Neutrino nature and neutrino mass

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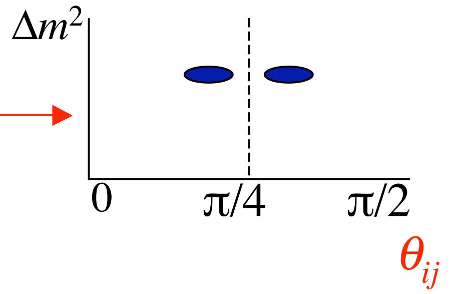
Summary

- **Status of neutrino mixing and mass spectrum. A compendium**
- **Next steps. A quick look**
- **Cosmic connection**
- **Double-beta decay**
  - **Are neutrinos and antineutrinos the same particle?**
  - **What are their masses**
  - *Is leptogenesis the origin of matter-antimatter asymmetry of the Universe?*
  - *How can neutrinos show us the new physics?*
- **Conclusions and outlook**

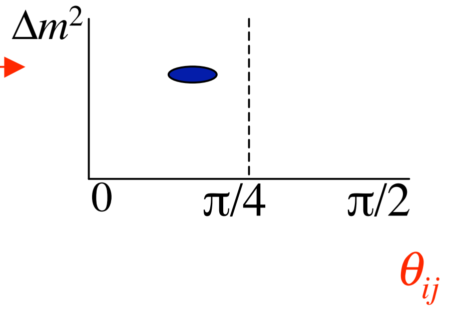
Lepton mixing

Neutrinos change flavour **in two different ways**

- **(vacuum) oscillation**
  - in the **kinetic** part of the Hamiltonian
    - observed in ν_μ produced by cosmic rays in the atmosphere
    - does not depend on $\theta_{ij}\Leftrightarrow\pi/2-\theta_{ij}$
    - does not depend on sign(Δm^2)



- **flavour conversion in matter** (Mikehev-Smirnov-Wolfestein effect)
  - **dynamical phenomenon**, due to the $\nu_e e$ **interaction** potential
    - observed as dominant process in solar ν_e's
    - depends on $\theta_{ij}\Leftrightarrow\pi/2-\theta_{ij}$
    - depends on sign(Δm^2)

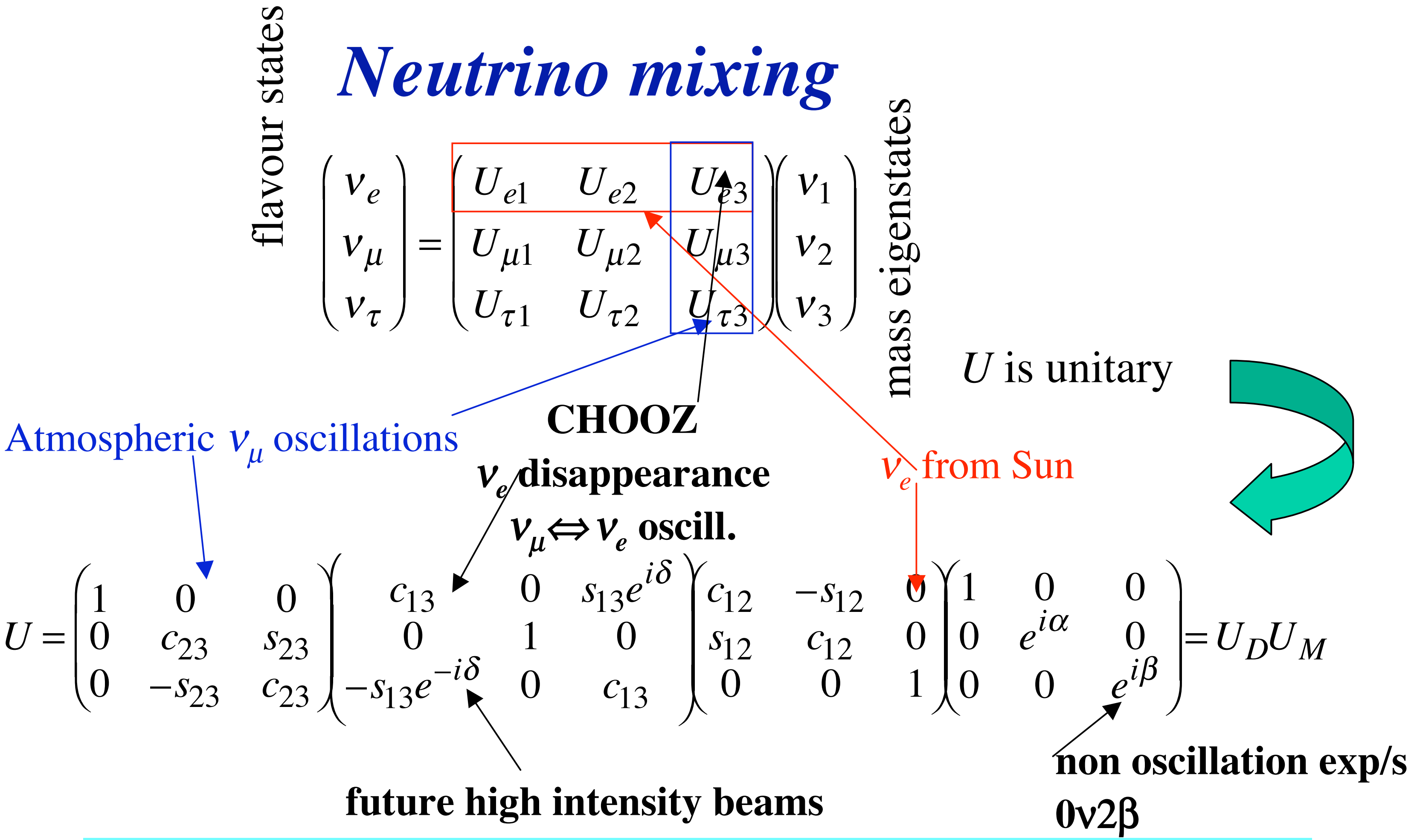


- Both phenomena imply that, contrarily to the Standard Model
  - neutrino masses are different, hence non-zero
  - lepton flavours are not conserved

Squared mass differences are very small ⇒ conversion times in both cases are long ⇒ oscillation or conversion distances at the relevant energies (MeV to GeV scales) are several km to several hundreds kilometres ⇒ non observable within accelerator laboratories perimeter

Neutrinos generated in the interactions (weak neutrinos) ν_e,ν_μ e ν_τ are not the states of definite mass $\nu_1,\nu_2,\nu_3,$ but linear combinations of them

Neutrino mixing



flavour states

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

mass eigenstates

U is unitary

Atmospheric ν_μ oscillations

CHOOZ

ν_e disappearance

$\nu_\mu \Leftrightarrow \nu_e$ oscill.

ν_e from Sun

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & -s_{12} & 0\\ s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha} & 0\\ 0 & 0 & e^{i\beta}\end{pmatrix} = U_D U_M$$

future high intensity beams

non oscillation exp/s
0ν2β

9 independent real parameters

- 3 masses m_1, m_2, m_3
- 3 “mixing angles” $\theta_{12}, \theta_{13}, \theta_{23}$ $\qquad$ $\theta_{ij} \in [0,\pi/2]$
- 1 phase ($\delta \Rightarrow$CP violation)
- 2 more phases (α,β), if neutrinos are Majorana particles
  CP violation - irrelevant for oscillations

What is known

The three mass eigenstates are linear superpositions of the flavour states

Define ν_1, ν_2, ν_3 in decreasing order of ν_e fraction

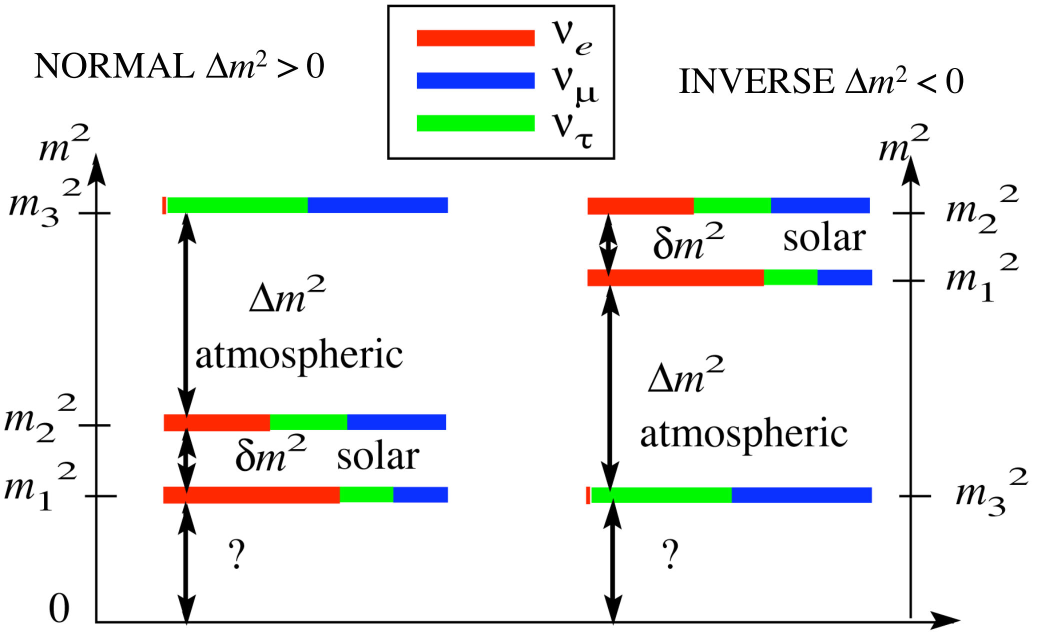
$\nu_1 \Rightarrow \approx 70\%\ \nu_e,\ \nu_2 \Rightarrow \approx 30\%\ \nu_e,\ \nu_3 \Rightarrow \approx 0\%\ \nu_e$

solar squared mass difference $\Rightarrow \delta m^2 = m_2^2 - m_1^2$ (>0 from solar neutrinos)

atmospheric squared mass difference $\Rightarrow |\Delta m^2| = |m_3^2 - m_2^2| \approx |m_3^2 - m_1^2|$

Global fits give $|\Delta m^2| = 2400 \pm 300\ \mathrm{meV}^2$ $\delta m^2 = 83 \pm 3\ \mathrm{meV}^2$

Hierarchic parameter $\alpha = \delta m^2 / \Delta m^2 \approx 0.03$



$m_3 > \sqrt{\Delta m^2} \approx 50\ \mathrm{meV}$

$m_2 > \sqrt{\delta m^2} \approx 8.5\ \mathrm{meV}$

$m_1, m_2 >\approx 50\ \mathrm{meV}$

$m_3 >\approx 8.5\ \mathrm{meV}$

Measured values

$\theta_{12} = 33^\circ \pm 2^\circ$

$\theta_{23} = 45^\circ \pm 3^\circ$

$\theta_{13} < 10^\circ$

We do not know

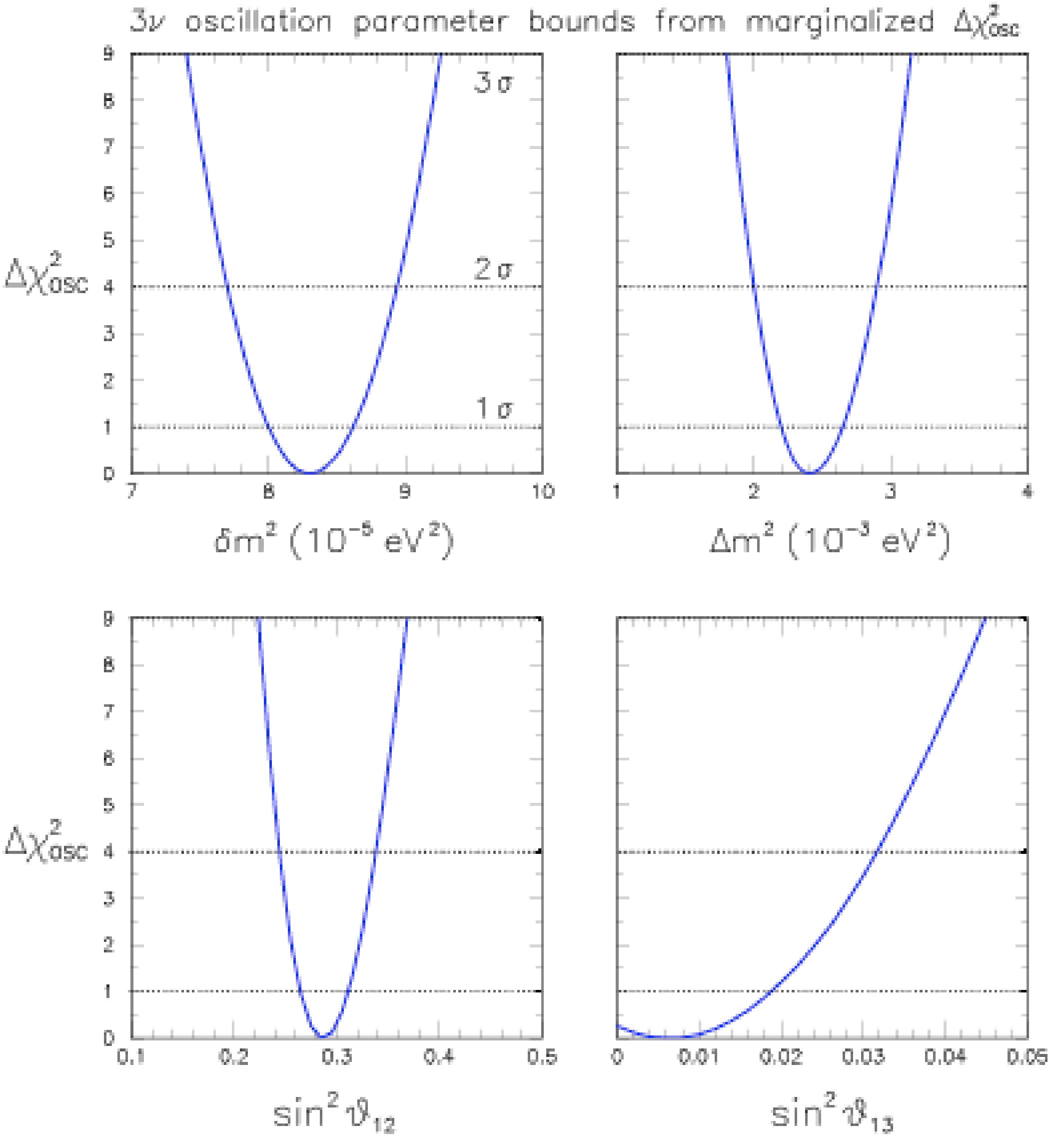
- **The absolute scale**
- **The sign of Δm^2**

From cosmology

$m_1, m_2, m_3 < 130 - 500\ \mathrm{meV}$

Status of neutrino oscillations >Neutrino 2004

G.L. Fogli et al. hep-ph/0408045. After Neutrino 2004



δm^2=83±3 meV^2

Δm^2=2400±300 meV^2

θ_{12}= 33°±2°

θ_{23}= 45°±3° (old)

θ_{13}< 10° (2σ)

Fit includes all available data: fluxes, spectra, Day/Night

Only recently $\Delta\chi^2$ curves are well parabolic

$\sin^2\theta_{13} \neq 0$ not statistically significant

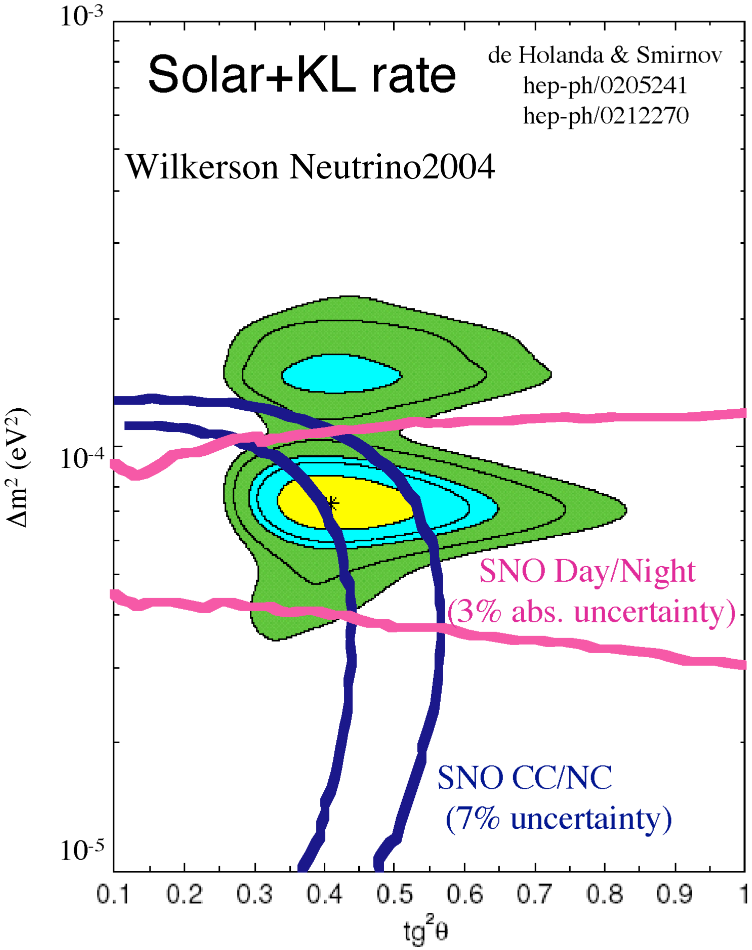
Next few years

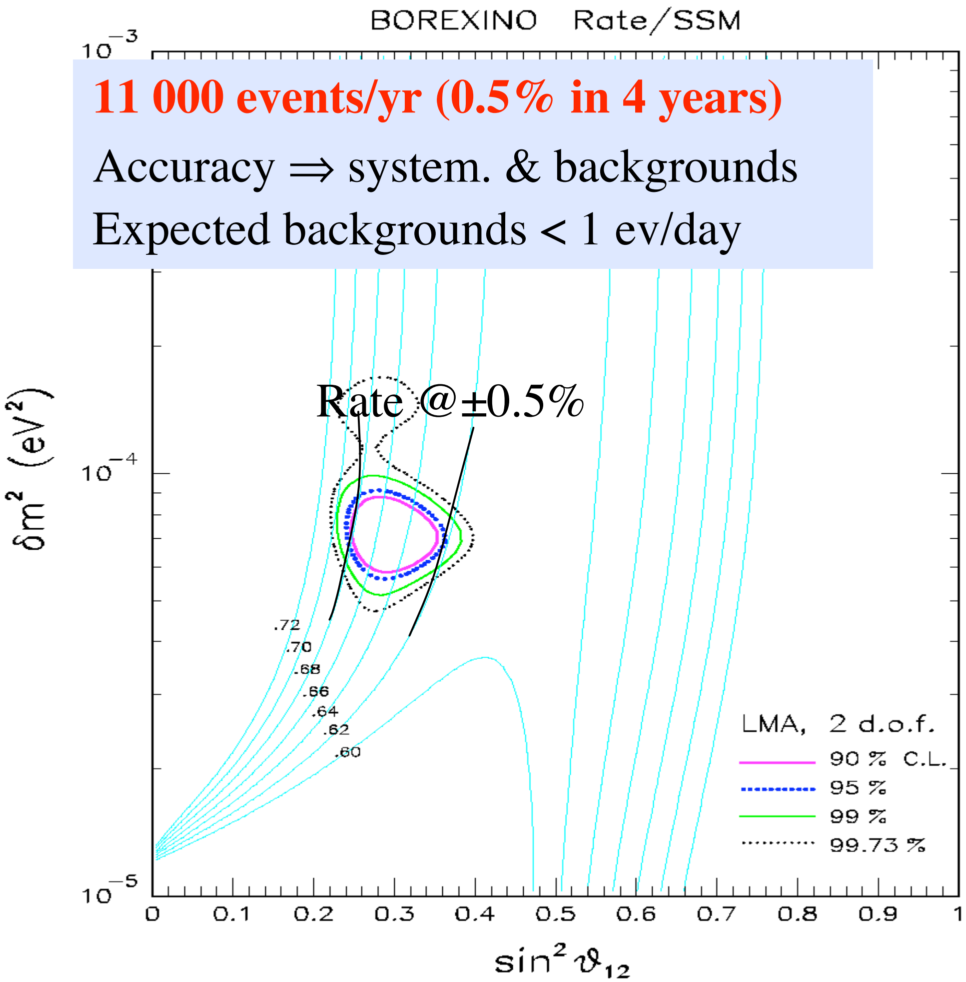
Improvement on $\delta m^2 \Rightarrow$ KamLAND (+ SNO3 Day/Night ⇒ CPT test)

Improvement on $\theta_{12} \Rightarrow$ Solar experiments

- SNO 3rd phase: x2 improvement in NC/CC (2 1/2 yrs data taking)
- BOREXINO, KamLAND-solar

Astrophysics: BOREXINO, KamLAND-solar crucial for ^{7}Be flux





11 000 events/yr (0.5% in 4 years)

Accuracy ⇒ system. & backgrounds

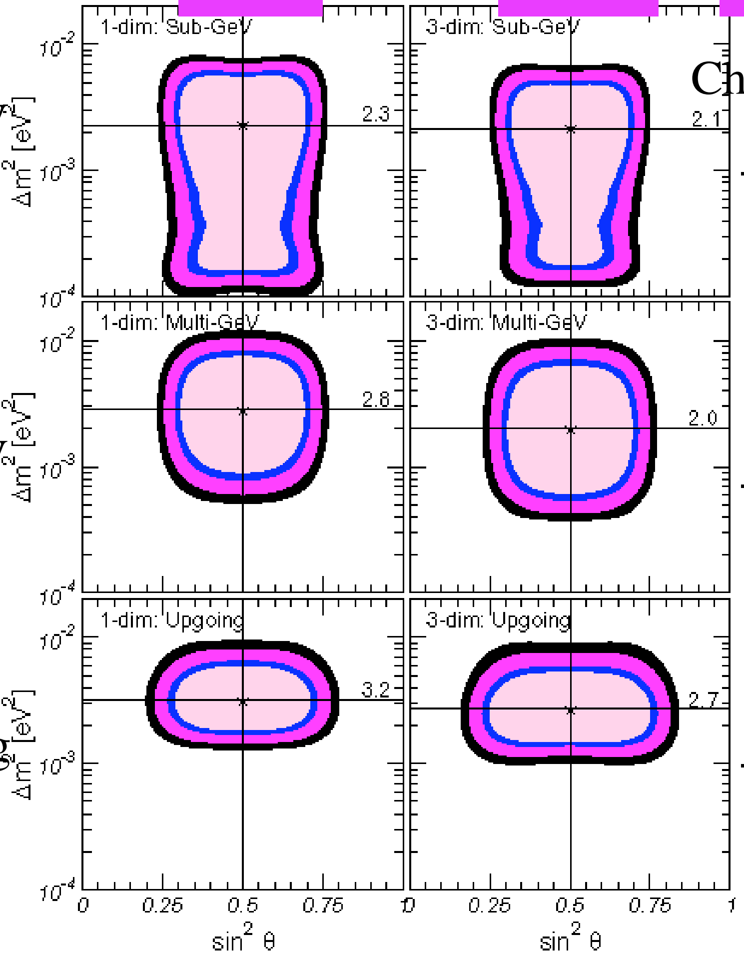
Expected backgrounds < 1 ev/day

Atmospheric oscillation

New analysis including
- three-D fluxes
- improved cross-sections which agree better with K2K near detectors

OLD NEW

Analysis by Gonzalez+Maltoni hep-ph/0406056



Sub-GeV

Multi-GeV

Up-going

Change in Δm^2

-200 meV^2

-800 meV^2

-500 meV^2

Systematic uncertainties due to
- energy independent flux normalisation
- uncertainty in energy dependence ($E^{-\gamma}$ parametrisation)

Ultimate limit to the precision on oscillation parameters from atmospheric neutrinos: we do not have the equivalent of the SSM for robust evaluation of systematic uncertainties

Final value and uncertainty for Δm^2 will come from NUMI+MINOS and CNGS

Appearance experiments

Disappearance experiments do not give the final proof of the oscillation/matter conversion phenomena

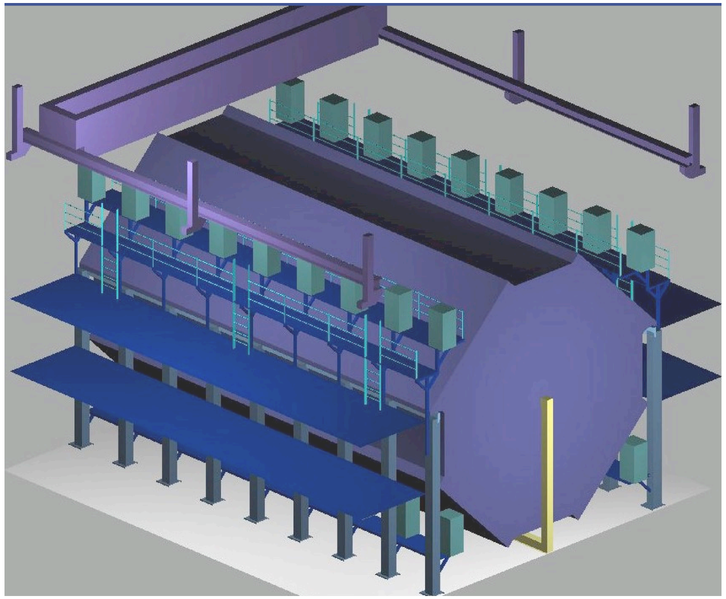
SNO has proven $\nu_e \Rightarrow a\nu_\mu + b\nu_\tau$ @ the “solar” δm^2

τ appearance experiments will check oscillation into ν_τ hypothesis

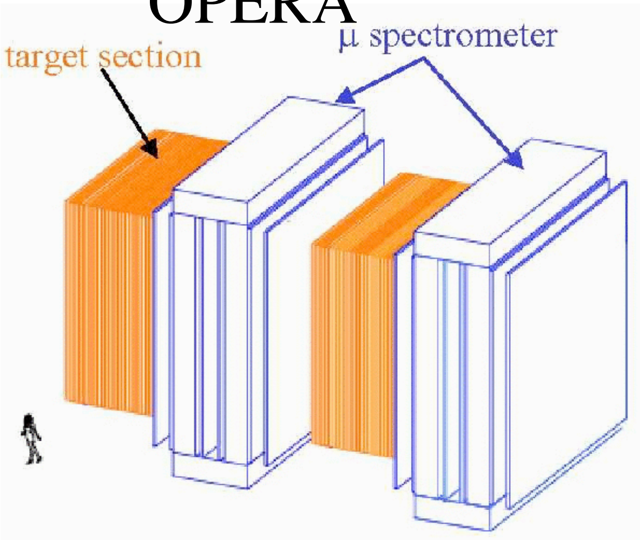
- **NUMI+MINOS @ Fermilab (ongoing)**
- **CNGS program LNGS+CERN (starts in 2006)**
  - **OPERA (in construction)**
  - **ICARUS**

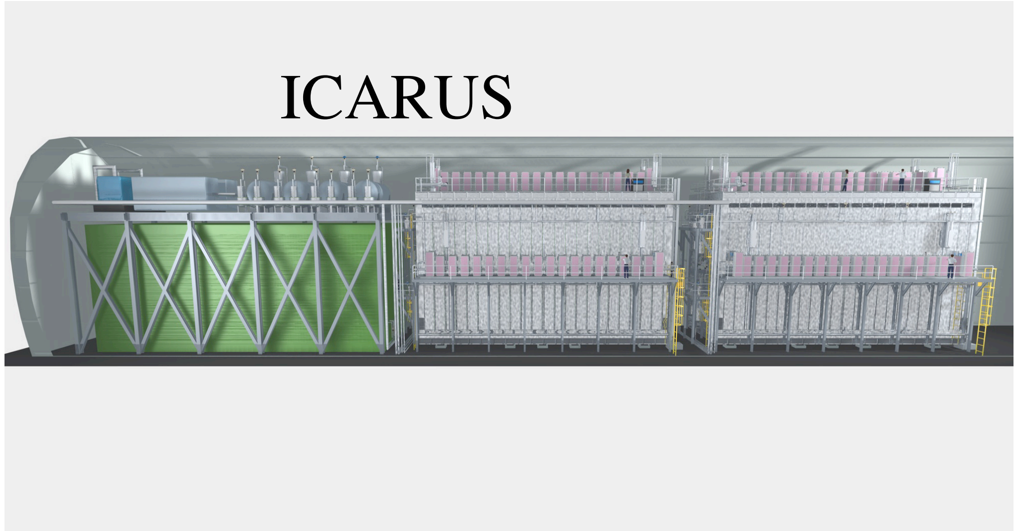
All will be sensitive to the (minority) ν_e appearance

MINOS



OPERA





U_{e3}

Two (complementary) options to measure $|U_{e3}| = \sin\theta_{13}$

1. **appearance**: ν_μ beam from an accelerator (several GeV energy), look for "minority" ν_e appearance (few hundreds kilometers), NUMI+MINOS, CNGS, T2K (dedicated, on oscillation maximum)

$$A(\nu_\mu \to \nu_e) = \sin^2(\theta_{23})\sin^2(2\theta_{13}) \approx 2\theta_{13}^2$$

1. **disappearance**: $\bar{\nu}_e$ from reactors (several MeV energy), look for disappearance @ ≈ 2 km

$$A(\nu_e \to \nu_x) = \sin^2(2\theta_{13}) \approx 4\theta_{13}^2$$

$$\nu_e \Rightarrow \approx \frac{1}{\sqrt{2}}(\nu_\mu + \nu_\tau)$$

$E = 0$ - 9 MeV $\Rightarrow L =$ 1 - 2 km for oscillation maximum $\quad \bar{\nu}_e p \to e^+ n \quad np \to d\gamma$ delayed

Present limit by CHOOZ, a reactor experiment: one underground (300 mwe) far detector

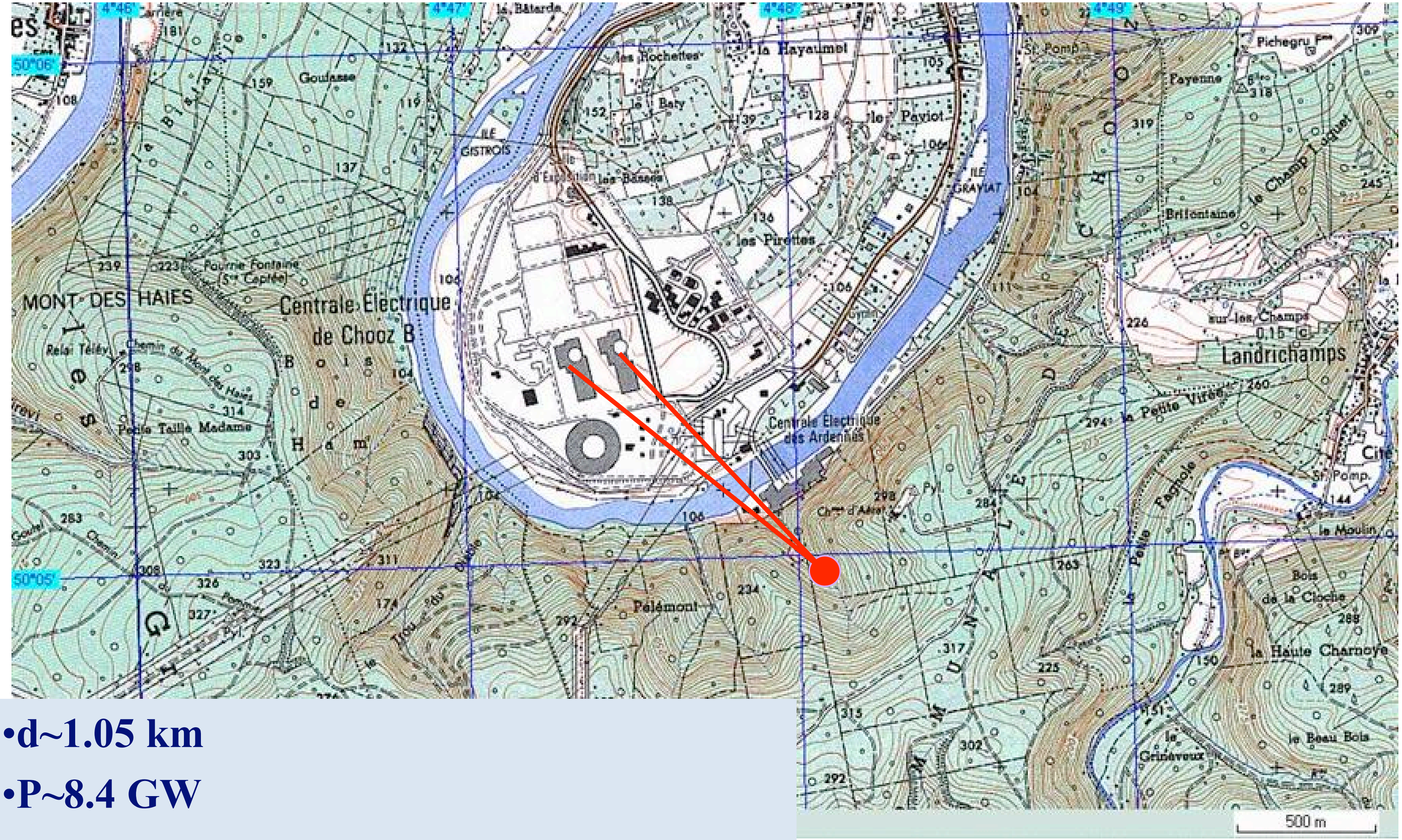
Improvement needs better control of the initial $\bar{\nu}_e$ flux & energy spectrum

two (near and far detectors). Aim for background conditions as equal as possible

several proposals world-wide; white paper: M. Goodman hep-ex/0402041

In Europe: Double-CHOOZ proposal (including US Groups) aims to

The Double-CHOOZ Proposal



- **d~1.05 km**
- **P~8.4 GW**
- **300mwe far detector**
- **no excavation necessary for far detector**

D-CHOOZ Targets

Final sensitivity ⇒ $|U_{e3}|^2 = \sin^2\theta_{13} \approx 5 \times 10^{-3}$ ($\theta_{13} \approx 4^\circ$) from design simulations

Completely dominated by systematics, in particular equality of background conditions @ near (on surface) and @ far (underground) stations

Planned schedule

2007	Start data taking with the FAR detector @ the CHOOZ location
2008	Improve X2 CHOOZ limit
2009	Start NEAR detector

The cosmic way

Neutrino masses from cosmology

Cosmology provides a potentially very sensitive, albeit indirect, means for measuring or limiting neutrino absolute neutrino mass

Neutrinos stream freely above the structures, suppressing their formation at scales <d_{FS}

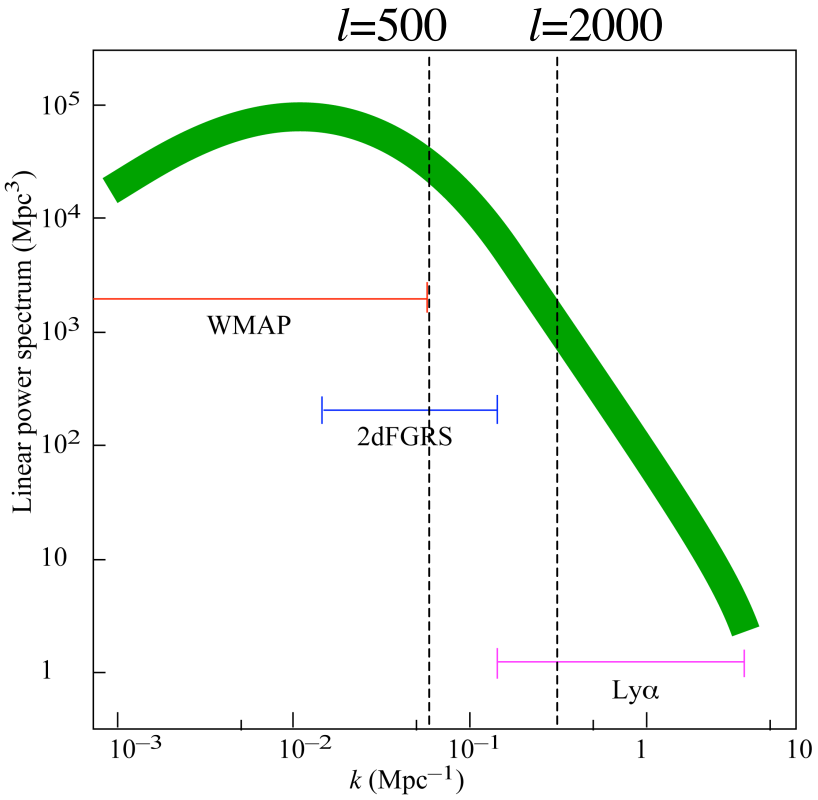
$$d_{FS}(\mathrm{Gpc}) \approx 1/m_\nu(\mathrm{eV})$$

The crucial issue is the large structures power spectrum, determined by

- **CMB spectrum at the largest scales**
- **Galaxy power spectrum at intermediate scales**
  High precision galaxy surveys (2dFGRS and SDSS)
- **Lyα forest at smaller scales**
  Model dependence of the e xtraction of spectrum from data
- **Possibly other sources in future**

A limit on neutrino mass density gives a limit on the sum of neutrino masses

$$\Omega_\nu \approx \frac{\sum_{i=1}^{3} m_i}{94h^2} \approx \frac{\sum_{i=1}^{3} m_i}{47}$$



The power spectrum $P(k)$ is the Fourier transform of the masses correlation function

The spectrum of the large scale structures

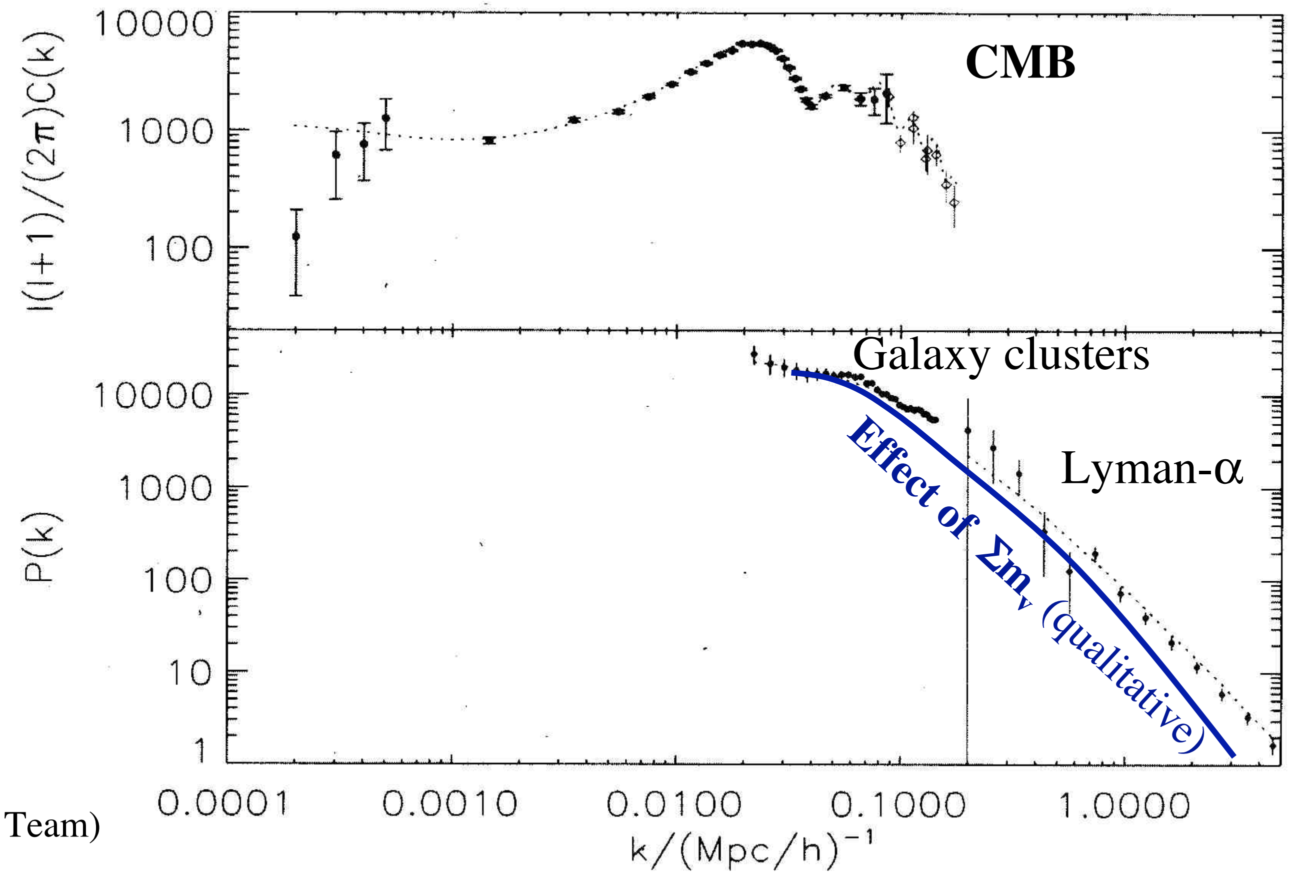
- ν's cold @ last scattering epoch ⇒ little effect on CMB: z=1000 (linear, $\delta\rho/\rho$<<1)
- effect sizeable in the LSS region: z=0.1-0.2 (large non-linearity)
- effect large in Lyα region: z=2-4 (moderate non-linearity)
- cosmology measures $f_\nu=\Omega_\nu/\Omega_m$

d_{FS}(Gpc)≈1/m_ν(eV)

Fit of CMB (WMAP+ACBAR+CBI) and LSS (2dFGRS) gives the limit

m_ν< 230 meV

without Ly-α forest data, which have large systematic uncertainty



H. Peiris (for the WMAP Science Team)
Cont. Phys. **46** (2005) 77-91

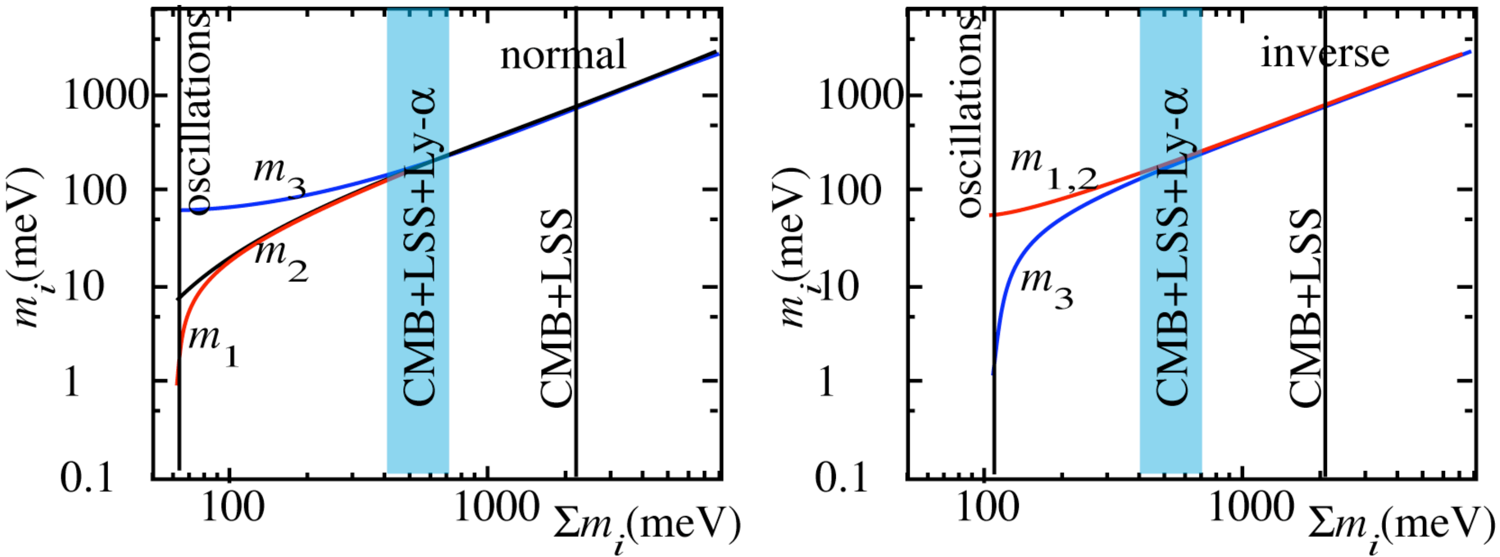
Limits on neutrinos masses

Cosmology is sensitive to very low neutrino masses. But, limits depend

- **set of basic parameters (not completely defined; degeneracies are present)**
- **assumptions on priors**
- **cosmological model is very good, but it is purely phenomenology**

CMB+LSS (astro-ph 0302209) $\sum m_i < 690 \text{ meV} \Rightarrow m_i < 230 \text{ meV}$

CMB+LSS(astro-ph 0310723) $\sum m_i < 2100 \text{ meV} \Rightarrow m_i < 700 \text{ meV}$



NEW analysis of SDSS Ly-α data (astro-ph 0405013) and galaxy bias (astro-ph 0406594)

CMB+LSS+Lyα (Seljak et al. astro-ph 0407372) $\sum m_i < 420 \text{ meV} \Rightarrow m_1 < 130 \text{ meV}$

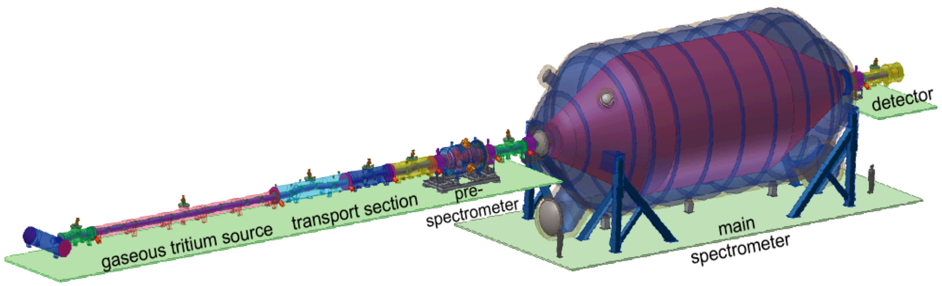
CMB+LSS+Lyα (Fogli et al. astro-ph 0408045) $\sum m_i < 470 \text{ meV} \Rightarrow m_i < 157 \text{ meV}$

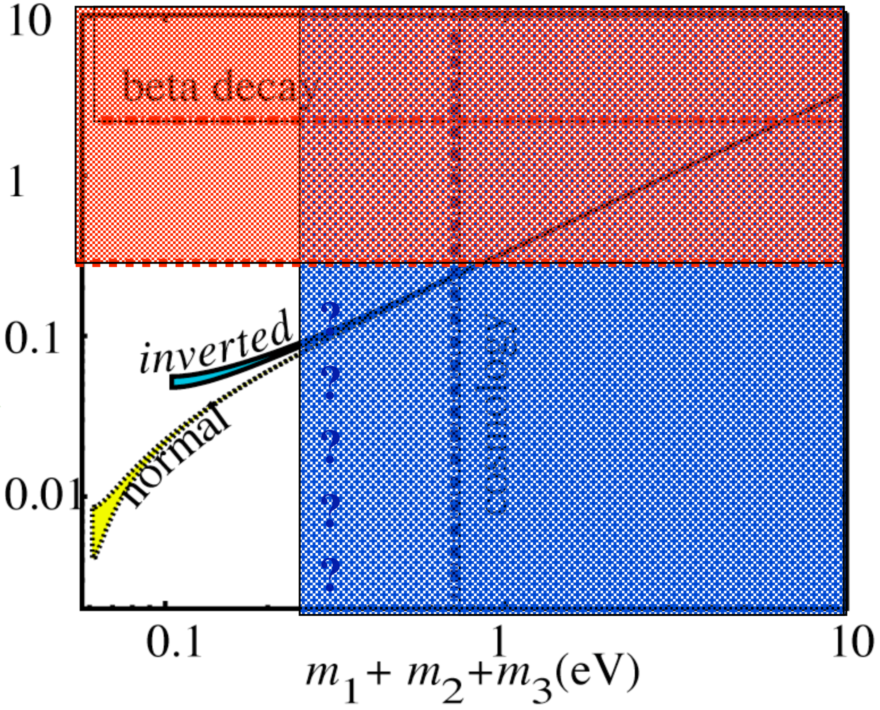
Neutrino mass from beta decay

Tritium β decay $\;{}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e \;\Longrightarrow\; \langle m_{\nu e}^2 \rangle = |U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2$

Present limits $\langle m_{\nu e}\rangle < 2.2$ eV from Mainz and Troitsk experiments

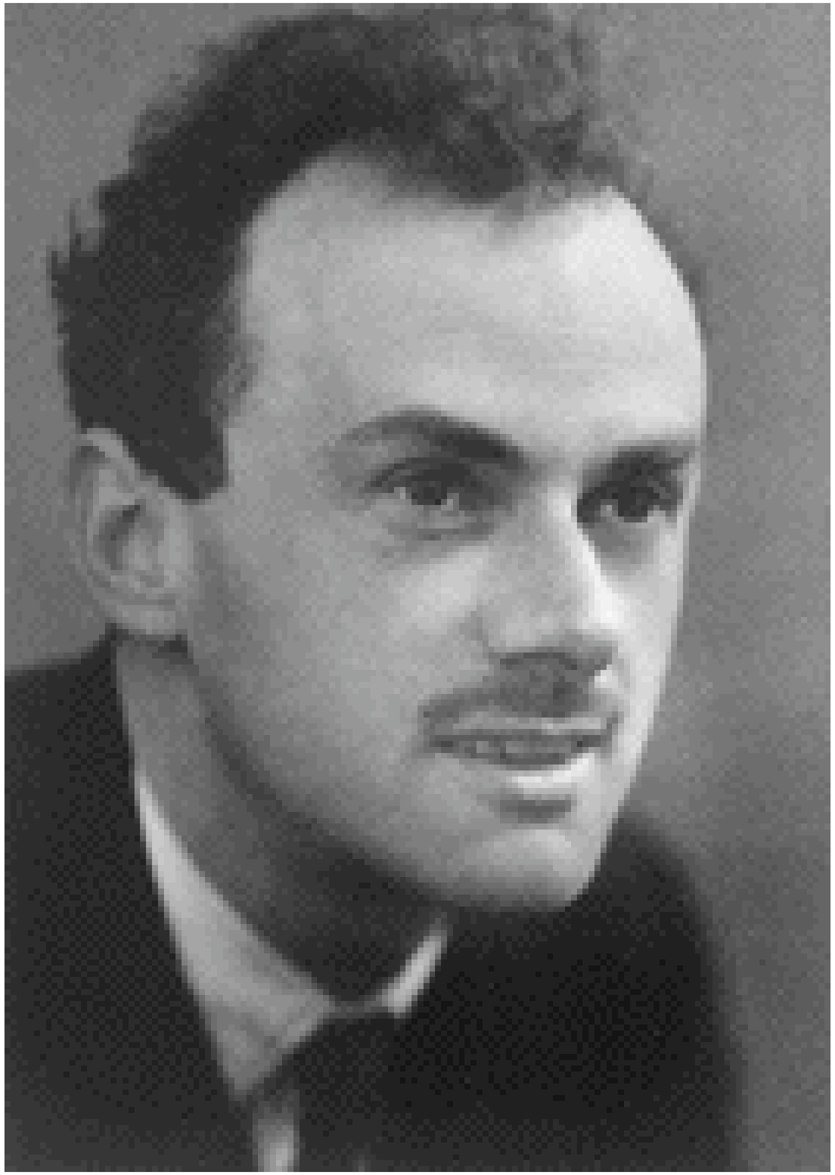
FUTURE: KATRIN
Operational in 2008. In 3 years
push limit @ $\langle m_{\nu e}\rangle$ > 200 meV
discover with 4 σ @ $\langle m_{\nu e}\rangle$ =350 meV



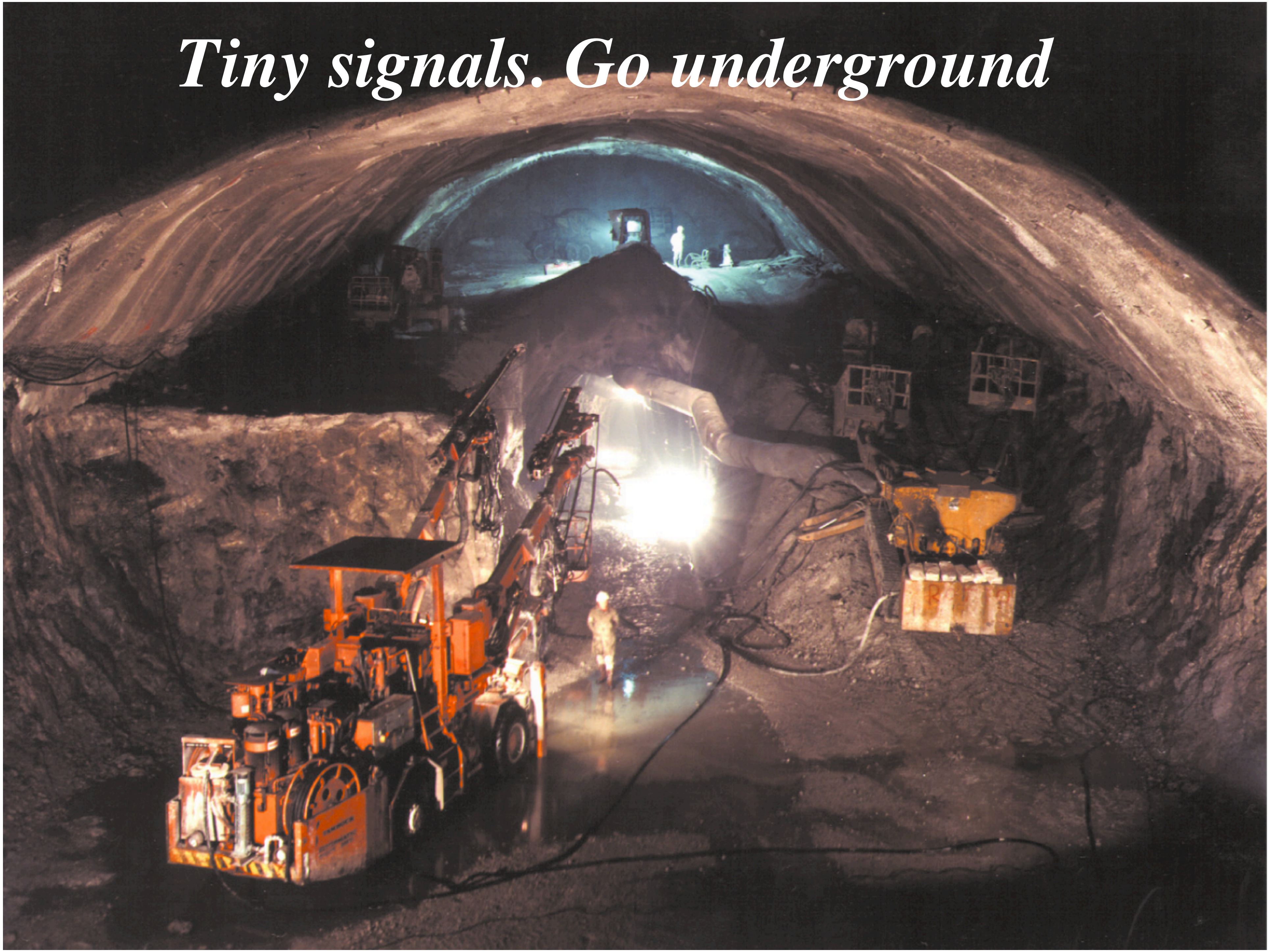


Need direct measure also to fix model dependence of cosmological results
Will be sensitive in the Klapdor + cosmology region

The Nature of Neutrinos



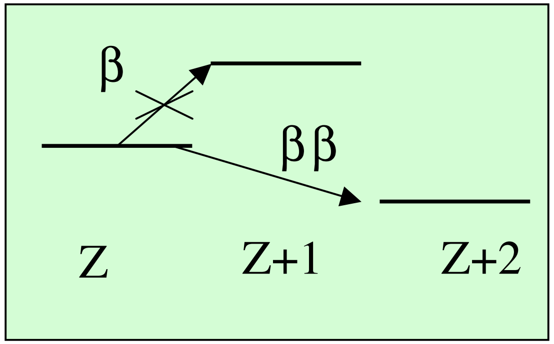
Tiny signals. Go underground



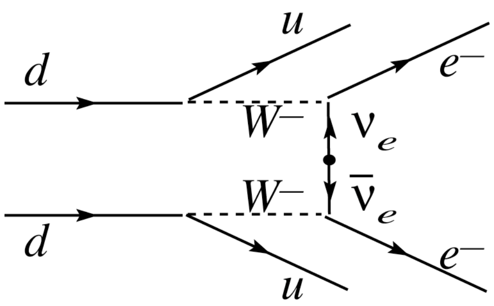
Majorana or Dirac particle?

SM neutrinos are massless, described by a 2-component (left) spinor
If lepton number is not conserved and if neutrinos are massive
Neutrino and antineutrino may be two states of the same particle (distinguished by the chirality)

$$m_\nu \neq 0, \quad \nu_e^C = \nu_e$$



0νββ may happen, if beta decay is forbidden



$$M_{ee} = \left|\,|U_{e1}|^2 m_1 + |U_{e2}|^2 e^{2i\alpha_{12}} m_2 + |U_{e3}|^2 e^{2i\alpha_{13}} m_3\right| \approx \left|\,|U_{e1}|^2 m_1 + |U_{e2}|^2 e^{2i\alpha_{12}} m_2\right|$$

Cancellations may happen due to the phase factors

The decay rate (**1/τ**) of 0νββ depends on **kinematic parameters**, the **“Maiorana neutrino mass”** parameter M_{ee} and a **nuclear matrix element M_{nucl}**

Lifetime, measured or limited **$1/\tau = G(Q,Z)\,|M_{nucl}|^2\, M_{ee}^2$**

Phase space $\propto Q^5$

Nuclear matrix elements M_{nucl} uncertain by factors > 3-4

Need to search in different nuclei (a peak may be an unforeseen background)

Factor of Merit of Different Isotopes

$$f \equiv \frac{<\eta> a\varepsilon}{W}\sqrt{\frac{M}{b\times\Delta E}}$$

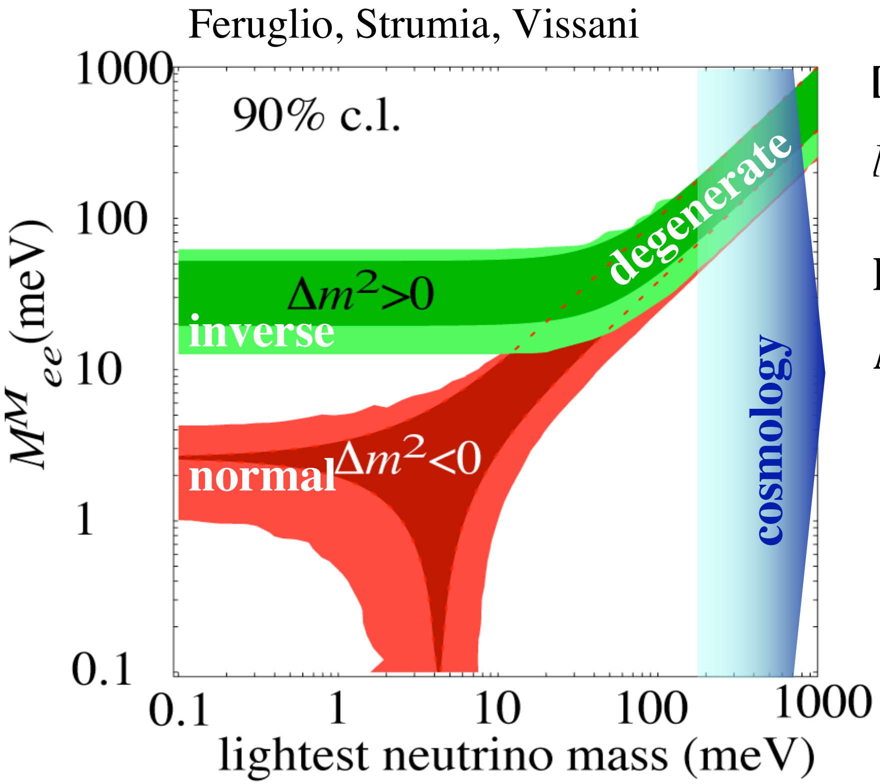
a isotopic abundance; ***ε*** efficiency; ***W*** molecular mass; ***M*** sensitive mass, ***b*** background rate, **Δ*E*** resolution

$<\eta> = G(Q,Z)\, |M_{nucl}|^2\, 10^{13}\ y^{-1}$ Average on nuclear models by

Isotope	<η>	Transition energy (keV)	Natural abundance (%)
^{48}Ca	0.54	4272	0.018
^{76}Ge	0.73	2038.7	7.44
^{82}Se	1.70	2995	9.19
^{100}Mo	10.0	3034	9.63
^{116}Cd	1.30	2805	7.49
^{130}Te	4.20	2529	34
^{136}Xe	0.28	2479	8.9
^{150}Nd	57.0	3367	5.64

Adapted from F. Avignone Neutrino 2004

“Majorana mass”



If spectrum almost degenere, a lower limit exists

$$M_{ee} \geq m \, || U_{e1}|^2 - |U_{e2}|^2 | = m\cos 2\theta_{12} \approx 0.4m$$

If spectrum is inverse, a lower limit exists

$$M_{ee} \geq \Delta m \, || U_{e1}|^2 - |U_{e2}|^2 | = \Delta m\cos 2\theta_{12} \approx 0.4\Delta m$$

no lower limit in the normal pattern

M_{ee} = 50 meV ⇒ $O(10^{26}$-10^{27} yr)

a reasonable, but very difficult, target for next generation experiments

uncertainty in matrix elements demands to search in more than one nuclide

Sensitivity to Majorana mass of all other processes is irrelevant. The most sensitive

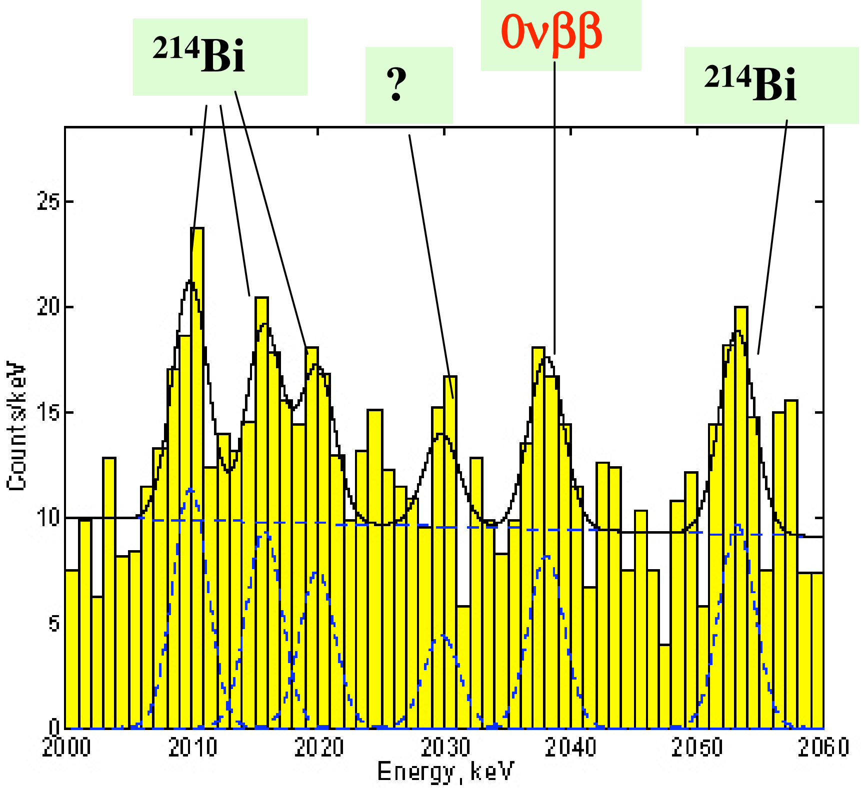
$$\mu^- + Z \to e^+ + (Z-2) \quad \Rightarrow \quad M_{\mu e} < 17 \text{ MeV}$$

Evidence from Heidelberg-Moscow @ LNGS

MT = 10.9 kg (86% ^{76}Ge) x 13 yr
(7.6 x 10^{25} ^{76}Ge nuclei)
Exposure: 71.7 kg y
b = 0.11 count./(keV kg y) before PSA
b = 0.06 count./(keV kg y) after PSA
Resolution on 8 years ΔE = 3.27 keV

Claimed evidence of 0νββ @ 4σ
$T_{1/2}$ = (0.3 - 2.0) x 10^{25} y
M_{ee}= 200-1000 meV

Expected position of 0νββ line well known
$Q_{\beta\beta}$=2039.006±0.05 keV
found @ $Q_{\beta\beta}$=2038.7±0.44 (+2.1 σ)



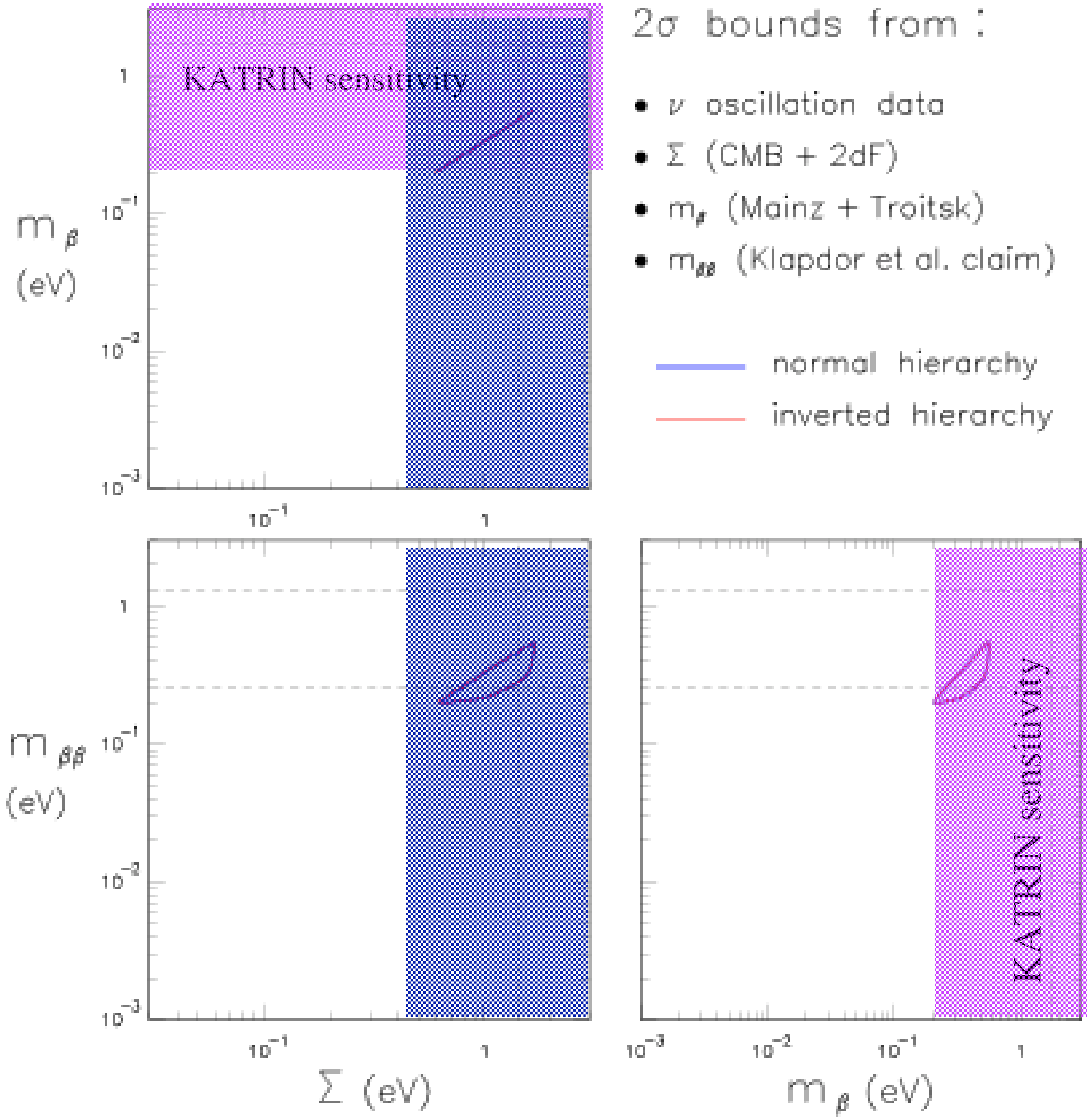
Background model assumes 4 ^{214}Bi lines + linear shape
Lines are indeed found in the expected positions
To be precise the centres of three of them are a bit [+ (2-3) σ] off
Some tension in the intensities too (but they depend on the location of Bi)

IGEX, the other experiment with Ge diodes and similar sensitivity, gives an upper limit M_{ee} < 0.33-1.3 eV
no other experiment sensitive @ this level

Fogli et al hep-ph/0408045/

Believing all evidence

Plot correlations between the three observables



If both Klapdor et al. evidence and limits from cosmology, then

- neutrino spectrum is degenerate
- 0ν2β experiments CUORICINO and/or GERDA may confirm soon
- cosmology may have positive evidence soon

- KATRIN will have a signal

More aggressive (or soon-to-be) limits from cosmology including Ly-α forest produce strong tension with DBD evidence, but

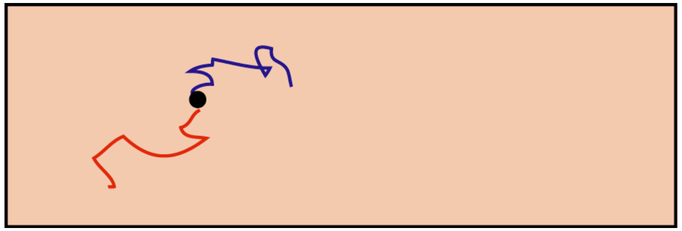
- uncertainties on matrix elements
- uncertainties on information extraction from Ly-α
- degeneracies (e.g. σ_8 & running)

DBD experiments and proposals

Exp.	Stat.	Source	Technique	ΔE (keV) FWHM	Sensitivity $T_{1/2}$ (yr)	Sensitivity M_{ee} (meV)	Year
NEMO 3	Run	^{100}Mo+	7 kg, enriched, tracking	420	5×10^{24}	200-500	2008
CUORICINO	Run	^{130}Te	40 kg natural, thermal	8	6×10^{24}	100-300	2007
CUORE	App	^{130}Te	750 kg natural, thermal	5	3×10^{26}	15-120	2011
GERDA 1	App	^{76}Ge	15 kg, enriched, in LN2	4	3×10^{25}	300-900	2006
GERDA 2		^{76}Ge	35 kg, enriched, in LN2/Ar	4	2×10^{26}	90-300	2009
MAJORANA	Prop	^{76}Ge	500 kg, enriched, segmentation. PSA	4	10^{27}	20-70	
GERDA 3	Prop	^{76}Ge	O(500 kg), enriched, global collaboration	4			
super-NEMO	Prop	^{100}Mo/ ^{82}Se	Foils in magnetic tracking	125	10^{26}	40-80	2011
EXO	Prop	^{136}Xe	1-10 t, enriched, daughter Ba^{+} ion identification	160?(*)	8×10^{26}	50-150	
MOON phase 1,2,3	Prop	^{100}Mo	1kg, 250 kg, 750 kg Mo foils between plastic scint. (tracking & energy)		6×10^{25}- -3×10^{27}	100-20	

(*) could not find a written reference

Two experimental approaches



Source = detector

Measure sum energy with calorimetric techniques

Ge semiconductor, bolometers

\+ very large sensitive mass

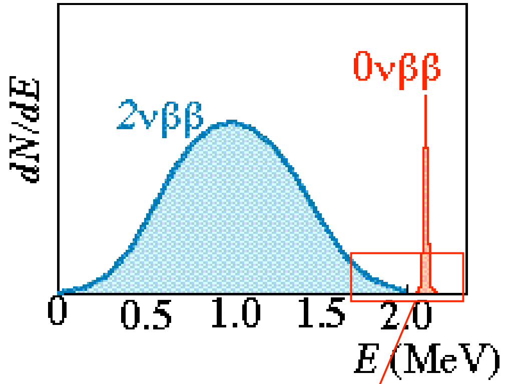
demonstrated ≈ 50 kg

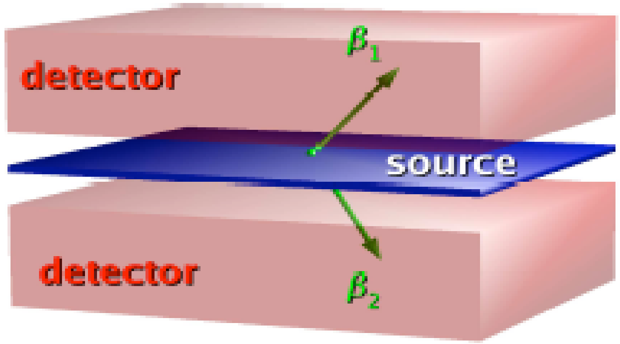
proposed 1000 - 10000 kg

\+ per-mille energy resolution

Ge, bolometers

– only a few nuclides





Source ≠ detector

Tracking (gas or liquid TPC, drift chambers, etc)

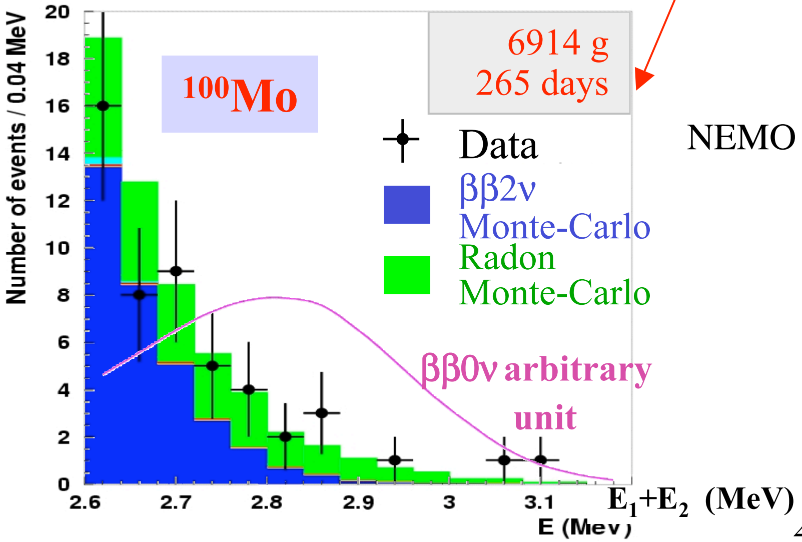
Magnetic field

– low sensitive masses (few kg)

– poor energy resolution

\+ several nuclides in the same detector

\+ very good reconstruction of event topology



NEMO III

Sensitivity of the 2β0ν experiments

In presence of background
b ct/(keV kg yr)
sensitivity to τ

Detector mass

Exposure time

$$F_\tau \propto \left(\frac{MT}{b\Delta E}\right)^{1/2}$$

Energy resolution

sensitivity to $\dfrac{1}{M_{ee}^{M}} \propto F_M = \left(\dfrac{MT}{b\Delta E}\right)^{1/4}$

Sensitivity depends on the isotope $\propto \sqrt{Q}\left|M_{nucl}\right|F_M$

If b=0 during T, in a energy window of a few ΔE with (a few keV for Ge and bolometers) sensitivity on $M_{ee} \propto$ **2nd root** of the exposure

$$F_M = \sqrt[2]{t \times M}$$

Background reduction and energy resolution are the key features

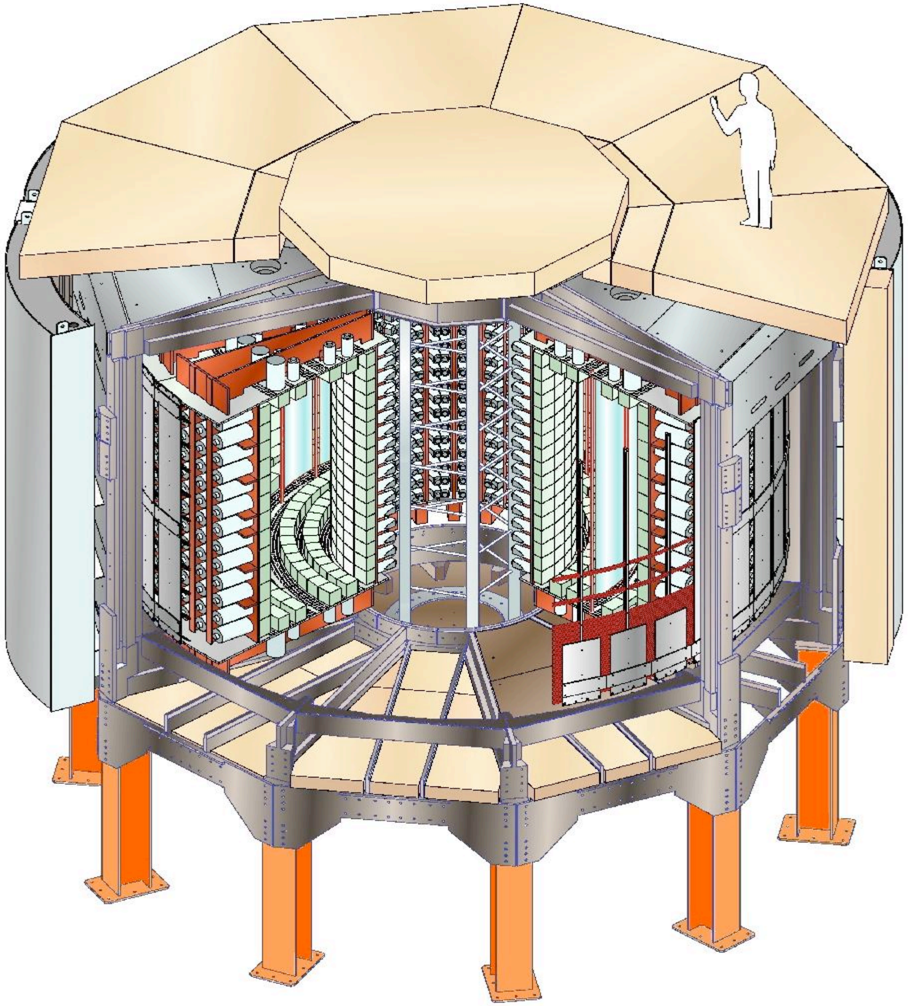
Background is everywere

Background is everything

NEMO 3

Adapted from Sarazin @ Neutrino 2004

Data taking at Frejus Underground Laboratory since February 2004



Sources:

6.9 kg of ^{100}Mo ($Q_{\beta\beta}$ =3034 keV)
0.9 kg of ^{82}Se ($Q_{\beta\beta}$ =2995 keV)
+several grams of ^{116}Cd, ^{96}Zr, ^{150}Nd, ^{48}Ca

Tracking detector:

drift wire chamber operating in Geiger mode (6180 cells)

Calorimeter:

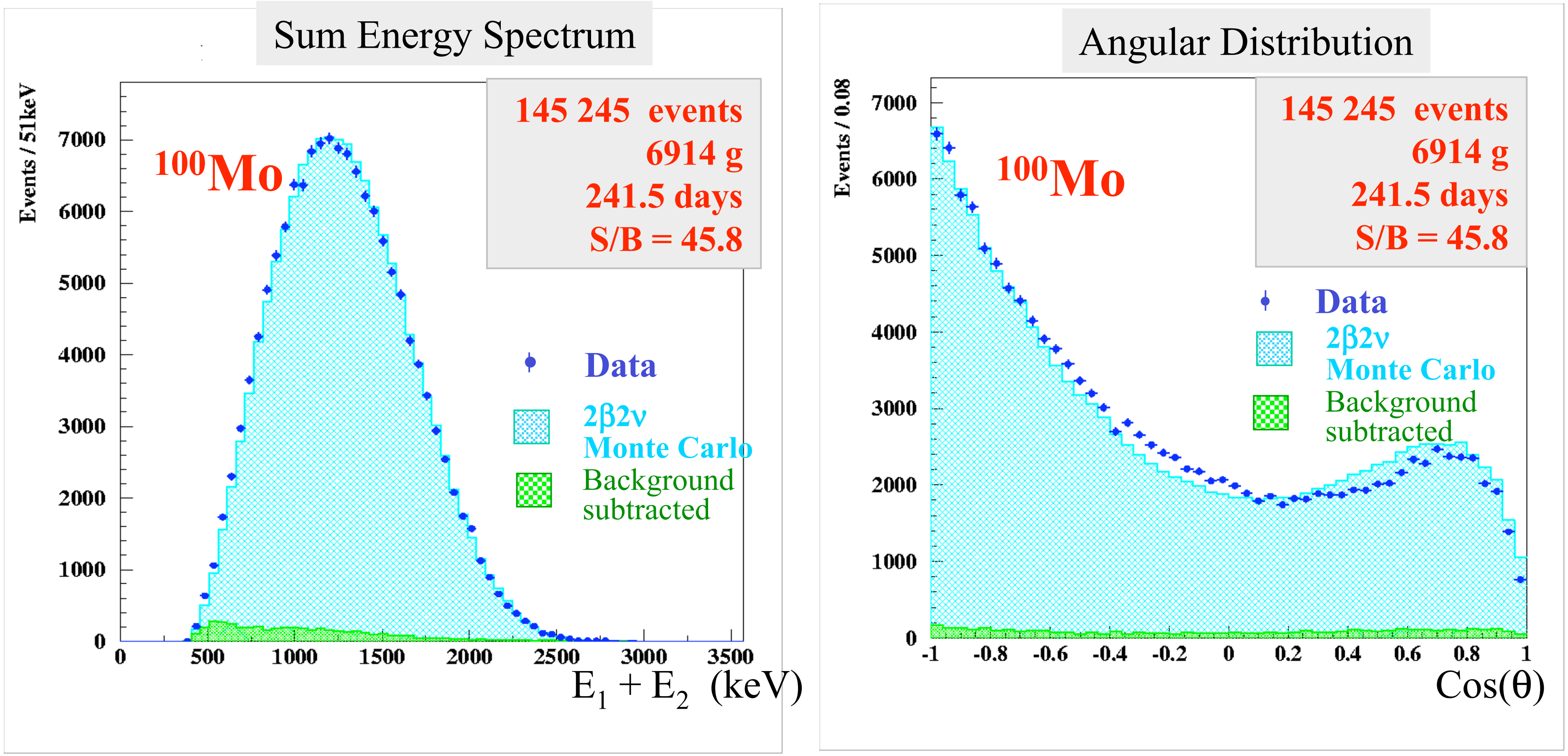
1940 plastic scintillators
Energy res. FWHM @ 1MeV = 14-17%

Magnetic field: 2.5 mT
e^+/e^- confusion = 3% @ 1 MeV
Gamma shield: Pure Iron (t = 18 cm)
Neutron shield: 30 cm water (ext. wall)
40 cm wood (top and bottom)

➡ **Able to identify e$^-$, e$^+$, γ and α**

NEMO3 - ^{100}Mo 2β2ν - preliminary

Sarazin @ Neutrino 2004

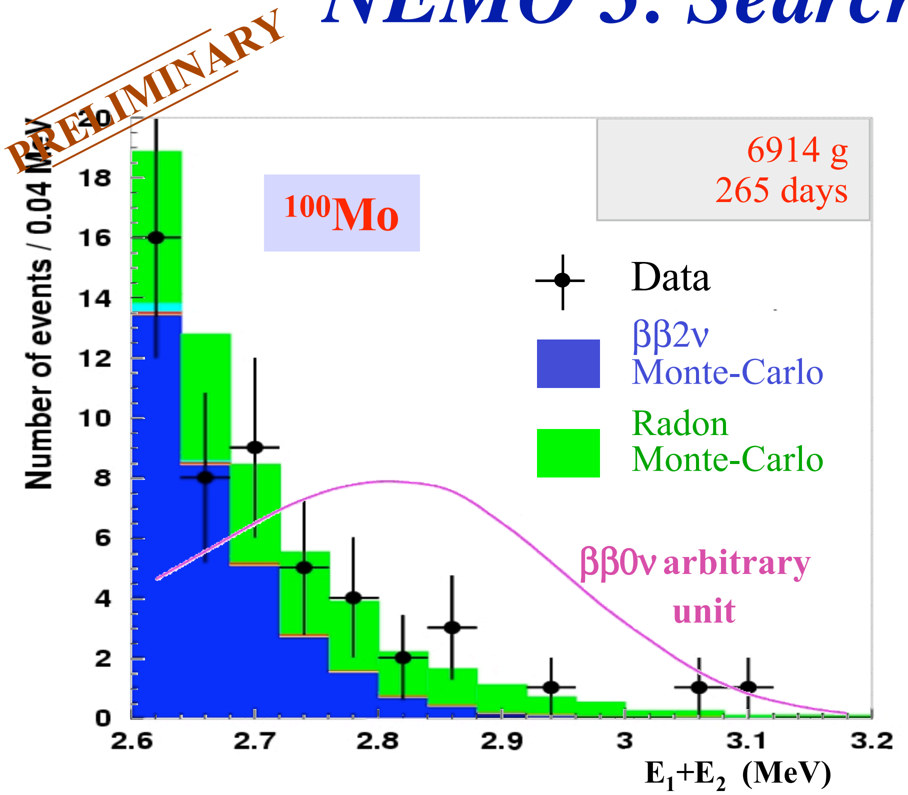


4.57 kg.y

$T_{1/2} = 7.72 \pm 0.02$ (stat) ± 0.54 (syst) $\times 10^{18}$ y

Sum energy spectra measured (less statistics) also for ^{82}Se, ^{116}Cd, ^{150}Nd, ^{96}Zr

NEMO 3. Search for $0\nu 2\beta$ decay



Poor energy resolution (420 keV FWHM)

Two dominating backgrounds within $2.8<E_1+E_2<3.2$ MeV

• ^{222}Rn	$b = 2.8\times10^{-3}$ c/(kg keV yr)
• $2\nu\beta\beta$	$b = 0.75\times10^{-3}$ c/(kg keV yr)
•internal	$b = 0.25\times10^{-3}$ c/(kg keV yr)

$T_{1/2} > 3.5\times10^{23}$ yr

$M_{ee} < 700$ - 1200 meV

	$2.6<E_1+E_2<3.2$	$2.8<E_1+E_2<3.2$
^{100}Mo $2\beta 2\nu$ M-C	**32.3 ± 1.9**	**1.4 ± 0.2**
Radon M-C	**23.5 ± 6.7**	**5.6 ± 1.7**
TOTAL M-C	**55.8 ± 7.0**	**7.0 ± 1.7**
DATA	**50**	**8**

New enclosure of the detector & Rn air purification system. Expected Rn background reduction factor = 75

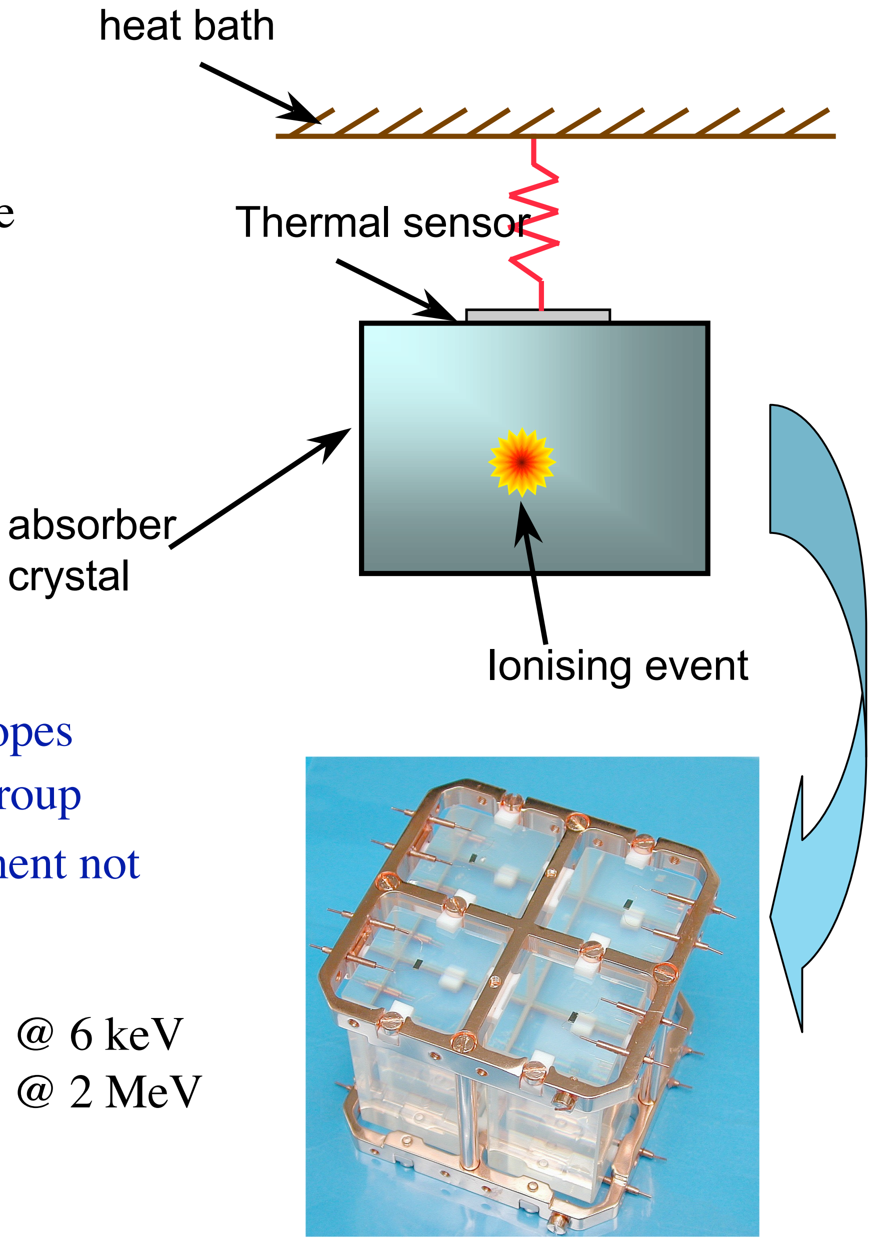
Expected limits in 5 years

$T_{1/2} > 4\times10^{24}$ yr

$M_{ee} < 200$ - 500 meV

Adapted from Sarazin @ Neutrino 2004

Principle of Thermal Detectors



A true calorimeter

Detect energy deposit as $\Delta T \Rightarrow \Delta V$

Very low specific heat at a few mK temperature

Source = detector

$$\Delta T = \frac{Q}{C_V}$$

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

Technique in principle suitable for several isotopes

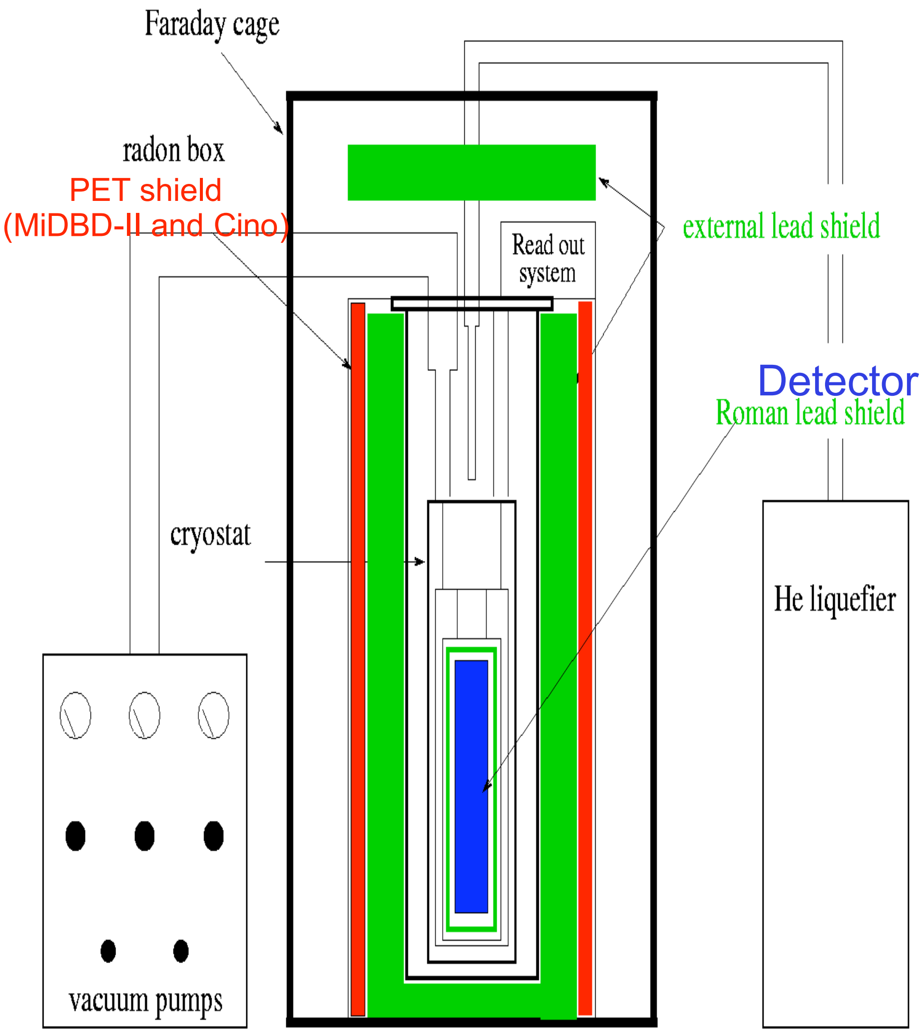
TeO_2 crystals detectors developed by Milano group

Natural abundance of ^{130}Te = 34% ⇒ enrichment not necessary

Excellent resolution	<1 eV	~ 4 eV	@ 6 keV
	~10 eV	~keV	@ 2 MeV

Kindly by E. Fiorini

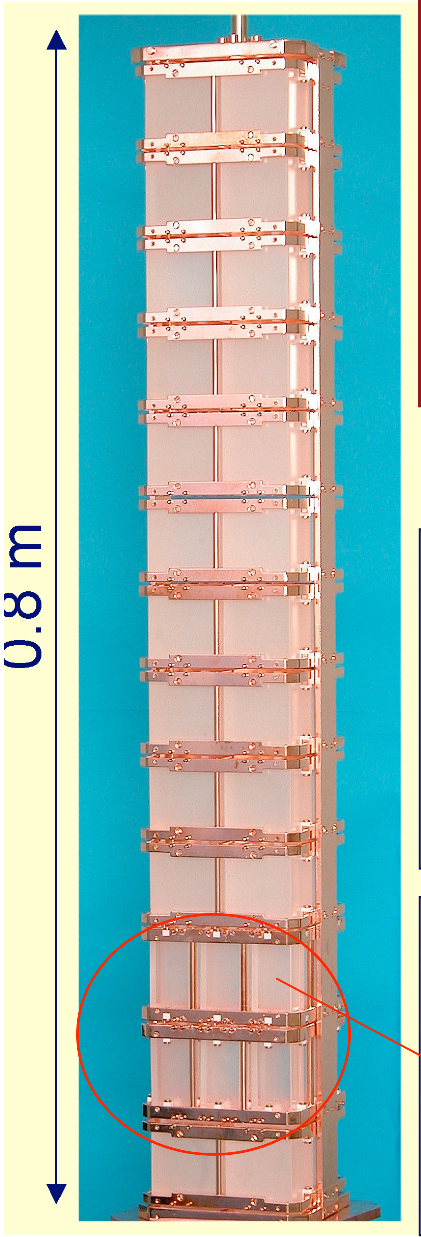
CUORICINO



- **Running at LNGS since February 2003**
- **Dilution refrigerator (10 mK)**
- **Cu shields**
- **Roman Pb inner shield**
- **N2 over-pressure**
- **20 cm thick commercial Pb external shield**
- **Faraday cage**

CUORICINO

40.7 kg “tower”



One tower = 18 (3x3x6) cm^3 + 44 (5x5x5) cm^3 TeO$_2$ crystals

$\Rightarrow$5 10^{25} ^{130}Te nuclei

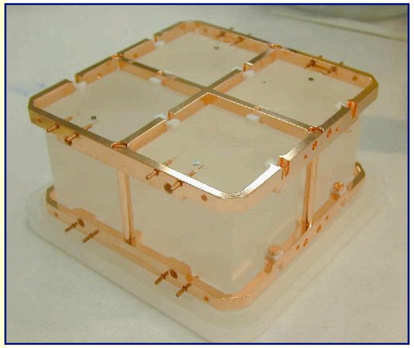
Operational since February 2003. MT = 10.9 kg yr

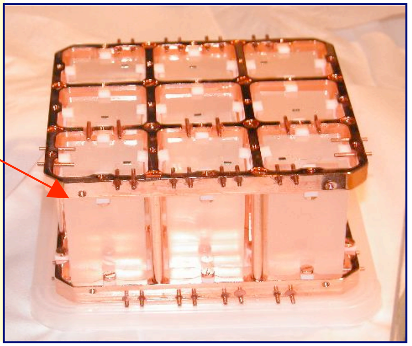
ΔE= 7.7 keV; b=0.18±0.02 c/(keV kg yr)

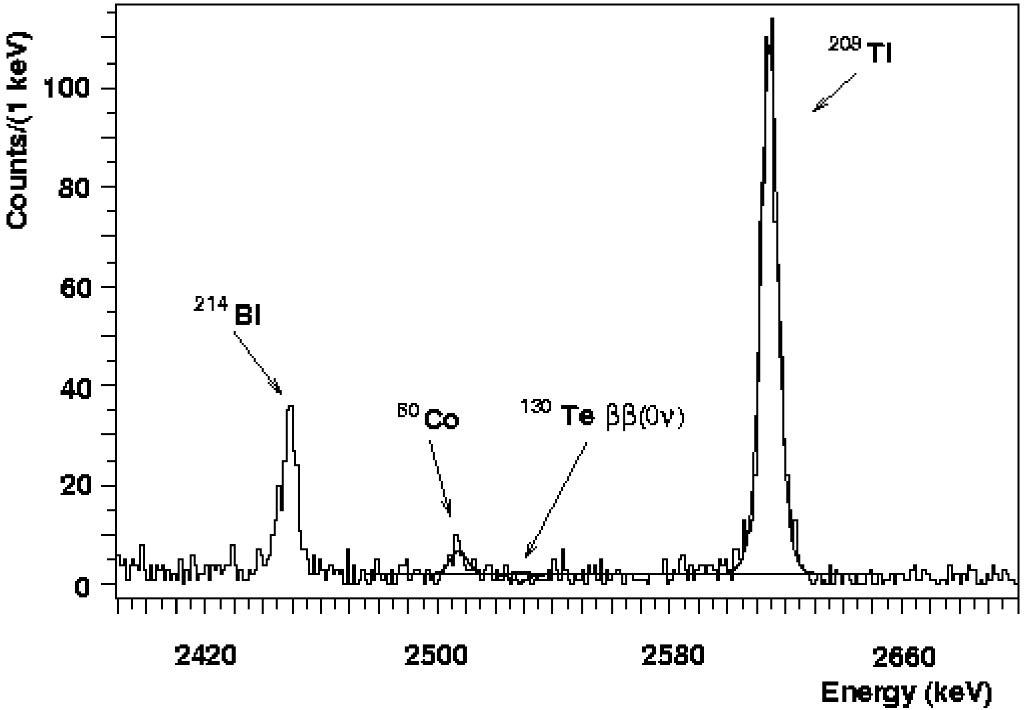
$T_{1/2} > 1.8 \times 10^{24}$ y (90% c.l.) $\Rightarrow M_{ee} < 200 - 1100$ meV

in 3 years $\Rightarrow M_{ee} < 150 - 350$ meV

Klapdor 100-900 meV
No signal in Te cannot falsify Ge
check must be done with Ge





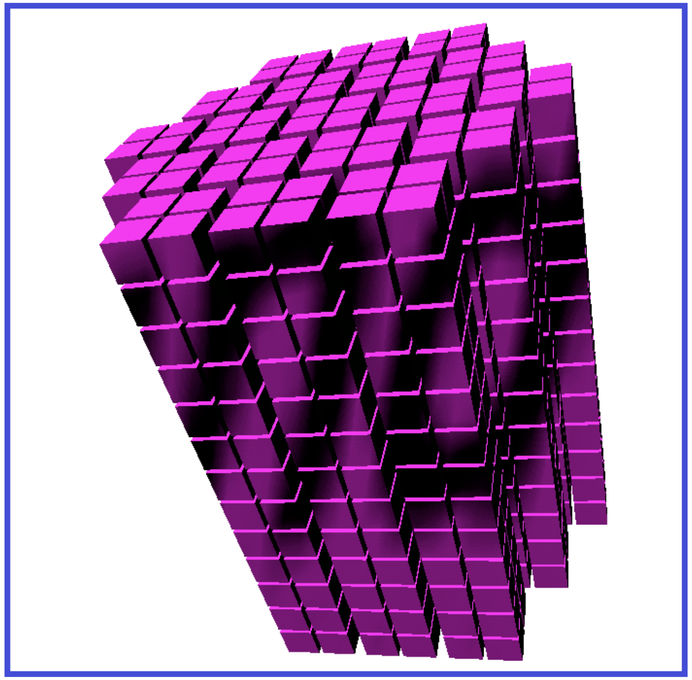


CUORE

Approved by LNGS and by INFN

Structure of 988 closed packed detectors arranged in CUORICINO-like towers

741 kg of $TeO_2 \Rightarrow$ 600 kg of Te
$\Rightarrow$ 203 kg of ^{130}Te



CUORICINO data help in constructing a reliable background model for CUORE

Montecarlo simulation shows that present bulk contamination allows $b=10^{-3}$ c/(keV kg yr)

Background from Cu shields and supports can be eliminated

Surface contamination $\boldsymbol{b=4\ 10^{-2}}$ **c/(keV kg yr)**

Develop both passive and active techniques

$\Rightarrow$ $\boldsymbol{b=10^{-3}}$ **c/(keV kg yr)**

Sensitivity in T = 10 yr

Pessimistic

b = **0.01 ev/(keV kg y);** ΔE**=10 keV**

$\Rightarrow M_{ee} < 24 - 133$ **meV**

Optimistic

b = **0.001 ev/(keV kg y);** ΔE**=5 keV**

$\Rightarrow M_{ee} < 11 - 62$ **meV**

Next generation Ge experiments

Analysis of the H-M data shows that (that) Ge is extremely radio-clean

Main background sources are outside Ge detectors (shields, electrical contacts, supports,…)

Aim to a background index b=10^{-3} /(kg keV yr) ⇒ no background in a few-keV window with a few 100 kg*yr exposure ⇒ sensitivity in $M_{ee} \propto \sqrt{\text{exposure}}$

Heuser in 1995 and Klapdor (**GENIUS** proposal to LNGS) in 1997 ⇒ **bare Ge diodes (1 t) in a shield of liquid N2**

use the techniques for extreme radiopurity liquids developed for BOREXINO (10^{-16} g/g)

GENIUS-TF test facility in operation at LNGS shows the concept viable

Majorana US proposal (1999): 0.5 t of **segmented ^{76}Ge array**

2004. GERDA proposal at LNGS

February 2005. Approval by LNGS Director

GERDA at LNGS

1st phase. Use the H-M and IGEX enriched Ge diodes (17 kg)

Background models on HM data show that internal background index is small

$b<10^{-2}$ ev/(kg keV yr)

Reduce external background to **$b=10^{-3}$ ev (kg keV yr)$^{-1}$**

⇒ if H-M signal OK

observe in 1 year 6.0±1.4 signal/0.5 bkgr

2nd phase. Reach 100's kg yr exposure

with overall $b=10^{-3}$ ev (kg keV yr)$^{-1}$

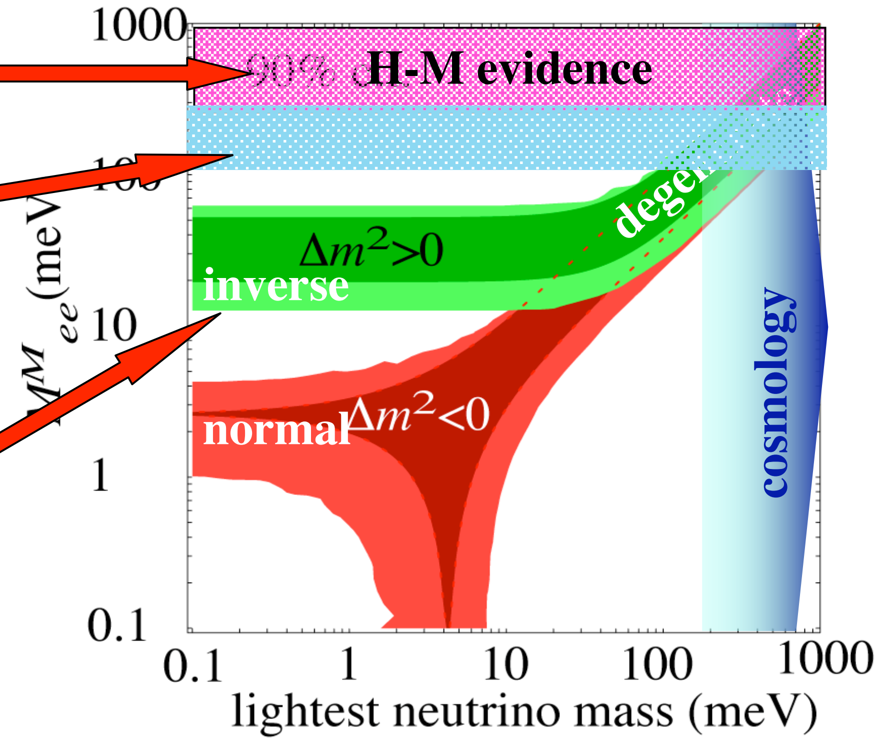
⇒ sensitivity $T_{1/2}>2\ 10^{26}$ yr @90%c.l.

$M_{ee}<90$ - 290 meV

3rd phase ⇒ O(1 t), $M_{ee}<10$-20 meV

define actions on the base of backgrounds' understanding in phase 2

world-wide effort



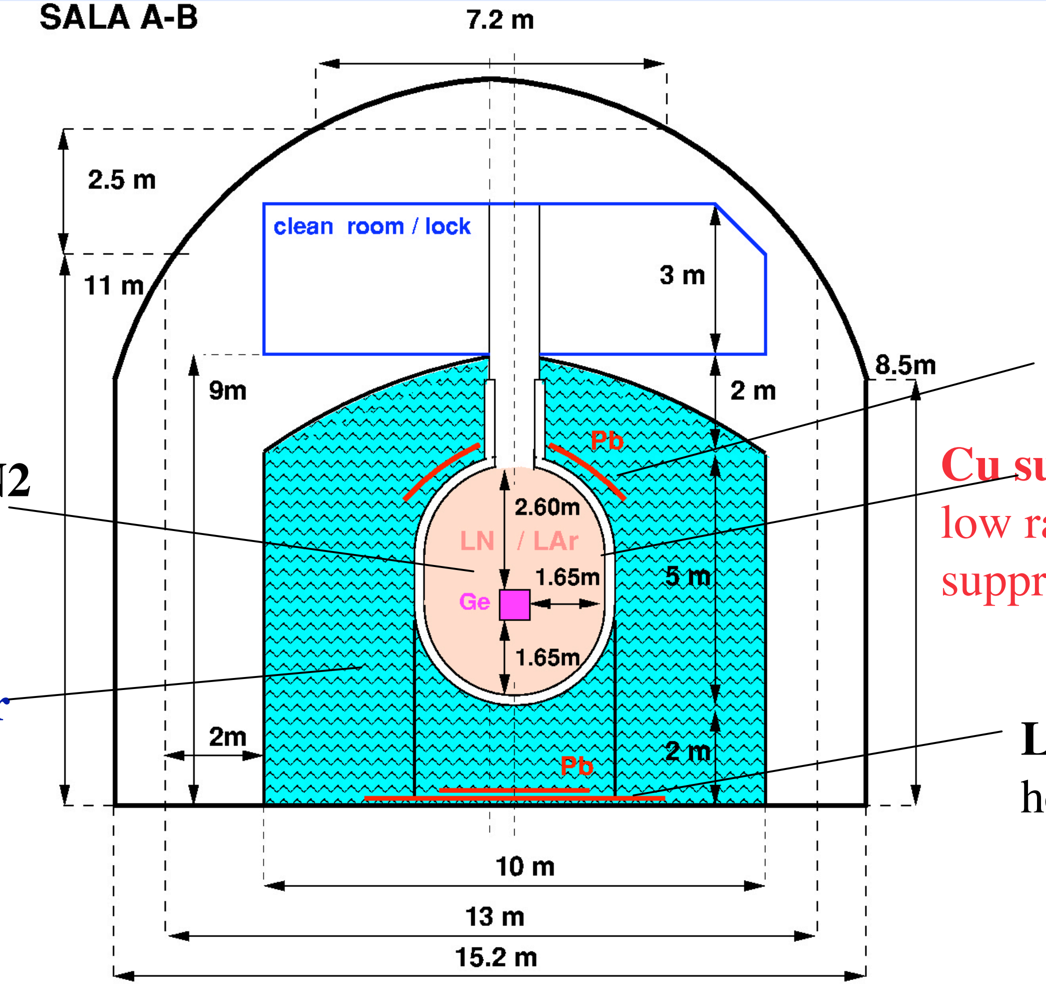
Baseline design of GERDA

External backgrounds are filtered using graded shields

Use only ultra-pure materials: H_2O, LN_2; or pure: Cu

Water layer thickness (≥ 1.5 m) ⇒ neutrons moderator & Cherenkov medium to detect μ's

Gamma (^{208}Tl 2.616 MeV) flux suppression by $2.5\ \ 10^{-8} \Rightarrow b = 10^{-3}$/(keV kg yr)



Ultra-pure LN2

Ultra-pure water

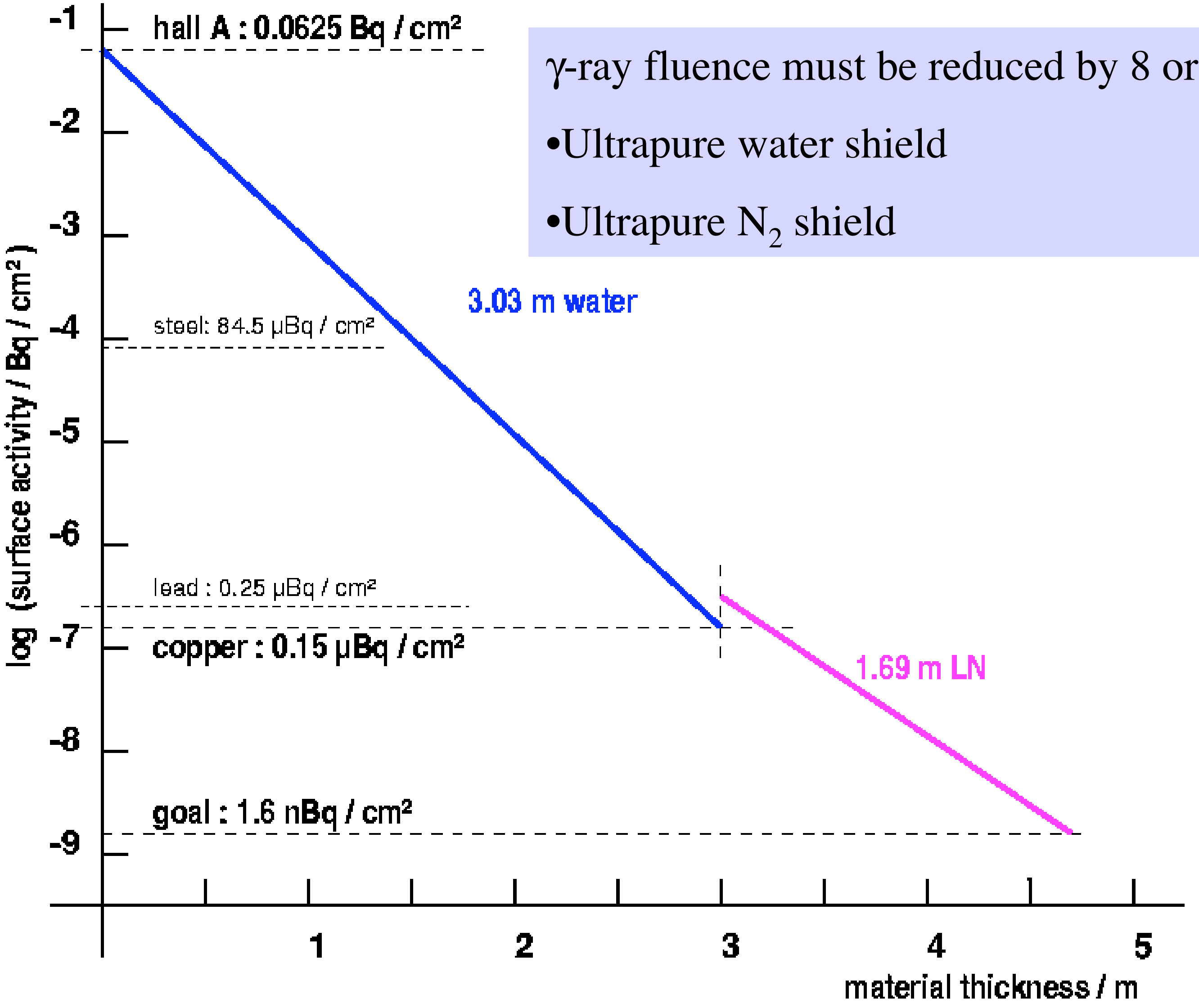
Cu super-insulated tank
low rate radiation suppressed by LN_2

Lead
helps H_2O shield

The shielding

γ-ray fluence must be reduced by 8 orders of magnitude by

- Ultrapure water shield
- Ultrapure N_2 shield



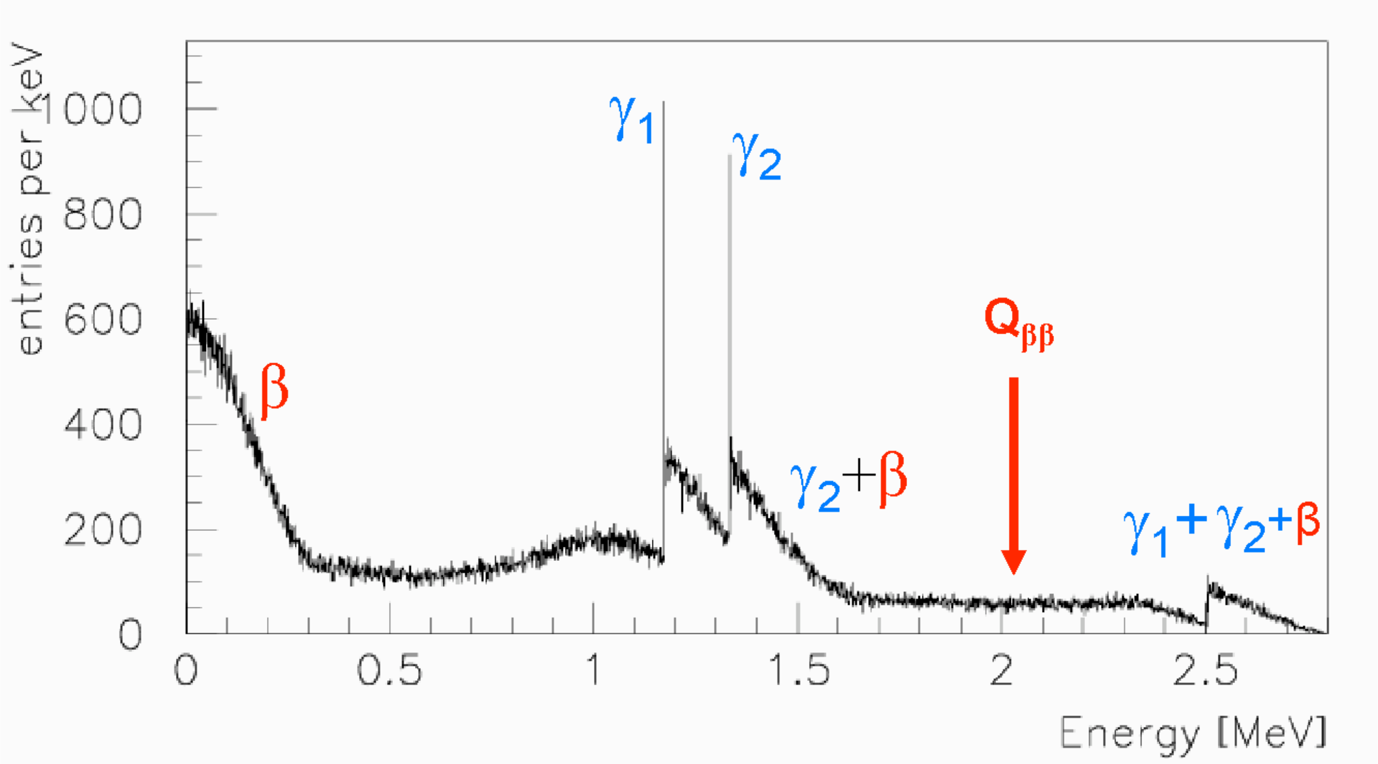
Internal background: cosmogenic ^{60}Co

T_0 for cosmic rays exposure = end of mono-zone refinement

10 exposure days ⇒ 0.17 μBq/kg (Avignone 92)⇒ 0.9 10^{-3}/(keV kg y)

Kurchatov existing crystals in 2006 5 10^{-3}/(keV kg yr)

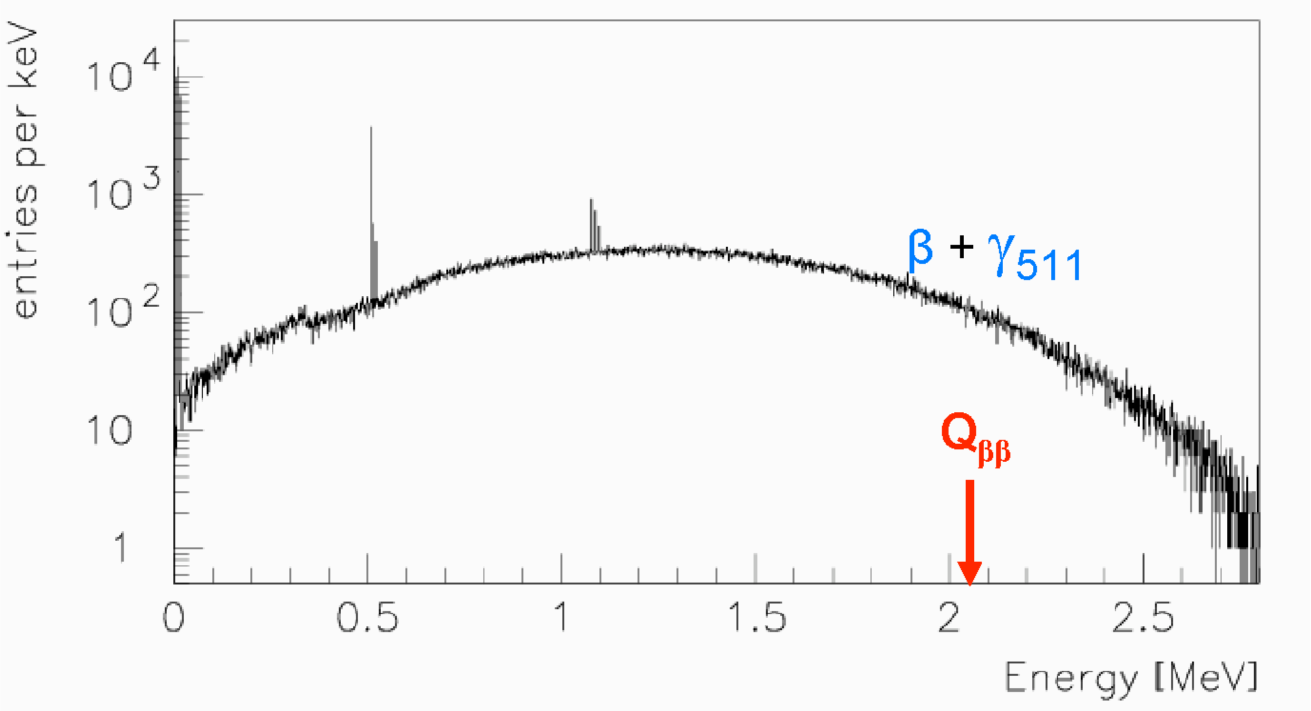
Conservatively we calculate for 30 days exposure ⇒ 2.5 10^{-3}/(keV kg y)



Internal background: cosmogenic ^{68}Ge

T_0 = end of enrichment process ⇒ initial background @ $Q_{\beta\beta}$ $b = 12 \times 10^{-3}$ cts/ (keV kg y)
^{68}Ge has moderately short lifetime $T_{1/2} \approx 270$ d ⇒1/16 after 3 years
But we can do better than waiting

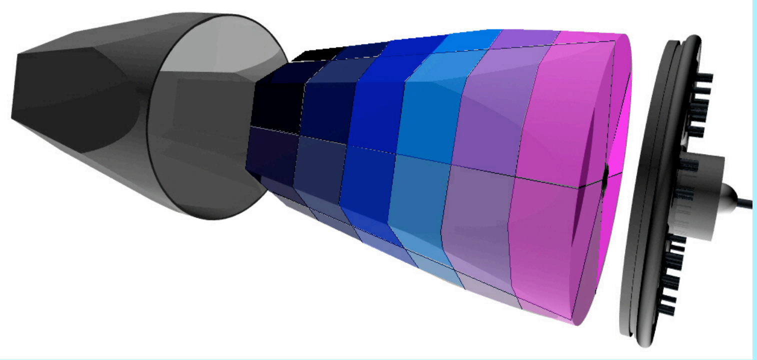
⇒ 0.3 10^{-3} cts/(keV kg y) on the first year



Background reduction techniques

- **Anticoincidences** between components of the detector structure
  - possibly including LAr scintillation light
- Coincidence in the decay chain, **tagging** the decay **^{68}Ge ⇒ ^{68}Ga**
- **Discriminate between SS (Single site) and MSE (Multiple site) events**
  - Segmentation of one read out electrode
  - Pulse shape analysis (PSA), improving on Heidelberg Moscow experience

- Profit of the developments of **AGATA** **A**dvanced **Ga**mma **R**ays **T**racking **A**rray
  - Much advanced in detector design, R/O electronics, event shape models, event shape recognition, etc.
  - Problems are similar, but not identical



- Co-operate with **Majorana proposal**
  - Background discrimination mainly active

Conclusions and outlook

- **Neutrino physics experiments (in underground labs) have shown for the first time physics beyond the Standard Model**
- **We reasonably know the shape of the mass spectrum (a doublet and a singlet) and two (large) mixing angles**
- **Cosmology, beta decay and double beta decay are complementary for fixing the absolute value of the mass scale and understanding one of the main bridges between particle physics and cosmology**
- **Double beta decay is the only source of information on neutrino charge conjugation properties**
  - **Several experimental proposed approaches, but few viable in the next few years**
  - **Backgrounds are different in the different cases and need to be fully controlled**
  - **Nuclear matrix elements are still uncertain. More work needed**
  - **Experiments on different isotopes are necessary**
- **Understanding the origin of neutrino mass is not less important than checking the mass-generation scheme of the SM**