Quenchings in crystals

Why are they important?

Some Models

Light Quenching (few comments)

Ionization Quenching

Measurements

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Quenching

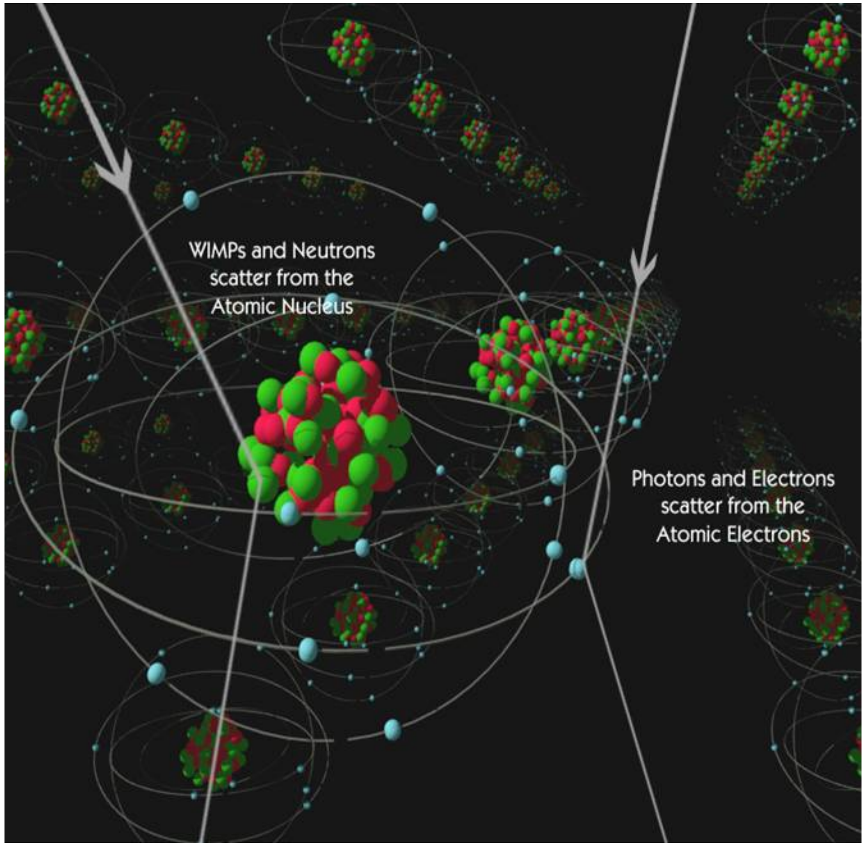
Background

- E in keV-equivalent-electron (keV_{ee})
  - Calibration with γ rays (produce an electron recoil)
  - Monoenergetic sources easily available

WIMP signal

- E in keV-equivalent-nuclear-recoil (keV_{NR})
  - Calibration with neutron scattering (produce a nuclear recoil)
  - Monoenergetic neutron source not as easily available
  - Monoenergetic neutrons produce a continuous recoil energy spectrum

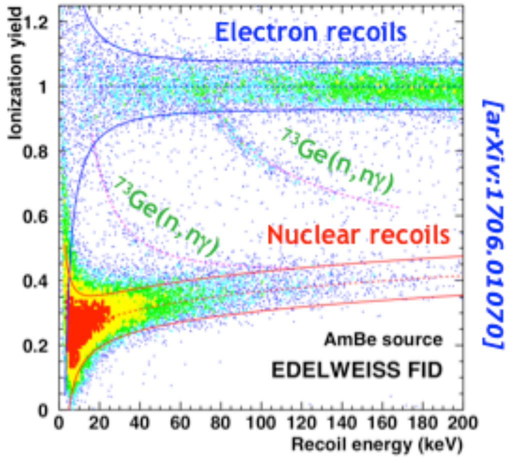
- Q = factor to convert keV_{ee} to keV_{NR}

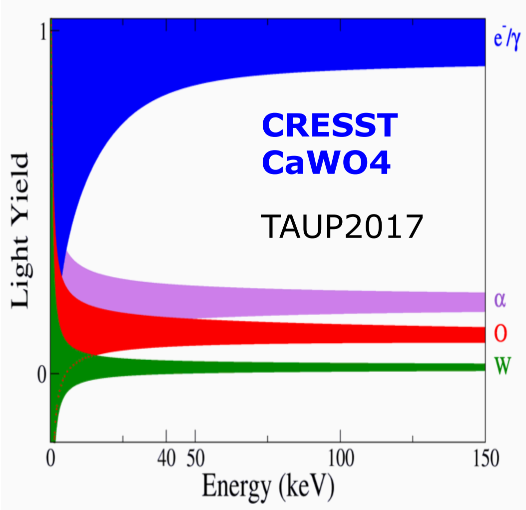


cdms.berkeley.edu

Why do we need quenching?

- Needed for energy scale (non-phonon detectors) DAMIC, CoGeNT, DAMA… … COHERENT
- Two-signal detectors: e⁻/NR/phonon-only discrimination



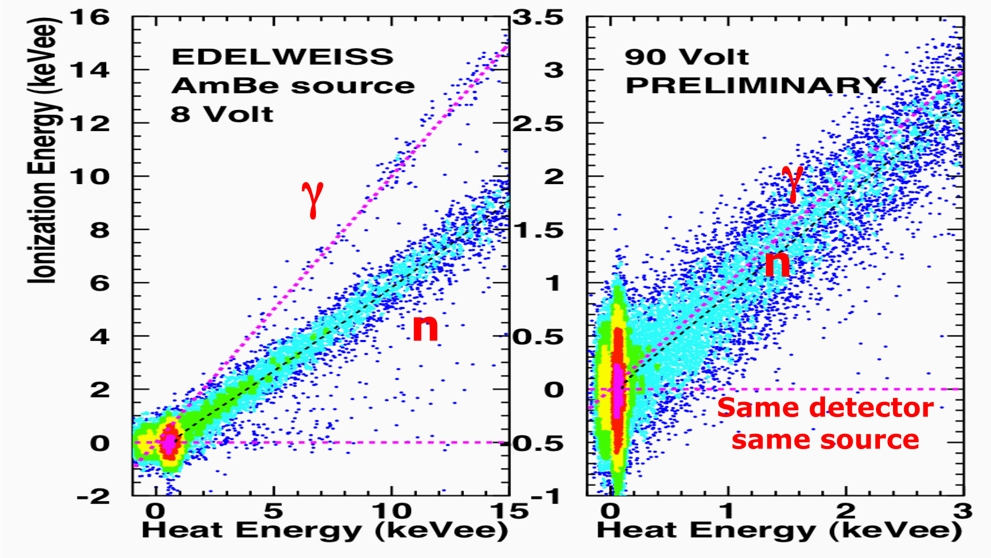


Signal	Quenching Needed for Energy scale	Provides good e⁻/NR discrimination	Good discrim. against phonon-only events
Phonon	No*		
Charge	YES	YES	YES (Q~0.3)
Scintillation	YES	YES	Not always (Q~0)

Why do we need quenching?

- Luke-Neganov amplification of phonon signal transforms "phonon signal" into "charge signal"

CDMS Lite
EDELWEISS-LT



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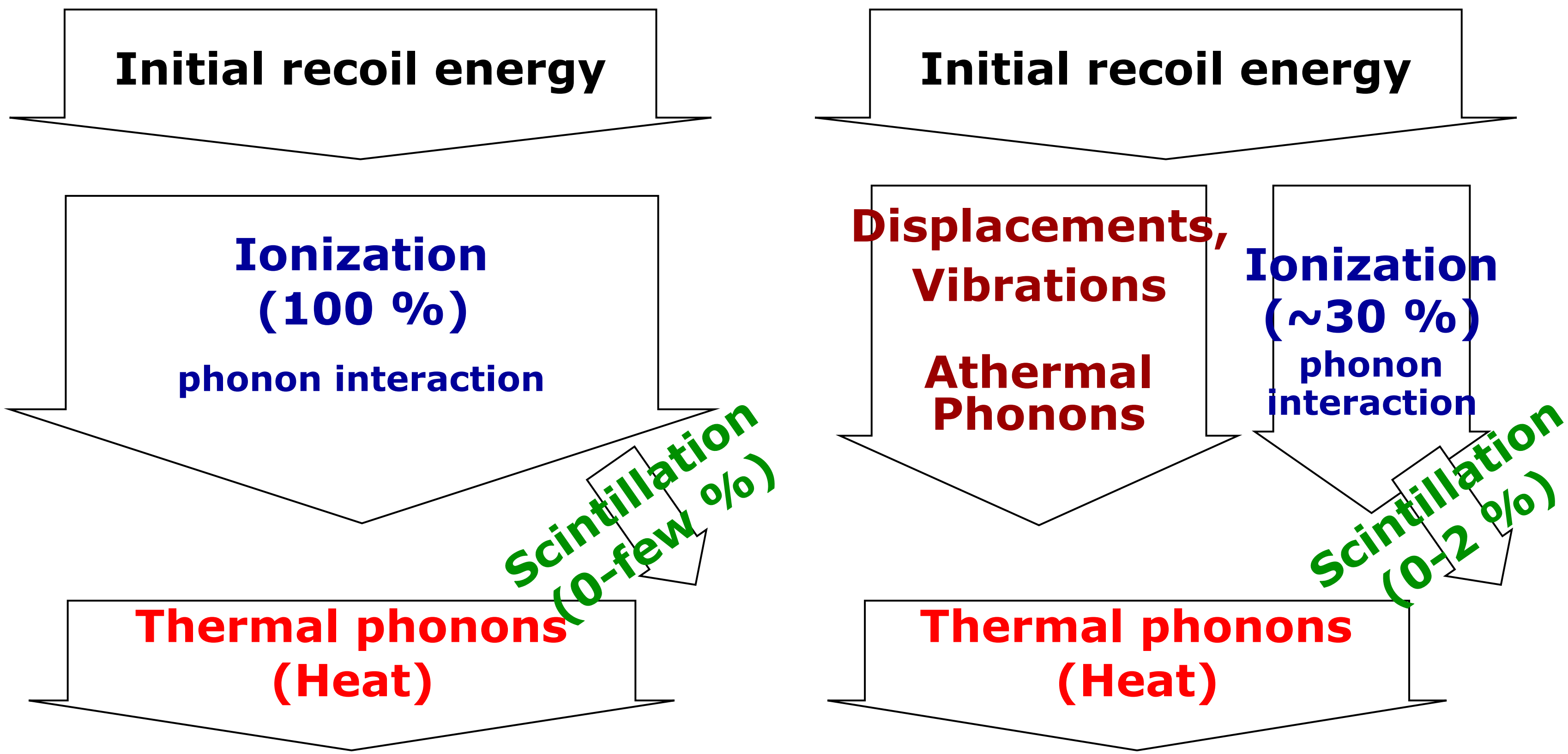
Signals from recoils

Electron recoil vs Nuclear recoil



(+ No permanent crystaline defects?)

(+ Permanent crystaline defects?)

Electron recoil energy scale (denominator)

Ionization yield (charge/eV)

- $\langle E_{e+e\text{-}pair} \rangle = E_{GAP} + \langle E_{kinetic} \rangle + \langle E_{phonon} \rangle$
- eV/pair : 3.0 in Ge, 3.6 in Si
- Very small temperature dependence between 0 and 77K (kT=0.006 eV)

Light yield (photoelectron/eV)

- Depends on scintillation center concentration in crystal
- Depends on density of energy deposition
- Non-linearities at low energy (NaI, CsI)
- Large temperature dependence time constants) in general
- ~20 eV typical value

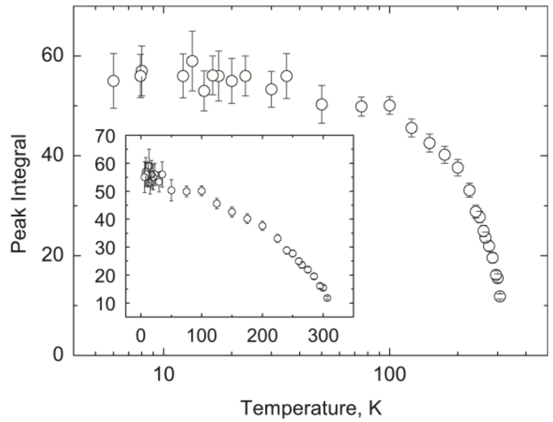


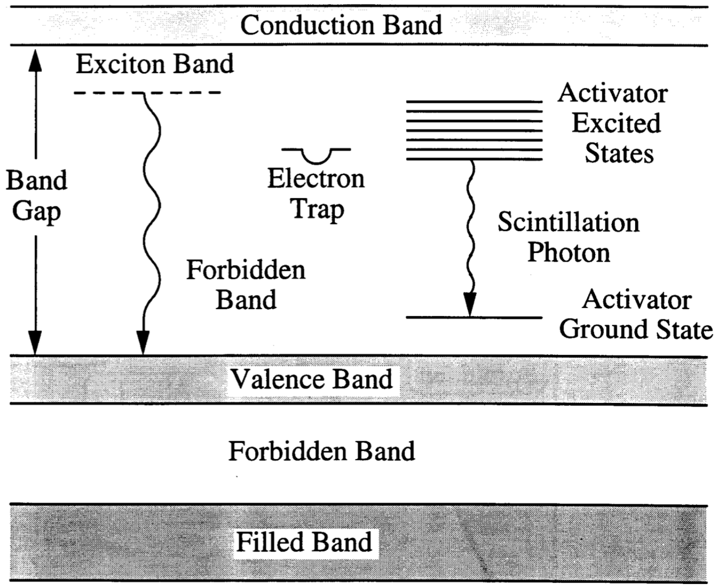
Fig. 1. Temperature dependence of the scintillation light response of BGO under α-excitation (^{241}Am). The inset shows the dependence on a linear temperature scale.

Inorganic scintillators (NaI, CsI, $CaWO_4$, ...)

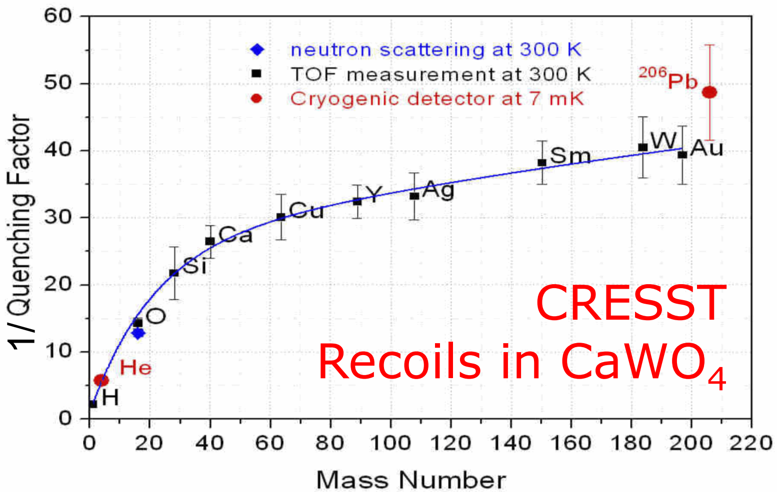
- A good scintillator should NOT reabsorb its own light

  Emission $h\nu > E_{gap}$ from e^- conduction band is easily absorbed by valence e^-
- *Emission from less abundant in-gap states is much less absorbed*
- ~Birk's rule: if dE/dx is large, the population of the in-gap states is saturated: reduced emission per incident keV.
- Electron recoils are subject to this (E-dependent) quenching.

  Additional Lindhard quenching for nuclear recoils.
- Scintillation time constants may be affected: pulse shape discr.

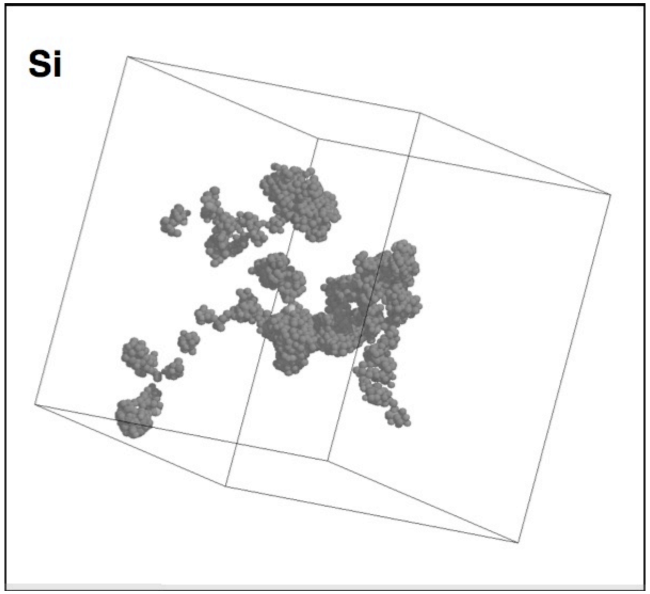


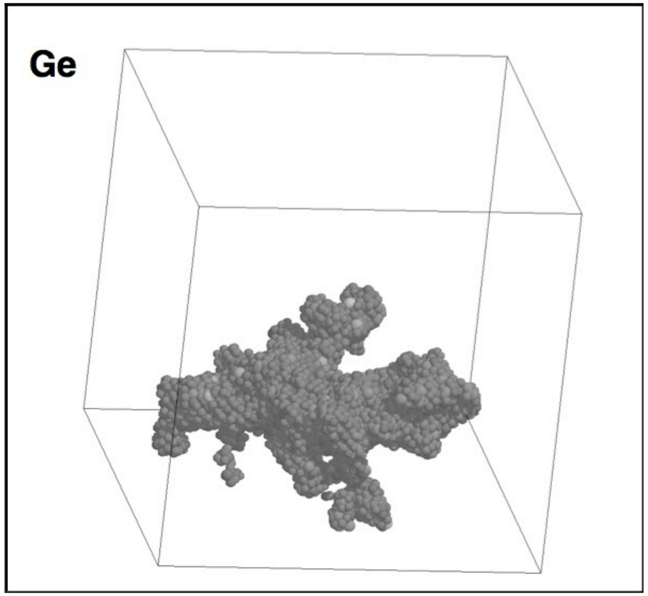
Derenzo

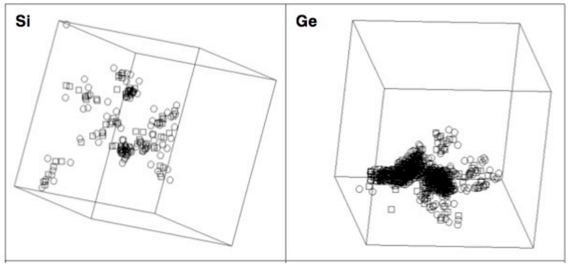


MD simulations of nuclear recoils

- Molecular Dynamic Simulations of « hot » atoms produced by a 10 keV Si or Ge recoil (Nordlund, 1998)



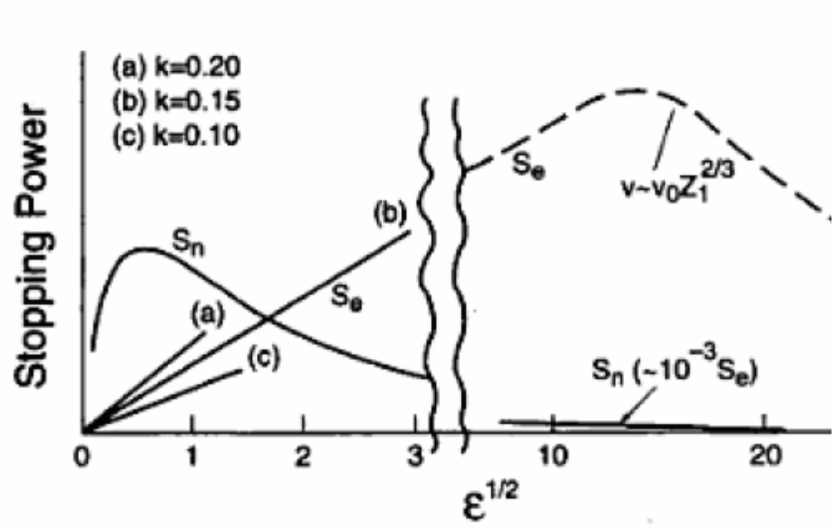




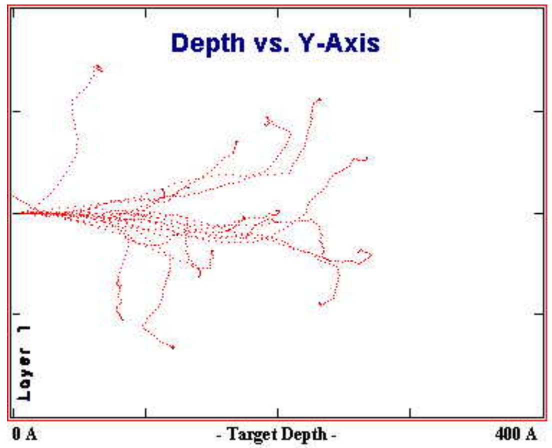
Permanent damages due to this « femtoGray » dose
(negligible in metals, but maybe not in semiconductors?)

Ion recoils in crystal

- S_n and S_e: Nuclear and electronic stopping power dE/dx
  - S_n peaked at low energy (100 keV for Ge recoils in Ge)
  - $S_e = k\sqrt{\varepsilon}$ at low energy, and small compared to S_n at 100 keV
- Lindhard, Scharff and Schiøtt (1963): use S_n and S_e to model of the energy loss during the cascade of ion-ion collisions to calculate the range, *the ionization yield* and its dispersion
- Model extensively used and tested, parameterized (k) using data



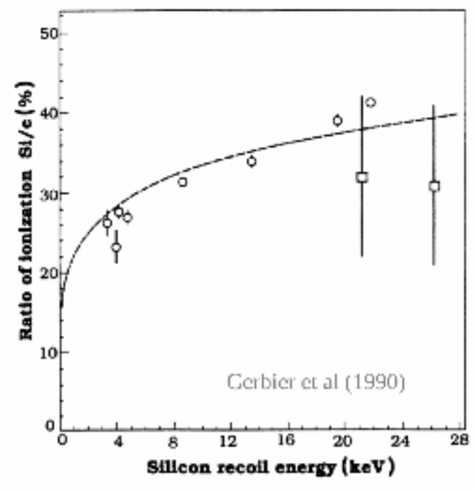
20 keV Ge recoils in crystal Ge:
Range ~20 nm

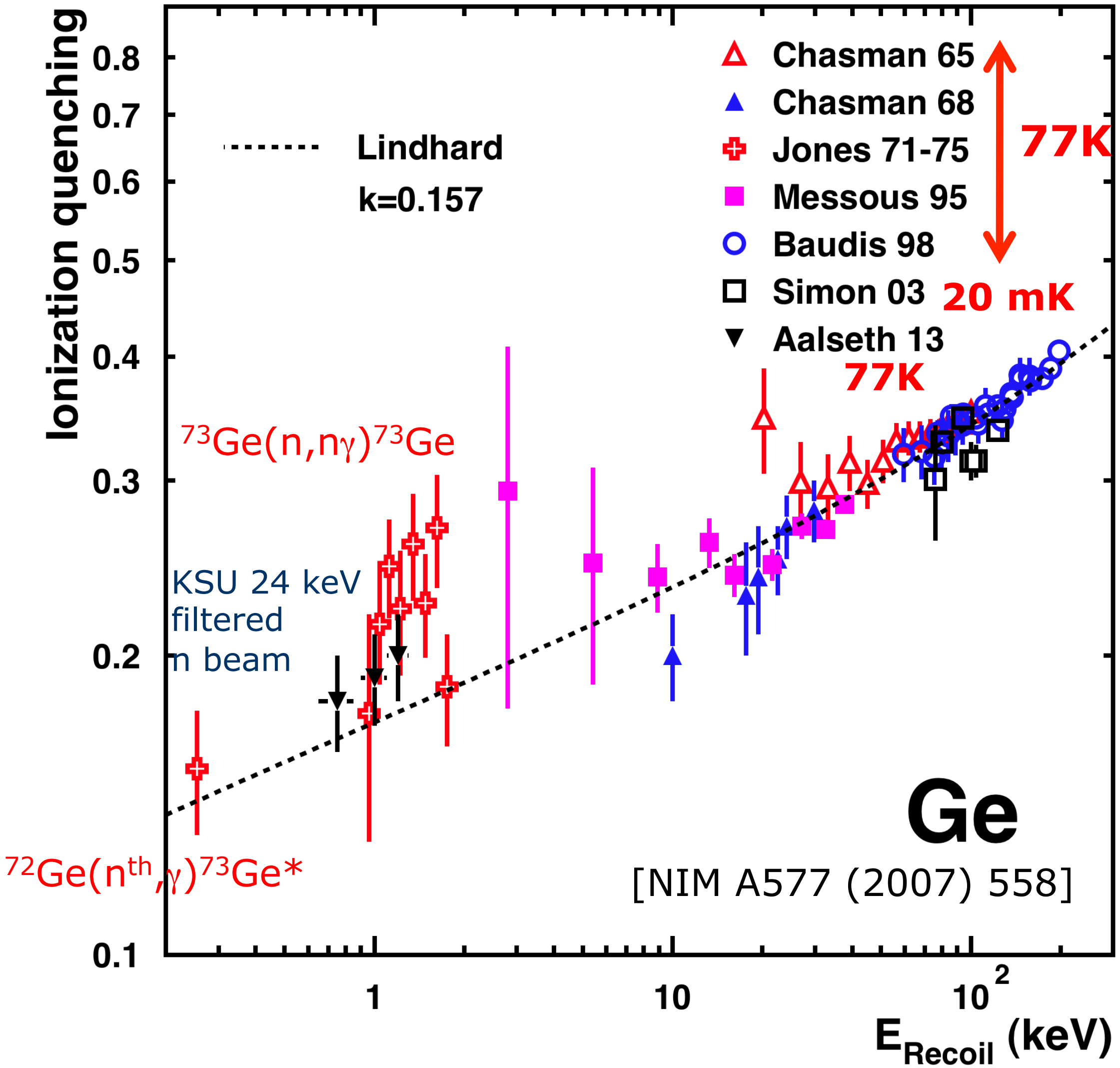


SRIM

Lindhard vs Data

- Tested since 1965: simple model fits well 10-100 keV range
- Measurements more difficult around 1 keV



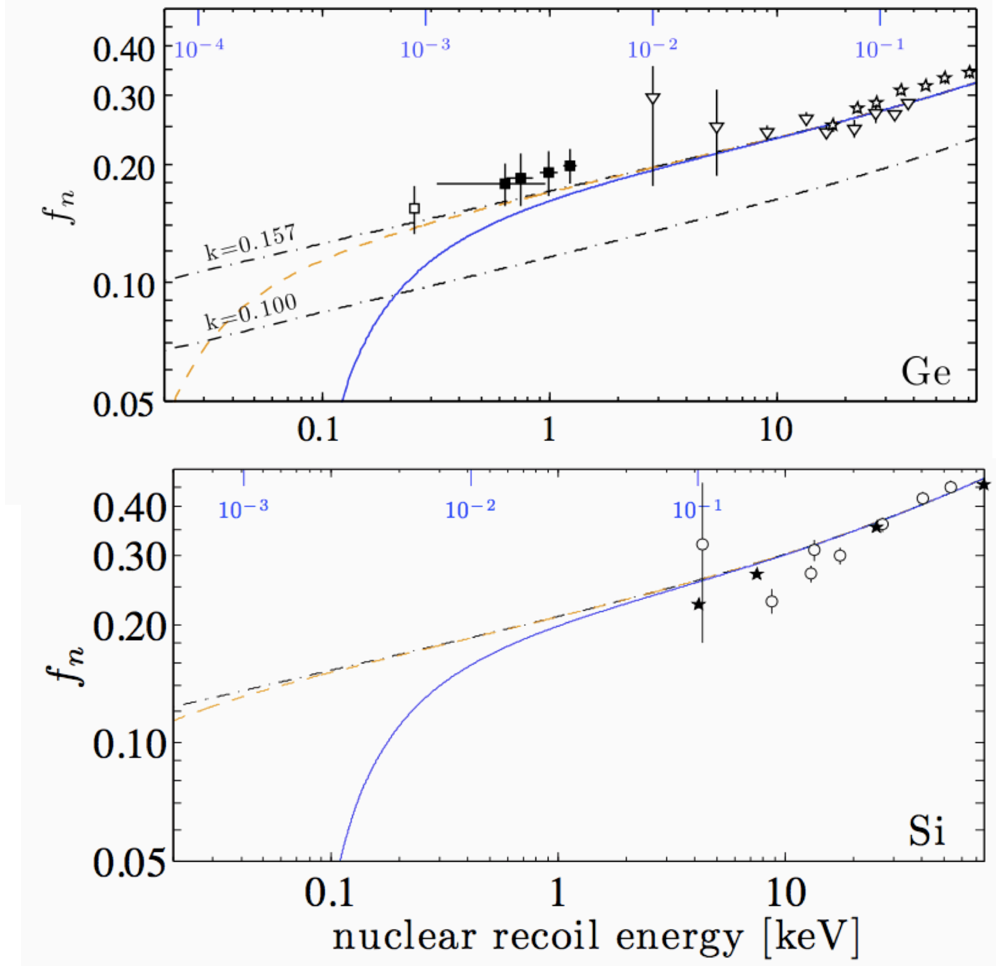


Lindhard critique: threshold effects

See e.g. Sorensen, PRD91 (2015) 083509
Also in: https://kicp-workshops.uchicago.edu/2015-lowecal/index.php

- Lindhard model assumes interaction between two neutral atoms (with screened Coulomb potential)… too simple?

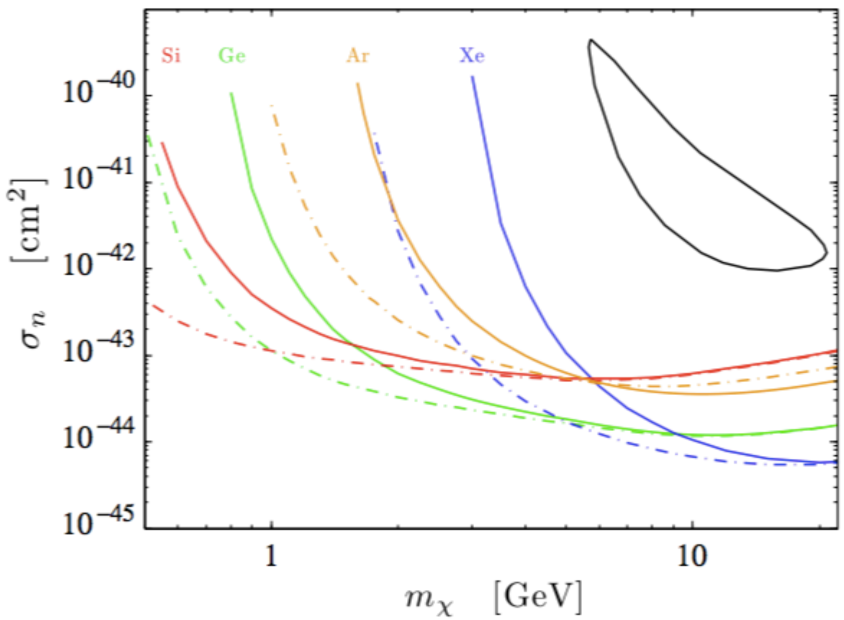
- But: Threshold energy to excite a e^+h^- pair (0.7 eV gap) ~100 eV for Ge?
- Also: average energy to ionize an e^- should play a role?
  $S_e = k\sqrt{\varepsilon} - cte$



Effect on threshold?

This matters if you are…

- Searching for O(1) GeV dark matter via nuclear recoil scattering
- Searching for CENNS from low-energy (e.g. reactor) neutrinos



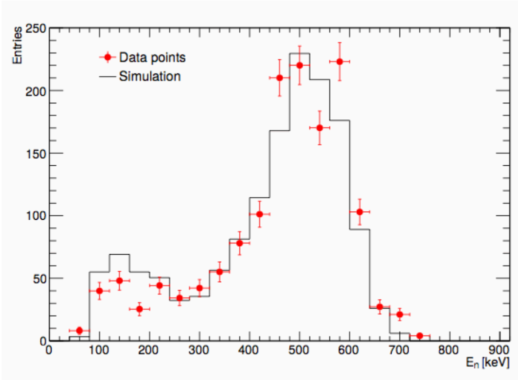
Peter Sorensen 25 Sept 2015 23

Measurement issues

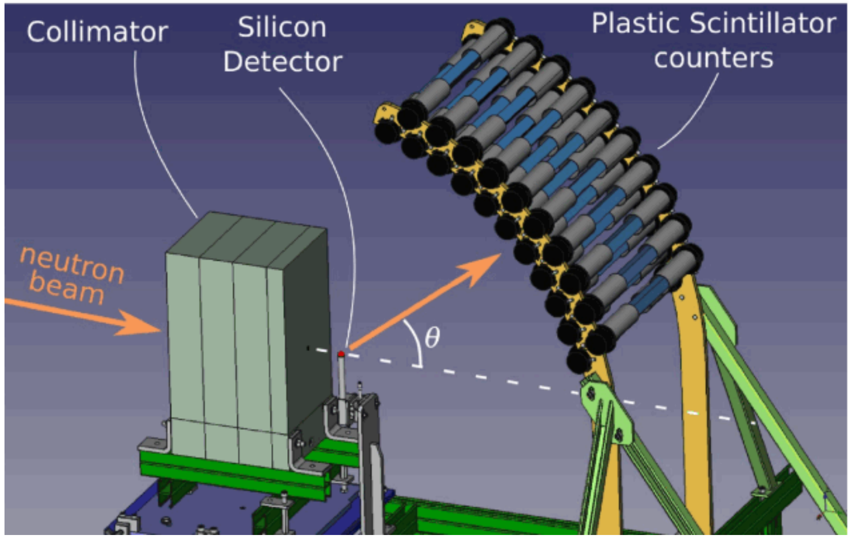
- Neutron beam/source
  - Monoenergetic or broad band? Try to avoid MC dependence…
- Detector size, surroundings
  - Multiple scattering inside the detector
  - Scattering of neutron before/after hitting the target
- Detector calibration near its threshold
  - Difficulty of low-energy γ-ray lines throughout the bulk of the detector
  - Efficiency measurement / trigger bias
- Tag of neutron scattering angle to reconstruct recoil energy

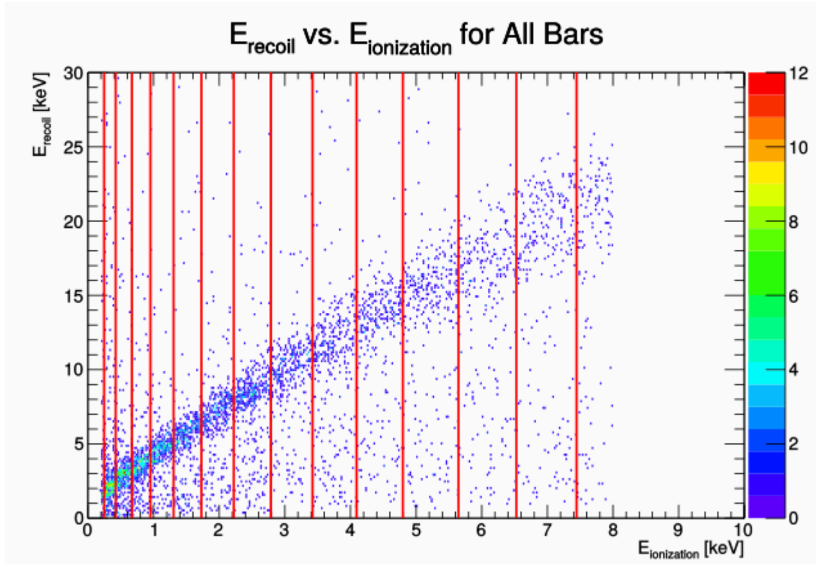
Measurements: Si with tagged n beam

- Antonella [arxiv:1702.00873]
- <700 keV Neutron beam



- 29 mg Si drift diode target (minimal multiple scattering)
- Recoil energy deduced from scattering angle + Time of Flight in plastic scintillator counters

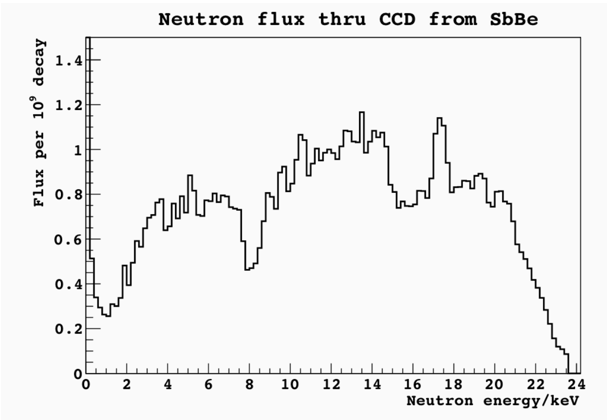




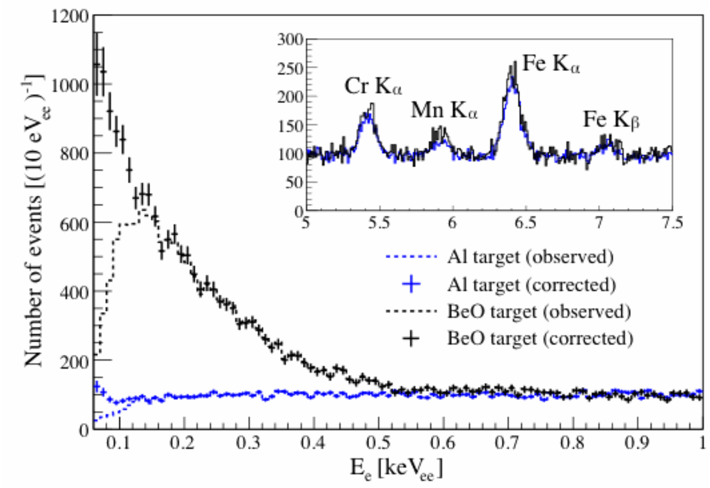
Si with ^{124}Sb-^{9}Be source

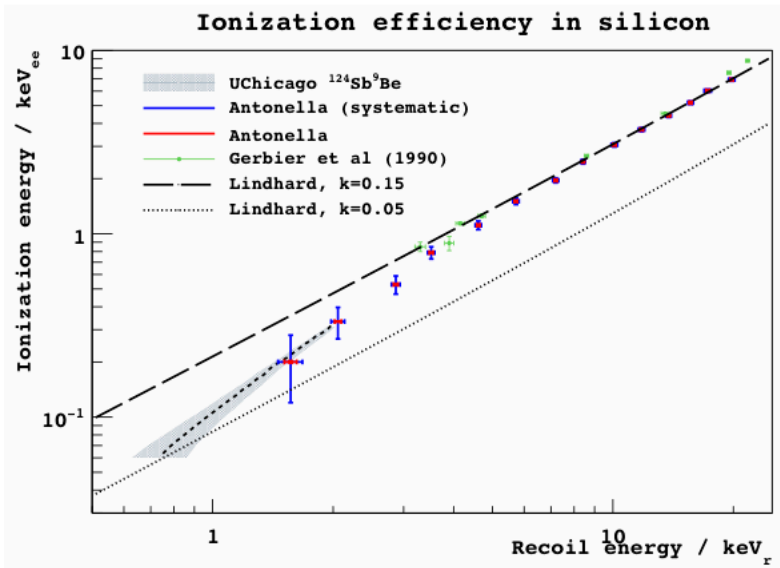
arXiv:1608.00957

- ^{9}Be(γ,n): continuous spectrum of <20 keV neutrons



- Use MC to fit Q model to data
- Both Si measurements show decrease wrt Lindhard close to 1 keVNR

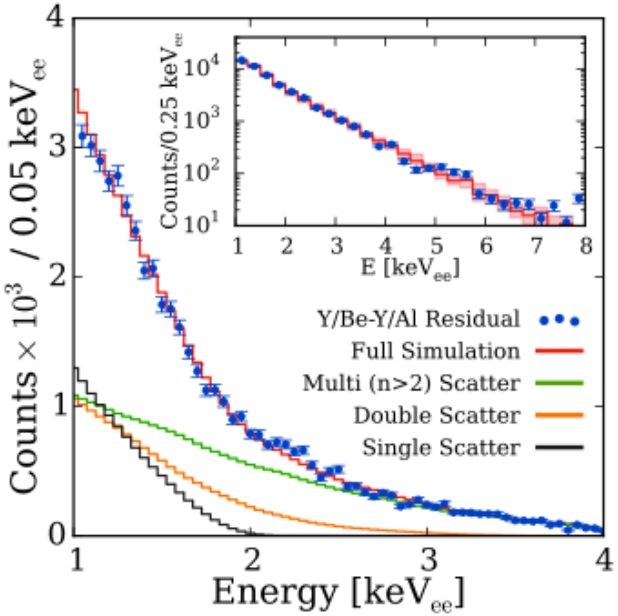


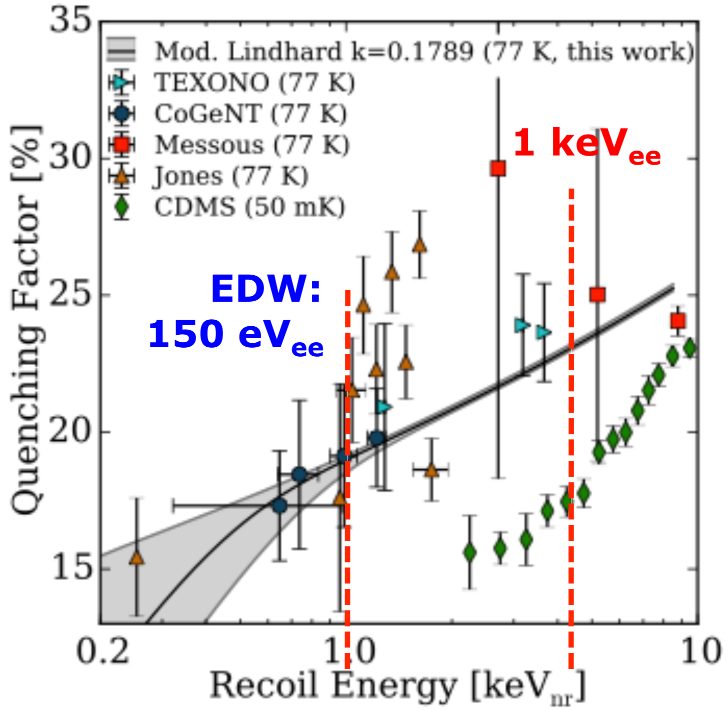


Ge: recent Y/Be measurement

arxiv:1608:03588 / PRD 94 (2016) 122003

- 475g PPC detector
- Fit k_LINDHARD: 0.179 ±0.001 dow to 0.3 keV_{NR}
- But… data starts at 1 keV_{ee}?



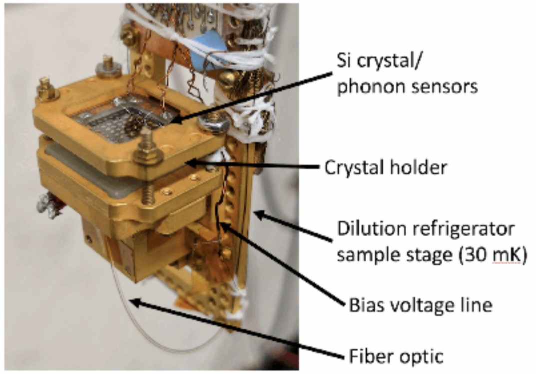


- "trick": >30% of 1 keV_{ee} events are N≥3 or multiple hits
- Reliable probe of recoils down to 300 eV_{NR} ~ 40 eV_{ee}?
- *Advantage of a global fit of one model instead of bin-by-bin fit*

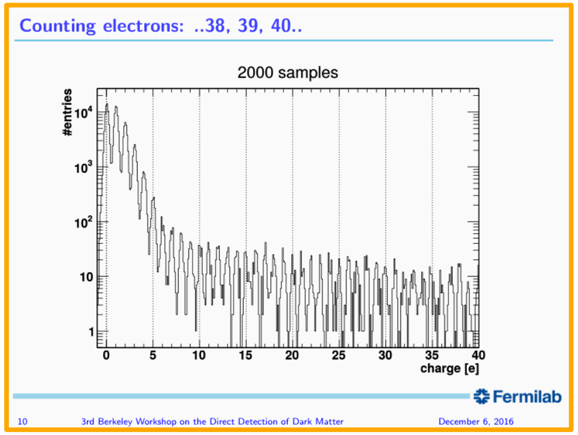
New idea: e-h pair counting

arXiv:1710.09335

- Electron-hole pair quantization in a high voltage (160V) cryogenic silicon detector (1 g) [CDMS phonon sensor]
- Here: pairs created by electron recoil (laser): 3.8 eV/pair in Si



- Comparable to e-h pair counting achievable in skipper CCDs (SENSEI)



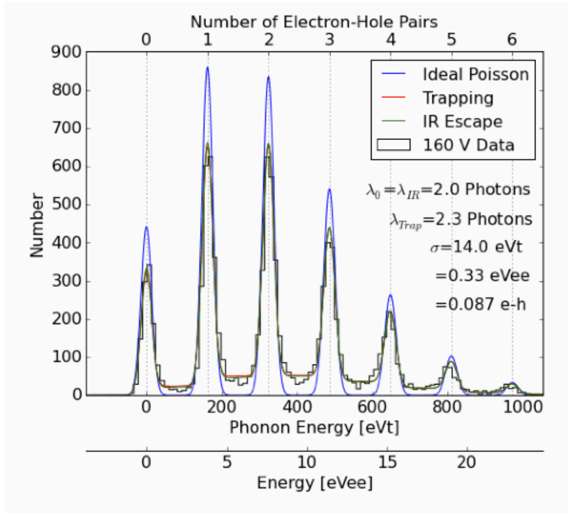


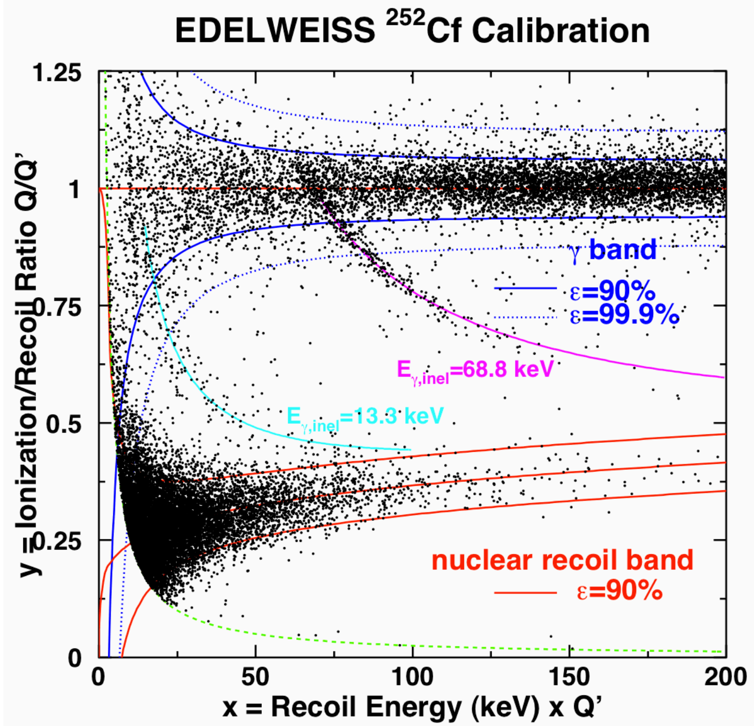
FIG. 5. (color online) Histogram of summed A+B data from Fig. 2 showing the excellent fit for a Poisson distribution. A small non-linearity is taken out of the data prior to the fits (see text). The integer number of e^-h^+ pairs is shown above, the phonon crystal energy below (eVt), and an electron-equivalent energy scale (eVee) at bottom using the standard 3.8 eV per e^-h^+ pair.[13] Fits are performed including trapping and impact ionization (see text).

Idea: Spacing should change when observing nuclear recoil: spacing = 3.8 eV/Qion

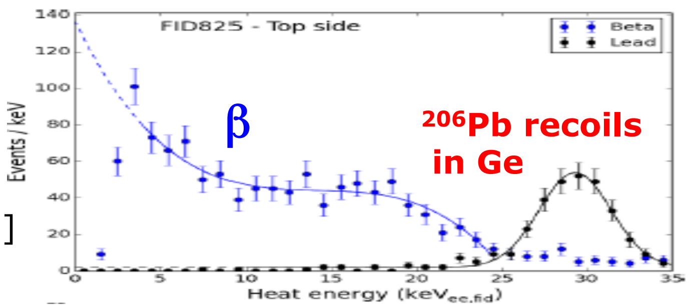
Ge: phonon quenching?

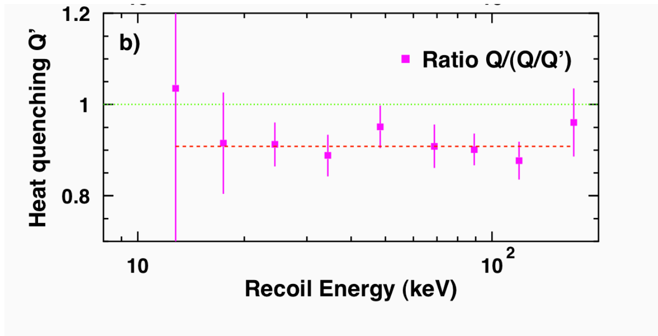
EDELWEISS, NIM A 577 (2007) 558

- If energy loss to permanent damage in nuclear collision, phonon quenching: $E_{phonon} = Q_{phonon} E_{recoil}$
- Q_{phonon} extracted by comparing apparent ionization Q_{ion} in cryogenics Ge detectors to direct Q_{ion} measurements
- Results: damage loss ~ 9±5%, consistent with measurement of Pb recoils in bolometers, and dominated by systematics on calibration and simulation of multiple scattering



EDELWEISS tagged surface events
[JCAP05 (2016) 019]





Conclusions

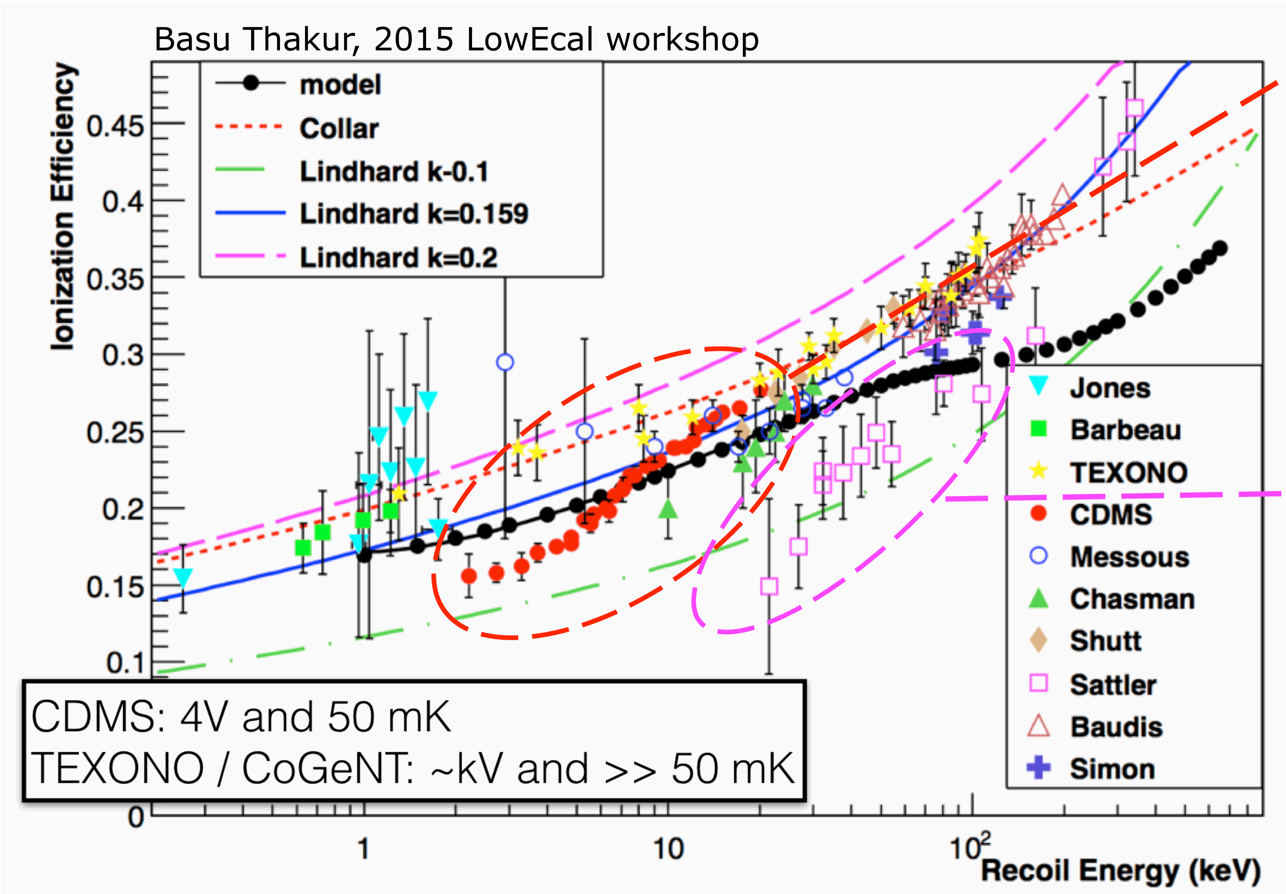
- Ionization quenching measurements in Ge & Si at low energy very important to set the energy scale in the experiments DAMIC (Si) and EDELWEISS-LT (Ge)

- Threshold effects in Lindhard model hunted since 1968, first positive hints in recent Si measurements? To be confirmed in Ge [same physics?].

- A detailed understanding of detector physics and of systematic effects is required
  - Clear benefits of discussions within the community
- New ideas, strategies and collaborations are welcome

Quenching the Ge quenching controversies

- Caution: sometimes data shown in a way to exacerbate discrepancies
- … as often, in fields where new models abound…



CDMS thesis,
Not published
Systematics?
(see e.g. next slide)

Sattler 65 results refuted by Chasman 67,68 (bad analysis of continuum data)