A review on

neutrinoless double beta decay

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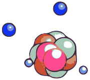
Double Beta Decay: real and virtual neutrinos



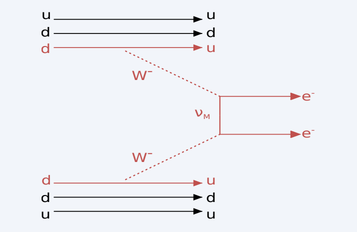
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e \qquad (2\nu\beta\beta)$$

$$(A, Z) \rightarrow (A, Z+2) + 2e^- \qquad (0\nu\beta\beta)$$

- *L*-violation, i. e. creation of a pair of electrons
  - a discovery of 0νββ would imply

    a violation of the SM global symmetries
- 0νββ key tool to study neutrinos
  - Majorana or Dirac nature
  - ν mass scale and ordering
  - *CP*-violation in the lepton sector

Feynman diagram



Review: **Adv. High En. Phys. 2016, 2162659 (2016)**

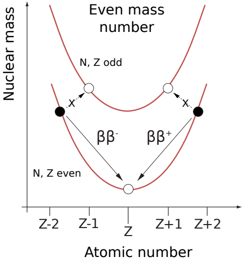
0νββ half-life time

- 0νββ is a *nuclear process*
  - 2nd order transition: $(A, Z) \to (A, Z+2)$
  - even-even nuclei: β-decay is forbidden
- half-life expression can be factorized as

$$\left[t^{0\nu}_{1/2}\right]^{-1} = G_{0\nu}\,|\mathcal{M}|^2\,|f(m_i, U_{ei})|^2$$

  - $G_{0\nu}$ = Phase Space Factor (atomic physics)
  - $\mathcal{M}$ = Nuclear Matrix Element (nuclear physics)
  - $f(m_i, U_{ei})$ = mechanism (particle physics)

$\to$ 3 light neutrino exchange: $f(m_i, U_{ei}) \equiv \dfrac{m_{\beta\beta}}{m_e}$ (Effective Majorana mass)

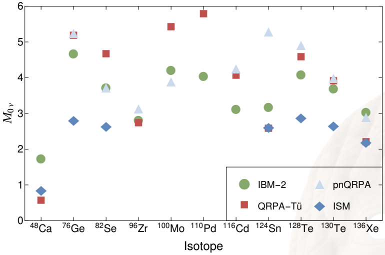


Caveat In order to extract the information on the neutrino mass, it is necessary to pass through *atomic* and *nuclear* physics

Models for the nuclear matrix elements

- calculation of the NMEs for the $0\nu\beta\beta$ is difficult
  - complex nuclear structure with many nucleons
  - ground + multiple excited states to be considered
- different theoretical models
  - Quasiparticle Random Phase Approximation
  - Intermediate Boson Model
  - Interacting Shell Model
  - ...

QRPA / IBM-2 within $\sim 30\%$



QRPA-Tü: F. Šimkovic *et al.*, **Phys. Rev. C 87, 045501 (2013)**
pnQRPA: J. Hyvärinen *et al.*, **Phys. Rev. C 91, 024613 (2015)**
IBM-2: J. Barea *et al.*, **Phys. Rev. C 91, 034304 (2015)**
ISM: J. Menéndez *et al.*, **Nucl. Phys. A 818, 139 (2009)**

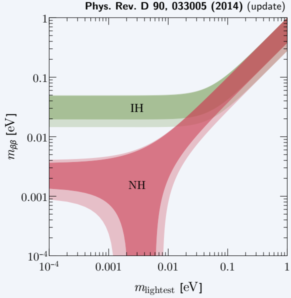
Assessing the uncertainties

- estimate of the uncertainties on PSFs/NMEs is crucial to constrain $m_{\beta\beta}$
- theory of PSFs is known / mostly computational difficulties $\Rightarrow \sim 7\%$
- quite large uncertainties for the NMEs
  - error on single calculations of $\sim 20\%$ / still hard to give an overall value
  - calculations *vs*. rates discrepancies $\gg 20\%$ for known processes (β, *EC*, 2νββ)
- $\mathcal{M} \equiv g_A^2 \mathcal{M}_{0\nu} = g_A^2 \left(\mathcal{M}_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A} \right)^2 \mathcal{M}_F^{(0\nu)} + \mathcal{M}_T^{(0\nu)} \right)$
  - significant effect of g_A: uncertainty on its values $\Rightarrow$ larger uncertainty on $\mathcal{M}$
  - the value of g_A in the nuclear medium is not reliably known
    - from 1.27 (free nucleon) to < 1 (quenching)

Effective Majorana mass (3 light neutrino exchange)

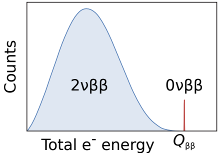
- $m_{\beta\beta}$ is the key quantity in the 0νββ
  - absolute value of the ee-entry of the neutrino mass matrix
  - $m_{\beta\beta} = \left| \sum_{i=1,2,3} e^{i\xi_i} \, |U_{ei}^2| \, m_i \right|$
  - 1 CP-violating + 3 Majorana phases
  - U can be identified with the mixing matrix of the oscillation analysis
  - $U \equiv U|_{\text{osc.}} \cdot \text{diag}\left(e^{-i\xi_1/2}, e^{-i\xi_2/2}, e^{i\phi - i\xi_3/2}\right)$
  - only two phases play a *physical* role
- $m_{\beta\beta} = \left| e^{i\alpha_1} \cos^2\theta_{12} \cos^2\theta_{13} m_1 + e^{i\alpha_2} \cos^2\theta_{13} \sin^2\theta_{12} m_2 + \sin^2\theta_{13} m_3 \right|$

$m_{\beta\beta}$ vs. m_{lightest}



Experimental search for 0νββ

- **detection**: energy (track) of the 2 emitted e^-
  - monochromatic peak at $Q_{\beta\beta}$
  - smearing due to finite energy resolution



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

- **observable**: decay half-life of the isotope, $t^{0\nu}_{1/2}$
  - in the case of a peak in the energy spectrum

$$t^{0\nu}_{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{N_{\beta\beta}}{N_{\text{peak}}} \qquad \left(\frac{\delta t^{0\nu}_{1/2}}{t^{0\nu}_{1/2}} = \frac{\delta N_{\text{peak}}}{N_{\text{peak}}} \right)$$

  - if no peak is detected, the sensitivity corresponds to the maximum signal that can be hidden by the background fluctuations $n_B = \sqrt{M\,T\,B\,\Delta}$

$$S^{0\nu}_{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{n_{\beta\beta}}{n_\sigma \cdot n_B} = \ln 2 \cdot \varepsilon \cdot \frac{1}{n_\sigma} \cdot \frac{x\,\eta\,N_A}{\mathcal{M}_A} \cdot \sqrt{\frac{M\,T}{B\,\Delta}}$$

(M = detector mass T = measuring time B = background level Δ = energy resolution)

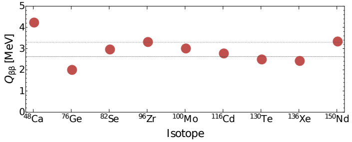
Choice of the isotope

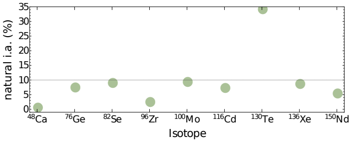
- value of $Q_{\beta\beta} \rightarrow$ influences the bkg
  - 2.6 (3.3) MeV end-point of main γs (βs)
  - avoid radioactivity peak position

    obs. suitability depends on detector features
- high isotopic abundance
  - ease of material enrichment

    (technologically + economically)
- availability of the isotope
  - tonnes required for future 0νββ experiments

    → high cost + large procurement time
- compatibility with a detection technique





Promising isotopes

^{48}Ca ^{76}Ge ^{82}Se

^{96}Zr ^{100}Mo ^{116}Cd

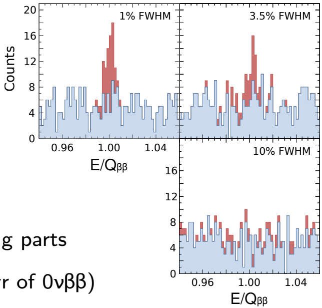
^{130}Te ^{136}Xe ^{150}Nd

Most suitable **isotope + detector** combination

Detector requirements

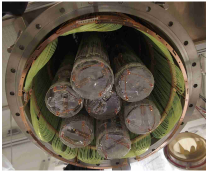
- good energy resolution
  - only protection against $2\nu\beta\beta$ spectrum tail
  - $R_{0\nu/2\nu} \propto \left(\frac{Q_{\beta\beta}}{\Delta}\right)^6 \frac{t^{2\nu}_{1/2}}{t^{0\nu}_{1/2}}$
- very low background
  - underground location + shielding
  - radio-pure materials for detector and surrounding parts
    $((10^9 - 10^{10})$ yr from natural chains *vs.* $> 10^{25}$ yr of $0\nu\beta\beta)$
  - analysis rejection techniques
- large isotope mass
  - present: some tens up to hundreds of kg
  - tonnes required to cover the IH region

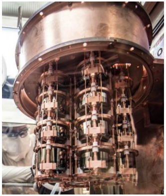
PoS (GSSI2014), 004 (2015)



How to get the best sensitivity?
It is up to the experimentalists to choose **which aspect to privilege**

Experimental techniques (I)





- Ge-diodes
  - high-purity enriched crystals
  - high energy resolution ($\lesssim 0.2\%$ @ $Q_{\beta\beta}$)
  - bkg rejection by pulse shape analysis

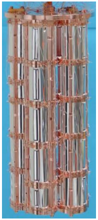
Heidelberg-Moscow   IGEX

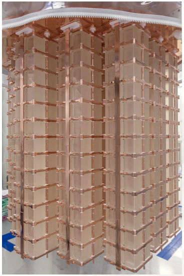
GERDA   MAJORANA Demonstrator   LEGEND

- bolometers
  - high energy resolution (close to Ge-diodes)
  - many compounds with $0\nu\beta\beta$ emitters
  - large source masses
  - complex cryogenic infrastructure

Cuoricino   CUORE-0   CUPID-0

AMoRE   CUORE   CUPID

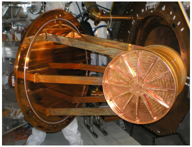


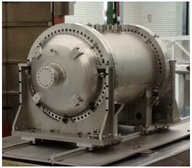


Experimental techniques (II)

- Xe liquid . . .
  - Xe easily enrichable
  - event topology reconstruction
  - low energy resolution ($\sim$ 3%)
- . . . and gaseous TPCs
  - higher energy resolution
  - lower signal efficiency ($\sim$ 30%)

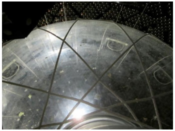
EXO-200 NEXT nEXO PandaX-III





- liquid scintillators loaded with $0\nu\beta\beta$ isotope
  - poor energy resolution ($\sim$ 10%)
  - huge amount of material
  - very low background

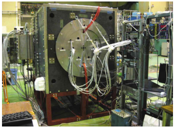
KamLAND-Zen SNO+



Experimental techniques (III)

- tracker + calorimeter
  - almost no limitations in the choice of the isotope
  - large isotope masses hardly achievable
  - low energy resolution
  - event topology reconstruction

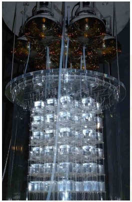
NEMO-3   SuperNEMO

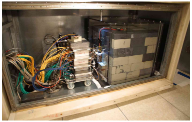


- others
  - variations on the previous, or new techniques
  - numerous running prototypes and R&D projects

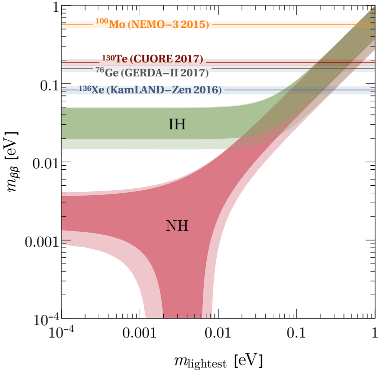
CANDLES   COBRA   ZICOS

DCBA/MTD   FLARES   ...





Present sensitivity



$$m_{\beta\beta} \leq \frac{m_e}{g_A^2\, \mathcal{M}_{0\nu} \sqrt{G_{0\nu}\, t_{1/2}^{0\nu}}}$$

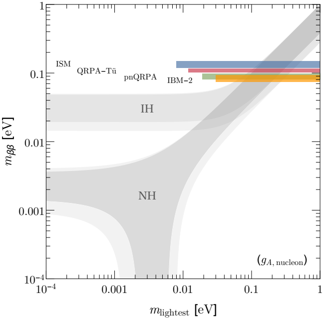
NMEs (IBM-2): **Phys. Rev. C 91, 034304 (2015)**
PSFs: **Phys. Rev. C 85, 034316 (2012)**
$g_A = 1.269$

obs. *fixing the NME model* allows to compare different experimental sensitivities, but it *underestimates* the uncertainties

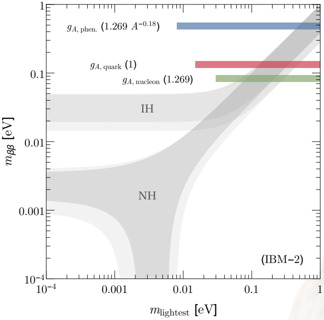
Isotope	$t_{1/2}^{0\nu}$ (90% C. L.) [yr]	$m_{\beta\beta}^{\text{min}}$ [eV]	Reference
^{100}Mo	$1.1 \cdot 10^{24}$	0.569 ± 0.053	**Phys. Rev. D 92, 072011 (2015)**
^{130}Te	$1.5 \cdot 10^{25}$	0.186 ± 0.017	**Phys. Rev. Lett. 120, 132501 (2018)**
^{76}Ge	$8.0 \cdot 10^{25}$	0.159 ± 0.014	L. Pandola, *results presented @ TAUP 2017*
^{136}Xe	$1.1 \cdot 10^{26}$	0.083 ± 0.009	**Phys. Rev. Lett. 117, 082503 (2016)**

Effect of the nuclear uncertainties: Xe case

- different NMEs / fixed g_A
  - $73\,\text{meV} < m_{\beta\beta} < 149\,\text{meV}$



- different g_A / fixed NMEs
  - $73\,\text{meV} < m_{\beta\beta} <$ (149) $542\,\text{meV}$



$$t^{0\nu}_{1/2} \propto g_A^{-4}\, \mathcal{M}_{0\nu}^{-2}$$

Towards the next generation of $0\nu\beta\beta$ experiments

- attaining a sensitivity of the order of **10^{28} yr or more** is important or even essential, allowing to test the type of **neutrino mass spectrum**
- this goal imposes **stringent requirements to the detectors**
  - the feasibility and effectiveness of the proposed technique have to be tested by means of demonstrators or extensive R&D programmes
  - money, i. e. $/mole of *detectable* isotope, must be included in sensitivity studies
    $\rightarrow$ technological costs: procurement, enrichment/purification, infrastructures. . .
    $\rightarrow$ efficiency of detector/setup scalability to tonne-size
  - merging of experiments sharing the same technology and studying different nuclei with a specific detector should be considered
- a **large effort** has to be put **in the nuclear studies** (NMEs and effective value of g_A) in order to maximize the information that can be extracted from the experimental searches

A crucial issue: background suppression

- recall: $S^{0\nu}_{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{n_{\beta\beta}}{n_\sigma \cdot n_B} = \ln 2 \cdot \varepsilon \cdot \frac{1}{n_\sigma} \cdot \frac{x\,\eta\,N_A}{\mathcal{M}_A} \cdot \sqrt{\frac{M\,T}{B\,\Delta}}$
- when B is sufficiently low $\rightarrow$ **zero background condition**
    - transition region in between: $M\,T\,B\,\Delta = \mathcal{O}(1)$ (no expected events in the ROI)
- $S^{0\nu}_{1/2,\,0B} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{N_{\beta\beta}}{n_\sigma \cdot n_B} = \ln 2 \cdot \varepsilon \cdot \frac{x\,\eta\,N_A}{\mathcal{M}_A} \cdot \frac{M\,T}{N_S}$
    - the sensitivities scales linearly with the exposure!

The zero bkg condition depends on M: **the larger the detector mass, the more strict the request on the background**

- the same bkg level can suffice for a kg-size experiment, but not for a tonne-size one

Future players: CUPID

- CUORE Upgrade with Particle IDentification

  (Cryogenic Underground Observatory for Rare Events)

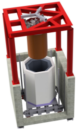
  - 750 kg bolometric array of enriched crystals
  - TeO_2 or Mo/Se compounds
  - background in ROI: 0.1 c keV^{-1} t^{-1} yr^{-1}
  - energy resolution: 5 keV FWHM @ $Q_{\beta\beta}$
  - sensitivity goal on 0νββ half-life:

    $5 \cdot 10^{27}$ yr

- from the experience of CUORE

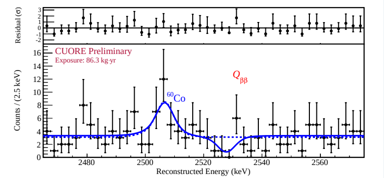
  - use CUORE cryogenic infrastructure
  - light collection (Čerenkov / scintillation)

  → α *vs.* β/γ separation ⇒ bkg reduction



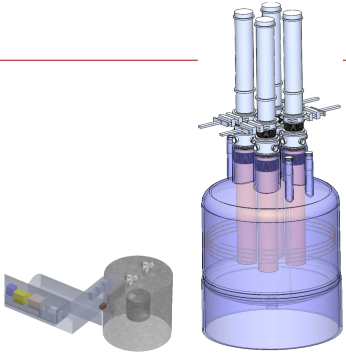
CUORE first results (Oct 2017)

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

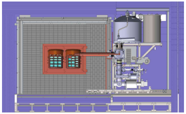


$t_{1/2}^{0\nu}(^{130}\mathrm{Te}) > 1.5 \cdot 10^{25}$ yr @ 90% C. L.

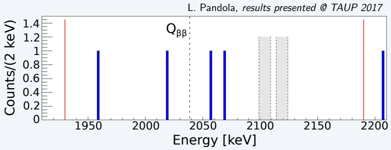
Future players: LEGEND



- Large Enriched Germanium Experiment for Neutrinoless ββ Decay
  - 200 kg → 1 t of ^{76}Ge enriched HPGe-diodes
  - background in ROI: 0.1 c keV $^{-1}$ t $^{-1}$ yr $^{-1}$
  - energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$
  - sensitivity goal on 0νββ half-life: 10^{28} yr
- best of GERDA & MJD
  - water + LAr for low-A shielding (G)
  - LAr active veto (G)
  - radio-pure material, especially Cu (M)
  - low-noise electronics (M)



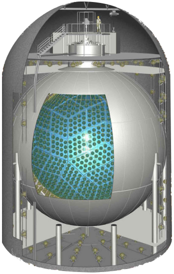
GERDA-II new results (Jul 2017)



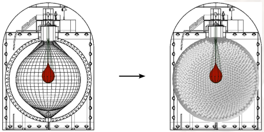
$t^{0\nu}_{1/2} > 8.0 \cdot 10^{25}$ yr @ 90% C. L.

Future players: KamLAND2-Zen

- Kamioka Liquid scintillator Anti-Neutrino Detector 2 - Zero neutrino
  - 1 t of ^{136}Xe enriched xenon dissolved in LS
  - background in ROI: 0.01 c $keV^{-1}\,t^{-1}\,yr^{-1}$
  - energy resolution: 50 keV FWHM @ $Q_{\beta\beta}$
  - sensitivity goal on $0\nu\beta\beta$ half-life: 10^{27} yr



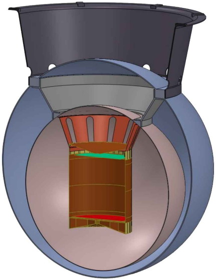
- from the experience of KamLAND-Zen
  - improved light collection (new LS & PMTs + collectors)
  - scintillating balloon (^{214}Bi tagging)
  - new method for LS purification
  - pressurized Xe-LS

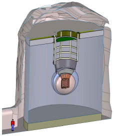


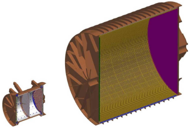
Future players: nEXO

- next Enriched Xenon Observatory
  - liquid TPC with 4.7 t of active ^{136}Xe enriched xenon
  - background in ROI: 0.01 c keV^{-1} t^{-1} yr^{-1}
  - energy resolution: 60 keV FWHM @ $Q_{\beta\beta}$
  - sensitivity goal on 0νββ half-life: $9 \cdot 10^{27}$ yr
- from the experience of EXO-200
  - 3x larger size ⇒ 30x mass/volume
  - improved design & components
  - increased light collection

    (larger coverage + APDs → SiPMs)







A major challenge: Ba tagging

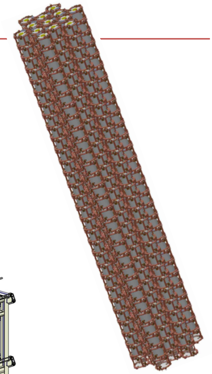
- $^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2\,e^-$
- complete background elimination
- **40x** in expected sensitivity: $4 \cdot 10^{28}$ yr

Summary

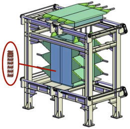
- $0\nu\beta\beta$ is a unique tool to study lepton number violation and ν masses
- today, sensitivities of the order of $(10^{25}$ - $10^{26})$ yr on the decay half-life time have been reached
- the next generation of detectors aims at $(10^{27}$ - $10^{28})$ yr sensitivities
  - money will represent a critical issue for the experiments
  - reaching the zero background condition will be of crucial importance
- a better understanding of the nuclear physics is needed ($\rightarrow$ probing IH)
- the field is very active, with ambitious experimental proposals and numerous R&D programmes

Thank you!

Future players: AMoRE-II



- Advanced Mo-based Rare process Experiment - II
  - 200 kg bolometric array of ^{enr}Mo-based crystals
  - background in ROI: 0.1 c keV^{-1} t^{-1} yr^{-1}
  - energy resolution: 10 keV FWHM @ $Q_{\beta\beta}$
  - sensitivity goal on 0νββ half-life: $5 \cdot 10^{26}$ yr
- result of the AMoRE programme
  - new underground laboratory: ARF
    @ Handeok Iron Mine (1100 m overburden)
  - new cryogenic infrastructure
  - improved detector performance

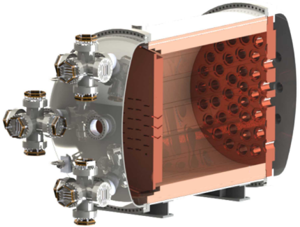


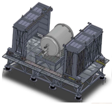
AMoRE pilot

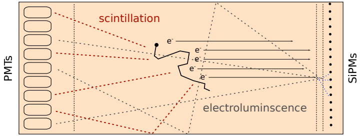
- 6 crystals of $^{40}Ca^{100}MoO_4$ (∼ 1.8 kg)
- several upgrades in detector/system design
- FWHM @ ^{208}Tl: 43 keV → 10 keV

Future players: NEXT-100

- Neutrino Experiment with a Xenon TPC
  - gas TPC with 100 kg of ^{136}Xe enriched xenon
  - background in ROI: 0.1 c keV^{-1} t^{-1} yr^{-1}
  - energy resolution: 15 keV FWHM @ $Q_{\beta\beta}$
  - sensitivity goal on 0νββ half-life: $5 \cdot 10^{25}$ yr
- result of a strong R&D programme
  - NEXT-WHITE: final validation prototype
  - signal amplification by electroluminescence
  - tracking plane (SiPMs) + energy plane (PMTs)





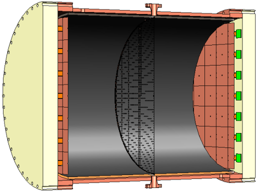


The NEXT program

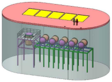
- NEXT-100 → NEXT-250 → NEXT-ton
- background estimate: 0.05 c keV^{-1} t^{-1} yr^{-1}
- final expected sensitivity: 10^{27} yr

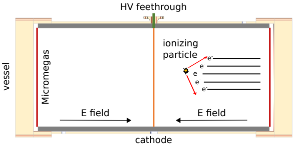
Future players: PandaX-III

- Particle and astrophysical Xenon Detector - III
  - 5 gas TPCs with 200 kg of ^{136}Xe enriched xenon
  - background in ROI: 0.01 c keV^{-1} t^{-1} yr^{-1}
  - energy resolution: 75 keV FWHM @ $Q_{\beta\beta}$
  - sensitivity goal on 0νββ half-life: 10^{27} yr



- 0νββ search with the PandaX programme
  - symmetric TPC instrumented with Microbulk MicroMegas
  - extensive material screening campaign
  - commissioning of prototype TPC (10 kg Xe) ongoing



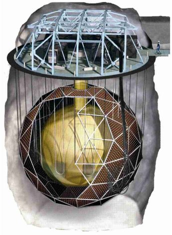


First 200 kg module

- energy resolution: 225 keV FWHM @ $Q_{\beta\beta}$
- background in ROI:0.1 c keV^{-1} t^{-1} yr^{-1}
- expected sensitivity: 10^{26} yr

Future players: SNO+

- Sudbury Neutrino Obrservatory +
  - 3.9 t of tellurium dissolved in LS
  - background in ROI: 0.1 c keV^{-1} t^{-1} yr^{-1}
  - energy resolution: 270 keV FWHM @ $Q_{\beta\beta}$
  - sensitivity goal on $0\nu\beta\beta$ half-life: $2 \cdot 10^{26}$ yr
- commissioning ongoing
  - tellurium stored underground
  - purification system under construction
  - calibration system ready
  - loading of LS forthcoming

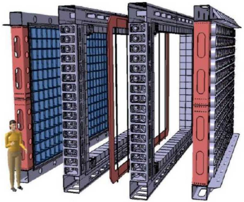


SNO+ $0\nu\beta\beta$ programme

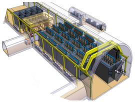
- Te concentration in LS: 0.5% → 5%
- 13.3 t of isotope mass
- expected sensitivity: $> 10^{27}$ yr

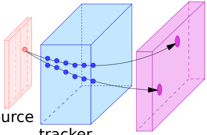
Future players: SuperNEMO

- Super Neutrino Ettore Majorana Observatory
  - tracker + calorimeter with 100 kg of ^{82}Se $\beta\beta$ source
  - background in ROI: 5 c keV^{-1} t^{-1} yr^{-1}
  - energy resolution: 120 keV FWHM @ $Q_{\beta\beta}$
  - sensitivity goal on $0\nu\beta\beta$ half-life: 10^{26} yr



- from the experience of NEMO-3
  - improved detector design + modularity
  - increased detector radio-putity
  - increased source radio-purity



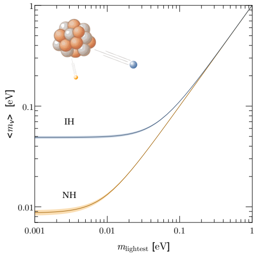


superNEMO demonstrator

- first produced module (1 of 20)
- 7 kg of isotope mass
- expected sensitivity: $6 \cdot 10^{24}$ yr

Assessing the neutrino masses

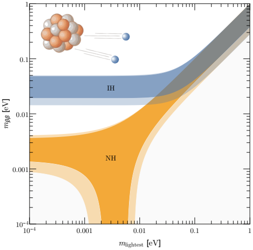
Direct measurement



- effect of electron neutrino mass in β decay
- model independent: relies on pure kinematic considerations
- sensitive to effective electron neutrino mass:

$$\langle m_\nu \rangle = \sqrt{\sum_{i=1}^{3} \left| U_{ei}^2 \right| m_i^2}$$

Search for 0νββ

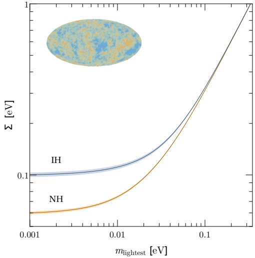


- *requires* Majorana neutrinos
- large theoretical uncertainties
- sensitive to Majorana mass:

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 \; m_i \right|$$

- bands due to Majorana phases

Cosmology



- strong model dependence
- very stringent bounds
- sensitive to sum of neutrino masses:

$$\Sigma \equiv \sum_{i=1}^{3} m_i$$

Implication for the 0νββ search (I)

- $\Sigma = m_1 + m_2 + m_3$

$$= m_l + \sqrt{m_l^2 + a} + \sqrt{m_l^2 + b}$$

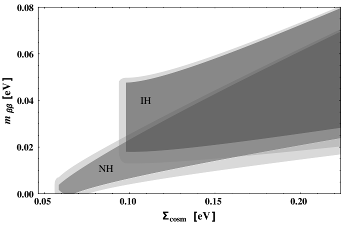
  - NH: $a = \delta m^2$

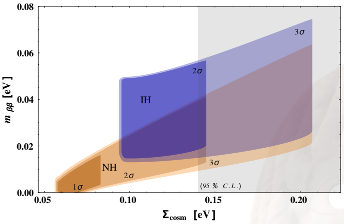
    $b = \Delta m^2 + \delta m^2/2$
  - IH: $a = \Delta m^2 - \delta m^2/2$

    $b = \Delta m^2 + \delta m^2/2$

- it is possible to include the new constraints on Σ by considering:

$$\frac{(y - m_{\beta\beta}(\Sigma))^2}{(n\,\sigma[m_{\beta\beta}(\Sigma)])^2} + \frac{(\Sigma - \Sigma(0))^2}{(\Sigma_n - \Sigma(0))^2} < 1$$

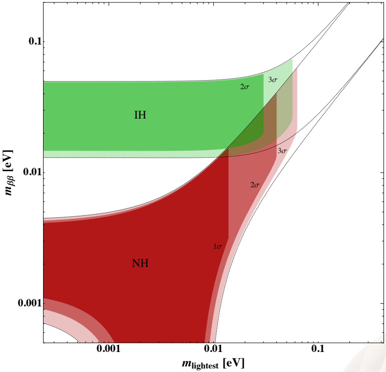




Implication for the 0νββ search (II)

$$\frac{(y - m_{\beta\beta}(m))^2}{(n\,\sigma[m_{\beta\beta}(m)])^2} + \frac{m^2}{m(\Sigma_n)^2} < 1$$

Mass spectrum	$m_{\beta\beta}^{max}$ [meV] (C. L. on Σ)		
	1σ	2σ	3σ
NH	16	41	64
IH	-	57	75



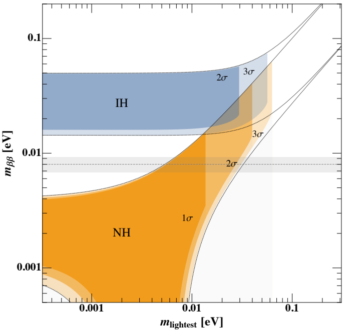
The IH region is excluded at 1σ

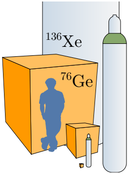
J. Cosm. Astropart. Phys. 1512, 023 (2015)

Further future challenges

- let us require a sensitivity: $m_{\beta\beta} = 8\,\text{meV}$
  - sign of Δm^2
  - test of cosmology
- $M\,T\,B\,\Delta = \mathcal{O}(1) \;\Rightarrow\; S^{0\nu}_{1/2,\,0B} \propto M\,T$

Isotope	$S^{0\nu}_{1/2,\,0B}$ [yr]	Exposure [t yr]	$(B\,\Delta)_{0B}$ [kg^{-1} · yr^{-1}]
$g_{A,\,\text{nucleon}}$			
^{76}Ge	$3.0 \cdot 10^{28}$	5.5	$1.8 \cdot 10^{-4}$
^{130}Te	$8.1 \cdot 10^{27}$	2.5	$4.0 \cdot 10^{-4}$
^{136}Xe	$1.2 \cdot 10^{28}$	3.8	$2.7 \cdot 10^{-4}$
$g_{A,\,\text{quark}}$			
^{76}Ge	$7.9 \cdot 10^{28}$	14	$7.0 \cdot 10^{-5}$
^{130}Te	$2.1 \cdot 10^{28}$	6.5	$1.5 \cdot 10^{-4}$
^{136}Xe	$3.0 \cdot 10^{28}$	9.8	$1.0 \cdot 10^{-4}$
$g_{A,\,\text{phen.}}$			
^{76}Ge	$6.9 \cdot 10^{29}$	125	$8.0 \cdot 10^{-6}$
^{130}Te	$2.7 \cdot 10^{29}$	84	$1.2 \cdot 10^{-5}$
^{136}Xe	$4.0 \cdot 10^{29}$	130	$7.7 \cdot 10^{-6}$





(Many-)tonne scale detectors needed