Neutrinoless Double Beta Decay (Experiment)

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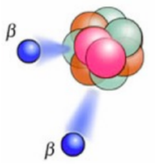
Symmetry Tests in Nuclei and Atoms

Kavli Institute for Theoretical Physics, UC Santa Barbara, Sep 19-23, 2016

Double-β decays

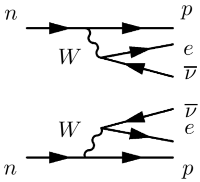
Second order nuclear transitions $\rightarrow$ decay of two neutrons into two protons:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \dots$$



2-neutrino double-β decay ($2\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- allowed in the Standard Model
- measured in several isotopes (^{48}Ca, ^{76}Ge, ^{82}Se...)
- $T^{2\nu}_{1/2}$ in the range $10^{19} - 10^{24}$ yr



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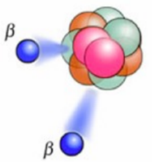

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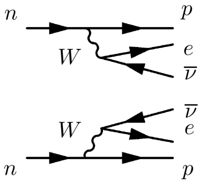
- $T_{1/2}^{2\nu}$ in the range $10^{19} - 10^{24}$ yr



$T_{1/2}^{2\nu}$ up to a hundred trillion times the age of the universe (13 billion years)

Double-β decays

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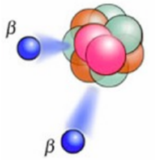
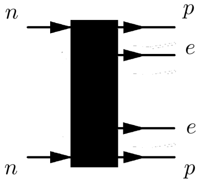


Neutrinoless double-β decay ($0\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- foreseen by many extensions of the Standard Model
- possible for several isotopes (^{48}Ca, ^{76}Ge, ^{82}Se...)
- $T^{0\nu}_{1/2}$ limits in the range $10^{21} - 10^{26}$ yr



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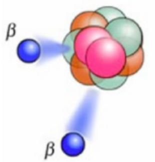

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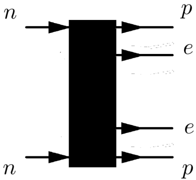
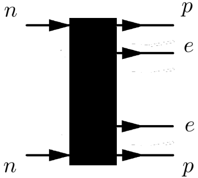


$<$ 50% probability for an atom to decay in a trillion trillion years

Why to look for neutrinoless double-β decay?

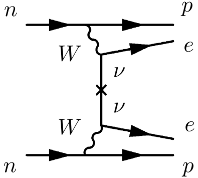
Independently from underlying physics:

- lepton-genesis process measurable in lab
  $\Rightarrow$ matter-antimatter asymmetry of the universe
- ν has non-null Majorana mass component



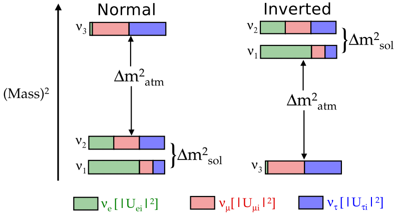
Assuming light-Majorana ν exchange:

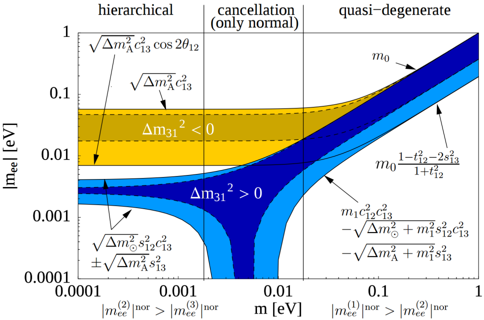
- constrains on $|m_{\beta\beta}| \equiv \left|\sum_i U_{ei}^2 m_i\right|$
- constrains on the lightest neutrino mass eigenstate
- mass hierarchy
- interplay with other neutrino mass observables



Neutrinoless double-β decay & neutrino physics

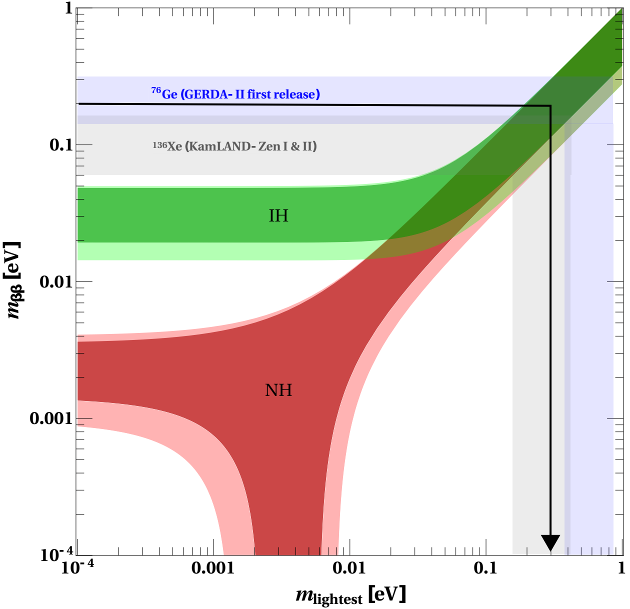
- ν phenomenology: 3 mixing angles, 3 mass eigenvalues, 3 phases
- ν oscillations provide info only on mixing angles, Δm^2 and one phase
- $|m_{\beta\beta}| \equiv \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}\right|$





[Phys. Rev. D 73, 053005]

Current constrains



[Dell'Oro et al, Adv.High Energy Phys. 2016 (2016)]

Most stringent limits:

$T^{0\nu}_{1/2}(^{76}\text{Ge}) > 5.2 \cdot 10^{25}$ yr

$\Rightarrow |m_{\beta\beta}| < (150 - 330)$ meV

$T^{0\nu}_{1/2}(^{136}\text{Xe}) > 10.7 \cdot 10^{25}$ *yr*

$\Rightarrow |m_{\beta\beta}| < (61 - 165)$ meV

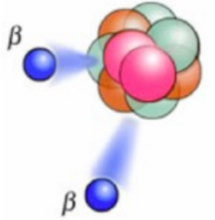
$\Rightarrow |m_{\text{light}}| < (180 - 480)$ meV

Target next generation: IH

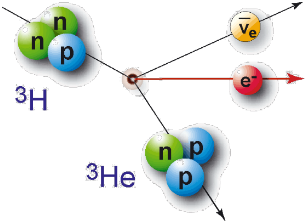
$\Rightarrow T^{0\nu}_{1/2} \sim 10^{27}$ yr

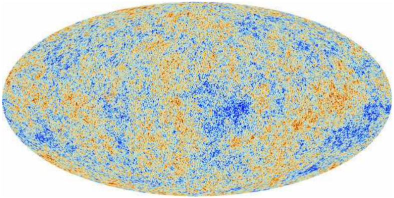
Neutrino mass observables

$0\nu\beta\beta$: $|m_{\beta\beta}| \equiv \left|\sum_i U_{ei}^2 m_i\right|$



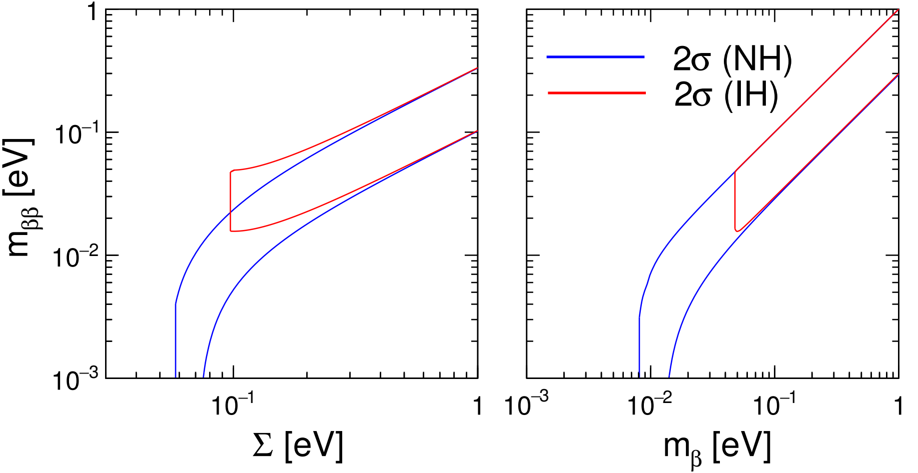
β-decay [KATRIN]:
$\langle m_\beta \rangle \equiv \sqrt{\sum_i |U_{ei}|^2 \, m_i^2}$





Cosmology $\Sigma \equiv \sum_i m_i$

Neutrino mass observables



[adapted from Capozzi et al, Nucl.Phys. B908 (2016)]

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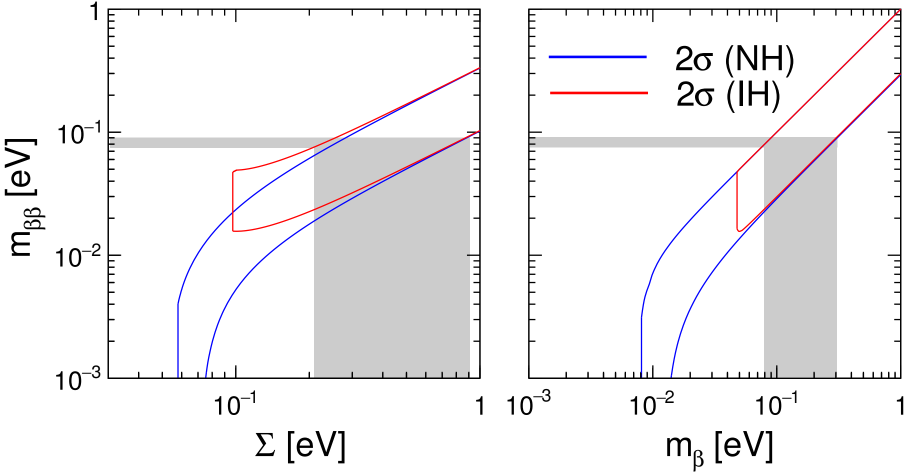

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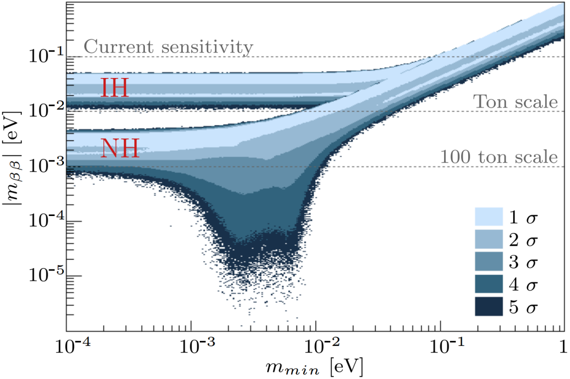
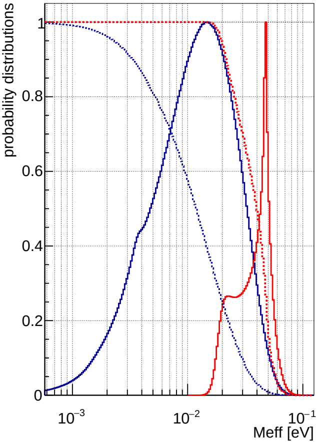
Discovery potential assuming "naturalness"

- The value of $|m_{\beta\beta}|$ could be fixed by a symmetry
  $\Rightarrow$ all parameter space must be explored
- The value of $|m_{\beta\beta}|$ could be accidental:
  $\Rightarrow$ parameter space not equiprobable
  $\Rightarrow$ higher discover power



[G. Benato, EPJC (2015) 75]

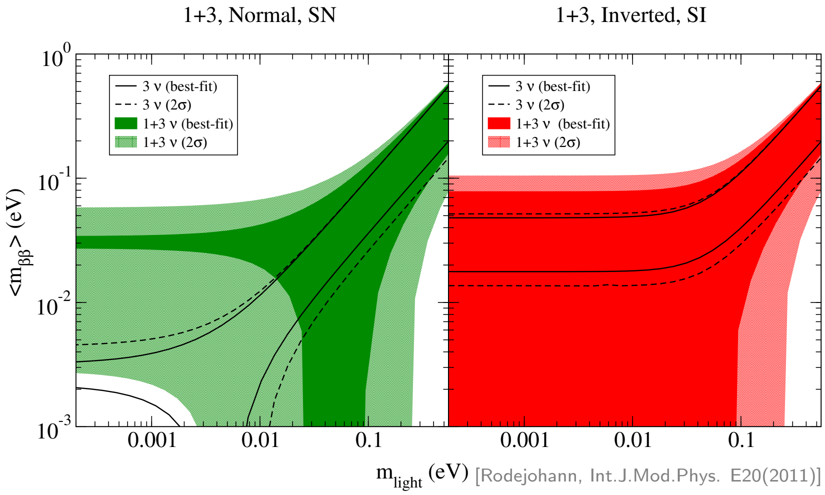
With cosmological constrains:



[M.A. and G. Benato, in preparation]

$\Rightarrow$ Next generation is sensitive also to normal hierarchy!

Discovery potential assuming light sterile neutrinos

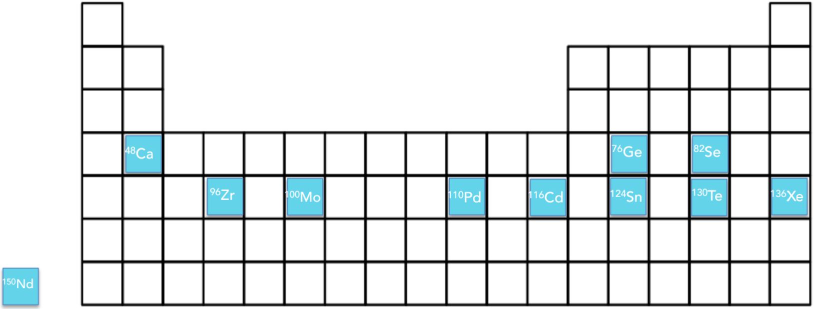


[Rodejohann, Int.J.Mod.Phys. E20(2011)]

A discovery could be very far but also around the corner!

Double-β decaying isotopes

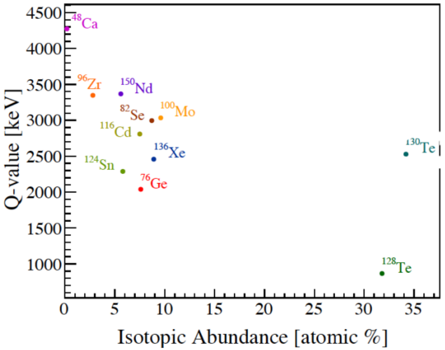
35 isotopes available, ~ 9 used for $0\nu\beta\beta$ searches:

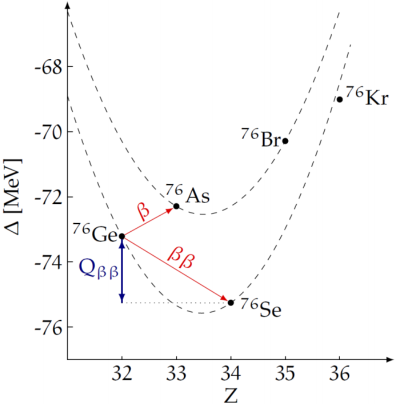


[from K. Schäffner]

Double-β decaying isotopes

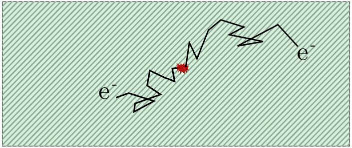
- single β-decay must be energetically forbidden
- $(T_{1/2}^{0\nu})^{-1} \propto G_{0\nu}(Q_{\beta\beta}, Z) \propto (Q_{\beta\beta})^5$
- isotopic enrichment
- different detection techniques for different isotopes





Detection approaches

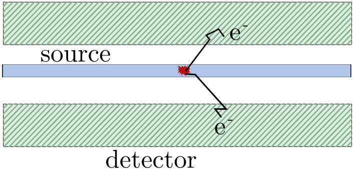
Calorimeter: source = detector



[adapted from Dell'Oro et al, Adv.High Energy Phys. 2016 (2016)]

- hight efficiency
- good energy resolution
- large masses

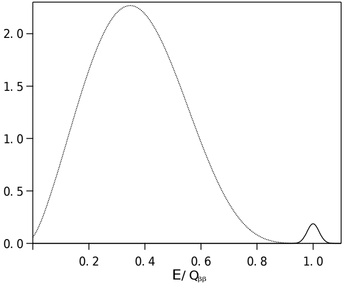
External-source detector



- smoking gun signature
- single electron information
- possible to study different isotopes

Electron sum energy spectrum:

- $(A, Z) \to (A, Z+2) + 2e^- + 2\nu$
  $\Rightarrow$ continuum energy distribution
- $(A, Z) \to (A, Z+2) + 2e^-$
  $\Rightarrow$ energy $= Q_{\beta\beta}$

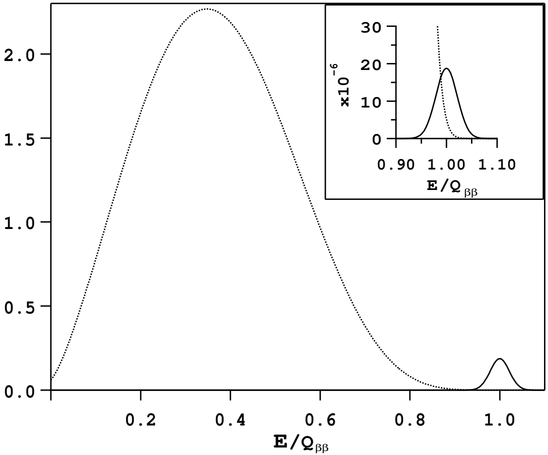


[S. Elliot et al., Ann.Rev.Nucl.Part.Sci. 52 (2002)]

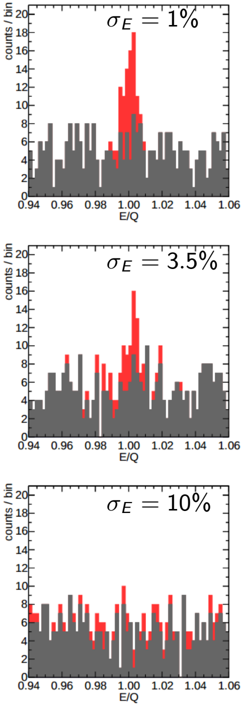
Energy resolution and background

Good energy resolution needed

$\rightarrow$ mitigation of $2\nu\beta\beta$ and other backgrounds



[Ann.Rev.Nucl.Part.Sci. 52 (2002)]



[J. J. Gòmez-Cadenas et al., PoS (GSSI2014), 004 (2015)]

Signal and background rates

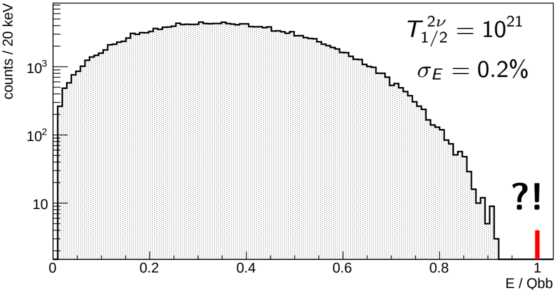
Number of expected $0\nu\beta\beta$ events:

$$N_{0\nu\beta\beta} = \ln 2 \cdot \varepsilon \cdot N_{atoms} \cdot \frac{t}{T^{0\nu}_{1/2}} \qquad \begin{cases} \varepsilon\text{: detection efficiency} \\ N_{atoms}\text{: number of target } 0\nu\beta\beta\text{-decaying atoms} \\ t\text{: data taking time in yr} \end{cases}$$

Let's assume:

- 100 kg of target material $\Rightarrow N_{atoms} = 10^{26} - 10^{27}$
- $\varepsilon = 70\%$
- $T^{0\nu}_{1/2} = 10^{26}$ yr

$\Rightarrow N_{0\nu\beta\beta} = \mathcal{O}(1)$ event/yr

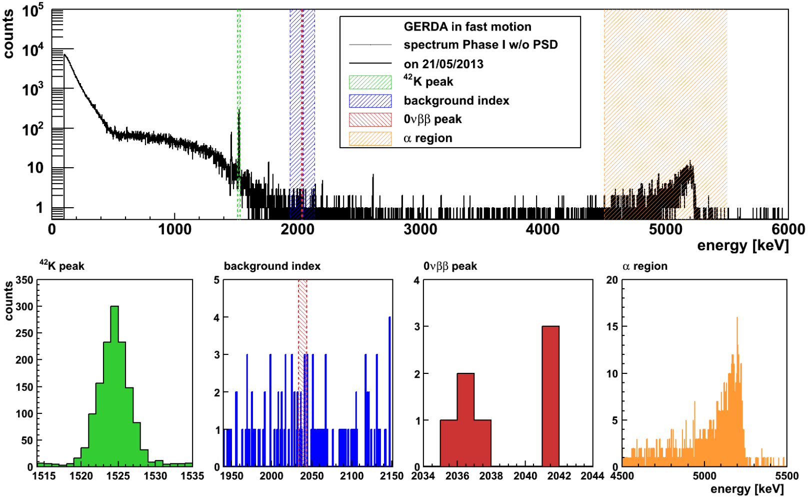


The background events in the ROI ($Q_{\beta\beta} \pm 2\sigma$) must also be $\mathcal{O}(1)$ event/yr

$\Rightarrow$ background level below 0.01 cts/(keV· kg· yr)

Background rate (GERDA Phase I with ^{76}Ge)

Exposure: $\sim$20 kg·yr   ROI width: 5 keV   BI=0.01 cts/(keV· kg· yr)



Experimental sensitivity

ROI background free:

$$T^{0\nu}_{1/2} > \ln 2 \cdot \varepsilon \cdot (mass \cdot time)$$

$$mass \cdot time = exposure$$

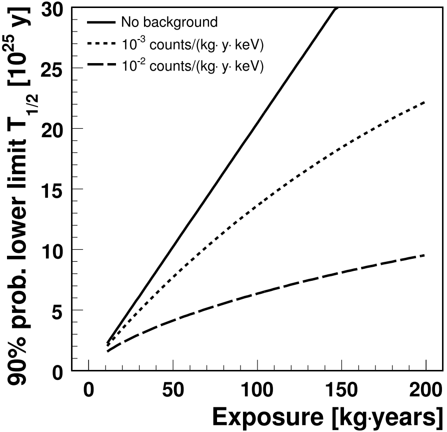
ROI background limited:

$$T^{0\nu}_{1/2} > \ln 2 \cdot \varepsilon \cdot \sqrt{\frac{mass \cdot time}{\Delta E \cdot \mathrm{BI}}}$$

ΔE energy resolution

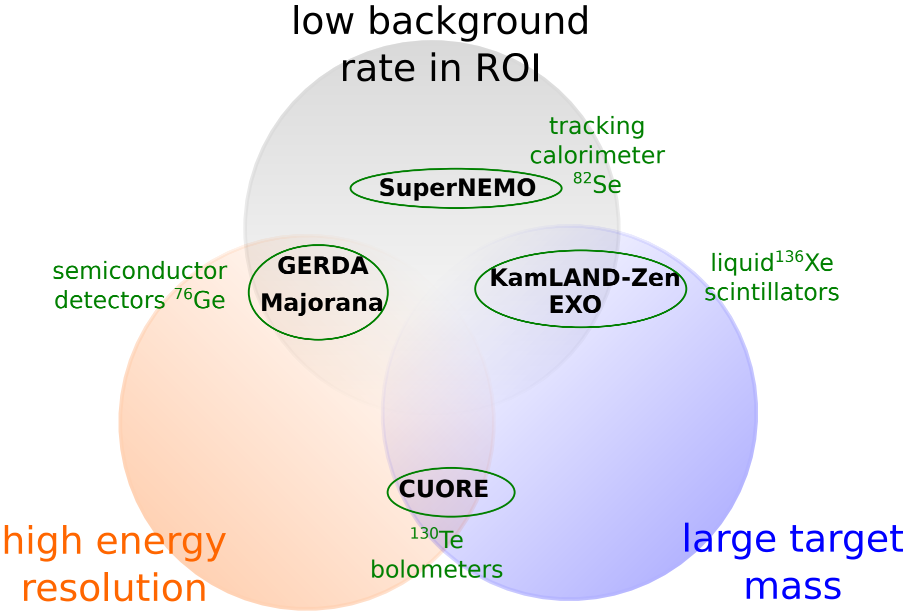
BI: background level at $Q_{\beta\beta}$

Assuming a ROI of a few keV:



important parameters:	mass	energy resolution	background at $Q_{\beta\beta}$
current experiments:	10-1000 kg	0.1-10%	10^{-3}-10^{-2} cts/(keV· kg· yr)

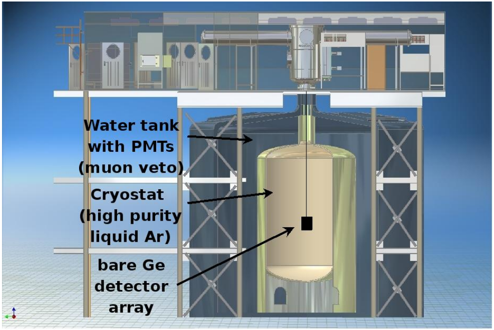
Experimental approaches

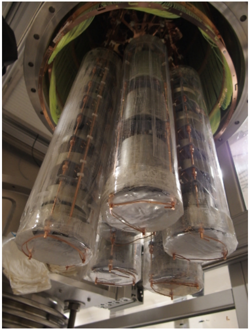


GERDA Phase II @ LNGS (Italy)

Isototope:	^{76}Ge ($Q_{\beta\beta}$=2039 kev)
Resolution:	3-4 keV FWHM
Background:	10^{-3}cts/(keV· kg· yr)
Mass:	30 kg
Technology:	Ge semiconductor detectors
	+ LAr scintilation veto
Status:	running

- 37 detectors
- 7 strings

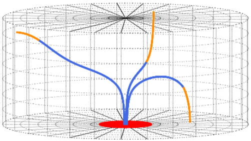




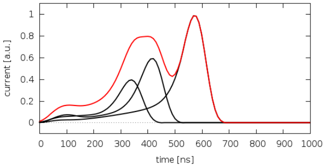
GERDA: active background suppression

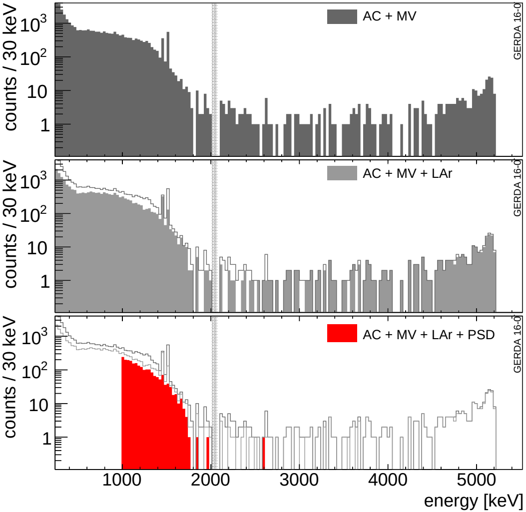
Pulse shape discrimination

- $0\nu\beta\beta$: point like events
- background: multi site / surface events



M. Agostini et al.
JINST 6 (2011) P03005



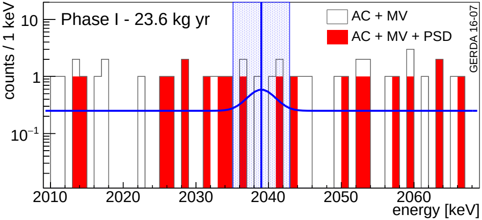


Exposure (BEGe only) $=5.8\,\mathrm{kg{\cdot}yr}$

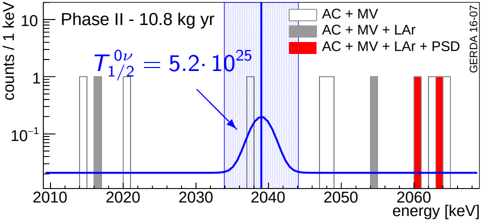
BI$=\ 7^{+11}_{-5}\cdot 10^{-4}\,\mathrm{cts/(keV{\cdot}\,kg{\cdot}\,yr)}$

GERDA: background free

Phase I:



Phase II:



- combined Phase I+II sensitivity:

  $T^{0\nu}_{1/2} > 4.0 \cdot 10^{25}$ yr (90% C.L.)

- blind analysis, no $0\nu\beta\beta$ signal:

  $T^{0\nu}_{1/2} > 5.2 \cdot 10^{25}$ yr (90% C.L.)

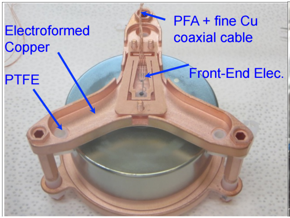
  $|m_{ee}| <$ [160,260] meV (90% C.L.)

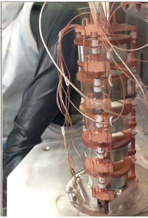
- just started Phase II data taking

[M.A. talk at Neutrino 16]

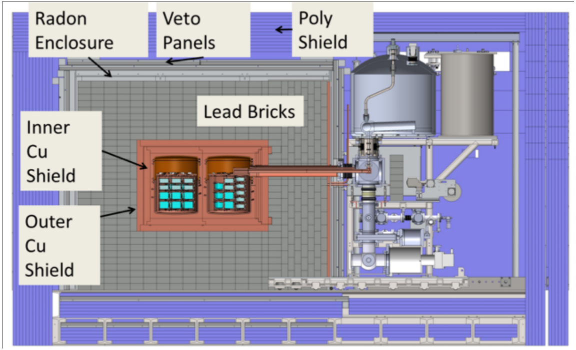
Majorana Demonstrator @ Sanford (USA)

Isototope:	^{76}Ge ($Q_{\beta\beta}$=2039 kev)
Resolution:	4-5 keV FWHM
Background:	10^{-3}cts/(keV· kg· yr)
Mass:	26 kg
Technology:	Ge semiconductor detectors
	+ electroformed Cu
Status:	running





- 37 detectors of PPC type
- two independent cryostat
- low-background passive shield (Cu+Pb)
- Cu produced underground to avoid cosmogenic activation



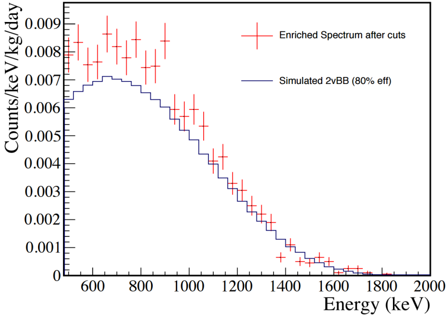
Majorana Demonstrator: first data

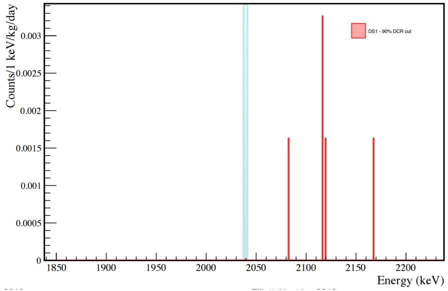
- data taking with module 1 in since fall 2015
- data taking with module 2 just started
- first results with 1.66 kg·yr from module 1 (Dec 15 - Apr 16):

  $$\mathrm{BI} = 7.5^{+4.5}_{-3.4} \cdot 10^{-3}\ \mathrm{cts/(keV \cdot kg \cdot yr)}$$

  $$T^{0\nu}_{1/2} > 3.7 \cdot 10^{24}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

- data taking on-going, soon new results

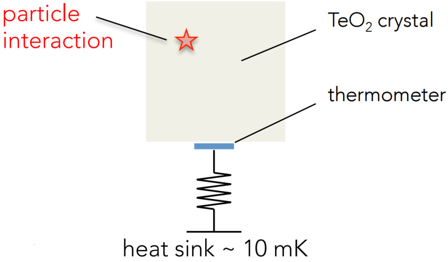


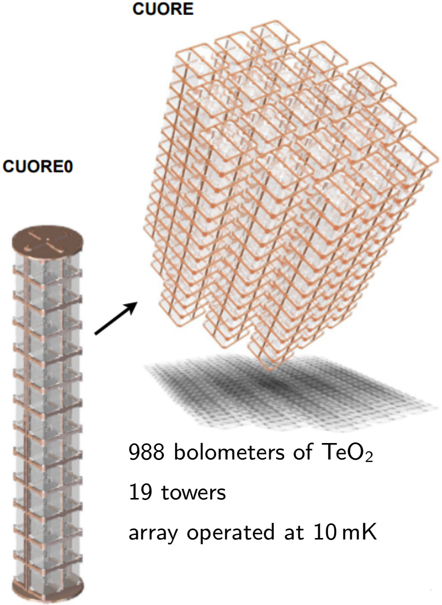


[S. Elliot talk at Neutrino 16]

CUORE @ LNGS (Italy)

Isototope:	^{130}Te ($Q_{\beta\beta}$=2527 kev)
Resolution:	5 keV FWHM
Background:	10^{-2}cts/(keV· kg· yr)
Mass:	206 kg
Technology:	cryogenic bolometers
Status:	in construction





988 bolometers of TeO_2

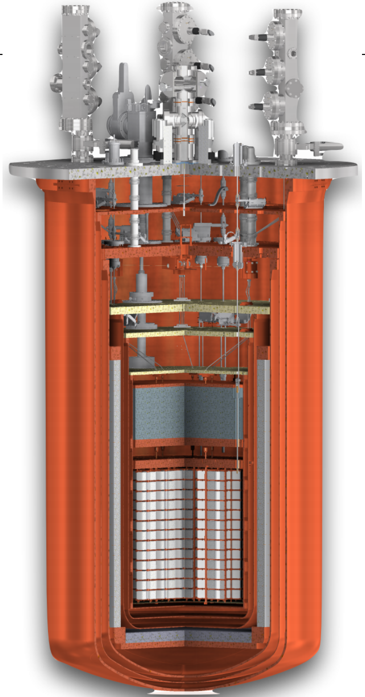
19 towers

array operated at 10 mK

CUORE @ LNGS (Italy)

Isotope:	^{130}Te ($Q_{\beta\beta}$=2527 kev)
Resolution:	5 keV FWHM
Background:	10^{-2}cts/(keV· kg· yr)
Mass:	206 kg
Technology:	cryogenic bolometers
Status:	in construction

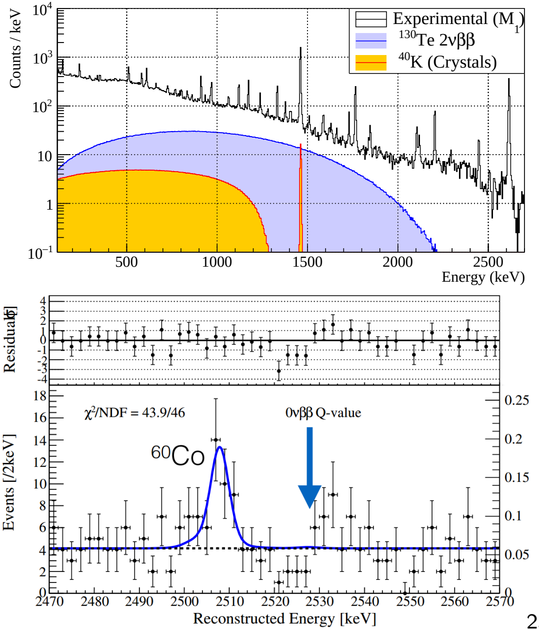
- challenging cryogenic systems
- 6 cryogenic stages
- all towers mounted, cryostat ready for cool down
- first commissioning data within 2016



CUORE @ LNGS (Italy)

CUORE-0:

- R&D with single tower in old cryostat
- exposure 33 kg·yr
- BI$= 6 \cdot 10^{-2}$cts/(keV· kg· yr)
- $T_{1/2}^{0\nu} > 3 \cdot 10^{24}$ yr 90% CI



[arXiv:1609.01666]

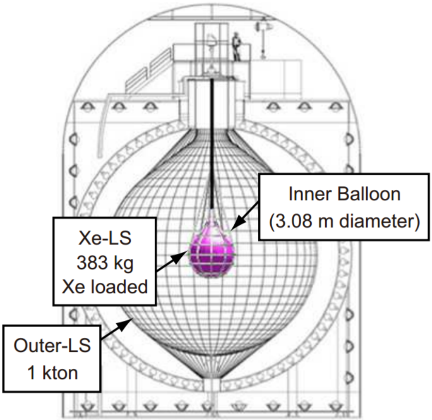
[Phys. Rev. C 93, 045503 (2016)]

KamLAND-Zen Phase II @ Kamioka (Japan)

Isotope:	^{136}Xe ($Q_{\beta\beta}$=2458 kev)
Resolution:	240-270 keV FWHM
Background:	$\lesssim 10^{-4}$cts/(keV$\cdot$ kg$\cdot$ yr)
Mass:	350 kg
Technology:	Xe-loaded liquid scintillator
Status:	completed/upgrading

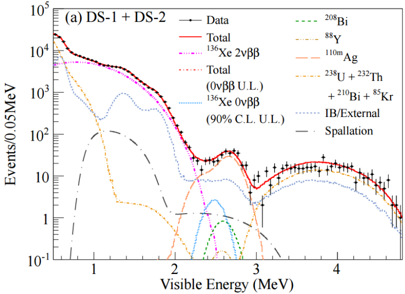
Structure from outside:

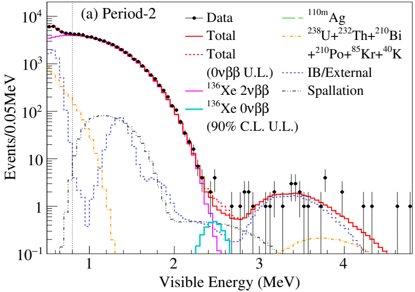
- 3200ton water Cherenkov detector
- 1879 PMT's
- 13 m-diamater balloon
  -> 1 kt LS (Dodecane+PC+PPO)
- mini-baloon:
  -> 25 μm thick nylon
  -> 383 kg Xe-loaded Decane-based LS



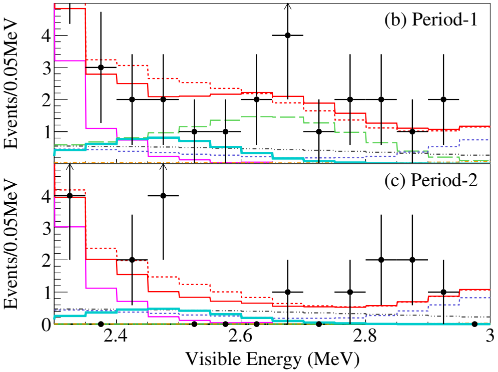
KamLAND-Zen: backgrounds

- Phase 1 (Oct 11 – Jun 12):
  - 89.5 kg·yr
  - background dominated by ^{110m}Ag
  - $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr 90% CL
- Xe-LS Purification (Jul 12 – Oct 13)
- Phase 2 (Nov 13 – Oct 15)
  - 504 kg·yr
  - dominant background is now ^{214}Bi on the baloon
  - volume cut optimized
- Calibrations campaign (Oct 15):
  - energy bias <1%
  - vertex bias <1.0 cm





KamLAND-Zen: new results



- combined Phase 1+2 sensitivity:

  $T_{1/2}^{0\nu} > 5.6 \cdot 10^{25}$ yr (90% C.L.)

- no $0\nu\beta\beta$ signal:

  $T_{1/2}^{0\nu} > 10.7 \cdot 10^{25}$ yr (90% C.L.)

  $|m_{ee}| < [61{,}165]$ meV (90% C.L.)

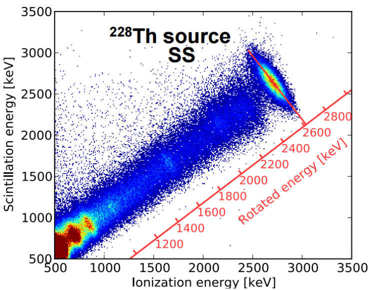
  $|m_{\rm light}| < (180 - 480)$ meV (90% C.L.)

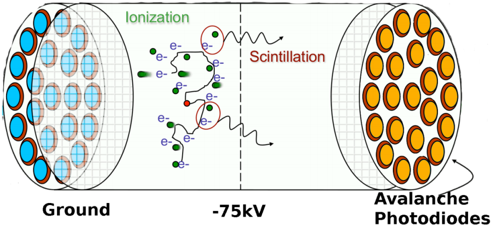
- currently under upgrade

[Phys.Rev.Lett. 117 (2016) no.10, 109903]

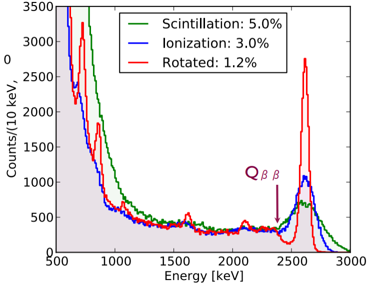
EXO-200 (@WIPP, New Mexico)

Isototope:	^{136}Xe ($Q_{\beta\beta}$=2458 kev)
Resolution:	$\sim$90 keV FWHM
Background:	$\lesssim 10^{-3}$cts/(keV· kg· yr)
Mass:	75 kg
Technology:	Xe TPC
	(ionization + scintillation)
Status:	running

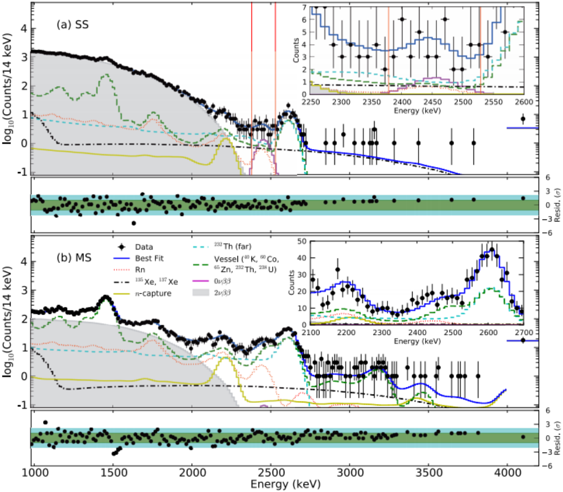




[Nature 510 (2014) 229-234]



EXO-200: results



- Exposure: 100 kg·yr
- Sensitivity:

  $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr (90% C.L.)
- no $0\nu\beta\beta$ signal:

  $T^{0\nu}_{1/2} > 1.1 \cdot 10^{25}$ yr (90% C.L.)

  $|m_{ee}| <$ [190,450] meV (90% C.L.)
- running, expected sensitivity improvemet by a factor 3

[Nature 510 (2014) 229-234,
L. Yang talk at Neutrino 16]

SuperNEMO

Isototope:	^{82}Se ($Q_{\beta\beta}$=2995 kev)
Resolution:	~120 keV FWHM
Background:	$\lesssim 5 \cdot 10^{-4}$cts/(keV· kg· yr)
Mass:	100 kg
Technology:	particle charge identification + track
Status:	demonstrator module in construction

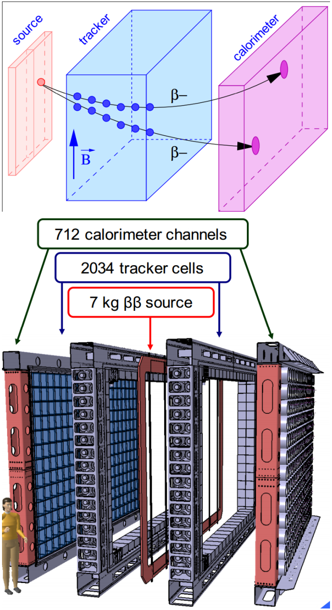
Results from NEMO-3 (90% C.L.):

$T^{0\nu}_{1/2}(^{110}\mathrm{Mo}) > 1.1 \cdot 10^{24}$ yr

$T^{0\nu}_{1/2}(^{150}\mathrm{Nd}) > 2.0 \cdot 10^{22}$ yr

$T^{0\nu}_{1/2}(\,^{82}\mathrm{Se}\,) > 2.5 \cdot 10^{23}$ yr

[PRD 92, 072011 (2015), arXiv:1606.08494, D. Waters talk at Neutrino 16]



Prospects

Many other good R&D/experiments not discussed, e.g.:

- Amore: Mo-based crystals and metallic magnetic calorimeters
- NEXT: high-pressure xenon gas
- SNO+: ^{130}Te loaded LS
- ...

Large collaboration forming for nex-generation ton-scale experiments:

- NG-Ge76: Next Generation ^{76}Ge
- CUPID: CUORE Upgrade with Particle IDentification
- KamLAND2-Zen: new LS + PMT's
- nEXO: 5 t LXe TPC (+ Ba tagging?)

Conclusions

- $0\nu\beta\beta$: lepton genesis process measureble in the lab with strong implications for neutrino physics
- experimenal $0\nu\beta\beta$ search very hot and challenging field, a discovery is possibly around the corner (or very far...)
- current experiments will get close/touch the IH band, next generation will cover it completely
- many candidate isotototopes $\Rightarrow$ totally different detecton techniques
- to be convincing, a signal must be observed by more than an experiment