Neutrinoless Double-Beta Decay

FPCP 2011
Kibbutz Maale Hachamisha, Israel
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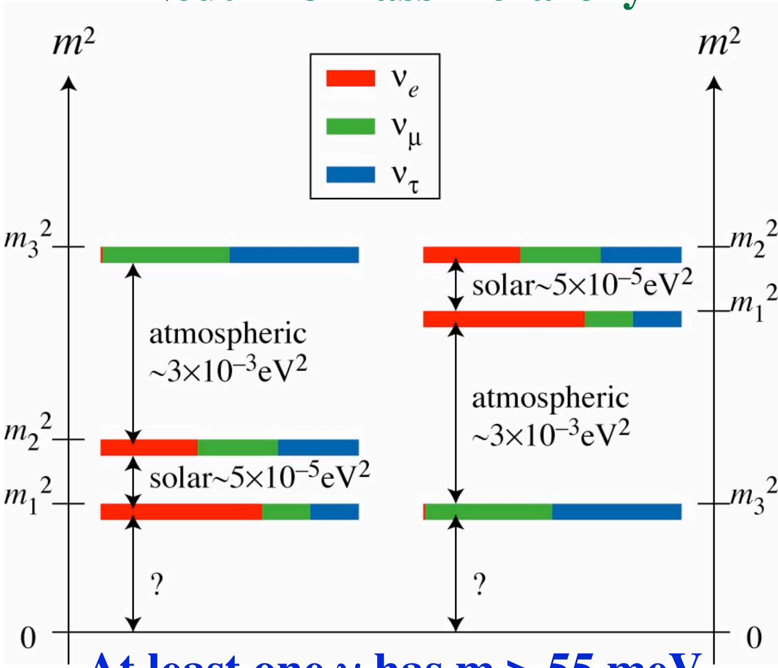
On Behalf of CUORE Collaboration

Neutrino Physics Landscape

Neutrino mass hierarchy

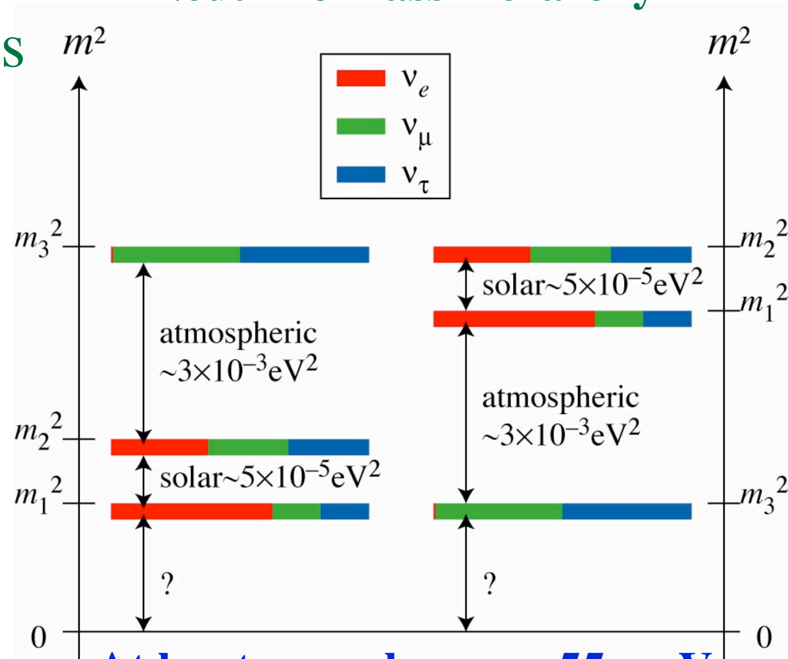


At least one ν has m > 55 meV

Neutrino Physics Landscape

- Compelling evidence for
  - Neutrino flavor-changing oscillations
  - (therefore) finite neutrino masses
  - Two of three mixing angles are very well measured

Neutrino mass hierarchy



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Neutrino Physics Landscape

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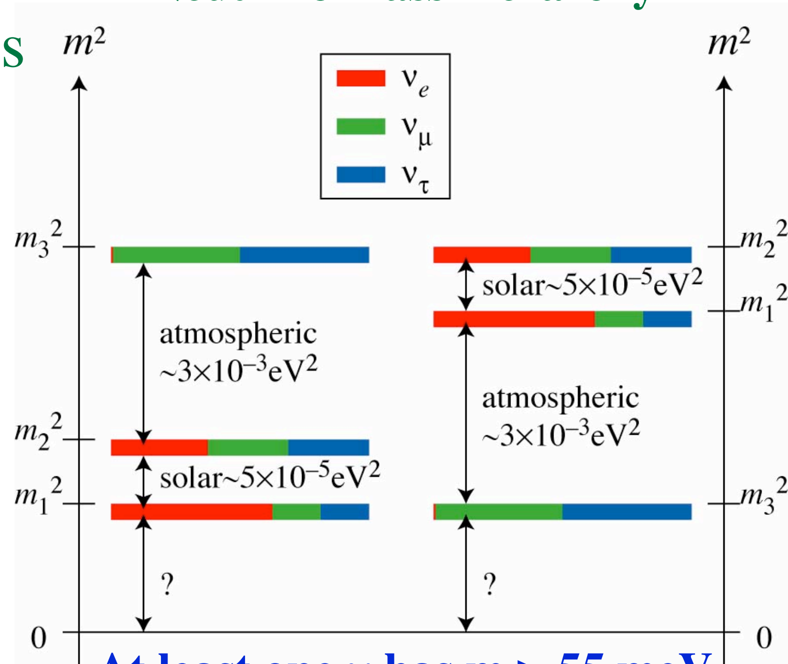
  - (therefore) finite neutrino masses
  - Two of three mixing angles are very well measured
- Open questions in ν Physics:
  - How many neutrinos?
    - ☞ Sterile neutrinos ?
  - CP violation in lepton sector ?
    - ☞ What is the magnitude of θ_{13} ?
  - What is absolute scale of ν mass ?
  - Majorana or Dirac neutrinos ?

Neutrino mass hierarchy



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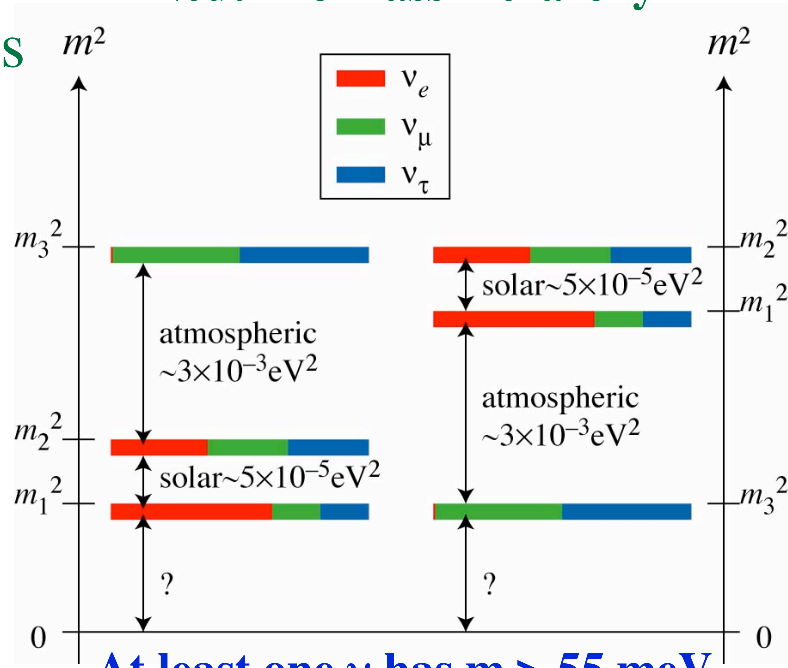
(See Boris' talk for more profound questions)

Neutrino mass hierarchy



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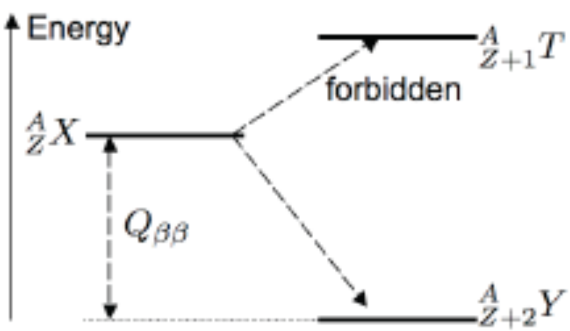
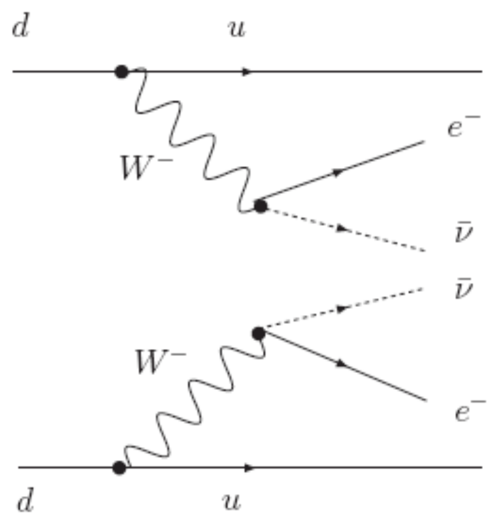
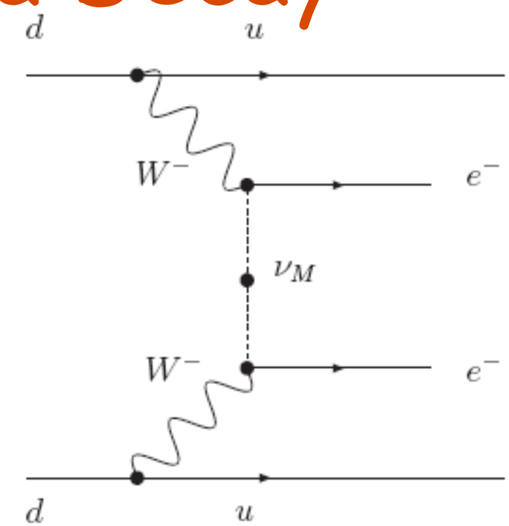




Standard Model 2νββ decay
$\tau \geq 10^{19}$ y



0νββ $\tau \geq 10^{25}$ y

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

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

0νββ Rate and Neutrino Mass

0νββ rate

Phase space ∝ Q^5

Nuclear matrix element

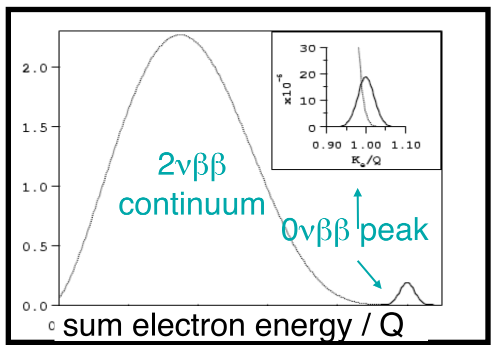
Effective neutrino mass

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

high Q candidates preferred

large phase space

low background



^{238}U γ end at 2.4 MeV

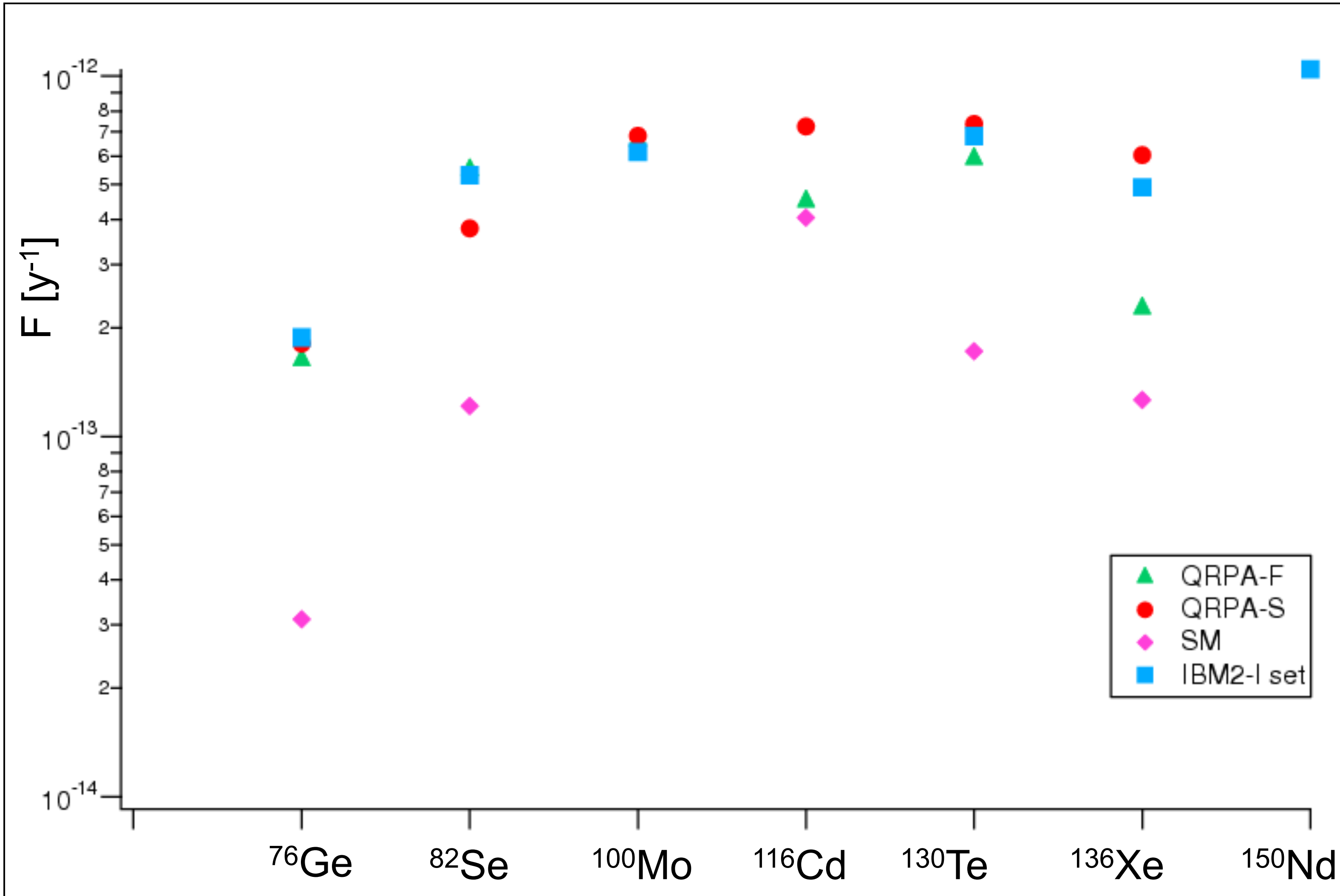
^{232}Th γ end at 2.6 MeV

[2039 keV (^{76}Ge) ⇔ 4271 keV (^{48}Ca)]

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

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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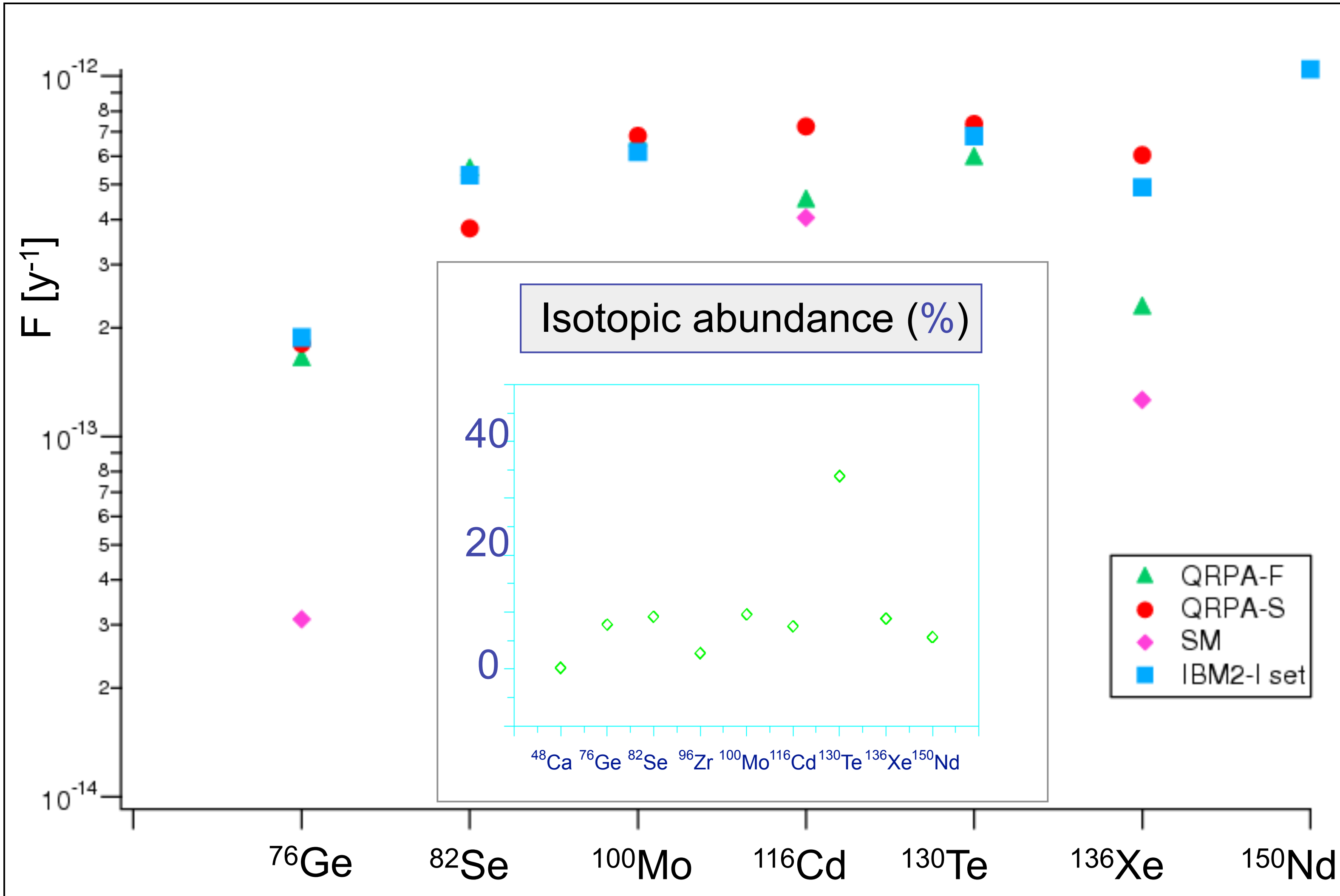


Experimental Sensitivity

Standard sensitivity for a counting analysis (nonzero background):

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.17\times10^{26}}{n_\sigma}\left(\frac{a\varepsilon}{W}\right)\sqrt{\frac{Mt}{(1+\zeta)b\delta(E)}}$$

Efficiency

Detector mass (kg)

Isotopic abundance

Exposure time (y)

Desired sensitivity in σ

ROI (keV)

Atomic weight

SNR (assume 0)

Background (c/kg/y/keV)

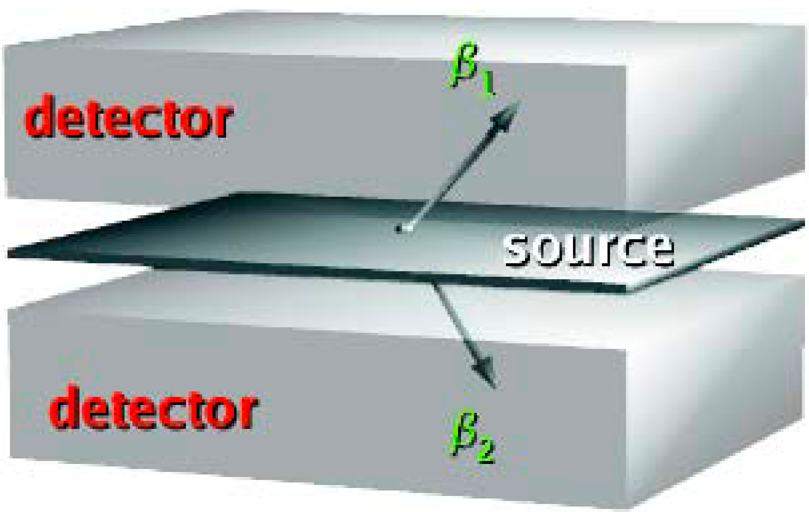
Experimental challenge:

- ✓ Increase *M* as high as possible (200-1000 kg for current experiments): $$, R&D
- ✓ Increase *a*: $$
- ✓ Decrease *b* as much as possible (to 2νββ limit): radio purity, active rejection
- ✓ Decrease δ (highest resolution possible): technology choice

Two Experimental Techniques

Source external to detector

Ex: NEMO, SuperNEMO, others



+: event topology, background rejection, multiple isotopes possible

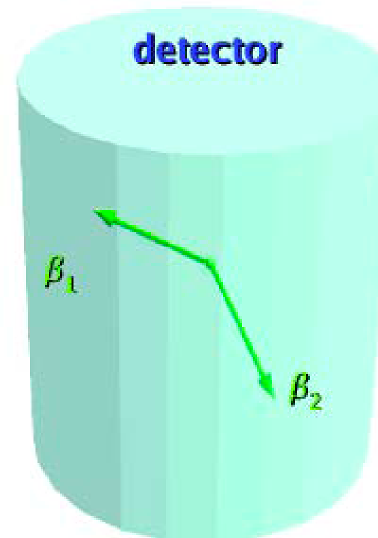
–: detector mass, resolution, acceptance

Technology: typically tracking detectors

May prove invaluable to test models once $0\nu\beta\beta$ is discovered

Source internal to detector

Ex: Gerda, Majorana, EXO, CUORE, SNO+, KamLAND-Zen, and others



+: detector mass, resolution, acceptance

–: event topology, background rejection

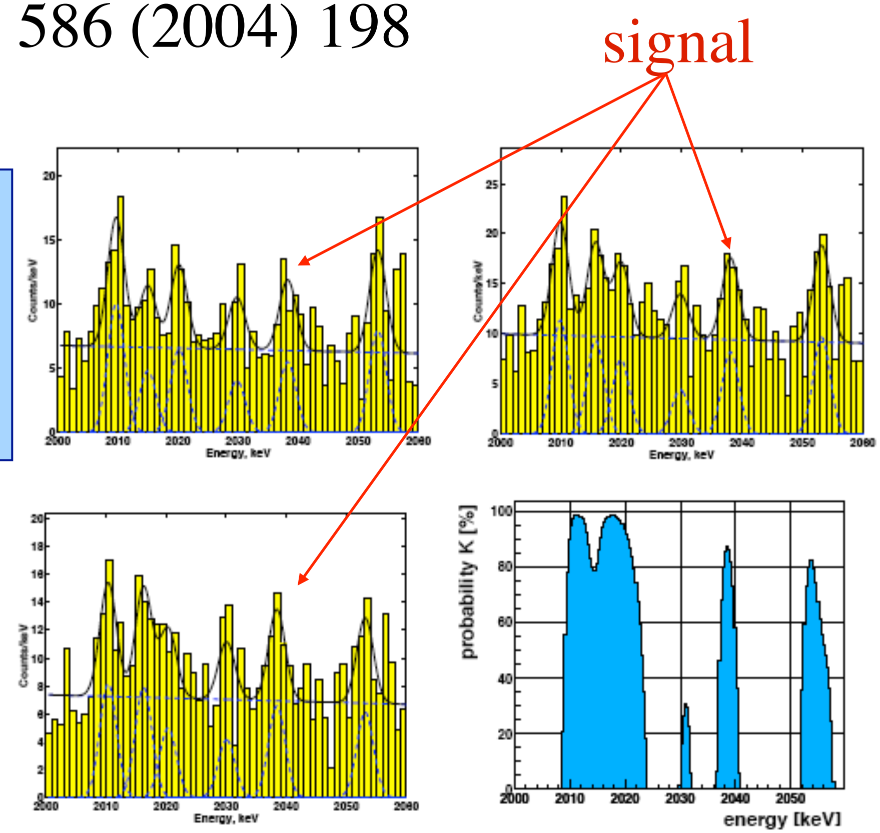
Technology: calorimeters (bolometers, ionization, scintillation), tracking

Typically aimed at $0\nu\beta\beta$ discovery

Possible Evidence: Klapdor et al

- Heidelberg-Moscow Ge experiment
  - 11 kg of enriched ^{76}Ge, 72 kg*y exposure
  - Fraction of the collaboration (KKDC) claim discovery
    - ☞ Klapdor et al., Phys. Lett B 586 (2004) 198

$T = (0.7 - 4.2) \times 10^{25}$ years (3σ C.L.)
$m_{\beta\beta} = (0.2 - 0.6)$ eV (3σ C.L.)
$m_{\beta\beta\ best} = 0.28$ eV
4.2σ claim



Intriguing, but not universally accepted…

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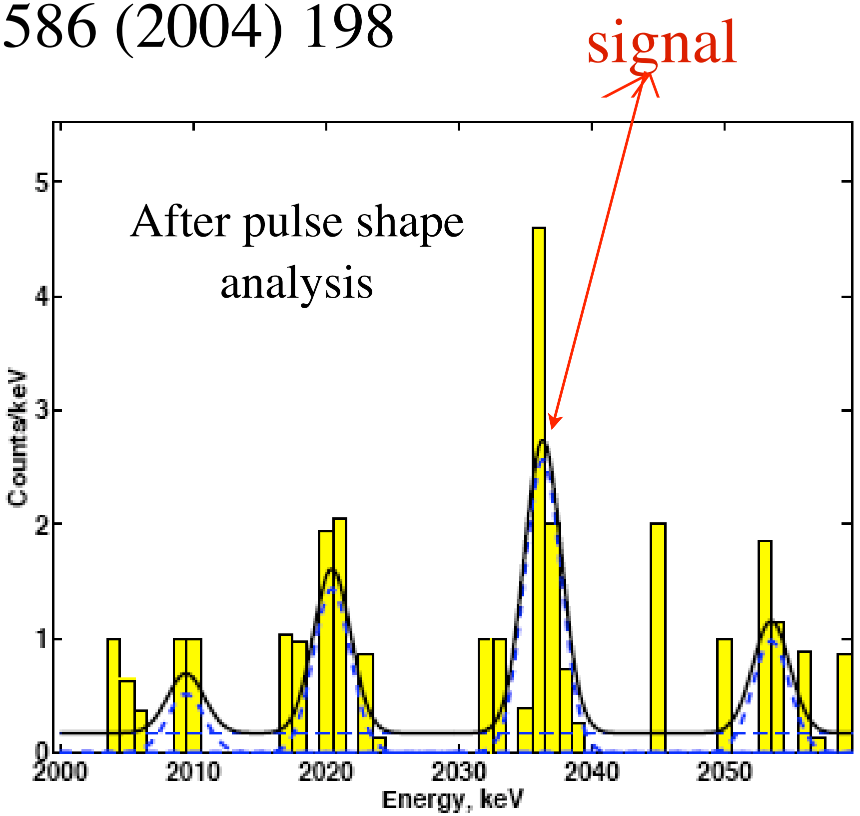

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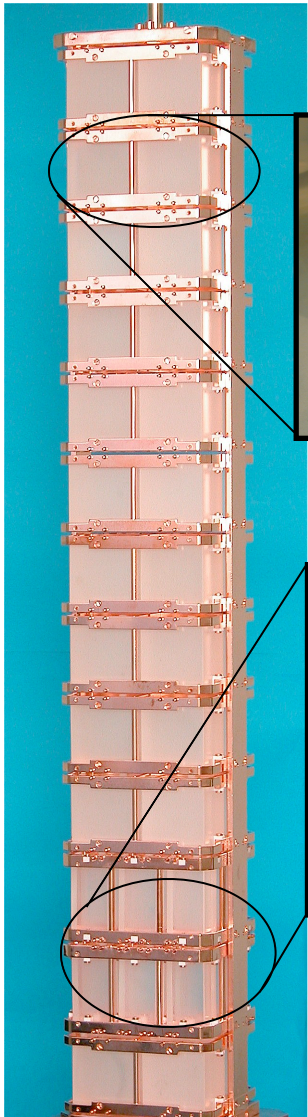
Search for Double-Beta Decay

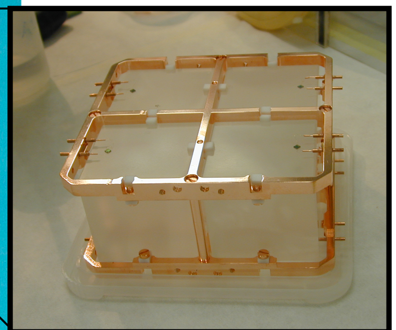
- $0\nu\beta\beta$ is one of the top priorities in neutrino physics
  - ❑ Multiple experiments, variety of techniques
- Present: ~10 kg active mass ($m_{\beta\beta}$ ~ 300–700 meV)
  - ❑ Hidelberg-Moscow, Cuoricino, NEMO
- Near term: ~200 kg active mass ($m_{\beta\beta}$ ~ 50–100 meV)
  - ❑ Address KKDC claim
    - ☞ Different isotopes: reduce sensitivity to nuclear matrix elements
    - ☞ Different methods (tradeoffs of background, resolution, efficiency)
  - ❑ In case of negative result
    - ☞ Rule out the degenerate hierarchy
    - ☞ Explore inverse hierarchy
- Near-term upgrades: ~1 ton detectors ($m_{\beta\beta}$ ~ 20–50 meV)
  - ❑ Perhaps combined with Dark Matter experiments
  - ❑ In case of negative result
    - ☞ Rule out inverse hierarchy
    - ☞ Or (if oscillation experiments confirm inverse hierarchy) prove Dirac nature of neutrinos
- Longer term: aim for normal hierarchy ($m_{\beta\beta}$ ~ 5 meV)
  - ☞ Multi-ton detectors, low backgrounds: requires substantial R&D

Cuoricino, the prototype for CUORE



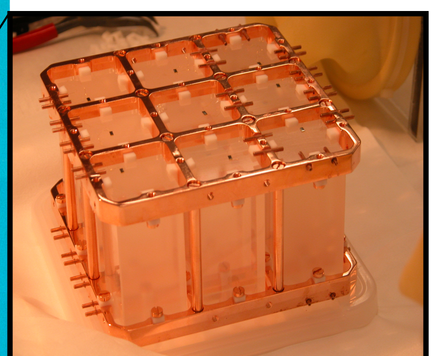
Gran Sasso National Lab (Italy)

Bolometer detectors
Cooled to 10mK



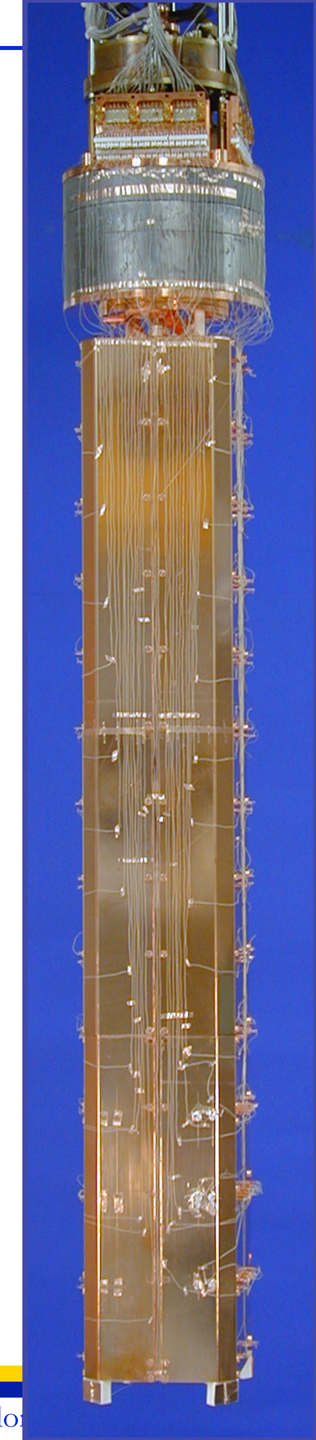
11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 790 g
44 x 0.79 = 34.76 kg of TeO_2

Encased in a cryostat, lead shield, nitrogen box, neutron shield, and Faraday cage



2 modules x 9 crystals each
crystal dimension: 3x3x6 cm^3
crystal mass: 330 g
18 x 0.33 = 5.94 kg of TeO_2

Total detector mass: 40.7 kg TeO_2 ⇒ **11.34 kg ^{130}Te**

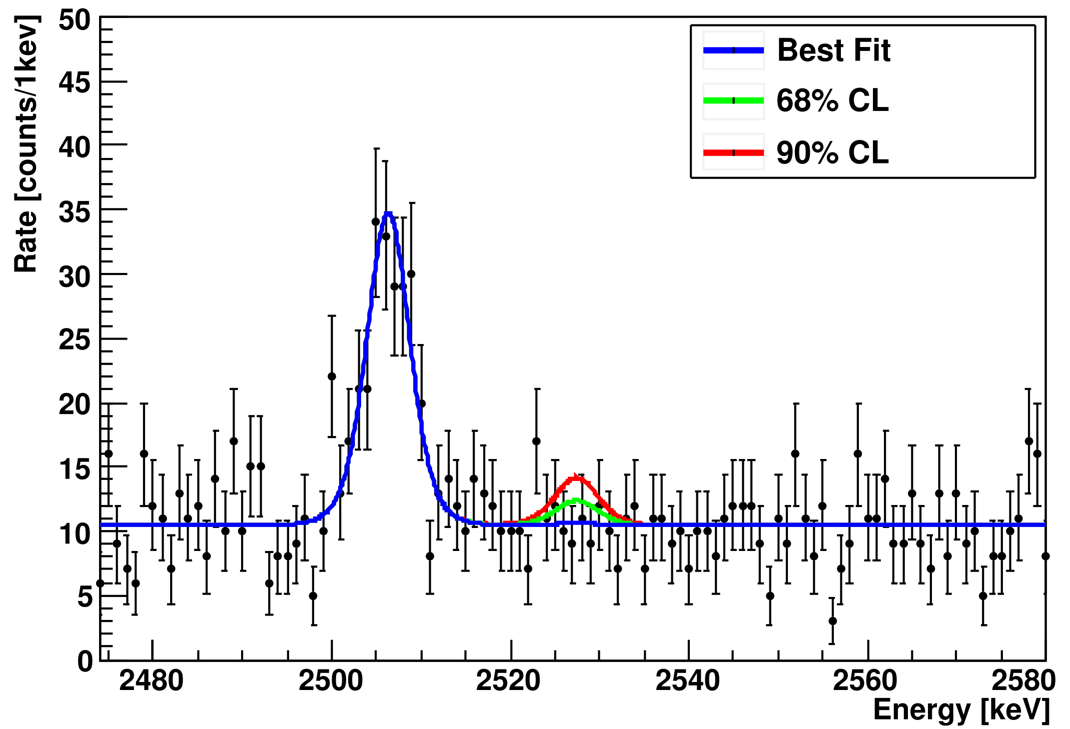


Cuoricino Results (2010)

Exposure
= 19.6 kg y

Resolution:
FWHM at 2615 keV ~7 keV

Background:
In the $\beta\beta0\nu$ region (large crystals)
= 0.153 ± 0.006 counts /(keV kg y)



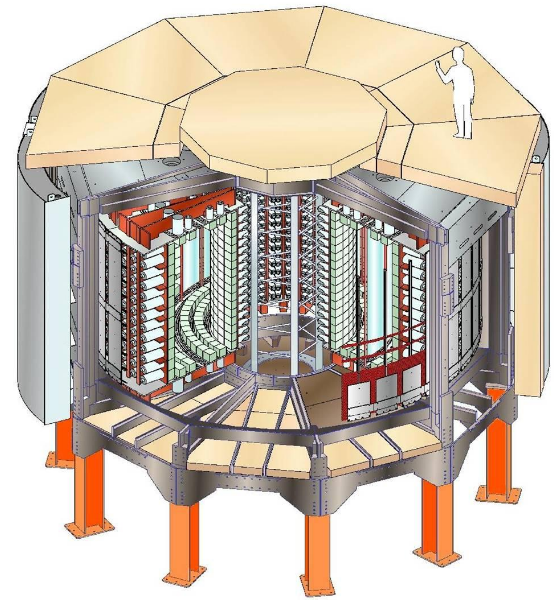
E. Andreotti et al., Astr. Phys. **34**, 822 (2011)

No peak found
$\tau^{0\nu}_{1/2} > 2.8\times10^{24}$ y at 90% C.L.
$m_{\beta\beta} < 0.3 - 0.7$ eV

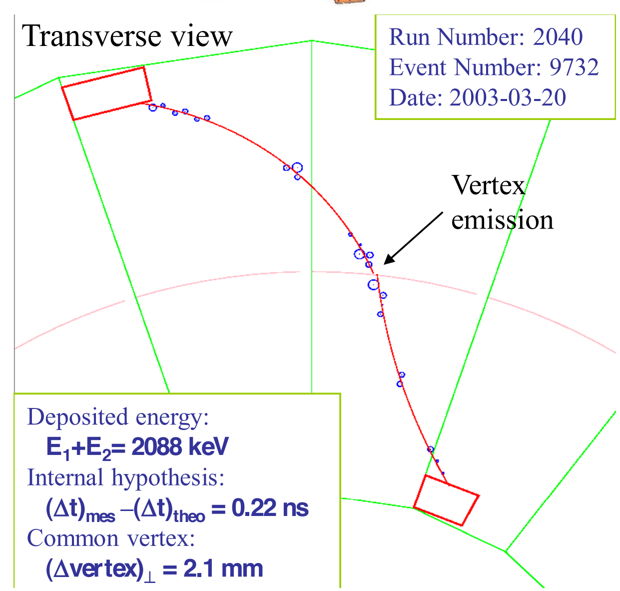
Spread is due to a range of published matrix elements

NEMO-3

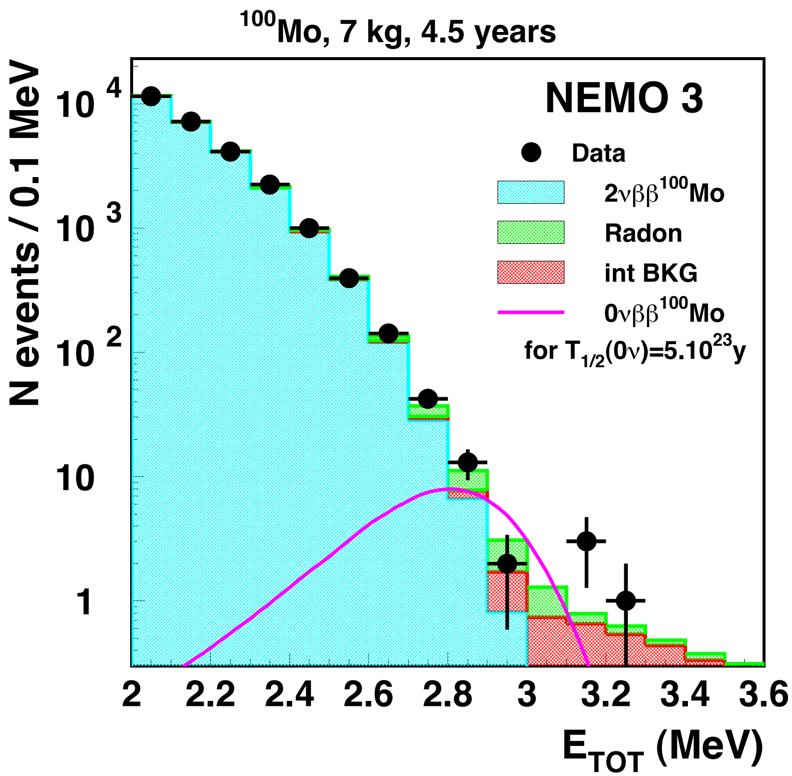
Frejus Underground Lab (France)

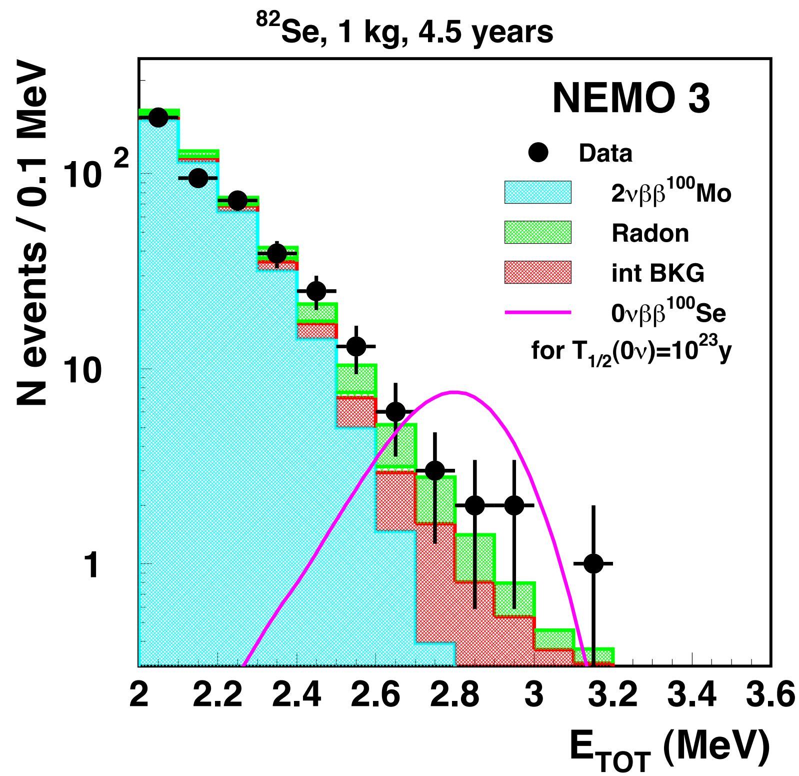


- Source: ~10 kg of ββ isotopes
  - cylindrical foils (20 m²)
    - ☞ Measure 2νββ decays and search for 0νββ
- Tracking detector
  - Drift chamber operating in Geiger mode
    - ☞ He+4%alcohol+1% Ar
- Calorimeter: plastic scintillator, low-activity PMTs
- 25 Gauss magnetic field
  - ☞ Ability to identify γ, α, β+, β-
  - ☞ Low background (except for 2νββ → 0νββ)
  - ☞ Reconstruct decay kinematics: sensitivity decay dynamics
  - ☞ But: ΔE/E ~8% @ 3 MeV (FWHM)



NEMO-3 Results





[2.8-3.2] MeV: 18 evts (data) vs 16.4±1.4 (MC)

$\tau^{0\nu}_{1/2}>1.0\times10^{24}$ years @ 90% C.L.

$m_{\beta\beta}<(0.47-0.96)$ eV

[2.6-3.2] MeV: 14 evts (data) vs 10.9±1.3 (MC)

$\tau^{0\nu}_{1/2}>3.2\times10^{23}$ years @ 90% C.L.

$m_{\beta\beta}<(0.9-2.5)$ eV

Plus measurements of $2\nu\beta\beta$ lifetimes for 7 isotopes Phys. Rev. C 80, 032501 (2009)

Planned Experiments

- Four complementary approaches, multiple isotopes
  - High-resolution calorimeters (source=detector)
    - Bolometers: CUORE (^{130}Te)
    - Ionization: GERDA (^{76}Ge), MAJORANA (^{76}Ge), COBRA (^{130}Te, ^{116}Cd)
  - Tracking detectors (source=detector)
    - Liquid Xe or high-pressure gas TPC: EXO-200, NEXT (^{136}Xe)
  - Tracking detectors (source≠detector)
    - SuperNEMO, MOON, DCBA
  - DBD-loaded scintillators (source=detector)
    - SNO+ (^{150}Nd), KamLAND-Zen (^{136}Xe), XMASS (^{136}Xe), CANDLES (^{48}Ca)
- Will describe the most developed project next

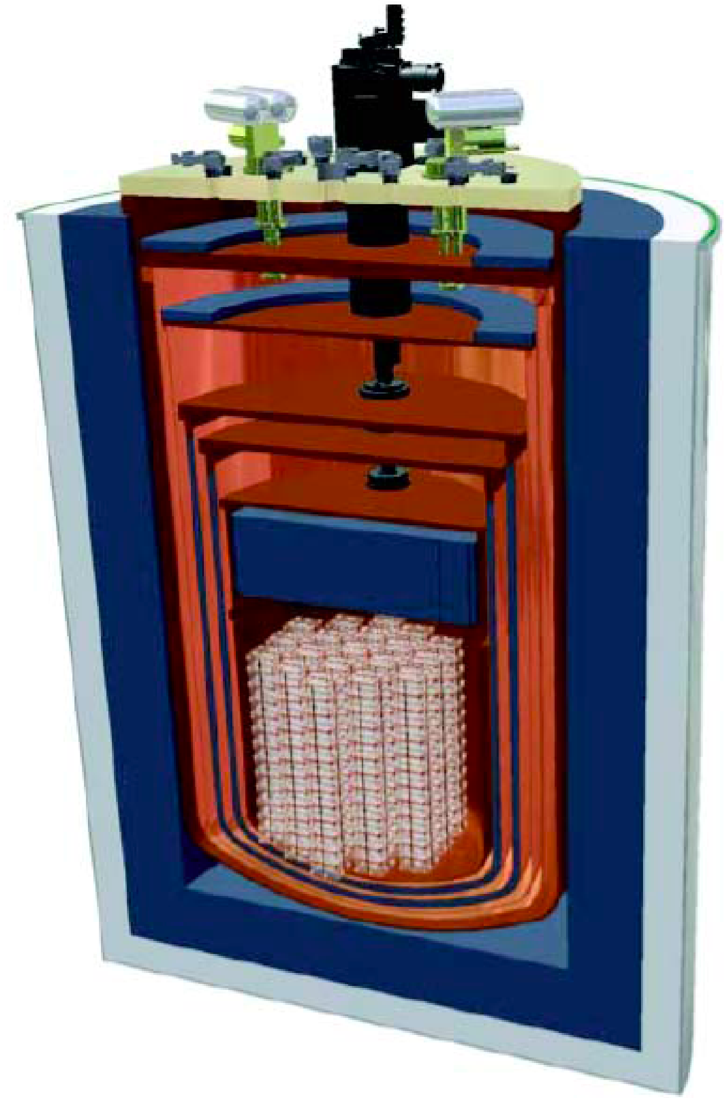
CUORE

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: 33.8% natural isotope abundance

750 kg TeO_2 => 200 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 completion by end of 2013)



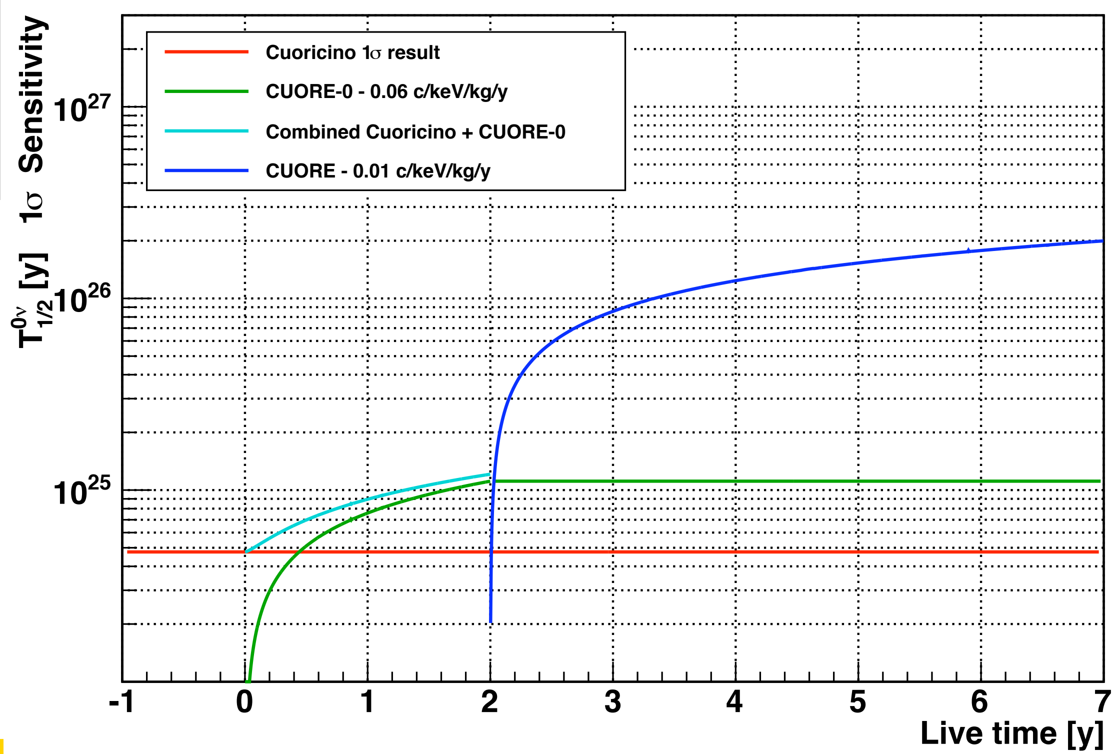
CUORE Sensitivity

5 year sensitivity

Background	ΔE_{FWHM}	$\tau_{1/2}^{0\nu}$	m_{ee} [meV]			
[c/keV/kg/y]	[keV]	[y] @ 68%C.L.	R(QRPA)[1]	pn(QRPA)[2]	ISM[3]	IBM-2[4]
0.01	5	2.1×10^{26}	35÷66	41÷67	65÷82	41
0.001	5	6.5×10^{26}	20÷38	23÷38	37÷47	23

Five year sensitivity based on detector resolution (5 keV FWHM), background, and matrix element spread

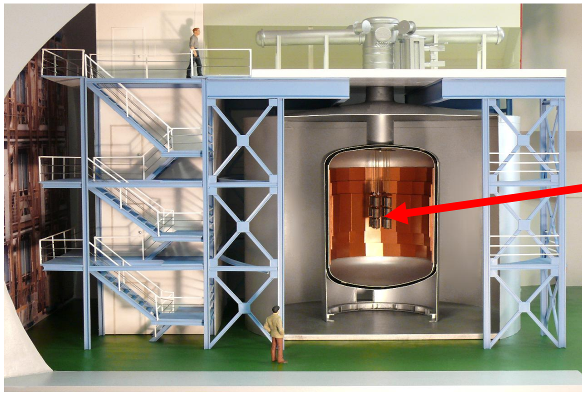
First tower (CUORE-0) to be assembled in Cuoricino cryostat by end of 2011 and operated until the start of CUORE.

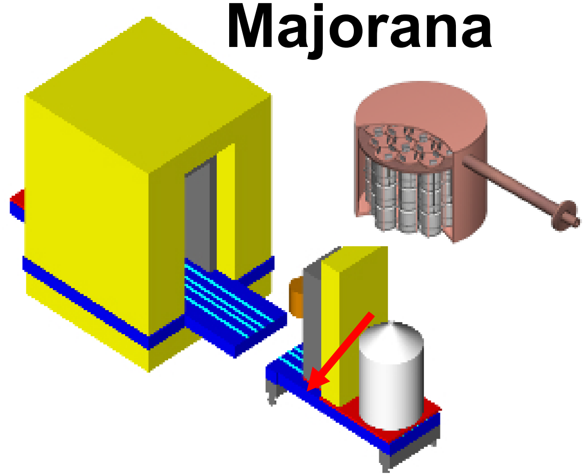


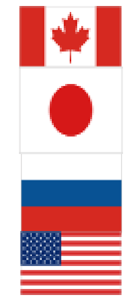
Two New ^{76}Ge Experiments

GERDA

Majorana







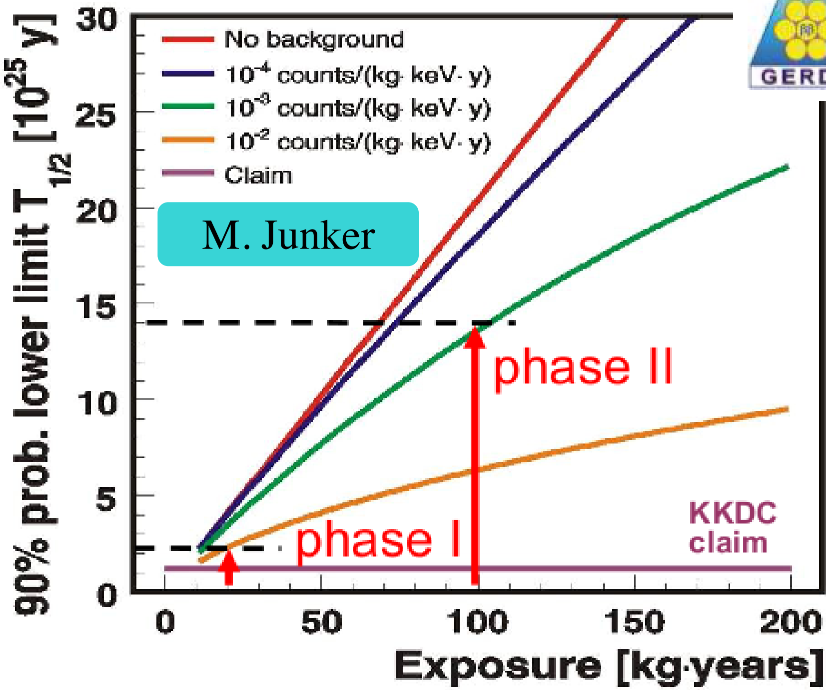
- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX) / 15 kg nat.
- Phase II: add ~20 kg new enr. Detectors; total ~40 kg

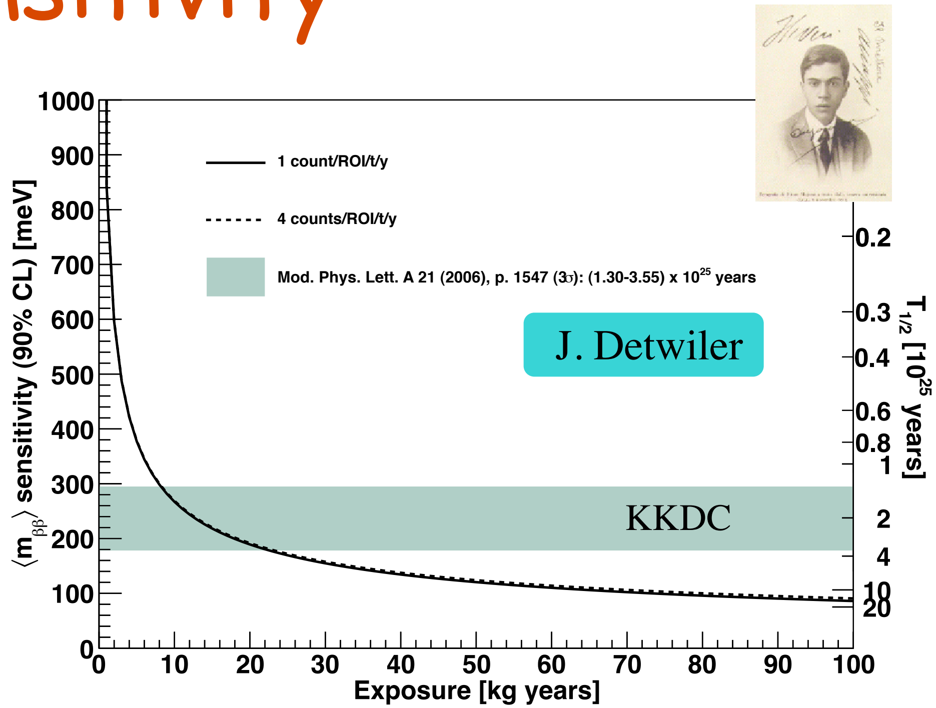
- Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~60 kg (30 kg enr.)

Physics goals: degenerate mass range
Technology: study \of bgds. and exp. techniques

LoI
- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for O(1 ton) exp. (inv. Hierarchy) selecting the best technologies teste in GERDA and Majorana

^{76}Ge Sensitivity





Commissioning of Phase-I (~17 kg of ^{76}Ge) detector ongoing (2010, LNGS)

Phase-II detectors in production (add 20 kg of ^{76}Ge with pulse-shape discrimination): 2012-2014

R&D on detection of scintillation in LAr for additional background suppression

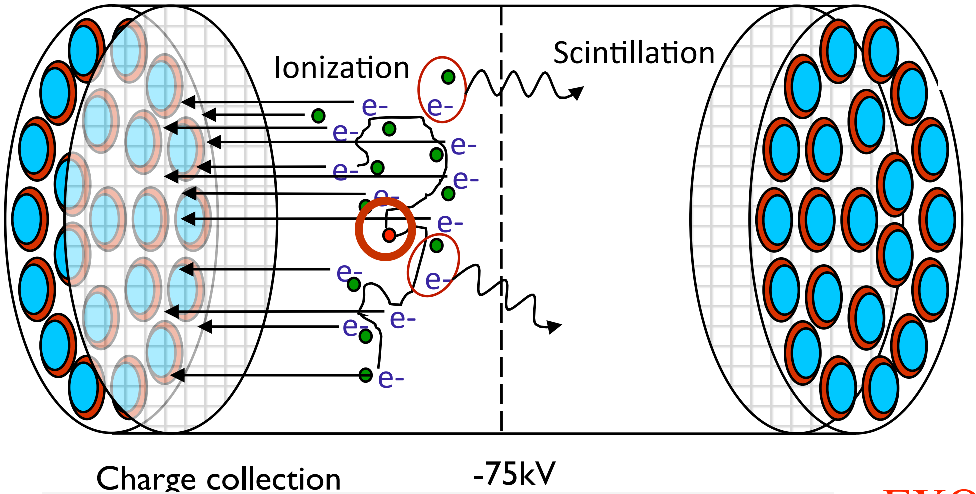
Demonstrator approved (30 ^{nat}Ge, 30 kg ^{enr}Ge), to be deployed at Sanford Lab (2012-2013)

Novel point-contact HPGe detectors

High resolution, pulse-shape discrimination of α vs β

Aim for ~1 evt/ton/keV/year background

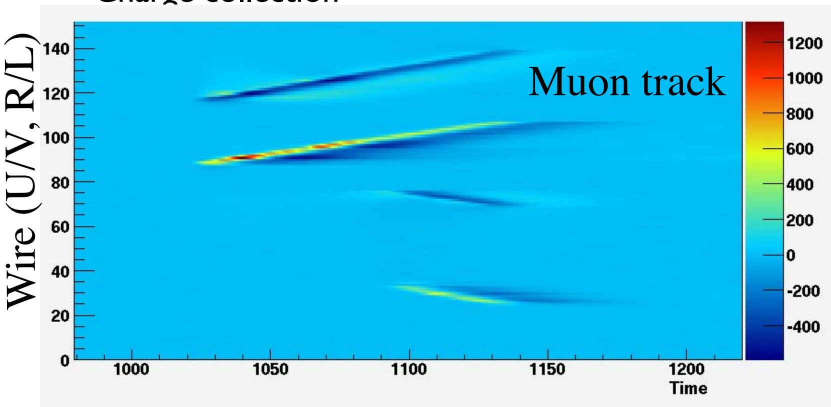
EXO



EXO-200: 200 kg of LXe (80% ^{136}Xe): TPC +Scintillation

Prototype for a 1-ton detector, aiming at ~100 meV $m_{\beta\beta}$ sensitivity

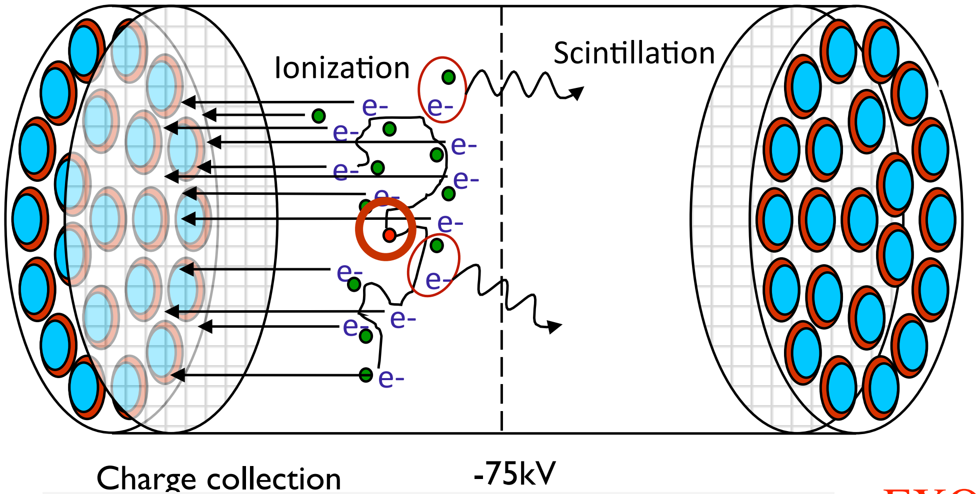
Commissioning since ~Nov. 2010, coming along well



EXO-200 Sensitivity

Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu\beta\beta}$ (yr, 90%CL)	$m_{\beta\beta}$ (meV)
0.2	70	2	1.6	40	6.4×10^{25}	133-186

EXO



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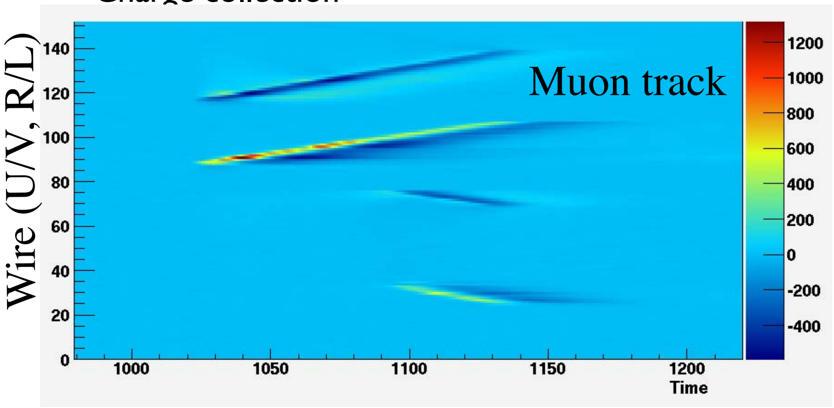

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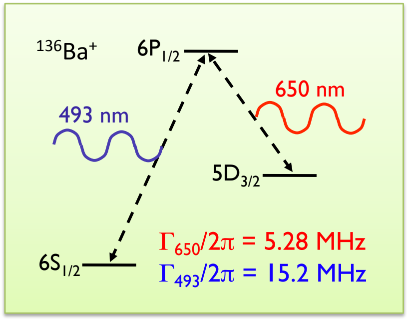
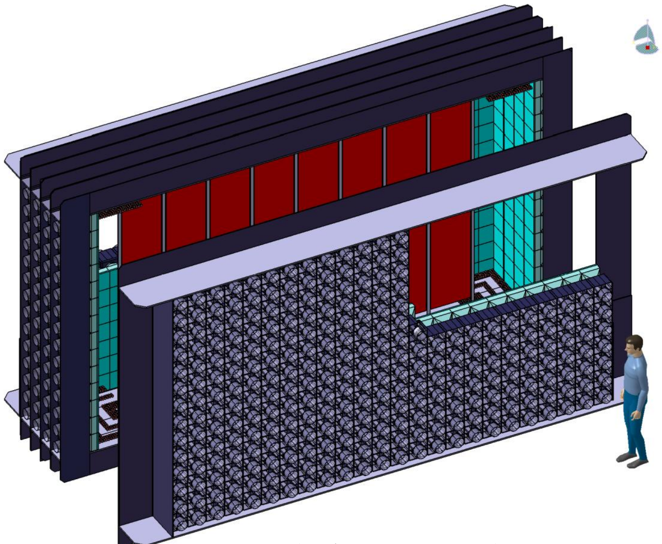
EXO-1000: 1 ton LXe TPC

Barium ion extraction and atomic spectroscopy tagging: potential for zero-background detection (except for $2\nu\beta\beta\rightarrow0\nu\beta\beta$)



SuperNEMO



20 modules (Modane)

	NEMO-3	SuperNEMO
Isotope	^{100}Mo	^{82}Se or ^{100}Mo
Isotope mass	7 kg	100-200 kg
Resolution @ 3 MeV	8% FWHM	4% FWHM
Efficiency ($0\nu\beta\beta$)	18%	~30%
Radiopurity	^{208}Tl < 20μBq/kg ^{214}Bi ~ 300μBq/kg	^{208}Tl < 3μBq/kg ^{214}Bi < 10μBq/kg
Sensitivity	$\tau^{0\nu}_{1/2}>2\times10^{24}$ y $m_{\beta\beta}<0.3\text{-}1.0$ eV	$\tau^{0\nu}_{1/2}>(1\text{-}2)\times10^{26}$ y $m_{\beta\beta}<40\text{-}140$ meV

R&D directions: ββ foil production, radio-purity, resolution

Demonstrator (1 module): ~2013

Full detector construction start ~2014

Aim for ~50 meV sensitivity by 2019

SNO+ and KamLAND-Zen

SNO+: ^{150}Nd dissolved in liquid scintillator

Pros: large mass (up to 500 kg of Nd), high purity, well understood backgrounds

Con: poor energy resolution

Stage-1: ^{nat}Nd (44-120 kg of ^{150}Nd), reach $m_{\beta\beta}$~80-150 meV

Possible Stage-2: ^{enr}Nd (1 ton of ^{150}Nd), reach $m_{\beta\beta}$~50 meV

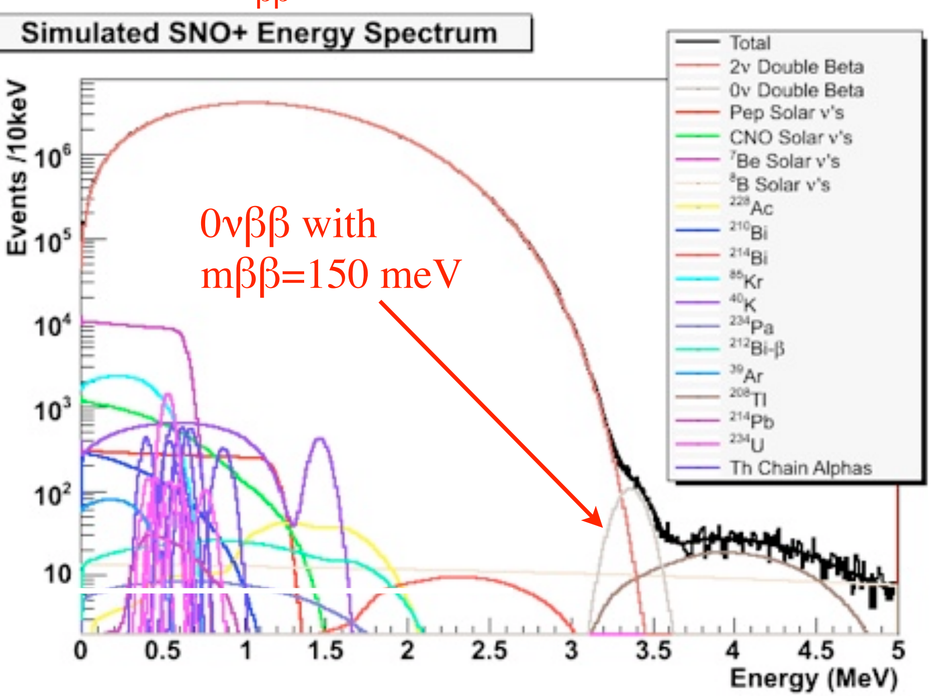
KamLAND-Zen: ^{136}Xe dissolved in liquid scintillator (mini-balloon inside KamLAND)

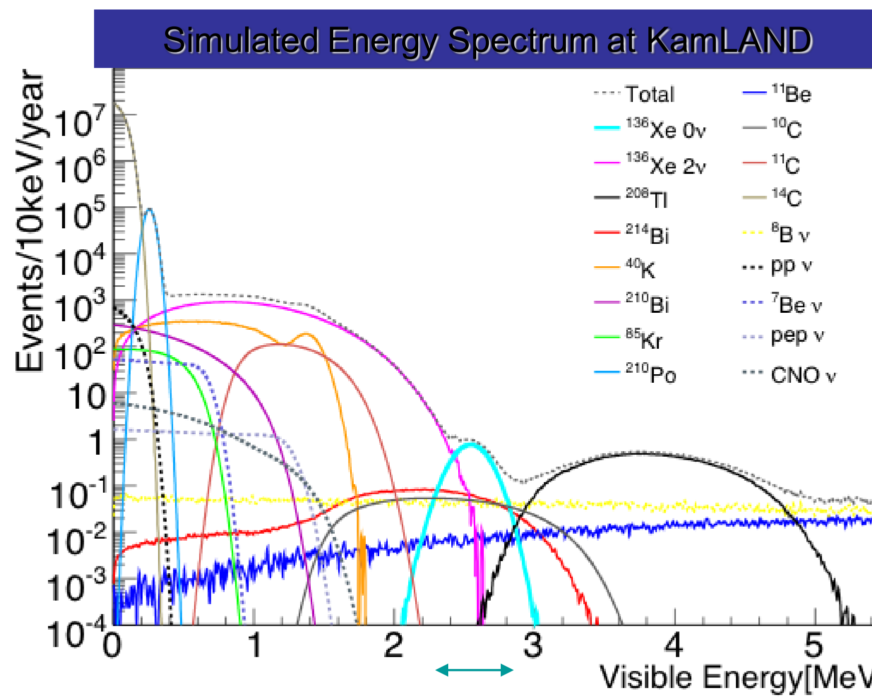
Pros: very large mass (up to 1 ton of ^{136}Xe), high purity, well understood backgrounds

Con: poor energy resolution

Stage-1: $m_{\beta\beta}$~60 meV by end of 2013

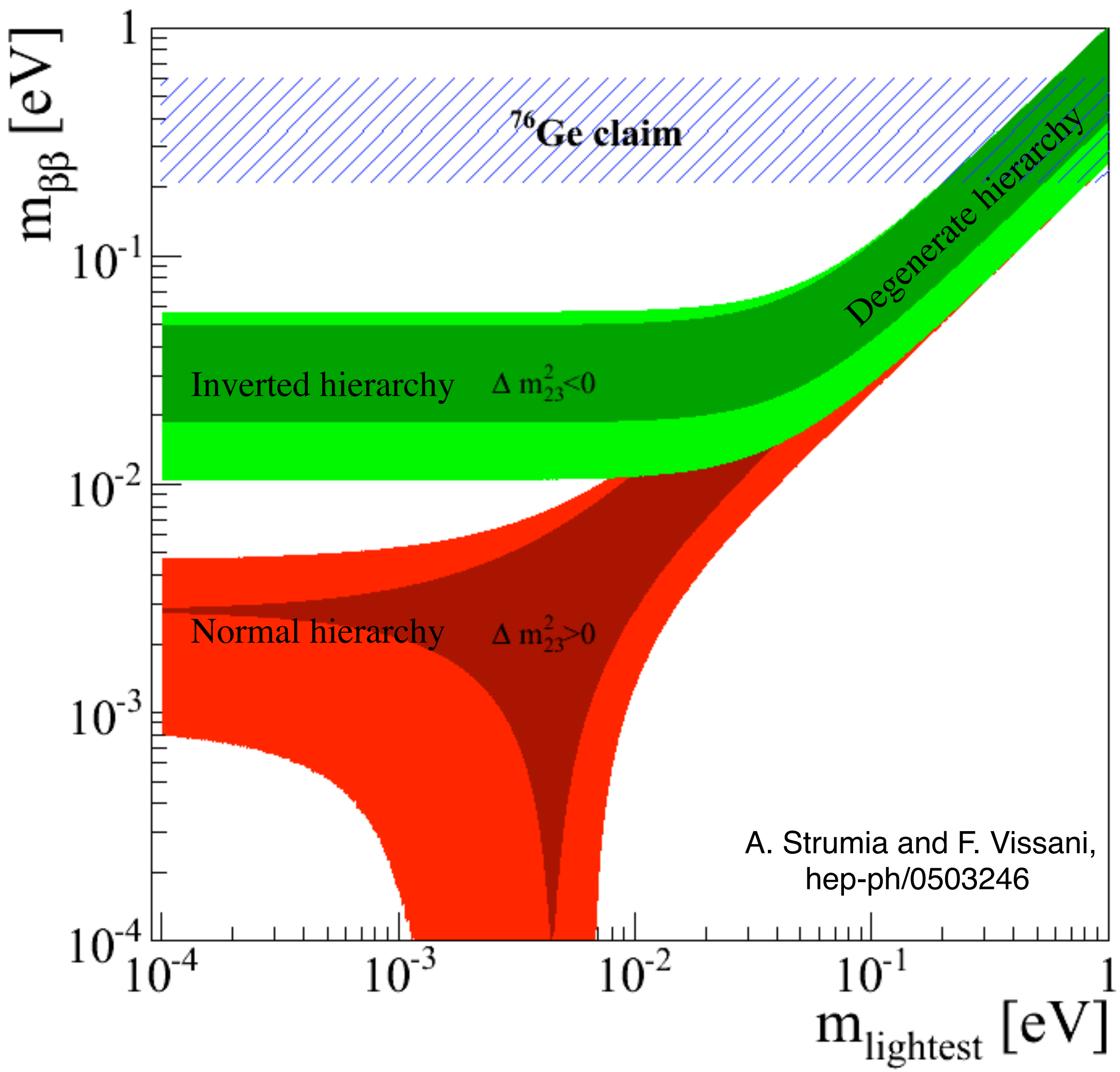
Stage-2: 1 ton of ^{136}Xe (depends on funding)





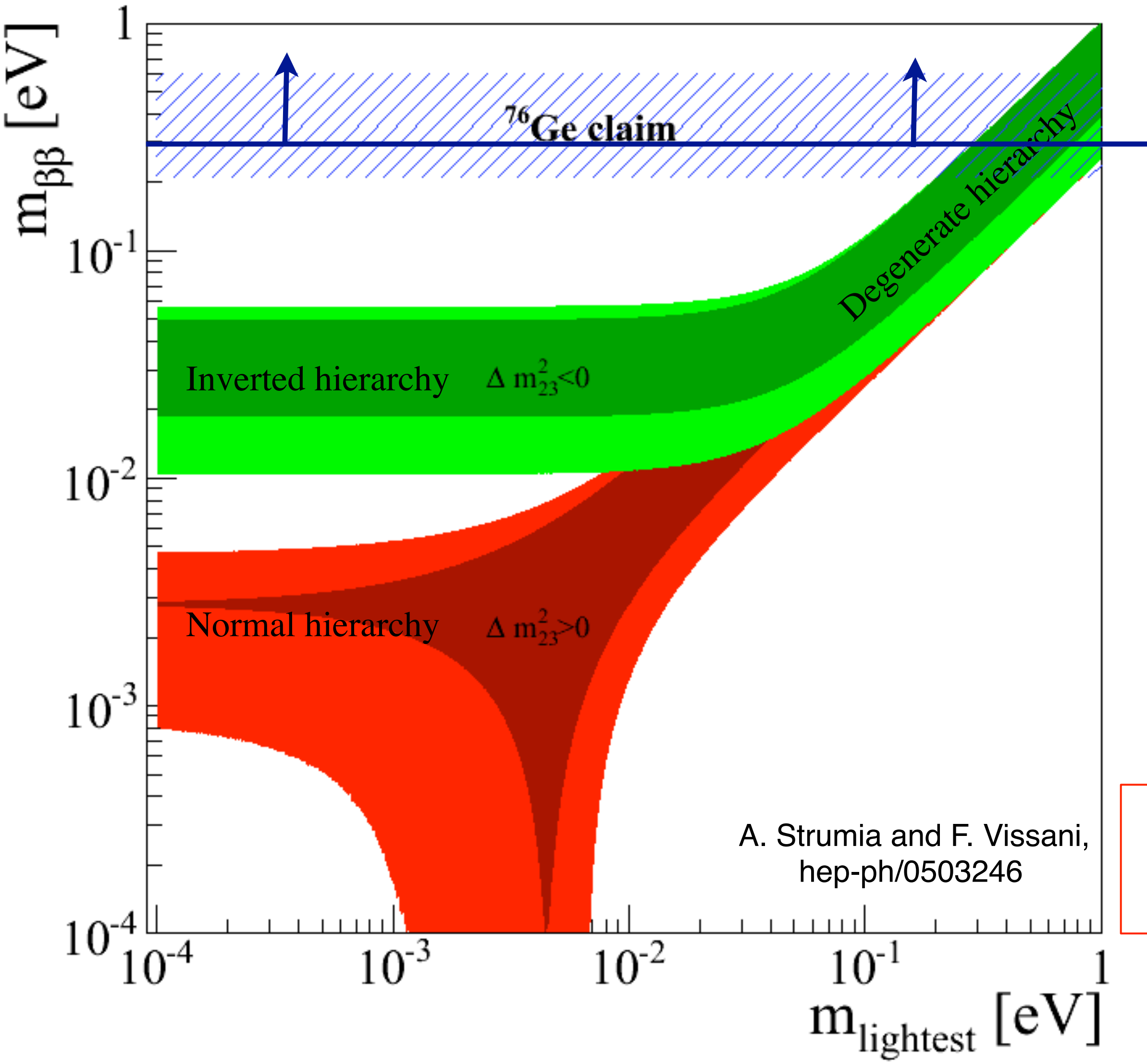
Masayuki Koga ICHEP2010

DBD and Neutrino Mass



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

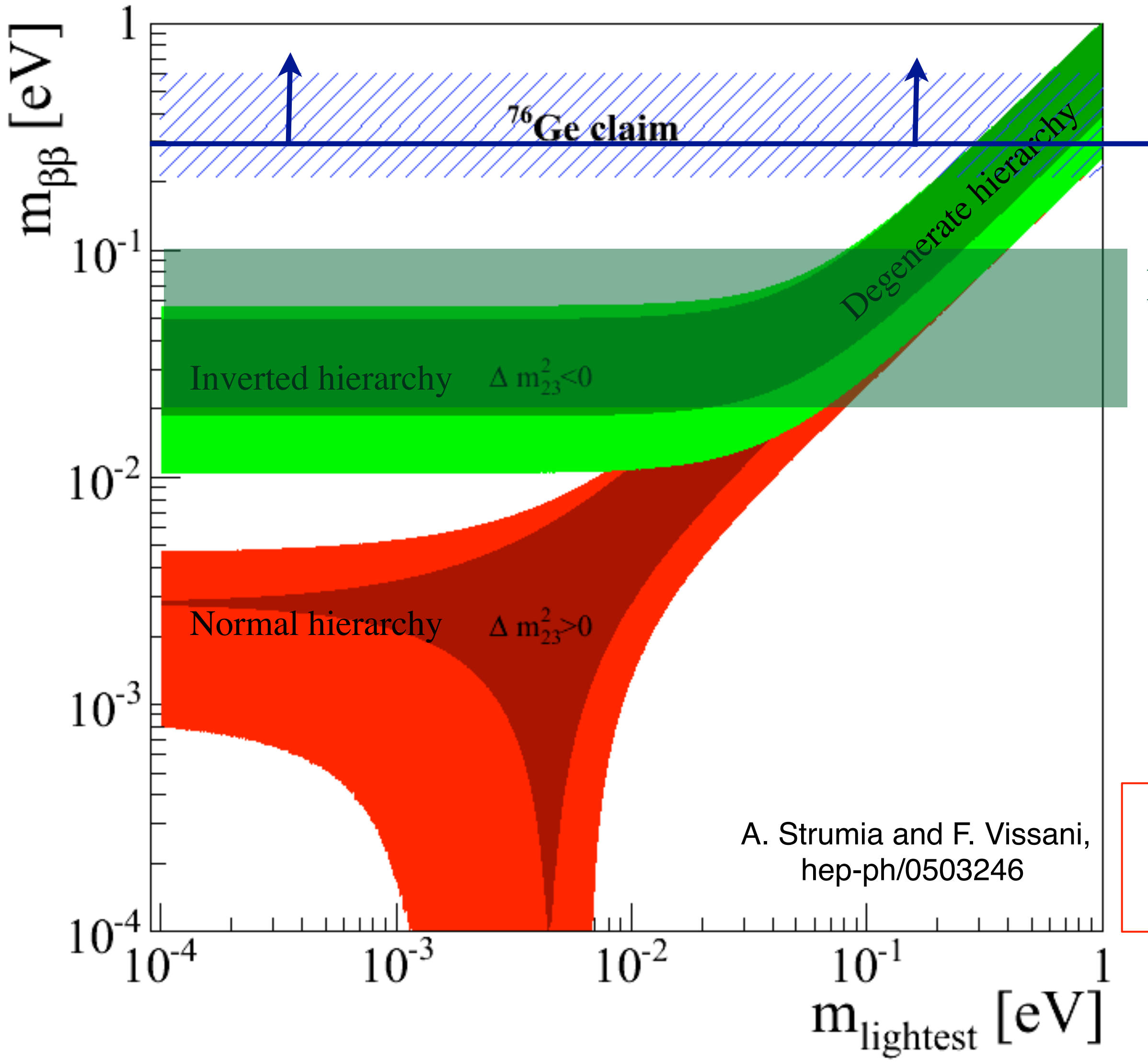
DBD and Neutrino Mass



Recent experiments (CUORICINO, NEMO-3)

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

DBD and Neutrino Mass

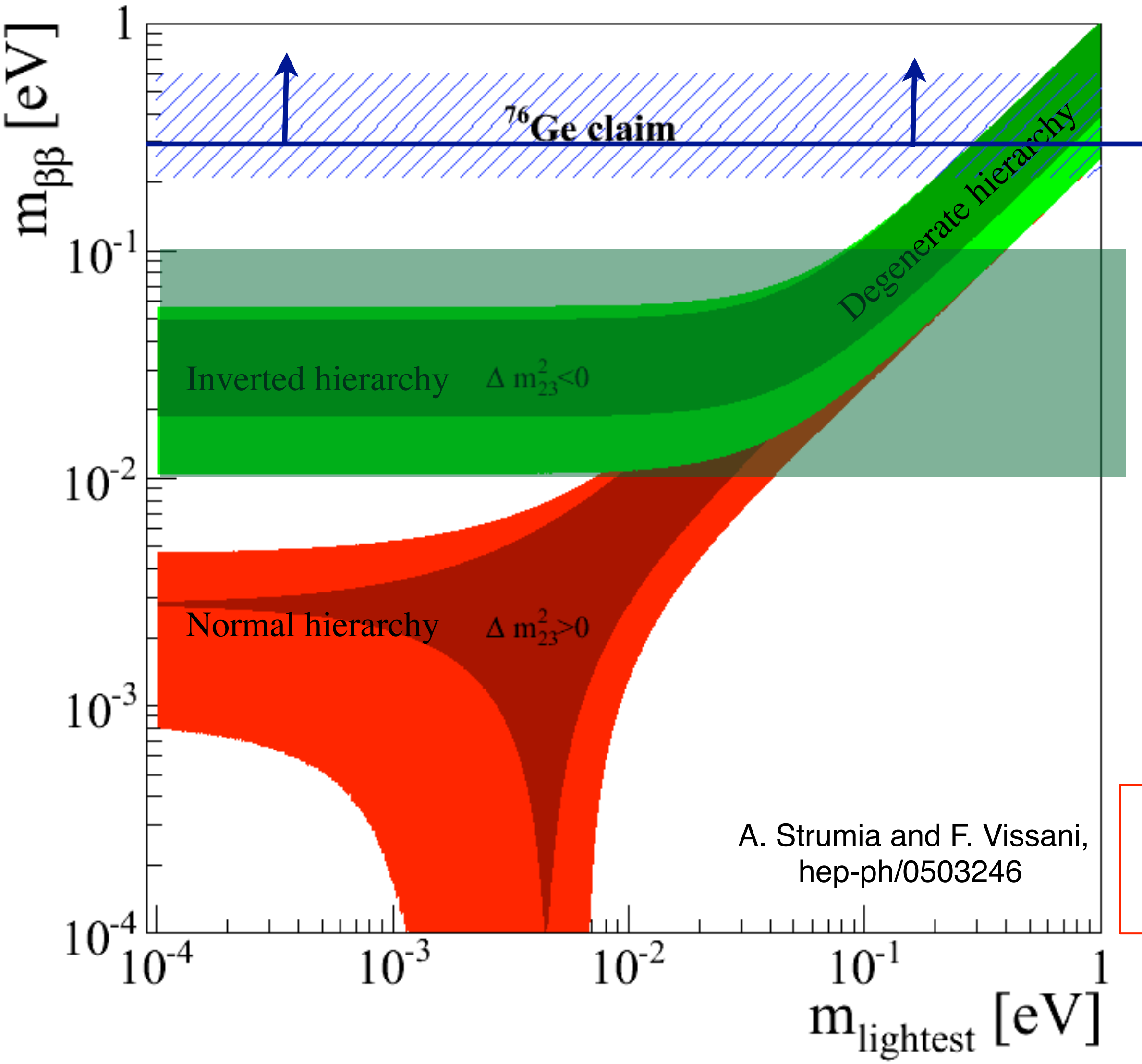


Recent experiments (CUORICINO, NEMO-3)

Next generation of experiments (~1–10 counts/ton/year)

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

DBD and Neutrino Mass



Recent experiments
(CUORICINO, NEMO-3)

Next generation of experiments
(~1–10 counts/ton/year)

Plus upgrades
(0.1–1 counts/ton/year)

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

Summary

Experiment	Isotope	Mass [kg]	$\tau^{0\nu}_{1/2}$ [y]	$m_{\beta\beta}$ [meV]	When
CUORE	^{130}Te	200	2×10^{26}	35-80	2014-2019
GERDA	^{76}Ge	17 40 1000	3×10^{25} 2×10^{26} 6×10^{27}	180-500 70-200 10-40	2010-2012 2012-2014 2015-2025
MAJORANA	^{76}Ge	33 1000	1.5×10^{26} 6×10^{27}	70-200 10-40	2012-2013 2015-2025
EXO	^{136}Xe	200 1000	6×10^{25} 8×10^{26}	130-190 30-60	2010-2012 2015-2025
SuperNEMO	^{82}Se	100-200	$(1\text{-}2)\times10^{26}$	40-140	2013-2019
KamLAND-Zen	^{136}Xe	400 1000	4×10^{26} $\sim10^{27}$	40-80 25-50	2011-2013 2014-2016
SNO+	^{150}Nd	44-120 500	5×10^{24} 3×10^{25}	80-130 40-100	2013-2016 2016-2020

After A.S.Barabash, Phys.Atom.Nucl. **73**, 162 (2010)

Approved R&D

0νββ: one of the top priorities in neutrino physics

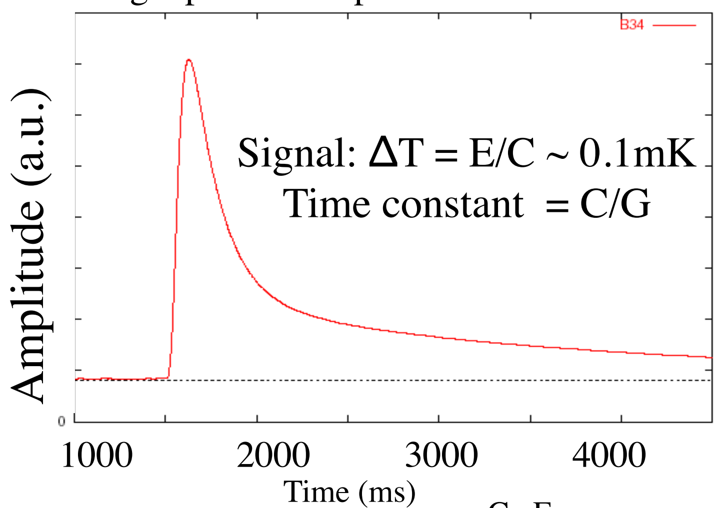
- Probe Majorana nature of neutrinos and the absolute scale of neutrino mass
- Next generation experiments: probe inverted hierarchy
- Multiple experiments and isotopes: complementary approaches and cross-checks
- Expect first results from the current crop of experiments by 2013

→ Stay tuned !

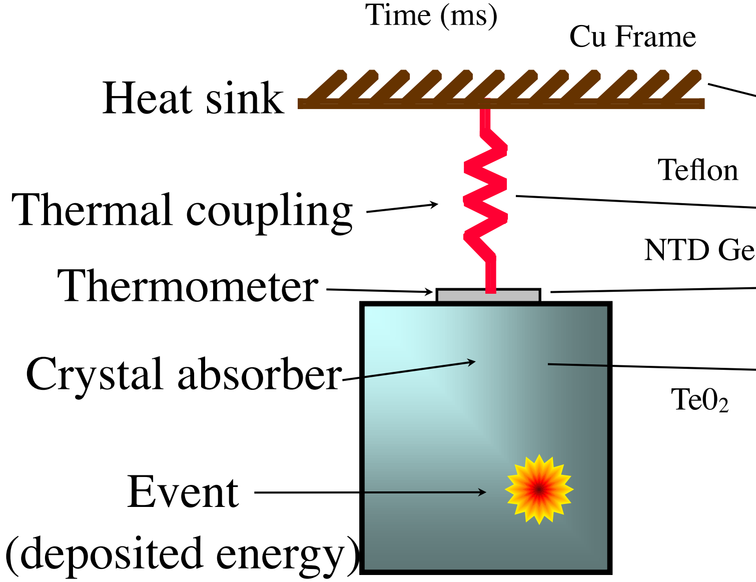
Backup

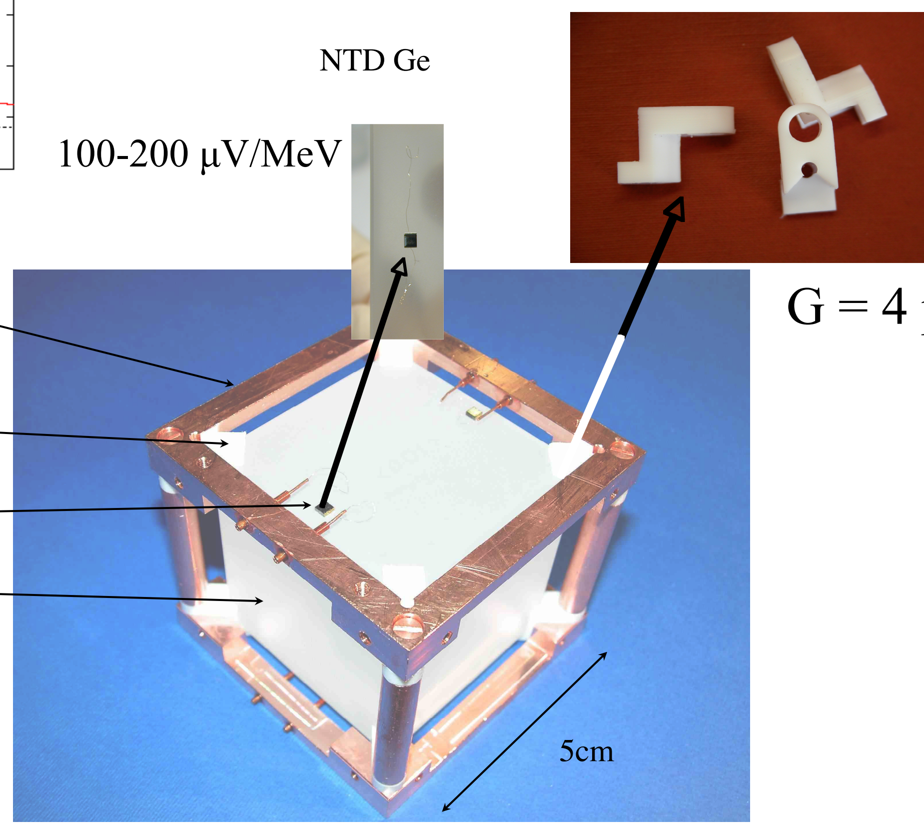
Cryogenic Bolometers

Single pulse example



- Dielectric diamagnetic materials
- Low temperatures (~10mK)
- Low heat capacity
  - C~2 nJ/K = 1 MeV / 0.1 mK

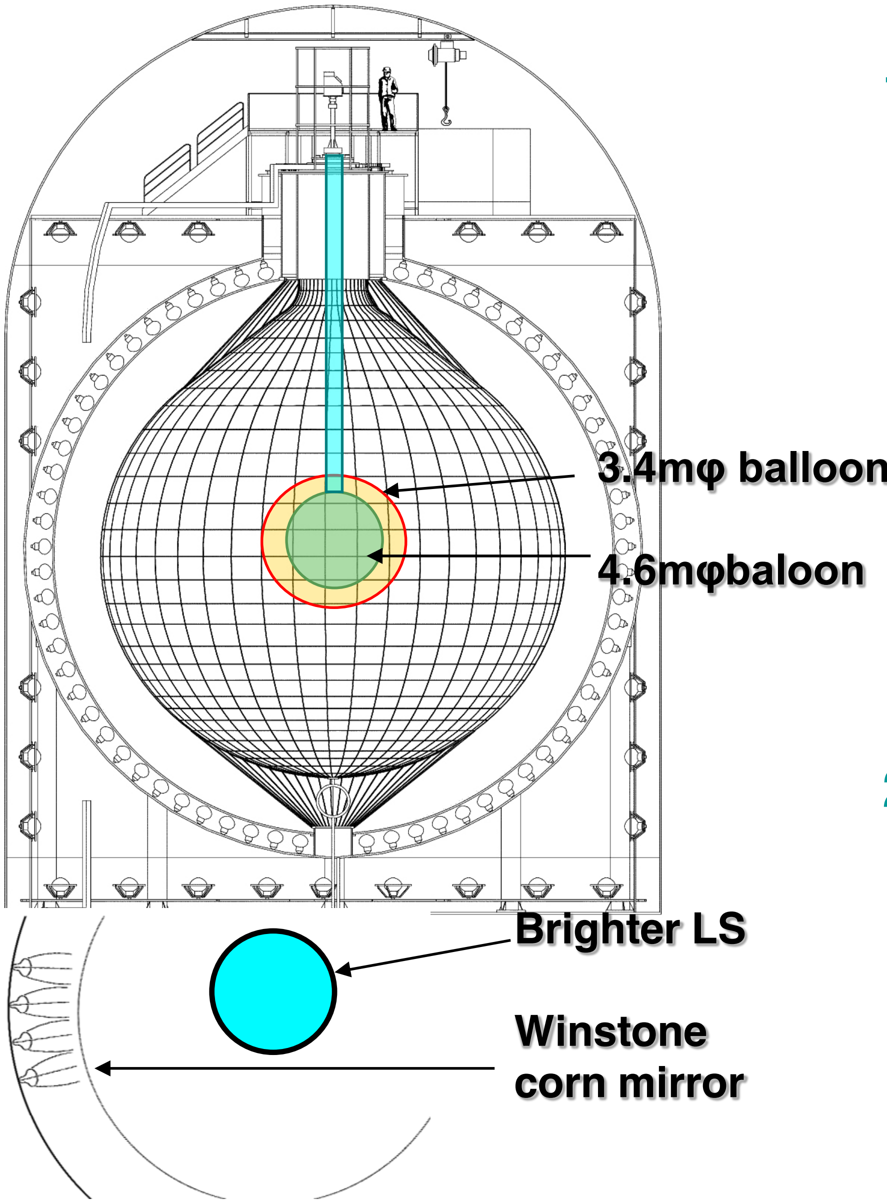




Teflon

G = 4 pW/mK

KamLAND-Zen



1st phase enriched Xe 400kg

R=1.7m balloon

$V=20.5m^3, S=36.3m^2$

LS : C10H22(81.8%)+PC(18%)
+PPO+Xe(~2.5wt%)

ρLS : 0.78kg／ℓ

high sensitivity with low cost

↓ tank opening (2013 or 2015)

2nd phase enriched Xe 1000kg

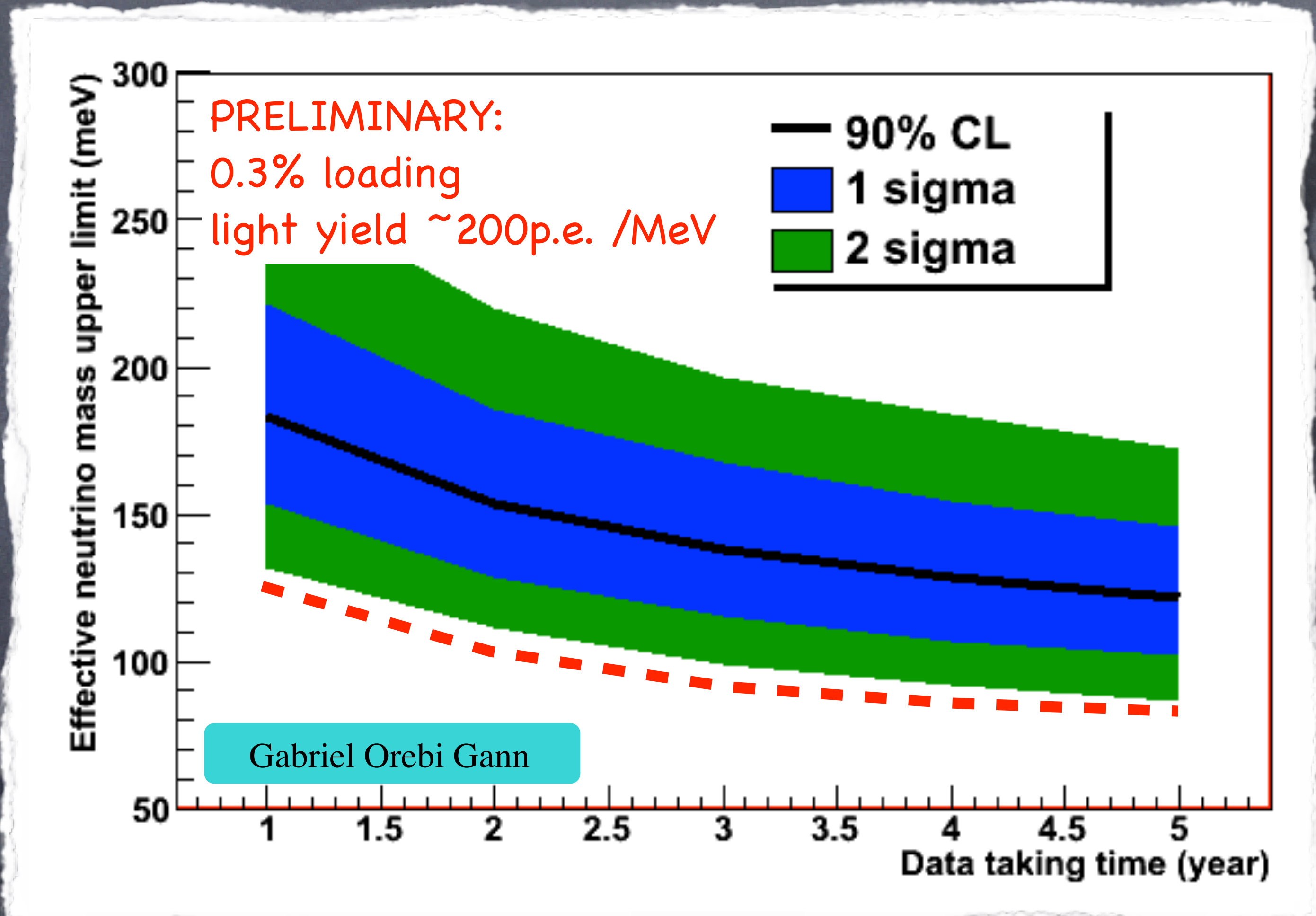
R=2.3m balloon

$V=51.3m^3, S=66.7m^2$

improvement of energy resolution
(brighter LS, higher light concentrator)

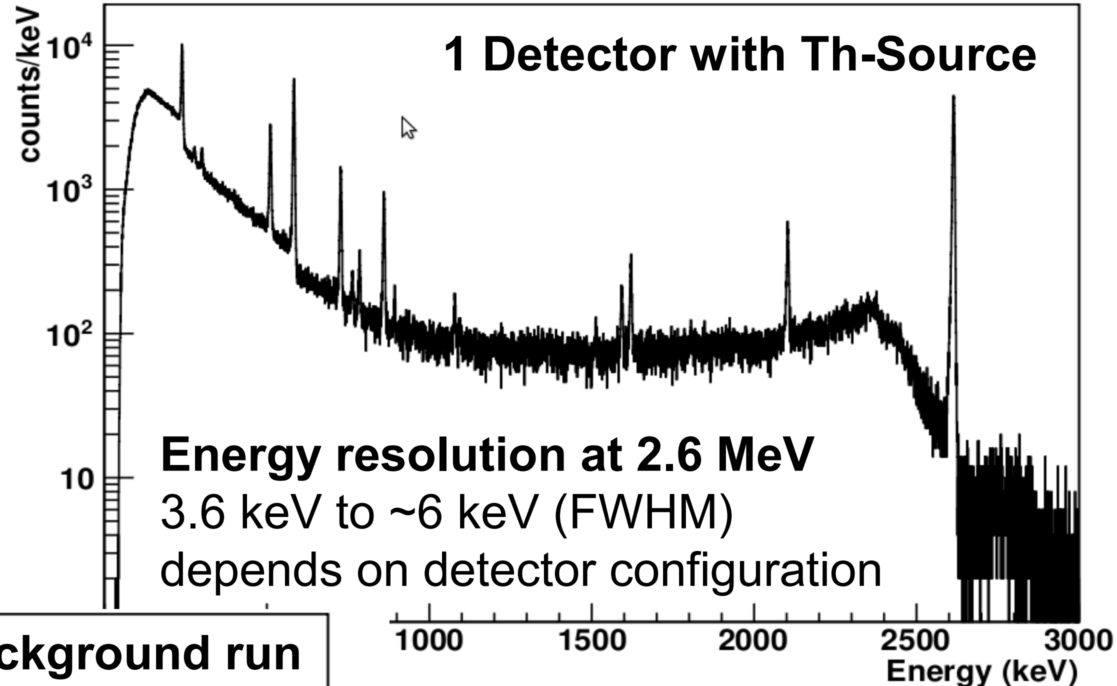
SNO+ Sensitivity

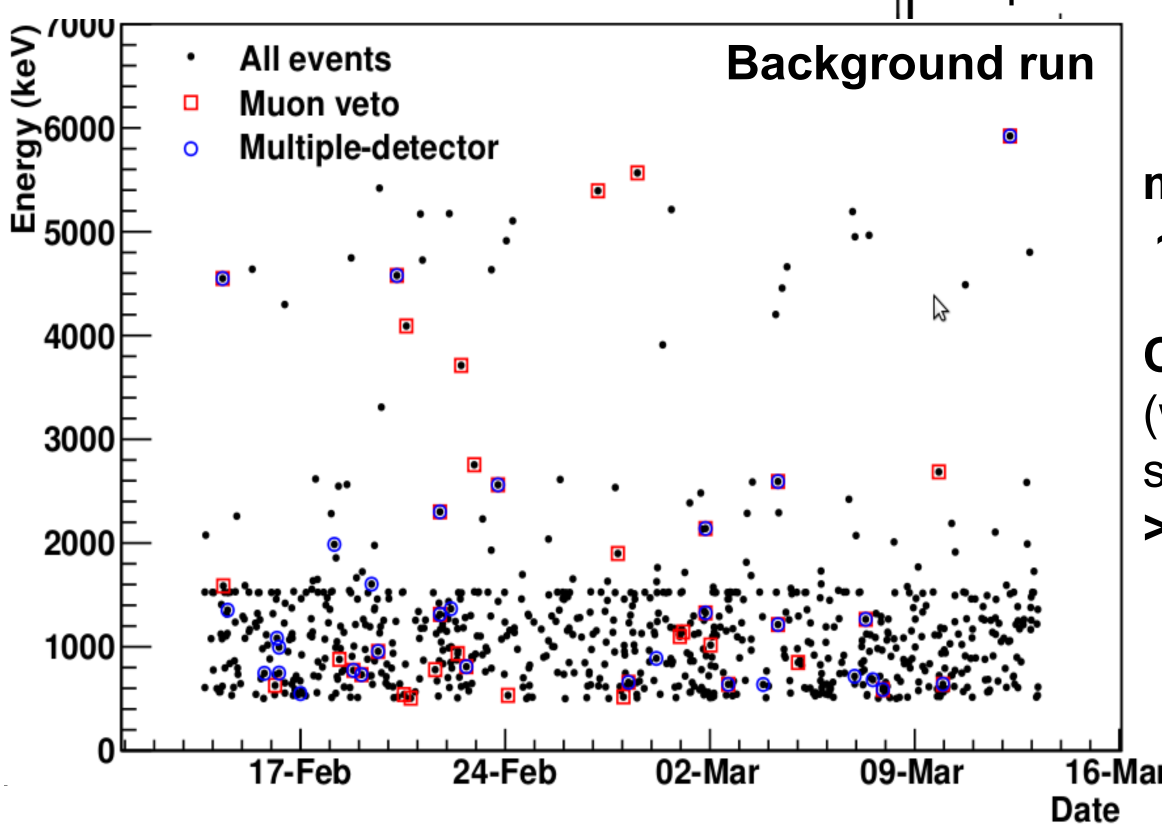
0.1% loading natural Nd ⇒ 44kg ^{150}Nd   light yield ~400p.e. /MeV



Uses IBM-2 NME (Most conservative NME calc for ^{150}Nd)   Uses QRPA

Commissioning Run
- one string with
  three non-enriched detectors
- Exposure: 30 days
  0.587 kg * y)



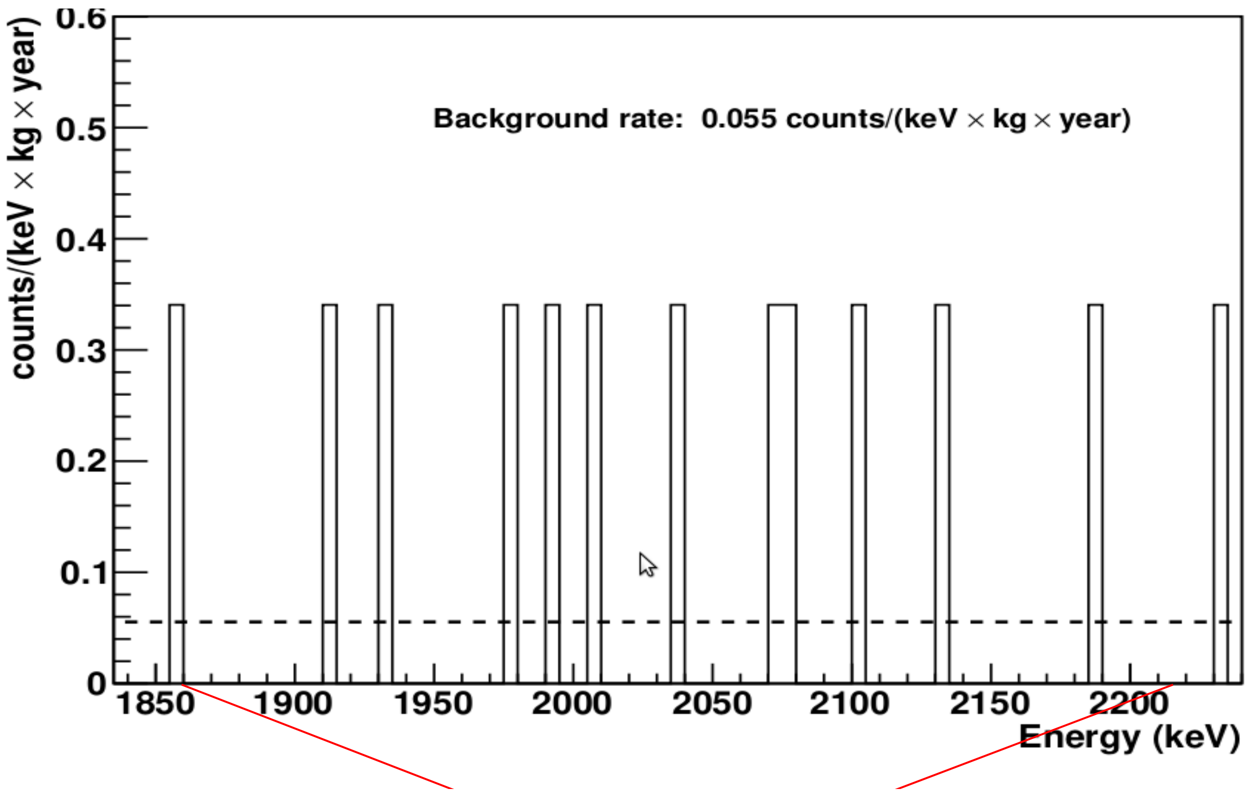


muon induced rate
~ $1 \cdot 10^{-2}$ cnts/(keV·kg·year)

Cosmic ray Veto efficiency
(water Cherenkov only; plastic scintillator panels to be completed)
>94% (preliminary)

Commissioning Run

- one string with
- three non-enriched detectors
- Exposure: 30 days
  0.587 kg * y)
- Anti coincidence
- Muon Veto



background rate in RoI ($Q_{\beta\beta}$±200 keV):
0.06 counts/(keV·kg·year)

- Background rate significant lower than previous experiments (HdM, IGEX), but still higher than Phase I goals (0.01 counts/(keV·kg·year))
- Few more commissioning runs to optimize background (e.g. electric field configuration)

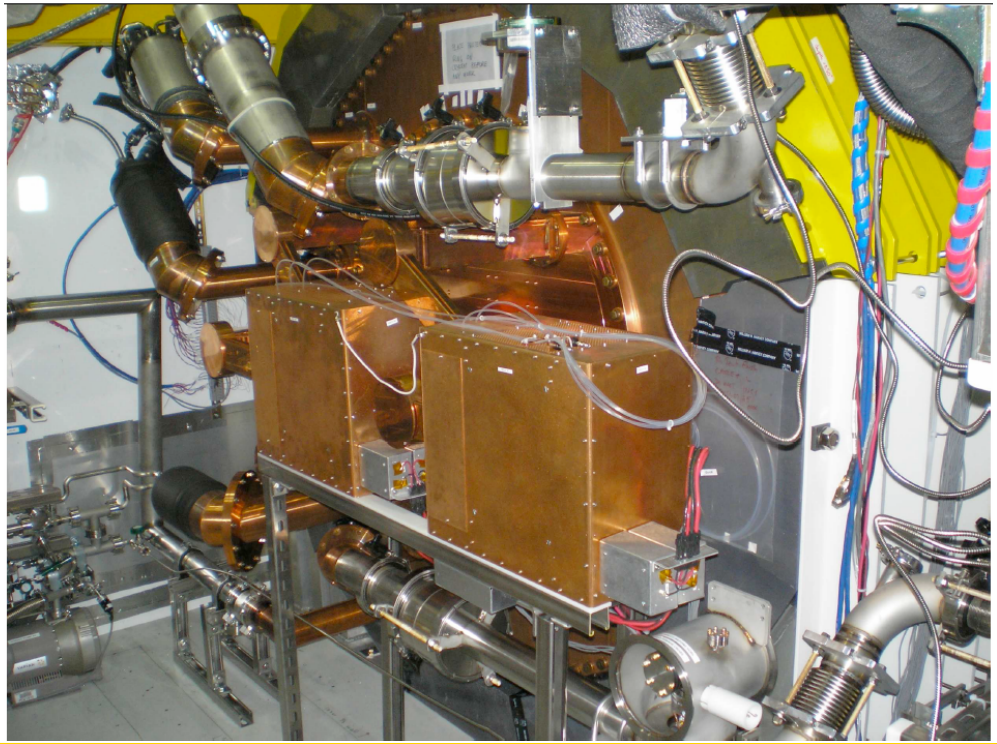
⇒ Deployment of 3 enriched detectors

Status of EXO-200

EXO-200 engineering run Dec 2010

- Check stability of all LXe/GXe systems
- Check Xe purity
- Check electronics
- Generally test detector performance
- Test Xe emergency recovery

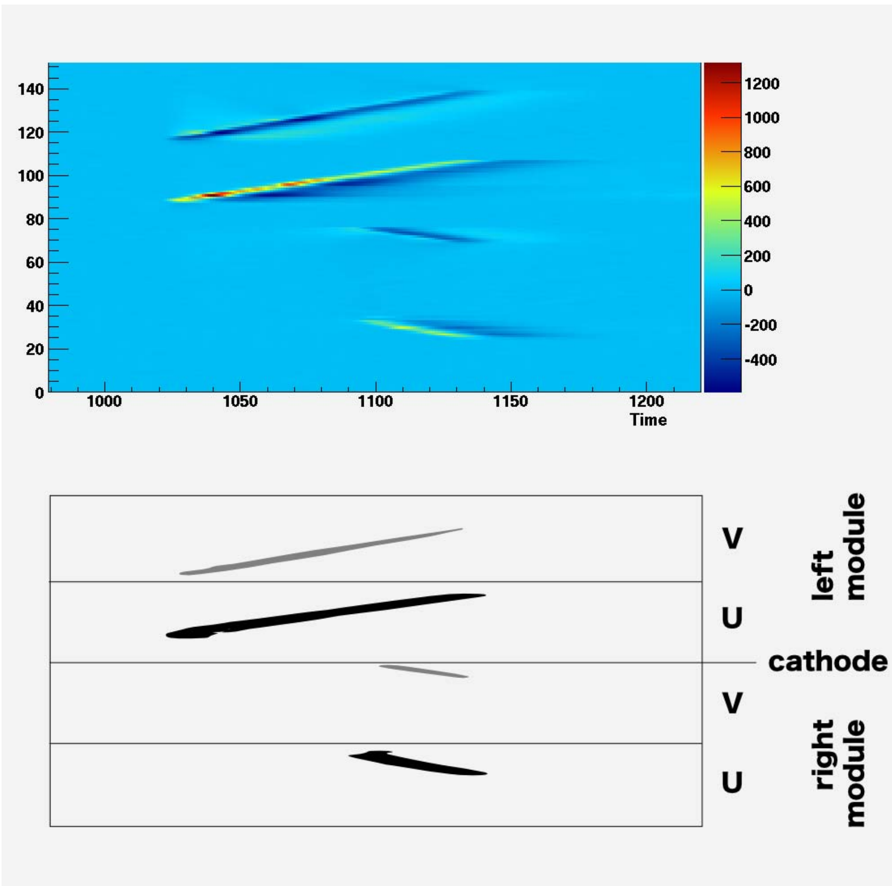
- No front shielding
- No Rn enclosure
- No Rn trap in Xe system
- No veto counter



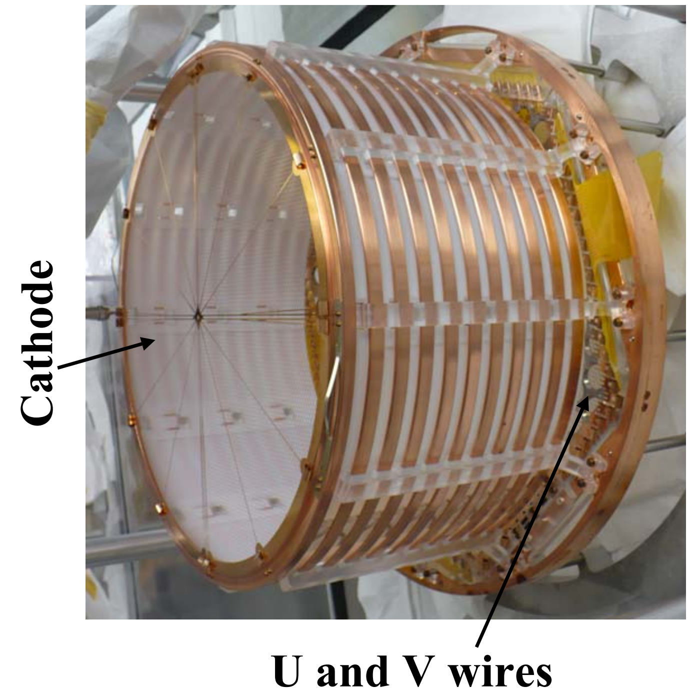
Giorgio Gratta

Status of EXO-200

Muon track in EXO-200 (Dec 2010)



One of the two TPC modules



A track from a cosmic-ray muon in EXO-200. The horizontal axis represents time (uncalibrated for now) while the vertical is the wire position (see sketch). V-wires, in front of the charge-collecting U-wires report a smaller inductive signal. The two sets of wires cross at 60º angle. The muon in the present event traverses the cathode grid, leaving a long track in one TPC module and a shorter one in the other.