European Research Council
Established by the European Commission

Neutrinoless double beta decay

J.J. Gómez Cadenas
IFIC (CSIC & UVEG)

LNGS hands-on school, August, 2014

Motivation to search for ββ0ν

Deus ex machina

The phrase comes from Horace's where he instructs poets that they must never resort to a god from the machine (mekhane) to solve their plots.

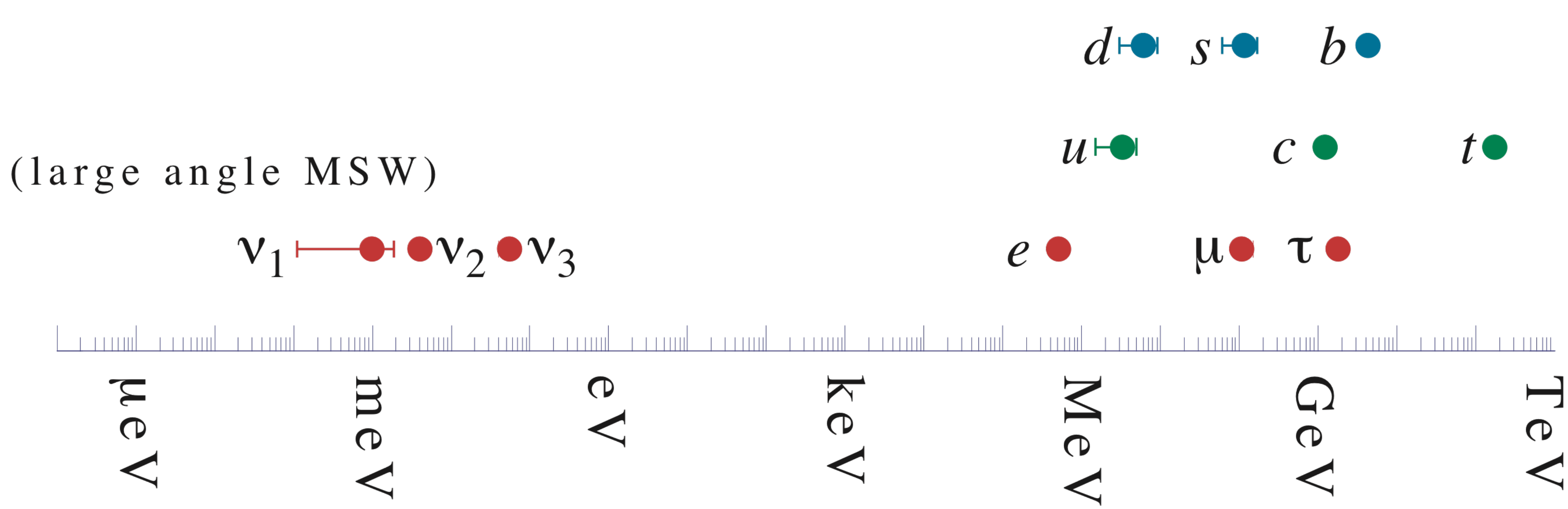
A deus ex machina Latin: "god from the machine" is a plot device whereby a seemingly unsolvable problem is suddenly and abruptly solved with the contrived and unexpected intervention of some new event, character, ability, or object. Depending on usage, it can be used to move the story forward when the writer has "painted themselves into a corner" and sees no other way out, to surprise the audience, or to bring a happy ending into the tale.

The mystery of the missing antimatter

- **The Big-Bang theory of the origin of the Universe requires matter and antimatter to be equally abundant at the very hot beginning.**

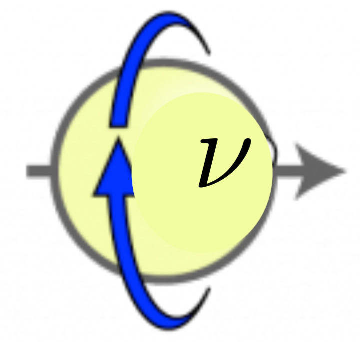
- **Is it possible to generate the asymmetry between matter and antimatter without deus ex machina?**

The mystery of neutrino masses

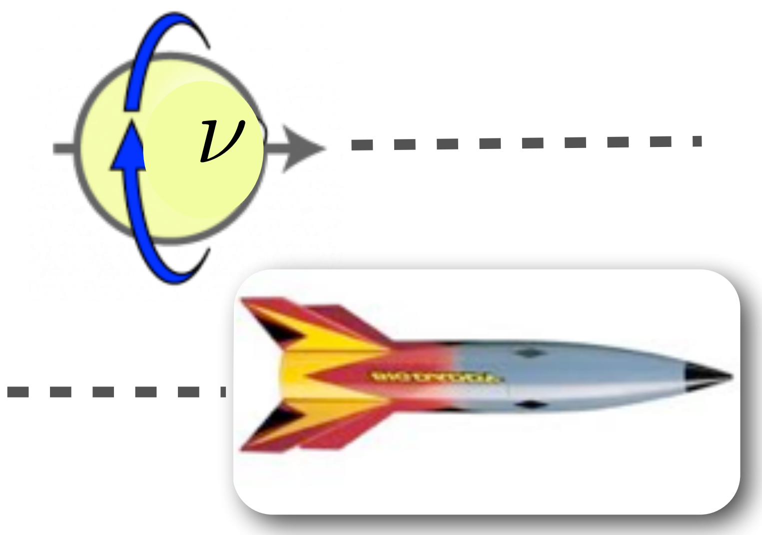


- **Is it possible to explain the smallness of neutrino masses without deus ex machina?**

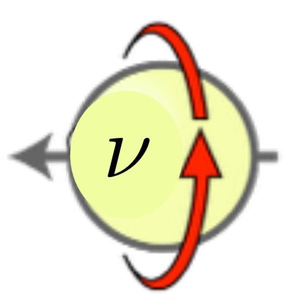
Neutrinos through the looking glass



•In the Standard Model neutrinos are massless and left handed (antineutrinos are right handed)

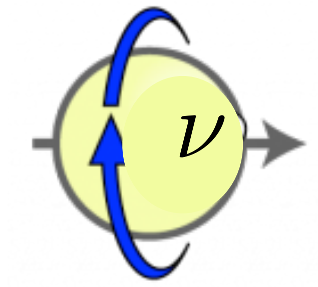


•It would be possible to turn a left handed neutrino into a right handed neutrino by jumping in a reference frame that moves faster than the neutrino. But a massless neutrinos moves at the speed of light and cannot be overtaken

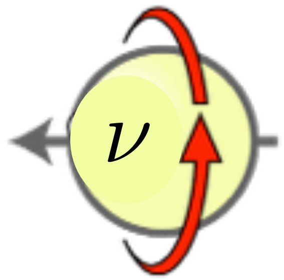


•Therefore we could live without right handed neutrinos and without left-handed antineutrinos. Standard model neutrinos do not reflect in the mirror!

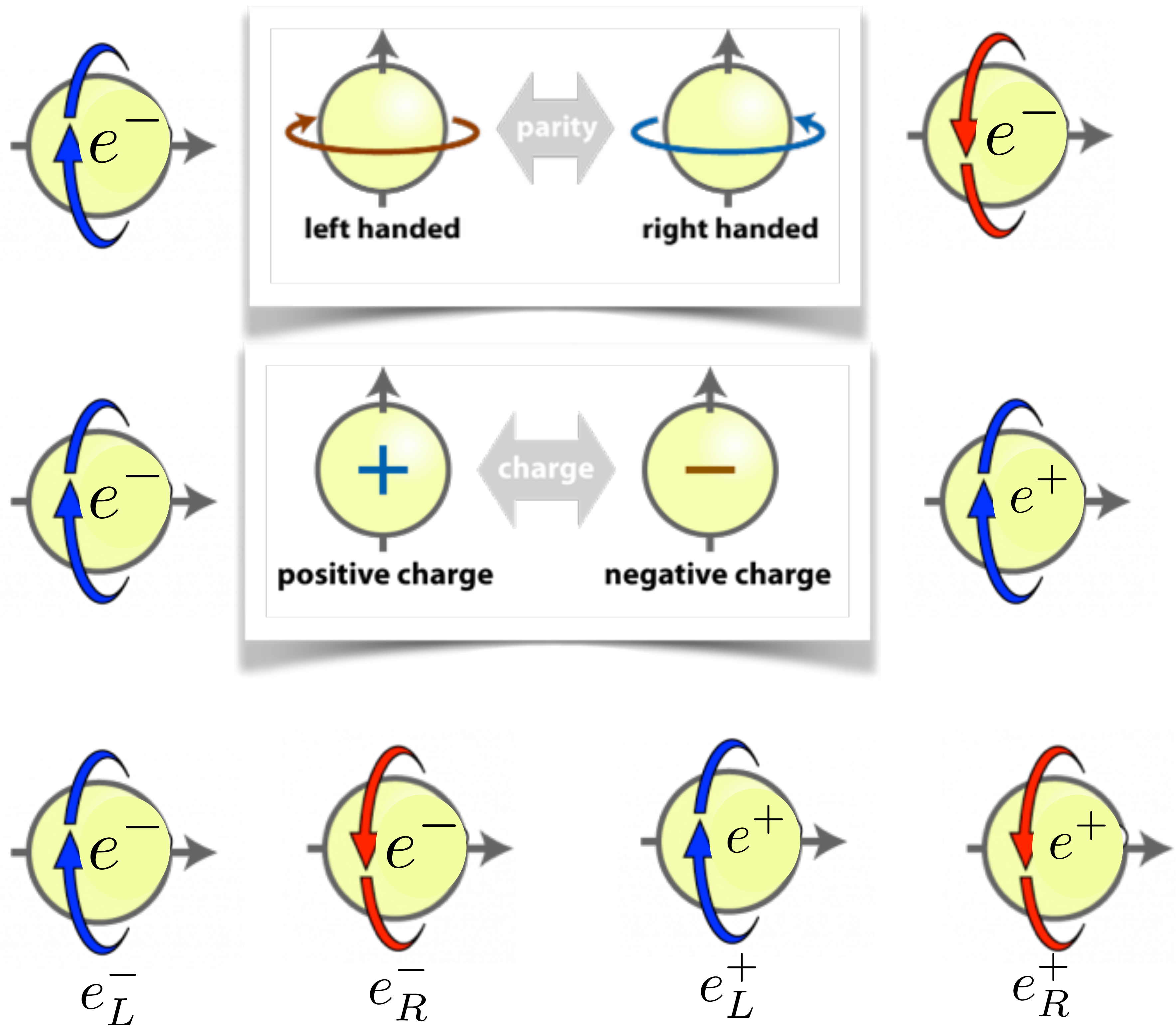
But neutrinos are massive…



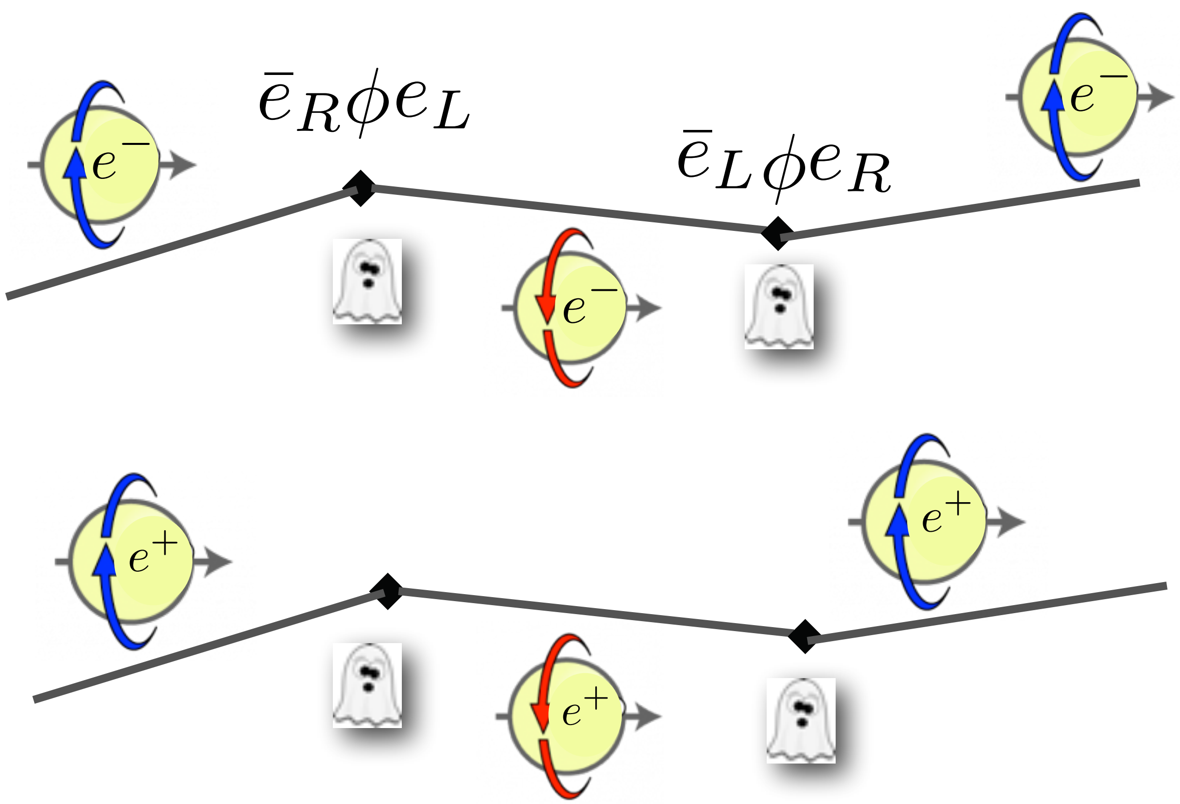
•**Reversing the argument, if neutrinos are massive, left-handed and right-handed neutrinos are guaranteed to exist. How does a massive neutrino reflects in the mirror?**



Electrons through the looking glass



Electron mass

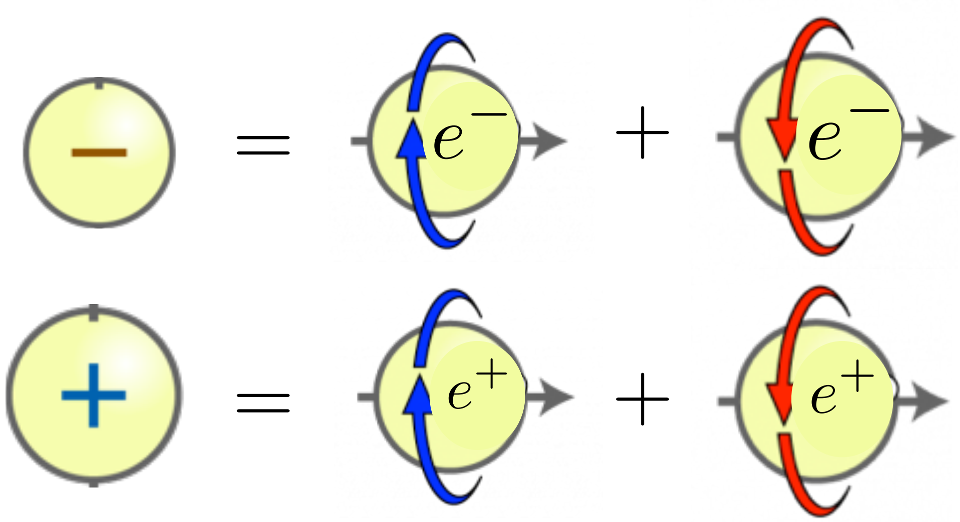


left and right handed states bump against the Higgs field

$$\mathcal{L}_D = \bar{e}_L m_e e_R + h.c.$$

$$\lambda\bar{e}_R\phi e_L \to \lambda v\bar{e}_R e_L$$

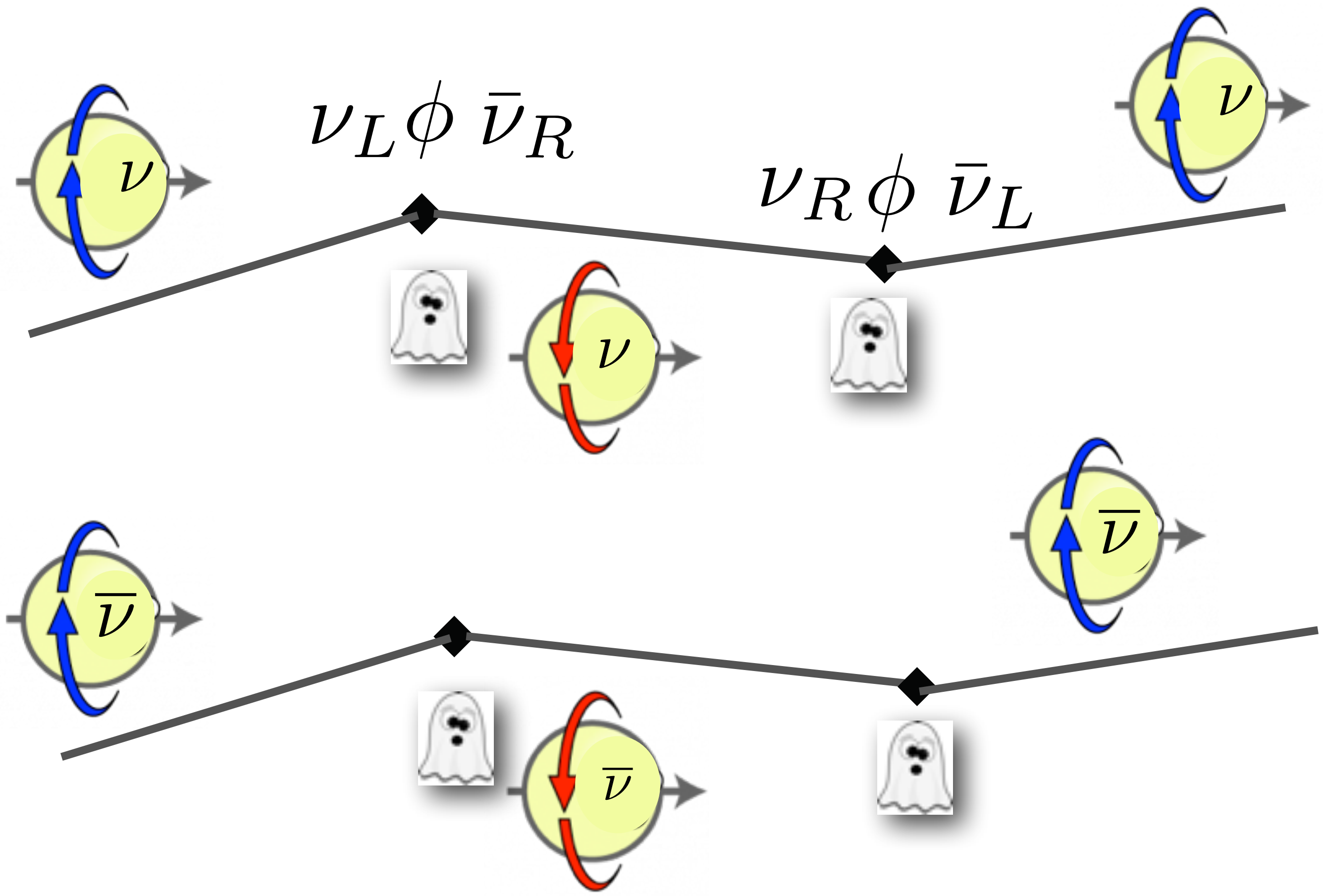
$$m_e = \lambda_e v$$

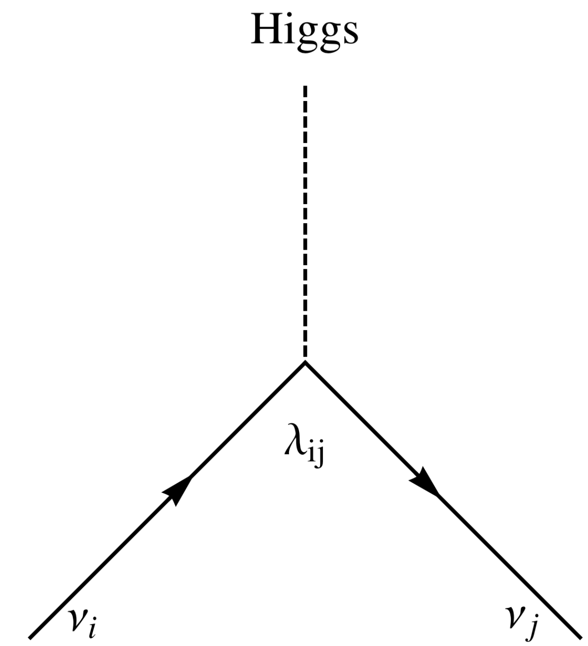


$$e^- = e^-_L + e^-_R$$

$$e^+ = e^+_L + e^+_R$$

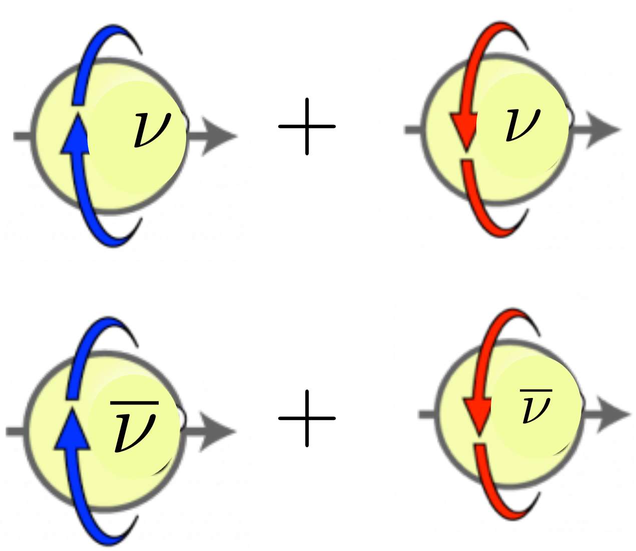
Dirac neutrinos





$$-\mathcal{L}_{\text{Dirac}} = \bar{\nu}_L m_\nu \nu_R + h.c.$$
$$m_\nu = \lambda_\nu v$$

ν =

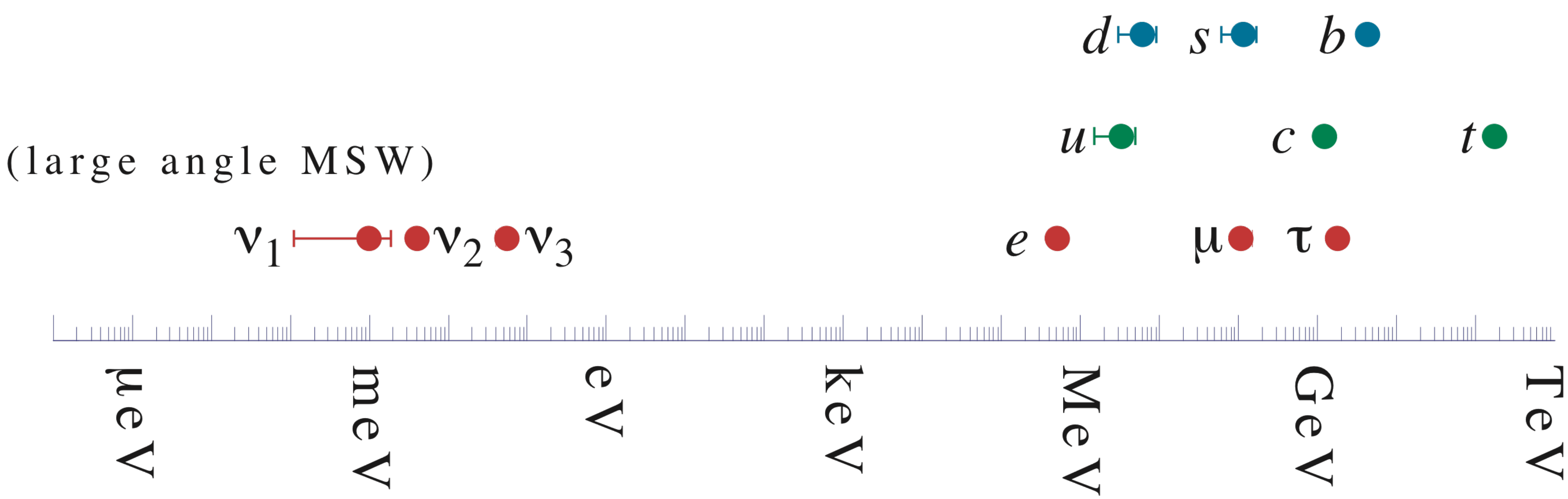


$\overline{\nu}$ =

$$\nu = \nu_L + \nu_R$$

$$\nu^C = (\nu_L)^C + (\nu_R)^C$$

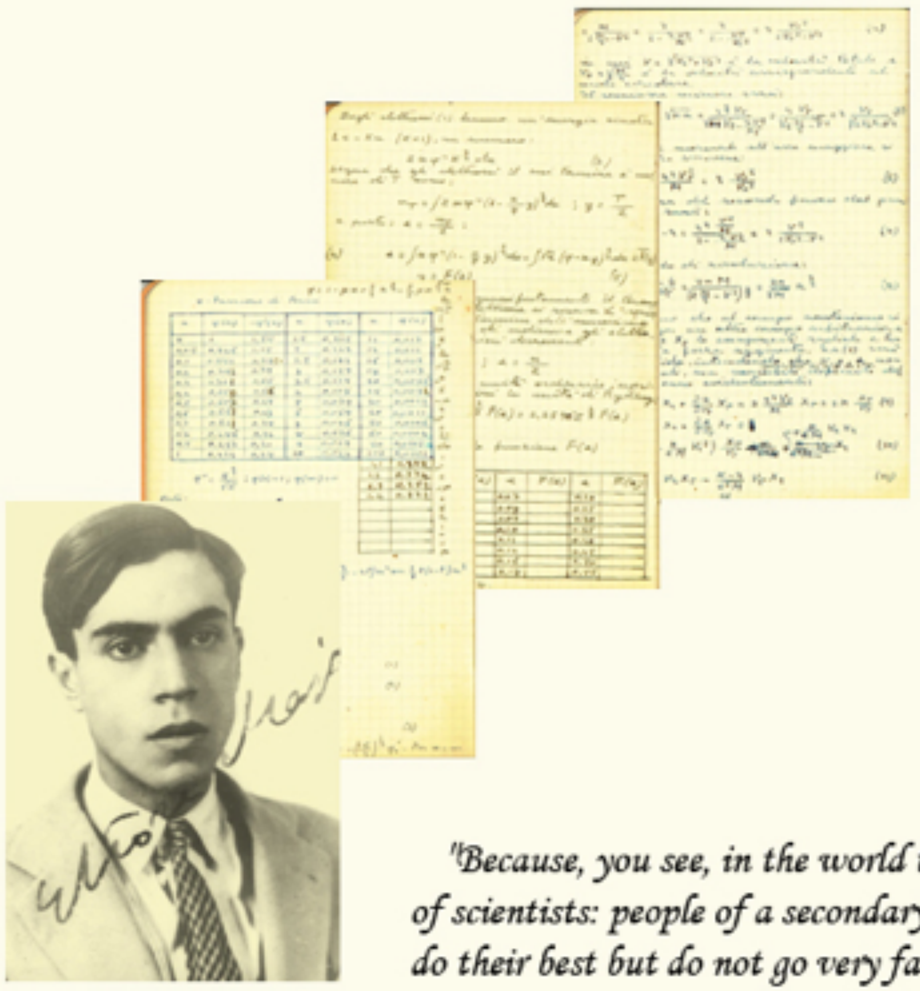
Dirac neutrinos and the hierarchy problem



$$\lambda_\nu << \lambda_e?$$

Nature has painted herself into a corner and sees no other way out to explain small neutrino masses than to resort to arbitrarily small coupling constant… here is the God from the machine...

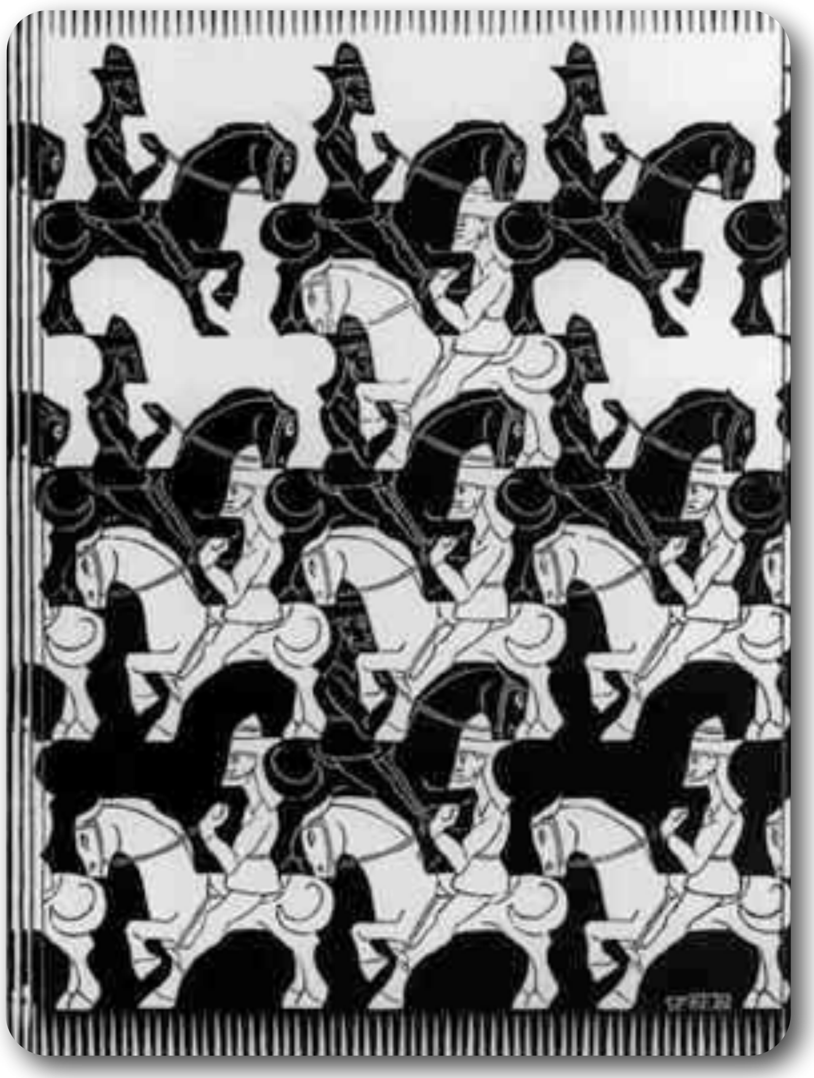
Ettore Majorana bold proposition



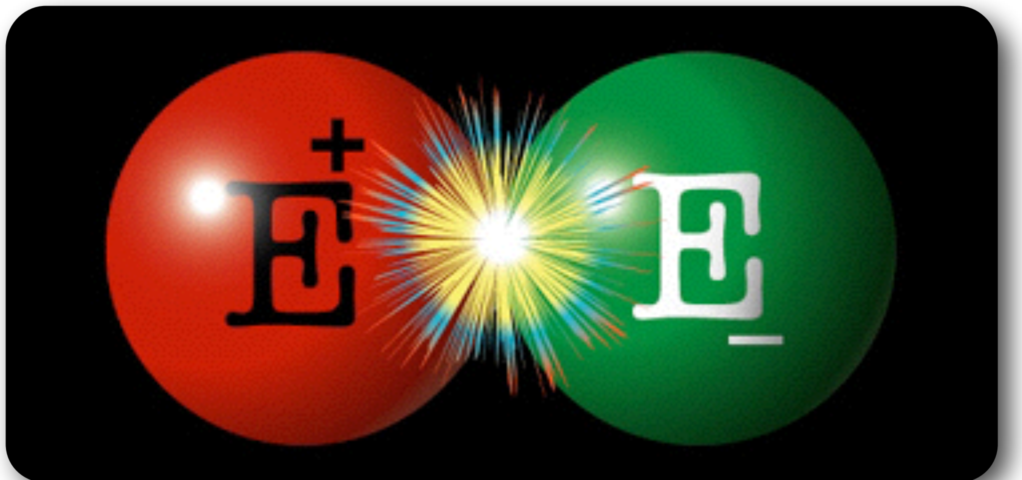
"Because, you see, in the world there are various categories of scientists: people of a secondary or tertiary standing, who do their best but do not go very far. There are also those of high standing, who come to discoveries of great importance, fundamental for the development of science.

But then there are geniuses like Galileo and Newton. Well, Ettore was one of them. Majorana had what no one else in the world had".

E. Fermi



Neutrino’s charge conjugation

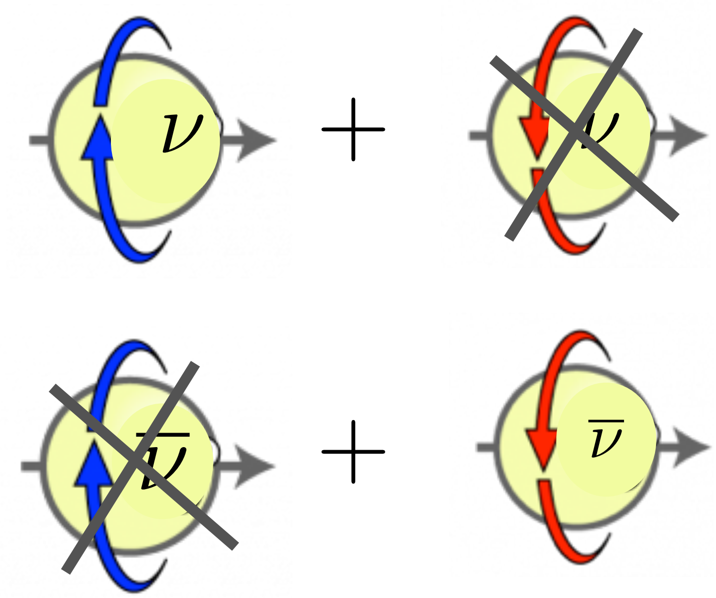


Charge conjugation reverses the electric charge of the electron.

But the neutrino has no electric charge that needs to be conserved.

Majorana neutrinos

ν =

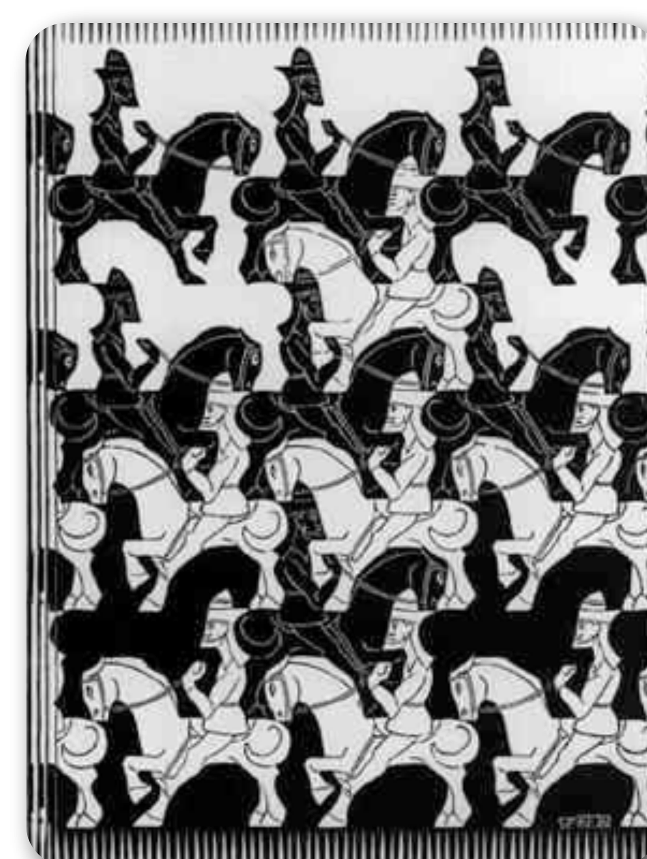


$$\nu = \nu_L + \nu_R$$

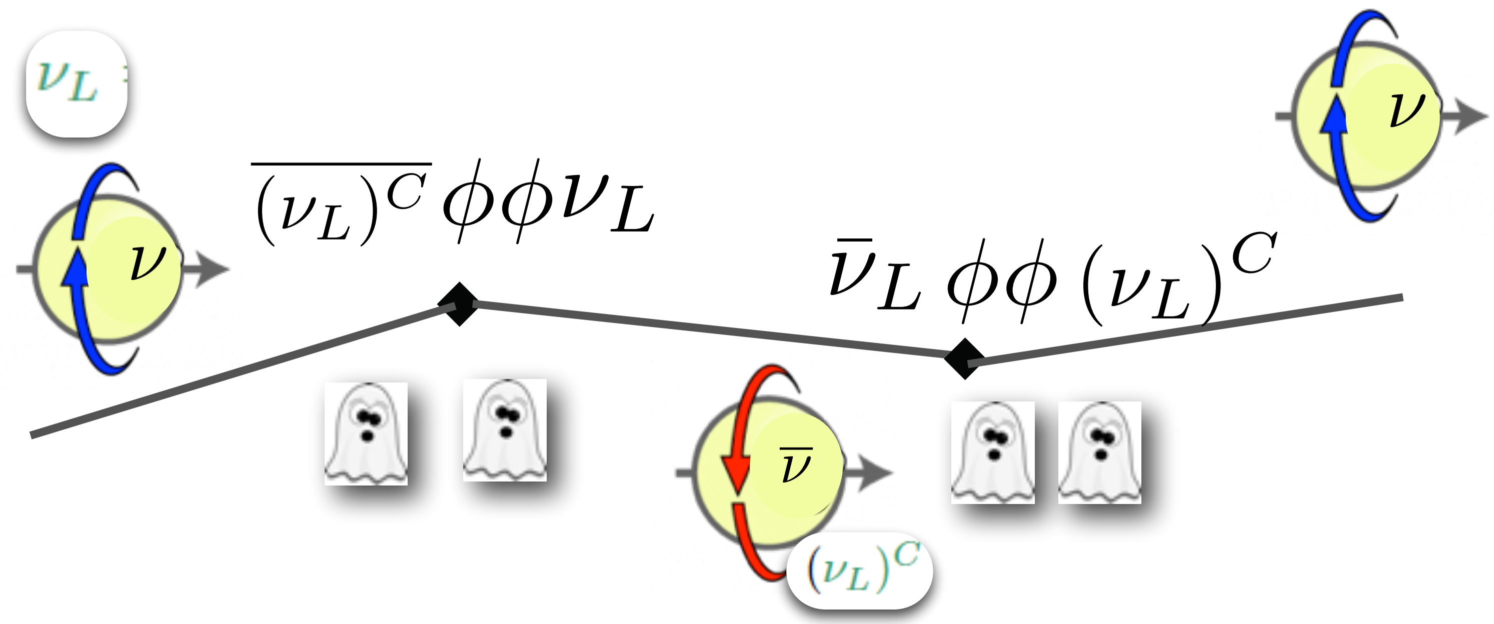
$$\nu^C = (\nu_L)^C + (\nu_R)^C$$

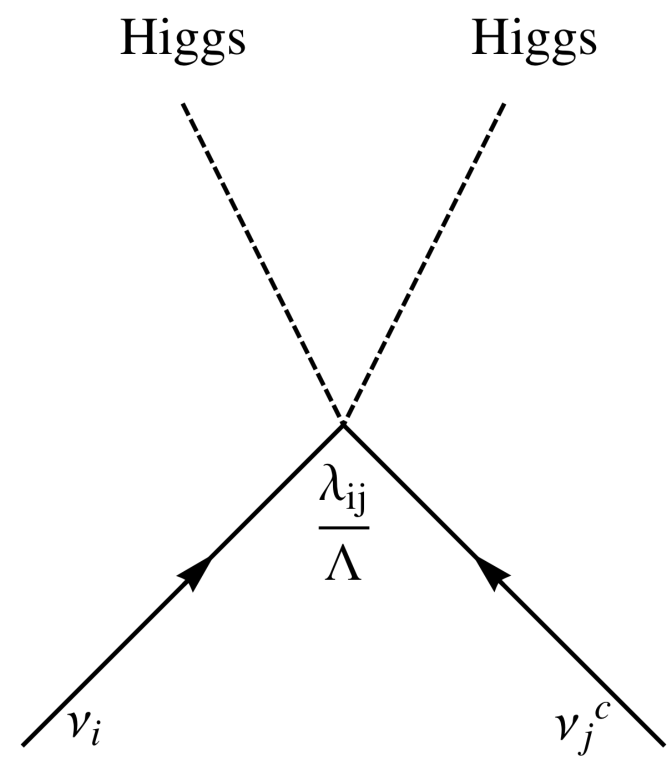
$$\nu = \nu_L + \nu_L^C \qquad \nu^c = \nu$$

$$\nu = \bar{\nu}$$



Neutrino mass (Majorana's recipe)



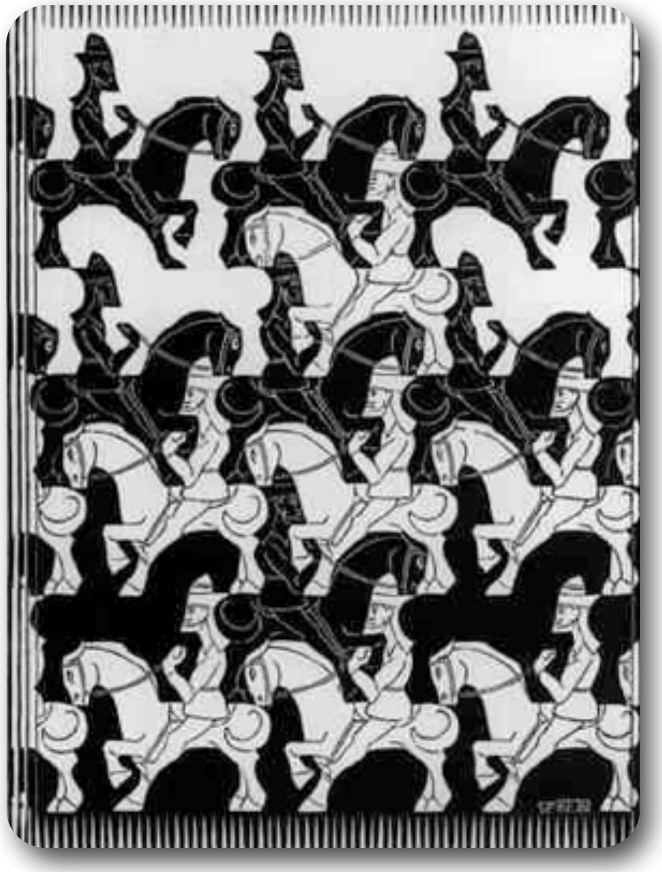
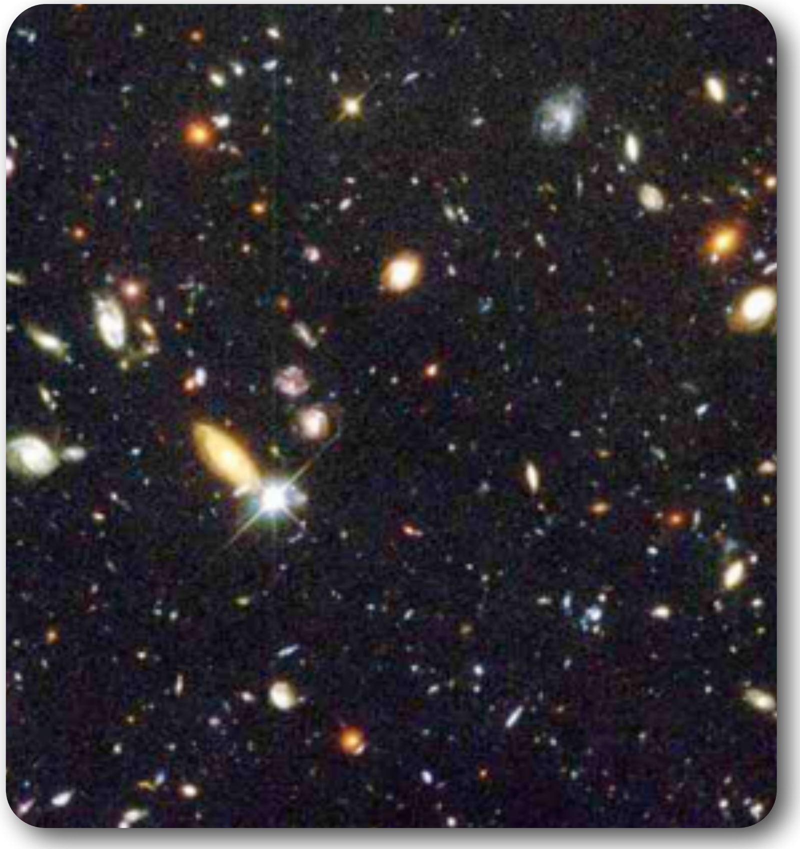


$$\nu_L = (\nu_R)^C \qquad (\nu_L)^C = \nu_R$$

$$-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c.$$

$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$

A formula for the universe

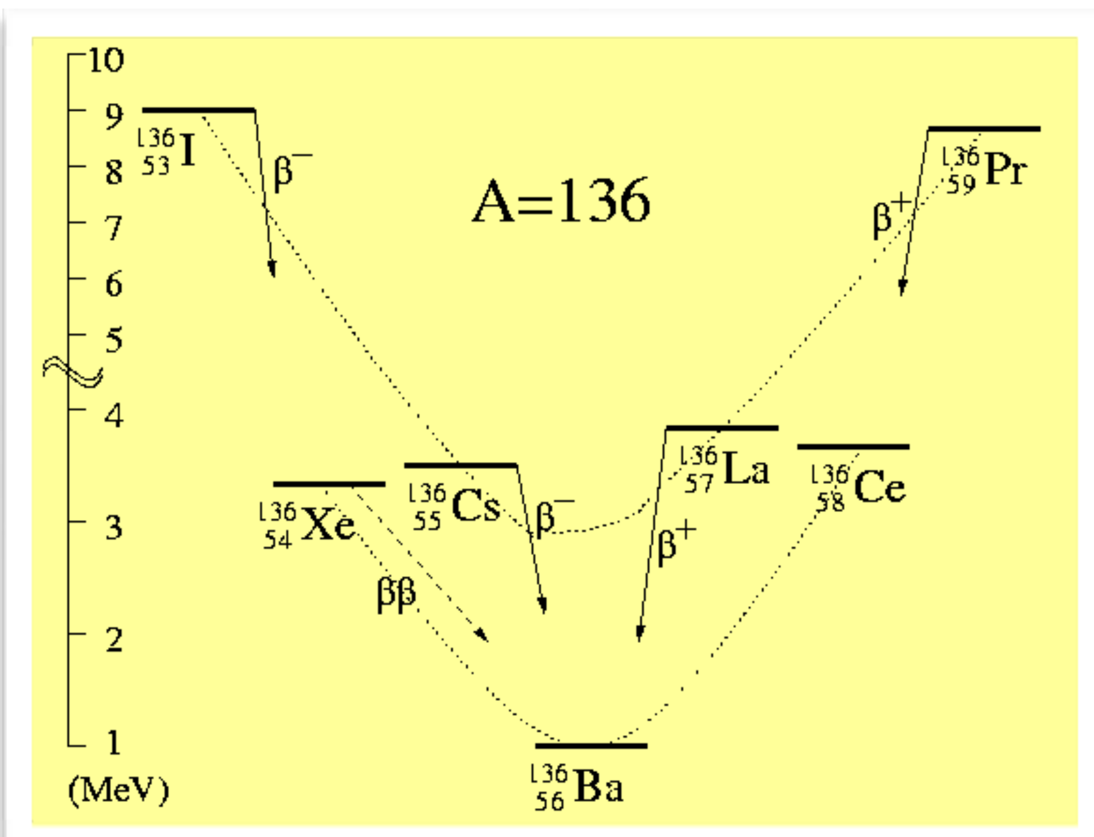
 +  = 

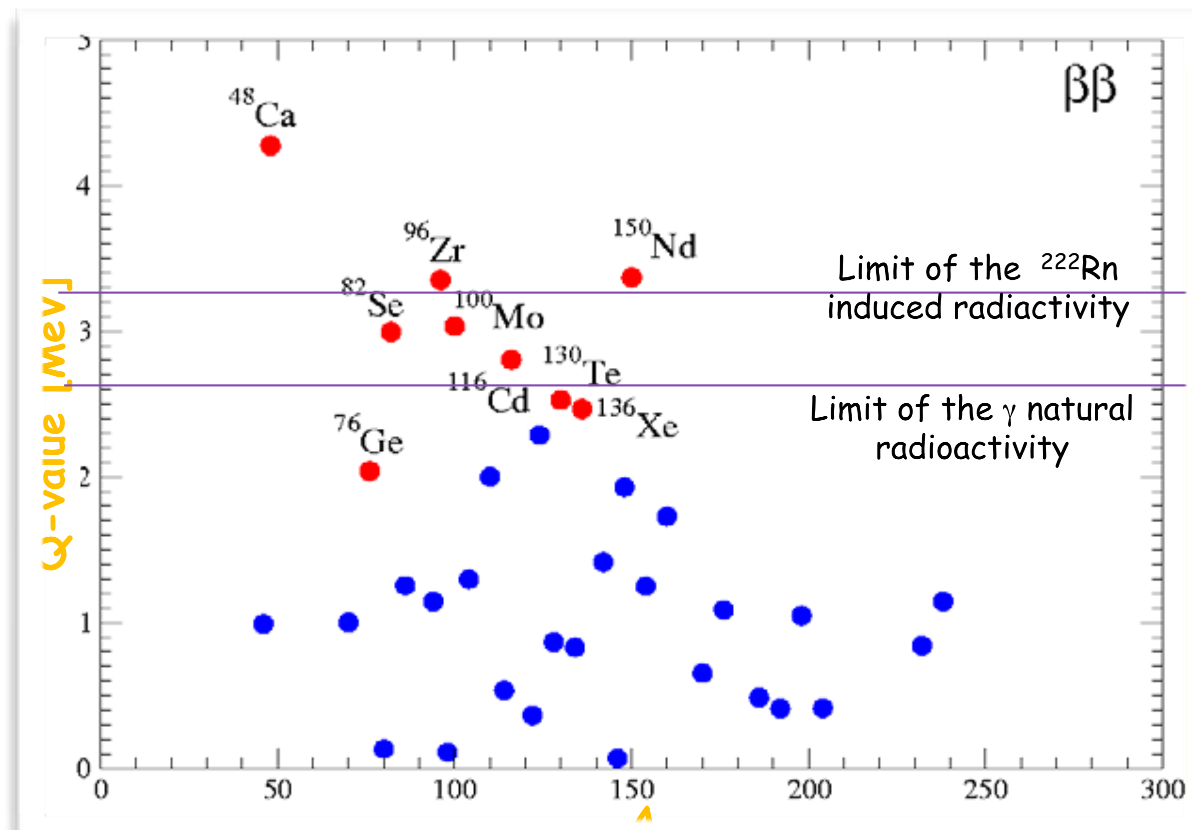
$$N \rightarrow e^{-} + H^{+} \quad \text{and} \quad N \rightarrow e^{+} + H^{-}$$

Standard-Model Higgs

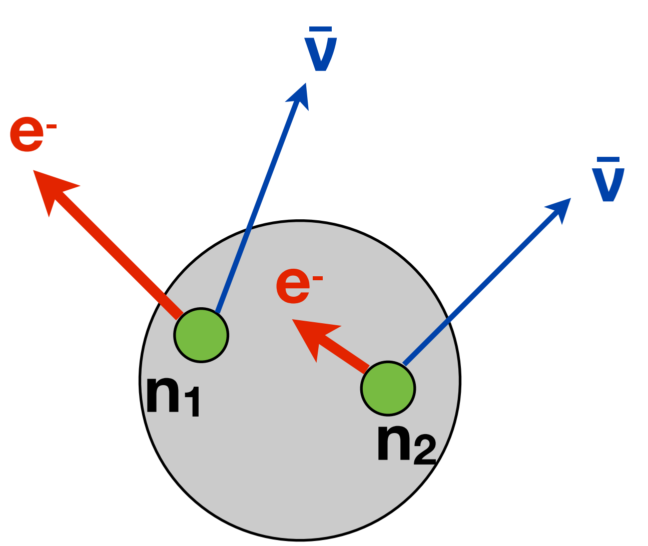
$\beta\beta0\nu$

Double beta decay





ββ2ν

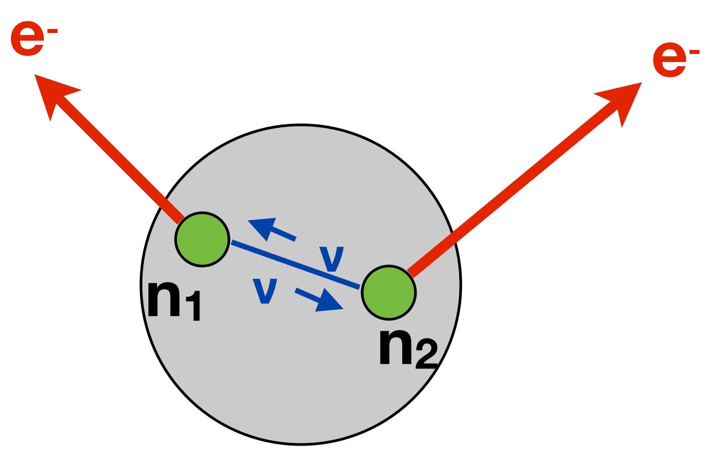


Two neutrino mode

- Observed in several nuclei
- 10^{19}-10^{21} yr half-lives
- Standard Model allowed

Neutrinoless double beta decay

ββ0ν



Neutrinoless mode

- Requires Majorana neutrinos
- Not observed yet in Nature
- $>10^{25}$ yr half-lives
- Would signal Beyond-SM physics

Lepton number violating process implying massive Majorana neutrinos

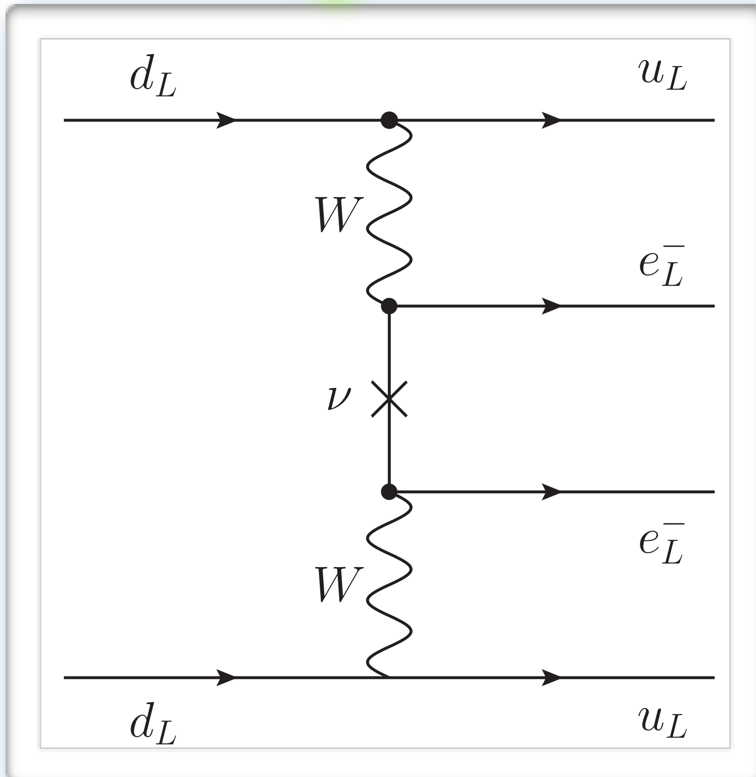
Identity

Mass scale

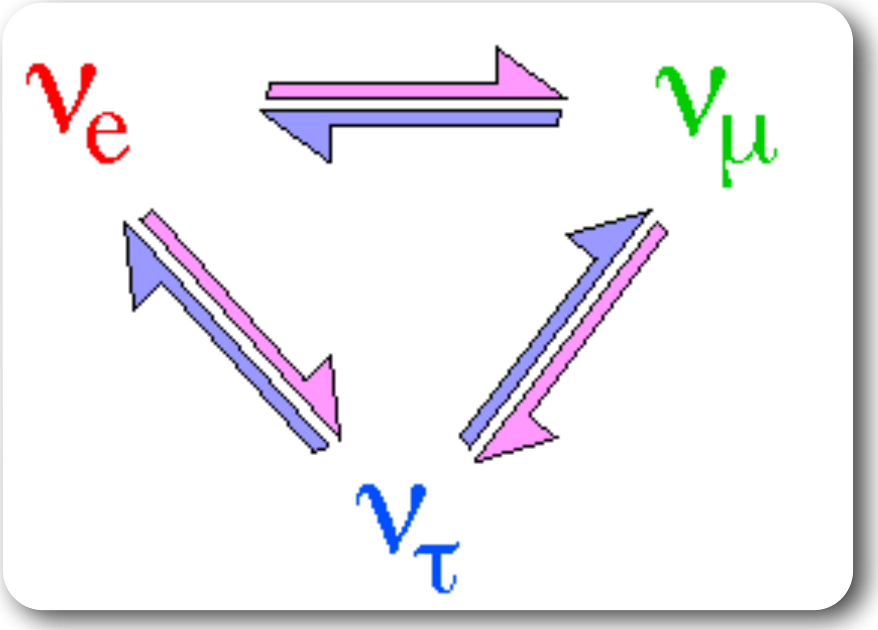
Mass ordering

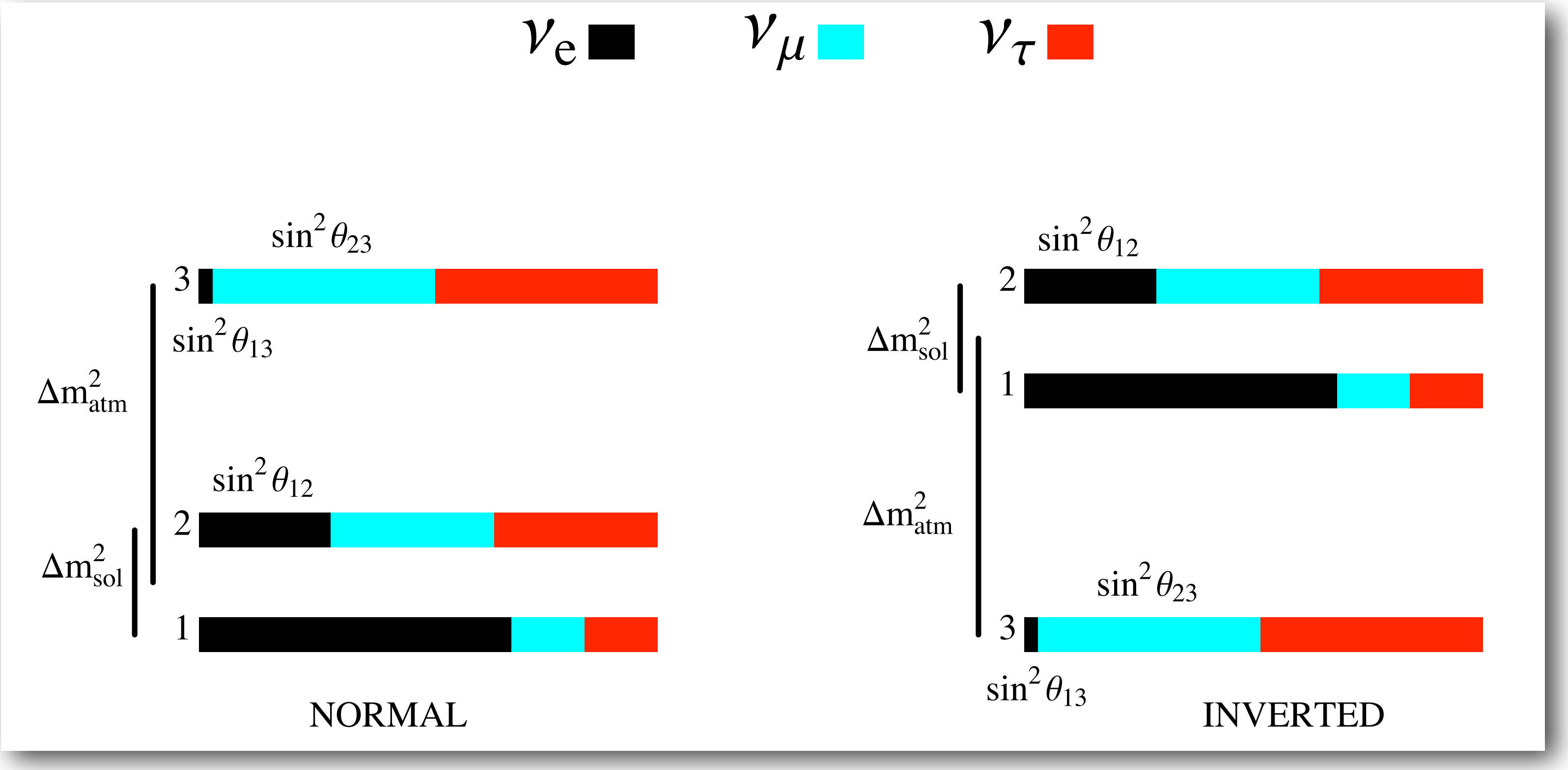
Mixing

Species



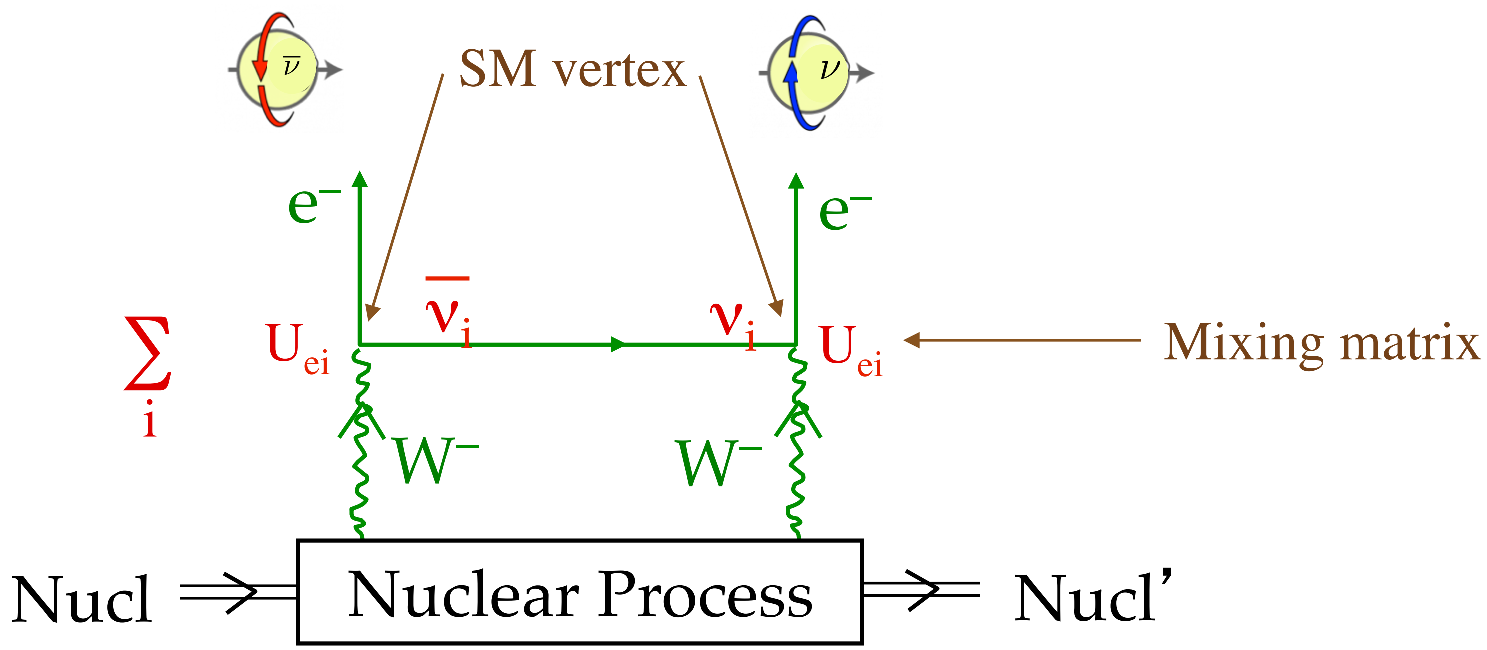
Massive neutrinos and neutrino oscillations





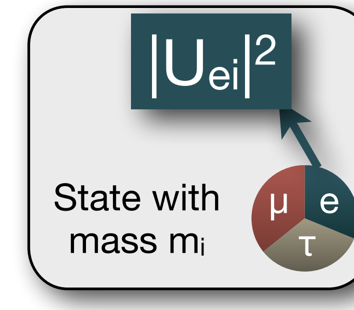
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

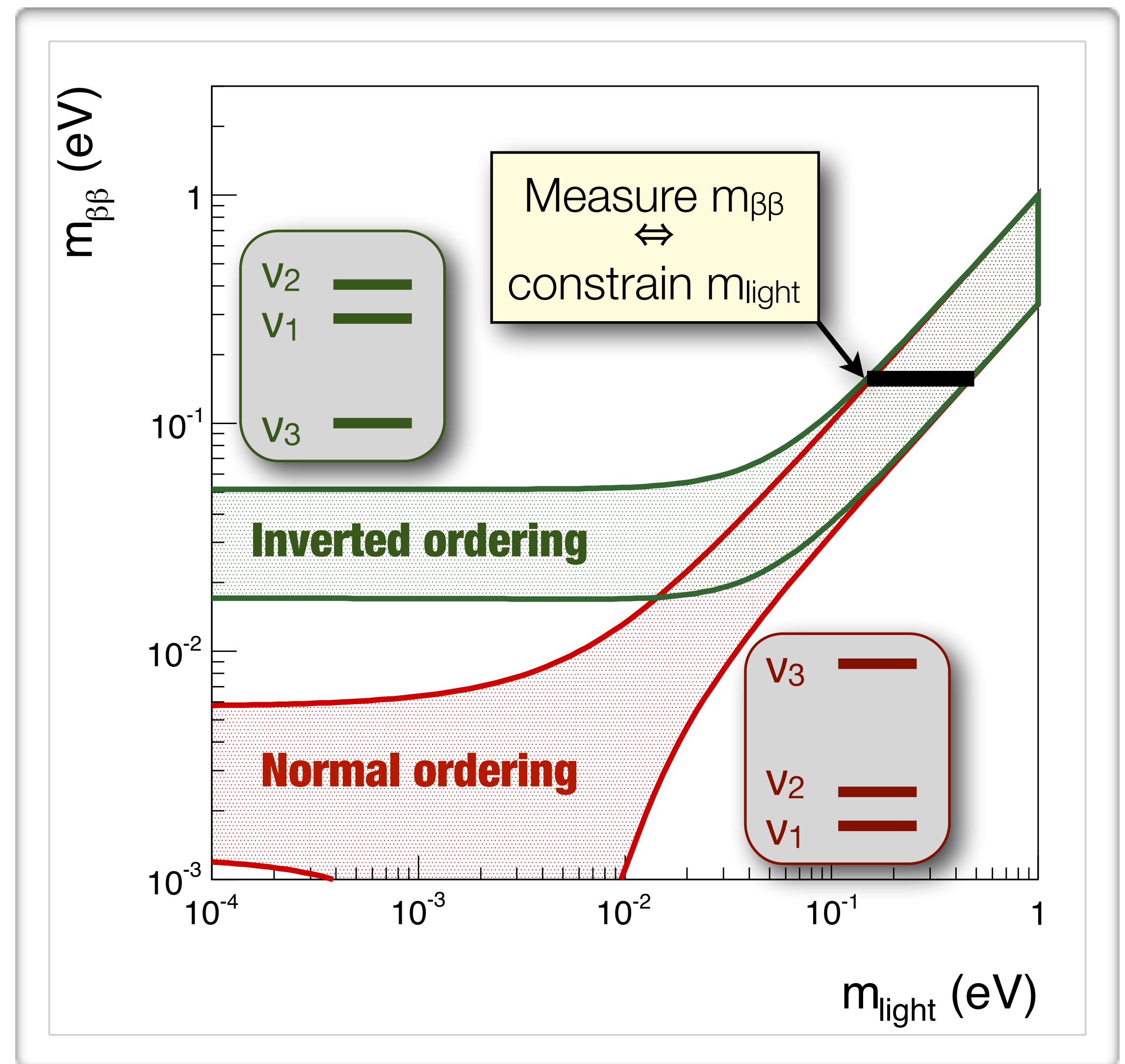
Neutrinoless double beta decay and the neutrino mass



$(\text{Rate})_{\beta\beta0\nu} \propto m_{\beta\beta}^2$

Majorana ν mass:
$m_{\beta\beta} \equiv \left| \sum_i m_i U_{ei}^2 \right|$

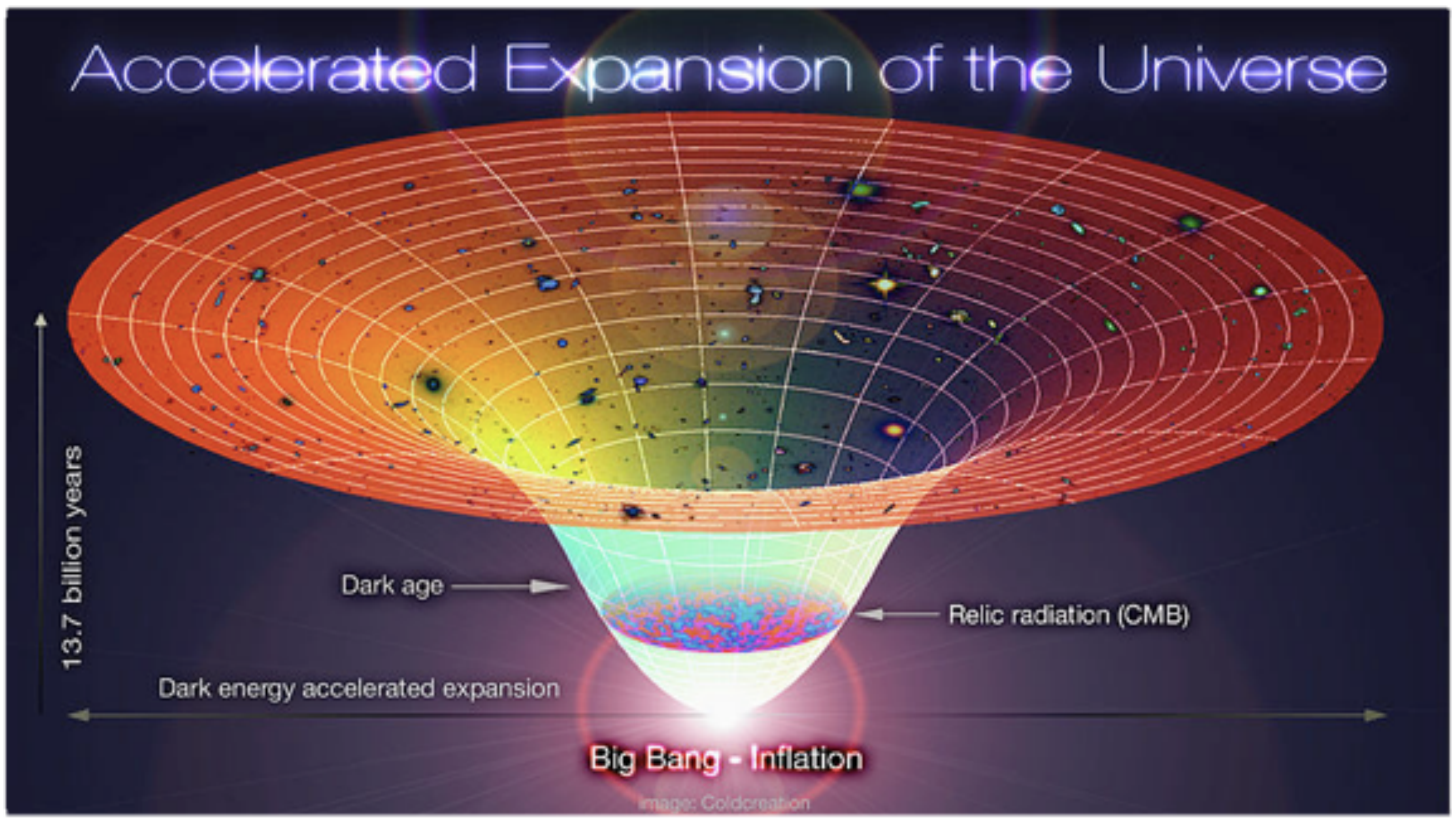




→ **helicity flip** $\propto \dfrac{m_i}{E}$

$\mathcal{A} \propto m_i$ **for each** ν_i

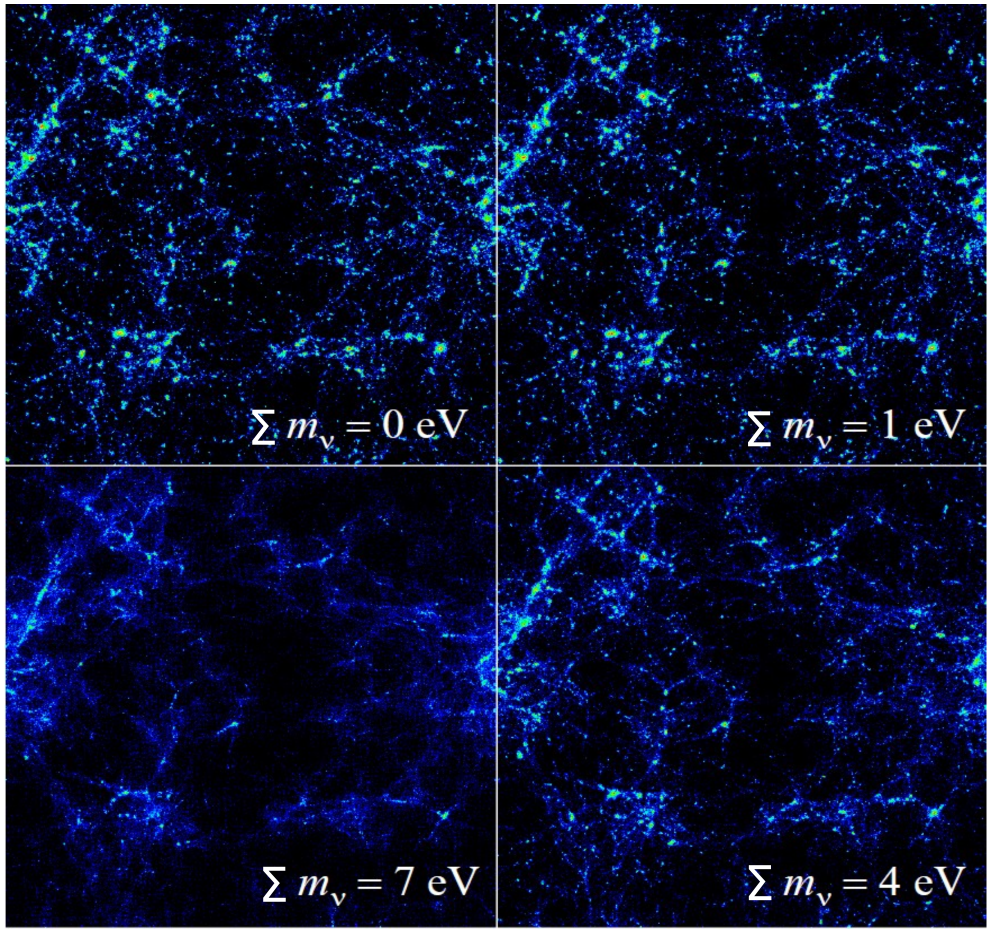
Massive neutrinos and cosmology



$$m_{cosmo} = \sum_{i=1}^{3} m_i$$

- ΛCDM: Big-bang + Inflation (CMB)
- Dark energy (73% of energy density), cold dark matter (23%) ordinary matter (4.5%)
- Light neutrinos can enter extensions of the ΛCDM model as “hot dark matter”

Cosmological measurements of neutrino masses



simulation Chung-Pei Ma 1996

- **Neutrinos masses affect the structure of CMB and the large scale structure of the universe.**
- **Measurement sensitive to the sum of neutrino masses.**
- **“Model dependent”**

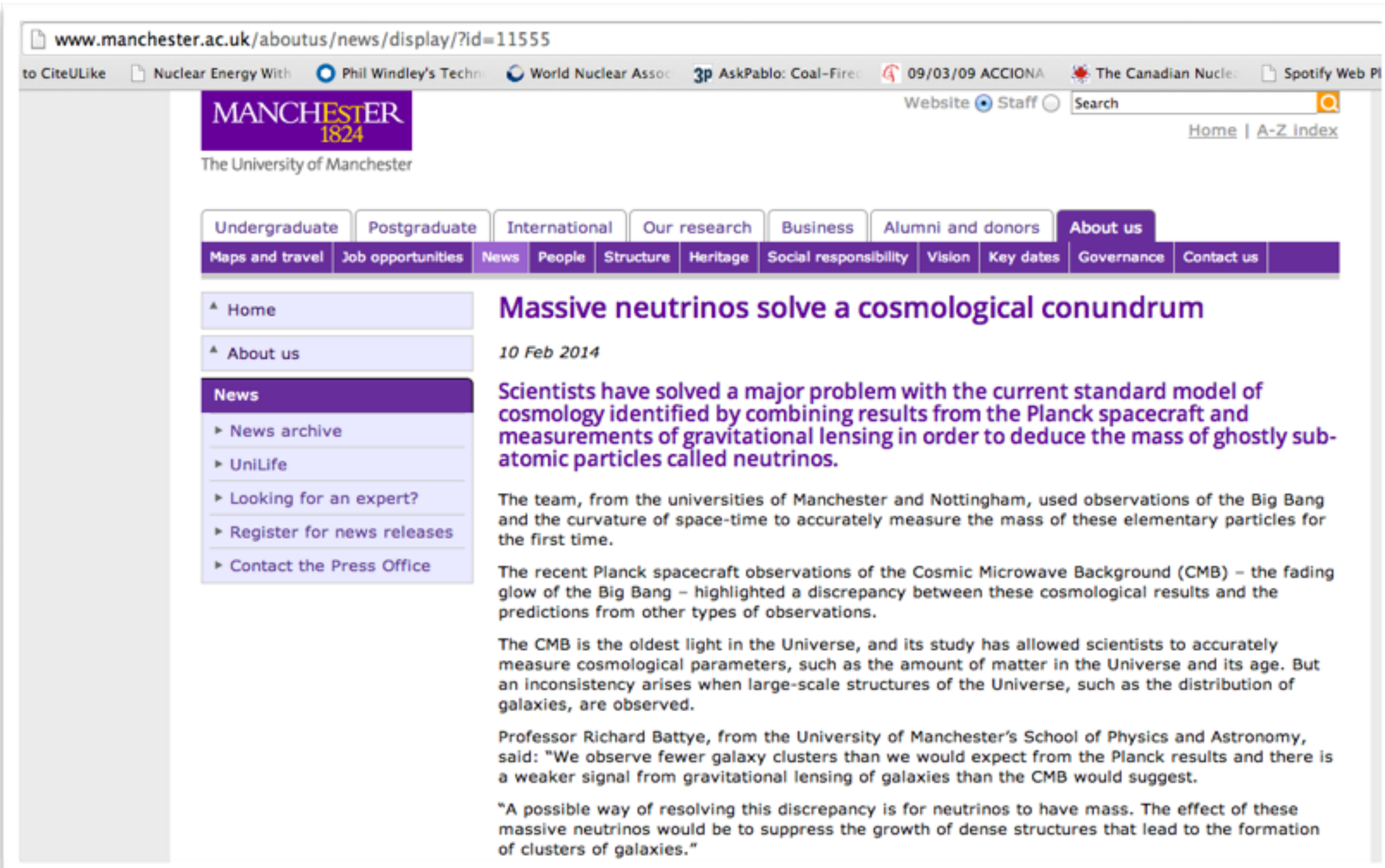
WMAP CMB only	$\sum m_i \leq 1.3eV$
CMB+BAO	$\sum m_i \leq 0.58eV$
CMB+BAO+ H0	$\sum m_i \leq 0.48eV$
Physical Review Letters, 105 (3)	$\sum m_i \leq 0.23eV$

Evidence for Massive Neutrinos from Cosmic Microwave Background and Lensing Observations

Phys. Rev. Lett. 112, 051303 (2014)

$$\sum m_i = 0.32 \pm 0.11eV$$

Massive neutrinos and cosmology



www.manchester.ac.uk/aboutus/news/display/?id=11555

MANCHESTER 1824

The University of Manchester

Undergraduate | Postgraduate | International | Our research | Business | Alumni and donors | About us

Maps and travel | Job opportunities | News | People | Structure | Heritage | Social responsibility | Vision | Key dates | Governance | Contact us

- Home
- About us

News

- News archive
- UniLife
- Looking for an expert?
- Register for news releases
- Contact the Press Office

Massive neutrinos solve a cosmological conundrum

10 Feb 2014

Scientists have solved a major problem with the current standard model of cosmology identified by combining results from the Planck spacecraft and measurements of gravitational lensing in order to deduce the mass of ghostly sub-atomic particles called neutrinos.

The team, from the universities of Manchester and Nottingham, used observations of the Big Bang and the curvature of space-time to accurately measure the mass of these elementary particles for the first time.

The recent Planck spacecraft observations of the Cosmic Microwave Background (CMB) – the fading glow of the Big Bang – highlighted a discrepancy between these cosmological results and the predictions from other types of observations.

The CMB is the oldest light in the Universe, and its study has allowed scientists to accurately measure cosmological parameters, such as the amount of matter in the Universe and its age. But an inconsistency arises when large-scale structures of the Universe, such as the distribution of galaxies, are observed.

Professor Richard Battye, from the University of Manchester's School of Physics and Astronomy, said: "We observe fewer galaxy clusters than we would expect from the Planck results and there is a weaker signal from gravitational lensing of galaxies than the CMB would suggest.

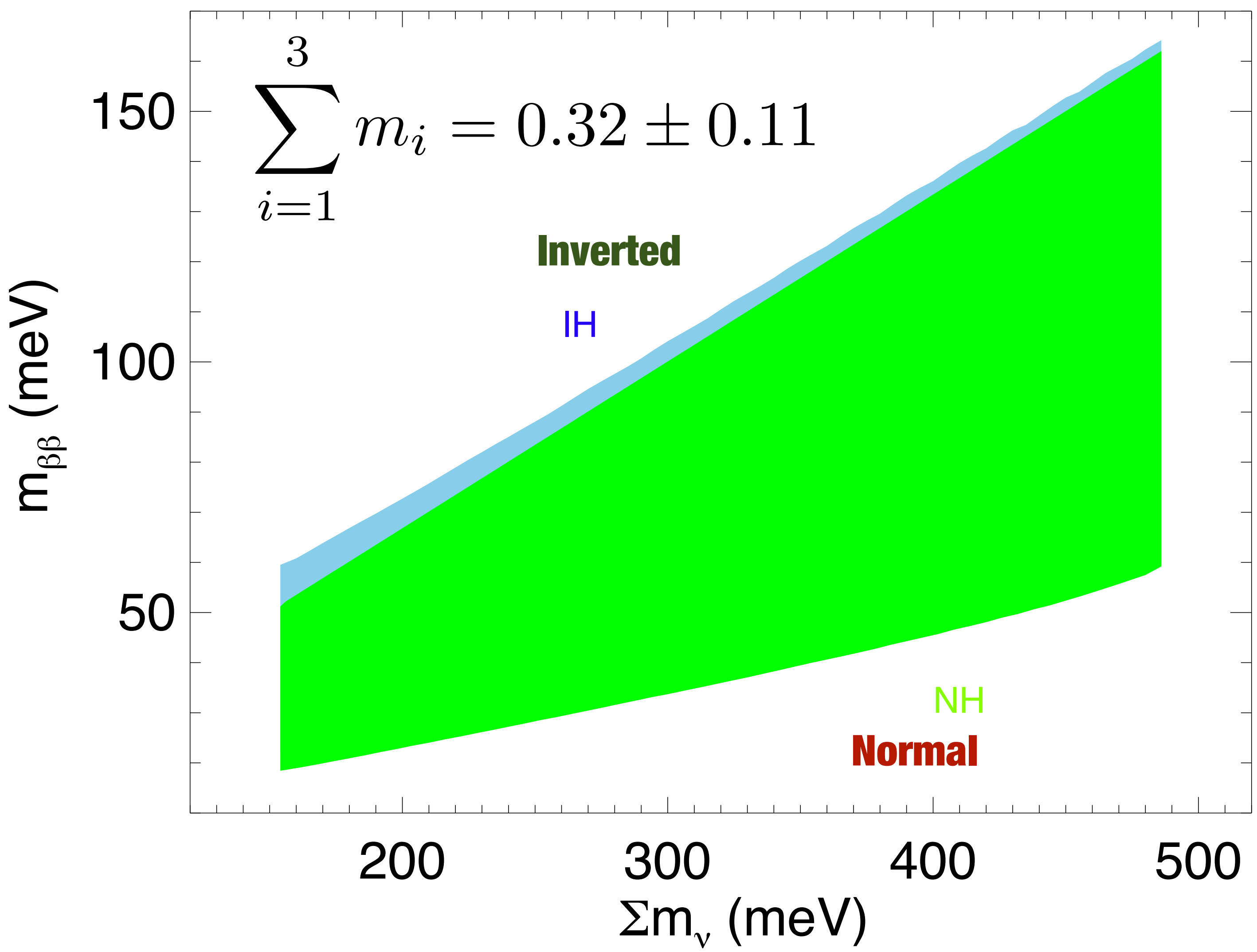
"A possible way of resolving this discrepancy is for neutrinos to have mass. The effect of these massive neutrinos would be to suppress the growth of dense structures that lead to the formation of clusters of galaxies."

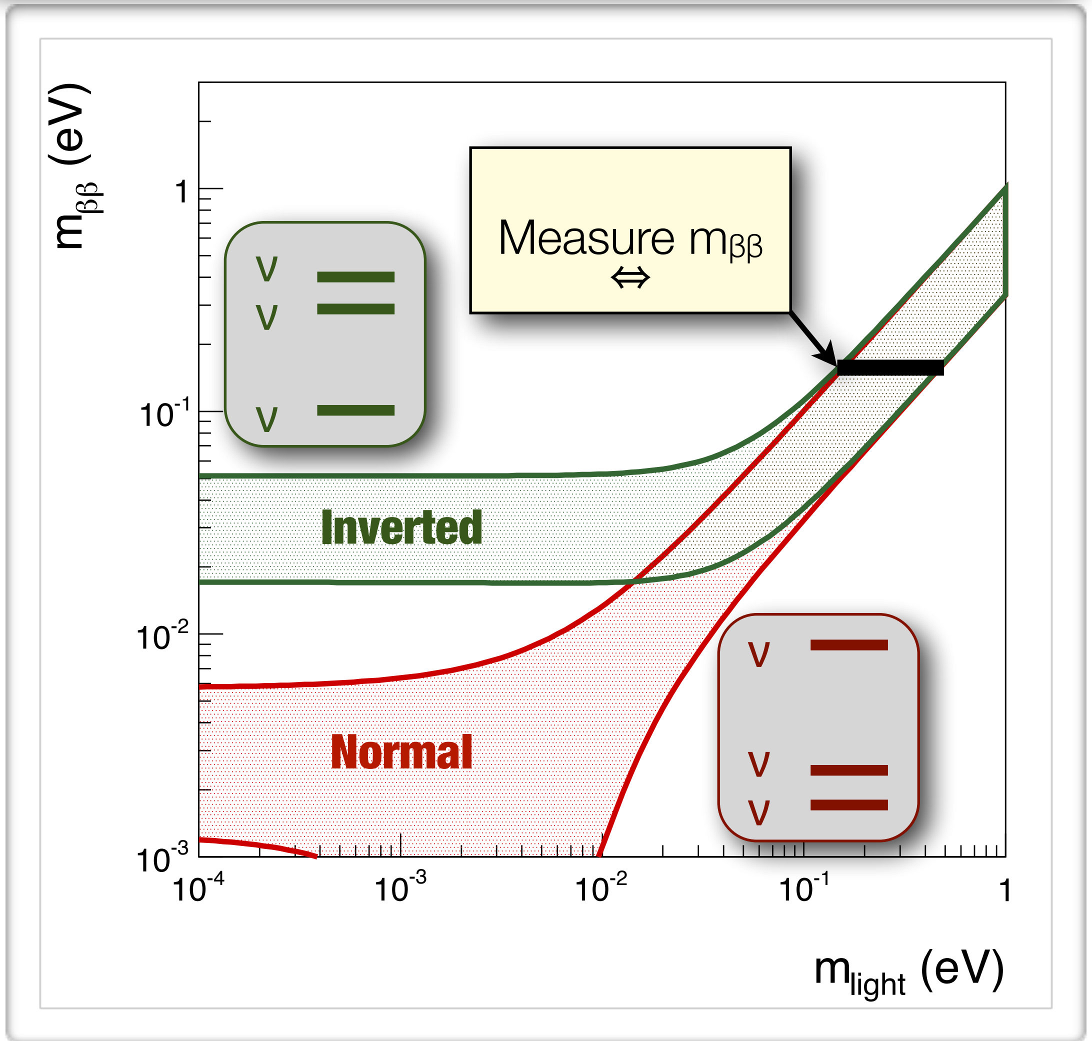
Majorana landscape revisited

Evidence for Massive Neutrinos from Cosmic Microwave Background and Lensing Observations

Phys. Rev. Lett. 112, 051303 (2014)

- Discovery window: 15 meV-170 meV
- Bot hierarchies give almost the same "phase space".



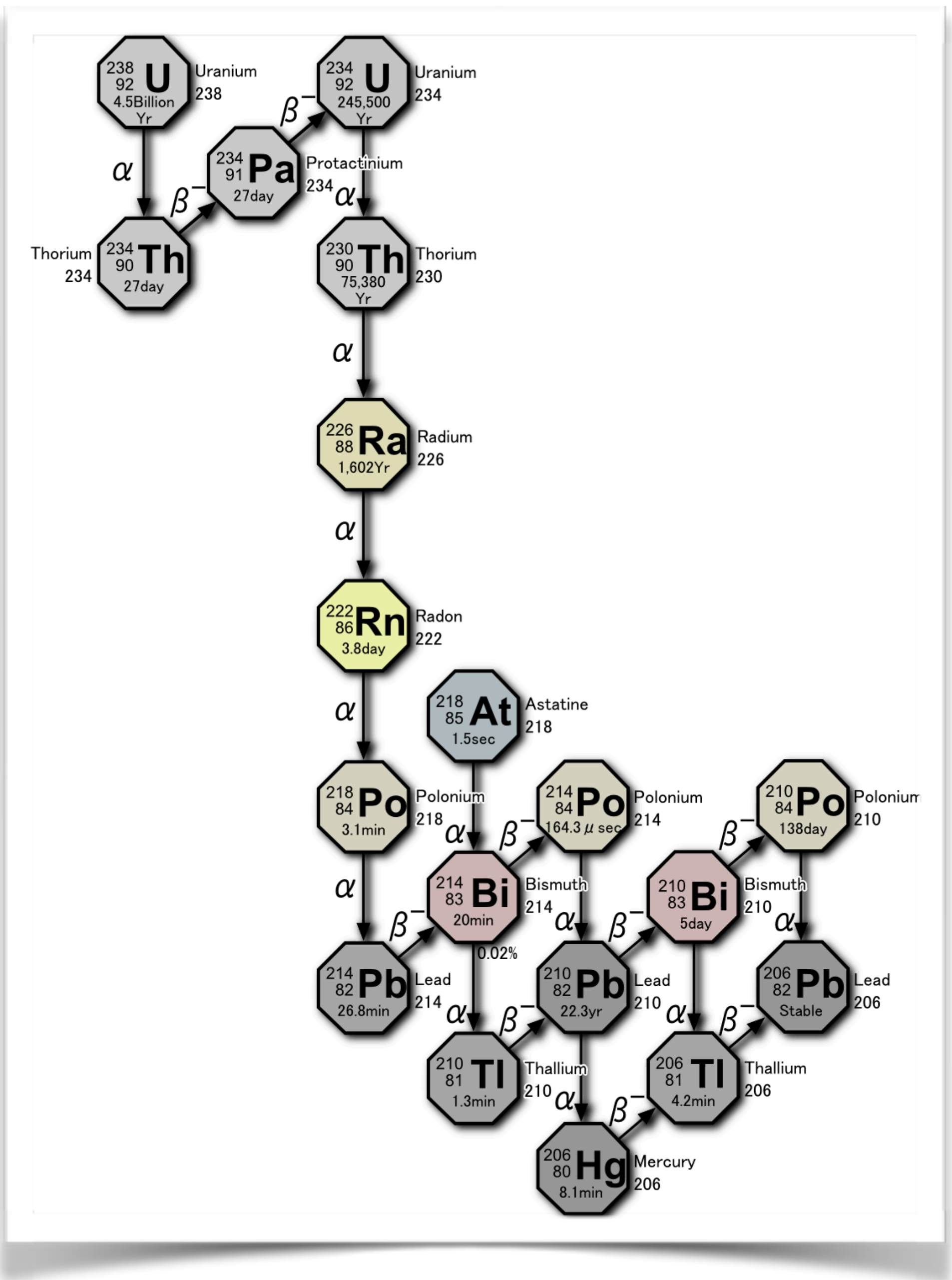


Discovery potential of xenon-based neutrinoless double beta decay experiments in light of small angular scale CMB observations

JCAP 1303 (2013) 043

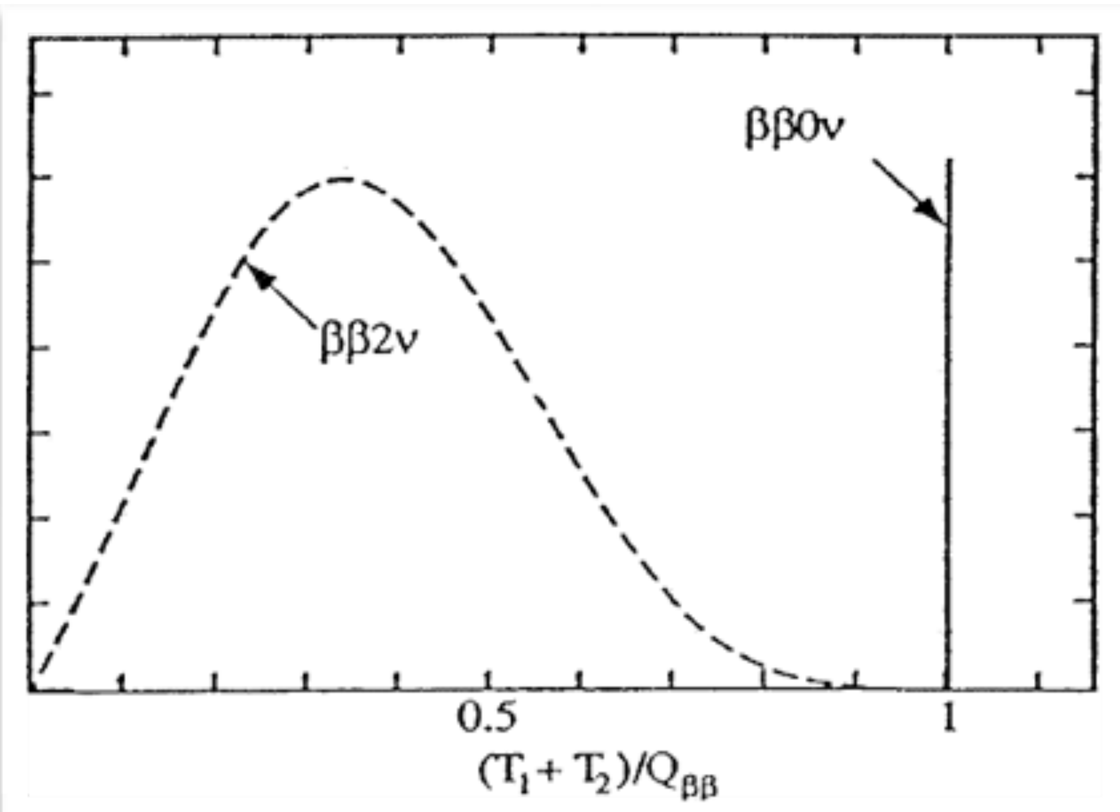
Experimental challenges

Why ββ0ν experiments are difficult



- Earth is a very radioactive planet. There are about 3 grams o U-238 and 9 grams of Th-232 per ton of rock around us.
- This is an intrinsic activity of the order of 60 Bq/kg of U-238 and 90 Bq/kg of Th-232.
- The lifetime of U-238 is of the order of 10^9 y and that of Th-232 10^{10} y. We want to explore lifetimes of of the order of 10^{26} -10^{27} y.
- The problem is much harder than finding a needle in a haystack

Measuring ββ0ν in an ideal experiment



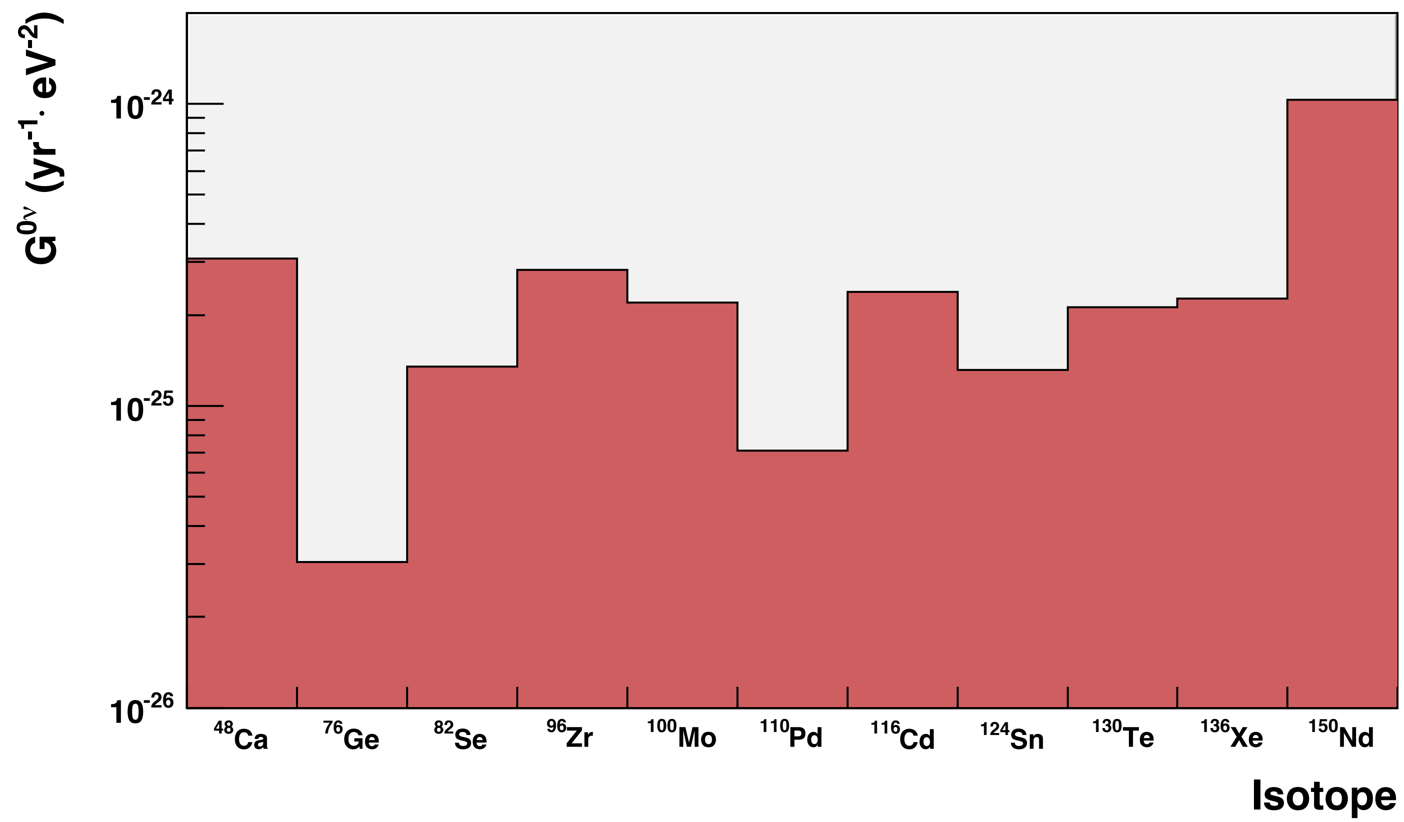
- Get yourself a detector with perfect energy resolution
- Measure the energy of the emitted electrons and select those with (T1+T2)/Q = 1
- Count the number of events and calculate the corresponding half-life.

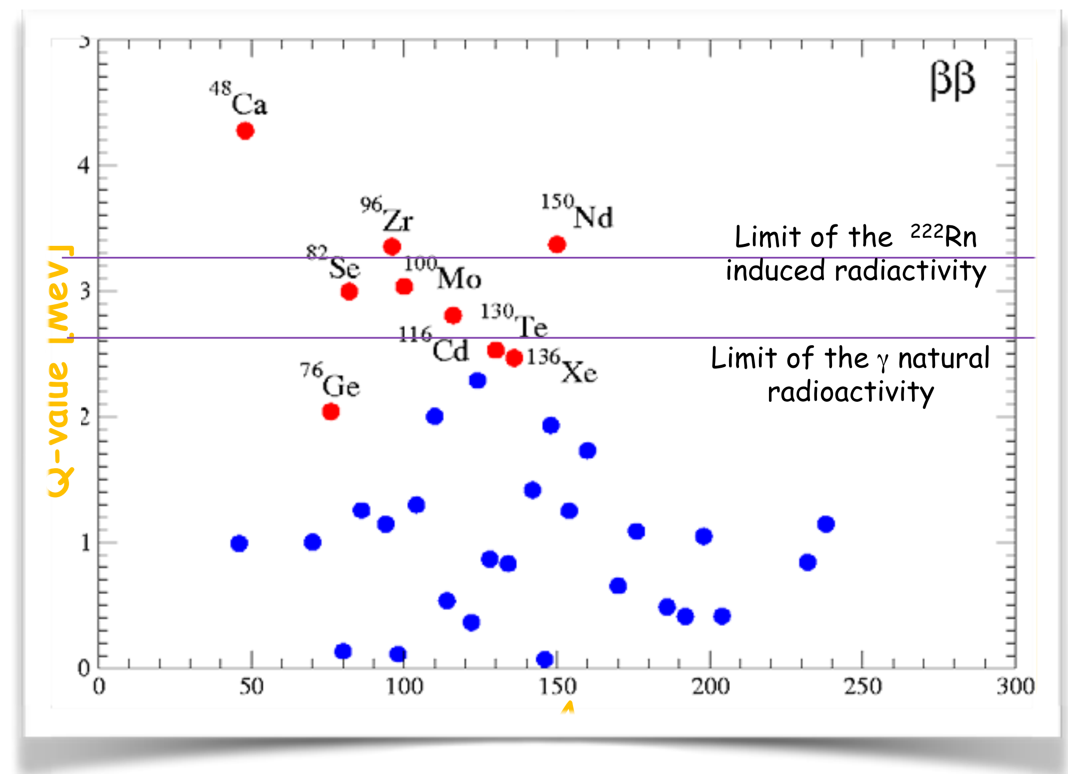
$$N_{0\nu} = \frac{a \cdot N_A}{m_A} \frac{\log 2}{T_{1/2}^{0\nu}} \epsilon \cdot M \cdot t$$

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m_{\beta\beta}^2$$

The Phase space

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

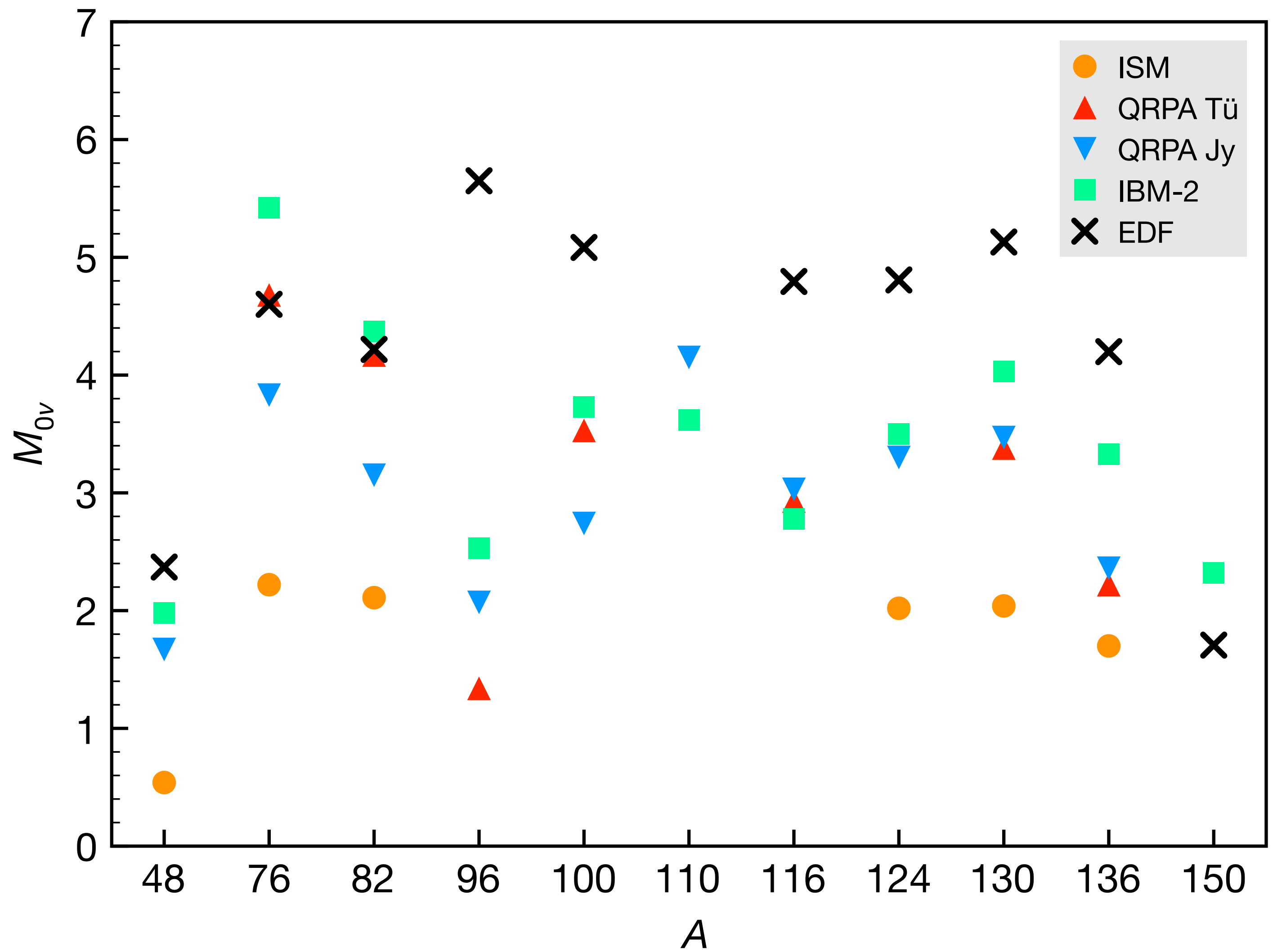




- **Phase space is rather democratic for interesting isotopes, with the notable exception of Ge-76 (lower) and Nd-150 (higher).**

The NME

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$



- **Difference between models can be up to a factor 3 in M →factor 10 in mββ**
- **The discrepancy in NME is a major source of uncertainty (in particular if no discovery is made)**

The signal and the noise

Signal

$$N_{0\nu} = \frac{a \cdot N_A}{m_A} \frac{\log 2}{T_{1/2}^{0\nu}} \epsilon \cdot M \cdot t$$

Period

$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

Background

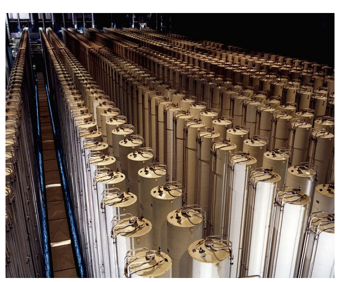
$$N_{bkg} = M \cdot t \cdot B \cdot E$$

- The background depends on the exposure (Mt) and on the product ΔExB. The signal depends on Mt.
- Increasing Mt without decreasing ΔExB implies that the background grows at the same rate of the signal, and therefore the sensitivity to the period only increases with the √Mt and the sensitivity to mββ only increases with $(MT)^{1/4}$
- Thus, a Golden Law: every time that you increase the mass by a factor α you must reduce the background by the same factor.

Building the perfect ββ0ν experiment

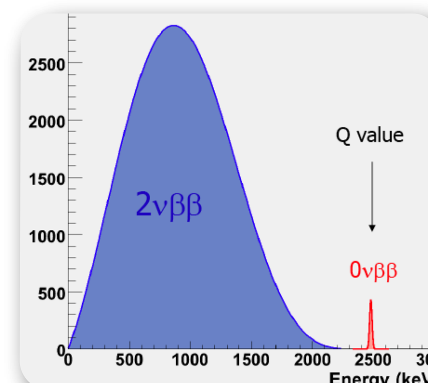
$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

Isotope



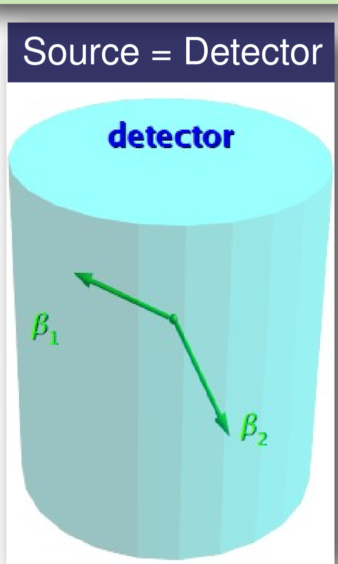
Find an isotope with large Q, no long lived radioactive isotopes, easy to procure and cheap.

ΔE

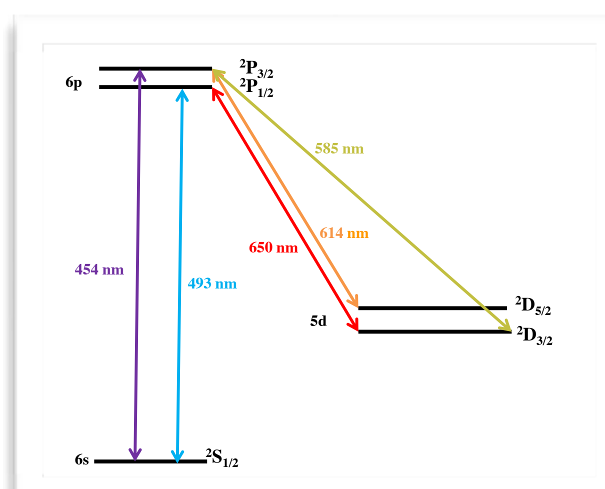


Build a detector with the best possible resolution

Scalability



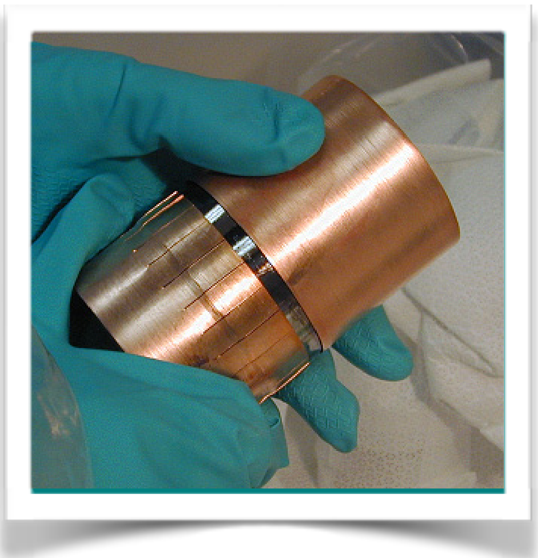
Build a detector with no dead areas, and economy of scale



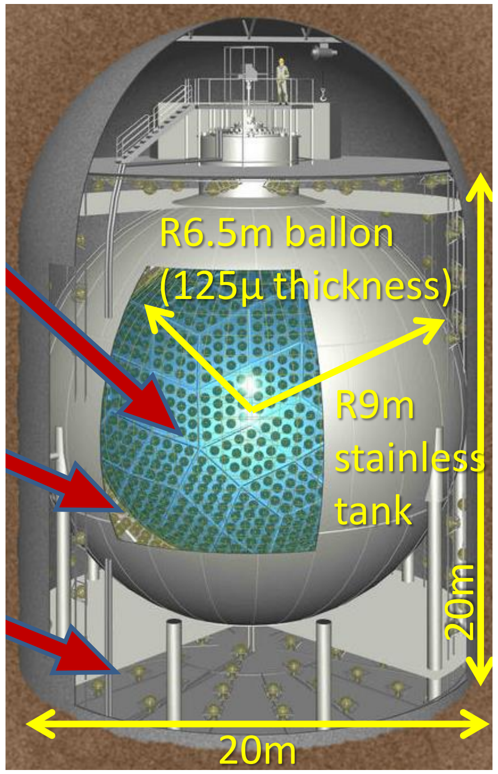
Background

Detector provides extra handles to reduce background

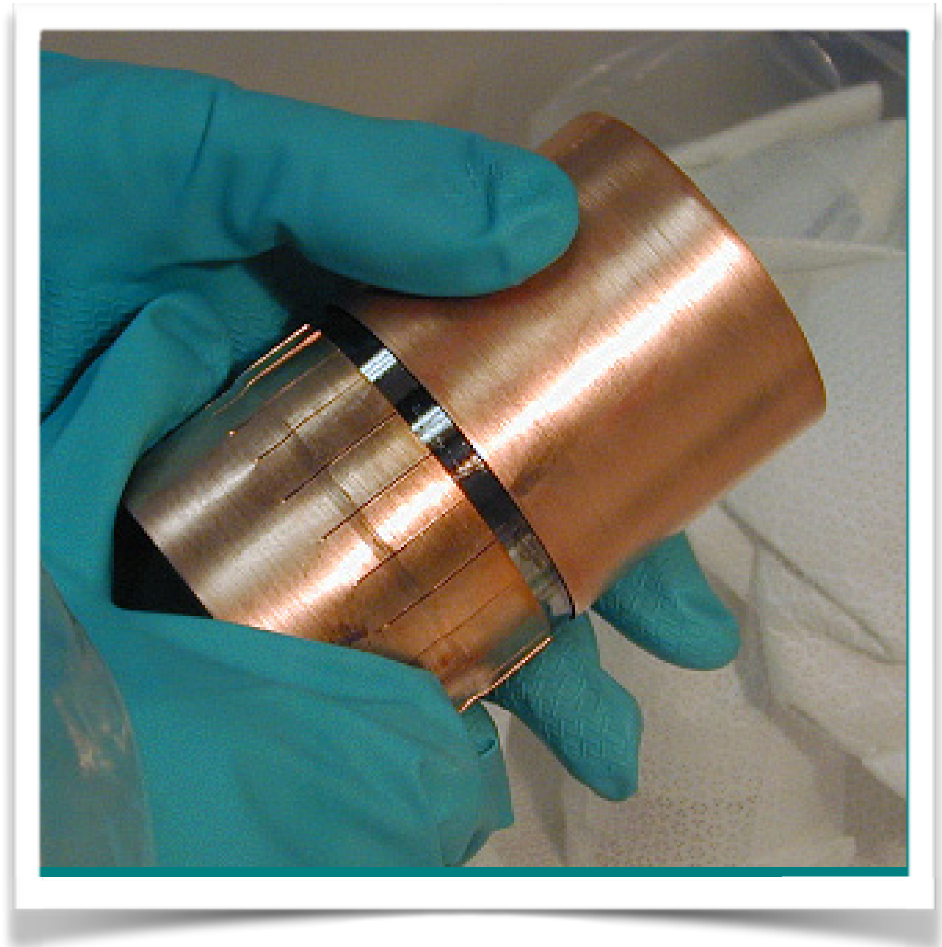
Radiopurity



- Build everything out of extremely radiopure materials.
- Solide state apparatus (GERDA, CUORE), display very low activities in detector material in the range of µBq/kg.



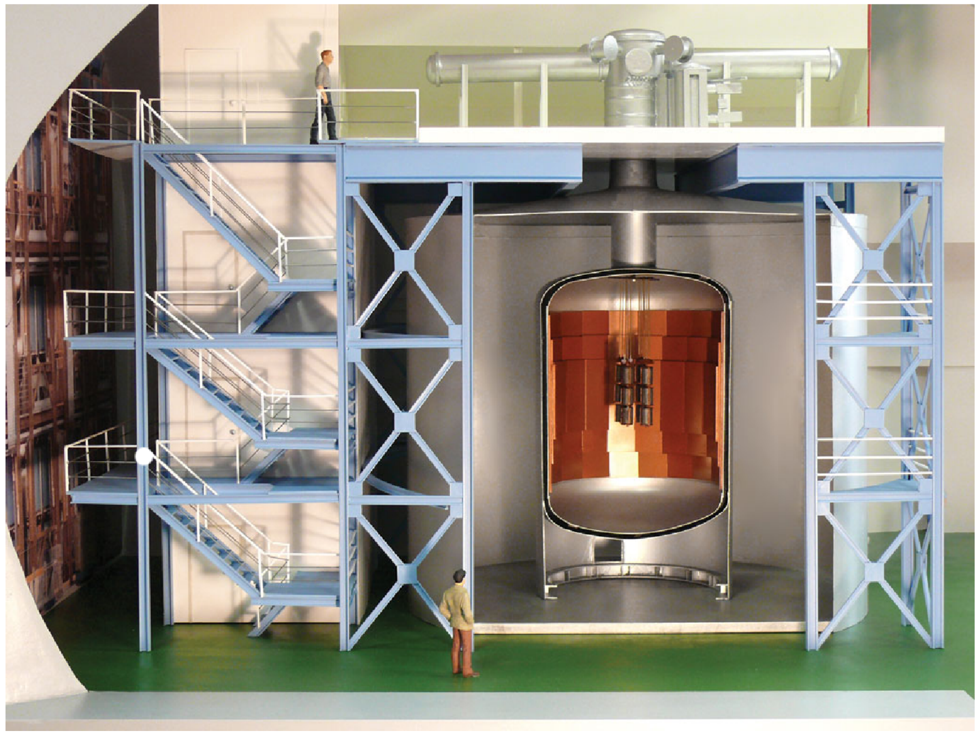
- TPCs (EXO, NEXT), have larger radioactive budget, due to their sensors (PMTs, APDs, SiPMs), but their ability to define a fiducial region away from surfaces, eliminates a whole class of backgrounds (α particles).
- In Super-NEMO the signal is constrained to come from the target, but the background also accumulates in the target and α particle background is relevant.
- LS calorimeters are capable of self-shielding from most backgrounds.



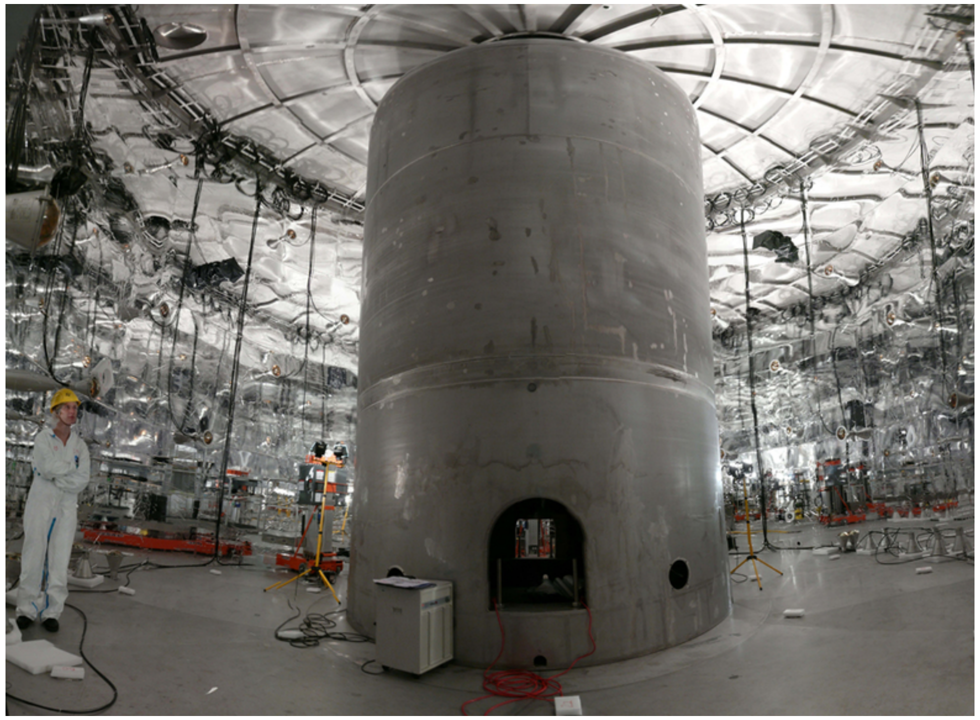
High resolution experiments: Ge diodes, Te bolometers and scintillation bolometers

(see John F. Wilkerson lecture)

GERDA



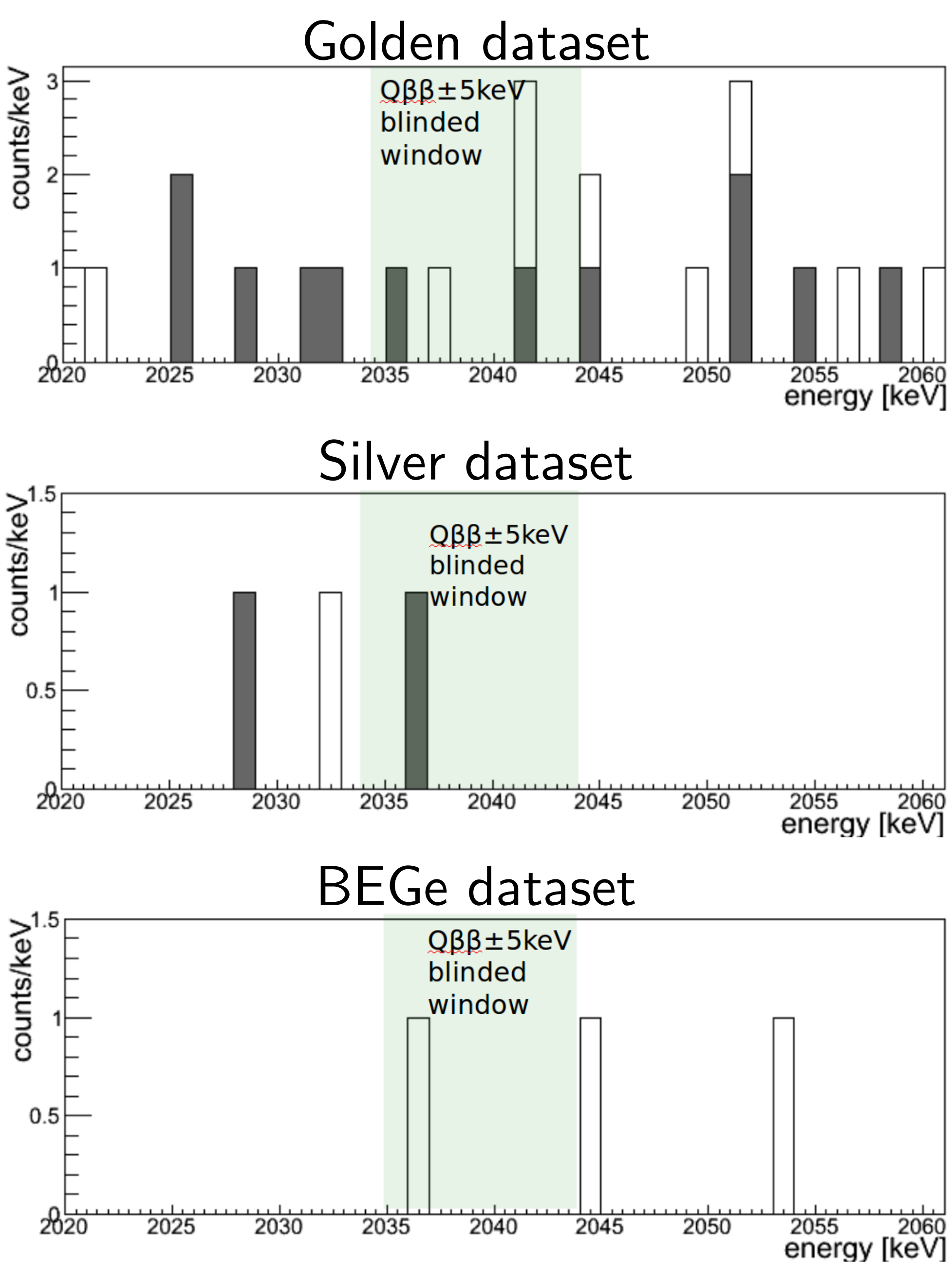
- Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN
- 3800 mwe overburden
- Array of bare enriched Ge detectors in liquid argon (LAr)
- Minimal amount of material in proximity of the diodes



Experiment structure

- 590 m^3 Water Tank to absorb neutrons and veto cosmic muons
- 64 m^3 Liquid Argon (LAr) for cooling and shielding (and vetoing)
- Plastic scintillators above the cryostat to further veto cosmic

GERDA Phase I result



Profile Likelihood Method

- best fit $N^{0\nu} = 0$
- No excess of signal over bkg
- 90% C.L. lower limit:

$$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}\ \text{yr}$$

- Median sensitivity: $2.4 \cdot 10^{25}$ yr

Bayesian Approach

- Flat prior for $1/T^{0\nu}_{1/2}$ in $[0; 10^{-24}]\ \text{yr}^{-1}$
- best fit $N^{0\nu} = 0$
- 90% credibility interval:

$$T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}\ \text{yr}$$

- Median sensitivity: $2.0 \cdot 10^{25}$ yr

Phys. Rev. Lett. 111 (2013) 122503

Do it yourself: reproducing Gerda results

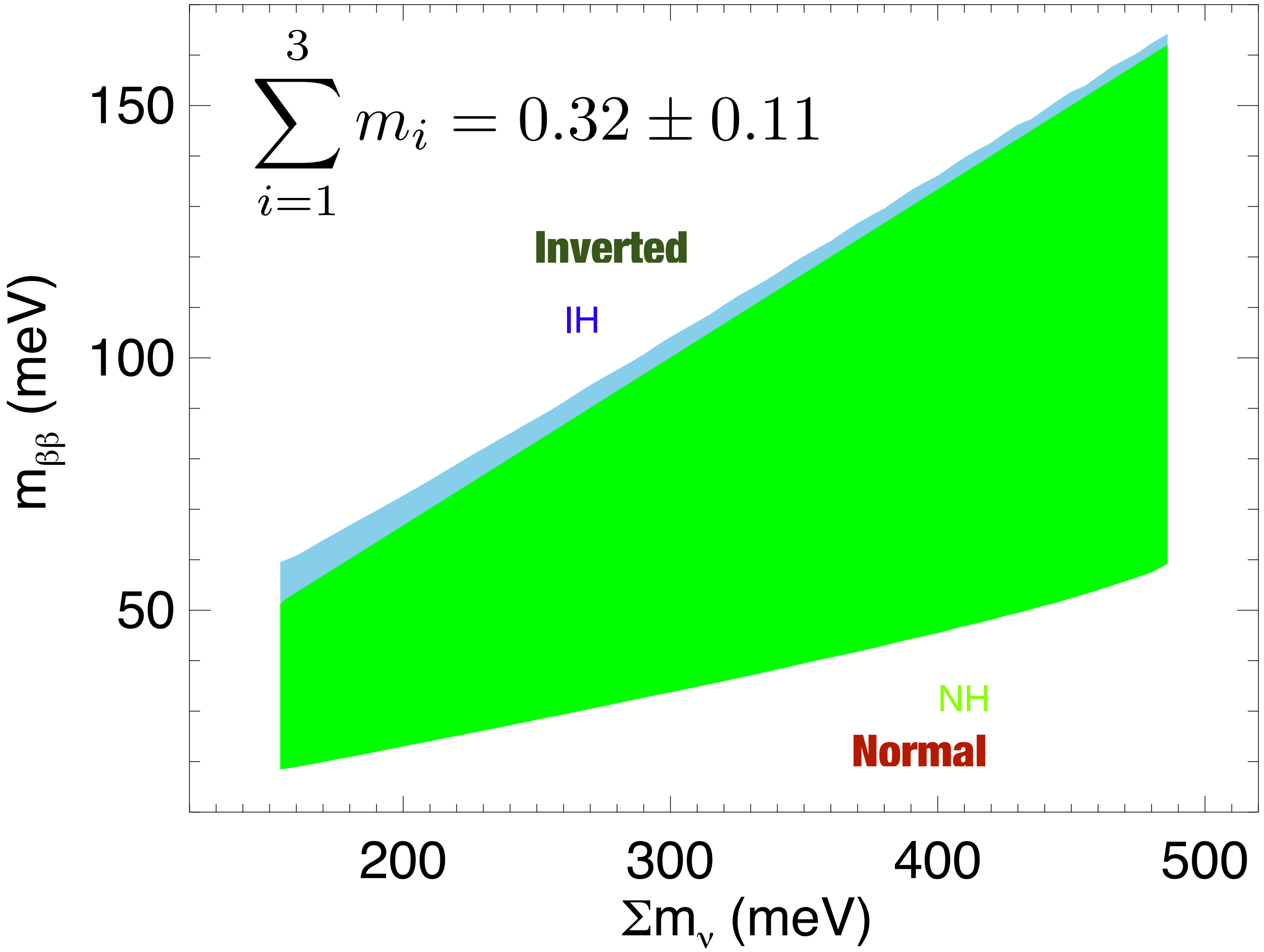
- **Run example GERDAI.py in pybbsens software**
- **Input:**
- efficiency = 0.62
- ΔE = 0.02 % at 2040 MeV
- B = 1.32 x 10^{-2} ckky
- Exposure = 21.6 kg x y
- **Statistical approach**
- 90 % CL using Feldman & Cousins.
- Result
- **$T^{0\nu}$ = 2.2 x 10^{25} y**

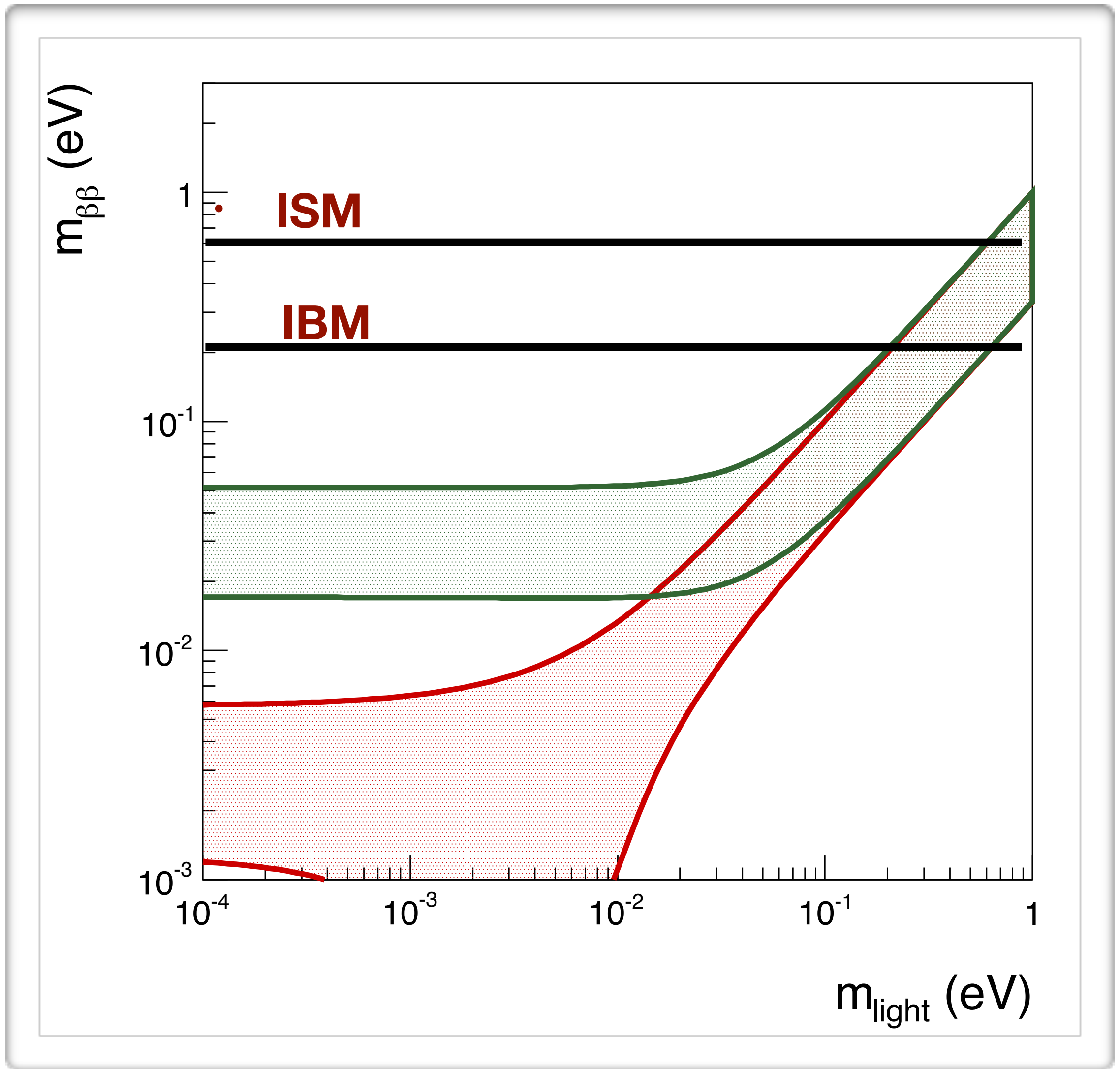
- **Run example GERDAII.py in pybbsens software**
- **Input:**
- efficiency = 0.62
- ΔE = 0.01 % at 2.6 MeV
- B = 1. x 10^{-3} ckky
- Exposure: 200 kg x y
- Mass 50 kg BeGe
- Time 4 x 1.5 ~6 years
- **Statistical approach**
- 90 % CL using Feldman & Cousins.
- Result
- **$T^{0\nu}$ = 2.3 x 10^{26} y**

https://github.com/jmalbos/pybbsens

- **Go to directory EXAMPLES**

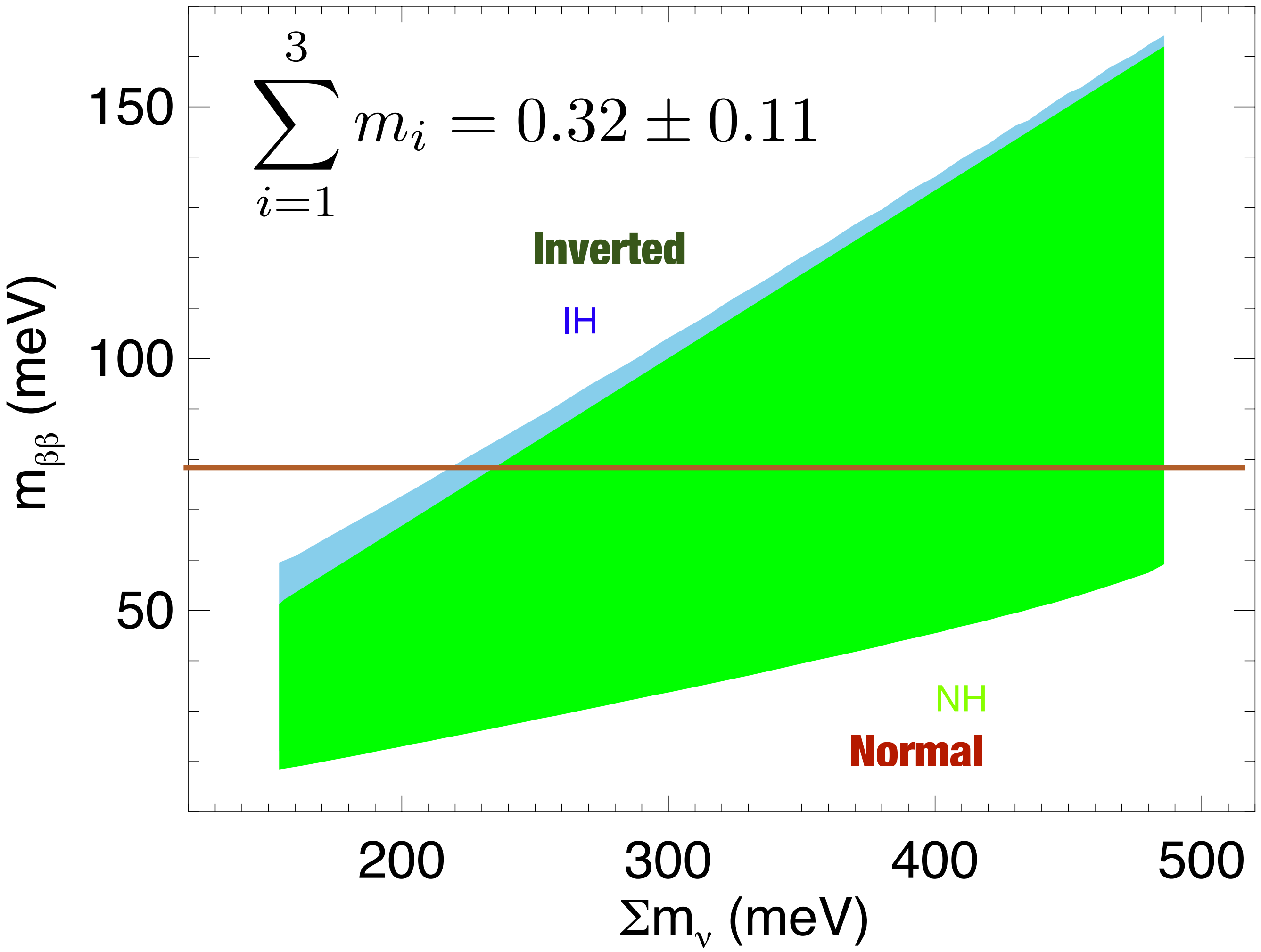
GERDA I

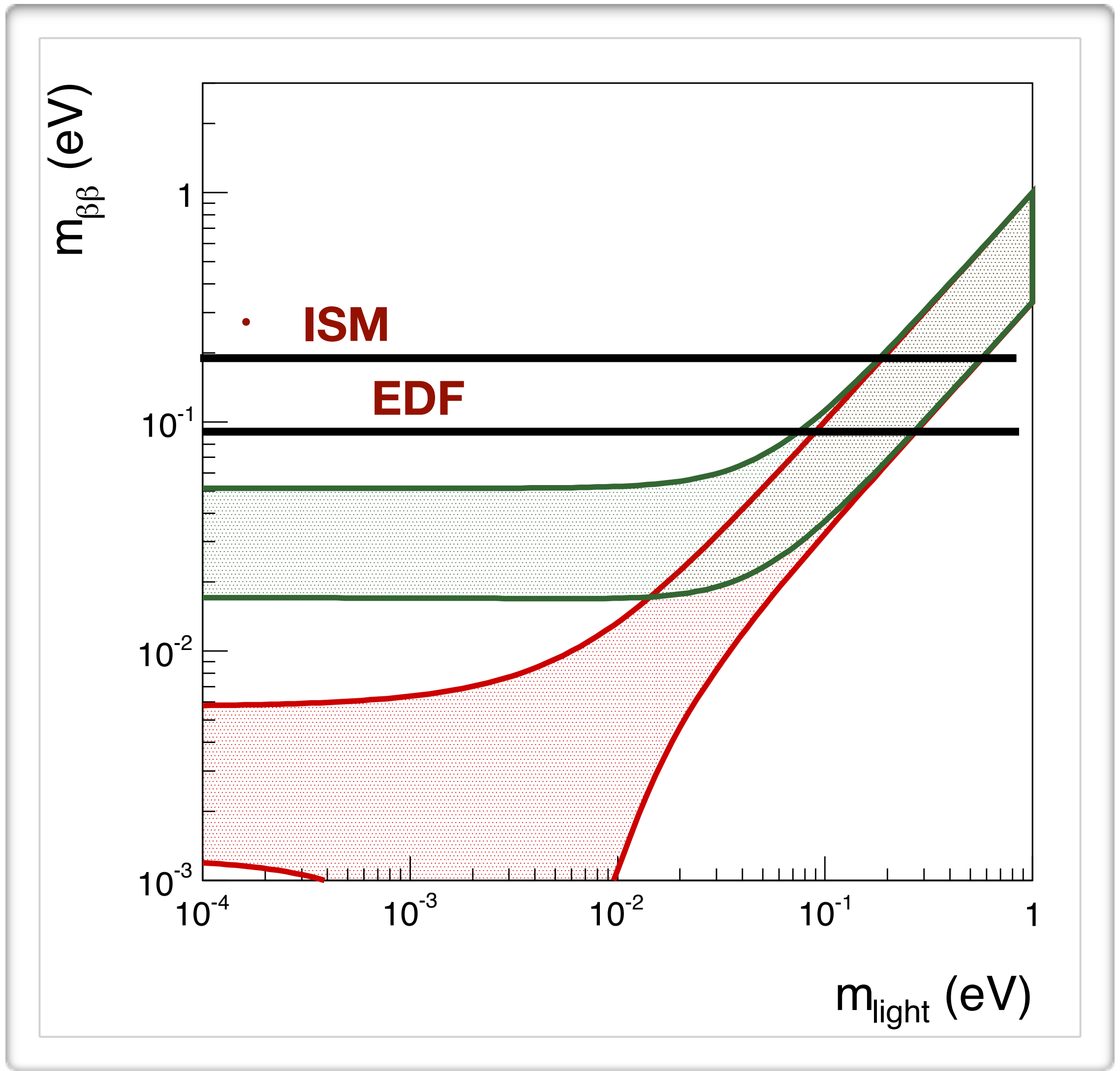




- **In terms of $m_{\beta\beta}$**
- ISM (worst case): **648.7 meV**; IBM2 (best case): **257.8 meV**
- **Not yet in “cosmo-region”**

GERDA II





- **In terms of $m_{\beta\beta}$**
- ISM (worst case): **200 meV**; IBM2 (best case): **80 meV**
- **Gerda II will explore a fraction of the "cosmo-region", but still "degenerate hierarchy"**

Bolometers using natural Te: CUORE

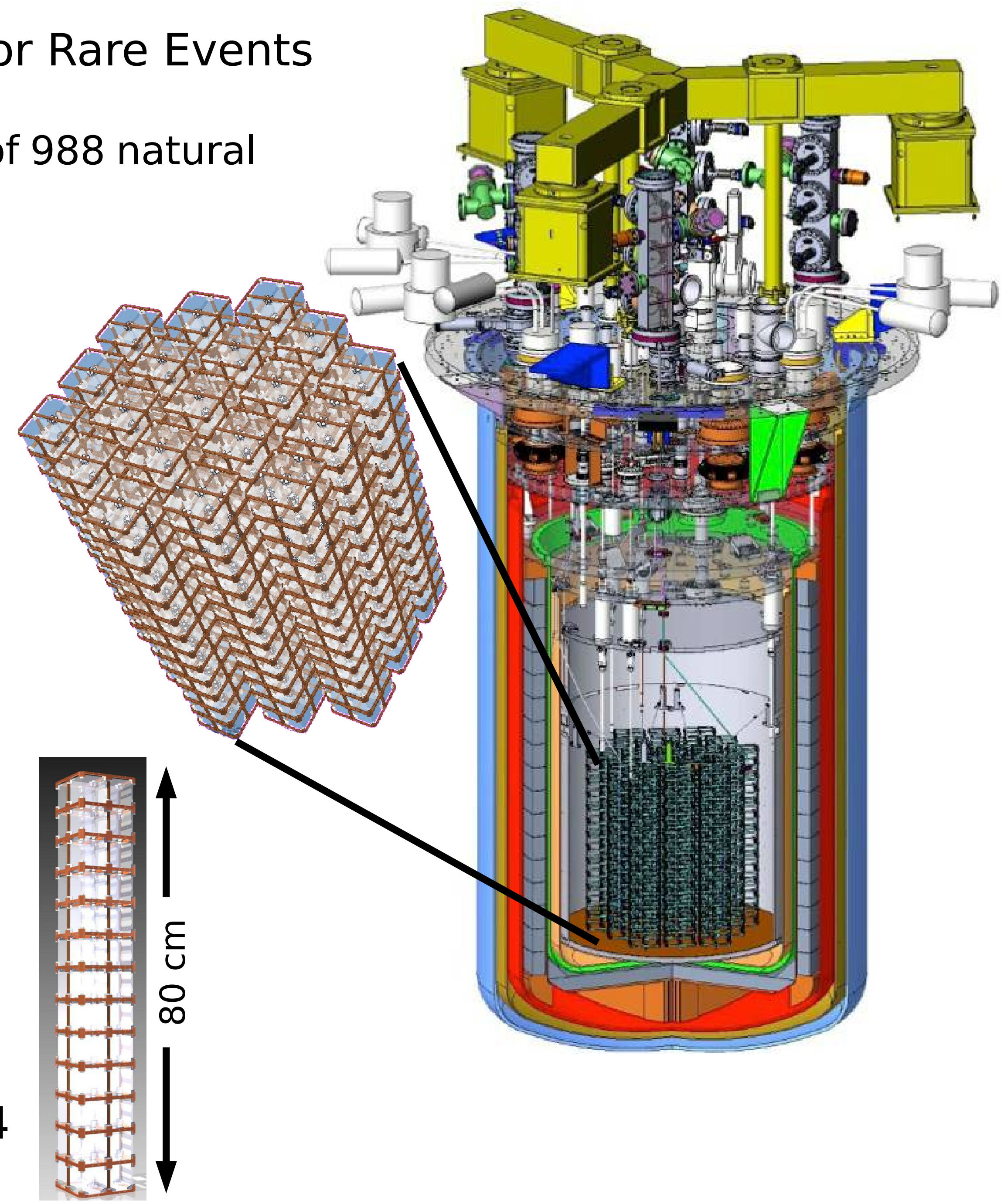
Cryogenic Underground Observatory for Rare Events

- Search for 0vDBD in ^{130}Te using an array of 988 natural TeO_2 bolometers

Detector parameters:
- ^{130}Te mass: 206 kg (~10^{27} nuclei)
- 988 TeO_2 bolometers (741 kg)
  - 19 towers
  - 52 bolometers/tower
- Single bolometer:
  - 5x5x5 cm^3 TeO_2 crystal

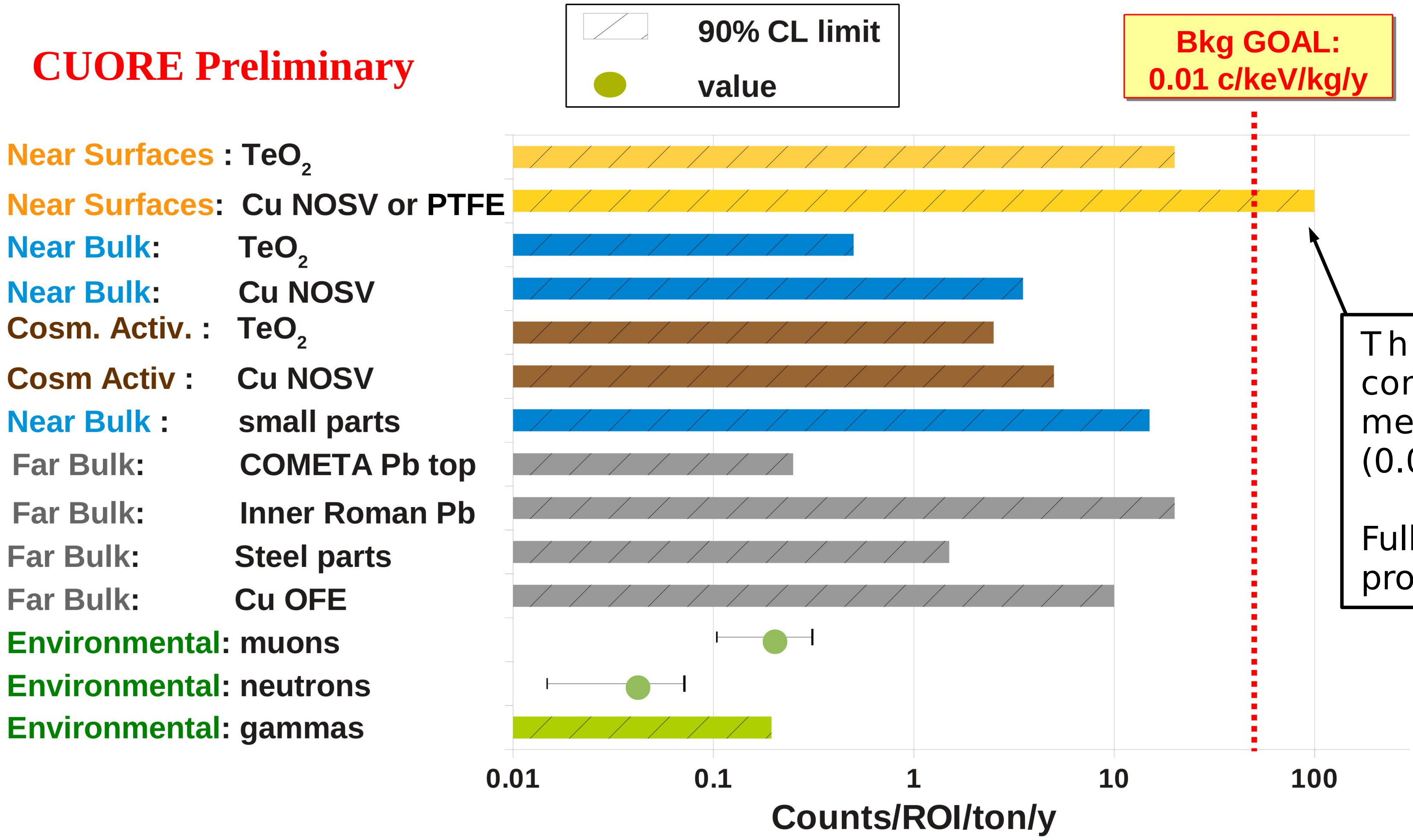
Goals:
- Resolution: 5 keV FWHM at 2.5 MeV
- Bkg: 0.01 counts/(keV kg y)

Detector cool down at the end of 2014



Background budget

- New cryostat with radio-pure materials: γ contributions are made negligible
- Less copper surface facing the crystals: α bkg from copper surfaces can be reduced
- More crystal surfaces facing each others: more effective anticoincidence, negligible α bkg from crystal surfaces

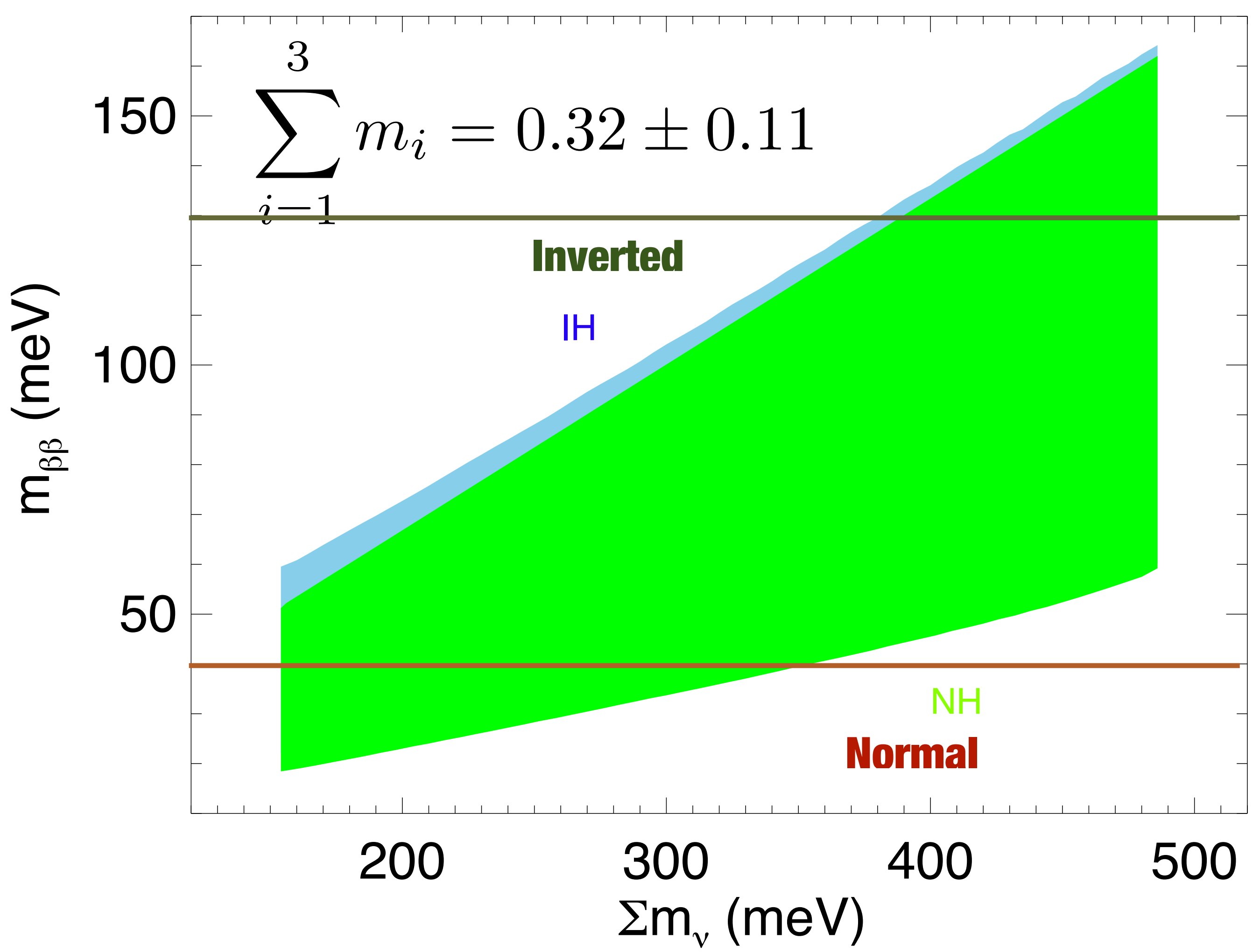


Conservative upper limits

This is the "alpha" continuum background measured in CUORE-0 (0.019 counts/(keV kg y)

Full MC simulation still in progress

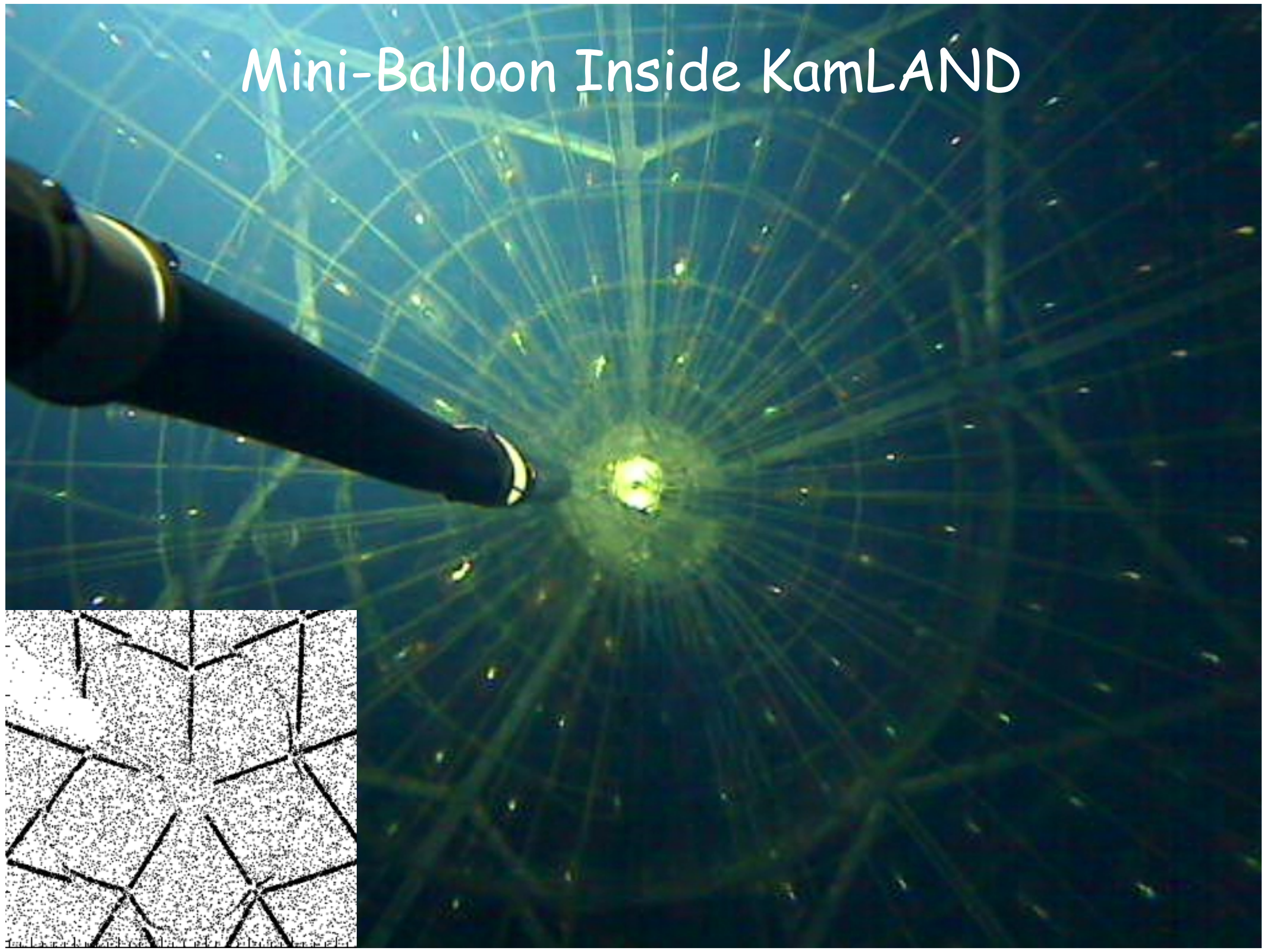
Predicting CUORE results



- **Run example CUORE.py in pybbsens software**
- **Input:**
- efficiency = 0.87
- ΔE = 0.02 % at 2600 MeV
- B = 1. x 10^{-2} ckky (projected)
- Exposure =1000 kg x y
- **Statistical approach**
- 90 % CL using Feldman & Cousins.
- Result
- **$T^{0\nu}$ = 1 x 10^{26} y**

- Mass 206 kg
- Time ~5-7 years
- **$m_{\beta\beta}$ = 41-129 meV**

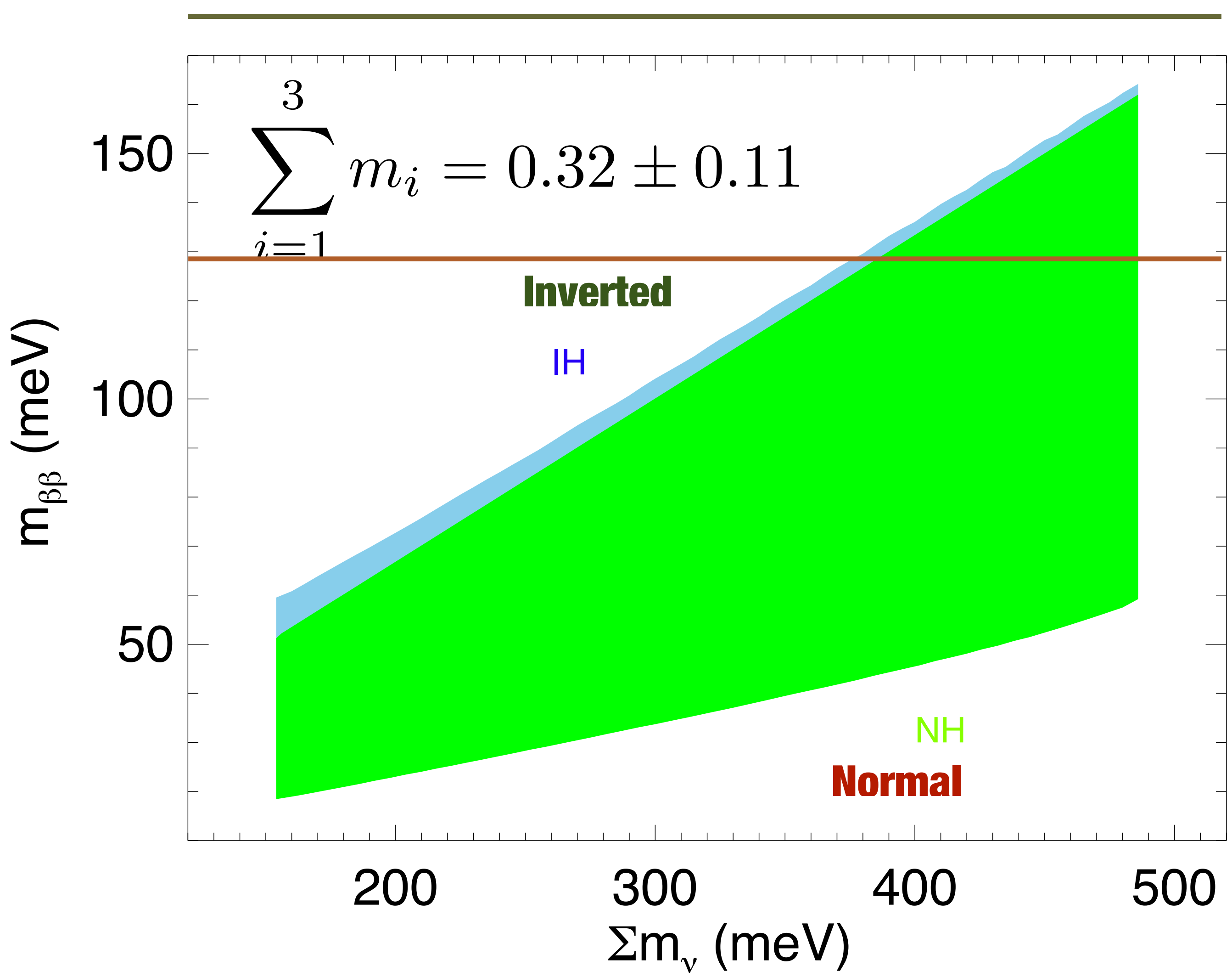
- **Reaches similar sensitivity on period than GERDA-II but more sensitive to $m_{\beta\beta}$.**
- **Will cover a significant fraction of the cosmo-region (depending on NME)**



Low resolution, high self-shielding experiments: LS calorimeters, KamLAND-ZEN and SNO+

(see John F. Wilkerson lecture)

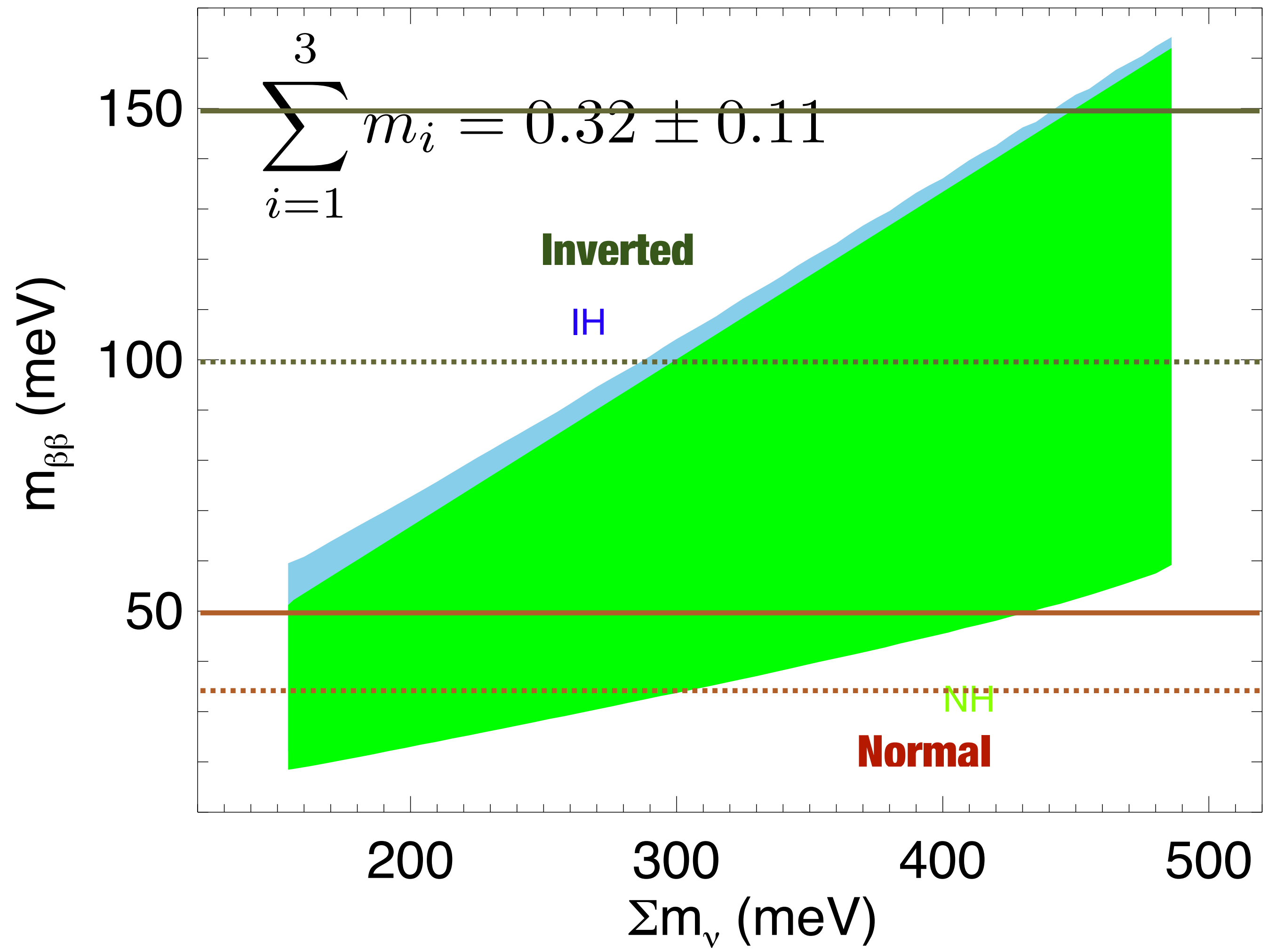
Reproducing KamLAND-Zen results



- **Run example KZEN.py in pybbsens software**
- **Input:**
- efficiency = 0.55
- ΔE = 10 % at $Q_{\beta\beta}$
- B = 6 x 10^{-4} ckky
- Exposure =89.5 kg x y
- **Statistical approach**
- 90 % CL using Feldman & Cousins.
- Result
- **$T^{0\nu}$ = 2.0 x 10^{25} y**

- Mass 170 kg in fiducial volume
- **$m_{\beta\beta}$ = 127-355 meV**

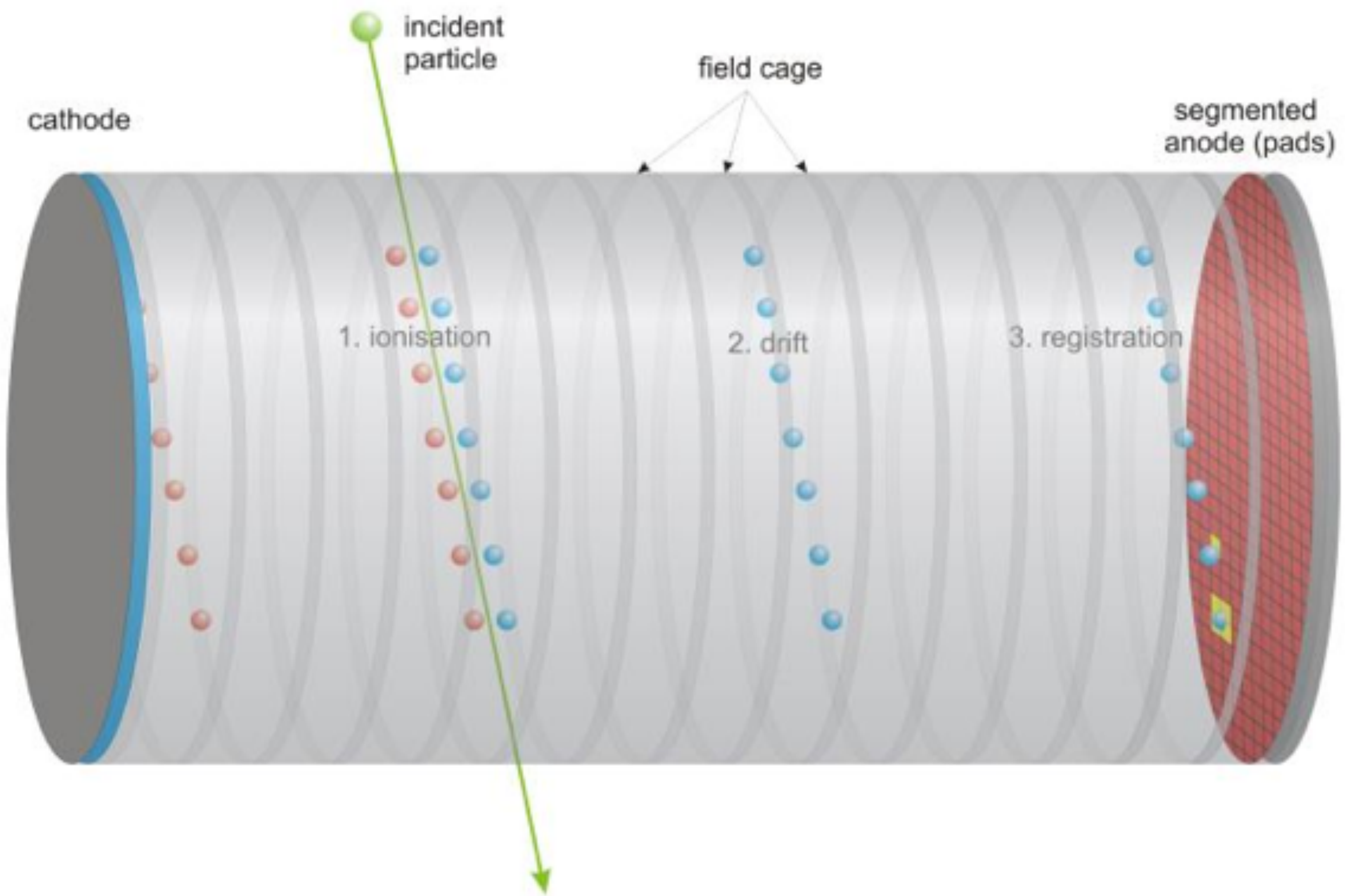
Second phase: the 600 kg run



- **440 kg x 5 yr ~2200 kg x yr**
- **B=6 x 10^{-4} ckky ⇒**
  - **$T^{0\nu}$=1 x 10^{26}⇒$m_{\beta\beta}$ = 53-149 meV**
- **B=10^{-4} ckky ⇒**
  - **$T^{0\nu}$=2.7 x 10^{26}⇒$m_{\beta\beta}$ = 35-98 meV**

- **The second phase of KamLAND-ZEN appears to be capable of covering a very large fraction of the cosmo-region. The crucial issue is to understand the background index, which is very low and very difficult to measure.**

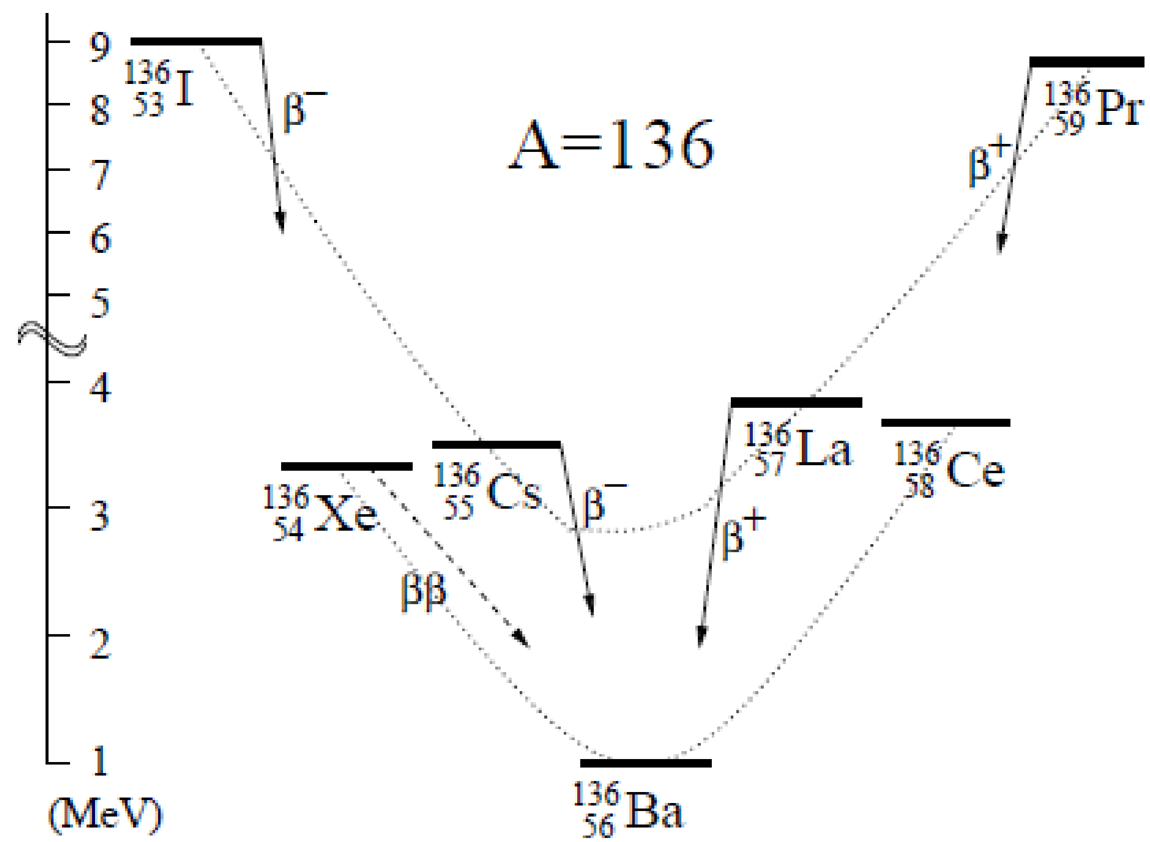
Xenon TPCs



- **The Time Projection Chamber (TPC). Invented by Dave Nygren, is one of the most successful detectors in nuclear and particle physics.**
- **It provides 3D image of tracks and if track contained also energy by calorimetric measurement.**

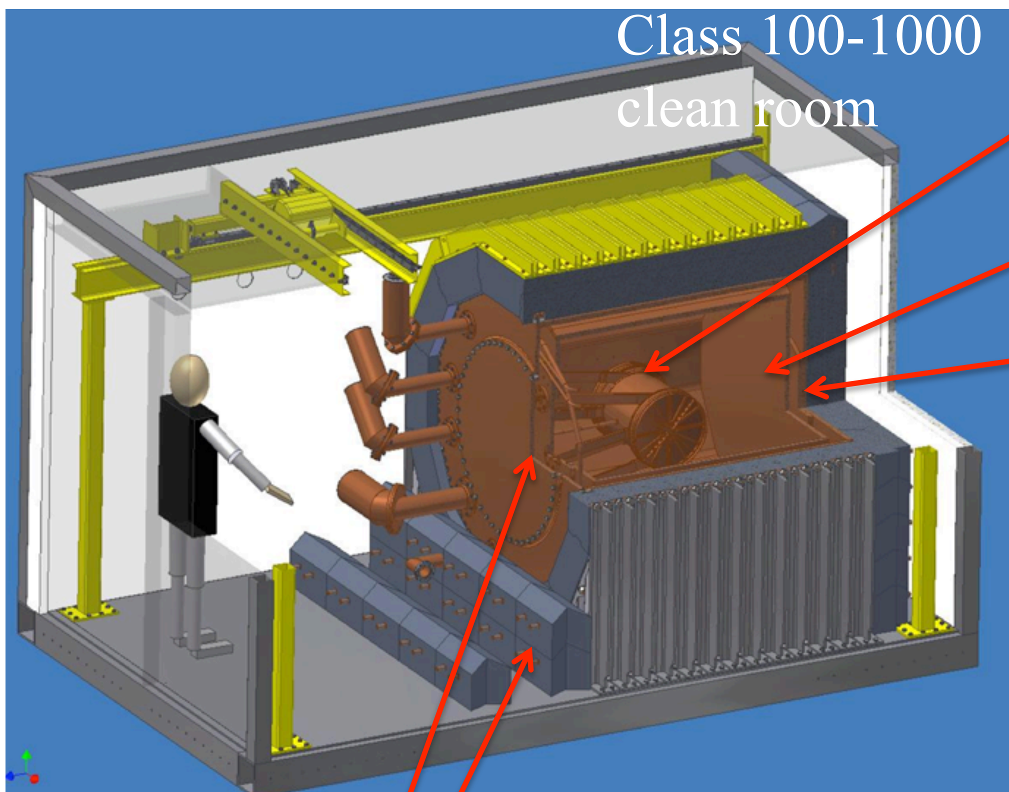
Xenon is a noble gas: one can build at Xenon TPC

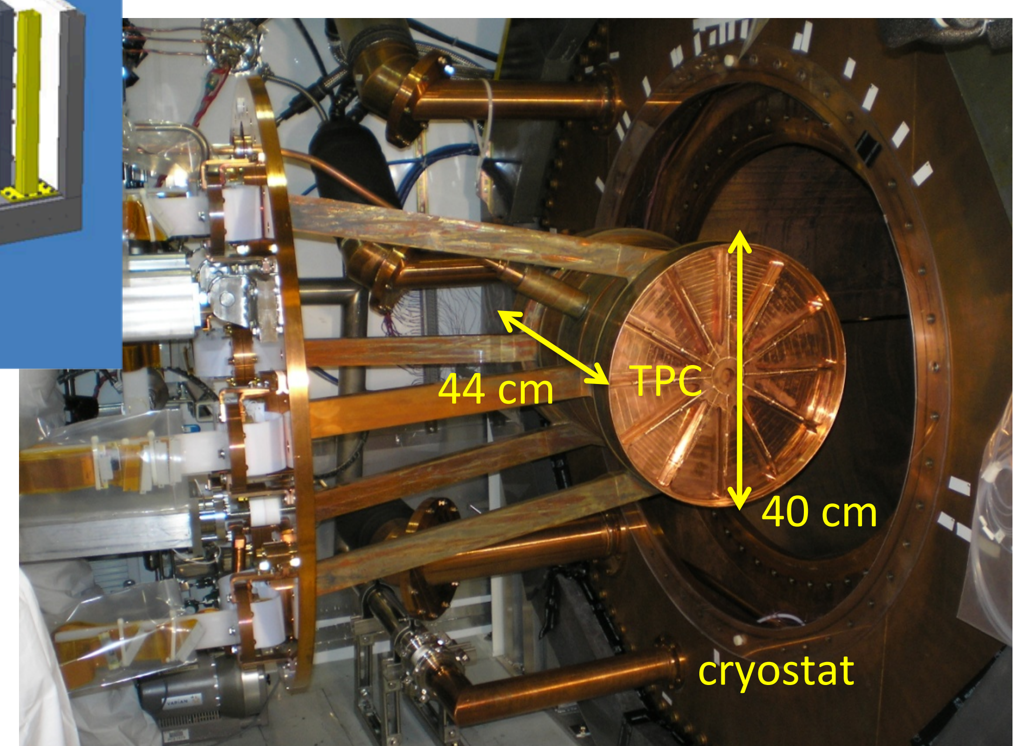
- Xenon is a good candidate for bb0n search
  - Q-value larger than energy of gammas from most natural radionuclides
  - Relatively easy to enrich in Xe-136 isotope
    - (no chemistry, centrifuge eff ~ dm=4.7 a.m.u.)
  - No need to grow high-purity crystals, continuous purification is possible (and relatively easy for a noble gas), more easily scalable
  - No long-lived cosmogenically activated isotopes
  - Final state (Ba-136 ion) can, in principle, be tagged, greatly reducing backgrounds



EXO

- 200 kg of Xe enriched to 80.6% Xe-136 total procured
  - 175 kg in liquid phase inside a cylindrical Time Projection Chamber
  - ~100 kg current fiducial mass

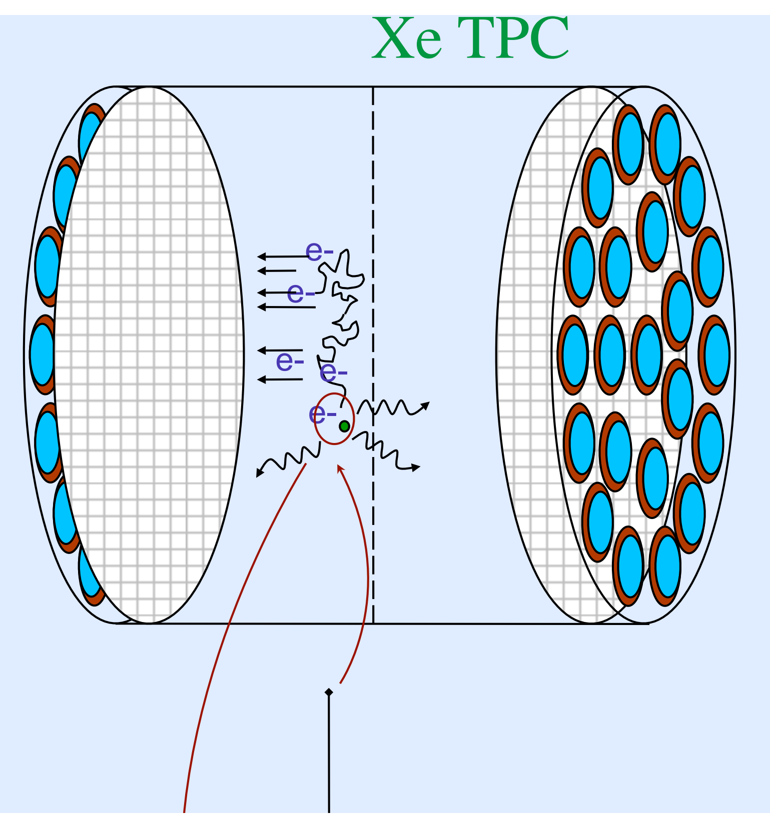




EXO detection strategy

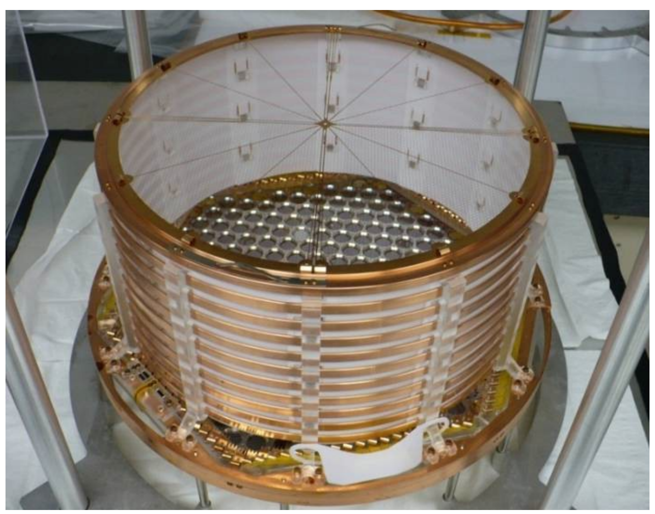
detect the 2 electrons
(ionization + scintillation in xenon TPC)

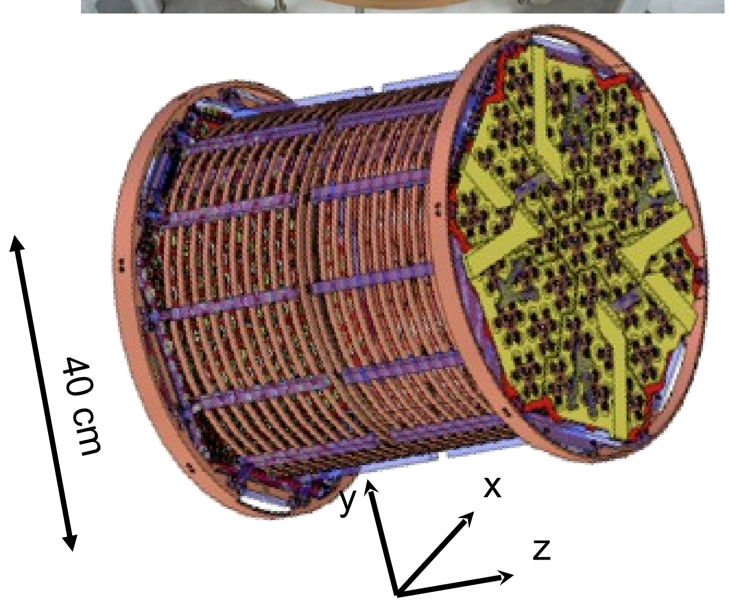
$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}\ (+\ 2\nu_e)$



EXO TPC

- 200 kg of Xe enriched to 80.6% Xe-136 total procured
  - 175 kg in liquid phase inside a cylindrical Time Projection Chamber
  - ~100 kg current fiducial mass





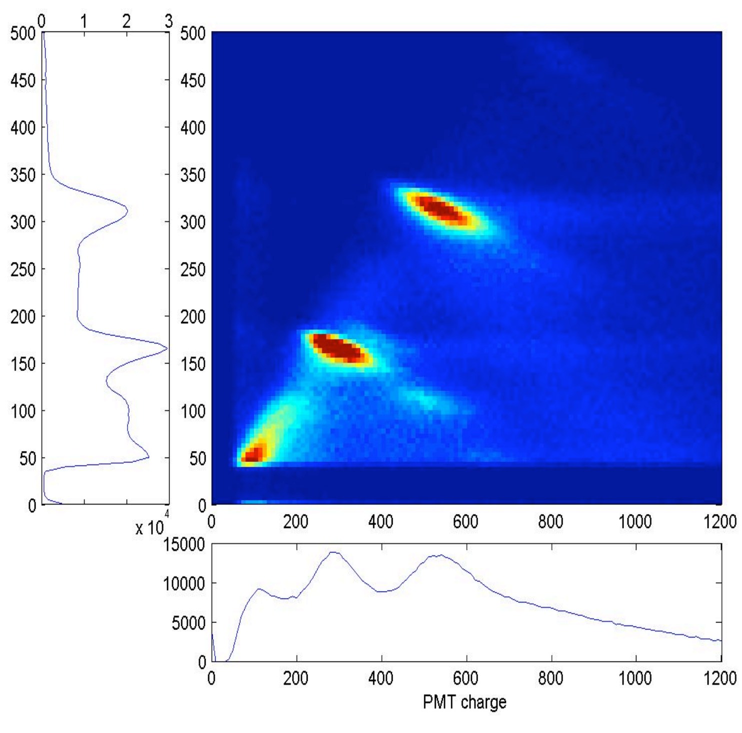
- Common cathode + Two Anodes
  - 376 V/cm drift field
- Each half records both charge and scintillation information with
  - 38 U (charge collection) + 38 V (charge induction) triplet wire channels, crossed at 60 degrees
    - Wire pitch 3 mm (9 mm / channel)
    - Photo-etched Phosphor bronze
  - 234 large area avalanche photo-diodes, in groups of 7 (178 nm Xe light)

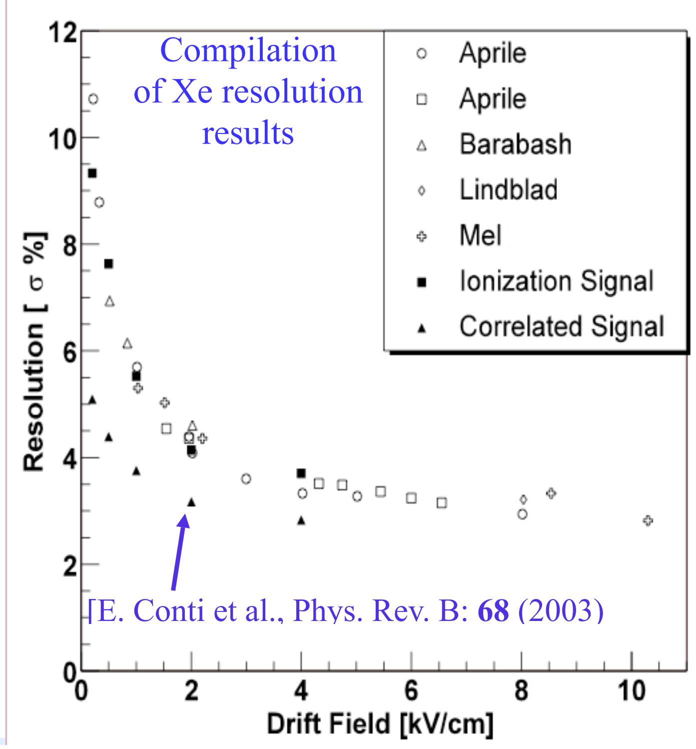
Energy resolution

Anti-correlated ionization and scintillation improves the energy resolution in LXe

Ionization alone:
σ(E)/E = 3.8% @ 570 keV
or 1.8% @ $Q_{\beta\beta}$

Ionization + Scintillation:
σ(E)/E = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$



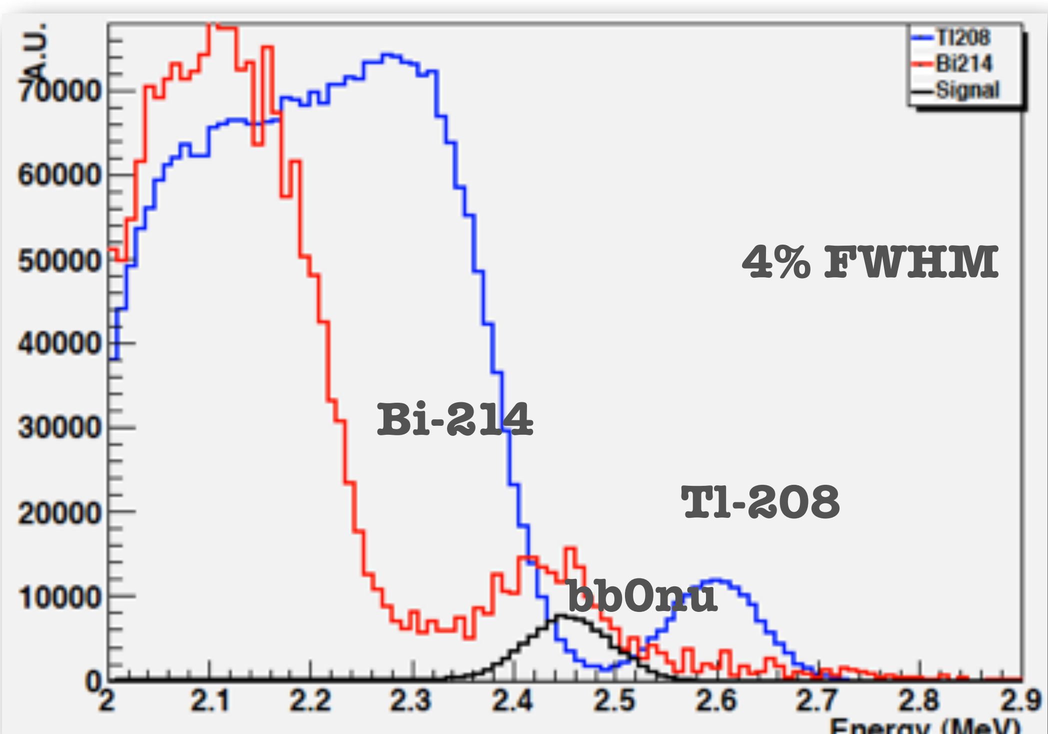


$$\frac{\Delta E}{E}(FWHM) = 2.4 \times \frac{\Delta E}{E}(rms) = 3.6\%$$

EXO main backgrounds

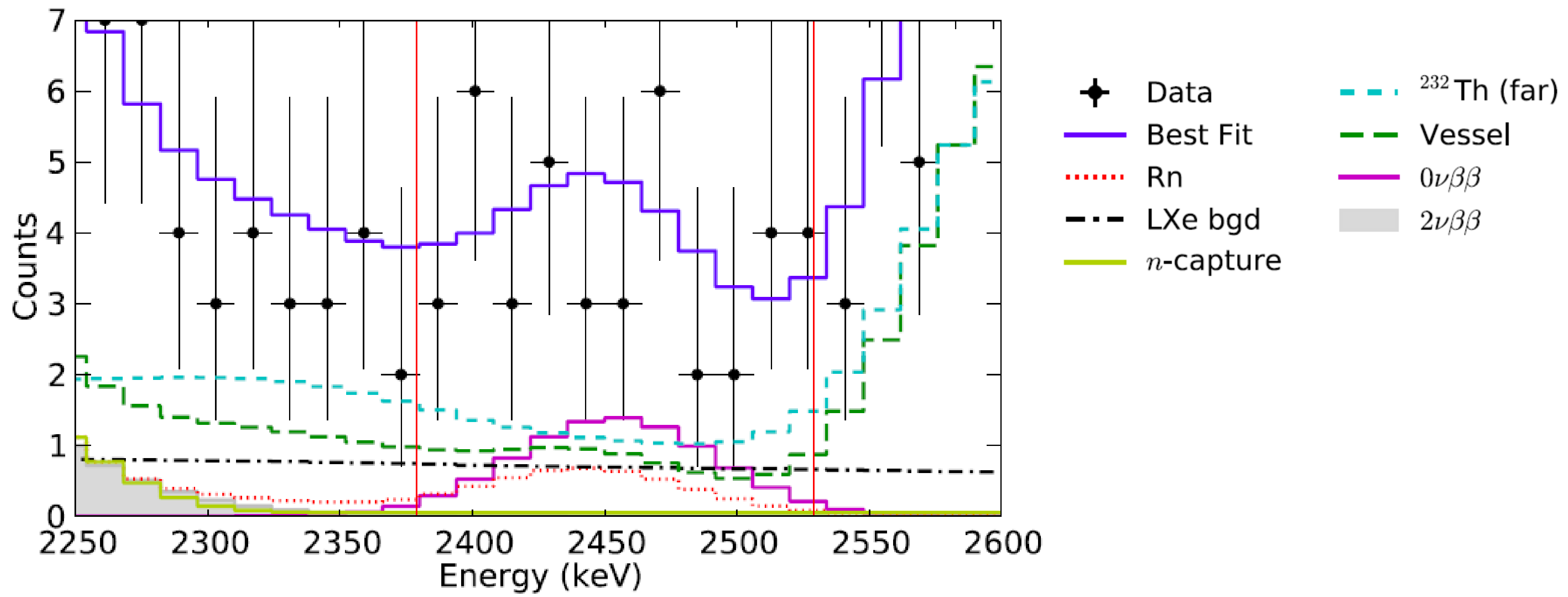
- γ (2449 keV) from ^{214}Bi decay (from ^{238}U and ^{222}Rn decay chains)
- γ (2615 keV) from ^{208}Tl decay (from ^{232}Th decay chain)
- γ (1.4 MeV) from ^{40}K (a concern for the $2\nu\beta\beta$)
- ^{60}Co: 1173 + 1333 keV simultaneous γ's (from ^{63}Cu(α,n)^{60}Co)
- other γ's in ^{238}U and ^{232}Th chains
- other cosmogenics of Cu (a concern for the $2\nu\beta\beta$)
- in situ cosmogenics in Xe, neutron capture de-excitations, ...

- ^{222}Rn anywhere (Xe, HFE, air gaps inside lead shield)



- **TPC fiducialization (only events in the fiducial volume, away from surfaces), and good 3D location eliminates all alpha background (a concern for Ge, bolometers) leaving only high energy gammas.**
- **However ~4% FWHM energy resolution does not allow to separate signal peak from leading Bi-214 and Tl-208 peaks**

Fit results close up

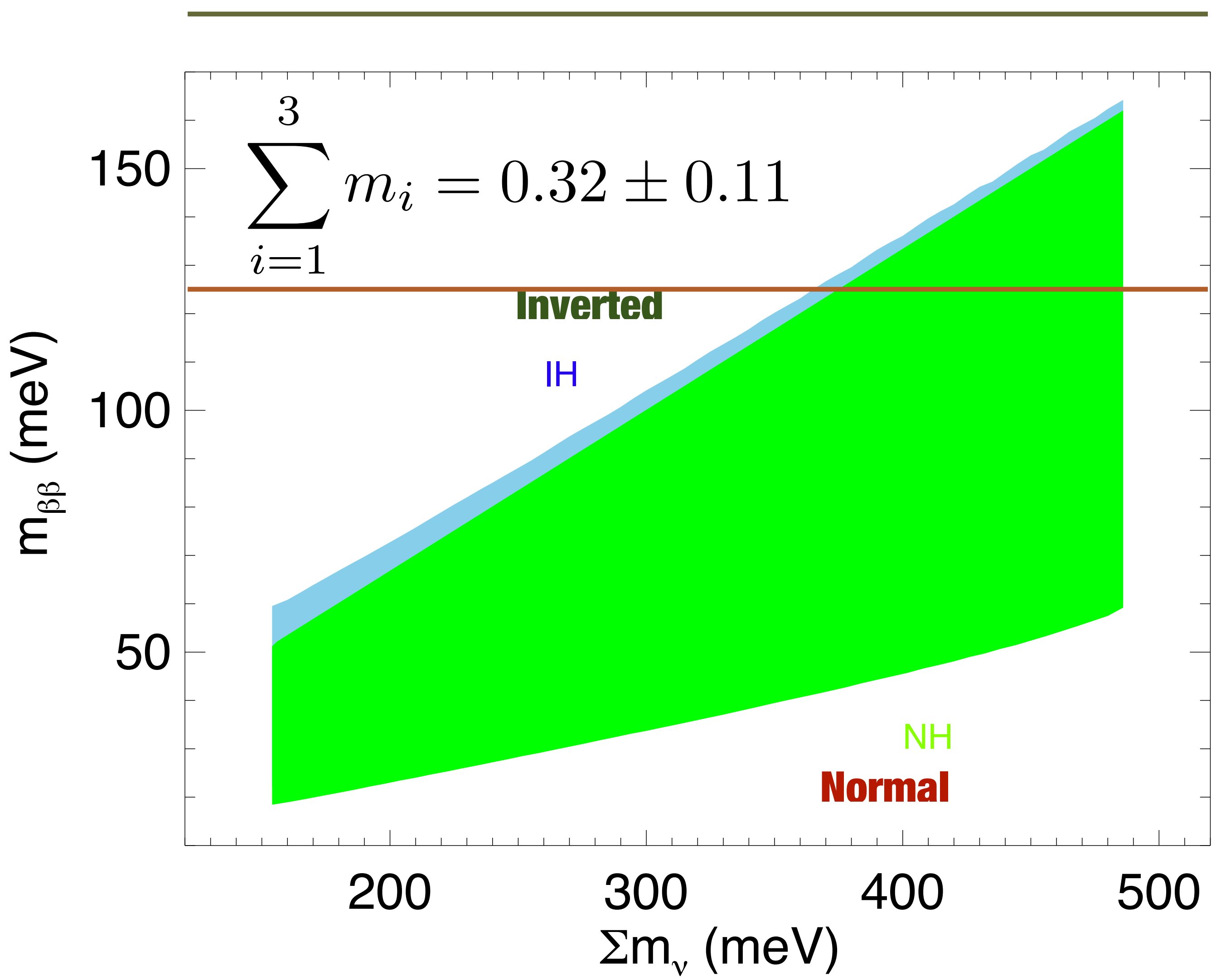


2 sigma ROI breakdown for major backgrounds

	Events	BI, 1e-3 /kg/yr/keV*
Th-232	16.0	
U-238	8.1	
Xe-137	7.0	
Total	31.1±1.89(stat)±3.3(syst)	1.7±0.2

- **BI ~4 x 10^{-3} ckky**

EXO

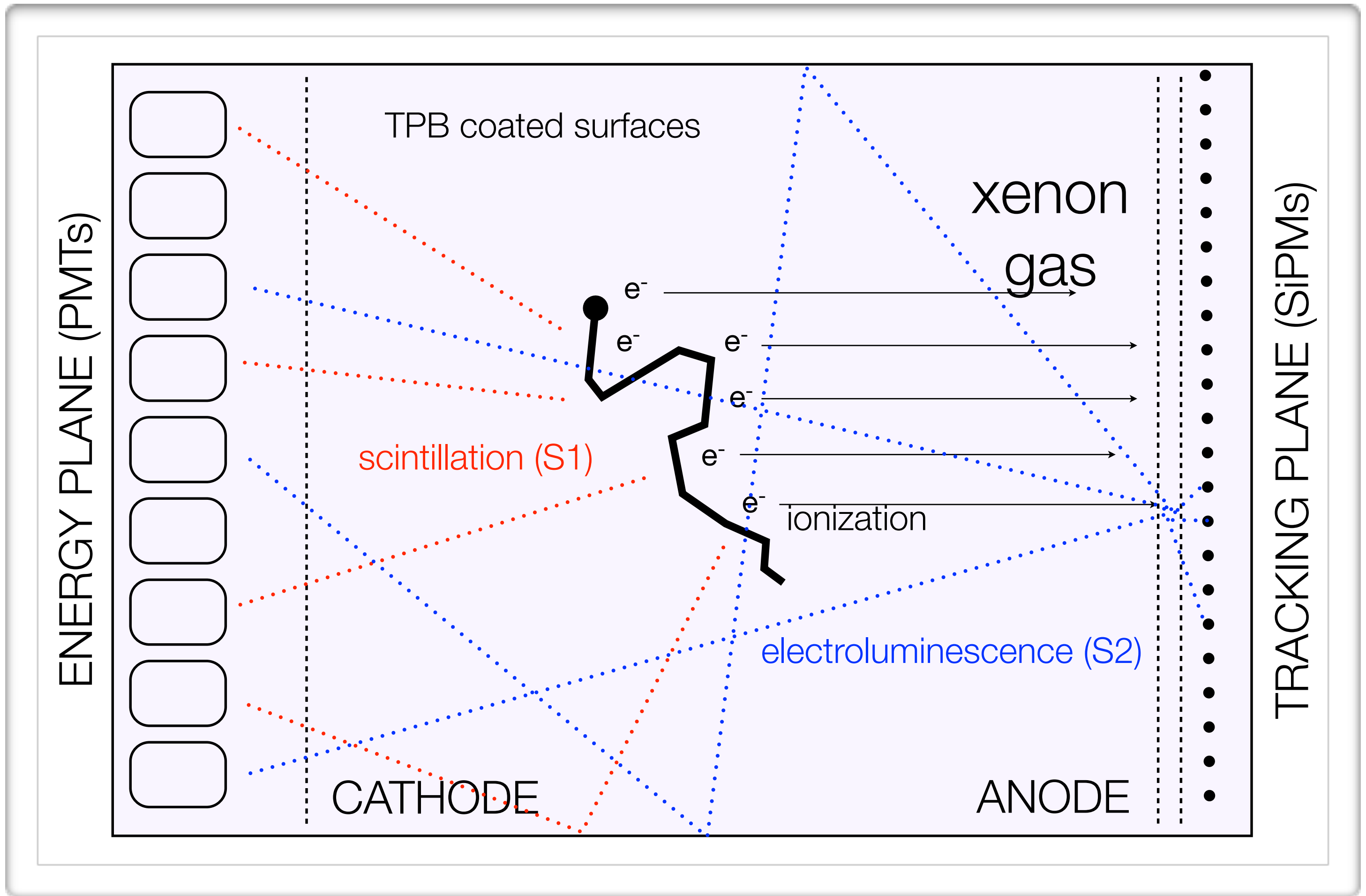


- **100 kg yr**
- **ΔE=3.6 % FWHM at $Q_{\beta\beta}$**
- **B=4 x 10^{-3} ckky ⇒**
  - **$T^{0\nu}$=2 x 10^{25}⇒**
  - **$m_{\beta\beta}$ = 125-352 meV**

- **Similar result to that of KamLAND-ZEN.**

Neutrino Experiment with a (High Pressure Gas) Xenon TPC

NEXT: A light TPC

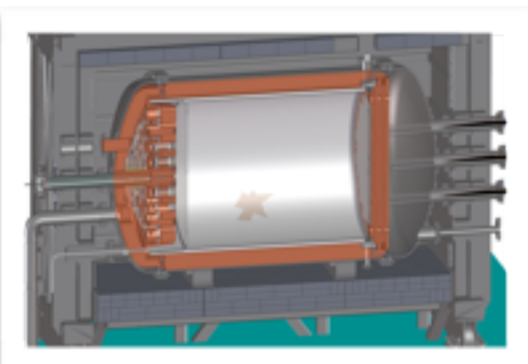


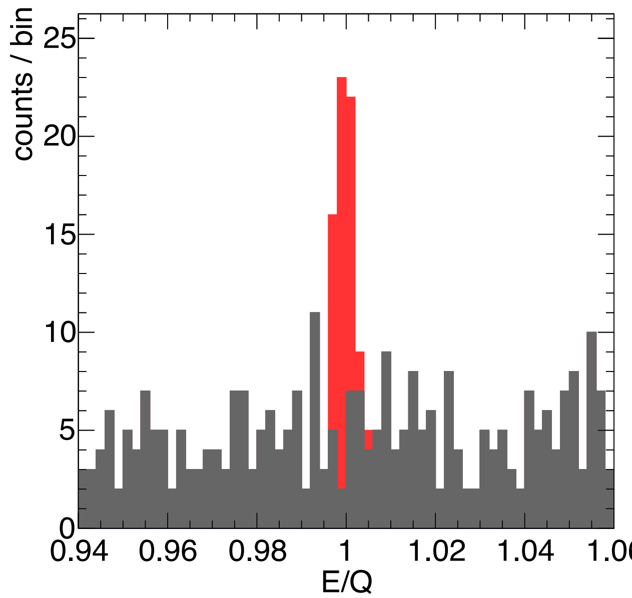
EL mode is essential to get lineal gain, therefore avoiding avalanche fluctuations and fully exploiting the excellent Fano factor in gas

- It is a High Pressure Xenon (HPXe) TPC operating in EL mode.
- It is filled with 100 kg of Xenon enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane), which also provide t0.
- The event topology is reconstructed by a plane of radiopure silicon pixels (MPPCs) (tracking plane).

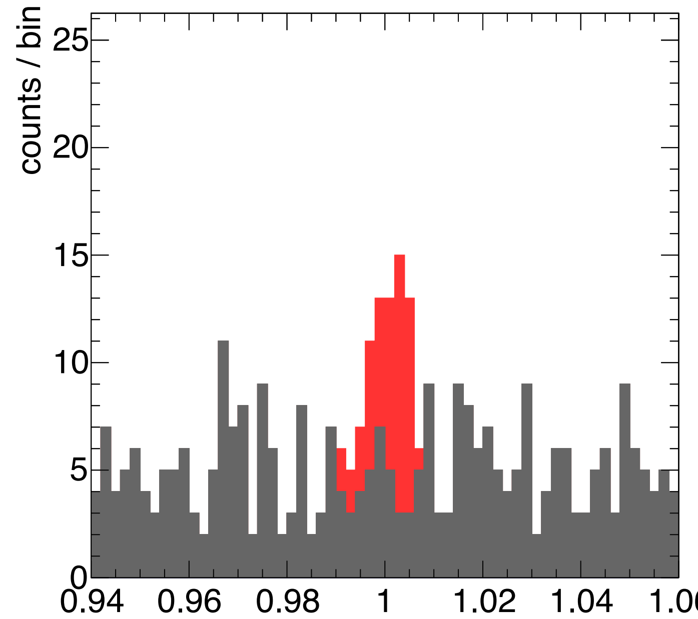
Energy resolution makes a difference

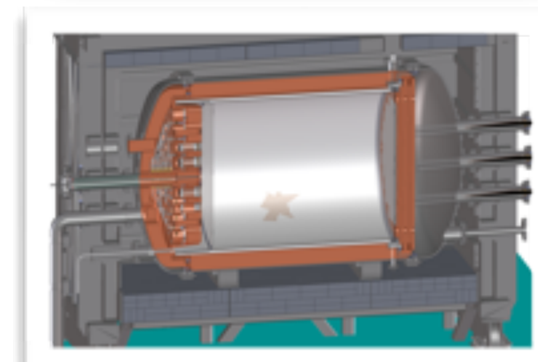
0,5 % FWHM



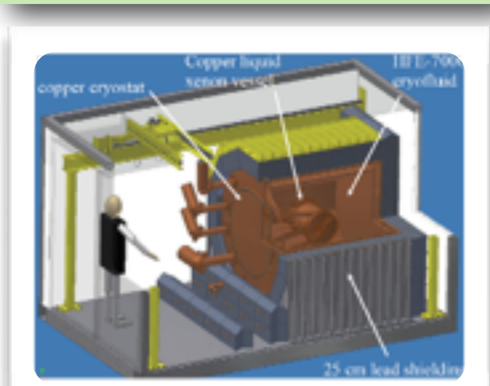


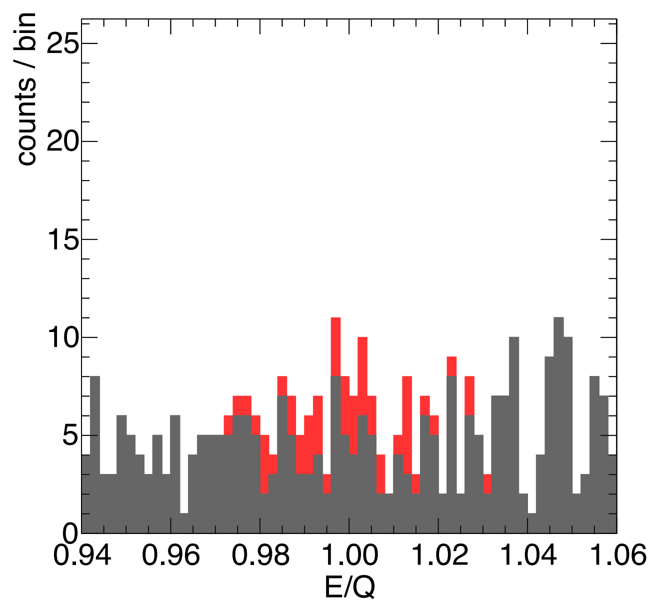
1,0 % FWHM



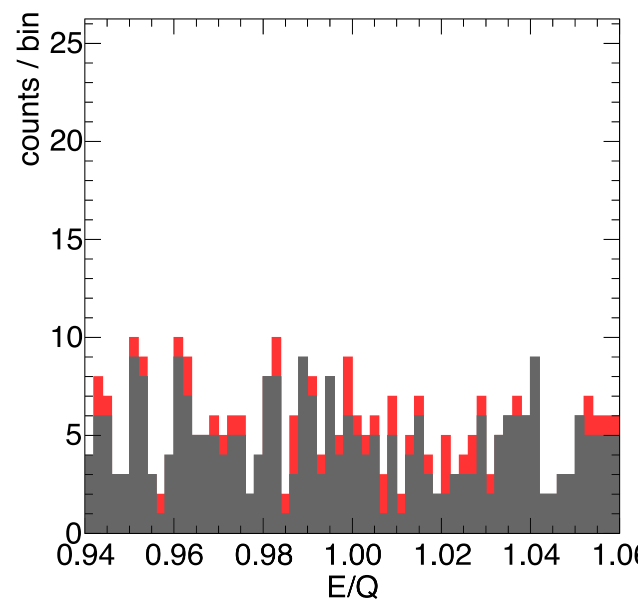


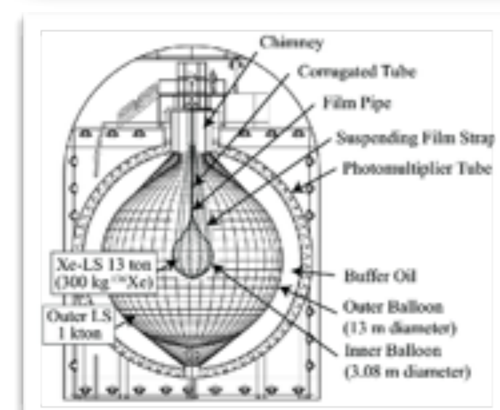
3.5 % FWHM





10 % FWHM

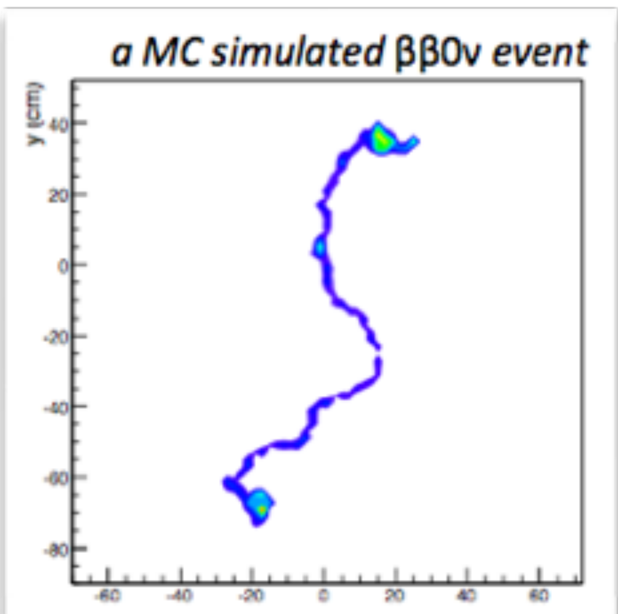


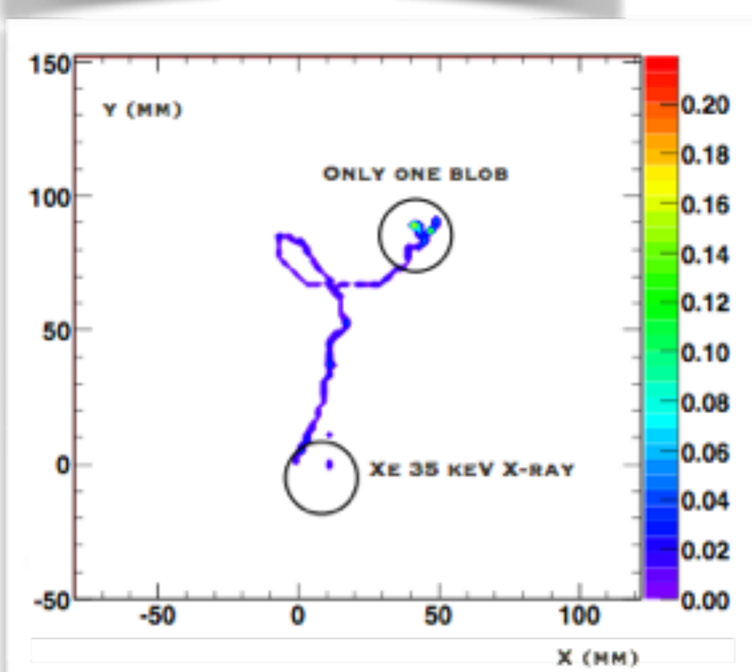


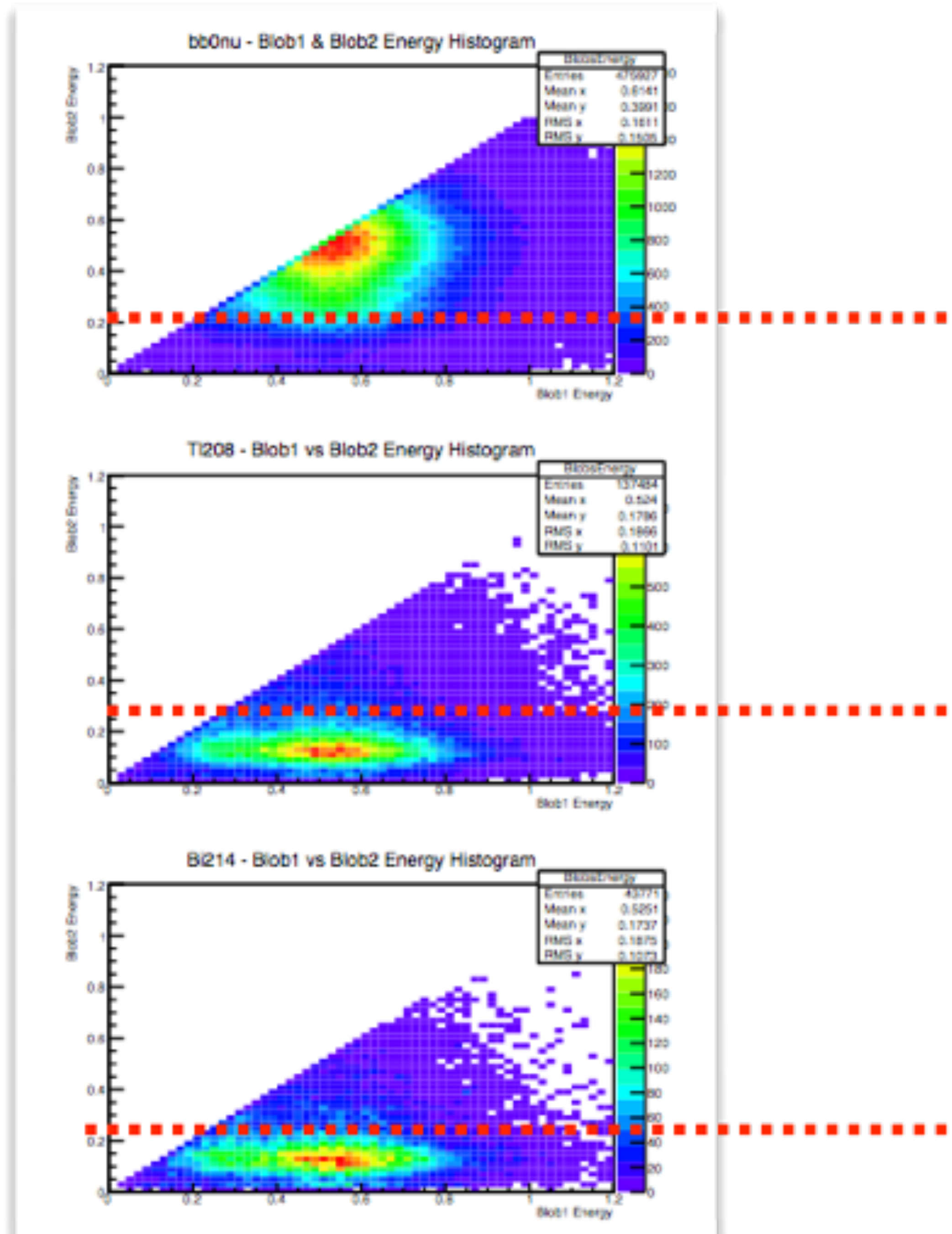
Signal and backg

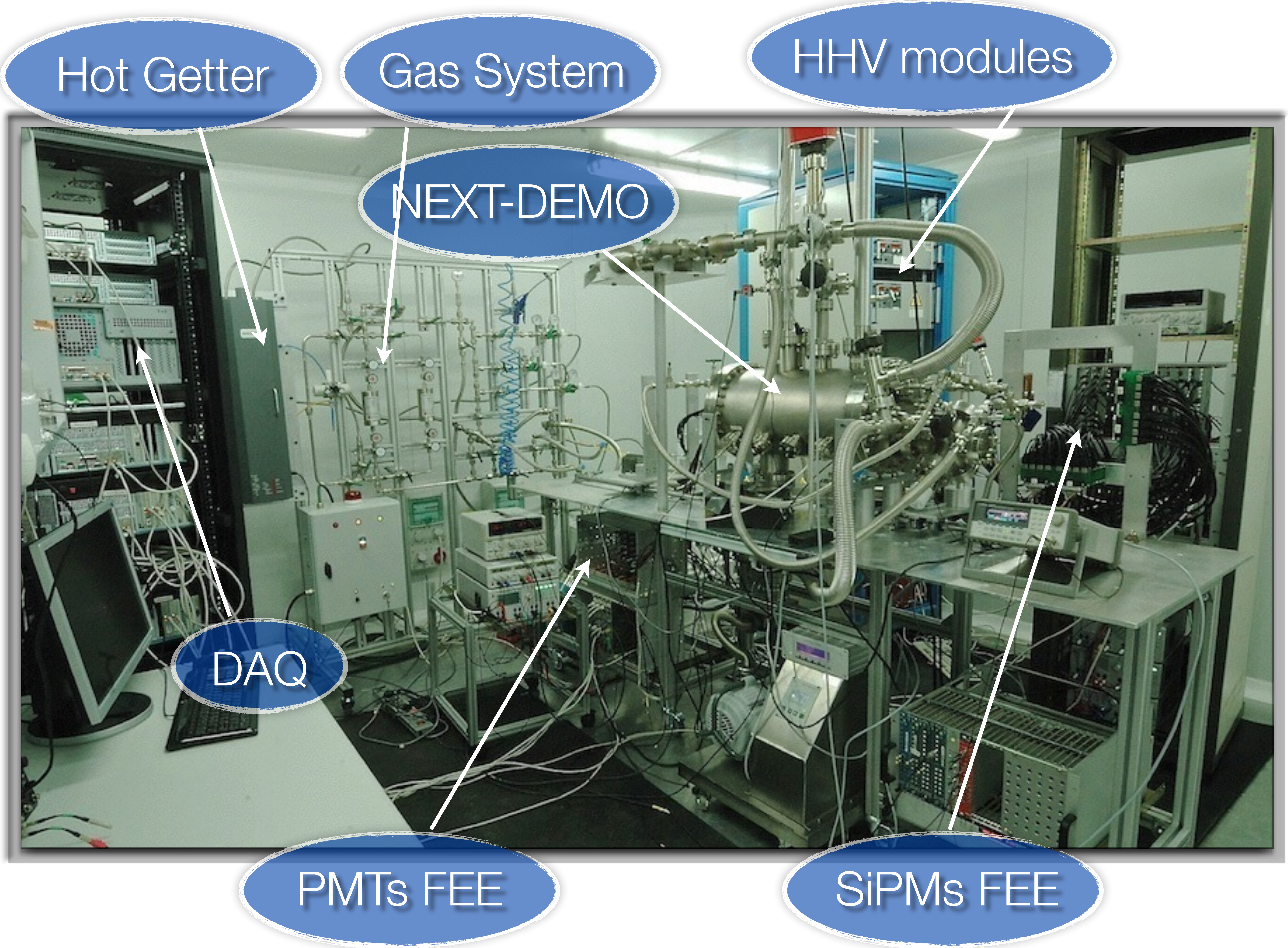
- Signal: 50 events, $T^{0\nu} = 5\ 10^{25}$ y and an exposure of 1 ton year.
- Background 1 count/keV/ton/year.

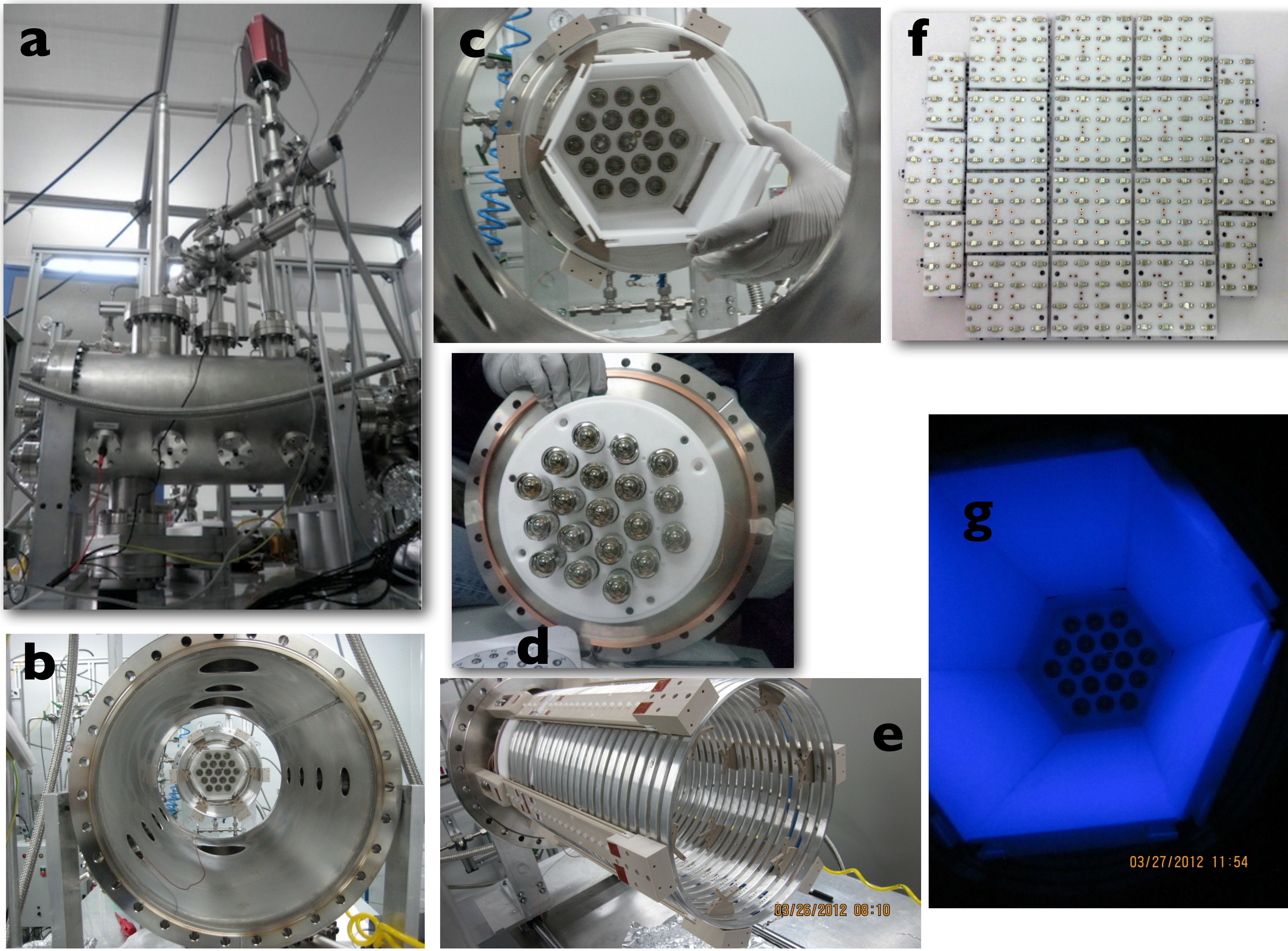
Topological background reduction







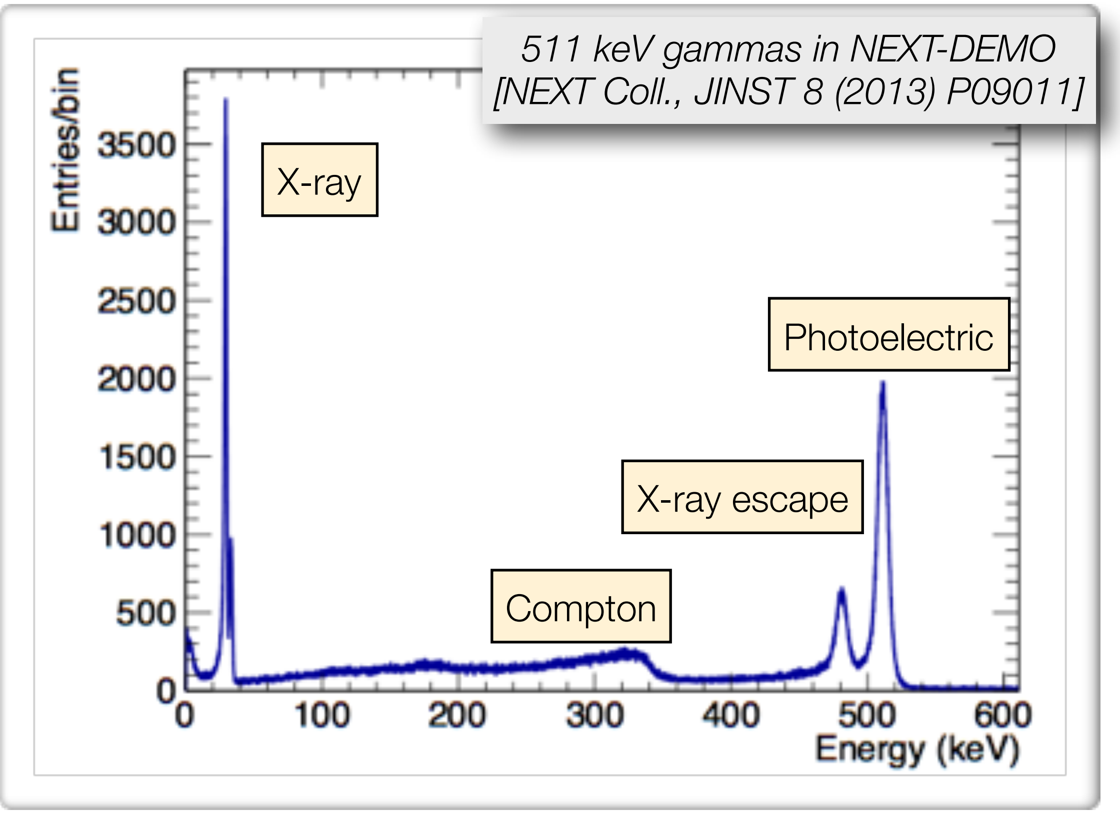

Hot Getter
Gas System
HHV modules
NEXT-DEMO
DAQ
PMTs FEE
SiPMs FEE


a
c
f
d
b
e
g
03/26/2012 08:10
03/27/2012 11:54

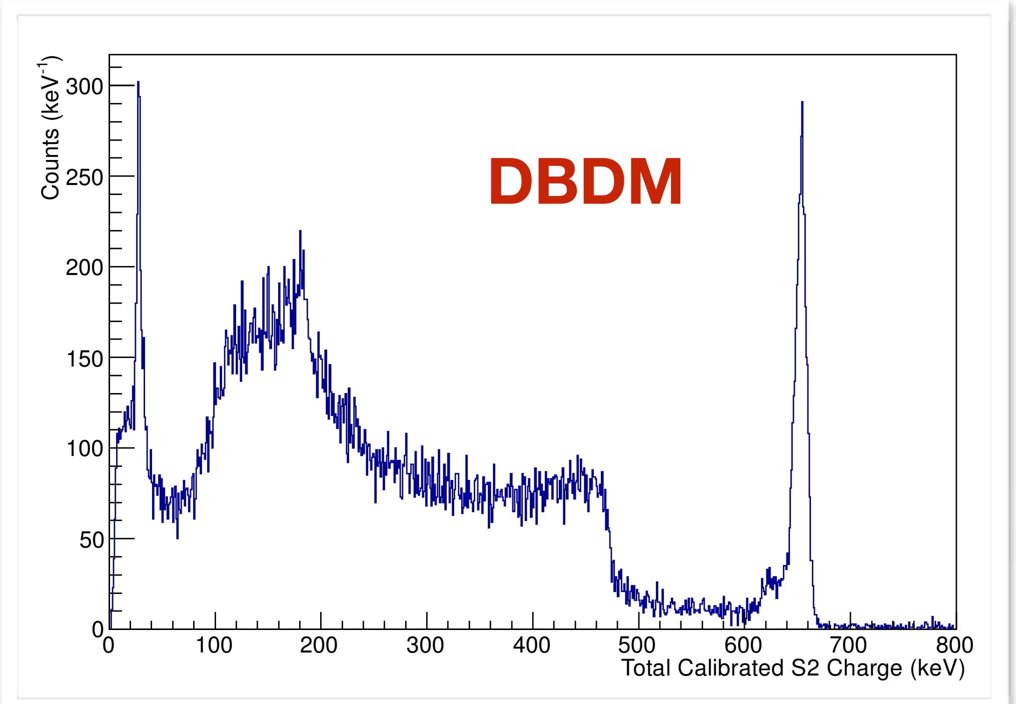
NEXT R&D: detector performance achievements

- 1.8% FWHM energy resolution for 511 keV electrons over large fiducial volume

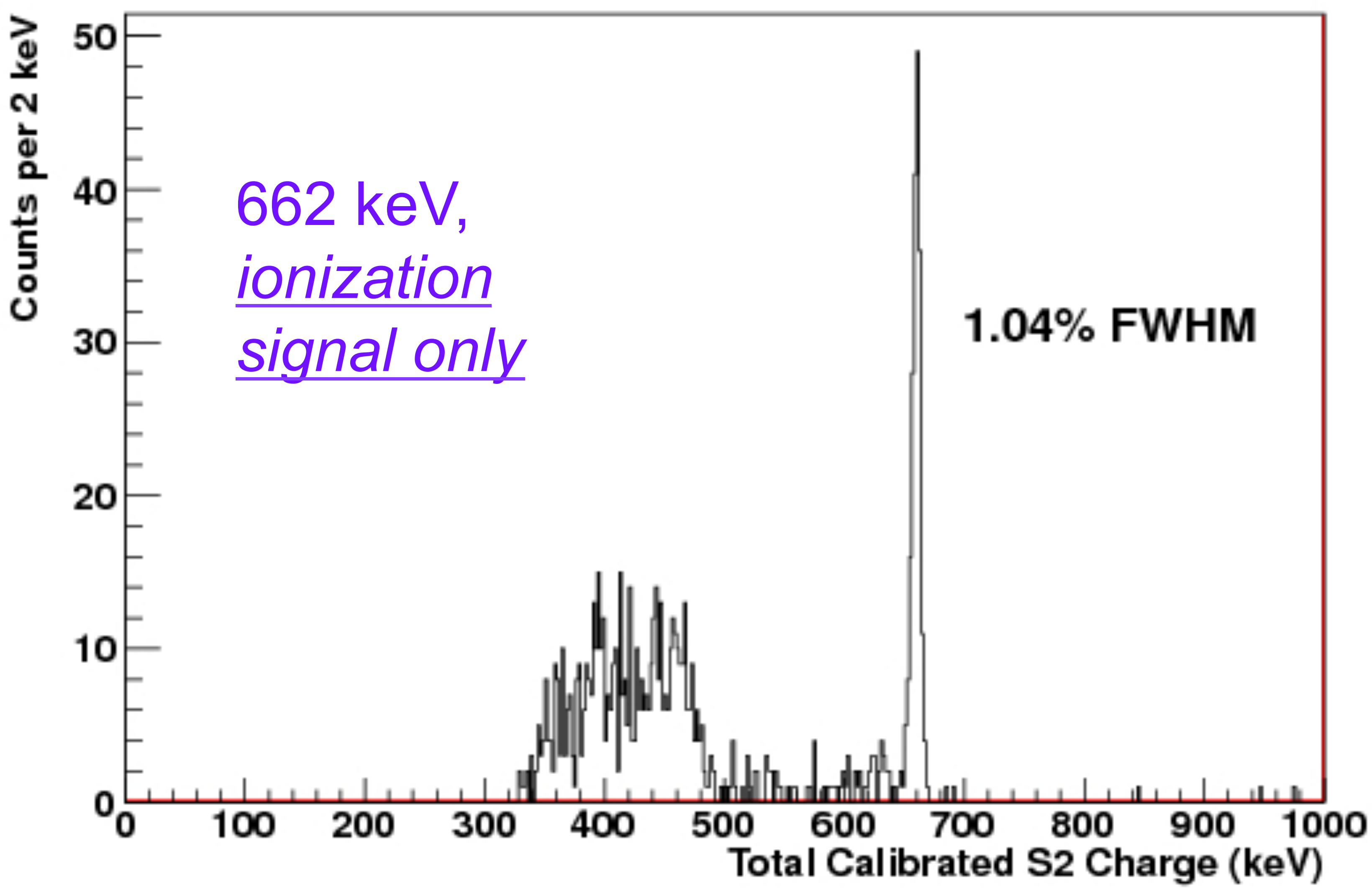
- Extrapolates to 0.75% FWHM at $Q_{\beta\beta}$ energy of 136Xe decay



- The DBDM prototype at LBNL extrapolates to **0.5 % FWHM** at $Q_{\beta\beta}$ using 660 Cs-137 electrons



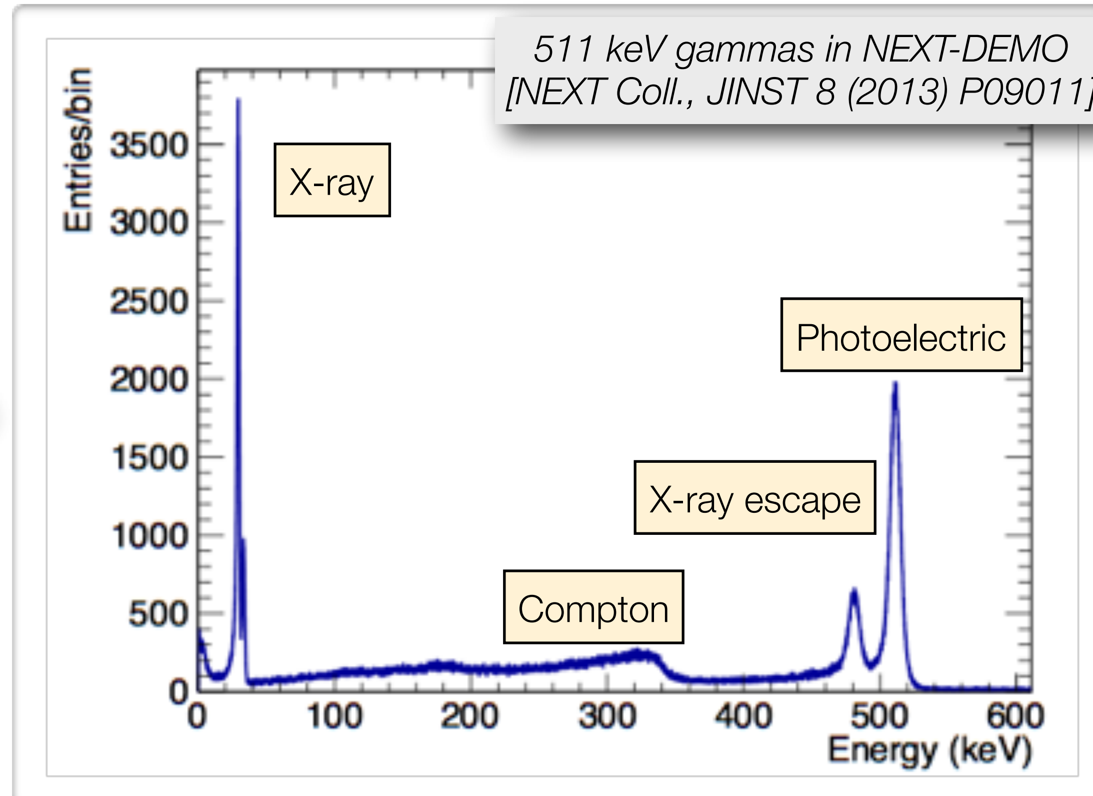
The beauty of resolution



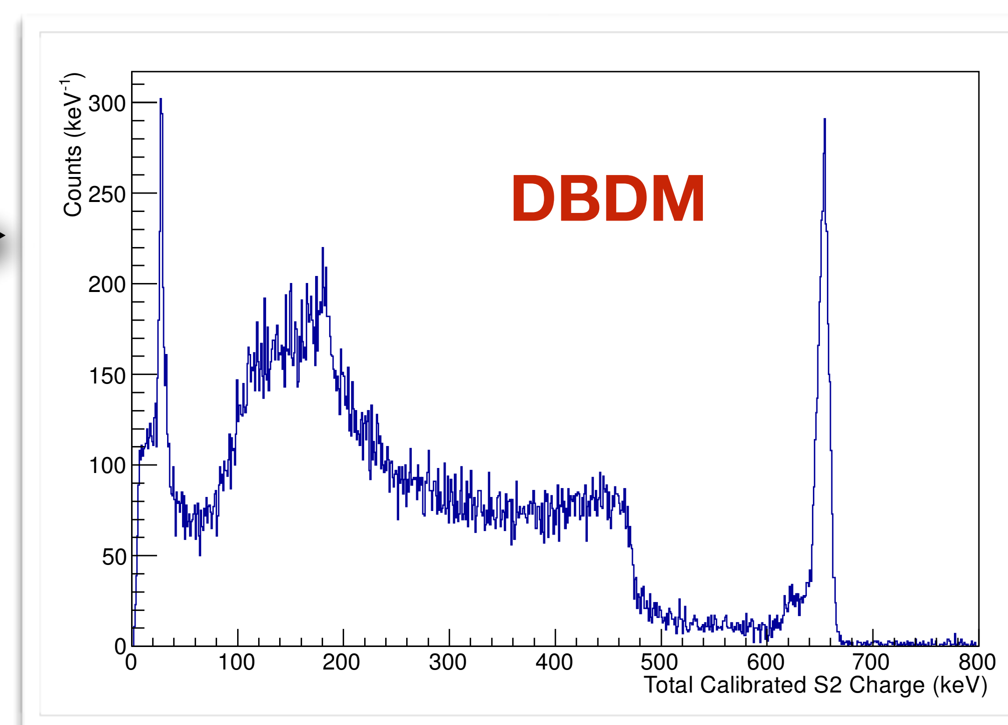
NEXT R&D: detector performance achievements

- 1.8% FWHM energy resolution for 511 keV electrons over large fiducial volume

- Extrapolates to 0.75% FWHM at $Q_{\beta\beta}$ energy of 136Xe decay

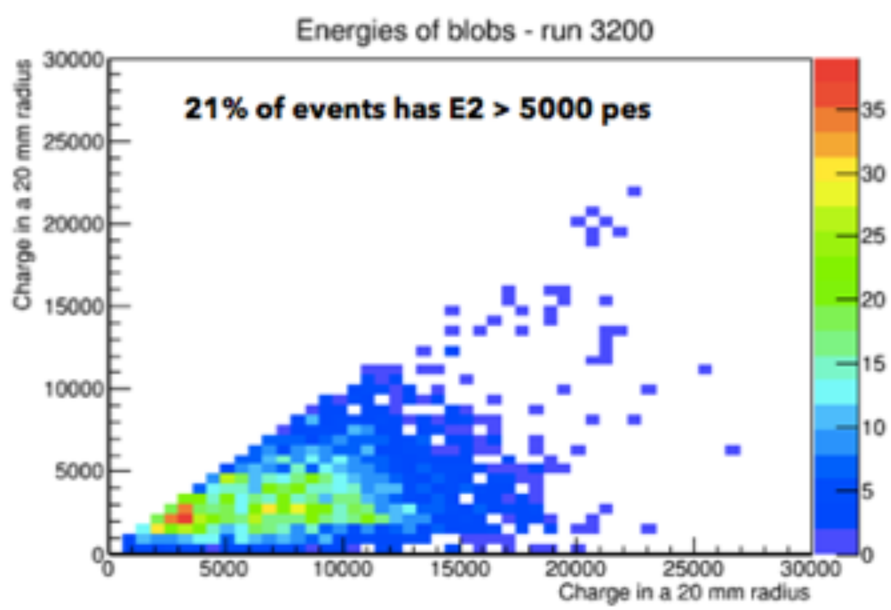


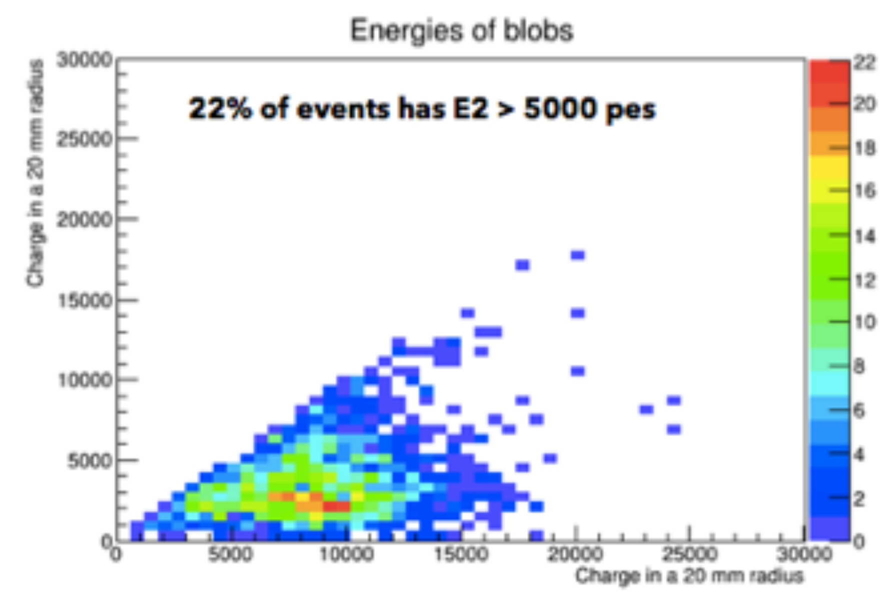
- The DBDM prototype at LBNL extrapolates to **0.5 % FWHM** at **$Q_{\beta\beta}$** using 660 Cs-137 electrons



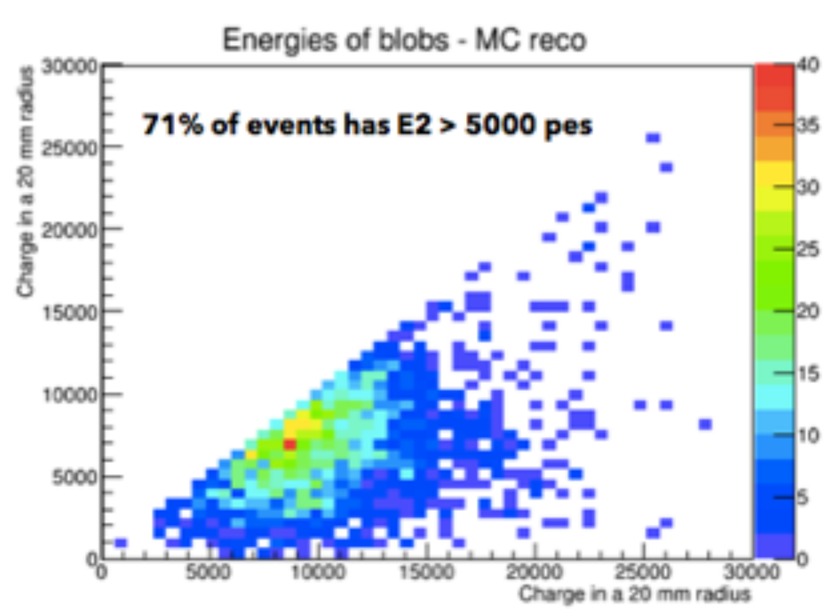
Topological background reduction

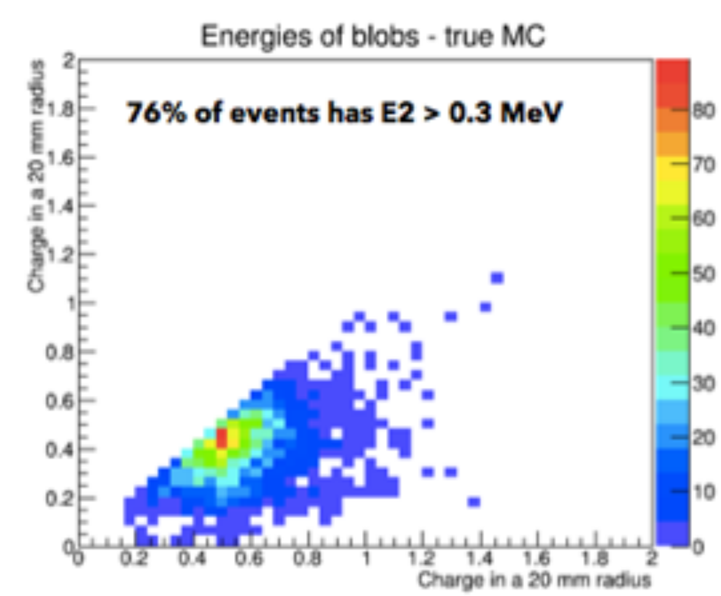
Na22 high energy gamma - data from run 3200 vs reco MC





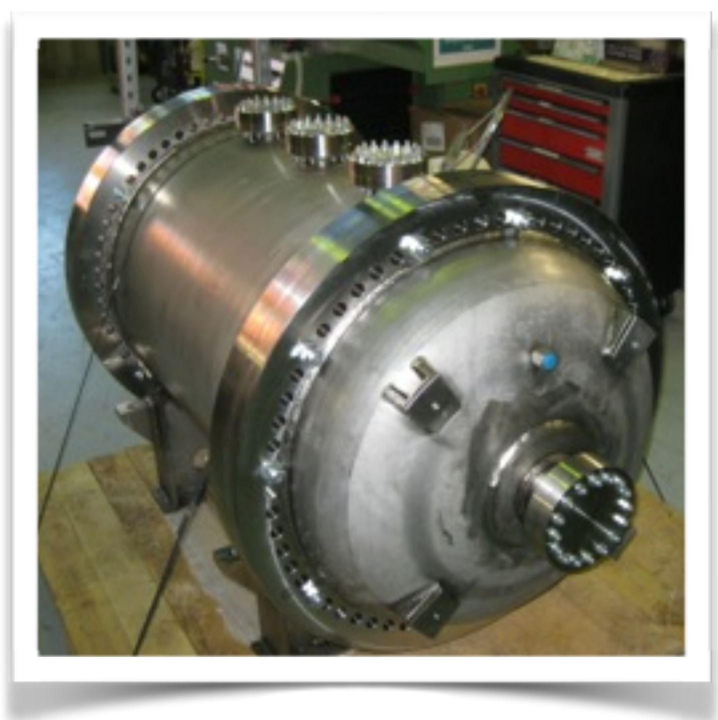
Tl208 double escape peak - reco vs true MC

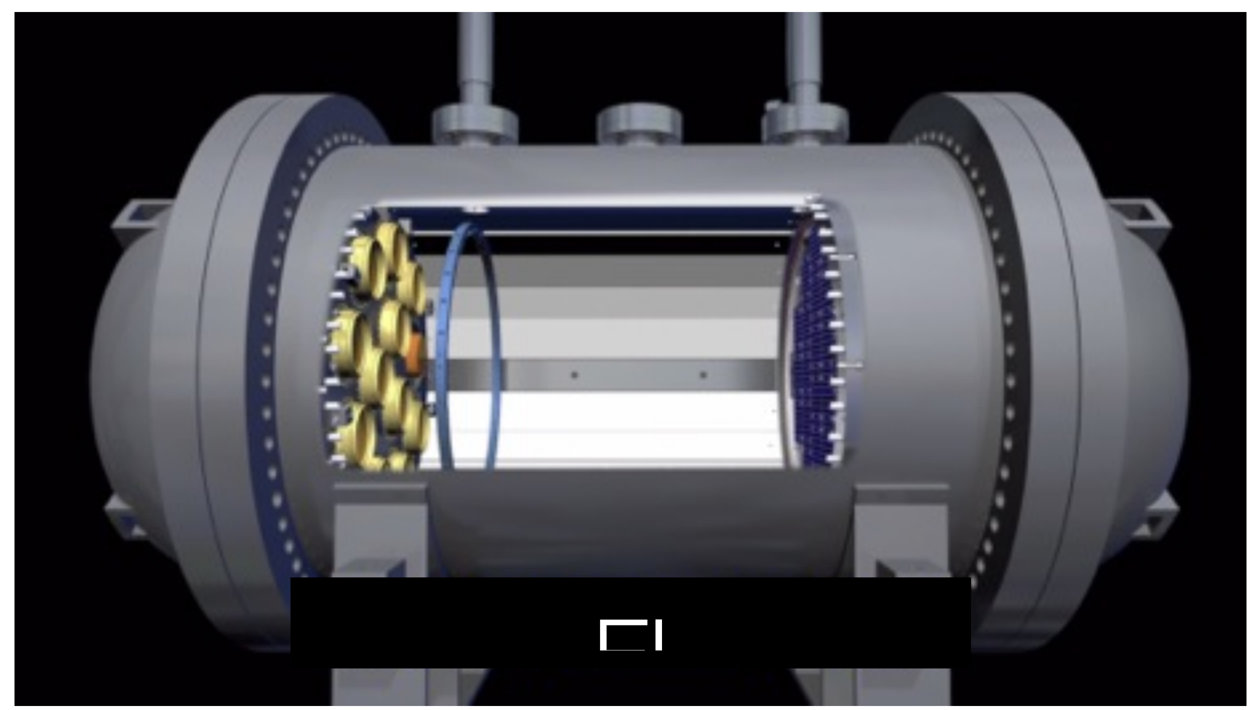




R&D (2008-2013)

ββ2ν (2014-2016)



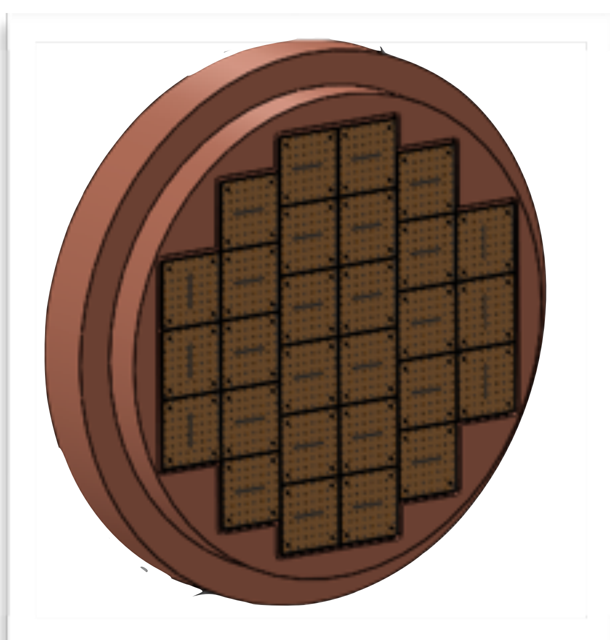


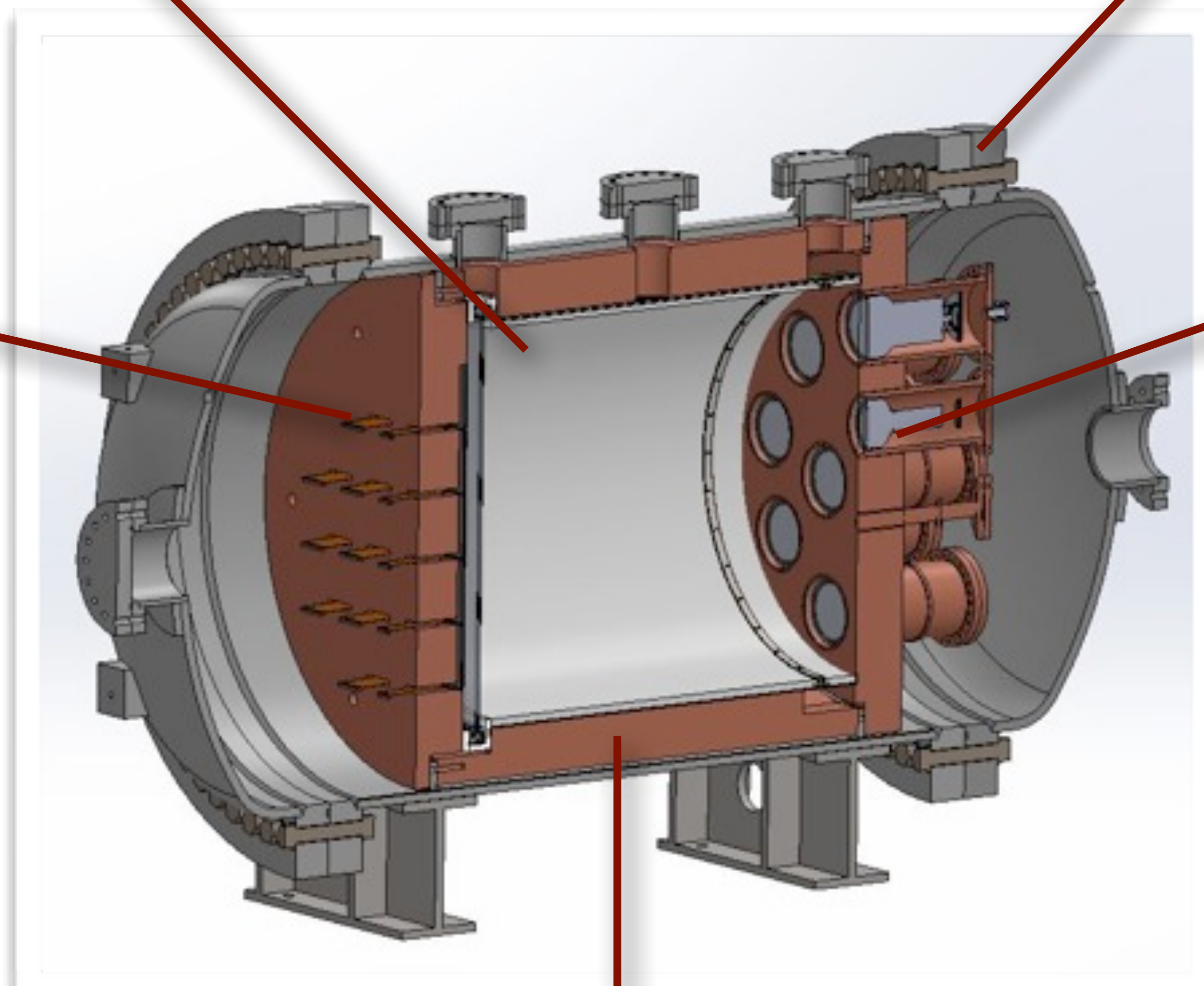
NEW (NEXT-WHITE) at glance

Time Projection Chamber:
10 kg active region, 50 cm drift length

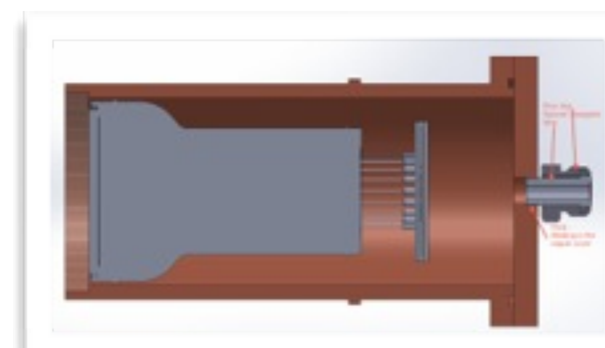
Pressure vessel:
316-Ti steel, 30 bar max pressure

Tracking plane:
1,800 SiPMs,
1 cm pitch



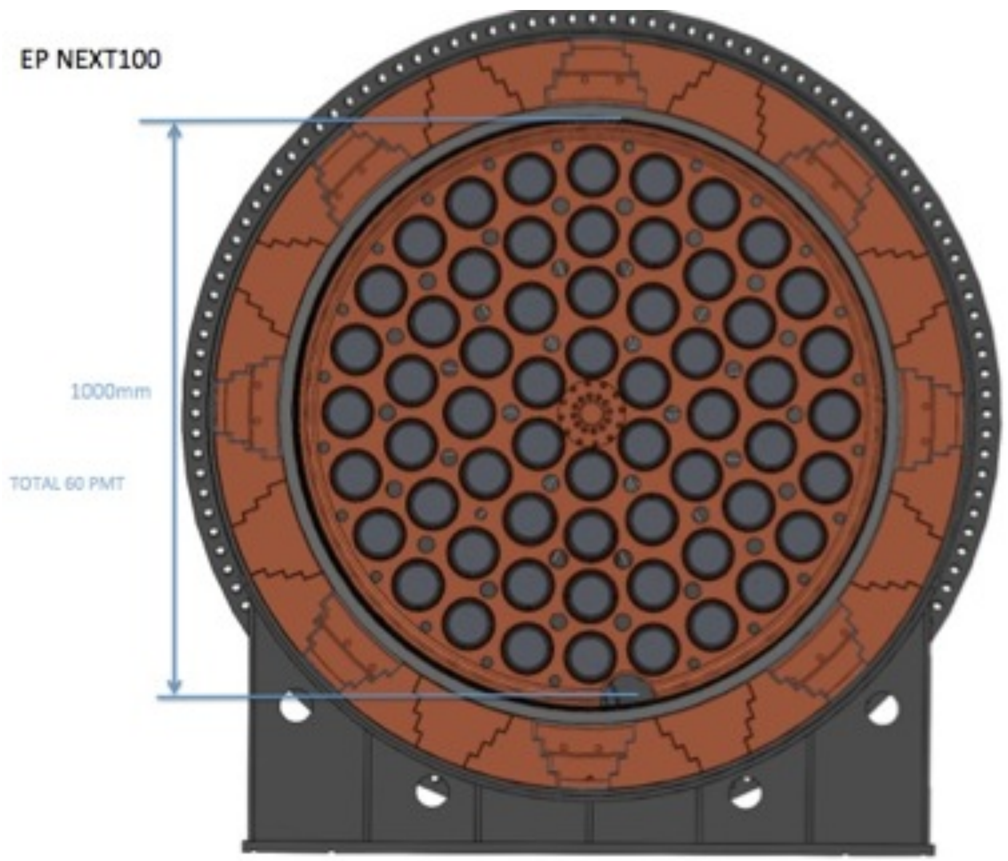


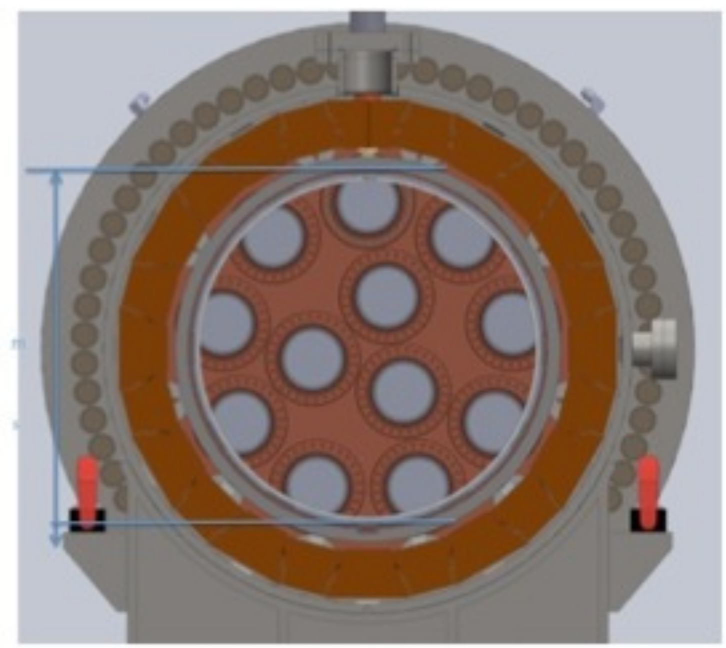
Energy plane:
12 PMTs,
30% coverage

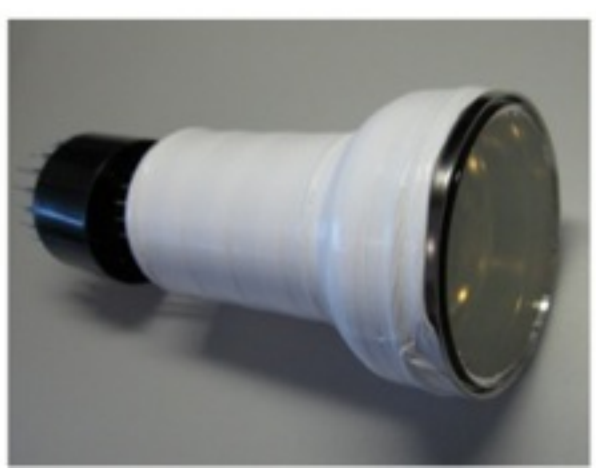


Inner shield:
copper, 6 cm thick

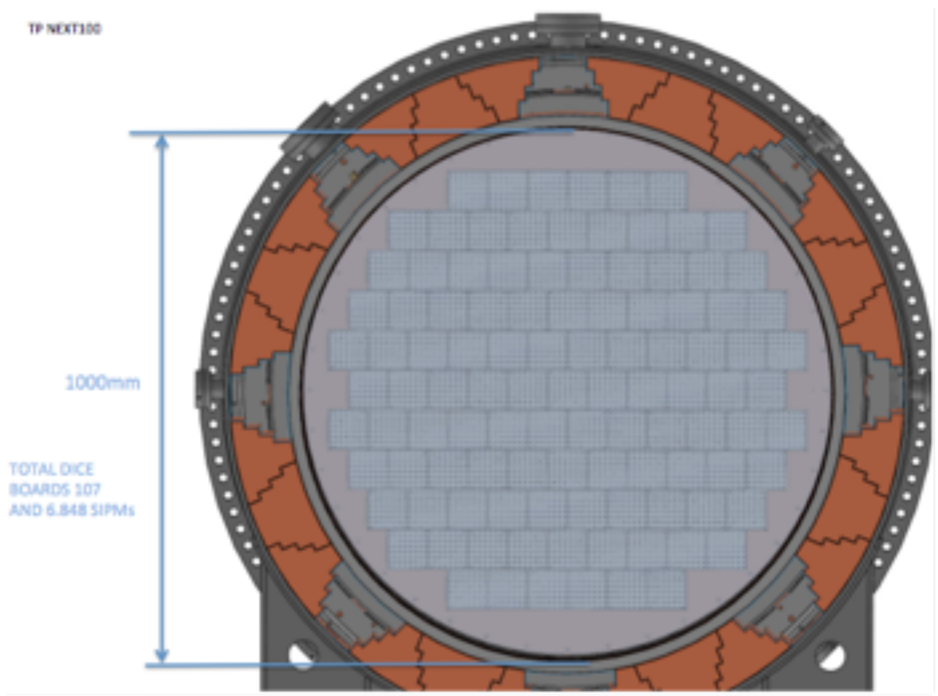
NEW and NEXT-100

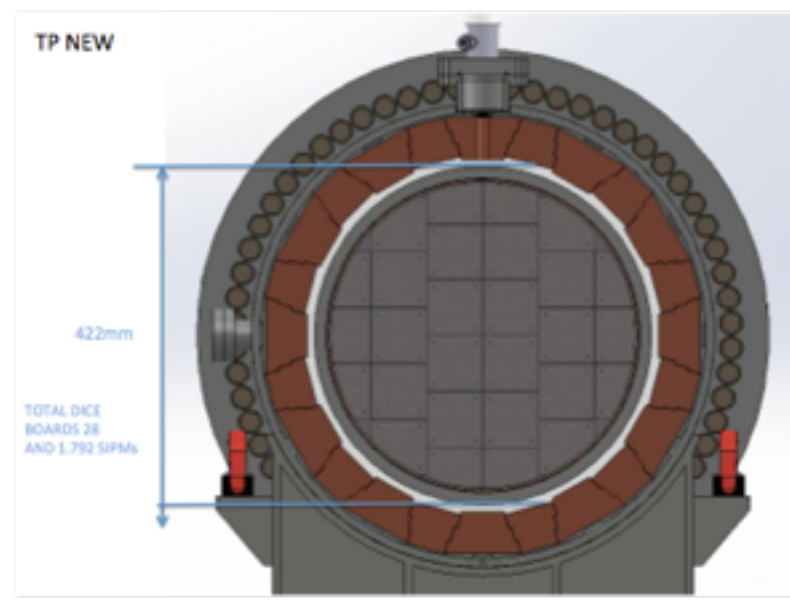


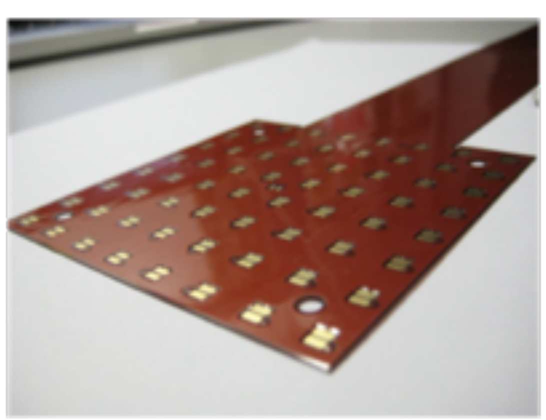


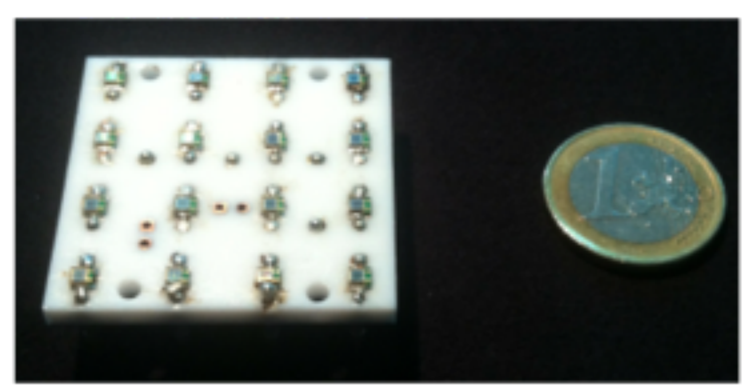


NEW and NEXT-100

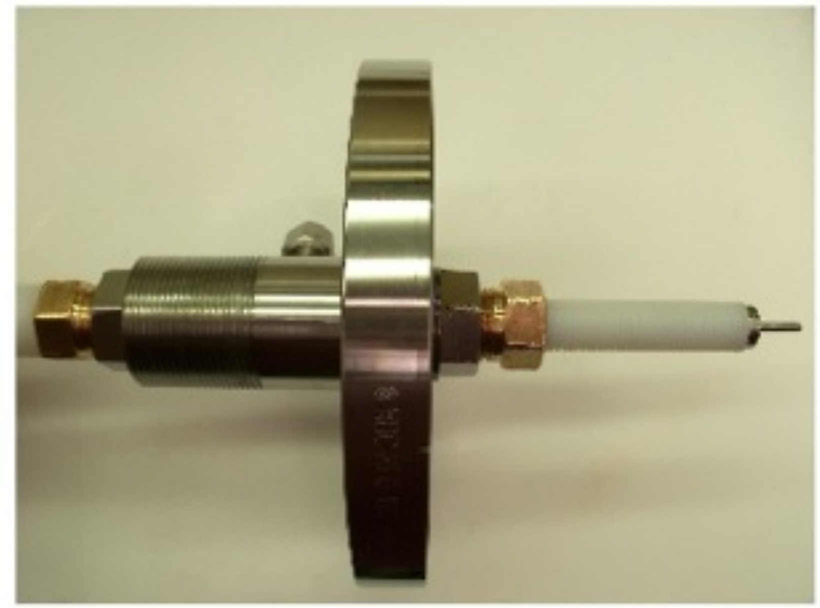


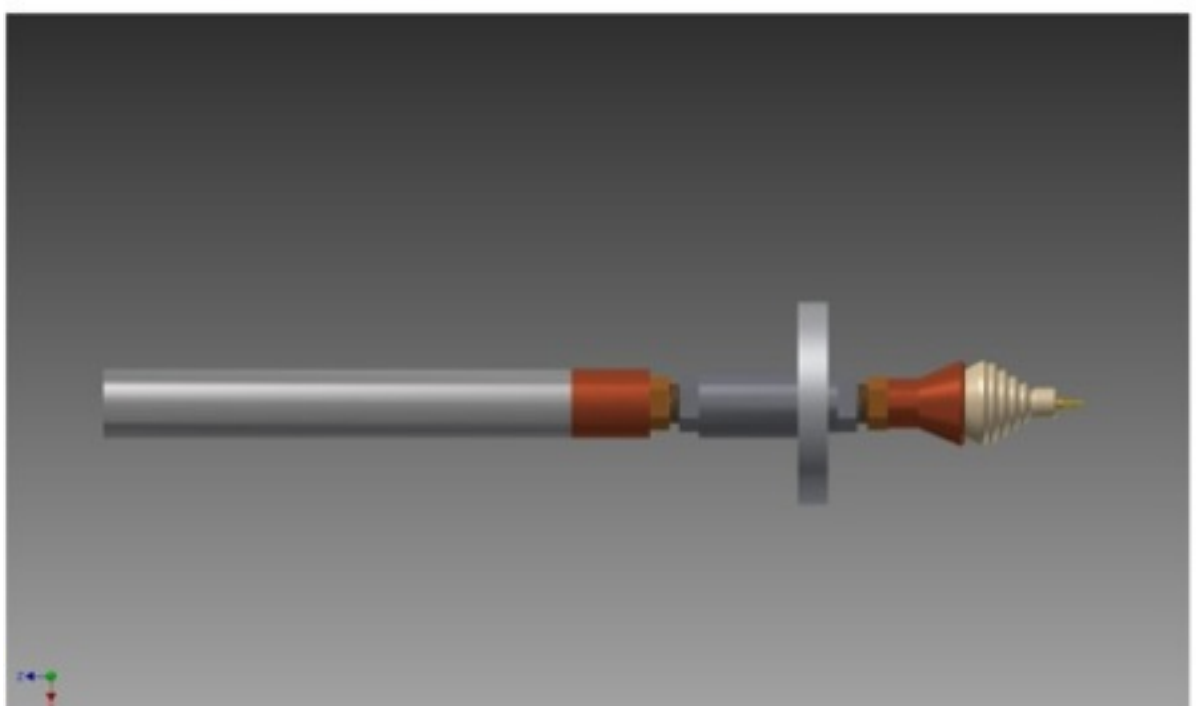


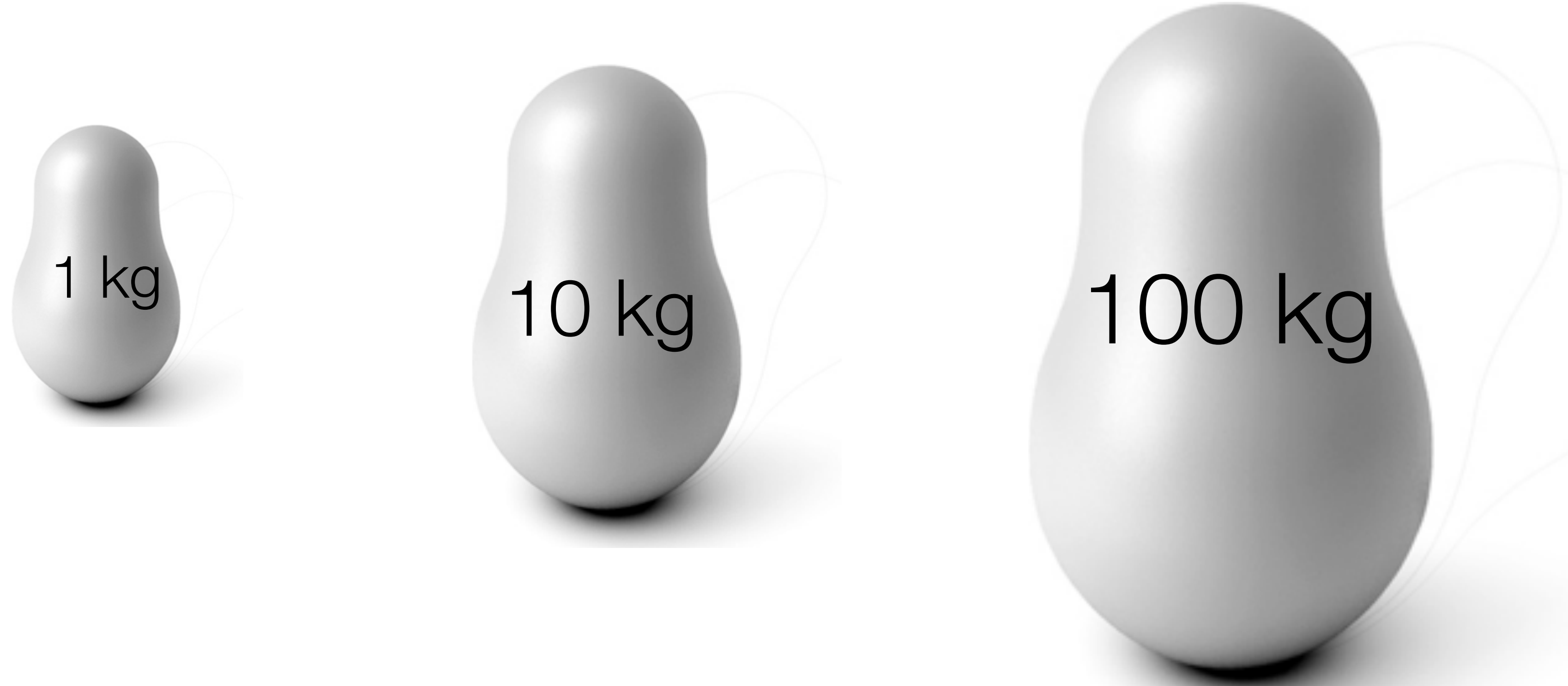




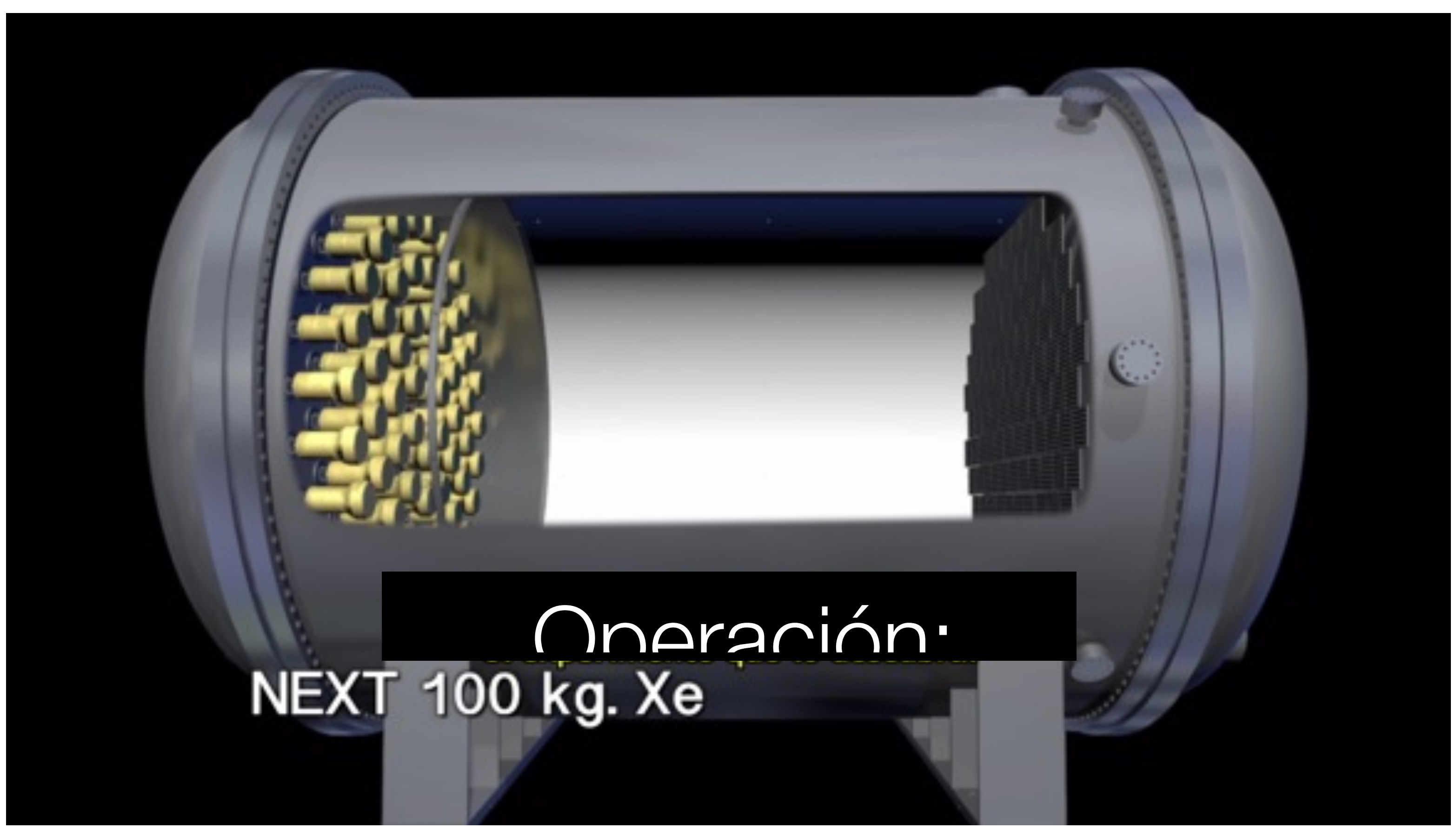
NEW Field Cage



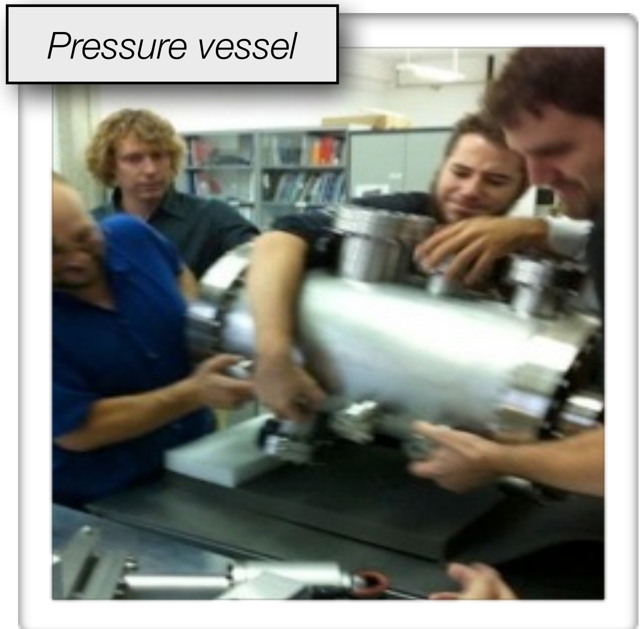


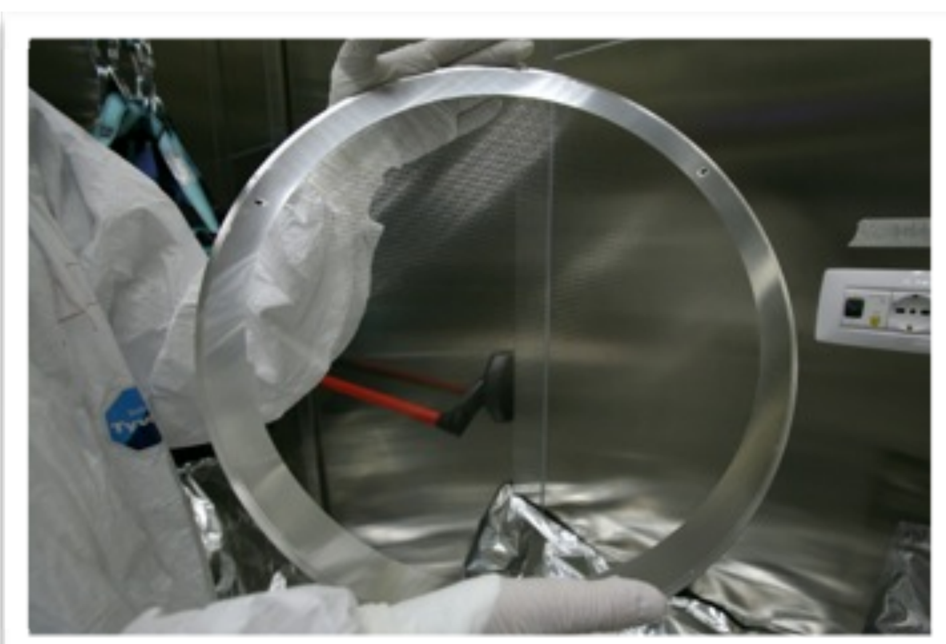


(2008-2013)	(2014-2016)	(2016-2020)
R&D	ββ2ν	ββ0ν (100 meV)



Pressure vessel



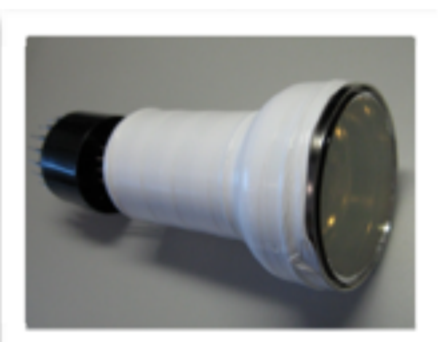


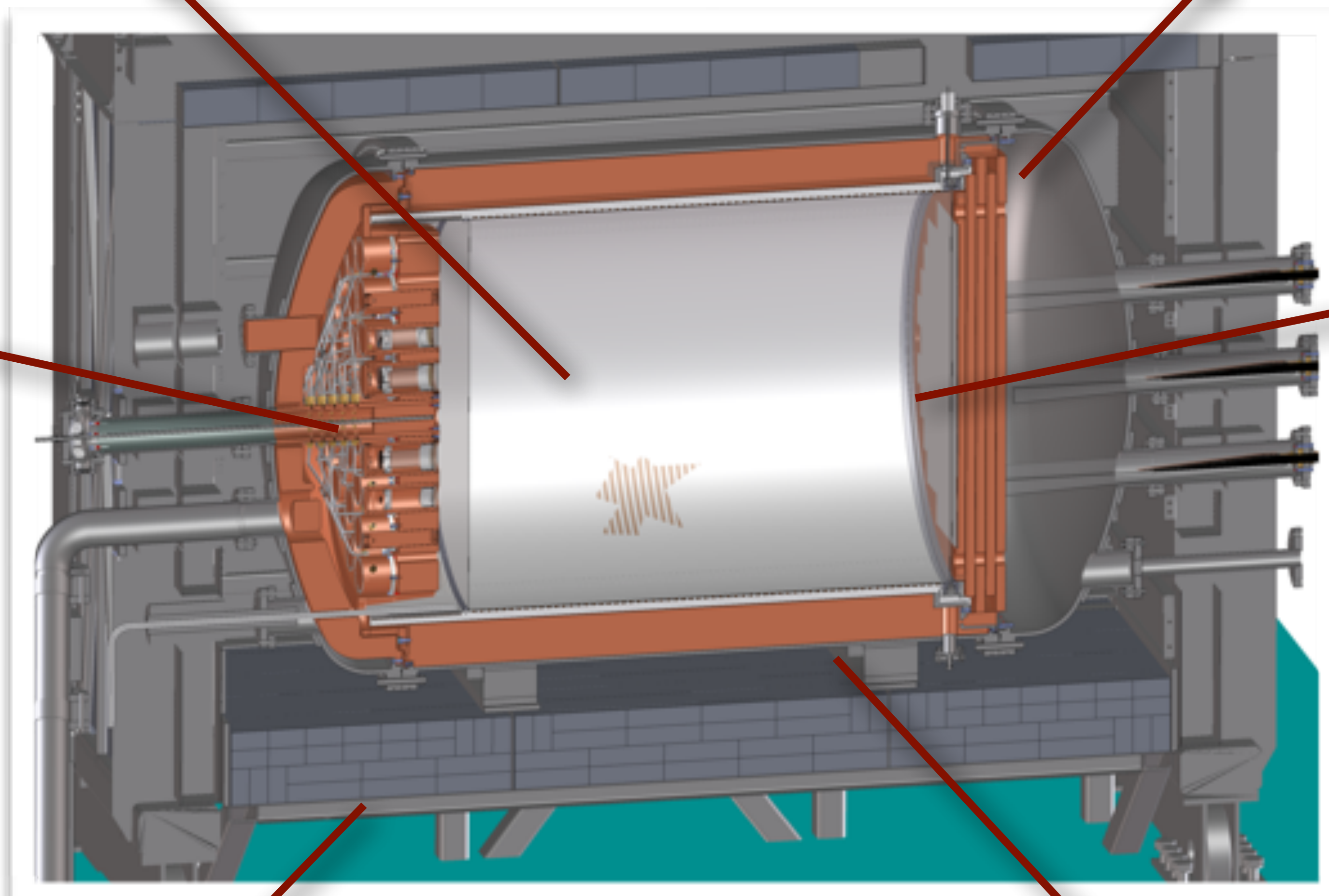
NEXT 100 kg detector at LSC: main features

Time Projection Chamber:
100 kg active region, 130 cm drift length

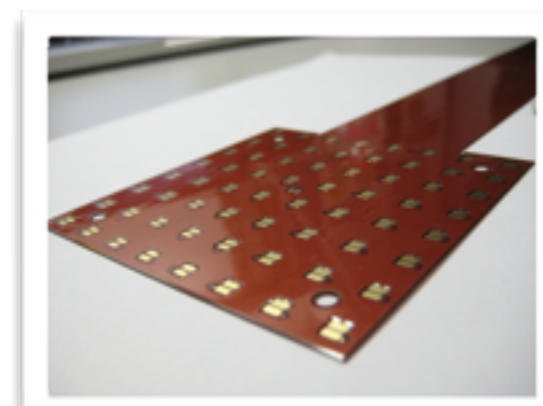
Pressure vessel:
stainless steel,15 bar max pressure

Energy plane:
60 PMTs,
30% coverage





Tracking plane:
7,000 SiPMs,
1 cm pitch



Outer shield:
lead, 20 cm thick

Inner shield:
copper, 12 cm thick

NEXT 100 kg radioactive budget

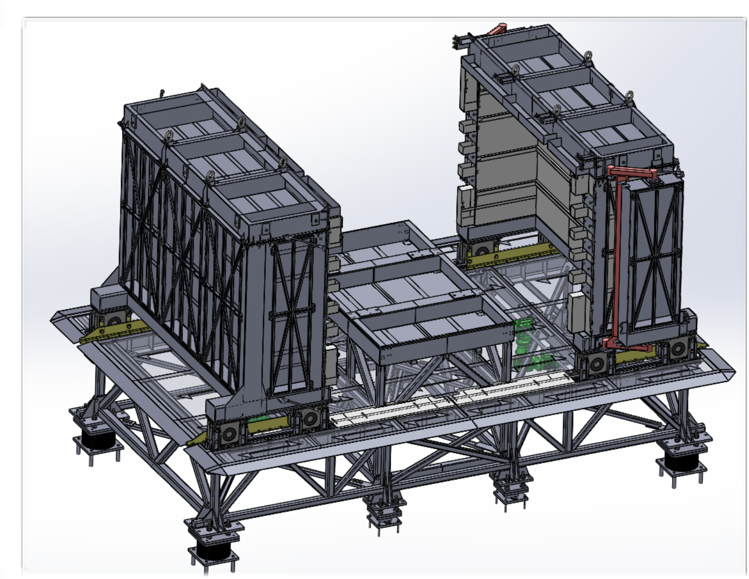
Vessel

- Stainless steel 316Ti; 1121 kg
- Activity Tl-208: <0.150 mBq/kg
- Activity Bi-214: <0.460 mBq/kg

Activity shielded by ICS

Shielding

- Lead; 13000 kg
- Activity Tl-208: <0.031 mBq/kg
- Activity Bi-214: <0.35 mBq/kg

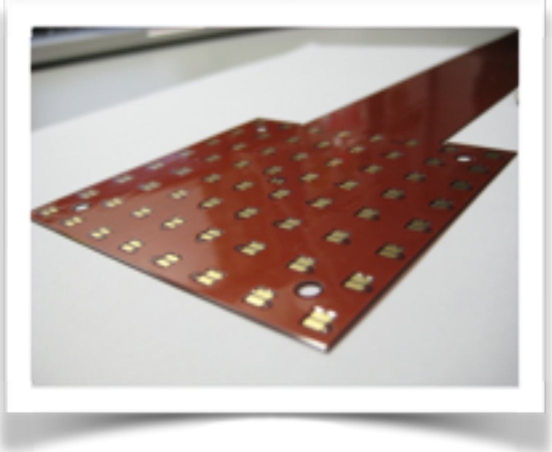


Lead Castle and Pressure Vessel:
Activity shielded by ICS.

NEXT 100 kg radioactive budget

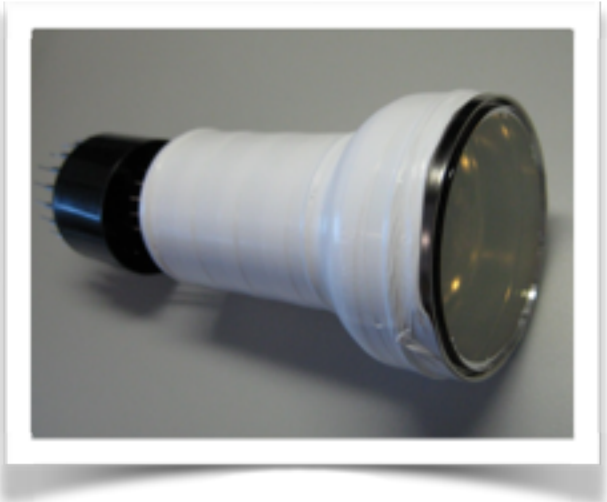
Kapton Dice boards

- Kapton and copper;107 units
- Activity Tl-208: —0.040 mBq/unit
- Activity Bi-214: —0.030 mBq/unit



PMTs

- Hamamatsu R11410-10; 60 units
- Activity Tl-208: —0.140 mBq/unit
- Activity Bi-214: —0.500 mBq/unit

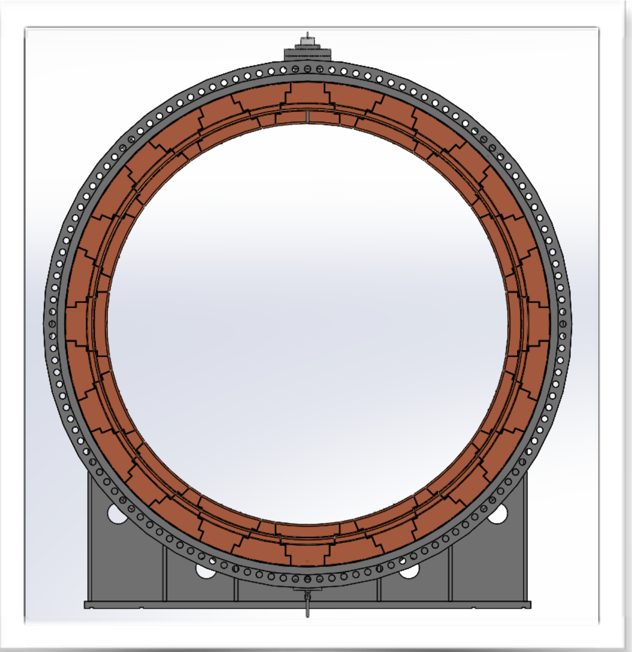


Sensors:
Activity level ~3 mBq per plane. Actual measurements. Not shielded.

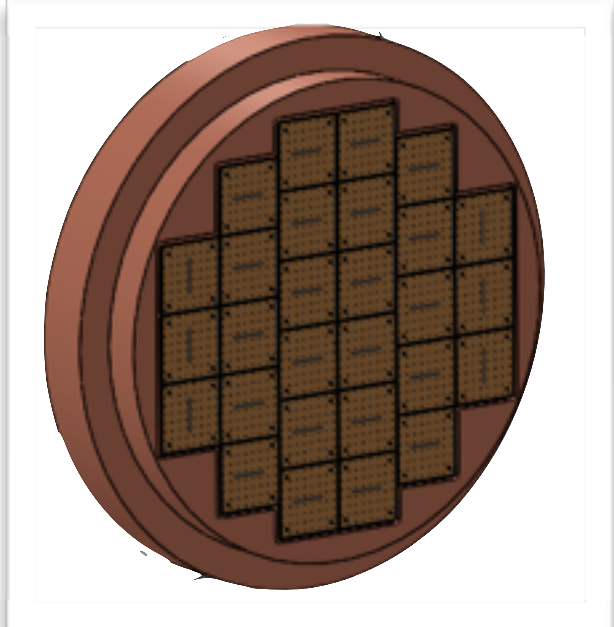
NEXT 100 kg radioactive budget

ICS, and support plates

- Copper (CuA1); ~9500 kg
- Activity Tl-208: <0.001 mBq/kg
- Activity Bi-214: <0.012 mBq/kg

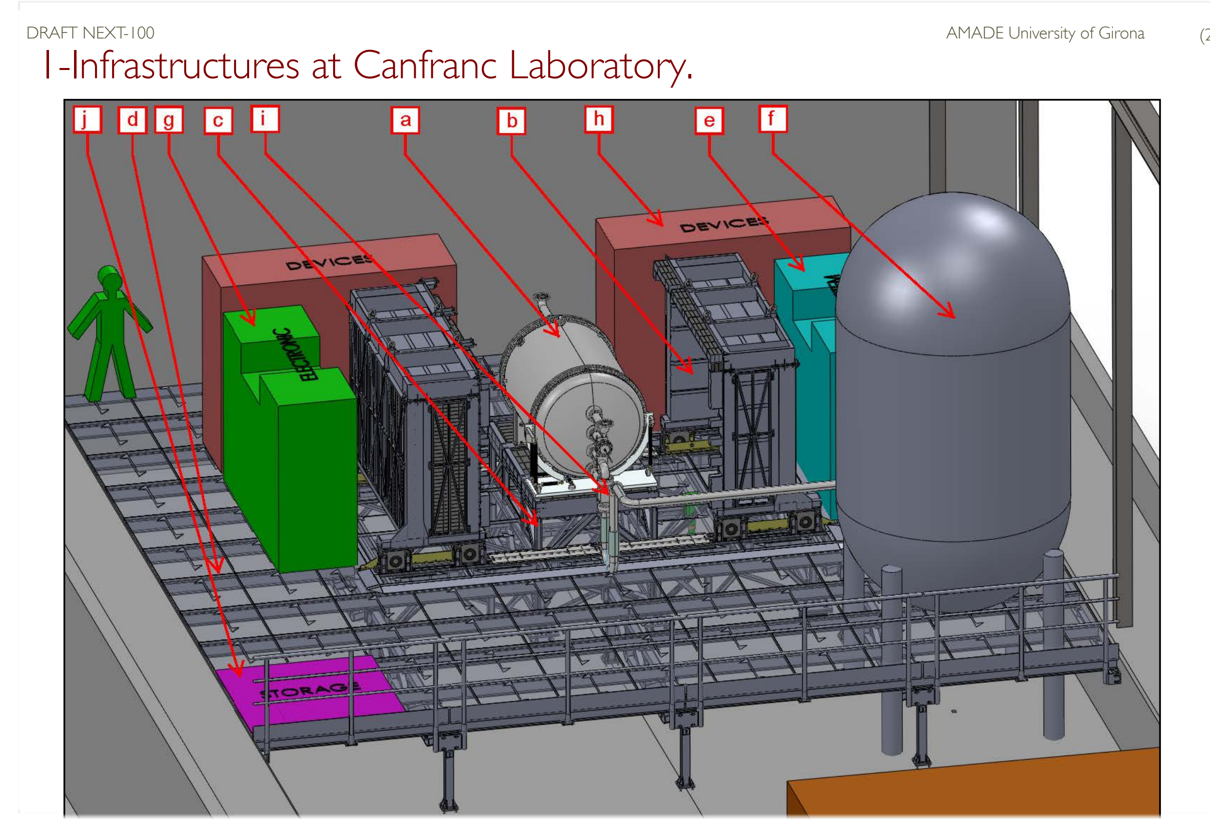


Copper
Electroformed commercial copper. Current measurements show our stock to be very radio pure, but only limits so far.



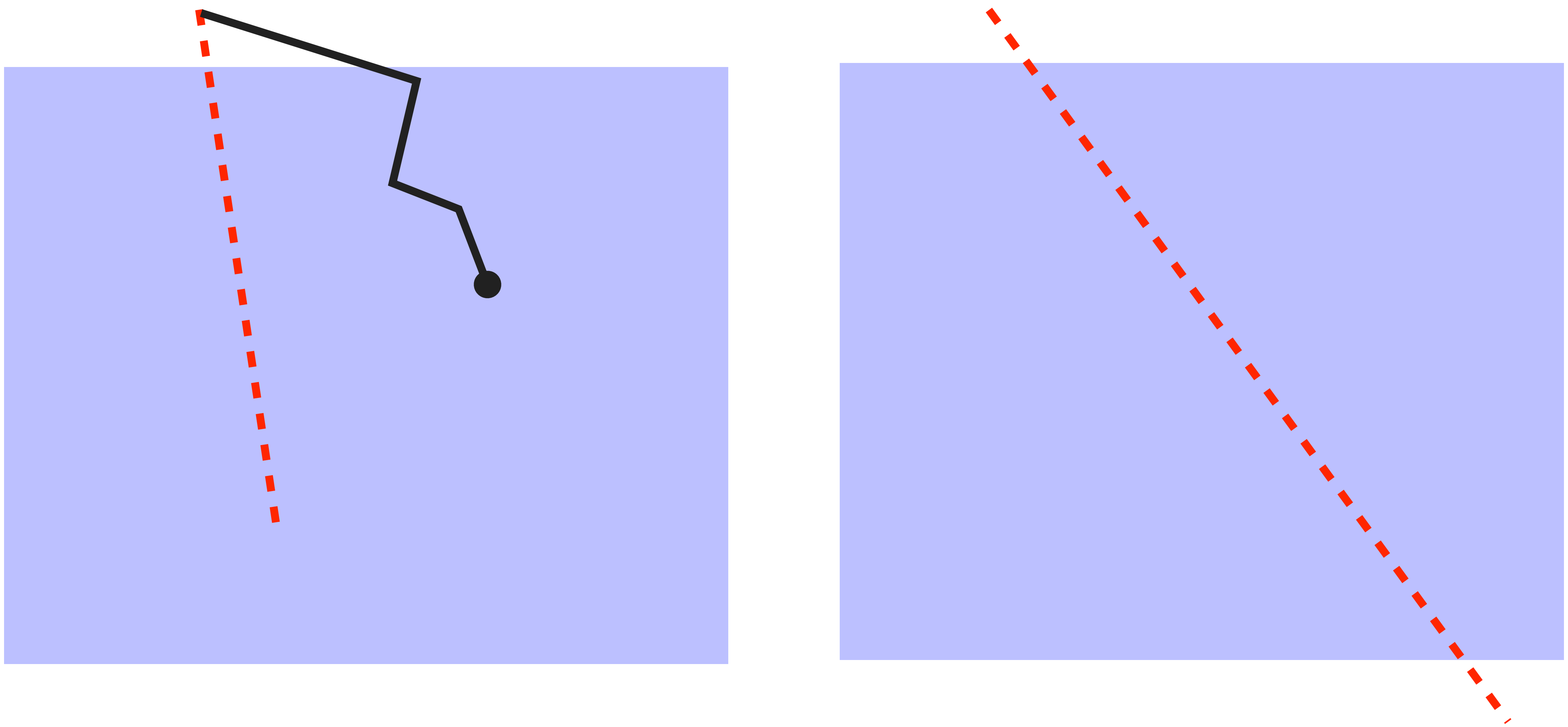
Residual radioactivity of ICS partially shielded (self-shielding)

NEXT at LSC



Infrastructures: platform, lead castle, gas system, emergency recovery system, completed. First phase of experiment starts in 2015. In stock, 100 kg of enriched xenon and 100 kg of depleted xenon.

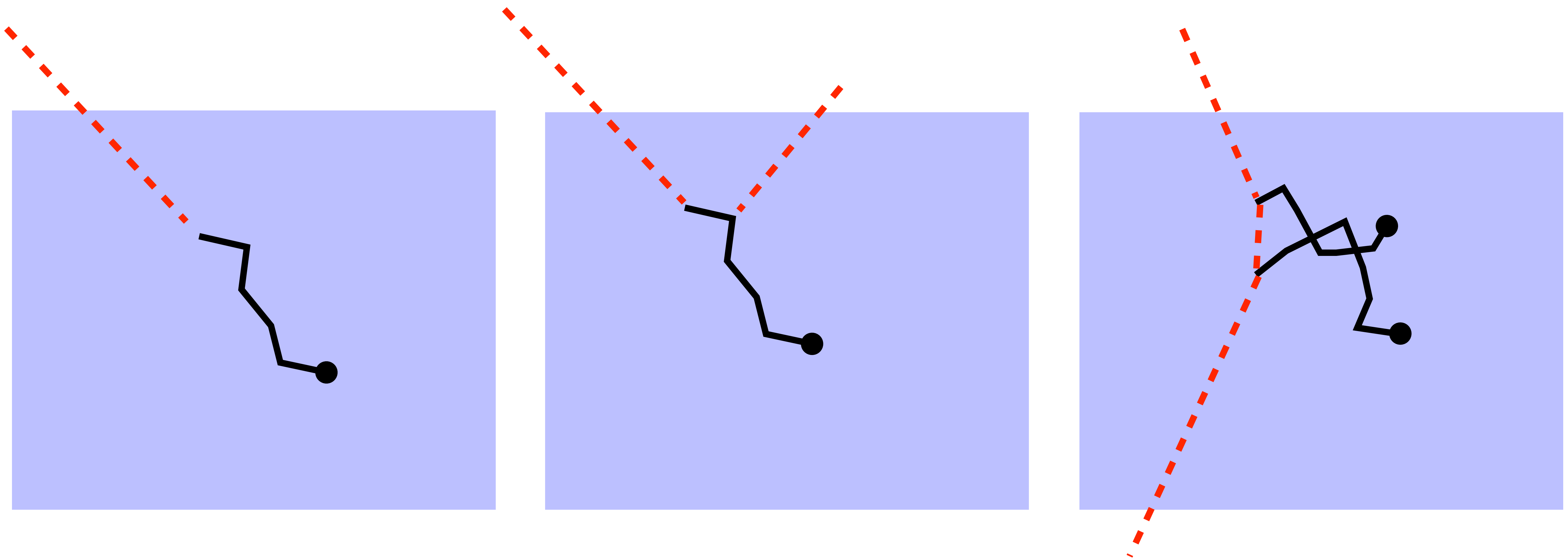
NEXT100 rejection of backgrounds



<ins>A transparent target, away from surfaces</ins>

- Veto of effectively all charged backgrounds entering the detector (left). High-energy gammas have a long interaction length (>3 m) in HPXe.

NEXT100 rejection of backgrounds



The 2-electron signature

- Interaction of high-energy gammas (from Tl-208 and Bi-214) in the HPXe can generate electron tracks with energies around the Q value of Xe-136. However, electron often accompanied of satellite clusters and single blob deposit

NEXT100 rejection of backgrounds

	$0\nu\beta\beta$	Tl-208	Bi-214
Fiducial E>2 MeV	67.86%	0.25%	0.01%
ROI	95.52%	8.99%	64.66%
1 track	74.60%	1.86%	12.54%
2 blobs	73.76%	9.60%	9.89%

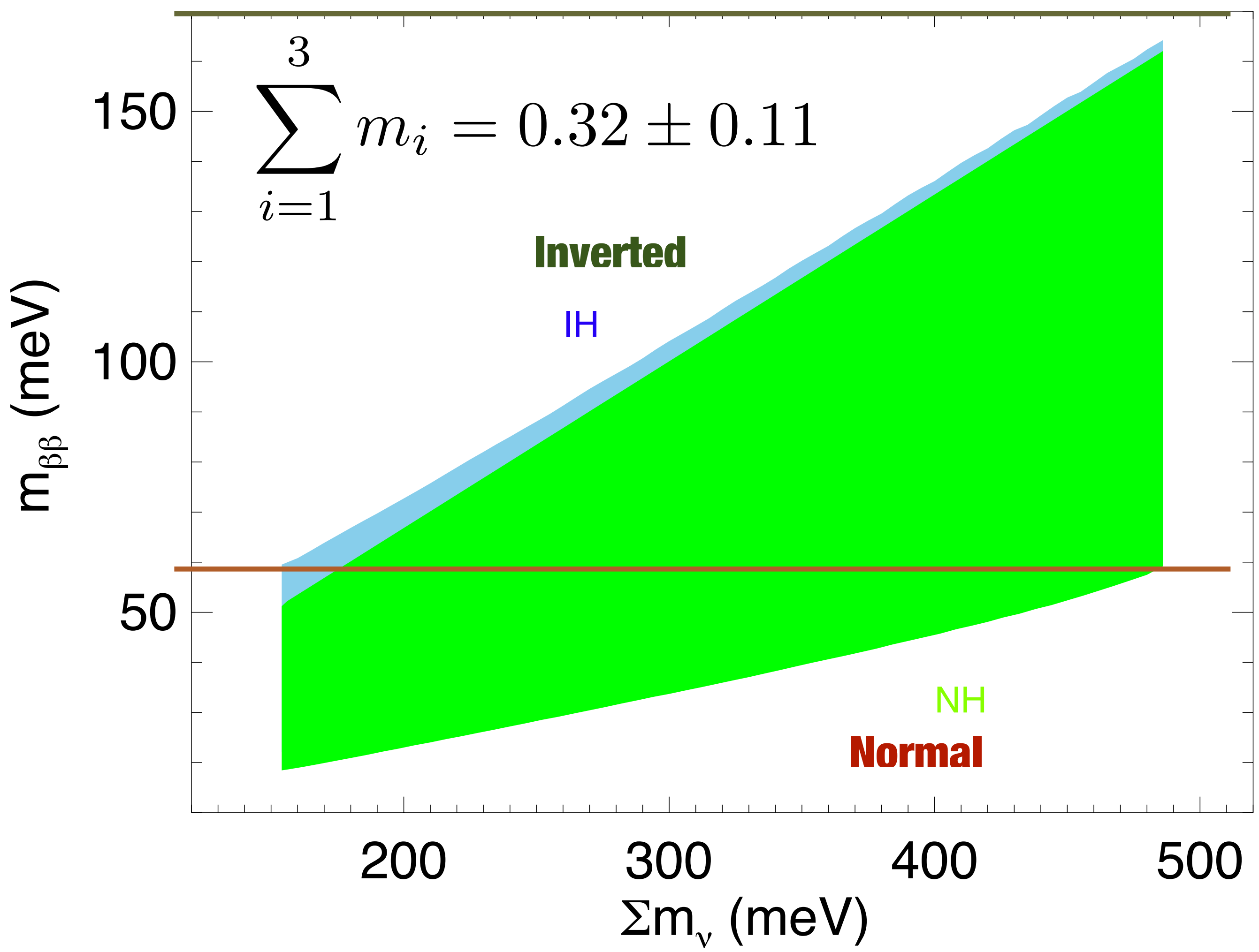
The 2-electron analysis

- Effect of the filters (cuts) defining an event with 2 electrons and energy in a ROI of 2σ around $Q_{\beta\beta}$.
- Efficiency for signal ~35% for suppression factors 4-8 x 10^{-7}
- Topology rejection is the product of 1 track x 2 blobs conditions

NEXT 100 expected background

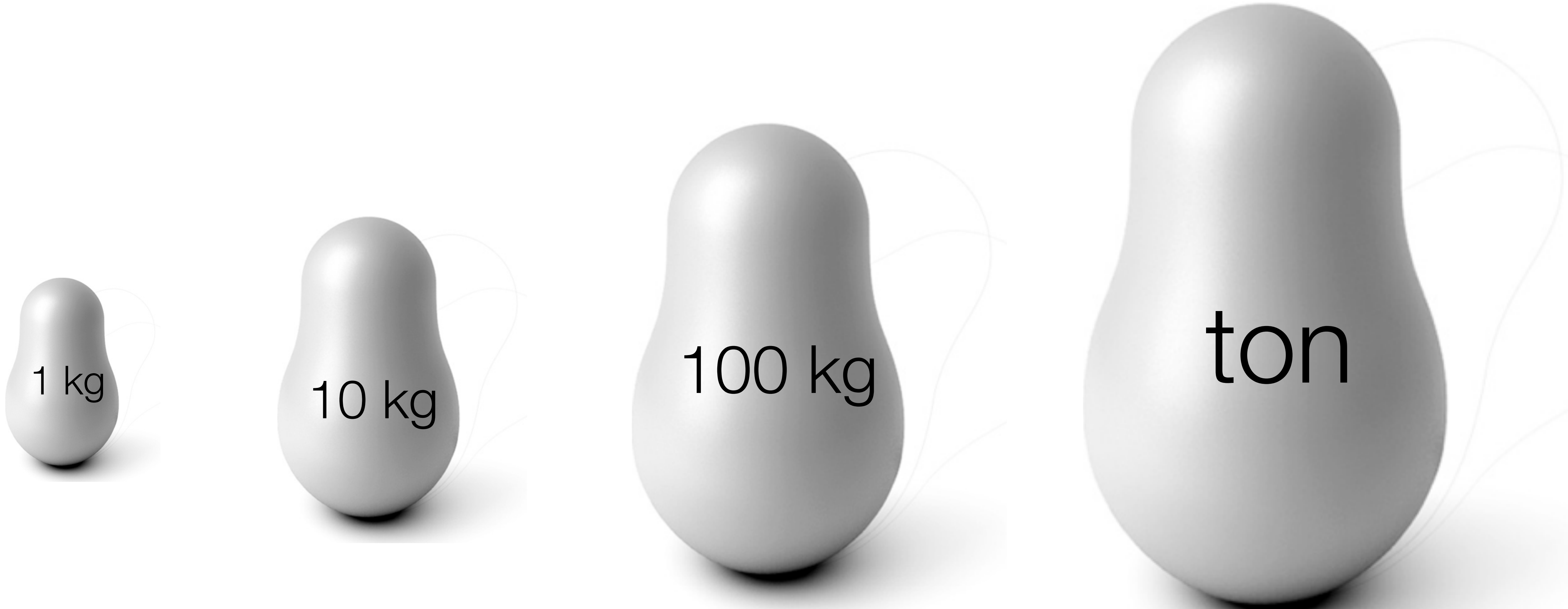
	Activity (Bq)		Rejection Factors		Final rate (ckky)	
	Tl-208	*Bi-214*	*Tl-208*	*Bi-214*	*Tl-208*	*Bi-214*
Dice Boards	4,28E-03	3,21E-03	7,90E-07	8,85E-07	3,047E-05	2,560E-05
PMTs	8,40E-03	3,00E-02	3,30E-07	2,68E-07	2,498E-05	7,244E-05
Field Cage	4,38E-03	1,53E-02	5,30E-07	8,02E-07	2,091E-05	1,107E-04
ICS	1,326E-02	1,105E-01	1,100E-07	8,400E-08	1,315E-05	8,365E-05
Vessel	1,66E-01	5,16E-01	1,10E-08	2,80E-09	1,644E-05	1,301E-05
Shielding Lead	6,266E-01	1,084E+00	2,000E-09	1,000E-10	1,129E-05	9,763E-07
SUBTOTAL	8,23E-01	1,76E+00			1,172E-04	3,063E-04
TOTAL BKGND	2,58E+00				**4,24E-04**	

NEXT sensitivity



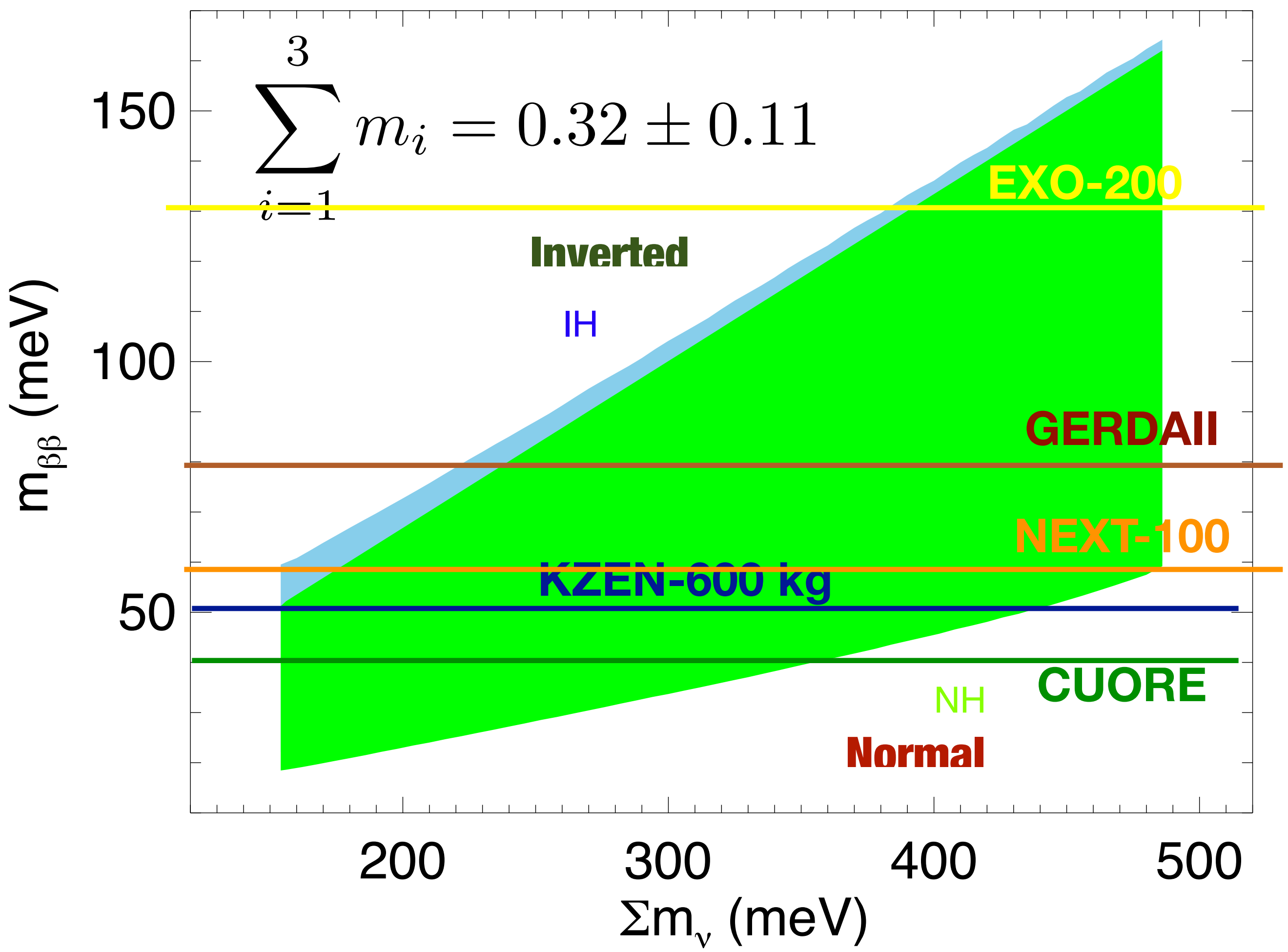
- **400 kg yr in 5 years**
- **ΔE=0.5 % FWHM at $Q_{\beta\beta}$**
- **B=5 x 10^{-4} ckky ⇒**
  - **$T^{0\nu}$=6 x 10^{25}⇒**
  - **$m_{\beta\beta}$ = 60-168 meV**

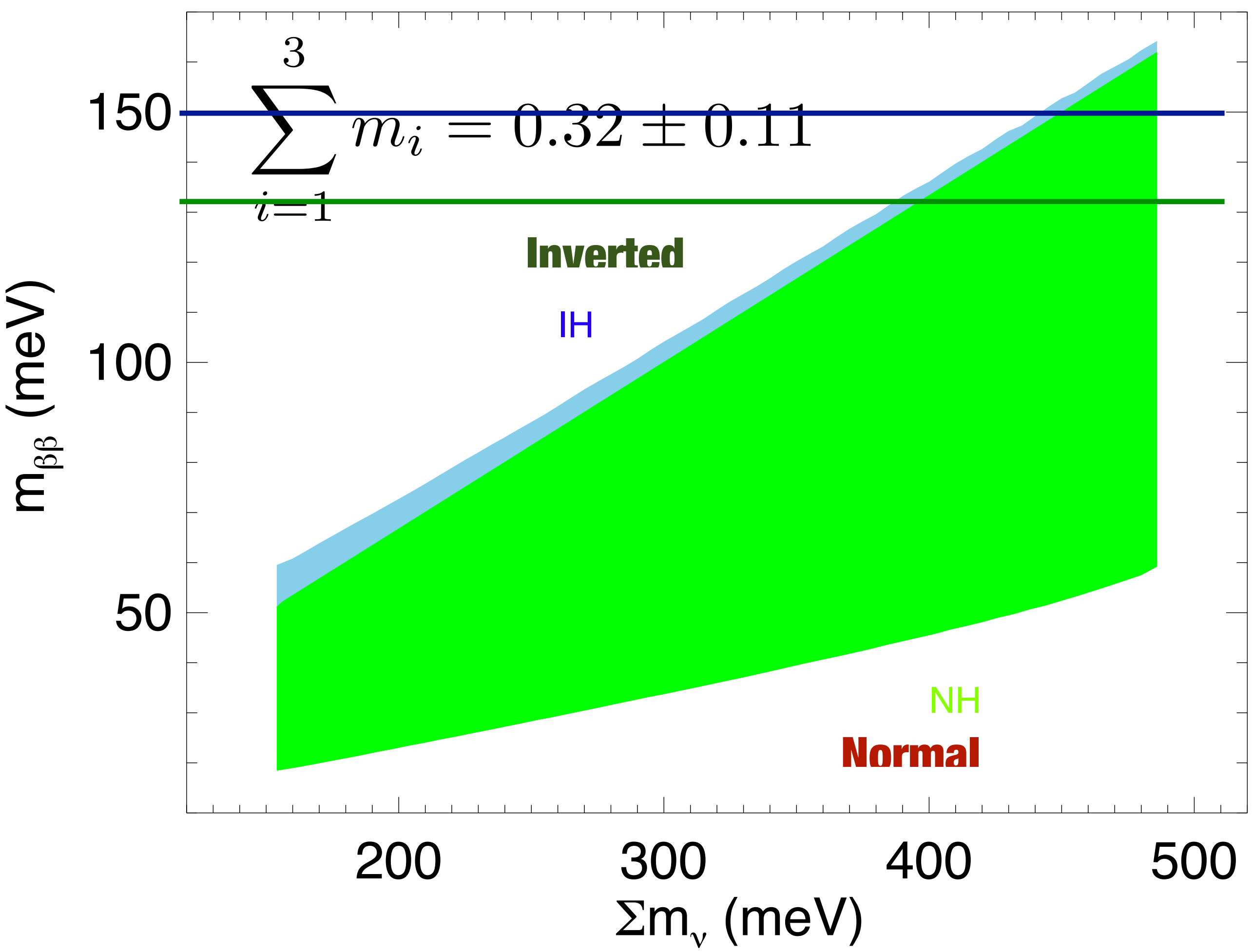
- **Will Cover a significant fraction of cosmological region.**



R&D	ββ2ν	ββ0ν (100 meV)	ββ0ν (20 meV)
(2008-2013)	(2014-2016)	(2016-2020?)	(2020?)

Majorana landscape circa 2020

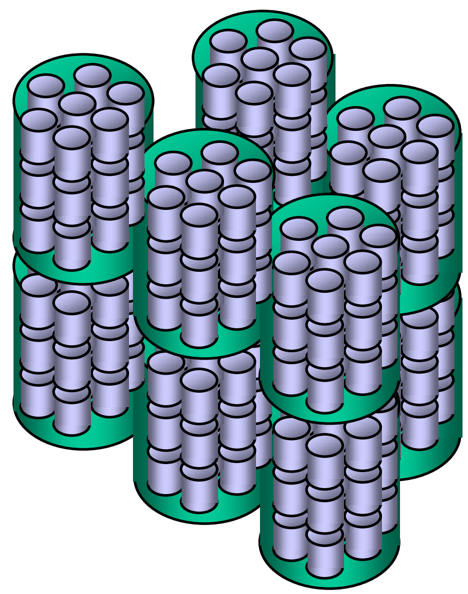




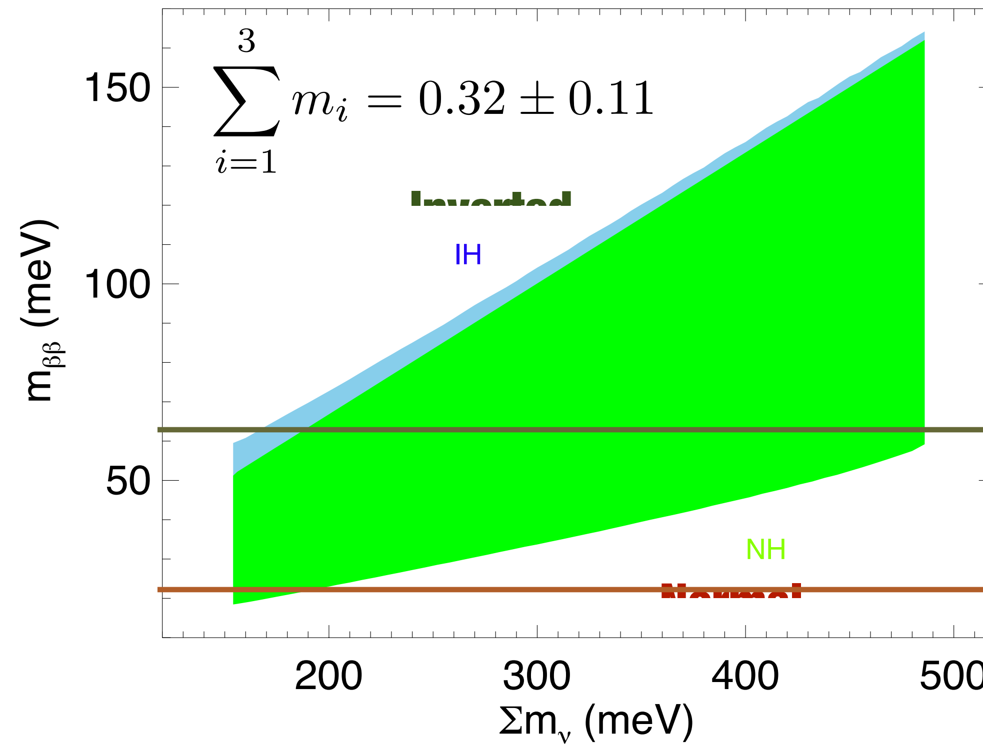
- **Larger NME**
- **Smaller NME**
- **How do we cover the cosmo-region even for small NME?**

SuperGerda/Majorana

- **Mass ~500-1000 kg = 10 (20)GERDA II**
- **Effective exposure = 5 ton year**

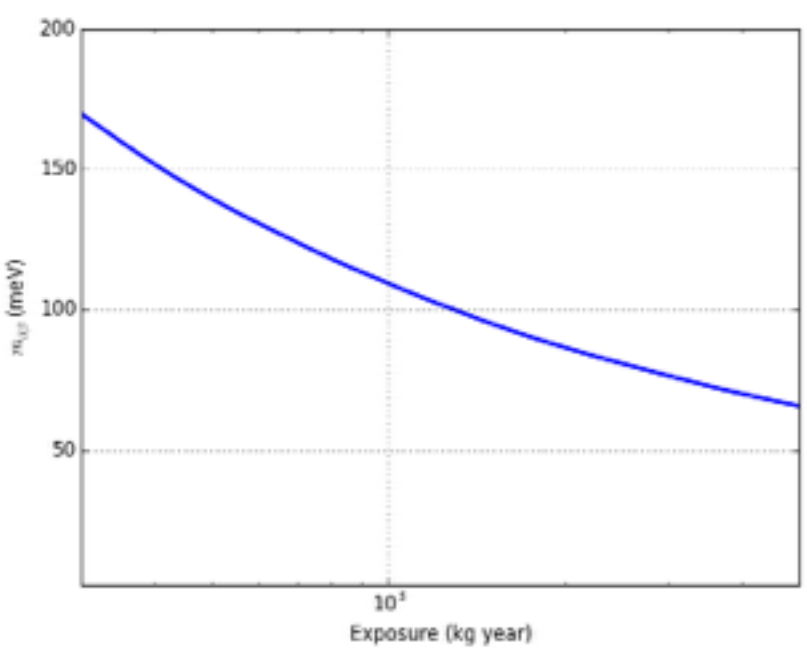


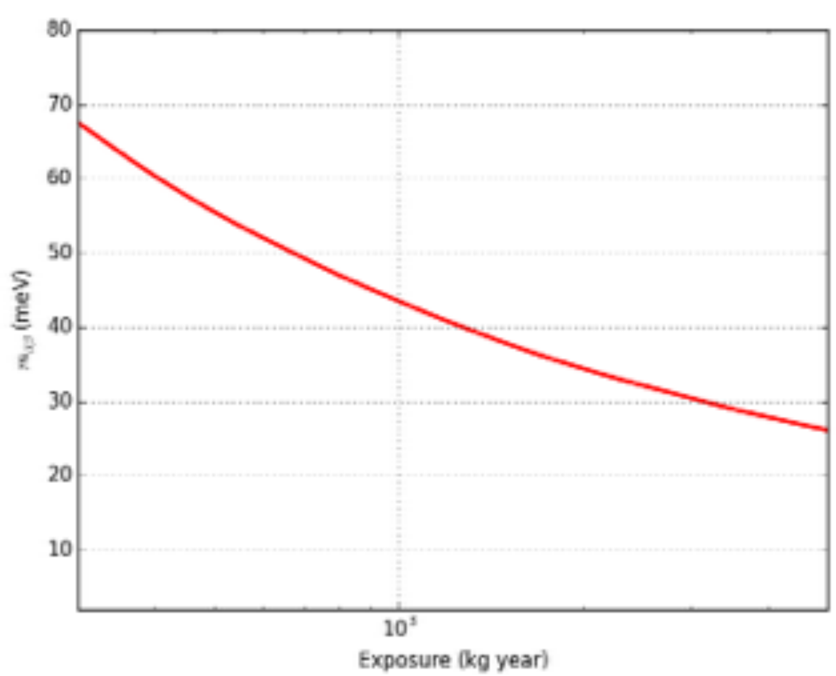
210 2.35 kg crystals



SuperGerda ISM
mββ=66 meV

SuperGerda IBM2
mββ=26 meV





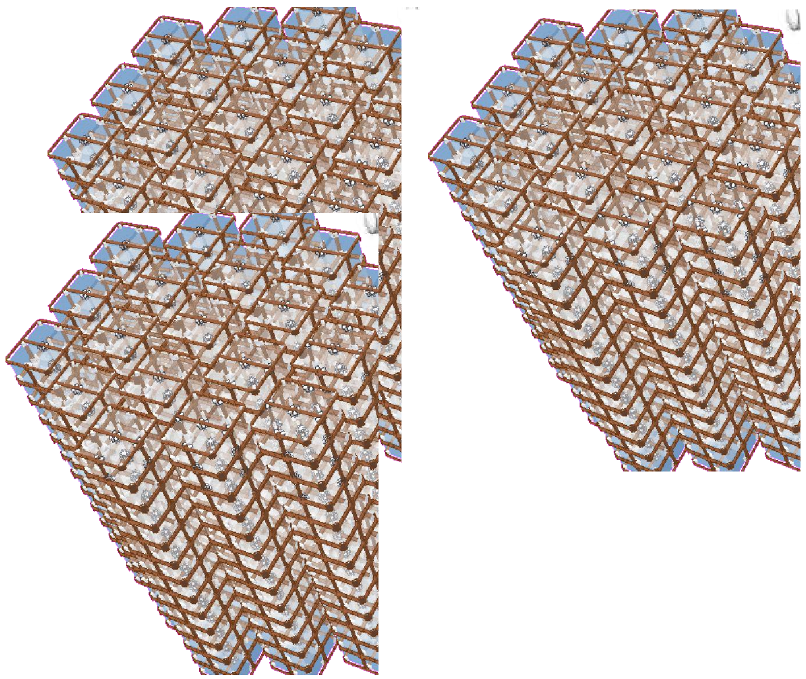
efficiency = 0.62

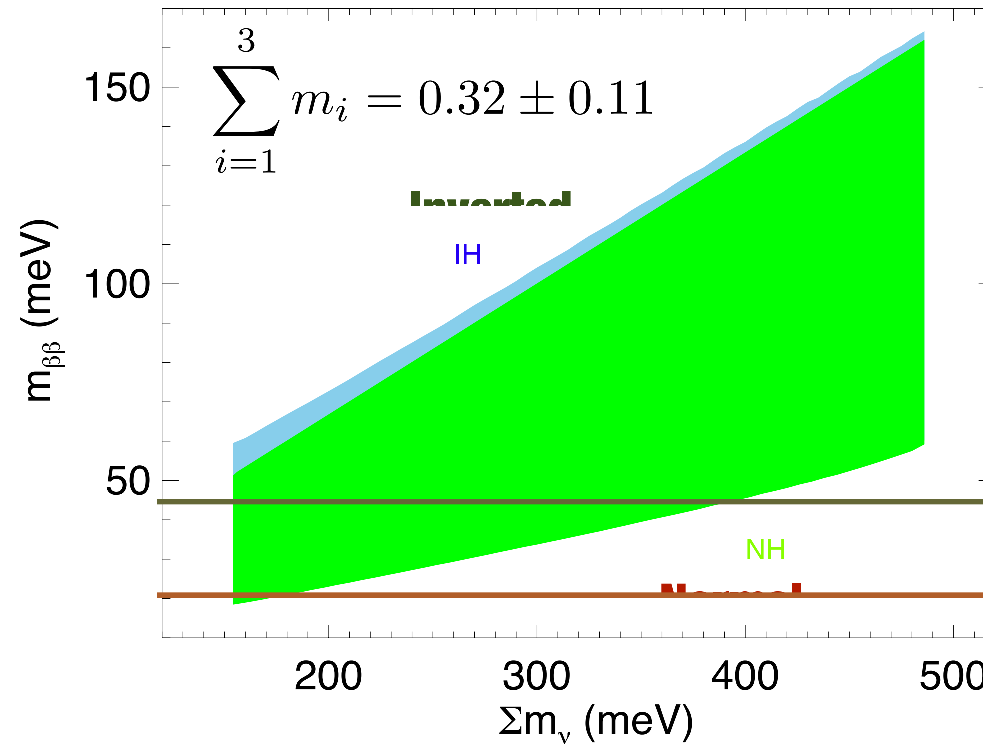
ΔE = 0.1 % at 2.6 MeV

B = 1. x 10^{-3} ckky

SuperCuore

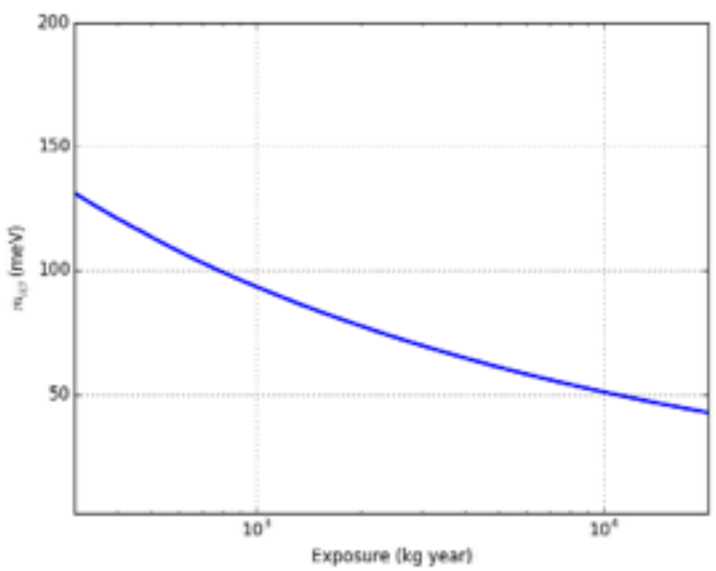
- **Mass (isotope) ~2 ton = 10 x CUORE**
- **3 super-towers + enriched TI**
- **Effective exposure = 20 ton year**

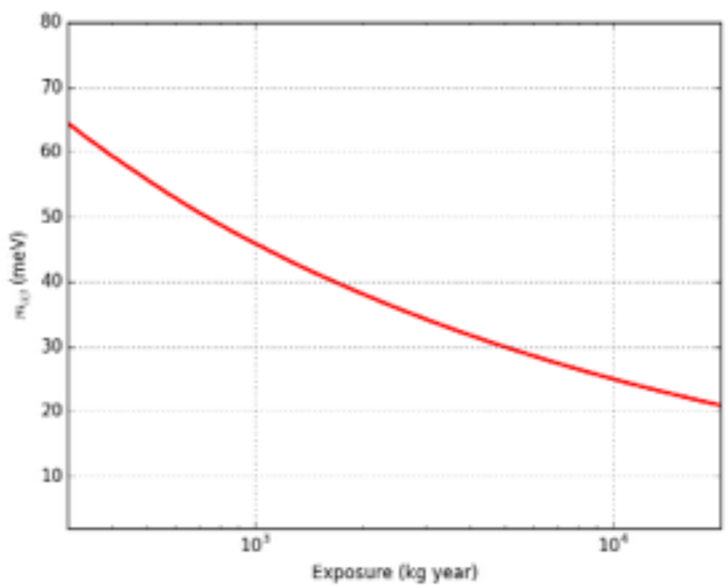




SuperCUORE ISM
mββ=43 meV

SuperCUORE IBM2
mββ=21 meV

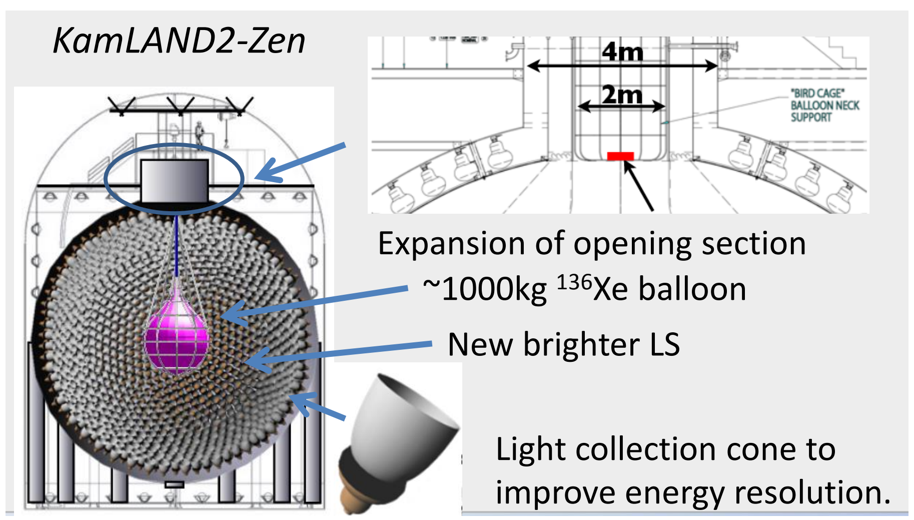


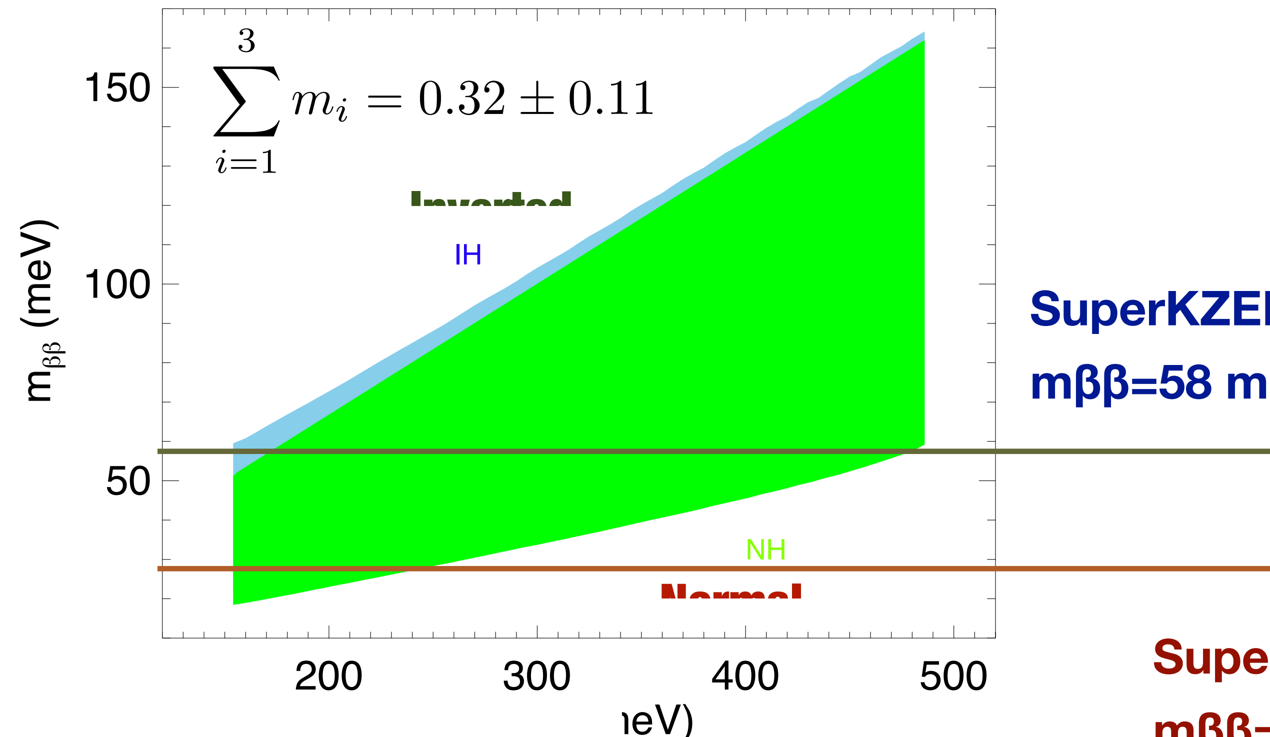


- efficiency = 0.87
- ΔE = 0.2 % at 2.6 MeV
- B = 1. x 10^{-2} ckky

KZen-II

- **Mass (isotope) ~1 ton = 10 x KZENI**
- **Improve resolution to 6% FWHM**
- **Effective exposure = 10 ton year**



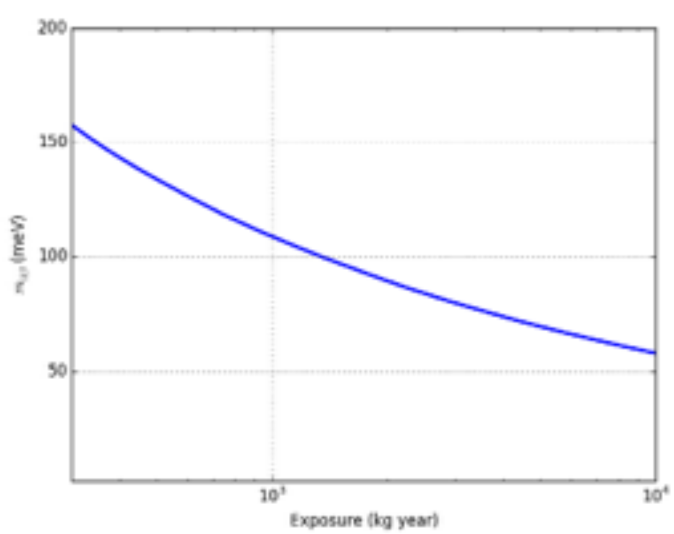


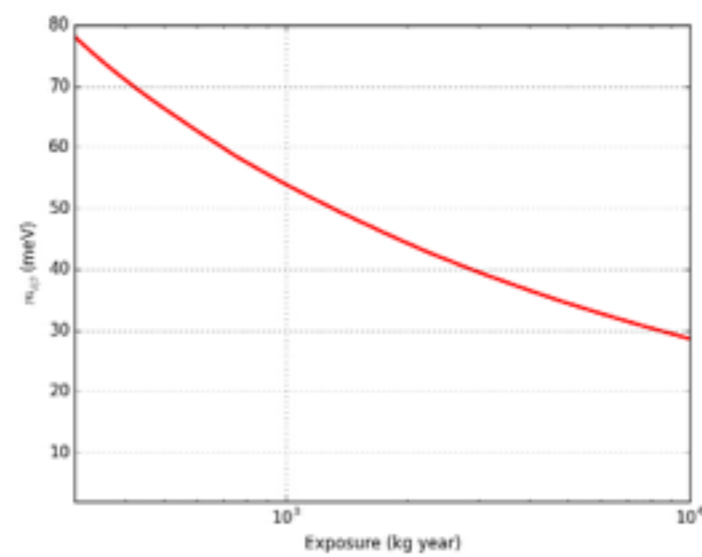
SuperKZEN ISM

mββ=58 meV

SuperKZEN IBM2

mββ=29 meV

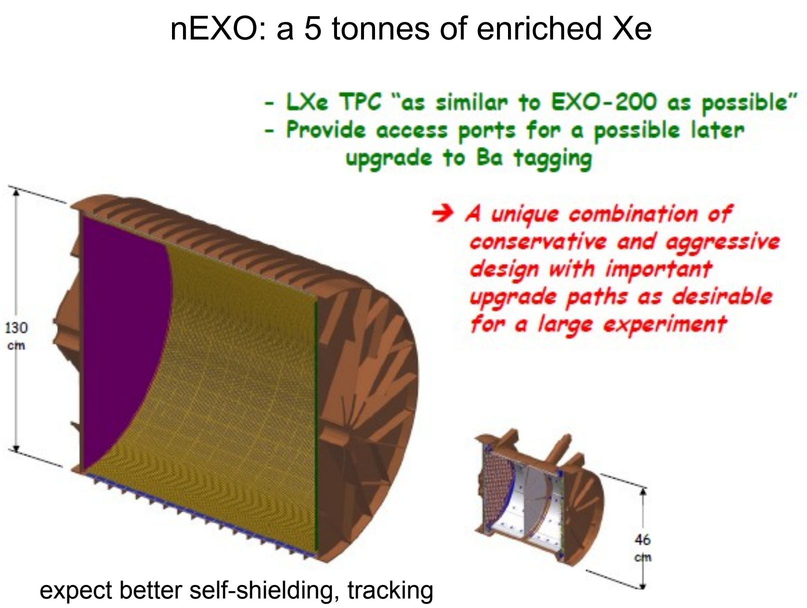


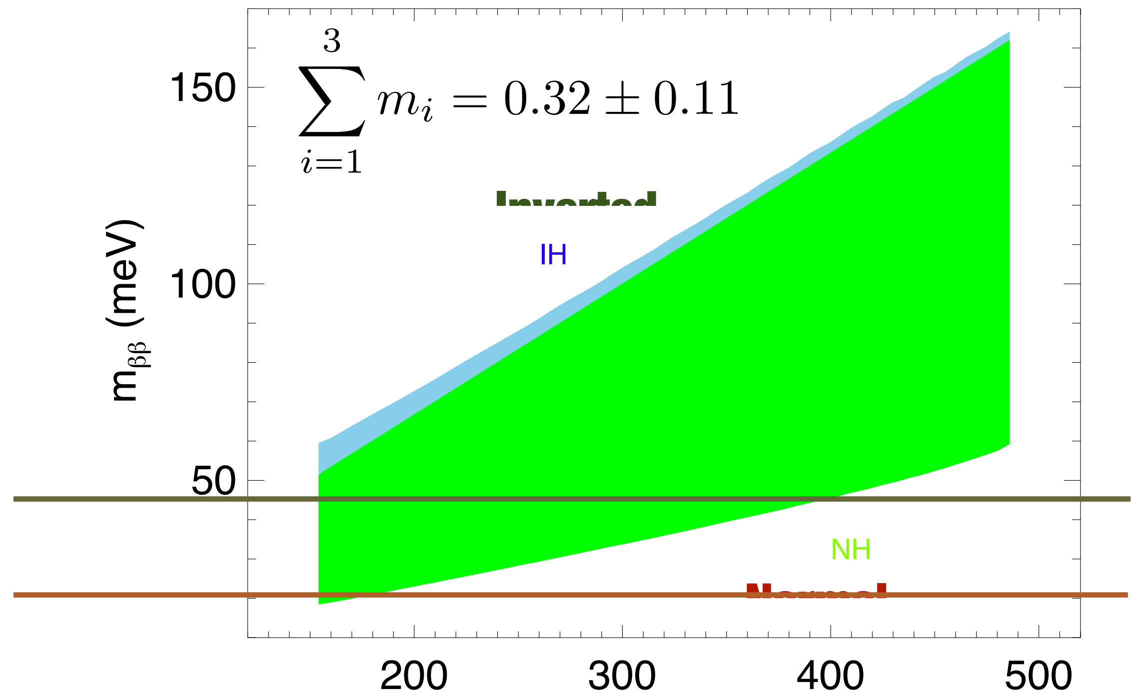


- efficiency = 0.55
- ΔE = 6 % at 2.5 MeV
- B = 1. x 10^{-4} ckky

NEXO

- **Mass ~5 ton = 20 x EXO-200**
- **Effective mass: ~3 ton Effective exposure = 30 ton year**



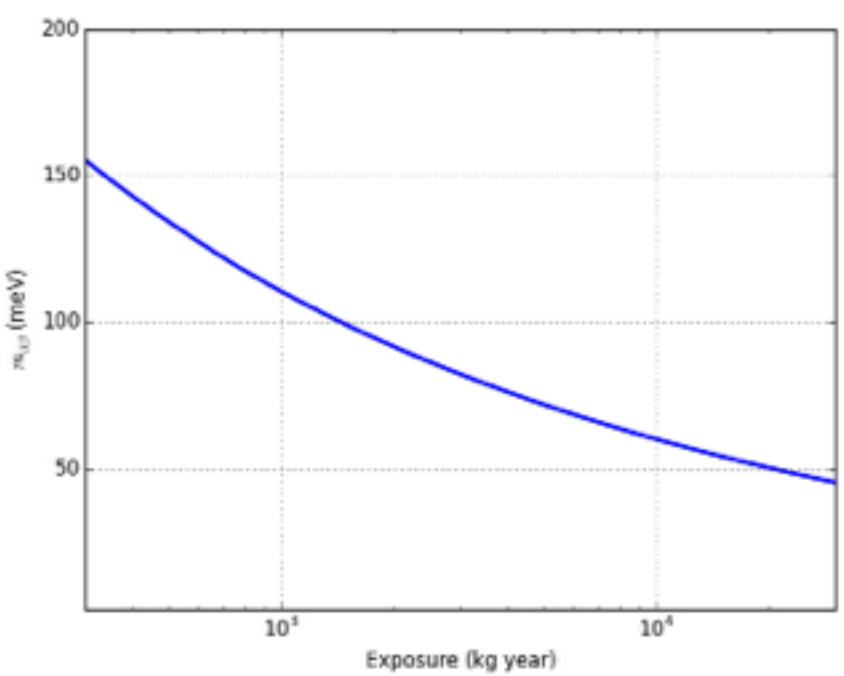


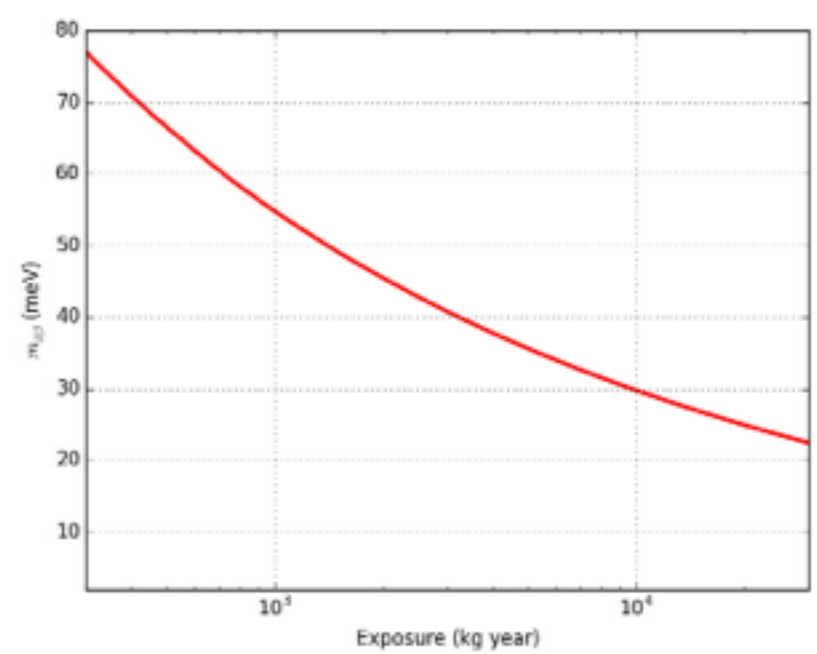
NEXO ISM

mββ=45 meV

NEXO IBM2

mββ=23 meV

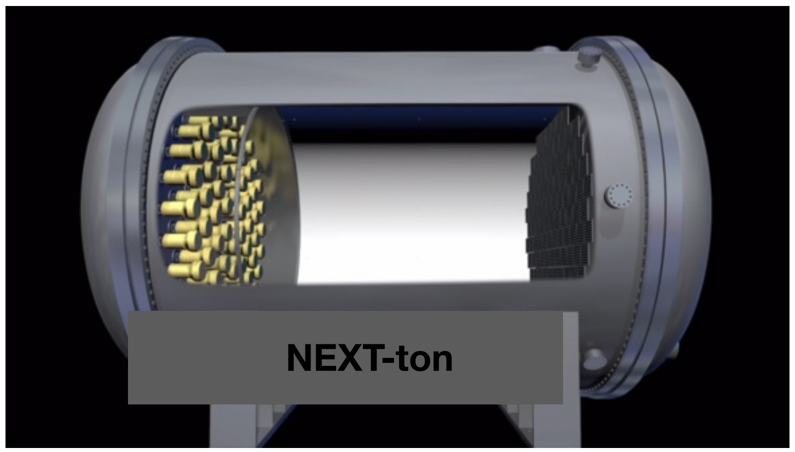


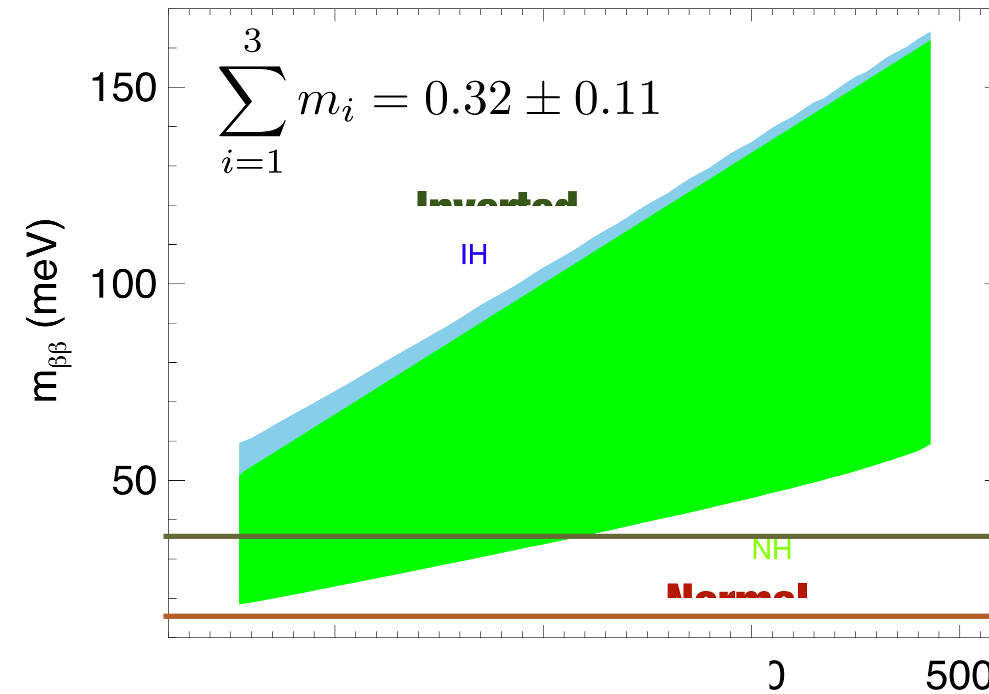


- efficiency = 0.85
- ΔE = 3.6 % at 2.5 MeV
- B = 5. x 10^{-4} ckky

NEXT-ton

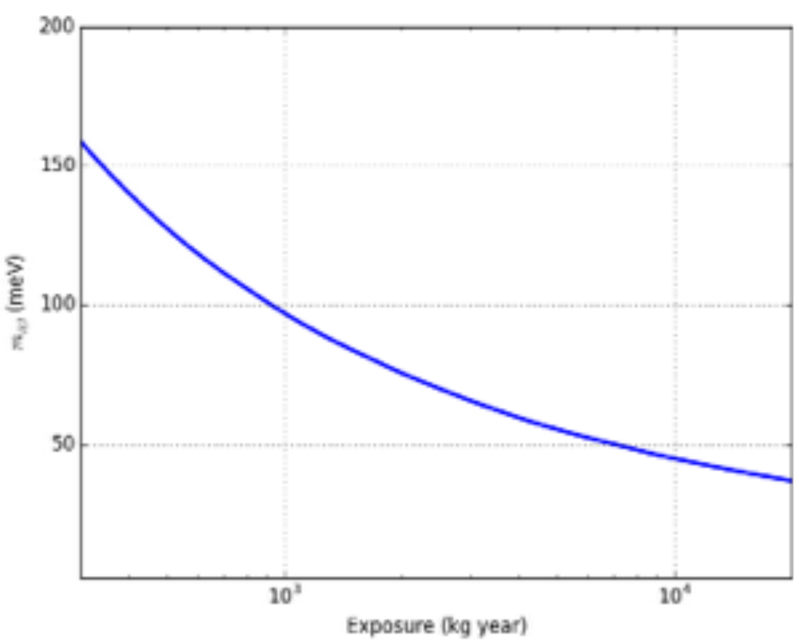
- **Mass ~2 ton = 20 x NEXT-100**
- **Increase pressure to 20 bar**
- **Effective exposure = 20 ton year**

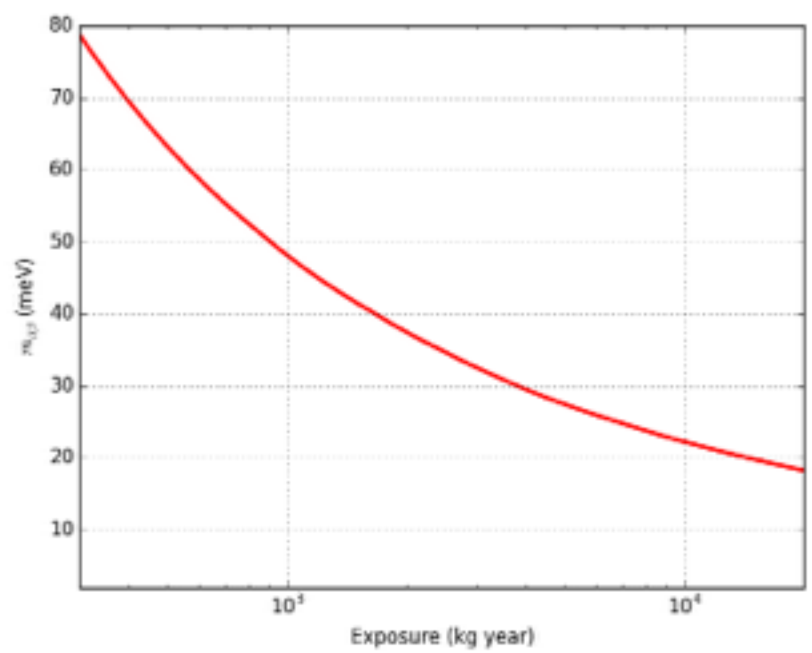




NextTon ISM
mββ=37 meV

NextTom IBM2
mββ=18 meV

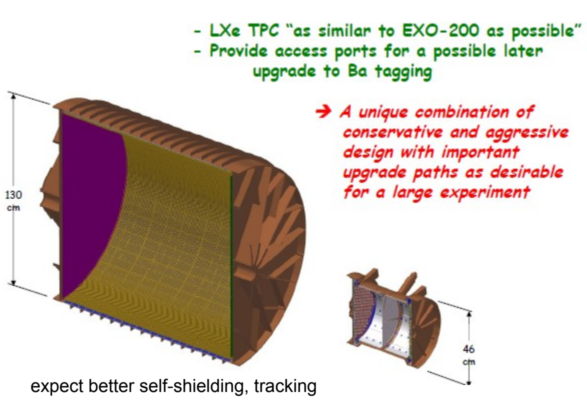




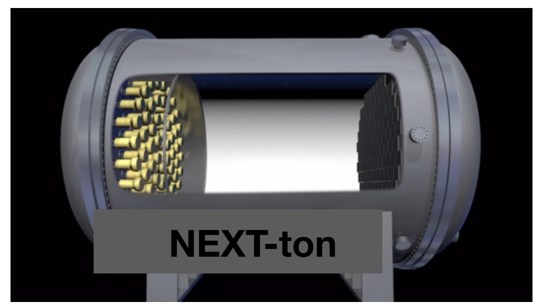
- efficiency = 0.3
- ΔE = 0.5 % at 2.5 MeV
- B = 1. x 10^{-4} ckky

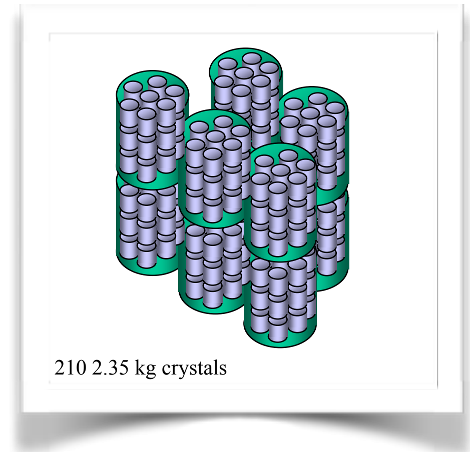
Assessment: The next generation

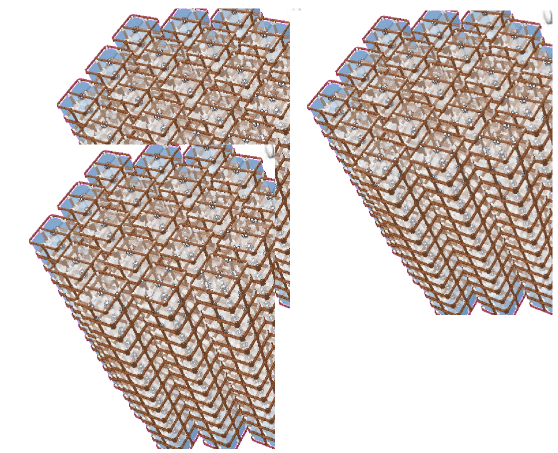
nEXO: a 5 tonnes of enriched Xe

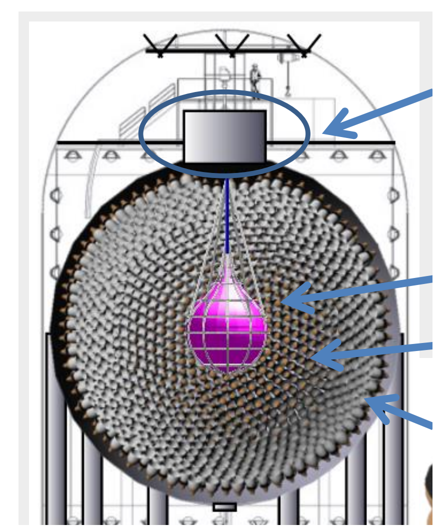


expect better self-shielding, tracking

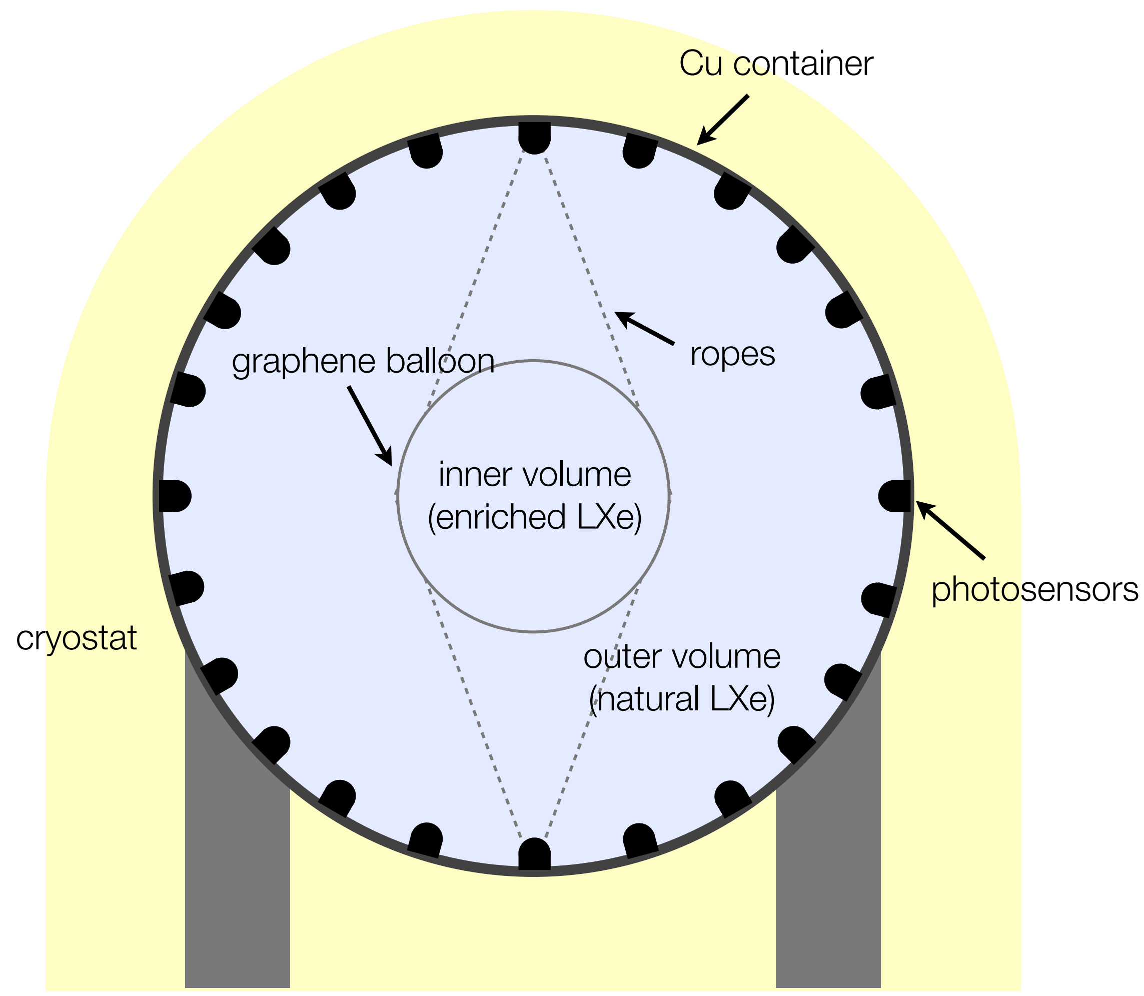








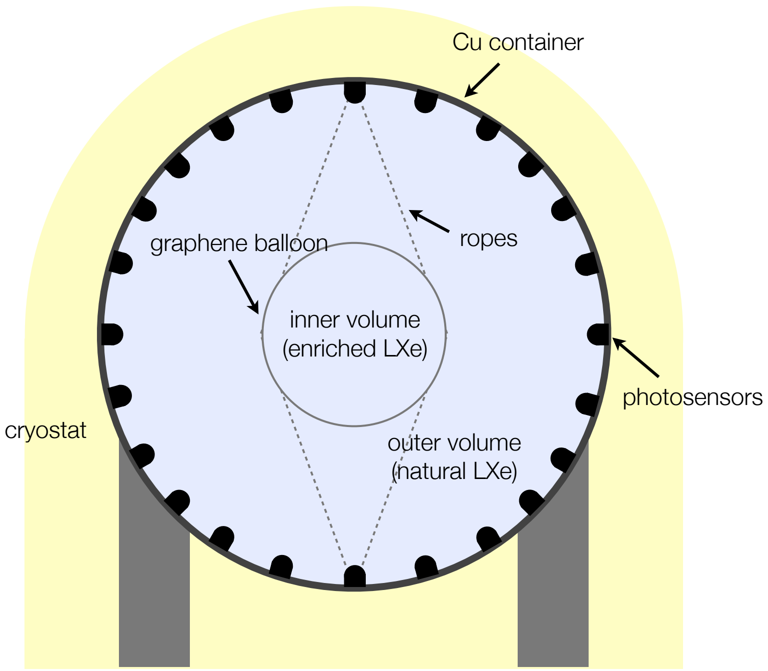
- **Super-Gerda: 26-66 meV**
- **Super-Cuore: 21-43 meV**
- **KamLAND-Zen-II: 29-48 meV**
- **NEXO: 23-45 meV**
- **NEXT-TON: 18-37 meV**
- **Cover the cosmological relevant region (inverse hierarchy) only if NME is high**

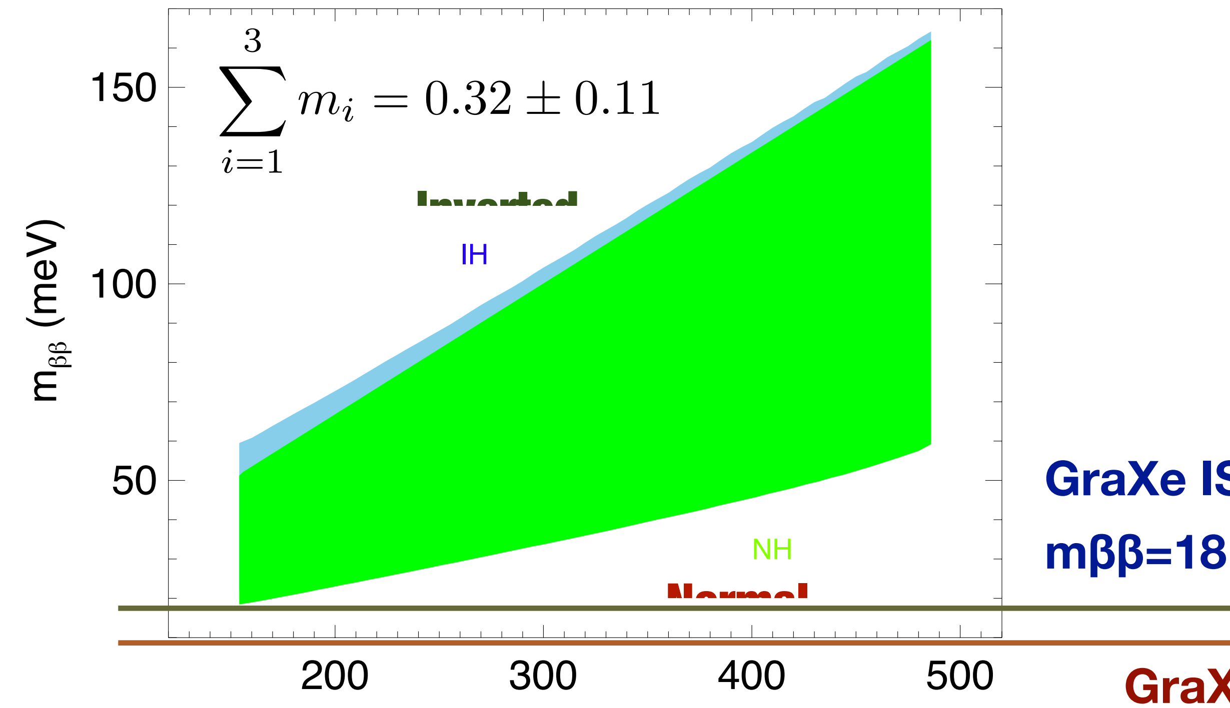


Exploring new ideas

GraXe

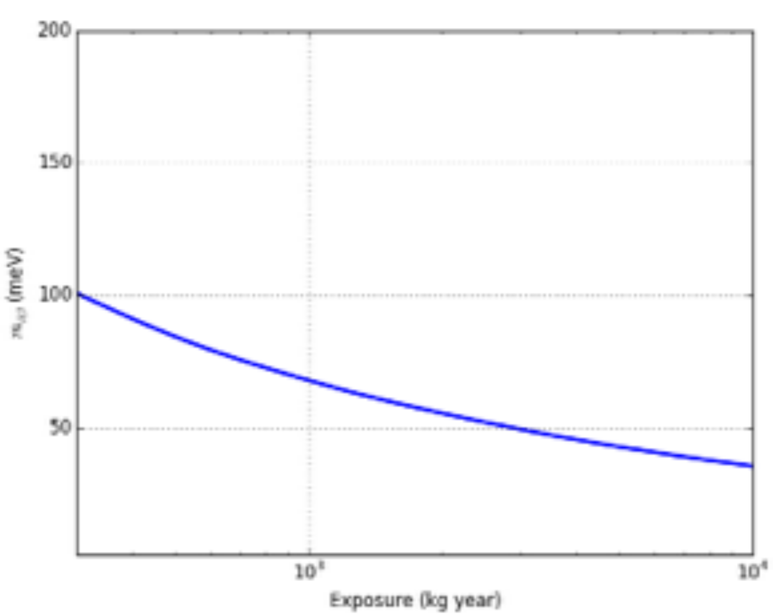
- **Mass ~3ton enriched in balloon, 20 ton LXe shield**
- **Effective exposure = 30 ton year**

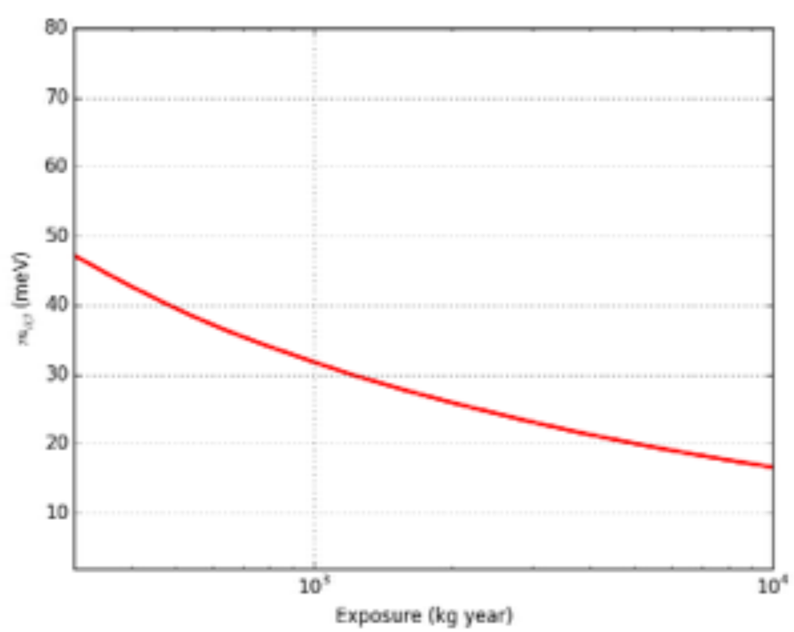




GraXe ISM
mββ=18 meV

GraXe IBM2
mββ=9 meV

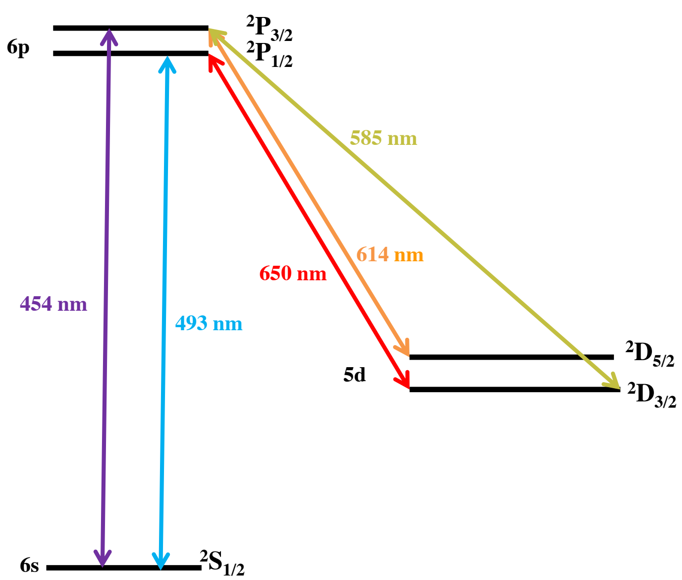


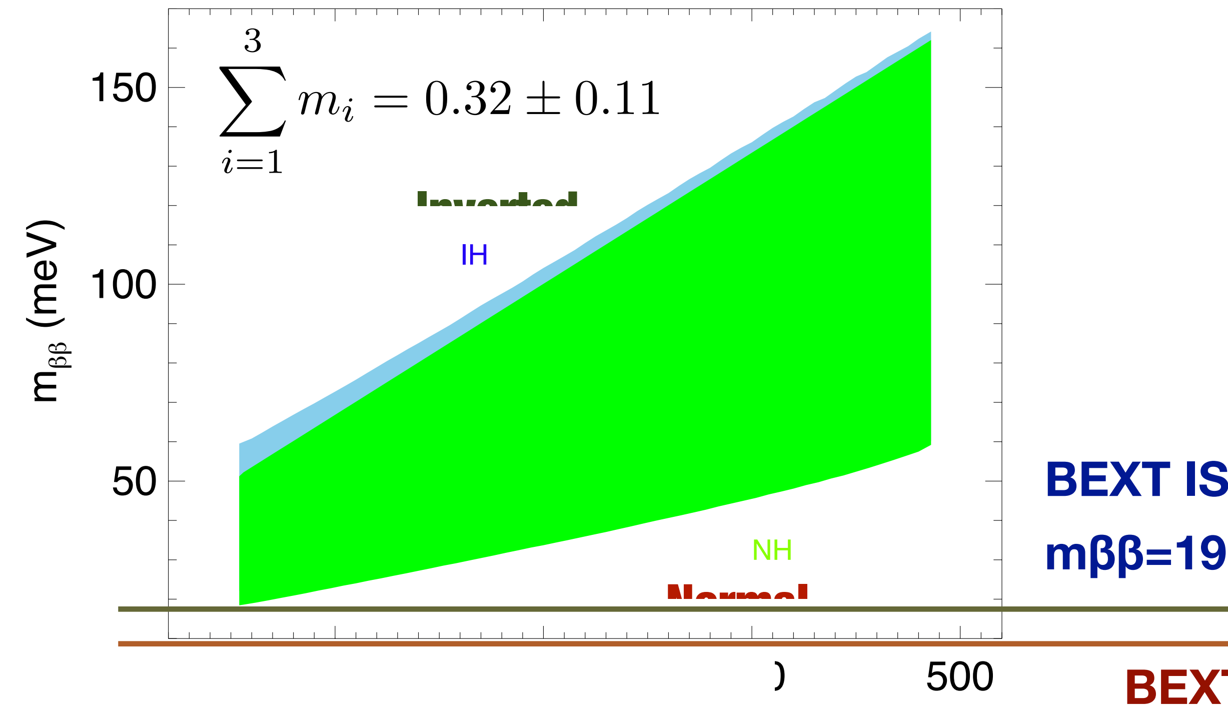


- efficiency = 0.85
- ΔE = 3.6 % at 2.5 MeV
- B = 1. x 10^{-5} ckky

BEXT

- **Mass ~2 ton Effective exposure = 20 ton year**



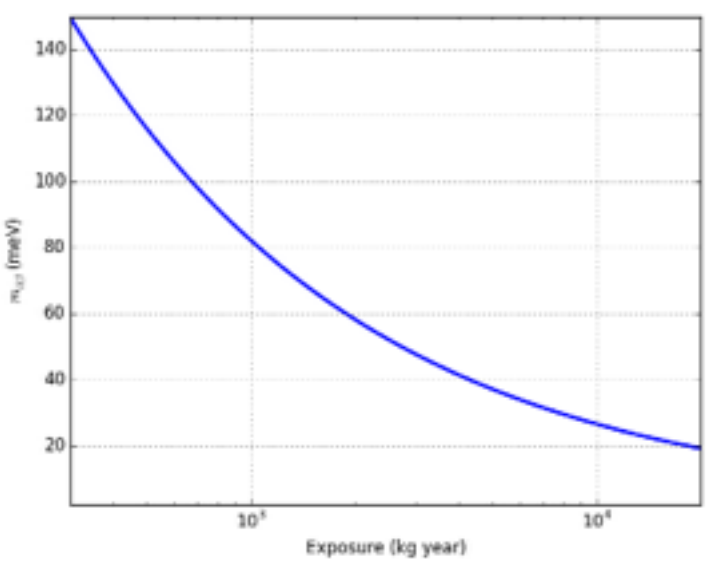


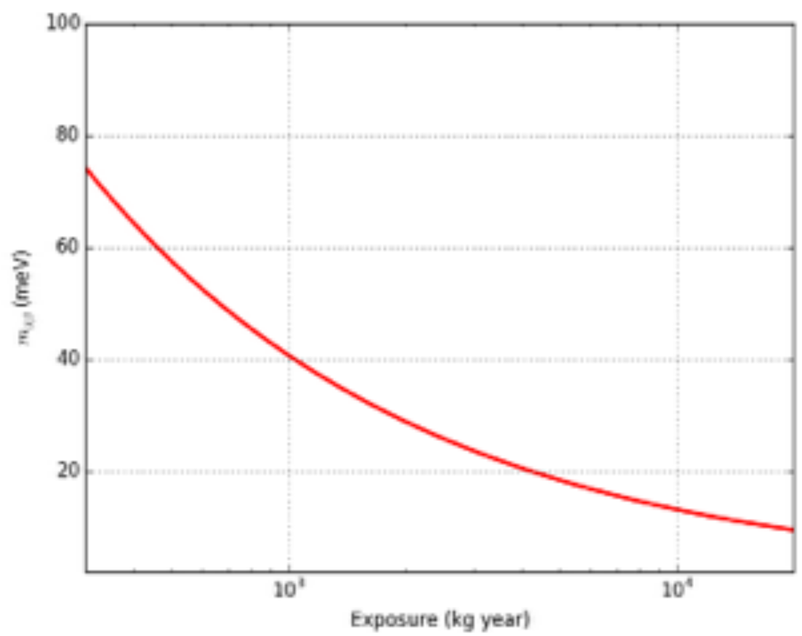
BEXT ISM

mββ=19 meV

BEXT IBM2

mββ=9 meV





- efficiency = 0.3
- ΔE = 0.5 % at 2.5 MeV
- B = 1. x 10^{-6} ckky

- Finding the rare signal that DBD experiments are searching is equivalent to identify an specific grane of sand in a large beach or finding the light of a single star in 10 universes… The magic of science is that it can be truly done!