Neutrinoless Double-Beta Decay and Bolometric Search with CUORE

May 11, 2016
Tokyo, Japan

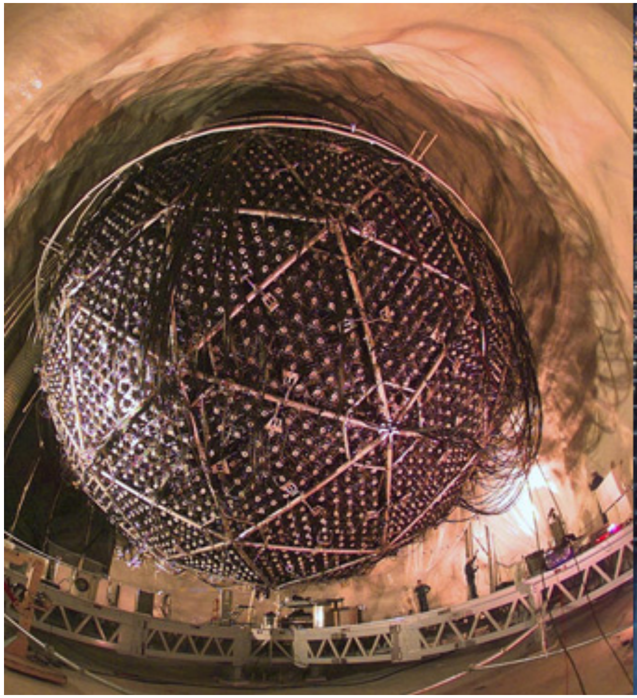
Yury Kolomensky
UC Berkeley/LBNL

Overview

- Neutrinoless Double Beta Decay
- CUORE: tonne-scale bolometric $0\nu\beta\beta$ experiment
  - CUORE-0 Results
  - CUORE status and outlook
- Future upgrade: CUPID

Year of Neutrinos

Year of Neutrinos



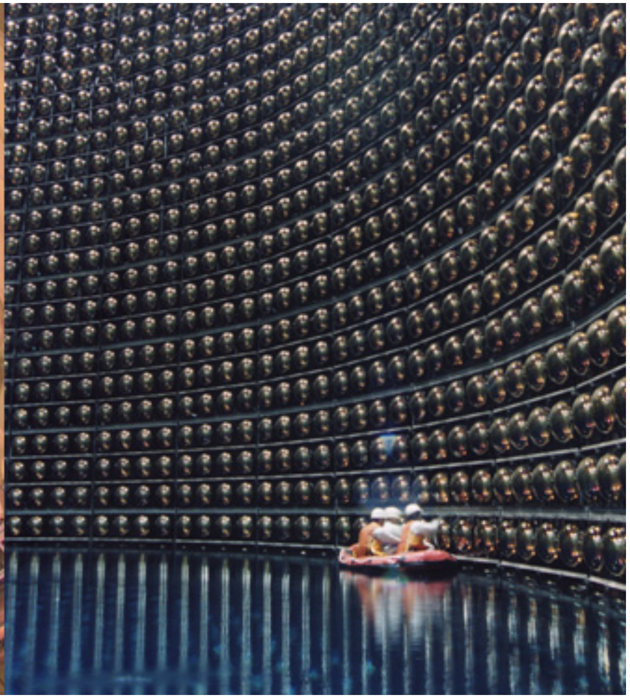


Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

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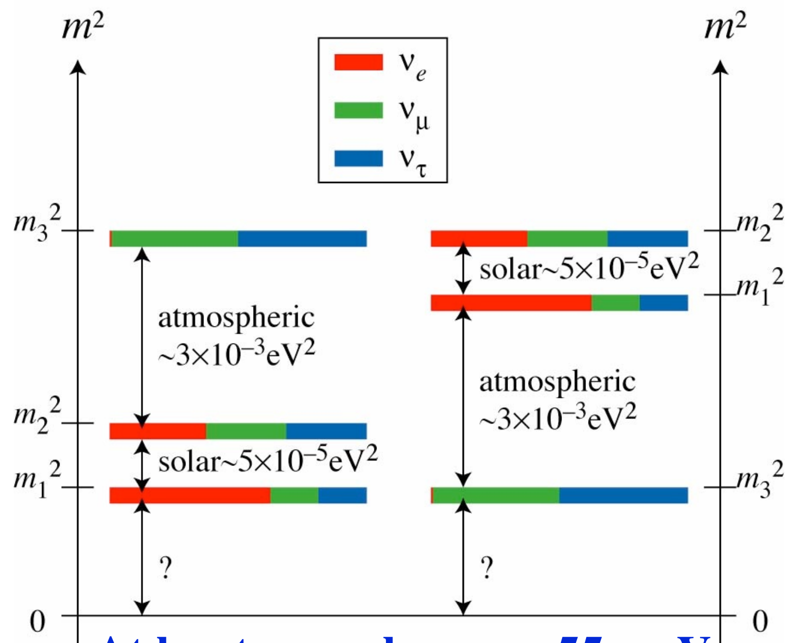
CUORE

Year of Neutrinos

Neutrino Physics Landscape

Neutrino mass hierarchy

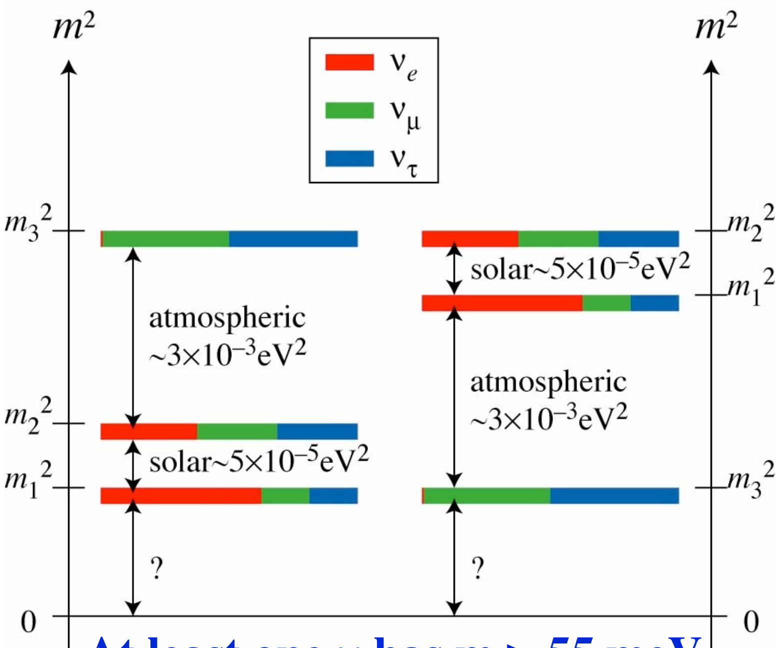


At least one ν has m > 55 meV

Neutrino Physics Landscape

- Compelling evidence for
  - Neutrino flavor-changing oscillations
  - (therefore) finite neutrino masses
  - Mixing angles are well measured

Neutrino mass hierarchy

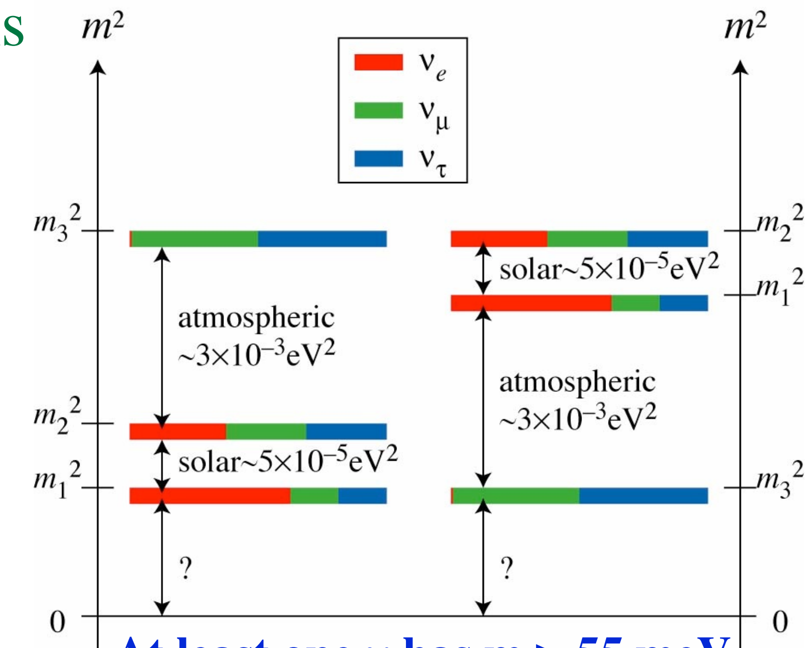


At least one ν has m > 55 meV

Neutrino Physics Landscape

- Compelling evidence for
  - Neutrino flavor-changing oscillations
  - (therefore) finite neutrino masses
  - Mixing angles are well measured
- Open questions in ν Physics:
  - How many neutrinos?
    - ☞ Sterile neutrinos ?
  - What is absolute scale of ν mass ?
  - How are masses arranged ?
  - Are neutrinos responsible for matter-antimatter asymmetry ?
  - Majorana or Dirac neutrinos ?
  - Is Lepton Number conserved ?

Neutrino mass hierarchy



At least one ν has m > 55 meV

Dirac vs Majorana Neutrinos

- Understanding how neutrinos acquire mass is of fundamental importance

- Dirac
  - Requires new fundamental global symmetry $U(1)_{\text{lepton number}}$
    - ☞ New physics ?
    - ☞ Matter and antimatter are fundamentally different

- Majorana
  - Cannot be explained by "standard" Higgs Yukawa coupling
    - ☞ New physics ?
    - ☞ Potentially sensitive to very high mass scales
    - ☞ Can generate matter⇔antimatter transitions

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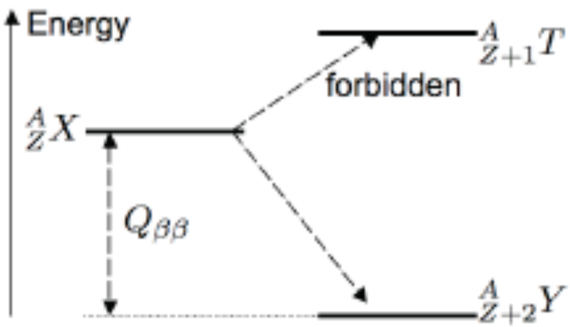
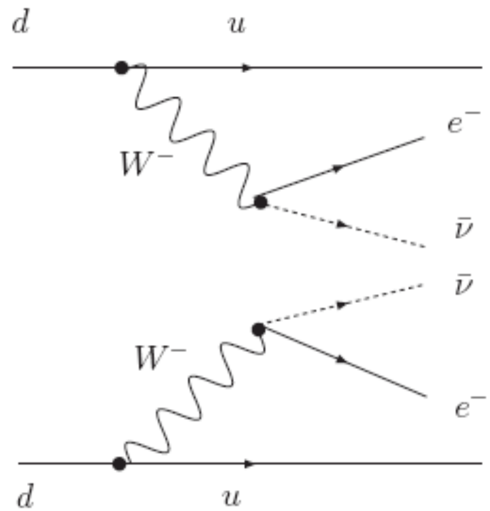
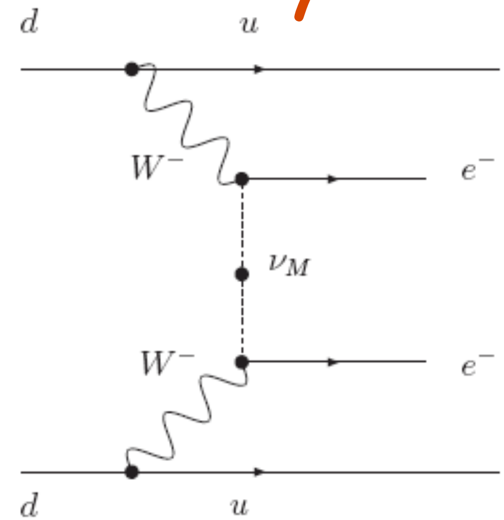
?

Neutrinoless Double-Beta Decay

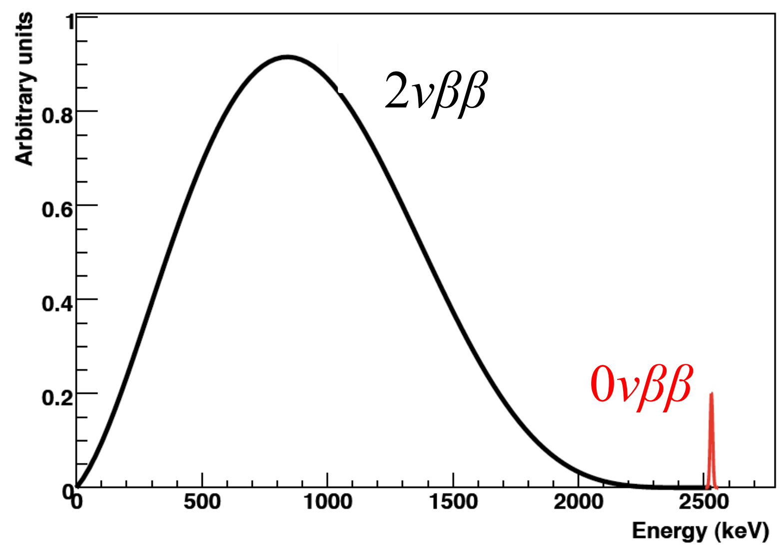




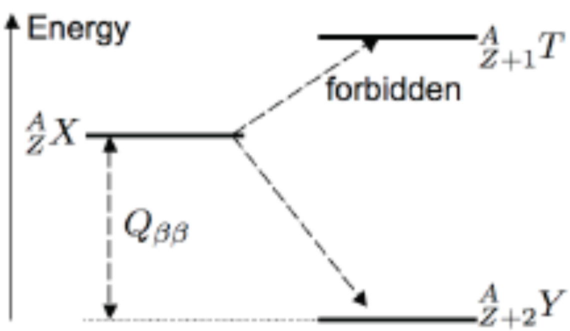
SM 2νββ decay $\tau \geq 10^{19}$ y

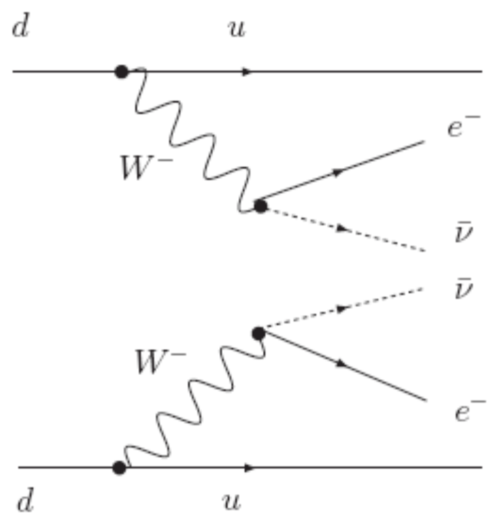


0νββ $\tau \geq 10^{25}$ y



Neutrinoless Double-Beta Decay





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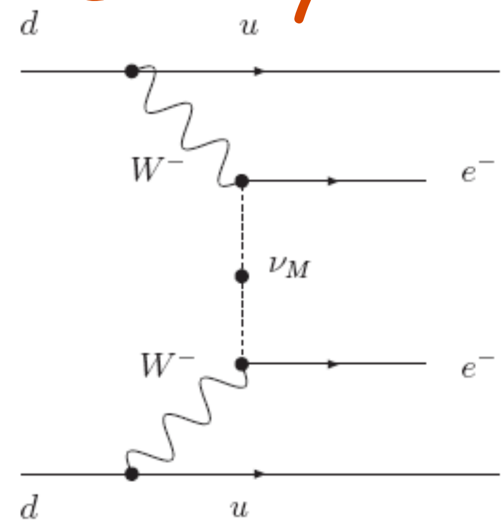
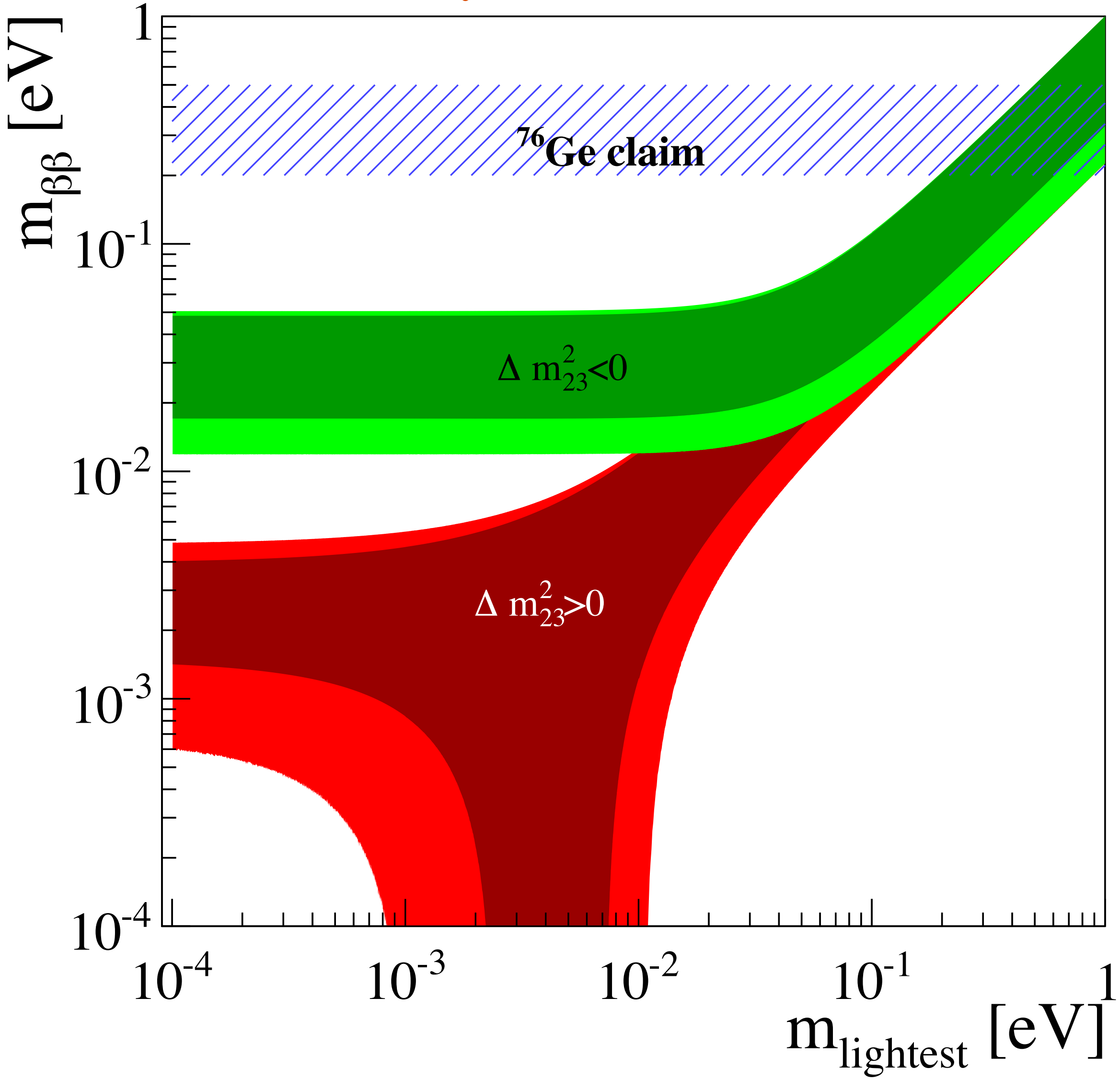


0νββ $\tau \geq 10^{25}$ y

- Observation of 0νββ would mean
  - Lepton number violation
  - Neutrinos are Majorana particles
  - Rate measures (effective) electron neutrino mass

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

Experimental Sensitivity



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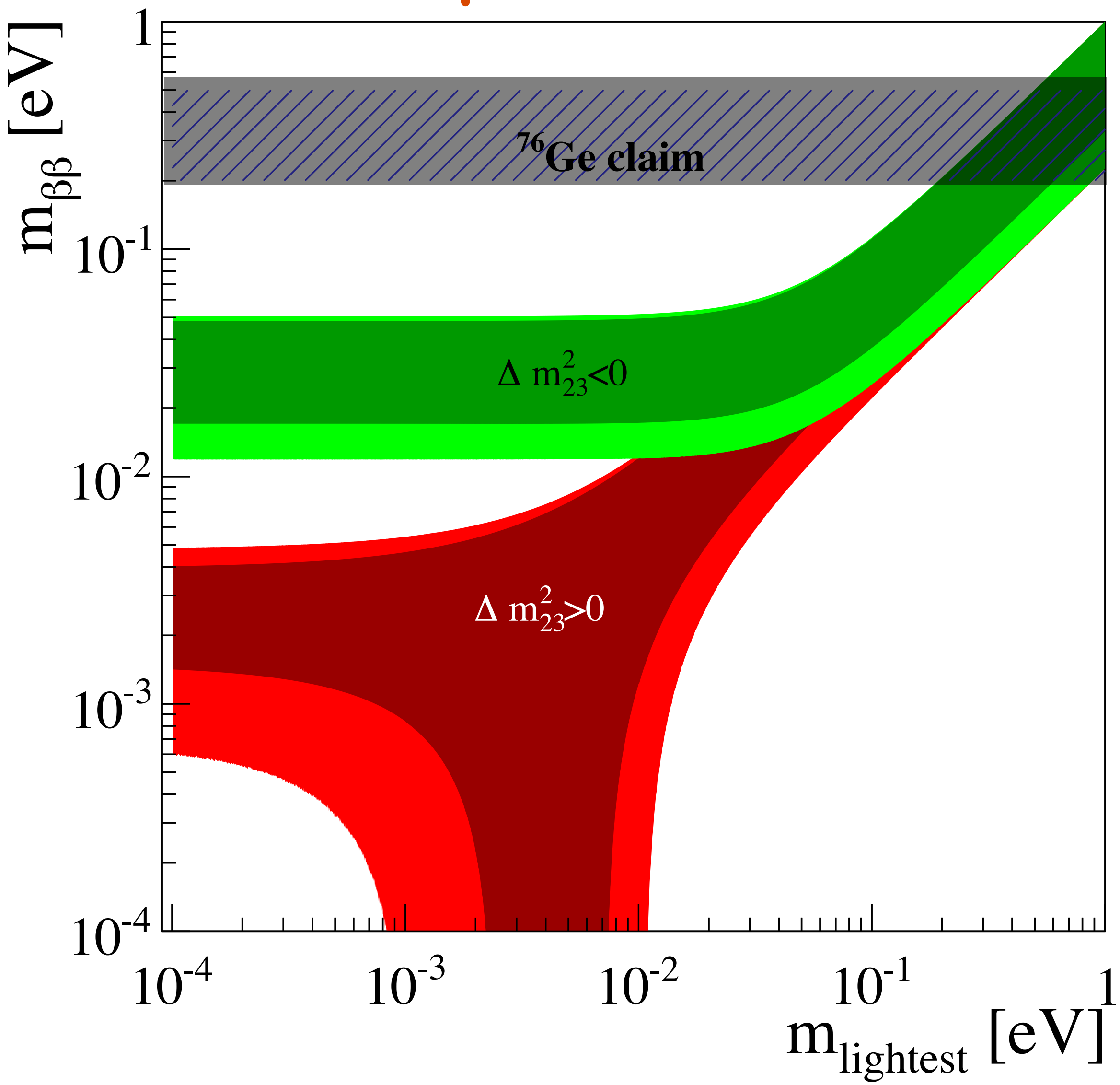
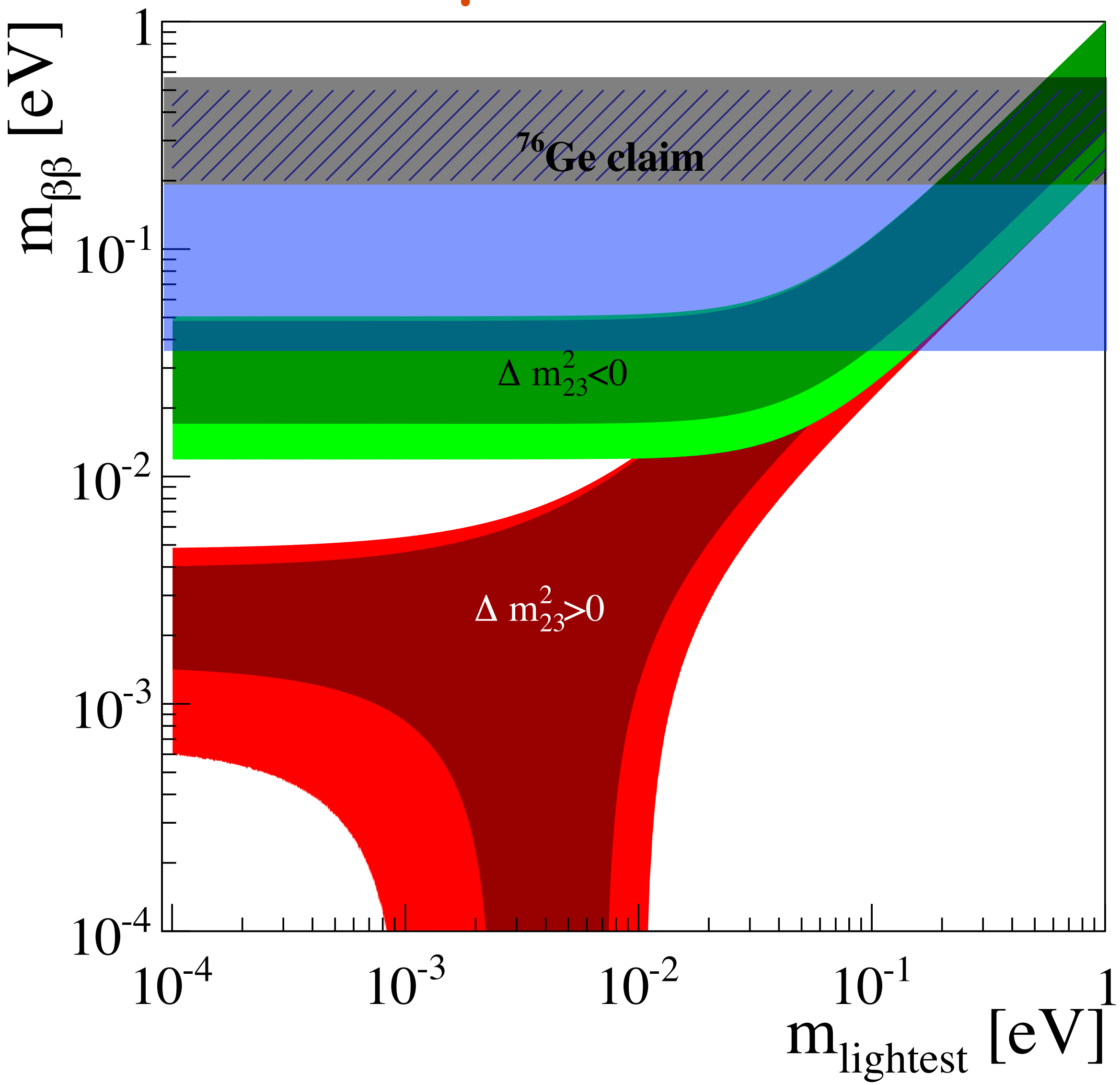


Past and present (~10 kg)

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

Experimental Sensitivity

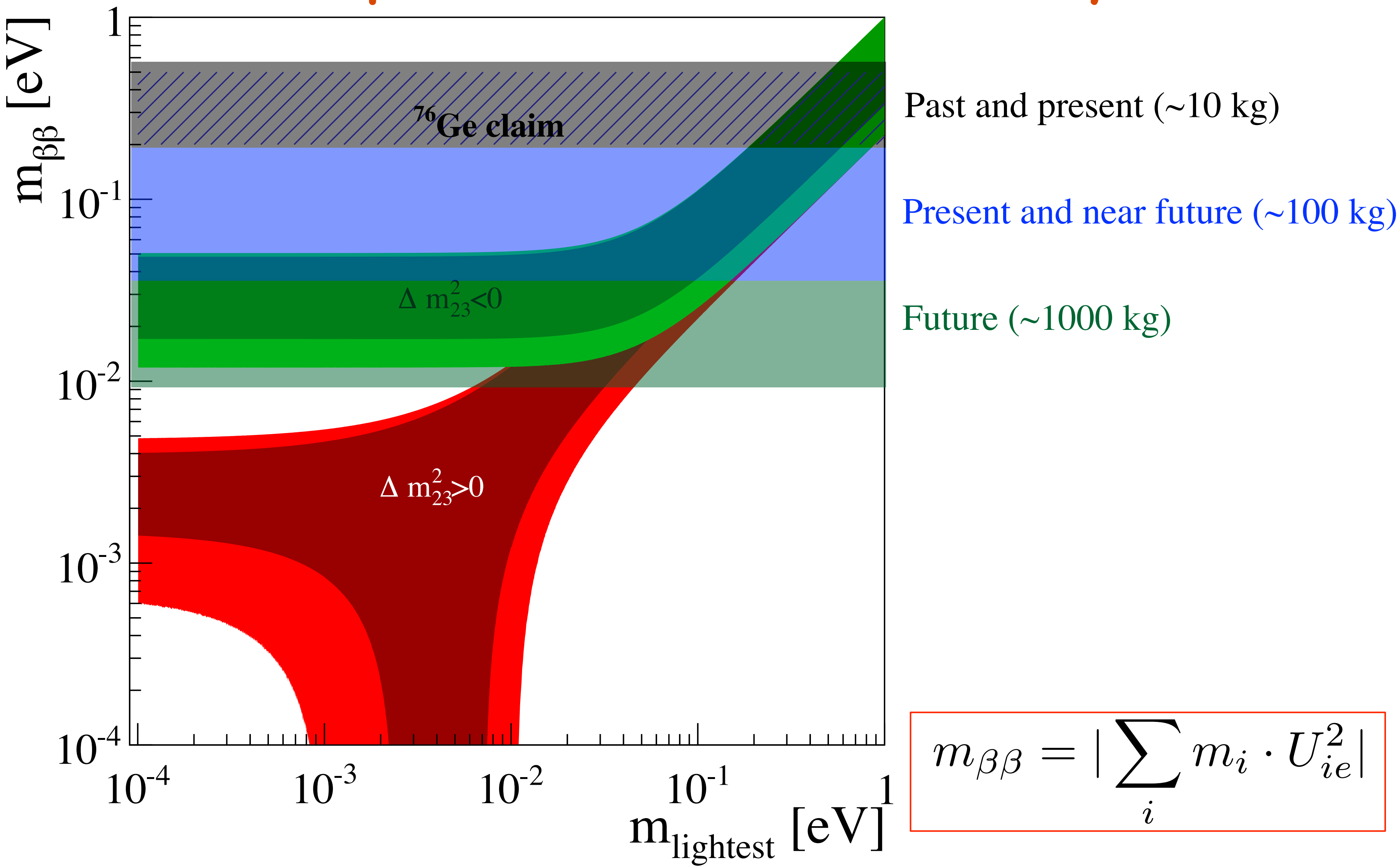


Past and present (~10 kg)

Present and near future (~100 kg)

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

Experimental Sensitivity



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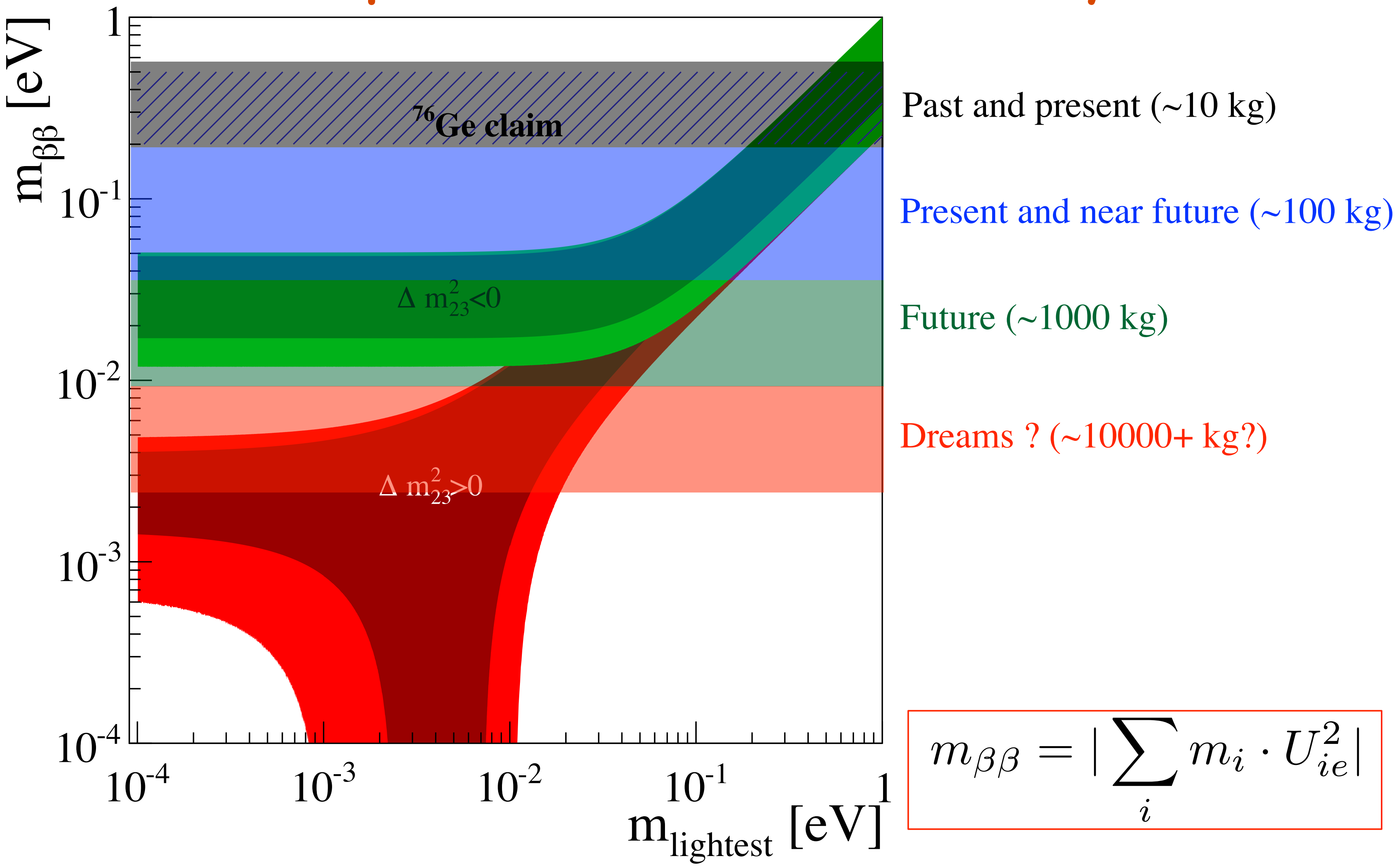


$$m_{\beta\beta} = \left| \sum_i m_i \cdot U_{ie}^2 \right|$$

$0\nu\beta\beta$ Rate and Neutrino Mass

$0\nu\beta\beta$ rate

Phase space $\propto Q^5$

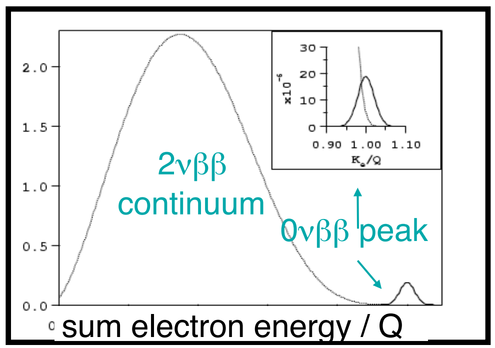
Nuclear matrix element

Effective neutrino mass

$$\Gamma = 1/\tau = G_F^2 \Phi(Q,Z) \, |M_{0\nu}|^2 \, \langle m_{\beta\beta} \rangle^2$$

high Q candidates preferred

large phase space



low background

^{238}U γ end at 2.4 MeV

^{232}Th γ end at 2.6 MeV

[2039 keV (^{76}Ge) $\Leftrightarrow$ 4271 keV (^{48}Ca)]

$\tau^{0\nu} \sim 10^{24}$–10^{26} years: large mass and extremely low backgrounds needed (underground labs, ultra purity materials, active rejection of backgrounds)

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

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)

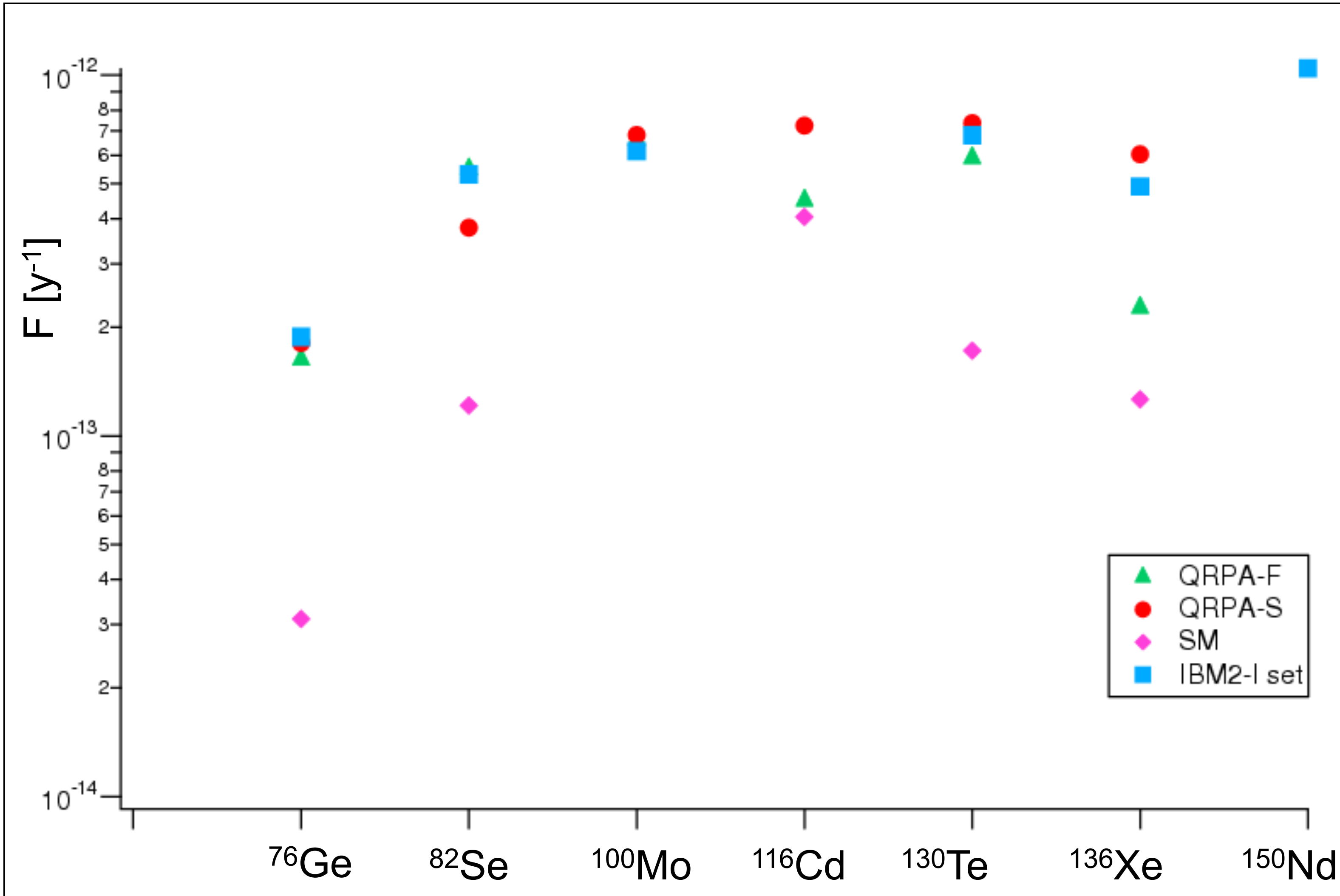
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$ (background-free)

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

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)



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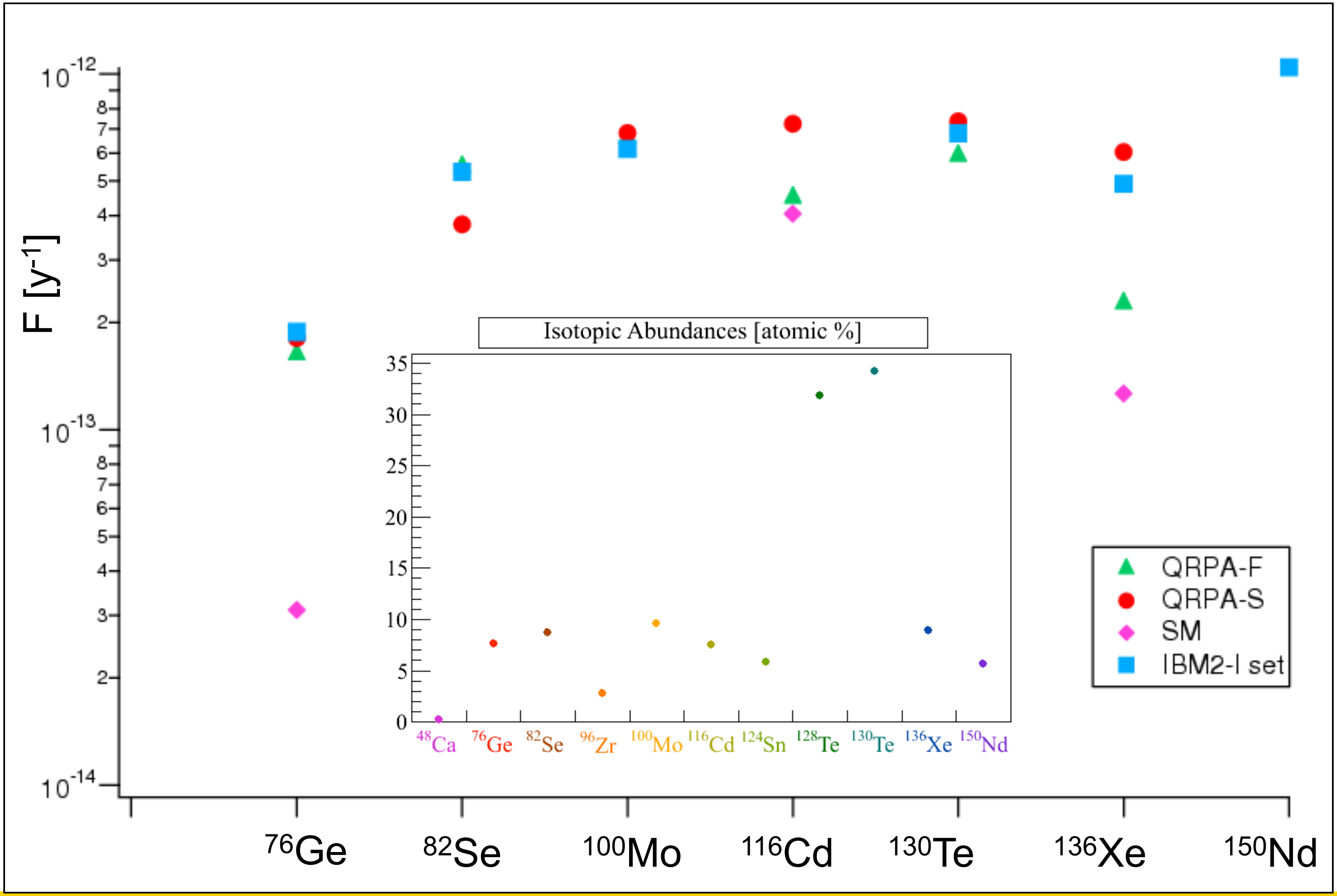
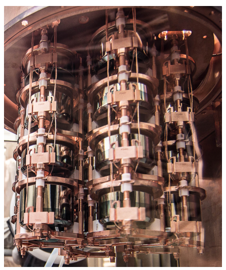
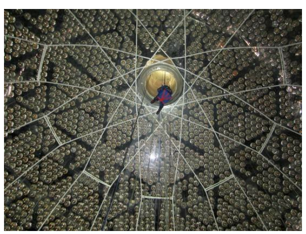
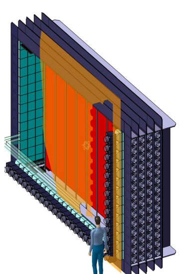
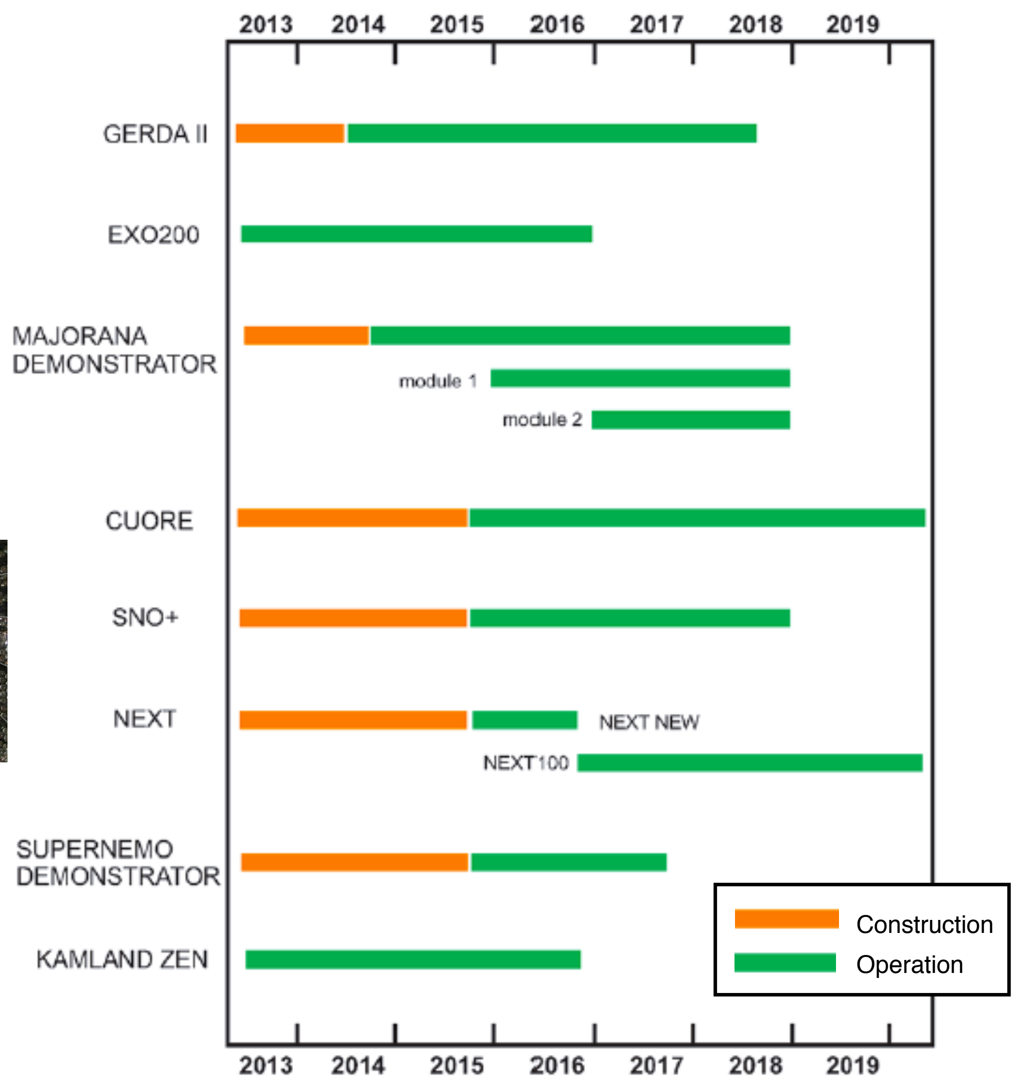
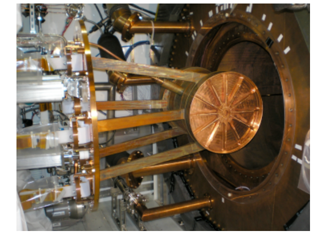


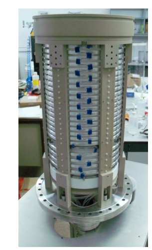
Diverse, Vibrant Program

NLDBD Sub Committee Report to NSAC (2014)

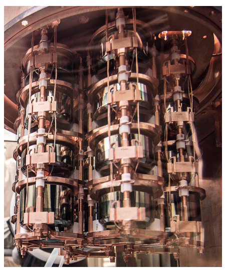


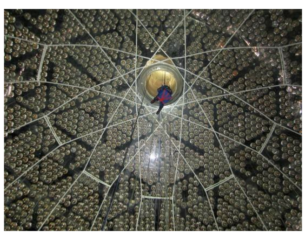


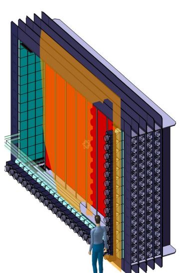



J.F. Wilkerson

Diverse, Vibrant Program







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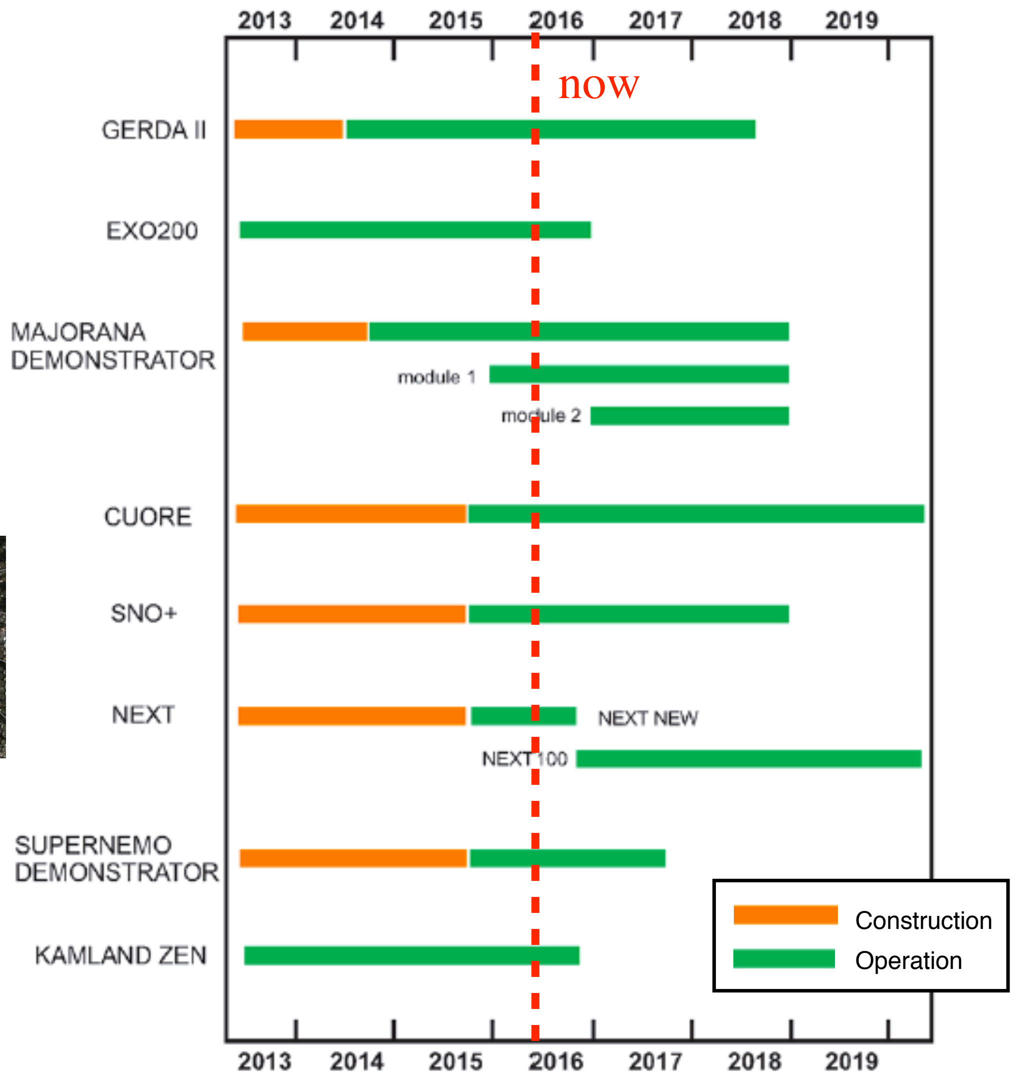
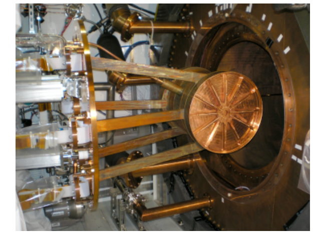
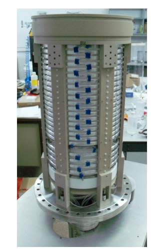
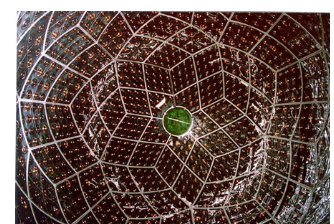


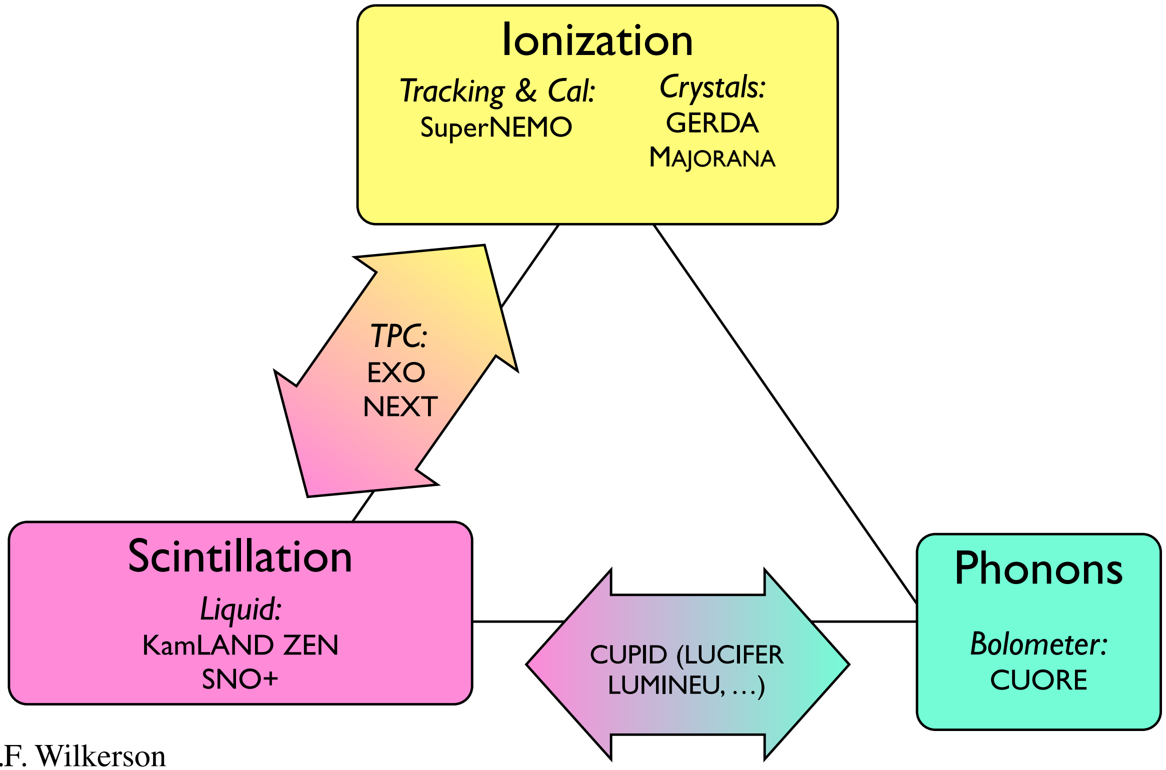






J.F. Wilkerson

Detection Techniques



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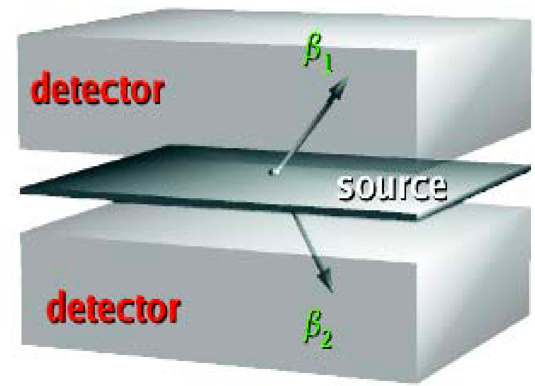
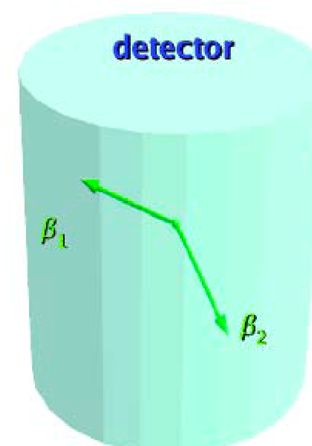
Source external to detector
(NEMO, SuperNEMO)



Source internal to detector
(most common)



CUORE

Cryogenic Underground Observatory for Rare Events

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE

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

Massachusetts Institute of Technology

CSNSM

SHANGHAI JIAO TONG UNIVERSITY 1896

SAPIENZA UNIVERSITÀ DI ROMA

BERKELEY LAB

UNIVERSITY OF SOUTH CAROLINA

UCLA

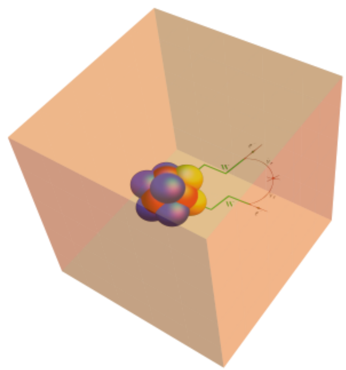
UNIVERSITAS STUDII PADUANI

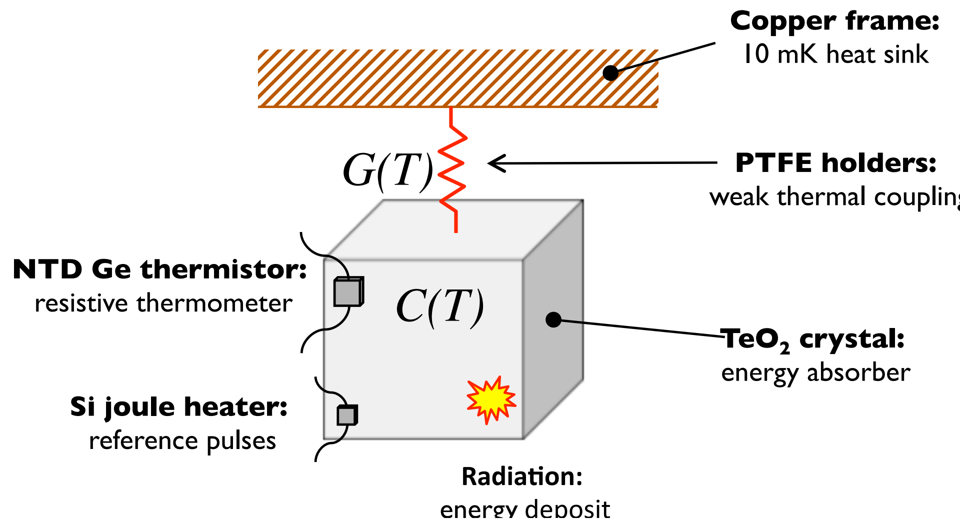
THE UNIVERSITY OF CALIFORNIA 1868

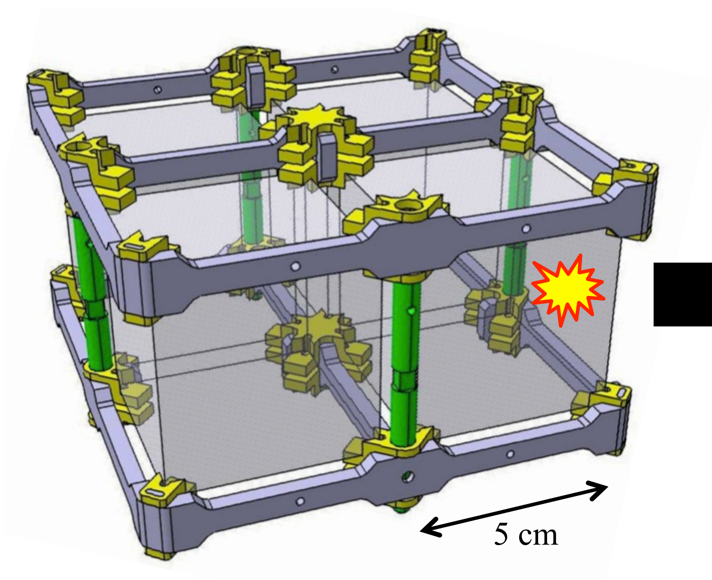
CUORE

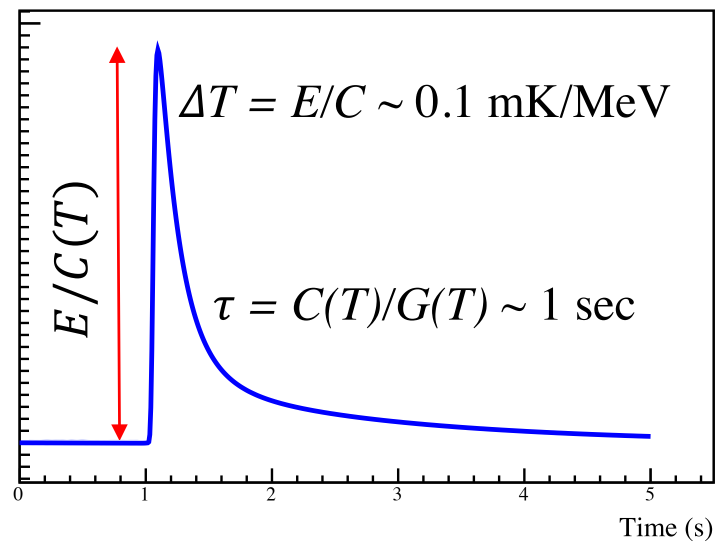
Cryogenic Bolometers

Source = Detector



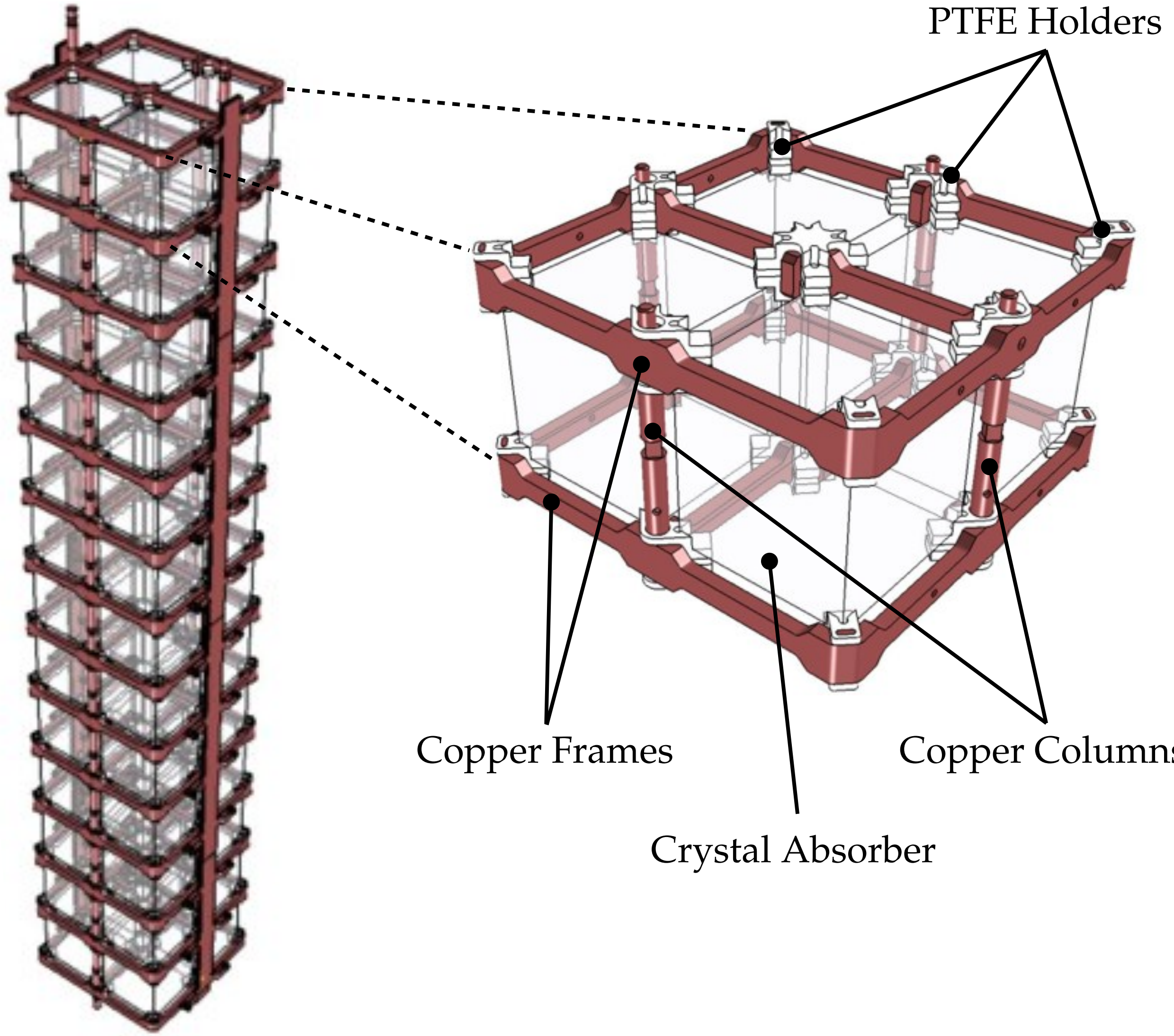






Ultra-cold TeO_2 crystals function as very sensitive calorimeters

Cryogenic Bolometer Array



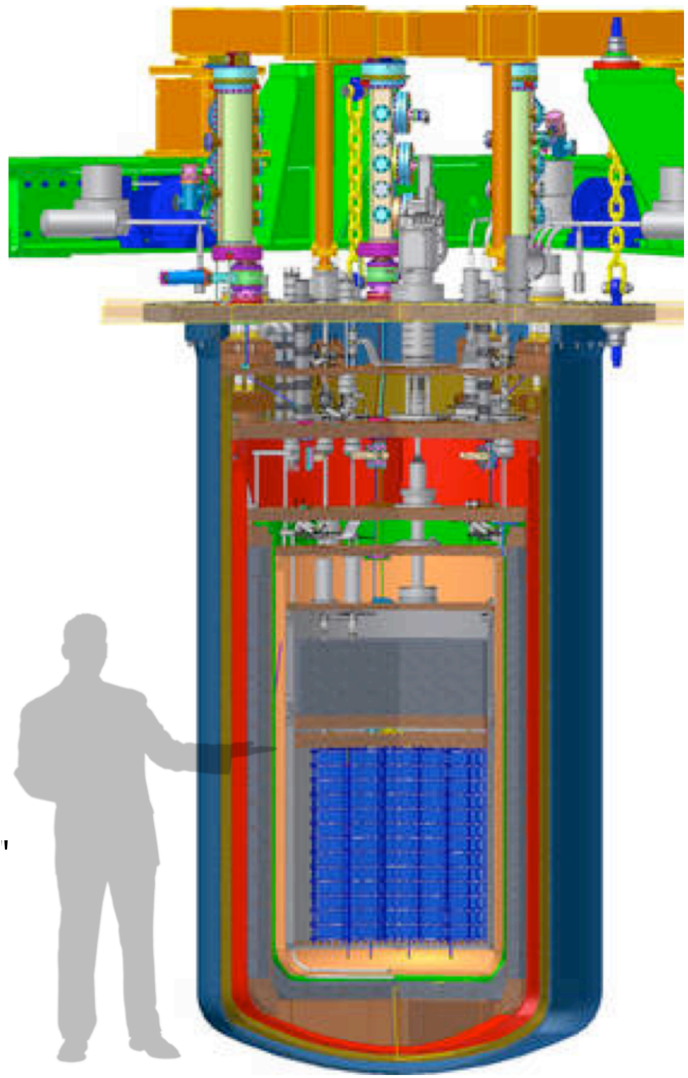
CUORE

Array of 988 TeO_2 crystals

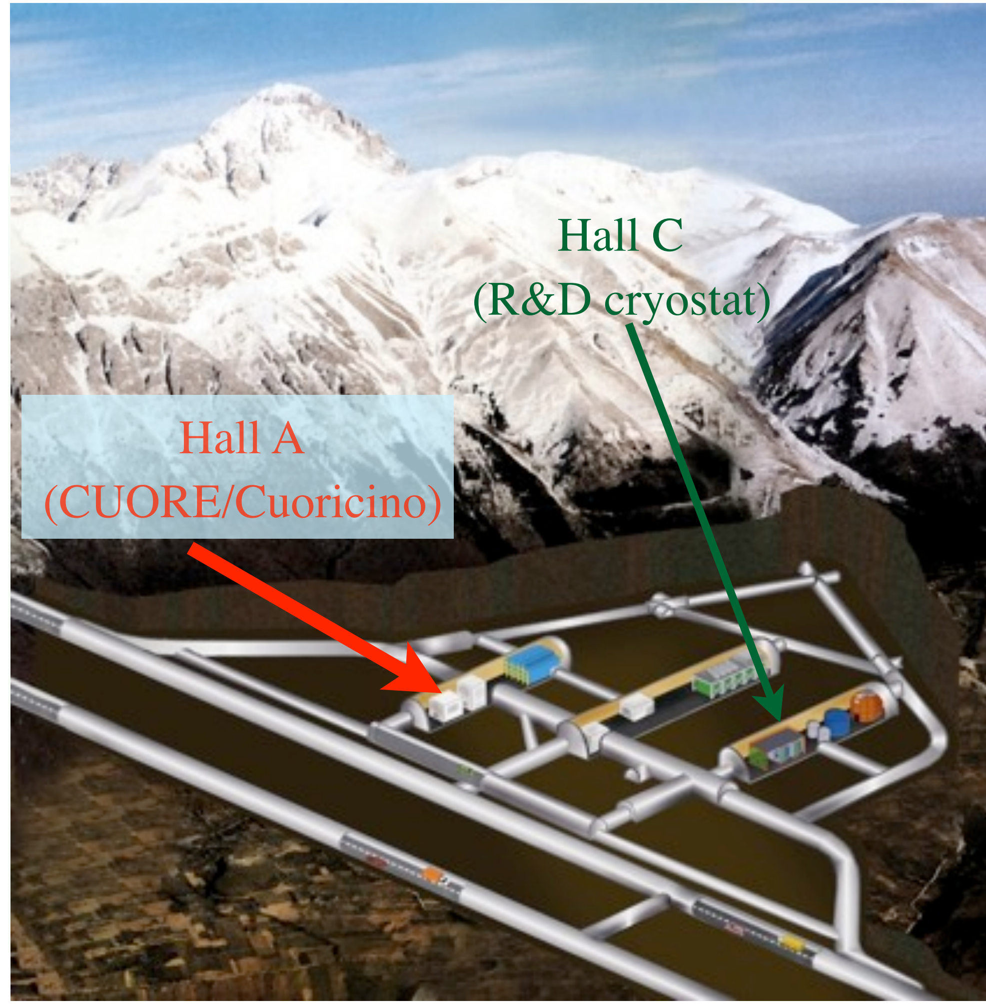
- **19** towers suspended in a cylindrical structure
- **13** levels, **4** crystals each
- 5x5x5 cm^3 (750g each)
- ^{130}Te: 34.2% natural isotope abundance

750 kg TeO_2 => 206 kg ^{130}Te

- New pulse tube refrigerator and cryostat
- Radio-purity techniques and high resolution achieve low backgrounds
- Joint venture between Italy (INFN) and US (DOE, NSF)
- Under construction (expected start of operations in early 2016)
- Expect energy resolution of 5 keV FWHM and background of ~0.01 counts/(kg*keV*year) in ROI



Gran Sasso Laboratory



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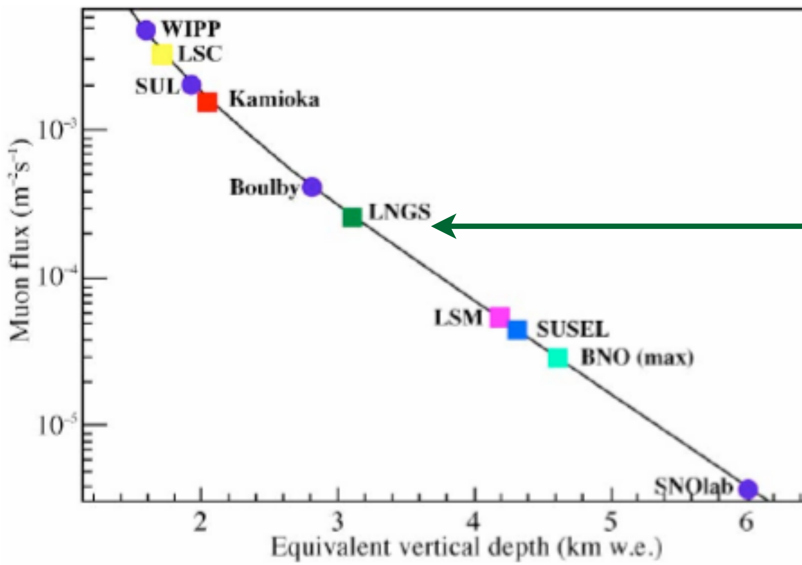
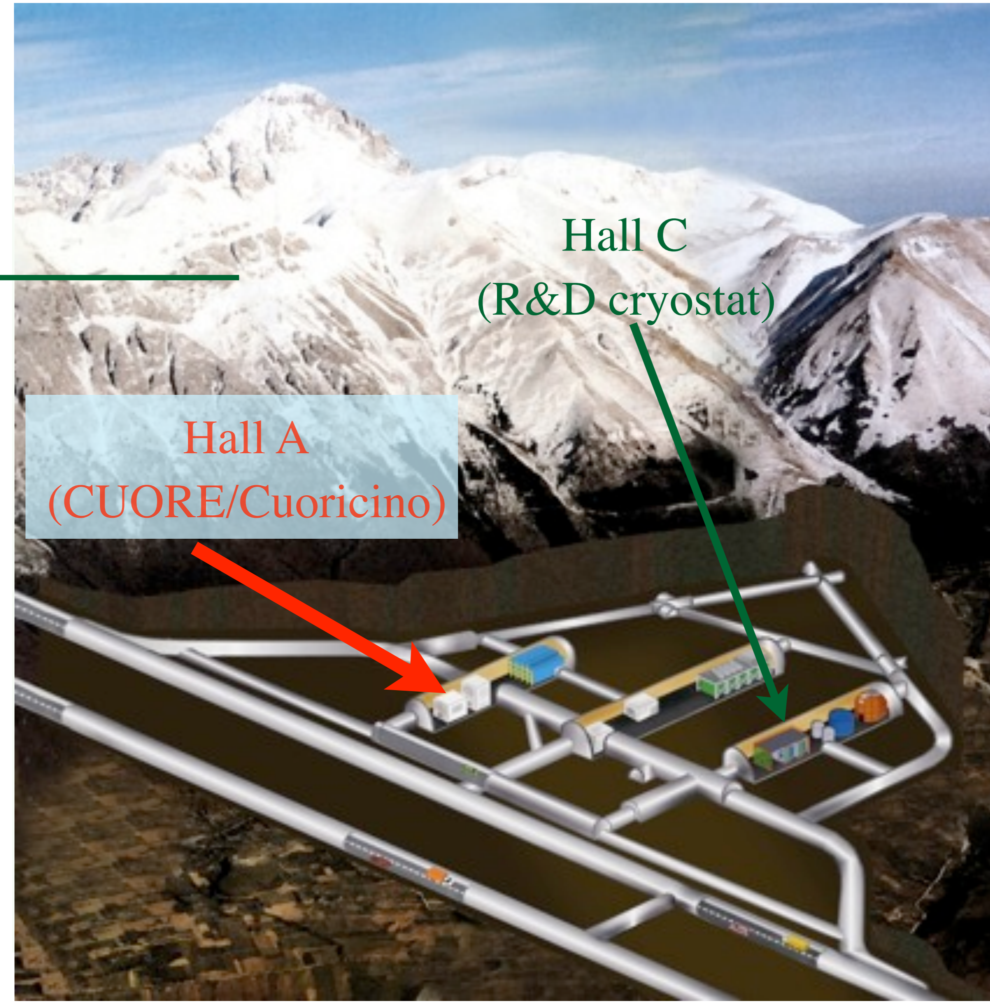


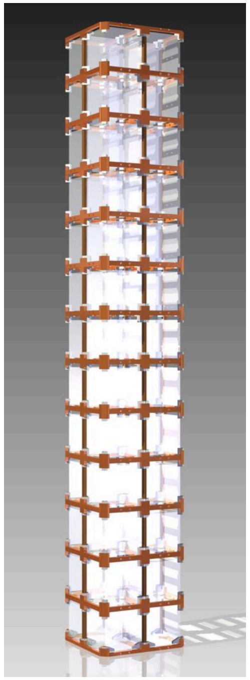


Shielding: ~3650 m.w.e.
Muons: ~2 x 10^{-8}/cm^2-s
Thermal neutrons: ~1 x 10^{-6}/cm^2-s
Epithermal neutrons: ~2 x 10^{-6}/cm^2-s
> 2.5 MeV Neutrons: 2 x 10^{-7}/cm^2-s

The CUORE Program

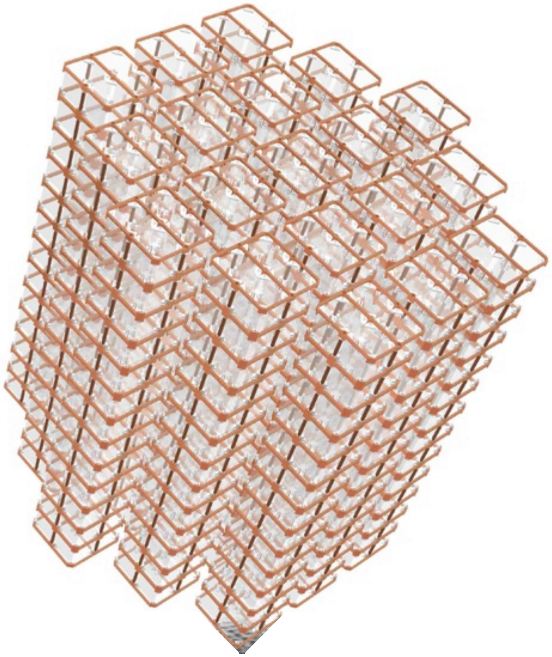
Cuoricino
2003-2008
11 kg of ^{130}Te

Complete



CUORE-0
2003-2008
11 kg of ^{130}Te

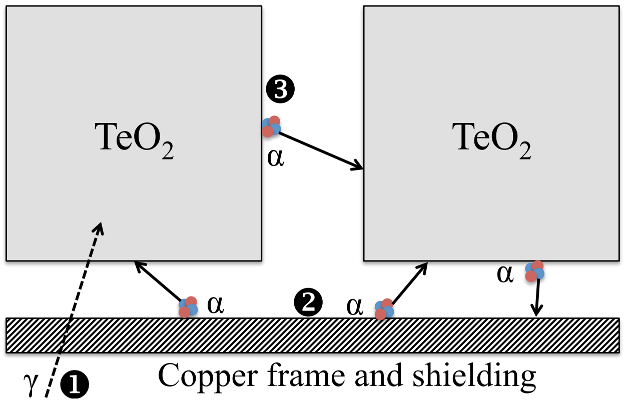
Complete

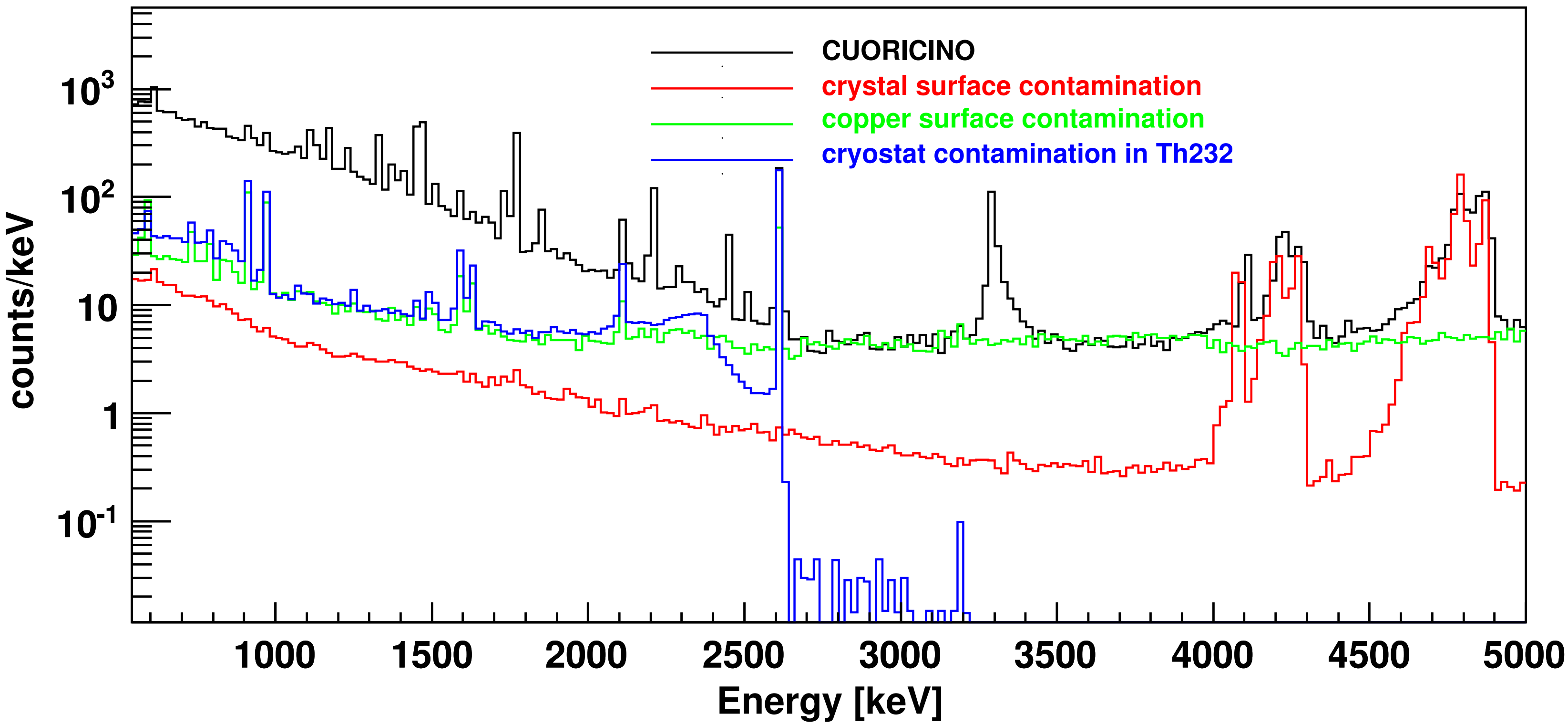


CUORE
2016-202x
206 kg of ^{130}Te

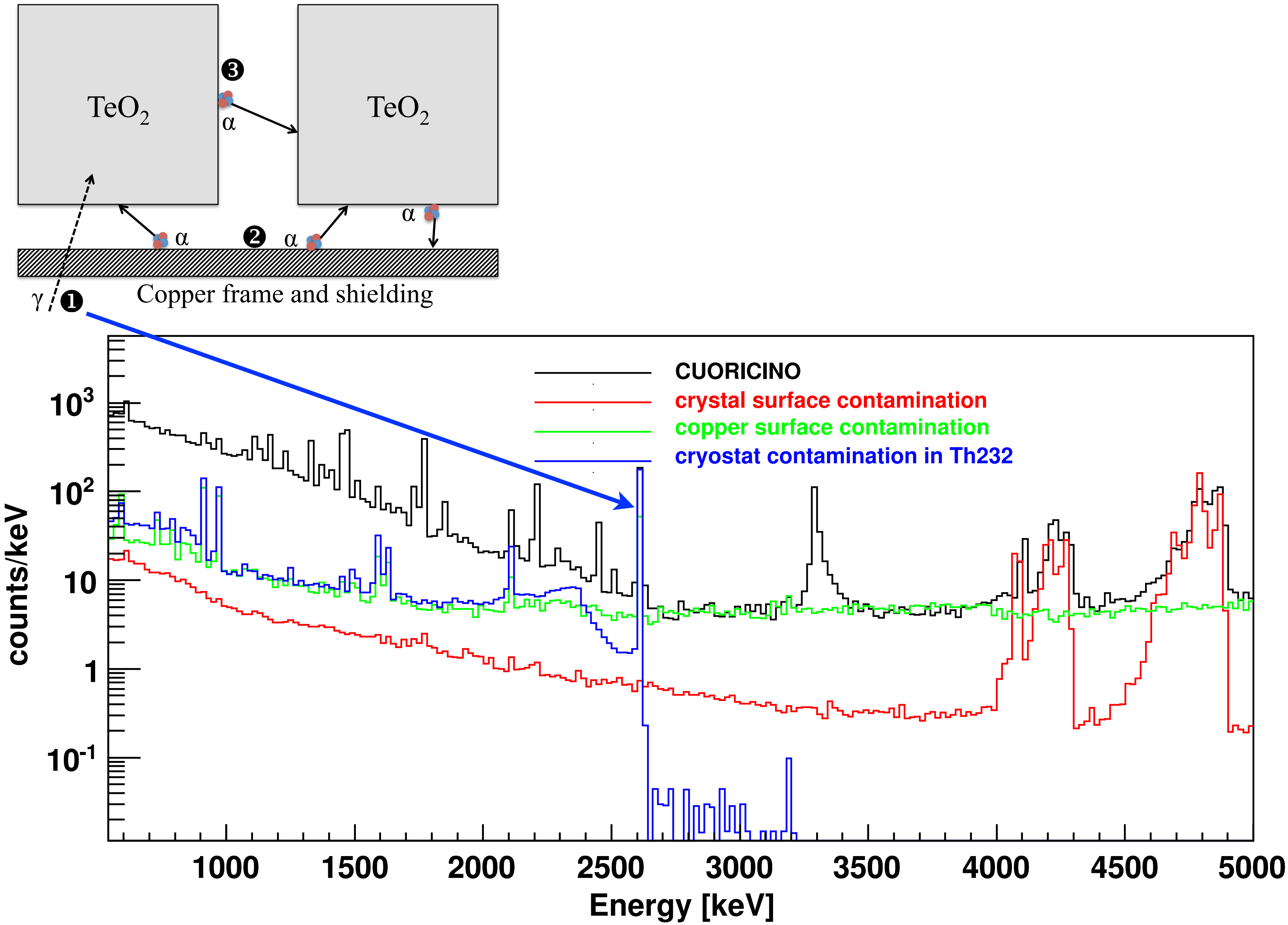
Under Construction

Cuoricino Backgrounds





Cuoricino Backgrounds



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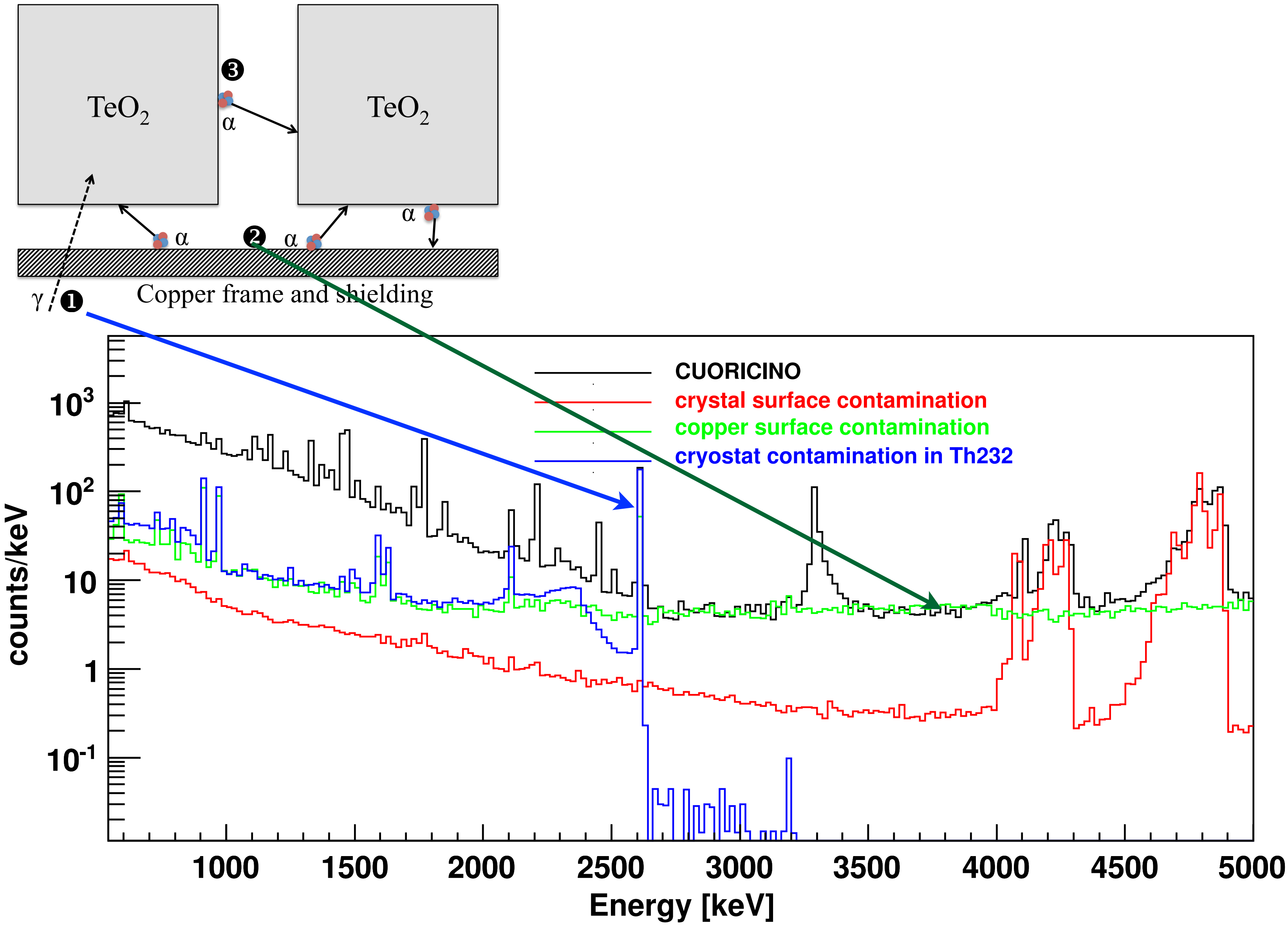
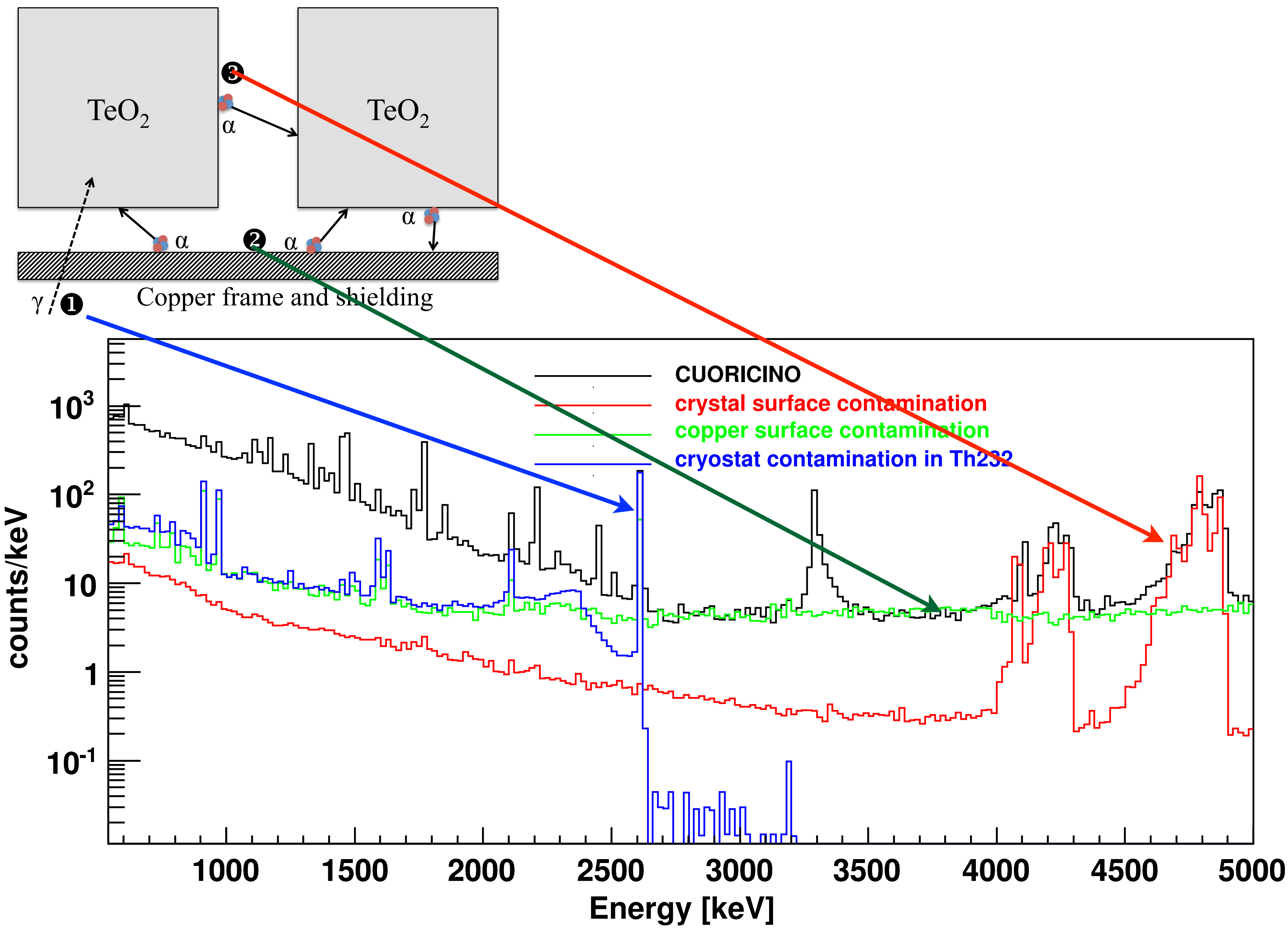
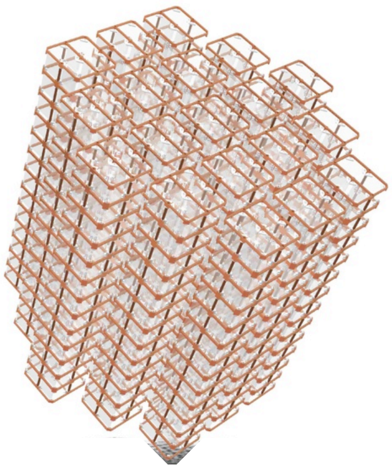


Cuoricino Backgrounds



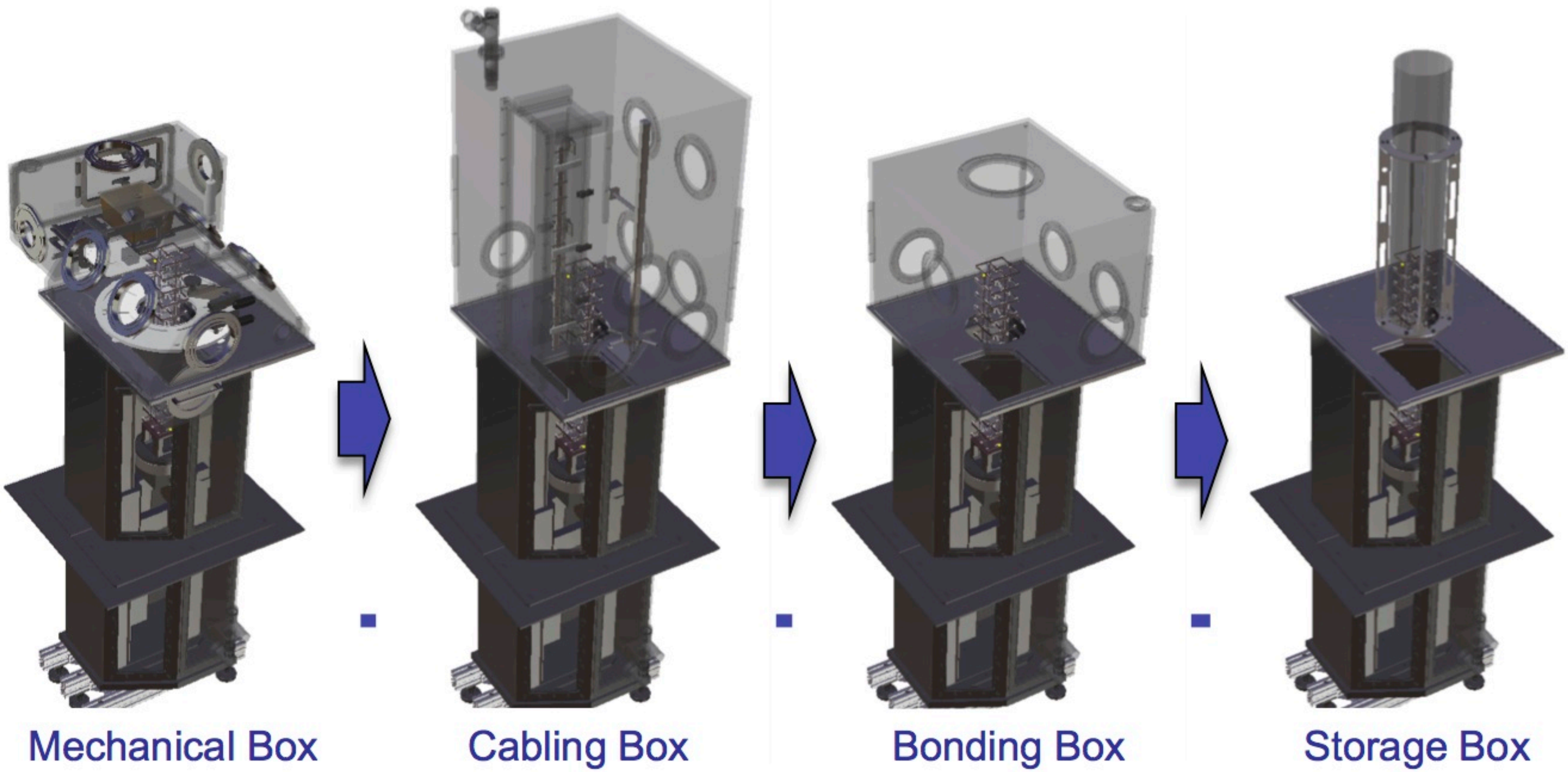
From Cuoricino to CUORE

- Larger
- Cleaner crystals
- Cleaner copper, and less of it per kg TeO_2
- Cleaner assembly environment
- More robust assembly methods, better wiring
- Better self-shielding & anticoincidence coverage
- Better fit tolerances, hence less vibration

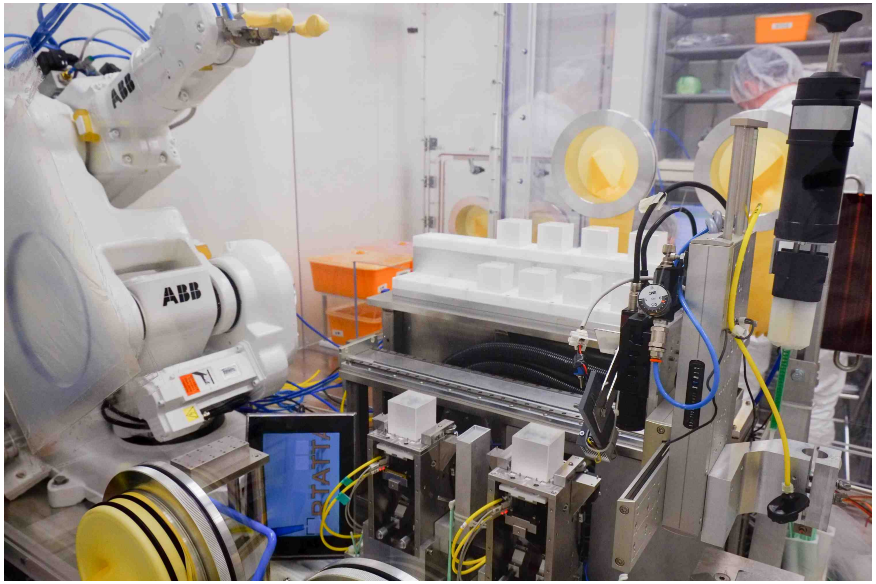


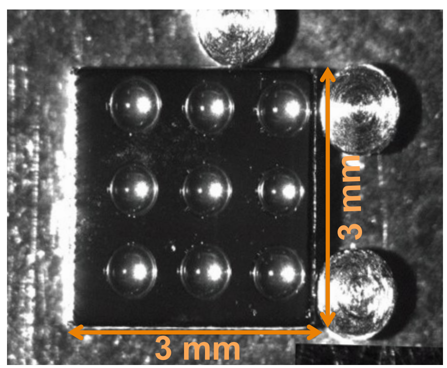
	Cuoricino	CUORE-0	CUORE
^{130}Te mass (kg)	11	11	206
Background (c/keV/kg/y) @ 2528 keV	0.17	0.06	0.01
E resolution (keV) FWHM @ 2615 keV	5.8	4.9	5
$T_{1/2}$ sensitivity (10^{24} yr) @ 90% C.L.	2.6	2.9	95

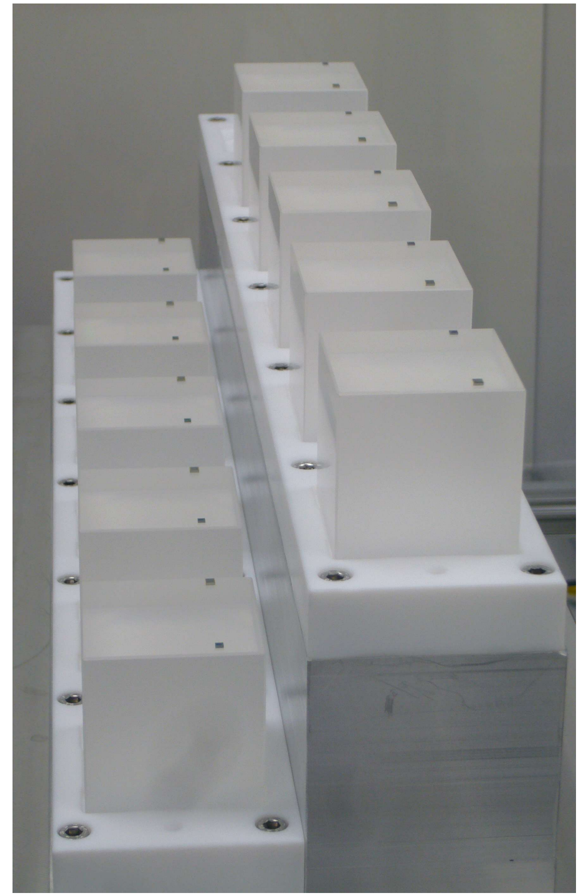
CUORE Assembly Line



Sensor Gluing

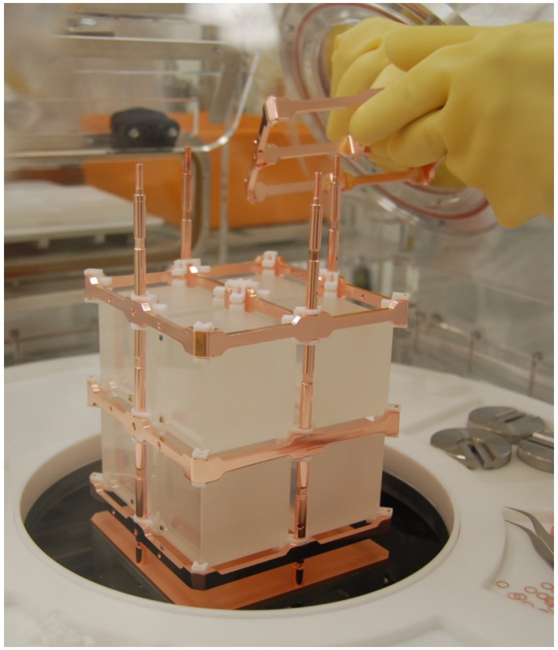




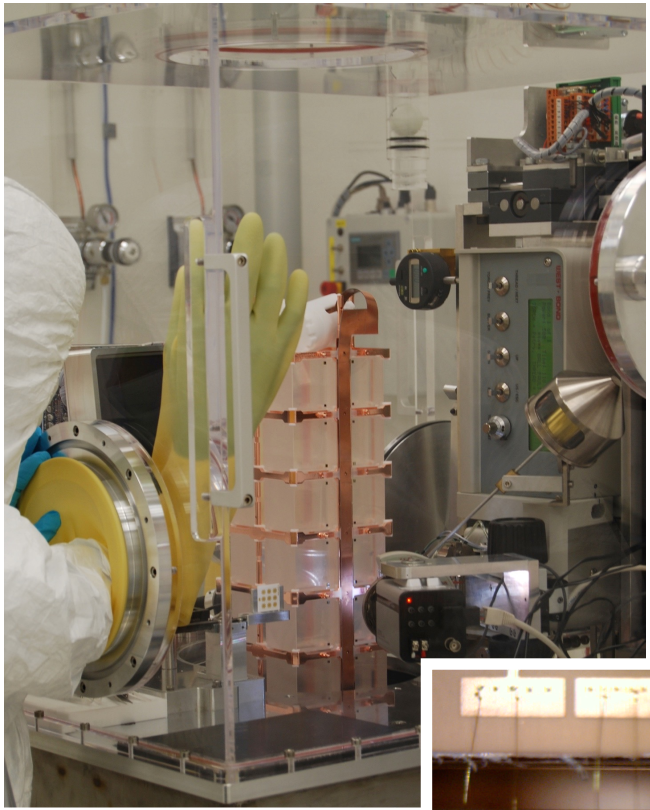


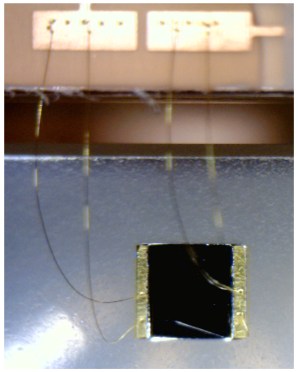
Semi-automated, glovebox-enclosed system used to glue sensors to crystals in consistent, reproducible fashion

CUORE-0 Tower Assembly

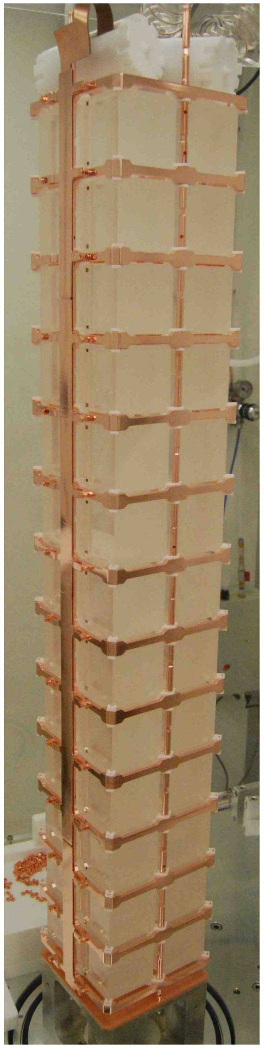


Physical assembly





Wire bonding



Complete

CUORE-0 assembly:

✦ 51/52 thermistors connected

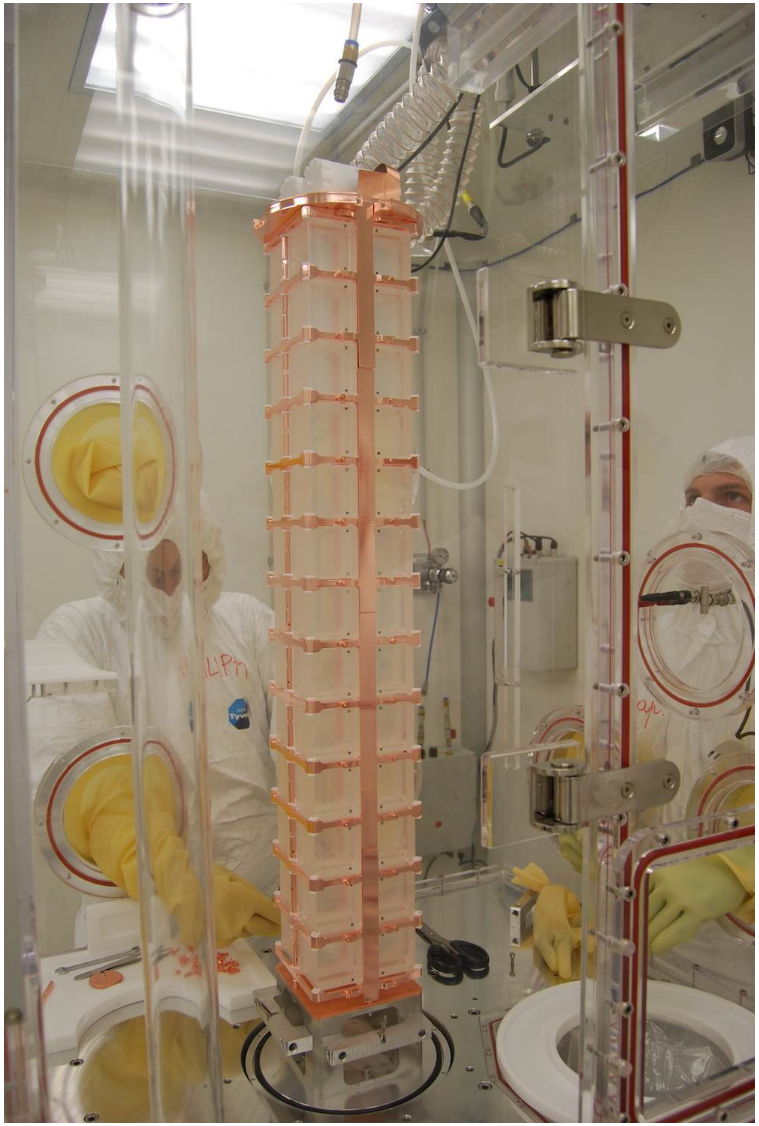
✦ 50/52 heaters connected

CUORE assembly:

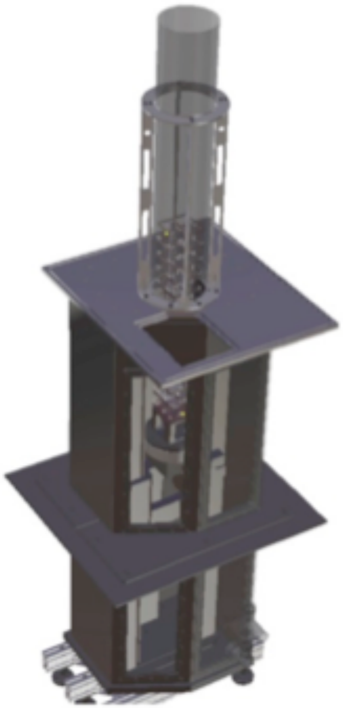
✦ 988/988 thermistors connected

✦ 988/988 heaters connected

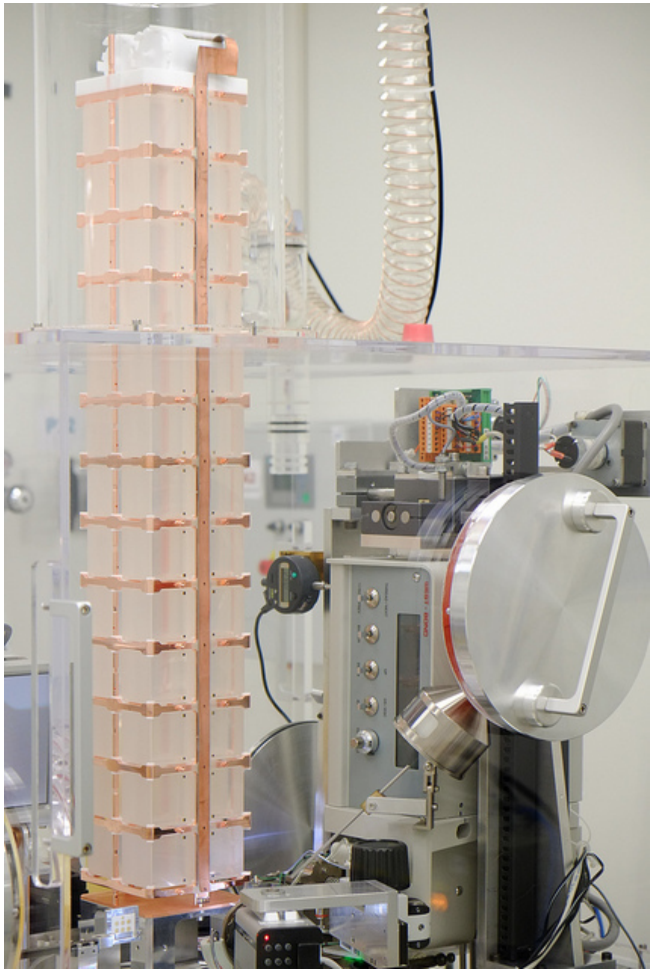
Complete Tower

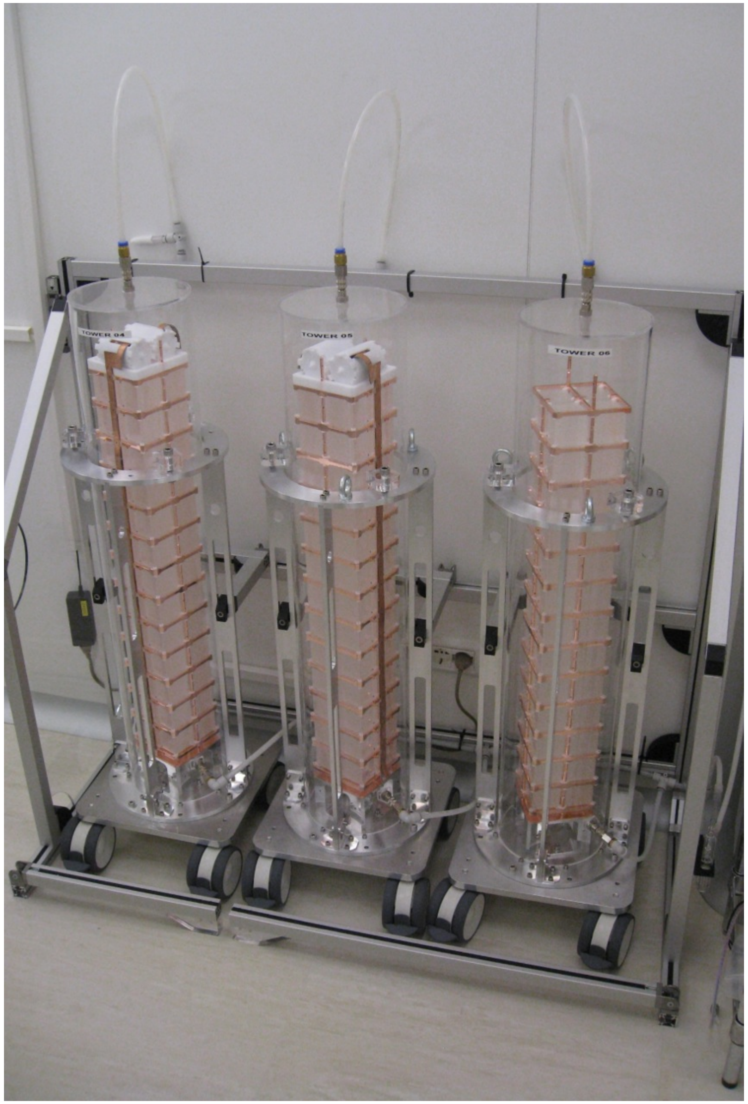


Tower Storage and Transfer



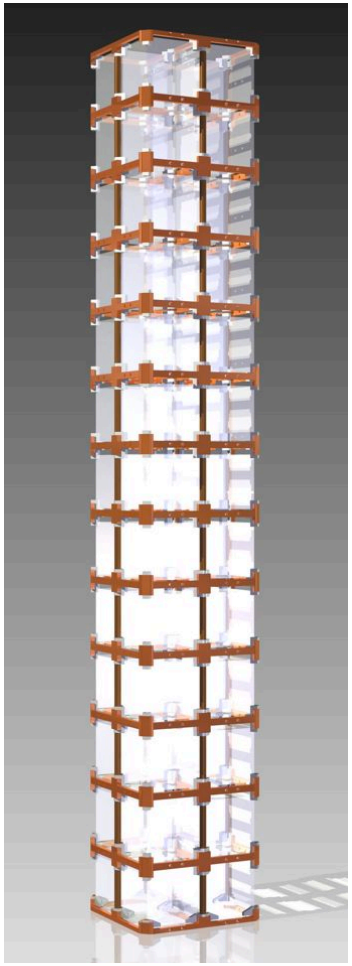
Storage Box



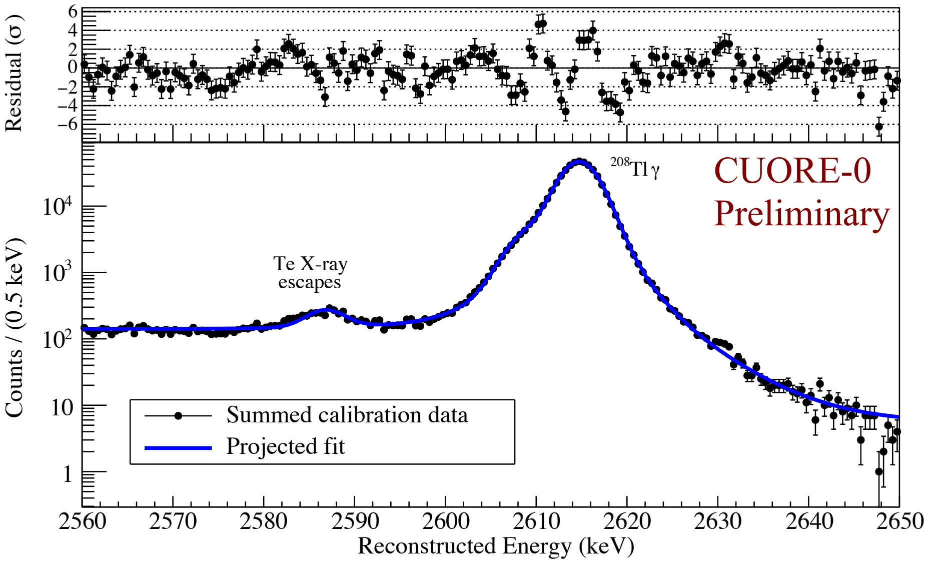


CUORE-0

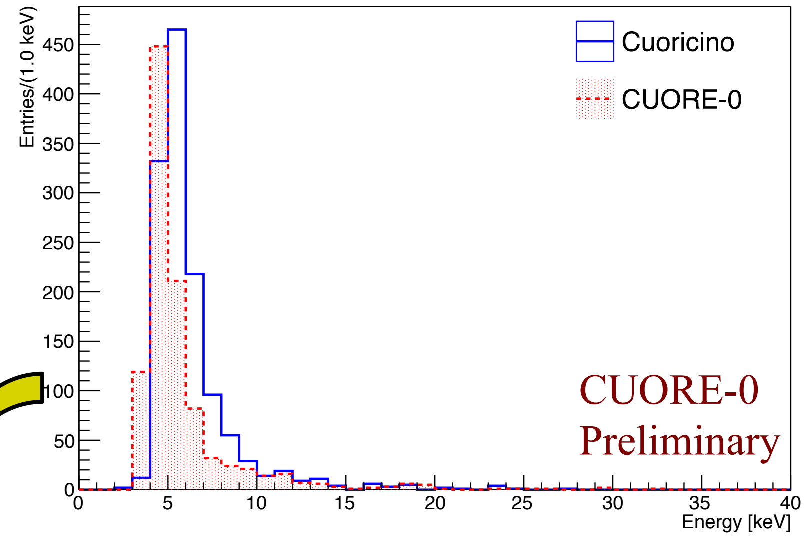
- First tower from the CUORE detector assembly line
- 52 TeO_2 crystals, total mass = 39 kg TeO_2 = 10.9 kg ^{130}Te
- Purpose:
  1. Commission assembly line
  2. Run as standalone experiment while CUORE is being constructed, with aim of surpassing Cuoricino
  3. Validate CUORE detector design
  4. Provide test bed for developing DAQ & analysis framework for CUORE
- Operating in former Cuoricino cryostat since March 2013



Energy Resolution



Bolometer-dataset FWHMs @ 2615 keV

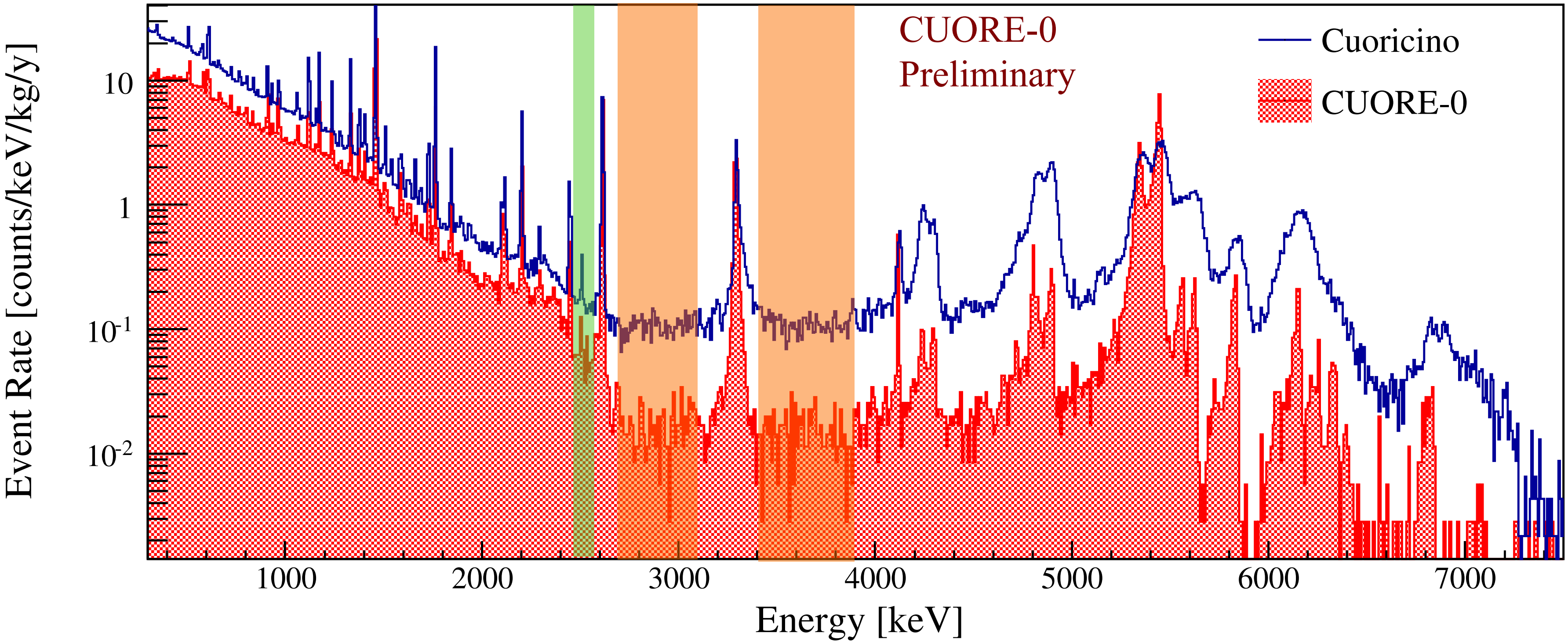


Weight FWHMs by corresponding physics exposure

	FWHM harmonic mean (keV)	FWHM dist RMS (keV)
Cuoricino	5.8	2.1
CUORE-0	4.9	2.9

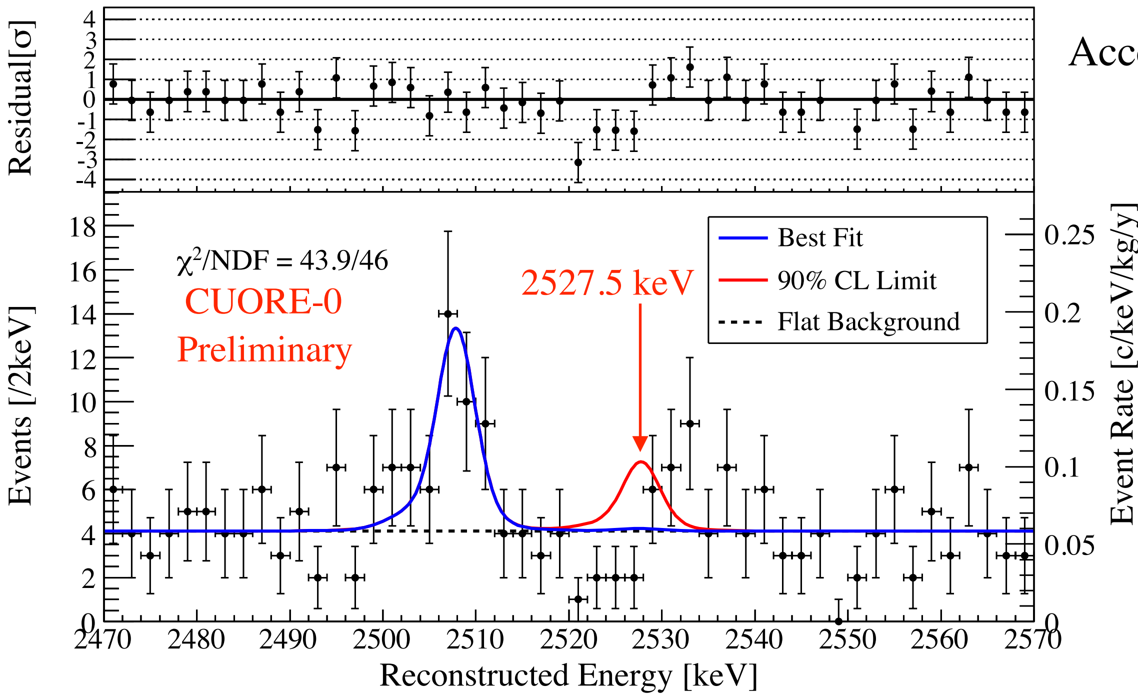
- We evaluate the energy resolution for each bolometer and dataset by fitting the ^{208}Tl photopeak in the calibration data
- We achieved the 5 keV resolution goal of CUORE!

Backgrounds



Experiment	Background rate (counts/keV/kg/y)	
	$0\nu\beta\beta$ decay region	Alpha region (excl. peak)
Cuoricino	0.169 ± 0.006	0.110 ± 0.001
CUORE-0	0.058 ± 0.004	0.016 ± 0.001

CUORE-0 Results



Accepted to PRL

Fitted background: 0.058 ± 0.004 (stat.) ± 0.002 (syst.) counts/keV/kg/yr

Best-fit decay rate: $\Gamma^{0\nu\beta\beta}(^{130}\mathrm{Te}) = 0.007 \pm 0.123\ (\mathrm{stat.}) \pm 0.012\ (\mathrm{syst.}) \times 10^{-24}\ \mathrm{yr}^{-1}$

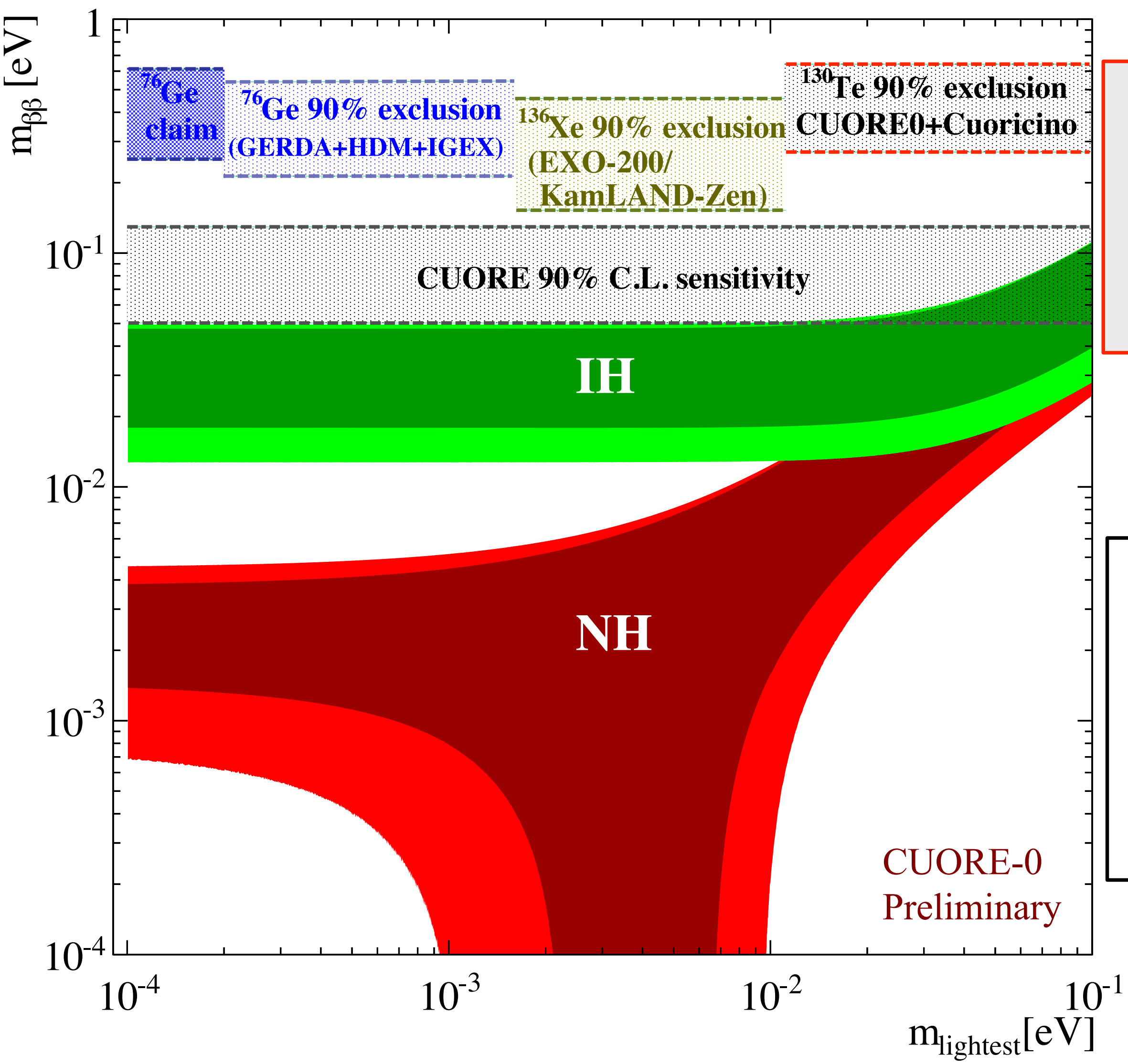
90% C.L. limits (Bayesian):

$$\Gamma^{0\nu\beta\beta}(^{130}\mathrm{Te}) < 0.25 \times 10^{-24}\ \mathrm{yr}^{-1}$$

$$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > 2.7 \times 10^{24}\ \mathrm{yr}$$

CUORE-0+Cuoricino limit: $T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > 4.0 \times 10^{24}\ \mathrm{yr}$ (90% C.L.)

CUORE-0 Reach



$\langle m_{\beta\beta} \rangle < 270 - 650$ meV

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) ISM (NPA 818, 139 (2009))
5) EDF (PRL 105, 252503 (2010))

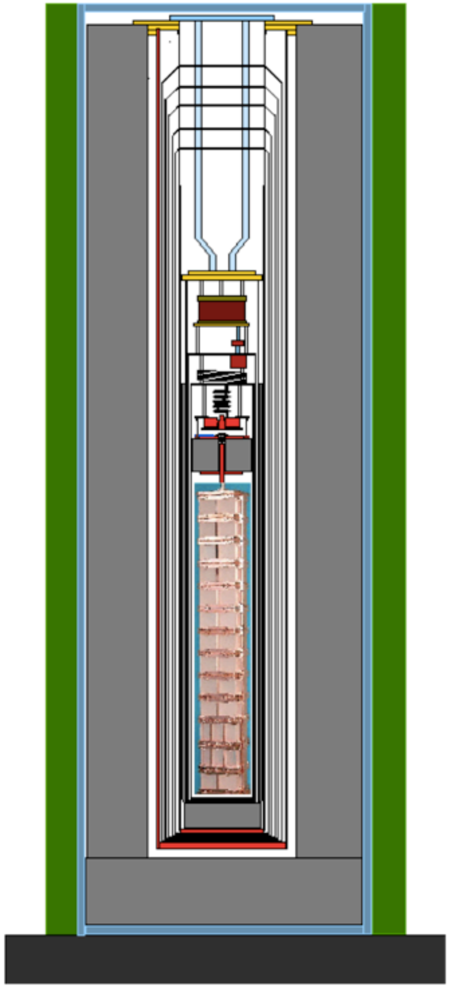
Including additional Shell-Model NME

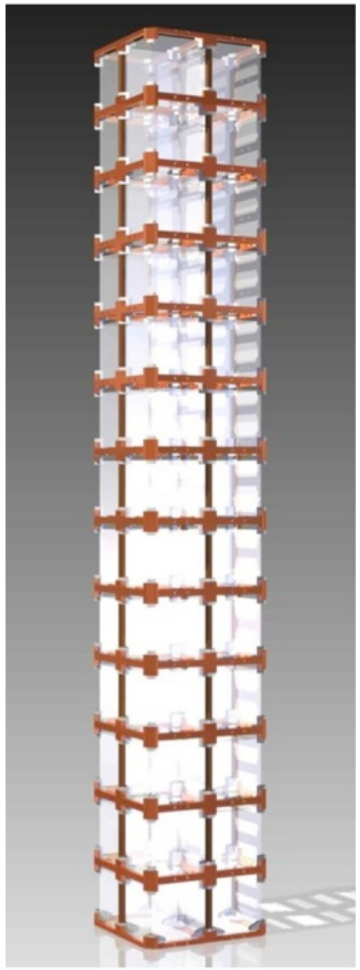
$\langle m_{\beta\beta} \rangle < 270 - 760$ meV

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

From CUORE-0 to CUORE

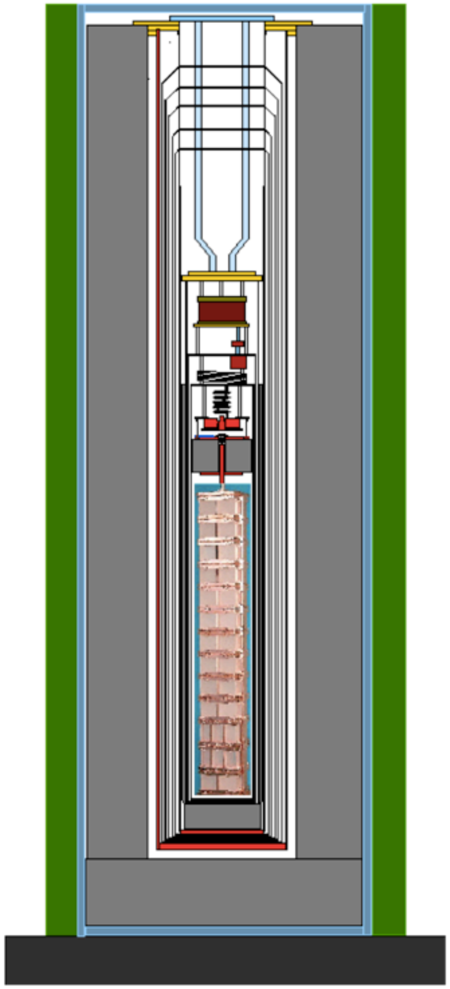
CUORE-0





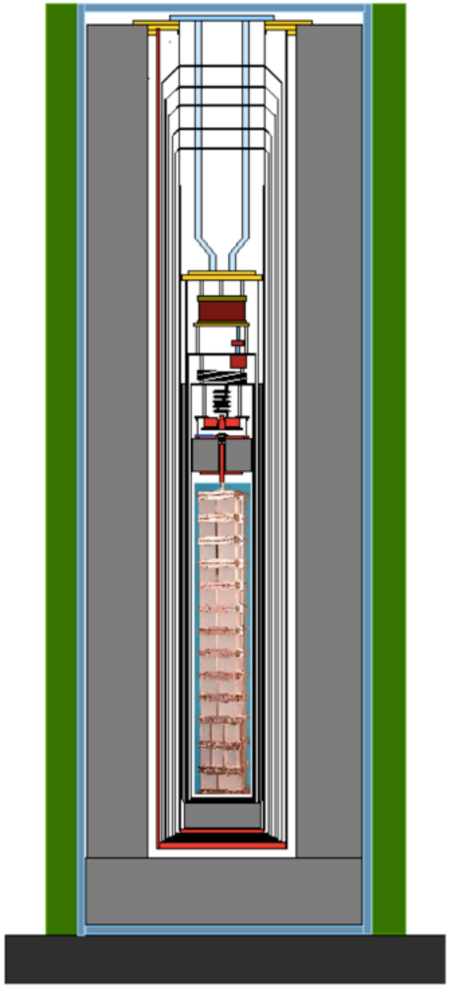
From CUORE-0 to CUORE

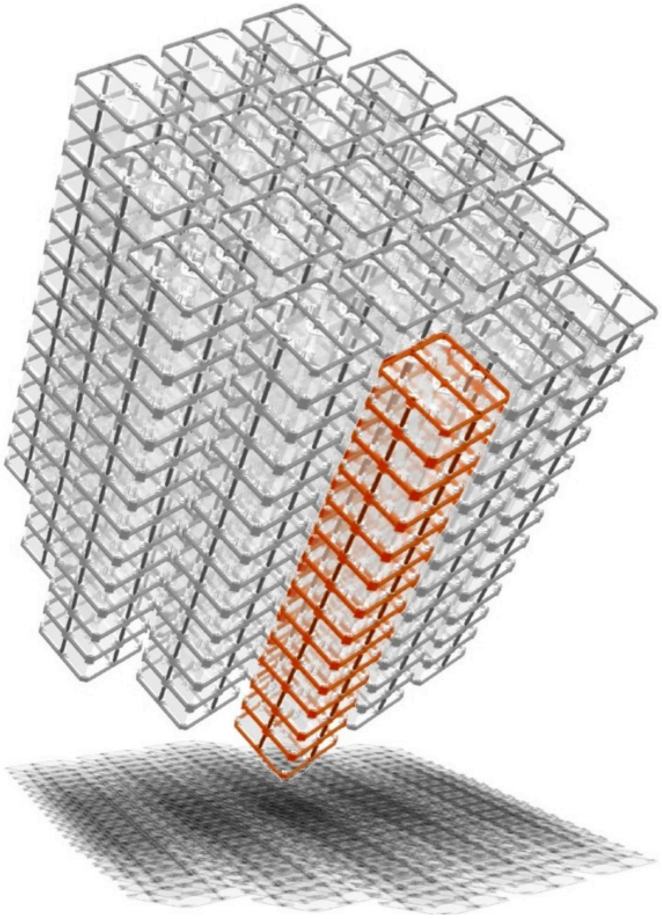
CUORE-0



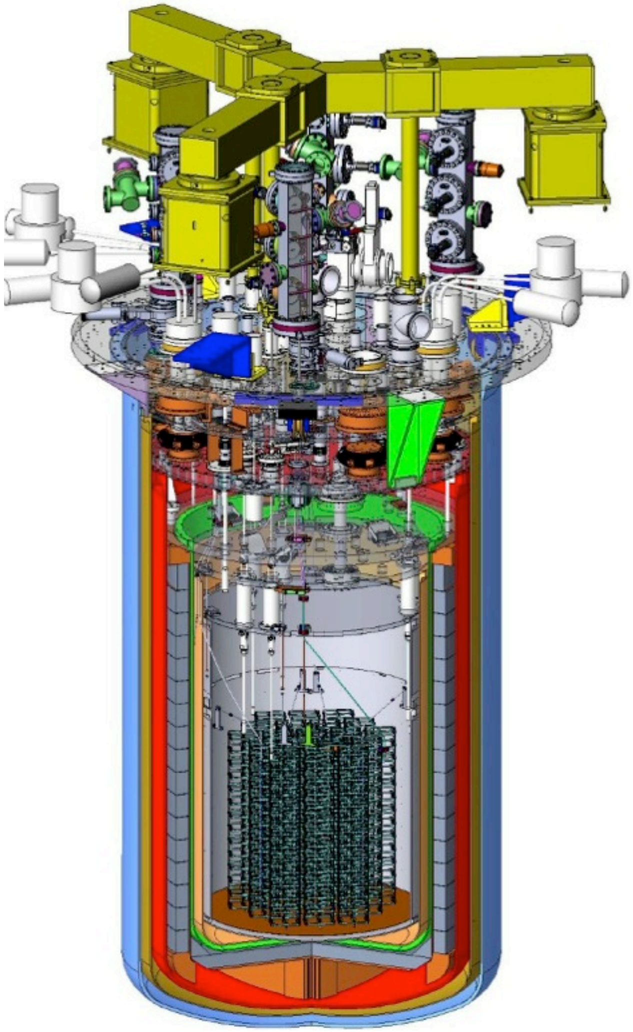
From CUORE-0 to CUORE

CUORE-0



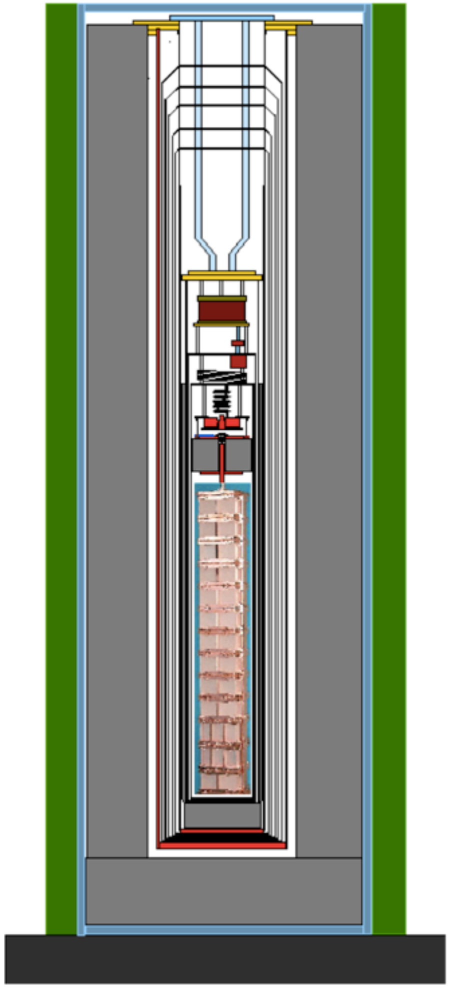


CUORE

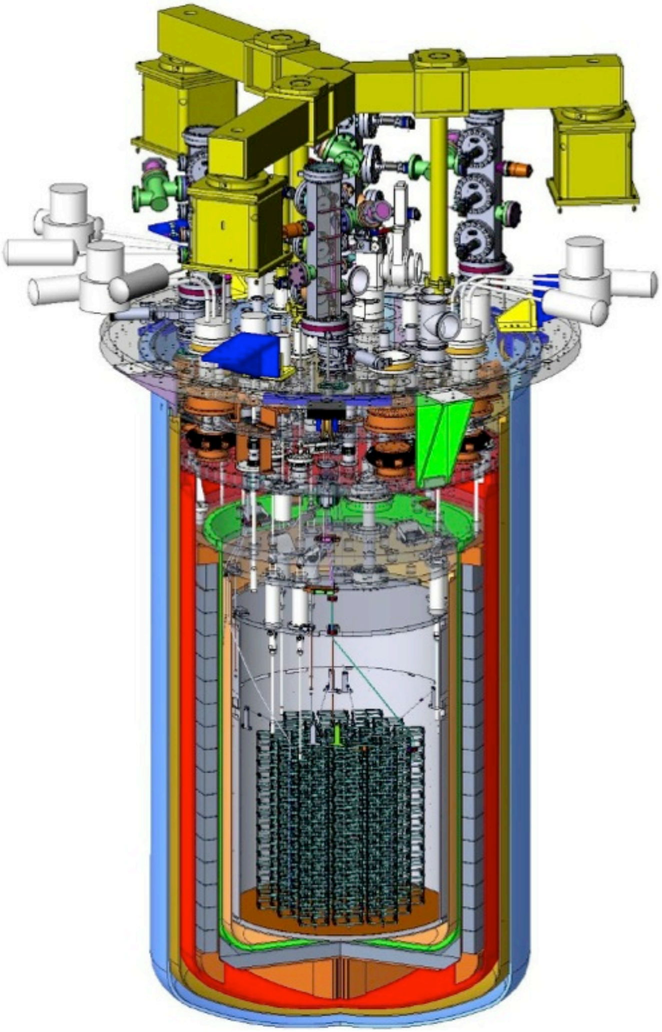


From CUORE-0 to CUORE

CUORE-0

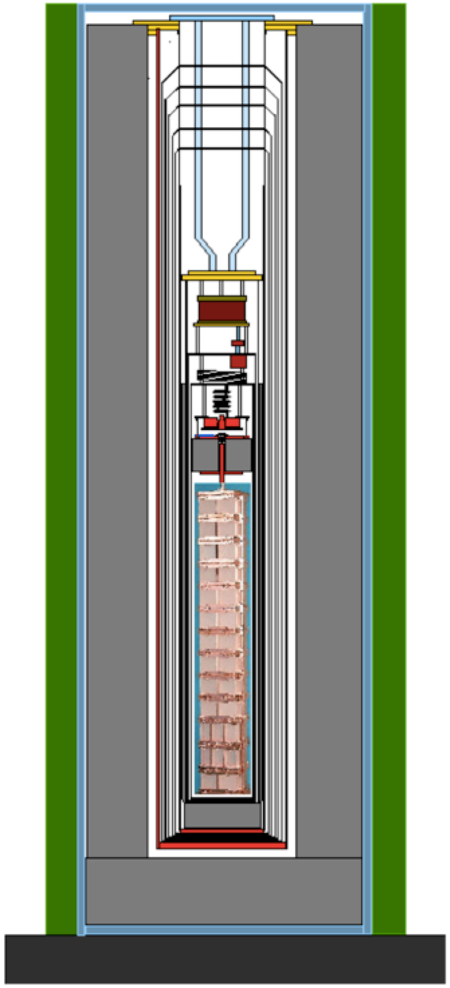


CUORE



From CUORE-0 to CUORE

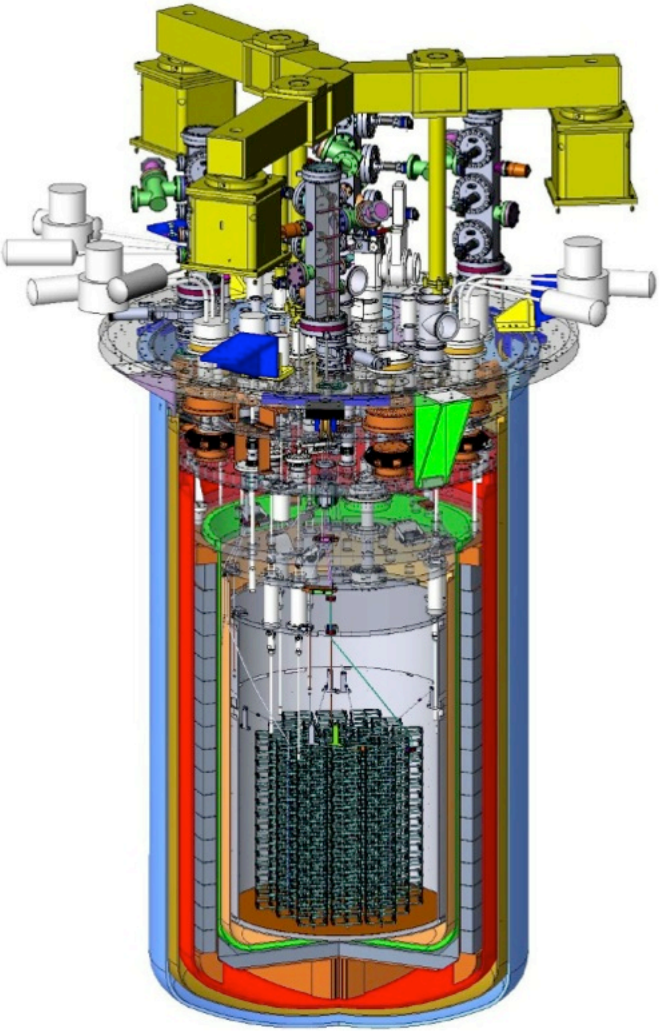
CUORE-0



CUORE-0 results are of critical importance for understanding CUORE scientific reach, and validating CUORE construction procedures

Background extrapolation to CUORE looks very good

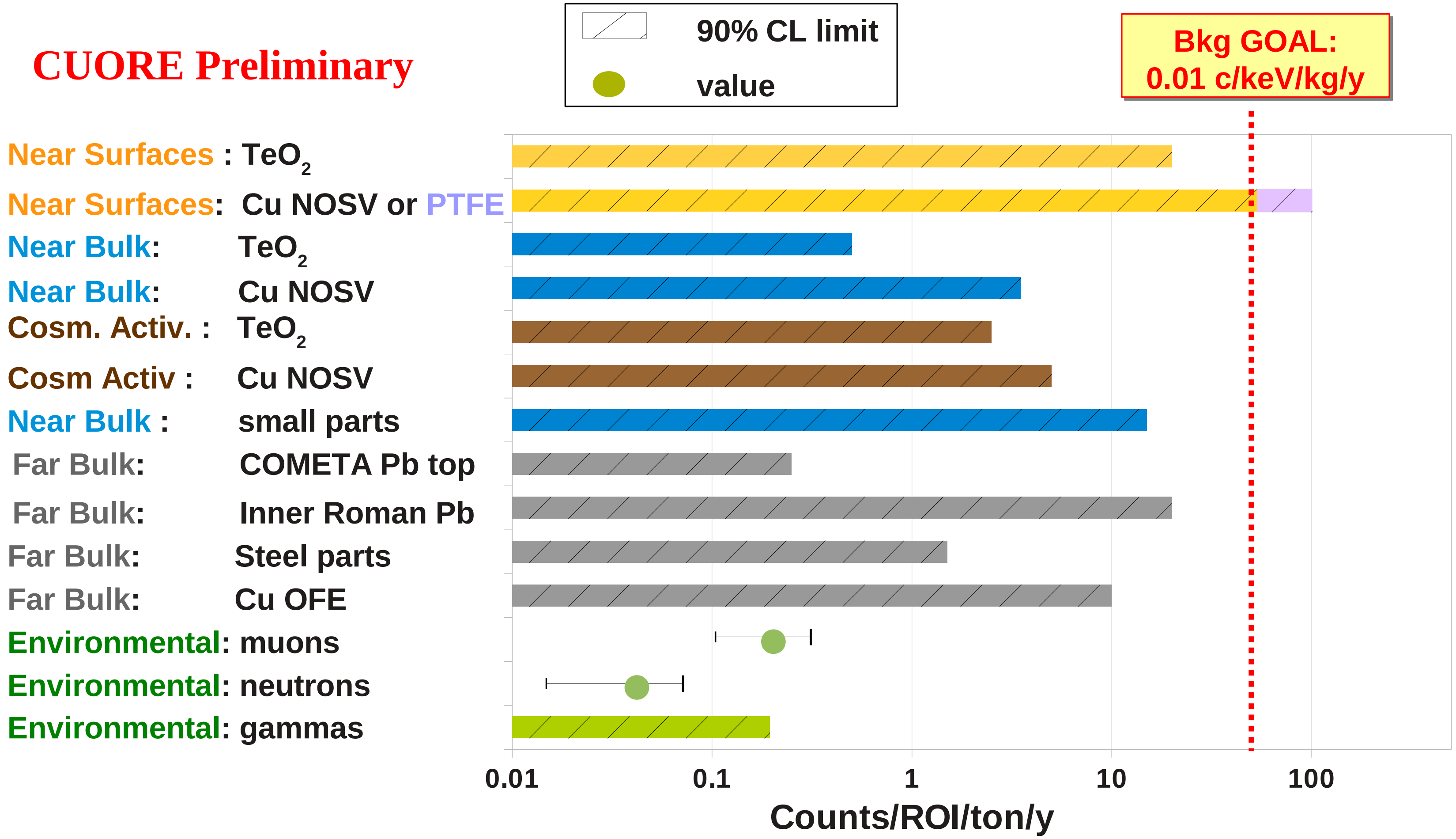
CUORE



CUORE

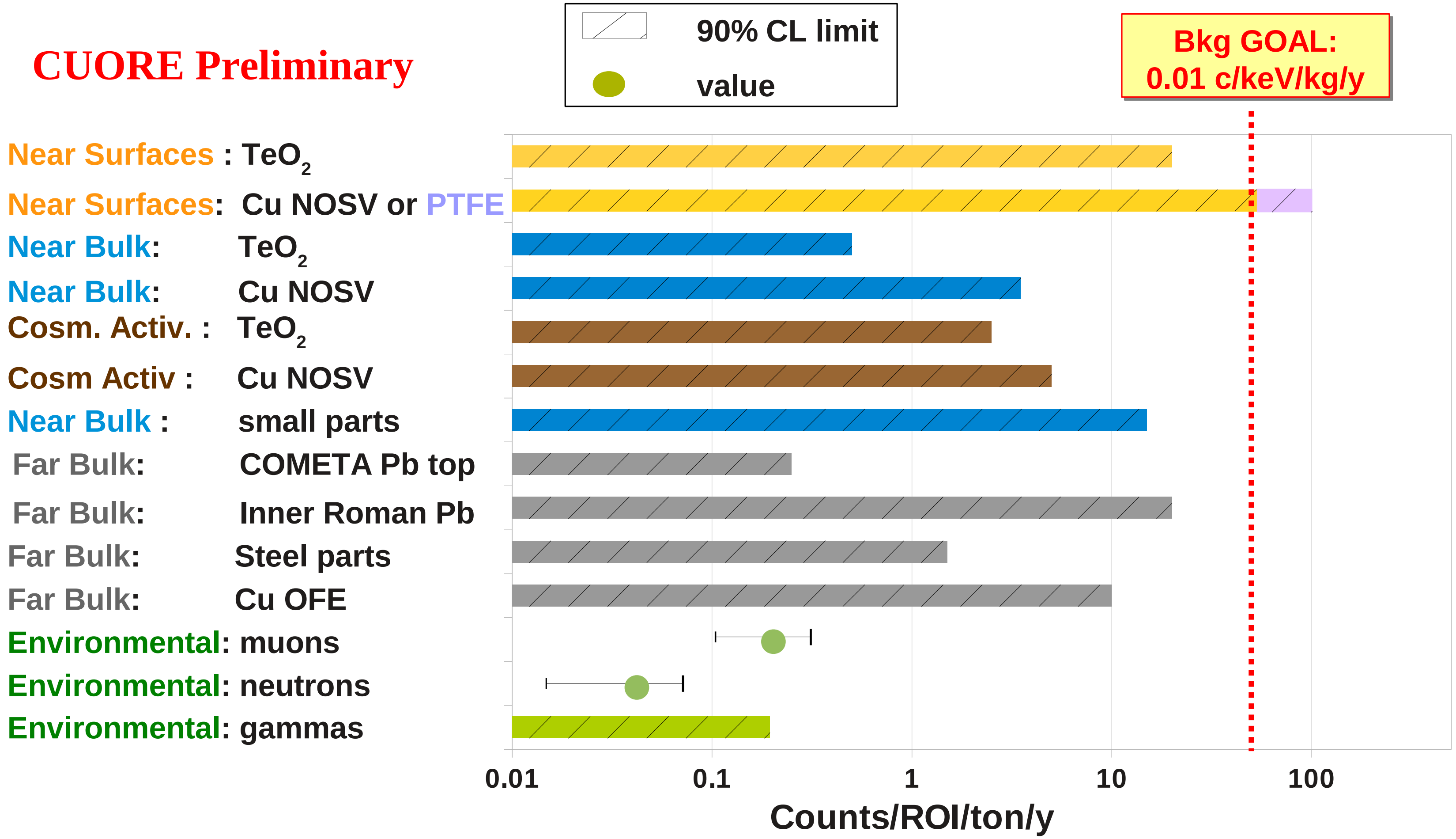
CUORE Background Model

CUORE Preliminary



R. Artusa et al., “Projected background budget of the CUORE experiment”, in preparation

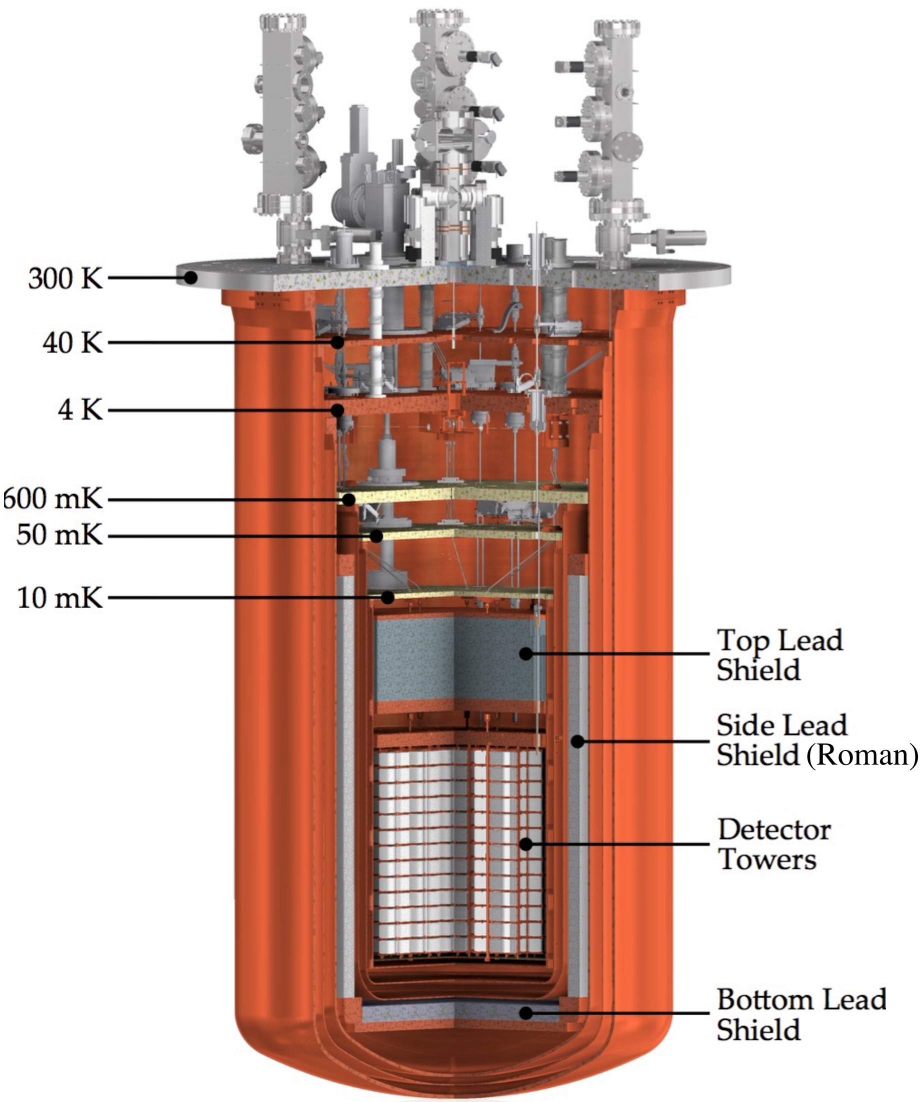
CUORE Background Model



R. Artusa et al., "Projected background budget of the CUORE experiment", in preparation

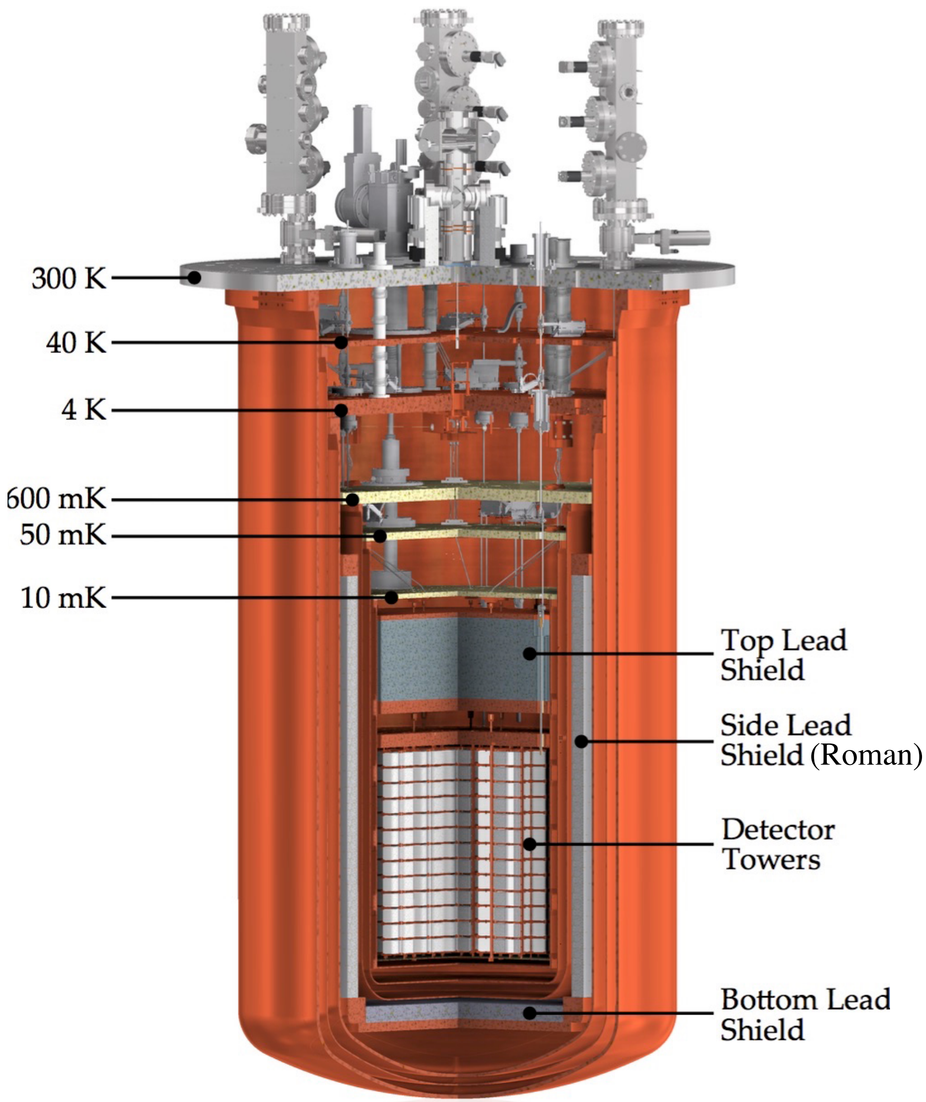
CUORE background goals now demonstrated

CUORE Cryostat



- 10 mK baseline temperature
  - 750 kg of crystals
  - Copper supporting structure
- ~20 tons at various low temperature
- Low background
  - Built with radio-pure materials
  - Roman lead shield from ancient shipwreck, <4mBq/kg ^{210}Pb
- Low vibrations
  - Separated suspension for the crystal tower and DR
- Minimal maintenance and dead time
  - Cryogen free DR

CUORE Cryostat

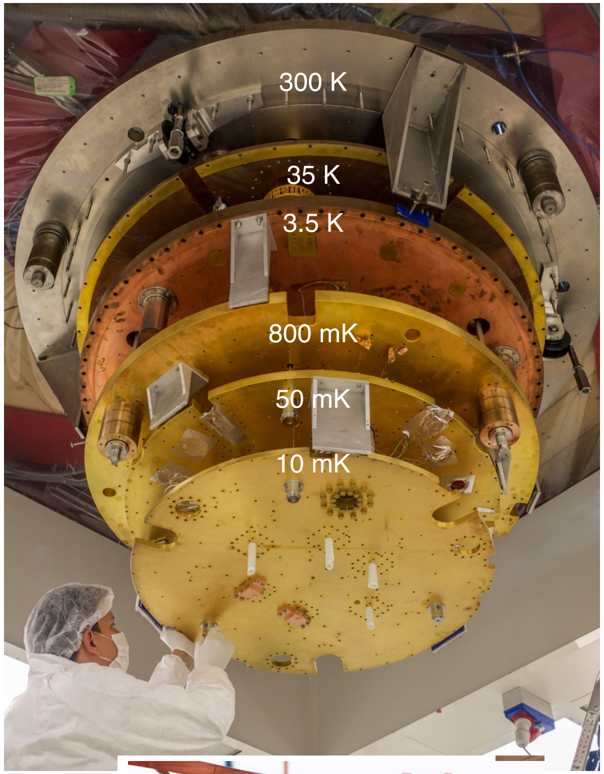


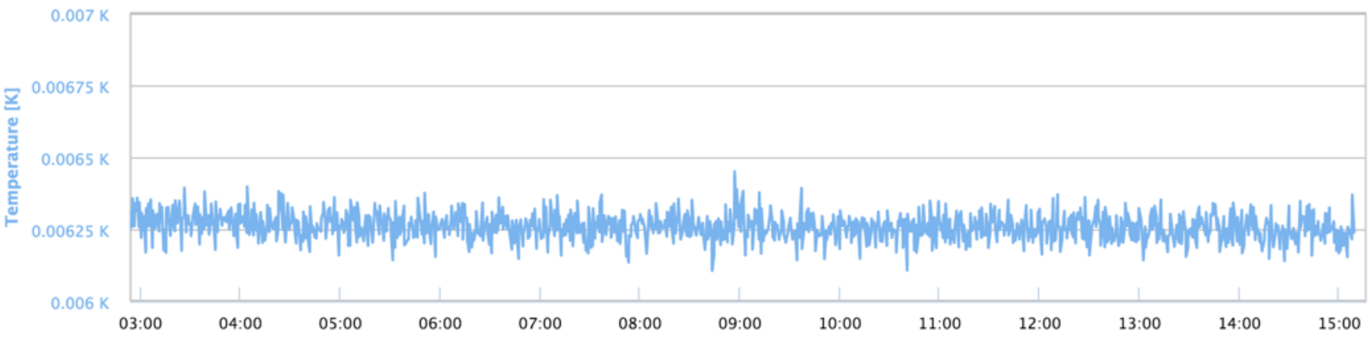
- 10 mK baseline temperature
  - 750 kg of crystals
  - Copper supporting structure
- ~20 tons at various low temperature
- Low background
  - Built with radio-pure materials
  - Roman lead shield from ancient shipwreck, <4mBq/kg ^{210}Pb
- Low vibrations
  - Separated suspension for the crystal tower and DR
- Minimal maintenance and dead time
  - Cryogen free DR

Coldest m^3 in known Universe !

Cryogenic Commissioning

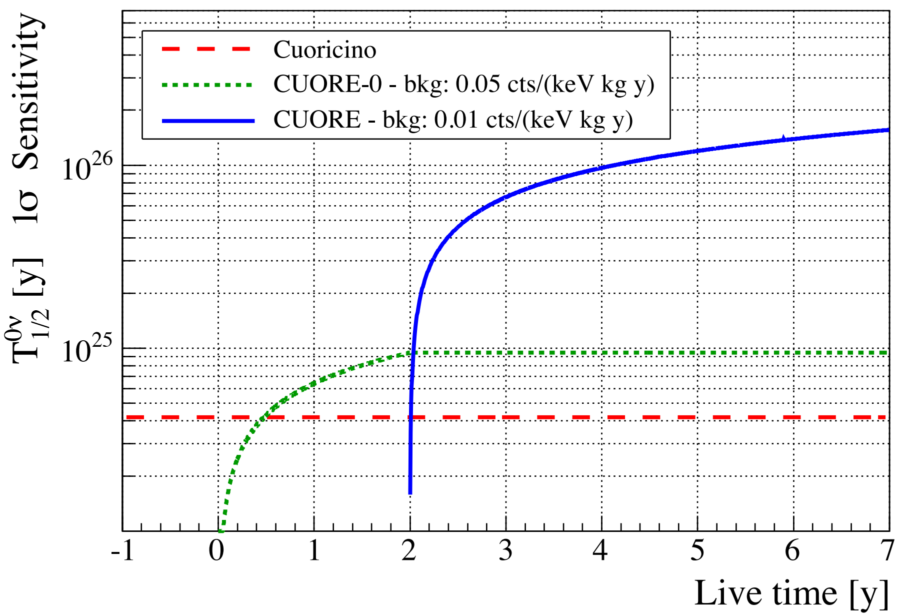
- Cryogenic commissioning complete
- Demonstrated stable base temperature ~6.3 mK, design cooling power (3μW @ 10 mK)
  - Fully loaded cryostat (>10 t of lead and copper)
  - 70 days of cryogenic operations
  - Operated 8-detector "mini-tower", commissioned temperature stabilization system, electronics, DAQ, Detector Calibration System
    - ☞ Good news for detector resolution and backgrounds

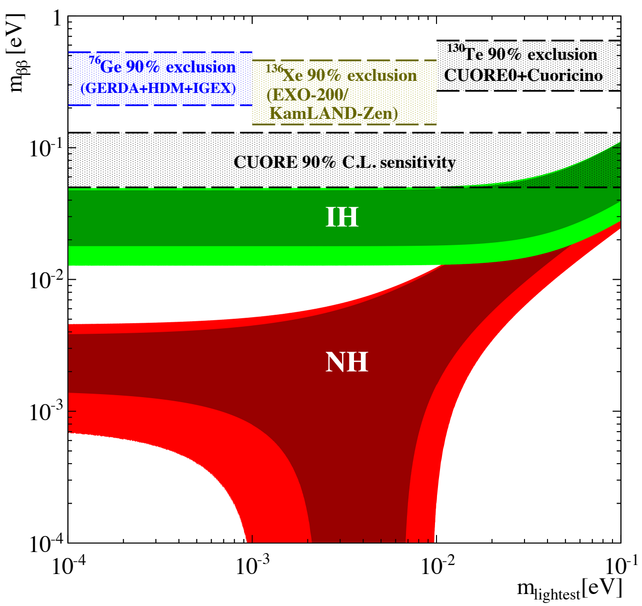




CUORE Status and Sensitivity

- Detector: all towers assembled, in underground storage
- Cryostat and dilution unit: commissioning complete
- Will install detectors and start operations by Fall 2016
- 5-year sensitivity: $T_{1/2}(^{130}Te)>9.5\times10^{25}$ years, $m_{\beta\beta}<52\text{-}120$ meV (@ 90% C.L.)





Beyond CUORE: CUPID

International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

1980 - 2007

2007 - 2017

2015 - 2025

J.F. Wilkerson

CUORE

International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

If $0\nu\beta\beta$ observed

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques

200-500 kg scale

1980 - 2007

2007 - 2017

2015 - 2025

J.F. Wilkerson

International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

Inverted hierarchy
$T_{1/2} \sim 10^{27}$-10^{28} y
(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

1980 - 2007

2007 - 2017

2015 - 2025

J.F. Wilkerson

International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

Inverted hierarchy
$T_{1/2} \sim 10^{27}$-10^{28} y
(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

If $0\nu\beta\beta$ Observed

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques

~ tonne scale

1980 - 2007

2007 - 2017

2015 - 2025

J.F. Wilkerson

International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

Inverted hierarchy
$T_{1/2} \sim 10^{27}$-10^{28} y
(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

Normal hierarchy
~5 meV
≥10's ton scale

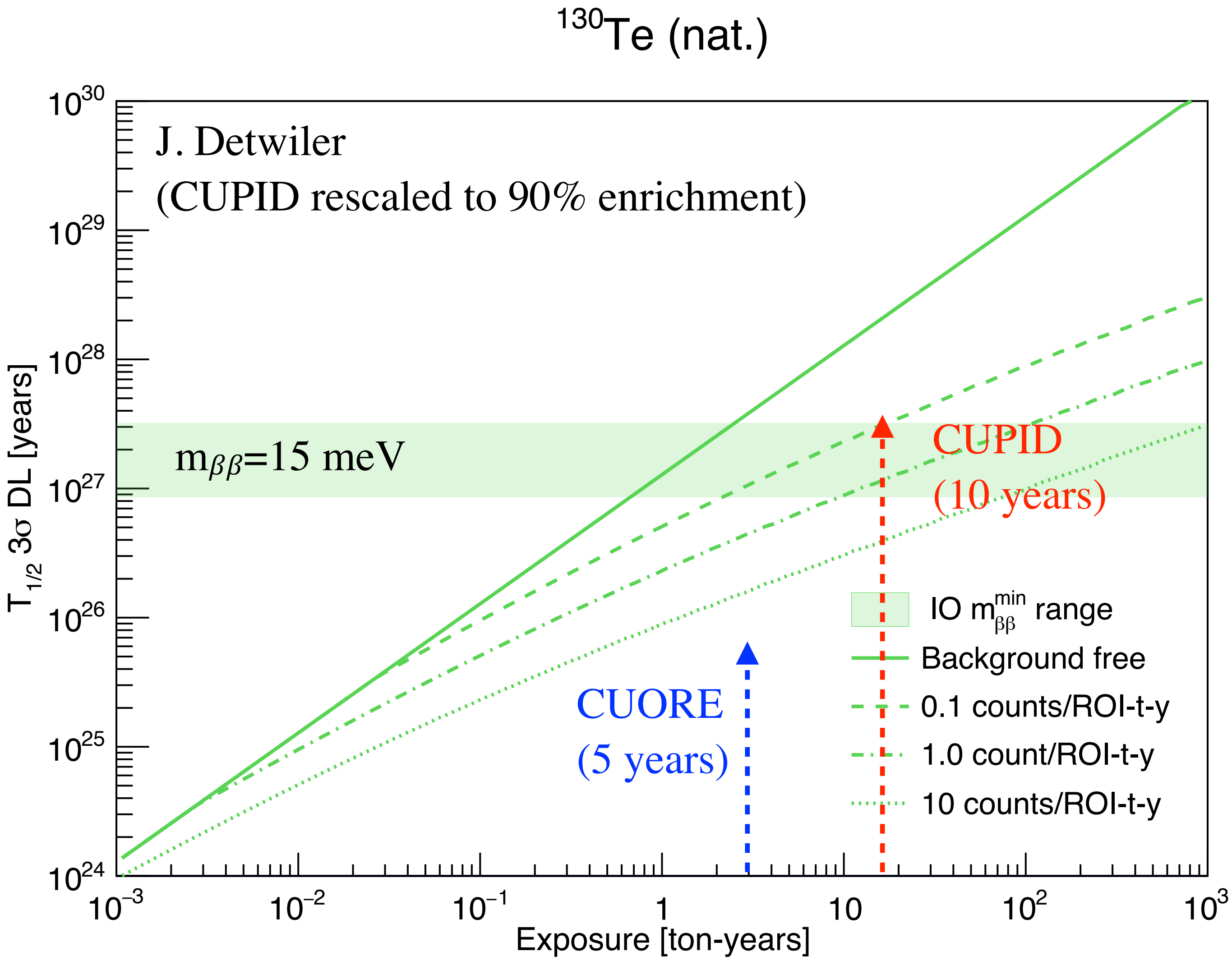
1980 - 2007

2007 - 2017

2015 - 2025

J.F. Wilkerson

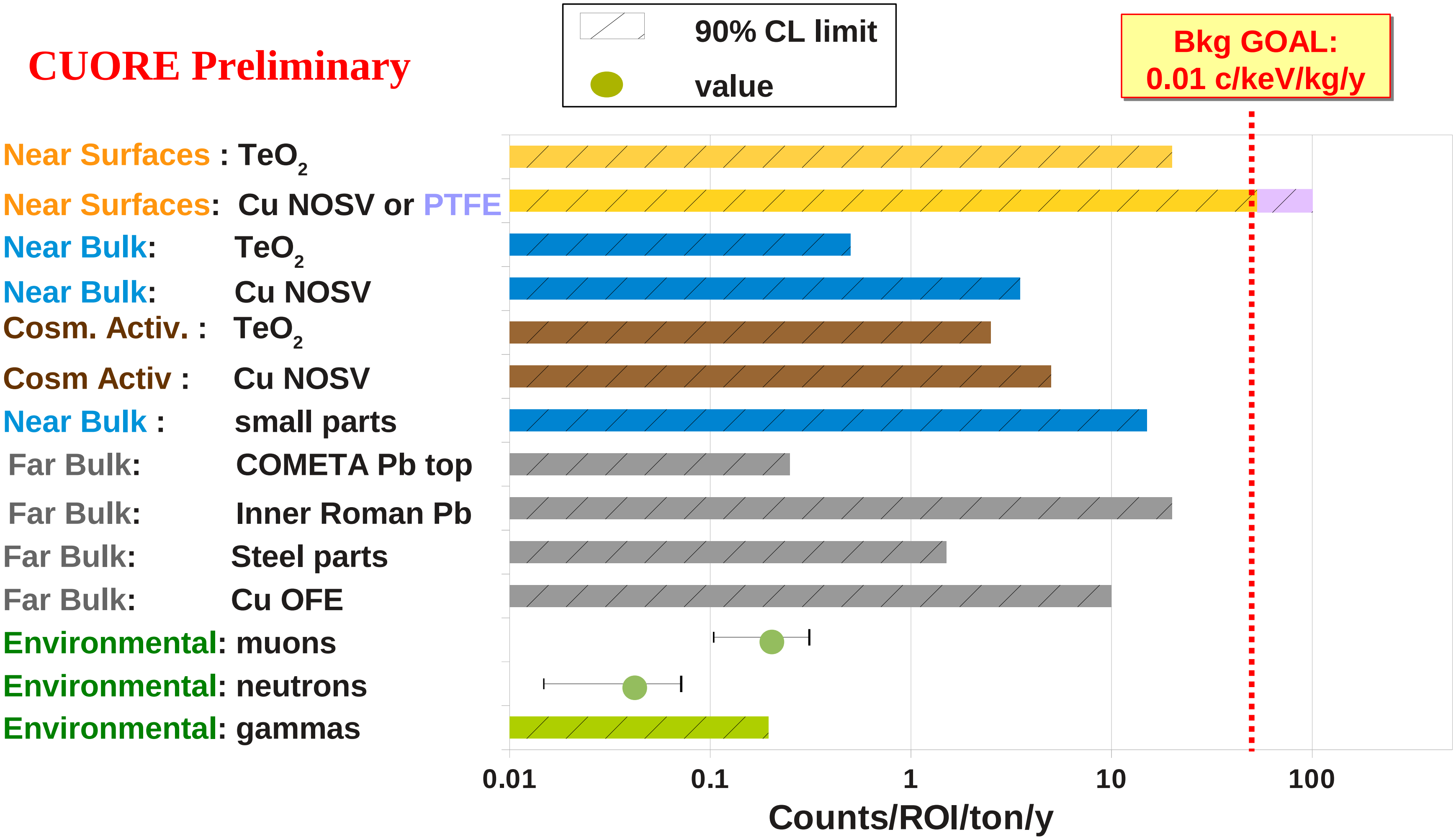
Required Sensitivity



(3σ discovery level for 50% of toy experiments)

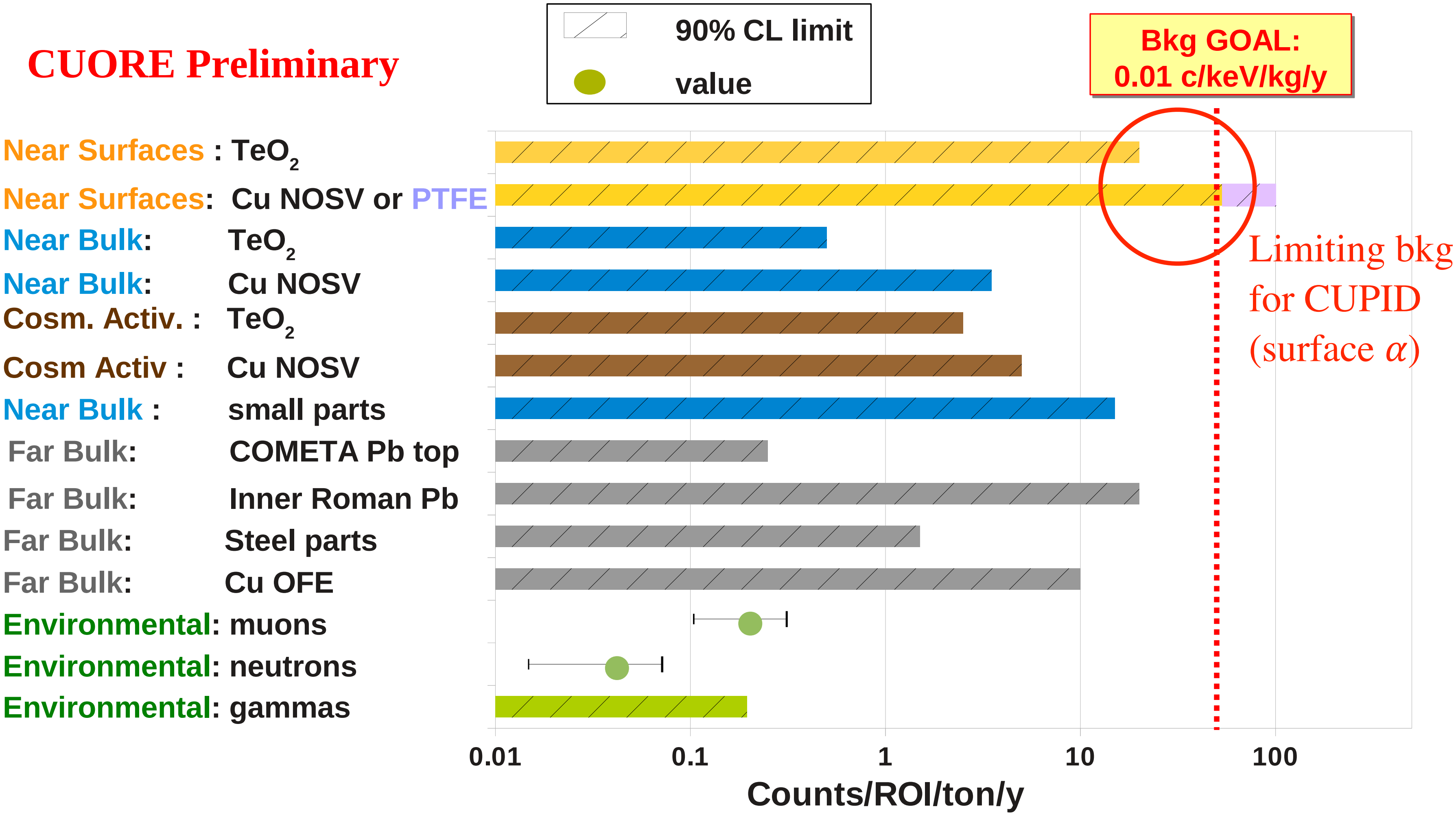
CUORE Background Model

CUORE Preliminary



K. Alfonso et al., "Projected background budget of the CUORE experiment", in preparation

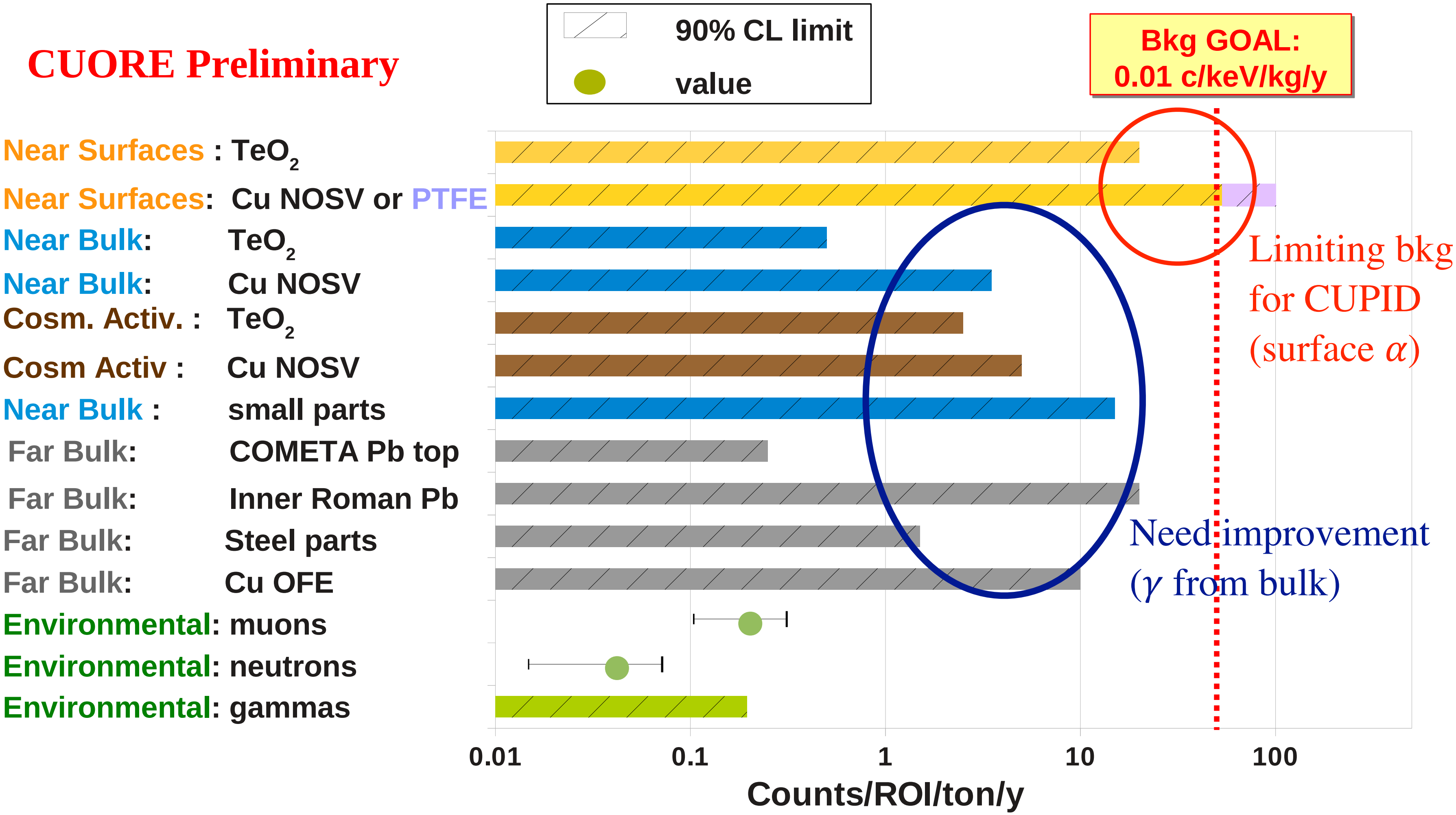
CUORE Background Model



K. Alfonso et al., "Projected background budget of the CUORE experiment", in preparation

CUORE Background Model

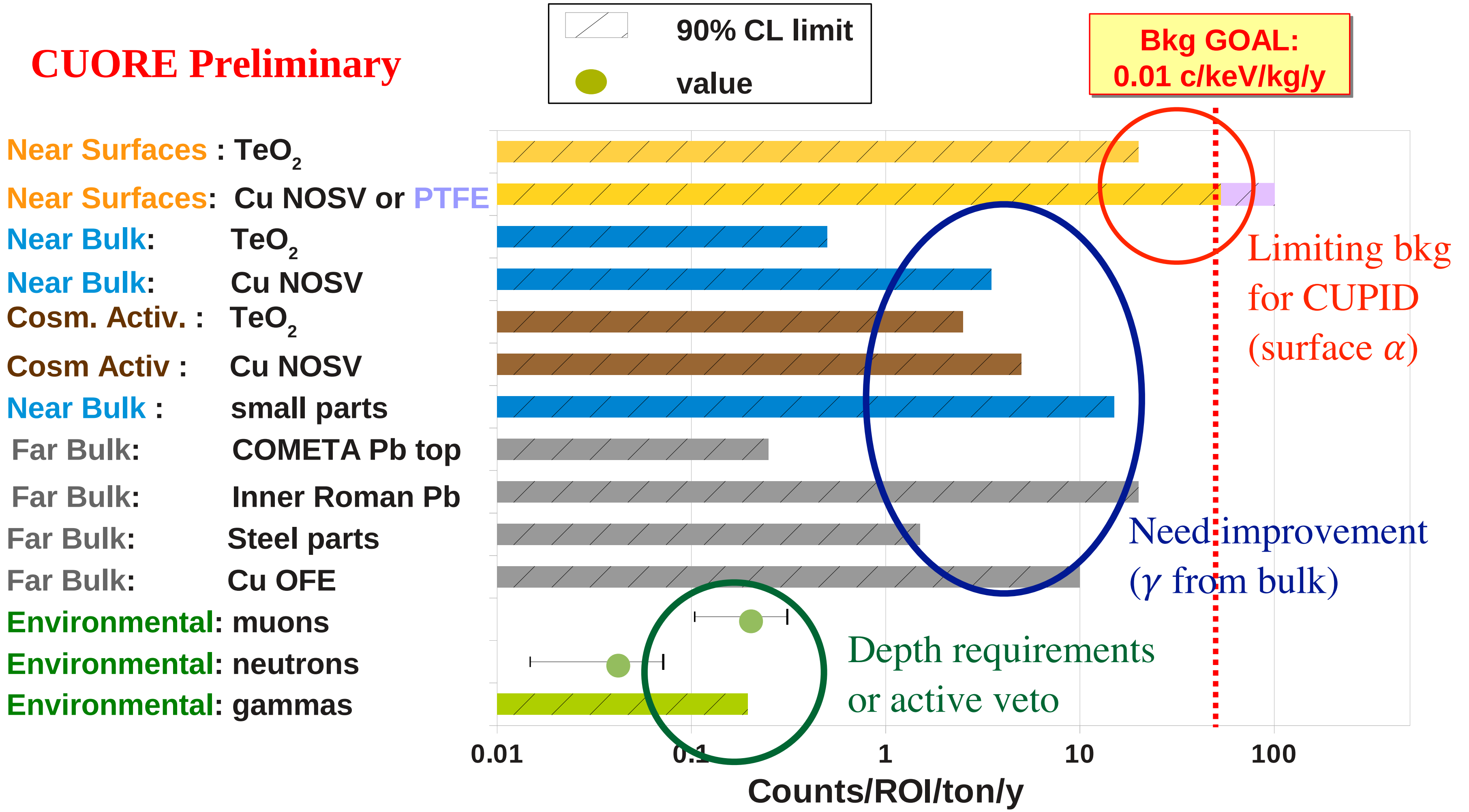
CUORE Preliminary



K. Alfonso et al., "Projected background budget of the CUORE experiment", in preparation

CUORE Background Model

CUORE Preliminary

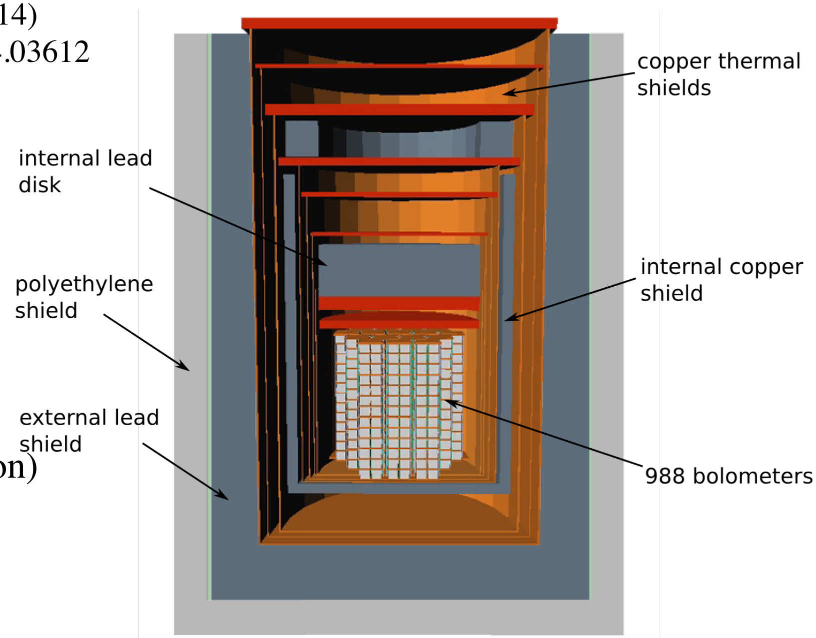


K. Alfonso et al., “Projected background budget of the CUORE experiment”, in preparation

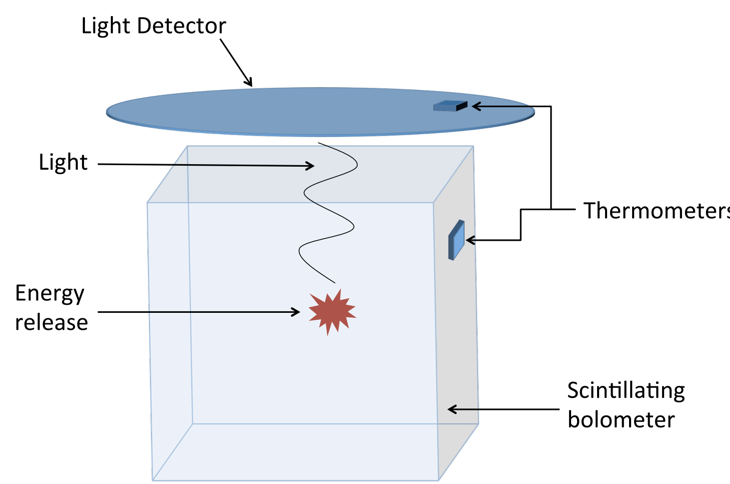
CUORE Upgrade with Particle ID (CUPID)

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

- Next-generation bolometric tonne-scale experiment
- Based on the CUORE design, CUORE cryogenics
- 988 enriched (90%) crystals, PID with light detection
  - 4 crystals considered:
    - ☞ TeO_2 : phonons + Cherenkov detector
    - ☞ Options: ZnSe, $ZnMoO_4$, $CdWO_4$ (phonons+scintillation)

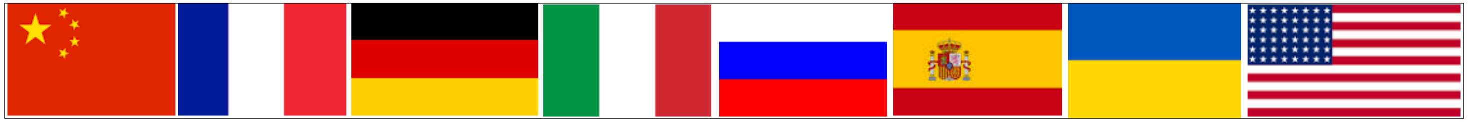


- Sensitivity to entire IH region
  - ☞ CUORE geometry and background model
  - ☞ Challenge: nearly zero background measurement background goal < 0.1 events / (ROI ton*year)
  - ☞ 99.9% α rejection @ >90% signal efficiency
  - ☞ 5 keV FWHM resolution
  - ☞ Half-life sensitivity (2-5)×10^{27} years in 10 years (3σ)
  - ☞ $m_{\beta\beta}$ sensitivity 6-20 meV (3σ)



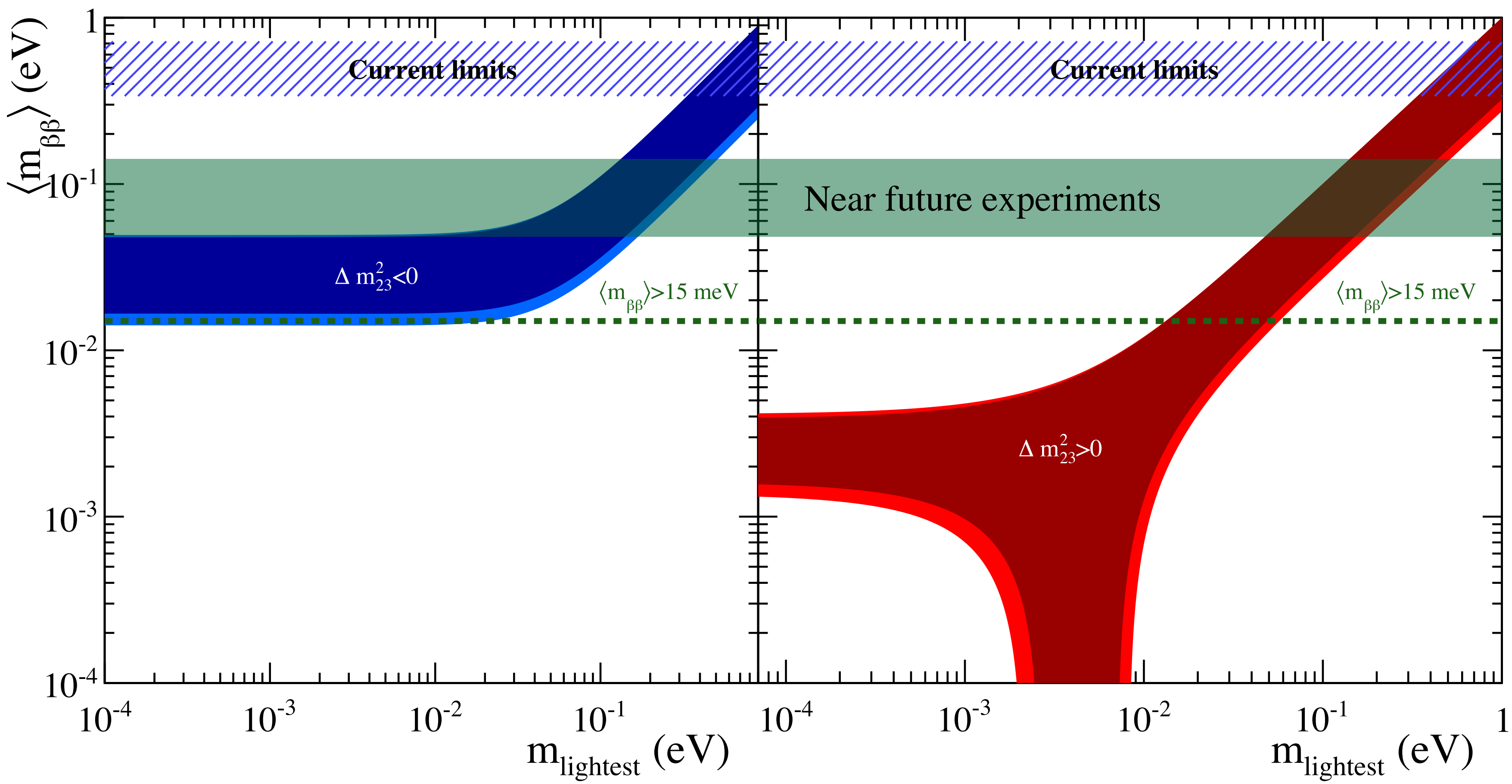
Subject of focused R&D effort in next 2-3 years

CUPID Interest Group



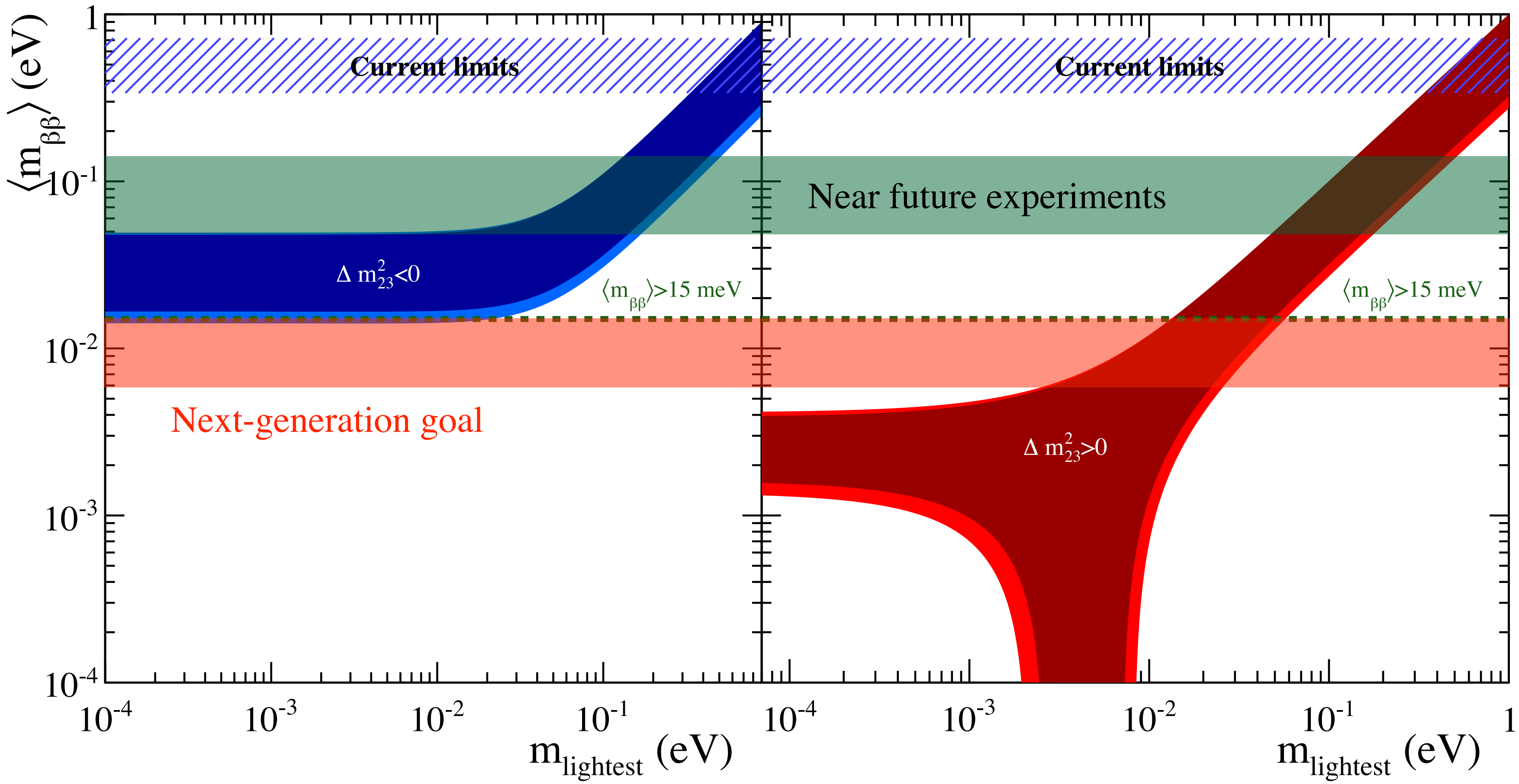
High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA
Materials Science Division, Argonne National Laboratory, Argonne, IL, USA
INFN - Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Department 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
State Scientific Center of the Russian Federation - Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
Max-Planck-Institut für Physik, D-80805 München, Germany
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
Institut de Chimie de la Matière Condensè de Bordeaux (ICMCB), CNRS, 87, Pessac, France
Dipartimento di Fisica, Università di Roma “La Sapienza” and INFN - Sezione di Roma, Roma, Italy
IFN-CNR, Via Cineto Romano, I-00156 Roma, Italy
Service de Physique des Particules, DSM/IRFU, CEA-Saclay, France
Physics Department, California Polytechnic State University, San Luis Obispo, CA, USA
Shanghai Institute of Applied Physics (SINAP), China
Institut de Physique Nuclèaire de Lyon, Universitè Claude Bernard, Lyon 1, Villeurbanne, France
Wright Laboratory, Department of Physics, Yale University, New Haven, CT, USA
Laboratorio de Fisica Nuclear y Astropartculas, Universidad de Zaragoza, Zaragoza, Spain

DBD and Neutrino Mass



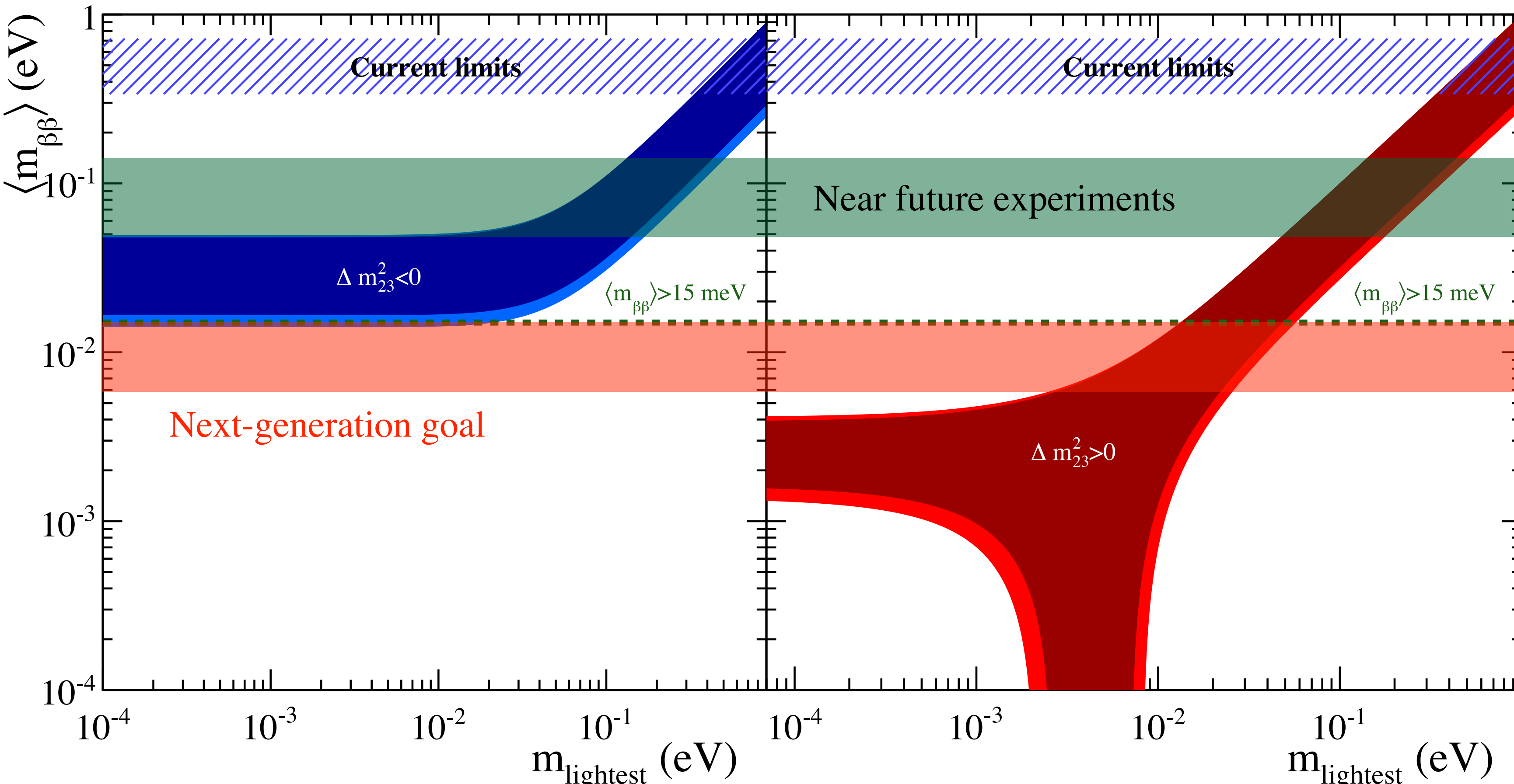
$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

DBD and Neutrino Mass



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

DBD and Neutrino Mass



Exciting future ahead !

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

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