Neutrino Physics at LNGS

DESY February 25,26, 2003

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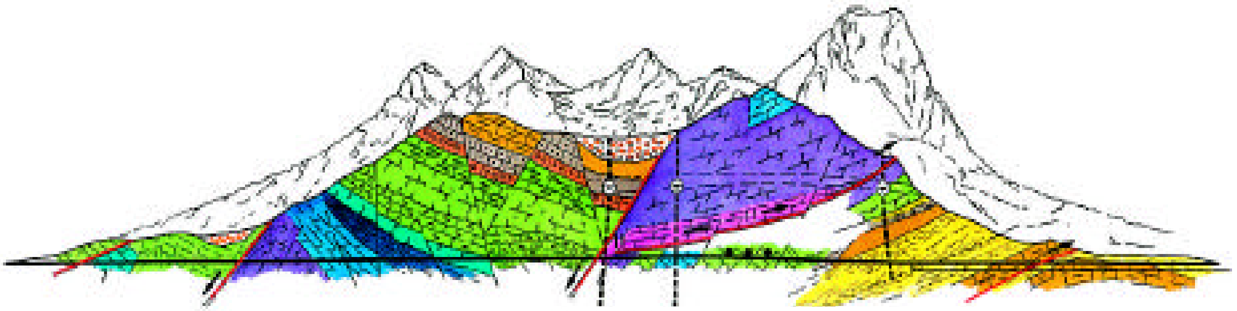
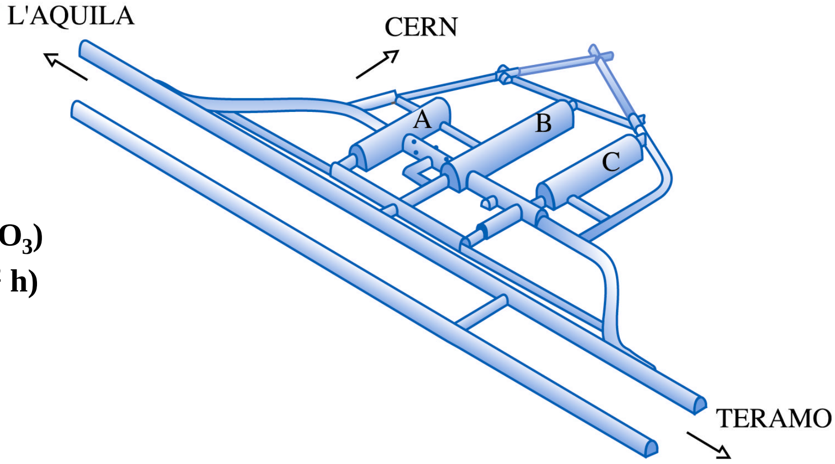
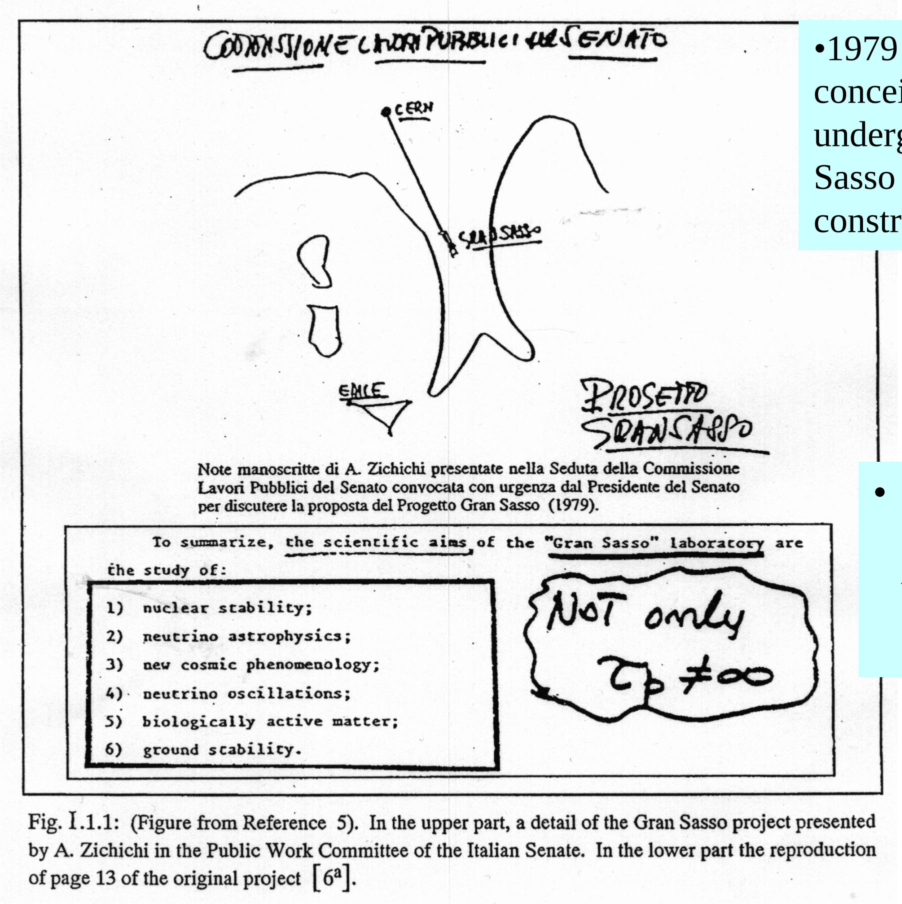




- **1400 m rock overburden**
- **Flat cross-section**
- **Neutron fluence attenuation 10^{-3} ($CaCO_3$)**
- **Cosmic μ flux attenuation = 10^{-6} (1 /m^2 h)**
- **Underground area 18 000 m^2**
- **Support facilities on the surface**
- **Drive-in to the experiments**

History



COMMISSIONE LAVORI PUBBLICI del SENATO

PROGETTO GRANSASSO

Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).

To summarize, the scientific aims of the "Gran Sasso" laboratory are the study of:

1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

NOT only $\tau_p \neq \infty$

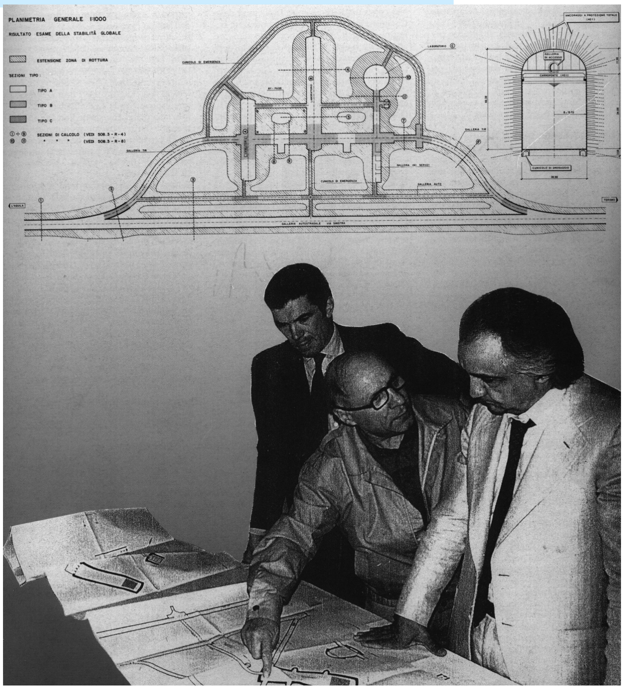
Fig. I.1.1: (Figure from Reference 5). In the upper part, a detail of the Gran Sasso project presented by A. Zichichi in the Public Work Committee of the Italian Senate. In the lower part the reproduction of page 13 of the original project [6^a].

•1979 A. Zichichi (President of INFN) conceives the idea to build a large underground laboratory close to the Gran Sasso freeway tunnel then under construction

- 1982 The Italian Parliament passes a law with the first bill for the construction

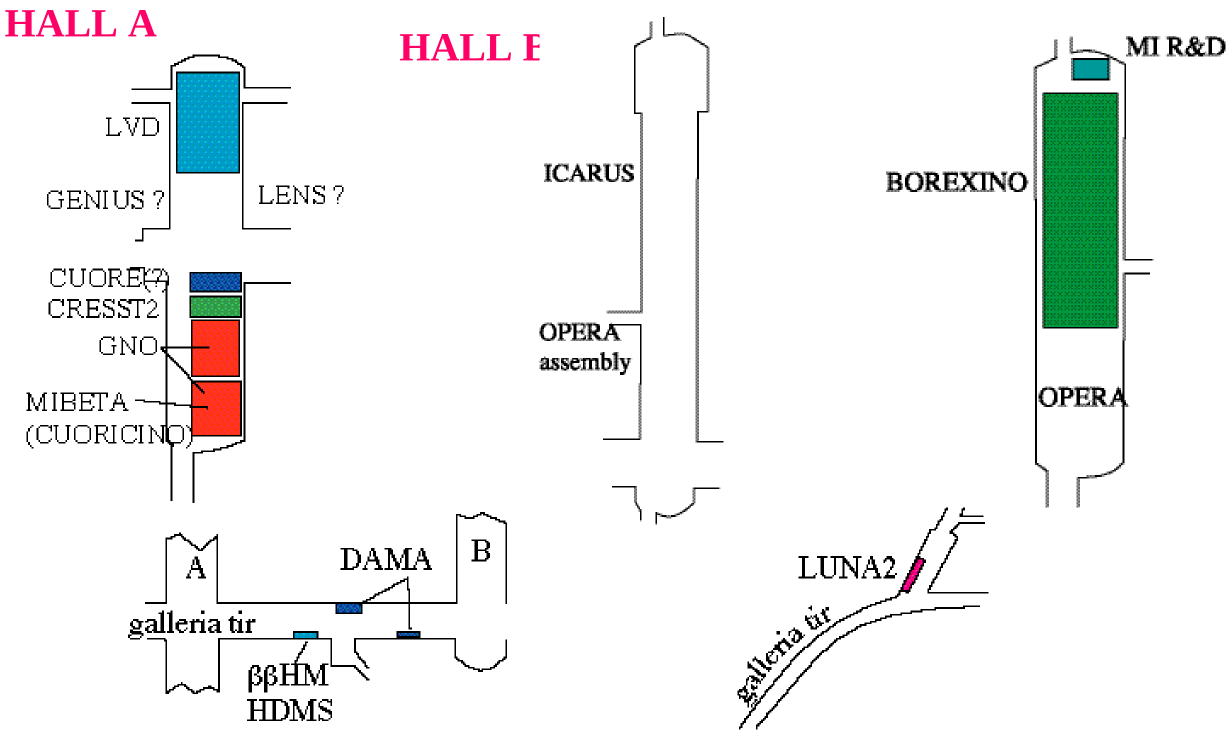
History

1983 Digging of the underground halls begins
1987 End of the civil engineering. First experiments are commissioned
1989 First large experiment (MACRO) running
1990 Parliament approves the third law, appropriating a bill for the construction of two new halls and a dedicated access tunnel



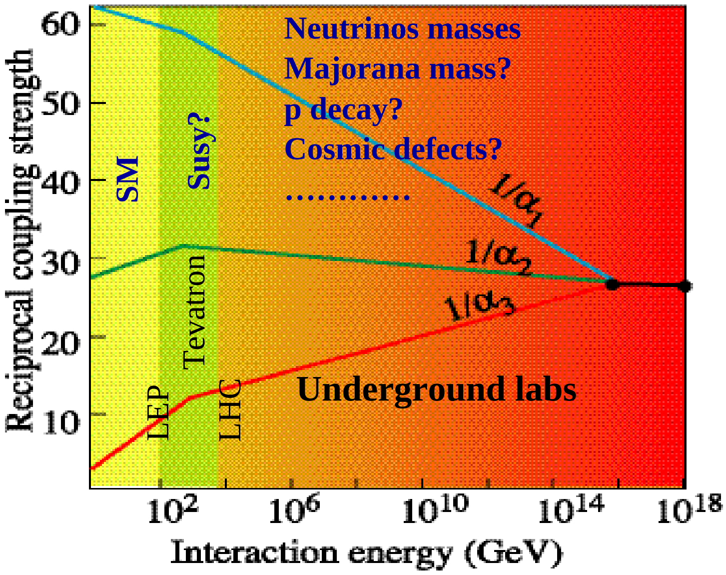
Preparing the next phase

Space has been made available for the next phase.
Many new ideas and experimental proposals from the community



The forces

The Standard Theory has been tested with extreme precision with accelerators & colliders
But only at very low energies, compared to the unification and to the Planck scale
We are approaching the limits of accelerator physics
energy, luminosity, costs, size of collaborations, time to results, etc
For one of the basic forces, gravity, we don't have yet a quantum theory
Look for extremely violent events? (merging n stars, supermassive BH's,….)



Explore the high energy frontier searching for extremely rare signals

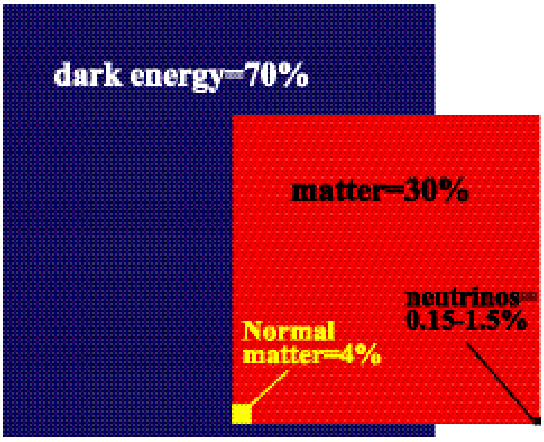
The Standard Model of Cosmology

Matter is only a fraction of the total

≈ 80% of matter is non baryonic

≈ 90% of baryonic matter is dark

contrib. of neutrinos to dark matter is (very) small



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

The standard cosmological model is based on:

- **A dark matter we don't see**
- **A dark energy we don't understand**
- **A fraction of baryons we can't find**

Cosmologic theories cannot be experimentally proven
Prove is consistency not reproducibility

Standard Cosmology gives us clear guidelines on what to search for
new elementary particles
new elementary vacuum

New neutrino physics

Two independent pieces of evidence for Physics beyond the Standard Model

Both from experiments in underground laboratories on

1. electron neutrino from the Sun
2. muon neutrinos from the atmosphere

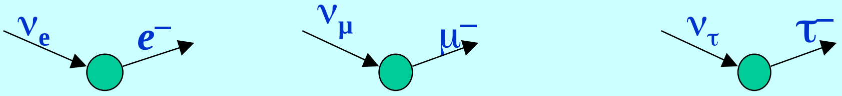
have shown the. oscillation phenomena at different square mass differences

Δm^2 ("atmospheric")

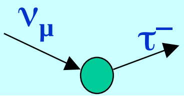
δm^2 ("solar")

Implications

- ν_e, ν_μ and ν_τ are not mass eigenstates (ν_1, ν_2, ν_3) but superpositions of these
  If eigenstates are orthogonal, need to measure
  - •three "mixing angles" $\theta_{12}, \theta_{13}, \theta_{23}$
  - •three phases (one if Dirac)
    - •CP violation
- ν_1, ν_2 e ν_3 have m_1, m_2 and m_3 $\neq 0$
- leptionic charges are not conserved
  - •not only



  - •but also

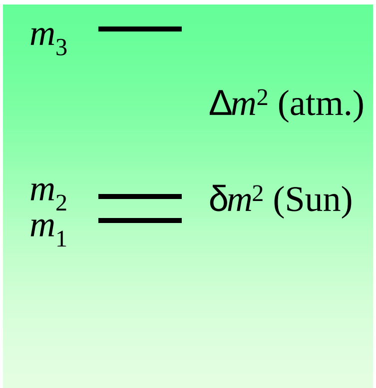


just wait enough

Neutrino masses

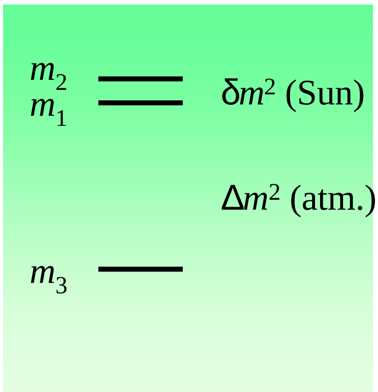
Spectrum is a doublet plus a singlet. Define:
Doublet = m_1, m_2 with $m_2 > m_1$ and $\delta m^2 = m_2^2 - m_1^2$
Singlet = m_3 and $\Delta m^2 = m_3^2 - m_2^2$

NORMAL
$\Delta m^2 > 0$



$$m_3 > \sqrt{\Delta m^2} \approx 50 \text{ meV}$$
$$m_2 > \sqrt{\delta m^2} \approx 8.5 \text{ meV}$$

INVERTED
$\Delta m^2 < 0$



Oscillation probabilities depend on the absolute values of the differences between the squares of the masses (the eigenvalues)
We don't know the absolute scale
Hierarchic or. degenerate spectrum?

Seesaw mechanism

$$m_i = \frac{M_D^2}{M}; \quad \text{with} M_D = M_{top} \text{ and } m_3 = 50\text{meV}$$

M **≈ 10^{15} GeV, the lepton number violation scale is close to the GUT scale!**

The unit for neutrino masses is the **millielectronvolt**

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

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

future high intensity beams

non oscillation exp/s

0ν2β

9 independent real parameters

- 3 masses ***m_1, m_2, m_3***
- 3 “mixing angles” θ_{12}, θ_{13}, θ_{23}
- 3 phases (CP violation)
- 2 (Majorana) phases (α,β), zero if neutrinos are Dirac particles irrelevant for oscillations

Flavour conversion in vacuum

Transitions between different flavour pairs take place in a three-state system (neutrinos).

Transition probabilities formulas more complicated than for two-state

For L/E close to maximal ($1/\Delta m^2$) one oscillation dominates

$$P_{\nu\mu\to\nu\tau} = \sin^2(2\theta_{23})\cos^4(\theta_{13})\sin^2\left(1.27\Delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

$$P_{\nu\mu\to\nu e} = \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(1.27\Delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

Oscillations period depends on absolute value of the squared mass difference
Oscillation amplitudes are not equal to $\sin^2 2\theta$
Oscillation amplitude is different for different oscillations
“Mixing angles” ranges are $0 - \pi/2$ not $0 - \pi/4$
Talking of “electron neutrino mass” is misleading
Variables like $\theta_{\mu\tau}$ are misleading (may lead to wrong conclusions)
Beware mistakes of PDG

Flavour conversion in matter

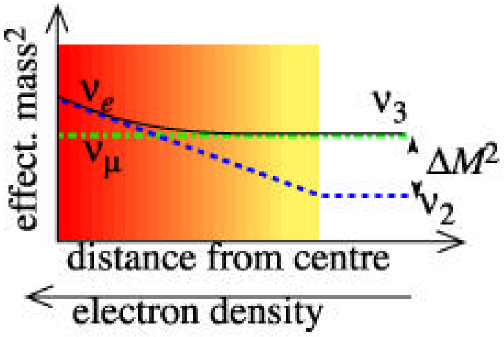
The MSW effect

In matter ν_e interact with the electrons via CC, (refraction index)

ν_1, ν_1, ν_3 are not the mass eigenstates

Gives complementary information w.r.t. oscillation experiments

Level crossing possible @ critical value of density*energy

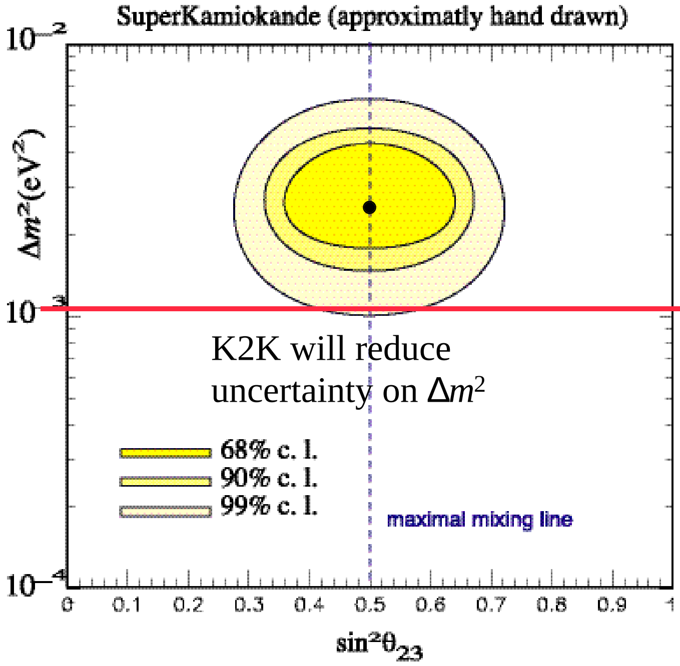


Important in Sun, in Earth, in a Supernova

If matter effects, "effective mixing angle" range is 0 – $\pi/2$, even for two neutrino flavours

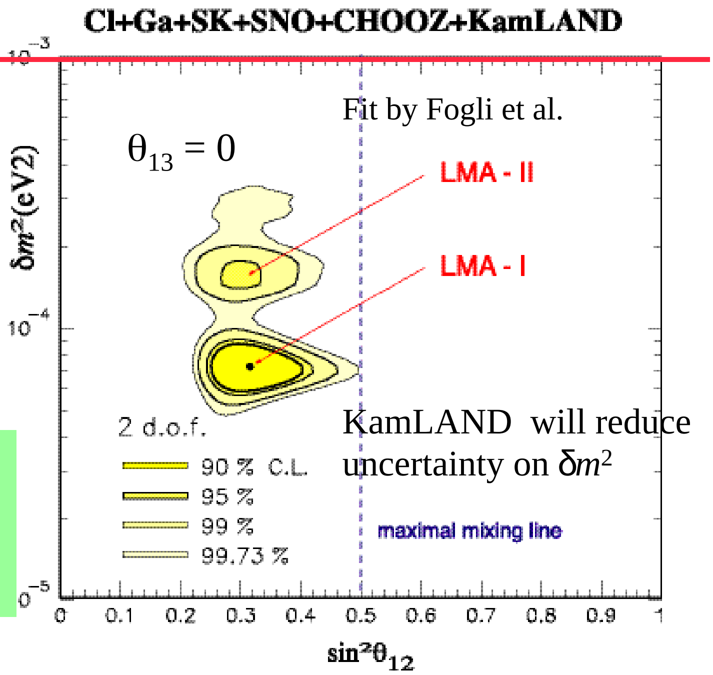
Need MSW to
break symmetry

Status of neutrino oscillations



K2K will reduce
uncertainty on Δm^2

N.B.
Fit assumes all experiments and their uncertainties to be correct
We do not yet have a direct measurement of solar neutrino flux below 5 MeV, 99.99% of the total



Fit by Fogli et al.

$\theta_{13} = 0$

KamLAND will reduce
uncertainty on δm^2

Combining CHOOZ with solar data
$\theta_{13}^2 \approx |U_{e3}|^2 < 0.025$
JHF (0.75 MW) to SK $\theta_{13}^2 < 0.0015$
JHF (4MW) + HK, another order of magnit.

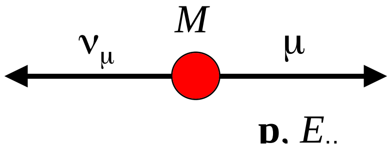
Meson decay spectrum

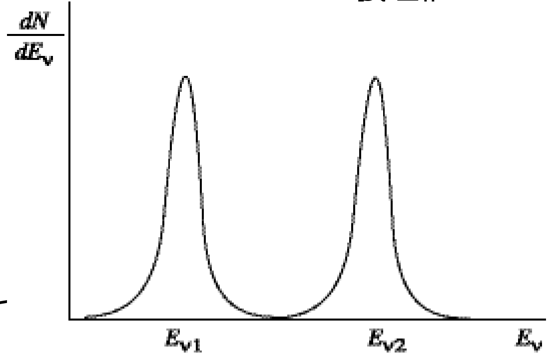
Only two neutrinos for simplicity: ν_1 and ν_2, with masses m_1 and m_2
Suppose ν_μ and ν_τ were maximum mixings of ν_1 and ν_2

$$\nu_\mu = \frac{1}{\sqrt{2}}(\nu_1 + \nu_2)$$

$$\nu_\tau = \frac{1}{\sqrt{2}}(\nu_1 - \nu_2)$$

Consider the decay of a meson of mass M into a μ and a ν_μ
To determine neutrino masses measure muon energy and get neutrino energy E_ν





We should find a dichromatic spectrum corresponding to the two masses m_1 and m_2

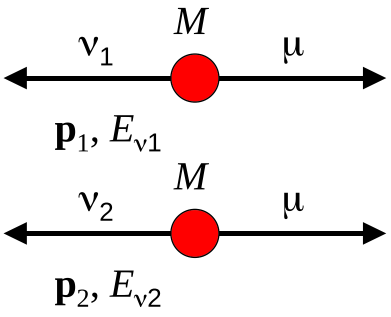
We can then tag a sample of ν_1 for example

$$\nu_1 = \frac{1}{\sqrt{2}}(\nu_\mu + \nu_\tau)$$

Neutrinos of this sample, hitting a nucleus will produce both μ's and τ's with equal probabilities

Absurd??

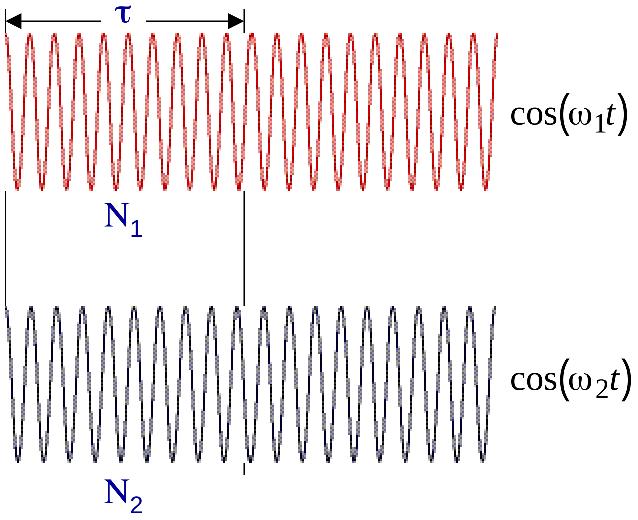
How much energy resolution?



Need enough energy resolution to measure $E_{\nu 2} - E_{\nu 1} \approx \frac{\Delta m^2}{4E_\nu}$

Neutrino beam is a dichromatic wave with periods $T_1 = 1/E_{\nu 1}$ and $T_2 = 1/E_{\nu 2}$

Count the crests in time interval τ, large enough to see the difference



$N_1 = \tau / T_1 = \tau E_{\nu 1}$ and $N_2 = \tau / T_2 = \tau E_{\nu 2}$

Condition to resolve: $N_2 - N_1 \geq O(1)$

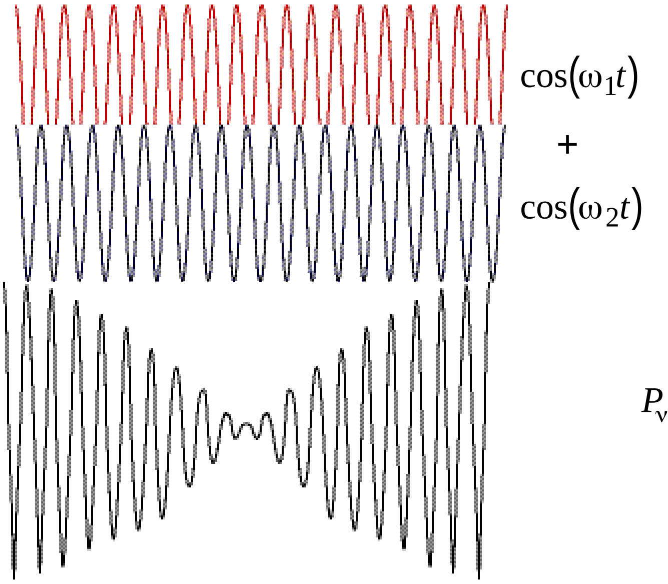
$\tau (E_{\nu 2} - E_{\nu 1}) > 1$ Uncertainty relation

$$\tau > \frac{1}{E_{\nu 2} - E_{\nu 1}} \approx \frac{E_\nu}{\Delta m^2}$$

Counting the crests of the wave function

In practice we cannot count the crests of the wave functions N_2 and N_1 , but <u>we do have a way to count the difference</u> $N_2 - N_1$ by beating the two waves (it happens naturally)

Take τ _______(minimum) _____________ in which, say $N_2 - N_1 = 1/2$.
At this time the two waves, initially in phase, are in phase opposition. If their amplitudes are equal (maximum mixing) the resulting amplitude vanishes.



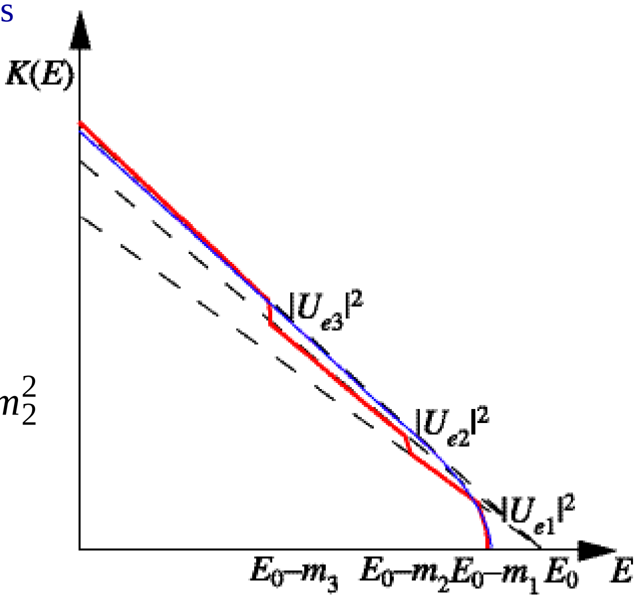
$L=E_\nu/\Delta m^2$ is the length (half period) for flavour oscillations

After this time both μ's and τ's are produced colliding an originally muon neutrino beam

$$P_{\nu\alpha\to\nu\beta} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2\left(\mathrm{eV}^2\right)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

Neutrino masses from beta decay

"Mass" is a property of a stationary state: ν_e, or ν_μ , or ν_τ "mass" is improper
Its meaning depends on what and how one measures
Example: Tritium β decay $^3H \rightarrow {}^3He + e^- + \overline{\nu}_e$



In practice (even in principle) the different "steps" are not resolved (blue curve)

$$< m_{\nu e}^2 > = |U_{e1}|^2 \; m_1^2 + |U_{e2}|^2 \; m_2^2 + |U_{e3}|^2 \; m_3^2$$

From solar oscill. & CHOOZ

$$< m_{\nu e}^2 > \approx (0.7 - 0.5) m_1^2 + (0.3 - 0.5) m_2^2$$

$<m_{\nu e}>$ < 2.2 eV from Mainz experiment
Troitsk experiment has similar limit, but with a non understood systematic effect

FUTURE: KATRIN
New spectrometer for **tritium β decay, planned to push the limit to $<m_{\nu e}>$ > 300 meV**

Beta decay experiments do not look capable to reach the ultimate neutrino mass scale

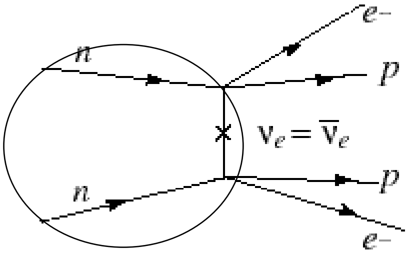
Majorana masses of electron neutrinos

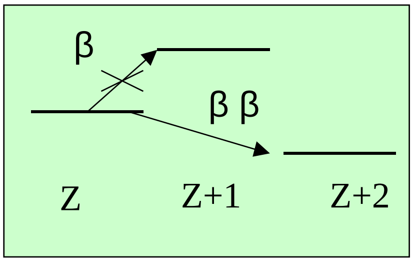
SM neutrinos are massless, described by a 2-component (left) spinor
If lepton number is not conserved and if neutrinos are massive (chirality is frame dependent)

$$\nu_e^C = \nu_e$$

Majorana neutrino

Measure $0\nu\beta\beta$ lifetimes





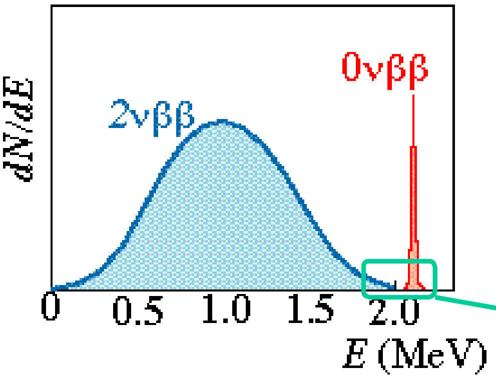
$$M_{ee}^{M} = \left|\, |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{2i\alpha_{12}} m_2 + |U_{e3}|^2 e^{2i\alpha_{13}} m_3 \right|$$

Cancellations are possible

Best limits: $M^M_{ee} < 270\, h$ meV (Heidelberg-Moscow at LNGS) and similar from IGEX
$h = \mathcal{M}_o / \mathcal{M}$ uncertainty in nuclear matrix element: factor 2-3

How to improve limits

Measure total energy
of two electrons



Next generation experiments must reach ultimate background = 2ν2β decay
Energy resolution is a must

t = Exposure time

M = Detector mass

limit on $\frac{1}{M^{M}_{ee}}$ $\sqrt[4]{\frac{tM}{\Delta b}}$

Δ = Energy resol.

b = Background rate

Progress requires increase the sensitive mass <u>and</u> decrease the background per unit mass <u>without</u> compromising on energy resolution.

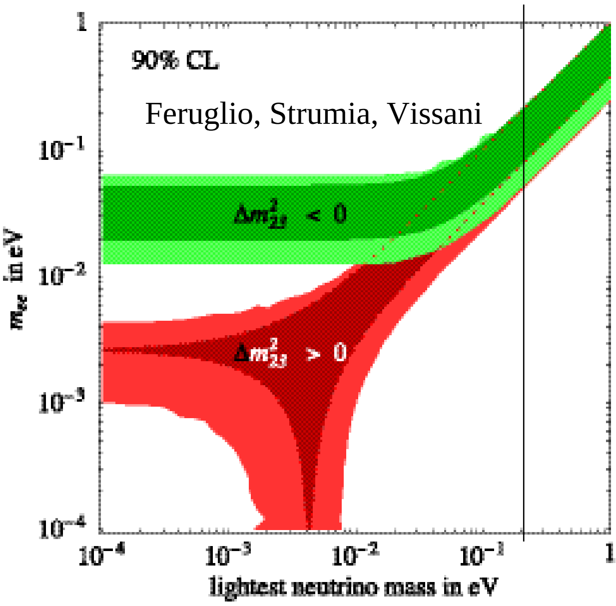
To gain <u>one order of magnitude</u> in neutrino mass

increase by <u>two orders of magnitude</u> sensitive mass
decrease by <u>two orders of magnitude</u> background

Theoretical effort needed to reduce the uncertainty on nuclear matrix elements for ^{76}Ge, ^{130}Te, etc., even if difficult.
Factor 3 uncertainty corresponds to a factor 100 in detector mass
Which further experimental input is needed?

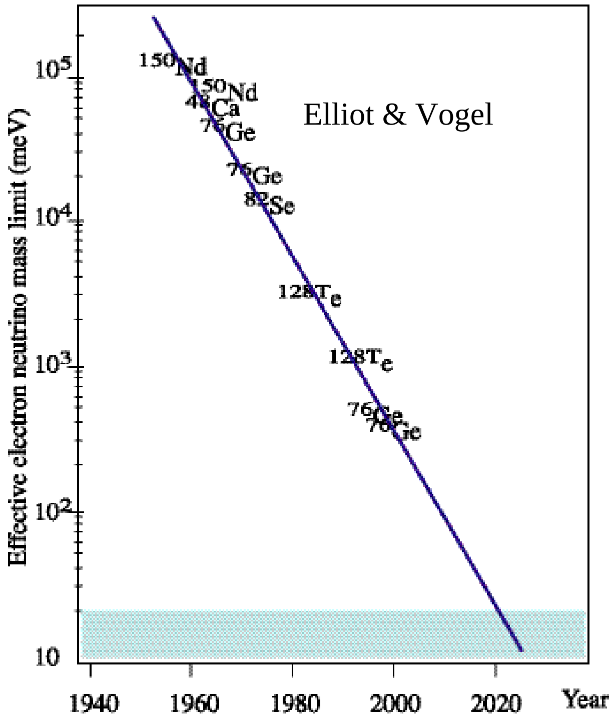
Towards (absolute) neutrino mass

There is not an absolute lower limit for M^{M}_{ee} < 270 *h* but expected signal @ a few tens meV in many scenarios



Feruglio, Strumia, Vissani

Experiments have progressed enormously in the past decades



Elliot & Vogel

LNGS programme

Heidelberg-Moscow
Technique: **Enriched ^{76}Ge detect.**
b **= 0.17±0.01 ev/(kg keV y)**
without pulse shape analysis
Limit: M_{ee}<270 meV (best)
Exposure: 46.5 kg kg y

GENIUS-TF
Test facility for GENIUS
With the present HM Ge and
b **= 6 x 10^{-3} ev/(kg keV y)**
M_{ee}<100 meV in 6 years
Status. Approved

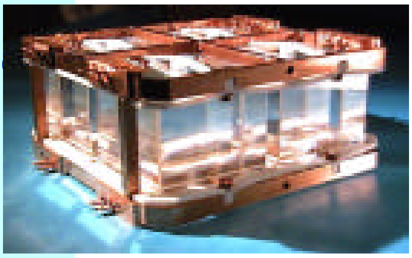
GENIUS
Naked enriched Ge crystals in LN_2
b **= $3x10^{-4}$ ev/(kg keV yr))**
Sensitive mass: 1000 kg ^{76}Ge
M_{ee}< 20-30 meV
Status. Experimental tests requested (GENIUS-TF)

The struggle for background reduction

MIBETA (Milan)
Technique:**natural TeO_2 bolometers (^{130}Te = 34%)**
^{130}Te mass = 2.3 kg
b = 0.5 ev/(kg keV yr)
Limit: M_{ee} < 2 eV (2nd best)

CUORICINO (expected)
Sensitive ^{130}Te mass = 14.3 kg
b = 0.02-0.05 ev/(kg keV yr)
Limit: M_{ee} < 200-400 meV
Status. Approved

CUORE propos. (expecte
^{130}Te mass = 250 kg
b = $2x10^{-3}$ ev/(kg keV yr)
Limit: M_{ee} < 50 meV



Neutrino masses from cosmology

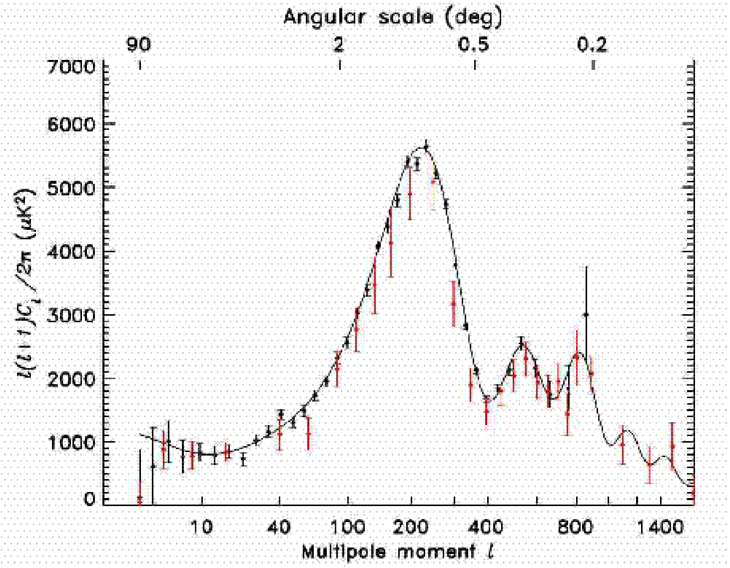
The number densities of the three neutrino states are independent on their masses

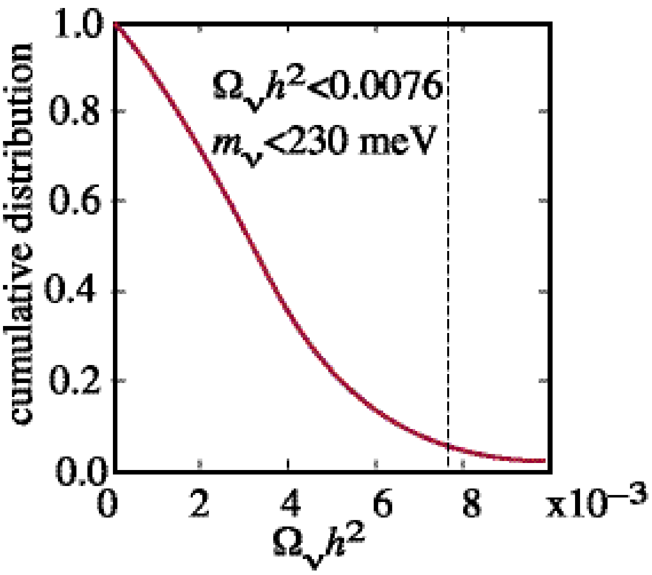
Limits on neutrino mass density gives a limit on the sum of neutrino masses

New data from WMAP on CMB anisotropy of unprecedented statistical accuracy (not on angular resolution)

Combining with other measurements (astro-ph/0302209, astro-ph/0302217`)

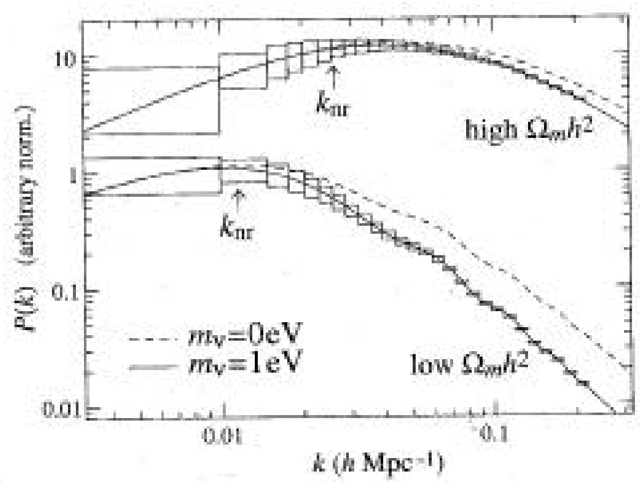
Present best limit $\sum m_i < 690$ meV $\Rightarrow$ $m_1, m_2, m_3 < 230$ meV





Neutrino masses from cosmology

Next step (?): accurate measurement of large scale (but smaller than CMB) spectrum (LSS)
Sloan Digital Sky Survey (SDSS) expected to measure the spectrum at **1%** accuracy.
During matter domination neutrinos suppress amplitude fluctuations at smaller scales
Comparison of amplitude fluctuations in LSS and CMB gives information on neutrino density
Combine with other precision measurements. Mainly CMB
Get limit (or evidence) on neutrino masses (Hu, Eisenstein and Tegmark, Phys. Rev. Lett. **80** (1998) 5255)
N.B. Variations of other cosmological parameters give effect similar to neutrino masses



Discovery limit @ 2 σ = $\sum m_i$ = 300 meV

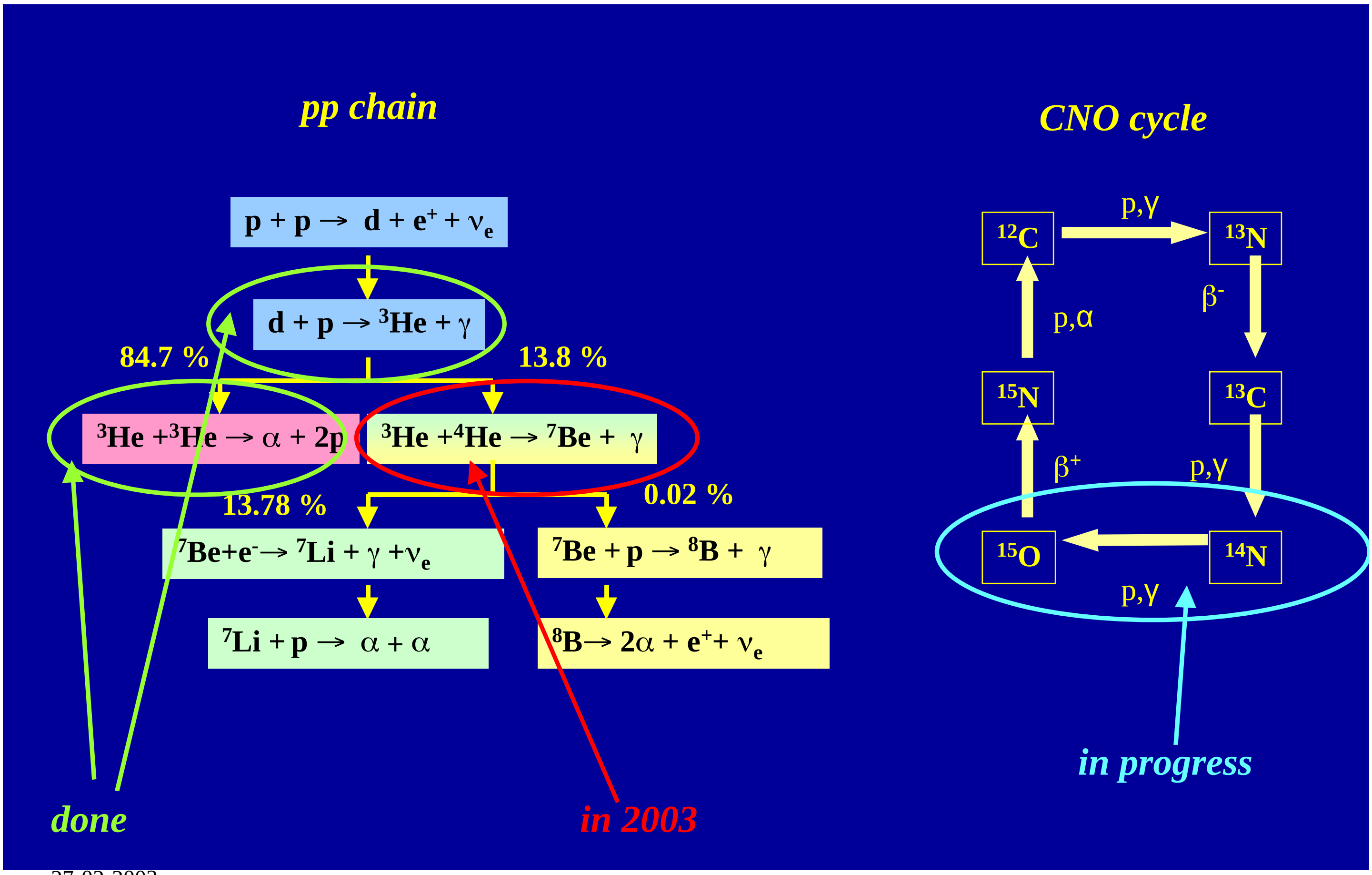
50% uncertainty due to poor knowledge of other parameters

Standard Cosmology is becoming a sound Theory

Not very far from lower limit $\sum m_i$ = 60 meV from atmospheric + solar oscillation lower bound

- high: Ω_m=1, h = 0.5; low: Ω_m=0.2, h = 0.65

LUNA scientific program



pp chain

$p + p \rightarrow d + e^+ + \nu_e$

$d + p \rightarrow {}^3He + \gamma$

84.7 %

13.8 %

${}^3He + {}^3He \rightarrow \alpha + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

13.78 %

0.02 %

${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow \alpha + \alpha$

${}^8B \rightarrow 2\alpha + e^+ + \nu_e$

done

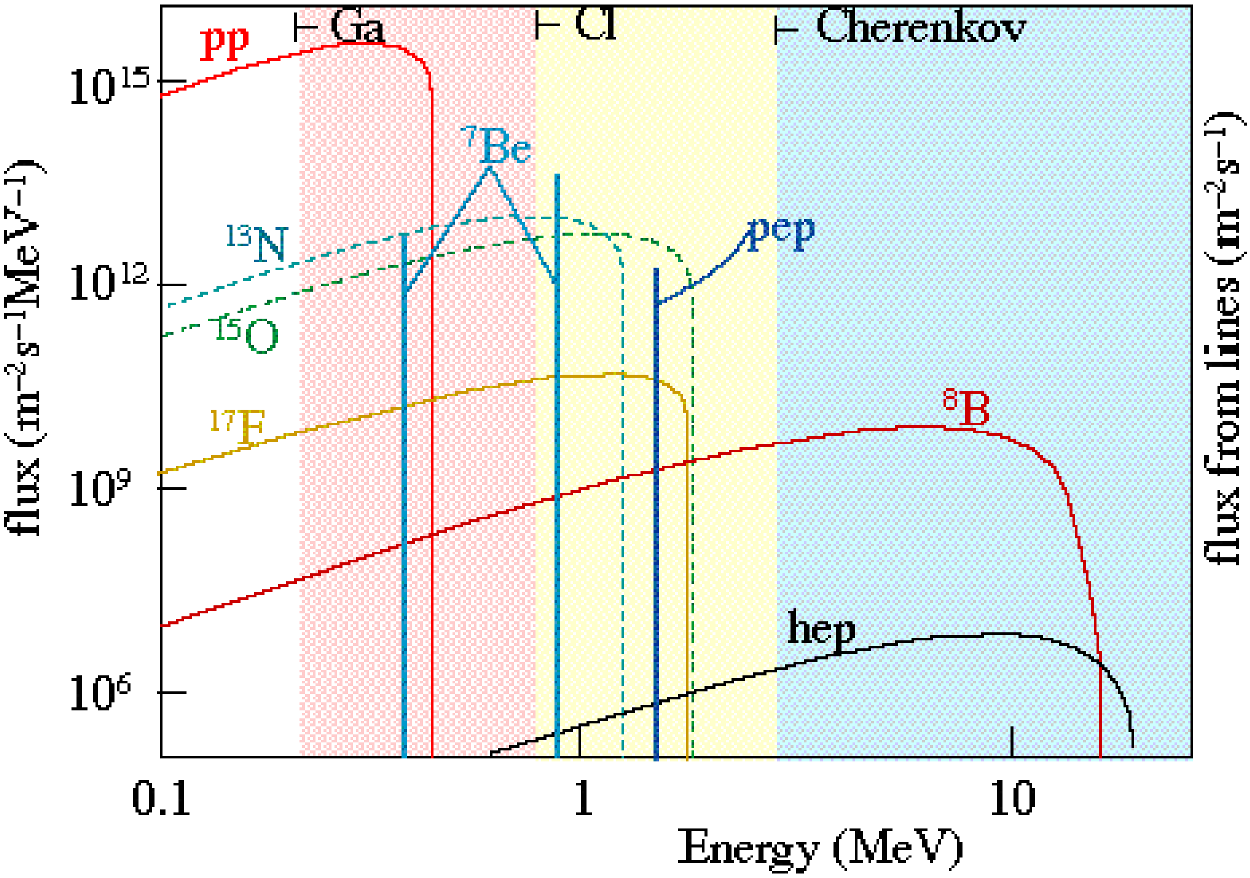
in 2003

CNO cycle

$$\begin{tikzcd} {}^{12}C \arrow[r, "p{,}\gamma"] & {}^{13}N \arrow[d, "\beta^-"] \\ {}^{15}N \arrow[u, "p{,}\alpha"] & {}^{13}C \arrow[d, "p{,}\gamma"] \\ {}^{15}O \arrow[u, "\beta^+"] & {}^{14}N \arrow[l, "p{,}\gamma"] \end{tikzcd}$$

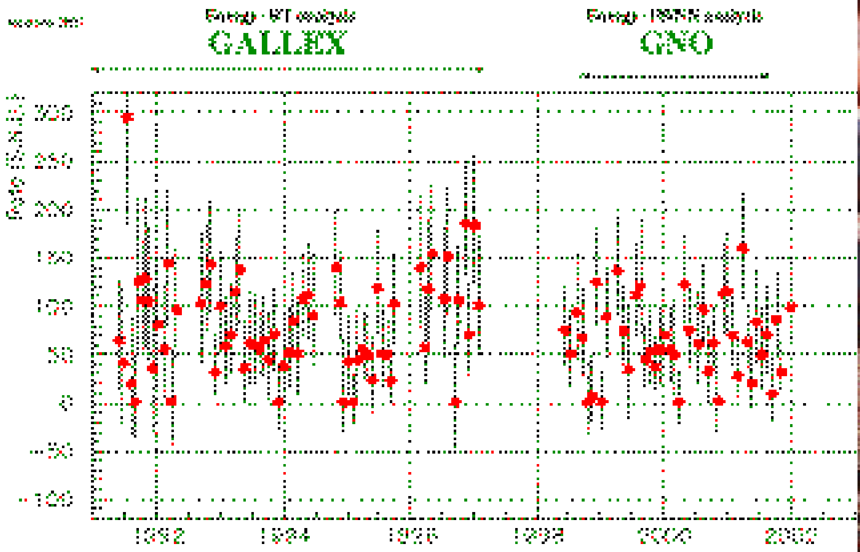
in progress

Solar electron-neutrino spectrum



GNO

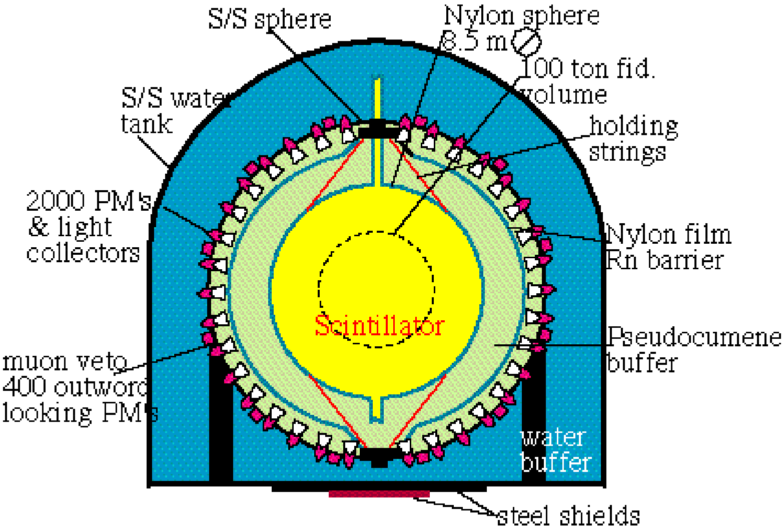
Continuously collect data for a long period
Better low background (cryogenic) detectors efficiency)
Target: bring uncertainty below 5%. Reached 4.6%
A further source calibration foreseen
Then decide on continuation or else



GALLEX	65 SR	77.5 +-- 6.2 (stat) +-- 4.5 (sys) SNU
GNO	43 SR	65.2 +-- 6.4 (stat) +-- 3.0 (sys) SNU
GNO+GALLEX	108 SR	70.8 +-- 4.5 (stat) +-- 3.8 (sys) SNU

BOREXINO

Real time neutrino (all flavours) detector
Threshold $E > 0.4$ MeV
Measure mono-energetic (0.86 MeV) **^{7}Be** neutrino flux
    Very sensitive to δm^2 and θ_{12}
    40 ev/d if SSM
Physics run in 2003



300 t liquid scintillator (PC + PPO) in a nylon bag
Innermost 100 t: fiducial volume
S/S sphere, 13.7 m diam. Supports the PMs & optical concentrators
Space inside the sphere contains purified PC
Second nylon bag (11 m diam.) to block radon
Purified water outside the S/S sphere (18 m diam., 16.9 m height)

The SS Sphere

Scintillator purification
(H_2O extraction and Si-gel column)

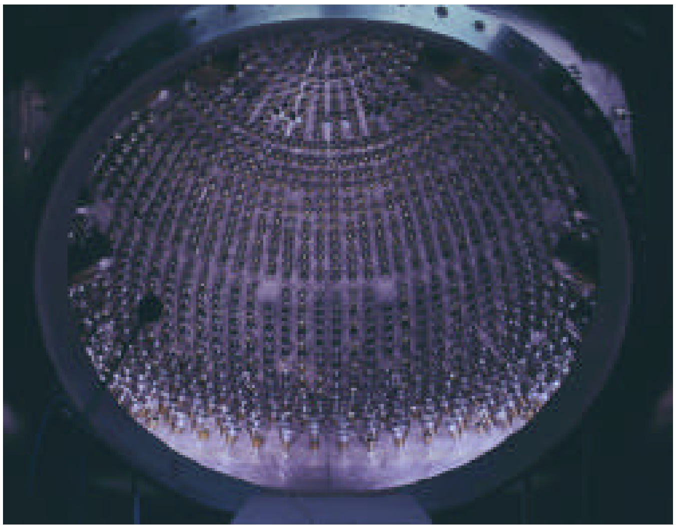
	Requirements (g/g)	Achieved (g/g)
Cd	$3 . 10^{-8}$	$< 8 . 10^{-15}$
In	$3 . 10^{-11}$	$< 1 . 10^{-13}$
La	$1 . 10^{-11}$	$< 4 . 10^{-16}$
Lu	$4 . 10^{-14}$	$< 4 . 10^{-16}$
K	$8 . 10^{-14}$	$< 6 . 10^{-12}$
Rb	$3 . 10^{-13}$	$< 1 . 10^{-13}$
Th	$2 . 10^{-15}$	$< 2 . 10^{-16}$
U	$1 . 10^{-16}$	$< 1 . 10^{-17}$

Expected background in 100 t fiducial volume in the ^{7}Be region = 0.4 counts/d.
Signal is 50 counts/day if SSM

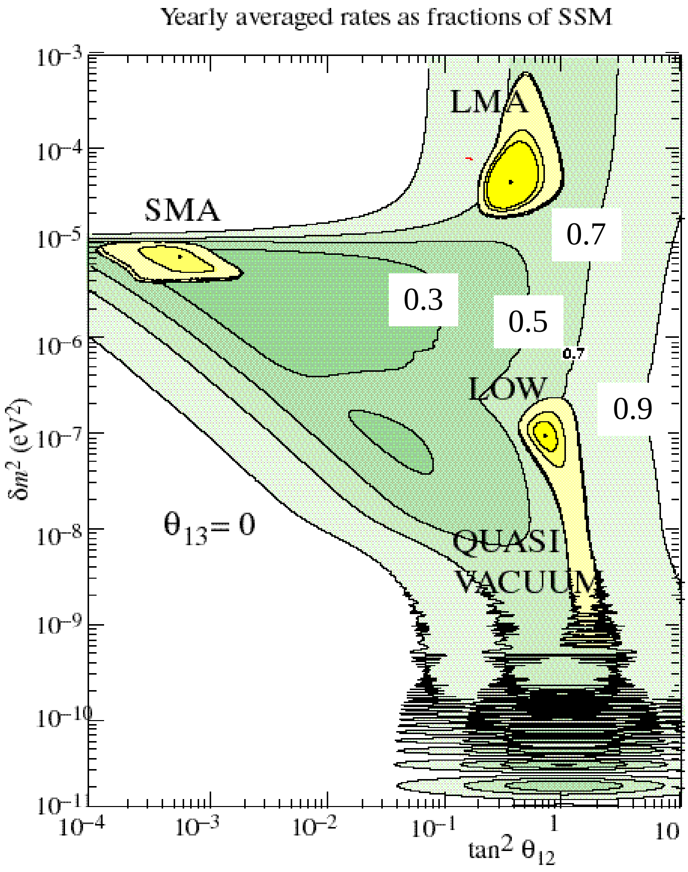
Schedule

Start of filling	**Autumn 2002**
Start of data taking	**January 2003**

Delayed by wrong manoeuvres resulted in PC spill in the environment



BOREXINO and Solar solutions



In the LMA sensitive to mixing angle (complementary to KamLAND)

Even if we know now that the solar neutrino oscillation solution is LMA, we still need a direct measurement of the flux below 5 MeV, 99.99 % of the total (John Bahcall).

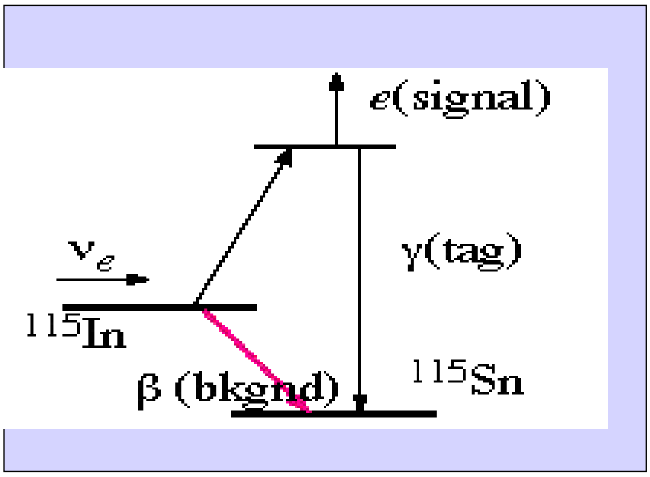
LENS proposal

Both pp and Be fluxes should be measured to complete the picture
“*Perhaps higher* (>5MeV) *data have not yet revealed the full richness of the weak interaction phenomena*” J. Bahcall

LENS program: Prove oscillations with a single experiment
Determine solution with a single experiment
- sensitivity to the low energy (pp) neutrinos in real time
- flavour sensitivity
- source sensitivity (pp. ^{7}Be,^{8}B)

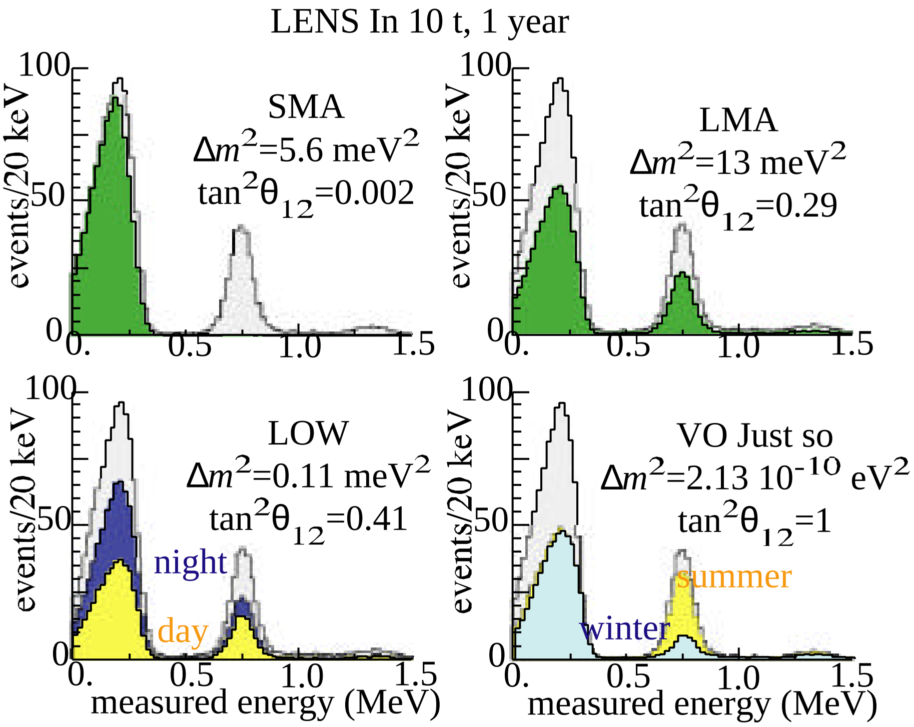
Techniques have been developed at LNG

Than LENS returned to In



R&D is necessary on
- **liquid scintillator stability**
- **radio purity**
- **calibration sources**
- **etc.**

LENS potentiality



CNGS. CERN to Gran Sasso Neutrino Project

Beam energy p	400 GeV
CCν_μ inter/kt*yr	**2630**
ν_τ inter/kt*yr	**15**

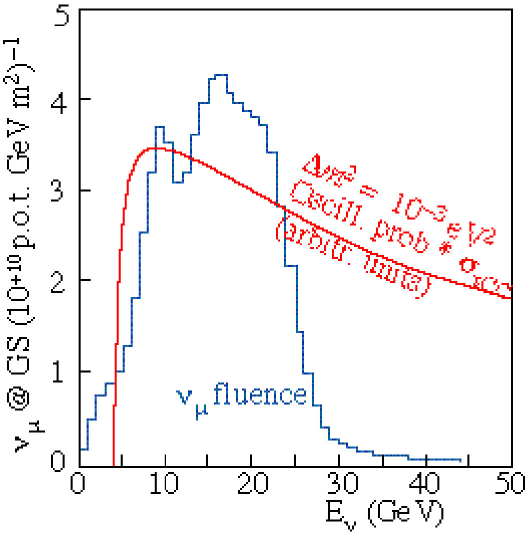
@ full mixing and
$\Delta m^2 = 2.500$ meV^2

Further optimisation (> 1.5) possible

Ready in spring 2006

Beam and experiments optimised for τ appearance

Complementary to K2K and NUMI+MINOS



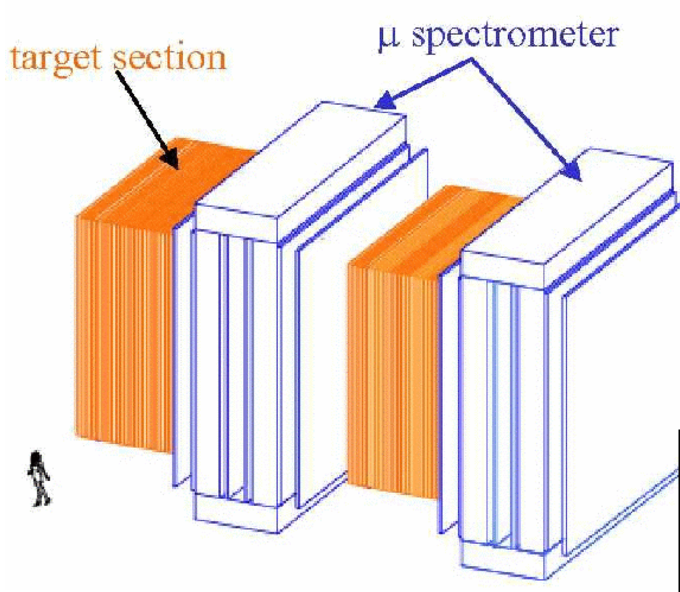
Produce τ's via CC interactions

$$\nu_\tau + N \rightarrow \tau^- + X$$

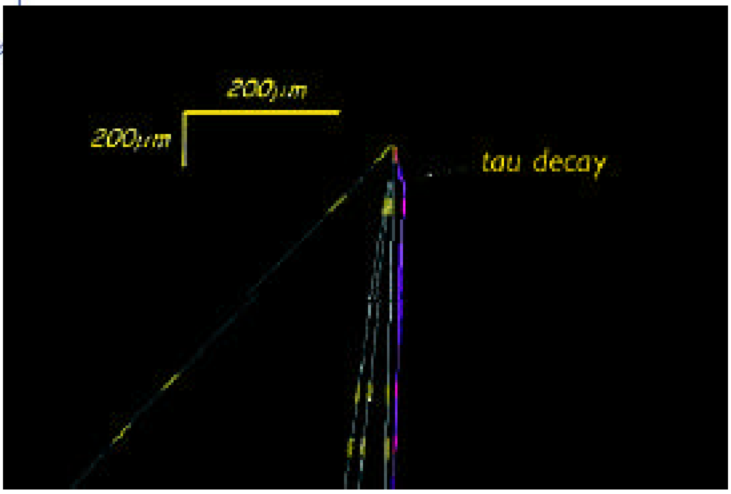
Detect τ^- through its charged decay products

$\mu^- \nu_\tau \nu_\tau$	18%
$h^- \nu_\tau n\pi^0$	50%
$e^- \nu_\tau \nu_e$	18%
$\pi^+ \pi^- \pi^+ n\pi^0$	14%

OPERA



2 super-modules
1800 t sensitive mass
μm scale granularity
sub-μm resolution

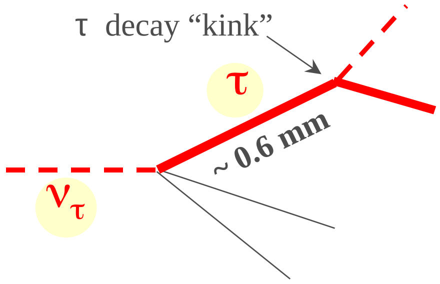


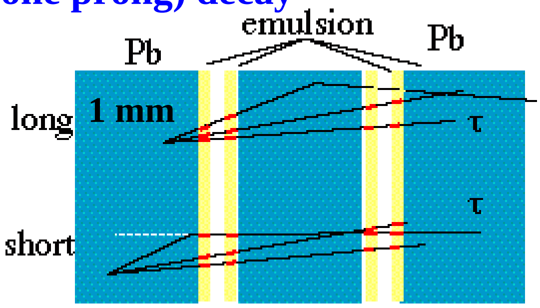
Detected τ's in 5-year run CNGSx1.5.
Maximal mixing
6.6 ev. @1300 meV^2
15.8 ev. @2500 meV^2
40.2 ev. @4000 meV^2
backgr 0.6 ev. (further reduction possible)

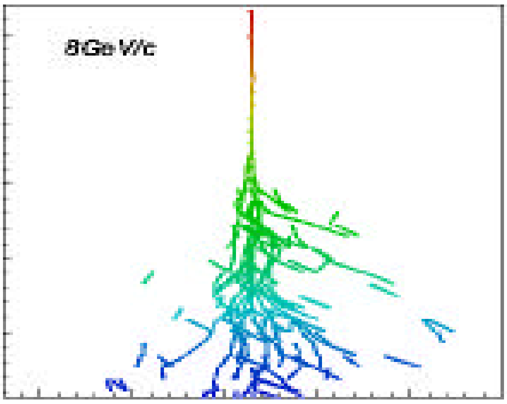
Identify τ's by decay topology

ν_oscillation → massive target
ν_ decay topology → micrometer resolution
Lead – nuclear emulsion sandwich*"Emulsion Cloud Chamber" (ECC)*

Main channel is τ → μ (one prong) decay

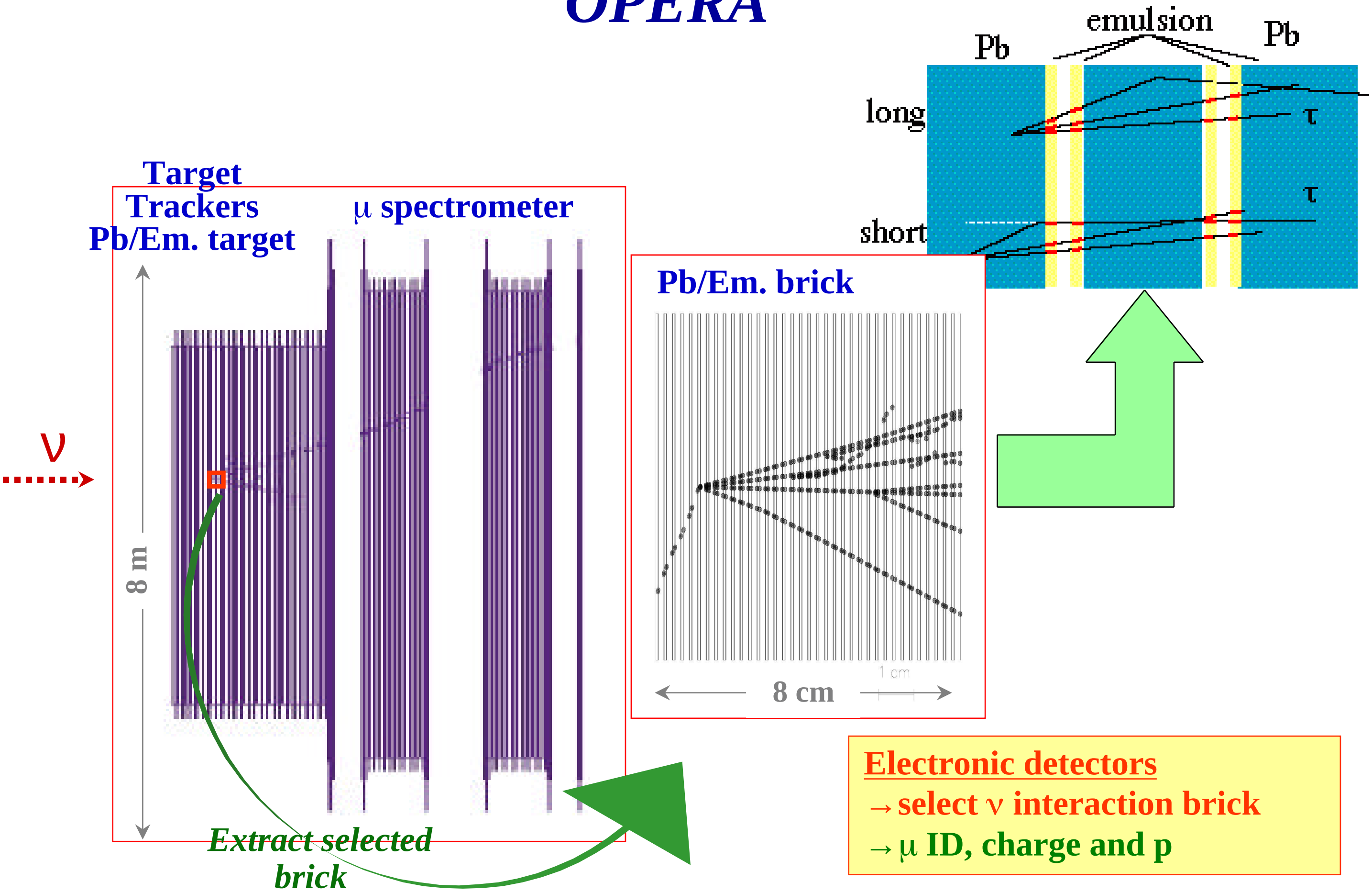






- ***electron detection for τ → e decays and search for ν_μ-ν_e appearance***
- ***momentum measurement by multiple scattering***

OPERA

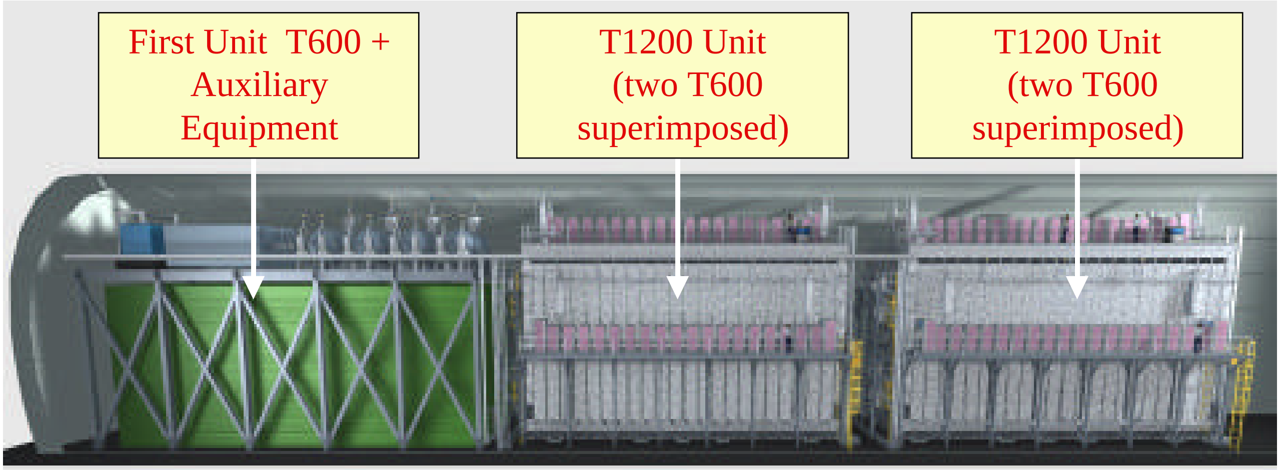


Electronic detectors

→ select ν interaction brick

→ μ ID, charge and p

ICARUS T3000 proposal



First Unit T600 + Auxiliary Equipment

T1200 Unit (two T600 superimposed)

T1200 Unit (two T600 superimposed)

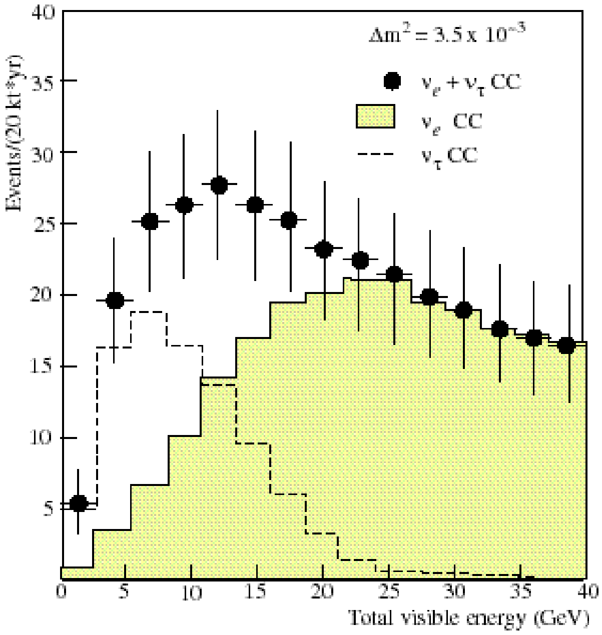
First half of T600 module successfully operated in Pavia
Power dissipation problems being tackled
Risk analysis under way
Expect to install T600 early 2003
T3000 detector proposed as a series of five T600 modules
Proposed to be operational by summer 2005

- Wide physics program
  - _ν_τ and ν_e appearance on CNGS
  - atmospheric neutrinos
  - supernova neutrinos
  - solar neutrinos
  - proton decay

ICARUS T3000 on CNGS

Tau detected mainly through electronic channel, selected mainly on the basis of visible energy

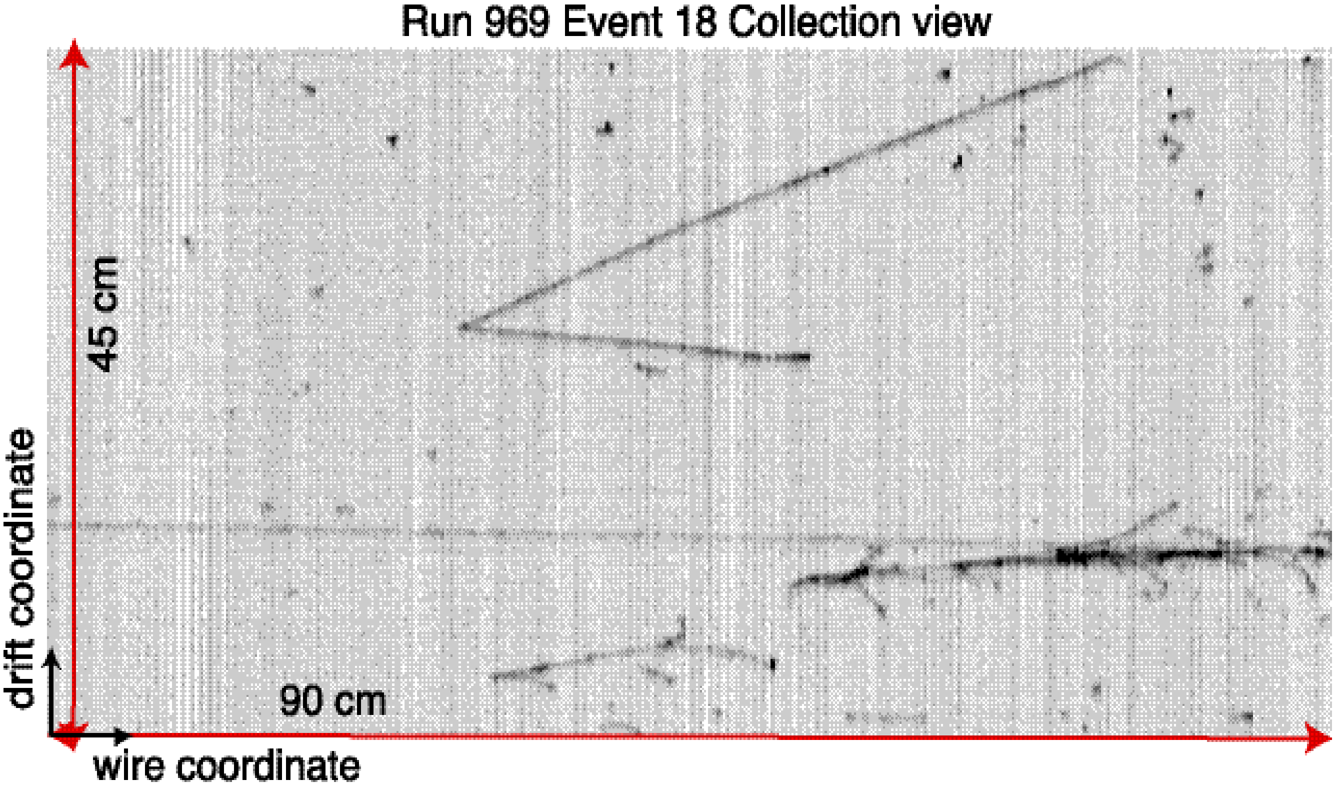
Discriminate signal from background using likelihood function based on kinematical variables
Strong reduction of background



$\Delta m^2 = 2500\ \mathrm{meV}^2$
Maximum mixing
Exposure = 15 kt*y
(5 x 600 t modules x 5 years)
After kinematic cuts
$\tau \Rightarrow$ e 9 events
$\tau \Rightarrow$ h 3 events
Backgr 0.7 events

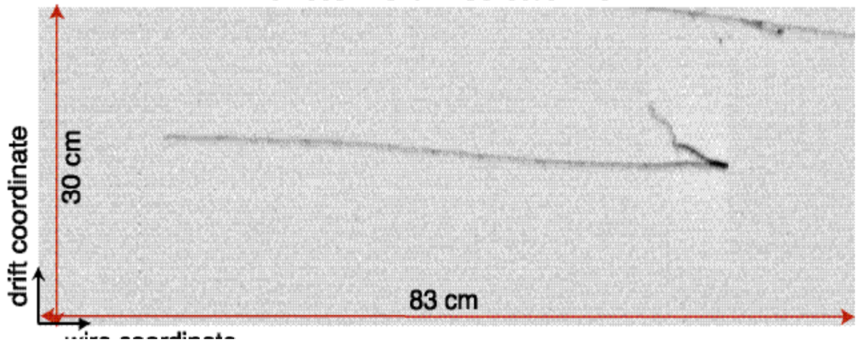
If no signal of ν_e appearance with 20 kt*yr (8 years) exposure push CHOOZ limit on $|U_{e3}{}^2| \approx$
$\theta_{13}{}^2$ ——————————5

A V^0 candidate from T600



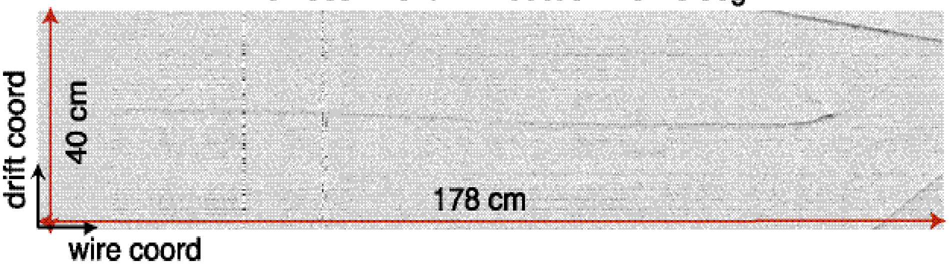
Three coordinate read-out of T600

Run 909 Event 21 Collection view



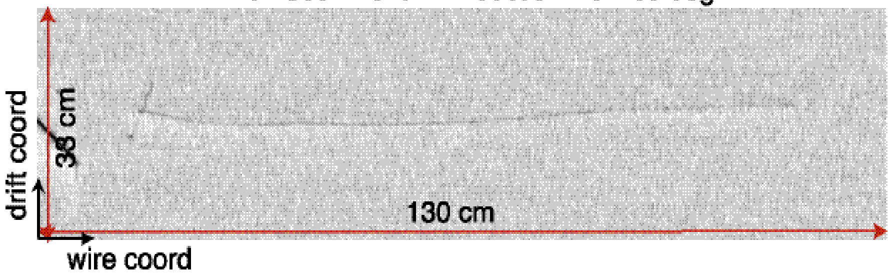
Collection

Run 909 Event 21 Induction view 0 deg



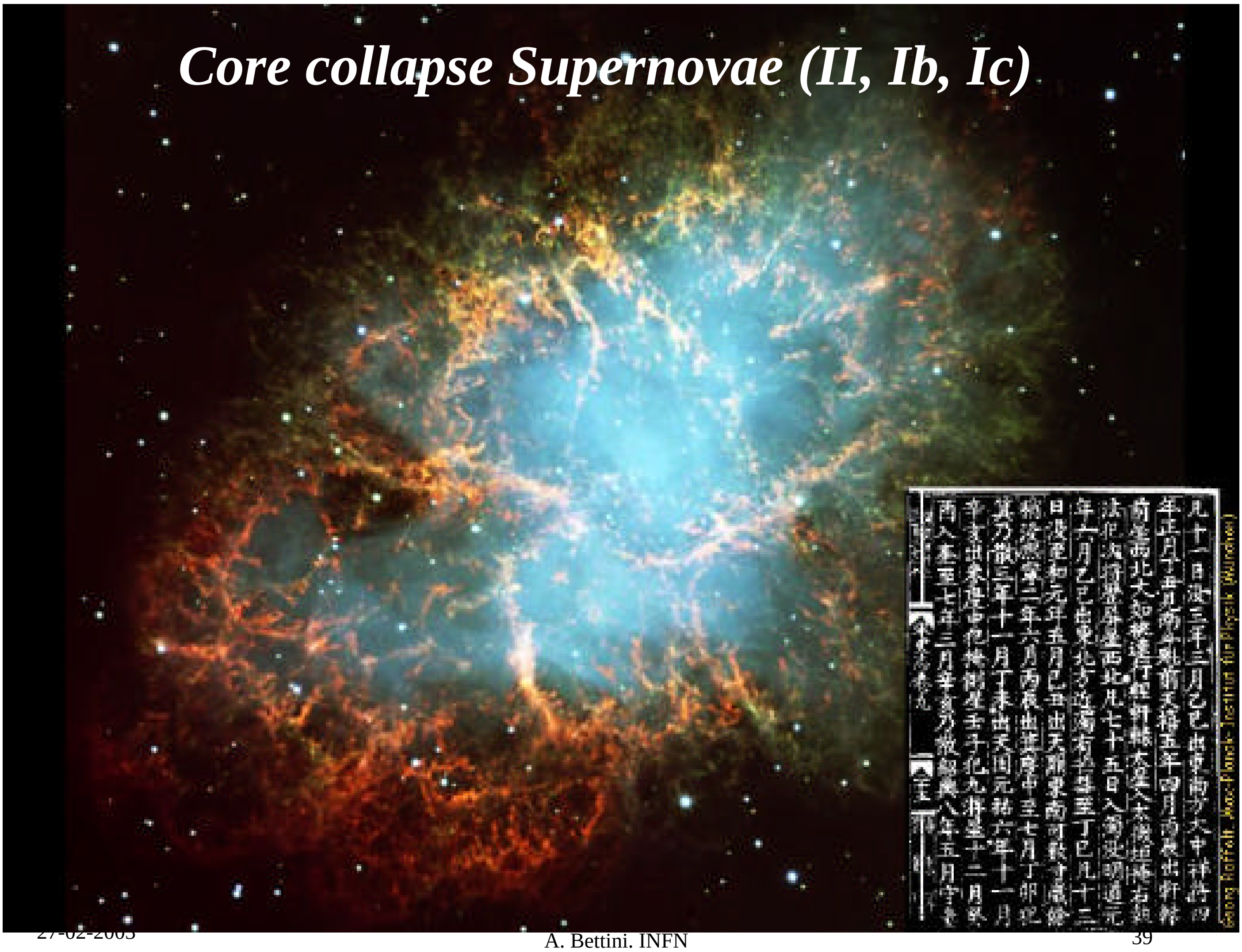
Induction 1

Run 909 Event 21 Induction view 60 deg



Induction 2

Core collapse Supernovae (II, Ib, Ic)



Georg Raffelt, Max-Planck-Institut für Physik (München)

Core collapse Supernovae

- Evolution of massive stars, which have lost Hydrogen may lead to the collapse of the core.
- Neutrino signal detectable only for SN in our Galaxy or Magellanic Clouds
  - **2 - 4 events/century expected in our Galaxy. Plan for multidecennial observations**

•Neutrinos of all flavours are produced in the core

• ν_e <E> about 12 MeV. ν_μ and ν_τ <E> about 20 MeV, with large uncertainties

•Change flavour in the mantle via MSW mechanism

  •depending on mixing and mass-spectrum

Flavour conversions not important for SN physics (matter potential too small)

•Early warning of neutrino burst important for astronomical observations with different messengers (light curve, Gravitational Waves)

•SNEWS = Supernova Early Warning System

  •LVD, SNO, SuperK , in future: Kamland, BOREXINO

•No information on neutrino masses

Mass eigenstates ν_1, ν_2 and ν_3 (not ν_e, ν_μ e ν_τ) propagate from SN in vacuum

•The flux of a flavour measured on Earth may be very different from that produced in the Supernova core

Detection of a delay for neutrinos of a flavour does not give a limit on the "mass" of that flavour (as still claimed by some experimental proposal)

LVD

Mainly sensitive to $\bar{\nu}_e$
Expected counts for a collapse in the centre of Galaxy (8.5 kpc)

$\bar{\nu}_e + p \to n + e^+$ 300- 600 evts

Measurement of electron neutrino <u>and</u> antineutrino spectra may give information on mixing angles, mainly θ_{13}
Depending on the size θ_{13}, flavour conversions (MSW) in SN may make harder ν_e or $\bar{\nu}_e$ spectrum depending on **sign of Δm^2**

$\bar{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$ **E_{thresh} = 14.4 MeV**
${}^{12}B \to {}^{12}C + e^- + \bar{\nu}_e$

$\nu_e + {}^{12}C \to e^- + {}^{12}N$ **E_{thresh} = 17.3 MeV**
${}^{12}N \to {}^{12}C + e^+ + \nu_e$

$\nu_x + {}^{12}C \to \nu_x + {}^{12}C^*$ **E_{thresh} = 15.1 MeV**
${}^{12}C^* \to {}^{12}C + \gamma$

Liquid scintillator 1000t
High modularity
up-time 99.7% in 2001

$\Phi(\nu_e)/\Phi(\bar{\nu}_e)$ determines sign of Δm^2

Independent on oscillations

Conclusions

- The first stage (not completed yet) of new neutrino physics (beyond the Standard Model) with solar and atmospheric neutrino experiments
- Next steps will aim to
  - Verify ν_τ appearance with artificial ν_μ beam
  - Understand the nature of neutrinos (Majorana or Dirac) through $0\nu2\beta$ decay experiments
  - Measuring absolute neutrino masses ($0\nu2\beta$ decay, cosmology,…)
  - Sign of doublet-singlet mass difference (SN neutrinos, next generation magnetic detectors for atmospheric neutrinos, high luminosity neutrino sources,…)
  - Precision determination of mixing angles (solar neutrinos, high luminosity neutrino sources,…)
  - Phases and CP violation mechanism (2nd generation high luminosity neutrino sources, $0\nu2\beta$ decay, …)
- Neutrino masses are much smaller than quark masses, pointing to lepton number violation scale close to the unification scale
- Elementary particle physics community should invest more (not only financially) in neutrino sector
- and in the search for cold dark matter

The JHF to Kamioka neutrino project

Adapted from hep-ex/0106019