What surfaces in the operation of noble liquid dual-phase detectors

"If in the first act you have hung a pistol on the wall, then in the following one it should be fired" Anton Chekhov

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LLNL

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LLNL-PRES-XXXXXX
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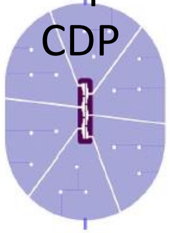
Lawrence Livermore National Laboratory

Excessive low-energy background (dark matter and coherent neutrino scattering) Variety of detectors and readout techniques

Super-SDMS-CDP



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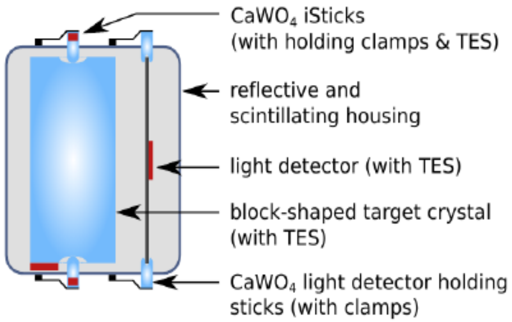
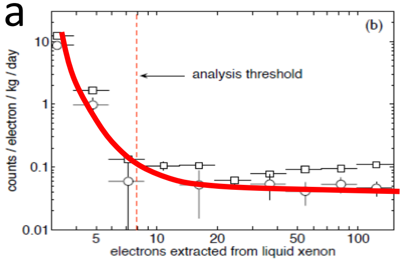


a



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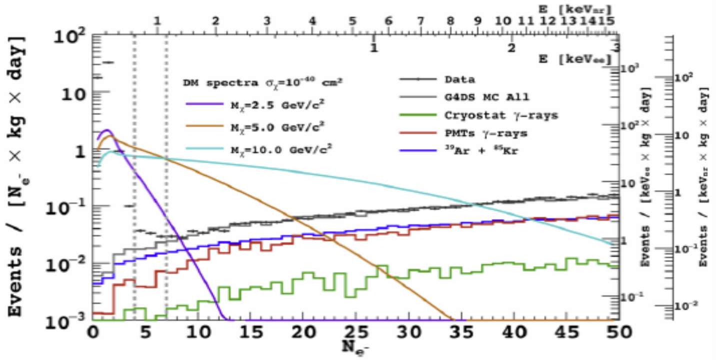

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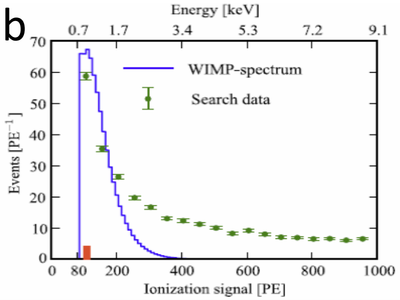

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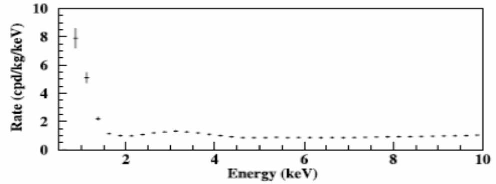
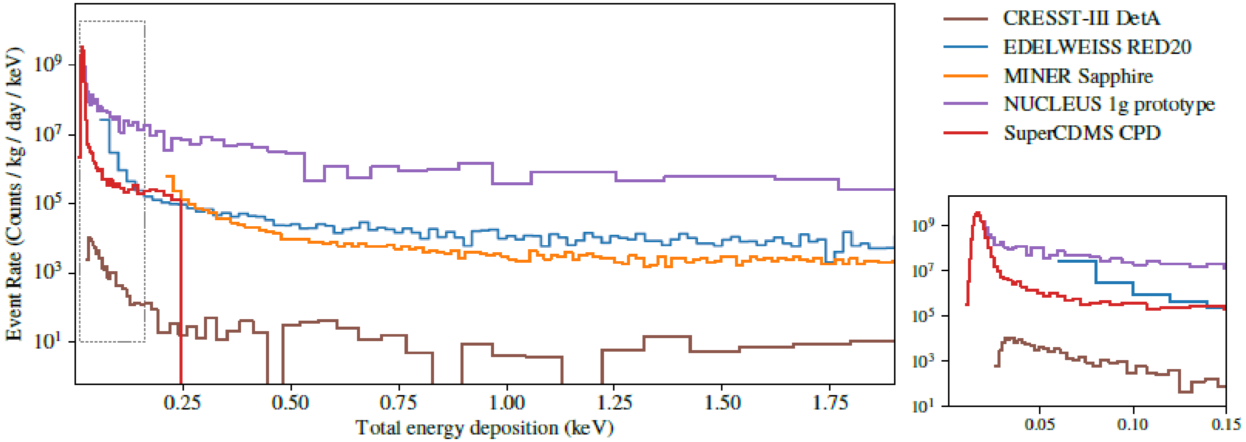




a: Xenon 10 experiment, b: Xenon 100,
c: Dark Side 50 experiment, 50 kg liquid Ar TPC;
d: DAMA-LIBRA experiment, NAI(Tl) scintillator, energy deposition of 1 keV results here in registration 5.5-7.5 photons (Nygren paper0

EXCESS workshop: Descriptions of rising low-energy spectra arXiv:2202.05097

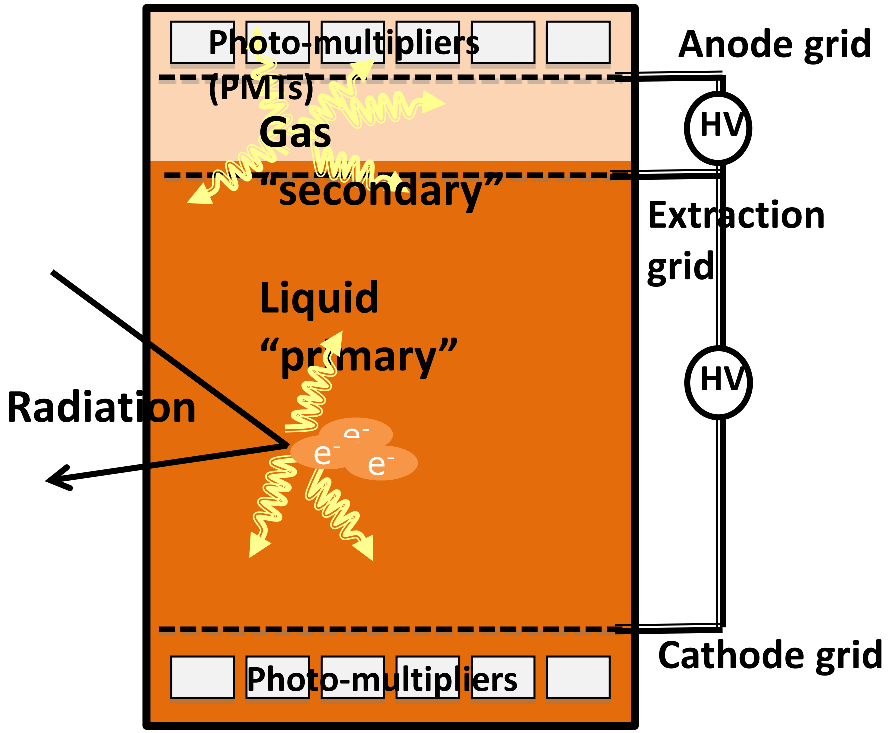
Common features: a sharp rise in the number of low-energy events near material excitations energies

Also: long, (history-dependent, glass-like) relaxation processes; background depends on impurities, defects, stress, etc.,

RESEMBLANCE OF ENERGUY ACCUMULATION AND RELEASES, SELF-ORGANIZED CRITICALITY SCENARIO

Noble liquid dual-phase TPC: reliable, versatile technique
But: energy /charge accumulation and releases effects

Dual-phase detector



No revisions of the model since 1990 –es…

Past and present:

Xenon 10, Xenon 100, Xenon 1ton, LUX, LZ, Xenon N ton, …

Ar detectors: DarkSide50,…

Future:

Larger Ar detectors: DUNE,…Large Xe detectors: DARWIN,…

Low background detectors: LBECA, …

Non-elastic scattering, multi-vertex events: Migdal effect,…

But,

Noble liquids and solids specific energy and charges accumulation effects and internal interactions

Traceable to liquid He studies back to 1980- es

Why:

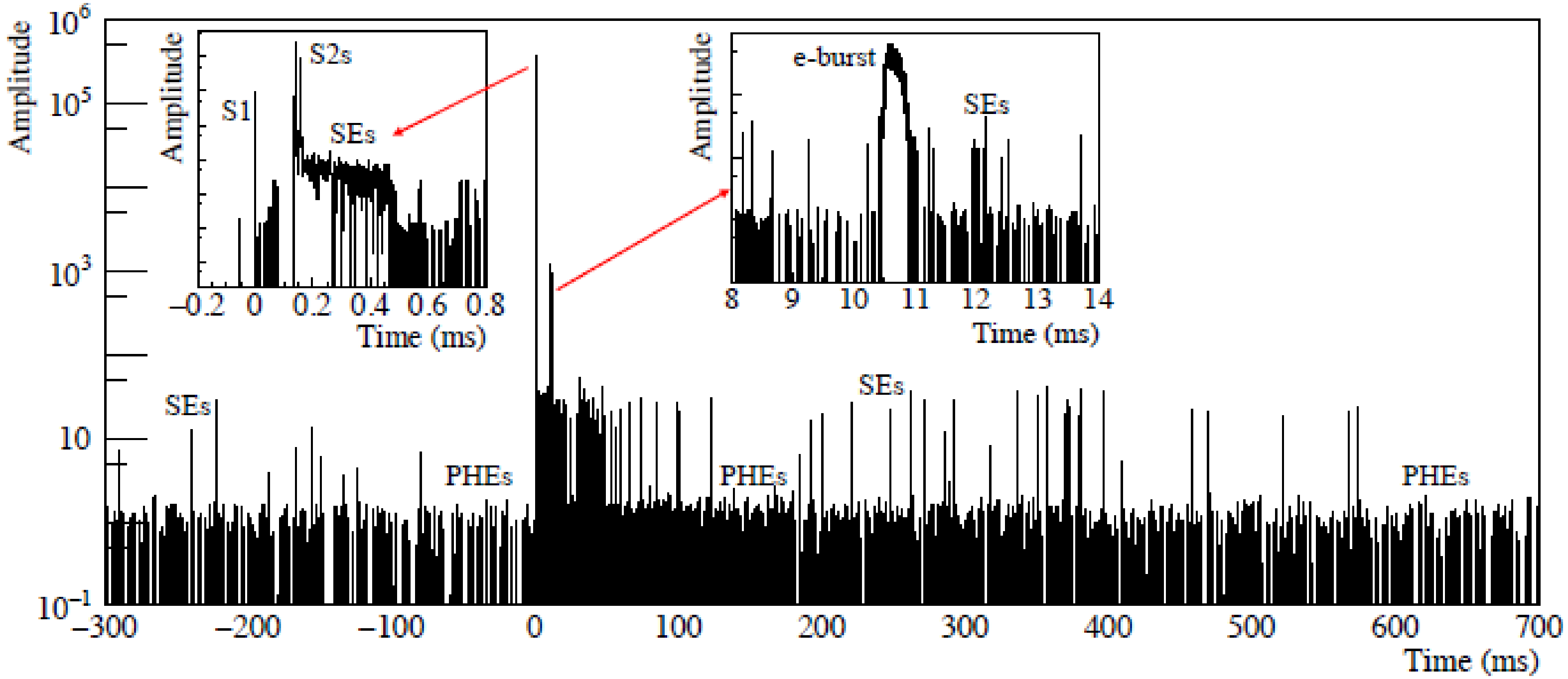
EXCESS low-energy background, rare material events;

scaling: backgrounds, purity, electric breakdowns; **multi-vertex events**

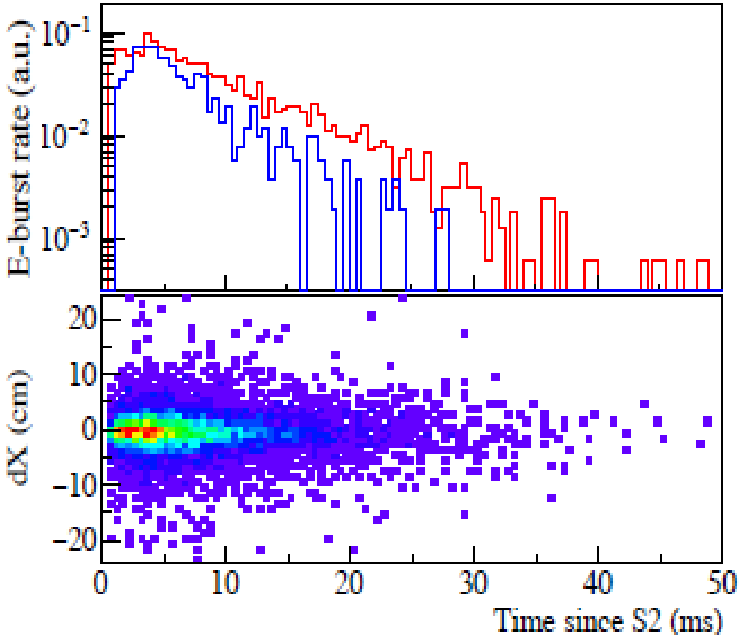
Compare contradictions we see in understanding detectors physics and known internal interactions and effects in noble liquids and

The large ionization events in LUX detector: e-bursts, unextracted electrons dwelling time and "immobility"

D. S. Akerib et al., Investigation of background electron emission in the LUX detector. **Phys. Rev. D 102, 092004 (2020)** Analysis of Jingke Xu



LUX waveform over one second. one 2.3 MeV gamma ray interacts here; background electrons are observed to follow the S1 and S2 pulses. insets - zoomed-the S1-S2 event and an electron cluster (\e-burst") and single electron (SE) pulses and photoelectron (PHE) pulses.

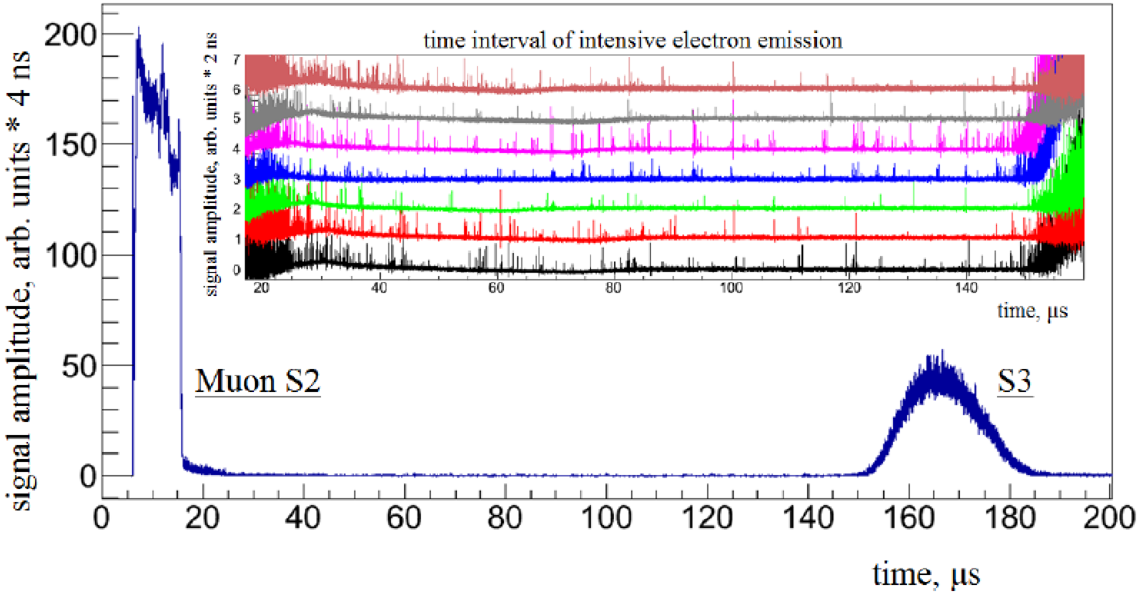


Time delay of e-bursts from preceding S2s for top (red) and bottom (blue) interactions in LUX ; The X position difference between e-bursts and preceding S2s as a function of the time delay.

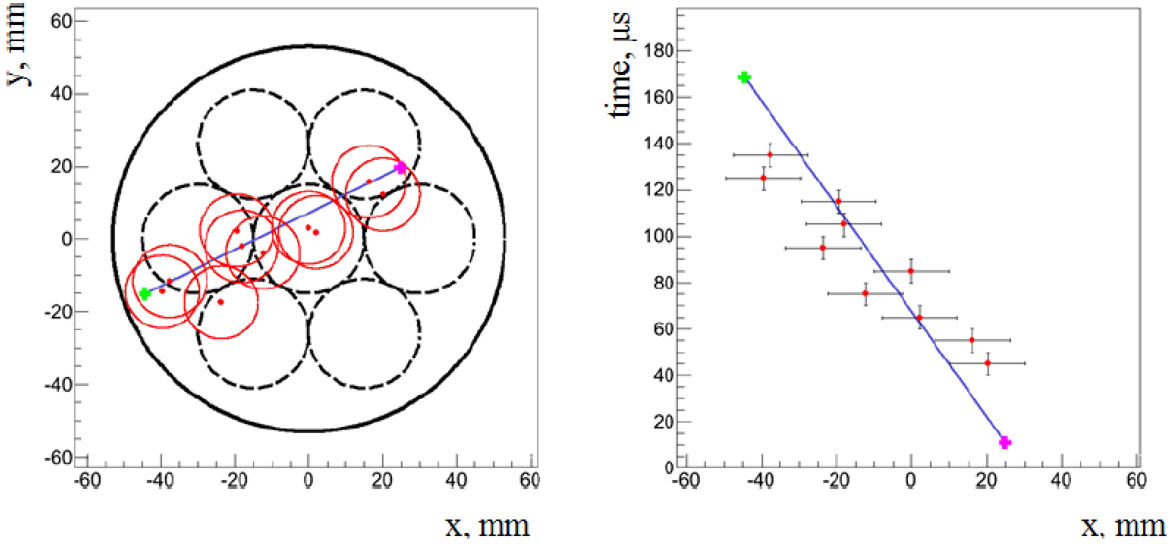
Unextracted electron cloud "freeze at place;" several charged surface instabilities can show up at the S2 location with up to 50 ms delays; possibly suppressed few-electron emission events rate, single electrons correlations with past events

Muon track (not-single-vertex) unextracted electron cloud motion reconstruction: electron emission between S2 & S3

D.Y. Akimov et al., Observation of delayed electron emission in a two-phase liquid xenon detector. **JINST 11, C03007 (2016)**.



A muon S2 signal and the following S3, the sum of waveforms from all seven PMTs (dark blue). The inset -the part of the time interval between S2 and S3 with intensive electron emission signals on it; different colors -different PMTs (baselines shifted for clarity). The amplitude of the S2 is distorted due to saturation.



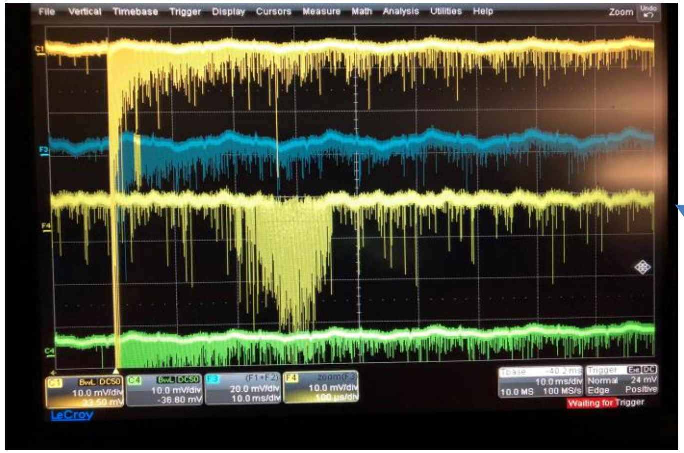
Spatio-temporal reconstruction of one muon event: a-projection onto the horizontal plane, b—projection onto the vertical plane to which the x-axis belongs. The magenta cross represents muon effective position and time; the green cross represents S3 position and time; red dots correspond to subinterval positions and times (red circles represent position reconstruction uncertainty); a blue line connecting magenta and green crosses – a hypothetical drifting path of trapped electrons.

Unextracted Electron cloud drift time is below ~ 100 μs

m

Unextracted electron cloud drift fast to the perimeter of active region. Some emission of unextracted electrons on the way-mechanism of this emission into gas not clear (S3- charged surface instability?)

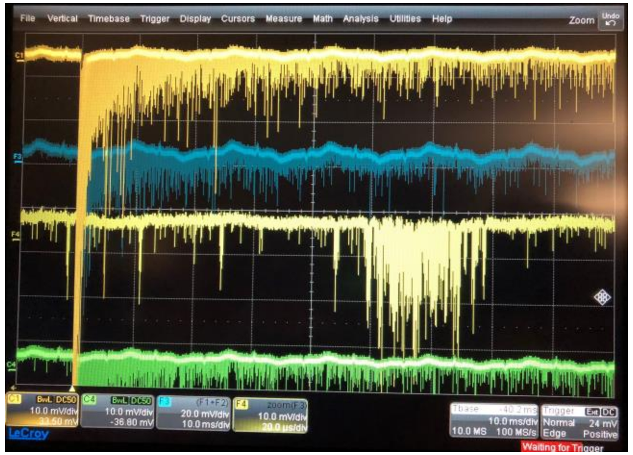
E-bursts in XeNu: up to 20 ms after S2
anticorrelation of E-burst with single-vertex events

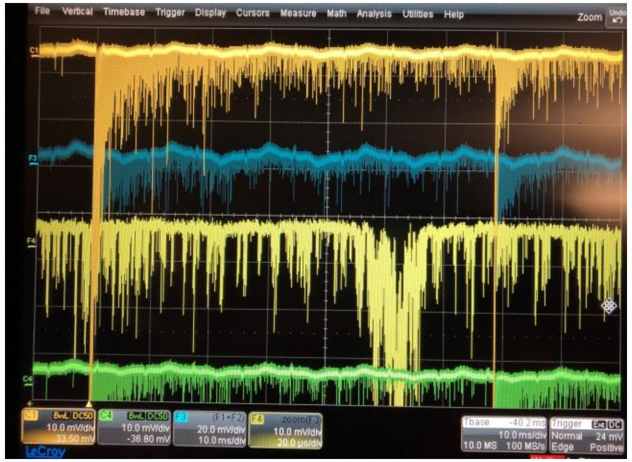


10 ms/div

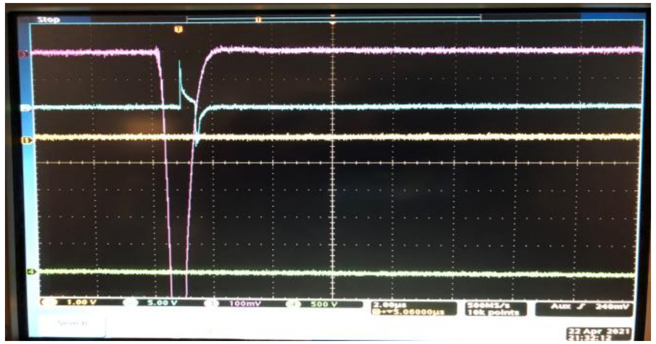
100 µs/div

20 µs/div



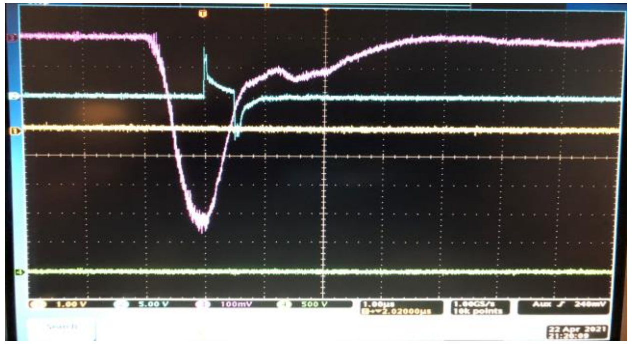


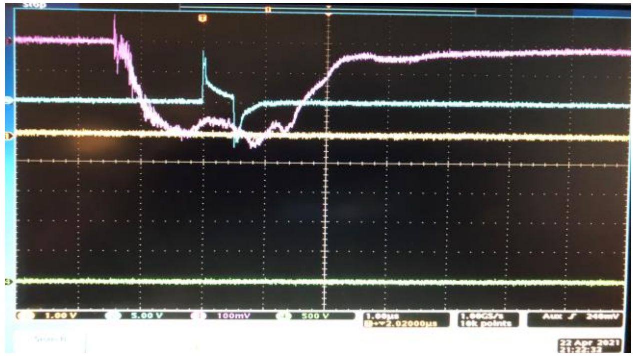
Blue line (f3) sum or 4 top PMT; 100 ms/div; f4- zoom into f3 (note total length of event in 100 ms)



2µs/div

1µs/div



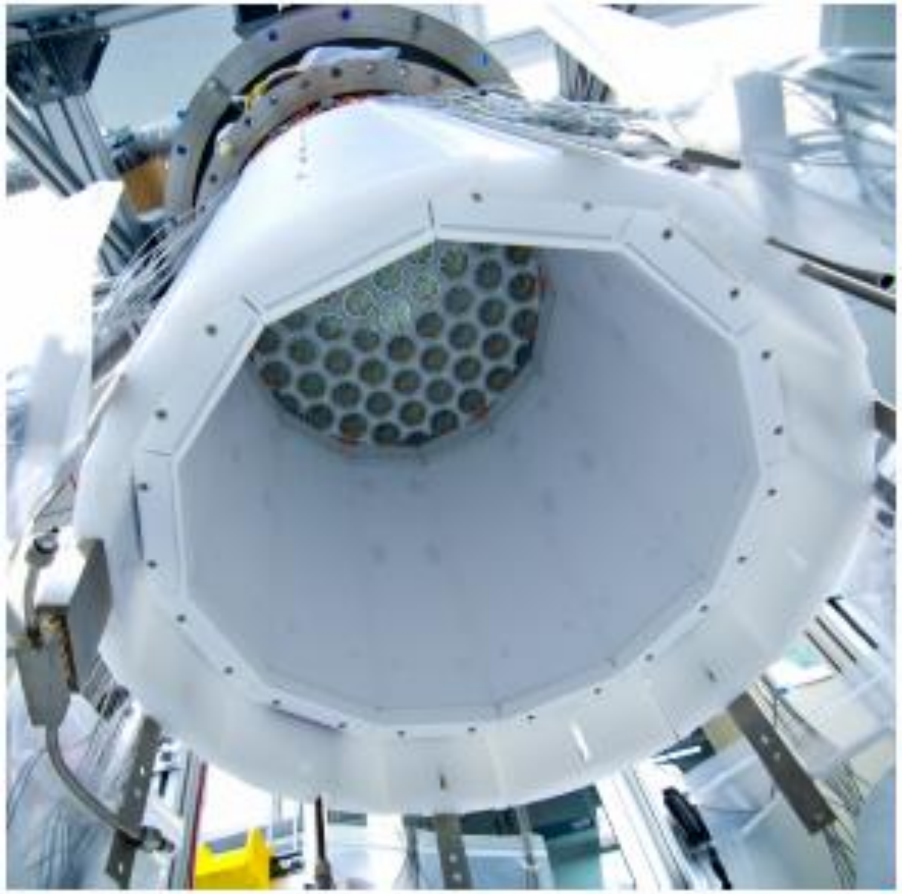


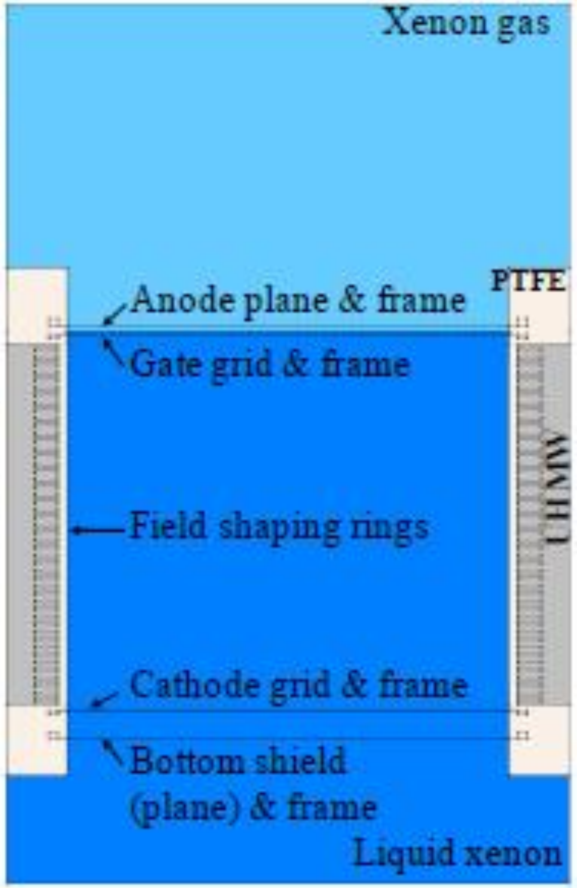
Pink- bottom PMT (low voltage);
short S2 – single-vertex event

Pink- bottom PMT (low voltage); long S2 -multi-vertex, event or muon
Long S2- predictor for E-burst

Several E-burst possible after strong S2 events with up to 20 ms delay, but no E-bursts after single-vertex events
(interference of waves caused by extraction? self-heating leading to larger extraction efficiency?)

LUX: electrodes and grid holders embedded in PTFE- difficulty for electrons to leave area under anode

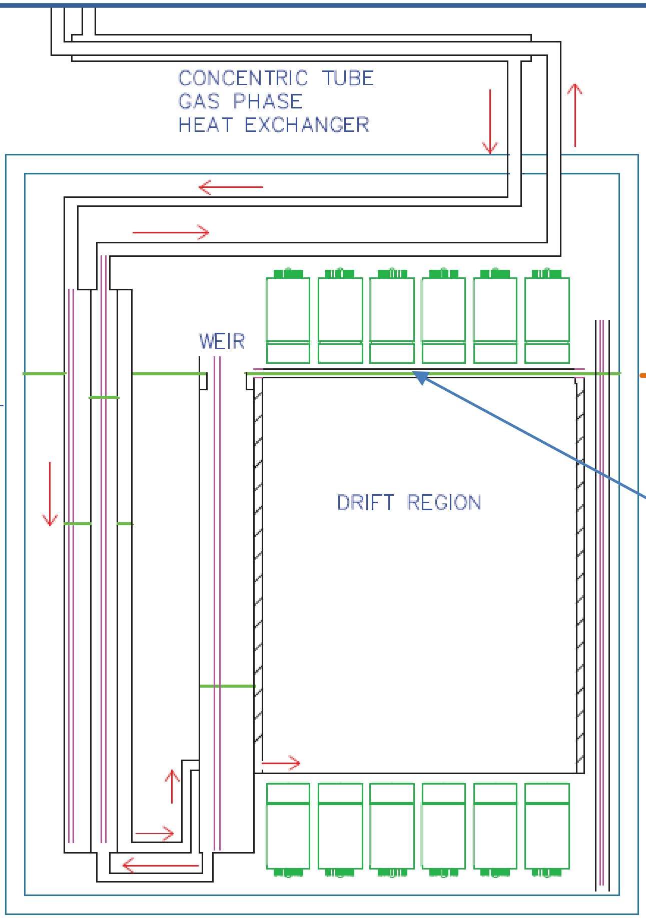




Only small openings/windows in PTFE are left in LUX where surface-bound electrons can leave an active area (see next slide)

Electrons cannot leave freely area under the anode through opening in the PTFE wall in front of copper weir reservoir: liquid level rise in electric field makes a potential barrier for surface electrons in LUX and XeNu

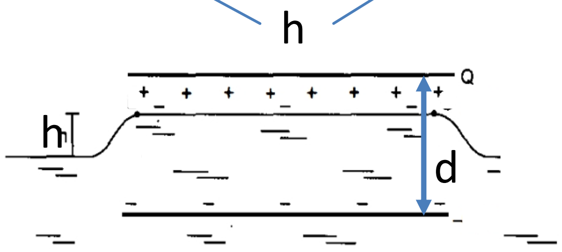
LUX



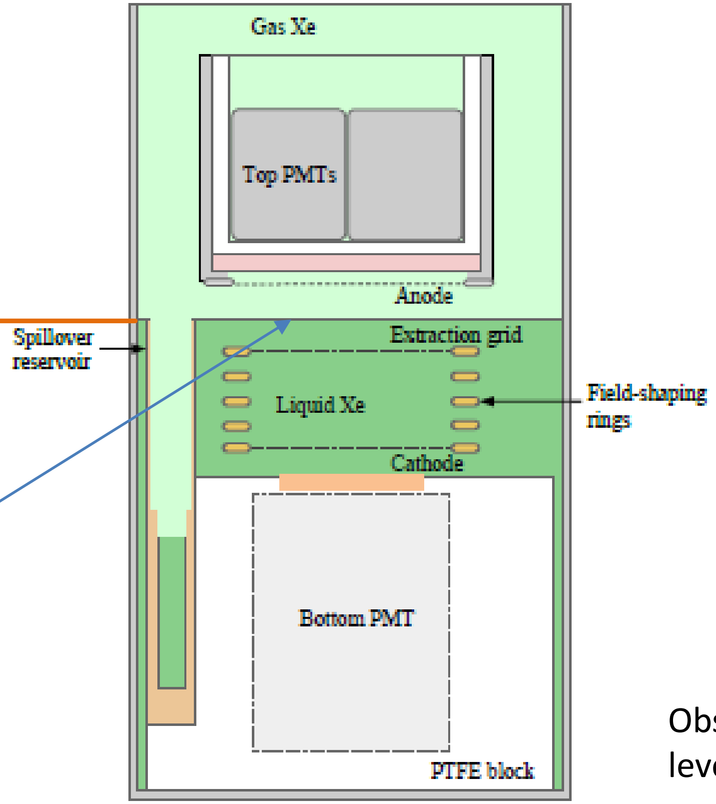
$h \approx E_0^2 \varepsilon_0 (\varepsilon - 1)/(\rho g)$

$E_0 = V/d$

The liquid level will rise in electric field



LLNL XENU



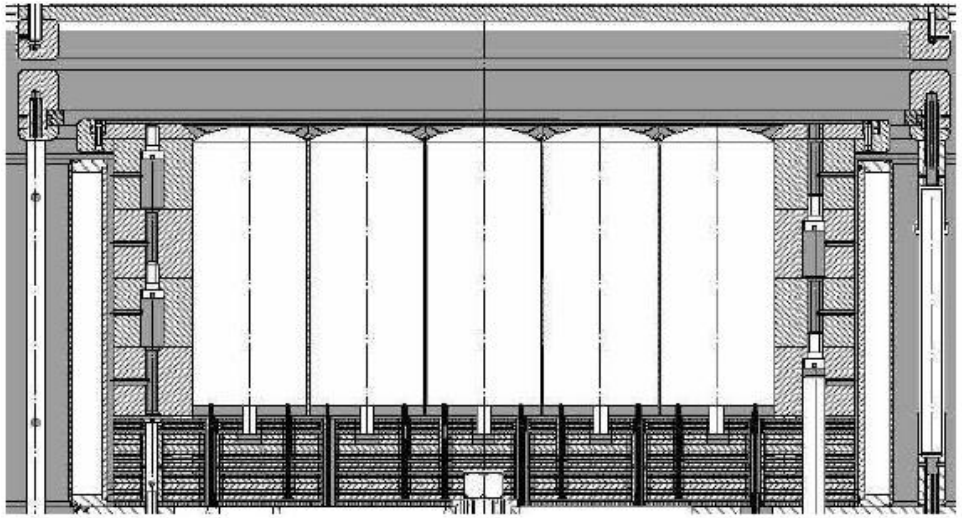
h~ 0.12 mm for 10 kV applied to 10 mm space in between grids

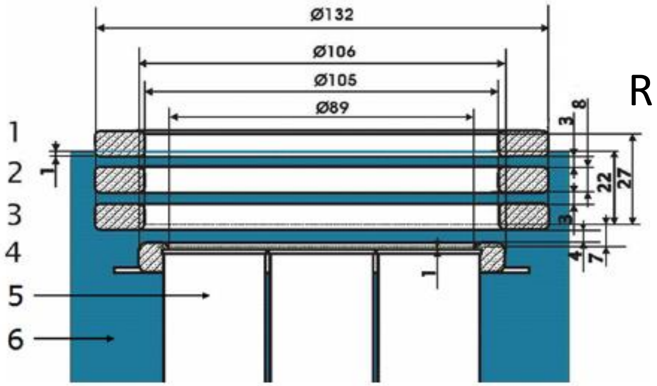
Observation of the liquid level rise under the anode is mentioning in Alexander Bolozdynya book on emission detectors

A liquid surface is a surface of the constant electrochemical potential for Xe atoms, but not for electrons; up to 100 V potential barrier (much larger than T) for surface electrons in LUX and XeNu (and other detectors)

No barrier for surface-bound electrons to leave to the wall in RED1, ZEPLINIII, RED100

D.Y. Akimov et al., The ZEPLIN-III dark matter detector: Instrument design, manufacture and commissioning. Astroparticle Physics, V. 27, pp.46-60, (2007)



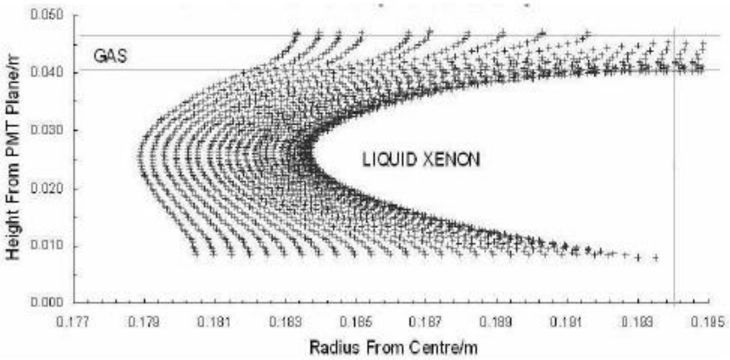


RED1

Metal anode grid holder touch liquid surface in RED1, ZEPLIN III

S3 were present only when gas between anode ring and charged liquid surface (D. Akimov, private communication)

ZEPLINIII



Electric field line tangential to the liquid surface at the perimeter- electrons are driven out

In RED1, ZEPLINII (and RED100)- surface electrons can escape to the metal electrode touching surface- no E-bursts;
Hypothesis: S3 and E-bursts - charged surface instability in high field

Anode grid sagging and extraction grid buckling In strong electric field

Electric field cause attraction between anode and gate (extraction grid)

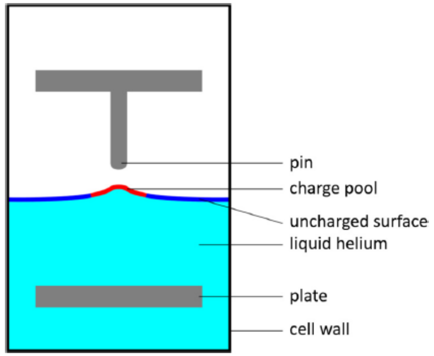
For anode in gas and gate in liquid, force on the gate is factor 1/ε smaller

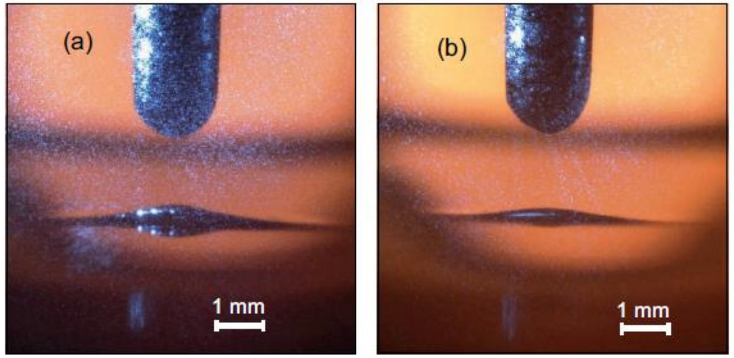
Anode sagging leads to tangential field component pushing surface electrodes toward center/ from the walls
Effects are larger for a larger detector diameter

The RED1 and ZEPLIN III detectors have metal mirror instead anode grid,
and gate buckling produce tangential field component pushing surface electrons off the center to the walls

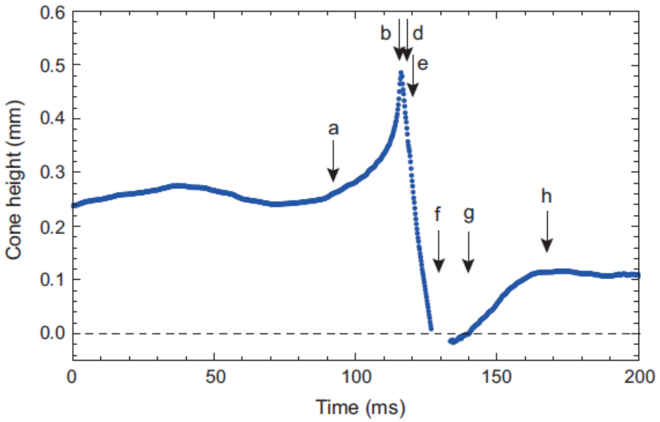
The RED100 detector has an anode grid, so electron accumulation is likely;
We need to look closer for surface electron accumulation effects there. (but: institutions now in a sanctions list)

Hypothesis1: e-bursts are charged liquid surface instabilities
Example: charged He surface in an inhomogeneous electric field; instability development in time



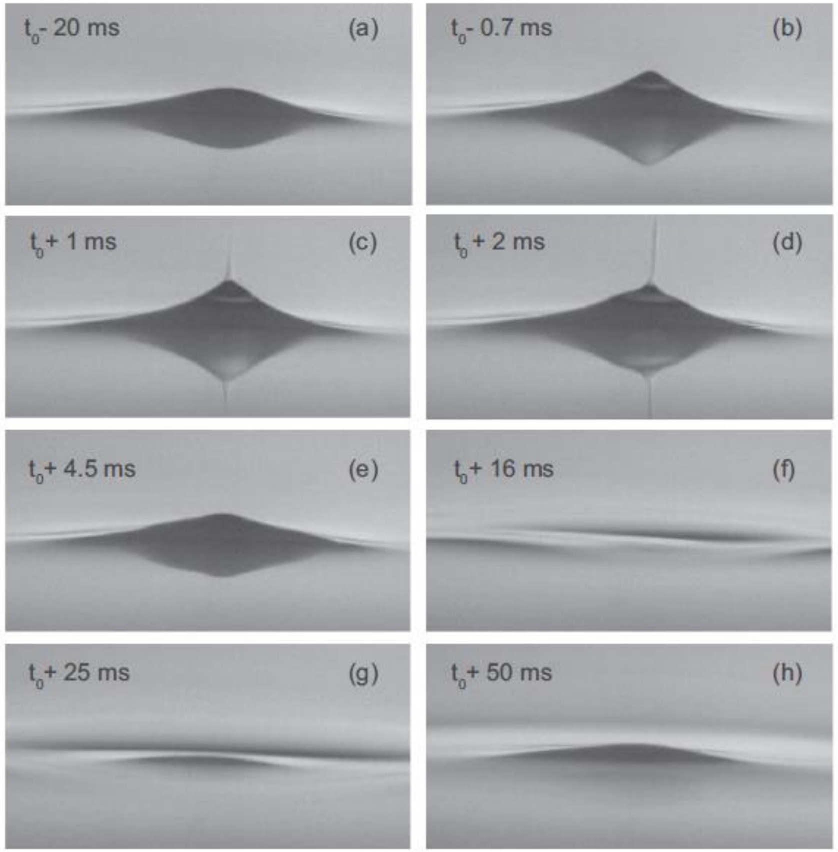


Static deformation of the free surface of superfluid He (Taylor cone) due to the trapped charge (a) Negative charge rapped; (b) positive charge. T = 2.1 K.



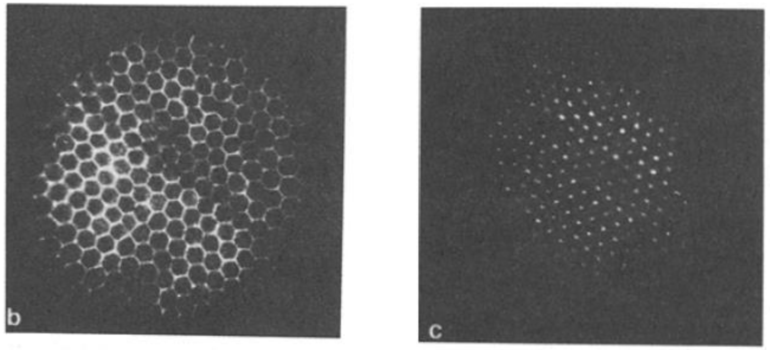
Time dependence of the height of the Taylor cone corresponding to the video recording. The dashed line shows the undisturbed liquid level.

P. Moroshkin, P. Leiderer, Phys. Rev .E (2017)



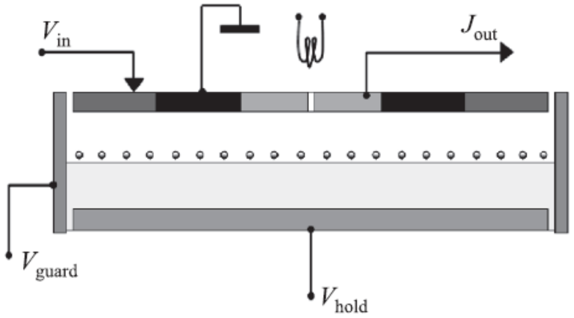
Frames of a fast video recording of the charge escape from the Taylor cone. Upin = −390 V, Uplate ≈ +900 V (ramp from +800 to +1800 V), T = 2.1 K, single-frame time ≈0.19 ms; time $t = t0$ corresponds to the beginning of the jet emission.

Hypothesis2: electrons can form an immobile rigid charged crust on the liquid under the Anode -hillock crystal; Example: Wigner crystallization on liquid He, or solid H_2

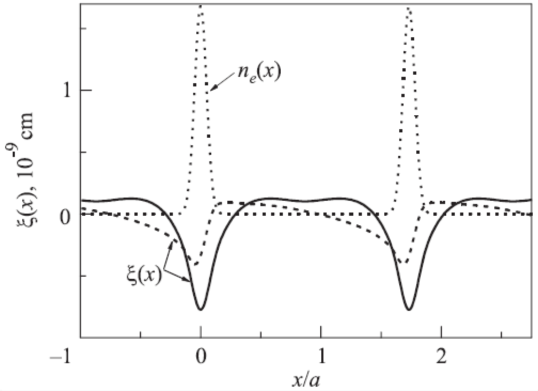


From P. Leiderer revue paper (1992).

A typical scheme of the measuring cell.



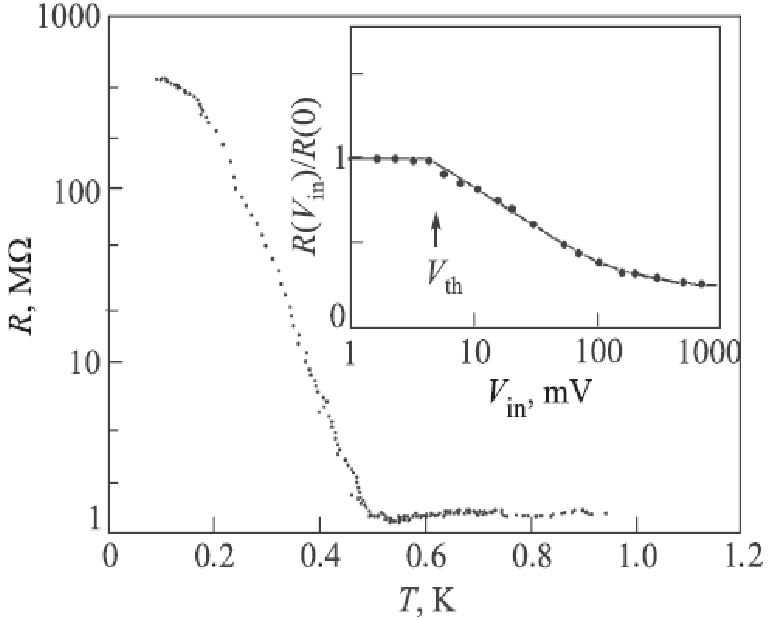
Formation of a dimple lattice on a ^{4}He surface (T=3.5 K) charged with electrons from above. The image plane in (b) was chosen such that local maxima appear bright; in (c) bright areas correspond to the center of the dimples). The distance between adjacent rows of dimples is close to the wavelength of the soft ripplons, 0.24 cm here



The surface relief of liquid ^{3}He, induced by a fixed WC (solid line) and a crystal, moving at high velocity (dashed line).

Picture will be reversed for Xe and Ar: a "hillock crystal" instead of a "dimple crystal" on He

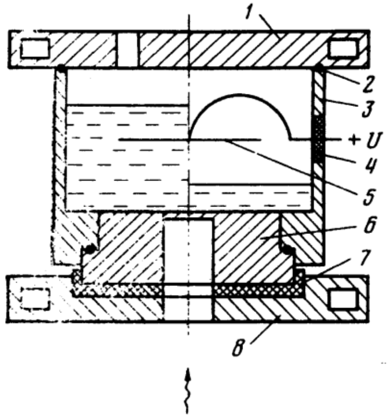
From Yu. Monarkha, Appl. Phys. Review 021319 (2019)



WC pinning on the defects:
The resistance of WC on the surface of helium film covering a rough solid substrate, as a function of temperature for ne=2x10^2 cm^{-2} ^{2} and D =380 A. Inset - dependence of the resistance on the low-frequency excitation voltage at n= =5x10^9 cm^{-2}, d =320A, T= 690 mK.

Suppression of signal electron extraction by “charged crust”

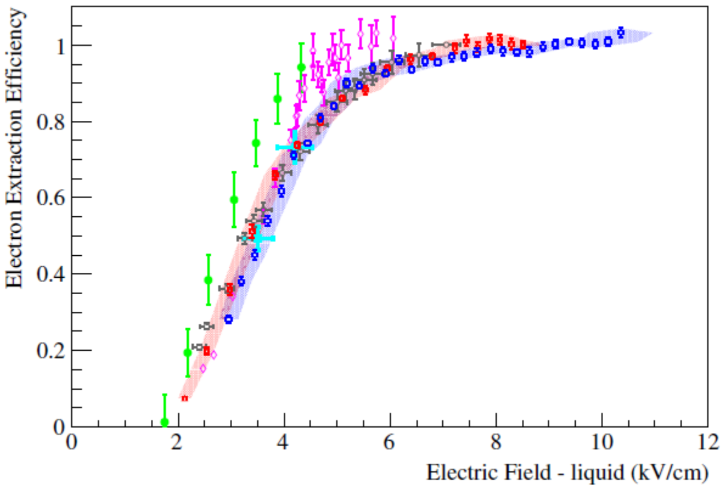
Early evidence



“This "emission" polarization is due to accumulation ***of*** negative charge on the phase separation boundary because ***of*** incomplete departure of the electrons. This is confirmed both by the absence of a similar polarization at K =1, and by the fact that removal of the electric field for a short time restores completely the emissivity of the material.”

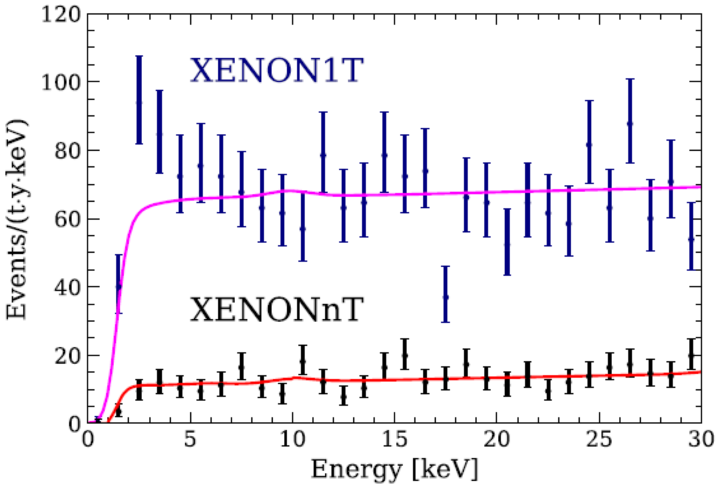
Gushchin et al., Sov. Phys. JETP **49(5),** May **1979**

Electron extraction efficiency



XENON100 (magenta diamonds) and PIXeY (grey circles), the absolute EEE results- Gushchin et al. (green dots), and LUX (cyan squares), XeNu- LLNL (red and blue)
Relative EEE was calculated by normalizing on some maximum value taken as as 100% difference in between detectors will not be seen this way. XeNu data taking vetoed for I s after significant events or any activity 3 ms before Ar37 event- likely, exclude high surface electron time intervals
Note: PIXeY has continuous PTFT wall; single electron background order of magnitude larger than in XeNu

Xenon nT (at LIDINE2022)



XENONnT : continuous PTFT wall around liquid surface+ grid sagging+level rize- is difference from Xe1T due to lagre surface electron concentration?
Extraction field limited by rise of electron emission – is it due to surface electrons?
What ionization signal only comparison will tell?

More condensed matter questions fifty shades of dark

Formation of solid physisorbed layers of noble gases on surfaces at low temperatures
Up to 10 monolayers of He was demonstrated (Paul Liederer)
Positive ions can stack in solid layers and affect electron emission; up 1 eV red shift of photo effect observed
Instabilities can take place as impurity positive ions accumulated in solid physisorbed layer

Structure of condensed He, or Ar, Xe around excess electron, positive and negative ions, excimer molecules
Electrons forms microscopic bubbles in condensed He and Ne because of short-range exchange repulsion from atomic S-shell
Excimer He_2^* molecule form bubble in condensed He
Positive ions forms “snowballs” in all noble liquids because of polarization attraction
Extraction energy for charged electronegative impurities can lower than for free (delocalized) electron in Xe, Ar

Encagement leading to long lifetime of reaction intermediates and radicals in liquid and solid Xe and Ar
Thermally-stimulated luminescence and electron emission from solid Xe and Ar after irradiation
Energy storage by radical, formation of clusters of radicals- a-la nano-explosives

Discussion

- ❑ **The accumulation of unextracted electrons can result in**
  - false signals originated at the surface
  - suppression of electrons extraction from real small events by "charged crust" (already in LUX, LZ, XENONnT?)
- ❑ **Electron extraction can cause surface waves (momentum transfer to liquid) and self-heating**
  - interference in multi-vertex events nucleates charged surface instabilities?
  - reconstruction of multi-vertex events distorted by the interaction of surface electrons and waves
  - self-heating increase EEE in significant single-vertex events?
- ❑ Electron emission after significant events is not a "reliable measure" for the remaining density

- ❑ **Ideas and tools developed in condensed matter physics are essential for model-independent confirmation of direct dark matter particles interactions.**
  - When we are looking for low-energy interactions with external particles, low-energy interactions and releases in material need to be considered
  - Hiring frees of new faculty in helium and ultra-low temperature physics in 80-is and 90-is is possible cause of lagging detector physics lagging; ***interactions with different Science Cultures are important***

Conclusions

- **Present insufficient understanding of liquid surface- electrons effects produces uncertainties for HEP experiments;** extended goals in light dark matter particles and CEvNS for multi-tons detector projects are at risk.

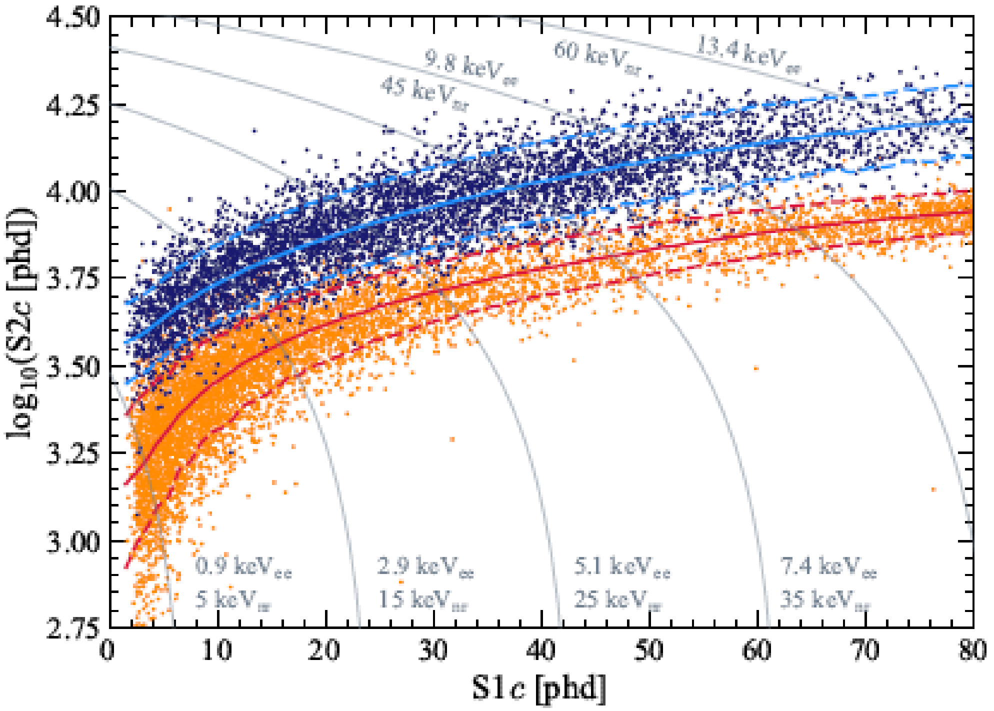
- ***Interdisciplinary research efforts between HEP and BES would be beneficial:*** to combine ideas and tools of high energy /particle physics and condensed matter physics /low temperature/helium physics

- ***Inclusivity, diversity, engagement, and workforce training***

- including condensed matter physicists in committees and panels on new detectors
- presenting detector physics works on condensed matter and material science conferences in appropriate terms comprehensible to these communities
- educate HEP students and post-docs in what we know and what we do not know in condensed matter physics

Lawrence Livermore National Laboratory

LZ- continuous calibration with Tritium- not sensitive to changes in surface electron concentration



Electron recoils (Tritium) - dark blue,
Neutron recoils (DD generator)- orange

This method not too sensitive to change of electron extraction efficiency

BUT: need 1 s veto after muons

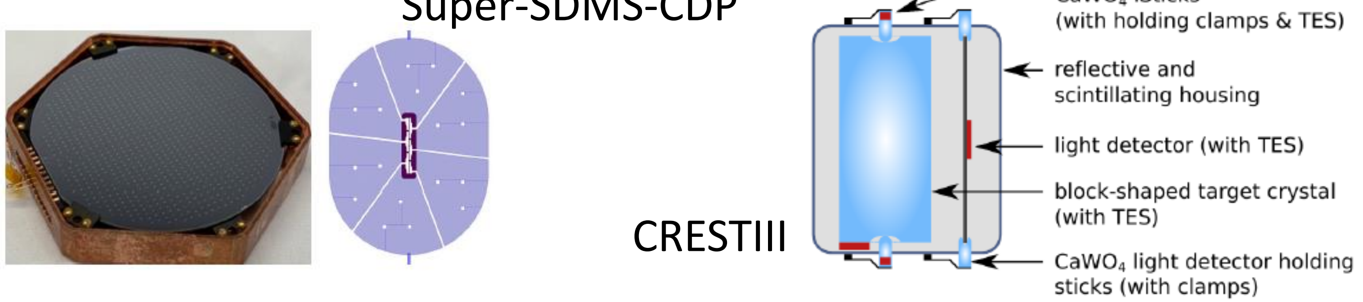
Suppression of EEE can show up at low energies:
ionization signals only analysis?
Search for solar neutrinos ?

LUX have not published ionization only analysis; background paper states small number of few-electron events-

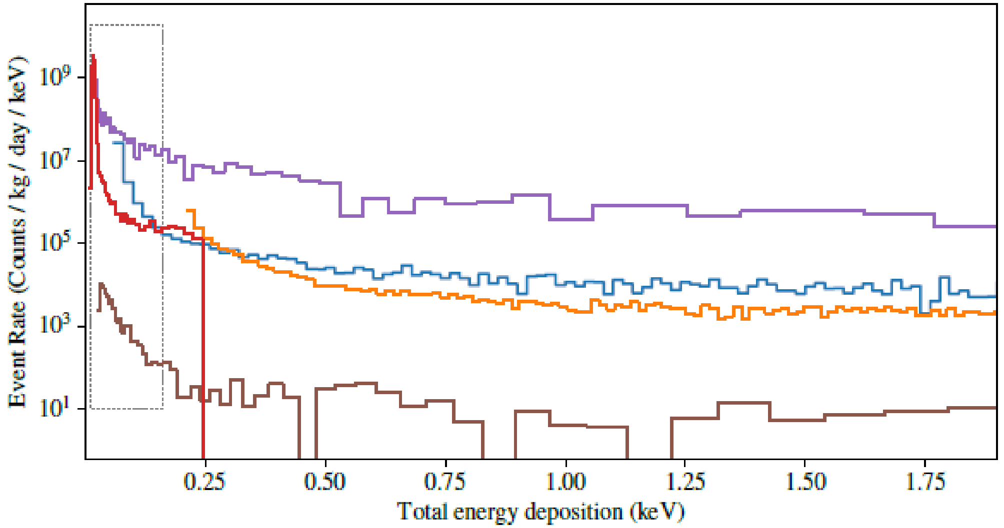
Excessive low-energy background (dark matter and coherent neutrino scattering) Variety of crystals and readout techniques

Super-SDMS-CDP

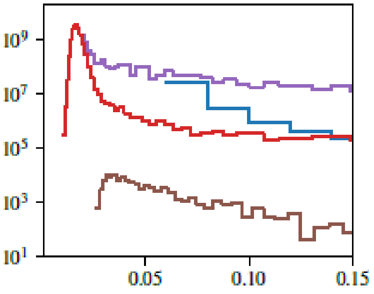
CRESTIII



Measurement	Target	Sensor	Exposure (kg days)	Operation Temperature	Depth (m.w.e.)
CRESST III DetA	23.6 g $CaWO_4$	Tungsten TES	5.594	15 mK	3600 (LNGS)
EDELWEISS RED20	33.4 g Ge	NTD	0.033	17 mK	above ground
MINER Sapphire	100 g Al_2O_3	QET	2.72	7 mK	above ground
NUCLEUS 1g prototype	0.49 g Al_2O_3	Tungsten TES	0.0001	15-20 mK	above ground
SuperCDMS CPD	10.6 Si	QET	0.0099	41.5 mK	above ground
DAMIC	40 g Si	CCDs	10.927	140 K	6000 (SNOLAB)
EDELWEISS RED30	33.4 g Ge	NTD, NTL amplification	0.081	20.7 mK	4800 (LSM)
SENSEI	1.926 g Si	Skipper CCD	0.0955	135 K	225 (Fermilab)
Skipper CCD	0.675 g Si	Skipper CCD	0.0022	140 K	above ground
SuperCDMS HVeV Run 1	0.93 g Si	QET, NTL amplification	0.00049	33-36 mK	above ground
SuperCDMS HVeV Run 2	0.93 g Si	QET, NTL amplification	0.0012	50-52 mK	above ground



In units of deposited energy



EXCESS workshop report on arXiv

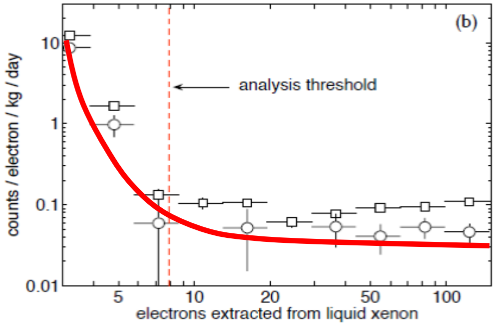
NB: decoherence!

Common features: a sharp rise in the number of low-energy events

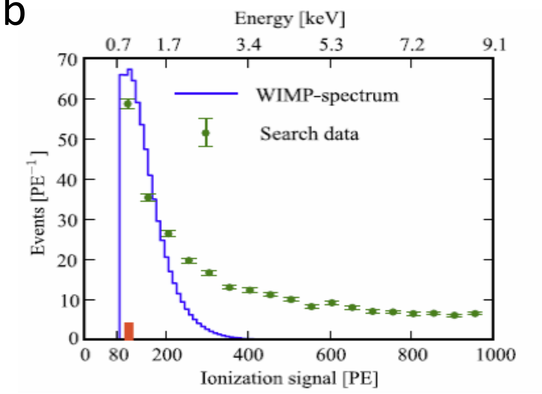
SP: Long, (history-dependent, glass-like) relaxation processes after cooling down; background depends on the crystal support, etc.

Excessive low-energy background
Nobel Liquids dual-phase detectors, NaI(Tl) scintillator

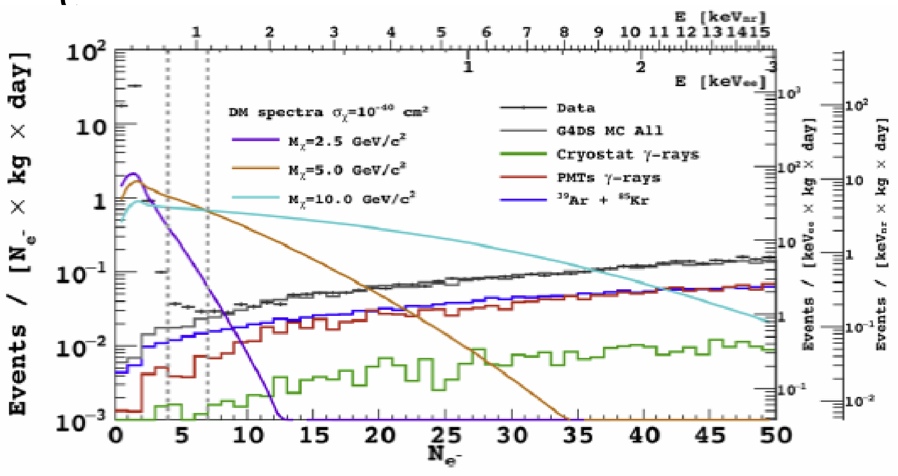
a



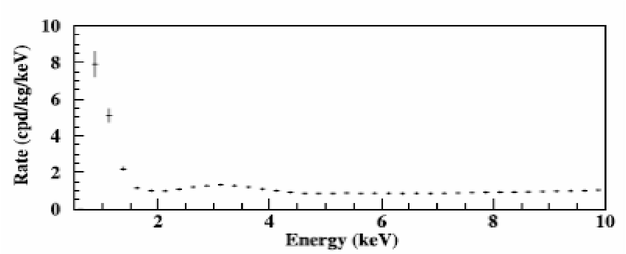
b



c



d



Dark matter particle detectors operating underground (low background).
A: Xenon 10 experiment, 10 kg liquid Xenon TPC
B: Xenon 100,
C: Dark Side 50 experiment, 50 kg liquid Ar TPC;
D: DAMA-LIBRA experiment, NAI(Tl) scintillator, energy deposition of 1 keV results here in registration 5.5-7.5 photons by PMTs; figure from David Nygren paper

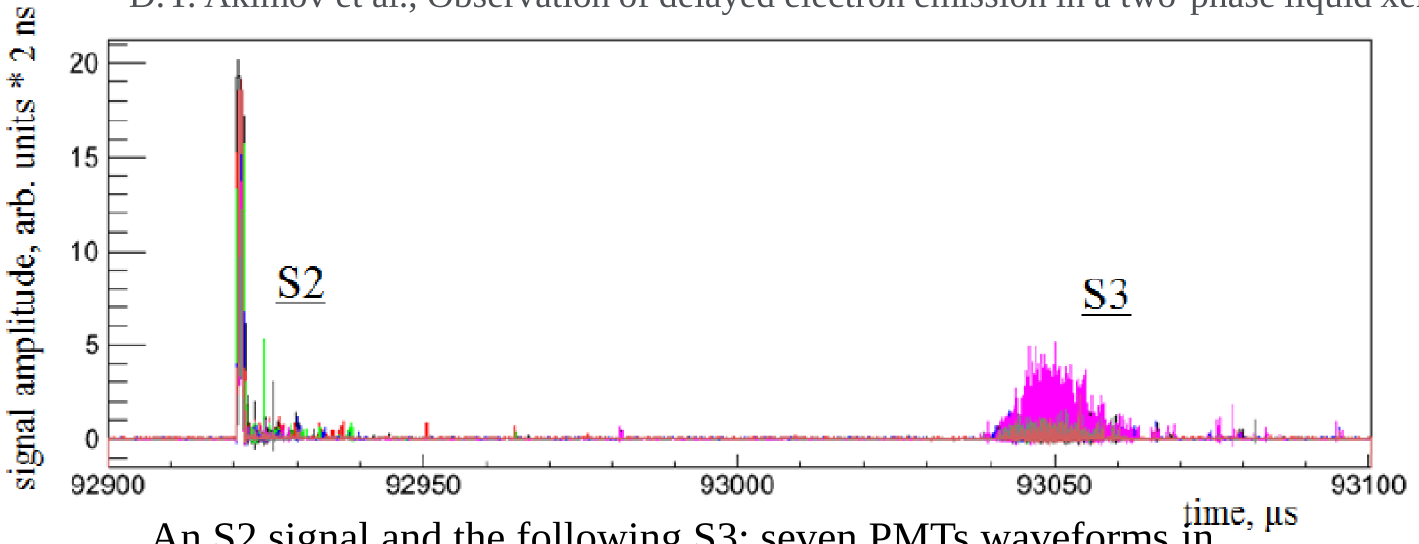
Current experiments are on 1-10 ton scale
LUX, LZ, Xenon 1 ton, Xenon n ton

30 -100 ton scale detectors are discussed
(- b$ cost scale)

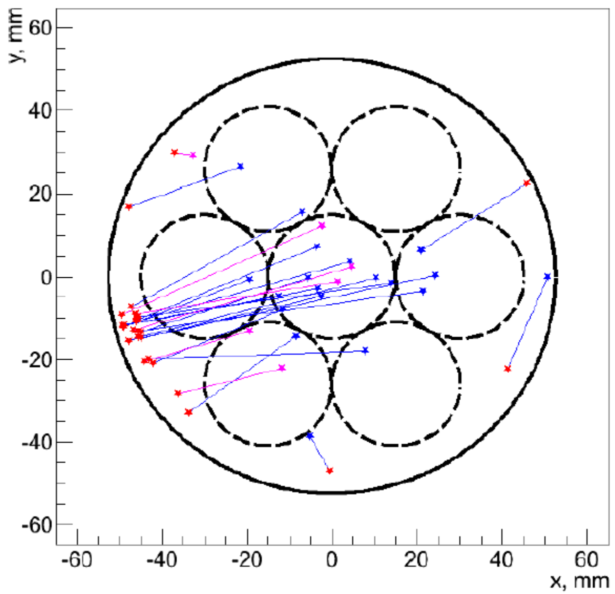
Common feature- sharp rise in number of low-energy events
(as energies approaching excitations in materials)

RED1 (Russian Emission Detector): S3 events, short dwelling time of unextracted elections on the surface

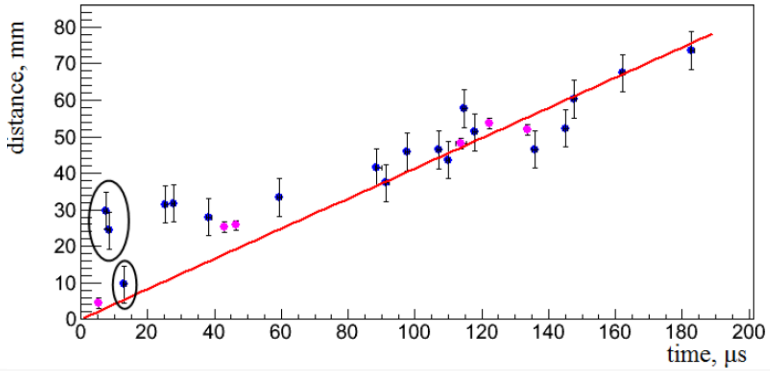
D.Y. Akimov et al., Observation of delayed electron emission in a two-phase liquid xenon detector. **JINST 11, C03007 (2016)**.



An S2 signal and the following S3; seven PMTs waveforms in different colors; S2 signal is distorted due to saturation.



Reconstructed positions of initial signals and S3. The outer solid line - edge of the sensitive volume; dashed lines - PMTs; red stars- reconstructed positions of S3 after **single vertex events**; initial interactions reconstructed by S2 (magenta stars) or by S1 (blue stars).



Distance between the initial interaction and the following S3 vs. drift time. position of an initial signal reconstructed by S1 (blue) or S2 (magenta). The points encircled by black ellipses -events with S3 at x > -5mm (outside "hot spot") The data are fitted with a linear function $d = v_{drt}$ in red.