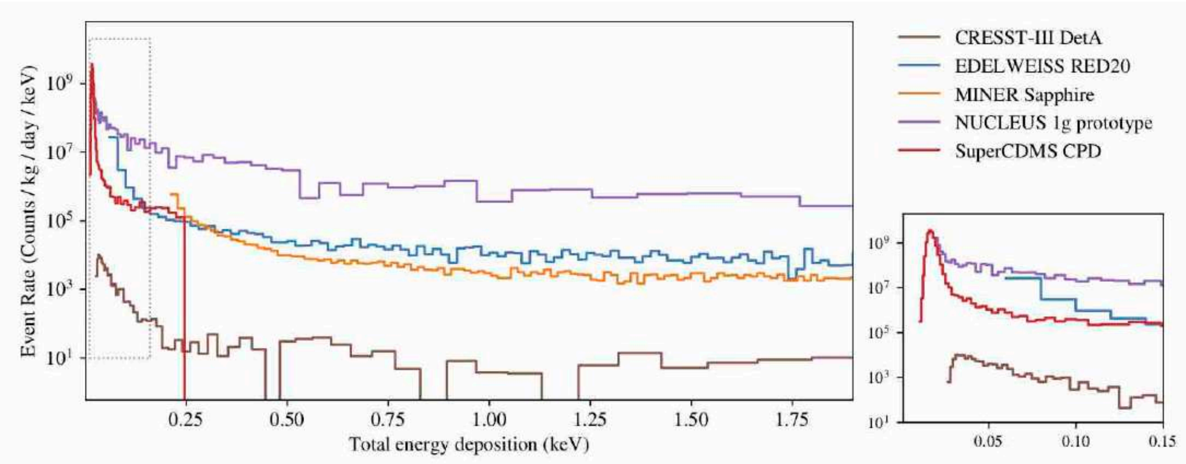
Low-energy EXCESS signals at low energy in cryogenic detectors



- Sensor & Detectors
- Measurements
- Explanations?
- MMC results

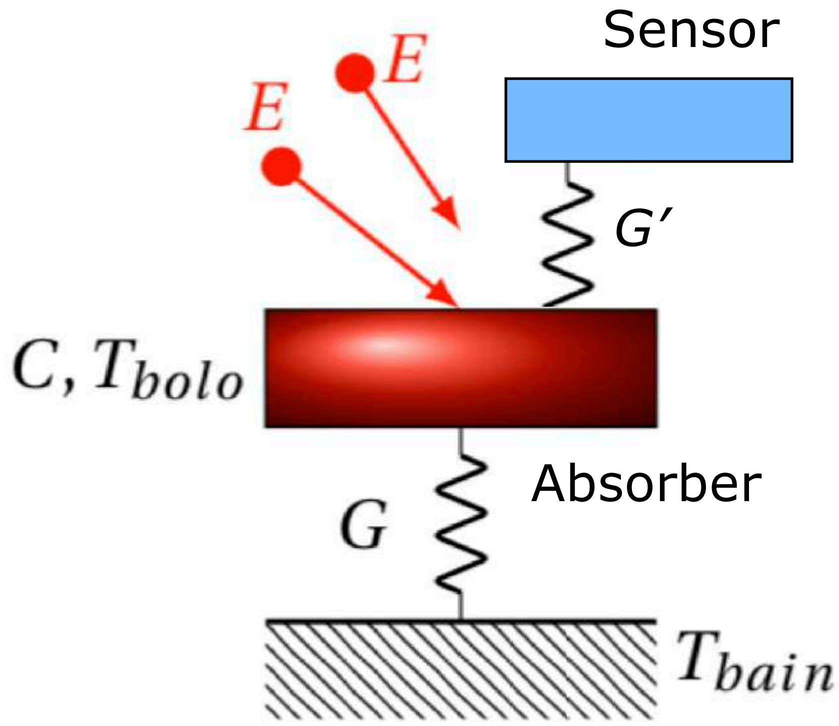
J. Gascon
Lyon 1, CNRS/IN2P3/IP2I

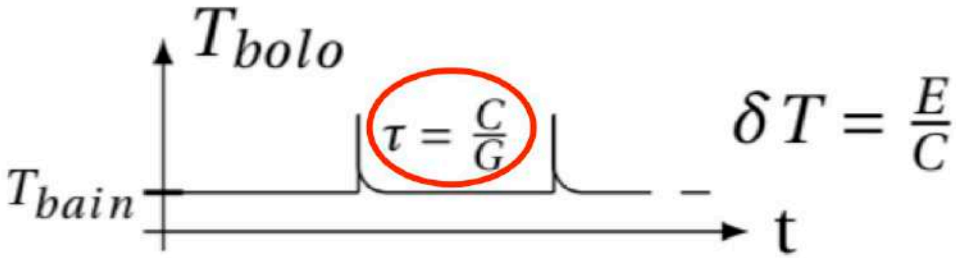
Cryogenic detector principle

Simple picture: sensor + absorber + cold bath

- Signal amplitude = Energy /heat capacity
- Decay time => thermal coupling between absorber and cold bath: C/G
- Rise time => thermal coupling between absorber and thermometer: C/G’

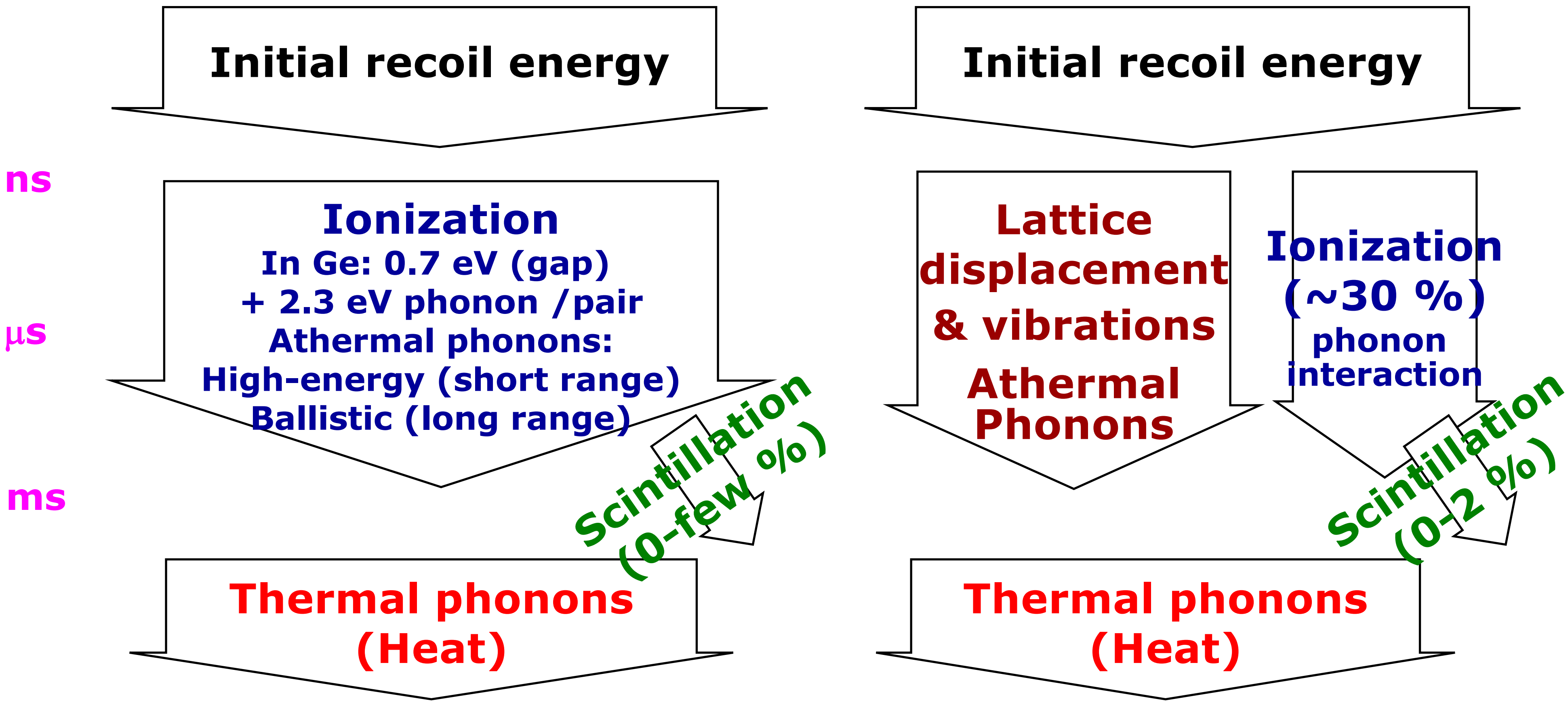
- **Overly simple: *energy transfer in sensor via athermal phonons***





Cryogenic detectors: Phonon/ionization/scintillation

Electron recoil vs Nuclear recoil

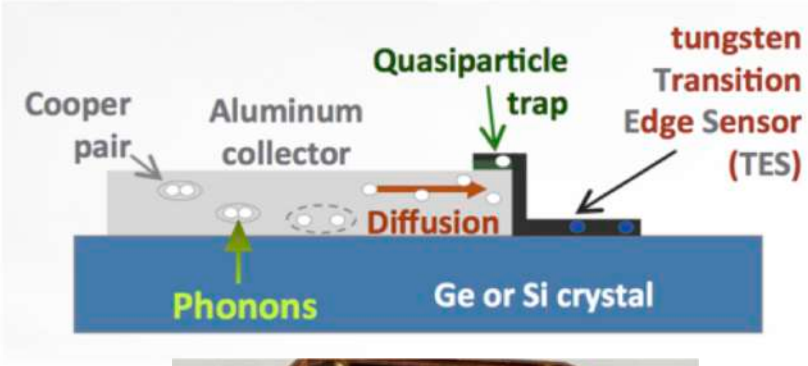


(+ No permanent crystaline defects?)

(+ Permanent crystaline defects?)

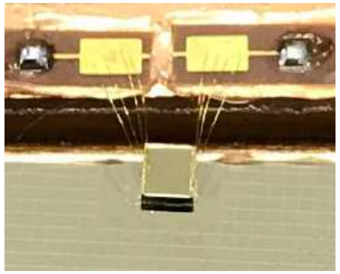
Phonon sensors

- Transition Edge sensors
  - Fast (<<ms risetime) response to athermal phonons
  - Sensitivity to ballistic phonons:
    - Lifetime in absorber / surface
    - Surface of sensor wrt total surface
  - CRESST: single W-TES
  - SuperCDMS: array of W-TES with Al phonon collectors

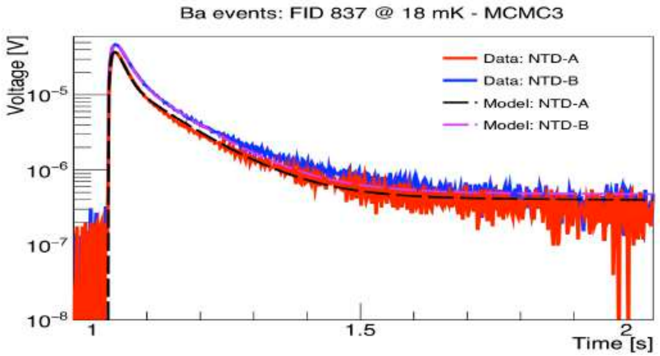


46 cm^2

4 mm^2



- Ge-NTD
  - Thermistance (few mm^2)
  - Glued on Ge or electrode
  - Slow (1-10 ms risetime) response of thermistance to thermal phonons
  - However, study of pulse shape shows some ballistic phonons inject energy directly in NTD, bypassing thermalization inside the absorber



Neganov-Luke-Trofimov amplification

- Ionization channel: electrode **keV_{ee}**
  - Electron Recoils: $N_{pairs} = E_{recoil} / \varepsilon_\gamma$
  - Ge: ε_γ = 3.0 eV, Si: ε_γ = 3.8 eV
  - **Independent of bias V**
  - E(keV_{ee}) defined as $\varepsilon_\gamma N_{pairs}$: given directly by gamma-ray calibration
  - Dispersion of ε_γ : Fano factor

Neganov-Trofimov-Luke (NTL) heating

[equivalent to Joule effect] **keV**

$$E_{phonon} = E_{recoil} + N_{pairs} V$$

- Reduced ionis. yield for.

  Nuclear Recoils or Heat-Only events

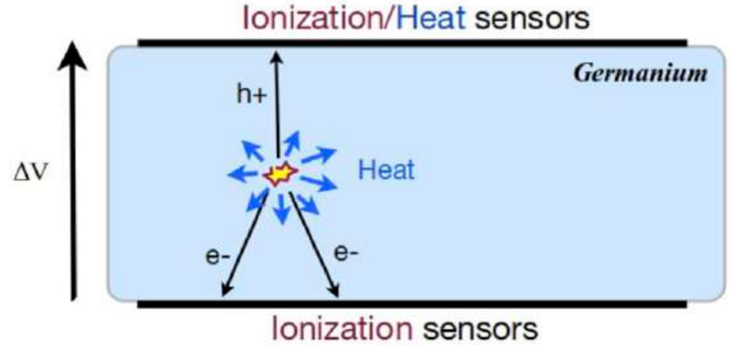
  $N_{pairs} = Q * E_{recoil} / \varepsilon_\gamma$ eV

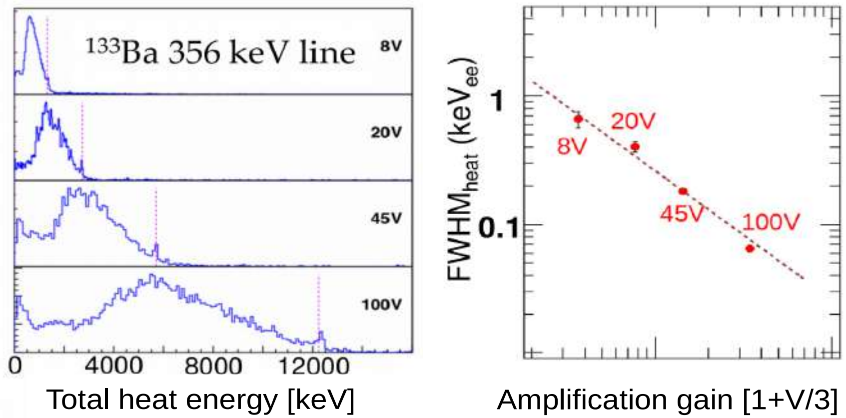
  with Q ~ 0.2 for 5 keV NR

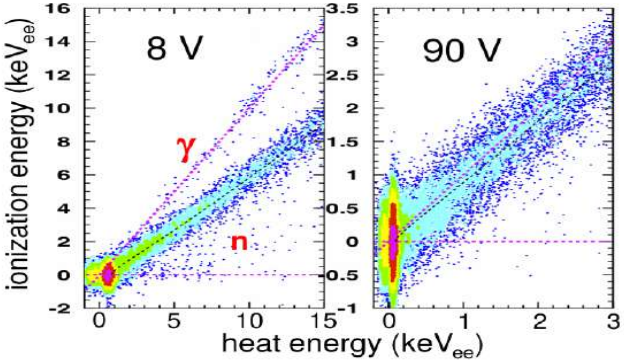
  $$E_{phonon} = E_{recoil} (1 + Q V / \varepsilon_\gamma)$$

Quenching : see Mobarak talk

Works with athermal phonon too!







Improved resolution

Loss of ER/NR discrimination

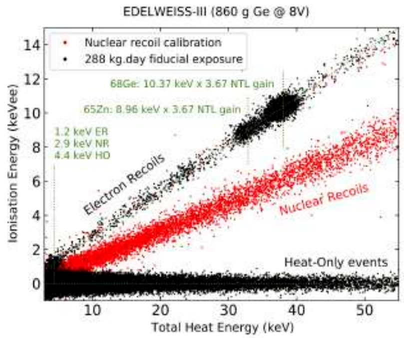
Cryogenic detectors (EXCESS 2021)

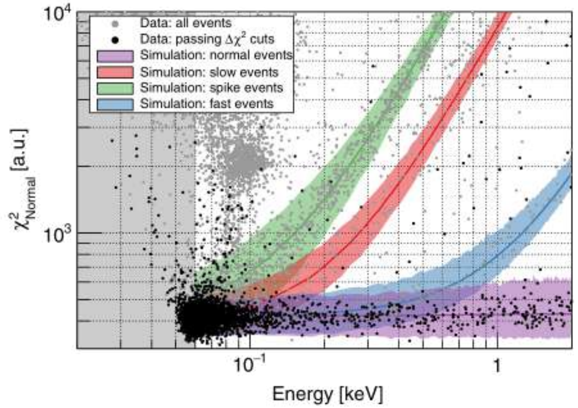
Detector	Absorber	Sensor	Depth (mwe)	NTL amplification
CRESST	24g CaWO4	W TES	3600	-
NUCLEUS	0.5 Al2O3	W TES	~10	-
SuperCDMS CPD	11g Si	QE-TES	~10	yes
SuperCMDS HVeV	0.9g Si	QE-TES	~10	yes
MINER	100g Al2O3	QE-TES	~10	-
EDELWEISS RED20	34g Ge	Ge-NTD	~10	No
EDELWEISS RED30	34g Ge	Ge-NTD	4800	yes

since then:
+ EDELWEISS 200g with NbSi TES (arxiv:2203.03993)
+ SuperCDMS-HVeV comparison of backgrounds at 0-60-100V (arxiv:2204:08038)
+ SuperCDMS-CPD runs @ SNOLAB (Underwood thesis, 02/22: M. Pyle@EXCESS2022)

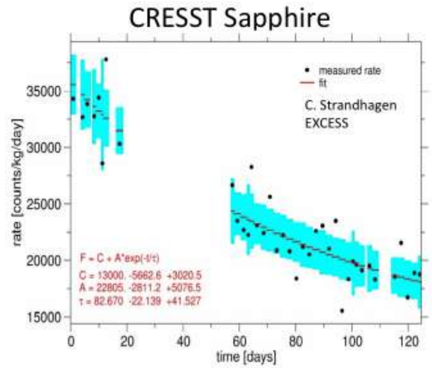
Background in cryogenic detectors

- **Same risetime / decay time as ER event**
  - Faster/slower pulse: indications of nature/location of event
- **Non-ionizing**
  - No signal on electrode (high E)
  - No NTL amplification (low E)



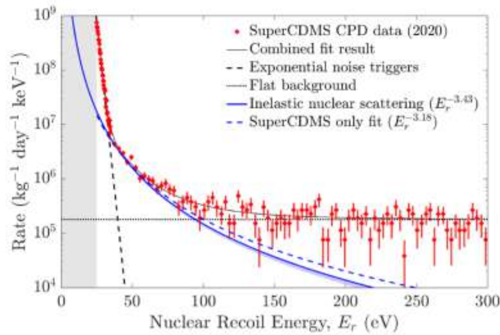


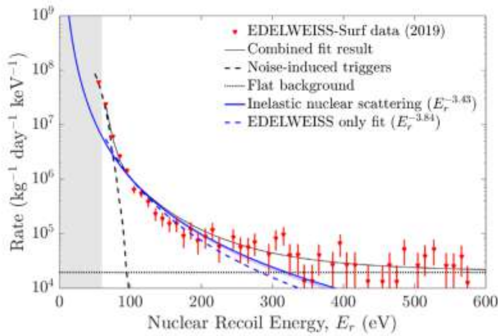
- **Timing**
  - No coincidence with external events
  - Correlation between successive events indication of "stress" release



- **Slow variation of rate with time since cool-down**
  - Inconsistent with known radioactive backgrounds
  - Suggest also accumulated stress as potential source
- **Energy range**
  - Steep rise at low energy
  - May depend on source / sensor

Abbamonte et al [arxiv:2202.03436]: power-law comparisons between SuperCDMS-CPD and EDELWEISS-surf (+talk at EXCESS2022 in Feb.)





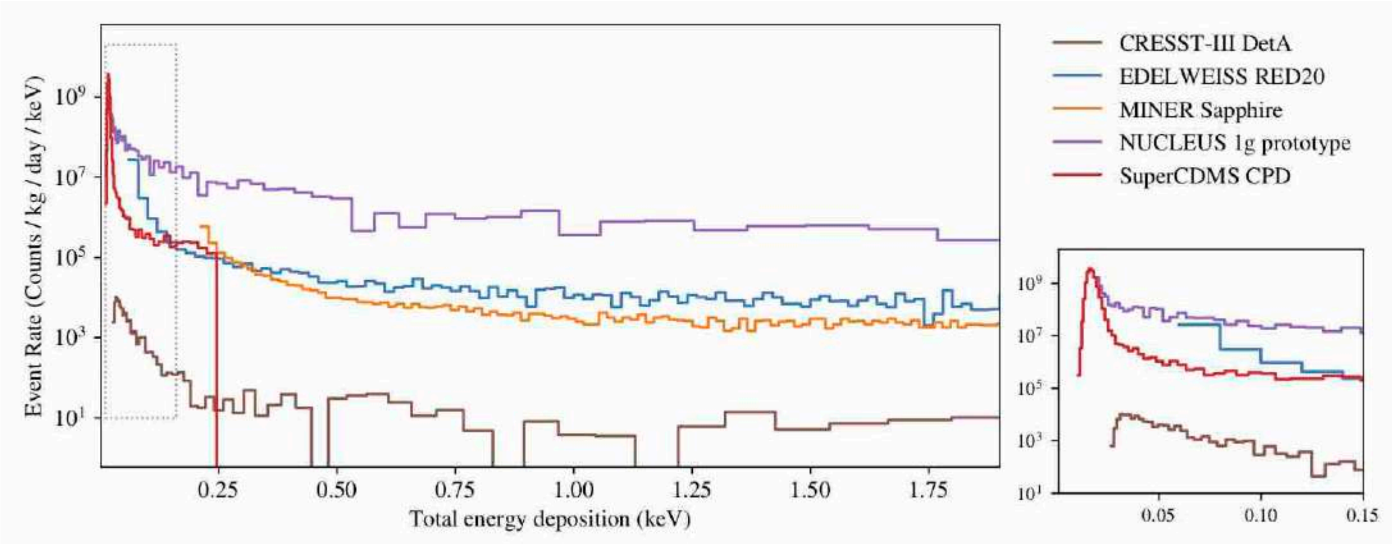
EXCESS 2021 spectra [arxiv:2202.05097]

EXCESS2021:

- Low energy rise observed in all cryogenic detectors – but not at same rates (CRESST underground unequalled so far!)

Since then:

- Abbamonte et al [arxiv:2202.03436], power-law comparisons between SuperCDMS-CPD and EDELWEISS-surf (+talk at EXCESS2022 in Feb.)
- Albakry et al [arxiv:2204.08038] SuperCDMS-HVeV bkg comparison at 0/60/100V
- Background measurement in EDELWEISS 200g with NbSi TES [arxiv:2203.03993]
- + contributions in this workshop

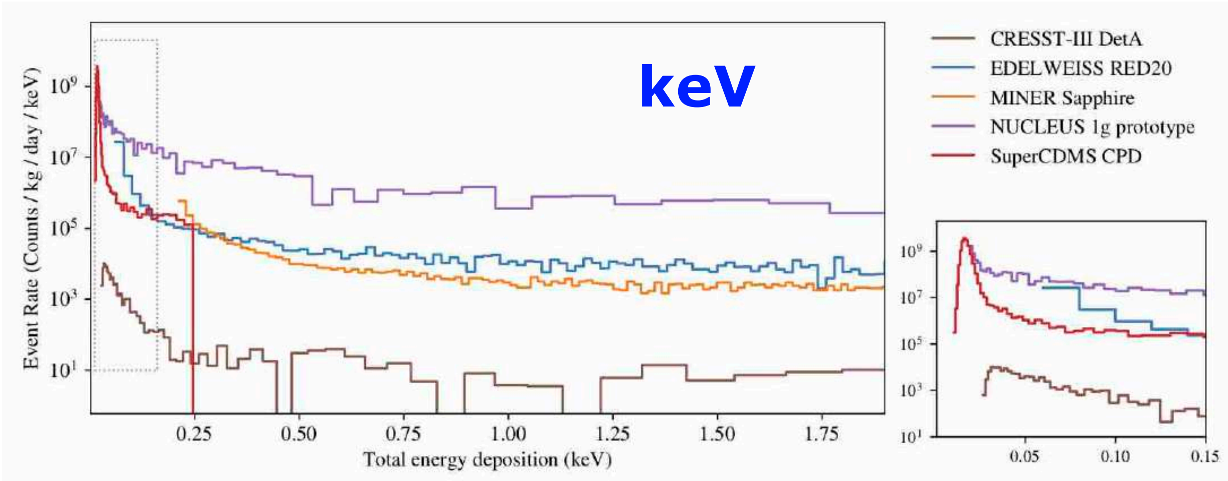


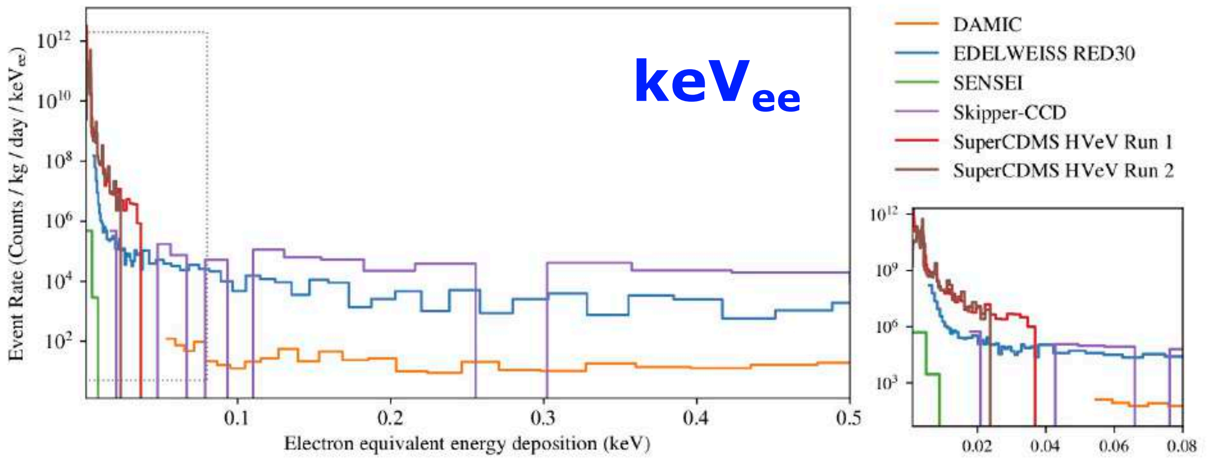
Ionizing vs Cryogenic background

Identification of electron in CCD helps reduce the background at very low energy

Identification of the low-energy rise in cryogenic detectors essential to fully exploit their potential, especially if the searches need to be extended for signal below ~3 eV

CRESST-III still best background above 100 eV





Measurement status

- Cf M. Pyle summary at EXCESS in Feb. 2022

Low Energy Excess Fact Summary:

	CPD / CDMS	EDELWEISS	CRESST
1) Same above and below ground	mostly	mostly	
2) Broad Energy Scale	Yes	Yes	
3) Rate varies significantly between detectors	Yes	Yes	Yes
4)Time variation with time since cooldown	Yes (since run 11?)	Yes	Yes (partial)
5) Low Energy Excess is Non-Ionizing	Probably?	Yes	?

- Since then (+ new material to be presented later today)
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- **Albakry et al [arxiv:2204.08038] SuperCDMS-HVeV bkg comparison at 0/60/100V**
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see Lattaud talk on NbSi TES results

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New data: see Fuchs talk on CRESST

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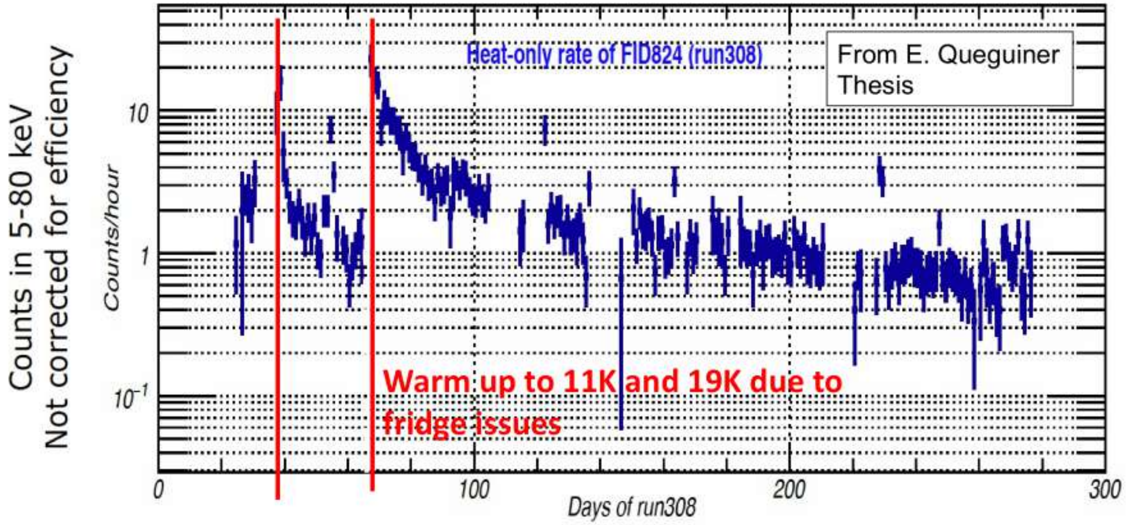
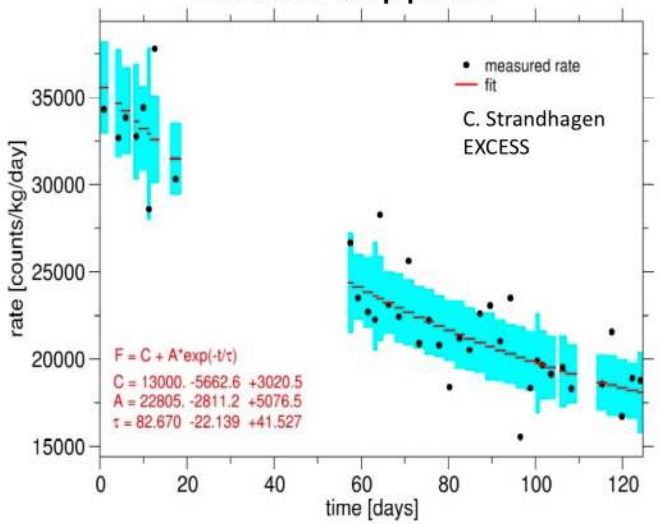
Time dependence

- Investigation in EDELWEISS, CRESST & SuperCDMS
- *Different energy ranges*
- Dependence on thermal cycling suggest gradual release of energy in crystal.
- Source of this energy?
- More than one source?

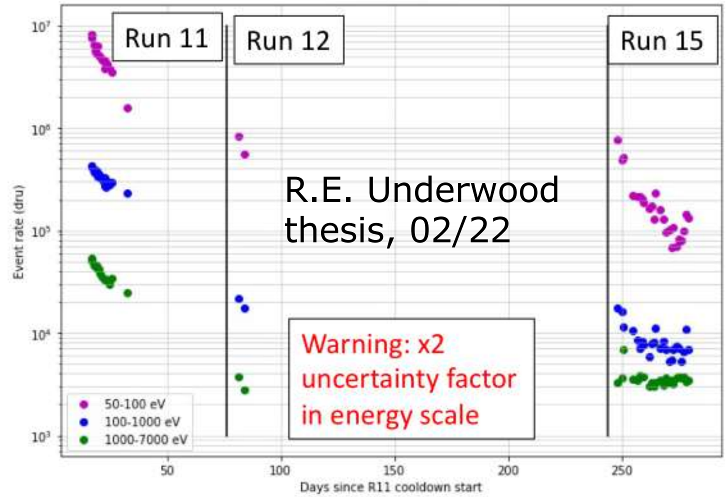
EDELWEISS Low Energy Excess (FID 824)



CRESST Sapphire



CPD@CUTE



Stress-induced energy

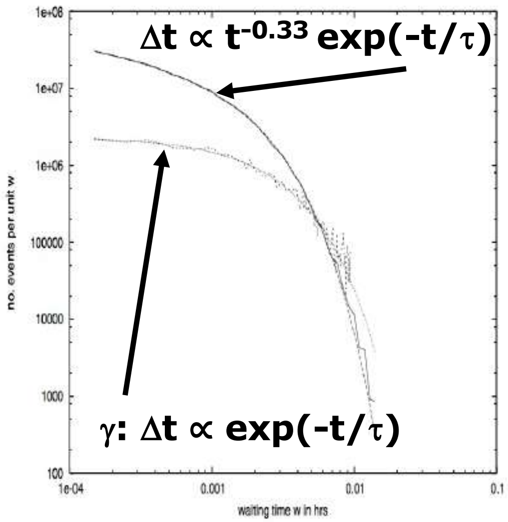
Seminal work: *Fracture processes studied in CRESST* [NIMA 559 (2006) 754]

- 262 Al_2O_3 crystal, TES readout
- *5 to 500 keV energy scale !*
- Energy release (<μs),

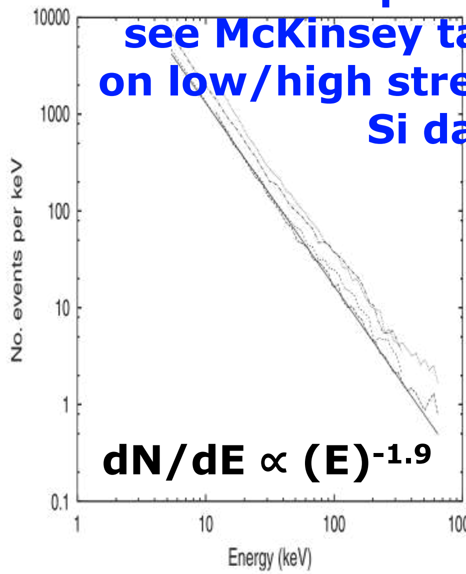
  as fast as ER or NR

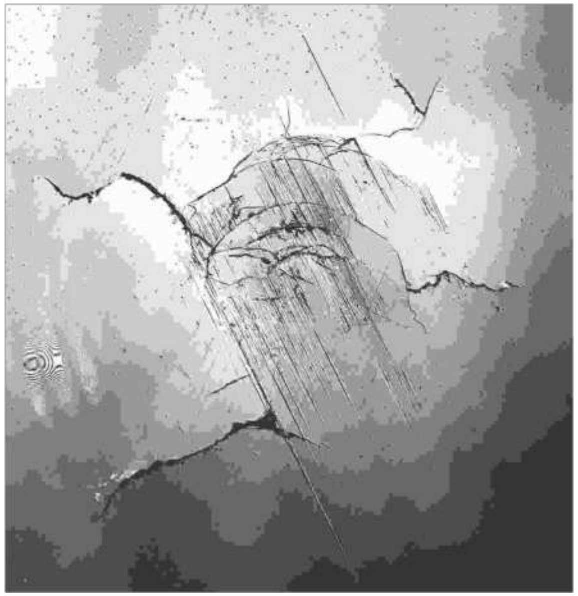
Similarity with earthquakes!

- Time correlation between events
- Power law spectrum



Update: see McKinsey talk on low/high stress Si data





Confocal microscopy confirms ~2mm wide region affected by pressure applied by supporting sapphire balls

Problem solved by loosening clamp pressure (also: equipping support pieces with TES in some detectors)

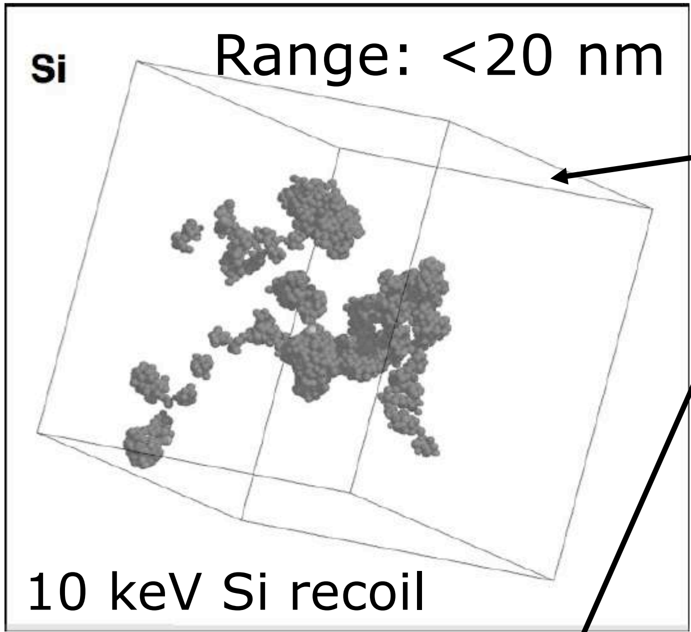
Visible defects -> >> keV events.
What about eV energy range? (single site “defect” ~ few eV)

Other sources of stress: gluing, thermal stress at interface

Relaxation in glass: see Pereverzev talk

MD simulations of nuclear recoils

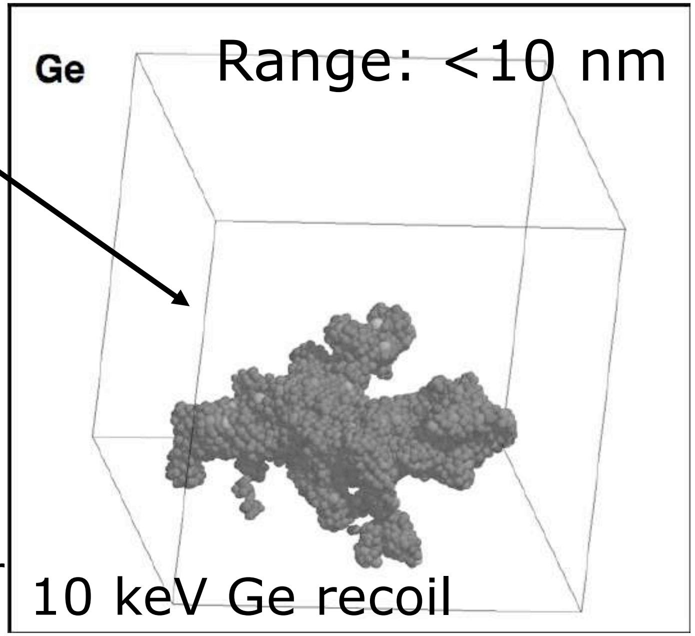
- Displaced atoms following nuclear recoil stopping in solid
- Molecular Dynamic Simulations of « hot » atoms (Nordlund, 1998) : amount of long-term stored damage depends on crystal temperature

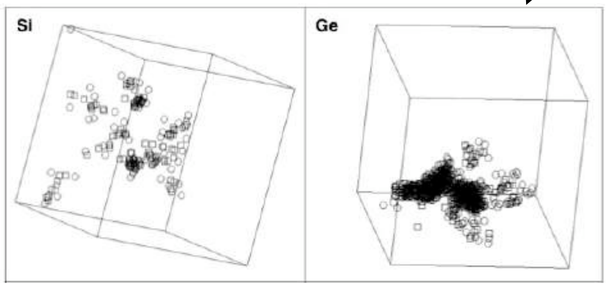


Displaced atoms (before self-annealing)

Long-term damage

Can this energy be released over time?





Permanent damages due to this « femtoGray » dose (...depends on T) (negligible in metals, but could be few % of initial energy in Si or Ge)

New 40 mK calculations: see Heikinheimo talk

Measurement of stored energy in defects

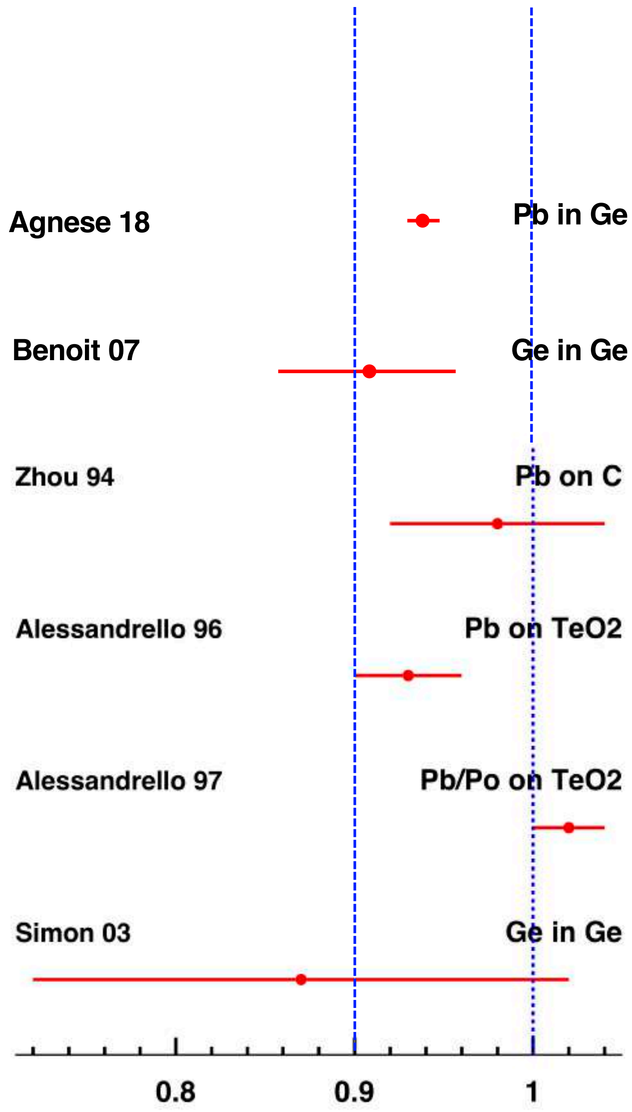
- Measurements of "quenching" of phonon signal

Most recent measurements:

- Pb recoils at Ge surface: Agnese et al, Appl. Phys. Lett. 113, 092101 (2018)
- Ge recoils in Ge: Benoit, A 577 (2007) 558

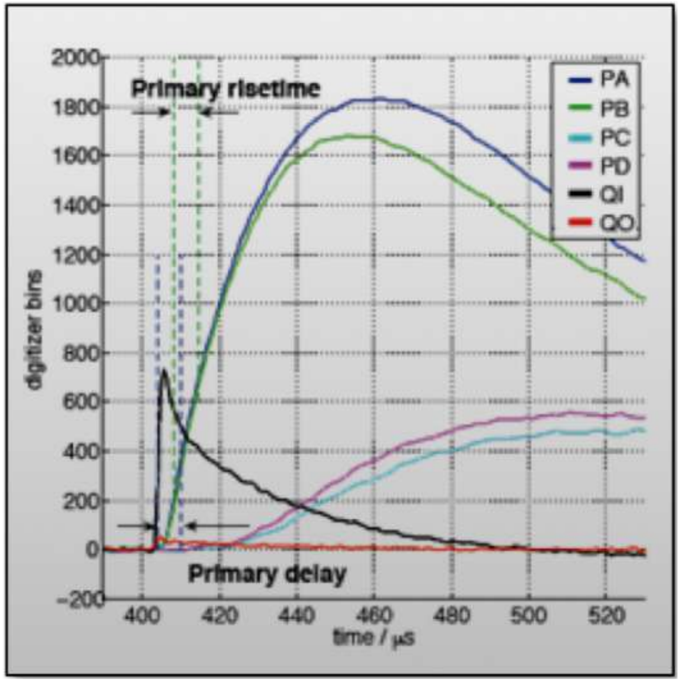
- Mostly consistent with ~6% loss in permanent, i.e. close to SRIM estimate

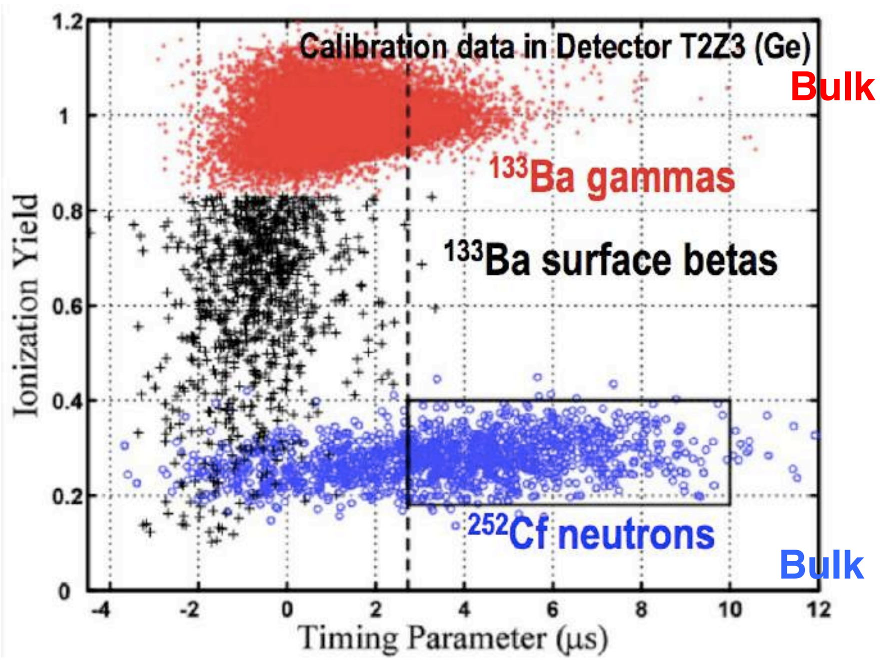
New developments on losses in crystals: see Heikinheimo & Lasserre talks



Phonon time discrim. in SuperCDMS iZIP detectors

- Risetimes: Phonon < 50 μs, Ion < 1 μs
- « Timing parameter » combines *rise time* and *phonon-ionization delay*
- Difference in pulse shape in different sectors used for event localization
- Nuclear/electronic recoil discrimination!





- Sensivity to « z »? (no, works even if sensors on only one side)
- Due instead to a difference between the phonons produced in the primary interaction and in the Luke-Neganov process.
- ***Can "promptness" of NTL phonon be used to reject non-ionizing events?***

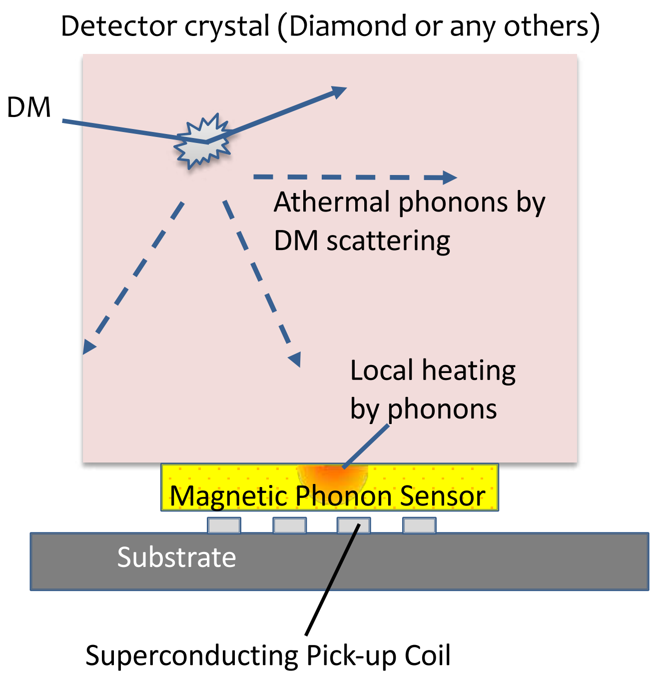
Conclusions

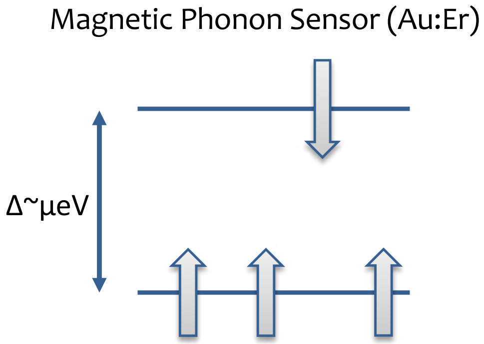
- Hunt for origin of low-energy excess in cryogenics continues
  - Non-ionizing nature confirmed in many cases
  - Try to get discrimination back at low energy?
- Microfractures due to stress release: main suspect for (most of?) the previously-reported excesses in the 100 eV – 10 keV range
  - Dependence on time-since-cooldown
  - Rate not related to radioactive levels
  - Energy too large for single
  - Work going on to determine the origin(s) of that stress
- **More recent news in the coming talks today!**

Geonbo Kim’s contribution (more on INDICO)

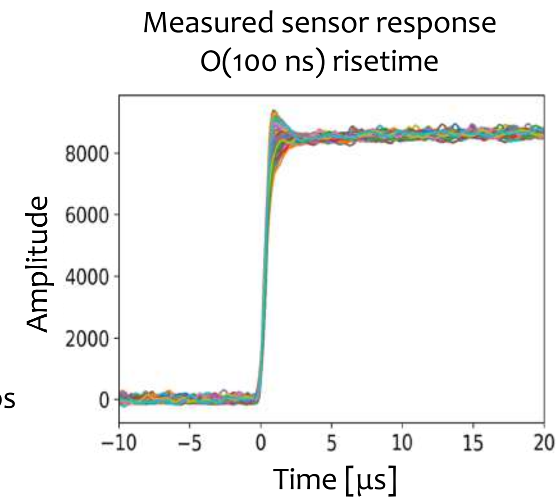
PULSE SHAPES IN EXCESS EVENTS WITH MMC SENSORS

MAGNETO-χ: Fast Phonon Sensing for Sub-GeV DM Detection





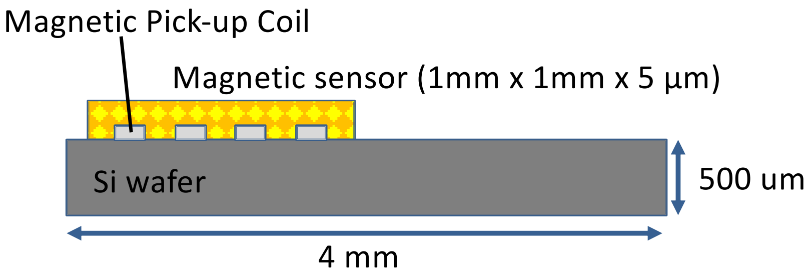
- Phonon absorption leads local spin flips
- No full thermalization is needed

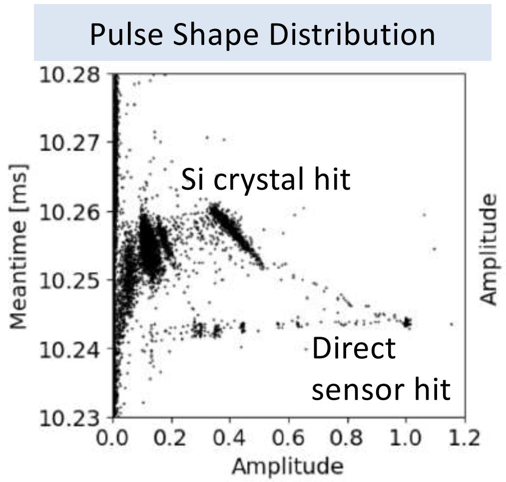


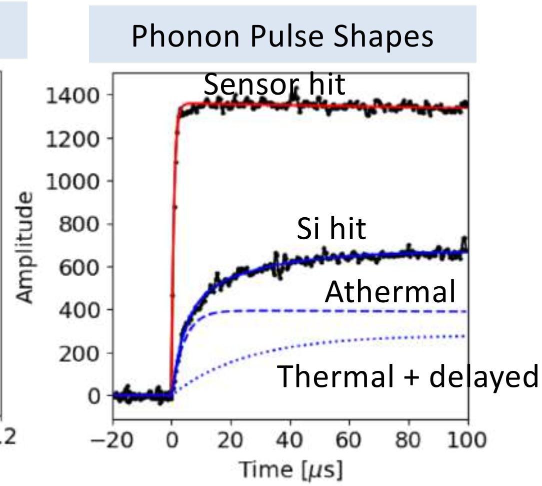
- **DM-Nucleon scattering detection**
- **Flexible choice of detector material**
- **Fast sensor response of O(100ns)**
- **Phonon PSD for sub-keV background reduction**

MAGNETO R&D: Sensor Response and Phonon Transport

- To study phonon collection efficiency and timing info
- With an Am-241 source



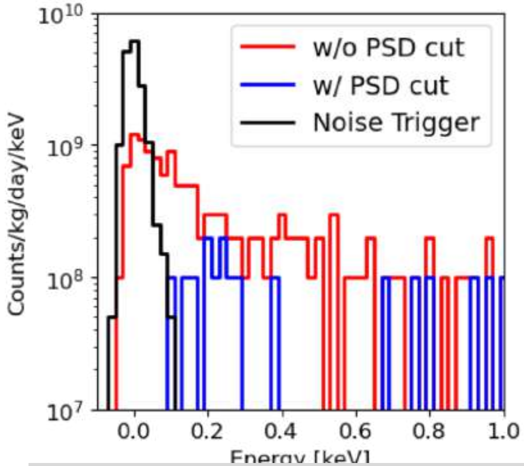


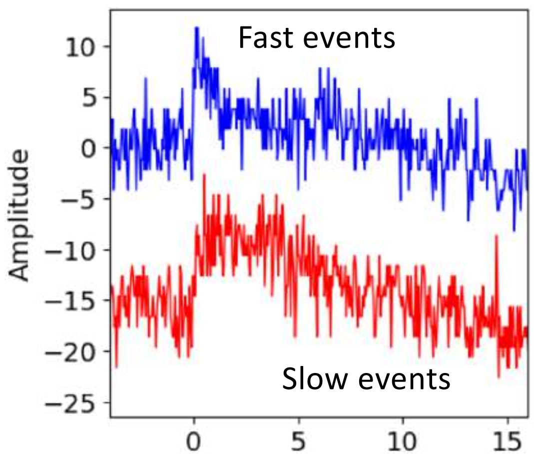


- Sensor response: 0.8 μs   Athermal collection time: 4.2 μs
- Athermal collection efficiency: 28.8%
- Thermal phonon contribution: 16.2%   Energy loss to substrate: 45.1%

Low E Excess in MAGNETO R&D Data

- Test data for 2 days, background (2.3 MeV α calibration)
- Trapezoid shaping was used, despite loss of resolution, because optimal filter estimates incorrect amplitudes for different pulse shapes





PSD cut: Ratio of slow/fast shaping amplitudes

- Gradual rate increase in slow events (~100 us), but not in fast events.
- Need further investigation with lower threshold.
- More R&D Data will be discussed in the EXCESS workshop.

Contact: Geon-Bo Kim
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BACKUP

Phonons (3 different kind)

- Initial high-energy phonons
  - Keep memory of momentum of initial particle
  - High-energy phonon with very short pathlength
  - Rapidly degrade down to lower energy phonons

Position dependence (if sensor very close by)

- Ballistic phonons
  - Lower energy = longer lifetime (some μs)
  - Path >> detector size: multiple scattering on. surfaces, random position and direction
  - Degrade down through scattering on impurities and defects in crystals (mostly at surface: traps, amorphous layer, electrodes)

Fast response (<<ms)
Detection $\propto$ surface sensor/absorber

- Thermal phonon
  - Lifetime = C/G (tuned >> ms by adjusting the thermal link)
  - Insensitive to position of interaction
  - Sensor can be very small

Slow (ms to >100ms)
Most reliable energy measurement