Stored energy releases: material problem in dark matter search and quantum computing

Sergey Pereverzev
LLNL, **R**are **E**vents **D**etection Group

"We are nearing another scientific revolution"
Ian Shipsey   at CPAD 2021
"Studies of excess background mechanisms are Blue Sky projects"
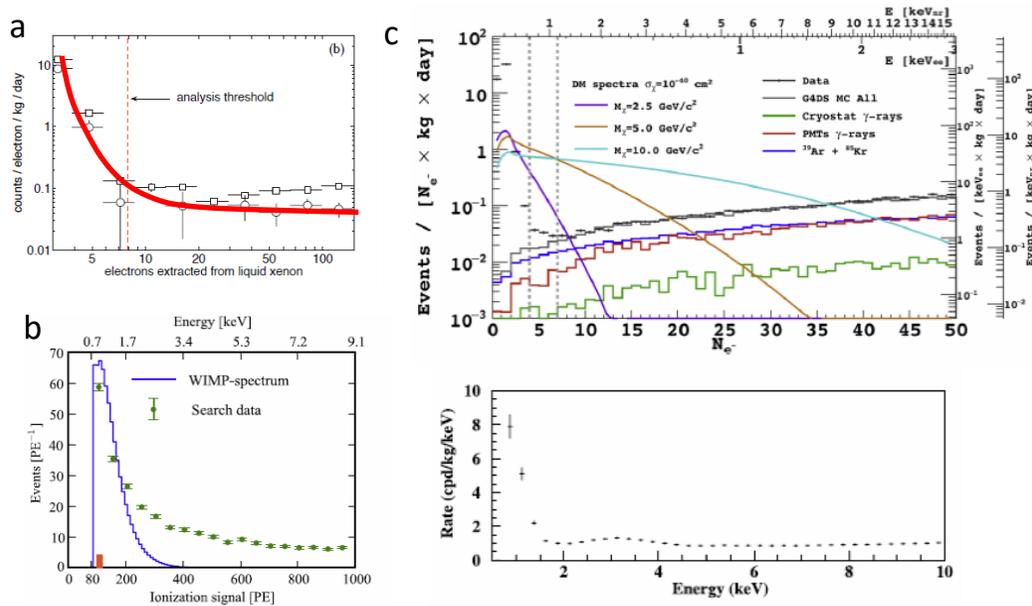Helmut Marsiske at CPAD2024

Ian Shipsey, 1959-2024

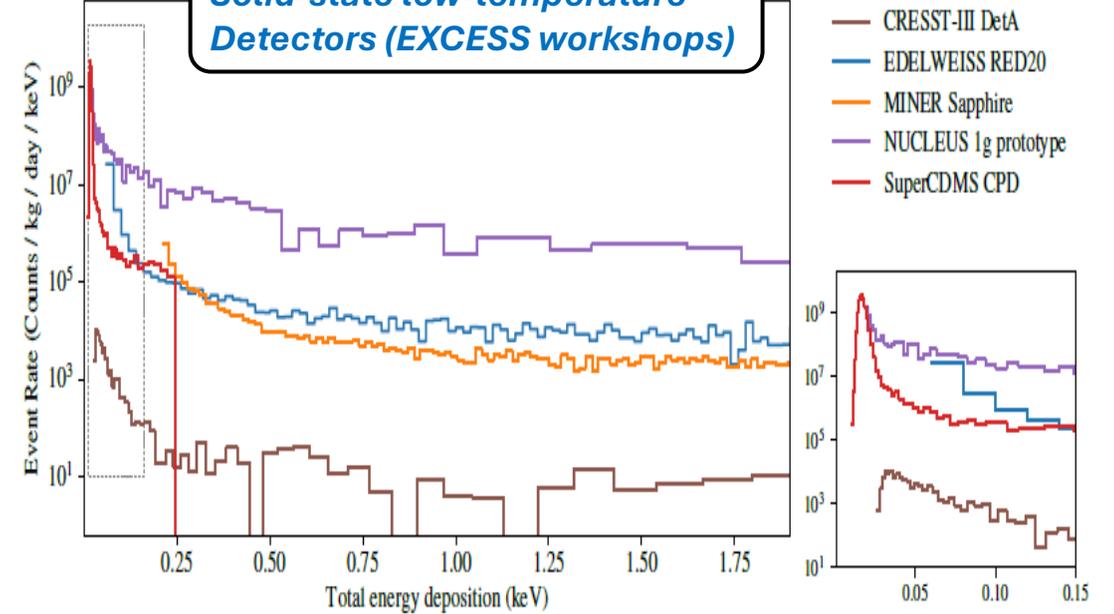Lawrence Livermore National Laboratory

Similar excess background spectra and scenarios

Excess : 20 years of dark matter searches

Solid-state low-temperature Detectors (EXCESS workshops)

a: Xenon10,
b: Xenon100,
c: DarkSide50
d: NaI(Tl),
DAMA-LIBRA

Number of events rises sharply toward low energies

Energy often coming out as burst of photons, phonons, quasiparticles, electrons

clear examples of energy coming out-

not quantum or thermodynamic fluctuations!

Ilia Prigone's system with energy flow

Computer models (SOC theory) suggest 1/f power noise spectrum and reverse-polynomial distribution for avalanche energy releases

Energy accumulation and releases phenomenology

❑ **Present in solids, gases, liquids, solids, and surfaces and interfaces**

❑ **Storage:**

Stress, defects, chemical energy, metastable electron states and traps in bulk and surfaces

❑ **Releases:**

Light, heat, exaelectron emission, conductivity burst

❑ **Activations/triggers:**

Thermal, mechanical, photons (UV-microwaves), particles, tunneling

Examples:

Thermally-stimulated luminescence (personal dosimeters) –in NaI(Tl), solid Xe & Ar

Thermally stimulated exaelectron emission (solid Xe & Ar)

Thermally stimulated conductivity (semiconductors, dielectrics)

Light-induced luminescence (more energetic photons emission)

No examples of material where these effects are absent
Liquid surface charges obscure these effects in Xe detectors

Energy accumulation and releases effects are common, but no adequate theoretical models to estimate excess backgrounds.
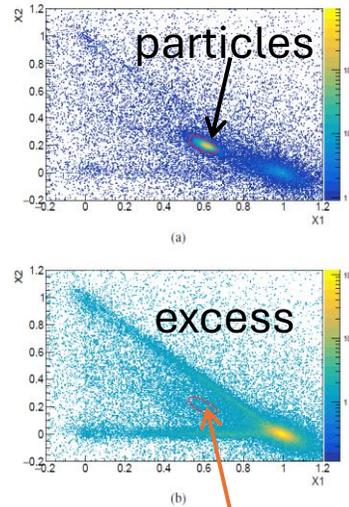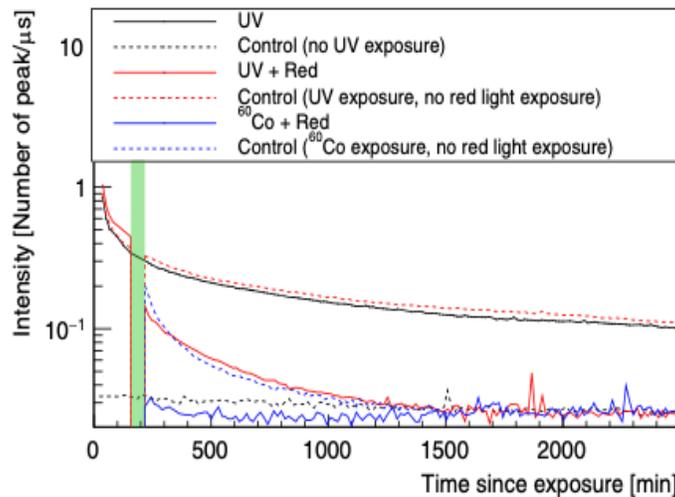
Takeaway points

❑ **Excess backgrounds –events of energy releases -contradict expectations that noises are decreasing with cooling till eventually reach plateau due to quantum diffusion, tunneling , multi-particle tunneling. EXCESS points on basic condensed matter/ thermodynamic problem.**

❑ **Excess / delayed backgrounds present in LUX/LZ, ADMx-G2, Sper-CDMS-SNOWLAB, (about 8-10 % of Cosmic Frontiers budget), affect searches for CEvNS of low-energy reactor and solar neutrinos in HEP intensity frontiers and NP. Studying these effects would be Blue-Sky projects.**

❑ **Relevance to QIS: energy releases/ energy accumulation and release dynamics mimic particle interactions and should lead to correlated quantum errors and decoherence but are much more frequent** (not only energy down transition of qubits, but spontaneous up-transitions are observed).

Questions: can we detect and use (for sensing)
destruction of 'superposition state
Change of relative phases in superposition state

Learning from examples:
Common approaches to material-specific mechanisms

UV exposure, muons produce after-luminescence
(days after UV) . Can be quenched by red /IR light.
Random photons flux, but photon bunches can pass through
DAMA-LIBRA pulse-shape filter. **Phys. Rev. D 107, 032010 (2023)**

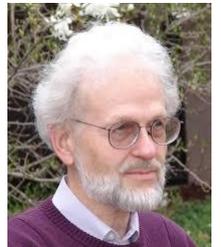## NaI(Tl) and DAMA-LIBRA: storage by electron traps

Testable Hypothesis 1: *Flash irradiation with red/IR after muons/large events will remove seasonal modulation (by energy quenching).*

Modulation by neutrino / dark matter triggering energy releases?

Testable Hypothesis 2: *If one pumps energy by UV, low-energy nuclear recoils by neutrons produce detectable signals (Nano-explosive detector) .*

S. Pereverzev , CPAD2024

Energy accumulation and releases in DAMA-LIBRA first suggested by **David Nygren**
arXiv:1102.0815 (2011)

Semiconductors and 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)

Cross-cutting comparisons of material-specific effects are important
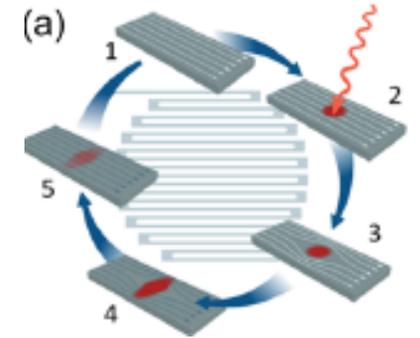
SNSPD, MKID, Hot-electron nanobolometer, TES :
Puzzling observations and possible resolutions

(a)

o **SNSPD and MKID with Al nanowire sensor detect mid-IR photons with low dark counts (no excess?)**

– Main source of EXCESS is microcracking. Low sensitivity to hot phonons because of small nanowire volume. Phonon to electron energy transfer depends on volume.

o **Recovery time (at 250 mK) : SNSPD – ns scale, but "nanowire MKID" at ms scale**

– For Al type 1 sensor, quasiparticles recombination restricted by electron-phonon interaction; and cooling time ~$1/T^3$. Voltage pulse in type II nanowire with high bias current could be due to vortex flow avalanche with low quasiparticles production

No pair breaking by signal photon but vortex avalanche in type II nanowire

o **Volume of hot electron nanobolometer (Ti nanobridge with Nb contacts) is small, but dark counts large ---**
    – in SNSPD and MKID no pairbreaking/*minimal losses by readout*.Hot electron nanobolometer ,(and TESs) operates on transition with losses /pair braking by applied bias current

o **Can microwave losses lead to energy accumulation in dielectric substrate and in sub-gap states to increase dark conts?**
    –good question for experiment

Cross-device comparisons leads to experimentally-verifiable questions and ideas of practical importance for detector and qubits
Standardizing relaxation properties- different sensors on same substrates
Eventuallyat low energies (differentiating relaxation and particles signals

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)

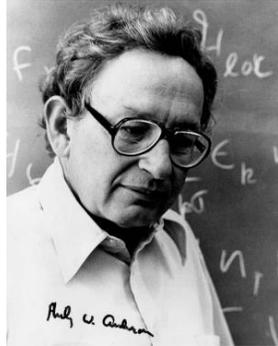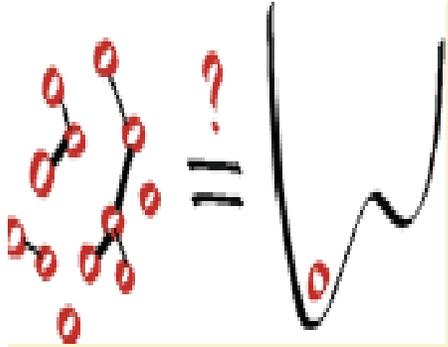# We should see more EXCESS at mK and below, and at sub-meV energies

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.

Tunneling Two-Level Systems
or energy accumulation and correlated releases?

IP.W, Anderson

?

Ilya Prigogine

Energy accumulation and releases

Dug Osheroff

Tony Leggett[

are "smoking gun" test 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 $\rho(\epsilon, \Delta) = \dfrac{const}{\Delta}$

Still, small number of microscopic models for TLS

Systems with energy flow (Prigogine): dissipative structures, irreversibility, complexity, order out of chaos (Noble prize 1977)
Self-Organized Criticaliy: complexity, 1/f noise explained (1988)

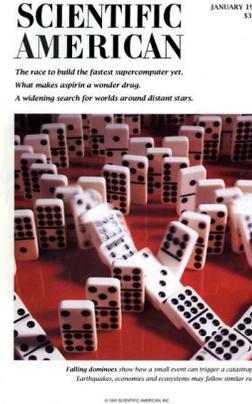## Is "smoking gun" test allready here?

TLS model incomplete- energy source and release dynamics are "outside"
We do not know all excitations and interactions to build realistic numeric models

1. Per Back, Cho Tang, and Kurt Weisenfeld, "*Self-organized criticality: An explanation of 1/f noise*", Phys. Rev. A 38, 364 (1988).
2. S. Rogge, D, Natelson, and D. Osherof, *Evidence for the Importance of Interactions between Active Defects in Glasses*, Phys. Rev. Lett. 76, 3136, (1996).
3. 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).
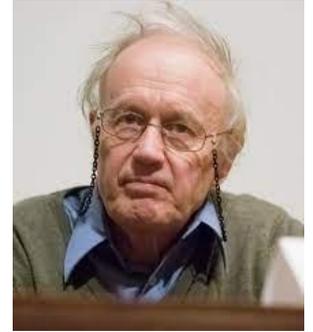4. P. W. Anderson , B. I. Halperin & c. M. Varma Philosophical Magazine, 25:1, 1-9 (1972),

Cross-cutting group /RDC on non-equilibrium dynamics

Cross-cutting group -RDCs7&8- or new RDC- will allow more inter-disciplinary connections, more effective studies and understanding of fundamental effects
Collaboration with RDR5/RDq (CERN): RDR5 already developed long-term plan.
We can explicitly formulate fundamental science   questions in condensed matter, thermodynamics and quantum physics and work in collaboration with BES and QIS divisions within DOE

New inter-office collaborative   program is difficult to organize
We can use existing collaborative centers and programs within BES and QIS
 and recent NOFO **DE-FOA-0003600**

cross-cutting group/RDC will have direct and immédiate goals - 1.to inform managers of existing programs how we can help in their programs using detector techniques and 2. to participate in their meetings to discuss common fundamental scientific and technical problems, so they can help us with EXCESS.

Examples: HEP–QIS (QuantISED) on the HEP side; and, on the BES side, **Experimental Condensed Matter Physics** (explicitly non-*equilibrium* and *metastable* states), **Theoretical CMP** (*out-of-equilibrium quantum dynamics*), **Physical Behavior of Materials** (defects, superconductivity, transport in complex/disordered systems), plus **QIS in MSE** and **Scattering** programs (X-ray, Neutron, Electron/SPM) that emphasize **dynamic, transient** phenomena and ultrafast measurement.

Actions list/programs and connections

Detector R&D (Blue-Sky): Helmut Marsiske.
 HEP–QIS (QuantISED): Zachary Goff-Eldredge
Cosmic Frontier (Dark Matter): Manuel Bautista; Kathy Turner, **Bryan Field**
 BES / MSE ECMP: Claudia Cantoni, Tim Mewes.
TCMP: Matthias Graf, Claudia Mewes.
PBM: (MSE program).
QIS in MSE: Athena Sefat.
X-ray / Neutron: Helen Kerch.
 Electron & SPM: Jane Zhu.
BES Collaborative Research Division (gateway to EFRCs/Hubs/Earth shots):
new division announcement (context + role).
QIS Centers (NQISRCs): SC program pages & lab call.

Would we succeed (in short time) to get programs/managers interested; we feedback this information and responses for all HEP RDS.
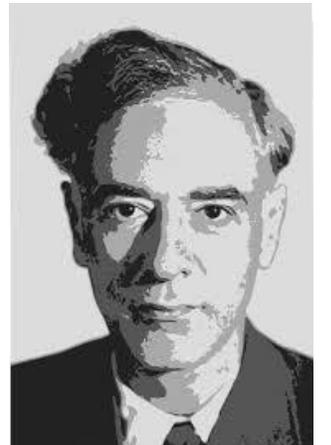
Can we have support to do this (I FTP between RDC7&8?)1/?

Conclusions

❑ Non-equilibrium effects are strongly connected to the excess backgrounds in neutrino and dark matter particles detectors, excess (non-thermal) noise in quantum (superconducting) sensors, and decoherence & quantum errors in qubits.

❑ It is a s fundamental as energy conservation: while stored in metastable states and defects, it is coming out unsteadily and capable of producing measurable and confusing effects; stored energy need to be accounted

❑ We have a large work to characterize and standardize relaxational processes in many materials on production photons, phonons, quasiparticles, and effects this produce in different sensors. It is ongoing- at EXCESS workshops (but need be broader). Material mechanism are different, but general scenarios are common- coordination and ideas exchange inside HEP RDCs and DRD5/RDq are important.

❑ We encounter basic material problem, and HEP can investigate it faster and deeper in collaboration with BES and QIS divisions. We need reach out, translate problems on common languages, and have it included in BES and QIS calls, plans for existing and planned interdisciplinary centers. **This is immediate and clear task for cross-cutting RDC.**

"A method is more important than a discovery, since the right method will lead to new and even more important discoveries"

Lev Landau

Lev Landau 1908-1968
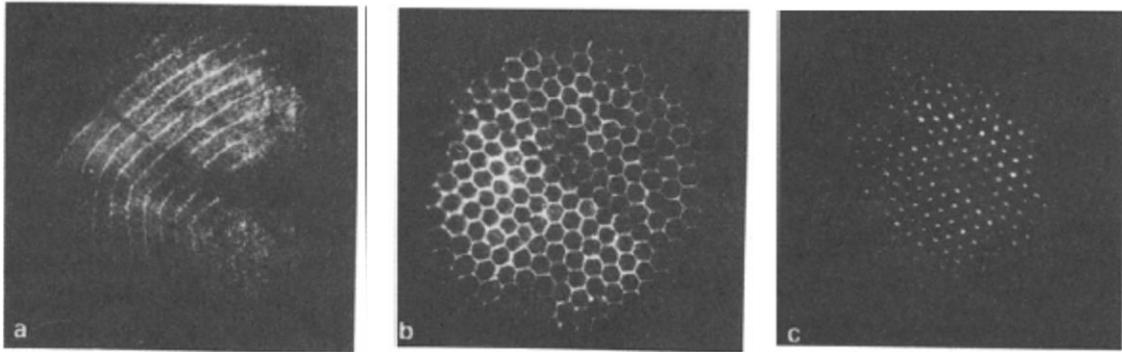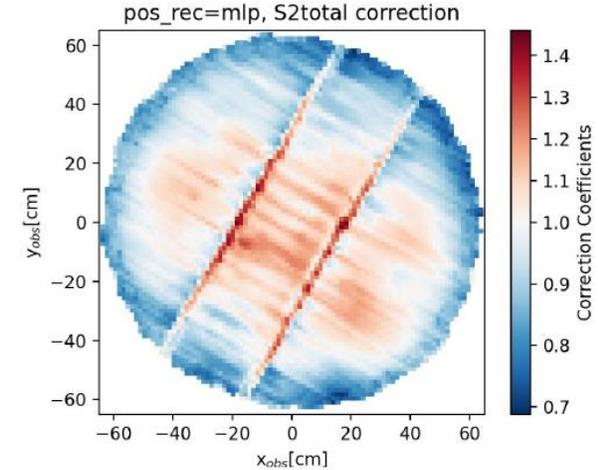
Additional Slides

Connection to AI

How to train AI to look for contradictions in explanations of experimental observations and in existing research programs, and look for inter-disciplinary connections and analogies?

Material-specific effects in noble

Noble liquids dual-phase detectors- small apacity to store energy and charge (chemical radicals in bulk, liquid-gas interface trapped charges). Russian detectors (RED1, ZEPLINIII, RED100) take care of interface charges and see excess /delayed backgrounds. Charges accumulation on liquid surface can suppress extraction of small signals (few electrons) and LUX, LZ , XENONnT may lost sensitivity both to particle signals and delayed emission. Taking care of interface charges and removing impurities should help to avoid confusion and suppress delayed few-electron emission background

S. Pereverzev 2023 *JINST* **18** C07011 **also at CPAD2024**

pos_rec=mlp, S2total correction

([19]). Schlieren images (shadowgraph) of the surface deformation approximately 2s (a) and 6s ((b)and (c)) after the field had been increased above critical value E꜀. The image plane was chosen that convex deformation of the surface (local maxima) appears bright in (a) and (b); in (c) bright correspond to local minima (dimple's bottoms). The distance between adjacent rows of dimples is close to 0.24 cm.

XENONnT- many charged liquid surface effects: single electron emission, enhancement of signals, change of pulse shape – at same locations of wire crossing

XENONnT and LZ have different extraction grid design, and may have different pattern of charged surface instability. Lines in XENONnT and lattice of hillocks in LZ. Surface mobility and mechanisms of charge removal can be different, and so delaye emission and variation oin electron extraction probability. LZ result on solar neutrino can be contradictory to XENONnT results.

Crocodile problem

Peter Kapitsa

Ernest   Rutherford

Kapitsa commissioned Eric Gill (who he considered "the leading sculptors in the modern school" in England) to produce a plaque featuring Rutherford's profile, and an engraving of a crocodile - nickname for Rutherford (cannot look back)
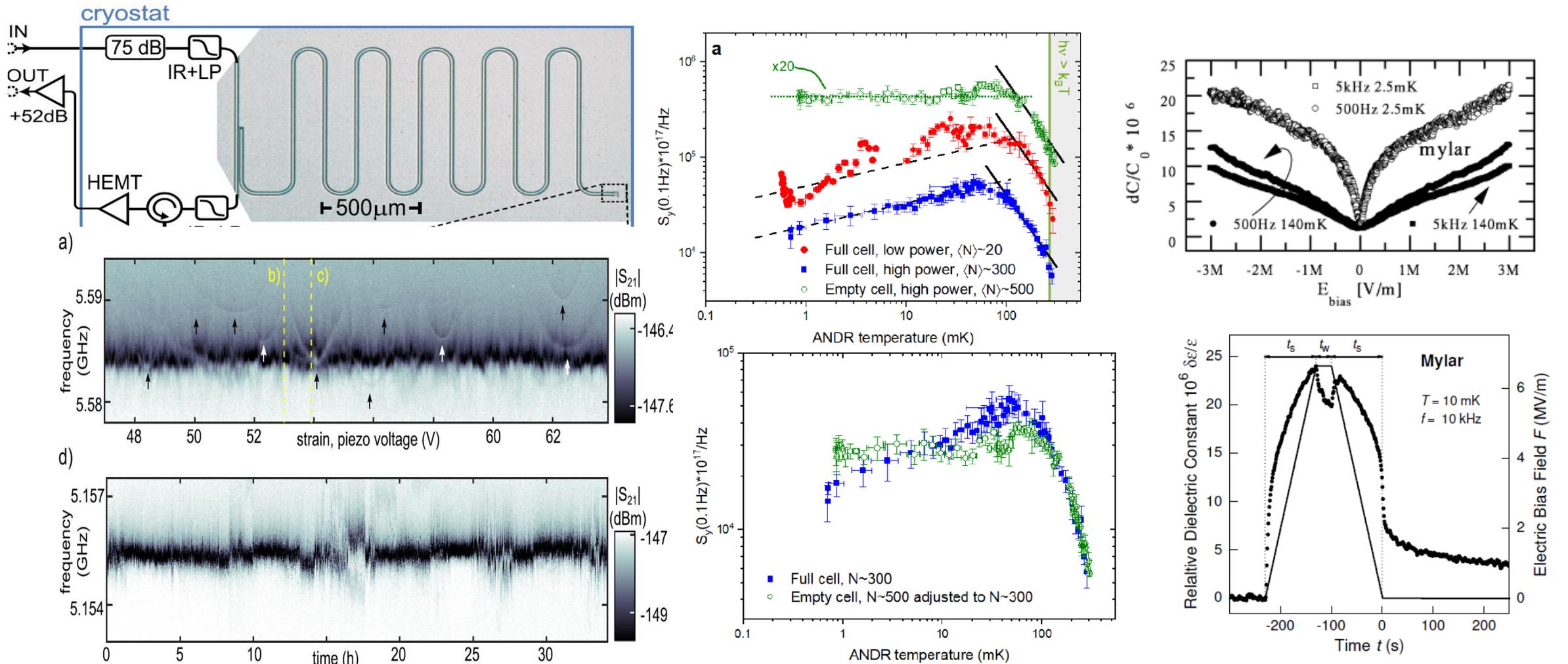
Still on the wall of the Mond Laboratory (since 1930)

We have a crocodile problems with TLS & SOC, and with Xe detectors

Re-examine the role of TLS and SOC-like dynamics in noise and decoherence

Clarify effects of electrons on liquid Xe / Ar surface -for 3% of XLZD cost

Most unexpected: With huge bandwidth of SNSPDs, we can non-invasively "visualize" live cell processes in real time using luminescence IR spectroscopy

Non-equilibrium effects: material flow & defects, stress & strain, interactions of bulk and surface processes

J.D. Brehm, A. Bilmes, et al. Transmission-line resonators for the study of individual two-level tunneling systems. *Appl. Phys. Lett.* 111, 112601 (2017)

Lucas, M., Danilov, A.V., Levitin, L.V. *et al*. Quantum bath suppression in a superconducting circuit by immersion cooling. *Nat Commun* **14**, 3522 (2023).

S. Rogge, D, Natelson, and D. Osherof, *Evidence for the Importance of Interactions between Active Defects in Glasses,* Phys. Rev. Lett. 76, 3136, (1996).

Memory effects in amorphous solids below 20 mK- Phys. Rev. Lett. **90**, 195501 (2003), non-equilibrium dynamics...- JLTP, V. 137, p.925 (2004)
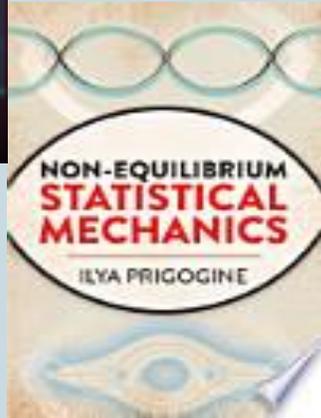
Systems with energy flow &   Self-Organized Criticality

Ilya Prigogine (Noble Price 1977)

Systems with energy flow

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 always present
Thermally-stimulated luminescence & electron emission
Thermally-stimulated conductivity
TSL presents in NaI(Tl)

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)

- **Polynomial events spectrum (catastrophes possible)**
- **Noise power spectrum close to 1/f**
- **No characteristic time/size for avalanche**
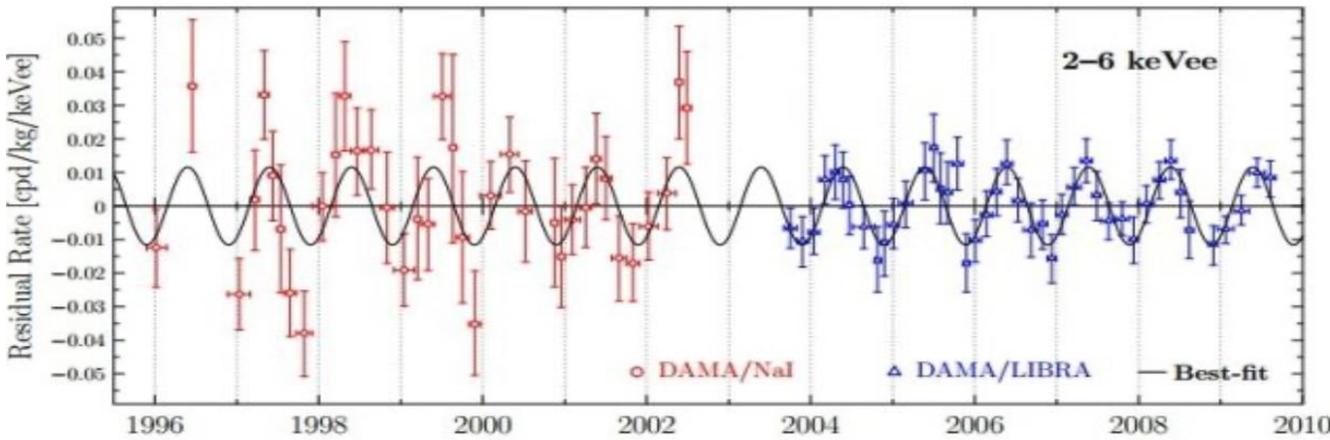- **Low energy particles cause "large events" up-conversions?**

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**

We do not know qll internal excitations and interterations; no GEANT 4 CMP models yet
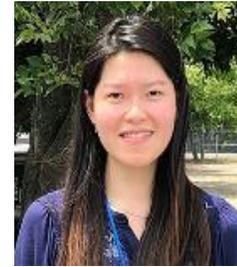
The only Dark Matter claim:

DAMA-LIBRA: ~20 years (now) of low-energy background seasonal oscillations in the most radiopure NaI(Tl)) underground (Grand Sasso, Italy). No other detector type or less pure NaI(Tl) experiment reproduce seasonal oscillations.
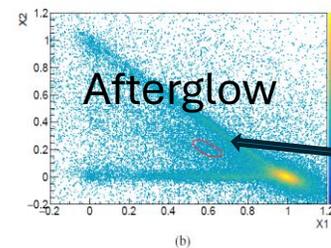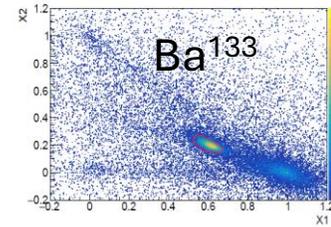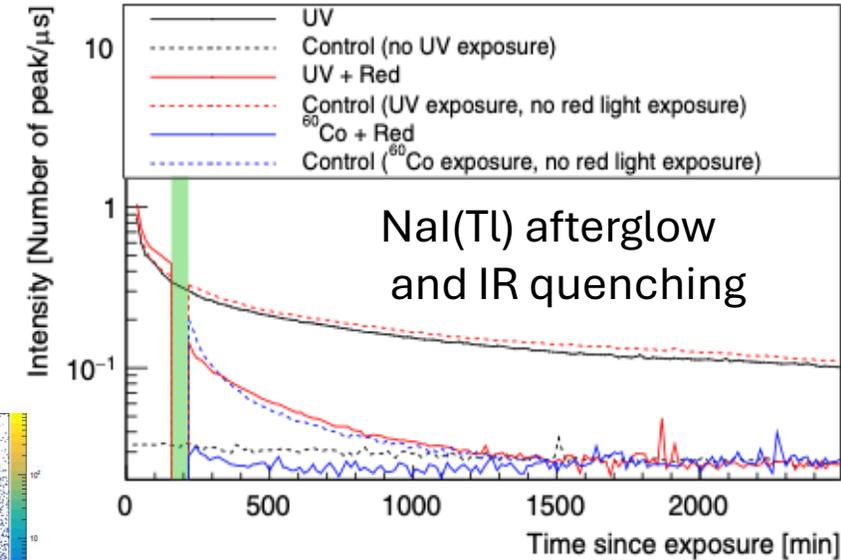
2–6 keVee

o DAMA/NaI   △ DAMA/LIBRA   — Best-fit

David Nygren: **Can this be stored energy**?
arXiv:1102.0815 (2011)

**Pumping /quenching energy by UV/IR light:
F. Sutanto, et al., Phys. Rev. D 107, 032010 (2023)**

NaI(Tl) afterglow and IR quenching

UV
Control (no UV exposure)
UV + Red
Control (UV exposure, no red light exposure)
^{60}Co + Red
Control (^{60}Co exposure, no red light exposure)

Energy releases in between muon, and residual radioactivity events (where D-L is searching for small particle-shape luminescence) are sensitive to seasonal environmental factors. **But** energy releases can be triggered by low-energy nuclear recoils- which are below "normal sensitivity limit" without stored energy Residual radioactivity is effectively killing long-living trapped electron states, while muons (minimally ionizing particles) and UV light are producing them.
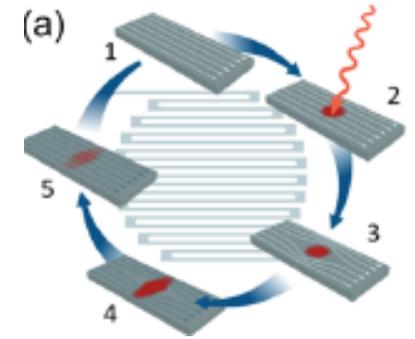
Ba^{133}

Afterglow

After-glow is mostly random photon flux, but we can find bunches with shape alike real events passing D-L time-shape discrimination

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

NaI(Tl) in internal amplification mode detects ultra-light DM but other detectors not!?

Comparing superconducting sensors SNSPD, MKIDs, Hot-electron nanobolometer, TES, and more

SNSPD	**250 mK**	**WSi (Tc~130 mK)**	**Type II**	**detect 29 μm photons**	**recovery ~ns**	**Low dark counts**
MKID nano-wire	**250 mK**	**Al**	**Type I**	**detect 26 μm photons**	**recovery ~ms**	**Low dark counts**
Hot electron nano-bridge	**30-250 mK**	**Ti nano-bridge, Nb contacts**	**Type I**	**detect 10 μm with 30% energy resolution**	**recovery ~ms**	**High dark counts**
MKID Not nano, with Al fins	**10-300 mK**	**Al fins detect hot phonons**	**Type I**	**detect 10-100 mV energy**	**recovery ~ms**	**High dark counts/ excess**

(a)

No pair breaking in hot spot, but vortex avalanche in type II nanowire?

Experimentally verifiable hypotheses and questions

- Small nanowire volume- low sensitivity to hot phonon, immunity to lattice relaxation
- Low recovery time- negligible pair breaking, voltage pulse due to vortex flow avalanche in type II nanowire
- Now or low dissipation by readout in ilde- nanovire detectors and MKIDs
- Large dissipation by bias current in TES, in hot-electron nanobolometer (on transition) – larger noise
- Effects of continuous dissipations by Josephson generation in STJ? Do capacitance detector resolve single photons?

**We can use different sensors on same substrate to characterize relaxation-induced excess in substrates,
to (eventually) differentiate particles and excess /relaxation events**