EMFCSC
International School of Subnuclear Physics

GRAVITY AND MATTER
IN THE SUBNUCLEAR WORLD

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Are Neutrinos and Antineutrinos the same particle?

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Summary

- **Majorana vs Dirac spin 1/2 particles**
- **Two-neutrinos and neutrino-less double beta decay**
- **Backgrounds and energy resolution**
- **Examples of leading edge experiments**
- **Limits on effective Majorana mass**
- **Hints from atomic and supramolecular physics**
- **Conclusions**

1937 *Majorana anti*$\nu=\nu$*?*

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

The new approach allows to "*not only to give a symmetric form to the electron-positron theory, but also* ***to build a substantially novel theory for the particles deprived of electric charge (… hypothetical neutrinos***)"

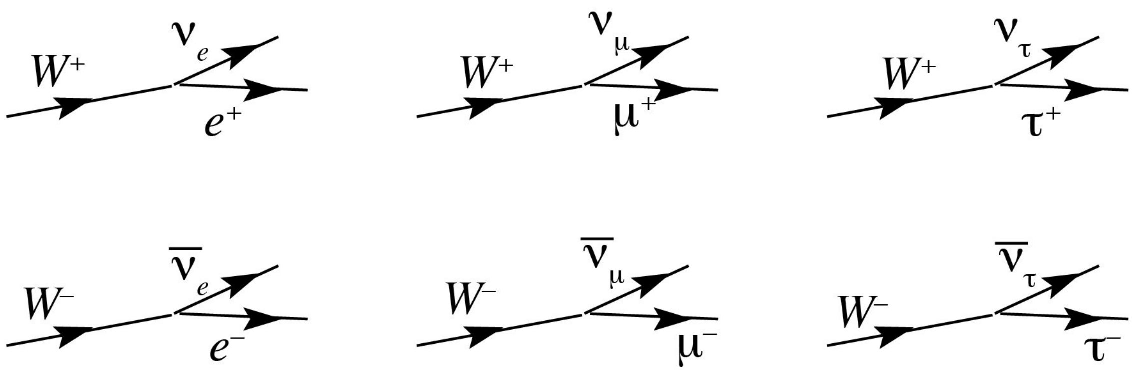
…….it is probably "*not yet possible to ask to the experience to decide between this new theory and the simple extension of the Dirac equation to the neutral particles*"

Definitions

ν_e is the neutral particle produced with an e^+ (e.g. β^+ decay)
"anti" ν_e is the neutral particle produced with an e^- (e.g. β^- decay)
Same for ν_μ and ν_τ and their "anti" particles

neutrinos

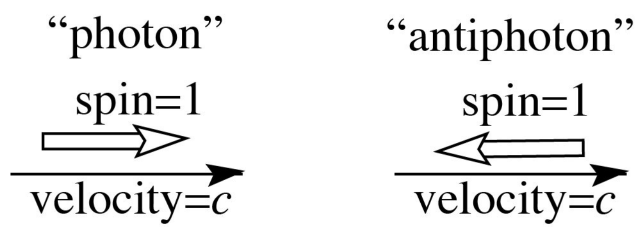
antineutrinos



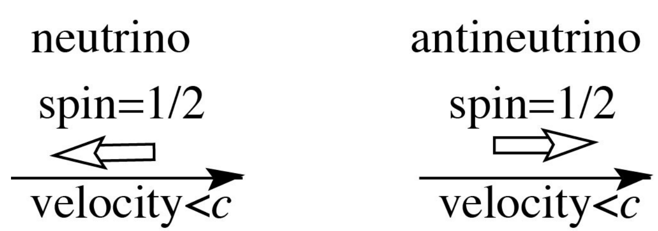
Majorana: *The advantage of this procedure….is that there is now no reason to assume the existence of … antineutrinos.*

Matter or antimatter?

Photon is a completely neutral particle, no charge-type quantum number
The antiparticle of the photon is the photon. Just invert helicity



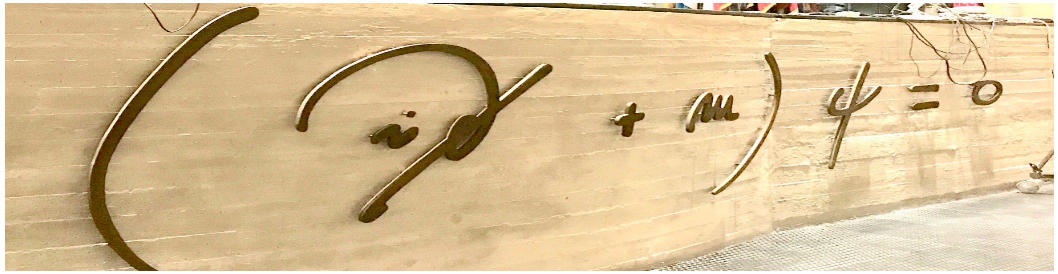
Neutrino and antineutrino in the SM are assumed to be different particles, distinguished by the lepton number. No experimental evidence
If lepton number is not a good quantum number neutrino and antineutrino may be two states of the same particle, distinguished by helicity (negative vs positive)



Frame dependent

If neutrino and antineutrino are two states of the same particle, the matter-antimatter asymmetry in the Universe can find an explanation

Majorana vs Dirac equation



Dirac

$$\psi = \begin{pmatrix} \varphi \\ \chi \end{pmatrix}$$

$$\left(i\partial_t - i\vec{\sigma}\cdot\vec{\nabla}\right)\varphi = m\chi$$

$$\left(i\partial_t + i\vec{\sigma}\cdot\vec{\nabla}\right)\chi = m\varphi$$

Majorana

$$\psi_M = \begin{pmatrix} \varphi \\ i\sigma_2\varphi^* \end{pmatrix}$$

$$\left(i\partial_t - i\vec{\sigma}\cdot\vec{\nabla}\right)\varphi = im\sigma_2\varphi^*$$

If m=0, Dirac = Majorana

$$\psi_M^C = C\gamma^0\psi_M^* = \begin{pmatrix} 0 & -i\sigma_2 \\ i\sigma_2 & 0 \end{pmatrix}\begin{pmatrix} \varphi \\ i\sigma_2\varphi^* \end{pmatrix}^* = \begin{pmatrix} \varphi \\ i\sigma_2\varphi^* \end{pmatrix} = \psi_M$$

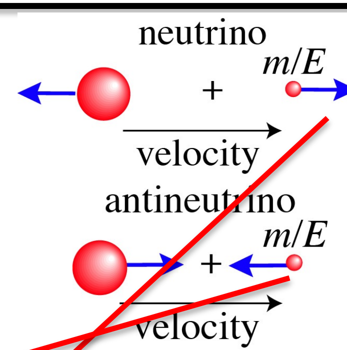
Majorana particles are **completely neutral spin 1/2 particles** (like γ, Z, etc. for bosons)

Is neutrino completely neutral?

V–A only left-handed field ($\gamma_5 = -1$)

ν_e :dominant negative helicity + m/E positive helicity

$\overline{\nu_e}$:dominant positive helicity + m/E negative helicity

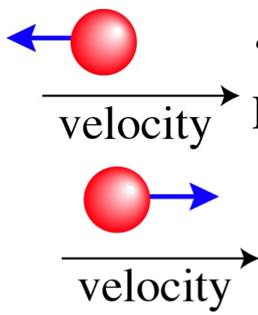


Dirac

Produces e^-

Produces e^+

Majorana



'Neutrino' Produces e^-

'Antineutrino' produces e^+

Only the extremely small m/E component distinguishes between Dirac and Majorana

Beam energy E_ν=10 MeV, m= 100 meV

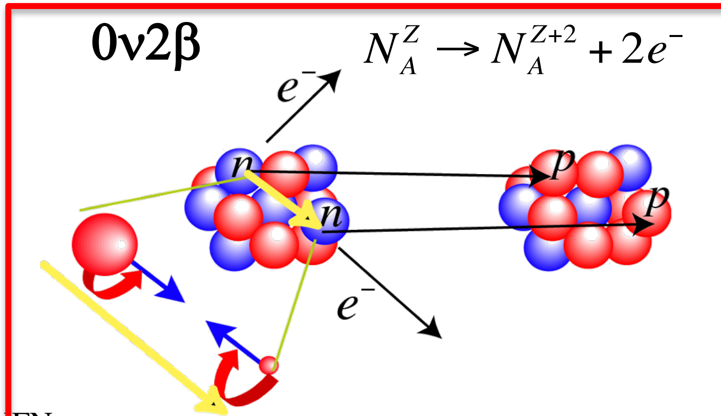
➔ $(m/E_\nu)^2 = 10^{-14}$

ν_e not producing e^+ do not prove lepton number conservation

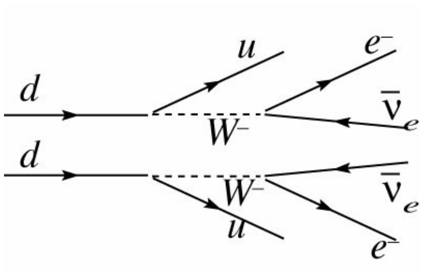
AVOGADRO, Help!

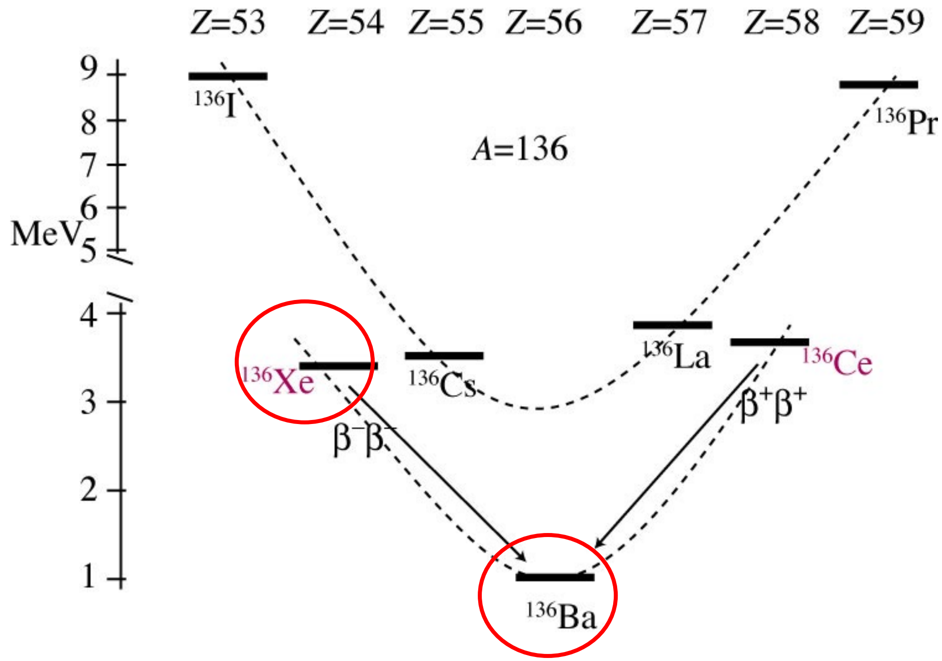
6 x 10^{26}

Have a large N



Double beta active isotopes





Two neutrino double beta decay
2nd order weak interaction
In nuclides stable against β decay

Nucleon level

$n + n \rightarrow 2e^{-} + 2p + \overline{2\nu_e}$

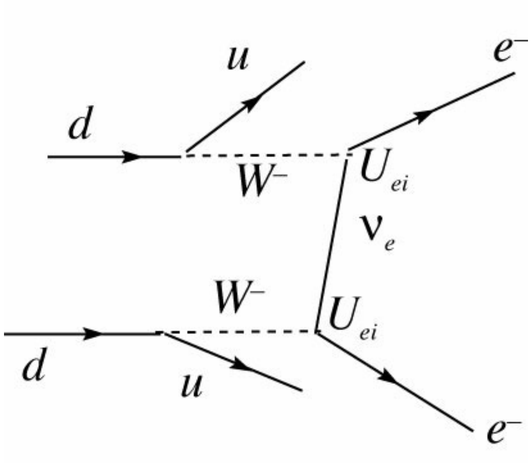
Nuclear level

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

Several have been measured

Isotope	$T^{2\nu}_{1/2}(10^{20}$ yr)
^{76}Ge	19.3±0.9
^{82}Se	0.94±0.06
^{100}Mo	0.07±0.002
^{130}Te	8.2±0.7
^{136}Xe	21.7±0.7

$2\beta0\nu$ Decay



Majorana neutrino couples to *W* as Dirac neutrino
The SM violation is in the propagator

At one vertex the (h=+) component matters, the (h=–) component at the other vertex

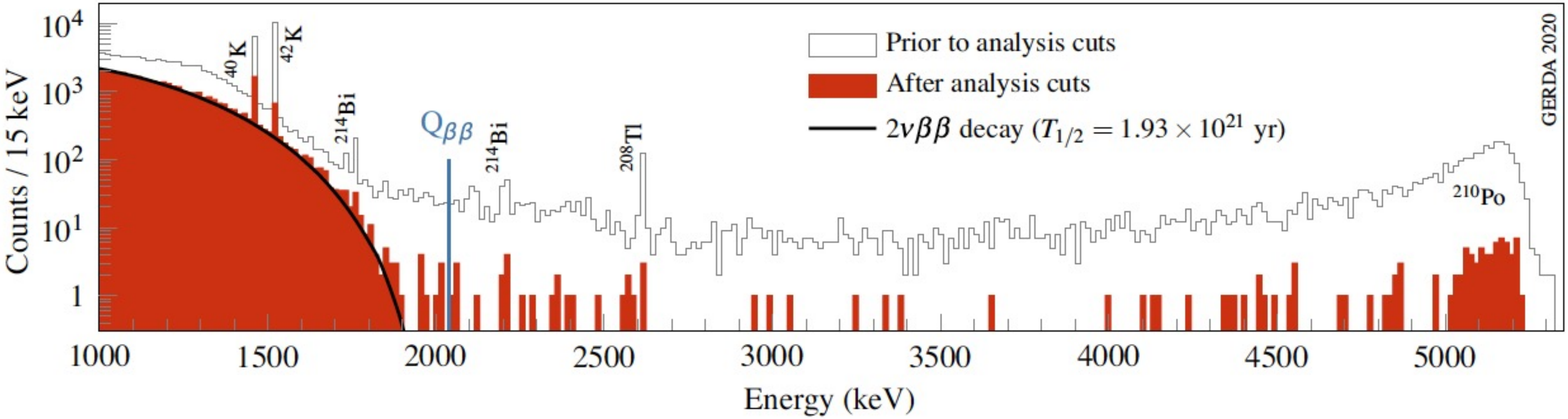
$$M_{ee} = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3\right| \sim \left|0.67 m_1 + 0.30 m_2 e^{2i(\eta_1 - \eta_2)} + 0.03 m_3 e^{2i(\eta_1 + \delta_{CP})}\right|$$

$$1/T_{1/2} = G(Q,Z)|NME|^2 M_{ee}^2$$

Sensitivity to M_{ee} scales as the (sensitivity to $T_{1/2}$)$^{1/2}$

Phase-space factor, PSF, $G(Q,Z)$ calculated taking into account that electrons are in an atom
Nuclear matrix element calculation quite uncertain (factor 2-3)

The sum-energy electrons spectrum



GERDA 2020 example

On the left 2ν2β continuous spectrum. Potential background for 0ν0β; need energy resolution

Signal: a line at $Q_{\beta\beta}$, which is **exactly known**; width = energy resolution *ΔE* (FWHM)

Backgrounds from radioactive sources reduced, by experimental cuts (see later)

Background index: *b* = counts per unit energy interval, unit sensitive mass, unit live time: counts/(keV kg yr)

Figure of merit: ***bΔE*** (counts/kg y) = total background in the region of interest (roi)

0-bkgrnd: *bΔE*<(0.5-1). Senstivity to $T_{1/2}$ grows **linearly** with exposure *MΔt*

non-0 bkgrnd. Senstivity to $T_{1/2}$ grows with **sqrt** of exposure $(M\Delta t)^{1/2}$

Isotope separation

With the exception of ^{130}Te, all nuclides require isotopic enrichment

ECP. Joint Stock Company. Production Association Electrochemical Plan", Zelenogorsk, Oblast' of Oremburg (near Kransnoyarsk), Siberia, Russia; http://www.ecp.ru/index en.shtml

Gas centrifuge processing: large number of centrifuges in series and parallel formations.

Large, background-free exposures

$0\nu2\beta$ signal might be at $T_{1/2}$ =10^{27}-10^{28} yr. Large exposure needed
For a few counts of $0\nu2\beta$ we need

- 10^{26} yr: 100 kg yr   now
- 10^{27} yr: 1 t yr   2027
- 10^{28} yr: 10 t yr   2037

If the signal is a few counts the background needs to be near to 0 (< 1 count)
An order of magnitude larger sensitive mass needs an order of magnitude lower background

The low background frontier

We live in a very radioactive world

human body: 6 10^{12}/(t yr)

Backgrounds in a FWHM per isotope ton per year.

Experiment	bΔE ($t^{-1}yr^{-1}$)
GERDA (^{76}Ge)	1.7
EXO-200 (^{136}Xe)	139
KamLAND-ZEN (^{136}Xe)	49
NEXT-100 (^{136}Xe)	8 expected
CUORE (^{130}Te)	418

Backgrounds

1. Cosmic muons

Almost exponentially decreasing with depth

An order of magnitude for about 650 m

Short delay effects (e.g.spallation)

Detect muon and anticoincide

Long delay effects (unstable nuclides, delayed decays)

Difficult to cut out if in the detector or in the shield

2. Neutrons from fission & (α,n) from U/Th in the rocks/environment

Depending on local geology, depth independent

Can be shielded

3. Gamma ambient flux (including radon & progeny)

Depending on local geology, depth independent

Can be shielded (but not Rn emanated inside detector)

4. Detector materials, supports, shielding, electrical connections, etc.

Use super clean components

Complete components assay

Avoid surfaces, especially in vacuum, identify surface events

Shielding example - GERDA

Water tank
moderates and absorbs neutrons

Liquid Ar cryostat
Absorbs gammas

Hyperpure copper
Absorbs radiation from steel wall

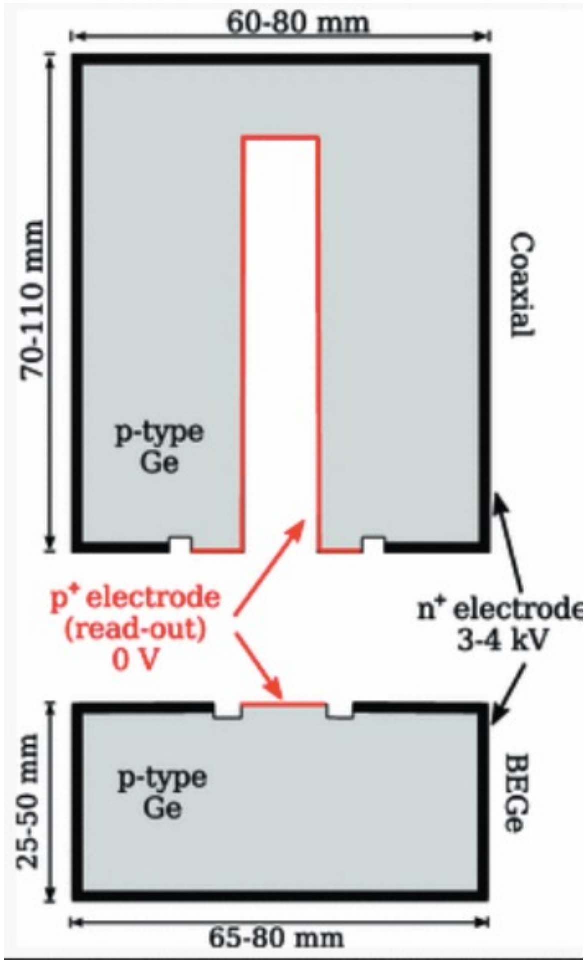
Ge detectors

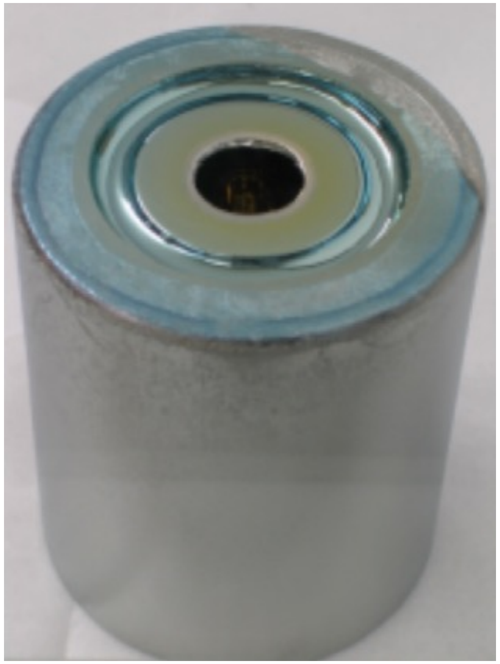
Shields are made “active” detecting backgrounds via scintillation (Ar) or Cherenkov (water) light

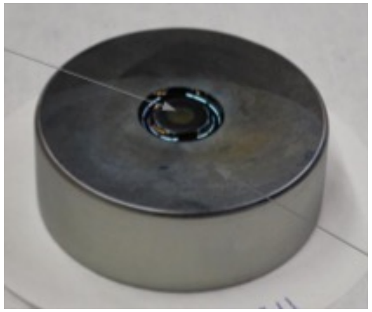
G. Heusser, Ann. Rev. Nucl. Part. Sci. 45 (1995) 543.

Ge – diode

Technique well devloped in gamma spectroscopy nuclear physics
Inverse polarisation, free chrages produced by ionosing radiation are collected and apmplified
Need criogenic temperatures







p+ contact = B implnted (thin)
n+ contact Li diffused
New in GERDA: naked in L Ar
Liquid Ar bath functions

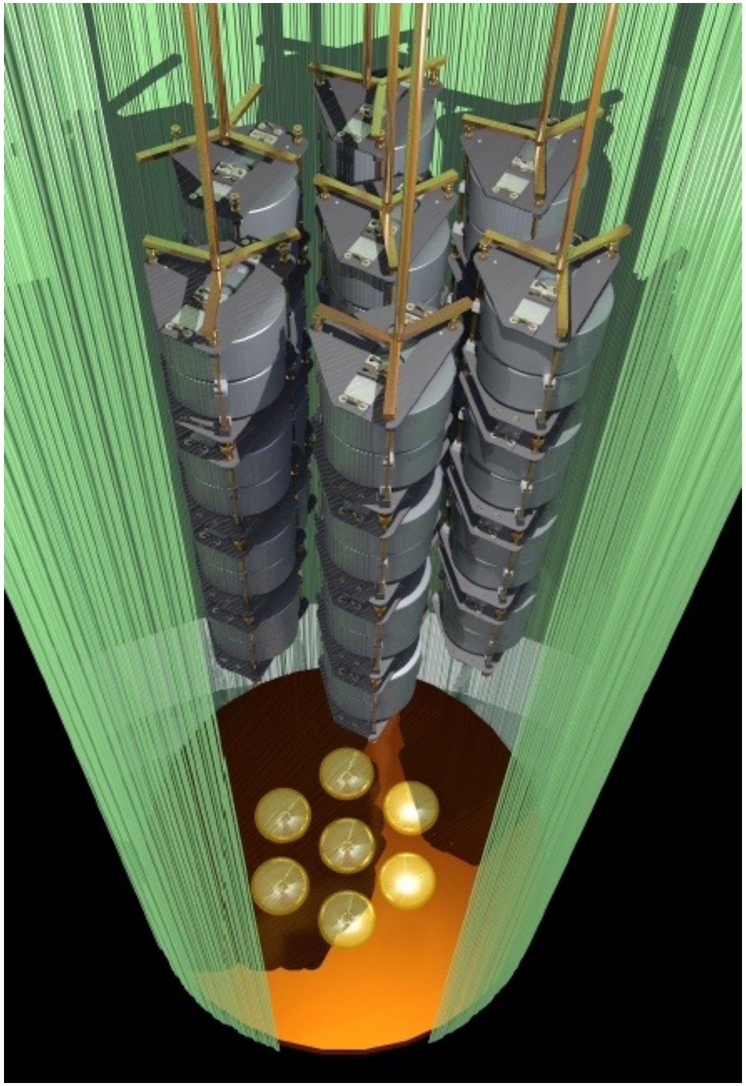
- **Low tempertature**
- **Passive shield**
- **Active veto for surface events**

GERDA. GE Detectors Array
Background sources and suppression

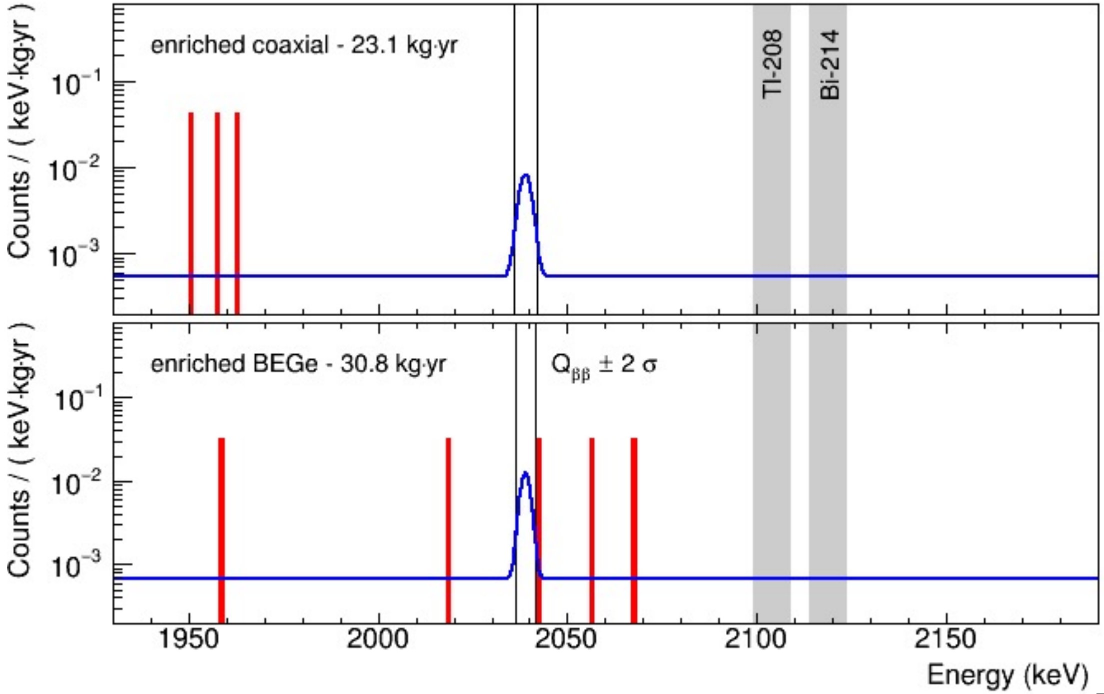
Strings of Ge diodes immersed in liquid Ar, acting as a cooler an a passive shield
The cryostat is immersed in ultrapure water tank sheldung from environmental radiation

Background model supported by data
Close sources (supports, cables, electronics, L Ar contaminants)
^{214}Bi, ^{228}Th, ^{60}Co in the detector assembly
^{42}K from ^{42}Ar in L Ar bath
Residual ^{222}Rn dissolved in L Ar
Surface α particles

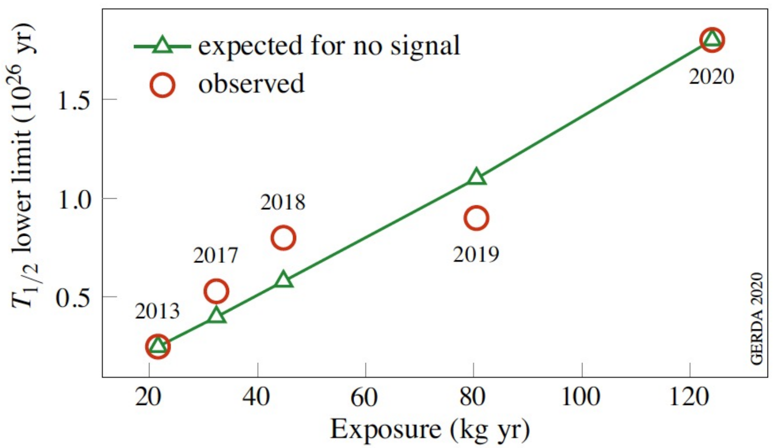
Suppress by
Anticoincidence between crystals
No light in the Ar (optical fibres)
Pulse shape analysis



GERDA. A background free experiment



M. Agostini et al PRL **125** 252502 (2020)



Exposure = 127.2 kg yr

$Q_{\beta\beta} = 2039.61 \pm 0.007$ keV

Energy resolution FWHM $\Delta E = 3.0 \pm 0.1$ keV (best)

$b = 5.2\times10^{-4}$ cts/(keV kg yr)

$b\ \Delta E$ = 1.7 counts/(FWHM t yr)

Median sensitivity $T_{1/2} > 1.8\times10^{26}$ yr (90% cl)

Limit $T_{1/2} > 1.8\times10^{26}$ yr (90% cl)

M_{ee} ^{76}Ge: <79-180 meV

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay (LEGEND). Members of GERDA, MAJORANA and others

Keep "**background free**" conditions while increasing Ge mass

200 kg. Starting (Infrastructures of GERDA)

Reduce background by 2.5

***b* ΔE = 0.7/(FWHM t y)**

Electroformed copper (MD)

Increase light collection in L Ar

MD type F/E electronics

Larger crystals ICPC (2 kg)

$T_{1/2}>10^{27}$ yr,

Exposure 1 t yr

1000 kg

BI< 10^{-5}/(keV kg y)

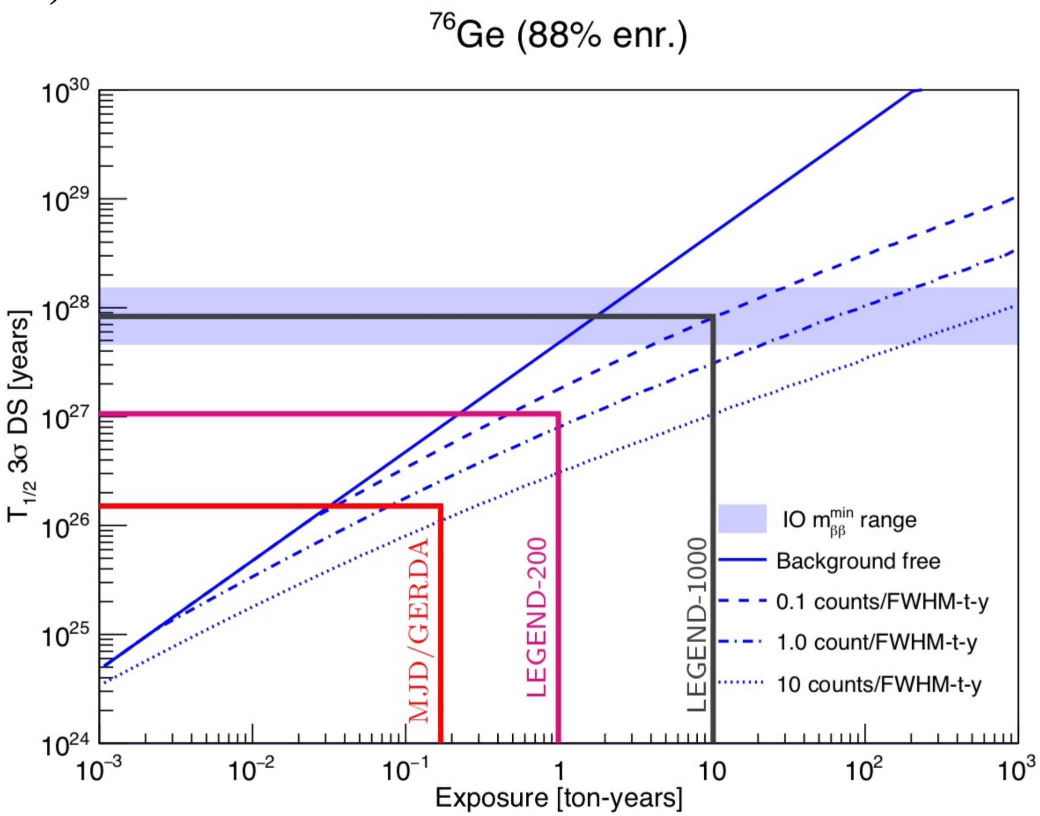
***b* ΔE = 0.025/(FWHM t y)**

New infrastructure

Suppress ^{42}K from ^{42}Ar: depleted Ar

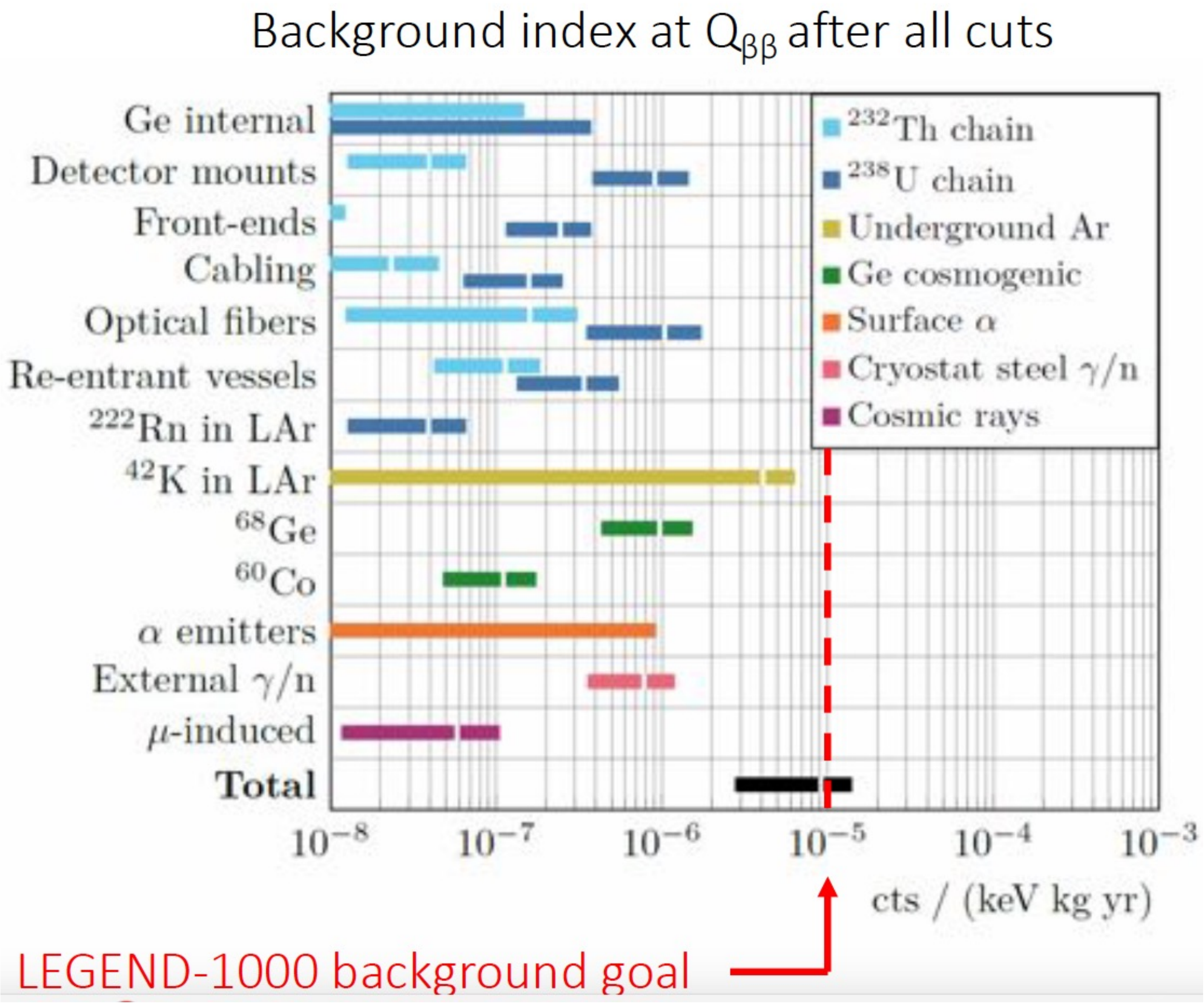
$T_{1/2}>10^{28}$ yr

Exposure 10 t yr



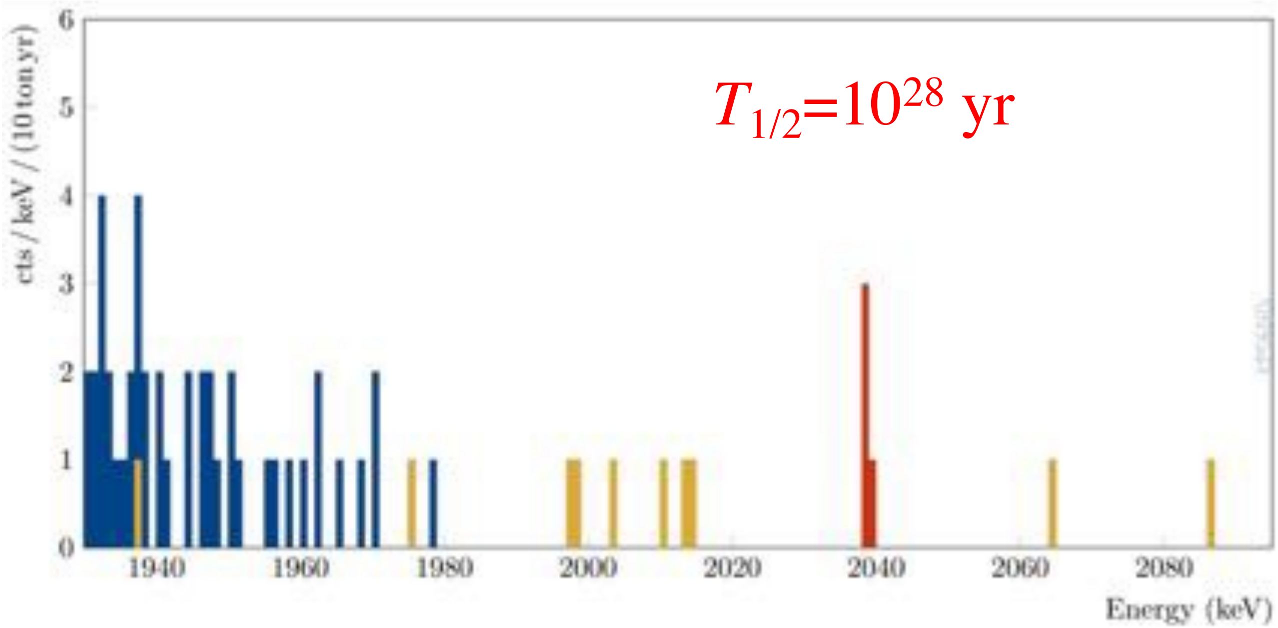
arXiv:1810.00849

LEGEND 1000 Background model



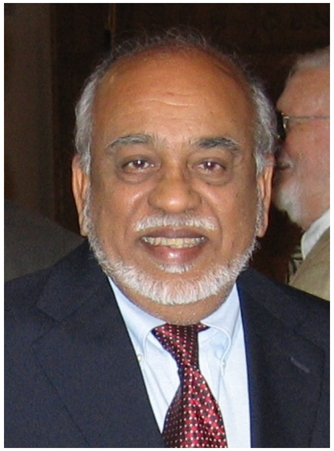
LEGEND 1000 - $0\nu2\beta$ at 10^{28} yt

Simulated LEGEND-1000 spectrum after 10 yr exposure with BI = 10^{-5} counts/(keV kg yr)



Flat residual background
No background peaks expected near $Q_{\beta\beta}$

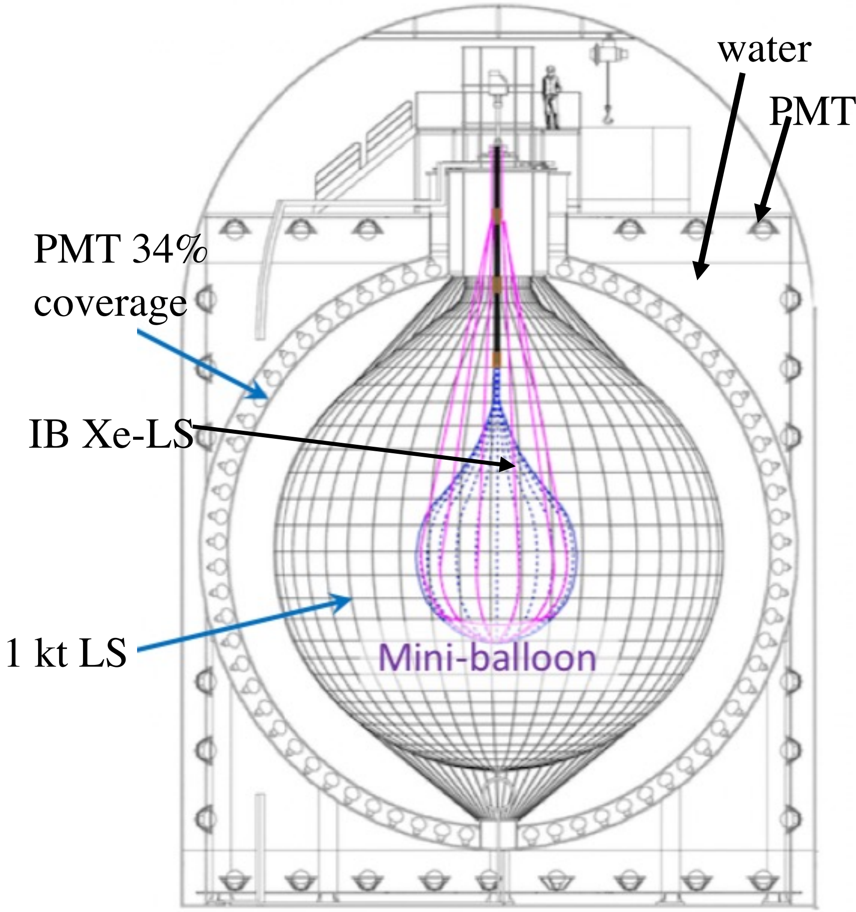
KAMLAND-ZEN



1994. R. Raghavan (1937-2011) proposal to load large masses of ^{136}Xe into a large-scale liquid scintillator detector PRL **72** 1411

Inner balloon contains ^{136}Xe doped LS
IB surface is source of background, reduced by geometrical cuts (**self shielding**)

Data collection 5.2.2018-8.5.2021
^{136}Xe mass = 750 kg
Ultra clean IB

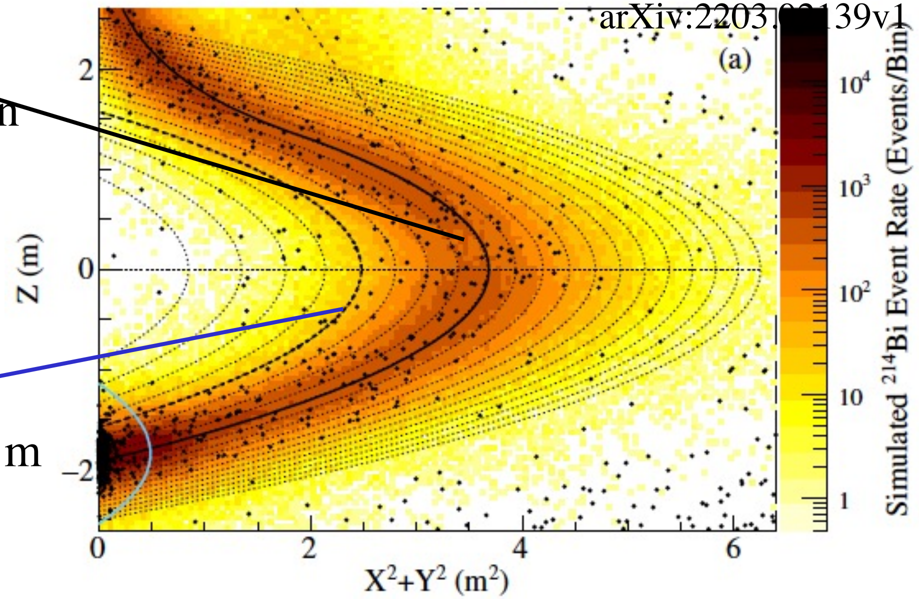


KAMLAND-ZEN-800

arXiv:2203.02139v1 2022

Inner Balloon

FV
r<1.57 m



Exposure= 970 kg yr

En. res FWHM ΔE = 265 keV (poor)

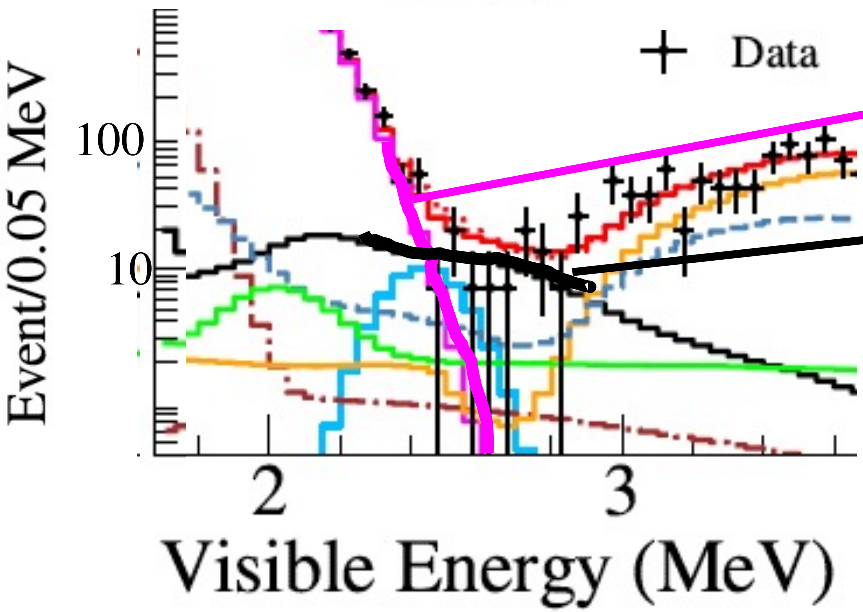
b =4 × 10^{-5} counts/(keVkg yr)

b ΔE = 11 /(FWHM t yr)

Median sensitivity $T_{1/2}$> 1.5 × 10^{26} yr

Limit $T_{1/2}$>2.3 × 10^{26} yr (90% cl)

S. Abe et al. arXiv:2203.02139

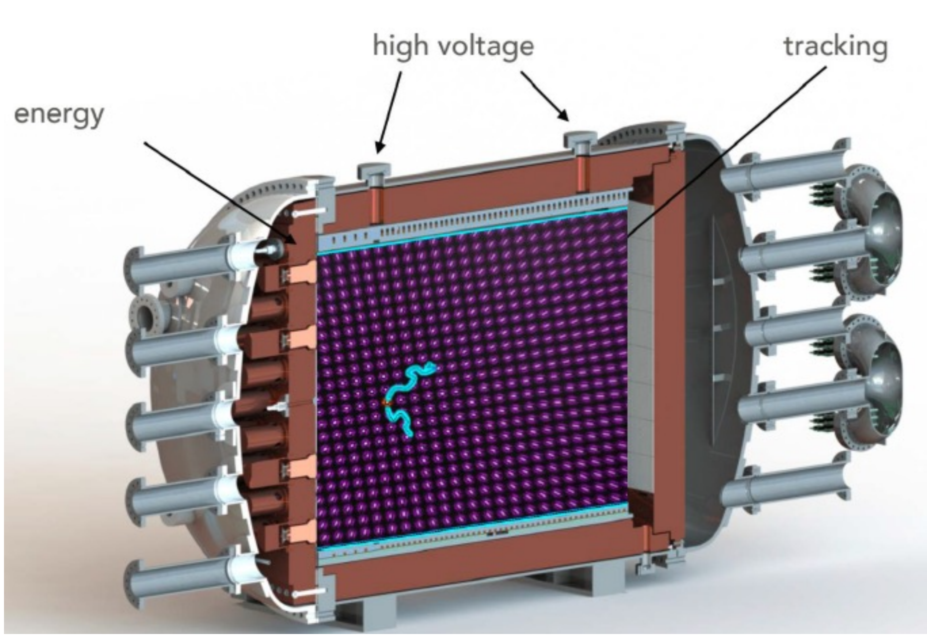


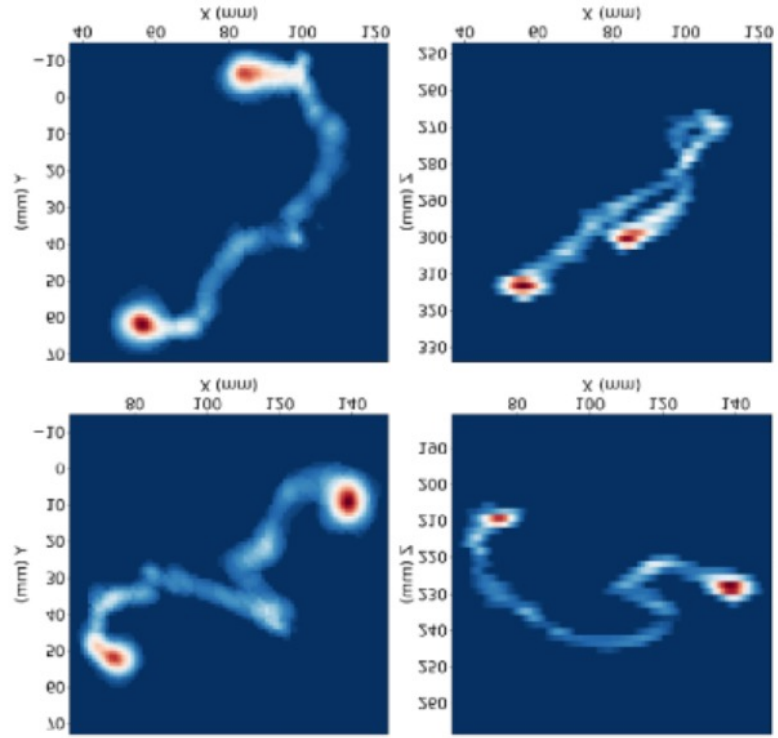
Tail of 2ν2β energy resolution

Spallation in Xe cosmogenic

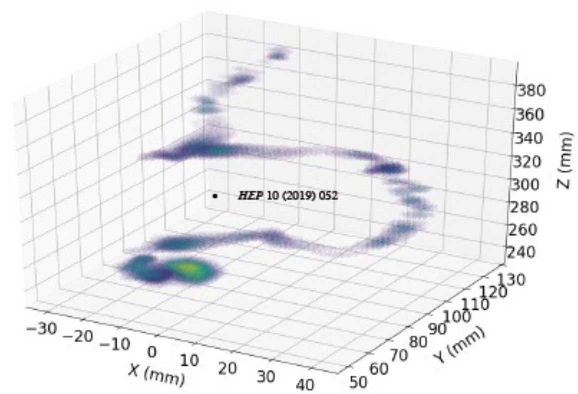
FUTURE: $T_{1/2}$=2 10^{27} yr
Improve light collection
Reject film backround
(scintillating IB)
Make entire volume FV

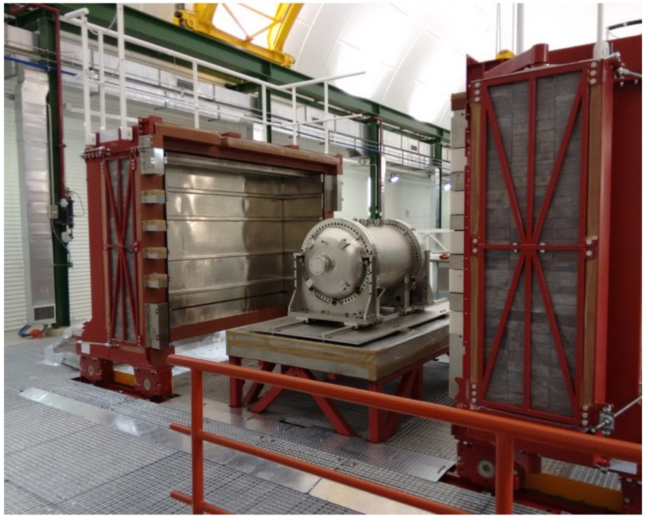
NEXT. Principle





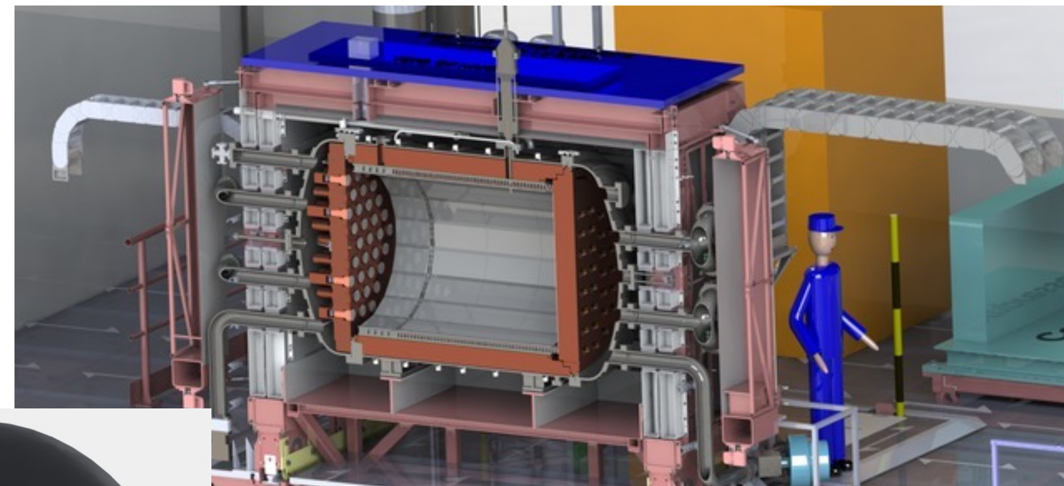
- High Pressure (10-15 Bar) gas Xe TPC
- Electro-Luminescence R/O
  $\Longrightarrow \Delta E$ (FWHM)/E<1%
- Topological signature (30% efficiency)
- Strong potential for Ba tagging in situ (^{136}Xe$\rightarrow$ ^{136}Ba^{++} + 2 e^{-})





NEXT. The phases

NEXT-White. **10 kg** ^{136}Xe:confirm design principles
2018-2021 at LSC. runs with enriched and depleted Xe
Energy resolution FWHM ΔE = 20 keV (0.8%) (good)
b =4 × 10^{-4} counts/(keVkg yr)
JHEP **10** (2019) 052



NEXT-100.
Construction in thesame infrastructure
To run 2022-2026
$b\ \Delta E$ = 8 /(FWHM t yr)
Sensitivity $T_{1/2}{\sim}10^{26}$ yr

NEXT-1t. 1000 kg TPC at 15 bar
Central cathode plane and two R/O planes
In water tank shield
Sensitivity with 5 t yr $T_{1/2} > 10^{27}$ yr
arXiv:2005.06467

Beyond 10^{27}. Look at the daughter

There's plenty of room at the bottom
Richard Feynman, 1960 (Nobel 1965)

There's even more room at the top
Jean-Marie Lehn, 1995 (Nobel 1987)

"Beyond molecular chemistry based on the covalent bond, there lies the field of **supramolecular** chemistry, whose goal it is to gain control over the intermolecular bond

Build a supramolecular structure able to **recognise** the Ba^{++} daughter of the ^{136}Xe, **fix** it, **change shape** to emitt a **different light**

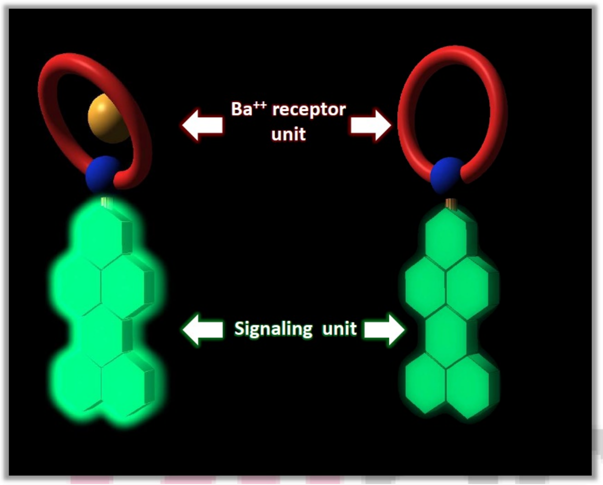
NEXT-BOLD. Barium Observation Light Detector

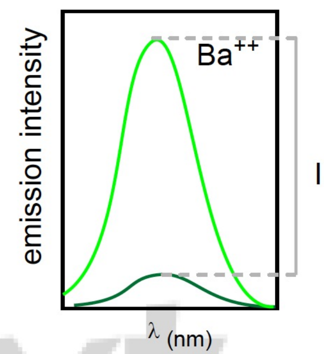
Expolit ***single molecule fluorescent imaging*** **(SMFI)** to visualize each single Ba ion as it reaches the TPC cathode

In ^{136}Xe gas phase (differently from in liquid phase) ~100% Ba^{++} remain ionised

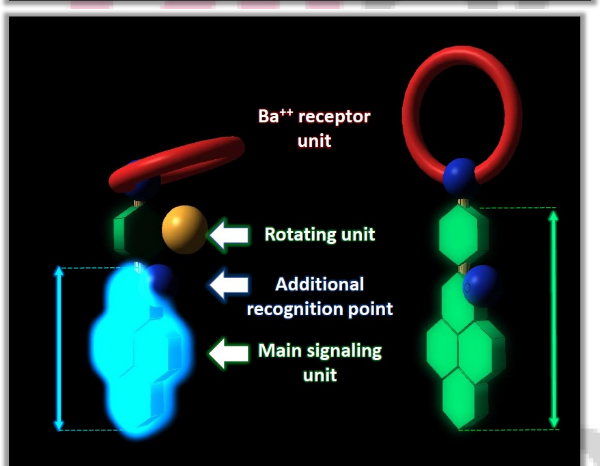
Develope a supramolecular structure that change fluorescence light after chelating Ba dications

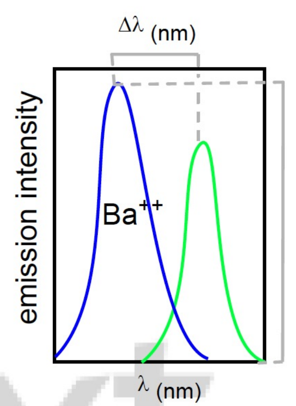
recognise Ba^{++} and **fix** (chelation) it (crown ether + flurophore + linker}





For efficient detection, chelation should not simply induce a change of **intensity** of fluorescence light (upon laser illumination)





Adding a unit to rotate the Ba^{++} receptor, a change of the fluorescence light **wavelength** is obtained

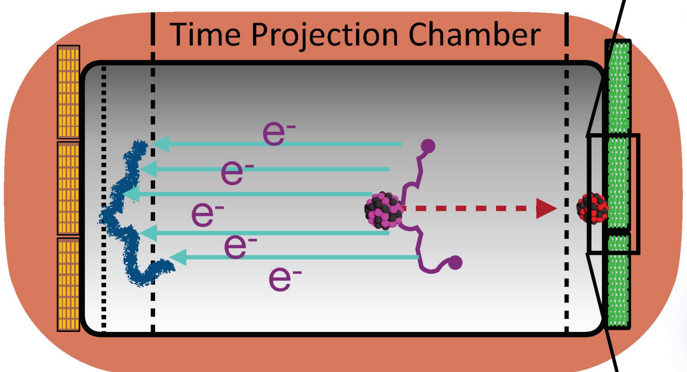
https://www.nature.com/articles/s41586-019-1169-4

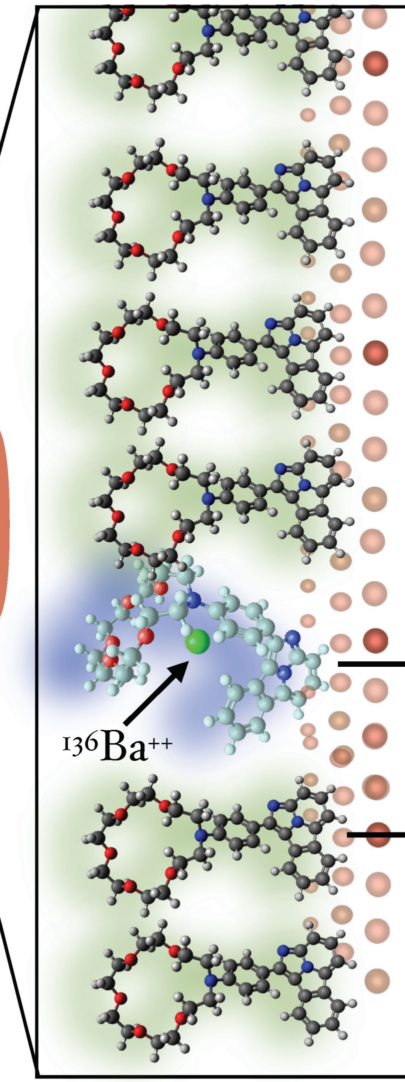
Fluorescence Bicolour Indicators

The FBI mantains its fluorescent properties in solid phase (silicagel)

Calculated discriminaton factor $FBI \cdot Ba^{++}$ vs FBI = $(2.5 \pm 0.6) \times 10^4$

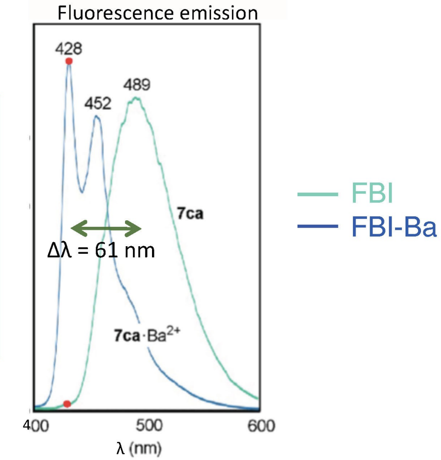
Barium tagging in NEXT:
A ML of Fluorescent Bicolor Indicators (FBI) traps the barium ion, thereby changing its optical properties.

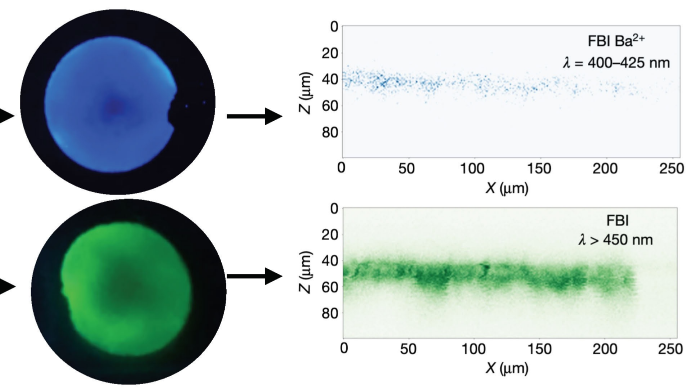




The stokes shift between free FBI (cyan) and $FBI \cdot Ba^{2+}$ (blue) is larger than 35 nm.

This effect is specific of Ba^{2+} chelation and does not appear for other ions.





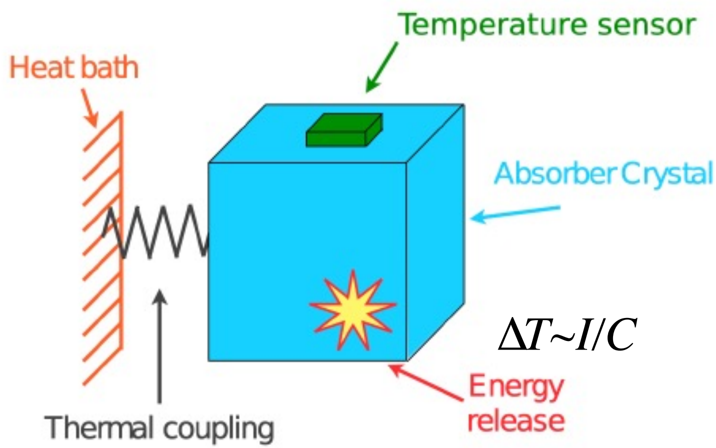
- First experiment of chelation in a dry medium:
- $Ba(ClO_4)_2$ was evaporated in UHV on silica pellets containing FBI. This changed its fluorescence from green to blue and proved that the trapping took place in UHV.

Microscopic tomographies were recorded for an unchelated (green) and a chelated (blue) pellet.

From J J Gomez Cadenas

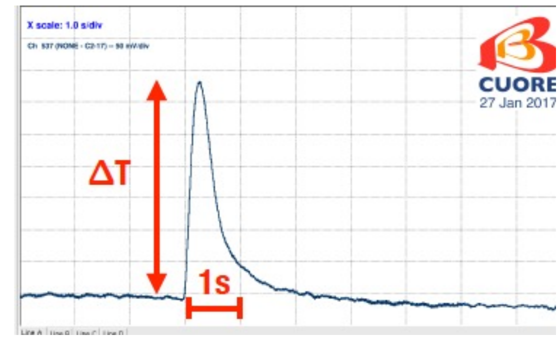
CUORE

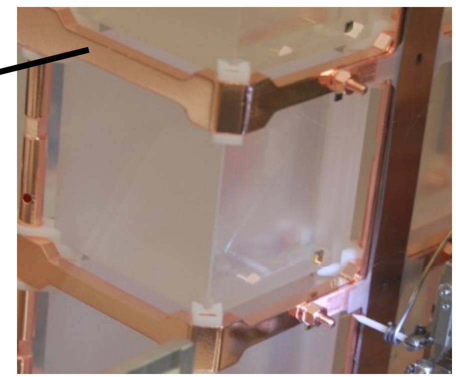
^{130}Te in an array of 988 TeO_2 natural Te bolometers operating at about 10 mK at LNGS
Total mass =741 kg (contributing to background). ^{130}Te mass about 206 kg (source of signal)



$\Delta T \sim I/C$

Voltage pulse induced in Ge thermistor used for R/O





b= **(5.36±0.14) × 10^{-2}/(keV kg$_{Te130}$ yr)**
Mainly degraded **α from the surfaces** of supports

2017-2021.
1038.8 kg(TeO2) yr = **288.8 kg(^{130}Te) yr**
En. Res. FWHM = 7.8±0.5 keV (very good)
b **ΔE = 418 /(FWHM t$_{Te130}$ yr)**

Median sensitivity (90%): 2.8 ×10^{25} yr
Limit: $T_{1/2}$>2.2×10^{25} yr
M_{ee} <90-305 meV
Will continue to 1000 kg yr ^{130}Te exposure

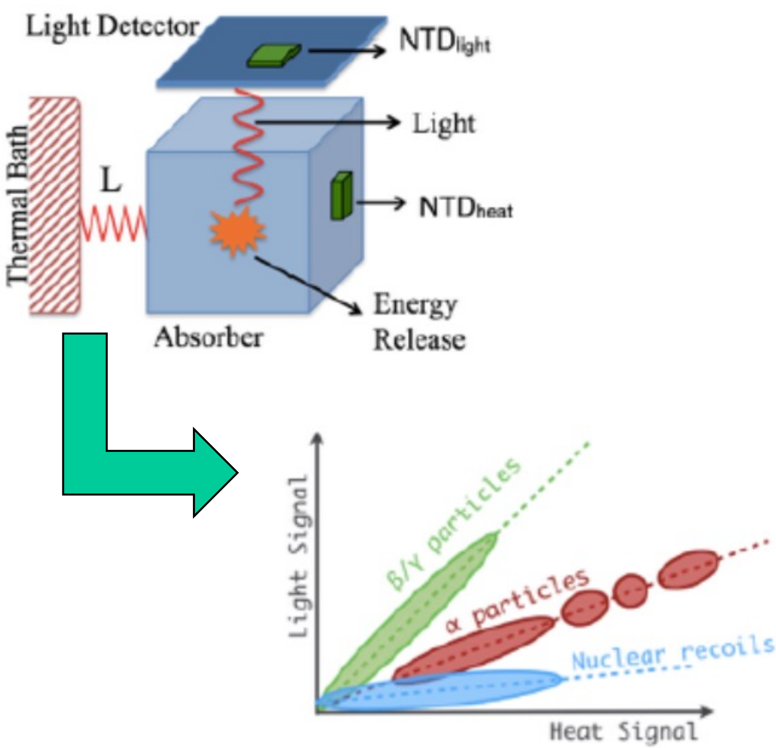
Azzolini et al Nature 604, 53 (2022)

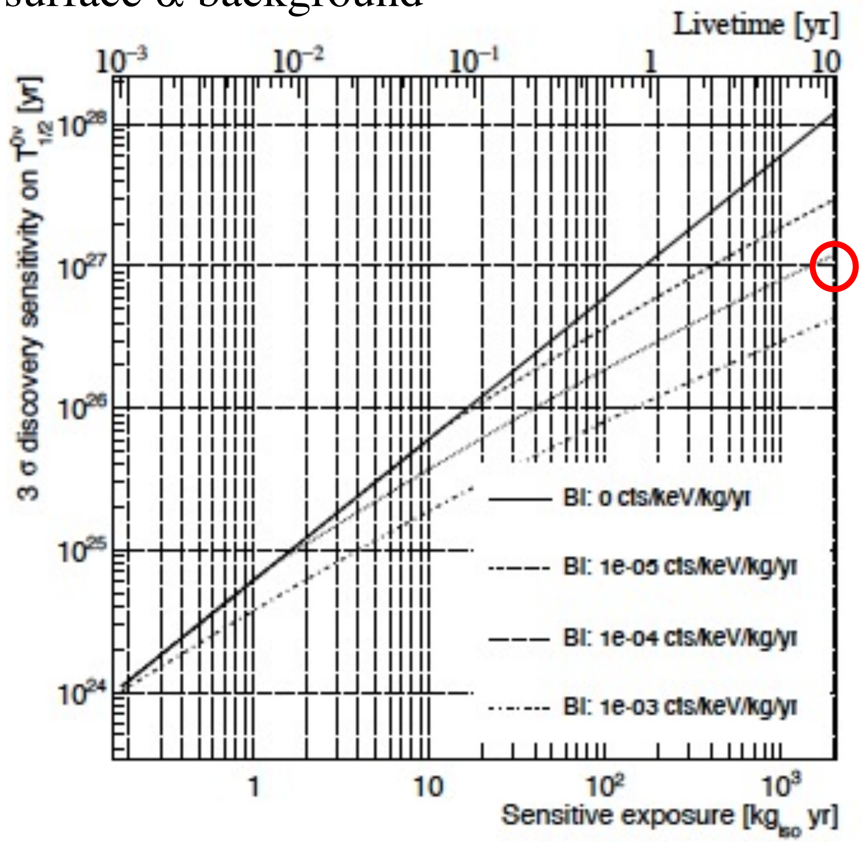
^{100}Mo CUPID

Will use the CUORE cryostat, after completion of the experiment

Source: $Li_2{}^{100}MoO_4$ scintillating crystals

Read out **HEAT and LIGHT**: identify and reject surface α background





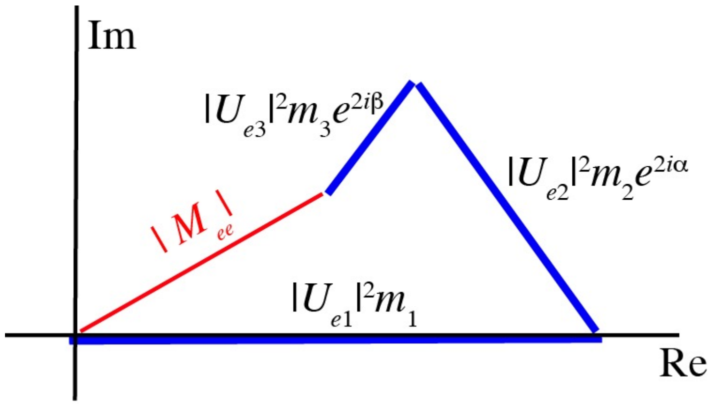
Prototype experiments (CUPID-0, CUPID-Mo,...), R&D programme aiming at improve ***b*** **by 1/100** and ***ΔE*** **by 1/2** relative to CUORE

$b\ \Delta E$ = 0.1/(keV $t_{100MoO4}$ yr) x 4 keV /(FWHM t yr)

Background free exposure of 2000 kg($^{100}MoO_4$) yr (1120 kg(^{100}Mo) to reach 10^{27} yr sensitivity

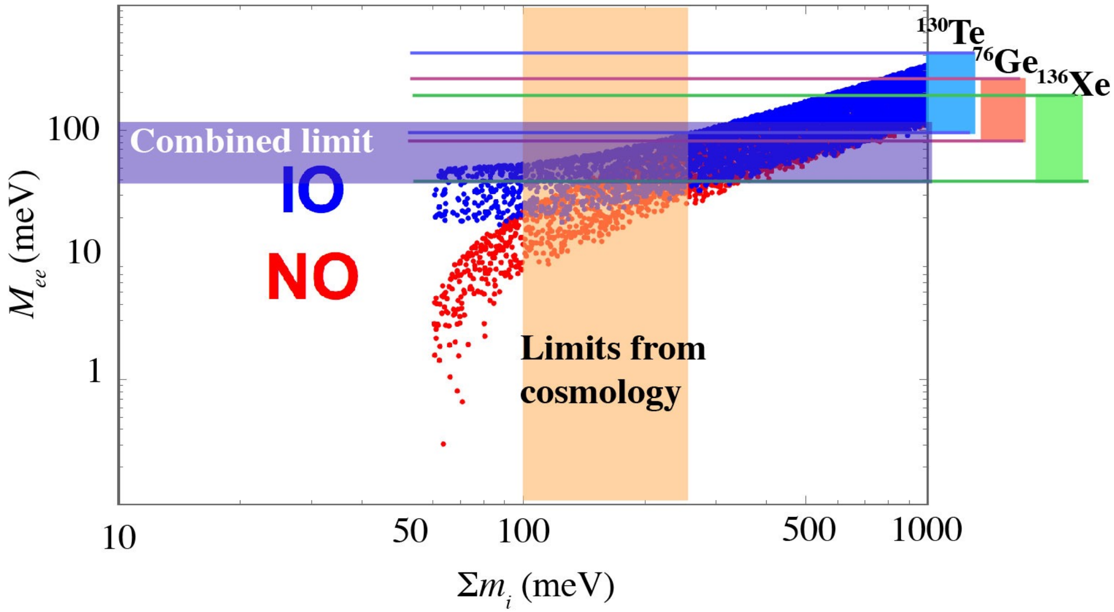
The stage

From cosmology Σm_i<150-200 meV model dependent
From $0\nu2\beta$ limits on M_{ee}
^{136}Xe: <36-156 meV
^{76}Ge: <79-180 meV
^{130}Te: <90-305 meV



IO and NO bands correspond to Majorana phases 0-2π
Dots from A. Ianni assuming random distribution of the phases
Combined 90% limit is from Lisi & Marrone arXiv:2204.0956
Depending on NME
g_A=1.276

$$M_{ee} < 35.4 - 117.7$$




dreams

Look at the bottom

There's plenty of room at the bottom

of the energy scale

CNB: the cosmic sea of primordial **neutrinos** around us: **336/cm^3**

$$T_\nu = (4/11)^{1/3} T_\gamma = 0.256 \text{ meV} = 1.95 \text{ K}$$

When neutrinos are non-relativistic the distinction between Dirac and Majorana becomes relevant
CNB, a laboratory to study neutrinos in unique kinematic regime

Dreaming on Cosmic Neutrino Background

In the hot and dense primordial universe neutrinos are in thermic equilibrium in the plasma

Having been produced by weak interactions, they were **flavour eigenstates** (6 in total) and **chirality eigenstates** with $\gamma_5=-1$

Flavour states soon decohere into **the mass eigenstates**, which populate the present CNB

Neutrinos had almost only helicity =–1, antineutrinos =+1

When the temperature dropped below ~ 1MeV neutrinos "froze out" from the plasma (CNB), **freely streaming** to us.

Chirality does not commute with the free Hamiltonian, it was not conserved

Helicity was conserved, being the particles non-interacting

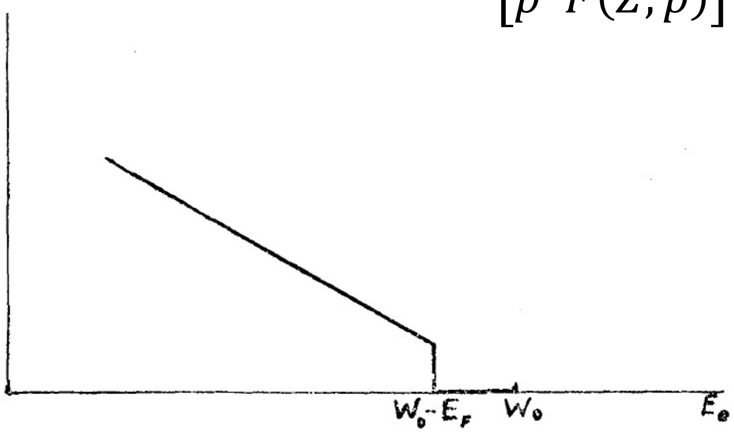
S Weinberg – Look at the end-point

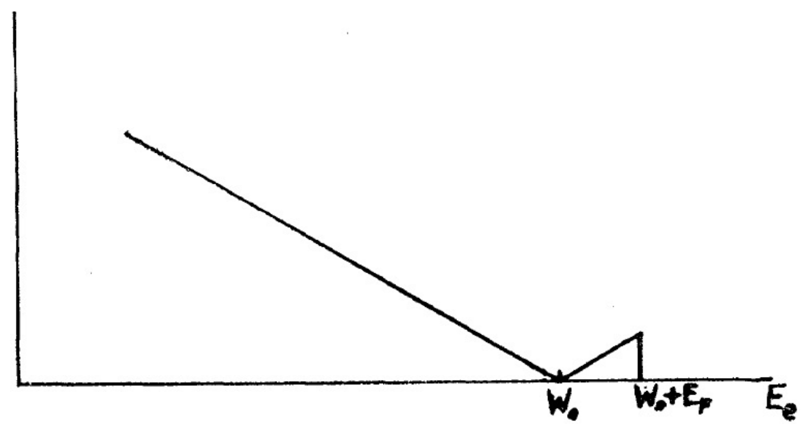
1962 S. Weinberg (1933 – 2021) proposes CNB detection via inverse beta decay, capture by a beta decaying nucleus, since this is a **zero-threshold process**

S. Weinberg. Phys Rev. **128** (1962) 1457

$$\nu_e + {}^3H \rightarrow e^- + {}^4He$$

Kurie function $K = \left[\frac{N(p)}{p^2 F(Z,p)}\right]^{1/2}$



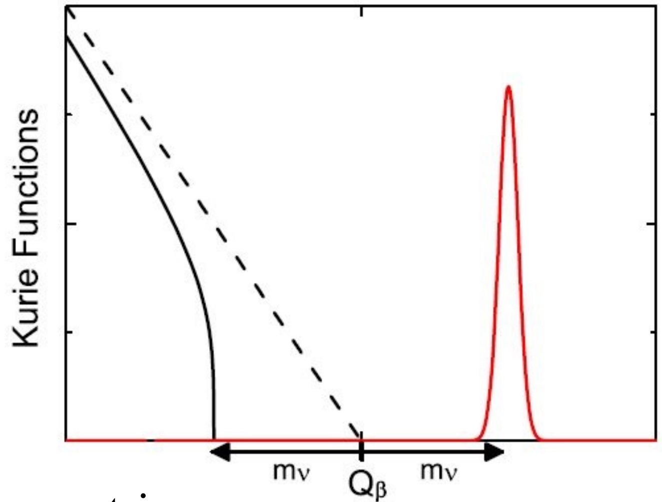


Electron neutrino mass KATRIN experiment

Detecting CNB

$$\nu_e + {}^3H \rightarrow e^- + {}^4He$$

Consider one neutrino only
A peak at twice the neutrino mass above the end-point of the beta-decay spectrum should be observed



Capture rate is **twice** as large for Majorana than for Dirac neutrinos

CNB contains negative helicity neutrinos and positive helicity antineutrinos. Being non-relativistic, both helicity states contain a negative chirality component, hence both can interact.

Dirac. The positive helicity antineutrino cannot be captured because $\bar{\nu}_e + p \rightarrow e^+ + n$ is energetically forbidden

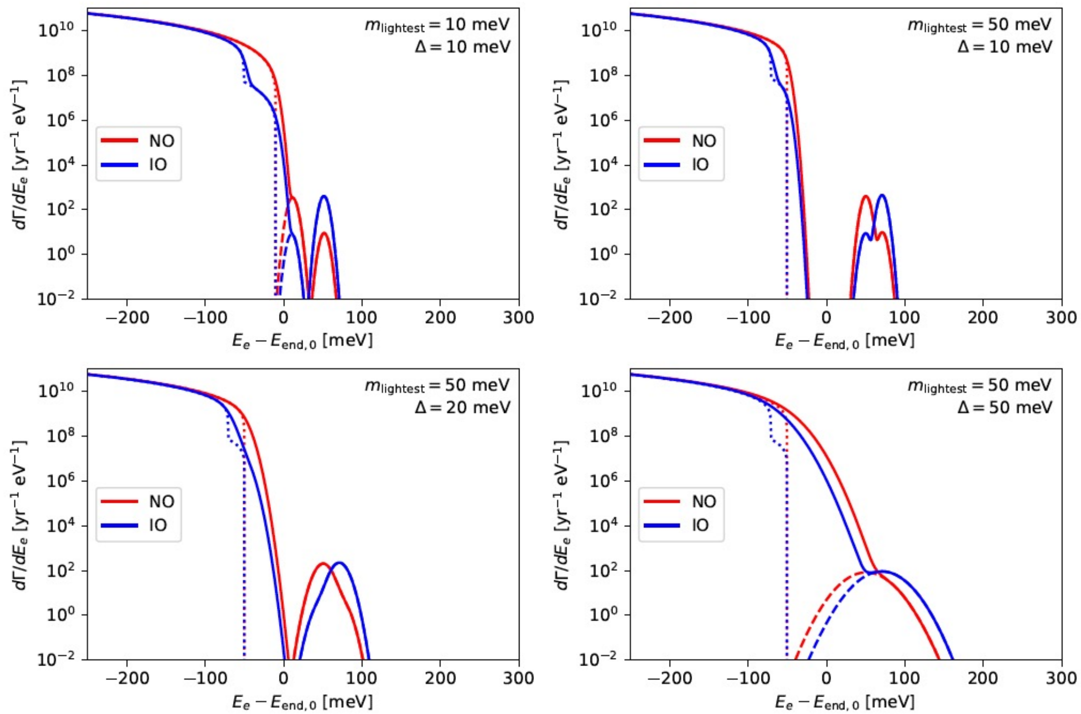
Majorana. ”Neutrino” and “antineutrino” are the same particle. Both helicity Majorana neutrinos interact weakly and can be captured

Long, Lunardini, Sabancilar JCAP08 (2014) 038

Challenges

Event rate. ^{3}H beta decay: about 10^{15} Bq/g. Target mass >100 g; presently impossible

Background from beta decay
Energy resolution should be beller than neutrino mass
$\Delta E < m_i$



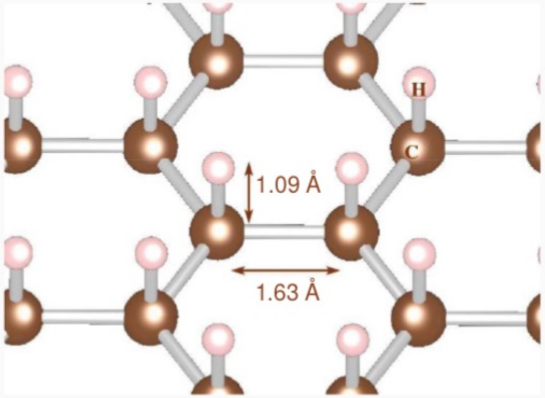
M. J. Betti et al. JCAP 07 (2017) 047 arXiv:1902.05508v1

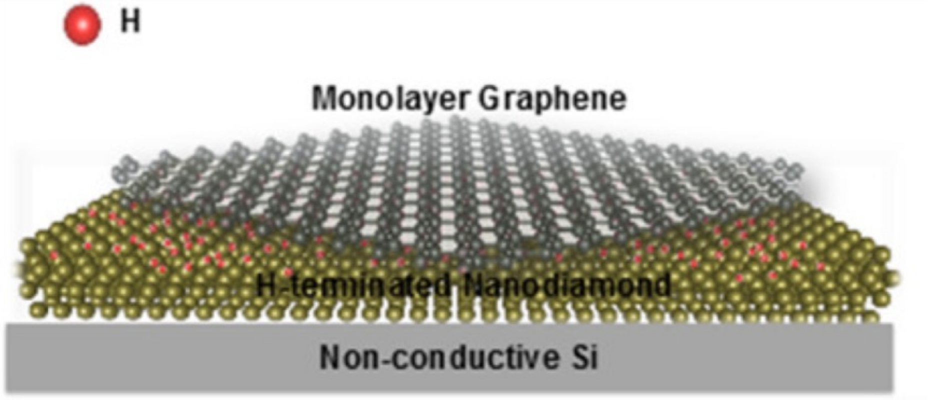
PTOLEMY @ LNGS

Be brave, dream the impossible
The PTOLEMY project
Prototypes forest being built

There's even more room at the top

Target = supramolecular link tritium atoms on graphene monolayr





- Monolayer graphene consists of carbon atoms arranged in a two-dimensional honeycomb lattice;
- Graphene substrates are suitable to hold monoatomic Tritium layer through chemical absorption;

From Andrea Giachero

Low Energy Frontier RENP

Neutrino mass scale : few 10^{-2} eV

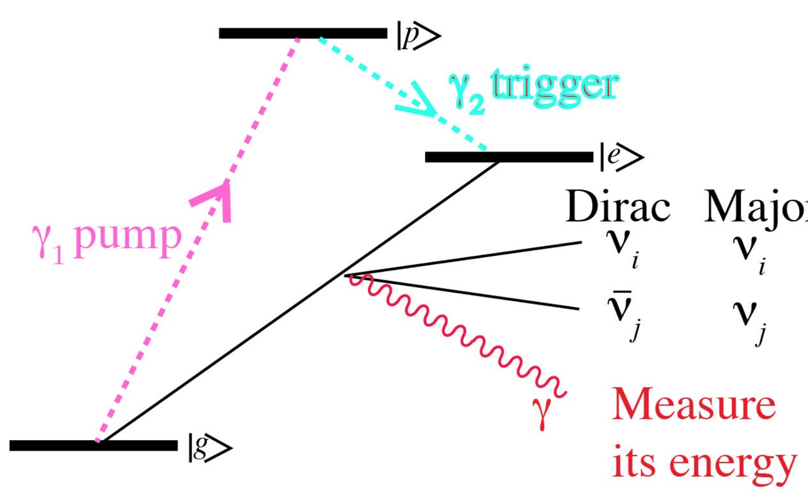
Atomic levels: **few eV ⇒ *E*/*m* order of 10^{-2}**. Option for neutrino mass spectroscopy

Molecular electronic levels: **few 0.1 eV ⇒ *E*/*m* order of 10^{-1}**. Majorana phases via interference?

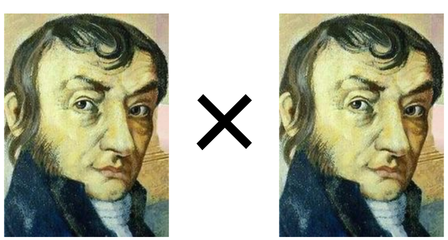
Research programme at Okayama led by Yoshimura since some 20 years

RENP = Radiative Emission of Neutrino Pairs

QED forbidden by Parity



Rates extremely small



AVOGADRO squared is 10^{53}

Coherence on macroscopic dimensins

From N to N^2 MACROCOHERENCE

Rate amplification by macroscopic coherence

Dicke super-radiance (Phys Rev **93** (1954) 99-110): coherent volume is proportional to $L\,\lambda^2$
Coherent de-excitation develops from stimulated decays along pulse propagation direction

$$\text{Rate} \propto \left|\sum_j^N e^{i\vec{k}\cdot\vec{r}_j} \times M_{(e\to g)}\right|^2 \propto N^2 \qquad \left(\text{for } |r_i - r_j| \leq \lambda\right)$$

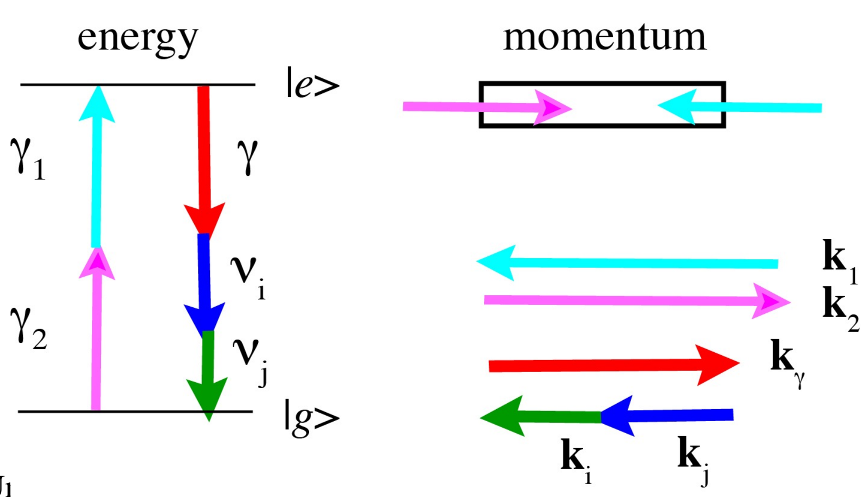
Observed: Skibanowitz et al, PRL **30** (1973) 309

For plural outgoing/ingoing particles phase matching condition is obtained through momentum conservation
Coherent volume NOT limited by λ, can be macroscopic

$$\text{Rate} \propto \left|\sum_j^N e^{i(\vec{k}_1+\vec{k}_2+\vec{k}_3)\cdot\vec{r}_j} \times M_{(e\to g)}\right|^2 \propto N^2 \qquad \left(\text{for } \vec{k}_1 + \vec{k}_2 + \vec{k}_3 = 0\right)$$

Employ 3 (or more) LASERs:
2 in opposite directions for excitation
1 to trigger the decay

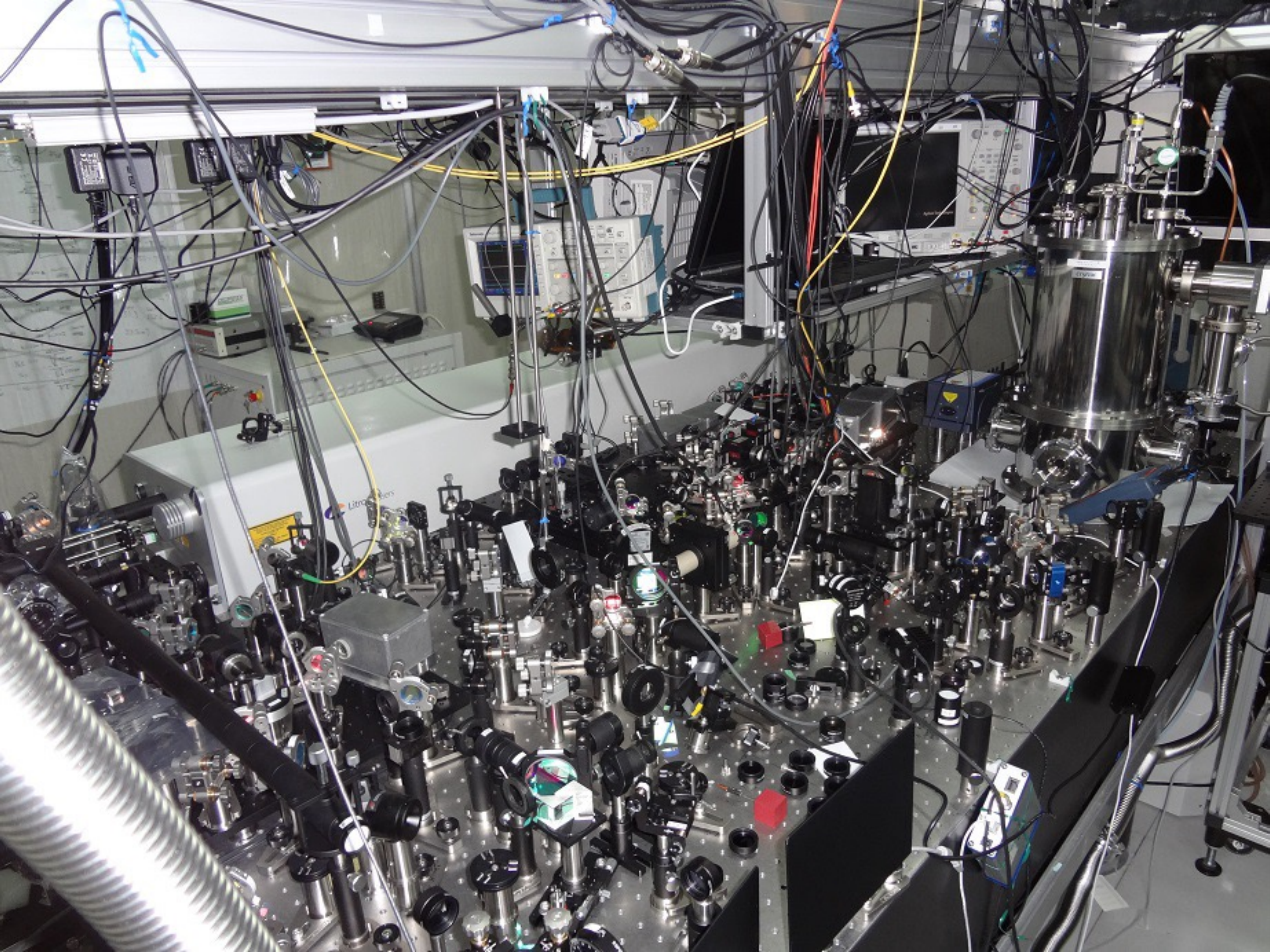
Typical trigger bandwidth
$\Delta E = 10^{-6}$ eV



Conclusions

- **The search for $0\nu2\beta$ decay is still the main route to Majorana particles**
- **Present sensitivity in $T_{1/2}$ above 10^{26} yr (M_{ee} around 100 meV)**
- **10^{27} yr (30 meV) in reach with ^{76}Ge, ^{136}Xe and ^{100}Mo in the current decennium (discovery possible)**
- **10^{28} yr (10 meV) will need substantial further reduction of the background (discovery very likely)**
- **Additional research routes on the low energy frontier are being opened**
  - **Need deep understanding and development in atomic, molecular and supramolecular physics**

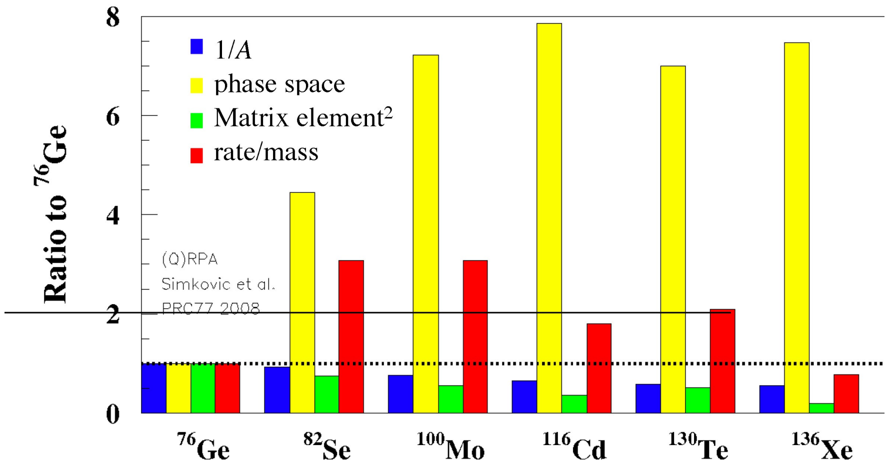
Thanks for your attention



Any favourable isotope?

Isotope	$Q_{\beta\beta}$(keV)	Abundance (%)	G (10^{-15} y^{-1})
^{76}Ge	2039.061(07)	7.8	2.36
^{100}Mo	3034.40(17)	9.6	15.91
^{130}Te	2527.5218(13)	33.8	14.20
^{136}Xe	2457.83(37)	8.9	14.56

PSF grows almost as Q^5. Partially compensated by a decrease of NME with increasing A



No significantly favoured isotope
Within a factor 3
Choice of the isotpe depends on
practical factors

PSF from F.F. Dappish et al. 2009.10119