IS THE NEUTRINO A MAJORANA OR A DIRAC PARTICLE ?

Ettore Fiorini, Bologna June 17 2005

ν=ν– or ν≠ν–

Lepton number conservation or violation

Has neutrino a finite mass

100 % chirality

ν	ν–
→	→
⇐	⇒

The Standard Model

$\nu_e\ (\bar{\nu}_e)\quad \nu_\mu\ (\bar{\nu}_\mu)\quad \nu_\tau (\bar{\nu}_\tau)$

Flavor conservation or violation

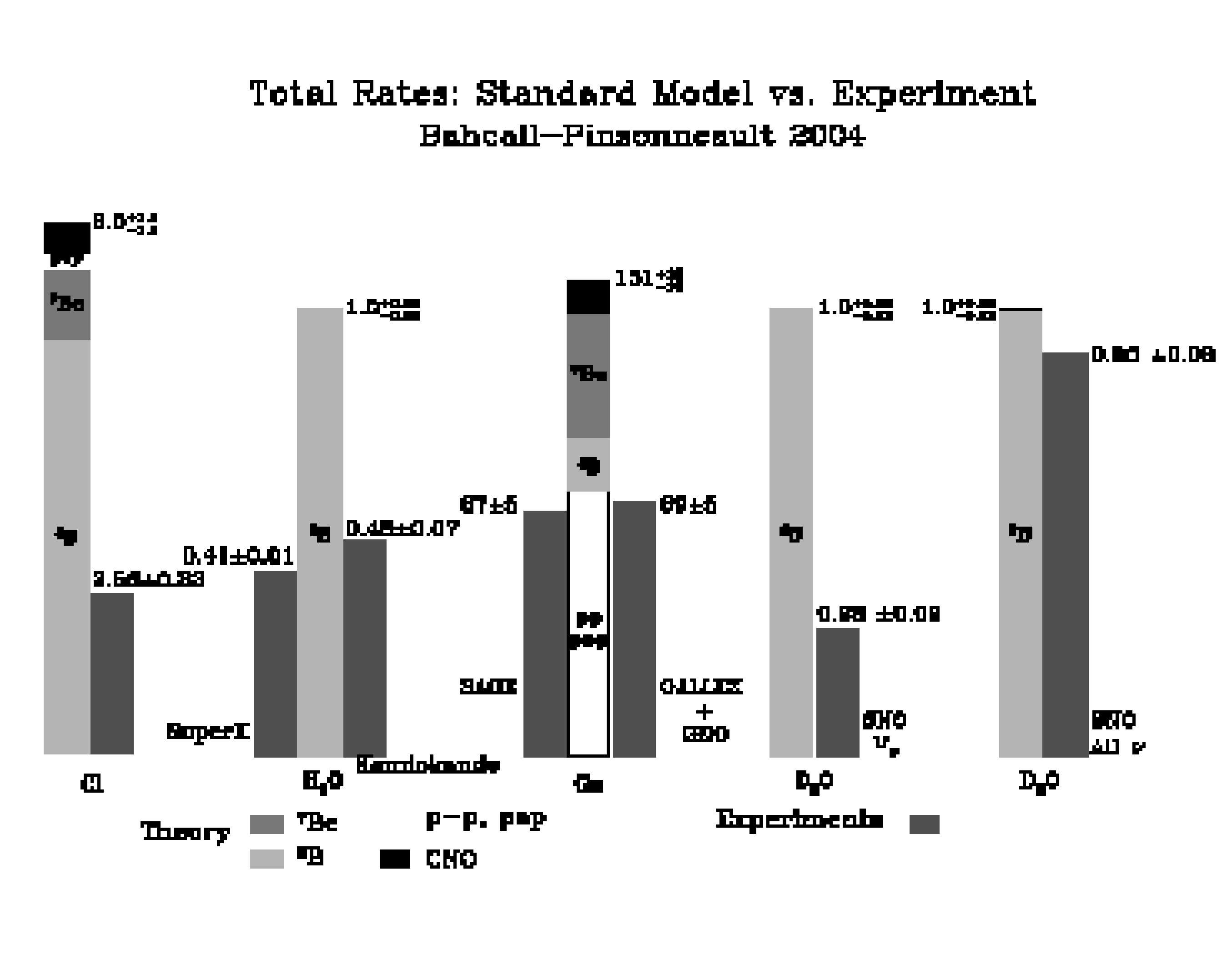
Neutrino oscillations need $m_\nu \neq 0$

$\nu_e \longrightarrow \nu_\mu$

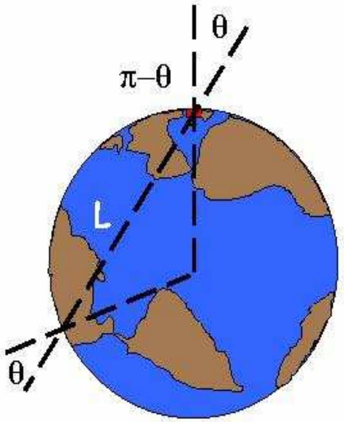
$\nu_e \longrightarrow \nu_\tau$

$$P(\nu_a - \nu_b) -> \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2_{ab}\,(\mathrm{eV}^2)\,\mathrm{L}(\mathrm{km}\,/m)}{\mathrm{E}\,(\,\mathrm{GeV}/MeV\,)})$$

Neutrino oscillations have been observed with solar, atmosperic and reactor neutrinos



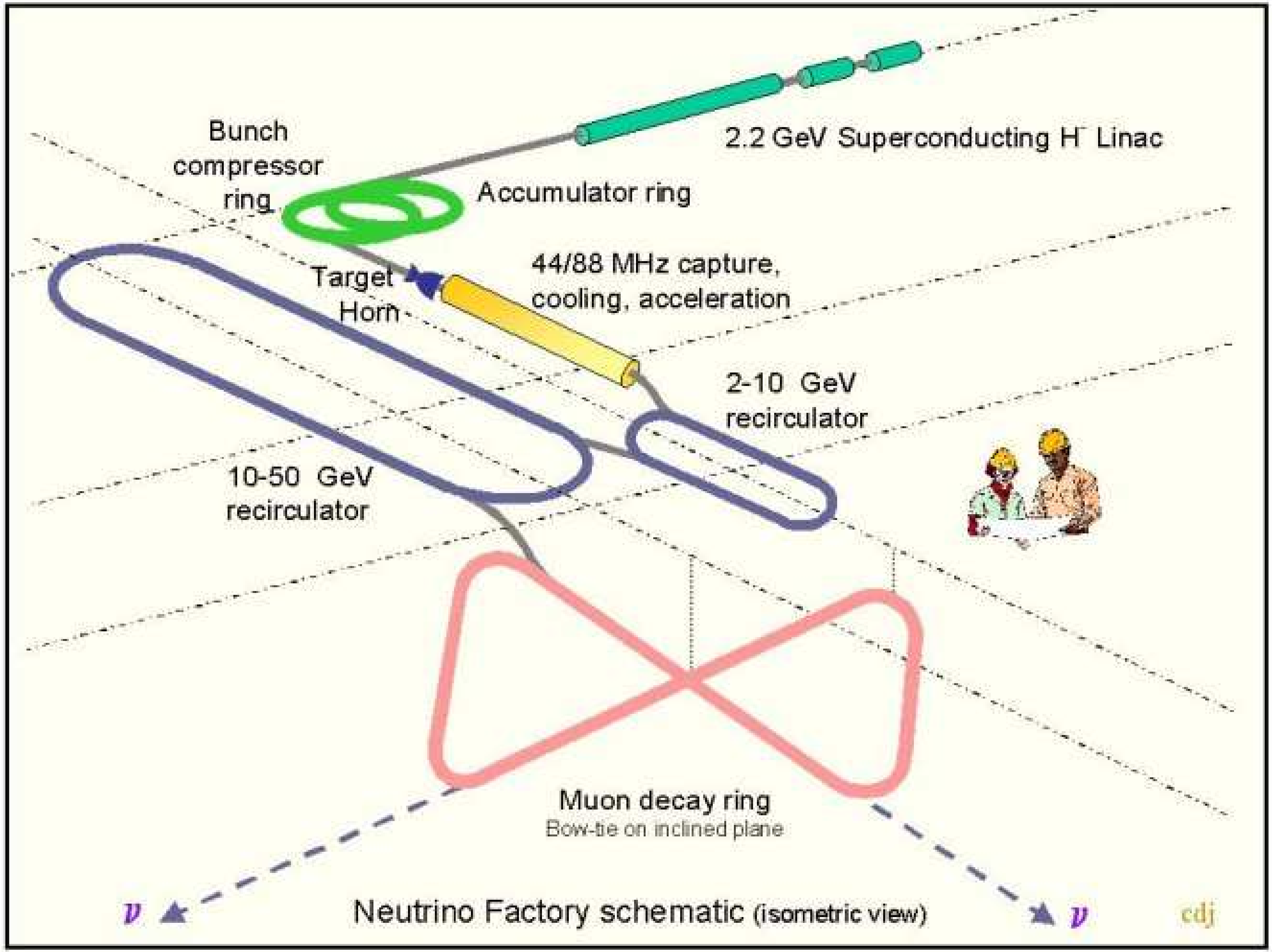
ATMOSPHERIC NEUTRINOS
Superkamiokande and MACRO



Reactor and long baseline experiments

Neutrino factories

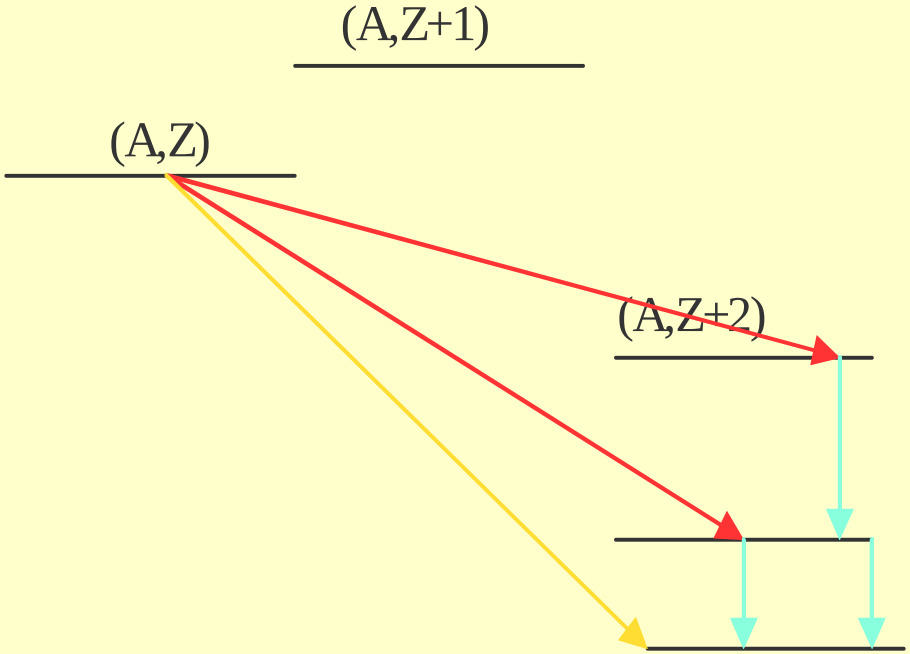
CERN to Gran Sasso Neutrino Beam

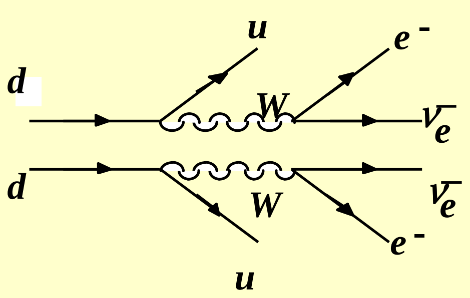


Neutrino Factory schematic (isometric view)

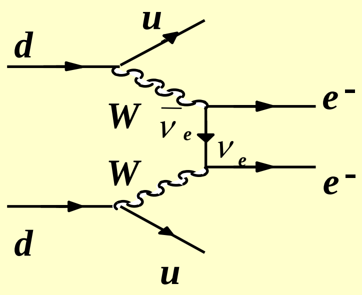
But oscillation experiments only indicate that $m_{\nu}^{2} \neq 0$ to determine $< m_{\nu} >$ => double beta decay

1. (A,Z) => (A,Z+2) + 2 e^- + **2** $\bar{\nu}_e$
2. (A,Z) => (A,Z+2) + 2 e^- + χ (…2,3 χ)
3. (A,Z) => (A,Z+2) + 2 e^-

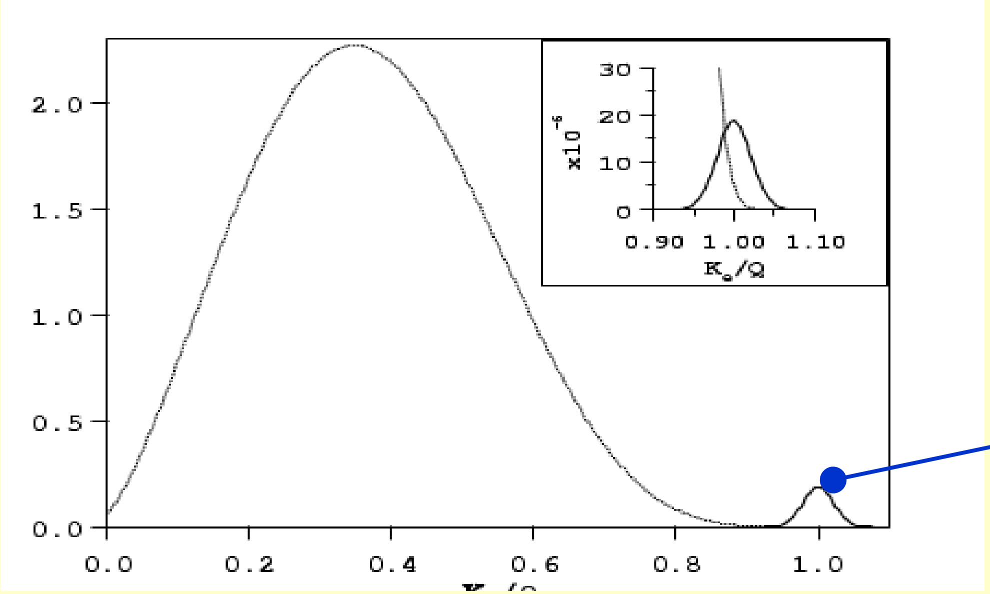




2ν - ββ decay

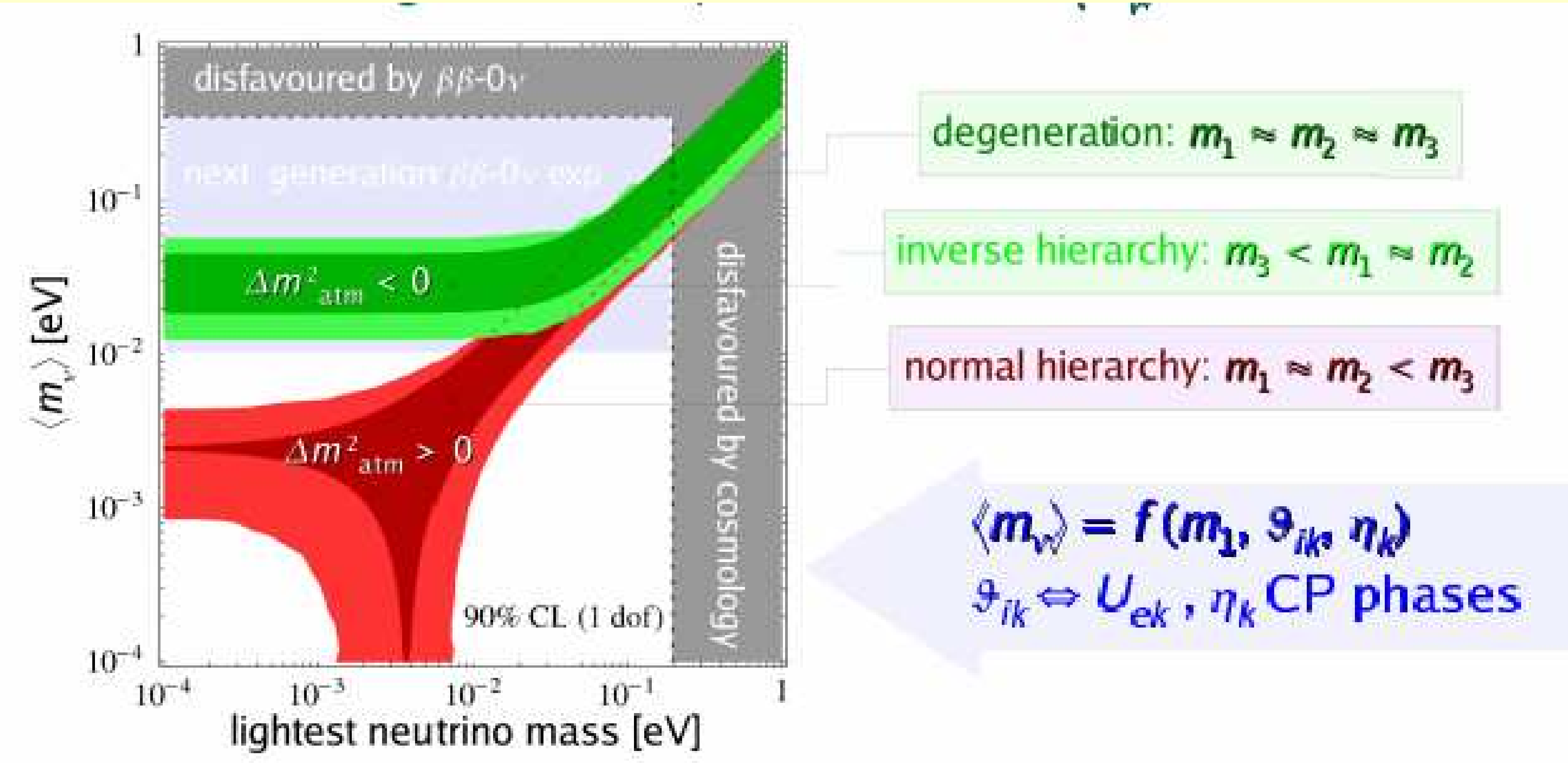


0ν - ββ decay



Neutrinoless ββ decay

Neutrinoless ββ decay would imply a non zero effective majorana neutrino mass as indicated by oscillation experiments



$\langle m_\nu \rangle = f(m_1, \vartheta_{ik}, \eta_k)$

$\vartheta_{ik} \Leftrightarrow U_{ek}$, η_k CP phases

Experimental approaches

Geochemical experiments

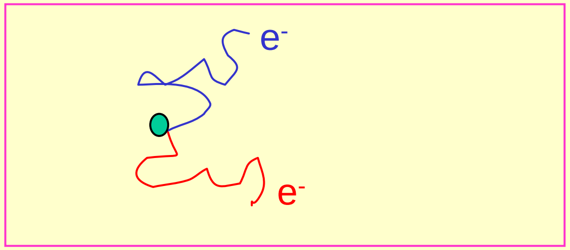
^{i82}Se = > ^{82}Kr, ^{96}Zr = > ^{96}Mo (?) , ^{128}Te = > ^{128}Xe (non confirmed), ^{130}Te = > ^{130}Te

Radiochemical experiments

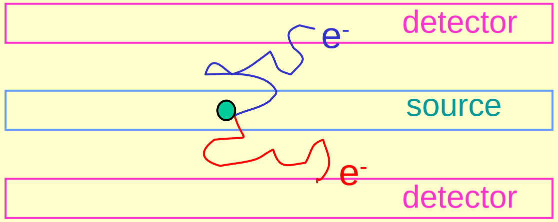
^{238}U = > ^{238}Pu (non confirmed)

Direct experiments

Source = detector (calorimetric)

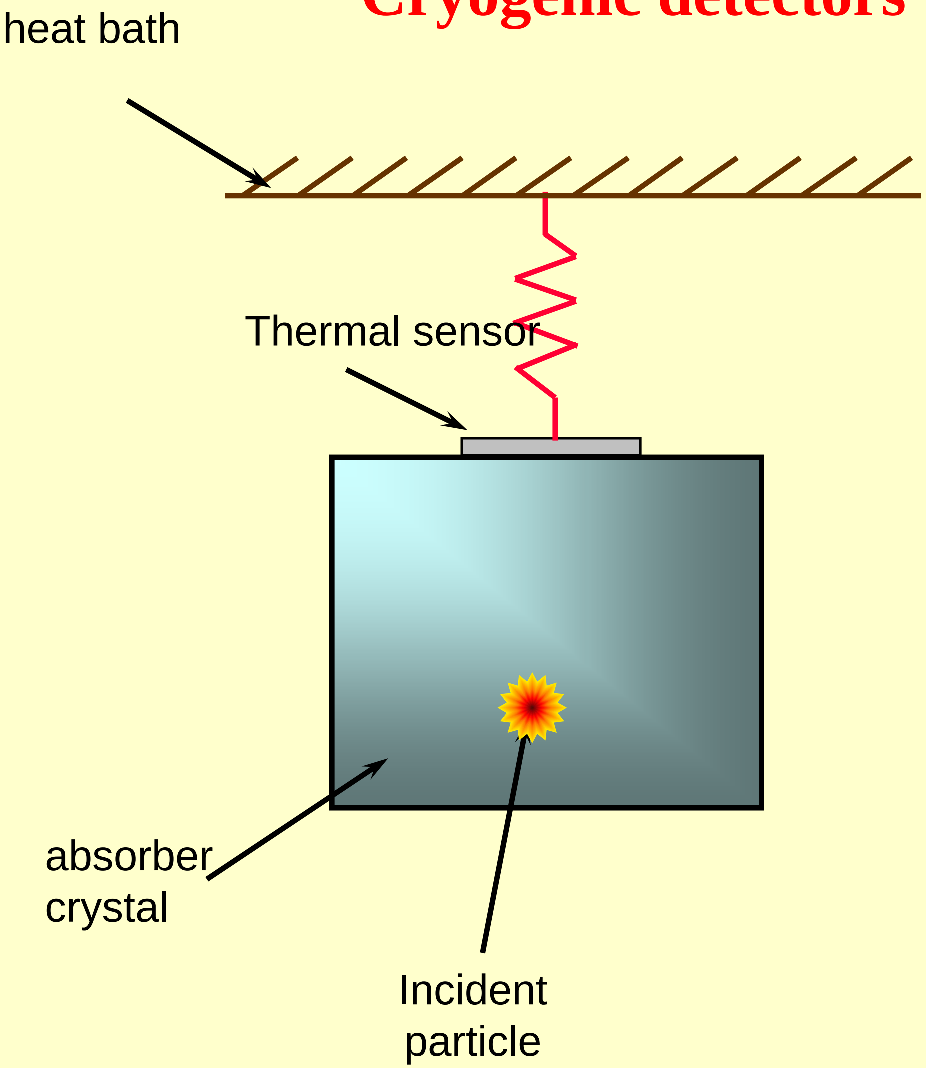


Source ≠ detector



Source ≠ Detector

Cryogenic detectors



$$C_V = 1944 \left(\frac{V}{V_m}\right)\left(\frac{T}{T_D}\right)^3 \ \mathrm{J/K}$$

$$\Delta E = \xi \sqrt{k\, C_V T^2}$$

ΔE @ 5 keV ~100 mk ~ 1 mg <1 eV ~ 5 eV

@ 2 MeV ~10 mk ~ 1 kg <10 eV ~ keV

Recent experiments on $\beta\beta 0\nu$

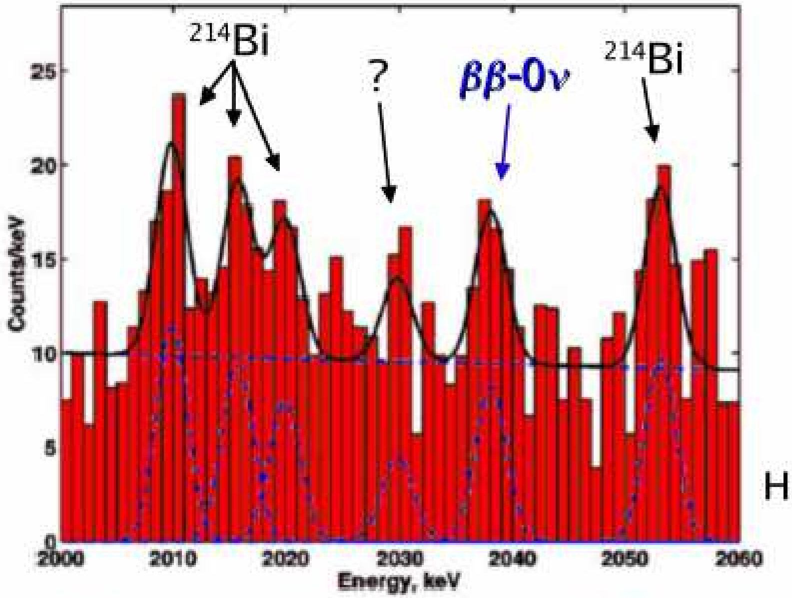
Experim	**Isotope**	**$\tau_{1/2}^{0\nu}$ (y)**	**m^*_{ee} (eV)**	**Range m_{ee}**
Heidelberg – Moscow 2001	**^{76}Ge**	**$> 1.9 \times 10^{25}$**	**< 0.35**	**$< 0.3 – 2.5$**
IGEX 2002		**$> 1.57 \times 10^{25}$**	**< 0.38**	**$< 0.3 – 2.5$**
Mi DBD – ν 2002	**^{130}Te**	**$> 2.1 \times 10^{23}$**	**< 1.5**	**$< 0.9 – 2.1$**
Bernatowicz et al. 1993 (GEO)	**^{128}Te^{geo}**	**$> 7.7 \times 10^{24}$**	**< 1.0**	**$< 1.0 – 4.4$**
Belli et al. 2003	**^{136}Xe**	**$> 1.2 \times 10^{24}$**	**< 1.0**	**$< 0.8 – 2.4$**
Bizzeti et al. 2003	**^{116}Cd**	**$> 1.7 \times 10^{23}$**	**< 1.7**	**$< 1.6 – 5.5$**
Ejiri et al. 2001	**^{100}Mo**	**$> 5.5 \times 10^{22}$**	**< 4.8**	**$< 1.4 - 256$**
Osawa I. et al. 2002	**^{48}Ca**	**$> 1.8 \times 10^{22}$**	**< 6.0**	

***** Staudt, Muto, Klapdor-Kleingrothaus Europh. Lett 13 (1990) 31

The “Klapdor ” effect => T= 1.2 x 1025 a => $<m_\nu> \sim 0.44$ eV

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

$\tau_{1/2}^{0\nu} = 1.2\times10^{25}$ years

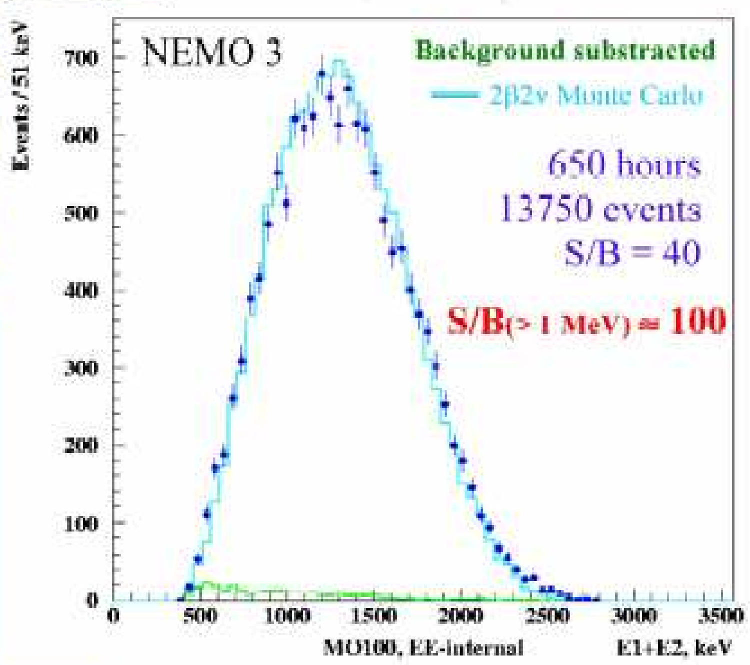
$\langle m_\nu \rangle = 0.44$ eV

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

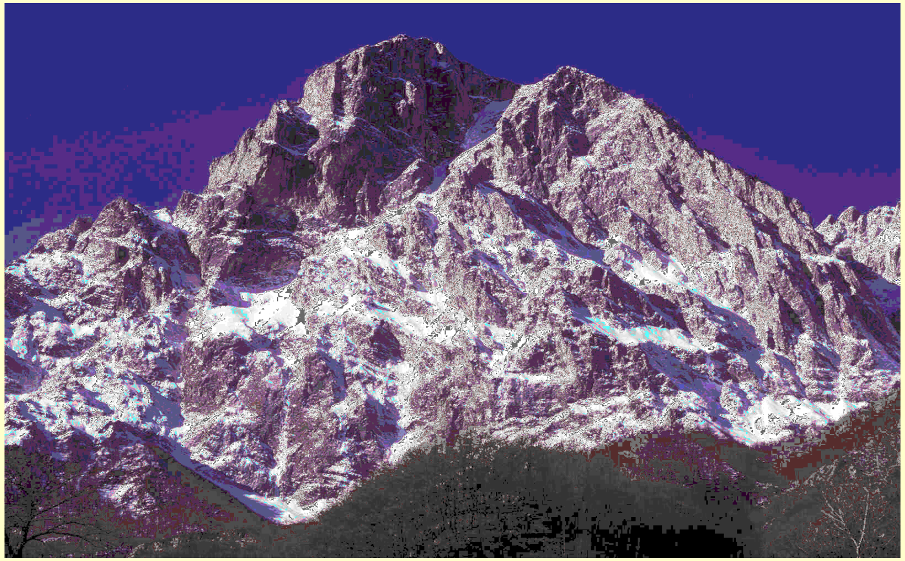
- still, community **does not fully accept the result**, because:
  - signal is indeed **too faint** (4 σ) to be *blindly* accepted: people still find some weak points in the published analysis
  - presence of **not understood peaks** around the signal and with *similar* significance
  - impossibility to check an **energy window larger** than the published one
- **nevertheless any future $\beta\beta$-0ν experiment will have to cope with this result**

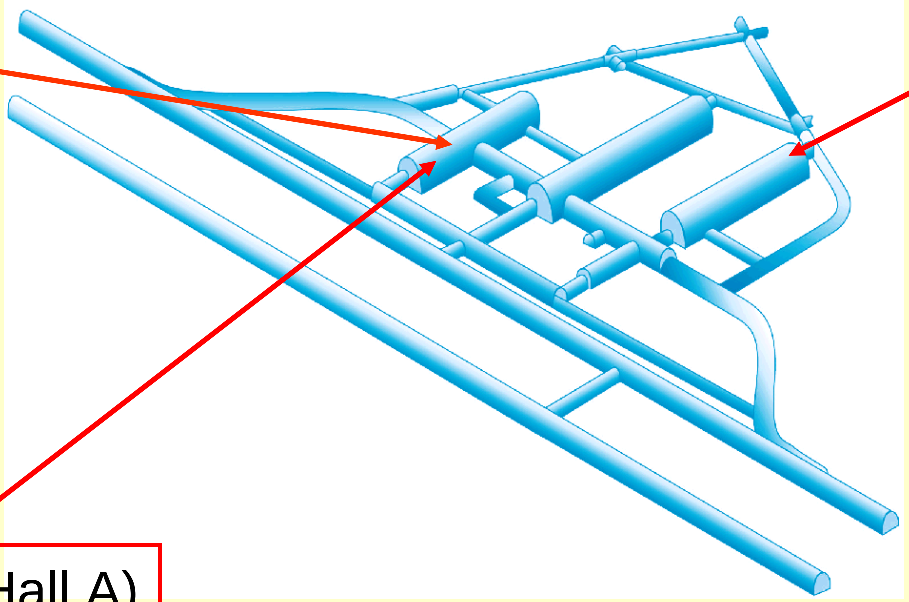
Two new experiments **NEMO III e CUORICINO**

NEMO



Searches with thermal detectors



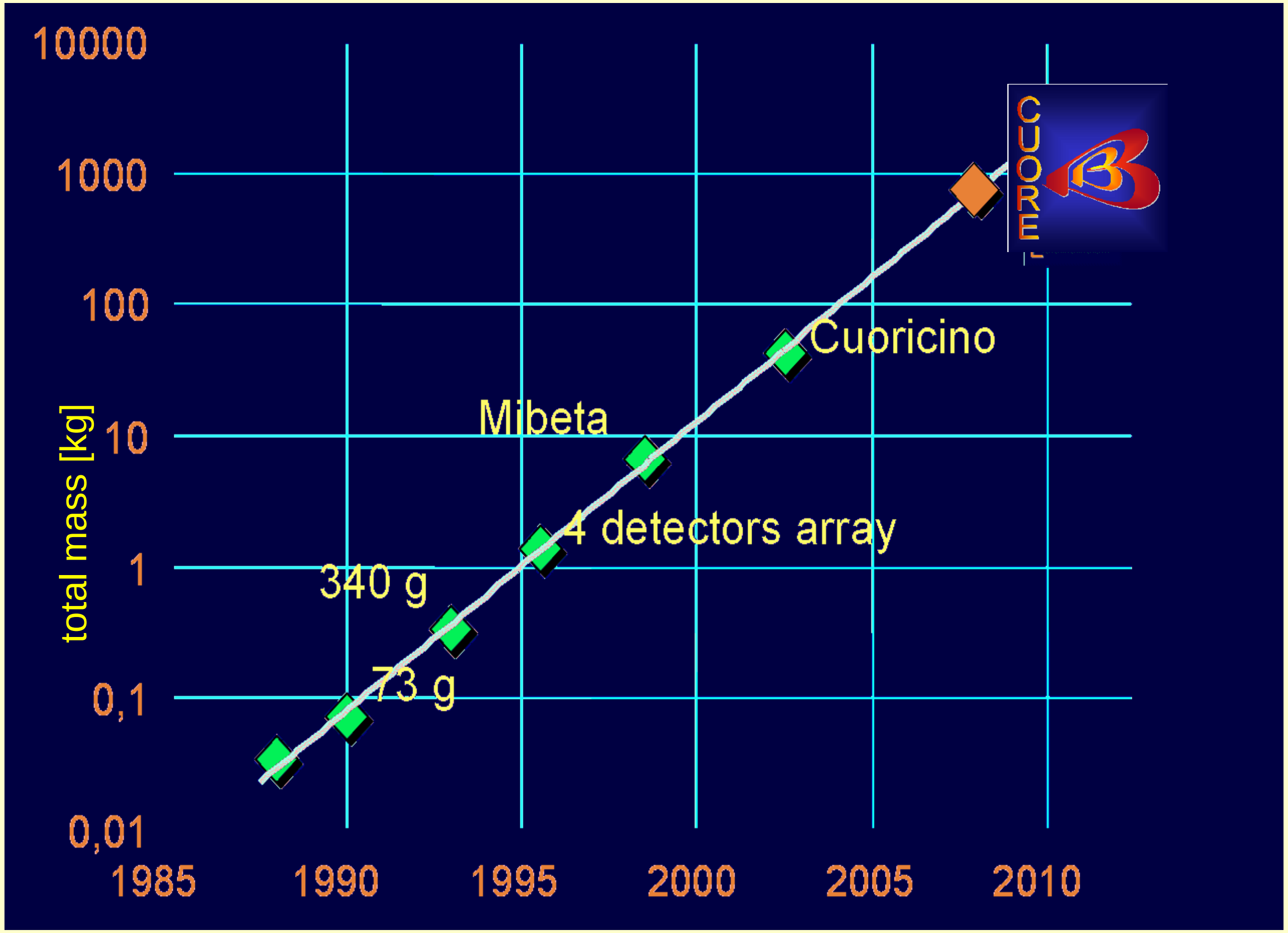


CUORE R&D (Hall C)

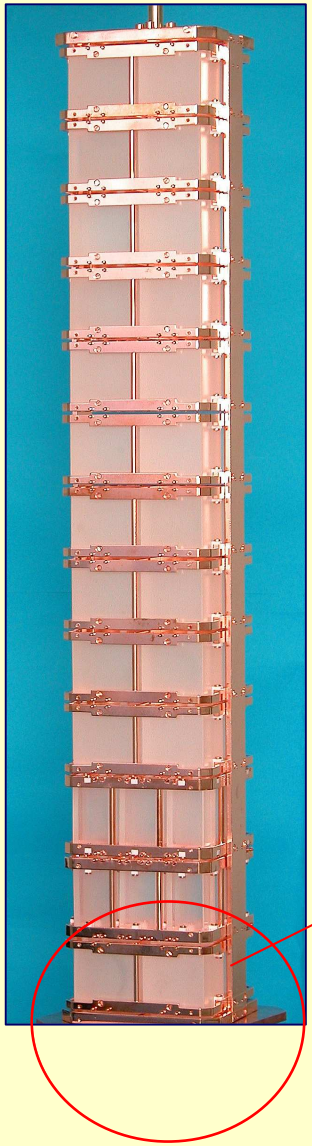
CUORE (Hall A)

Cuoricino (Hall A)

Crescita della massa dei bolometri

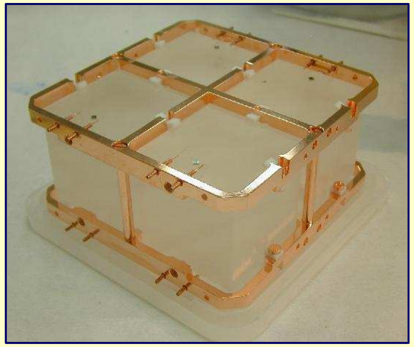


year



- ✓ Search for the $2\beta|_{0\nu}$ in ^{130}Te (Q=2529 keV) and other rare events
- ✓ At Hall A in the Laboratori Nazionali del Gran Sasso (LNGS)
- ✓18 crystals 3x3x6 cm3 + 44 crystals 5x5x5 cm3 = 40.7 kg of TeO2
- ✓Operation started in the beginning of 2003 => ~ 4 months
- ✓**Background .18±.01 c /kev/ kg/ a**
- ✓ **$T_{1/2}^{0\nu}$ (^{130}Te) > 1.8x 10^{24} y** **$<m_\nu>$ .2 -1. 1**

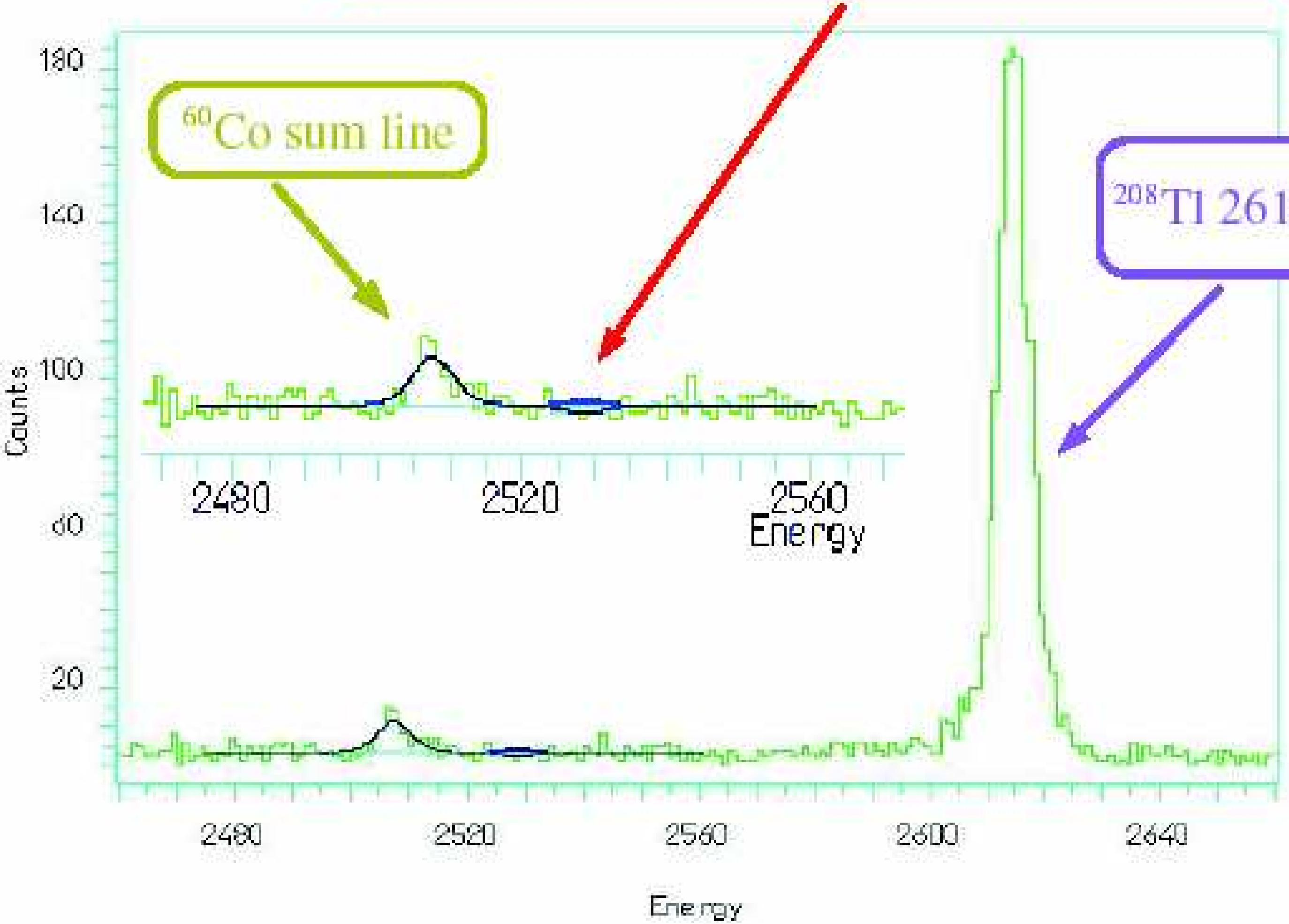
Klapdor 0.1 – 0.9



2 modules, 9 detector each,
crystal dimension 3x3x6 cm^3
crystal mass 330 g
9 x 2 x 0.33 = 5.94 kg of TeO_2

11 modules, 4 detector each,
crystal dimension 5x5x5 cm^3
crystal mass 790 g
4 x 11 x 0.79 = 34.76 kg of TeO_2

$\tau_{1/2} > 1.8\ 10^{24}$ at 90% C.L.

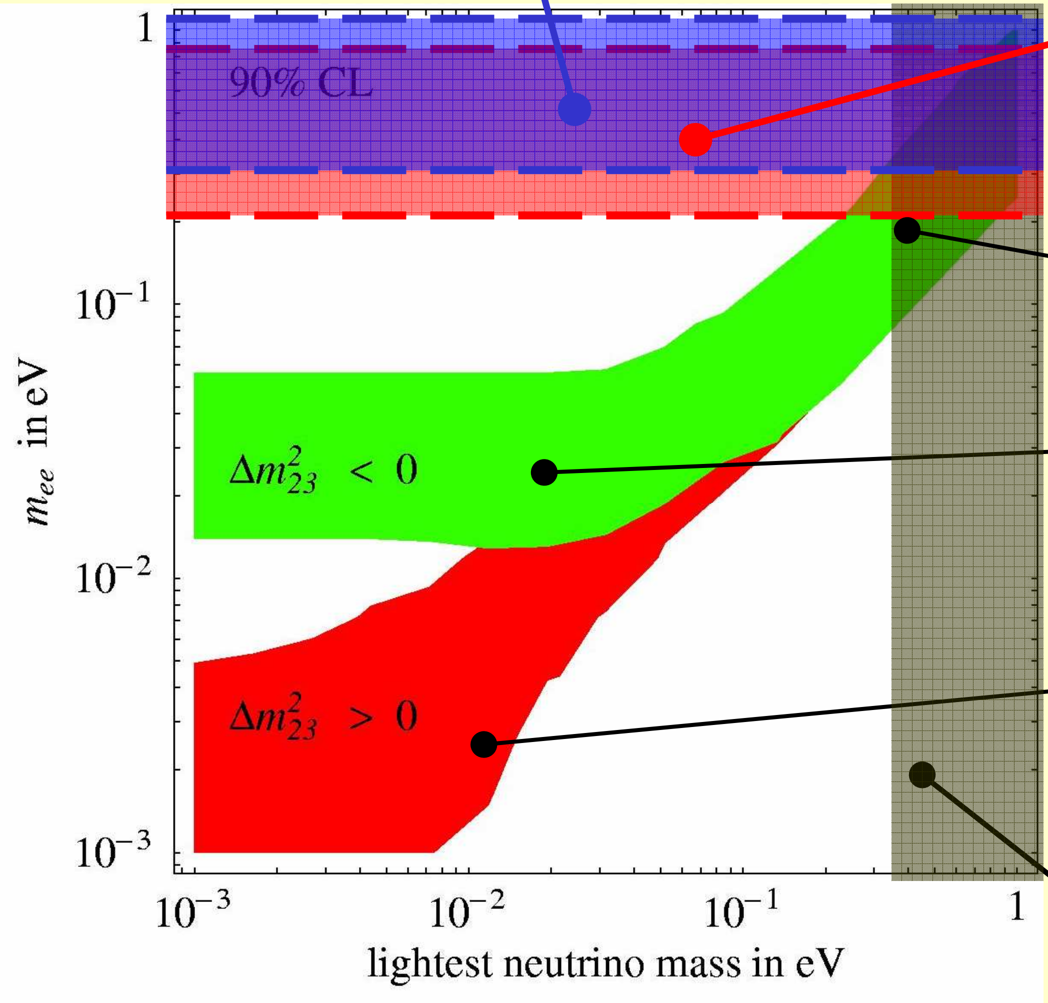


^{60}Co sum line

^{208}Tl 2615 keV line

Present Cuoricino region

Arnaboldi et al., submitted to PRL, hep-ex/0501034 (2005).



Feruglio F. , Strumia A. , Vissani F. hep-ph/0201291

Possible evidence (best value 0.39 eV)

With the same matrix elements the Cuoricino limit is **0.53 eV**

"quasi" degeneracy
$m_1 \approx m_2 \approx m_3$

Inverse hierarchy
$\Delta m^2_{12} = \Delta m^2_{atm}$

Direct hierarchy
$\Delta m^2_{12} = \Delta m^2_{sol}$

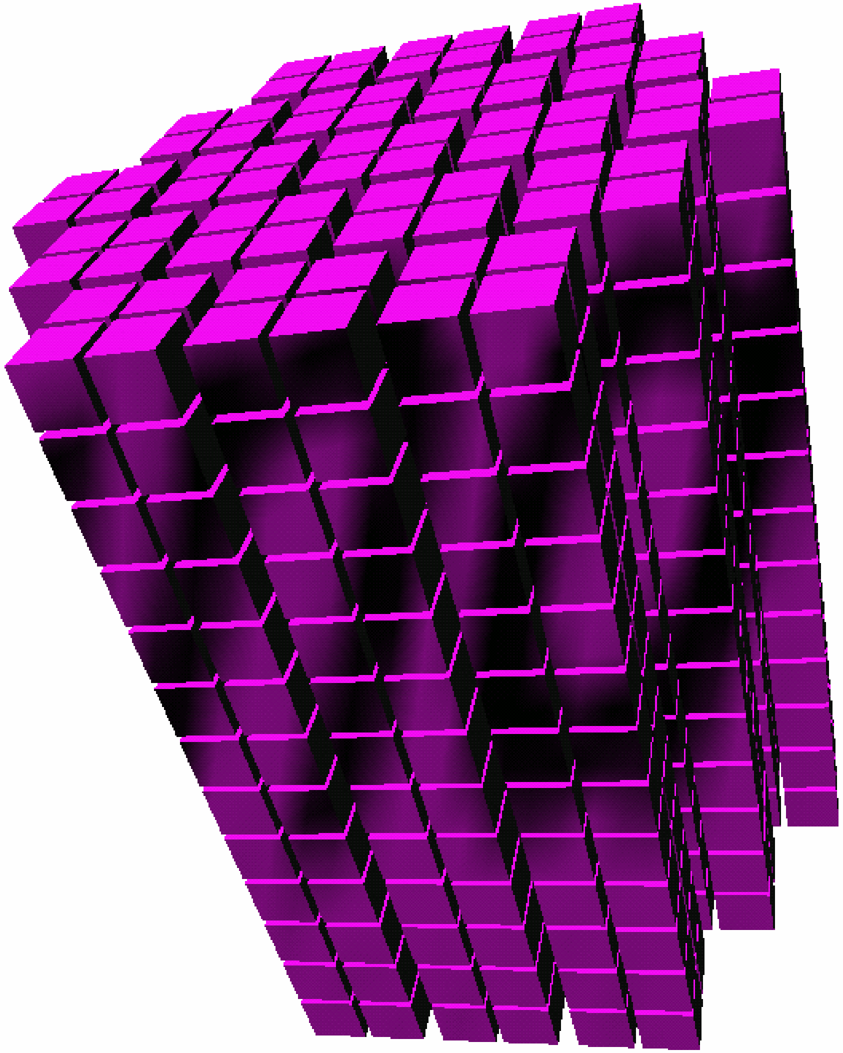
Cosmological disfavoured region (WMAP)

The CUORE project

988 bolometers in 19 colums od 13 flors of 4 crystals

750 kg TeO_2 => 600 kg Te => 203 kg ^{130}Te

Sensitivity of a few tens of eV



Ionization Detectors

- COBRA - CdTe
- GEM - ^{76}Ge (Ge Crystals in LN)
- GENIUS - ^{76}Ge (Ge Crystals in LN)
- Majorana - ^{76}Ge (Ge Crystals in Cryostat)
- MPI - ^{76}Ge (Ge Crystals in LN)

MPI ^{76}Ge Proposal for Gran Sasso

- Bare Ge detectors in pure LN/LAr
- Phase 1: ~ 20 kg, HM/IGEX; 86% ^{76}Ge
- Phase 2: Add 20 kg new enriched detectors

Physics Reach

- Phase 1: refute claim at 99.6% or confirm at 5
- Phase 2: 10% measurement if KKDK correct. Push limit to 2×10^{26} years if not.
- Start construction early 2005
- Begin data acquisition 2006

Scintillation Detectors

- CAMEO - ^{116}Cd ($CdWO_4$ crystals in liq. scint.)
- CANDLES - ^{48}Cd (CaF_2 crystals in liq. scint.)
- CARVEL - ^{48}Cd ($CaWO_4$ scintillators)
- GSO - ^{160}Gd (Gd_2SiO_4 crystals in liq. scint.)
- Xe - ^{136}Xe (Xe dissolved in liq. scint.)

Time Projection, Tracking , & Drift Chambers

- DCBA - ^{150}Nd (Nd foils in a drift chamber)
- MOON - ^{100}Mo (Mo foils in plastic scint. - tracking chamber)
- NEMO/Super NEMO - ^{82}Se (Se foils in a magnetic tracking chamber)
- EXO - ^{136}Xe (Gas or liquid Xe TPC with $^{+}$Ba identification)

DCBA

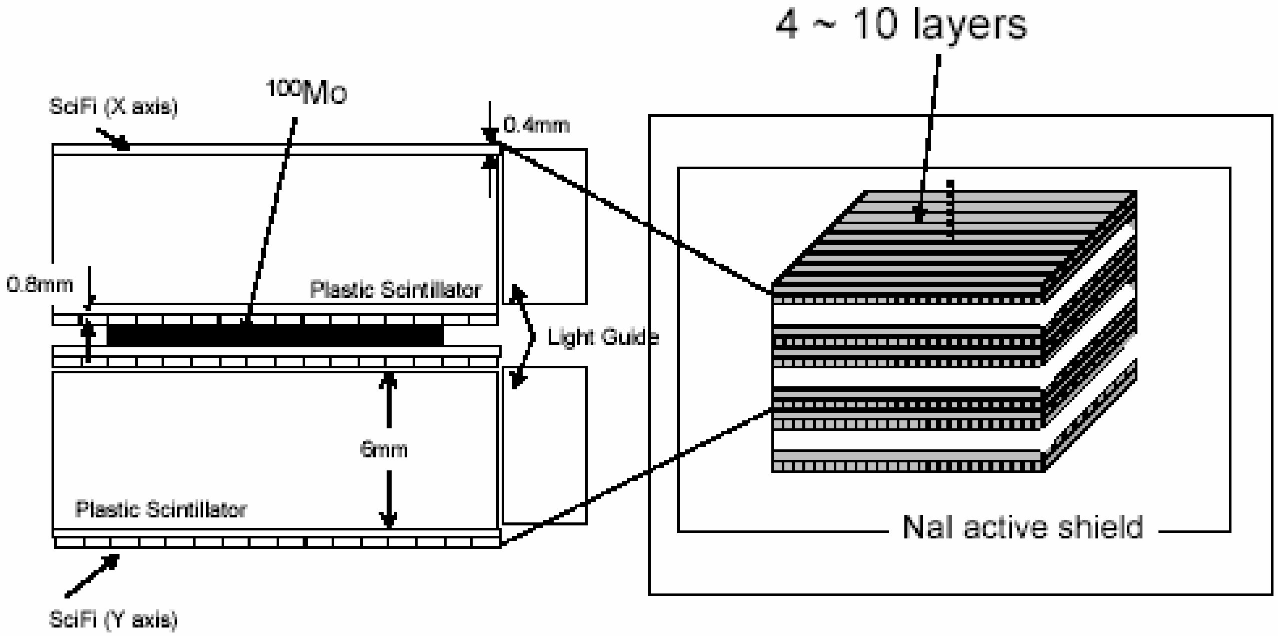
Drift Chamber Beta-ray Analyzer

- DCBA-T (Test apparatus for technical development)
- DCBA-I (4xDCBA-T - Standard Module (SM) with natural Nd source)
- DCBA-II(1) (100-SM with natural Nd - 7.7 mol ^{150}Nd)
- DCBA-II(2) (100-SM with 124 mol ^{150}Nd enriched source)
  - Sensitivity to effective neutrino mass ~0.05eV

Molybdenum Observatory Of Neutrinos (MOON)

- Molybdenum foils between plastic scintillators for energy readout optical fibers for position readout
- MOON-I: 1 kg, 3 y, $T_{1/2}$~$6x10^{25}$ y (m$_{ee}$~0.1 eV)
- MOON-II: 250 kg, 3 y, $T_{1/2}$~$8x10^{26}$ y (m$_{ee}$~0.03 eV)
- MOON III: 750 kg, 7 y, $T_{1/2}$~$3x10^{27}$ y (m$_{ee}$~0.02 eV)
- Tracking with angular resolution

MOON



Size ; Plastic Scintillator ~ 50cm X 50cm

^{100}Mo foil ~ 30cm X 30cm

The Super-NEMO Double-Beta Decay Expression of Interest

- At least 10 times the capacity of NEMO-3
  - ~ 100 kg of enriched isotopes
- Sensitivity $\langle m_\nu \rangle \sim 30$ meV
- ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe

Enriched Xenon Observatory

- ^{136}Xe - 40 m^3 at 10 Atm. (2000 kg)
- 80% ^{136}Xe (Xe is a good scintillator.)
- Energy resolution ~2% at 2.5 MeV
- Possible Liquid Version
- R&D on tagging $^{+}$Ba daughter ion
- 200 kg Prototype (no tagging) was approved and is funded. It will be located in the DOE WIPP site in Carlsbad, New Mexico.

CONCLUSIONS

The discovery of neutrino oscillations to which Masatoshi contributed so much exists and $\Delta m^2 \neq 0$

We need to determine the Majorana nature of the neutrino and the absolute value of $< m_\nu >$

Neutrinoless double beta decay would indicate not only lepton number violation , but also $< m_\nu > \neq 0$

This process has been indicated by an experiment (Klapdor) with a value of ~0.44 eV but not confirmed by CUORICINO

Future experiments on neutrinoless double beta decay will allow to reach the sensitivity predicted by oscillations

Their peculiar multiplinarity involves nuclear and e subnuclear physics , astrophysics , radioactivity, material science, geochronology etc