Looking Ahead

October 23, 2017
LNGS, Italy

Yury Kolomensky
UC Berkeley/LBNL

CUORE

Cryogenic Underground Observatory for Rare Events

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE – SOL PER NOCTEM – 1979

SINAP

LUX ET VERITAS

INFN Istituto Nazionale di Fisica Nucleare

CAL POLY SAN LUIS OBISPO

Lawrence Livermore National Laboratory

ALMA MATER STUDIORUM A.D. 1088 UNIVERSITÀ DI BOLOGNA

Massachusetts Institute of Technology

CSNSM

SHANGHAI JIAO TONG UNIVERSITY 1896

SAPIENZA UNIVERSITÀ DI ROMA

BERKELEY LAB

UNIVERSITY OF SOUTH CAROLINA

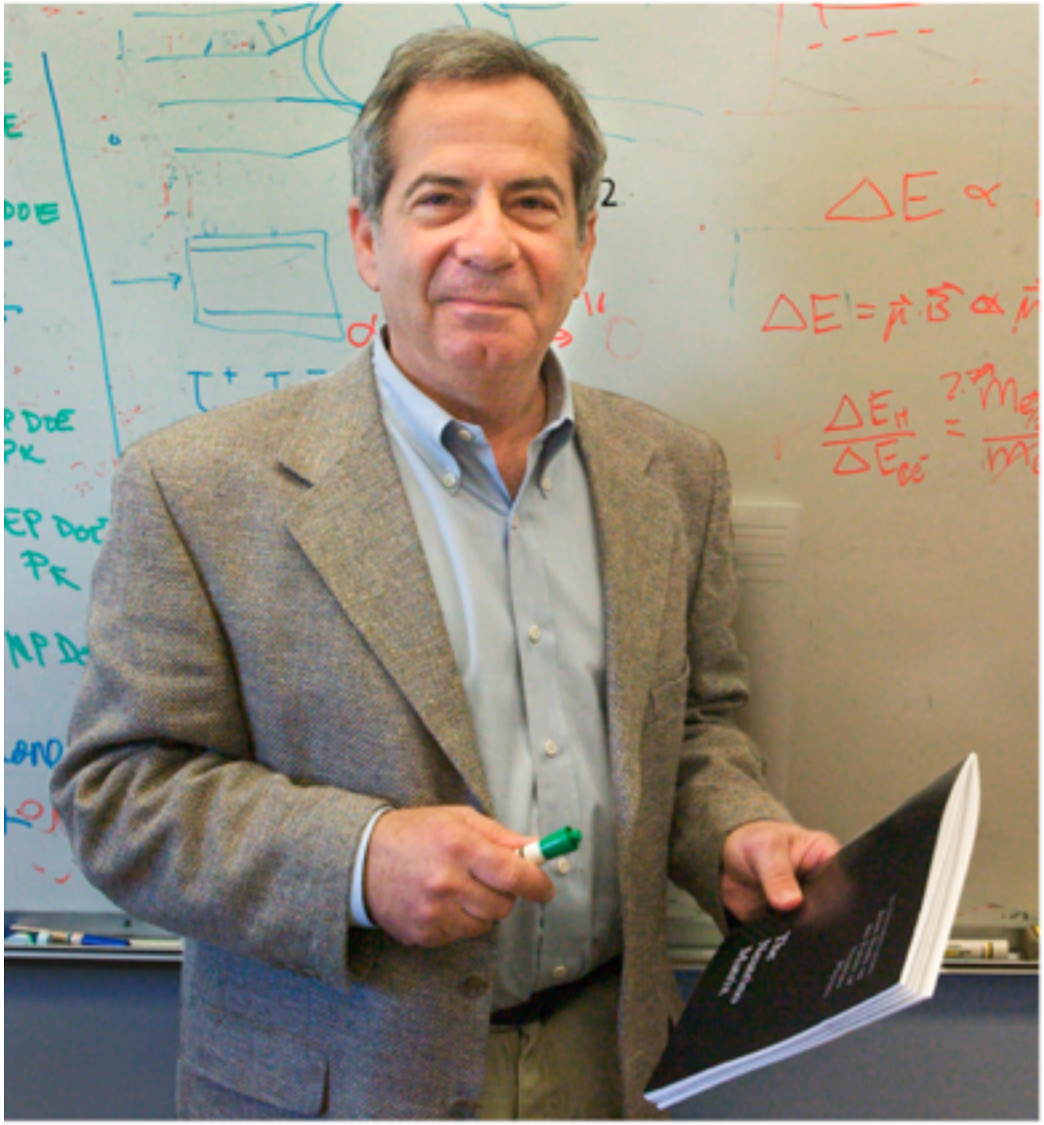
UCLA

UNIVERSITAS STUDII PADUANI MCCXXII

THE UNIVERSITY OF CALIFORNIA 1868 LET THERE BE LIGHT

CUORE

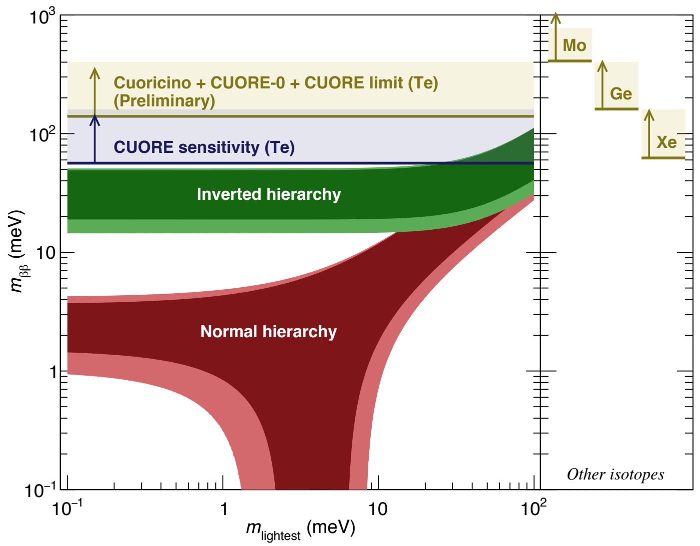
Stuart Freedman

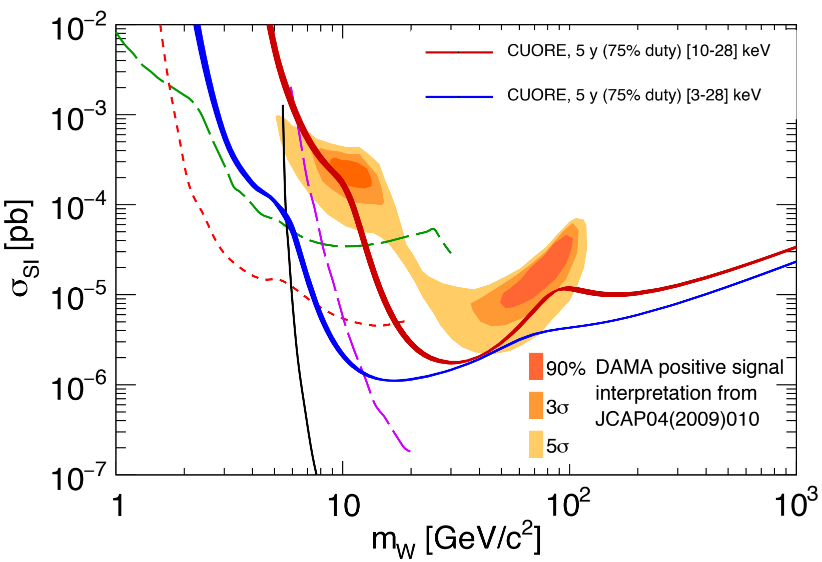


Stuart Jay Freedman
January 13, 1944-
November 9, 2012

CUORE Science

- Rich physics program
  - ✓ Neutrinoless double-beta decay
  - ✓ Two-neutrino double-beta decay
  - ✓ Exotic searches at high energies (Majoron etc)
  - ✓ Exotic searches at low energies (axions, dark matter)
  - ✓ Detailed background model: setting up for the future

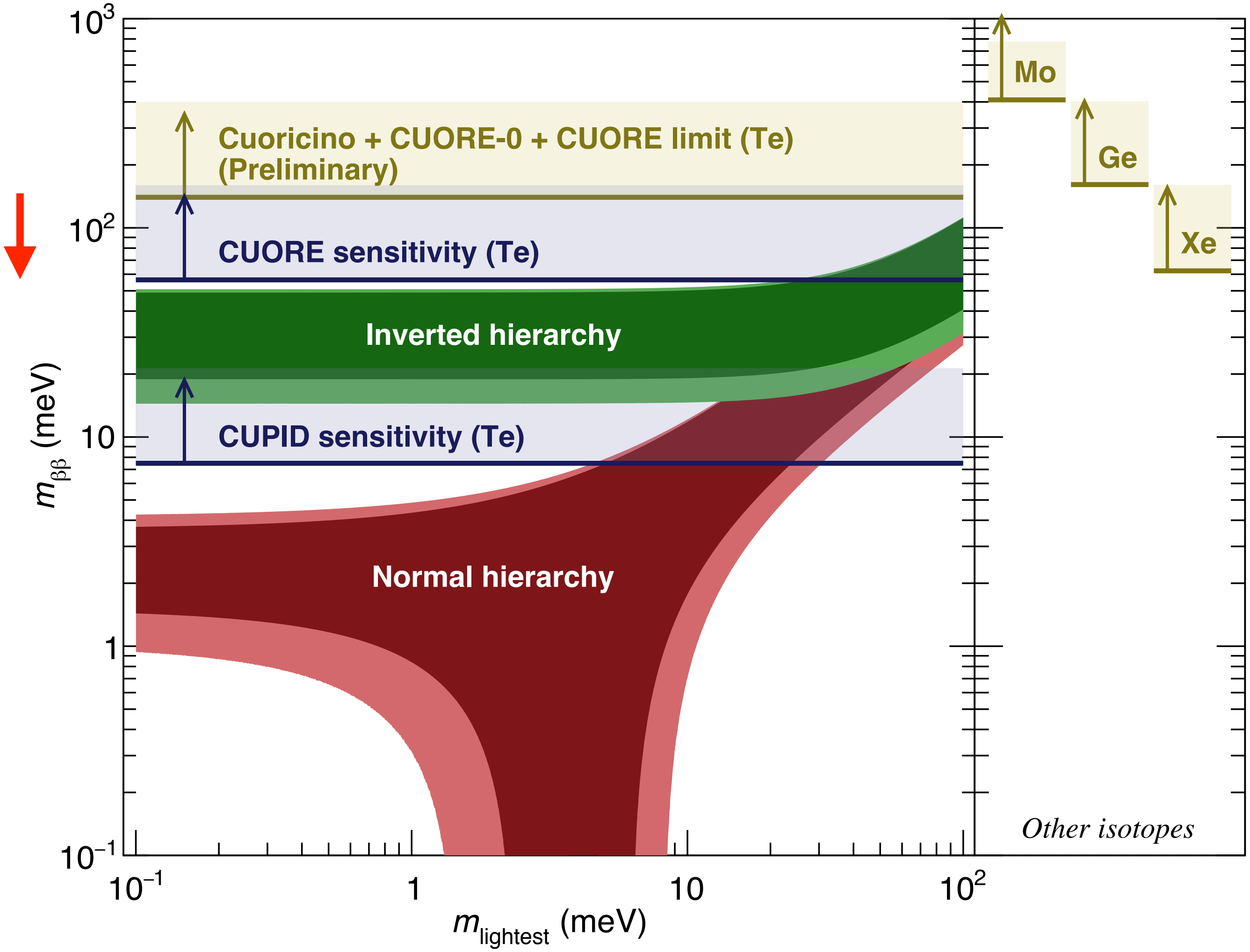




Exploring the Unexplored

5 years of CUORE data

Next-generation



Experimental Sensitivity

Half-life	Expected Signal (counts/tonne-year)
5×10^{25}	~100
5×10^{26}	~10
5×10^{27}	~1
5×10^{28}	~0.1

CUPID goal → 5×10^{27}

Sensitivity scaling:

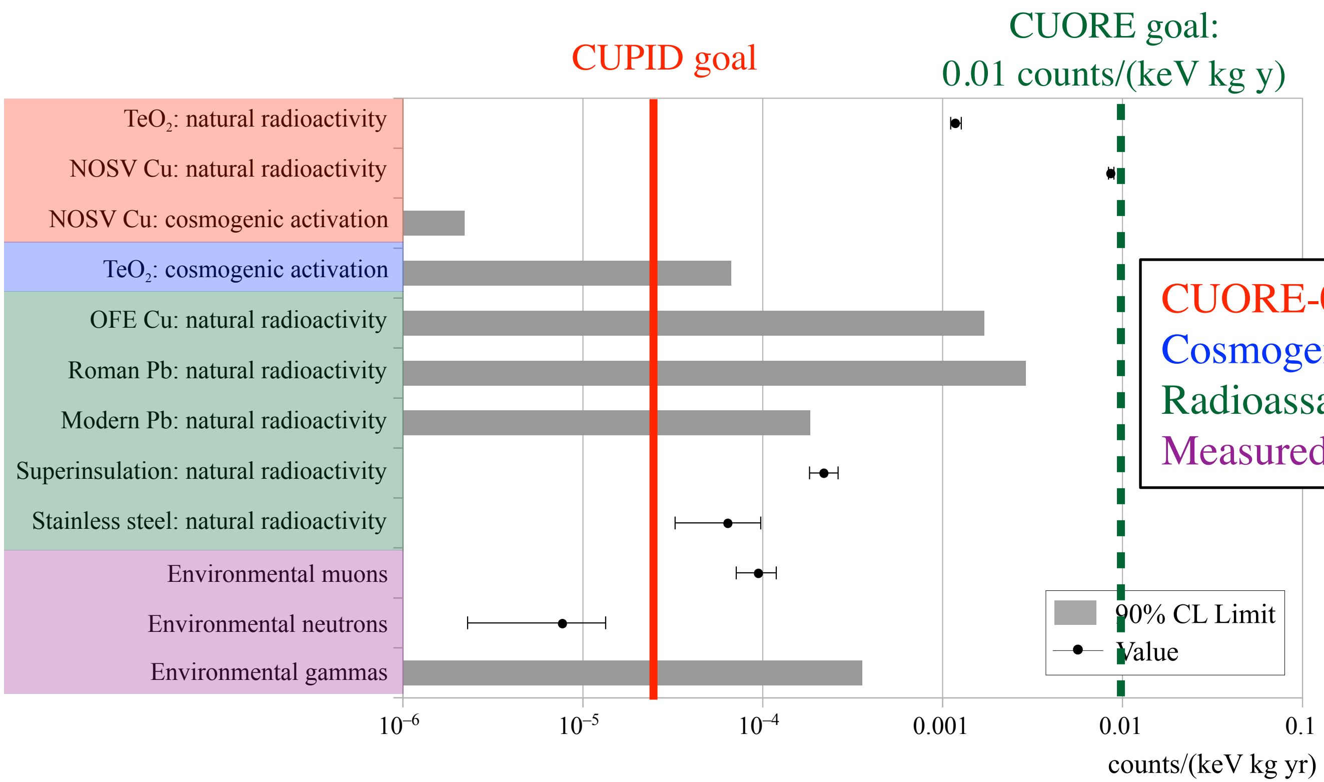
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$ (background-limited)

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$ (background-free)

Experimental challenge:

- ✓ Increase *Mass* (200-1000 kg for current experiments): $$, R&D
- ✓ Increase *Isotopic Abundance*: $$
- ✓ Decrease *Bkg* (ultimately to 2νββ limit): radiopurity, active rejection
- ✓ Decrease *ΔE*: technology choice

CUPID Background Goal



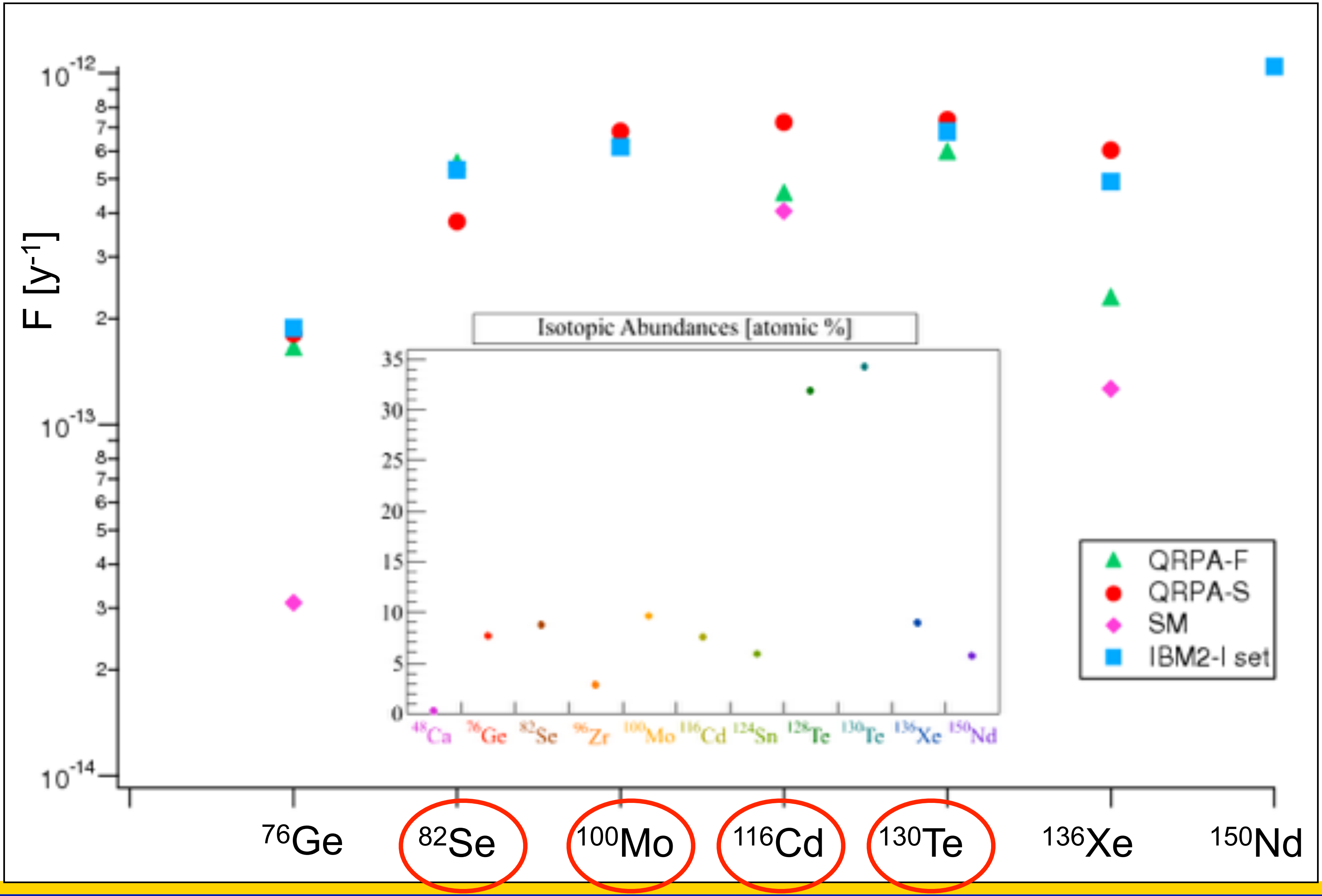
Eur.Phys.J. **C77**, 543 (2017)

CUORE-0 bkg model
Cosmogenic activation of Te
Radioassays (HPGe, NAA, ICPMS)
Measured μ, γ, n fluxes at LNGS

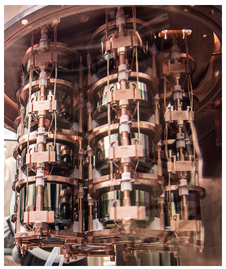
CUORE results consistent with the background model

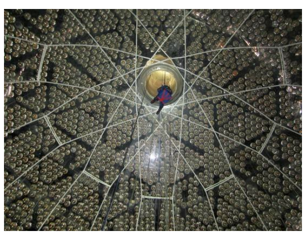
0νββ Isotopes: Figure of Merit

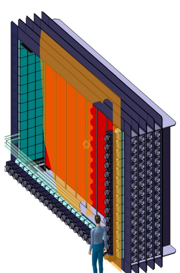
$F = G_F^2 \Phi(Q,Z) |M_{0\nu}|^2 m_e^2$ [y^{-1}] (Want as high as possible)



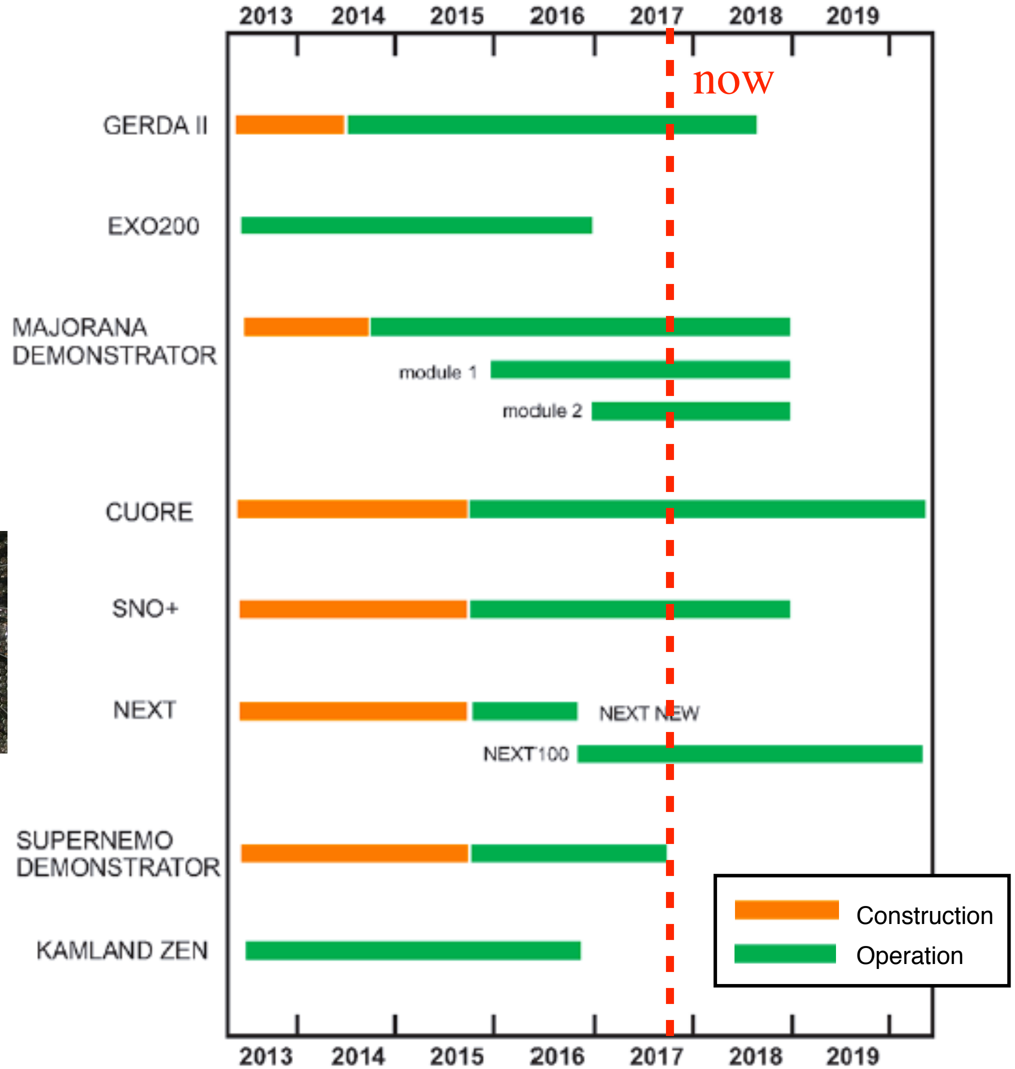
Diverse, Vibrant Program

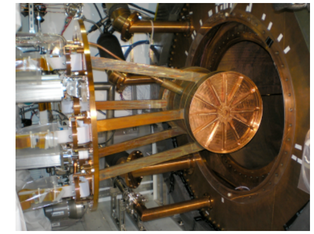


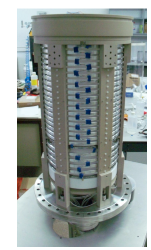


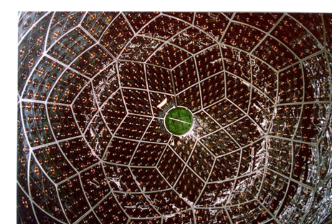


NLDBD Sub Committee Report to NSAC **(2014)**





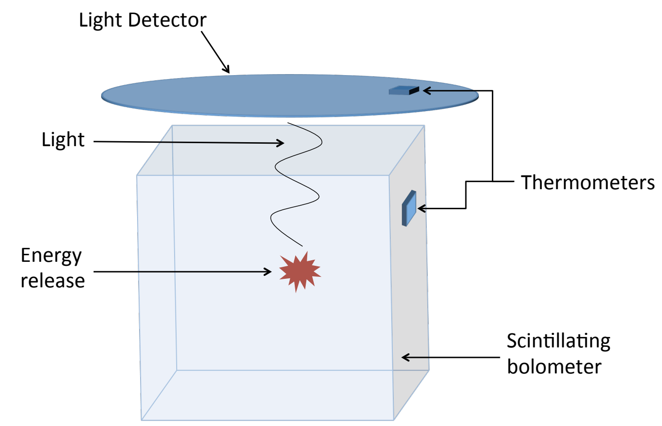




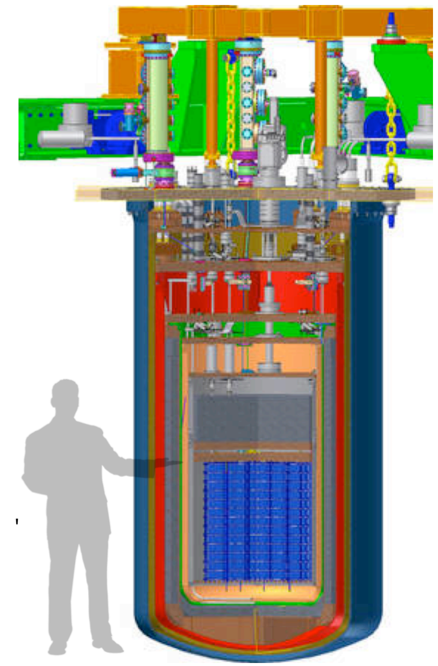
J.F. Wilkerson

CUORE Upgrade with Particle ID (CUPID)

R. Artusa et al., Eur.Phys.J. **C74**, 3096 (2014)
White papers: arXiv:1504.03599 & arXiv:1504.03612

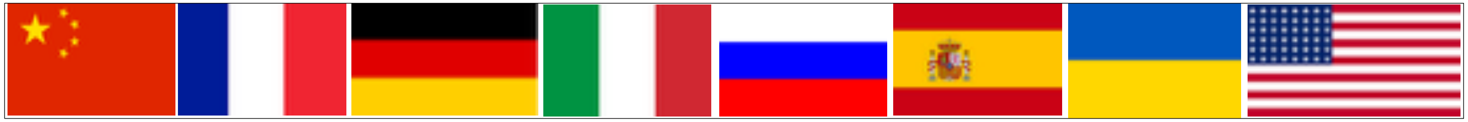


- Next-generation bolometric tonne-scale experiment
- CUORE design, proven CUORE cryogenics
- 988 enriched (90%) crystals, α rejection by detecting light (Cherenkov, scintillation)
  - Goal: nearly zero background measurement: background goal < 0.1 events / (ROI ton*year)



Subject of focused R&D effort, pilot experiments in next 1-2 years

CUPID Interest Group



High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA
Materials Science Division, Argonne National Laboratory, Argonne, IL, USA
INFN - Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Department of Nuclear Engineering, University of California, Berkeley, CA, USA
Department of Physics, University of California, Berkeley, USA
Università di Bologna and INFN Bologna, Bologna, Italy
Massachusetts Institute of Technology, Cambridge, MA, USA
Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
Technische Universität München, Physik-Department E15, Garching, Germany
Dipartimento di Fisica, Università di Genova and INFN - Sezione di Genova, Genova, Italy
Institute for Nuclear Research, Kyiv, Ukraine
INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy
Lawrence Livermore National Laboratory, Livermore, CA, USA
Department of Physics and Astronomy, University of California, Los Angeles, CA, USA
INFN sez. di Milano Bicocca and Dipartimento di Fisica, Università di Milano Bicocca, Italy
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Nikolaev Institute of Inorganic Chemistry, SB RAS, Novosibirsk, Russia
Sobolev Institute of Geology and Mineralogy, SB RAS, Novosibirsk, Russia
Centre de Sciences Nuclèaires et de Sciences de la Matière (CSNSM), CNRS/IN2P3, Orsay, France
INFN - Sezione di Padova, Padova, Italy
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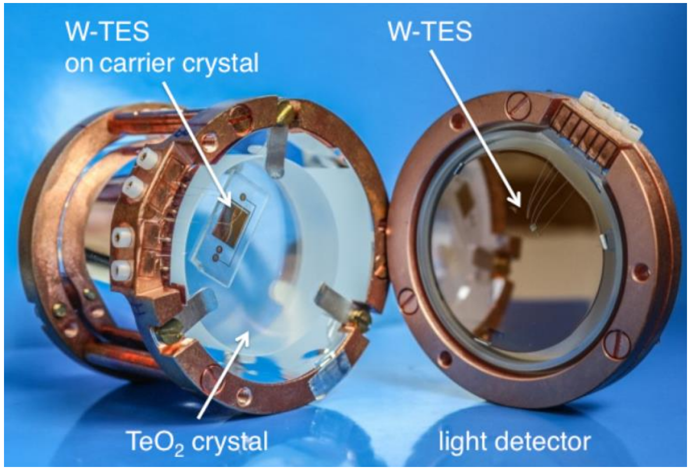
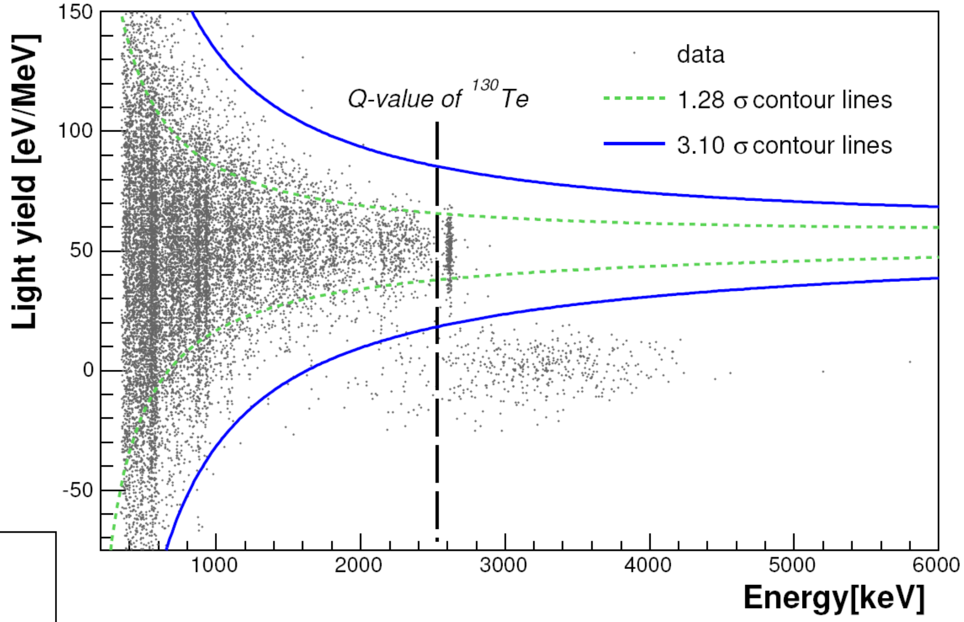
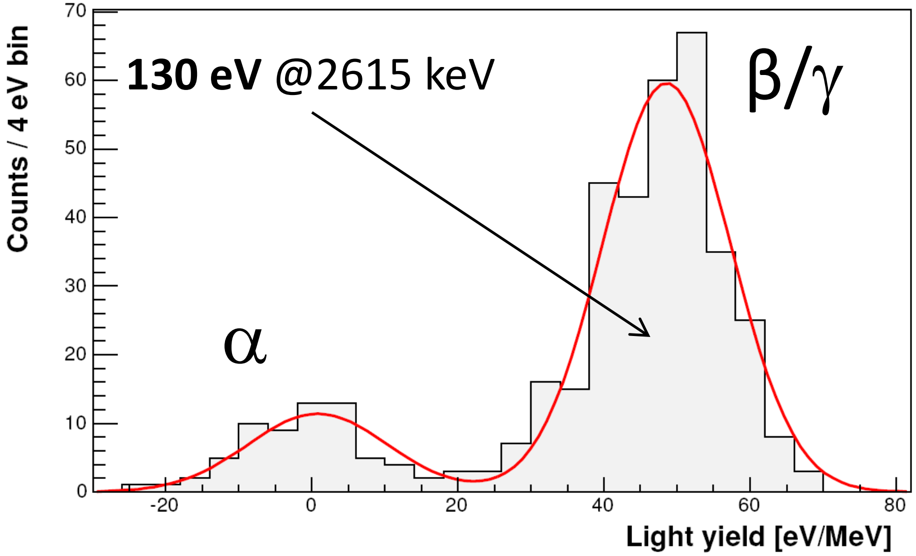
Wright Laboratory, Department of Physics, Yale University, New Haven, CT, USA
Laboratorio de Fisica Nuclear y Astropartculas, Universidad de Zaragoza, Zaragoza, Spain

Cherenkov Detection in TeO_2







Event-by-event α/β discrimination requires light detectors with ~15-20 eV resolution

TES-based light detectors:

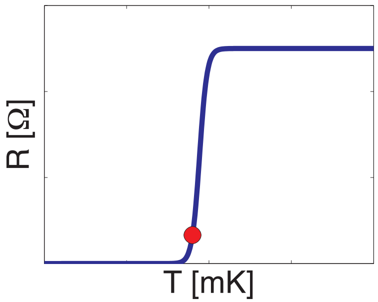
- CRESST/LUCIFER: W-based detectors
- US (Berkeley/Argonne): bilayer TES

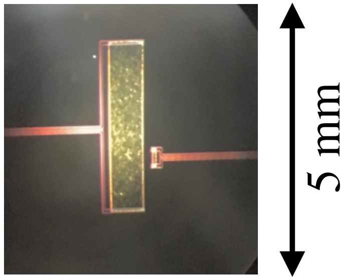
K. Schaeffner et al, Astrop. Phys. 69, 30 (2015)

R&D: Superconducting Sensors

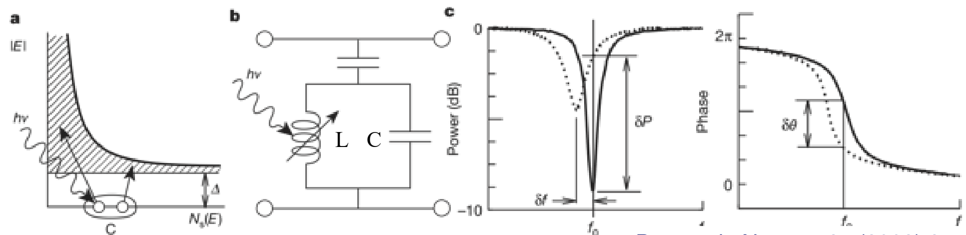
Transition-Edge Sensors (TES)

Bias point

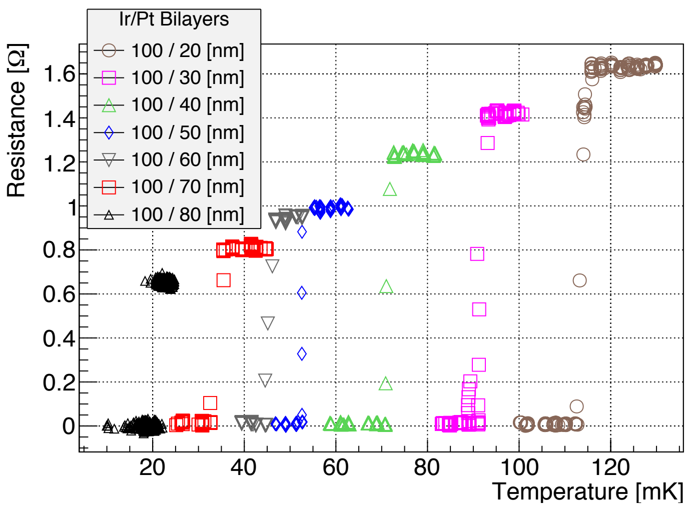




Kinetic Inductance Detectors (KID)



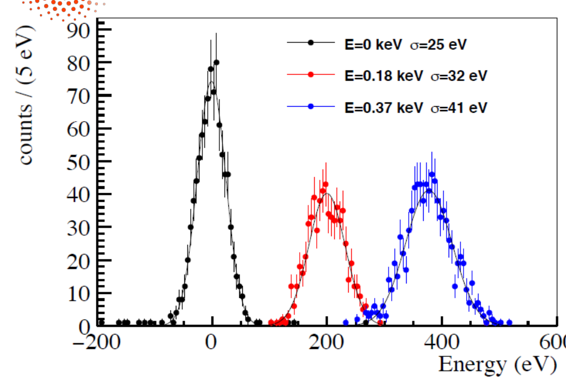
Day et al., Nature 425 (2003) 817



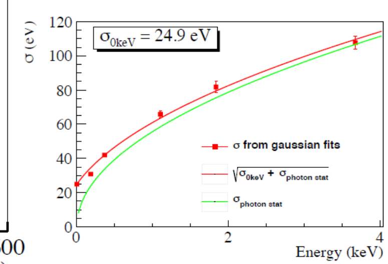
R. Hennings-Yeomans et al., in preparation
LBNL, UCB, ANL

CALDER: ERC Advanced Grant

Energy scan with optical fiber

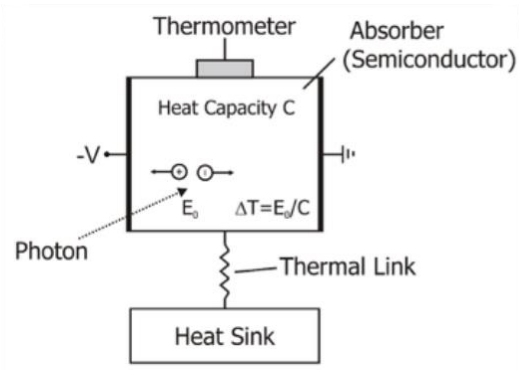


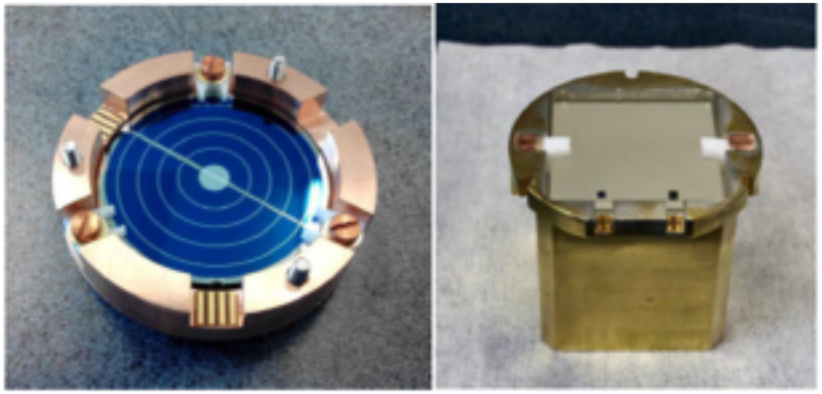
Self-calibrated with photon statistics

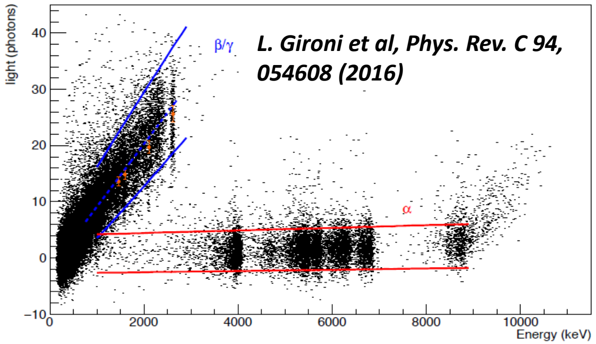


E.S. Battistelli, et al, EPJ C75 (2015) 353
L. Cardani et al, APL 110 (2017) 033504

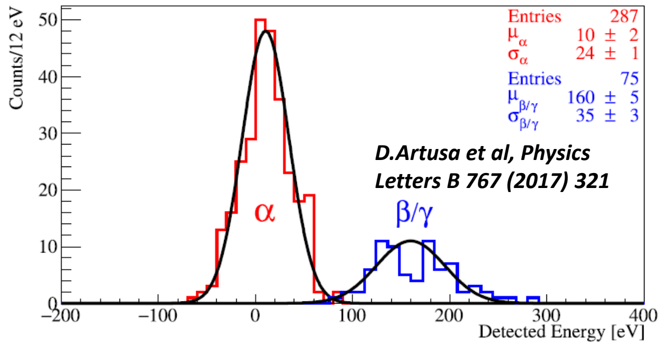
R&D: Luke-Neganov Light Detectors



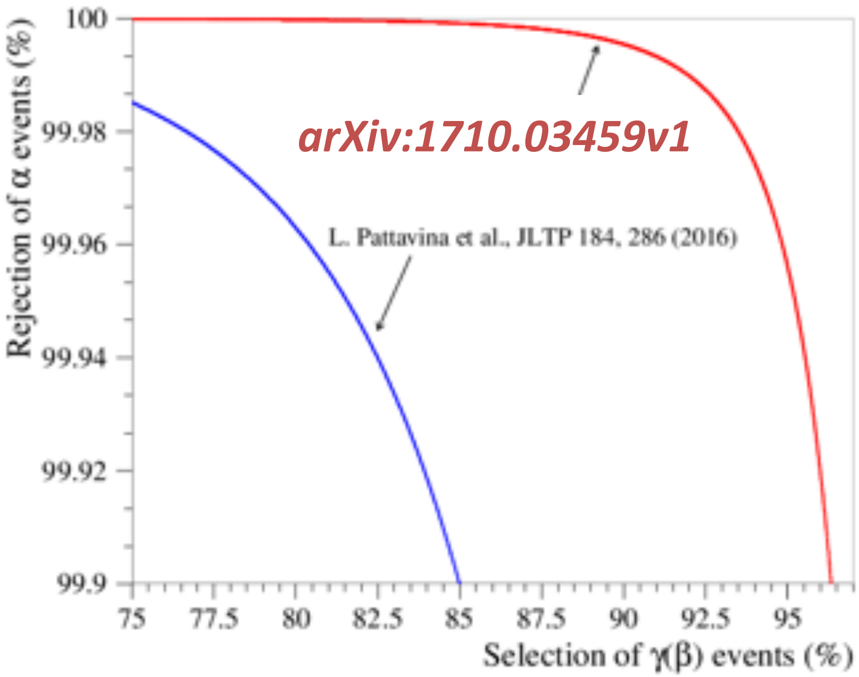




L. Gironi et al, Phys. Rev. C 94, 054608 (2016)

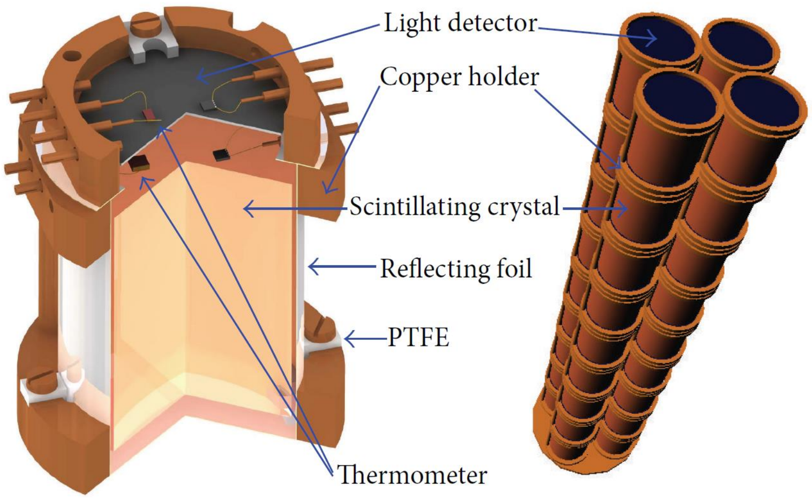


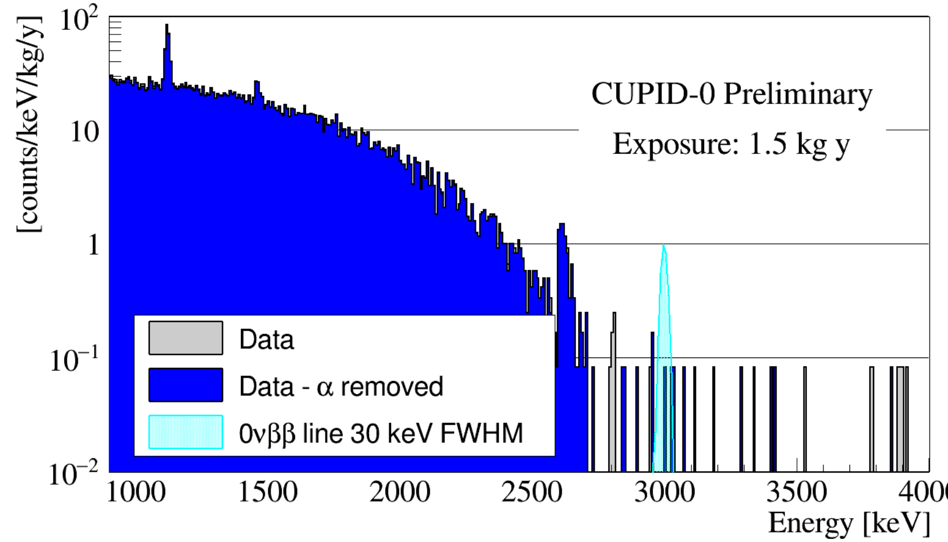
D.Artusa et al, Physics Letters B 767 (2017) 321



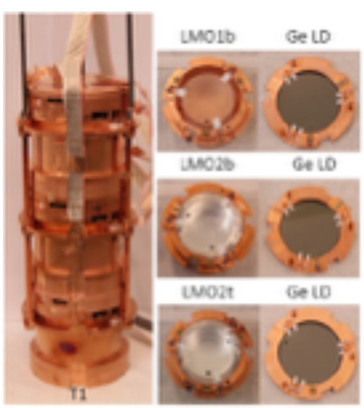
Scintillating Bolometer Pilot Experiments

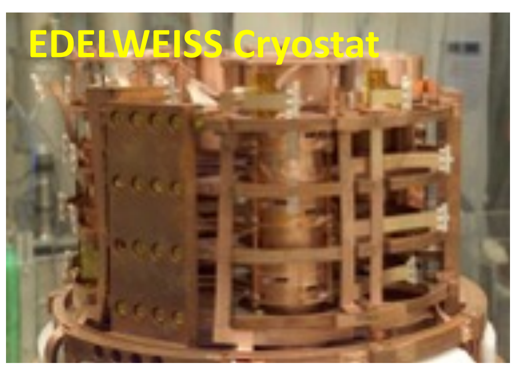
CUPID-0/Se @ LNGS: $Zn^{82}Se$: 2017

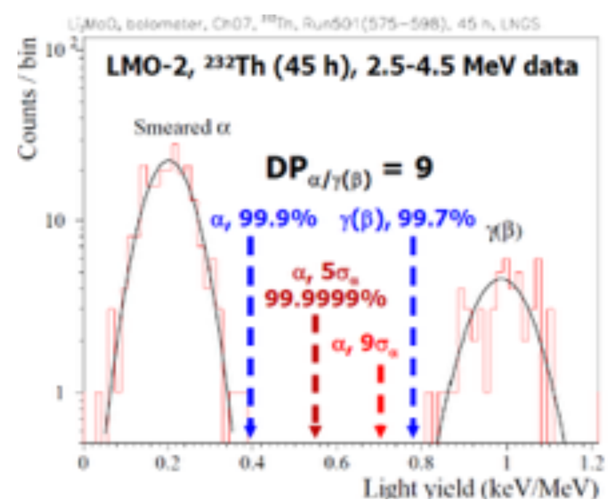




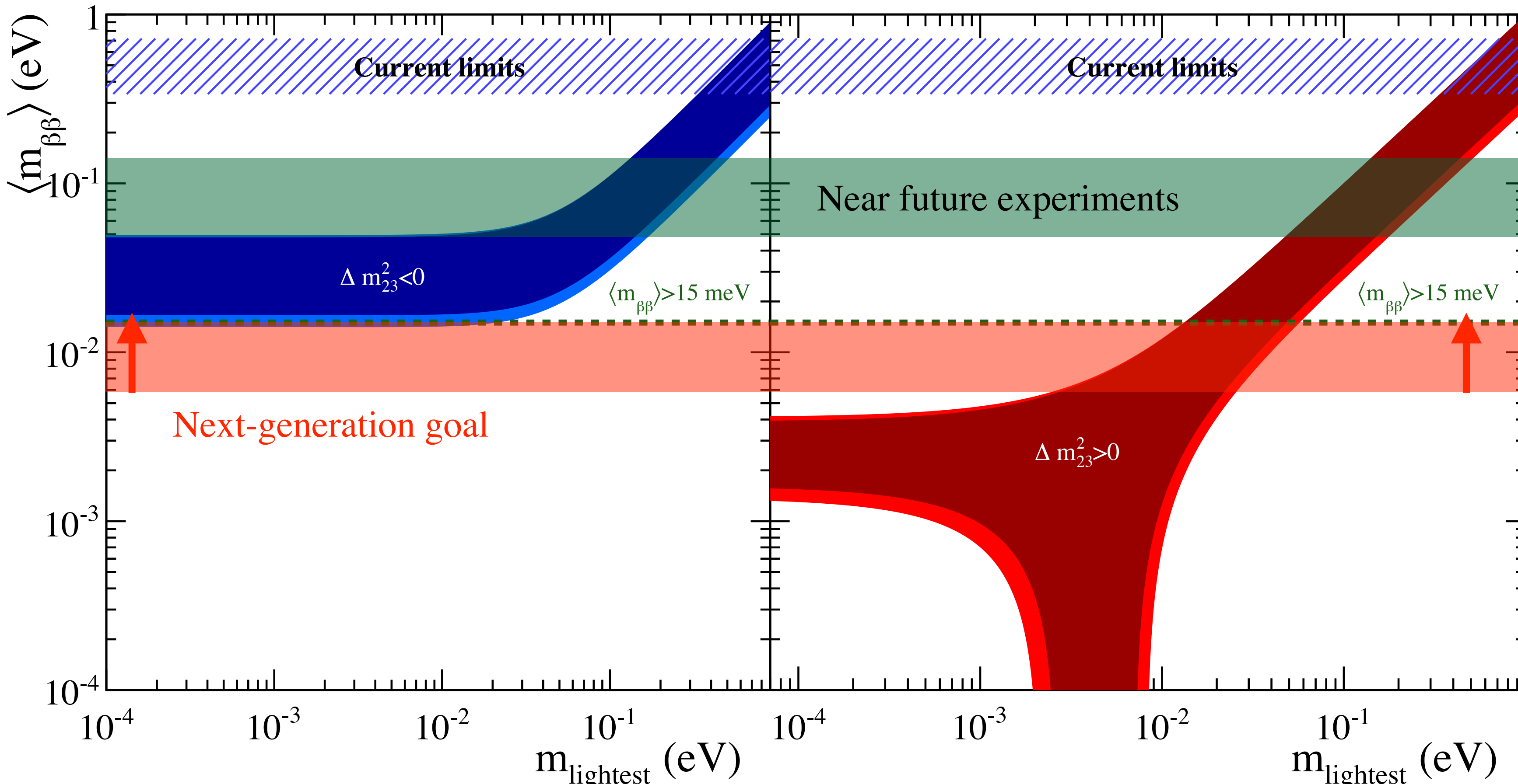
CUPID-0/Mo @ Modane: $Li_2{}^{100}MoO_4$: early 2018







DBD and Neutrino Mass



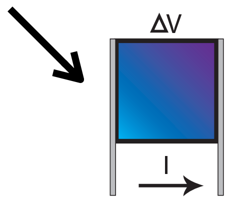
Exciting future ahead !

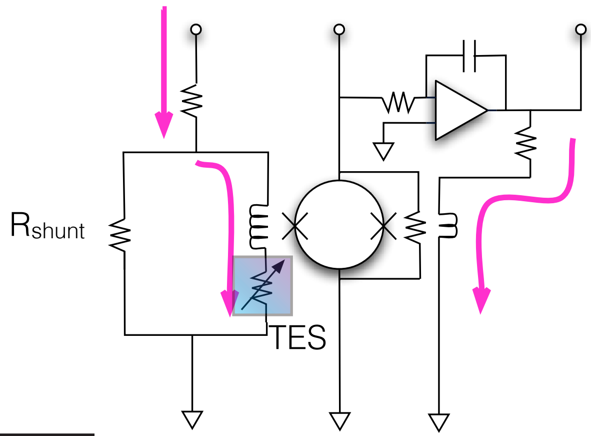
$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

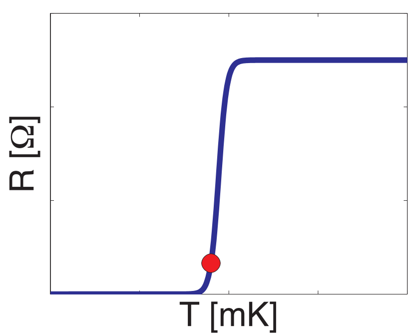
Backup

Transition Edge Sensors

Superconducting Film







$$\Delta E_{rms} = \sigma_E \approx \sqrt{\frac{4k_B T^2 C_{tot}}{\alpha}\sqrt{\frac{\beta+1}{2}}},$$

C_{tot} = C_{bolo} (~T^3) + C_{TES} (~T) + C_{other} (e.g. caused by impurities in the crystal)

K.D. Irwin, Appl. Phys. Lett. Vol. 66, 1998 (1995)

$$\alpha \equiv \frac{T}{R}\frac{dR}{dT}$$

β: determined by thermal conductivity between the TES and absorber/heat-bath

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Low Tc TES fabrication:

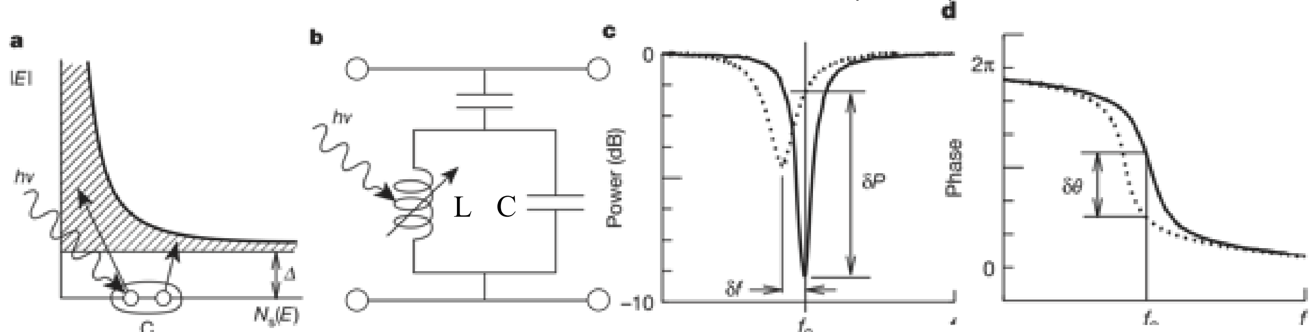
- W-TES may be possible through ion implantation
- Grow W-alpha phase for Low Tc
- Or we can utilize superconducting bilayers as TES (proximity effect)
- Minimize # TES and SQUIDs on detector
- SQUIDs can be readout in arrays al large as up to 10,000

R. Hennings-Yeomans

Kinetic Inductance Detectors

CALDER R&D

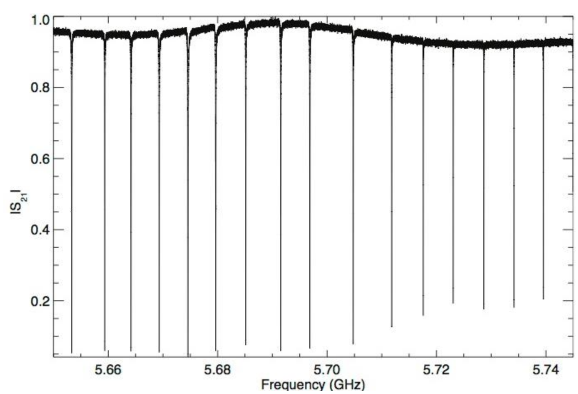
Kinetic Inductance Detectors (KIDs)



Day et al., Nature 425 (2003) 817

Cooper pairs (cp) in a superconductor act as an inductance (*L*). Photons or phonons can break cp and change *L*.

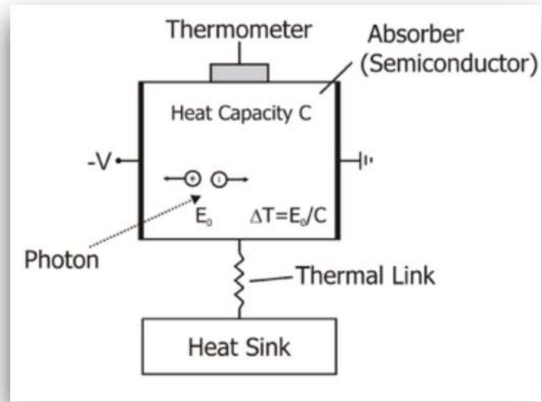
High quality factor (*Q*) resonating circuit biased with a microwave (GHz): signal from amplitude and phase shift.



- ✓ Multiplexing: different resonators can be coupled to the same feedline.
- ✓ A single cryogenic amplifier can be used to read up to 1000 detectors.
- ✓ High reproducibility and ease of fabrication.
- ✓ Insensitive to microphonic noise, week temperature dependence.

Ezio Previtali – 103° Congresso Nazionale SIF – Trento 15-9-17

Luke-Neganov Amplification



Total energy deposited in the absorber with applied field V:

$$E_{TOT} = \frac{E}{\epsilon} eV + E$$

Ec   Voltage

Amplification Factor

$$G = 1 + \frac{eV}{\epsilon}$$

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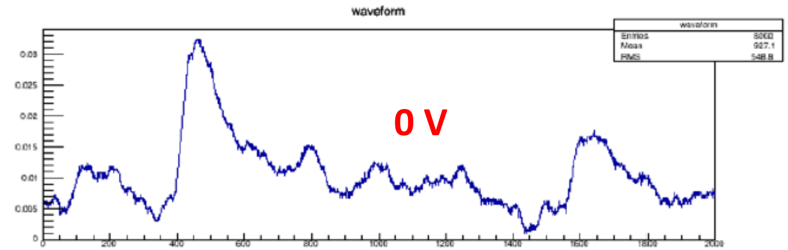
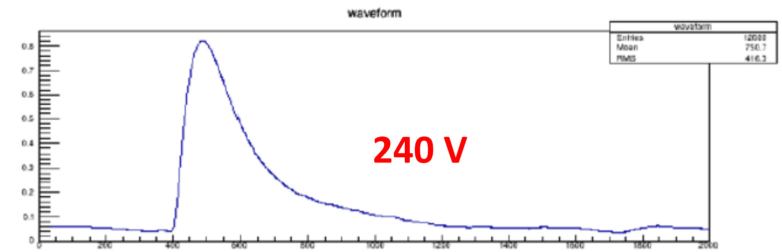
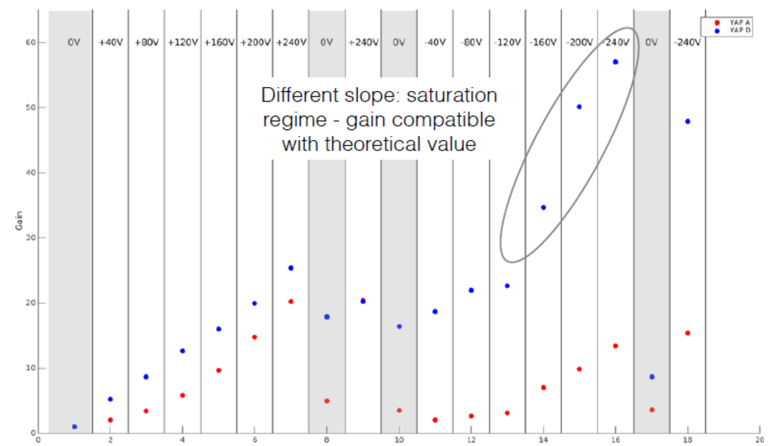
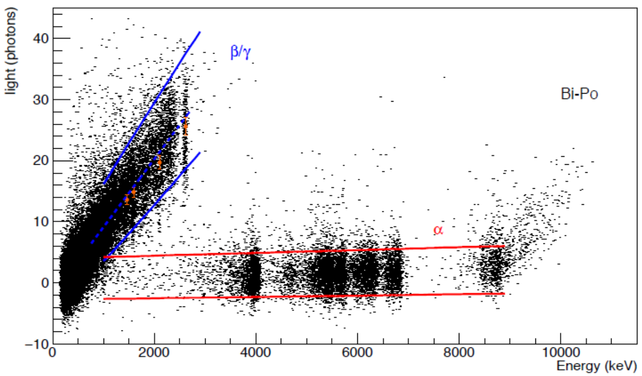


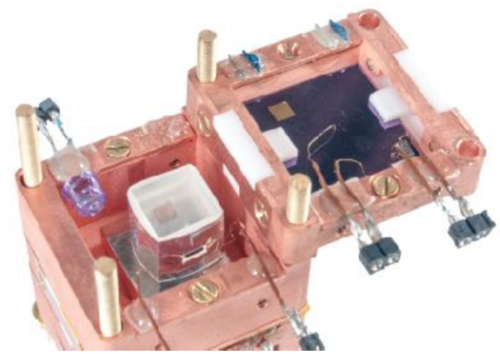




α Discrimination in LN Detectors

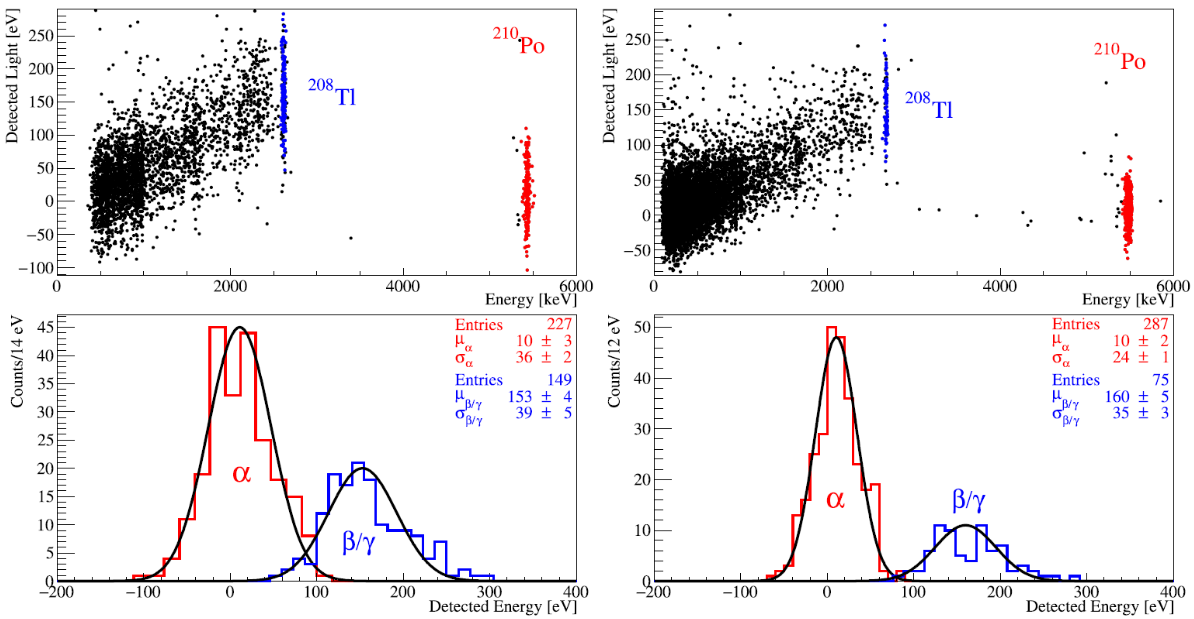
CUORE





Cerenkov light measured with **Si-Luke light detecto** on **small (1x1x1 cm³) TeC crystal**

L. Gironi et al, Phys. Rev. C 9 054608 (2016)



Cerenkov light measured with **Ge-Luke** light detector on **CUORE like (5x5x5 cm³) TeO_2 crystal**

D.Artusa et al, Physics Letters B 767 (2017) 321

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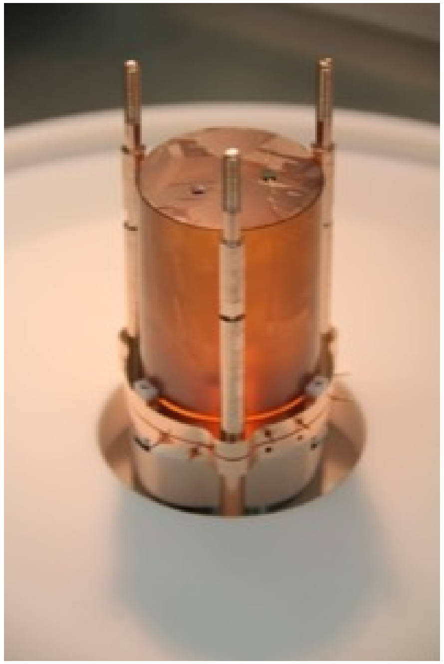
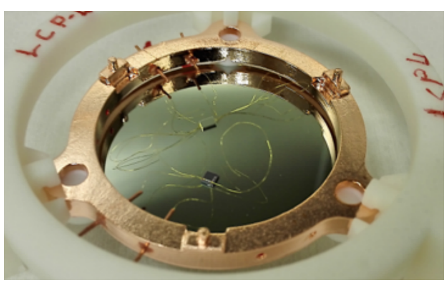
CUPID-0/Se





24 $Zn^{82}Se$ CRYSTALS

Mass = 9.65 kg
Se enrichment in ^{82}Se at 96%
^{82}**Se** Mass = 5.17 kg $N_{\beta\beta} = 3.8\ 10^{25}$

2 $ZnSe$ CRYSTALS

Mass = 0.85 kg
Se natural ^{82}Se at 8.7%

31 Ge LIGHT DETECTORS

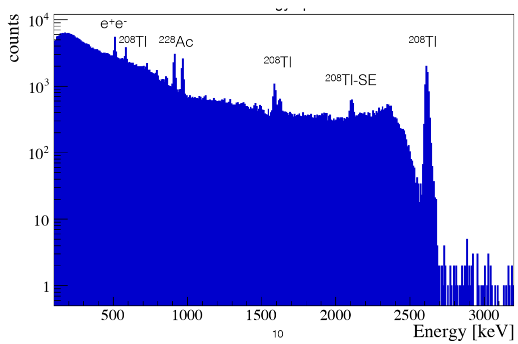
hyperpure Ge wafers
diameter = 44.5 mm ($\simeq$ ZnSe crystals)
thickness = 0.17 mm

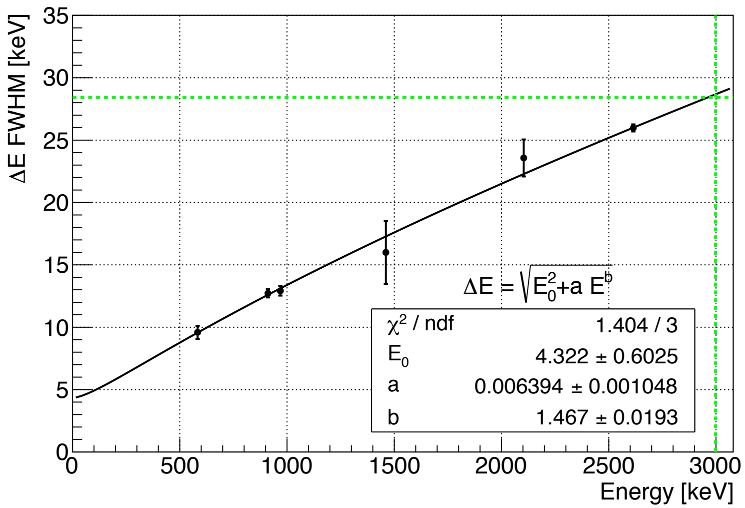
M. Pavan

CUPID-0/Se

sum calibration spectrum

M. Pavan





<FWHM>

noise $\rightarrow \sim 0.4\ keV$

2615 $keV \rightarrow \sim 25\ keV$

major contribution from crystal quality

at ^{82}Se $Q_{\beta\beta} = 2998\ keV$ resolution is extrapolated

<FWHM> at $Q_{\beta\beta}$

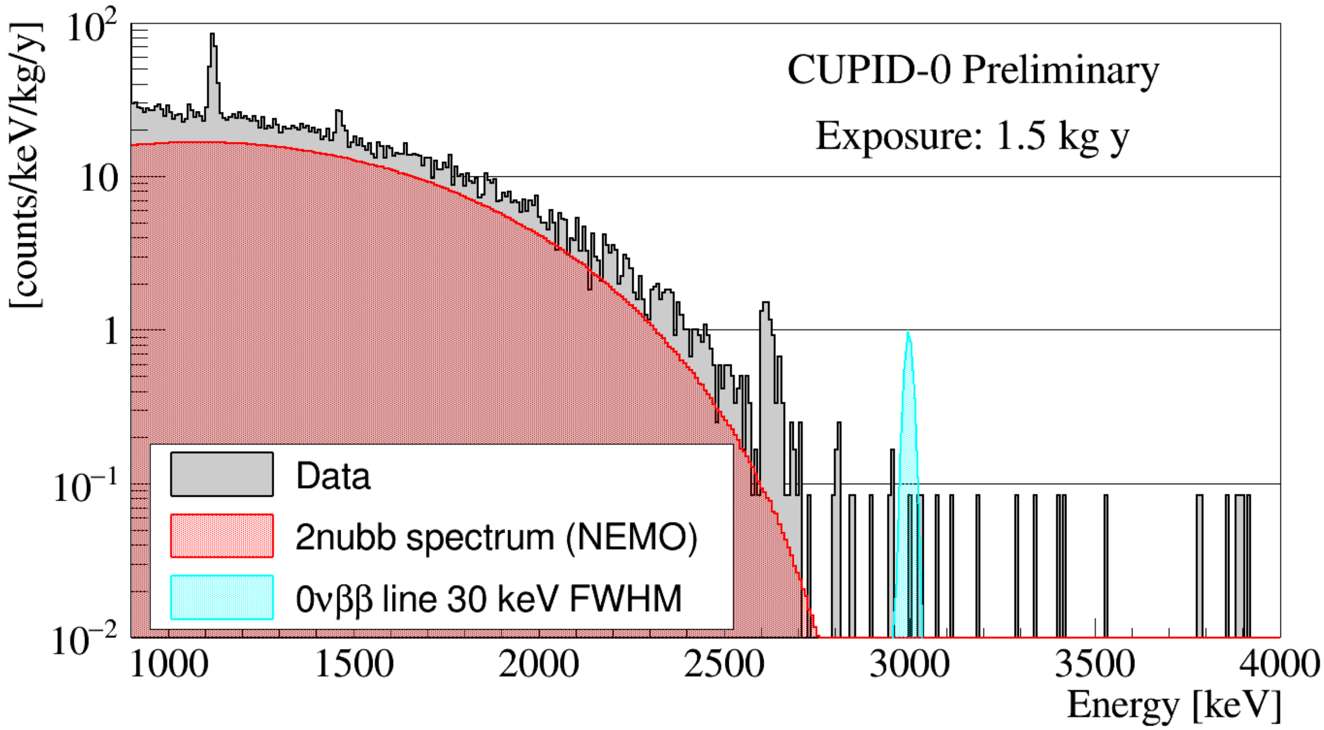
SR1 $\rightarrow 29.2 \pm 2.0\ keV$

SR2 $\rightarrow 27.0 \pm 1.0\ keV$

CUPID-0/Se

M. Pavan

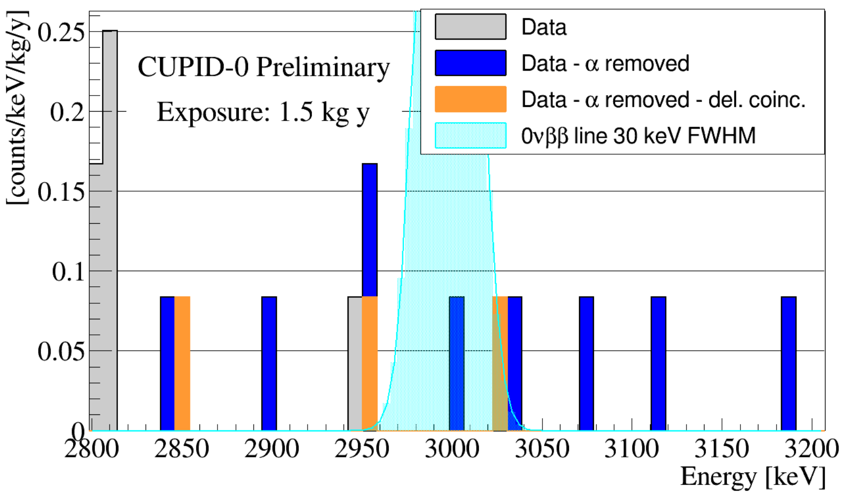
- M1 (only single hit events) + PSA on HEAT
- $\beta\beta2\nu$ spectrum normalized to NEMO [1]

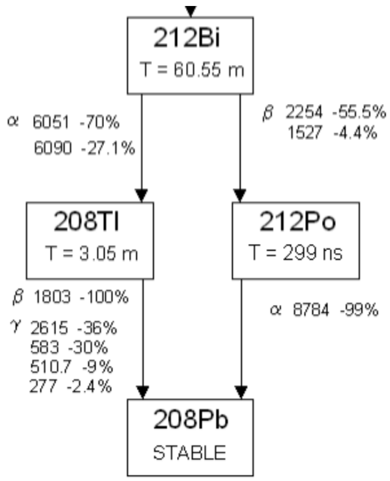


[1] NEMO measurement of ^{82}Se $\beta\beta2\nu$ half-life (arXiv:1105.2435 [hep-ex])

CUPID-0/Se

M. Pavan





CUTS summary

M1 (single hit cut)
PSA on HEAT
PSA on LIGHT (remove α)
Delayed Coinc.

ROI = [2800, 3200] keV

N. of Events = 3
$[2.2\text{-}8.6]\cdot 10^{-3} c/(keV\ y\ kg)$
$\epsilon_{0\nu\beta\beta} \sim 80\%$
$\epsilon_{cuts} > 85\%$

Surface-Sensitive Bolometers

ERC advanced grant CROSS (start 1/1/2018)

Cryogenic **R**are-event **O**bservatory with **S**urface **S**ensitivity

CROSS is a bolometric experiment to search for 0ν-DBD

- **Core of the project** (high risk / high gain)
  Background rejection through **pulse shape discrimination**
  - **Surface sensitivity** through **superconductive Al film coating**
  - **Fast NbSi high-impedance TES** to replace / complement NTDs

  → **get rid of light detectors**
- Complete crystallization of available ^{100}**Mo (10 kg)** in Li_2MoO_4 elements
- Purchase / crystallize ^{130}**Te (up to 15 kg)** in TeO_2 elements
- Run demonstrator in a dedicated cryostat (LSC – Spain)

A. Giuliani