Neutrino-less Double-beta Decay Search with the CUORE Experiment

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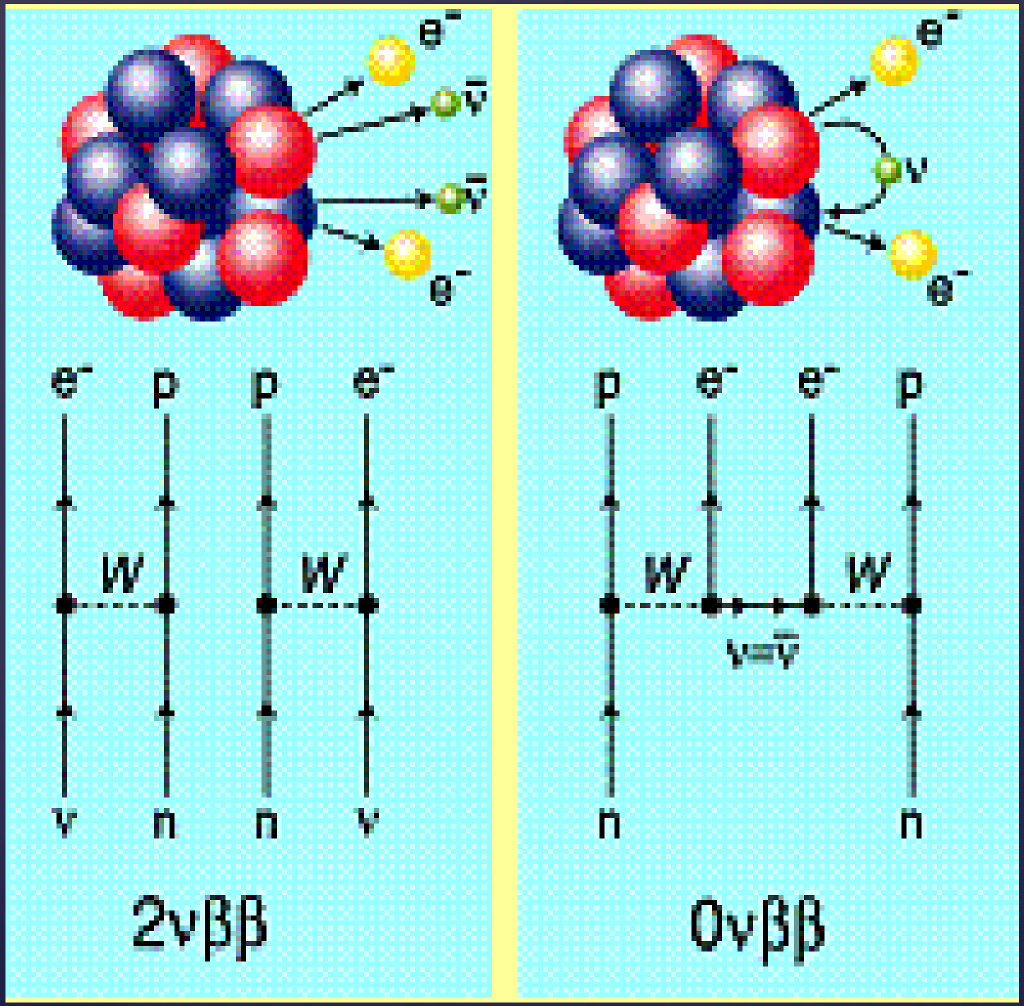
SPACETIME ODTSSEY CONTINUES

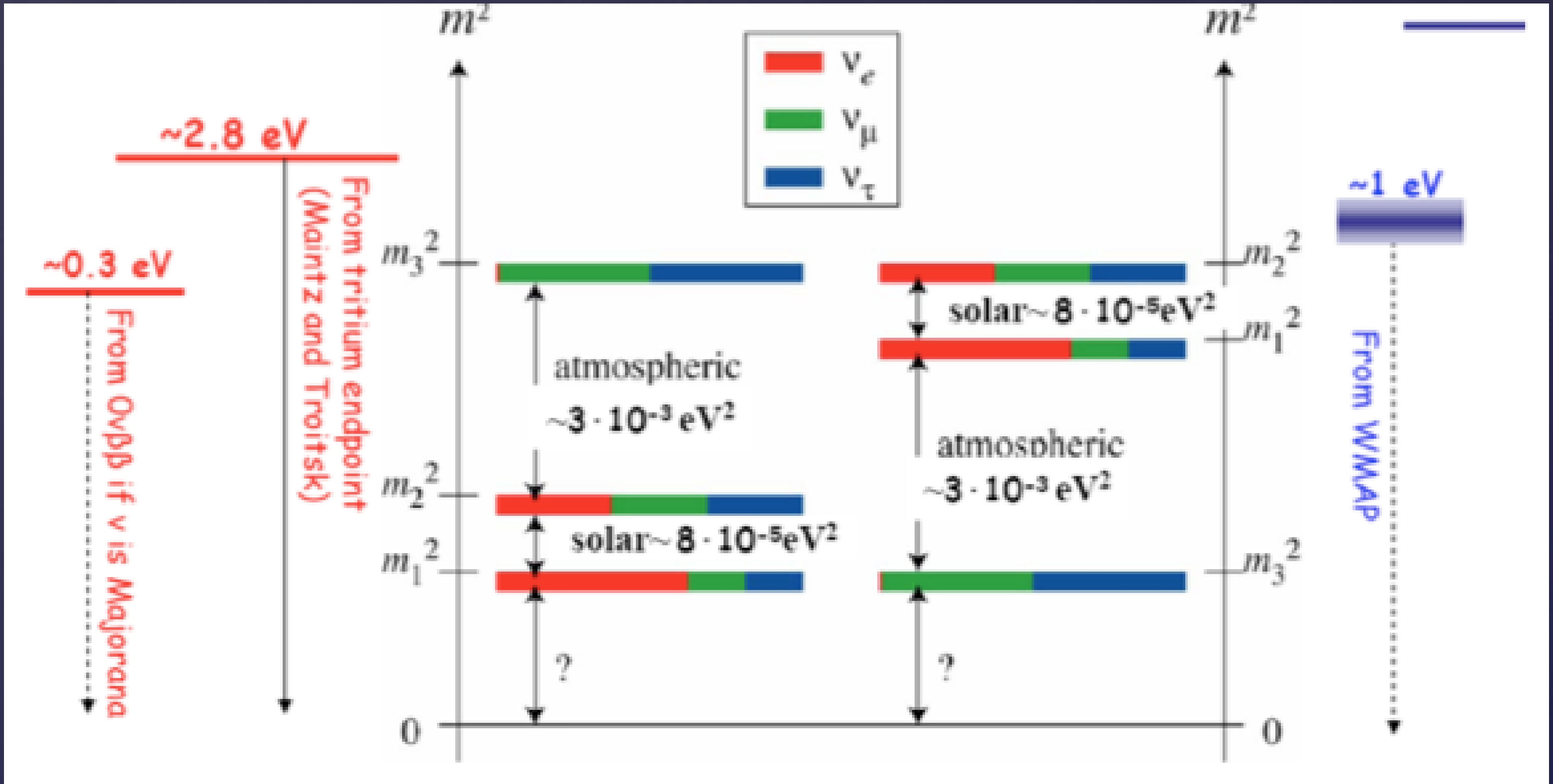
NORDITA, Stockholm, Sweden
June 3rd 2015

Neutrino-less Double-Beta Decay



$$\frac{1}{T_{1/2}^{0\nu}} = \frac{\left|\langle m_\nu \rangle\right|^2}{m_e^2} G^{0\nu} \left|M\right|^2 ,$$

The Neutrino Hierarchy Problem



Neutrino oscillation experiments when analyzed all together, give us this picture; however, there are only bounds on the lightest neutrino mass eigenstate

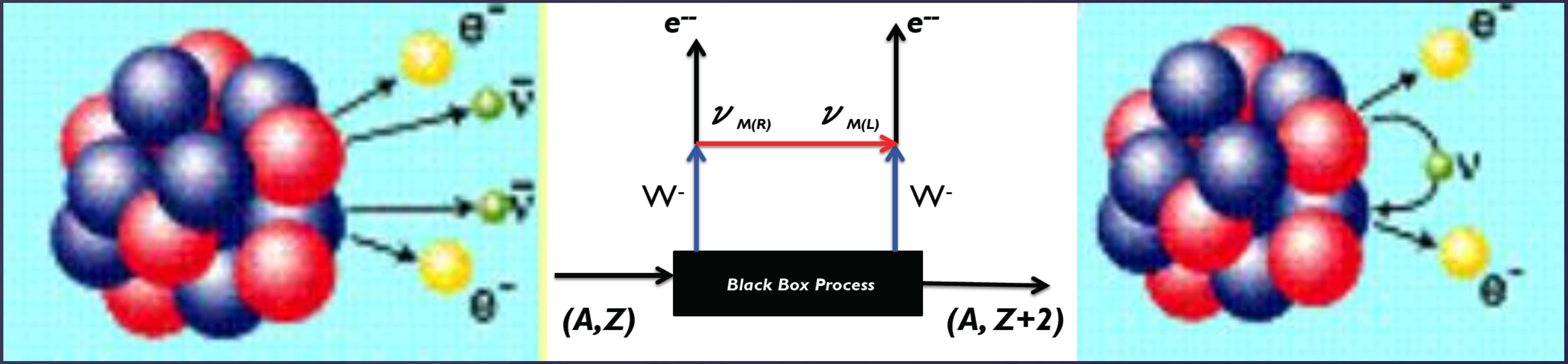
Neutrino-less Double-Beta Decay

The only practical way to determine that neutrinos are Majorana particles is by direct observation of neutrino-less double-beta decay.

Neutrino-less double beta-decay would violate the conservation of lepton number.

The measurement of the half life of neutrino-less double-beta decay would yield the Majorana-neutrino mass scale, although nuclear model dependent.

Neutrino-less Double-Beta Decay

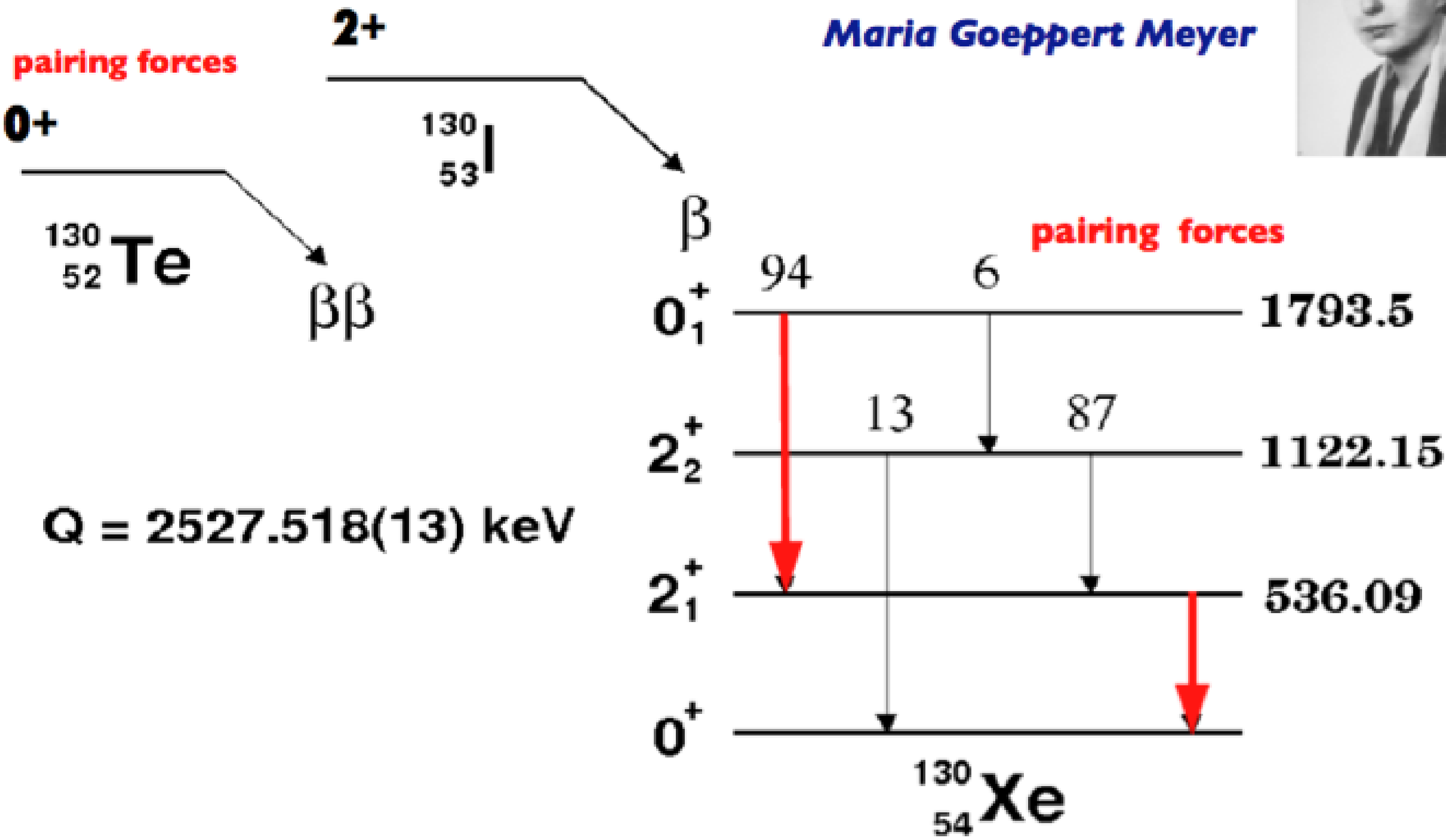


All decay modes that engender 0-neutrino double-beta decay require that the neutrinos involved are Majorana particles: This was shown by Schechter and Valle in their Black-Box theorem and also independently by Boris Kayser and Peter Rosen.

^{130}Te Double-Beta Decay Level Scheme

Can a nucleus like ^{130}Te decay by 2-beta decays, 1935 ?

Maria Goeppert Meyer



Half Life and Neutrino Mass Relation

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(E_0,Z)\left|\frac{\langle m_\nu\rangle}{m_e}\right|^2 \left|M_f^{0\nu} - (g_A/g_V)^2 M_{GT}^{0\nu}\right|^2$$

Effective Majorana mass of the electron neutrino

$$|\langle m_\nu\rangle| \equiv \left| \left(u_{e1}^L\right)^2 m_1 + \left(u_{e2}^L\right)^2 m_2 e^{i\phi_2} + \left(u_{e3}^L\right)^2 m_3 e^{i(\phi_3+\delta)} \right|$$

$$|\nu_\ell\rangle = \sum_{j=1}^{3} \left|U_{\ell j}^L\right| e^{i\delta_j} |\nu_j\rangle$$

$$m_{\beta\beta}^{inv} = \sqrt{m_3^2 + \delta m_A^2}\left(c_{12}^2 c_{13}^2\right) \pm \sqrt{m_3^2 + \delta m_S^2 + \delta m_A^2}\left(s_{12}^2 c_{13}^2\right) + m_3 s_{13}^2$$

CUORE

Cryogenic Underground Observatory
for Rare Events

A search for neutrino-less double-beta decay of ^{130}Te in the Laboratori Nazionali del Gran Sasso, Assergi, Italy

CUORE uses the Bolometric Technique with TeO_2 single crystal bolometers

The CUORE Collaboration

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

CAL POLY SAN LUIS OBISPO

SAPIENZA UNIVERSITÀ DI ROMA

Lawrence Livermore National Laboratory

Universidad Zaragoza

SINAP

UNIVERSITY OF SOUTH CAROLINA

CSNSM

UCLA

Berkeley Lab

LUX ET VERITAS

CUORE

^{130}Te: Double-Beta Decay Candidate

Large Natural Abundance of ^{130}Te, 33.167%

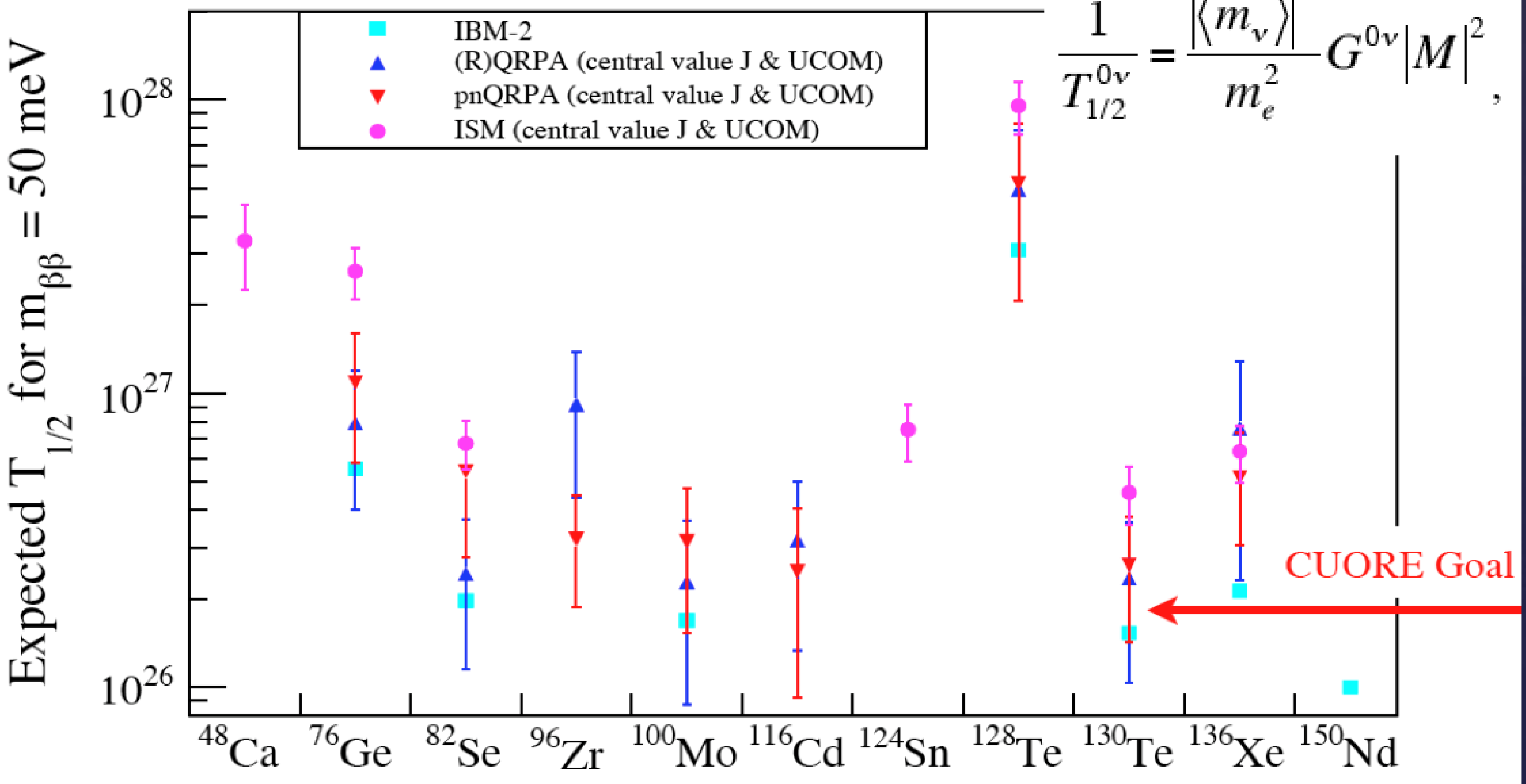
High transition energy: 2527.518 (13) keV *

It has an encouragingly large theoretical nuclear matrix element, hence a fast decay rate.

The bolometer technique ran in CUORICINO, with 40.7 kg of TeO_2 run at 8-mK for 3 years.

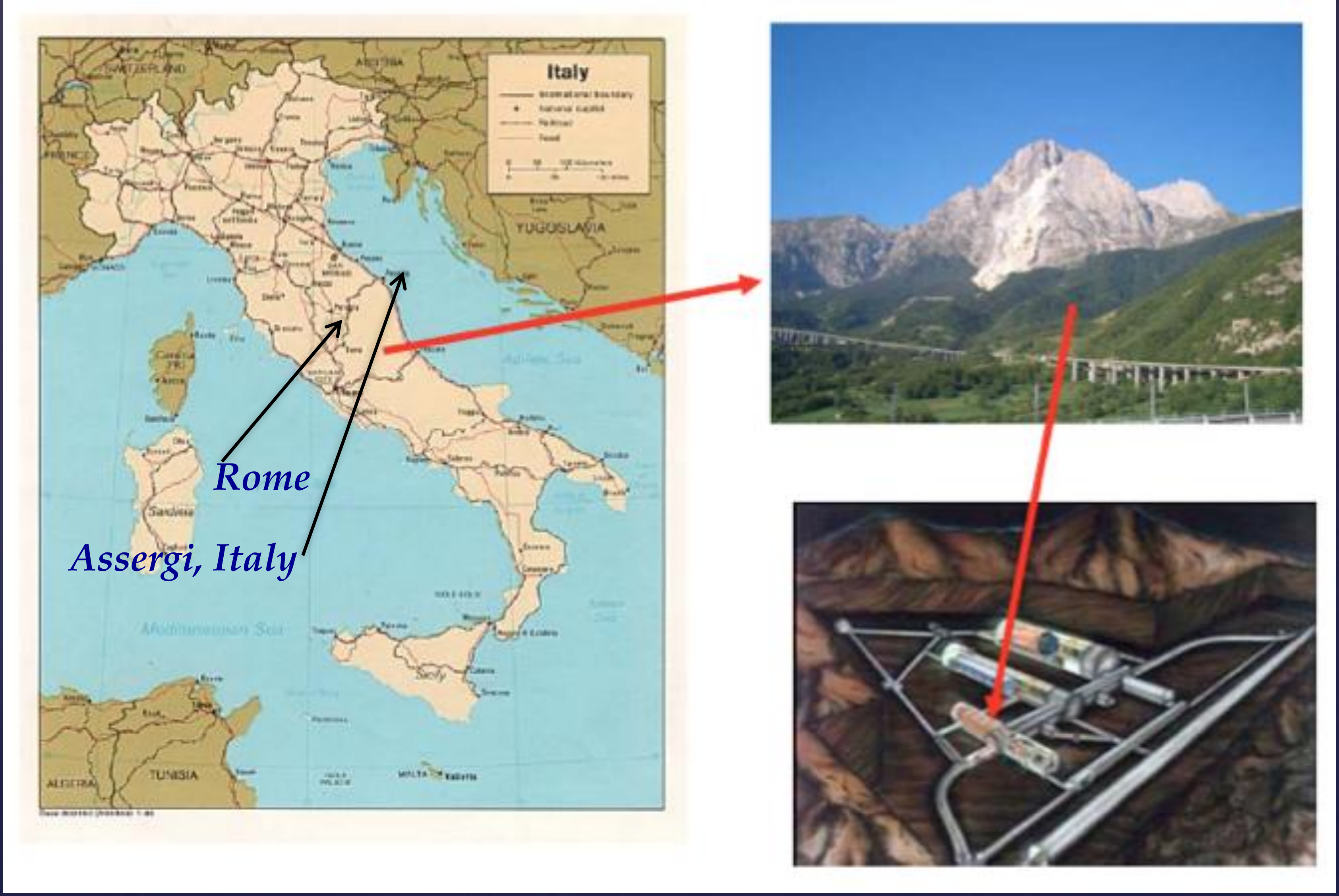
* Florida state group measured by the cyclotron frequency ratios of pairs of triply charged ions simultaneously trapped in a Penning trap, Redshaw et

Required Half-life Sensitivity

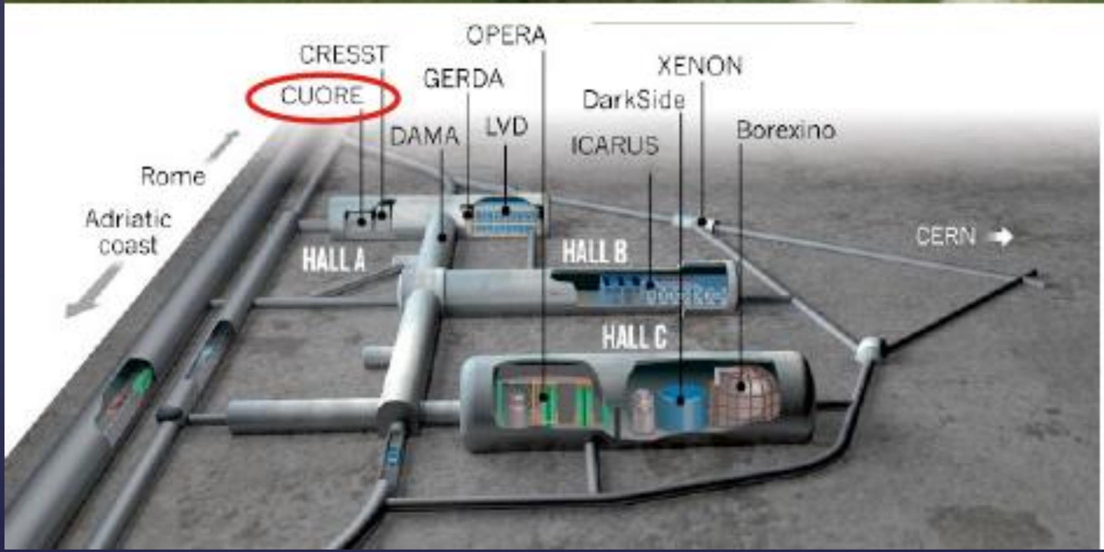


$$\frac{1}{T_{1/2}^{0\nu}} = \frac{\left|\langle m_\nu \rangle\right|^2}{m_e^2} G^{0\nu} \left|M\right|^2,$$

Laboratori Nazionali del Gran Sasso



I Laboratori Nazionali del Gran Sasso



3650 m.w.e

$$\Gamma_\mu \sim 2.6 \times 10^{-8} \mathrm{s}^{-1} \mathrm{cm}^{-2}$$

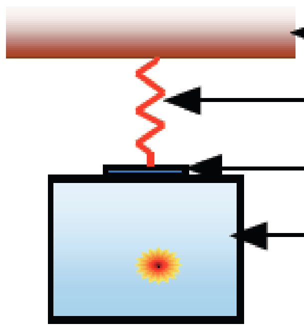
$$\Gamma_N \sim 4 \times 10^{-6} \mathrm{s}^{-1} \mathrm{cm}^{-2}$$

Bolometric Detectors

The detection technique depends on the thermal physics of phonons in pure single crystals or bolometers, operated at ~0.008 K.

The technique was developed for large detectors for double-beta decay over many years by Ettore Fiorini of the Universita` di Milano Bicocca and his colleagues and students.

Principles of the Bolometer Detector



Heat sink: Cu structure (8 mK)

Thermal coupling: Teflon (G = 4 pW/mK)

Thermometer: NTD Ge-thermistor (dR/dT ≅ 100 kΩ/μK)

Absorber: TeO_2 crystal (C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

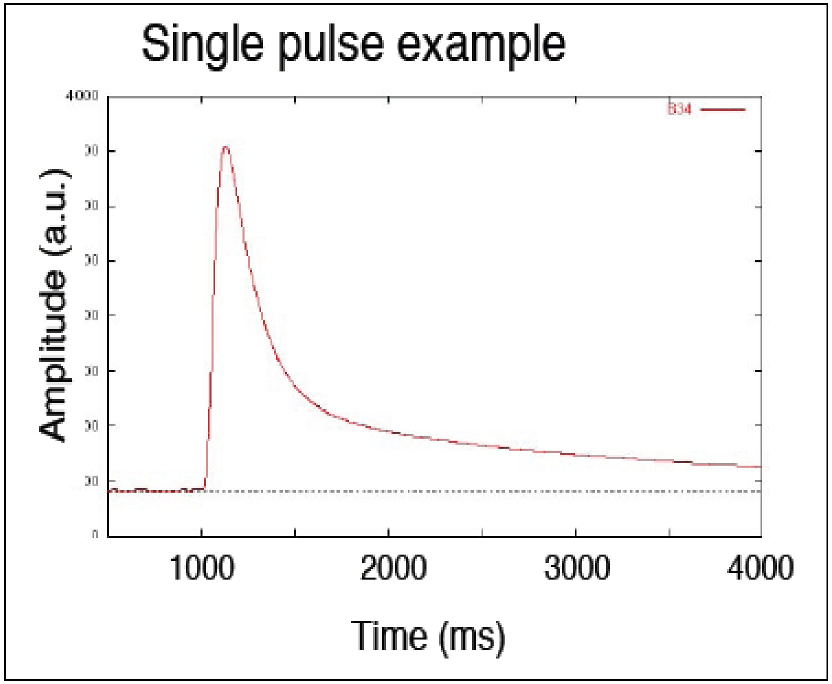
For E = 1 MeV:

- **ΔT = E/C ≅ 0.1 mK**
- **signal size: 1 mV**

Time constant:

- **τ = C/G = 0.5 s**

Energy resolution (FWHM):
~ 5-10 keV at 2500 keV

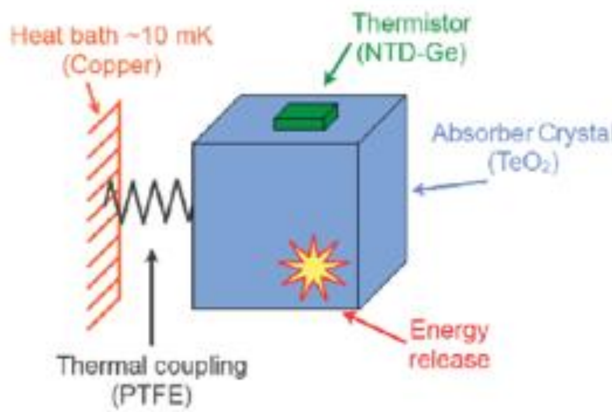


Bolometric Detectors and CUORE

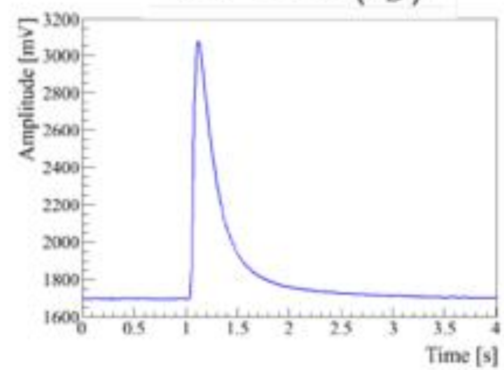
$$\Delta T(t) \approx \frac{\Delta E}{C} e^{-\frac{t}{\tau}}$$

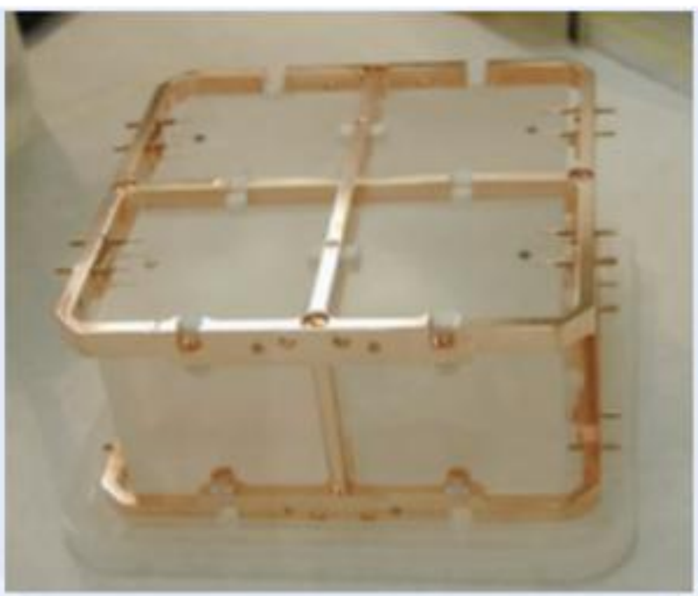
$$\tau = \frac{C}{G}$$

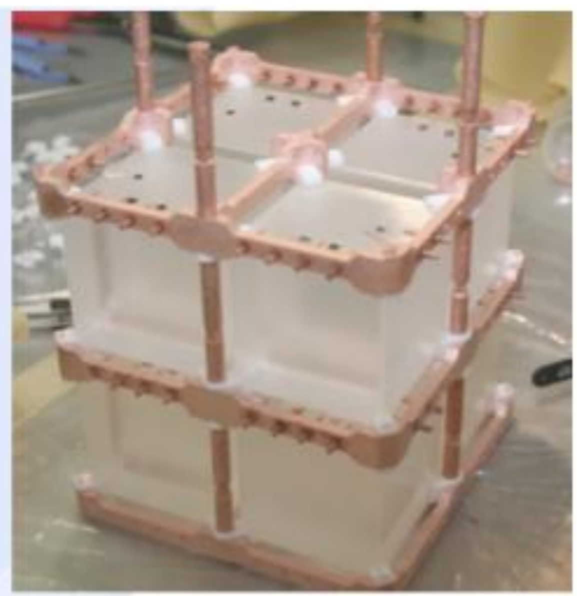
C = heat capacity
G = thermal conductance

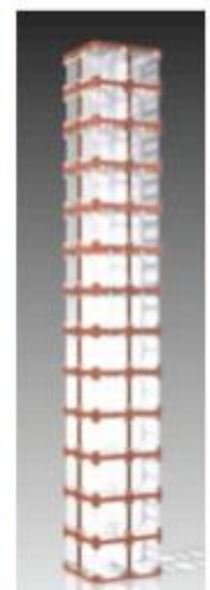


$$C(T) = const \left(\frac{T}{T_D}\right)^3$$

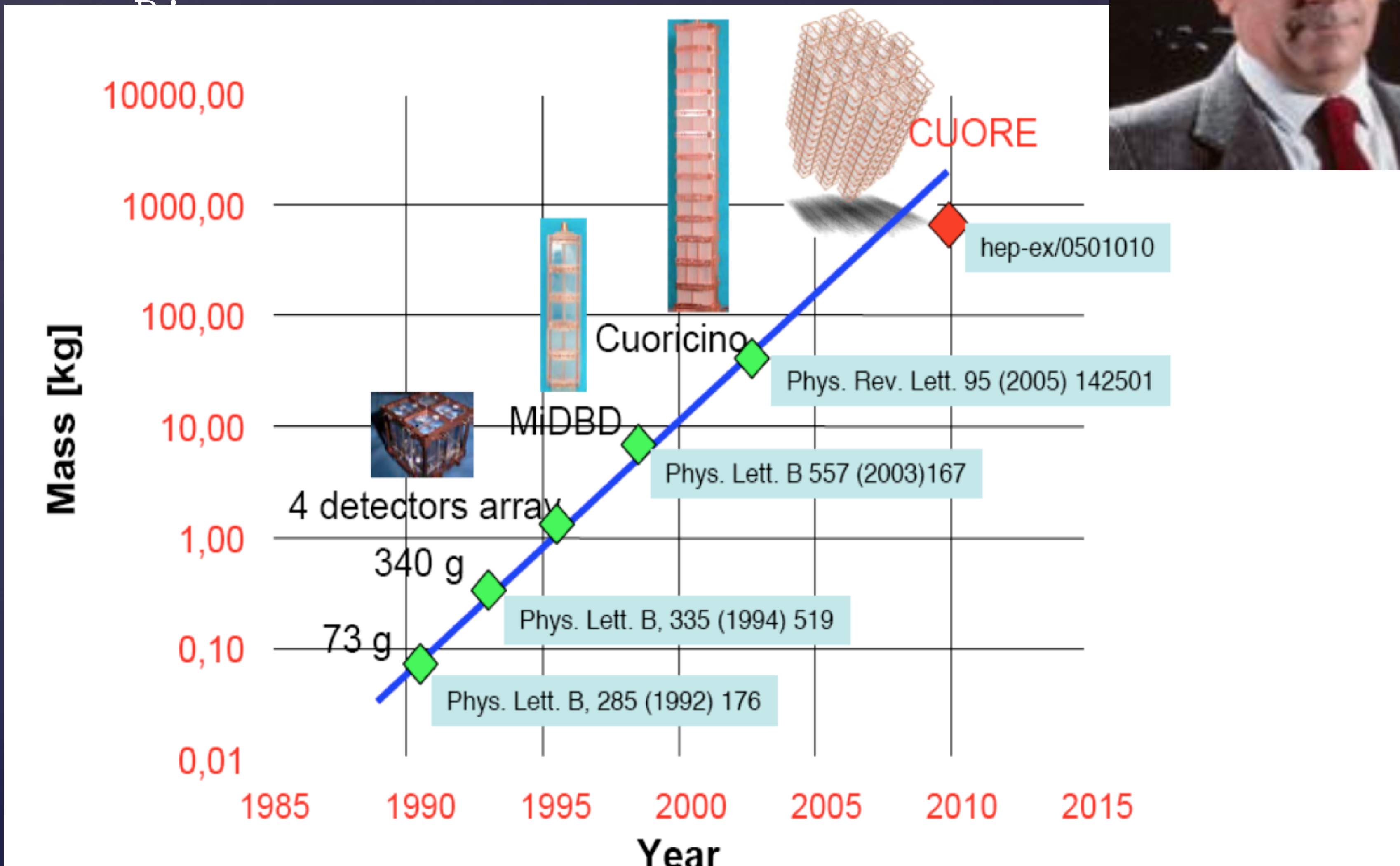








The Development of CUORE Led by Ettor Fiorini of Universita de Milano



CUORICINO, the Prototype for CUORE

11 modules
4 detectors each
Dimension: 5x5x5 cm^3
TeO_2 crystal mass: 790 g

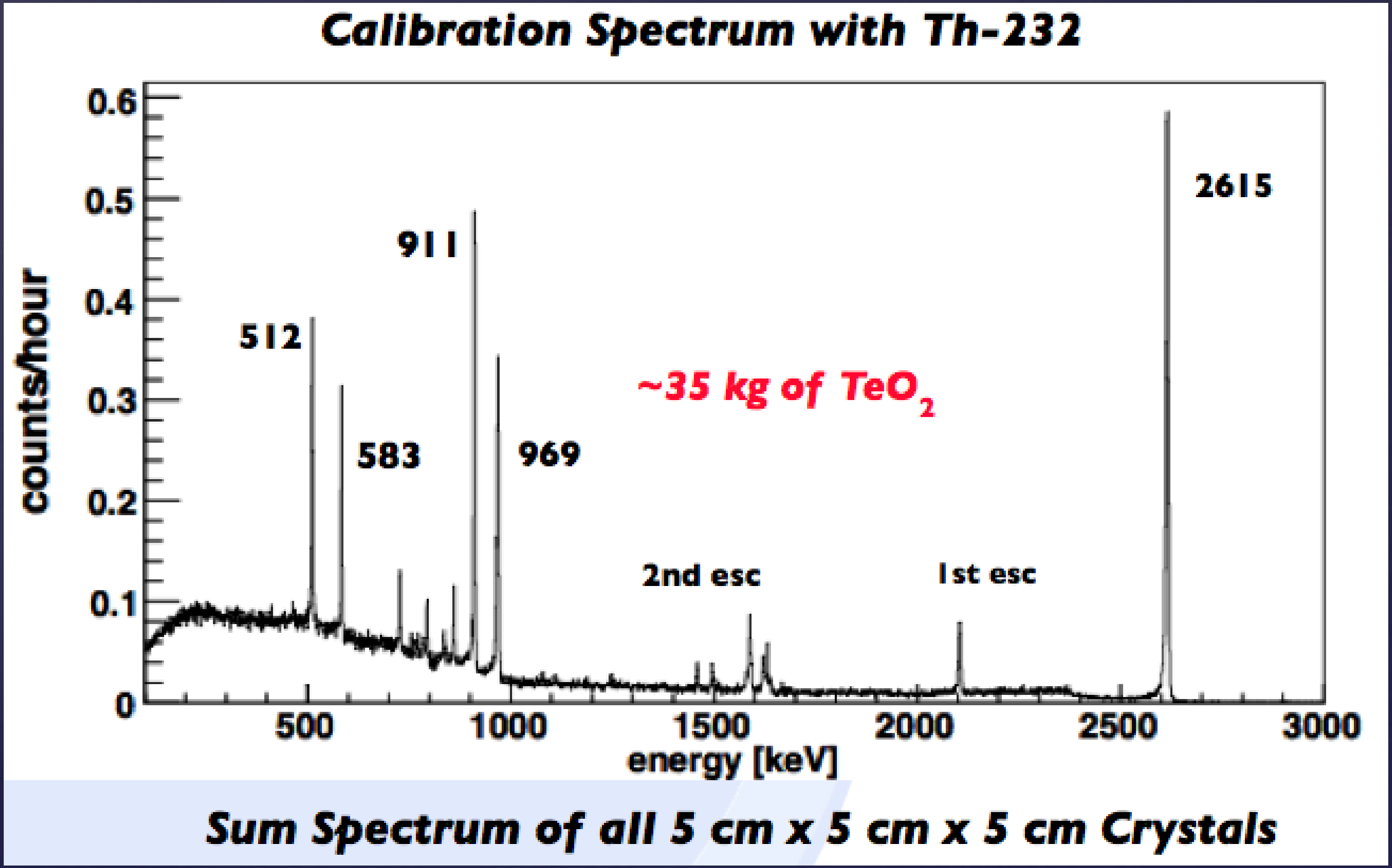
Total mass
40.7 kg

^{130}Te mass
11 kg

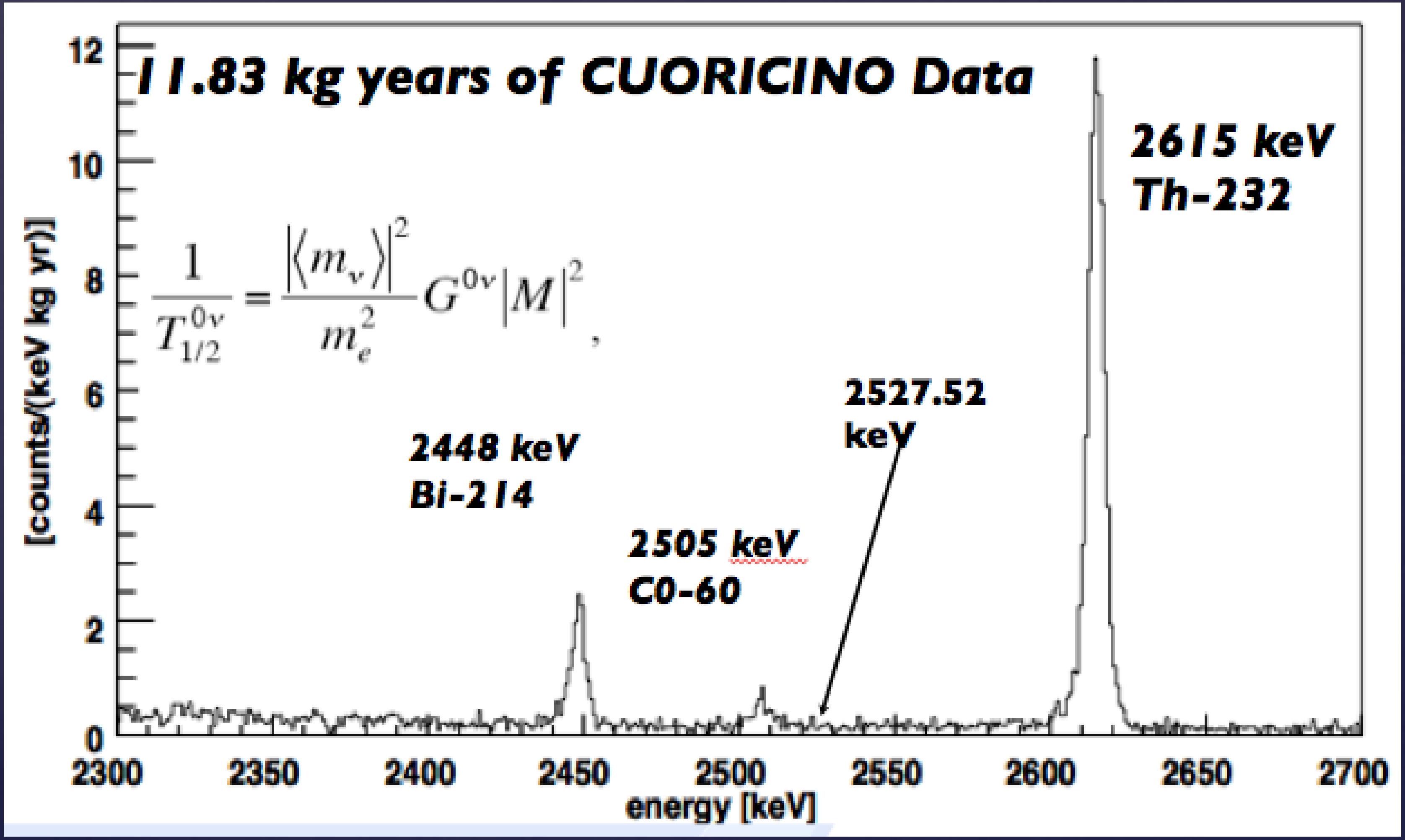
~ 5×10^{25}
^{130}Te nuclei

2 modules
9 detectors each,
Dimension: 3x3x6 cm^3
TeO_2 crystal mass: 330 g

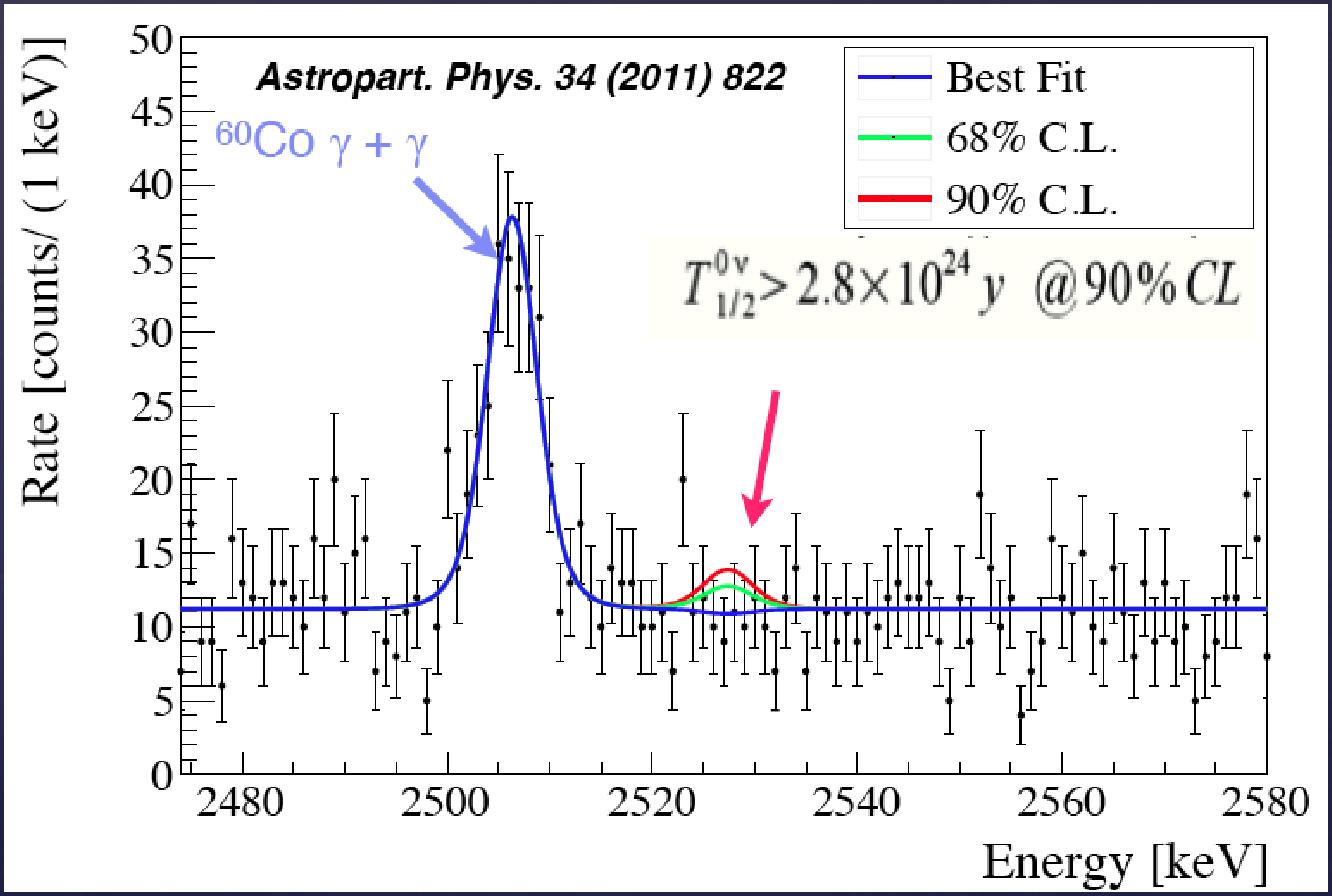
The Response of the Array



The Double-Beta Decay Search

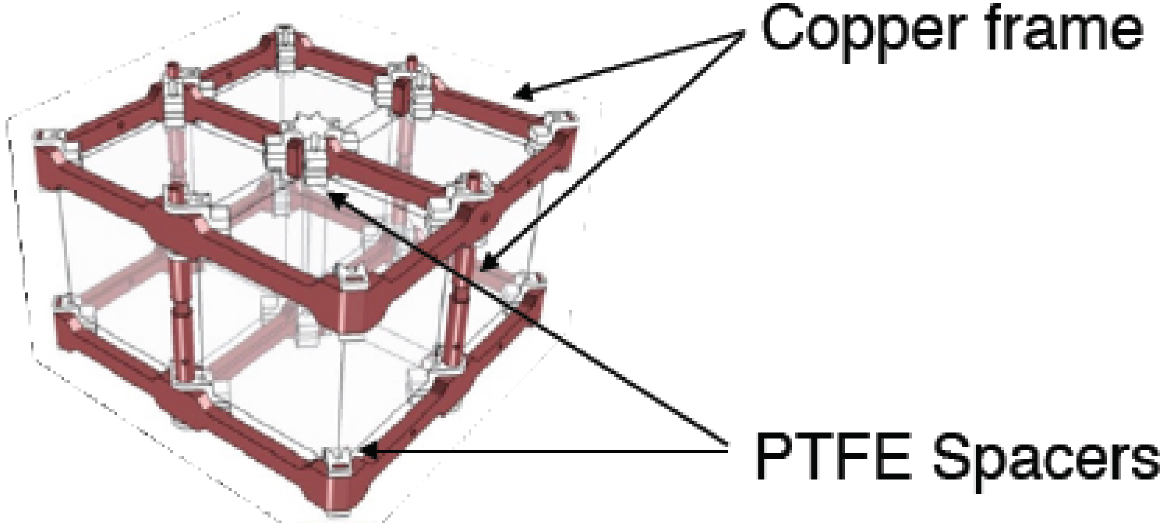


CUORICINO Final Result 19.75 kg-y



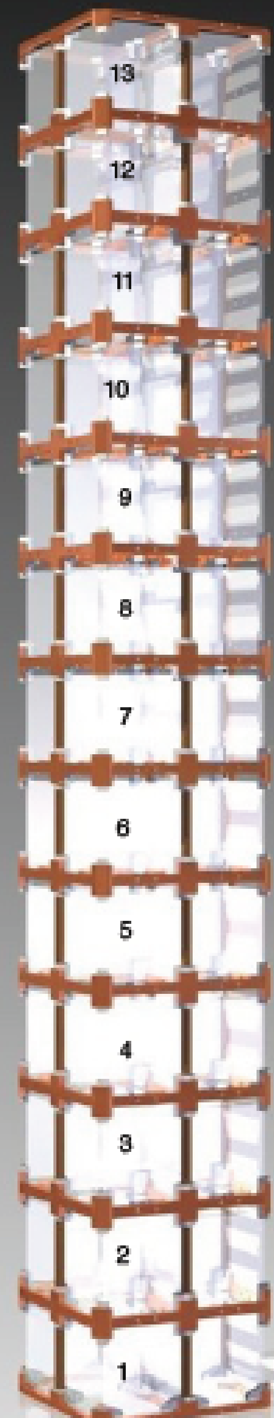
CUORE-0

- A CUORE-style tower assembled between Fall 2011 - Spring 2012
  - 4 crystals per floor, 13 floors

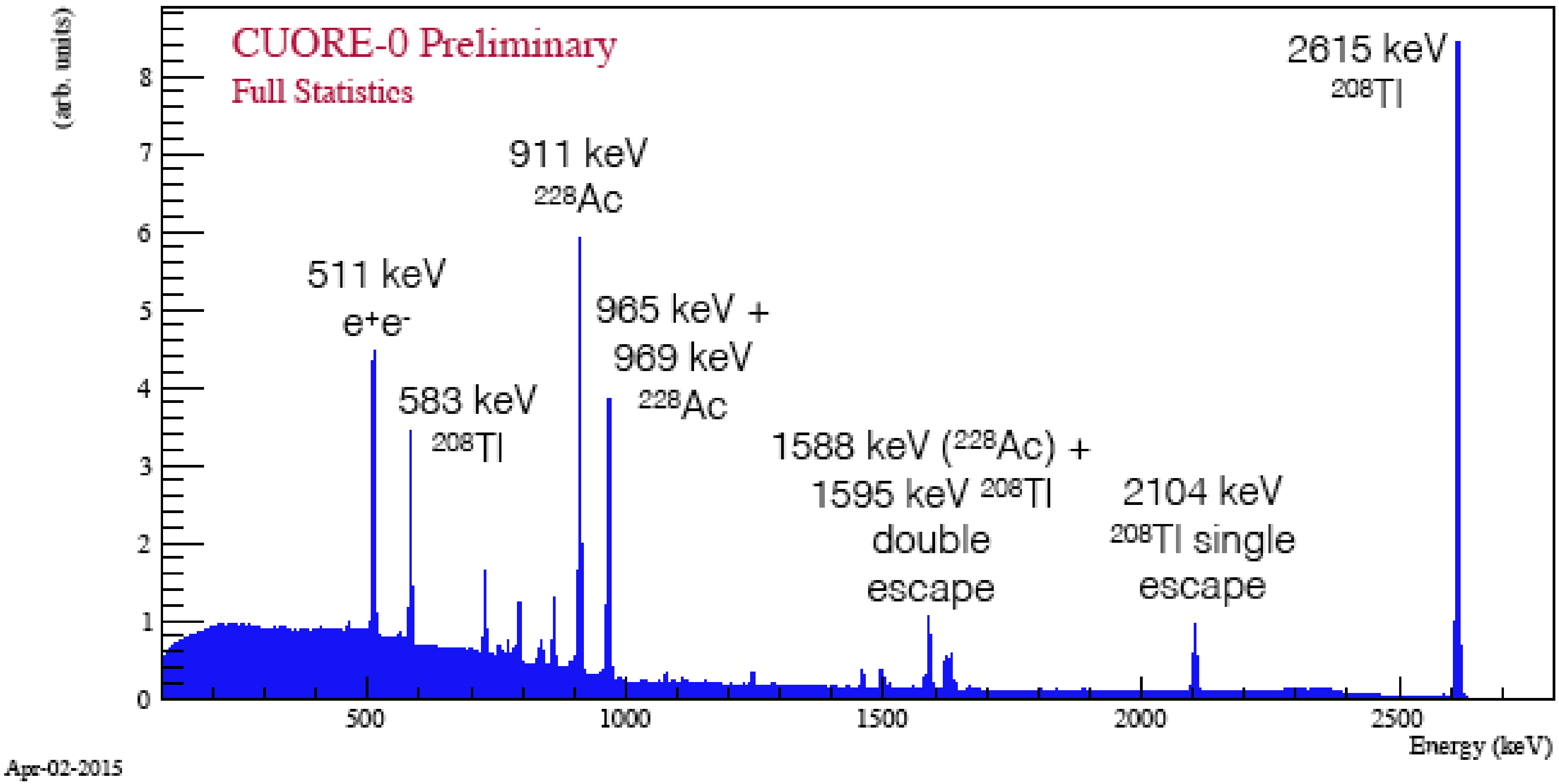


  - 39 kg TeO_2 => 10.9 kg ^{130}Te

- First tower assembled with the new CUORE assembly line

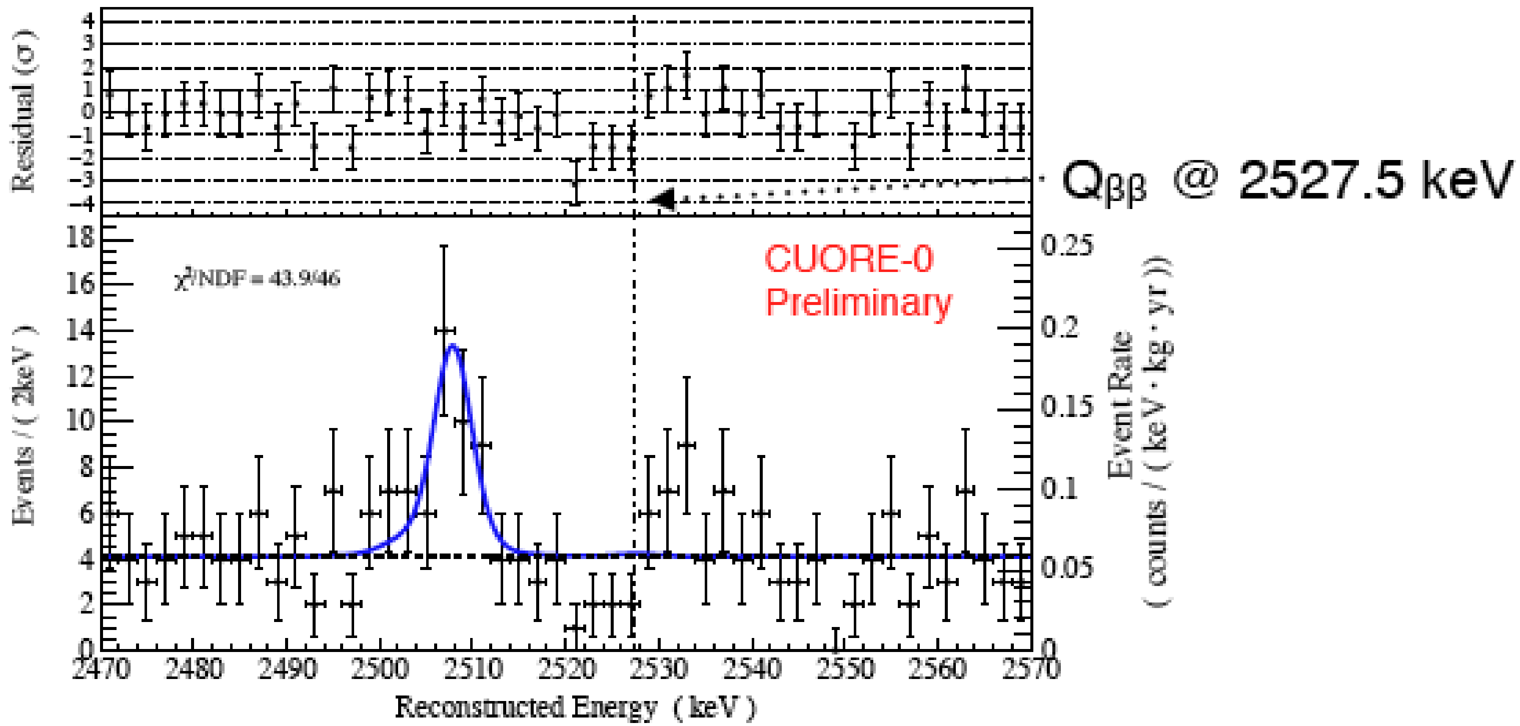


CUORE-0 Calibration Spectrum



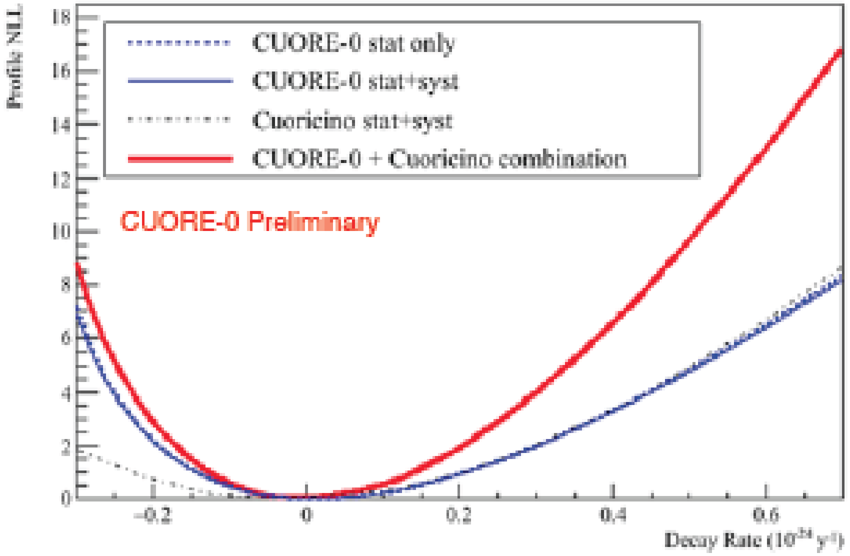
- We calibrate the detector using two thoriated tungsten wires source placed in between the outermost cryostat shield and the external lead shield.

CUORE-0 Fit to the Data



$\Gamma_{0\nu}$	$0\nu\beta\beta$ decay rate	0.01 ± 0.12 (stat.) $\pm\, 0.01$ (syst.) $\times\, 10^{-24}$ yr^{-1}
$N_{^{60}\mathrm{Co}}$	Number of ^{60}Co events	XX ??
$\Delta\mu(^{60}\mathrm{Co})$	^{60}Co energy offset	1.9 ± 0.7 keV
Γ_B	Background rate	0.058 ± 0.004 (stat.) $\pm\, 0.002$ (syst.) counts/(keV · kg · yr)

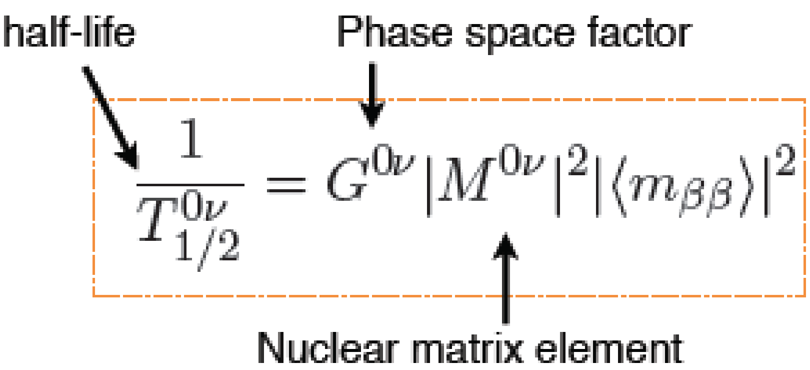
Combination with CUORICINO Data



- The 90% C.L. (Bayesian) lower limit based on the combined profile function

$$T_{1/2}^{0\nu} > 4.0 \times 10^{24} \text{ yr}$$

- This is the most stringent limit to date on this half-life !



$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

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

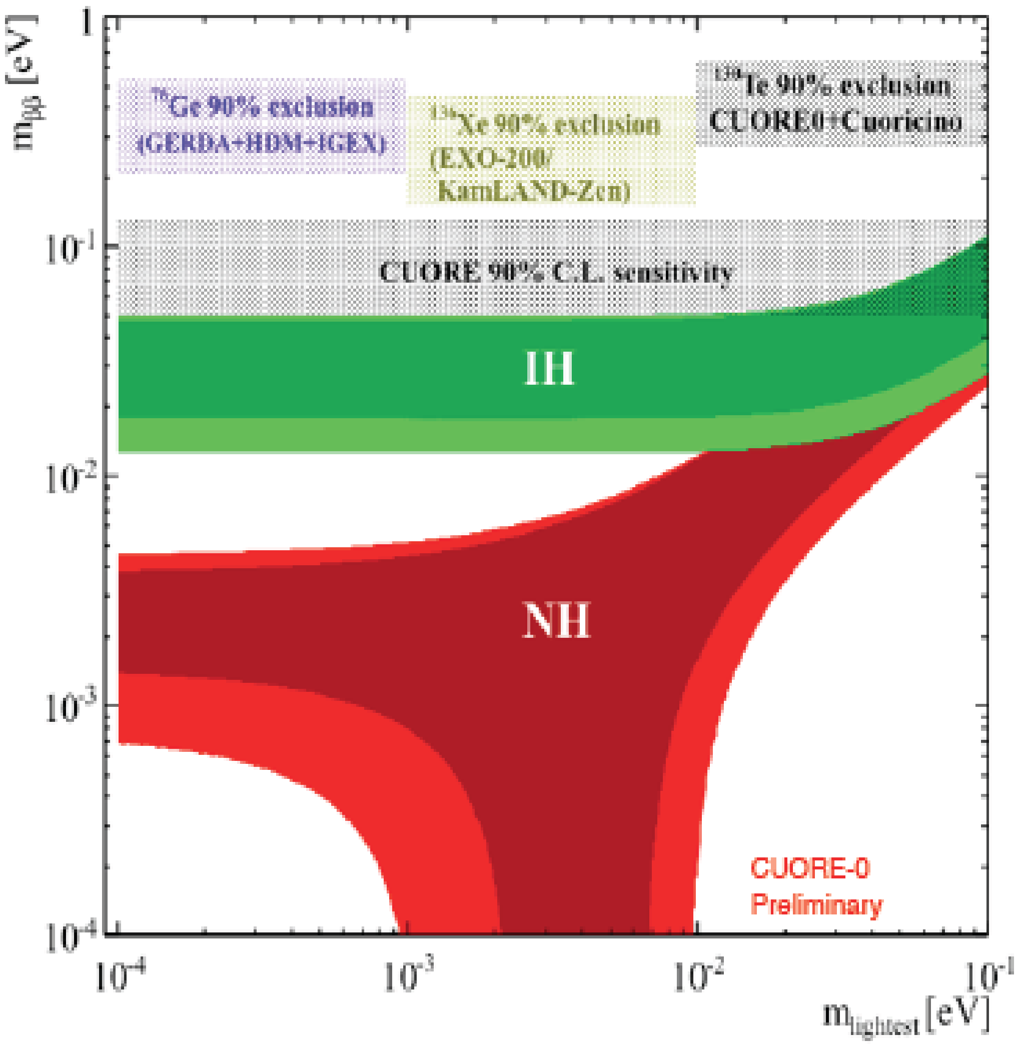
$\langle m_{\beta\beta}\rangle < 270 - 760$ meV

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))

Effective Majorana neutrino mass:

$$m_{\beta\beta} \equiv \left|\sum^{3} U_{ei}^2 m_i\right|$$

Comparison with Other Data



- Exclude shell-model NME for comparison with limits from other isotopes in the field

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

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
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$$\langle m_{\beta\beta} \rangle < 270 - 760 \text{ meV}$$

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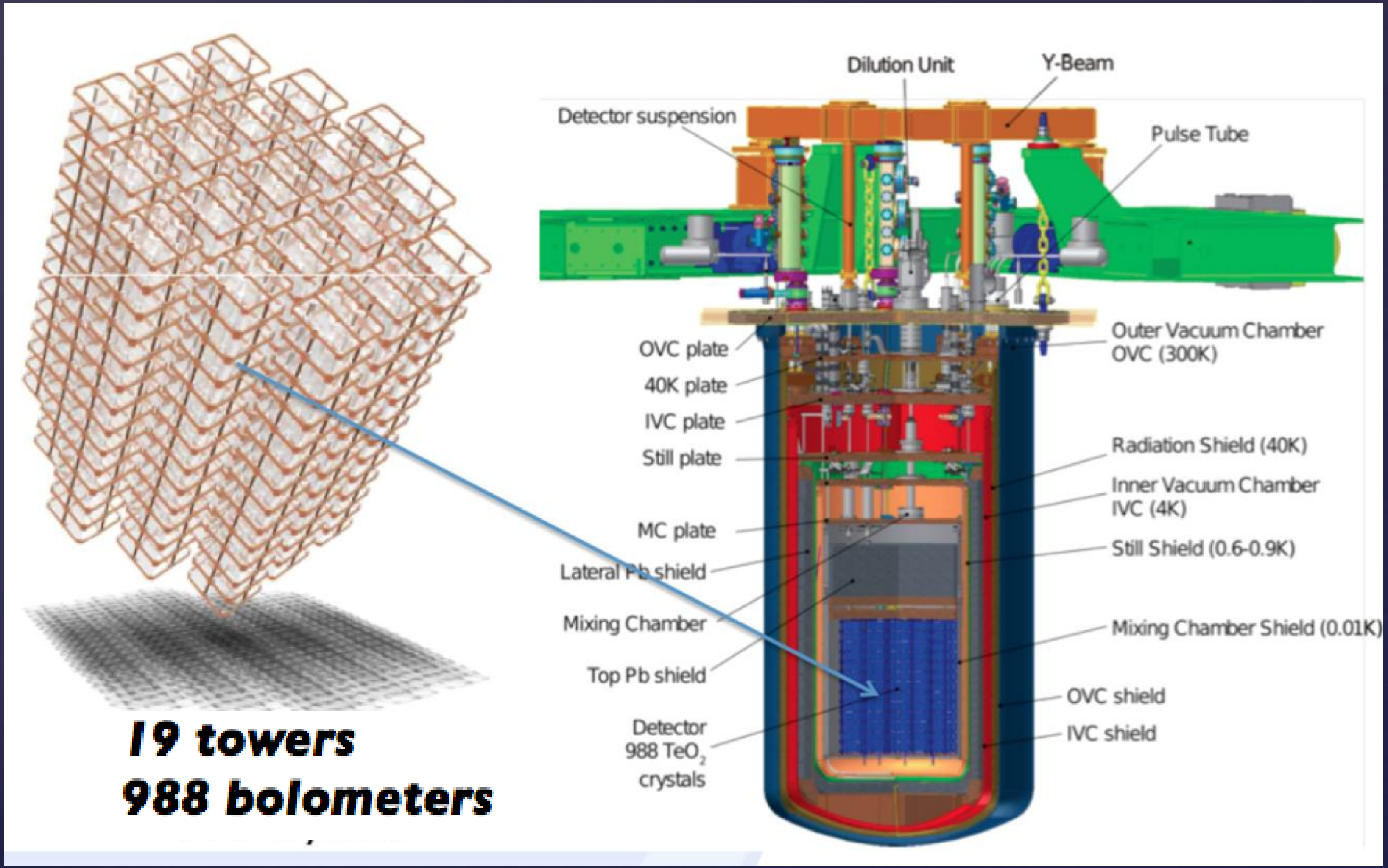
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

Including additional Shell-Model NME

19-Tower, 988 Bolometer Array Inserted in the Shielded Cryostat



Custom cryogenic system

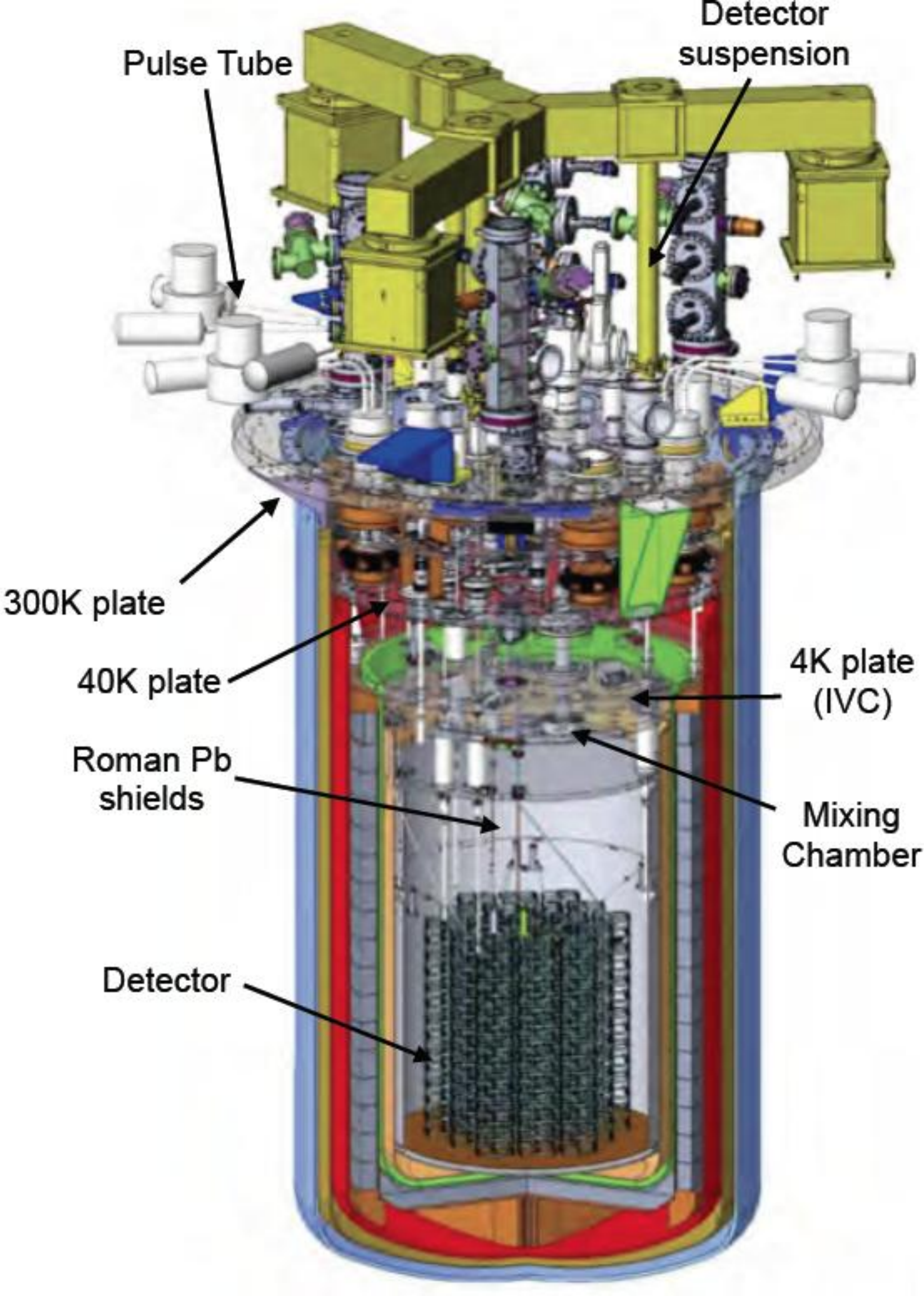
Close pack geometry

No cryogenic liquids

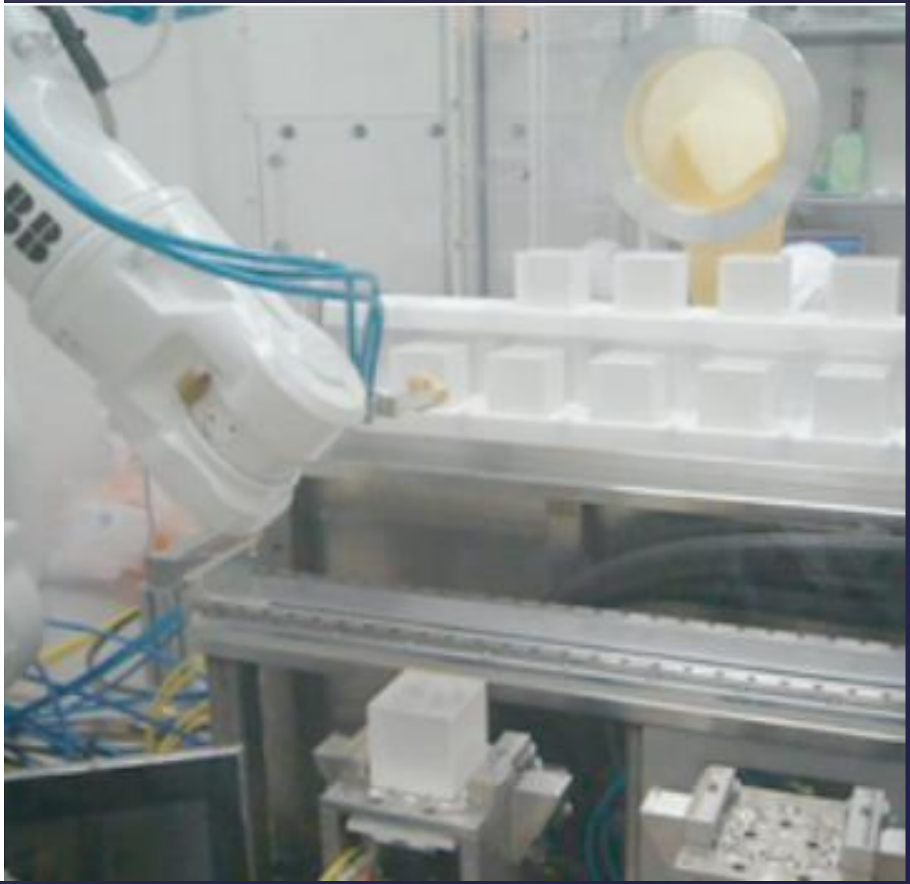
Mechanical suspension of detector isolated from DR

988 bolometers = 741-kg = ~200-kg of ^{130}Te

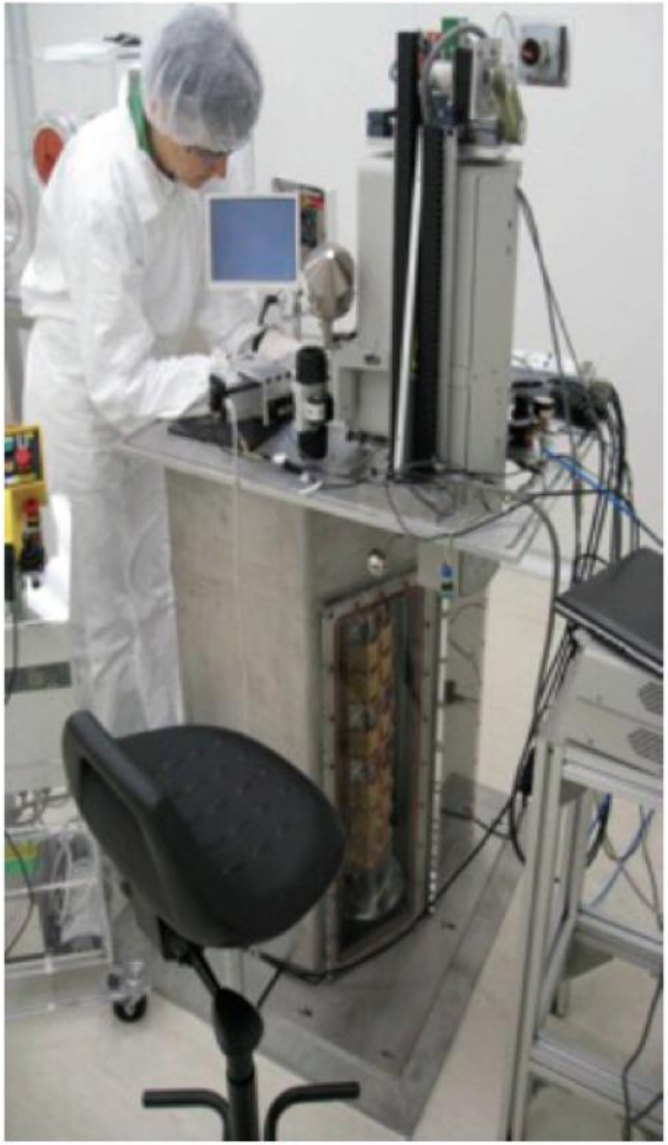
Radioactivity control on all components



Automatic Gluing of the Thermistors

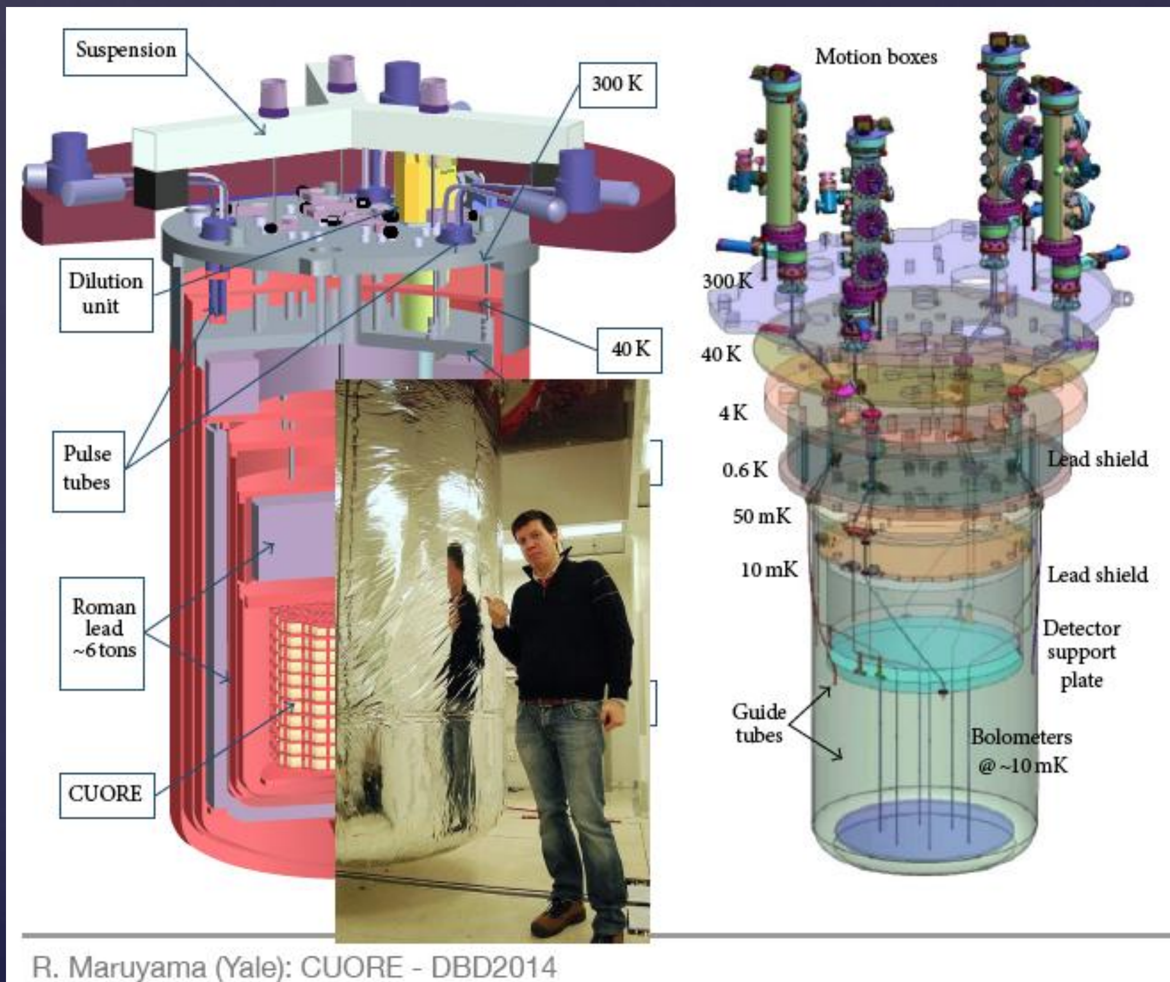


Building the Towers



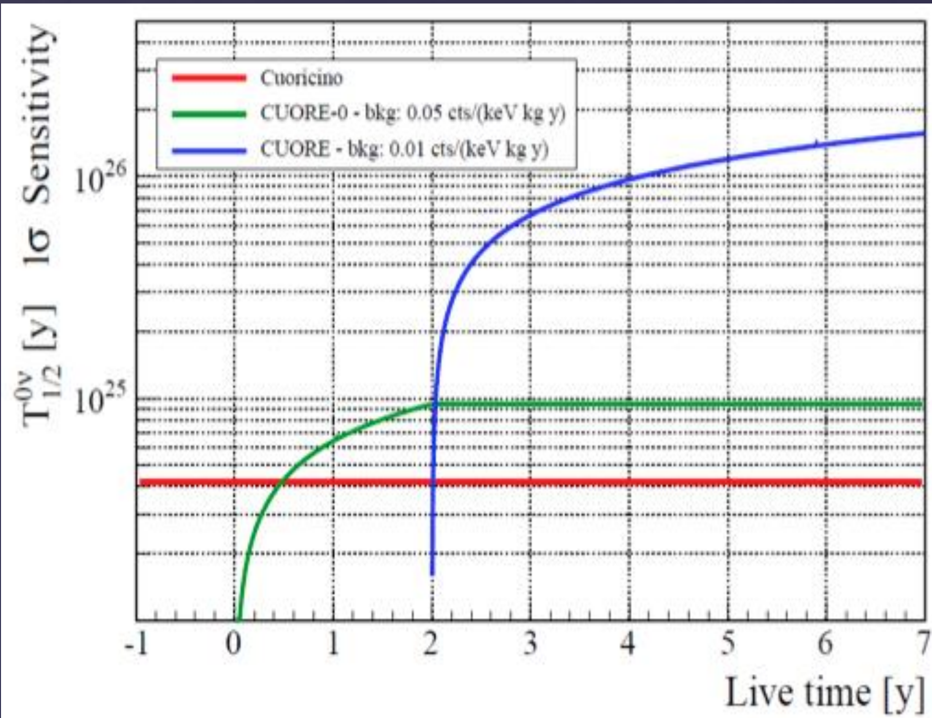
Dilution Unit and Cryostat

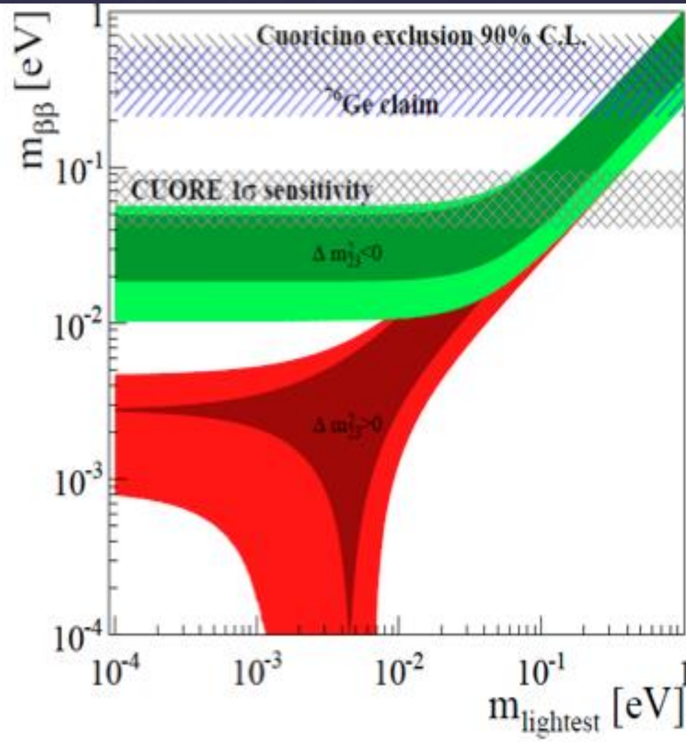
Paolo Gorla, 183 cm Tall, Stands Near the Outer Vacuum Chamber (OVC)



The Detector will have 19 Towers of 52 Bolometers of 750-g Each, or 988 Bolometers with a total of 740-kg

Predicted Sensitivity of CUORE

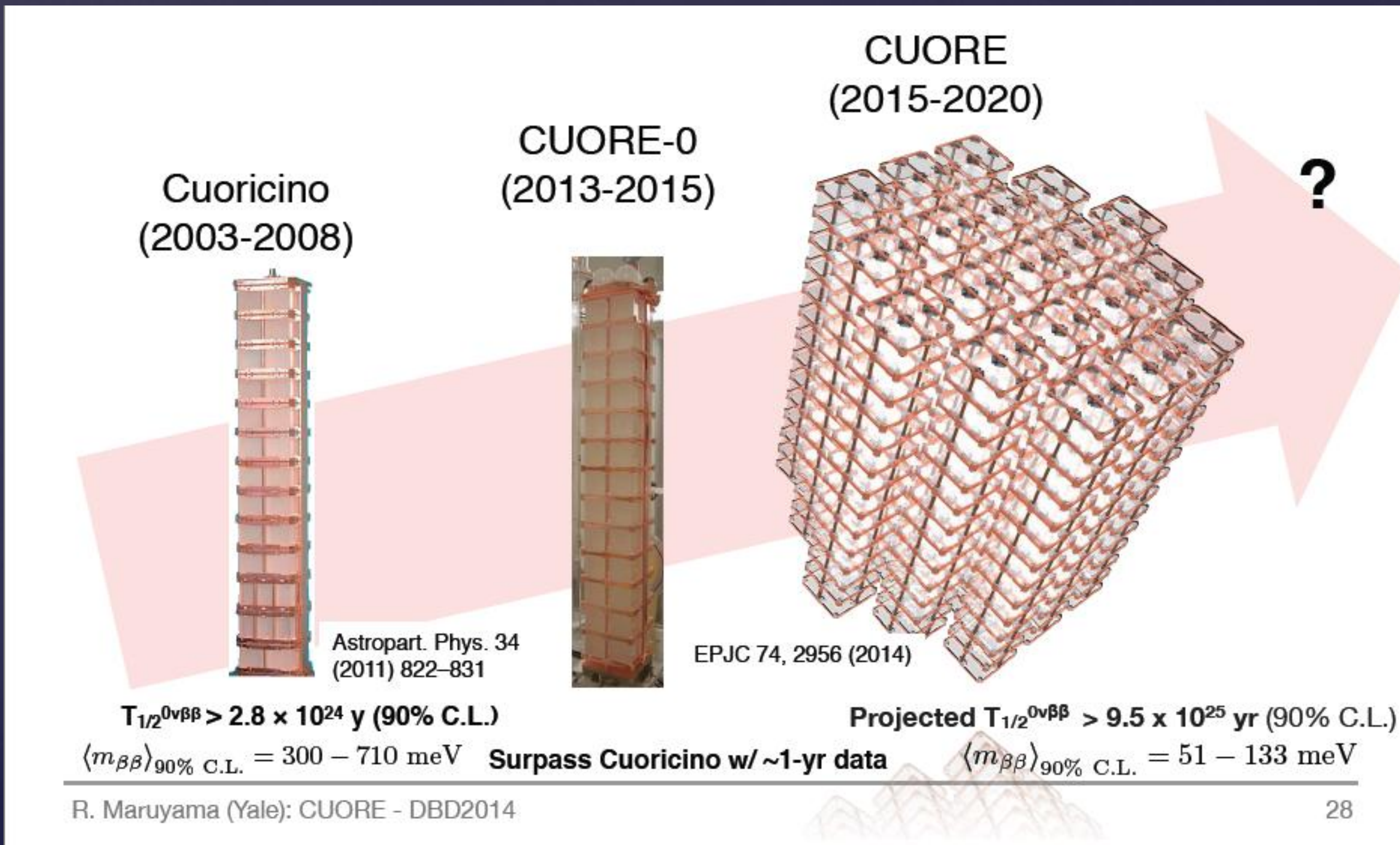




In CUORE, we expect to achieve
5 keV FWHM RESOLUTION
0.01 counts/(keV kg y) BACKGROUND
5 years LIVE TIME

Expected 1σ sensitivity:
$T_{1/2}^{0\nu}(^{130}Te) > 1.6 \times 10^{26}$ y
$m_{\beta\beta} < 41 - 95$ meV*

Where Do We Go From Here? What Can There Be After CUORE

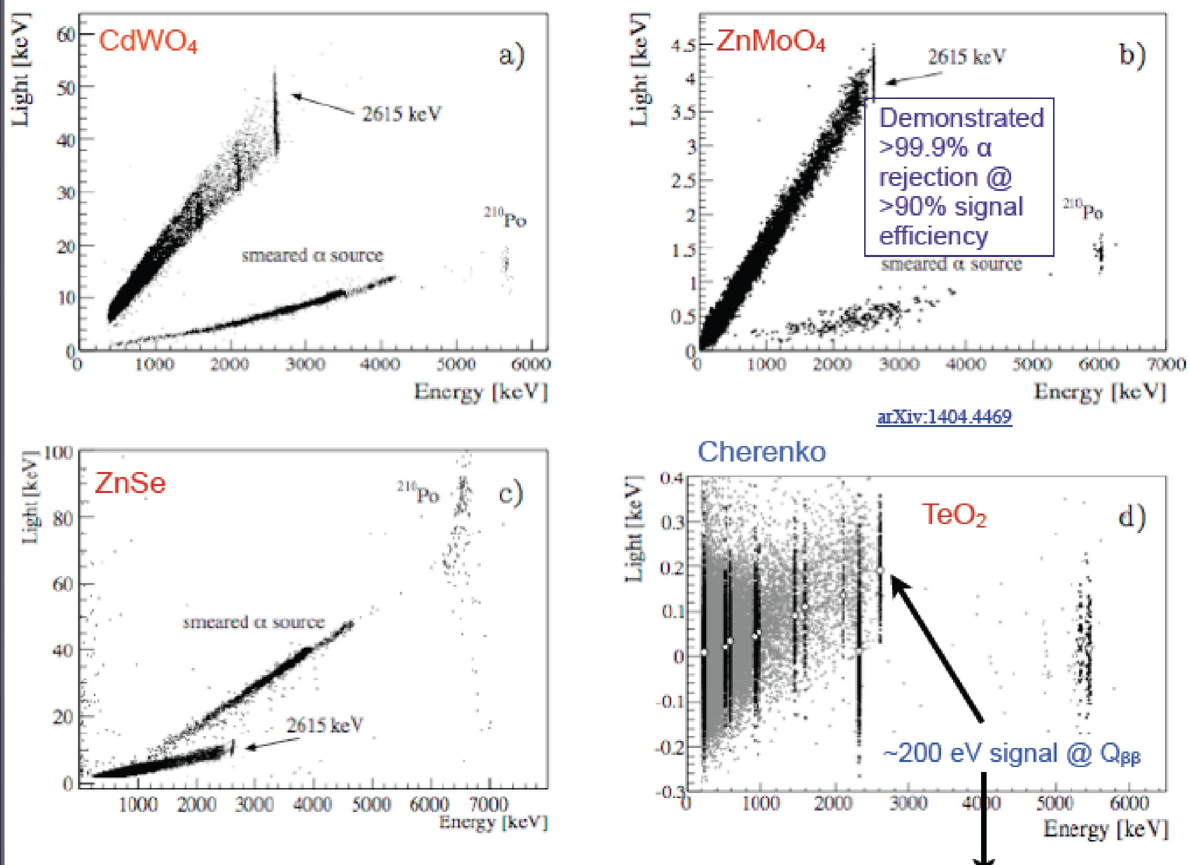


To Go Beyond CUORE

- Enrich the Te to 95% in ^{130}Te
- Identify Background Events with Scintillating Bolometers
- Separate Background Events with Čerenkov Light

Background Reduction Via Scintillating Bolometers

from: D.R.Artusa et al., arXiv:1404.4469 [hep-ex]

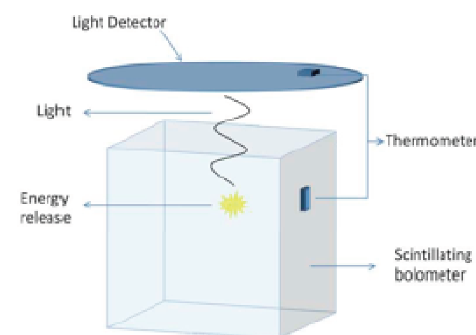


Requires ~40 eV resolution for >99.9% α rejection @ >90% signal

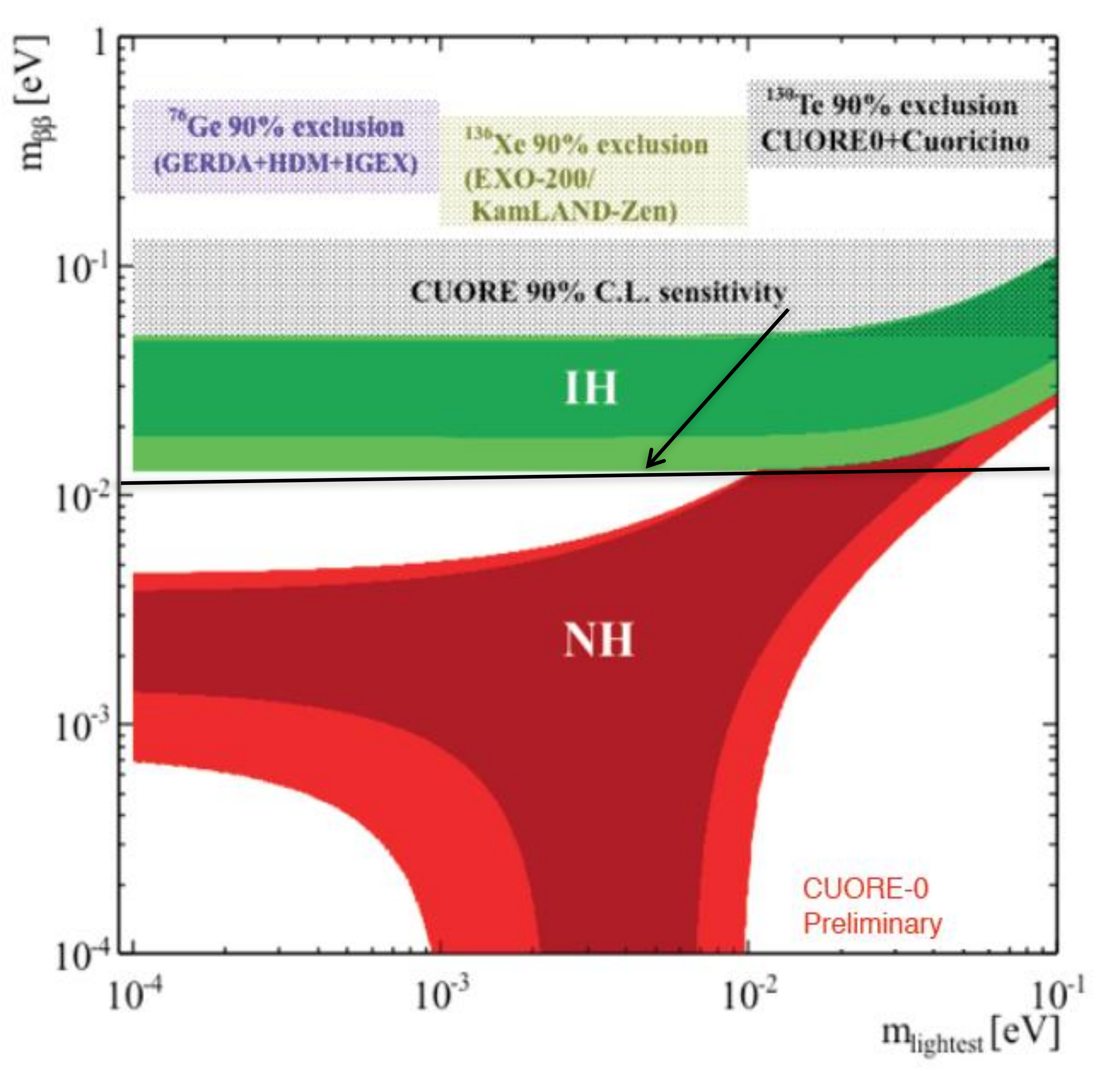
Cherenkov light or scintillation to distinguish α from β/γ:

- $^{130}TeO_2$, $Zn^{82}Se$, $^{116}CdWO_4$ and $Zn^{100}MoO_4$
- more rejection power needed

Critical element: light detector



(a) C. Arnaboldi et al., 34, 143 (2010)
(b) J. Beeman et al., Phys. Lett. B 710, 318 (2012)
(c) C. Arnaboldi et al., 34, 344 (2011)
(d) J. Beeman et al., Astropart. Phys. 35, 558 (2012)



$m_{\beta\beta}$ [eV]
^{76}Ge 90% exclusion
(GERDA+HDM+IGEX)
^{136}Xe 90% exclusion
(EXO-200/
KamLAND-Zen)
^{130}Te 90% exclusion
CUORE0+Cuoricino
CUORE 90% C.L. sensitivity
IH
NH
CUORE-0
Preliminary
$m_{lightest}$ [eV]

Change Gears from Neutrinos to Axions and Axion-Like Particles from the Sun

High Resolution Search for Solar-Axions and ALPs

Solar axion flux from the axion-electron coupling

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Javier Redondo

JCAP 12 (2013) 008

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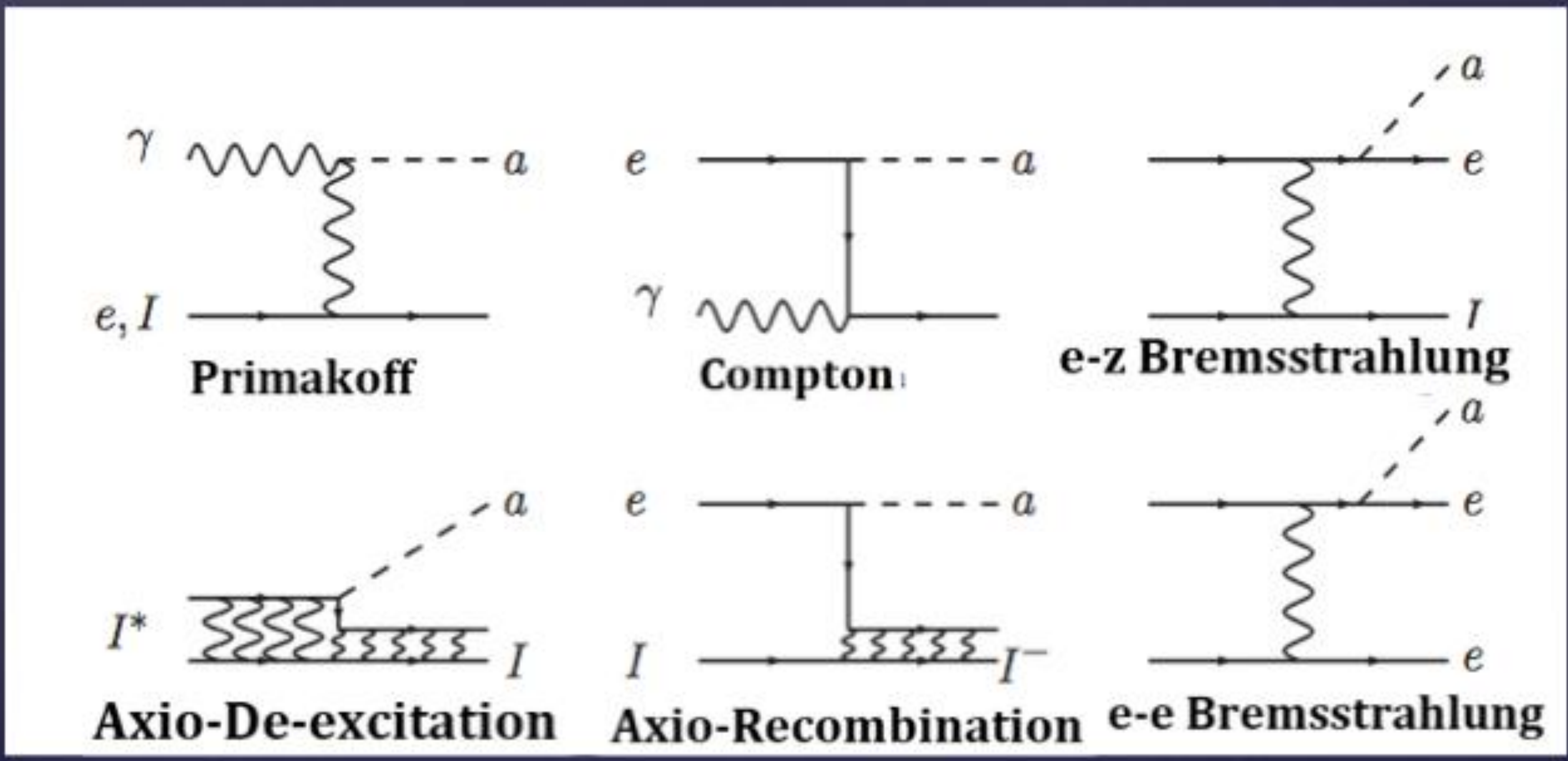
[b]Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany *

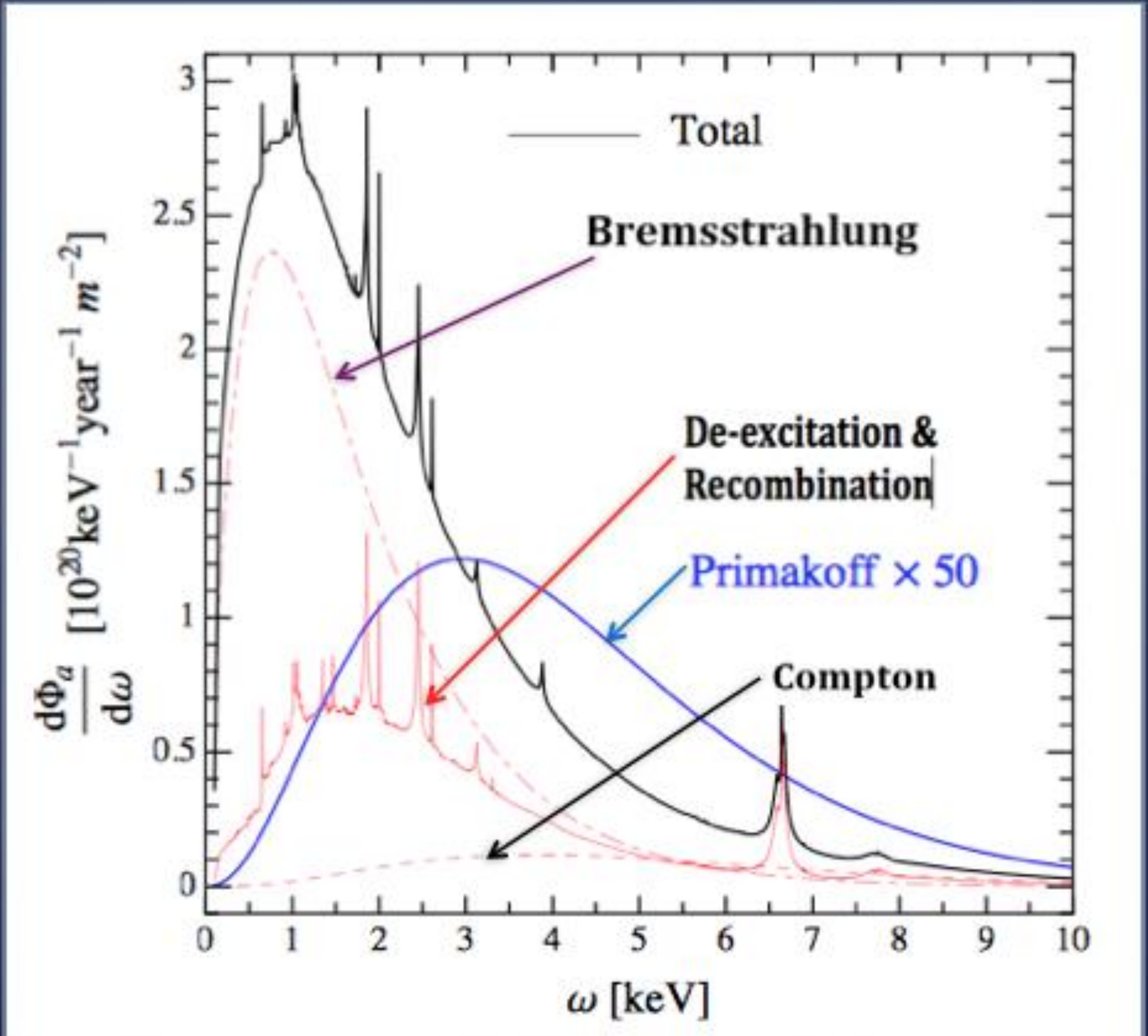
E-mail: redondo@mpp.mpg.de

Abstract. In non-hadronic axion models, where axions couple to electrons at tree level, the solar axion flux is completely dominated by the ABC reactions (Atomic recombination and deexcitation, Bremsstrahlung and Compton). In this paper the ABC flux is computed from available libraries of monochromatic photon radiative opacities (OP, LEDCOP and OPAS) by exploiting the relations between axion and photon emission cross sections. These results turn to be $\sim 30\%$ larger than previous estimates due to atomic recombination (free-bound electron transitions) and deexcitation (bound-bound), which where not previously taken into account.

* Presently at the University of Zaragoza.

Javier calculated the solar-axion fluxes from all six processes. Five involve direct coupling to electrons.




Total
Bremsstrahlung
De-excitation &
Recombination
Primakoff × 50
Compton
$\frac{d\Phi_a}{d\omega}$ [10^{20}keV^{-1}year^{-1} m^{-2}]
0
0.5
1
1.5
2
2.5
3
0 1 2 3 4 5 6 7 8 9 10
ω [keV]

Javier Rodondo calculated the flux under this peak especially for us

$$\Phi(6.4-keV)=g_{ae}^{2}\{4.7\times10^{33}\,cm^{-2}s^{-1}\}$$

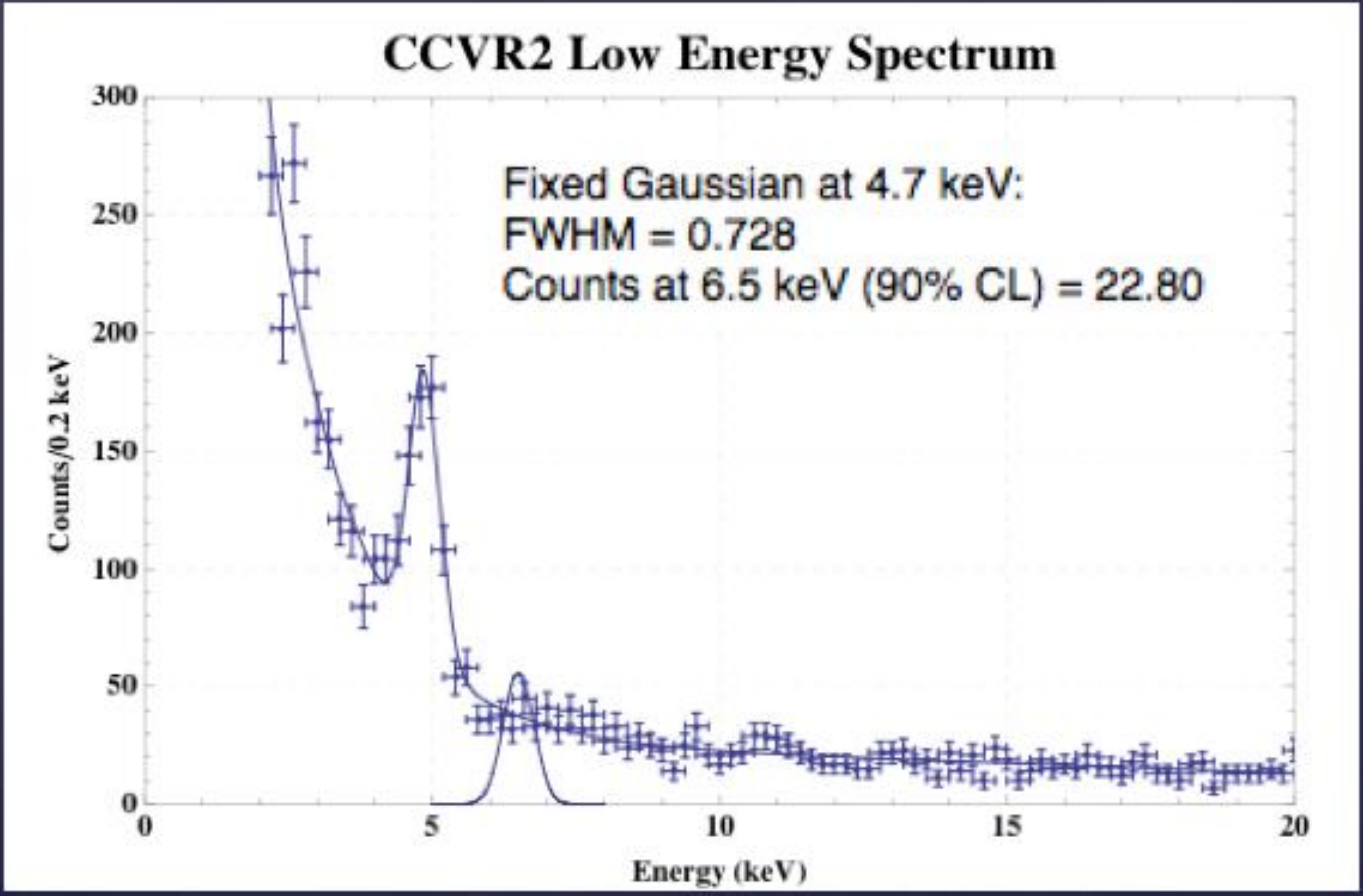
$$\Phi(6.4-keV)=g_{ae}^{2}\{4.06\times10^{38}\,cm^{-2}d^{-1}\}$$

The Axio-Electric Cross Section

$$\sigma_{ae}(E_a) = \frac{g_{ae}^2}{\beta}\frac{3E_a^2}{16\pi\alpha m_e^2 c^4}\left(1-\frac{\beta^{2/3}}{3}\right)\sigma_{pe}(E_a)$$

From: A. Derevianko et al., Physical Review D 82, 065006 (2010).
The same used by the XMASS and EDELWEISS, and XENON100 Collaborations.

CCVR2: a Small-Sample Trial



CCVR2 Example Continued
42.65 kg-d

$$N\sigma_{ae}\Phi_{ea}t = g_{ae}^{4}\{7.41\times10^{42}\}$$

$$g_{ae} \leq \sqrt[4]{\frac{N\sigma_{ae}\Phi_{ae}t}{7.41\times10^{42}}} = \sqrt[4]{\frac{90\%C.L.\mathrm{lim}it}{7.41\times10^{42}}}$$

$$g_{ae} \leq \sqrt[4]{\frac{22.8}{7.41\times10^{42}}} = 4.1\times10^{-11}$$

Possible bounds for CUORE running for 5 years with 40% low energy data

UPPER LIMIT (90% C.L.)	Coupling Constant
50	< 4.85 x 10 (-12)
100	< 5.77 x 10 (-12)
150	< 6.38 x 10 (-12)
200	< 6.71 x 10 (-12)

Assume twice the fraction of data is good at low energy and assuming a five year running time.

21 May 1998

PHYSICS LETTERS B

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Theory for the direct detection of solar axions by coherent Primakoff conversion in germanium detectors

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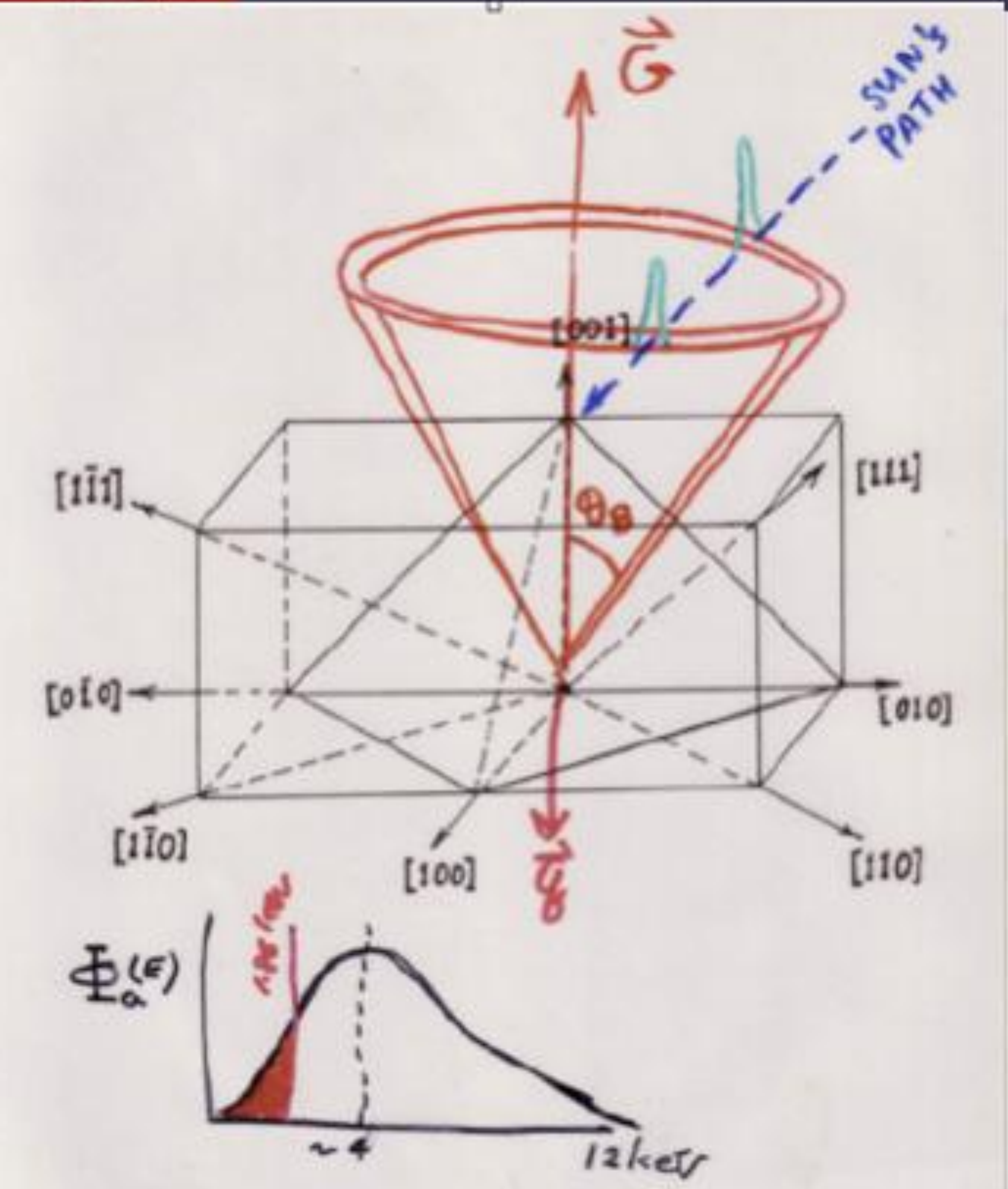
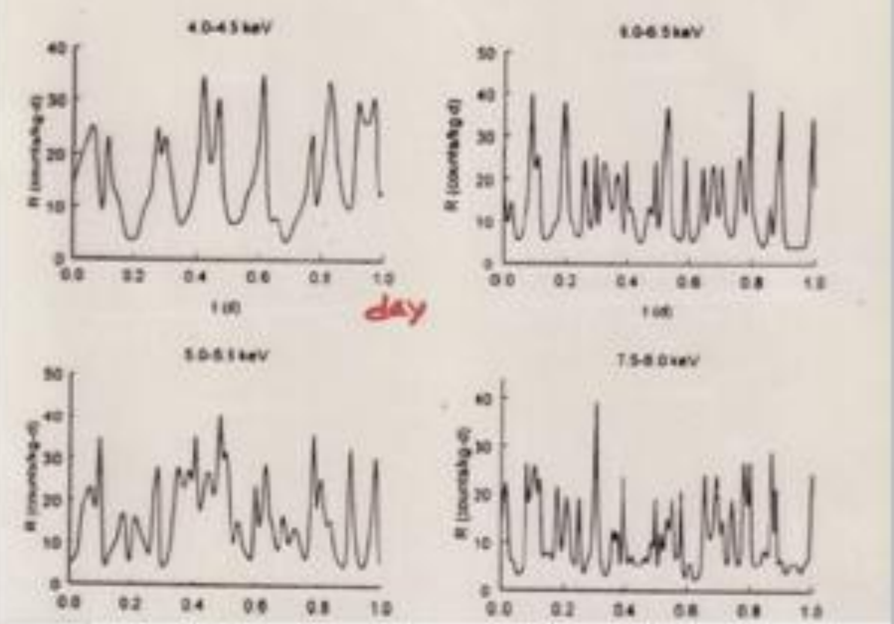
Coming Next Collaboration Meeting
Coherent Primakoff Modulation



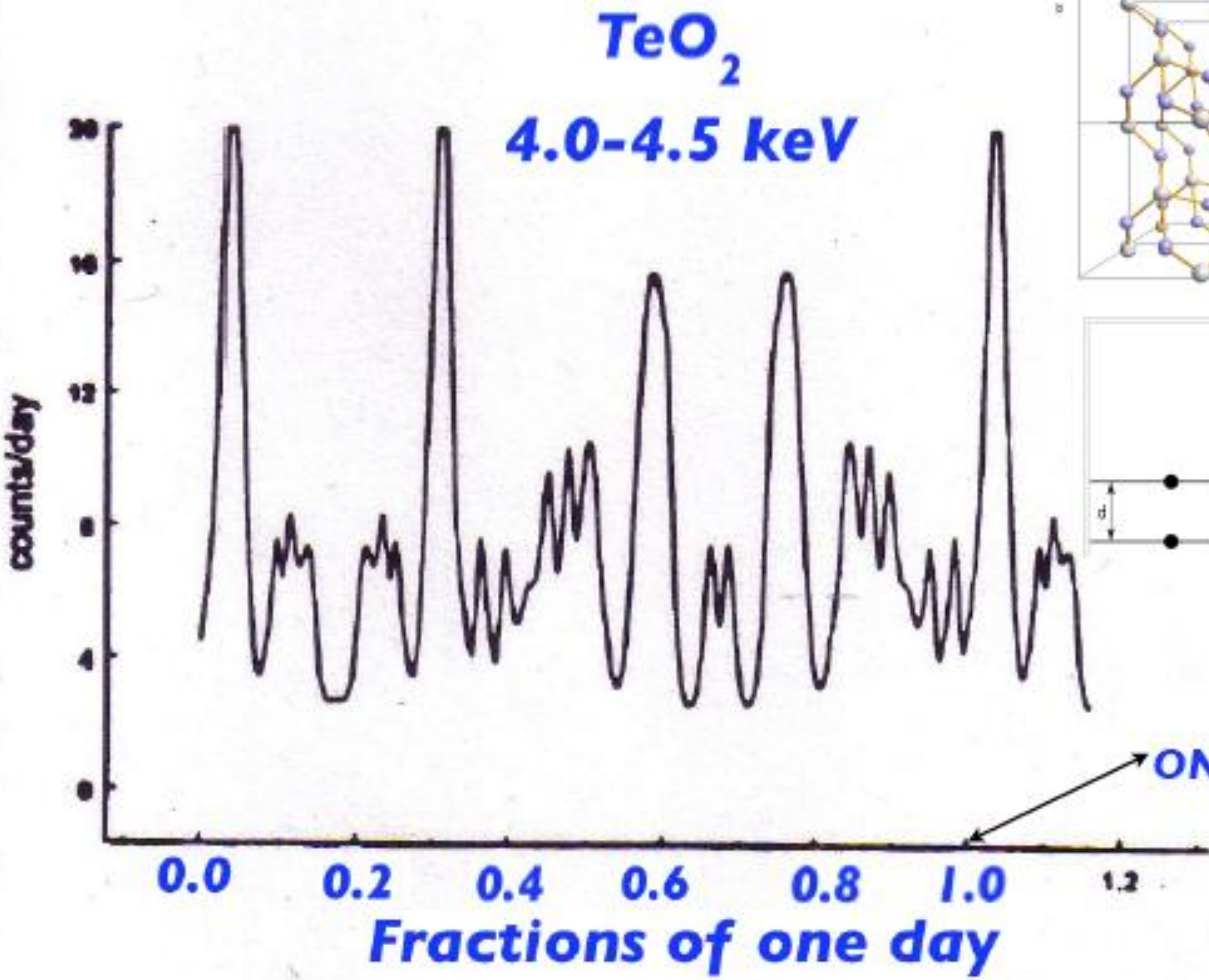
$$\frac{d\dot{N}}{dE}(\hat{k},\epsilon) = \lambda M_d \dot{N}_0 \sum_{g} |S(g)|^2 \left[\frac{4\epsilon^2 - g^2}{g^2+\gamma^2}\right] \frac{\epsilon^3}{e^{\beta\epsilon}-1} \times \delta(\epsilon - \epsilon(\vec{g}))$$

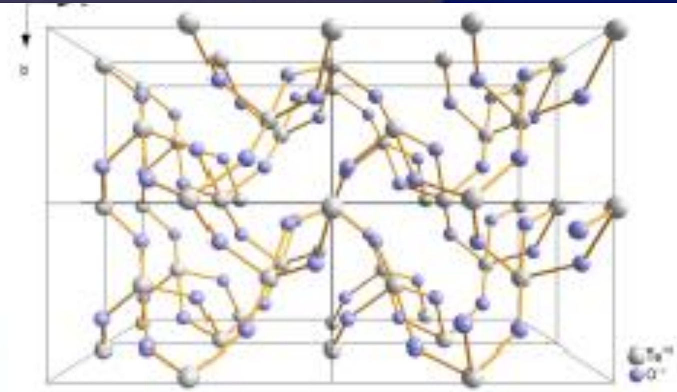
where M_d is the mass of the detector in kg, $\vec{g} = (h,k,l)$, $\gamma = a_0/r_0$, $\beta = \frac{2\pi\hbar c}{a_0 E_0}$, $\epsilon(\vec{g}) = \frac{g^2}{2\hat{k}\cdot\vec{g}}$, and $\dot{N}_0 \equiv \frac{\sigma_0 \Phi_0 \beta^2}{\rho(2\pi a_0)^3} = 0.61/kg \cdot d$ for germanium.

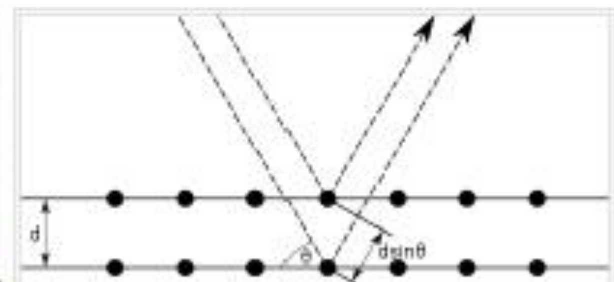
$$S(G) = [1 + e^{\frac{i\pi}{2}(h+k+l)}][1 + e^{i\pi(h+k)} + e^{i\pi(h+l)} + e^{i\pi(k+l)}].$$



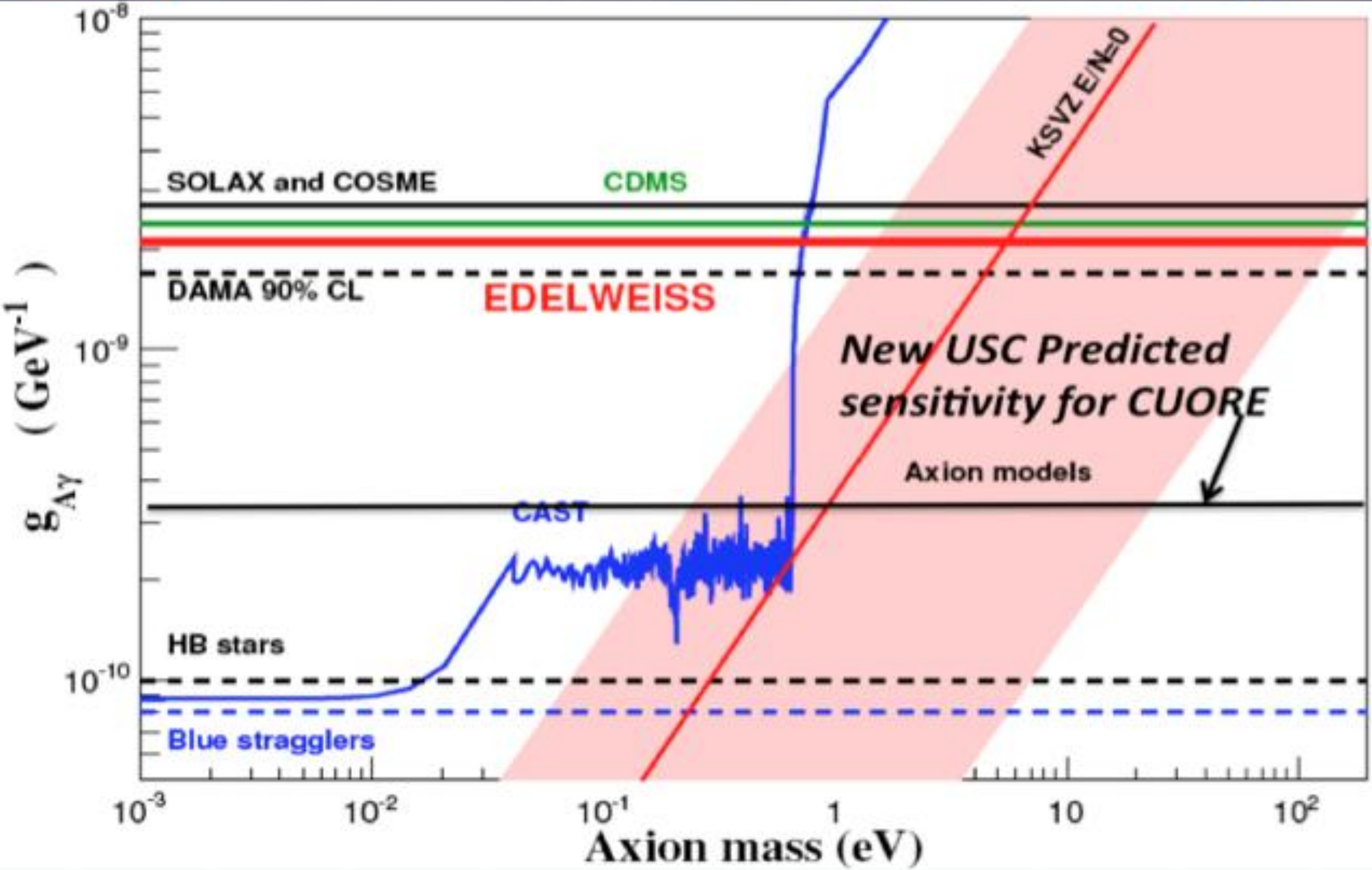
Coherent Bragg-Primakoff Peaks







New Theoretical Analysis with Realistic Electron Density Calculations: Dawei Li



Conclusions About Neutrinos

1. Neutrino-less double-beta decay could answer several important questions in particle physics and cosmology.

Are neutrinos Majorana particles (Leptogenesis)?
Is lepton conservation violated?
What is the neutrino mass scale?

2. The CUORE Experiment construction is near completion in the Laboratori Nazionali del Gran Sasso, Assergi, Italy.

3. CUORE-0, the first constructed CUORE tower operated for ~ two years in the CUORICINO cryostat.

4. CUORE is projected to begin operations in late 2015.

CONCLUSIONS

About Axions and ALPs

- The CUORE-type bolometers make good detectors to search for these axion processes.
- CUORE-0 data is potentially very competitive and will probably produce an excellent bound with this method.
- CUORE could in the future produce the most sensitive search for axion-electron coupling of any technique.

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Laboratory limits on solar axions from an ultralow-background germanium spectrometer

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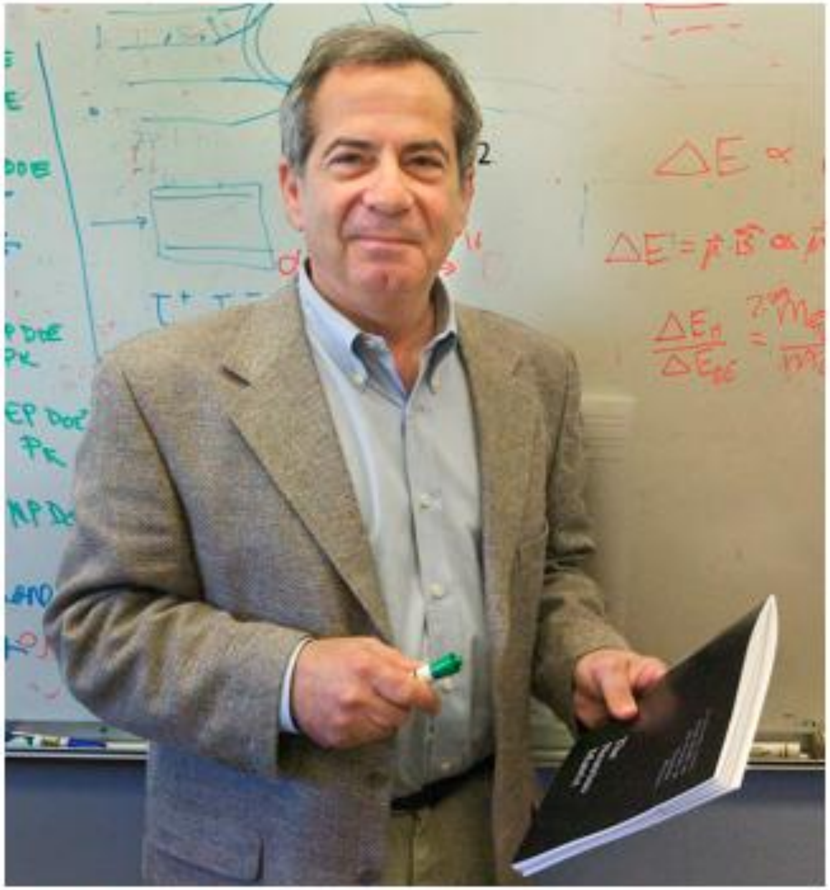

Stuart Freedman (photo Roy Kaltschmidt, Lawrence Berkeley National Laboratory)

Late US Spokesman and DOE Project Manager of CUORE