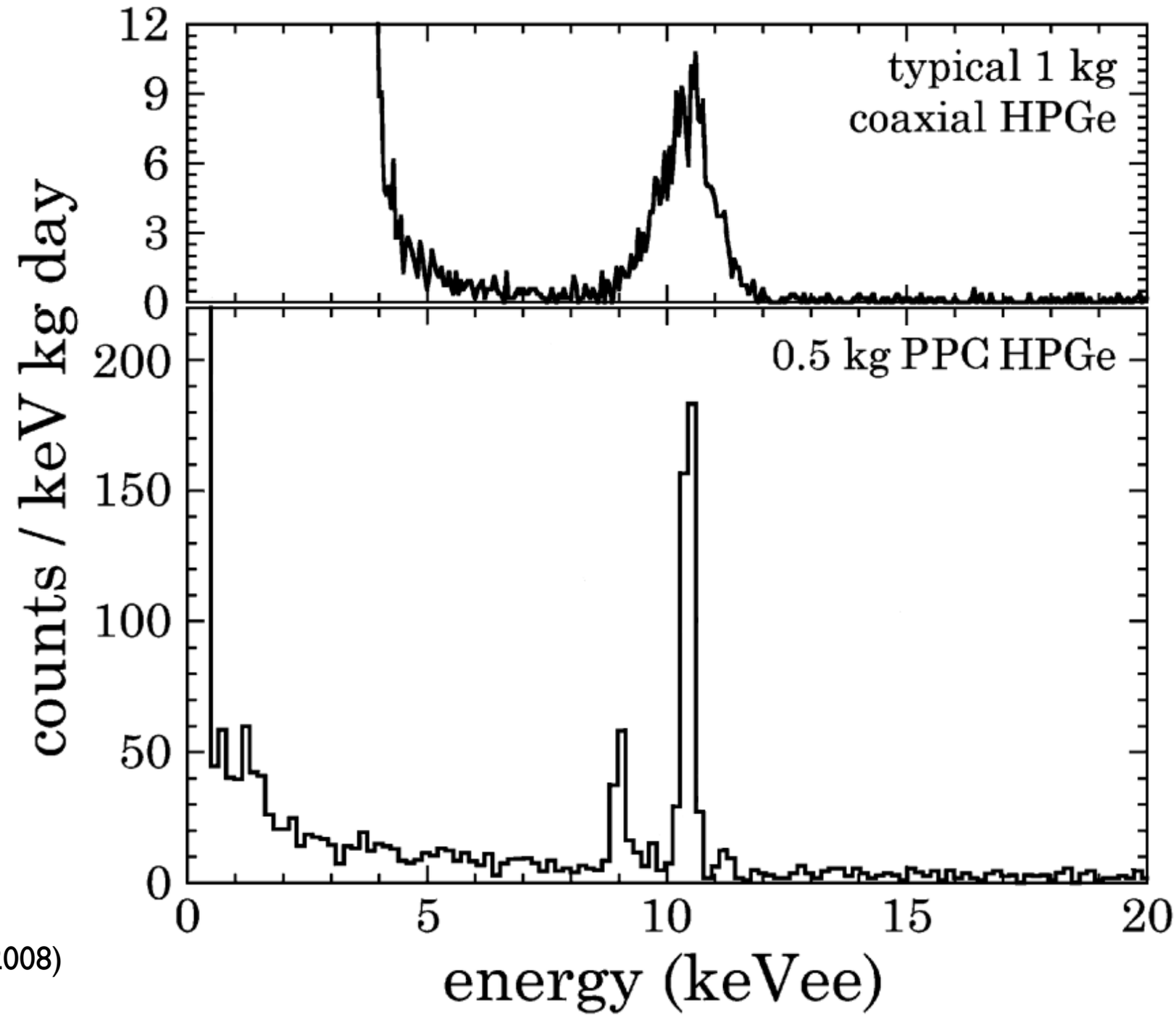


Using A/E technique from: Budjáš, et al. JINST **4** (2009) P10007

Background reduction

- Low noise, low threshold (< 1keV)
- X-ray tagging (enhanced ^{68}Ge rejection)
- Low-energy physics



Aalseth, et al., PRL **101**, 251301 (2008)

Background Reduction: ^{68}Ge

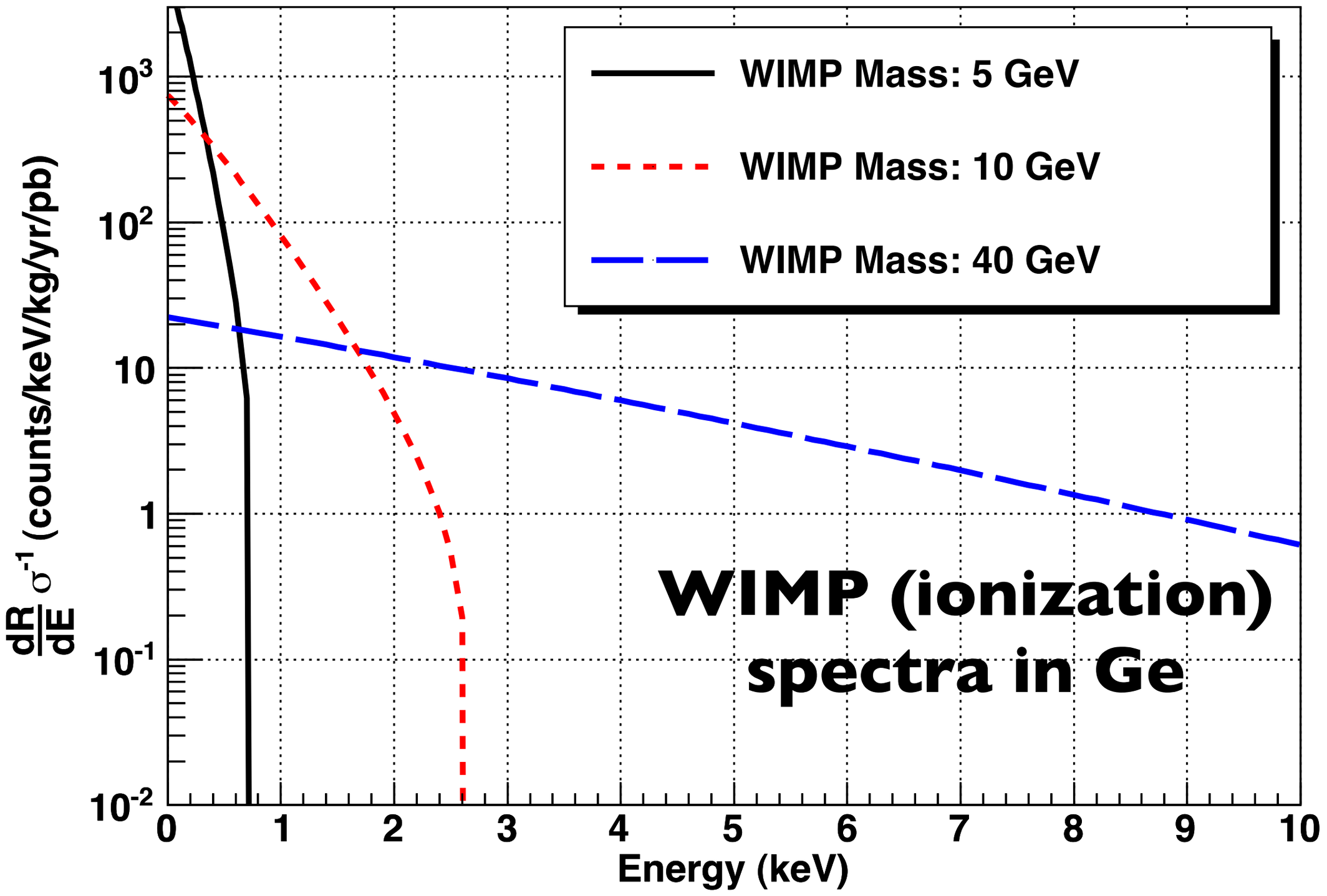
$$^{68}\mathrm{Ge} \xrightarrow{\epsilon,\ \mathrm{T}_{1/2}=271\ \mathrm{d}} {}^{68}\mathrm{Ga} \xrightarrow{\epsilon,\ \mathrm{T}_{1/2}=68\ \mathrm{m},\ \mathrm{Q}=2921\ \mathrm{keV}} {}^{68}\mathrm{Zn}$$

Goal: Tag ^{68}Ge when it initially decays, veto for a few ^{68}Ga half-lives.

^{68}Ge decays	Percent	Energy (keV)
K-capture	86.4%	10.3
L-capture	11.5%	1.3
M-capture	2.0%	∼0.1

Low Threshold ⟶ Opportunistic Science

P-PC Detectors for Dark Matter



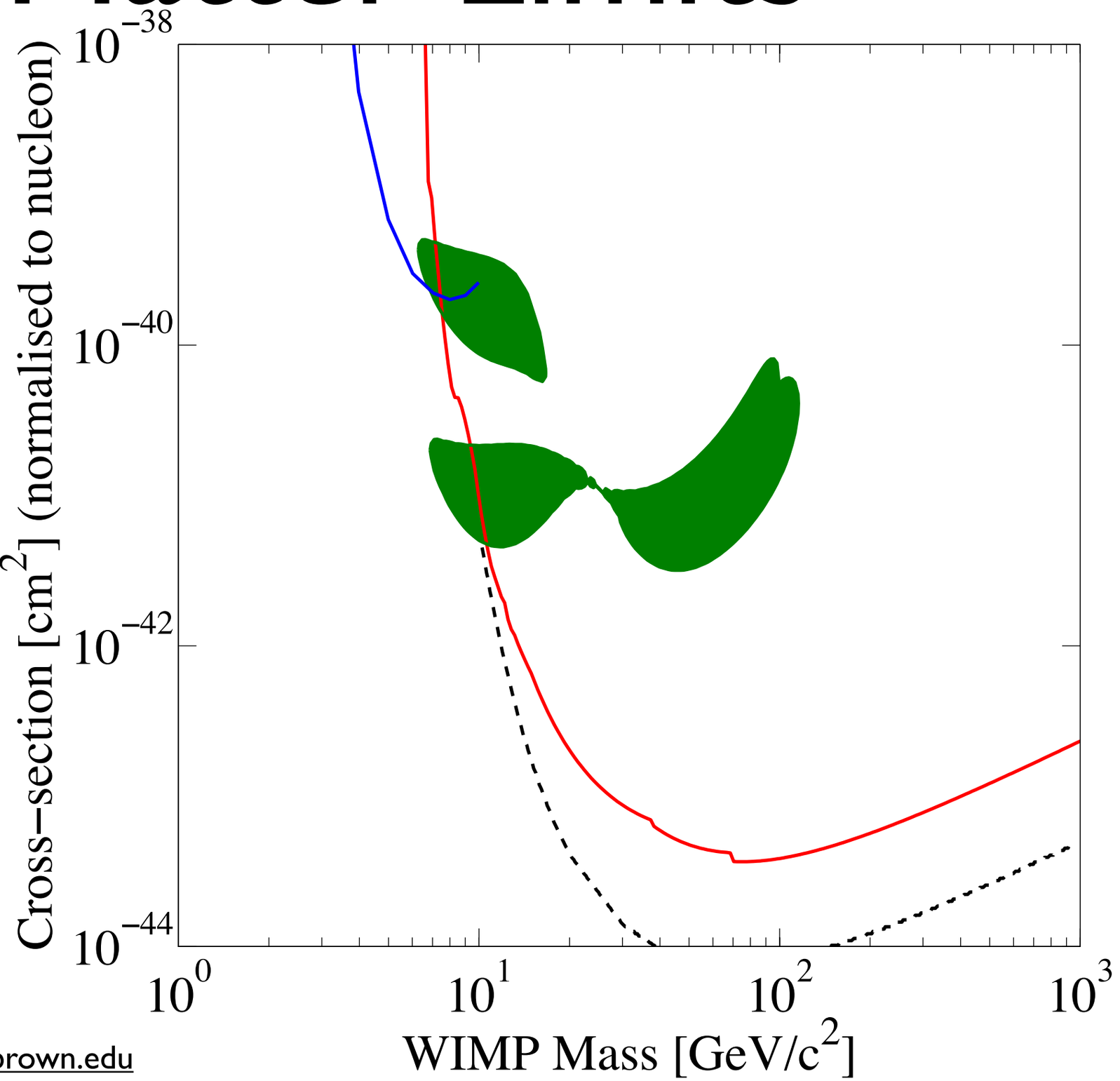
Dark Matter Limits

CDMS, 612 kg-d

CoGeNT, 8.4 kg-d

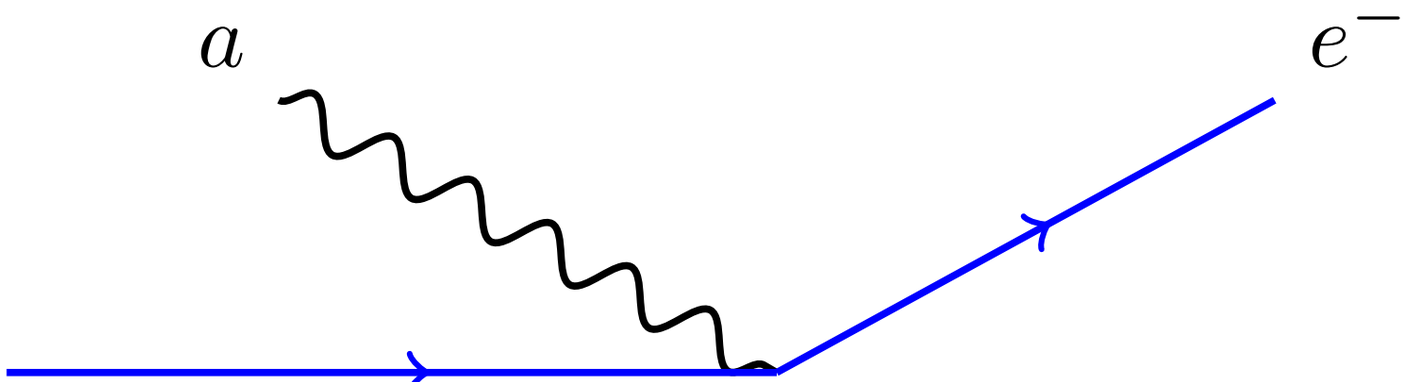
DAMA, 3σ allowed region

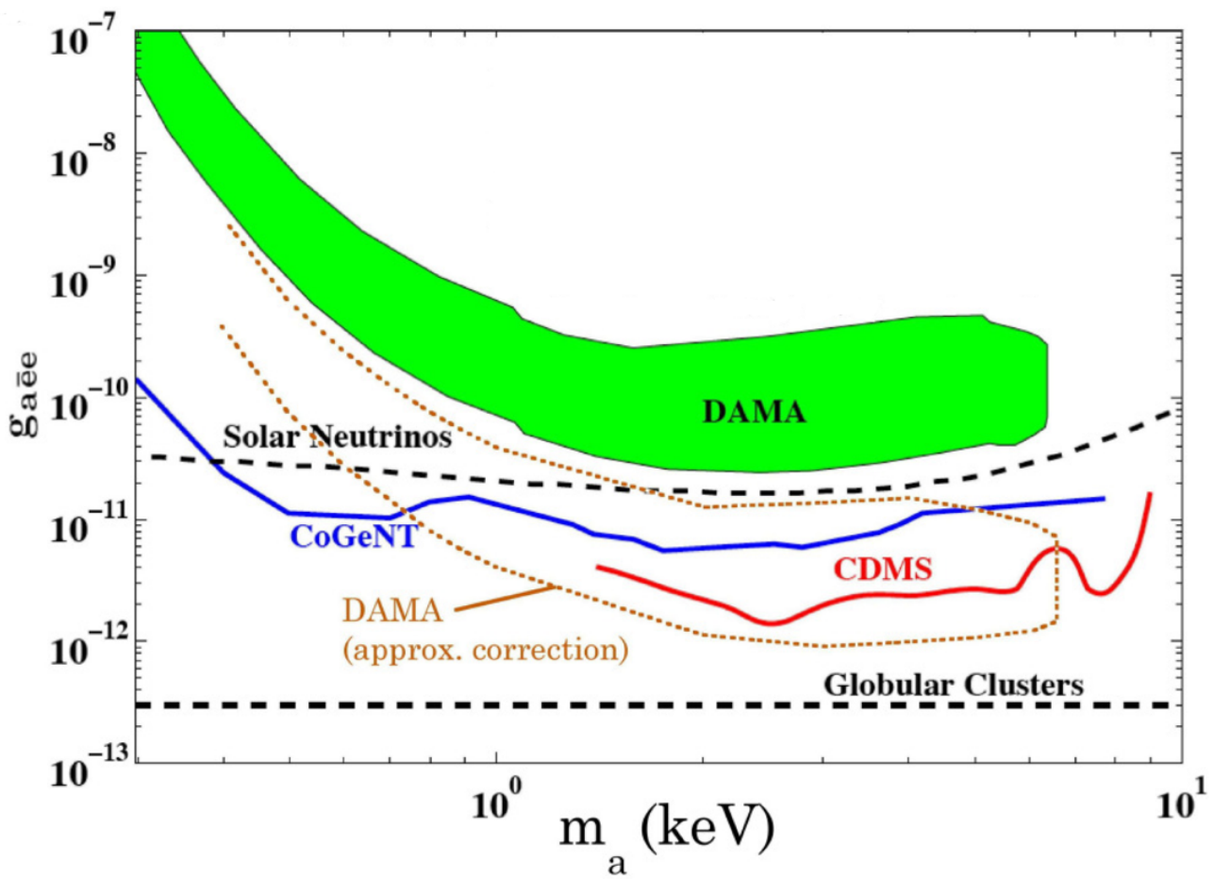
CDMS Collaboration, arXiv:0912.3592;
Aalseth, et al., PRL **101**, 251301 (2008);
DAMA Collaboration, EPJ **C56** (2008), 333, arXiv:0804.2741
DEAP/CLEAN 25 kg (proj), McKinsey 2007



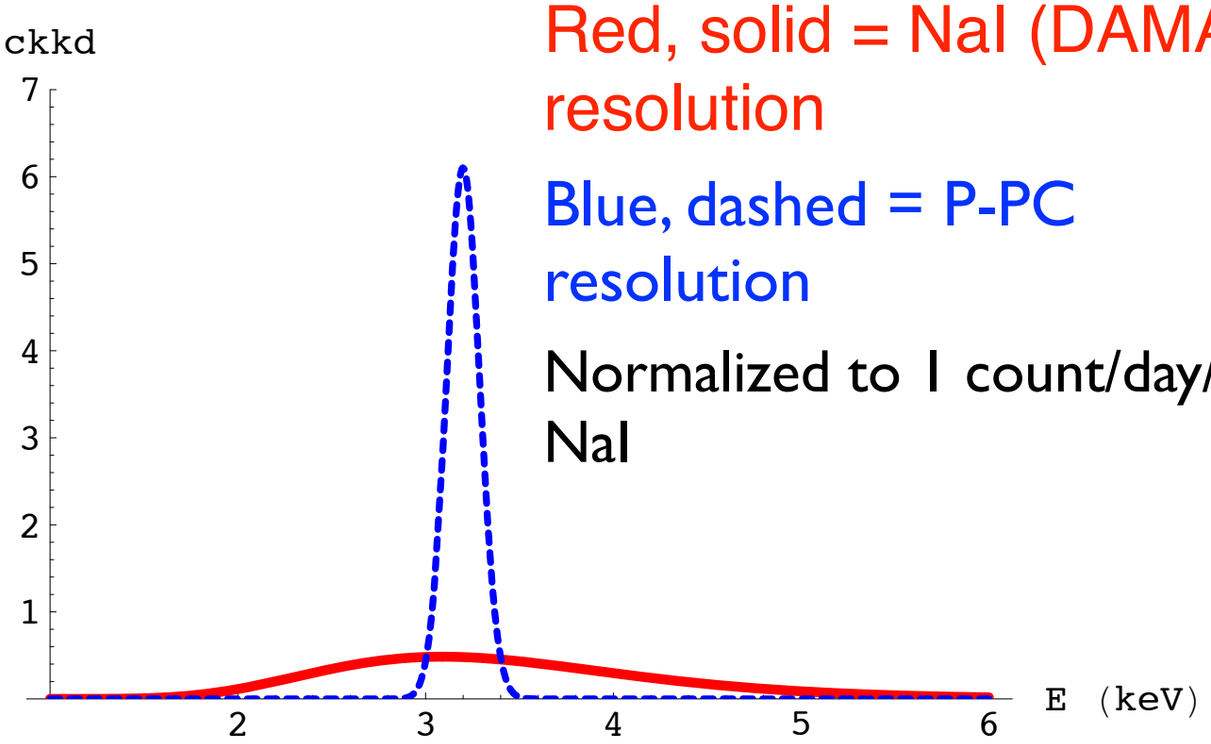
Plot generated using DMTools, http://dmtools.brown.edu

More exotic DM interactions: axioelectric effect





J. I. Collar, M.G. Marino: arXiv:0903.5068v1 [hep-ex]



Red, solid = NaI (DAMA) resolution

Blue, dashed = P-PC resolution

Normalized to 1 count/day/kg in NaI

MAJORANA (R&D) Detectors

Institution (Detector Name)	Dimensions	Mass	Resolution (1.33 MeV)	Manufacturer (Crystal Grower)	Impurity Gradient
U Chicago (PPC I)	50 mm Ø x 44 mm	460 g	1.82 keV	Canberra (Canberra)	2.8
PNNL (PPC II)	50 mm Ø x 50 mm	527 g	2.15 keV	Canberra (Canberra)	1.6
LBNL (SPPC)	62 mm Ø x 44 mm	800 g	2.11 keV	LBNL (AMETEK)	1.7
LANL (MJ70)	72 mm Ø x 37 mm	800 g	2.15 keV	PHD's (UMICORE)	0.8
ORNL (MJ60)	62 mm Ø x 46 mm	740 g	4-4.5 keV	PHD's (UMICORE)	1.2
U Chicago (BEGe)	"standard"	450 g	<2 keV	Canberra (Canberra)	
LBNL (Mini-PPCs)	20 mm Ø x 10 mm	17 g		LBNL (AMETEK)	
ORNL (Big BEGe)	90 mm Ø x 25 mm	850 g	1.95 keV	Canberra (Canberra)	
LANL (MJ BEGes)	70 mm Ø x 30 mm	579 g	<2.2 keV	Canberra (Canberra)	

10-20 kg of these

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10-20 kg of these

Introduction Summary

- P-PC detectors have characteristics beneficial to $0\nu\beta\beta$, but also to searching for Dark Matter
- Physics results possible from small detectors: Table-top Dark Matter Experiments?
- The Majorana experiment is currently pursuing R&D with P-PC detectors: good opportunity for thesis work!

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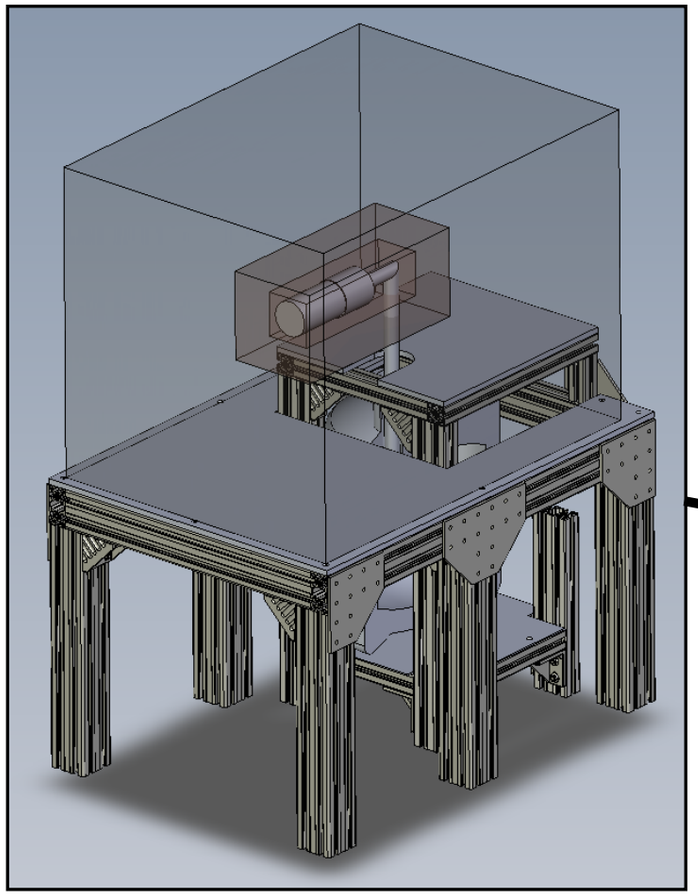
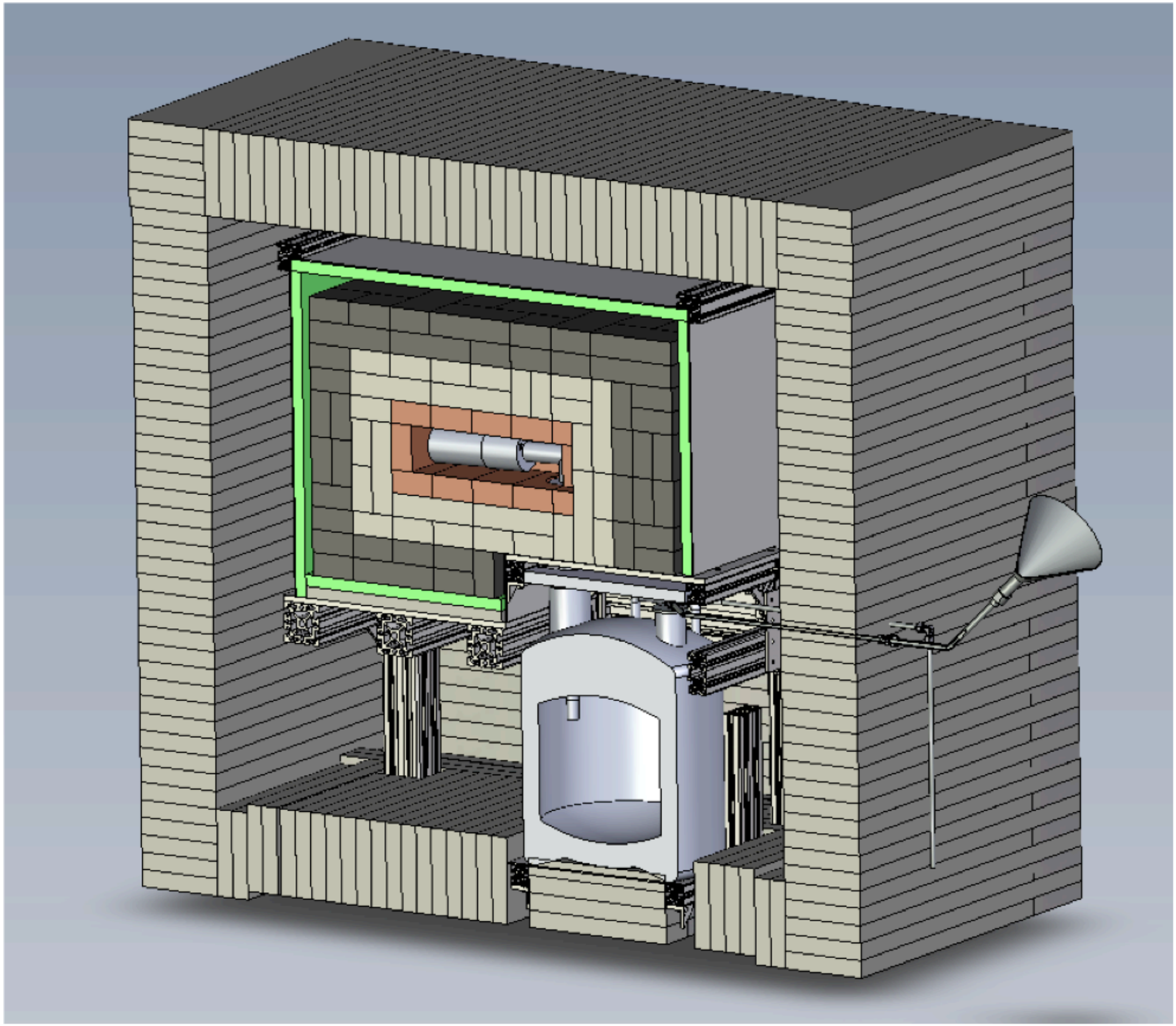
PNNL P-PC R&D Detector

- Originally deployed underground at Soudan, MN., by J. Orrell et. al from PNNL
- Made available to collaboration for R&D
- My goals:
  - Develop and test a MAJORANA-like data acquisition (DAQ) system in a "low"-background, deployed environment
  - Setup an analysis framework using tools developed for MAJORANA
  - Get physics results?



grey vertical wall

Slide: J. Orrell



E. Fuller, J. Orrell

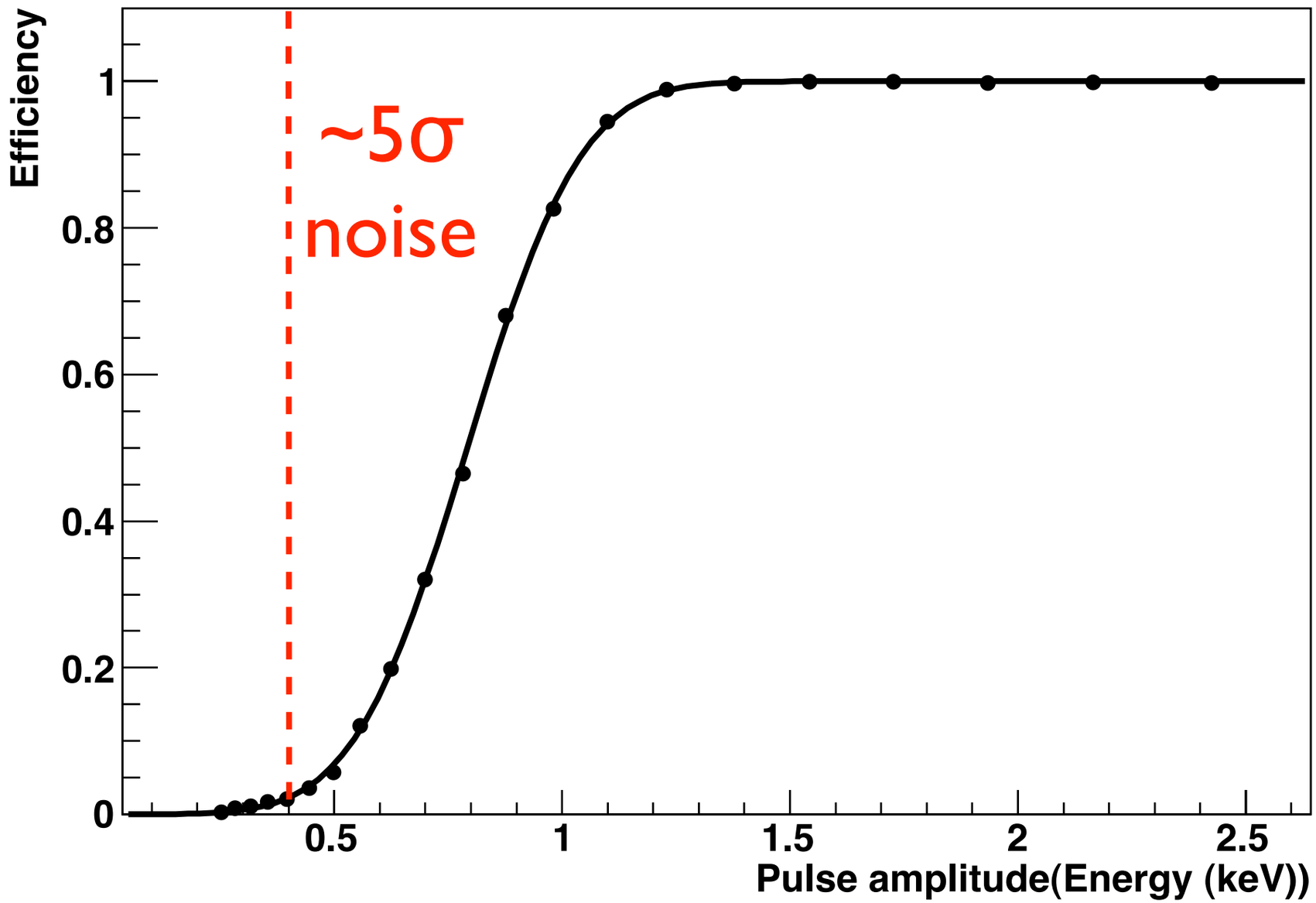
E. Fuller, J. Orrell

Some run vitals

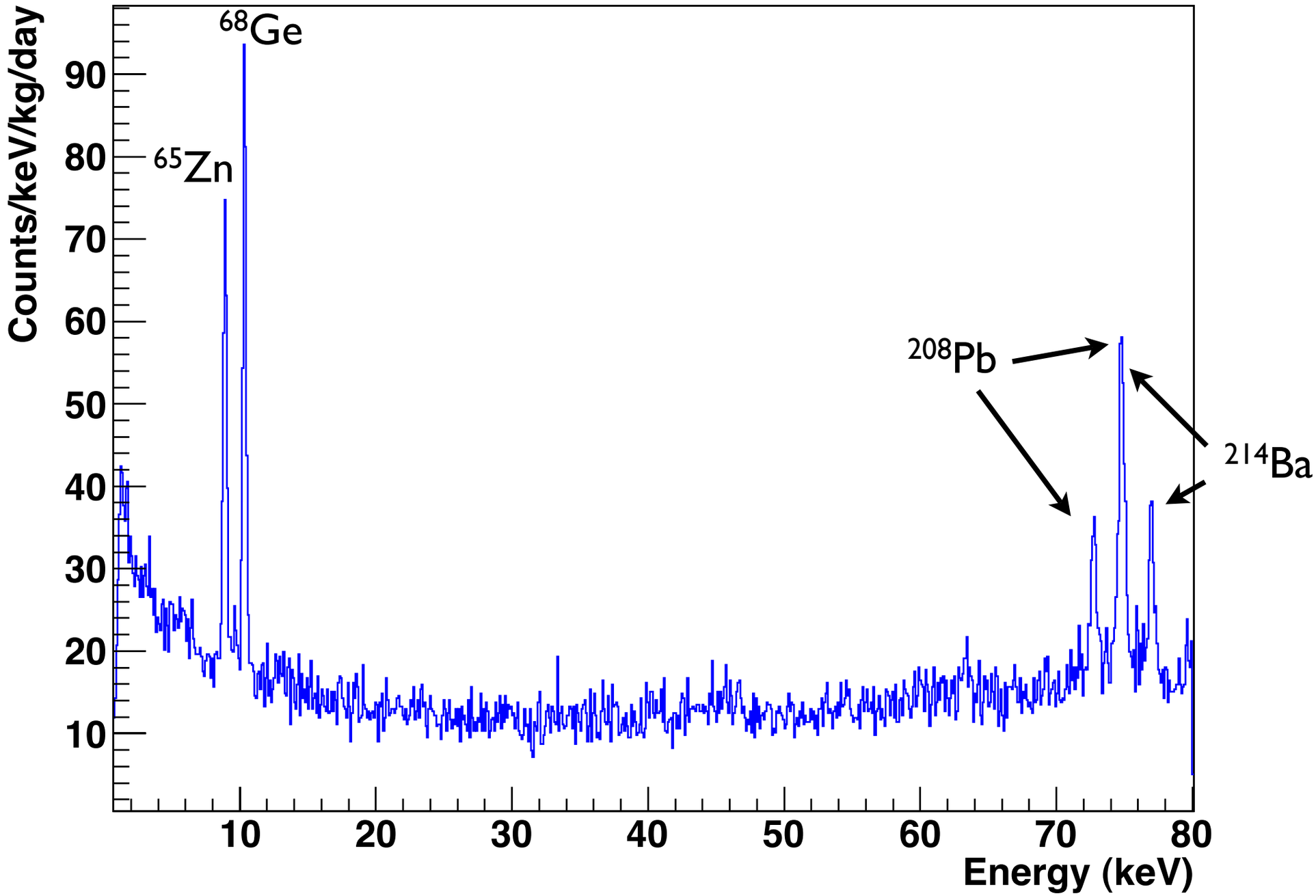
- Ran for ~6 months
  - DAQ, Analysis chain tests
  - Counting runs
- Acquired 70.4 days of livetime

Measured Trigger Efficiency

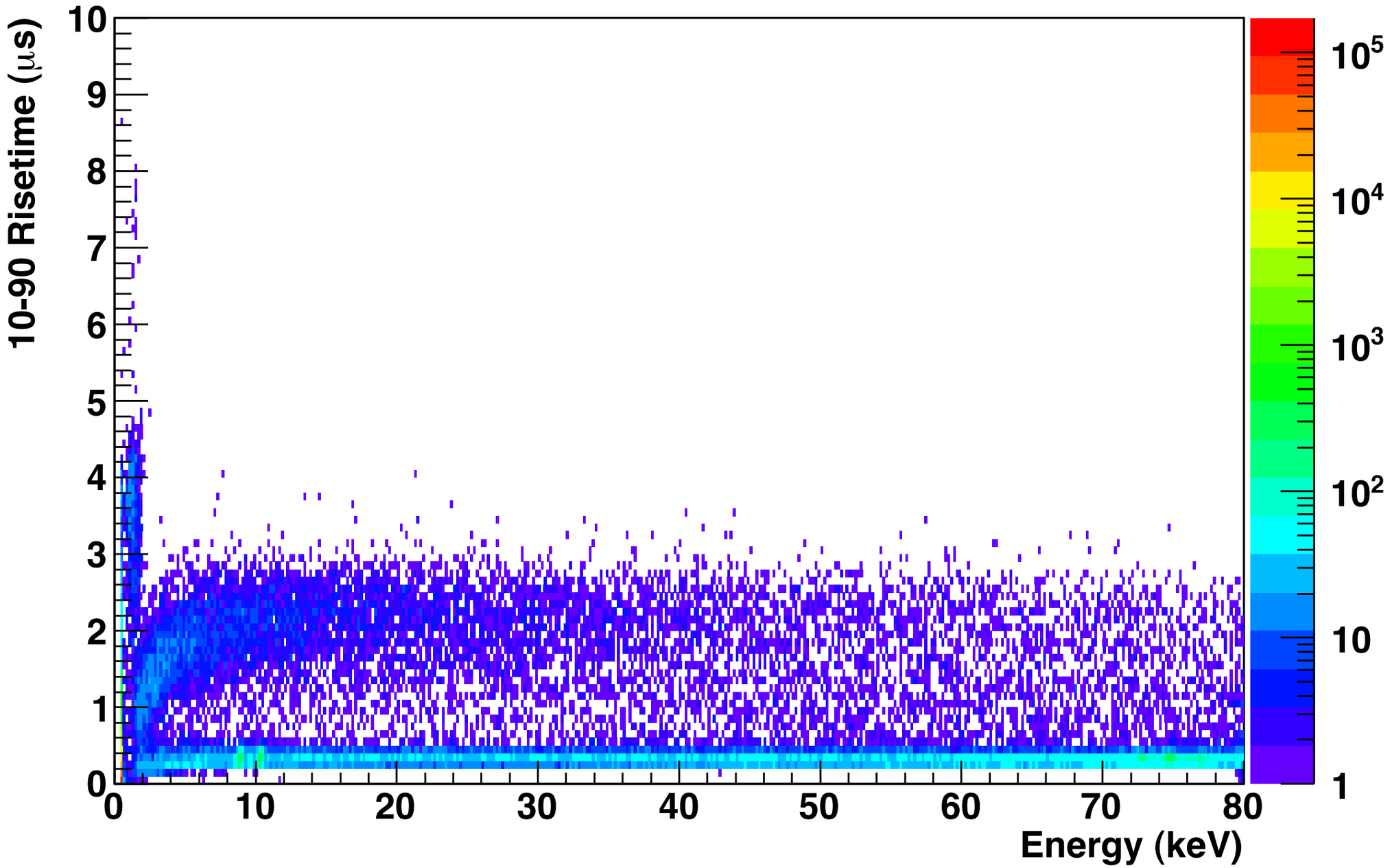
Fit to: $\frac{1+\mathrm{erf}\left(s(E-\sigma)\right)}{2}$



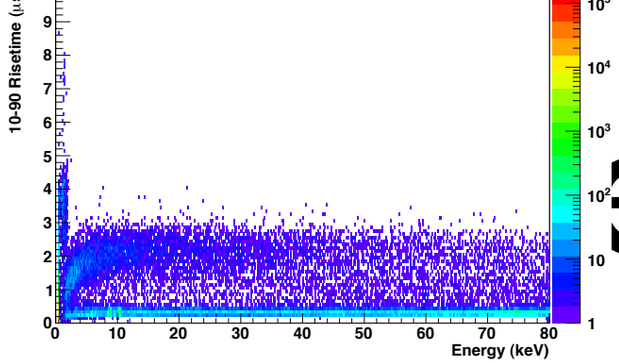
Raw Energy Spectrum

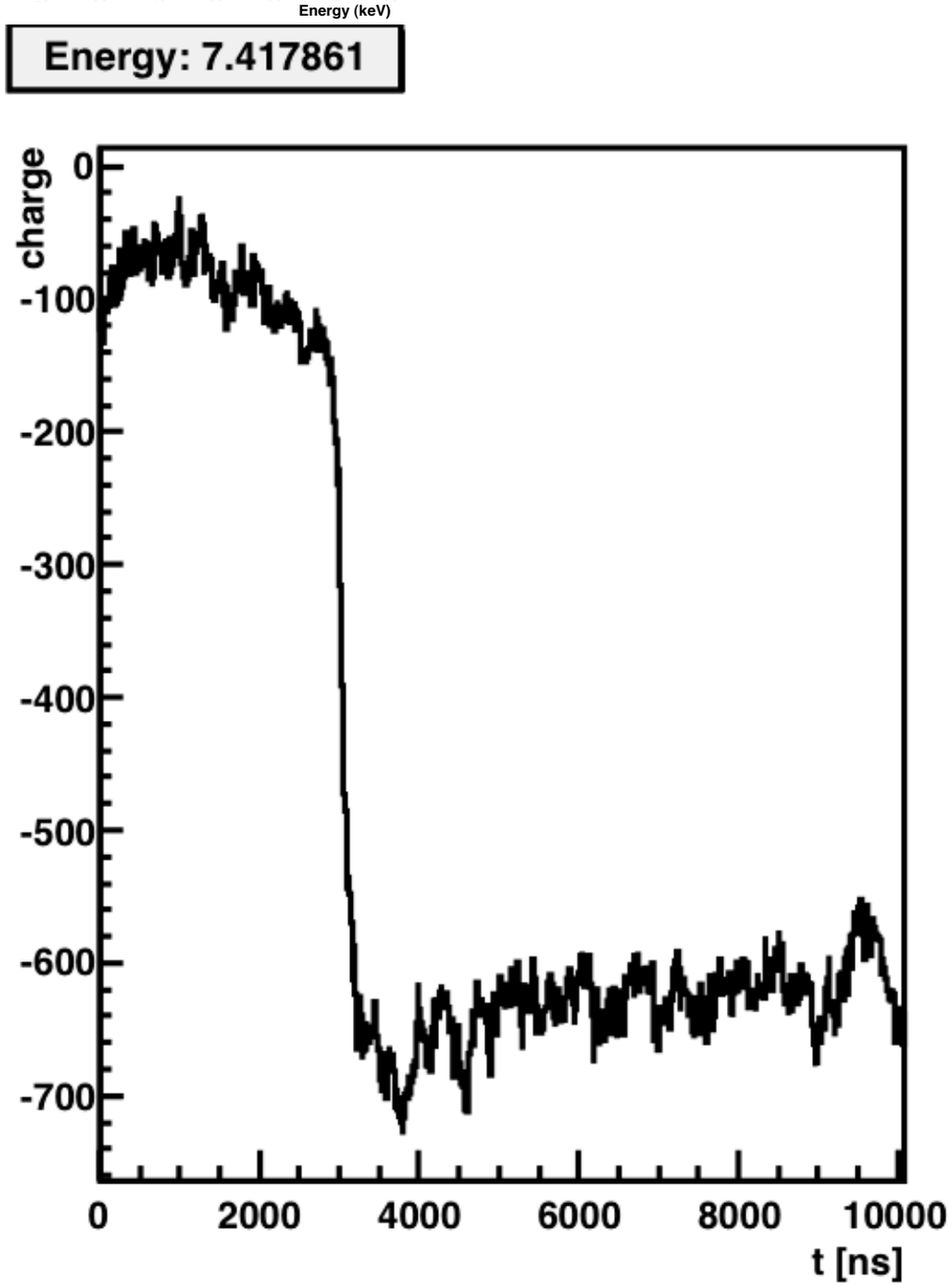


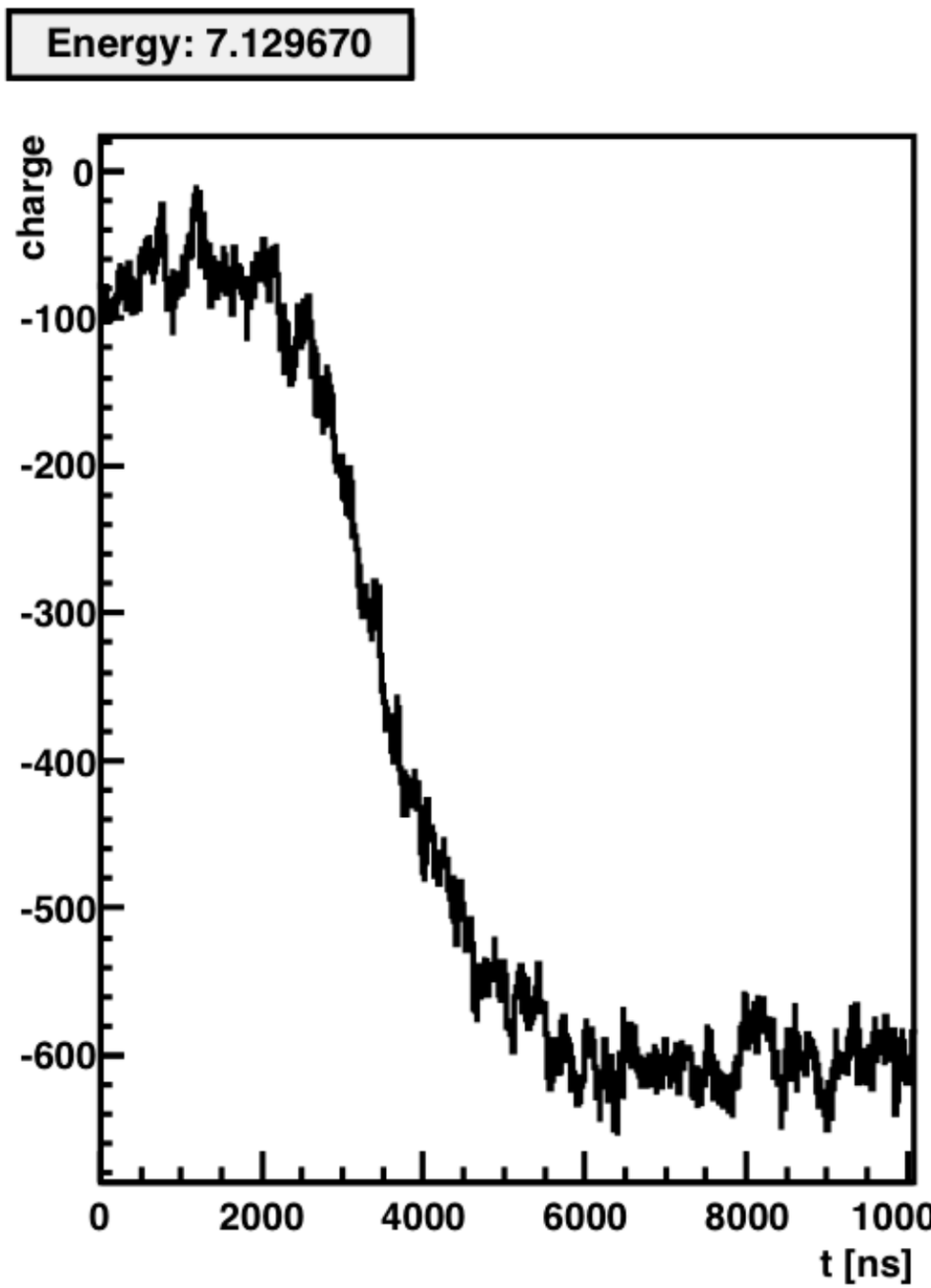
Rise-time vs. Energy



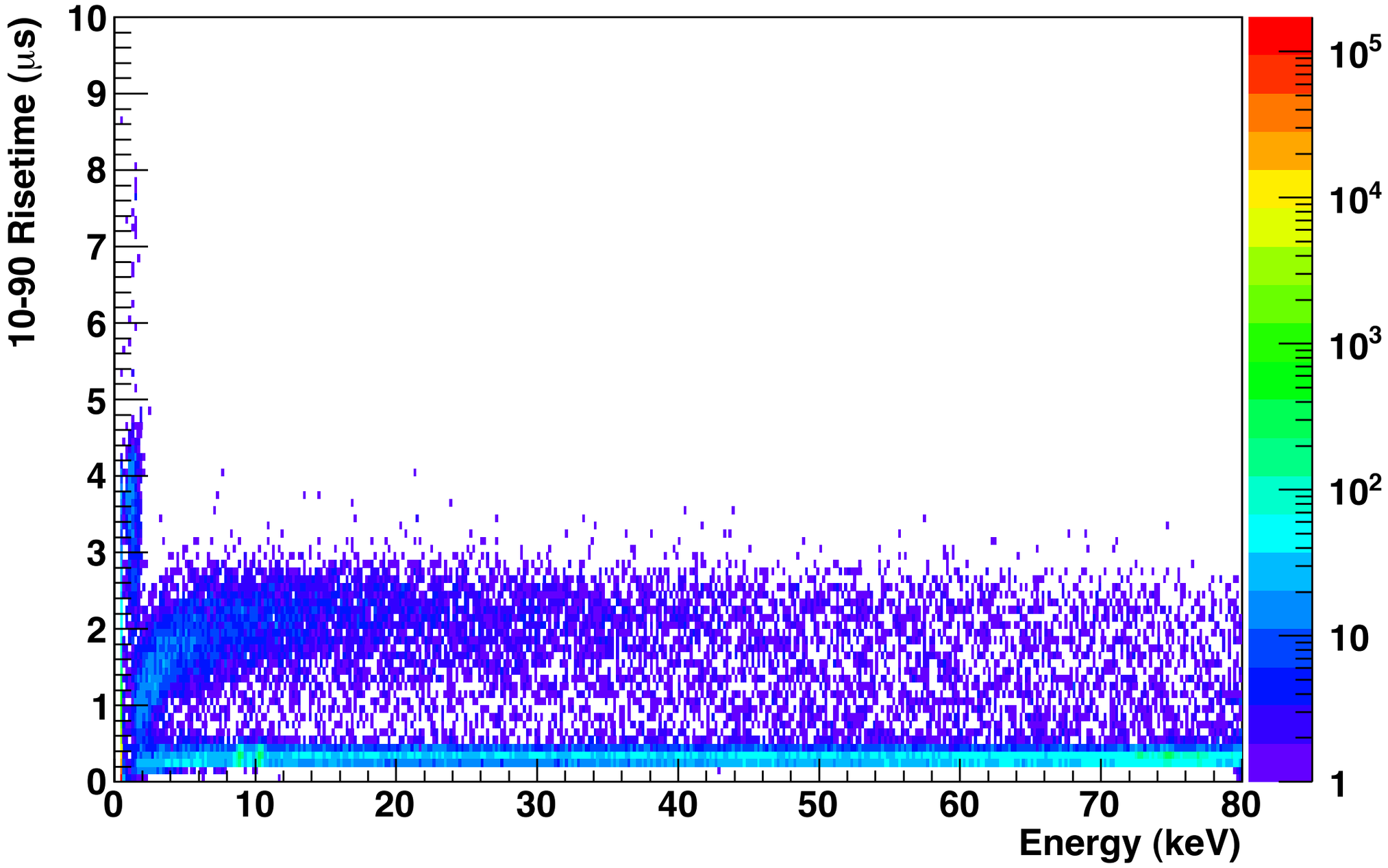
e-time vs. Energy



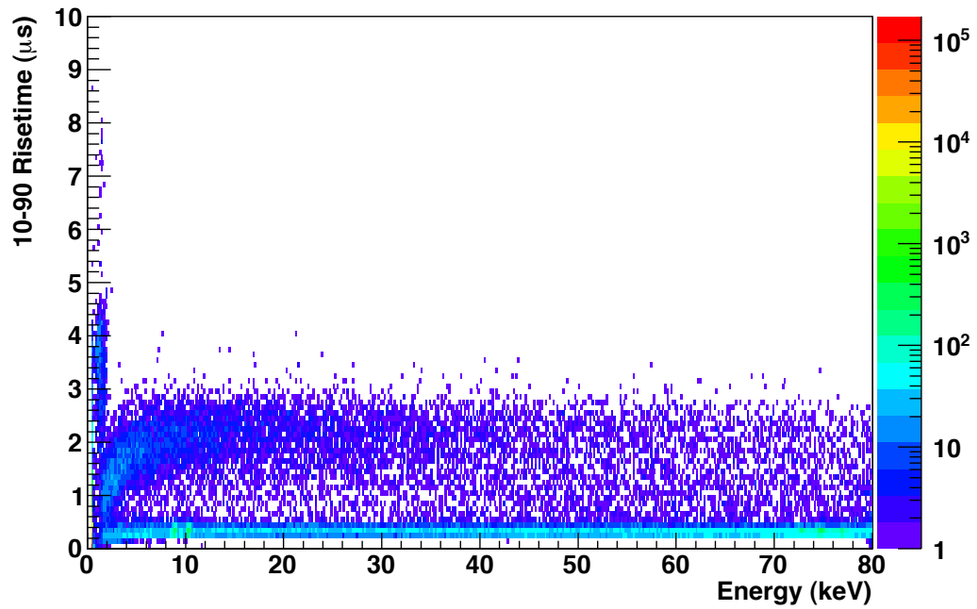


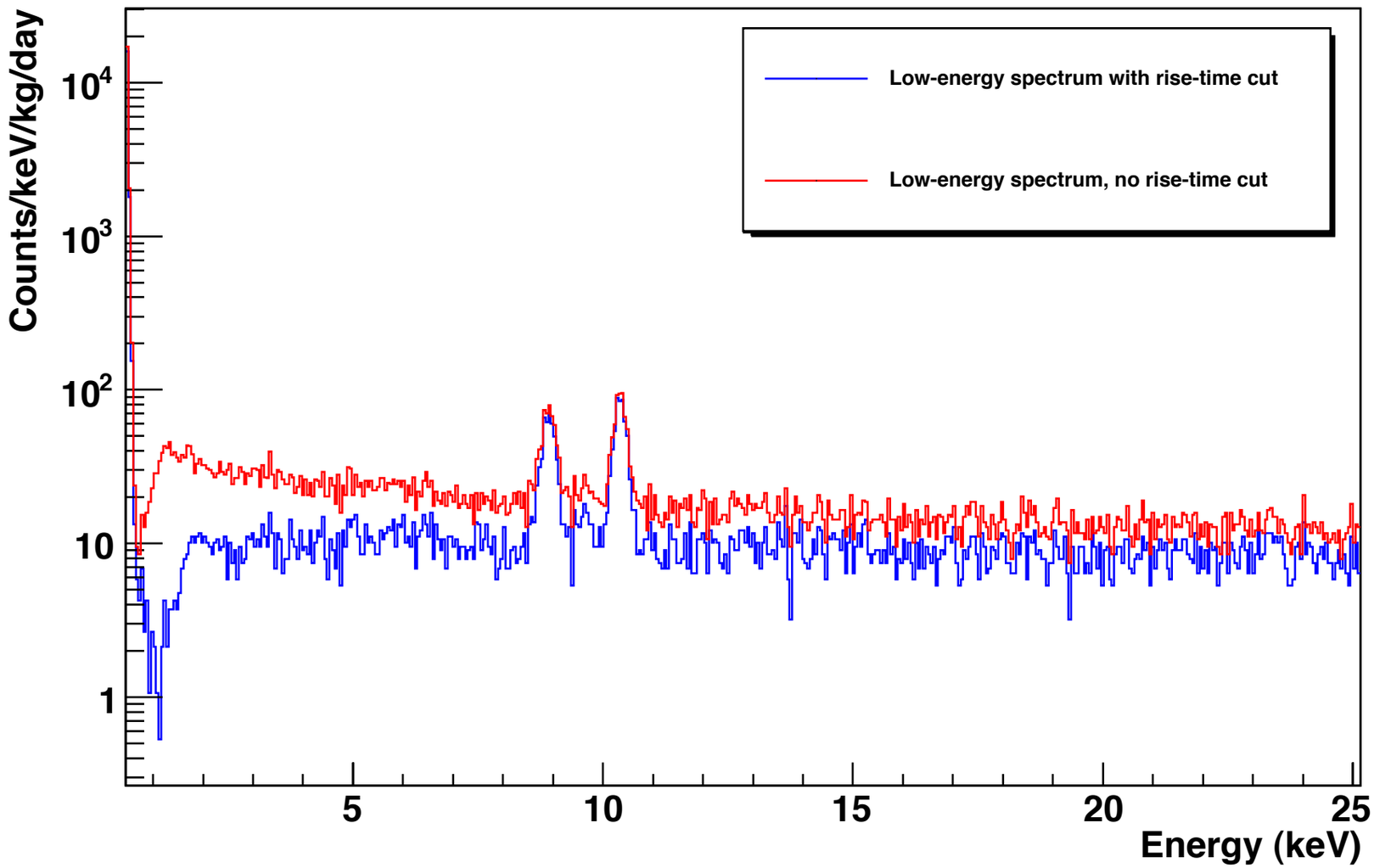


Rise-time vs. Energy



Rise-time vs


10-90 Risetime (μs)
Energy (keV)
0
10
20
30
40
50
60
70
80
1
2
3
4
5
6
7
8
9
10
1
10
10^2
10^3
10^4
10^5

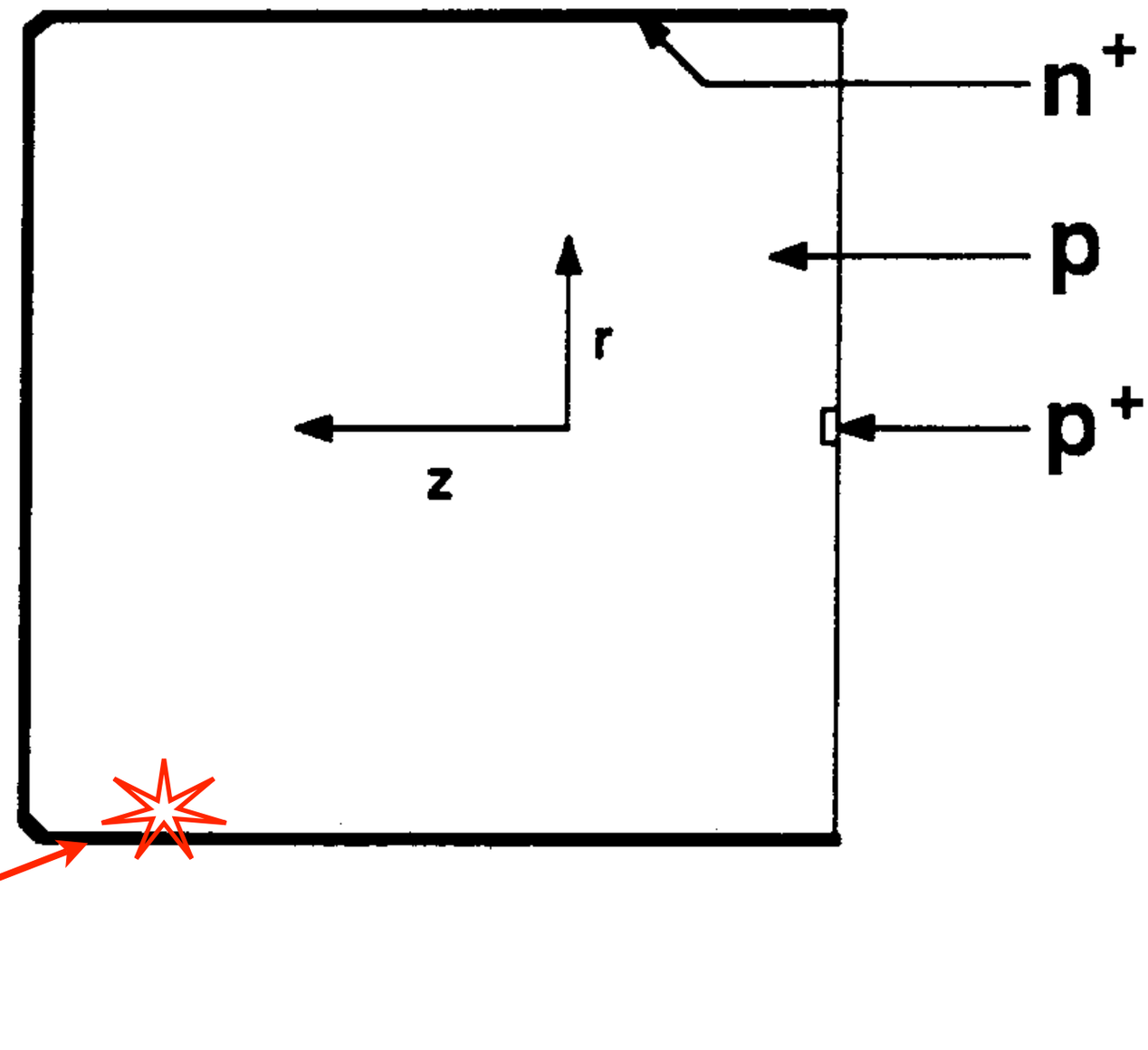

Counts/keV/kg/day
Energy (keV)
Low-energy spectrum with rise-time cut
Low-energy spectrum, no rise-time cut
1
10
10^2
10^3
10^4
5
10
15
20
25

Slow pulse origin

- Incomplete charge collection near the dead layer?

Strauss and Larsen, NIM **56** (1967) p. 80

Sakai, IEEE Trans. Nucl. Sci. **18** (1971) p. 208



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^{71}Ge (~11 day half-life) decays in a similar P-PC detector

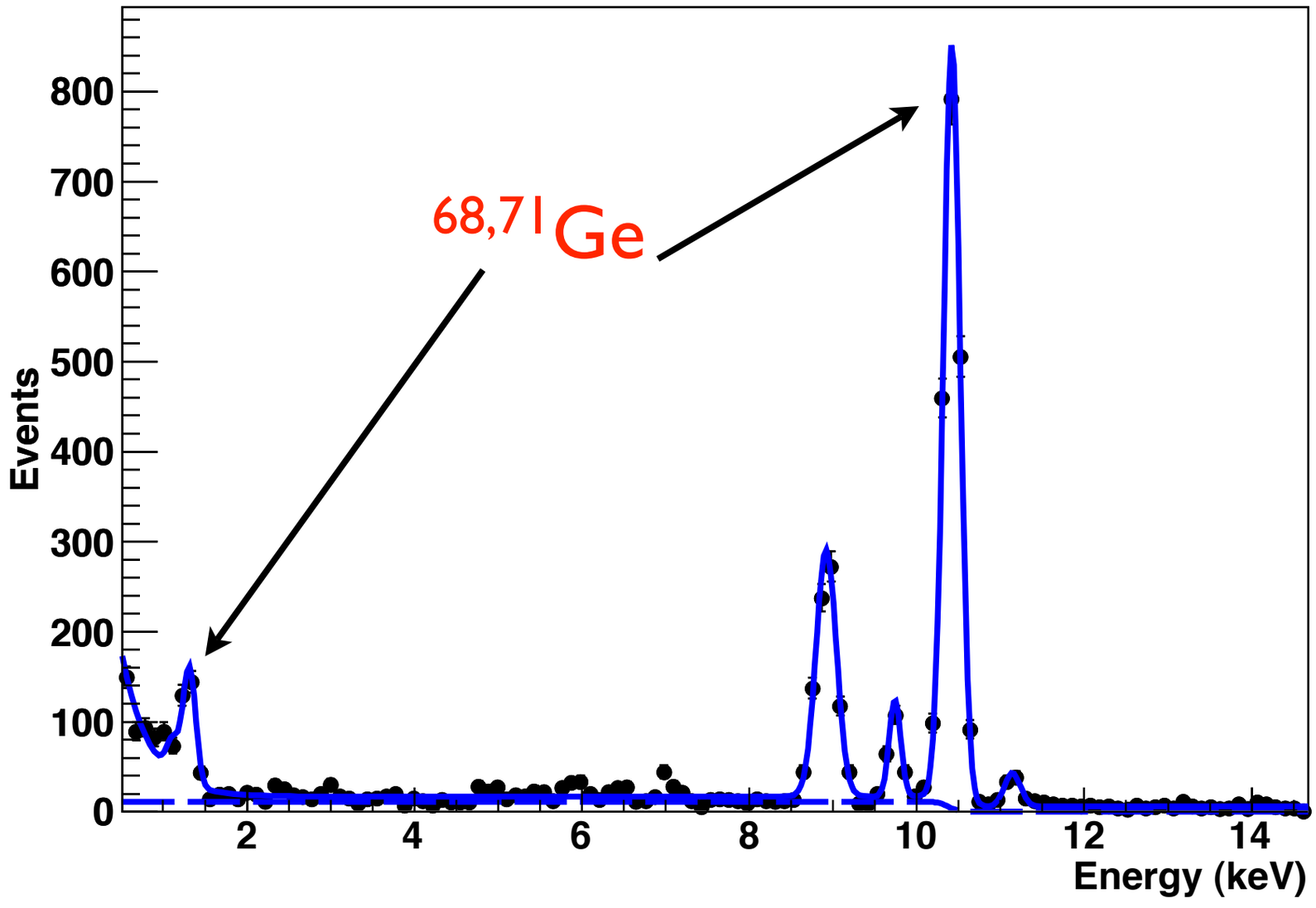

Figure arXiv:1002.4703v2 [astro-ph]

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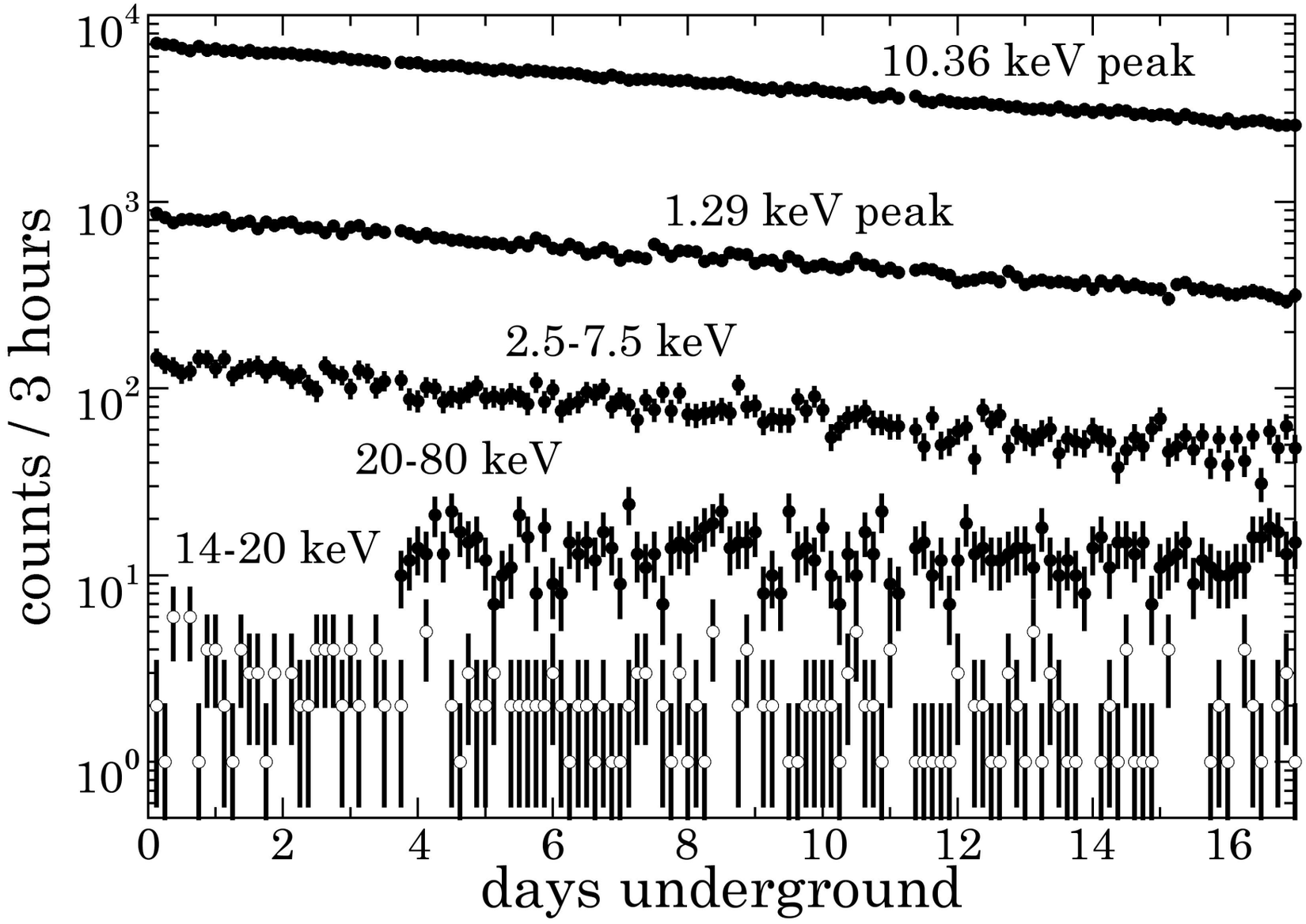

Figure arXiv:1002.4703v2 [astro-ph]

Conclusions from Soudan

- DAQ:
  - Trigger performance insufficient for low-energy threshold
  - Must explore other DAQ options
- Analysis chain
  - Stably run for ~1 year, flexible implementation
- Physics
  - Slow pulses, a source of background?
  - Backgrounds/threshold too high for DM analysis

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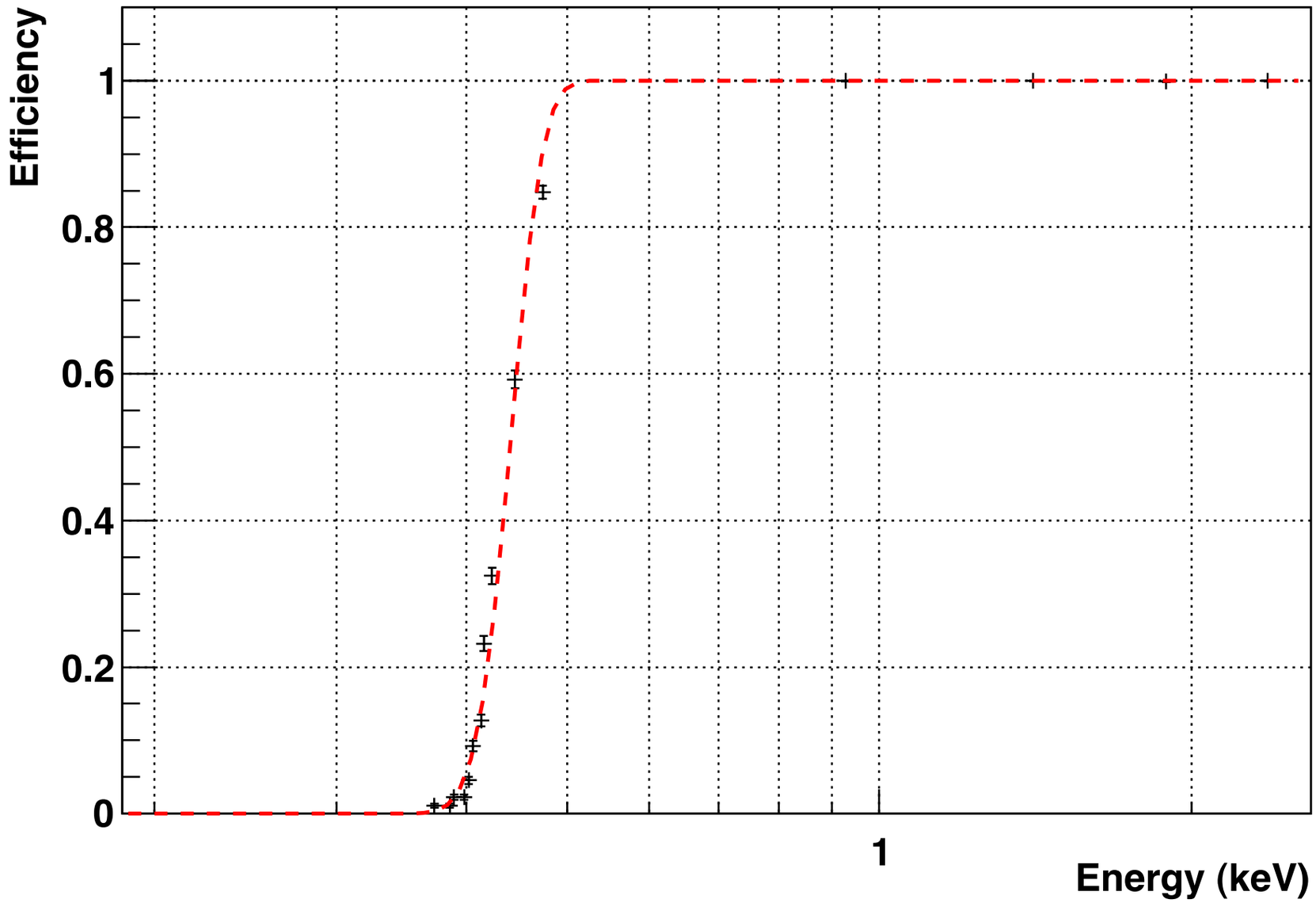
Address deficiencies

- A - B swaps:
  - New detector with lower background: Canberra **B**road-**E**nergy **Ge**rmanium detector BEGe (U Chicago, J. Collar) (0.44 kg)
  - Internal shield changed to ancient Pb
  - Swap DAQ to one with low threshold
- Plug in to existing Analysis chain

Run information

- Underground since Aug 2009
- DAQ deployed Dec 2009
- Results from first 2 months: arXiv: 1002.4703v2
- This talk: preliminary analysis from ~150 days livetime

Triggering efficiency

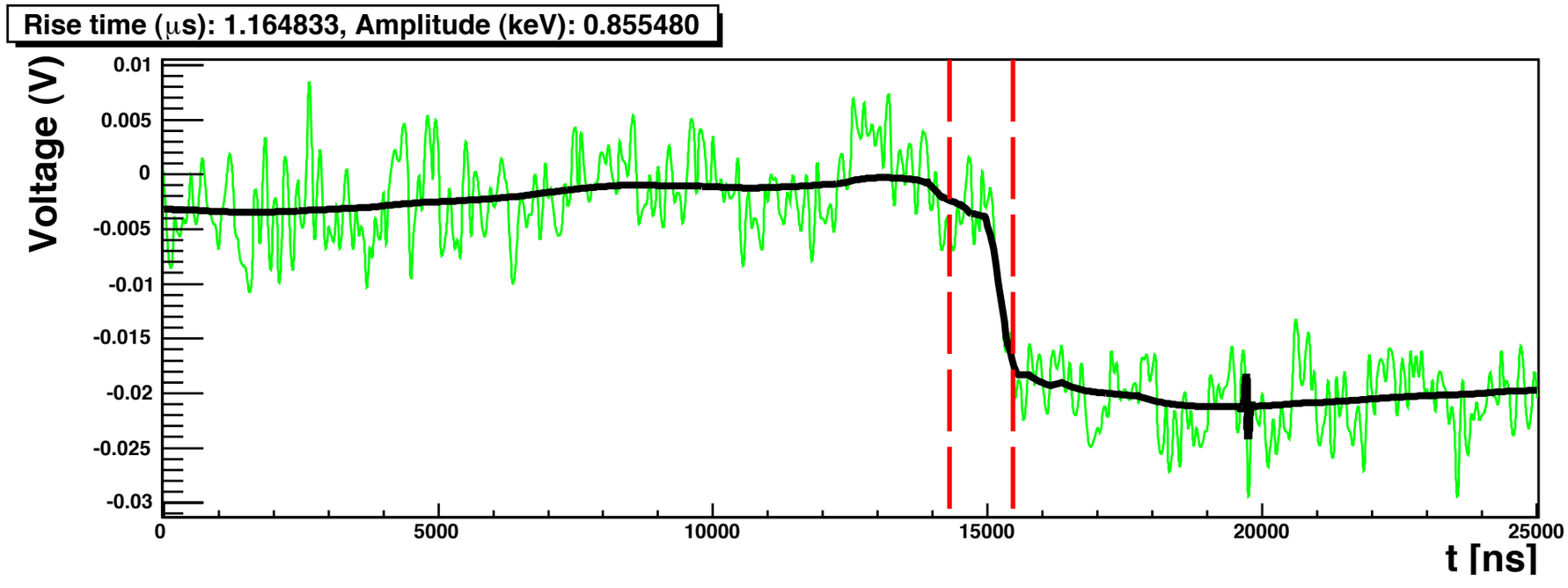


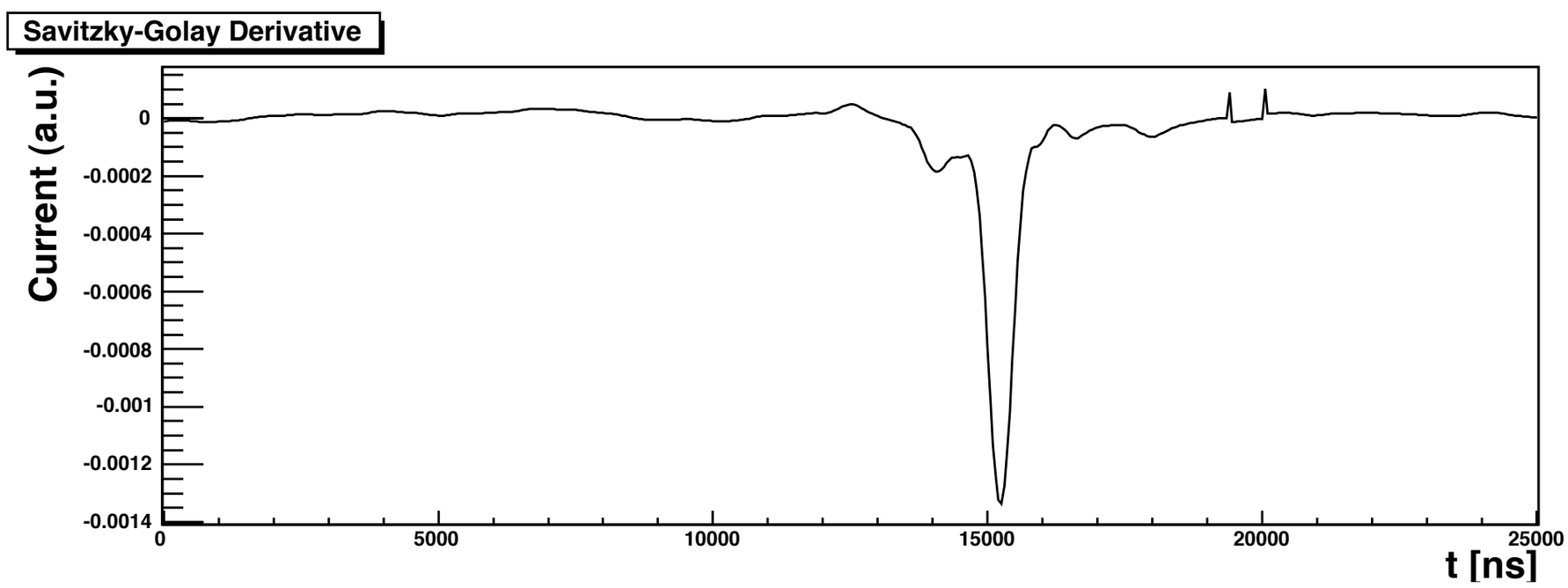
~80% at 460 eV, fit to: $\frac{1+\mathrm{erf}\left(s(E-\sigma)\right)}{2}$

Background reduction

- Microphonics cuts - analyze ratios of shaped channels (Morales, et al., NIM A **321** (1992) 410)
- Rise-time cuts - Previous results indicated slow-pulse 'contamination'

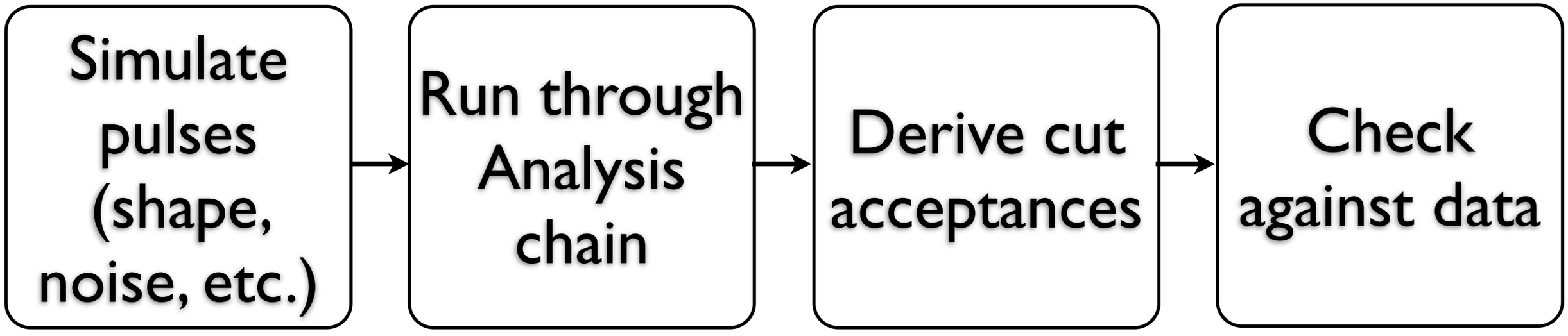
Rise-time measurements



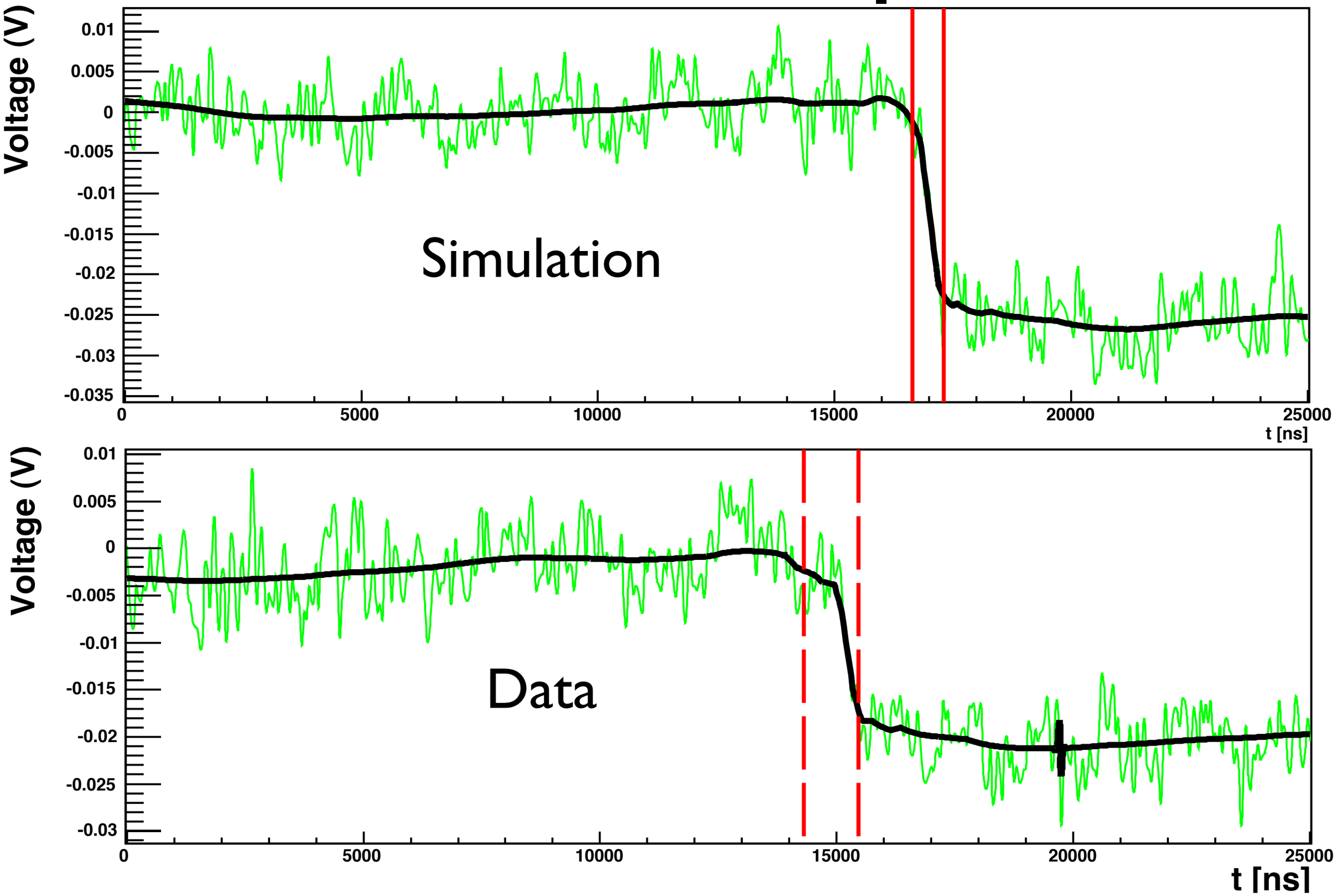


Wavelet denoising to measure rise-times at low S/N

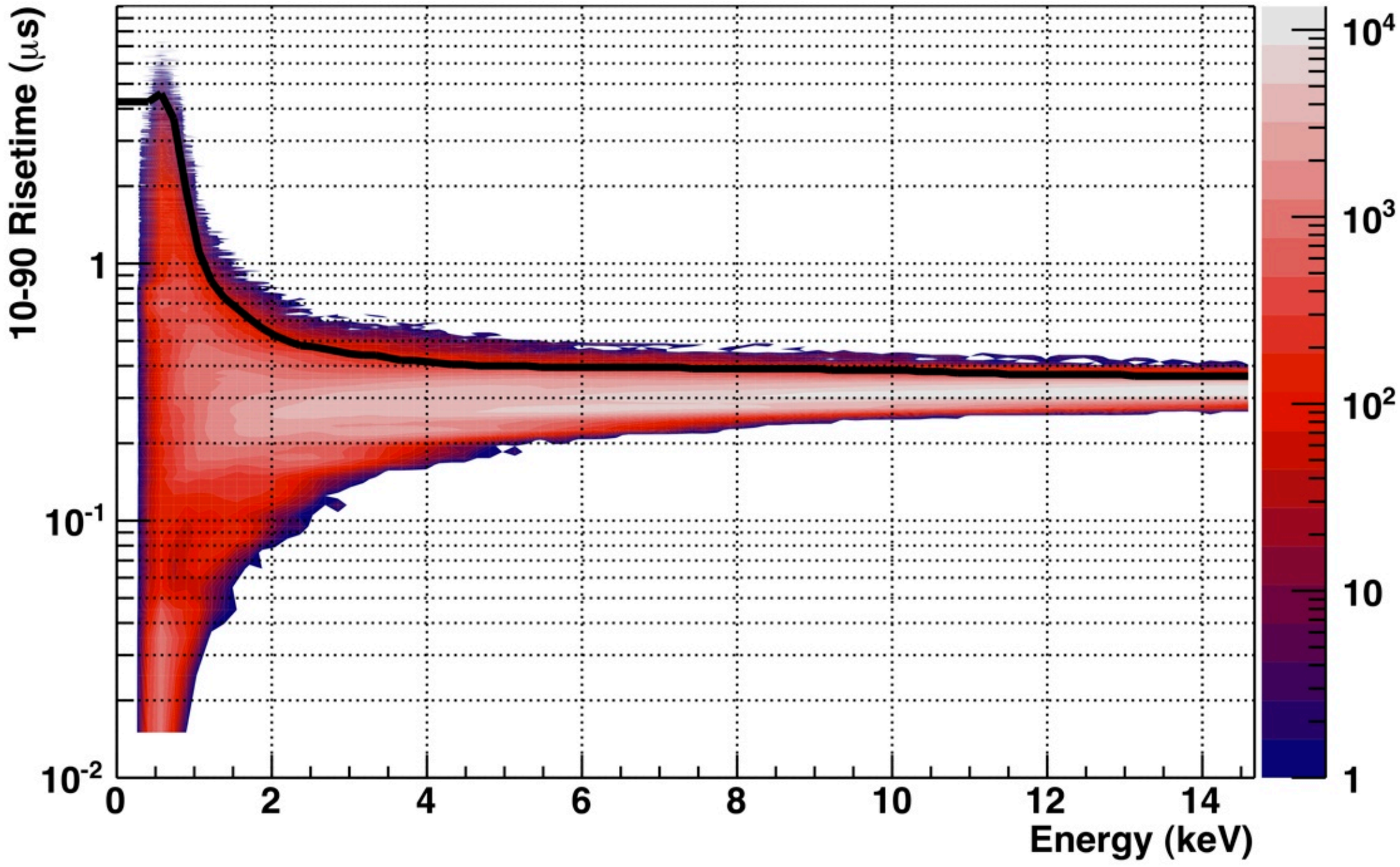
Rise-time studies, estimating efficiencies



Sim vs. Data pulse

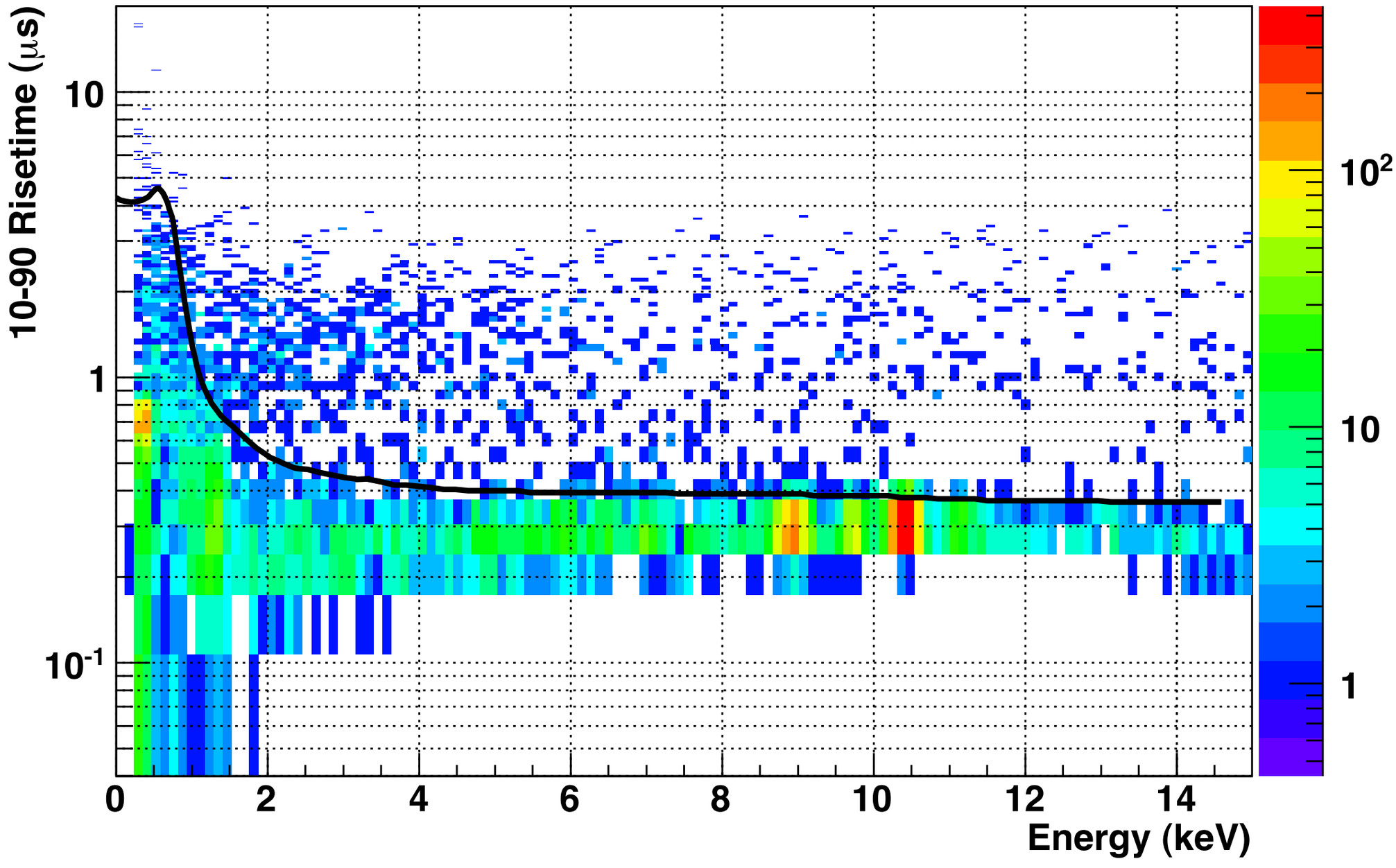


Simulation



Line is calculated 99% acceptance contour

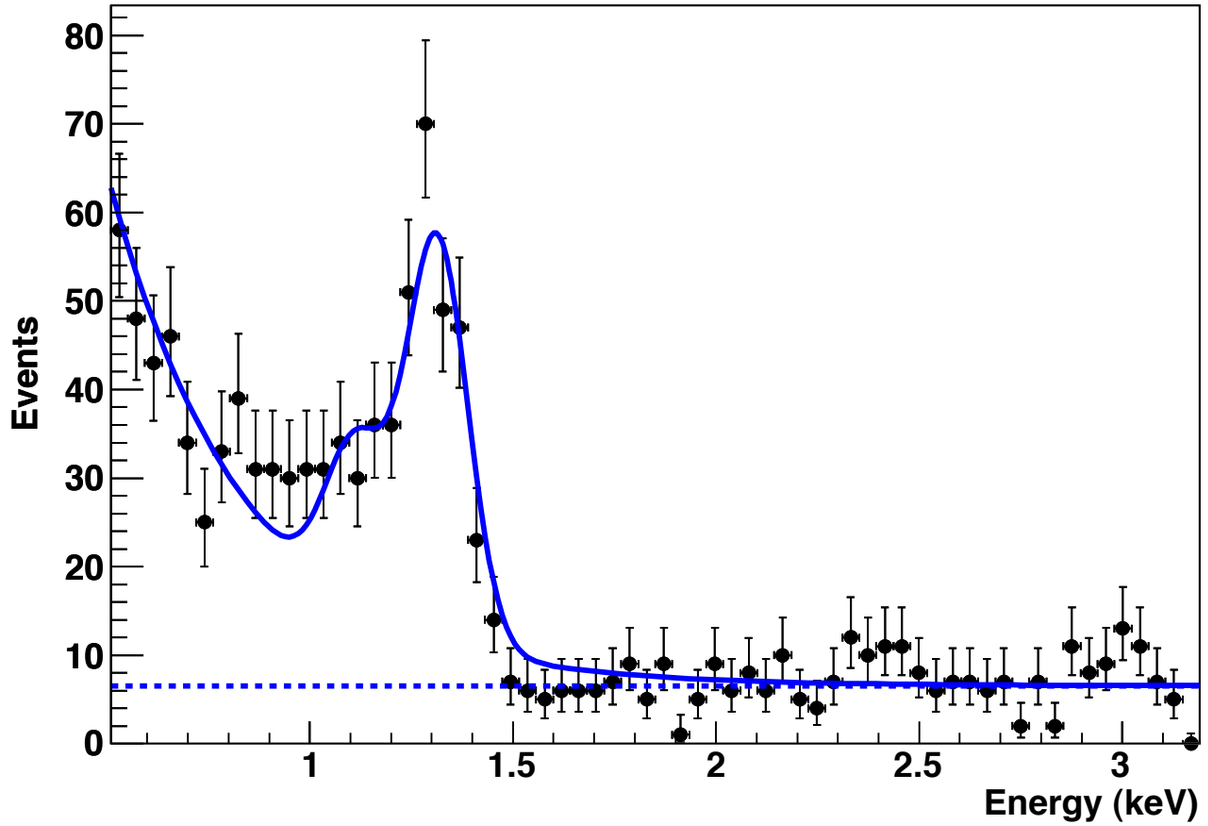
Compare to data

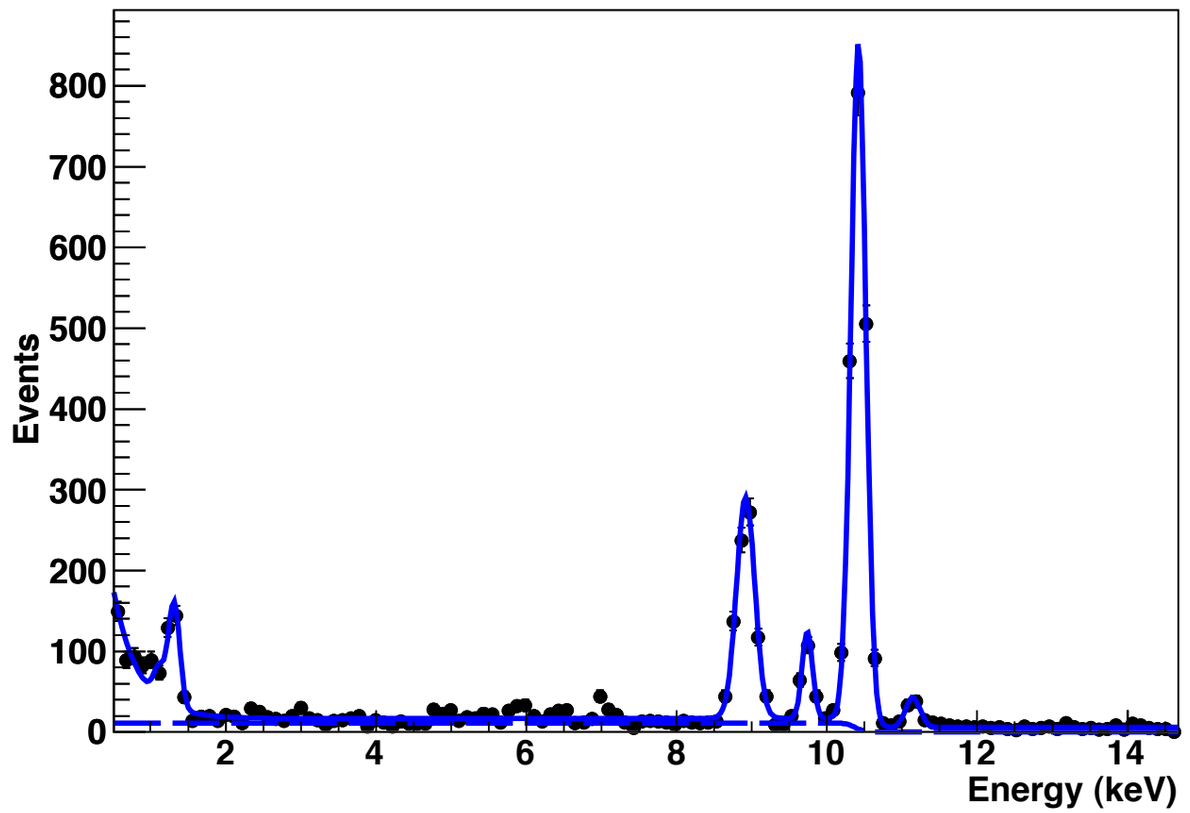


Line is calculated 99% acceptance contour

Check cut against data

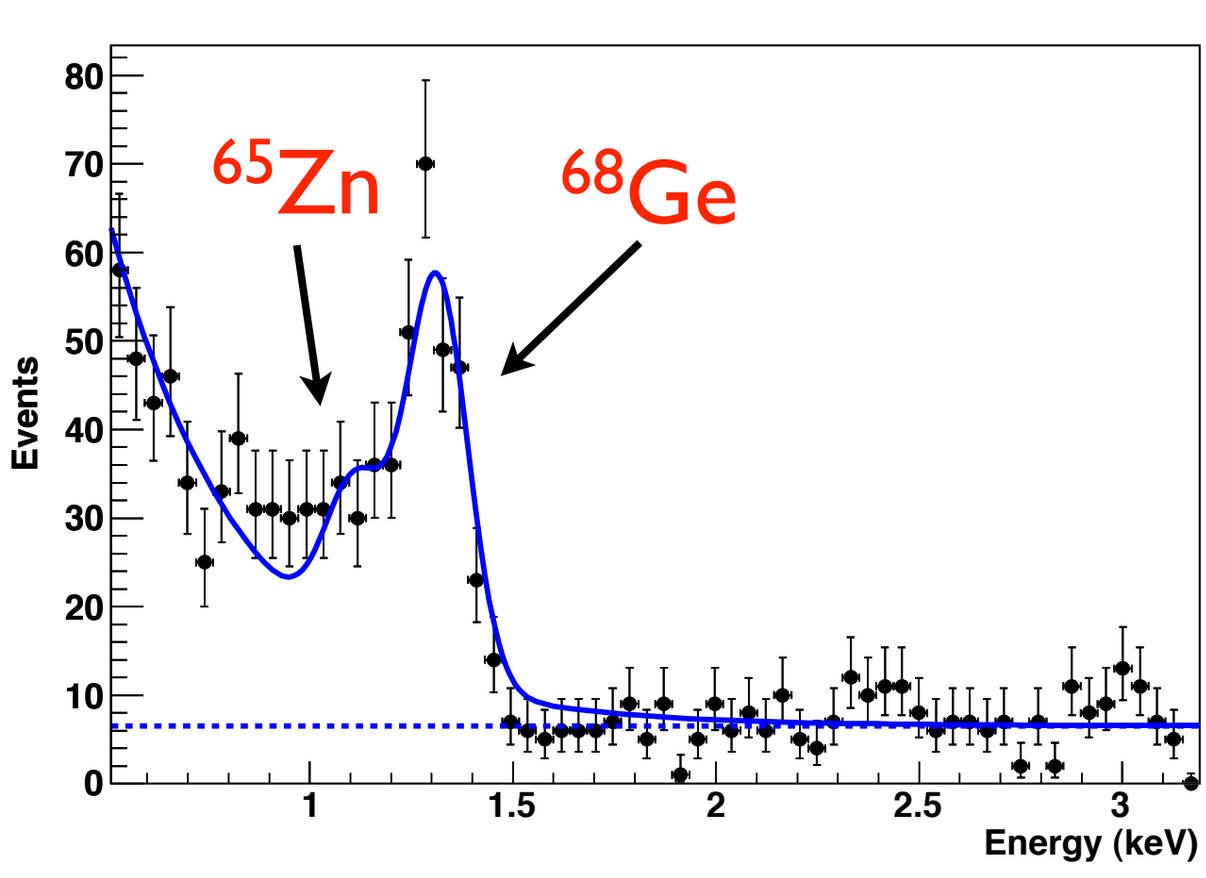
- Take cut
- Fit spectrum (peaks + exponential + flat background)
- Extract component amplitude information

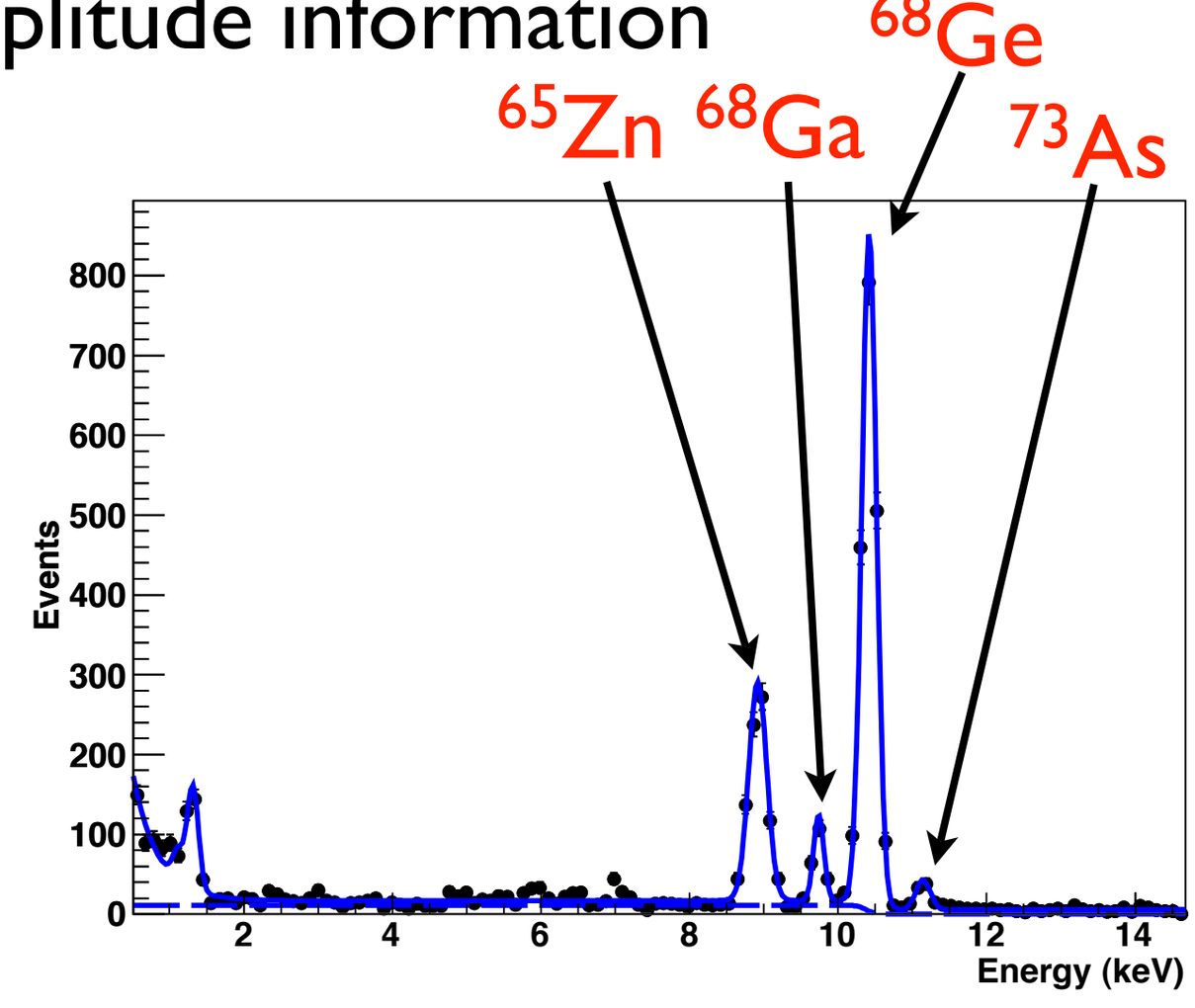




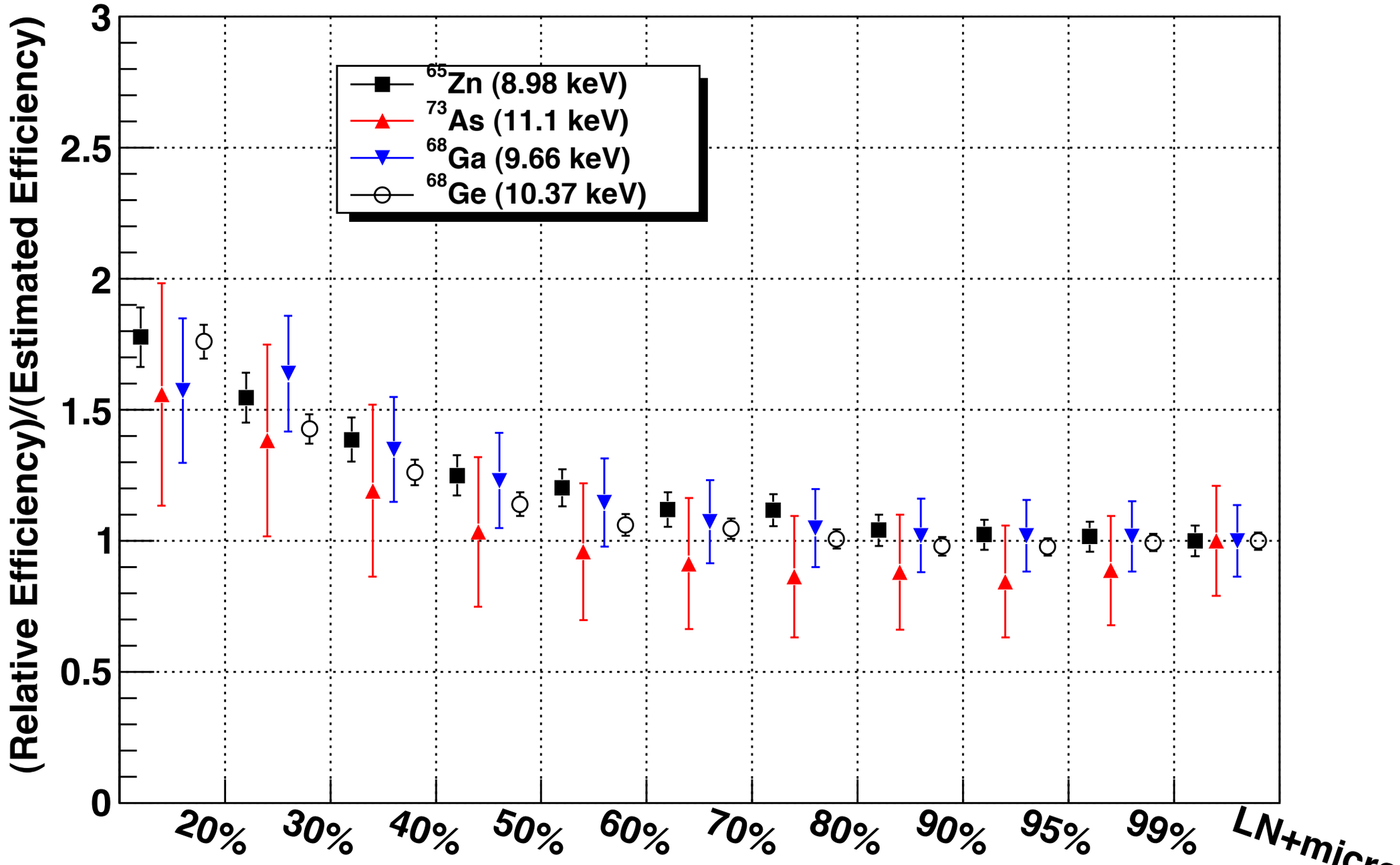
Check cut against data

- Take cut
- Fit spectrum (peaks + exponential + flat background)
- Extract component amplitude information

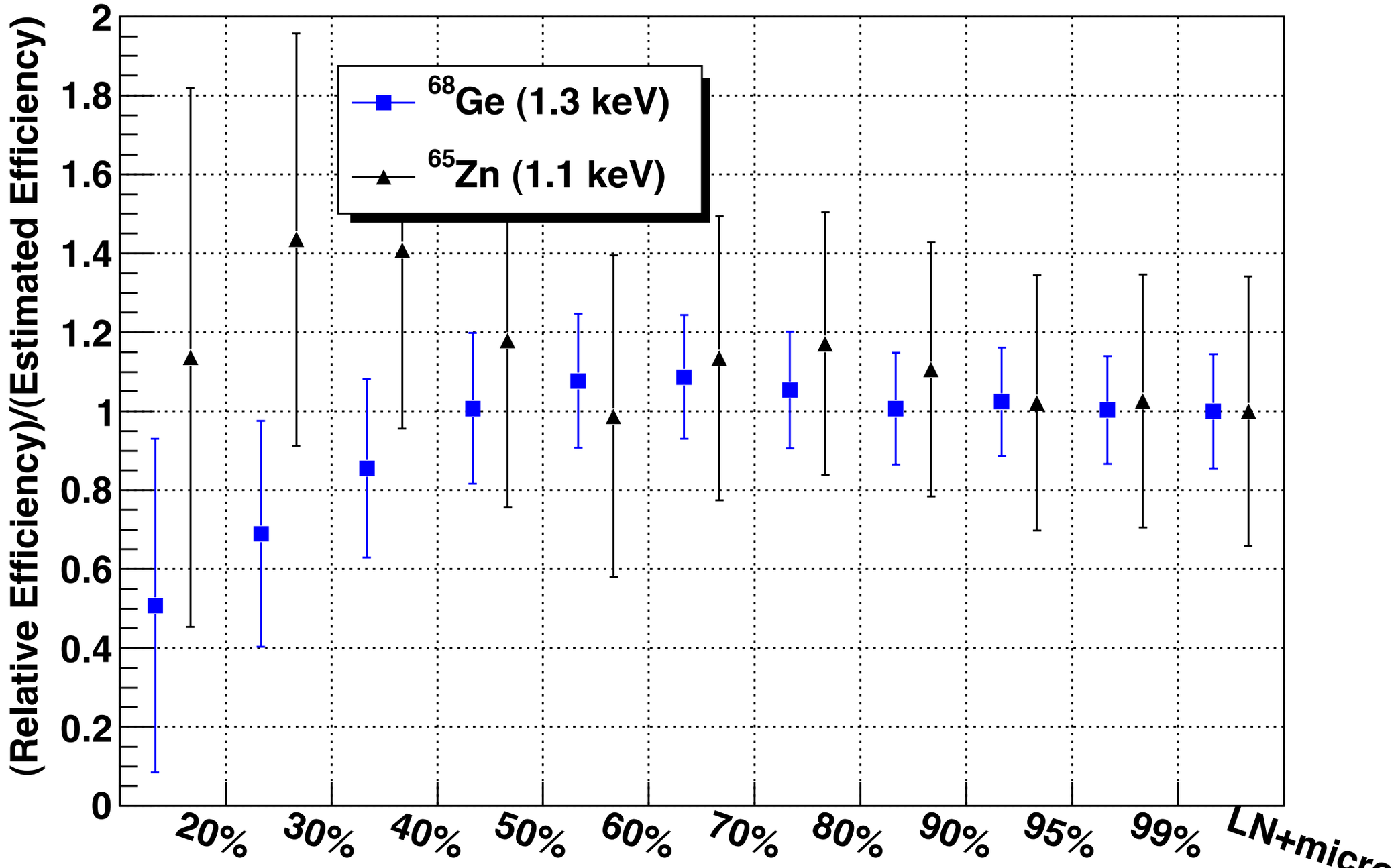




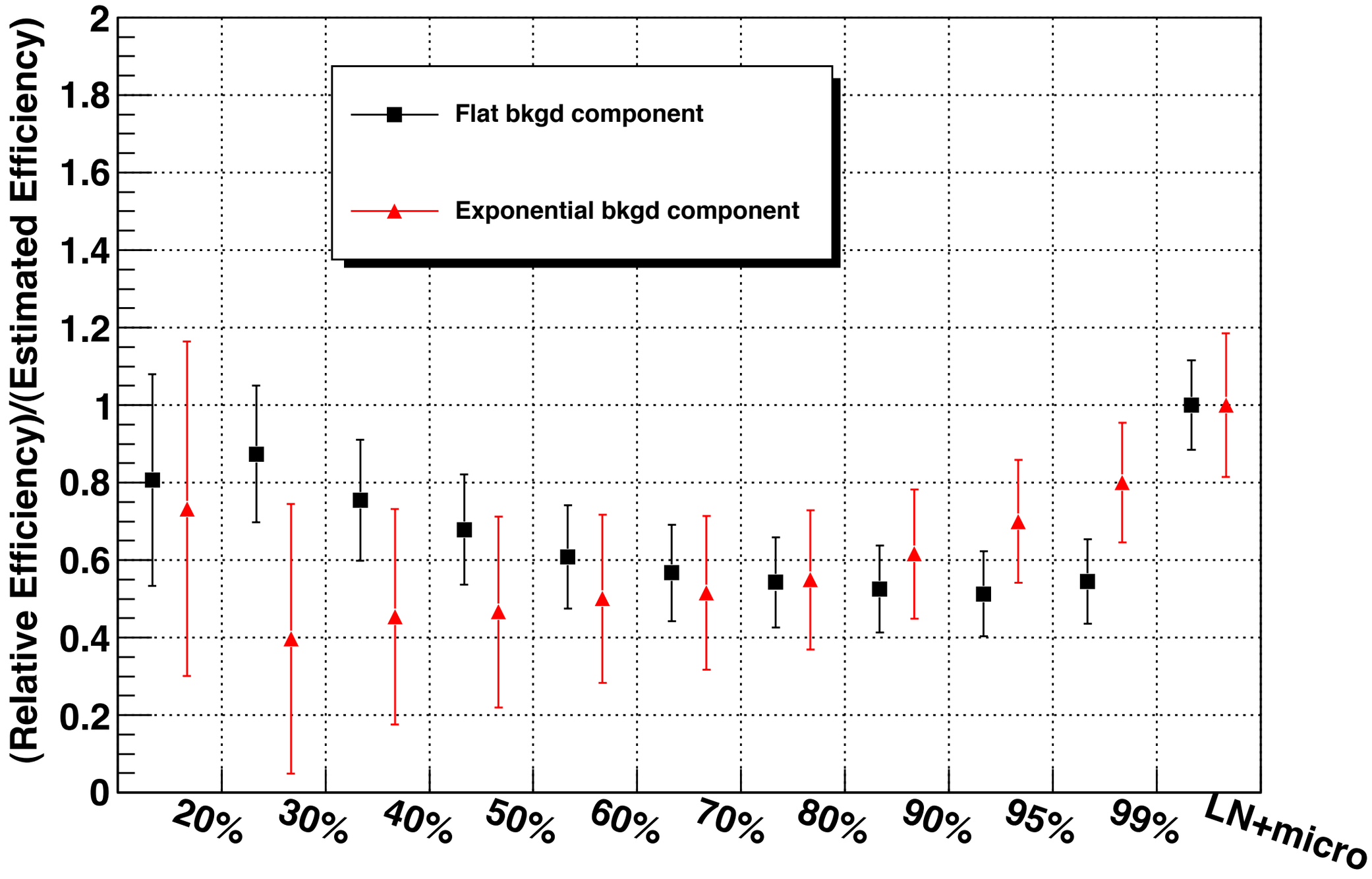
Check cuts against data



Check cuts against data



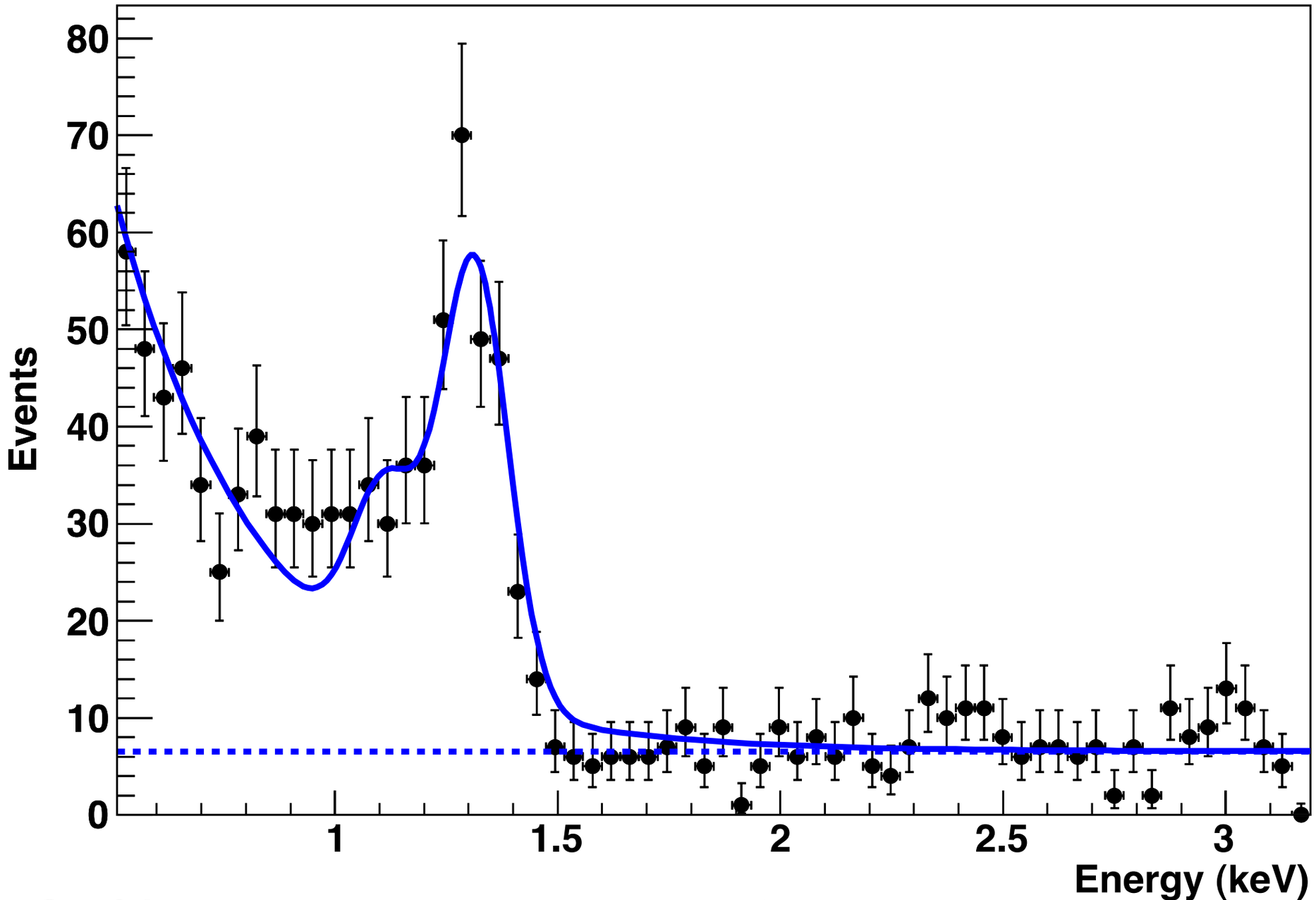
Check cuts against data



Rise-time summary

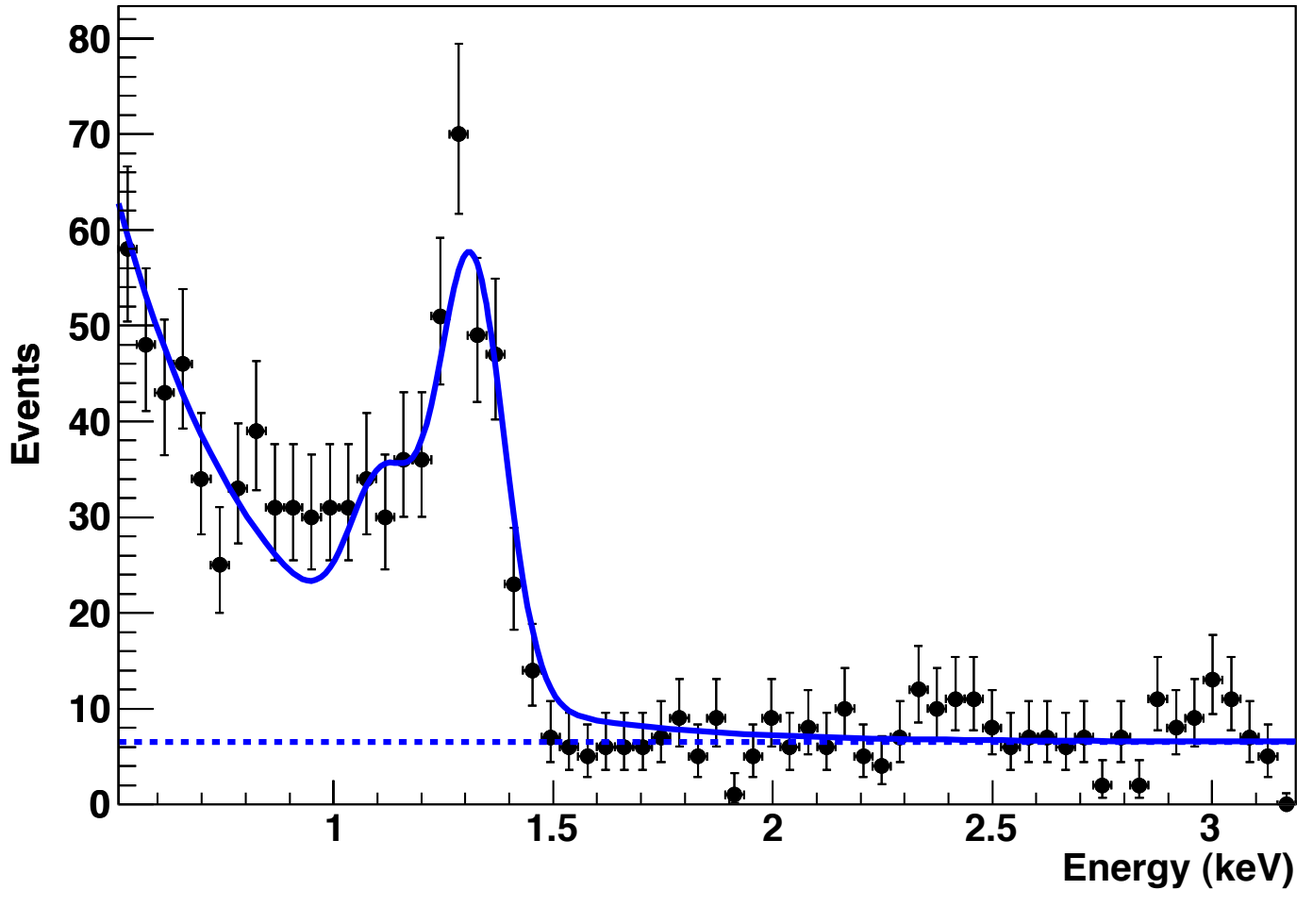
- Cuts work well to at least 1 keV, acceptance efficiency good estimation ≥ 70%
- Fiducial volume cut: 0.4 → 0.33 kg active mass
- Further quantitative tests underway to investigate origin

Spectrum after cuts



95% Rise-time + microphonics cuts applied

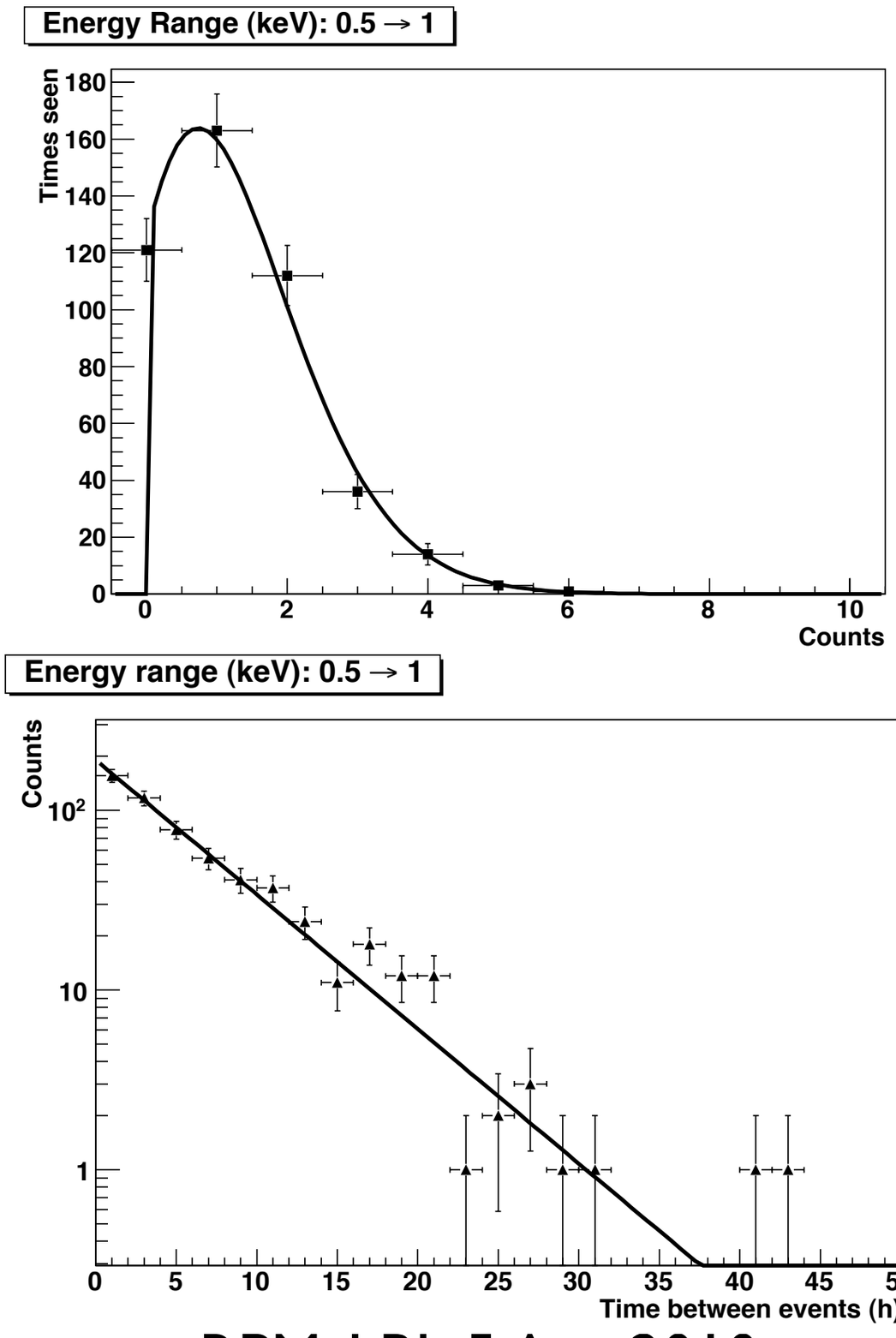
Low-energy exponential



- Neutrons?
- Noise fluctuations?
- Remaining slow-pulse contamination?
- Uncaught microphonics events?

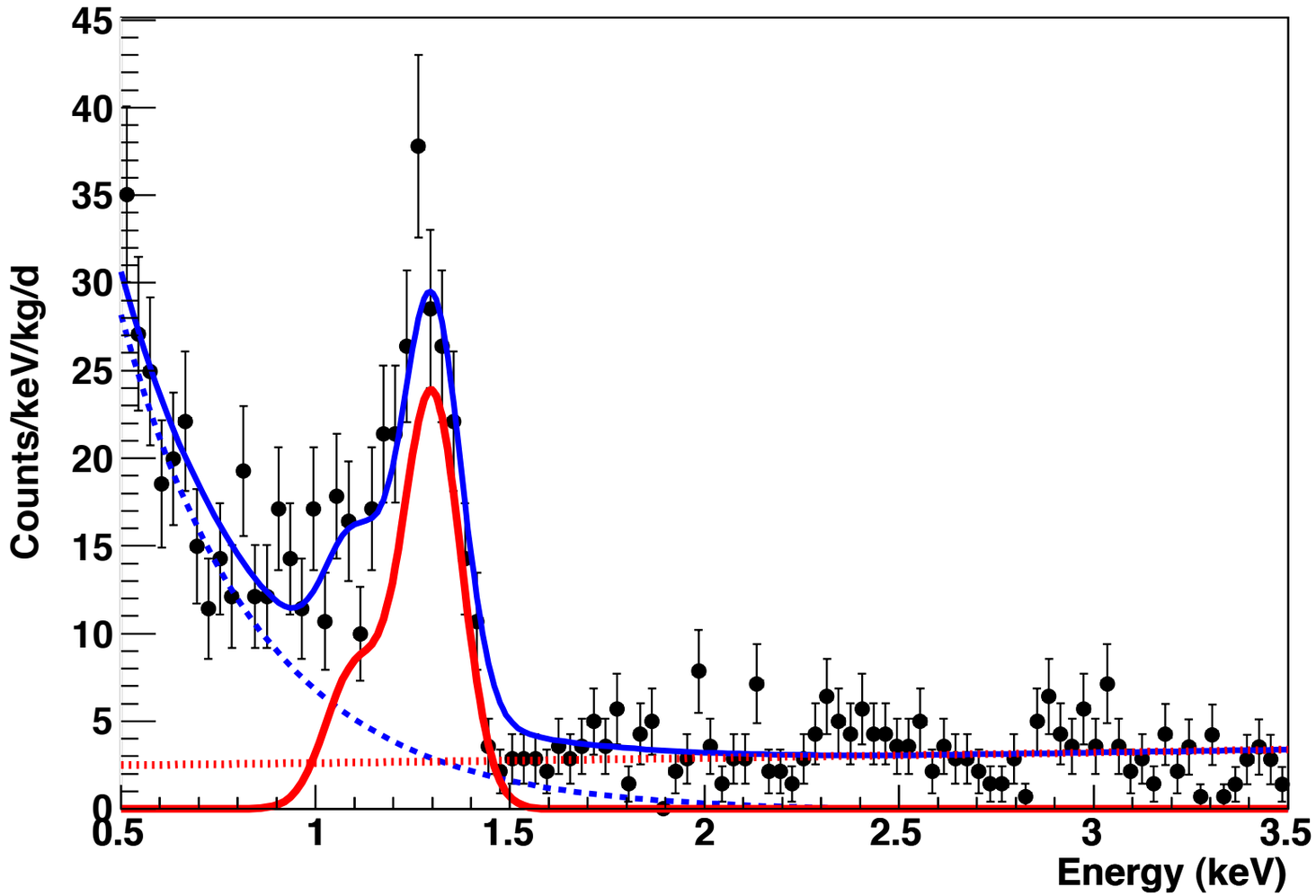
Other systematic tests

- Rate tests - ensuring that count rate is Poisson
- Time correlations
- Parameters over time



Extracting WIMP limits

- ML-based exclusion calculation
- Background uncertainty handled as nuisance pars:



90% CL exclusion of 8 GeV WIMP

Rolke, et al., NIM A **551** (2005) 493

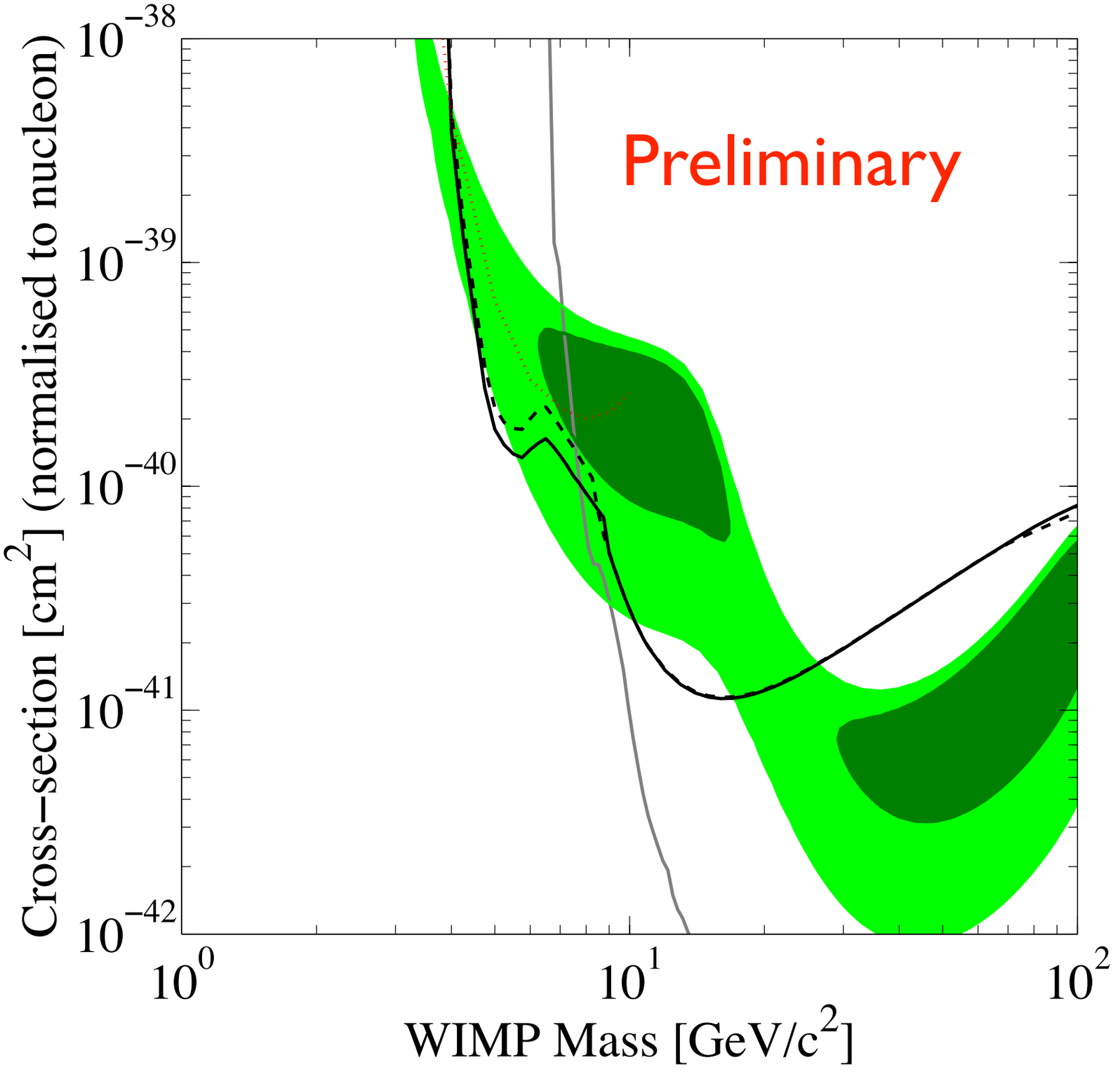
Low-mass WIMP limits

Black:
solid 70% RT cut
dashed 95% RT cut

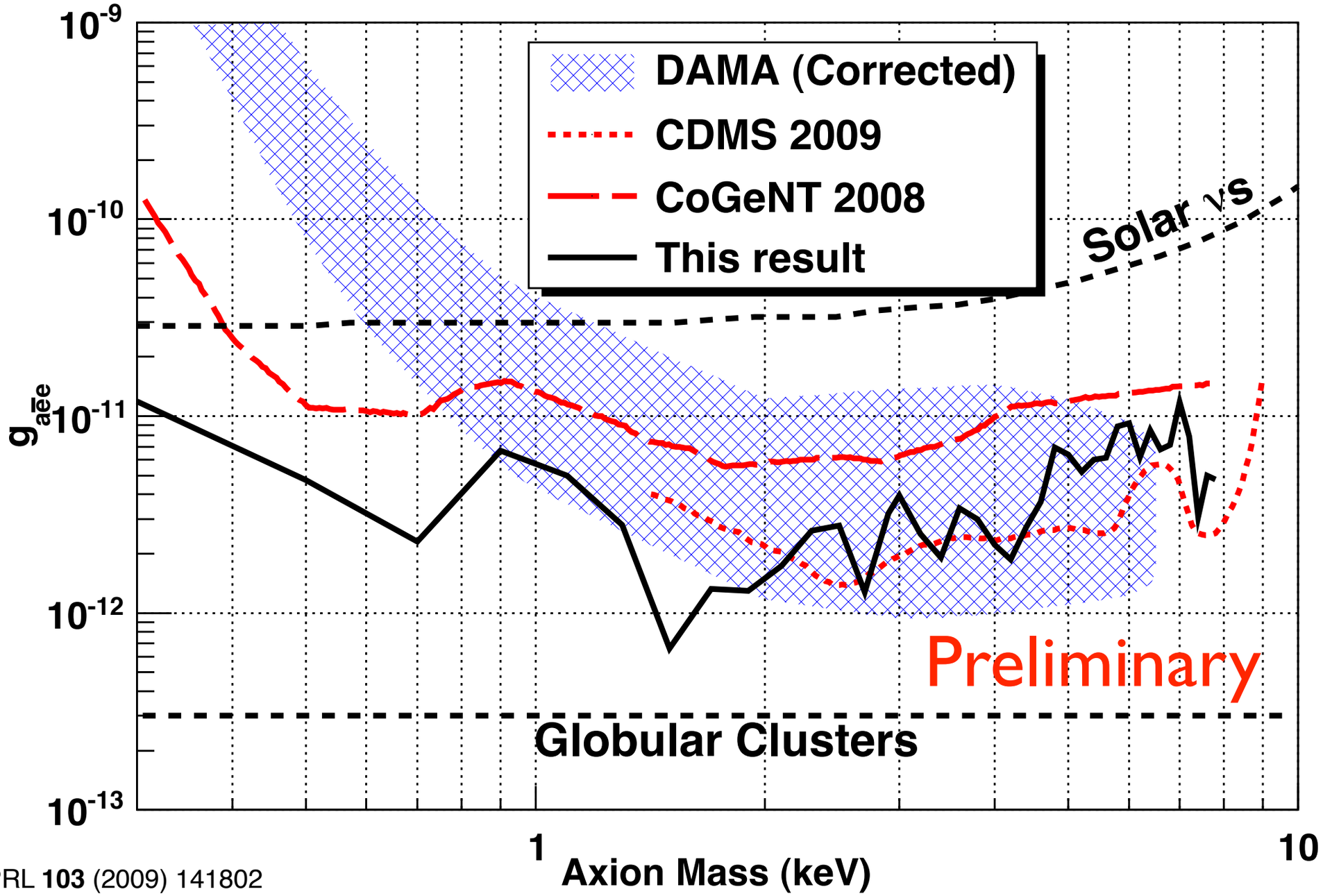
CDMS, 612 kg-d

DAMA, 3σ, 5σ
allowed region

CDMS Collaboration, arXiv:0912.3592;
DAMA Collaboration, EPJ **C56** (2008), 333, arXiv:0804.2741



Axioelectric Limits



CDMS: PRL **103** (2009) 141802

Solar neutrinos: PRD **79** (2009) 107301

Globular clusters PRD **51** (1995) 1495

Conclusions

- P-type Point Contact detectors have properties beneficial to 0νββ and are sensitive to dark matter.
- P-PC detectors can exclude space in low-mass WIMP region
- P-PC detectors have good sensitivity to the axioelectric effect.

Thanks

- Soudan work:
  - CoGeNT collaboration
    - J. Collar (UC), J. Orrell (PNNL), M. Miller (UW), J. Wilkerson (UNC)

What about MAJORANA?

- Assumptions:
  - Flat background: 0.001 counts/keV/kg/d
  - background from ^{3}H, assumed exposure 15 days, 200 atoms/kg/day production
- 20 kg array, 1-5 yrs exposure

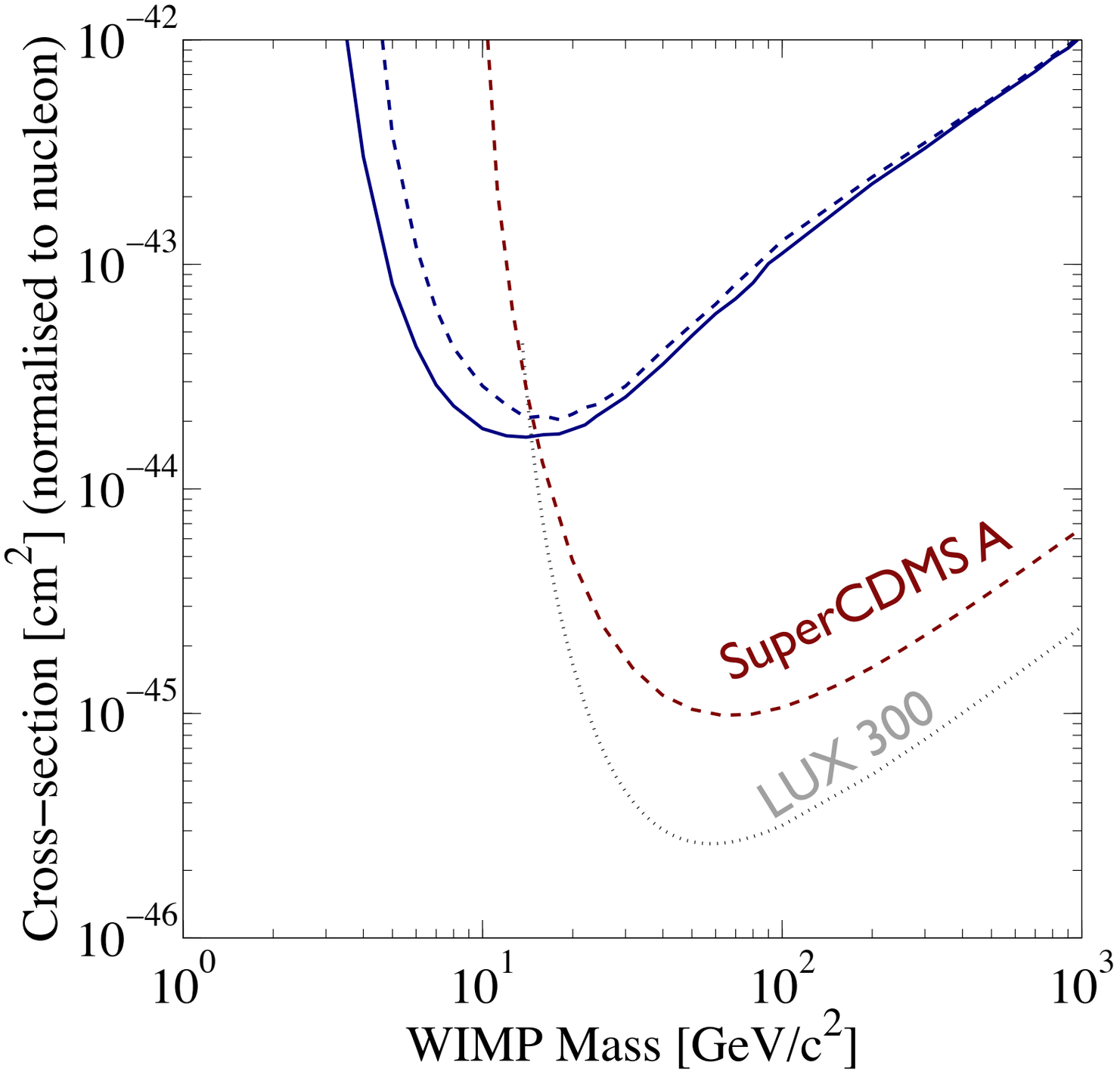
What about MAJORANA?

MAJORANA with thresholds 0.3 and 0.5 keV

Plot generated using DMTools,
http://dmtools.brown.edu

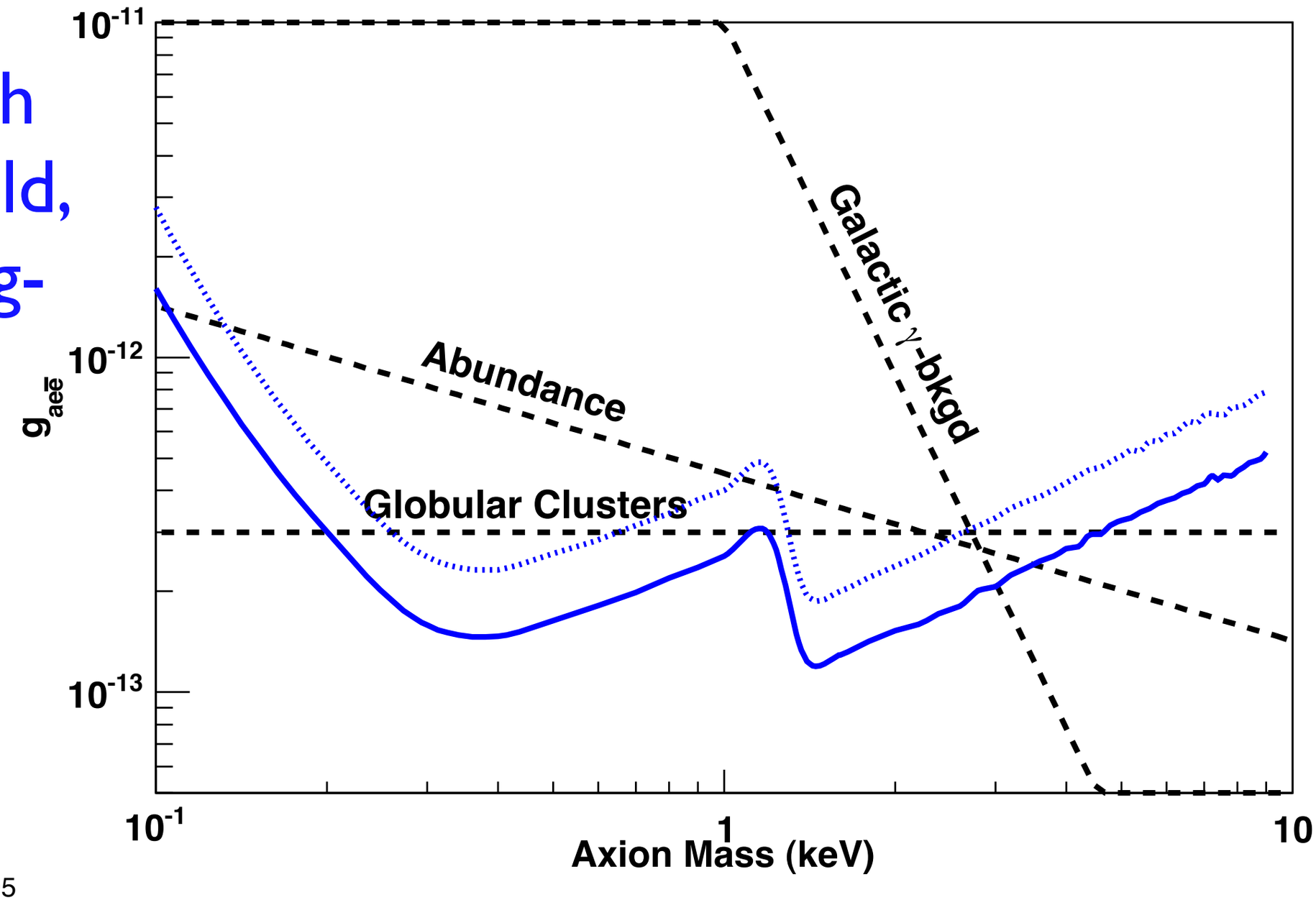
LUX 300: http://lux.brown.edu/experiment_sens.html

SuperCDMS Phase A: NIM A **559** (2006) 411



What about MAJORANA?

MAJORANA with 0.3 keV threshold, 20 kg-yr, 100 kg-yr exposure



Globular clusters: PRD **51** (1995) 1495

Axion abundance, gamma bkgd: PRD **78** (2008) 115012

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