This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
LLNL-CFPRES-2025875

Energy release and material-state dynamics: a common challenge for detectors and qubits

CPAD 2026

Sergey Pereverzev
LLNL, Rare Events Detection Group

Detectors measure released energy. Qubits and resonators probe changes in their local environment. Together, they can reveal material relaxation.

"Studies of excess background mechanisms are Blue Sky projects"
Helmut Marsiske, CPAD 2024



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

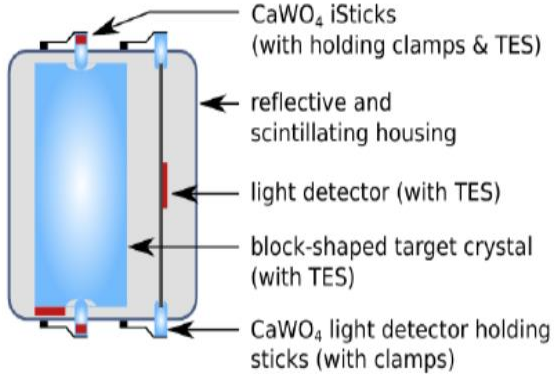
Low-energy excess in cryogenic detectors

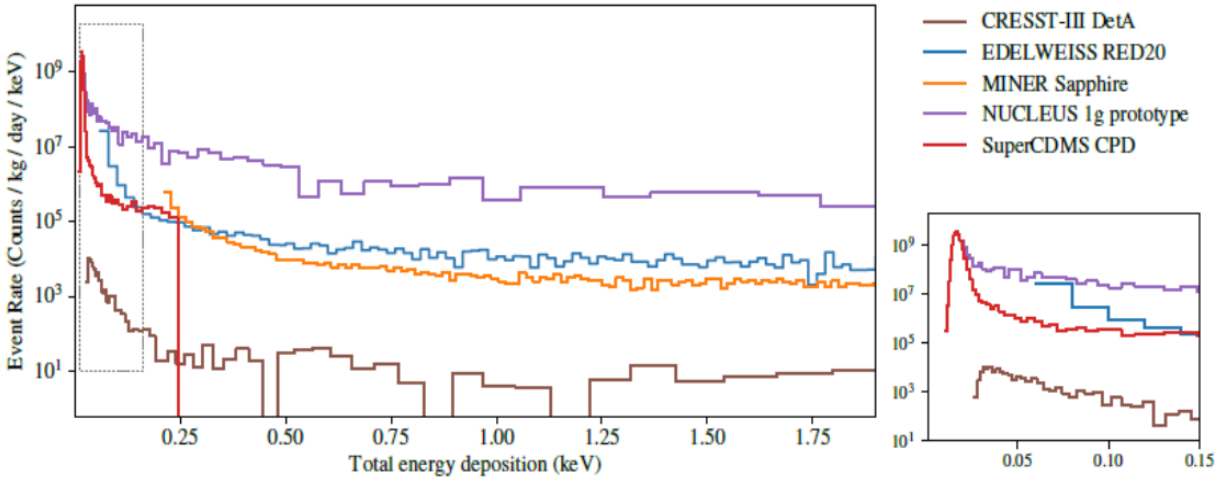
Mechanical boundary conditions can strongly change low-energy backgrounds.

SuperCDMS CPD

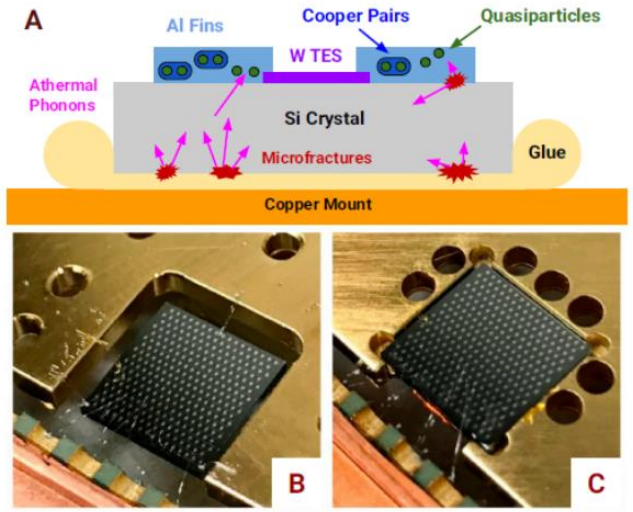


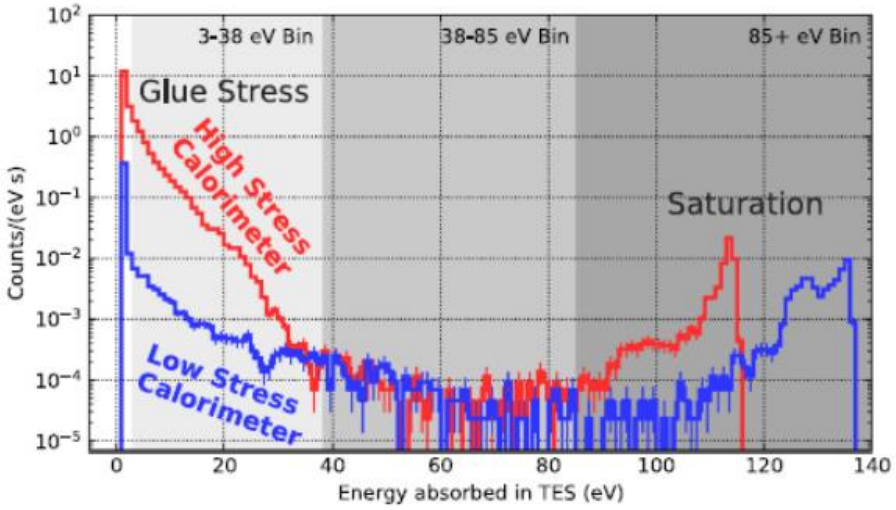
CRESST-III





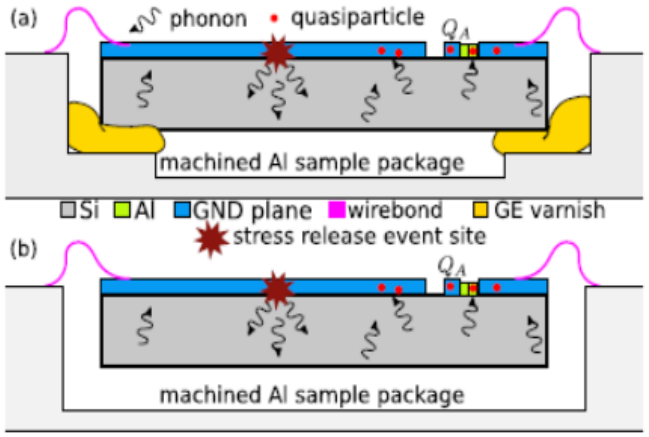
Adari et al., SciPost Phys. Proc. 9, 001 (2022)



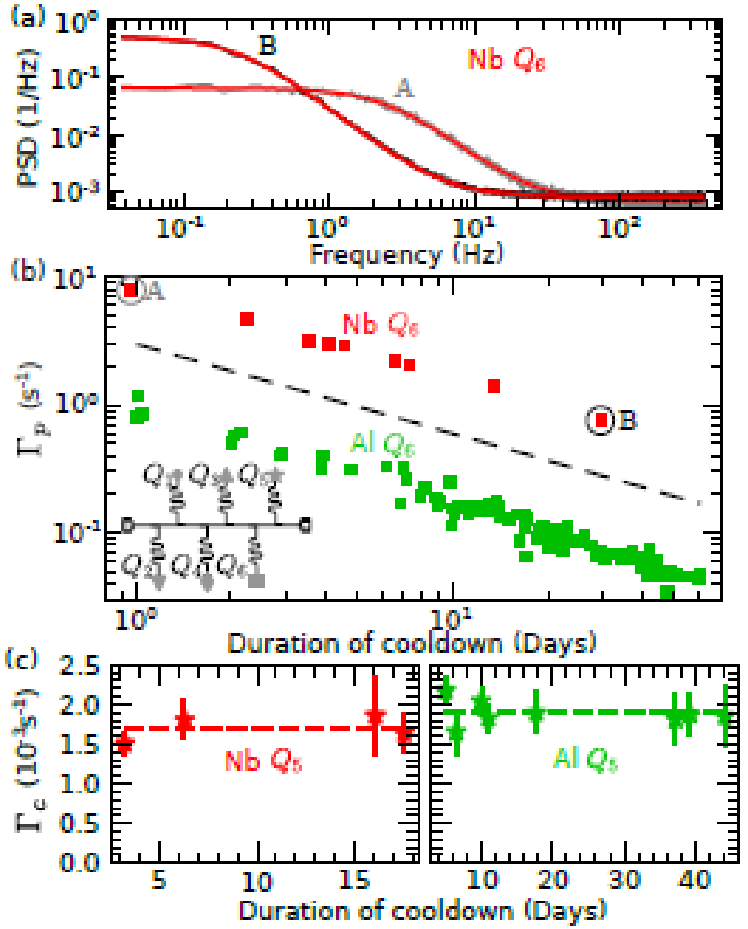


Anthony-Petersen et al., Nat. Commun. 15, 6444 (2024)

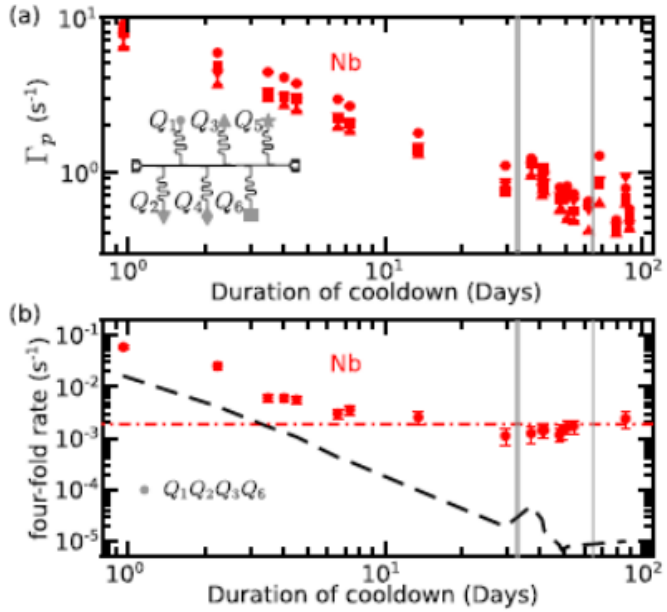
Correlated quasiparticle poisoning after cooldown



Mounting and stress pathways



Parity-switching rate decreases



Correlated event rate decreases

Poisoning decreases. The offset-charge jump rate stays constant- for a nonionizing phonon source.

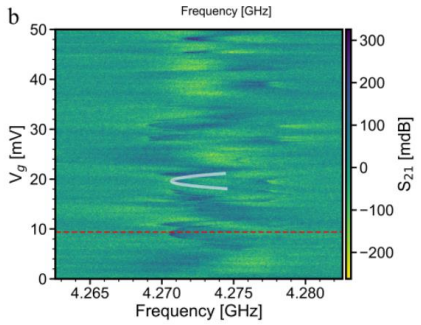
Combined phonon and charge measurements help identify the energy pathway.

E. Yelton et al., Phys. Rev. Lett. 135, 123601 (2025), Figs. 1–3

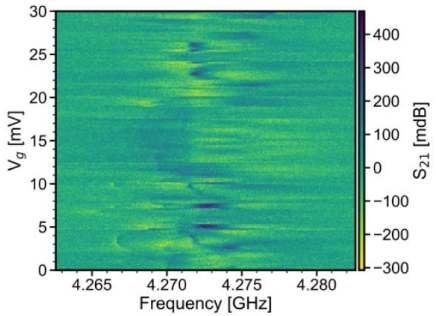
TLS spectra, dielectric memory, and material history

Cryogenic alternating bias stimulation (CABS)

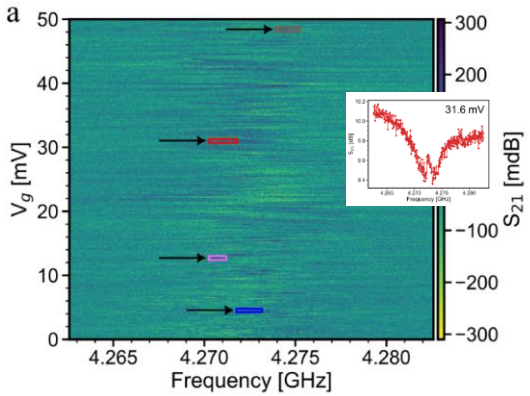
Before CABS



After a 10 K thermal cycle



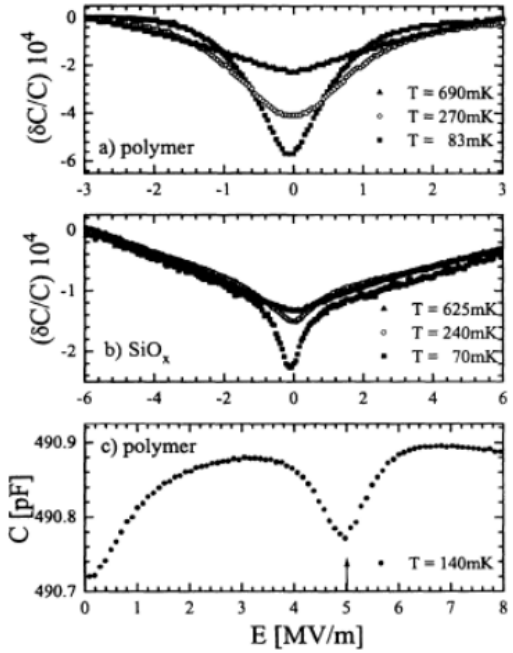
After CABS



Stable lines give way to transient crossings.

Average microwave loss changes little.

Dielectric memory in glasses



The response remembers field history and relaxes over long times.

Does a changing defect environment connect these observations?

Average microwave loss alone does not characterize material-state stability.

Iaia et al., Phys. Rev. Applied 25, 064025 (2026). Salvino et al., PRL 73, 268 (1994). Rogge et al., PRL 76, 3136 (1996).

Stored-energy reservoirs and quantum TLS
How are they connected?

Two complementary observations. Their microscopic relationship remains open.

	Energy reservoirs and relaxation	Spectroscopically resolved TLS
Physical picture	Stored stress, trapped charge and other metastable configurations [A]	Low-energy transitions in defects. Selected TLS support quantum coherence.
Measured scales	Detector: total energy per event (0.01-1eV-scale and larger examples). Broad waiting and relaxation times.	Spectroscopy: individual splitting 1–25 GHz ≈ 4–103 μeV. Measure drift, T_1 and T_2 separately.
Role of coherence	Collective release can occur without coherent superpositions. Quantum triggering remains possible.	Selected TLS show coherent exchange with qubits and with other TLS. [B] Only part of the defect population.

Do releases excite TLS, shift their local environment, or both?

Can TLS dynamics influence later energy release?

Detectors measure released energy. Qubits and TLS probe local changes.

[A] Anthony-Petersen et al., Nat. Commun. 15, 6444 (2024): stress-associated phonon bursts.
[B] Lisenfeld et al., Nat. Commun. 6, 6182 (2015): coherent interactions between individual TLS.

Understanding material relaxation: benefits for detectors and quantum devices

Observed: correlated relaxation and avalanches. TLS excitation lifetimes can exceed 1 s [1].
Coherent defect interactions can correlate multiple qubits [2].

Hypothesis to test: short-lived TLS quantum coherence may strongly change the pathways and outcomes of much slower collective relaxation.

Application	What understanding the mechanisms could enable
HEP/NP detectors	Suppress excess and delayed backgrounds. Improve response stability and materials selection for lower usable thresholds.
Particle interactions and new sensors	Extract additional track and energy-partition information from charge, strain and defect changes. Explore calibrated qubit/TLS sensing.
Qubits and QEC	Improve coherence and stability. Reduce correlated errors [3]. Use measured correlations and detector tags to inform QEC.

Joint energy sensors and quantum probes can connect these observations.

[1] Féchant et al., arXiv:2610.21853 (2026 preprint): intrinsic TLS $T_1 > 1$ s. Intrinsic T_2 remains unmeasured.
[2] Gao et al., arXiv:2605.23385 (2026 preprint): one coherent TLS couples two spatially separated qubits.
[3] Guimarães et al., arXiv:2609.31280 (2026 preprint): 20 µs–1 ms memory and delayed qubit re-excitation.

LLNL–Fermilab workshop and BES roundtable

A fundamental condensed-matter problem shared by detectors and QIS

1. Proposed LLNL–Fermilab workshop extending EXCESS

Participants — Invite BES program managers, BES-supported materials researchers, and QIS researchers alongside the HEP/NP detector community.

Possible venue — LLNL could host a small workshop, jointly organized with Fermilab.

Workshop goals — Bring the fundamental materials problem to BES attention. Define common physical questions, benchmark tests and joint pilot studies.

2. Request a BES-organized roundtable

Seek BES leadership on energy storage and release, defect/TLS interactions and evolving material states during low-temperature operation.

BES 2017 [4] — Build on its treatment of defect origins, fabrication, noise and coherence. Develop a coordinated research agenda across BES, HEP/NP and QIS.

CPAD request: help organize the workshop and engage BES program managers.

[4] BES, Next-Generation Quantum Systems (roundtable, October 2017), pp. 13–14 and 21–22. Full references in notes.

QPU design: detectors and qubits on a segmented substrate

Proposal: qubit blocks with local energy sensors and weakly connected substrate islands.

Design element	Proposed function
Co-fabricated detectors	Tag disturbance time, location and energy with on-chip MKIDs/TESs. Use calibrated sensor tags to inform QEC decoding. [4,5]
Fast energy transport	Restrict substrate phonon transmission with cuts and narrow bridges. Use absorbers and film design to limit quasiparticle poisoning. [1]
Slow material dynamics (hypothesis)	Test whether cuts and grounded walls reduce the spread of delayed defect rearrangements, TLS drift and correlated qubit changes.

Detector precedent: BULLKID uses segmented Si with a common surface layer. [3]

Quantum-biology motivation: transient coherence may alter later relaxation. [7]

Benchmark: prompt and delayed correlations, local recovery and logical errors.
Check new surface defects, sensor back-action, heat removal and gate performance.

[1] Iaia et al., Nat. Commun. 13, 6425 (2022): phonon downconversion. [3] Cruciani et al., APL 121, 213504 (2022): BULLKID.
[4] Orrell & Loer, PR Applied 16, 024025 (2021): sensor-assisted QEC. [5] Yang et al., arXiv:2602.23544: co-fabricated devices.
[7] Pusuluk, arXiv:2604.04069v2, Fig. 3(b): quantum-biology perspective. Full references and experimental details in notes.

Conclusions: shared materials research for national priorities and HEP/NP discovery

Combine BES materials science, HEP/NP sensors and QIS quantum probes to advance national priorities and build sustained support for detector R&D.

Quantum Genesis [9]	Characterize material relaxation and correlated errors. Test integrated detectors for QEC decoding and mitigation.
CHIPS / microelectronics R&D [10]	Test stored-energy releases as sources of noise, drift and faults in cryogenic silicon and superconducting logic (SFQ/RSFQ).
HEP/NP experiments	Seek shared testbeds, fabrication access and cryogenic readout R&D for lower backgrounds, lower thresholds and new measurements.

Next step: an LLNL workshop and a proposed BES-led roundtable

Define common problems, benchmark tests and joint pilot projects.
Use demonstrated contributions to build coordinated support for HEP/NP sensor R&D.

[9] DOE Quantum Genesis (2026): scientifically relevant, fault-tolerant quantum computing.
[10] NIST CHIPS R&D / Metrology: semiconductor materials, measurements and technology development.

Afterthought: living and nonliving systems
Shared principles of memory and adaptation?



TAME: Technological Approach to Mind Everywhere [6]

Levin's framework for studying memory, adaptive behavior and goal-directed regulation across living, engineered and hybrid systems.

Question for materials

Can energy flow through interacting defects create persistent responses to drive patterns? Can brief coherence change later relaxation? [7]

Experimental connection

Combine energy detectors and quantum probes. Vary drive history and connectivity to test memory, correlations and recovery.

Possible connections to national research

Quantum Genesis: materials diagnostics for correlated errors. [9]
CHIPS / DOE microelectronics: sensing and neuromorphic hardware. [11]
BRAIN Initiative: sensors and readout for neural activity and network dynamics. [13]

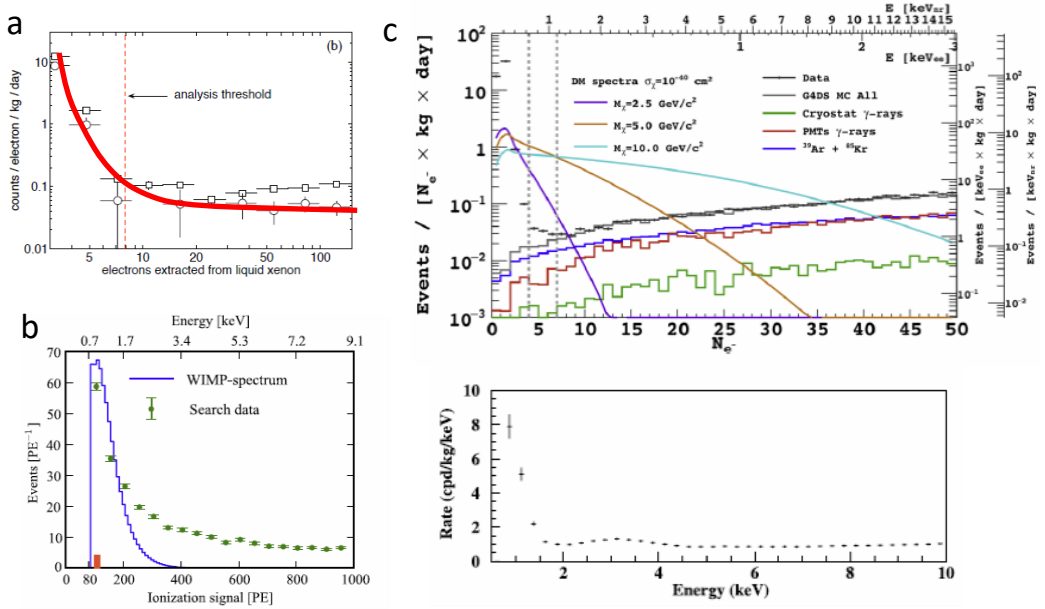
Quantum coherence adds dynamical possibilities. TAME also applies to classical systems.

[6] Levin, Front. Syst. Neurosci. 16, 768201 (2022). [7] Pusuluk, arXiv:2604.04069v2: transient correlations.
[9] DOE Quantum Genesis. [11] DOE MSRCs (2024). [13] NIH BRAIN: Neural Recording and Modulation / Systems Neuroscience.

Backup slides

Low-energy excesses across detector materials

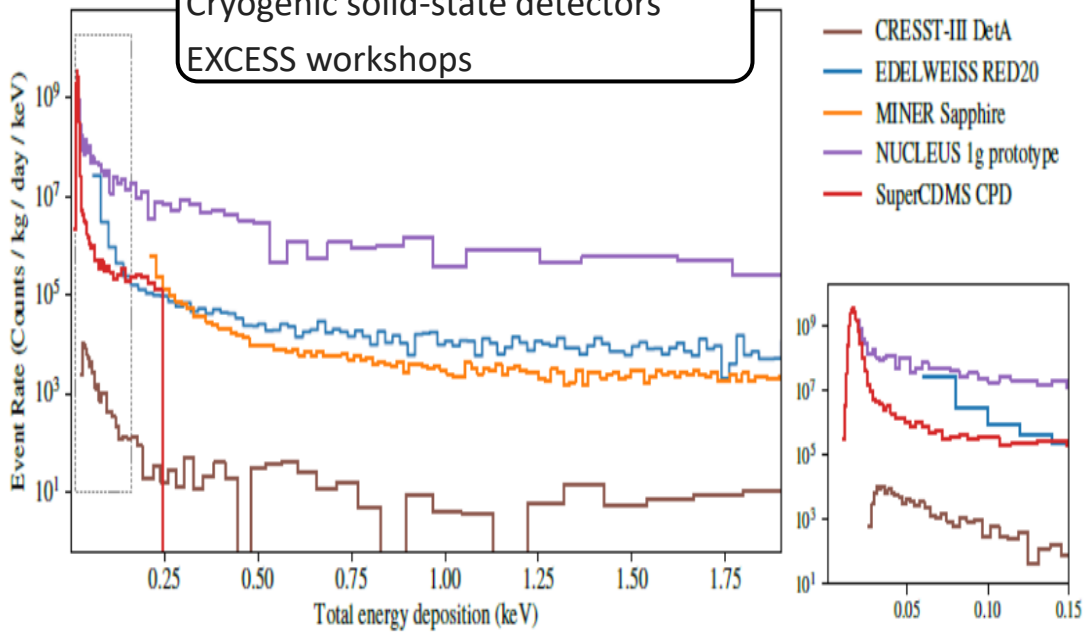
Examples of low-energy excess spectra



a: XENON10 | b: XENON100 | c: DarkSide-50 | d: DAMA/LIBRA

Cryogenic solid-state detectors

EXCESS workshops



Many spectra rise toward lower energies.

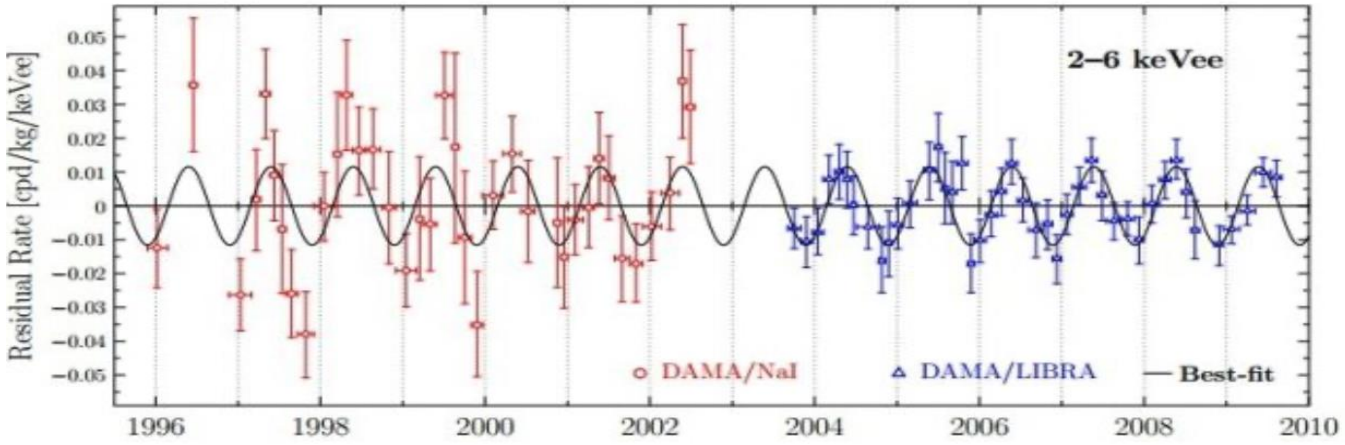
Stored-energy release is one possible source of electron, photon, phonon, or quasiparticle signals.

Similar spectra alone do not establish a common microscopic mechanism.

Driven systems and avalanche models motivate tests of event clustering, relaxation, and sensitivity to controlled excitation.

NaI(Tl) afterglow and the DAMA/LIBRA question

DAMA/LIBRA reports annual modulation at Gran Sasso.
Independent NaI(Tl) experiments have not confirmed it.
ANAIS-112's six-year result challenges the modulation.





D. Nygren: a testable stored-energy hypothesis
arXiv:1102.0815 (2011).

Optical pumping and quenching
F. Sutanto et al., Phys. Rev. D 107, 032010 (2023).

Hypotheses to test

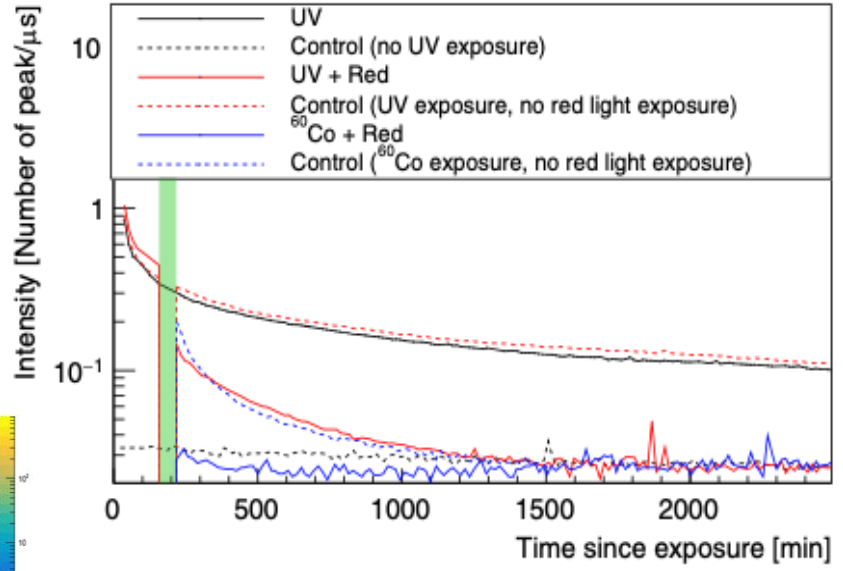
Environmental changes may alter trap populations and lifetimes.

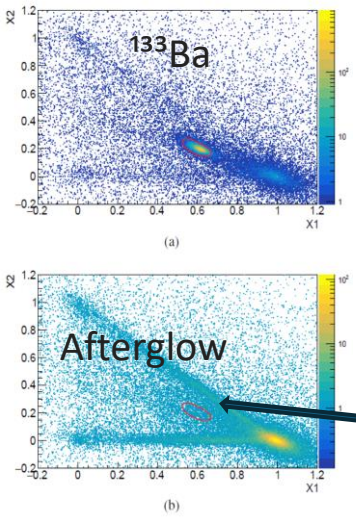
Radiation can populate or quench different traps.

A low-energy recoil may release stored energy.

Test these processes with optical pumping, quenching, and neutron exposure.





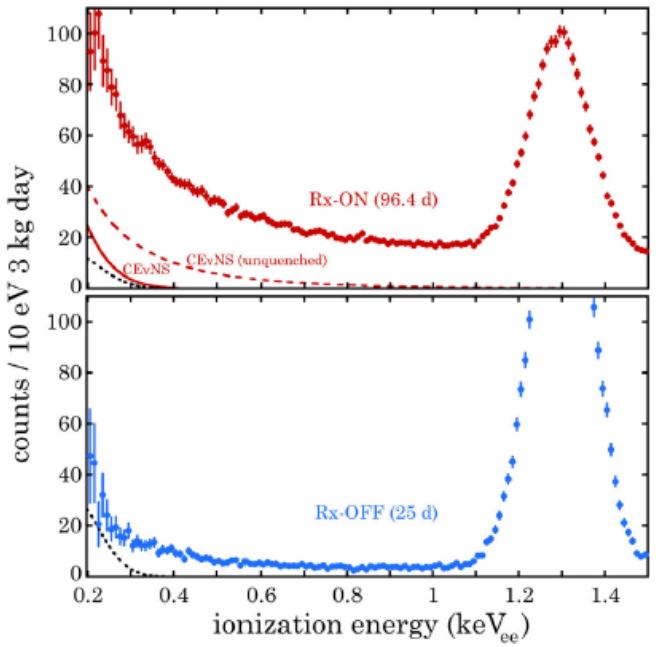


Most afterglow photons are uncorrelated. A quantitative rate and acceptance study is needed for pulse-like coincidences.

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

Could stored energy provide internal amplification in NaI(Tl)?

Semiconductor detectors and reactor CEvNS



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).

Spontaneous generation of athermal phonon bursts within bulk silicon causing excess noise, low energy background events and quasiparticle poisoning in superconducting sensors

C.L. Chang, Y.-Y. Chang, M. Garcia-Sciveres, et al., arXiv:2505.16092 (2025)

SOC-like dynamics in HPGe: energy stored by crystal defects and electron traps

computer modeling of defect production by ionizing radiation and subsequent annealing demonstrate SOC-like dynamics .

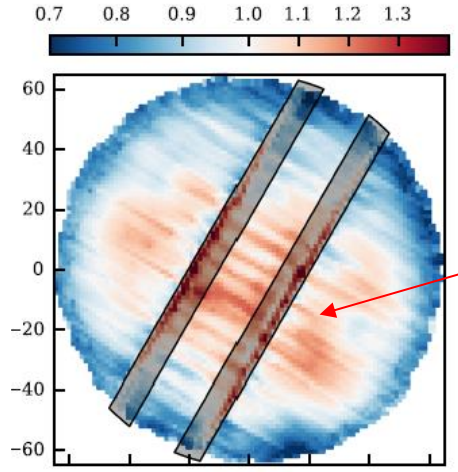
arXiv:2408.07518 [cond-mat.mtrl-sci])

Particles can pump energy in, cause quenching, and trigger avalanches.

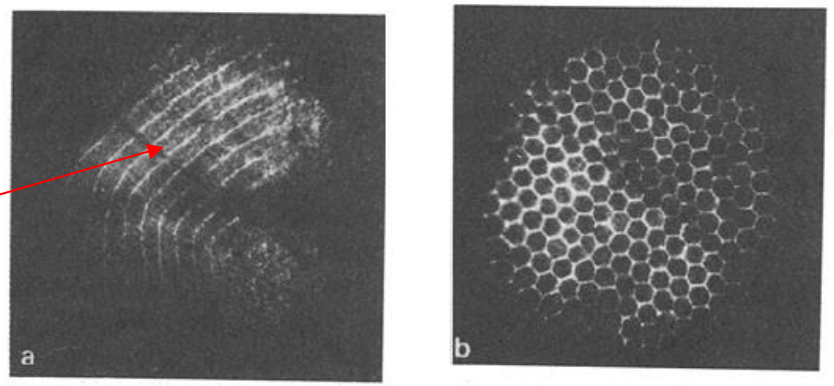
In reactor antineutrino detection with HPGe, change in reactor on/off spectra can increase (by pumping) or decrease (by quenching) low-energy excess (S. Pereverzev, Magnificent CEvNS 2025)

Progress: Case study with noble liquid detectors

1. LXe TPCs achieved exceptionally low radiogenic backgrounds; some excess instrumentation backgrounds may be related to energy accumulation
2. Studied hypothesis of unextracted electrons at liquid surface forming lattices and suppressing small signals, transforming into single-electron emission –from comparing Russian RED reactor CEvNS data and XENONnT

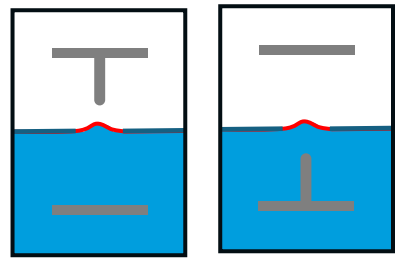


XENONnT- anomalous calibration signal at wire crossings – data removed from analysis



P. Leiderer, *J. Low Temp. Phys.* **87** (1992) 247-278

Instabilities patterns observed for liquid He. Lines can be stabilized by wire pattern in XENONnT. Lattice can be formed in homogenous field for LUX, LZ



P. Moroshkin, P. Leiderer, et al., Phys. Rev. E **95** (2017) 053110

At LLNL small signal extraction can be measured as function of surface charge state

Progress: paper comment "*Charged liquid surface instabilities and detection of Solar neutrino by XENONnT*", presented to CERN DRD meeting and CPAD2025, submitted to arXiv

Low temperatures & energies, superconducting detectors

Storage:

- **Mechanical stress, dislocations, crystal defects- in metals, dielectrics**
- **Electron, ion traps in bulk dielectrics, semiconductors, in oxide layers on metals**
- **Depleted or enriched charged layers on surfaces and interfaces, Schottky barriers**
- **Electron spins in oxide films on metals, semiconductors**
- **Localized spins, paramagnetic impurities, nuclear magnetic moments**
- **Trapped vortexes, excitations on vortex cores**

Pumping

- **particles, stress, changes of T, E, H, applied and leaking RF signals, etc.***

Sub-systems interactions:

- **through electrons (RKKY) , phonons, lattice deformations**

With cooling to mK, more material subsystems demonstrate glass-like relaxation*

*many references in S. Pereverzev, SciPost Phys. Proc. 12, 009 (2023)

We should see more EXCESS at mK and below, and at sub-meV energies

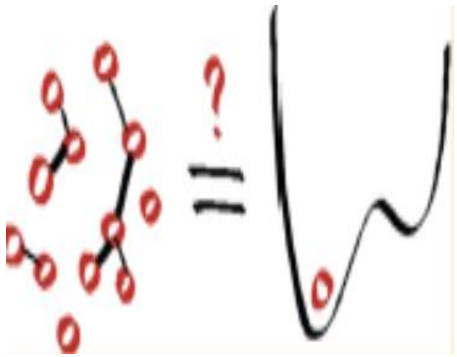
Temperature works like oiling helping to release stored energy

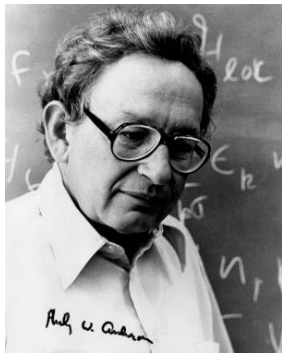
Will we see more decoherence /changes of related quantum phases?

More experiments with immersing cooling by liquid He3 needed.

While more glass-like effects at low T, surface spins thermalize better and SOC-like event at higher energies can be suppressed.

Interacting defects and correlated energy release



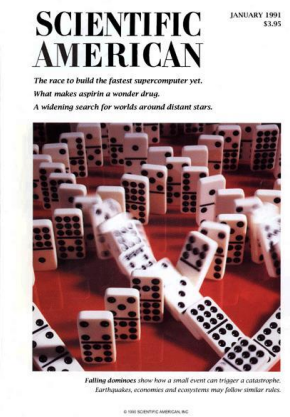


P. W. Anderson

?



Ilya Prigogine



Energy storage and release



Douglas Osheroff



Anthony Leggett

Are decisive tests possible?

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 $\rho(\epsilon, \Delta) = \dfrac{\text{const}}{\Delta}$

Microscopic realizations and interactions of two-level systems remain active research topics.

Prigogine: driven systems and dissipative structures

Bak, Tang, and Wiesenfeld: avalanche dynamics and self-organized criticality

Proposed tests: controlled pumping, relaxation, and correlation measurements.

A detector model must describe both stored excitations and their release dynamics.

Interacting-defect models and nonequilibrium mechanisms can be tested together.

P. Bak, C. Tang, and K. Wiesenfeld, Self-organized criticality, Phys. Rev. A 38, 364 (1988).

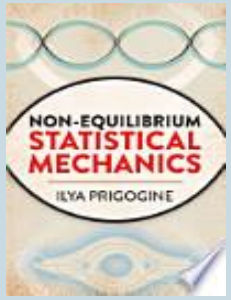
S. Rogge, D. Natelson, and D. D. Osheroff, Phys. Rev. Lett. 76, 3136 (1996).

A. J. Leggett and D. C. Vural, J. Phys. Chem. B 117, 12966–12971 (2013).

P. W. Anderson, B. I. Halperin, and C. M. Varma, Philos. Mag. 25, 1–9 (1972).

Driven systems and self-organized criticality





Ilya Prigogine

Nobel Prize in Chemistry, 1977

Systems with energy flow

Energy flow can sustain collective structures.

Interactions can correlate release events.

Classical avalanches alone do not establish quantum entanglement.

Related detector perspectives

S. Pereverzev, Phys. Rev. D 105, 063002 (2022), arXiv:2107.14397.

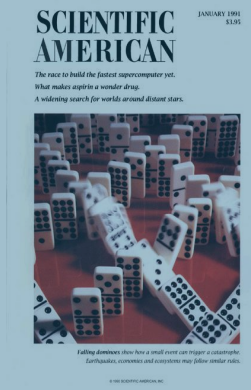
S. Pereverzev, SciPost Phys. Proc. 12, 009 (2023), arXiv:2212.13964.

Energy storage and release

Thermally stimulated luminescence, electron emission, and conductivity

NaI(Tl): a relevant example





Possible avalanche signatures

Power-law event sizes

Broad relaxation times

1/f-like noise in some models

Small triggers, larger releases

Suppression through faster relaxation

SOC requires tests of scaling and correlations.

Per Bak, Chao Tang, and Kurt Wiesenfeld

Phys. Rev. Lett. 59, 381 (1987).

Detector models need the relevant excitations, their populations, and their interactions.