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NEUTRINOLESS DBD EXPERIMENTS

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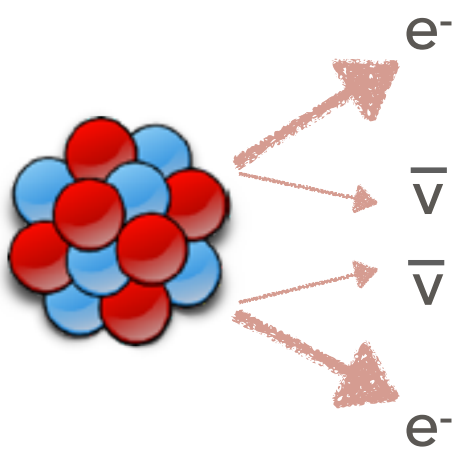
Karlsruhe, Sept 4th 2018

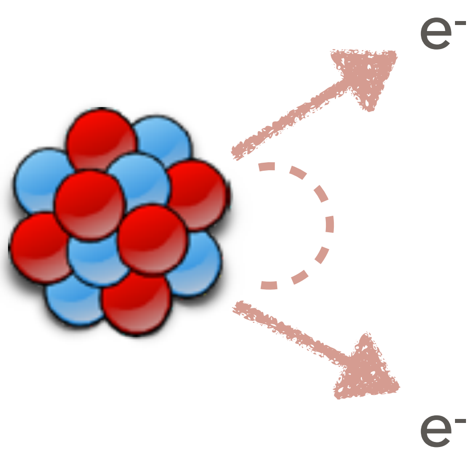
Neutrinoless Double Beta Decay Experiments

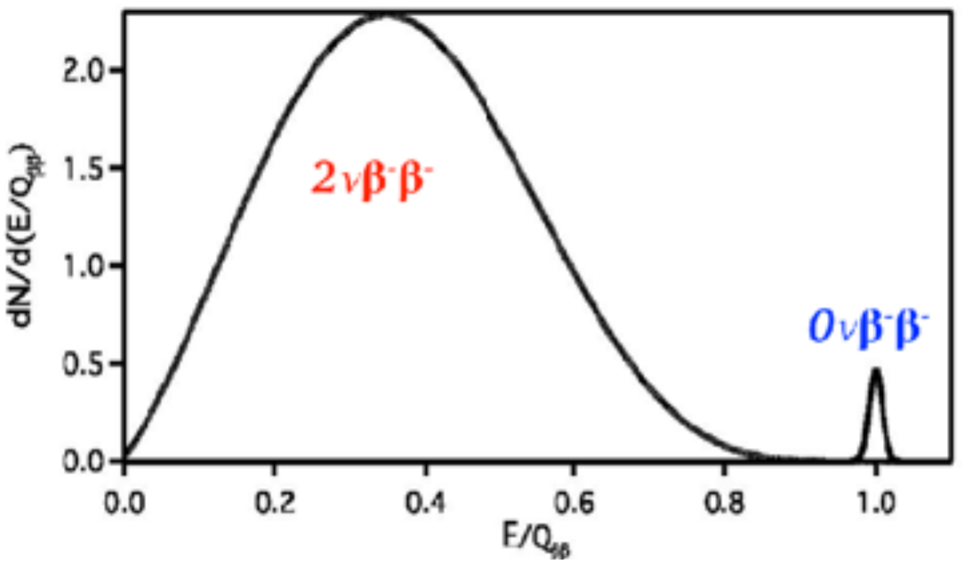
A VERY UNUSUAL REVIEW…

- Short Intro with best Physics Results
- Open Questions
- Controversial Issues
- Impact or Input on/from other fields

Neutrino-less Double Beta Decay: a short intro…







To date, 0νββ is the only viable option to show that neutrinos are Majorana particles ($\underline{\nu} = \nu$)

Experimental observation of neutrino-less double beta decay will…

Establish the **violation of lepton number** in particle physics

Shed light on the **mass generation mechanisms** and the smallness of neutrino masses

Open a window to understand **matter dominance** in the universe

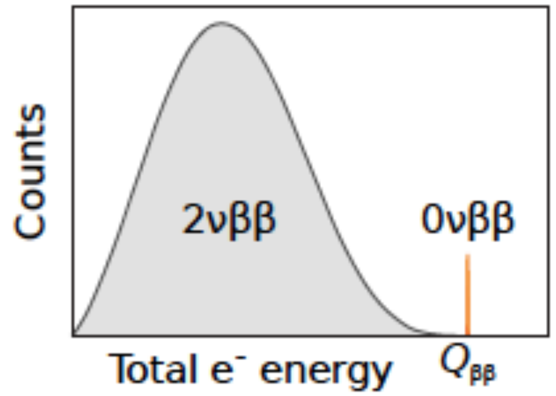
Provide information on the **size and pattern** of neutrino masses

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

$$\left(t^{0\nu}_{1/2}\right)^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Experimental search for 0νββ

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



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

- **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 $n_B = \sqrt{M\,T\,B\,\Delta}$

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

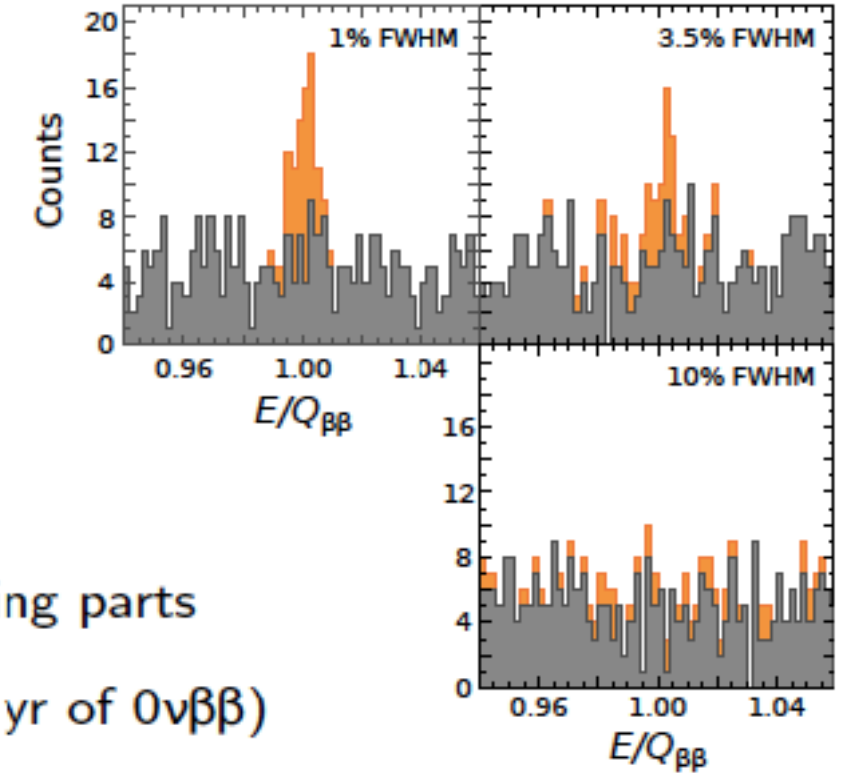
(M = detector mass T = measuring time B = background level Δ = energy resolution)

Detector requirements

- good energy resolution
  - ☐ only protection against 2νββ spectrum tail
  - ☐ $R_{0\nu/2\nu} \propto \left(\frac{Q_{\beta\beta}}{\Delta}\right)^6 \frac{t_{1/2}^{2\nu}}{t_{1/2}^{0\nu}}$
- 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 0νββ)
  - ☐ 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)

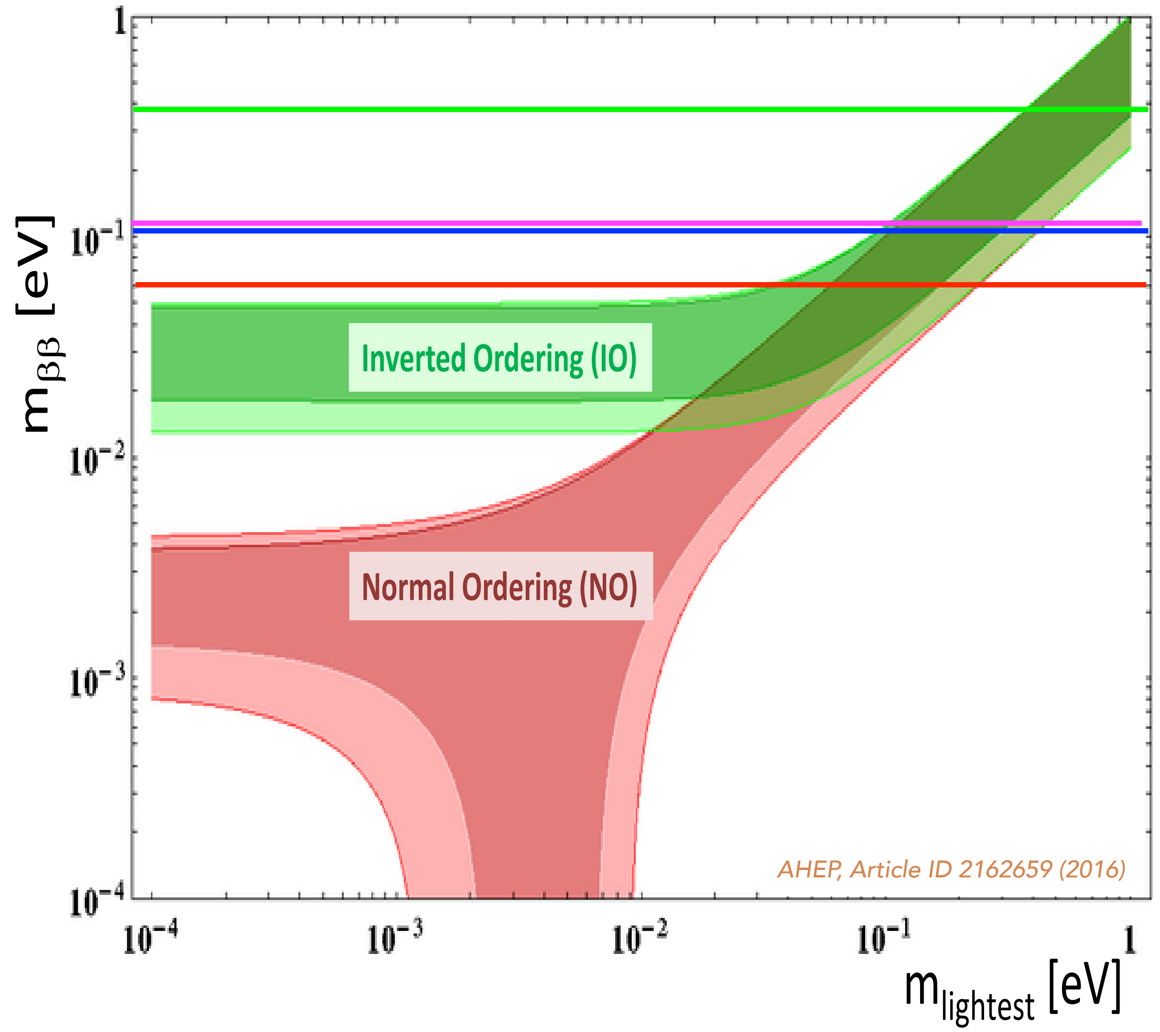


It is up to the experimentalists to choose **which aspect to privilege** in order to get the best sensitivity

Present sensitivity

Effective Majorana mass

$$m_{\beta\beta} \equiv \left|\sum_i U_{ei}^2\, m_i\right| = \left|e^{i\xi_1}\, \cos^2\theta_{12}\cos^2\theta_{13} m_1 + e^{i\xi_2}\, \cos^2\theta_{13}\sin^2\theta_{12} m_2 + \sin^2\theta_{13} m_3\right|$$

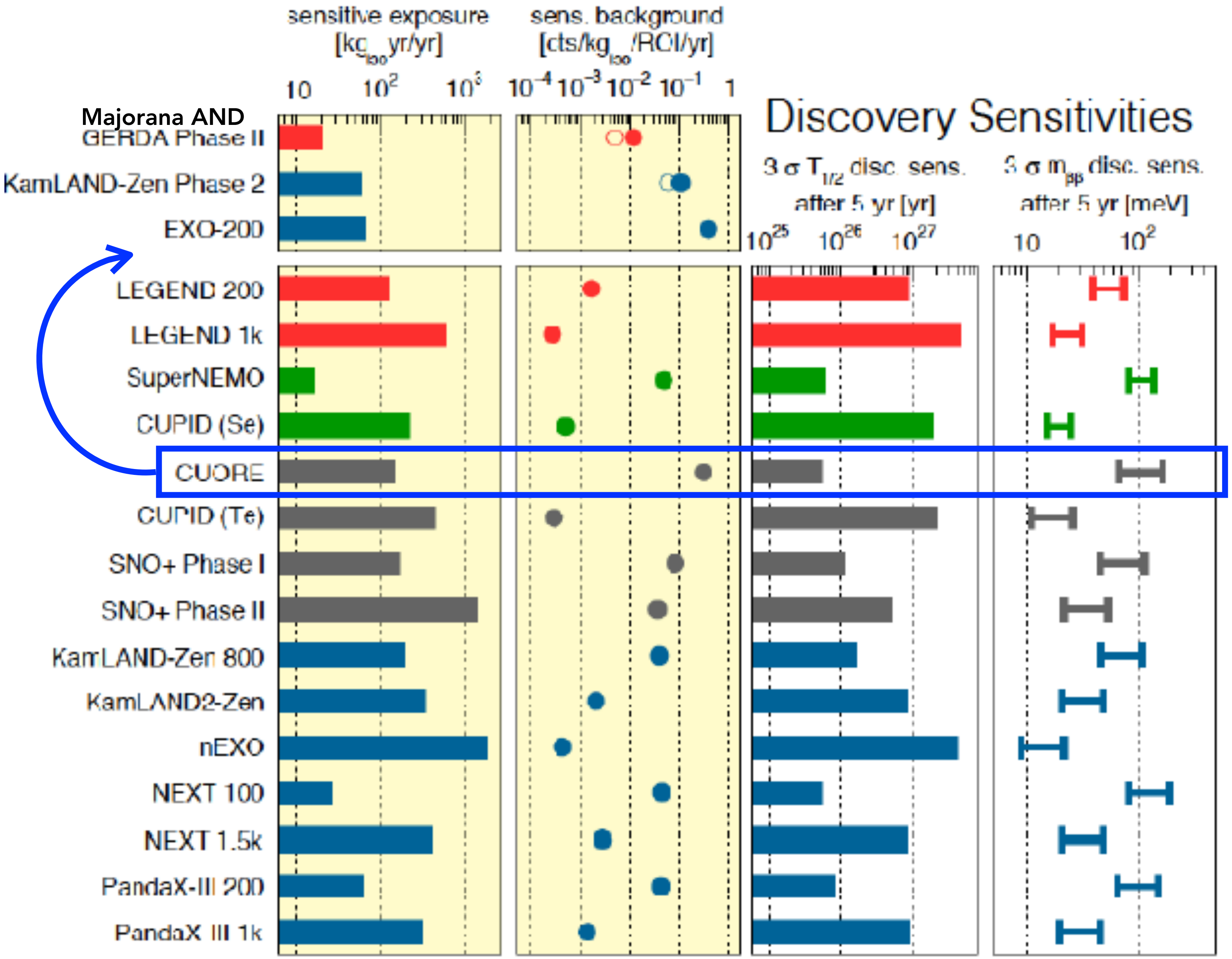


AHEP, Article ID 2162659 (2016)

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

Isotope	$t^{0\nu}_{1/2}$ (90% C. L.) [yr]	$m_{\beta\beta}^{\text{min}}$ [eV]	
^{82}Se	$2.4 \cdot 10^{24}$	0.38	🟩
^{130}Te	$1.5 \cdot 10^{25}$	0.11	🟦
^{76}Ge	$8.0 \cdot 10^{25}$	0.12	🟪
^{136}Xe	$1.1 \cdot 10^{26}$	0.06	🟥

Comparison of the (future) experiments



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 → **zero background condition**
  - ☐ transition region in between: $M\,T\,B\,\Delta = \mathcal{O}(1)$ (no expected events in the ROI)
- $$S^{0\nu}_{1/2,\,0B} = \ln 2 \cdot \varepsilon \cdot \frac{x\,\eta\,N_A}{\mathcal{M}_A} \cdot \frac{M\,T}{N_S}$$

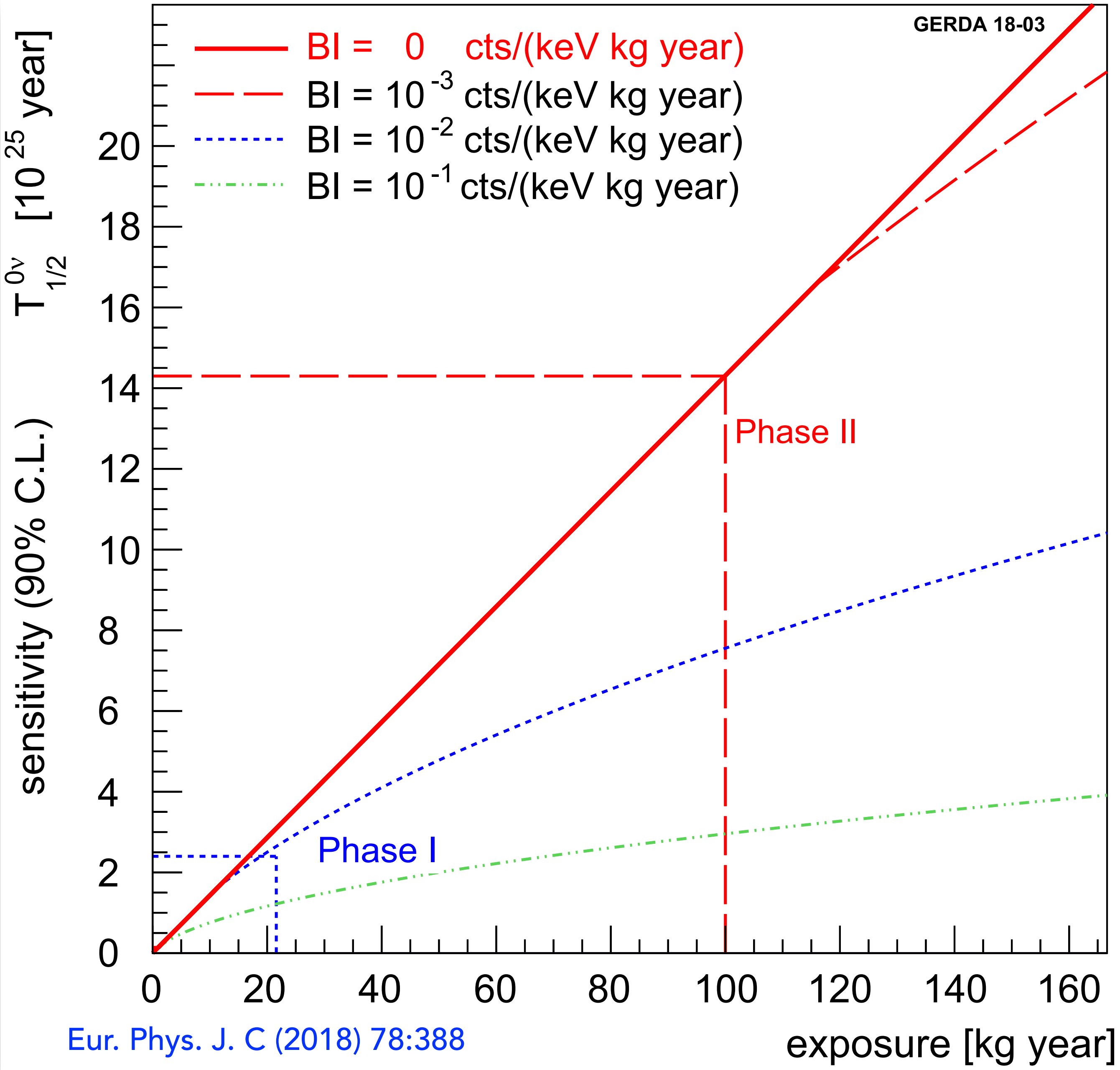
  max n. of counts compatible with 0 bkg

  - ☐ 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

Zero Background Condition? The GERDA case



Eur. Phys. J. C (2018) 78:388

An efficient upgrade needs to increase exposure together with improving the BI towards the "zero-bkg regime"

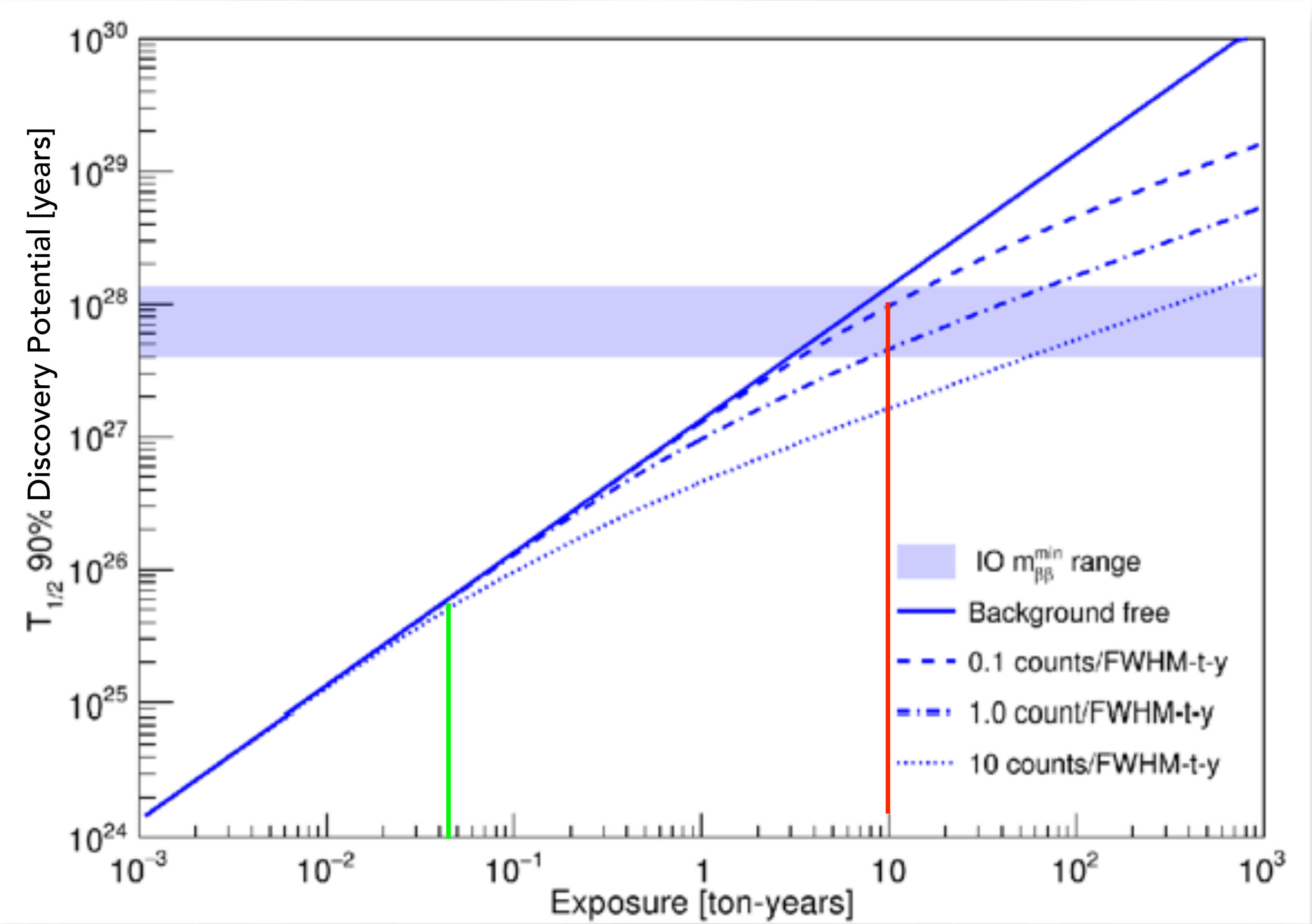
GERDA Phase 1:

BI = 10^{-2} cts/(keV kg y) enough

GERDA Phase 2:

BI = 10^{-3} cts/(keV kg y) needed (and reached…)

Sensitivity or Discovery Potential? The GERDA - LEGEND case



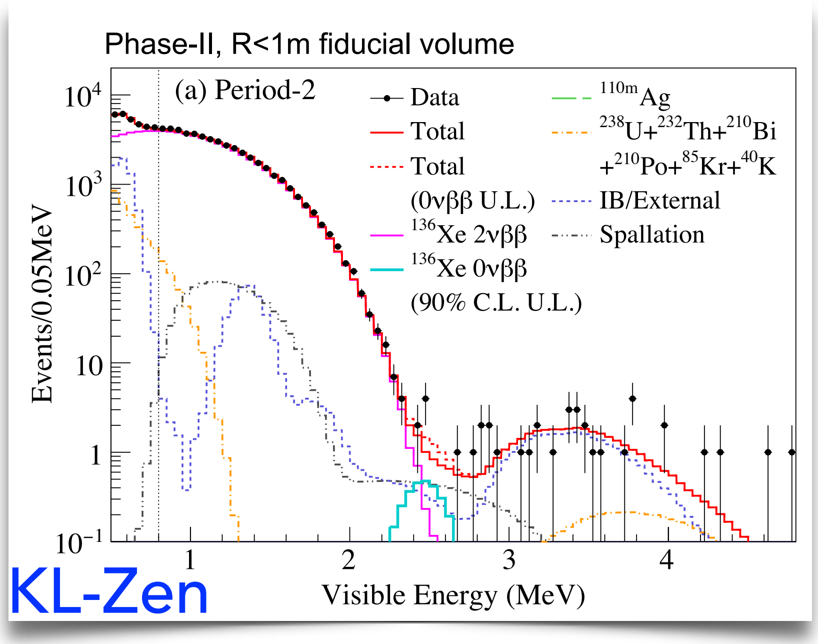
Courtesy of J. Detwiler

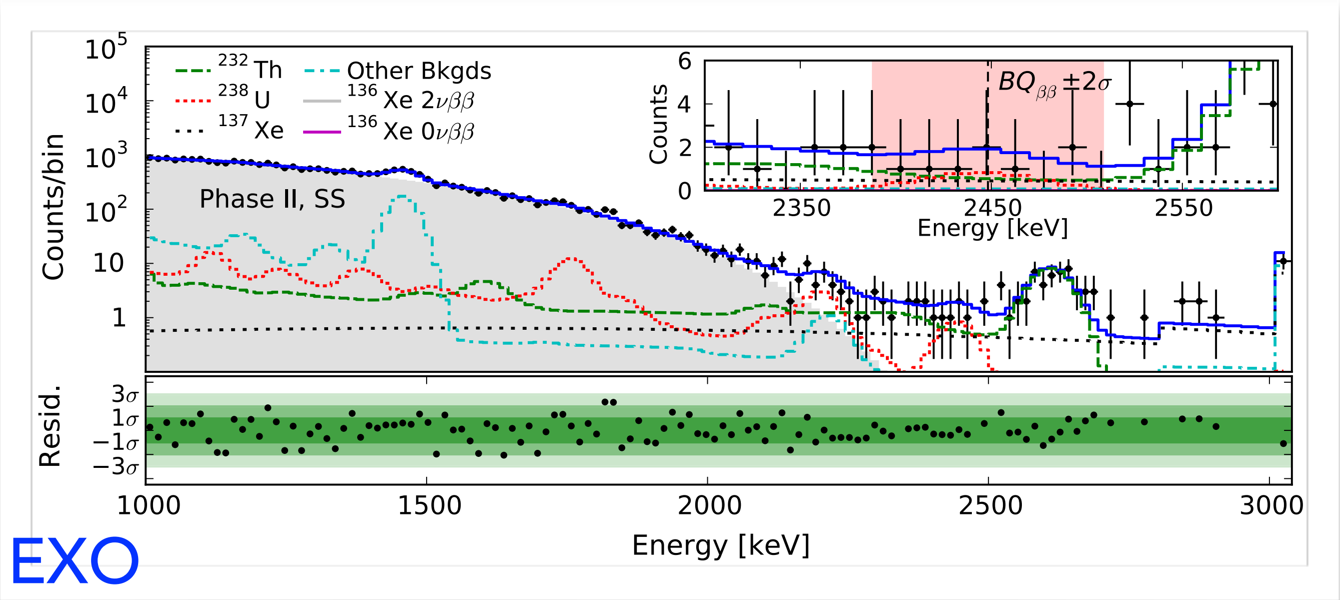
In THIS case
GERDA Phase 2
has already left the
"zero bkg regime"

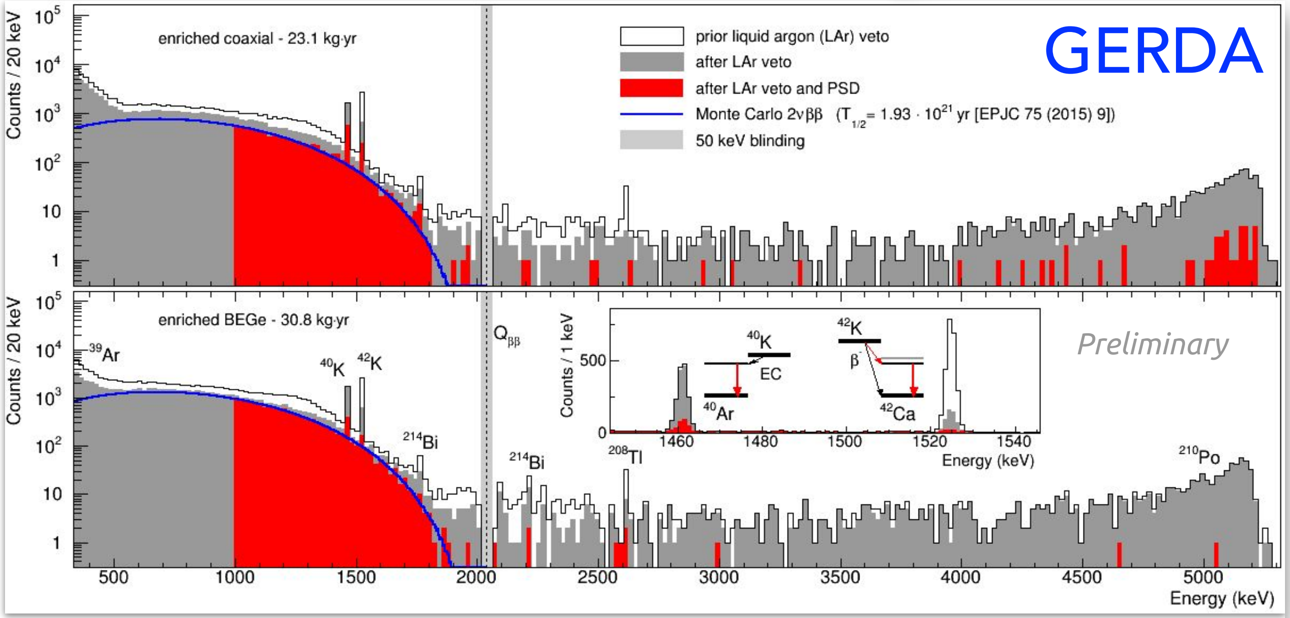
LEGEND bkg goal:
BI = 0.1 cts/(FWHM t y)
to ALMOST cover
the IO m_{bb} range in 10 t y

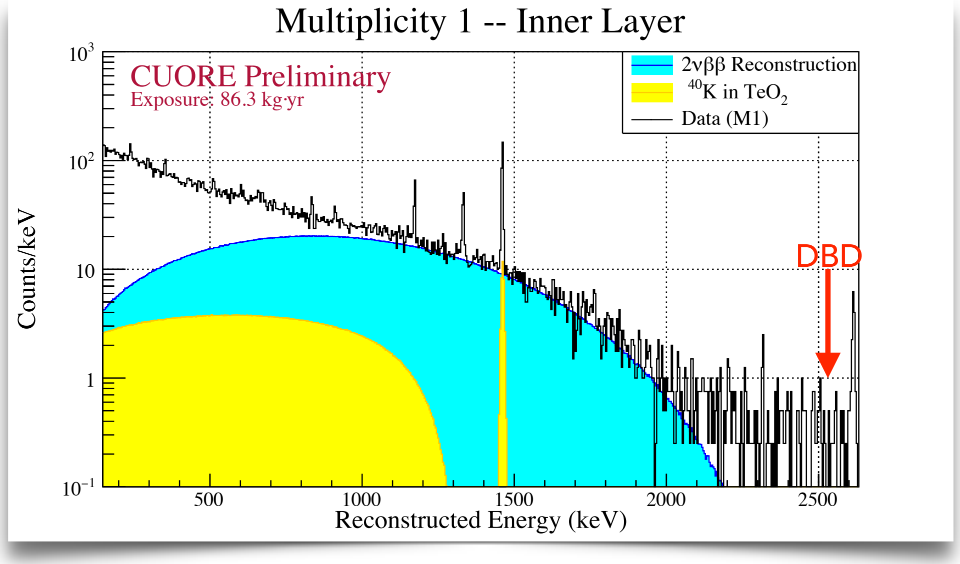
2νββ: a (searched) signal, a MC test, a (major?) bkg

From Nu2018









Choice of the isotope

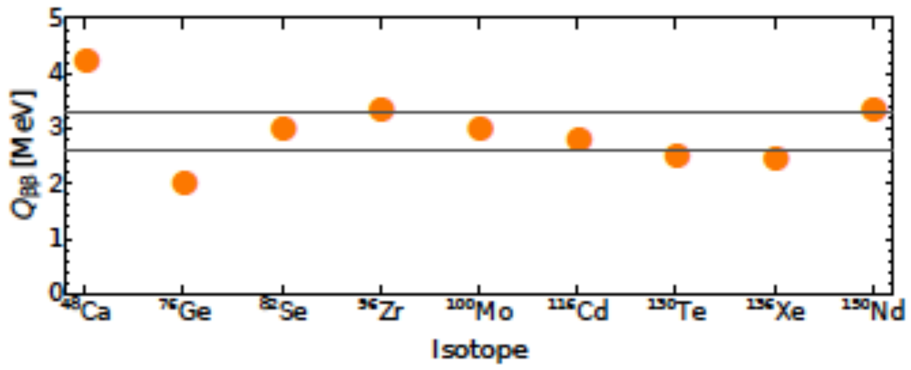
- $Q_{\beta\beta} \rightarrow$ influences the bkg
  - ☐ 2.6 (3.3) MeV end-point of main γs (βs)
  - ☐ avoid radioactivity peak position

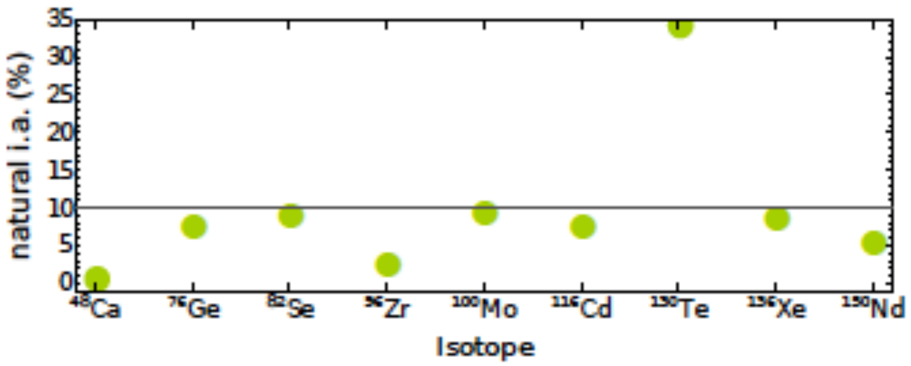
    obs. suitability depends on detector features
- high isotopic abundance
  - ☐ ease of material enrichment

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

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

Most suitable **isotope + detector** combination





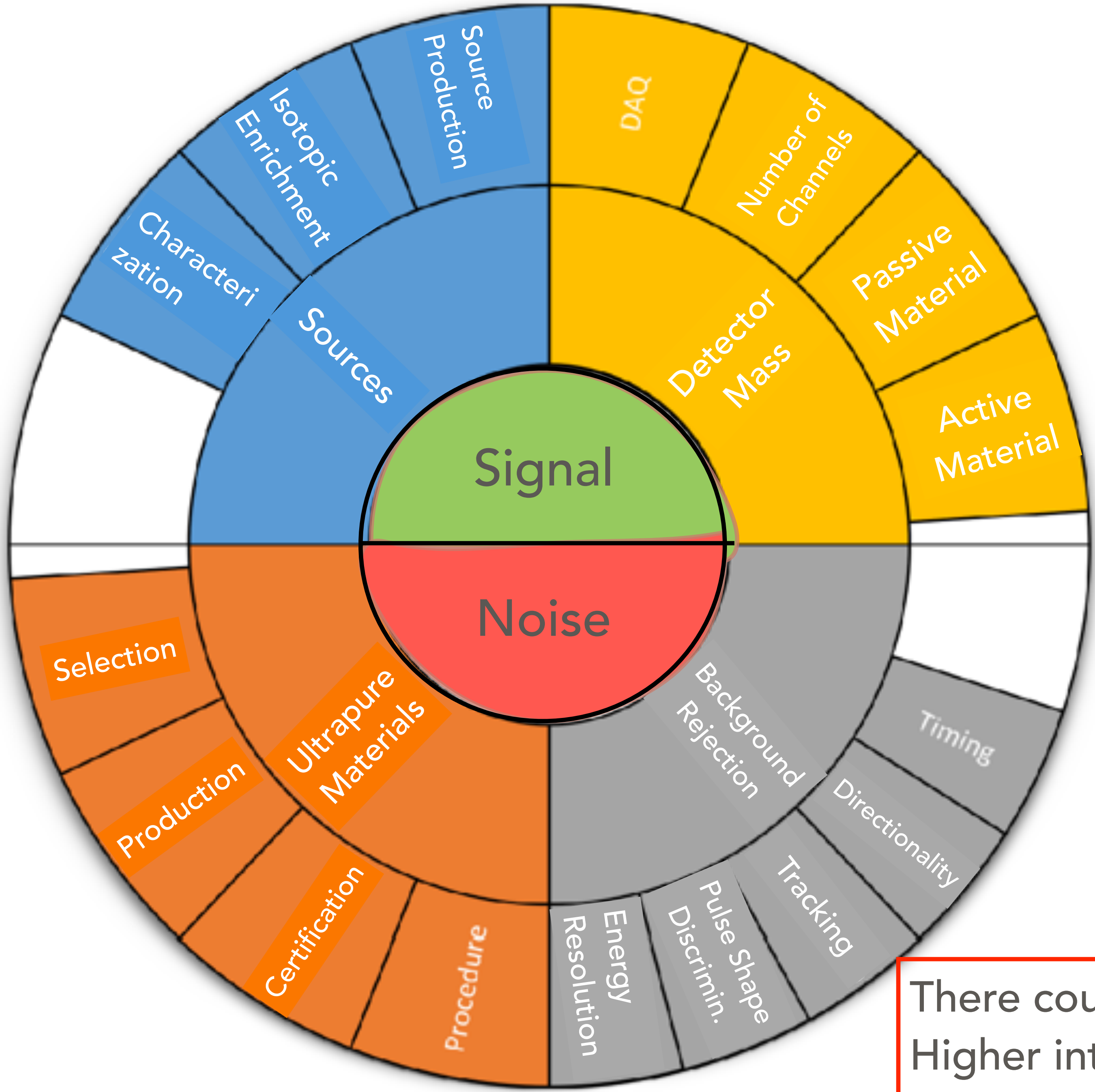
Promising isotopes

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

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

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

Technological Requirements



All detector parameters have to be more and more optimised

Increase of:

- Complexity
- Costs
- Development time

Many aspects are in common to different experimental searches

There could (should?) be common developments
Higher integration among different communities
Identification of common strategies

An example: ultrapure materials

What has been learned in a field/experiment is utilized in other applications

Scintillator: From BOREXINO to JUNO

^{40}K	$<10^{-16}$ g/g (10^{-8} Bq/kg)
^{232}Th	$<10^{-15}$ g/g ($4\ 10^{-9}$ Bq/kg)
^{238}U	$<10^{-15}$ g/g (10^{-8} Bq/kg)

Cu: from HD-M to GERDA and CUORE

^{40}K	$<10^{-12}$ g/g (10^{-4} Bq/kg)
^{232}Th	$<10^{-13}$ g/g ($4\ 10^{-7}$ Bq/kg)
^{238}U	$<10^{-13}$ g/g (10^{-6} Bq/kg)

and more: KamLAND --> KamLAND-Zen SNO --> SNO+ …

Production but also certification are important

ICP-MS
HPGe gamma spectr.
radio-chemestry
…

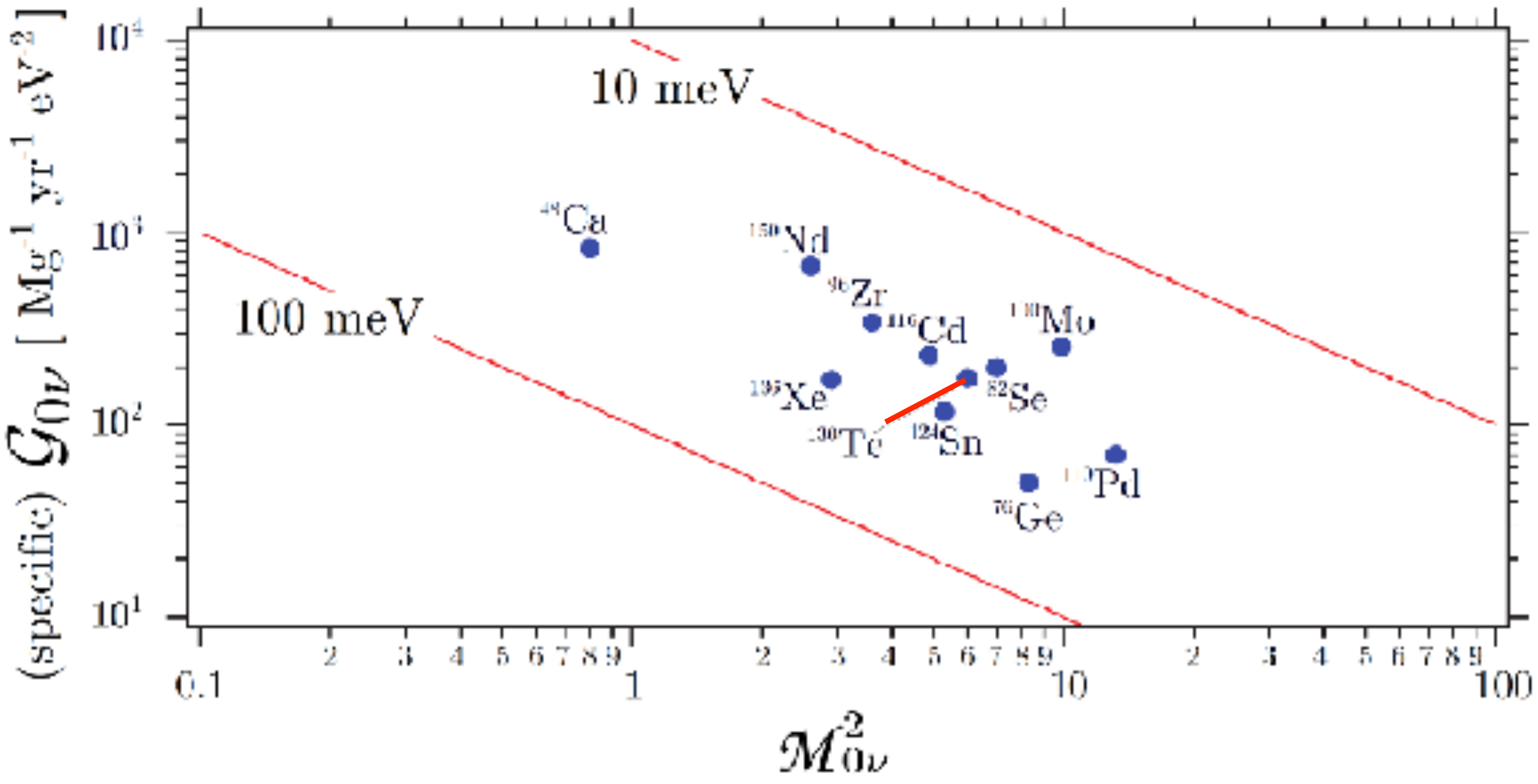
In the future the today-det. will be the screening instrument for the future exp.

Choice of the isotope: theoretical side

In principle, isotopes with the best Nuclear Factor of Merit $(G_{0\nu} \cdot |M_{0\nu}|^2)$ should be favoured

A surprising inverse correlation has been observed between (specific) phase space and the square of the nuclear matrix element.

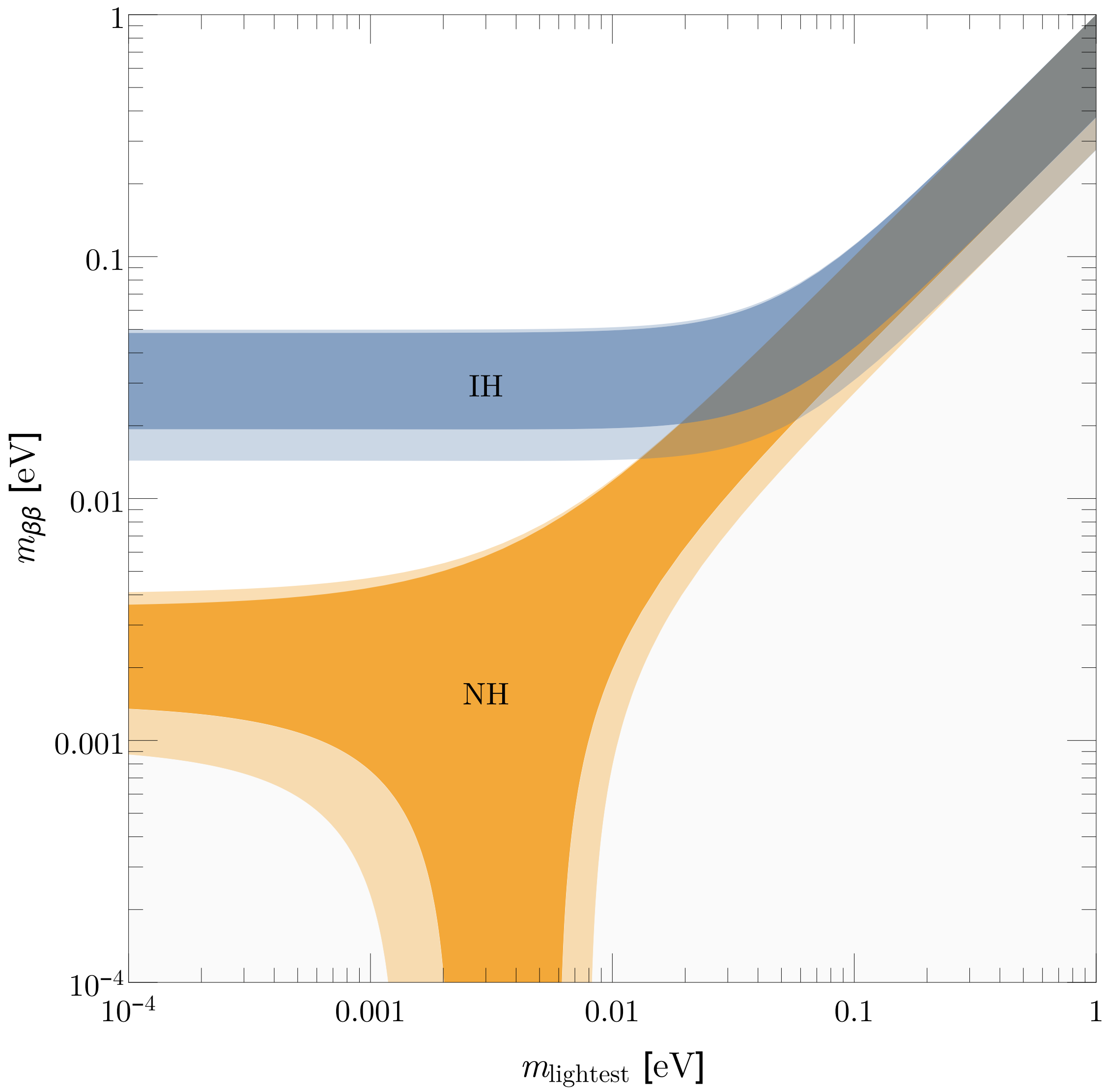
R. Robertson, Mod. Phys. Lett. A, Vol. 28, No. 8 (2013) 1350021



No preferred isotope ... within a factor 2-3

Constraints from oscillations: $m_{\beta\beta}$ vs m_{lightest}

Since $\left(t_{1/2}^{0\nu}\right)^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot \left|\frac{m_{\beta\beta}}{m_e}\right|^2$ you can put constraints on the half-life trough constraints on $m_{\beta\beta}$



- it is possible to put a first series of constraints on $m_{\beta\beta}$
  - $m_{\beta\beta}^{\max} = \sum_{i=1}^{3} |U_{ei}^2| m_i$
  - $m_{\beta\beta}^{\min} = \max\left\{2|U_{ei}^2| m_i - m_{\beta\beta}^{\max}, 0\right\}$

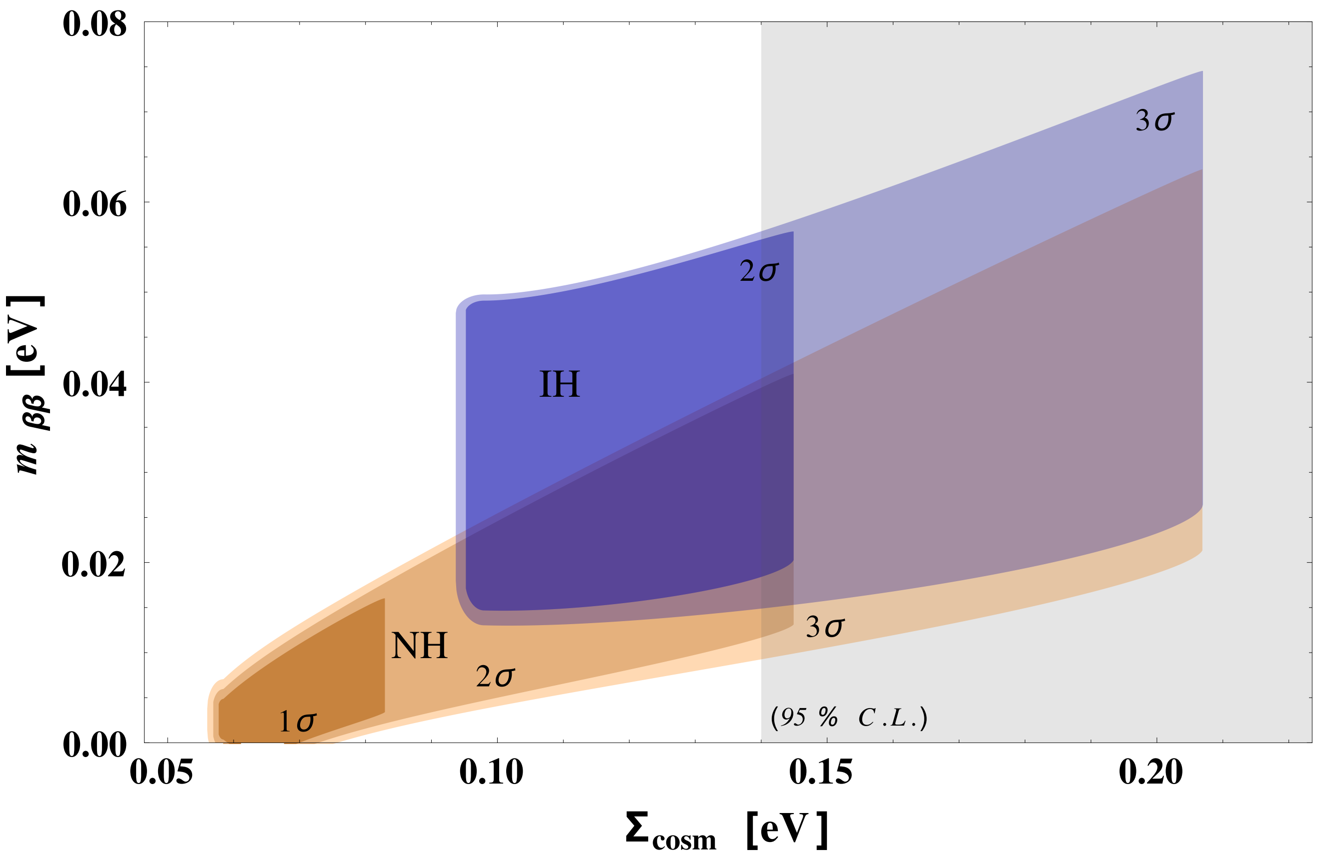
    $i - 1, 2, 3$
- $\xi_{1,2}$ are left free

Constraints from cosmology: $m_{\beta\beta}$ vs Σ

- **Σ** < 140 meV (95% C.L.) by combining:

Lyα-forest from BOSS + CMB data from Planck + BAO data from BOSS
(limits within the ΛCDM model)

S. Dell'Oro, S.Marcocci, M. Viel, F. Vissani, J. Cosm. Astropart. Phys. 1512, 023 (2015)



Σ < 84 meV (1σ C.L.)

Σ < 146 meV (2σ C.L.)

Σ < 208 meV (3σ C.L.)

From oscillation data:
Σ min ~ 60 meV (NO)

~ 100 meV (IO)

At the 1**σ** level, the IO is excluded, as (recently) claimed also from oscillations

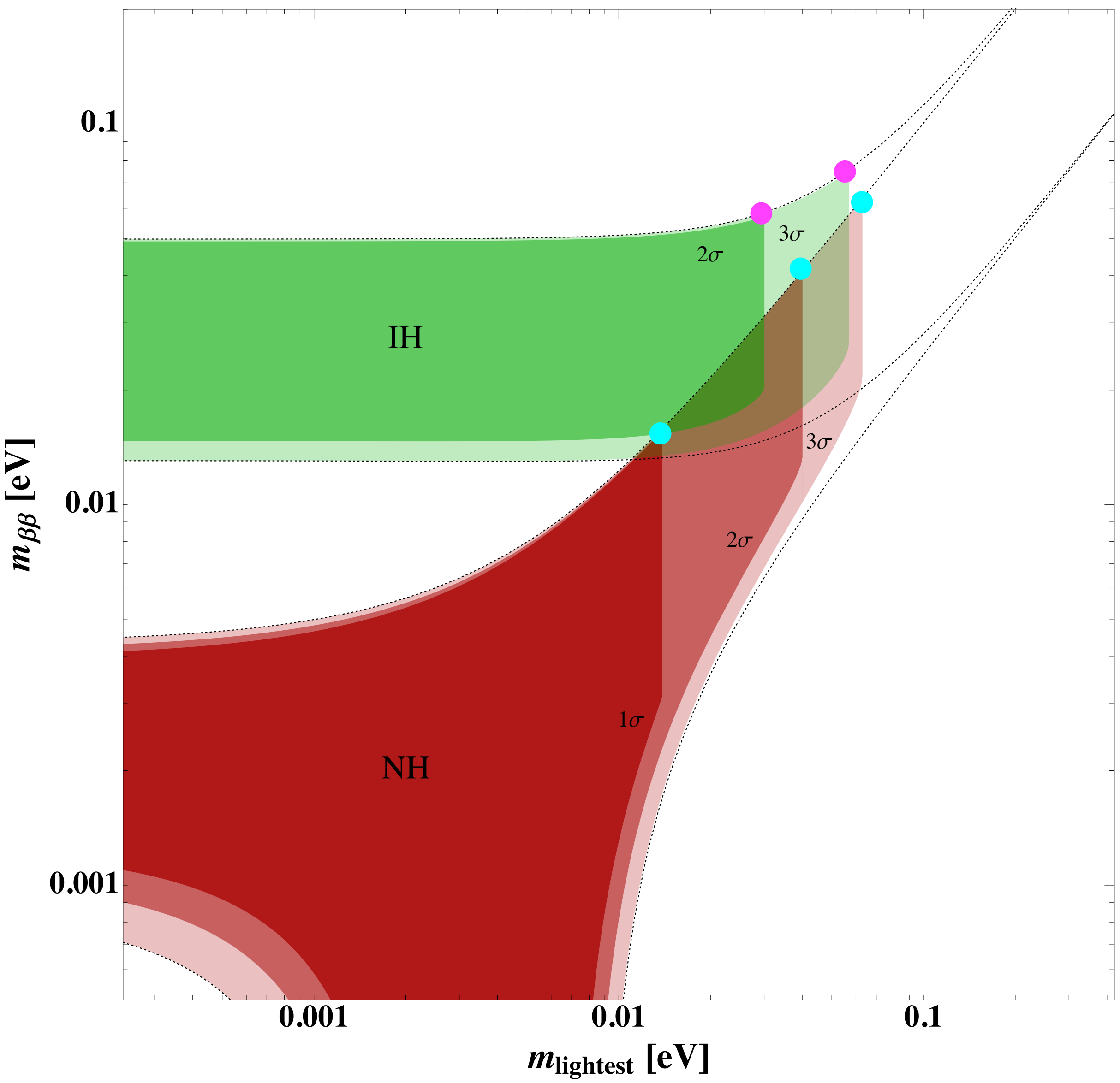
Implications for the $0\nu\beta\beta$ search

Depending on the ordering and on the C.L. we want to consider, $m_{\beta\beta}$ can at most have the following values:

Mass spectrum	Max $m_{\beta\beta}$ [meV] (C.L. on Σ)		
	1σ	2σ	3σ
NO	16	41	64
IO	-	57	75

Except for the 1σ C.L. they are still at the level reachable by the present experiments

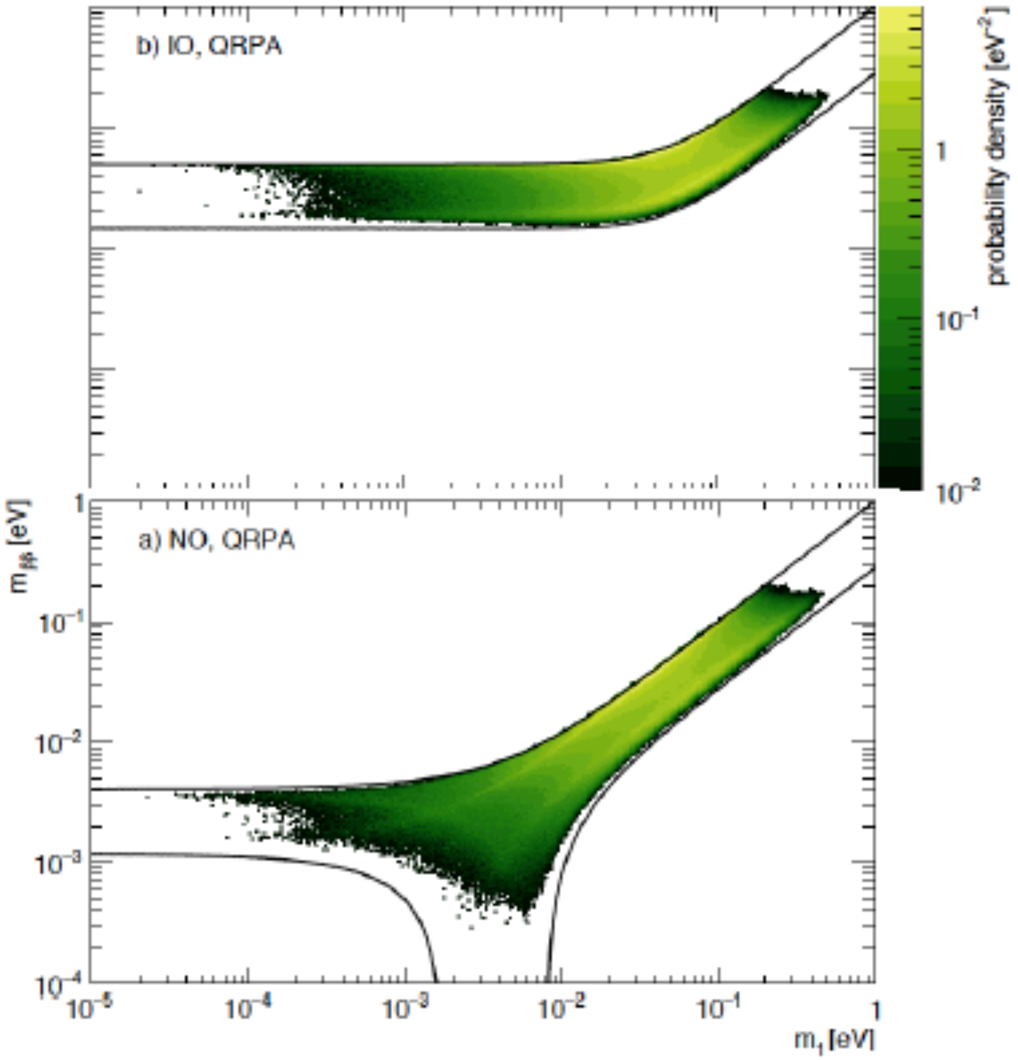
S. Dell'Oro, S.Marcocci, M. Viel, F. Vissani, J. Cosm. Astropart. Phys. 1512, 023 (2015)



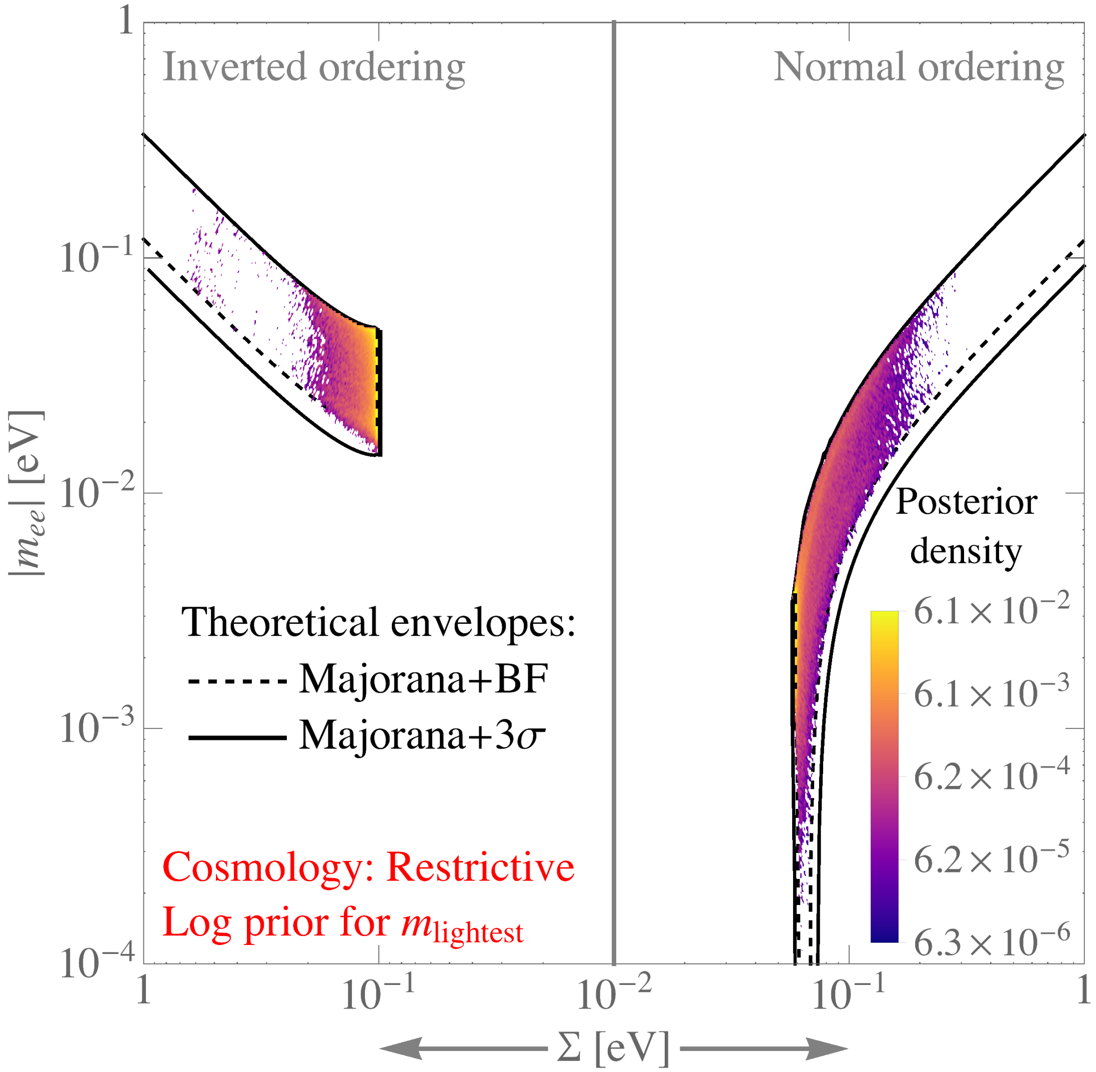
Discovery probabilities: a shot in the arm?

- Global Bayesian analysis including ν-oscillation, m_β $m_{\beta\beta}$, Σ
- Priors:
  - Majorana phases (flat)
  - m_1 (scale invariant)

2 different approaches: lin prior or log prior



M. Agostini, G. Benato and J. A. Detwiler, Phys. Rev. D96 (2017) 053001



Cosmology: Restrictive
Log prior for m_{lightest}

A. Caldwell et al., Phys. Rev. D **96**, 073001

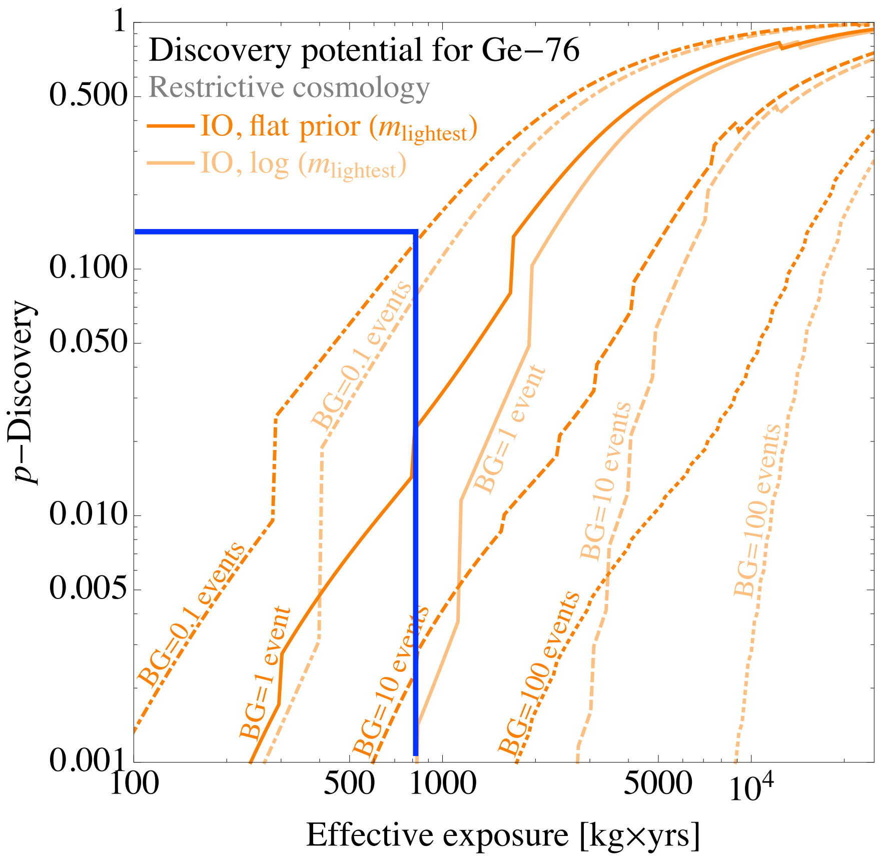
Discovery probabilities: controversial, but still interesting

Apart presenting data in a different way,
the 2 groups reach quite different results

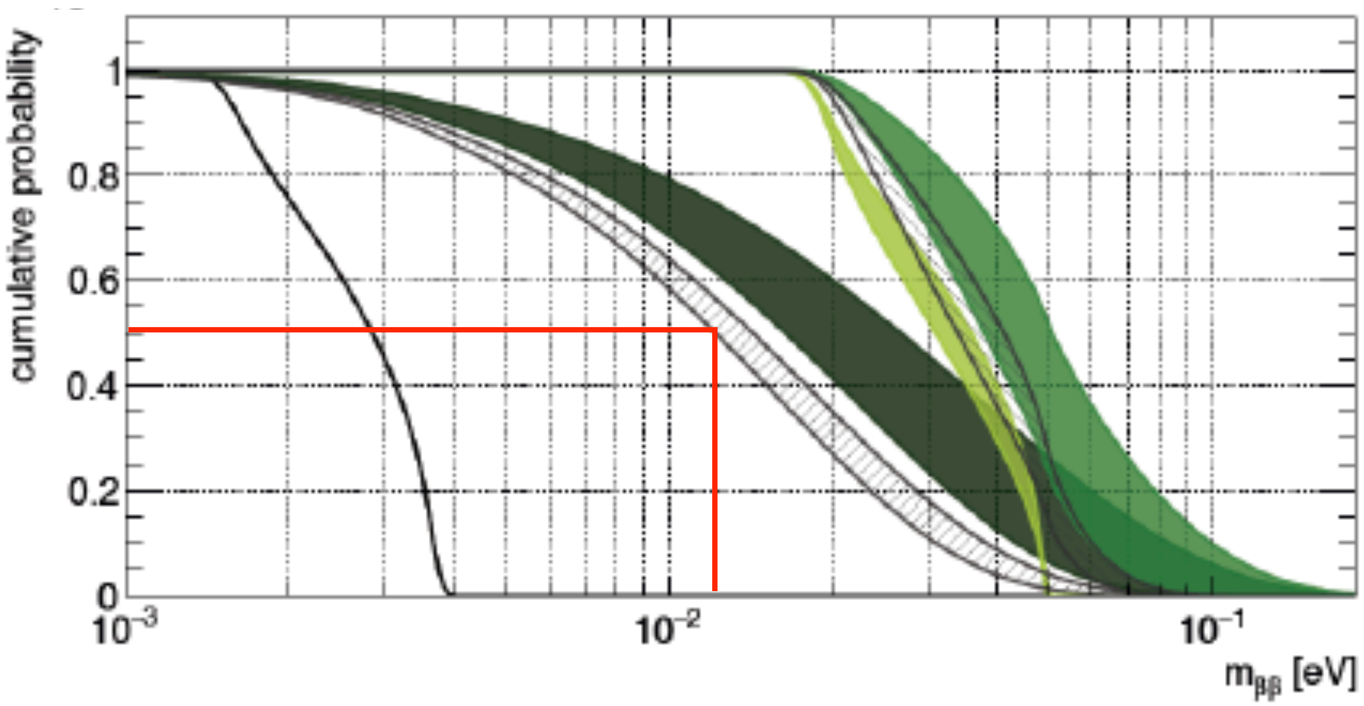
Is it a mere philosophical problem?

Will we have in a short time a hint on
how to disentangle the issue?

A. Caldwell et al., Phys. Rev. D **96**, 073001



M. Agostini, G. Benato and J. A. Detwiler, Phys. Rev. D96 (2017) 053001



A big Challenge for 0νββ Discovery

- a convenient parametric description of the NME can be:

$$\mathcal{M} \equiv g_A^2 \mathcal{M}_{0\nu} = g_A^2 \left(\mathcal{M}_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A} \right)^2 \mathcal{M}_F^{(0\nu)} + \mathcal{M}_T^{(0\nu)} \right)$$

  - $\mathcal{M}_{0\nu}$ depends only mildly on g_A
  - relatively small intrinsic error of ~ 20%

- fix the g_A renormalization to account for the differences between calculations and rates for processes "similar" to 0νββ (β, EC, 2νββ)

- important effect of g_A
  - any uncertainty on its values ⇒ a larger uncertainty factor on $\mathcal{M}$

Size of g_A

- $g_A \simeq 1.27$ in weak interactions and decays of nucleons (measured)
- *renormalization* in nuclear medium, value appropriate for quarks
- *strong quenching*: $g_A < 1$
  - limited model space of the calculation
  - contribution of non-nucleonic degrees of freedom
  - renormalization of the GT operator due to two-body currents
- still unknown if the quenching in $0\nu\beta\beta$ and $2\nu\beta\beta$ is the same

$$g_A^{\text{quark}} = 1$$
$$g_A^{\text{nucleon}} = 1.27$$
$$g_A^{2\nu\beta\beta} = 1.27 \cdot A^{-0.18}$$
$$g_A^{0\nu\beta\beta} = \ ??$$

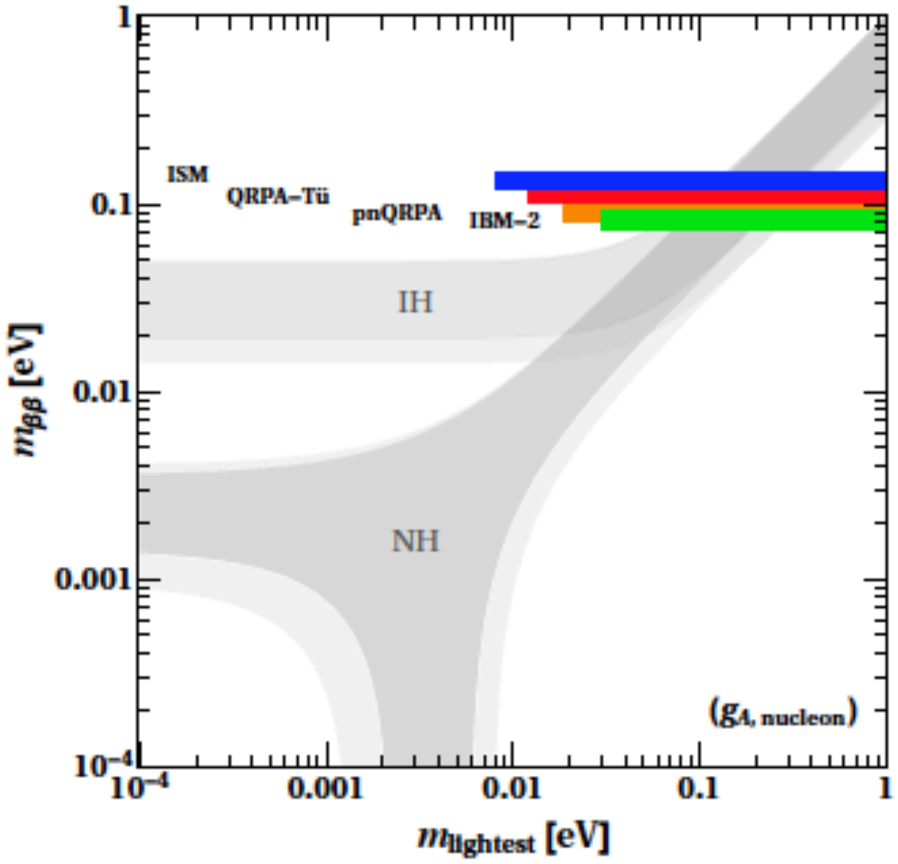
BUT WHY SHOULD IT BE THE SAME?

0νββ decay is a high-momentum transfer process
(q ~ 100 MeV)⇒ less quenching

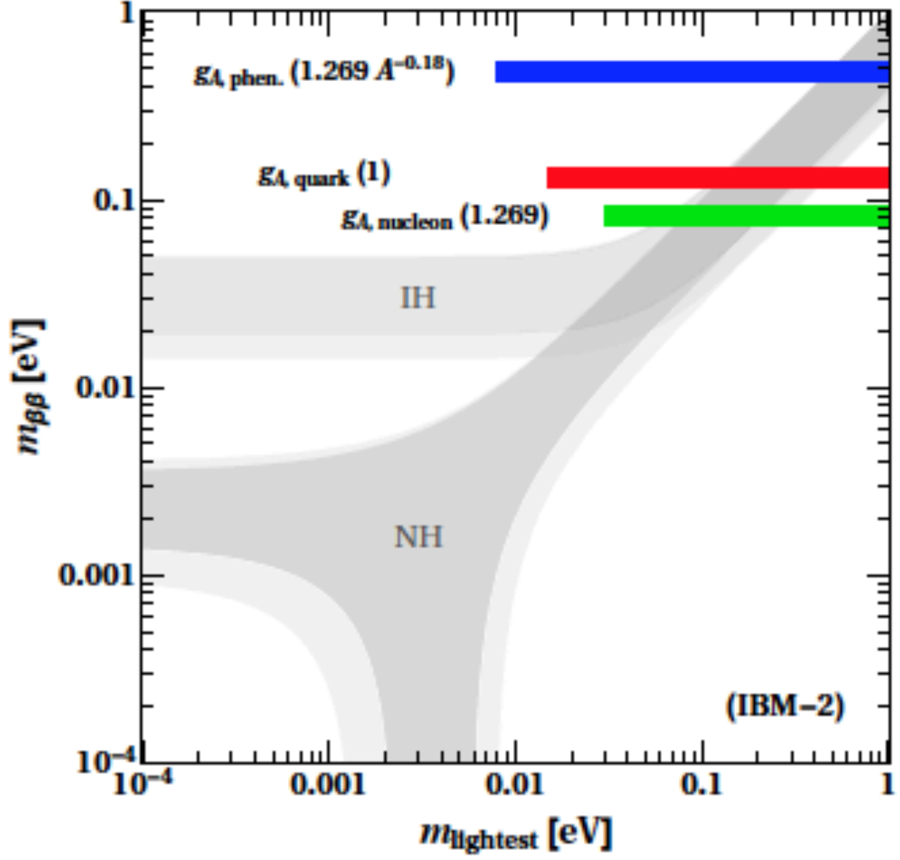
(J. Menéndez, D. Gazit, A. Schwenk, PRL 107 (2011) 062501

Effect of the nuclear uncertainties: Xe case

- different NMEs / fixed g_A
  - $74\,\text{meV} < m_{\beta\beta} < 149\,\text{meV}$
- different g_A / fixed NMEs
  - $74\,\text{meV} < m_{\beta\beta} < (149)\,542\,\text{meV}$



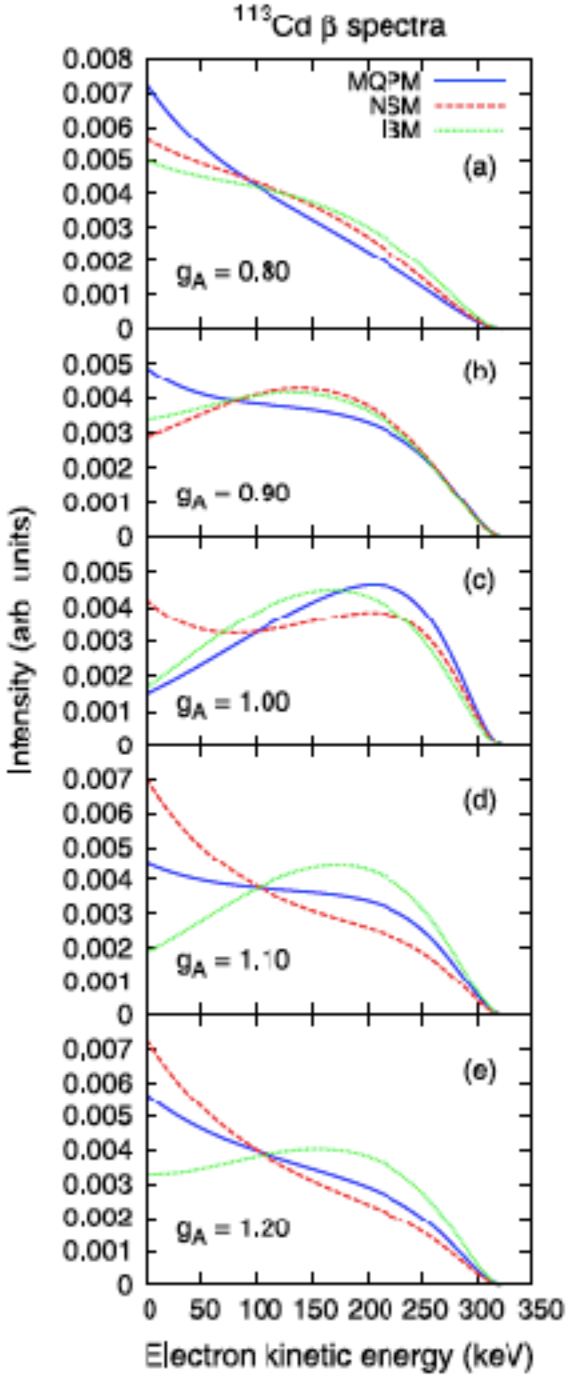
Courtesy of S. Dell'Oro



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

the main uncertainty consists in the determination of the *true value* of g_A

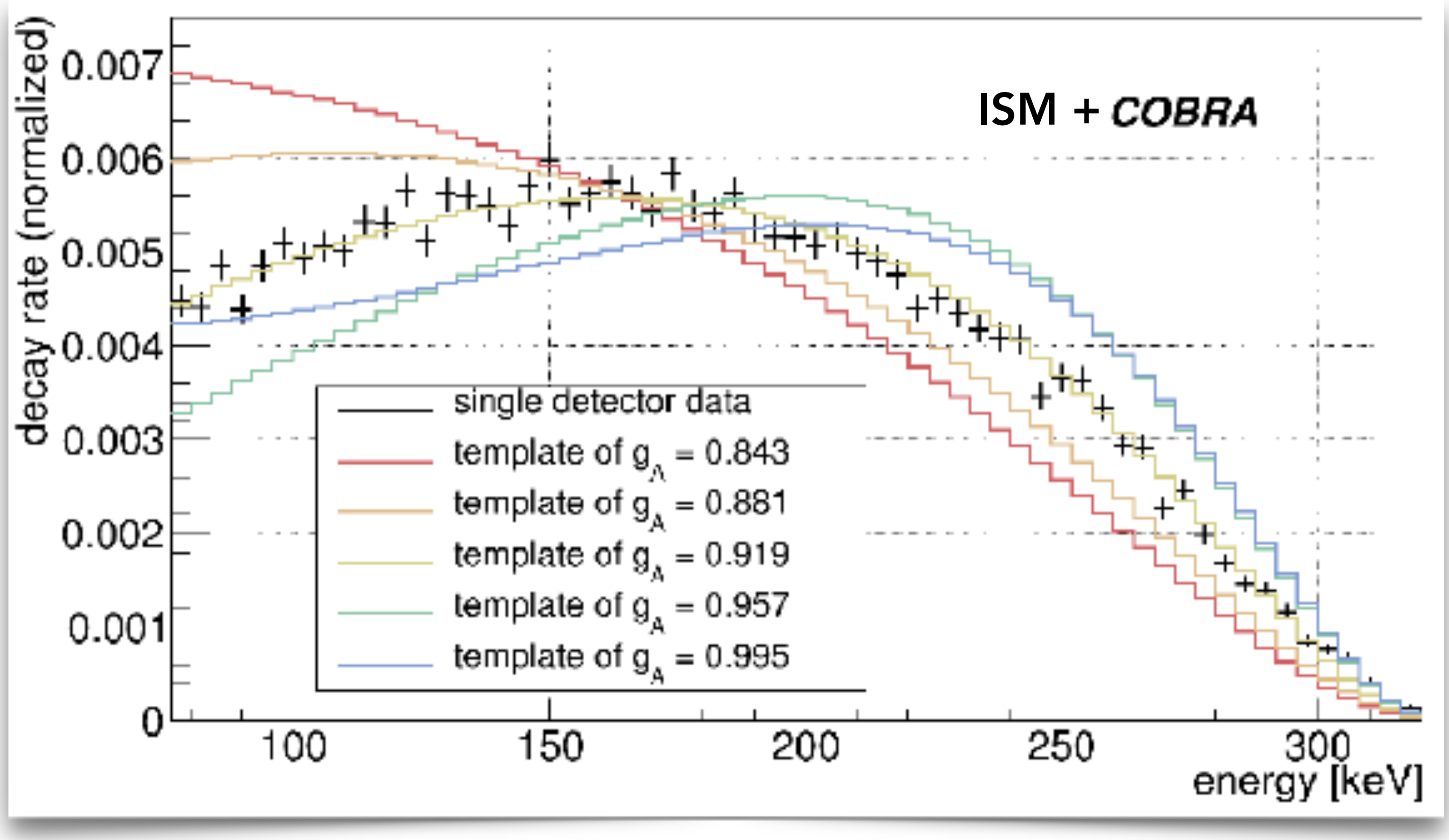
How can the experimentalists help?



Suhonen: extract g_A for forbidden **β** decays looking at the shape spectra

$$\bar{g}_A(\text{ISM}) = 0.915 \pm 0.021,$$
$$g_A(\text{MQPM}) = 0.911 \pm 0.009,$$
$$g_A(\text{IBFM-2}) = 0.943 \pm 0.090.$$

arXiv:1806.02254v1

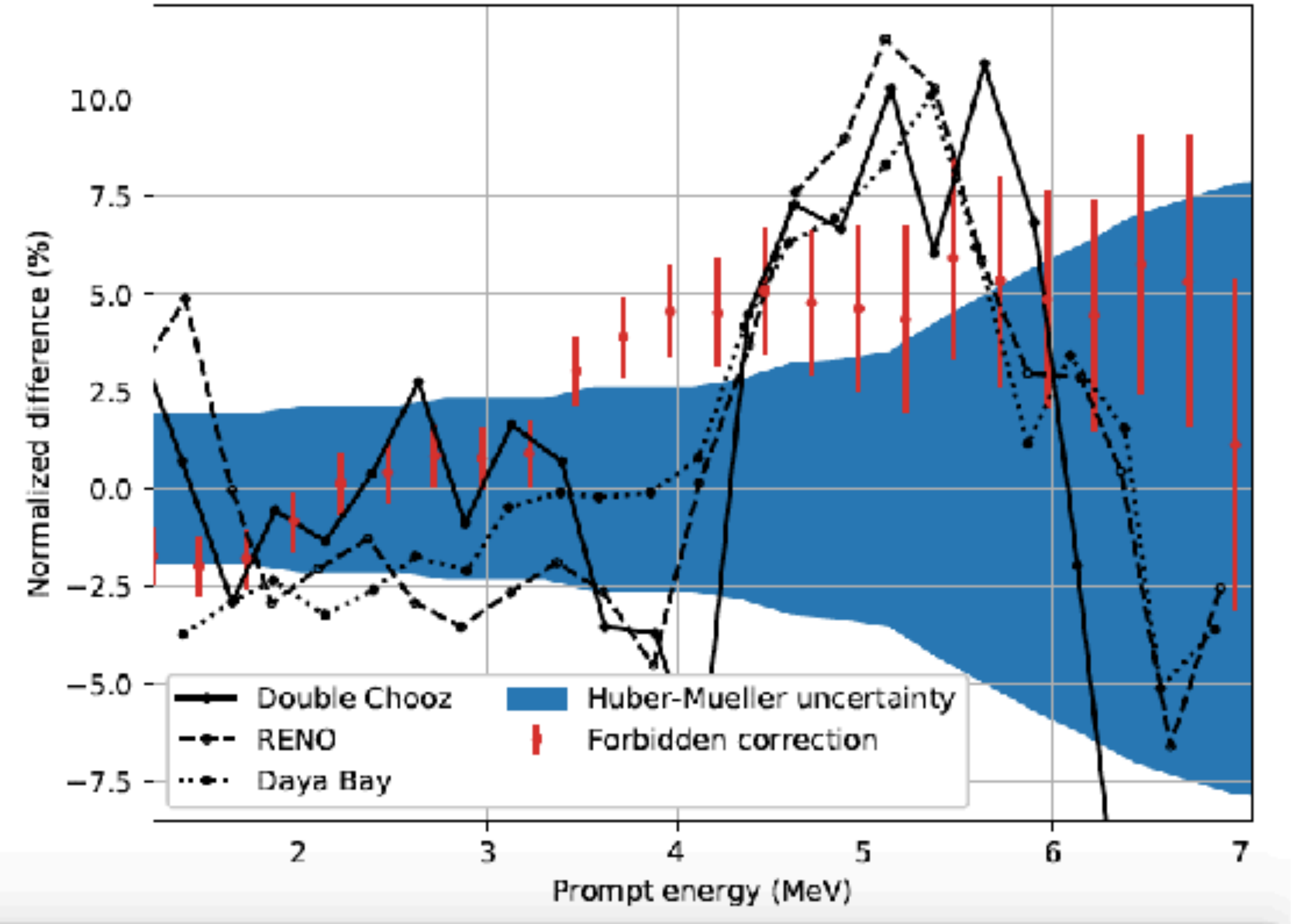


More shape spectra to be measured to extract a "general law"

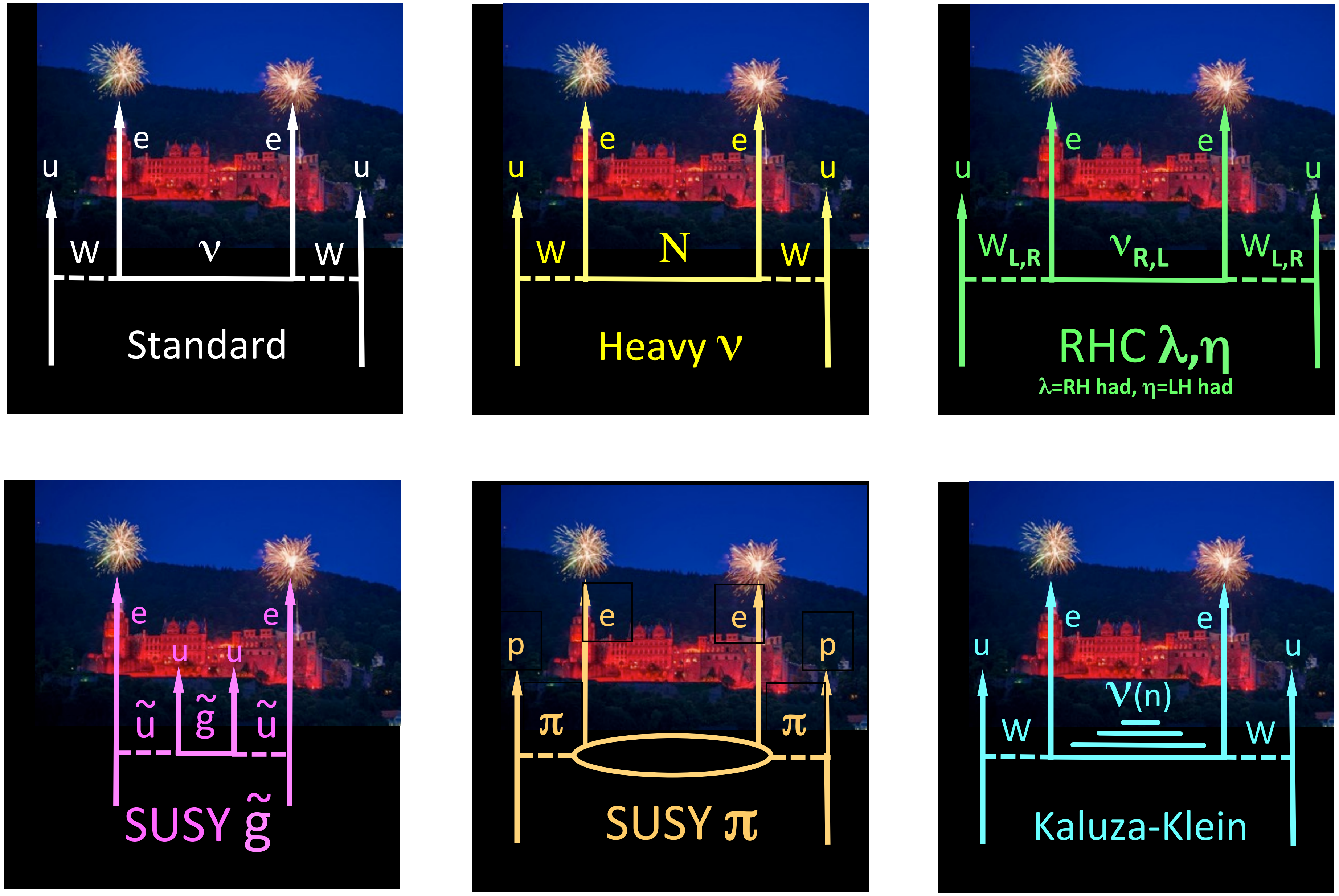
Will not give the quenching of g_A for $0\nu\beta\beta$, but…

A by-product from forbidden β decays studies for g_A

Studying the forbidden unique and non unique β decays is extremely important also for the Reactor Anomaly



Warning: **don't stick to $m_{\beta\beta}$ metric, just go on with $T_{1/2}$!** Variety of 0νββ mechanisms:

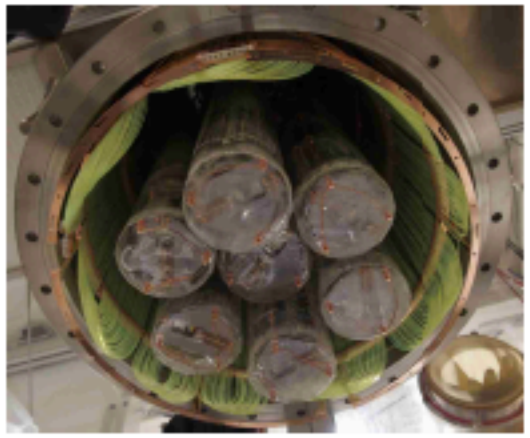


0νββ from any mechanism → **Majorana nature of ν would be established anyway**

From: E.Lisi, Nu2018

BACKUP SLIDES

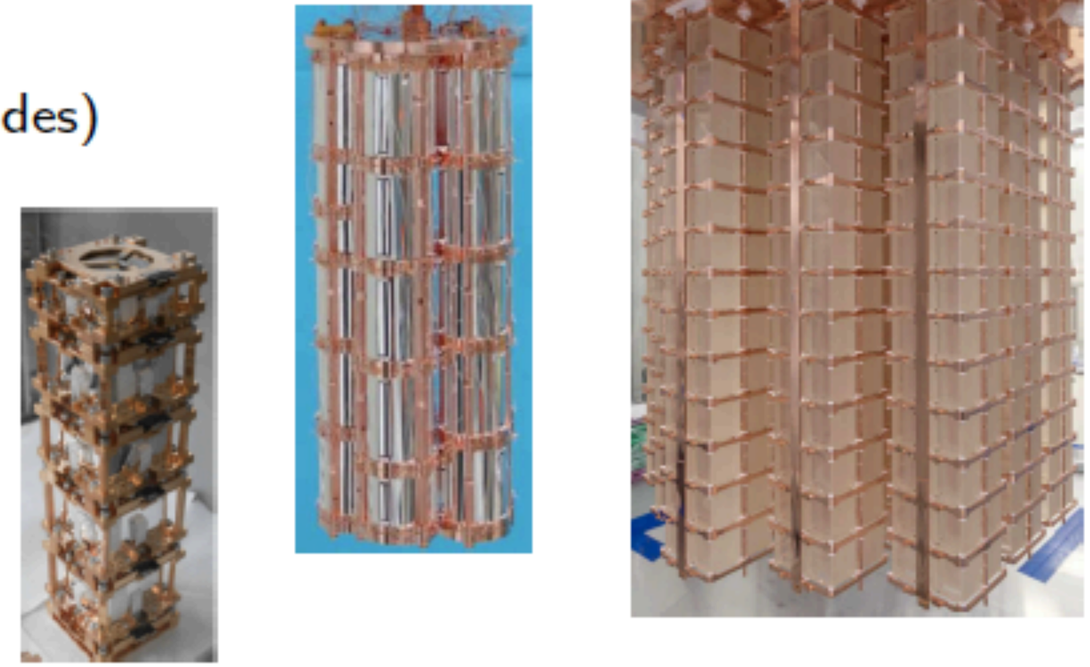
Experimental techniques (I)




- 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



- bolometers
  - ☐ high energy resolution (close to Ge-diodes)
  - ☐ many compounds with 0νββ emitters
  - ☐ large source masses
  - ☐ complex cryogenic infrastructure

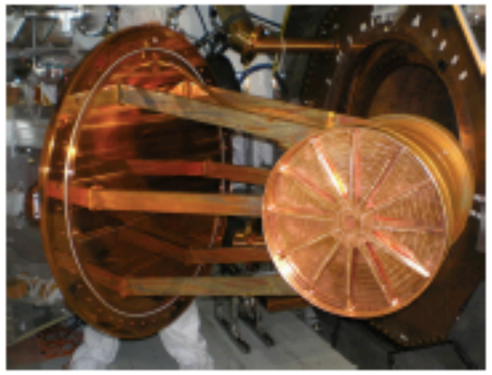
Cuoricino CUORE-0

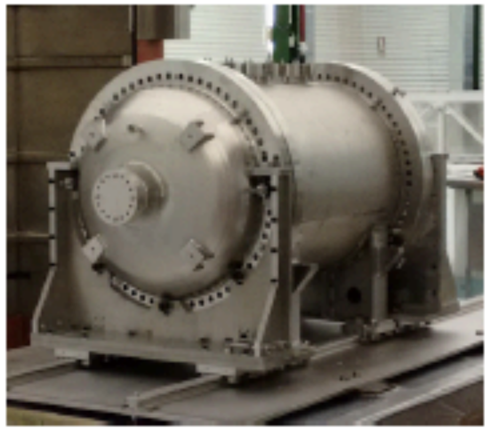
AMoRE CUPID-0 CUORE

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 ($\sim 30\%$)

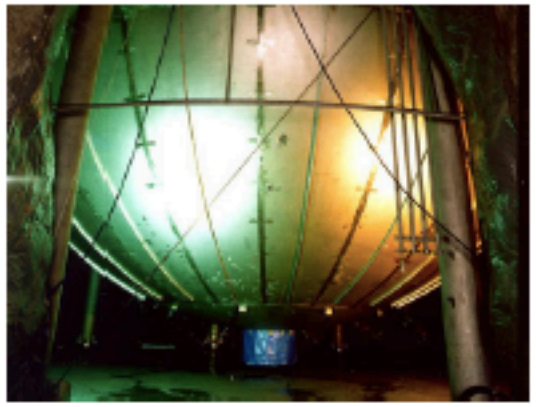
EXO-200 NEXT



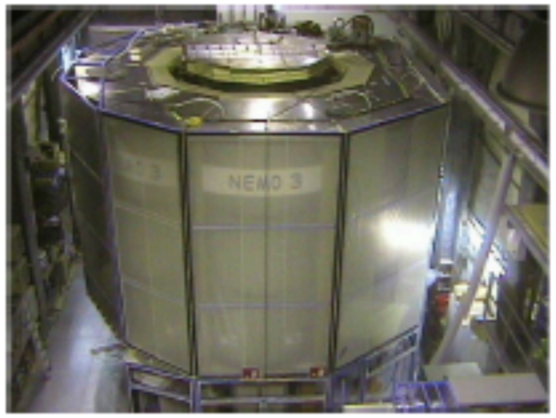


- liquid scintillators loaded with $0\nu\beta\beta$ isotope
  - poor energy resolution ($\sim 10\%$)
  - huge amount of material
  - very low background

KamLAND-Zen SNO+

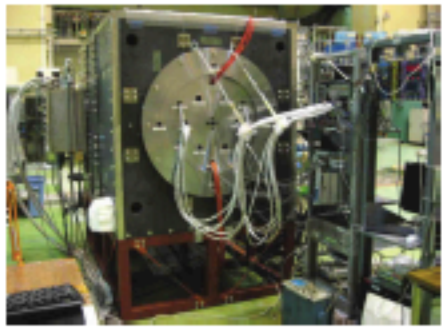


Experimental techniques (III)



- 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



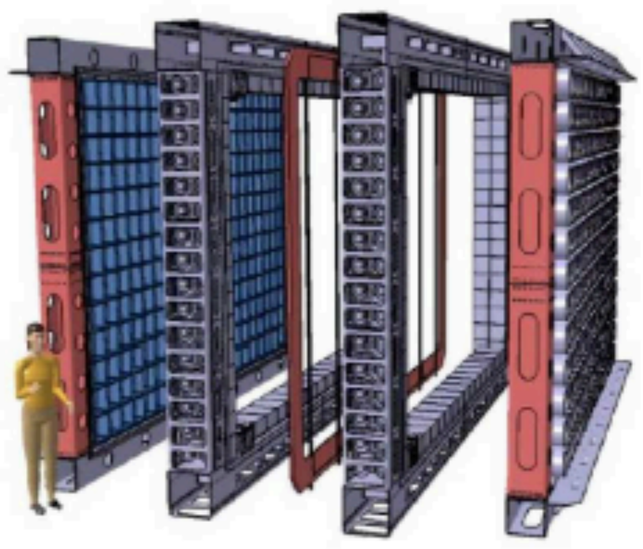
- others
  - ☐ variations on the previous, or new techniques
  - ☐ numerous running prototypes and R&D projects

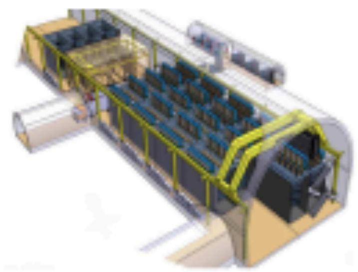
CANDLES COBRA ZICOS

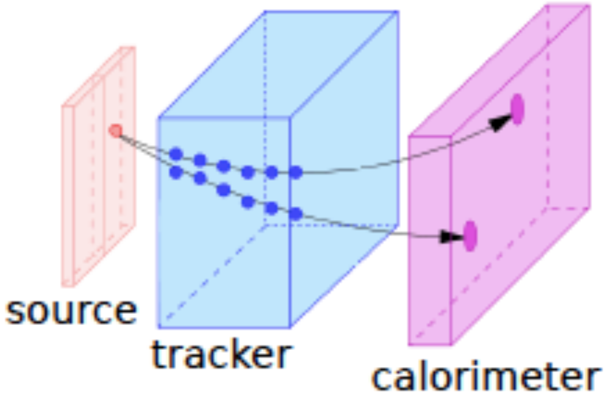
DCBA/MTD FLARES . . .

Future players: SuperNEMO

- SuperNEMO
  - ☐ tracker + calorimeter with 100 kg of ^{82}Se ββ source
  - ☐ background in ROI: 5 c keV^{-1} t^{-1} yr^{-1}
  - ☐ energy resolution: 120 keV FWHM @ $Q_{\beta\beta}$
  - ☐ sensitivity goal on 0νββ half-life: 10^{26} yr
- from the experience of NEMO-3
  - ☐ improved detector design + modularity
  - ☐ increased detector radio-putity
  - ☐ increased source radio-purity





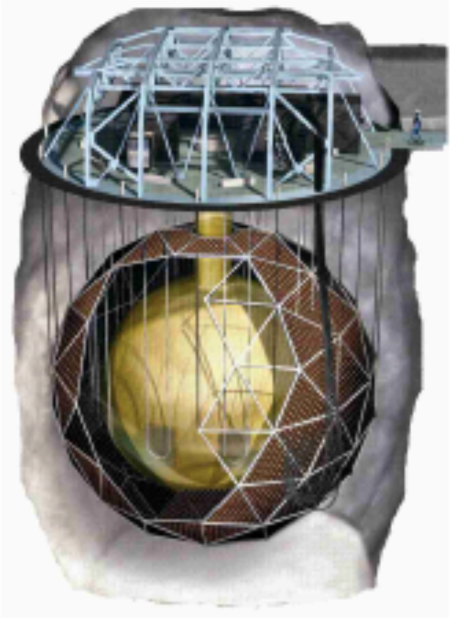


superNEMO demonstrator

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

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 0νββ half-life: $2 \cdot 10^{26}$ yr
- commissioning ongoing
  - ☐ tellurium stored underground
  - ☐ purification system under construction
  - ☐ calibration system ready
  - ☐ loading of LS forthcoming

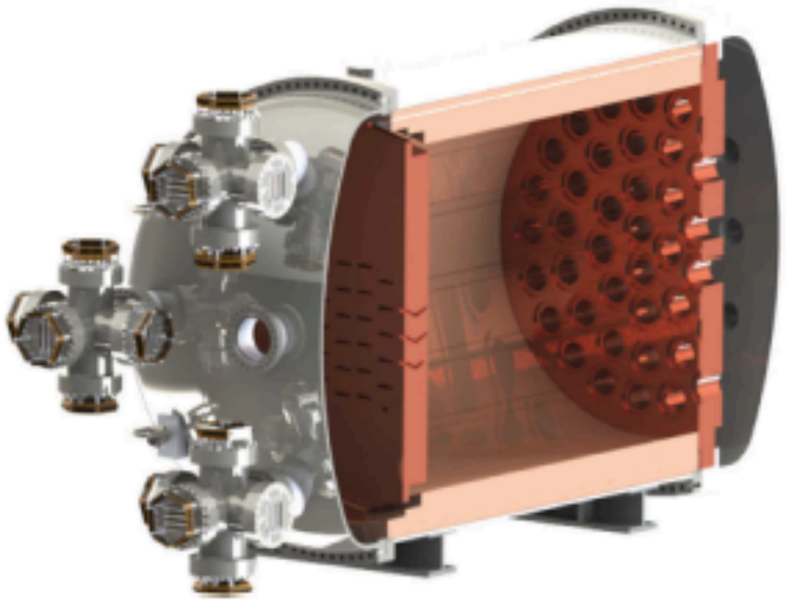


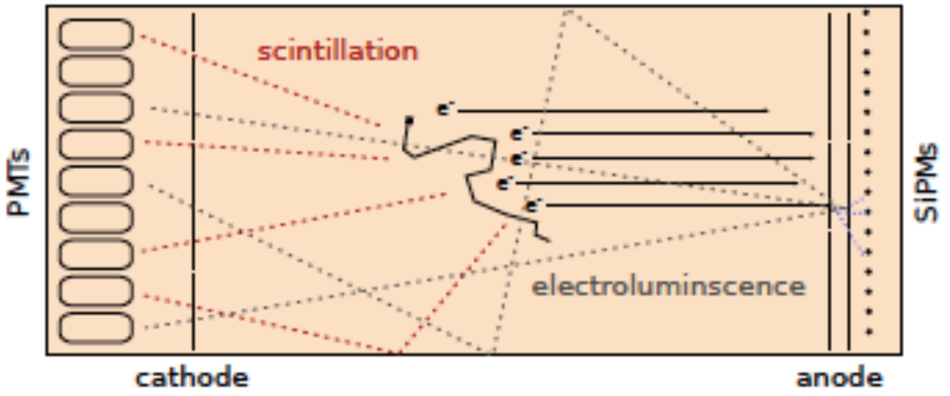
SNO+ 0νββ programme

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

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)

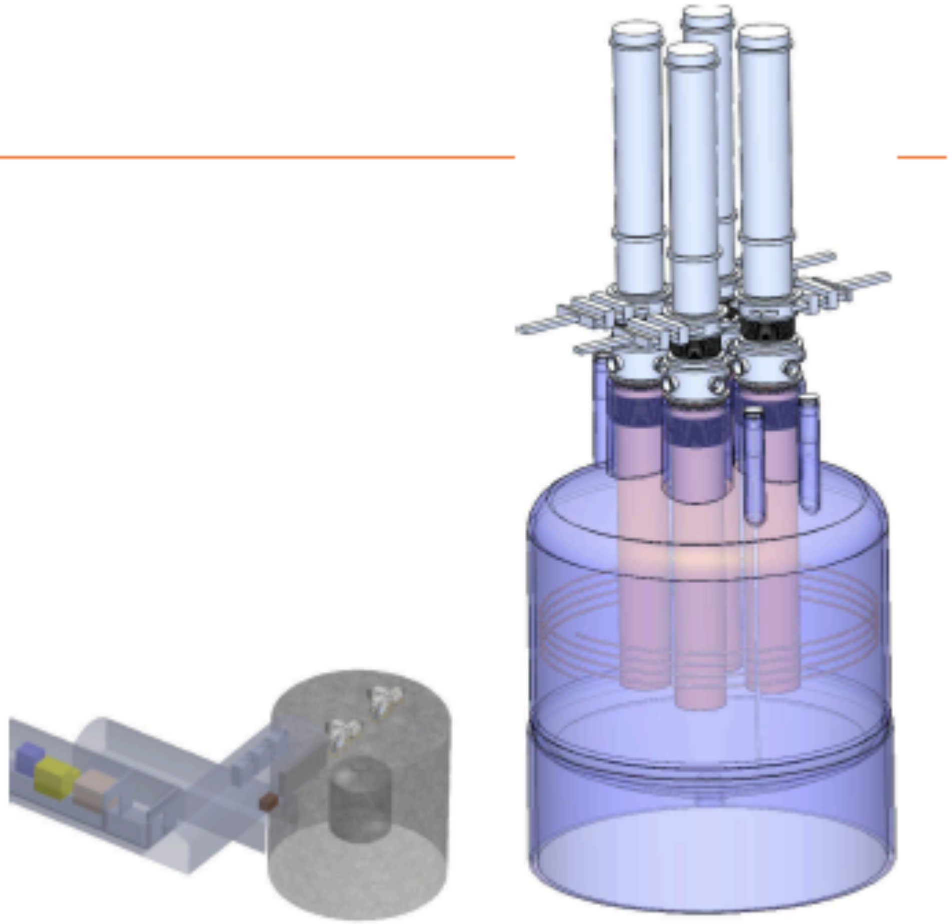




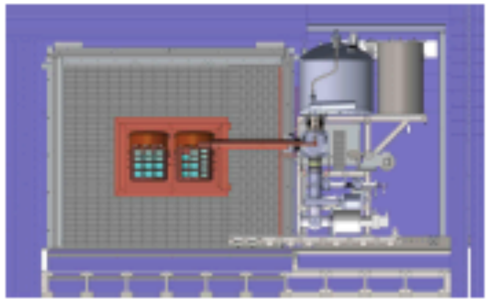
The NEXT program

- 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: LEGEND

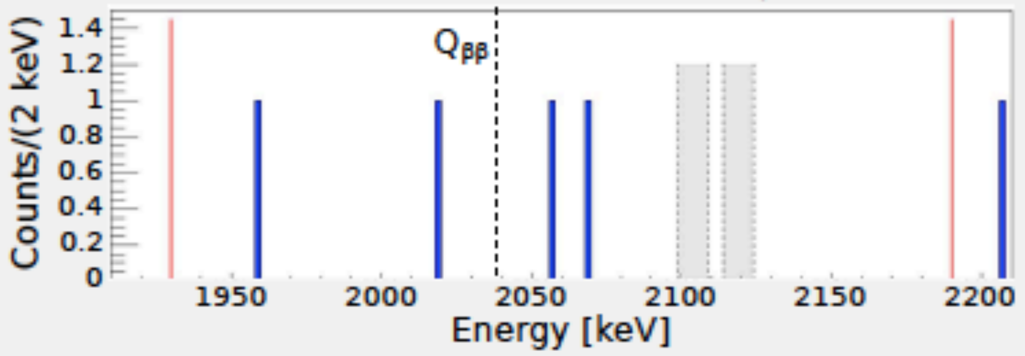


- Large Enriched Germanium Experiment for Neutrinoless ββ Decay
  - ☐ 200 kg → 1 t of ^{76}Ge enriched HPGe-diodes
  - ☐ background in ROI: 0.1 c keV^{-1} t^{-1} yr^{-1}
  - ☐ energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$
  - ☐ sensitivity goal on 0νββ half-life: 10^{28} yr
- best of GERDA & MJD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



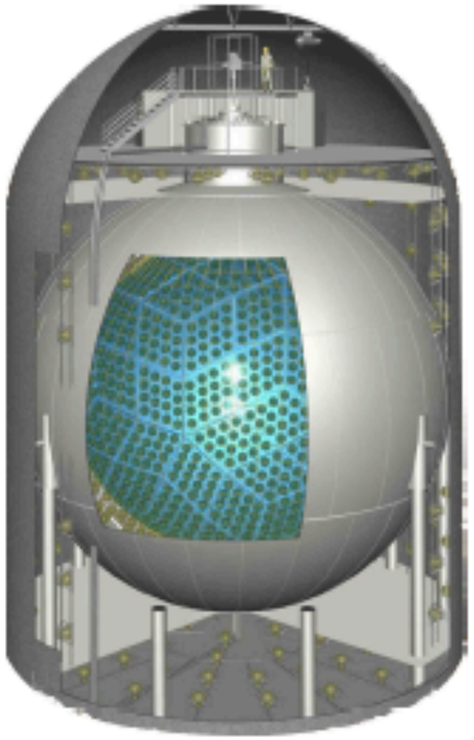
GERDA-II new results (Jul 2017)

L. Pandola, *talk @ TAUP 2017*

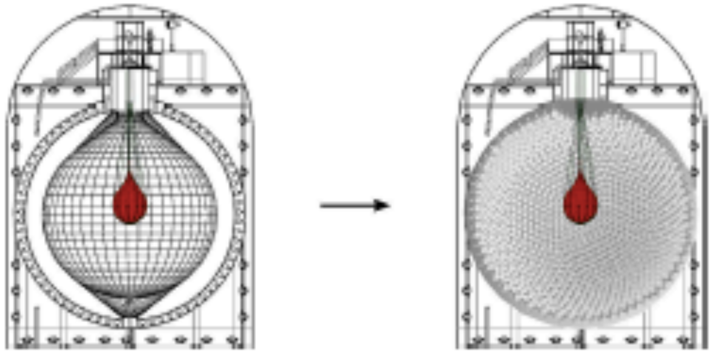


$t^{0\nu}_{1/2} > 8.0 \cdot 10^{25}$ yr @ 90% C. L.

Future players: KamLAND2-Zen



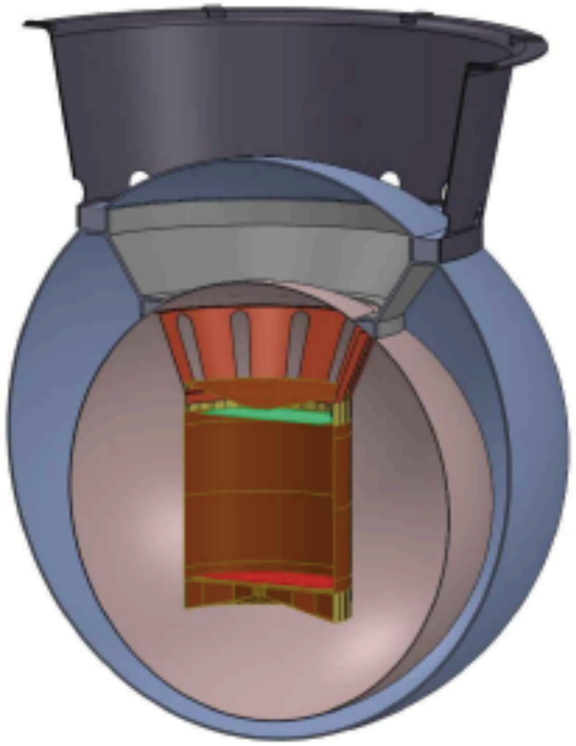
- Kamioka Liquid scintillator Anti-Neutrino Detector 2 - Zero neutrino
  - ☐ 1 t of ^{136}Xe enriched xenon dissolved in LS
  - ☐ background in ROI: 0.01 c keV^{-1} t^{-1} yr^{-1}
  - ☐ energy resolution: 50 keV FWHM @ $Q_{\beta\beta}$
  - ☐ sensitivity goal on 0νββ half-life: 10^{27} yr
- from the experience of KamLAND-Zen
  - ☐ improved light collection (new LS & PMTs + collectors)
  - ☐ scintillating balloon (^{214}Bi tagging)
  - ☐ new method for LS purification
  - ☐ pressurized Xe-LS

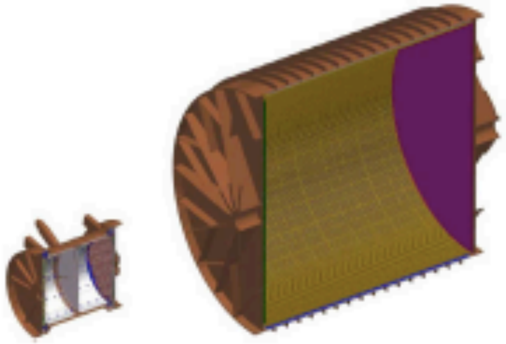


Future players: nEXO

- 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)

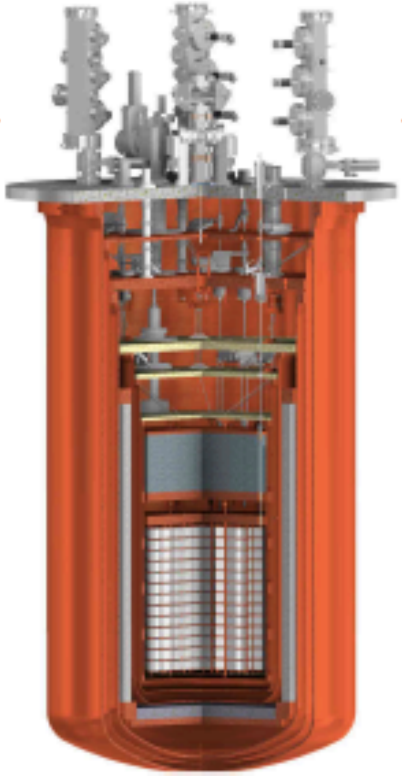




A major challenge: Ba tagging

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

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:

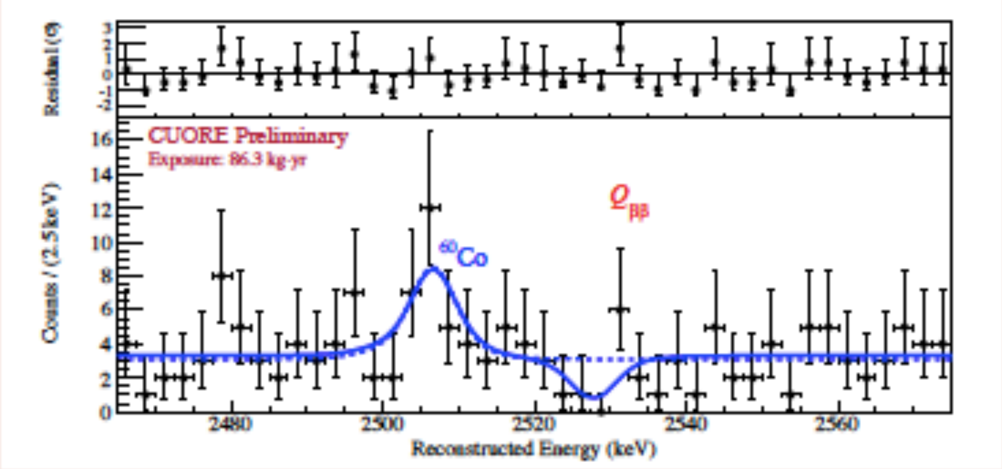
    $5 \cdot 10^{27}$ yr

- 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)

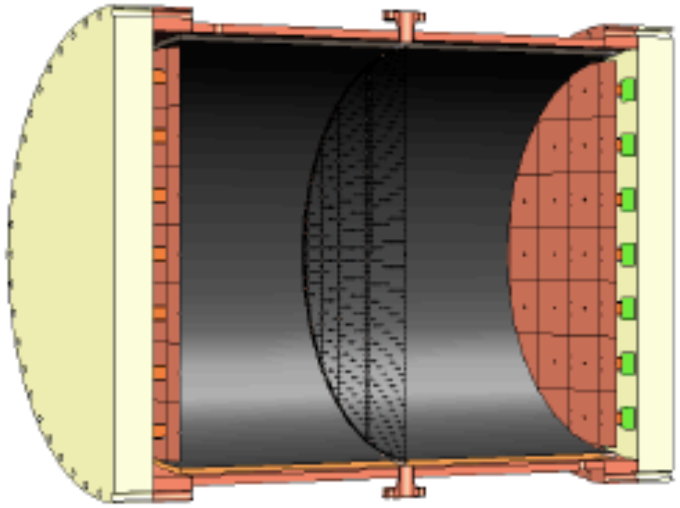
arXiv:1710.07988 [nucl-ex]



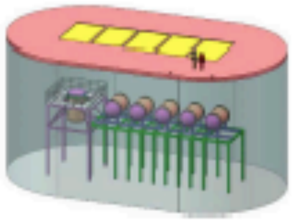
$t^{0\nu}_{1/2}(^{130}Te) > 1.5 \cdot 10^{25}$ yr @ 90% C. L.

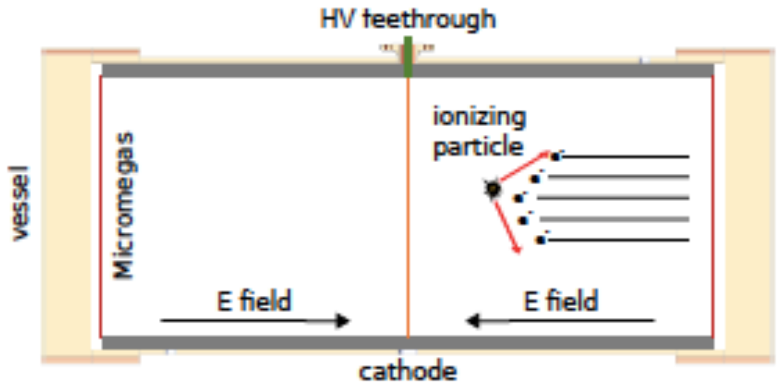
Future players: PandaX-III

- 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

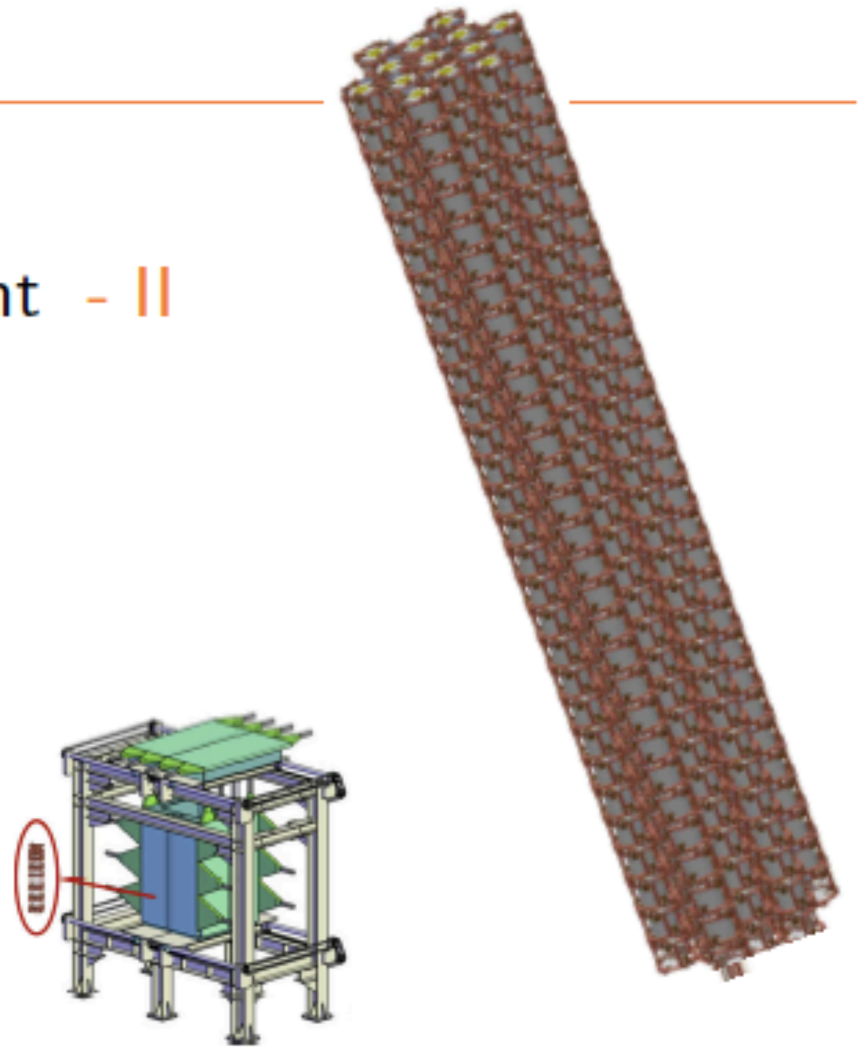




First 200 kg module

- 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: 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 $0\nu\beta\beta$ 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