A new neutrinoless double beta decay experiment: R2D2

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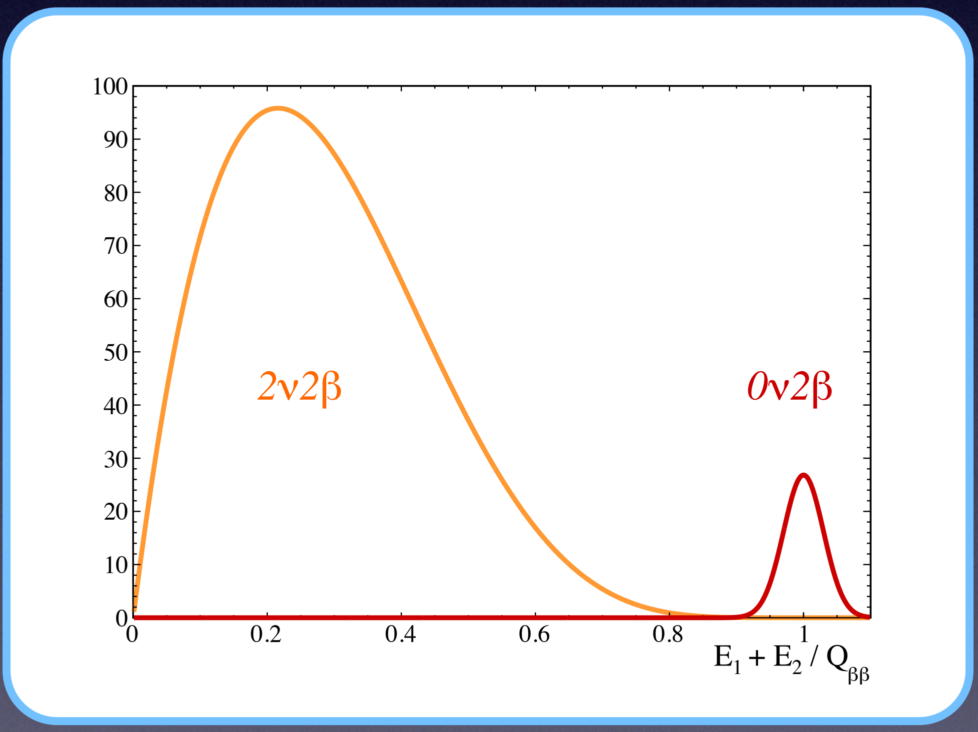
Introduction (1)

- To demonstrate the Majorana nature of neutrino the most sensitive experimental way is an observation of the so called **$0\nu\beta\beta$ decay**.
- The measurement relies on the observation of a peak in the distribution of the energy of the two electrons corresponding to the $Q_{\beta\beta}$ of the reaction.



Requirements

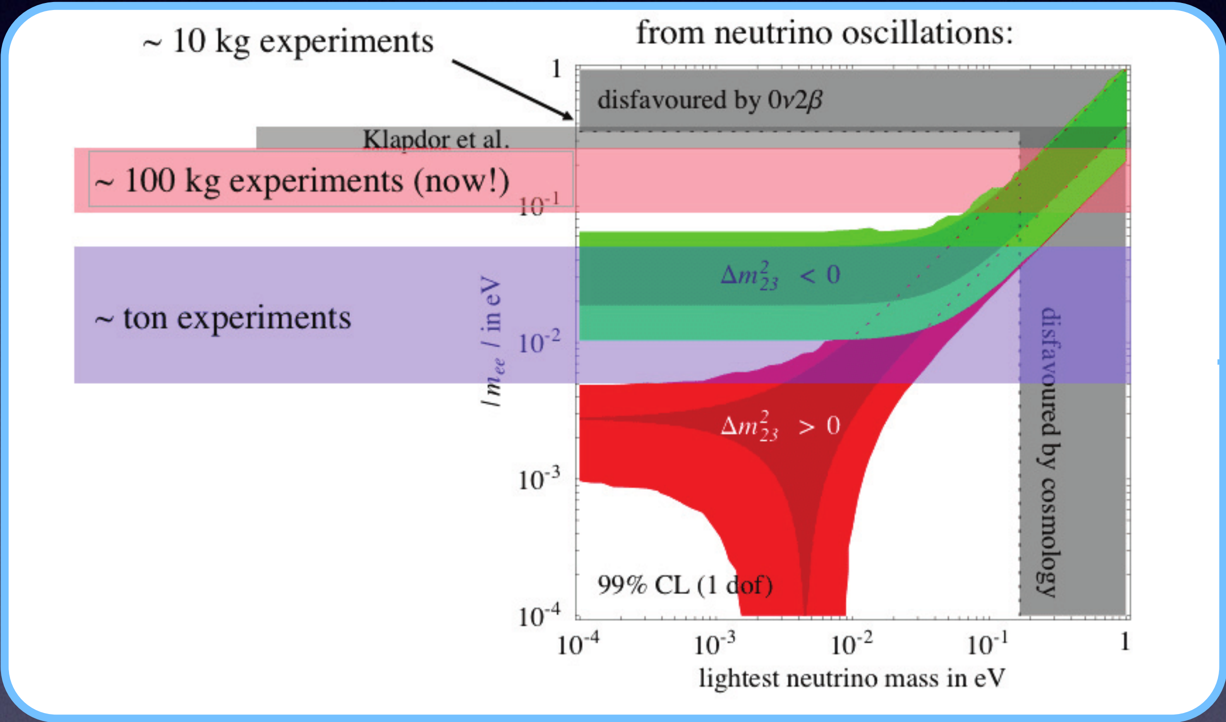
Excellent energy resolution

Low background

The most natural way to achieve low background is to have a low material budget detector

Introduction (2)

- Experiments so far are just hitting the inverted mass hierarchy region and to fully cover it we need a ton scale experiment.



Requirements

Large masses of isotopes

Gaseous isotopes have the advantage of reaching large masses easily and at relatively low cost, with an extremely low radioactive contamination with respect to solid isotopes

Status

- Presently used technologies do not meet all the requirements at the same time.

	Energy resolution	Low background	Large isotope masses
Solid state detectors	**Extremely good (0.1% at Q value)**	**Extremely low (zero background)**	**Large number of crystals/ electronics channels Difficult scalability to large masses**
Liquid Xenon experiments	**Order of 4% at Q value**	**Far from zero background**	**Ton scale easily achievable**
Gaseous Xenon experiments	**Order of 1% at Q value**	**Far from zero background**	**Complex detector Feasible at ton scale?**

Can we meet all the requirements at the same time? → **goal of R2D2**

R2D2 is an R&D program aiming at the development of a zero background ton scale detector to search for the neutrinoless double beta decay.

The R2D2 project (1)

- R2D2 stands for Rare Decays with Radial Detector.
- The idea is to use a **high pressure Xenon gas TPC spherical detector** to search for the $\beta\beta0\nu$ decay, profiting from the following features:
  - High energy resolution (goal of 1% FWHM at ^{136}Xe $Q_{\beta\beta}$ of 2.458 MeV)
  - Low detection threshold at the level of 30 eV i.e. single electron signal.
  - High detection efficiency (about 65% after selection cuts).
  - Simplicity of the detector readout with only one (or few in the upgraded version) readout channels.
  - Extremely low (zero?) background due to the very low material budget.
  - Scalability to large isotope masses.

R2D2 is an R&D program aiming at validating all these detector features paving the way for a future ton scale detector

The R2D2 project (2)

- A proto-collaboration has been recently formed.
- R2D2 is today approved as IN2P3 R&D to assess in particular the possibility to reach the desired energy resolution which is the major showstopper.

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The R2D2 Roadmap

Prototype 1

Under commissioning - Funded by IN2P3 R&D

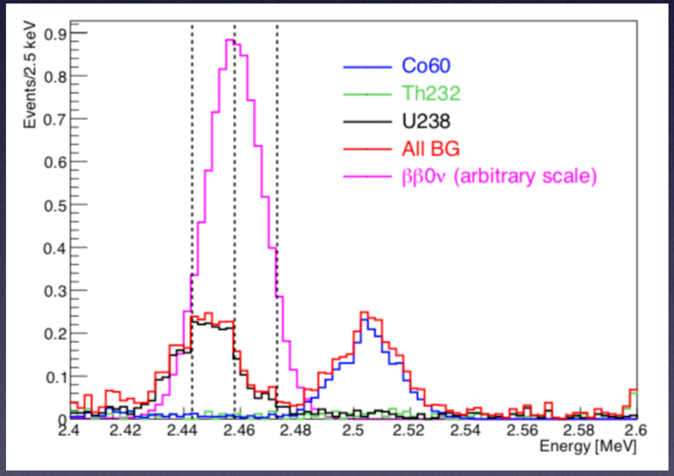
Up to 7.9 kg (40 bars) Xenon prototype (no low radioactivity) to demonstrate the detector capability in particular on the energy resolution

If prototype 1 successful and prototype 2 funded

Prototype 2

Sensitivity studies carried out

50 kg Xenon detector (low radioactivity) with LS veto for first physics results to demonstrate the almost zero background



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Depending on the results and fundings

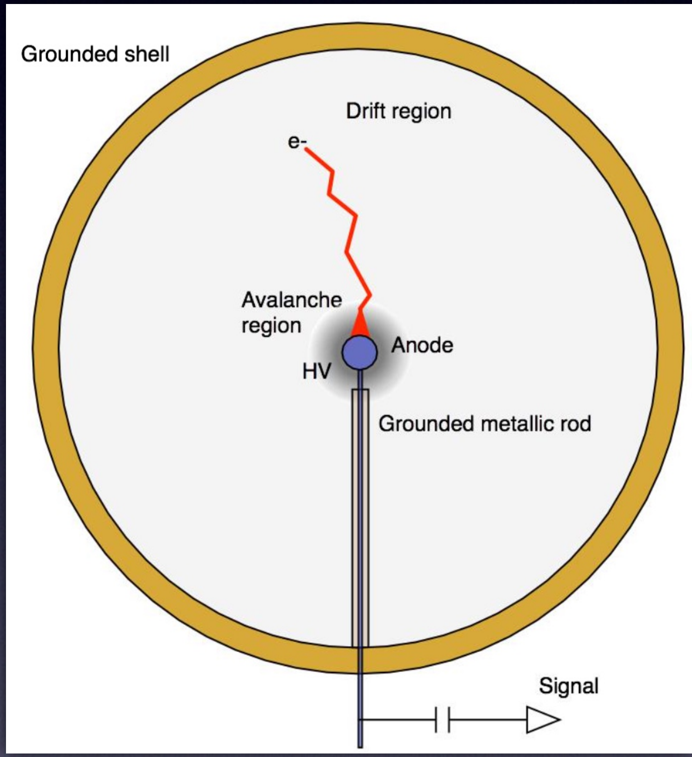
Experiment

Going towards a 1 ton background free detector

Exploit the detector with other gases to cross check the background and possibly obtain interesting results selecting higher $Q_{\beta\beta}$, as well as the possibility to do tracking

The detector

- The detector is a spherical Xenon gas TPC as proposed by Giomataris et al. and used today in the NEWS-G collaboration for the search of dark matter.
- The design has to be optimised for the background reduction in the $\beta\beta0\nu$ search with ^{136}Xe ($Q_{\beta\beta}$ of 2.458 MeV).



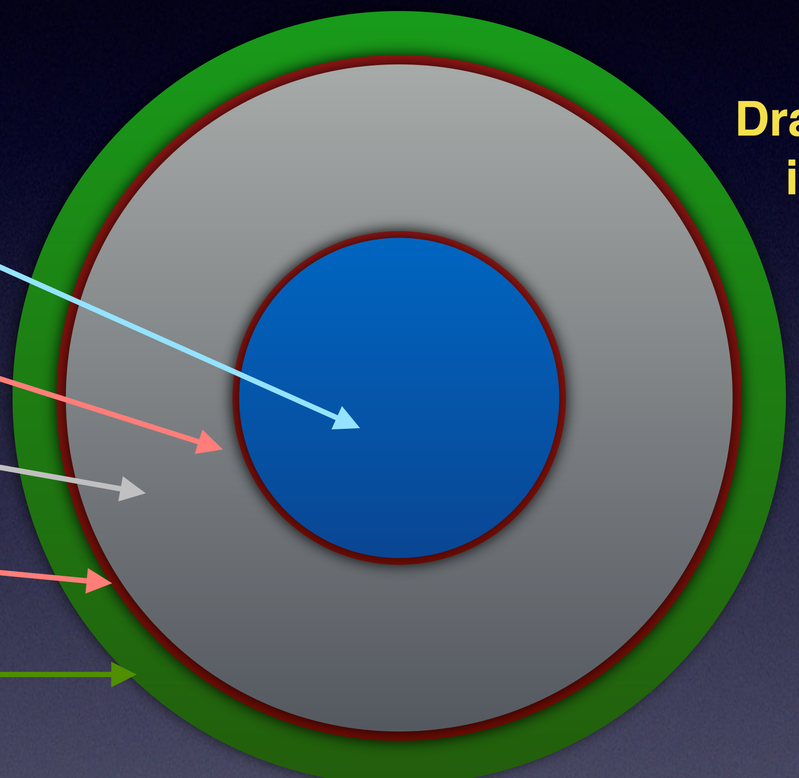
3 key requirements for 0$\nu\beta\beta$

- **Energy resolution** → To be validated
- **Low background** → Low material budget
- **Large masses of isotopes** → Easily scalable (1ton = 1m radius) or multiple spheres

Prototype 2

Sensitivity studies

- The first step is a **full Monte Carlo simulation** to assess our capability to reject background and to evaluate the possible sensitivity on the searched signal.
- We considered a geometry including active and passive veto and a small mass of 50 kg of xenon corresponding to the foreseen prototype.



Xenon active volume

Mass of 50 kg

Radius of 37 cm

Pressure of 40 bar

This choice, based on the results of a pressure and radius scan, is driven by the need of containing at least 80% of the $\beta\beta0\nu$ electrons.

Liquid scintillator volume

Thickness of 1.5 m

Assumed to be LAB

The thickness is chosen in order to have a background rate below 0.1 events per year from the ^{208}Tl contamination of the liquid scintillator vessel.

Shielding volume

20 cm Lead

5 cm Copper

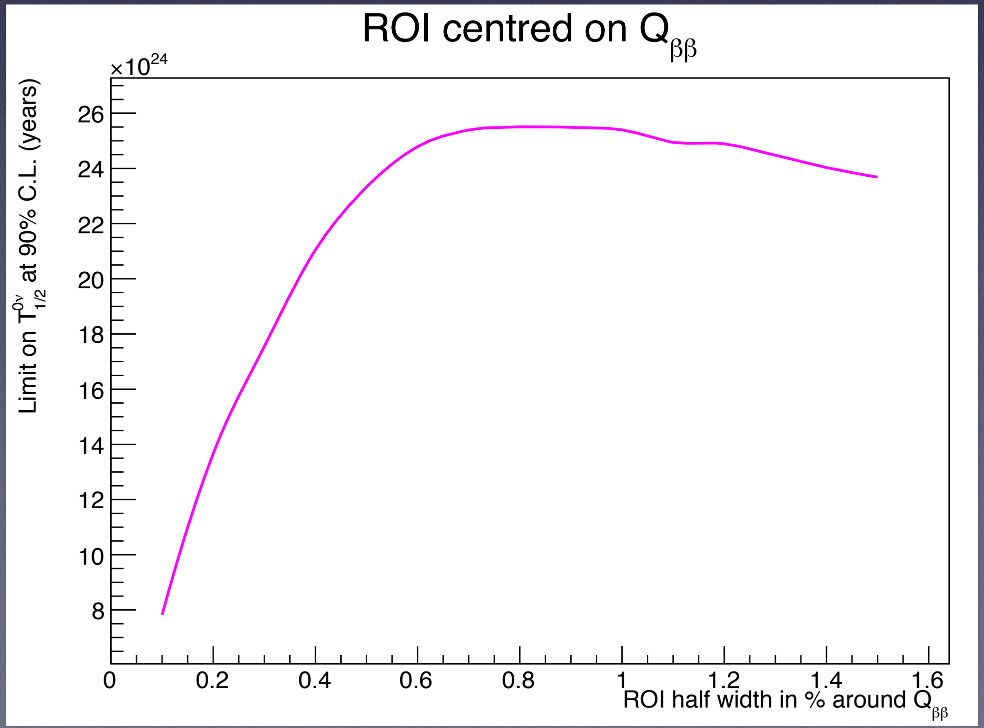
The choice was made to match the shielding used in measurements performed at LSM to have a reliable and less complicated MC.

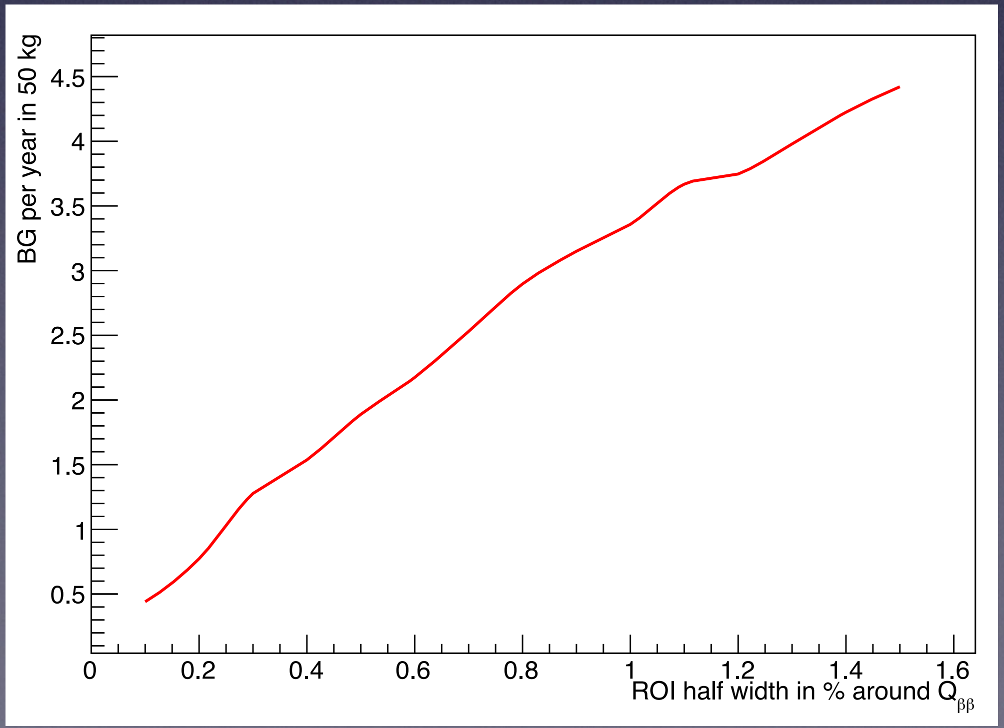
Results

- We studied the intrinsic background coming from the vessel material and all the additional external background which we reduced at a level of less than 0.1 events per year.

- We could set in one year a **limit on the $\beta\beta0\nu$ half life of 2.5 $\times$ 10^{25} years** (<$m_{\beta\beta}$> < (160 - 330) meV) with a **signal efficiency of 64%** and a **background at the level of 2 events per year** in 50 kg under the following assumptions:
  - Energy resolution of 1% FWHM at the $Q_{\beta\beta}$ of 2.458 MeV.
  - Optimized ROI of $Q_{\beta\beta}$ ± 0.6%.
  - Possibility of performing a radial energy deposition reconstruction.
  - A threshold as low as 200 keV for the liquid scintillator.
  - Copper activity of 10 μBq/kg.

Goal of the R2D2 R&D

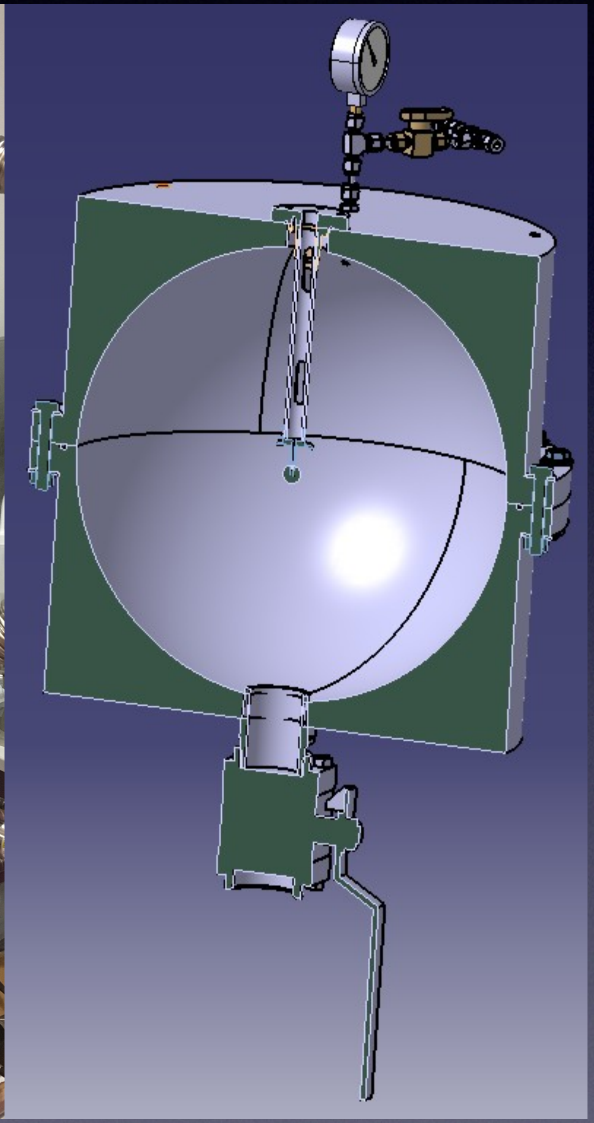




Prototype 1

R2D2 R&D

- In 2018 the R2D2 was funded as R&D by the IN2P3.
- The main goal of the R&D is the demonstration that the desired energy resolution can be achieved.
- To do that the idea is to use a smaller detector (20 cm radius) made of Aluminium i.e. no low background but much cheaper.
- The setup is under commissioning at CENBG.



Energy resolution

- The energy resolution is the **most critical point to be validated**.

- A resolution of 0.6% FWHM at 662 keV in proportional counter has already been demonstrated (this could be rescaled to 0.3% at the Xenon Q value of 2.458 MeV).

- Current liquid Xenon based experiments reached energy resolution at the level of 3-4%.

- NEXT, combining charge and light readout reached 1% FWHM.

- R&D on multi ball sensor at Saclay demonstrated a resolution of 27% FWHM at 5.9 keV (this could be rescaled to 1.3% at the Xenon Q value of 2.458 MeV).

A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370

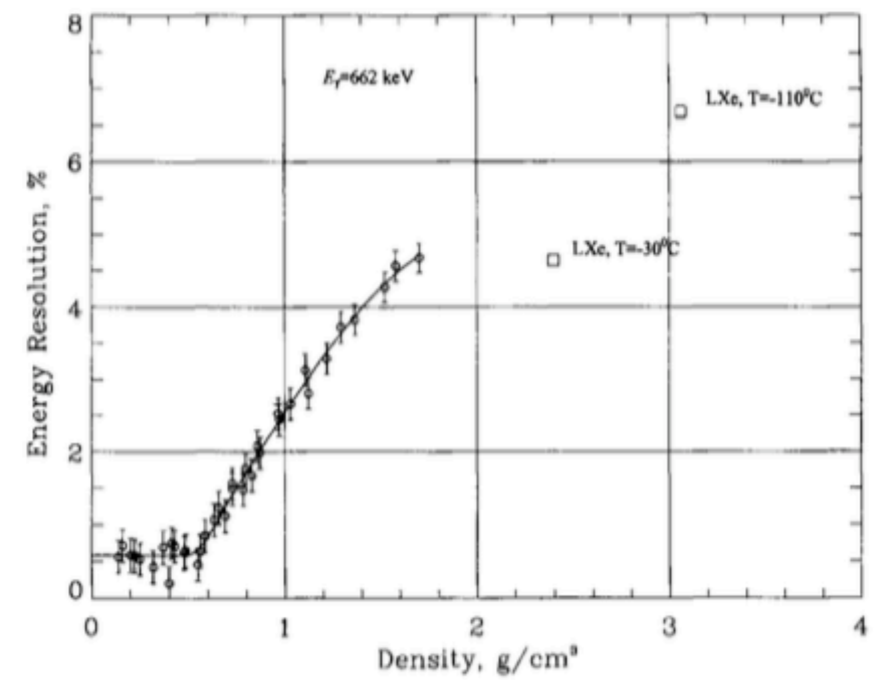


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

→ **In principle the ultimate showstopper could be given by inhomogeneities of the central sensor but a resolution at the level of 1% could be reached.**
R&D ongoing

Developments (1)

- Several further developments are under study and could be tested on the prototype 2 to enhance the signal over background ratio.

Electronics

- The signal waveform analysis is a critical ingredient for a particle identification i.e. for background reduction.
- We need an electronics that allows for a signal waveform reconstructions without affecting the energy resolution.
- Custom made electronics are under developments at CENBG/CEA.

Materials

- Needless to say the activity of materials used has a critical impact on the background.
- We assumed a copper activity of 10 μBq/kg which is conservative considering that on the market copper with an activity of 1 μBq/kg can be found.

Developments (2)

Light readout

- The radial position reconstruction is today based on a waveform analysis (basically the width of the signal normalised by its amplitude).
- The knowledge of the T0 given by the Xenon scintillation would be an important piece of information to have a more precise position reconstruction.
- In addition it would make the coincidence with the external liquid scintillator veto signal much shorter and easier.
- Given the impossibility to have PMT directly in the liquid scintillator sphere, and the difficulty to extract the light with fibers, an option of deposing small regions of photocathode is under study.

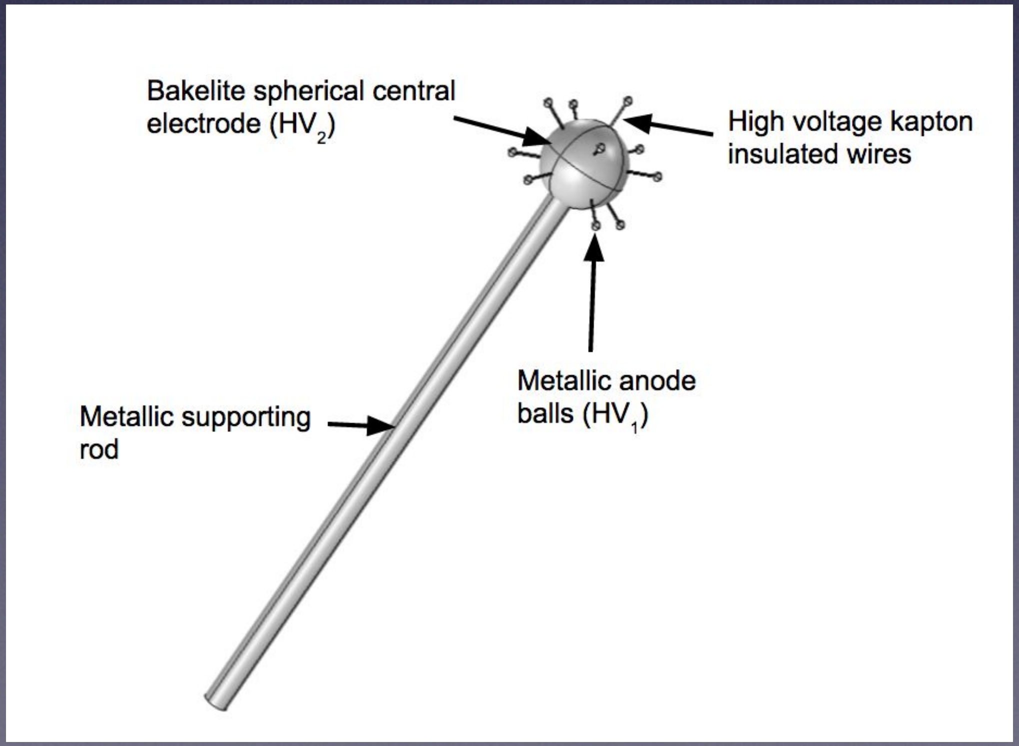
Gases

- The use of different gases in the same TPC (i.e. same background sources) could be an advantage to understand and benchmark the background.
- In addition gases with $\beta\beta$ emitters at higher $Q_{\beta\beta}$ would result in a smaller background.

Developments (3)

Central sensor

- High pressure and large spheres require a high voltage on the central anode.
- It seems that a reasonable limit before reaching technical difficulties is about 10 kV.
- A solution might come from a multi-ball readout (ACHINOS) developed at Saclay (*arXiv:1707.09254*): with a smaller HV on each anode we could have the same field far from the anode and a higher amplification with respect to a single central ball.
- The anodes could be read independently giving a coarse detector segmentation (i.e. **coarse tracking**) which could result into an additional handle for background rejection (studies in progress).



Status and outlook

- The R2D2 proto-collaboration has been formed and the R&D has been approved by IN2P3.
- Preliminary studies showed that we could have competitive sensitivity with small masses and **potentially zero background detectors with large masses**.
- One additional of the advantages of such a detector would be the possibility to use different gases in the same detector. If the technology will be proven successful the use of Xenon will be only a first phase of a more complete project.
- An R&D program has started with the main goal of assessing the achievable energy resolution, which is the first possible showstopper.
- Depending on the success of the R&D we hope to move on in order to build a prototype allowing for real physics results.

Interested people are welcome to join the project