

Neutrinoless Double Beta Decay

Matteo Agostini

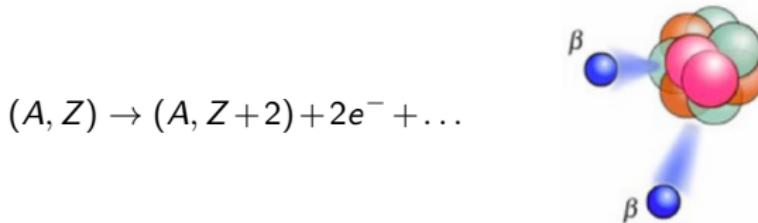
Gran Sasso Science Institute (INFN), L'Aquila, Italy

1st GSSI Scientific Fair
November 3-6, 2015



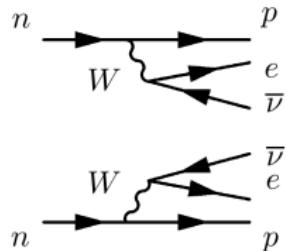
Double- β decays

Second order nuclear transitions → decay of two neutrons into two protons:



2-neutrino double- β decay ($2\nu\beta\beta$):

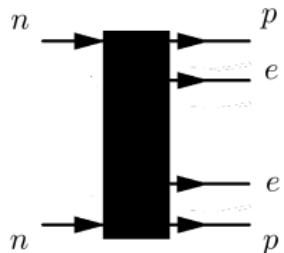
- (A, Z) → (A, Z + 2) + 2e⁻ + 2 $\bar{\nu}_e$
- allowed in the Standard Model
- measured in several isotopes
- $T_{1/2}^{2\nu}$ in the range $10^{19} - 10^{24}$ yr



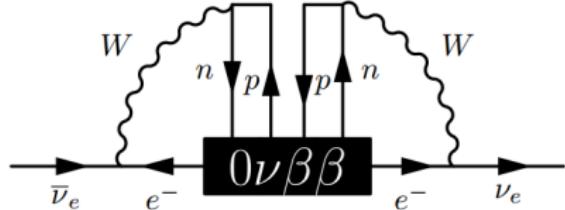
Double- β decays

Neutrinoless double- β decay ($0\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z + 2) + 2e^-$
- foreseen by many extensions of the Standard Model
- lepton number violation ($\Delta L = 2$)
- $T_{1/2}^{0\nu}$ limits in the range $10^{21} - 10^{26}$ yr



- Lepton-genesis process measurable in lab
- ν has non-null Majorana mass component
- ν phenomenology...

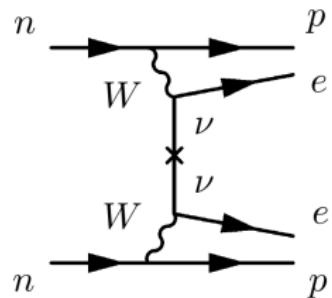


Neutrinoless double- β decay & neutrino physics

Assuming light-Majorana neutrino exchange as dominant $0\nu\beta\beta$ channel:

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) |\mathcal{M}_{0\nu}(A, Z)|^2 |m_{\beta\beta}|^2$$

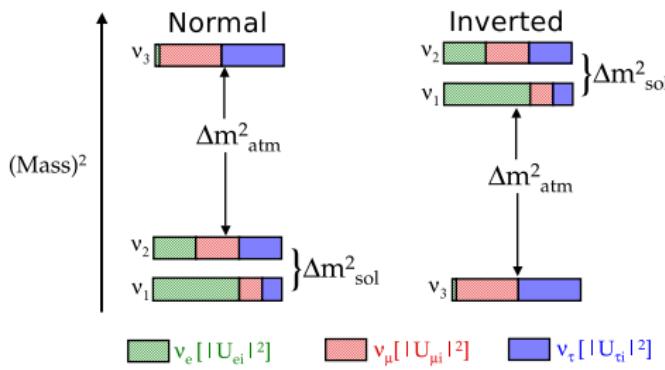
- $G_{0\nu}$ phase space factor
- $\mathcal{M}_{0\nu}$ nuclear matrix element
- $|m_{\beta\beta}|$ effective Majorana mass



$$\begin{aligned} |m_{\beta\beta}| &\equiv \left| \sum_i U_{ei}^2 m_i \right| \\ &= \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i2\alpha} + s_{13}^2 m_3 e^{i2\beta} \right| \end{aligned}$$

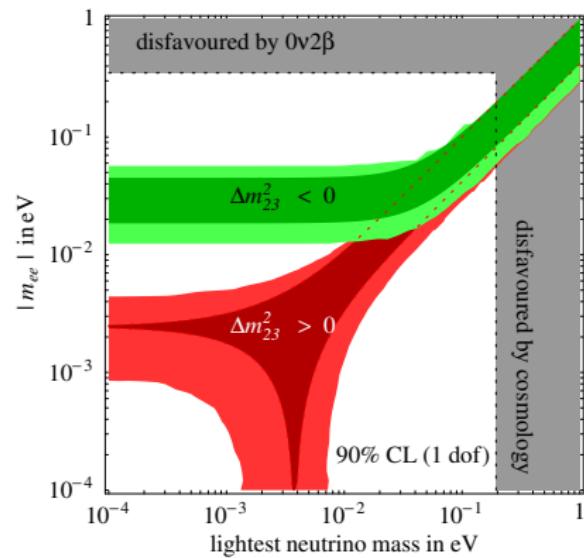
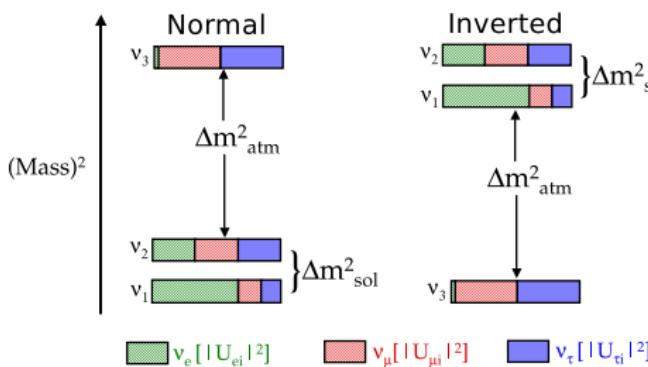
Neutrinoless double- β decay & neutrino physics

- ν phenomenology: 3 mixing angles, 3 mass eigenvalues, 3 phases
- ν oscillations provide info only on mixing angles, Δm^2 and one phase
- $|m_{\beta\beta}| \equiv \left| \sum_i U_{ei}^2 m_i \right| = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i2\alpha} + s_{13}^2 m_3 e^{i2\beta} \right|$
info about ν mass spectrum, absolute mass scale, phases...



Neutrinoless double- β decay & neutrino physics

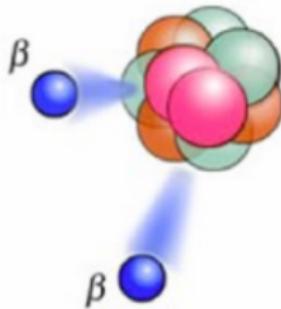
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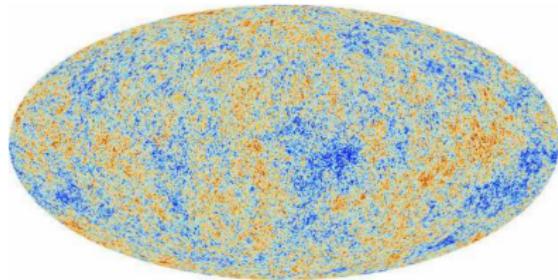
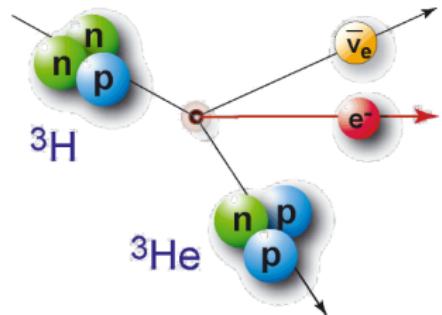
[Phys. B 637, 345 (2002)]

Neutrino mass observables

$$0\nu\beta\beta: |m_{\beta\beta}| \equiv |\sum_i U_{ei}^2 m_i|$$



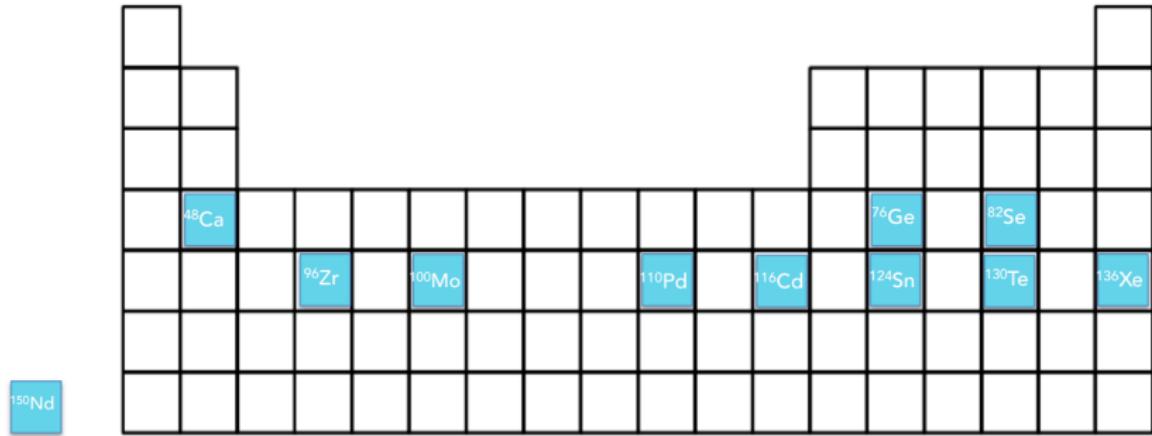
$$\beta\text{-decay [KATRIN]: } \langle m_\beta \rangle \equiv \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$



$$\text{Cosmology } \Sigma \equiv \sum_i m_i$$

Double- β decaying isotopes

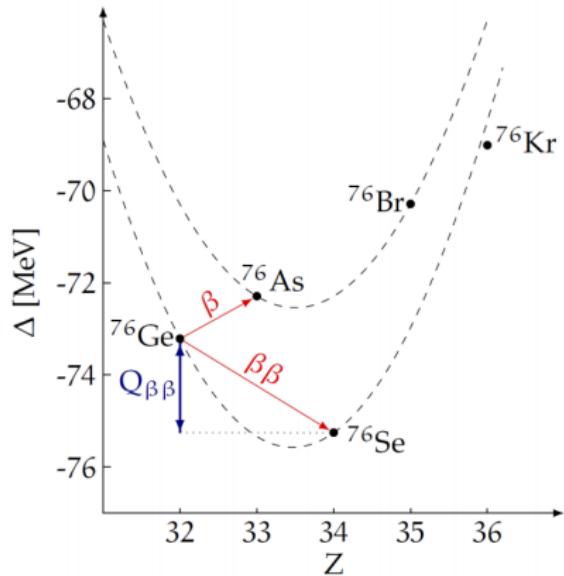
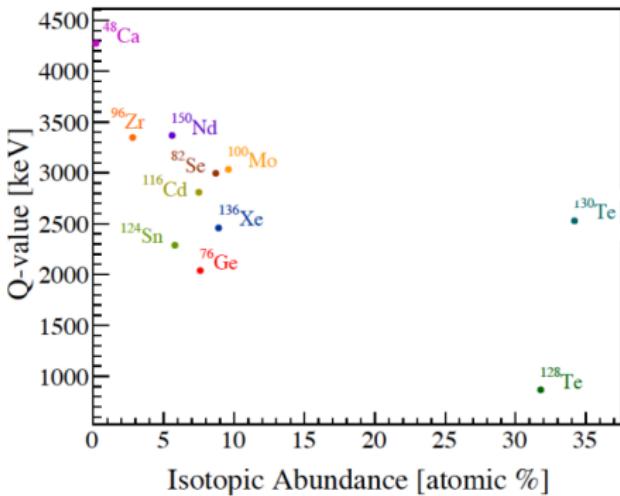
35 isotopes available, interesting for $0\nu\beta\beta$ searches only 11:



[from K. Schäffner]

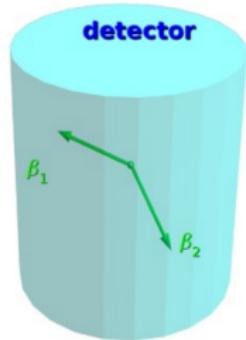
Double- β decaying isotopes

- single β -decay must be energetically forbidden
- $(T_{1/2}^{0\nu})^{-1} \propto G_{0\nu}(Q_{\beta\beta}, Z) \propto (Q_{\beta\beta})^5$
- different detection techniques for different isotopes

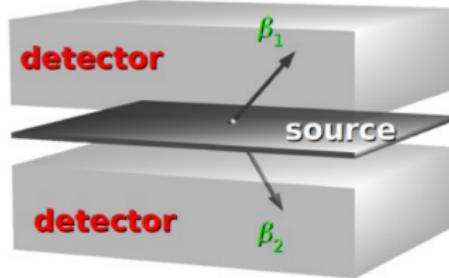


Detection approaches

Calorimeter (source = detector):



External-source detector:



[from O. Cremonesi]

Calorimeters:

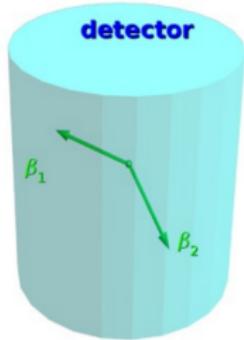
- high efficiency
- good energy resolution
- large masses

External-source detectors:

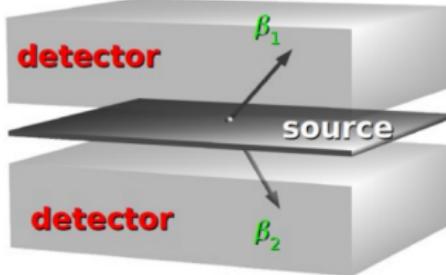
- smoking gun signature
- single electron information
- possible to study different isotopes

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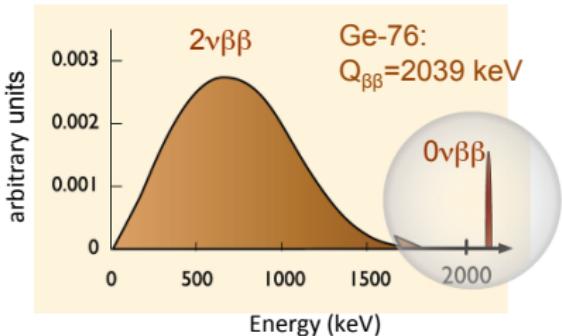
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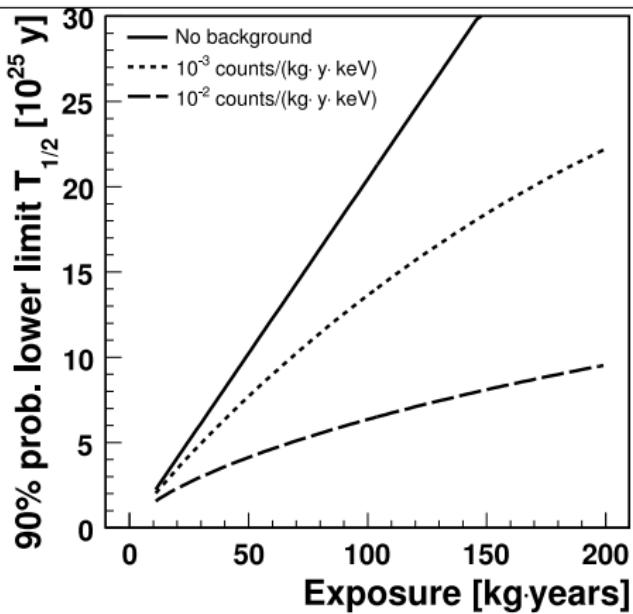
Experimental sensitivity

Number of expected $0\nu\beta\beta$ events:

$$N_{0\nu\beta\beta} = \ln 2 \cdot \varepsilon \cdot N_{atoms} \cdot \frac{t}{T_{1/2}^{0\nu}}$$

- ε : detection efficiency
- N_{atoms} : number of target $0\nu\beta\beta$ -decaying atoms
- t : data taking time in yr

► just a few counts in an experiment



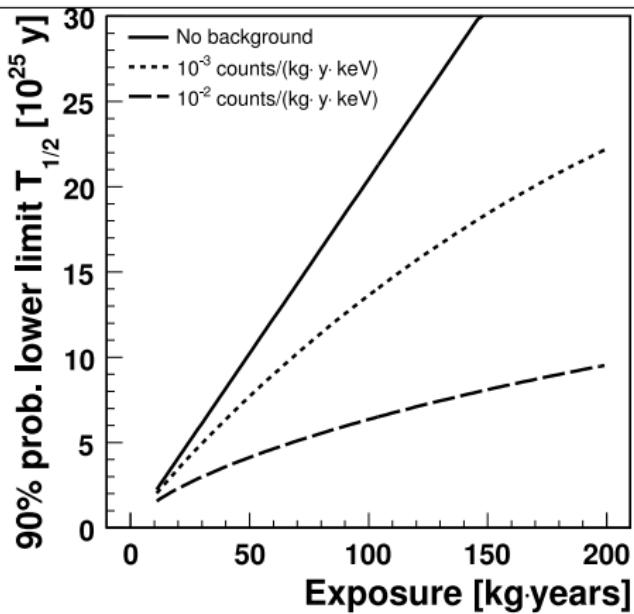
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background free

$$T_{1/2}^{0\nu} > \ln 2 \cdot \varepsilon \cdot (\text{mass} \cdot \text{time})$$

$\text{mass} \cdot \text{time} = \text{exposure}$

background limited

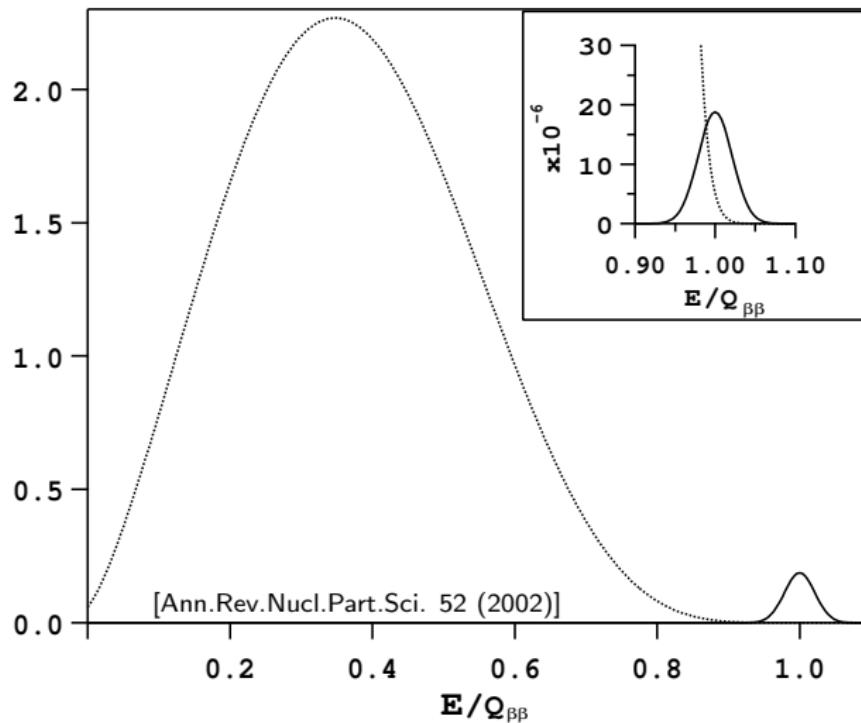
$$T_{1/2}^{0\nu} > \ln 2 \cdot \varepsilon \cdot \sqrt{\frac{\text{mass} \cdot \text{time}}{\Delta E \cdot BI}}$$

ΔE energy resolution

BI: background index [cts/(keV·kg·yr)]

Energy resolution

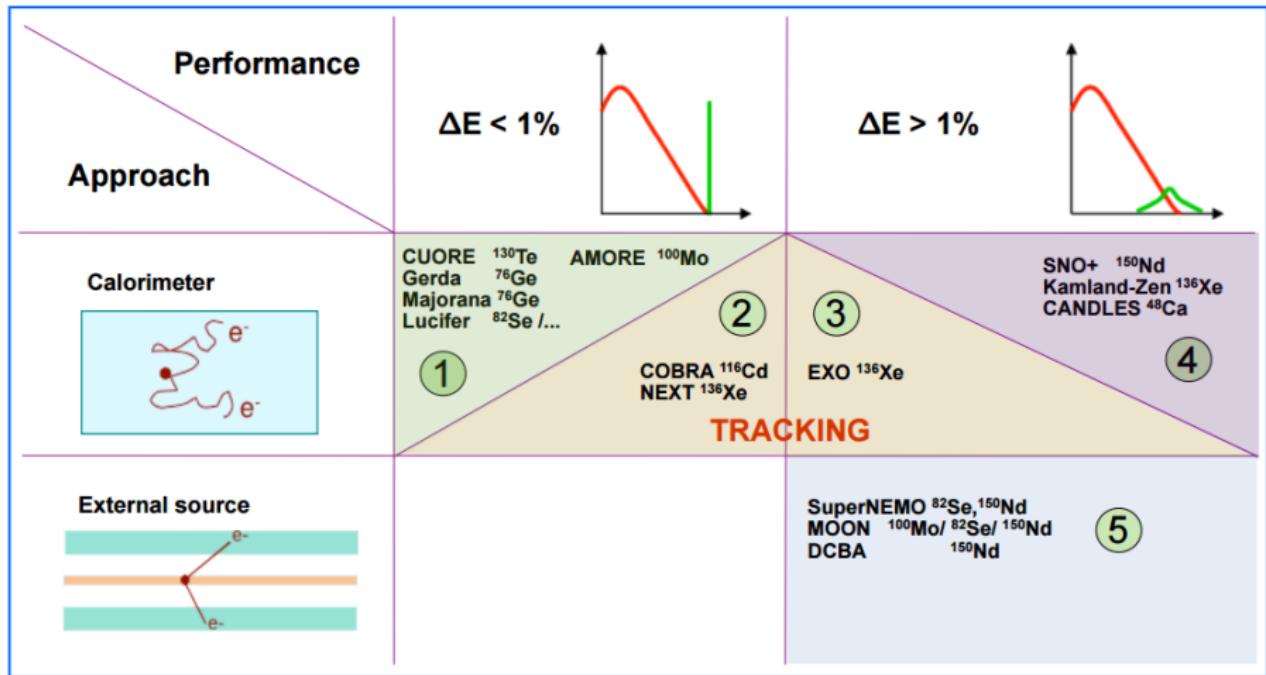
Good energy resolution needed → mitigation of $2\nu\beta\beta$ background



Background Index (GERDA with ^{76}Ge)

Background Index (GERDA with ^{76}Ge)

Present/future experiments

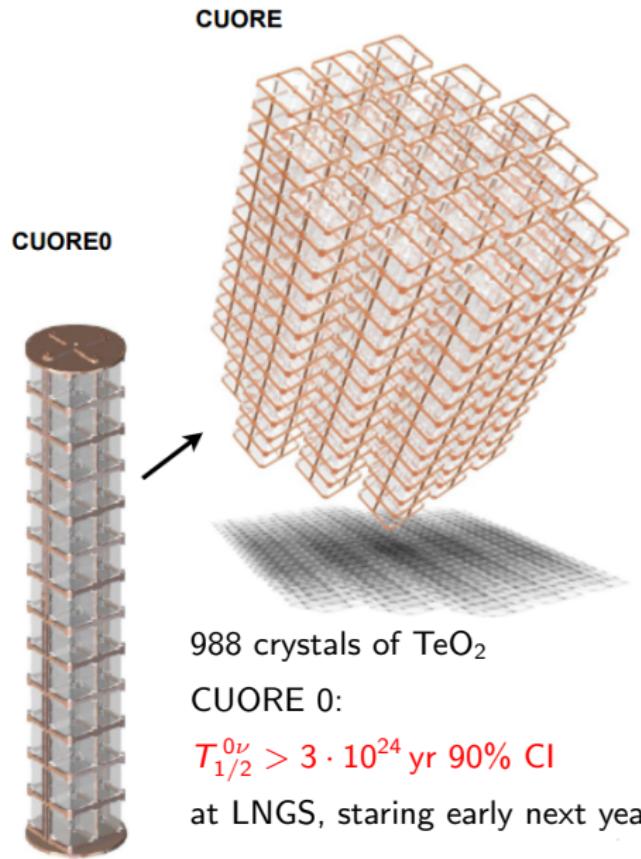
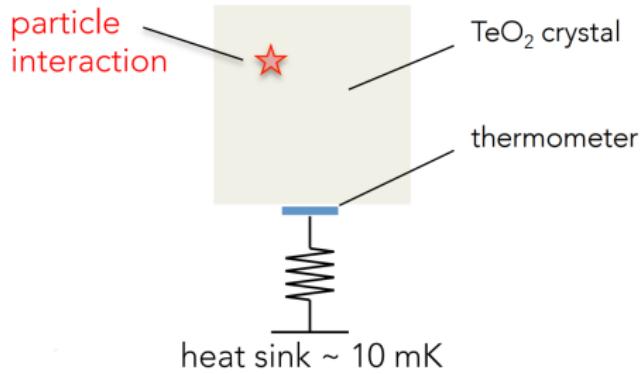


[from O. Cremonesi]

At LNGS: CUORE (^{130}Te), GERDA (^{76}Ge), LUCIFER (^{82}Se), COBRA (^{116}Cd)

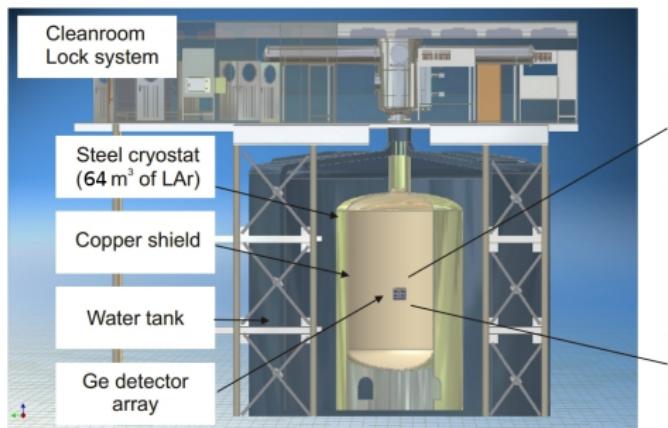
CUORE (@LNGS)

- cryogenic bolometers @ 10mK
- 206 kg fiducial mass of ^{130}Te
- $\Delta E \sim 5 \text{ keV}$ @ Q-value
- BI < $10^{-2} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$



GERDA (@LNGS)

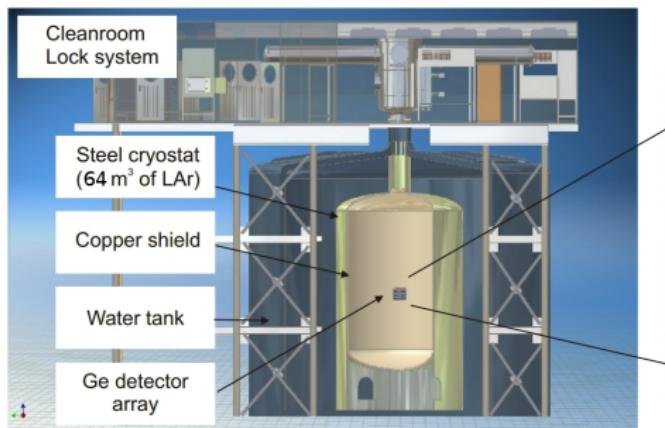
- Ge semiconductor detectors
- LAr shielding and active veto
- 40 kg target mass (87% ^{76}Ge)
- $\Delta E \sim 3\text{ keV}$ @ Q-value
- $\text{BI} < 10^{-3}\text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$



- Phase I concluded in 2013:
best ^{76}Ge experiment
 $T_{1/2}^{0\nu} > 2 \cdot 10^{25}\text{ yr}$ 90% CL
- Phase II commissioning on-going (double mass, lower BI)

GERDA (@LNGS)

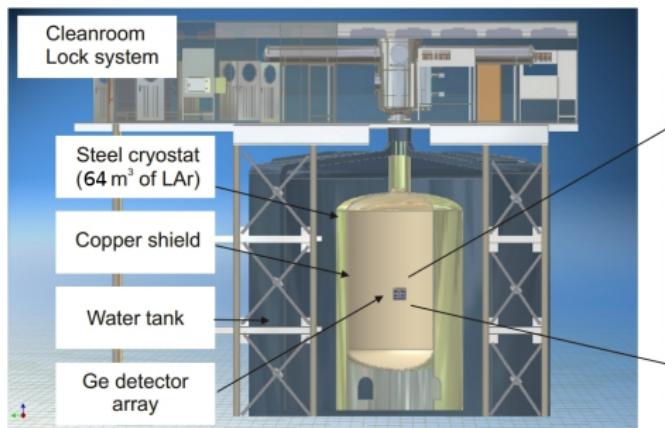
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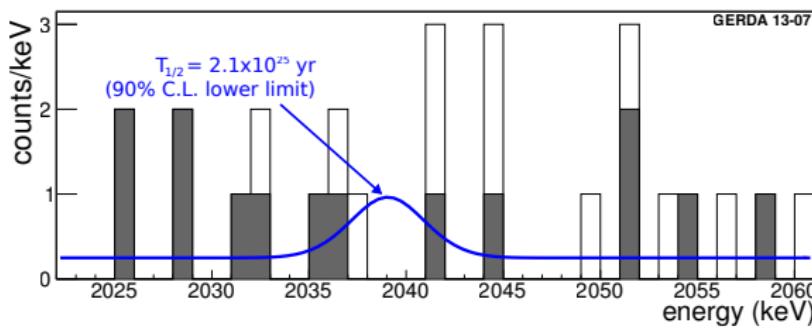
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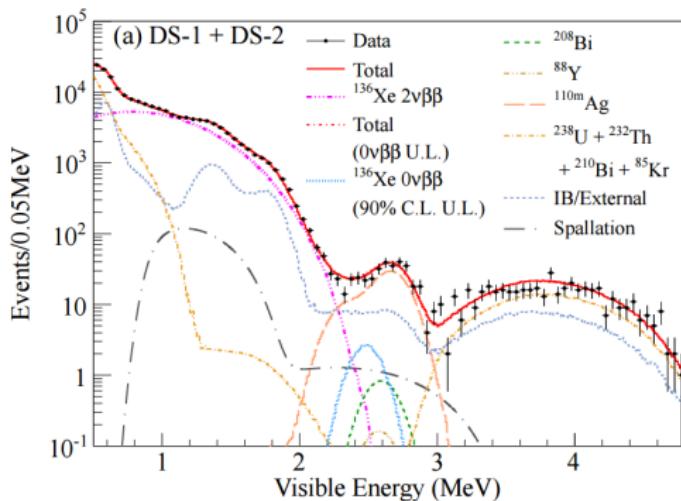
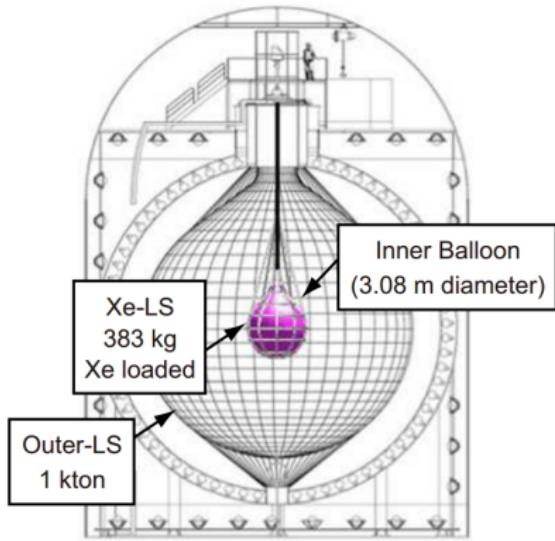
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 $T_{1/2}^{0\nu} > 2 \cdot 10^{25} \text{ yr}$ 90% CL
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KamLAND-Zen (@Kamioka, Japan)

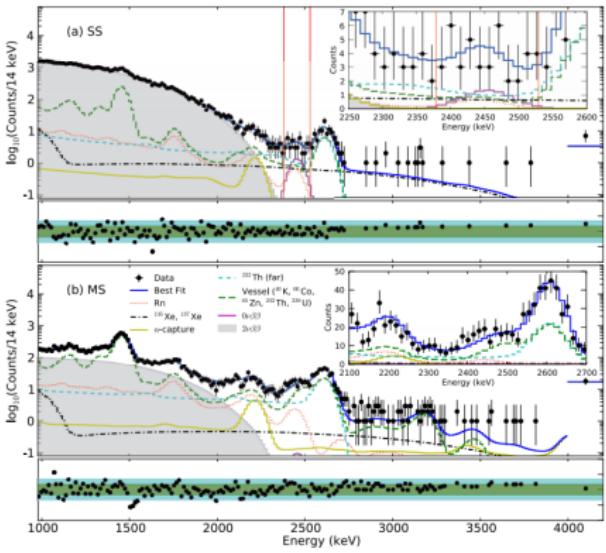
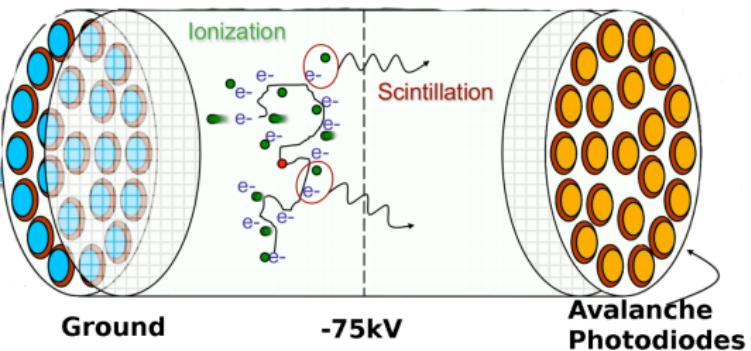
- Xe-loaded organic liquid scintillator
- 300-400 kg target mass (80% ^{136}Xe)
- $\Delta E \sim 250 \text{ keV} @ \text{Q-value}$



$$T_{1/2}^{0\nu} > 2 \cdot 10^{25} \text{ yr } 90\% \text{ CL}$$

EXO-200 (@WIPP, New Mexico)

- ~1 ton liquid Xe TPC
- ionization + scintillation signal
- 200 kg target mass (80% ^{136}Xe)
- $\Delta E \sim 100 \text{ keV}$ @ Q-value



$$T_{1/2}^{0\nu} > 1 \cdot 10^{25} \text{ yr } 90\% \text{ CL}$$

Outlook



- ▶ $0\nu\beta\beta$ very fascinating process:
 - lepton-genesis
 - majorana ν
- ▶ exciting time for $0\nu\beta\beta$ at LNGS
- ▶ COBRA, CUORE, GERDA, LUCIFER: all taking data next year
- ▶ future R&D's:
 - CUPID: R&D bolometers (LUCIFER, CUORE)
 - LSGE: large scale ^{76}Ge exp (GERDA, Majorana)

[DOE Nuclear Science Advisory Committee (2014)]

To know more...

- CUORE: Carlo Bucci
- GERDA: Matteo Agostini, Valerio D'Andrea, Matthias Laubenstein
- LUCIFER/CUPID: Sergey Nagorny, Lorenzo Pagnanini, Karoline Schäffner