SFB 1258 Neutrinos Dark Matter Messengers

Neutrinoless Double-β decay

Creation of Matter & Portal to New Physics

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Technical University of Munich (TUM)

Double-Beta Research in France Workshop, Set 4 2018, Paris, France

Neutrinoless Double-β decay

- Theoretical contextualization
    - model independent
    - minimal extension of the 3-neutrino framework
    - other extensions of the 3-neutrino frameworks
- Experimental aspects
- Review of on-going experiments
- Experiment comparison and prospects

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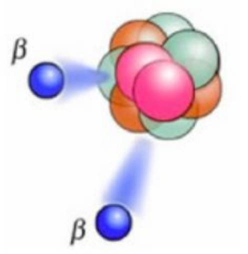
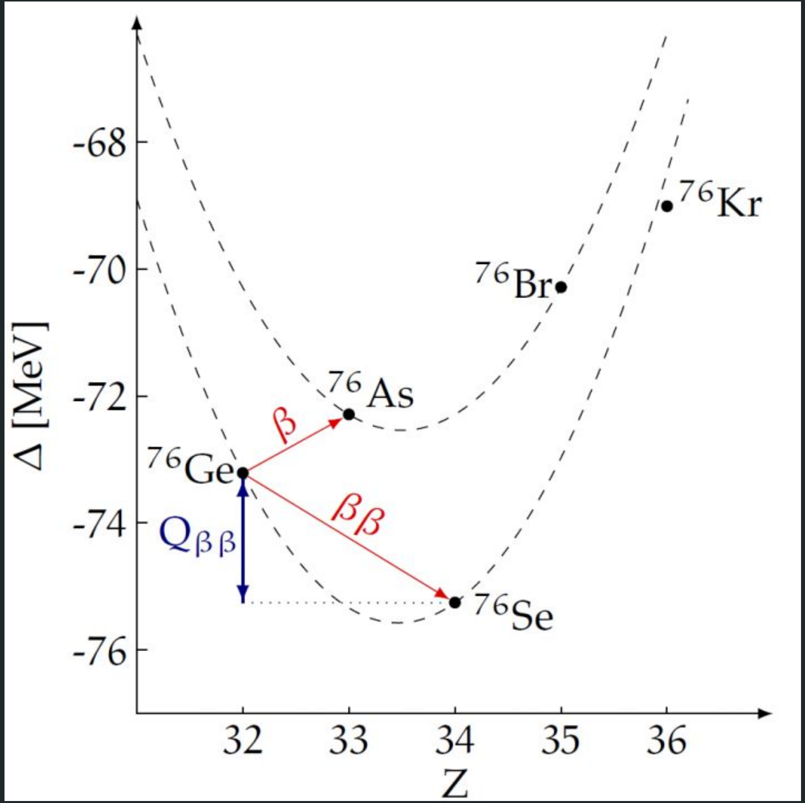
Neutrinoless Double-β Decay ($0\nu\beta\beta$)

Hypothetical second order nuclear transition: $(A, Z) \rightarrow (A, Z+2) + 2e^-$



- foreseen by many extensions of the Standard Model
- possible in many isotopes for which single β decay is be forbidden
- $T_{1/2}$ limits in the range 10^{21} - 10^{26} yr

< 50% chance for an atom to decay
in a hundred trillion times the age of the universe



[Courtesy of G. Benato]

A portal to Physics beyond the Standard Model

$0\nu\beta\beta$ at the level of nucleons:

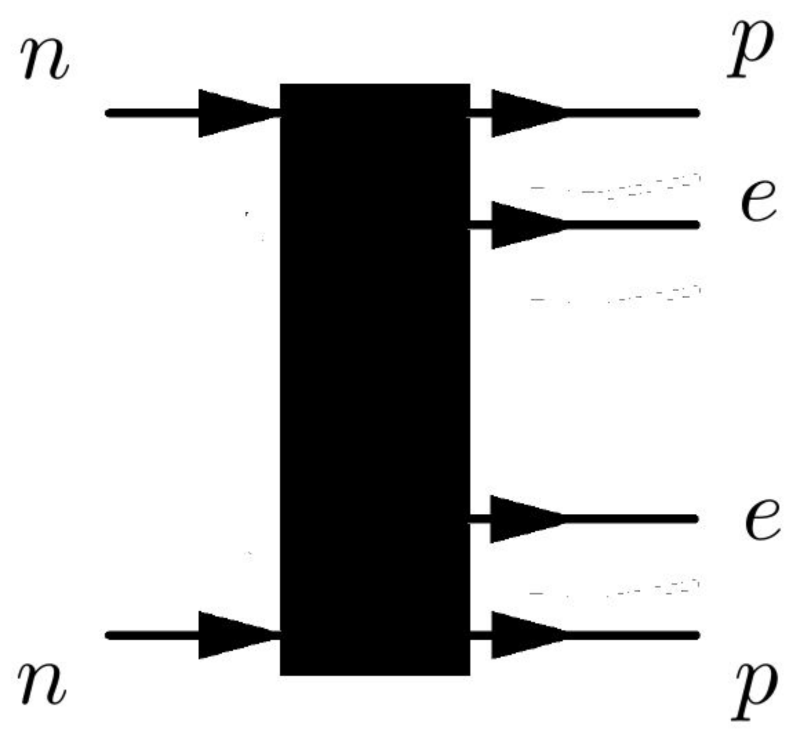
$$2n \rightarrow 2p + 2e^-$$

2 leptons are produced out of energy:

- ➢ matter creation ("leptogenesis")
- ➢ need letpon-number-violating physics beyond the SM (ΔL=2)

Fundamental process:

- ➢ $0\nu\beta\beta$ as important as proton decay
- ➢ Baryo/Leptogenesis requires the violation of baryon number and lepton number ($B - L$ is the only conserved quantity)



A portal to Physics beyond the Standard Model

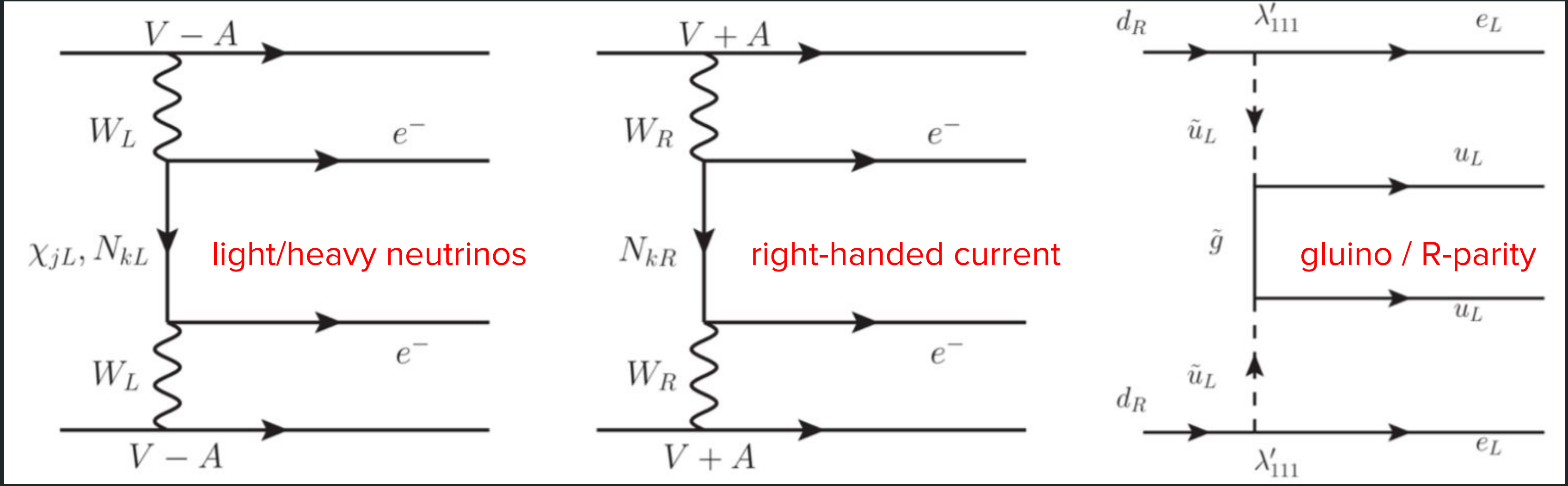
The rate of the process ($1/T_{1/2}$) is proportional to the coherent sum of all mechanisms involved:

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}(Q,Z) \cdot \left|\sum_{\text{mech. } i} \mathcal{M}_i \cdot \eta_i\right|^2$$

Phase Space Factor

Nuclear Matrix Element

Mechanism



light/heavy neutrinos

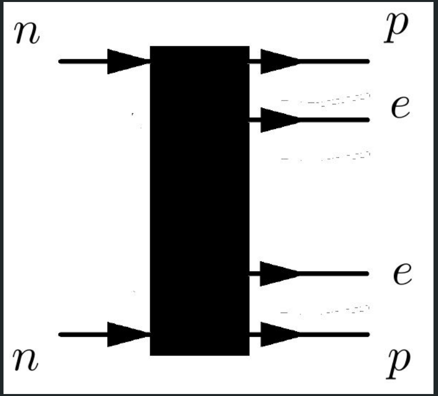
right-handed current

gluino / R-parity

[Faessler et al, PRD, 83, 11 (2011), 113003]

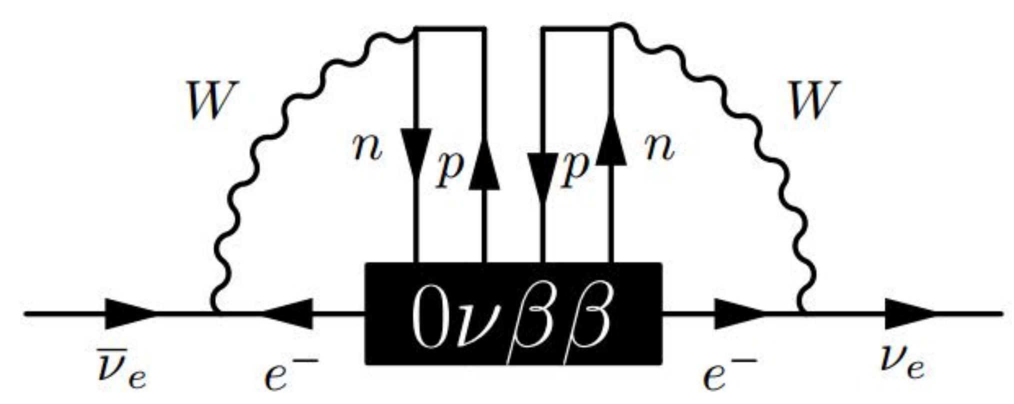
$0\nu\beta\beta$ and the Origin of Neutrino Masses

Independently from underlying physics: if $0\nu\beta\beta$ decay exists, neutrinos are Majorana particle!



Black Box theorem:
$0\nu\beta\beta$ operator can be rearranged to produce a neutrino/antineutrino oscillation (i.e. a Majorana mass term)

[Schechter, Valle, PRD 25 (1982) 2951]



Note: bulk of neutrino mass not given by $0\nu\beta\beta$ operator

[Duerr et al., JHEP 1106 091,2011]

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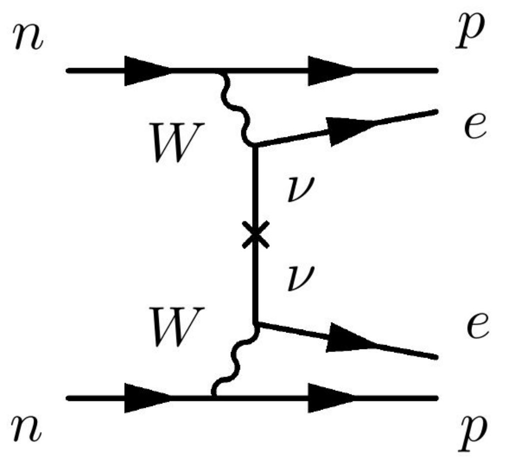
Vanilla Channel

Exchange of light-Majorana neutrinos:

- possible in a minimal extension of the SM (massive + majorana neutrinos)
- dominant channel for most of the models

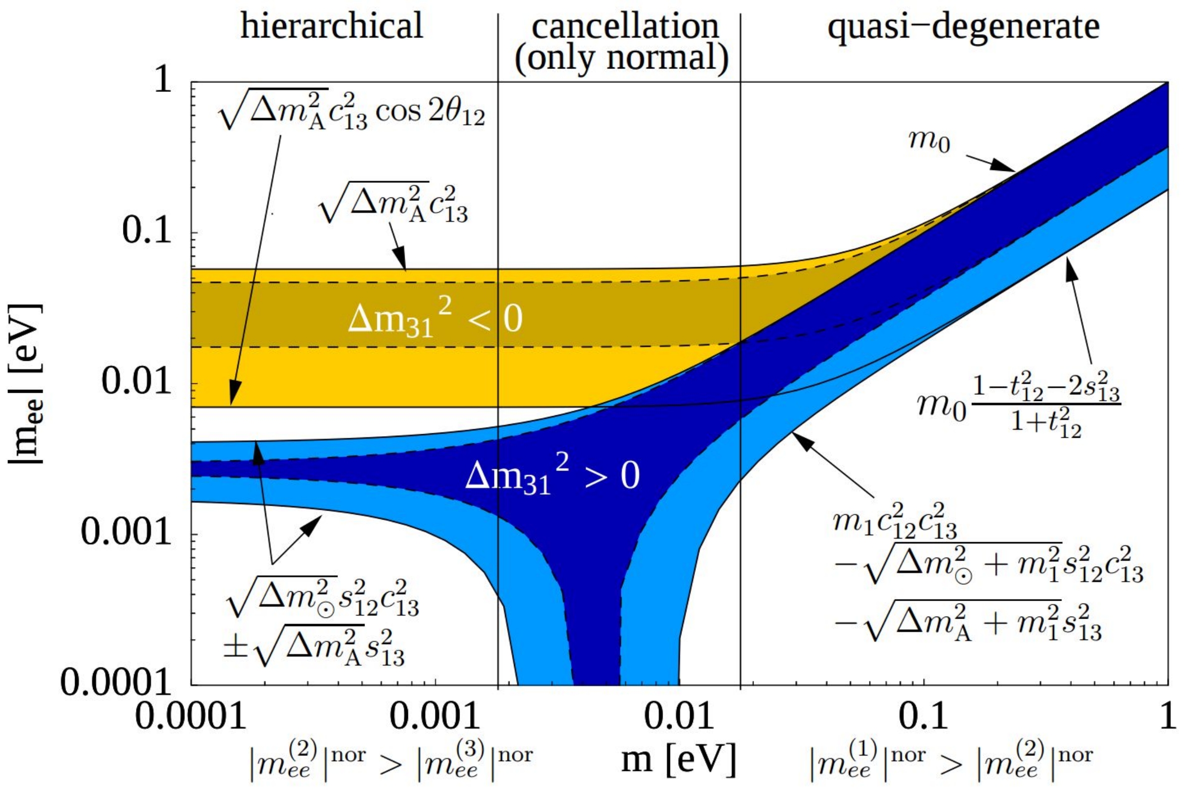


$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu} \cdot |\mathcal{M}_{0\nu}(A,Z)|^2 \cdot |m_{\beta\beta}|^2$$

$$|m_{\beta\beta}| = \left|\cos^2\theta_{12}\,\cos^2\theta_{13}\,m_1 + \sin^2\theta_{12}\,\cos^2\theta_{13}\,m_2\,e^{i2\alpha_1} + \sin^2\theta_{13}\,m_3\,e^{i2\alpha_2}\right|$$

Vanilla Channel

- The parameter space for mbb is limited by the constraints from oscillation experiments
- $m_{\beta\beta} > 17$ meV for IO
- no constraints on majorana phases



[Lindner, Merle, Rodejohann et al, Phys. Rev. D 73, 053005]

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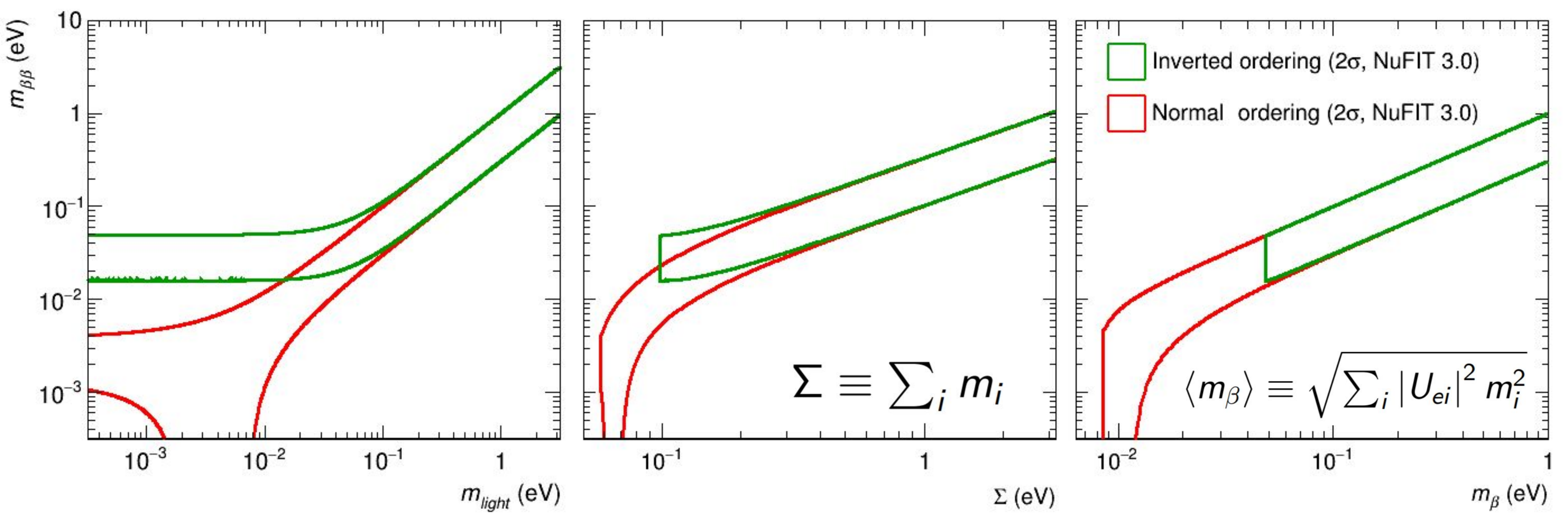
Neutrino Mass Observables

Cosmology (Planck, Euclid)
sum of neutrinos masses

Beta-decay kinematic (KATRIN)
electron neutrino mass



- ➢ Degenerate Majorana masses probed!
- ➢ Next target inverted ordering band
- ➢ $0\nu\beta\beta$ searches, cosmological surveys and direct mass measurements give complementary information!

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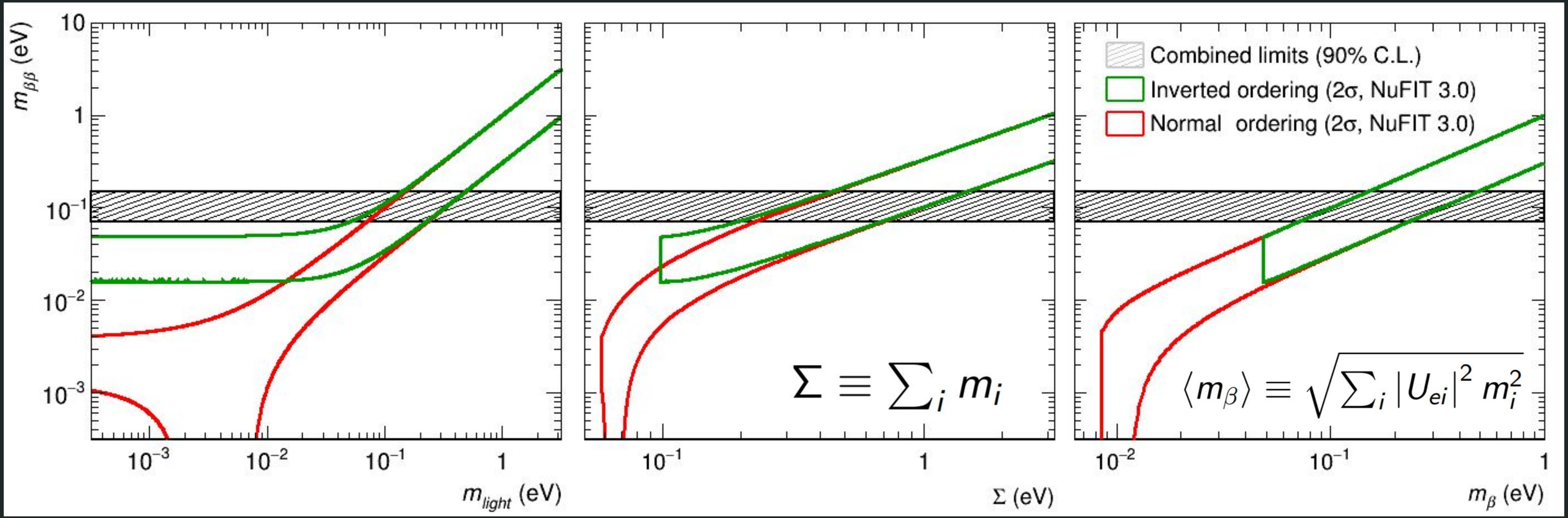

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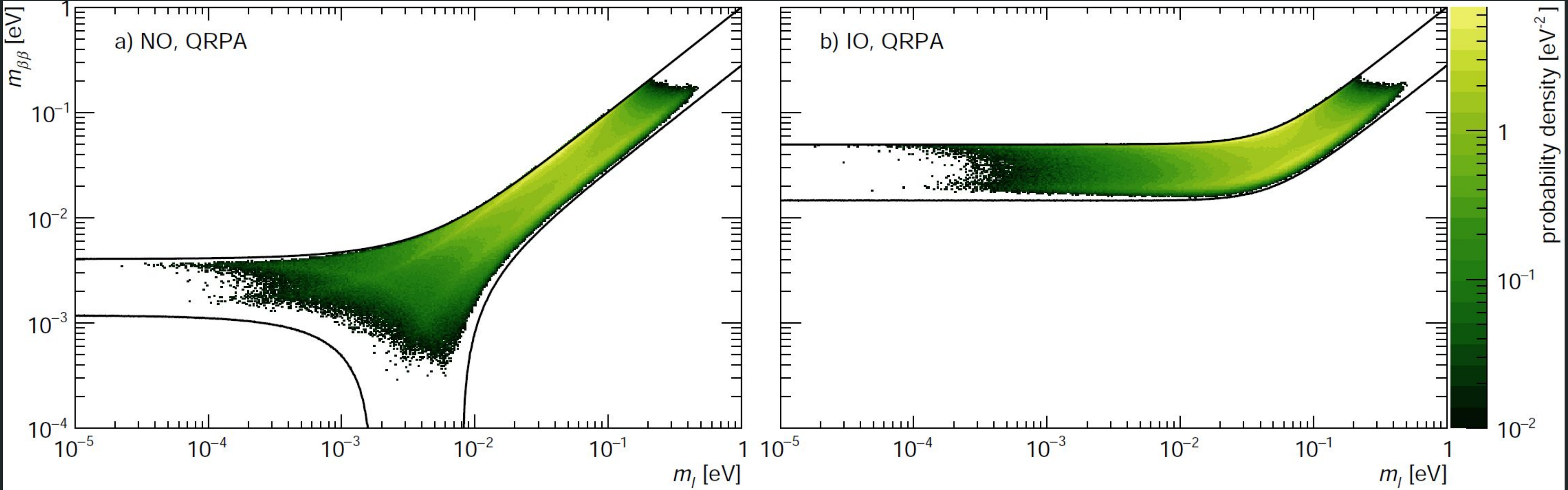
Probability Density from Global Fits

In absence of neutrino mass mechanisms or flavour symmetries that fix the value of the Majorana phases or drive $m_{lightest}$ to zero, the probability distribution for $m_{\beta\beta}$ is pushed to large values:



[**M.A.**, G Benato and J A Detwiler, PRD 96, 053001 (2017)]

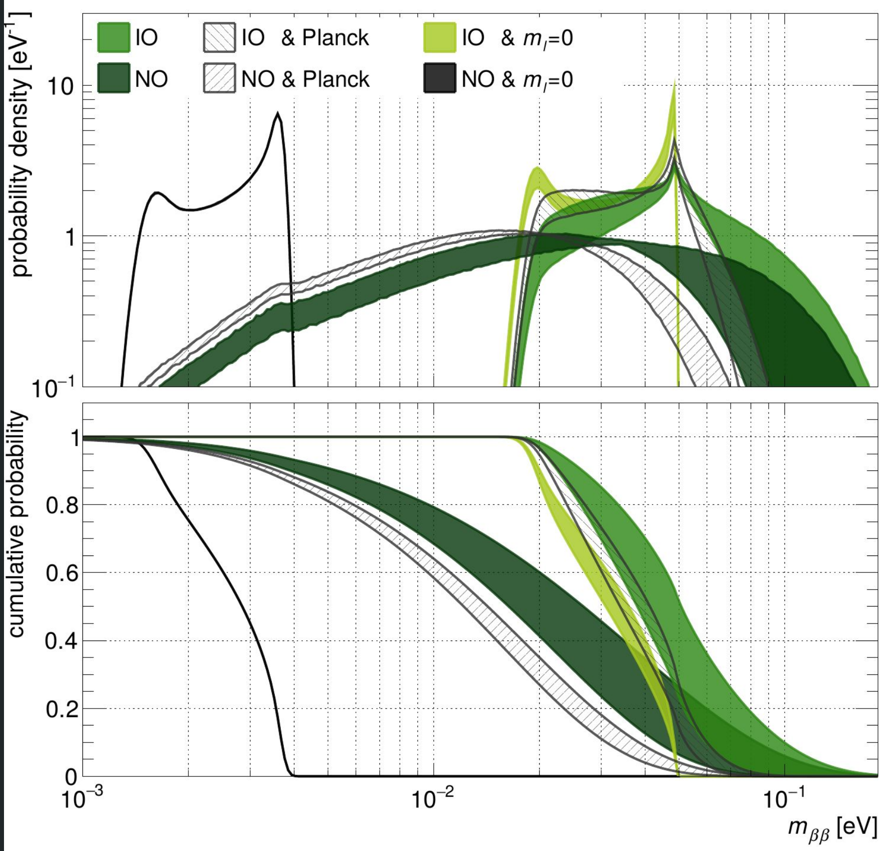
Flat prior for the Majorana phases ➔ small $m_{\beta\beta}$ values require a fine tuning of the parameters

Probability density from global fits

- data in the analysis: oscillations + $0\nu\beta\beta$ + (cosmology)
- bands shows deformation due to NME uncertainty
- $0\nu\beta\beta$ constraints on $m_{lightest}$ competitive with cosmology

Bulk of probability at reach with next generation experiments

[**M.A.**, G Benato and J A Detwiler, Phys. Rev. D 96, 053001 (2017)]
see also [A Caldwell et al, Phys.Rev. D96 (2017) no.7, 073001]



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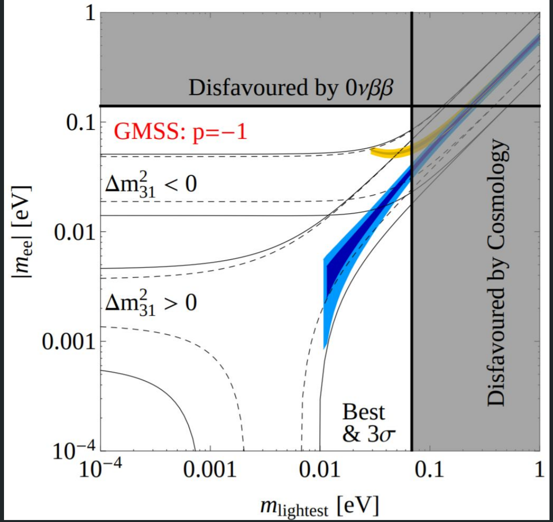
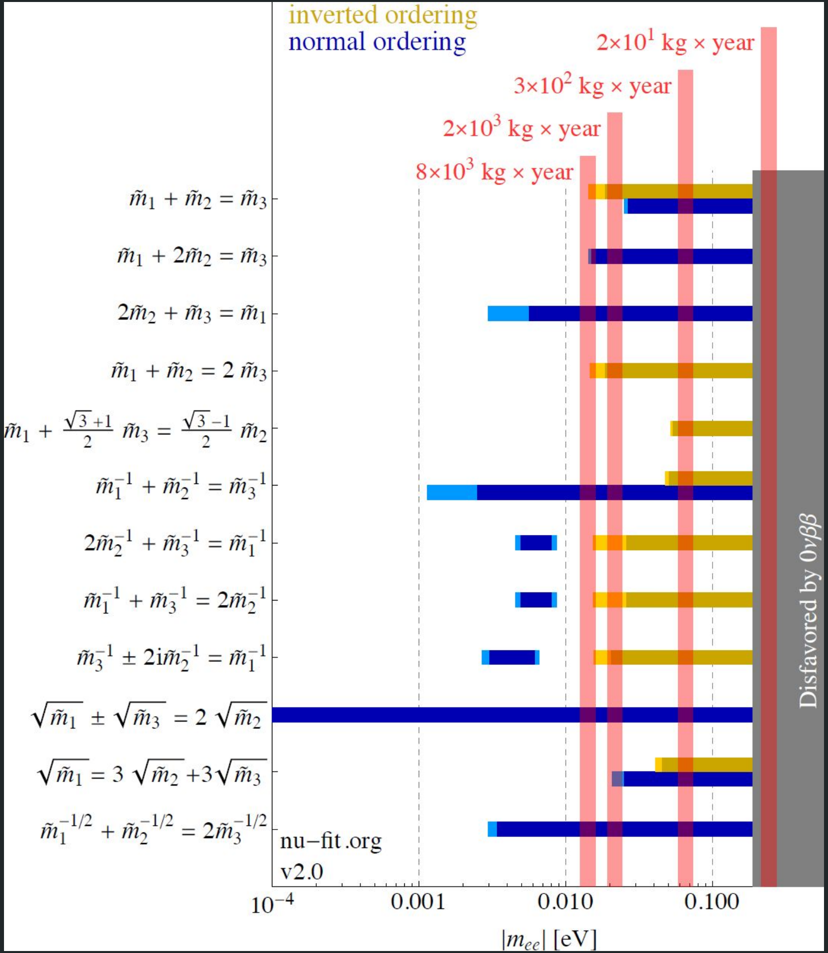
[King, Merle, Stuart, JHEP 1312, 005 (2013)]
[**M.A.**, Merle, Zuber EPJ C76 (2016) no.4, 176]

Flavour Models

3-neutrino framework extended with additional finite symmetry groups to explain the values of mixing angles and mass eigenstates:

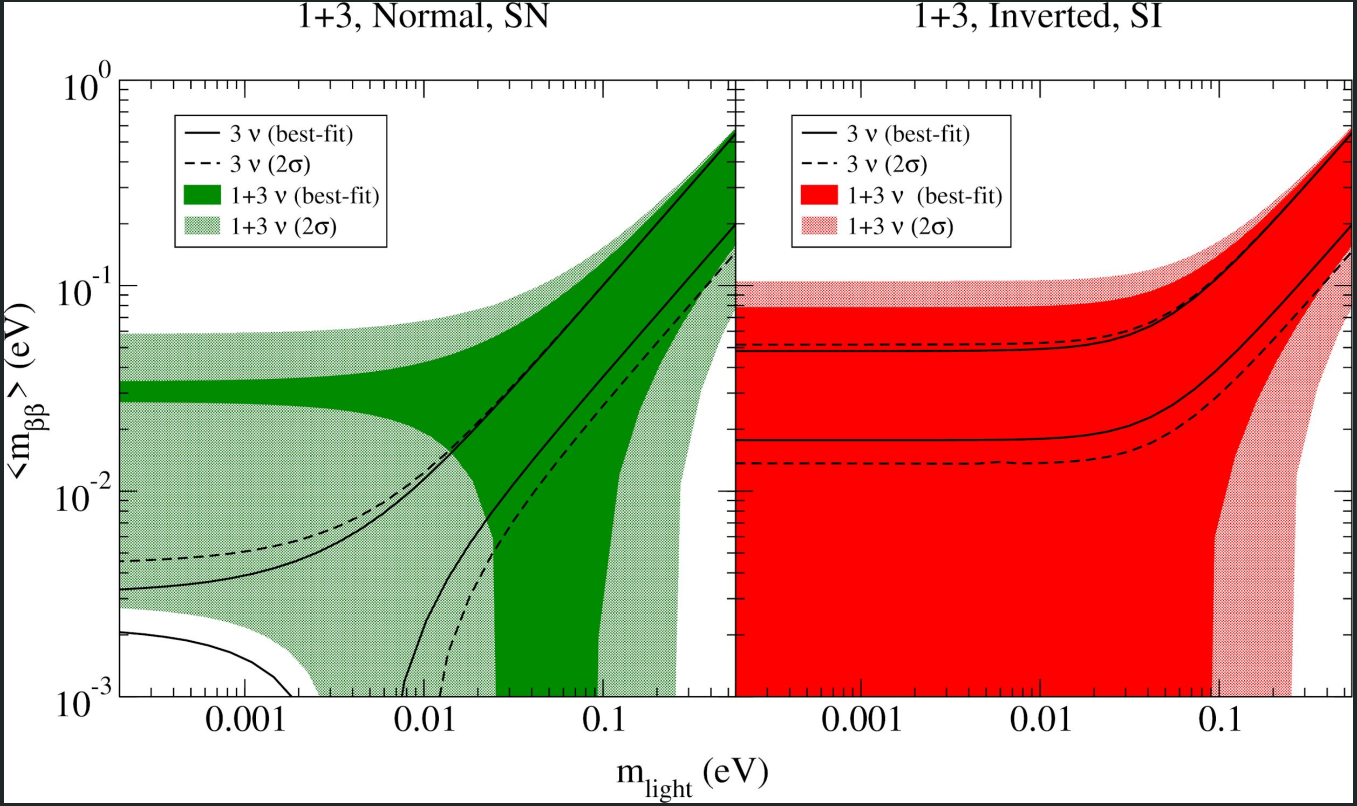
- ➢ new correlations between observables (sum rules) schrink range allowed for $m_{\beta\beta}$
- ➢ some models will be probed with early stages of the next-generation experiments





3+1 Models

Adding a sterile neutrino changes dramatically the parameter space of interest. Current experiments are testing the IO horizontal band!



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

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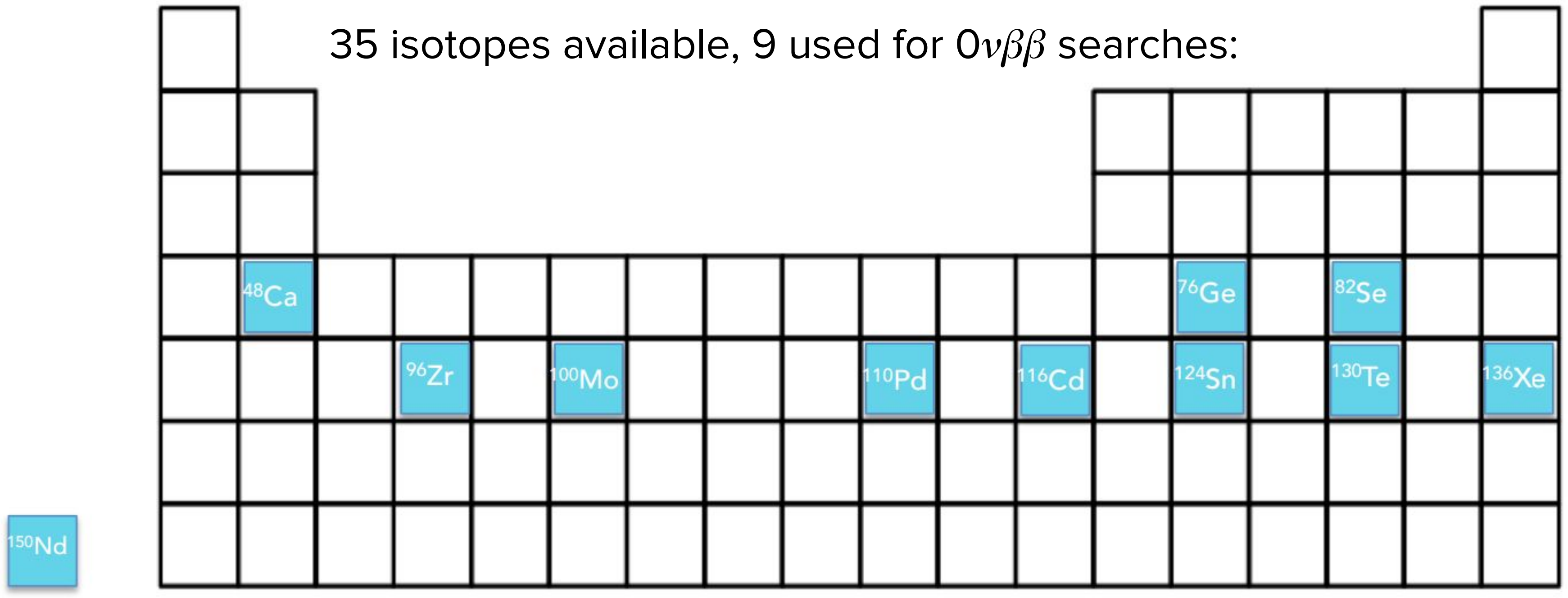
Double-β Decaying Isotopes



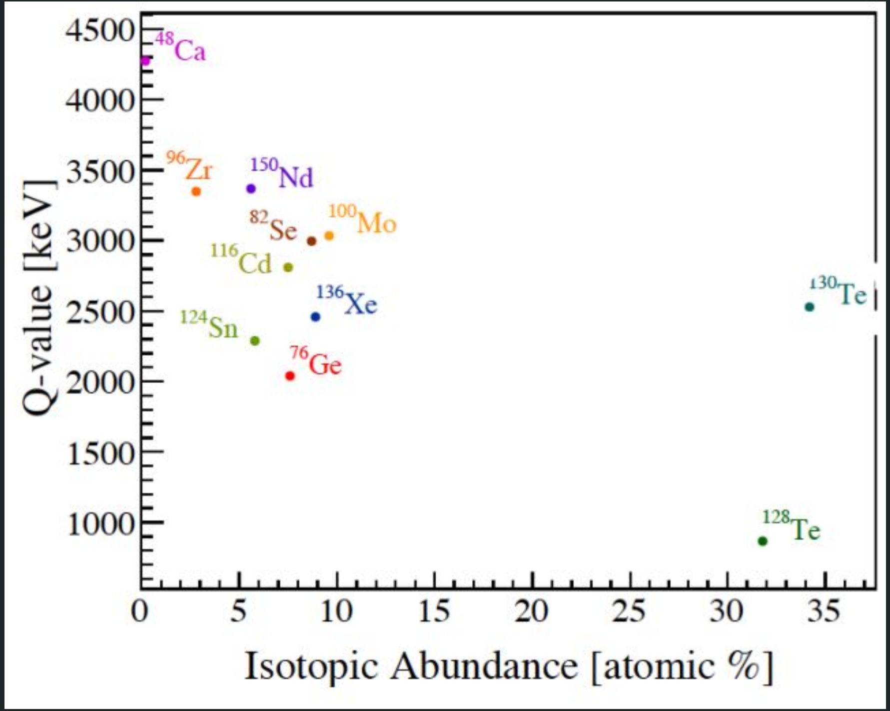
35 isotopes available, 9 used for $0\nu\beta\beta$ searches:

[Courtesy of K. Shaefner]

Double-β Decaying Isotopes

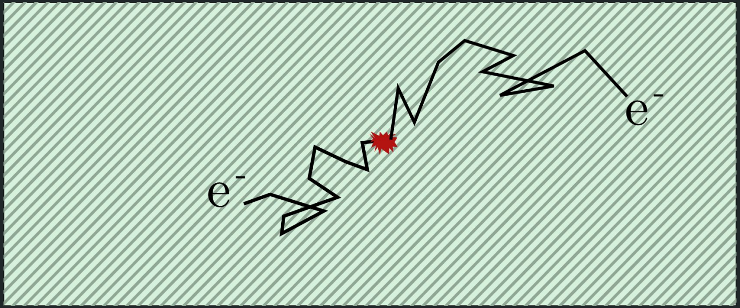
- cost depends on natural enrichment
- the higher is $Q_{\beta\beta}$ the better:
  - $1/_{2}T_{1/}\propto G^{0\nu}(Q,Z) \propto (Q_{\beta\beta})^5$
- NMEs differes up to a factor 3
- very different detection technologies according to isotope

There is no “best” isotope. The detection technique can compensate for unfavorable parameters!



Standard Detection Approach

double-β isotope encompassed in the detector active material and behave as calorimeters



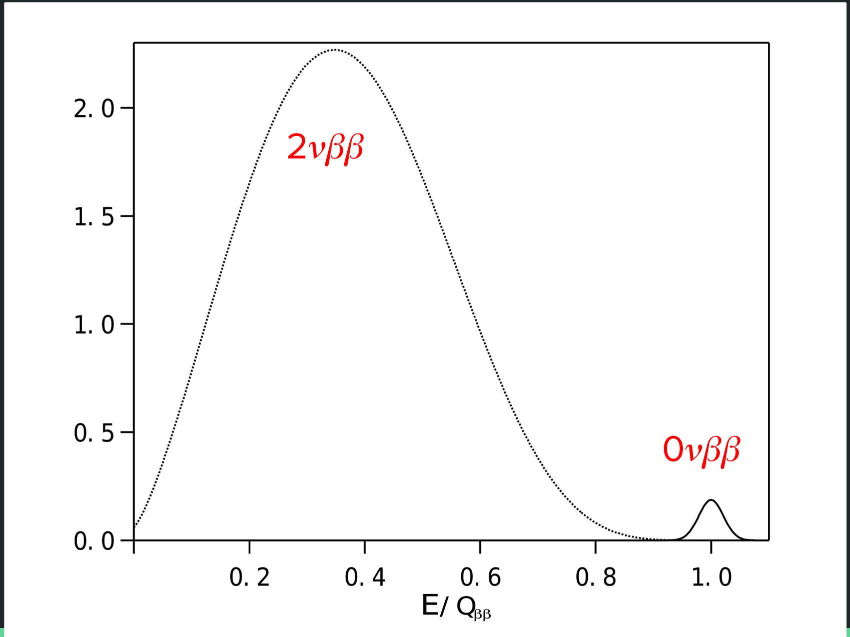
Most of the experiments have also other handles, however energy is the one observable that is both necessary and sufficient for discovery.

Measuring of the electron energy sum:

$0\nu\beta\beta$: (A, Z) -> (A, Z + 2) + 2e -> peak at $Q_{\beta\beta}$

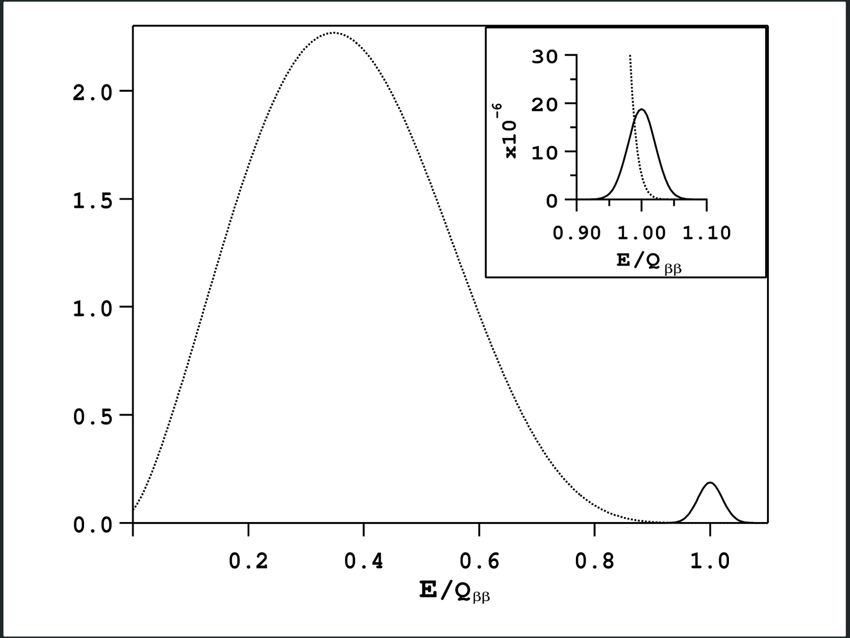
$2\nu\beta\beta$: (A, Z) -> (A, Z + 2) + $2e^-$ + 2ν -> continuum

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



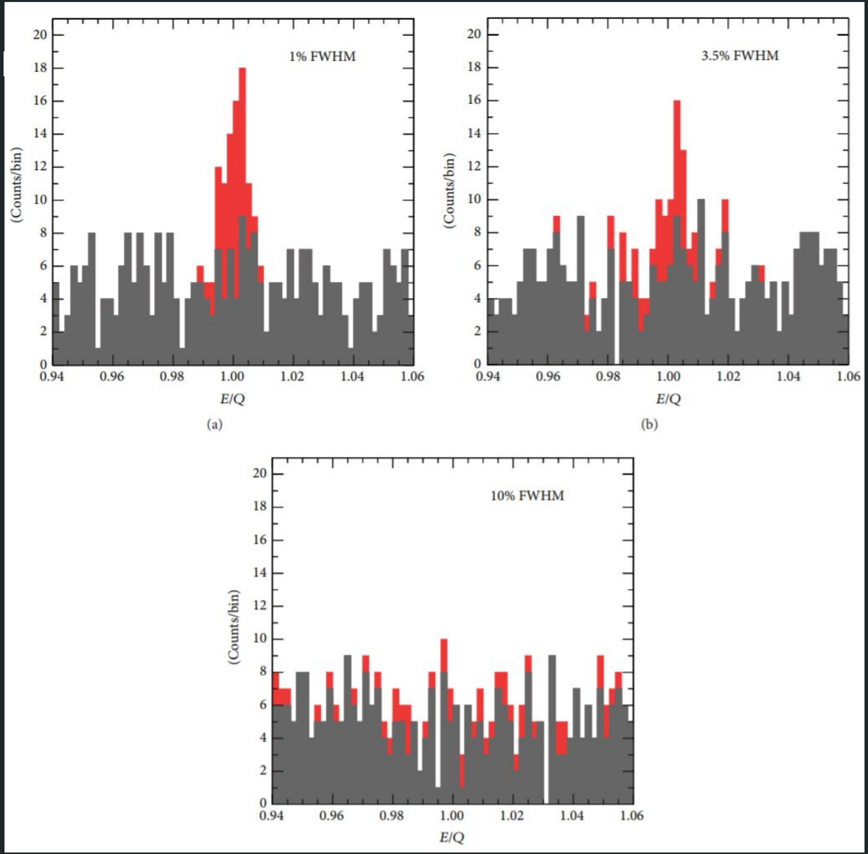
Energy Resolution and Background

Energy resolution important for background mitigation ($2\nu\beta\beta$ and others) and convincing signal identification



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

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



Signal and Background rates

[**M.A.**, G Benato and J A Detwiler, PRD 96, 053001 (2017)]

$$N_{0\nu\beta\beta} = \ln 2 \cdot \varepsilon \cdot N_{atoms} \cdot \frac{t}{T_{1/2}^{0\nu}}$$

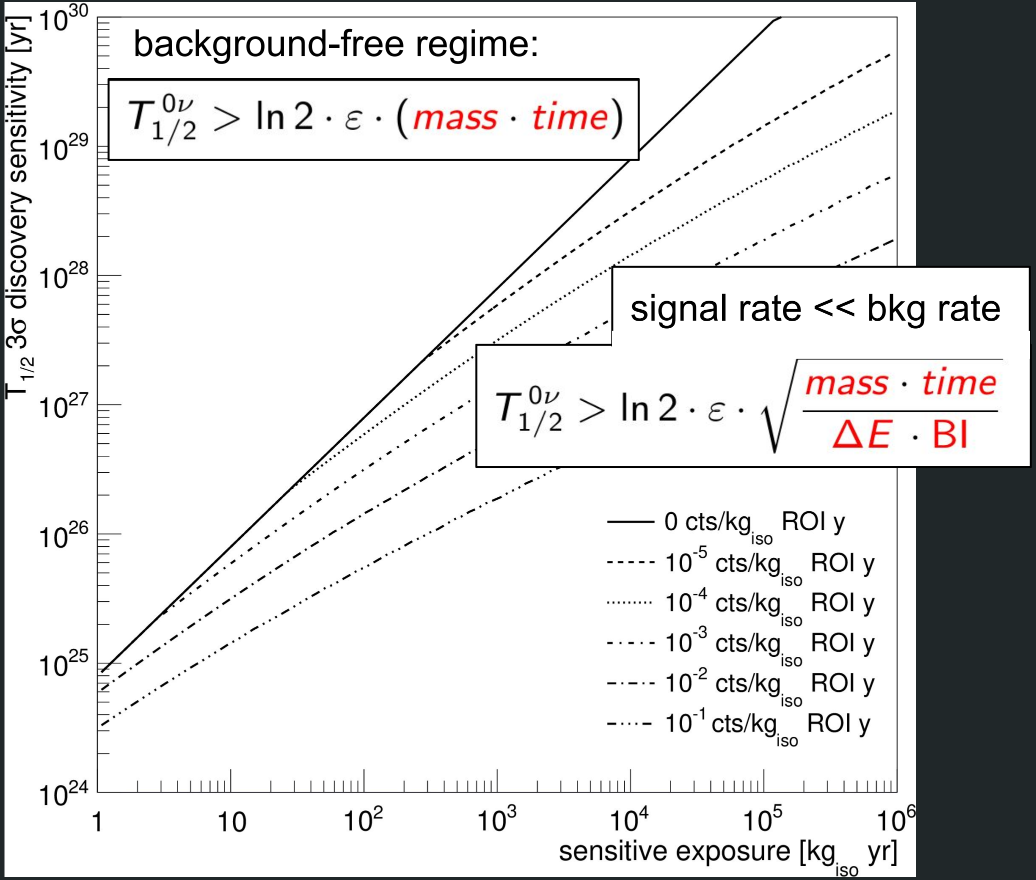
$T_{1/2} = 10^{25}$ yr -> $O(1)$ event / (10 kg yr)

$T_{1/2} = 10^{26}$ yr -> $O(1)$ event / (100 kg yr)

$T_{1/2} = 10^{27}$ yr -> $O(1)$ event / (1 t yr)

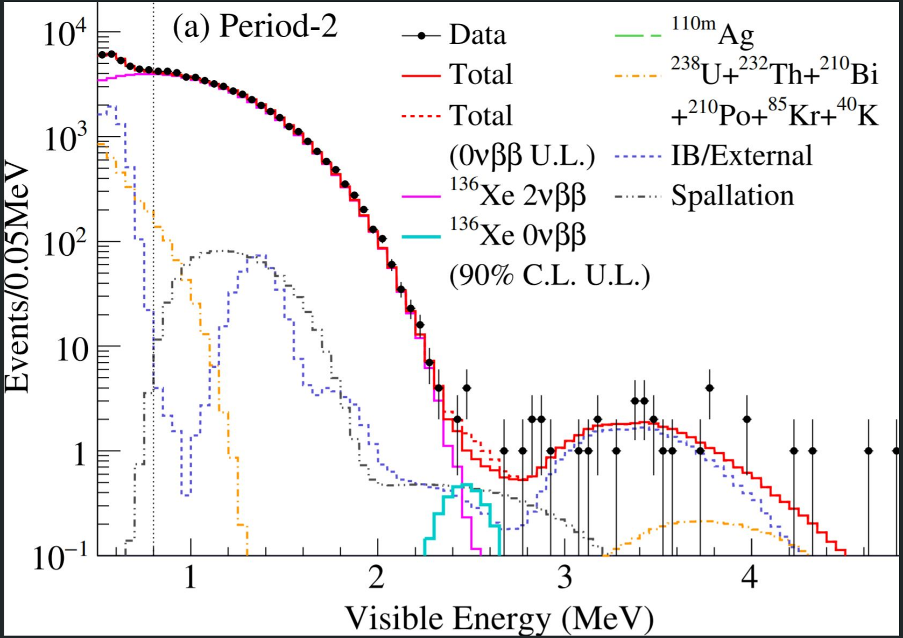
$T_{1/2} = 10^{28}$ yr -> $O(1)$ event / (10 t yr)

For a discovery, background rate in ROI ($Q_{\beta\beta}$± 1-2 σ) must be similar to signal rate



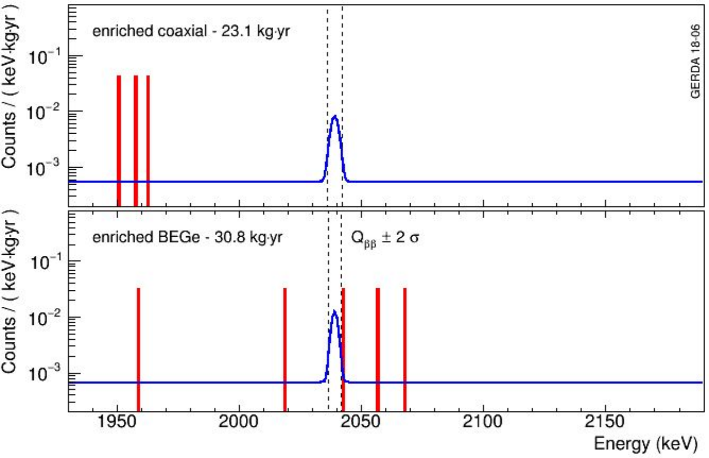
Signal Extraction and background shape uncertainty

KamLAND-Zen: *O*(10) cts/ROI + complex shape

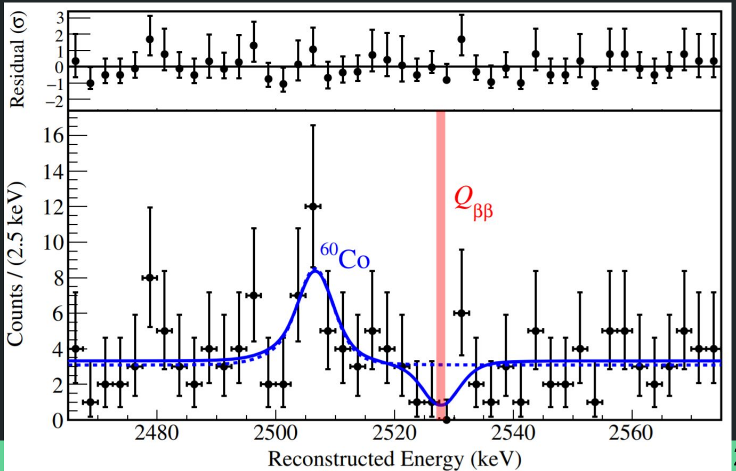


[PRL. 117 (2016) no.10, 109903]

GERDA: *O*(0.1) cts/ROI + simple shape



CUORE: *O*(10) cts/ROI + simple shape



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[Adapted from A Giuliani, Neutrino2018]

Major $0\nu\beta\beta$ experiments

		current gen	mid-term	long-term
Gas/Liquid detector Scalable self-shielding typically low efficiency 1-10% energy resolution	Liquid scintillator + time of flight event reconstruction (scintillation)	KZ	KZ-800 SNO$^+$ phase I	KamLAND2-Zen SNO$^+$ phase II
	Time Projection chambers (ionization + scintillation)	EXO NEXT-10	NEXT-100 PANDA-X-III	nEXO NEXT-2.0 PANDAX-III 1t
Solid detectors multi-detector design granularity high-efficiency 0.1% energy resolution	Bolometers (heat + scintillation)	CUORE CUPID-0 AMORE	AMORE II	CUPID
	Ge semiconductor (ionization)	GERDA MJD	LEGEND-200	LEGEND-1000
External detectors	Magnetized tracking	NEMO	SUPERNEMO	

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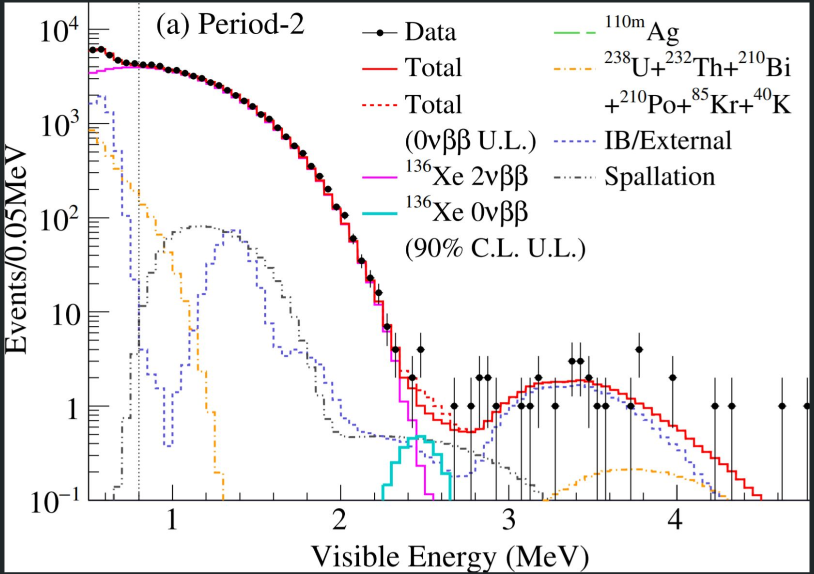
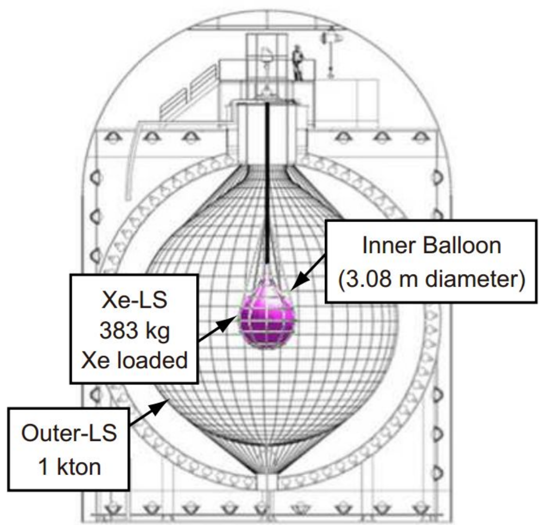
KamLAND-Zen (best achieved performance)

Location	Kamioka, Japan
Isotope	^{136}Xe [$Q_{\beta\beta}$=2458 keV]
Technology	Xe-loaded liquid scintillator
Isotope Mass	350 kg
$0\nu\beta\beta$ efficiency	16%
Resolution [σ]	100-120 keV
Status	commissioning next phase
Latest results	$T_{1/2} > 1.1\cdot10^{26}$ yr (90% CL)
Sensitivity	$T_{1/2} > 5.6\cdot10^{25}$ yr (90% CL)



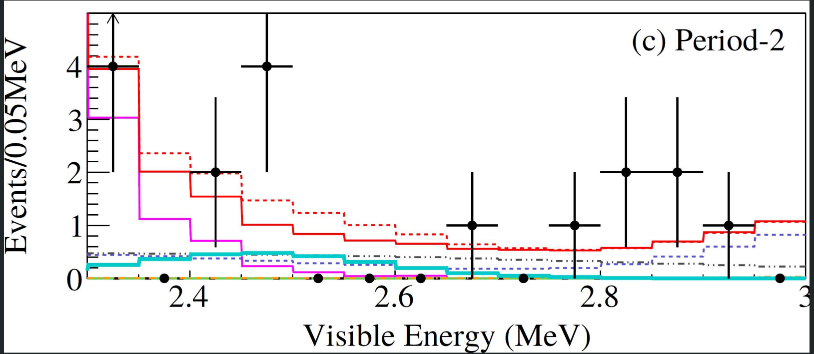


Next Phase KZ-800:

- ➢ 750 kg of isotope
- ➢ New nylon balloon
- ➢ starting this year!

Future: KamLAND2-Zen:

- ➢ 1 t of isotope
- ➢ improve resolution: brighter LS + new PMTs



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

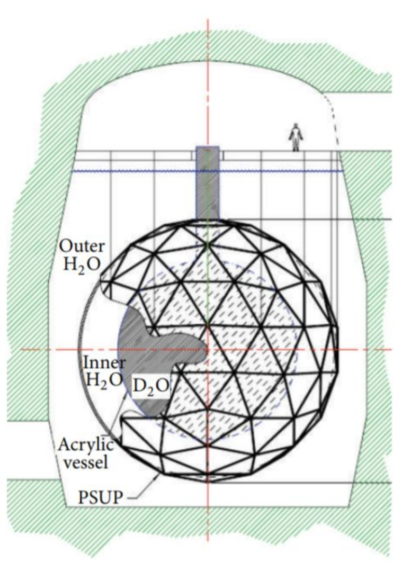
SNO^+ (expected Phase I performance)	
Location	SNOLAB, Canada
Isotope	^{130}Te [$Q_{\beta\beta}$=2527 keV]
Technology	Te-loaded liquid scintillator
Isotope Mass	1300 kg
$0\nu\beta\beta$ efficiency	12%
Resolution [σ]	81 keV
Status	commissioning first phase

Phase I

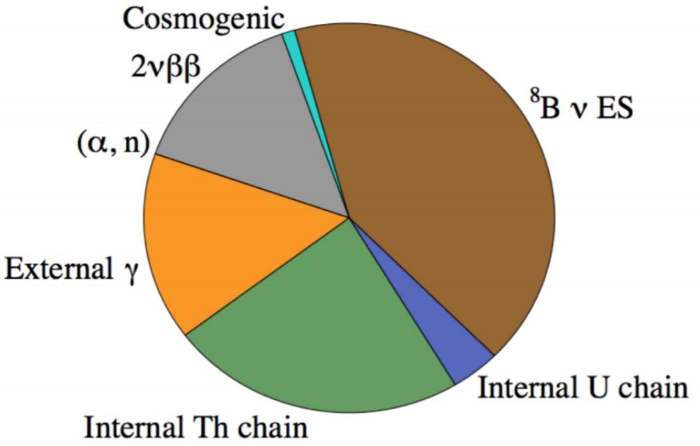
- ➢ 780 t LAB (+ PPO + Te-ButaneDiol)
- ➢ 0.5% loading -> 1300 kg ^{130}Te
- ➢ currently filled with water
- ➢ Filling with unloaded liquid scintillator later this year

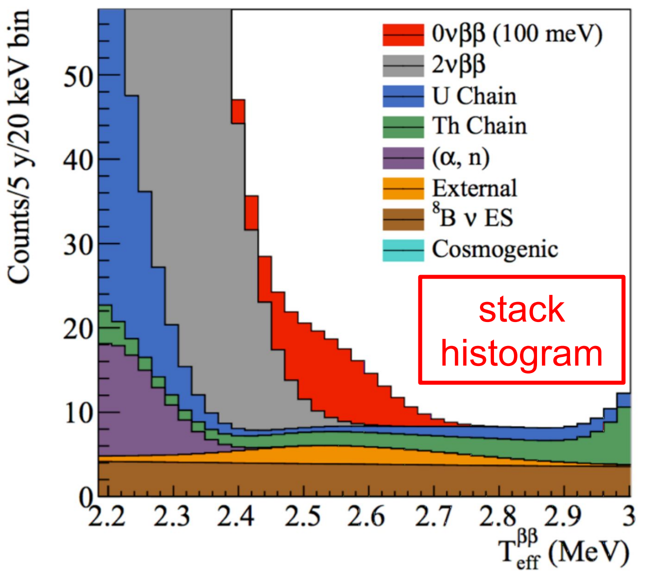
Phase II

- ➢ Increase ^{130}Te concentration (8 t)
- ➢ Increase light yield, transparency, light detectors



[Orebi Gann, Gabriel. (2018, June). SNO+. Zenodo]





stack histogram

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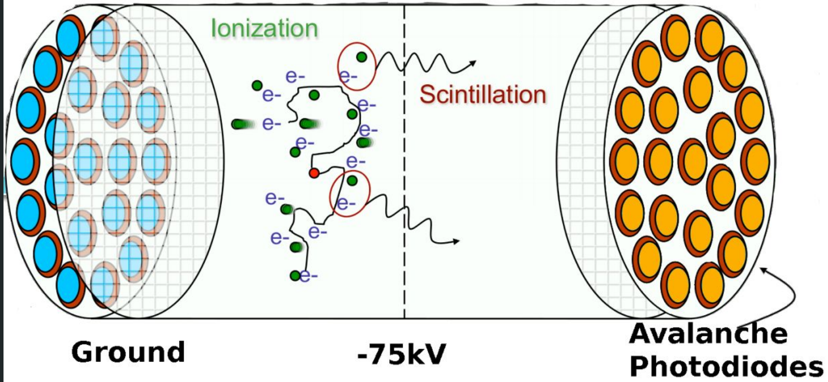
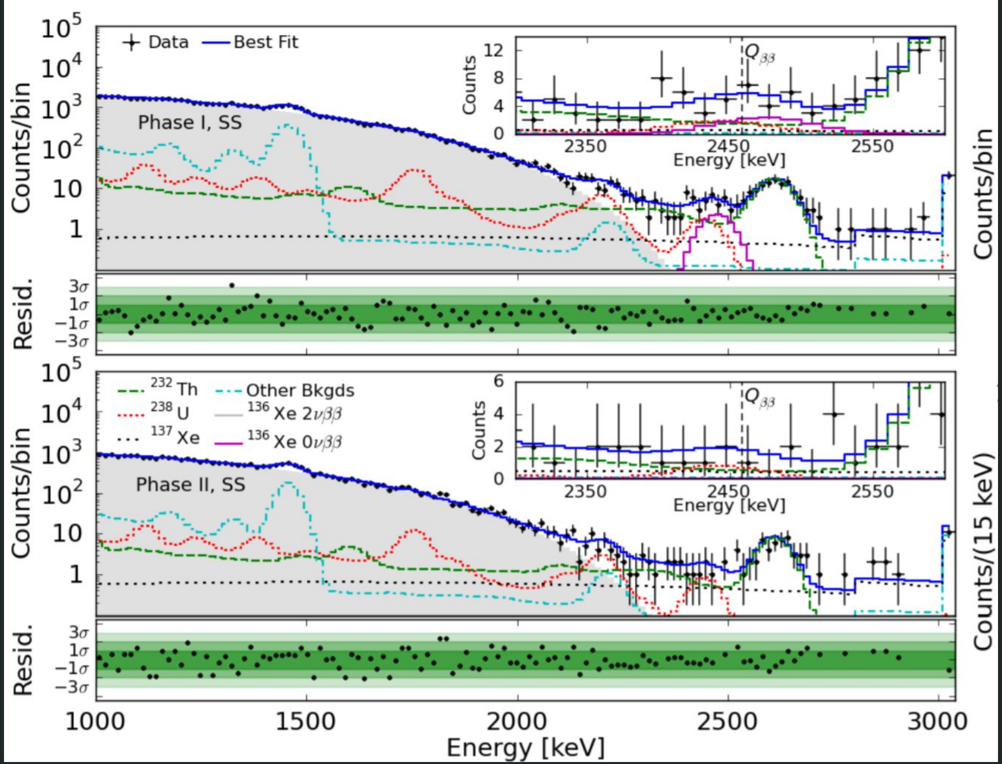
EXO-200 (best achieved performance)

Location	WIPP, New Mexico, USA
Isotope	^{136}Xe [$Q_{\beta\beta}$=2458 keV]
Technology	TPC with liquid Xe
Isotope Mass	76 kg
$0\nu\beta\beta$ efficiency	80%
Resolution [σ]	34 keV
Status	designing next phase
Latest results	$T_{1/2} > 1.8\cdot10^{25}$ yr (90% CL)
Sensitivity	$T_{1/2} > 3.7\cdot10^{25}$ yr (90% CL)



[Phys.Rev.Lett. 120 (2018) no.7, 072701]

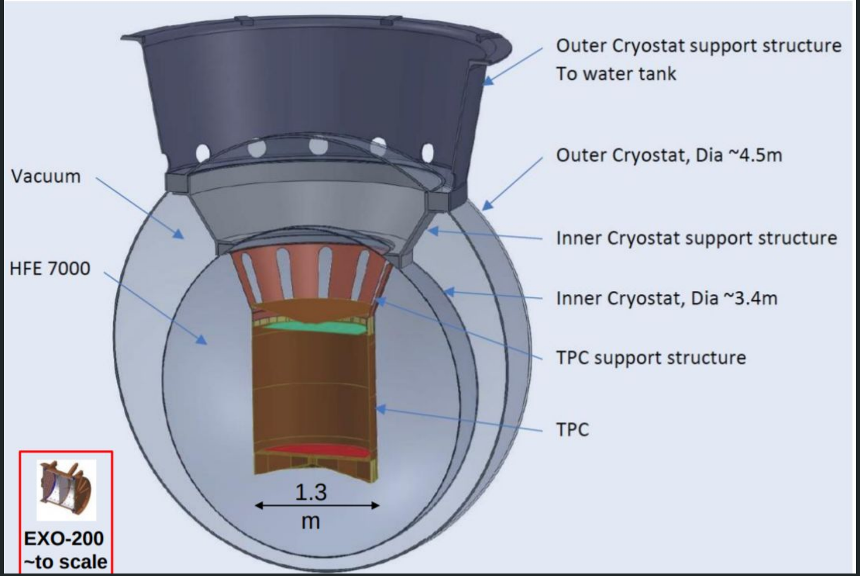


- ➢ resolution achieved combination scintillation & ionization
- ➢ background budget dominated by external gammas
- ➢ signal extracted through multi-variate fit (energy vs boosted decision tree)

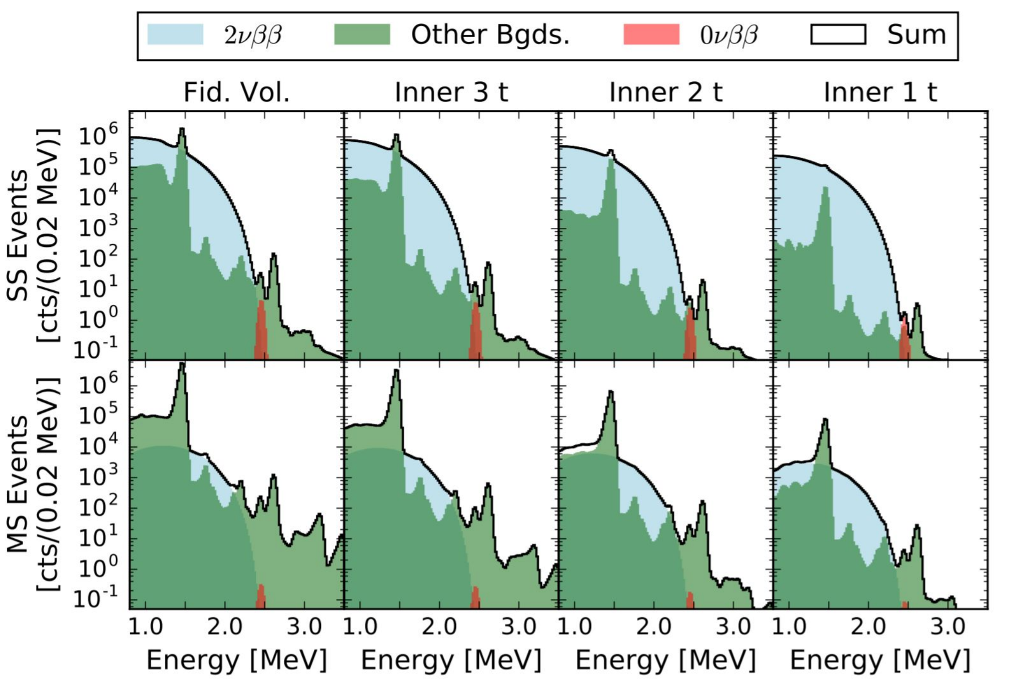
nEXO (expected performance)

Location	SNOLAB, Canada
Isotope	^{136}Xe [$Q_{\beta\beta}$=2458 keV]
Technology	TPC with liquid Xe
Isotope Mass	4500 kg
$0\nu\beta\beta$ efficiency	40%
Resolution [σ]	25 keV
Status	designing

[arXiv:1805.11142]



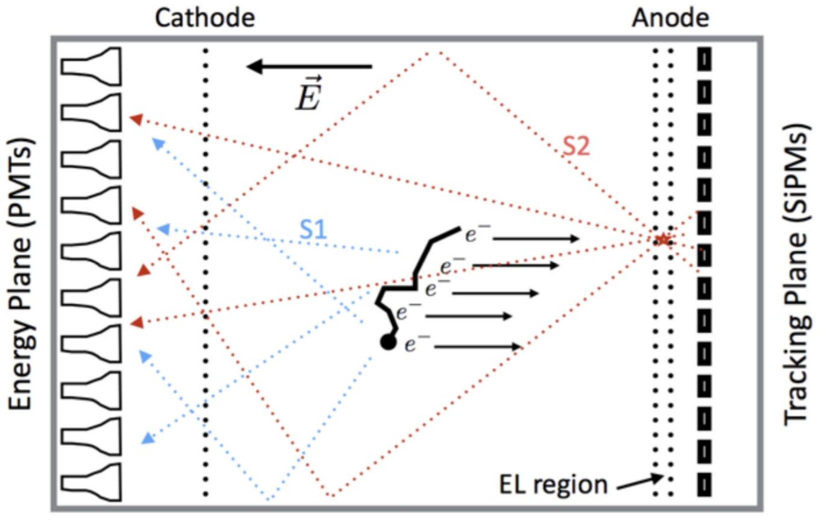
Background dominated by ext gamma -> MV fit (radius + E)

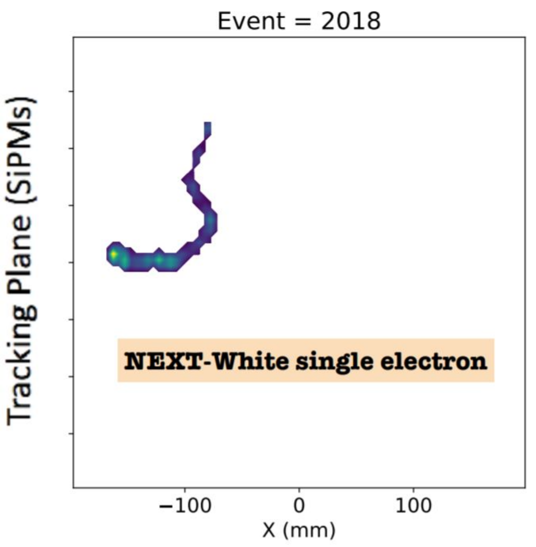


Major changes w.r.t EXO-200:
- ➢ Only one drift volume
- ➢ ASIC electronics in LXe
- ➢ Silica substrate charge collection tiles
- ➢ VUV SiPMs (~4.5m^2)
- ➢ Little plastics in the TPC (Sapphire, Silica)

NEXT (expected next phase performance)	
Location	Canfranc @ Spain
Isotope	^{136}Xe [$Q_{\beta\beta}$=2458 keV]
Technology	TPC with gass Xe
Isotope Mass	90 kg
$0\nu\beta\beta$ efficiency	69%
Resolution [σ]	8 keV
Status	designing

[arXiv:1804.02409]





High pressure TPC

- ➢ immediate scintillation gives t_0 and therefore the z coordinate
- ➢ Electroluminescence proportional amplification:
  - ➢ 1% energy resolution (PMT plane)
  - ➢ tracking (SiPMs plane) in x and y
- ➢ beginning of operations planned for 2020

NEXT-2.0

- ➢ improved tracking performance and background budget
- ➢ Promising detection of single Ba++ ions at a surface using Single Molecule Fluorescence Imaging

Major $0\nu\beta\beta$ experiments

		current gen	mid-term	long-term
Gas/Liquid detector Scalable self-shielding typicall low efficiency 1-10% energy resolution	Liquid scintillator + time of flight event reconstruction (scintillation)	KZ	KZ-800 SNO^+ phase I	KamLAND2-Zen SNO^+ phase II
	Time Projection chambers (ionization + scintillation)	EXO NEXT-10	NEXT-100 PANDA-X-III	nEXO NEXT-2.0 PANDAX-III 1t
Solid detectors multi-detector design granularity high-efficiency 0.1% energy resolution	Bolometers (heat + scintillation)	CUORE CUPID-0 AMORE	AMORE II	CUPID
	Ge semiconductor (ionization)	GERDA MJD	LEGEND-200	LEGEND-1000
External detectors	Magnetized tracking	NEMO	SUPERNEMO	

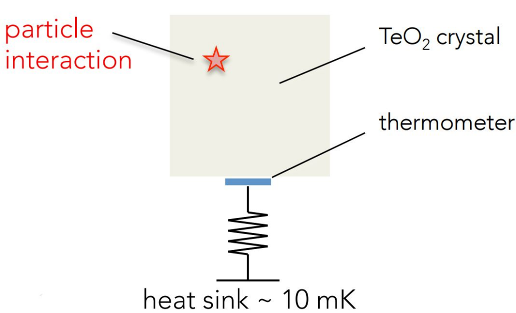
CUORE (achieved performance)

Location	LNGS, Italy
Isotope	^{130}Te [$Q_{\beta\beta}$=2527 keV]
Technology	Cryogenic calorimeters
Isotope Mass	206 kg
$0\nu\beta\beta$ efficiency	68%
Resolution [σ]	3.3 keV
Status	running
Latest results	$T_{1/2} > 1.5\cdot10^{25}$ yr (90% CL)
Sensitivity	$T_{1/2} > 0.7\cdot10^{25}$ yr (90% CL)

[Phys. Rev. Lett. 120, 132501 (2018)]

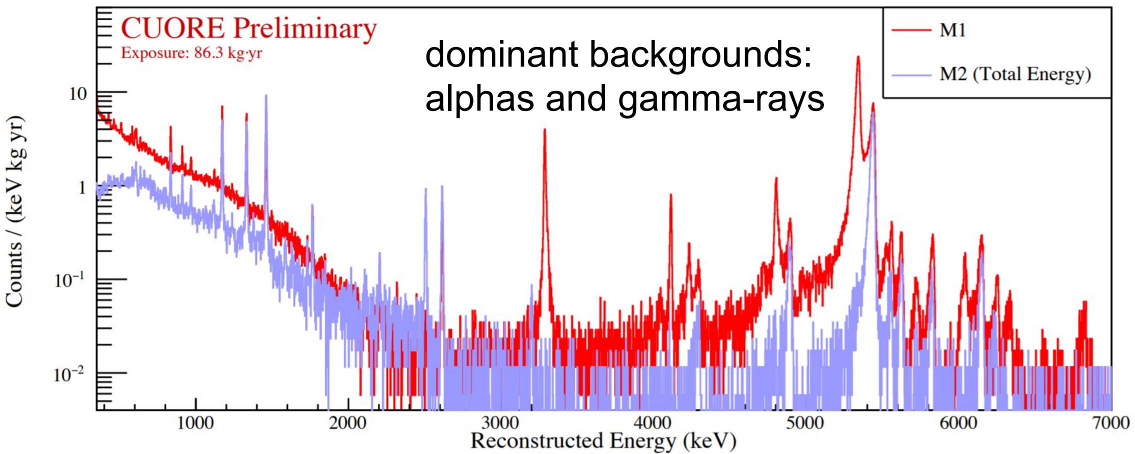
Bolometers:

- ➢ TeO_2 crystals
- ➢ operated at ~10 mK
- ➢ Read out with Ge Neutron Transmutation Doped thermometer

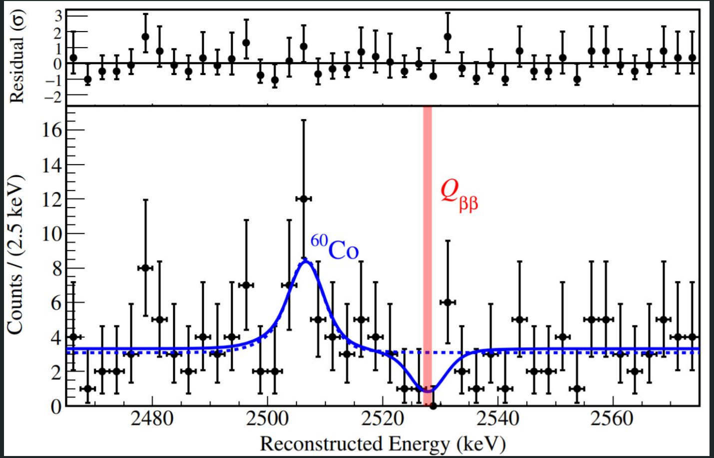


Design and challenges:

- ➢ operation of 1000 detectors
- ➢ cryostat must keep detectors at stable temperature (Coldest Cubic Meter in the Known Universe!)
- ➢ background screening with lead and ancient lead



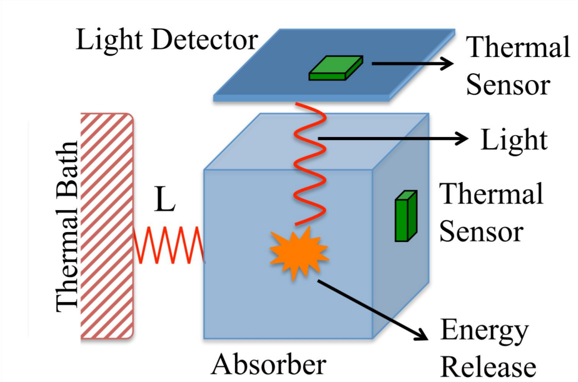
dominant backgrounds: alphas and gamma-rays



CUPID (expected performance)	
Location	LNGS, Italy
Isotope	^{100}Mo [$Q_{\beta\beta}$=2527 keV]
Technology	scintillating calorimeters
Isotope Mass	212 kg
$0\nu\beta\beta$ efficiency	69%
Resolution [σ]	2.1 keV
Status	R&D

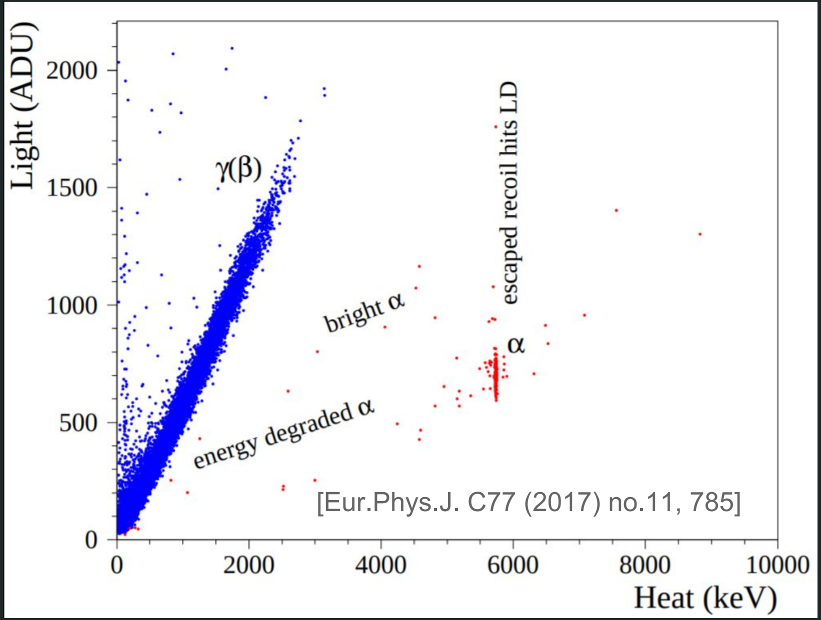
Alpha-beta separation:

- heat + light
- light can be scintillation or Cherenkov
- increase complexity of the detectors



pursued R&D for a future background-free experiment:

- $^{130}TeO_2$ [heat + Cherenkov light]
  alpha-beta separation achieved with CUORE-size crystal and Neganov-Luke amplification
- $Zn^{82}Se$ [heat + scintillation light]
  CUPID-0 running at LNGS, great background achieved
- $Li_2{}^{100}MoO_4$ [heat + scintillation light]
  CUPID-Mo Phase-I with 2.34 kg ^{100}Mo in commissioning
  <u>Chosen as baseline alternative</u>



[Eur.Phys.J. C77 (2017) no.11, 785]

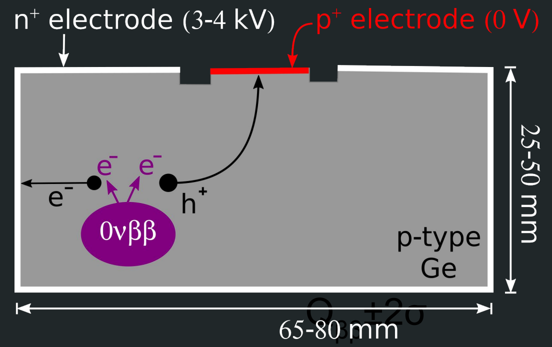
Major $0\nu\beta\beta$ experiments

		current gen	mid-term	long-term
Gas/Liquid detector Scalable self-shielding typically low efficiency 1-10% energy resolution	Liquid scintillator + time of flight event reconstruction (scintillation)	KZ	KZ-800 SNO$^+$ phase I	KamLAND2-Zen SNO$^+$ phase II
	Time Projection chambers (ionization + scintillation)	EXO NEXT-10	NEXT-100 PANDA-X-III	nEXO NEXT-2.0 PANDAX-III 1t
Solid detectors multi-detector design granularity high-efficiency 0.1% energy resolution	Bolometers (heat + scintillation)	CUORE CUPID-0 AMORE	AMORE II	CUPID
	Ge semiconductor (ionization)	GERDA MJD	LEGEND-200	LEGEND-1000
External detectors	Magnetized tracking	NEMO	SUPERNEMO	

GERDA (achieved performance)	
Location	LNGS, Italy
Isotope	^{76}Ge [$Q_{\beta\beta}$=2039 keV]
Technology	Semiconductor Ge detectors
Isotope Mass	35 kg
$0\nu\beta\beta$ efficiency	65%
Resolution [σ]	1.3 keV
Status	running
Latest results	$T_{1/2} > 0.9\cdot10^{26}$ yr (90% CL)
Sensitivity	$T_{1/2} > 1.1\cdot10^{26}$ yr (90% CL)

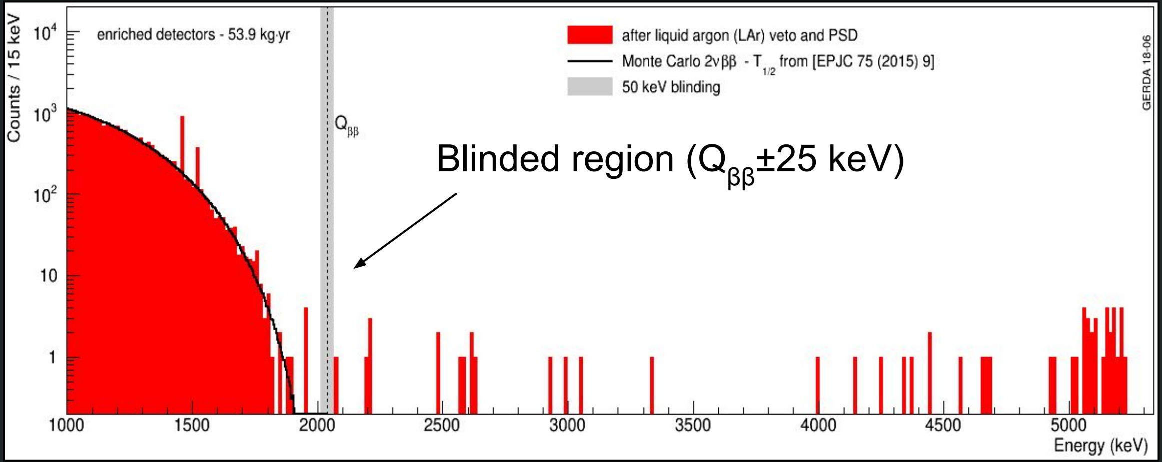
Ge detectors are operated in ultra-pure liquid Ar:

- ➢ shielding
- ➢ scintillates

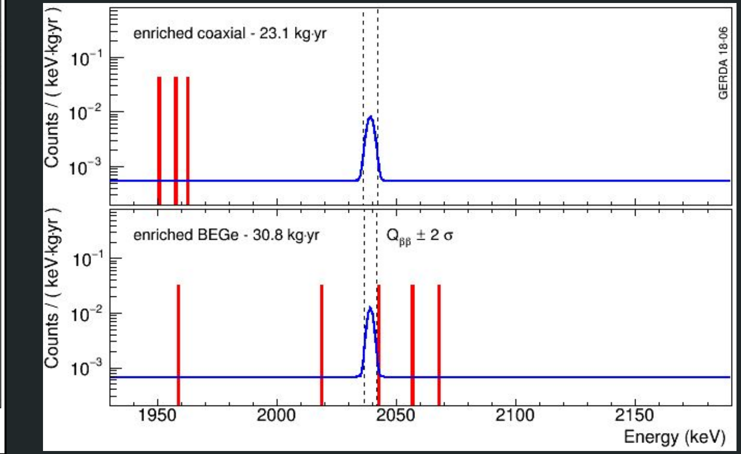


Background events are identified through:

- ➢ detection of LAr scintillation light
- ➢ detection of a signal in multiple detectors
- ➢ pulse shape analysis

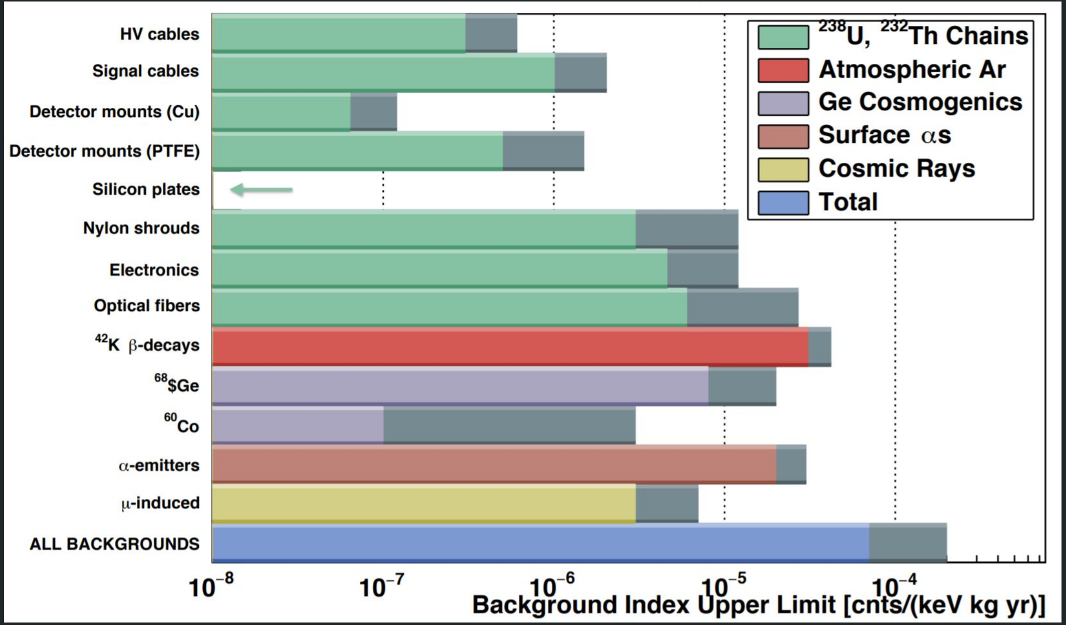


Blinded region ($Q_{\beta\beta}$±25 keV)



LEGEND (expected performance)

Location	LNGS, Italy (first phase)
Isotope	^{76}Ge [$Q_{\beta\beta}$=2039 keV]
Technology	Semiconductor Ge detectors
Isotope Mass	174 kg
$0\nu\beta\beta$ efficiency	65%
Resolution [σ]	1.3 keV
Status	under design



LEGEND builds upon the successful experience of GERDA and MAJORANA:

- ➢ GERDA → LAr active veto system
- ➢ MAJORANA → low background material
  → front-end electronics

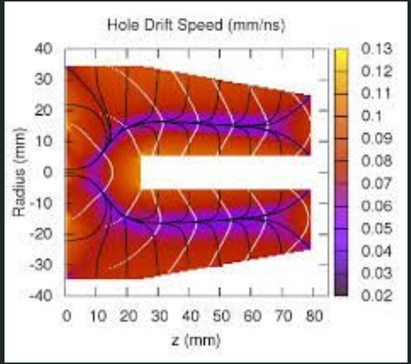
Stages approach:

- ➢ LEGEND-200 → 200 kg of detectors in the current GERDA infrastructure
- ➢ LEGEND-1000 → 1000 kg of detectors in a new setup (location not defined yet)

From GERDA to LEGEND-200:

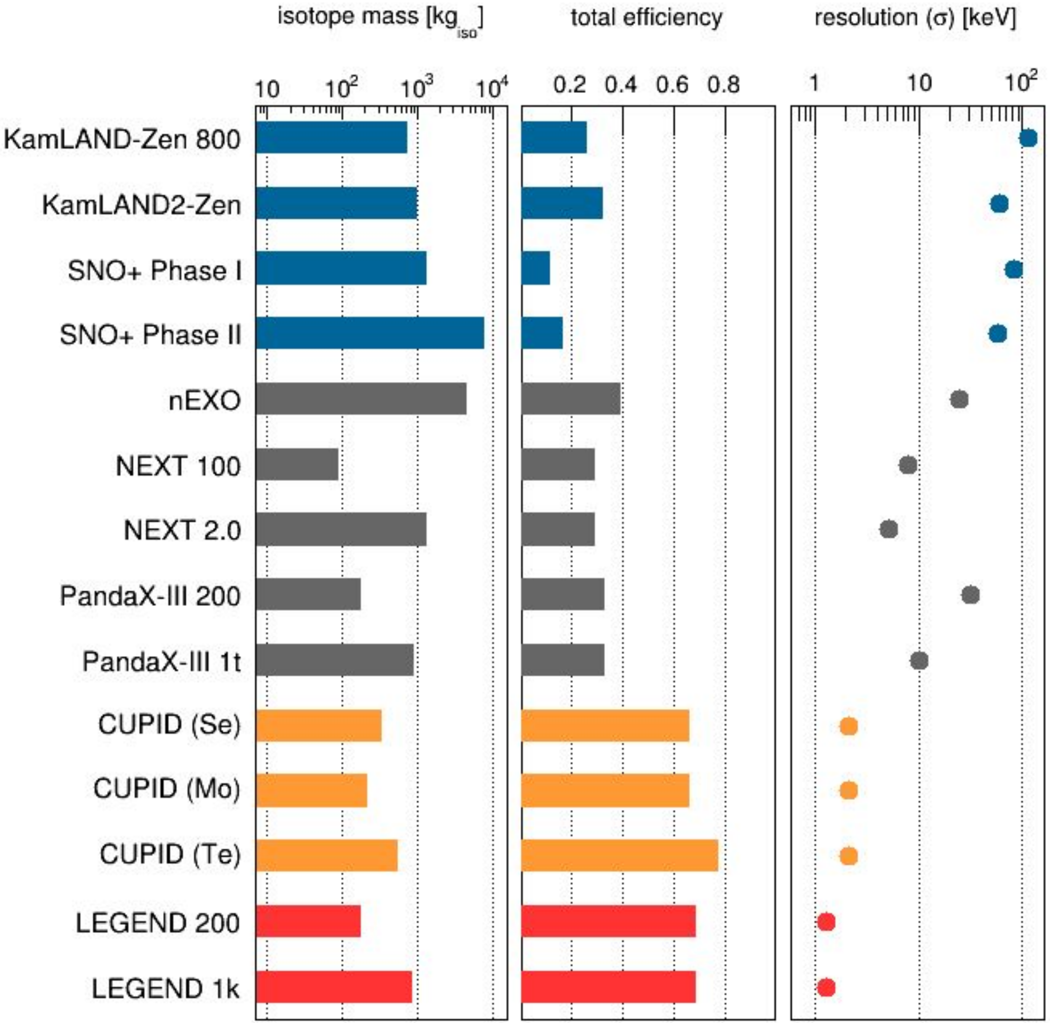
- ➢ new detectors (inverted coax)
- ➢ increased LAr veto efficiency
- ➢ Cleaner materials
- ➢ Improved electronics

Funding for L200 secured!
Commissioning in 2020
Physics data taking in 2021



Neutrinoless Double-β decay

- Theoretical contextualization
  - model independent
  - minimal extension of the 3-neutrino framework
  - other extensions of the 3-neutrino frameworks
- Experimental aspects
- Review of on-going experiments
- Experiment comparison and prospects

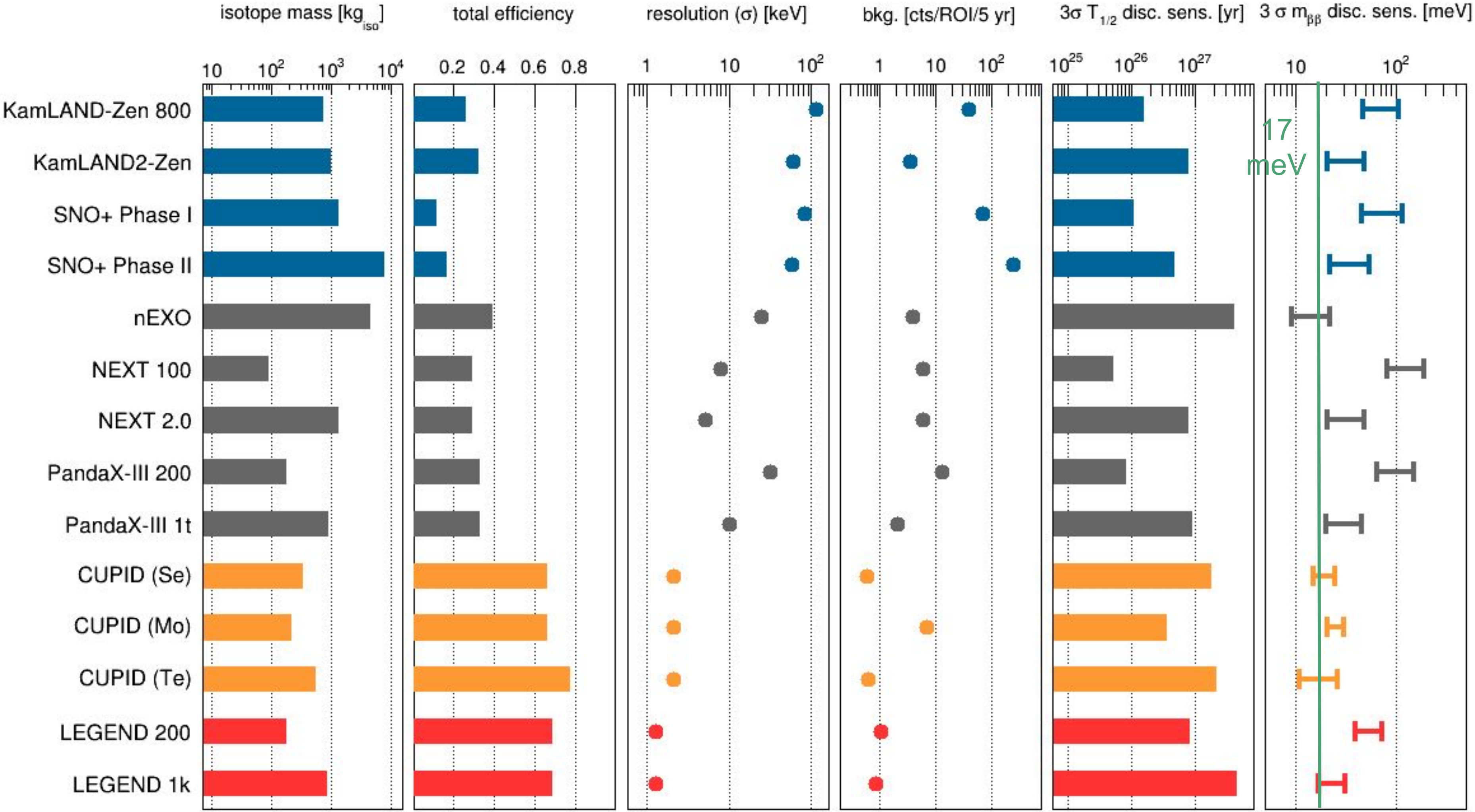


Exp Parameters

Efficiency includes:

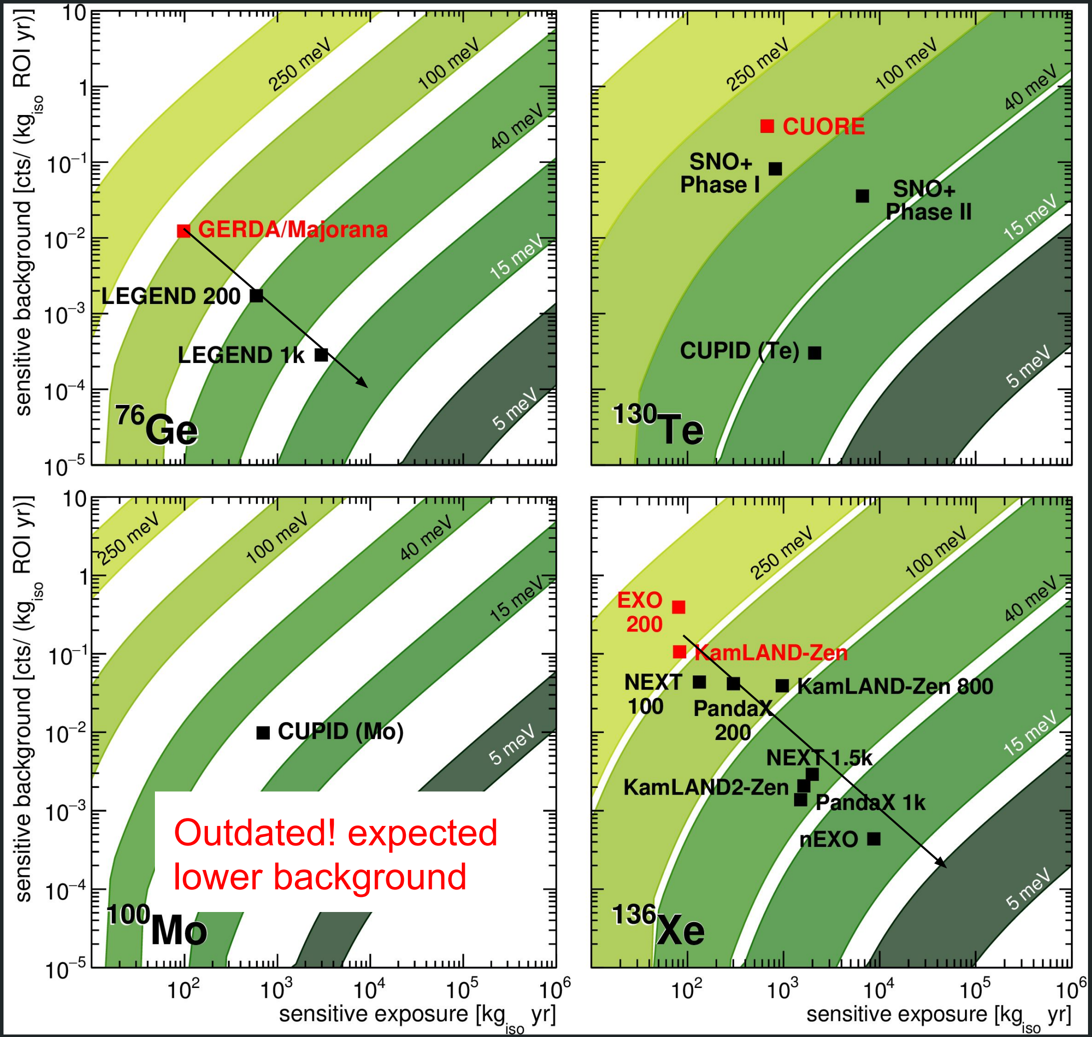
- ➢ sensitive Volume
- ➢ sensitive ROI
  - ➢ bgk-free: $Q_{\beta\beta} \pm 2\,\sigma$
  - ➢ gauss bkg: $Q_{\beta\beta} \pm 1.2\,\sigma$
  - ➢ poor-resolution: $[Q_{\beta\beta}, Q_{\beta\beta} \pm 1.2\,\sigma]$
- ➢ containment
- ➢ analysis cut (e.g. pulse shape)

Adapted from [**M.A.** et al., PRD 96, 053001 (2017)]
[Courtesy of Christoph Wiesinger]


isotope mass [kg$_{iso}$]
total efficiency
resolution (σ) [keV]
bkg. [cts/ROI/5 yr]
3σ $T_{1/2}$ disc. sens. [yr]
3 σ $m_{\beta\beta}$ disc. sens. [meV]
10
10^2
10^3
10^4
0.2
0.4
0.6
0.8
1
10
10^2
1
10
10^2
10^{25}
10^{26}
10^{27}
10
10^2
KamLAND-Zen 800
KamLAND2-Zen
SNO+ Phase I
SNO+ Phase II
nEXO
NEXT 100
NEXT 2.0
PandaX-III 200
PandaX-III 1t
CUPID (Se)
CUPID (Mo)
CUPID (Te)
LEGEND 200
LEGEND 1k
17 meV

Sensitivity

- ➢ Ge experiments pursue a staged approach. Each stage as background level and exposure goals such to be background free
- ➢ Xe experiments reduce the background by self-shielding. Development along a clear direction with the attempt to get background free (helps for discovery)
- ➢ Sensitivity does not take into account the uncertainty/reliability of the signal extraction



Outdated! expected lower background

[**M.A.**, G Benato and J A Detwiler, PRD 96, 053001 (2017)]

Conclusion and Outlook

- 0νββ: matter creating process measurable in the lab
- Strong implications for particle physics, cosmology and neutrinos. Important not to focus on a single mechanism!
- Huge experimental effort, many ton-scale experiments in preparation
- The discovery probability of next-generation experiment is high and a discovery could be around the corner. Important to keep on increasing the $T_{1/2}$ sensitivity for each isotope
- Variety of the field is a strength! Absolutely needed to observe the signal in multiple isotopes and with different experimental techniques