Double beta decay experiments in the US

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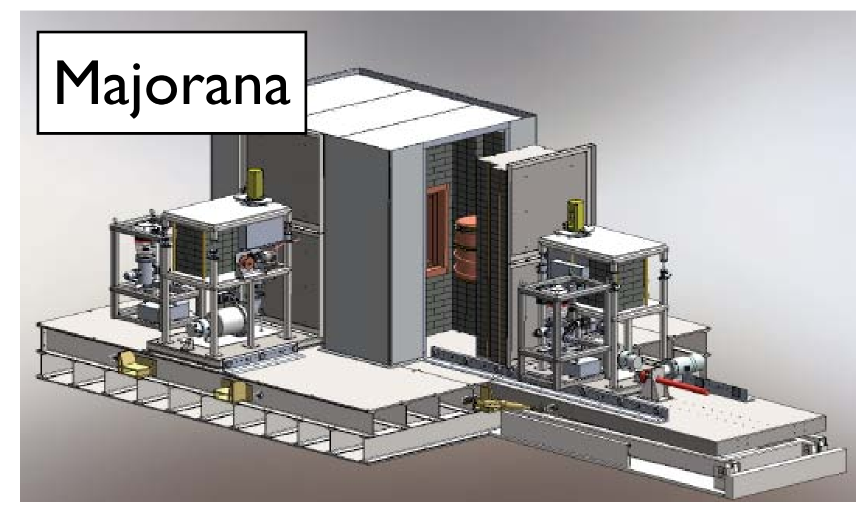
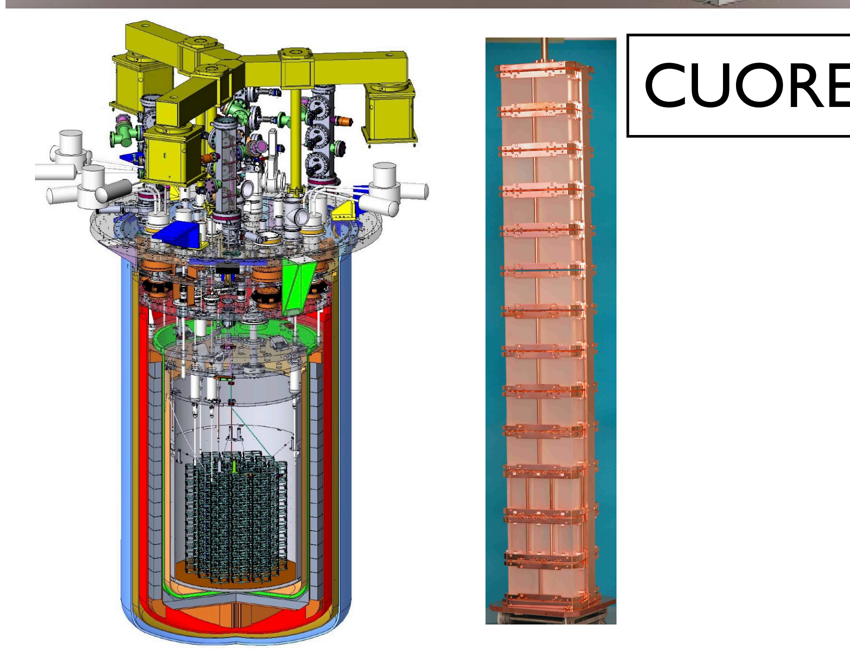
SLAC

US participation in many 0νββ searches

- EXO
- CUORE
- Majorana
- SNO+
- NEXT
- KamLAND ZEN
- NEMO
- COBRA

Many great experiments with US collaboration, but concentrating on these today



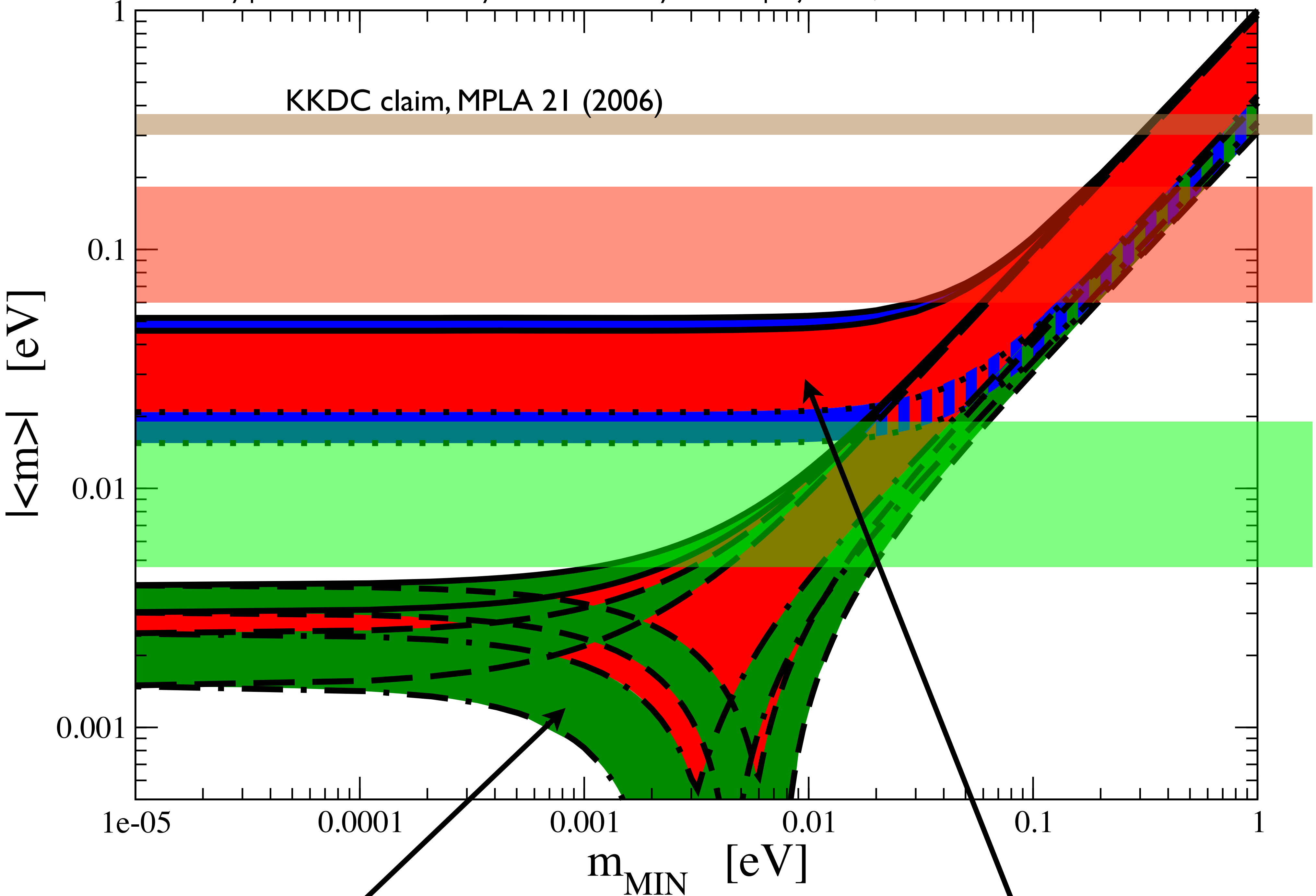


EXO, CUORE, MAJORANA

- EXO (Enriched Xenon Observatory)
  - EXO-200: ~150 kg liquid ^{136}Xe TPC, operational spring 2011, located at WIPP (1600 mwe), 4e-3 c/keV/kg/yr demonstrated, recently observed $2\nu\beta\beta$ (PRL 107, 212501, 2011)
  - Full-EXO: 2-10 ton liquid or gas ^{136}Xe TPC with final state nucleus tag for radioactive background reduction/elimination
- CUORE
  - CUORICINO: 11.3 kg ^{130}Te bolometric measurement, located at LNGS (3050 mwe), 0.17 c/keV/kg/yr demonstrated, 2003-2008
  - CUORE0: 11 kg ^{130}Te, new cryostat, 2012-2014
  - CUORE: 206 kg ^{130}Te, goal 1e-2 c/keV/kg/yr, 2014-?
- MAJORANA
  - DEMONSTRATOR: 30 kg ^{enr}Ge (86%) + 10 kg Ge PPCs, goal 2.5e-4 c/keV/kg/yr = 1 c/keV/tonne/yr, 2013-? underground at SURF (4850’, 4300 mwe)
  - Future ton-scale effort in collaboration with GERDA, depending on performance of GERDA and DEMONSTRATOR

Reach of current and next generation 0νββ experiments

Figure courtesy PDG 2010
Discovery potential bands added by hand from survey of latest projections, and not meant to be exact.



~100 kg class 0νββ experiments (~ 100 meV sensitivity)

Ton-class 0νββ experiments (~ 5 meV sensitivity)

$$\left|\sum_i m_i U_{ei}^2\right| \equiv \left|\left\langle m_{\beta\beta}\right\rangle\right|$$

Normal hierarchy

Inverted hierarchy

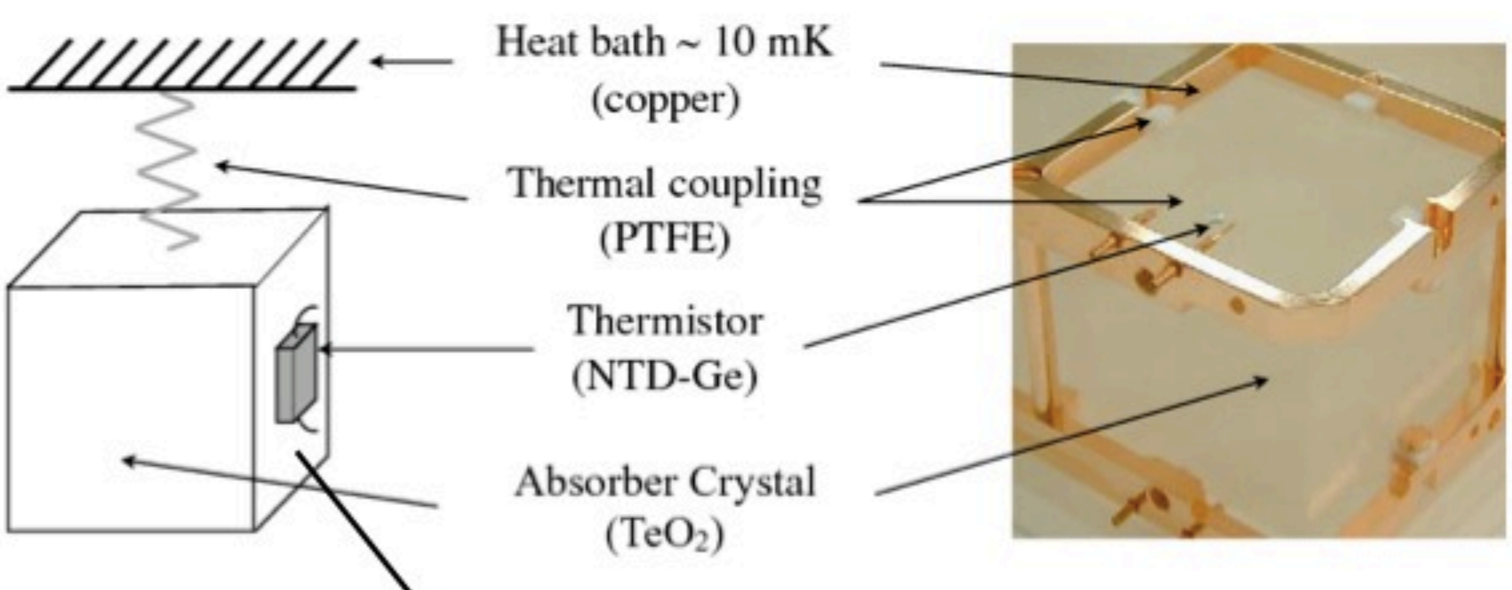
Assumes Majorana neutrinos

CUORE: A bolometric search for 0νββ
Successor to Cuoricino

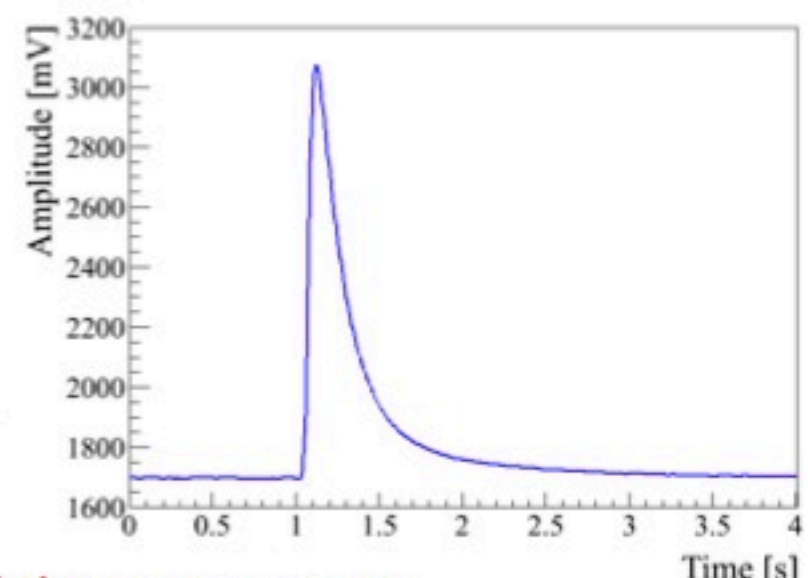
The basic detector unit is a TeO_2 crystal (^{130}Te natural abundance 34.167%). A decay deposits energy in the crystal, causing a temperature rise:

$$\Delta T(t) = \frac{\Delta E}{C} e^{\left(-\frac{t}{\tau}\right)}, \qquad \tau = \frac{C}{G}$$

crystals' heat capacity $C \propto T^3$ → keep array in a cryostat at 8-10 mK

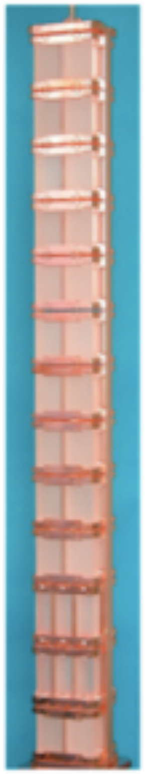


$$R(T) = R_0 e^{\sqrt{\frac{T_0}{T}}}$$



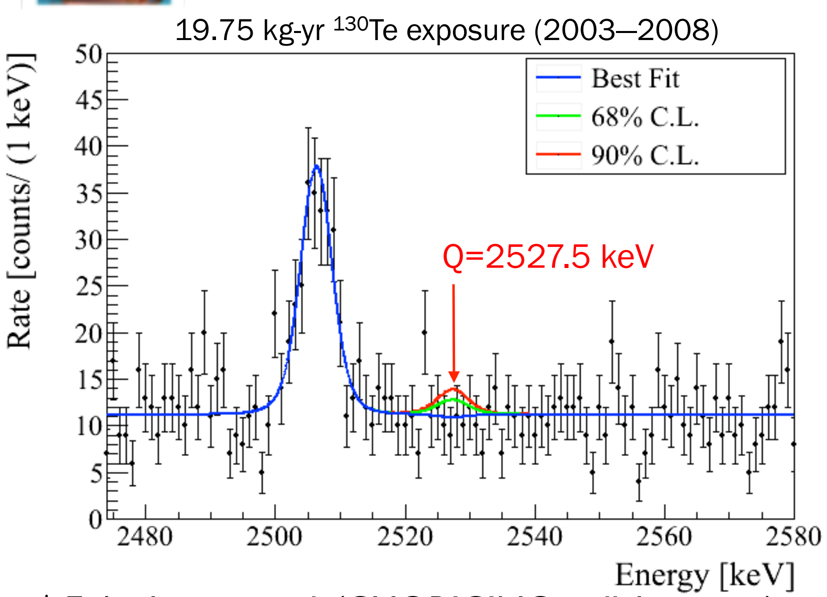
Voltage signal → calibrated with known γ source at multiple energies

Cuoricino → CUORE-0 → CUORE



Cuoricino (2003-2008):
44 5x5x5 cm³ and 18 3x3x6 cm³ TeO_2 crystals
detector mass 40.7 kg
^{130}Te mass 11.3 kg
standard dilution refrigerator

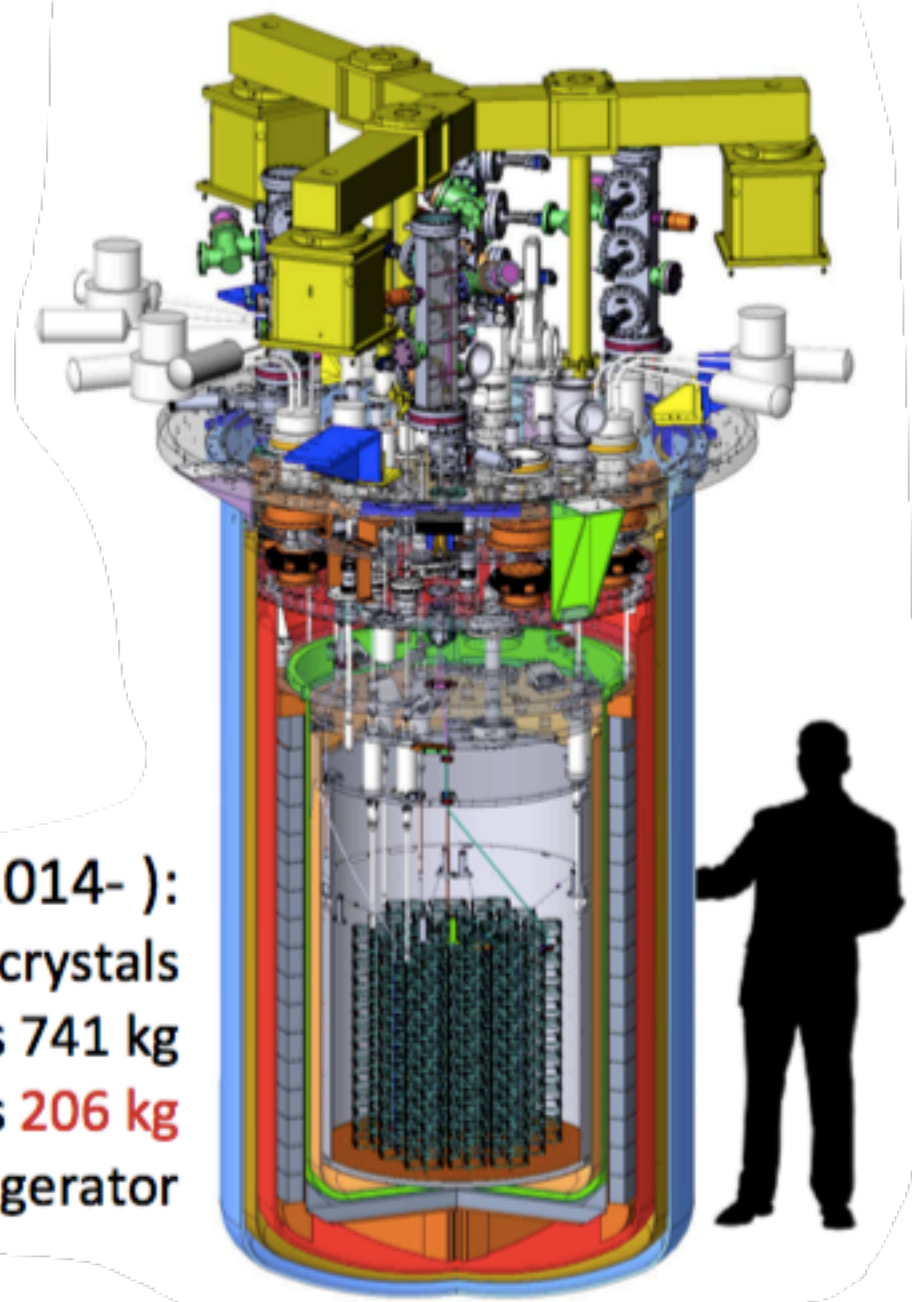
Cuoricino set a limit of
$T_{1/2}$ > 2.8 x 10^{24} y (90% C.L.)
on the 0νββ of ^{130}Te
$\langle m_{\beta\beta} \rangle$ < 300-710 meV *
19.75 kg-yr exposure



* E. Andreotti et al. (CUORICINO collaboration), Astropart. Phys. 34: 822-831 (2011)

CUORE-0 (2012-2014):
the first CUORE-like tower
52 5x5x5 cm³ TeO_2 crystals
detector mass 39 kg
^{130}Te mass 11 kg
refurbished Cuoricino cryostat

CUORE (2014-):
988 5x5x5 cm³ TeO_2 crystals
detector mass 741 kg
^{130}Te mass 206 kg
cryogen-free dilution refrigerator



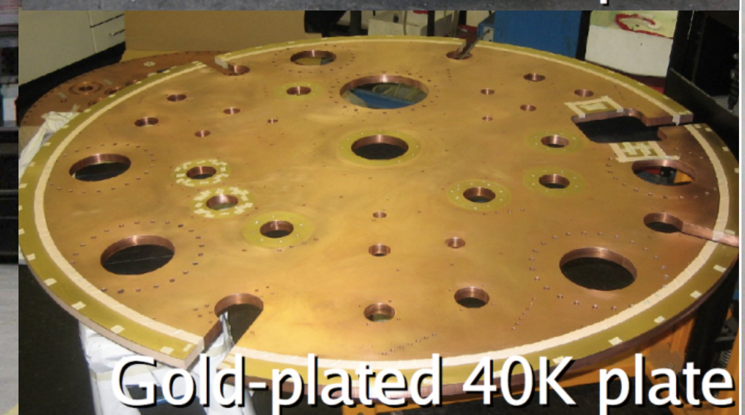
<u>CUORE goals</u>
5 keV FWHM resolution
0.01 c/keV/kg/yr bkgnd
5 yr livetime

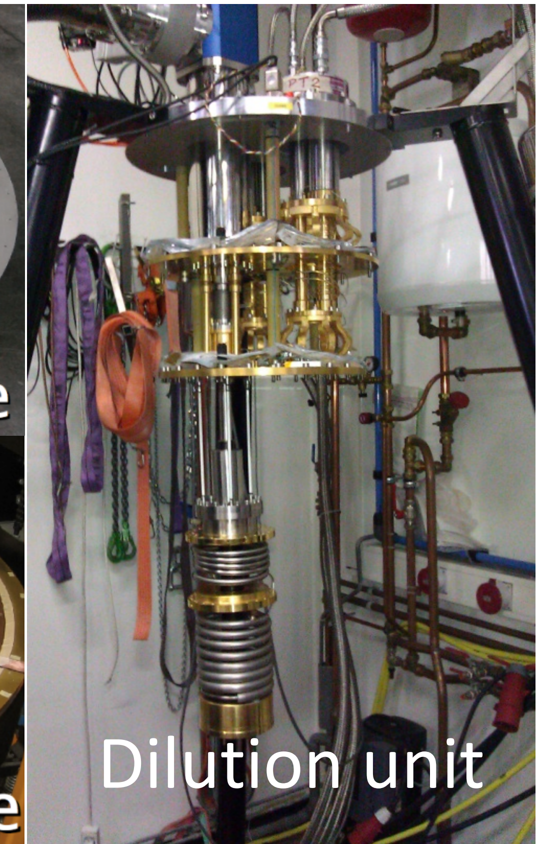
→

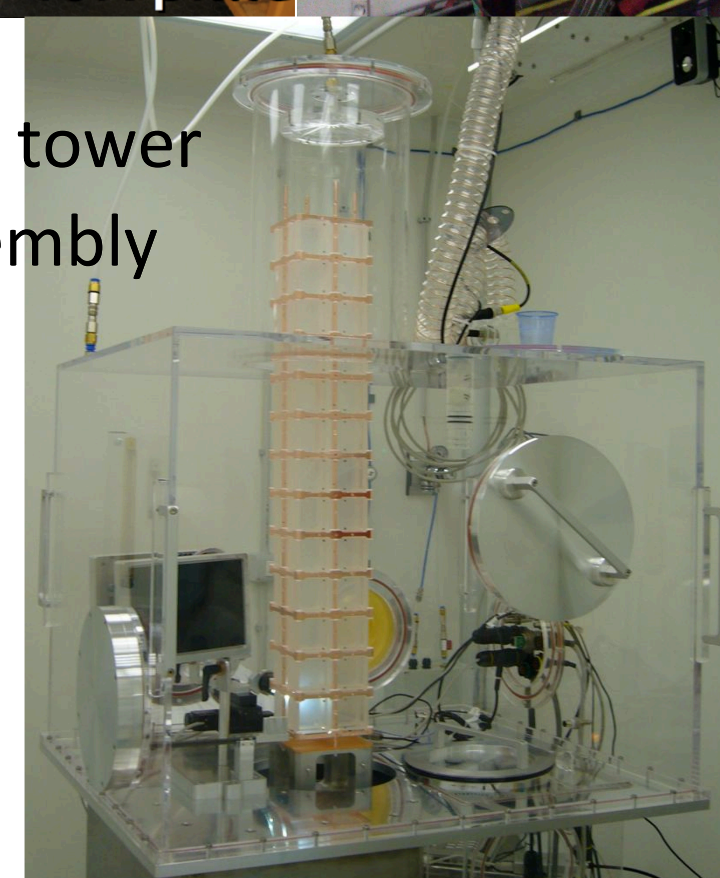
$T_{1/2}^{0\nu}(^{130}Te)$ > 1.6e26 y (68% CL)
$m_{\beta\beta}$ < 41-95 meV

$T_{1/2}^{0\nu}(^{130}Te)$ > 9.5e25 y (90% CL)
$m_{\beta\beta}$ < 52-120 meV

CUORE hardware status (LNGS)





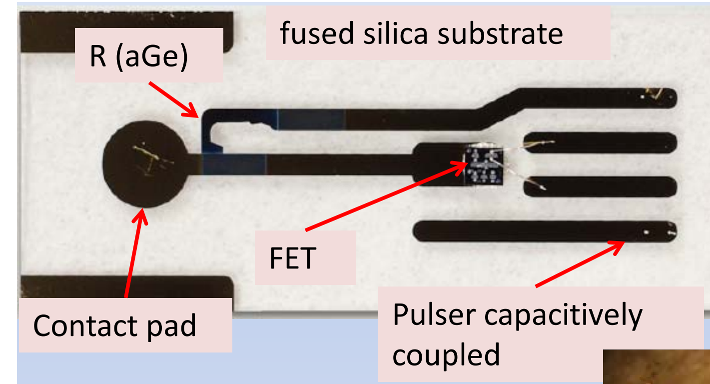


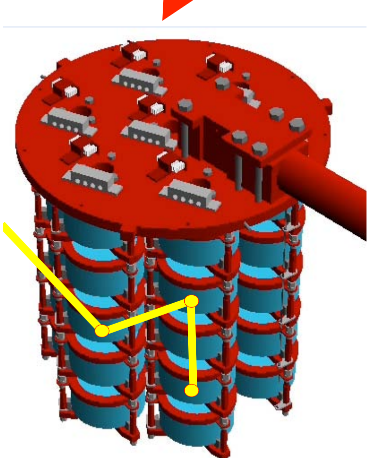
R&D of CUORE collaborators for future bolometric searches

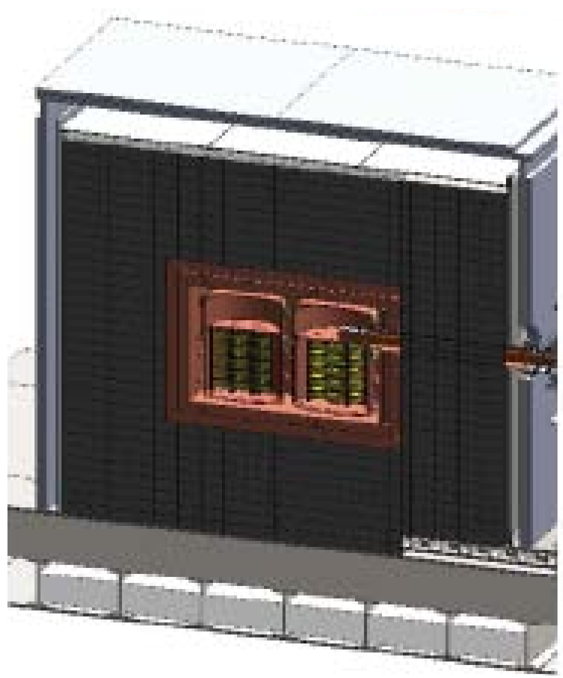
- Te enrichment methods
- Active background discrimination methods (current thermal signal collection time ~ sec)
  - Cerenkov light (cone, fast ~ ps) emission from $2\nu\beta\beta$, discriminate between α, β/γ, $\beta\beta$
  - Scintillating bolometers (other crystal types)

Majorana Demonstrator: First phase of the Majorana experiment

- **Phase 1**: above-ground test, ^{nat}Ge, mechanical and MC testing, summer 2012
- **Phase 2**: underground electroformed Cu, 3 strings ^{enr}Ge, 4 strings ^{nat}Ge, spring 2013
- **Phase 3**: 7 strings ^{enr}Ge, 2 crysotats, "conventional" shielding, active μ-veto, Rn box, *test KKDC ~ 1 yr data ($T_{1/2}$ > 4.5e25 y), starting fall 2014*
- Will also test:
  - low background components & electronics
  - Cu electroforming underground at SURF and PNNL
  - Pulse shape analysis (PSA) for gamma background rejection
  - Monte Carlo

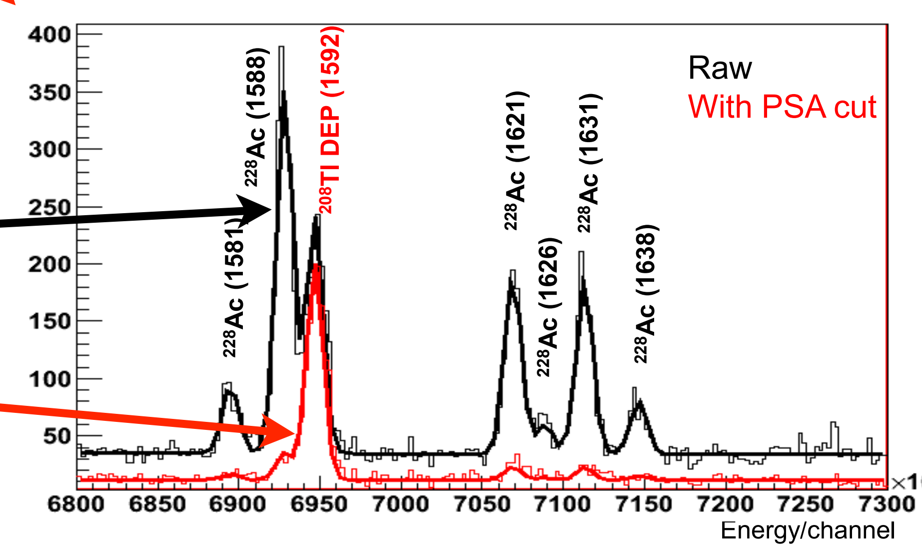






Multiple site events (gamma backgrounds)

True single site events (similar to ββ events)

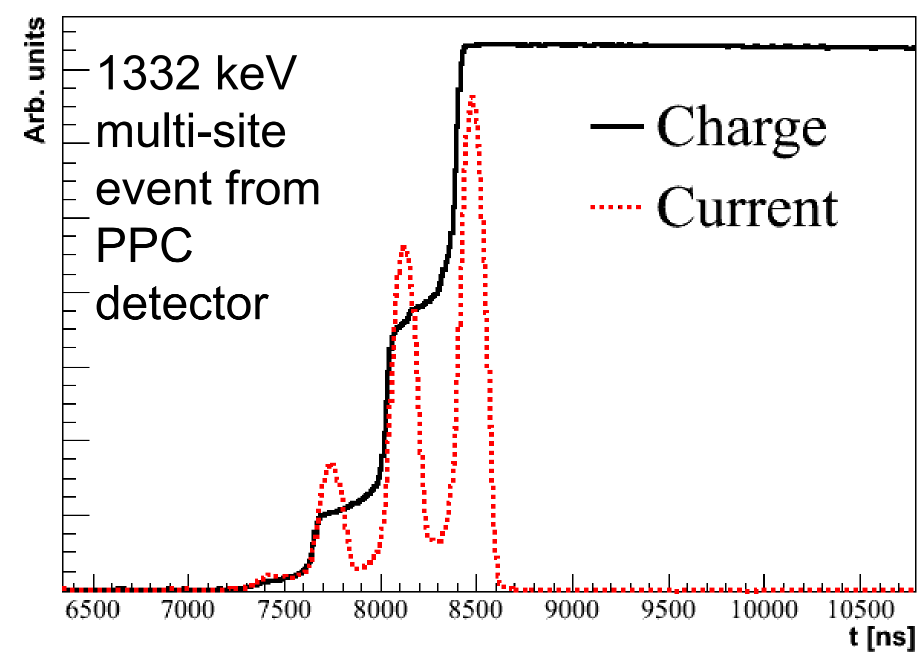


Majorana Demonstrator: PPCs

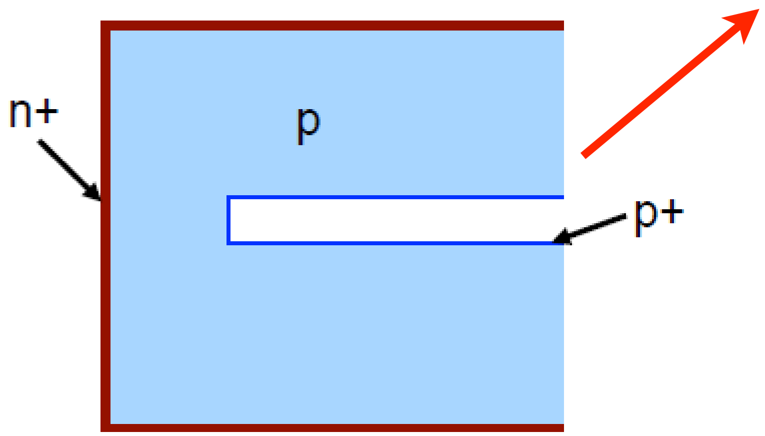
- PPCs (P-type point contact HPGe), ~ 0.6 kg/diode
- Small capacitance (0.5-1.5 pF) → low noise
- Excellent energy resolution (goal 4 keV FWHM at Q = 2039 keV, or ~ 0.2%)
- Pulse shape discrimination for discriminating multi/single site interactions (demonstrated 98% retainment of DEP, 1% contamination of SEP, see spectrum in last slide)
- Most backgrounds at ~2 MeV are multi-site
- Developed and improved in US by multiple groups, incorporated by GERDA

Point contact detector (PPC)

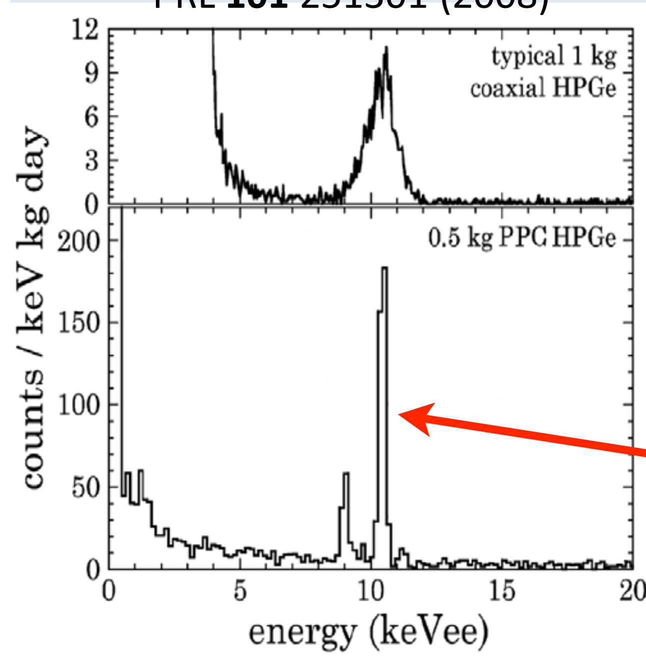
•P. N. Luke, F. S. Goulding, N. W. Madden, R. H. Pehl, IEEE T. Nucl. Sci. **36** (1989) 926
•P. S. Barbeau, J. I. Collar, O. Tench, J. Cosmol. Astropart. Phys. **0709** (2007) 009.
•E. Aguayo et al. [The Majorana Collaboration], http://arxiv.org/abs/1109.6913 (2011)

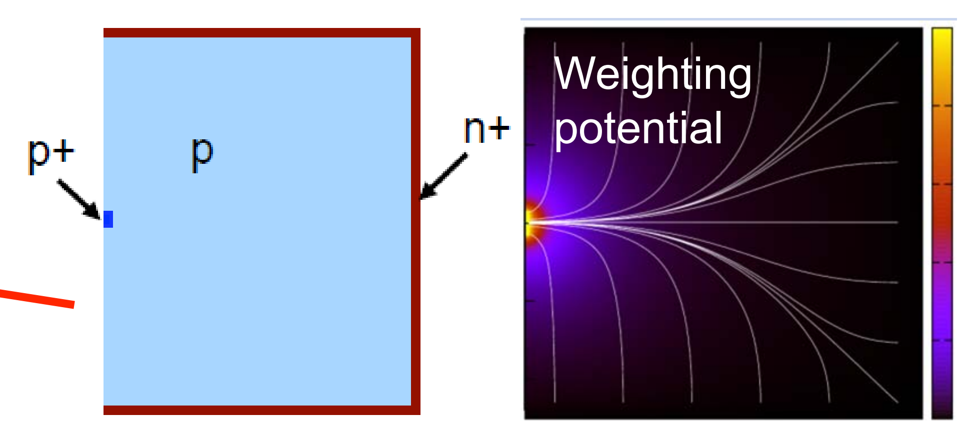


Coaxial HPGe



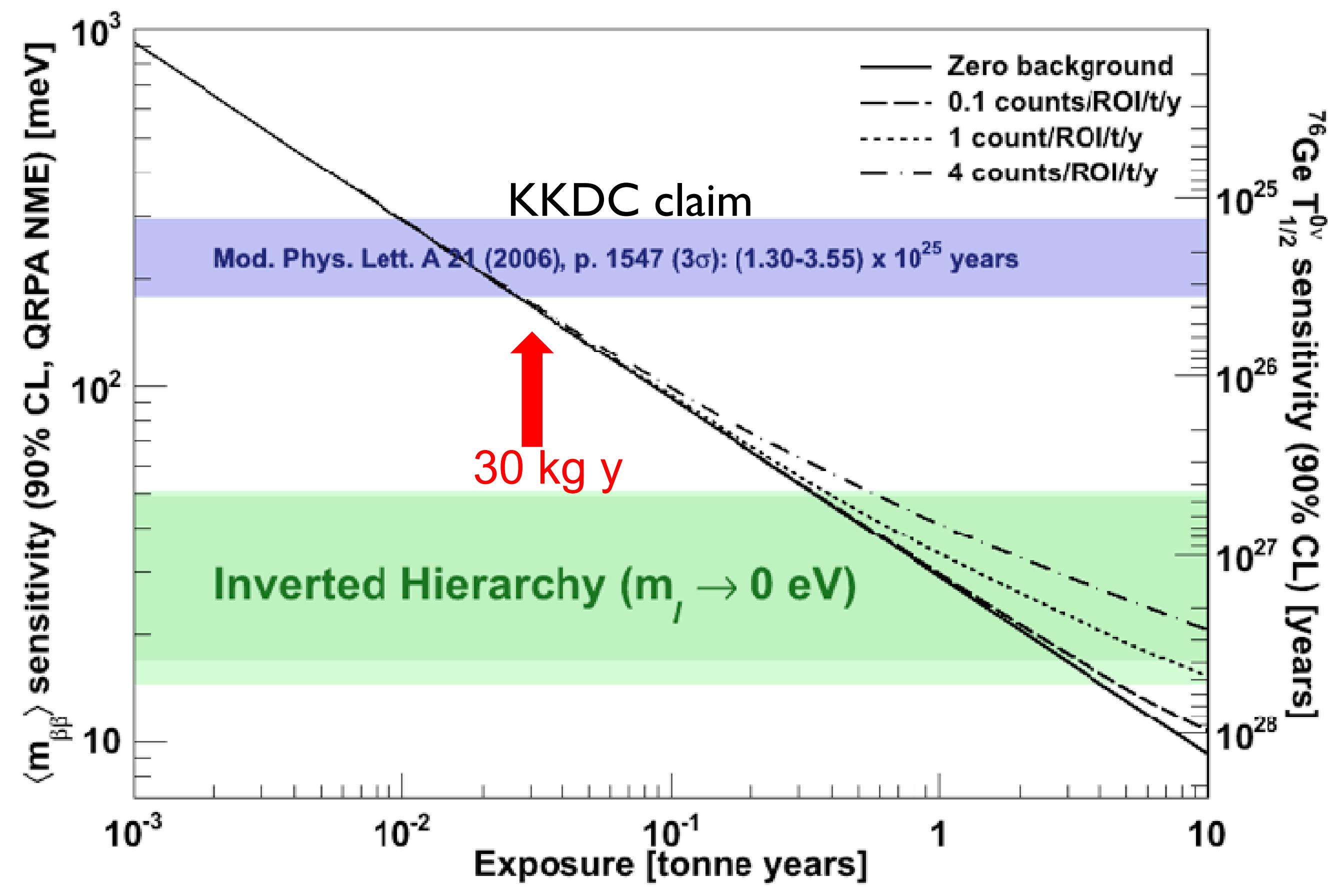
PRL **101** 251301 (2008)





Ton-scale ^{enr}Ge detector outlook

- Technology will be based on outcome of R&D and results from Majorana Demonstrator and GERDA
  - Backgrounds
    - 4 c/ton/yr/ROI Demonstrator goal (4 keV ROI)
    - 1 c/ton/yr/ROI ton-scale goal (4 keV ROI)
  - Component performance
  - Performance at depth
  - Pulse shape analysis with PPCs
  - Shielding (active LAr vs. active water vs. Pb)
- ~ 2016 est. convergence of Demonstrator and GERDA phase II results (~ 100 kg yr)*

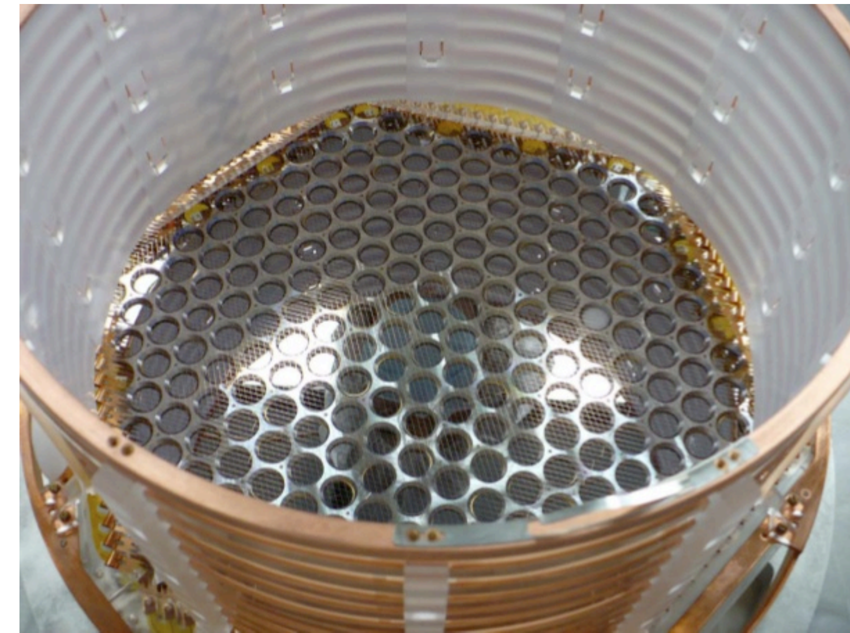


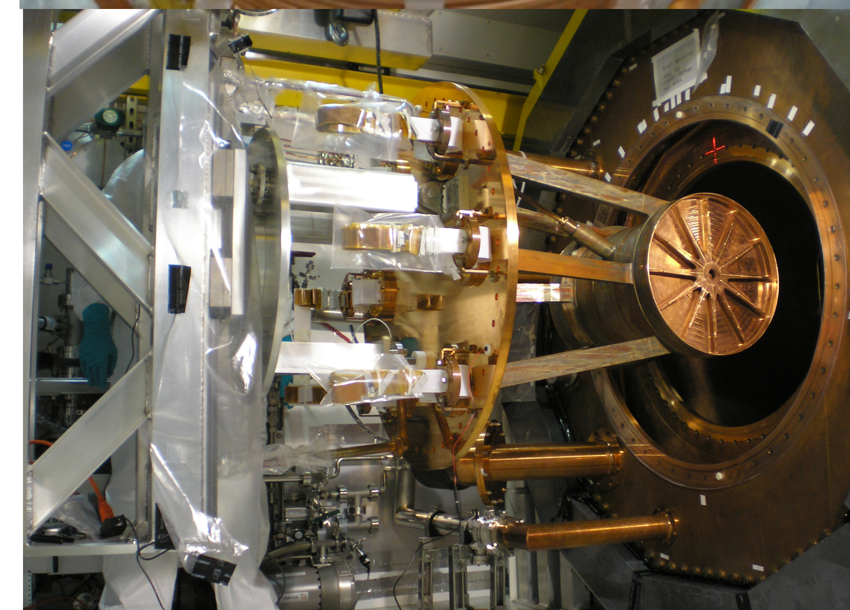
Source: arXiv::1109.6913v1

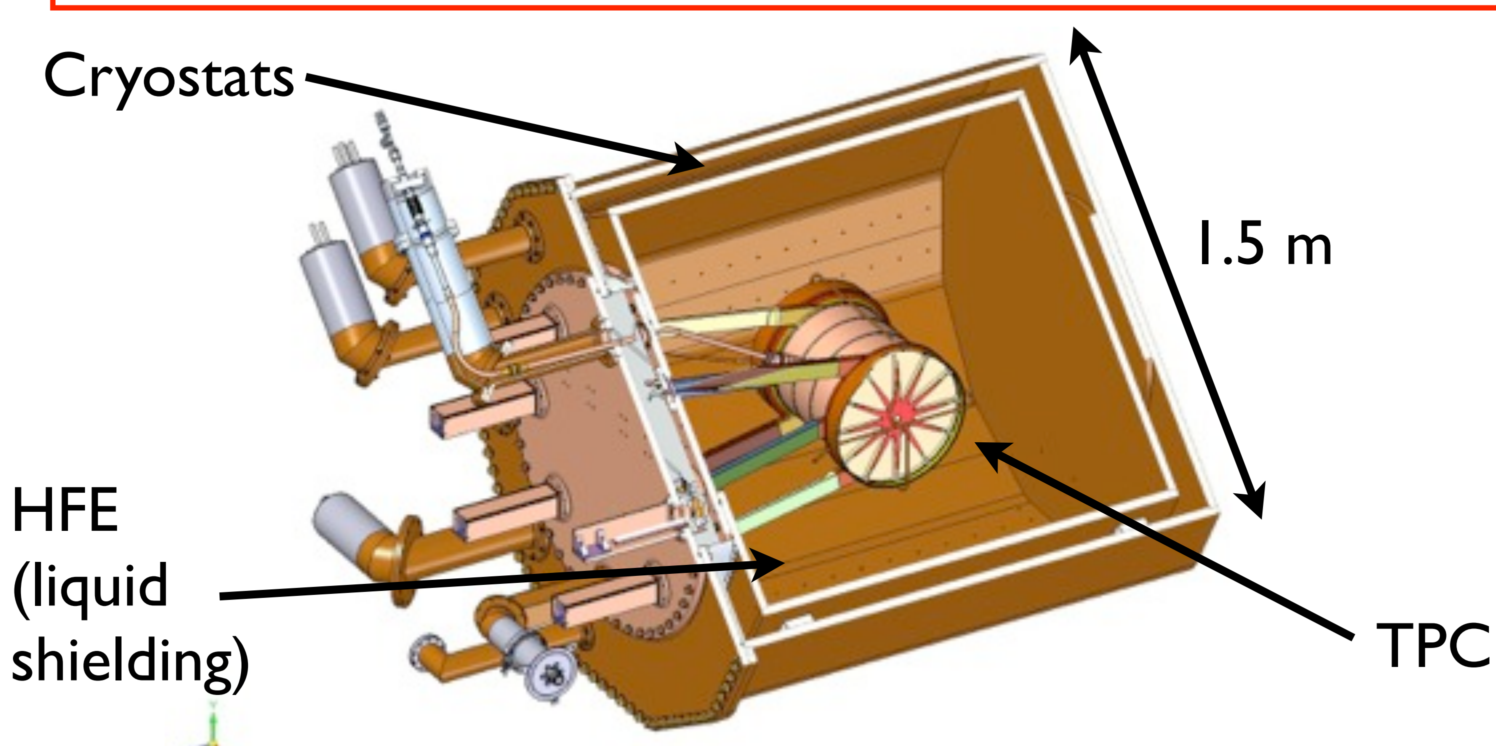
* Taken from slide by R. Martin, DBD 2011, Osaka

EXO-200

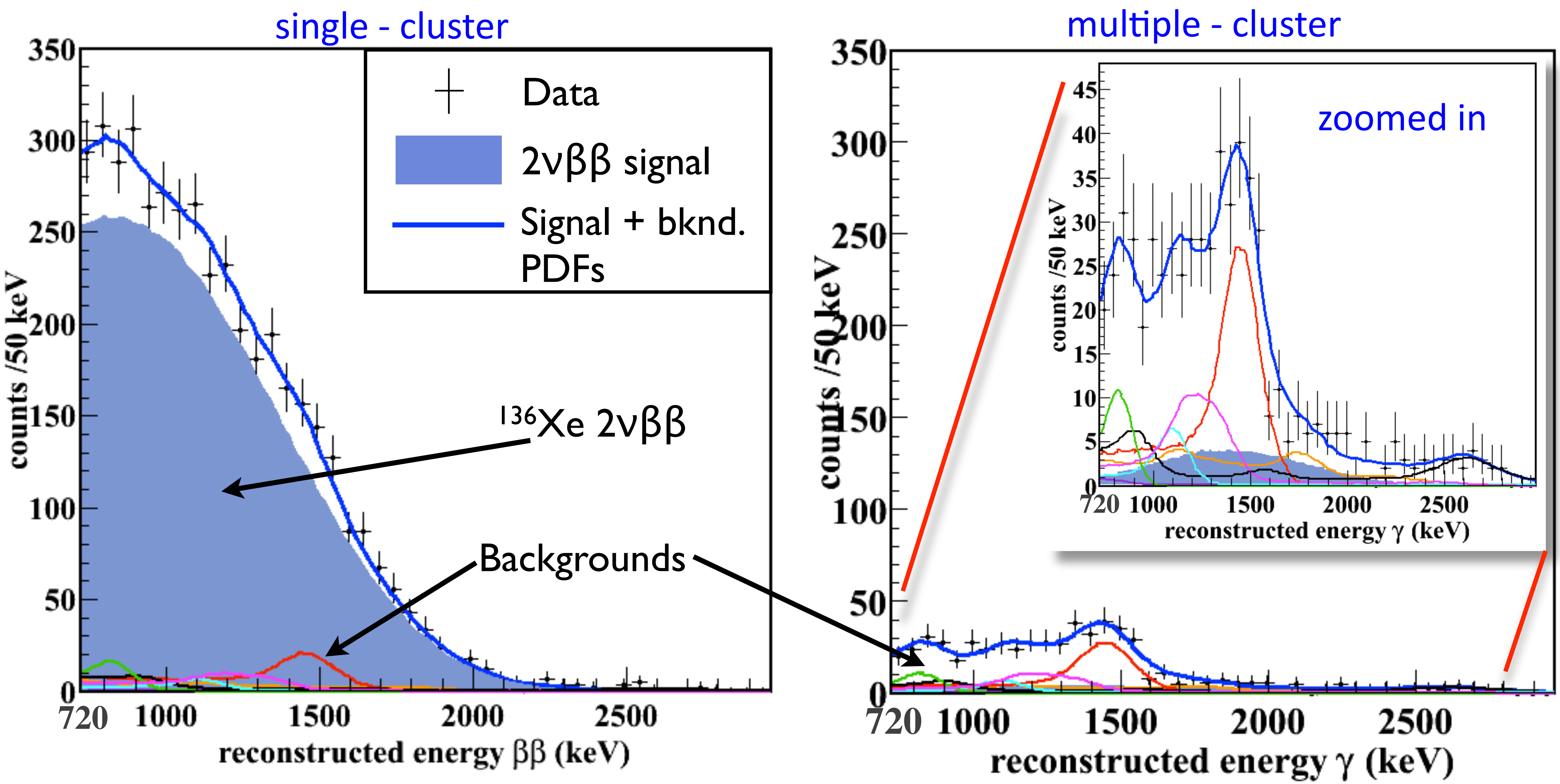
- ~150 kg liquid ^{136}Xe (81%) TPC, low background construction
- Detect ionization + scintillation
- Full 3D event reconstruction, 3D single/multi site discrimination
- Low activity Pb, ultra-clean liquid shielding
- Active μ-veto
- ***Taking data, Spring 2011***
  - First observation of $2\nu\beta\beta$ in ^{136}Xe, 31d data, PRL 107, 212501, 2011
  - 4e-3 c/kev/kg/yr demonstrated
  - 10 ms e- lifetime (110 μs drift time → charge losses negligible)







Recent observation of 2νββ in ^{136}Xe with EXO-200

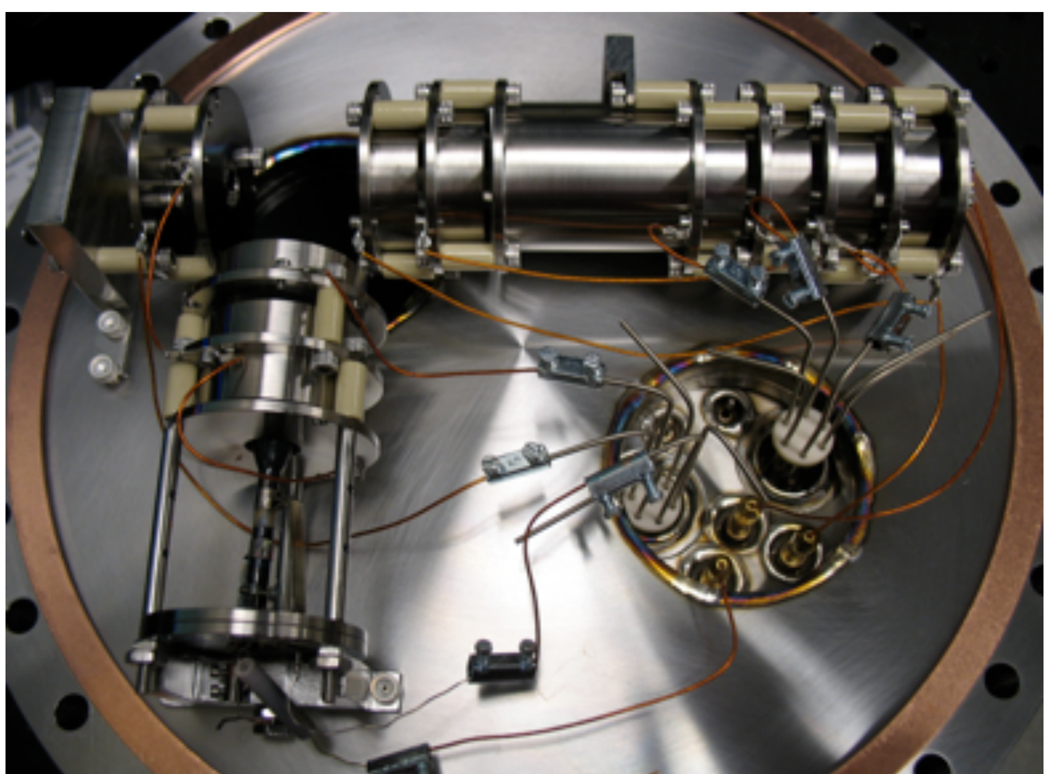


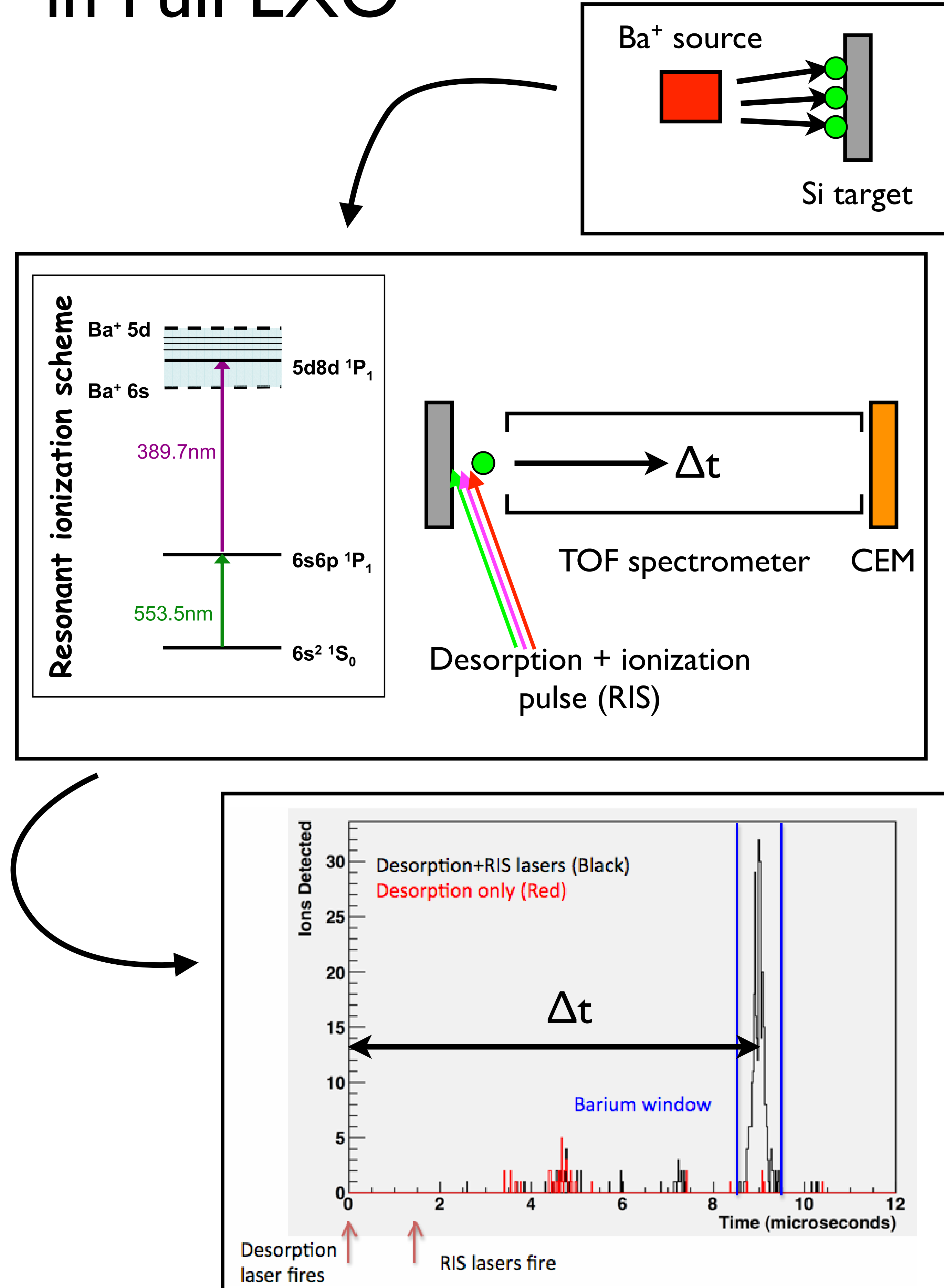
- 31 live-days of data
- 63 kg active mass
- Signal / Background ratio 10:1
  - -as good as 40:1 for some extreme fiducial volume cuts

$T_{1/2} = 2.11 \cdot 10^{21}$ yr (± 0.04 stat) yr (± 0.21 sys) PRL 107, 212501 (2011)

"Ba tagging" in Full EXO

- Identify 0νββ via final state nucleus spectroscopy (M. Moe, PRC44, 1991, 931)
- $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$
- ~ 2% efficiency obtained in lab with setup shown here
- More R&D required to assess viability
- DOE timeframe ~ 3 yrs





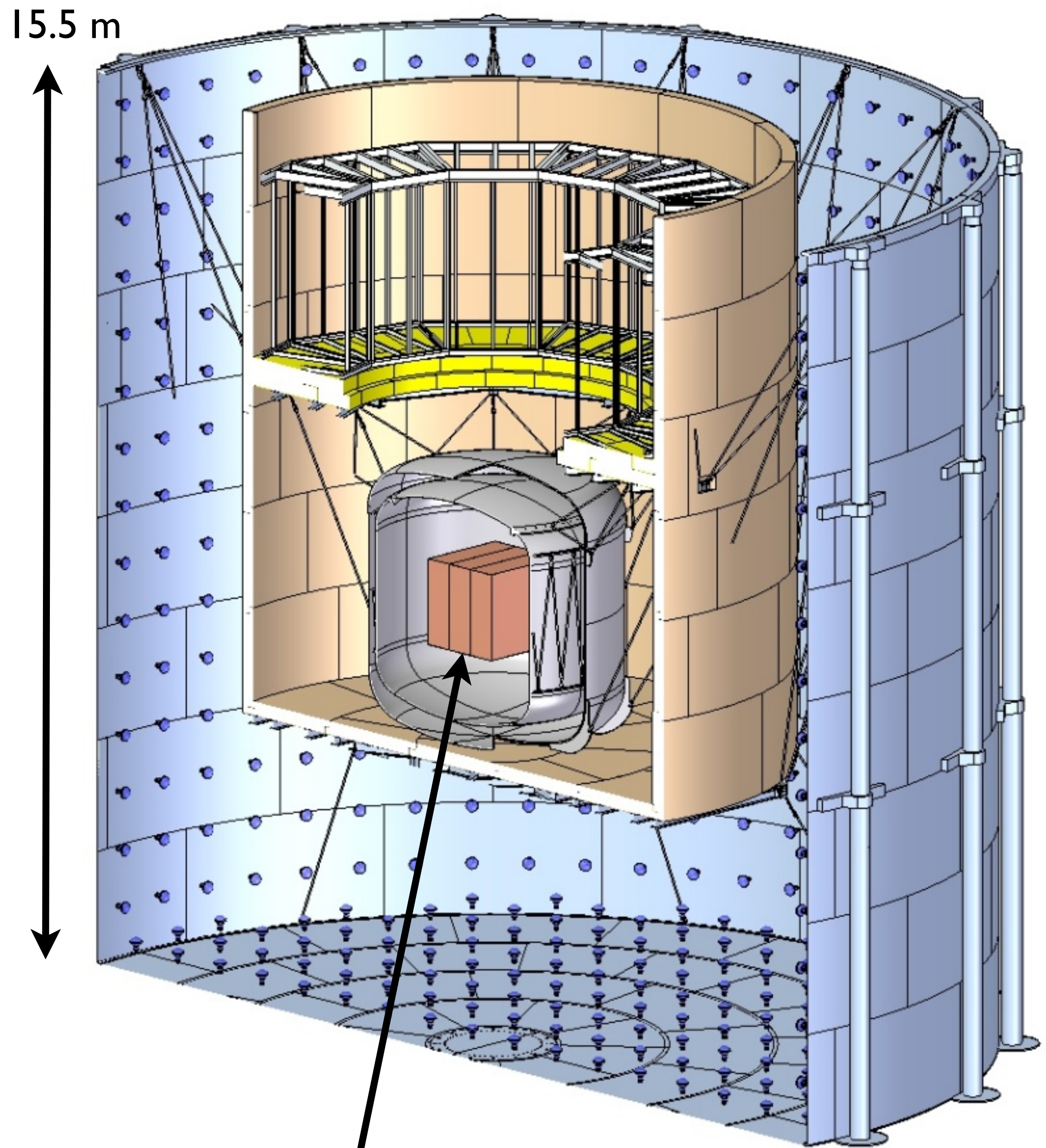
Full-EXO (2-10 ton)

- Conceptual design phase
- Current emphasis on Monte Carlo for background estimation and shielding planning
- Water or Pb shielding considered
- General ^{136}Ba tagging system interface
- Modular TPC design, max drift distance 25 cm
- **2-ton, 5-yr sensitivity 2.8e27 yr (90% CL)**
- **10-ton, 10-yr sensitivity 3.4e28 yr (90% CL)**

Assumptions:
1) 80% enrichment in 136
2) 68% overall efficiency:
   95% energy cut * 80% tracking effic * 90% lifetime fraction from EXO-200 analysis
3) Intrinsic low background + Ba tagging eliminate all radioactive background
4) Energy res only used to separate the 0ν from 2ν modes:
   Select 0ν events in a ±2σ interval centered around the 2457.8 keV endpoint
5) Use for 2νββ $T_{1/2}=2.11\cdot10^{21}$yr (Ackerman et al. arXiv:1108.4193, 21 Aug 11)

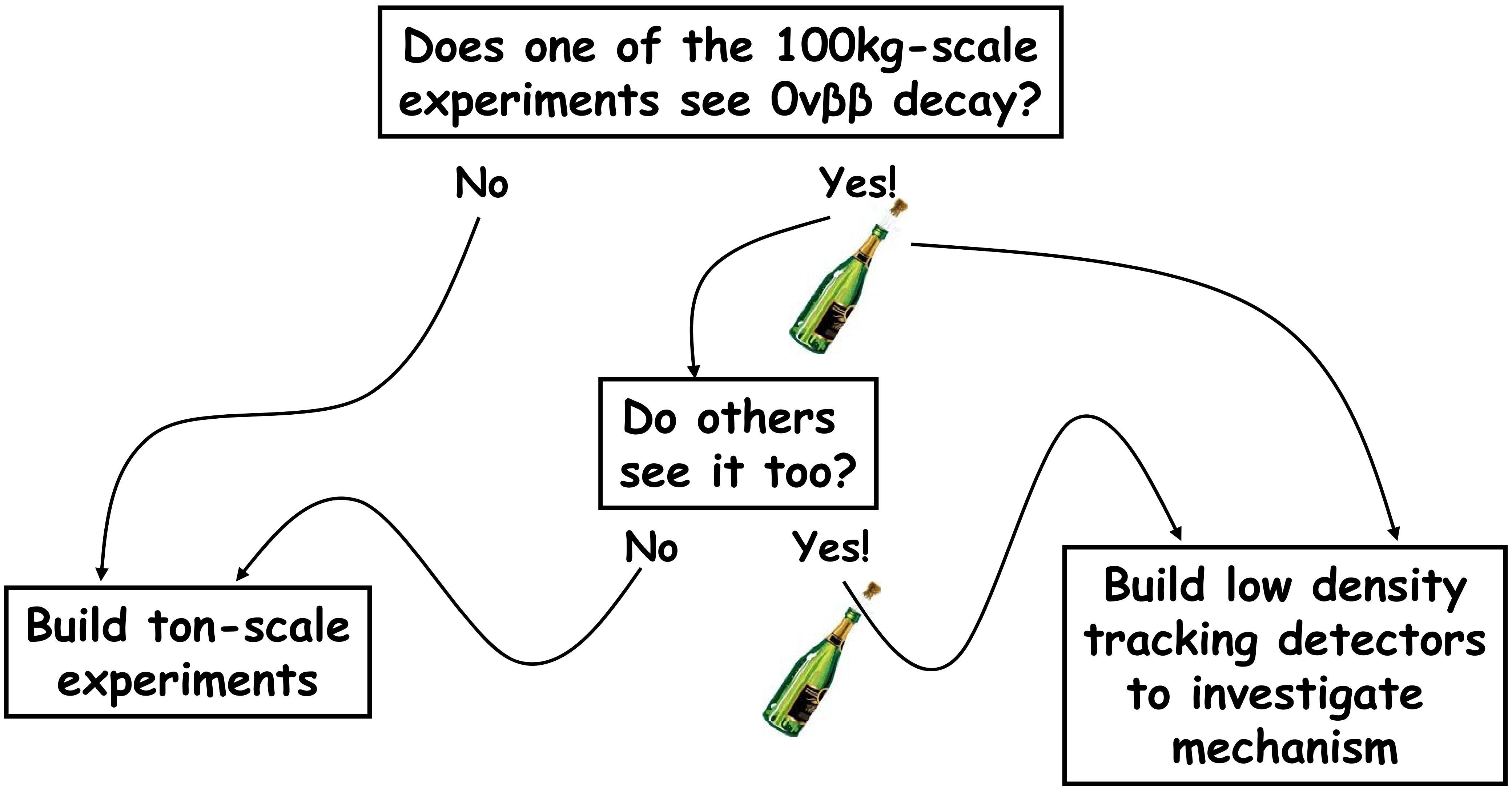
Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	2νββ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA‡	Majorana mass (meV) NSM#
Conservative	2	68	5	1.6*	5.0	2.8×10^{27}	16	20
Aggressive	10	68	10	1†	3.4	3.4×10^{28}	4.7	5.8

* σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
† σ(E)/E = 1.0% considered as an aggressive but realistic guess with large light collection area
‡ F.Simkovic et al., *Phys. Rev.* C79, 055501 (2009)
\# Menendez et al., *Nucl. Phys.* A818, 139 (2009)



3x 3-ton modules
50 cm x 150 cm x 160 cm

A $0\nu\beta\beta$ roadmap



- Multiple isotopes and detector technologies required
- Innovative techniques needed to improve our discovery potential
- We have to be flexible with our future roadmap

The MAJORANA Collaboration

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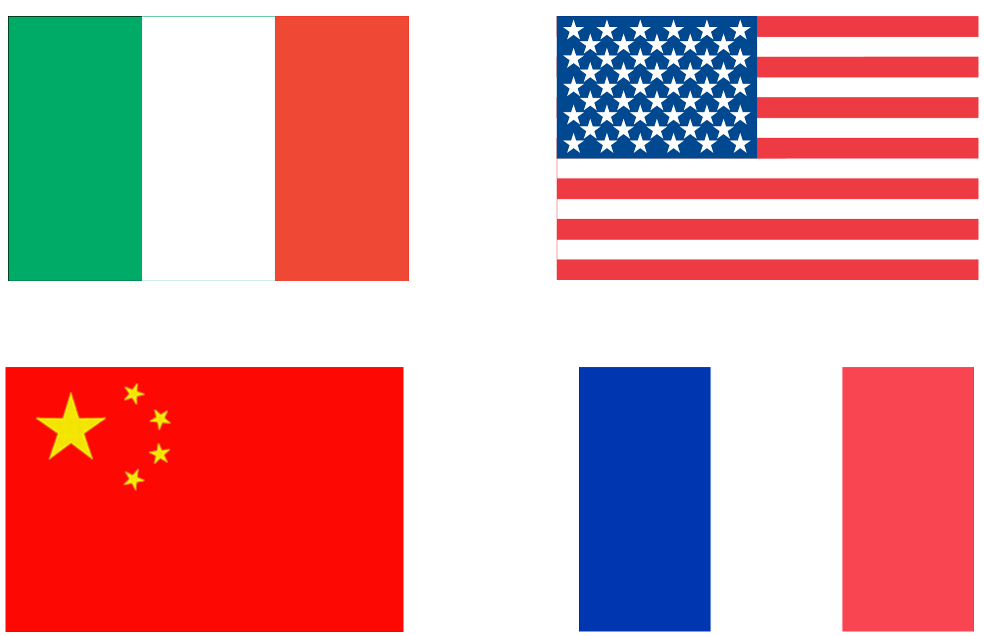
Students in red

CUORE Collaboration



The EXO Collaboration

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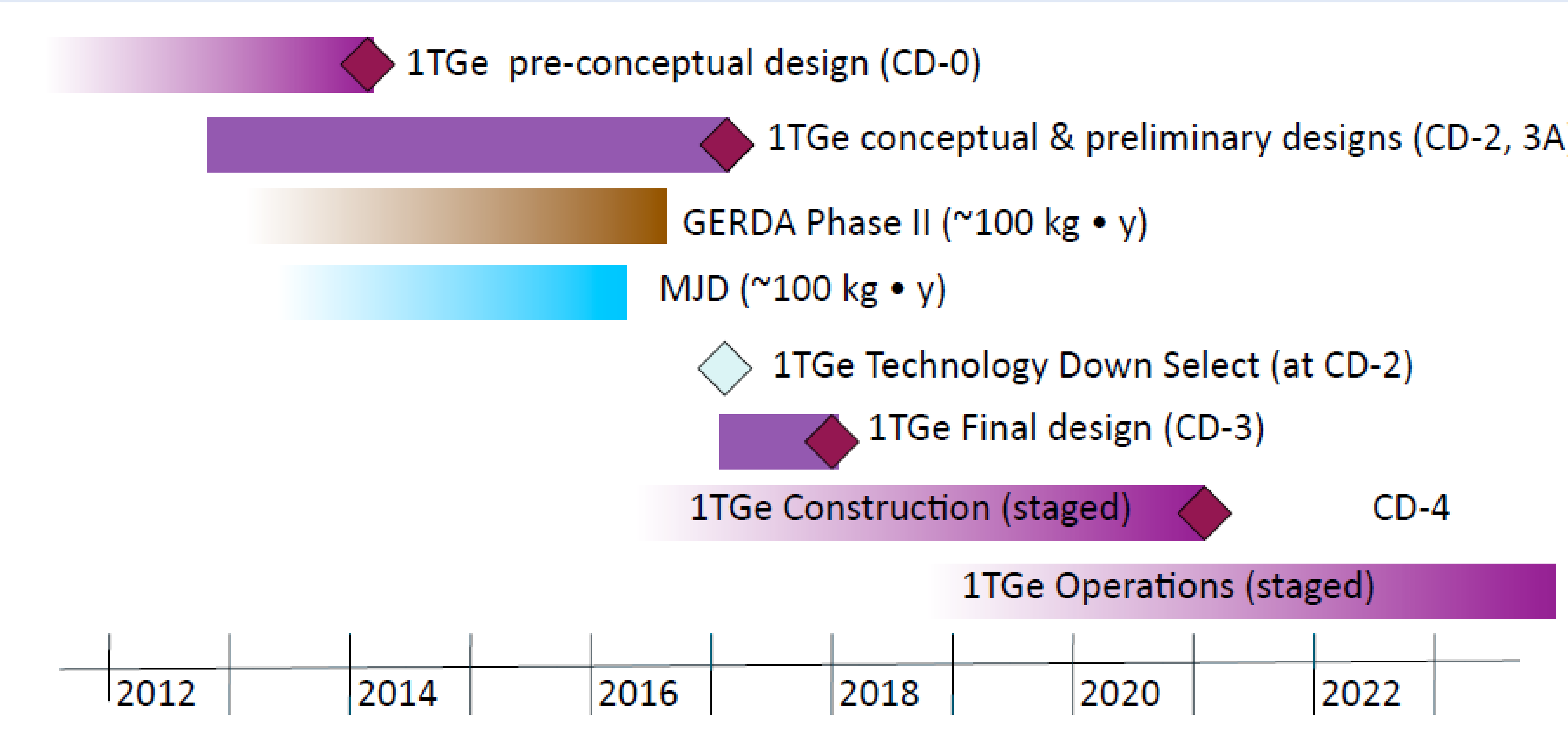
BACKUP AND REFERENCE

Tonne-scale schedule



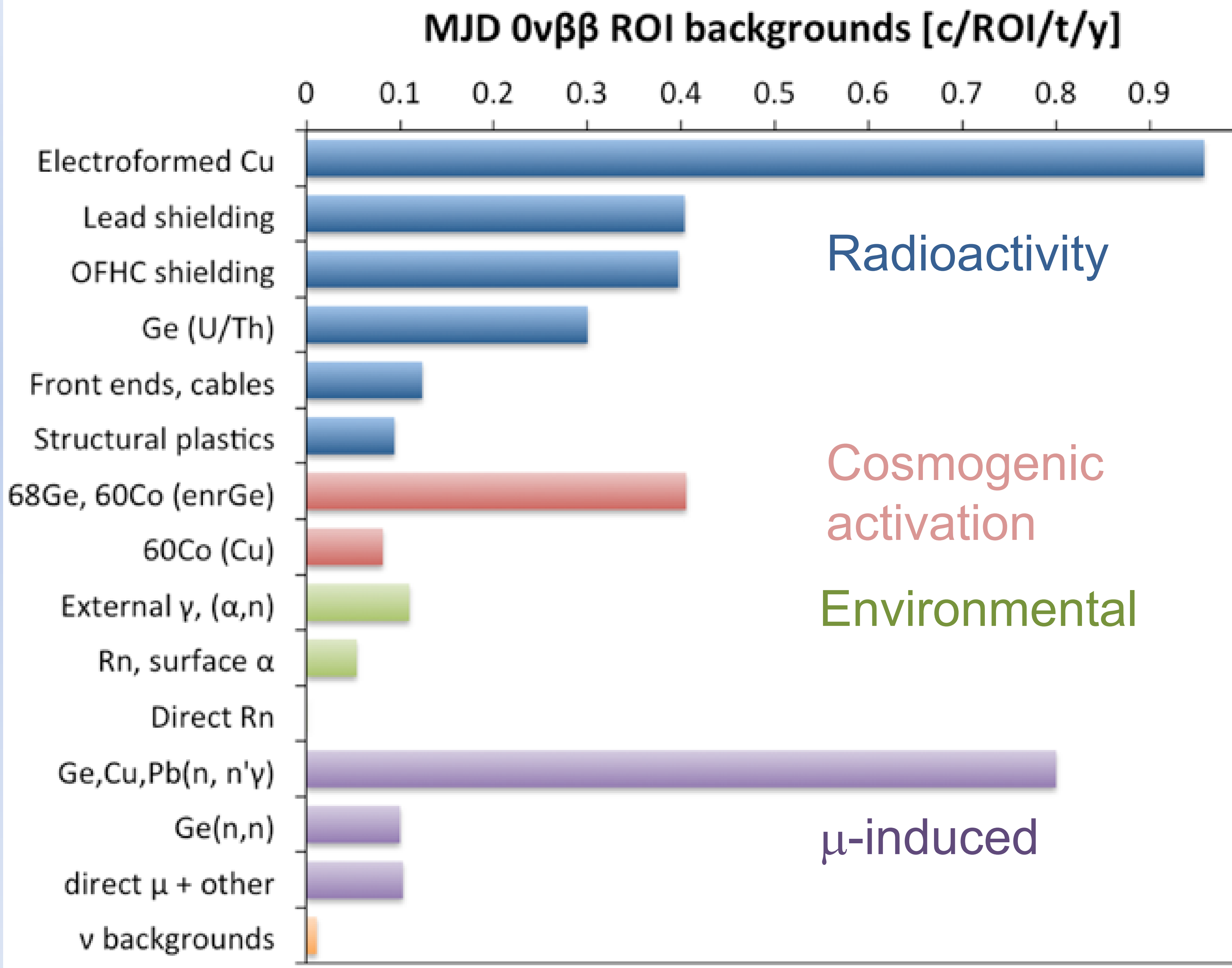
- Technology selection will be based on outcome of R&D and results from MJD and GERDA

Slide courtesy Tom Banks, DBD 2011, Osaka

Slide courtesy R. Martin, DBD 2011, Osaka

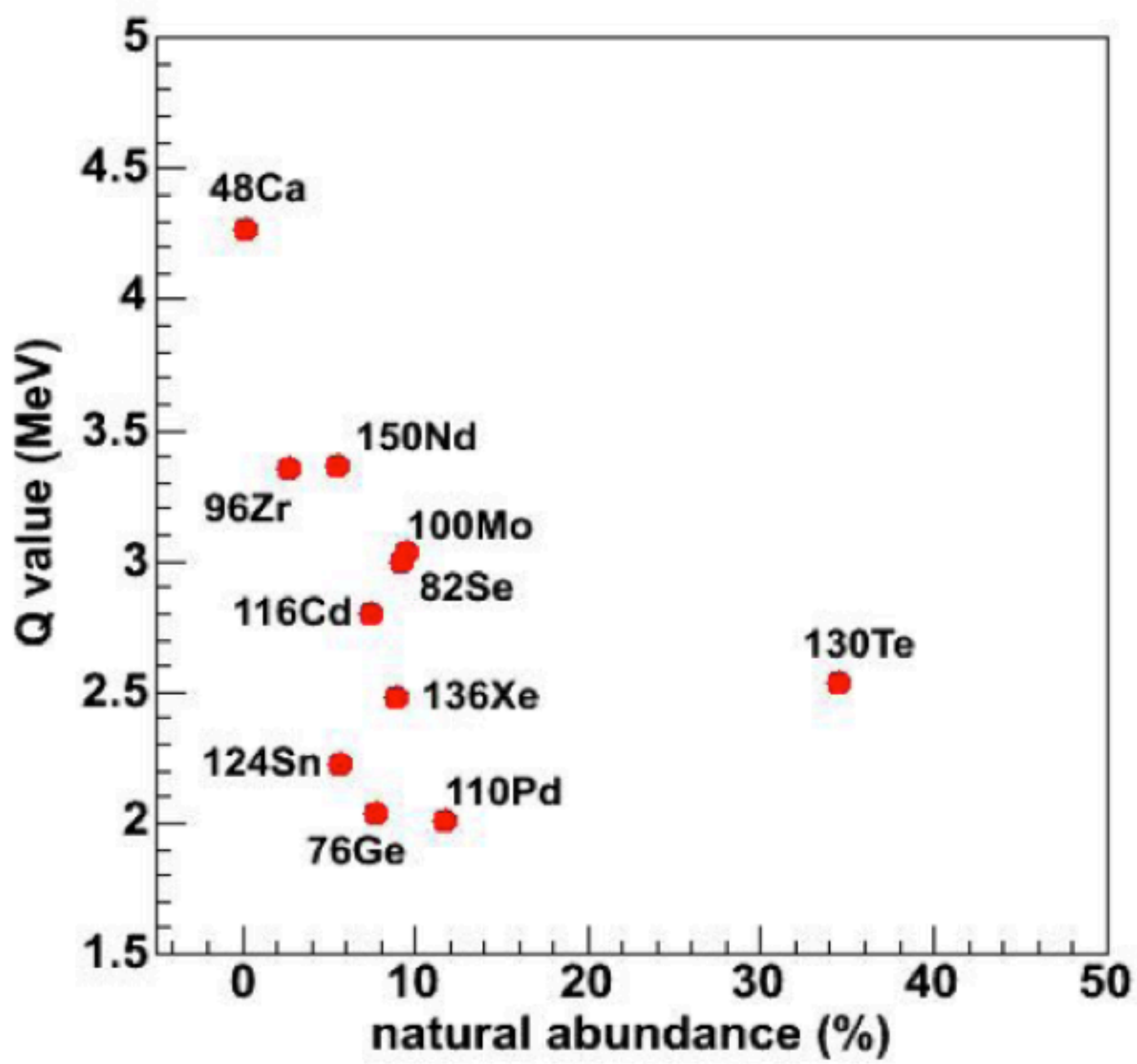
MJD Background Model

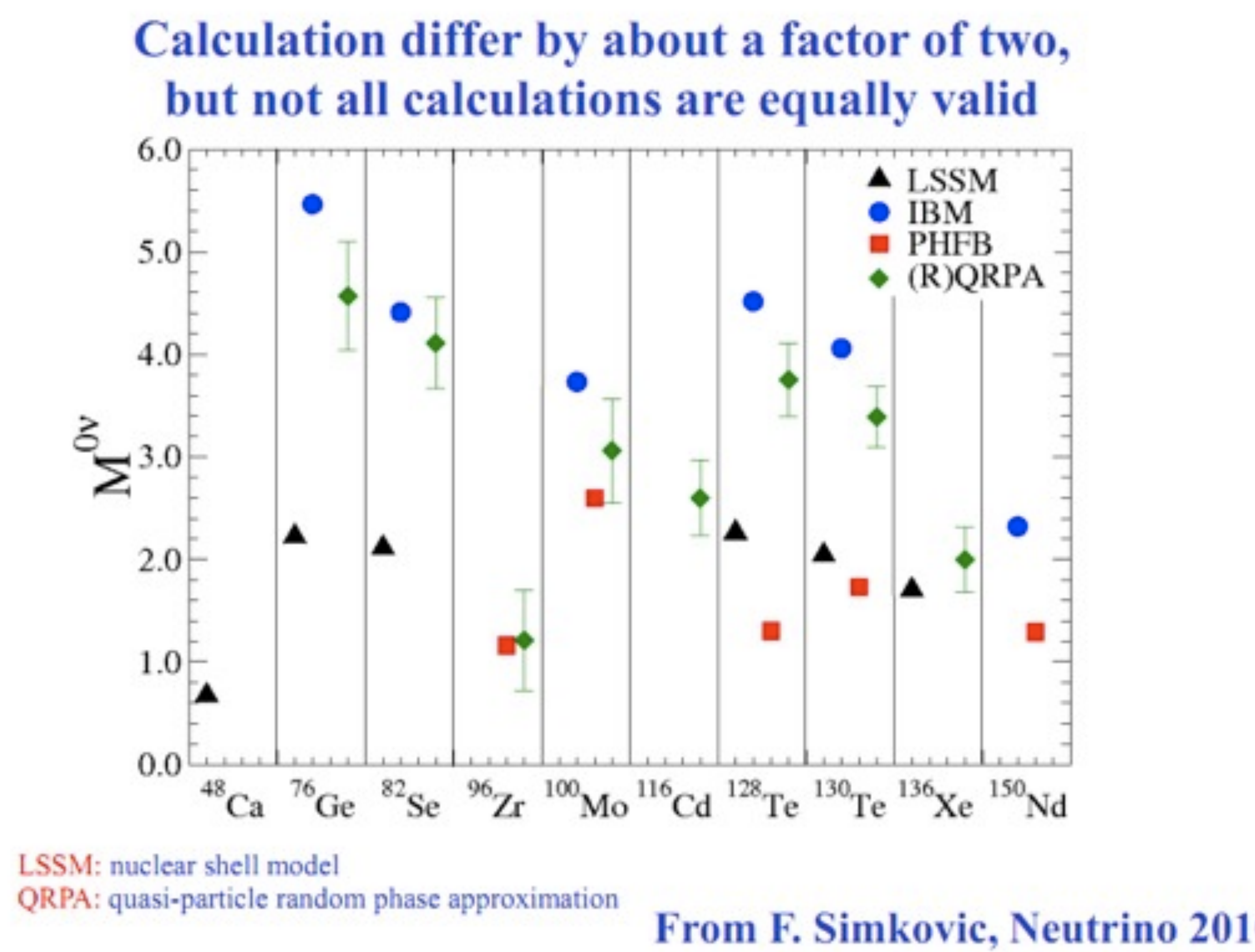
- Detailed background model produced
- Based on previous assays and reasonable expectations
- Expect 4c/t/y/ROI in MJD
- Translates to 1c/t/y/ROI for tonne-scale experiment:
  - More self-shielding
  - Longer cooldown for ^{68}Ge
  - Deeper (or improved shielding)



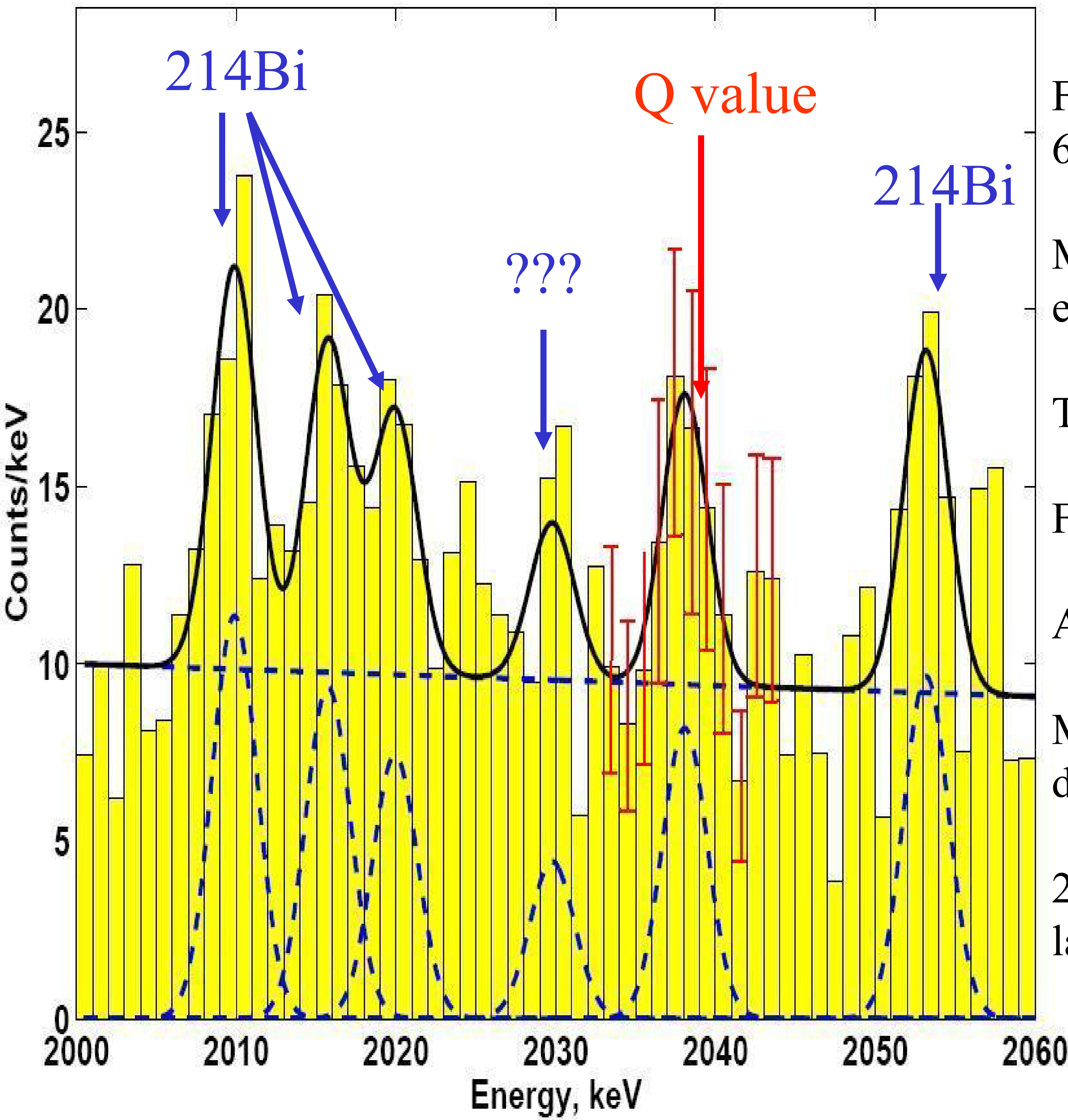
Ryan Martin, The Majorana Demonstrator 31

Q values, abundances, and matrix elements





ββ0ν discovery claim - 2004



Fit model:
6 gaussians + linear background.

Mean, width and intensity of each gaussian floats in the fit.

Total of 20 free parameters.

Fit intensity @ $Q_{\beta\beta}$ = 28.75   6.86.

Authors claim significance of 4.2 σ.

Mean value of ββ0ν candidate line displaced from $Q_{\beta\beta}$ by 2.1 σ.

214Bi intensity from fit is 2 – 2.5 σ larger than MC prediction.