Double Beta Decay: Experiments and Theory Review

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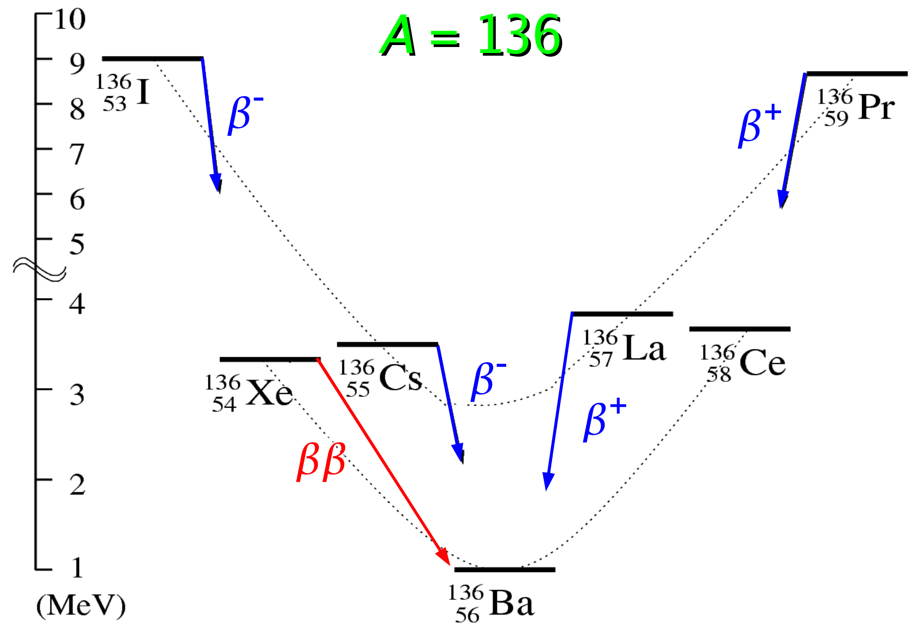
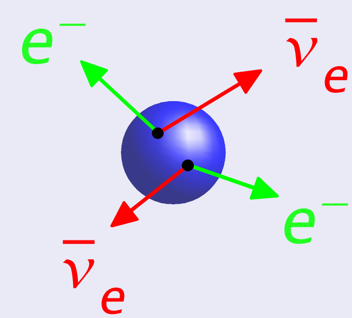
Introduction: double beta decay

second order weak decay of **even-even nuclei** in *A* even multiplets



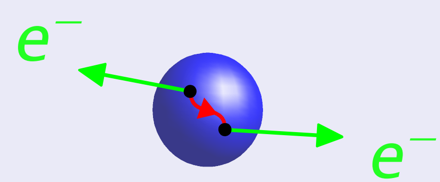
$\beta\beta$-2ν: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

- allowed in Standard Model
- observed with $\tau_{1/2} > 10^{19}$ years



$\beta\beta$-0ν: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

- not allowed in Standard Model (ΔL=2)
- expected $\tau_{1/2} > 10^{25}$ years
- only one *criticized* evidence to date



Present knowledge about neutrino properties

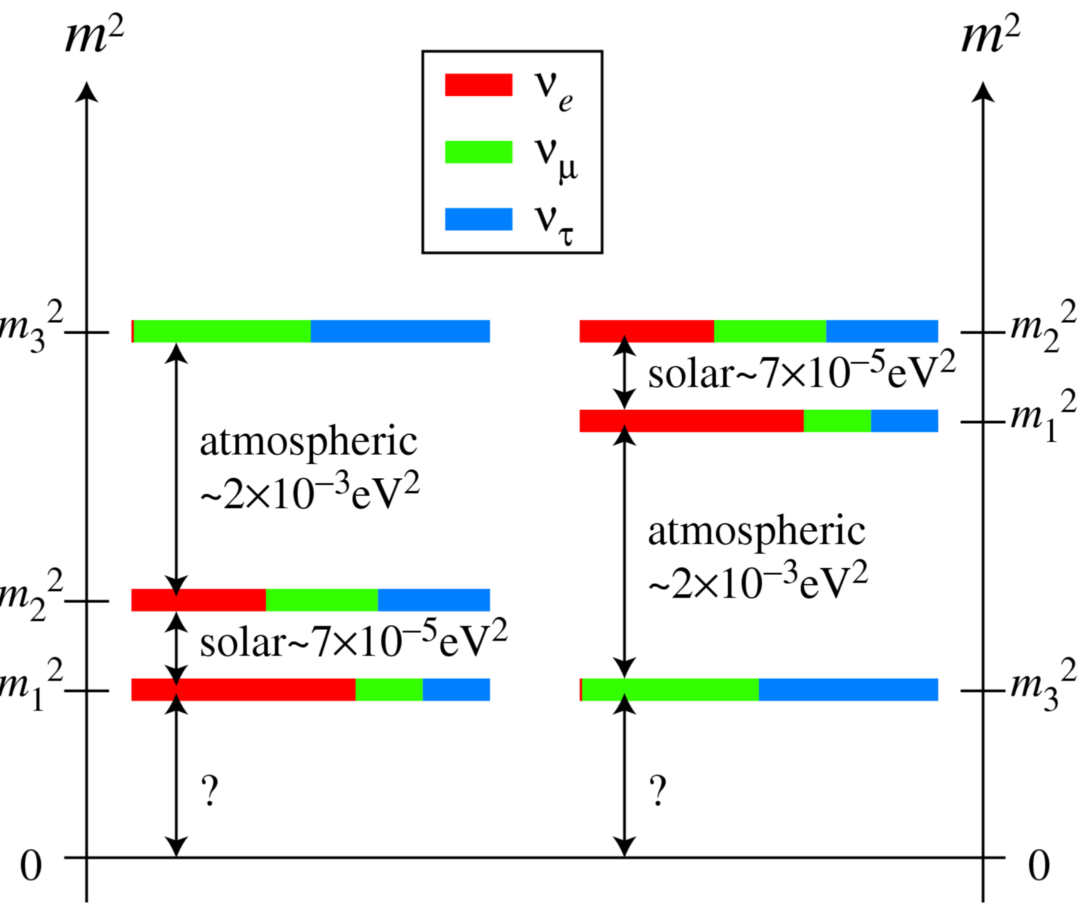
- **neutrinos have mass and mix!**
- **neutrino oscillation experiments**
  - $\Delta m_{ik}^2 = |m_i^2 - m_k^2|$ and $\sin^2 2\vartheta_{ik} = f(|U_{lk}|^2)$
- **direct neutrino mass measurements** (^{3}H exp)
  - $m_{\nu e} < 2.2$ eV 95% CL
- **cosmology** (WMAP+2dFGRS+...)
  - $\sum m_\nu < \approx 1.0$ eV (but model dependent...)

neutrino mixing matrix

neutrino mass eigenstate

$$|\nu_l\rangle = \sum_k U_{lk} |\nu_k\rangle$$

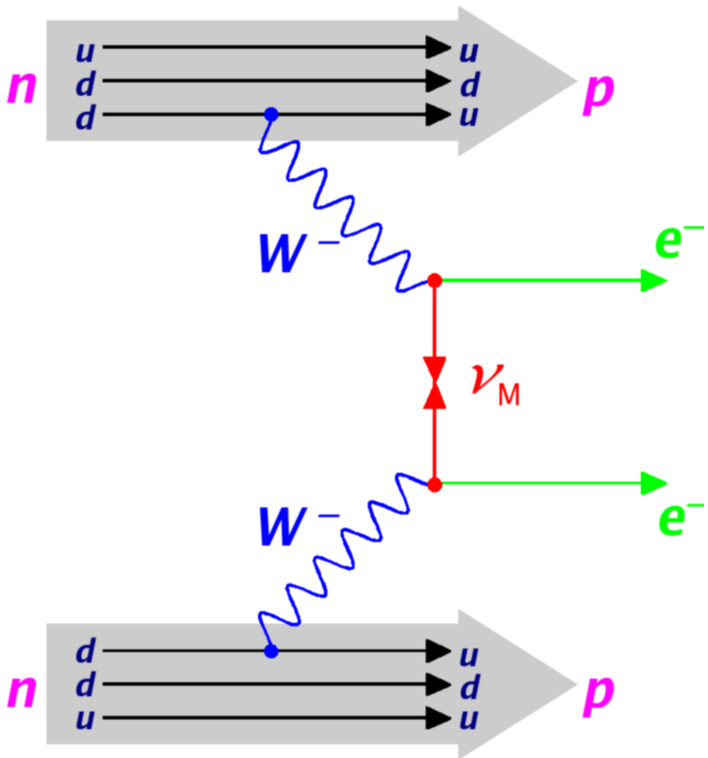
neutrino flavor weak eigenstate



still missing

- mass scale (i.e. mass of the lightest ν)
- hierarchy
  - $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$?
- Dirac or Majorana particle?
- CP violation in the lepton sector

$\beta\beta$-0ν and neutrino properties



- a virtual neutrino is exchanged
  - neutrino must have **mass** to allow helicity non conservation $\Rightarrow \Delta H=2$
  - neutrino must be a **Majorana particle** to allow lepton number non conservation $\Rightarrow \Delta L=2$

$$\beta\beta\text{-}0\nu \Leftrightarrow \begin{cases} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{cases}$$

- these conditions hold even if other mechanisms are possible and may dominate

light Majorana ν mediated $\beta\beta$-0ν decay rate

$$\frac{1}{\tau^{0\nu}_{1/2}} = \frac{\langle m_\nu \rangle^2}{m_e^2} \cdot F_N$$

nuclear structure factor

$$F_N \equiv G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2$$

$G^{0\nu}$: phase space

$M^{0\nu}$: matrix element

effective neutrino Majorana mass

$$\langle m_\nu \rangle = \left| \sum_k m_{\nu_k} \eta_k |U_{ek}|^2 \right|$$

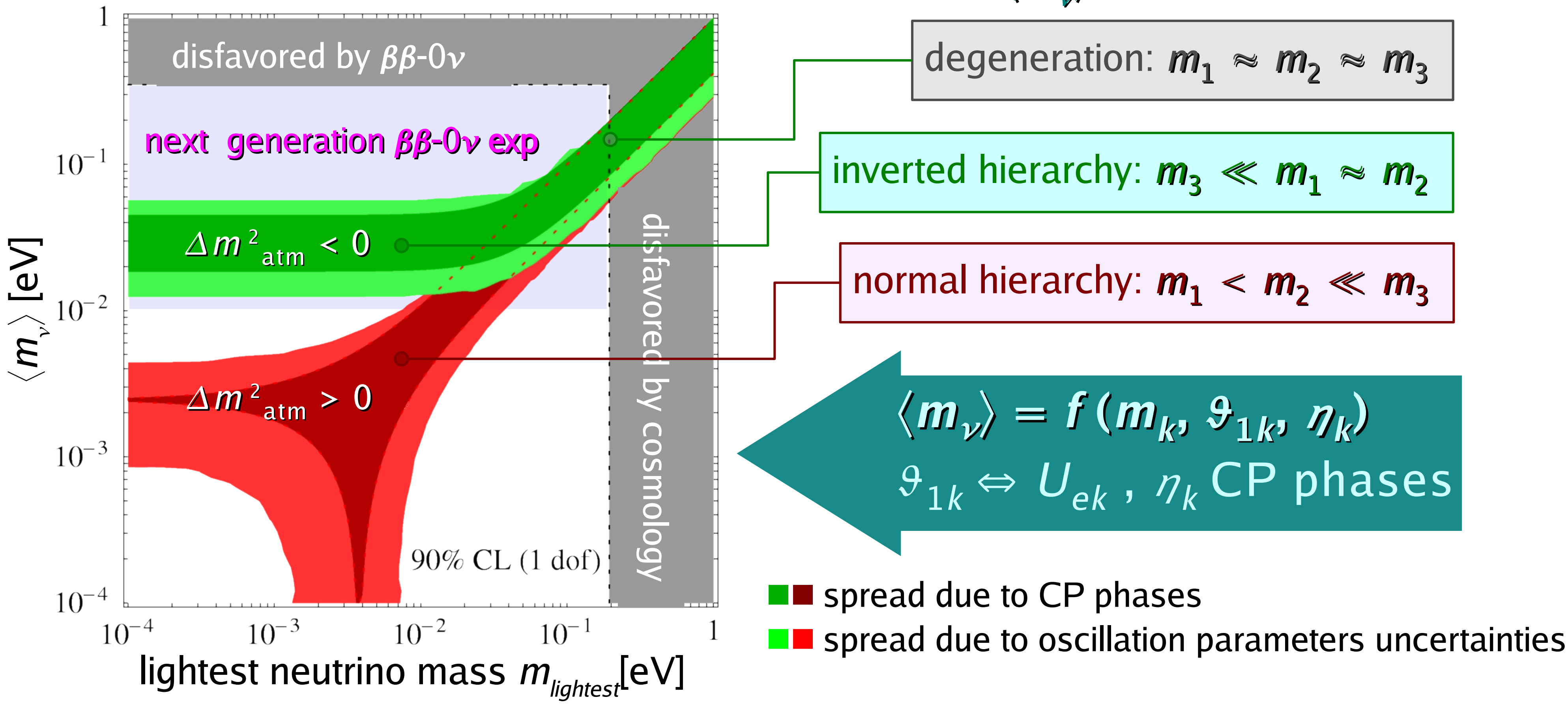
η_k: CP phases*

U_{ek}: neutrino mixing matrix

* CP conservation $\Rightarrow \eta_k = \pm 1$

Role of $\beta\beta$-0ν in future neutrino physics

- next generation experiments aim at $\langle m_\nu \rangle \approx 10$ meV

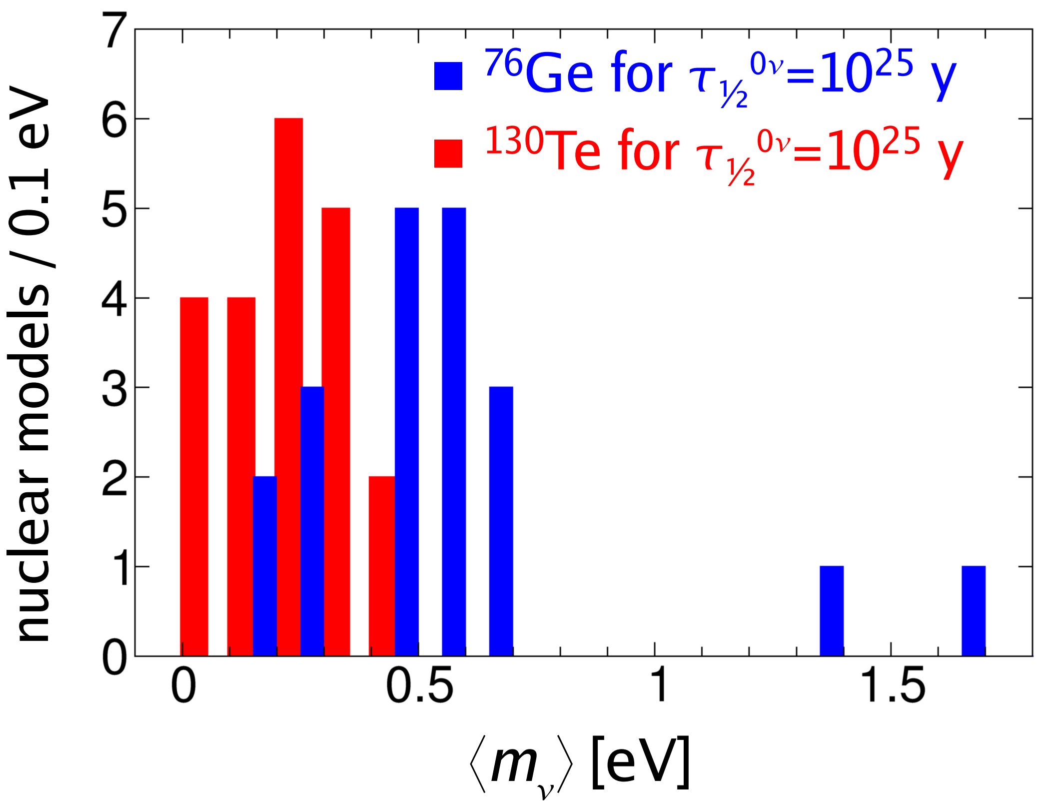


- discovery with $\langle m_\nu \rangle \geqslant 10$ meV
  - the neutrino is a **Majorana particle**
  - $\langle m_\nu \rangle \geqslant \approx 50$ meV $\Rightarrow$ **degeneration** and **absolute ν mass scale** fixed
- upper limit with $\langle m_\nu \rangle < 10$ meV
  - **if** neutrinos are Majorana particles $\Rightarrow$ normal hierarchy

$\beta\beta$-0ν and nuclear physics

$$\langle m_\nu \rangle^2 = \frac{1}{F_N} \cdot \frac{m_e^2}{\tau_{1/2}^{0\nu}} \qquad F_N \equiv G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2$$

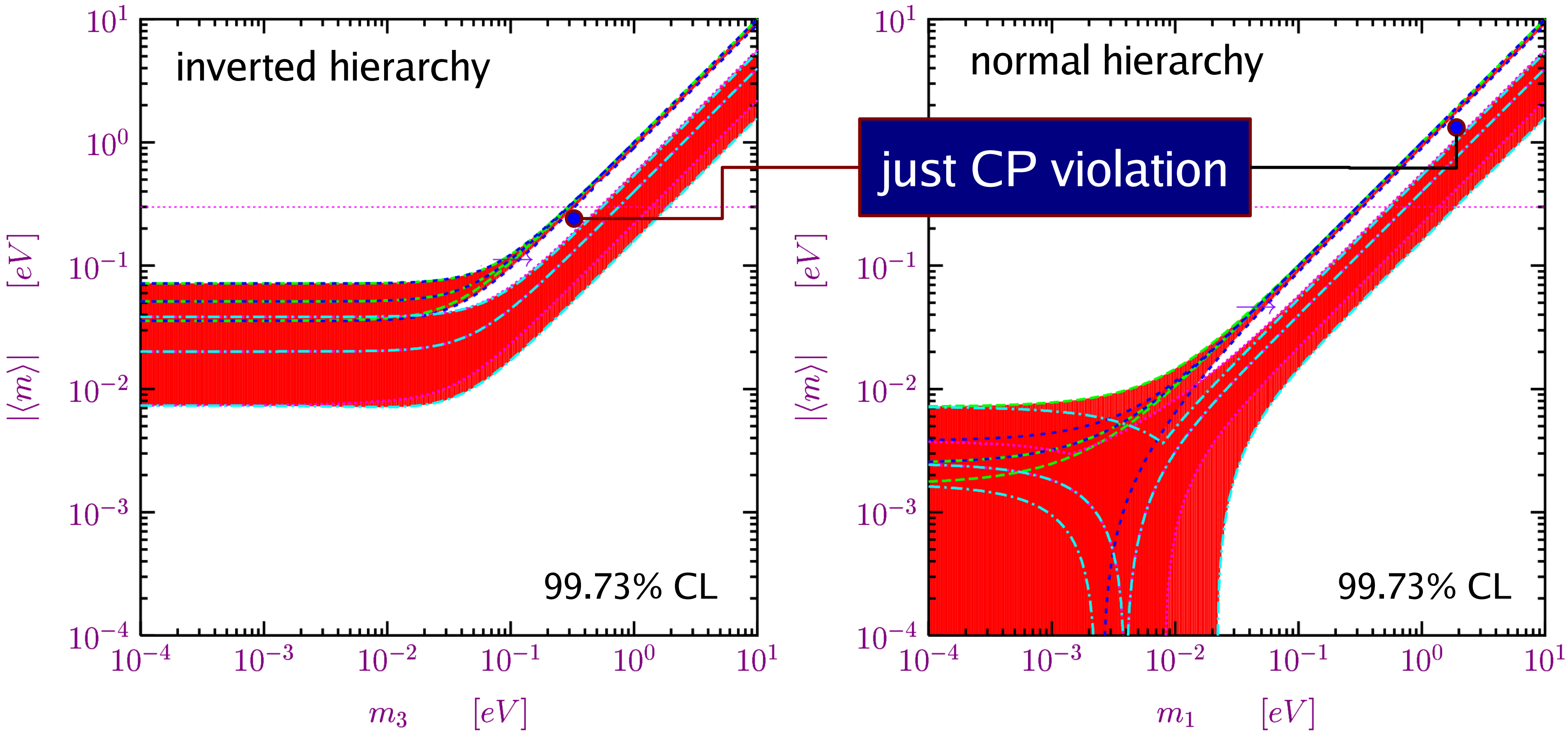
- phase space $G^{0\nu}(Q_{\beta\beta},Z) \propto Q_{\beta\beta}{}^5$ can be precisely evaluated
- matrix element $|M^{0\nu}|$ contains details of **nuclear physics** source of uncertainties
  - $\langle m_\nu \rangle$ is affected by large uncertainties (a factor $\approx$3)



- accurate measurements of $\tau_{½}^{2\nu}$ can help reducing spread in nuclear model predictions (QRPA)
  V.A. Rodin et al., Nucl. Phys. A766 (2006) 107
  M. Kortelainen et al., 0705.0469v1 [nucl-th]
- search $\beta\beta$-0ν for as many different isotopes as possible

$\beta\beta$-0ν and CP violation

- $\langle m_\nu \rangle$ depends on **Majorana CP violation phases** in the neutrino mixing matrix
  - baryon asymmetry in Universe through Leptogenesis theory

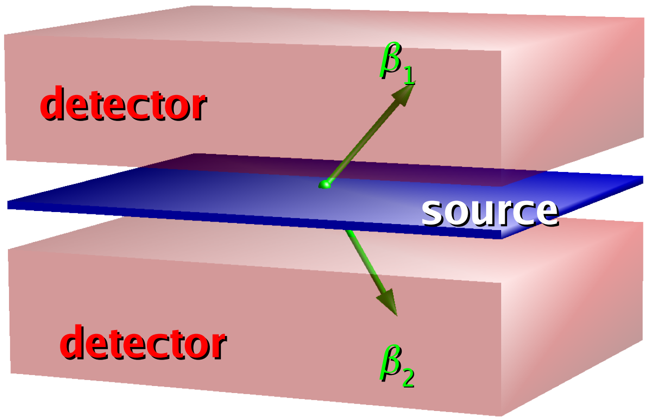


- it is very difficult to establish **CP violation in $\beta\beta$-0ν**

S. Pascoli et al. hep-ph/0505226, S. Pascoli et al. Phys. Lett. B549 (2002) 177, V. Barger et al. Phys. Lett. B540 (2002) 247

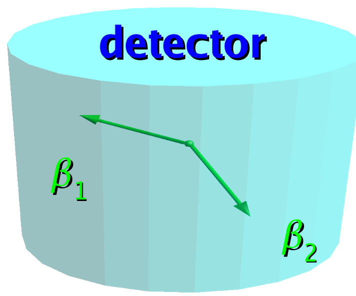
- **possible only for some values of the parameters**
- uncertainties in the oscillation parameters
- uncertainties in the determination of $\langle m_\nu \rangle$ and $m_{lightest}$ (or Σm_ν)
- uncertainties in the nuclear matrix elements

Experimental approaches for $\beta\beta$-0ν



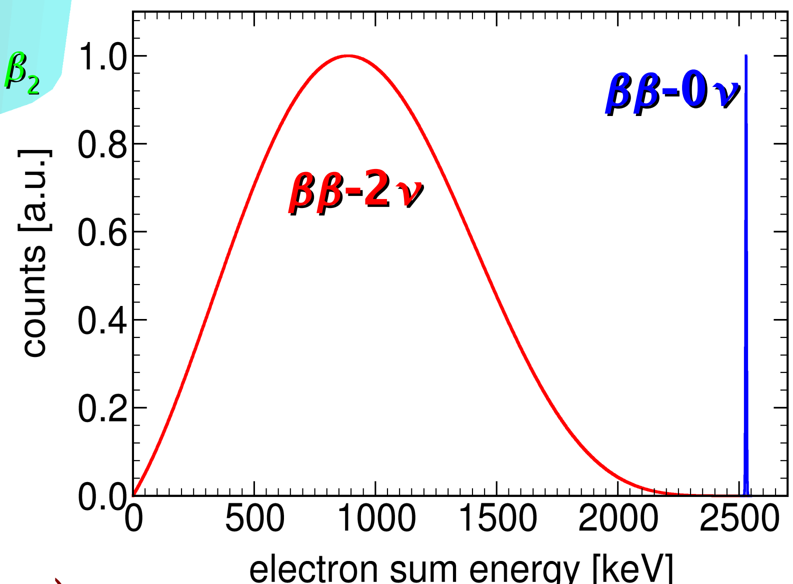
Source ≠ detector

- source in foils
- electrons analyzed by TPCs, scintillators, drift chambers,...
  - ▲ background rejection by event topology
  - ▲ angular correlation gives signature of mass mechanism
  - ▲ any isotopes with solid form possible
  - ▼ small amount of material
  - ▼ poor efficiency
  - ▼ poor energy resolution



Source ⊆ detector (calorimetry)

- detector measures sum energy $E = E_{\beta_1} + E_{\beta_2}$
  - ▶ $\beta\beta$-0ν signature: a peak at $Q_{\beta\beta}$
- scintillators, bolometers, semiconductor diodes, gas chambers
  - ▲ large masses
  - ▲ high efficiency
  - ▲ many isotopes possible
- depending on technique
  - high energy resolution (bolometers, semiconductors)
  - moderate topology recognition (Xe TPC, semiconductors)



Experimental sensitivity for $\beta\beta$-0ν

$$m_\nu \propto \sqrt{1/\tau_{1/2}^{0\nu}}$$

Experimental $\beta\beta$-0ν rate

- with $N_{\beta\beta}$ decays observed

$$\tau_{1/2}^{0\nu} = \ln 2 \frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

number of active nuclei N_{nuclei} = $i.a. \mathcal{N}_A M / A$

measuring time [y]

Experimental sensitivity to $\tau_{½}^{0\nu}$

- with no decay observed
  - $N_{\beta\beta} \leqslant (bkg \cdot \Delta E \cdot M \cdot t_{meas})^{½}$ at 1σ

$$\sum(\tau_{1/2}^{0\nu}) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M t_{meas}}{\Delta E \cdot bkg}}$$

detector mass [kg]

detector efficiency

isotopic abundance
atomic number

energy resolution [keV]

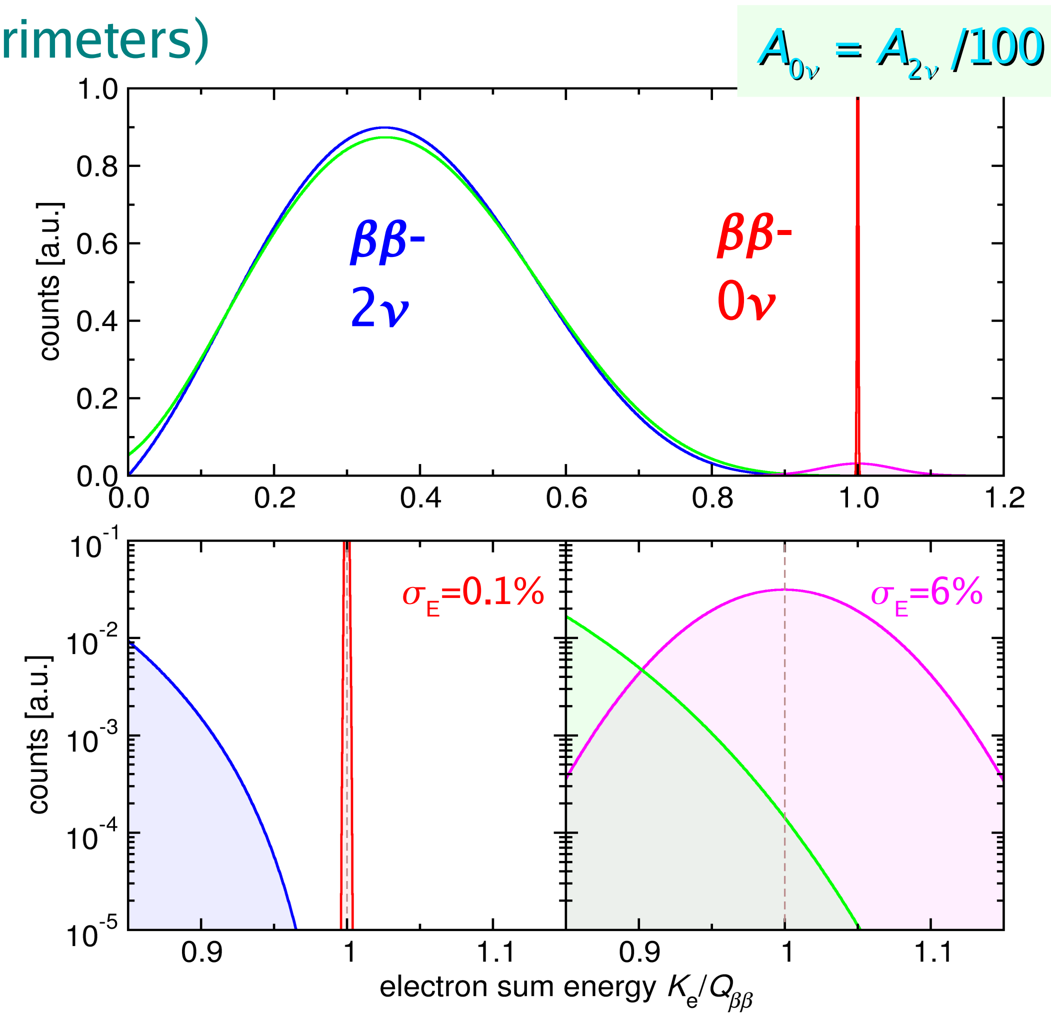
specific background [c/keV/kg/y]

- for $bkg = 0 \Rightarrow N_{\beta\beta} \leqslant 3$ at 2σ

$$\sum(\tau_{1/2}^{0\nu}) \propto \frac{\epsilon\, i.a.}{A} M t_{meas}$$

Background in $\beta\beta$-0ν experiments

- **depends on technique**
  - internal to source (and detector for calorimeters)
    - primordials (^{238}U, ^{232}Th, ^{40}K, ...), artificial
    - cosmogenic activation
  - external
    - primordials and artificial in close materials
    - neutrons
    - cosmic rays
  - specific to techniques
    - quenched αs for scintillators
    - primordials on surface for bolometers



- ***ββ*-2ν tail** is an unavoidable background
  - importance of energy resolution
- **solutions also depend on technique**
  - heavy shielding and underground
  - material selection and purification
  - short exposure to cosmic rays
  - PSD, tracking, segmentation, signatures ...
  - profit of Borex, SNO and SK experience and/or clean environment (⇒ ***immersion***)
- **background estimate and reduction is becoming hard (few counts per year)**
  - **intermediate size experiments are often required**

Present experimental situation

- **best result** per isotope to date
- exposure: **exp = $M \times t_{meas}$**
  - □ positive result
  - ■ running experiments

$$\sum \left(\tau^{0\nu}_{1/2}\right) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

isotope	experiment	latest result	$Q_{\beta\beta}$ [keV]	i.a. [%]	enrich [%]	exp [kg×y]	tech	material	$\tau_{1/2}^{0\nu}$ [10^{23} y]	$\langle m_\nu \rangle$ [eV] min	$\langle m_\nu \rangle$ [eV] max	$\tau_{1/2}^{0\nu}\|_{10meV}$ [10^{28} y] max
^{48}Ca	Elegant VI	2004	4271	0.19	-	4.2	s	CaF_2	0.14	7.2	44.7	8.8
^{76}Ge	Heidelberg/Moscow	2004	2039	7.8	87	71.7	i	Ge	120.0	0.44		17.7
^{82}Se	NEMO-3	2007	2995	9.2	97	1.8	t	Se	1.2	1.6	4.5	5.6
^{100}Mo	NEMO-3	2007	3034	9.6	95-99	13.1	t	Mo	5.8	0.6	2.4	3.9
^{116}Cd	Solotvina	2003	3034	7.5	83	0.5	s	$CdWO_4$	1.7	*1.7*		4.7
^{130}Te	Cuoricino	2006	2529	33.8	-	11.8	b	TeO_2	30.0	0.16	0.84	5.8
^{136}Xe	DAMA	2002	2476	8.9	69	6.4	s	Xe	12.0	1.1	2.9	12.1
^{150}Nd	Irvine TPC	1997	3367	5.6	91	0.01	t	Nd_2O_3	0.012	*3.0*		0.1
^{160}Gd	Solotvina	2001	1791	21.8	-	1.0	s	Gd_2SiO_5	0.013	*26.0*		0.9

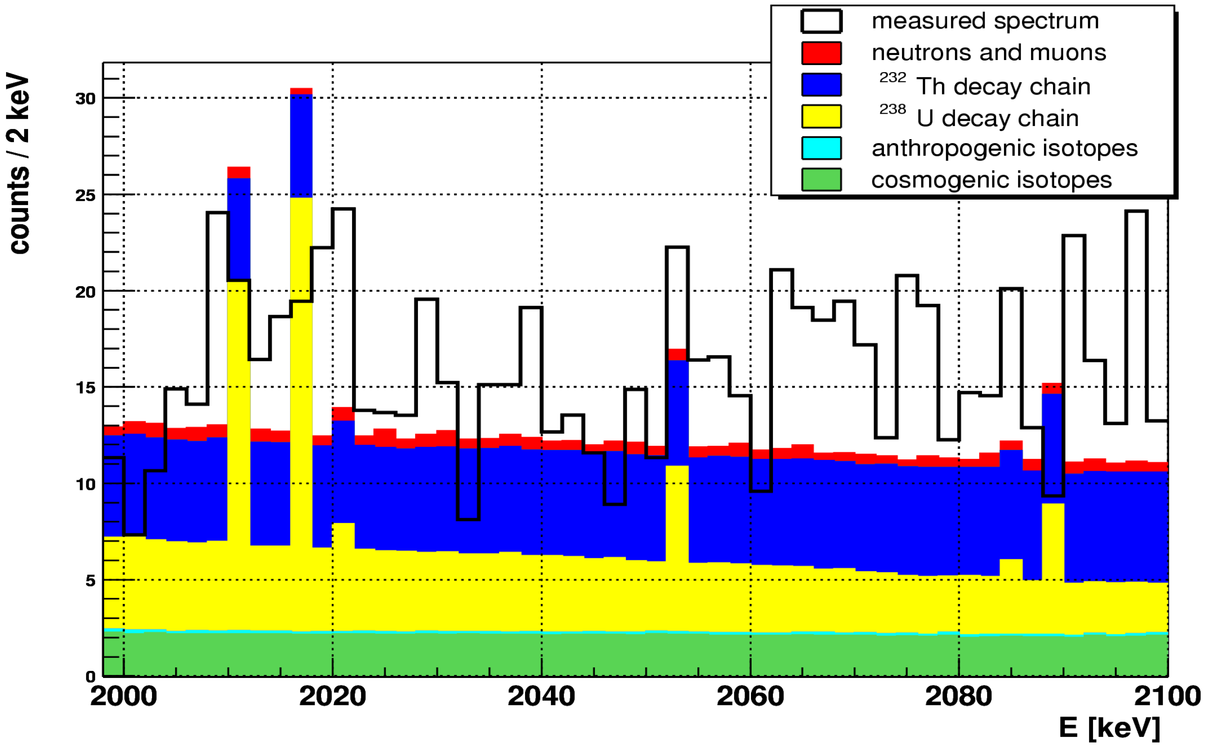
s scintillation
i ionization
t tracking
b bolometric

spread due to uncertainties in F_N

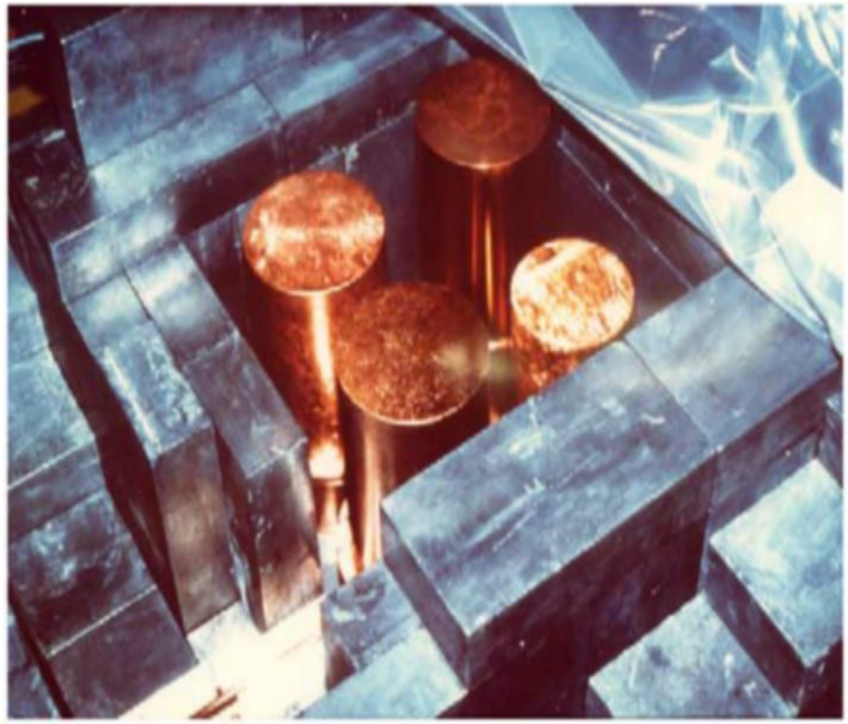
half-life expected for $\langle m_\nu \rangle$ = 10 meV and the **less favorable F_N**

^{76}Ge Heidelberg-Moscow experiment

- calorimetric experiment with Ge semiconductor detectors
- 5 HP-Ge crystals, enriched to 87% in ^{76}Ge
  - total active mass of 10.96 kg ⇒ 125.5 moles of ^{76}Ge
- run from 1990 to 2003 in Gran Sasso Underground Laboratory
- total exposure 71.7 kg×y
  - 820 moles×y
- main background from U/Th in the set-up
  - $b \approx 0.11$ c/keV/kg/y at $Q_{\beta\beta}$



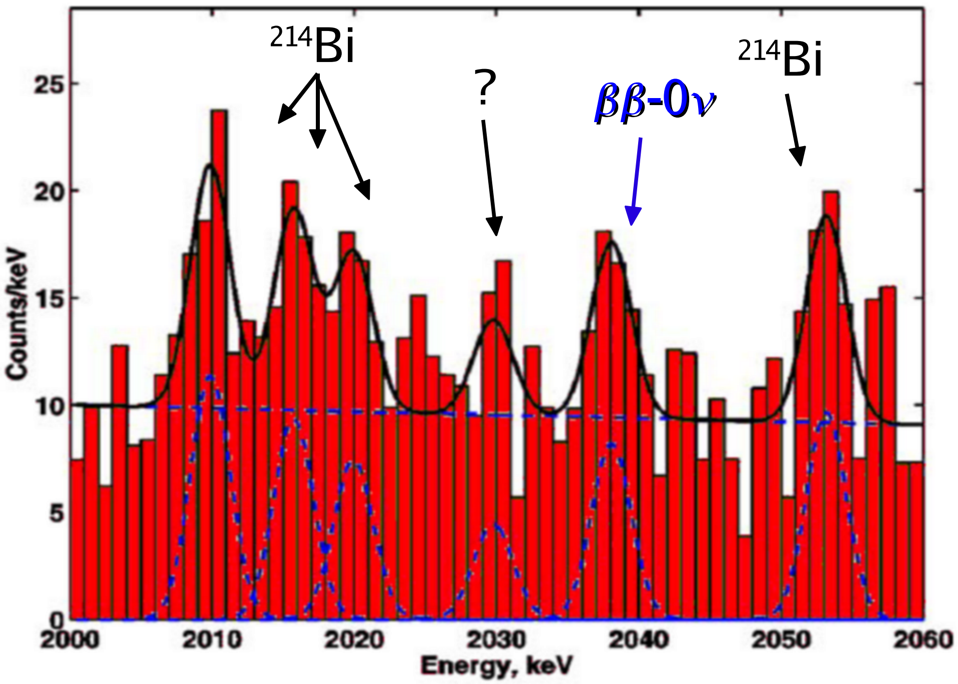
H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B 586 (2004) 198



- PSD since end of 1995 for 4 detectors (51.4 kg×y) to reduce bkg
  - $\beta\beta$ decays and double escape γ peaks are Single Site Events
  - γ interactions are usually Multiple Site Events
  - also internal βs are SSE

Heidelberg-Moscow exp.: evidence for $\beta\beta$-0ν of ^{76}Ge

- best exploitation of the Ge detector technique proposed by E. Fiorini in 1960
  - longest running experiment (13 years) with largest exposure (71.7 kg×y)
  - Status-of-the-art for low background techniques and for enriched Ge detectors
  - reference for all last generation $\beta\beta$-0ν experiments



1990 – 2003 data, all 5 detectors

exposure = 71.7 kg×y

$\tau_{1/2}^{0\nu}$ **= 1.2×10^{25} years**

$\langle m_\nu \rangle$ **= 0.44 eV**

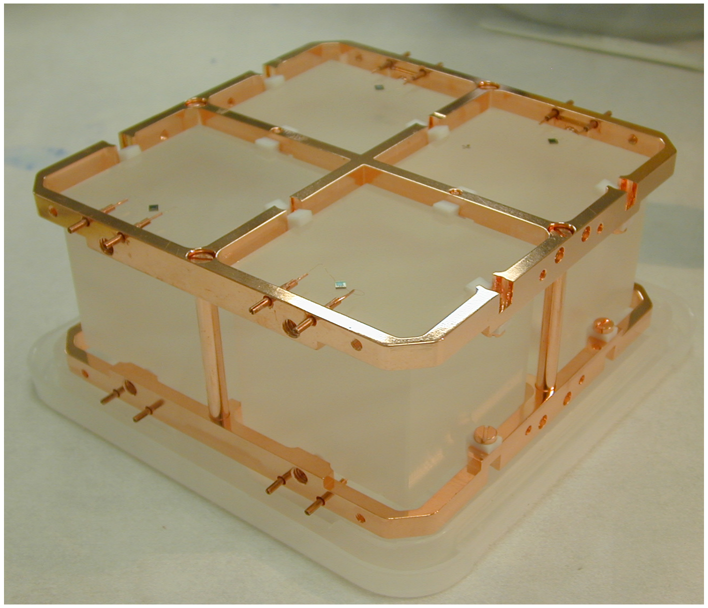
H.V.Klapdor-Kleingrothaus *et al.*, Phys. Lett. B 586 (2004) 198

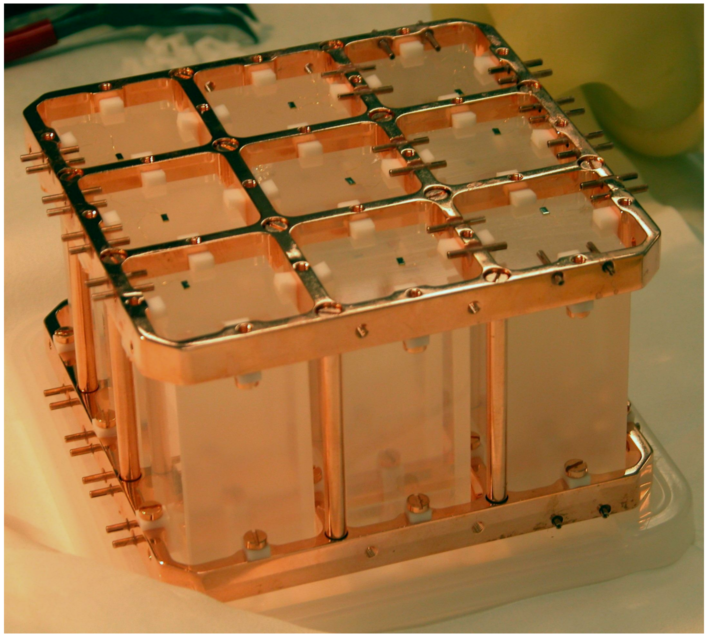
- the neutrino physics community **is still careful to accept the result**, because:
  - signal is indeed **very faint (4 σ)**: statistical significance strongly depends on continuum background level H.V.Klapdor-Kleingrothaus *et al.*, NIM A 522 (2004) 371
  - presence of **not understood peaks** around the signal and with *similar* significance
  - impossibility to check an **energy window larger** than the published one
- **nevertheless any future $\beta\beta$-0ν experiment will have to challenge this result**

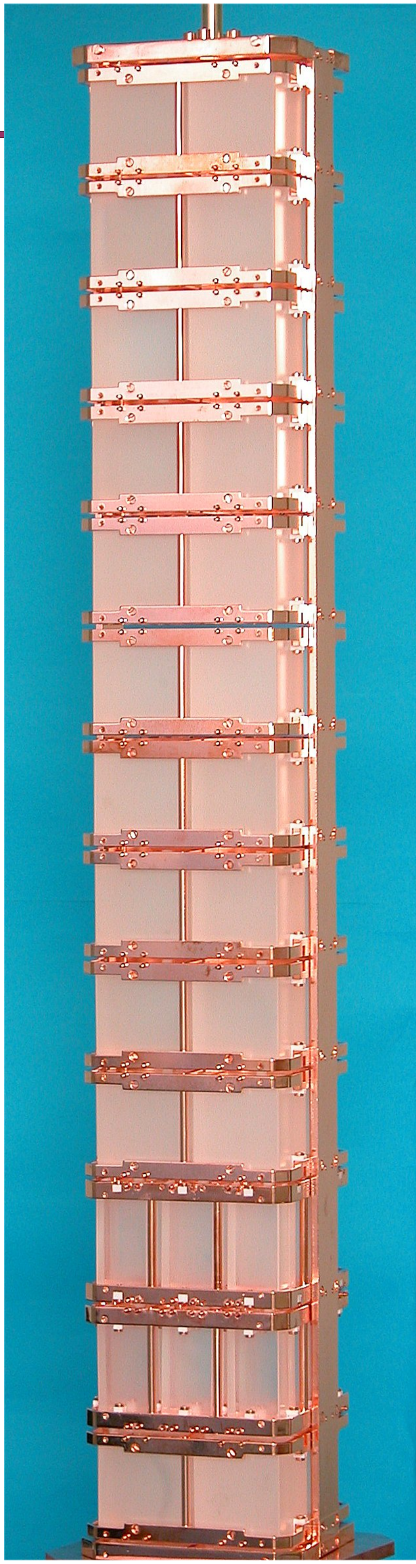
^{130}Te CUORICINO experiment / 1

TeO_2 thermal calorimeters

- **Active isotope ^{130}Te**
  - natural abundance: a.i. = 33.9%
  - transition energy: $Q_{\beta\beta}$ = 2529 keV
  - "short" predicted half life
    $\langle m_\nu \rangle \approx 0.3$ eV $\Leftrightarrow$ $\tau_{1/2}^{0\nu} \approx 10^{25}$ years
- **Absorber material TeO_2**
  - low heat capacity
  - large crystals available
  - radiopure





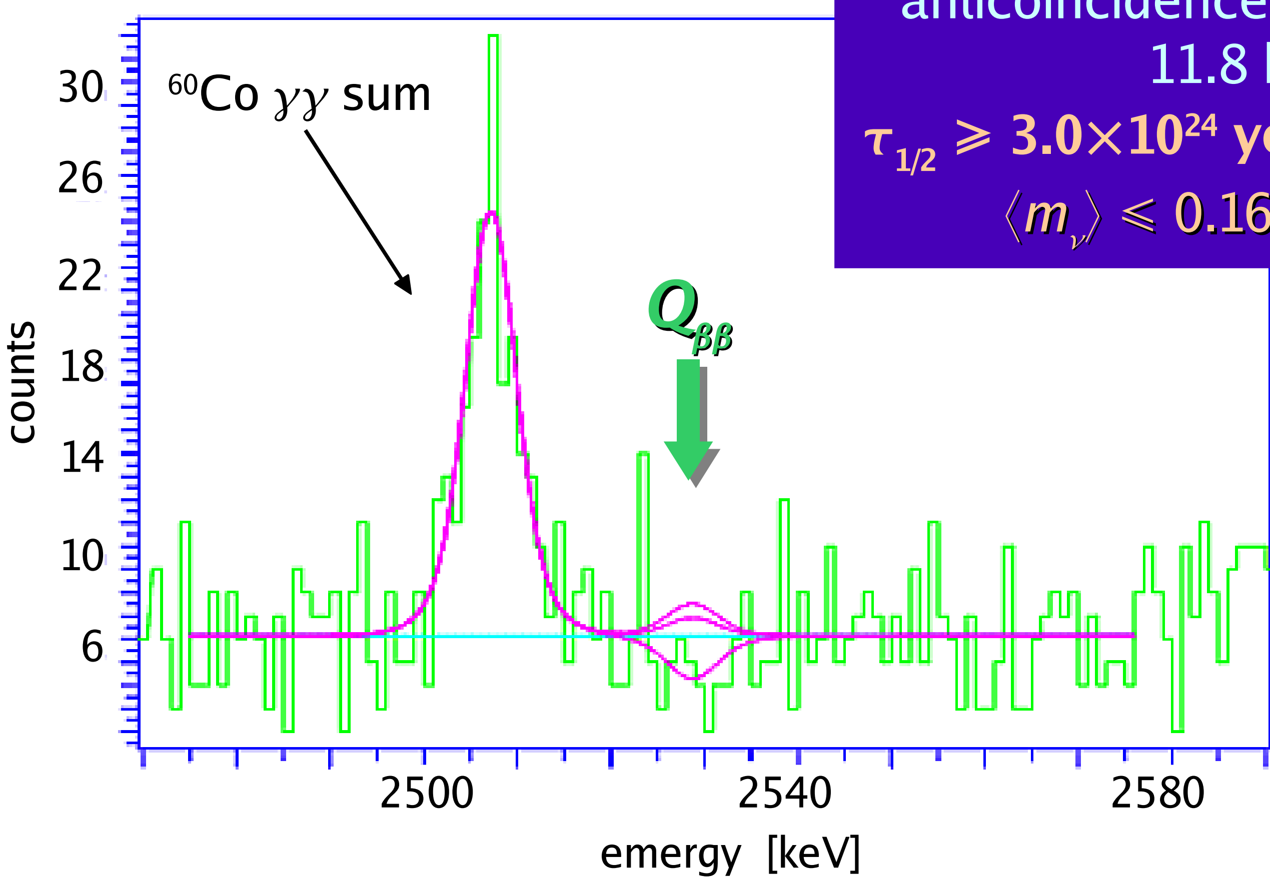


CUORICINO experiment

- running @ LNGS since 2003
- 62 TeO_2 detectors in the ***tower*-like structure** foreseen for **CUORE**
- ~0.01 K operating temperature
- 330 and 790 g crystals
  - ▷ **total TeO_2 mass 41 kg (11 kg ^{130}Te)**
- ▶ **intermediate size $\beta\beta$ experiment**
- ▶ **test for radioactivity**

^{130}Te CUORICINO experiment / 2

- total exposure 11.8 kg×y
  - 90.7 moles×y of ^{130}Te
- energy resolution FWHM $\Delta E = 8$ keV at $Q_{\beta\beta}$ (σ_E=1.3‰)
- anticoincidence applied to reduce surface U/Th background and external γs
- background mainly from U/Th on Cu and TeO_2 surfaces (α and β)
  - $b \approx 0.18$ c/keV/kg/y at $Q_{\beta\beta}$



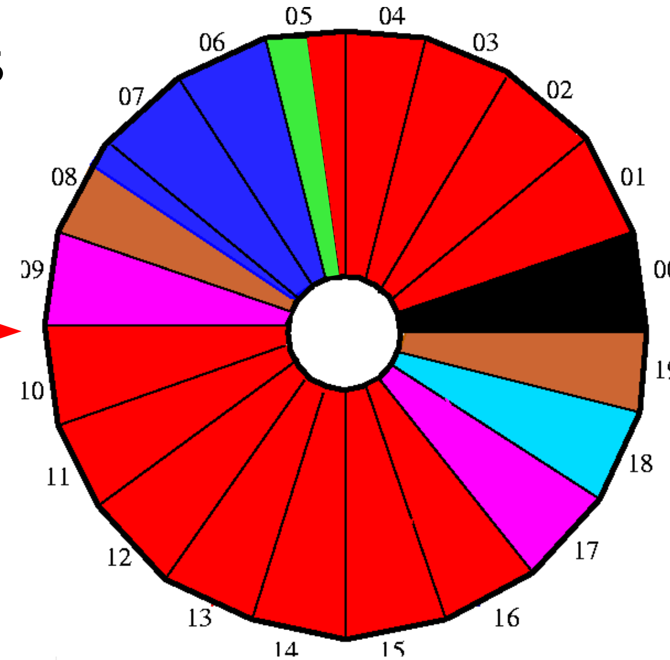
anticoincidence sum spectrum
11.8 kg×y
$\tau_{1/2} \geqslant 3.0\times10^{24}$ years at 90% C.L.
$\langle m_\nu \rangle \leqslant 0.16 \div 0.84$ eV

- experiment still running
- in 3 y ⇒ 120 kg×y
  - **$\tau_{1/2} \geqslant 5\times10^{24}$ y at 1σ**
  - **$\langle m_\nu \rangle \leqslant 0.1 \div 0.6$ eV**

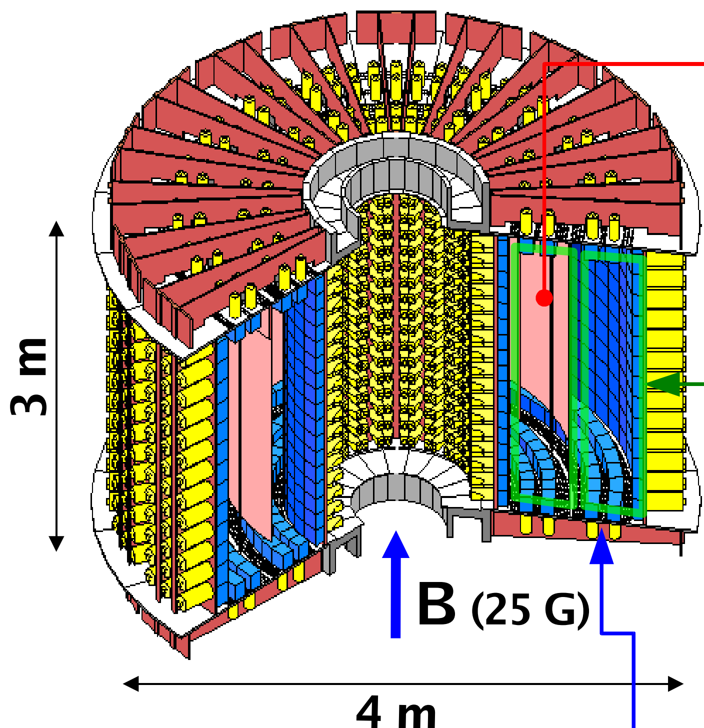
Latest results presented by E. Fiorini at NOW2006
To be published

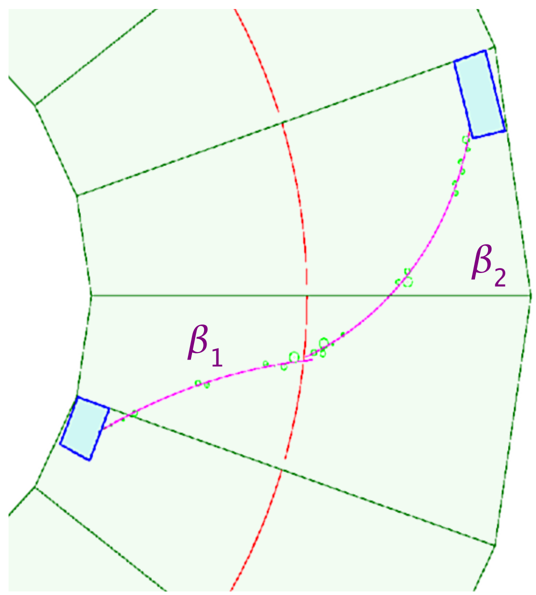
NEMO-3 experiment on ^{100}Mo and ^{82}Se / 1

- **Tracking detector for $\beta\beta$-2ν and $\beta\beta$-0ν @ Frejus**
  - 10 kg of enriched material in foils
  - 6180 Geiger cells ⇒ drift wire chamber
  - 1940 plastic scintillators + PMTs
- can identify e^-, e^+, γ and α



sources in foils





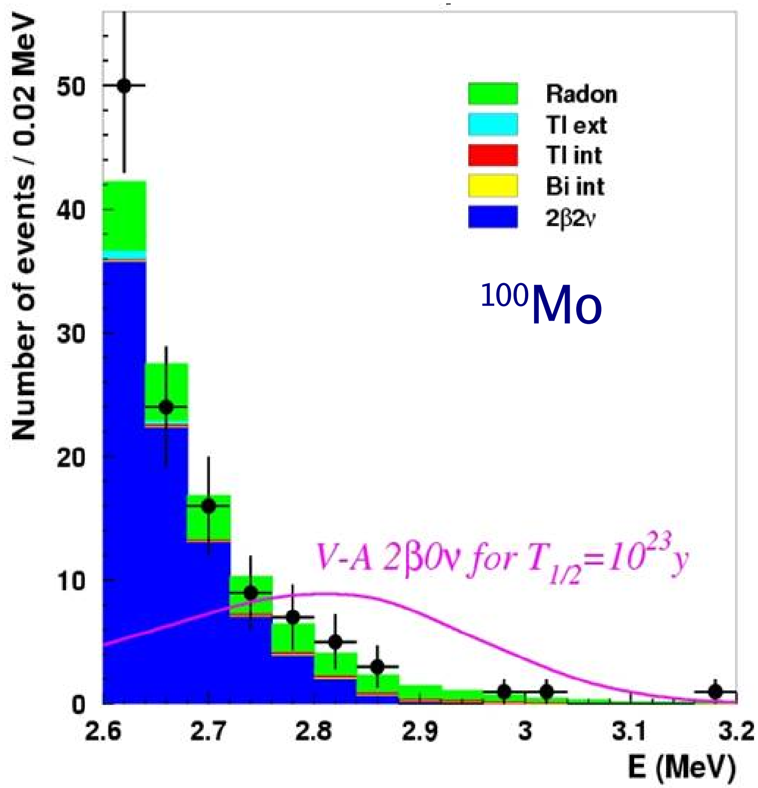
calorimeter (scintillators)

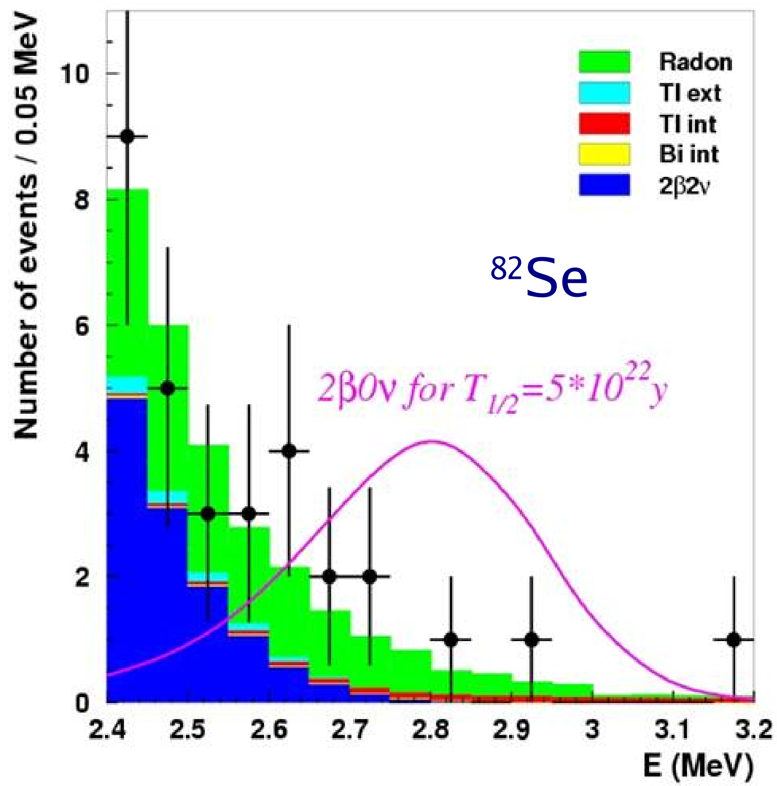
tracking volume (drift wire chamber)

^{100}Mo	(6.9 kg)	➡ $\beta\beta$-0ν
^{82}Se	(0.9 kg)	
^{130}Te	(0.5 kg)	
^{116}Cd	(0.4 kg)	
^{150}Nd	(37g)	
^{96}Zr	(9.4 g)	
^{48}Ca	(7.0g)	
^{nat}Te	(0.6 kg)	
Cu	(0.6 kg)	

NEMO-3 experiment on ^{100}Mo and ^{82}Se / 2

Phase I+II
693 days





- main background sources (^{100}Mo): $\beta\beta$-0ν like events with $2.8<E_1+E_2<3.2$ MeV
  - **radon** (0.11 c/kg/y), **$\beta\beta$-2ν** (0.3 c/kg/y), **^{208}Tl in the foils** (0.1 c/kg/y)
- **likelihood analysis with 3 variables**:
  - $Ec_1 + Ec_2$ (sum of kinetic energies)
  - angle between 2 electron tracks
  - Ec_{min} energy of slower electron
- expected sensitivity (90% CL) end 2009:
  - $\tau_{1/2}^{0\nu} > 2\times10^{24}$ y for ^{100}Mo
  - $\langle m_\nu\rangle \leqslant 0.3\div1.3$ eV for ^{100}Mo

^{100}Mo: $\tau_{1/2}^{0\nu} > 5.8\times10^{23}$ years (90% CL)
$\langle m_\nu\rangle < 0.6\div2.4$ eV

^{82}Se: $\tau_{1/2}^{0\nu} > 1.2\times10^{23}$ years (90% CL)
$\langle m_\nu\rangle < 1.6\div4.5$ eV

Latest results presented by X. Sarazin at LAUNCH 2007

Next generation $\beta\beta$-0ν experiments

- next generation experiments must confirm or reject HM ^{76}Ge result
  - **confirmation**: similar $\langle m_\nu \rangle$ from $\beta\beta$-0ν of other isotopes
  - **rejection**: no $\beta\beta$-0ν in more sensitive ^{76}Ge experiments or much more sensitive experiments on other isotopes
- a ~10 meV sensitivity on $\langle m_\nu \rangle$ gives good chances to **observe** $\beta\beta$-0ν

- promote as many experiments on different isotopes as possible
- reduce uncertainties on nuclear matrix F_N
- increase sensitivity

increase isotopic abundance by enrichment

$$\sum \left(\tau_{1/2}^{0\nu}\right) \propto \epsilon \cdot \frac{a.i.}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

increase experimental mass and measuring time

•reduce background by:
- material selection and proper handling
- choosing proper technique
- using signatures
- improving energy resolution

$bkg = 0 \Rightarrow \sum(\tau_{1/2}^{0\nu}) \propto M\, t_{meas}$

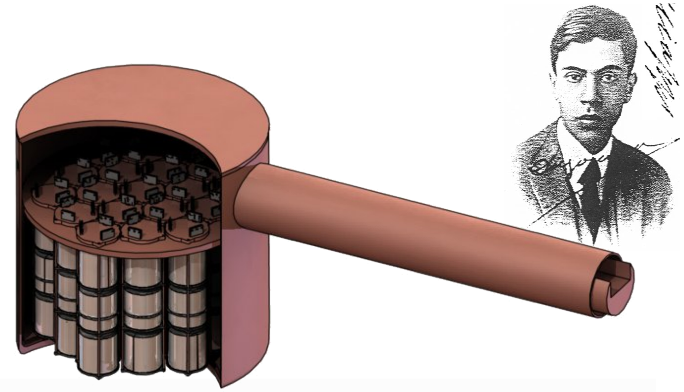
Calorimetric experiment with ionization detectors

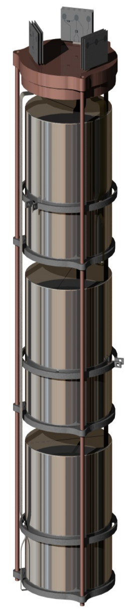
- **Germanium diode experiments**
  - ▲ well known technique
  - ▲ high energy resolution
  - ▲ large masses
  - ▲ segmentation and PSD to reduce background
  - ▼ cost of enrichment
  - ▶ naked crystals in cryogenic liquids (scintillating)
    - Genius/GEM and New Ge experiment at LNGS (GERDA)
  - ▶ standard cooling in ultra low background cryostats
    - Majorana experiment
- **CdTe or CdZnTe diode experiments**
  - ▲ many isotopes at once (including $\beta^+\beta^+$)
  - ▲ segmentation (tracking) to reduce background
  - ▼ new technique, still *poor* energy resolution and small masses
    - COBRA

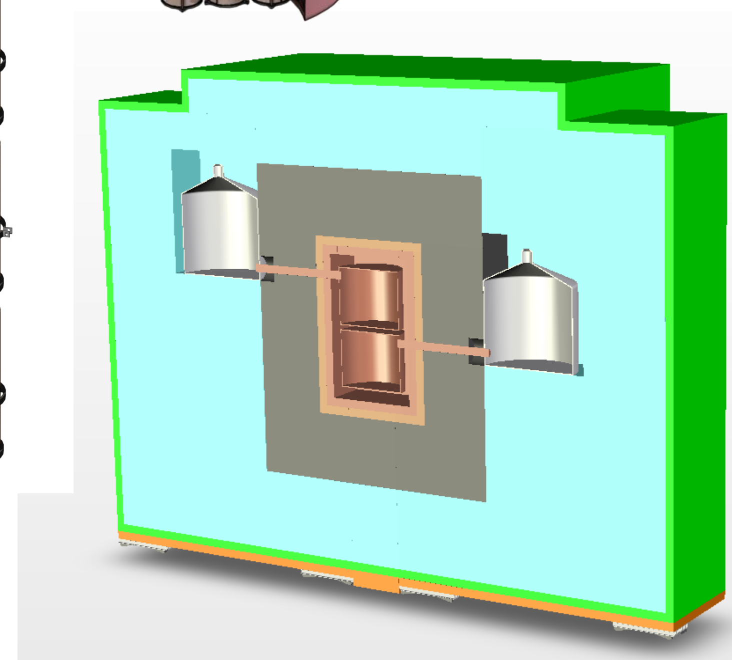
Majorana

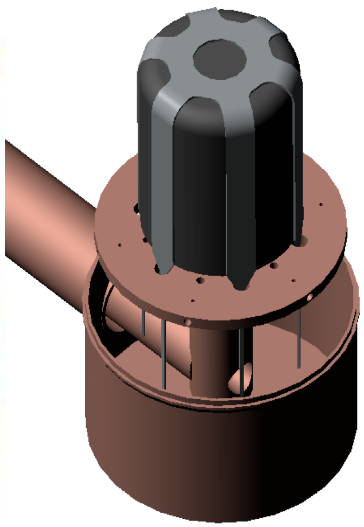
White paper nucl-ex/0311013

- **idea**: **cosmogenics** main background source in Igex
  - **1 ton Ge crystals in ultra low background cryostats**
  - 85% enriched ^{76}Ge
  - granularity, segmentation and PSD to achieve bkg≈0.25 c/keV/t/y
- 2 preliminary phases: SEGA and MEGA
- **staged approach** with 60 kg detector assemblies
- MoU with Gerda for a joint 1 ton experiment









Segmented Enriched Germanium Array

- segmented detectors
- design test

Multi Element Germanium Assay

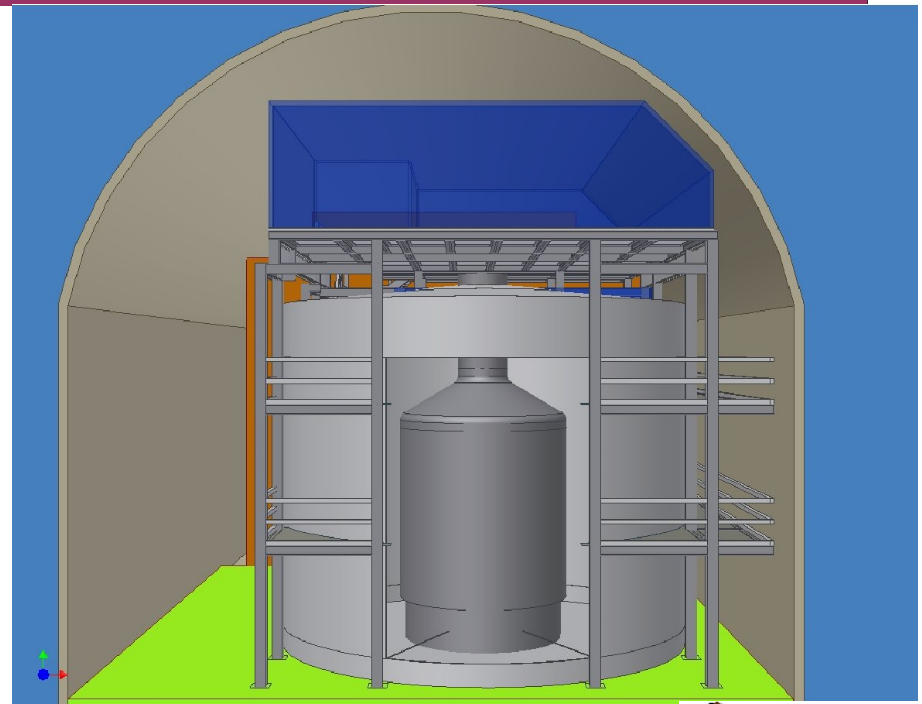
- 2+16 detectors
- design test
- material selection

Majorana 120

- two 60 kg modules (114 detectors)
- in DUSEL or SNOlab from **2010**
  - $\tau_{1/2} \geq 7\times10^{26}$ y in 5 years
  - $\langle m_\nu \rangle \leq 0.09$ eV (90% CL)

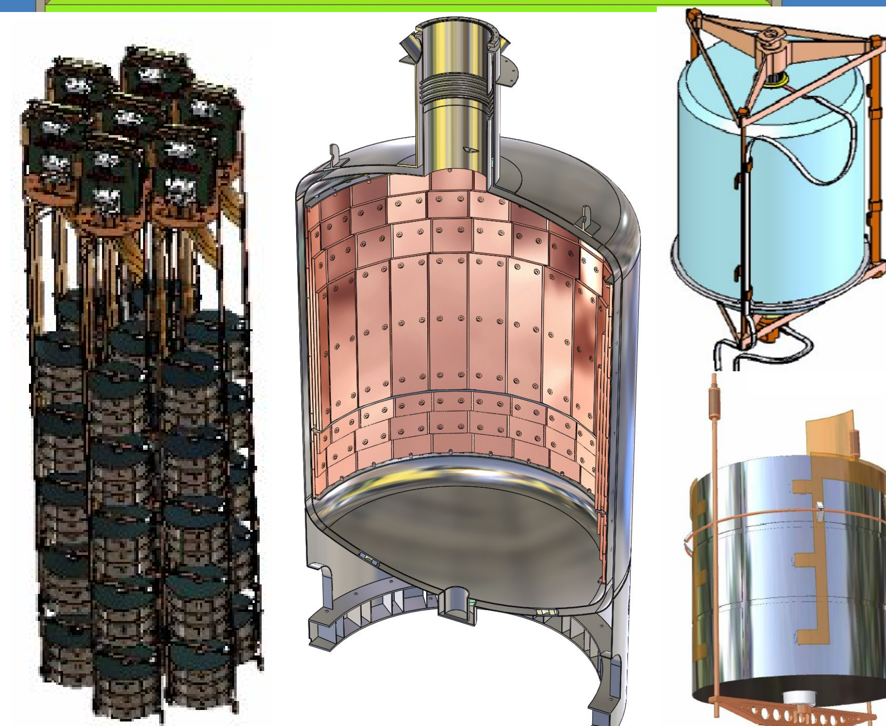
Majorana 180?

New ^{76}Ge Double Beta Decay exp. @ LNGS (aka GERDA)



LoI 16 March 2004, hep-ex/0404039

- **idea**: scrutinize HM evidence in a short time using existing ^{76}Ge enriched detectors (HM, Igex)
- approach similar to GENIUS but smaller
  - **naked Ge crystals in LAr**
  - 4 m LAr + 10 m water
  - active shielding through LAr scintillation
- 3 phases experiment
- **Phase I (start in 2009)**:
  - ≈20 kg refurbished ^{76}Ge from HM and Igex
  - bkg $\leqslant$0.01 c/keV/kg/y (intrinsic)
  - **check at 5σ HM evidence**
  - 15 kg×y ⇒ **6±1 $\beta\beta$ events on 0.5 bkg events**
- **Phase II (funded, in preparation)**:
  - add ≈20 kg **new enriched segmented detectors** with special care for activation
  - bkg ≈0.001 c/keV/kg/y
  - $\tau_{1/2} \geqslant 2\times10^{26}$ y with 100 kg×y
  - $\langle m_\nu \rangle \leqslant 0.09 \div 0.29$ eV
- **Phase III**: $\langle m_\nu \rangle \leqslant$ **0.01 eV with 1 ton Ge**
  - worldwide collaboration (MoU with Majorana)



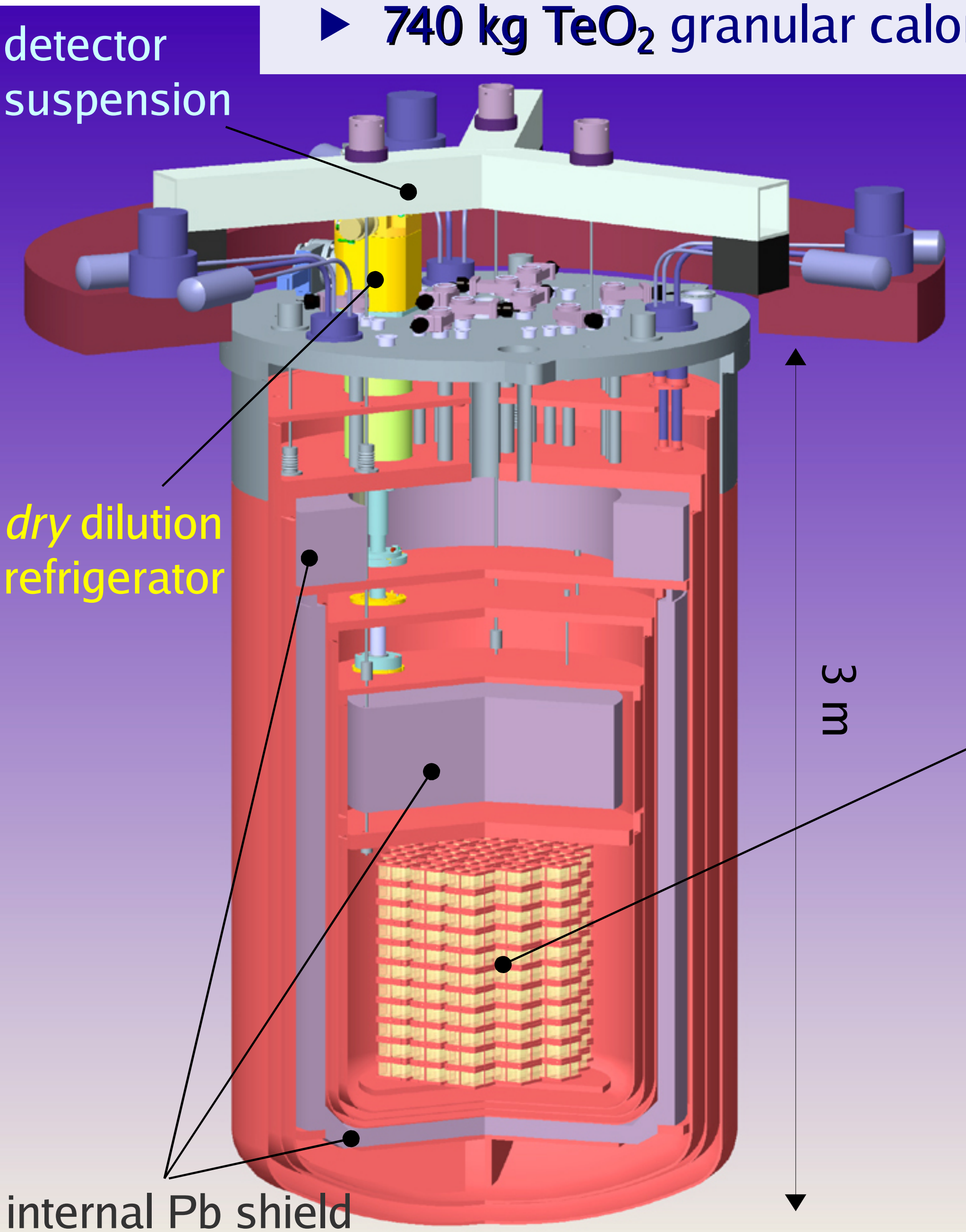
Calorimetric experiments with cryogenic detectors

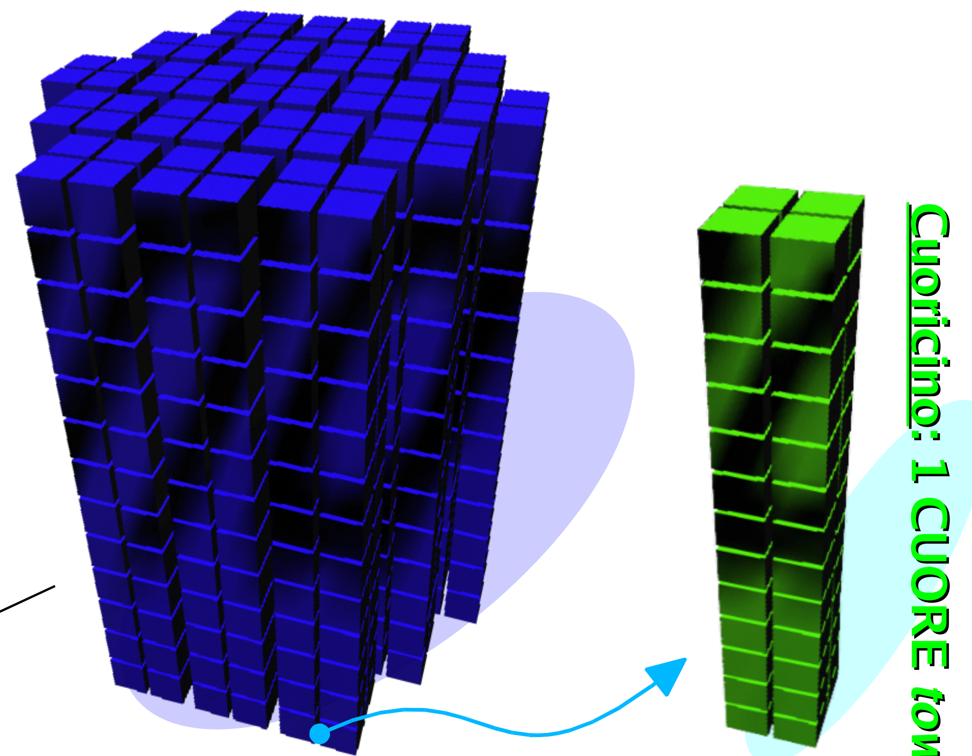
- ▲ true calorimeters
- ▲ wide isotopes choice ^{48}Ca, ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd
- ▲ high energy resolution
- ▲ large masses
- ▲ segmentation to reduce background
- ▼ fully sensitive to surface radioactivity
- ▼ difficult to reduce close materials (holders, wires, cryostats,...)
- ▼ not easy to run stable
- ■ hybrid detectors can do particle identification (i.e. e/γ - α)
  - heat + scintillation detection
  - heat + ionization detection (with PSD + segmentation)
- ▶ CUORE (^{130}Te)
- ▶ Edelweiss (^{76}Ge)
- ▶ MOON (^{100}Mo)?

CUORE / 1

Cryogenic Underground Observatory for Rare Events

- array of 988 natural TeO_2 crystals 5×5×5 cm^3 (750 g) @ LNGS
  - **740 kg TeO_2** granular calorimeter ⇒ **200 kg of ^{130}Te**





CUORE detector
19 *towers* - 52 detectors each

C. Arnaboldi *et al.*, *CUORE: A Cryogenic Underground Observatory for Rare Events*, NIM A 518 (2004) 775; hep-ex/0212053

CUORE / 2

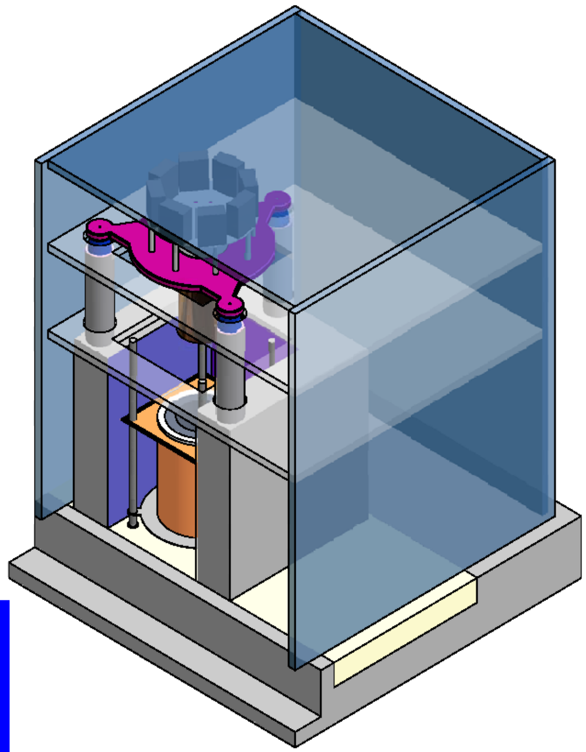
- **compact and granular** ⇒ self shielding detector
- work in progress to **reduce surface radioactivity** (1/100th of CUORICINO)
  - advanced cleaning techniques
  - new **surface sensitive detectors** for active bkg rejection under test

Present status

- **full scale experiment approved and funded**
- dilution refrigerator commissioned
- underground building ready by end 2007
- cryostat design ready for reviewing
- material selection and cleaning procedure settling

Full CUORE experiment

- **start data taking in 2011 @ LNGS**

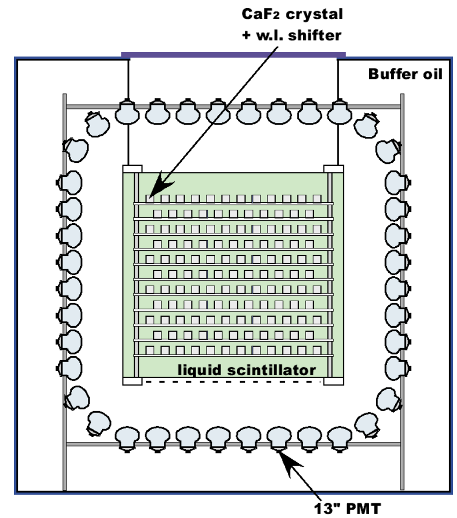


- for $b = 1$ count/ton/year/keV
  and $\Delta E_{FWHM} = 5$ keV
  in 5 years
  - $\tau_{1/2}^{0\nu} \geqslant 6.5 \times 10^{26}$ years at 1σ
  - $\langle m_\nu \rangle \leqslant 11 \div 57$ meV

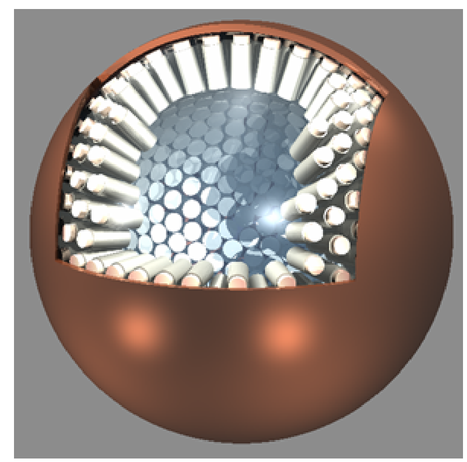
C. Arnaboldi *et al.*, *Physics Potential and Prospects for the Cuoricino and CUORE experiments*, Astropart. Phys. 20 (2003) 91

Calorimetric experiments with scintillators

- ▲ large masses (solid or liquid)
- ▲ well known *simple* techniques
- ▲ wide isotopes choice ^{48}Ca, ^{116}Cd, ^{136}Xe, ^{160}Gd
- ▲ *immersion* in clean liquids to reduce background (Borexino, SNO, SK...)
- ▲ PSD to reduce background
- ▼ poor energy resolution
- ▼ in some cases difficult to have radiopure crystals
- ▼ background from PMTs
- ▶ CANDLES and Carvel (^{48}Ca)
- ▶ XMASS (^{136}Xe) (Dark Matter experiment and solar ν)
- ▶ CAMEO (^{116}Cd)
- ▶ Xenon in Borex (or SNO) (^{136}Xe)
- ▶ *nanocrystals* in SNO (^{48}Ca, ^{82}Se, ^{96}Zr, ^{116}Cd, ^{130}Te, ^{150}Nd)

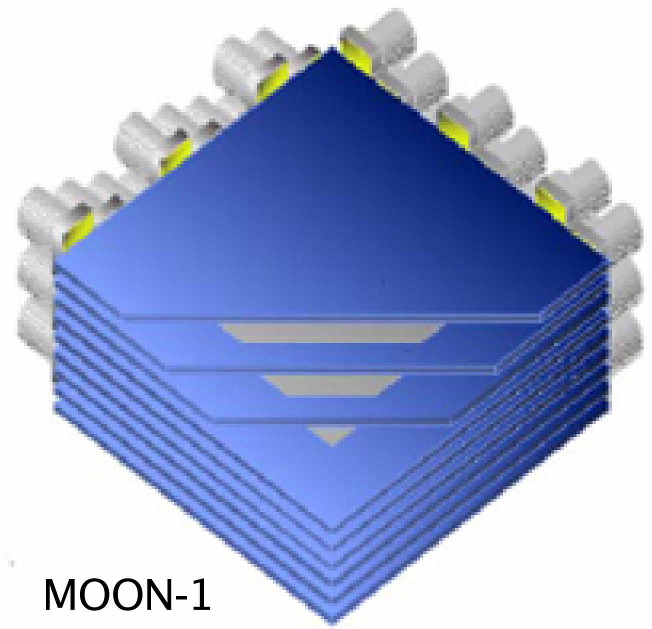


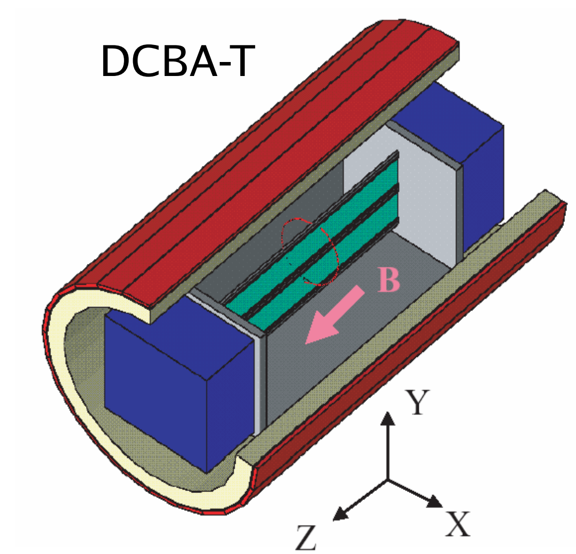
CANDLES IV

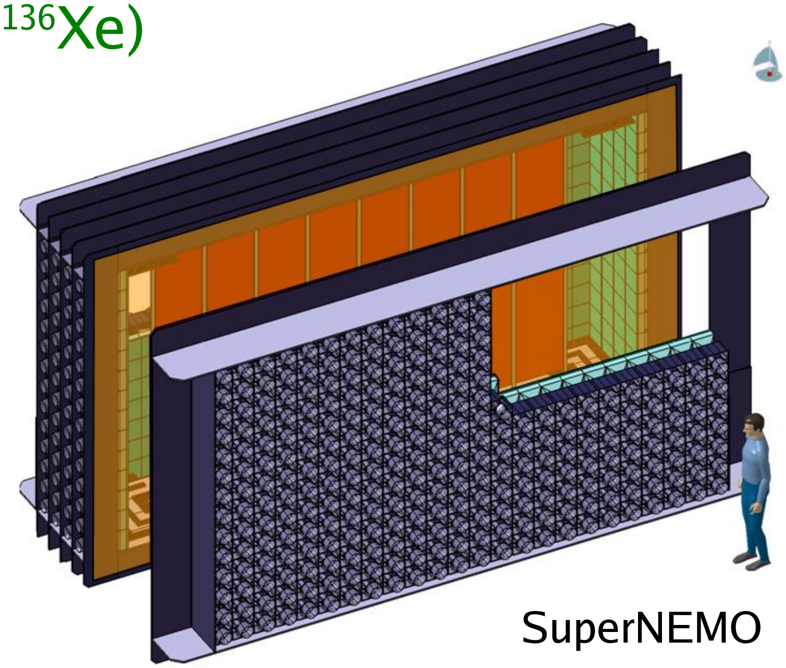

XMASS 800kg

Tracking experiments

- ▲ background reduction by vertex and track reconstruction
- ▲ mass mechanism demonstration by electron angular correlation
- ▼ poor energy resolution
- ▼ small masses and/or low efficiency ⇒ enrichment necessary
- ▶ MOON (^{100}Mo) (solar ν experiment)
- ▶ DCBA (^{82}Se, ^{150}Nd)
- ▶ SuperNEMO (100 kg of isotopes: ^{150}Nd, ^{82}Se, ^{96}Zr, ^{116}Cd, ^{130}Te, ...)
- ▶ EXO, a calorimeter with some tracking (^{136}Xe)







Summary of future experiments

- incomplete list of **proposals** and **experiments**
- only the **CUORE** experiment is **approved and funded** to be constructed **full size**
- $\tau_{1/2}^{0\nu}$ sensitivity **strongly depends** on ***bkg*** estimation and F_N choice

	isotope	$Q_{\beta\beta}$ [keV]	technique	i.a. [%] *	*M* [kmol]	t_{meas} [y]	σ_E [keV]	*bkg* [c/y] **	$\tau_{1/2}^{0\nu}$ [10^{28} y]	$\langle m_\nu \rangle$ [meV] min	max	project status
CANDLES IV+	^{48}Ca	4271	s	2	1.8	5	73	0.35	*0.30*	30		R&D (III: 5 mol)
Majorana 120	^{76}Ge	2039	i	86	1.6	4.5	2	0.1	0.07	90		R&D – reviewing
GERDA II	^{76}Ge	2039	i	86	0.5	5	2	0.1	0.02	90	290	funded+R&D (I: 0.3 kmol)
MOON III	^{100}Mo	3034	t	85	8.5	10	66	*3.8*	0.17	15		R&D (I: small)
CAMEO III	^{116}Cd	2805	s	83	2.7	10	47	4	0.10	20		proposed
COBRA	^{116}Cd	2805	i	90	1.3	10	12	4.8	0.01	*60*	*190*	R&D
CUORE	^{130}Te	2533	b	*35*	1.7	10	2	3	0.07	11	57	**construction**
EXO	^{136}Xe	2476	t	65	60.0	10	25	*1*	4.10	11	15	R&D (1.5 kmol)
SuperNEMO	^{150}Nd	3367	t	90	0.7		57	10	0.01	50		R&D
DCBA-F	^{150}Nd	3367	t	80	2.7		85		0.01	20		R&D (T2: small)
GSO	^{160}Gd	1730	s	*22*	2.5	10	83	200	0.02	60		proposed

s scintillation
i ionization
t tracking
b bolometric

* □ natural isotopic abundance (i.e. no enrichment required)

** □ only $\beta\beta$-2ν background considered

Conclusions

- neutrinoless double beta decay searches with 10 meV sensitivities can
  - find neutrino nature (Majorana or Dirac particle)
  - fix absolute neutrino mass scale

- HM experiment claims a 4σ evidence for $\langle m_\nu \rangle$ = **440 meV**
- running experiments (Cuoricino and NEMO-3) will reach **100÷300 meV**
  - but they will not be able to fully check HM result

- next generation experiment will reach sensitivities around **10 meV**
  - they will be able to check HM result
  - they will be exploring the physically interesting parameter space
- lot of work is being devoted to
  - theoretical nuclear structure calculations
  - active and passive background reduction
  - isotope enrichment
- many interesting experiments are being proposed for many isotopes
  - only very few can start in a short time (< 5 years)
  - **only CUORE is in the full experiment construction phase**