New generation of double beta decay experiments

Challenges, prospects and techniques

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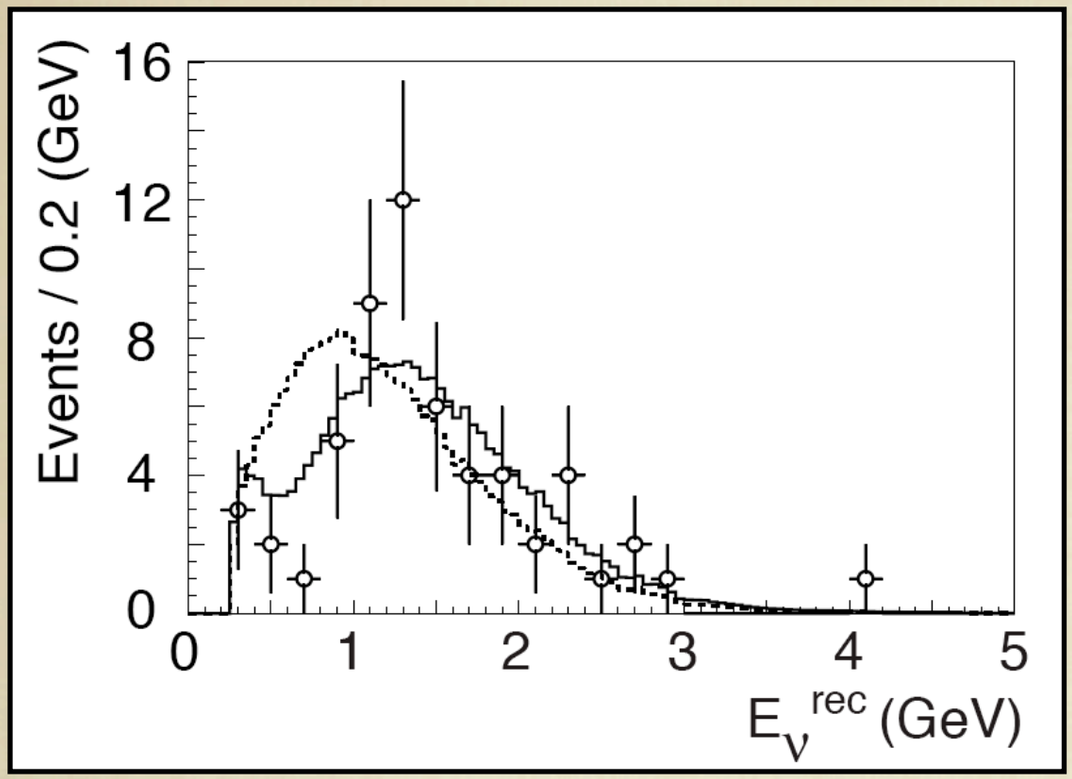
An old subject

- (1935) M. Goeppert-Mayer calculates ββ2ν rate.
- (1937) Ettore Majorana historic paper.
- (1937) Racah suggests to use ββ0ν to test Majorana theory.
- (1939) Furry calculates approximate rates for ββ0ν.
- (1950's-1980's) Geochemical measurements of ββ2ν.
- (1987) Elliott, Hahn, Moe: ββ2ν first direct observation (Irvine TPC).
- (1990's) Heidelberg-Moscow experiment.
- (2003) Klapdor-Kleingrothaus' claim.
- (Today) New generation of experiments.

Motivations



K2K experiment.

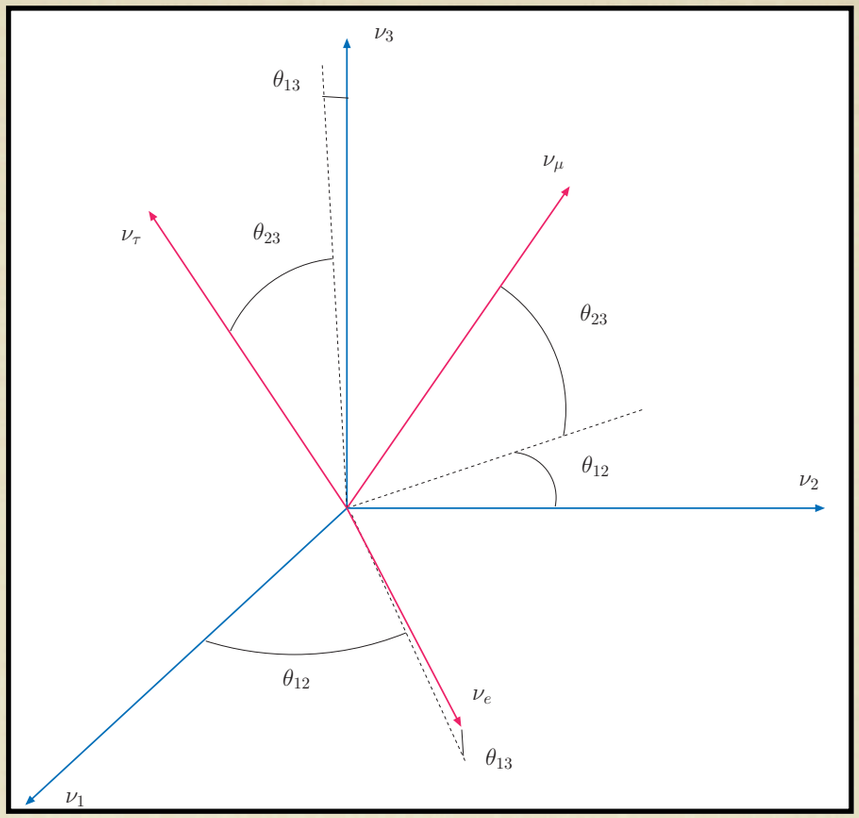
Oscillation experiments:
evidence of massive neutrinos
...but some remaining
questions.

- Absolute scale of neutrino masses.
- Neutrino mass hierarchy.
- Dirac or Majorana particle?

Neutrino mixing

Neutrino flavour eigenstates are linear combinations of the massive ones.

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{k L}$$



PMNS mixing matrix

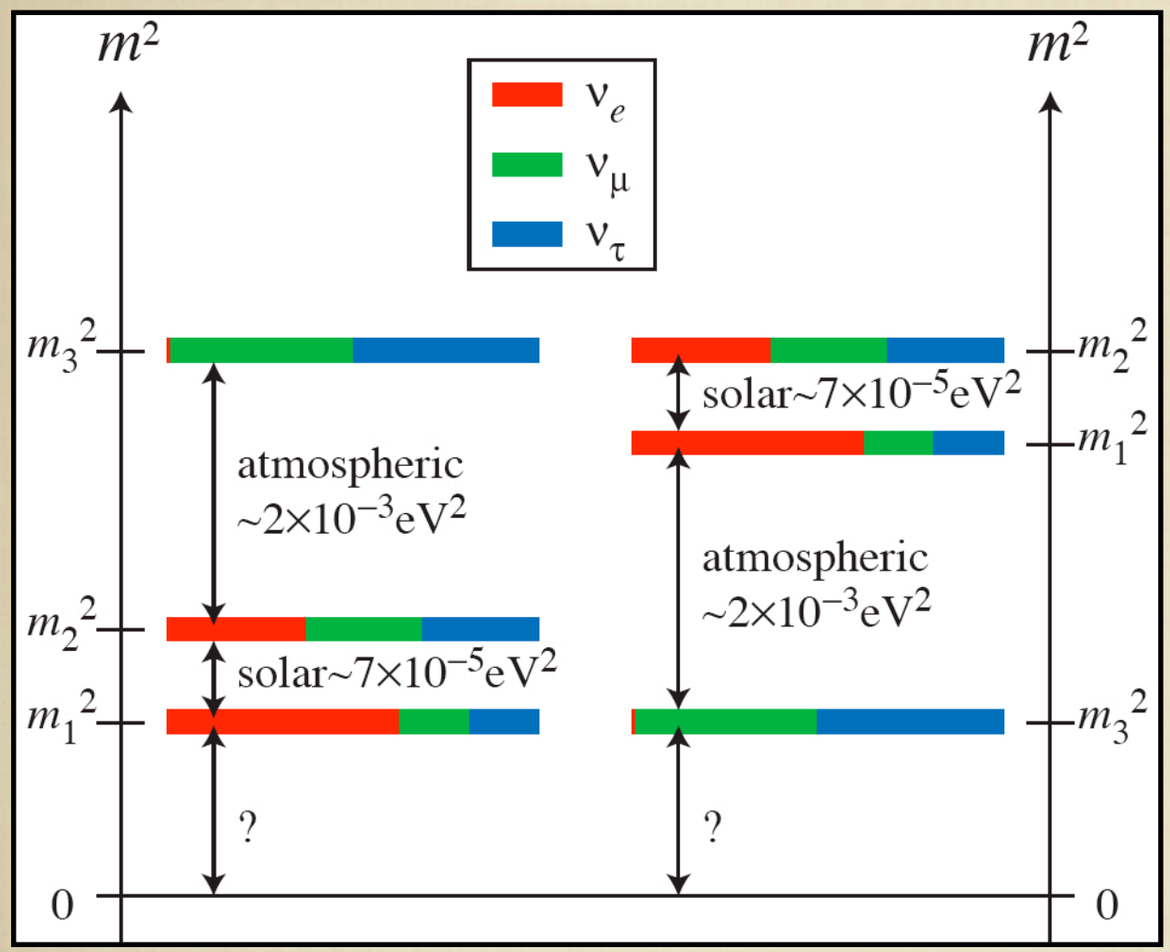
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric neutrinos

link between solar and atmospheric neutrinos

solar neutrinos

Neutrino mass hierarchies



$$
\begin{aligned}
\Delta m^2_{21} &= 7.9\,{}^{+0.27}_{-0.28}\,({}^{+1.1}_{-0.89}) \times 10^{-5}\ \mathrm{eV}^2, \\
|\Delta m^2_{31}| &= 2.6 \pm 0.2\ (0.6) \times 10^{-3}\ \mathrm{eV}^2, \\
\theta_{12} &= 33.7 \pm 1.3\,({}^{+4.3}_{-3.5}), \\
\theta_{23} &= 43.3\,{}^{+4.3}_{-3.8}\,({}^{+9.8}_{-8.8}), \\
\theta_{13} &= 0.0\,{}^{+5.2}_{-0.0}\,({}^{+11.5}_{-0.0}), \\
\delta_{\mathrm{CP}} &\in [0, 360]
\end{aligned}
$$

C. González-García and M. Maltoni, arXiv:0704.1800 [hep-ph]

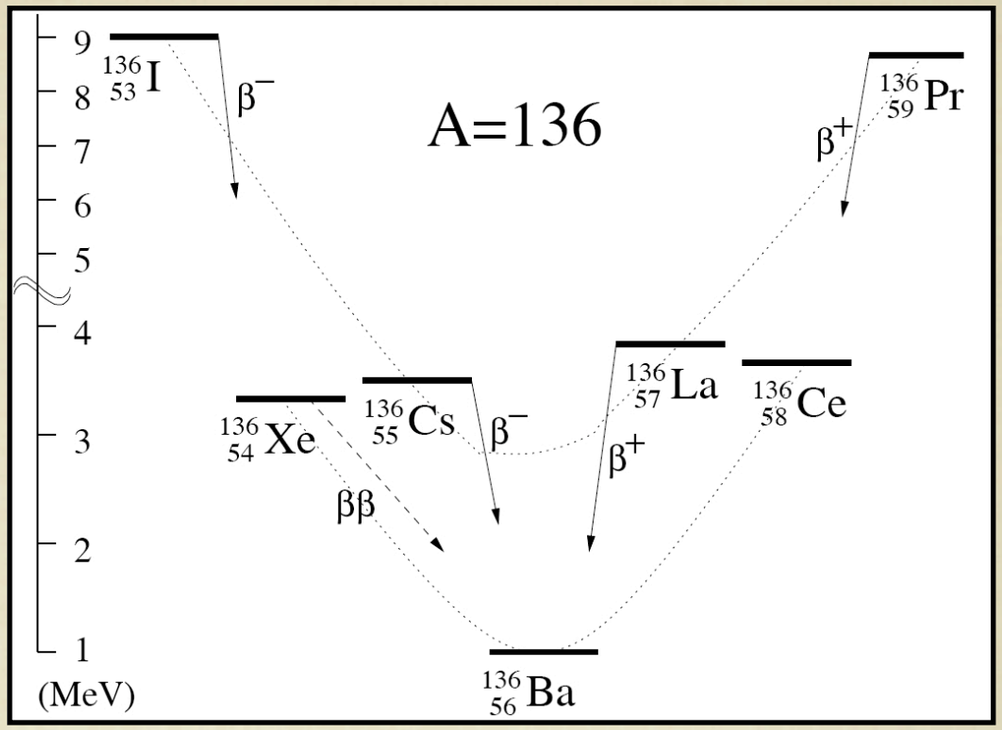
Two modes of double beta decay

ββ2ν: two simultaneous β decays

$$(Z, A) \rightarrow (Z + 2, A) + e_1^- + e_2^- + \overline{\nu}_{e_1} + \overline{\nu}_{e_2}$$

$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q, Z)|M^{2\nu}|^2$$

$$T_{1/2} \simeq 10^{18} - 10^{20} \text{years}$$

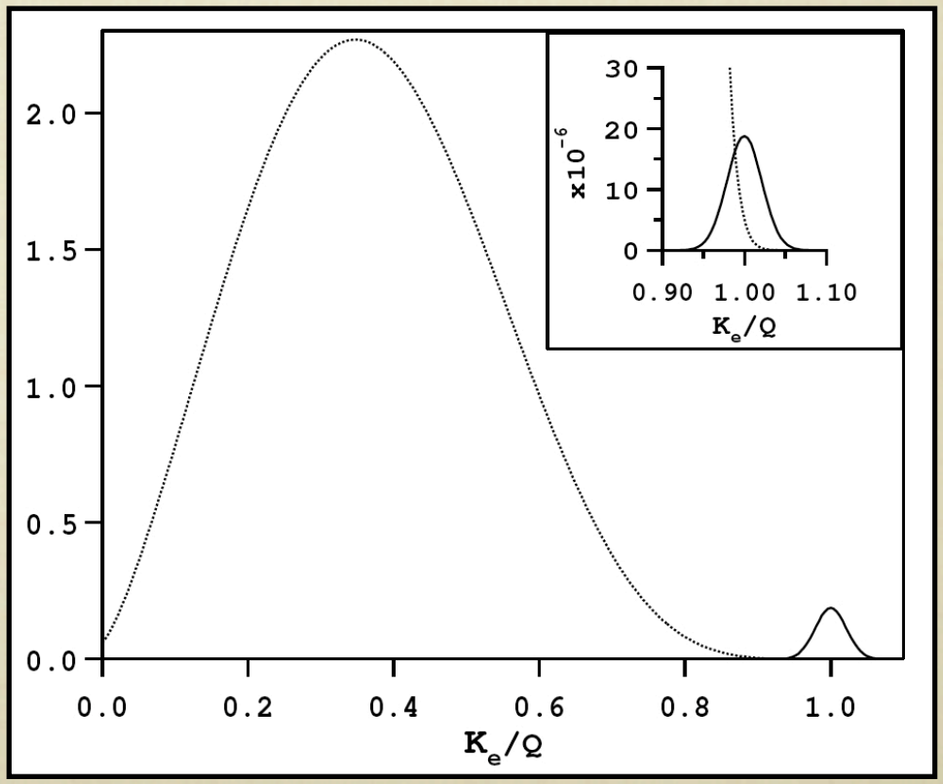


ββ0ν: Non-SM process. Requires massive Majorana neutrinos.

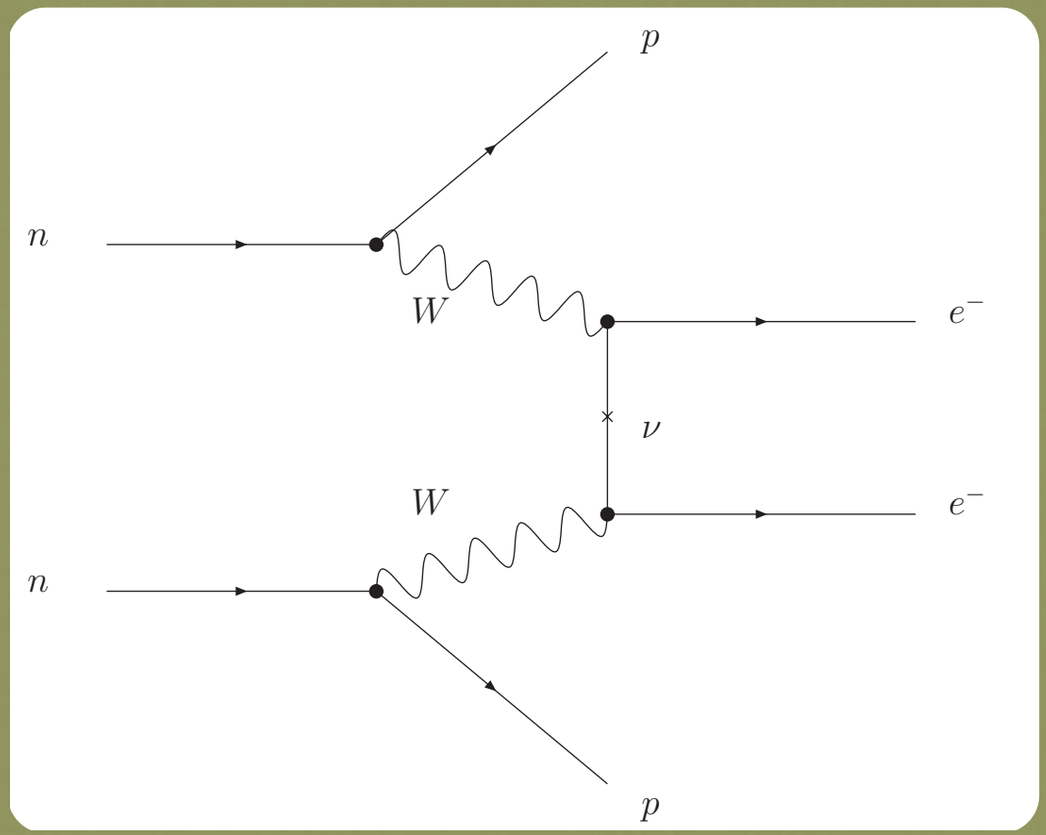
$$(Z, A) \rightarrow (Z + 2, A) + e_1^- + e_2^- + \cancel{\overline{\nu}_{e_1} + \overline{\nu}_{e_2}}$$

$$(\Delta L = 2)$$

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

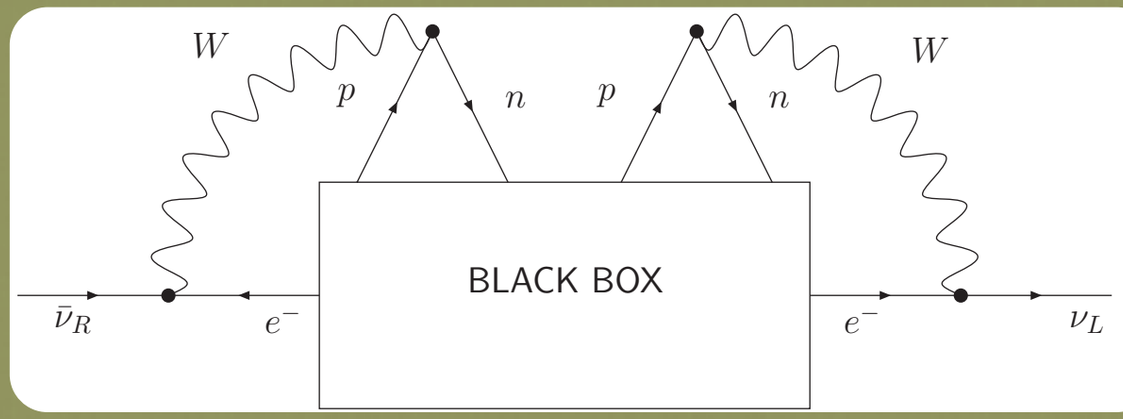


ββ0ν *mechanism*



Exchange of light Majorana neutrinos

Other mechanisms are possible, but all of them imply a Majorana neutrino mass.

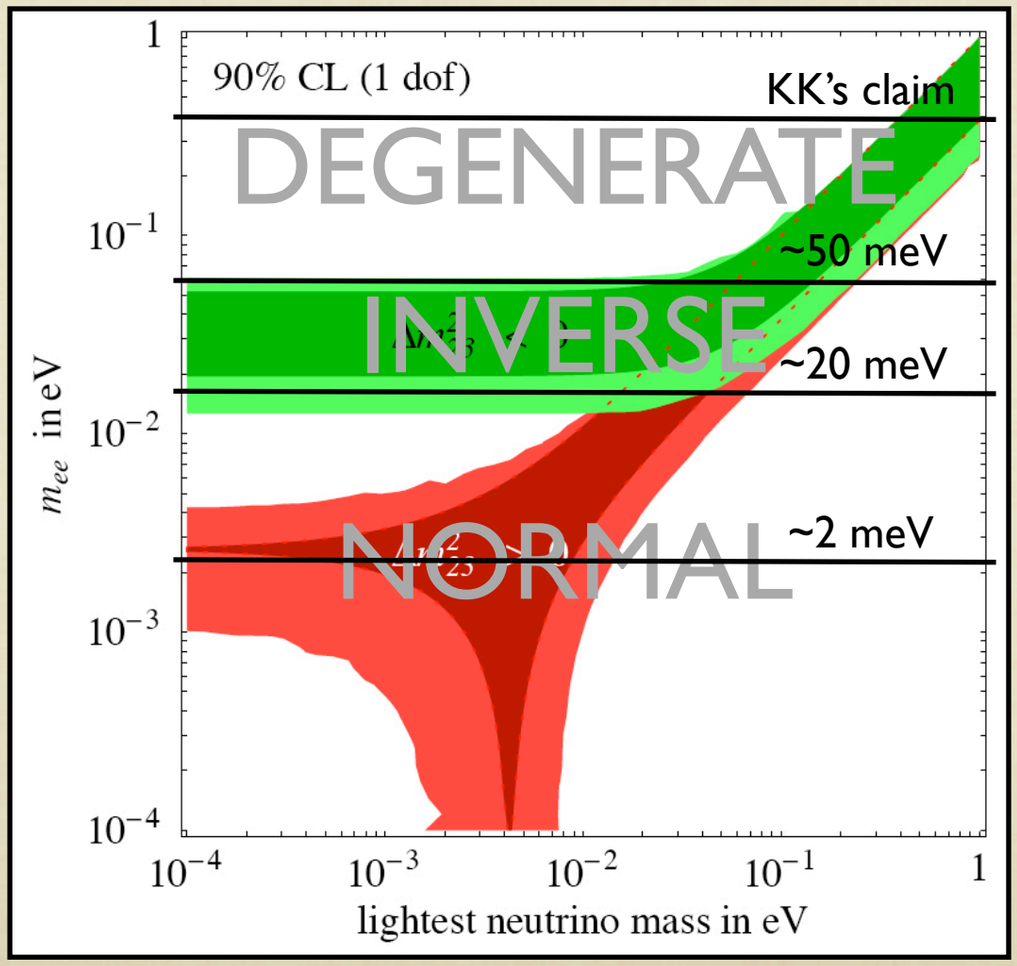


J. Schechter and J. W. F. Valle, Phys. Rev. D **25** (1982) 2951.

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2 \boxed{\langle m_{\beta\beta}\rangle^2}$$

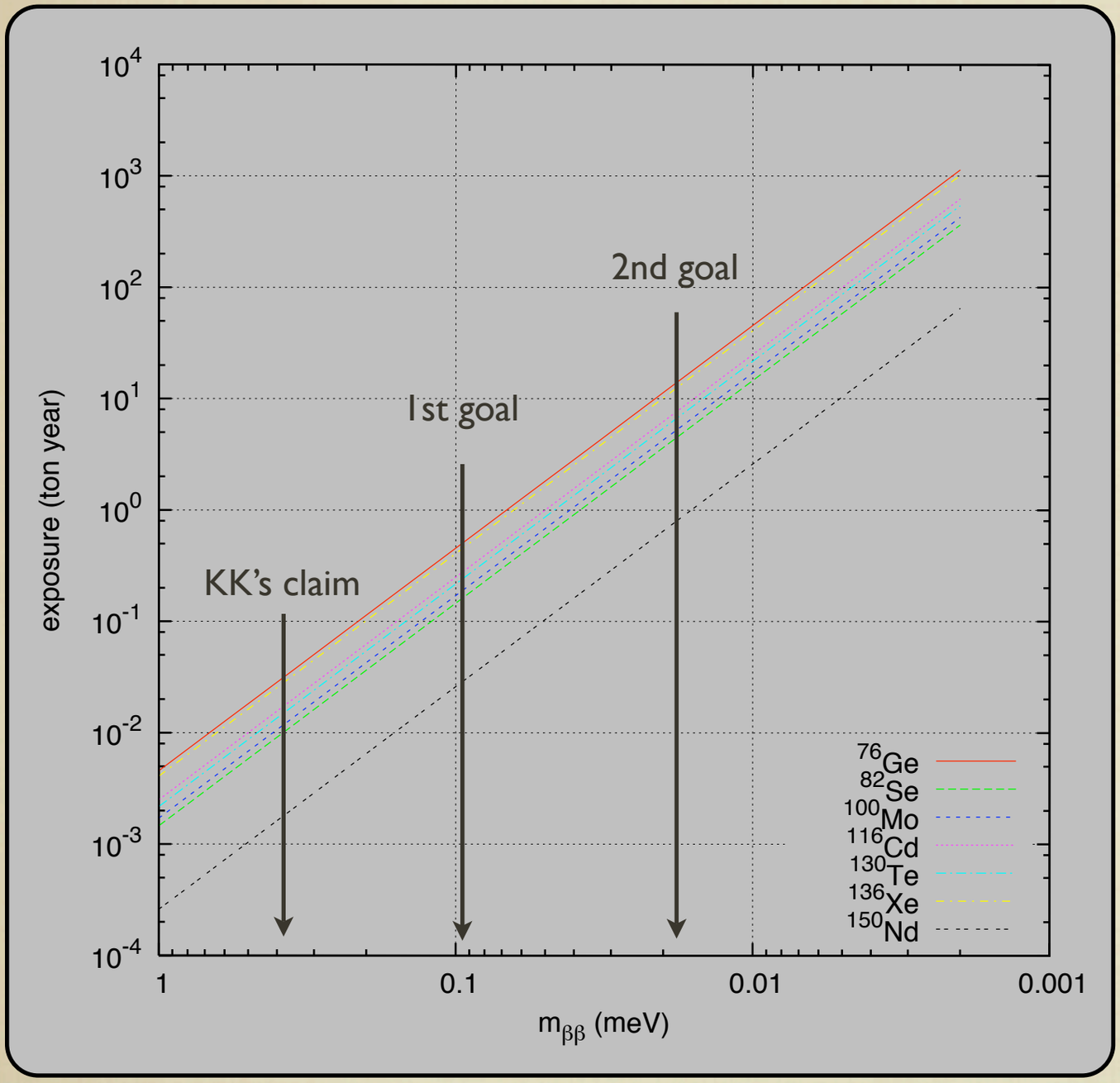
Effective neutrino mass: related to the mixing angles, neutrino masses and Majorana phases.

$$\begin{aligned}\langle m_{\beta\beta}\rangle &= \left|\sum_j m_j |U_{ej}|^2\right| \\ &= \left|\cos^2\theta_{13}(|m_1|\cos^2\theta_{12} + |m_2|e^{2i\alpha_1}\sin^2\theta_{12}) + |m_3|e^{2i(\alpha_2-\delta)}\sin^2\theta_{13}\right|\end{aligned}$$



F. Feruglio, A. Strumia and F. Vissani [arXiv: hep-ph/0201291]

Experimental objectives



exposure (*M*·*t*) needed to collect ten counts

zero-background experiment

$$T_{1/2} = \ln 2 \, \frac{N_A \times 10^3}{A \; N_{\beta\beta}} \; Mt$$

1st goal (100 meV): O(0.5) ton·y

2nd goal (20 meV): O(10) ton·y

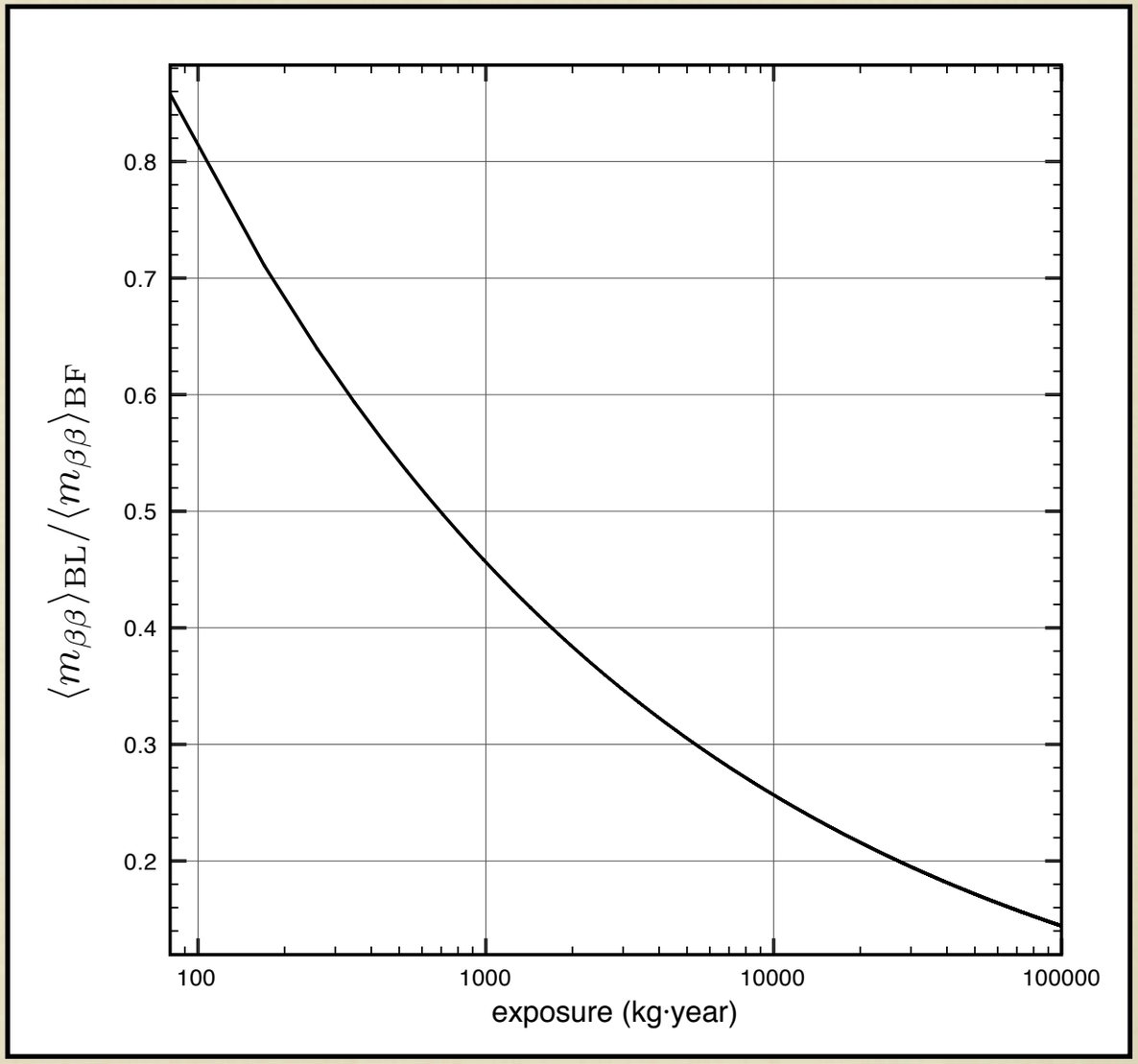
Background limits the sensitivity

background-free

$$\langle m_{\beta\beta} \rangle \propto (Mt)^{-1/2}$$

background-limited

$$\langle m_{\beta\beta} \rangle \propto (Mt)^{-1/4}$$

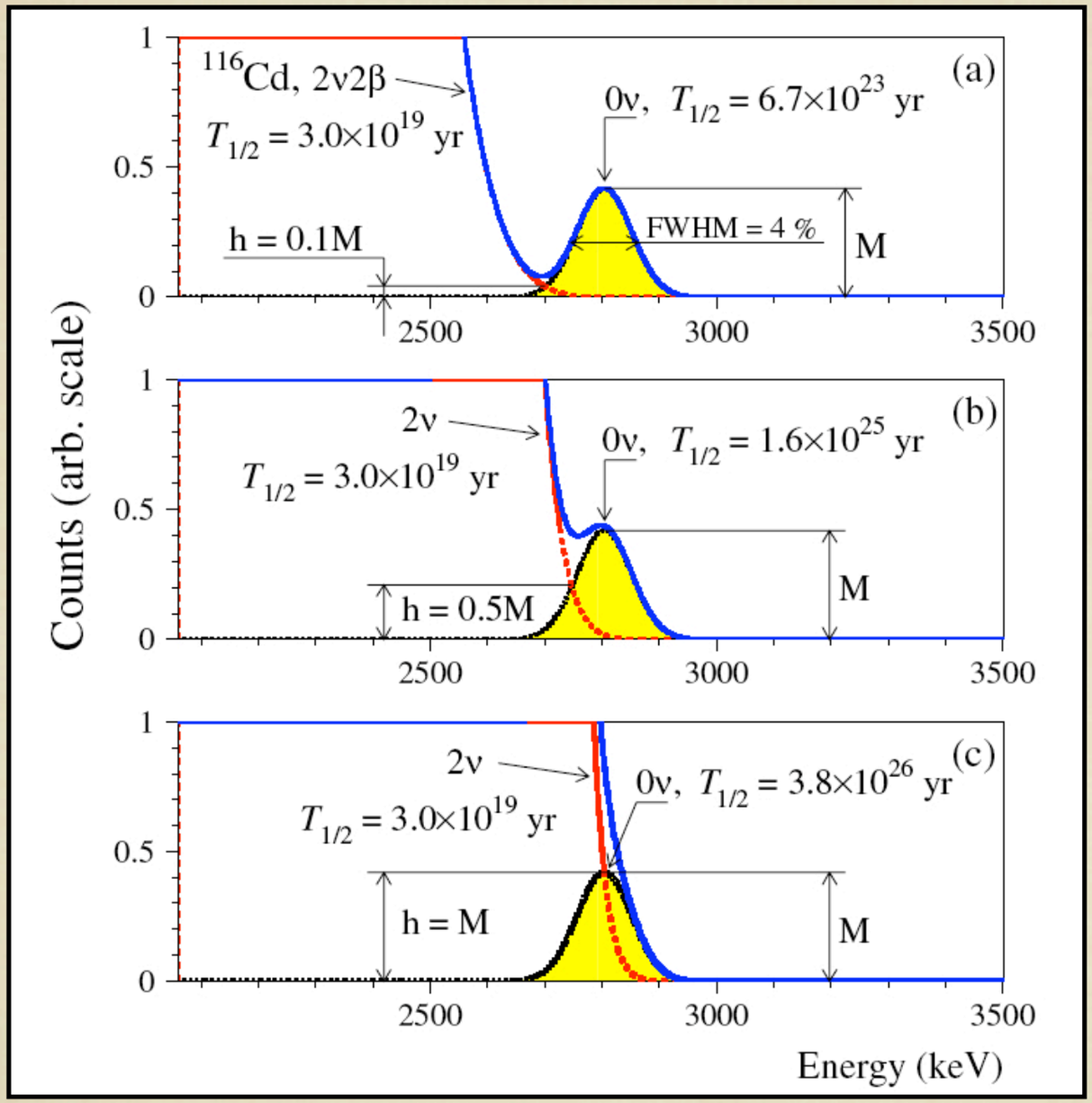


BL/BF sensitivities ratio for a typical Ge experiment

Suppressing backgrounds

Current best rates have been achieved in Ge experiments	0.8–1 mBq (15 c/kg·keV·y)
New-generation requirements	<10 μBq
Human body natural radioactivity (^{40}K)	$\sim$4000 Bq

Intrinsic background (ββ2ν)

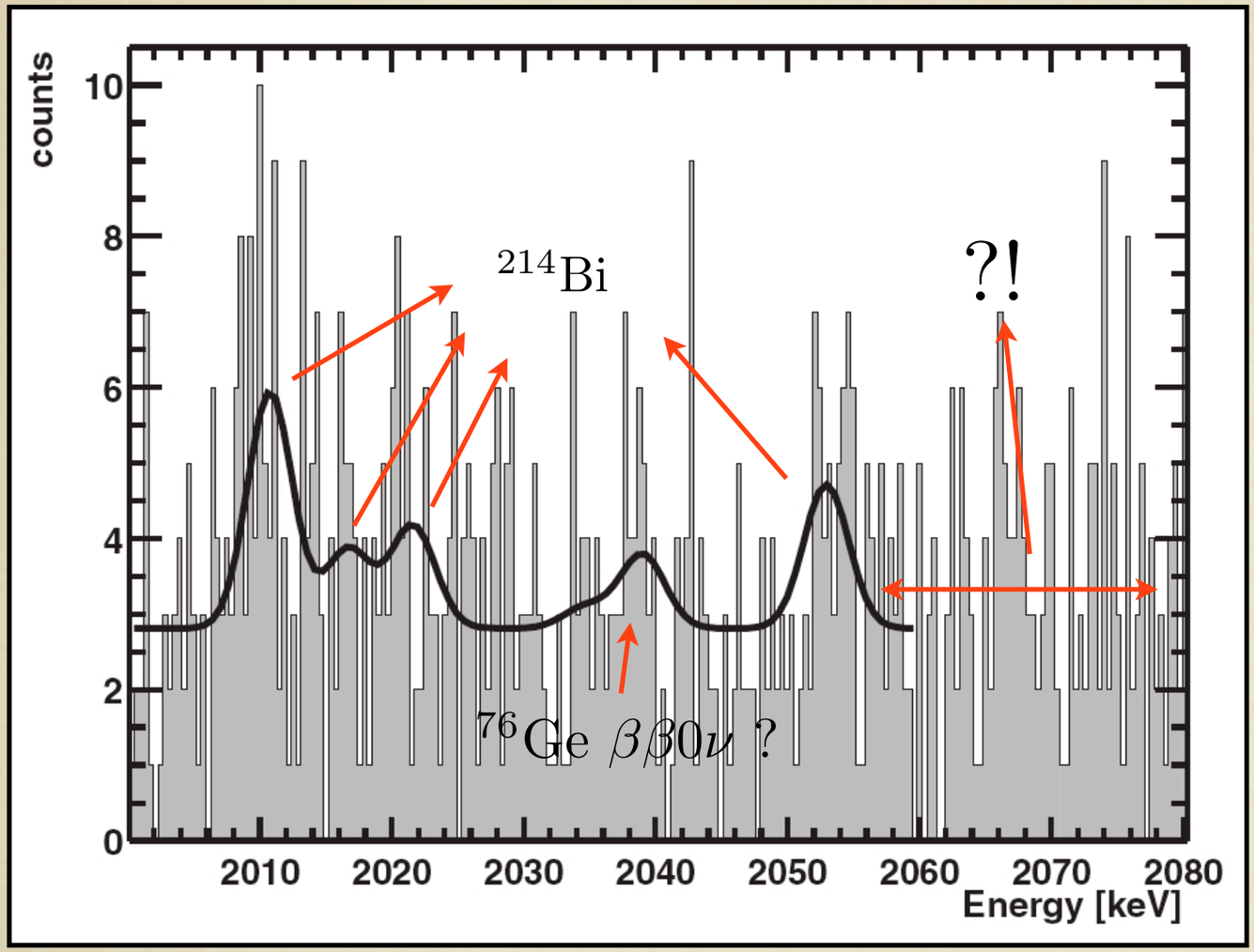


Y. G. Zdesenko *et al.*, J. Phys. G **30** (2004) 971-981

Resolution requirement depends on 2ν half-life.

Energy resolution is a *must*!

Other backgrounds



Klapdor-Kleingrothaus *et al.*, [arXiv: hep-ph/0302248].

Common sources

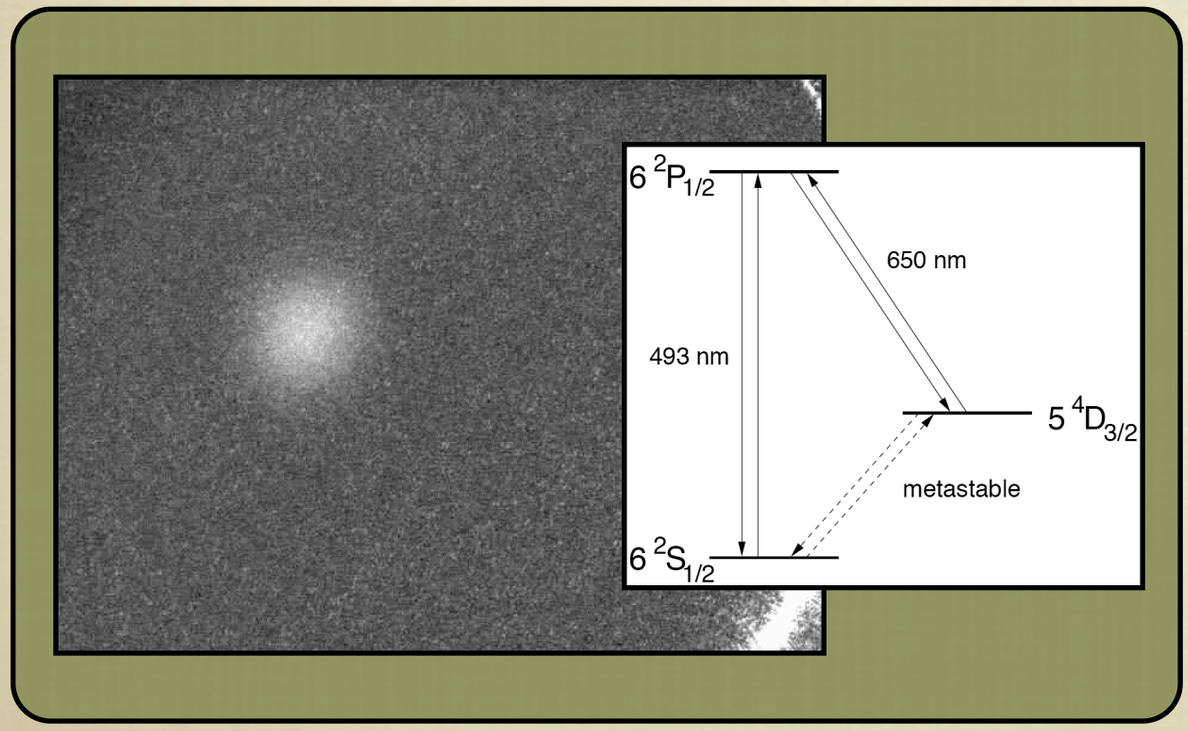
- Natural radioactivity (radon)
- Cosmogenic backgrounds
- *Exotic* backgrounds

Resolution may not be enough:
extra handles required!

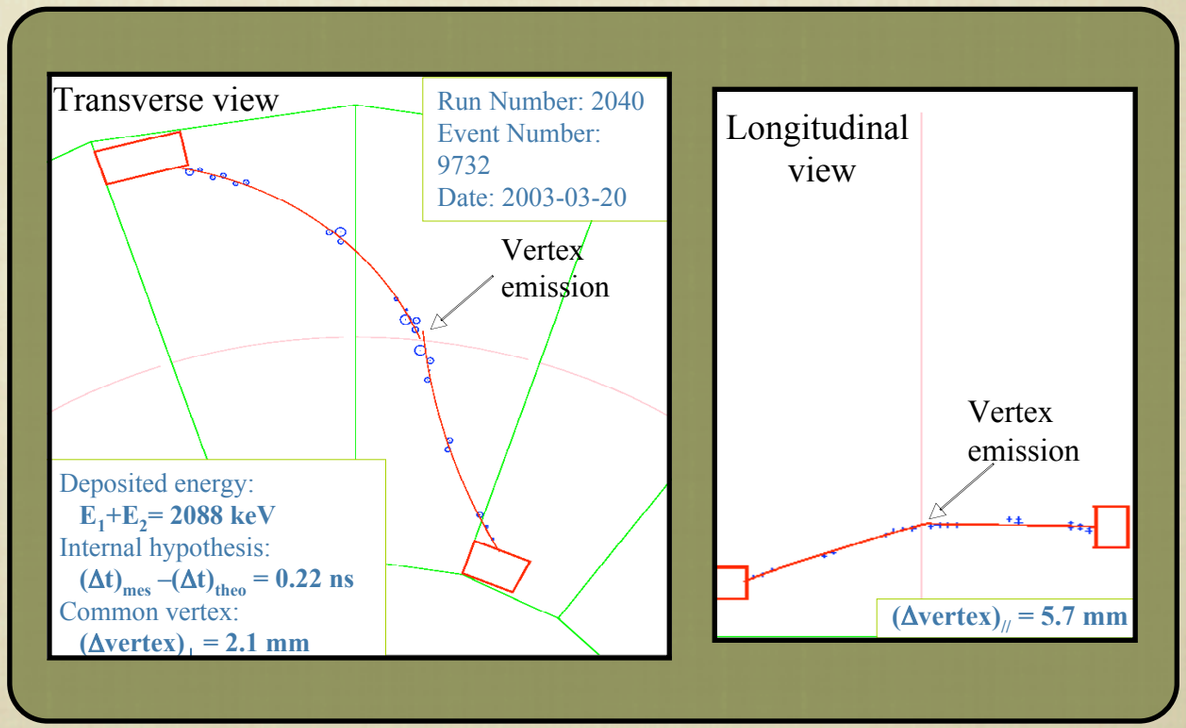
Extra handles

- Kinematics: electrons individual energy, time of flight, etc.
- d*E*/d*x*
- Tagging of the daughter nucleus
- ...

Ba$^+$ ion tagging: EXO experiment.



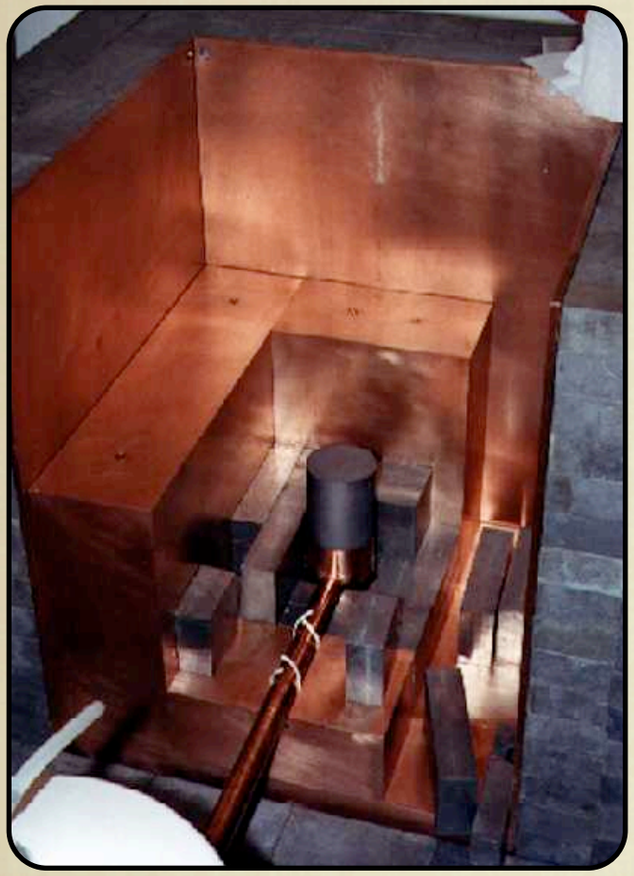
Electrons track reconstruction: NEMO-3 experiment.



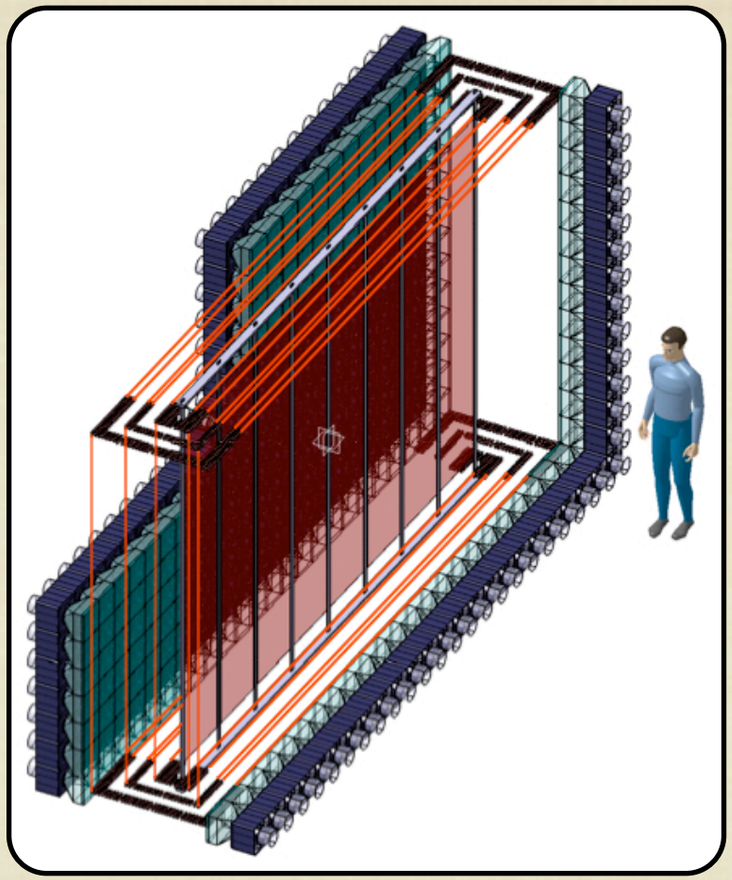
An ideal experiment

General design	- High efficiency. - Very good energy resolution. - Mass scalability. - Compact size. - Ultra-radiopure materials. - Ability to study several isotopes. - Measurement of event kinematic information. - Extra signatures.
Isotope	- Isotope with large Q value. - Isotope with high i.a. or easy to enrich. - Good FN. - NME with small theoretical uncertainties.

Proposals for new experiments

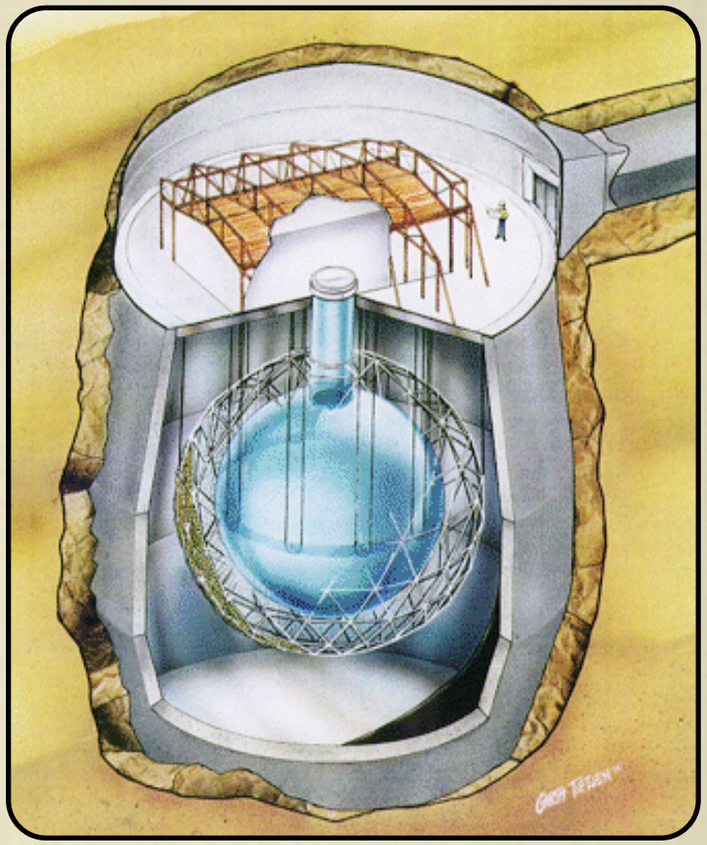


<u>Diodes & Bolometers</u>
GERDA
Majorana
Cuore
COBRA



<u>Calo+Tracko</u>
SuperNEMO

<u>Xenon TPCs</u>
EXO

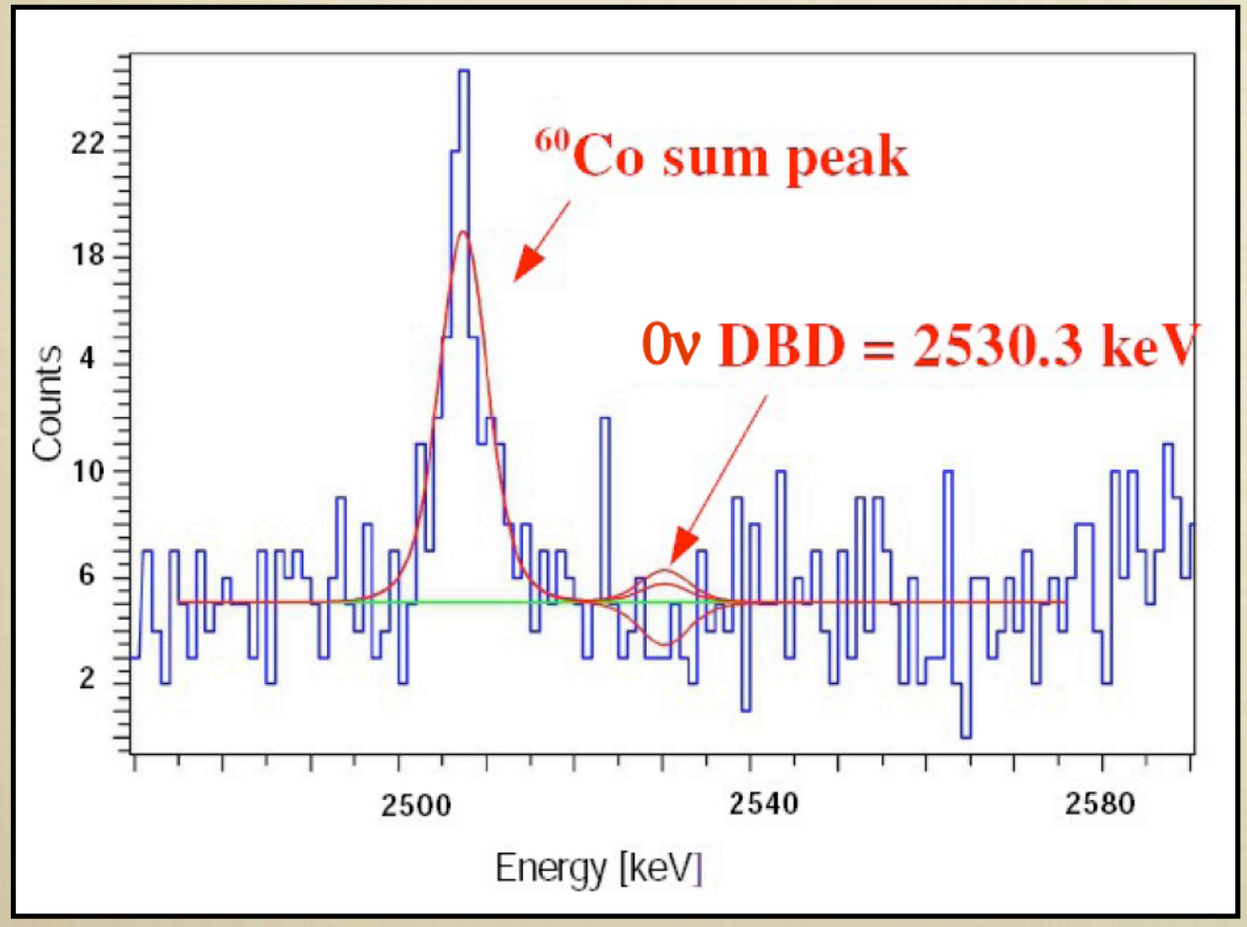


<u>Liquid Scintillator</u>
CANDLES, CAMEO, SNO+

Diodes & Bolometers

- Impressive energy resolution: <1% FWHM @ Q
- High efficiency: >75 %

- No extra handles.
- Expensive enrichment.
- Challenging mass scalability.



CUORICINO spectrum.

- **Ge diodes:** Majorana, GERDA
- **Te bolometer:** Cuore
- **Cd diodes:** COBRA

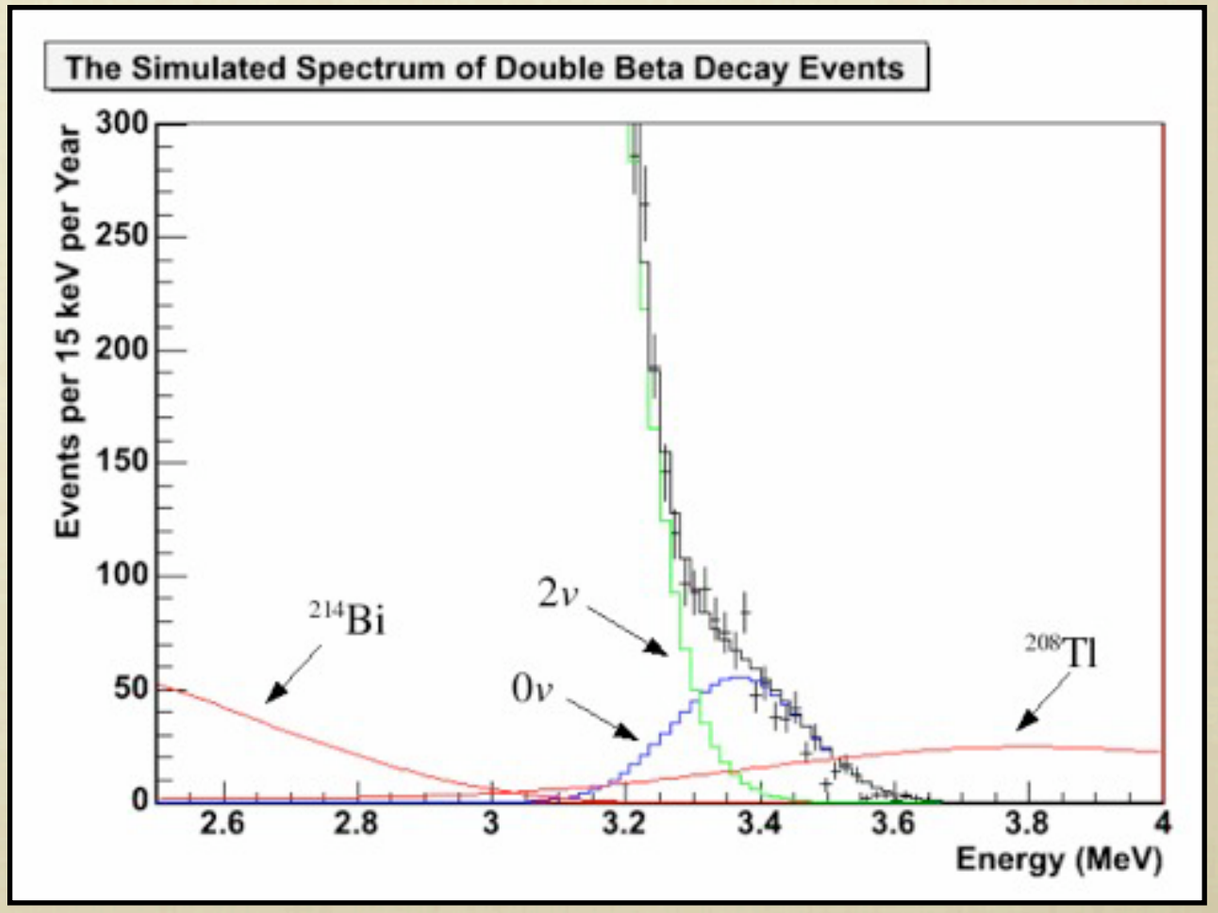
Liquid scintillator

- Large masses.
- High efficiency: >85%

- Poor energy resolution: ~8% FWHM @ 1MeV
- No extra handles.

- CAMEO (Cd)
- CANDLES (Ca)
- SNO+ (Nd)

SNO+ simulated spectrum.



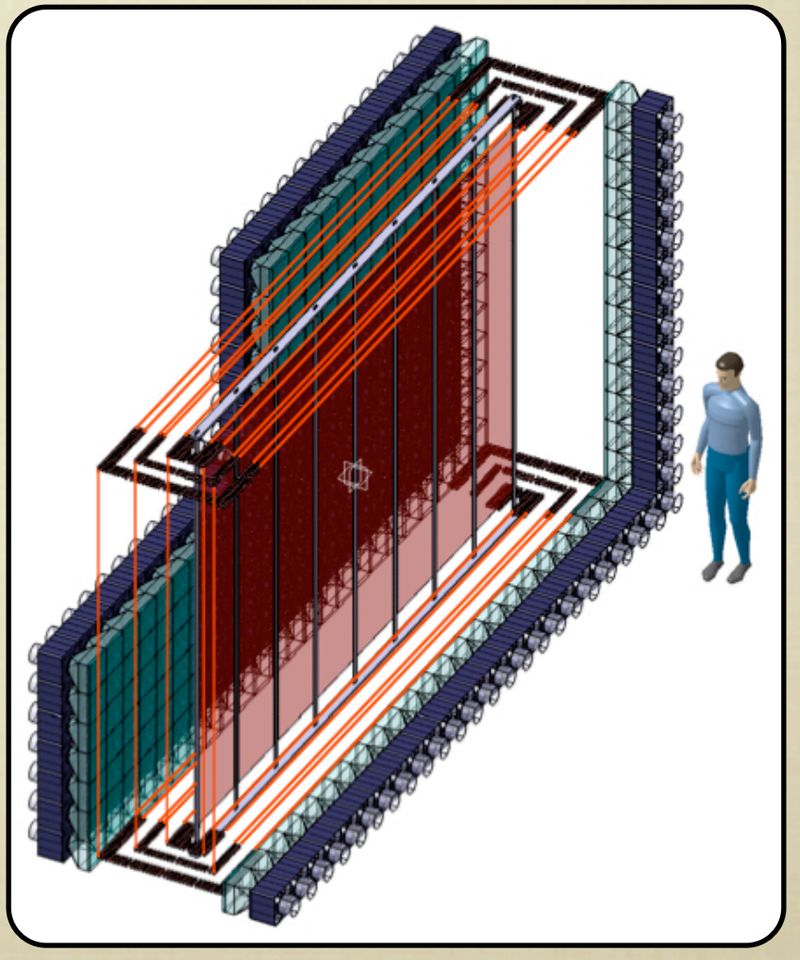
Tracko-calo

- Event kinematics: *measurement* of backgrounds.
- Any isotope can be studied.

- Poor energy resolution: >8% @ 1 MeV
- Modest efficiency: ~40%
- Very difficult scalability.

<u>SuperNEMO</u>

- Only next-generation tracko-calo experiment.
- Modular design:
  - + Source foil: 3×4 m^2, 40 mg/cm^2 (~5 kg).
  - + Tracking chamber: Wires in geiger mode.
  - + Calorimeter: Plastic scintillator.



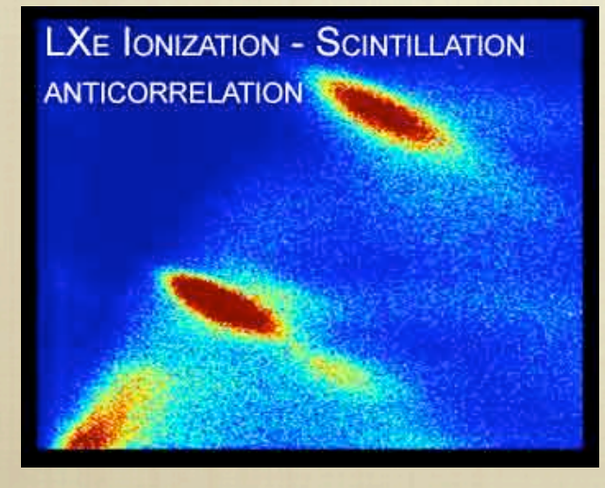
LXe TPCs

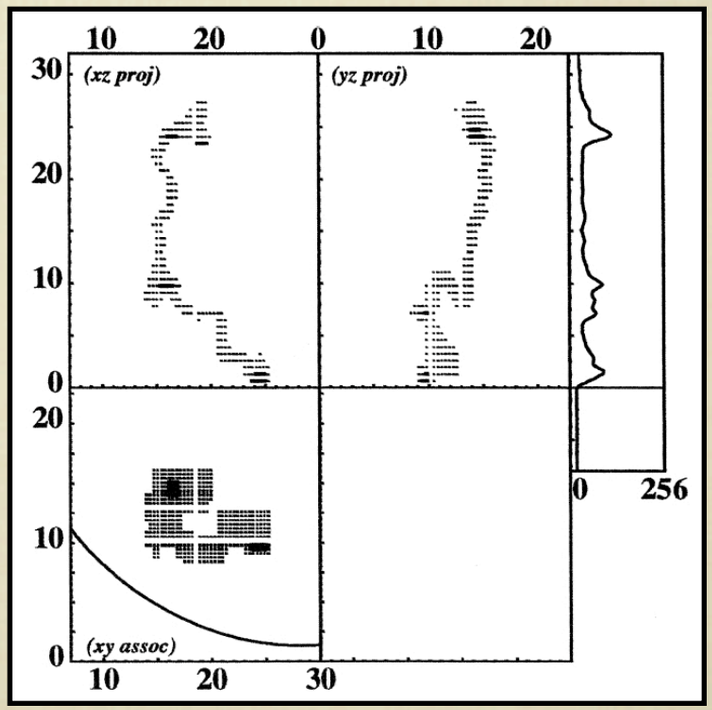
- Mass scalability.
- Ba+ tagging.

- Modest energy resolution.
- Lost of tracking capabilities.
- Engineering difficulties (tagging + cryogenics).

EXO

- Control backgrounds using Ba+ tagging.
- EXO-200 without Ba+ tagging.





Gotthard GXe TPC tracks.

Pros & Cons

Technique	Resolution	Efficiency	Mass scalability	Kinematics	Extra handles	Isotope
Semiconductors Bolometers	⊕	⊕	⊙	⊖	⊖	⊙
Liq. scintillator	⊖	⊕	⊕	⊖	⊖	⊕
Tracko-calo	⊖	⊙	⊖	⊕	⊙	⊕
LXe TPC	⊖	⊕	⊕	⊖	⊕	⊙
GXe TPC	⊕	⊕	⊕	⊕	⊕	⊙

Conclusions

- Double beta decay experiments will shed light on several fundamental questions of neutrino physics.

- Current generation of experiments will explore degenerate region of neutrino masses.

- None of the techniques has demonstrated so far to be able to explore the inverse hierarchy. New ideas are needed!

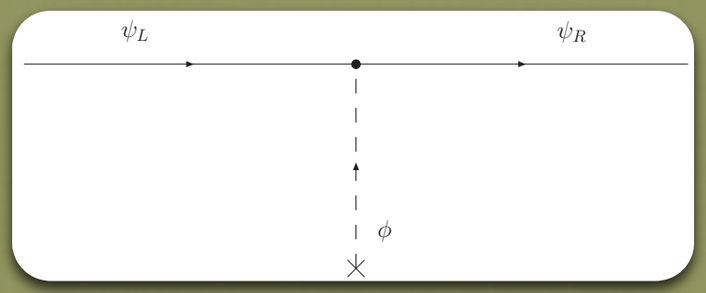
Backup slides

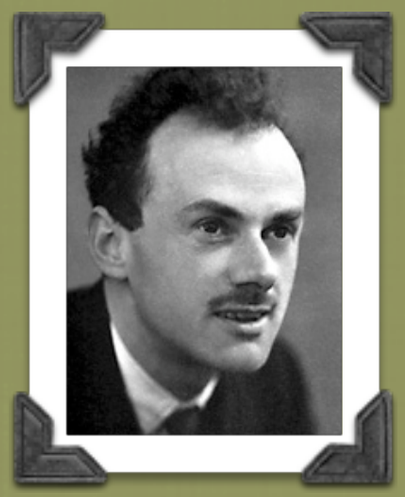
Massive neutrinos

Dirac neutrino

$$\lambda \bar{\psi}_R \phi \psi_L \xrightarrow{\text{SSB}} \lambda \upsilon \bar{\psi}_R \psi_L$$

$$m_\nu \equiv \lambda \upsilon$$





Lepton number conservation

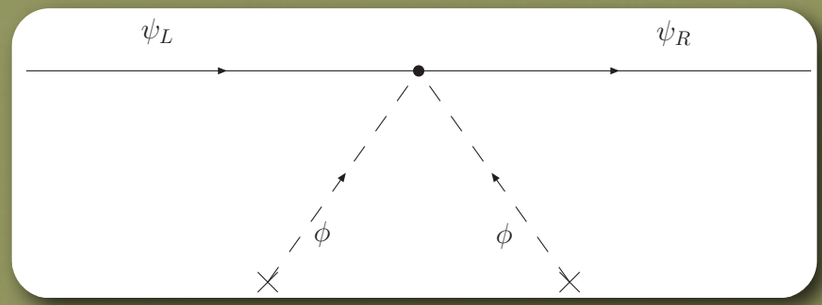
Hierarchy problem

Why **λ** is so small for neutrinos compared to the other fermions?

Majorana neutrino

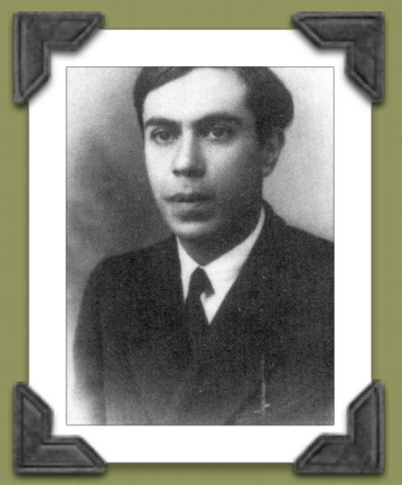
$$\frac{1}{\Lambda}(\bar{\psi}_L \phi)(\phi^T \psi_L^c) \xrightarrow{\text{SSB}} \frac{\lambda \upsilon^2}{\Lambda} \bar{\psi}_L \psi_L^c$$

$$m_\nu \equiv \lambda \frac{\upsilon^2}{\Lambda}$$



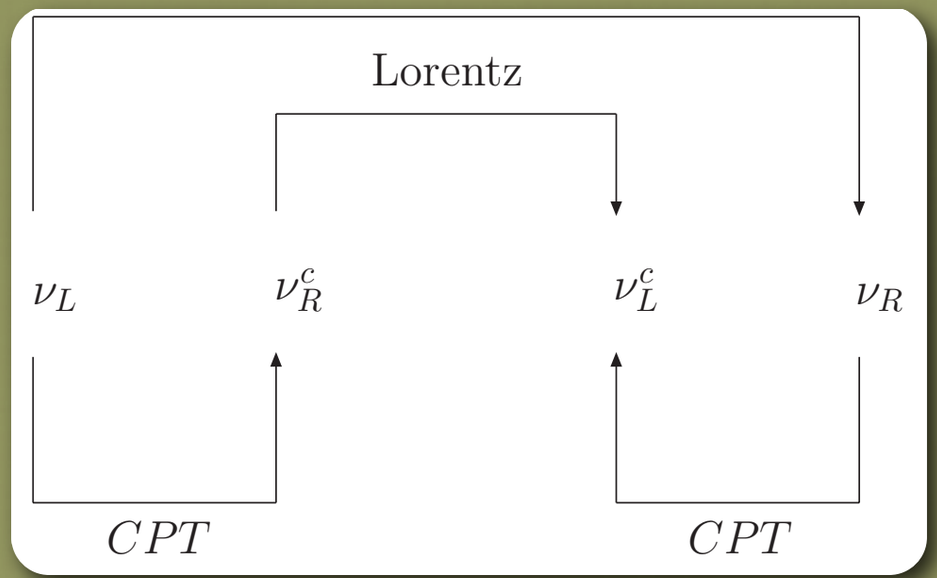
Λ → new physics scale

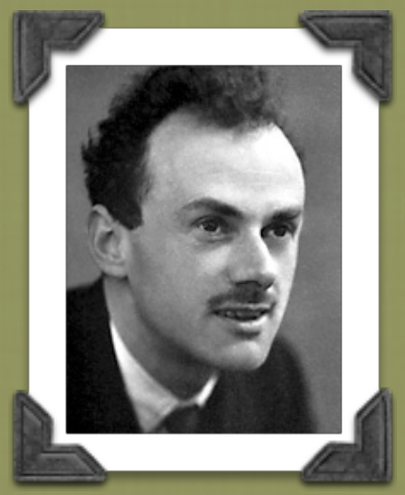
Λ very large → neutrino mass very small



Particle/Antiparticle nature

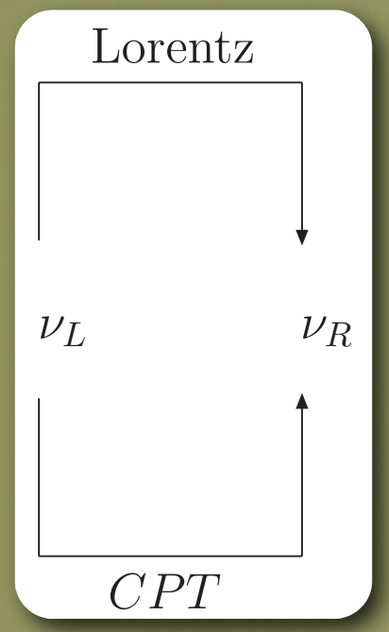
Dirac neutrino



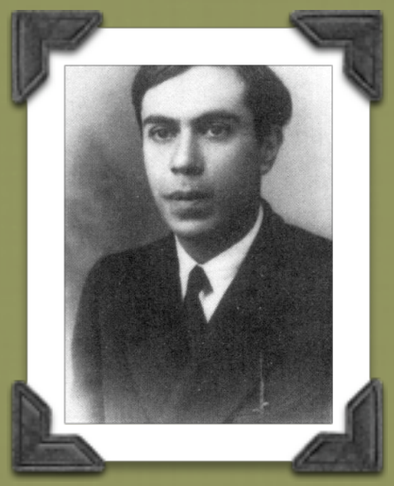


neutrinos are like the
other fermions
(four distinct states)

Majorana neutrino



neutrino = antineutrino
(two distinct states)



Isotopes

Isotope	$Q_{\beta\beta}$ (keV)	i.a. (%)	$T^{2\nu}_{1/2}$ (y)	FN (10^{-24} meV$^{-1}\cdot$y^{-1})
^{48}Ca	4271 ± 4	0.187	$(4.2 \pm 1.2) \times 10^{19}$	
^{76}Ge	2039.6 ± 0.9	7.8	$(1.3 \pm 0.1) \times 10^{21}$	0.4
^{82}Se	2995 ± 6	9.2	$(9.2 \pm 1.0) \times 10^{19}$	1.3
^{100}Mo	3034 ± 6	9.6	$(8.0 \pm 0.6) \times 10^{18}$	1.4
^{116}Cd	2802 ± 4	7.5	$(3.2 \pm 0.3) \times 10^{19}$	1.1
^{130}Te	2528.8 ± 4	33.8	$(2.7 \pm 0.1) \times 10^{21}$	1.4
^{136}Xe	2479 ± 8	8.9	$> 8.1 \times 10^{20}$ (90% CL)	0.8
^{150}Nd	3367.1 ± 2.2	5.6	$(7.0^{+11.8}_{-0.3}) \times 10^{18}$	13.8

Data for FN from V. A. Rodin *et al.*, arXiv: 0706.4304 [nucl-th]