Excess backgrounds and releases of stored energy

Effects of energy accumulation and “correlated releases” in materials, detectors, qubits, and live systems

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LLNL-PRES-XXXXXX
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Excess low-energy backgrounds can be present in all dark matter and CEvNS detectors

- **Common scenario and phenomenology in different systems**
- **Material-specific processes, properties and questions**
- **The benefits of a general approach**

HEPHY

Fermilab

XVIII International Conference on Topics in Astroparticle and Underground Physics 2023

EXCESS workshop: a community effort towards understanding low energy excesses

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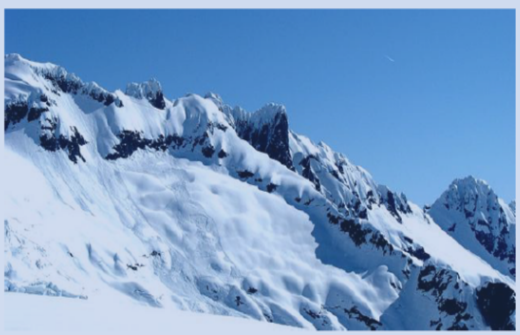
on behalf of the EXCESS workshop team

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP 2023), August 31, 2023

Panel of Experts

We appear to be observing different manifestations of long-lived metastable states releasing energy in our systems

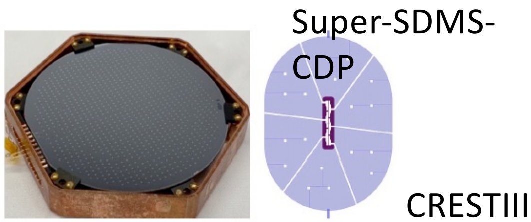
- Self-organized criticality
- Long-lived states can store massive amounts of energy >MeV that gets released in small bursts

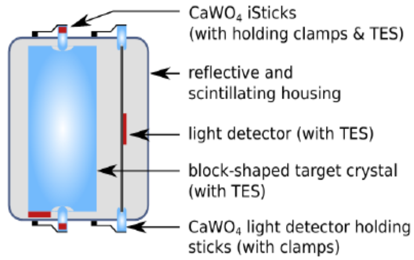


- How do you remove long-lived stored energy in a system?
- **Analogy: How do you prevent an avalanche?**

The community realized backgrounds due to releases of stored energy.
Related questions -
Noise and Decoherence in quantum devices
Studying natural micromachines

Excessive low-energy background in dark matter and coherent neutrino scattering detectors





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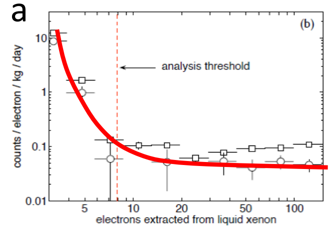

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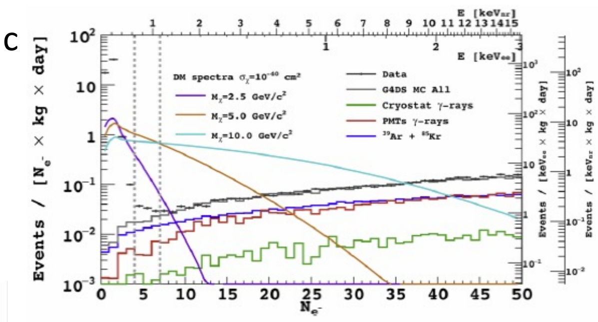

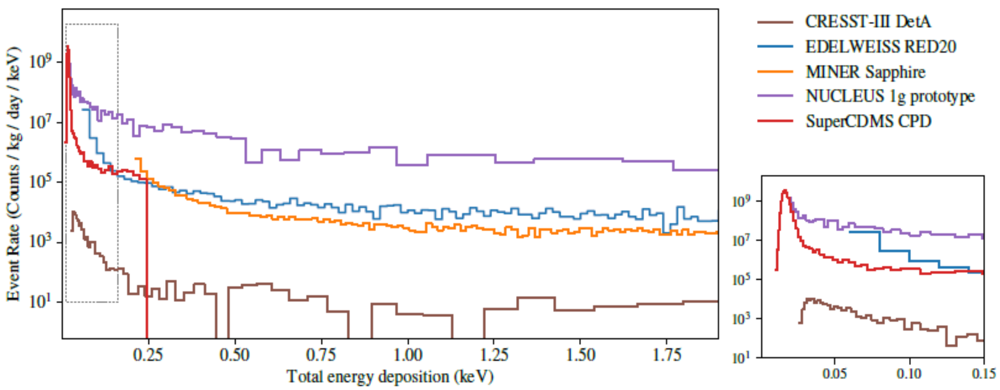

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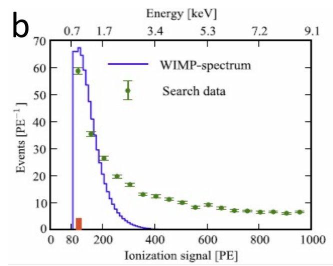

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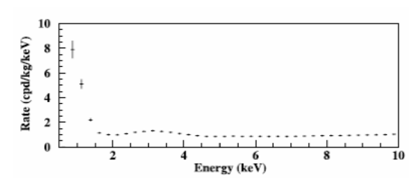
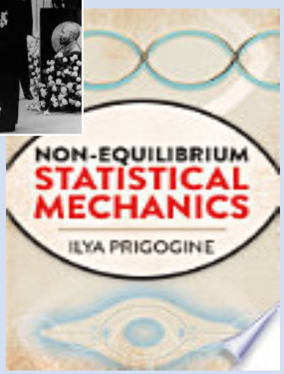


EXCESS workshops

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

Common features: a sharp rise in the number of low-energy events
Long, history-dependent (glass-like) relaxation processes after cooling down, application of stress, irradiation, etc.

Systems with energy flow & Self-Organized Criticality



Ilya Prigogine (Noble Price 1977)
Dissipative structures, **irreversibility**, **complexity**, **order out of chaos**
Emergence of new properties due to complex interactions inside systems
In other terms- correlations, quantum entanglement, squeezing in energy releases, in live systems

Energy storage & and release examples

Thermally-stimulated luminescence & electron emission
Thermally-stimulated spikes of conductivity

- **Polynomial events spectrum (catastrophes possible)**
- **Noise power spectrum close to 1/f**
- **No characteristic time/size for avalanche**
- **Low energy particles cause "large events" upconversions?**
- **Large events suppression by helping "small scale relaxation"**

Results of computer modeling of system with known interactions no "sufficient conditions" criteria for the presence of SOC

Per Back, Chao Tang and Kurt Wiesenfeld (1991 paper) **Self-Organized Criticality**

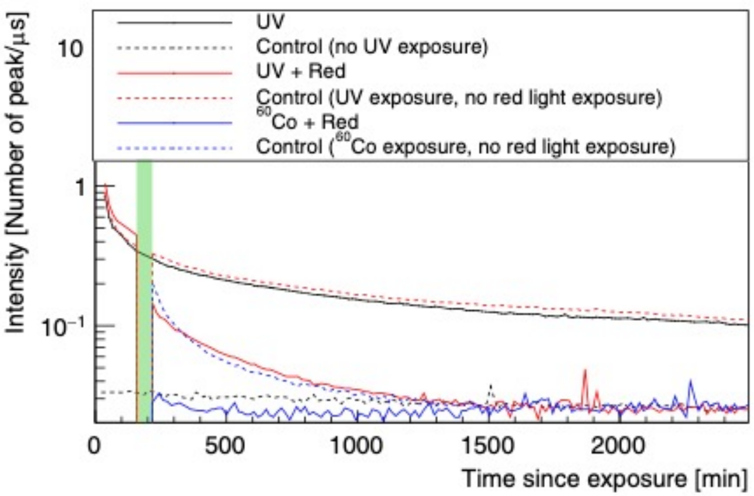
References on related ideas and material properties

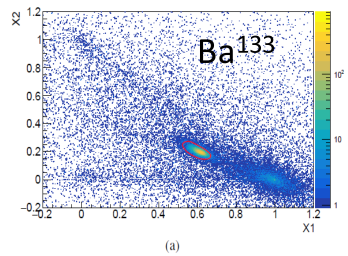
Phys. Rev. D 105, **063002 (2022)** [2107.14397] Detecting Low-Energy Interactions and the Effects of Energy Accumulation in Materials (arxiv.org)

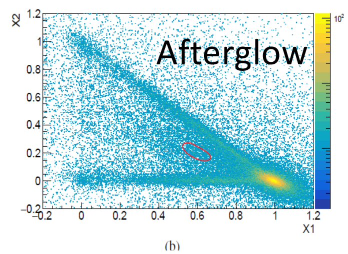
Proceedings of the IDM2022 conference, SciPost Phys. Proc. 12, 009 (2023) [2212.13964] Dark matter searches and energy accumulation and release in materials (arxiv.org)

GEANT 4 CMP is an important development, but not yet model energy releases

Material specific: NaI(Tl), natural nano-explosive material and phase of DAMA-LIBRA seasonal background modulation





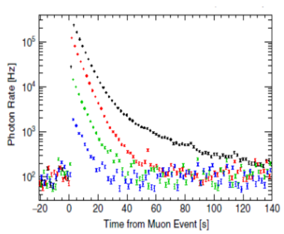


$$X_1 = \frac{A[100,600]\,ns}{A[0,600]\,ns}, X_2 = \frac{A[0,50]\,ns}{A[0,600]\,n.}$$

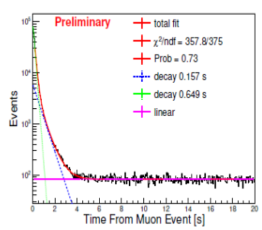
Afterglow following UV and ^{60}**Co** exposures

How long it will last after UV and then ^{60}Co ?

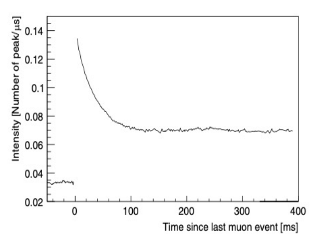
Muon afterglow Ice Cube (2016),



CONUS (2016),



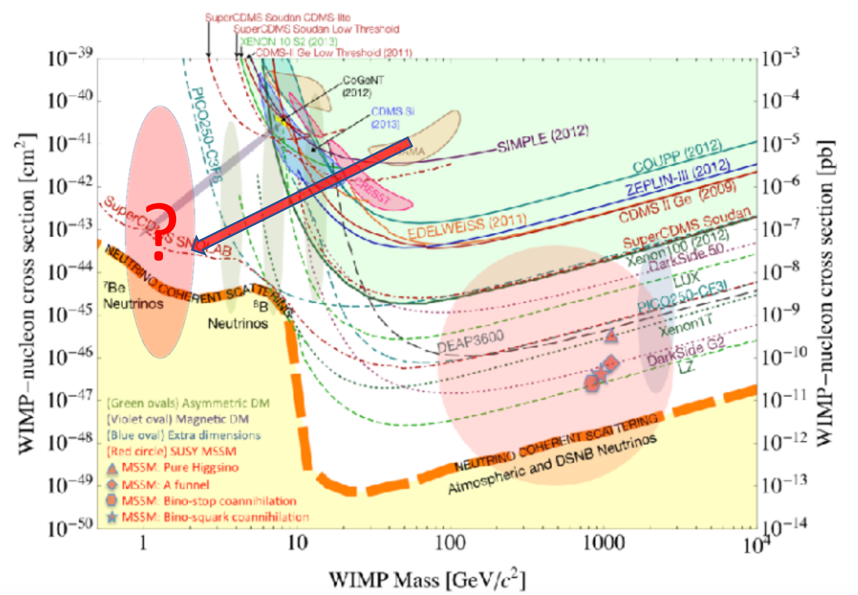
Our data (averaging)



Hypothesis

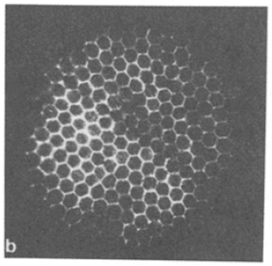
UV and muons can produce long-living excitations Which are effectively killed by the residual radiation.

What If excitations accumulate in DAMA-LIBRA, and sub-eV recoils can trigger energy releases?



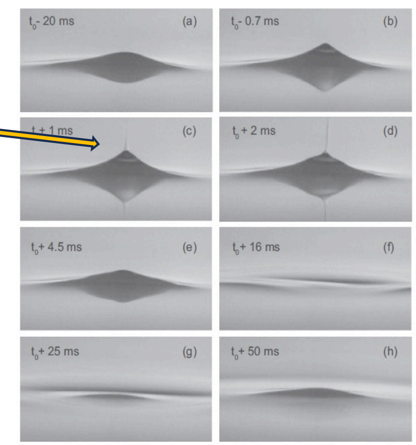
Material specific: Xe (Ar) dual-phase TPC:

a low number of extrinsic excitations, but "charged crust" blurs results



RED1, ZEPLIN III, RED100: suppressing/removing liquid surface charges by the design – fast drift of unextracted electrons, no e-bursts, single-electron, and multiple electron delayed emission events; **LUX, XENONnT, (LZ?):** not accounting in design barriers for liquid surface charges to leave – unextracted electrons "stay at place", E-bursts, delayed single electrons present, multiple delayed events suppressed;

Instabilities of charged liquid surface: "bumps lattice " at a few mm capillary length scale (immobilization, "stay in place") and (e-burst) droplets/jets//electrospraying
"Unexpected" interactions: liquid-gas interface charges affect free electron extraction efficiency; likely suppress extraction of small ionization signals



Xe, Ar detectors and solid-state low-temperature detectors

- large mass (tons scale)
- small number of energy/charge storing centers due to impurities in solid physisorbed films, and radicals/ions aggregates in bulk liquid

better chances to detect rare nuclear recoil in 100-1000 eV range

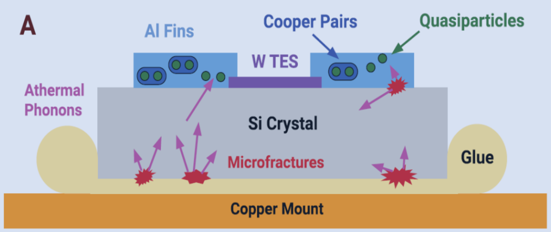
Multiple delayed electron emission events are the obstacle to detecting CEvNS with Xe detector under the reactor (RED100)

Delayed emission in Xe and Ar can be suppressed by increasing purity from ppb to ppt level

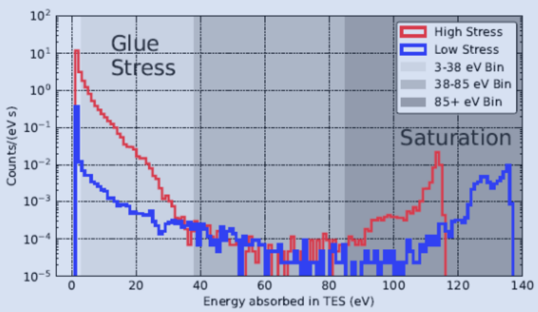
Effects of charge accumulation on the liquid surface can be smeared/complicated by vibrations and wave generation on the liquid surface
Moscow RED group is changing to liquid Ar in reactor CEvNS experiment (but has no resources to study specific impurity effects)

Solid-state low-temperature detectors

SOC-like dynamics on the smallest size and energy scale?



https://doi.org/10.48550/arXiv.2208.02790



observations of stress relaxation (crystal flow) in steps generating bursts of phonons, quasiparticles, photons, exaelectron emission, etc.

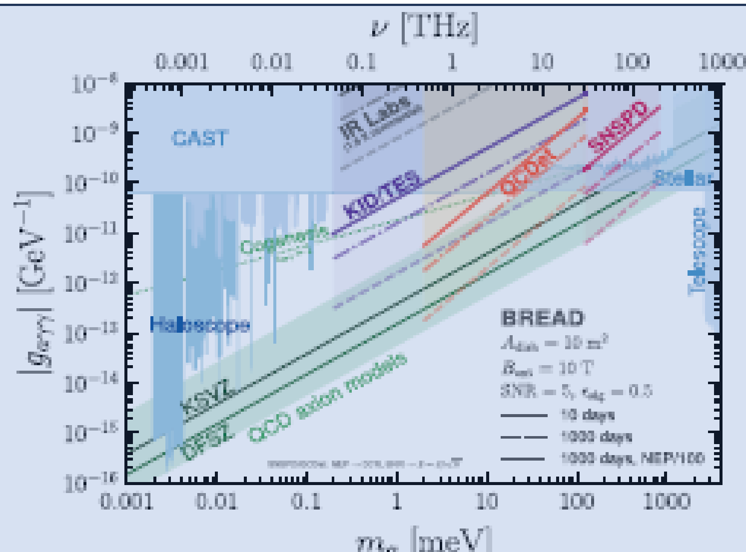
Down-going energy cascades
Are there energy releases at a small size/energy scale? Up-going energy cascades?

Long, history-dependent (glass-like) relaxation processes at cold:

- Charge/ion motion
- Magnetic moments (ions, nuclear spins) form spin-glass
- Contact potential difference /contact charged layers

Interactions: through electron system (RKKY) and phonons/displacements

Energy pumping by cycling temperature, electric, and magnetic field; particles, photons, IR, microwaves, RF signals, and more



AXION search (project BREAD) needs photon detection down to 1 mV energy . **Backgrounds for different low-energy threshold detectors?**

Superconducting sensors and SNSPD
Tentative answer?

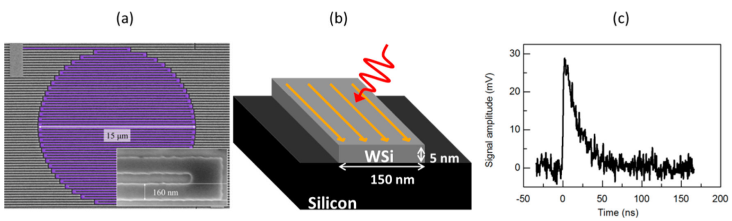
CMB and IR photon detectors:

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

MKIDs	TES with SQUID array readout	Superconducting nanowire
Sensors are integrated into microwave resonant circuits	TES are DC-coupled to array of SQUIDs Frequency multiplexing array redout	DC supercurrent in sensors while waiting for “click”; RSFQ - compatible*
Continuous Dissipation in sensors by microwave readout signals	Some leakage of RF signals to sensors, dissipation by DC current in TES	No dissipation by readout in sensor while waiting for photon

Superconducting sensors and qubits

Expanding limits for SNSPD to look for Axions and decoherence sources



nanowire detectors outperform other IR photon detectors (and PMTs)in energy sensitivity (30µm photons), quantum efficiency, low dark counts, short response time (5s time resolution) , have macroscopic pixel size, large arrays with reasonable pixel size (10-50 µm) available , etc.

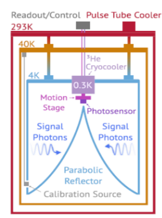
Why SNSPD development so successful?

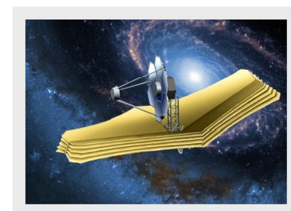
- Down-going cascades: Not sensitive to phonons below the gap
- Up-going cascades: no energy dissipation by readout while waiting for signal

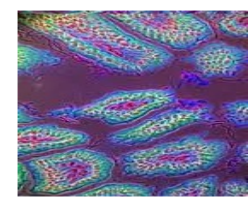
- lowering critical current/transition temperature
- decreasing working temperature
- suppressing noise from the environment
- suppressing down-cascades

detect lower energy photons
while preserving low dark counts

Important goals
Particles physics: QED axions- 1meV photons (BREAD)
Space Astronomy: THz minimum in CMB (ORIGIN)
Cell chemical imaging: 1-30µm(already there!)



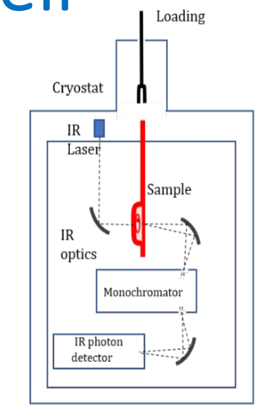




Strong connections to Quantum materials

Detector projects often exceed in scale and sensitivity past material science and condensed matter programs on related questions.
Excess background events should lead to quantum error and decoherence; SOC-like dynamics provide another mechanism for noise and a possible explanation to some properties of glasses in addition to the tunneling two-level systems (TLS) model.

Small sample size + cryogenic environment + multi-pixel SNSPD + high counting rate = timestamp all IR photons emitted by the cell



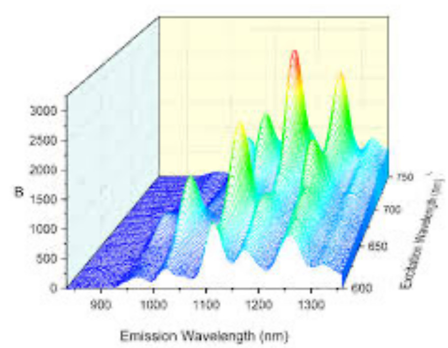
a

b

a. US patent N 9366574. Cells can be frozen or alive (S. Pereverzev)
*b. spectrometer with grating and focal-plane **detector array***
Simplify coupling of cryogenic spectrometer and detectors to live samples

- **100-1000 parallel channels allow timestamp with 5-10 ps resolution all photon –thermal radiation background and IR luminescence- arriving to the detector**
- **Coupling cryogenic to live sample with IR fiber**
- **High data acquisition speed, CL-AI pattern analysis required**

Fast multi-dimensional data acquisition



Outperform cell Raman imaging and synchrotron-based Cell IR absorption spectroscopy

Cell machinery operation in real-time?
Cell IR signaling?
Controlling cells by IR light?

Cell functional imaging would be a disruptive technology
Bio-photonics market exceeds radiation detectors; accelerate HEP detector development
Studying natural molecular machines and interactions can generate new approaches to QI

Energy accumulation and releases in material: a brief history of the problem

No theoretical models yet
But Physics is experimental science!

?

Tunneling,
Entanglement
Squeezing
In non-equilibrium
thermodynamics
& quantum
biology

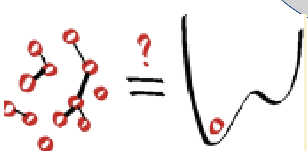
Phenomenology
Experimental studies
Physics of complex systems

?

HEP detectors
Quantum sensors
Condensed Matter

Chemical physics
Cell biology

2022: Excess Workshops
and glass-like relaxation
everywhere?



2010 Interacting TLS in
Quantum devises
1987 W.A. Phillips
1972 **P.W. Anderson** et al.,
Non-interacting tunneling
two-level systems

Glasses
stored energy
energy flow

1988 Self-Organized Criticality
1977 **Ilya Prigogine** (Noble prize)
Complex internal interactions
Systems with energy flow

Conclusions

- Stored energy releases are present in practically all materials
- Experiments are needed to build realistic phenomenological models, and the comparison of phenomenology in different systems allows the prediction of effects to look for.
- Stored energy releases should lead to quantum errors and decoherence- like energetic particles; it was overlooked in extensive material research programs aimed at quantum materials.
- GEANT -4 for condensed matter physics is an important development, it needs expansion to model energy accumulation and releases in material
- Experimental studies of SOC-like dynamics in superconducting/ quantum devices would be of importance for understanding excess backgrounds in detectors, non-thermal noise and decoherence in qubits, and future development of non-equilibrium statistical mechanics

Additional slides

Conclusions

- Classical HEP and NS problems of dark matter particles and neutrino detection are strongly connected –through the material science problems- to the Quantum and Chips for America initiatives, where problems of decoherence and excess noise are of great importance. Parallel application of ML/AI techniques and detector microscopic studies should help develop physics-based models and light on uncertainties

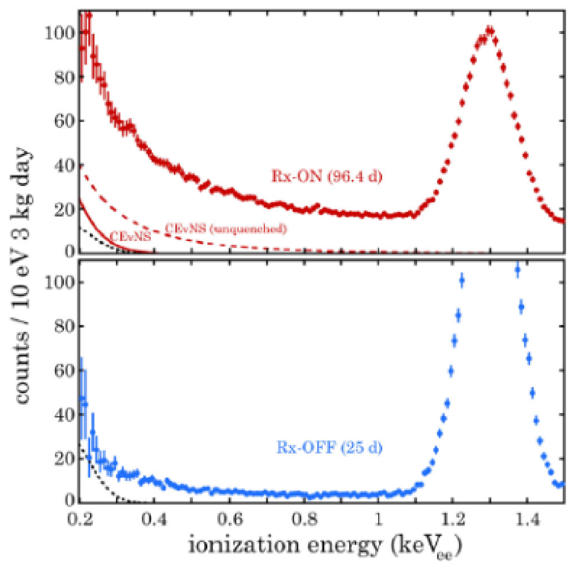
- Stored energy releases are present in practically all materials. Experiments are needed to build realistic phenomenological models. The comparison of phenomenology in different systems allows the prediction of effects to look for.

- Stored energy releases should lead to quantum errors and decoherence- like energetic particles; was overlooked in extensive material research programs aimed on quantum materials.

- GEANT for condensed matter physics is important development, needs expansion to model energy accumulation and releases in material

- Demonstration of SOC-like dynamics in superconducting device would be of importance for understanding non-thermal noise and decoherence and future development of non-equilibrium thermodynamics
- Studying natural molecular machines and interactions can generate new approaches to quantum computing and new funding for HEP detectors

Detecting CEvNS with High Purity Ge detectors



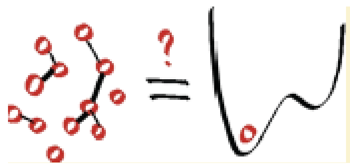
Energy spectra of PPC bulk events during Rx-ON and Rx-OFF periods. The CEvNS expectation (red line) uses the MHVE antineutrino spectrum and Fe-filter quenching factor (see text). A dashed red line illustrates the impact of quenching on CEvNS. Black dotted lines signal the 71Ge M-shell EC contribution, derived from L-shell EC at 1.29 keVee. This process is noticeable in Rx-OFF data, taken prior to the addition of neutron moderator (i.e., following intense 71Ge activation).

- **Stored energy releases are not an immediate reaction on energetic particles and cannot be excluded by muon veto or pulse-shape discrimination;**
- **No adequate models for these processes and experiments to build phenomenological models are required.**
- **Eventually, with a model for the excess background, we will be able to deduce the neutrino spectrum from a not-so-heavily-shielded detector**

Comparison at fixed background conditions is required to confirm CEvNS

Non-interacting Tunneling Two-Level Systems in condensed matter (1972- or Releases of energy by interacting excitations in chemical physics & biology (1977-

TLS introduced to describe glasses around 1972



with ϵ_i as the offset between the potential energy in the two configurations and Δ_i as the matrix element for tunneling between them. Then, we evidently have

$$E_i = (\epsilon_i^2 + \Delta_i^2)^{1/2}$$

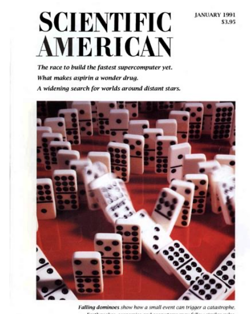
Spectrum: $\rho(\epsilon, \Delta) = \frac{\text{const}}{\Delta}$

P. w. Anderson , B. I. Halperin & c. M. Varma "Anomalous low-temperature thermal properties of glasses and spin glasses," Philosophical Magazine, 25:1, 1-9 (1972),
W. A. Phillips, "*Two-level states in glasses*", Rep. Prog. Phys. 50, 165723 (1987).

Still, no realistic microscopic models for TLS [4]

?

Ilya Prigogine



Energy accumulation and releases [3]

Dug Osheroff [1]

Tony Leggett[2]

Noble laureates criticizing TLS model

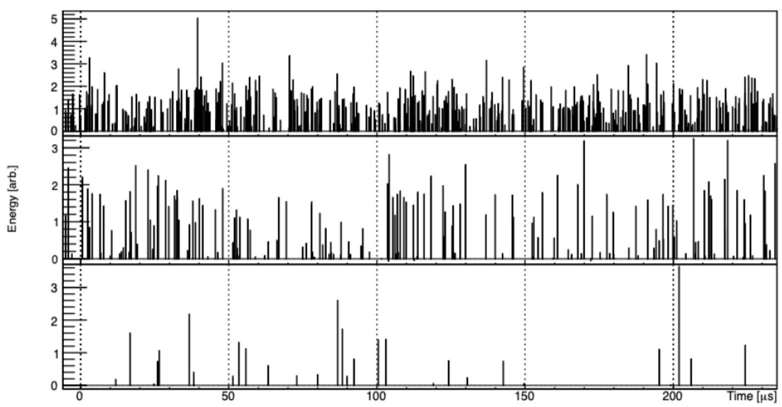
Systems with energy flow (Prigogine): dissipative structures, irreversibility, complexity, order out of chaos (Noble prize 1977)
Self-Organized Criticality: complexity, 1/f noise explained 1(988)

Excess workshops: excess background resembles SOC-like dynamics

Collaboration/ joint program with condensed matter: excess background, understanding of decoherence.

1. S. Rogge, D, Natelson, and D. Osherof, *Evidence for the Importance of Interactions between Active Defects in Glasses,* Phys. Rev. Lett. 76, 3136, (1996).
2. A.J. Leggett, D.C. Vural, *"Tunneling two-level systems" model of the low-temperature properties of glasses: are "smoking gun" test possible?" ,* The Journal of Physical Chemistry B, 117, pp. 12966-12971, (2013).
3. Per Back, Cho Tang, and Kurt Weisenfeld, "*Self-organized criticality: An explanation of 1/f noise*", Phys. Rev. A 38, 364 (1988).
4. C. Muller, J.H. Cole, J. Lisenfeld, *"Towards understanding two-level-systems in amorphous solids: Insights from quantum circuits"*, Reports on Progress in Physics, V.82, 124501 (2019).

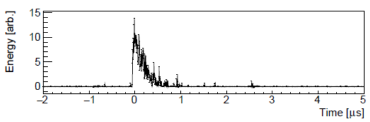
Delayed luminescence is mostly random flux of single photons, though leakage into “particle domain” is possible

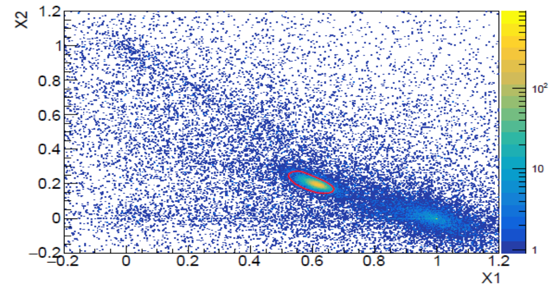


flux in 250 us data taking intervals right after UV exposure, at the middle of relaxation and close to equilibrium background

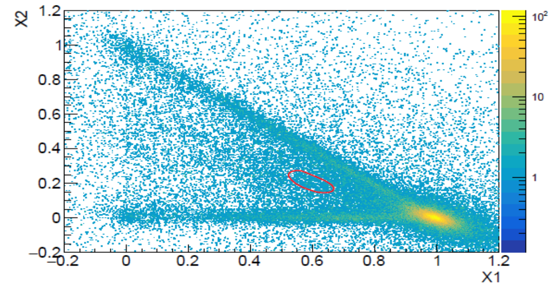
Ba^{133} data reveals the position of traditional NaI(Tl) pulse in the X1-X2 parameter space (a). UV-induced delayed light emission has the potential to leak into the X1-X2 region of genuine NaI(Tl) pulse (b).

$$X_1 = \frac{A[100, 600]\ ns}{A[0, 600]\ ns}, X_2 = \frac{A[0, 50]\ ns}{A[0, 600]\ ns}$$





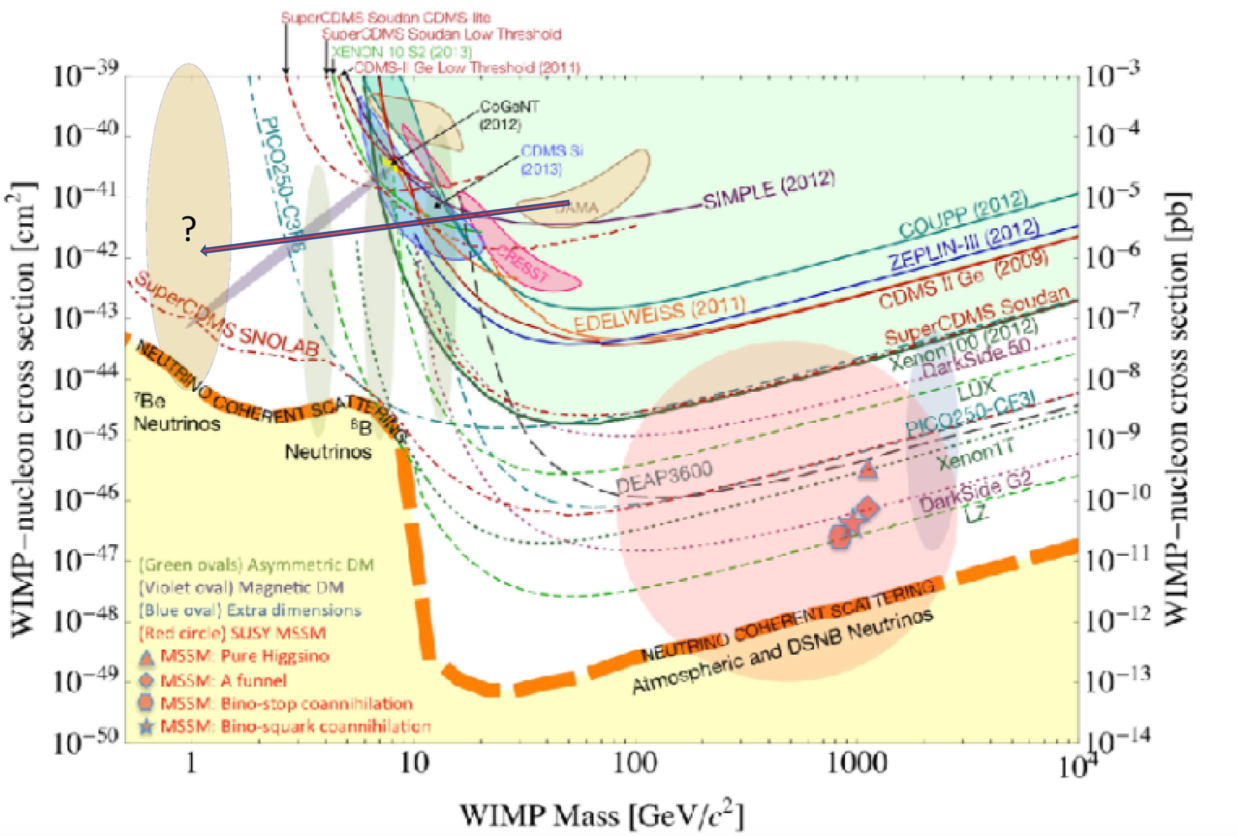
(a)



(b)

The ratio of energy in “immediate light response” and in “delayed luminescence” can be modulated by environmental factors: Temperature, pressure, electric and magnetic fields, AC modulation (Schuman resonances), microwave background, mechanical stress, and vibrations; bunching also can be modulated- so, accurate accounting of energy in&out fluxes is required.

Main hypothesis: low-energy interactions cause detectable releases of stored energy in NaI(Tl)



- Energy effectively pumped in by muons (minimally ionizing particles) and UV
- Residual radioactivity mostly destroys long-storage states
- Nuclear recoils below 1 eV due to Solar neutrino or low-mass DM trigger energy releases
- Multiple photon events (D-L signal) and the random delayed photon flux exhibit yearly modulation- phases can be different (no checks yet on random delayed photons