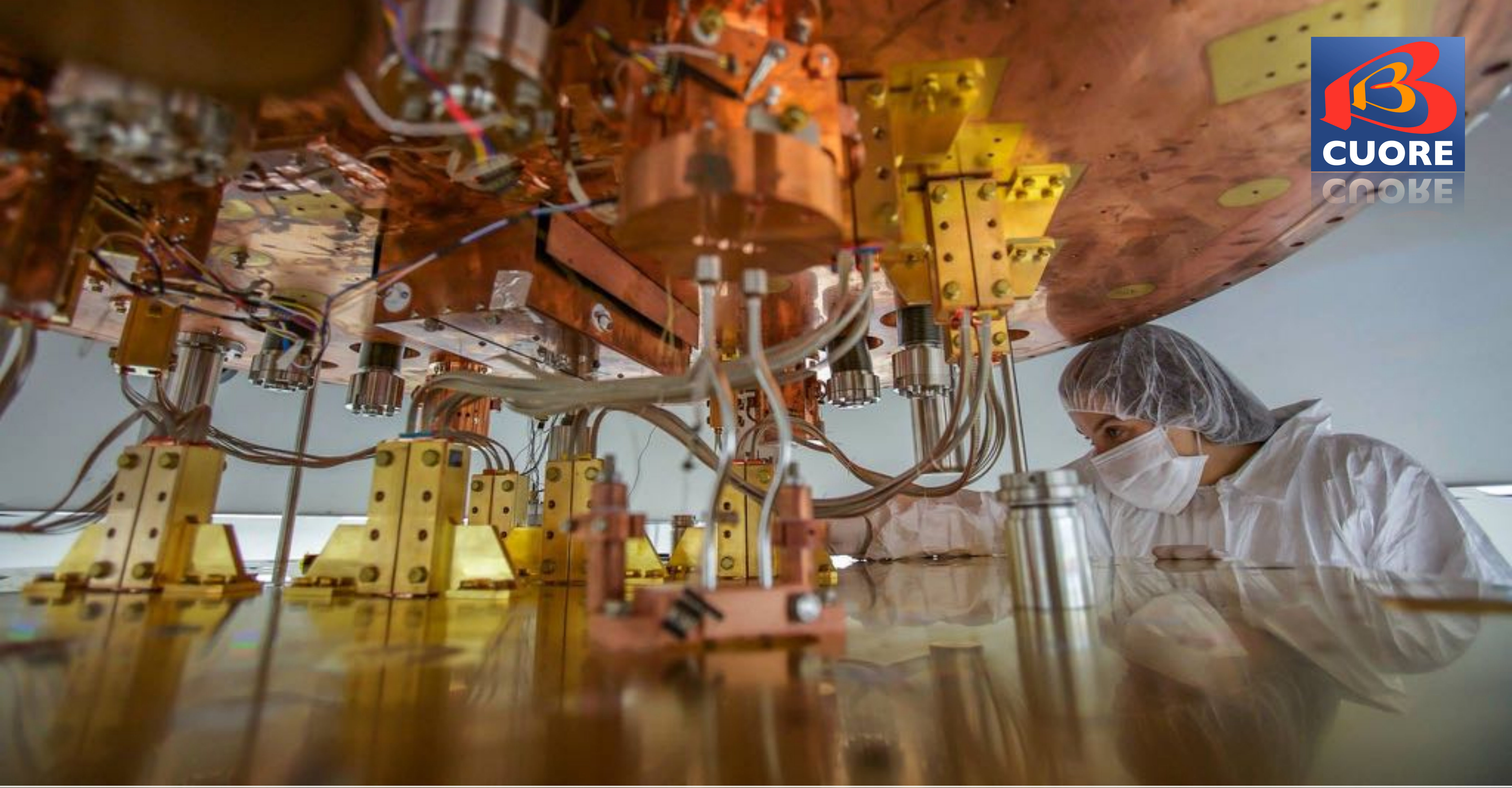


Search for WIMP-Induced Annual Modulation with the CUORE-0 Experiment

Kyungeun E. Lim on behalf of the CUORE collaboration

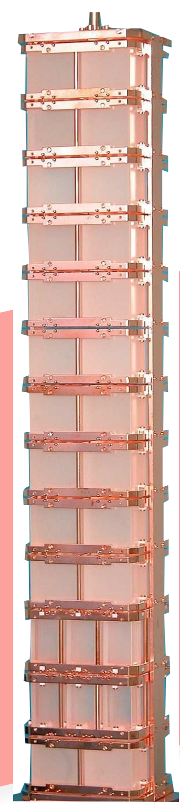
Oct. 14, 2016, APS Division of Nuclear Physics Meeting, Vancouver, Canada

LUX ET VERITAS

The CUORE Program

CUORE: Cryogenic Underground Observatory for Rare Events

Cuoricino (2003–2008)



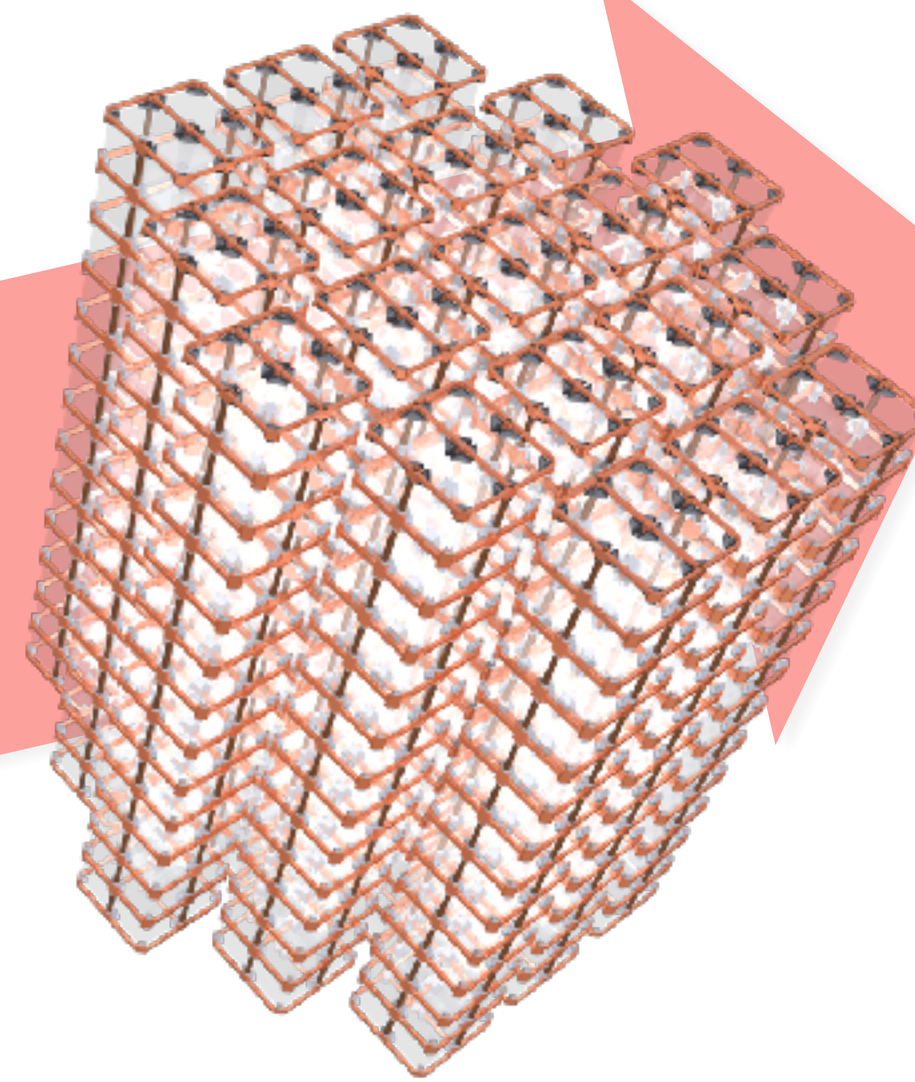
Completed (2008)

CUORE-0 (2013–2015)

Completed (2015)

$T_{1/2}^{0\nu}$ > 4.0×10^{24} yr (90% C.L.)

CUORE (2016–2020)



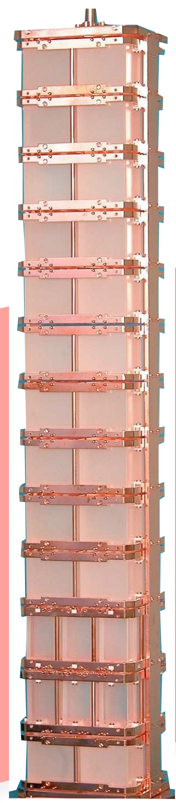
Projected (2020)

$T_{1/2}^{0\nu}$ > 9.5×10^{25} yr (90% C.L.)

The CUORE Program

CUORE: Cryogenic Underground Observatory for Rare Events

Cuoricino (2003–2008)



Completed (2008)

CUORE-0 (2013–2015)

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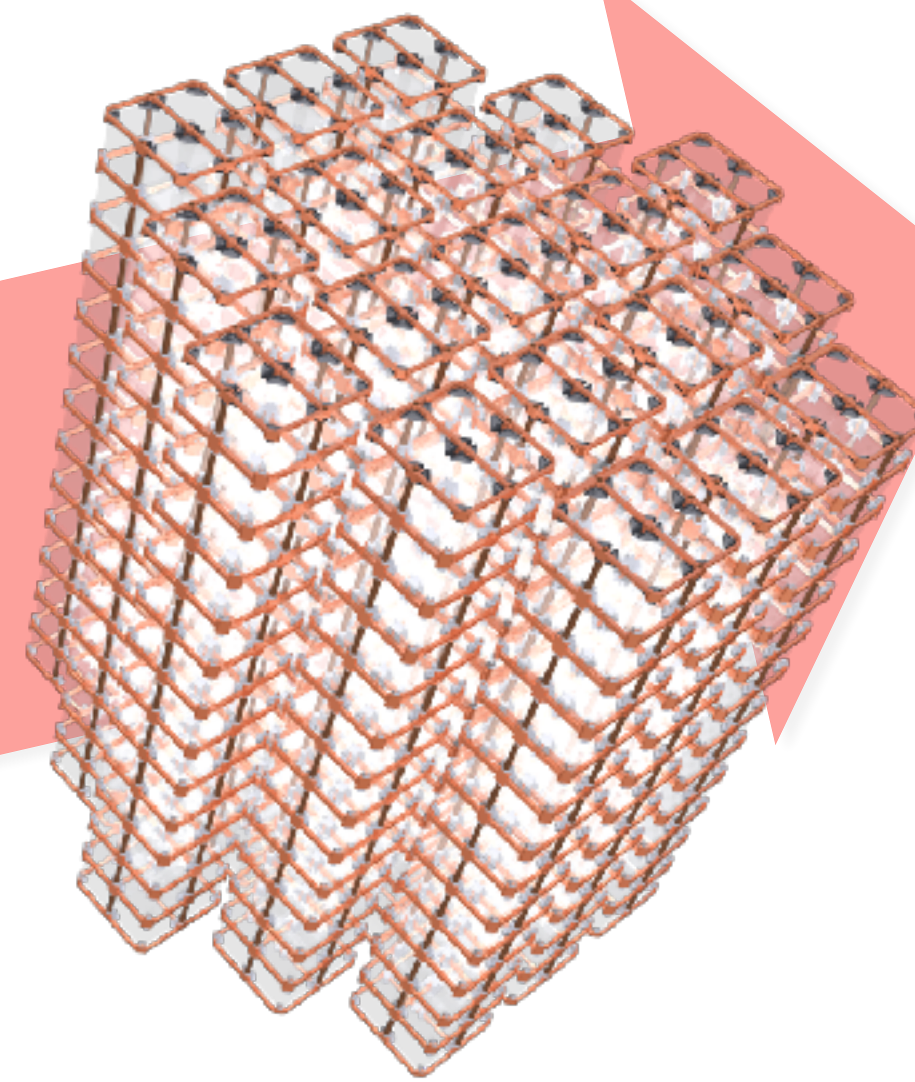
$T_{1/2}^{0\nu} > 4.0\times10^{24}$ yr (90% C.L.)

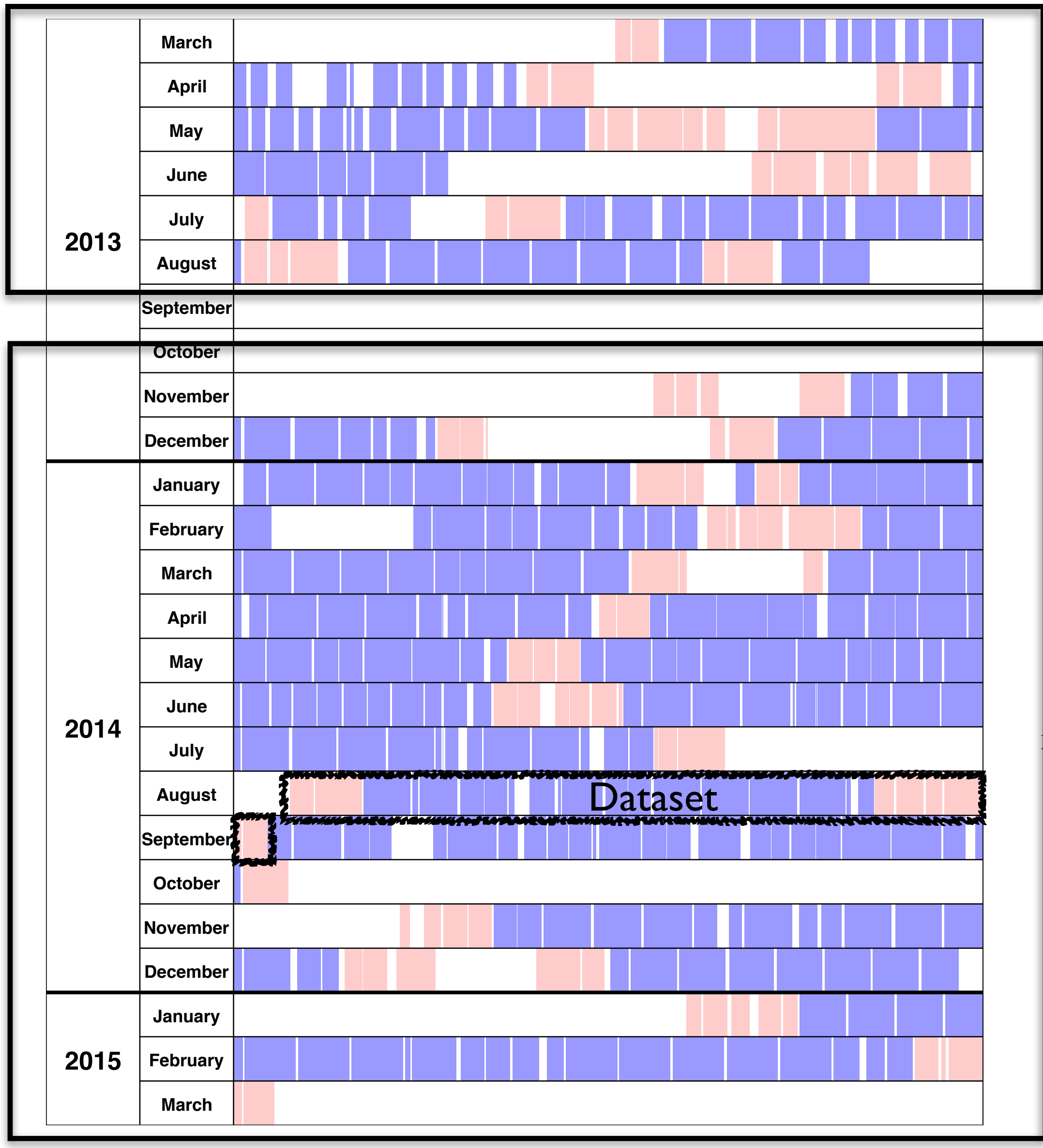
CUORE (2016–2020)

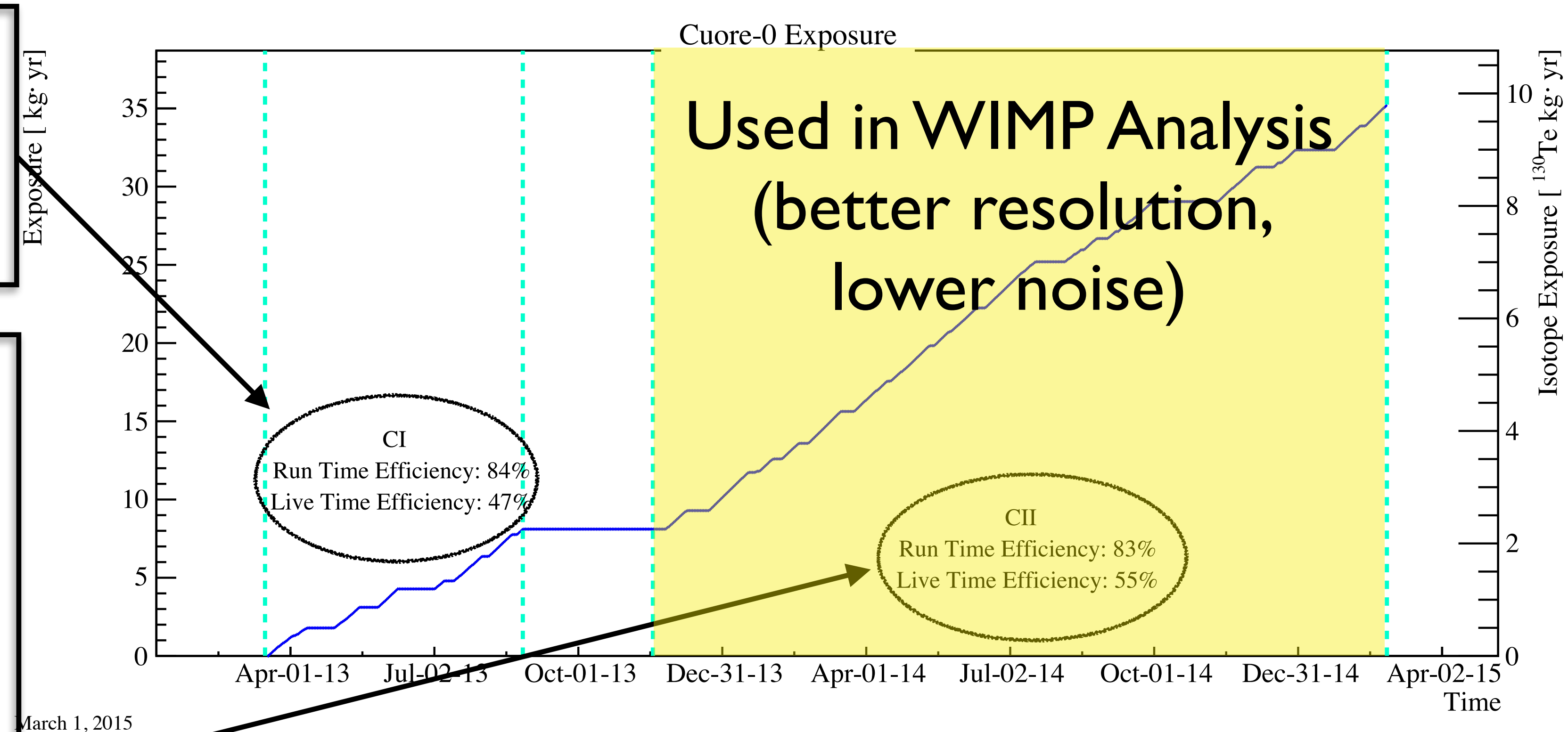


Projected (2020)

$T_{1/2}^{0\nu} > 9.5\times10^{25}$ yr (90% C.L.)

CUORE-0 Data





Physics data

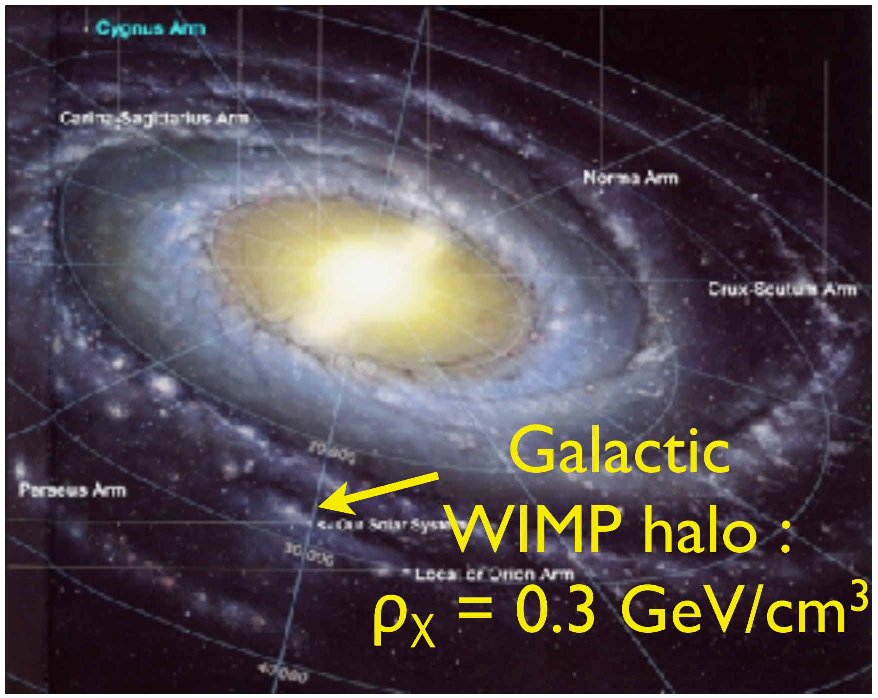
Calibration data

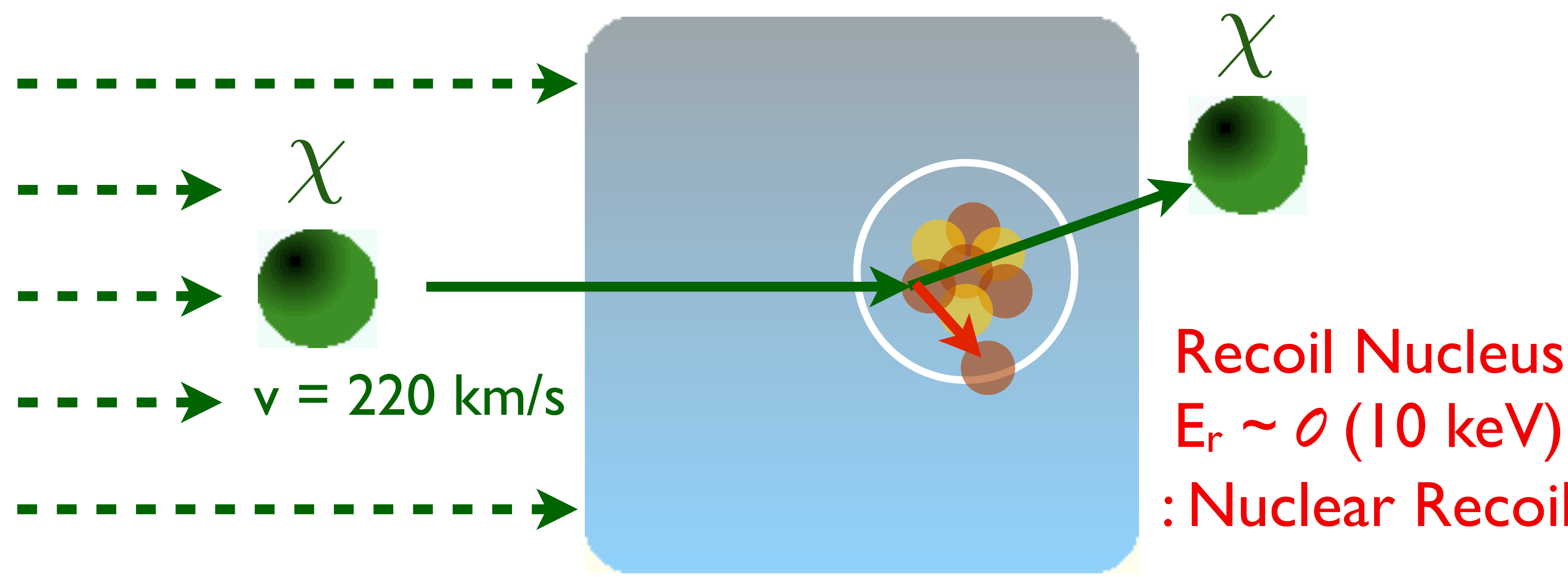
dataset: share calibration coefficients (~ 1 month)

- Reported the most stringent limit on the half-life of $0\nu\beta\beta$ of ^{130}Te with combination of Cuoricino results (Phys. Rev. Lett. 115, 102502 (2015), Phys. Rev. C 93, 045503 (2016))
- Measured the half-life of $2\nu\beta\beta$ of ^{130}Te with the highest precision (arXiv: 1609.01666)
- ***WIMP dark matter annual modulation analysis under finalization***

Principle of WIMP Direct Detection

Goodman and Witten: Elastic Scattering of WIMPs off Target Nuclei (1985)





Recoil Energy : $$E_\mathrm{r} = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$$

Expected Rate : $$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \langle v \rangle$$

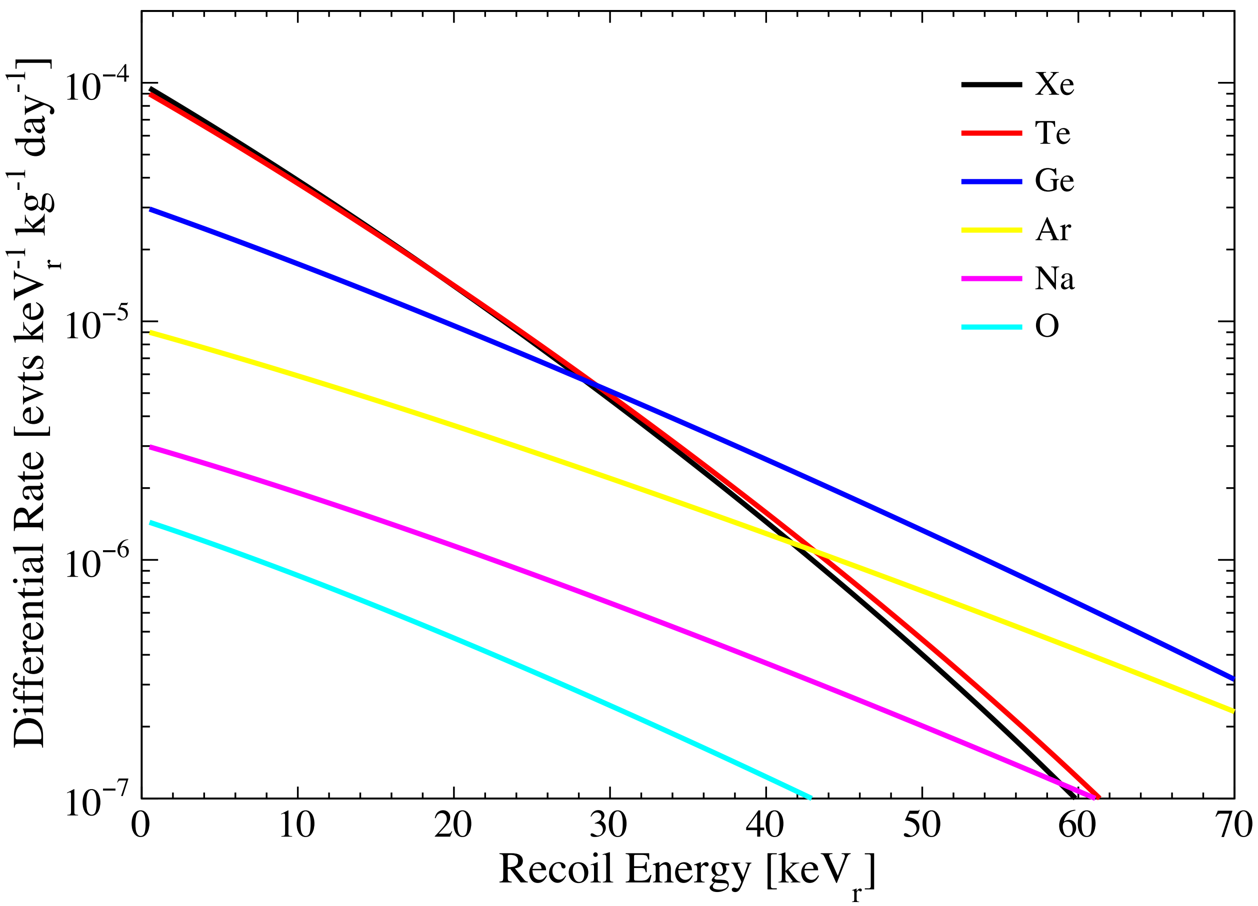
Astrophysics Input
(the local DM density at our position in galaxy)
(average WIMP velocity in the lab frame)

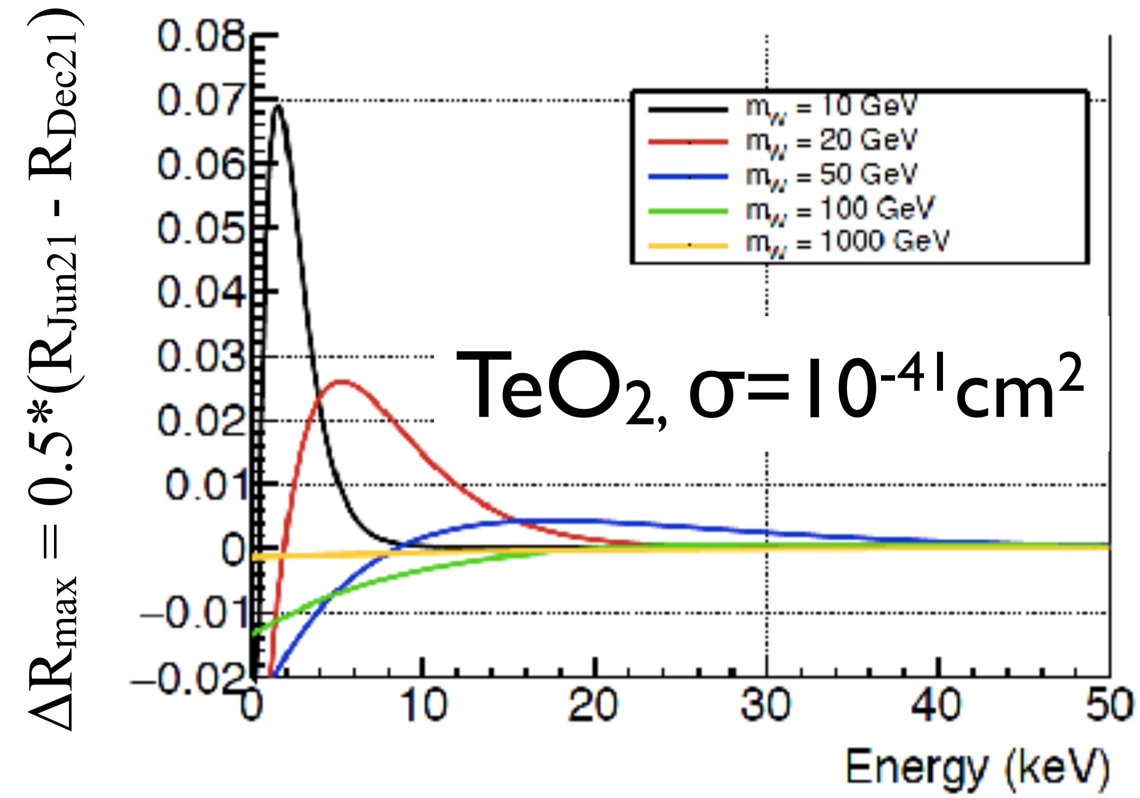
Detector Physics Input
(number of nuclei in target)

Particle Physics Input
(WIMP-nucleus elastic scattering cross section)
(WIMP mass)

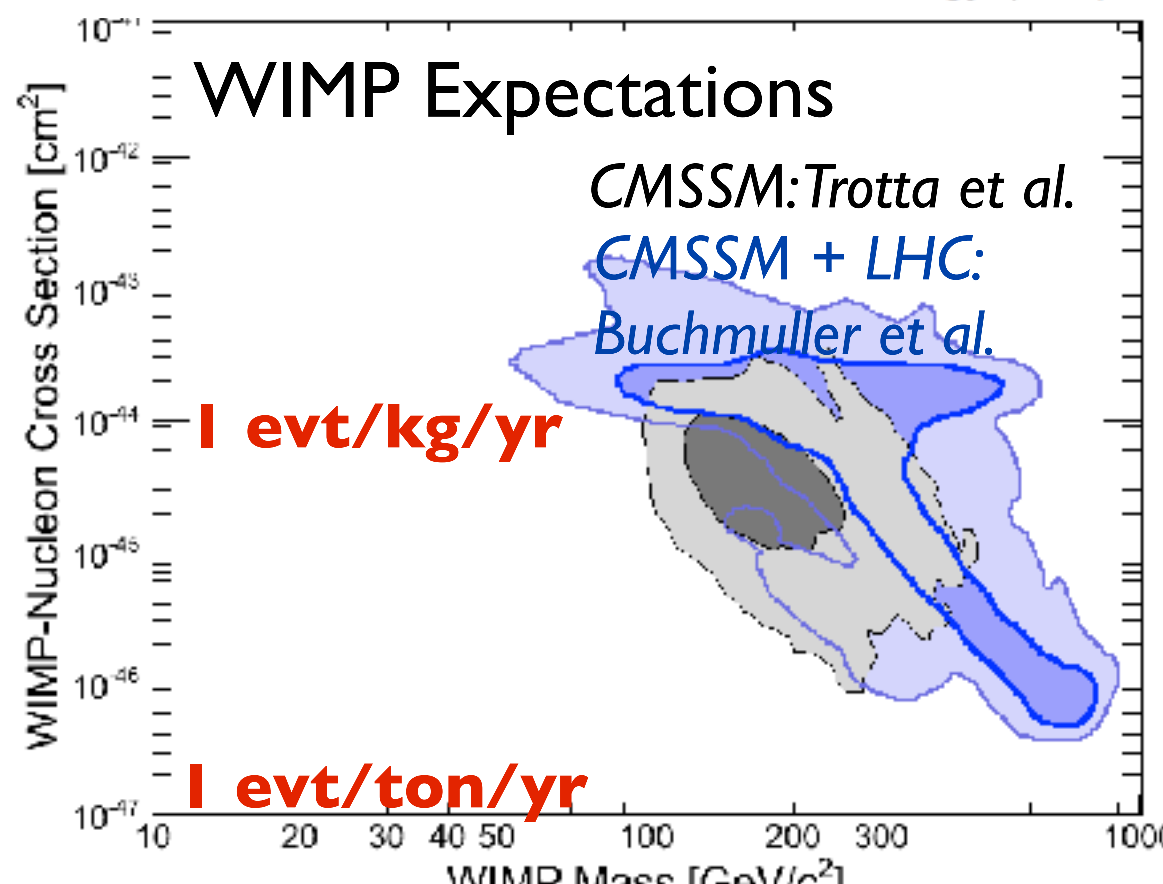
Expected WIMP Signal

CUORE

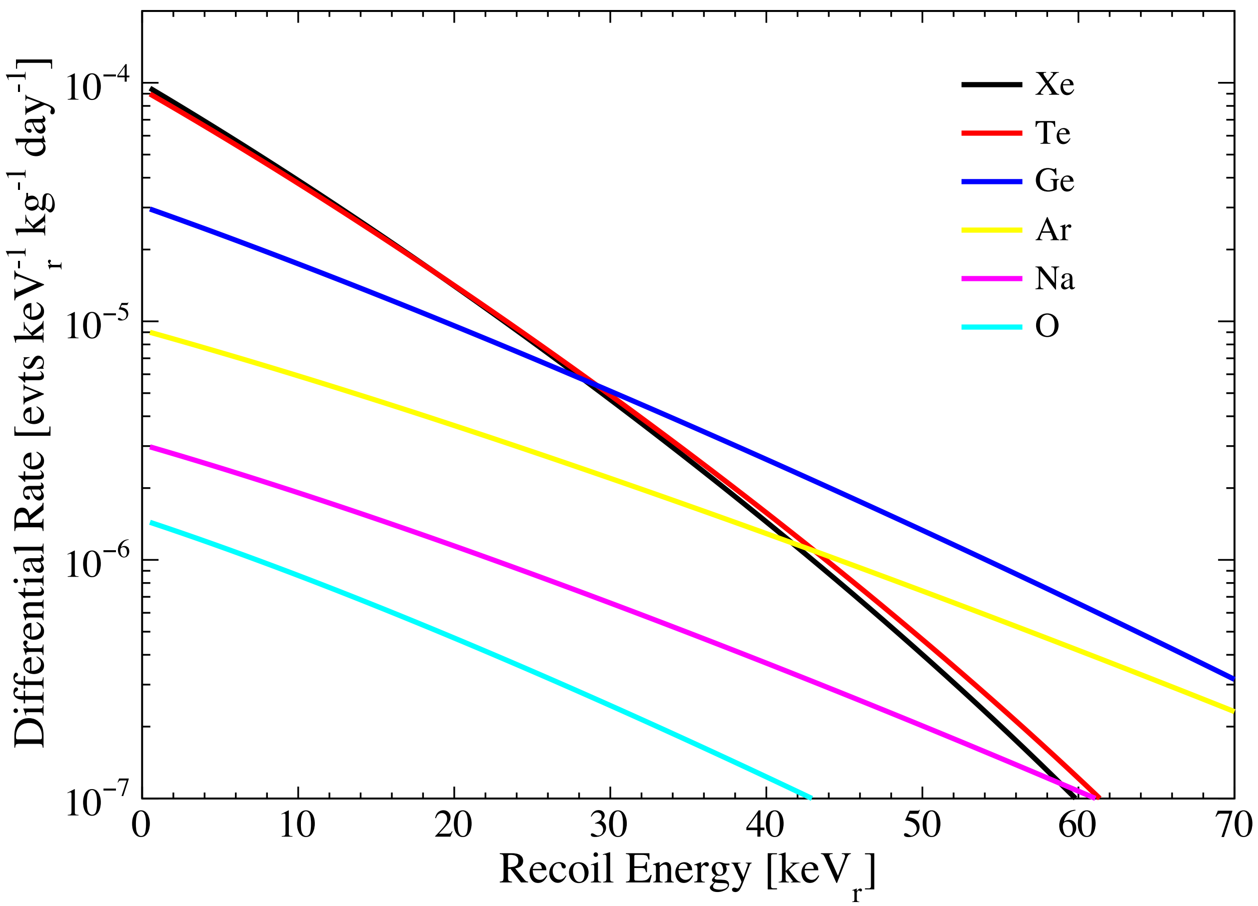


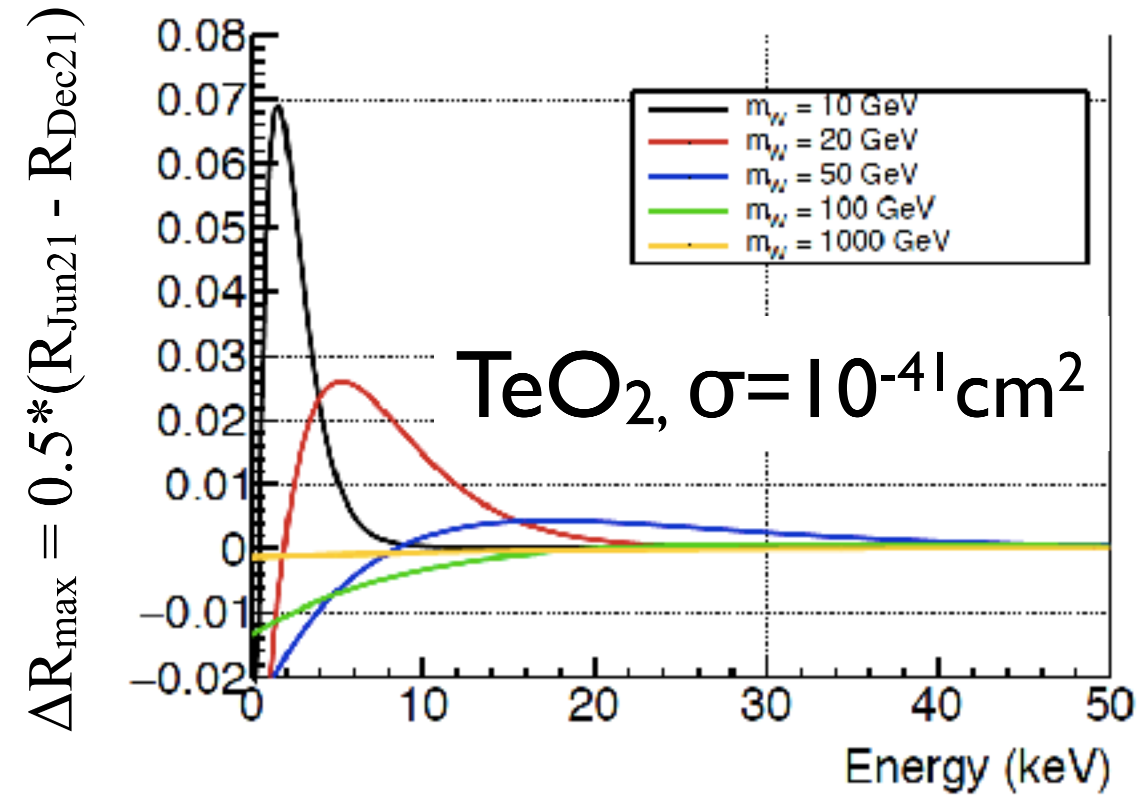


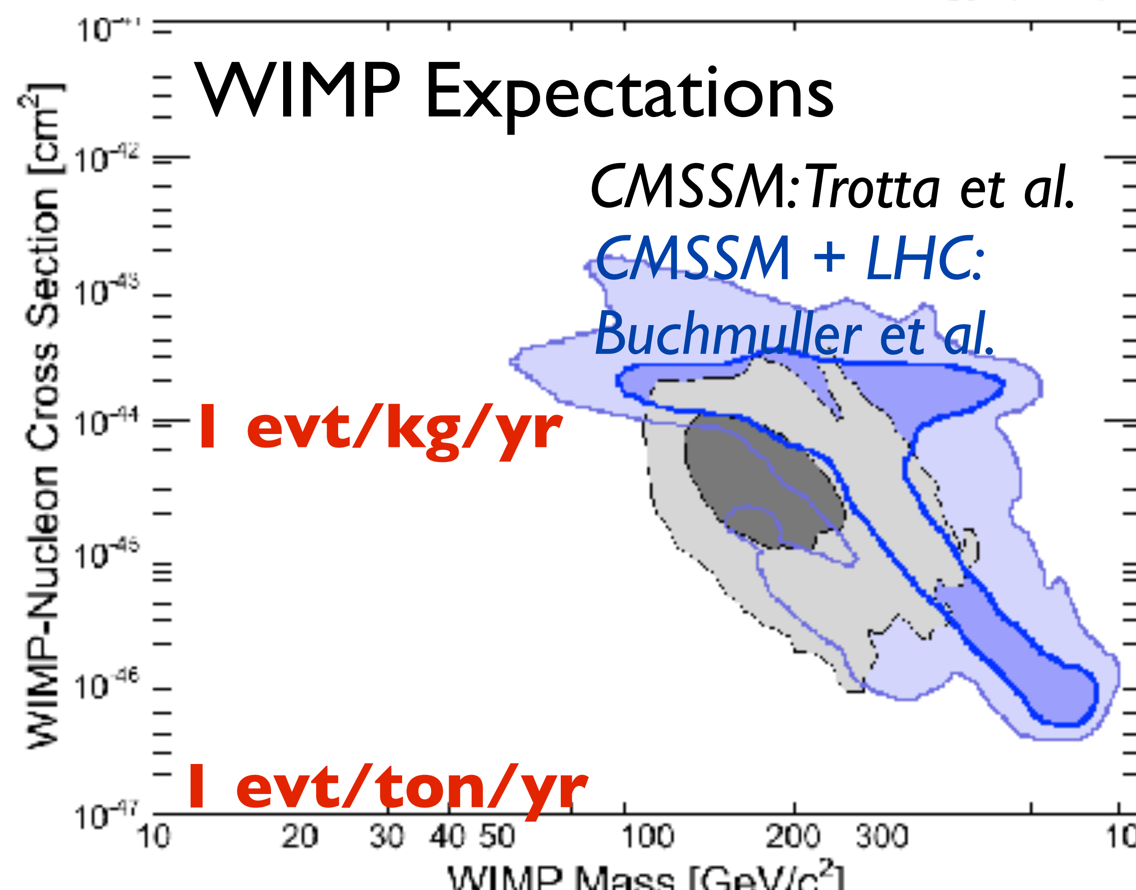
- Exponentially fall
- Annually modulate
- Tiny rate



Detector Requirements

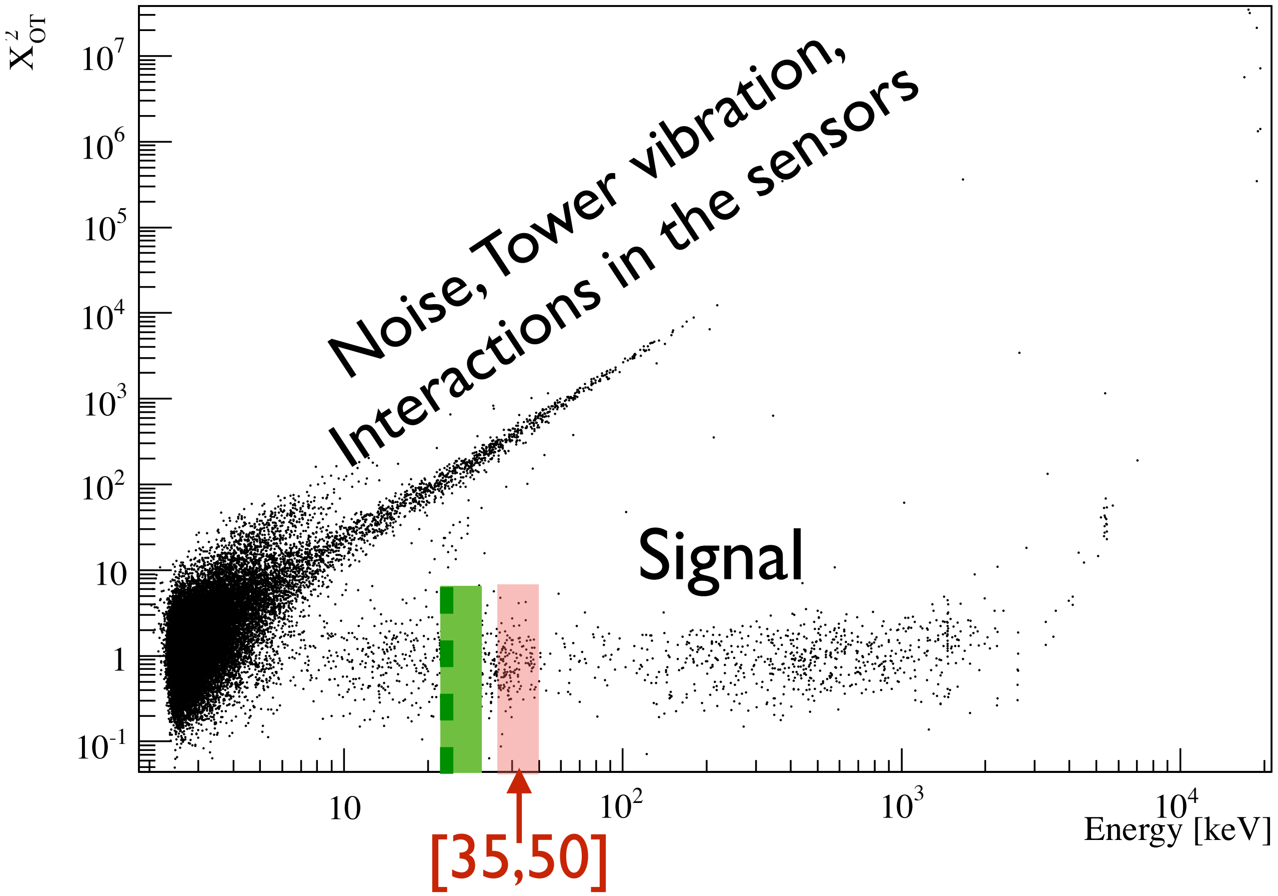


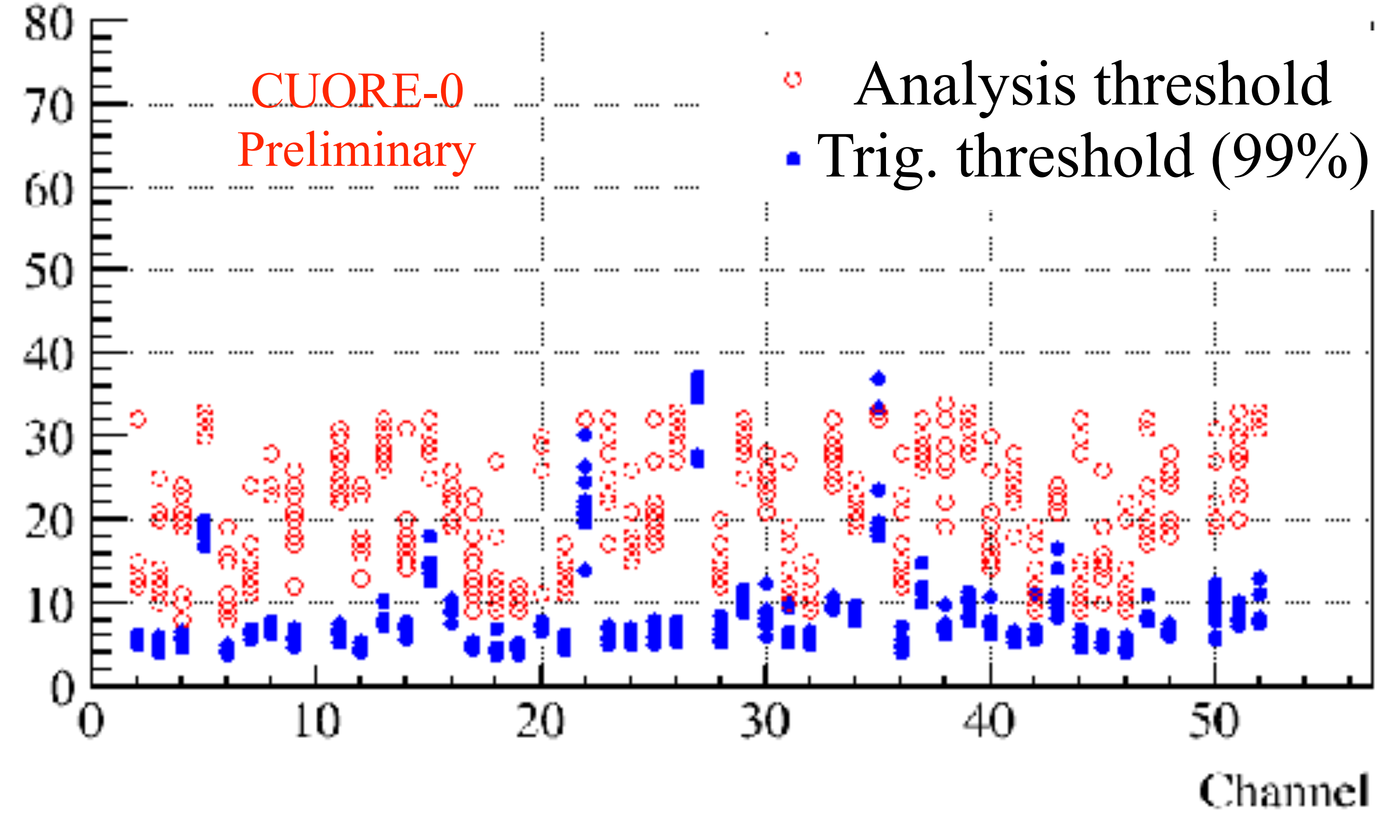




- Low energy threshold
- Stable detector operation
- Low background
- Large detector mass

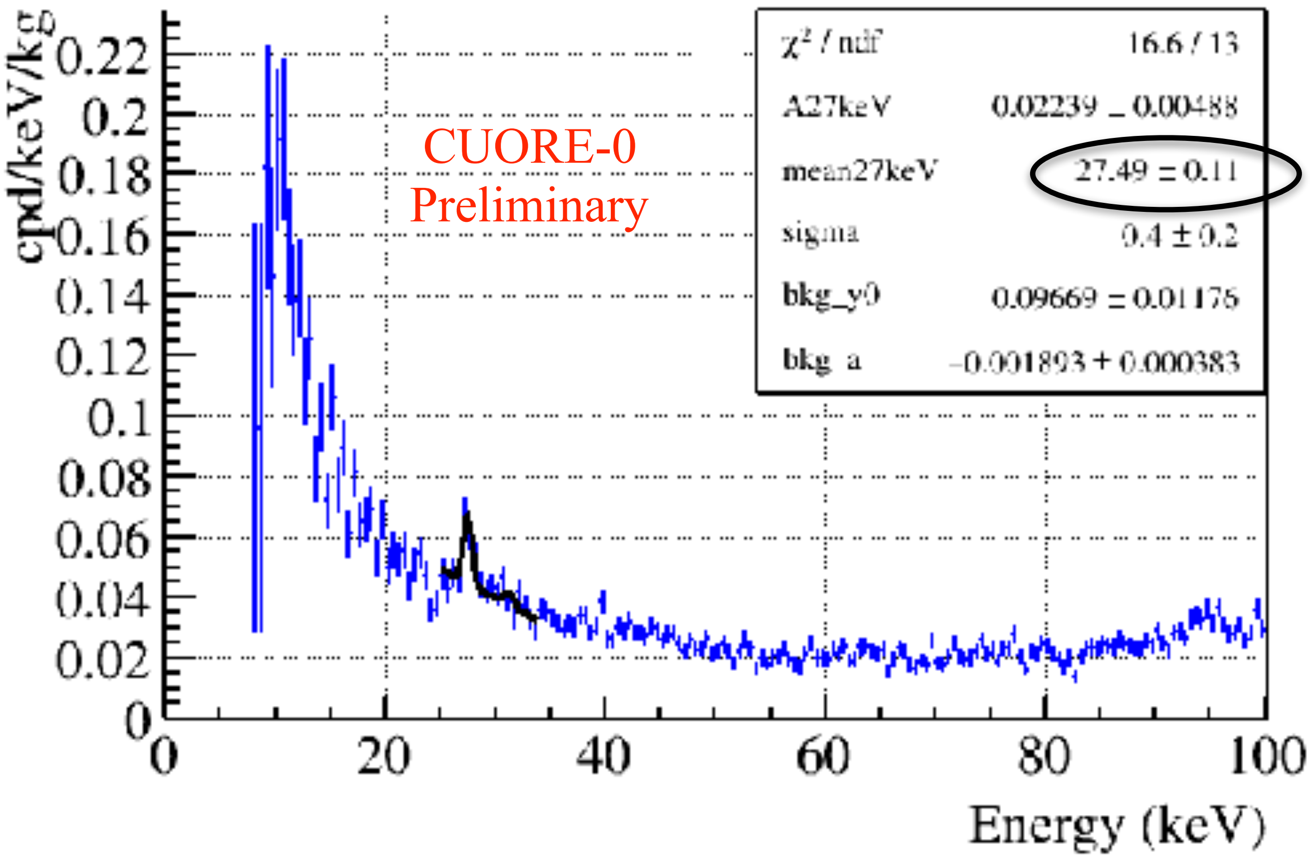
Low Energy Event Selection





- Use a pulse shape parameter (built upon χ^2 of a pulse with respect to an ideal pulse, χ^2_{OT}) to select legitimate signal candidates against non-physical events
- Energy thresholds for each channel-dataset (ch-ds) pairs are obtained using Kolmogorov-Smirnov test (compare y-axis projection of with , and choose the lower edge of where KS prob > 0.1)

Low Energy Calibration

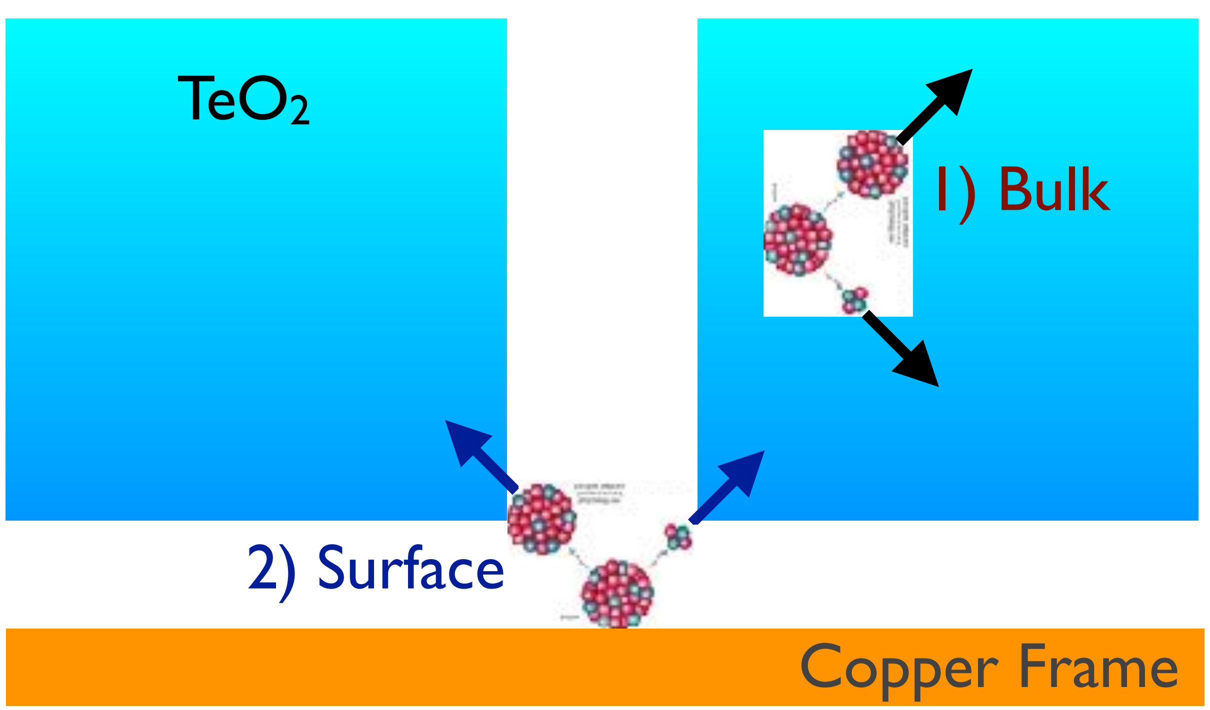


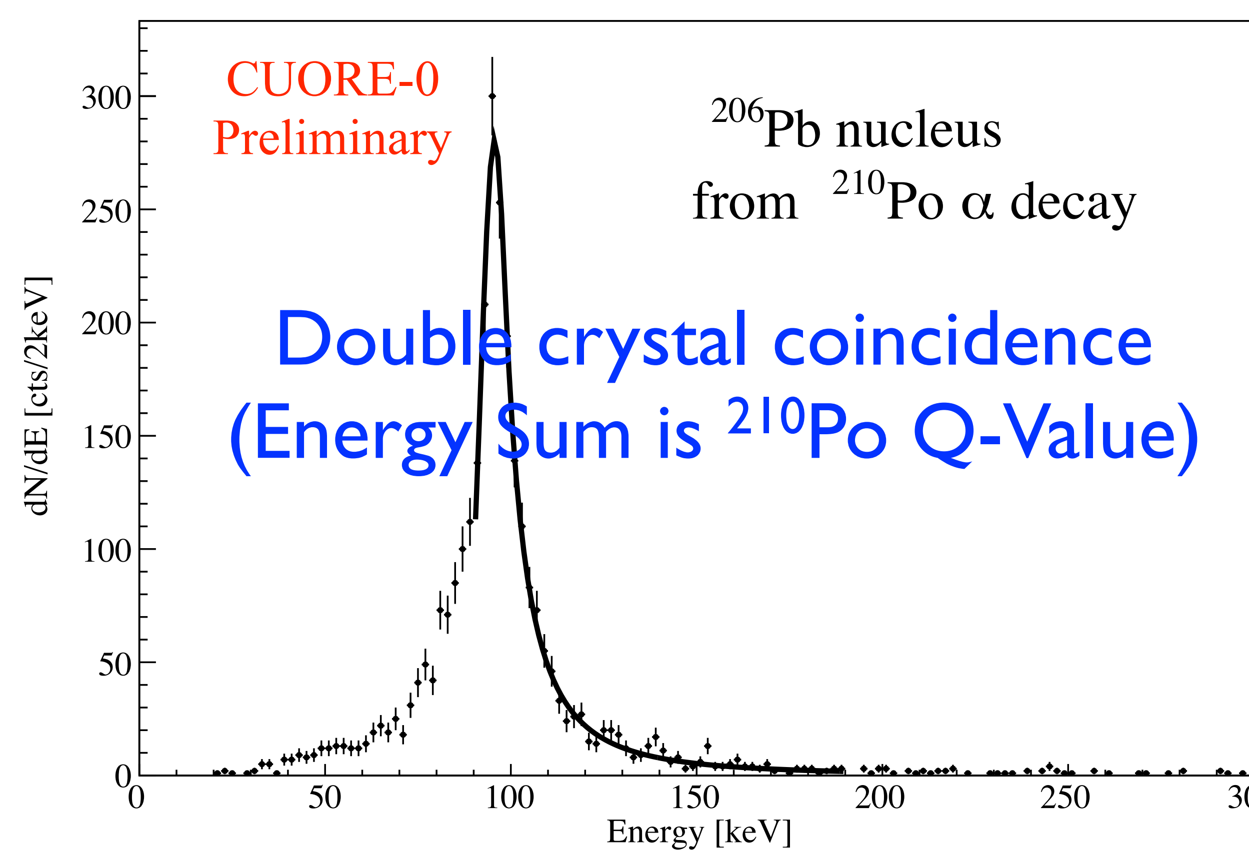
Expected value 27.38 keV

- Peak position of 27 keV X-ray from Te is firstly used to select the ch-ds pairs, as well as to evaluate uncertainty on the energy scale obtained from calibration
- For those ch-ds pairs with E_{th} > 27 keV selected with KS-test, their summed 40-keV peak position difference from those with 27-keV peak is evaluated to be 0.03 +/-0.06 keV, and is integrated as a part of uncertainty on the energy scale (see slide 12)

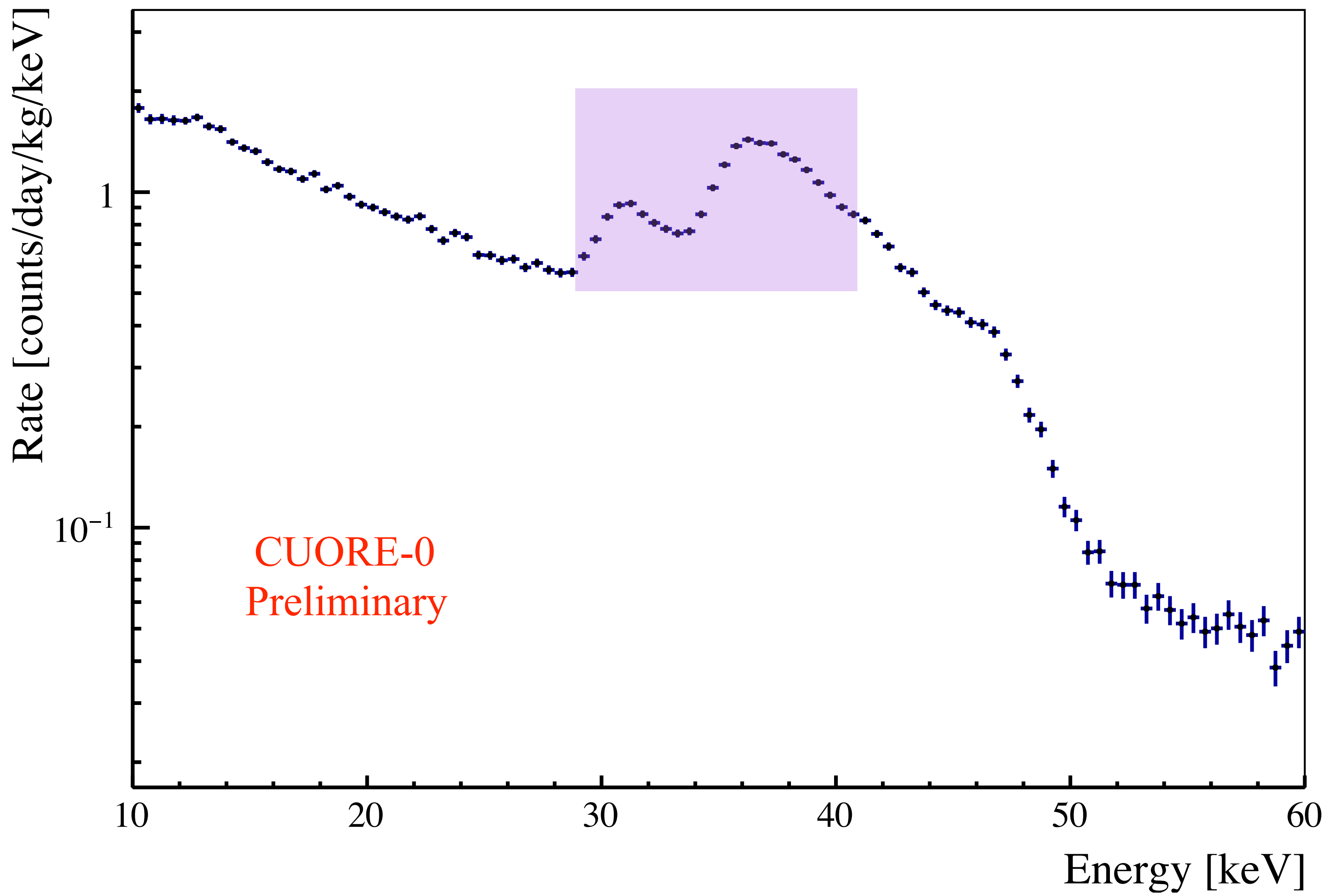
Nuclear Recoil Quenching of TeO_2

- Nuclear quenching factor of a bolometer (read only phonon signal) is expected to be 1
- Using surface alpha events, it is possible to measure nuclear quenching of recoiling nuclei from ^{210}Po, ^{222}Rn, ^{224}Ra, ^{218}Po decays
- The largest deviation from 1 (7%, measured by ^{206}Pb) is integrated as uncertainty on the energy scale



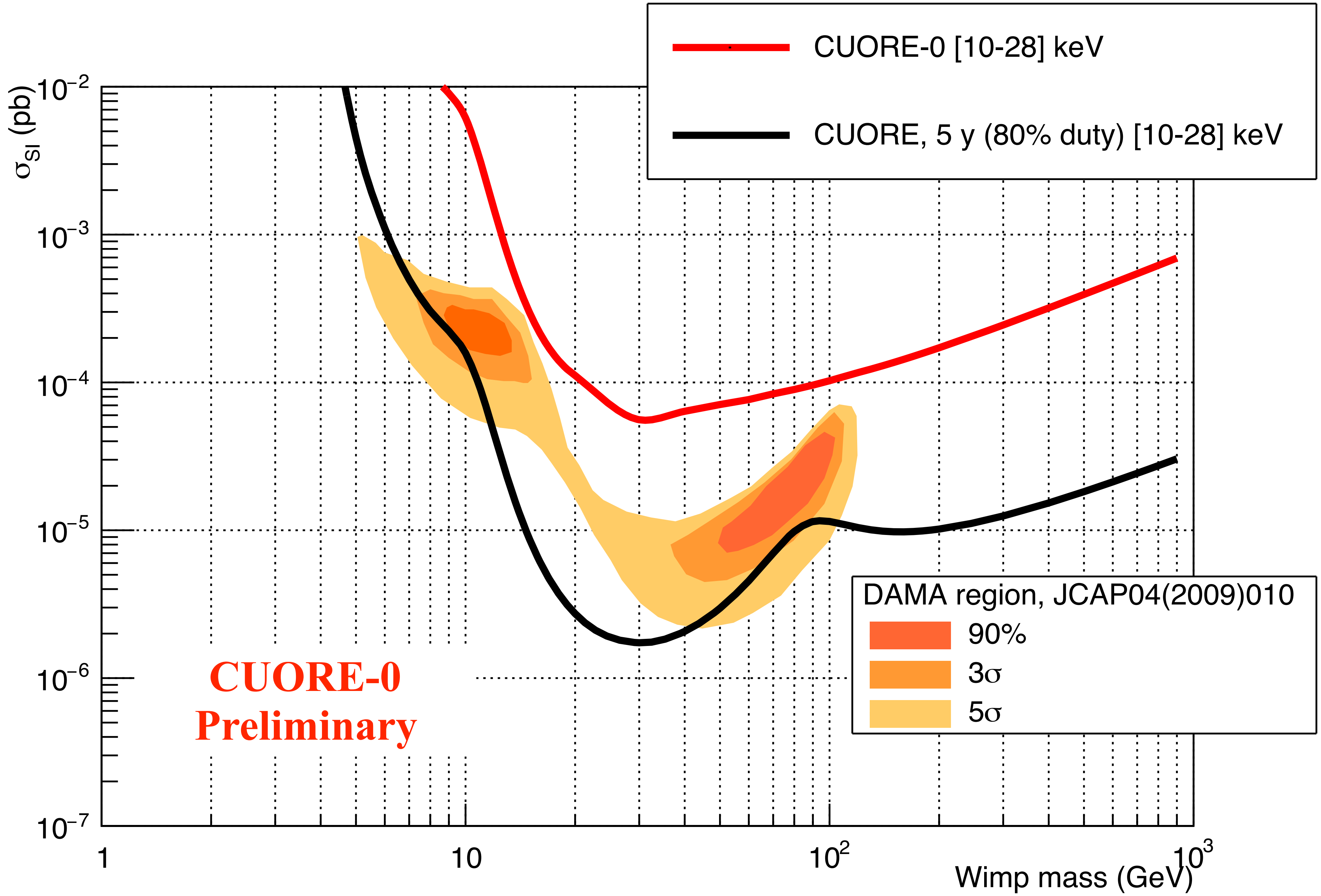


Low Energy Spectrum



- Origin of peaks around 40-keV is under investigation (most likely due to ^{210}Pb)
- Rates of these peaks are stable as a function of time

CUORE-0 and CUORE Sensitivities



- CUORE is expected to test the DAMA WIMP observation claim with 5 years of data accumulation

Summary

- CUORE, a competitive 0νββ decay search using 742 kg of TeO_2 crystals, is also suitable for low energy event searches thanks to its low energy event identification ability
- Nuclear recoil quenching using CUORE-0, the predecessor of CUORE, has been measured using surface alpha events
- WIMP-Induced annual modulation analysis of CUORE-0 is under finalization, and we will report dark matter results using Te as a target material with significant mass for the first time soon
- CUORE is expected to probe the DAMA WIMP observation region with 5 years of data-taking
- CUPID, beyond CUORE using particle discrimination to further suppress the background, will be a competitive dark matter search

CUORE Collaboration

CUORE

(Oct. 2, 2015 @ LNGS)

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE — SOL PER NOCTEM

SINAP

UNIVERSITAS STUDII PADUANI

INFN Istituto Nazionale di Fisica Nucleare

CAL POLY SAN LUIS OBISPO

Lawrence Livermore National Laboratory

ALMA MATER STUDIORUM A.D. 1088

SAPIENZA UNIVERSITÀ DI ROMA

Yale

SHANGHAI JIAO TONG UNIVERSITY

CSNSM

Massachusetts Institute of Technology

BERKELEY LAB

UNIVERSITY OF SOUTH CAROLINA

UCLA

THE UNIVERSITY OF CALIFORNIA 1868

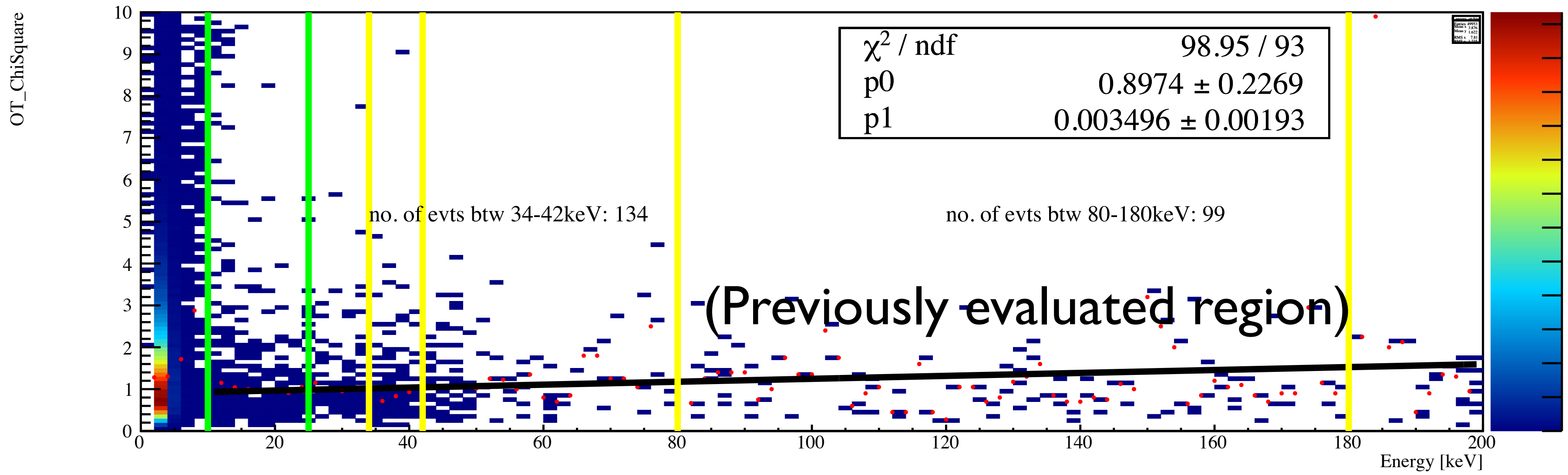
CUORE

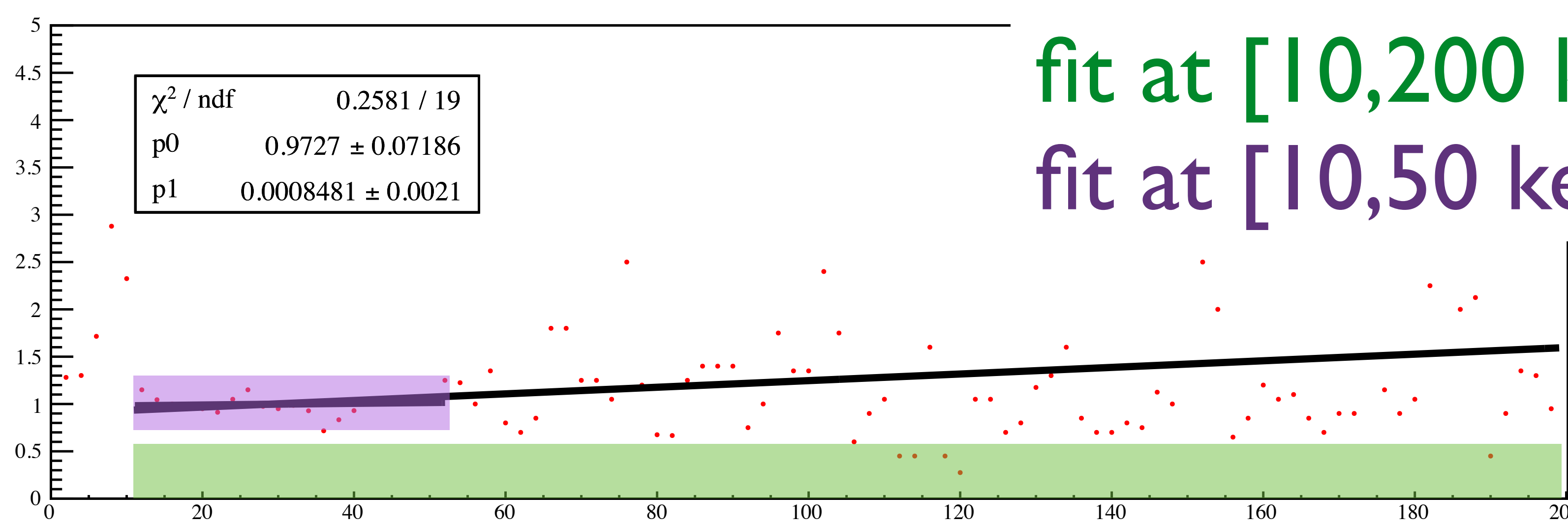
Extra Slides

χ^2_{OT} : Energy Dependence

- We evaluate the χ^2_{OT} efficiency using side band, so it is important to ensure this side bands behavior is similar at ROI
- Previously we were using 80-180 keV region to stay away from the noise but there's energy dependence on in the median value of χ^2_{OT} so we decided to move to 35-50 keV region

DS2100, Ch2





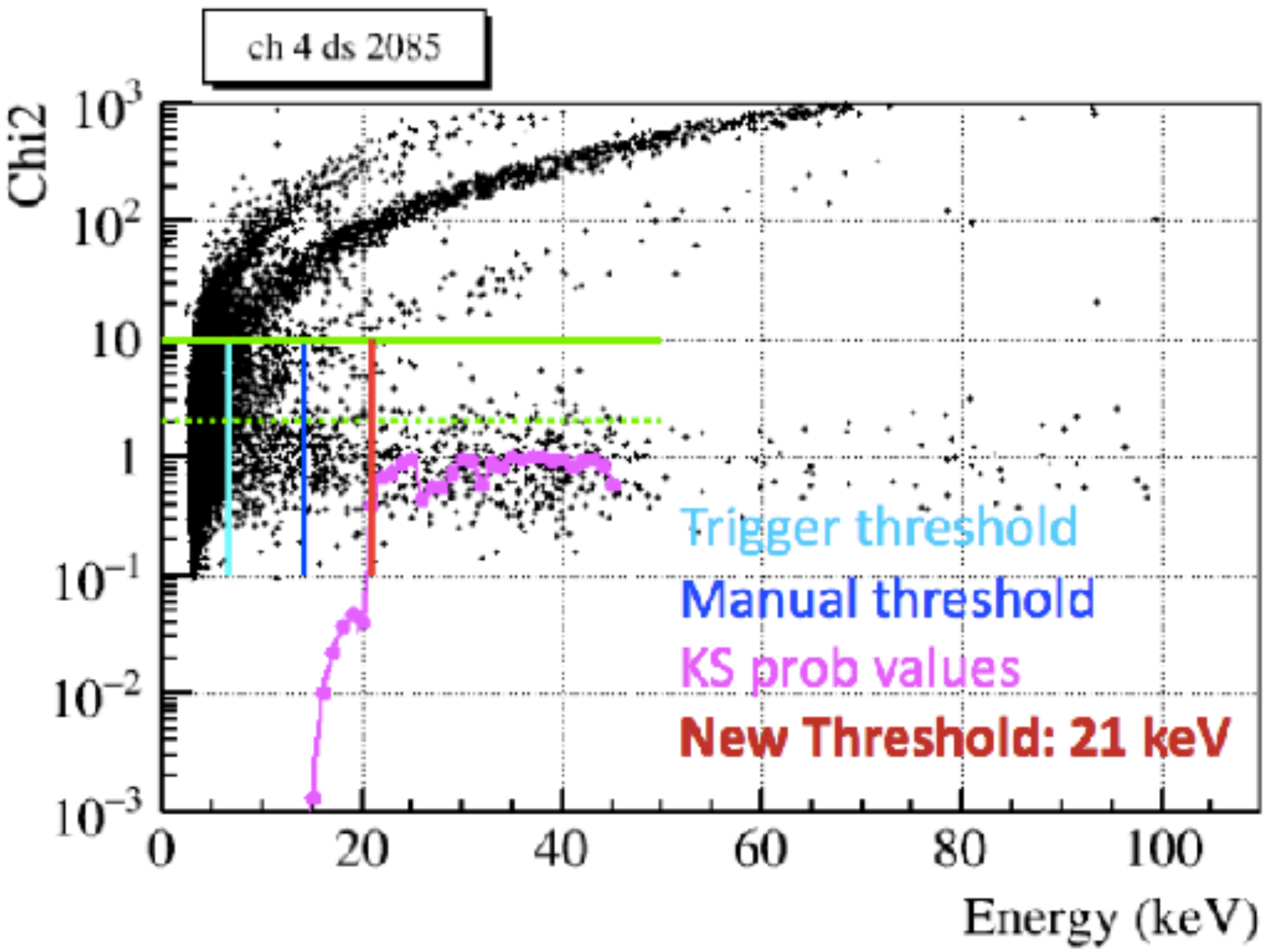
fit at [10,200 keV]: p1 0.003496

fit at [10,50 keV]: p1 0.0008481

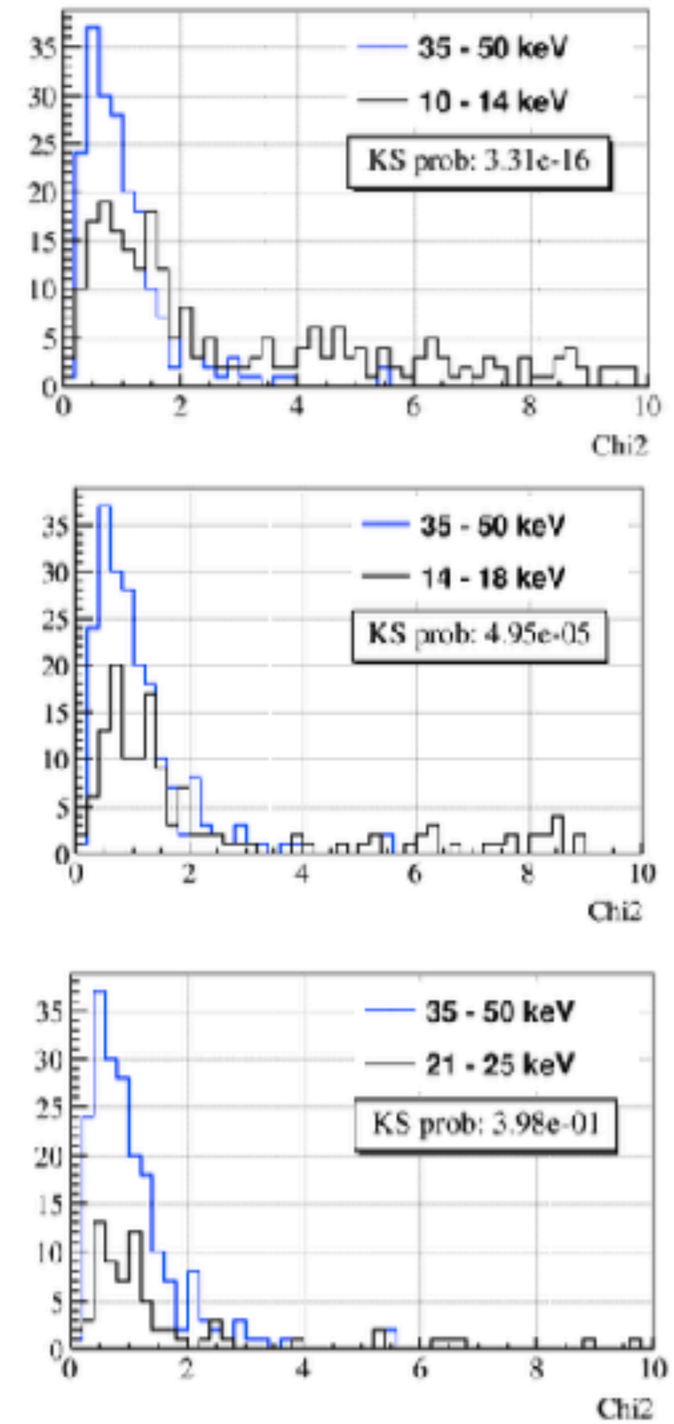
Energy Thresholds with KS Test

For every energy slice, compare the chi2 distribution with that of the events in 35-50 keV region and calculate the probability that both follow the same distribution by a Kolmogorov–Smirnov test

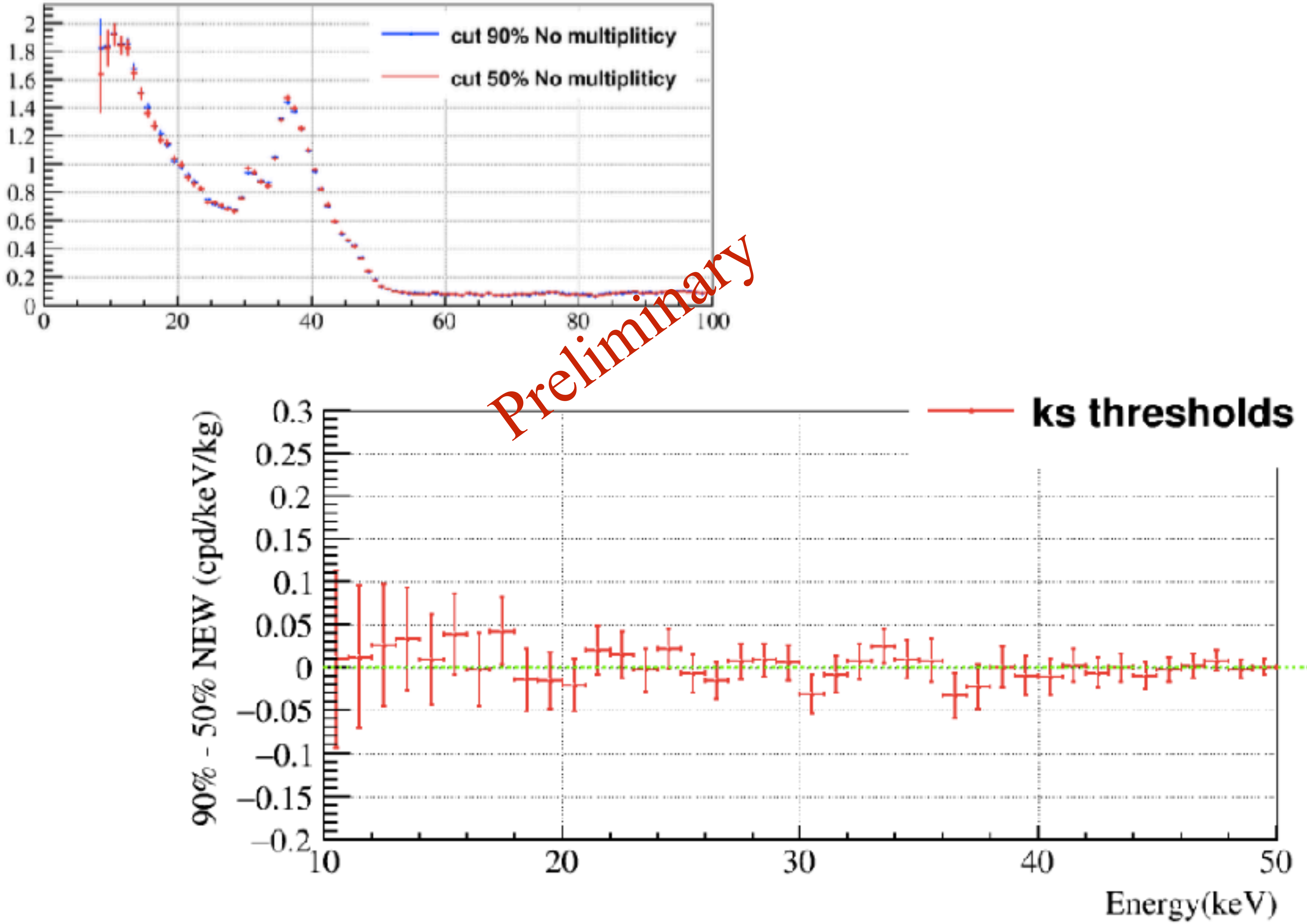
Put threshold when KS prob > 0.1



Slices energy bin: 4 keV



Residual between 90 and 50% χ^2_{OT} with KS Test



Optimum Trigger

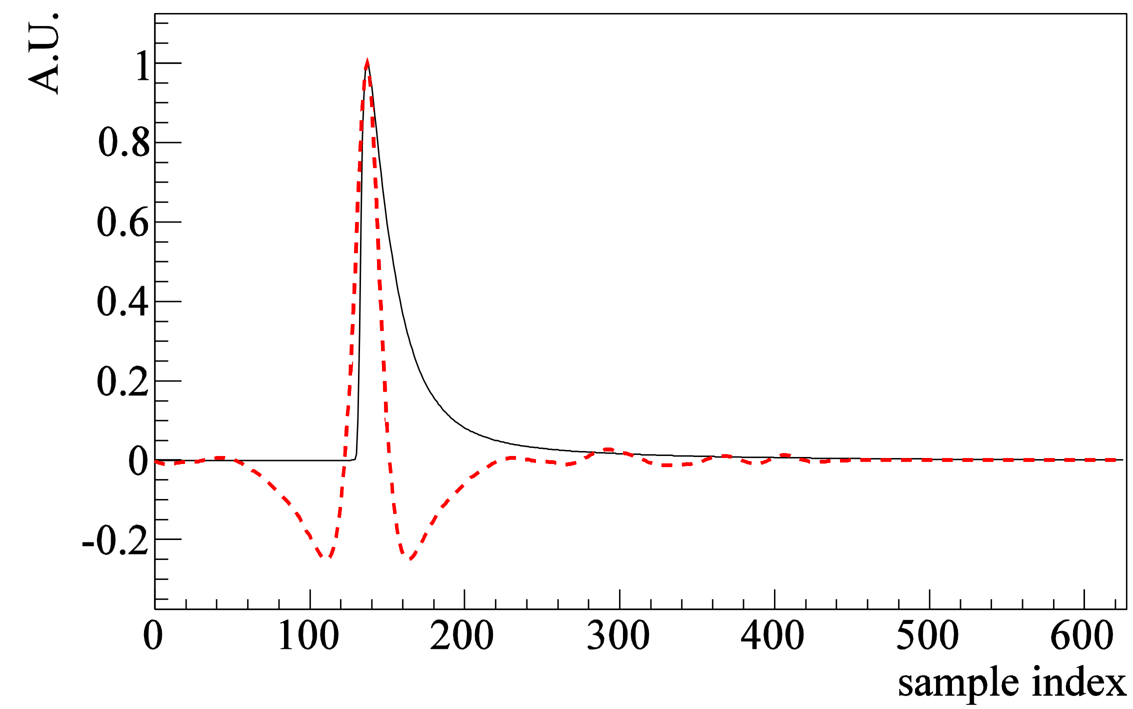
Optimum Trigger (OT) filters data buffer with a transfer function that maximizes the SNR cutting down the noise frequencies:

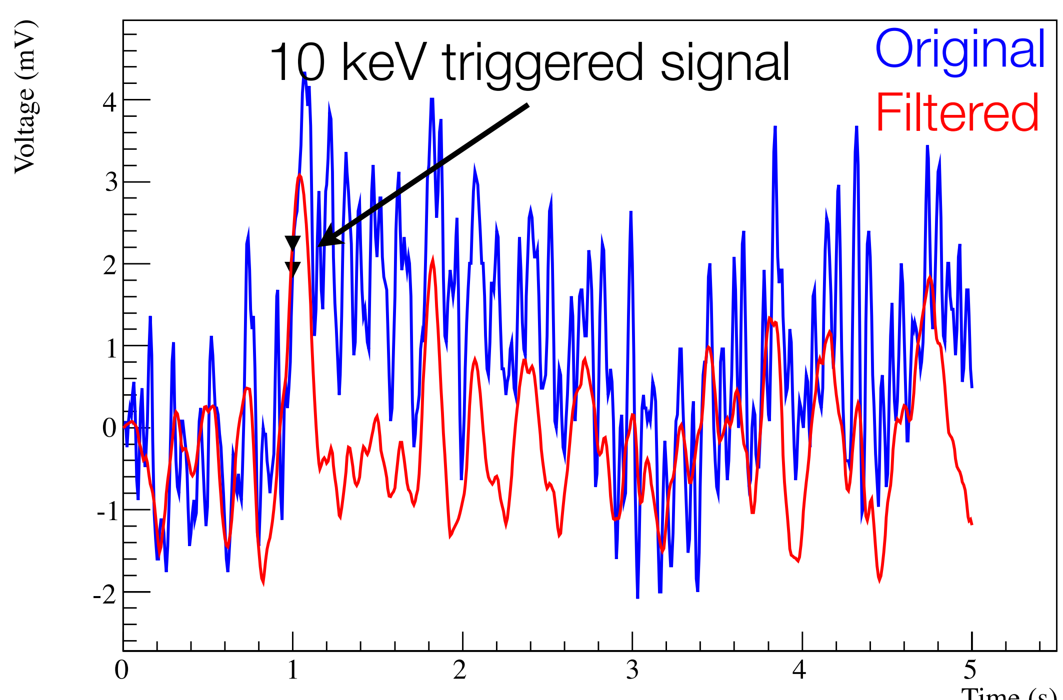
$$H(\omega) = \frac{S^*(\omega)}{N(\omega)} e^{-i\omega t_m}$$

average signal shape (from data)

noise power spectrum (from data)

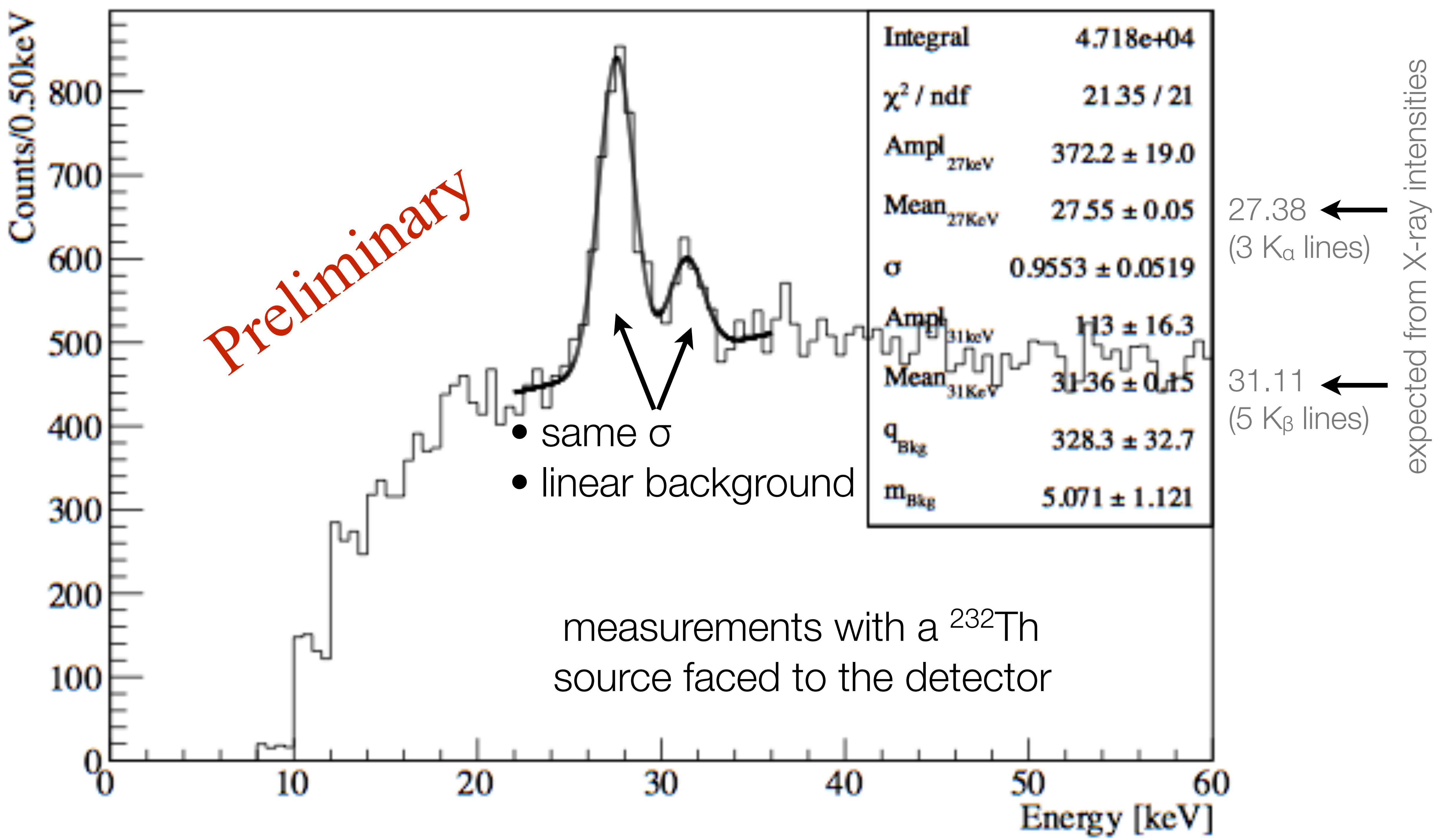
filter delay





- filtered pulses are less noisy
- lower threshold achievable with respect to the standard trigger

27 keV Peak : Calibration Data



Nuclear Quenching Factor of TeO_2

CUORE

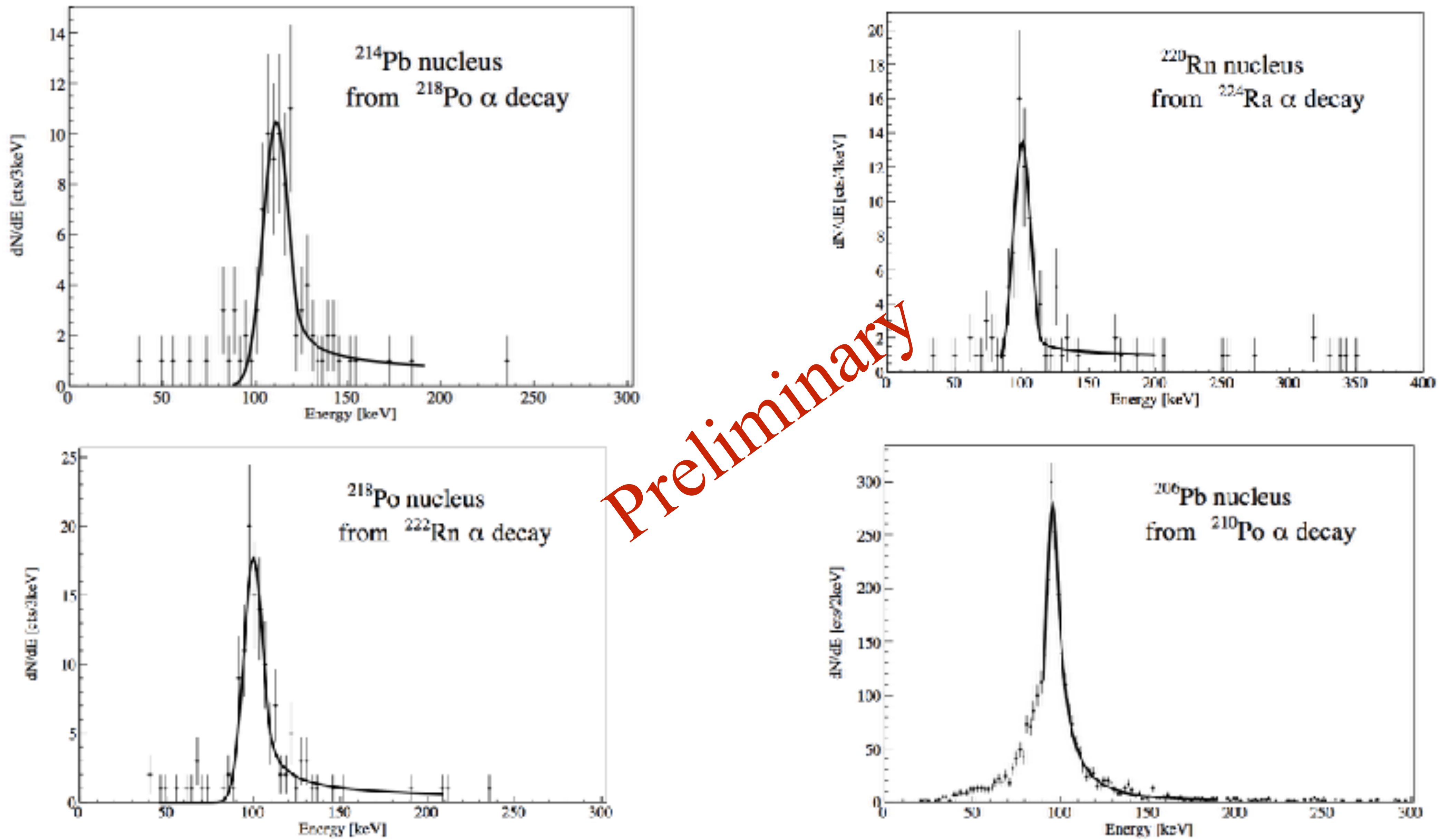
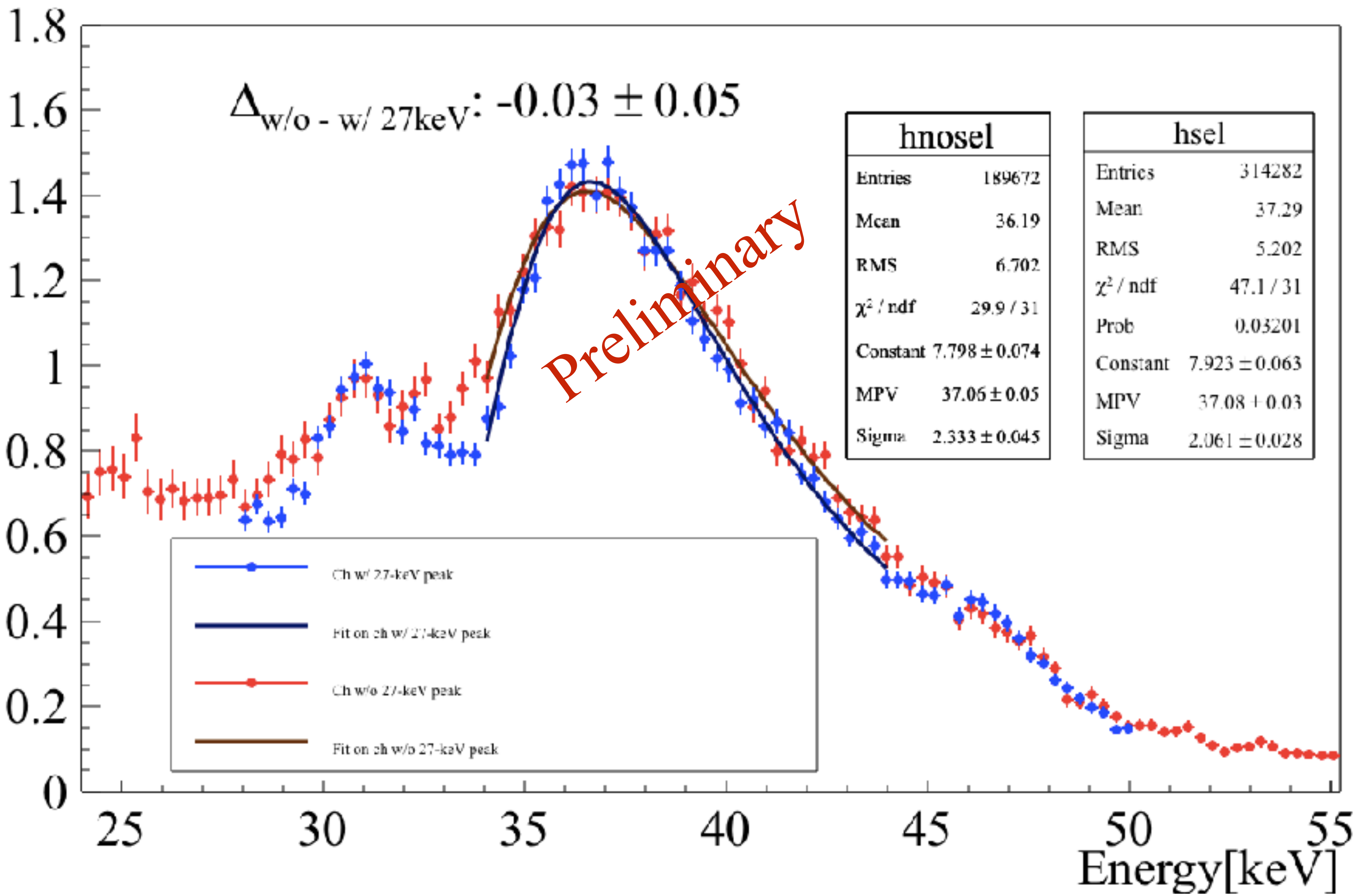


TABLE II: Obtained quenching factors for the selected nuclei

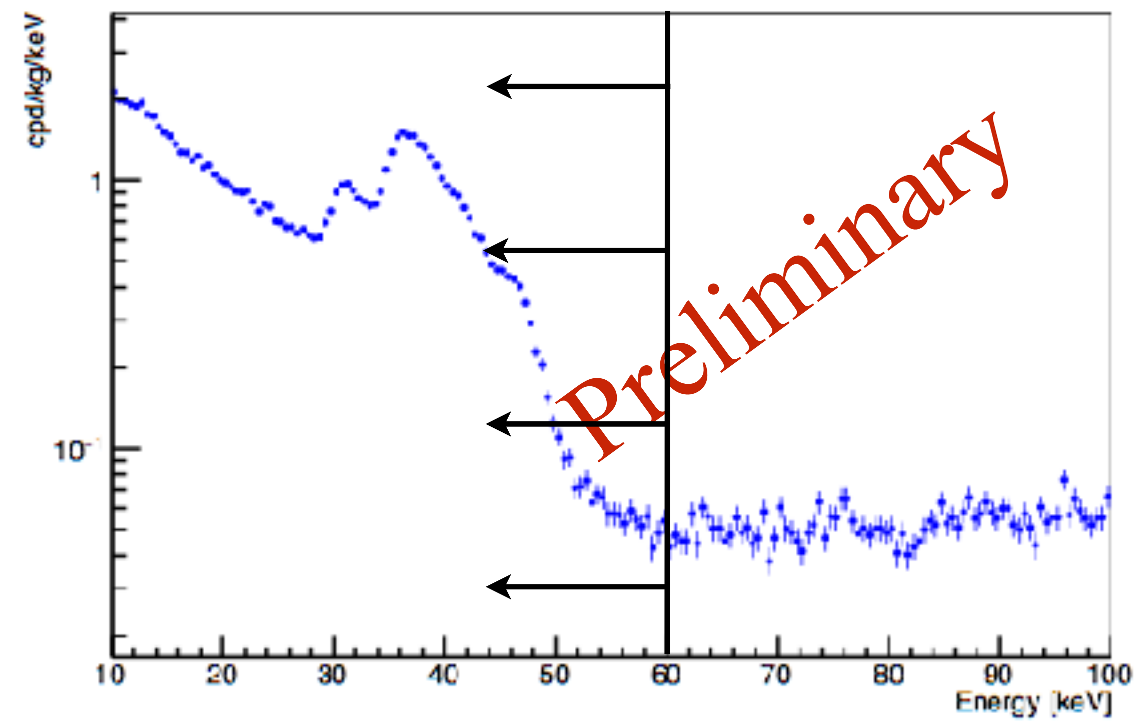
Daughter Nuclei	Fit Range	Expected Energy	Measured Energy	Quenching factor
^{206}Pb	[90,180]	103.12	95.62 ± 0.24	0.927 ± 0.002
^{218}Po	[45,210]	100.8	100.0 ± 0.9	0.992 ± 0.009
^{220}Rn	[84,200]	103.50	100.45 ± 1.21	0.971 ± 0.012
^{214}Pb	[87,192]	112.13	110.92 ± 0.96	0.989 ± 0.009

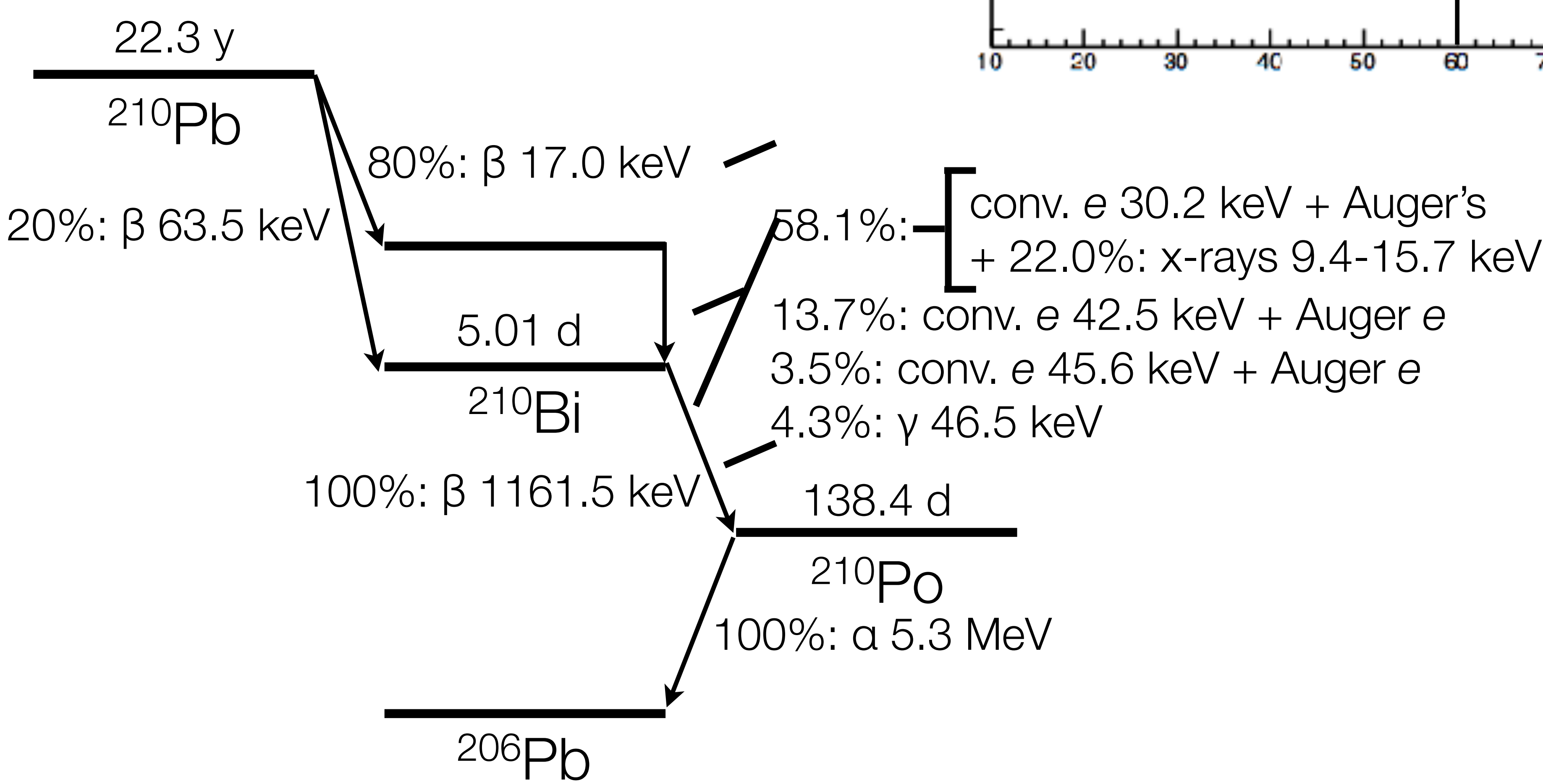
40-keV Peak Difference



Possible Origin of Peaks Below 60 keV

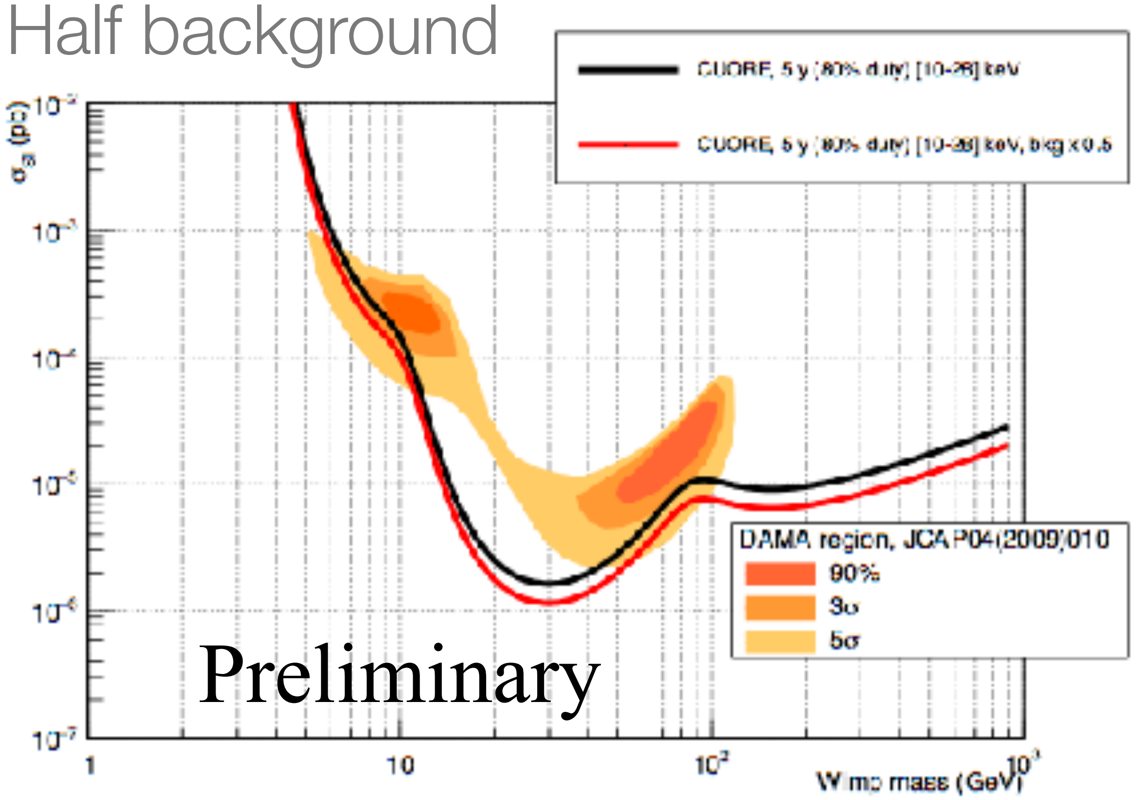
Possible explanation of the bumps and of the rise below 60 keV in the energy spectrum: inclusions of ^{210}Pb in the materials facing the crystals or in the crystals themselves



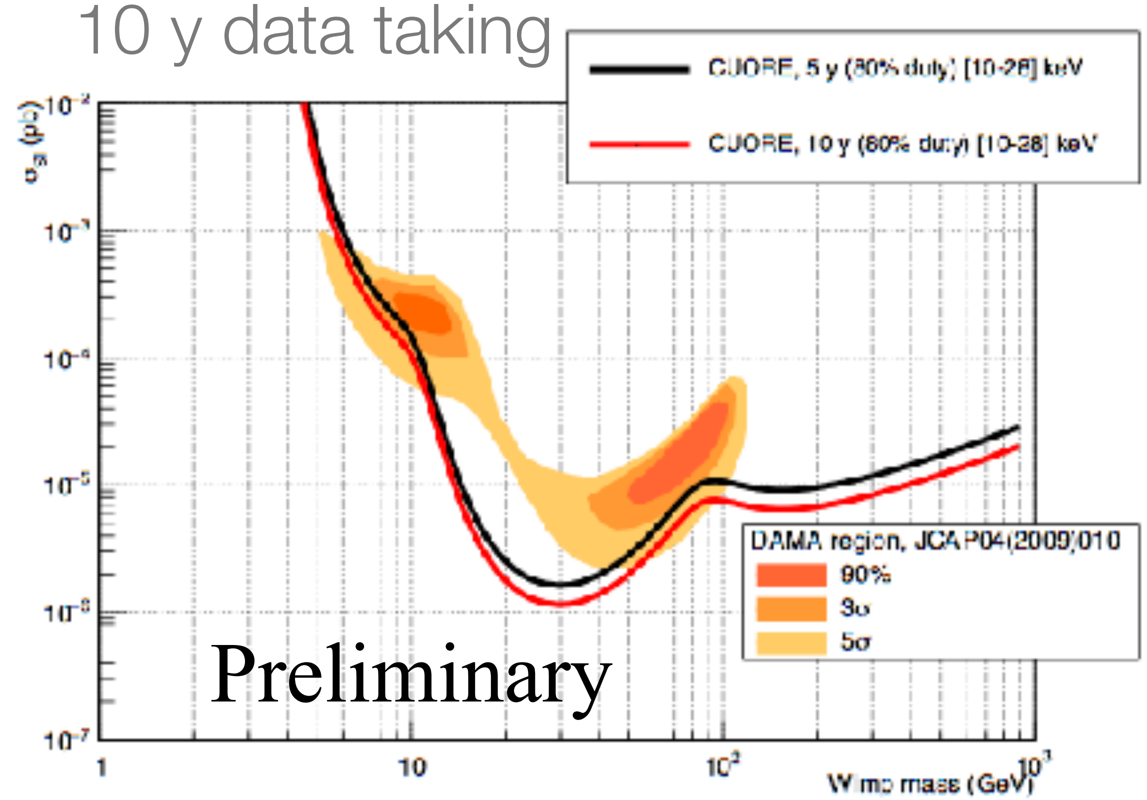


Robustness of the CUORE Sensitivity

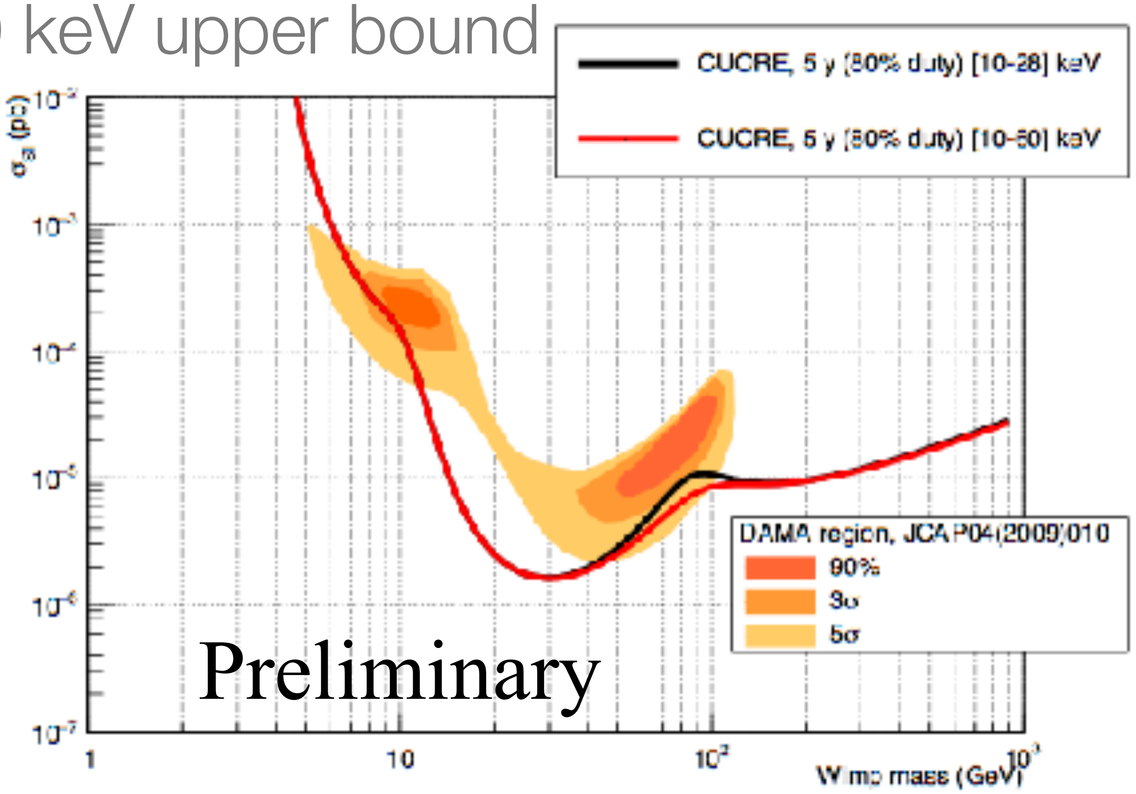
Half background



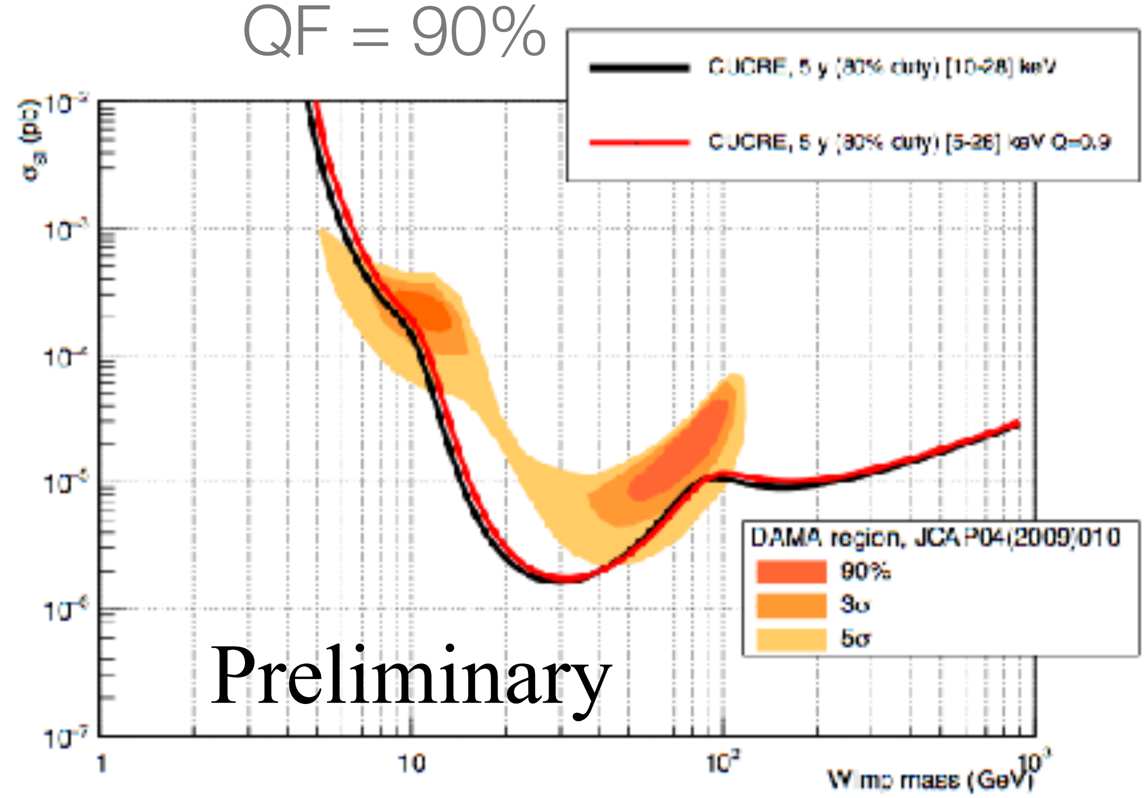
10 y data taking



60 keV upper bound



QF = 90%



X-rays from Te for Low Energy Calibration

Origin	Energy [keV]	Intensity per 100 vacancies in the K-shell [%]
$K_{\alpha 3}$	26.875	0.00202
$K_{\alpha 2}$	27.202	25.3
$K_{\alpha 1}$	27.472	47.1
$K_{\beta 3}$	30.944	4.25
$K_{\beta 1}$	30.995	8.19
$K_{\beta 5}$	31.237	0.075
$K_{\beta 2}$	31.704	2.37
$K_{\beta 4}$	31.774	0.363

Energies and intensity of K-lines originated from Te around 27 keV and 31 keV from http://nucleardata.nuclear.lu.se/toi/xray.asp?act=list&el=Te