A category of extremely-fast events (EFEs) in pPCGe detectors used in CDEX

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CDEX Collaboration

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Outline

- 1. pPCGe in CDEX
- 2. Extremely-fast events (EFEs) in pPCGe
- 3. What we learned from EFEs studies?
- 4. Summary

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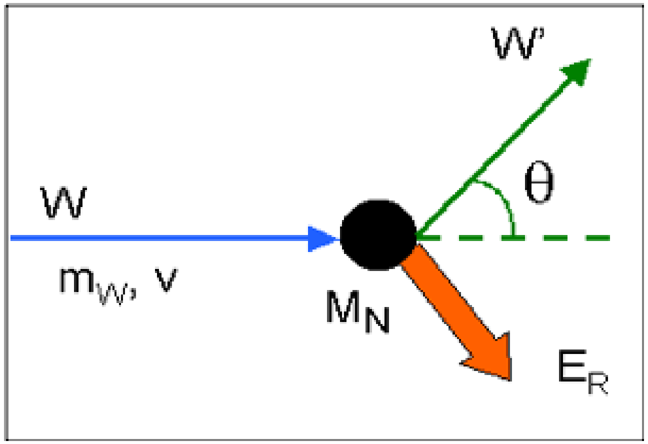
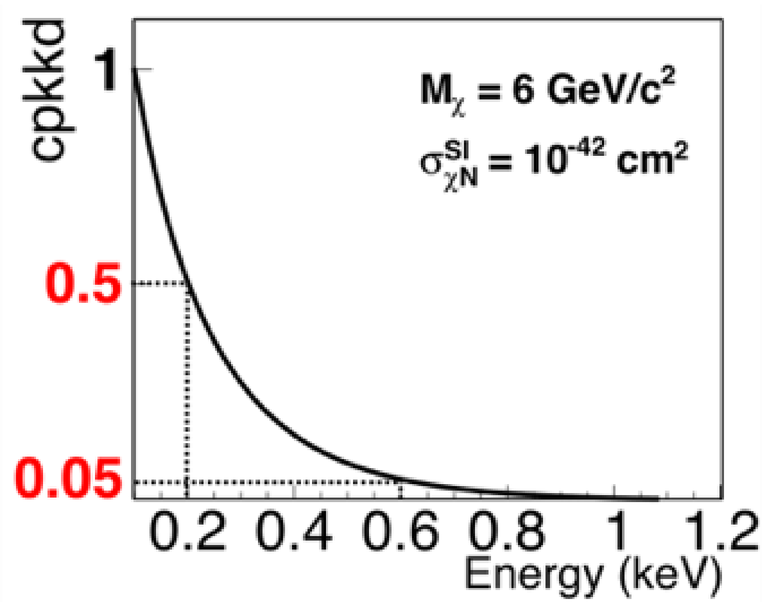
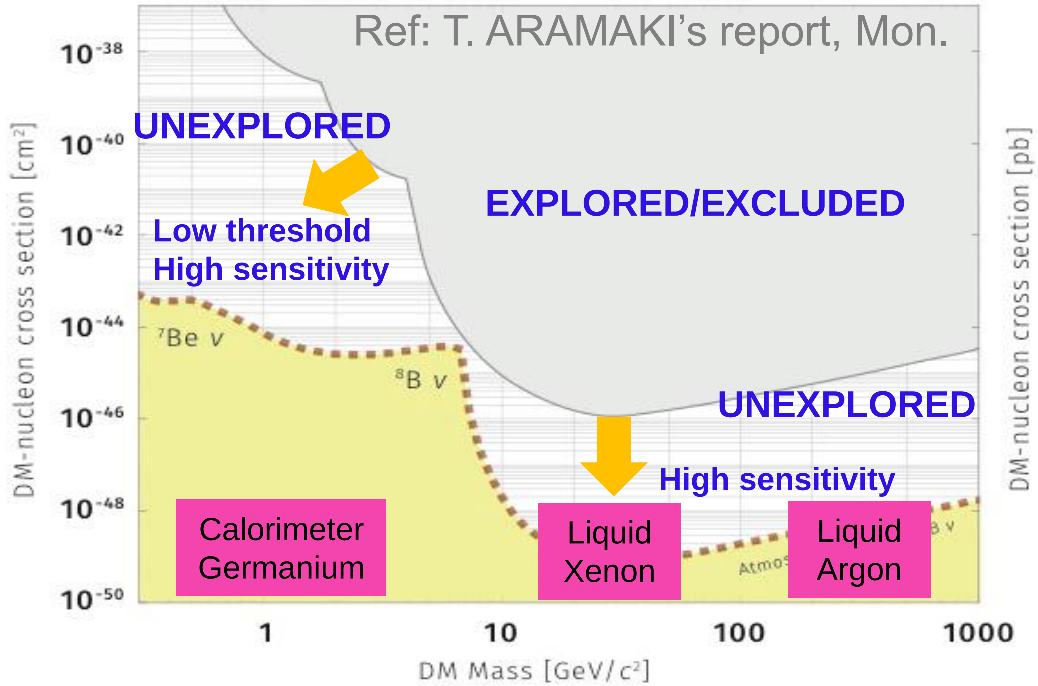
Direct detection of WIMP







Requirements for DM search:

- ✓ Low background
- ✓ Low threshold
- ✓ Particle discrimination
- ✓ Long-time stability

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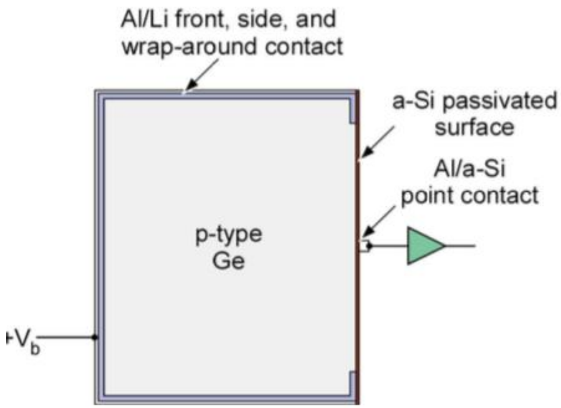
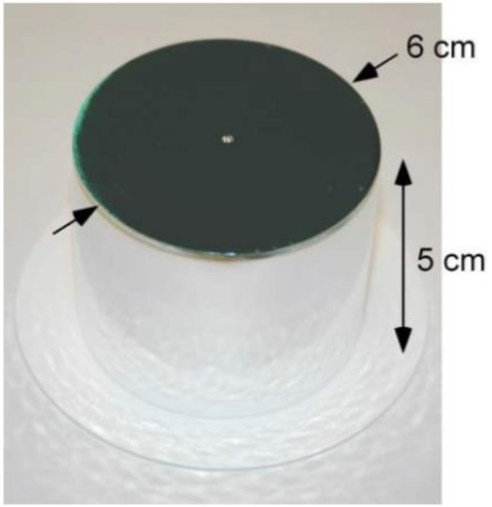
Point Contact Germanium (PCGe) detector





$$C_{PPC} = 2\pi\epsilon r$$

~1 pF possible

- **Good candidate for light DM**
  - ✓ Low threshold: ~ 200 eV
  - ✓ Excellent energy resolution: FWHM ~200 eV @ 10.37 keV, 4.3 keV @ 2039 keV (CDEX1A)
  - ✓ Long-time stability
- **Challenges**
  - ✓ Control the material background near PCGe
  - ✓ Decrease the cosmogenic background
  - ✓ No particle discrimination
  - ✓ Large mass

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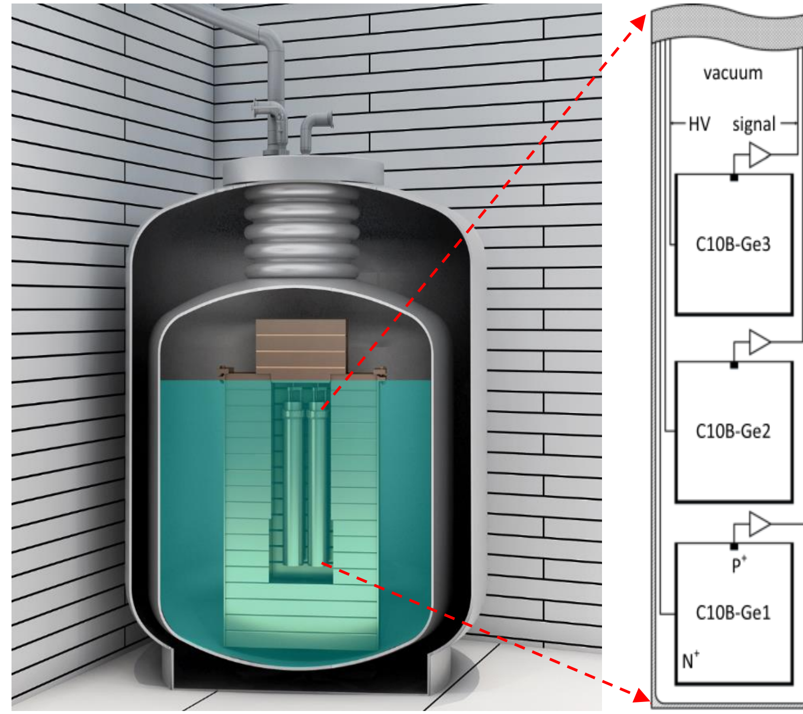
pPCGe in CDEX

PRL 120, 241301 (2018)

❖ Light WIMP searches with pPCGe

❖ CDEX-10 detectors:

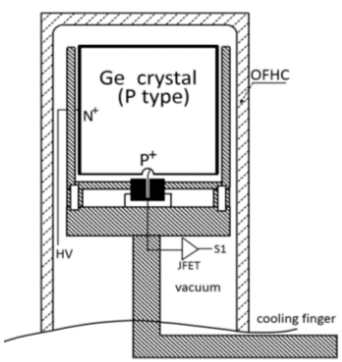
- ✓ three triple-element pPCGe strings
- ✓ total mass of about 10kg
- ✓ immersed in liquid nitrogen



LN2 tank: 1.5 m(D)*1.9m(H)

Based on the CDEX-1B prototype:

- ✓ 1kg-scale pPCGe
- ✓ Large-mass "prototype" (1008 g)
- ✓ Low energy threshold (< 160 eVee)



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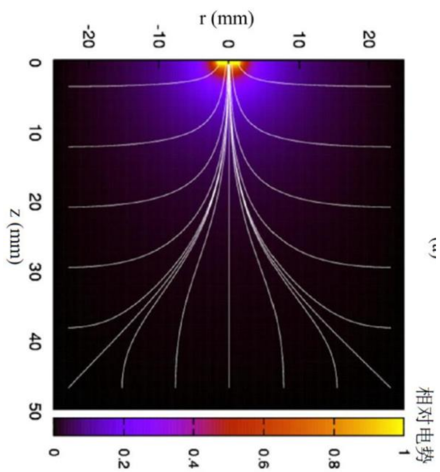
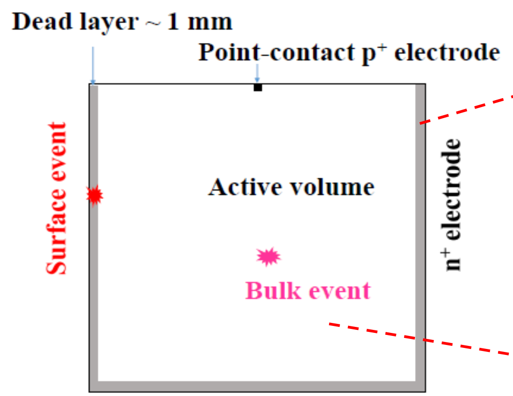
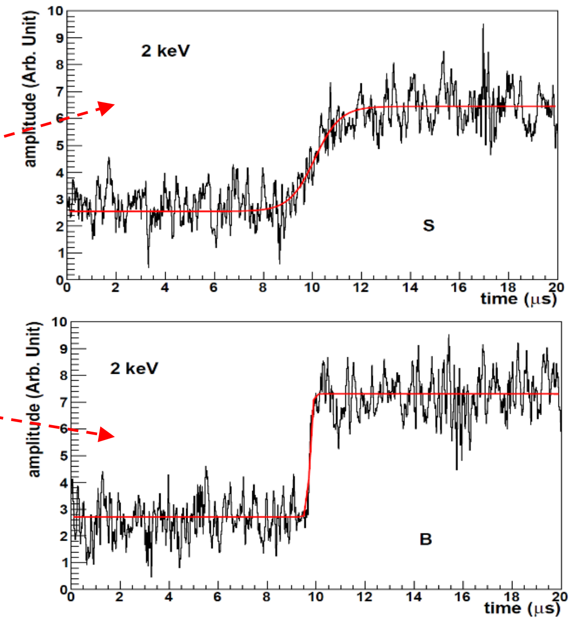
Bulk and Surface events in pPCGe

Dead layer:

- ✓ Lithium diffusion technology of surface N+ electrode;
- ✓ the electric field is weak, and the electron-hole pair drifts slowly;
- ✓ Surface event: Amplitude (Energy) loss, long rise time;
- ✓ “Self-shielding effect”: external low γ/X rays will be shielded by this layer;







The surface signals should be removed:

- ❖ **Active volume correction**

→dead layer thickness measurement: 0.88±0.12 mm (CDEX-1B)--939g

- ❖ **B/S identification efficiency correction** use rise time difference

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→BS discrimination method

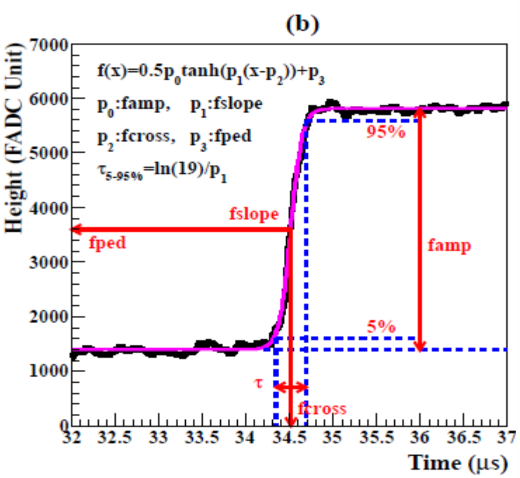
B/S discrimination

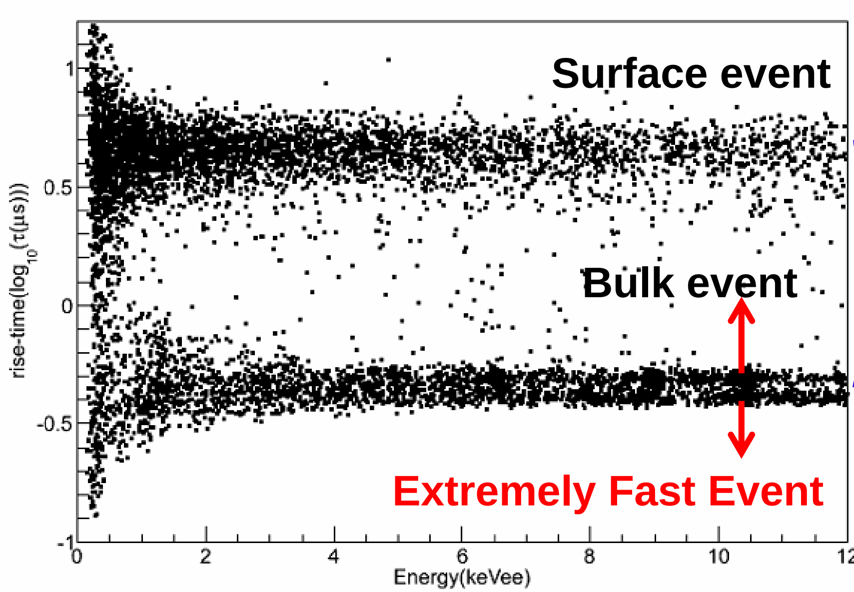
CDEX-10 background data:

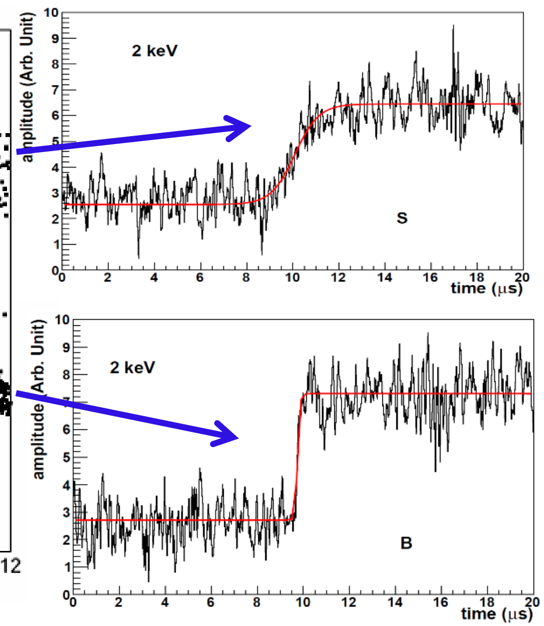
❖**Surface event:** longer rise time, false energy value;

❖**Bulk event:** events happened in the active bulk volume;

❖**Extremely-fast event:** faster rise time than Bulk events, happened at the strong electric field area near the point electrode; (has been confirmed by source experiments and the detector electric simulation)

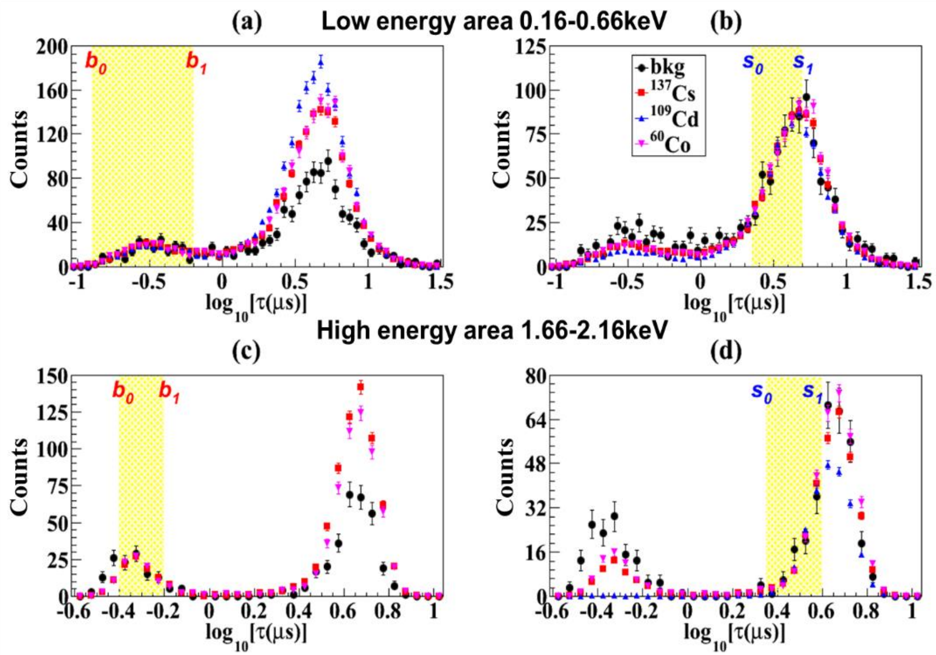


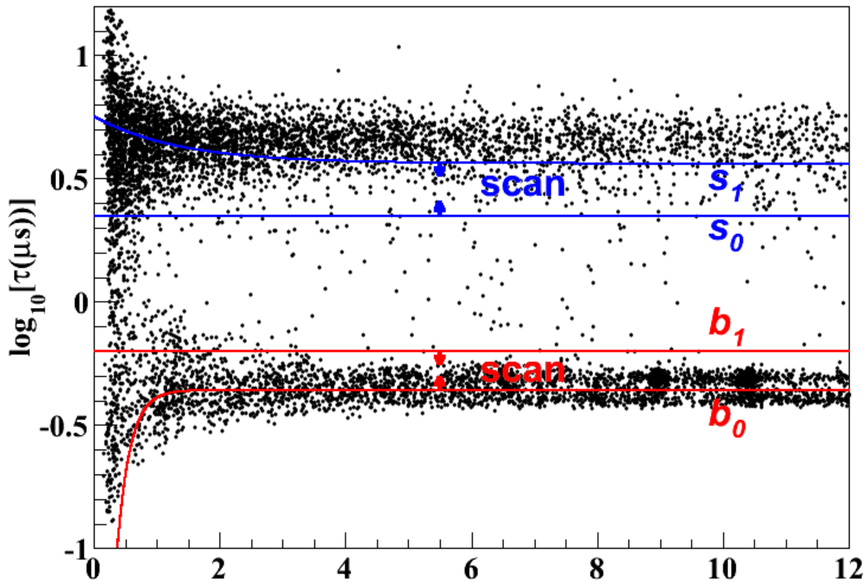




B/S discrimination

Assumption: **At low energies, different sources and background share the same rise-time PDFs $f_B(E,\tau)$ and $f_S(E,\tau)$ for bulk events and surface events.**





Sources-independent bulk/surface rise-time distribution PDFs

$$N_i(E,\tau) = N_{Bi}(E,\tau) + N_{Si}(E,\tau) \quad = \beta_i(E) f_B(E,\tau) + \xi_i(E) f_S(E,\tau).$$

sources index τ-independent

B/S disc. --Ratio Method

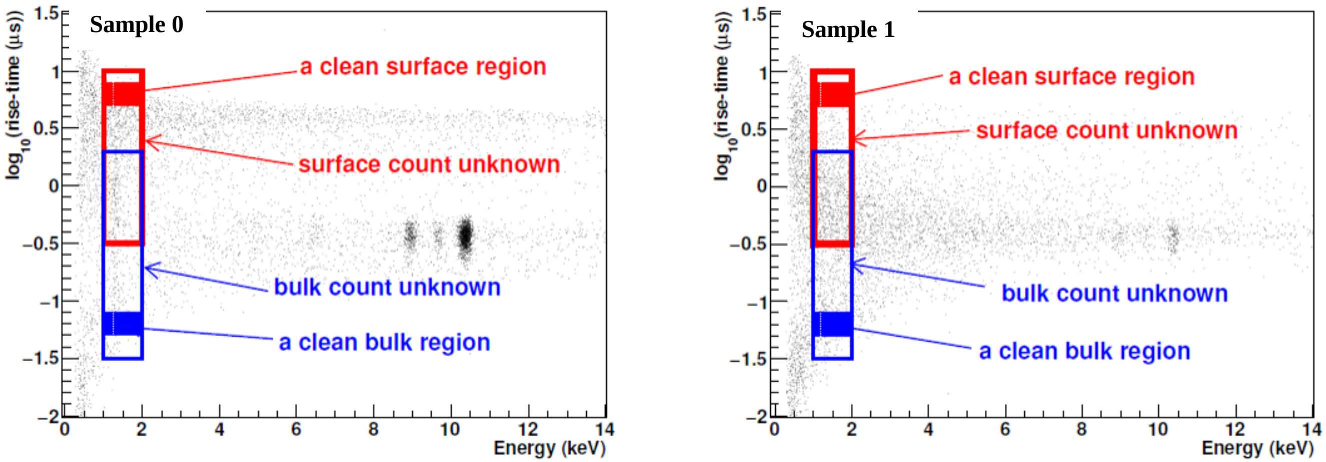
NIM A 886, 13 (2018),
Chinese Physics C 42, 023002 (2018)

Sources-independent bulk/surface rise-time distribution PDFs

$$N_i(E,\tau) = N_{Bi}(E,\tau) + N_{Si}(E,\tau) \quad = \beta_i(E) f_B(E,\tau) + \xi_i(E) f_S(E,\tau).$$

sources index   τ-independent

$$\beta_0(E) f_B(E,\tau) = \frac{N_1(E,\tau) - [\xi_1(E)/\xi_0(E)] N_0(E,\tau)}{[\beta_1(E)/\beta_0(E)] - [\xi_1(E)/\xi_0(E)]}.$$



$$\frac{\beta_i(\mathrm{E})}{\beta_j(\mathrm{E})} = \frac{\int_{b_0}^{b_1} \beta_i(\mathrm{E}) f_B(\mathrm{E},\tau)}{\int_{b_0}^{b_1} \beta_j(\mathrm{E}) f_B(\mathrm{E},\tau)} = \frac{\int_{b_0}^{b_1} N_i(E,\tau)}{\int_{b_0}^{b_1} N_j(E,\tau)} \qquad \frac{\xi_i(\mathrm{E})}{\xi_j(\mathrm{E})} = \frac{\int_{s_0}^{s_1} \xi_i(\mathrm{E}) f_s(\mathrm{E},\tau)}{\int_{s_0}^{s_1} \xi_j(\mathrm{E}) f_s(\mathrm{E},\tau)} = \frac{\int_{s_0}^{s_1} N_i(E,\tau)}{\int_{s_0}^{s_1} N_j(E,\tau)}$$

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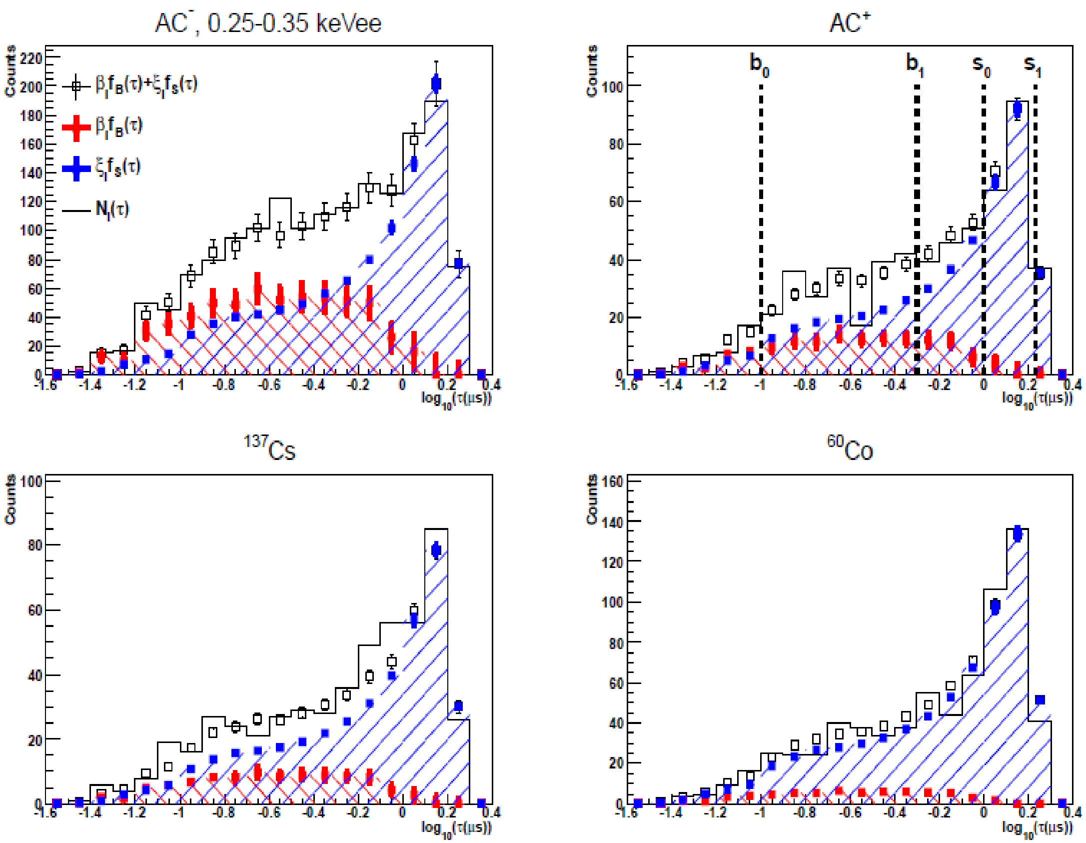
B/S disc. --Ratio Method

- For a collection of different sources with differing Bulk to Surface event ratios can be used to find N_{Bi} and N_{Si} by χ^2 minimization:

$$\chi^2(E,\tau) = \sum_i \frac{[\beta_i(E) f_B(E,\tau) + \xi_i(E) f_S(E,\tau) - N_i(E,\tau)]^2}{\Delta N_i(E,\tau)^2}.$$



- “pure” region: Cross-contamination regions

$$\beta_i^{(n)}(E) \quad = \quad \beta_i^0(E) - \int_{b_0}^{b_1} \xi_i^{(n-1)}(E)\ f_S^{(n-1)}(E,\tau)\ d\tau.$$

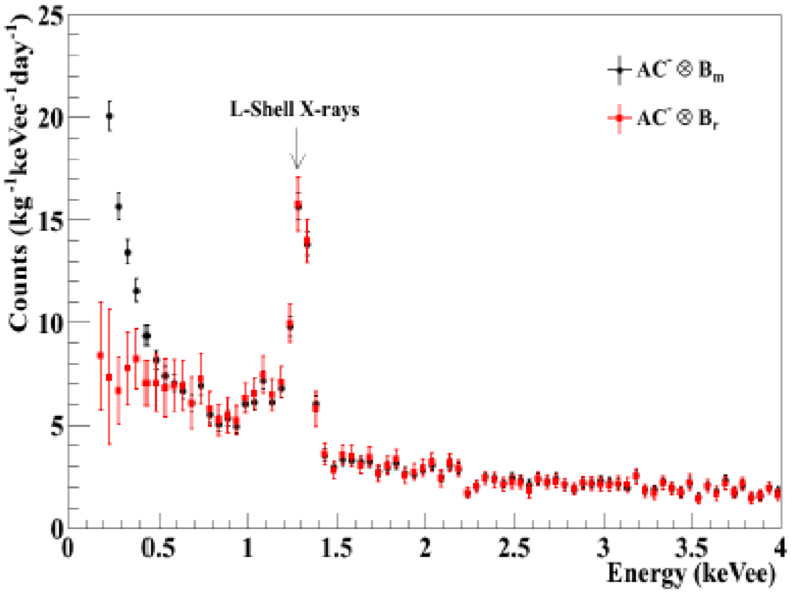
- Final $\boldsymbol{B_{ri}(E)}$ equals the integral of $\boldsymbol{\beta_i f_B(E,\tau)}$:

$$\begin{aligned} B_{ri}(E) &= \int_{all\ \tau} N_{Bi}(E,\tau)\ d\tau \\ &= \int_{all\ \tau} \beta_i^{(n)}(E)\ f_B^{(n)}(E,\tau)\ d\tau. \end{aligned}$$

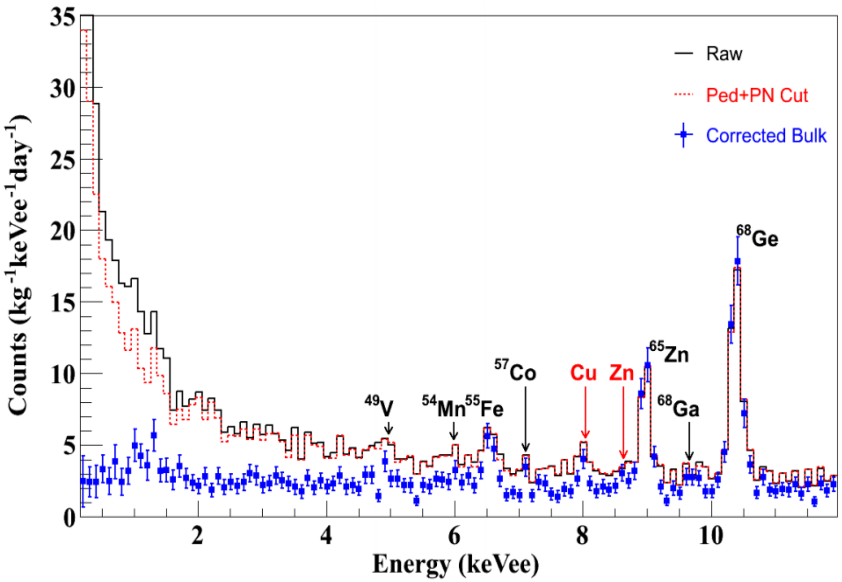
CJPL CDEX-1B result@0.25-0.35 keVee, for CDEX-10, PLS ref: PRL 120, 241301 (2018)

Ratio Method in CDEX-1 and CDEX-10

- ✓ **Analysis threshold: 160 eVee**
- ✓ **Count rate @160 eVee:**
  - ✓ Before BS discrimination: >30 cpkkd
  - ✓ After: ~8 cpkkd (CDEX-1B) and ~2.5 cpkkd (CDEX-10)

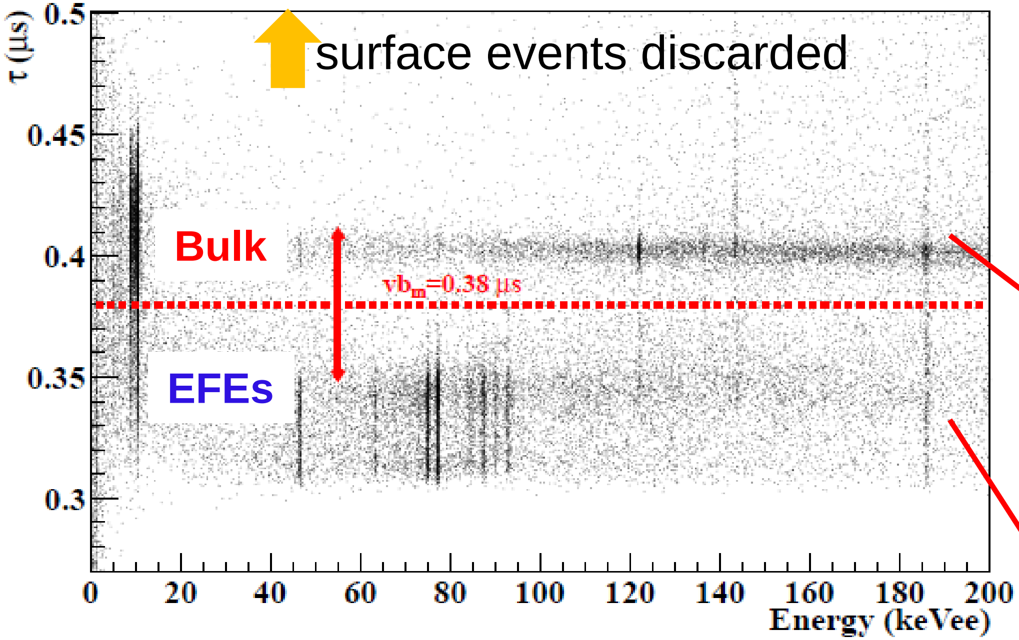


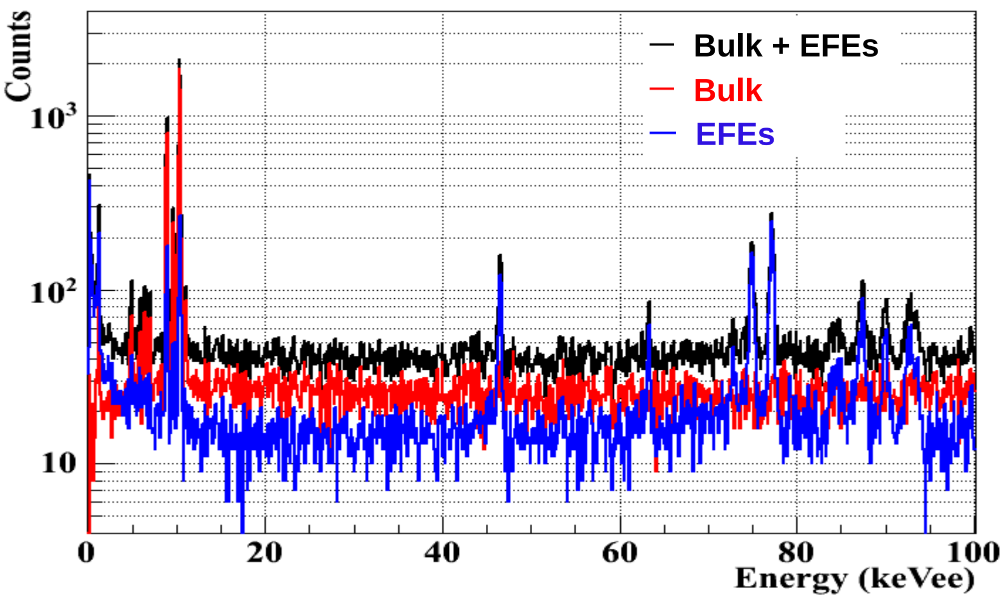
CDEX-1B



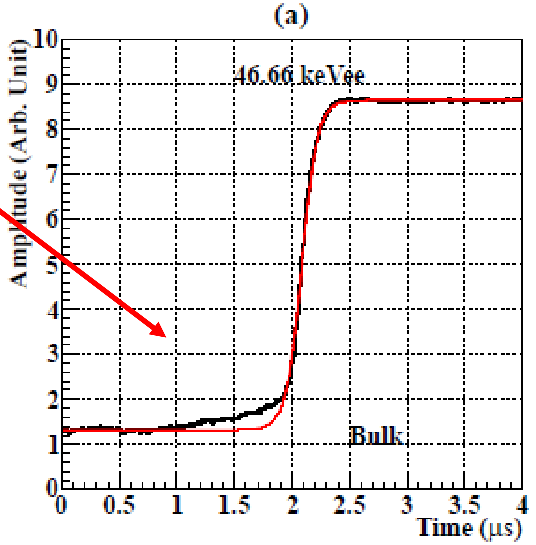
CDEX-10

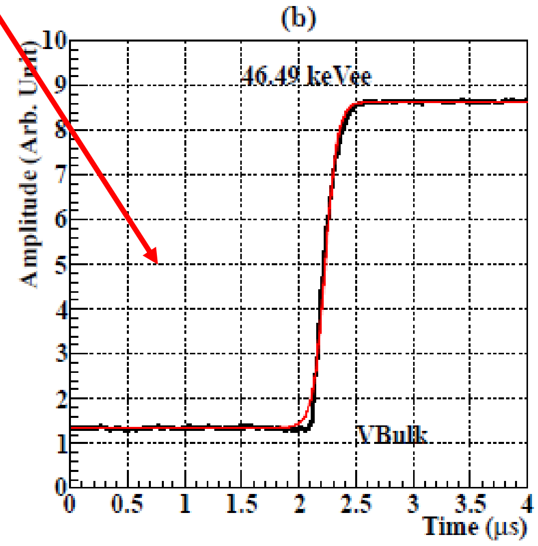
EFEs in CDEX-1B background data





❖ **Measured pulses:**
- ✓ **Top: Bulk event**
- ✓ **Bottom: EFE**

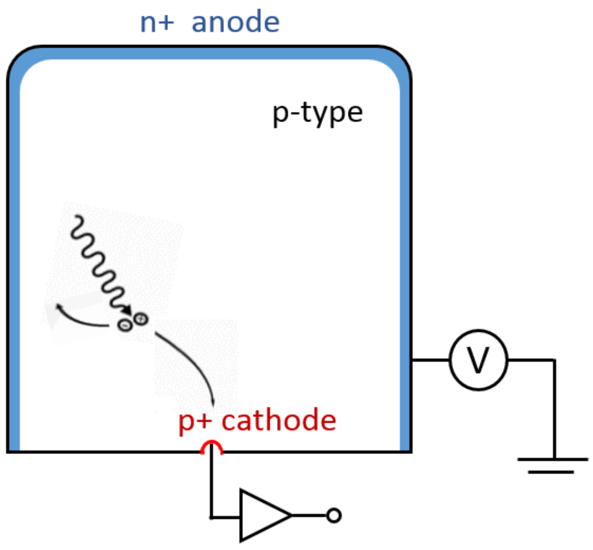




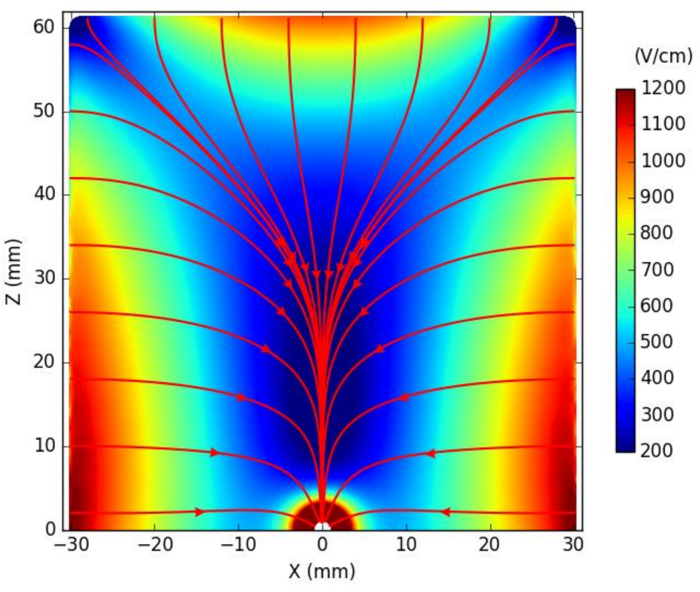
EFEs origin -- qualitative simulation

P-type Point-Contact **(PPC) detector:**

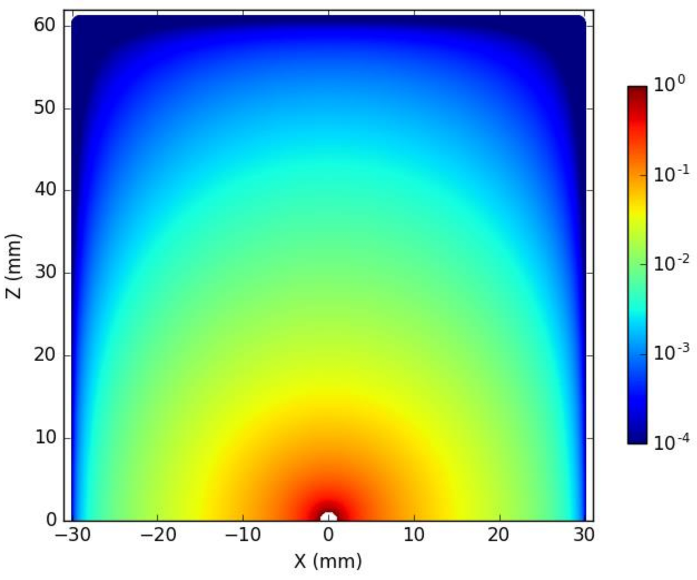
- Small point-like central contact
- Especially low capacitance (~ 1pF) gives superb energy resolution and low energy threshold



Electric field



Weighting potential



Impurity concentration:

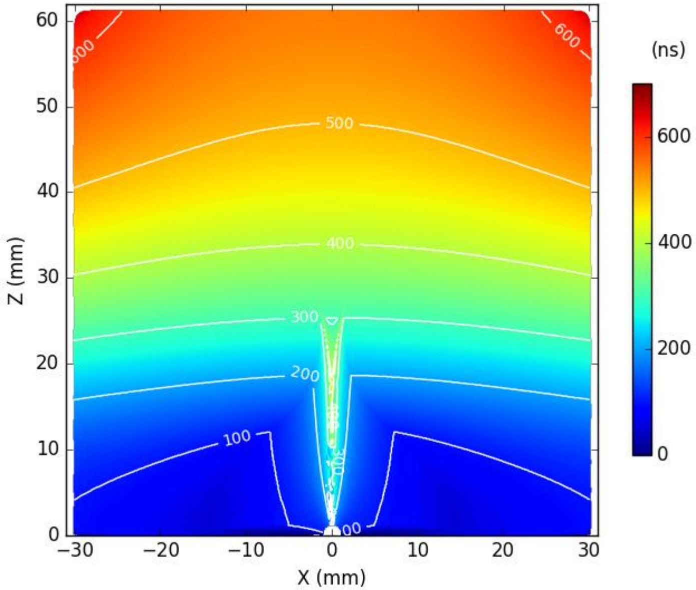
- [-0.5,-0.8]×10^{10}cm^{-3}
- no radial gradient

Bias Voltage:

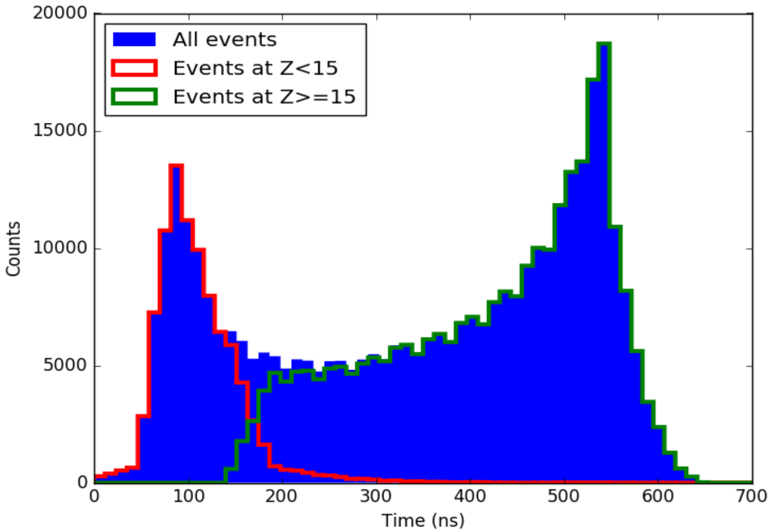
- + 3000V

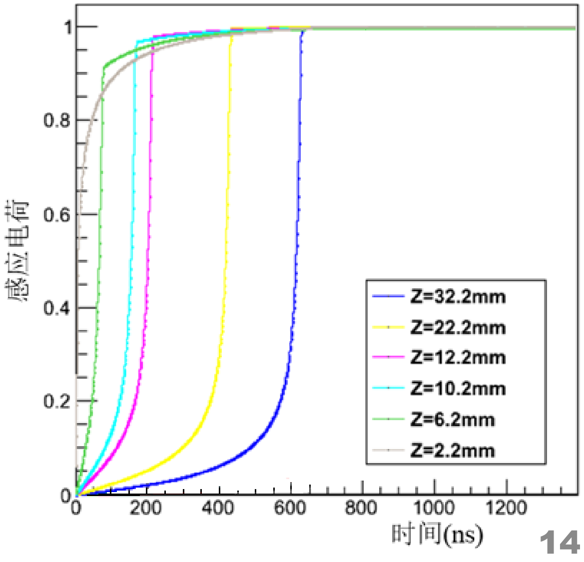
EFEs origin -- qualitative simulation

Drift time contour



Drift time distribution





- The very-bulk events mainly arise from the bottom part of the PPC detector
- Very-bulk events discrimination can probably be used for background rejection

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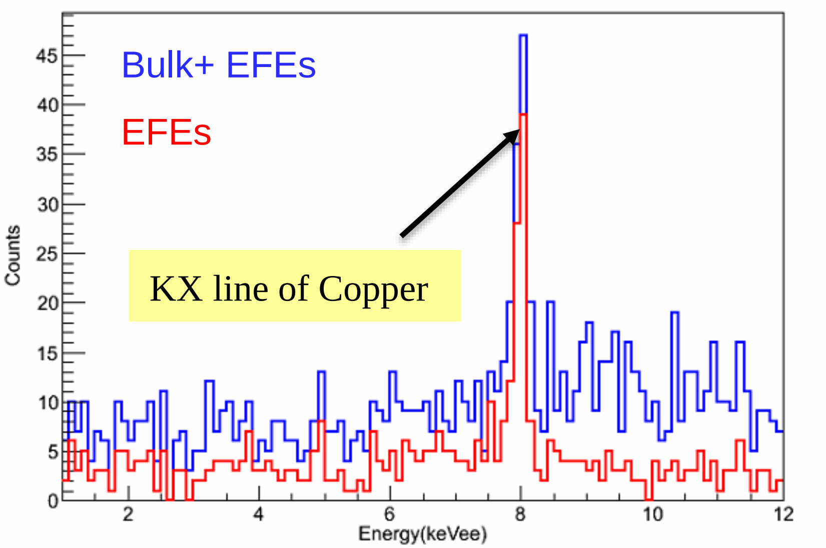
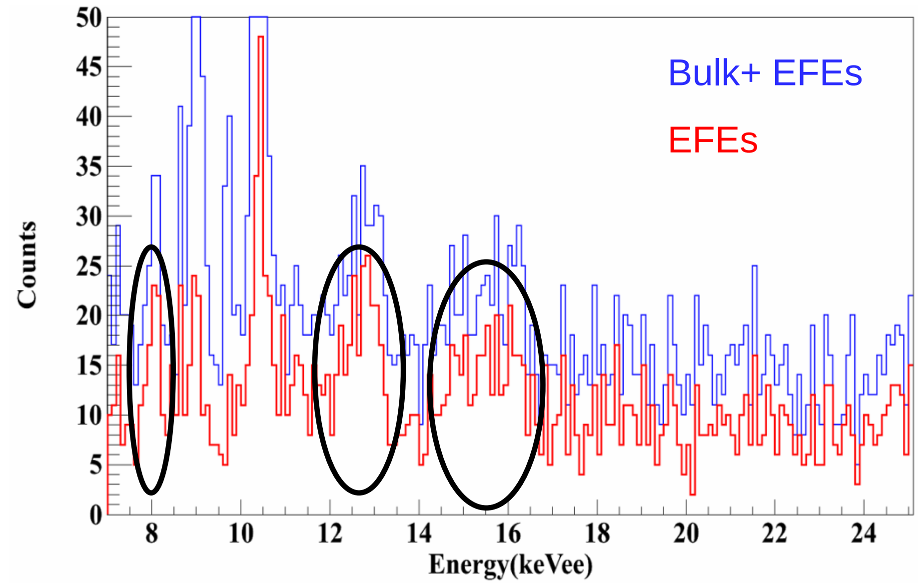
EFEs origin -- Experimental verification

^{109}Cd gamma source



Background spectrum



- 8 keV X-rays from Copper was observed in EFEs spectrum of the ^{109}Cd samples;
- In the background spectrum, there are some clear peaks (12-16keV), which are dominated as EFEs;
- Experimentally verified that the ultra-fast case comes from the end face of the point electrode where there is no dead layer.

Nuclide	Type	Energy(keV)
Cu	Lα	8.04
Pb	Lβ	12.62
Bi	Lβ	13.01
Th	Lα	12.85
	Lβ	15.62
		16.20
Ra	Lα	12.34
		12.20
	Lβ	14.84
		15.24

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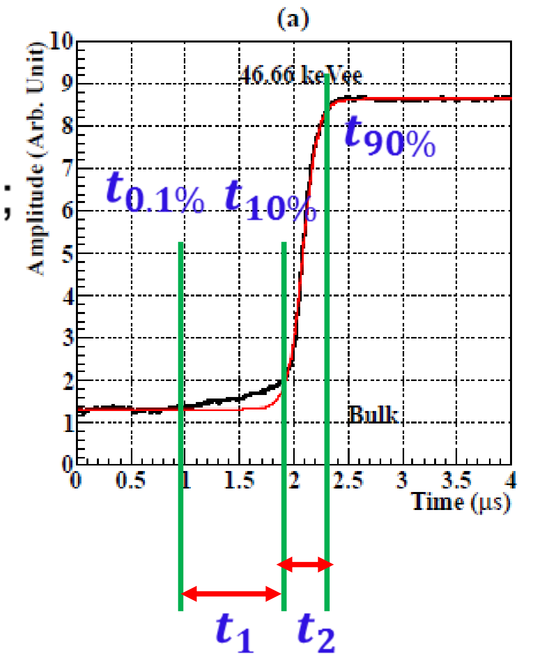
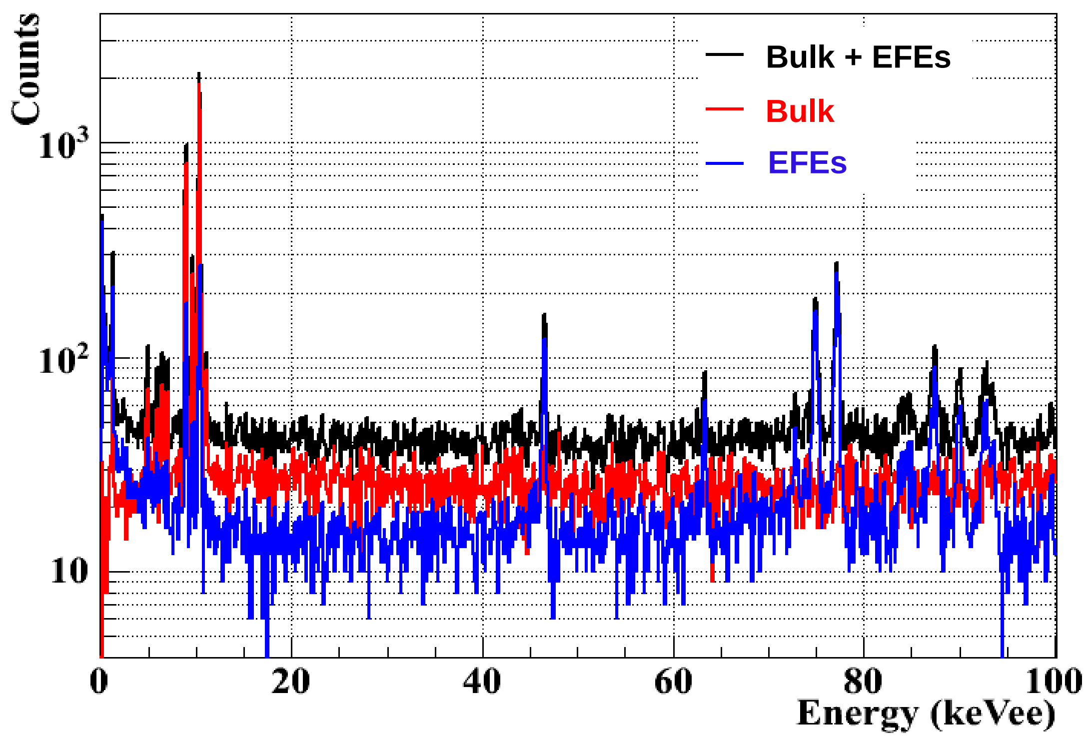
What we learned from EFEs studies? (1)

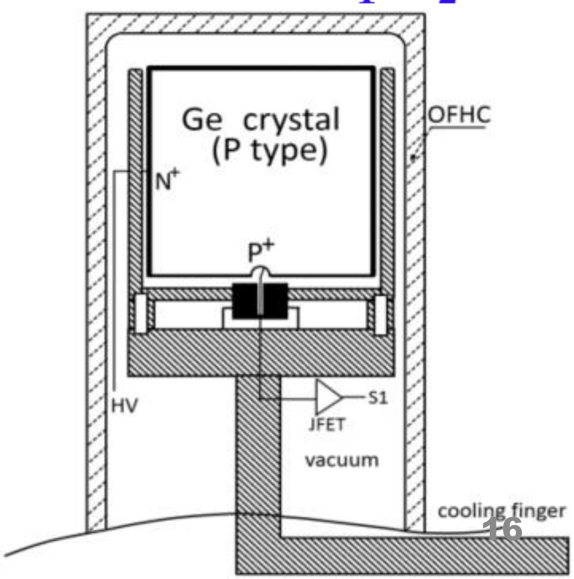
(1) Suppress the background level

define the drift time: $t_1 = t_{10\%} - t_{0.1\%}$

- Drift time is related to the energy deposition location;
- Possibility of fiducial volume selection, remove as much bkgs as possible while retaining as much fiducial mass as possible.





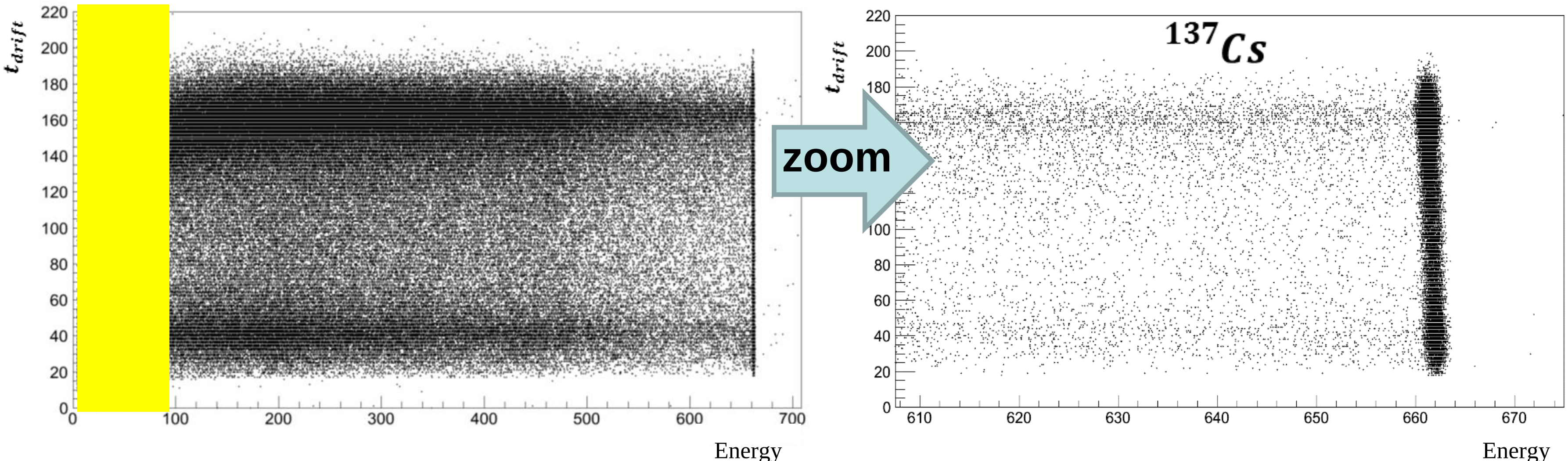


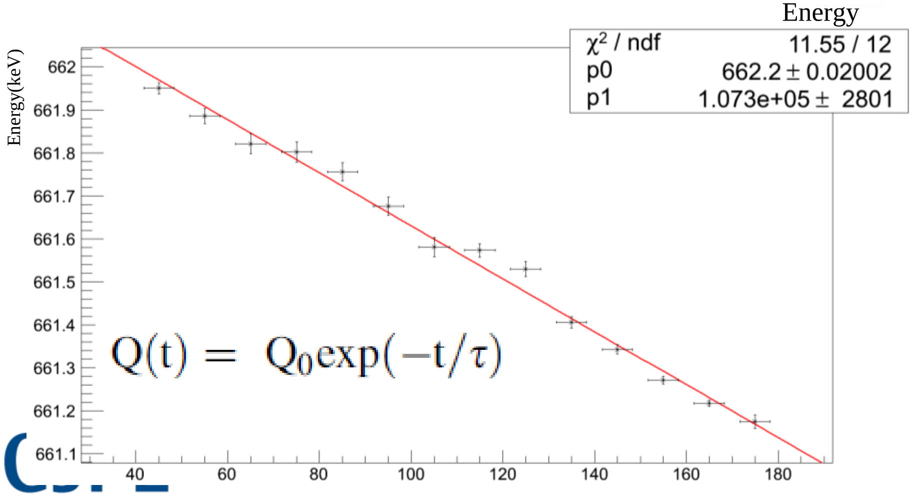
What we learned from EFEs studies? (2)

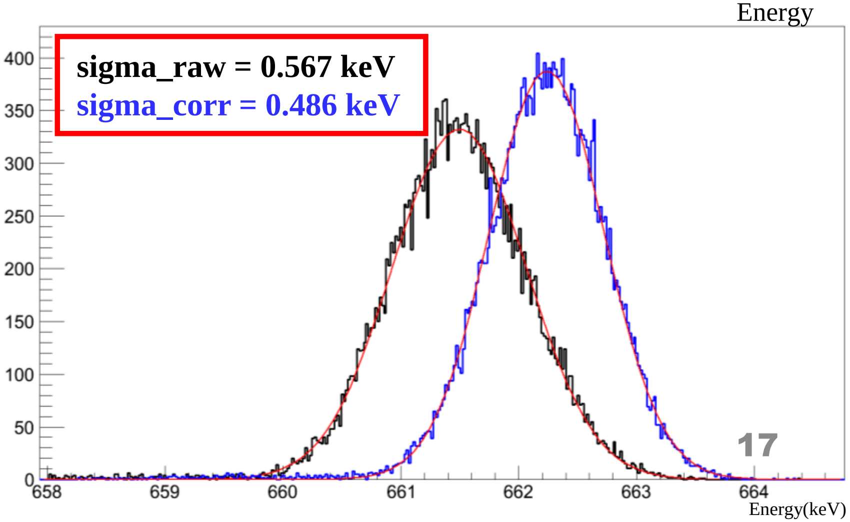
(2) Improve energy resolution

$$Q_{trapping} = Q_0 \cdot \left[1 - \exp\left(-\frac{t_{drift}}{\tau}\right)\right]$$

- Distribution of $t_{drift} - E$ provides information on τ of the carriers;
- Correct the energy to improve the energy resolution;





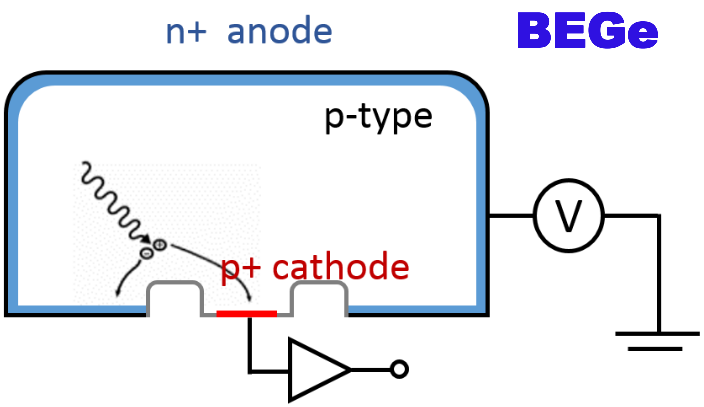


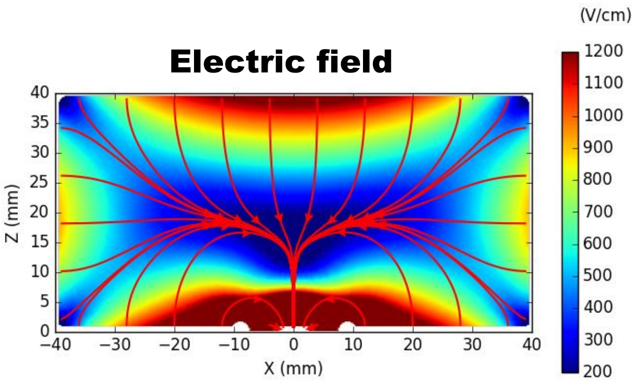
What we learned from EFEs studies? (3)

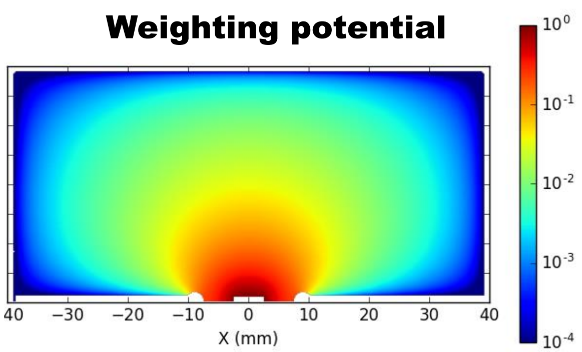
- ❖ n+ anode covers the front, lateral and most of the bottom part, which helps to shield the background events;
- ❖ Optimization of the ratio of diameter to height, short drift time length and uniform distribution results in better energy resolution.

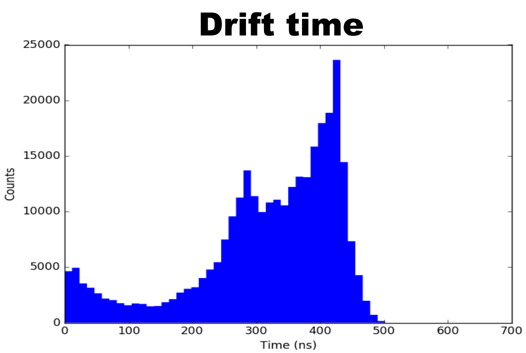
BEGe detectors with thick window:

- ✓ a planar p-type detector with a relatively small cathode on the bottom side
- ✓ relatively small capacitance (a few pF)
- ✓ smaller EFEs region near the p+ contact









Summary

- ✓ pPCGe has many advantages and has been used in CDEX for DM direct detection;
- ✓ The B/S discrimination in pPCGe can significantly reduce the background level;
- ✓ The study of Extremely Fast Events (EFEs) can help to better understand the background origins;
- ✓ The analysis of the drift time helps to improve the energy resolution at high energy ranges;
- ✓ This provides ideas for the structural design of detectors in future.


Thanks for your attention!

B/S discrimination issues

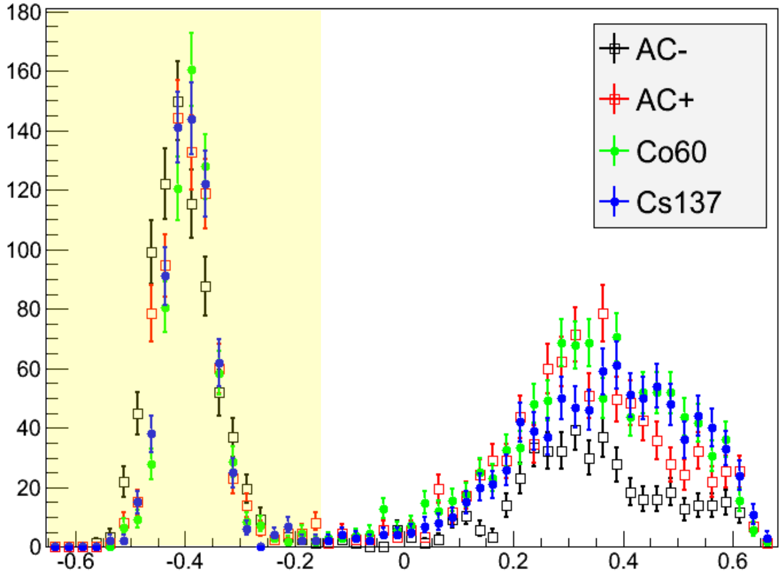
CDEX-1B data

- The validity of this analysis requires calibration source data with consistent rise-time distributions.

High energies:

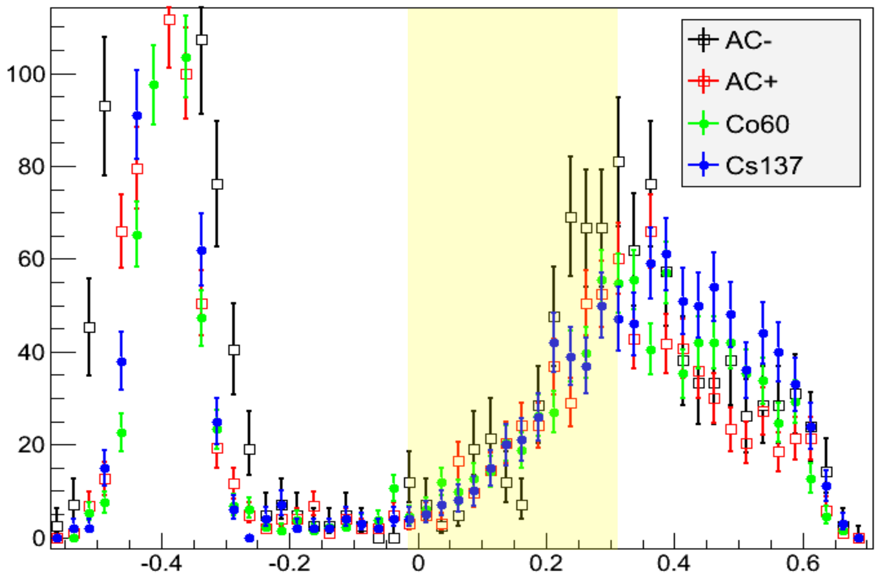
5.0-5.5 keV

Nor(-0.425 , -0.225)



5.0-5.5 keV

Nor(log10(0.9) , log10(1.6))



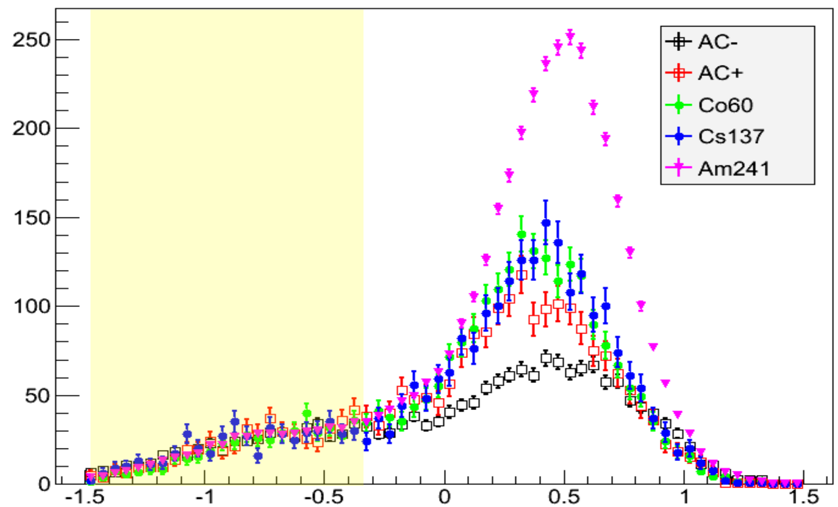
B/S discrimination issues

CDEX-1B data

Low Energies:

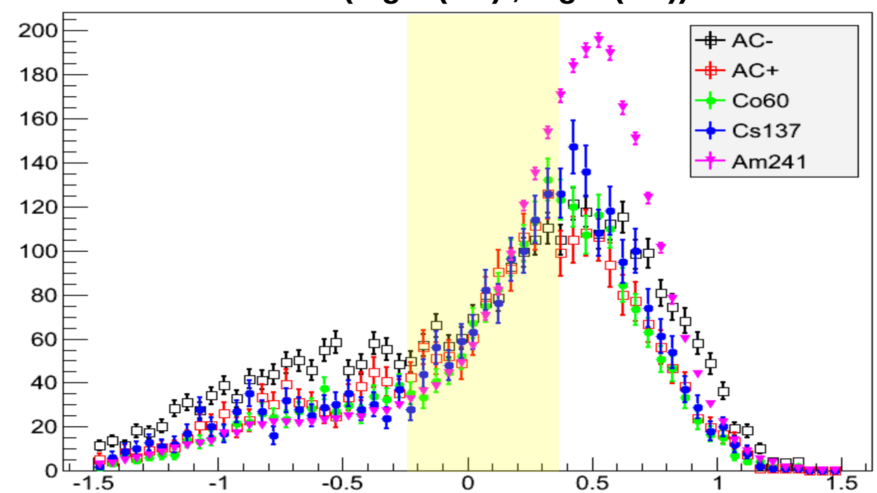
0.2-0.4 keV

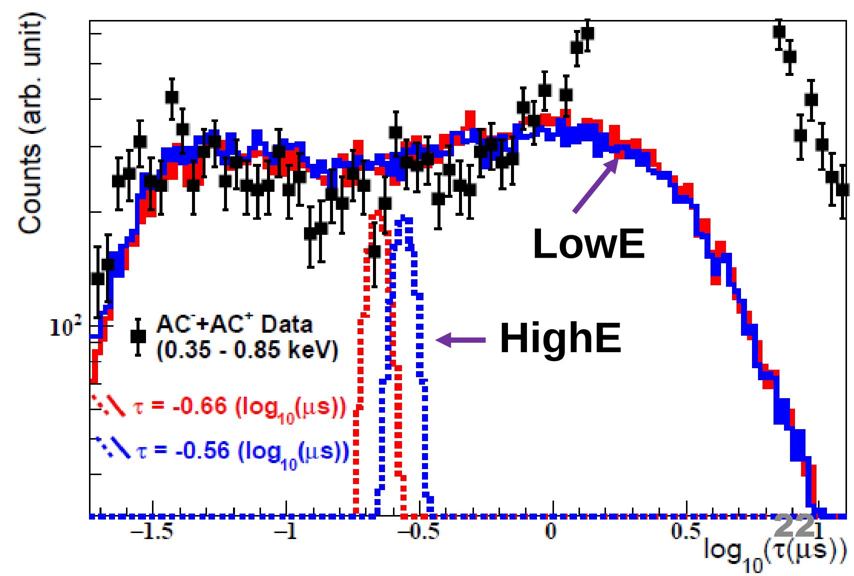
Nor(-1.0 , -0.5)



0.2-0.4 keV

Nor(log10(0.9) , log10(1.6))





Rise-time is related to the electric field distribution and the noise level:

- High energies: electric field dominated
- Low energies: noise smearing out effects dominated

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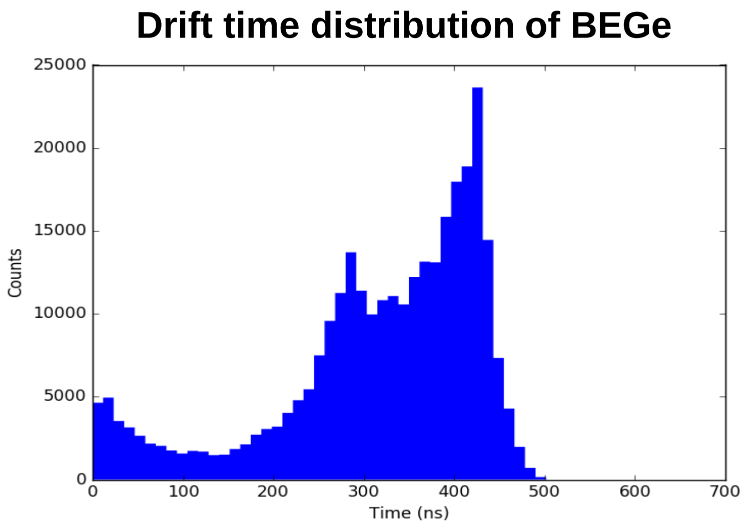
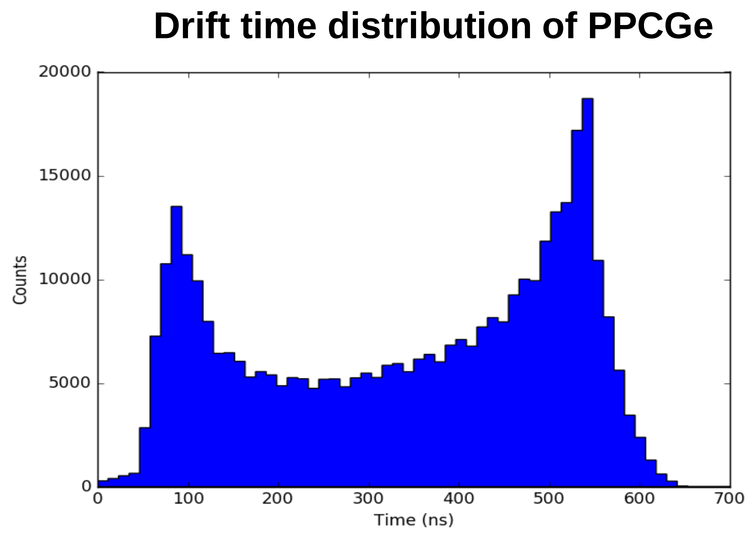
Pulse shape response





$$Q_{trapping} = Q_0 \cdot \left[1 - \exp(-\frac{t_{drift}}{\tau}) \right]$$

- Short drift time length and uniform distribution results in better energy resolution

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