Excess backgrounds in dark matter searches and superconducting photon detectors

Effects of energy accumulation and unsteady release in detectors and excess backgrounds in low-energy-threshold detectors

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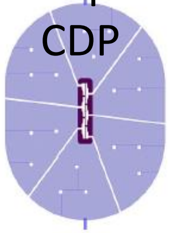
Excessive low-energy background (dark matter and coherent neutrino scattering) Variety of detectors and readout techniques

Super-SDMS-CDP



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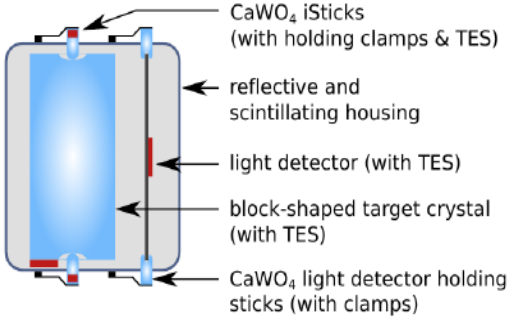
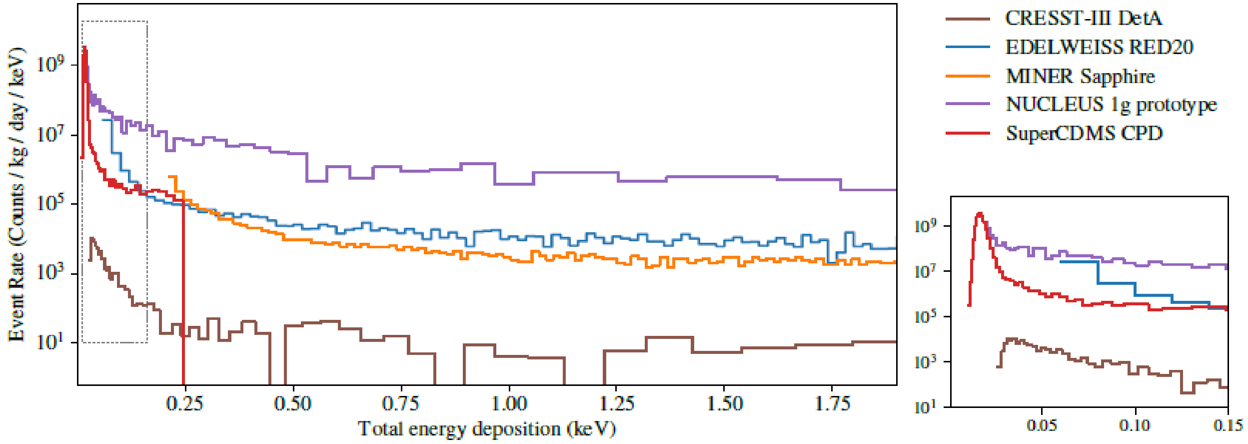
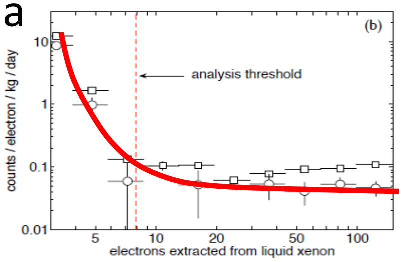




EXCESS workshop: Descriptions of rising low-energy spectra arXiv:2202.05097

a



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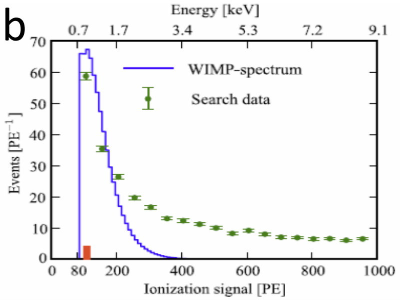

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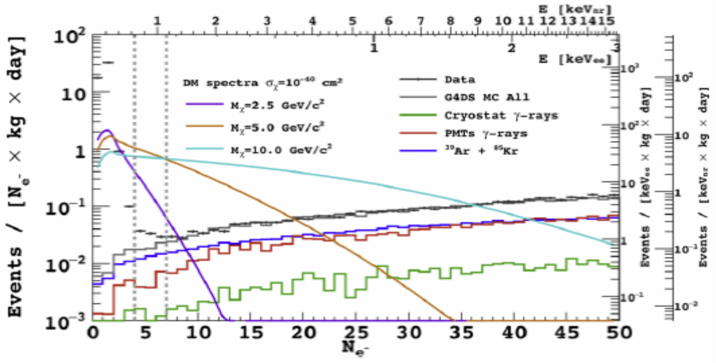

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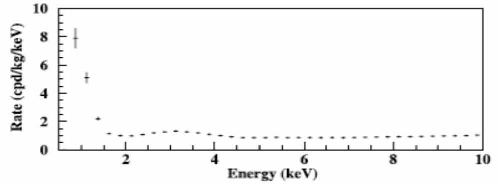


a: Xenon 10 experiment, b: Xenon 100,
c: Dark Side 50 experiment, 50 kg liquid Ar TPC;
d: DAMA-LIBRA experiment, NAI(Tl) scintillator, energy deposition of 1 keV results here in registration 5.5-7.5 photons (Nygren paper0

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

Outlook

- **Energy accumulation and delayed releases** present in many materials
- **Interactions** in between states, defects, configurations bearing excess energy **are important: emerging phenomena:** avalanche relaxation, correlations in energy releases; potentially **can mimic interactions with external particles**, produce complex effects in detectors.
- First-principles models not yet possible; knowledge of phenomenology is incomplete; **new effects are predictable by phenomenology analysis**
- Examples:
  - Energy accumulation and releases as luminescence in NaI(Tl), suppression by red light
  - Excess backgrounds in Low-temperature solid-state detectors- relaxation of mechanical stress and delayed relaxation of energy deposited by ionized radiation
  - Superconducting photon and phonon detectors, quantum sensors
  - Noble liquids (separate presentation)
- Unresolved problems in condensed matter, quantum information
- **Collaboration of HEP and BES** (Condensed Matter, Q) physicists) are required

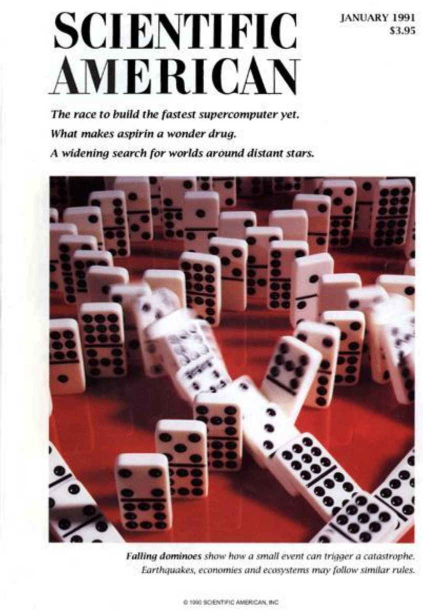
Systems with energy flow
Self-Organized Criticality

Ilya Prigogine (left)
Noble Price 1977

Emerging phenomena in In systems under energy flow

- Formation of dissipative structures
- Emerging of order out of chaos
- Emerging of complexity

Per Back, Chao Tang and Kurt Wiesenfeld   (1991 paper)
Self-Organized Criticality
Another avenue for **complexity**
1/f noise explained



Prigogine's nonequilibrium thermodynamics ideas are important for understanding of the origin of life and live system functioning, but they are applicable to many complex systems

SOC model (hypothesis) main features

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

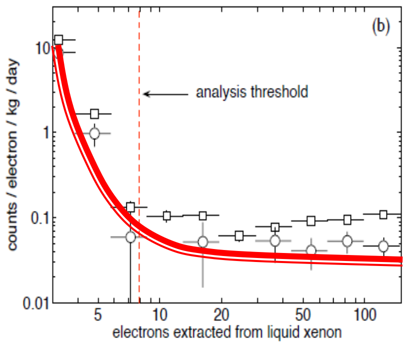
- Absence of characteristic time or size of avalanche region (a-la phase transition)

- 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…)



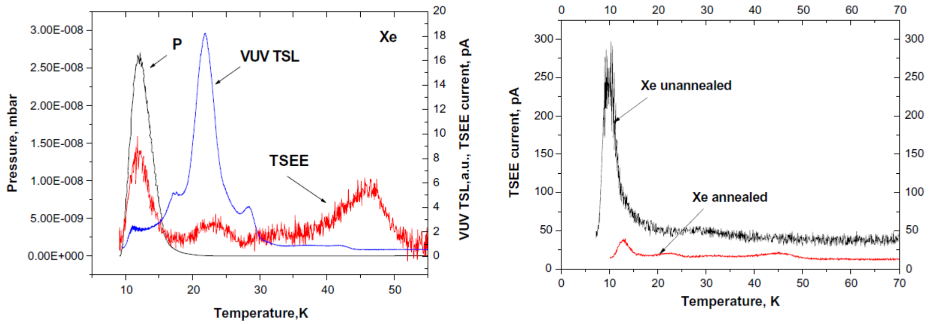
EXAMPLES

“soft condensed matter” - grows of the sand pile, when more material is added to the top and spreads horizontally by avalanches.

“hardcore condensed matter”- crack formation, a motion of quantized vortexes in the superconductor.

SOC results are obtained by computer modeling of multi-particles system with known interactions
SOC may be or may be not present; no “sufficient conditions” for the presence

Energy accumulation in material and delayed release after irradiation, stress, electric breakdown, etc.



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

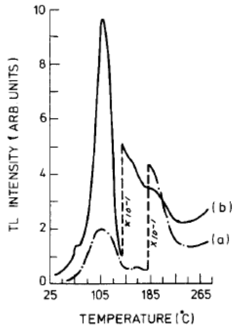


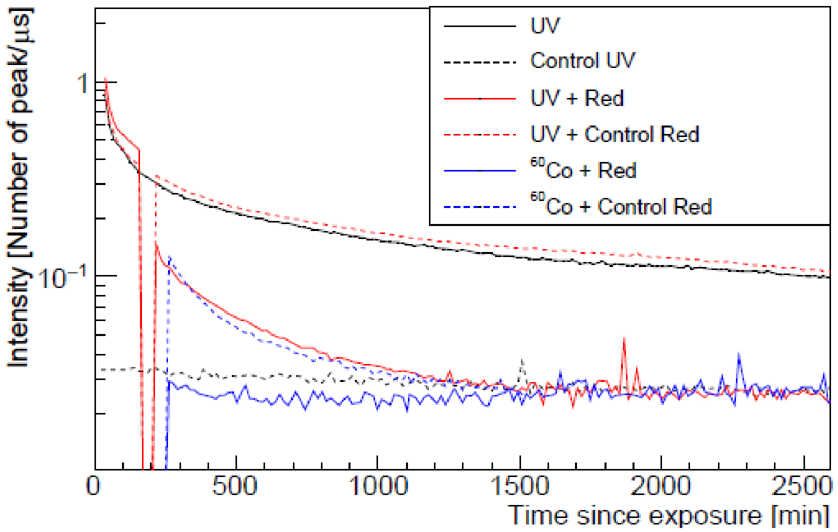
FIG. 1. TL glow curves for NaI crystals containing thallium activator: (a) 0.75 and (b) 1.5 millimolar fractions. Exposure 10^3 R.

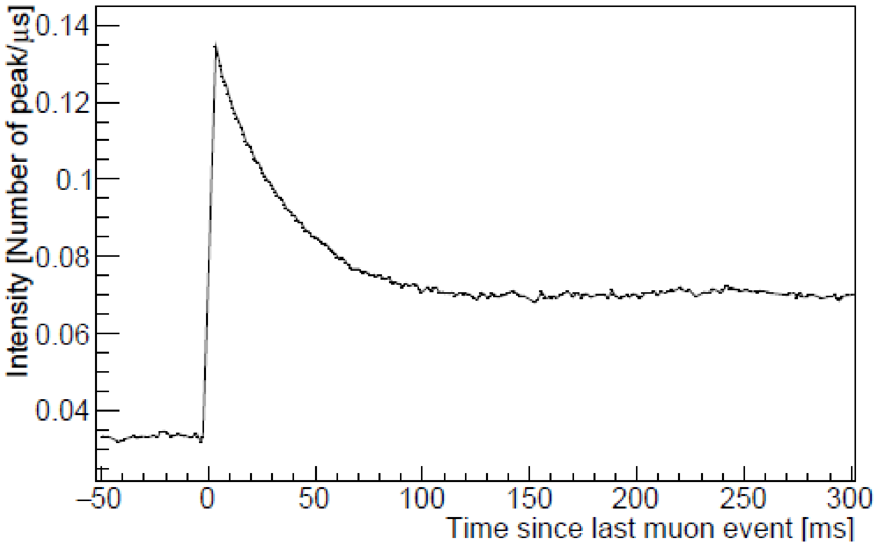
Thermoluminescence in Gamma-Irradiated NaI(Tl) Crystals Nucl. Tracs, Vol.10, pp/107-110, 1985

- ○ **Thermally stimulated luminescence, electron emission, conductivity**
- Al_2O_3(I) (personal dosimeters).
- Up to 13% of radiation energy can be converted to TSL
- Can be suppressed (erased) by sunlight and by microwave exposure.
- Light or mechanical stress are known to induce UV luminescence or electron emission in many irradiated materials.
- Thermoluminescence in alkali metal halides can be suppressed by red /IR light illumination
- Thermally stimulated conductivity in semiconductors and dielectrics.
- ○ **Mechanical stress/ deformations lead to delayed photon and exaelectron emissions from metals, semiconductors, dielectrics**
- Studies of deformations defect, dislocation motion in scanning microscopy, electron microscopy
- ○ **Noble liquids, gases- after-luminescence**, **appearance of free electrons** energy come from long-living excitations in physisorbed solid films on surfaces; slow ions and chemical radicals in bulk

Energy accumulations is possible in practically all common detector materials
Multiple pass ways for excess energy exchange between energy- bearing states/defects/configurations

Energy accumulation and releases in NaI(Tl), suppression of delayed luminescence by red light



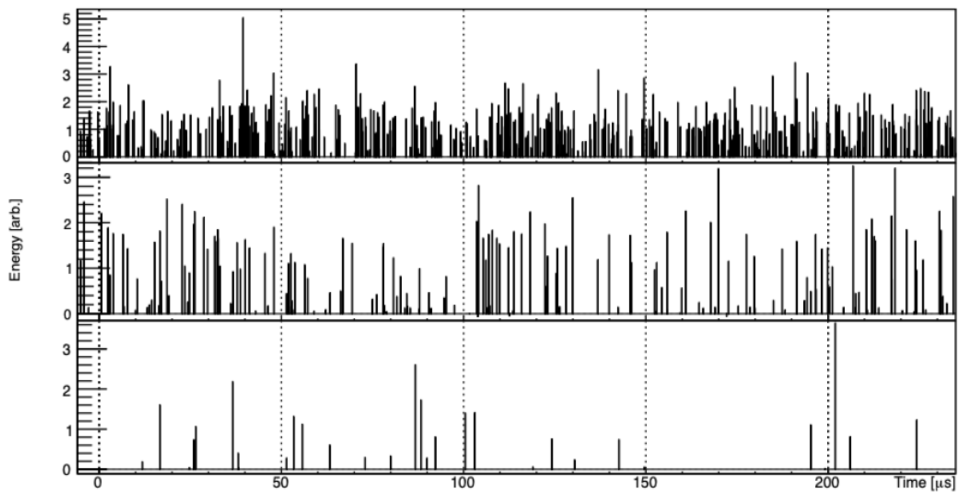


Felicia Sutanto, Jingke Xu, Adam Bernstein, Sergey Pereverzev ”Delayed luminescence in NaI(Tl),” to be published

Random triggering (from external generator) and photon counting in 1 us interval
Lasting delayed luminescence days after UV exposure, hours after Co60 exposure, present after muons.
Suppression of delayed luminescence by red light exposure after UV exposure, or simultaneous Co60 and red-light exposure.
Saint-Gobain claim: particle-like events after UV exposure -required more data analysis
(Suppression of background after red light exposure?)

Effect of red light exposure was expected ; other environmental factor also can affect delayed luminescence

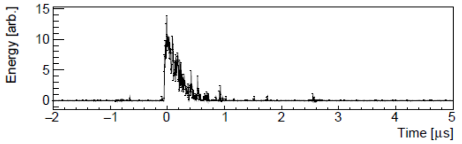
Delayed luminescence is mostly random flux of single photons, though leakage into "particle domain" is possible

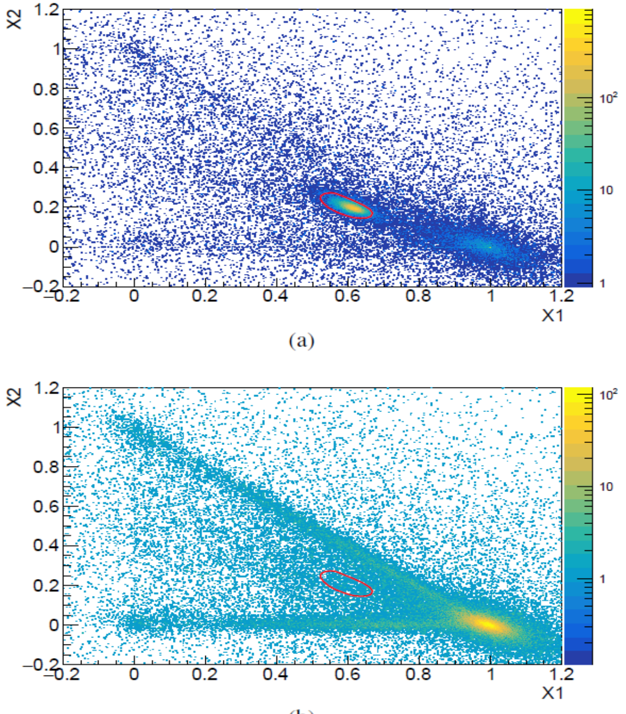


flux in 250 us data taking intervals right after UV exposure, at the middle of relaxation and close to equilibrium background

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).

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





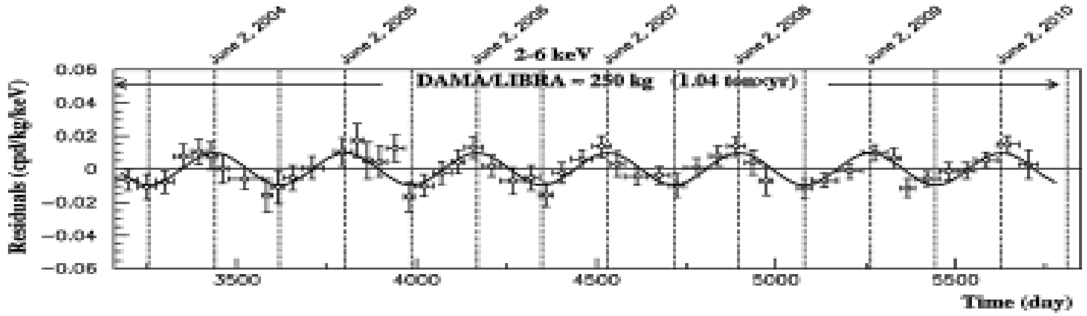
(a)

(b)

Felicia Sutanto, Jingke Xu, Adam Bernstein, Sergey Pereverzev "Delayed luminescence in NaI(Tl)," to be published

The amounts of energy in "immediate light response" and in "delayed luminescence" can be modulated by environmental factors: Temperature, pressure, electric and magnetic fields, AC modulations (Schuman resonances), microwave background, mechanical stress, and vibrations; bunching also can be modulated- so, accurate models of energy in and out fluxes are required.

Building realistic model (uncovering new phenomenology)



DAMA-LIBRA experiment
Observing yearly oscillation of low energy (1-8 kV) background for two decades; other experiments do not see this

- Delayed luminescence/background suppression by IR light (suppression of background after red light exposure?)

Effects of defects:
- On delayed luminescence
- Excitations trapping/clustering around defects- photon bunching
- Defects production (also by UV) and accumulation – irreproducibility/annealing

DAMA-LIBRA modulation phase:

- Muons and residual radioactivity: modulated energy influx
- Solar neutrinos: insufficient energy for luminescence, can trigger releases

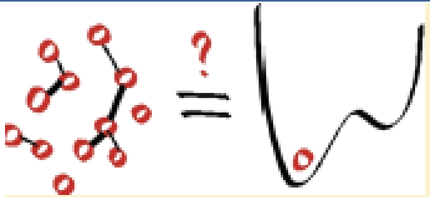
- Environmental factors (temperature, pressure ,EMF, microwaves, pressure oscillations, vibrations, etc.) can affect delayed and immediate luminescence
- No data taken on variation/phase of random delayed luminescence

- Photon bunching and leaking through pulse shape filters can be modulated by environmental factors

We do not yet uncover all relevant "macroscopic phenomenology " of the delayed luminescence microscopic processes and models - the next m complex task

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

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

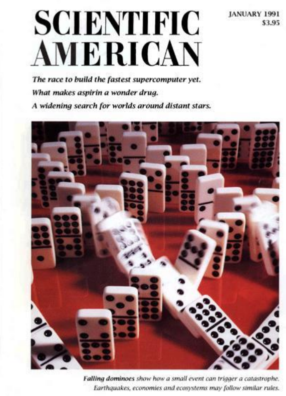
Spectrum: $\rho(\epsilon, \Delta) = \frac{\text{const}}{\Delta}$

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).

?

Ilya Prigogine



Energy accumulation and releases [3]

Dug Osheroff [1]

Tony Leggett[2]

Noble laureates criticizing TLS model

Systems with energy flow

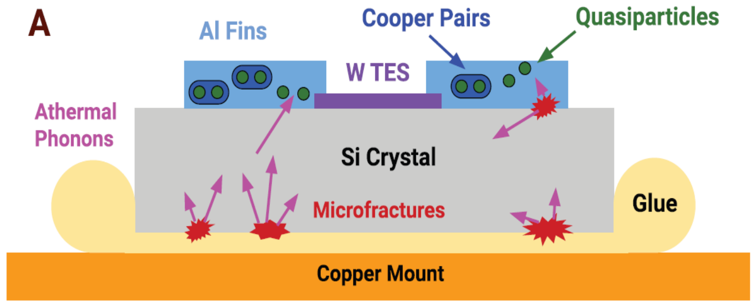
Self-Organized Criticality- like dynamics

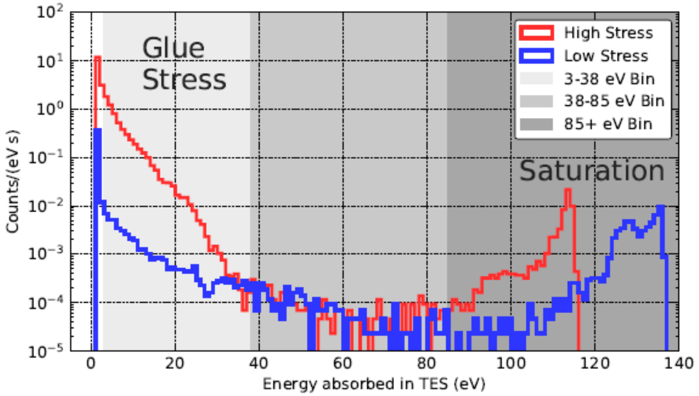
Difficulties with microscopic models for TLS [4]

- ❑ **Excess background resembles SOC-like dynamics**
- ❑ **Collabration/ joint program with condensed matter: excess background, glasses, 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).

Low-temperature solid-state detectors: phonon burst and quasiparticles production by stress and other energy sources





“Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning.” https://doi.org/10.48550/arXiv.2208.02790

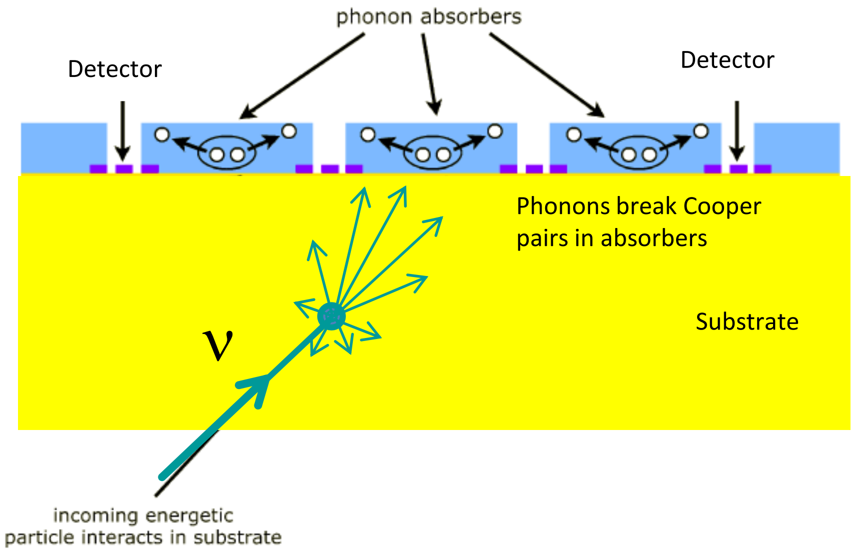
Excess background in solid-state detectors rising with stress

- Relaxation/ inelastic deformation in single crystals (semiconductors, dielectrics, metals) goes through dissipative transitions in small volumes: change of crystal structure, formation of twins boundaries, sliding plane, dislocations, dislocation motion, chemical transformation; can be accompanied by light emission and electron emission from the surface.

- In materials where irradiation led to energy accumulation (Thermally-Stimulated luminescence, Exaelectron Emission, Conductivity) one can expect burst of phonon, photons, quaseparticles, exaelectrons, etc. (see: Sergey Pereverzev, "Detecting low-energy interactions and the effects of energy accumulation in materials", Phys. Rev. D 105, 063002 (2022). https://arxiv.org/abs/2107.14397)

We cannot build first principles models yet; we can expect to find new phenomenology, glass-like effects at different energy scales; our empirical models are incomplete.

Multi-mode detection, photon imaging?

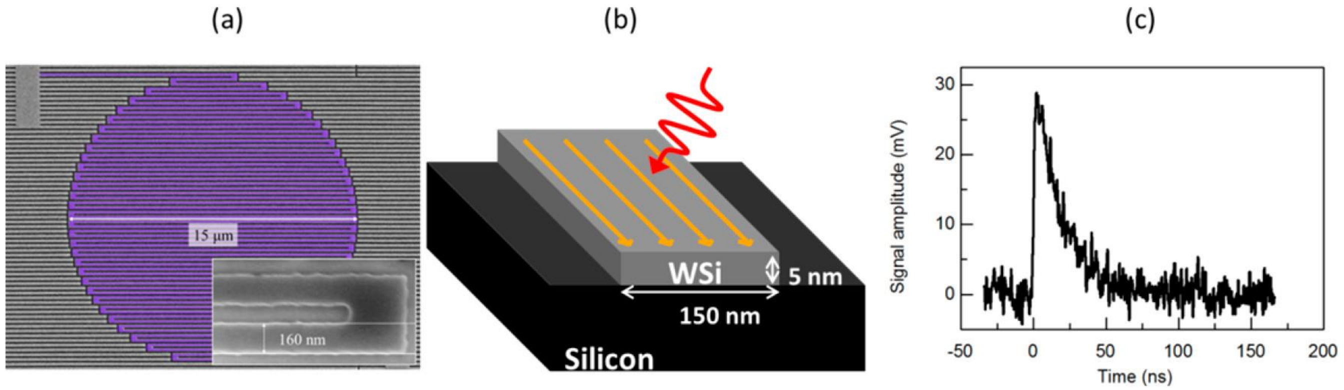


Multi-mode detection

- Simultaneous detection of photons, hot phonon, quasi-particles, magnons, etc.- can help to discriminate particles from relaxation events, or provide directionality, or other information.
- Photon and phonon detectors have stress, boundaries, trapped ions, excitons, other channels for energy accumulation and releases
- Will we see more burst-like events/spikes as energy sensitivity and time resolution of sensors are improving?

SOC- like dynamics in small low-temperature phonon and photon sensors, qubits?

Superconducting Nanowire Single-Photon Detectors



Detection of a single 5 µm photon with
Superconducting Nano-Wire Photon Detector (SNSPD).
(a) SEM image of an SNSPD with false color for clarity;
(b) (b) Absorption of a photon
produces a hotspot in a superconducting nanowire. This event destroys superconductivity across the entire width of the nanowire and can be detected as a voltage pulse -(c)
Thermal time constant = ~30 ns; Working temperature = ~250 mK-1.5 K

Li Chen et al., Accounts of Chemical Research, V. 50 pp1400-1409 (2017)
Detection of IR luminescence t photon level is demonstrated in this paper

nanowire detectors outperform other superconducting photon detectors
and PMTs in response time and quantum efficiency, low dark counts
have macroscopic sensor (pixel) areas, require cooling to 250- 300 mK, (1.5 K for Near-IR) ;
In development: large arrays, working temperature 1.5- 2 K

SOC-like dynamics and superconducting detectors & qubits

Our hypothesis: no dissipation in nanowire or substrate while waiting for photon, i.e. no energy pumping into material, so SOC-type noise production mechanism is suppressed.

Example: CMB and IR photon detectors:

<<< AC and DC heating <<< Noise equivalent power "energy sensitivity">>>

MKIDs	TES with SQUID array readout	Superconducting nanowire
Sensors are a parts of microwave resonant circuits	Sensors separated from array of SQUIDs; SQUIDS included in resonators	DC current in sensors while waiting for "click" RSFQ -compatible*

Microwave and RF signals (applied and leaking from the environment), changes in electric and magnetic fields, and thermomechanical stress are pumping energy into glass-like sub-systems in materials at low temperatures. Interactions of energy-bearing states (defects, charges, magnetic moments, spins, etc., can lead to SOC-like dynamics in sensors and qubits

Improving SNSPD and studying SOC-like effects in quantum systems

Increasing Energy sensitivity:

Decrease of temperature and decrease of Tc by:

- Materials/ impurities to lower Tc
- Suppression by magnetic field
- **Suppression by electric field in thin films**
- Removing low-lying states (including nuclear spins)*

SOC-type effects:

Pumping energy with photons below superconducting gap Should change of the dark counts

“dark states” spectroscopy

* Ultra low noise materials and devices for cryogenic superconductors and quantum bitts- US patent 10,318,880, S. Pereverzev

It is important to check if SOC-like dynamics possible in quantum sensors at low and ultra-low temperatures, i.e. in “quantum limit.” Is up-conversions possible? Spontaneous qubit transition in excited state for non-equilibrium thermal bath?

Conclusions

- **Discrimination of particles interactions from releases of stored energy in the detector materials became more difficult for small-energy interactions and rare events.**

- **We have no yet firs principle theoretical models/predictions for the dynamics of Complex System with energy flow; current empirical models seems incomplete.**

- **Similarities in phenomenology in glasses (disordered solids), relaxation of defects in solids, and energy accumulation and release dynamics points on possible new effects; making realistic phenomenological models required experiments to find boundaries of these effects/phenomenology.**

- **Checking for SOC-like dynamics in superconducting/quantum devices is important for understanding excess backgrounds in HEP experiments and non-thermal noise and decoherence.**

- **More collaboration between HEP and BES is required. These include *Inclusivity, diversity, engagement, and workforce training aspects.***

Possibilities for the “universal scenario” of energy accumulation and releases

- Energy accumulation and uneven releases
  - Different temperatures and energy scales
    - Activation over the barrier for energy release: more traps in play at low temperatures
    - More subsystem in material demonstrate glass-like relaxation properties at low temperatures
- Different energy sources/ energy pumping mechanisms:
  - Inelastic deformation/stress/thermomechanical stress
    - Produce defects, chemical transformation, electronic excitations, charges, trapped charges
  - Ionizing radiation
    - Produce ions, electronic excitations, trapped ions, defects
  - Not ionizing radiation: optical, IR, microwaves, changes of temperature, electric and magnetic field
    - In semiconductors, magnetics, superconductors, superfluid's: excitons, magnetic ordering, surface charges, quasiparticles, sub-gap excitations, quantized vortexes
  - Changes of pH, temperature, pressure, electric and magnetic field
    - In biological /chemical systems: chemical changes, molecular conformations, aggregations, etc.

Interactions between states and defects bearing excessive energy may lead to SOC-like dynamics or more complex correlations, and mimic interactions with particles.

Glasses/ disordered solids

We learn a lot about crystal materials in physics courses, but most substances around us are in a glass-like state

Relaxation processes in glasses at temperatures below glass transition became long, non-exponential, history-dependent

The time scale for relaxation could be long: from milliseconds to days and years;
Many types of relaxation processes:
Mechanical deformations (flow)
Changing of electric polarization when an electric field is applied,
Changing of optical transparency (level burning, when notch spectral transparency is induced by a powerful laser pulse)
Changes of Magnetization or magnetic susceptibility; spin glasses
magnetic moments (spins) can be positioned in a perfect crystal lattice; not a geometrical disorder,
but the presence of multiple energy minima as a function of magnetic moment orientation, frustration

History-dependent relaxation indicates that relaxation depends on the internal state of the material;
Excessive energy can be present; photon and electron emission after inelastic deformation are examples

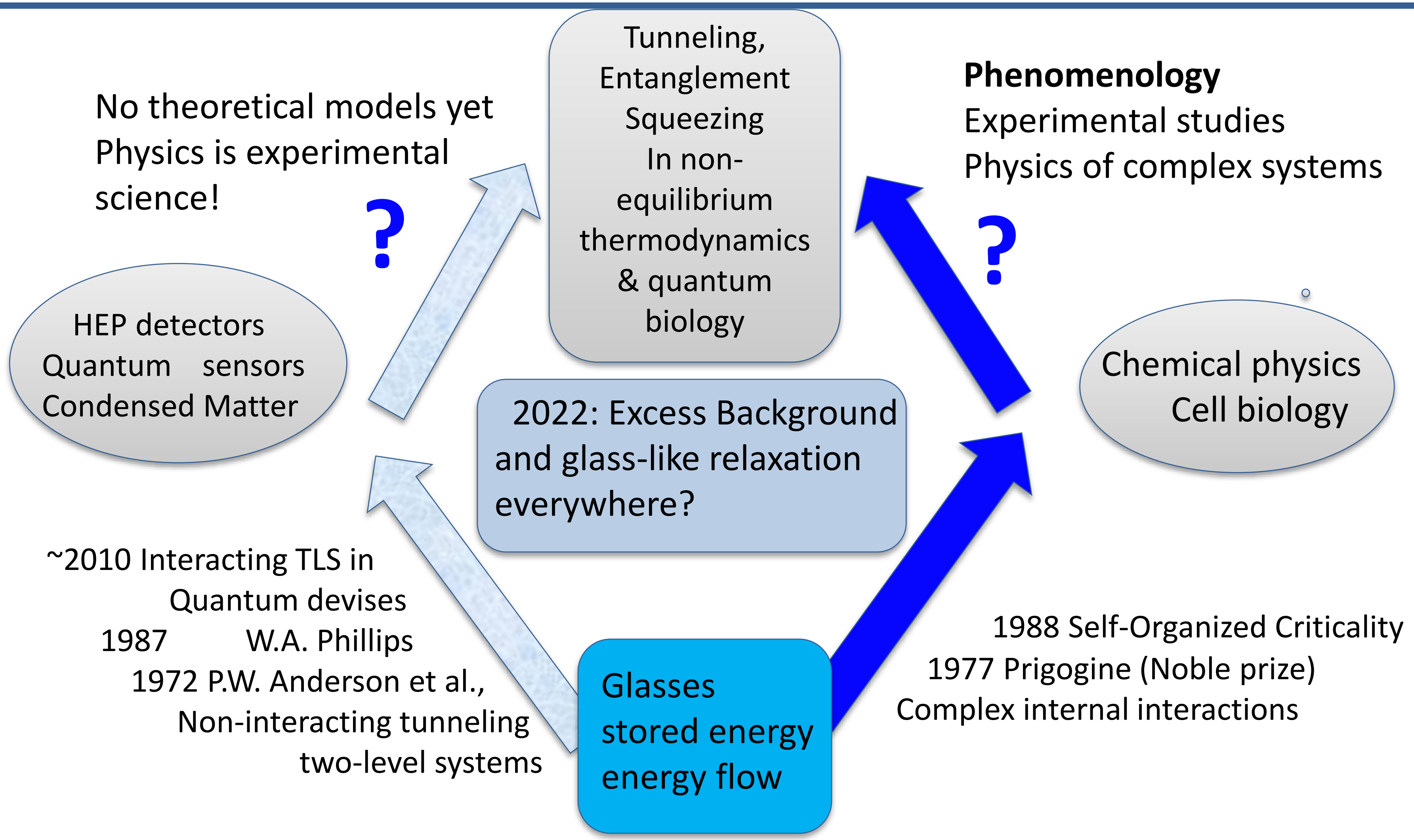
With cooling, more subsystems in materials can demonstrate glass-like relaxation: defects in crystals,
charges accumulate on surfaces and in bulk, magnetic moments and nuclear spins in metals and superconductors, etc.

Superconducting Nanowire Single Photon Detectors (SNSPDs)

Invented/ demonstrated	Wave Length	Working Temp	Pixel Size/ array size	Quantum efficiency	Dark counts	Time resolution
~2010	1-10 mm/	0.3- 1 K	30-100 mm/ > 1000 pixels	Internal ~1; 50-70%	~0;	~50 ps
Professor Gregory Goltzman, Moscow	Development to sub-mm? Hot phonon detection?	Low cooling power: cryocooler cryocooler +ADR cryocooler + ^{3}He	optimization for focal plane, spectrometer	Optimization for wavelength	SOC –like noise suppressed? No dissipation by readout!	Molecular dynamics studies possible
Current applications:	Space IR astronomy, long-distance communications, lidars, quantum communications, dark matter searches, IR spectroscopy					
Future development	Space microwave astronomy, quantum – room temperature computer interface, axions detection, CEvNS detectors, study of material sources of athermal noise & decoherence, **IR luminescence spectroscopy of live cells (IR BIOPHOTONICS)**					

Potentially breakthrough technology; important to bring to LLNL

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



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

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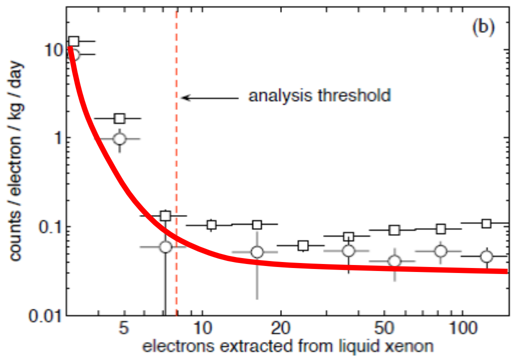

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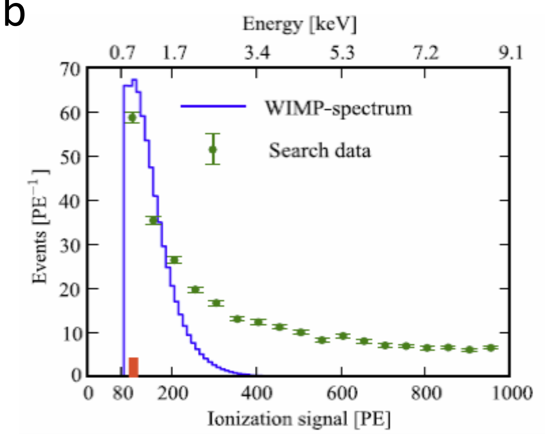

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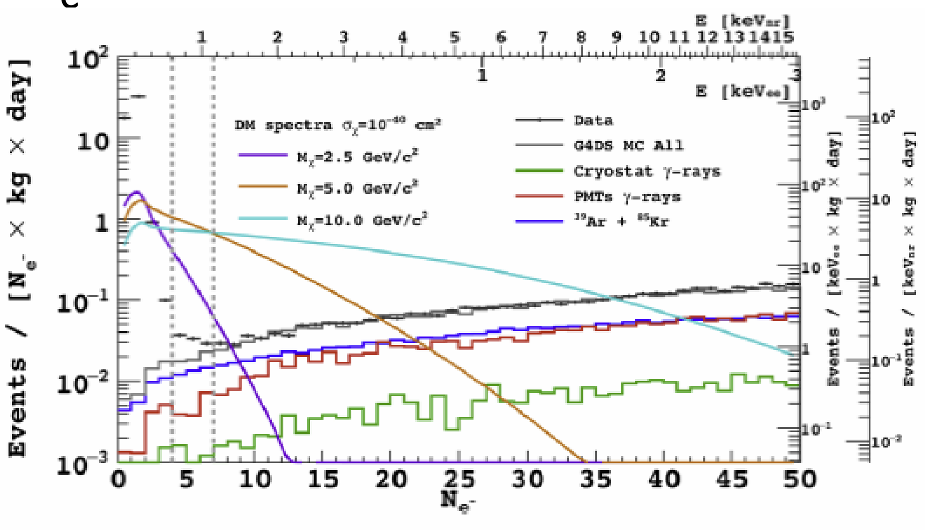

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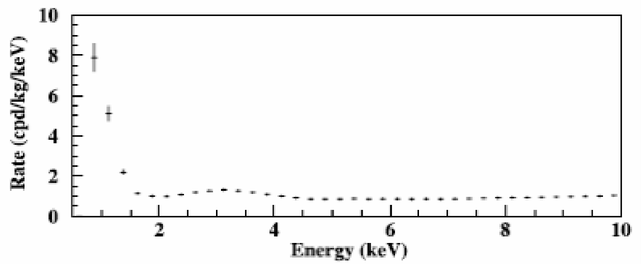

Dark matter particle detectors operating underground (low background). A: Xenon 10 experiment, 10 kg liquid Xe TPC; analysis of electroluminescence signal only; red curve illustrates contribution we expect due to energy accumulation effects in materials. B: Xenon 100 experiment, 100 kg liquid Xe TPC, analysis of electroluminescence signal only; the ~20 photoelectrons registered by PMTs in this experiment correspond to 1 electron extracted from the liquid; excessive few-electron noise is present, C: Dark Side 50 experiment, 50 kg liquid Ar TPC; small signals (below ~5 electrons) are excluded from this analysis; authors admit that they do not understand the excessive background in the range of 4–7 electron events; 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

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

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