International Symposium on
Multiparticle Dynamics

Bologna, September 8-12, 2014

$\beta\,\beta\ (0\,\nu)$ Search with CUORE-0 and CUORE

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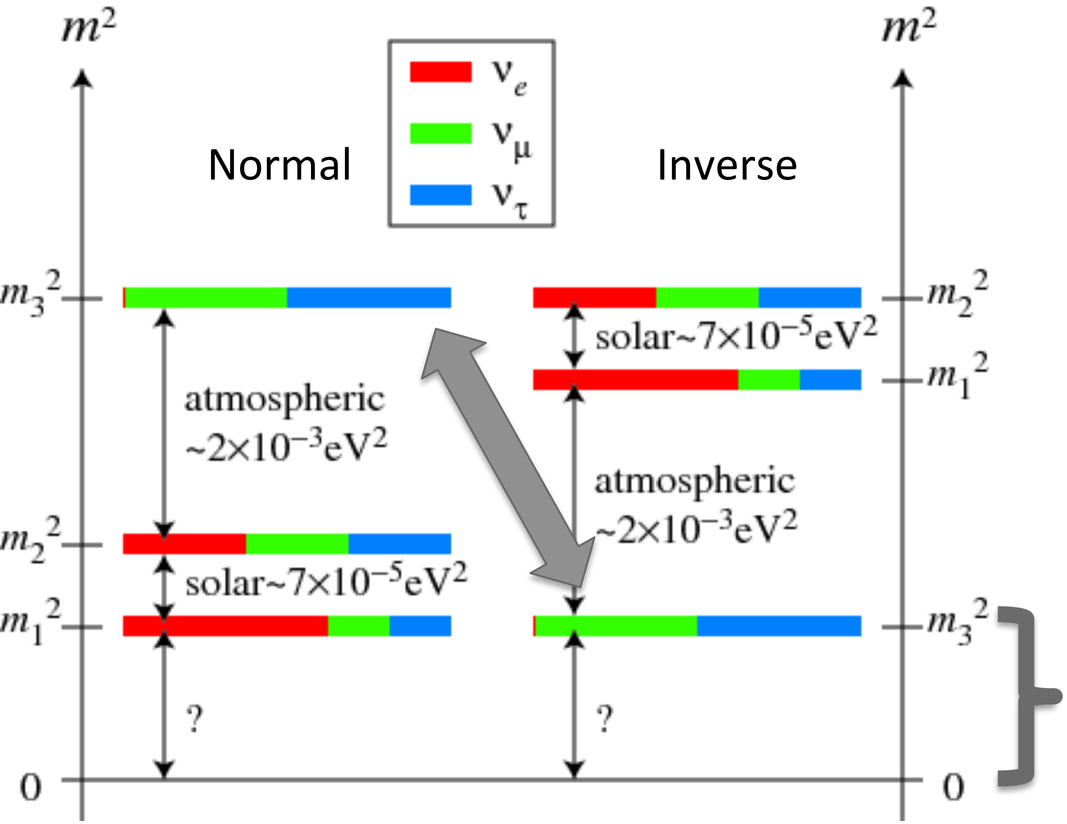
University of Bologna and INFN
on behalf of the CUORE collaboration

Outline

- Why search for ββ(0ν)
- Physics signal
- The experimental parameters
- A phased search program:
  Cuoricino → CUORE-0 → CUORE
- Preliminary CUORE-0 results
- CUORE status and projected sensitivity
- Conclusions

Some Neutrino Open Questions

1. Nature: Dirac or Majorana particles ?
   $\nu = \overline{\nu}$? → Lepton Number Violation
2. Mass: absolute scale, hierarchy of mass states

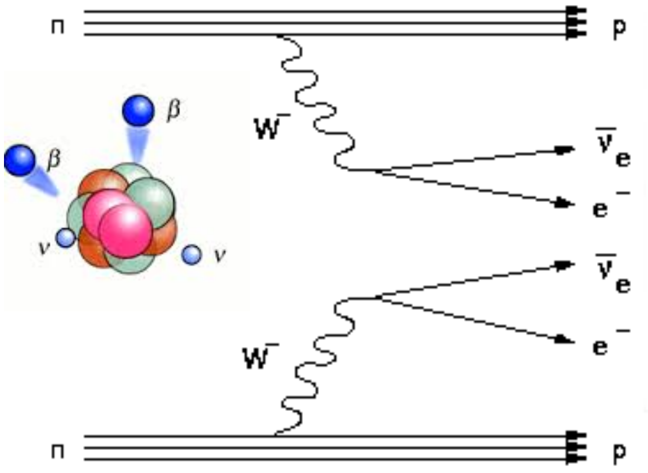


Sign of Δm^2_{23}

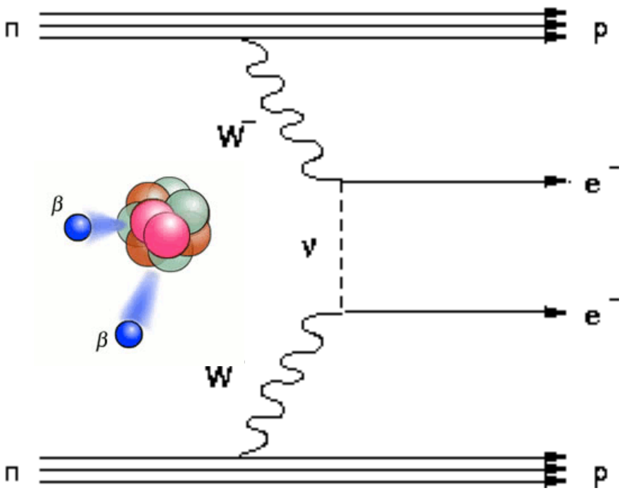
absolute offset from zero of lightest ν mass

$\beta\,\beta\,(0\nu)$

- Most sensitive method to investigate ν nature
- (Z, A) → (Z+2, A) +2e$^-$ (+2 ν)



"regular" ββ decay
Observed, $T_{1/2} \gtrsim 10^{19}$ y
Allowed by SM



0ν decay
Expected $T_{1/2} \gtrsim 10^{25}$ y
LNV ($\Delta L=2$)
Controversial discovery claim
[Phys. Lett. B 586 (2004) 198]

Other exotic mechanisms may explain LNV but **ββ**(0**ν**) exists only if **$\nu=\bar{\nu}$**

Decay Rate

If ββ(0ν) is found:

- ν is Majorana && LNV
- Constraints on the absolute ν mass scale

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Half-life
measured

Phase Space
calculated

Nuclear Matrix Element
calculated
uncertainty factor ~2

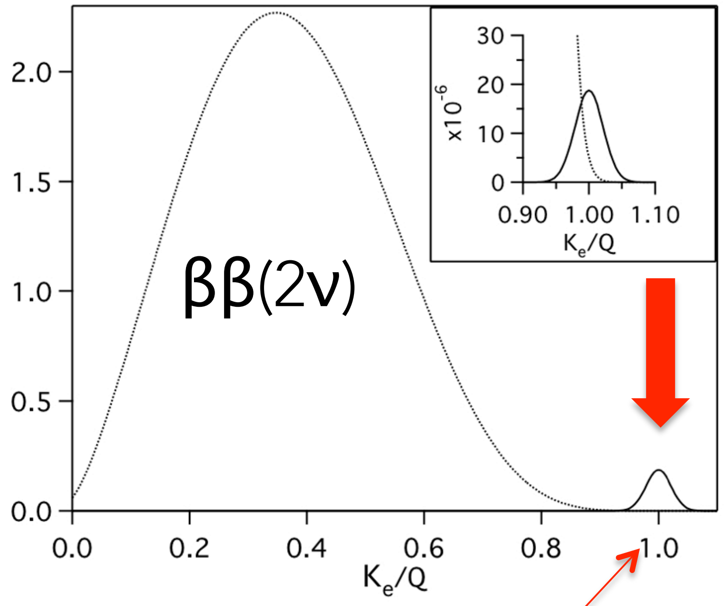
NB:
ν oscillations favor
$<m_{\beta\beta}>$=20-50 meV
for IH

Majorana ν "effective mass"
$= f\,(\theta_{12},\theta_{23},\theta_{13},\ \Delta m_{12},\pm\Delta m_{23},\ m_0)$

mixing angles hierarchy mass scale

Experimental Signature

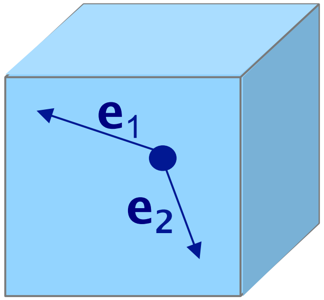
- Measure $E_{\beta\beta} = E_{\beta 1} + E_{\beta 2}$
- Signature: peak at $Q = m_n - m_p$



ββ(0ν) line
smeared by ΔE

Bolometric approach

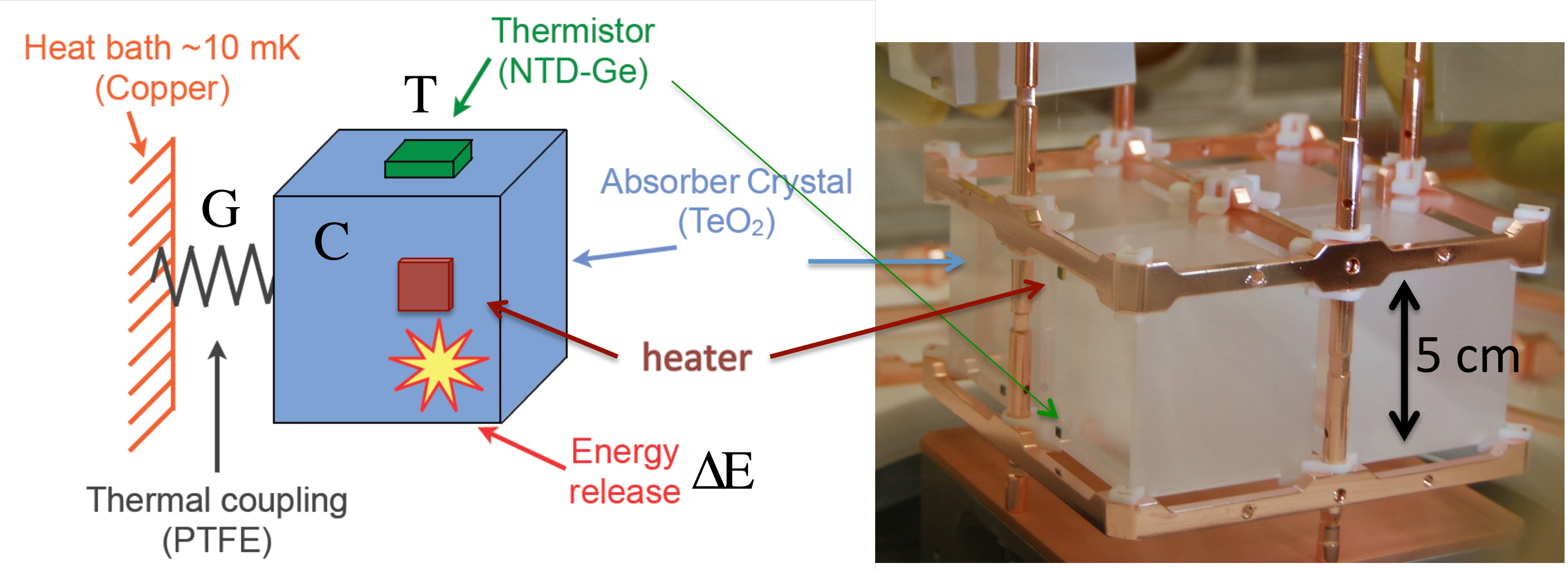
- measure $E_{\beta\beta}$ from ΔTemp
- source ⊆ detector



good ΔE
high **ε**
no topology recognition
slow response

- If ββ(0ν) observed: $T^{0\nu}_{1/2} = \ln(2) N_{\beta\beta} \dfrac{t}{N_{peak}} \varepsilon$

Bolometric Technique



$\mathrm{TeO_2}$ crystals

Size = 5x5x5 $\mathrm{cm^3}$
Weight = 750 g
Produced at
SICASS (China)

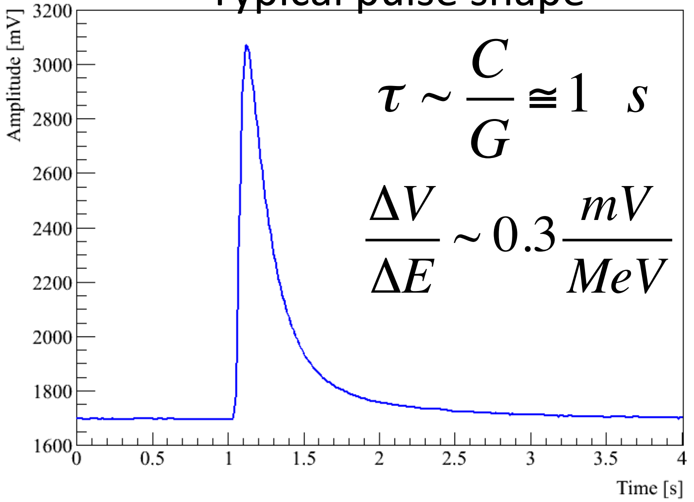
$$\Delta T \sim \frac{\Delta E}{C}$$

$$C \sim T^3$$

$$T \approx 10 \quad mK$$

$$\frac{\Delta T}{\Delta E} \sim 0.1 \frac{mK}{MeV}$$

Typical pulse shape



$$\tau \sim \frac{C}{G} \cong 1 \quad s$$

$$\frac{\Delta V}{\Delta E} \sim 0.3 \frac{mV}{MeV}$$

Sensitivity

If no ββ(0ν), we can express the sensitivity as the $T_{1/2}$ that corresponds to a signal mimicked by a 1σ fluctuation

N ββ(0ν) expected

$$S = k \cdot \underset{\text{isotopic abundance}}{(i.a.)} \cdot \underset{\text{tot active mass}}{M} \cdot \underset{\text{efficiency}}{\varepsilon} \cdot \frac{\overset{\text{detector live-time}}{t}}{T_{1/2}}$$

Mean num of bkg counts around Q

$$B = \underset{\text{background rate}}{b} \cdot M \cdot \underset{\text{energy resolution}}{\Delta E} \cdot t$$

Bkg constant in ROI
b measured independently
Bkg scales with total mass
Bkg ~gaussian

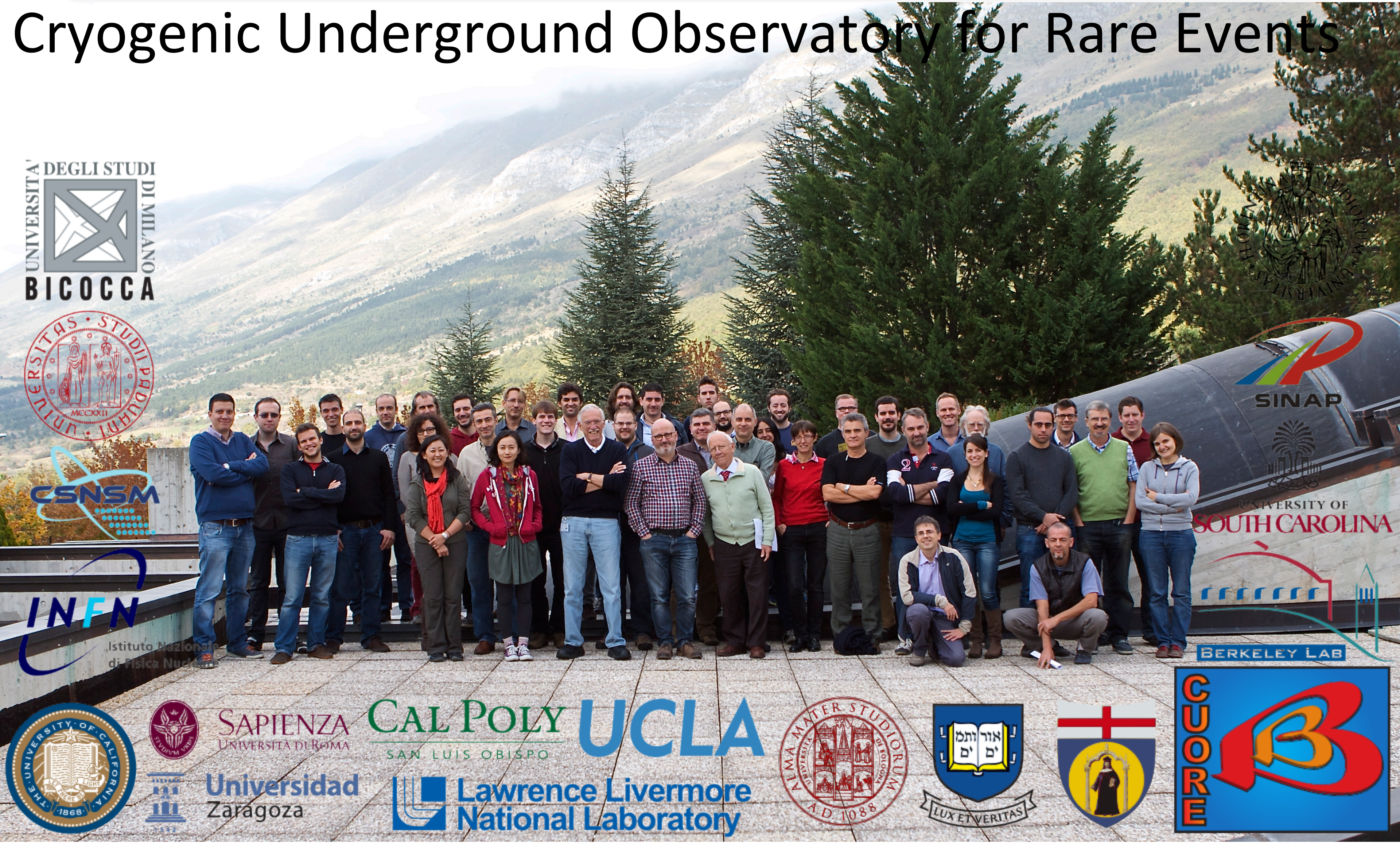
$$S = n_\sigma \sqrt{B}$$

$$@1\sigma \Rightarrow \hat{T}_{1/2} \propto (i.a.) \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}} \sim \sqrt{\frac{scale}{performance}}$$

N. Moggi, ISMD 2014

The Collaboration

Cryogenic Underground Observatory for Rare Events

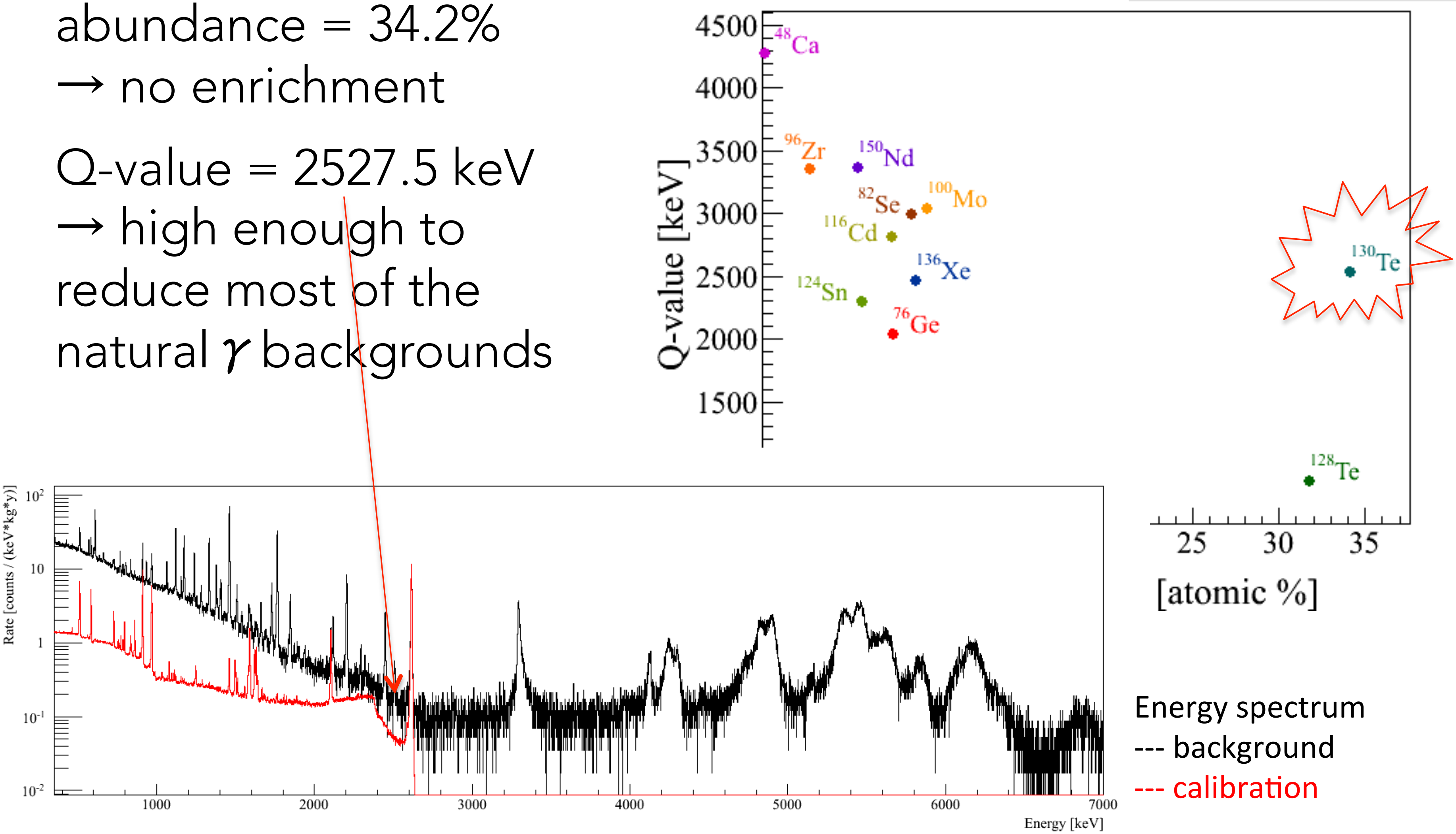


Choice of Isotope

$$\hat{T}_{1/2} \propto (i.a.) \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

^{130}Te Natural isotopic abundance = 34.2%
→ no enrichment

Q-value = 2527.5 keV
→ high enough to reduce most of the natural γ backgrounds

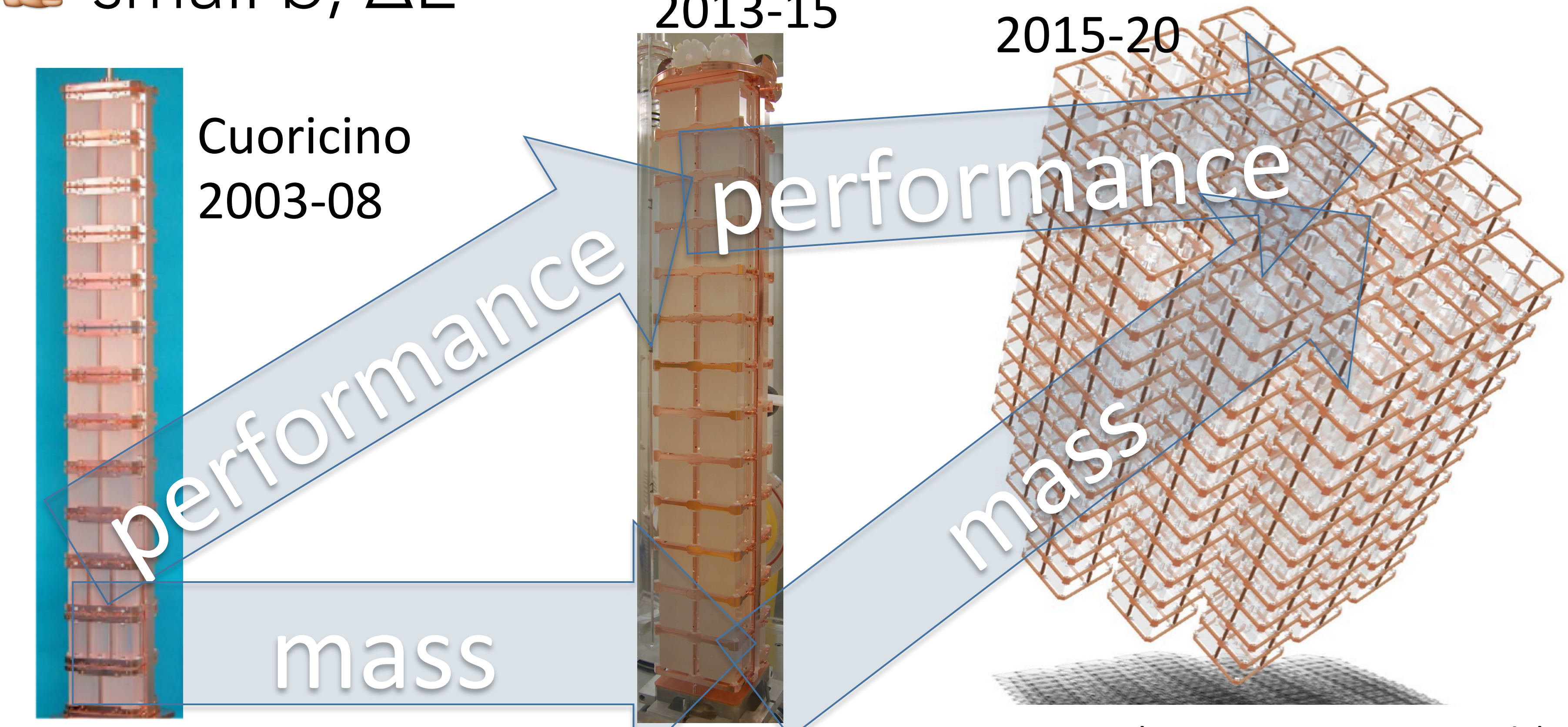


Energy spectrum
--- background
--- calibration

A Phased Search Program

$$\hat{T}_{1/2} \propto (i.a.)\cdot\varepsilon\cdot\sqrt{\frac{\boxed{M}\cdot t}{b\cdot\Delta E}}$$

- 👍 large i.a., M, t
- 👍 small b, ΔE



Cuoricino
2003-08

CUORE-0
2013-15

CUORE
2015-20

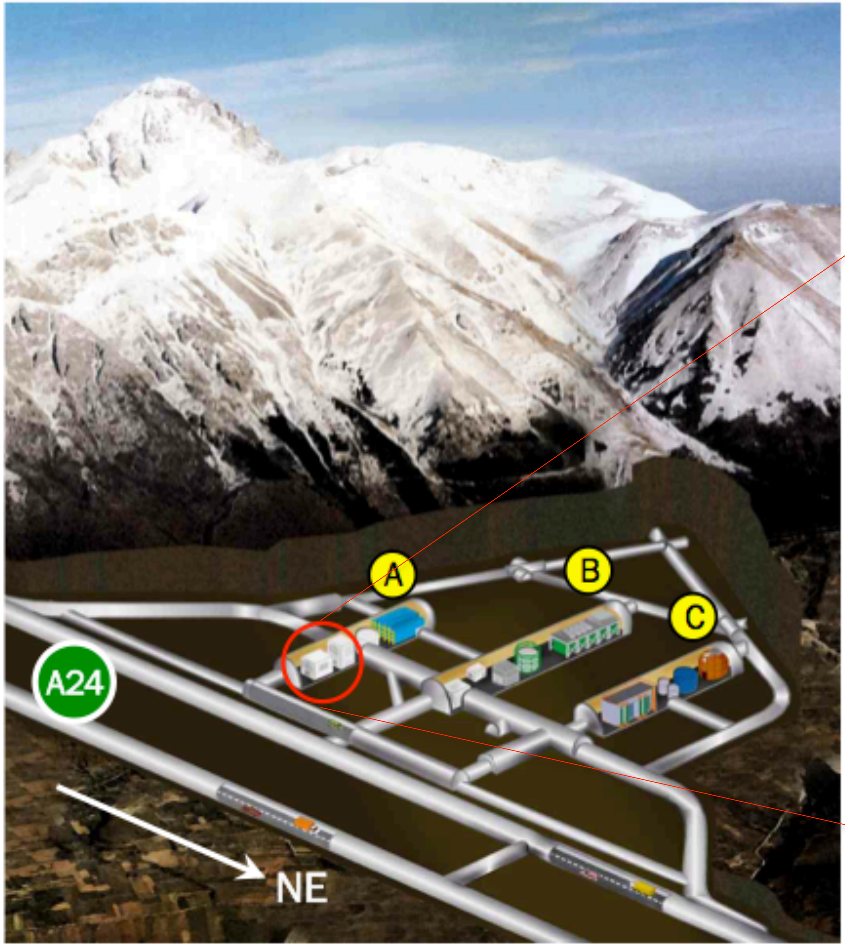
M=40.7 Kg (62 crystals)
M(^{130}Te)=9.15·10^{25} nuclei

M=39 Kg (52 crystals)
M(^{130}Te)=5·10^{25} nuclei

M=741 Kg (19 towers, 988 crystals)
M(^{130}Te)~10^{27} nuclei

Experimental Site

$$\hat{T}_{1/2} \propto (i.a.)\cdot\varepsilon\cdot\sqrt{\frac{M\cdot t}{\boxed{b}\cdot\Delta E}}$$



In A Hall of LNGS, Italy
(Laboratori Nazionali del Gran Sasso)

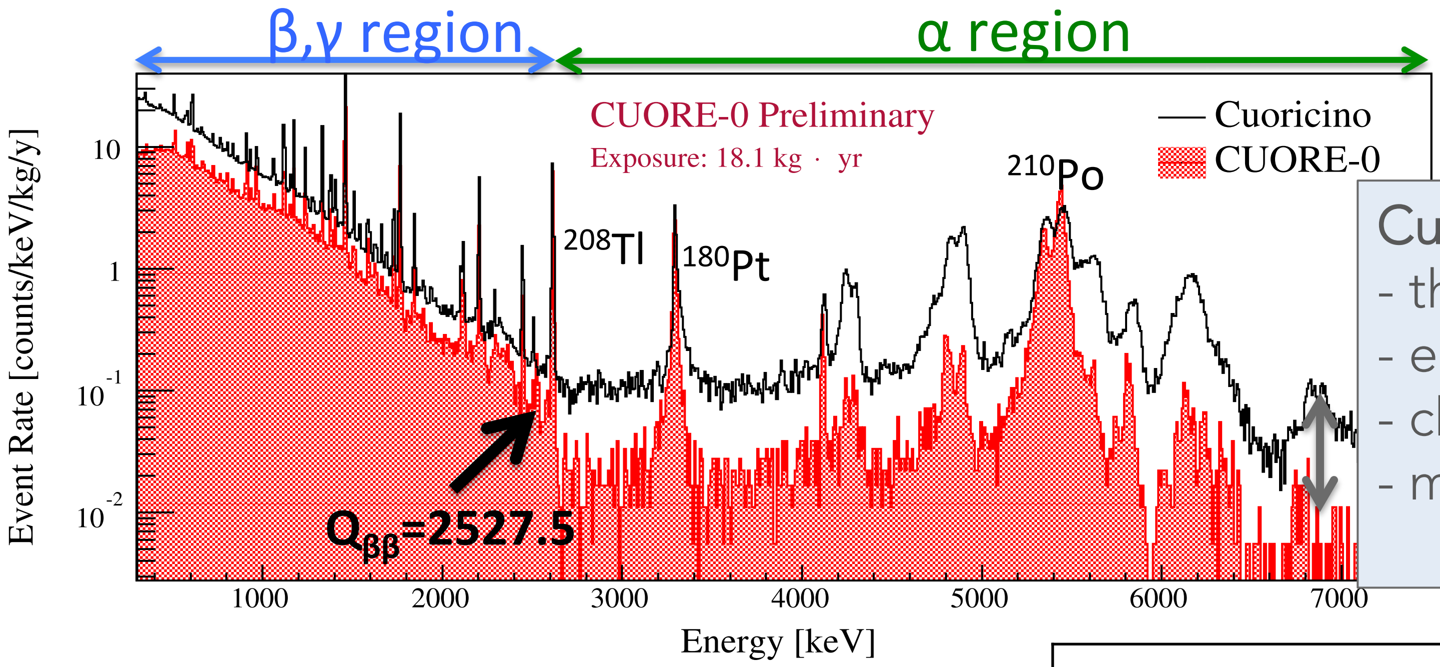
Average depth ~ 3650 m.w.e.
μ flux: $(2.58 \pm 0.3)\cdot 10^{-8}$ μ/s/cm^2
n flux <10 MeV: $4\cdot 10^{-6}$ n/s/cm^2
γ flux < 3 MeV: 0.73 γ/s/cm^2
Sum negligible after shielding

CUORE-0 Background

$$\hat{T}_{1/2} \propto (i.a.)\cdot\varepsilon\cdot\sqrt{\frac{M\cdot t}{b\cdot\Delta E}}$$

Bkg consistent with Cuoricino model…

..but reduction factor ~2 in ROI (~6 in α region)



Cu ultra cleaning:

- thumbling
- electropolishing
- chemical-etching
- magnetron plasma clean

Cryostat: γ from ^{232}Th decays (30±10%)

Cu & shield surfaces: α (50±10%)

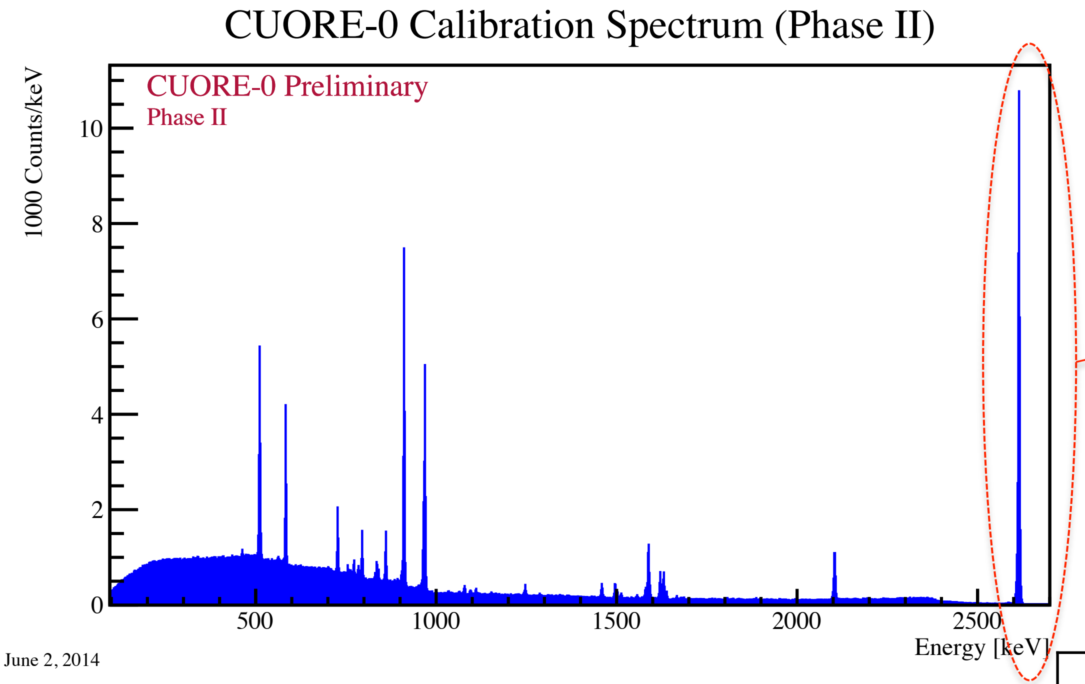
TeO_2 surfaces: α (10±5%)

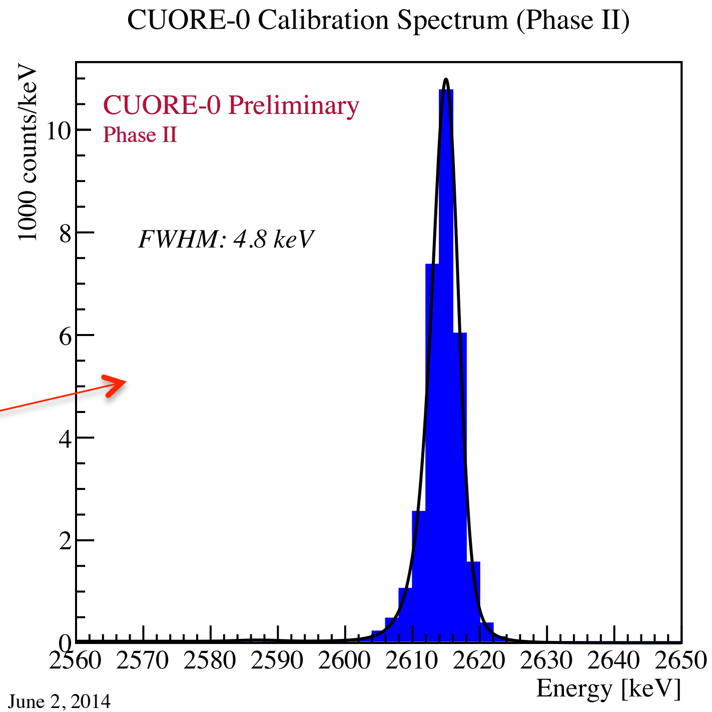
Bkg in ROI	Counts/(keV Kg y)
Cuoricino	0.153±0.006
CUORE-0	0.063±0.006
CUORE (predicted)	0.01

CUORE-0 Energy Resolution

$$\hat{T}_{1/2} \propto (i.a.) \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

Evaluated by CUORE-0 on the 2615 keV γ peak of ^{208}Tl



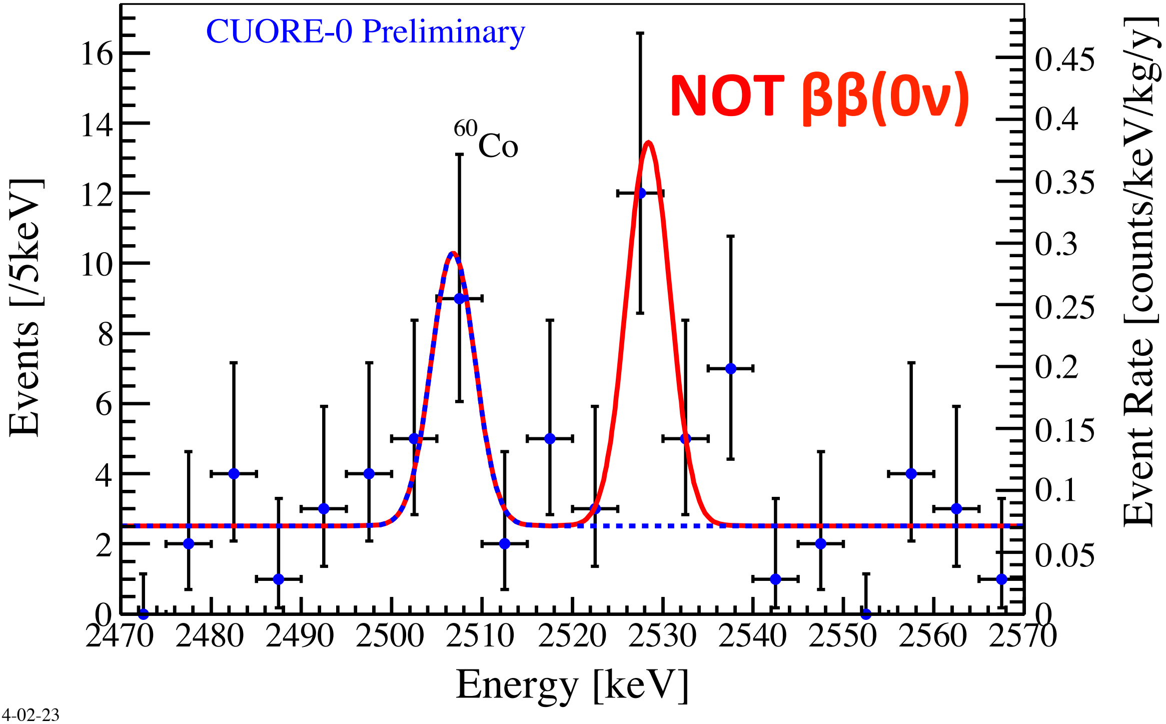


😃 Projected ΔE for CUORE = 5 keV already reached in R&D runs

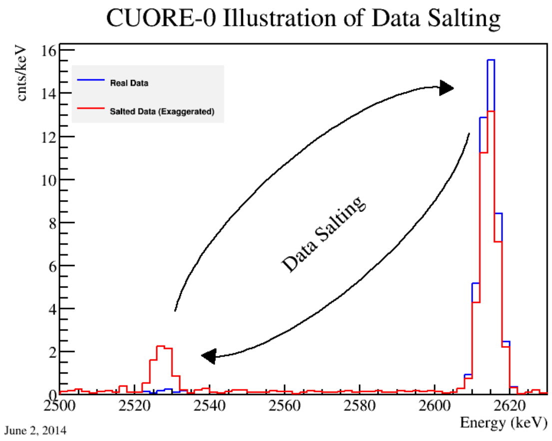
ΔE	keV
Cuoricino	6.3±2.5
CUORE-0	5.6±2.1
CUORE (predicted)	5

CUORE-0 Preliminary Results

- Cuoricino: $T_{1/2}^{0\nu} > 2.8 \cdot 10^{24}\, y \quad (90\% \quad C.L.)$ best ever
- CUORE-0: EPJC 74, 2956 (2014)
  - blinded (unblinding early 2015 ?)



2014-02-23



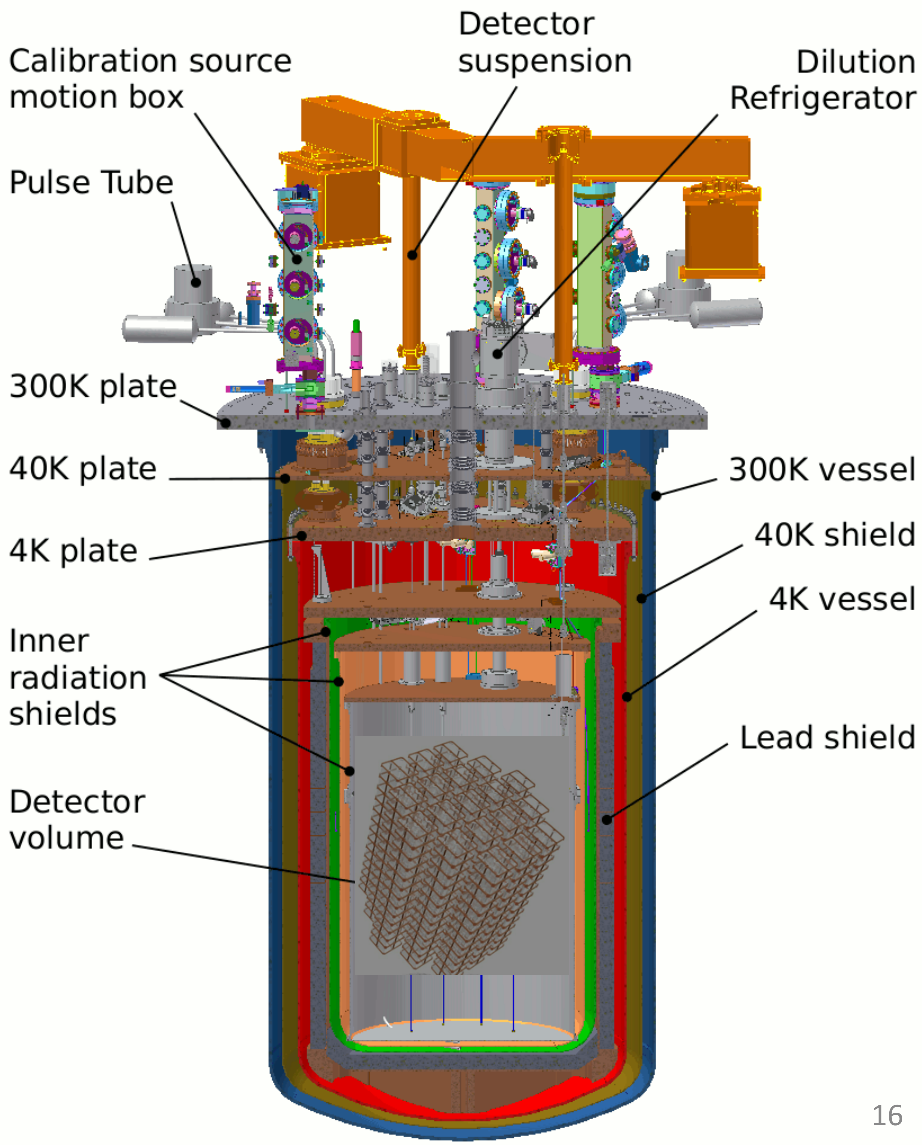
Blinding procedure: small (blinded) % of events in ±10 keV under ^{208}Tl peak exchanged with events ±10 keV around Q-value

CUORE Background

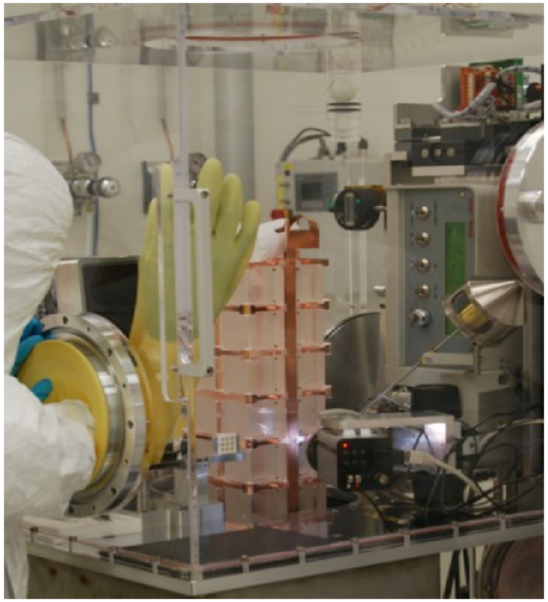
- More bolometers (self-shielding, coincidences, less crystals facing shields)
- Roman lead shield
- New cryostat
- T = 13 → 10 mK
- Improved operating conditions

😃 BKG = 0.01 c/(keV Kg y) within reach !

Cryostat



CUORE Status



- All 19 towers now ready
- Moving to detector integration
- Now: new cryostat commissioning, working on DAQ, data analysis tools, slow-control, Farady cage…
  - still copper cleaning

Cuore data taking expected in summer 2015

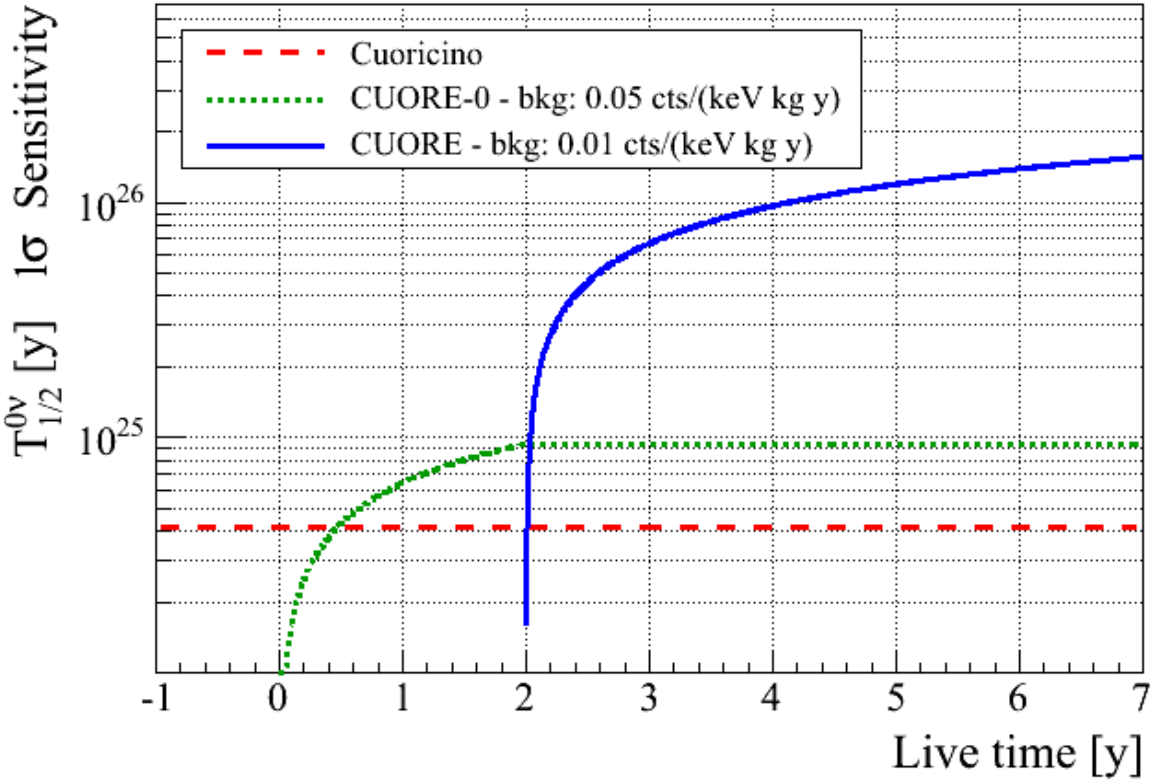
Projected Sensitivity

$$\hat{T}_{1/2} \propto (i.a.)\cdot\varepsilon\cdot\sqrt{\frac{M\cdot t}{b\cdot\Delta E}}$$

With ΔE=5 keV

b=0.05 c/(keV Kg y) (CUORE-0)

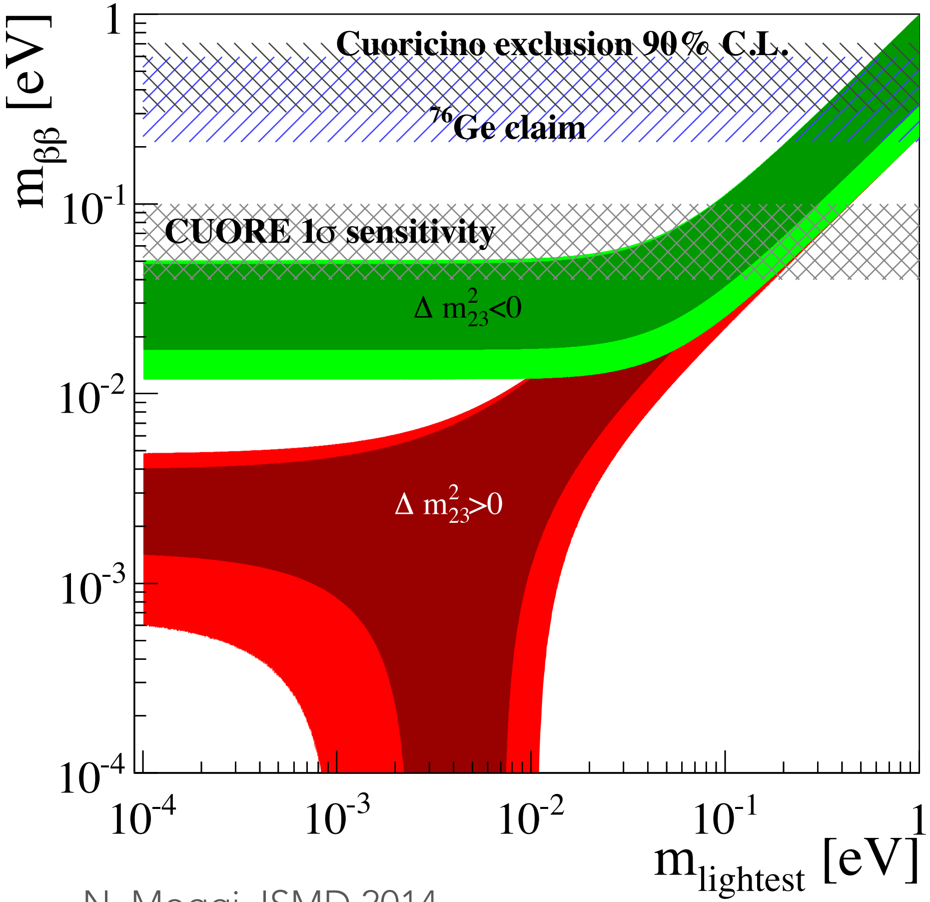
b=0.01 c/(keV Kg y) (CUORE)



Projected Sensitivity

Sensitivity on $T_{1/2}$ may be translated into sensitivity on $<m_{\beta\beta}>$ as:

$$< m_{\beta\beta} > \propto \sqrt[4]{\frac{b \cdot \Delta E}{M \cdot t}}$$



≃ 40-100 meV @ 1σ depending on NME

CUORE will likely just reach the $<m_{\beta\beta}>$ region favored by oscillation results for IH

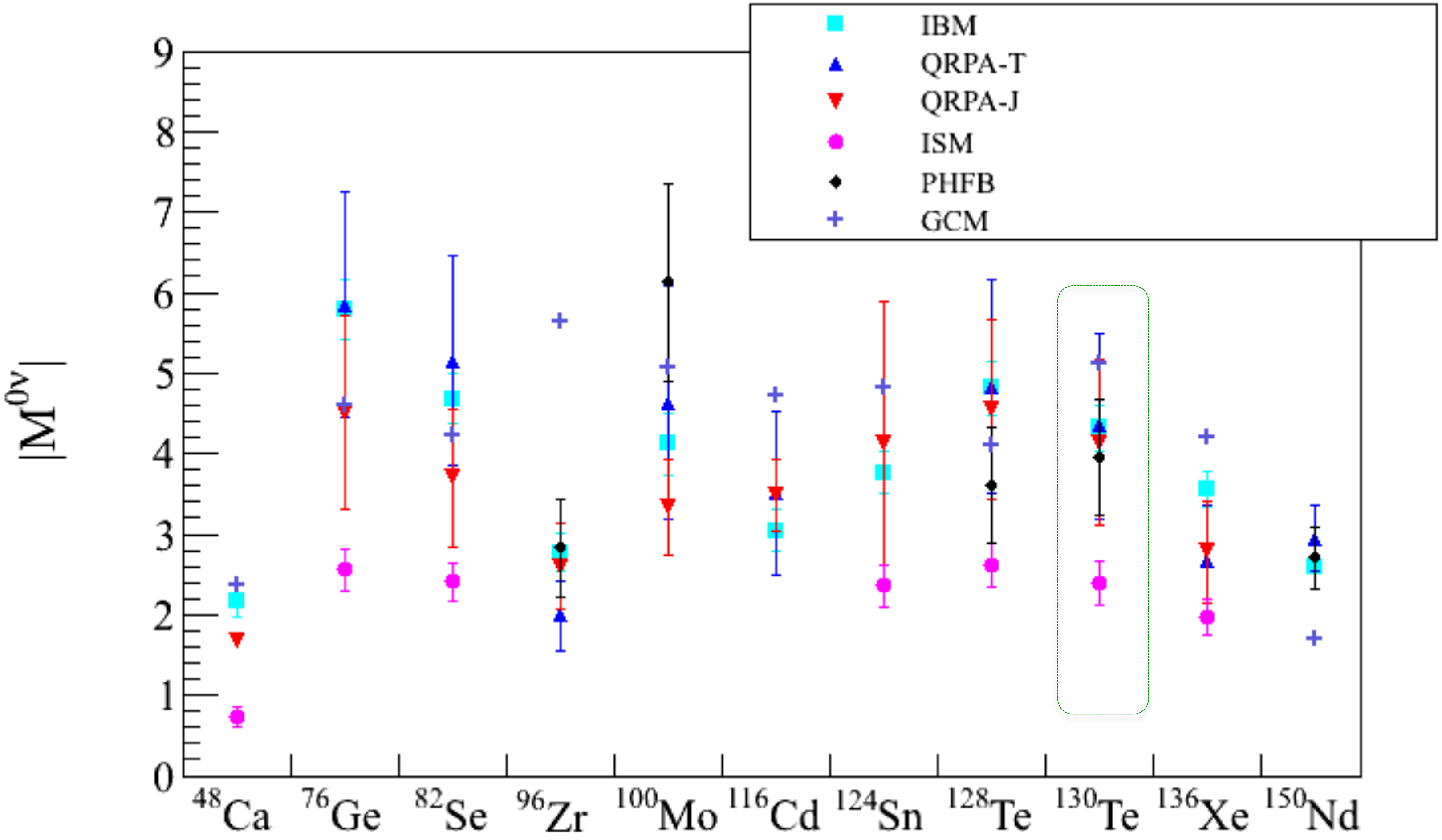
Conclusions

- CUORE-0 is taking data
  - confirms Cuoricino bkg model
  - demonstrates that $\Delta E \lesssim 5$ keV is achievable
- CUORE expected to start in summer 2015
  - observe **$\beta\beta(0\nu)$** → **ν** is Majorana && LNV
  - no observation → $T_{1/2}$ limit best ever
- Many R&D focused on bkg reduction
  - next generation experiments aim to reach IH $<m_{\beta\beta}>$ region

Thank you !

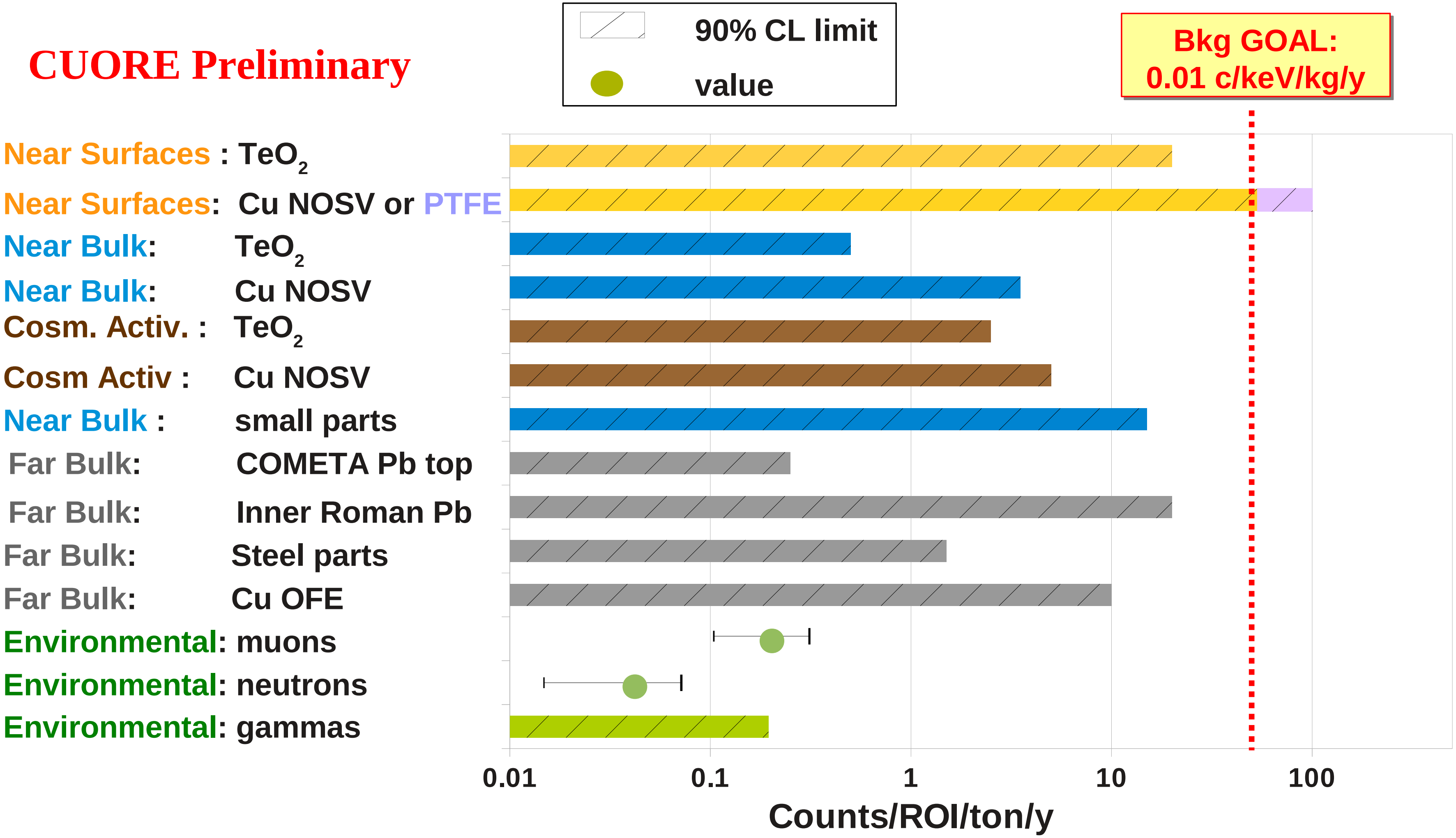
BACKUP SLIDES

NME


IBM
QRPA-T
QRPA-J
ISM
PHFB
GCM
$|M^{0\nu}|$
0
1
2
3
4
5
6
7
8
9
^{48}Ca
^{76}Ge
^{82}Se
^{96}Zr
^{100}Mo
^{116}Cd
^{124}Sn
^{128}Te
^{130}Te
^{136}Xe
^{150}Nd

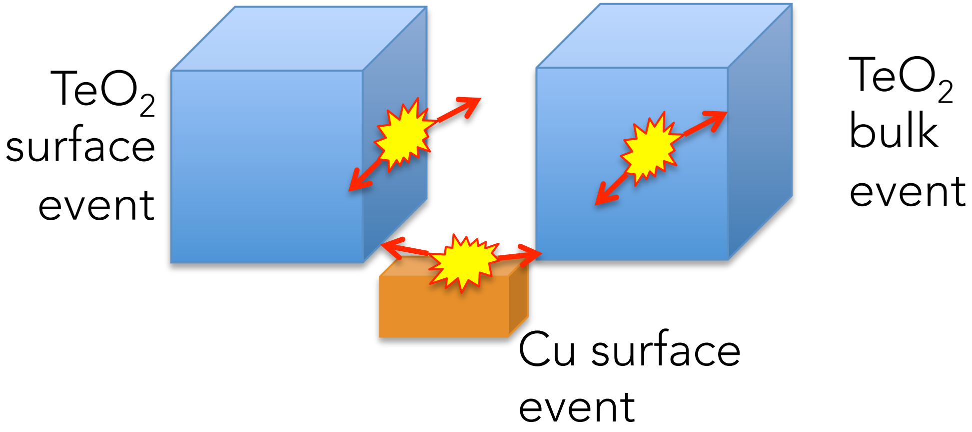
Background Budget

CUORE Preliminary

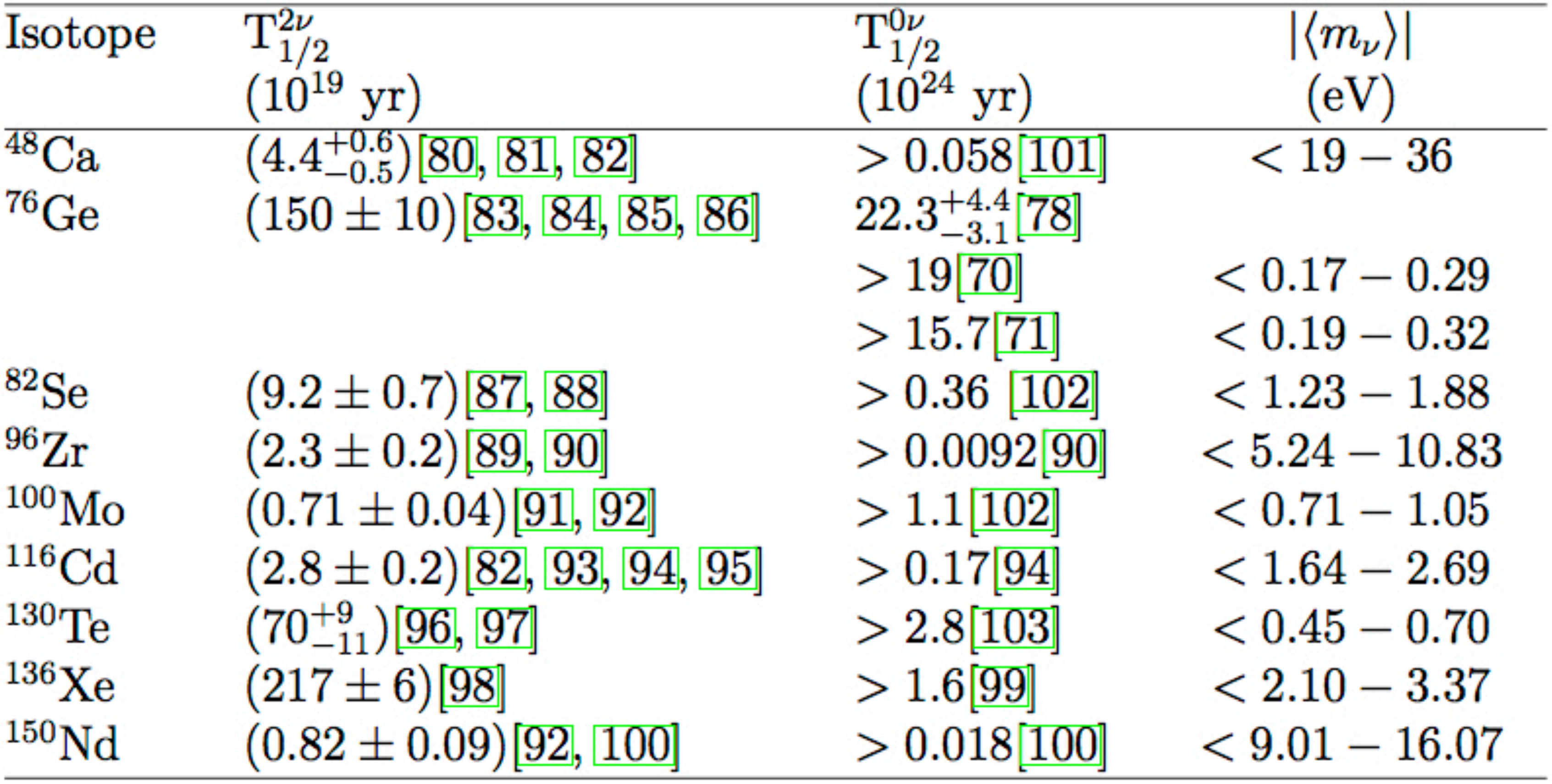


Signal Selection

- Only two signatures may distingush events from bkgs:
  - – Energy release
  - – Single hit : ββ(0ν) signal is confined in one single crystal → multi-hit events are very likely background



The Past Experiments



Isotope	$T^{2\nu}_{1/2}$ (10^{19} yr)	$T^{0\nu}_{1/2}$ (10^{24} yr)	$\lvert\langle m_\nu\rangle\rvert$ (eV)
^{48}Ca	$(4.4^{+0.6}_{-0.5})$ [80, 81, 82]	> 0.058 [101]	$< 19 - 36$
^{76}Ge	(150 ± 10) [83, 84, 85, 86]	$22.3^{+4.4}_{-3.1}$ [78]	
		> 19 [70]	$< 0.17 - 0.29$
		> 15.7 [71]	$< 0.19 - 0.32$
^{82}Se	(9.2 ± 0.7) [87, 88]	> 0.36 [102]	$< 1.23 - 1.88$
^{96}Zr	(2.3 ± 0.2) [89, 90]	> 0.0092 [90]	$< 5.24 - 10.83$
^{100}Mo	(0.71 ± 0.04) [91, 92]	> 1.1 [102]	$< 0.71 - 1.05$
^{116}Cd	(2.8 ± 0.2) [82, 93, 94, 95]	> 0.17 [94]	$< 1.64 - 2.69$
^{130}Te	(70^{+9}_{-11}) [96, 97]	> 2.8 [103]	$< 0.45 - 0.70$
^{136}Xe	(217 ± 6) [98]	> 1.6 [99]	$< 2.10 - 3.37$
^{150}Nd	(0.82 ± 0.09) [92, 100]	> 0.018 [100]	$< 9.01 - 16.07$

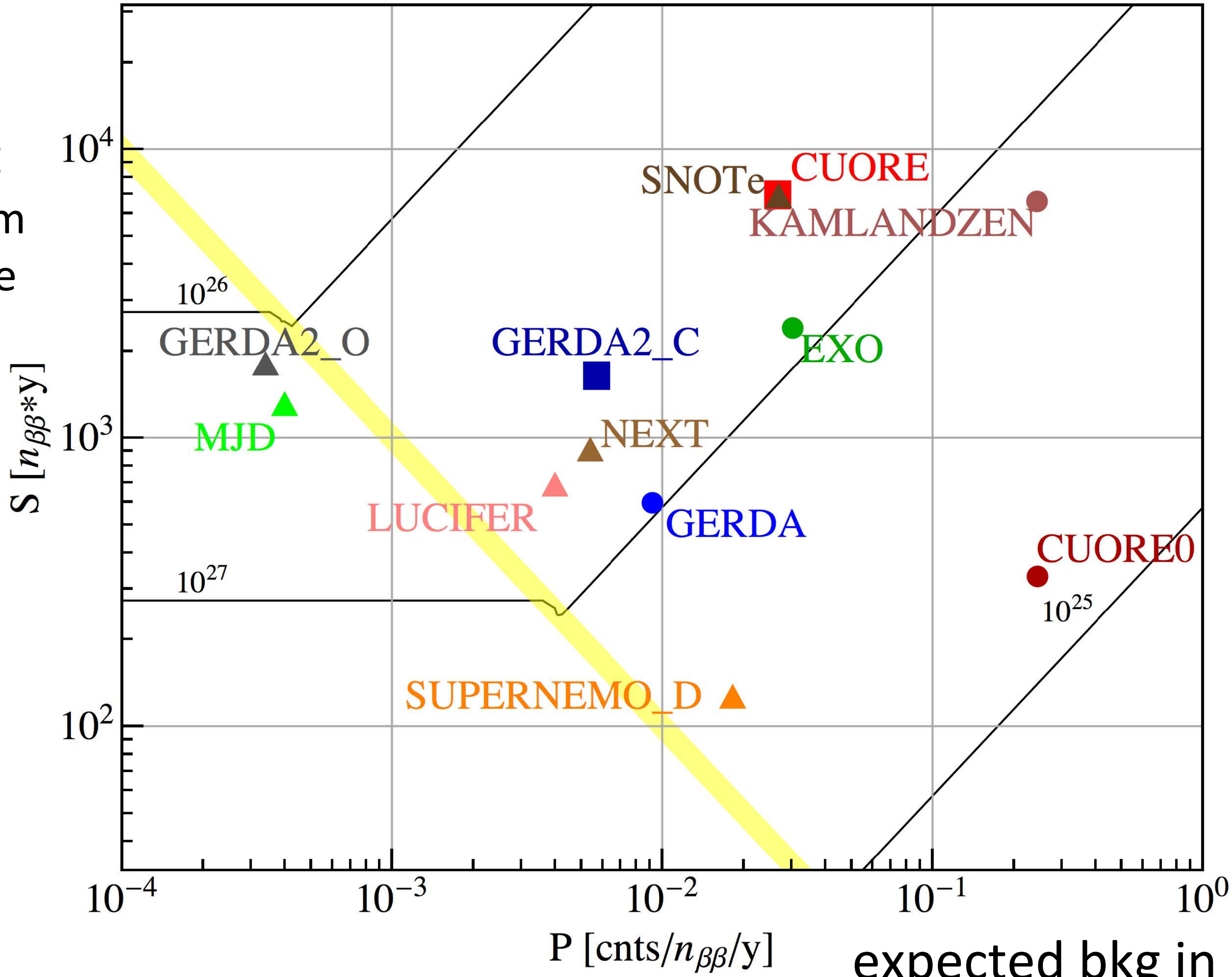
List of best reported results on ββ(0ν) process. Limits are at 90% C.L.
[arXiv.1310.4692v1]

The Competitors

“scale”

S = N_m t

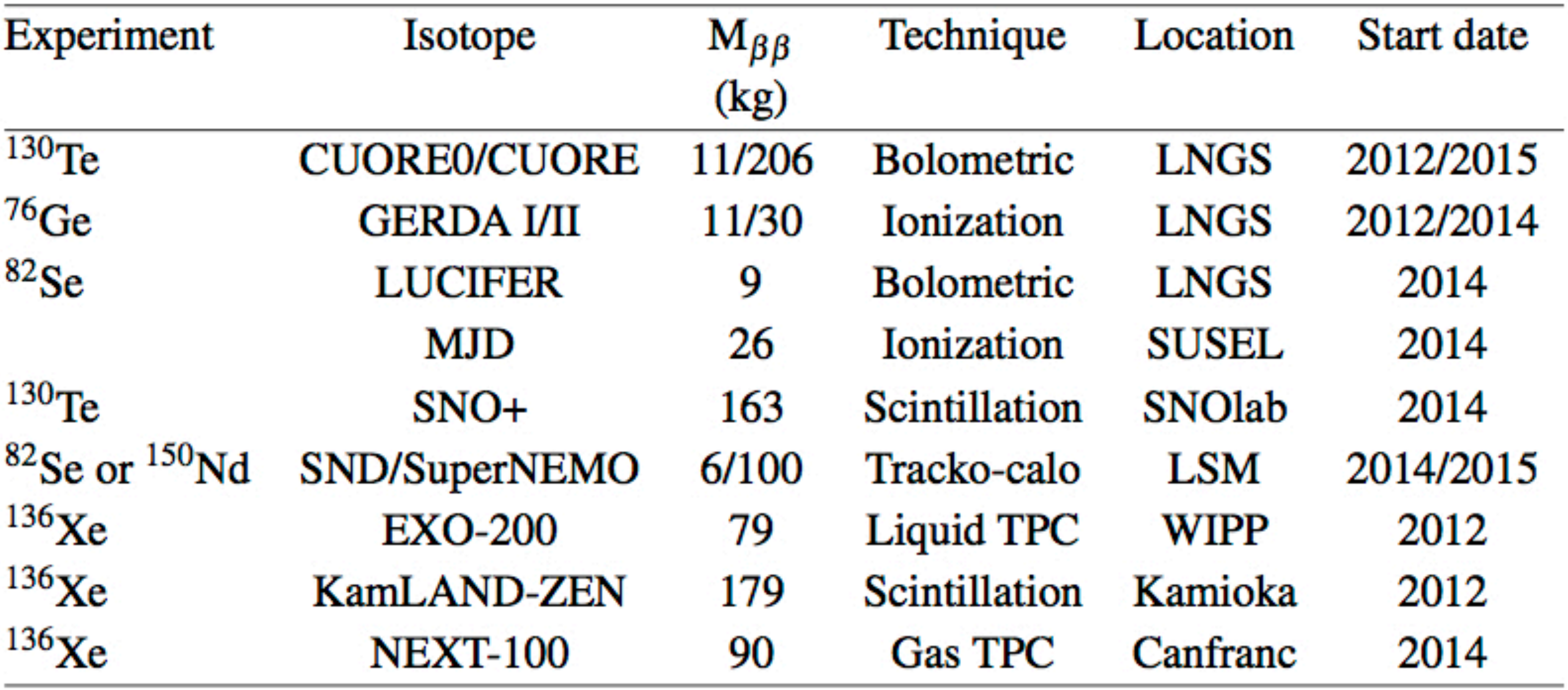
(N_m = num of isotope moles)



expected bkg in ROI

(per isotope mole, per year)

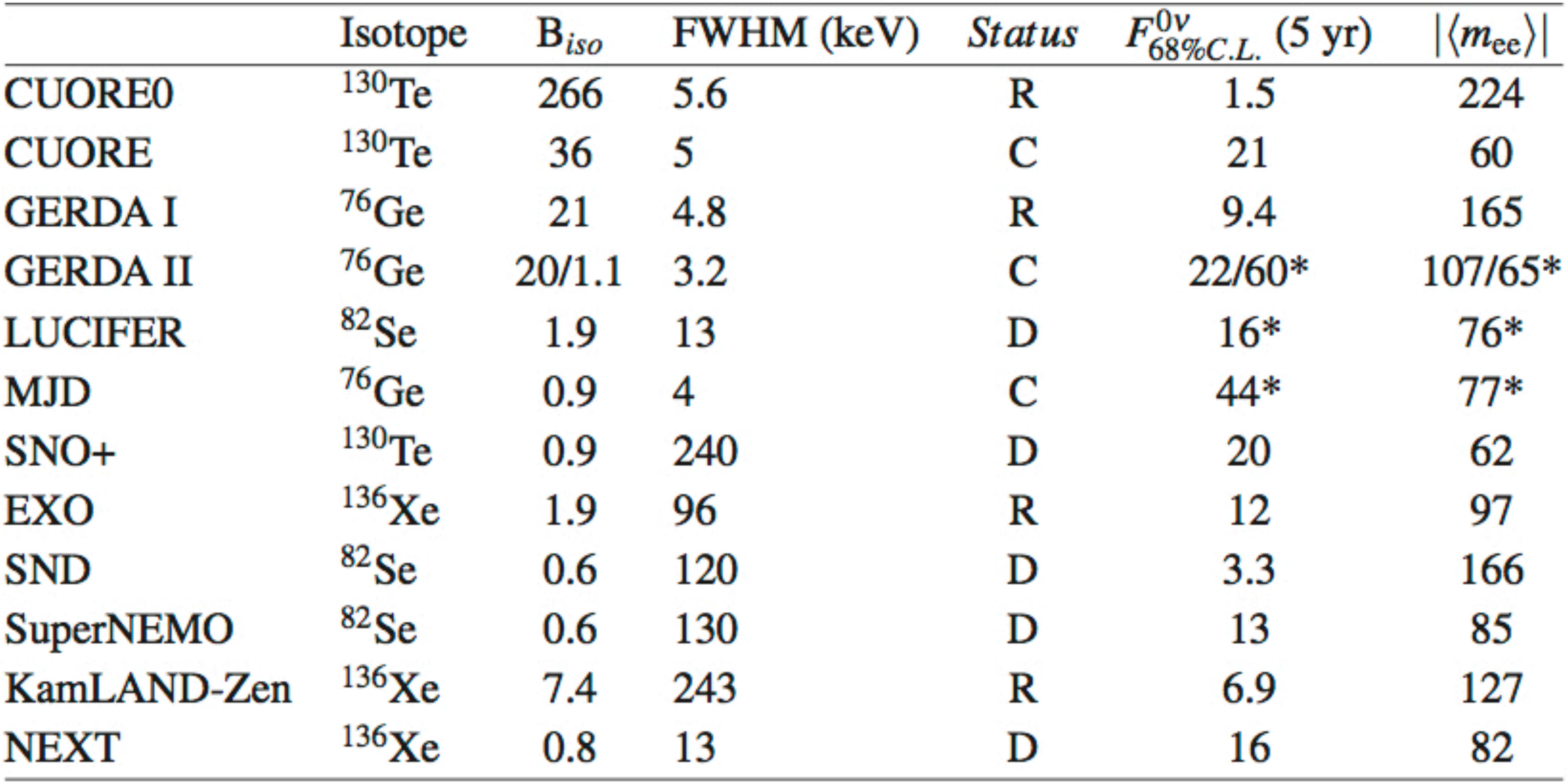
Next Generation



Experiment	Isotope	$M_{\beta\beta}$ (kg)	Technique	Location	Start date
^{130}Te	CUORE0/CUORE	11/206	Bolometric	LNGS	2012/2015
^{76}Ge	GERDA I/II	11/30	Ionization	LNGS	2012/2014
^{82}Se	LUCIFER	9	Bolometric	LNGS	2014
	MJD	26	Ionization	SUSEL	2014
^{130}Te	SNO+	163	Scintillation	SNOlab	2014
^{82}Se or ^{150}Nd	SND/SuperNEMO	6/100	Tracko-calo	LSM	2014/2015
^{136}Xe	EXO-200	79	Liquid TPC	WIPP	2012
^{136}Xe	KamLAND-ZEN	179	Scintillation	Kamioka	2012
^{136}Xe	NEXT-100	90	Gas TPC	Canfranc	2014

[O. Cremonesi, POS (EPS-HEP 2013) 146]

Next Generation



	Isotope	B_{iso}	FWHM (keV)	*Status*	$F^{0\nu}_{68\%C.L.}$ (5 yr)	$\|\langle m_{ee}\rangle\|$
CUORE0	^{130}Te	266	5.6	R	1.5	224
CUORE	^{130}Te	36	5	C	21	60
GERDA I	^{76}Ge	21	4.8	R	9.4	165
GERDA II	^{76}Ge	20/1.1	3.2	C	22/60*	107/65*
LUCIFER	^{82}Se	1.9	13	D	16*	76*
MJD	^{76}Ge	0.9	4	C	44*	77*
SNO+	^{130}Te	0.9	240	D	20	62
EXO	^{136}Xe	1.9	96	R	12	97
SND	^{82}Se	0.6	120	D	3.3	166
SuperNEMO	^{82}Se	0.6	130	D	13	85
KamLAND-Zen	^{136}Xe	7.4	243	R	6.9	127
NEXT	^{136}Xe	0.8	13	D	16	82

[O. Cremonesi, POS (EPS-HEP 2013) 146]

If Next Generation Fails

- if (IH region is reached && no ββ(0ν) is observed) then {we can still reach conclusions with some input from other experiments} :
  - input: ν is a Majorana particle → hierarchy is NH
    - will have to wait even longer
  - input: hierarchy is IH → ν is a Dirac particle
- if ν is a Dirac particle we have no hope of ββ(0ν) observation

The ββ(0ν) observation

- Claim and confirmations (subset of HDM Coll.):
  - H.V Klapdor-Kleingrothaus et al., *Phys. Lett.* B 586 (2004) 198
  - H.V Klapdor-Kleingrothaus, *International Journal of Modern Physics* E 17 (2008) 505-517

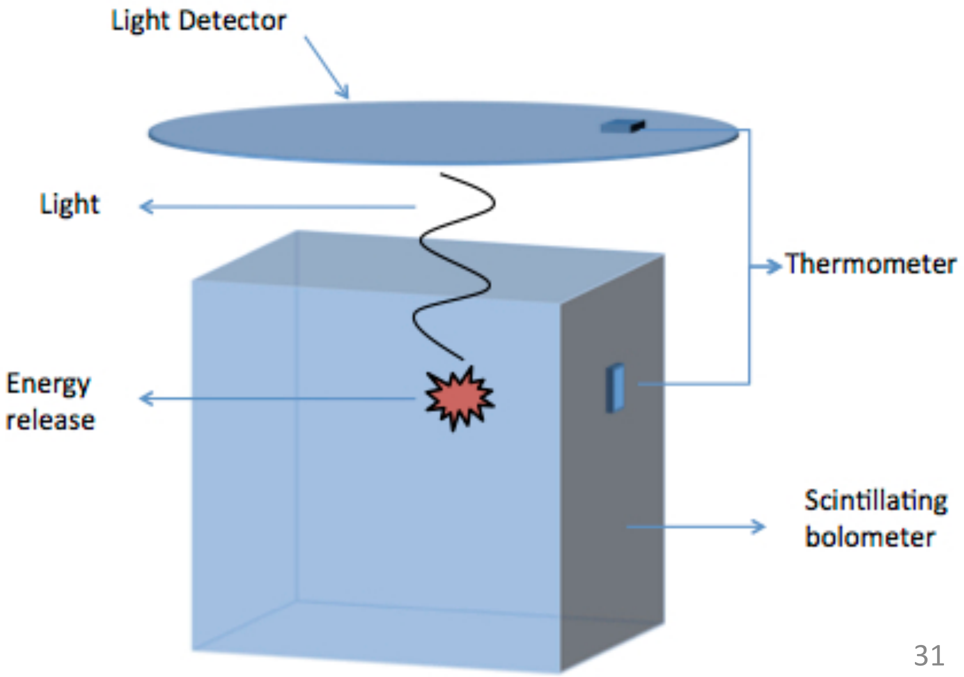
$$T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \times 10^{25} \quad yr \quad @6\sigma$$ in ^{76}Ge

- More recent null results:
  - M. Auger et al. (EXO Coll.) Phys.Rev.Lett **109**, 032505 (2012)
  - A. Gando et al. (KamLAND-Zen Coll.) Phys.Rev.Lett. **110** 062502 (2013)
  - M. Agostini et al. (GERDA Coll.) Phys.Rev.Lett **111** 22503 (2013)

$$T_{1/2}^{0\nu} > 3.0 \times 10^{25} \quad yr \quad @90\%C.L.$$ (combination)

Scintillating Bolometers

- Scintillating crystal + bolometric light detector → "heat" + "light"
- heat signal is ~ the same for all particles
- light signal depends on particle mass → PID
- Separate α (bkg. only) from β/γ (bkg. and signal) → remove all α bkg.



New technique

For scintillating bolometers the time shape of heat depends on particle type (light emission) → signal shape may be used without light detector

Zero background

In the 0-background limit, the sensitivity formula becomes:

$$T_{1/2}^{0\nu} \propto (i.a.) \cdot \varepsilon \cdot M \cdot t$$

- does not depend on background and energy resolution
- scales linearly with mass and live-time

Sensitivity to Dark Matter

- Low energy analisys ≲ 30 keV
- Dedicated trigger and pulse-shape ID to lower the energy threshold
- Bolometers unable to distinguish nuclear recoils from β,γ
- In principle CUORE could look for annual modulation:

  B+S(June+3)/B+S(Dec+3)
- Simulation of sensitivity assuming all DM is made of WIMP with spin-independent interactions