The Quest for Neutrinoless Double-β decay

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

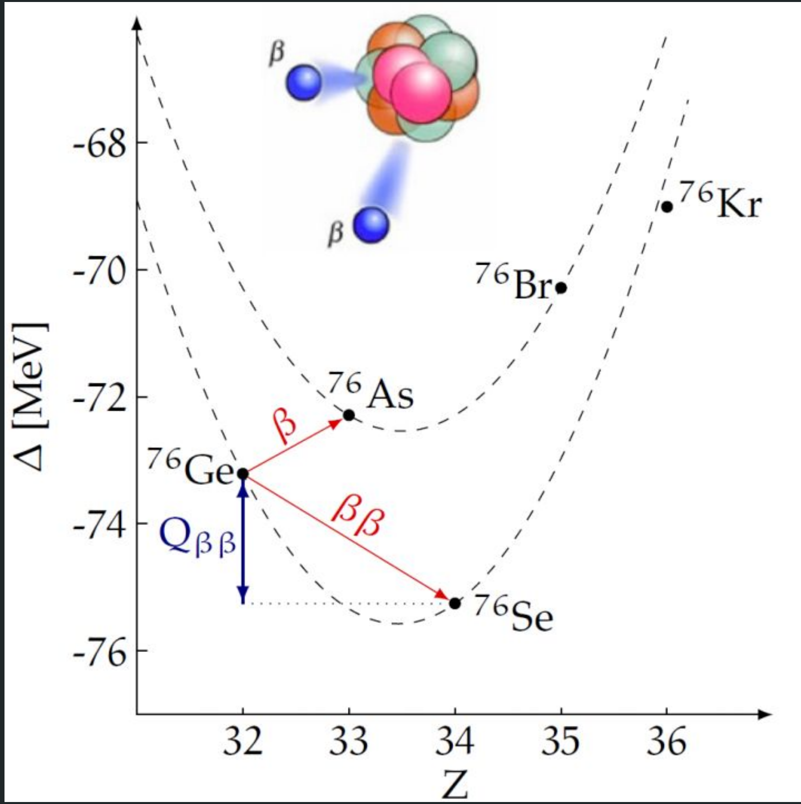
Neutrinoless Double-β Decay ($0\nu\beta\beta$)

Hypothetical second order nuclear transition:

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

- ➢ foreseen by most of the 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



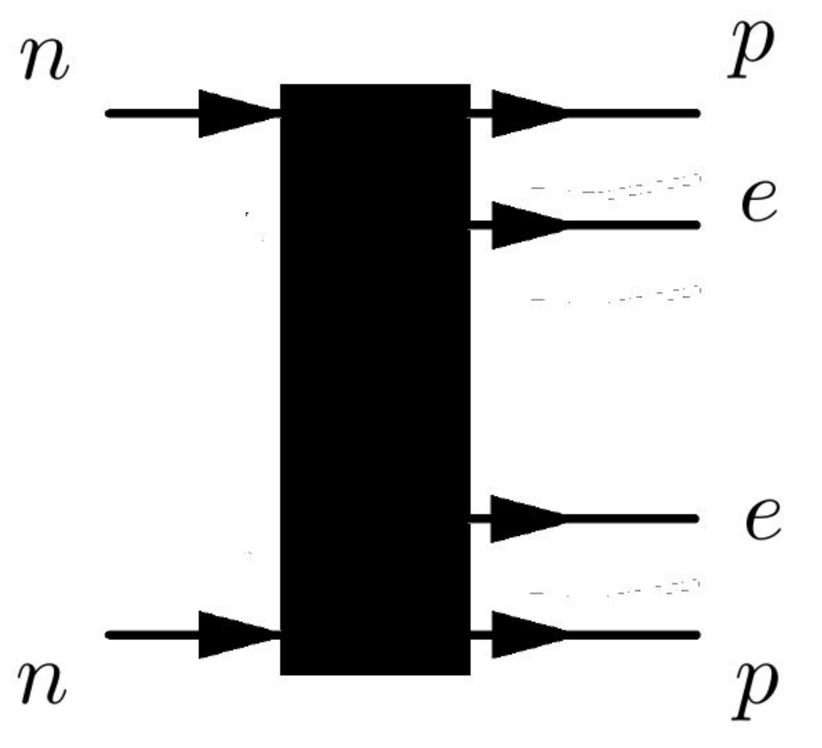
[Courtesy of G. Benato]

A portal to Physics beyond the Standard Model

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

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

2 leptons produced w/o balancing anti-leptons



If observed:

- ➢ lepton number is not conserved
- ➢ first observation of “matter creation"

Broad implications:

- ➢ $0\nu\beta\beta$ as fundamental as proton decay
- ➢ connected to matter-antimatter asymmetry in the Universe (Baryo and Leptogenesis)

A portal to Physics beyond the Standard Model

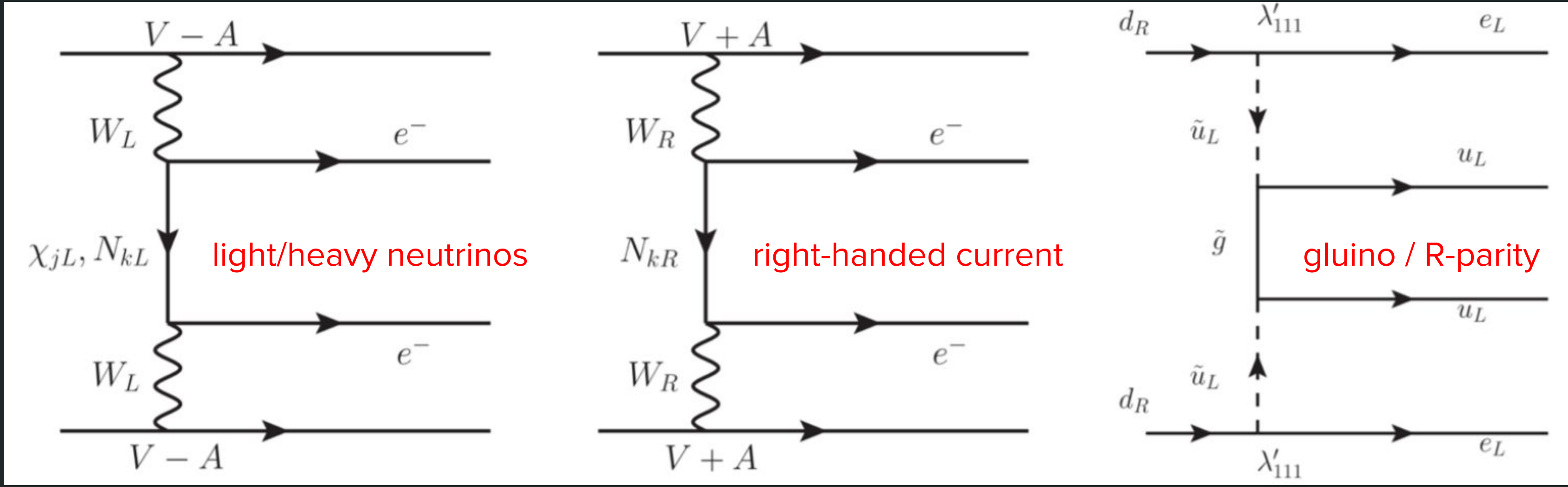
The probability of the process $[T_{1/2}]^{-1}$ is proportional to the coherent sum of all mechanisms involved:

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

Phase Space Factor

Nuclear Matrix Element

Mechanism



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

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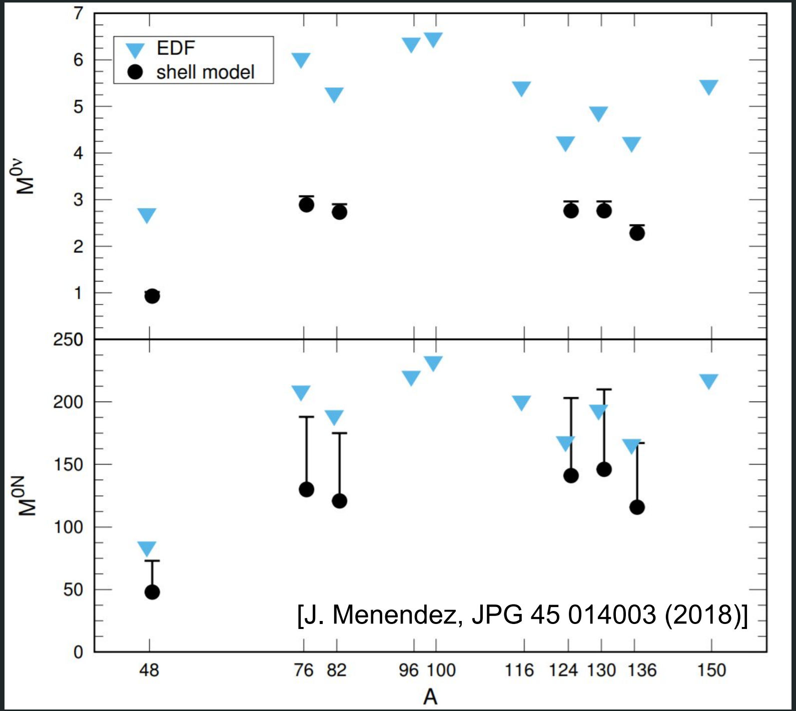
Mechanism

Nuclear Matrix Element



Nuclear Matrix Element:

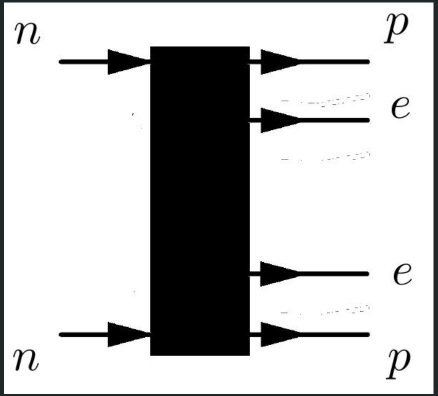
- ➢ depends on channel, in general can be expressed in terms of light and heavy neutrino exchange
- ➢ different computations currently within a factor 2-3
- ➢ ongoing effort to increase understanding

Mechanism:

- ➢ Scale of new physics connected to the to $[T_{1/2}]^{-1}$
- ➢ $[T_{1/2}]^{-1}$ is for $0\nu\beta\beta$ decay what √s is for LHC

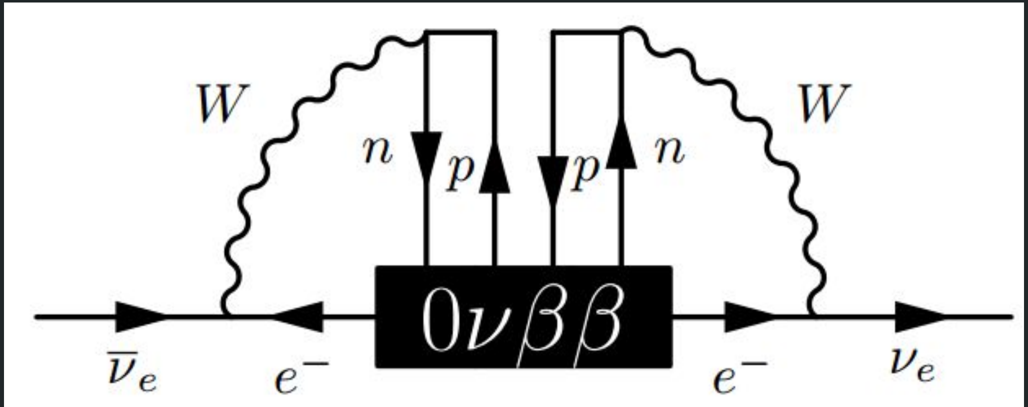
$0\nu\beta\beta$ and the Origin of Neutrino Masses

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]



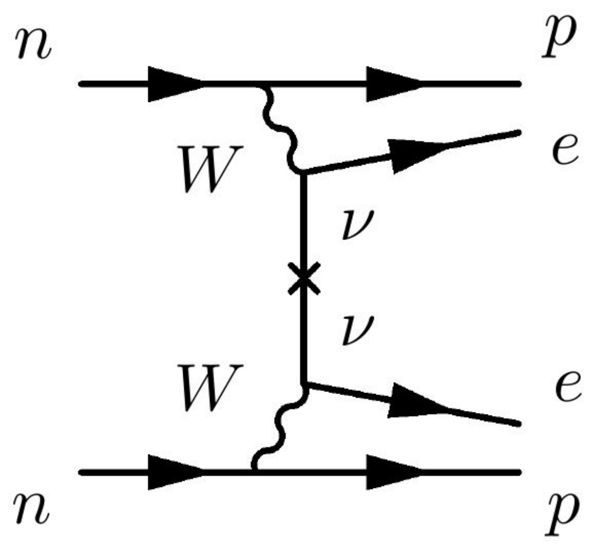
Note: bulk of neutrino mass not given by $0\nu\beta\beta$ operator

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

The Vanilla Channel

Exchange of light-Majorana neutrinos:

- requires minimal extension of the SM
  - neutrinos are massive ➔ already proved
  - neutrinos have a majorana nature
- dominant channel in most of the frameworks



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

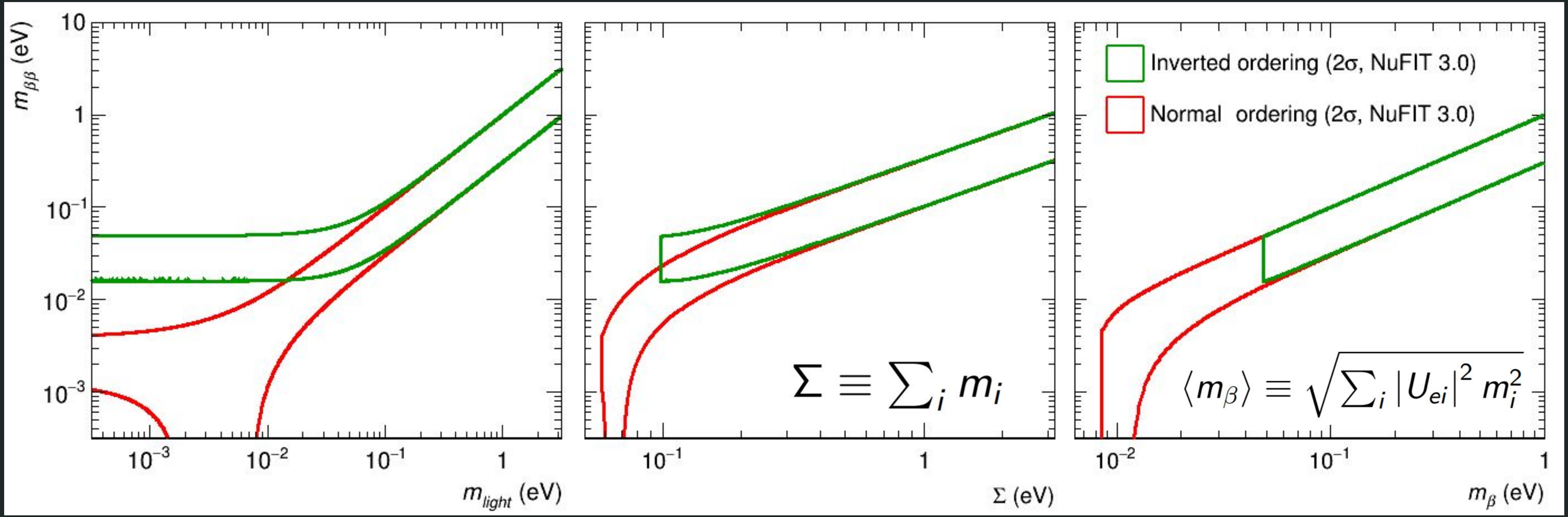
Effective Majorana Mass

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

Neutrino Mass Observables

Cosmology (Planck, Euclid)
sum of neutrinos masses

Beta-decay kinematic (KATRIN)
electron neutrino mass



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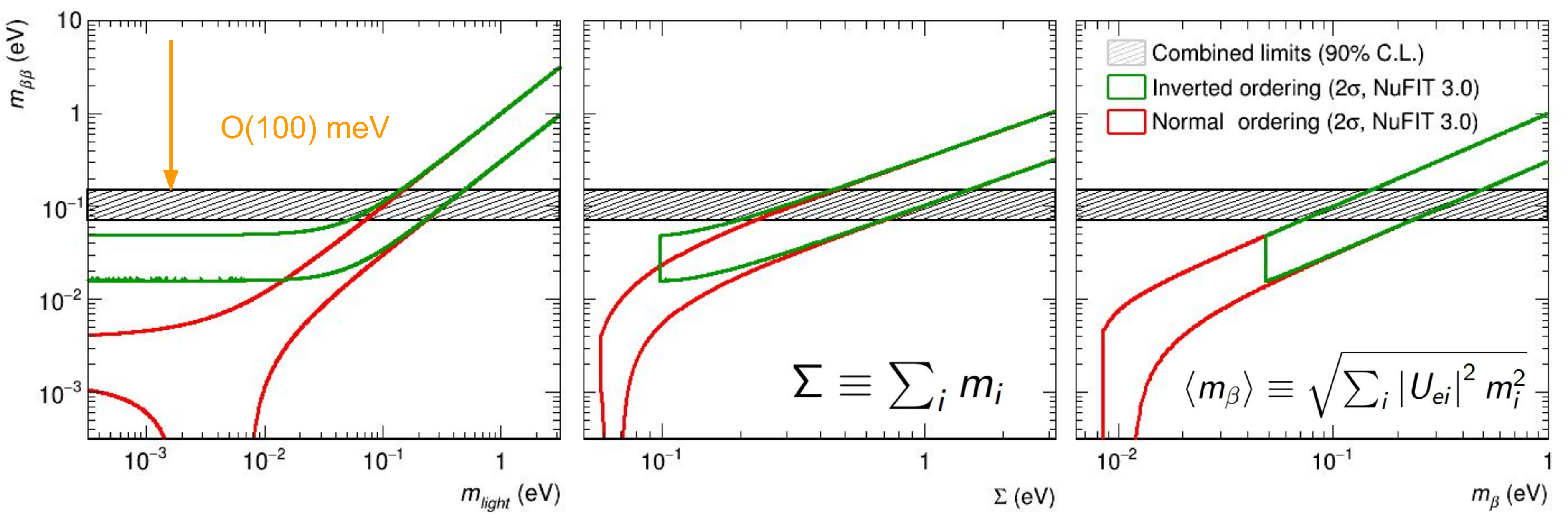

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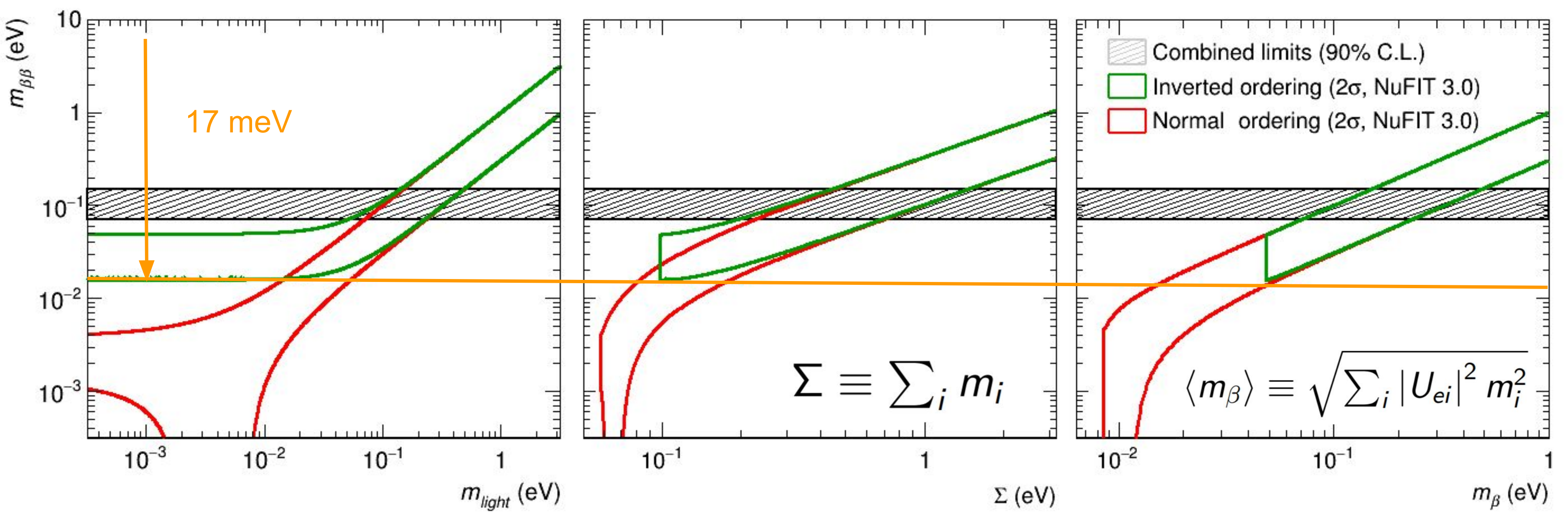
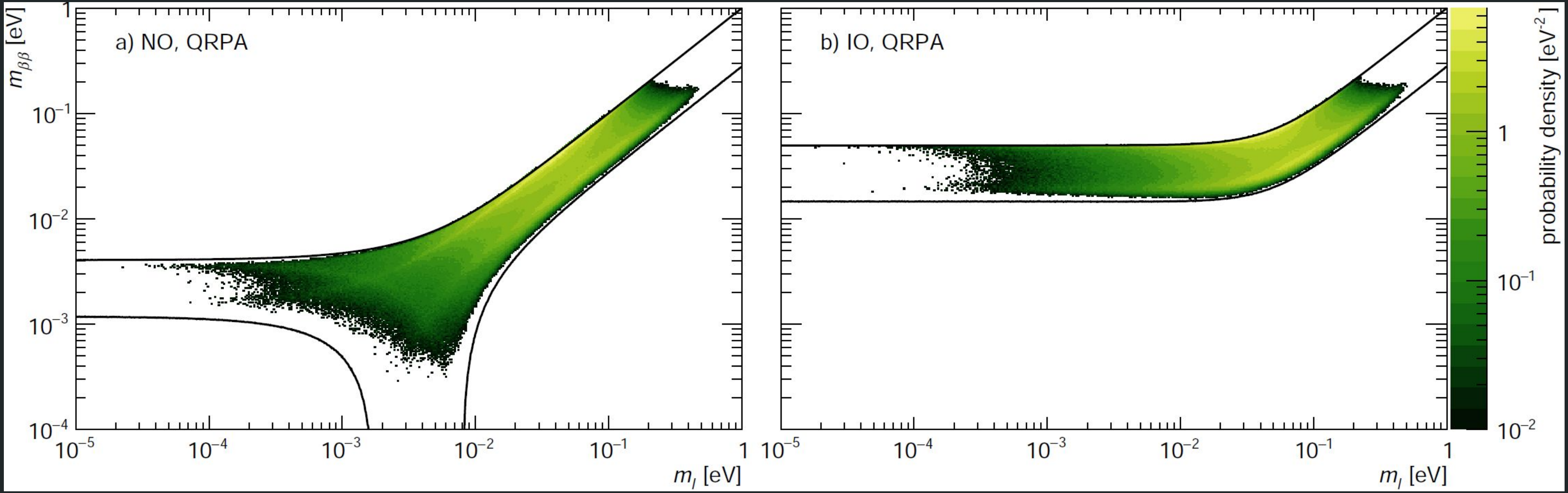


- Degenerate Majorana masses probed!
- Next target inverted ordering band

- $0\nu\beta\beta$ searches, cosmological surveys and direct mass measurements give complementary information!

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

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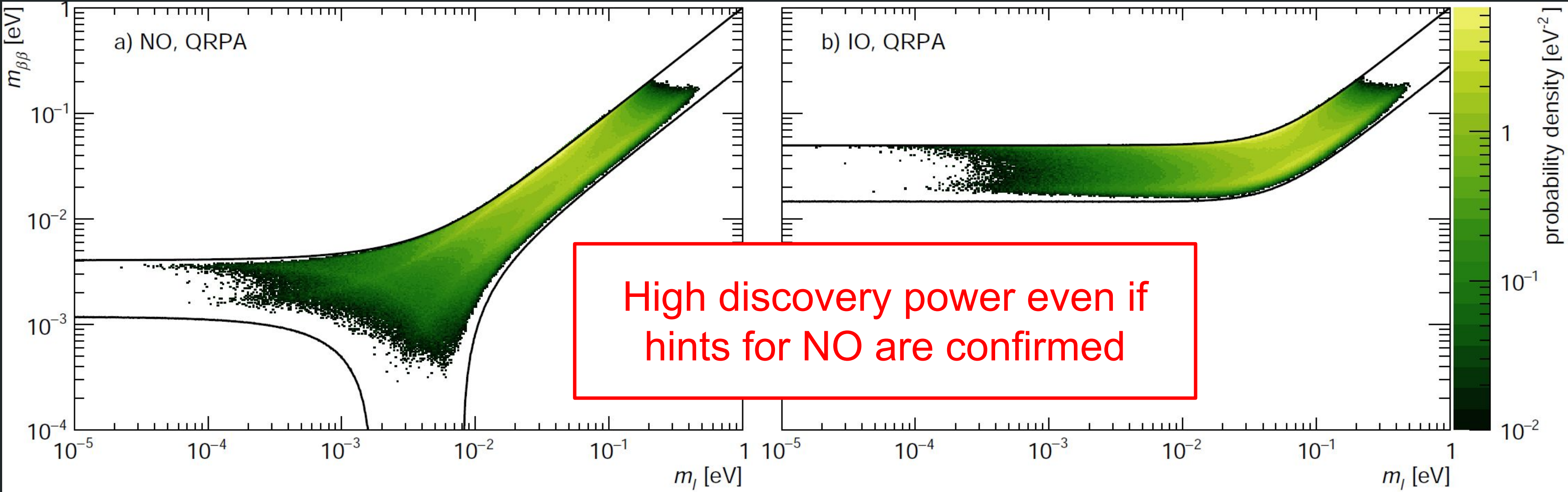

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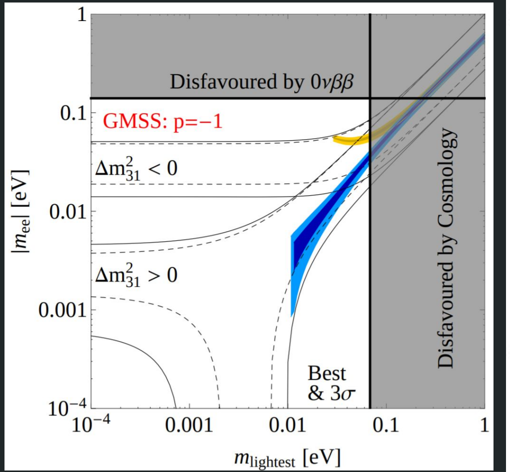
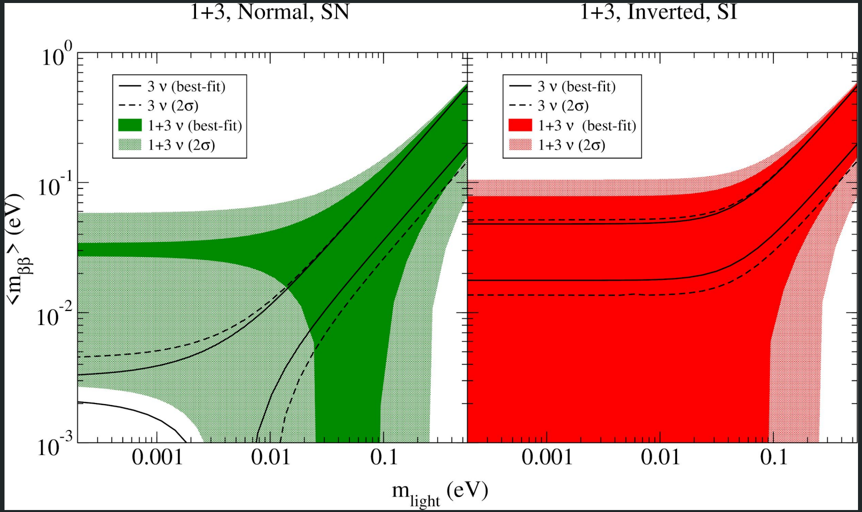
Other Extensions

- ➢ flavor models
- ➢ 3+1 sterile
- ➢ dim 7 and 9 operators
- ➢ …

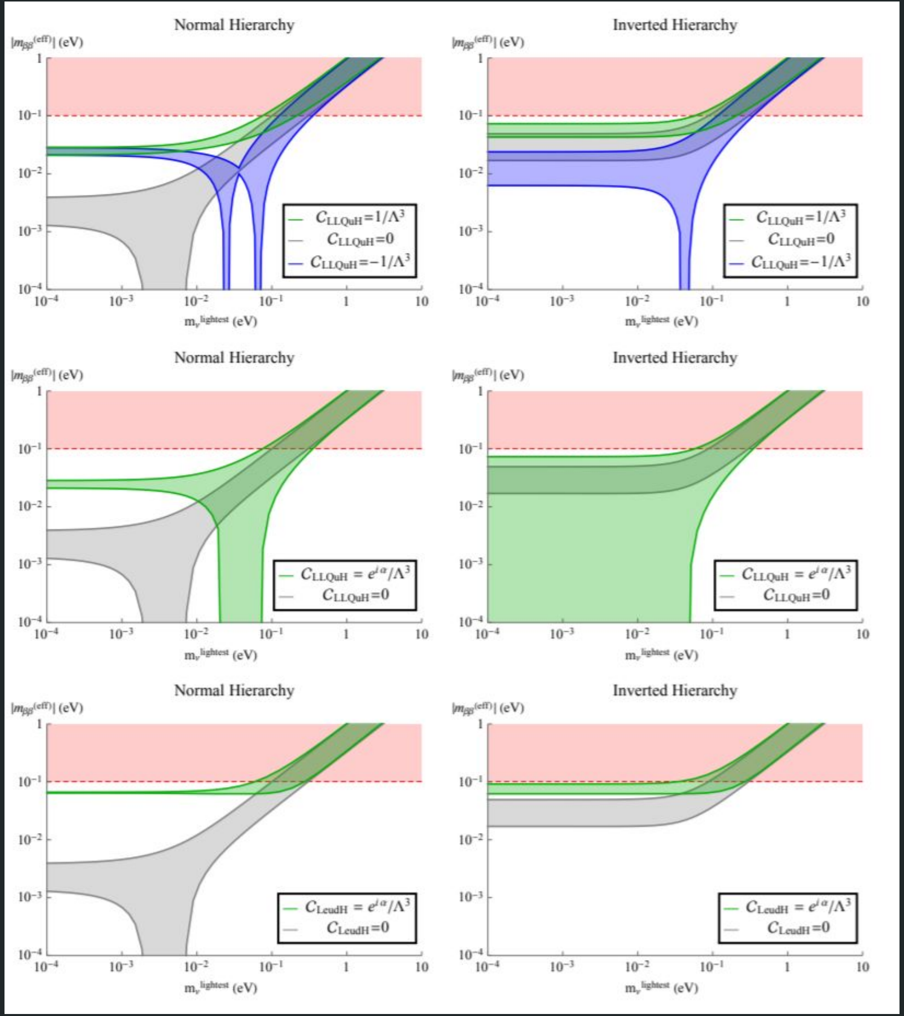
[King, Merle, Stuart, JHEP 1312, 005 (2013)]





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

[Cirigliano et al. JHEP 12 082 (2017)]



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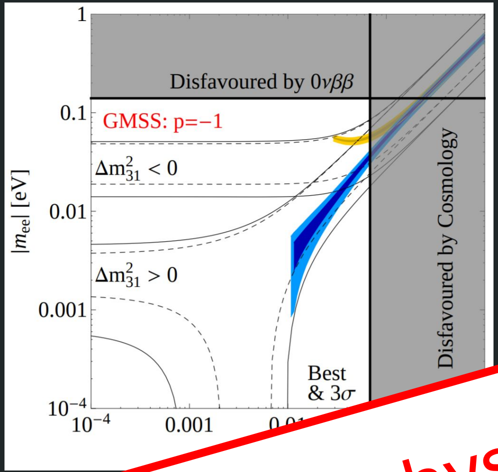
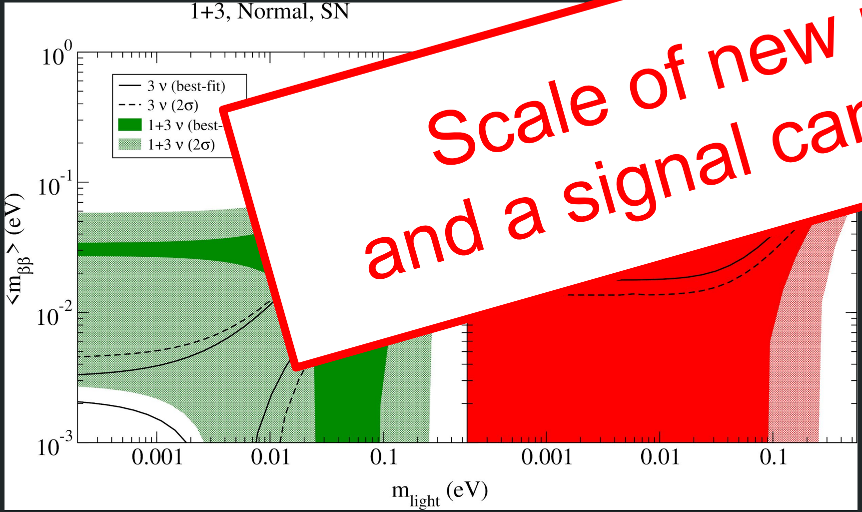
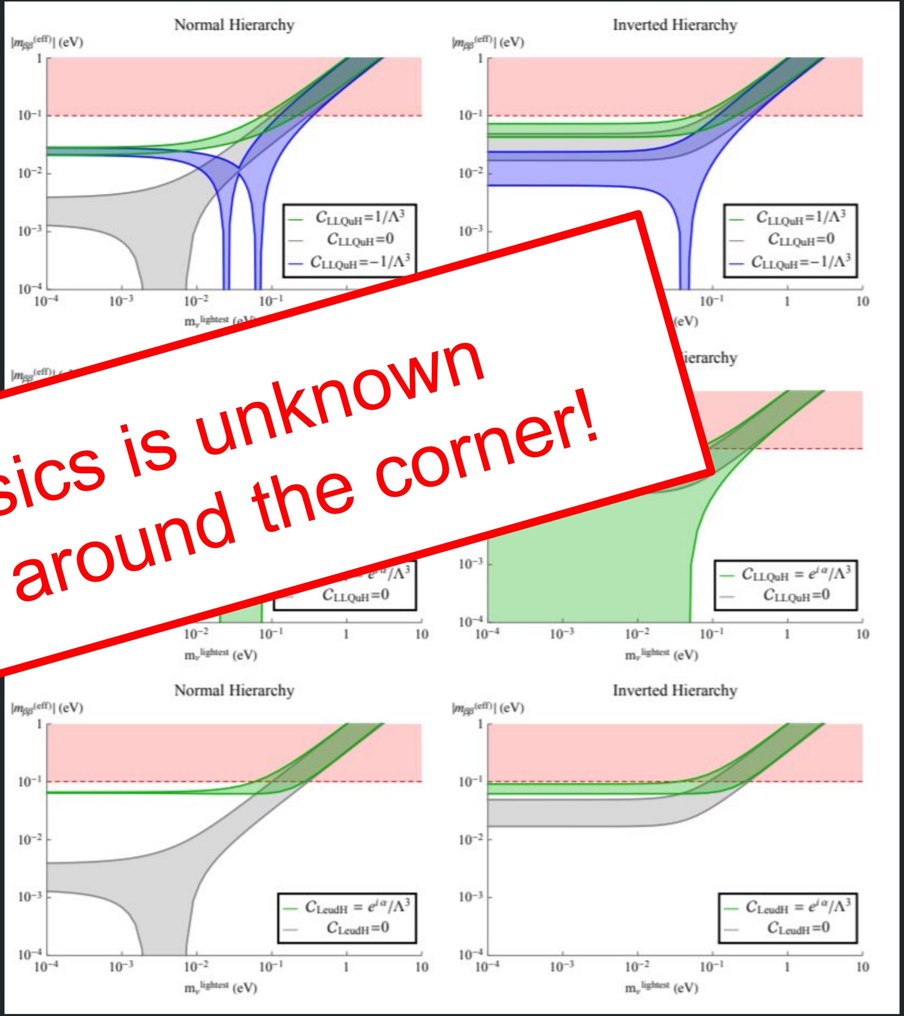




Int.J.Mod.Phys. E20(2011)]

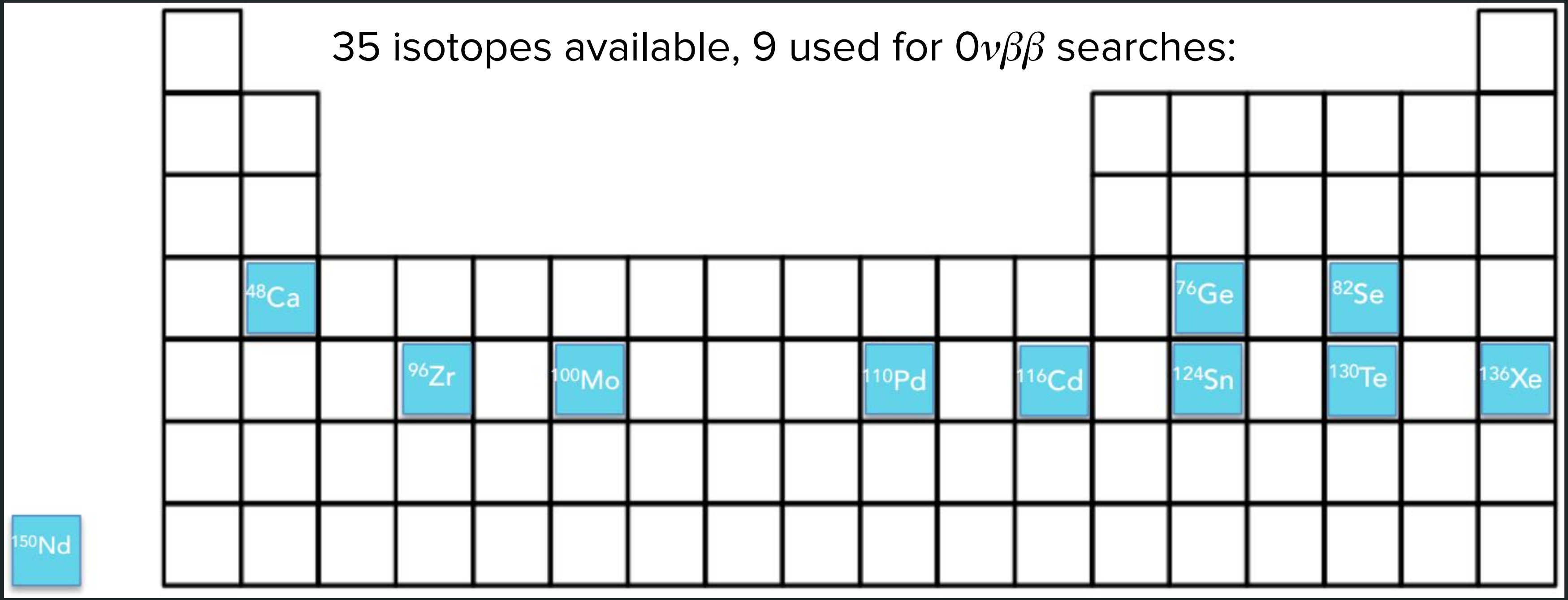


[Cirigliano et al. JHEP 12 (

Scale of new physics is unknown and a signal can be around the corner!

Experimental Aspects

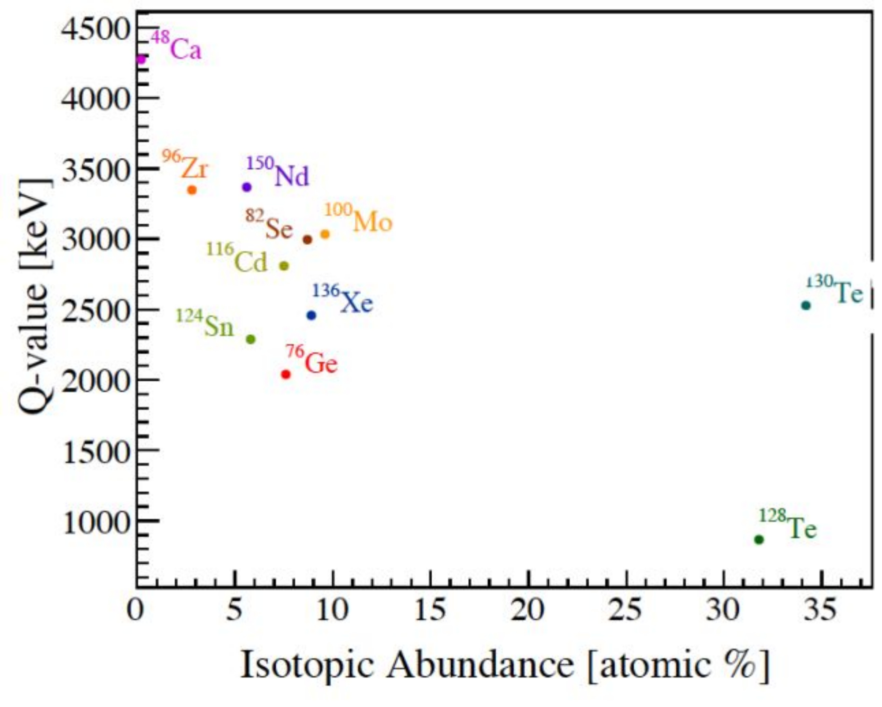
Double-β Decaying Isotopes



[Courtesy of K. Shaefner]

Double-β Decaying Isotopes

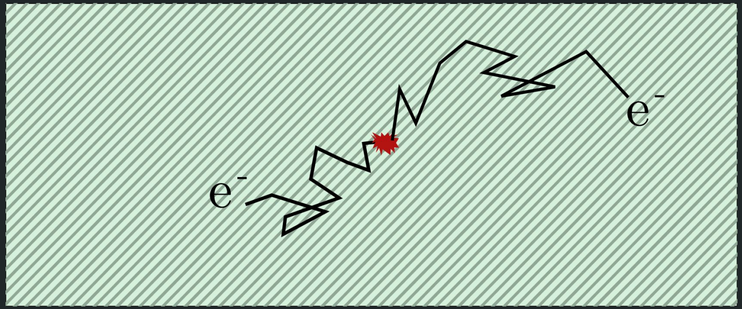
- cost depends on natural enrichment
- the higher is $Q_{\beta\beta}$ the better:
  - $[T_{1/2}]^{-1} \propto G^{0\nu}(Q,Z) \propto (Q_{\beta\beta})^5$
  - less background
- NMEs differes up to a factor 3
- very different detection technologies according to isotope



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

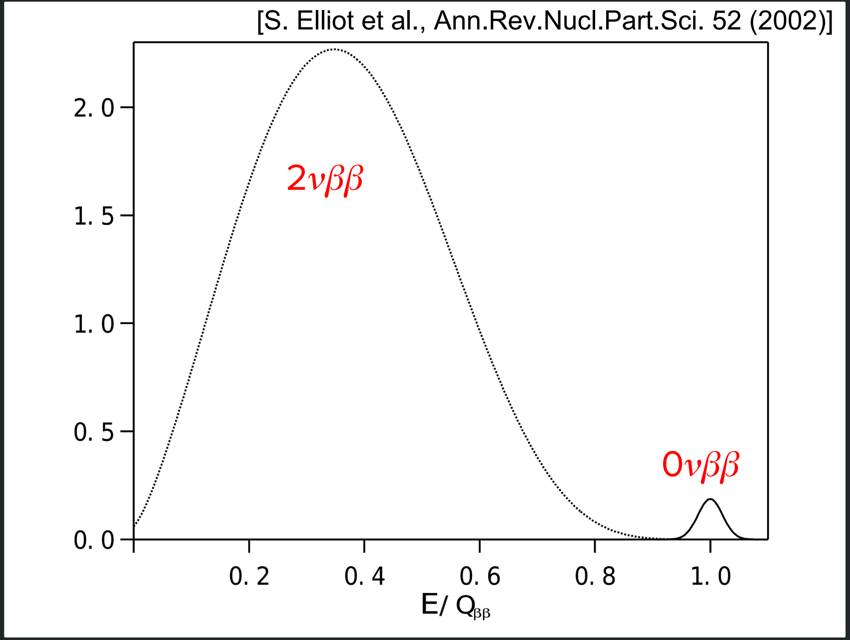


Most of the experiments have also other handles, however energy is the one observable that is both necessary and sufficient for discovery.

Measuring of the electron energy sum:

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

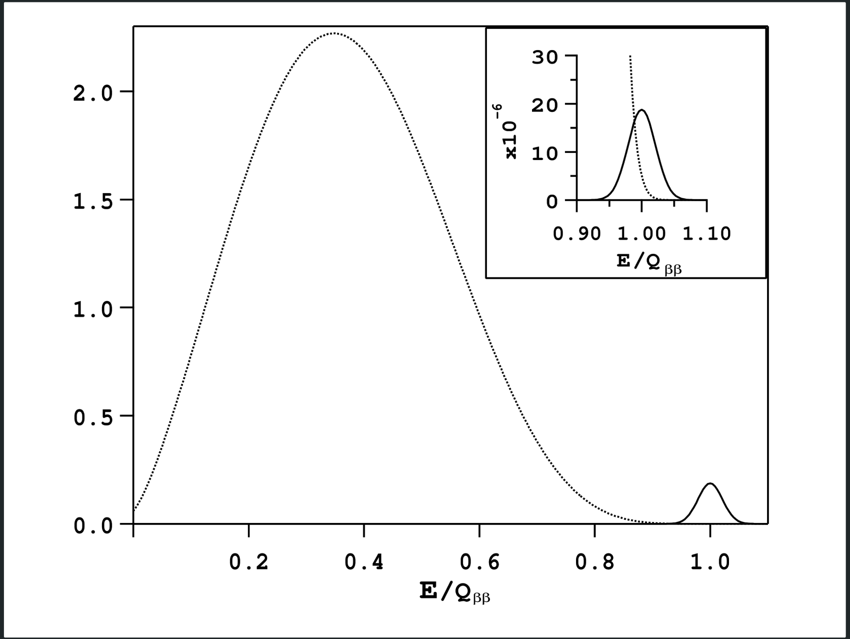
$2\nu\beta\beta$: (A, Z) -> (A, Z + 2) + $2e^-$ + 2ν -> continuum



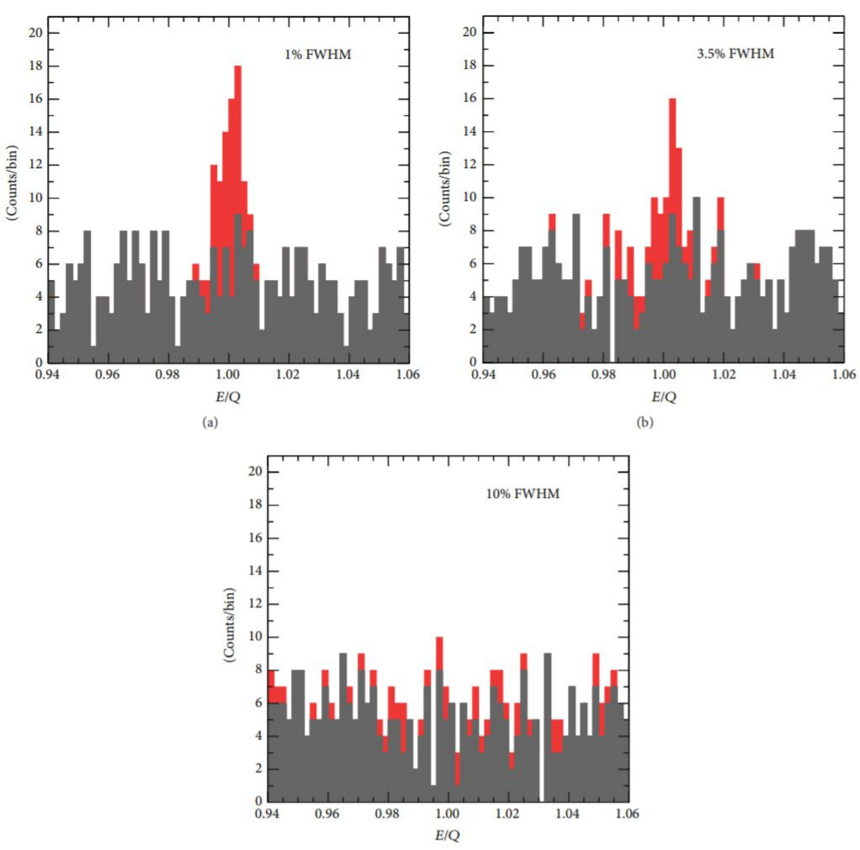
Energy Resolution & Background

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

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)]



Signal and Background rates

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

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

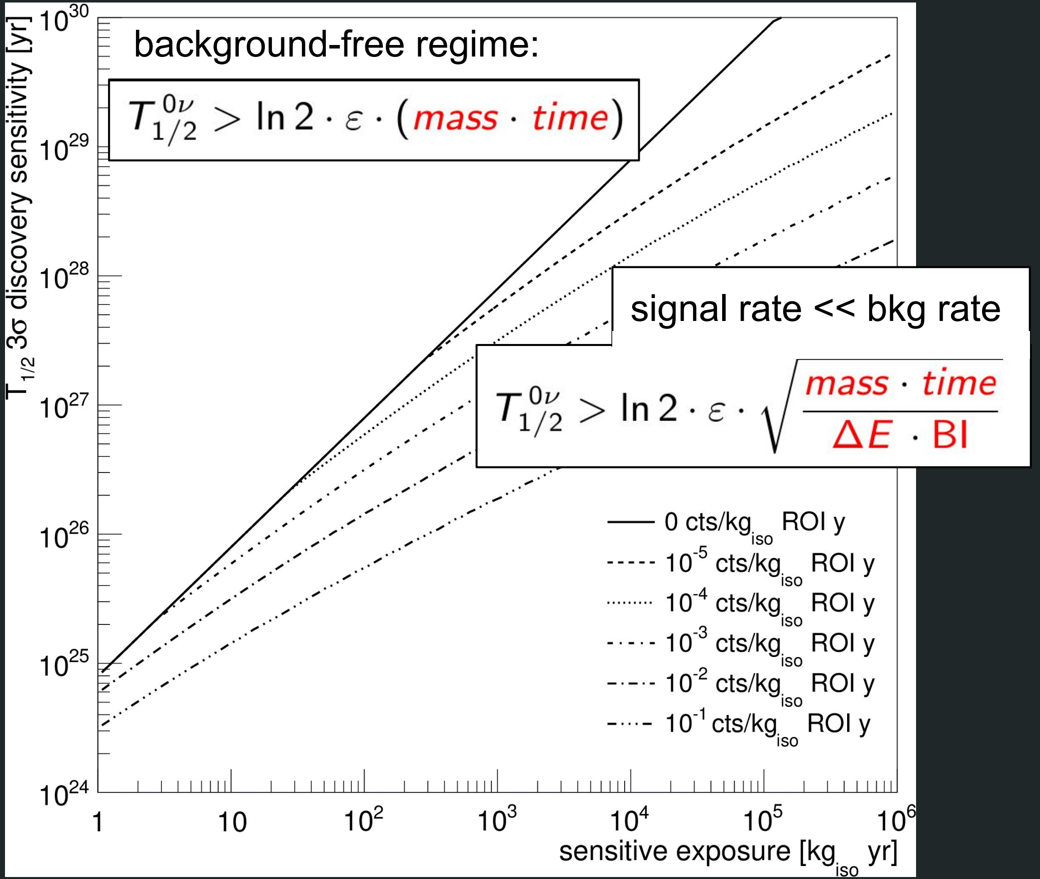
$T_{1/2} = 10^{25}$ yr -> $O(1)$ event / (10 kg yr)

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

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

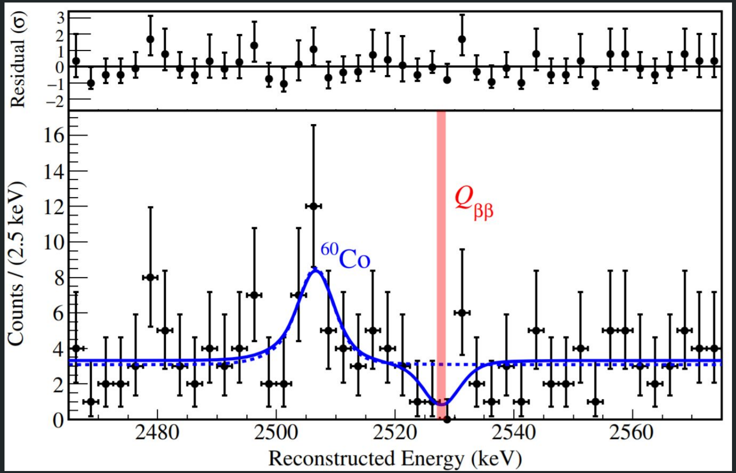
$T_{1/2} = 10^{28}$ yr -> $O(1)$ event / (10 t yr)

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



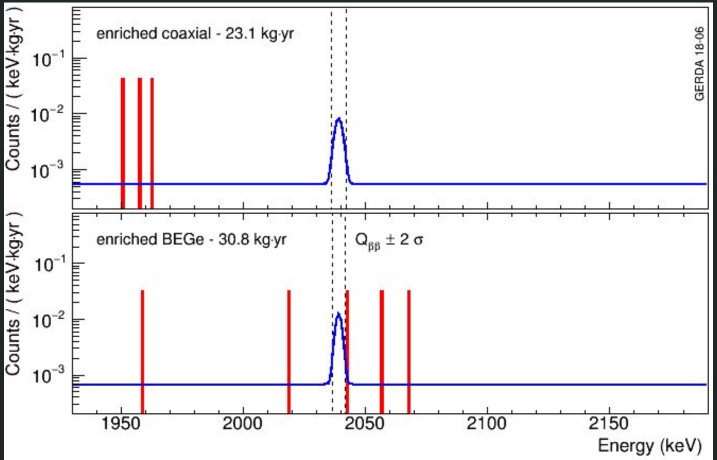
Signal Extraction and background shape uncertainty

CUORE: $\mathcal{O}(10)$ cts/ROI + simple shape

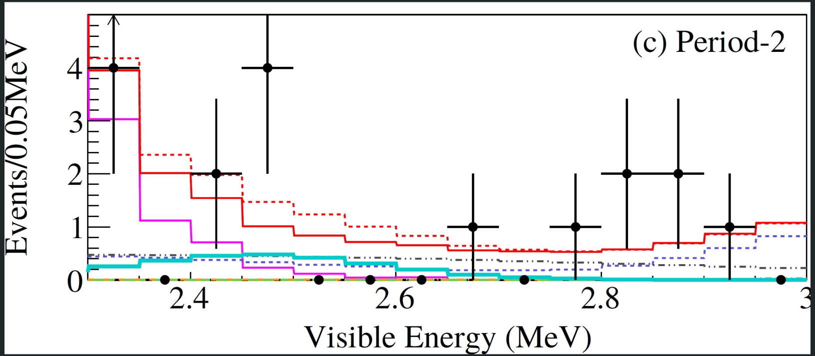


[Phys. Rev. Lett. 120, 132501 (2018)]

GERDA: $\mathcal{O}(0.1)$ cts/ROI + simple shape



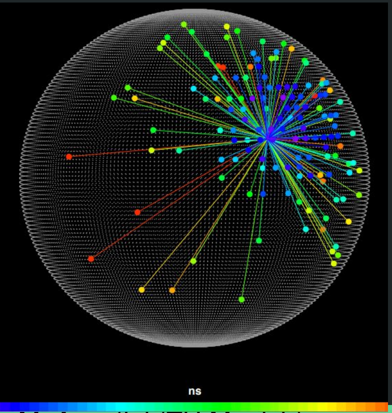
KamLAND-Zen: $\mathcal{O}(10)$ cts/ROI + complex shape

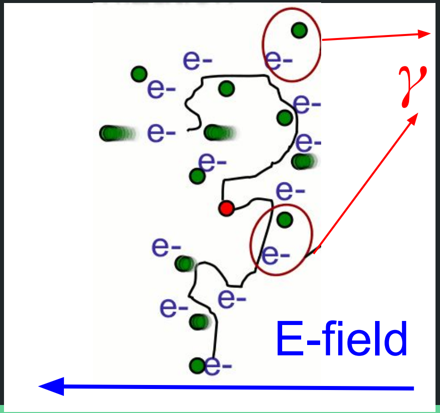


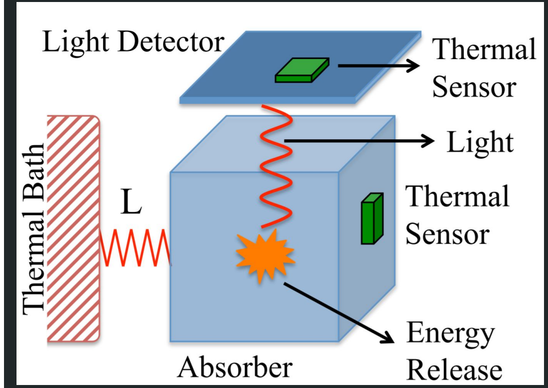
[PRL. 117 (2016) no.10, 109903]

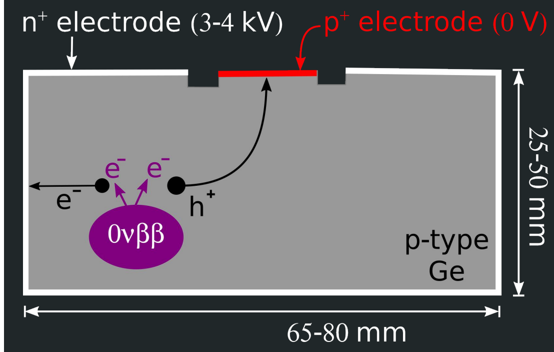
Most Sensitive Experiments

Detection Techniques	Large Liquid scintillator detectors	Time Projection Chambers	Cryogenic Calorimeters	Ge Semiconductor detectors
$0\nu\beta\beta$ Isotope Deployment	scintillator loaded with target isotope	Isotopically enriched xenon	crystals isotopically enriched	crystals isotopically enriched
Event Reconstruction	scintillation photons	scintillation photons and ionization electrons	temperature variation and scintillation	ionization electron-hole clusters
Background Mitigation	self-shielding and fiducialization	self-shielding, fiducialization, pulse shape analysis	energy resolution, array granularity	energy resolution, array granularity, pulse shape

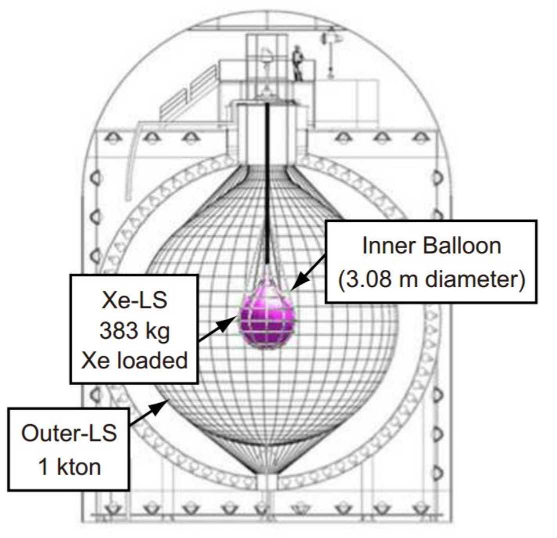






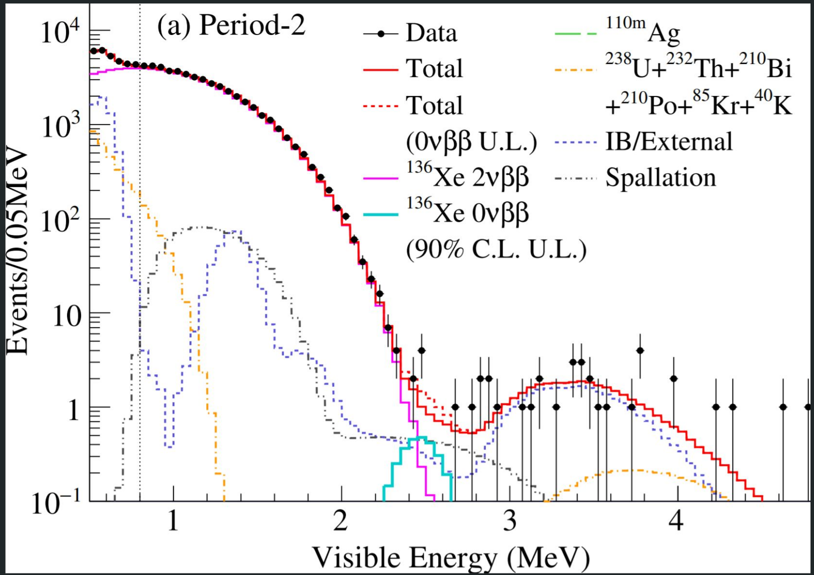


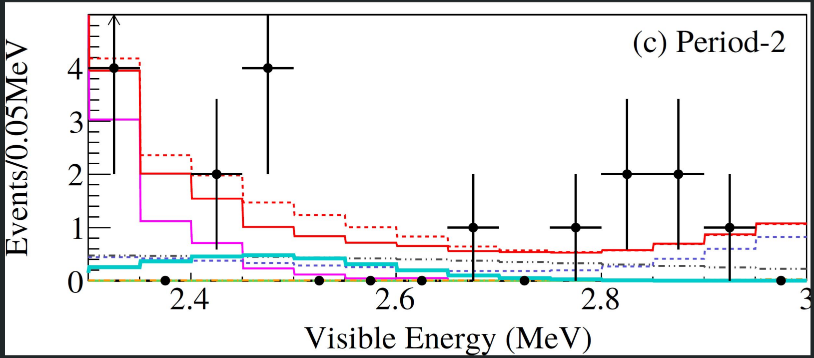
KamLAND-Zen	
Location	Kamioka, Japan
Isotope	^{136}Xe [$Q_{\beta\beta}$=2458 keV]
Technology	Xe-loaded liquid scintillator
Isotope Mass	350 kg
$0\nu\beta\beta$ efficiency	16%
Resolution [σ]	100-120 keV
Status	commissioning next phase
Latest results	$T_{1/2}$ > 1.1·10^{26} yr (90% CL)
Sensitivity	$T_{1/2}$ > 5.6·10^{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

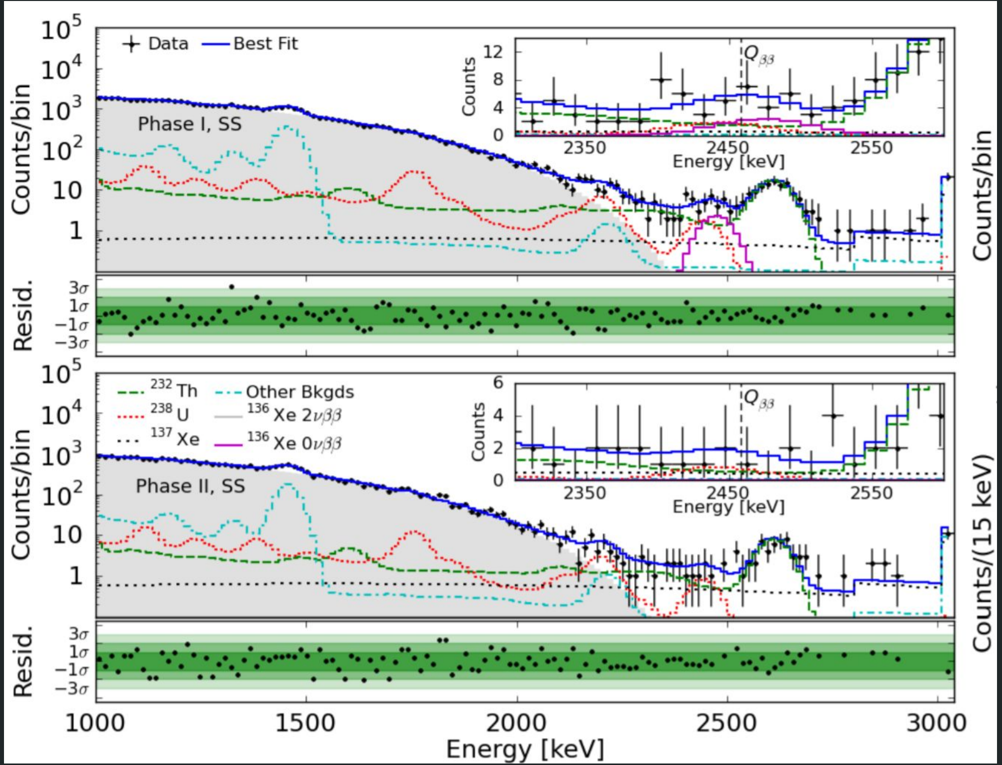


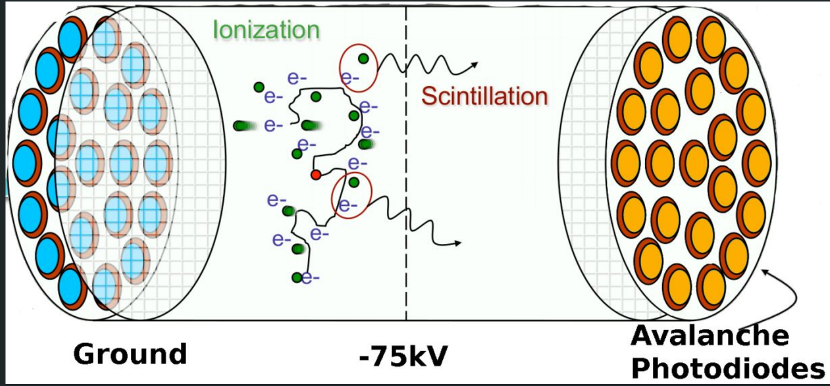


[Phys.Rev.Lett. 117 (2016) no.10, 109903]

EXO-200

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	completed
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]

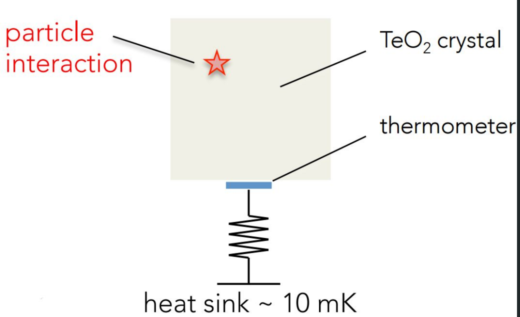
- ➢ energy reconstructed through scintillation & ionization
- ➢ main background due to external gammas
- ➢ multi-variate fit (energy vs boosted decision tree)

Future: nEXO (5 tons) at SNOLAB
New electronics and better resolution + self shielding

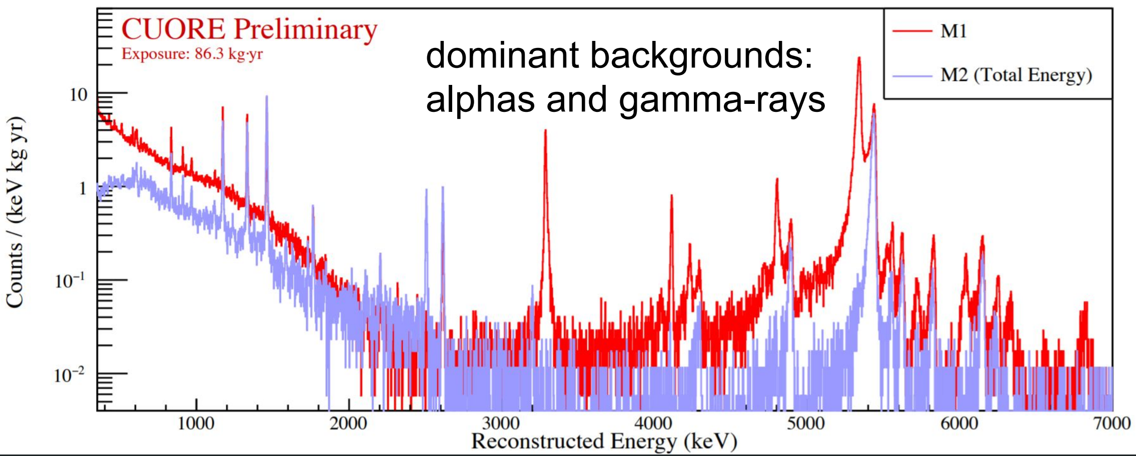
CUORE	
Location	LNGS, Italy
Isotope	^{130}Te [$Q_{\beta\beta}$=2527 keV]
Technology	Cryogenic calorimeters
Isotope Mass	206 kg
$0\nu\beta\beta$ efficiency	68%
Resolution [σ]	3.3 keV
Status	running
Latest results	$T_{1/2}$ > 1.5·10^{25} yr (90% CL)
Sensitivity	$T_{1/2}$ > 0.7·10^{25} yr (90% CL)

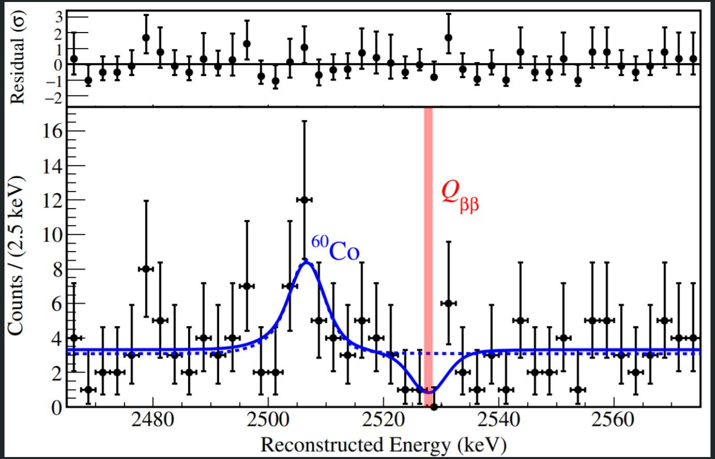
[Phys. Rev. Lett. 120, 132501 (2018)]

Bolometers:
- ➢ 1000 TeO_2 crystals
- ➢ operated at ~10 mK
- ➢ cryostat must keep stable temperature



Future is CUPID @ LNGS:
- ➢ alpha-beta separation through detection of heat + light
- ➢ $Li_2{}^{100}MoO_4$ chosen as baseline
- ➢ CUPID-Mo Phase-I with 2.34 kg ^{100}Mo in commissioning



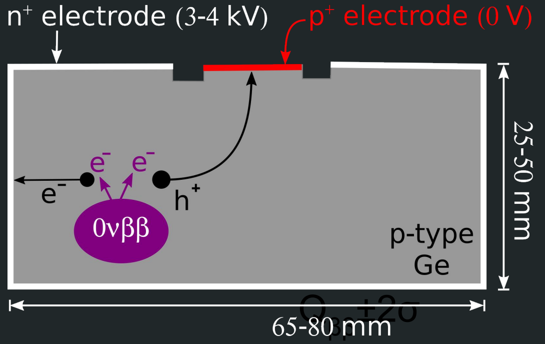


GERDA

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)

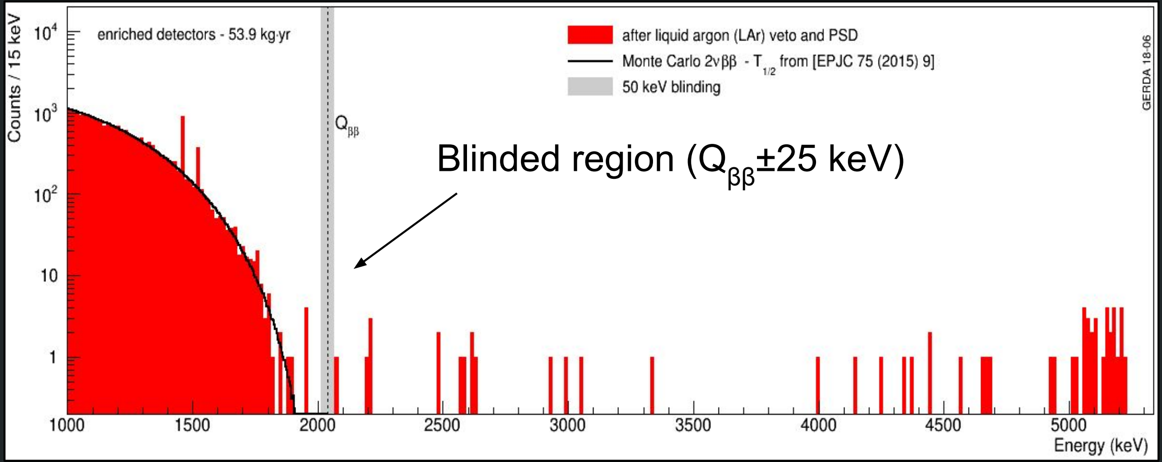
Ge detectors are operated in ultra-pure liquid Ar:

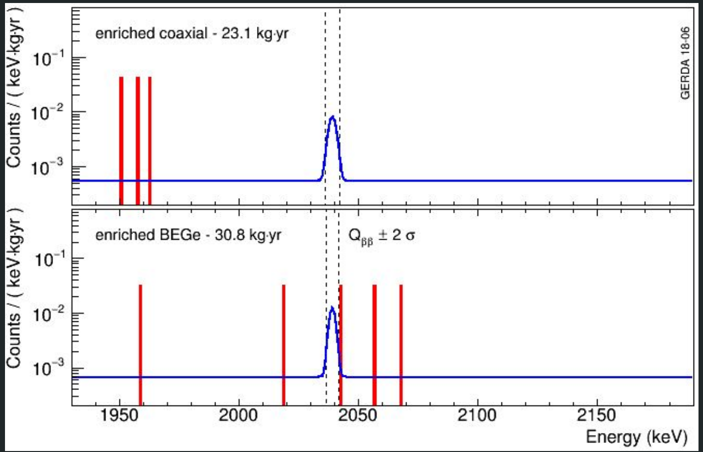
- ➢ shielding
- ➢ scintillates (veto system)
- ➢ pulse shape analysis



Future is LEGEND:

- ➢ LEGEND-200 → 200 kg of detectors in the current GERDA infrastructure (funded and scheduled for 2021)
- ➢ LEGEND-1000 → 1000 kg of detectors in a new setup (location not defined yet)





Mid-term and Long-term Projects

Major $0\nu\beta\beta$ Projects

current gen → mid-term → long-term

		current gen	mid-term	long-term
Gas/Liquid detector	Liquid scintillator	KZ	KZ-800 SNO^{+} phase I	KamLAND2-Zen SNO^{+} phase II
	Time Projection chambers	EXO NEXT-10	NEXT-100 PANDA-X-III	nEXO NEXT-2.0 PANDAX-III 1t
Solid detectors	Cryogenic Calorimeters	CUORE CUPID-0 AMORE	AMORE II	CUPID
	Ge semiconductor	GERDA MJD	LEGEND-200	LEGEND-1000
External detectors	Magnetized tracking	NEMO		SUPERNEMO

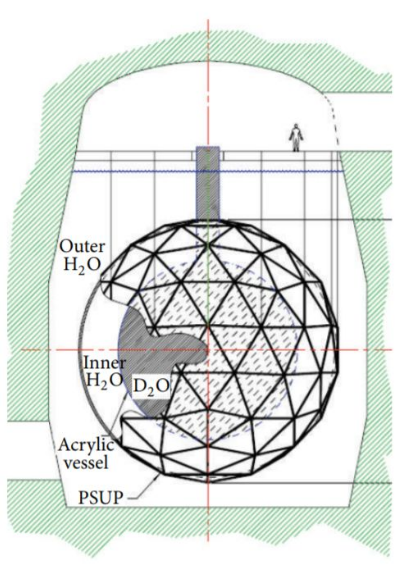
SNO⁺ (expected Phase I performance)	
Location	SNOLAB, Canada
Isotope	^{130}Te [$Q_{\beta\beta}$=2527 keV]
Technology	Te-loaded liquid scintillator
Isotope Mass	1300 kg
$0\nu\beta\beta$ efficiency	12%
Resolution [σ]	81 keV
Status	commissioning first phase

Phase I

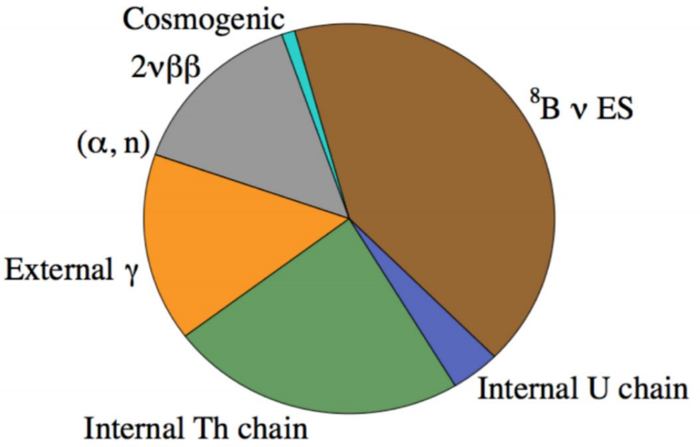
- 780 t LAB (+ PPO + Te-ButaneDiol)
- 0.5% loading -> 1300 kg ^{130}Te
- currently filled with water
- Filling with unloaded liquid scintillator later this year

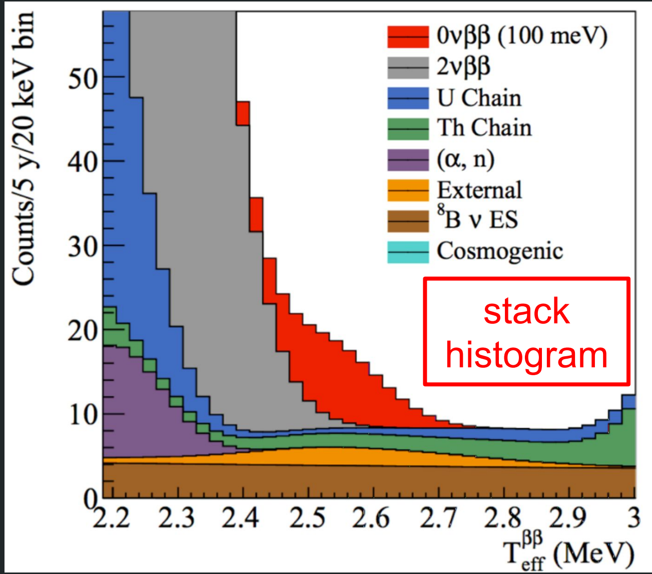
Phase II

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



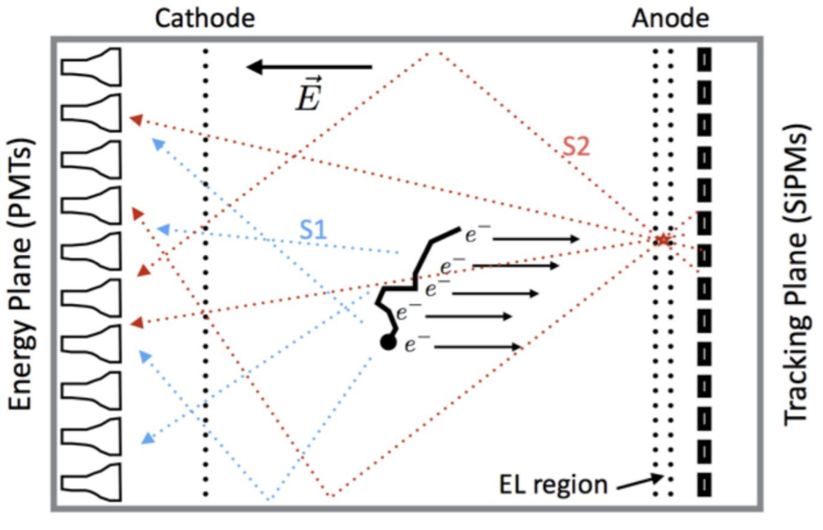
[Orebi Gann, Gabriel. (2018, June). SNO+. Zenodo]

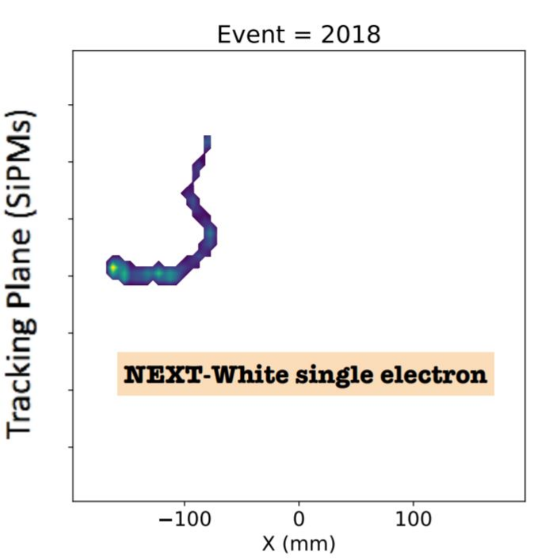




NEXT (expected next phase performance)	
Location	Canfranc @ Spain
Isotope	^{136}Xe [$Q_{\beta\beta}$=2458 keV]
Technology	TPC with gass Xe
Isotope Mass	90 kg
$0\nu\beta\beta$ efficiency	69%
Resolution [σ]	8 keV
Status	designing

[arXiv:1804.02409]





High pressure TPC

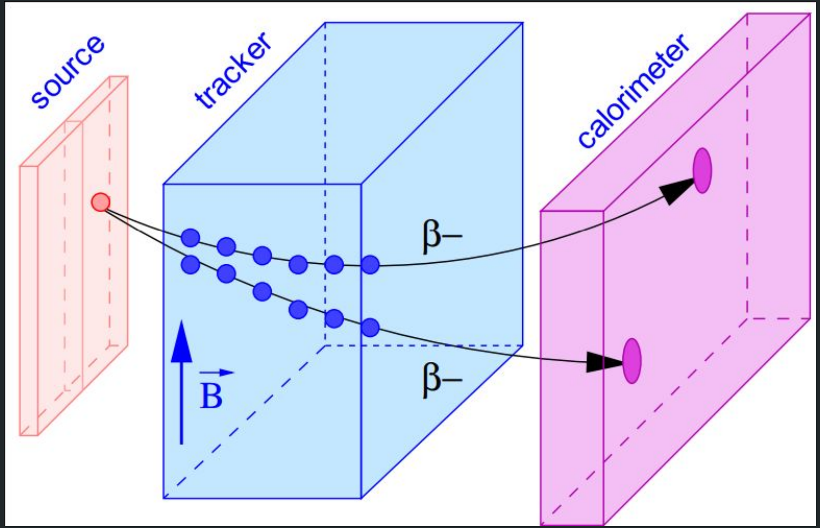
- immediate scintillation gives t_0 and therefore the z coordinate
- Electroluminescence proportional amplification:
  - 1% energy resolution (PMT plane)
  - tracking (SiPMs plane) in x and y
- beginning of operations planned for 2020

NEXT-2.0

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

SuperNEMO (expected performance)	
Location	Modan @ France
Isotope	^{82}Se [$Q_{\beta\beta}$=2995 keV]
Technology	particle identification + track
Isotope Mass	100 kg
$0\nu\beta\beta$ efficiency	16%
Resolution [σ]	51 keV
Status	construction demonstrator

[Arnold et al., EPJC 70, 927 (2010)]



Unique features:

- simultaneous measurement of energy and electron direction (angular correlations)
- potential to discriminate among $0\nu\beta\beta$ channels
- source embedded in foils separated from detector

Cons:

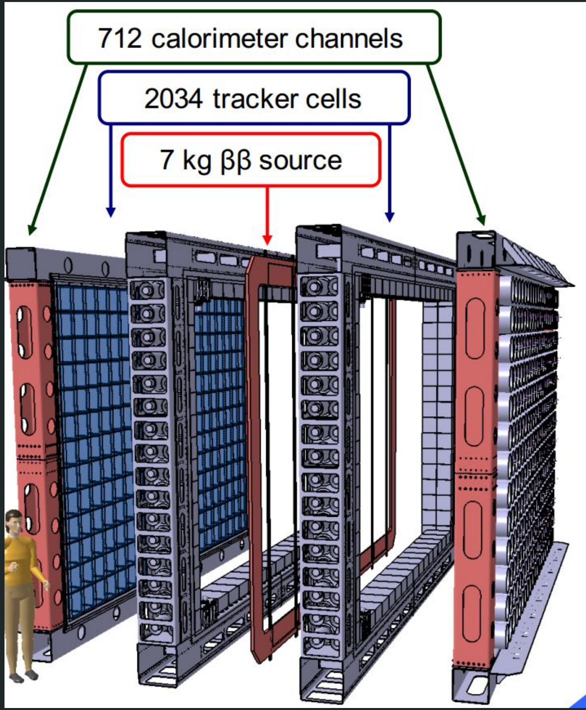
- low efficiency
- energy resolution and signal extraction

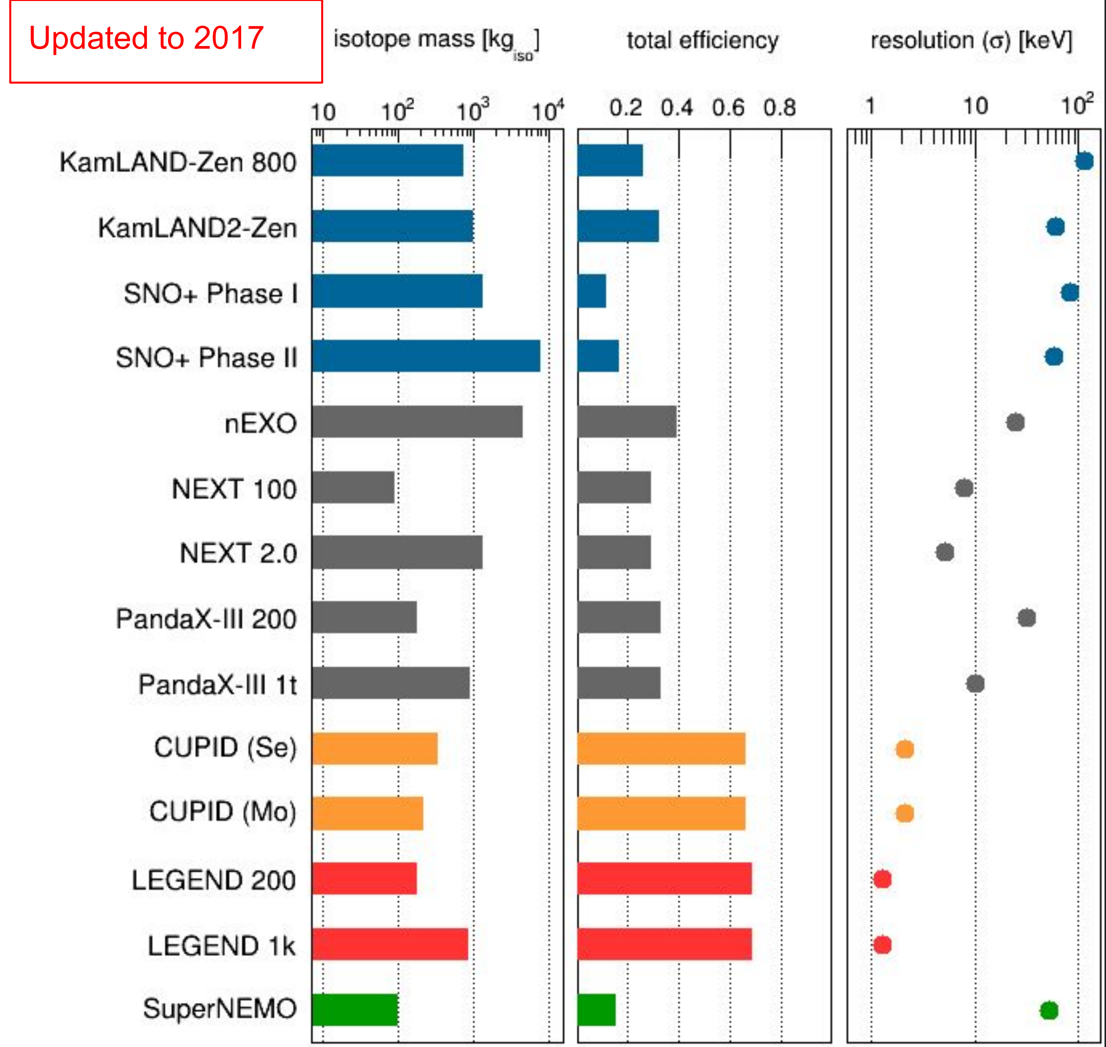
Phase 1:

- demonstrator module
- 6 kg of ^{82}Se
- commissioning and first data in 2018
- operations till 2020

Phase 2: 6 kg of ^{150}Nd

Phase 3: 100 kg scale goal



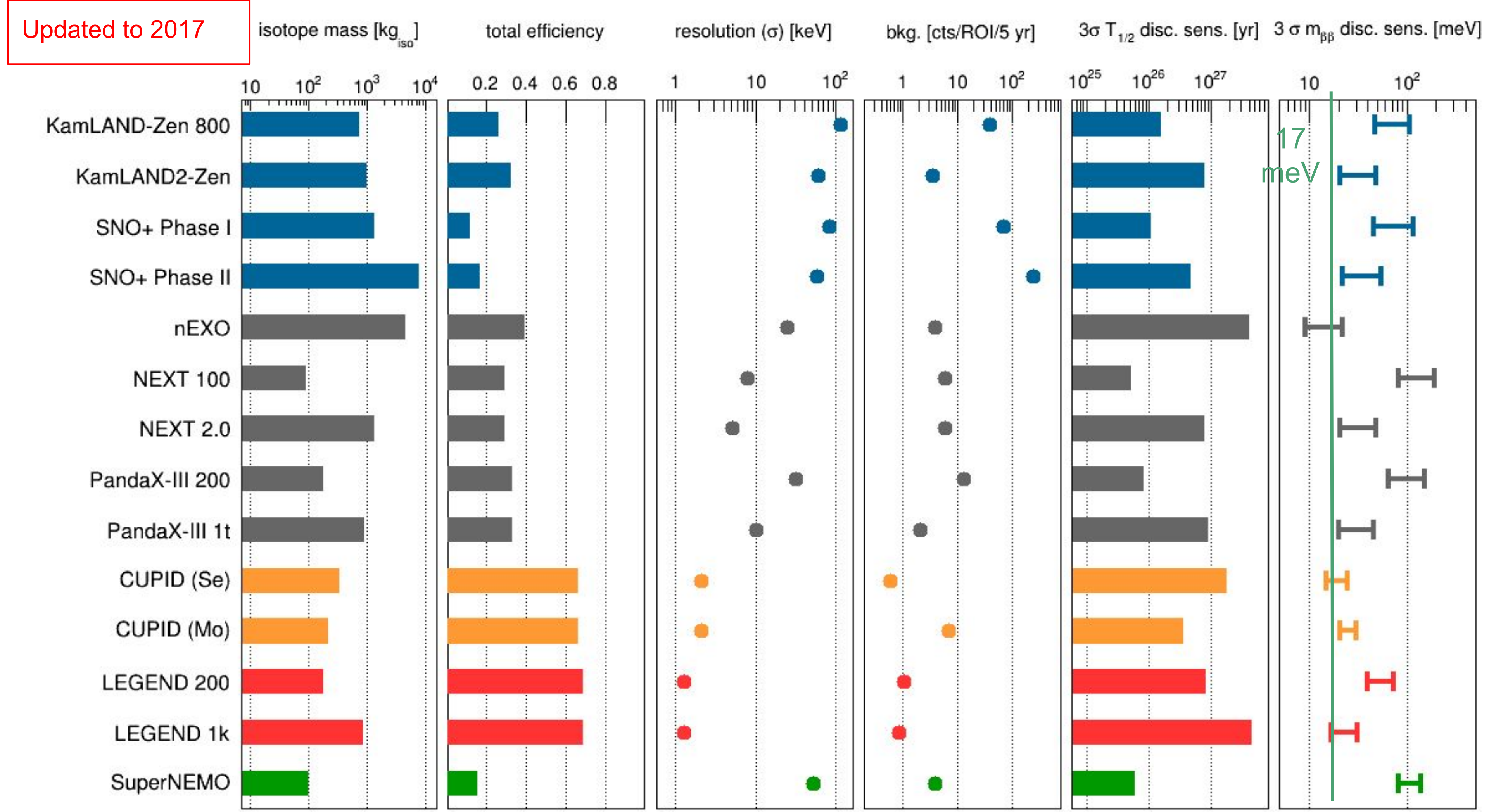


Exp Parameters

Efficiency includes:

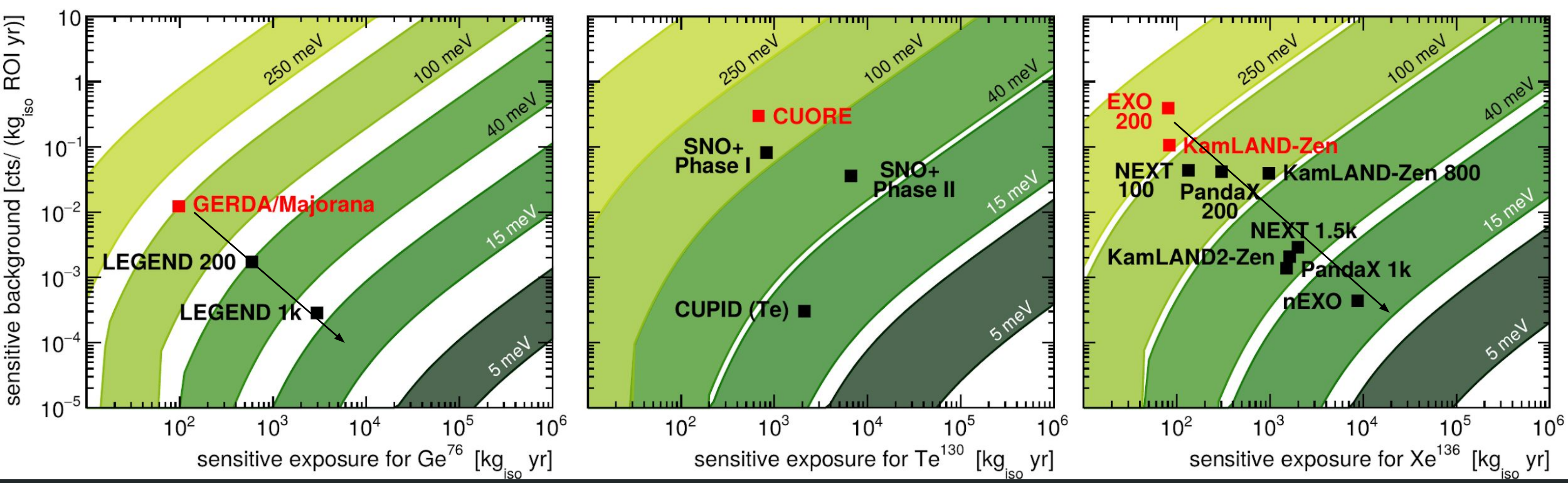
- sensitive Volume
- sensitive ROI
  - bgk-free: $Q_{\beta\beta} \pm 2\,\sigma$
  - gauss bkg: $Q_{\beta\beta} \pm 1.2\,\sigma$
  - poor-resolution: $[Q_{\beta\beta}, Q_{\beta\beta} \pm 1.2\,\sigma]$
- containment
- analysis cut (e.g. pulse shape)

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


Updated to 2017
isotope mass [kg_iso]
total efficiency
resolution (σ) [keV]
bkg. [cts/ROI/5 yr]
3σ T1/2 disc. sens. [yr]
3 σ mββ disc. sens. [meV]
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)
LEGEND 200
LEGEND 1k
SuperNEMO
17 meV

Sensitivity

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



Ge experiments

- ➢ staged approach
- ➢ each stage background free

Te experiments

- ➢ limited by existing setups
- ➢ CUPID baseline with Mo

Xe experiments:

- ➢ background reduction by self-shielding
- ➢ towards background free

Conclusion and Outlook

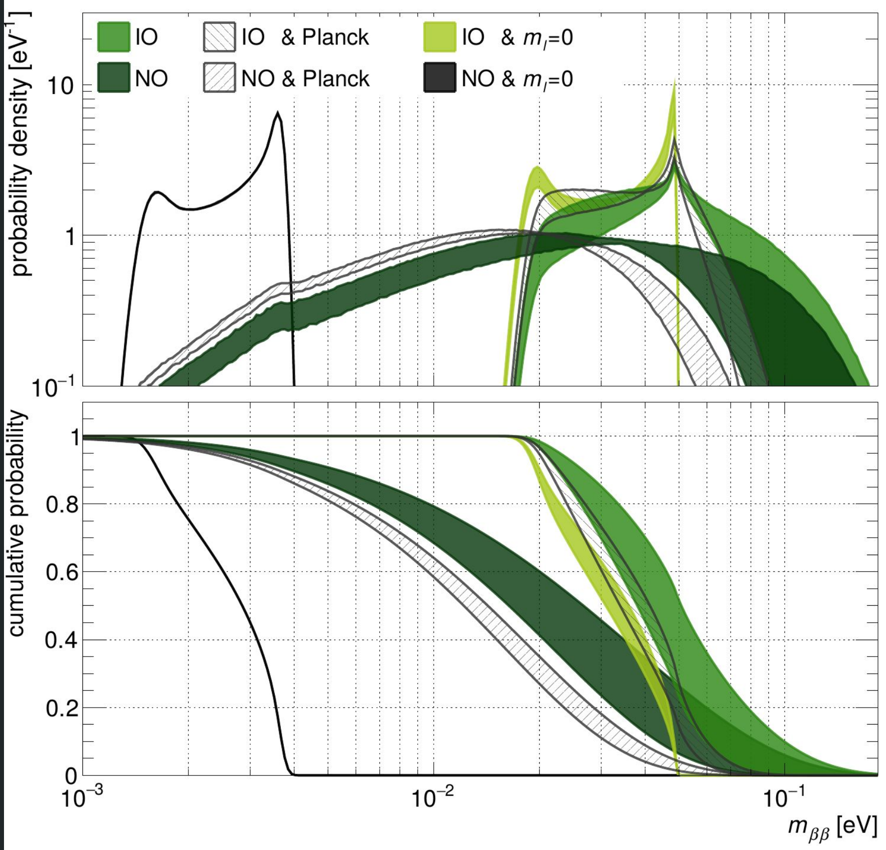
- 0νββ: matter creating process measurable in the lab
- Strong implications for particle physics, cosmology and neutrinos. Important not to focus on a single mechanism!
- Huge experimental effort, many ton-scale experiments in preparation
- The discovery probability of next-generation experiment is high 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

Backup slides

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

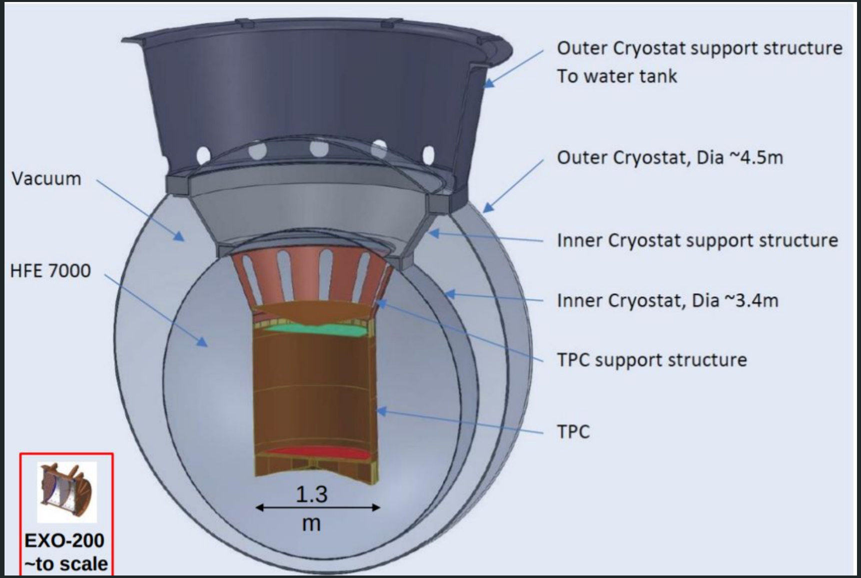


[**M.A.**, G Benato and J A Detwiler, Phys. Rev. D 96, 053001 (2017)]
see also [A Caldwell et al, Phys.Rev. D96 (2017) no.7, 073001]

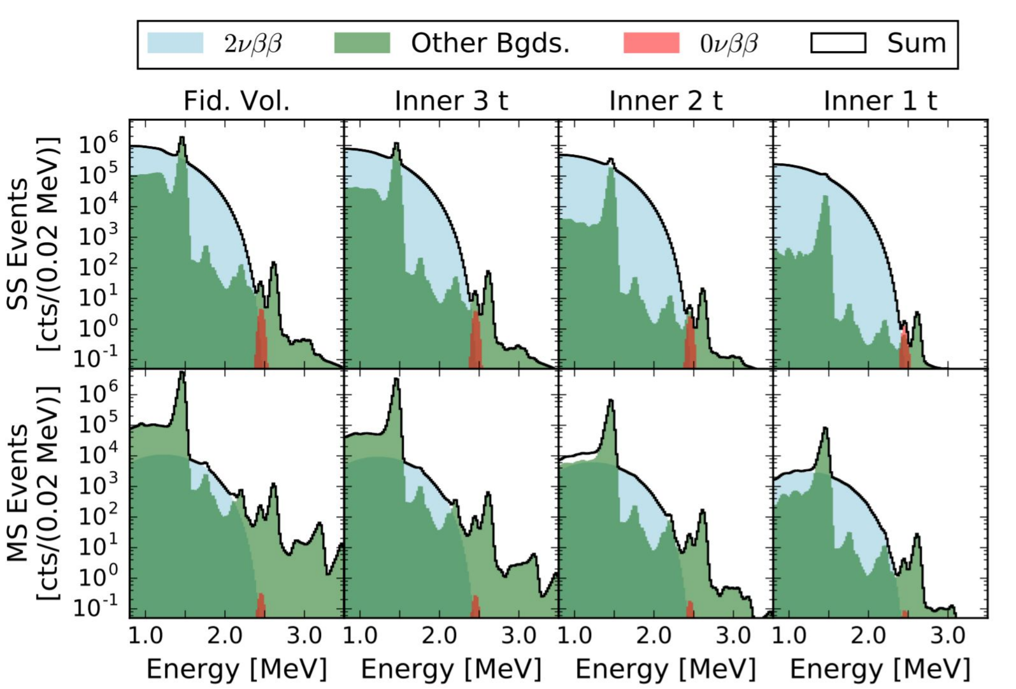
nEXO (expected performance)

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)



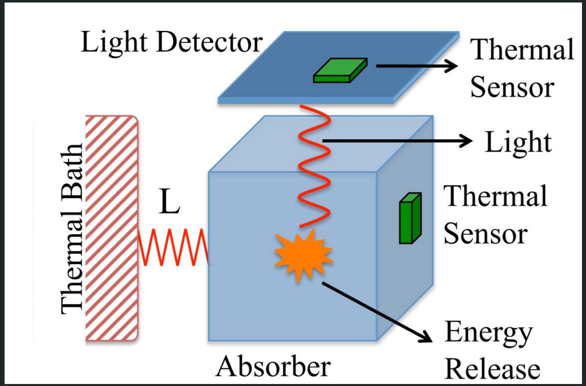
Major changes w.r.t EXO-200:

- ➢ 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)

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

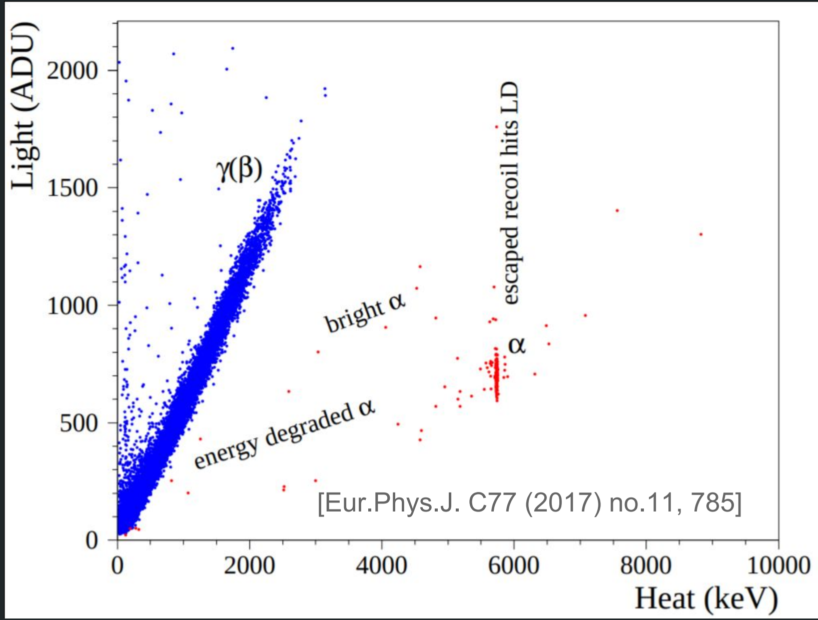
Alpha-beta separation:

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



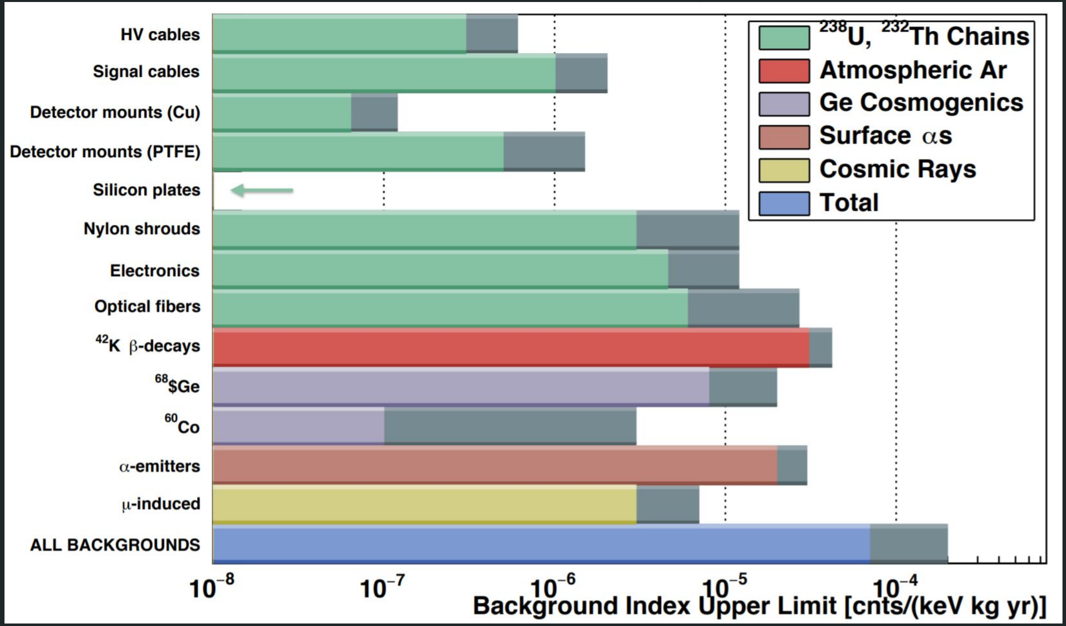
pursued R&D for a future background-free experiment:

- $^{130}TeO_2$ [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
  Chosen as baseline alternative



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:

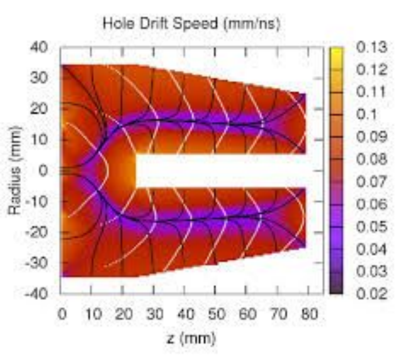
- ➢ GERDA → LAr active veto system
- ➢ MAJORANA → low background material
  → front-end electronics

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