Double Beta Decay APPEC Committee Report

NuPhys 2019

16 December 2019

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IPPP - Durham University

APPEC DBD Committee

A year ago APPEC SAC set up a committee to review the neutrino less double beta decay experimental programme in Europe and set a path for the future with the aim of maintaining a leading role.

Committee members: Andrea Giuliani, J.J. Gomez Cadenas, Silvia Pascoli (Chair), Ezio Previtali, Ruben Saakyan, Karoline Schaeffner and Stefan Schoenert.

Mandate: *The panel assessed the existing, planned and proposed technologies, their discovery potential and technical challenges, making a critical examination of resources and schedules, and reviewed the theoretical issues and the status and uncertainties on the nuclear matrix element evaluation.*

The committee met several times and prepared a report which was presented to SAC in June 2019. Following the feedback received, the report was revised and made public in Sep 2019:
https://arxiv.org/pdf/1910.04688.pdf

It was discussed at a dedicated town meeting in London on Oct 31 2019:
https://indico.cern.ch/event/832454/

The recommendations were reviewed by SAC which then reported to APPEC GA on Dec 3 2019.
APPEC GA strongly supports a DBD0nu programme in Europe.

Lepton number

Lepton number (LN) is a symmetry that happens to be conserved by the SM but does not play a special role in it. It is a global symmetry, as is baryon number.

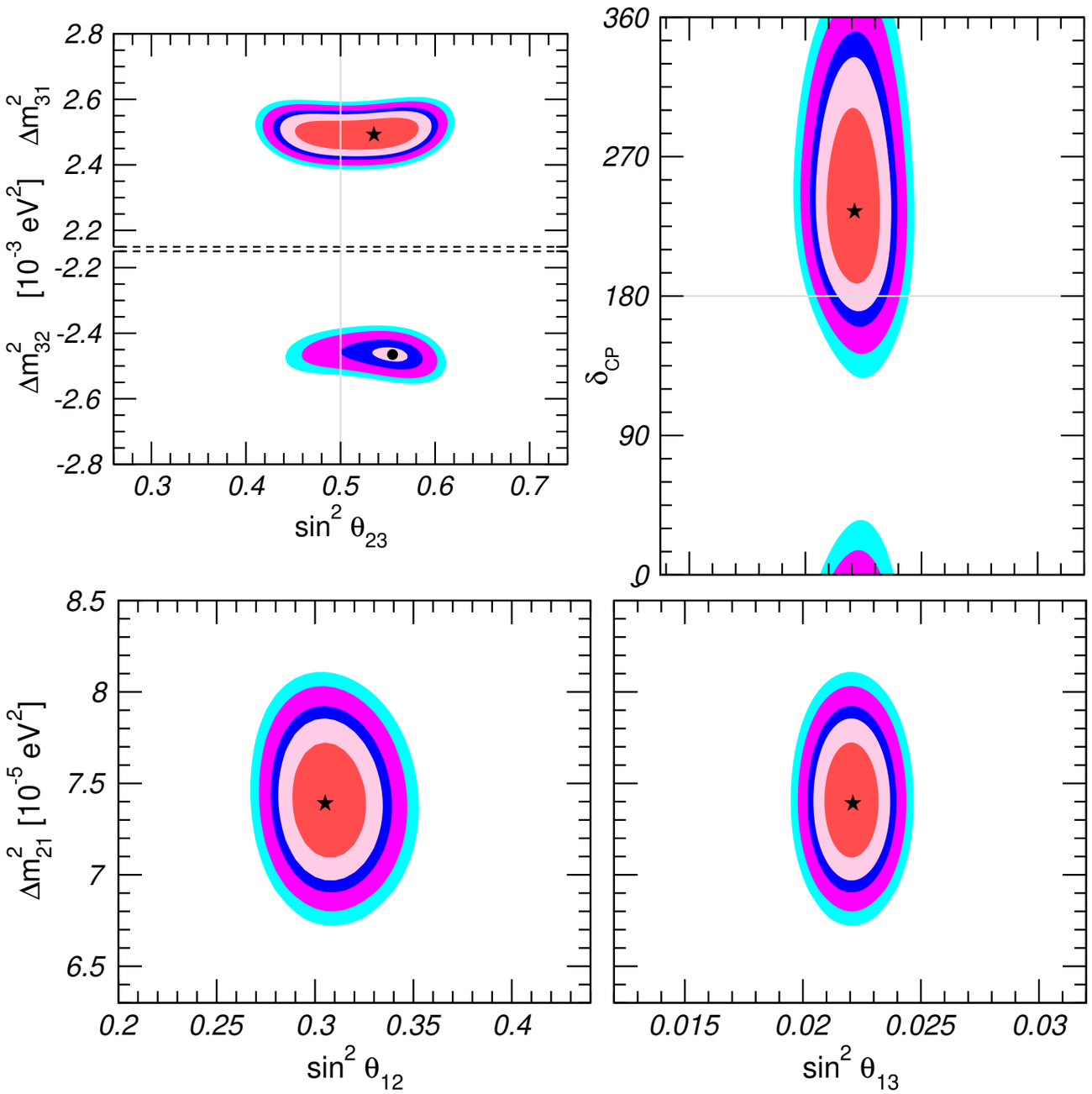
- **Is LN a fundamental symmetry of nature?**

- This is crucial information to understand the **Physics BSM: with or without L-conservation?**

- The **nature of neutrinos** (Dirac or Majorana particles) is intrinsically related to LNV.

- Lepton number violation is generically a necessary condition for **Leptogenesis**.

Neutrino properties after Neutrino 2018



NuFIT 4.0 (2018) http://www.nu-fit.org/

M. C. Gonzalez-Garcia et al., 1811.05487

Neutrinos have masses and mix!

Current knowledge of neutrino properties:

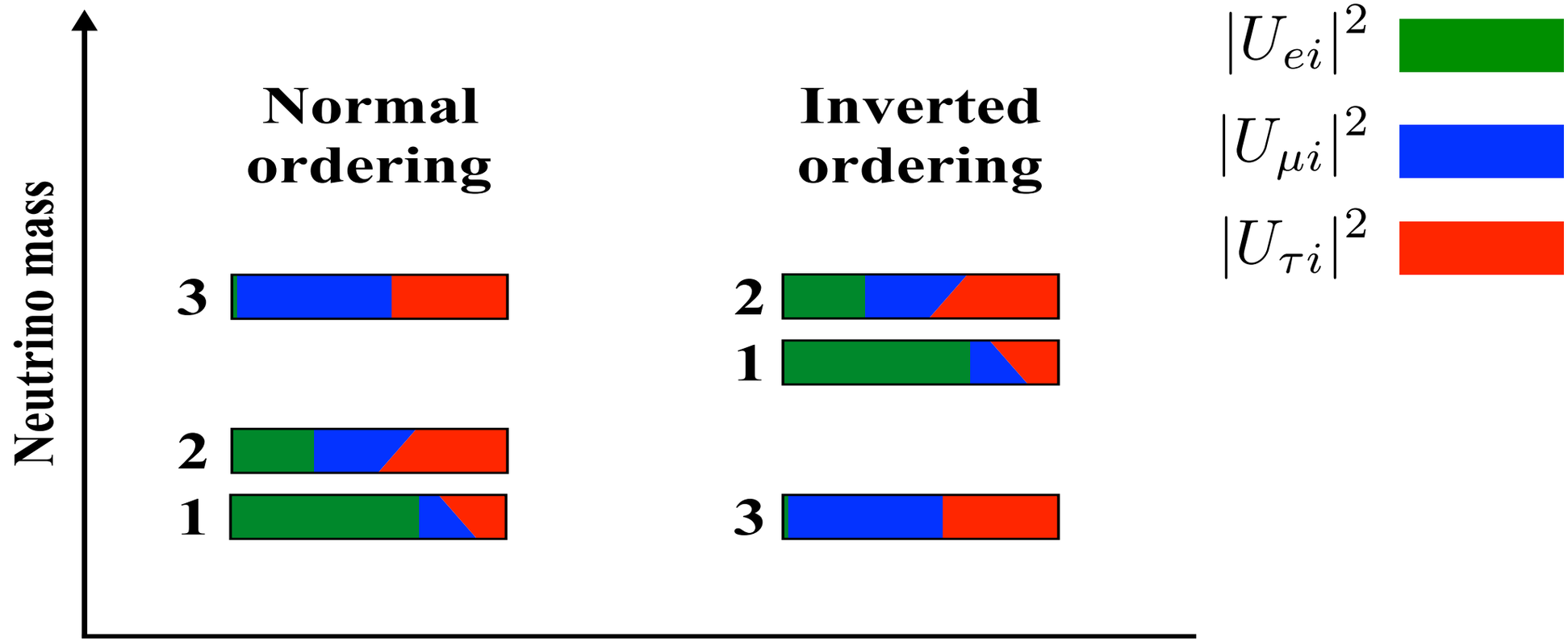
- 2 mass squared differences
- 3 sizable mixing angles,
- some hints of CPV

Massive neutrinos

Massive neutrinos can be **Majorana** (particle = antiparticle) or **Dirac** particles. In the SM only neutrinos can be Majorana because they are neutral.

Majorana neutrinos cannot carry conserved lepton number. The **nature of neutrinos** is linked to **Lepton number (LN)**.

$\Delta m^2_{\rm s} \ll \Delta m^2_{\rm A}$ implies at least 3 massive neutrinos.



Fractional flavour content of massive neutrinos

Phenomenology questions for the future

1. **What is the nature of neutrinos?**

2. **What are the values of the masses?** Absolute scale and the ordering.

3. **Is there CP-violation?**

4. **What are the precise values of mixing angles?**

5. **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Non-unitarity? Other effects?

Very exciting experimental programme now and for the future.

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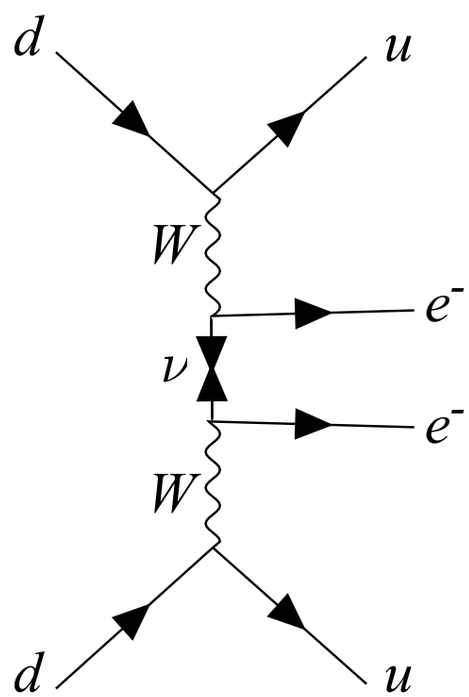
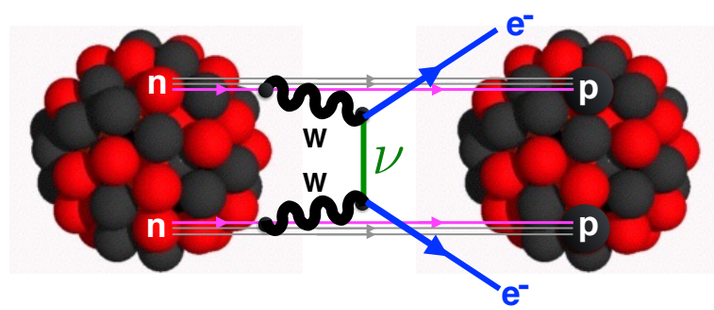
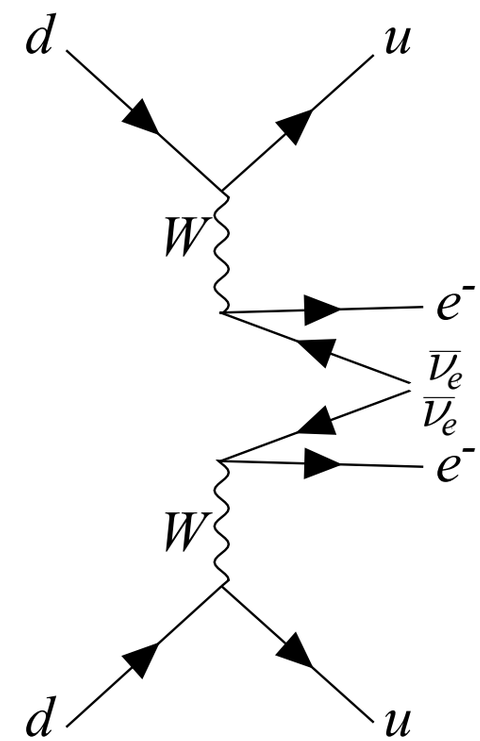
Very exciting experimental programme now and for the future.

Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2 e, will test the nature of neutrinos.







Massive Majorana neutrinos mediate this process.
It has a special role in the study of neutrino properties as it probes lepton number violation and the nature of neutrinos and can provide information on neutrino masses and (possibly) on CP-violation.

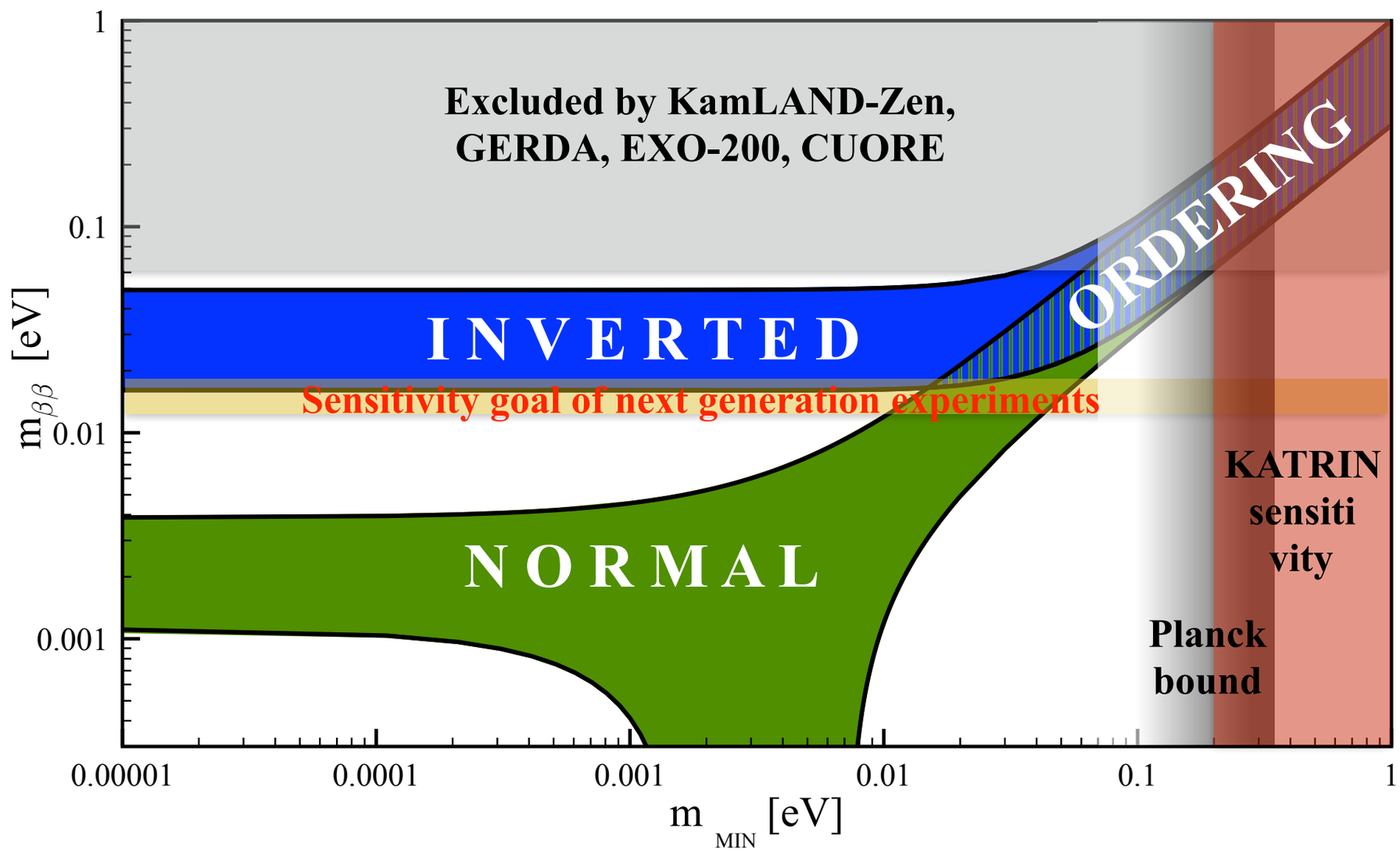
The decay rate depends on $T_{1/2}^{-1} \simeq \frac{G_{0\nu}}{m_e} |m_{\beta\beta}|^2 M_{\rm NUCL}^2$

via the effective Majorana mass parameter:

$$|m_{\beta\beta}| \equiv \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i(\alpha_{31} - 2\delta)} \right|$$

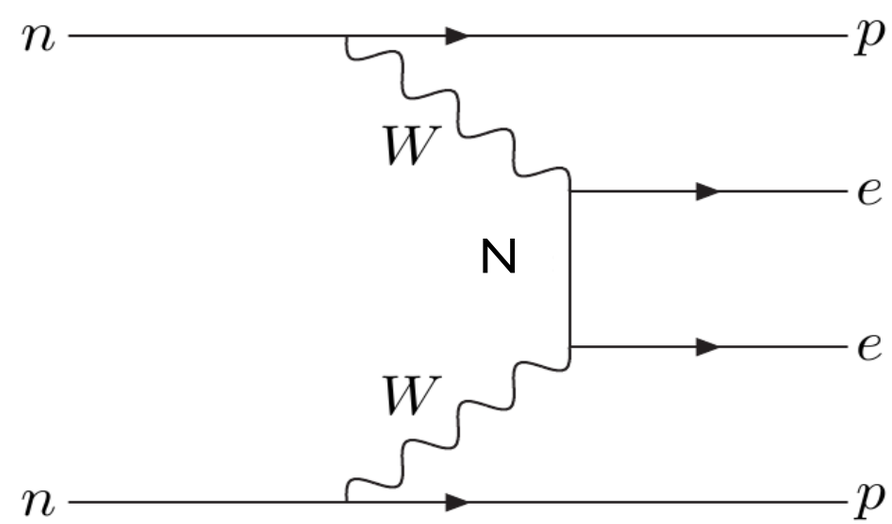
The predictions for m_{bb} depend on the neutrino masses

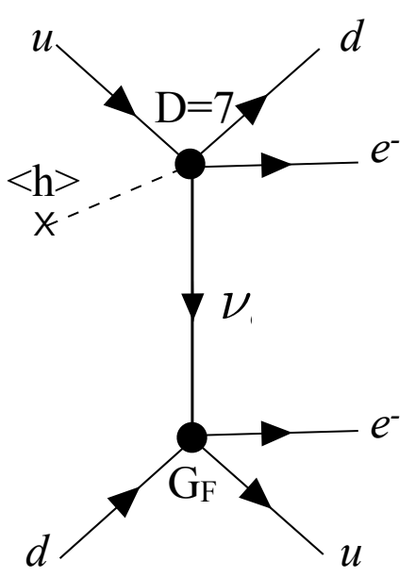
- IO and m_3~0 (m3<<m1~m2): 15 meV < $|m_{bb}|$< 50 meV

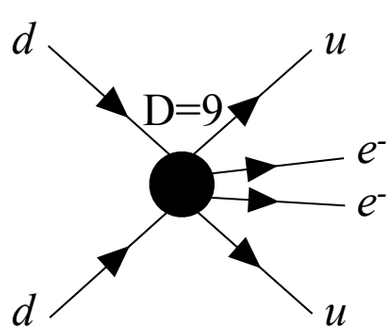


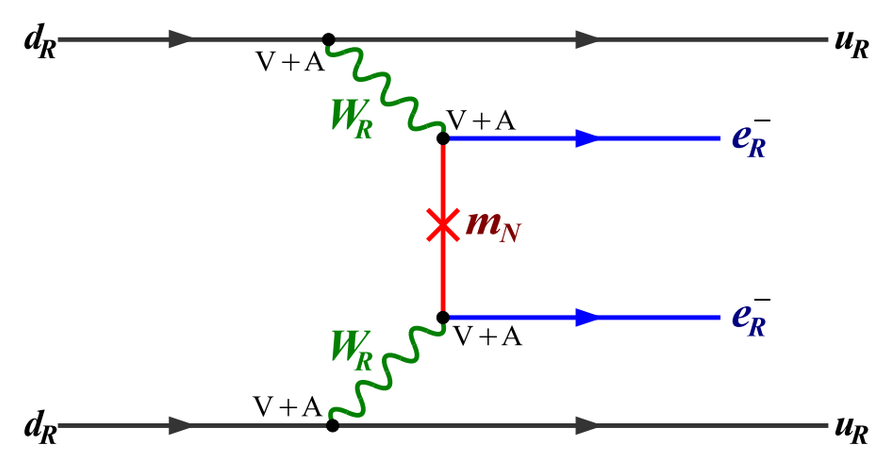
Other LNV mechanisms, possibly advocated for the origin of neutrino masses and/or leptogenesis, would also mediate neutrinoless double beta decay at some level.

- Light sterile neutrinos
- Heavy sterile neutrinos
- R-parity violating SUSY
- Extra dimensional models
- Left-Right models





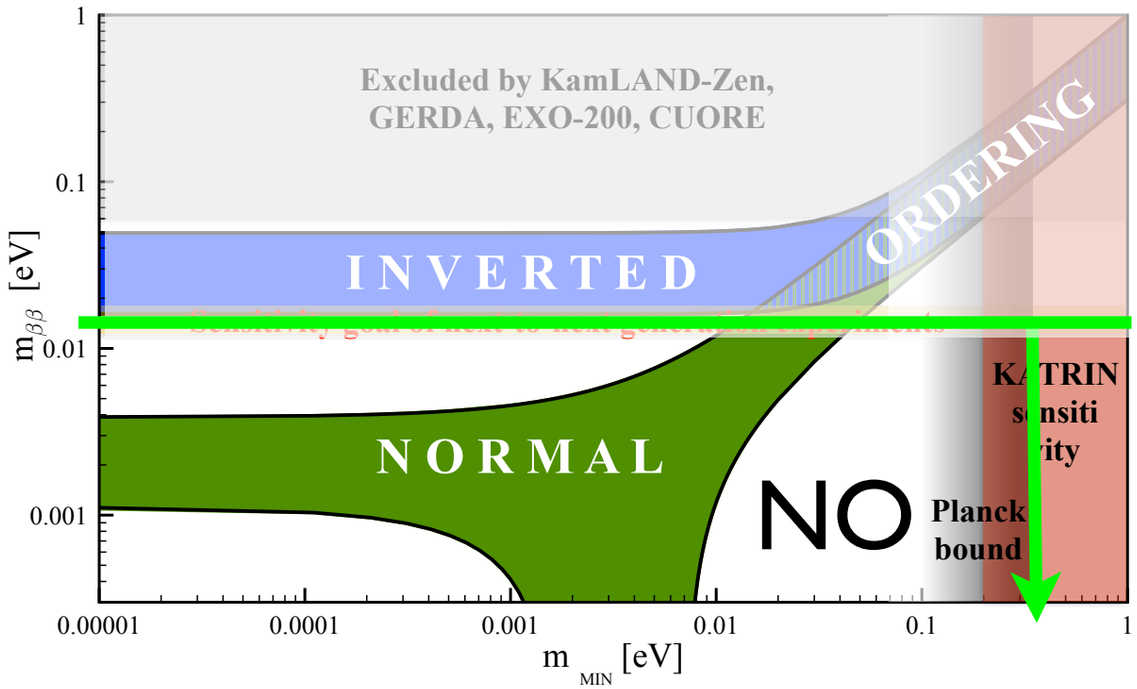




Deppisch, Hirsch, Pas, 1208.0727

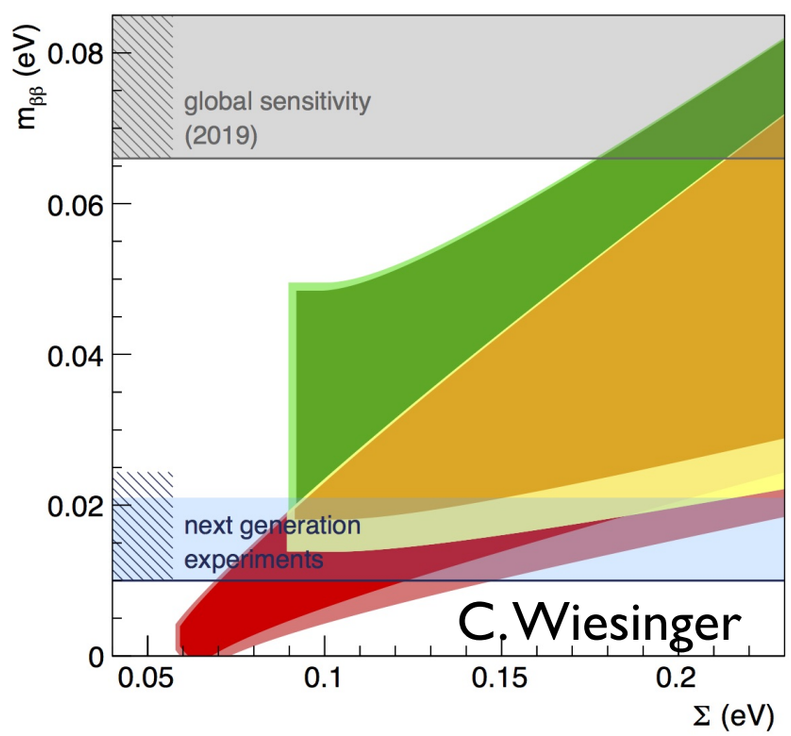
Complementarity with other searches

- DBD and neutrino experiments. Mass ordering via neutrino oscillations in matter or in vacuum.



- If no signal for $|m_{bb}|$~15 meV, then only NO is allowed (or cancellations). If LBL experiments find IO, neutrino are Dirac (without fine-tuned cancellations).

- DBD0nu and cosmology: Absolute neutrino mass scale.



Cosmology: $\sum_i m_i$

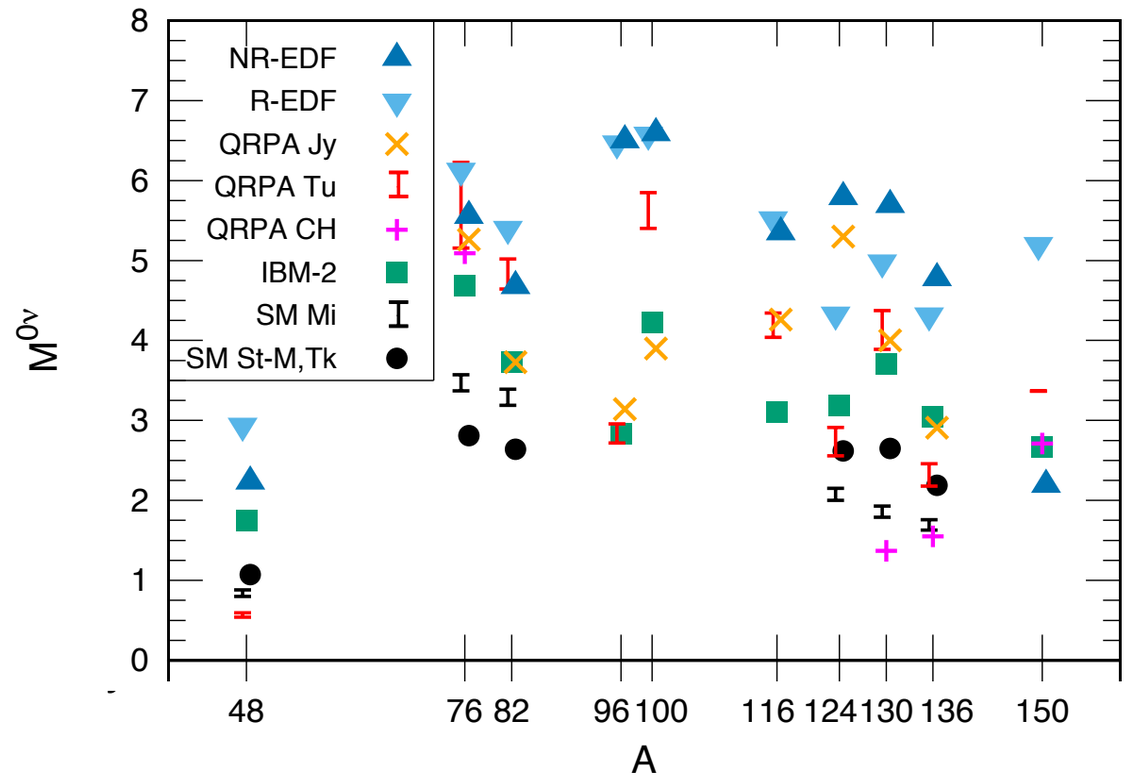
Beta decay: $m_\beta \simeq \sqrt{\sum_i |U_{ei}|^2 m_i}$

DBD0nu: $m_{\beta\beta}$

Nuclear Matrix Elements

The computation of NMEs relies on complex nuclear theory:

- Nuclear shell model
- Quasi random phase App.
- Energy Density Func. M.
- Interacting Boson Model



Engel, Menendez, ARRPP 2017

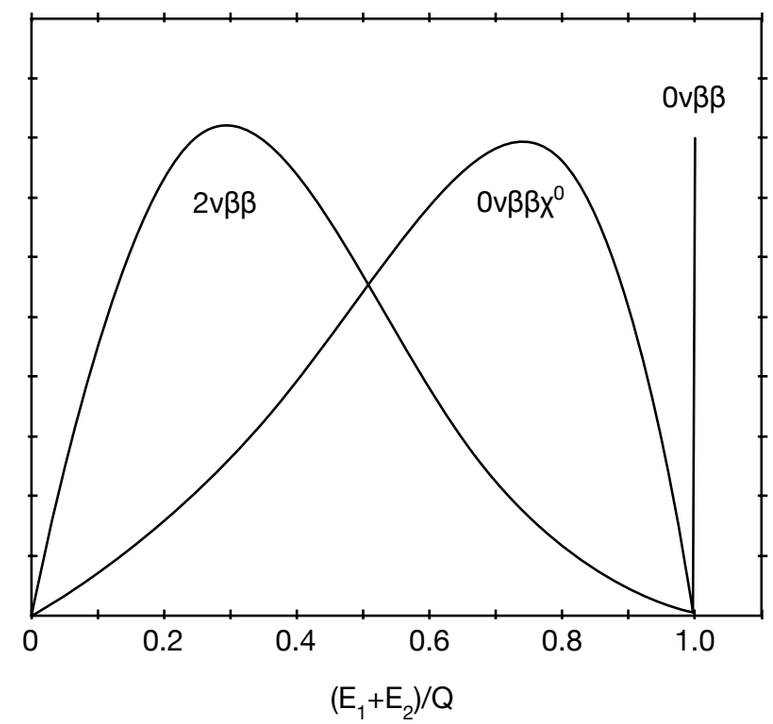
Typically an uncertainty of 2-3 is attributed to NME and affects the extraction of m_{bb} from $T_{1/2}$. Recent developments in terms of ab-initio computations are promising.

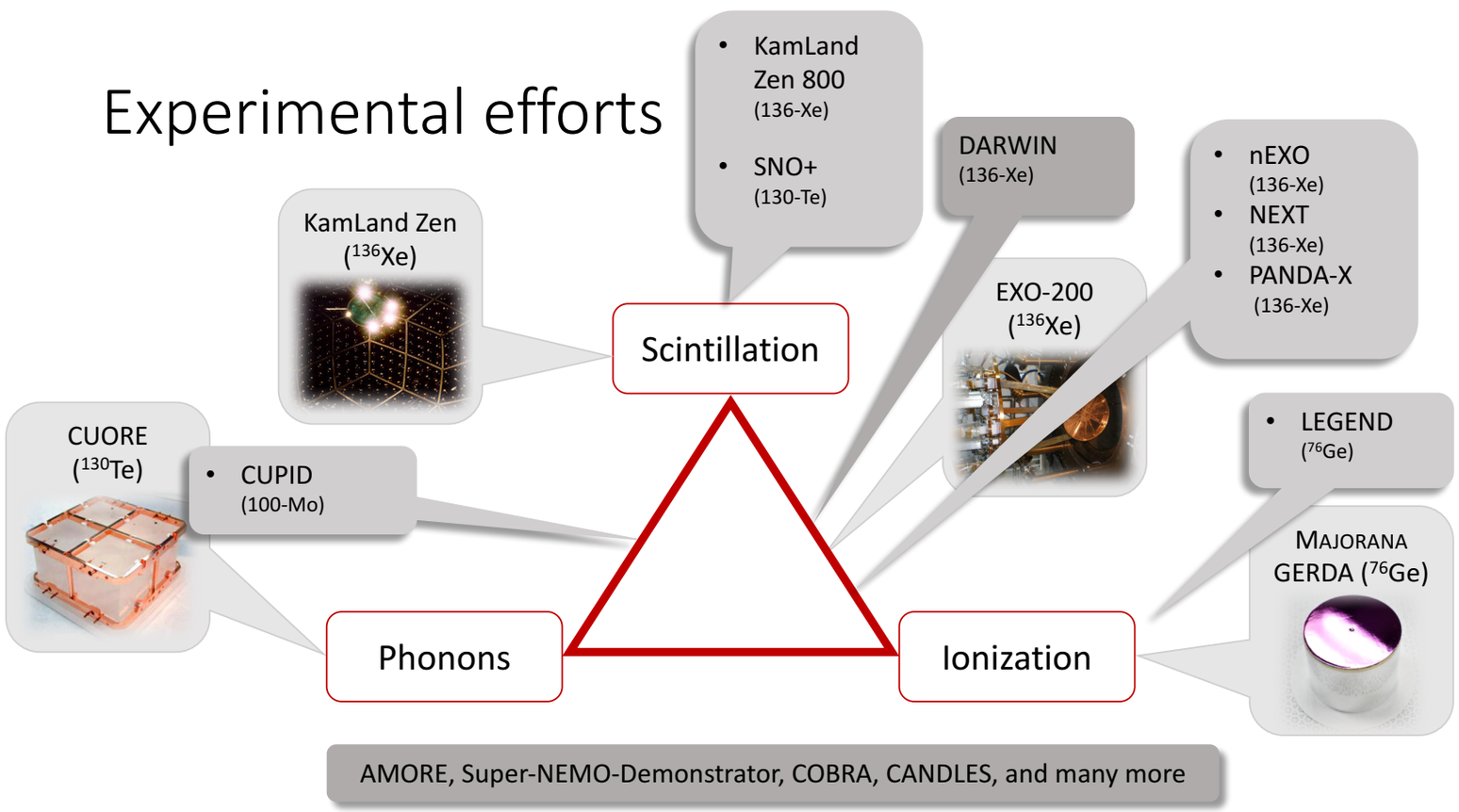
Data from other nuclear decays, muon capture and nu-N scattering are very useful. Valuable interaction with NUPEC.

Experimental Searches for DBD0nu

Neutrinoless double beta decay can be searched for in nuclei in which single beta decay is kinematically forbidden but double beta decay is allowed:

$^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd$



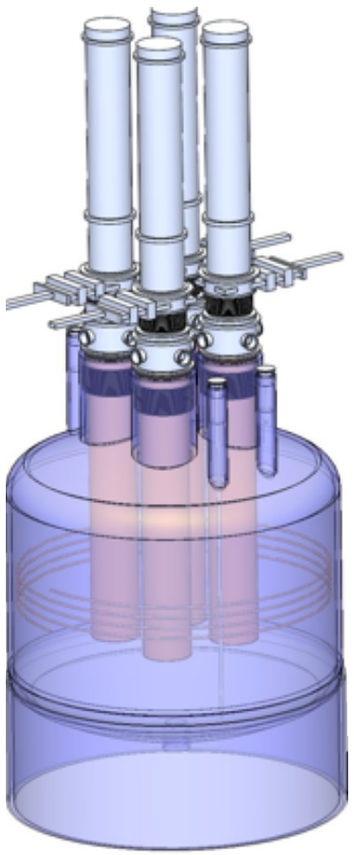


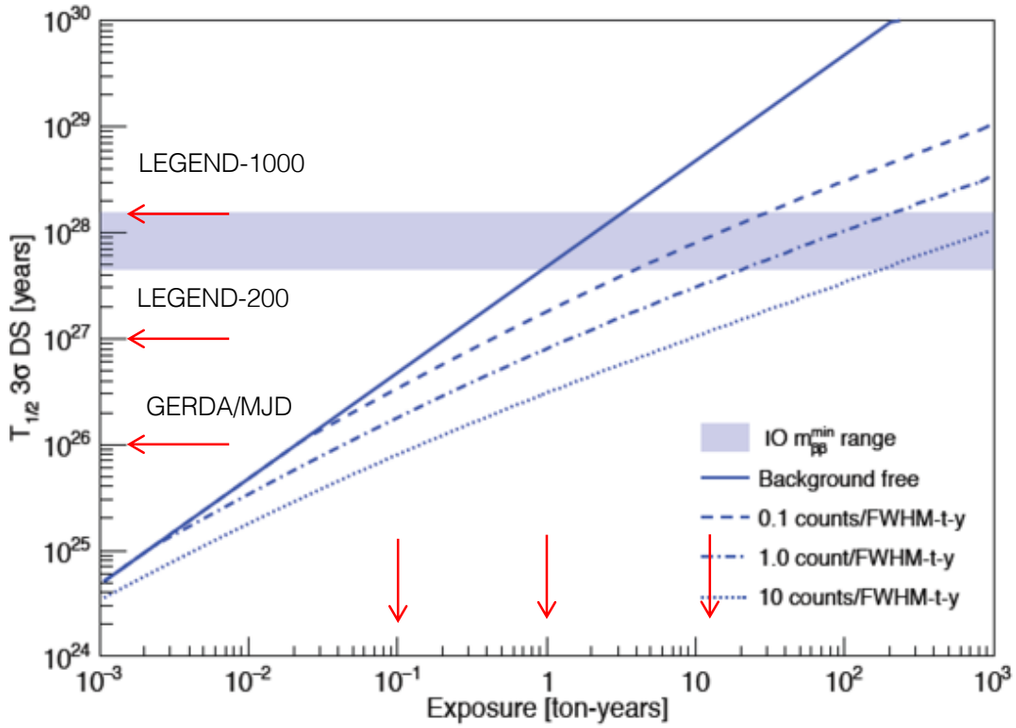
Europe is now playing a leading role (CUORE, GERDA, NEXT).

Focus: CUPID, LEGEND, NEXT.

S. Mertens at Granada CERN Open symposium

LEGEND200 - LEGEND1000





LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

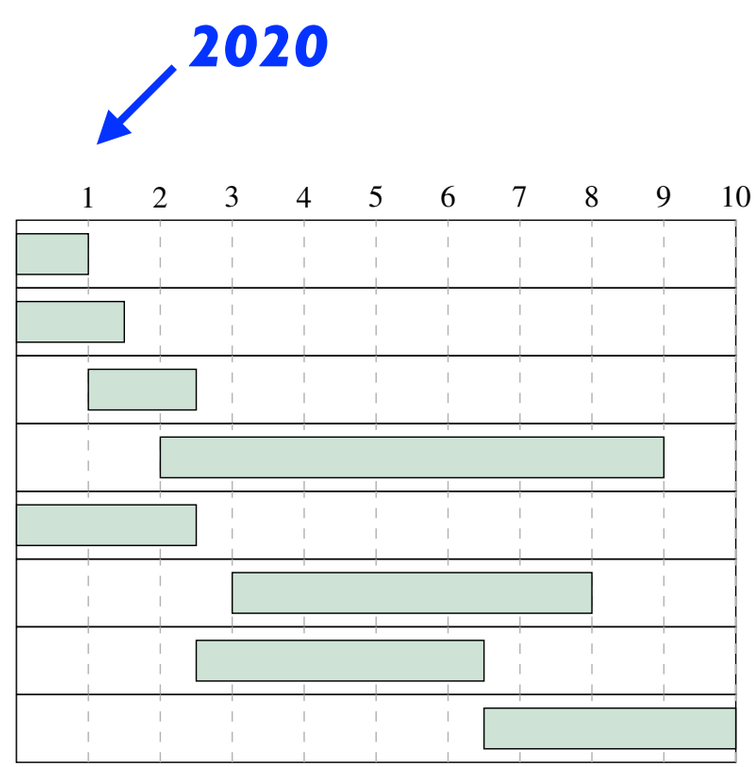
Use HPGe (^{76}Ge), build on GERDA, MJD.

LEGEND200: background reduction of 6 (7 10^{-4} cts/(kg yr) in ROI, 177 kg mass, energy resolution (1.1 keV), $T_{1/2}$ >10^{27} yrs.

LEGEND1000: background reduction of 10 (7 10^{-5} cts/(kg yr) in ROI, 883 kg mass, E (1.1 keV), $T_{1/2}$ >1.2 10^{28} yrs.

Tasks

1 GERDA completed (100 kg yr)
2 MJD completed (75 kg yr)
3 L200: upgrade of GERDA infrastruc.
4 L200: commissioning & physics runs
5 Ton-scale down select
6 L1000: produce isotopes & detectors
7 L1000: design, build, commiss. infrastr.
8 L1000: physics data taking



STRENGTHS

- HPGe diodes have best energy resolution (0.13% FWHM) and lowest background achieved in ROI; prerequisite for signal discovery.
- Background reduction of only a factor 6 for LEGEND-200 w.r.t. GERDA and factor 10 for LEGEND-1000 w.r.t. LEGEND-200.
- Efficient use of isotopes: total mass quasi equal to active mass given high signal acceptance efficiency.
- Efficient staging possible given design with separate payloads.
- Wide availability of Ge; procurement has no impact on global market.
- Two supplier for enrichment established and tested (Europe & Russia).
- Comparative low spread of NME (factor 2).

WEAKNESSES

- Requires deep underground laboratory and/or tagging for Ge-77m suppression.
- Underground Ar depleted in ^{42}Ar likely required for LEGEND-1000.
- Relatively low Q-value (2039 keV) implies smaller phase space factor which requires larger $T_{1/2}$ for same values of $m_{\beta\beta}$.

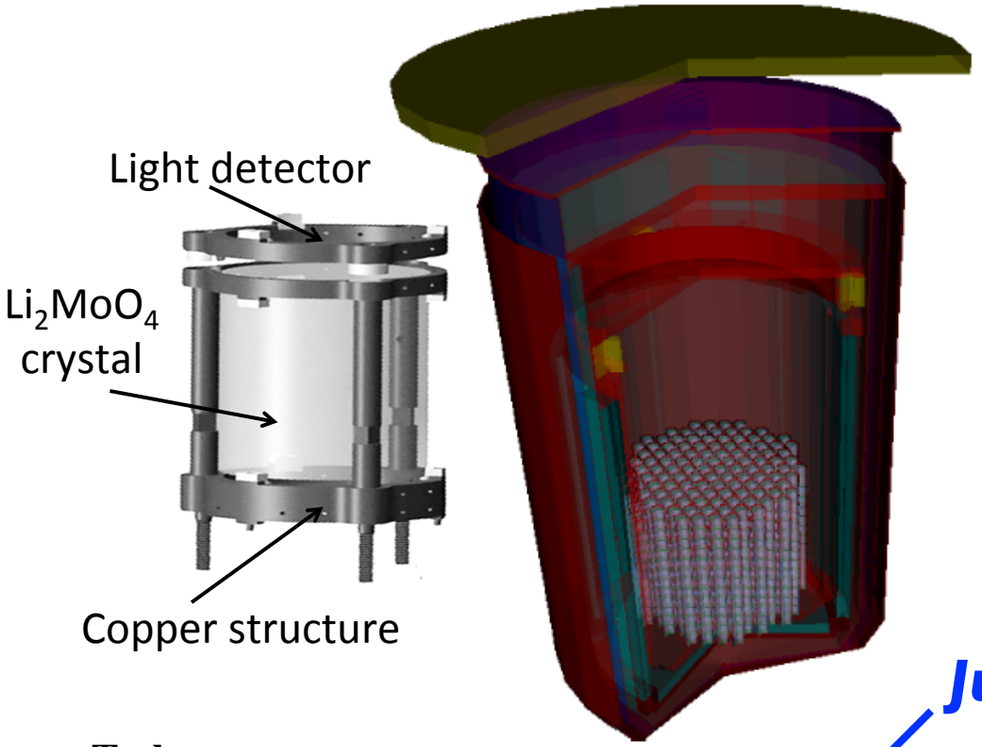
OPPORTUNITIES

- LEGEND-200 start in 2021;
  serves also as test bench for LEGEND-1000.
- Non-DBD0ν physics at low energies.
- Transatlantic cooperation and funding;
  opportunities for new groups.

THREATS

- Unknown background could appear at LEGEND-200 which might be difficult to mitigate.
- For LEGEND-1000 : no funding secured; poor coordination of funding agencies; DOE down-select might move ahead without European funding aligned.
- Underground argon production dependent on INFN/NSEF in context of DarkSide project.

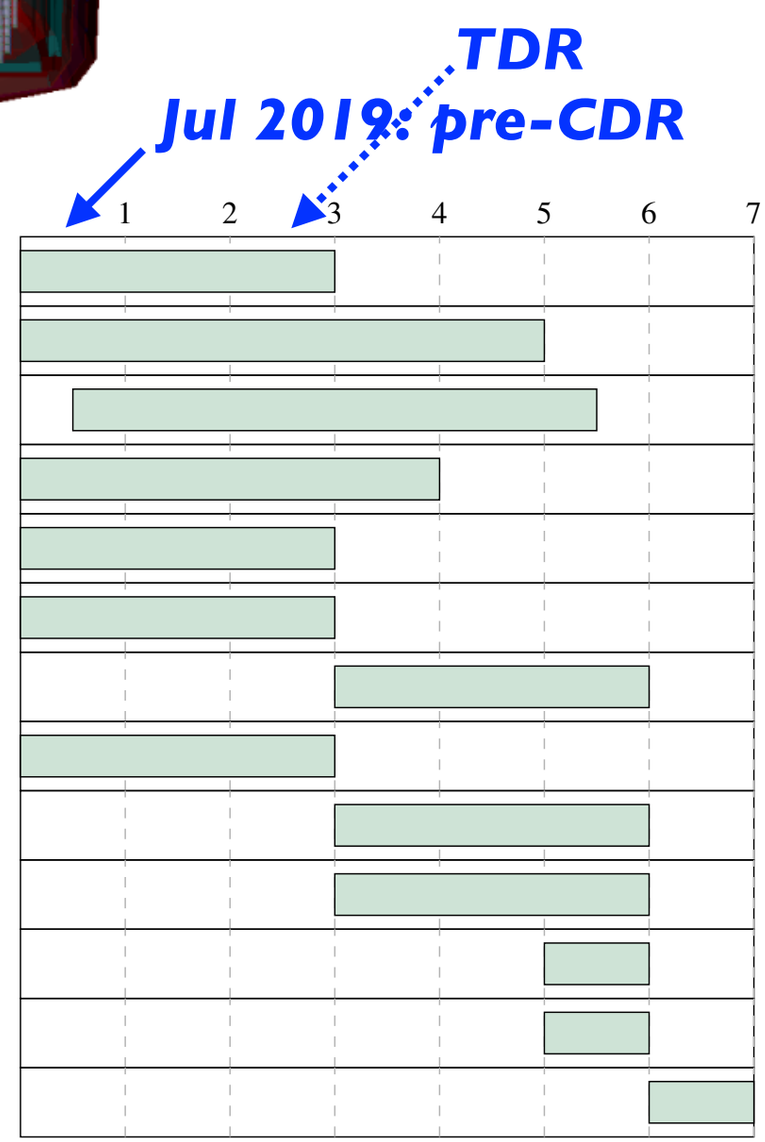
CUPID



- Builds on CUORE
- Scintillating bolometers
- Use ^{100}Mo (Q=3034 keV) in Li_2MoO_4 crystals.

Tasks

1 Demonstrator data taking and analysis
2 Enrichment of 300kg of ^{100}Mo
3 Li_2MoO_4 crystal production
4 Sensor production and characterization
5 Heater production and characterization
6 Front-end electronics and DAQ
7 Light detector production
8 Material selection and procurement
9 Detector structure production and cleaning
10 Assembly of detector towers
11 Wiring and cryostat upgrade
12 Detector installation
13 Commissioning and data taking



CUPID: background reduction of 100 w.r.t. CUORE (2 10^{-3} cts/(kg yr) in ROI, 250 kg mass, very good energy resolution (2.1 keV), $T_{1/2}$ >1.1 10^{27} yrs.

STRENGTHS

- Enrichment at large scale with medium prices
- High Q-value (3034 keV)
- Compatible with scintillating bolometer technique
- Excellent energy resolution
  $Li_2{}^{100}MoO_4$: 5 keV FWHM at 2615 keV
- Low background demonstrated in large crystal:
  $\sim$ 5 μBq/kg for ^{232}Th / ^{238}U; 5 mBq/kg for ^{40}K
- Source=Detector, modularity, high efficiency
- Event-type discrimination:
  α/β full rejection demonstrated
- Favourable Nuclear Factor of Merit
  (Phase Space x NME)

WEAKNESSES

- No tracking
- Short $2\nu2\beta$ half-life
  (potential background due to accidental pileup)
  $\Rightarrow$ develop faster light detector
- Scalability possible but costly;
  factor two looks feasible by setting up a second CUORE-like facility
- Cryogenic infrastructures are complicated and need onsite expertise

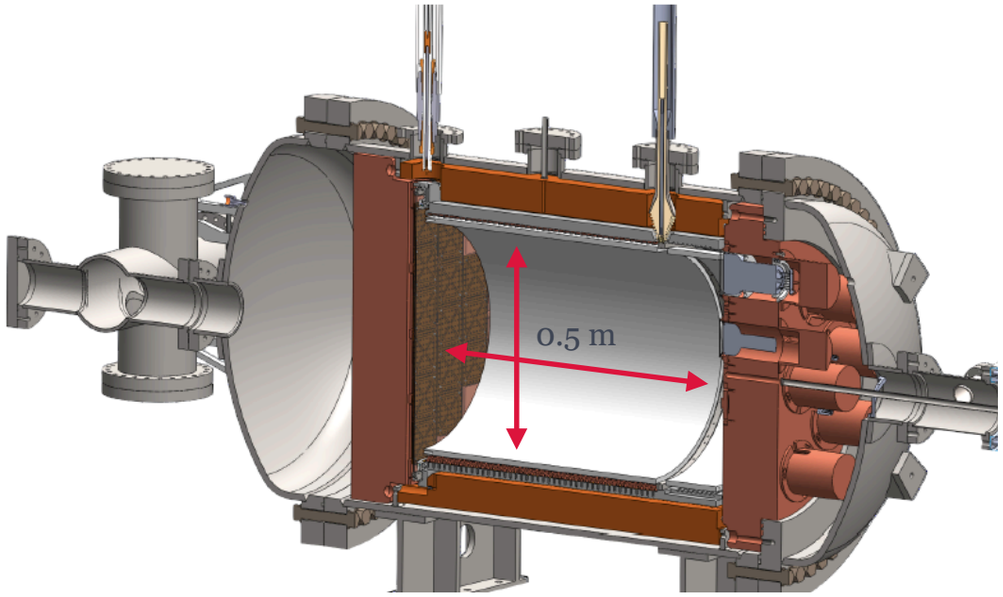
OPPORTUNITIES

- Cryogenic infrastructure well demonstrated in CUORE (space for 300 kg of ^{100}Mo-enriched detector available)
- Several crystal compounds compatible with the bolometric technique:
  $Li_2{}^{100}MoO_4$, $ZnMoO_4$, $CaMoO_4$
- High reproducibility of crystal quality
- Many producers on the market
- Alternative pulse shape discrimination techniques
- Second physics case (direct dark matter detection)
- New CUPID collaboration is chance for new collaborators/groups

THREATS

- Enrichment monopoly in Russia
- AMORE collaboration:
  120 kg of ^{100}Mo for bolometric experiment in Korea.
  This can be turned into an opportunity in case of a common CUPID-AMoRE bi-site experiment
- Funding of CUPID open

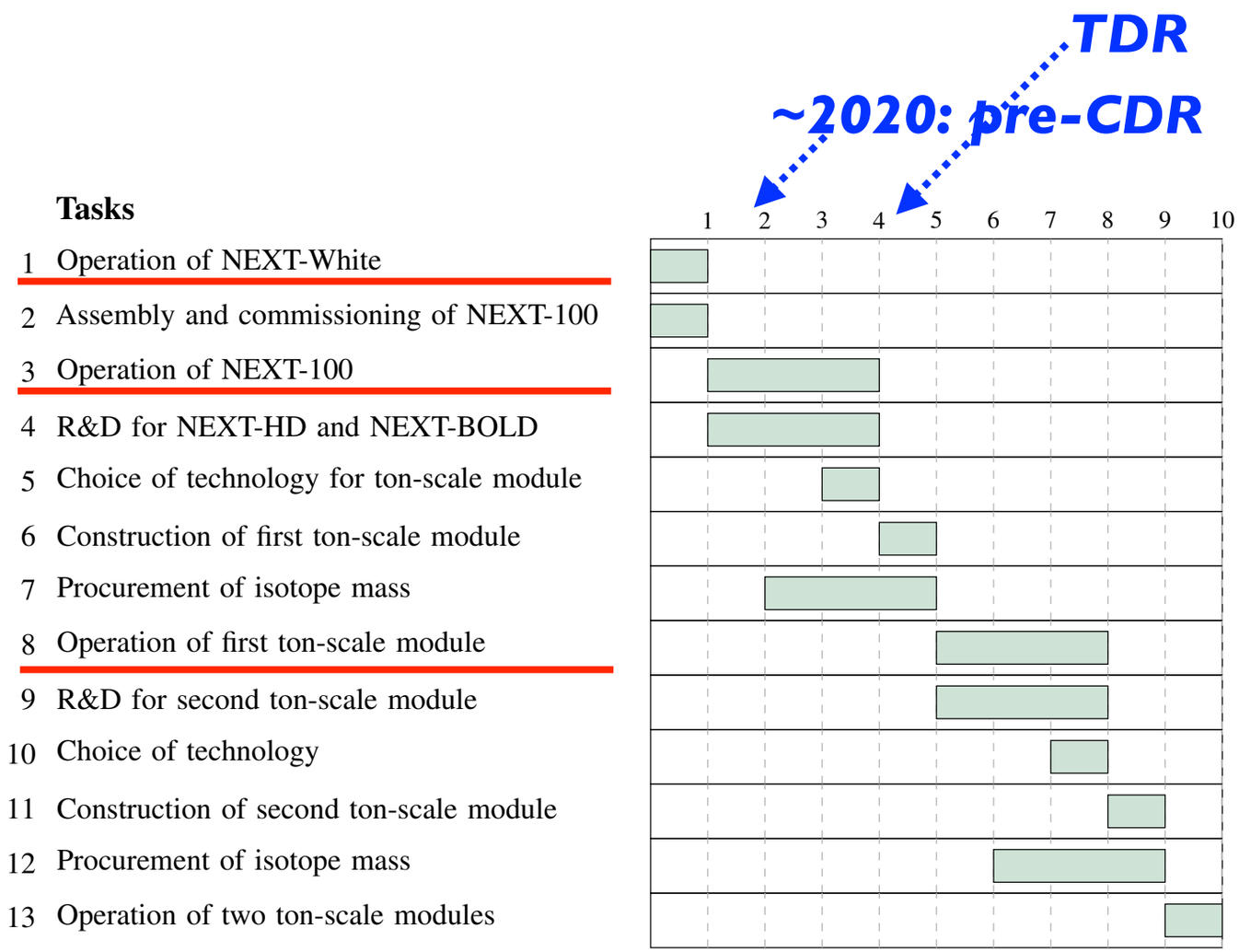
NEXT100 - NEXT-HD - NEXT-BOLD



NEXT-100: background (5 10^{-2} cts/(kg yr)) in ROI, 100 kg mass, good energy resolution (10 keV), $T_{1/2}$ > $6.9 10^{25}$ yrs.

NEXT-HD: background reduction of 10 (1 10^{-3} cts/(kg yr)) in ROI, ton mass, E (7.5 keV), $T_{1/2}$ >*8.9* 10^{26} yrs.

NEXT-BOLD: uses Ba tagging Bkgr (10^{-7} cts/(kg yr)) in ROI, ton mass, E (<7.5 keV), $T_{1/2}$ >*10^{28} yrs.*



STRENGTHS

- Enrichment at large scale with low prices (10 M€ per ton)
- Moderately high Q-value (2457 keV)
- Long $2\nu2\beta$ half-life
- Good energy resolution
  NEXT-White: 20 keV FWHM at 2457 keV
- NEXT-White: factor 20 reduction in background due to topological cuts.
- Source=Detector.
- Fiducial volume: only high energy gammas relevant, negligible background from α
- Reasonable Nuclear Factor of Merit (Phase Space x NME)
- Possibility of in-situ barium tagging, leading to a background-free experiment

WEAKNESSES

- Modest/low efficiency (30%)
- Less dense than liquid xenon
- Maximum size of modules about 500-1500 kg
  $\Rightarrow$ Possibility to build two modules
- Less developed than other DBD0ν technologies
- Physics potential (background index, barium tagging) still under investigation.

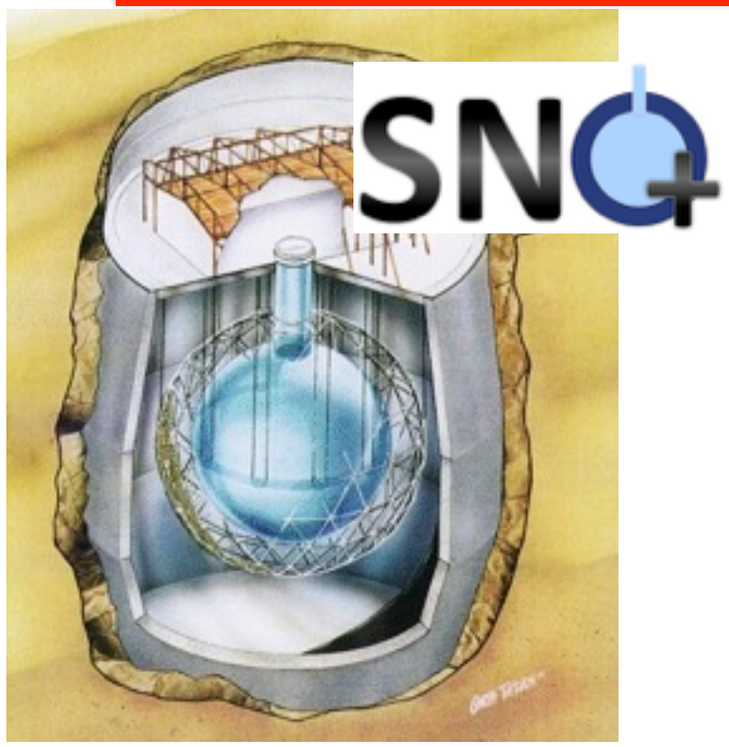
OPPORTUNITIES

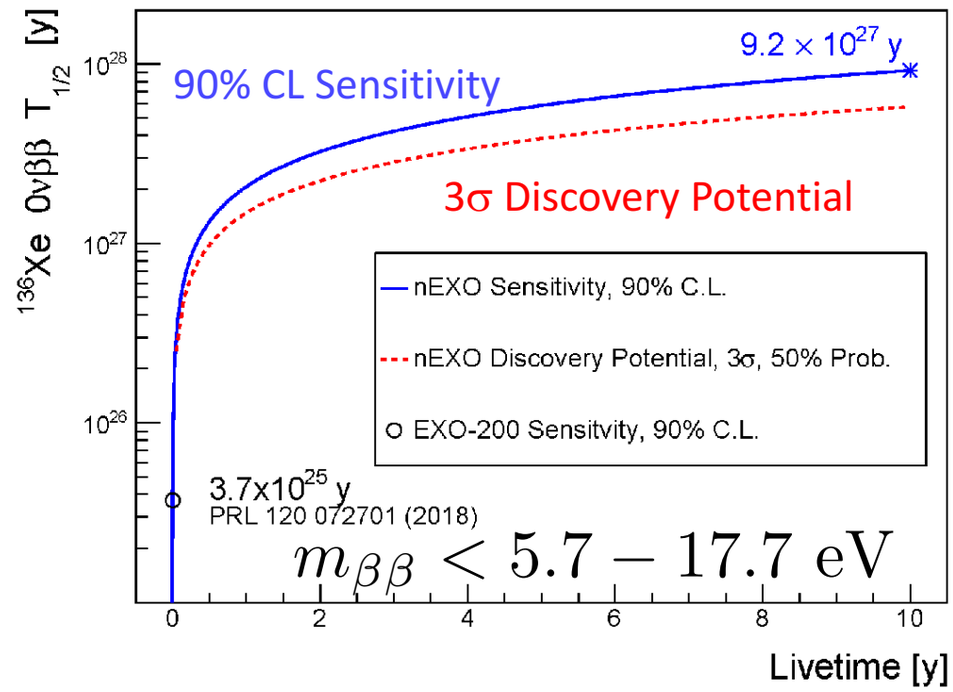
- Full infrastructure for operation of NEXT-100 and possible upgrades available at Canfranc Underground Laboratory
- NEXT-100 is a high profile scientific project in Spain
- US plays an important role in NEXT.
- Possibility of a major future US participation.
- Possibility of reusing other major infrastructures (BOREXINO at LNGS) for ton-scale modules
- Interest in HPXe in Japan (and China) with the possibility of convergence
- Potential synergy with dark matter experiments (Dark Side, DARWIN)

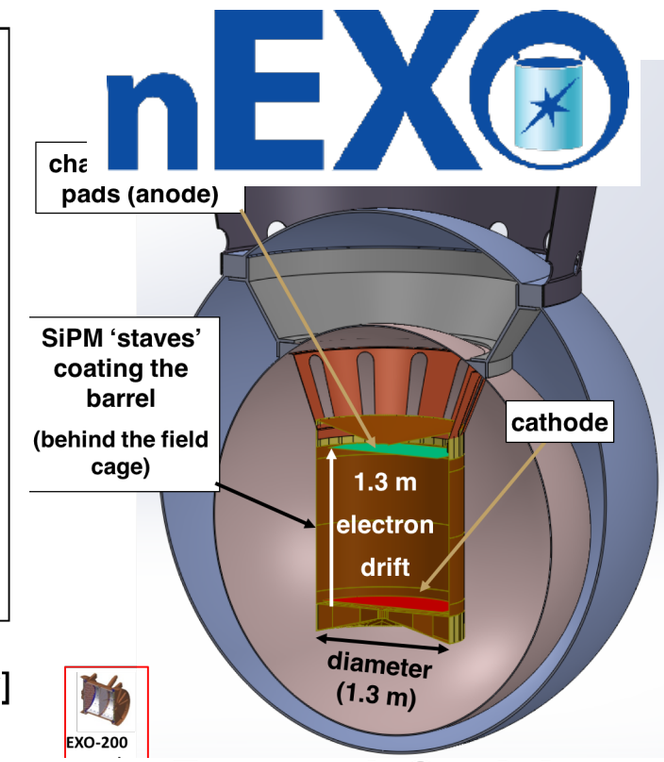
THREATS

- Xenon market potentially overloaded (dark matter experiments, neXO)
- Funding not yet guaranteed beyond NEXT-100
- Intense competition with other projects may lead to the technology not being selected in the US
- Interest in HPXe in Japan (and China) but possibility of *no* convergence.

International context

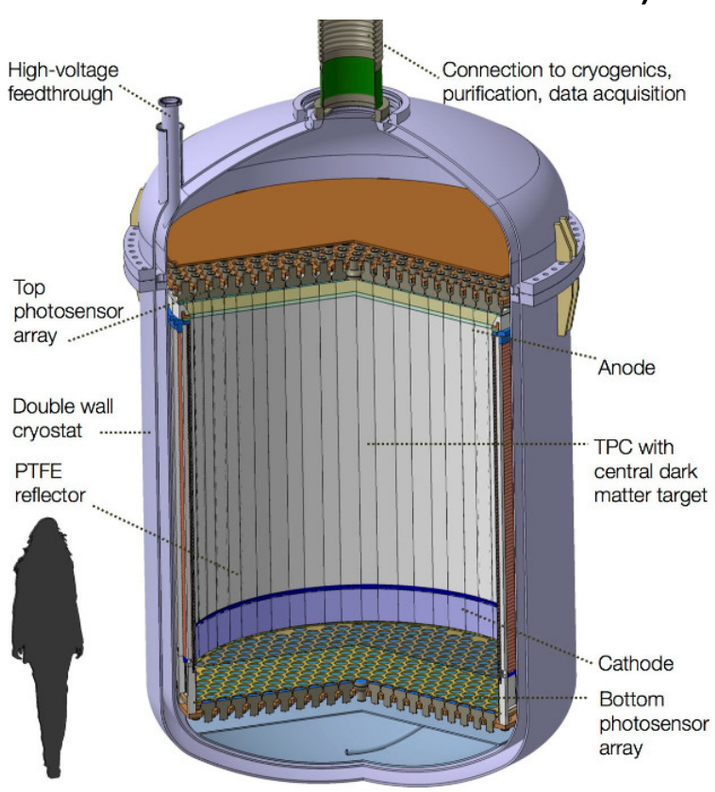


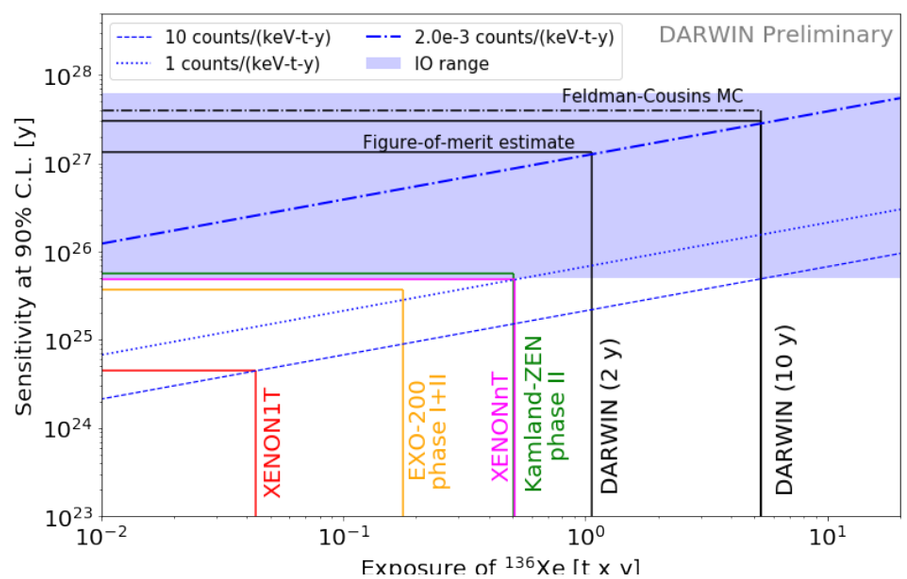


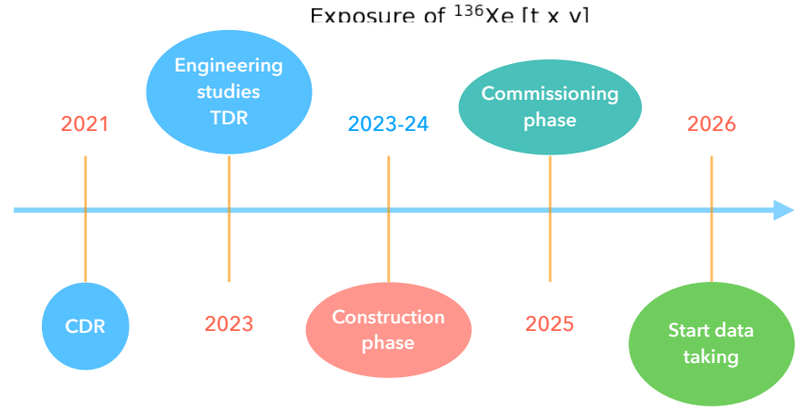


5 ton LSc Xe

40 t liquid Xe TPC **DARWIN**
(with 8.9% ^{136}Xe → 3.6 t of ^{136}Xe)



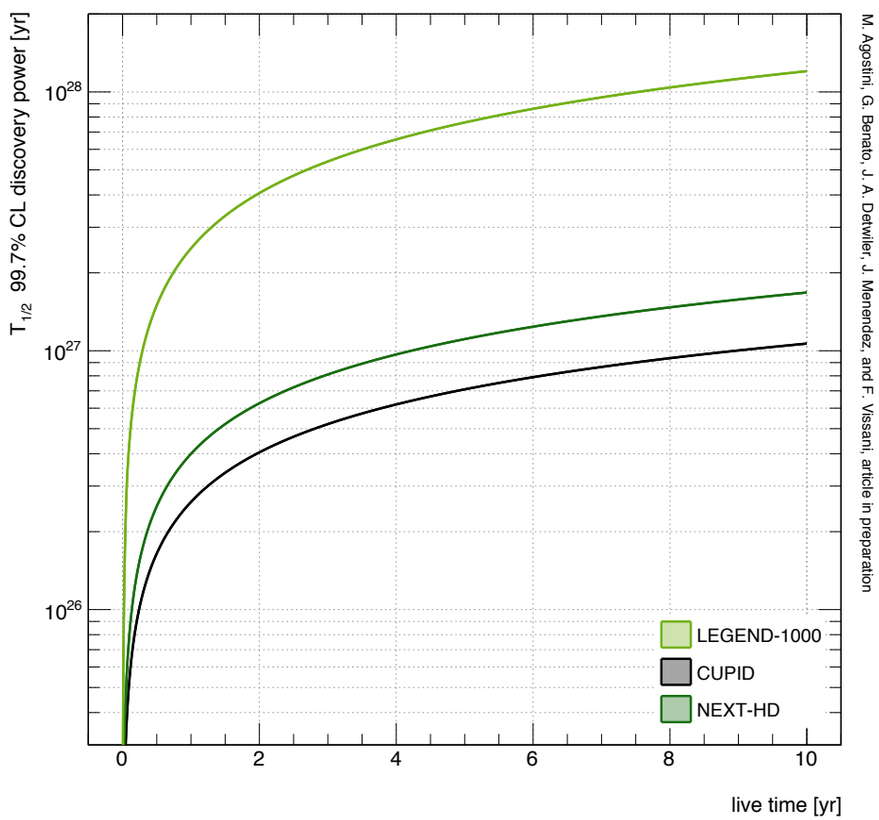


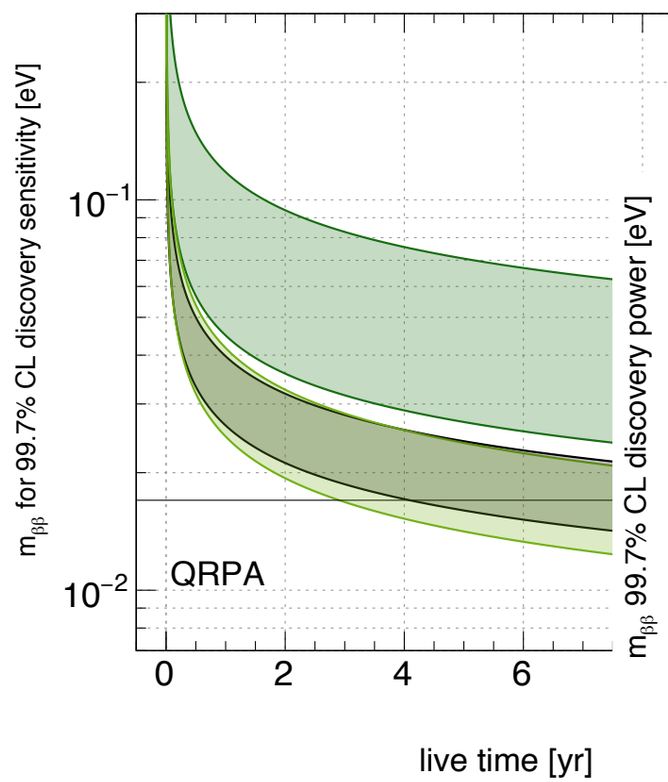


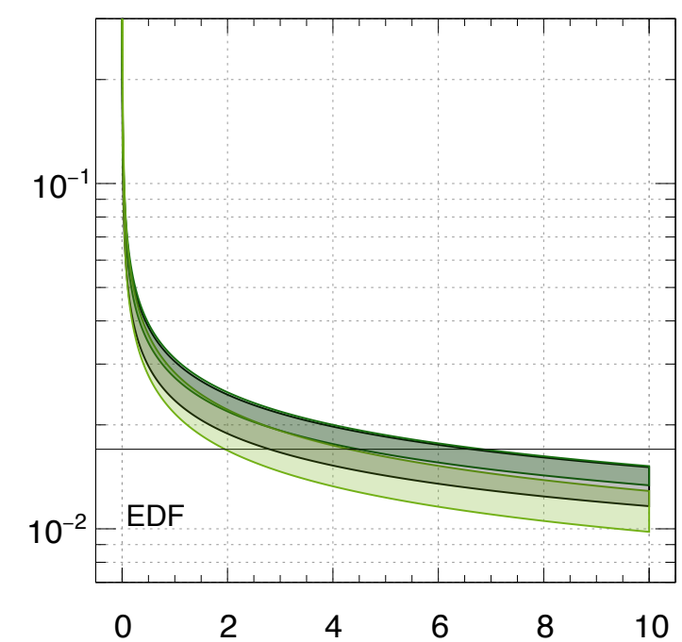
HPXe: PANDAX-III
Bolometers: AMoRE
Loaded LSc: KamLAND2-Zen, SNO+

Comparison

Current demonstrator	Iso	M_{iso} [kg]	σ [keV]	ROI [σ]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{\mathrm{kg}_{iso}\mathrm{yr}}{\mathrm{yr}}\right]$	$\mathcal{B}_{\mathrm{ROI}}$ $\left[\frac{\mathrm{cts}}{\mathrm{kg}_{iso}\mathrm{yr}}\right]$		
CUPID-0	^{82}Se	4,65	8.5	$-2.0, +2.0$	70	3.3	$2.2 \cdot 10^{-1}$	$3.5 \cdot 10^{24}$	311-638
CUPID-Mo	^{100}Mo	2.26	2.3	$-2.0, +2.0$	64	1.44	-	-	-
NEXT-White	^{136}Xe	91	10	$-1.0, +1.9$	26	-	-	-	-
Funded experiments	**Iso**	**M_{iso} [kg]**	**σ [keV]**	**ROI [σ]**	**ϵ_{sig} [%]**	**$\mathcal{E}$ $\left[\frac{\mathrm{kg}_{iso}\mathrm{yr}}{\mathrm{yr}}\right]$**	**$\mathcal{B}_{\mathrm{ROI}}$ $\left[\frac{\mathrm{cts}}{\mathrm{kg}_{iso}\mathrm{yr}}\right]$**	**3σ disc. sens.**	
								$T_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
LEGEND-200	^{76}Ge	177	1.1	$-2.0, +2.0$	70	123	$1 \cdot 10^{-3}$	$9.4 \cdot 10^{26}$	35–73
NEXT-100	^{136}Xe	87	10.4	$-1.0, +1.8$	26	23	$4 \cdot 10^{-2}$	$7.0 \cdot 10^{25}$	65–281
Future experiments	**Iso**	**M_{iso} [kg]**	**σ [keV]**	**ROI [σ]**	**ϵ_{sig} [%]**	**$\mathcal{E}$ $\left[\frac{\mathrm{kg}_{iso}\mathrm{yr}}{\mathrm{yr}}\right]$**	**$\mathcal{B}_{\mathrm{ROI}}$ $\left[\frac{\mathrm{cts}}{\mathrm{kg}_{iso}\mathrm{yr}}\right]$**	**3σ disc. sens.**	
								$T_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
LEGEND-1000	^{76}Ge	883	1.1	$-2.0, +2.0$	70	614	$7 \cdot 10^{-5}$	$1.2 \cdot 10^{28}$	10–20
CUPID	^{100}Mo	253	2.1	$-2.0, +2.0$	68	172	$2 \cdot 10^{-3}$	$1.1 \cdot 10^{27}$	12–20
NEXT-HD	^{136}Xe	991	7.7	$-1.3, +2.5$	32	317	$9 \cdot 10^{-4}$	$1.7 \cdot 10^{27}$	13–57







Conclusions

Recommendation 1. The search for neutrinoless double beta decay is a top priority in particle and astroparticle physics, as this process provides the most sensitive test of lepton number violation.

Recommendation 2. A sustained and enhanced support of the European experimental programme is required to maintain the leadership in the field, exploiting the broad range of expertise and infrastructure and fostering existing and future international collaborations.

Recommendation 3. A multi-isotope program exploiting different technologies at the highest level of sensitivity should be supported in Europe in order to mitigate the risks and to extend the physics reach of a possible discovery.

Recommendation 4. A program of R&D should be devised on the path towards the meV scale for the effective Majorana mass parameter.

Recommendation 5. The European underground laboratories should provide the required space and infrastructure for next generation double beta decay experiments. A strong level of coordination is required among European laboratories for radiopurity material assays and low background instrumentation development in order to ensure that the challenging sensitivities of the next generation experiments can be achieved on competitive timescales.

Recommendation 6. The theoretical assessment of the particle physics implications of a positive observation and of the broader physics reach of these experiments should be continued. A dedicated theoretical and experimental effort, in collaboration with the nuclear physics community, is needed to achieve a more accurate determination of the Nuclear Matrix Elements (NME).

SAC recommendations concerning Neutrinoless double beta decay report

November 2019

The APPEC-SAC discussed the final draft of the neutrinoless double beta decay report in its meeting on 26 November 2019 and concluded:

1) We endorse the scientific review carried out by the committee to summarize the main European efforts in neutrino less double beta decay.

2) We encourage the community to explore convergence towards 2-3 technologies with the potential to be scaled up to the tonne scale (and beyond).

3) We strongly endorse the importance of neutrinoless double beta decay searches. There should be at least two large experimental programmes globally, and at least one hosted in Europe.

4) This evaluation should be updated in 4 years, reflecting what is learned in the mean time from technology demonstrations, what we learn about normal vs. inverted hierarchy from neutrino oscillation experiments, and the international funding situation.

5) We endorse R&D towards new technologies to reach the normal hierarchy and for new physics searches.