CDMSlite:
A Search for Light WIMPs

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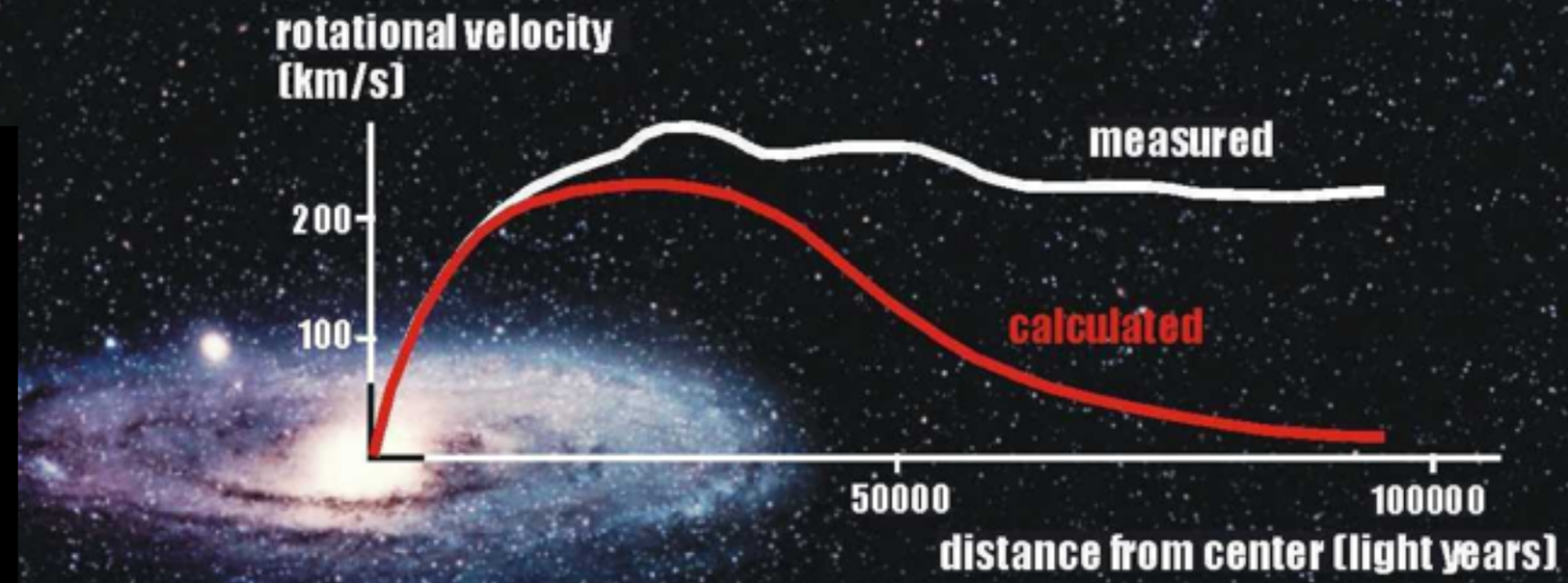
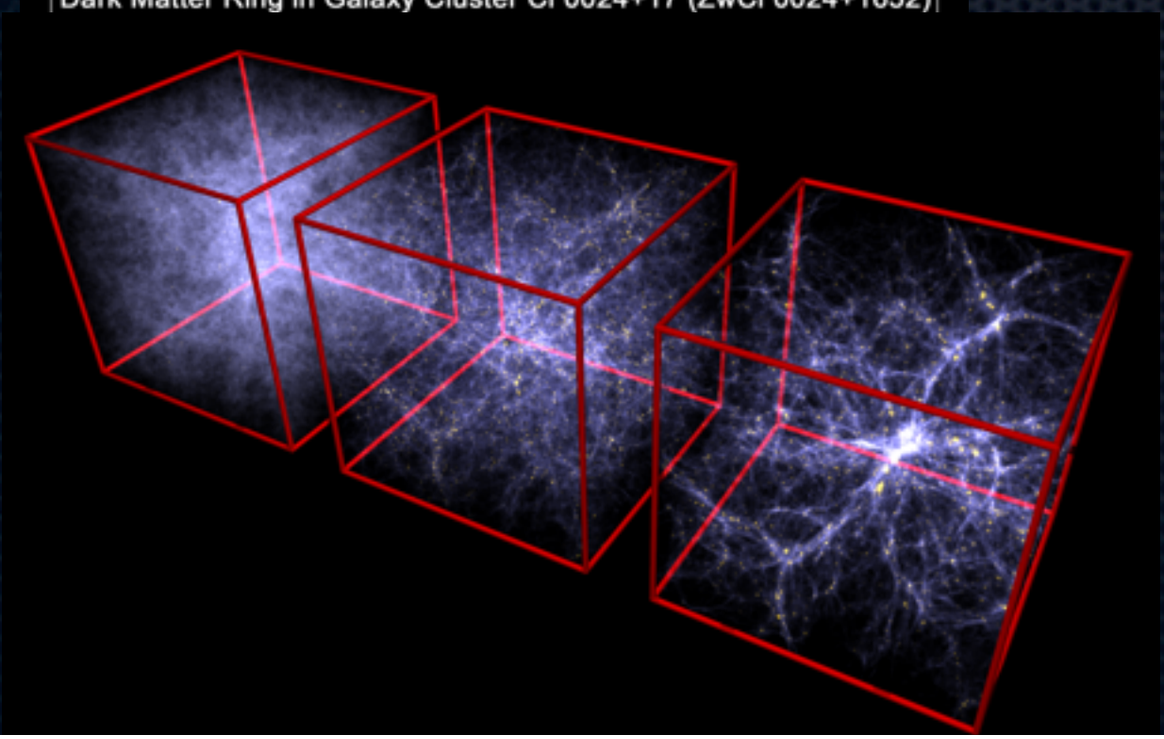
on behalf of the SuperCDMS collaboration

FCPA Seminar, Sept. 16th 2013

Dark Matter:

Dark Matter Ring in Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)





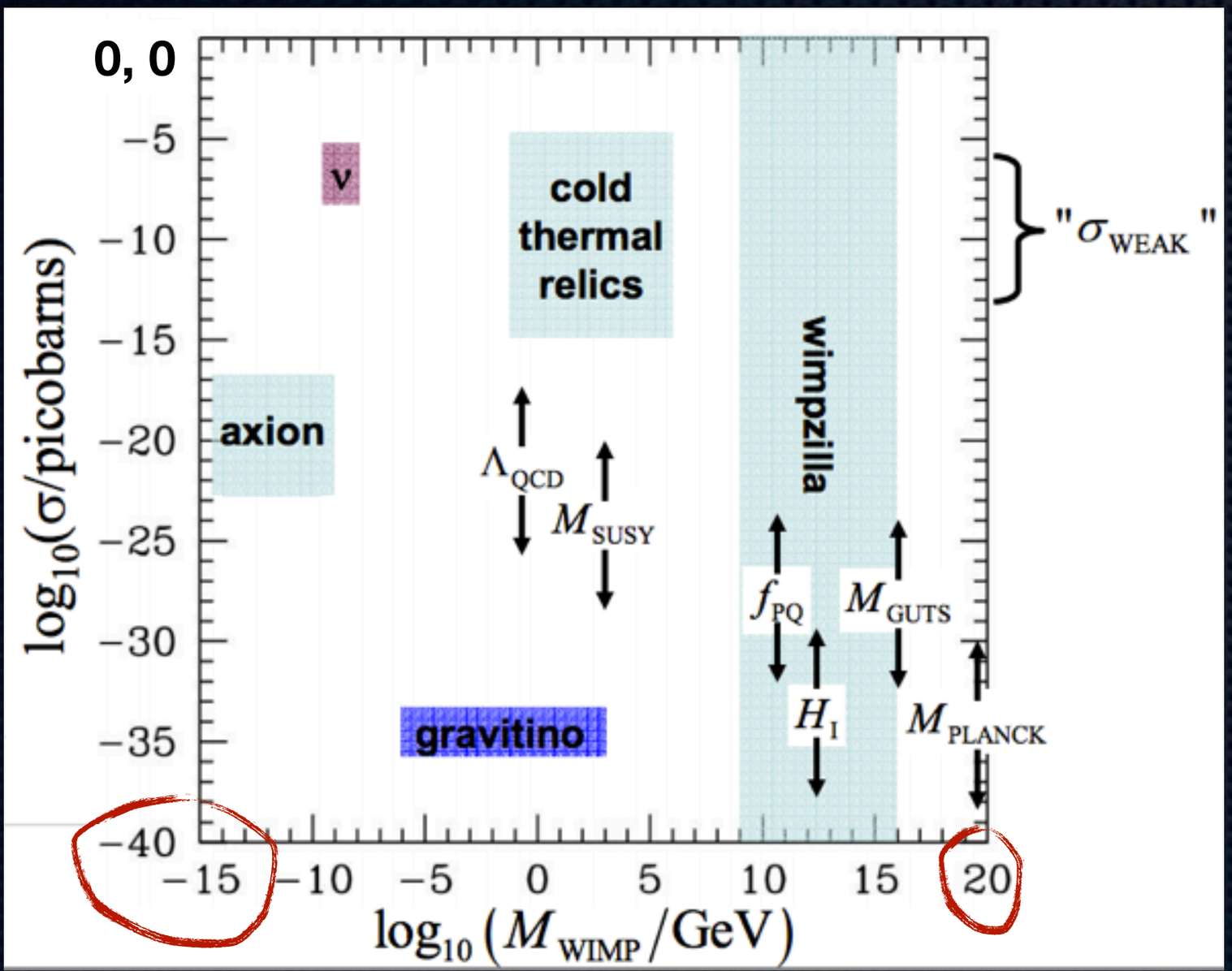
- Plethora of observational evidence that ~27% of the universe is DM

Structure formation, rotation curves, CMB physics, lensing etc.

- Simulations are in good agreement
- Only gravitational effects measured

Theoretical notions

The particle picture



- Popular candidates are WIMPs

→ stable, neutral, weakly interacting massive particles

- Cold thermal relics
- Motivated by weak freeze out
- Favored masses depend on models: MSSM likes neutralinos > 40 GeV, while Asymmetric DM theories prefer ~ 5 GeV WIMPs
- Current bounds:

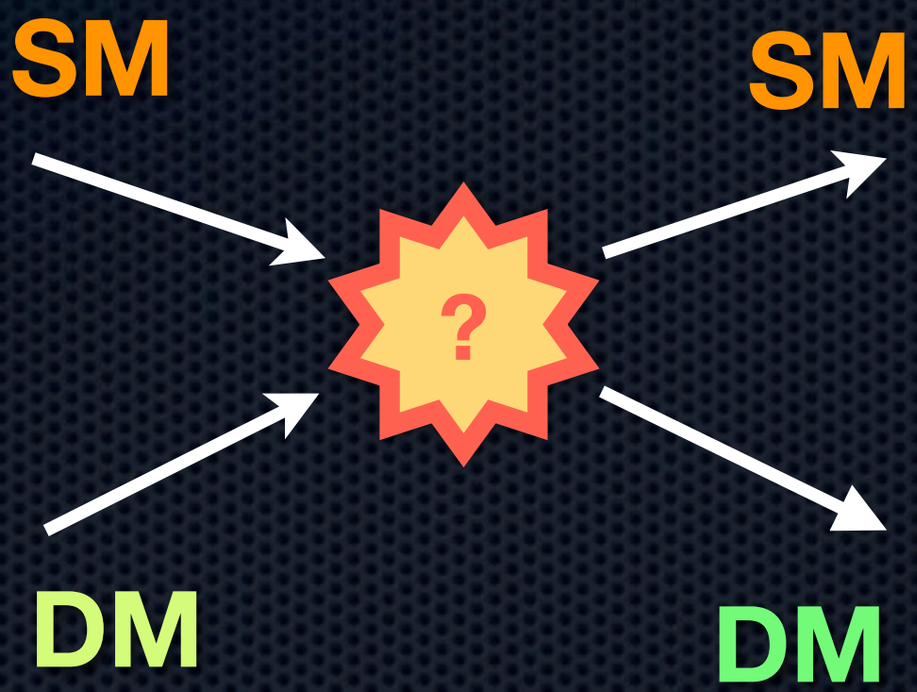
$$10^3\,\text{GeV} \gtrsim m_\chi \gtrsim 10\ \text{GeV}$$

$$\sigma_{\chi,n} < 10^{-40}\,\text{cm}^2$$

In general, it's a huge phase-space, but different theories may constrain the possibilities

Experimental pursuits:

Excess of SM particles from ***annihilating*** DM, in regions rich in DM (dwarf galaxies)



Missing energy / DM-***production*** searches at colliders

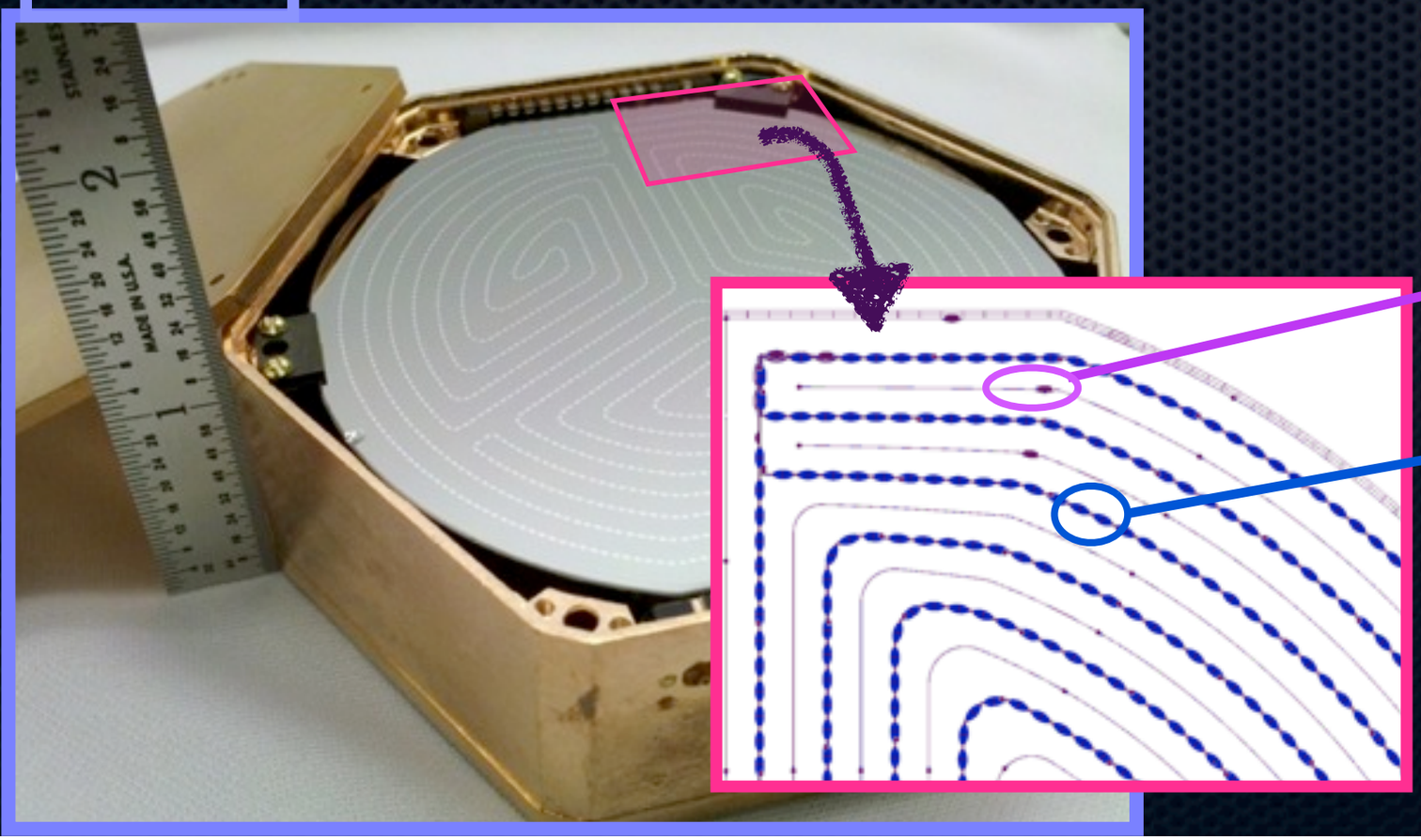
Look for nuclear recoils when a DM particle ***directly*** scatters off target nuclei.

SuperCDMS detectors

Measure atomic excitations / nuclear recoils when DM ***directly*** hits target nuclei.

CDMS measures charge & heat (phonon) deposited, which provides energy & particle identification on event-by-event basis

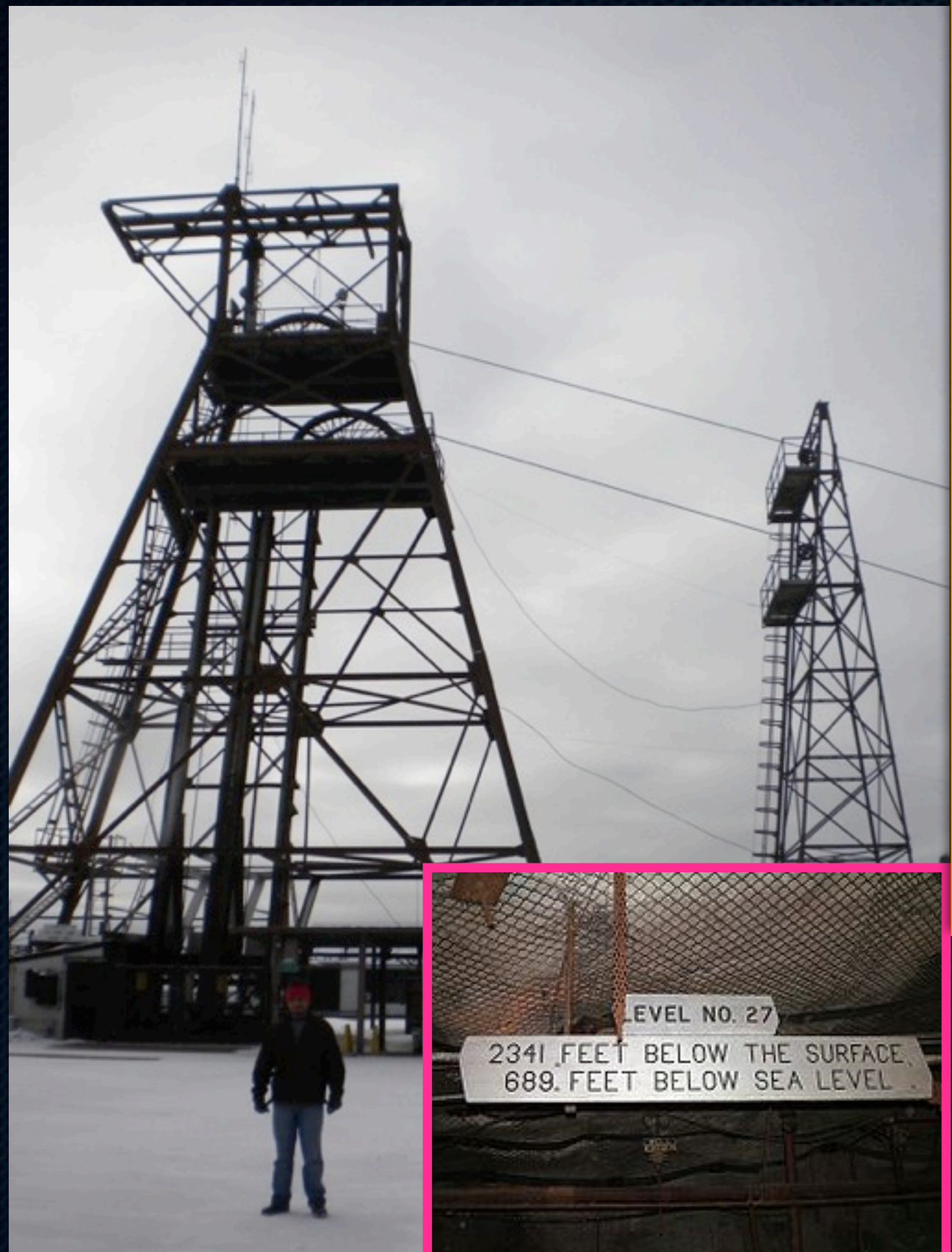
iZIPs:

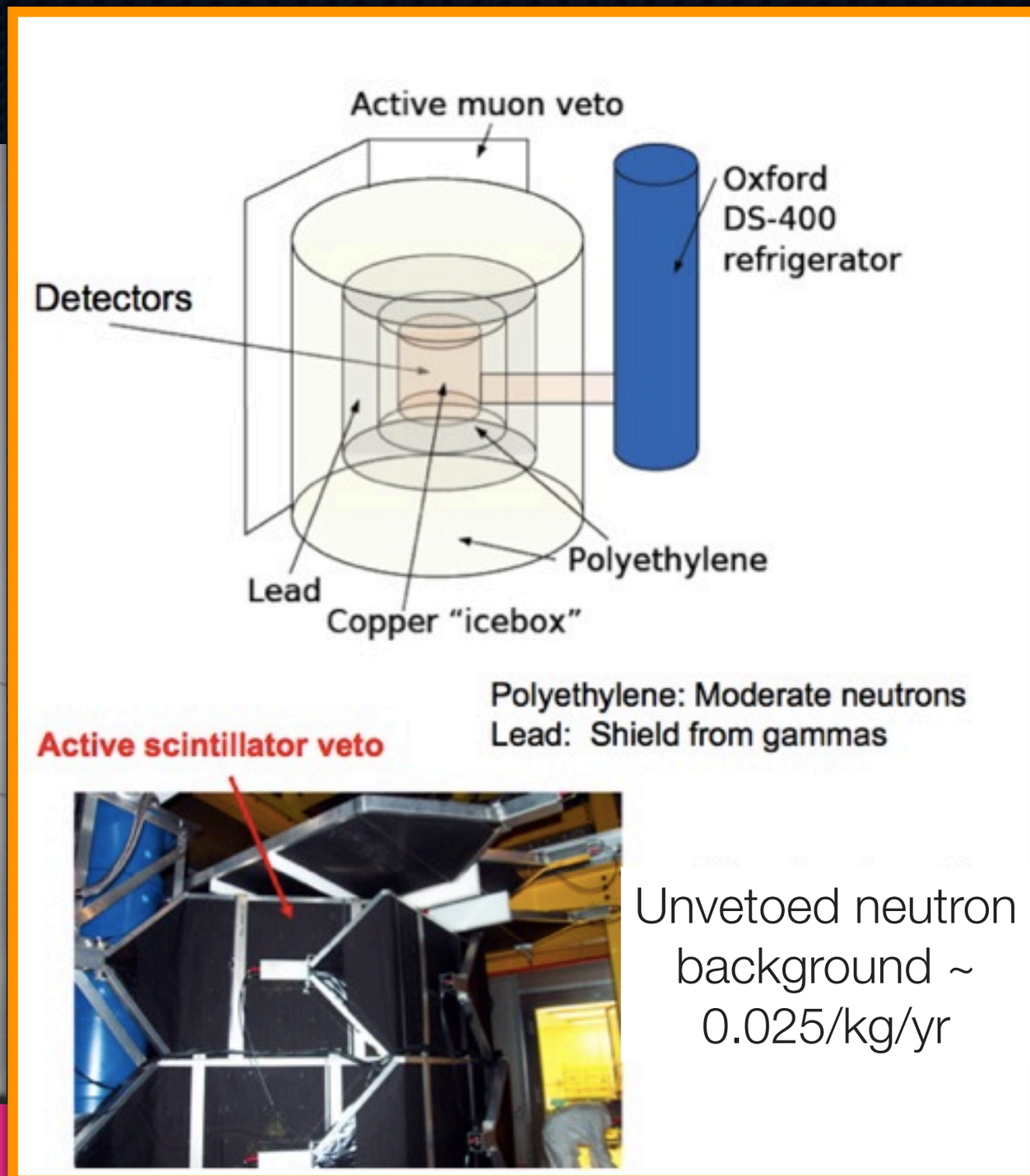


Charge electrodes

Transition **E**dge **S**ensors measure phonons created by interactions.

SuperCDMS Soudan



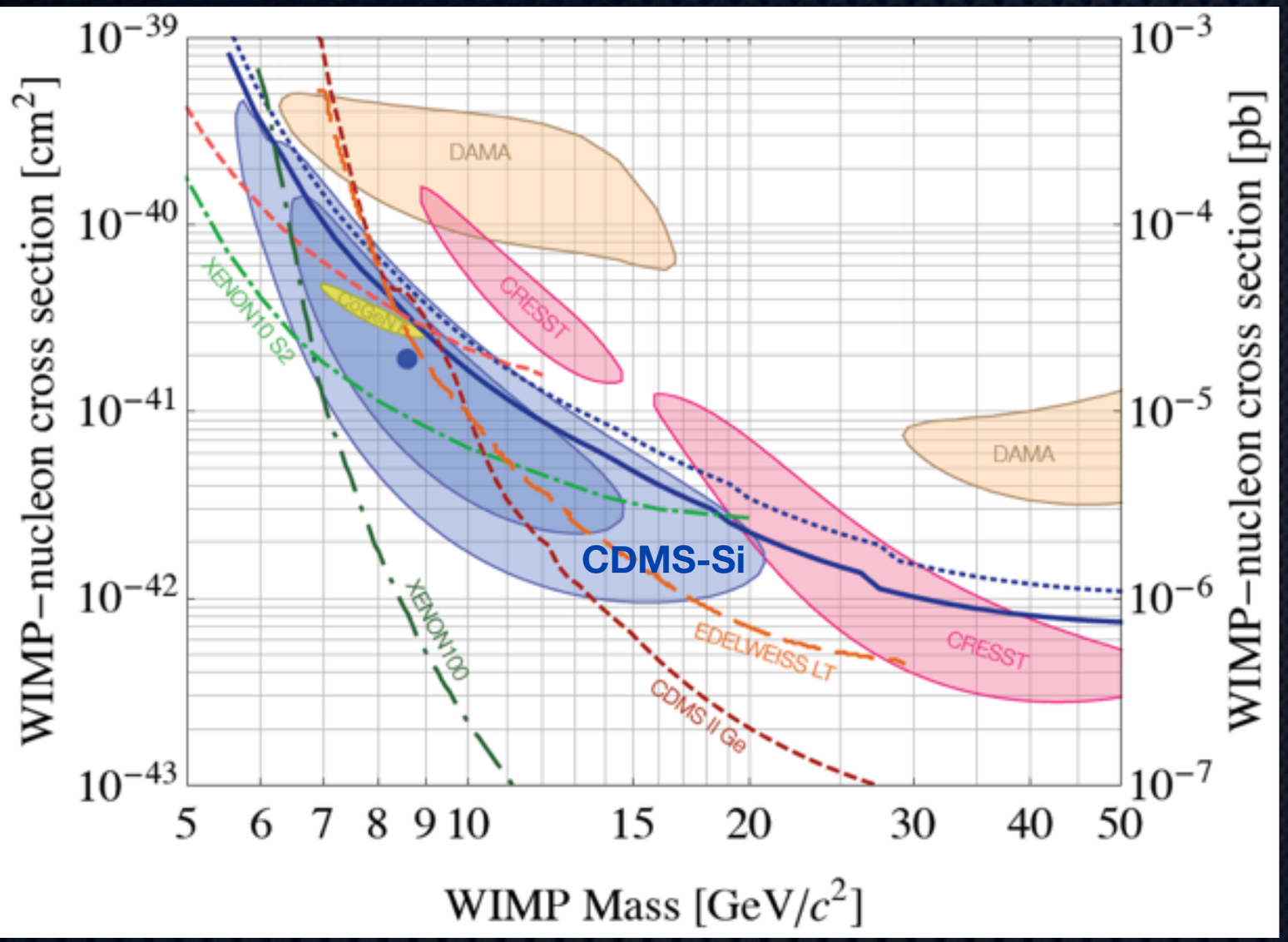


Unvetoed neutron background ~ 0.025/kg/yr

15 iZIP (~ 0.6 kg each) detectors inside icebox.

Direct Detection Landscape:

Low Mass



Experiments are in contention

Some experiments do report excesses at low energies

Others have limits which are in disagreement

No conclusive detection,

Low energy excesses may be interpreted as light WIMPS

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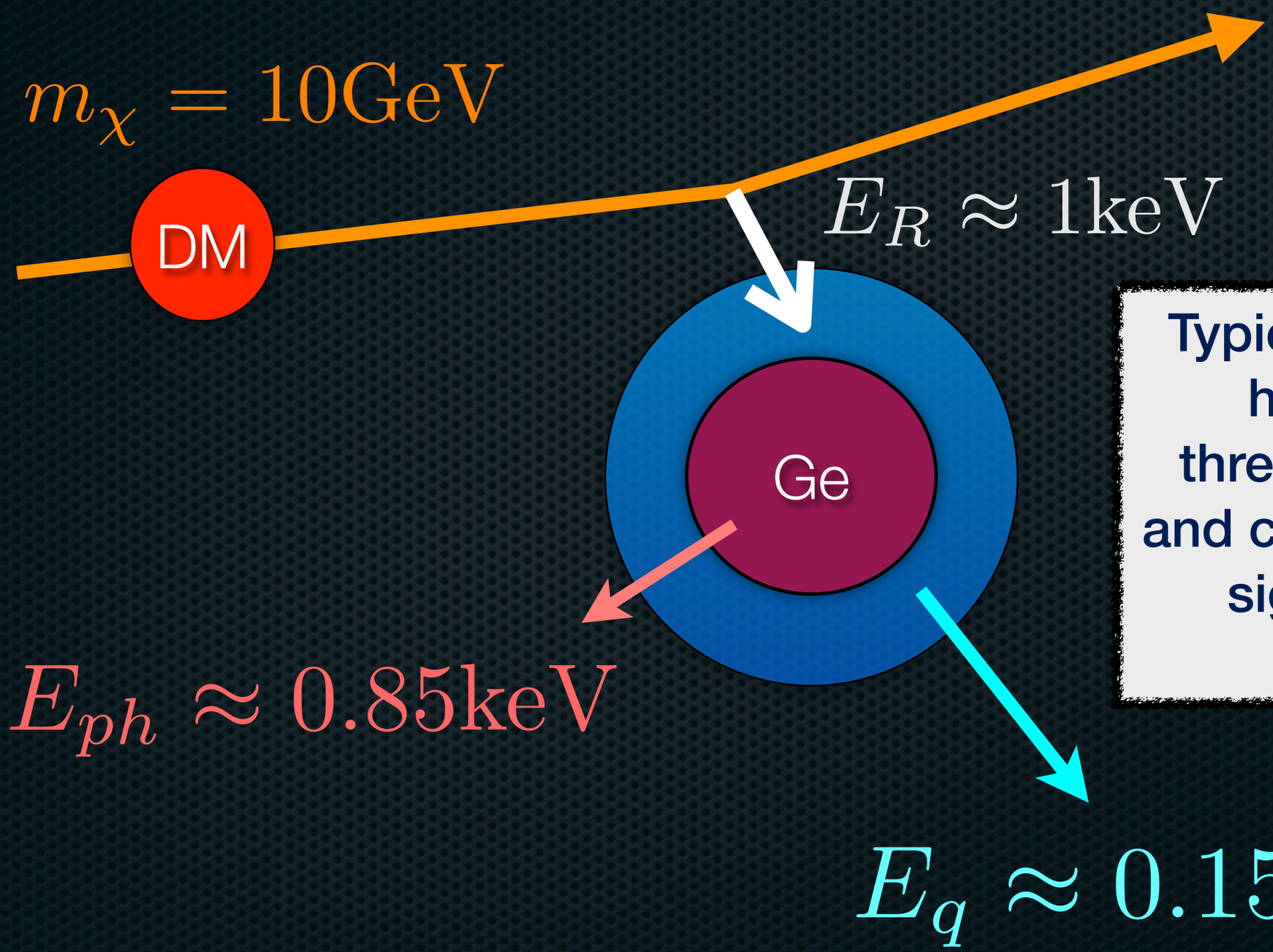
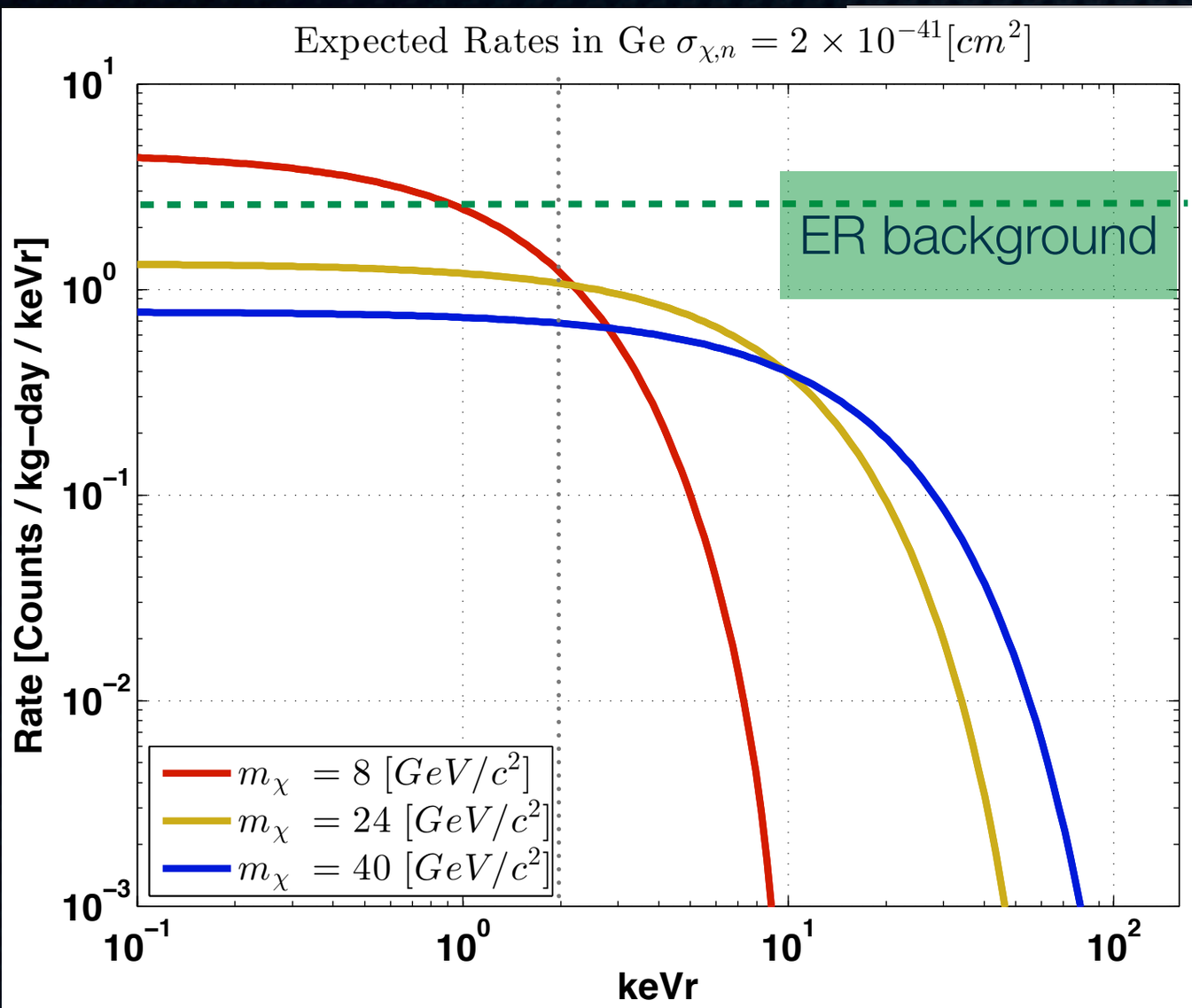
Light WIMP recoils:

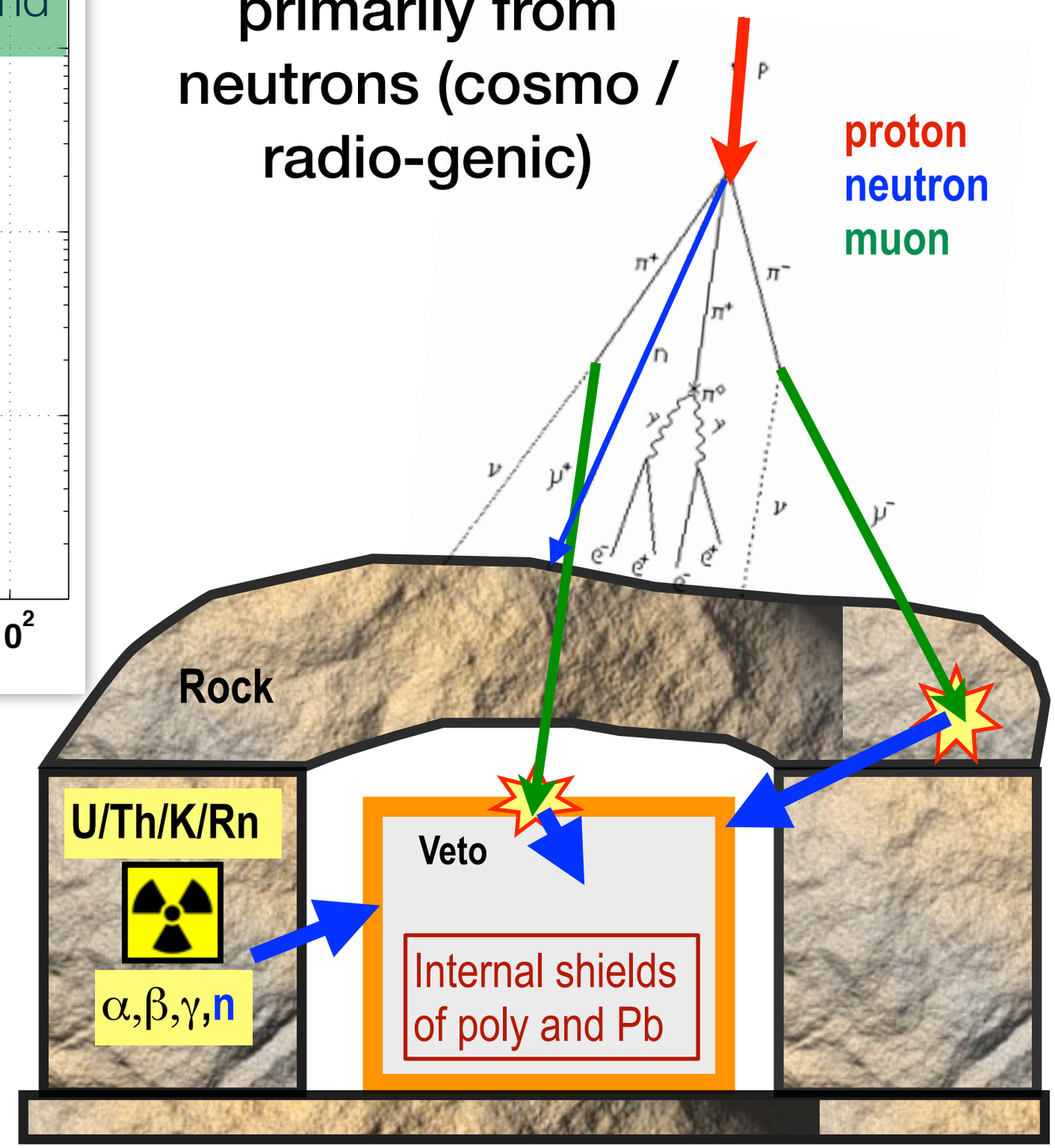


Typically experiments have ionization thresholds > 0.5 keV, and cannot detect such signals with high confidence

Signal and Backgrounds:



WIMP contamination is primarily from neutrons (cosmo / radio-genic)



Given expected backgrounds, light WIMP search requires very low thresholds

Challenges at low energies:

1. Environmental noise limits reach at low energies

Signals with low-energy / small-amplitudes aren't resolved

2. Backgrounds under 1 keV are not fully known

Hard to extract WIMP component of measured spectra

3. Atomic physics / detector response << 1 keV is not well understood

WIMP interpretation (NR/ER) is systematically affected

Solutions :

1. Environmental noise limits reach at low energies

So get Signal >> Noise.

2. Backgrounds under 1 keV are not fully known

Measure backgrounds < 1 keV.

Simulation work to “predict” backgrounds < 1 keV.

Material assay to reduce backgrounds.

3. Atomic physics / detector response << 1 keV is not well understood

Dedicated Solid State / Atomic Physics programs.

CDMS - low ionization threshold experiment

Ionization only experiment

Utilizes novel electron-phonon physics to get large signal gains

Potentially 85 eVee threshold

This low threshold will enable us to understand signals / backgrounds that exist at ~1 keVr.

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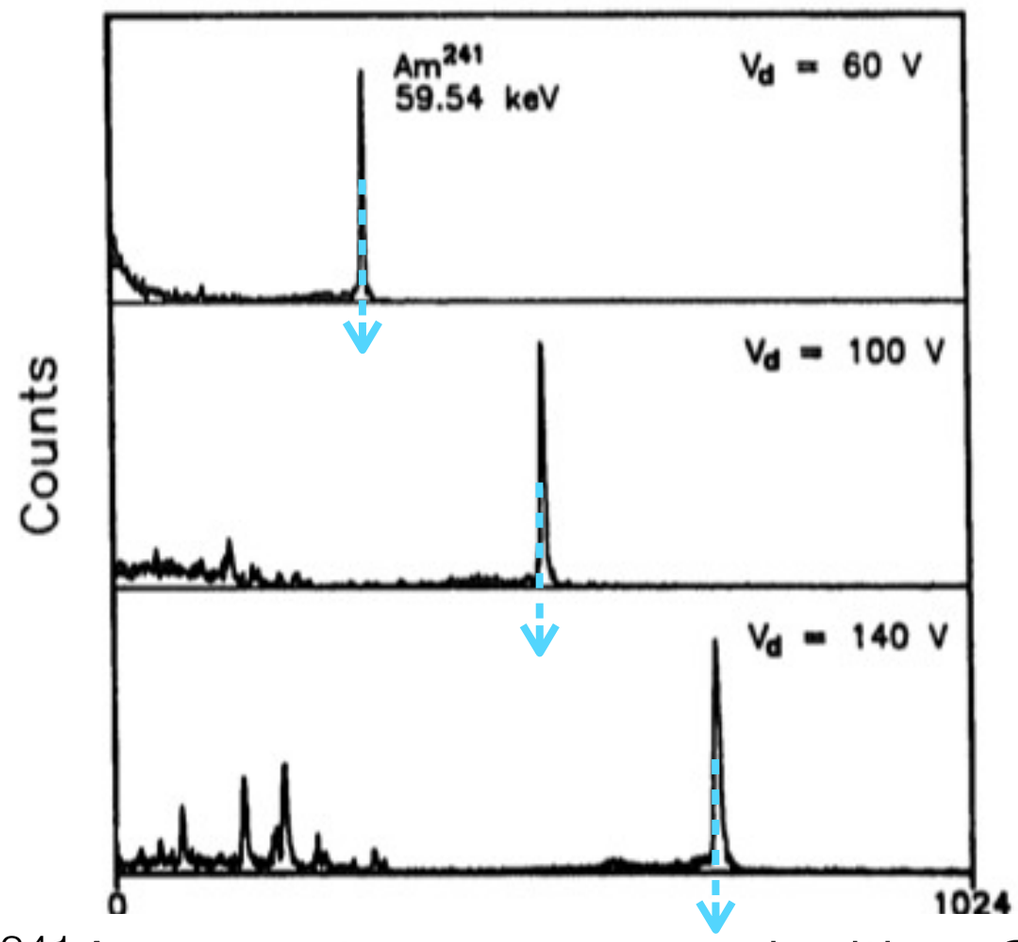
Luke-Neganov effect:

Linear Calorimetric amplification



^{241}Am spectrum measured with a Ge thermistor, with varying diode bias.

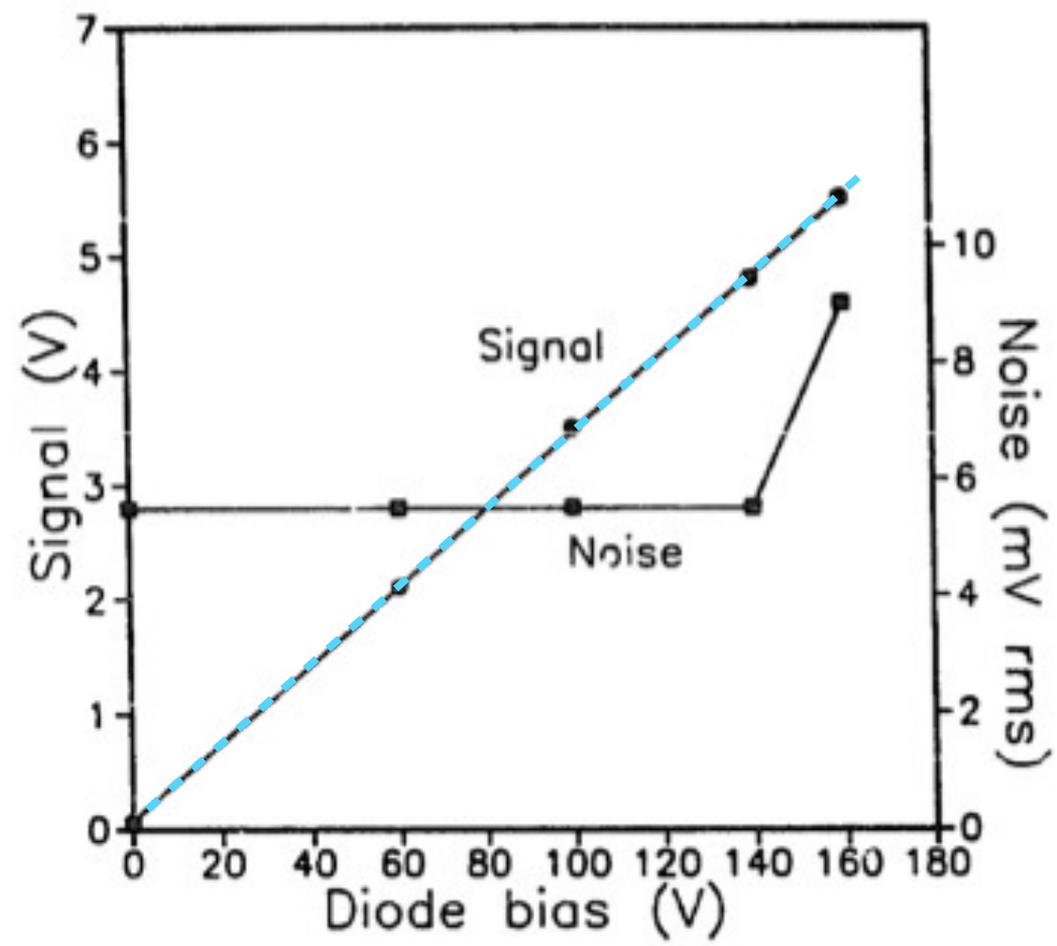
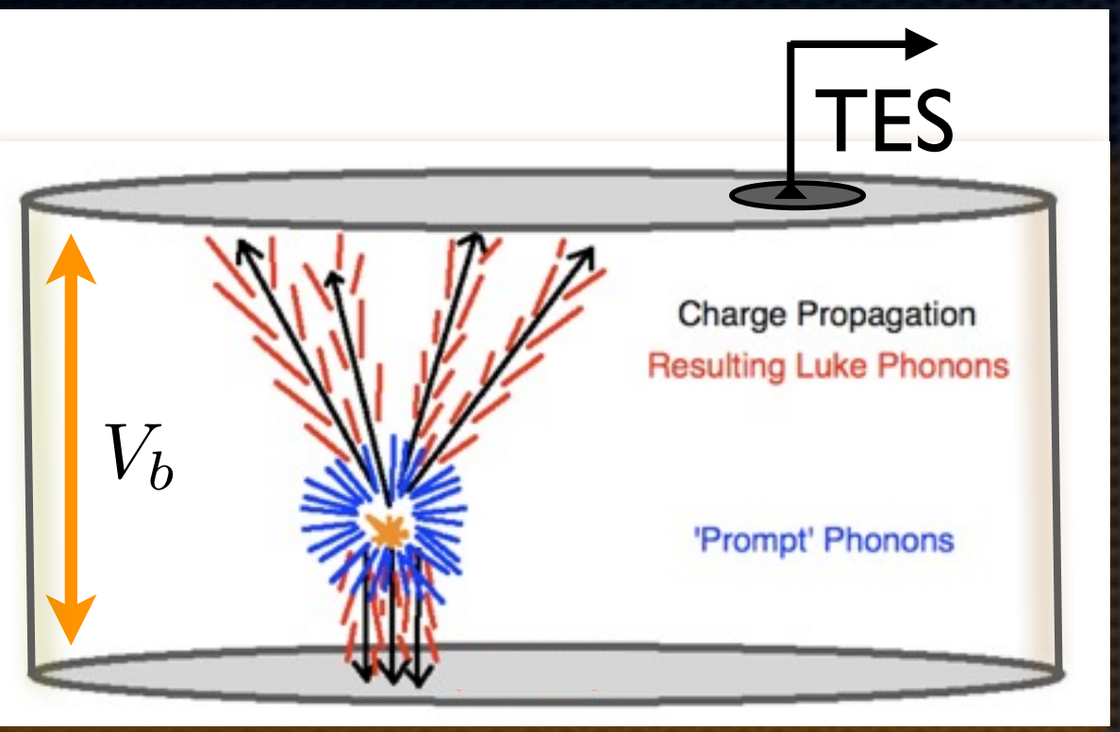


Fig. 5. Signal amplitude and rms noise as a function of diode voltage.

Luke's original experiment.

P.N. Luke et al., NIM A289, 406 (1990)

Luke Phonons in CDMSlite:



Bias voltage accelerates electrons / holes

e/h have "terminal velocity"

This "excess energy" is radiated as Luke phonons

Noise ~ constant with V_b

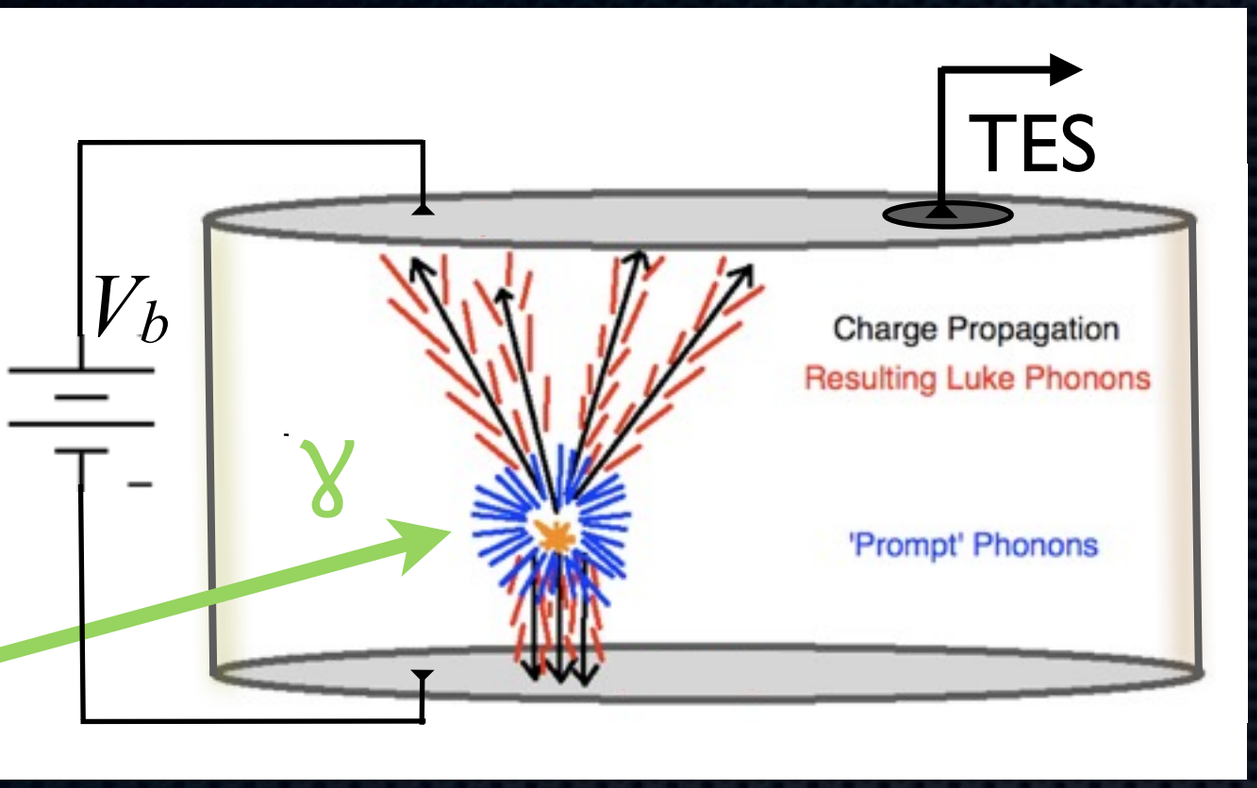
$$E_{Luke} = N_{e/h} \times eV_b$$

Small $N_{e/h}$ → increase V_b → increase phonon signal

Clear detection of low energy recoils

Luke amplification:

For Electron Recoils



TESs measure total phonon energy

$$E_{Total} = E_{recoil} + E_{Luke}$$

$$E_{Luke} = N_{e/h} \times eV_b$$

Number of excited charges, depends on **E**lectron or **N**uclear **R**ecoil

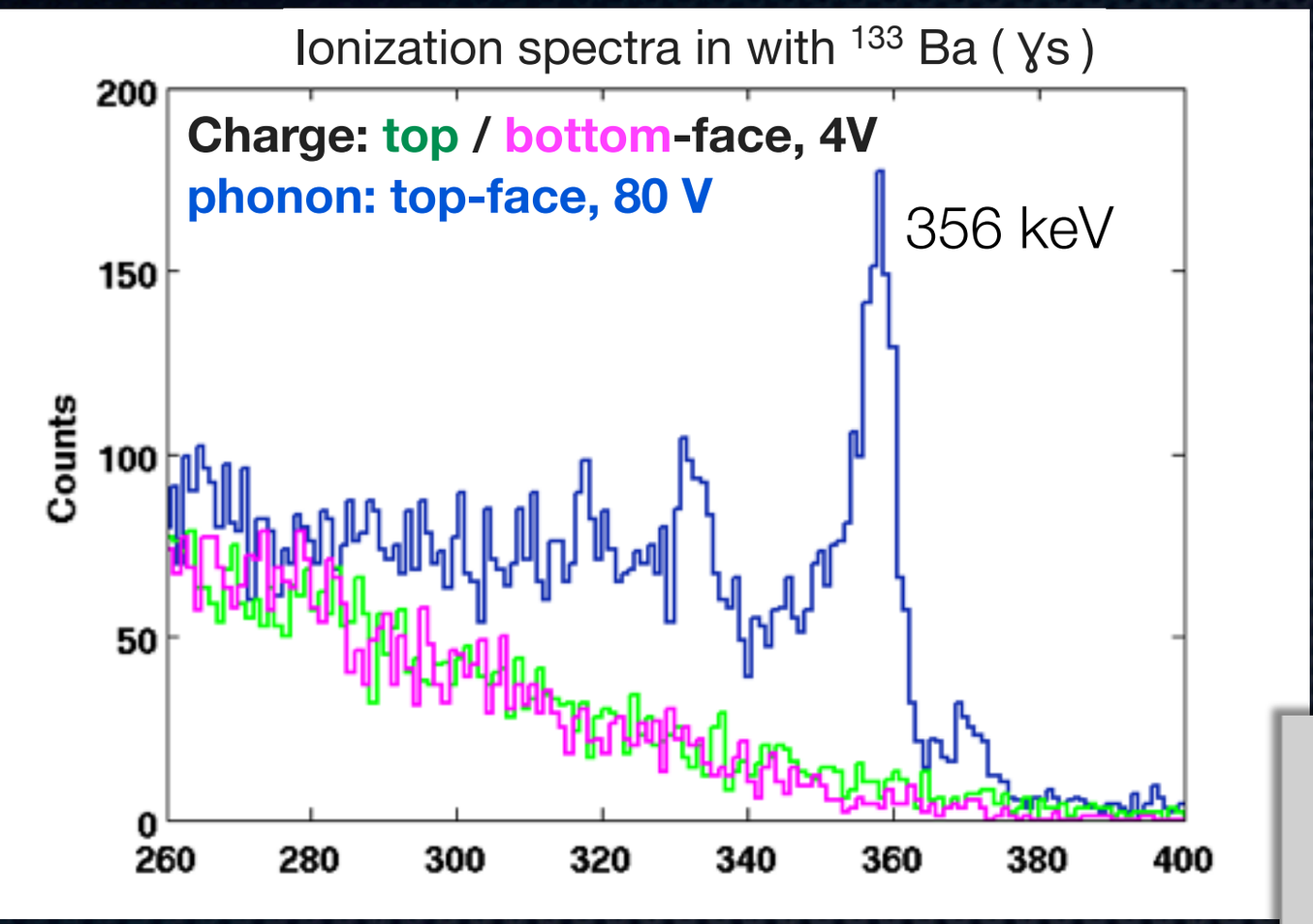
For ERs, $N_{e/h}$ = Ionization energy / excitation-quanta (3 eV in Ge)

$$E_{Total,ER} = E_{recoil} \times (1 + eV_b/3)$$

or x 24 for V_b= 69 V

CDMSlite tests:

SuperCDMS Soudan

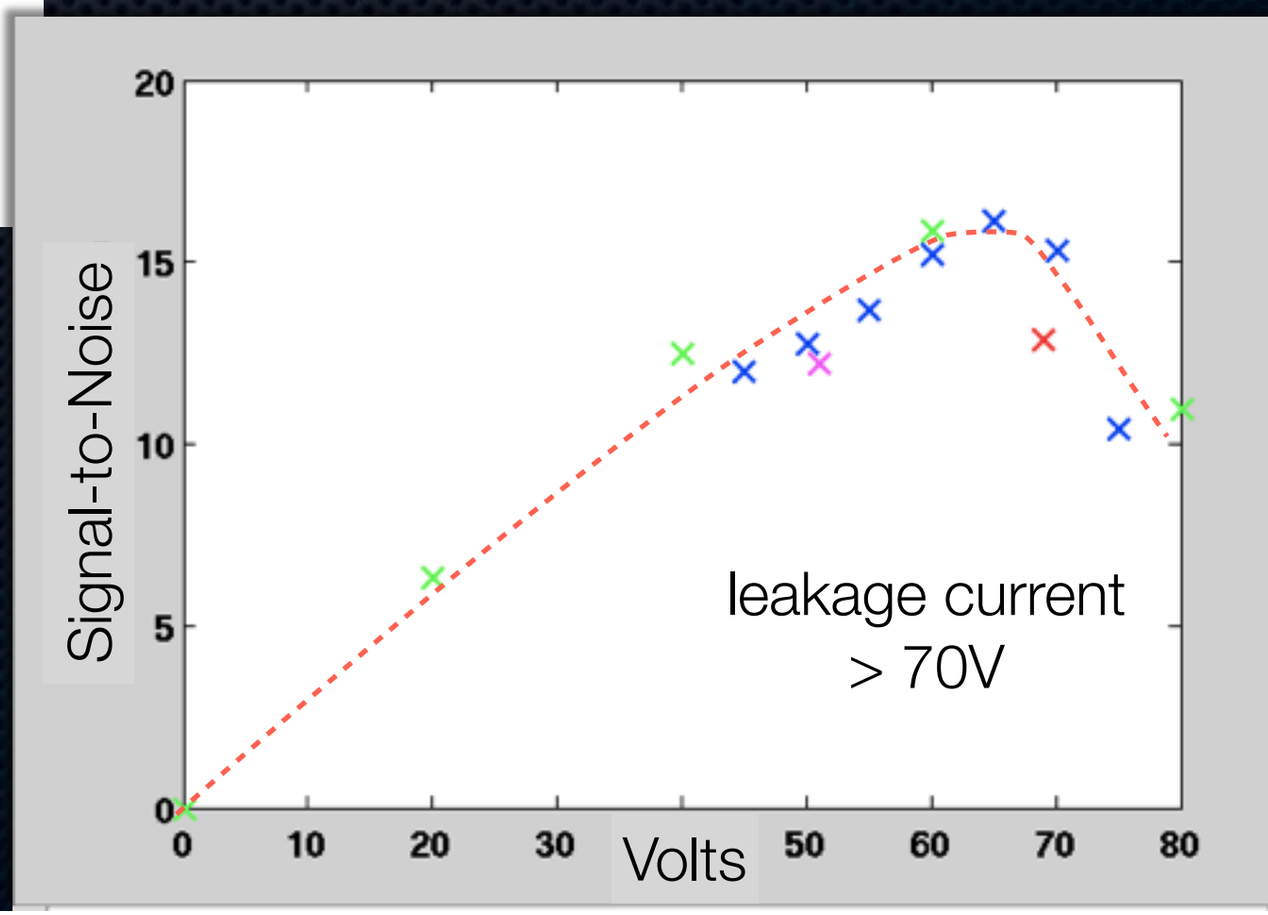


The CDMSlite detector has very good phonon resolution and is stable with 80 V across.

Clear Ba peaks seen in crude tests even though TES's railed & energy estimators were not optimized for this trial !

Optimal bias was chosen to maximize Signal-to-Noise.

69 V was nice round number, x 24 Luke gain for photons

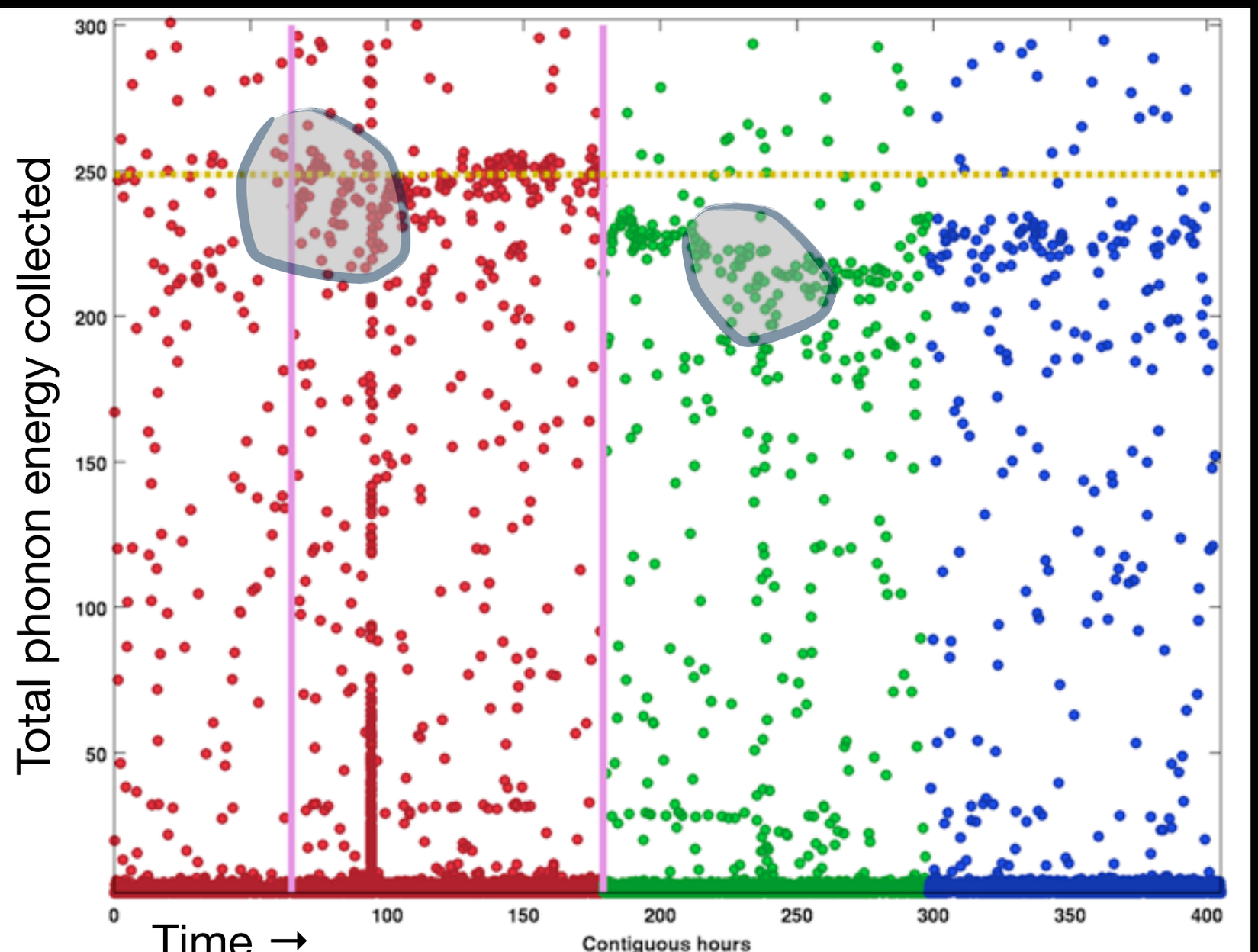


Calibration :

Tracked the 10.36 keV (K shell electron capture) activation line

The line can be "turned on" with a ^{252}Cf neutron source

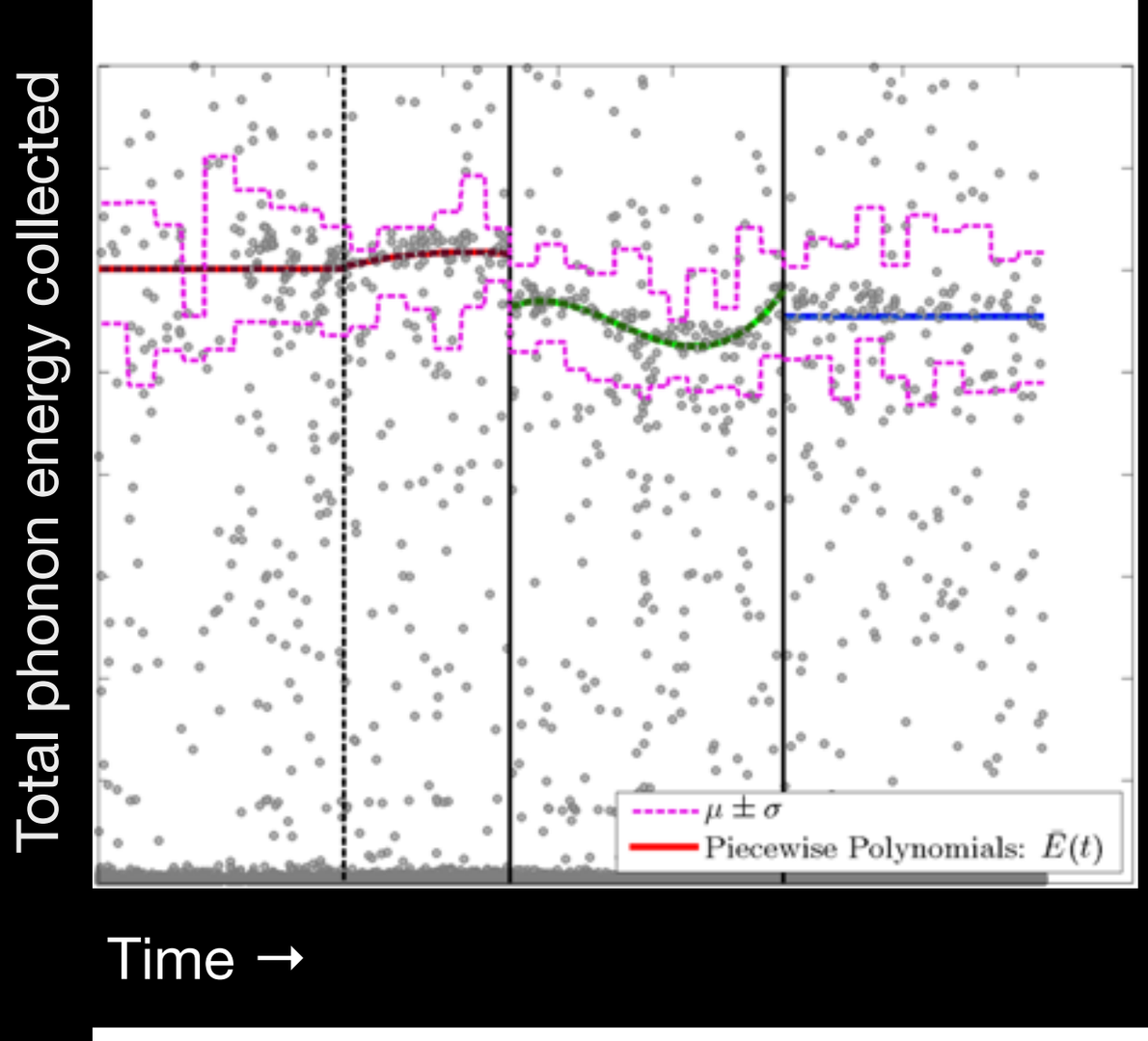
We saw the line close to 10.36 x 24, with drifts over time



Data was collected in 3 periods:

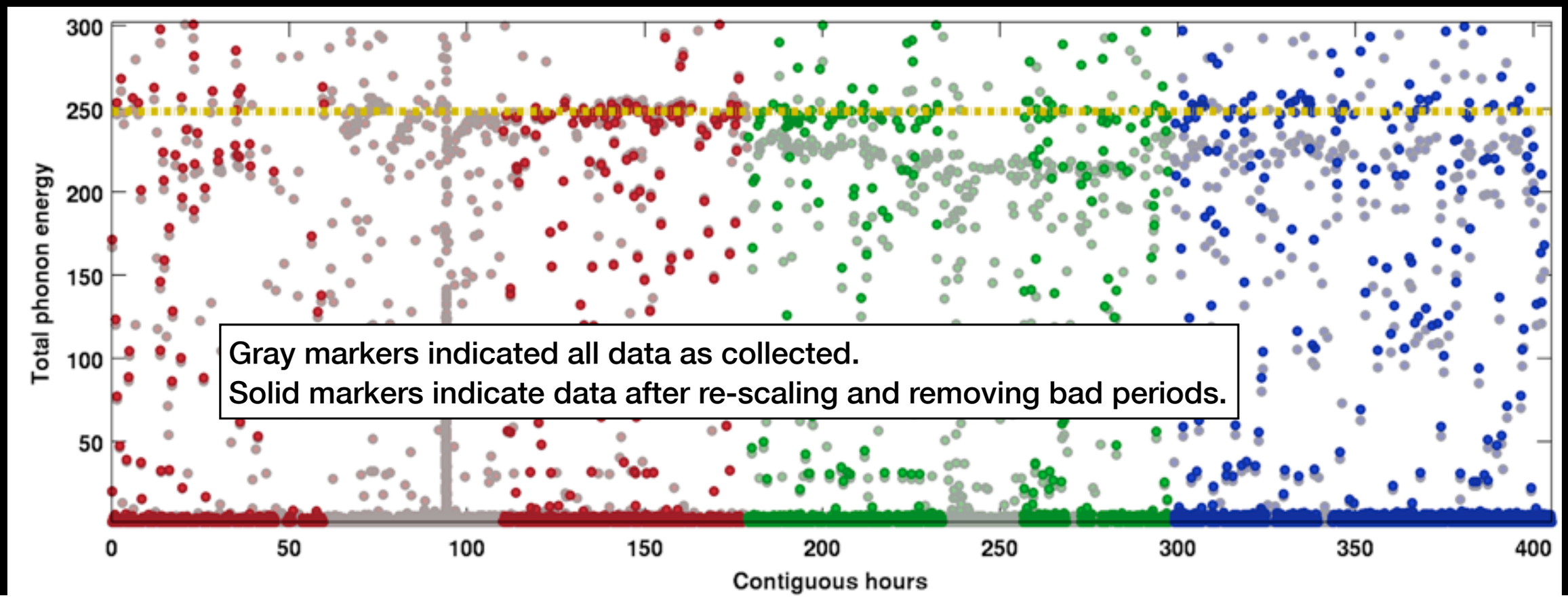
166.5 hours
111.2 hours
105.9 hours

Some questionable periods are removed.



In segments of time, polynomials were used to fit the line and scale the energy (time).

We also dropped time periods, where the line wasn't prominent and short runs



Energy scales :

The number 10.36 x 24, is in units of total phonon energy.

We want to scale this spectrum, such that this line appears at 10.36 i.e. the original Electron Recoil (ɣ) scale.

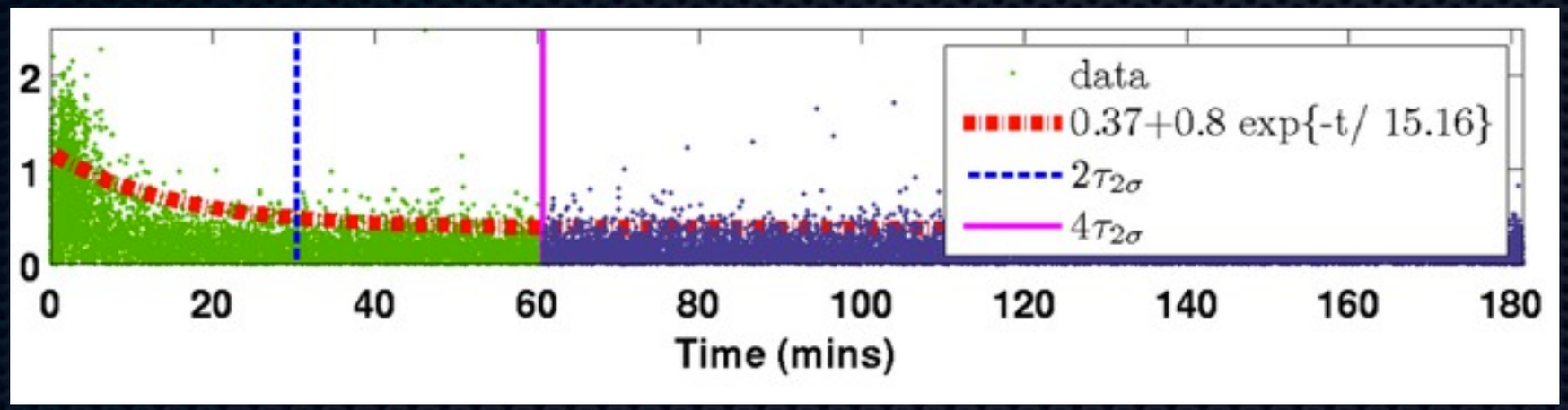
This is called the electron equivalent energy or keVee.

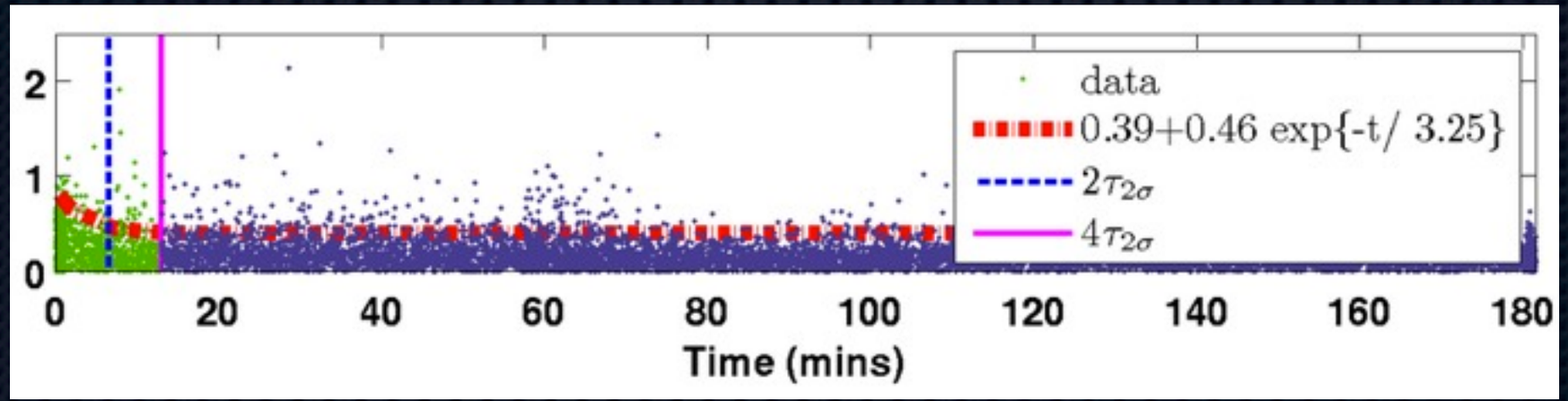
Relevant for WIMPs is the nuclear -recoil energy scale.

This will be called keVnr, and I will discuss this later.

Timing Cuts :

Once the crystal is biased, an exponentially decaying, leakage current is observed (as high noise)





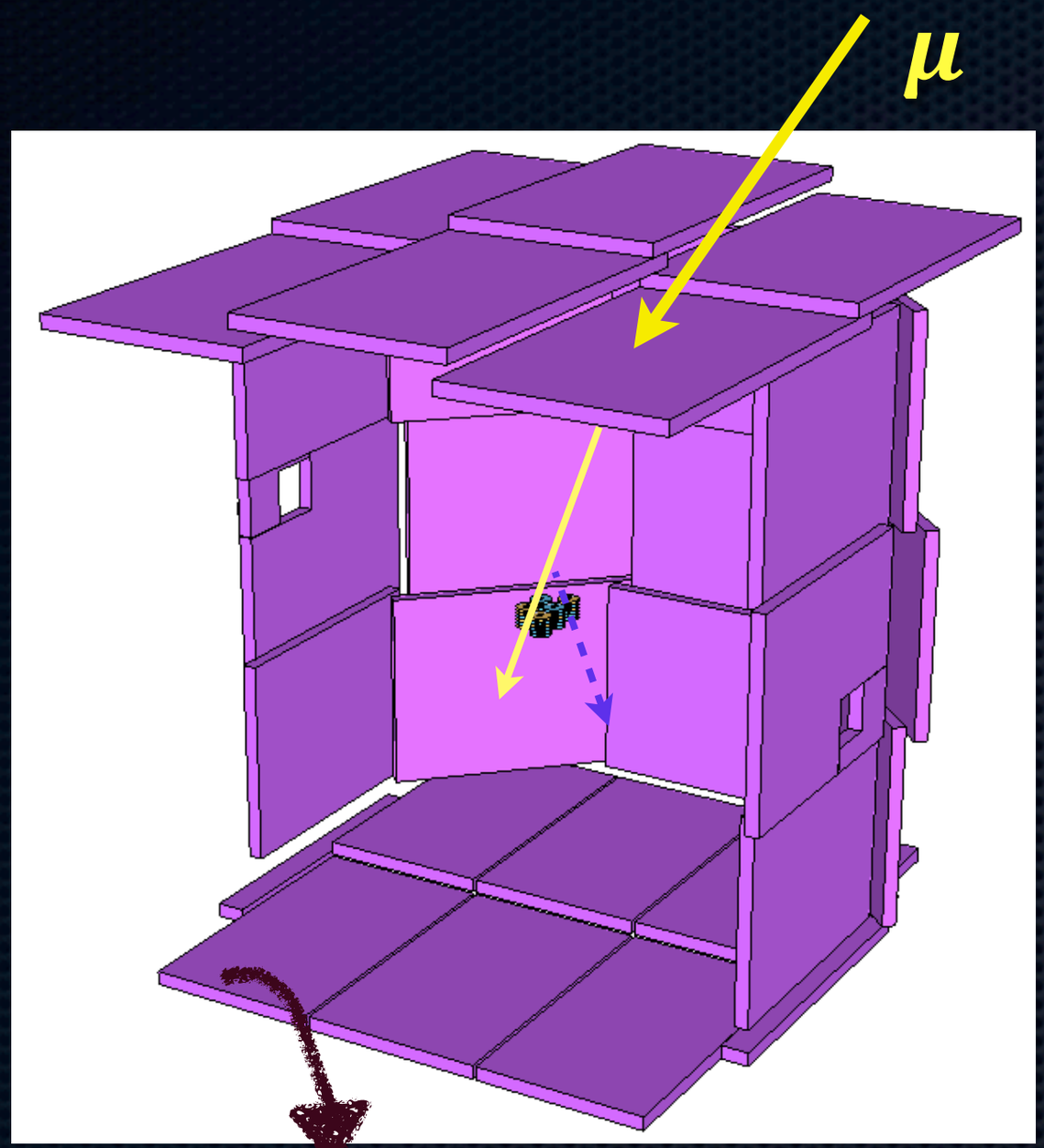
Time constants were between few to tens of minutes.
A cut was imposed to select events occurring 4 time-constants after the start of run.
Final live-time after all time cuts was 10.3 days

Data Quality cuts :

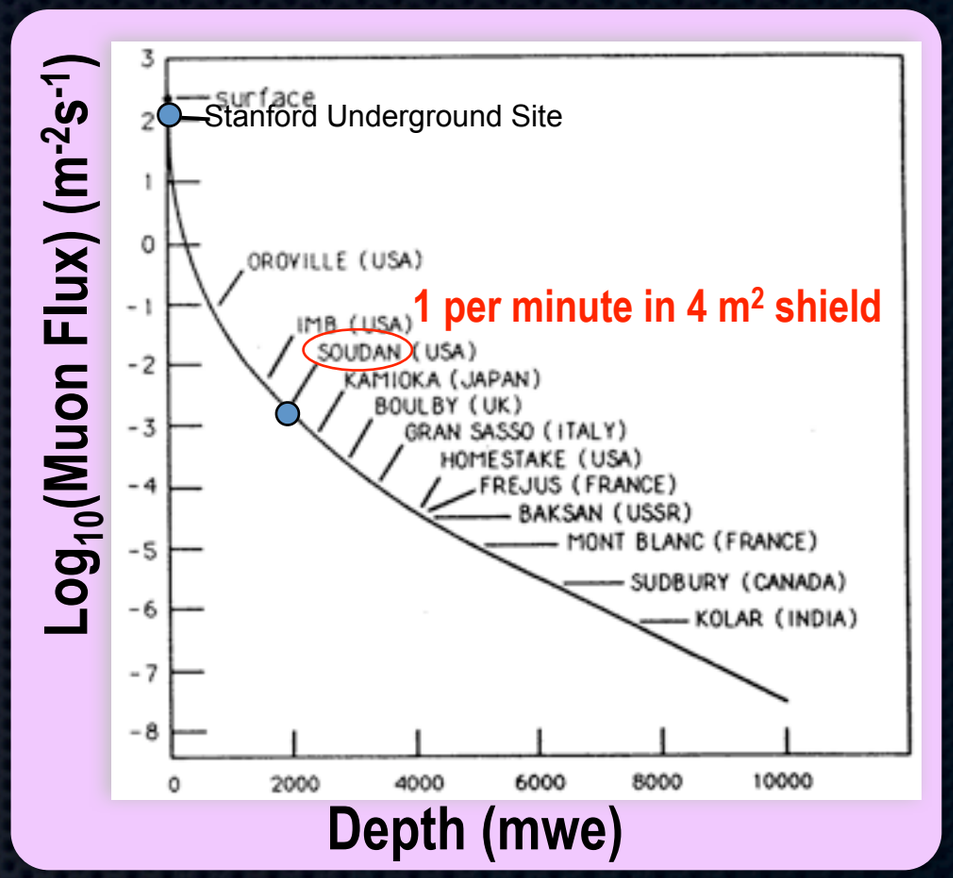
For WIMP search, these selection criteria were imposed to select good, single, low-energy recoils :

Rejection of Veto coincident events
Rejection of multiple scatters
Rejection of spurious electronic glitches
Rejection of low frequency noise

Rejection of Veto coincident events



Each panel has a PMT where scintillation light is measured.



Reject events if during that event a panel lit up, or there was a veto-hit in 50 μs history.

98.54% of randomly triggered events were not veto coincident

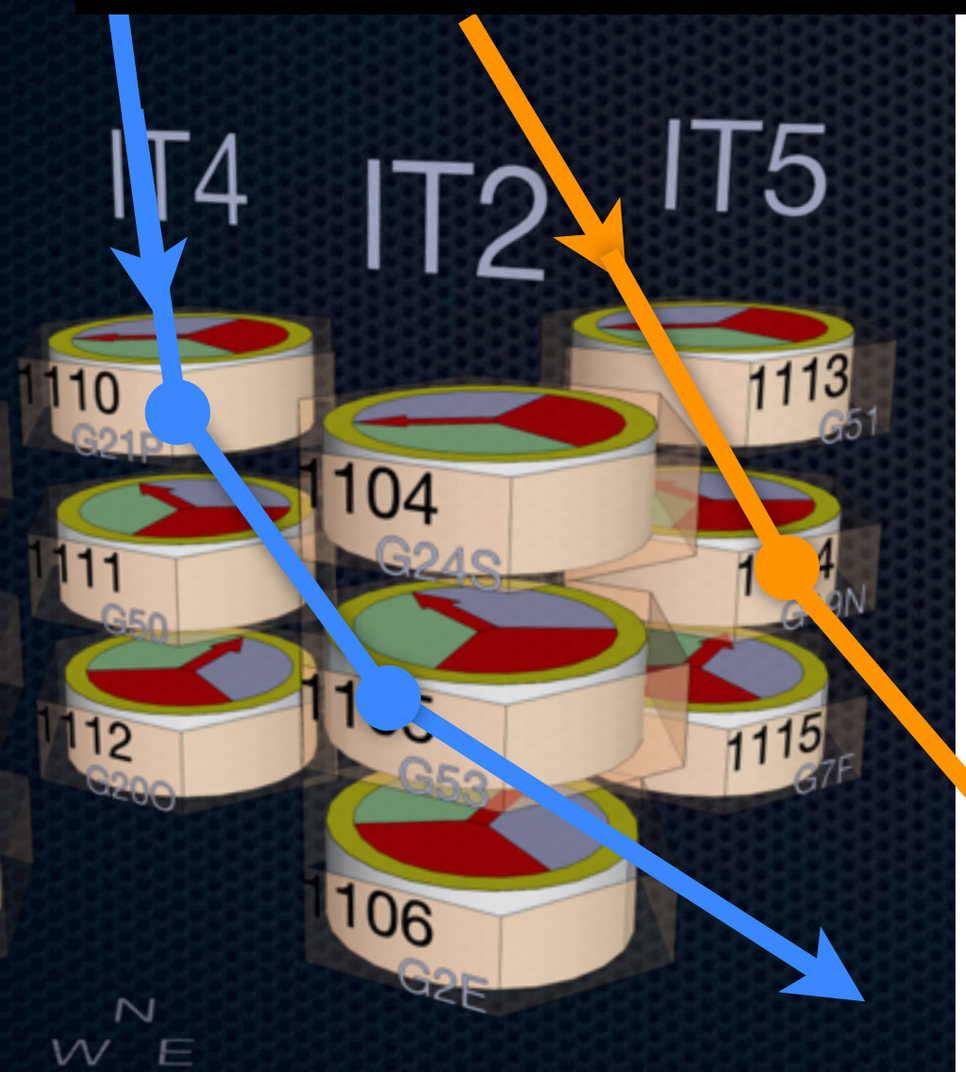
Rejection of multiple scatters

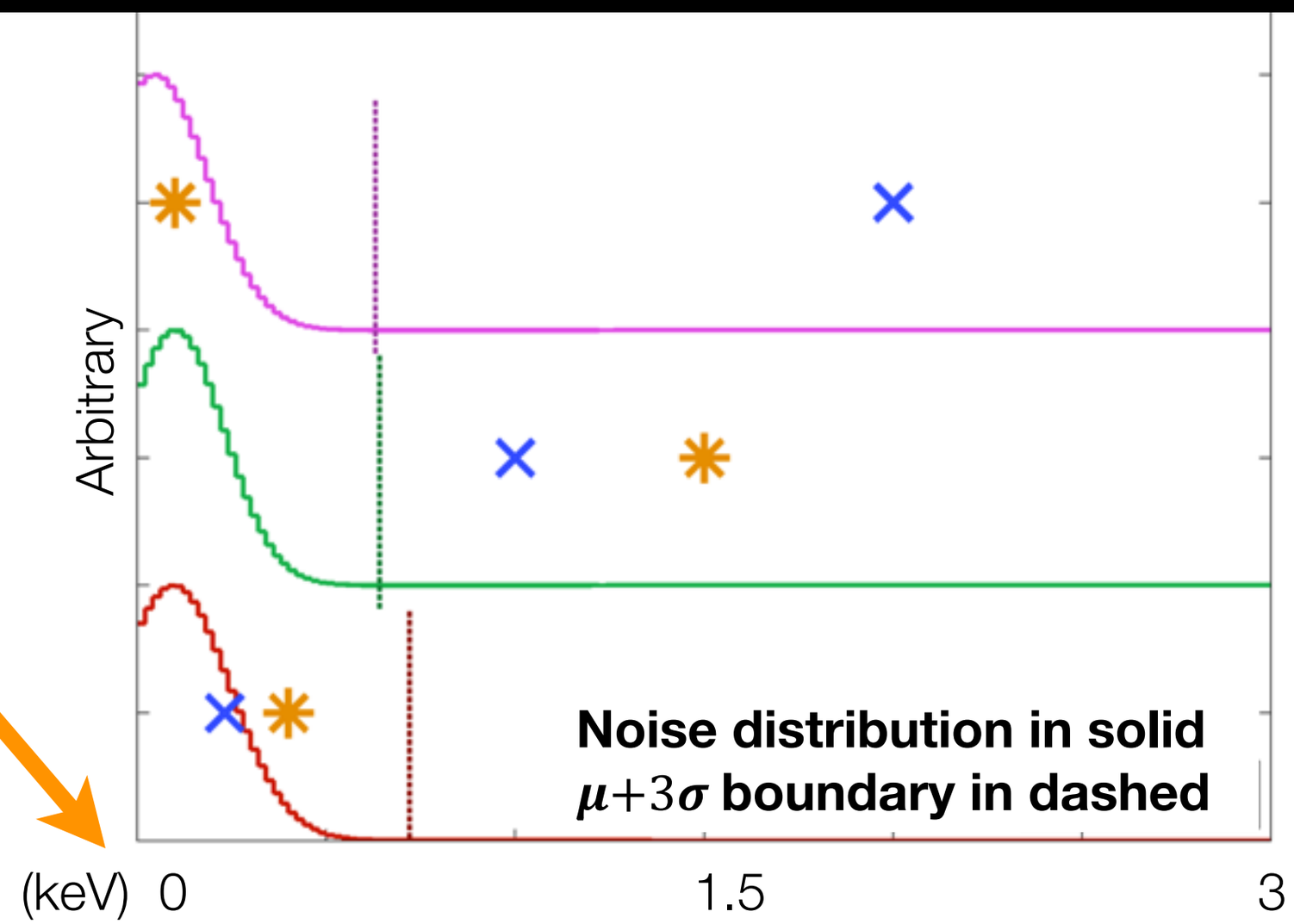
WIMPs should scatter at most once

Reject events where more than one detector records a signal

These are mostly Compton scatters

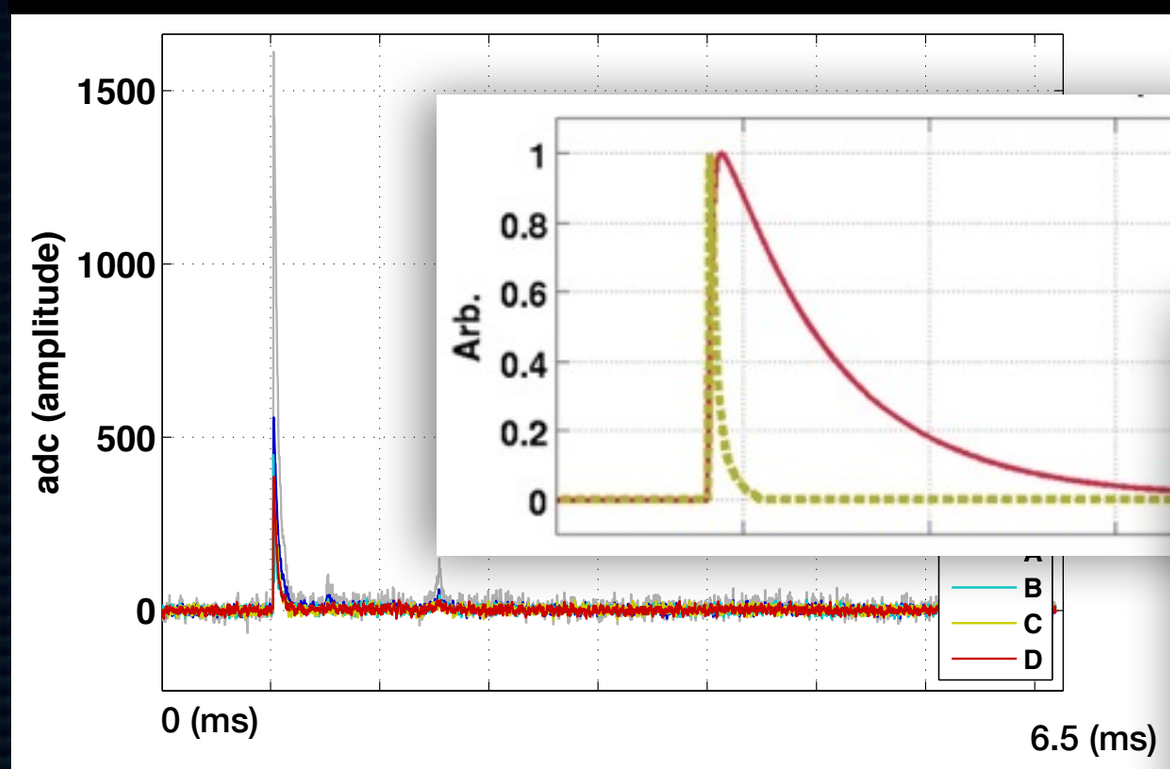
Efficiency from uniformly spread random triggers = 99.96%

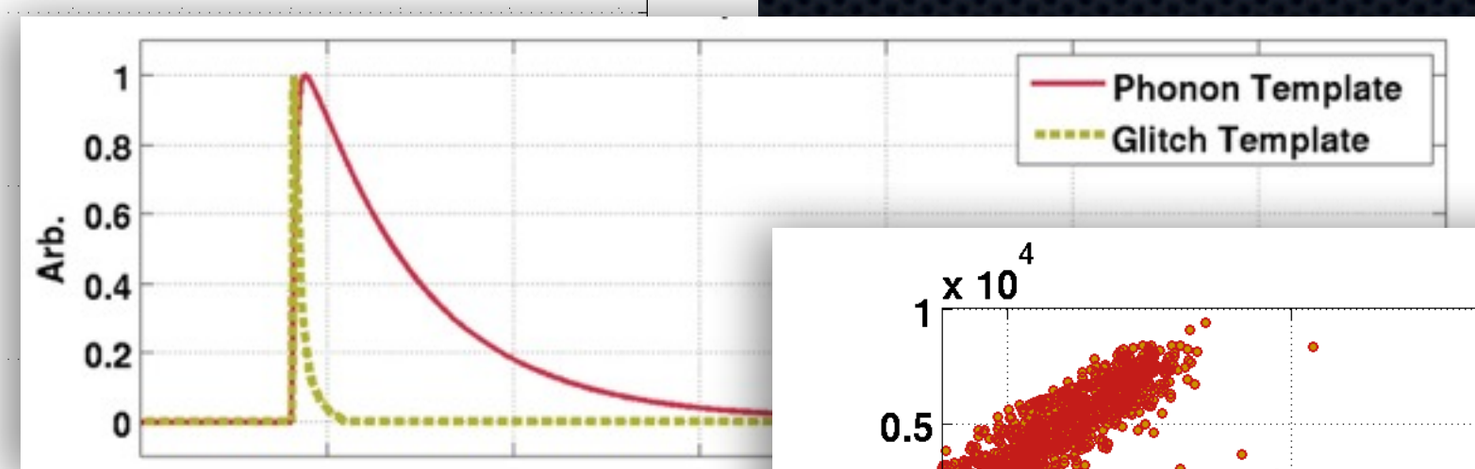


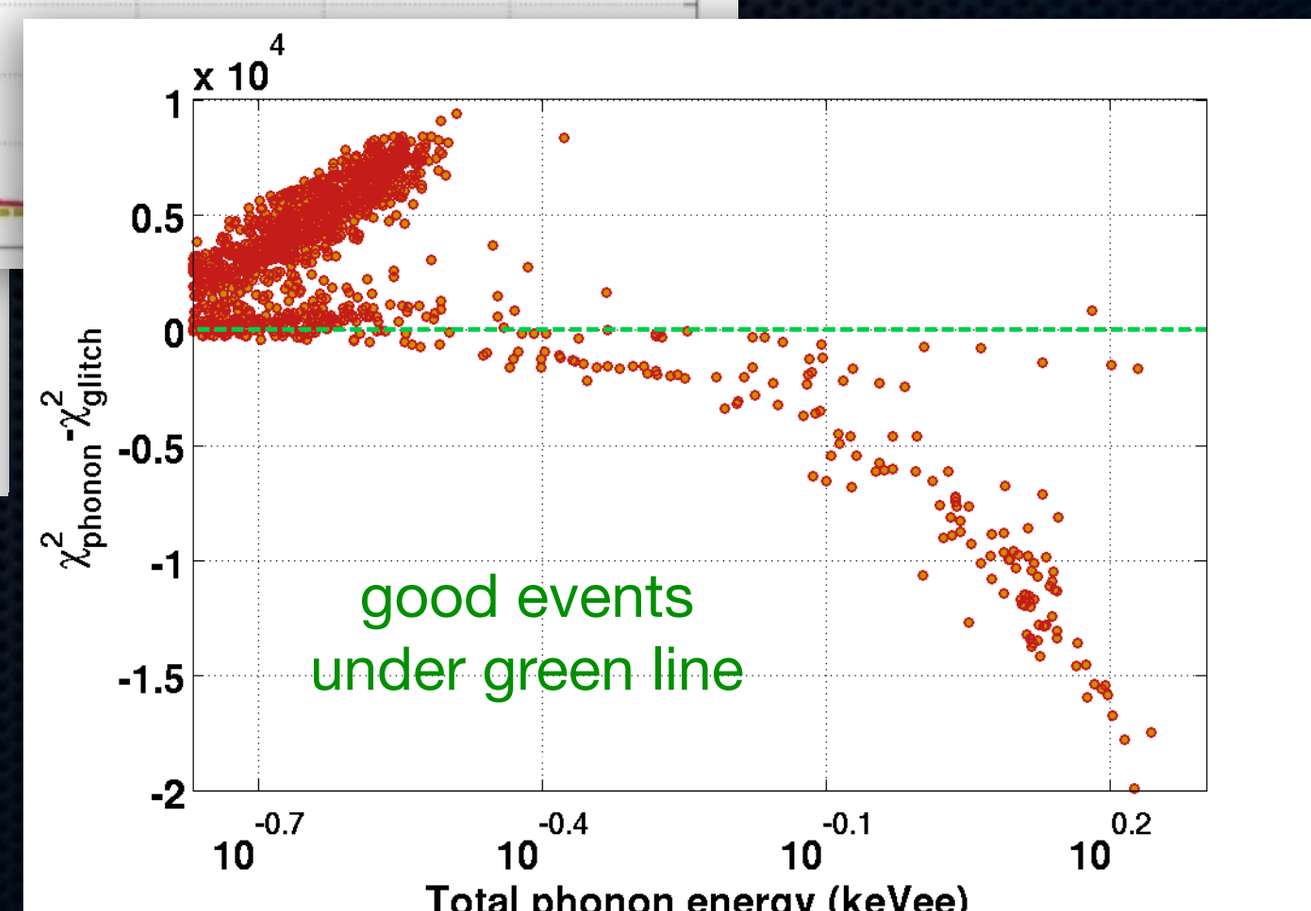


Rejection of spurious electronic glitches

Triggers may be issued by non-physics pulses.
Most trigger multiple detectors and are easily tagged.
Others are rejected using a template matching routine





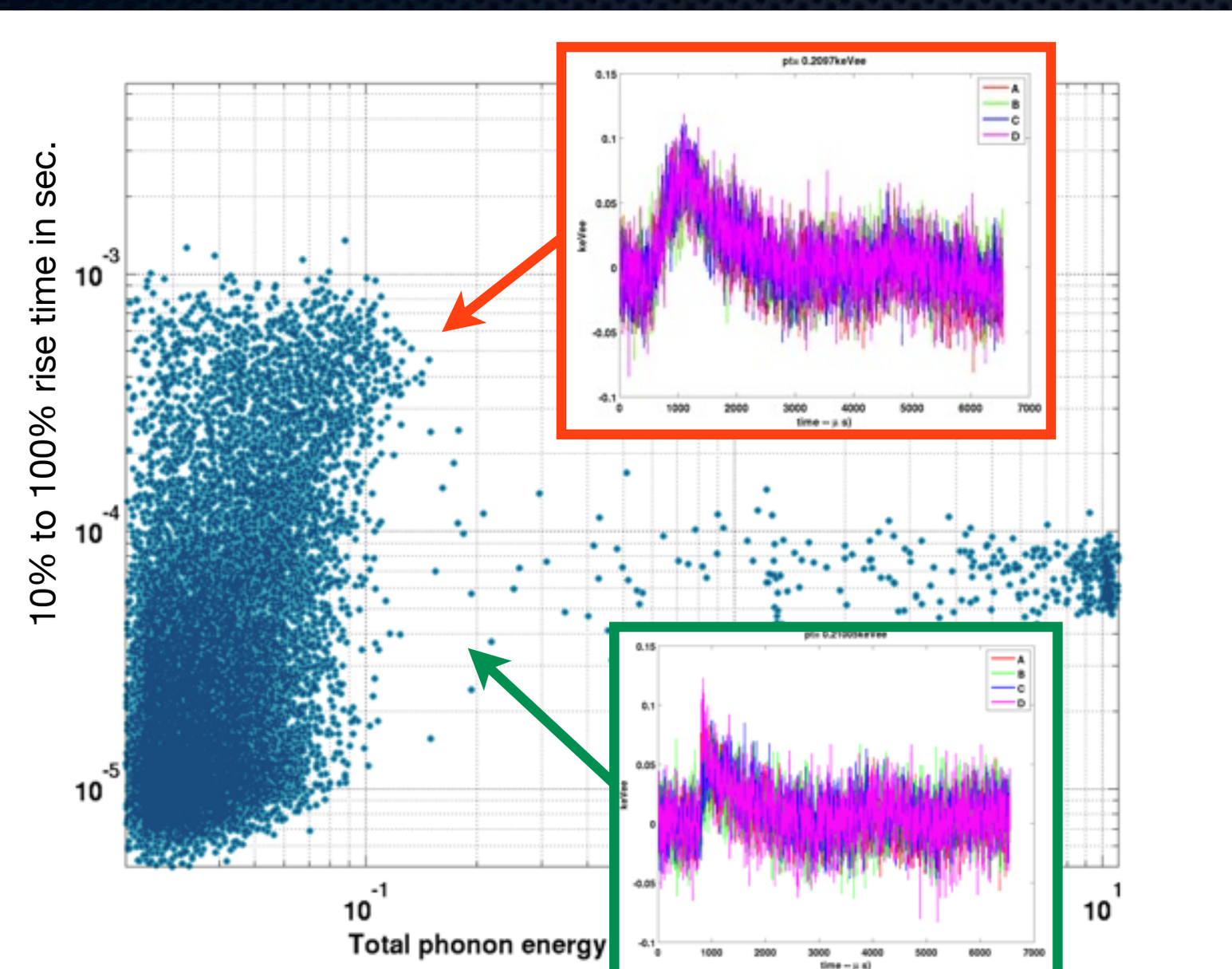


100% Efficiency (over 110 eVee) was calculated from data and verified with pulse + noise MC.

Rejection of low frequency noise

At very low amplitudes (energies) low frequency noise can trigger and be recorded as a low energy “event”.

➔ Slow rising edges & a simple rise-time cut is used.

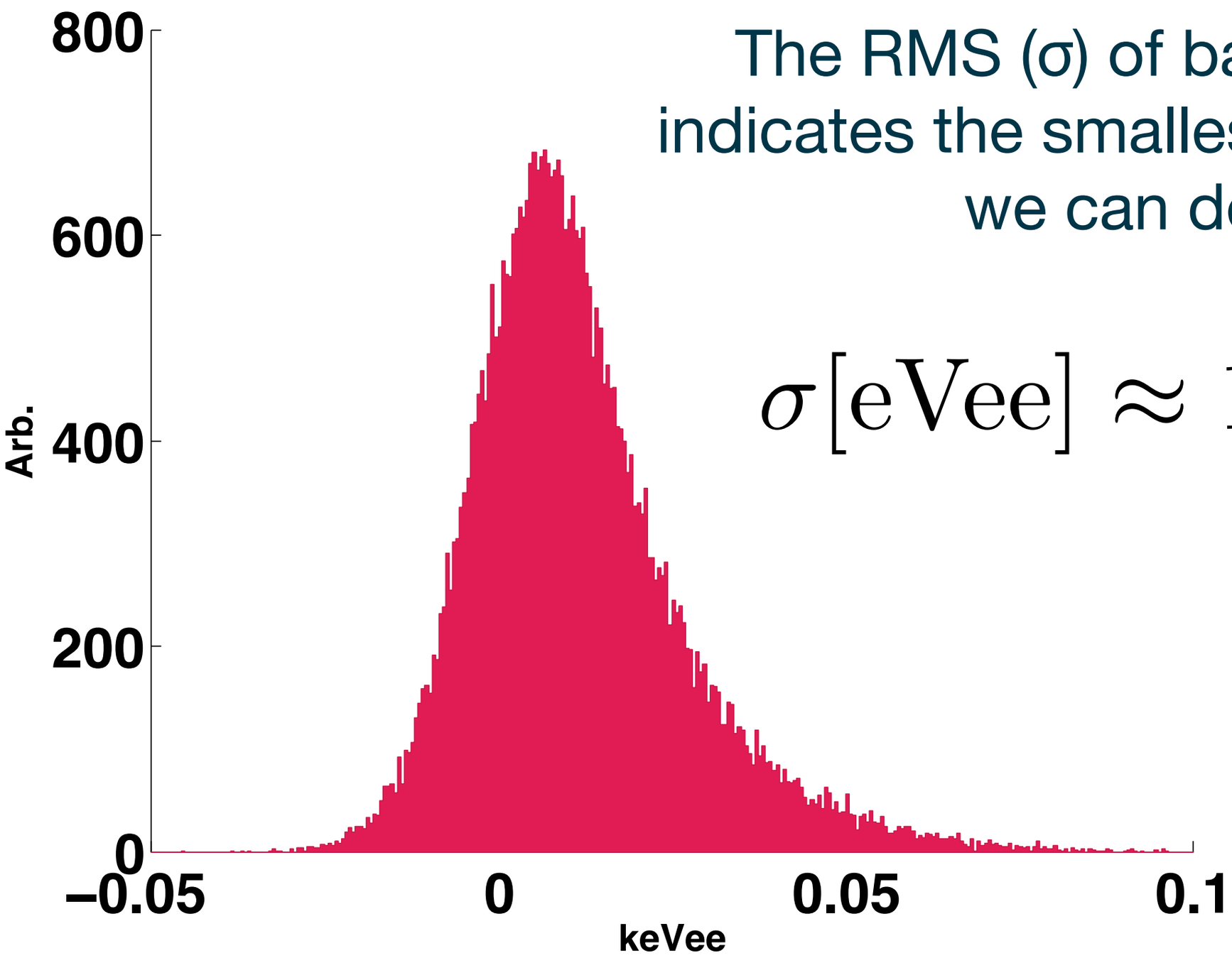


The cut was tuned on Ba calibration data and verified with a pulse +noise MC.

To minimize uncertainty in estimating efficiency of this cut it was constructed to be loose *(noise can be erratic)*

Threshold I : Base-line resolution

Theoretical limit to the experiment



The RMS (σ) of base-line noise indicates the smallest energy pulses we can detect.

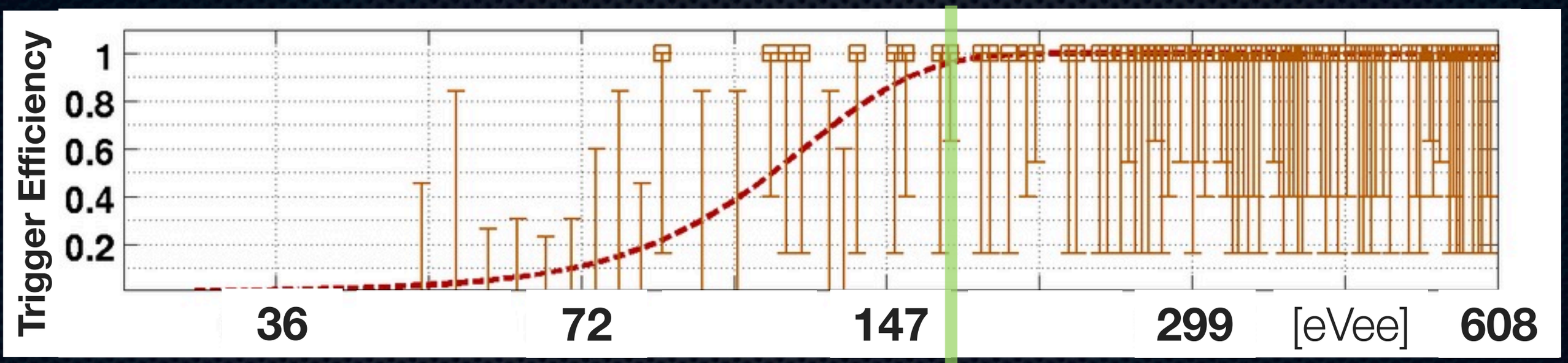
$$\sigma[\mathrm{eVee}] \approx 13.38\ \mathrm{eVee}$$

But ...

Threshold II : Trigger Efficiency

Practical limit to the experiment

Because of the large low freq. noise population, the trigger threshold on the DAQ cannot be lowered arbitrarily.



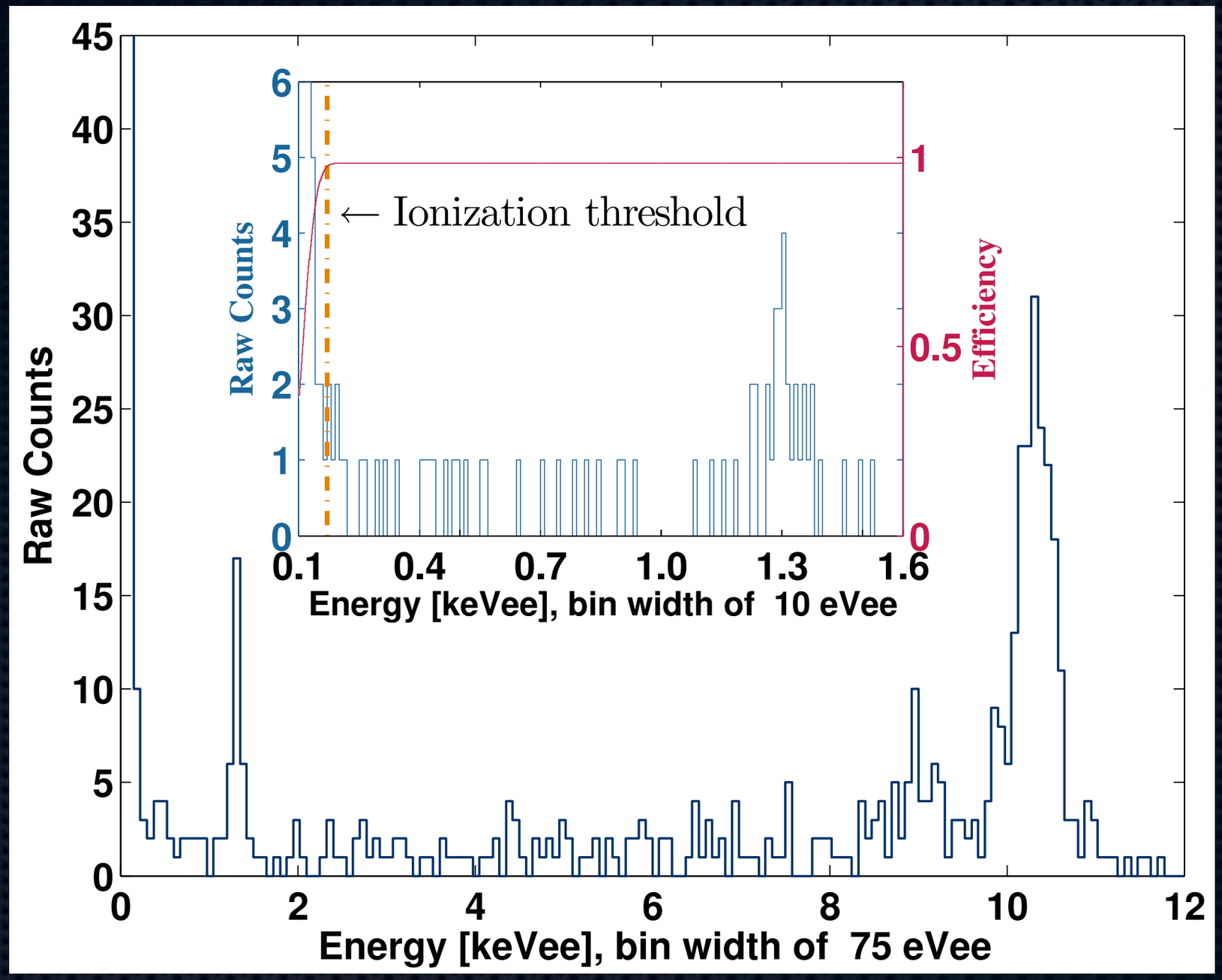
The calculation is done on good low energy events for which another iZIP triggered.

Fit done on statistically rich calibration data.

The result was verified on WIMP-search data.

Threshold is chosen at **170 eVee**:
Efficiency is 100% here and above.
Error on fit is < 2% here and above

WIMP-search spectrum in keVee



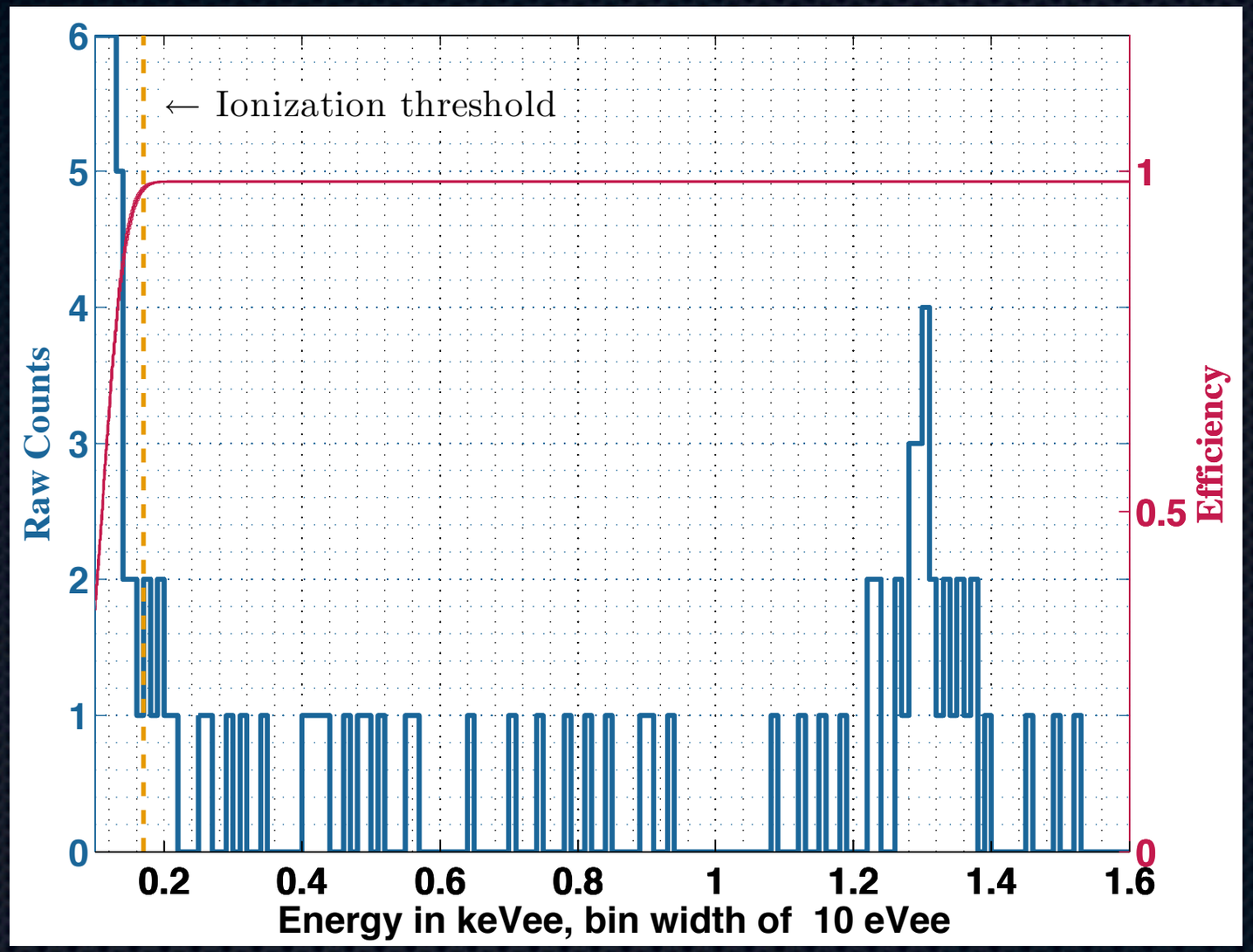
K and L-shell (E.C.) peaks seen at 10.36 and 1.29 keVee from ^{71}Ge decay.

Also 9.66 keV : Zn X-ray. ^{68}Ga decays into ^{68}Zn, and

8.98 keV : Cu X-ray. Cosmogenically generated ^{65}Zn will decay to 65Cu

WIMP search spectrum in keVee

Zoom in



Some counts and rates in 3 energy ranges:

0.17-1.07 keVee: 31 counts ⇒ 31 #/ (0.9 keVee)/ (6.256 kg-days) = 5.5 #/keVee/kg-day

1.5-7.5 keVee: 103 counts ⇒ 103 #/ (6 keVee)/ (6.256 kg-days) = 2.7 #/keVee/kg-day

12-22 keVee: 94 counts ⇒ 94 #/ (10 keVee)/ (6.256 kg-days) = 1.5 #/keVee/kg-day

Ionization yield

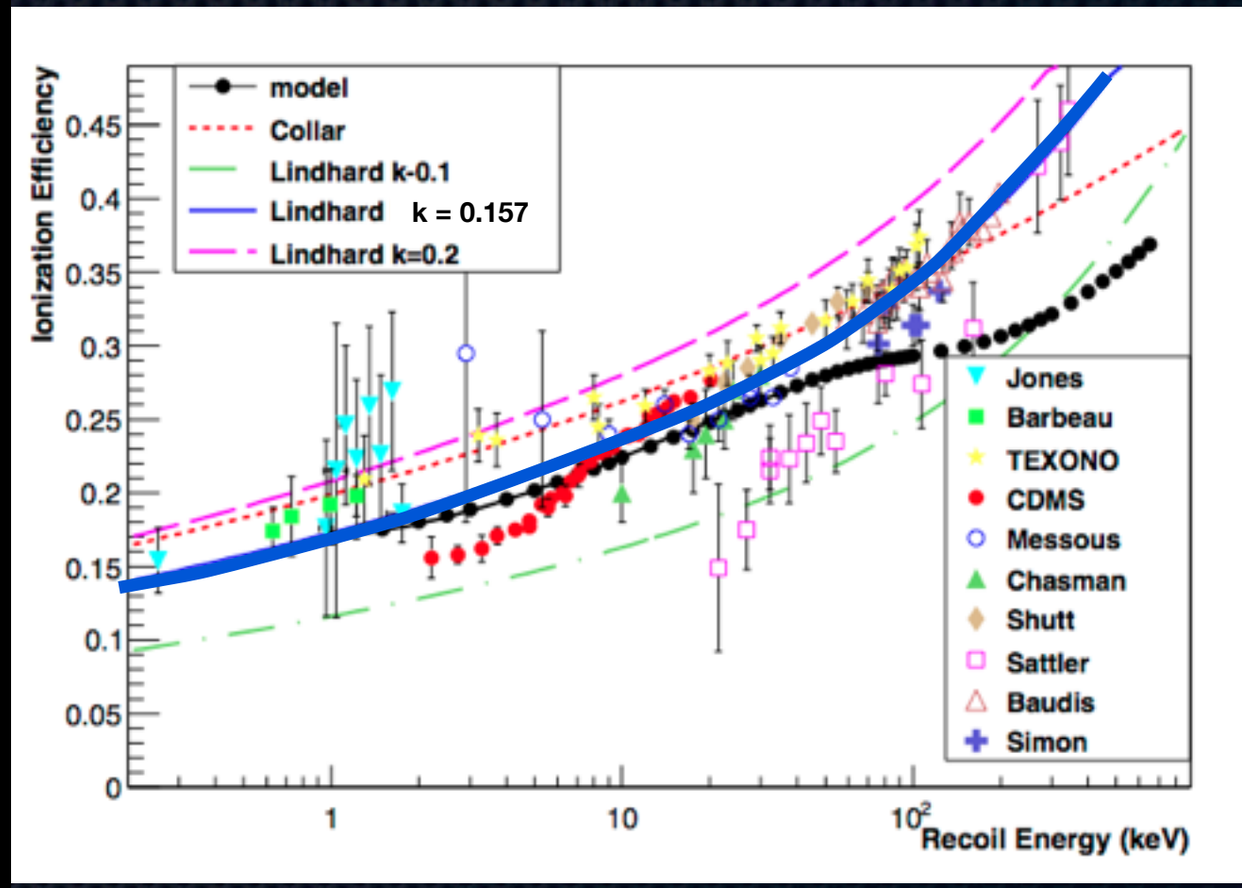
For some deposited recoil energy, the number of charges produced is modeled by the ionization yield function.

Yield = Ionization / Recoil -energies

The yield is constant with energy for Electron Recoils and is defined as unity.

For Nuclear Recoils it's modeled by the Lindhard theory.

Measurements exist, but unfortunately with noticeable diversity.



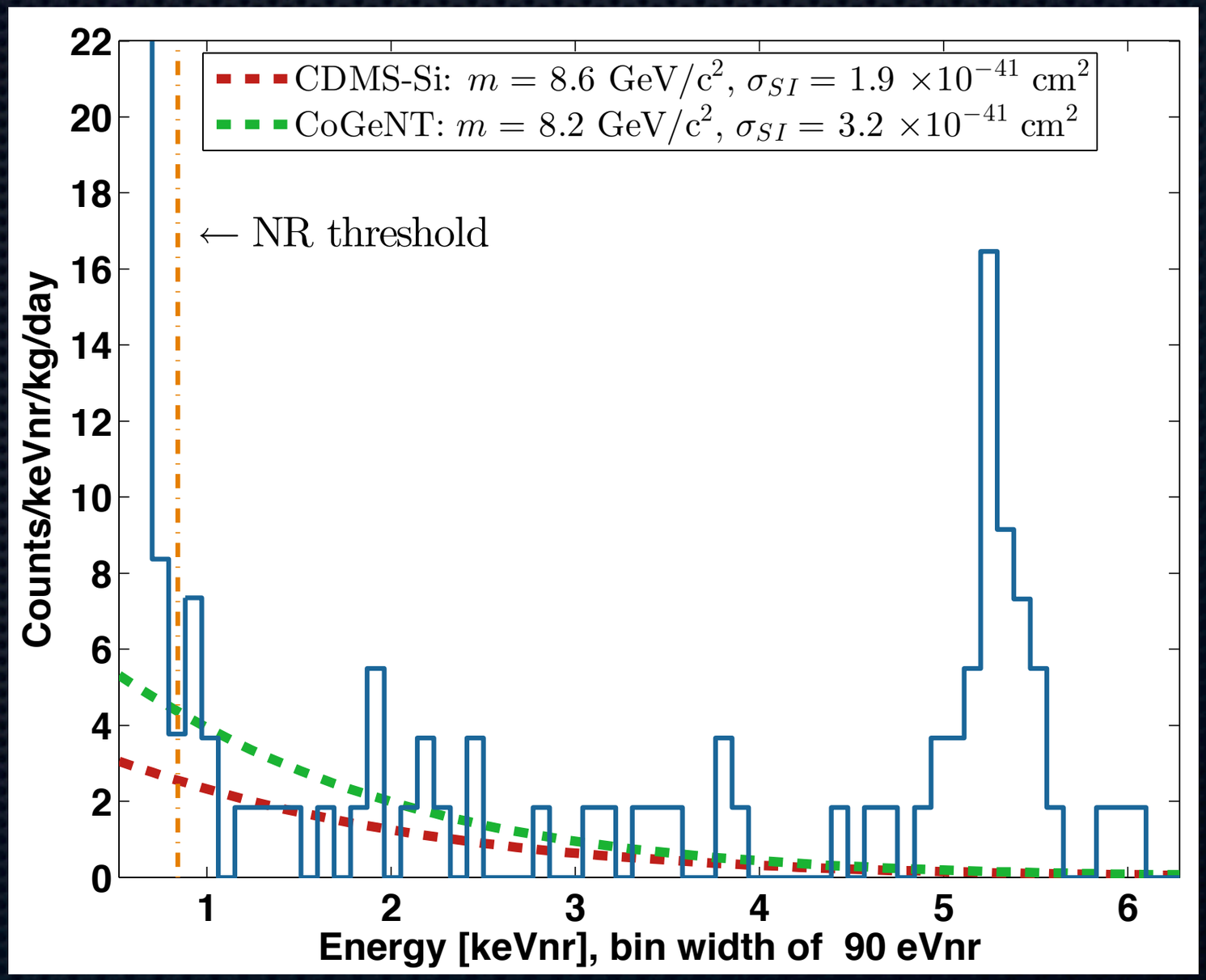
We use the "text-book" standard Lindhard (k = 0.157) version to go from keVee to keVnr scale

WIMP search spectrum in keVnr

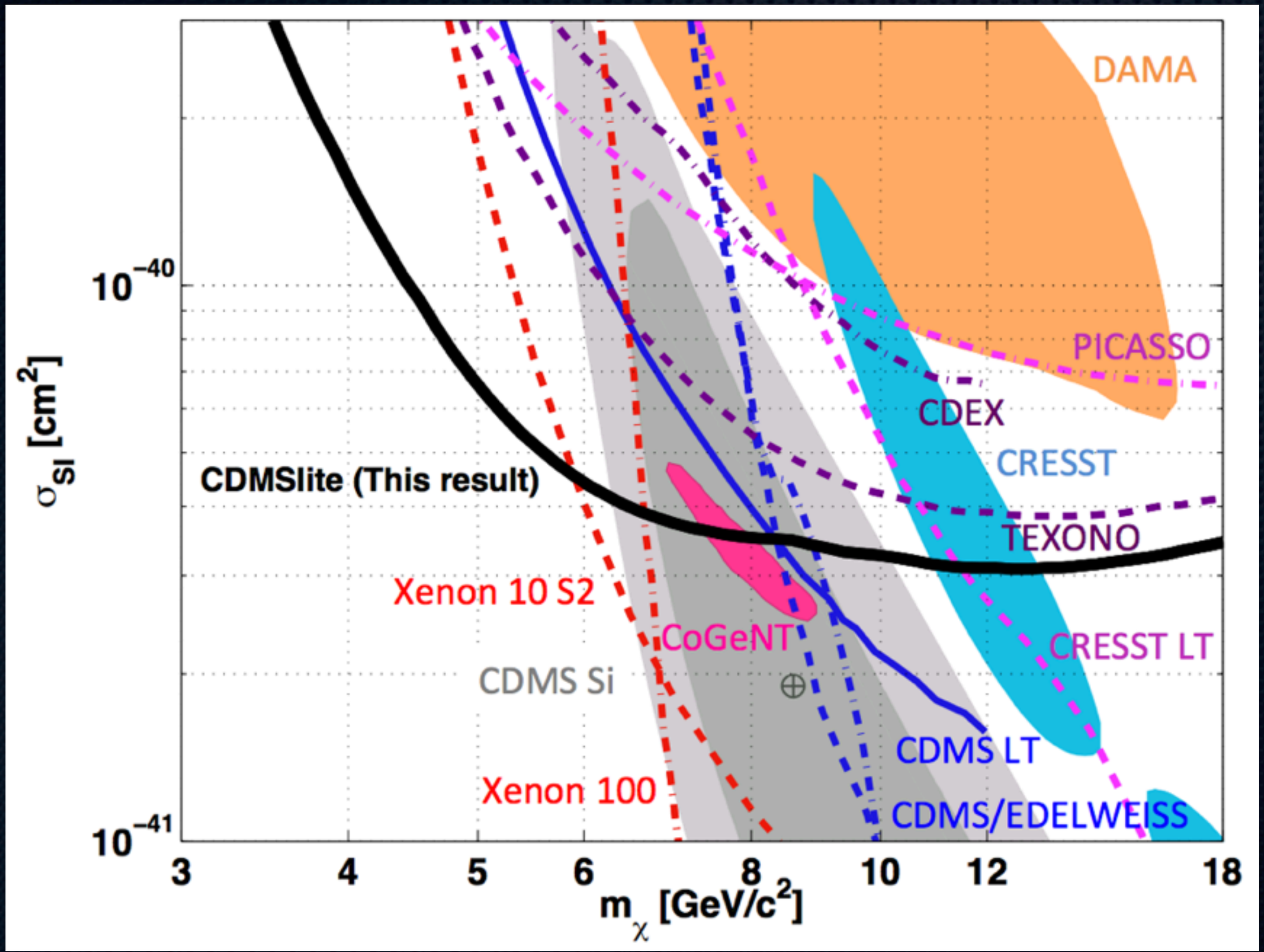
The keVee (ionization) spectrum is converted to keVnr (recoil) spectrum, assuming the standard Lindhard yield model

In this scale the threshold in 840 eVnr

Also shown are expected WIMP rates using the best fit values from the CDMS-Si and CoGeNT results.



WIMP search limits



Spectra used for WIMP-search:

Commentary

CDMSlite Run 1 had ~6 kg-days of exposure, no fiducial cuts, no background subtraction.

We compare our results to experiments which have:

Higher Exposure: CDMS-Si (140 kg-days), CoGeNT (269 kg-days).

Discrimination power: CDMS and XENON have excellent ER/NR discrimination. CoGeNT and TEXONO have surface event cuts.

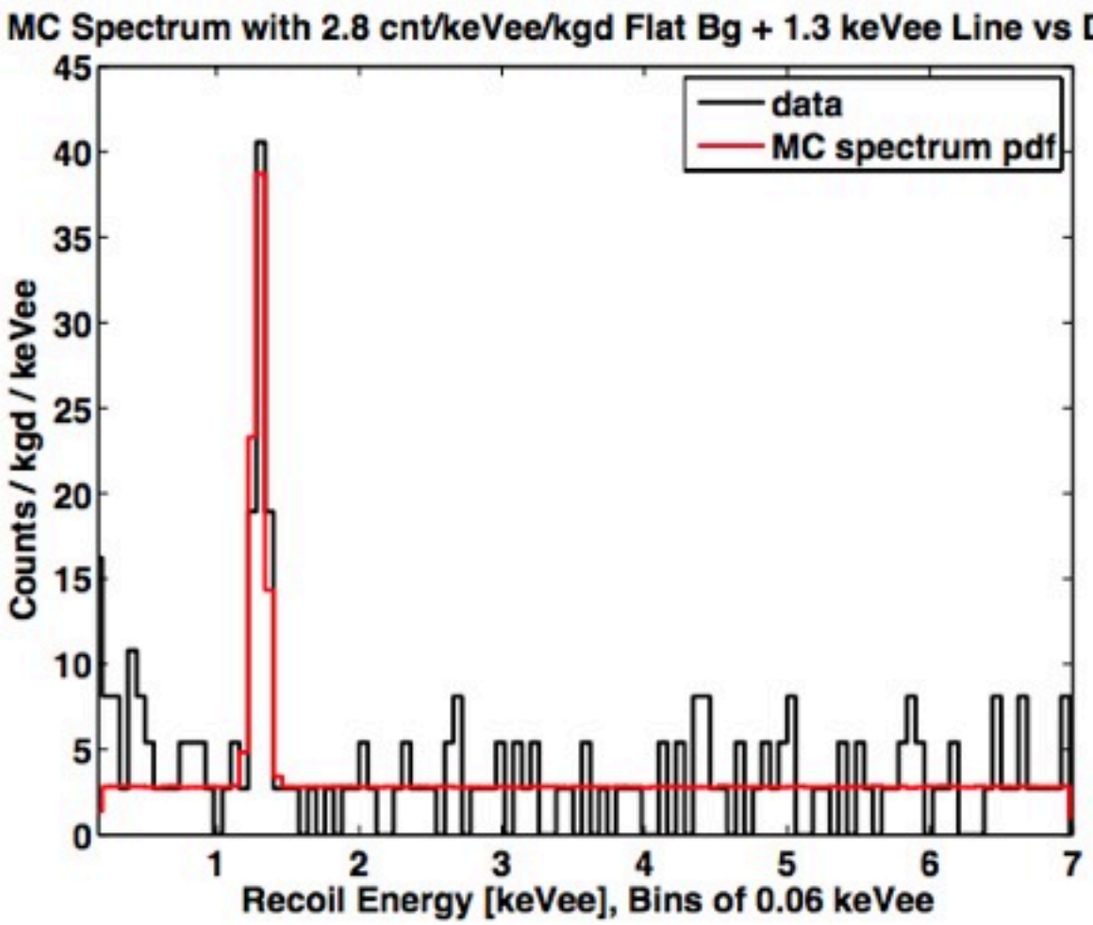
Subtraction: CoGeNT, TEXONO, CDEX model & subtract backgrounds.

Our limits are conservative

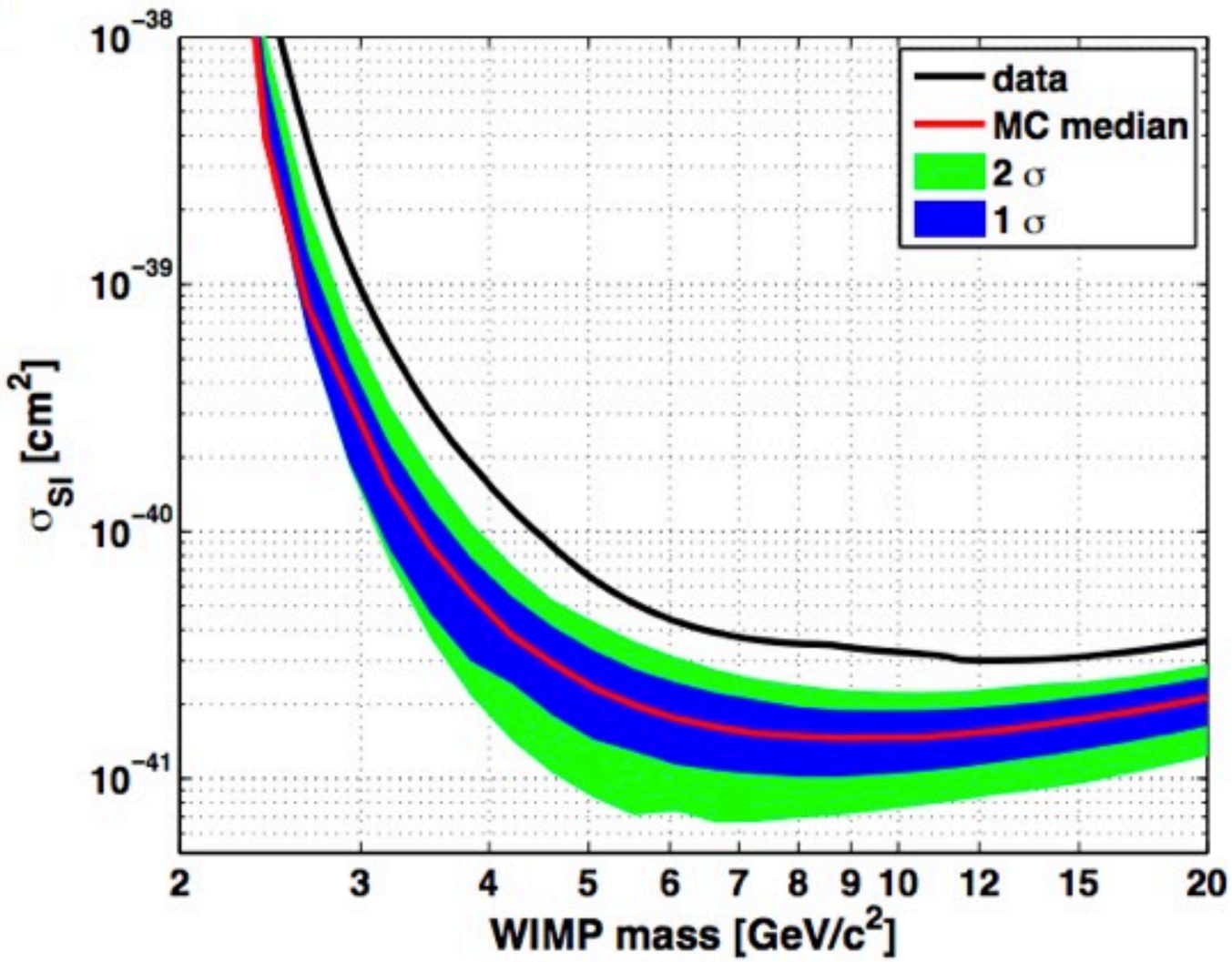
WIMP-search limits:

Commentary

The limit from the experiment is weaker than the projections.
Under 500 eVee, it is new territory.
Our projections were based a simple flat rate extrapolation, which was optimistic.



The blue spectrum was based on previous CDMS measurements of low energy electron recoil background rates. The red spectrum is based on extrapolating the CDMSlite spectrum from above the 1.3 keV L-shell capture line to below the line.



One and two sigma contours for limits from experiments thrown with the MC spectra in the figure to the left (red line.) The CDMSlite spectrum below the 1.3 keV L-shell capture line is more than two sigma higher than these flat extrapolations.

Conclusions

In CDMSlite Run 1 we obtained an amazing base-line resolution of 14 eVee, hence the superior promise of this technology.

In WIMP-search mode we achieved a very low energy threshold of 170 eVee. This was limited by environmental noise.

With ~6 kg-days of data, 90% CL were produced probing the parameter space of light-WIMPs.

New parameter space < 6 GeV has been tested and ruled out.

While we cut-out portions from the CDMS-Si & CoGeNT islands, the results do not rule out the best fit WIMP candidates.

Next steps

The 6 kg-day data set is statistically sparse. Hence we are yet to measure the background (or signal ☺) at a significant level

Thus we plan to initiate Run 2 end of this year

Following this we can purse background subtraction techniques.

We will also improve our hardware to stabilize and monitor gains (There was gain drift from humidity)

We may reduce the trigger thresholds. However the noise environment at these energies are erratic and may limit us.

Multiple detectors may be run to understand backgrounds.

The SuperCDMS Collaboration

California Inst. of Tech.
B. Cornell, S.R. Golwala, D.C. Moore, R.H. Nelson

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University of Minnesota
H. Chagani, P. Cushman, S. Fallows, T. Hofer, A. Kennedy, K. Koch, V. Mandic, M. Pepin, A.N. Villano, J. Zhang

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J. Sander

Extras :

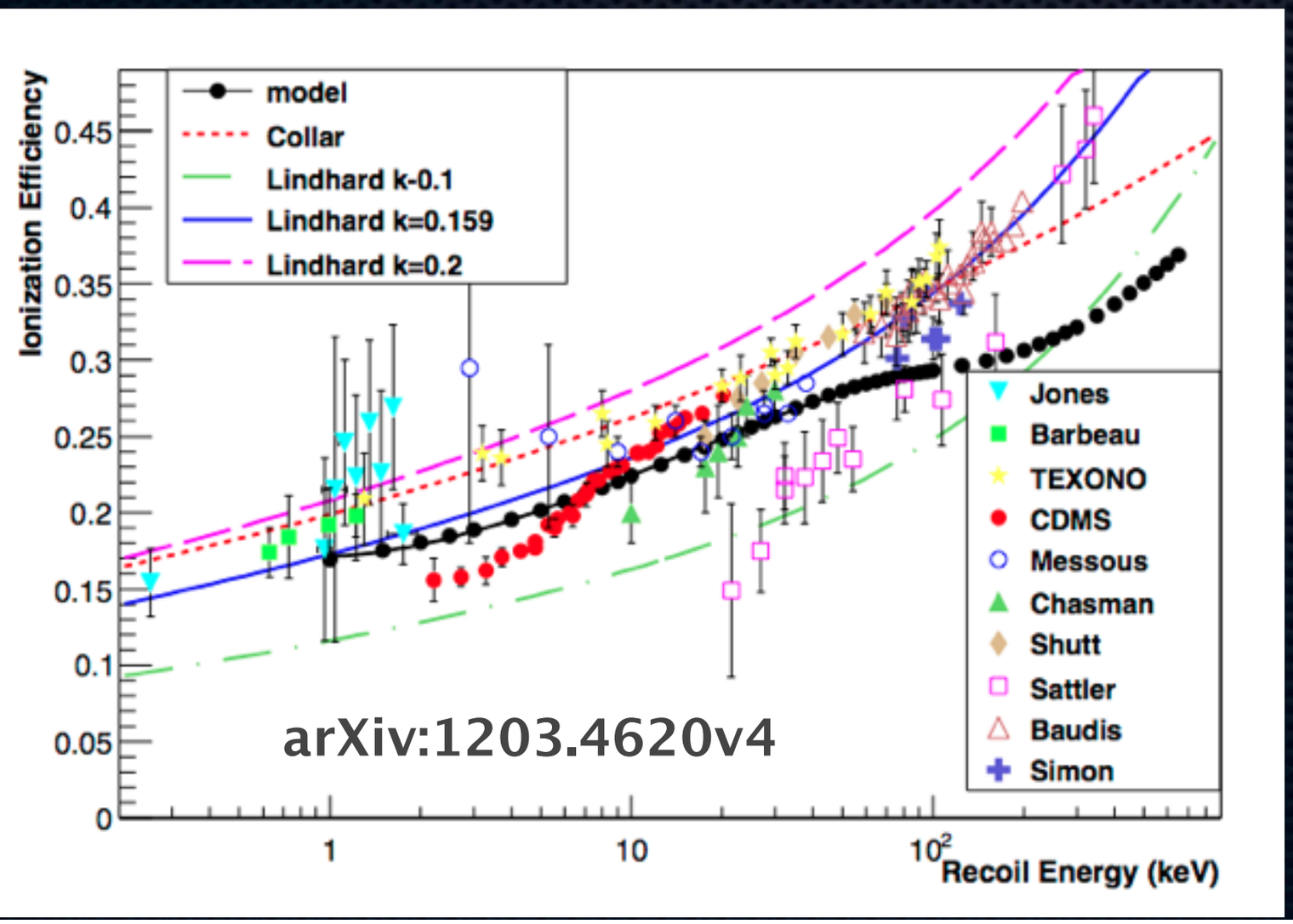
WIMP-search limits:

Commentary II

The limit is calculated from an “ionization” spectrum converted to “recoil” spectrum.

Hence systematic dependence on ionization yield models.

Ionization yield at low energies is not measured by SuperCDMS, and general measurements are somewhat scattered.



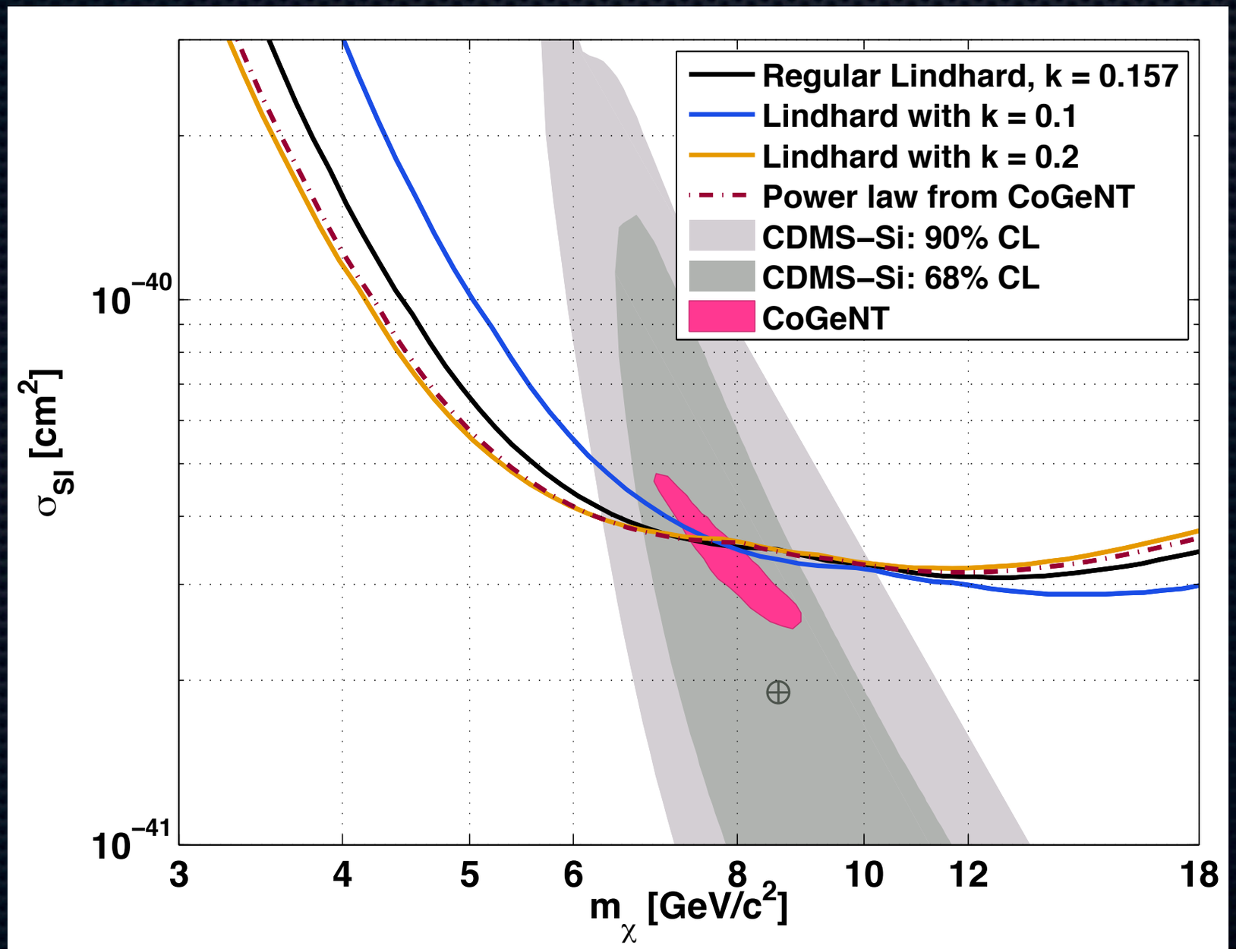
The “official” CDMSlite limit is calculated using the standard Lindhard yield model.

We also investigated the high and low (k = 0.2, 0.1) yield models from Barker & Mei and the power-law model from CoGeNT (left plot)

WIMP-search limits:

Commentary II

Effect on CDMSlite limits from choice of yield model



Energy Conversion

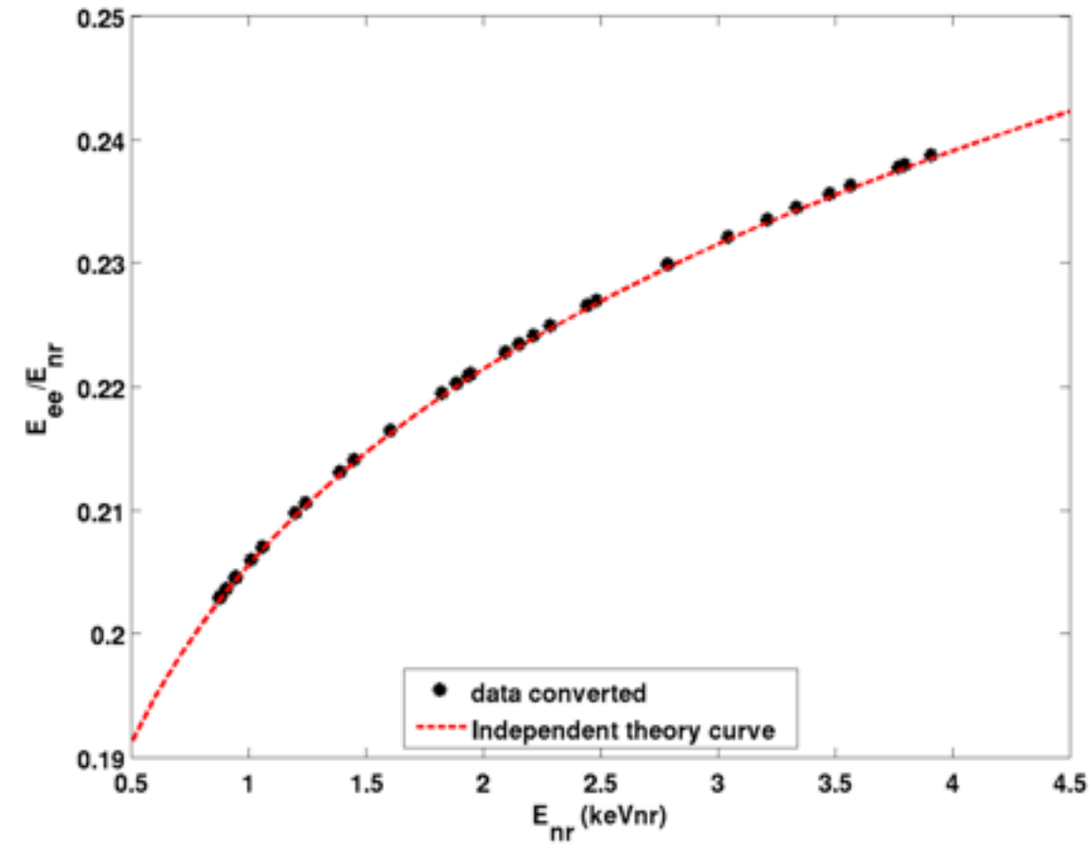
We measure total phonon energy and we are blind to the type of recoil. So for a given energy,

for an ER: $P_t = E_{r,ee}\left(1 + \frac{V}{3}\right)$

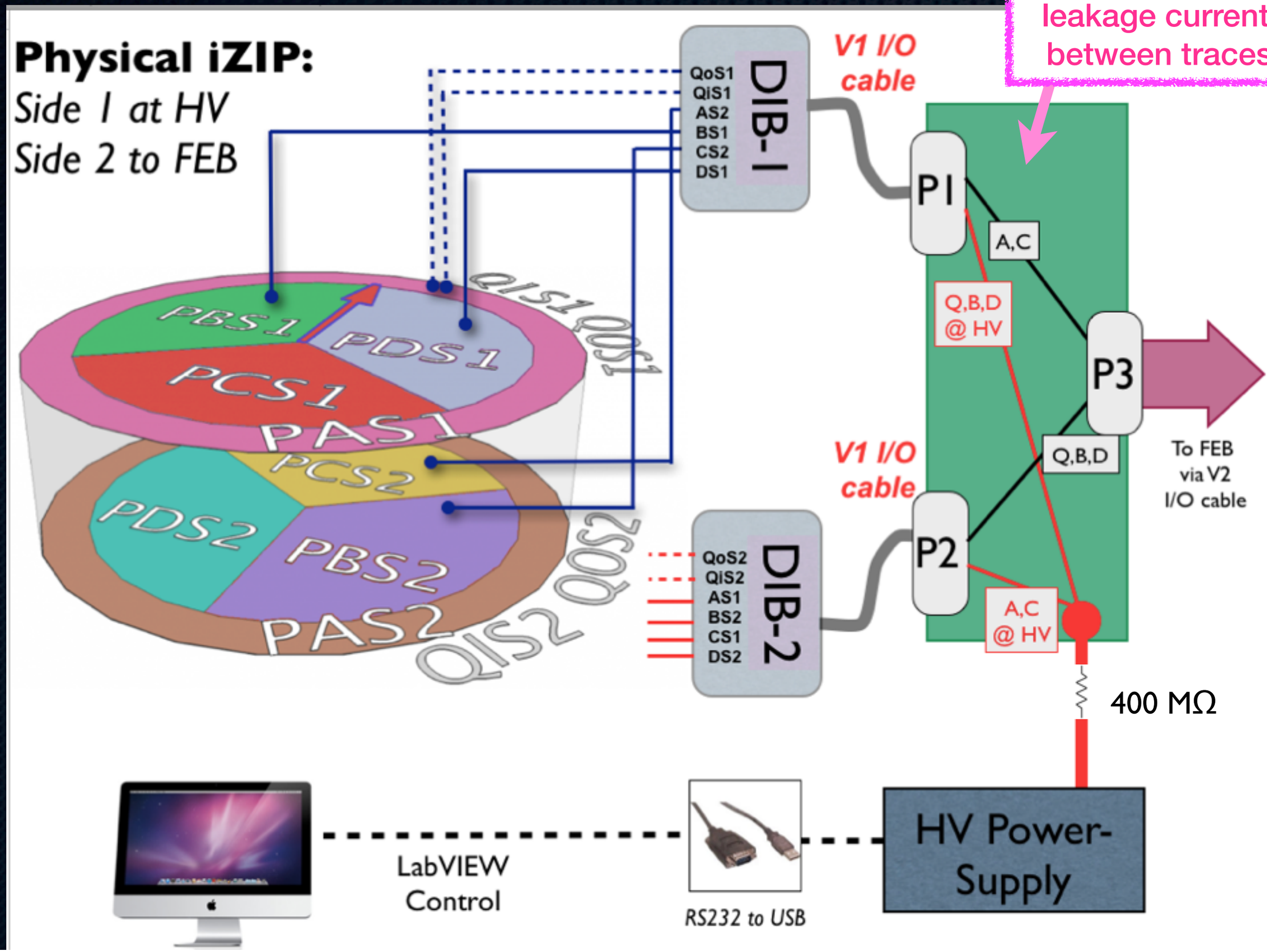
for a NR: $P_t = E_{r,nr}\left(1 + \frac{VY(E_{r,nr})}{3}\right)$

$$E_{\mathrm{nr}} = E_{\mathrm{ee}} \frac{(1 + \frac{eV_{\mathrm{b}}}{\varepsilon_\gamma})}{(1 + \frac{eV_{\mathrm{b}}}{\varepsilon_\gamma} Y(E_{\mathrm{nr}}))}$$

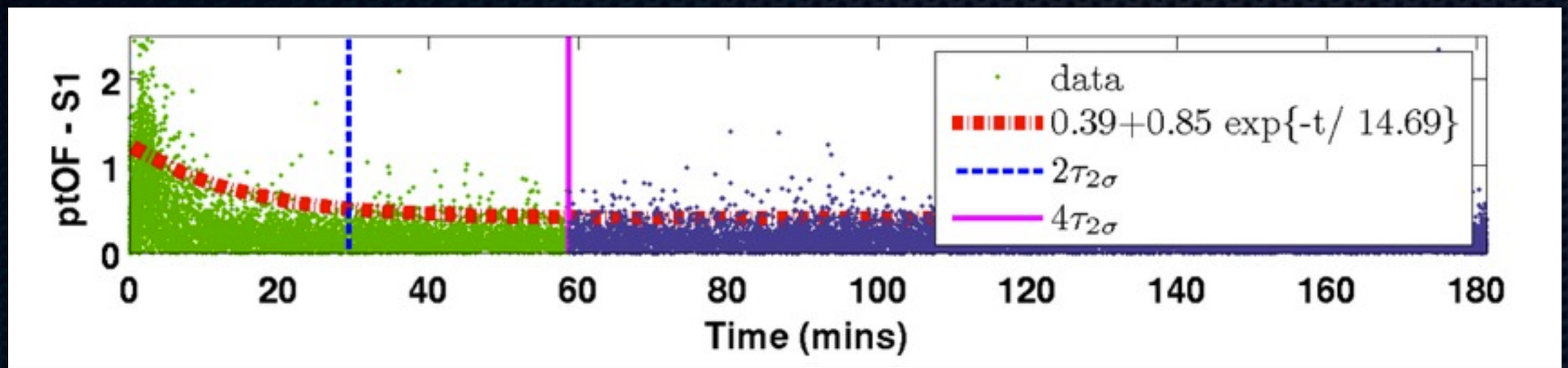
Assuming all are ERs, we have 100% charge collection and a yield model we go from keVee to keVnr

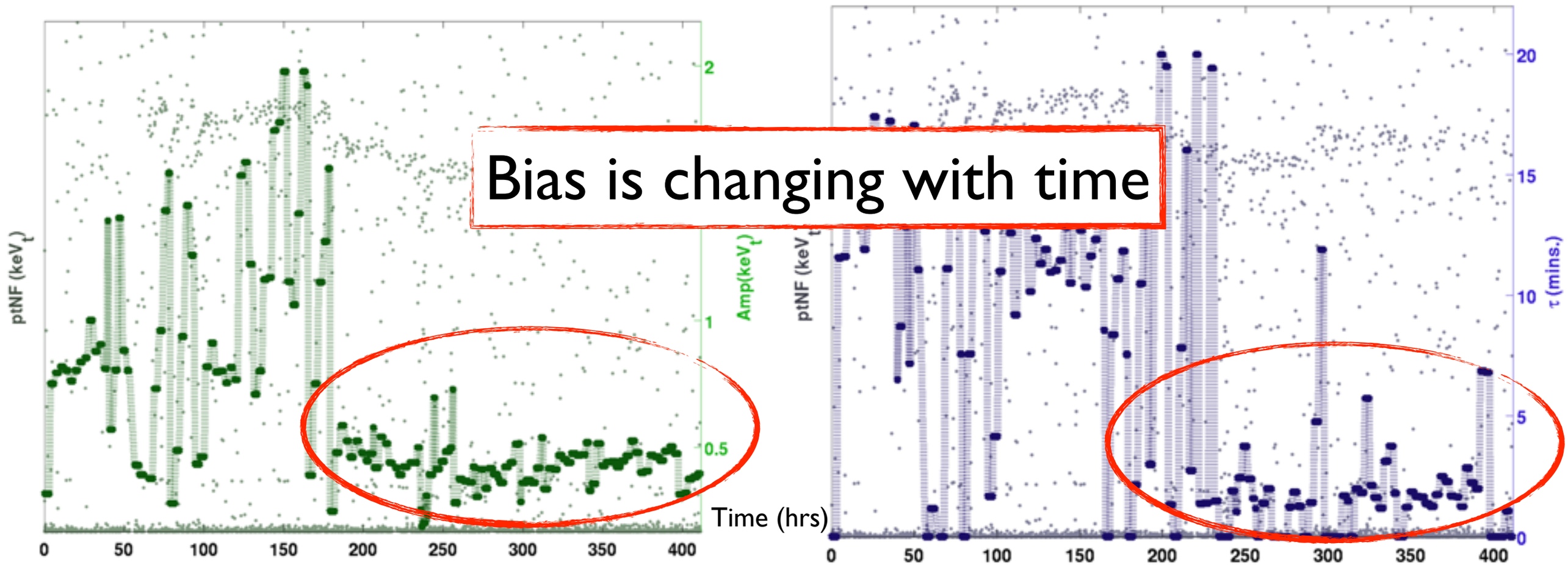


Hardware:


Physical iZIP:
Side 1 at HV
Side 2 to FEB
PBS1
PDS1
PCS1
PAS1
PCS2
PDS2
PBS2
PAS2
QIS1 QOS1
QIS2 QOS2
QoS1
QiS1
AS2
BS1
CS2
DS1
DIB-1
V1 I/O cable
Humidity causes leakage currents between traces.
P1
A,C
Q,B,D @ HV
P3
Q,B,D
To FEB via V2 I/O cable
V1 I/O cable
P2
A,C @ HV
QoS2
QiS2
AS1
BS2
CS1
DS2
DIB-2
400 MΩ
LabVIEW Control
RS232 to USB
HV Power-Supply

- Exponentially decaying leakage current.
- General measures depend on bias



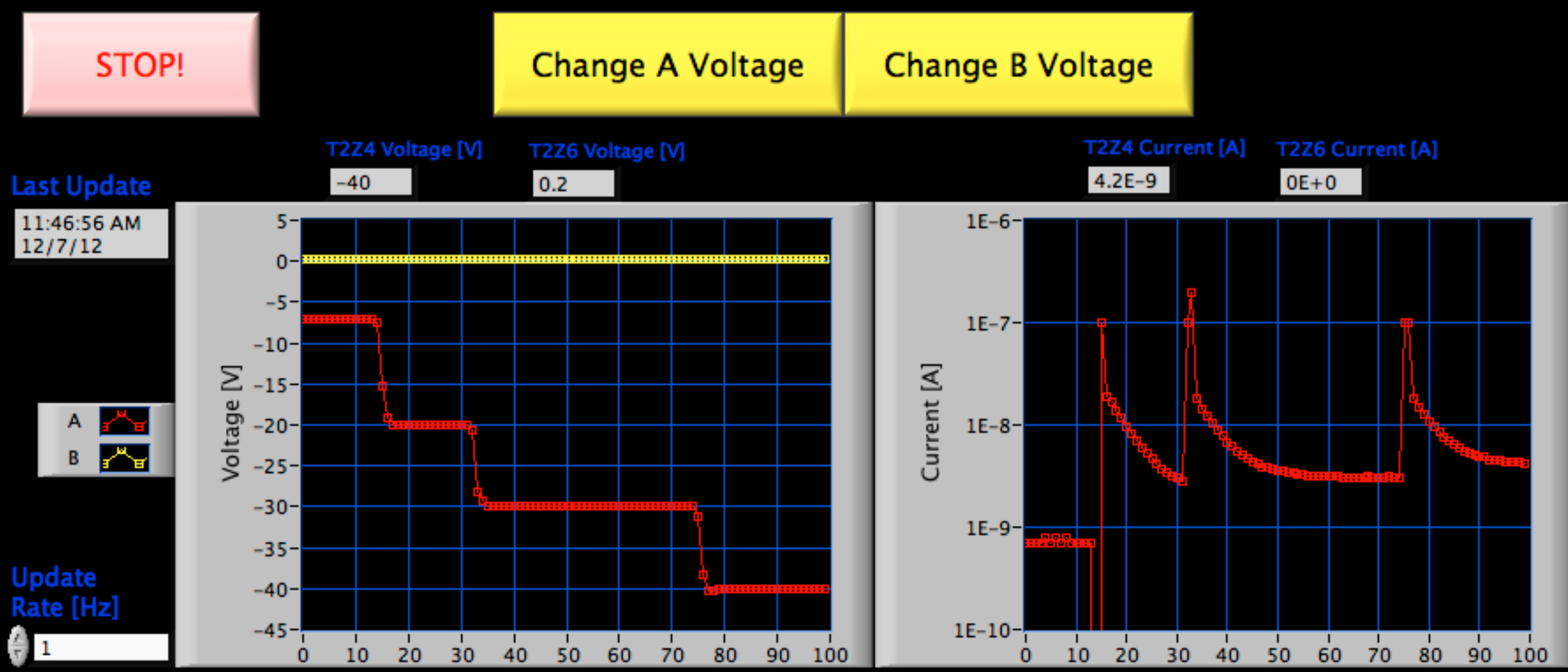


Bias is changing with time

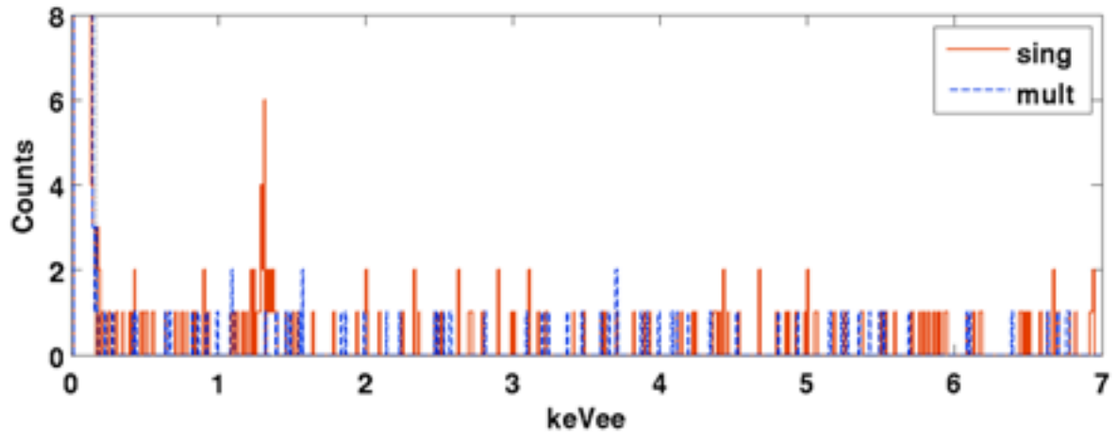
We know humidity can cause 10-100 MΩ short (Berkeley tests).

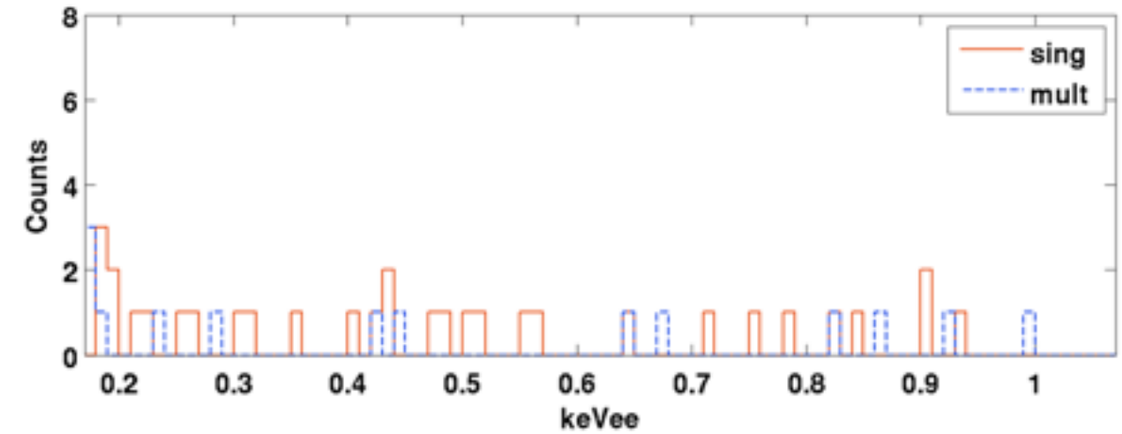
At Soudan we measured ~ GΩ short. Verified by HVPS meters.

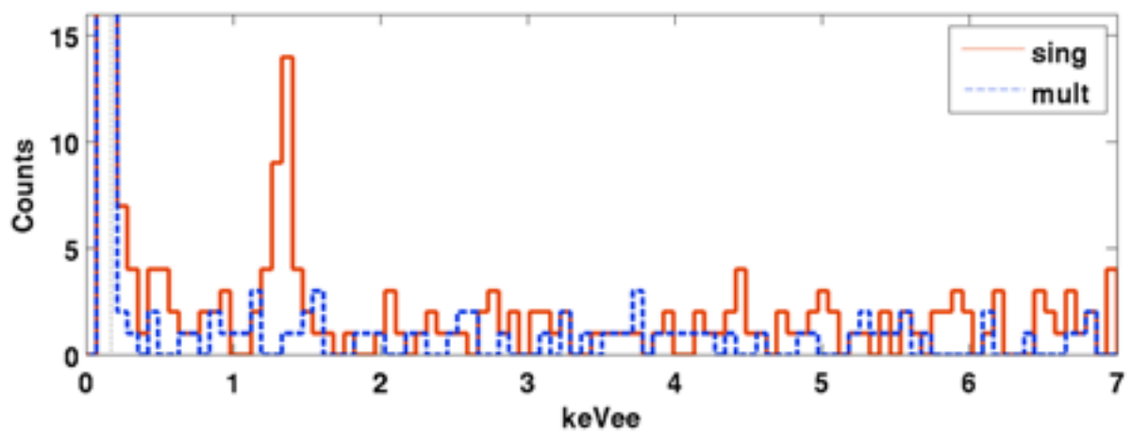
Boards will ultrasonically cleaned, sealed and 400 MOhm reduced

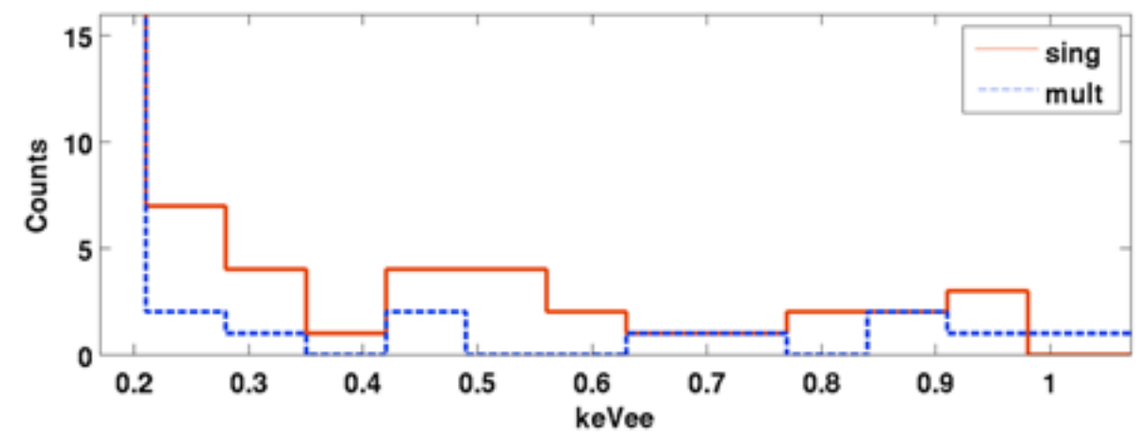


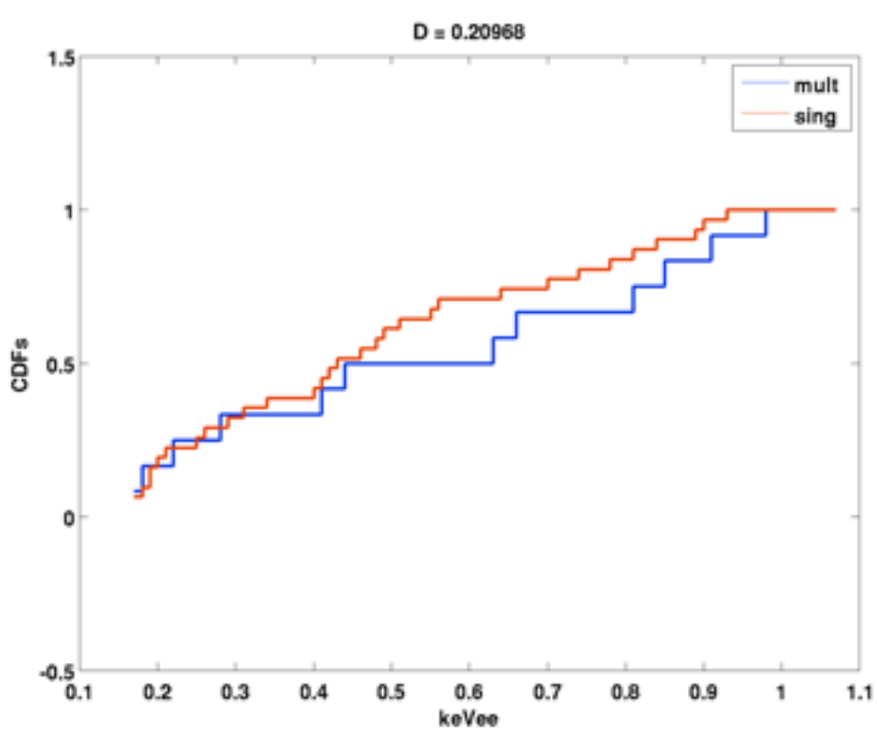
Multiples:





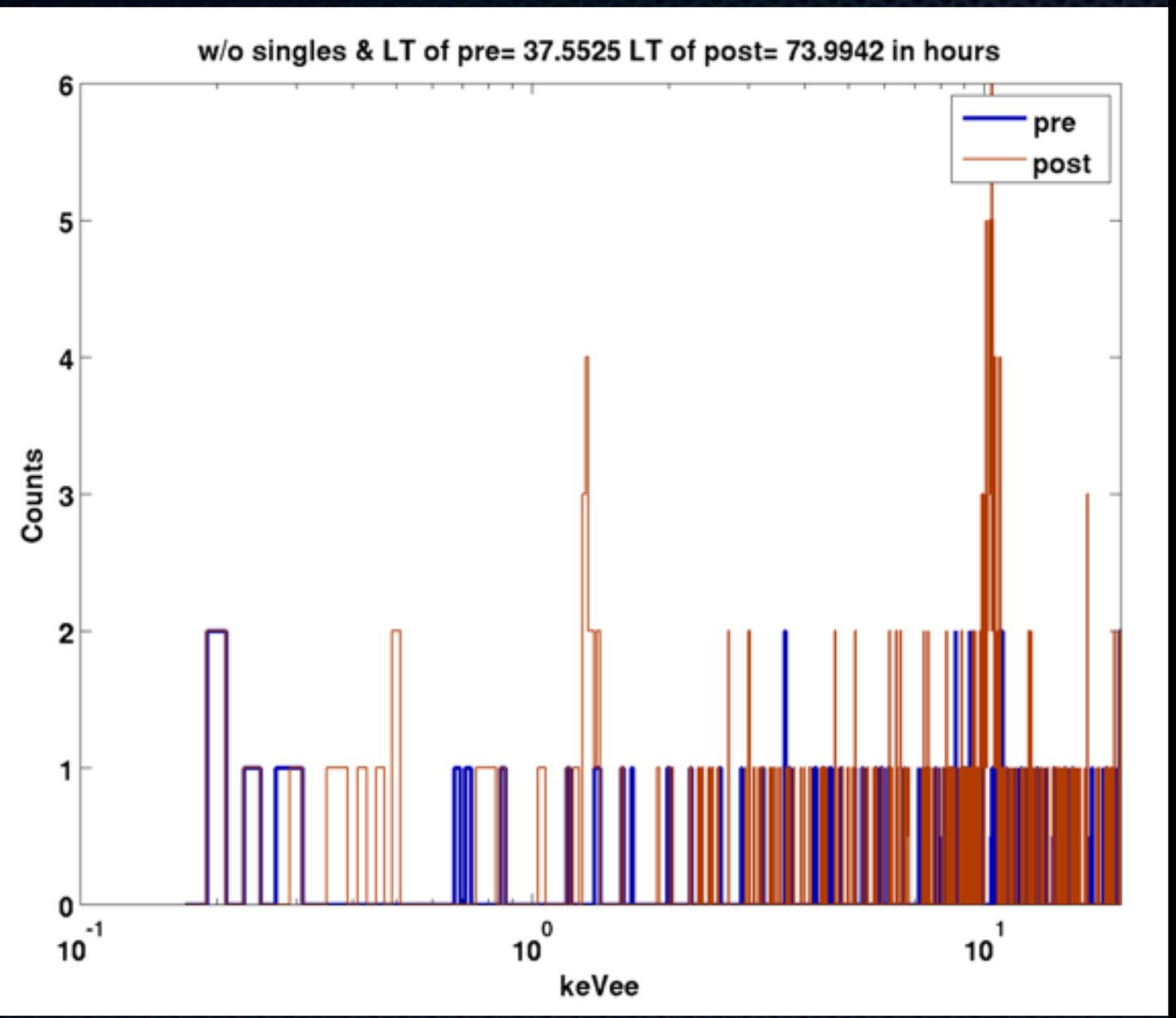






KS tests support the hypothesis that both samples are drawn from the same distribution.
We are data poor here.

Cf activation:



We can count up the number of events between threshold and 1 keVee.

In the pre / post periods the numbers are: 9 and 17. But the respective live times are 38 and 74
i.e. 9/38:17/74 ⇒ 1.03.

There is no major excess in the period after if we account for relative live times.