Recent progresses on BSM and Dark Matter searches with CUORE

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*on behalf of the CUORE Collaboration

IDM 2022 - 14th International Conference on Identification of Dark Matter
18-22 July 2022 - Vienna, Austria

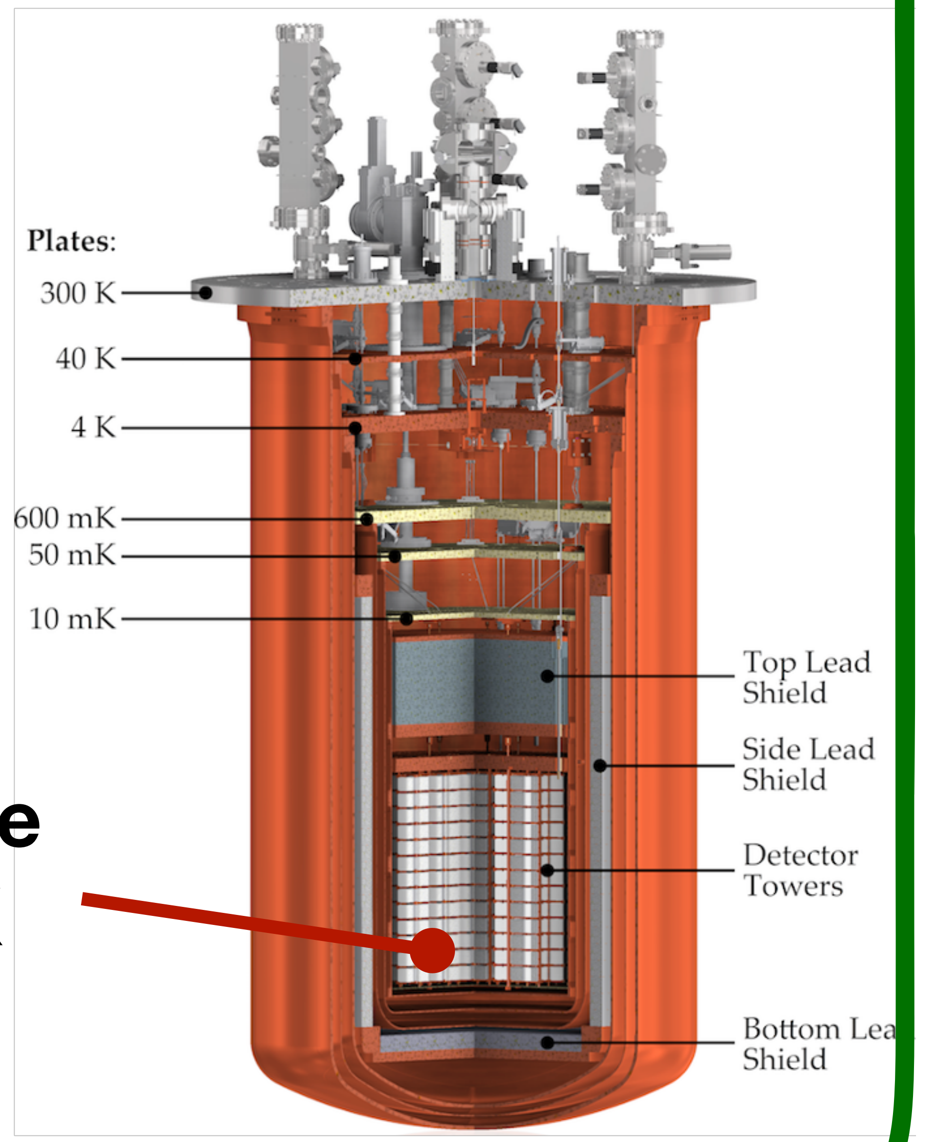
Outline

- The CUORE experiment;
- Status of data-taking and detector stability;
- Tools for BSM and DM physics in CUORE;
- BSM and DM analyses;
- Conclusions

The CUORE experiment

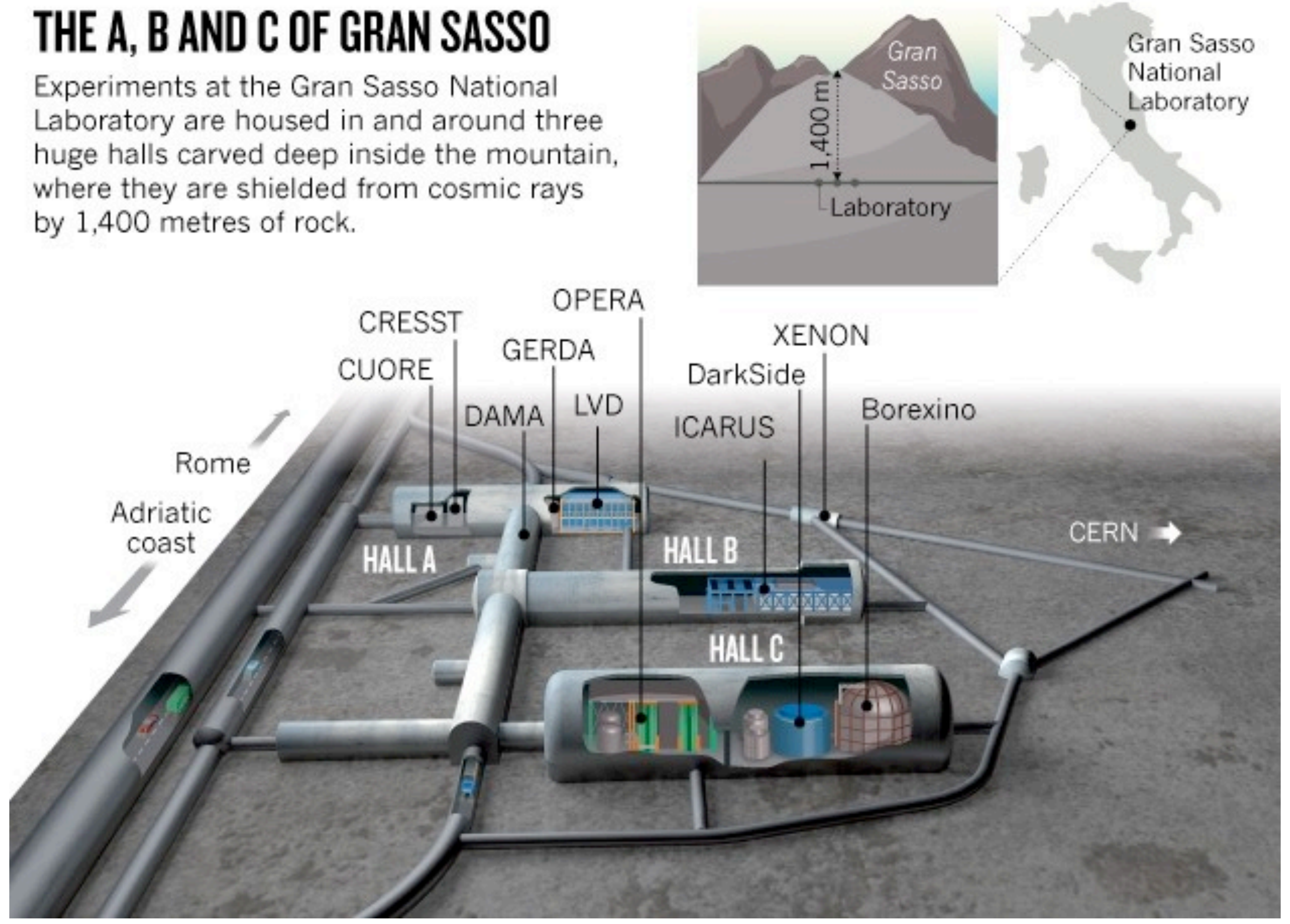
CUORE: Cryogenic Underground Observatory for Rare Events

First cryogenic detector exploiting bolometric technique @ tonne-scale

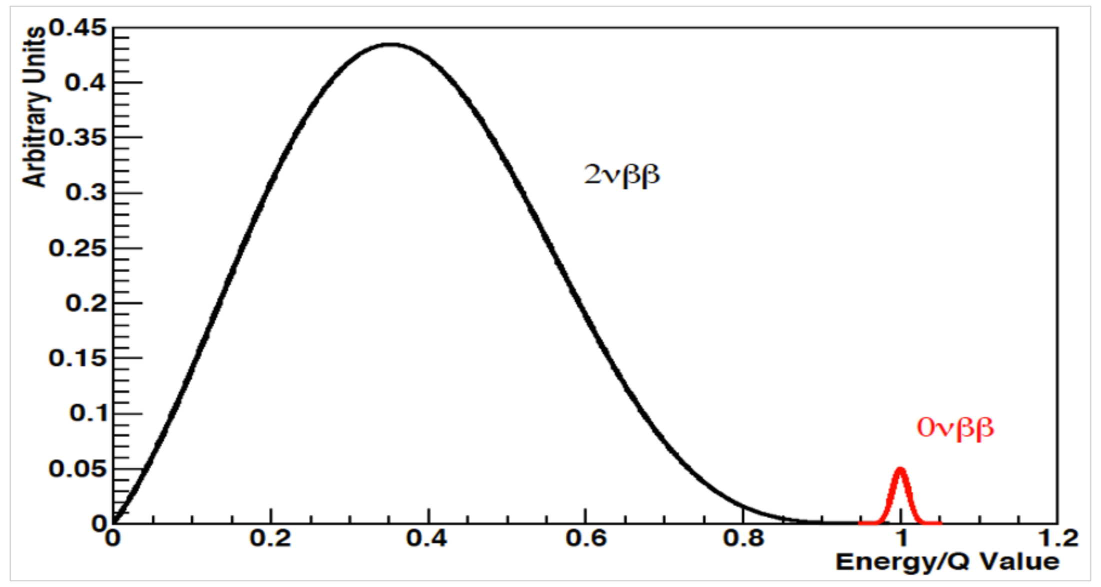


Detector core T @ ~10 mK

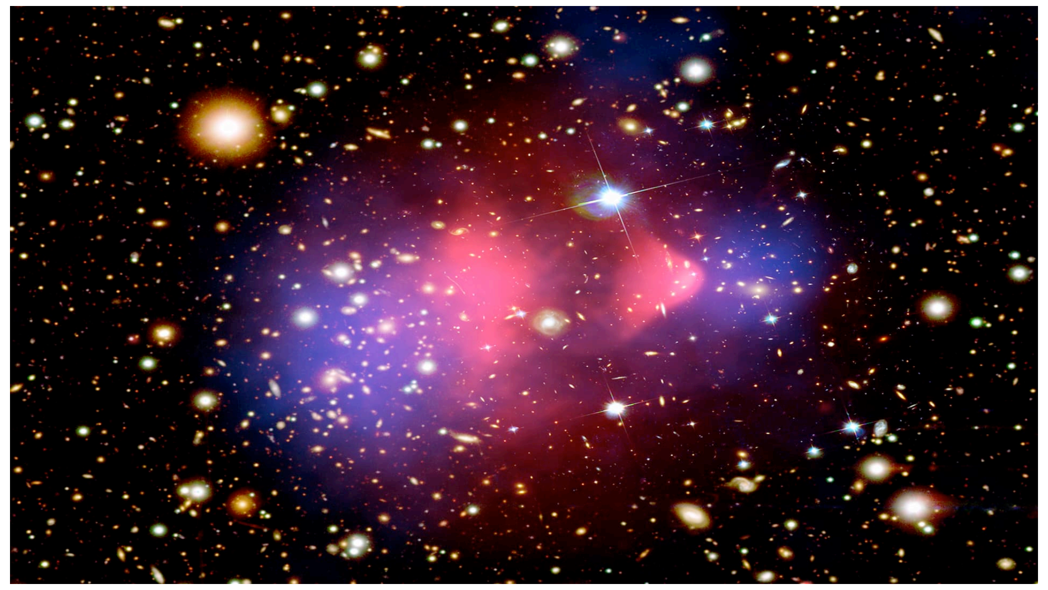
Running in Hall A, ~3600 m.w.e. @ LNGS



Built with primary goal to test lepton number violation through 0nuDBD

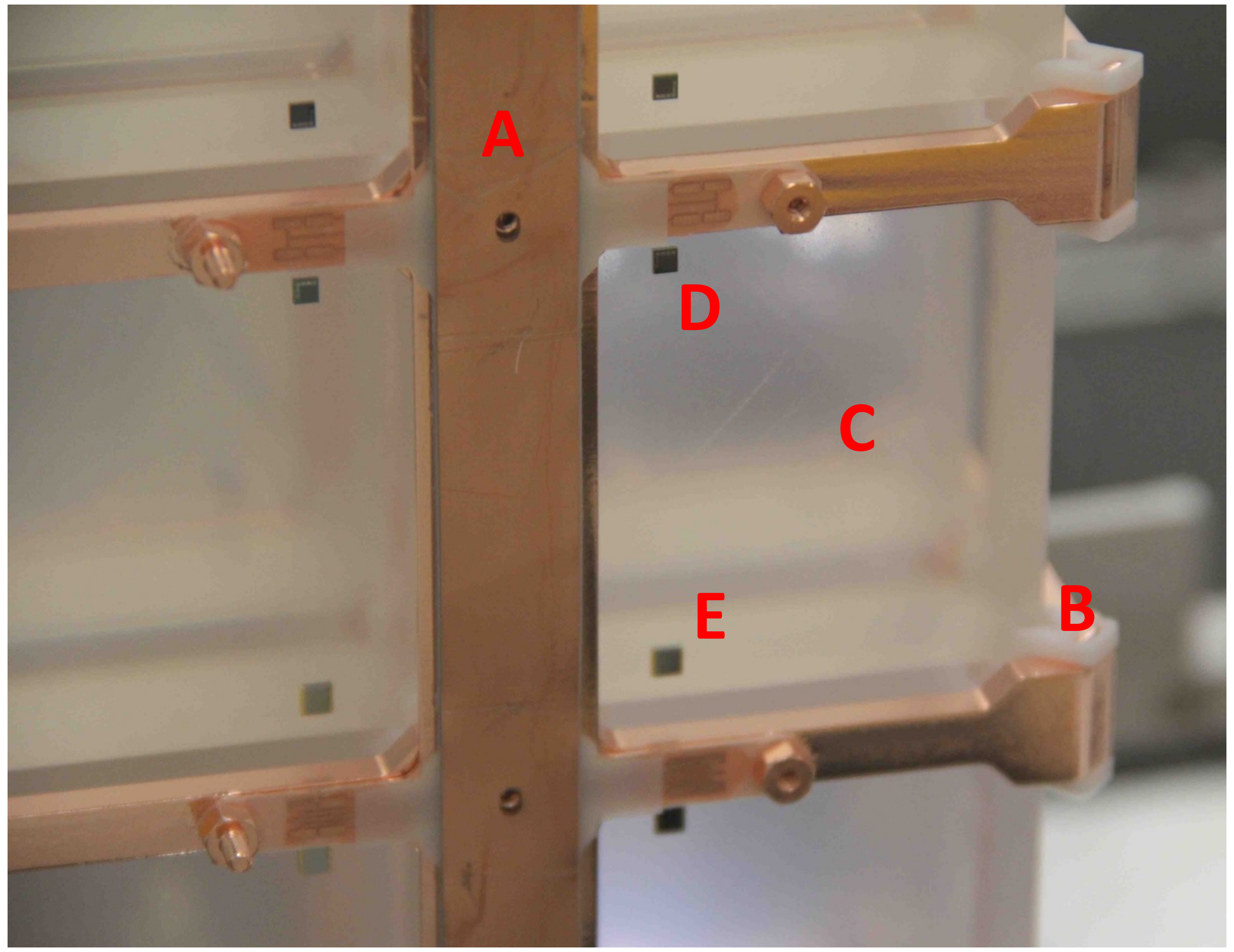


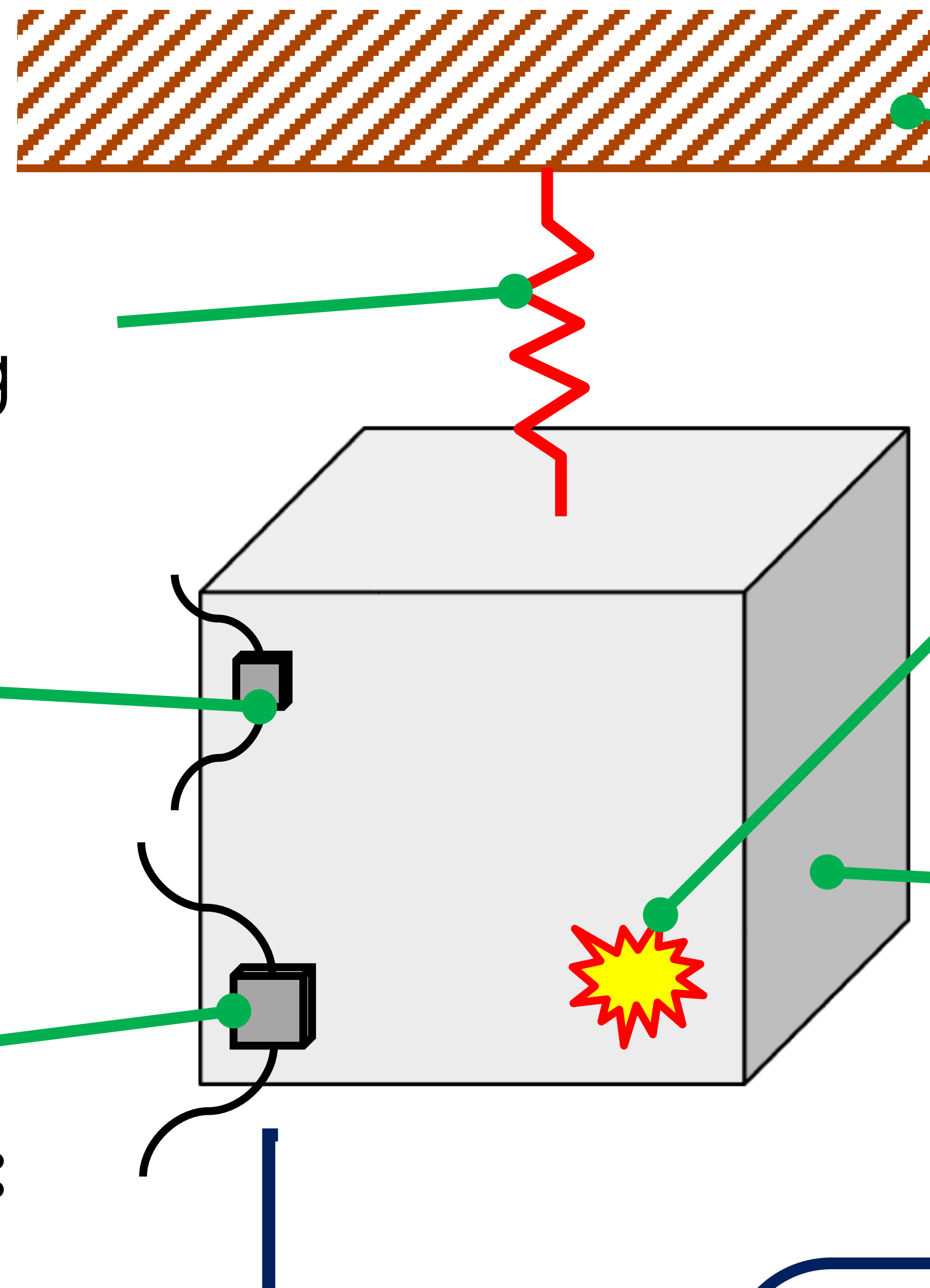
But also a powerful tool to go beyond…



- Dark Matter
- CPT violation
- …

Bolometric detectors in CUORE





(A) Copper frame:
10 mK heat sink

(B) PTFE holders:
weak thermal coupling

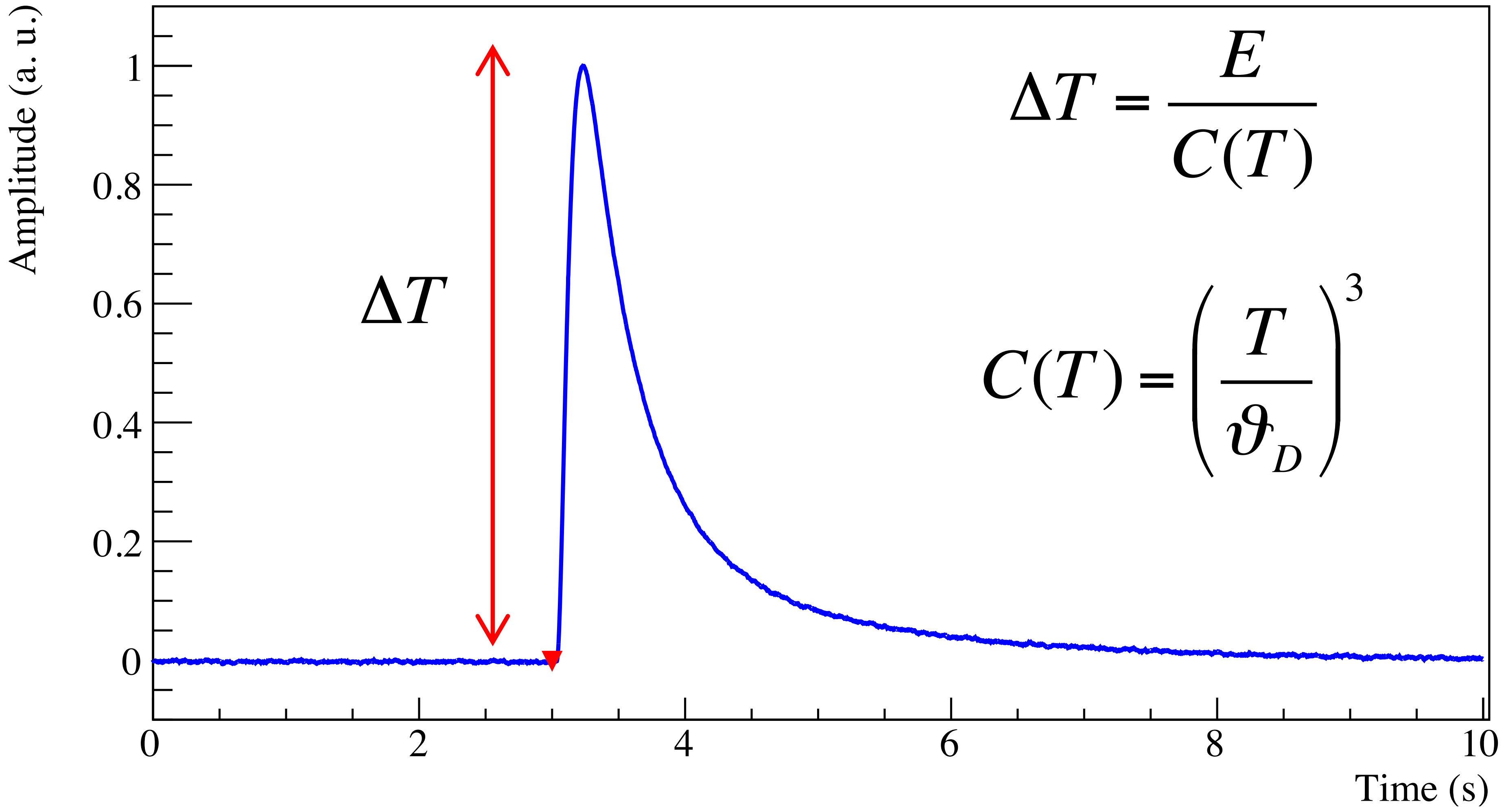
Radiation:
energy deposit

(D) Si joule heater:
reference pulses

(C) TeO_2 crystal:
energy absorber

(E) NTD Ge thermistor:
resistive thermometer

Readout

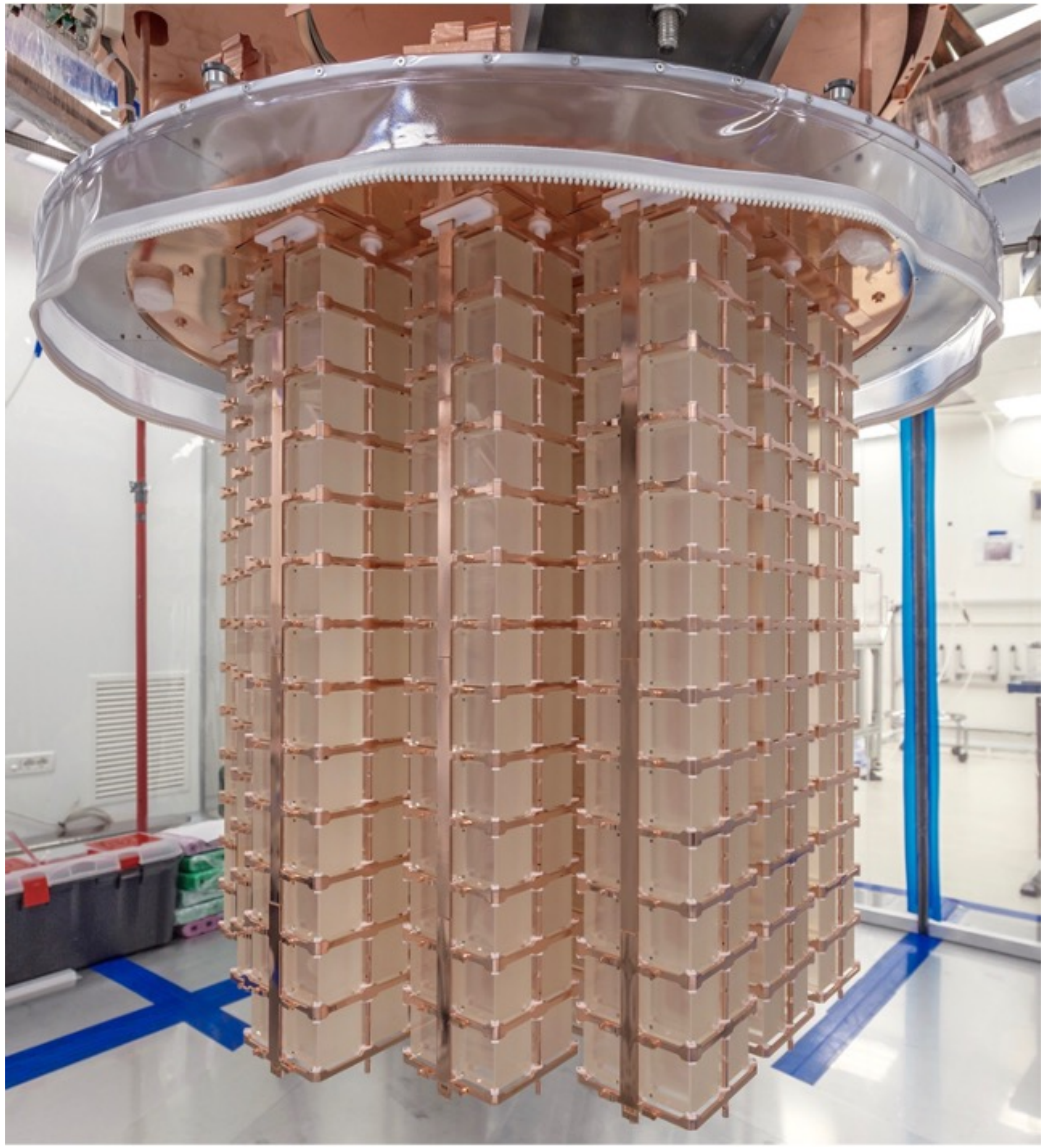


Low temperature needed: $@T = 10\ mK$

$$C \sim 10^{-9}\frac{J}{K};\quad \Delta T = 0.1\frac{mK}{MeV};\quad \tau \sim 1s$$

- high efficiency;
- excellent energy resolution;
- large masses achievable;
- ^{130}Te high natural isotopic abundance;
- ^{130}Te Q-value 2528 keV;

Detector core



Design specifics:

- Detector arrangement: 19 towers with 13 floors of 4 crystals each;
- 988 crystals, 5 cm^3, 750 g each;
- Total TeO_2 mass of 742 kg: 206 kg of ^{130}Te / 189 kg of ^{128}Te / 0.5 kg of ^{120}Te
- Minimisation of material/surface facing crystals;
- Closely packed detectors array with high granularity

Reduction & tagging
of radioactive backgrounds

Breakthrough technology for rare events searches

Cryogenic system: a challenging task -> cool down and keep at stable temperature ~15 tons @ T < 4 K / ~1.5 tons @ 10 mK

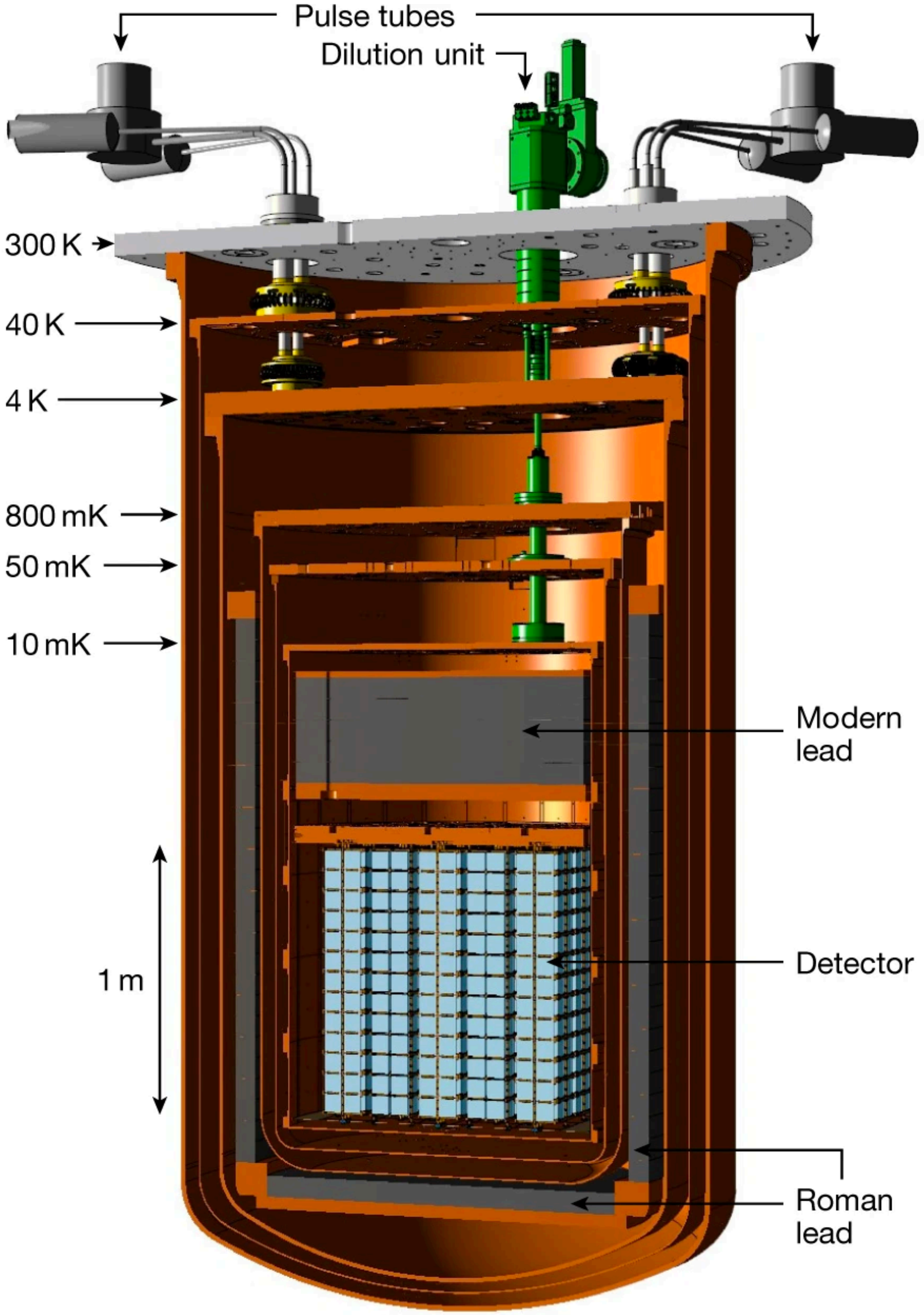
- multistage cryogen free (dry) cryostat -> high duty cycle:
  - 5 Pulse Tube cryocoolers (T ~ 4 K) and a (custom) Dilution Unit (T ~ 10 mK)

Mechanical decoupling: isolate mechanically from outside environment to mitigate energy dissipation from vibrations

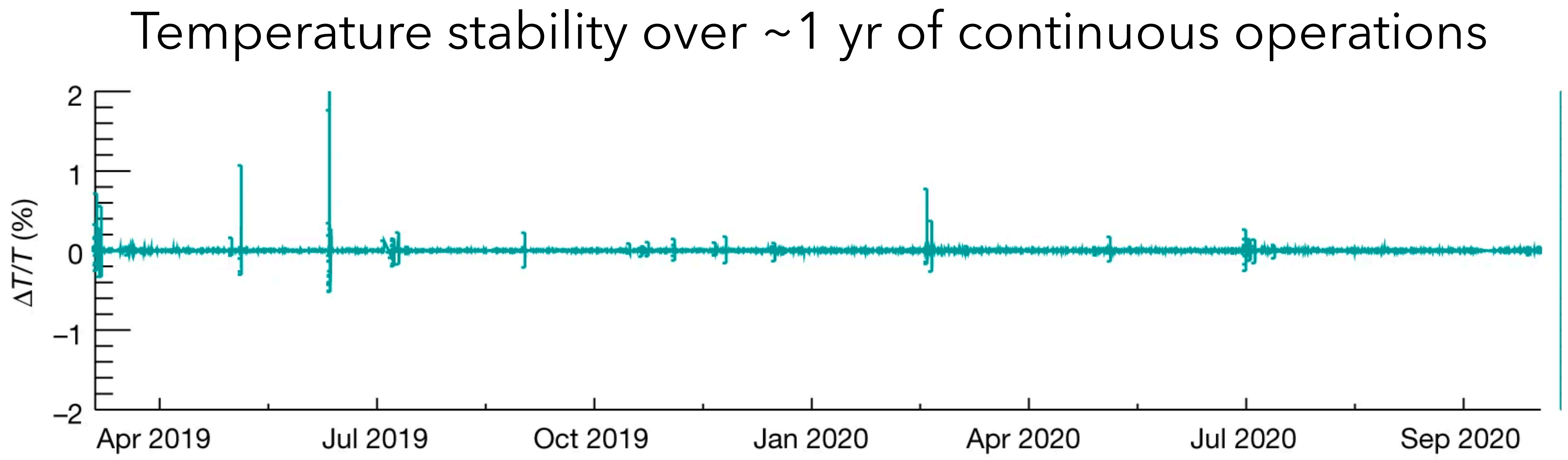
- detector suspension independent w.r.t. cryogenic/calibration system. Elastometers at the base of structure holding CUORE;

Reduction of radioactive background:

- from detector: material screening and accurate selection -> ensure radio purity (mainly pure copper) / cleaning of copper surface facing crystals / Roman and modern Pb shields / strict protocol for crystal growing;
- from outside: deep underground @ LNGS, outer neutron shield (polyethylene + boric acid) / other gamma shield (Pb);

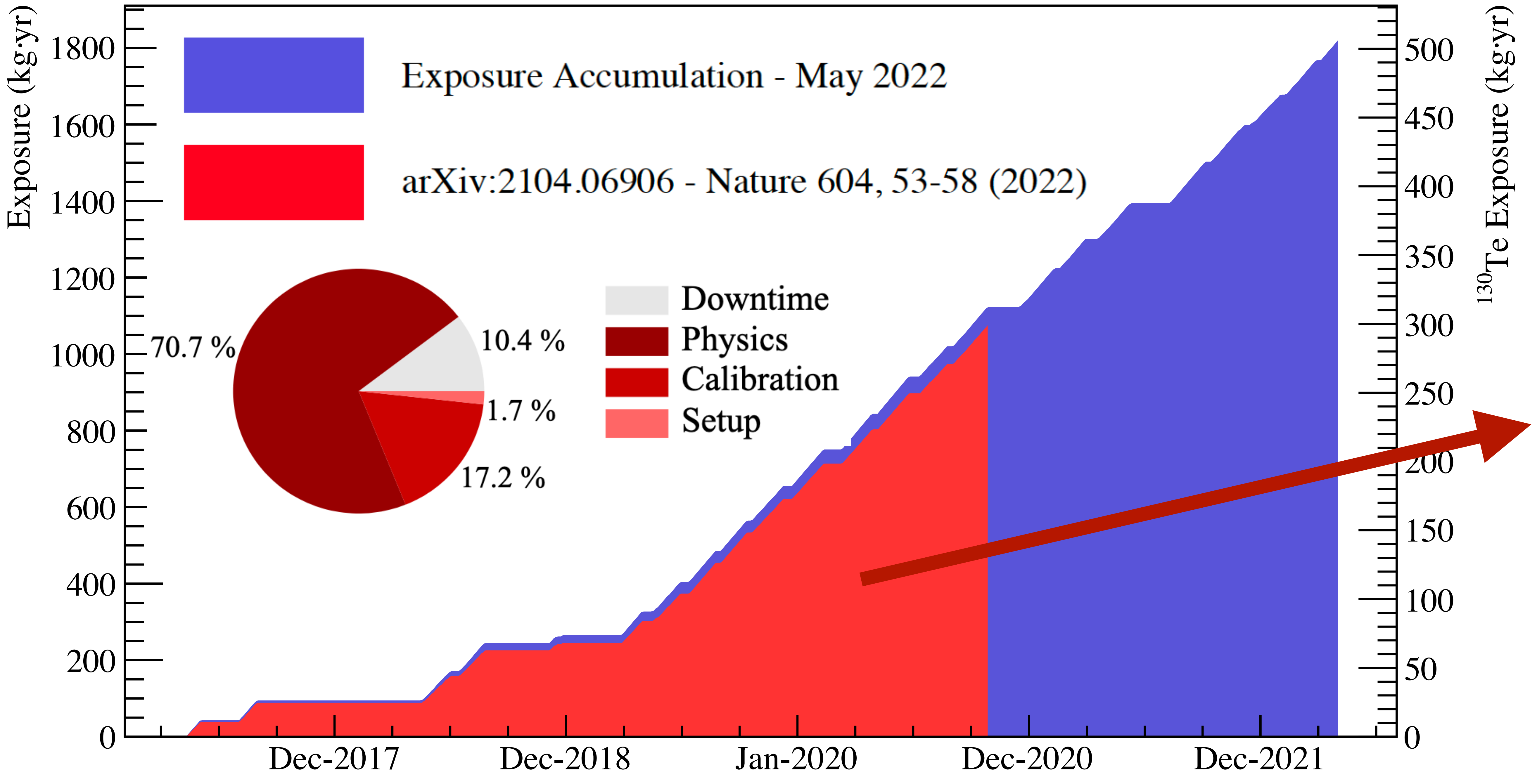


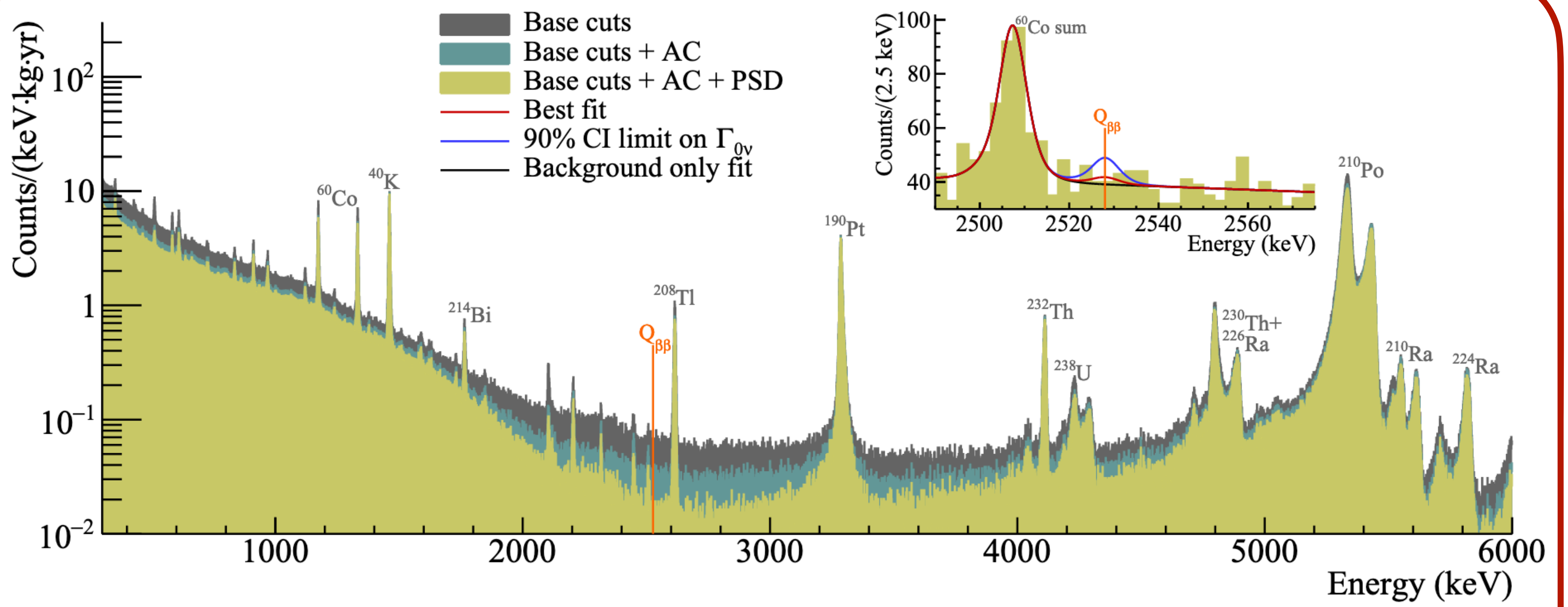
A reliable and stable detector!



- Started data-taking in Spring 2017: commissioning / optimisations / operations;
- Continuous data-taking since early 2019;
- Total uptime ~90% and more than 1.8 tonne yr exposure collected;
- Most sensitive ^{130}Te 0nuDBD decay measurement w/ 1 tonne yr exposure

C. Alduino et al. Nature **604**, 53-58 (2022)





$$T^{0\nu}_{1/2} > 2.2 \times 10^{25}\ yr \implies m_{\beta\beta} < 90 - 305\ meV\ (90\,\%\ C.I.)$$

With: bkg index @ ROI ~ $\sim 1.49(4) \times 10^{-2}\ ckky$ and energy resolution $7.8 \pm 0.5\ keV$ FWHM @ $Q_{\beta\beta}$

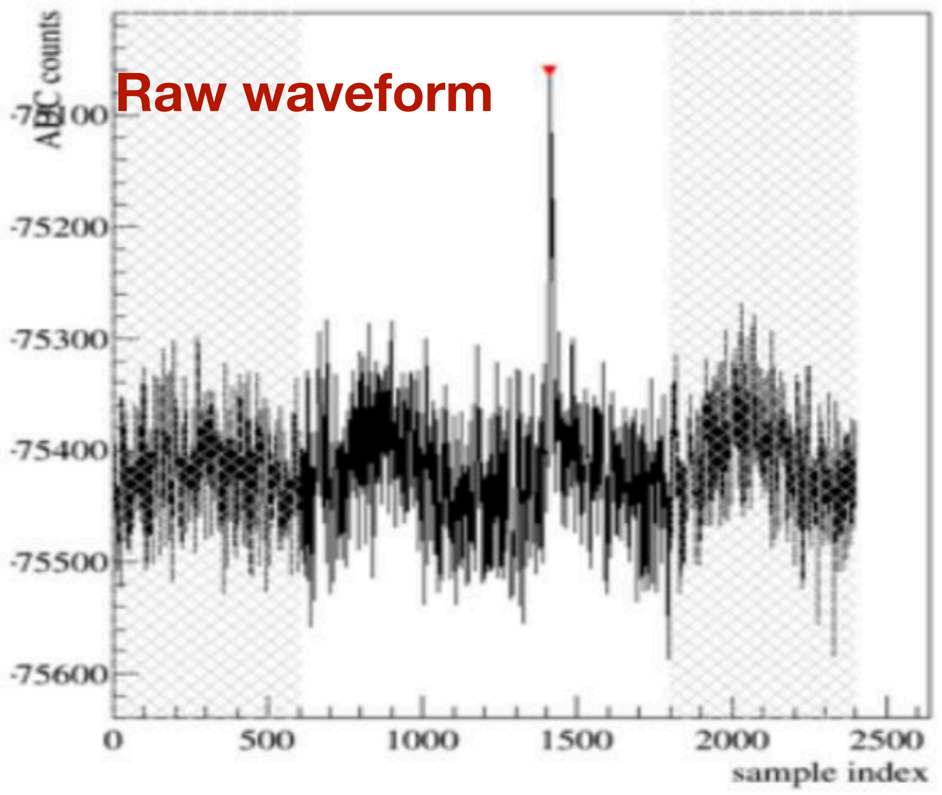
Ready for BSM: tools I

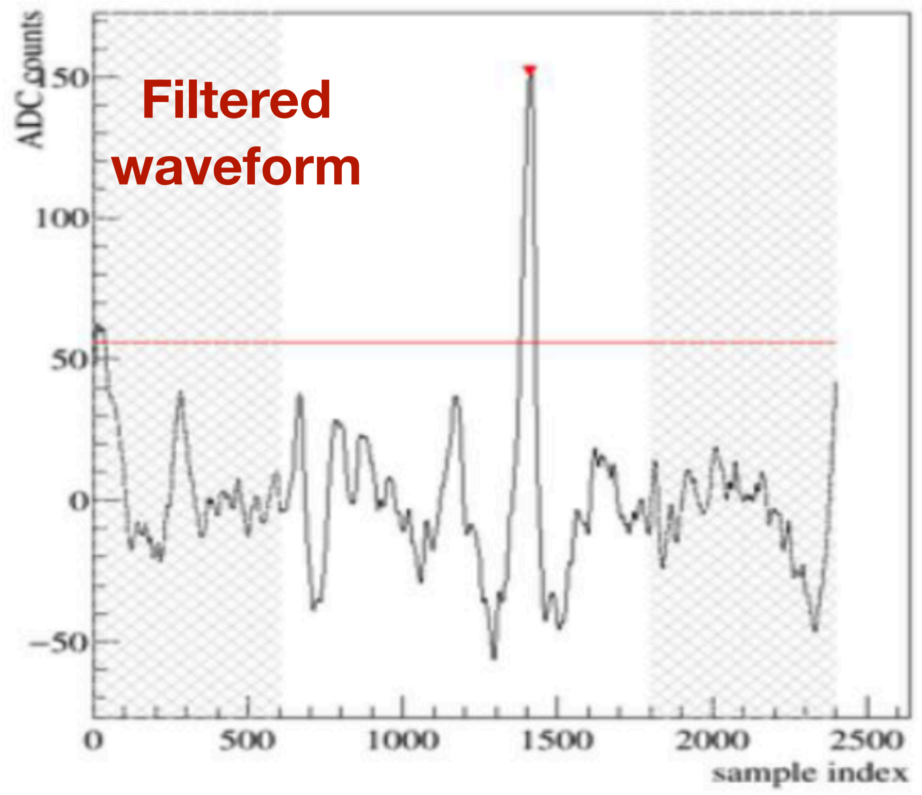
Identifying pulses (trigger):

CUORE @ TAUP19

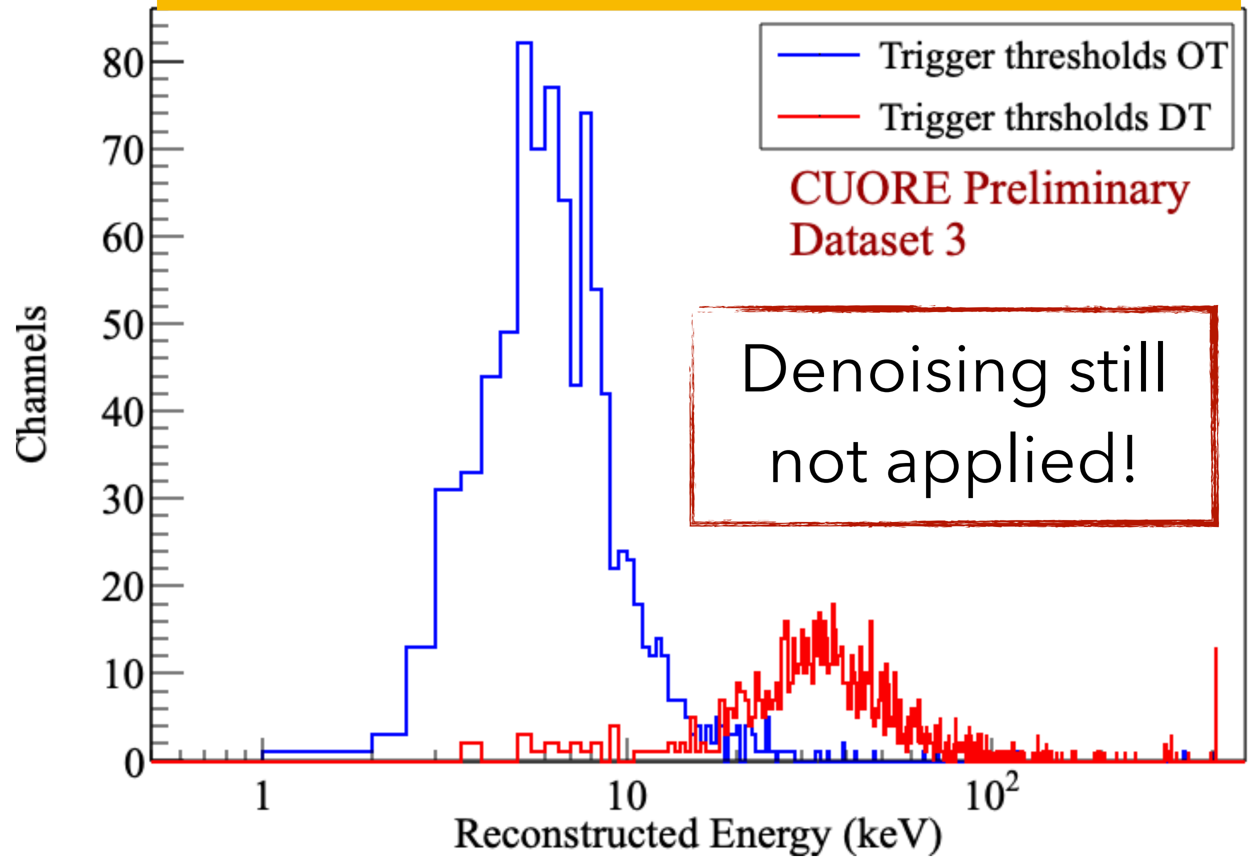
- Online: Derivative Trigger, DT, (threshold on the derivative of data-stream) -> used for on-the-fly data quality monitoring;
- Offline: optimal trigger, OT, (threshold on the OF filtered data-stream) -> used for all analyses;

Signal seen by OT and not by DT





DT vs OT thresholds



Thresholds @ 90% efficiency: $E_{DT} \sim 40\ keV$ / $E_{OT} \sim 4 - 5\ keV$

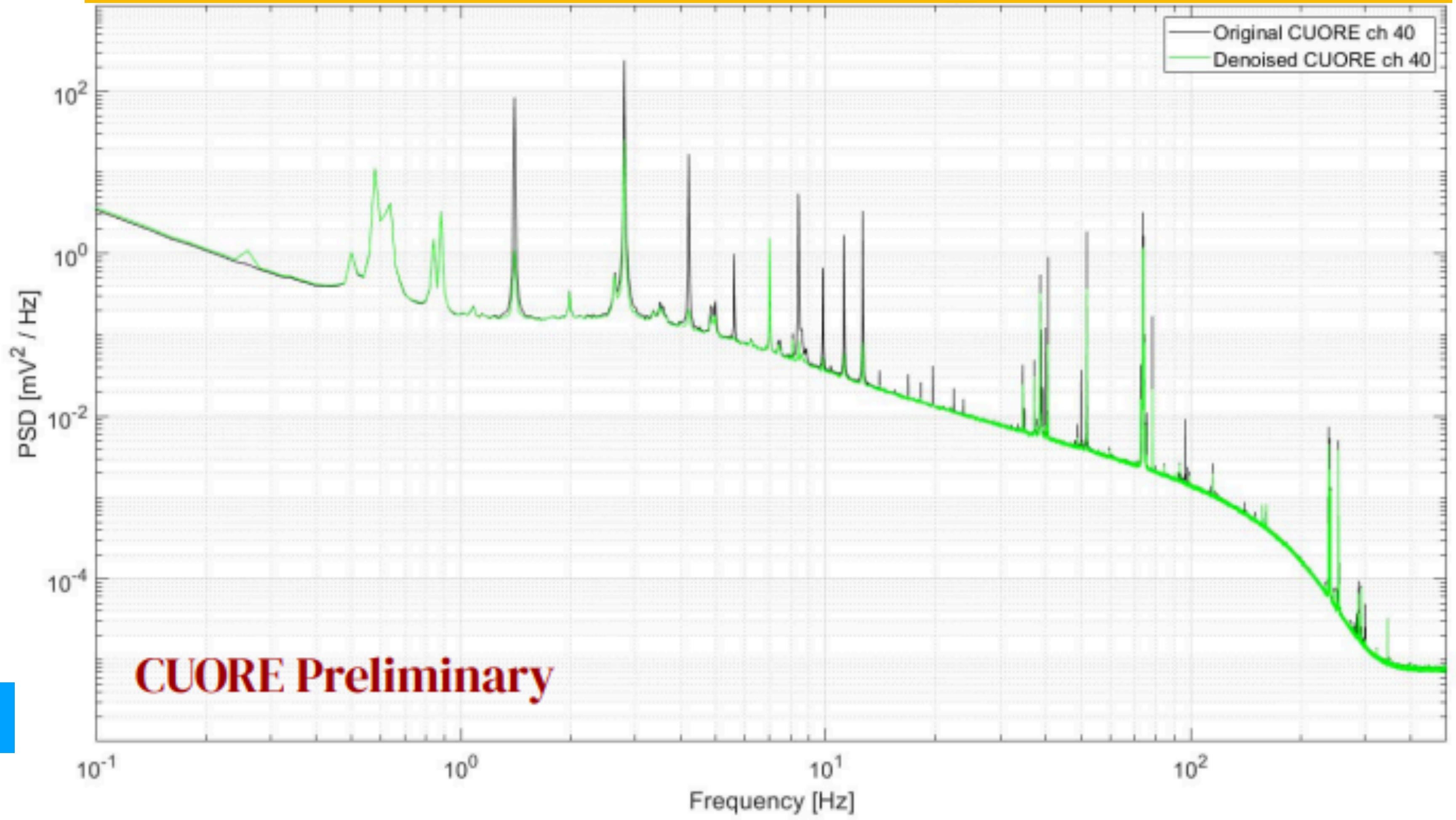
OT helps to reduce thresholds and multisite bkg events

Denoising continuous data:

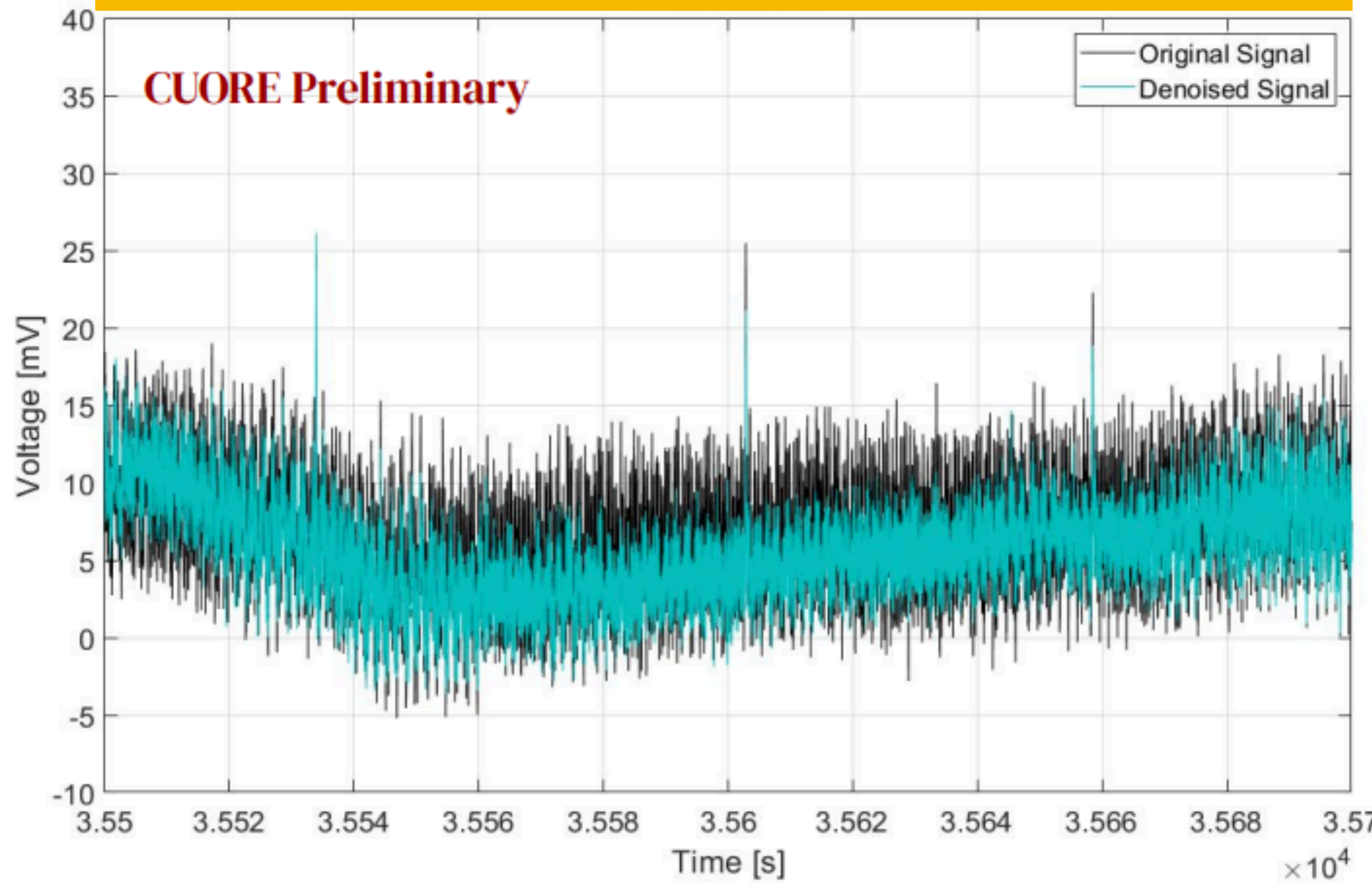
- Remove noise from each bolometric channel;
- Exploit accelerometers, antennae and microphones in order to identify and measure the source of noise;

CUORE denoising @ DNP 2021

Noise Power Spectrum: Raw-Data / Denoised



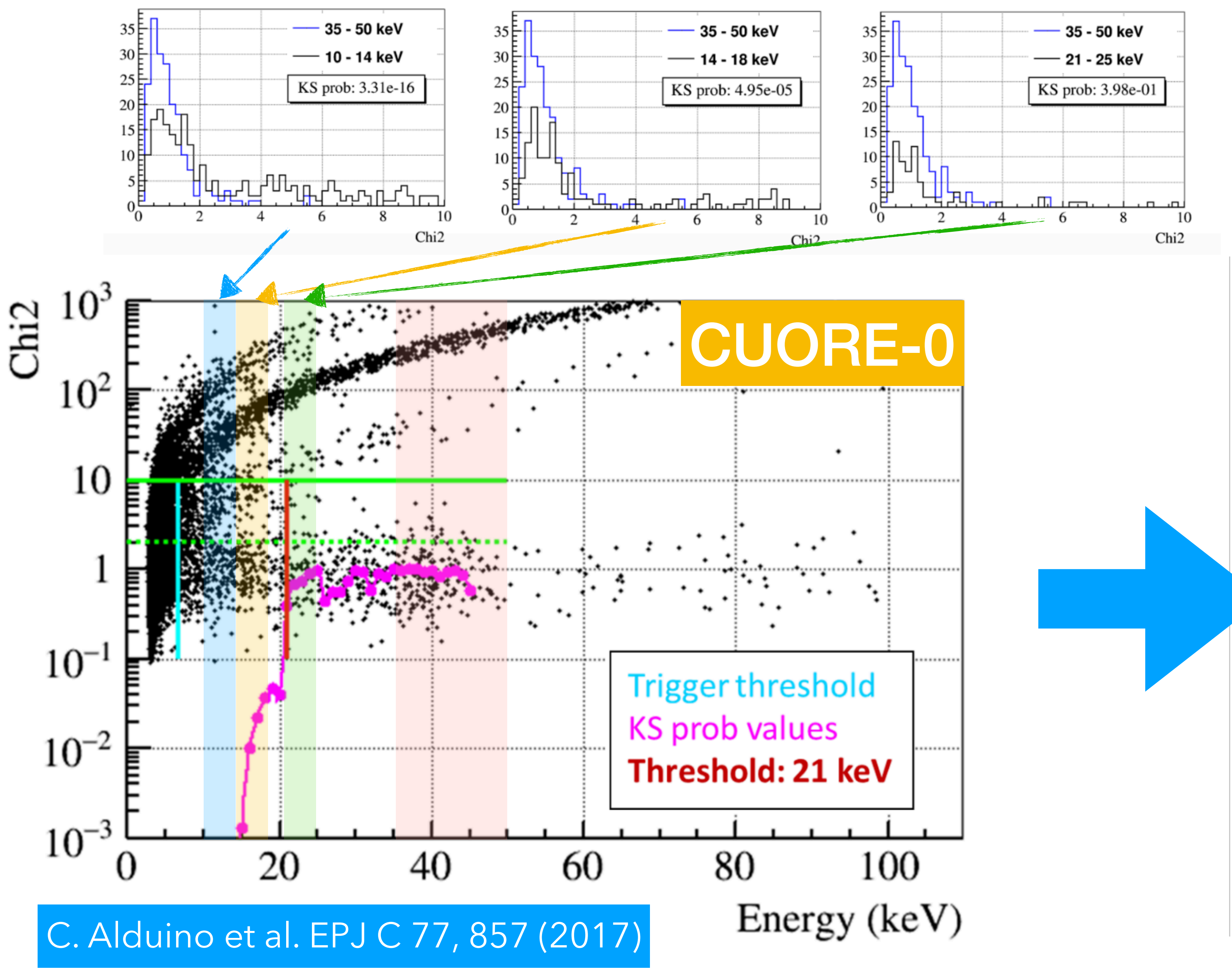
Data-stream: Raw-Data / Denoised



Ready for BSM: tools II

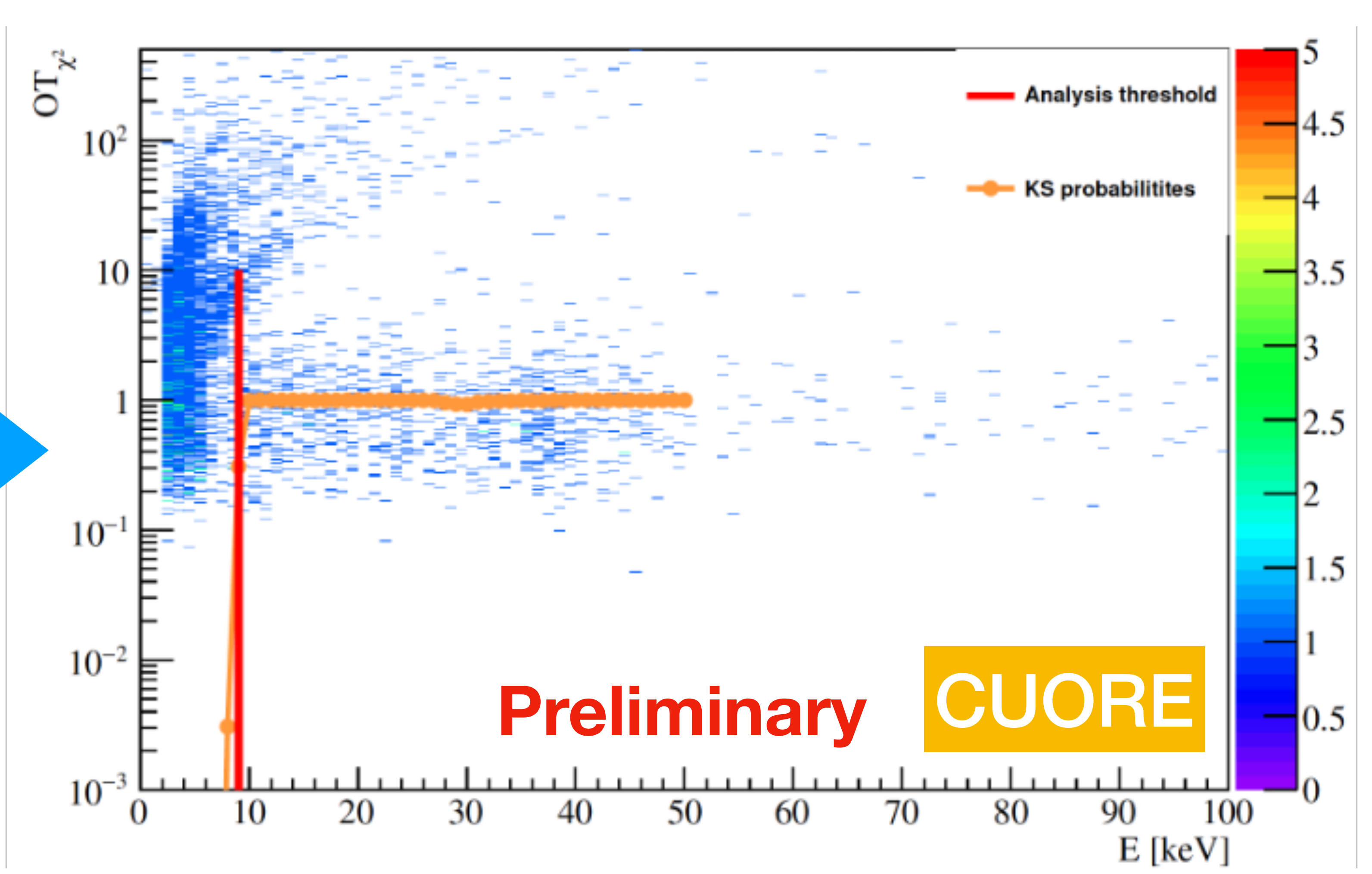
Building the low energy spectrum:

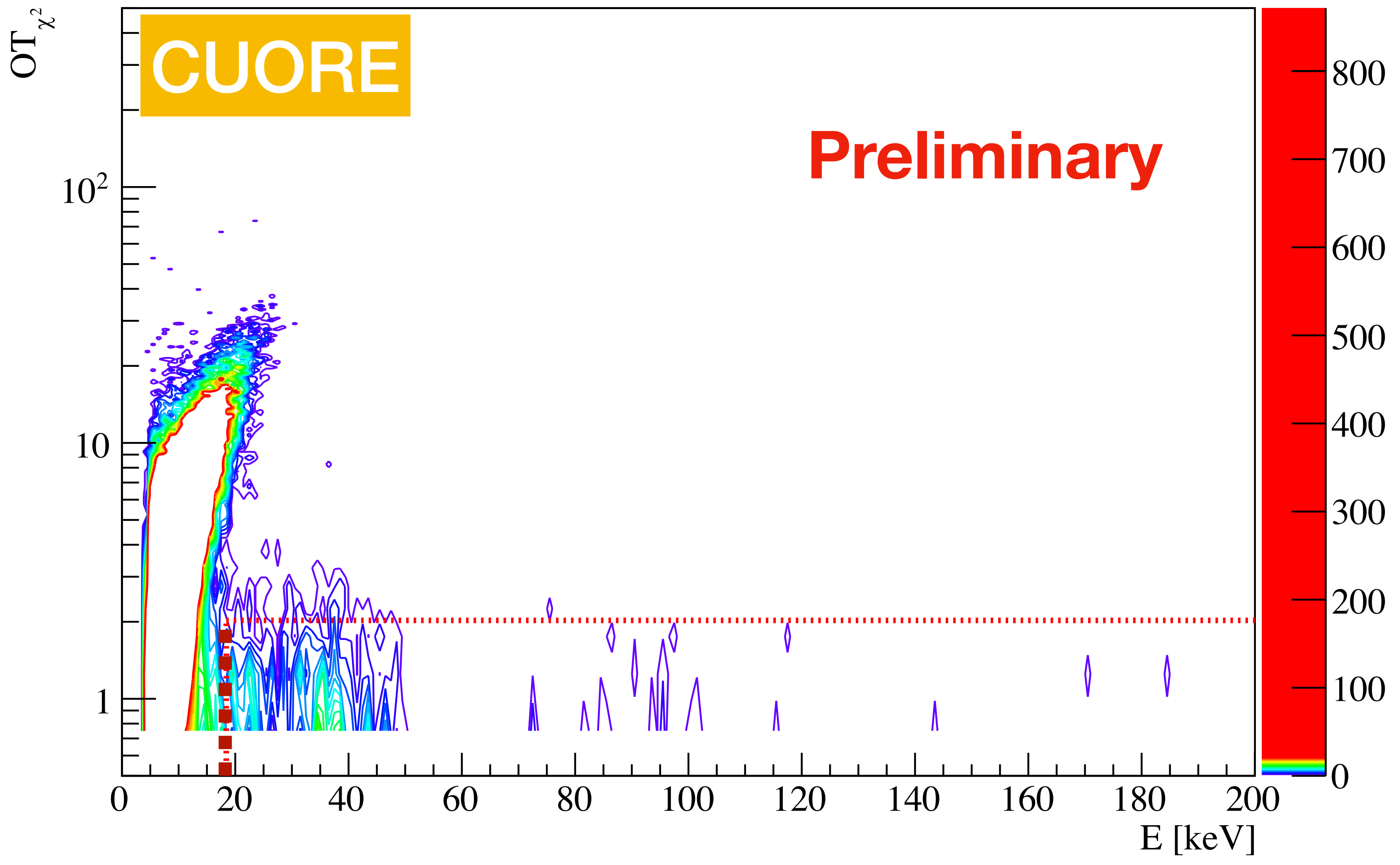
- Near trigger threshold, we need to discard non-physical events that could contribute to the spectrum;
- Noise contributions: tower vibrations / electronic noise / energy deposits in NTDs -> mimic signal pulses -> can survive the trigger cut;
- Build a low energy spectrum -> reject most of the non-physical events;
- Pulse-shape discrimination variable OT_{χ^2}: defined as the χ^2 from the fit of the pulse under test with a template drawn from the average pulse of the considered channel;
- Real signal events: lay in a band around $OT_{\chi^2}\sim 1$;
- Fake signal events: are squeezed at low energy values and in a band that extends to high OT_{χ^2} values;
- Analysis threshold algorithm: in CUORE-0 we used a KS based algorithm, in CUORE we are trying new approaches;



C. Alduino et al. EPJ C 77, 857 (2017)

The Kolmogorov-Smirnov (KS) approach has been ported to CUORE





Complementary

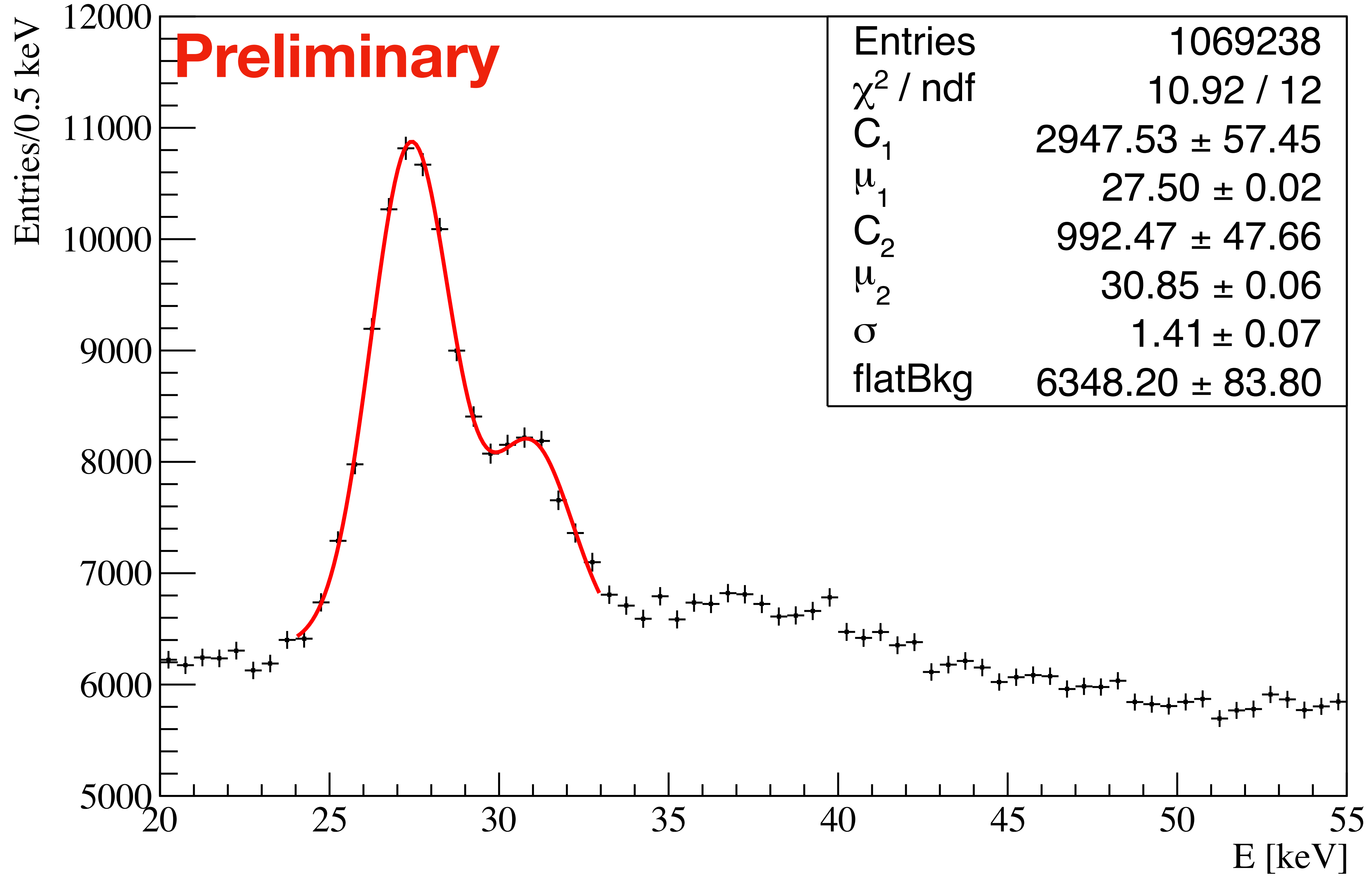
CUORE @ TAUP19

Instead of comparing the shapes of χ^2 w.r.t. reference signal region, we normalise the 2D distribution to the average expected signal content and throw away area with large ratios

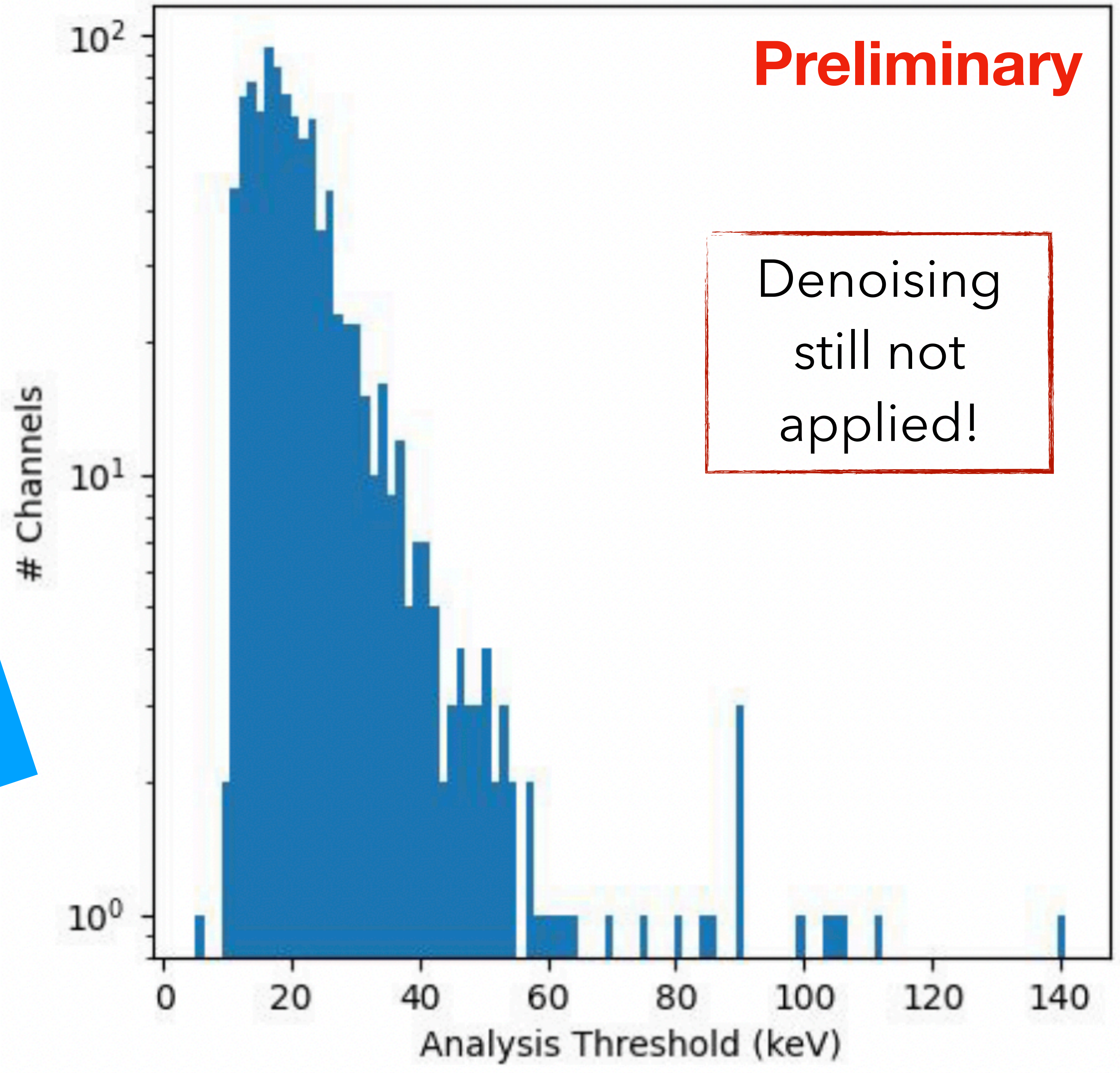
OT benchmark and calibration

- X-rays from Te can be produced following a γ ray interaction in a crystal;
- The X-ray can escape the crystal where is produced and be detected by an adjacent one;
- These low energy released in the crystals can be identified by selecting two events in adjacent crystals;

* 8 K-shell peaks give contributions;
* Primary and secondary peak in the reconstructed energy spectrum;



Analysis thresholds from a dataset



After computing the analysis thresholds, we can perform a cross check on the channels calibration by looking at the reconstructed position of the X-rays from Te

CPT violation search in 2nuDBD

- Standard Model -> invariant under Lorentz transformations -> invariance under CPT;
- Observations of violation of these symmetries -> existence of BSM physics;
- Standard Model Extension (SME) includes Lorentz violating operators, a subset of which also violates CPT (countershaded operators);
- ⭐ Effect of CPT breaking operator: modification of phase-space properties -> in 2nuDBD implies a modification of the form of the decay spectrum;

$$\frac{d\Gamma}{dK} = \frac{d\Gamma_0}{dK} + \frac{d\delta\Gamma}{dK}$$

with

Sum of kinetic energy of the two emitted electrons

$$K = (T_1 + T_2)/m_e$$

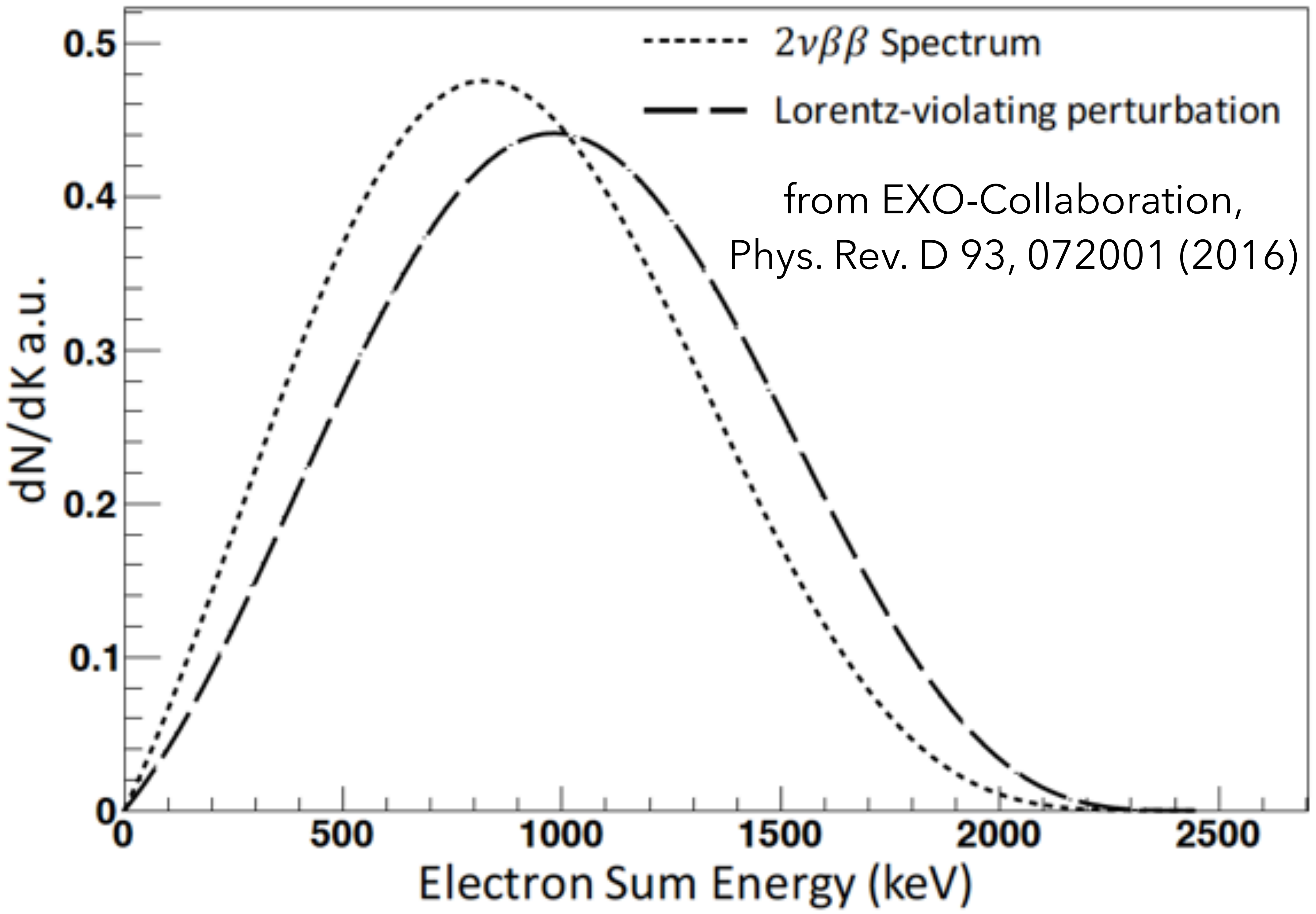
$$\frac{d\Gamma_0}{dK} \approx \zeta'(K^5 + 10K^4 + 40K^3 + 60K^2 + 30K)(Q_{\beta\beta} - K)^5$$

SM 2nuDBD

CPT violating term

$$\frac{d\delta\Gamma}{dK} \approx \zeta'(K^5 + 10K^4 + 40K^3 + 60K^2 + 30K)10\dot{a}^{(3)}_{of}(Q_{\beta\beta} - K)^4$$

Parameter of interest in the search



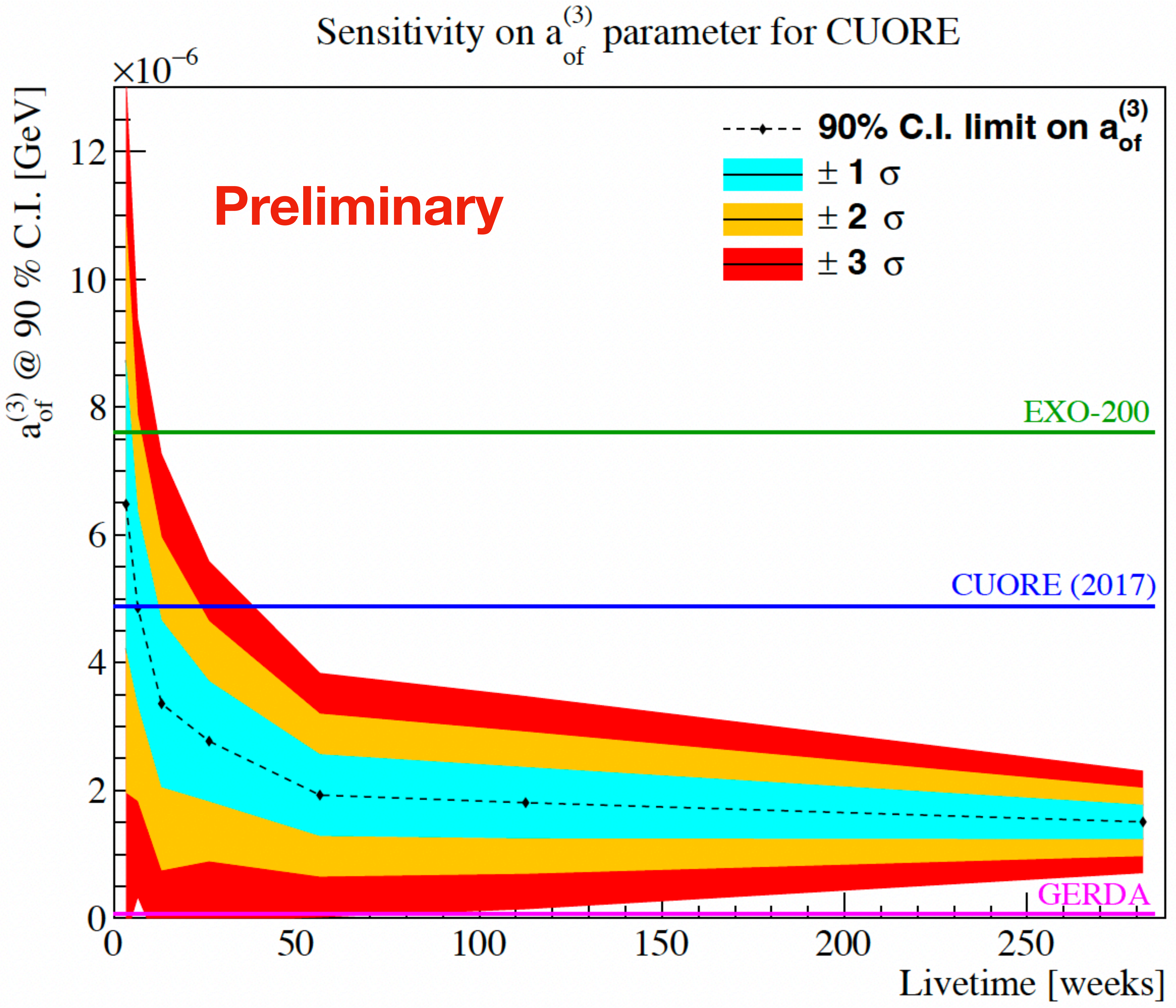
from EXO-Collaboration, Phys. Rev. D 93, 072001 (2016)

CPT violation search in 2nuDBD

Analysis strategy:

Ph.D. thesis I. Nutini 2019

- Background model for CUORE: from fit of simulated spectra from different contributions to measured energy spectrum (Bayesian fit with JAGS);
- 2nuDBD CPT violating term is included in the background model fit;
- Sensitivity study: for each given exposure, a set of toy-MC spectra are generated according to background only hypothesis; a fit with signal+background is performed on each toy-MC:
  - Likelihood marginalised over all nuisances;
  - posterior for the decay rate related to CPT violating term evaluated and 90% C.I. computed, from which exclusion sensitivity is obtained for parameter of interest;
  - Distribution of limits from the set of toy-MC allows to obtain a median sensitivity, w/ 1 and 2 sigma bands;
- Analysis of physics data: bayesian fit to the spectrum from data with signal+background model -> set an upper limit on parameter of interest (systematics not included);

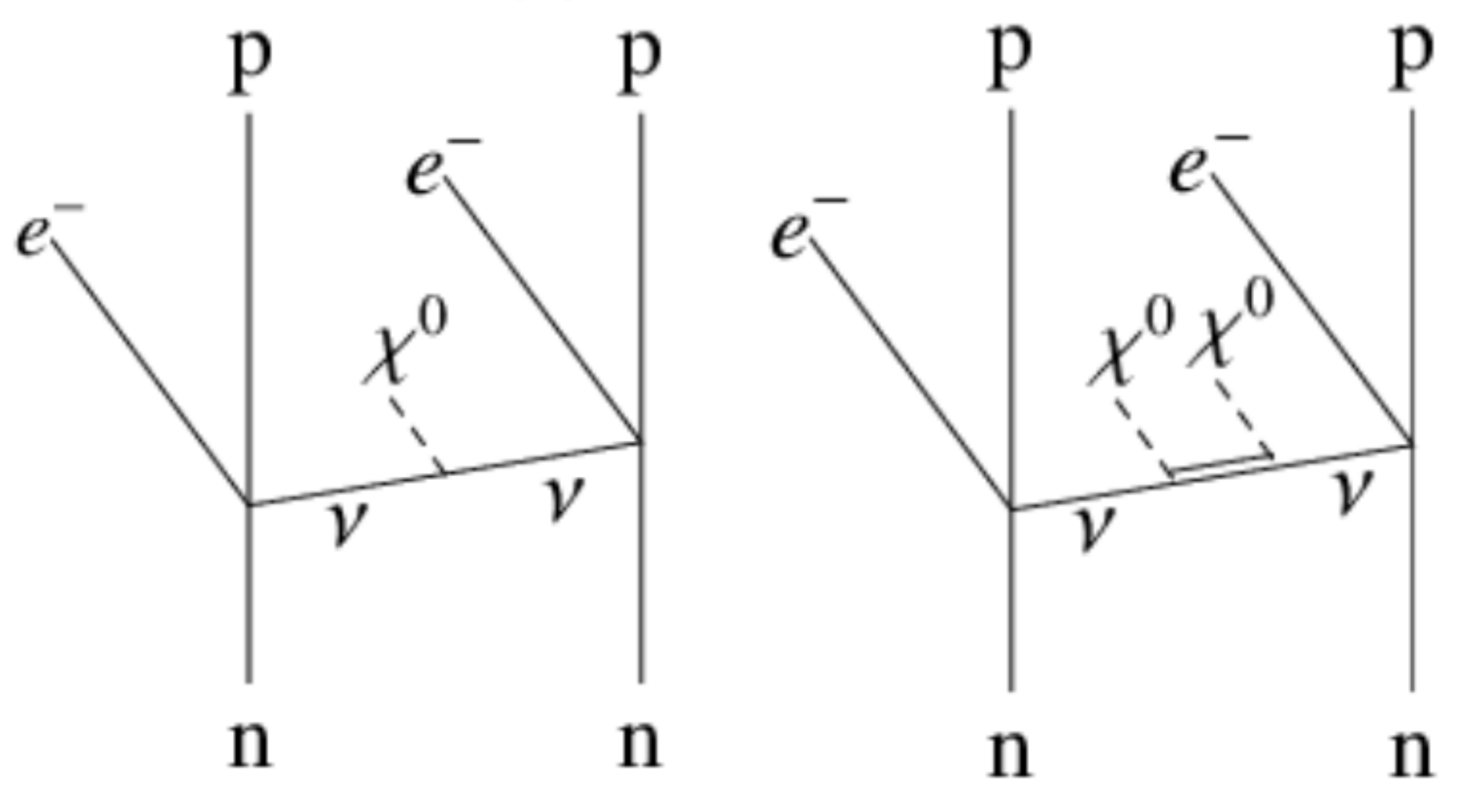


Only an exposure of 86.3 $kg \cdot yr$ used to develop and validate analysis procedure:

- update of the result with full available statistics ongoing;
- use of refined background model to improve sensitivity reach;

OnuDBD with Majoron emission

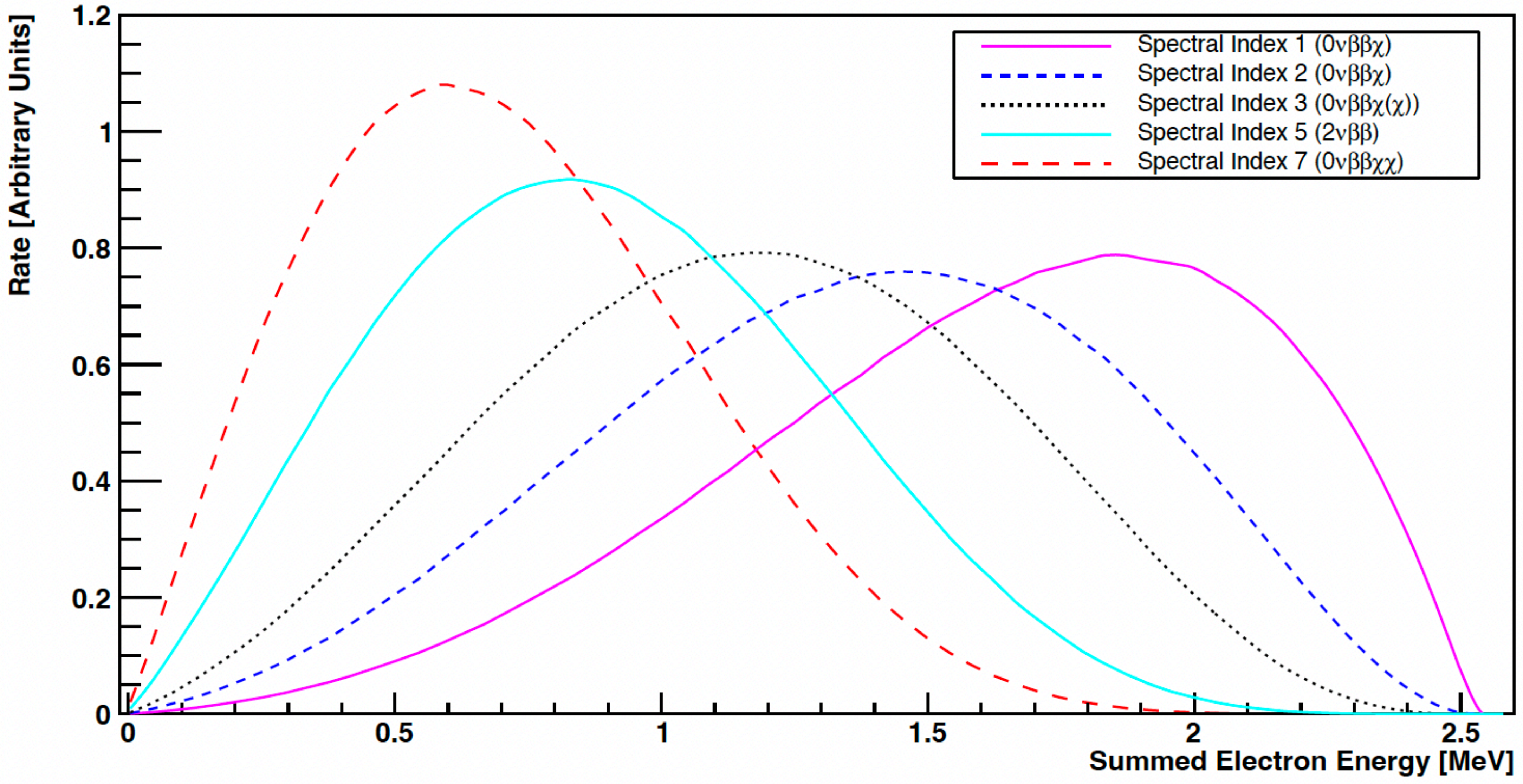
- 0nuDBD with only electrons in final state is not the only possible decay mode:
  - Proposed models predict the emission of 1 or 2 neutral bosons (Majoron) with the 0nuDBD
- Experimental signature: a continuous energy spectrum of the total energy from the two emitted electrons, with spectral index value depending on the considered model



$0\nu\beta\beta\chi$ $\quad$ $0\nu\beta\beta\chi\chi$

Model	Decay	G.B.	L.N.	S.I.
IB	$0\nu\beta\beta\chi$	no	0	1
IC	$0\nu\beta\beta\chi$	yes	0	1
ID	$0\nu\beta\beta\chi\chi$	no	0	3
IE	$0\nu\beta\beta\chi\chi$	yes	0	3
IIB	$0\nu\beta\beta\chi$	no	-2	1
IIC	$0\nu\beta\beta\chi$	yes	-2	3
IID	$0\nu\beta\beta\chi\chi$	no	-1	3
IIE	$0\nu\beta\beta\chi\chi$	no	-1	7
IIF	$0\nu\beta\beta\chi$	no	-2	3

Summed energy spectra of two electrons



- Energy distributions for different Majoron emission models corresponding to spectral indexes 1, 2, 3, 7;
- Spectral index 5 corresponds to 2nuDBD, reported as reference;

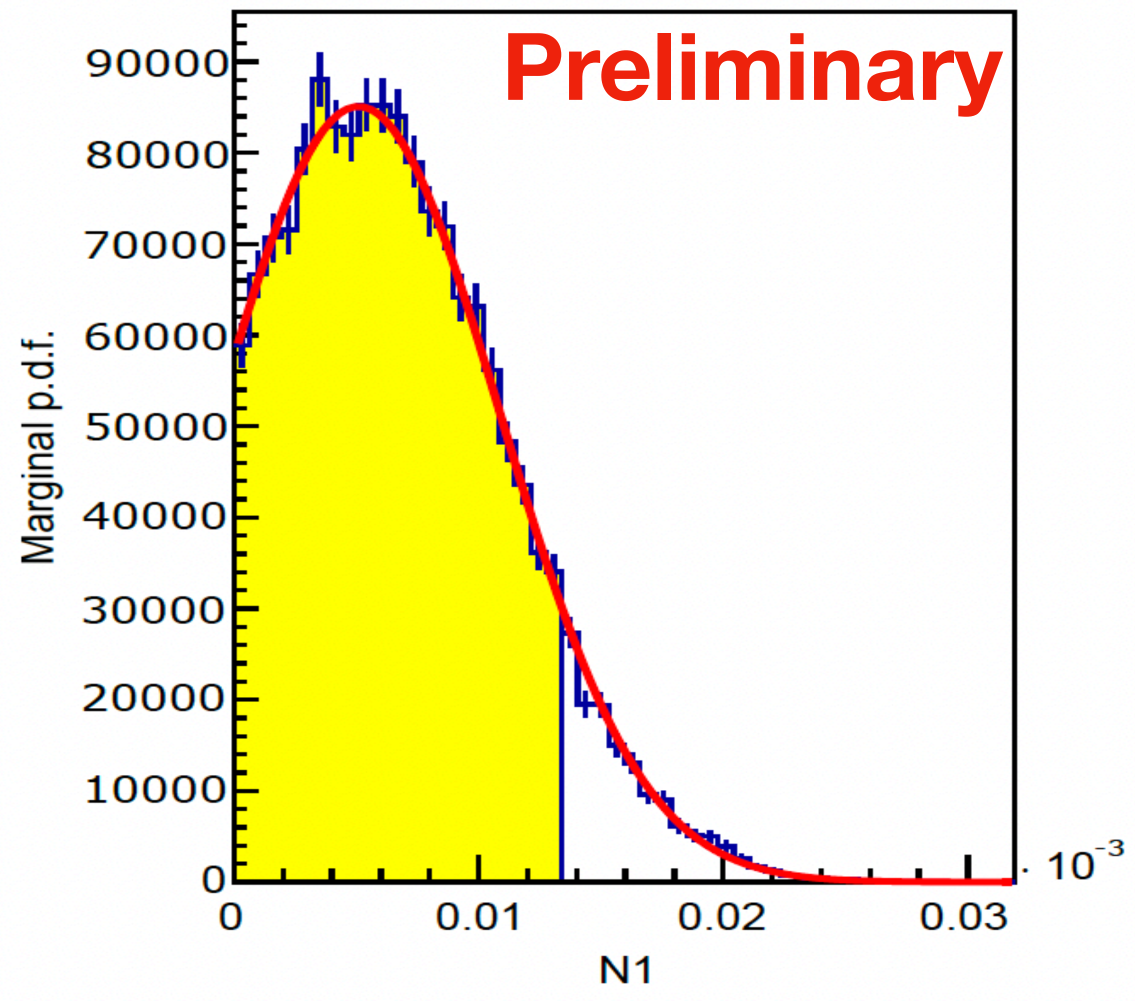
OnuDBD with Majoron emission

Analysis strategy:

Ph.D. thesis C. Davis 2019

- As for the CPT violation analysis, the background model for CUORE is an essential ingredient for this analysis;
- The component with given spectral index from a Majoron emission model is included in the background model fit;
- Analysis of physics data: bayesian fit to the spectrum from data with signal+background model -> set an upper limit on half-life of each Majoron model -> set a limit on the coupling constants g_α;

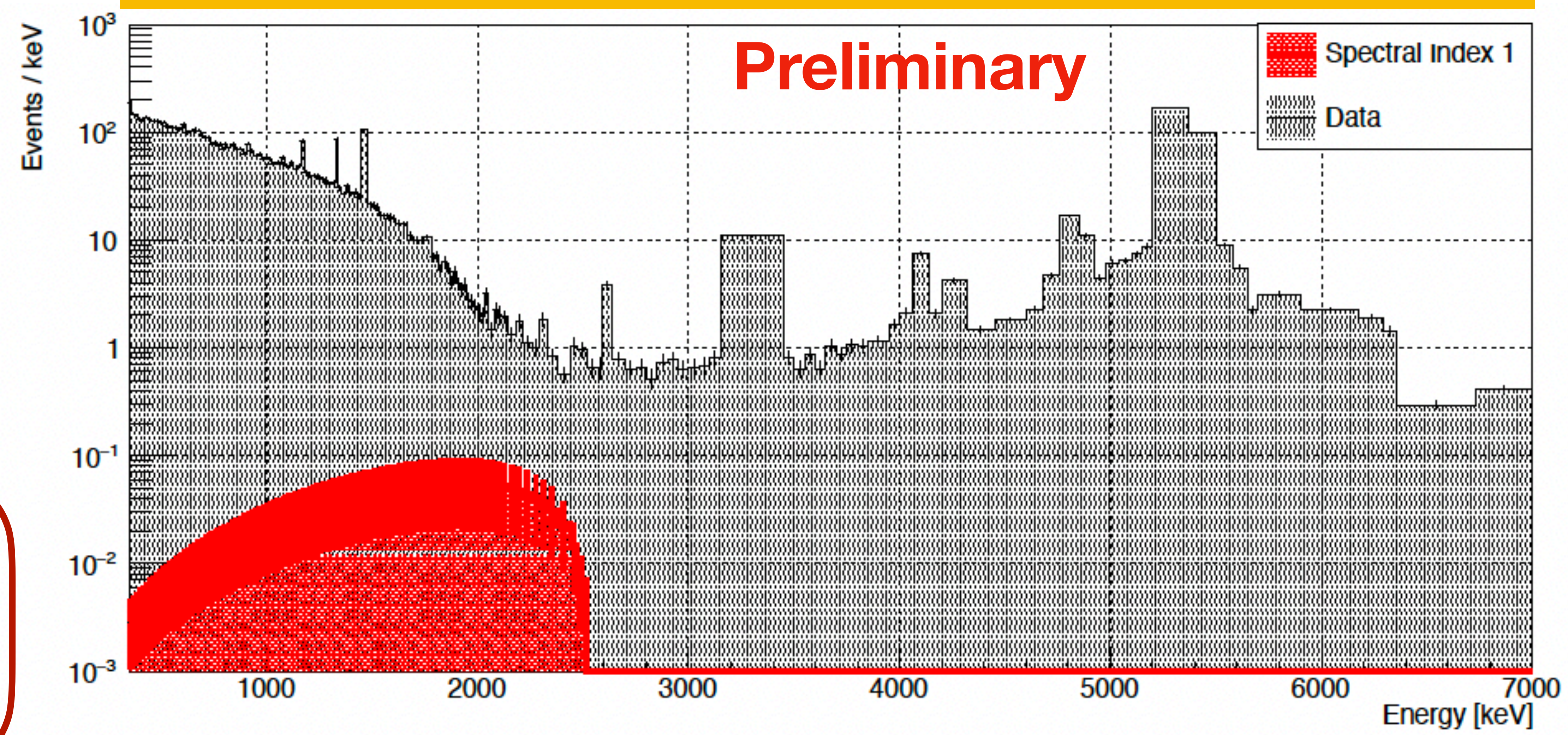
Posterior (SI = 1)



Model	S.I.	90% (C.L.) Half-life	$\|g_\alpha\|$
IB	1	$> 3.1 \times 10^{22}$ yr	$< (5.1 - 13.2) \times 10^{-5}$
IC	1	$> 3.1 \times 10^{22}$ yr	$< (5.1 - 13.2) \times 10^{-5}$
ID	3	$> 3.0 \times 10^{21}$ yr	< 0.35
IE	3	$> 3.0 \times 10^{21}$ yr	< 0.35
IIB	1	$> 3.1 \times 10^{22}$ yr	$< (5.1 - 13.2) \times 10^{-5}$
IIC	3	$> 3.0 \times 10^{21}$ yr	< 0.12
IID	3	$> 3.0 \times 10^{21}$ yr	< 0.35
IIE	7	$> 4.3 \times 10^{21}$ yr	$< (0.63 - 6.3)$
IIF	3	$> 3.0 \times 10^{21}$ yr	< 0.12

$$\frac{1}{T_{1/2}} = |\langle g_\alpha \rangle|^{2m} \cdot |M|^2 \cdot G_\alpha^{0\nu M}(Z, E_0)$$

Fitted contribution of Majoron decay (SI = 1)

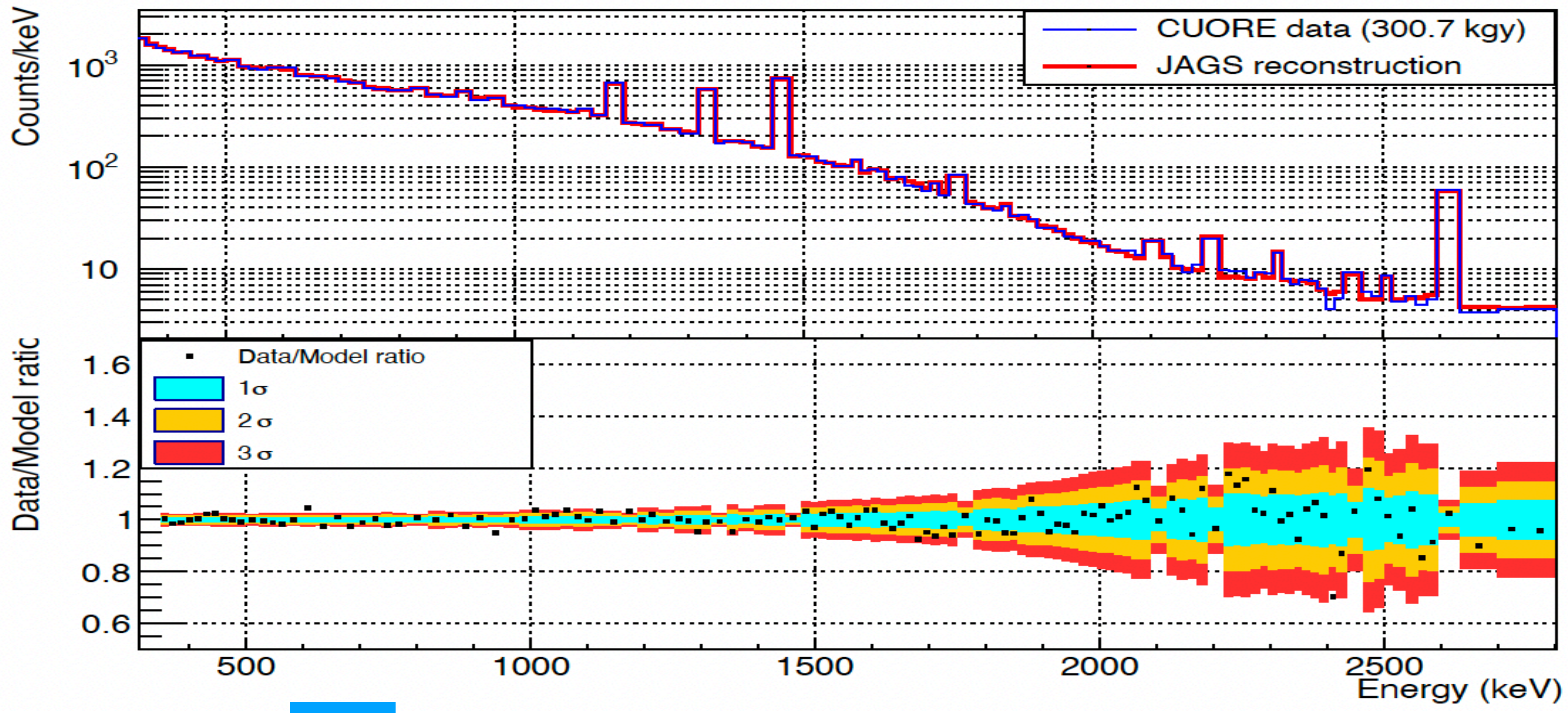


Exposure of 387.5 $kg \cdot yr$ used to develop and validate analysis procedure:

- update of the result with full available statistics ongoing;
- use of refined background model to improve sensitivity reach;

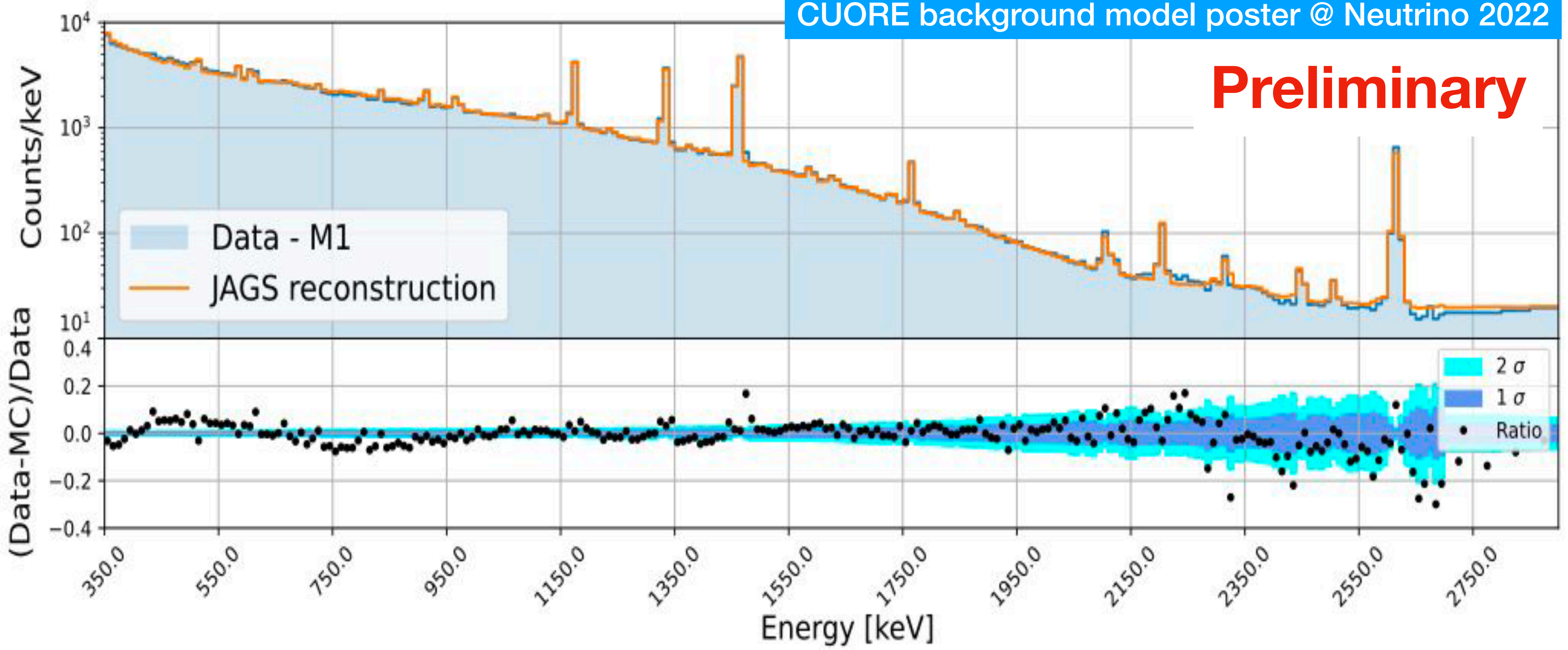
Background model improvement

- These analyses strongly rely on a good understanding of the background of CUORE experiment
- We already have a very reliable background model ;
- The model anyway keeps improving:
  - Larger statistics employed (1 ton-yr dataset);
  - More components spread across the cryostat (up to 73 now);
- The improved background model will certainly be beneficial to boost the sensitivity of the analyses based on spectral shape distortions;



Toward a more detailed and precise description

CUORE background model poster @ Neutrino 2022



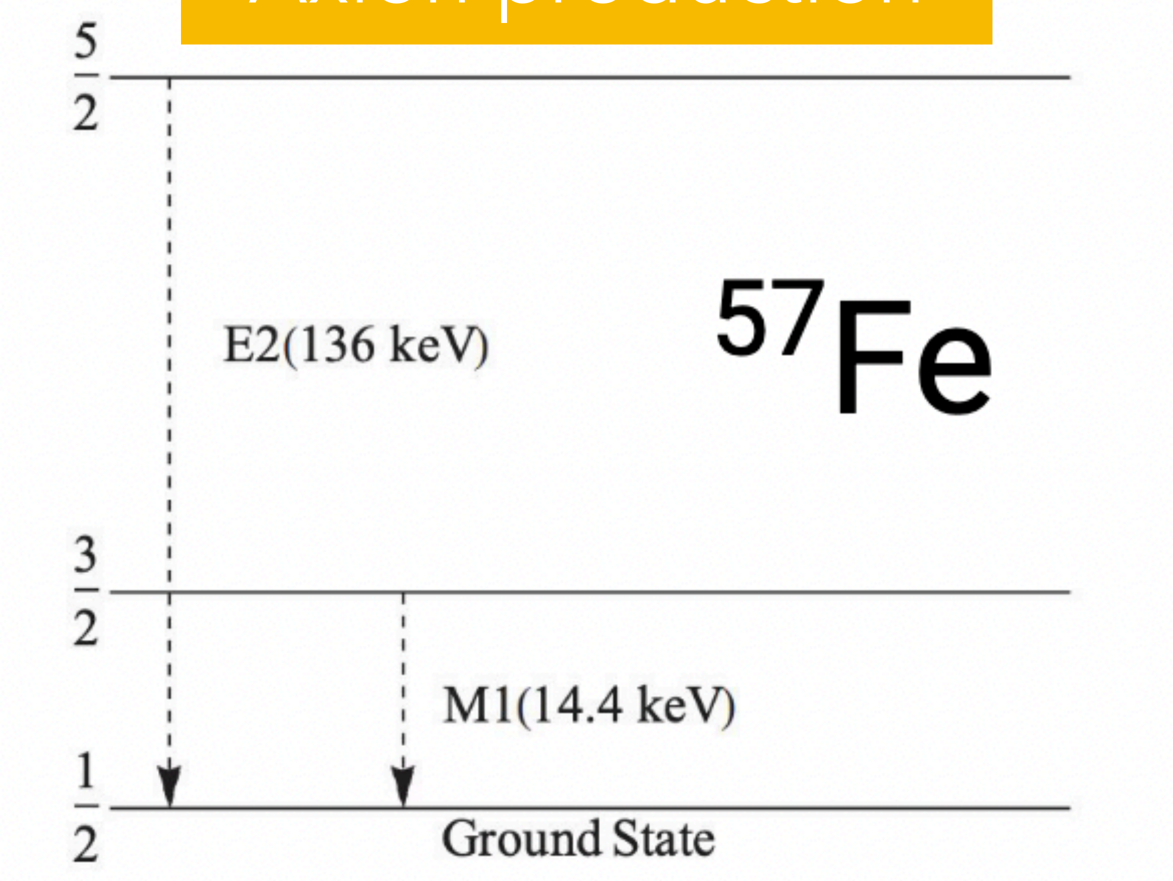
Search for solar axions

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

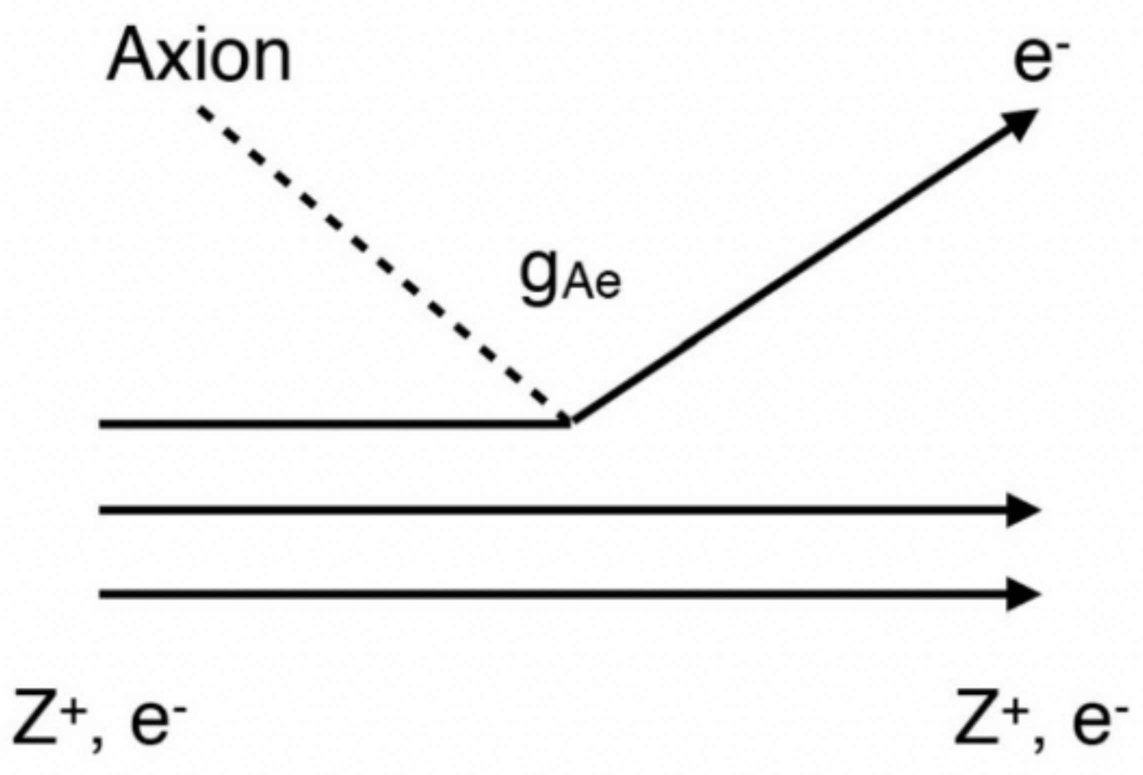
INFN Istituto Nazionale di Fisica Nucleare

CUORE

Axion production



Detection: axio-electric effect



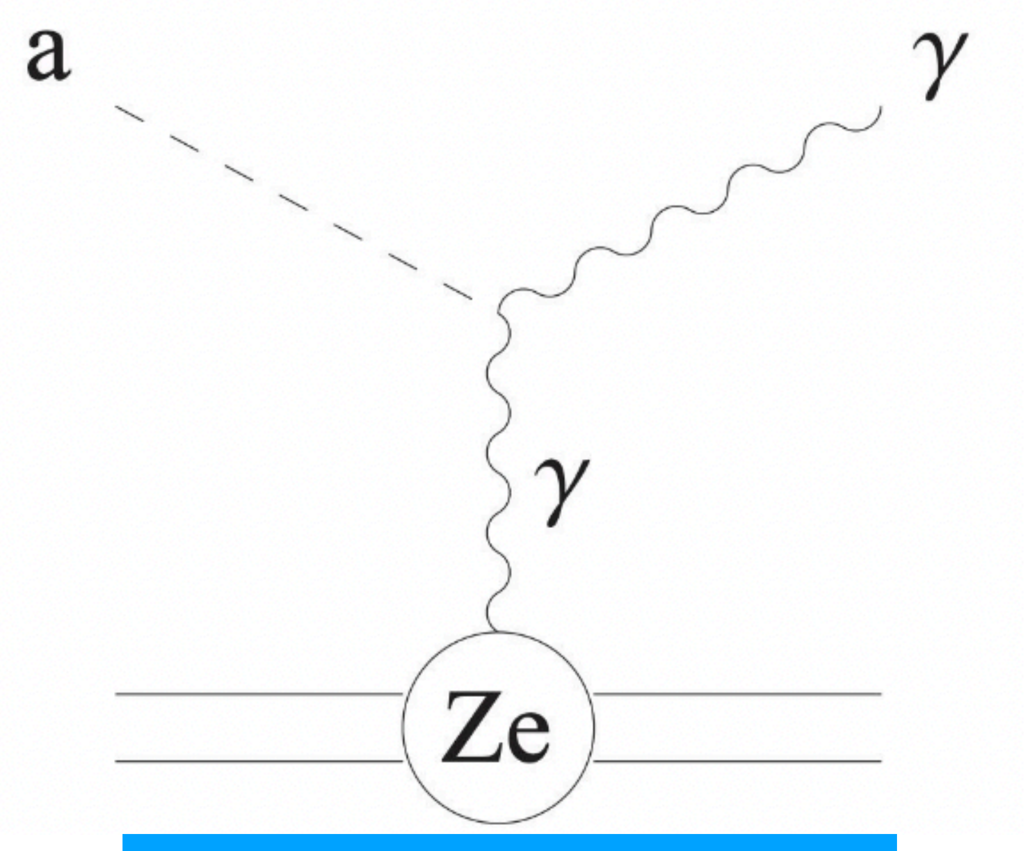
F. Alessandria et al JCAP01(2013)038
S Di Domizio et al 2011 JINST 6 P02007

- Solar axions emitted by de-excitation of the first ^{57}Fe level (thermally populated in the core of Sun);
- Detected in the TeO_2 crystals through axio-electric effect;
- Signature: peak in the energy spectrum @ 14.4 keV;
  - Analysis sensitive to the $g_{Ae} \times g_{AN}^{eff}$ coupling constant;

Analysis developed and validated in past CUORE crystal validation runs:

- Work in progress to implement the analysis in CUORE data;

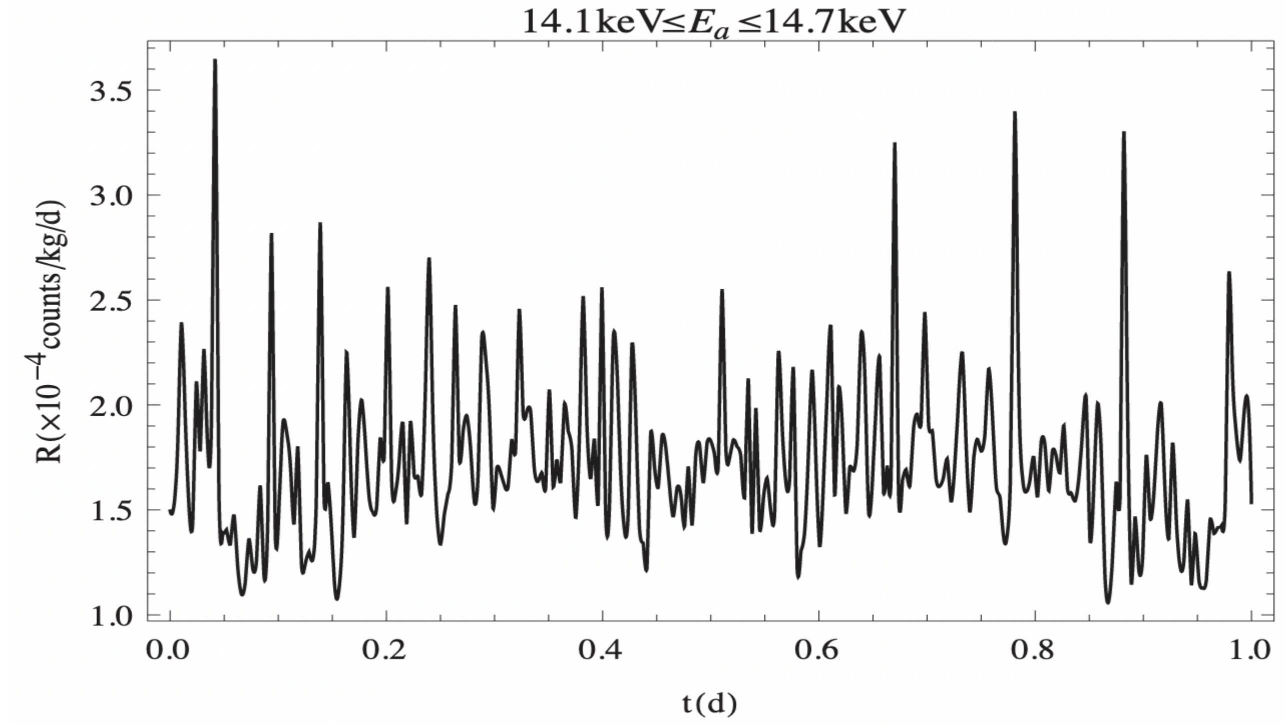
Detection: Inverse-Coherent Bragg-Primakov Conversion

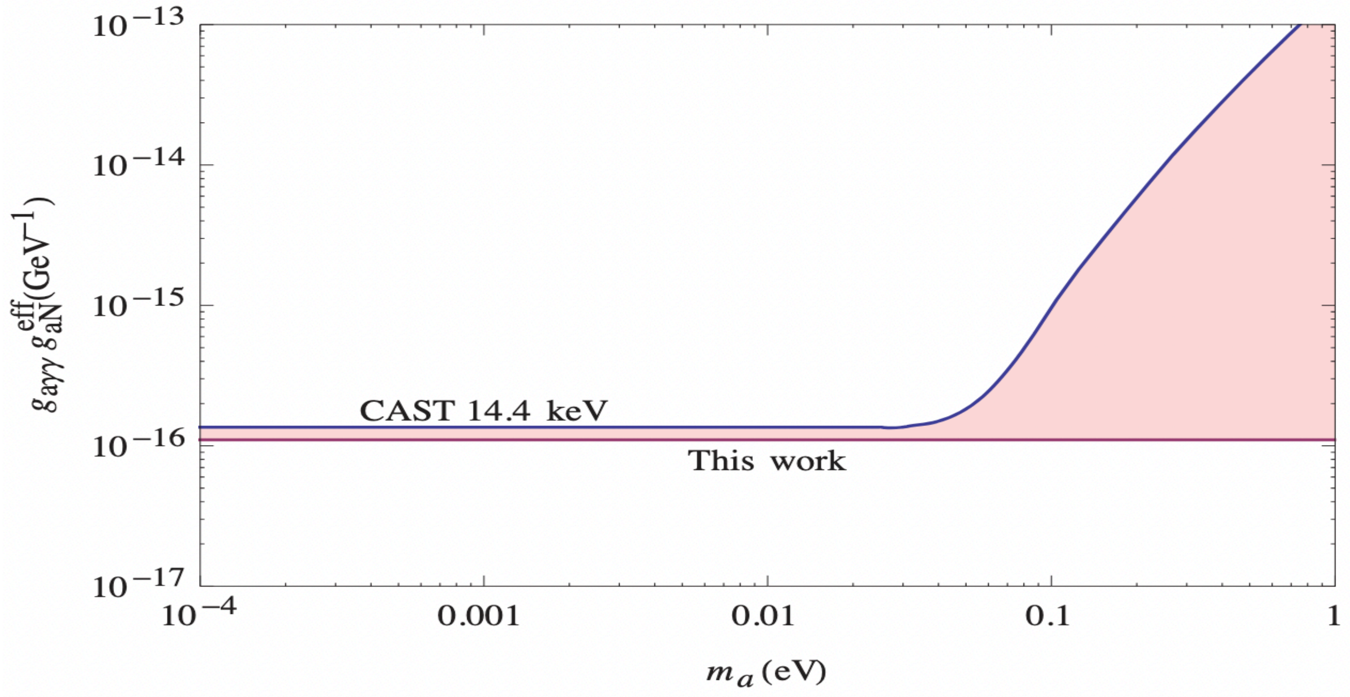


Dawei Li et al. JCAP10(2015)065

- Detected in the TeO_2 crystals through inverse-coherent Bragg-Primakov conversion;
  - Axion couples to the crystal lattice charge through a virtual photon;
  - Interaction produces a photon only if Bragg's condition is satisfied (Sun-CUORE angle dependence);
- Signature: look @ counting rate vs time over single day and analyze with time-correlation method;
  - Analysis sensitive to the $g_{A\gamma\gamma} \times g_{AN}^{eff}$ coupling constant;

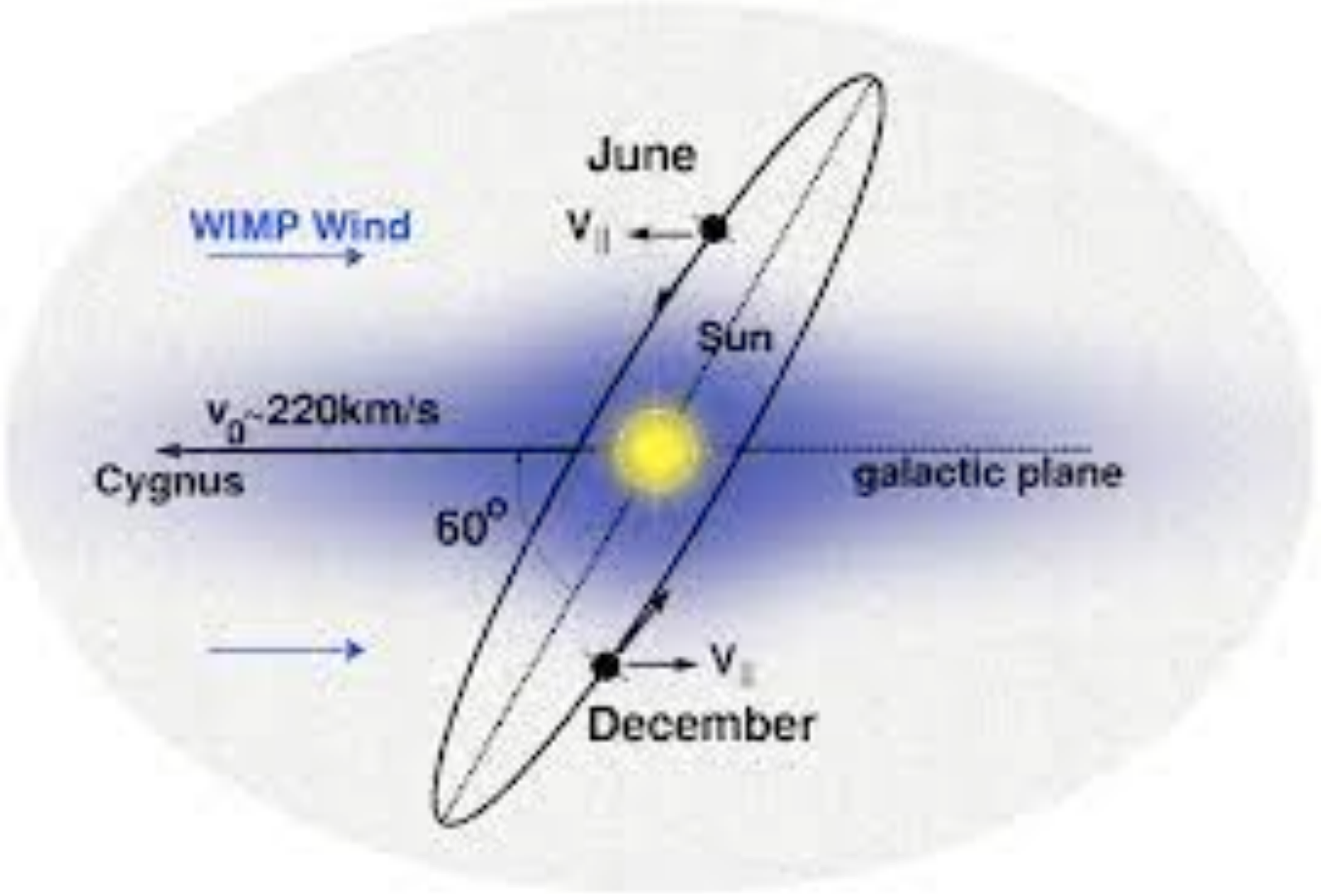
Analysis being developed for CUORE data

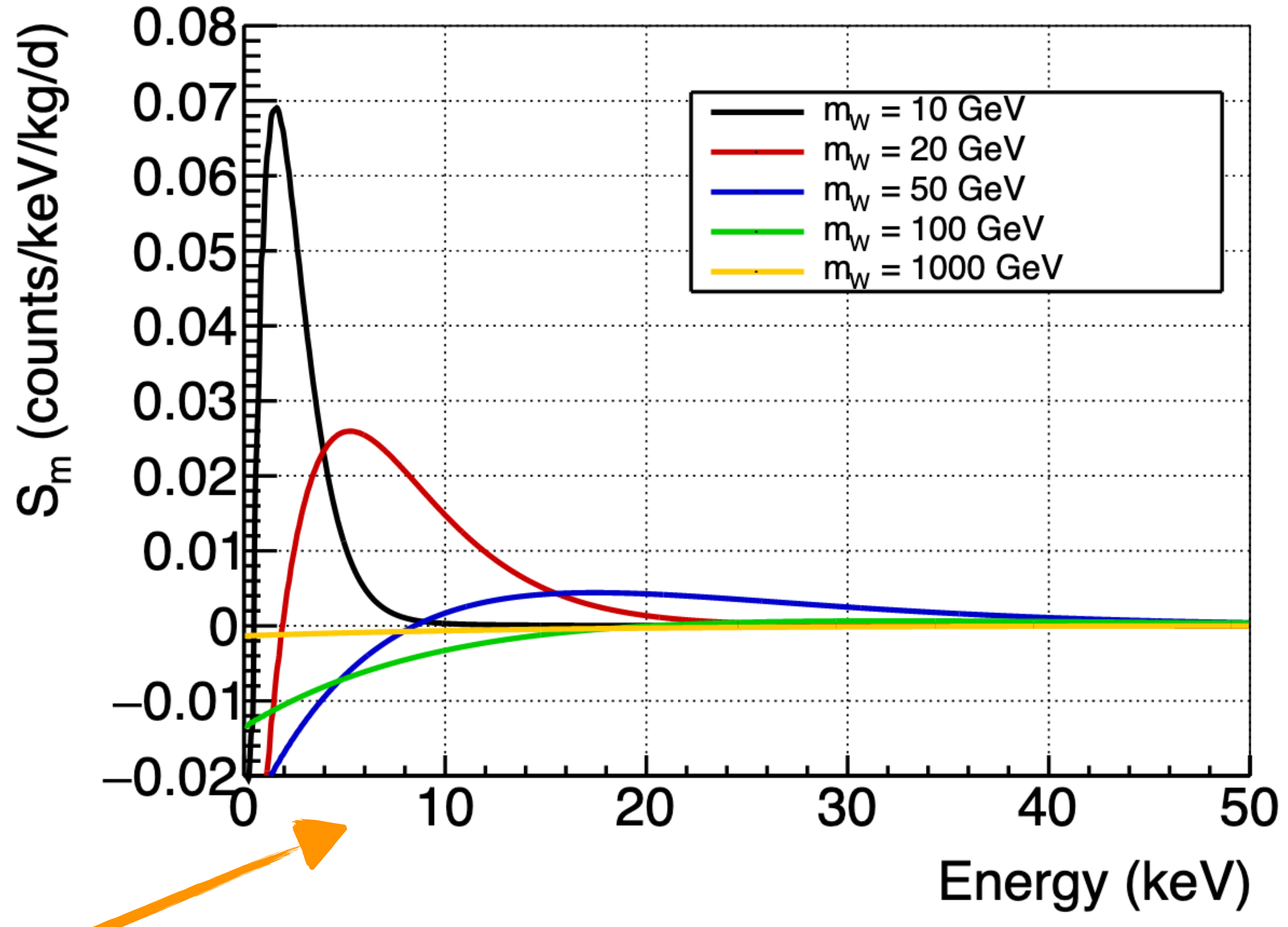




WIMP modulation search: analysis technique

WIMP recoil rate due to motion of Earth around Sun

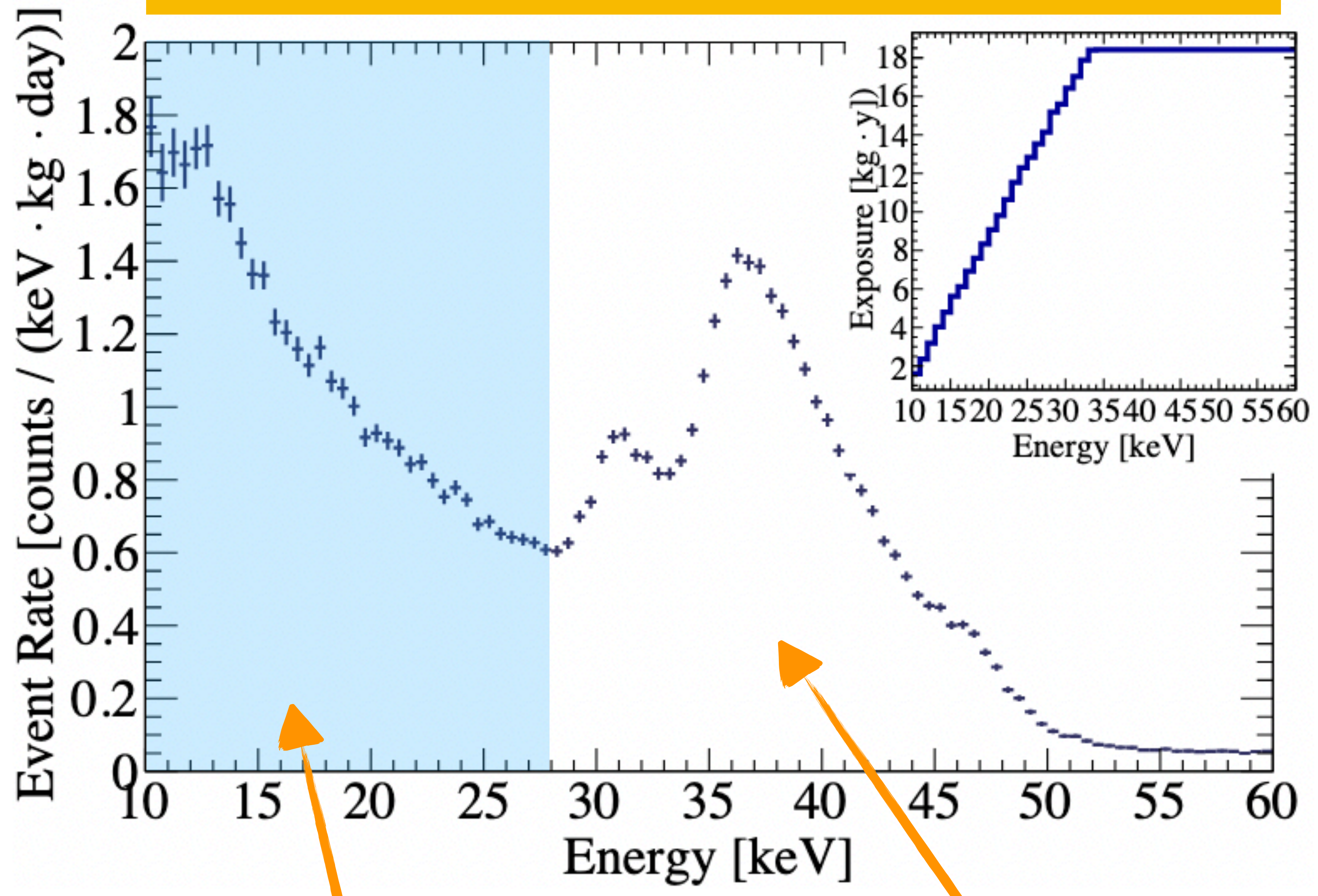




$$\frac{dR_W}{dE}(E,t) = S_0(E) + S_m(E)\cos[\omega(t-t_0)]$$

- TeO_2 a good target: combines heavy Te nucleus and light O nucleus -> enhances sensitivity to low WIMP masses;
- Exploit CUORE-0 result to estimate CUORE sensitivity:
  - Assumptions: same background rate and analysis thresholds;

CUORE-0 low-energy spectrum

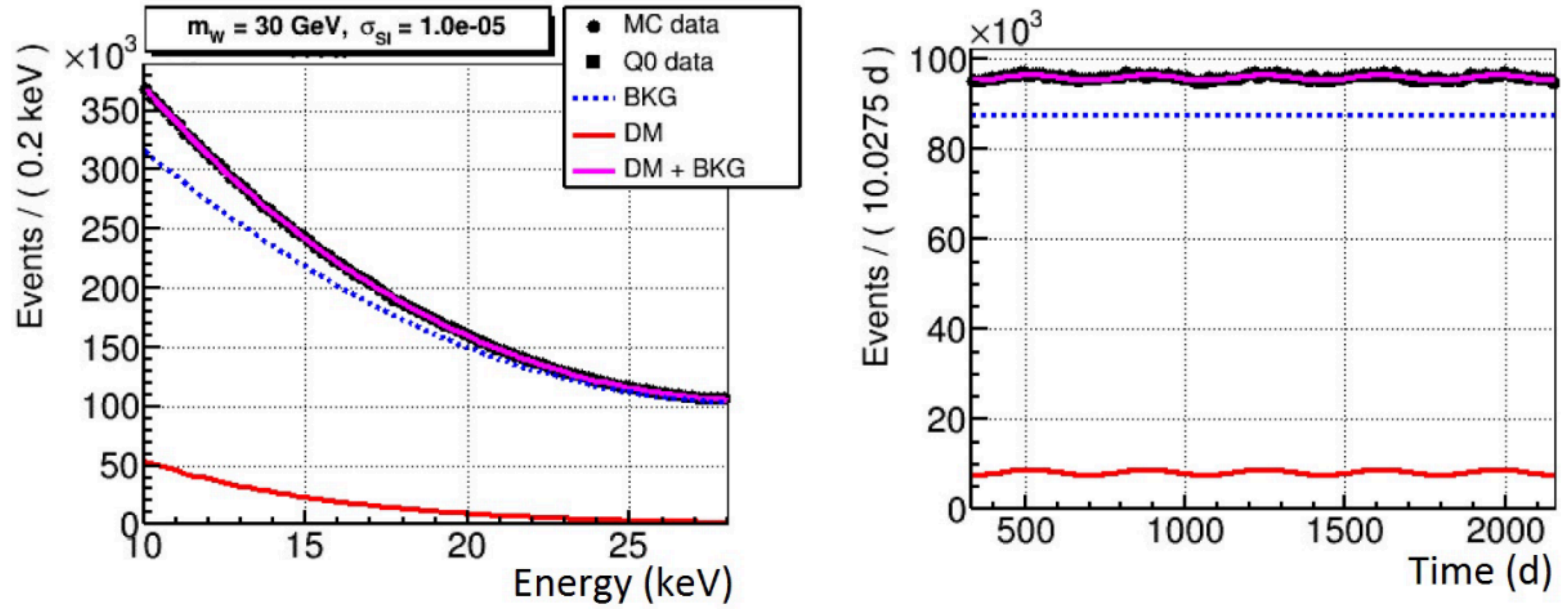


ROI for the WIMP search

Peak like structure excluded:

- Present in all crystals -> physical origin;
- Maybe due to contamination in material facing detector -> under investigation in CUORE

Toy-MC experiment from CUORE-0 background extrapolated to CUORE 5 year data-taking w/ signal+background model fit



$$\sigma_{SI} = 10^{-5}\ pb$$

$$m_W = 30\ GeV$$

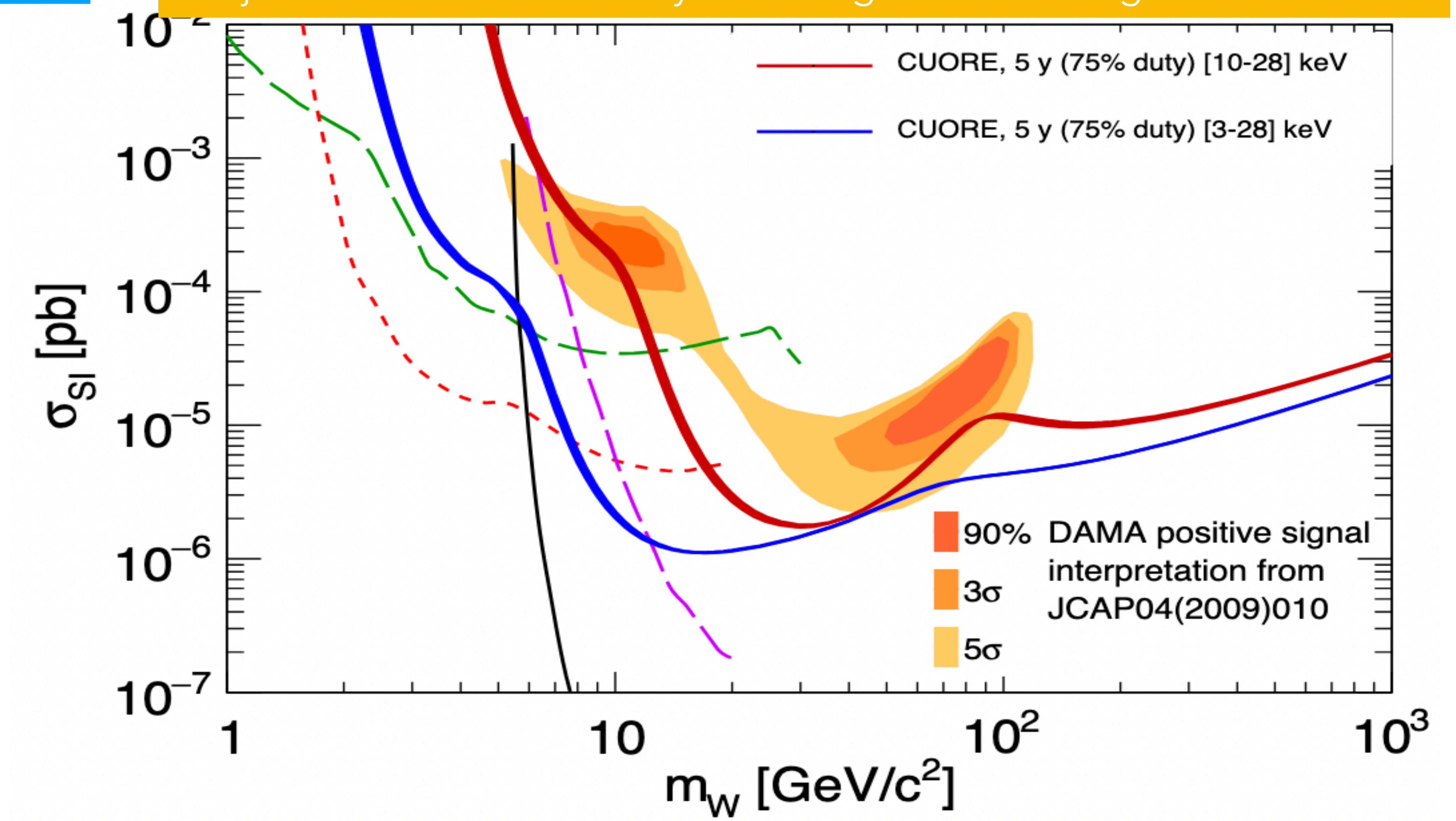
WIMP modulation search: sensitivity

C. Alduino et al. EPJ C 77, 857 (2017)

Strategy to extract sensitivity

- Scan (m_W, σ_{SI}) parameter space and for each point perform following steps:
- Fit energy spectrum (integrated in time) to signal+background and determine best-fit background coefficients;
- Obtained background parameters used to generate 100 toy-MC experiments from signal+background model;
- For each toy-MC the $\mathscr{L}_{AM}$ and $\mathscr{L}_{null}$ are maximised and the maximum likelihood ratio is computed;
- Experimental sensitivity is computed as the parameter space points for which at least 90% experiments prefer annual modulation hypothesis w.r.t. the null one;

Projected CUORE sensitivity assuming CUORE-0 bkg and thresholds



Now CUORE has the data to compute sensitivity and perform actual search!

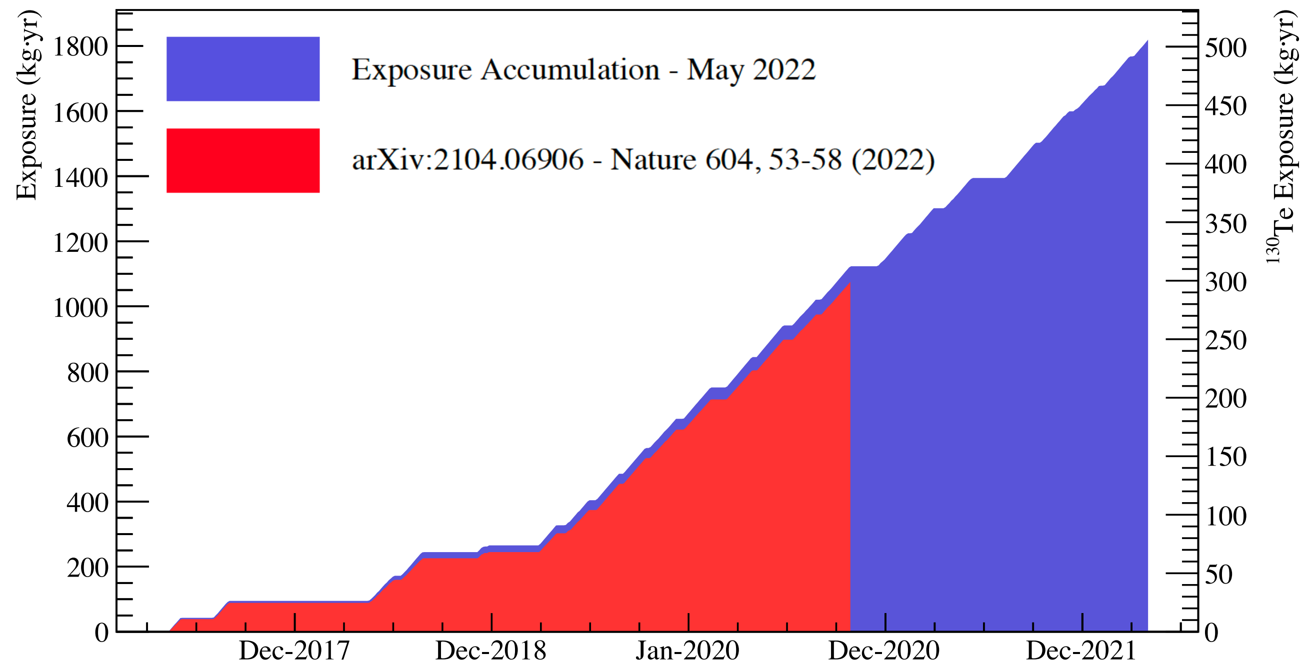
PDF used to compute $\mathscr{L}_{AM}$

Background PDF (Chevychev polynomial)

$$\phi = \frac{dR_W}{dE}(E,t;m_W,\sigma_{SI})M_{det}\varepsilon_{BoDs}(E,t) + \phi_b(E;a_i)\varepsilon_{BoDs}(E,t)$$

Target mass

Detection efficiency (dataset/crystal based)

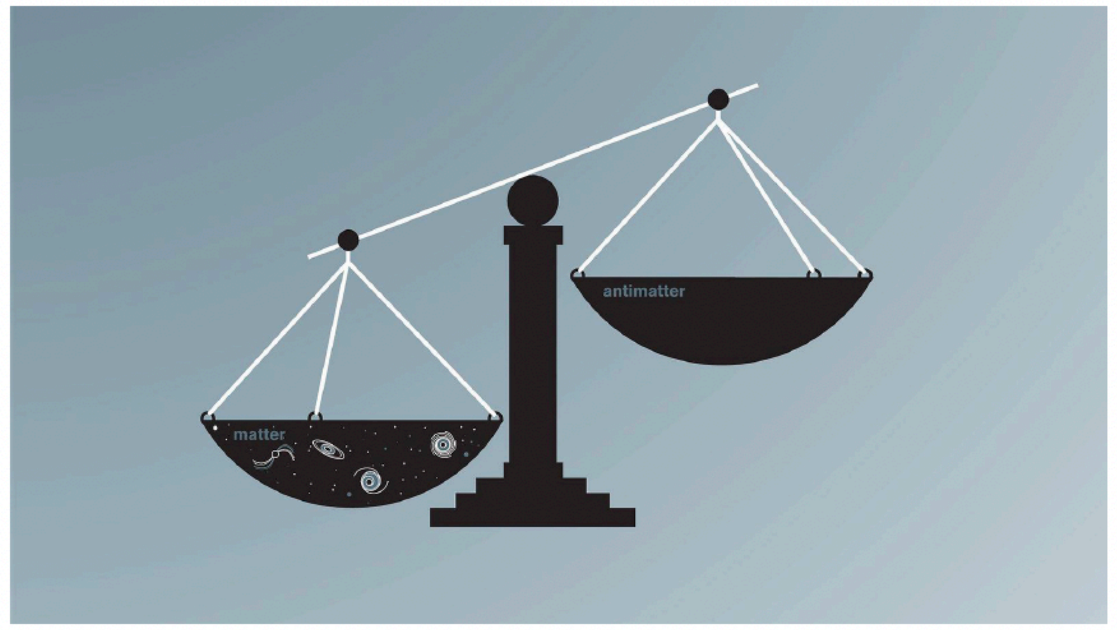


A. Branca @ IDM2022

Invisible tri-nucleon decay search

CUORE tri-nucleon decay poster @ Neutrino 2022

Violation of barion number essential to explain matter-antimatter asymmetry in the universe

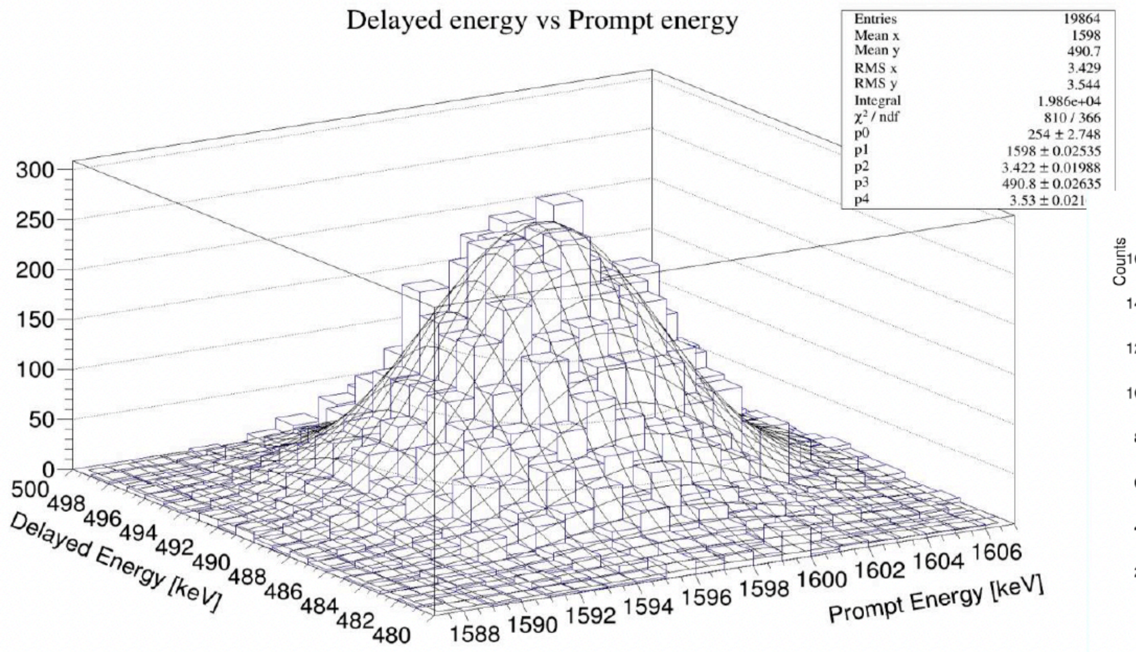


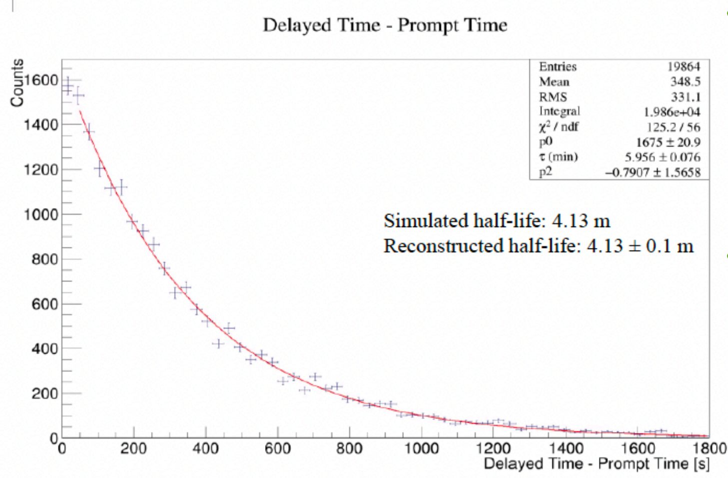
$$ppp \rightarrow e^+\pi^+\pi^+$$
$$ppn \rightarrow e^+\pi^+$$
$$pnn \rightarrow e^+\pi^0$$

In CUORE:

$$^{130}\mathbf{Te} \rightarrow \ ^{127}\mathbf{In} + e^+ + \pi^+ + \pi^+$$

Narrow-cut

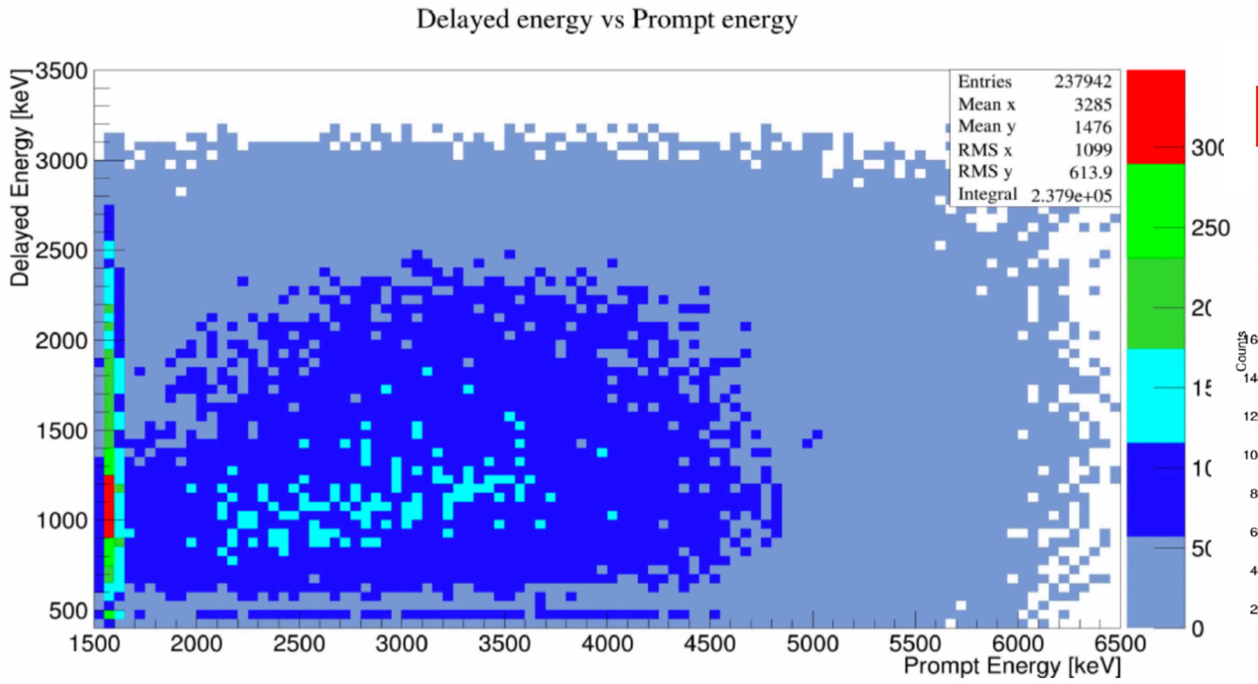


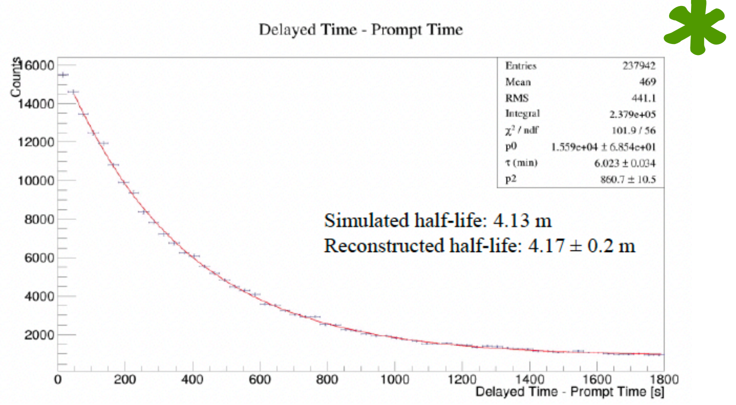


Preliminary

- Tag efficiency 2%;
- Peak position of 2D gaussian fit consistent with literature values;
- Correct decay time from fit to delay - prompt time difference

Broad-cut

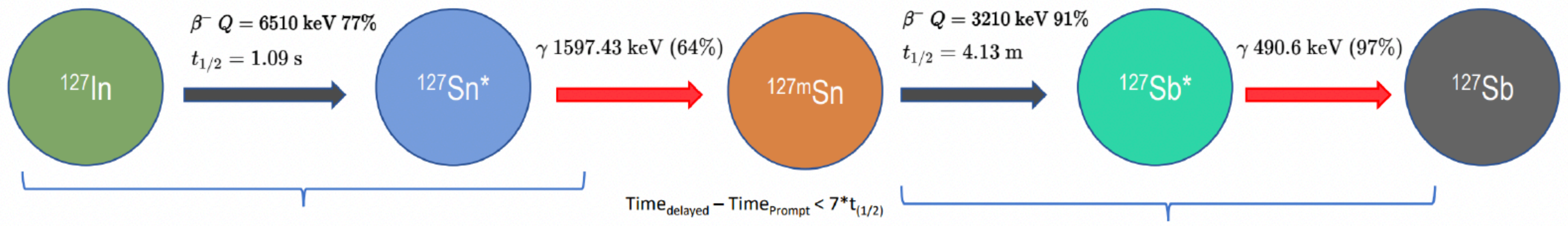




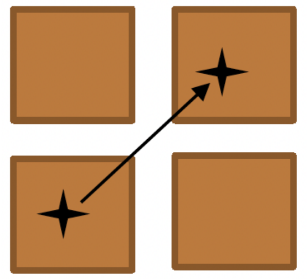
Preliminary

- Tag efficiency 18%, higher, but bkg risky;

- Simulated 10^6 ^{127}In with full CUORE G4 simulation and considering detector response;
- Backgrounds: accidental coincidences / neutron and muon spallation;



Tag prompt delayed signal in two crystals



1500 keV< $E_{\text{prompt total}}$<6500 keV — 400 keV< $E_{\text{delayed total}}$<3200 keV → **Broad-cut**: accounts for both gammas and betas

1587 keV< E_{prompt}<1607 keV — 470 keV< E_{delayed}<500 keV → **Narrow-cut**: accounts only for gammas

Conclusion

- CUORE is running in stable conditions:
  - Started 2017 -> commissioning + optimisations + operations;
  - Stable data-taking since 2019;
- Developed tools needed for BSM and DM searches:
  - Trigger and analysis thresholds;
  - Denoising;
- Developed and validated a set of BSM and DM searches:
  - CPT violation
  - Majorons;
  - Tri-nucleon decay;
  - Axions & WIMPs;
- Work in progress to apply to full available statistics;
  - Stay tuned for exiting new BSM & DM physics results in the near future!