



Toward lowering the detection threshold in NaI(Tl) detector

The possibility of nano-explosive detection regime in NaI(Tl)

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Excess backgrounds in dark matter and neutrino detectors

- ❑ P5 recommend a new ultimate generation of **dark matter experiments to reach neutrino fog**
- ❑ **Excess background due to releases of stored energy in materials prevents** detection of CEvNS of low-energy solar and reactor neutrinos
- ❑ Energy accumulation and delayed releases are universally present in some form (no contra examples yet...)

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 $> \text{MeV}$ that gets released in small bursts



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



EXCESS workshop: a community effort towards understanding low energy excesses

Daniel Baxter¹, Felix Wagner²

¹ Fermi National Accelerator Laboratory

² Institute of High Energy Physics of the Austrian Academy of Sciences

on behalf of the EXCESS workshop team

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

- ❑ **Community realized the problem and presence of avalanche energy releases (self-organized criticality)**
- ❑ **Prigogine's ideas on Systems with energy flow-dissipative systems, generation of complexity, order out of chaos; non-equilibrium statistical mechanics**
- ❑ **Energy releases should produce decoherence, excess non-thermal noise in quantum sensors- but these mechanisms were not considered in the past extensive material research programs**

Condensed matter problem emerged as radio-purity and sensitivity improved

Systems with energy flow & Self-Organized Criticality



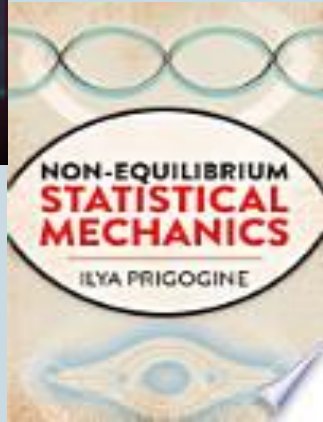
Ilya Prigogine (Noble Prize 1977)

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 \(arxiv.org\)](#)

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The race to build the fastest supercomputer yet.
The search for a new wonder drug.
A widening search for worlds around distant stars.



Falling dominos show how a small event can trigger a catastrophic.
Earthquakes, economies and ecosystems may follow similar rules.

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- 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?

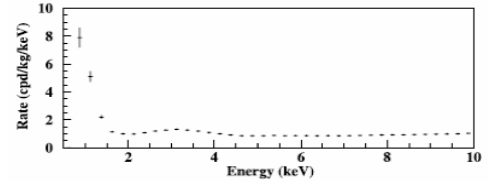
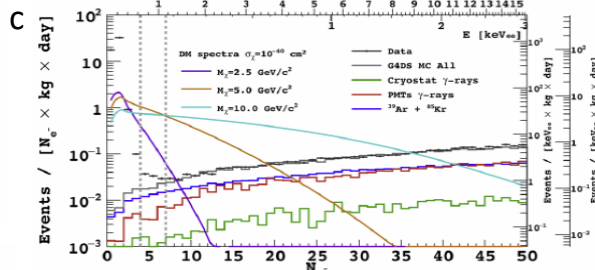
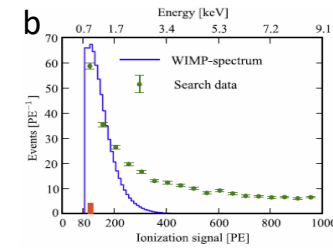
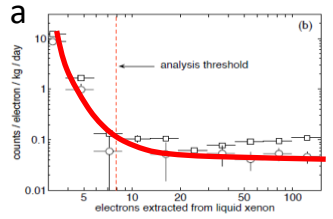
Results of computer modeling of system with known interactions no “sufficient conditions” criteria for the presence of SOC

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

We do not know qll internal excitations and interteractions; no GEANT 4 CMP models yet

Excess energy in materials causes background problems in detectors

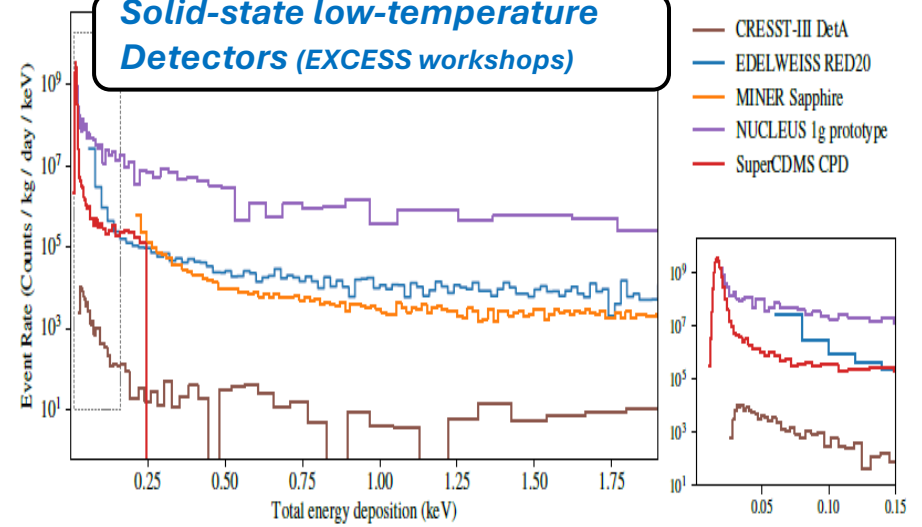
Excess backgrounds: 20 years of dark matter searches



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

Similar excess background scenarios and spectra shapes in all detectors

Solid-state low-temperature Detectors (EXCESS workshops)



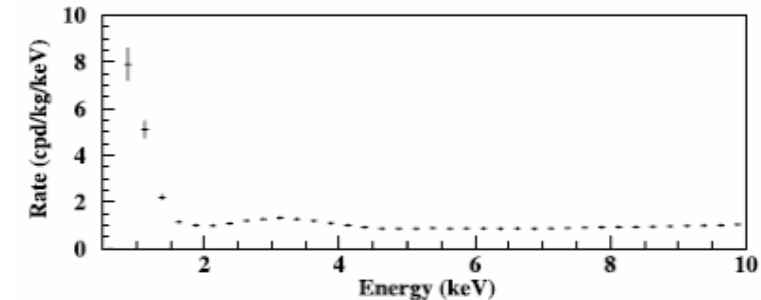
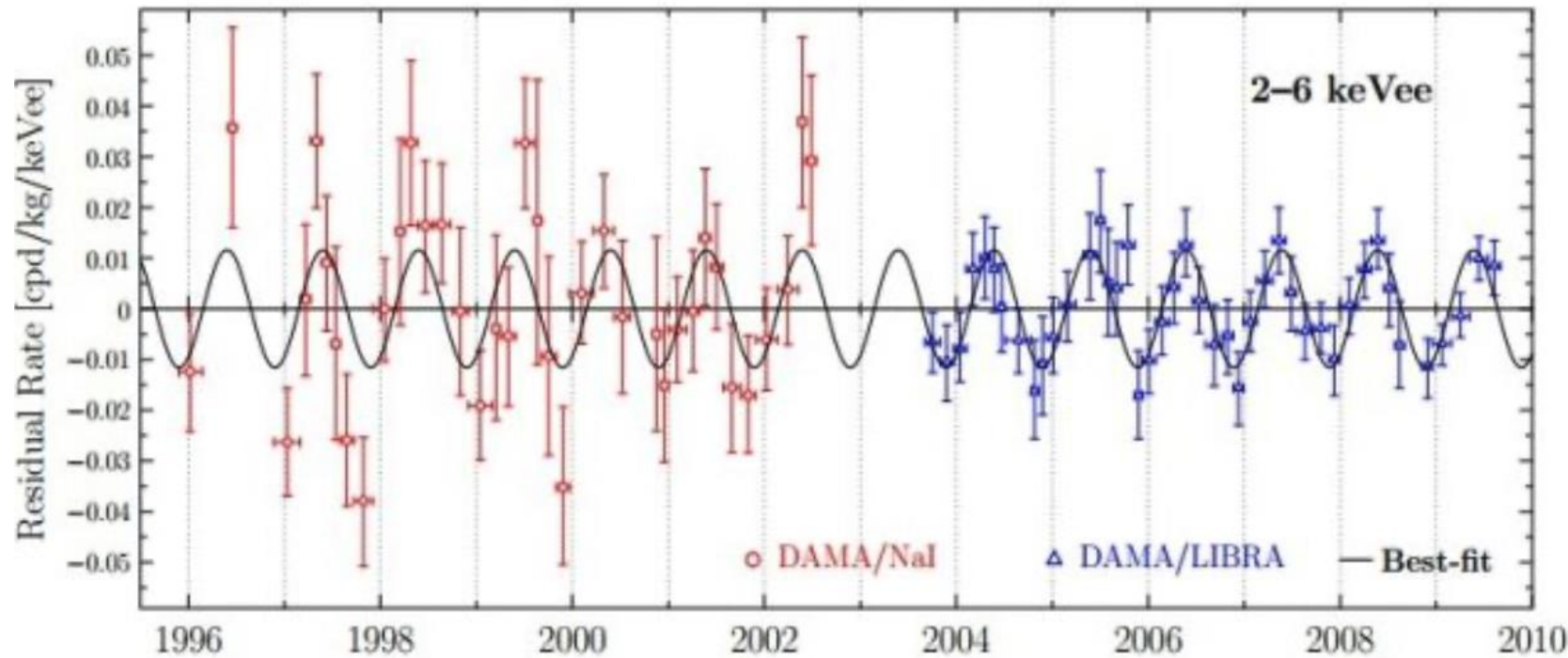
Spectra of Low-energy backgrounds close to energy reverse polynomial – as for energy accumulation and releases dynamics in Self-Organized Criticality theory
Excess background events are not an immediate responses to particles, nor thermal or quantum fluctuations (it is more like after-pulsing).
No quantitative models yet – one can not self-consistently predict “noise” at the design stage- experiments required

Particles pump energy into materials and particles can trigger stored energy release releases. Can we use this?

Xe/Ar: low “storage capacity”- unlikely to use, likely can be suppressed

NaI(Tl)-high “storage capacity”, one can “pump energy in” by UV (or muons?) But how low is the energy threshold for energy releases?

Seasonal modulation of low-energy background in NaI(Tl) DAMA-LIBRA underground experiment (Grand Sasso)



David Nygren
asked about
stored energy
[arXiv:1102.0815](https://arxiv.org/abs/1102.0815)
(2011)



In the most radiopure samples of NaI(Tl) in underground experiment oscillations of background recorded for about 20 years
Was interpreted as direct dark matter scattering events, 1-6 keV (electron recoil energy equivalent), modulated by Earth orbital motion parallel or antiparallel to DM particle orbiting our galaxy
No other experiment sees dark matter interaction in corresponding nuclear recoils energy range (nuclear recoils), and no background modulations

Simple explanation- energy releases driven by environmental factors

But: light mass DM that no other experiments now can see?

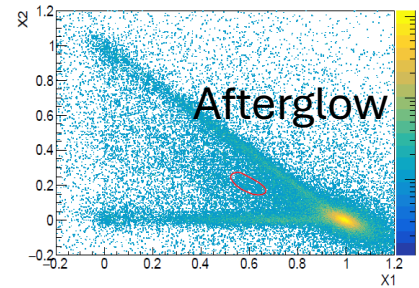
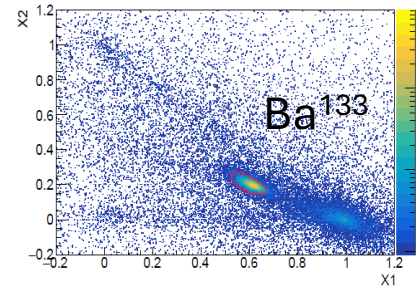
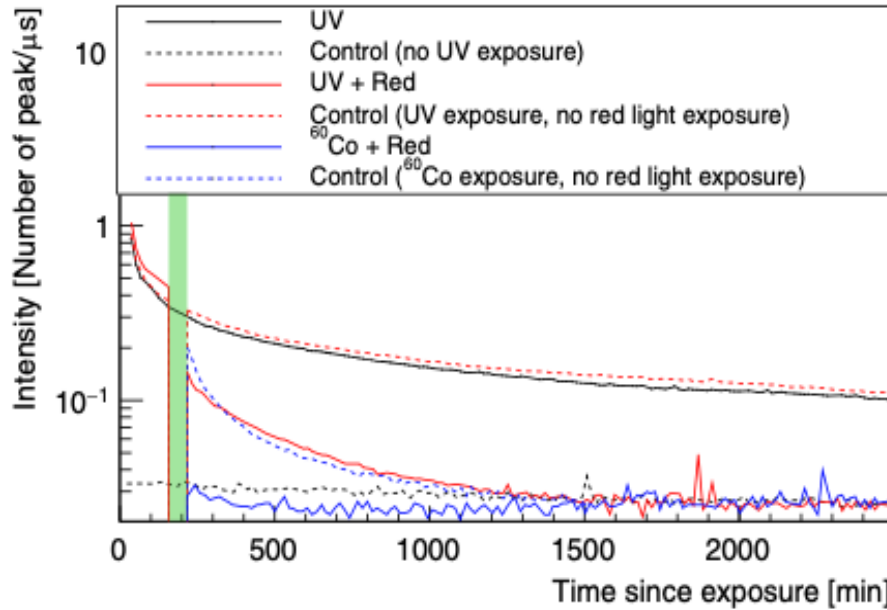
Triggered energy release in NaI(Tl)- nano-explosive detection?



Data: F. Sutanto, et al.,
Phys. Rev. D 107, 032010 (2023)

Further Hypothesis

- UV and muons can produce long-living excitations (trapped electron states)
- which are killed by the residual radioactivity.
- What If excitations accumulate in DAMA-LIBRA, and low-energy nuclear recoils trigger releases?
- Then the phase of DAMA-LIBRA modulation depends both(on the muon flux modulation AND the number of nuclear recoils (neutrino, light DM)



Afterglow following UV and ⁶⁰Co exposures

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

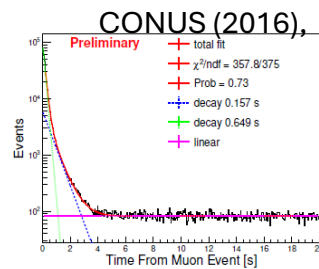
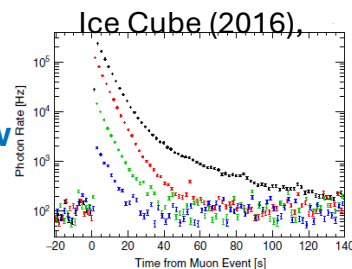
$$X_1 = \frac{A[100, 600] \text{ ns}}{A[0, 600] \text{ ns}}, X_2 = \frac{A[0, 50] \text{ ns}}{A[0, 600] \text{ ns}}$$

What to check?

- Will exposure of NaI(Tl) to Co60 after irradiation with UV light kill long two-days delayed luminescence?
- If we pump energy by UV pulses, will we see sub-keV recoils produced by epithermal neutrons (between ionization events)?

E. Gardenali Yukihiro,
Ceramics International 49
(2023) 24356–24369 “TL and
OSL as research tools in
luminescence,”

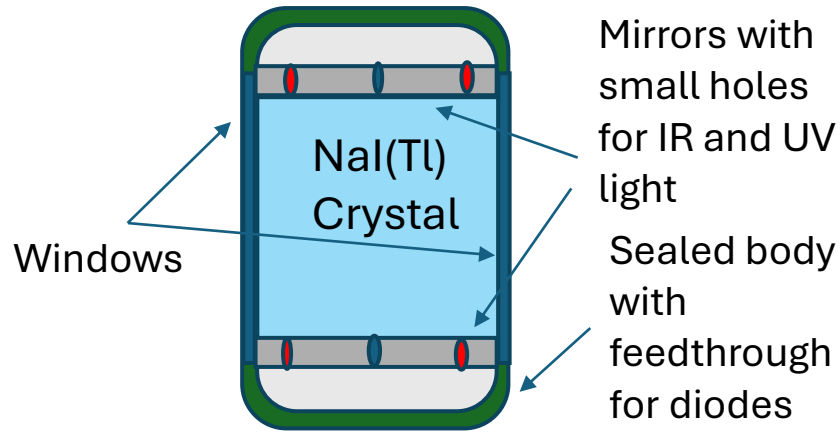
Muon
afterglow



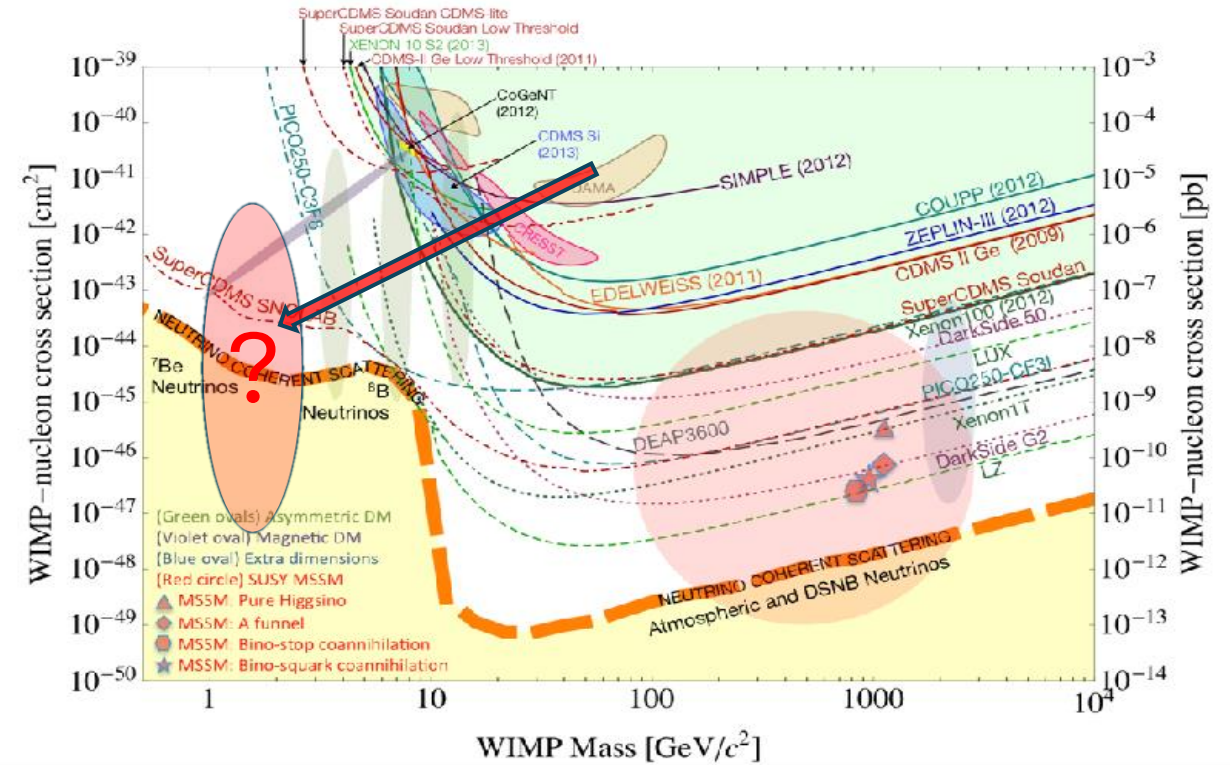
De-trapping of electrons (followed by recombination and luminescence) can be triggered by red light, residual radioactivity, and nuclear recoils

If the threshold for energy release by nuclear recoils (hot phonons) is low

A way to check the threshold



- Periodic exposure to UV light can increase the sensitivity of DAMA-LIBRA -like experiment to ultra-light dark matter particle recoils/modulation
- Multiple photon events (D-L signal) and the random delayed photon flux may exhibit yearly modulation- phases can be different (no checks yet on random delayed photons)



- Then DAMA-LIBRA modulation can be due to ultra-light dark matter particles,
- Or the number of low-energy neutrino scattering events is higher than expected.
- Other present detectors will not see this

Discussion

two other possibilities for phase explanation are possible

- The maximum in production of the specific trapped electron states is shifted in time from the muon flux maximum (like crystal shape and muon directions effects)
- Environmental factors can cause electron de-trapping: temperature or ambient pressure variations, vibrations, electromagnetic noise, Schumann resonances, etc.

An experimental check of the role of low-energy nuclear recoils and hot phonons in triggering relaxation processes in a material is important for understanding the excess backgrounds.

Example: how to make IR-microwave photon detectors not sensitive to hot phonons when we look for axions.

Energy accumulation and release processes in materials can be complex, but we can study them experimentally even in the absence of comprehensive theoretical models.

Can suggest alternative ways to look for “conventional” dark matter particles

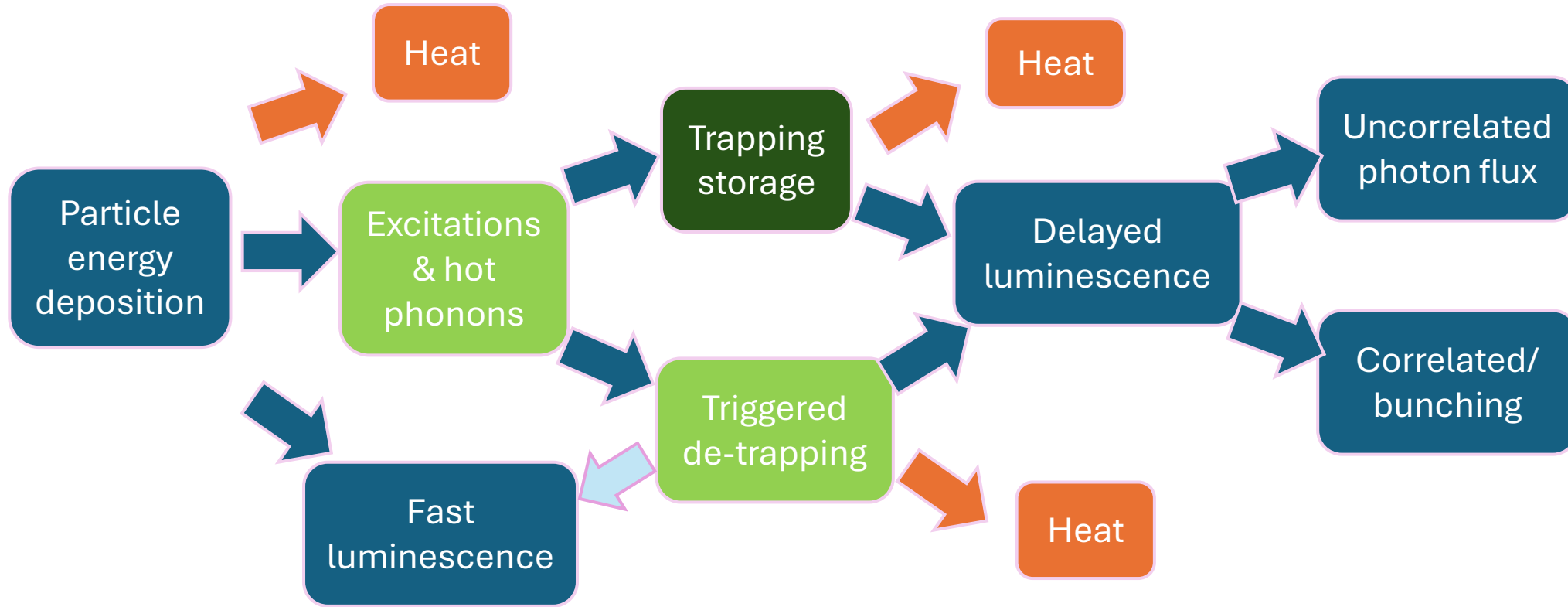
Can help in understanding decoherence in qubits

Additional Slides



TL and OSL as research tools in luminescence, E. Gardenali Yukihiro, *Ceramics International* 49 (2023) 103000

General model for material response



Environment (temperature, pressure, the electric and magnetic fields can modulate distribution from primary to heat, fast luminescence, and storage; from storage to heat and luminescence, and ratio between uncorrelated/correlated luminescence.

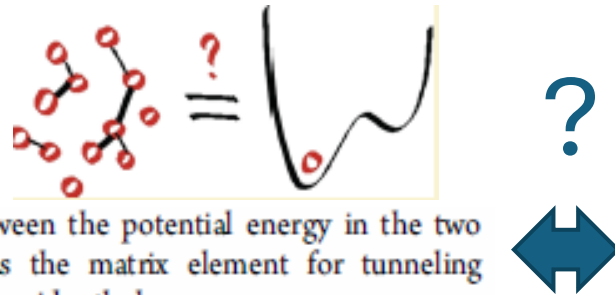
Micro-explosives: neutrinos/dark matter can cause de-trapping (without primary luminescence) and modulation.

One needs to monitor uncorrelated luminescence to check for environmental modulation

Temperature is a strong known factor. We need to stabilize and try changes in temperature (origin of irreproducibility?)

Non-interacting Tunneling Two-Level Systems in condensed matter (1972- Energy releases by interacting excitations in chemical physics & biology (1977-

TLS introduced to describe glasses around 1972



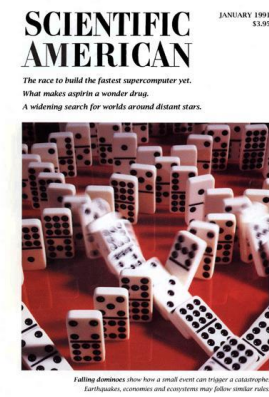
with ϵ_i as the offset between the potential energy in the two configurations and Δ_i as the matrix element for tunneling between them. Then, we evidently have

Spectrum $E_i = (\epsilon_i^2 + \Delta_i^2)^{1/2}$: $\rho(\epsilon, \Delta) = \frac{\text{const}}{\Delta}$

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).