Reactor neutrinos, double beta and beta decays
Experimental review

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Neutrino properties

- Oscillation parameter sin $2\theta_{13}$

-Absolute neutrino mass

- Nature of neutrino (Dirac $\nu \neq \bar{\nu}$ or Majorana $\nu = \bar{\nu}$)

- Neutrino mass scale

-Right Handed Current

- Majoron

……

Oscillations parameters and neutrino mass

Mixing angles

Atmospheric (SK)
Accelerators (K2K,Minos)

Reactors (CHOOZ)
Accelerators (JPARC)

Solar (SNO, SK)
Reactors (KamLAND)

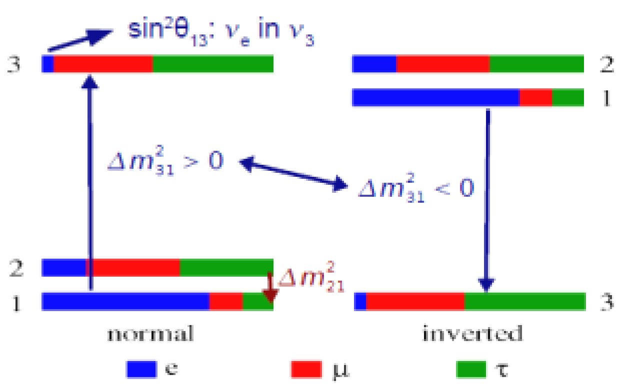
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \times \begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha/2} & 0\\ 0 & 0 & e^{i\alpha/2+i\beta}\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\tan^2\theta_{23}=1.0 \quad 0.3$ $\qquad \sin^2 2\theta_{13} < 0.16$ $\qquad \tan^2\theta_{12}=0.47 \quad 0.05$

α,β : CP Majorana phase

δ_{CP}: CP Dirac phase

Mass hierachy



$\Delta m^2_{sol} = \Delta m^2_{12} = (7.58 \pm 0.21)\ 10^{-5}\ eV^2$

$\Delta m^2_{atm} = \Delta m^2_{31} = (2.2 \pm 0.2\ )\ 10^{-3}\ eV^2$

Absolute neutrino mass

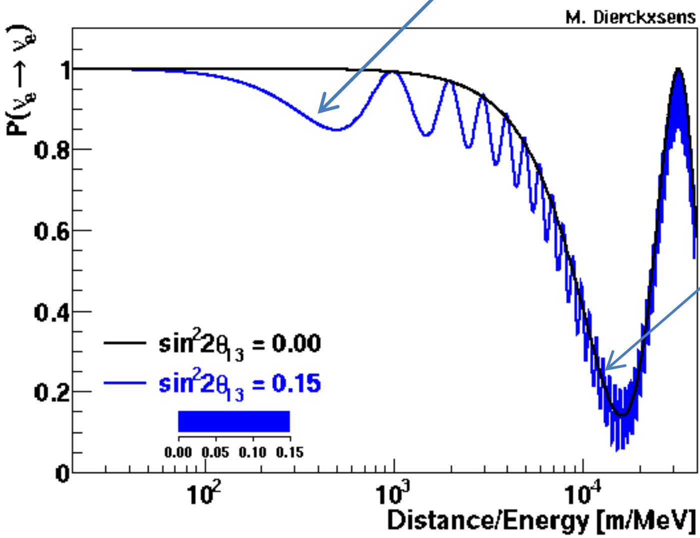
Beta decay : $|m_\nu| = \Sigma\ |U_{ei}|\ m_i$ < 2.6 eV (90 % CL)

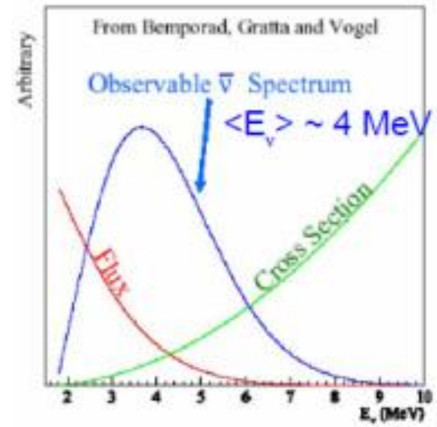
Double beta : $<m_{ee}> = |\Sigma\ U^2_{ei}\ m_i|$ < 0.3 – 0.7 eV (95% CL)

Cosmology : $m_\nu = m_1 + m_2 + m_3$ < 0.5 – 1 eV (95 % CL)

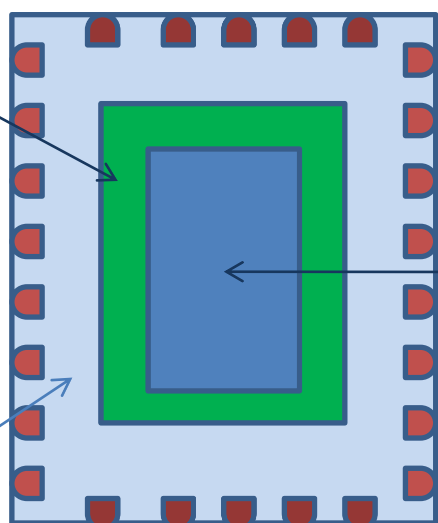
Reactor neutrinos

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\, L\, \Delta m^2_{31}}{E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\, L\, \Delta m^2_{21}}{E}\right)$$





Clean measurement of θ_{13}
Negligeable matter effect
No CP effect



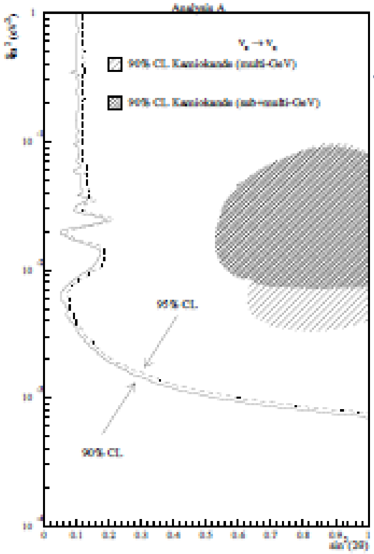
$\bar{\nu} + p \rightarrow e^+ + n$ $E_{th} = 1.8$ MeV

Prompt signal from e^+

Slowing down of the neutron

Delayed signal ~100 μs from n capture on H (2.2 MeV γ) or Gd (7 MeV γ)

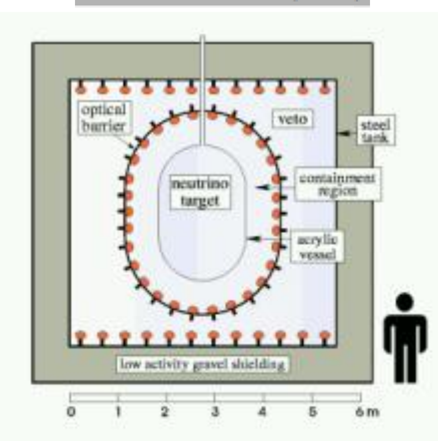
Reactor neutrino results



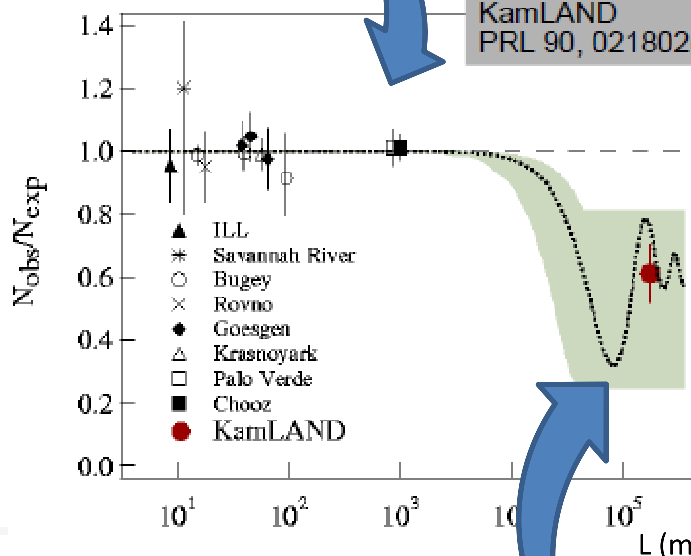
CHOOZ

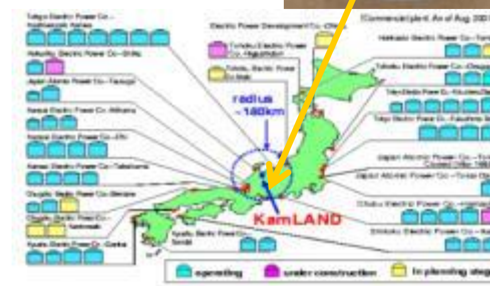
$\sin 2\theta_{13} < 0.16$ (90 %CL)

PL B466:415-430 (1999)

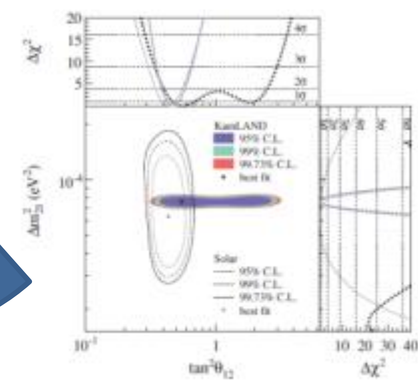


KamLAND
PRL 90, 021802(2003)





KamLAND + Solar neutrinos



$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

NP B Vol; 188 2009, 84-89

Reactor neutrinos

CHOOZ LIMIT **$\sin 2\theta_{13} < 0.16$** (90% CL)

Errors on the ratio $N_{observed}/N_{expected}$ **Statistical error =2.8% ,** **Systematical error= 2.7 %**

3 experiments to improve $\sin 2\theta_{13}$ sensitivity : Double Chooz (France),
Daya Bay (China)
RENO (South Korea)

See talks Masaki *Hishitsuka,* Cheng-Ju Lin, Soo-Bong Kim

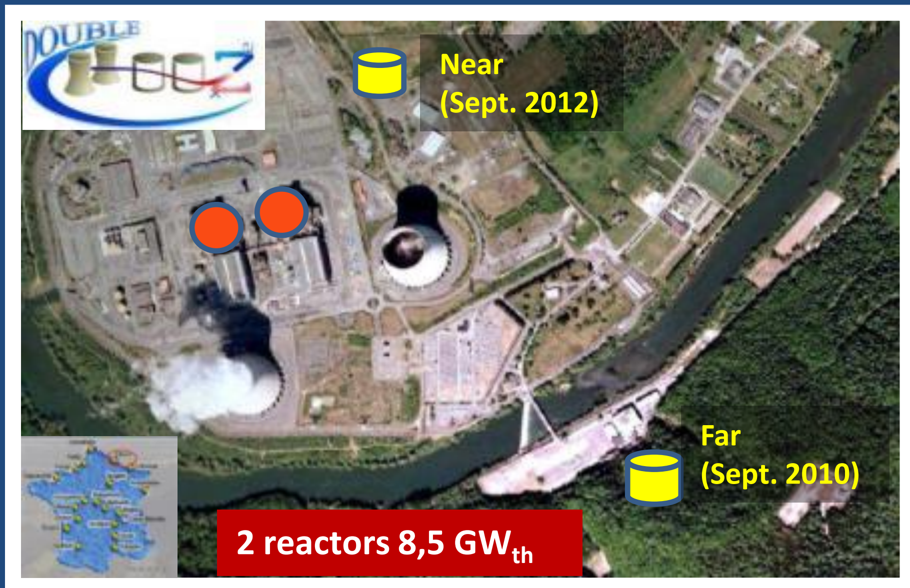
Near detector to cancel some systematics:
Cross section, flux from reactor, cut efficiency

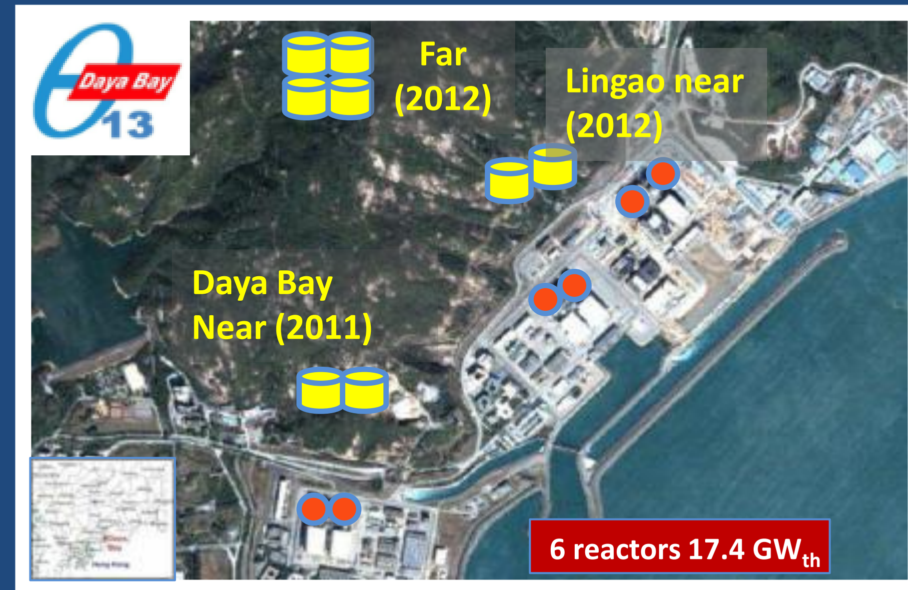
Higher statistic: More powerful reactors, longer time of running, larger mass of target

$\sigma_{stat} = 0.2 – 0.5\ \%$, $\sigma_{syst} = 0.4 – 0.6\%$ → $\sin 2\theta_{13} < 0.01 – 0.03$

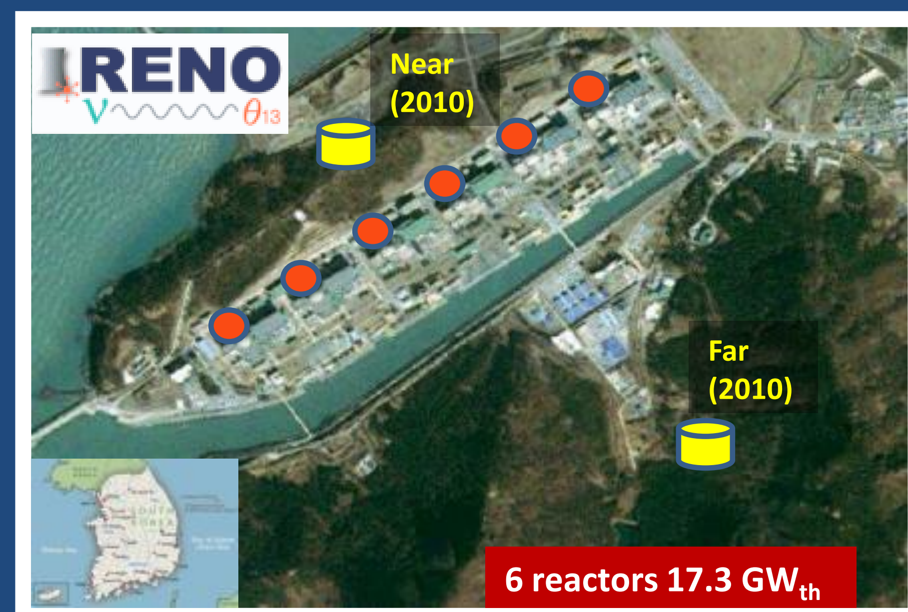
Backgrounds correlated with muons spallations (depth and muons tagging)
Uncorreleted background from natural radioactivity (low radioactive materials)

Reactor neutrinos

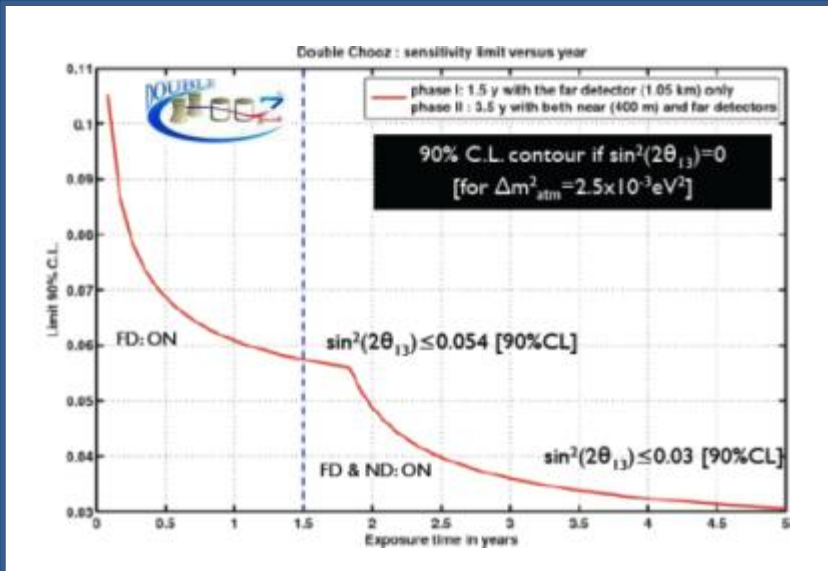


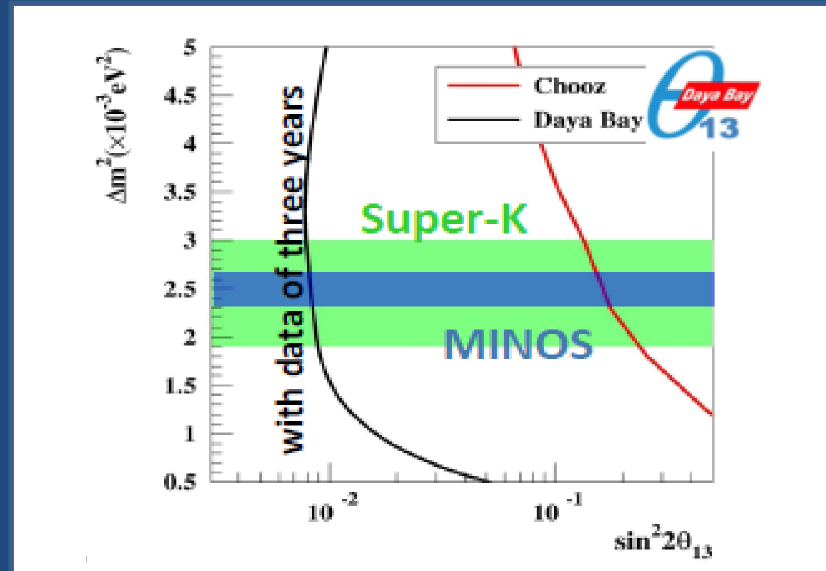


	Location	Thermal Power	Distance Near/far	Depth Near/far
Double Chooz	France	8.5	410/1050	120/300
RENO	South Korea	17.3	290/1380	120/450
DAYA BAY	China	17.4	360/1985 500/1613	260/910

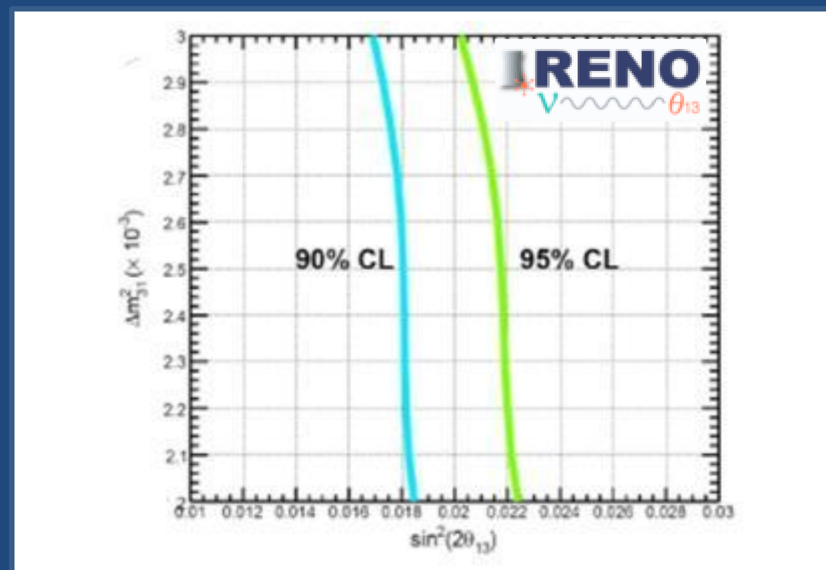


3 yr data sensitivities



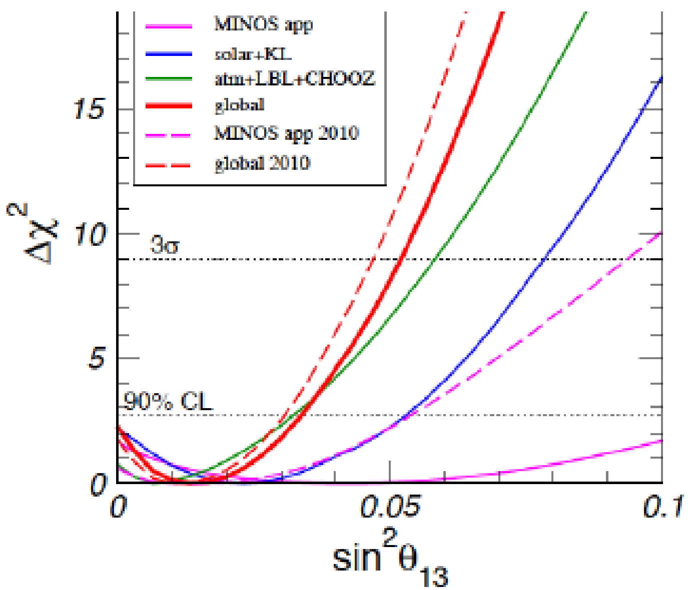


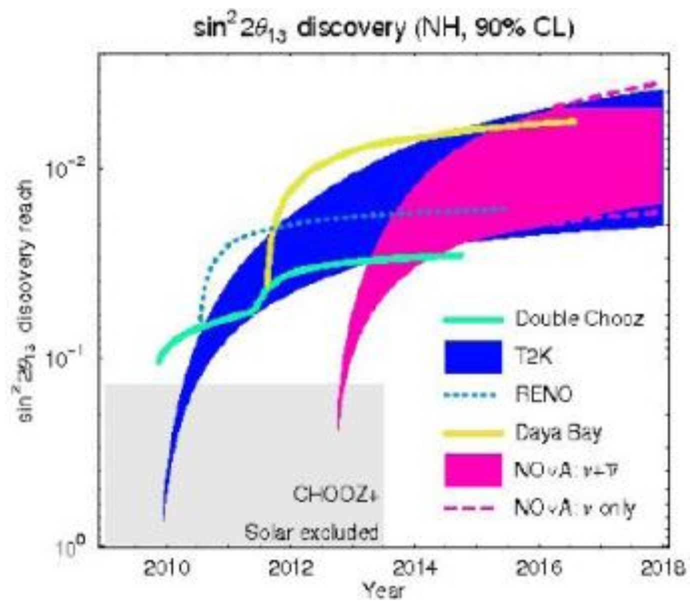
	σ_{stat} (%)	σ_{syst} (%)	sin $2\theta_{13}$ (90 % CL)
Double Chooz	0.5	0.6	< 0.03
RENO	0.3	0.5	< 0.02
DAYA BAY	0.2	0.4	< 0.01

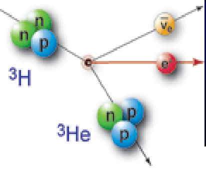


Reactor neutrinos

	Location	Thermal Power	Distance Near/far	Depth Near/far	Target mass (tons)	running	σ_{stat} (%)	σ_{syst} (%)	sin $2\theta_{13}$ (90 % CL)
Double Chooz	France	8.5	410/1050	120/300	8.6/8.6	2010 (far) 2012	0.5	0.6	< 0.03
RENO	South Korea	17.3	290/1380	120/450	16/16	Dec, 2010	0.3	0.5	< 0.02
DAYA BAY	China	17.4	360/1985 500/1613	260/910	20x2/40	DB 2011 Full 2012	0.2	0.4	< 0.01







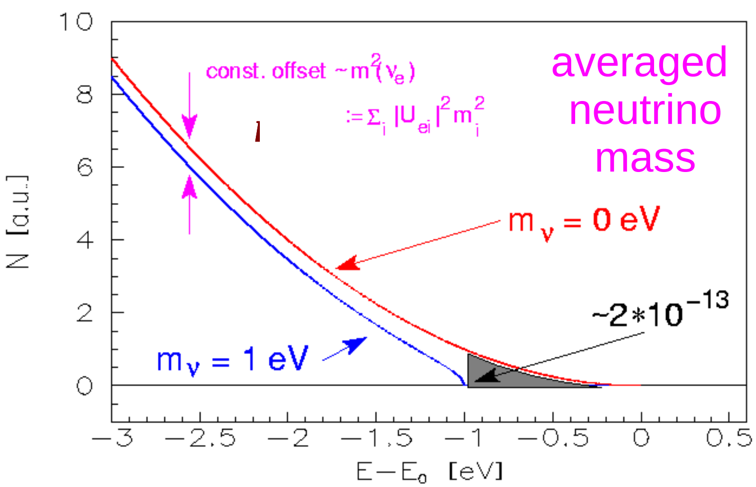
Beta decay

$(A,Z) \rightarrow (A,Z+1) + e^- + \overline{\nu}_e$

$$m_{\nu_e}^2 = \sum |U_{e_i}|^2 m_i^2$$

Direct measurement by cinematics

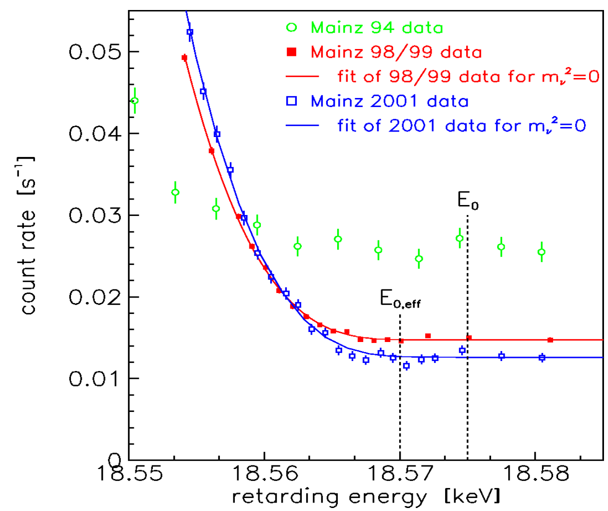
$dN/dE \sim [\, (E_0-E_e)^2 - m_{\nu i}^2 \,]^{1/2}$:



Fraction of decay in $[Q_\beta - m_\nu, Q_\beta] \sim (m_\nu/Q_\beta)^3$

lowest Q_β value ^{3}H (Q_β= 18.6 keV)
High counting rate
Low background
Energy resolution ~ m_ν

MAC-E spectrometers



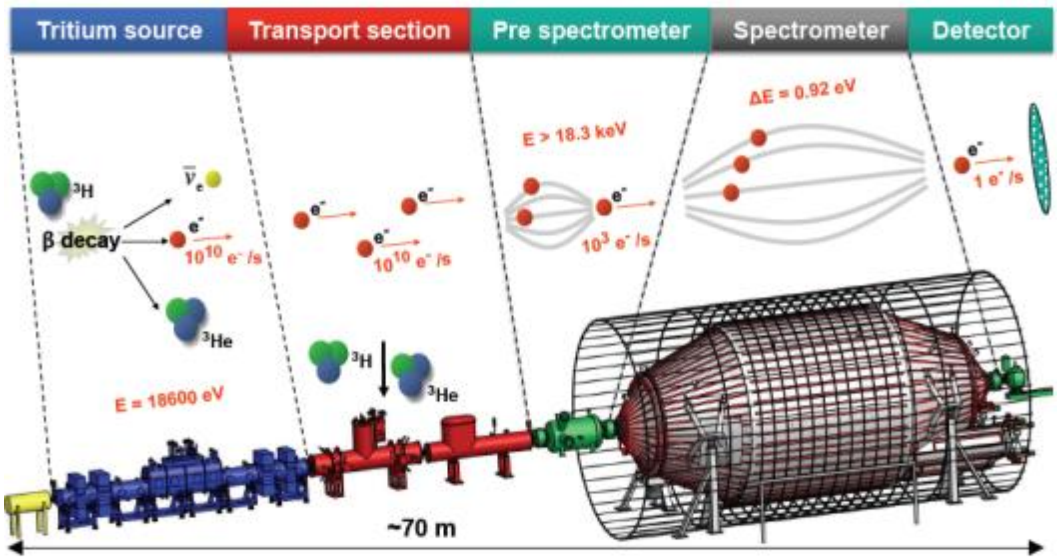
MAINZ: $m^2_\nu = -0.6 \pm 2.2 \pm 2.1$ eV²

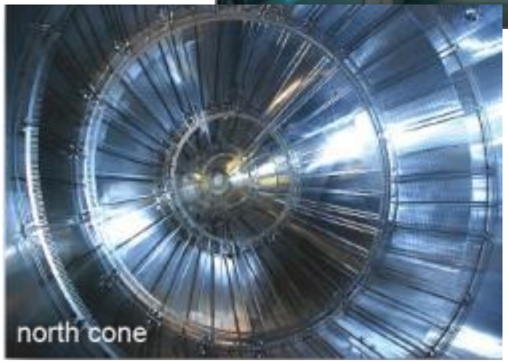
$m_\nu < 2.3$ eV (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

TROISK: $m^2_\nu = -2.3 \pm 2.5 \pm 2.0$ eV²
$m_\nu < 2.05$ eV (95% C.L.)
But systematics from end-point fluctuations not included

KATRIN experiment





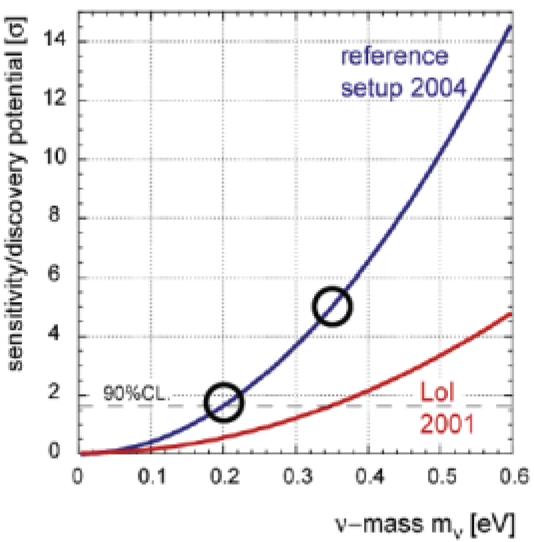
Improvement of ΔE: 0.93 eV (4.8 eV for Mainz)

Larger acceptance

Statistics 100 days → 1000 days

Tests of main spectrometer 2011

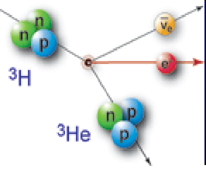
Complete system integration 2012



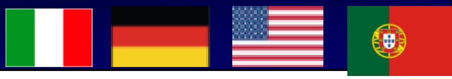
3 yr of data
(5 y real time)

discovery potential
m(ν) = 0.35 eV (5σ)

sensitivity (90% CL)
m(ν) < 0.2 eV

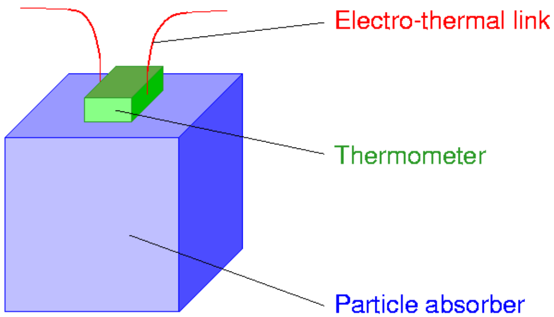


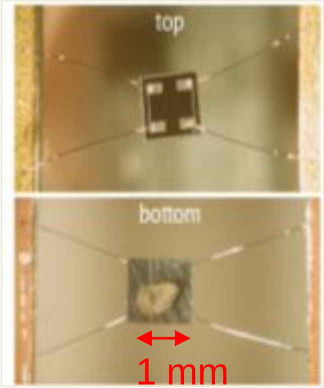
MARE experiment



MicroBolometers of ArReO4

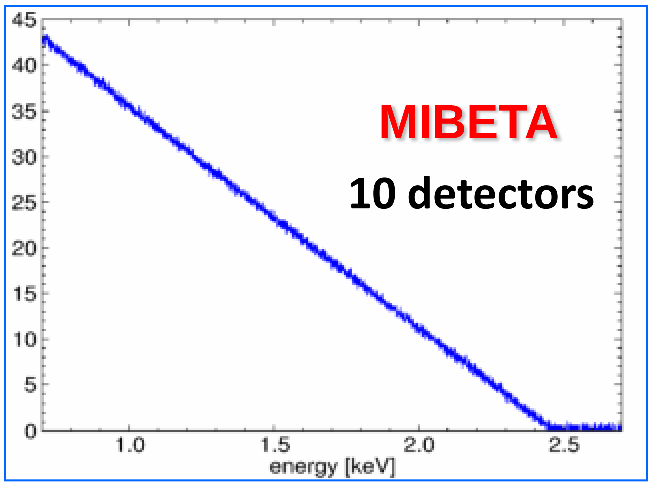
^{187}Re Q_β = 2.47 keV ($T_{1/2}$=4.4 10^{10} yr)





Full energy measurement
No systematic from source
But time response of sensor → pile-up

MARE-I: 300 detectors
FWHM ~20 eV
τ ~100 – 500 μs
$\langle m_\nu \rangle$ < 2 –4 eV (5 years)

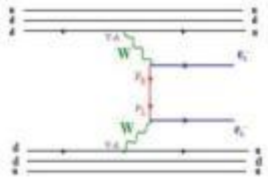


MARE – II : 5000 detectors (~2018)
FWHM ~20 eV
τ ~1 – 5 μs
$\langle m_\nu \rangle$ < 0.2 eV (10 years)

$\langle m_\nu \rangle^2 = -141 \pm 211_{stat} \pm 90_{sys}\ eV^2$

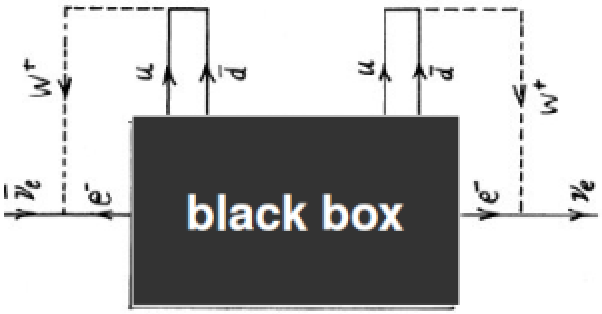
$\langle m_\nu \rangle$ < 15 eV (90% c.l.)

Studies for ^{163}Ho Electron capture
Q_{EC} ~2.6 keV, $T_{1/2}$ = 4600 yr



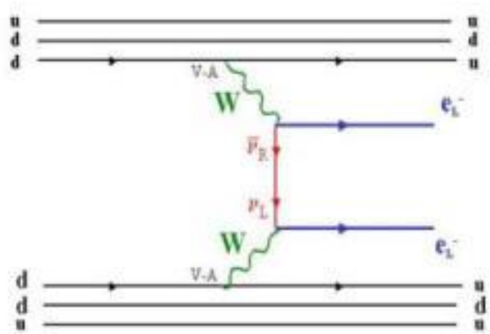
Neutrinoless double beta decay $\beta\beta(0\nu)$

$(A,Z) \longrightarrow (A,Z+2) + 2\,e^-$ $\quad \Delta L=2$



Non-conservation of leptonic number → Majorana neutrinos

Test of new physics : Right Handed Current, Majoron, SUSY,…



Light neutrino exchange

$T_{1/2}^{-1} = F(Q_{\beta\beta}^{5},Z)\ |M|^2 <m_{ee}>^2$

$<m_{ee}> = m_1|U_{e1}|^2 + m_2|U_{e2}|^2.e^{i\alpha 1} + m_3|U_{e3}|^2.e^{i\alpha 2}$

|Uei|: mixing matrix element, α1 et α2: Majorana phase

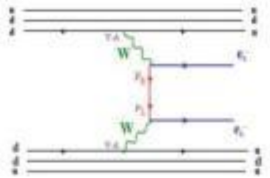
Experimentally

$T_{1/2}^{0\nu}(y) \propto \frac{\varepsilon}{A}\ M\ .\ t$

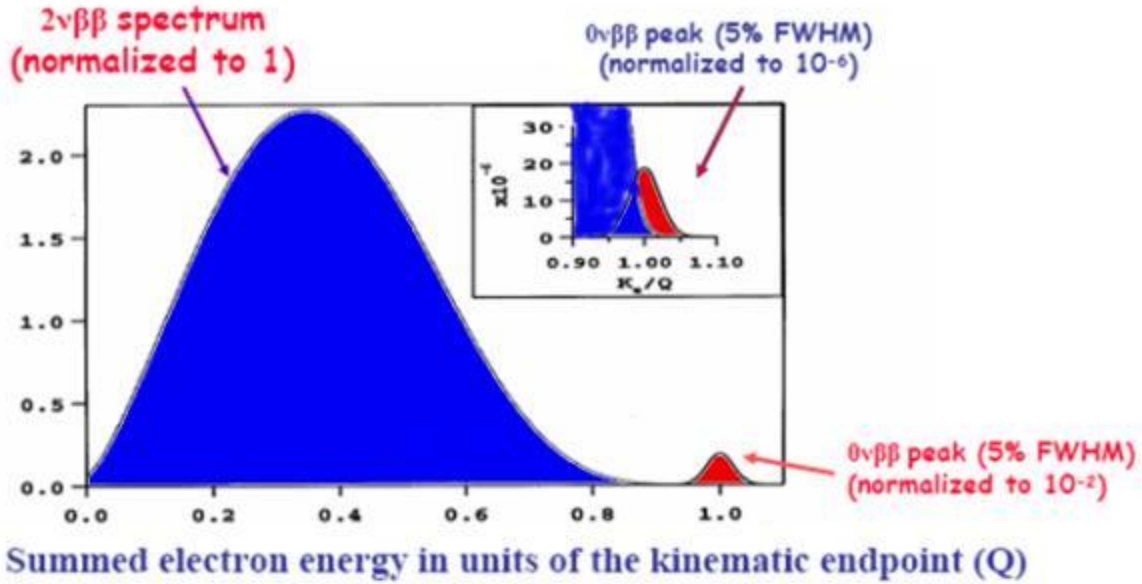
NO Background

$T_{1/2}^{0\nu}(y) \propto \frac{\varepsilon}{A}\sqrt{\frac{M\ .\ t}{N_{Bckg}\ .\ \Delta E}}$

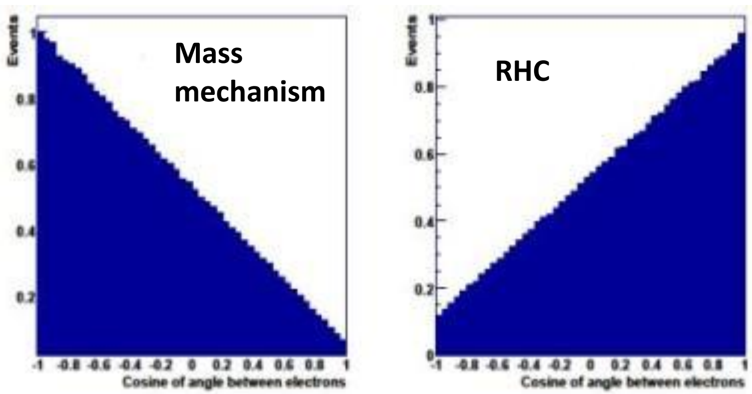
With Background



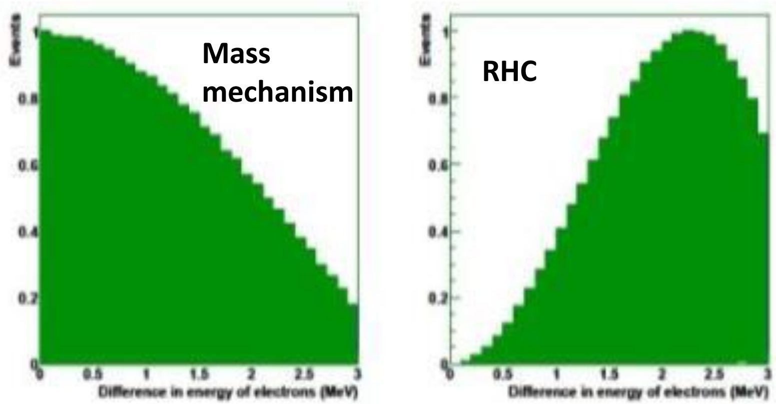
ββ(0ν) observables



From G. Gratta

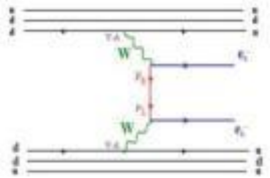


Angular distribution

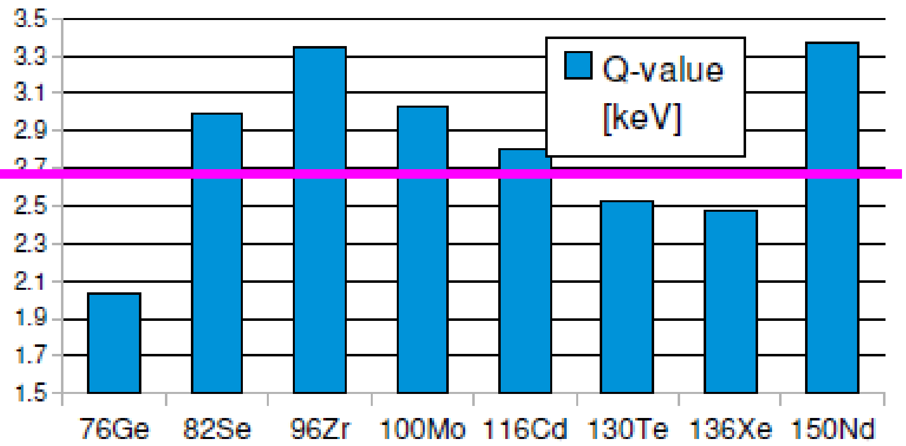


Ee1 – Ee2 distribution

150Nd distribution s arxiv: 1005.1241v1 [hep-ex]

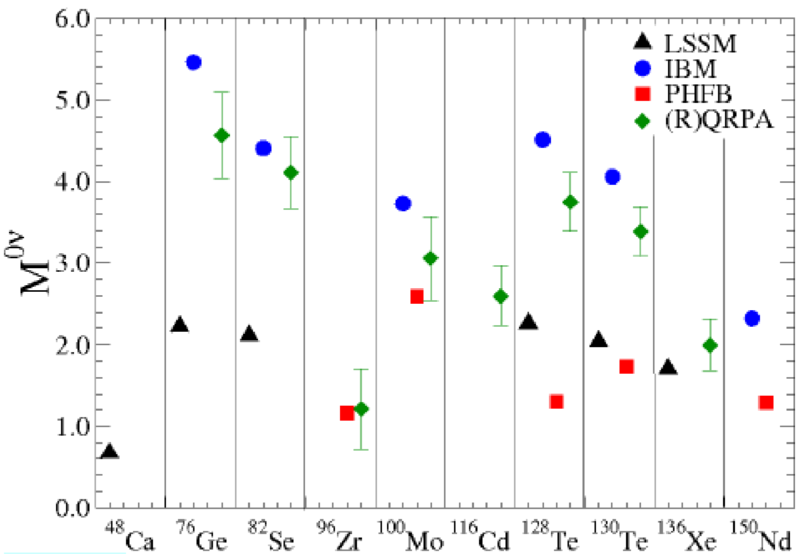


ββ(0ν): isotope choice



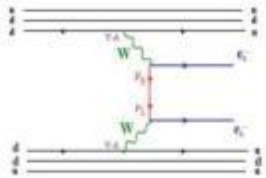
2.614 MeV
Highest gamma-ray
from natural radioactivity

Double beta decay isotopes



Nuclear matrix elements

From F. Simkovic (neutrino 2010)



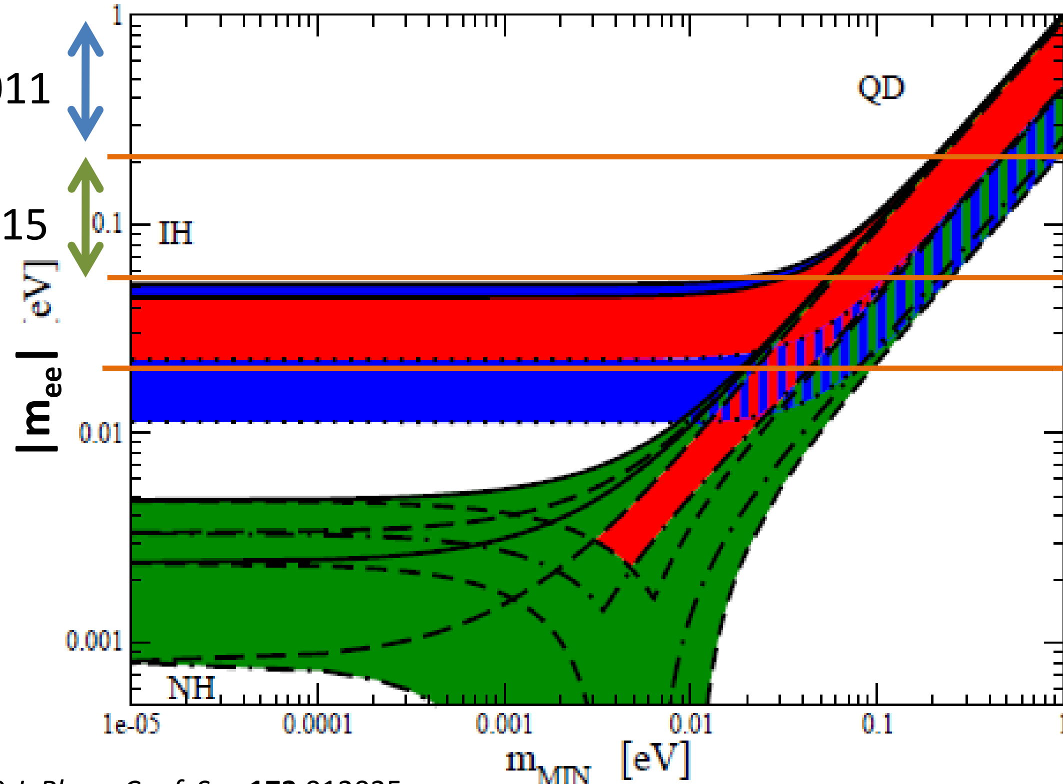
Effective neutrino mass and θ_{13}

$$|\langle m_\nu \rangle| = |\sum U_{e_i}^2 m_i| = |\cos^2\theta_{13}(m_1 \cos^2\theta_{12} + m_2 e^{2i\alpha} \sin^2\theta_{12}) + m_3 e^{2i\beta} \sin^2\theta_{13}|$$

Isotope mass

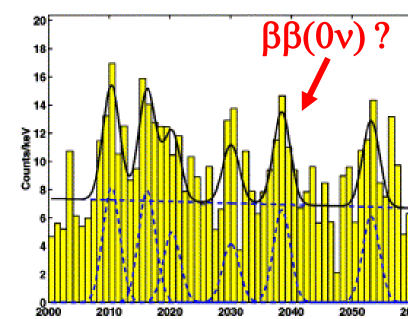
Required background level

Isotope mass		Required background level
~ 10 kg	2011	100 – 1000 cts/yr/ton
~ 100 kg	2015	1 – 10 cts/yr/ton
~ 1000 kg		0.1 – 1 cts/yr/ton



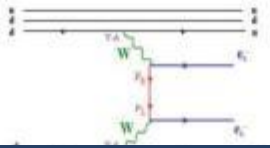
S T Petcov 2009 *J. Phys.: Conf. Ser.* **173** 012025

Heidelberg-Moscow (2001)
~11 kg of enriched Ge

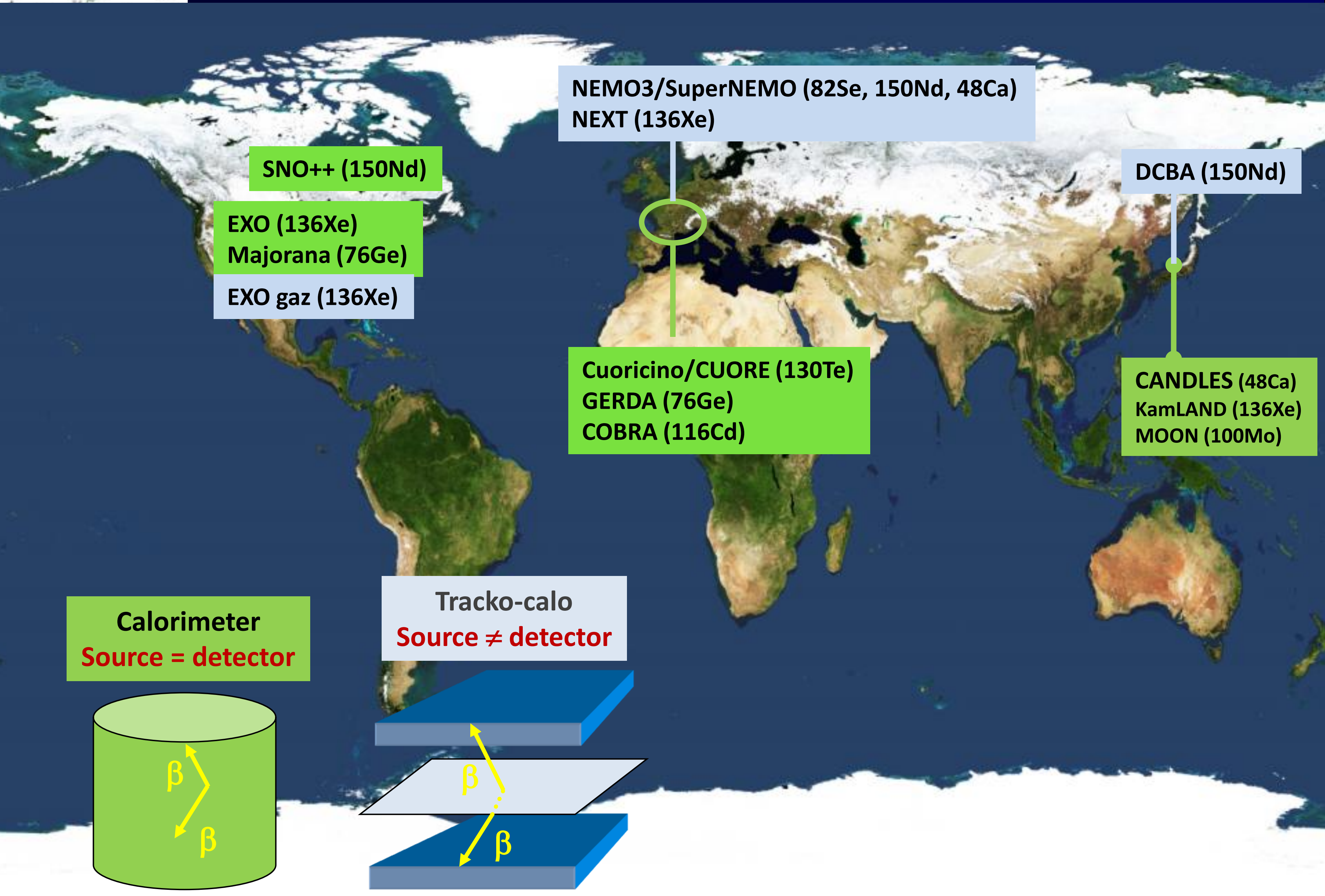


- PSA analysis (Mod. Phys. Lett. A21): (2.23 + 0.44 – 0.31)x10^{25} y (6σ)
- Tuebingen/Bari group (PRD79): m_{ee} /eV = 0.28 [0.17-0.45] 90%CL

Next step ~ 100 kg experiment 2011 - 2015

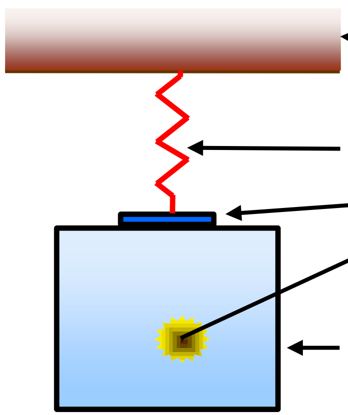


$\beta\beta(0\nu)$: experiments and projects



Cuoricino

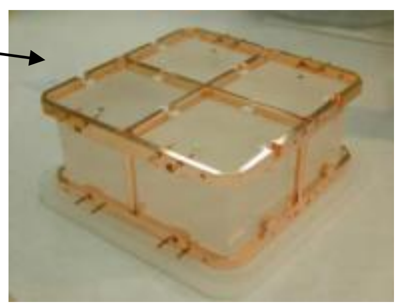
Bolometers of TeO_2 (33.8% of ^{130}Te) ($Q_{\beta\beta}$= 2.528 MeV)

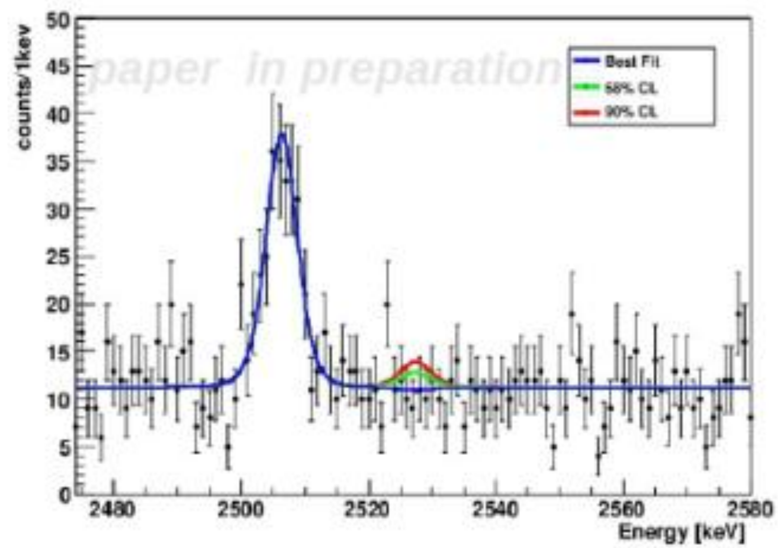


41 kg of ^{nat}Te → 11.6 kg of ^{130}Te

$\Delta E/E$ ~ 8 keV at 2 527 keV

Bckg: 0.169 cts/keV/kg/yr

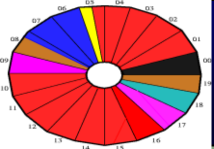




anti-coincidence sum spectrum
19.75 kg (^{130}Te) × y
$\tau_{1/2} \geq 2.8 \times 10^{24}$ years at 90% C.L.
$\langle m_\nu \rangle \leq 0.3 \div 0.7$ eV *

See talk A. Nucciotti

NEMO 3

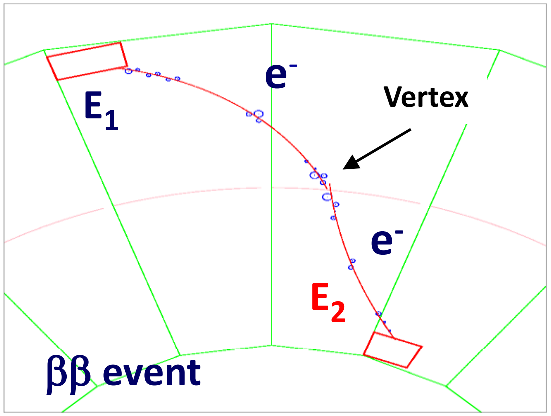


See talk Ch. Marquet

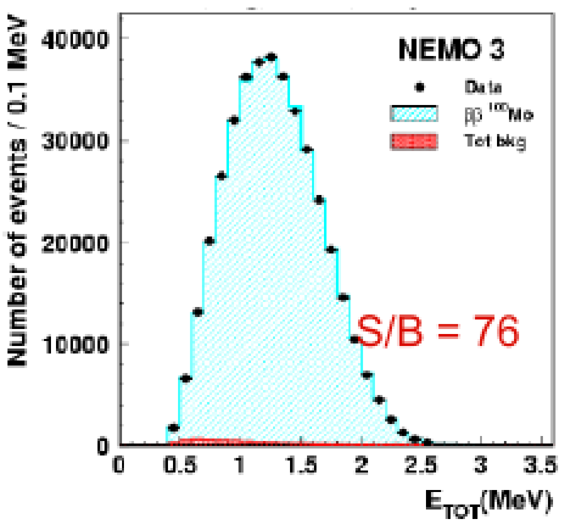
Tracko-calo detector

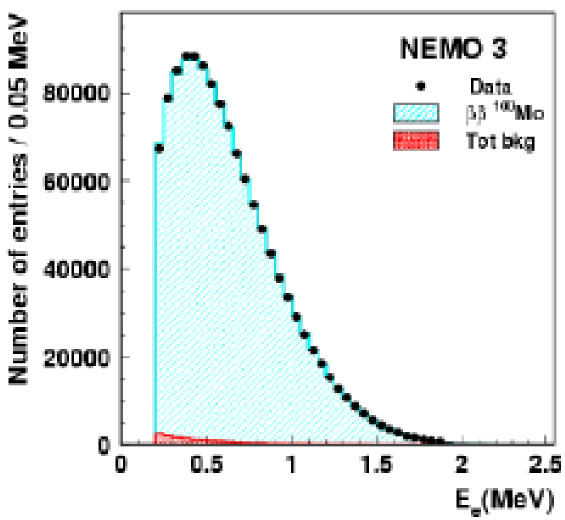
Drift chamber (6000 cells)
Plastic scintillator + PMT (2000)
10 kg of isotopes
Multi-isotopes
$\Delta E/E$ (FWHM) : 8 % @ 3 MeV

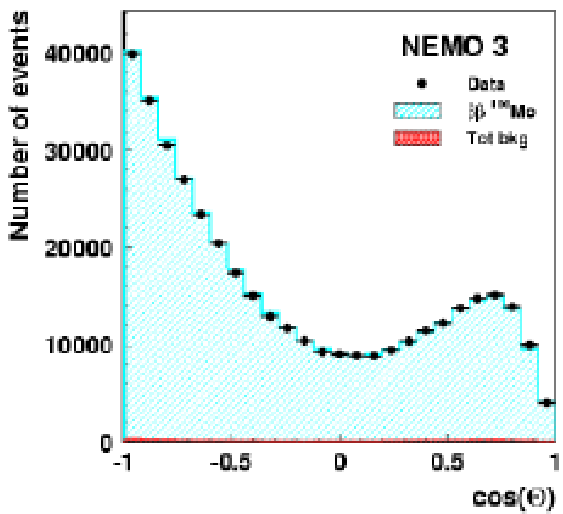
Bckg: 0.025 cts/keV/kg/yr



100Mo, 7 kg, 1275 days, 620 000 events



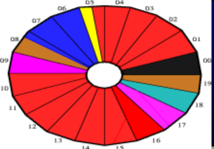




$$T_{1/2}(2\nu) = [7.17 \pm 0.01(stat) \pm 0.54(sys)] \times 10^{18}\ yr$$

to be compared with earlier published in PRL 95 (182302) 2005:

$T_{1/2}(2\nu) = [7.11 \pm 0.02(stat) \pm 0.54(sys)] \times 10^{18}$ yr ⇒ ~1 yr, Phase I, S/B = 40



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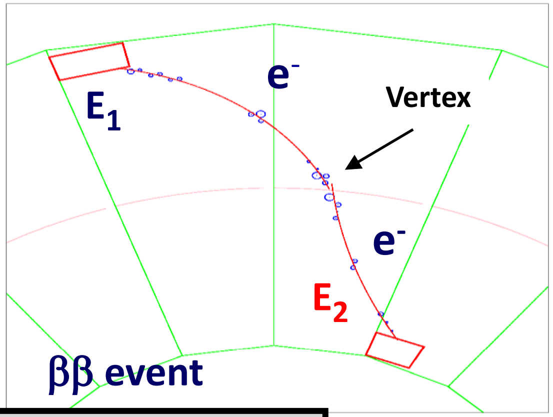
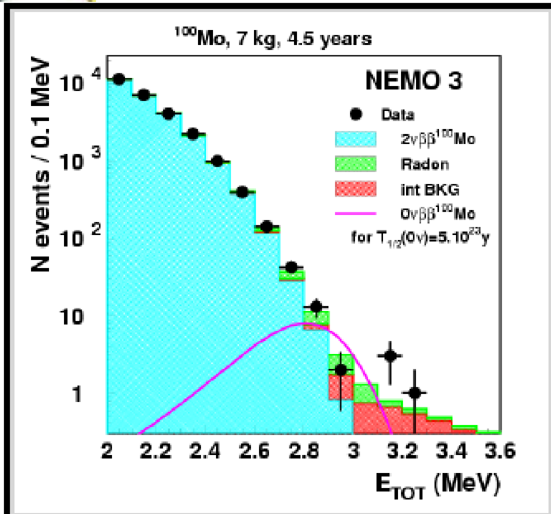


See talk Ch. Marquet

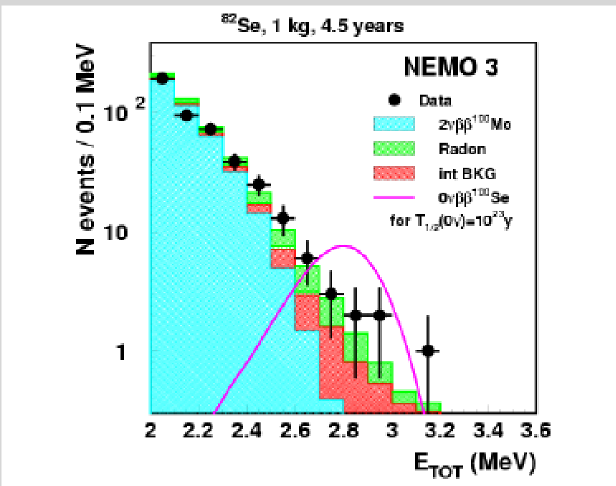


[2.8-3.2] MeV: DATA = 18; MC = 16.4±1.4

$T_{1/2}(0\nu) > 1.0\times10^{24}$ yr at 90%CL

$<m_\nu> < (0.47 - 0.96)$ eV

V+A: $T_{1/2}(0\nu) > 5.4\times10^{23}$ yr at 90%CL
Majoron: $T_{1/2}(0\nu) > 2.1\times10^{22}$ yr at 90%CL

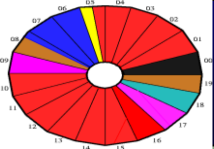


[2.6-3.2] MeV: DATA = 14; MC = 10.9±1.3

$T_{1/2}(0\nu) > 3.2\times10^{23}$ yr at 90%CL

$<m_\nu> < (0.94 - 2.5)$ eV

$\lambda < 1.4\times10^{-6}$
$g_{ee} < 0.5\times10^{-4}$ World's best result!



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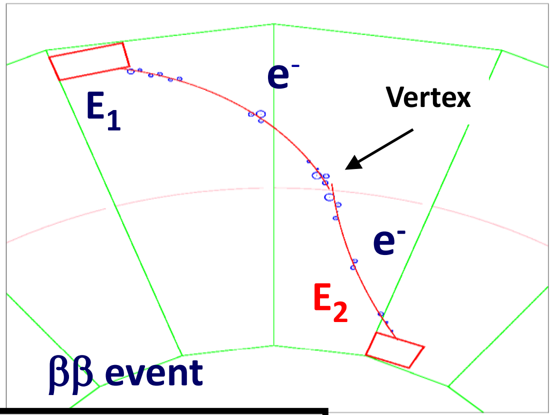
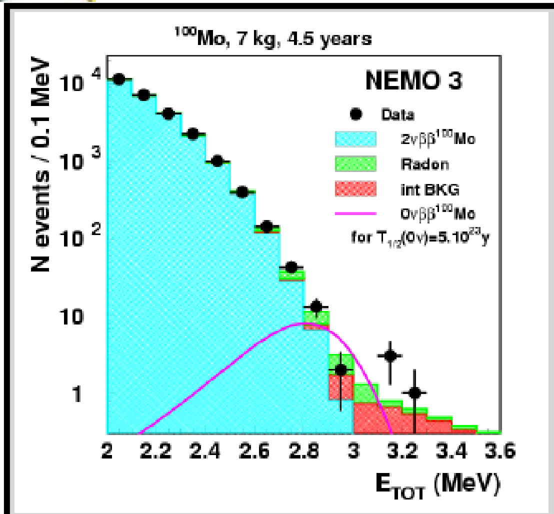
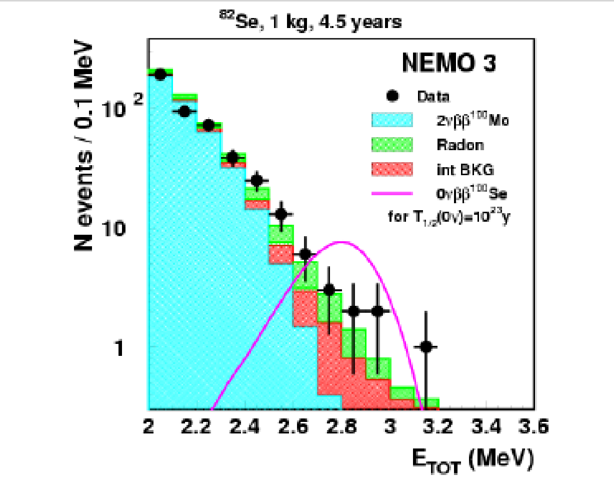


See talk Ch. Marquet





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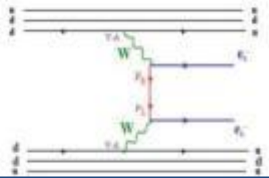
Also $T_{1/2}$ (2ν) and $T_{1/2}$ (0ν) for ^{48}Ca, ^{150}Nd, ^{116}Cd, ^{96}Zr, ^{130}Te, ^{82}Se and excited states, majoron, etc….

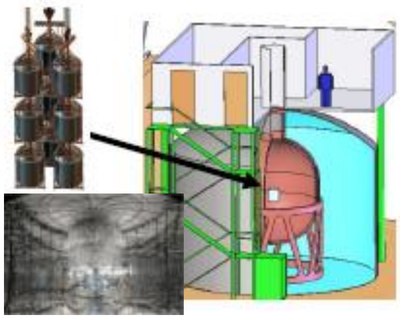


100 kg experiments

Step by step approach

See talks A. Nucciotti, Ch. Marquet

GERDA Ge diode in LAr



Gran Sasso laboratory

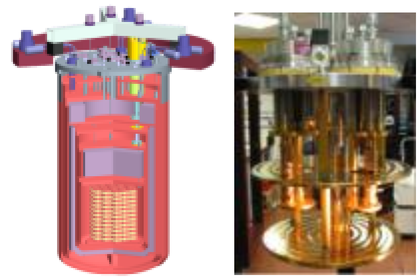
2010: 18 kg of ^{76}Ge
(HM and IGEX crystals)

1st results 2011

2012: 40 kg of 76Ge

+ Energy resolution

CUORE ^{130}Te bolometers



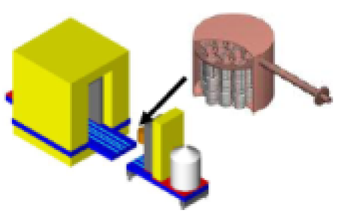
Gran Sasso laboratory

CUORE-0 39 kg of ^{nat}Te
13 kg of ^{130}Te
Data taking 2011

CUORE 200 kg
Data taking 2013
(scintillating bolometres ?)

+ Energy resolution
+ Natural Te

MAJORANA Ge segmented Diode



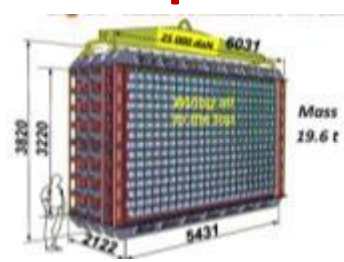
DUSEL laboratory

2011: 20 kg of ^{nat}Ge

2013 ? : 30 kg of ^{76}Ge

+ Energy resolution

SuperNEMO tracko-calo

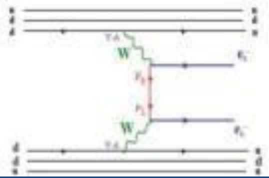


Modane laboratory

Module-0
7 kg of ^{82}Se (^{150}Nd)
Data taking 2013

20 Module 100 kg
Data taking 2015

+ Background rejection
+ Multi-isotopes



100 kg experiments

Agressive approach

See talks Carter Hall, Alfredo Thomas, Masayuki Koga

EXO liquid Xenon

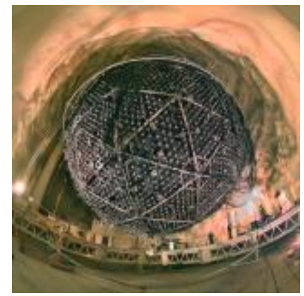
WIPPL laboratory

2010: 200 kg of ^{136}Xe
Results 2013

Ba tagging R&D

+ Large mass
+ Possibility to tag daughter nucleus

SNO++ Nd salt + liquid scintillator



SNOLAB laboratory

2010: 740 kg of ^{nat}Nd
(44 kg of ^{150}Nd)
Dissolved in scintillator

+ Large mass
+ low background detector

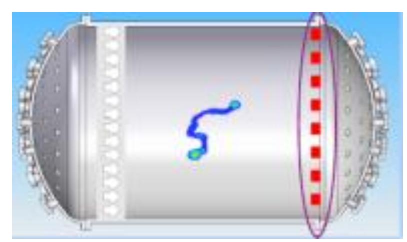
KamLAND-Zen Xe + liq. scintillator

Kamioka laboratory

2011: 400 kg of ^{136}Xe
Dissolved in
liq. scintillator

+ Large mass
+ low background detector

NEXT Xe high pressure TPC

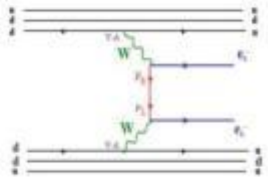


Canfranc laboratory

2011: 1 kg of ^{136}Xe

2013 : 100 kg

+ Background rejection



Sensitivities 2013 - 2018

	Technique	Location	Mass kg	start	Bckg Cts/keV/kg/yr	$T_{1/2}(0\nu)$ 5 yr	$\langle m_{ee} \rangle$ meV
EXO	Liquid Xe ^{136}Xe	WIPP (USA)	200	2010	0.002	$6.4\ 10^{25}$	< 109 - 135
GERDA	Diode Ge ^{76}Ge	Gan sasso (Italy)	18 40	2010 2012	0.01 0.001	$3.\ 10^{25}$ $3.\ 10^{26}$	< 250– 380 < 80 - 120
CUORE-0 CUORE	Bolometers ^{130}Te	Gan sasso (Italy)	13 200	2011 2013	0.12 0.01 0.001	$8.\ 10^{25}$ $2.1\ 10^{26}$ $6.5\ 10^{26}$	<100 - 200 < 41 -82 < 23- 47
SN module0 SuperNEMO	Tracko-calo ^{82}Se, ^{150}Nd	Modane (France)	7 100	2013 2015	0.0001 0.0001	$6.\ 10^{24}$ 10^{26}	< 200 –600 < 53 – 145
SNO+	Liq. Scint. ^{150}Nd	SNOLAB (Canada)	44	2012			< 100
KamLAND	Liq. Scinti ^{136}Xe	Kamioka (Japan)	400	2011			< 60 (2 yr)

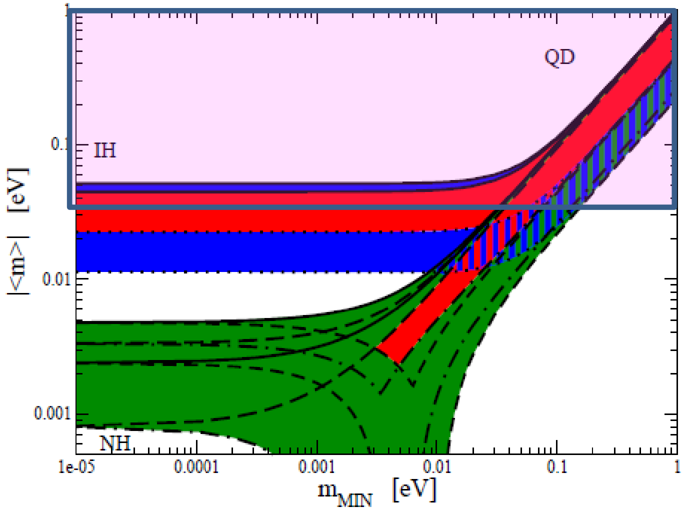
Summary

Measure of sin $2\theta_{13}$ with reactor neutrinos 2015 sin $2\theta_{13} < 0.01 – 0.03$

Direct m_ν measurement 2017 $m_\nu < 0.2$ eV

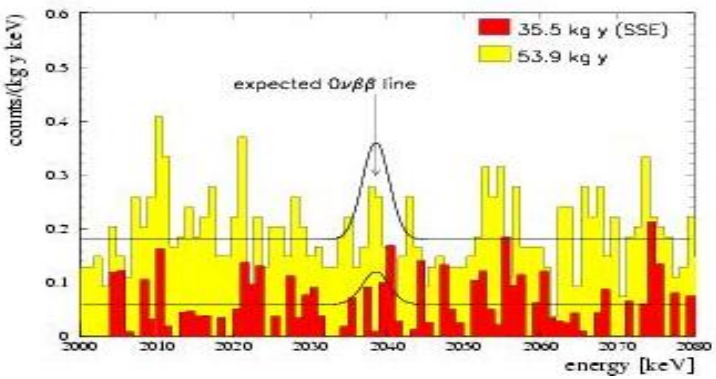
Double beta decay 2013 – 2018 100 kg experiments $<m_{ee}> < 40$ -100 meV

Need to know the results for 1 ton experiment choice (isotope, technique)
If discovery, tracking detector needed to determine the process



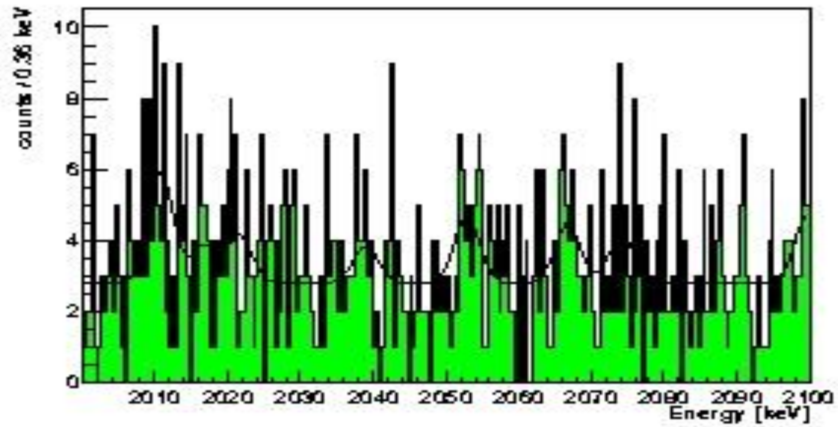
ββ(0ν) signal ? HM claim

2001



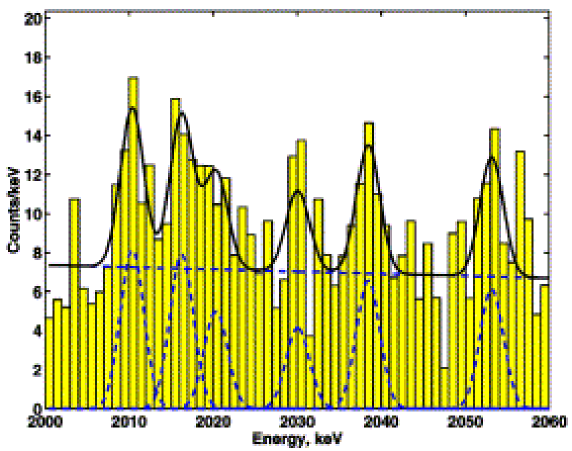
$T_{1/2}$ >1.9 10^{25} $<m_{■}>$ < 0.35-1.05 (90%)

2002 (3.1σ)



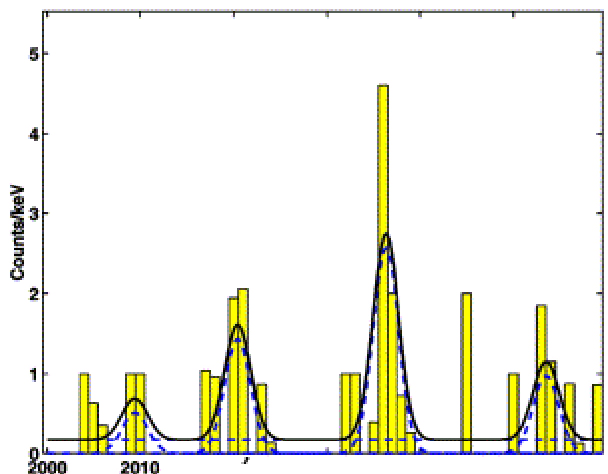
$T_{1/2}$= (0.8-18.3) 10^{25} yr $<m_{■}>$= 0.11 – 0.56 eV

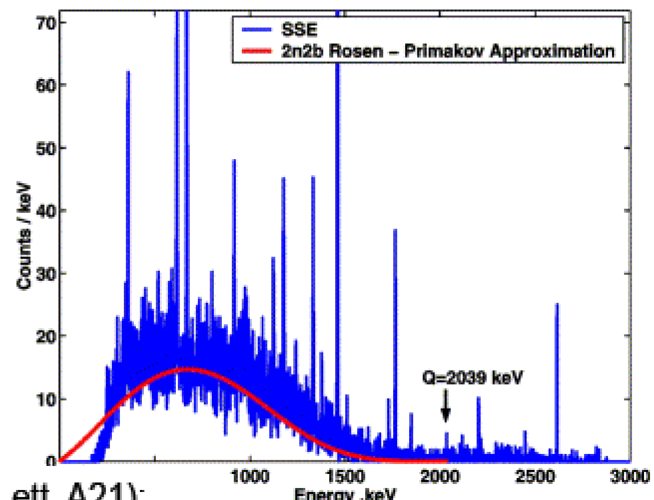
2004: new calibration (4σ)



$$T_{\frac{1}{2}} = (0.69 - 4.18) 10^{25} \, ans \, (90 \; CL)$$

$$\langle m_{\nu} \rangle = 0.28 - 0.58 \, eV$$



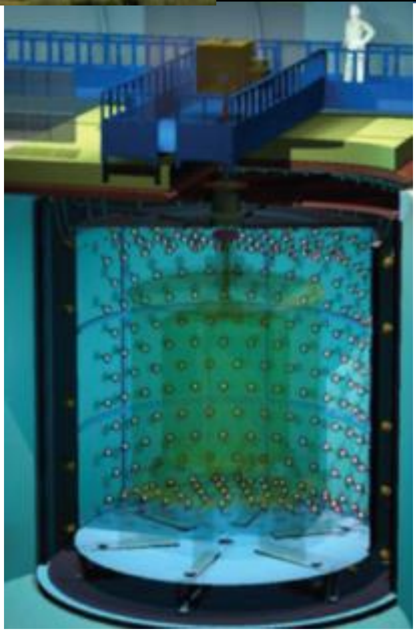


- PSA analysis (Mod. Phys. Lett. A21): (2.23 + 0.44 – 0.31)x10^{25} y (6σ)
- Tuebingen/Bari group (PRD79): m_{ee} /eV = 0.28 [0.17-0.45] 90%CL

Schedule for data taking

	Near detector	Far detector
Double Chooz	2012	2010
RENO	2010	2010
DAYA BAY	DB 2011 LA 2012	2012

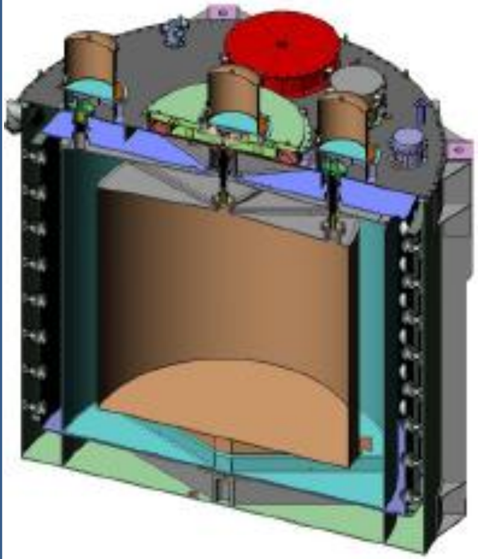
Detectors



410 m (120 m.w.e.)
400 ν/day

1050 m (300 m.w.e)
40 ν/day

Target: 8.6 t

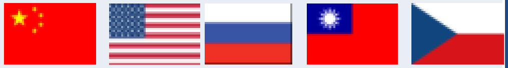
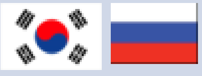


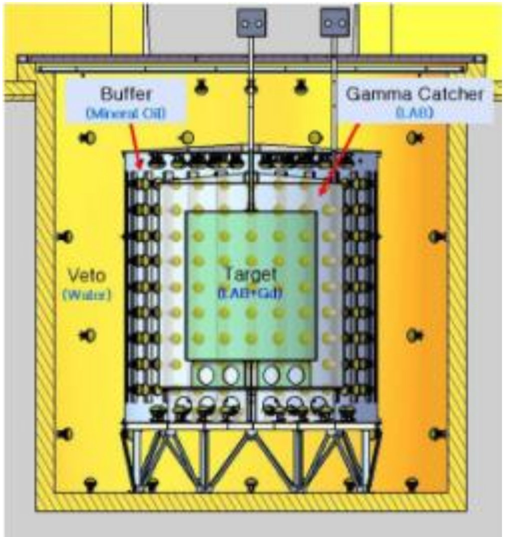
LA (260 m.w.e.) x2
740 ν/day

DB (300 m.w.e.) x2
840 ν/day

Far (910 m.w.e.) x4
90 ν/day

Target: 20 t/detector

	Collaborations
Double Chooz	
DAYA BAY	
RENO	



290 m (120 m.w.e.)
1280 ν/day

1380 m (450 m.w.e)
114 ν/day

Target : 16 t