Effects of energy accumulation in materials:

Self-Organized Criticality dynamics in low energy threshold ionization detectors for coherent neutrino scatter, dark matter searches and in superconducting sensors and qubits.

Sergey Pereverzev

Lawrence Livermore National Laboratory

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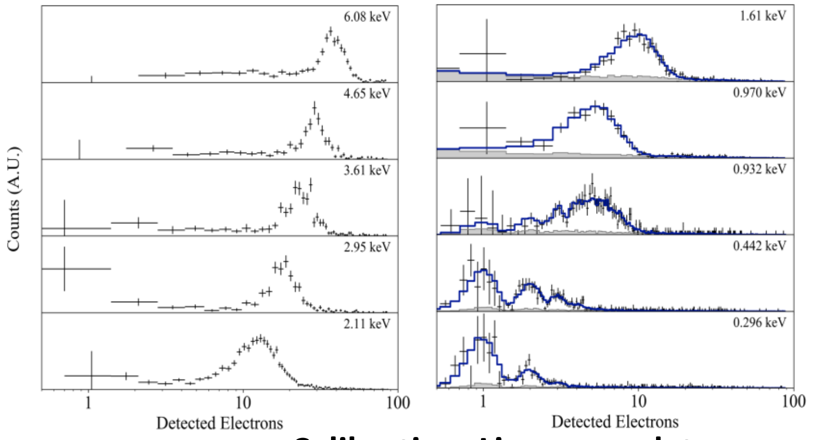
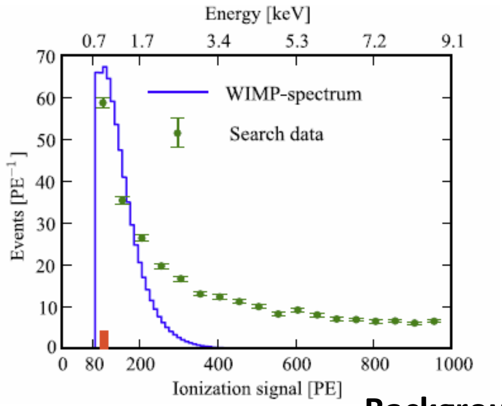
Responsivity and background

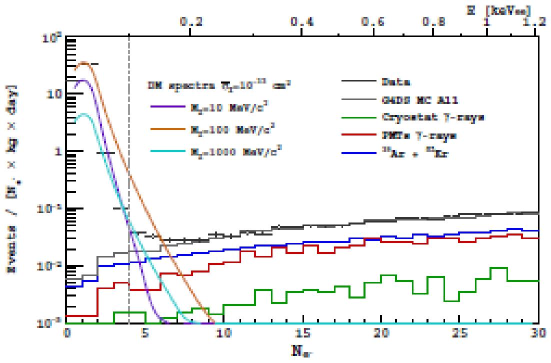
In Xe detector low energy nuclear recoils produce measurable response (calibrated!)
And , would we put reactor and detector deep underground, neutrinos coherent scattering likely can be measured!



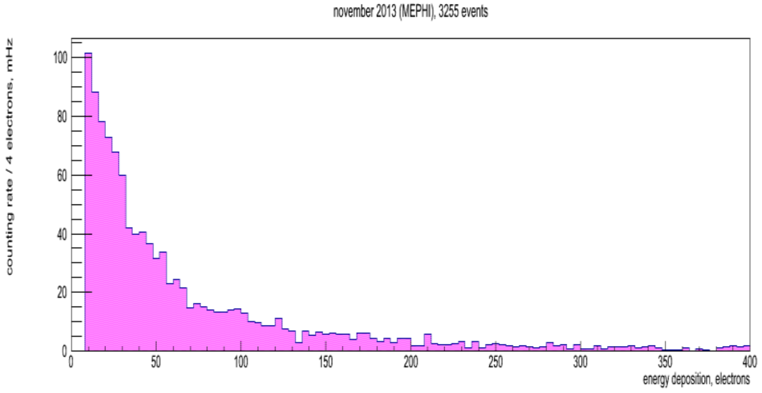
Calibration; Livermore data

- **We still do not understand all mechanisms for low energy background**
- **In above- ground detectors this low –energy background 3 -4 orders of magnitude larger than expected CEvNS signal from reactor**





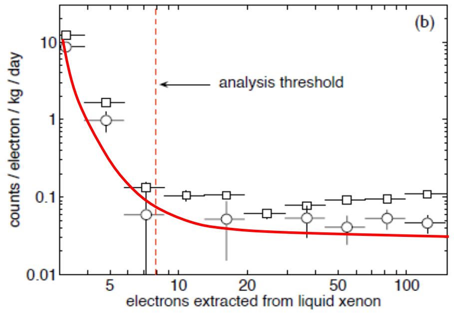
Background: Xe100, Dark Cide 50



Background spectrum above ground, small Xe detector in Moscow (prototype of Zeplin), courtesy of Dmitry Akimov

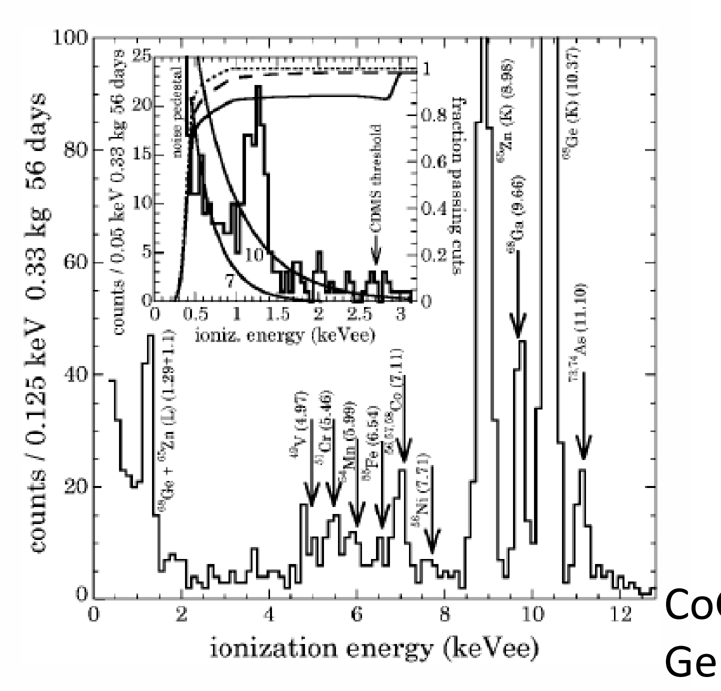
Many types of detectors have enough responsivity to detect CEvNS,
…but low energy background is not yet measured or understood…

Universal condensed matter mechanism?

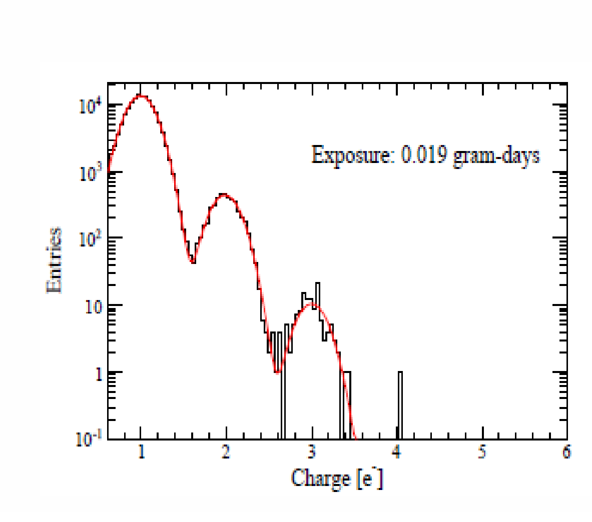


Xenon10

We hypothesize that there is rather universal condensed matter mechanism producing background which is sharply rising at energies nearing excitations in detector material
It also leads to self-correlations- like multiple electron emission events



CoGeNT
Germanium



Silicon- thick CCD sensor
dark counts (SENSEI experiment)

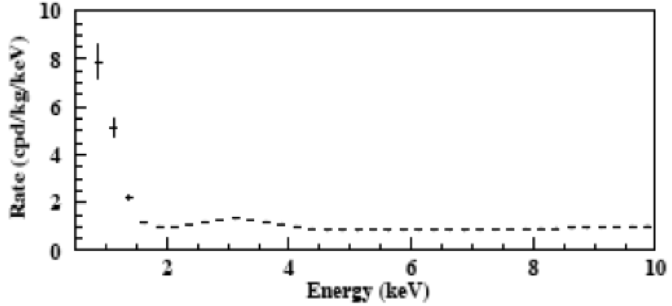
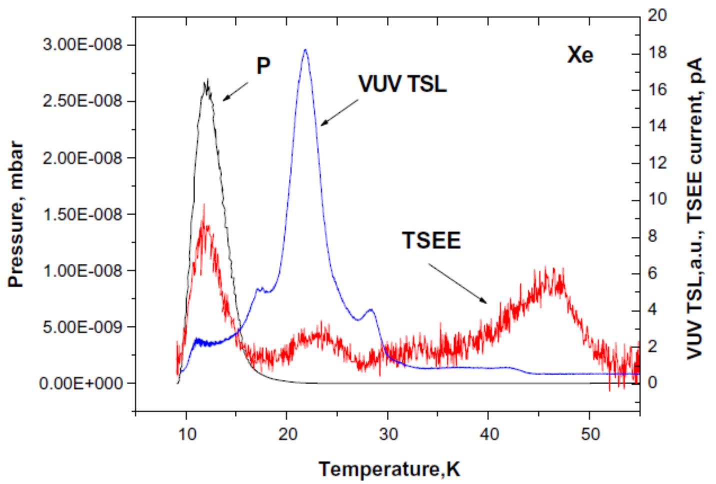


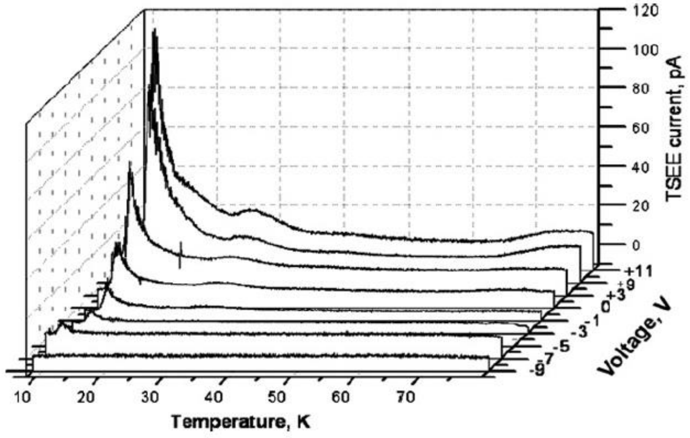
Figure 1: Cumulative low-energy distribution of the *single-hit* scintillation events (that is each detector has all the others as veto), as measured by the DAMA/LIBRA detectors in an exposure of 0.53 ton × yr. The energy threshold of the experiment is 2 keV and corrections for efficiencies are already applied.

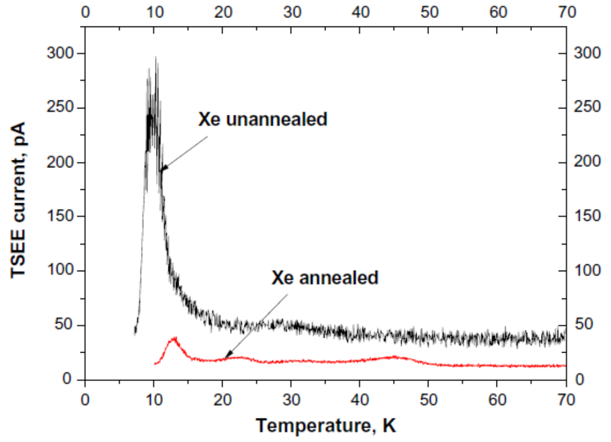
DAMA-LIBRA
NaI(Tl)

Energy accumulation in material under irradiation

Thermally stimulated luminescence & electron emission in solid Xe (Ar)







Radiation effects in atomic cryogenics solids, E.V. Savchenko *et al*, NIM B268, 2010
see also M.E. Fajardo and V.A. Apkarian, J.Chem.Phys. 87, 1988

Long (days) energy storage: Xe_2^+ /Ar_2^+ and O_2^- are involved (Savchenko et. al. 2010).

Exciplex complexes $Xe_2^+ X^-$ can be produced in solid Xe dopped with halogens(X=Cl, Br, F) which emit light and decay; but with 10^{-5} probability pair of trapped ions can be formed with long lifetime – effect is called *photolysis* (Apkarian, 1988).

Stabilization of *reaction intermediates* in solid Xe, Ar and other noble matrixes is known.

Energy accumulation in material under irradiation

Thermally stimulated luminescence in NaI(Tl) and other alkali halides,
Thermally stimulated conductivity and charges trapping in CDMS (germanium).

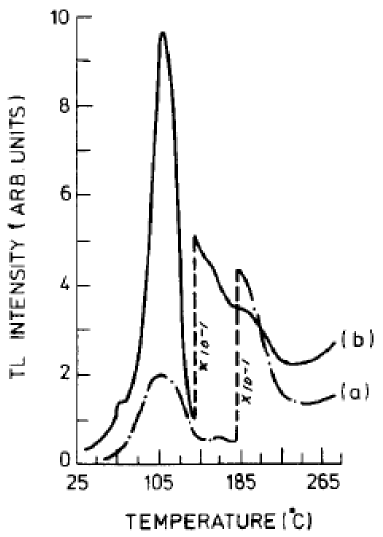


FIG. 1. TL glow curves for NaI crystals containing thallium activator: (a) 0.75 and (b) 1.5 millimolar fractions. Exposure 10^3 R.

Thermoluminescence in Gamma-Irradiated NaI(Tl) Crystals
Nucl. Tracs, Vol.10, pp/107-110, 1985

- Thermoluminescence is known for alkali metal halides; here no additional impurities is required; it is possible to suppress thermoluminescence by irradiation with red or IR light.

- Thermal luminescence in Al_2O_3(I) (personal dosimeters) can be suppressed by sunlight and by microwave exposure.
- Light or mechanical stress are known to induce UV luminescence or electron emission in many irradiated materials.

- Thermally stimulated conductivity is known for many semiconductors and dielectrics.
- Trapping of electrons and holes is known for Ge, and CDMS detector require periodical “purge” with light to liberate traps.

Important things about ion trapping

Thermally –stimulated luminescence and Exaelectron emission are ***very common*** for dielectrics crystals and films on metal substrate; thermally-induced conductivity is common for dielectrics and semiconductors.

- Potential barriers for de-trapping in common detector materials is small (below 0.05eV).
- Clustering of defects and impurities is common in solid materials   (zone melting purification)
- Avalanche recombination is possible for trapped ions, especially for clusters i.e. lattice deformation/ phonons from one pair recombination de-trap another ion and so on.
- Small environmental changers (pressure , temperature) can trigger single events and avalanches
- Hot phonons produced by CEvNS of low energy (solar) neutrinos can cause de-trapping and avalanches!
- NB! quenching factor for low energy recoils can change in presence of high energy background

Scientific American, Vol 254, pp.46-53 (1991)

Self-Organized Criticality

Large interactive systems naturally evolve toward a critical state in which a minor event can lead to a catastrophe. Self-organized criticality may explain the dynamics of earthquakes, economic markets and ecosystems

by Per Bak and Kan Chen

Classical "soft condensed matter" example - grows of sand pile, when material is added to the top and spreads horizontally by avalanches.

Applicable to "hardcore condensed matter"- crack formation, motion of quantized vortexes in superconductor, some interacting spin systems.

"Excitations" are slowly produced, accumulate and annihilate in avalanche- like events.

> Important features of Self-Organized Criticality dynamics are universal and do not depend strongly on details of interactions:

SOC dynamic features

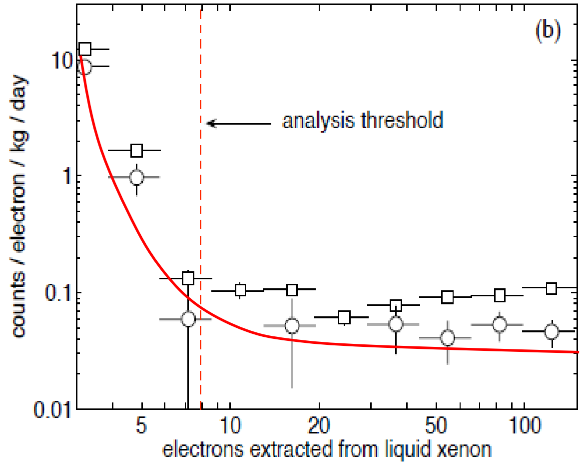
- Polynomial (not exponential) events spectrum- applicable to particles detectors; probability of a catastrophic event not negligible

- Noise power spectrum close to 1/f (pink noise)- applicable to superconducting detectors (SQUIDs, TES, etc., qubits)

- Low energy particles/ events can cause “large events”

- Suppression of “large events” by reinforcing relaxation at small scale-
(put sand pile on vibrating platform…)

Looks familiar?



These features can help to identify the problem and mitigate unwonted effects.
 M**icroscopic models are required** for excitations and their interactions

Main hypothesis

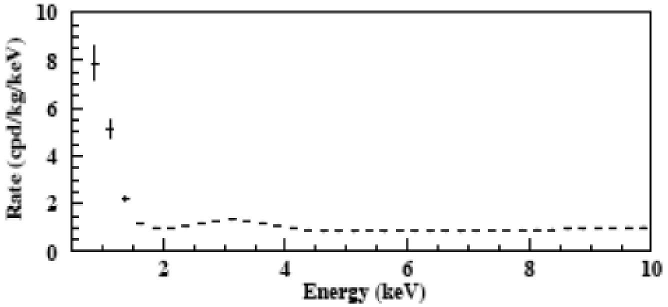
Due to the effects of clustered defects and impurities, and due to the small activation energy for charge de-trapping, in all materials where thermally stimulated luminescence, thermally stimulated electron emission, or thermally stimulated conductivity are present, the avalanche-like relaxation events that create bursts of conductivity or electron- or photon-emission will also be present.

Large ionization events both produce and destroy energy bearing states;
In between large events small relaxational avalanches destroy this states

Scintillator NaI(Tl) detectors

Ap-conversion for NaI(Tl) is known:

Saint-Gobain technical note : “With mild UV exposure, several pulses per second can be seen in the 6-10 keV region of a spectrum. If the crystal is stored in a dark area, this mild UV exposure will eventually disappear, although it may take from several hours to several days for the effects to stop.”



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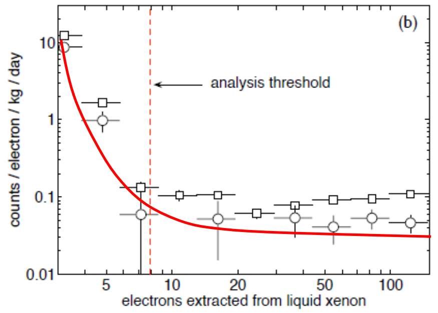
Suppression of TSL by IR/ red light is known, suppression of bursts after UV irradiation need to be checked.

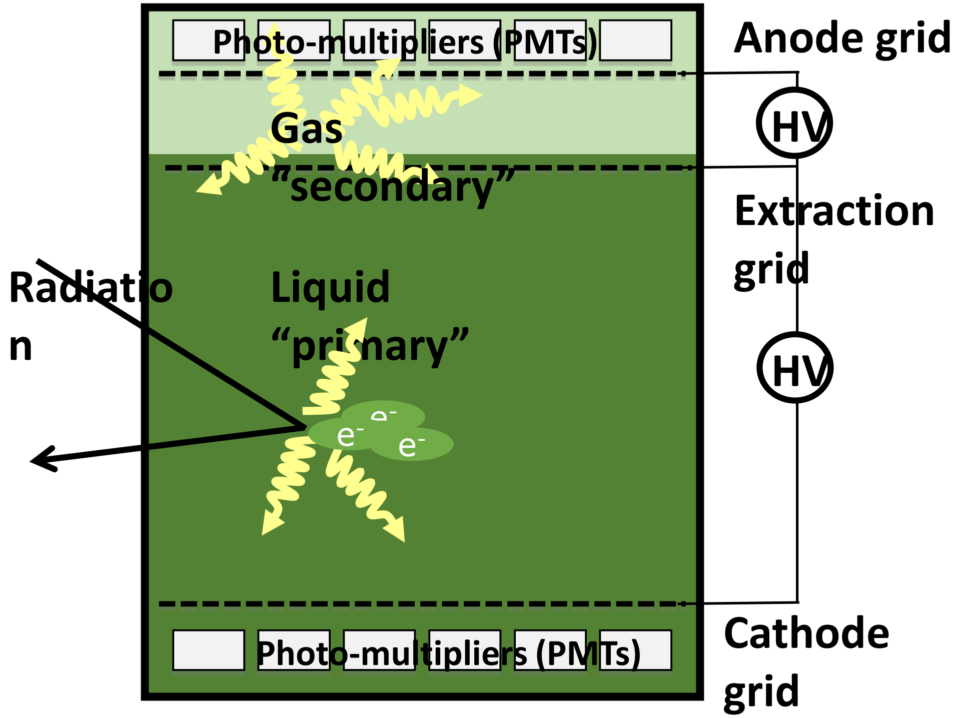
Prediction:
irradiation with red/ IR light should prevent energy accumulation and suppress effects from ionization load (muons), fluctuations of temperature and pressure, and solar neutrino flux, while not affect nuclear recoils caused by d dark matter particles.

Dual –Phase Xe and Ar detectors

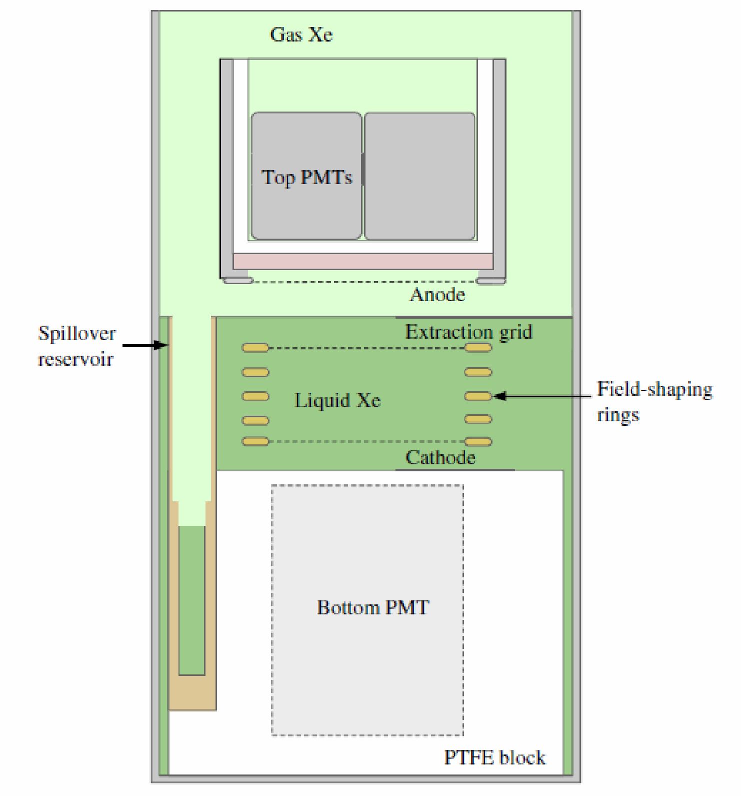
... don’t look don’t tell...



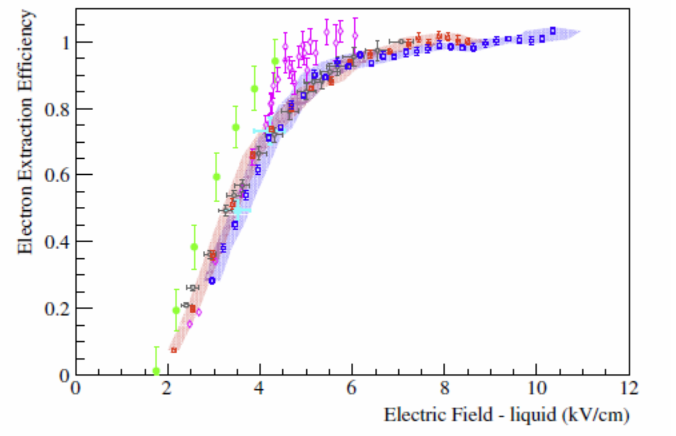
- RGS crystals: polynomial events spectra / up-conversion (bursts) in TSL and TSEE after irradiation / UV exposure -*Not checked yet .*
- Physiosorbed film of solid Xe and Ar ~8 monolayers are present on electrodes – *TSL and TSEE are imbedded into dual-phase detectors.*
- Natural explanation for multiple (1,2,3,…8) electron events
- Effects of re-emission from liquid surface (incomplete extraction)and by electronegative impurities, ionization of impurities by S2 light (electroluminescence) are present.
- May appears at the same please after drift time delay due to ionizing “ impurity trapped” electrons by “native” and following S2 pulses (to be checked for following!)
- S2 pulse also makes *imprint by photolysis* (ion pairs formation) in solid layer on extraction grid- decay / delays of this electron emission not related to electron drift time.



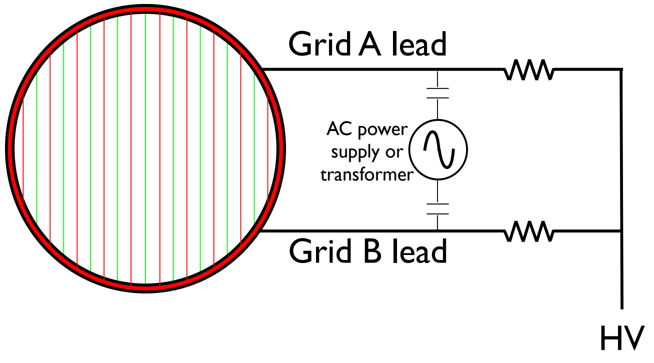
Where to look for: high purity, high extraction field, high AC field / … don't look don't tell…



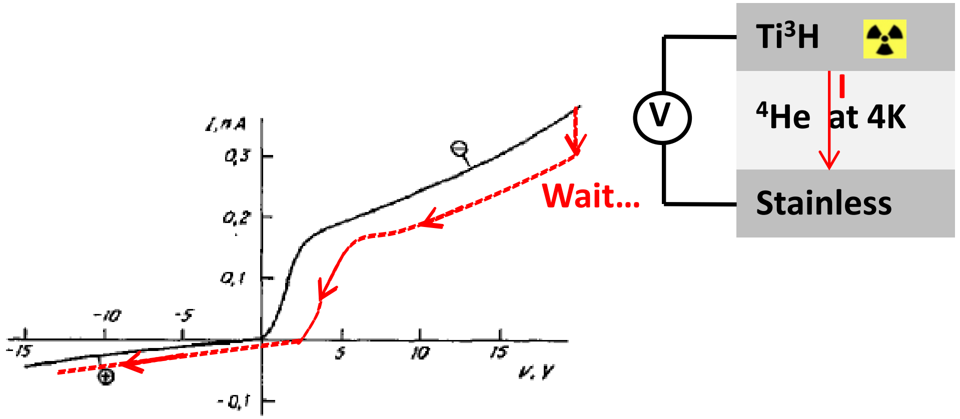
Remove plastics and TEFLON!

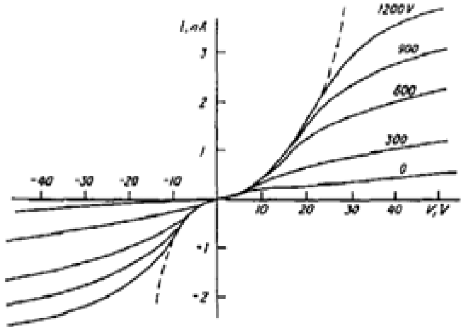


Large field / more UV production



AC modulation: 1kV p-p at ~3 MHz





AC modulation remove electrode charging(hysteresis) in Helium experiments

SOC dynamics and superconducting detectors & qubits?

- At low temperatures of system of interacting charges (on interfaces), spins (localized electrons, impurities, nuclei) , nuclear quadrupole moments, etc., are in glass-like state, so one can define a ‘generalized excitation’ as any non-equilibrium configurations of this system.
- Time-varying electric or magnetic fields applied to materials can produce the generalized excitation.
- More energy from driving fields into the system results in more noise and less “energy sensitivity”.

Example: CMB and IR photon detectors:

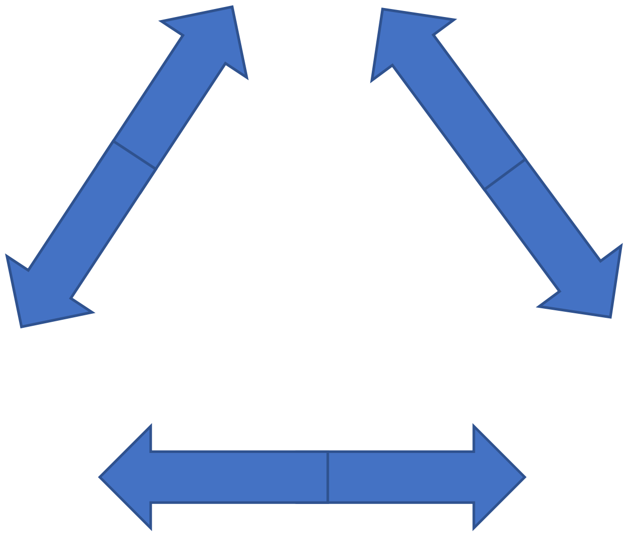
<<< AC field ‘drive’ intensity <<< Noise equivalent power “energy sensitivity”>>>

MKIDs	TES, SQUID array readout	Superconducting nanowire
Sensors are a microwave resonators	TES DC-connected to SQUIDs, SQUIDs included in resonators	DC current in sensors while waiting for “click”

SOC model – an addition or an alternative to Tunneling Two-Level Systems model for noise /decoherence. Prediction: in quantum devises (qubit, superconducting resonator) avalanche-like relaxation can lead to energy-up-conversion events- i.e. localized energetic excitation production- experiments are possible (“smoking-gun evidence” in Anthony Leggett terms?)

Instead of conclusions: Disentangling low energy events

Low energy event
In the detector



CEvNS events
Dark matter particles
Interactions beyond standard model

SOC dynamics
Excitations in material
Rare condensed matter events

With threshold below 0.1 eV, CEvNS of low energy solar neutrino could trigger SOC avalanches

We get new physics here: glasses are not good understood (while most common in nature).
Deeper understanding of underlying detector/ condensed matter physics is required

The end

Smile if you can