Neutrinoless double beta decay

Schule für Astroteilchenphysik

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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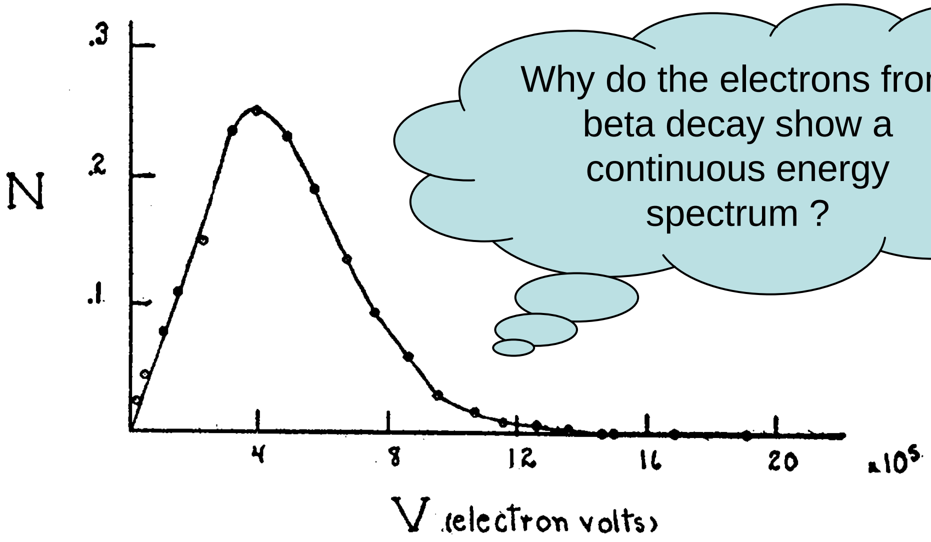
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Agenda

- **What is (neutrinoless) double beta decay ?**
- What can a measurement of the $0\nu\beta\beta$ half-life tell us ?
- What are the basic requirements for an experiment ?
- How do some experiments measure ?

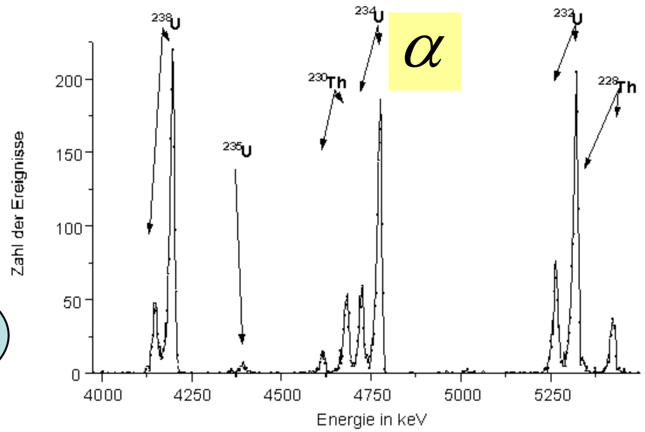
The problem with the beta decay in 1930

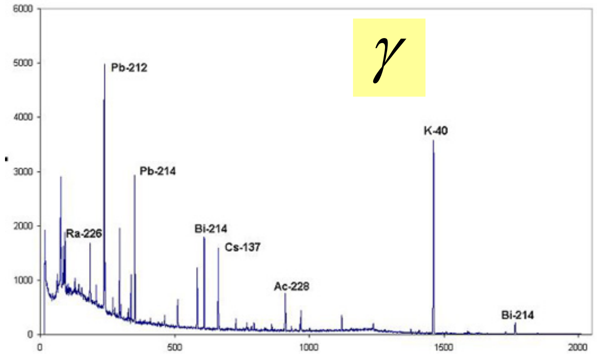
Thinking in 1930: $${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^{-}$$



Why do the electrons from beta decay show a continuous energy spectrum ?

FIG. 5. Energy distribution curve of the beta-rays.





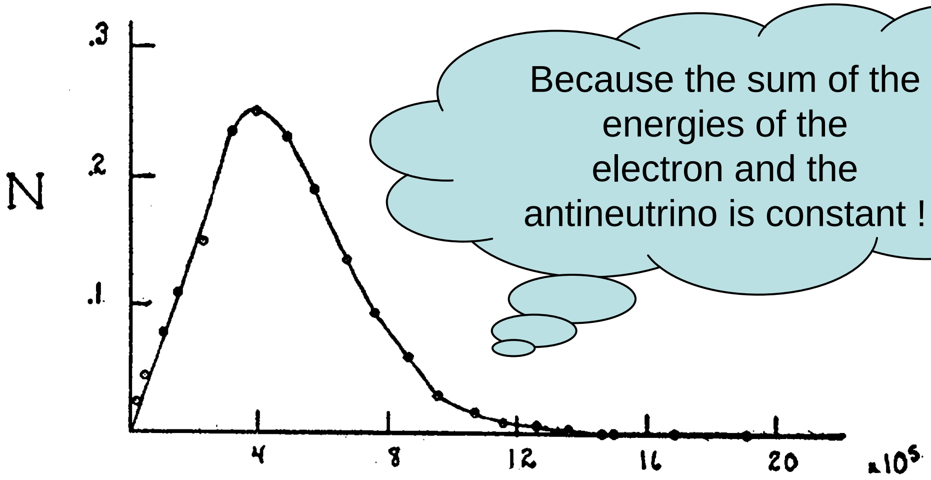
Electron energy spectrum: F. A. Scott, Phys. Rev. 48, 391 (1935)

The solution

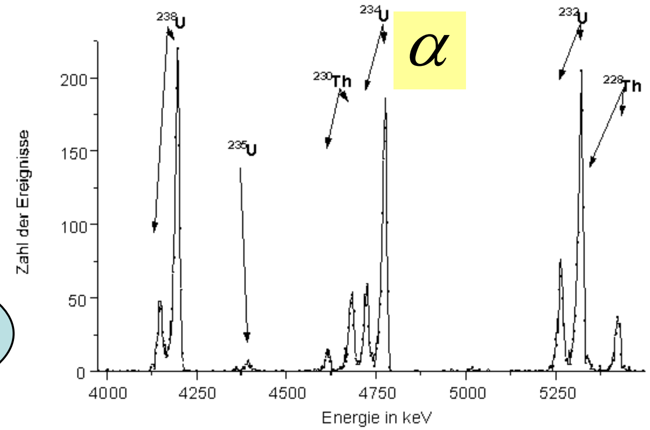
Today:

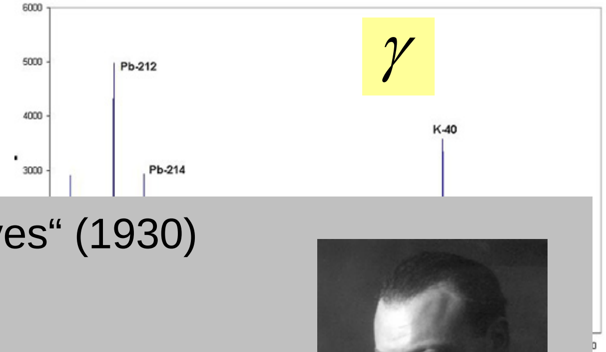
$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^{-} + \overline{\nu}_{e} $$

$$ n \rightarrow p + e^{-} + \overline{\nu}_{e} $$



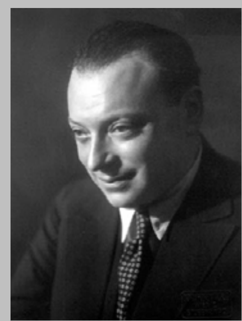
Because the sum of the energies of the electron and the antineutrino is constant !





Wolfgang Pauli in his famous letter to the „group of the radioactives“ (1930)

Liebe radioaktive Damen und Herren,
[…] Das kontinuierliche Betaspektrum wäre dann verständlich unter der Annahme, dass beim Betazerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist. […]
Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen mag […] Aber nur wer wagt, gewinnt […] Also, liebe Radioaktive, prüfet und richtet.

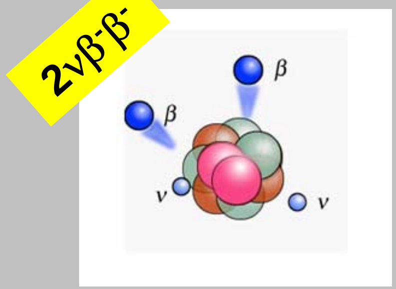


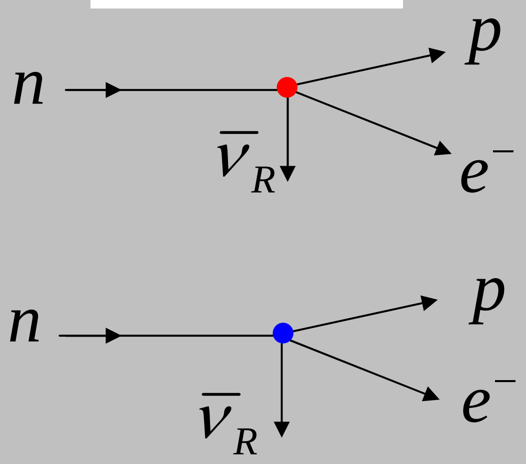
$2\nu\beta^-\beta^-$ and $0\nu\beta^-\beta^-$: two forms of double beta decays

Neutrino accompanied

Exists

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

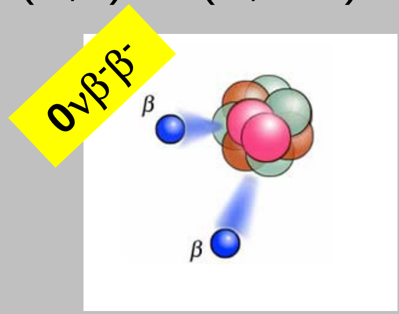


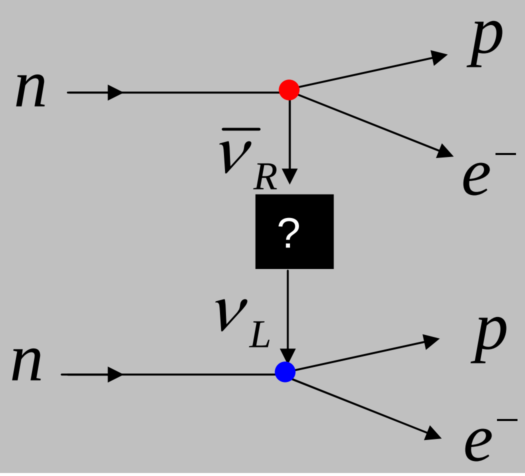


Neutrinoless

???

$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$



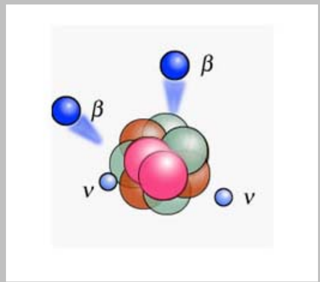


Double beta decays ($2\nu\beta^-\beta^-$ and $0\nu\beta^-\beta^-$)

$2\nu\beta\beta$: Neutrino accompanied

Exists

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

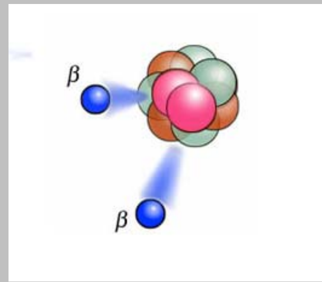


- Does NOT violate Lepton-number-conservation
- Is an allowed second order process in the SM
- Is possible with massless or massive Dirac or Majorana neutrinos
- Has been observed in a number of experiments/nuclei

$0\nu\beta\beta$: Neutrinoless

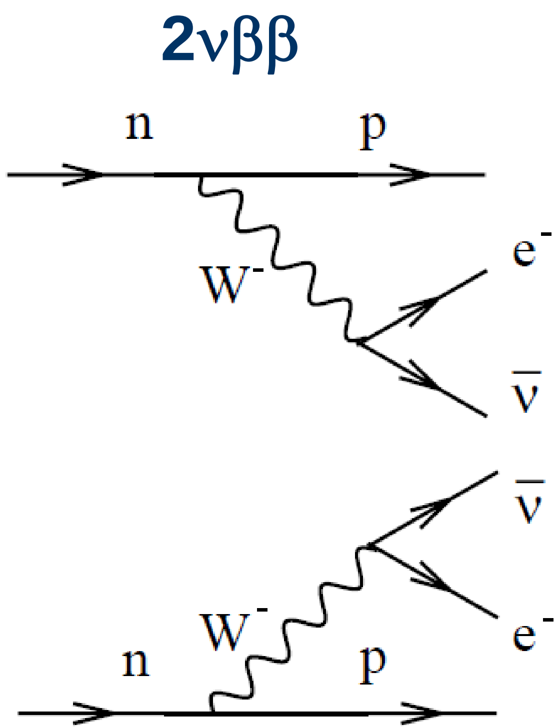
???

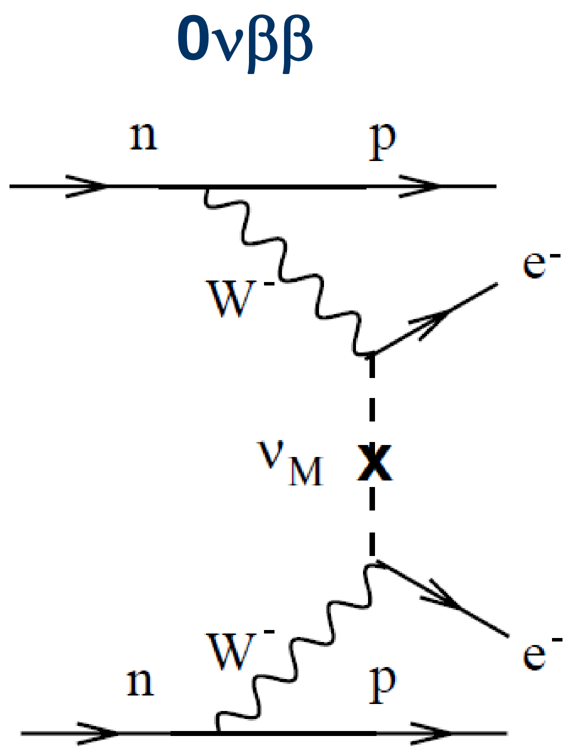
$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$



- Violates Lepton-number-conservation by $\Delta L=2$
- Is NOT allowed in the SM
- Requires non-zero rest mass (already prooved)
- Only possible if neutrino is its own antiparticle (**Majorana-particle**)

Generic diagrams





Schechter-Valle theorem (1982)

- Independent of the exact processes in the „BLACK BOX“, the appearance of the 0νββ decay implies the existence of an effective Majorana mass term

- This means: if 0νββ exists, neutrinos are Majorana particles

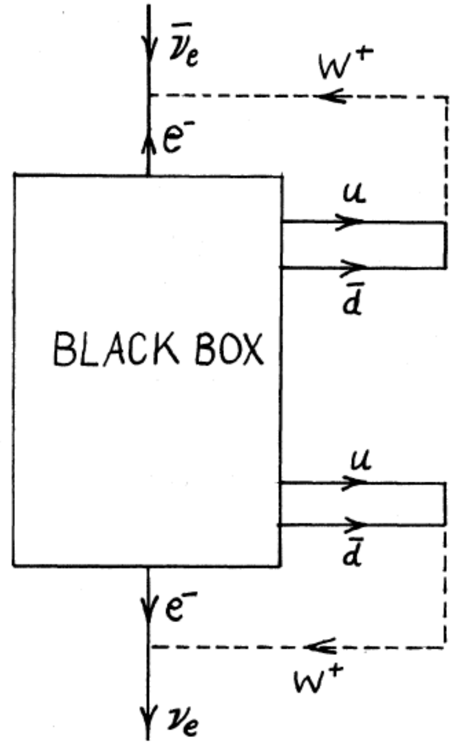
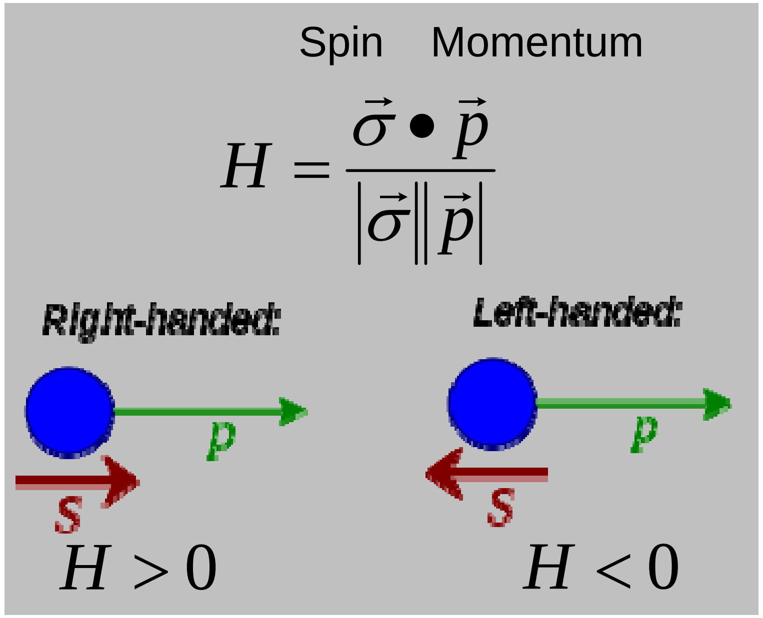
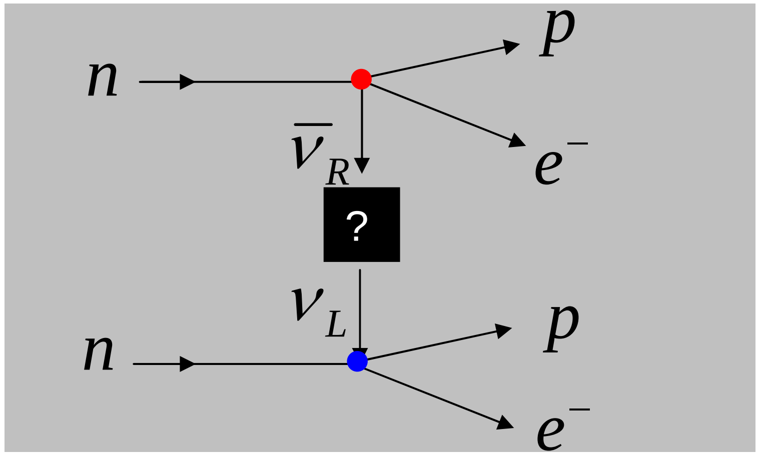


FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

Motivation of the non-zero rest mass needed for 0νββ



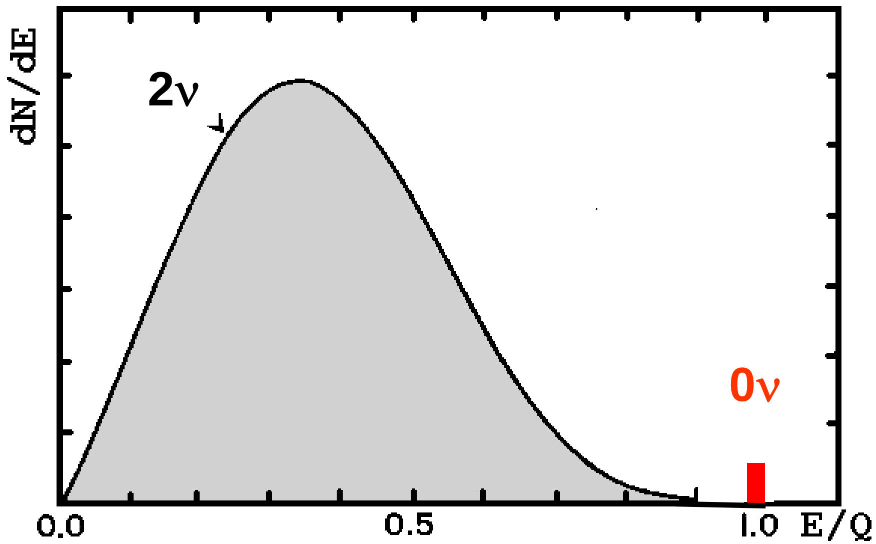


- Weak interaction couples only to (left/right)-handed (particles/anti-particles)
- Helicity not well defined for a massive particle

- Neverthless the following arguments are suggestive:
  - Emitted anti-neutrino ● has mass
  - A „virtual“ Lorentz transformation into a „faster“ system can be performed
  - Orientation of momentum is reversed in this system
  - Helicity changes sign
  - „Conversion“ from right-handed ● to left-handed particle ● (here I mix helicity with chiriality, which is in principle not correct)

How can we see 0νββ ?

Schematic sum energy spectrum of the 2 electrons in 2νββ and 0νββ



- Rate of 2νββ is several orders of magnitude higher than the rate of 0νββ
- The relation depends for example on the effective neutrino mass, the NME and phase space volume
- For sensitivity to $<m_{\beta\beta}> = 100$ meV:
  $T_{1/2}$ between 10^{26} - 10^{27} a
  (age of the universe (WMAP): 1,37 * 10^{10} a)

Half life/ Rate and effective Majorana mass

Half life: $T_{1/2}^{0\nu\beta\beta} \propto \frac{1}{<m_{\beta\beta}>^2}$

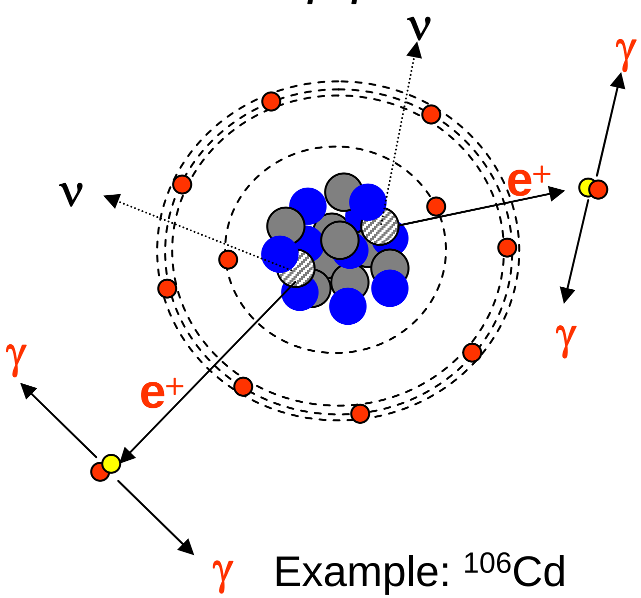
Decay rate: $\Gamma_{1/2}^{0\nu\beta\beta} = \left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} \propto <m_{\beta\beta}>^2$

Signature

- A peak in the sum energy spectrum at the full Q-value (for decays into ground state)
- Energy resolution should be as good as possible to keep contribution of **unavoidable** 2νββ decay in „peak region“ as low as possible

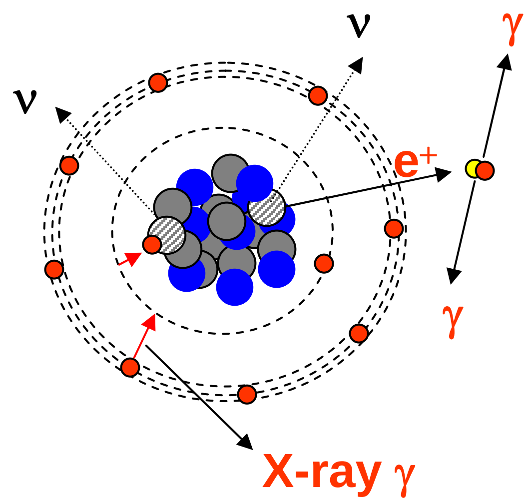
Other possible neutrino accompanied channels of second order

2ν $\beta^+\beta^+$



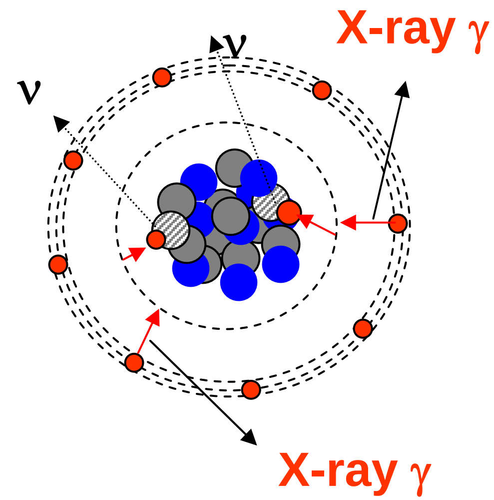
Example: ^{106}Cd

2ν β^+ / EC



Example ^{64}Zn

2ν EC / EC



Example: ^{106}Cd

In principle these decays could occur without neutrino emission, provided that neutrinos are of Majorana-type

History of double beta decay (1/2)

- 1935
  - Double beta decay considered in 1935 by Maria Goeppert-Mayer (suggestion of Eugene Wigner): estimated half-life of 10^{17} years with 2 electrons and 2 antineutrinos carrying 10 MeV
- 1937
  - Ettore Majorana developed theory in which neutrinos were their own antiparticles
  - Giulio Racah suggested test of Majorana theory with neutrinoless double beta decay
- 1939
  - Furry calculated approximate rates for $0\nu\beta\beta$
- 1950
  - First geochemical observation of $2\nu\beta\beta$ on ^{130}Te lead to half-life of

$$T_{1/2}^{\beta\beta}(^{130}Te) = 1.4 \times 10^{21}\, a$$

Ettore Majorana

History of double beta decay (2/2)

- 1952
  - Primakoff calculated electron-electron angular correlations and electron energy spectra for 2νββ and 0νββ
- 1955
  - Reaction (suggested by Majorana in 1937) was NOT found by Raymond Davis‘ chemical experiment $\bar{\nu}_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
- 1987
  - First laboratory observation of 2νββ by Elliot
- 2001
  - A subgroup of the Heidelberg-Moscow collaboration (Klapdor-Kleingrothaus et al.) reported observation of 0νββ in ^{76}Ge.
- Today:
  - Experiments like GERDA or MAJORANA are already on the way to test the claim.

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- **What can a measurement of the $0\nu\beta\beta$ half-life tell us ?**
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Neutrinos and their mixing

- Neutrino flavors $|\nu_\alpha\rangle$ (α=e,μ,τ) are mixtures of mass eigenstates $|\nu_i\rangle$ (i=1,2,3)

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

- Matrix U (Pontecorvo-Maki-Nakagawa-Sakata-Matrix, PMNS) can be parametrised as

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

where s_{ij} = sin (θ_{ij}) and c_{ij} = cos(θ_{ij}), θ_{ij} are the mixing angles,
δ is the Dirac-phase and α_{21}, α_{31} are the Majorana phases that are only relevant if neutrinos are of Majorana type

Some properties of neutrinos

Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m < 2$ eV (tritium decay)
Mean life/mass, $\tau/m > 300$ s/eV, CL = 90% (reactor)
Mean life/mass, $\tau/m > 7 \times 10^9$ s/eV (solar)
Mean life/mass, $\tau/m > 15.4$ s/eV, CL = 90% (accelerator)
Magnetic moment $\mu < 0.54 \times 10^{-10}\ \mu_B$, CL = 90% (solar)

Number of Neutrino Types

Number $N = 2.984 \pm 0.008$ (Standard Model fits to LEP data)
Number $N = 2.92 \pm 0.05$ (S = 1.2) (Direct measurement of invisible Z width)

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Mass, Mixing, and Oscillations" by K. Nakamura and S.T. Petcov in this *Review*.

$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$
$\Delta m^2_{21} = (7.59 \pm 0.20) \times 10^{-5}$ eV^2
$\sin^2(2\theta_{23}) > 0.92$ [i]
$\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 [j]
$\sin^2(2\theta_{13}) < 0.15$, CL = 90%

K. Nakamura *et al.* (Particle Data Group), JPG **37**, 075021 (2010) (URL: http://pdg.lbl.gov)

What can measured half-lifes of 0νββ tell us ?

2νββ

$$T_{1/2}^{2\nu} = \frac{1}{G_{2\nu}(Q_{\beta\beta}, Z)\left|M_{2\nu}\right|^2}$$

Phase space factor

Nuclear matrix element NME
(can be calculated with
good precision for 2νββ)

0νββ

$$T_{1/2}^{0\nu} = \frac{1}{G_{0\nu}(Q_{\beta\beta}, Z)\left|M_{0\nu}\right|^2 \left\langle m_{\beta\beta} \right\rangle^2}$$

NME introduces
uncertainties for 0νββ

Effective Majorana
mass shall be
determined

$$\left|\left\langle m_{\beta\beta} \right\rangle\right| \equiv \left| m_1 \left|U_{e1}\right|^2 + m_2 \left|U_{e2}\right|^2 e^{i\alpha_{21}} + m_3 \left|U_{e3}\right|^2 e^{i\alpha_{31}} \right|$$

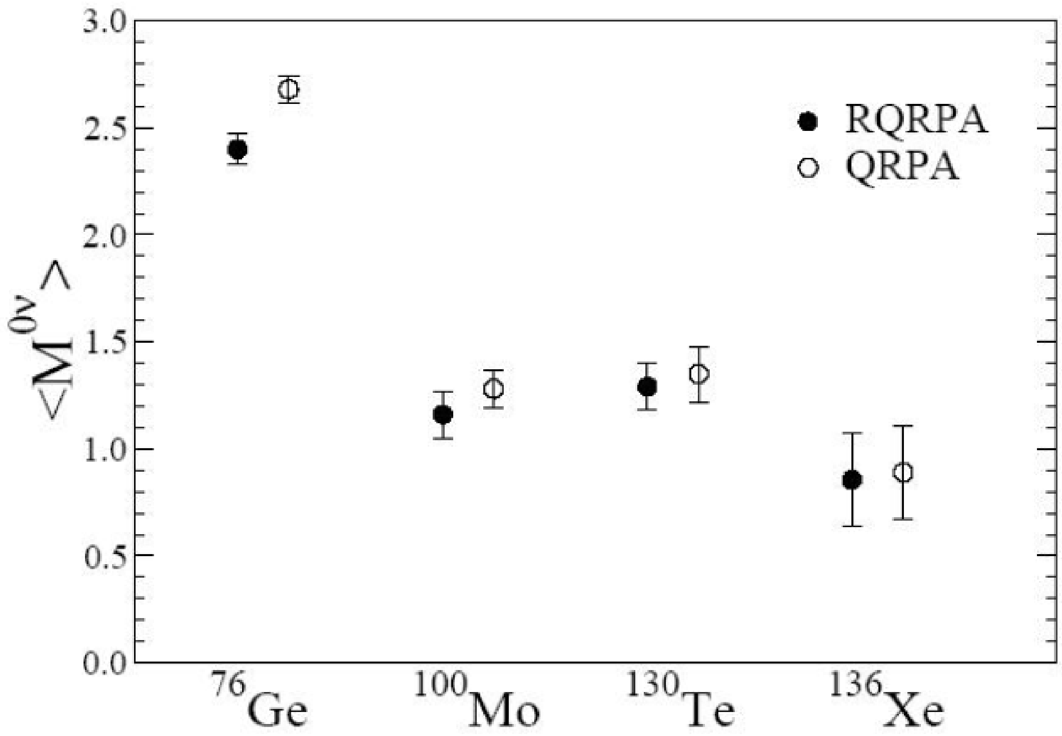
- Sensitive to Majorana phases
- Different from neutrino mass determined with beta decay experiments:

$$\left\langle m_\beta \right\rangle = \sqrt{\sum_{i=1}^{3} \left|U_{ei}\right|^2 m_i^2}$$

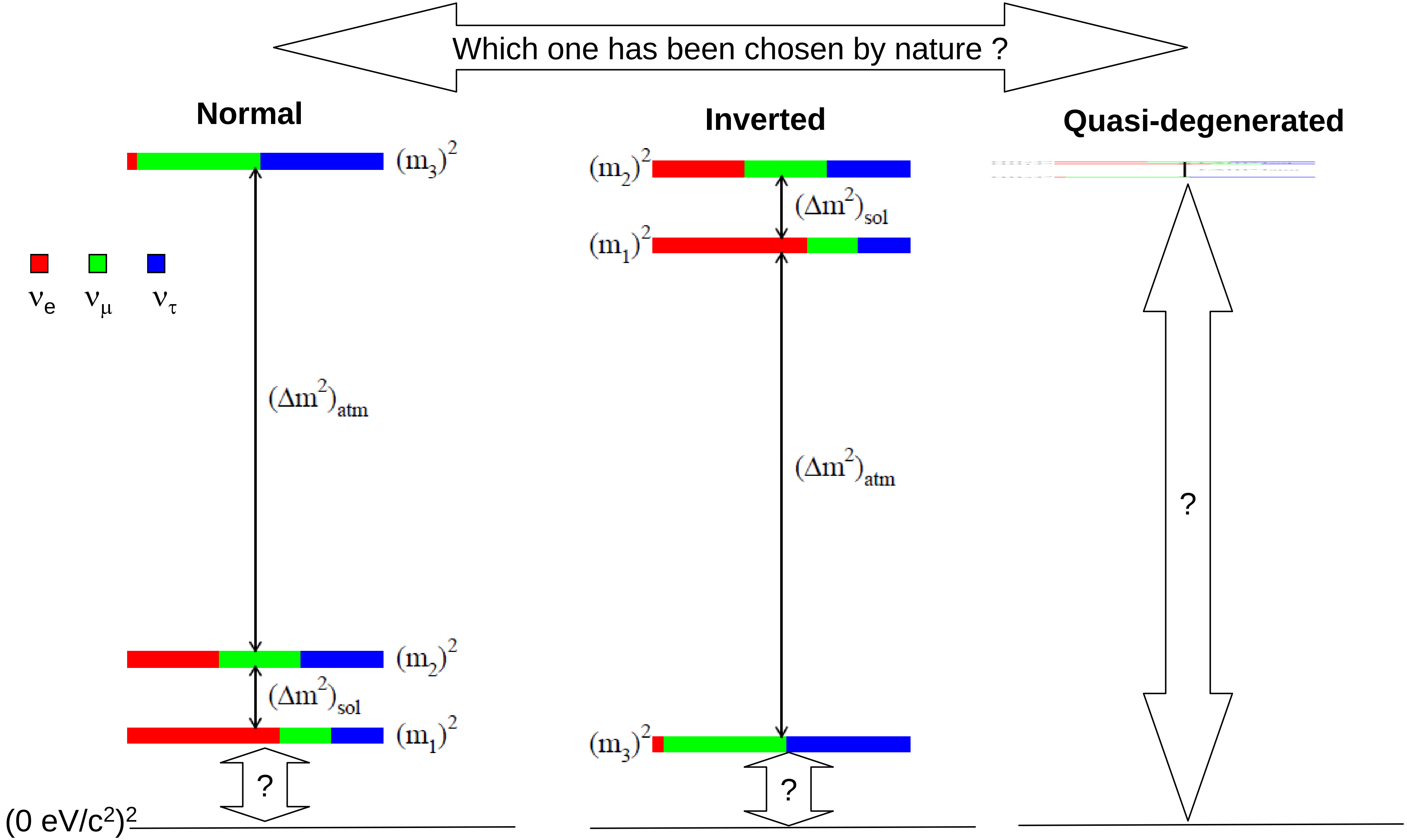
Nuclear matrix elements: sources of errors for calculations of the effective Majorana mass

- Use $2\nu\beta\beta$ data as a check for the calculation methods of NMEs
- Calculation methods:
  - Quasiparticle Random Phase Approximation (QRPA)
  - Renormalized QRPA
  - Shell Model
- Uncertainties in the NME of $0\nu\beta\beta$ at least 30 % (depending on isotope), but progress is being made
- Uncertainties depend on nucleus

$0\nu\beta\beta$



Neutrino mass hierarchies



Effective Majorana mass for the hierarchies

The effective Majorana mass is defined as $\left|\langle m_{\beta\beta}\rangle\right| \equiv \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} \right|$

Quasi-degenerate hierarchy $m_1 \approx m_2 \approx m_3 \equiv m_{\bar{\nu}_e}$

$$\left|\langle m_{\beta\beta}\rangle\right| \cong m_{\bar{\nu}_e} \left| \left(\cos^2\theta_{sol} + \sin^2\theta_{sol} \cdot e^{i\alpha_{21}}\right)\cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}} \right|$$

$\left|\langle m_{\beta\beta}\rangle\right|$ is sensitive to $m_{\bar{\nu}_e}$, α_{21} and α_{31}

Inverted hierarchy

$$\sqrt{\Delta m^2_{atm}}\cos 2\theta_{sol} \le \left|\langle m_{\beta\beta}\rangle\right| \cong \sqrt{\left(1 - \sin^2(2\theta_{sol})\sin^2\frac{\alpha_{21}}{2}\right)\Delta m^2_{atm}} \le \sqrt{\Delta m^2_{atm}}$$

Normal hierarchy

$$\left|\langle m_{\beta\beta}\rangle\right| \cong \left| \sqrt{\Delta m^2_{sol}}\cos^2\theta_{13}\sin^2\theta_{sol} + \sqrt{\Delta m^2_{atm}}\sin^2\theta_{13} e^{i\alpha_{31}} \right|$$

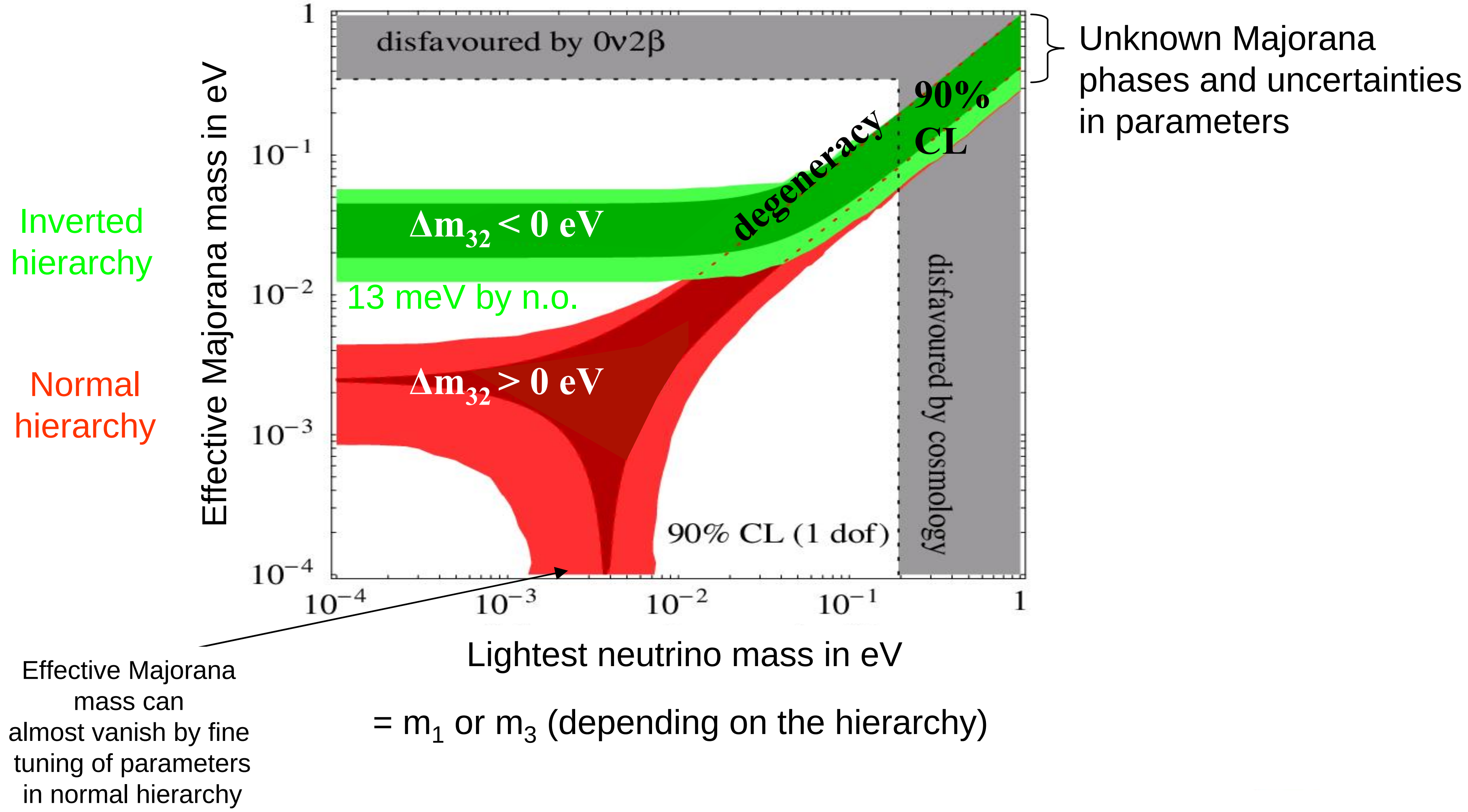
Estimated ranges

Quasi-degenerate: $\left|\langle m_{\beta\beta}\rangle\right| \ge 50 meV$

Inverted: $10 meV \le \left|\langle m_{\beta\beta}\rangle\right| \le 80 meV$

Normal: $few \cdot 10^{-4} eV \le \left|\langle m_{\beta\beta}\rangle\right| \le 8.5 meV$

The link between 0νββ and the neutrino mass hierarchy



= m_1 or m_3 (depending on the hierarchy)

F.Feruglio et al., Nucl. Phys. B 637(2002)

Dirac- and Majorana phases

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

Dirac-phase

- does affect neutrino oscillations
- can violate CP-invariance
- difficult to measure, but in principle possible with long baseline experiments

Majorana-phases

- do NOT affect neutrino oscillations
- can violate CP-invariance
- CP is NOT violated if $\alpha_{21}, \alpha_{31} \in \{0, \pm\pi\}$

Combination of

$\langle m_{\beta\beta} \rangle$ **and** $\langle m_{\beta} \rangle$

from 0νββ and beta decay experiments (like KATRIN) plus knowledge of mixing angles allow check of CP violation for neutrinos

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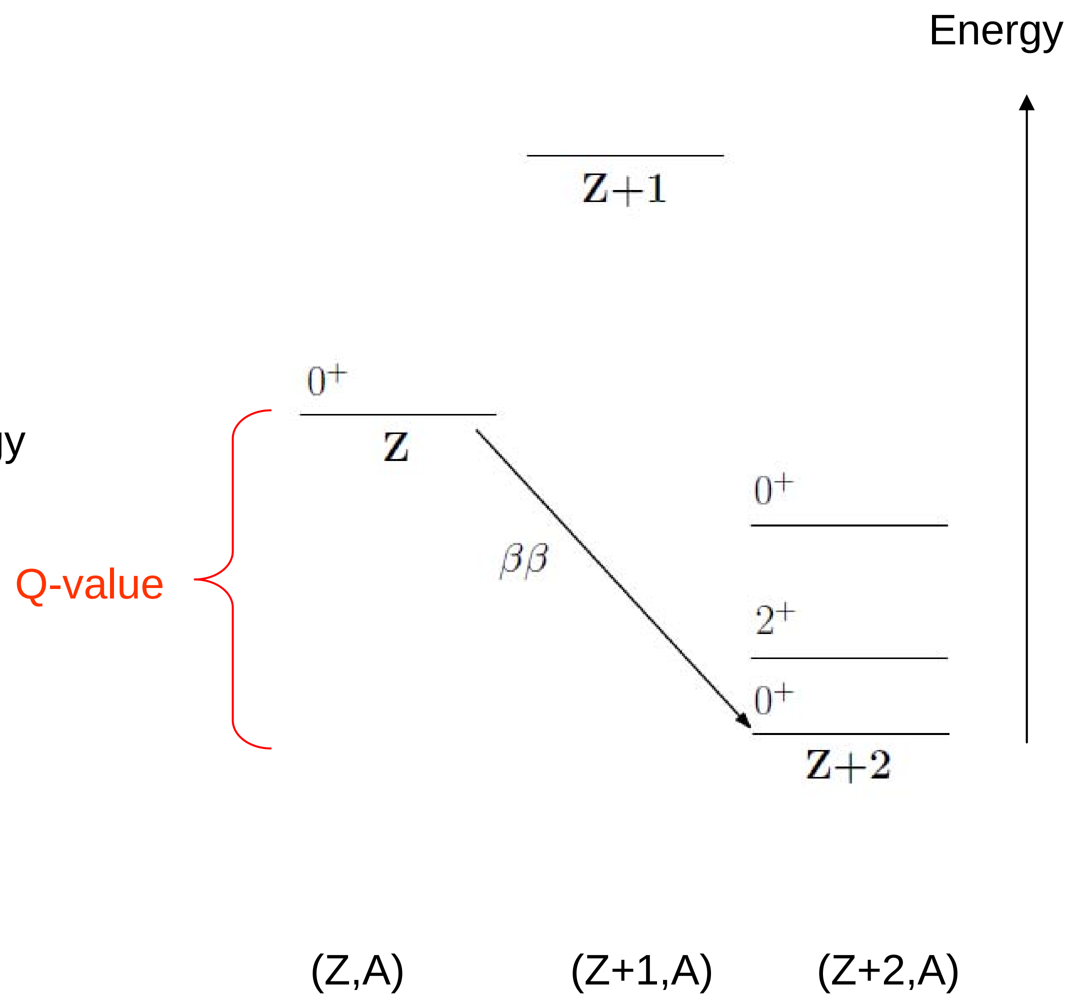
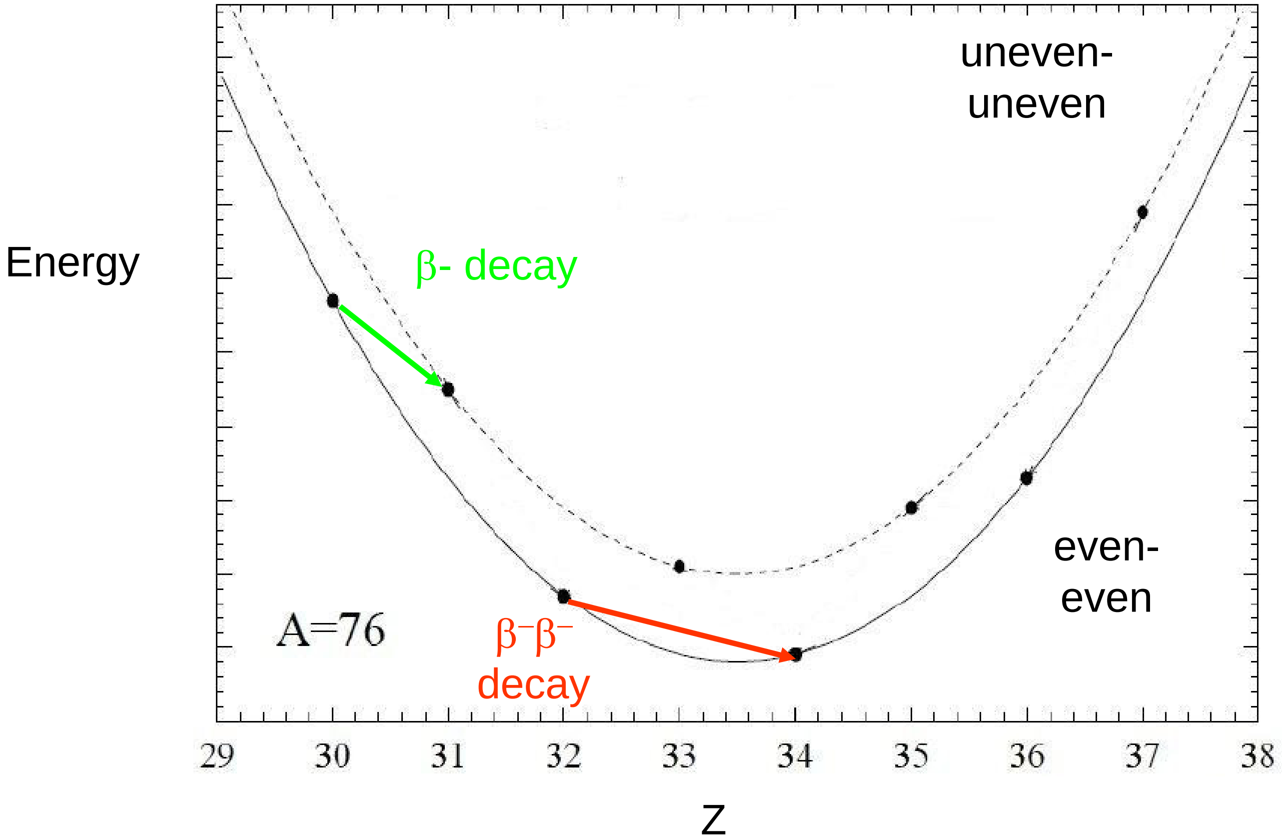
The „source“ nucleus selection

- Typical $0\nu\beta^-\beta^-$ or $2\nu\beta^-\beta^-$ nucleus is an even-even nulceus
- Pairing forces stronger than in (Z+1,A) neighbour, but weaker than in (Z+2, A) nucleus
- „Single beta decay“ is blocked by energy conservation
- There are only 35 candidates in the table of isotopes



The „source“ nucleus selection

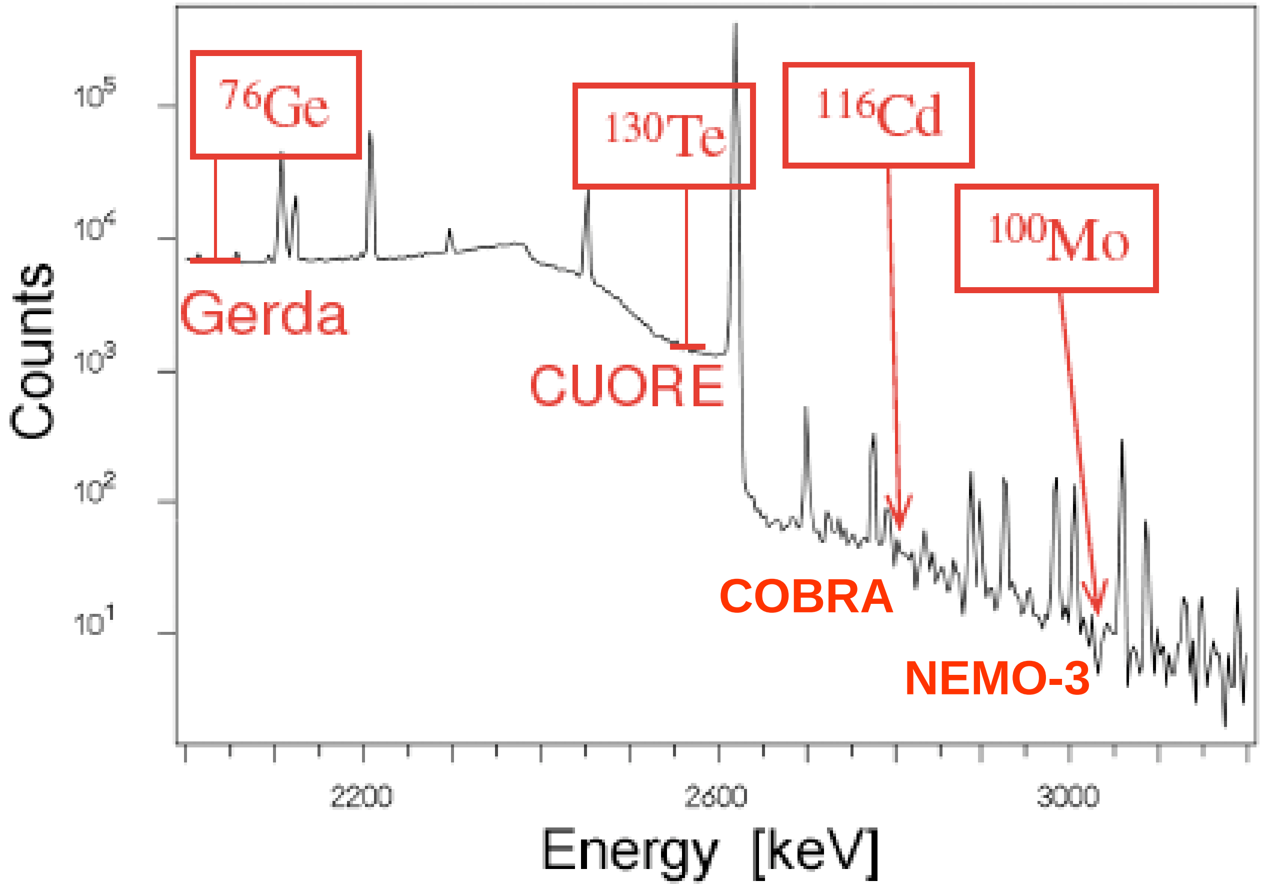
$$E_{\text{Bindung}} = \underbrace{a_V \cdot A}_{\text{Volume}} - \underbrace{a_O \cdot A^{\frac{2}{3}}}_{\text{Surface}} - \underbrace{a_C \cdot Z^2 A^{-\frac{1}{3}}}_{\text{Coulomb}} - \underbrace{a_S \cdot \frac{(N-Z)^2}{A}}_{\text{Symmetry N and Z}} + \underbrace{\begin{cases} +a_P \cdot A^{-\frac{1}{2}} & \text{für gg} - \text{Kerne} \\ 0 & \text{für ug und gu} - \text{Kerne} \\ -a_P \cdot A^{-\frac{1}{2}} & \text{für uu} - \text{Kerne} \end{cases}}_{\text{Pairing (Spin)}}$$



The „source“ nucleus - practical requirements

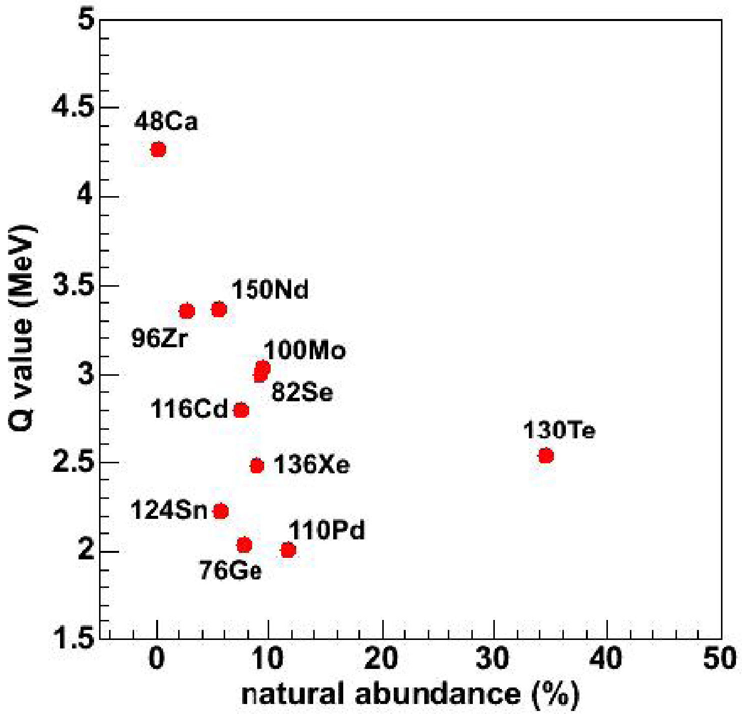
Wish	Good example
• Large natural abundancy: enrichment requires less process steps or no enrichment at all needed	• ^{130}Te (34.5%)
• Easy enrichment process	• ^{136}Xe
• Large Q-value: Phase space volume is proportional to Q^5 for $0\nu\beta\beta$ and so is the rate (statistics!)	• ^{48}Ca (Q=4.27 MeV), ^{150}Nd (Q=3.37 MeV)
• Low background in „source volume“: chemically clean and no long-lived radioactive isotopes	• ^{136}Xe
• If source = detector: the material must give a detector with good energy resolution	• ^{76}Ge
• Q-value > 2.615 MeV: No background from γ-lines of nuclides in natural $^{235/238}$U- and ^{232}Th-decay chains	• ^{116}Cd (Q=2.81 MeV)

Background reduction if Q-value is larger than the highest γ energy in natural decay chains (^{208}Tl)



Some candidates for the source nucleus

Isotope	Q-value [keV]	Natural abundance [%]
Ca 48	4271	0.187
Ge 76	2039	7.8
Se 82	2295	9.2
Zr 96	3350	2.8
Mo 100	3034	9.6
Pd 110	2013	11.8
Cd 116	2809	7.5
Sn 124	2288	5.64
Te 130	2529	34.5
Xe 136	2479	8.9
Nd 150	3367	5.6

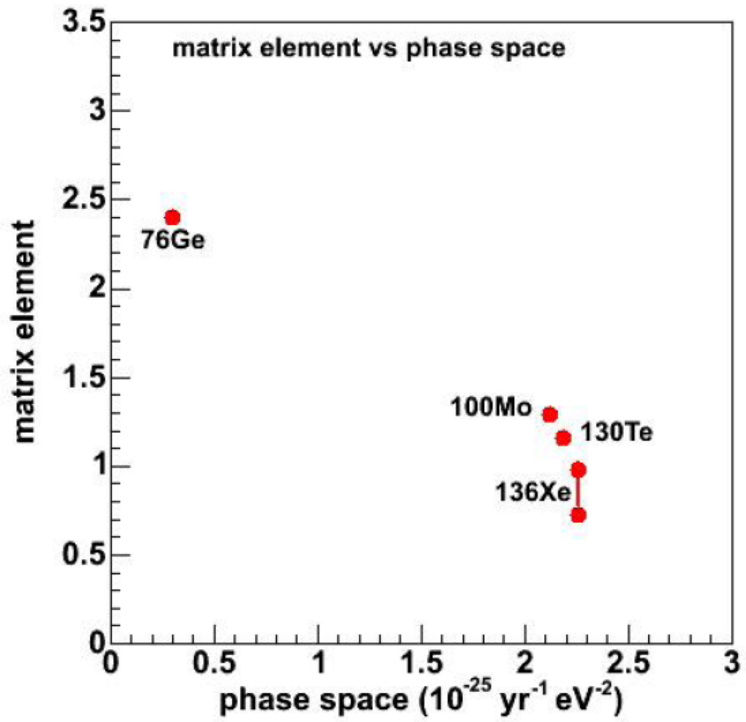


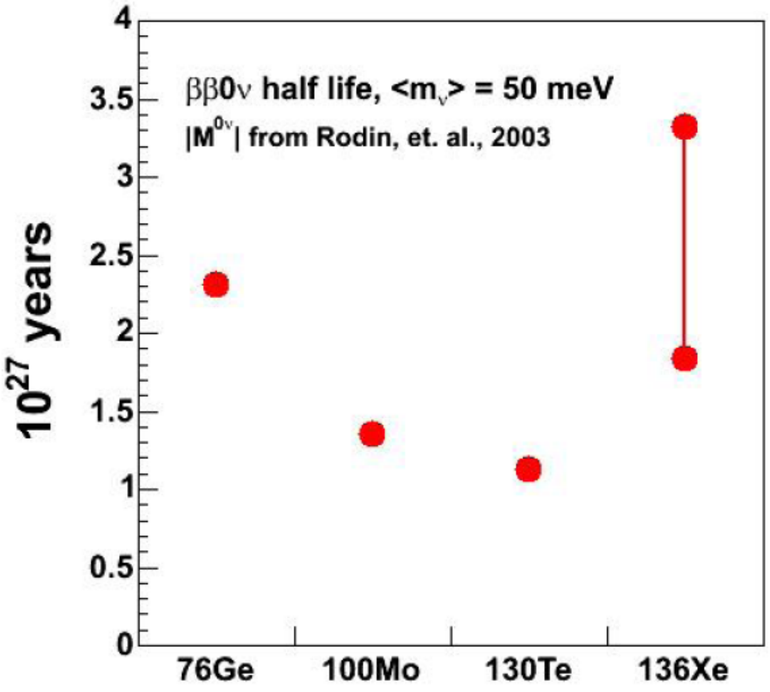
Material for semiconductor detectors (highlighted in green: Ge 76, Cd 116, Te 130)

Importance of the NME and the phase space

$$\Gamma_{1/2}^{0\nu} = G_{0\nu}(Q_{\beta\beta}, Z)\left|M_{0\nu}\right|^2\left|\langle m_{\beta\beta}\rangle\right|^2$$

Decay rate = Phase space volume X squared matrix element X squared effective Majorana mass





Current (2007) knowledge on 2νββ / 0νββ

2νβ⁻β⁻

Isotope	$T^{2\nu}_{1/2}$ (years)
^{48}Ca	$(4.2^{+2.1}_{-1.0}) \times 10^{19}$
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$
^{96}Zr	$(2.0 \pm 0.3) \times 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \times 10^{18}$
^{116}Cd	$(3.0 \pm 0.2) \times 10^{19}$
^{128}Te	$(2.5 \pm 0.3) \times 10^{24}$
^{130}Ba EC-EC(2ν)	$(2.2 \pm 0.5) \times 10^{21}$
^{130}Te	$(0.9 \pm 0.1) \times 10^{21}$
^{150}Nd	$(7.8 \pm 0.7) \times 10^{18}$
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$

low → ^{100}Mo

high → ^{128}Te

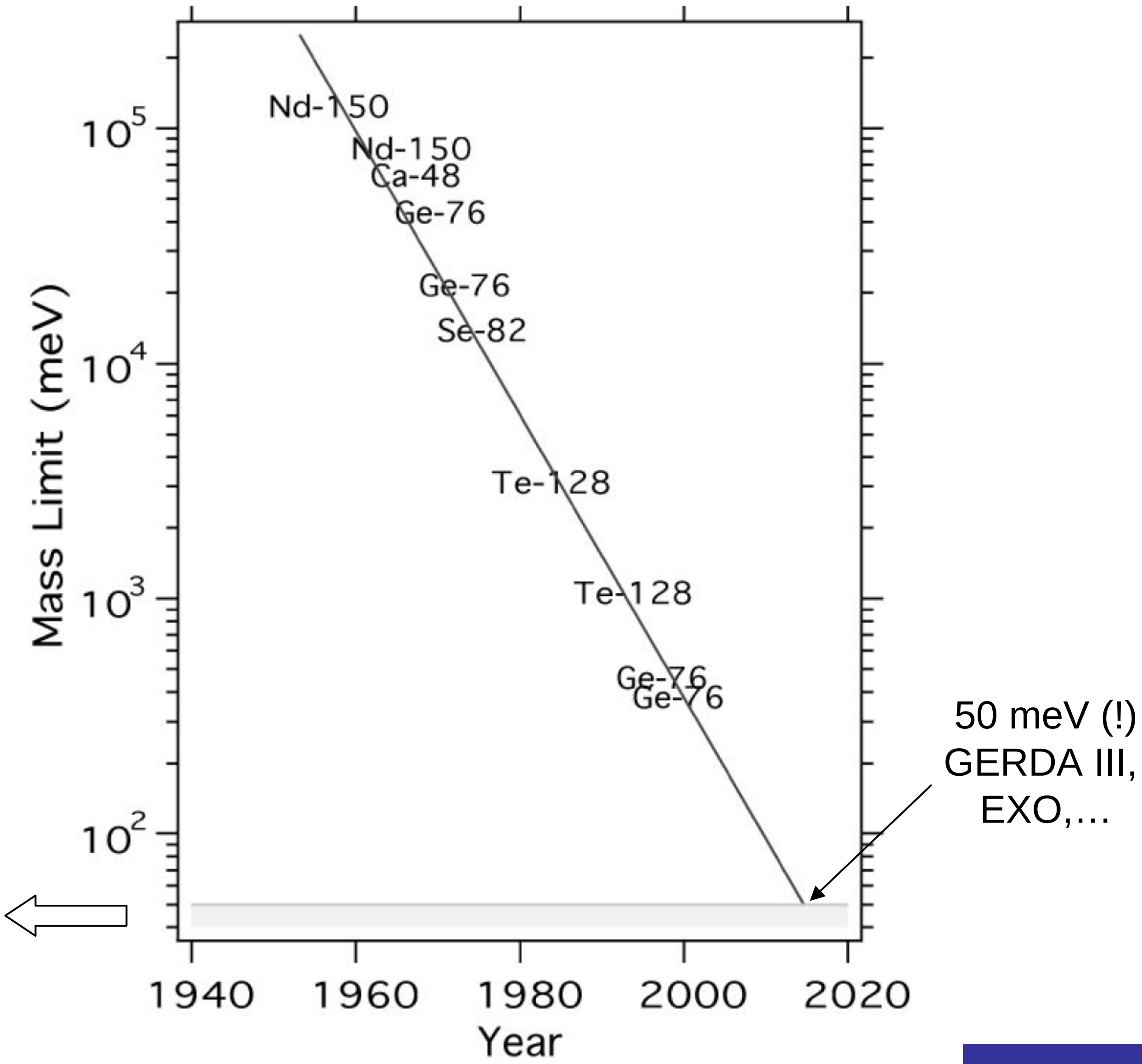
0νβ⁻β⁻

Highest limits

Isotope	Technique	$T^{0\nu}_{1/2}$
^{48}Ca	CaF_2 scint. crystals	$> 1.4 \times 10^{22}$ y
^{76}Ge	^{enr}Ge det.	$> 1.9 \times 10^{25}$ y
^{76}Ge	^{enr}Ge det.	$(2.23^{+0.44}_{-0.31}) \times 10^{25}$ y (1σ)
^{76}Ge	^{enr}Ge det.	$> 1.57 \times 10^{25}$ y
^{82}Se	Thin metal foils and tracking	$> 2.1 \times 10^{23}$ y
^{100}Mo	Thin metal foils and tracking	$> 5.8 \times 10^{23}$ y
^{116}Cd	$^{116}CdWO_4$ scint. crystals	$> 1.7 \times 10^{23}$ y
^{128}Te	geochemical	$> 7.7 \times 10^{24}$ y
^{130}Te	TeO_2 bolometers	$> 3.0 \times 10^{24}$ y
^{136}Xe	Liq. Xe scint.	$> 4.5 \times 10^{23}$ y[a]
^{150}Ne	Thin metal foils and tracking	$> 3.6 \times 10^{21}$ y

Frank T. Avignone III et al., http://arxiv.org/abs/0708.1033v2

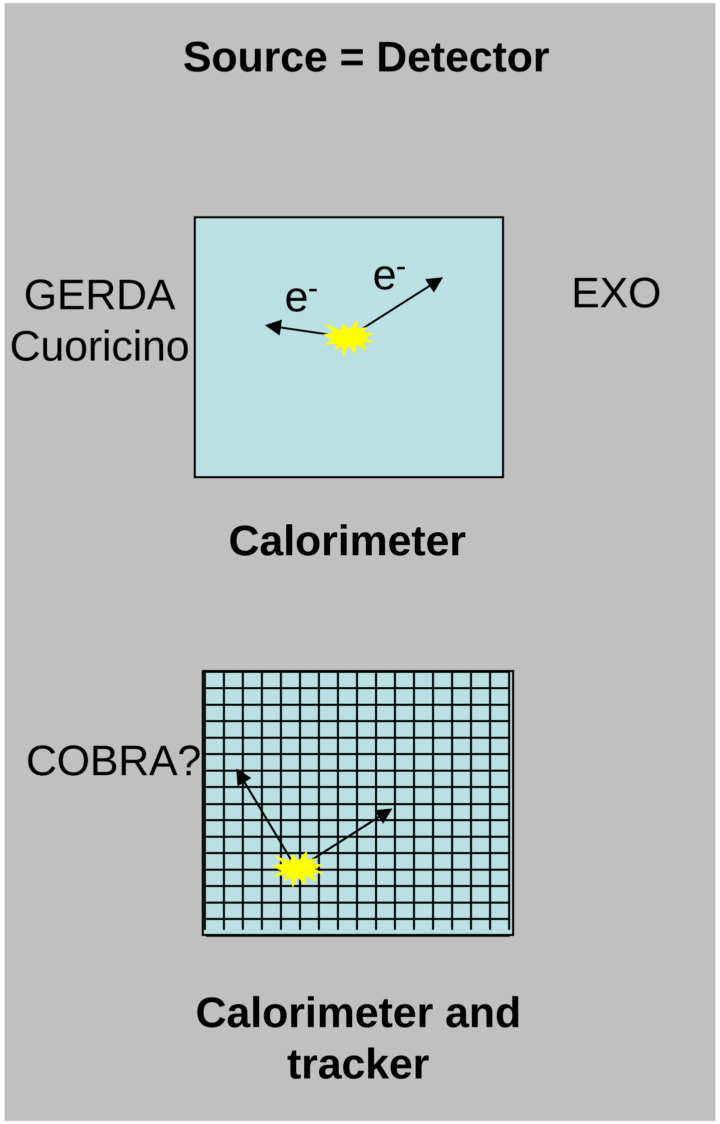
Moore‘s law of 0νββ searches

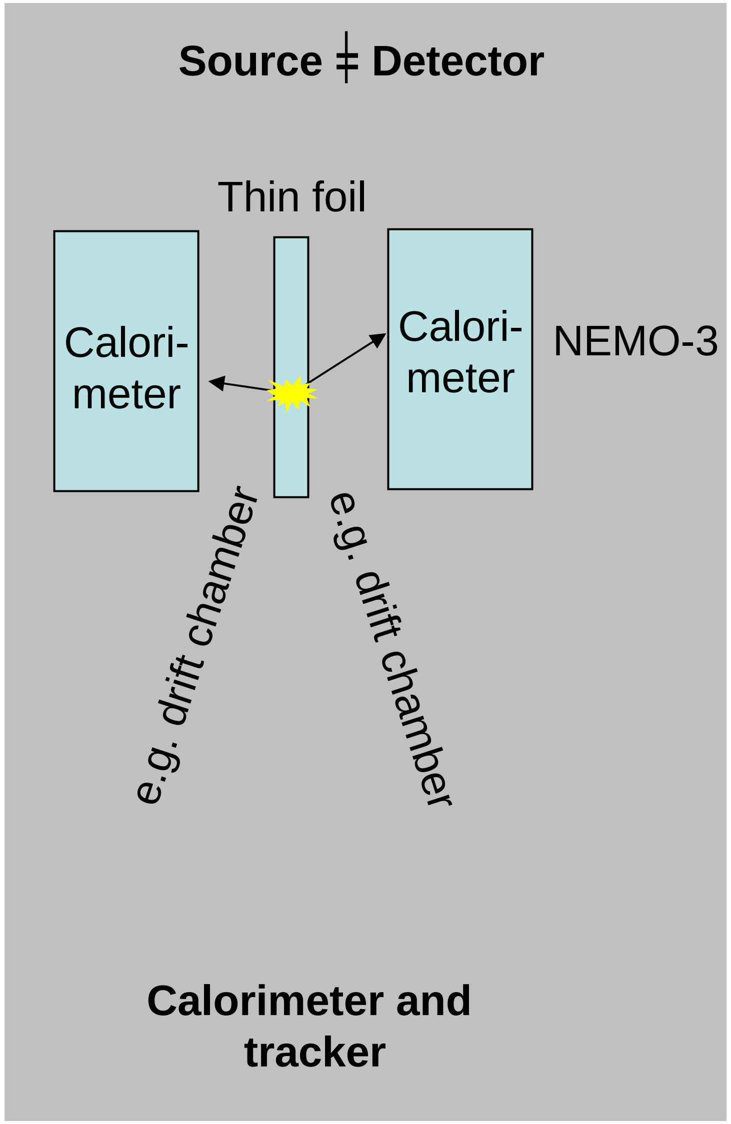


$\sqrt{\Delta m^2_{atm}}$

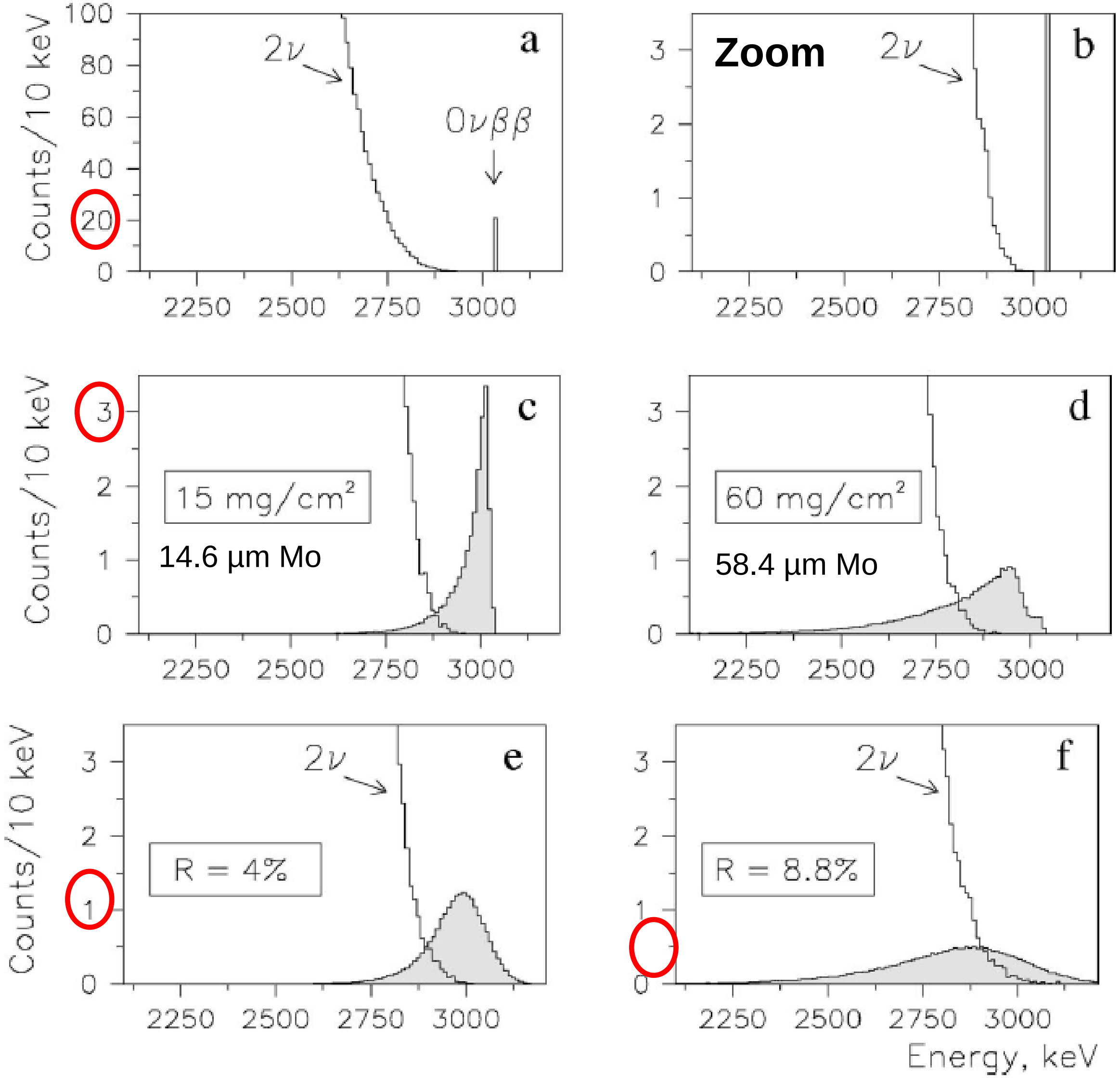
Modified from S. Elliott et al., Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51, doi: 10.1146/annurev.nucl.52.050102.090641

Three experimental approaches





The impact of energy resolution: simulations for ^{100}Mo



„Active source"-detector

10 keV (=0.33 %)
energy resolution

Passive source + calorimeter

10 keV energy resolution
(=0.33 %)

15 mg/cm^2 foil and
4 % (e) / 8.8 % (f)
energy resolution

Agenda

- What is (neutrinoless) double beta decay ?
- What will a measurement of the $0\nu\beta\beta$ half-life tell us ?
- What are the basic requirements for an experiment ?
- **How do some experiments measure ?**

Future experiments (some already started)

Experiment	Isotope	Experimental approach
CANDLES	^{48}Ca	Several tons of CaF_2 crystals in Liquid scintillator
COBRA	^{116}Cd, ^{130}Te	420 kg CdZnTe semiconductors
CUORE	^{130}Te	750 kg TeO_2 cryogenic bolometers
DCBA	^{150}Nd	20 kg Nd layers between tracking chambers
EXO	^{136}Xe	1 ton Xe TPC (gas or liquid)
GERDA	^{76}Ge	$\sim$ 40 kg Ge diodes in LN_2, phase 3 with MAJORANA
MAJORANA	^{76}Ge	$\sim$ 180 kg Ge diodes, expand to larger masses
MOON	^{100}Mo	several tons of Mo sheets between scintillator
SNO+	^{150}Nd	1000 t of Nd-loaded liquid scintillator
'LNGS'	^{150}Nd	10 ton Nd-loaded liquid scintillator
SuperNEMO	^{82}Se(?), ^{150}Nd (?)	100-200 kg of Se or Nd foils between TPCs
KamLAND	^{136}Xe	300 kg (2013) , 1 ton (2015?) of Xe in liquid scintillator
XMASS	^{136}Xe	10 t of liquid Xe
NEXT	^{136}Xe	High Pressure Xe TPC

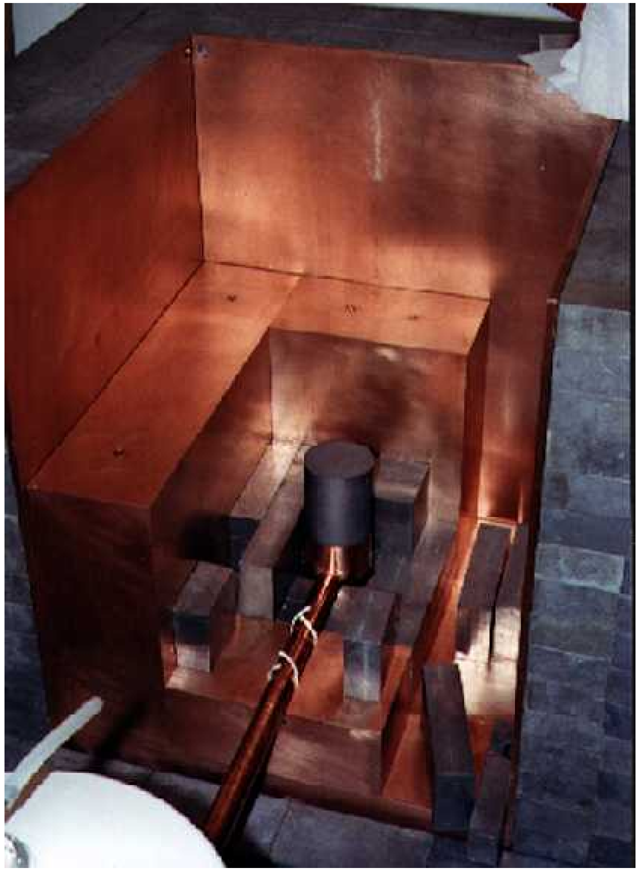
small scale experiments will expand, this is not a complete list !

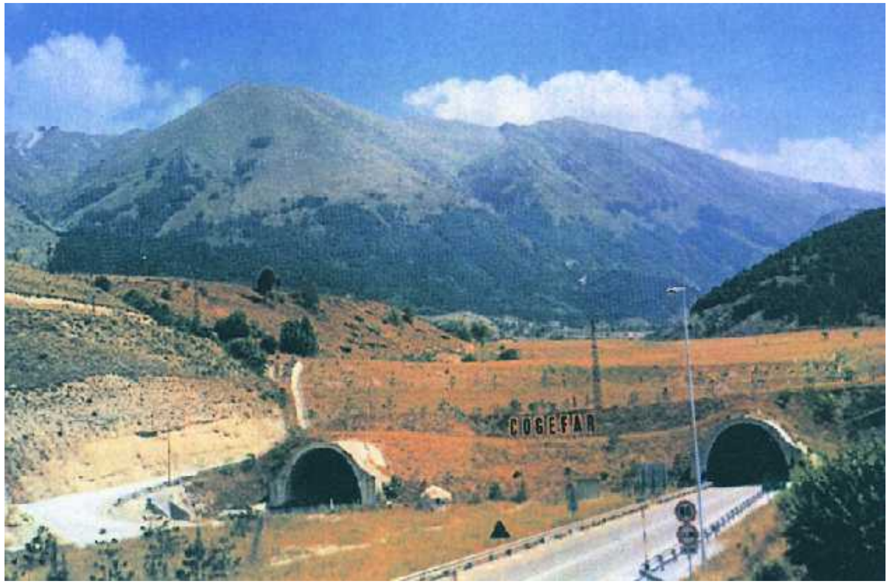
Some more details on experiment or predecessor experiment in this talk (red box: COBRA, CUORE, EXO, GERDA, SuperNEMO)

K. Zuber, Acta Polonica B 37, 1905 (2006), updated

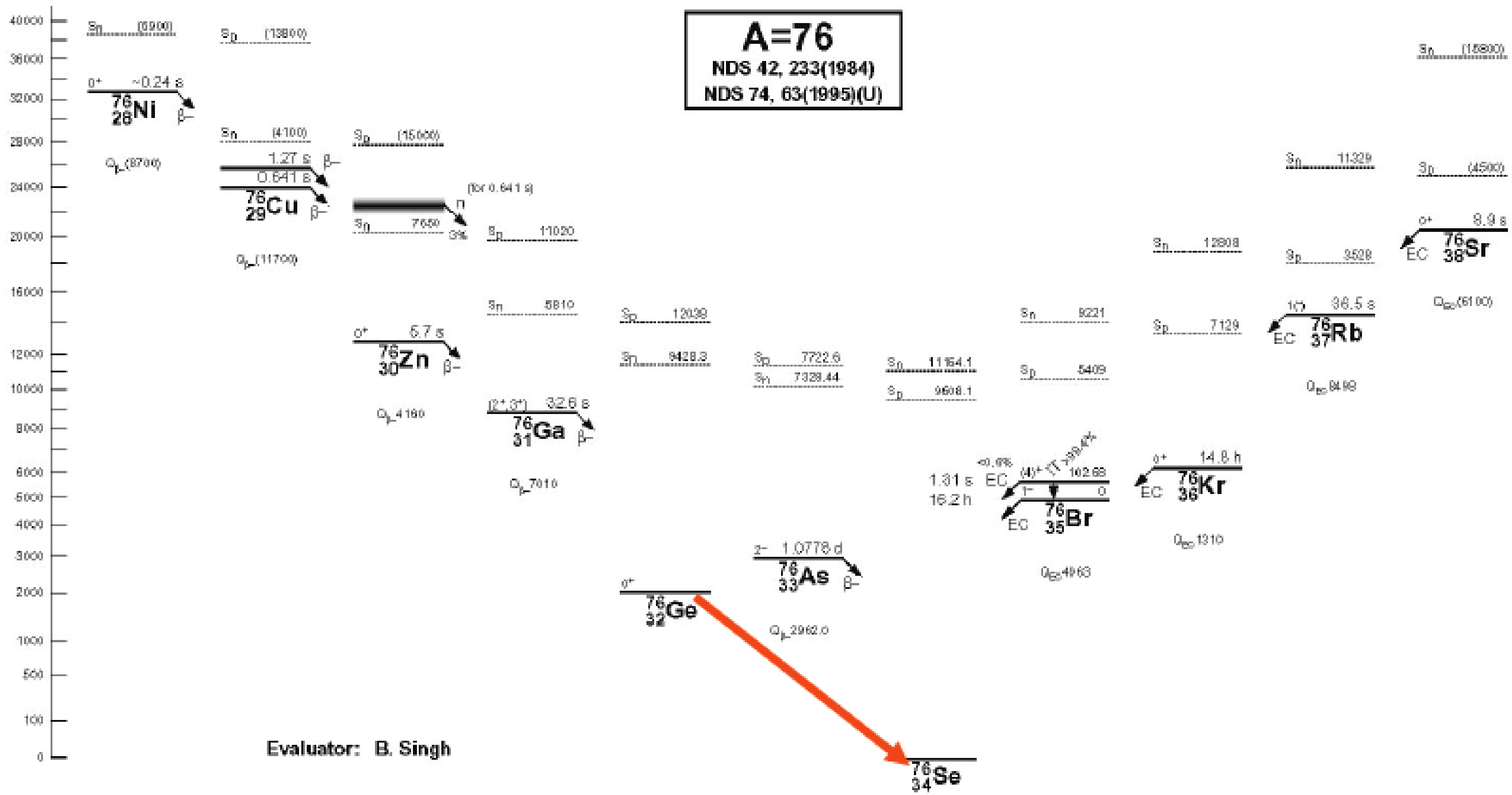
Heidelberg-Moscow

5 HPGe detectors in LNGS
(Gran Sasso underground
laboratory in Italy, 3400 m w.e.)

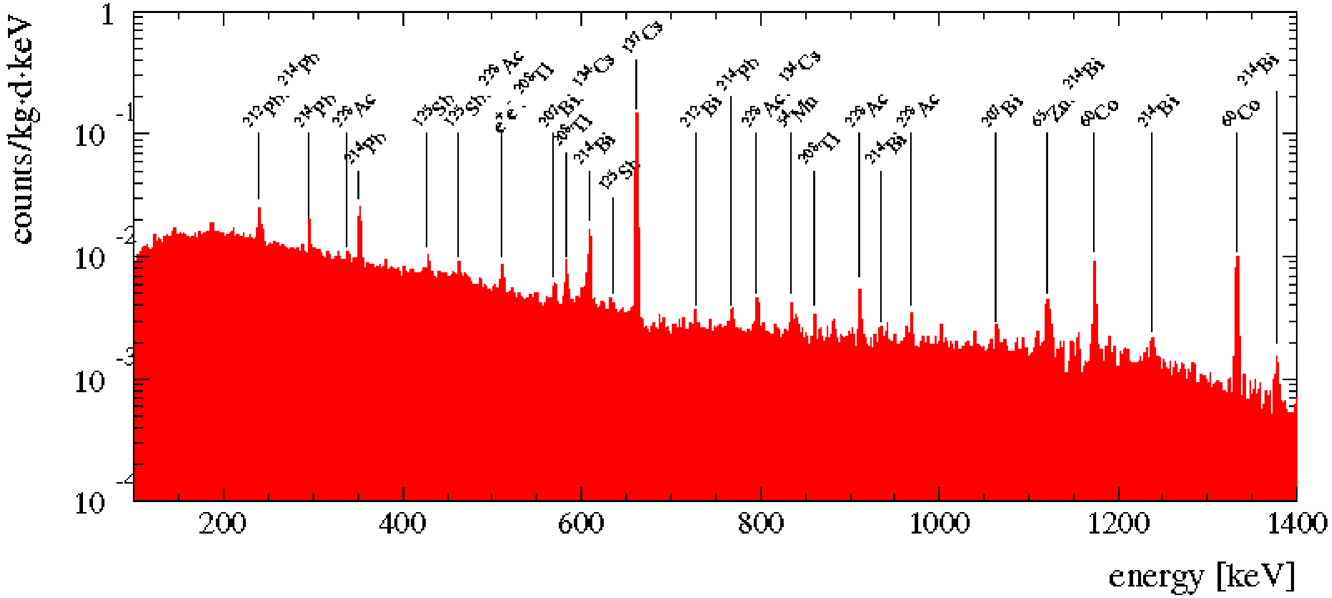


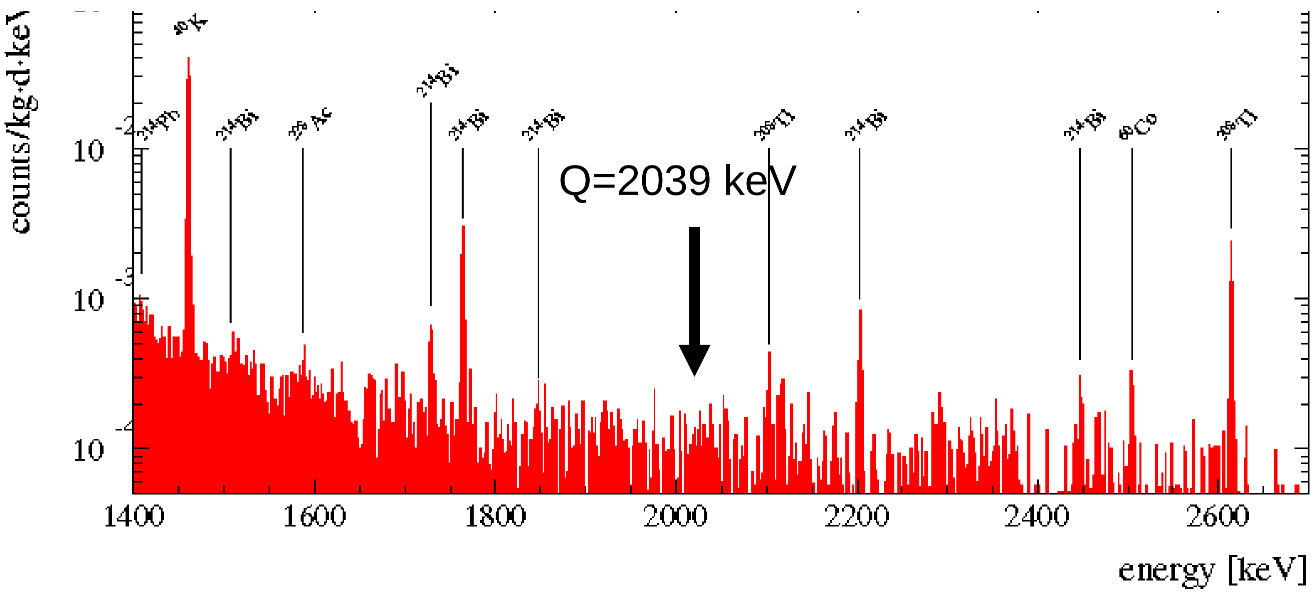


The ^{76}Ge candidate



Typical background spectrum





The sensitivity of a 0νββ experiment

The half life to which an experiment is sensitive with a certain confidence level can be expressed as:
(provided that the fluctuation of the background follows Gaussian distribution)

$$T_{1/2}^{0\nu\beta\beta}(n_\sigma) = \frac{4.14\times10^{26}\,a}{n_\sigma}\left(\frac{\varepsilon\cdot\eta}{W}\right)\sqrt{\frac{M\cdot T}{b\cdot\Delta E}}$$

with:

n_σ	Number of standard deviations characterizing C.L. (e.g. C.L. of 99.73 % corresponds to n_σ=3)
ε	Detection efficiency
η	Isotopic abundance
W	Atomic weight
M	Total mass of source material
T	Total measuring time
b	Specific background rate in peak region (cut) given in counts/(keV kg a)
ΔE	Spectral width of experiment (cut width) in keV

Frank T. Avignone III et al., http://arxiv.org/abs/0708.1033v2

Example: Estimation of potential half life sensitivity (4σ) of Heidelberg-Moscow (HM) experiment (^{76}Ge)

$$n_\sigma = 4$$

$$\varepsilon = 0.95$$

$$\eta = 0.86$$

$$W = 76$$

$$M \cdot T = 71.7 kg \cdot a$$

11 kg of enriched ^{76}Ge

$$b = 0.11 \frac{counts}{keV \cdot kg \cdot a} @ 2039 keV$$

$$\Delta E = 3.27 keV$$

If all numbers are correct, HM was able (4σ) to measure half-life for 0νββ (^{76}Ge) up to

$$T_{1/2}^{0\nu\beta\beta}(4\sigma, {}^{76}Ge, HM) = 1.9 \cdot 10^{25} a$$

The claim of a part of the HM-collaboration

- A sub-group of the HM-collaboration (Klapdor-Kleingrothaus et al.) claimed to have observed 0νββ
- Claimed values (99.97 % C.L.)

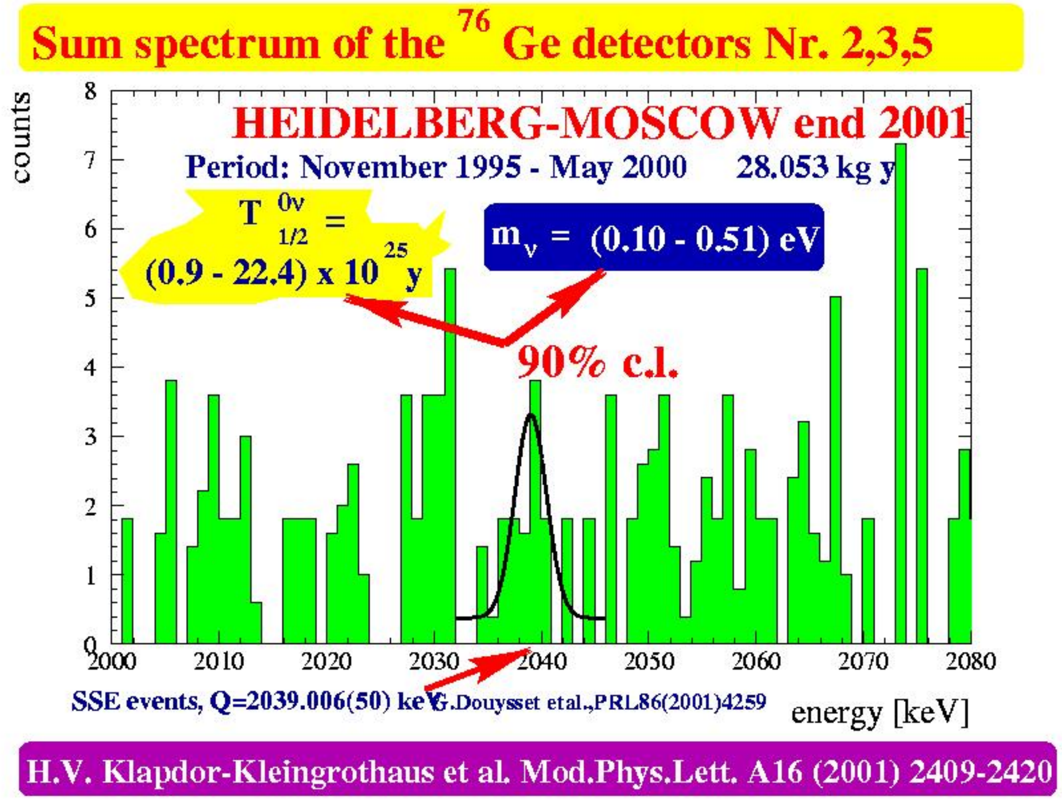
$$T_{1/2}^{0\nu} = (2.23 \pm 0.4) \cdot 10^{25} a$$

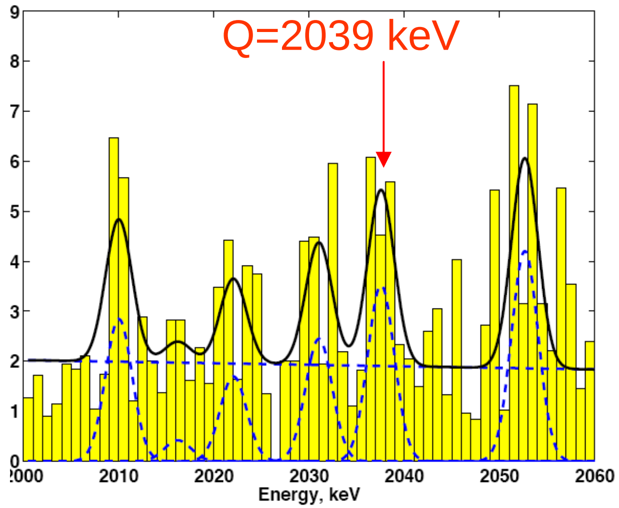
$$\langle m_{\beta\beta} \rangle = 0.32^{+0.03}_{-0.03} eV$$

http://www.klapdor-k.de

The observation

A subgroup of the Heidelberg-Moscow collaboration claimed to have seen (28.75 +- 6.86) $0\nu\beta\beta$-events in ^{76}Ge

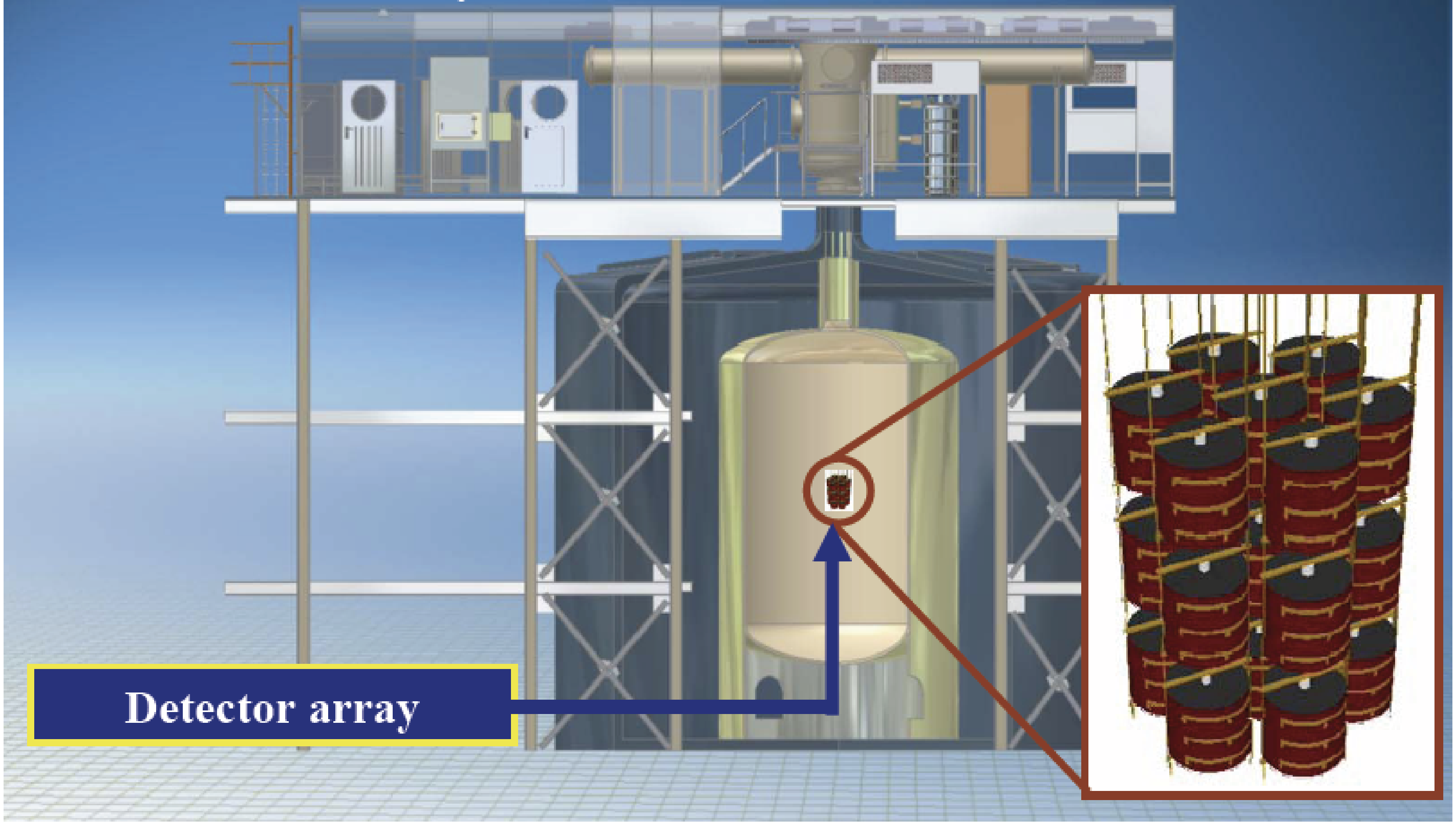




e.g. H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586, 198 (2004) and Mod.Phys.Lett.A21:1547-1566,2006

GERDA - the Germanium Detector Array

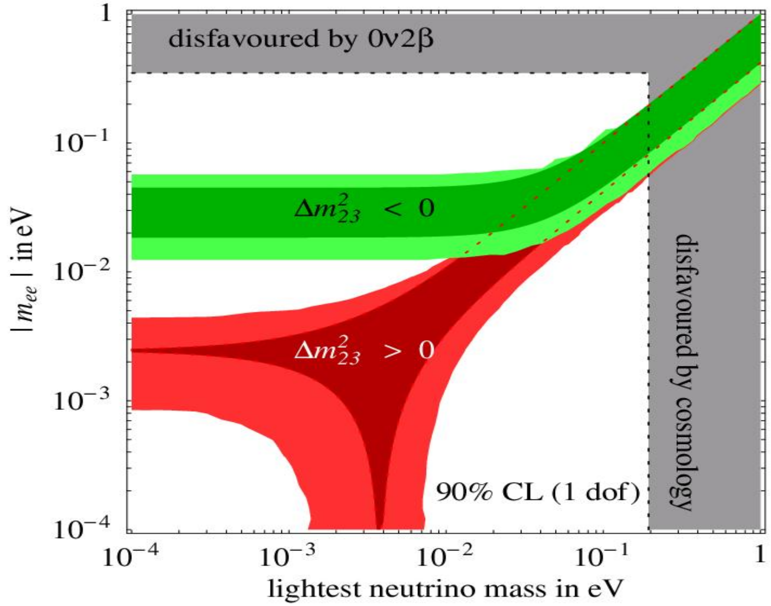
- Place array of naked HPGe-detectors enriched in ^{76}Ge in the center of a stainless cryostat filled with LAr.



3 phases of GERDA

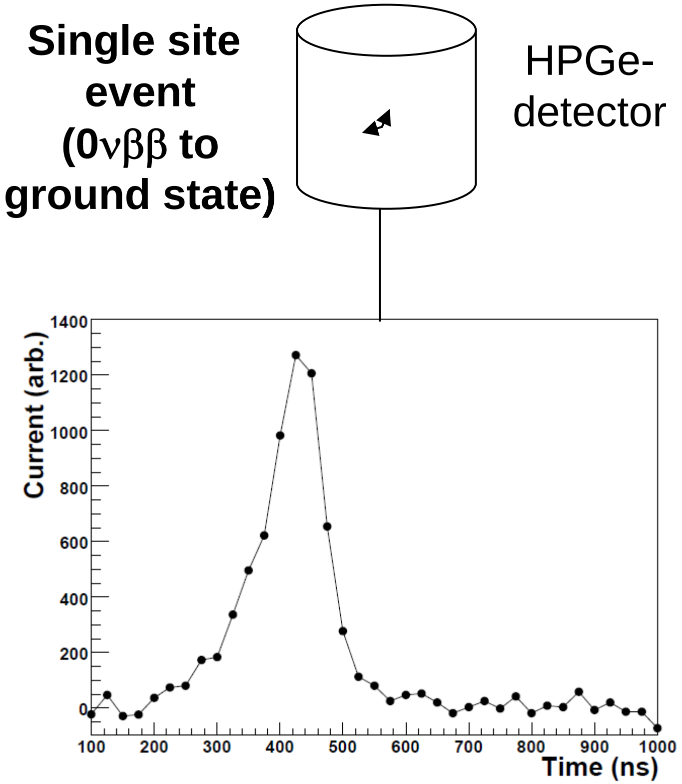
- **Phase I (2009-2011):**
  - 18 kg ^{76}Ge (from Heidelberg-Moscow and IGEX)
  - 15 kg ^{nat}Ge
  - Background level of 10^{-2} counts/kg/kev/a (=10 % of HM)
  - Half life limit: 2.2 x 10^{25} a (90 % C.L., 15 kg years)
  - Test existing claim within 1 year (6 counts with 0.5 counts background)

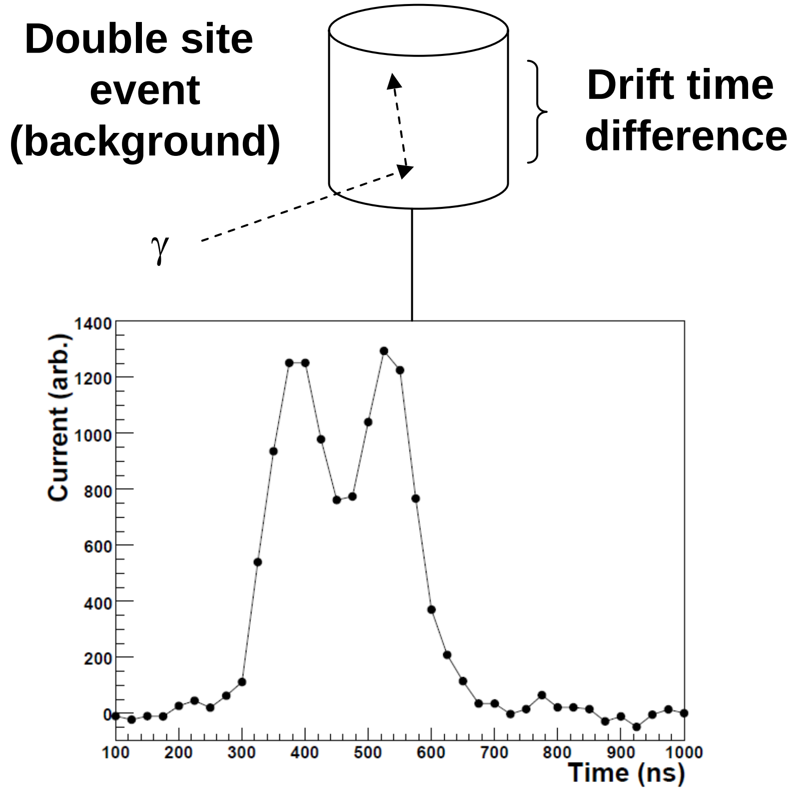
- **Phase II (>2011):**
  - Add 20 kg of segmented Ge-diodes
  - Background level of 10^{-3} counts/kg/keV/a
  - Several detectors depleted in ^{76}Ge (systematics check)
  - Half life limit: 2 x 10^{26} a (90 % C.L., 100 kg years)
  - Sensitivity to Majorana mass: 90 - 290 meV



- **Phase III (worldwide GERDA-MAJORANA collaboration):**
  - Depends on physics output of phases 1 and 2
  - Test to Majorana masses of (some) 10 meV

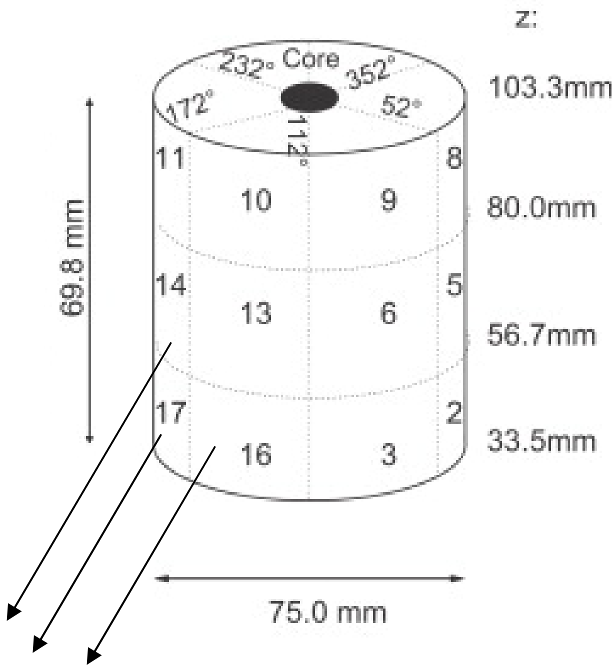
Pulse shape analysis: a way to discriminate multi-site background from single site signal





Pulse shapes from Majorana collaboration in Frank T. Avignone III et al., http://arxiv.org/abs/0708.1033v2

18-fold segmented coaxial HPGe-detectors for GERDA Phase II



Signal output of
18 segments (60° each)
in 3 rings

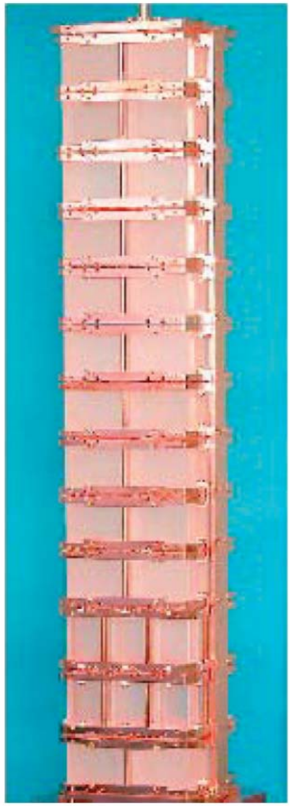
- High purity germanium detectors
- Cooled with LAr
- Full depletion at 2200 V
- Operating bias voltage >= 3000 V
- Multi site event: signal appears at output of several segments
- Improves background rejection

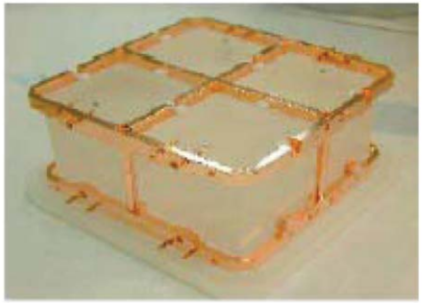
Figure (left) from Frank T. Avignone III et al., http://arxiv.org/abs/0708.1033v2 Figure (right): I. Abt et al, NIM A 577 (3) 2007: 574-584

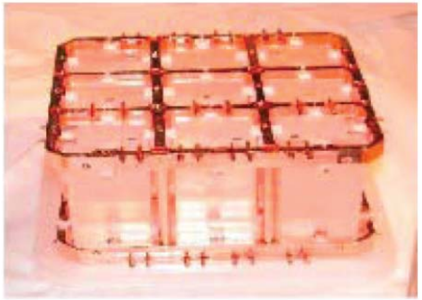
CUORICINO in LNGS

- 40.7 kg of $^{natural/130/128}TeO_2$ crystals at 8-10 mK
- Temperature change ΔT measured with high-resistance germanium thermistors thermally coupled to crystals
- $0\nu\beta\beta$–event causes $\Delta T = 1.77 \cdot 10^{-4}$ K
- M*T=11.83 kg*a of ^{130}Te
- Energy resolution 8 keV (FWHM)
- Background:

$$b = (0.18 \pm 0.01)\frac{counts}{keV \cdot kg \cdot a} @ 2530keV$$







Results (2008)

$$T_{1/2}^{0\nu}(^{130}Te) > 3.0 \times 10^{25} a$$ (90% C.L.)

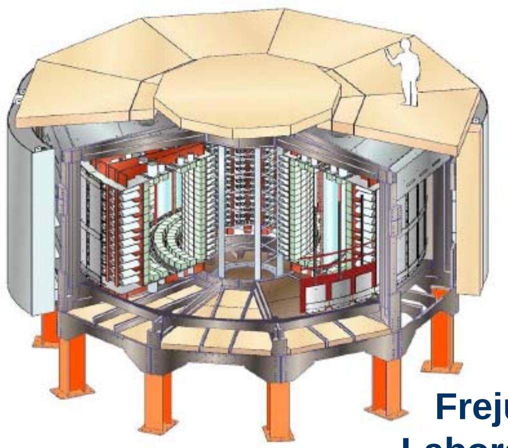
$$\langle m_{\beta\beta} \rangle < 0.19 - 0.68 eV$$

To be continued with CUORE (750 kg)

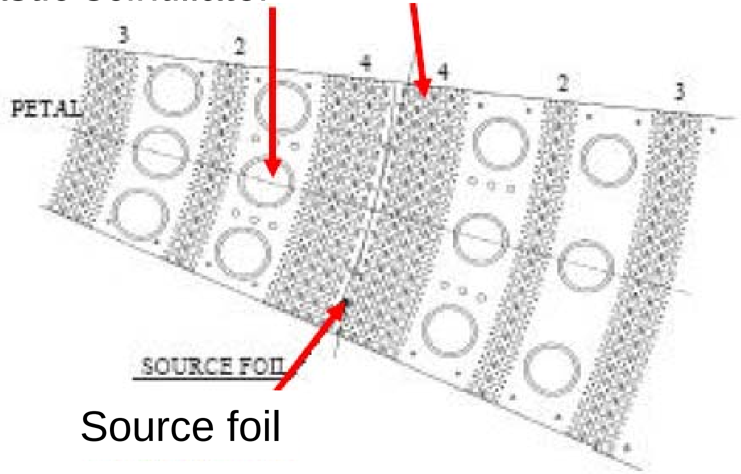
$$\langle m_{\beta\beta} \rangle_{sensitivity} = 0.02 - 0.05 eV$$

Arnaboldi et al., PHYSICAL REVIEW C 78, 035502 (2008)

The Neutrino Ettore Majorana Observatory NEMO-3



Nemo-3 in
Frejus Underground
Laboratory (4800 m w.e.)



Cross section: Talk of Carter Hall (SLAC)
„Neutrino Physics with Double Beta Decay", ASPEN 2005

- Source: various thin foils of different nuclides (e.g. 10 kg of ^{100}Mo)
- **Tracker:**
  - 6180 open Geiger drift cells
  - tracking vertex resolution of approx 1 cm at 1 MeV
- **Calorimeter:**
  - 1940 plastic scintillators coupled to low radioactivity photomultipliers
  - energy resolution of 15 % (FWHM) at 1 MeV
  - timing precision 250 ps at 1 MeV
- **Magnetic field:**
  - B=25 G produced by solenoid for e+/e- separation
- **Shielding:**
  - γ (18 cm iron)
  - n (borated water, wood)
  - Rn (air purification)

NEMO-3: Some results

$2\nu\beta\beta$

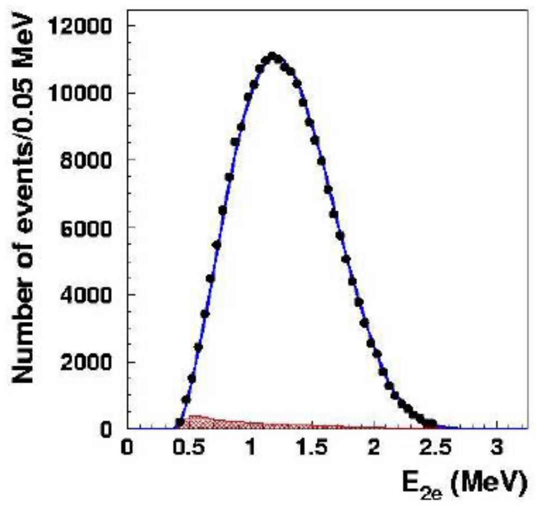


Figure 2. Sum energy spectrum of two electrons for $\beta\beta$ decay of ^{100}Mo (7.369 kg·y). Background is extremely low (S/N~40). Solid line is MC simulation.

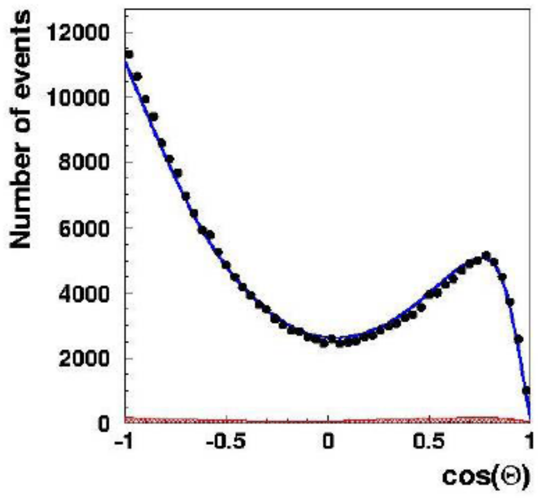


Figure 3. Angular distribution between two electrons for $\beta\beta$ decay of ^{100}Mo. Solid line is MC simulation using the acceptance of NEMO 3 detector.

$2\nu\beta\beta$ seems to be very well understood

$0\nu\beta\beta$

^{100}Mo

$$T_{1/2}^{0\nu}(^{100}Mo) > 5.8\times10^{23}\,a$$

90 % C.L.

$$\langle m_{\beta\beta}\rangle < 0.8 - 1.3\,eV$$

^{82}Se

$$T_{1/2}^{0\nu}(^{82}Se) > 2.1\times10^{23}\,a$$

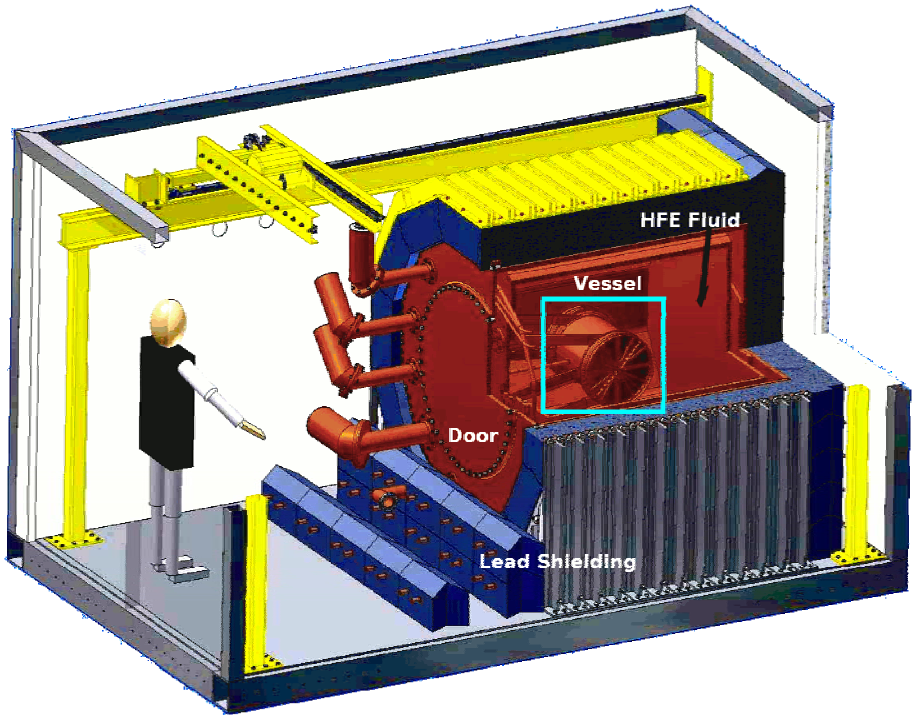
90 % C.L.

$$\langle m_{\beta\beta}\rangle < 1.4 - 2.2\,eV$$

EXO - the Enriched Xenon Observatory

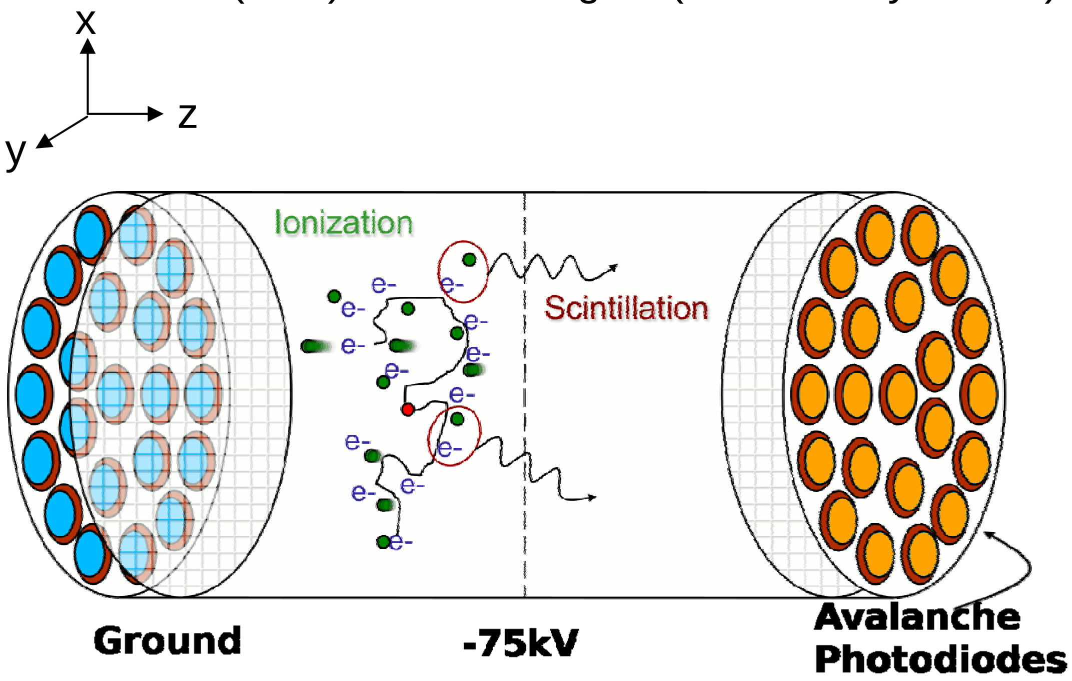
- EXO-200 is a prototype of the ton scale experiment EXO
- Search for $0\nu\beta\beta$ in ^{136}Xe (Q-value: 2479 keV)
- Source: 200 kg liquid Xe enriched to 80 % (^{136}Xe)
- Liquid Xenon volume is a Time-Projection-Chamber
- Expected energy resolution (σ) approx. 1.6 % at 2.5 MeV
- About 50.000 Xe-atoms ionized by 1 MeV electron
- EXO-collaboration: University of Alabama, Universität Bern,Caltech,Carleton University,Colorado State University, UC Irvine,ITEP (Moscow),Laurentian University,University of Maryland, University of Massachusetts - Amherst, SLAC, Stanford, Technische Universität München

The prototype (EXO-200) at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico (2000 m w.e.)

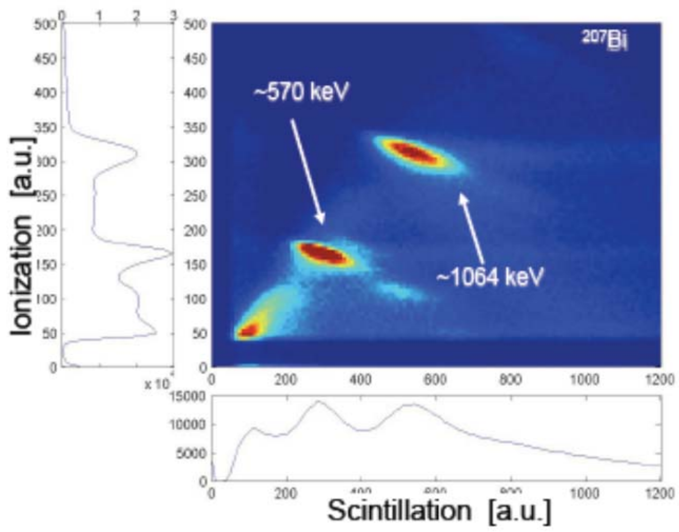


EXO-200

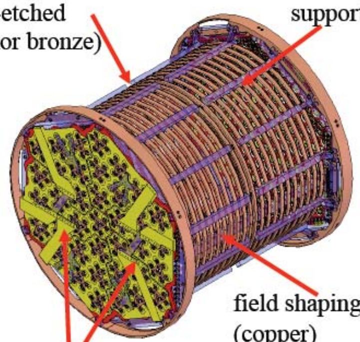
- **Ionization signal (later):**
  - electrons from ionization are drifted to wire grids (x,y) and form electric signal
  - z-coordinate is determined from time difference between prompt scintillation and the (later) ionization signal (drift velocity known)



- **Scintillation light (first signal):**
  - (optical) photons from recombination of (ionization) electrons with Xenon ions trigger avalanche-photodiodes (APD) in arrays
  - Strength anti-correlated with strength of ionization signal

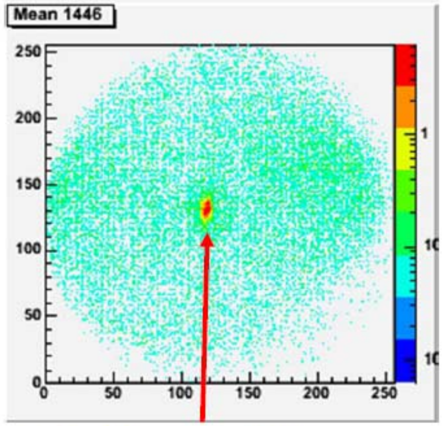


Expected sensitivity



Half chamber mock-up model

EXO: background free with barium tagging ?



A photo of a single Ba+ ion in vacuum

Expected sensitivity of EXO-200:

$$T^{0\nu}_{1/2,sensitivity}(^{136}Xe) = 6.4\times 10^{25}\,a$$

$$\langle m_{\beta\beta}\rangle_{sensitivity} = 133 meV \quad \textbf{(QRPA)}$$

$$\langle m_{\beta\beta}\rangle_{sensitivity} = 186 meV \quad \textbf{(Shell Model)}$$

Assumptions: T=2 a, M=200 kg, energy resolution 1.6 % at 2.5 MeV, 70 % efficiency

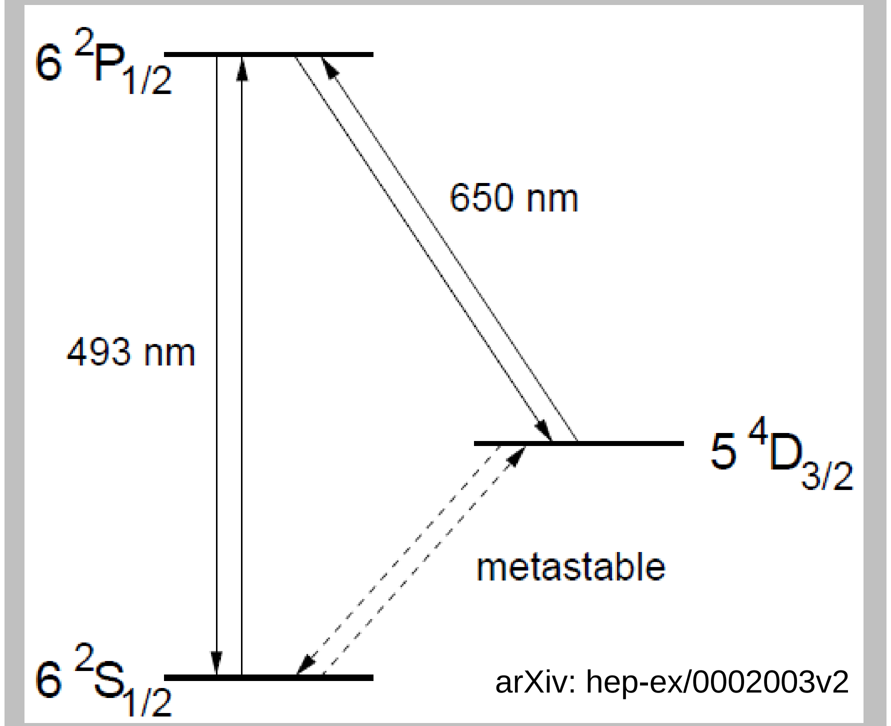
Barium tagging principle for EXO

$$ {}^{136}Xe \xrightarrow{0\nu\beta\beta,\ 2\nu\beta\beta} {}^{136}Ba^{++} + e^- + e^- $$

$$ {}^{136}Ba^{++} + e^- \rightarrow {}^{136}Ba^{+} $$

- ${}^{136}Ba^{+}$ is in $6^2S_{1/2}$ state
- A „blue“ laser excites it to $6^2P_{1/2}$
- With 30 % chance is relaxes to the metastable $5D^4_{3/2}$ with emission of a red photon (to be detected)
- About **60.000.000** „red“ photons per second can be produced in saturation of the cycle **BY ONE** Barium ion
- EXO: Tagging of daughter nulceus would improve significance dramatically (still R&D)

Atomic Level diagram of Ba^+

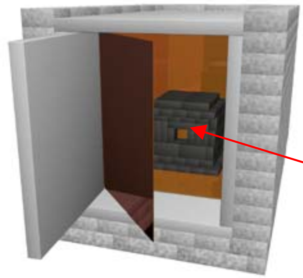


COBRA - search for neutrinoless double beta decay with an array of Cd(Zn)Te semiconductor detectors

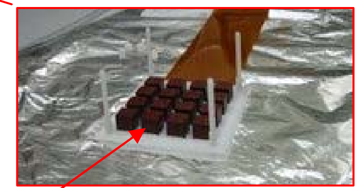
Idea

- In R&D phase
- Cd(Zn)Te semiconductor detectors (source=detector)
- Array of small crystals (1 cm^3) to identify double site events and identify decays into excited states
- 9 nuclei can be used with same detector technology

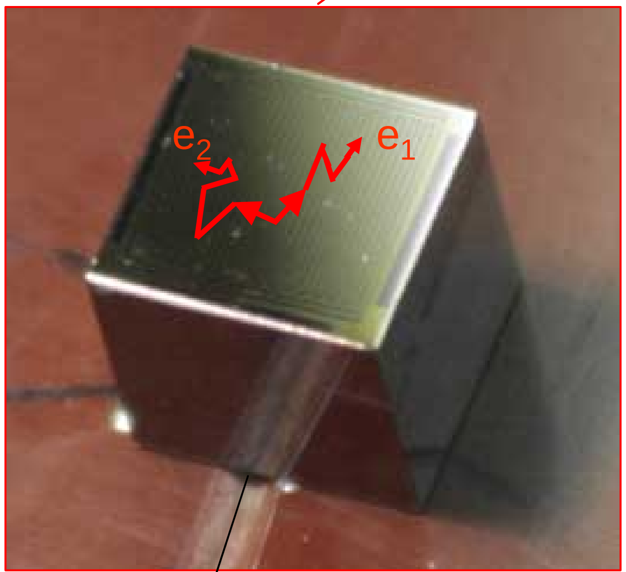
	Nat. abund.	Q [keV]	Decay mode	
Zn70	0.62	1001	ß-ß-	
Cd114	28.7	534	ß-ß-	
Cd116	7.5	2809	ß-ß-	Most promising
Te128	31.7	868	ß-ß-	
Te130	33.8	2529	ß-ß-	
Zn64	48.6	1096	ß+/EC	
Cd106	1.21	2771	ß+ß+	
Cd108	0.9	231	EC/EC	
Te120	0.1	1722	ß+/EC	



Shielding + Faraday cup



4x4 cubes



Cube (1cm^3) of Cd(Zn)Te

Elektrical signal $\propto (E_{e1} + E_{e2})$

COBRA - search for neutrinoless double beta decay with an array of Cd(Zn)Te semiconductor detectors

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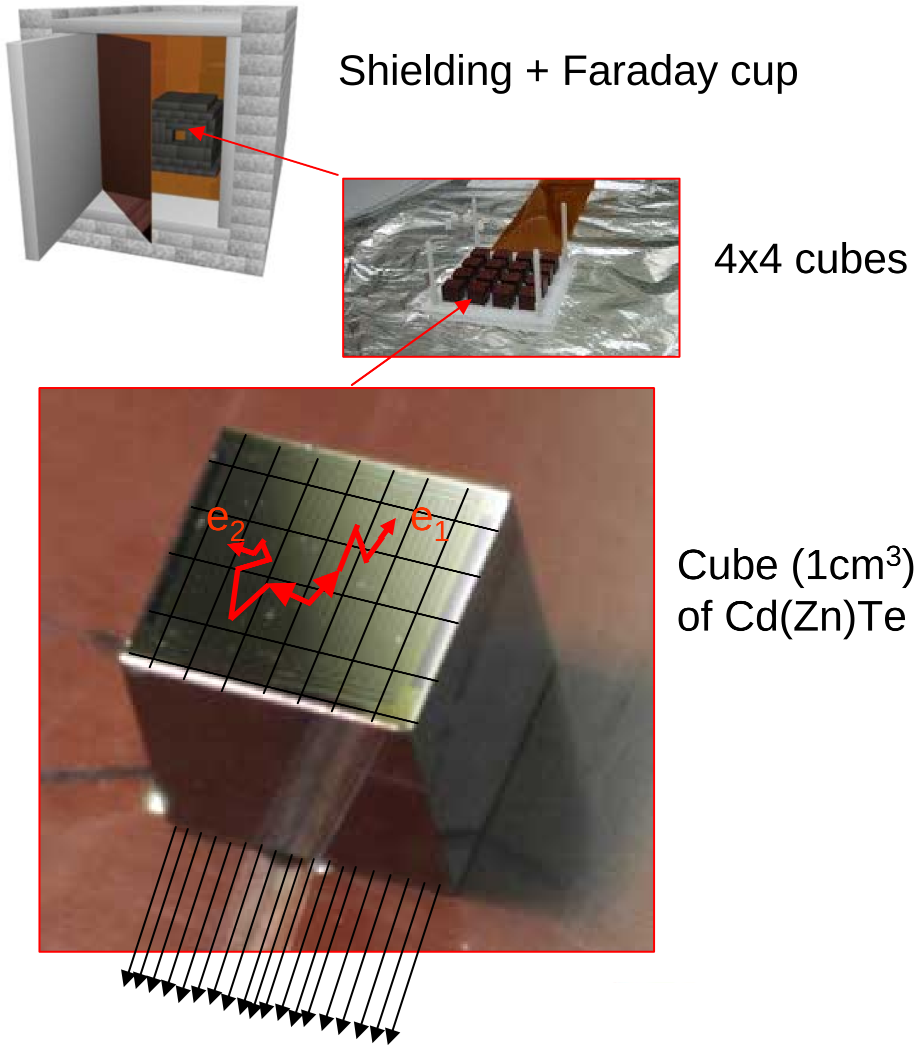
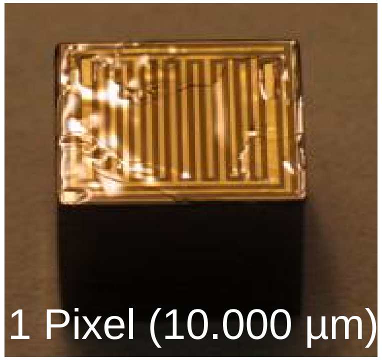
	Nat. abund.	Q [keV]	Decay mode	
Zn70	0.62	1001	ß-ß-	
Cd114	28.7	534	ß-ß-	
Cd116	7.5	2809	ß-ß-	Most promising
Te128	31.7	868	ß-ß-	
Te130	33.8	2529	ß-ß-	
Zn64	48.6	1096	ß+/EC	
Cd106	1.21	2771	ß+ß+	
Cd108	0.9	231	EC/EC	
Te120	0.1	1722	ß+/EC	



From solid calorimeter to solid tracking calorimeter

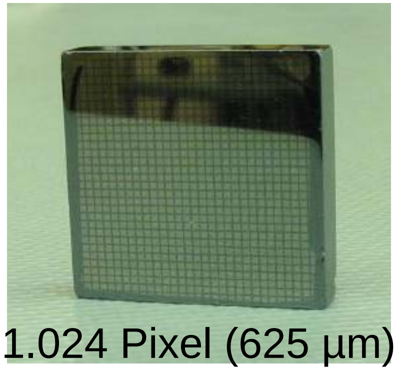
Today



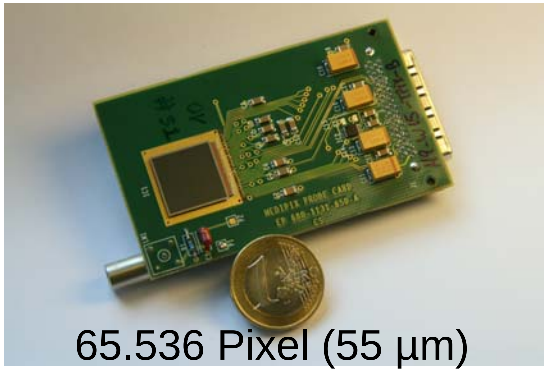
1 Pixel (10.000 µm)

- Large „pixels“ (1 cm^3)
- Only energy measurement
- Limited particle identification

Tomorrow ?



1.024 Pixel (625 µm)

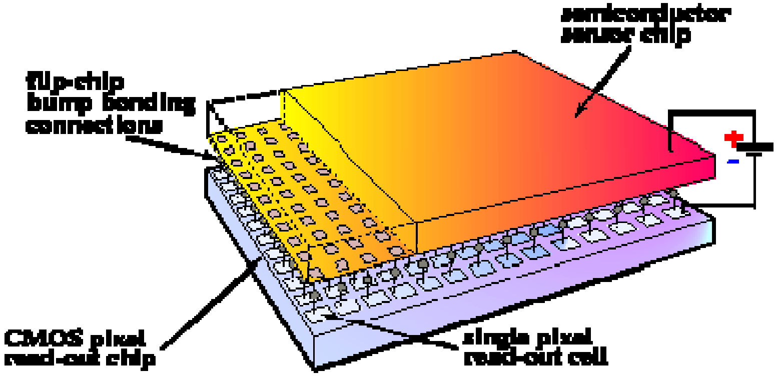


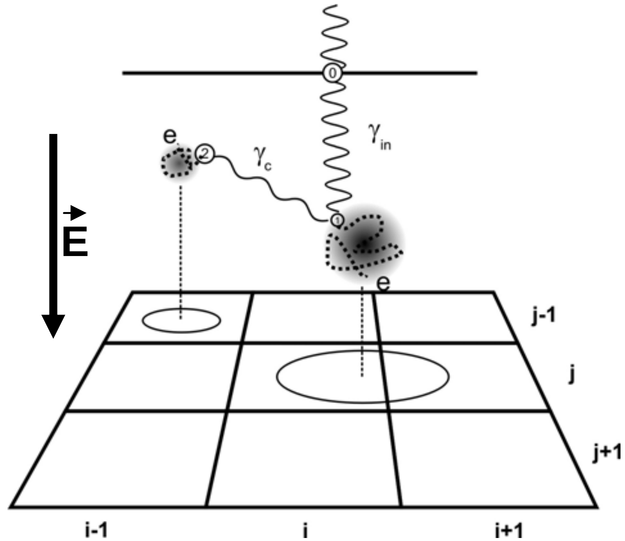
65.536 Pixel (55 µm)

- Small pixels (z.B. < 0.004 cm^3)
- Pixels -> tracking
- Energy measurement in each pixel
- Particle identification with to track analysis

COBRA collaboration:
Technical University Dresden, Technical University Dortmund, Material Res. Centre Freiburg, University of Erlangen-Nürnberg, University of Hamburg, Laboratori Nazionali del Gran Sasso, Washington University St. Louis, Czech Technical University Prague, University of Jyvaskyla, JINR Dubna, University of Bratislava; University of La Plata

One detector candidate: The hybrid pixel detector Timepix



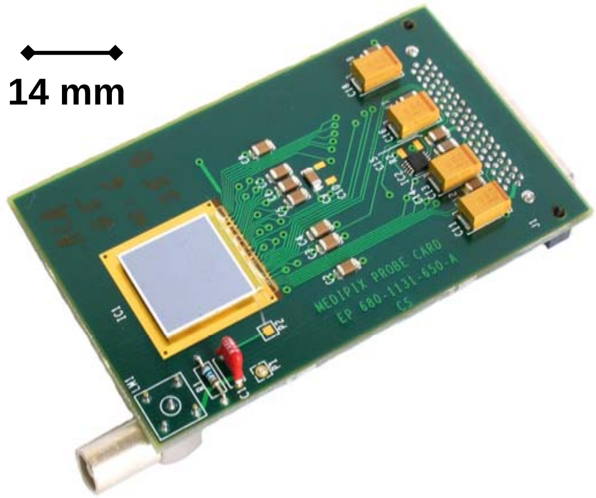


ASIC/Sensor:

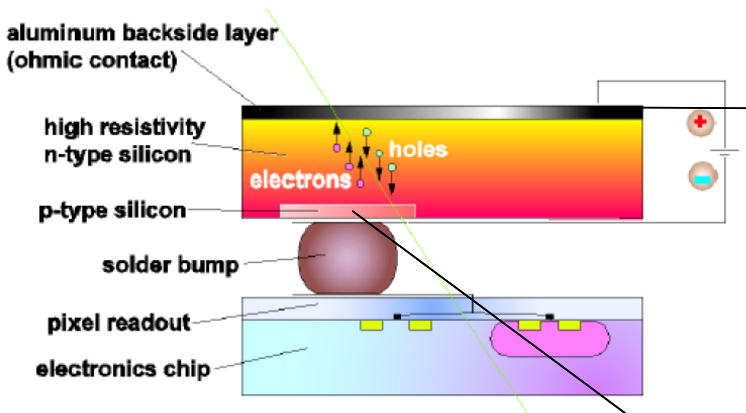
- Development: International Collaboration with seat at CERN
- Bump-bonded with Pb/ Sn alloy
- 65536 pixels
- Pixel pitch: 55 µm
- Size of the matrix: 14 mm (approx. 2 cm^2)
- 0.25 µm CMOS technology

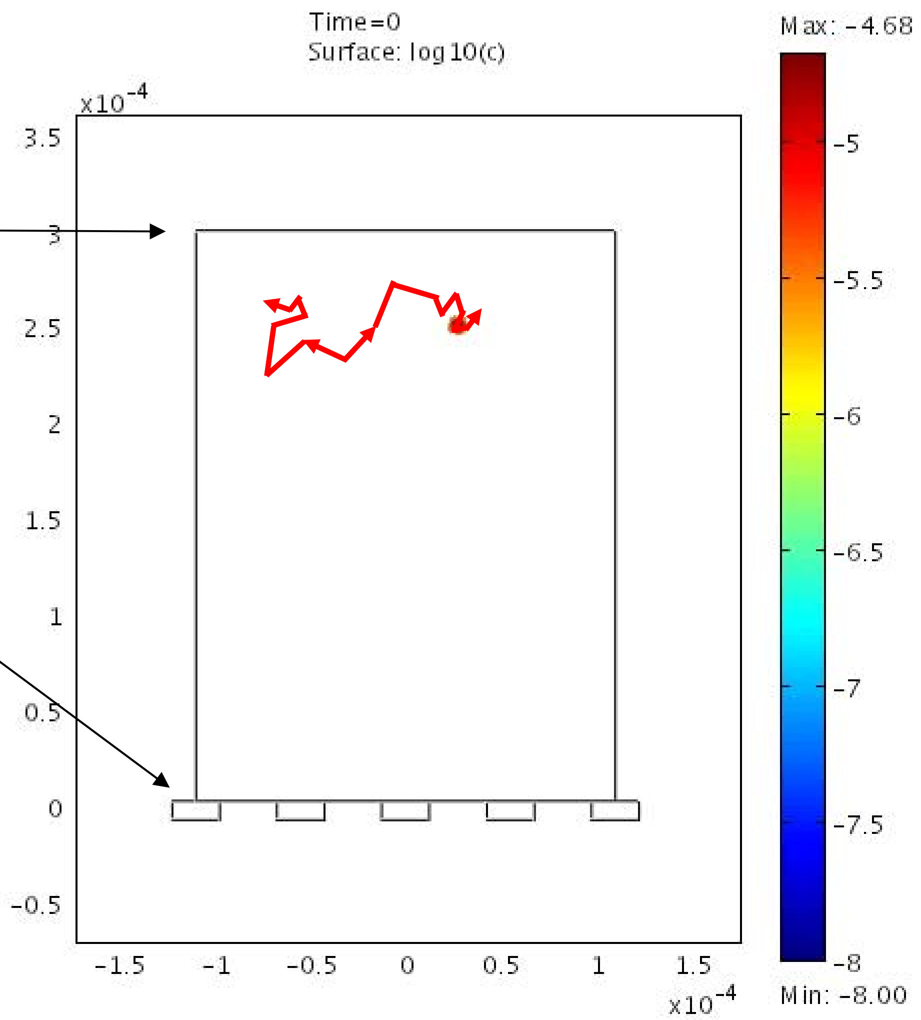
Sensor:

- Materials: Si, GaAs, CdTe
- Bias voltage: e.g. 150 V (300 µm Si)



Drift and diffusion of released charge carriers

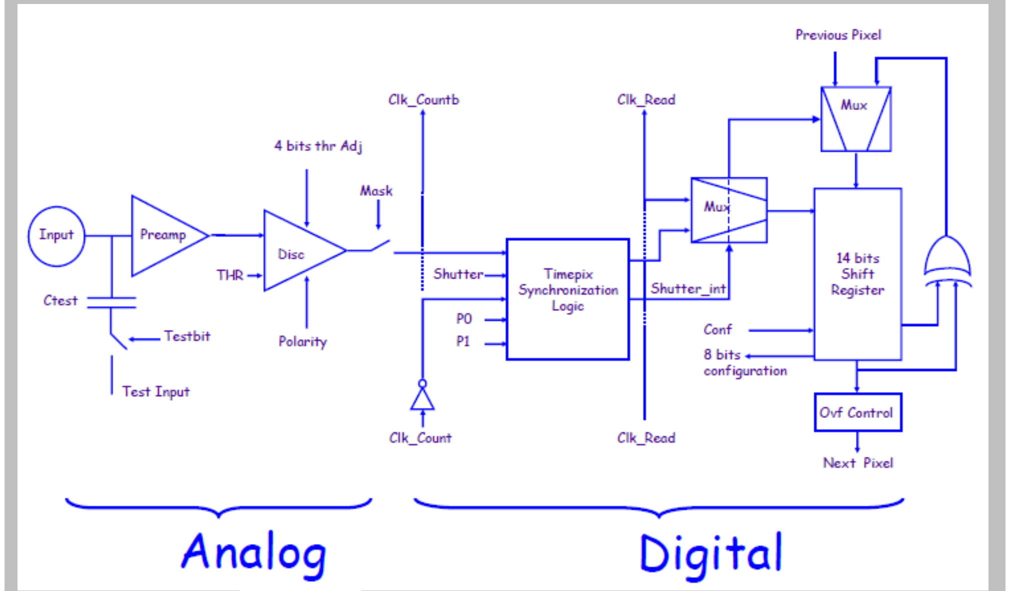




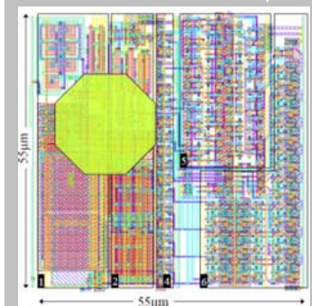
4.42 eV energy deposition for creation of one electron/hole-pair: More than 600.000 electron/hole-pairs in 0$\nu\beta\beta$ decay of ^{116}Cd created

The Timepix-ASIC

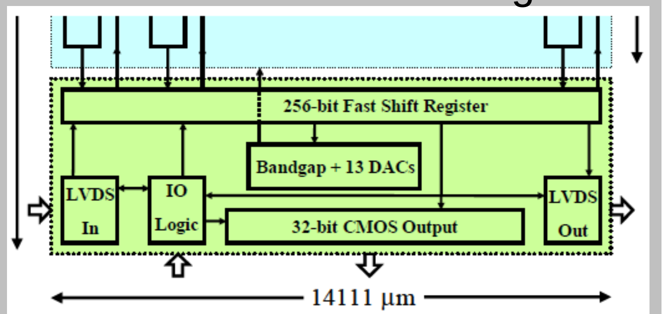
Pixel electronics



Pixel cell



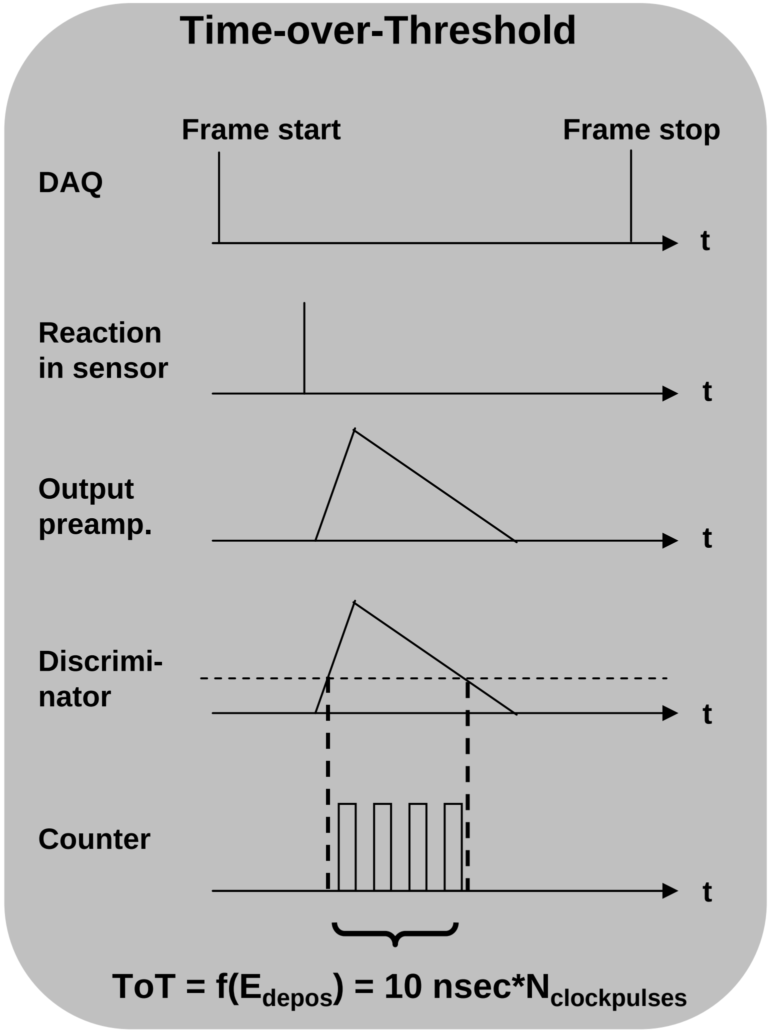
Readout zone block diagram

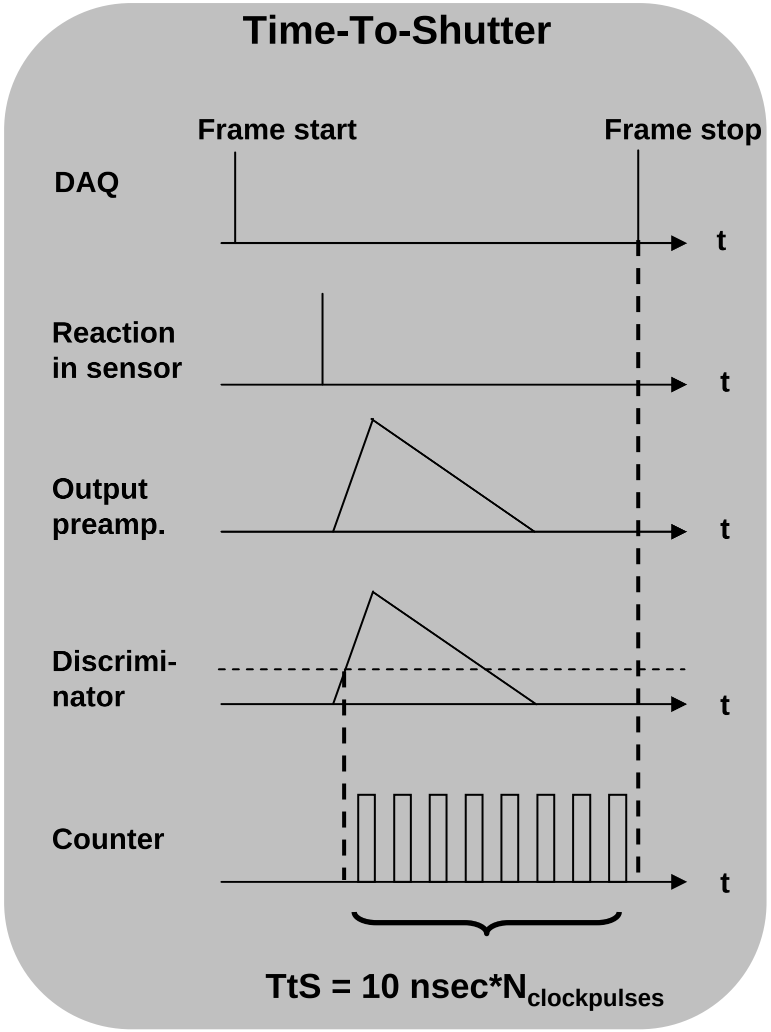


Principle

- **Pixel electronics**
  - Charge-Sensitive Preamplifier
  - 1 Discriminator (minimum threshold approx. 1000 e- = 3.6 keV)
  - 1 Counter in pixel
- **Operation modes**
  - Counting
  - Time-Over-Threshold
  - Time-Of-Arrival

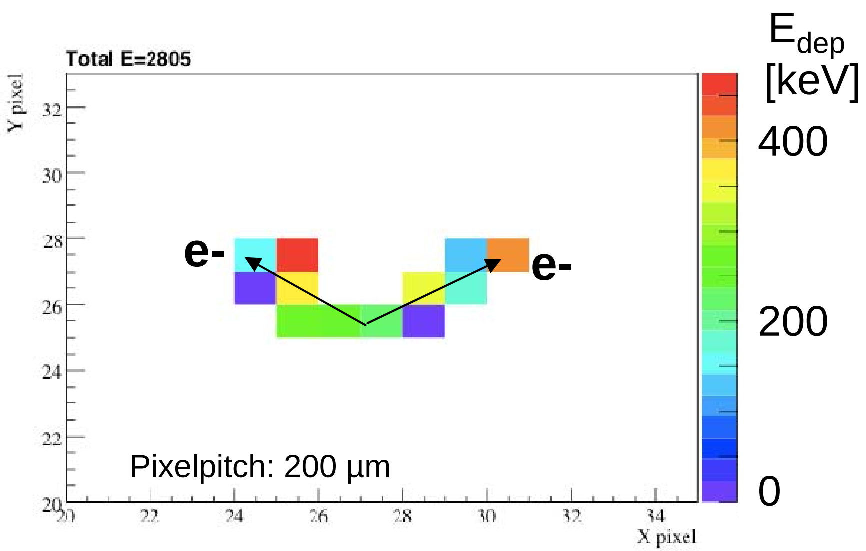
Timepix: counting or Time-Over-Threshold or Time-To-Shutter (exclusive ORs)



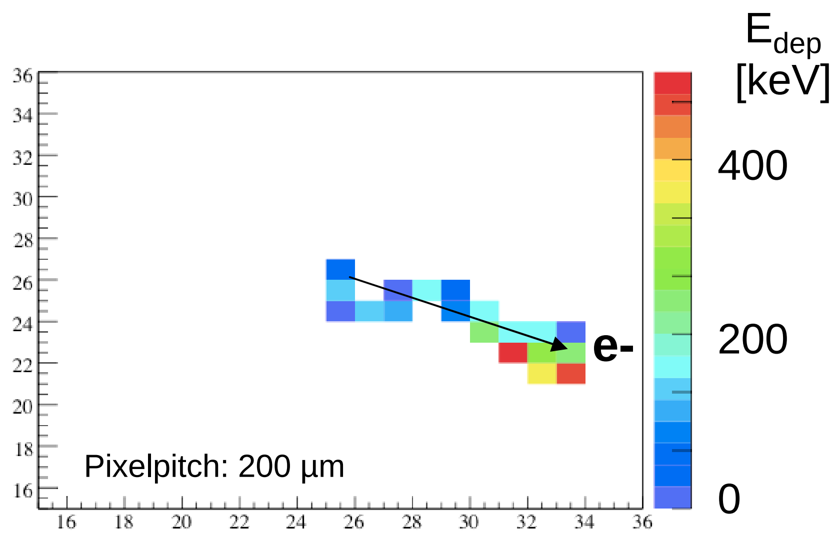


The power of pixels (simulation)

Signal: $0\nu\beta^-\beta^-$ from ^{116}Cd



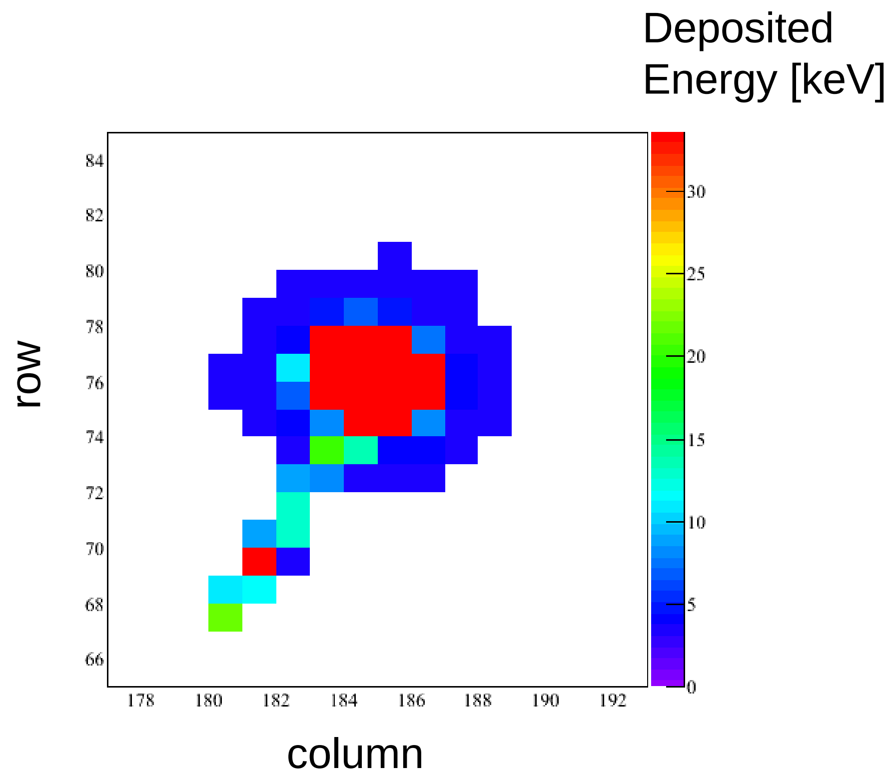
Background event: 3 MeV β

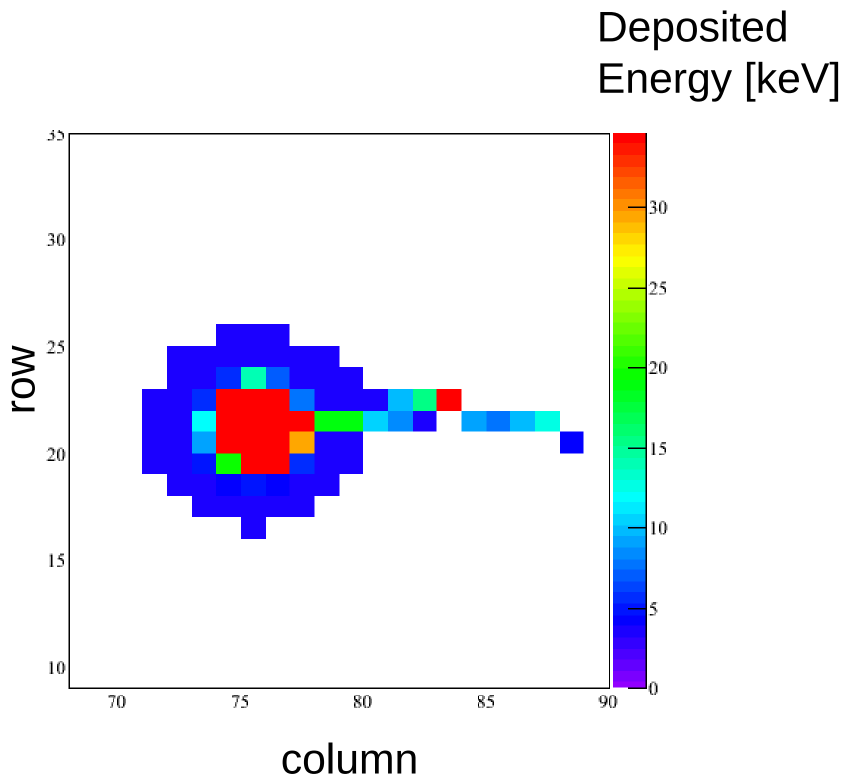


- Typical track length: 1.0 - 3 mm
- Pixelpitch < 200 µm reasonable
- Optimization between: energy resolution, leakage in neighbouring pixels, track resolution, number of channels, power consumption

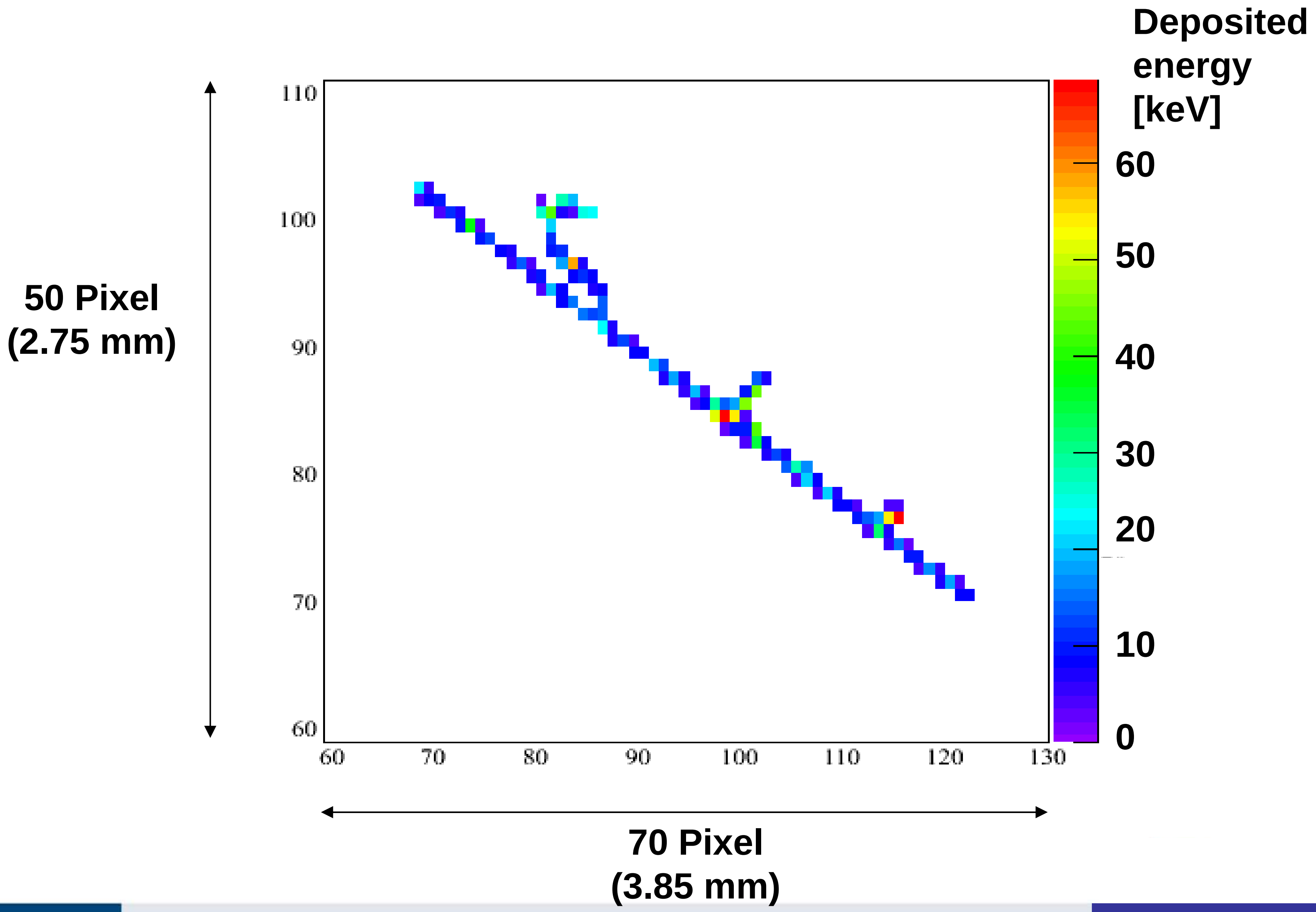
Main background source for this exp.: Electrons from beta decay of ^{214}Bi with 3.3 MeV endpoint energy

A decay electron from ^{214}Bi and the following ($T_{1/2}$=164 µs) α from ^{214}Po decay

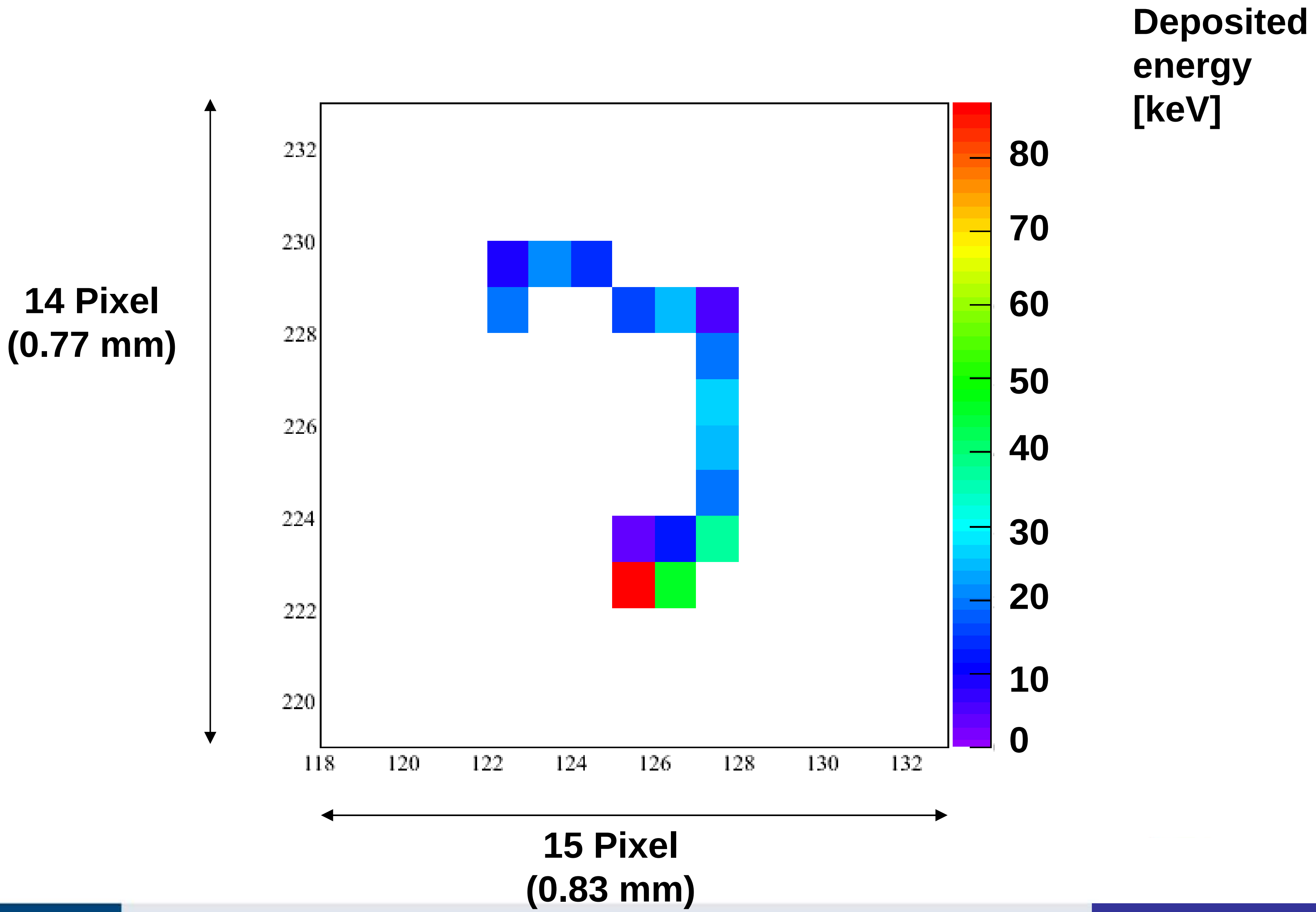




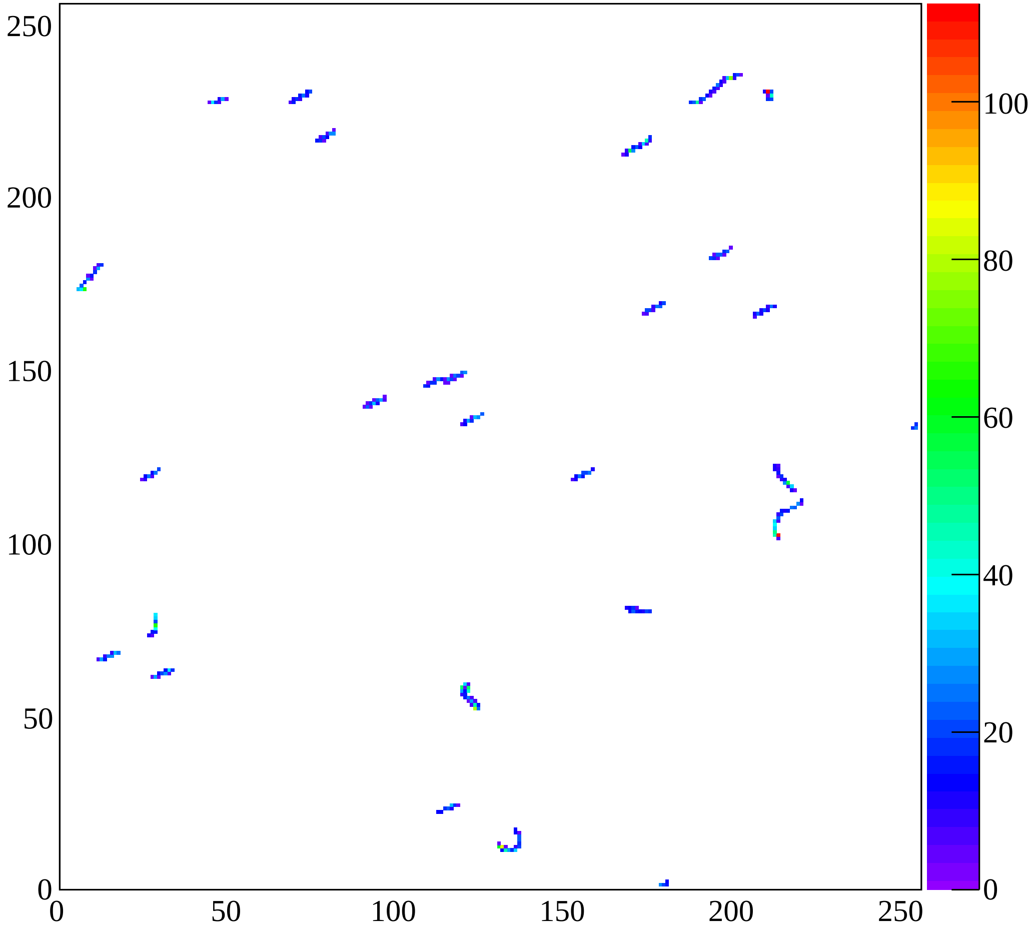
Example of a muon track



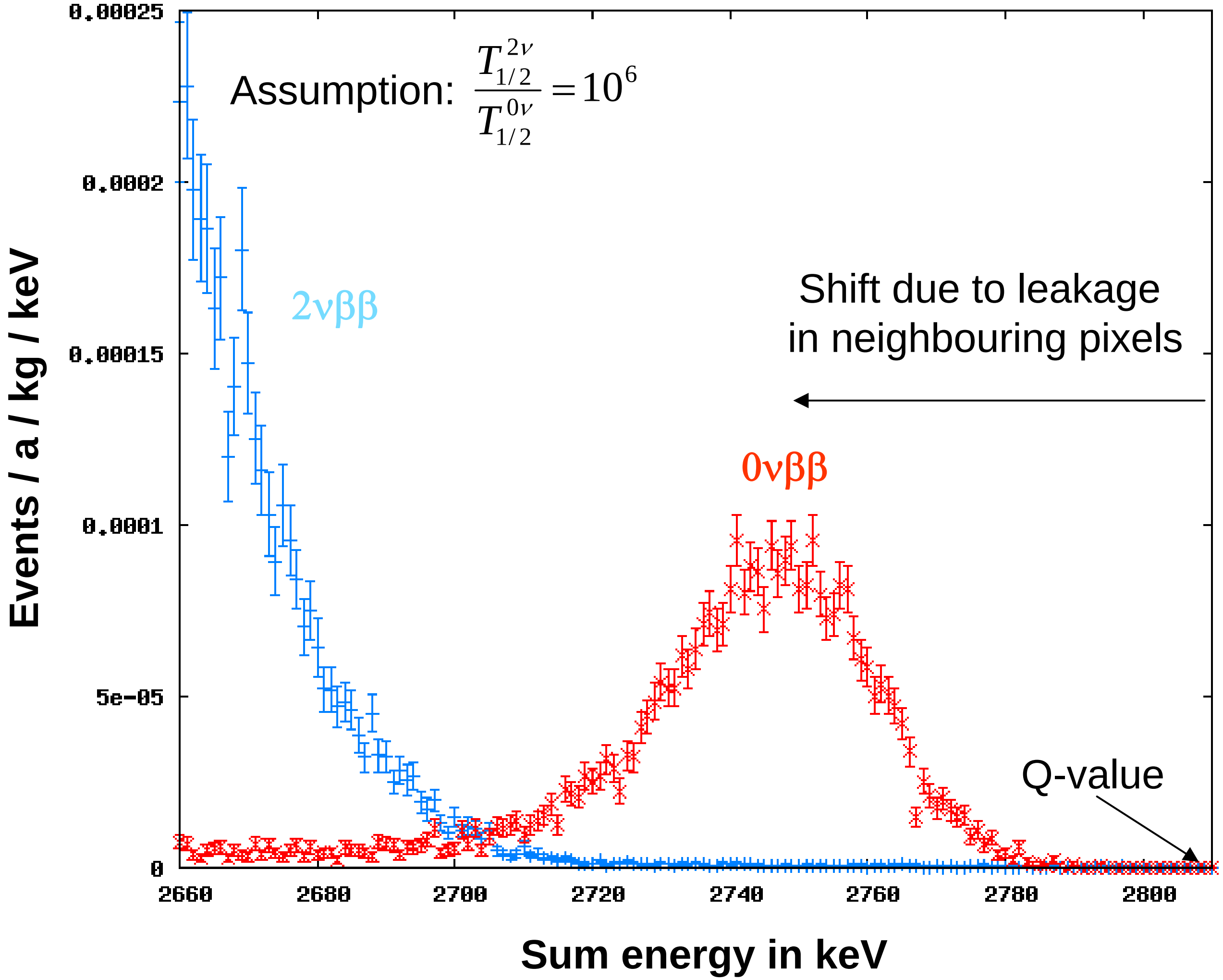
A 350 keV electron track



A cosmic shower in the Timepix



Simulation of signal (0νββ) and 2νββ-background (preliminary)



- Charge transport in sensor included
- 1.6 mm thick CdTe
- Pixelpitch: 110 µm
- 700 V Bias voltage
- Analog noise: 400 e- rms
- 7 keV threshold in pixels

$$\frac{\Delta E_{FWHM}}{E} = 1.3\%$$

- Optimization:
  - Thicker sensor
  - Face-To-Face
  - Threshold of 4 keV

What must experimentalists do ?

• Find a peak at the correct energy (Q-value) • Find only events that have single-site energy deposition • Demonstrate that the measured rate scales with isotope fraction	$0\nu\beta\beta$ probably exists
• Observe the 2 electron tracks • Show that kinematic distributions like single electron energies and opening angles are like the expected ones • Tag the daughter nucleus in coincidence • Indentify decays into the excited states (lower Q) and prove that decay rates fit to decay to ground state data	Almost convincing
• See most of this in several nulcei	Then it‘s for sure

Thank you very much
for your attention !