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
$0\nu 2\beta$

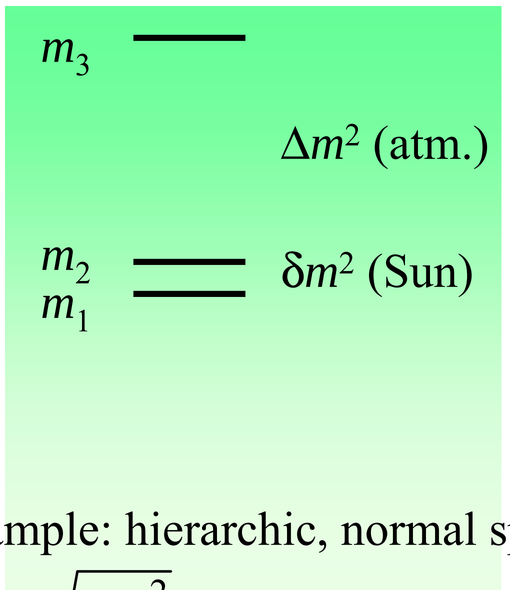
9 independent real parameters

- 3 masses m_1, m_2, m_3
- 3 "mixing angles" $\theta_{12}, \theta_{13}, \theta_{23}$ (ω, ϕ, ψ)
- 3 phases (CP violation)
- 2 (Majorana) phases (α,β), zero if neutrinos are Dirac particles irrelevant for oscillations

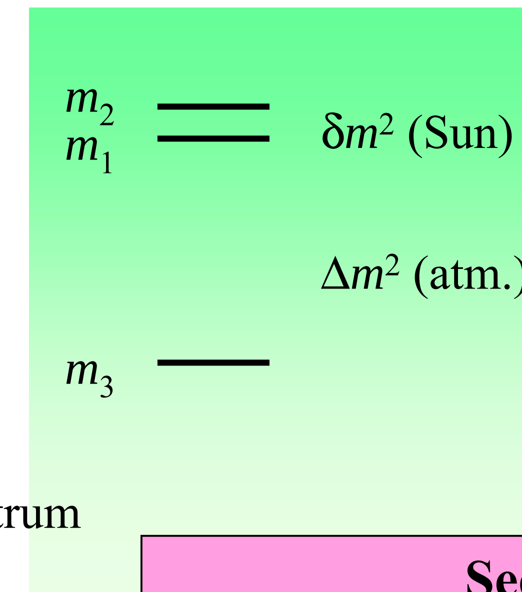
Neutrino masses

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
$\Delta m^2 > 0$



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?

Example: hierarchic, normal spectrum

$$m_3 = \sqrt{\Delta m^2} \approx 25 \text{ meV}$$

$$m_1 \approx m_2 = \sqrt{\delta m^2} \approx 10 \text{ meV - } 0.3 \text{ meV}$$

Likely, the unit for neutrino masses is the **millielectronvolt**

Seesaw mechanism

$$m_i = \frac{M_D^2}{M}; \text{ with } M_D = M_{top} \text{ and } m_3 = 25\text{meV}$$

M **≈ 10[15] GeV, the lepton number violation scale is close to the GUT scale!**

Flavour conversion

Oscillations in a vacuum @ L/E close to maximal ($1/\Delta m^2$)

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

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

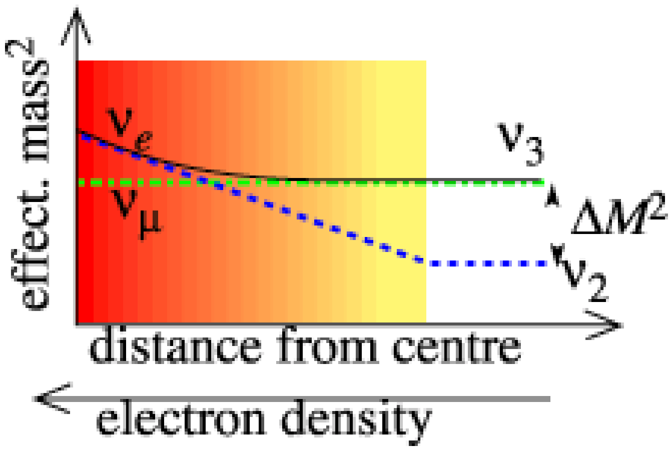
Oscillations period depends on absolute value of the squared mass difference
Oscillation amplitudes are not equal to $\sin^2 2\theta$
Oscillation amplitude is different for different oscillations
"Mixing angles" ranges are $0 - \pi/2$ not $0 - \pi/4$

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

Level crossing possible @ critical value of density*energy



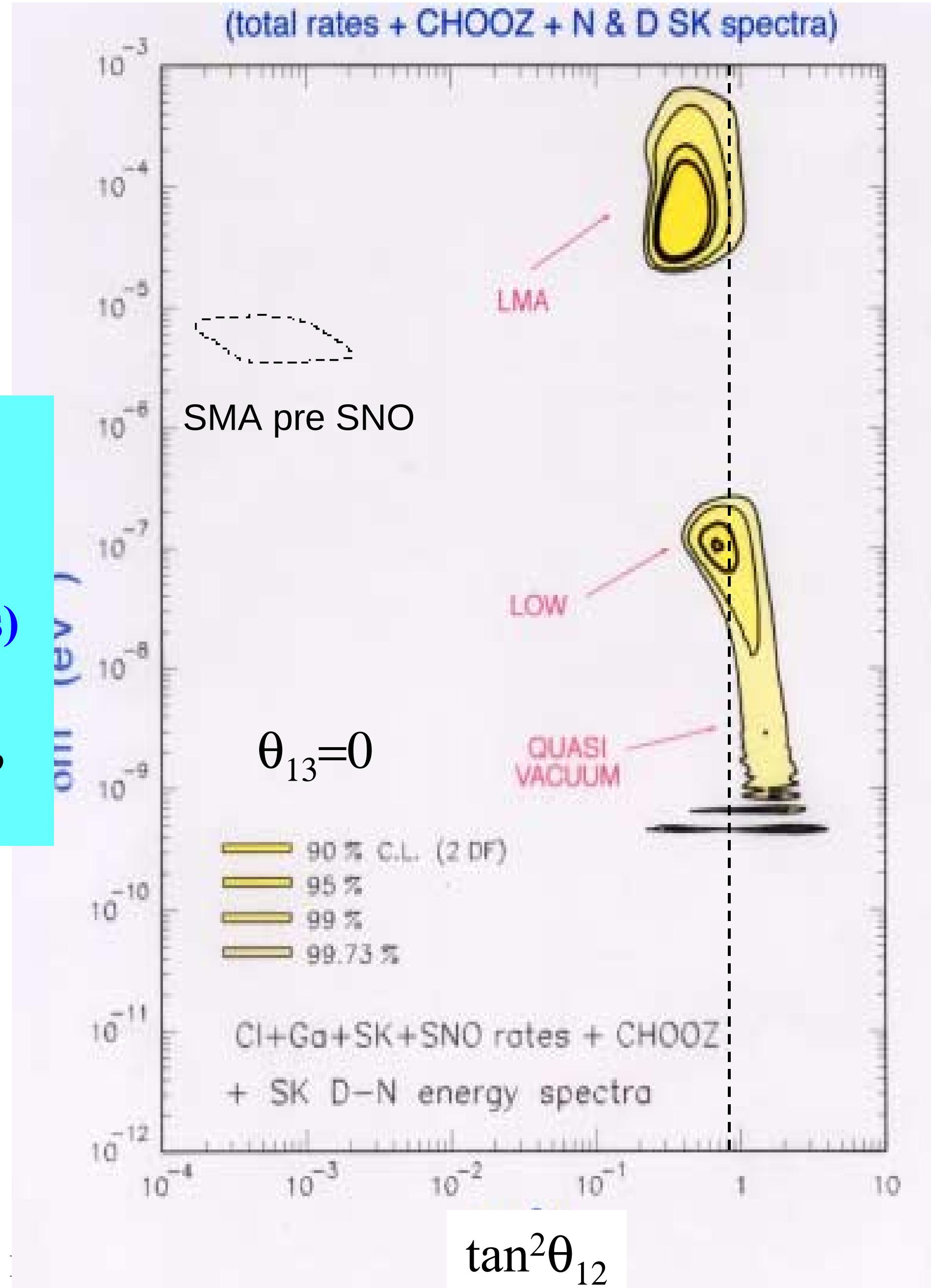
Important in Sun, in Earth, in a Supernova

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

Status of neutrino oscillations

CHOOZ
Reactor anti electron-neutrino disappearance (a few MeV, 1km)
Combining with solar data
$\theta_{13}^2 \approx |U_{e3}|^2 < 0.025$

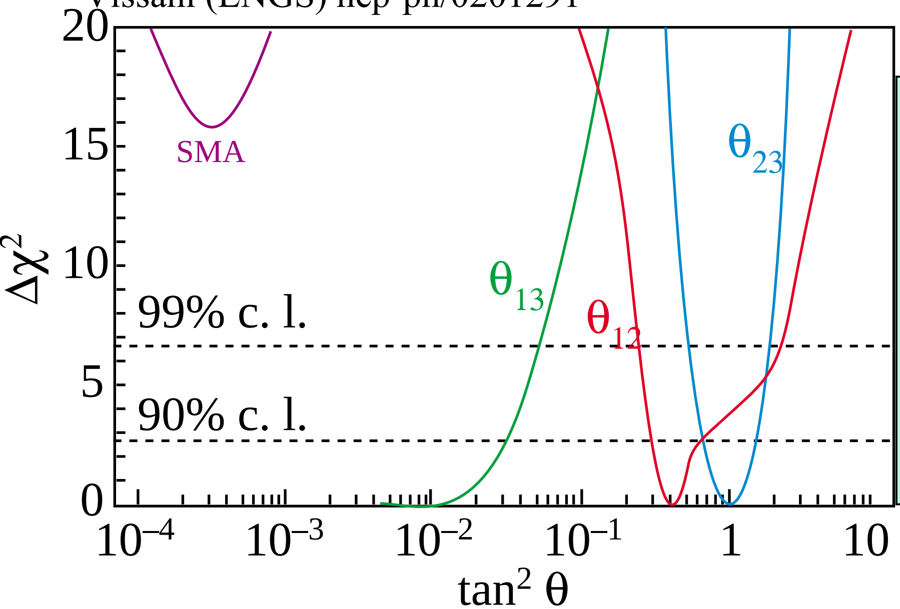
Muon-neutrinos from the atmosphere
(≈ GeV, 10-13 000 km)
Super-Kamiokande
Zenith angle distribution 1250 d (77 kt yrs)
Confirmed by MACRO
$1.8 \times 10^{-3} < \Delta m^2 < 4 \times 10^{-3}$ eV^2 (90% c.l.),
$\sin^2 2\theta_{23} > 0.88$



If LMA, KamLAND will see anti-ν_e disappearance
If LOW, BOREXINO will see strong deficit

Bimaximal mixing. *A new symmetry of Nature?*

Fit by Feruglio (PD), Strumia(CERN, PI), Vissani (LNGS) hep-ph/0201291



extreme case: $\theta_{13}=0,\ \theta_{23}=\pi/4,\ \theta_{12}=\pi/4$

$$U=\begin{pmatrix}\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0\\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}}\\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}}\end{pmatrix}$$

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

$$\nu_2=\frac{1}{\sqrt{2}}\left(-\nu_e+\nu_{\mu\tau}\right)$$

$$\nu_3=\frac{1}{\sqrt{2}}\left(-\nu_\mu+\nu_\tau\right)$$

with $\nu_{\mu\tau}=\frac{1}{\sqrt{2}}\left(\nu_\mu+\nu_\tau\right)$

ν_3 = maximum mixing of ν_μ and ν_τ

ν_1, ν_2 = orthogonal max mixings of ν_e and $\nu_{\mu\tau}$

Solar oscillation

$\nu_\mu \Leftrightarrow \nu_\tau$ full amplitude

Atmospheric oscillation

$\nu_e \Leftrightarrow \nu_{\mu\tau}$ full amplitude

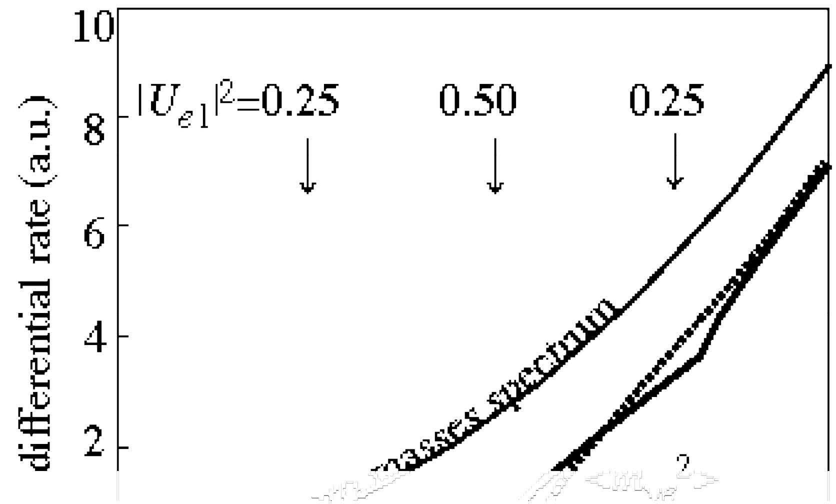
Fundamental questions

- How small is $|\theta_{13}|$? — Low energy ν_μ beam (off axis ν_e appearance)
- How small is $|\theta_{23}-\pi/4|$? — Low energy ν_μ beam (off axis ν_μ disapp.)
- How small is $|\theta_{12}-\pi/4|$? — Solar neutrinos

N.B. Nature is always imperfect

Neutrino masses from beta decay

"Mass" is a property of a stationary state: ν_e, or ν_μ, or ν_τ "mass" is improper
What does it mean?
 It depends on what and how one measures



If different "steps" are not resolved

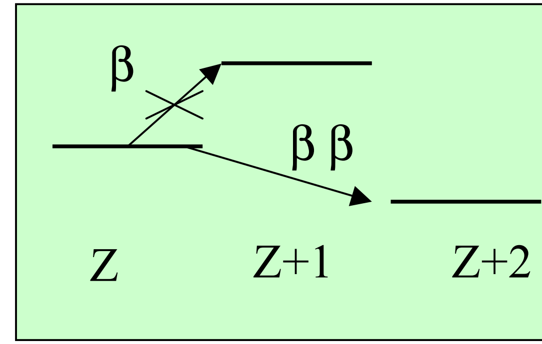
$$< m^2_{\nu e} >= |U_{e1}|^2 \; m_1^2 + |U_{e2}|^2 \; m_2^2 + |U_{e3}|^2 \; m_3^2$$

"Direct" measurements **(Tritium β decay)**
$<m_{\nu e}>$ < 2.2 eV from Mainz experiment
Troitsk experiment has similar limit, but with a non understood systematic effect

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

Majorana masses of electron neutrinos

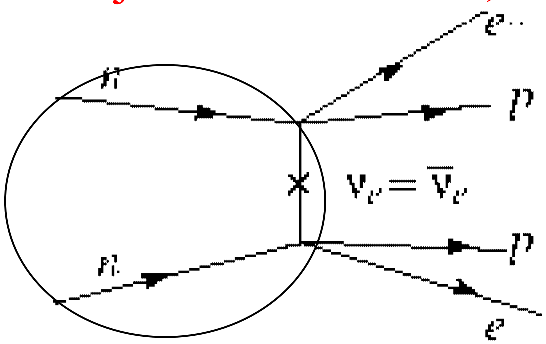
SM neutrinos are massless, described by a 2-component (left) spinor



Pure Majorana neutrino $\nu_e^C = \nu_e$ **$\Delta L = 2$**

The mass term $\frac{M_{ee}^M}{2}\left(\overline{\nu_L}\nu_R^C + h.c.\right)$

If Majorana and massive, measure 0νββ lifetimes



$$M_{ee}^M = || U_{e1}|^2 m_1 + |U_{e2}|^2 e^{2i\alpha} m_2 + |U_{e3}|^2 e^{2i\beta} m_3 |$$

Cancellations are possible

Best limits: M^M_{ee} < 270 *h* meV (Heidelberg-Moscow at LNGS) and similar from IGEX

$h = M_0/M$ uncertainty in nuclear matrix element: factor 2-3

90% C. L.	M^M_{ee} (meV)	$m_{\nu e}$ (meV)
almost degenerate	< 270 *h*	< 950 *h*
normal hierarchic	0.5 ÷ 5	3 ÷ 10
inverted hierarchic	10 ÷ 57	40 ÷ 57

discovery may be close (0ν2β or cosmol.)

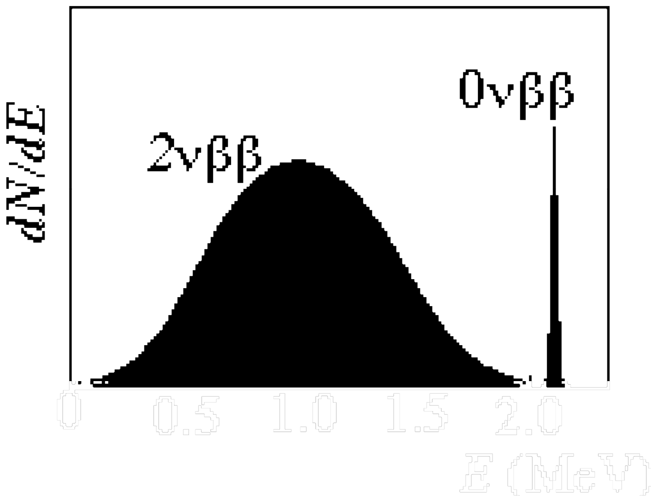
δm^2 and θ_{12} from solar to reduce uncert.

sign of Δm^2 from SN & high int. beam

Feruglio (PD), Strumia(CERN, PI), Vissani (LNGS) hep-ph/0201291

How to improve limits

Measure total energy of two electrons



t = Exposure time

M = Detector mass

nit on $\frac{1}{M_{ee}^{M}} \propto \sqrt[2]{T_{0\nu}} \propto \sqrt[4]{\frac{tM}{\Delta b}} \propto \sqrt[4]{\frac{M}{b}}$

= Half-life

Δ = Energy resolution

b = Background rate per unit time per unit mass in the peak region

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

To gain one order of magnitude in neutrino mass

increase by two orders of magnitude sensitive mass

decrease by two orders of magnitude background

Theoretical effort needed to reduce the uncertainty on nuclear matrix elements at least for ^{76}Ge, ^{130}Te, even if difficult.

Factor 3 uncertainty corresponds to a factor 100 in detector mass

Which further experimental input is needed?

LNGS program

Heidelberg-Moscow
Technique: **Enriched ^{76}Ge detect.**
***b* = 0.17±0.01 ev/(kg keV y)**
without pulse shape analysis
Limit: M_{ee}<340 meV (best)
Exposure: 372.2 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

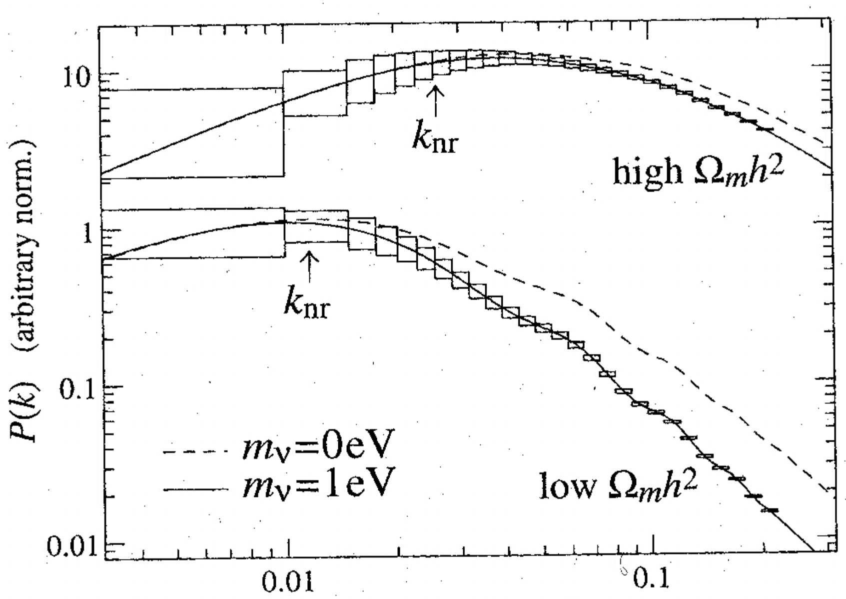
CUORE propos. (expecte
^{130}Te mass = 250 kg
b = 2x10^{-3} ev/(kg keV yr)
Limit: M_{ee} >< 50 meV

@ sensitivity levels of a few 10 meV neutrino effective mass may appear, sign of Δm^2 may be determined in some scenarios

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
Present best limit $\sum m_i < 4.5$ eV $\Rightarrow$ $m_1, m_2, m_3 < 1.5$ eV

Sloan Digital Sky Survey (SDSS) expected to measure the spectrum at **1%** accuracy.
Variations of other cosmological parameters give effect similar to neutrino masses
Combine with other precision measurements. Mainly CMB
Get limit (or evidence) on neutrino masses (Hu, Eisenstein and Tegmark, Phys. Rev. Lett. **80** (1998) 5255)



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

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

50% uncertainty due to uncertainty in other parameters

Standard Cosmology may become a sound Theory soon.

Then it might be the route to absolute neutrino mass scale (but sterile neutrinos)

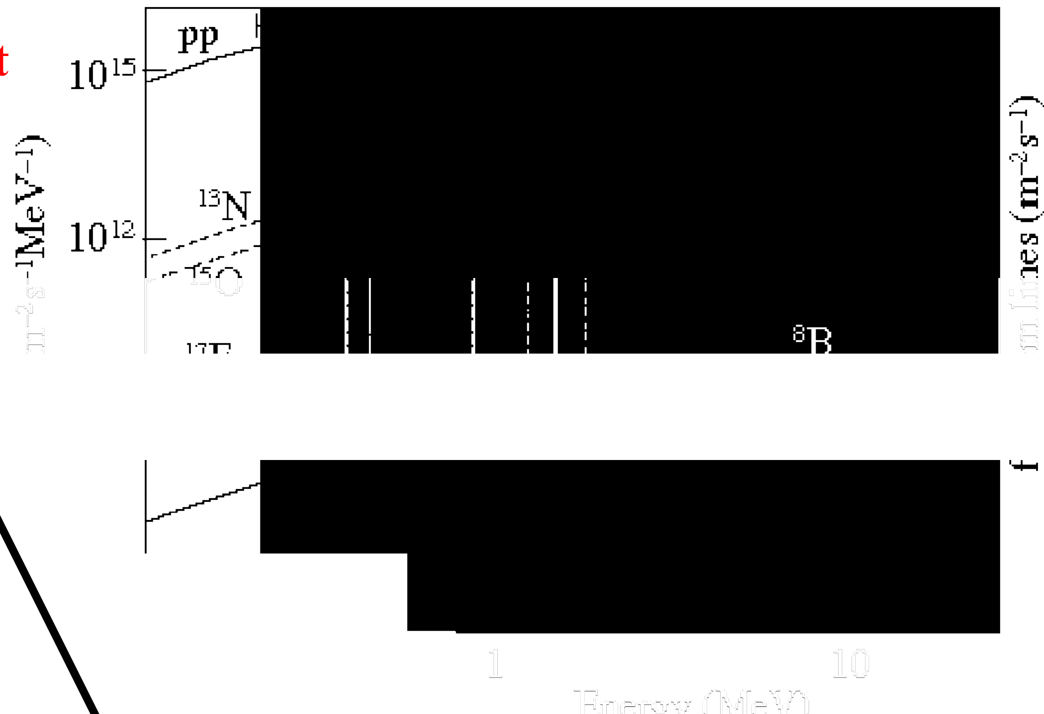
Need $\sum m_i$ = 50 meV sensitivity to reach atmospheric oscillation lower bound

Thermonuclear reactions in the Sun

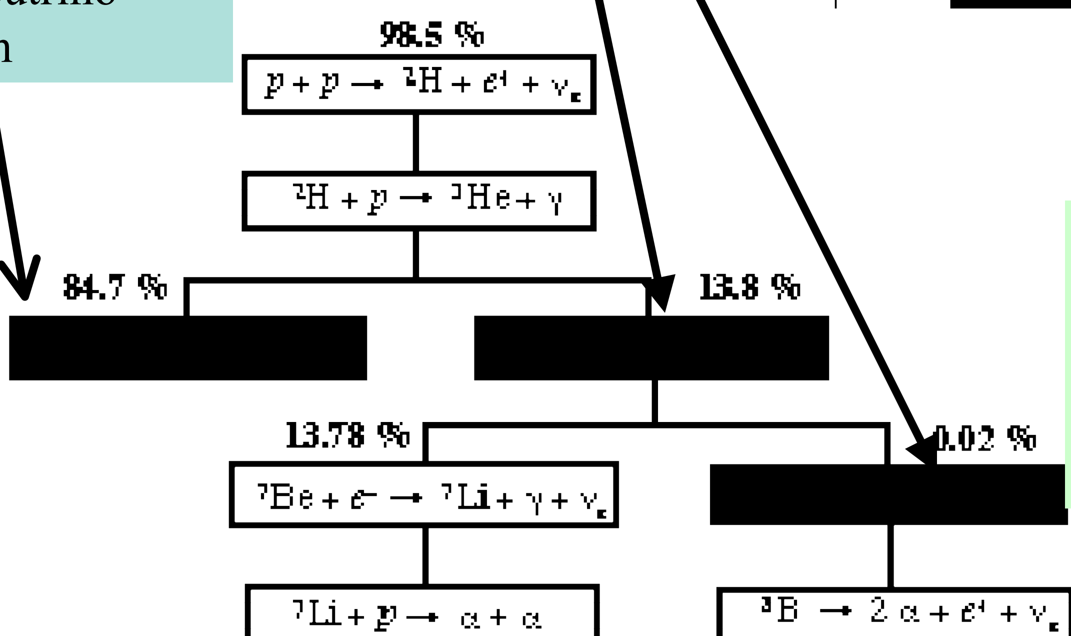
Measure thermonuclear cross-sections in the energy range of astrophysical interest (Gamow peak)

LUNA. 50 kV accelerator.

LUNA2. Accelerator energy 400 kV. BGO detector. **Installed and working.**



Measured: no nuclear solution of solar neutrino problem



LUNA2. Programme

^{14}N (p, γ) ^{15}O

^{7}Be (p, γ) ^{8}B (most important)

^{3}He (^{4}He, γ) ^{7}B (2nd import.)

and more

GALLEX

Previous evidence from Homestake and Kamiokande: strong deficit of higher energy e-neutrinos (but expected flux model dependence). The **solar neutrino puzzle**.

Detect low energy electron-neutrinos from pp fusion.

Flux known @ ±2% from solar luminosity

Reaction	$^{71}Ga\ (\nu_e, e^-)\ ^{71}Ge$
Threshold	233 keV
SSN prediction	**129±7 SNU**
minimum from luminosity	**80 SNU**
GALLEX final	**76±8 SNU**

The Be neutrino puzzle

$\Phi_{Be} = \Phi_{GALLEX} - \Phi_{Luminosity} - \Phi_{B\ (Super\text{-}K)} < 0$

But Be must be present

because B comes from Be

No astrophysical solution

Neutrino behaviour is not as expected

Must probably

neutrino oscillations

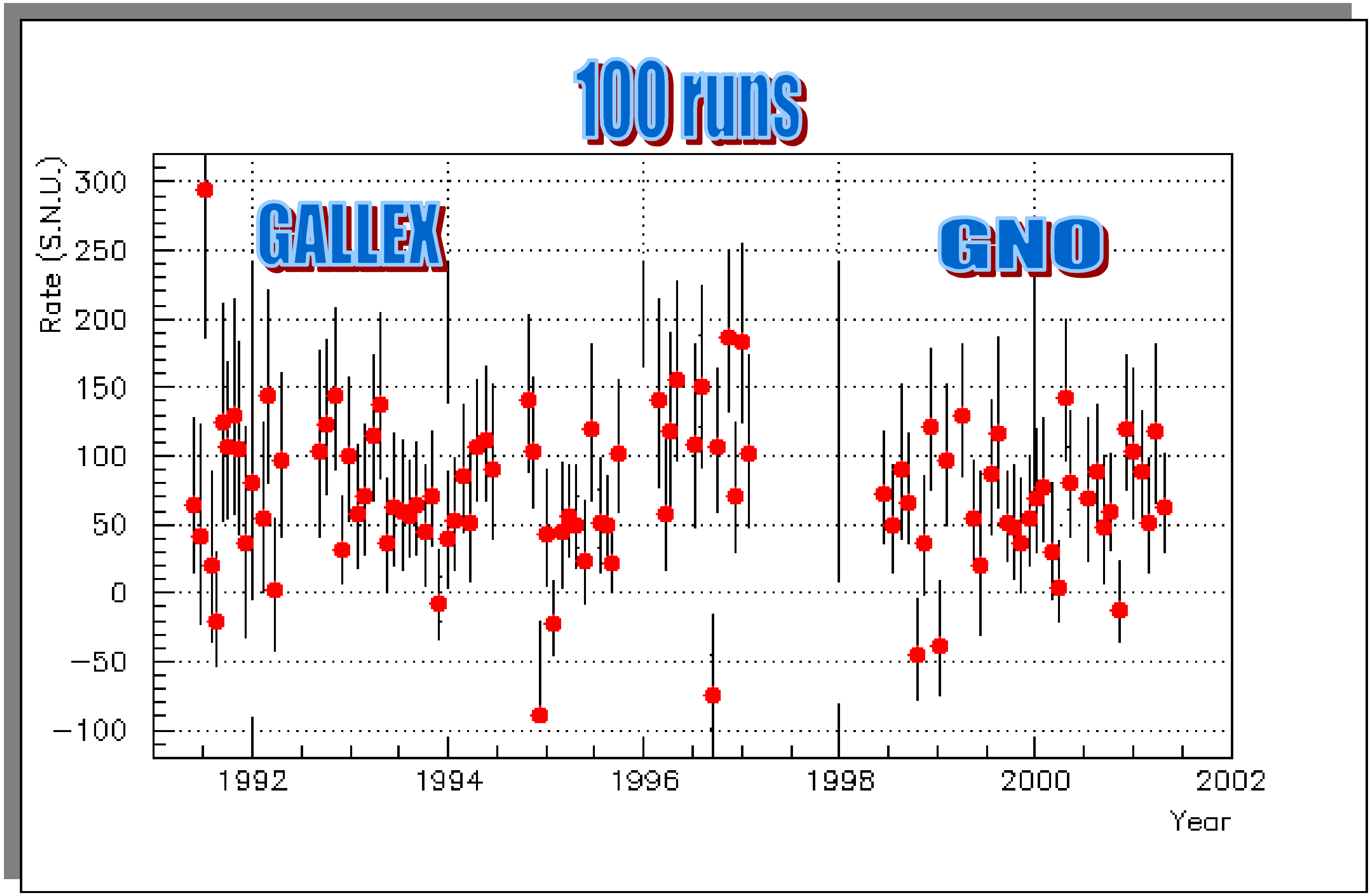
Calibrations with ν_e source

^{51}Cr 62 PBq

1994	R=1.0±0.1
1995	R=0.83±0.1

GNO

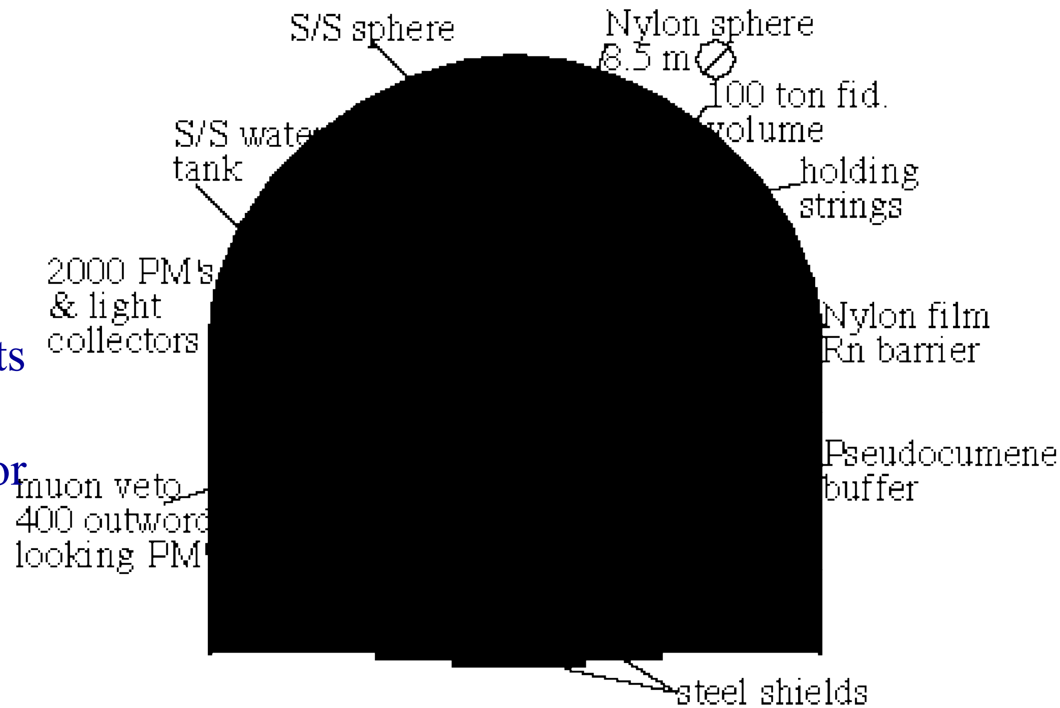
Continuously collect data for a long period
Better low background (cryogenic) detectors (increase efficiency)
Bring uncertainty below 5%
GNO (35 solar runs) = 68.9±7.3(stat)±3.2 (syst [4.6%]) SNU
GALLEX+GNO = 73.9±4.7±4.0



BOREXINO

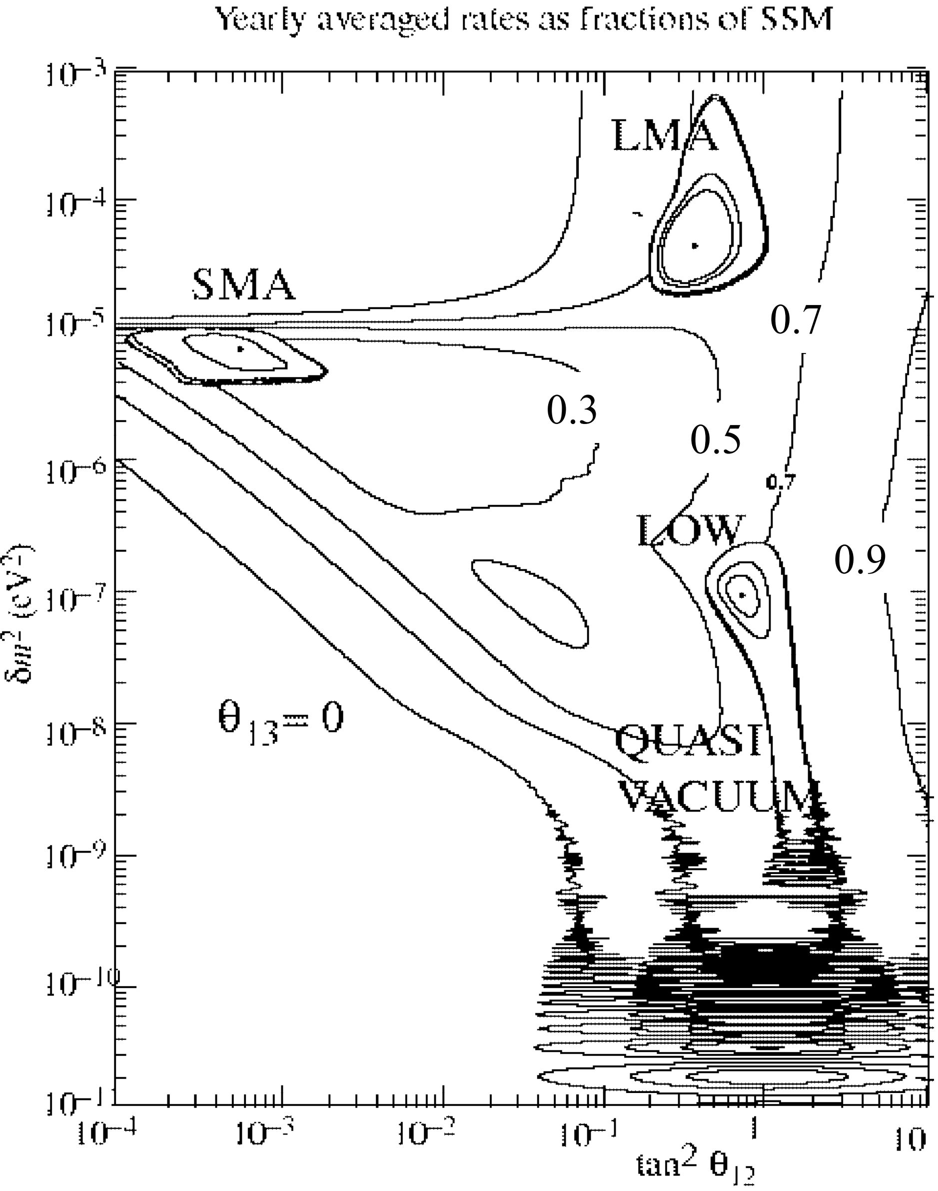
Real time neutrino detector.
Threshold E >0.4 MeV
Physics run in 2003

- Measure mono-energetic (0.86 MeV) ^{7}**Be** neutrino flux
- Very sensitive to parameters
  - δm^2 and mixing matrix elements
- 40 ev/d if SSM, 0 for some solution
- large day-night and seasonal effects for some solutions

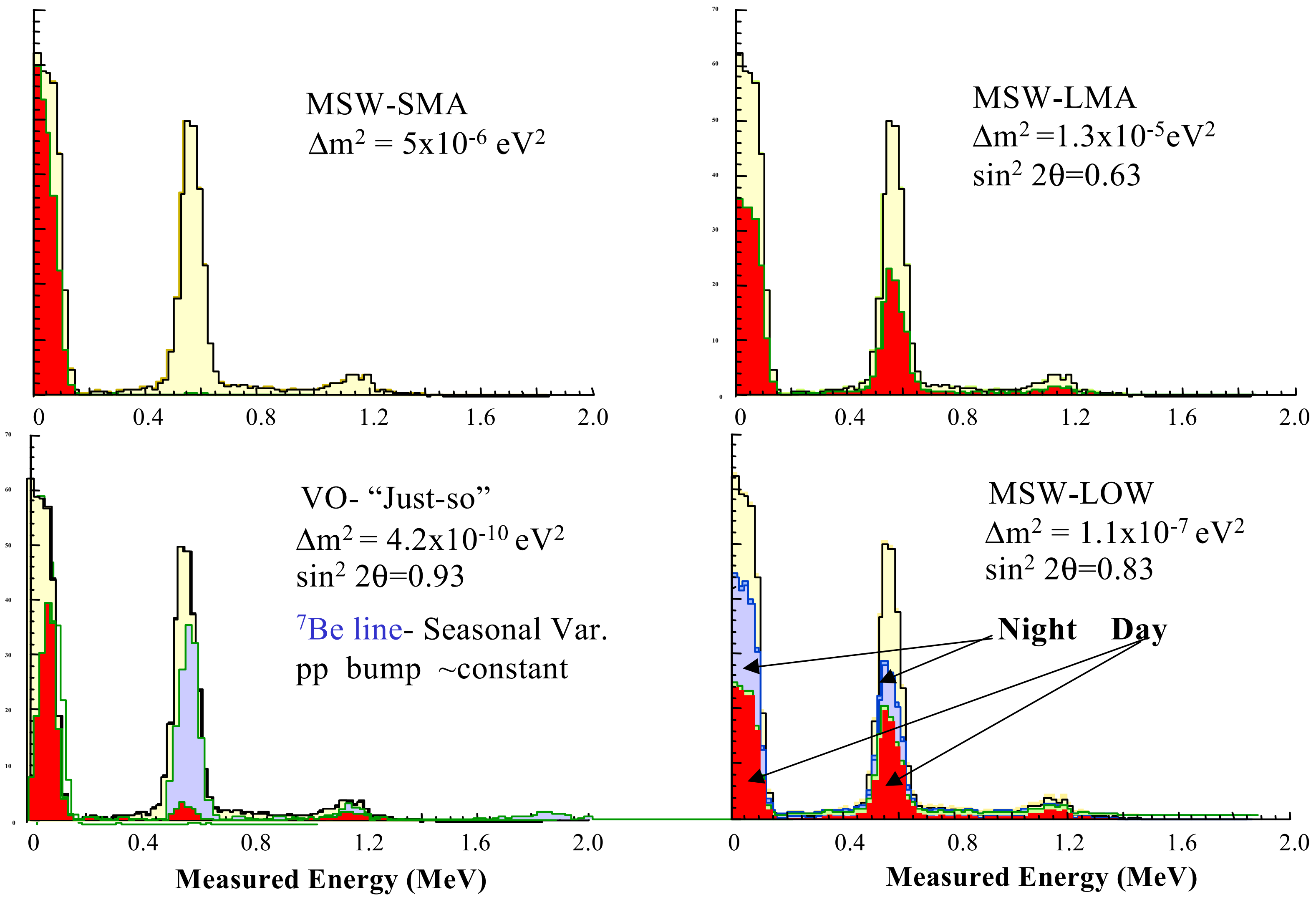


300 t liquid scintillator (Pseudocumene + PPO) in a nylon bag
Innermost 100 t: fiducial volume
S/S sphere, 13.7 m diam. Supports the P□Ms & optical concentrators
Space inside the sphere contains purified PC
Second nylon bag (11 m diam.) to block radon
Purified water outside the S/S sphere (18 m diam.,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

BOREXINO and Solar solutions



LENS potentiality



Muon neutrinos from the atmosphere. MACRO

Tracking:LST.

0.2° angular resol.

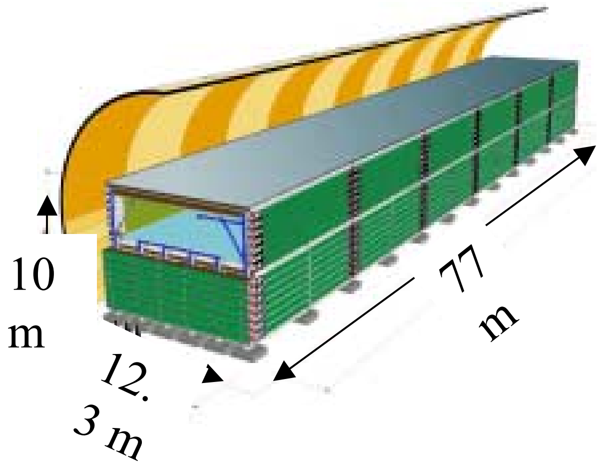
3 mm spatial resol.

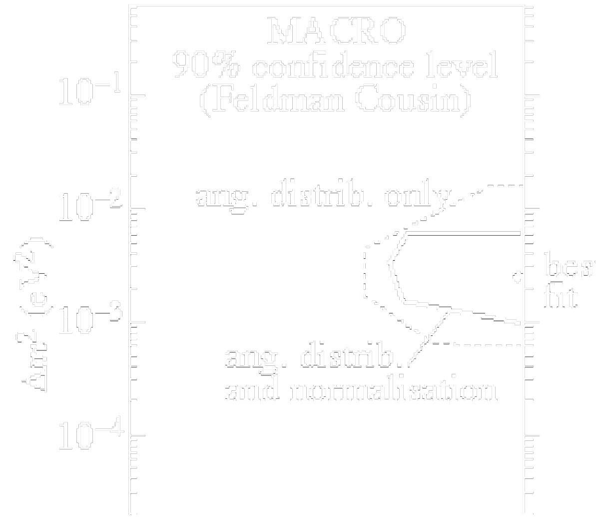
Timing: scintillators

0.5 ns resol

Completed in 2000

Decommissioned





Upward-going μ's from ν_μ interactions in the rocks

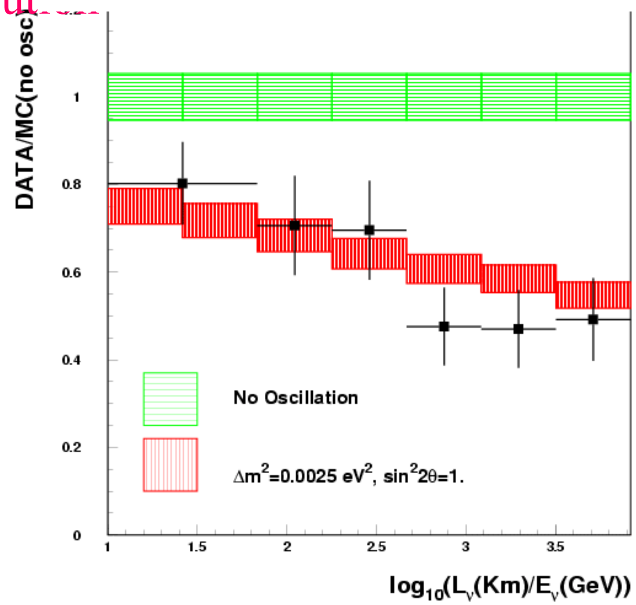
Good time resolution (up vs. down). Good angular resolution

Blind to electrons

Select energy bins from multiple scattering information, get L/E distribution

Incompatible with no oscillations

Oscillation parameters similar to SuperK

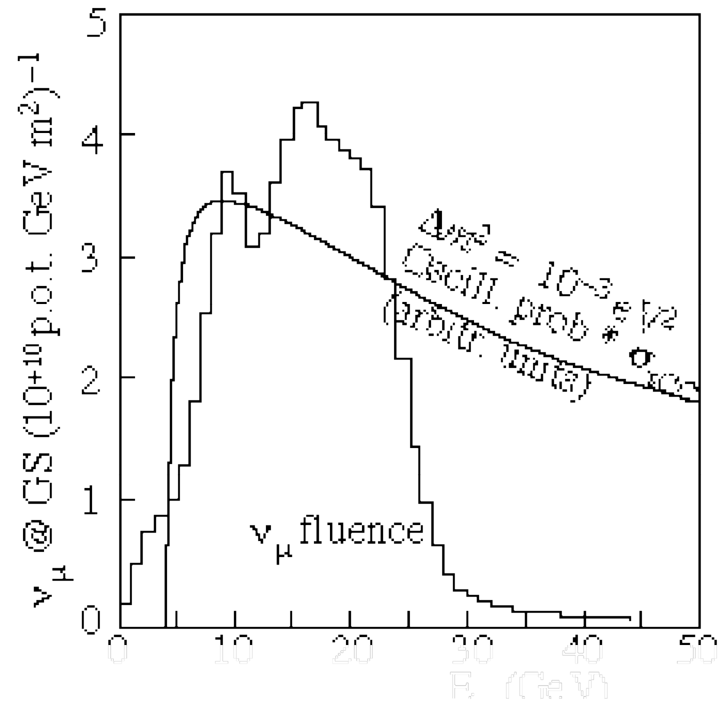


CNGS. CERN to Gran Sasso Neutrino Project

Beam energy p 400 GeV
CCν_μ inter/kt*yr 2500
ν_τ inter/kt*yr 25
@ full mixing and
$\Delta m^2 = 3.2 \times 10^{-3}$ eV^2
Further optimisation (> 1.5) possible
(present limit due to target techn.)
Ready in May 2005

Beam and experiments optimised for τ appearance

Complementary to K2K and NUMI+MINOS



Produce τ's via CC interactions

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

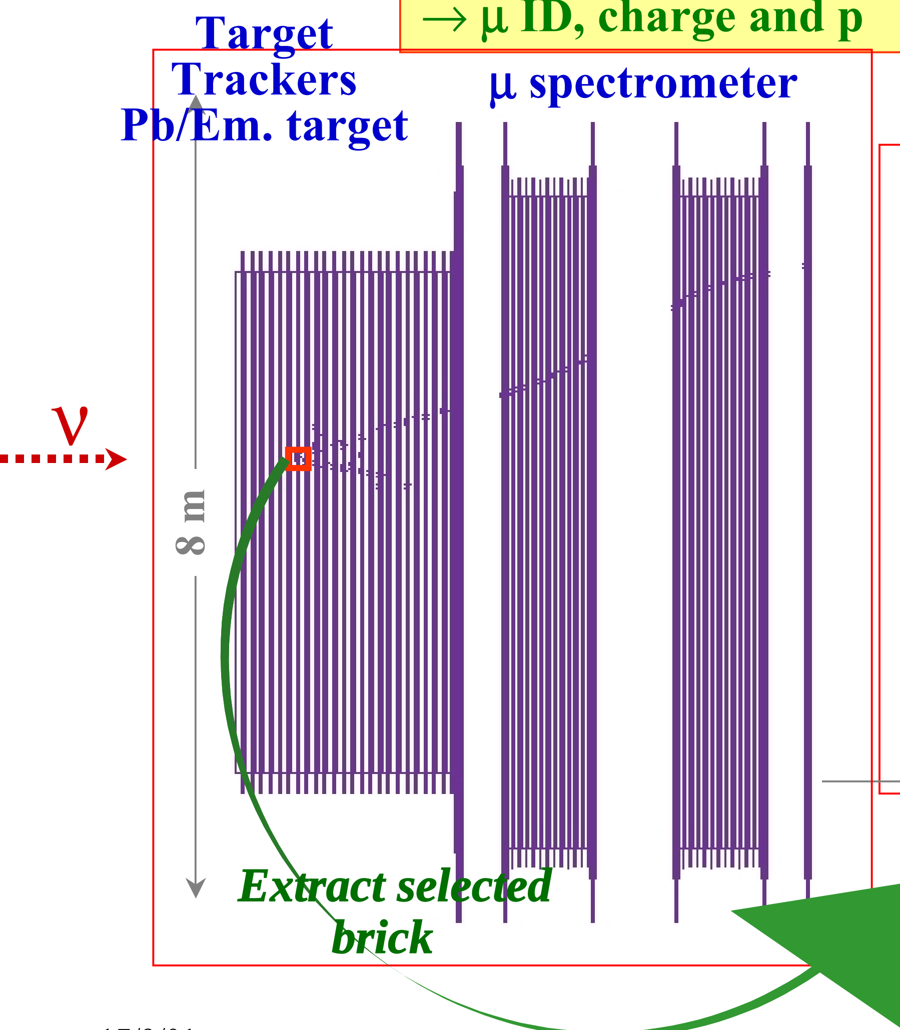
Detect τ^- through its charged decay products

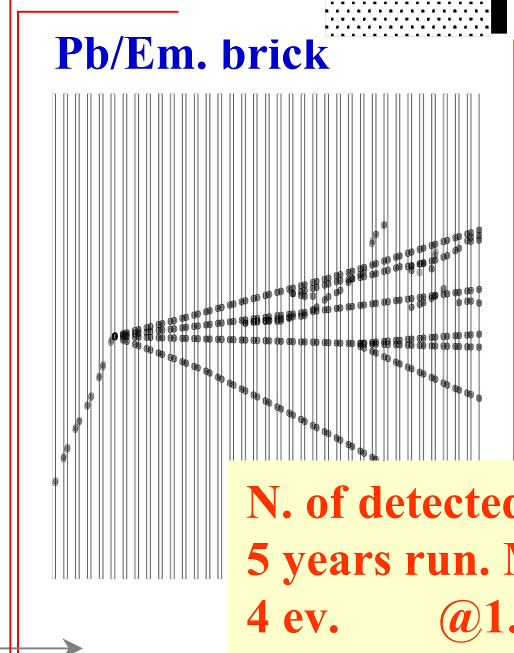
$\mu^- \nu_\tau \nu_\tau$	18%
$h^- \nu_\tau n\pi^0$	50%
$e^- \nu_\tau \nu_e$	18%
$\pi^+ \pi^- \pi^+ n\pi^0$	14%

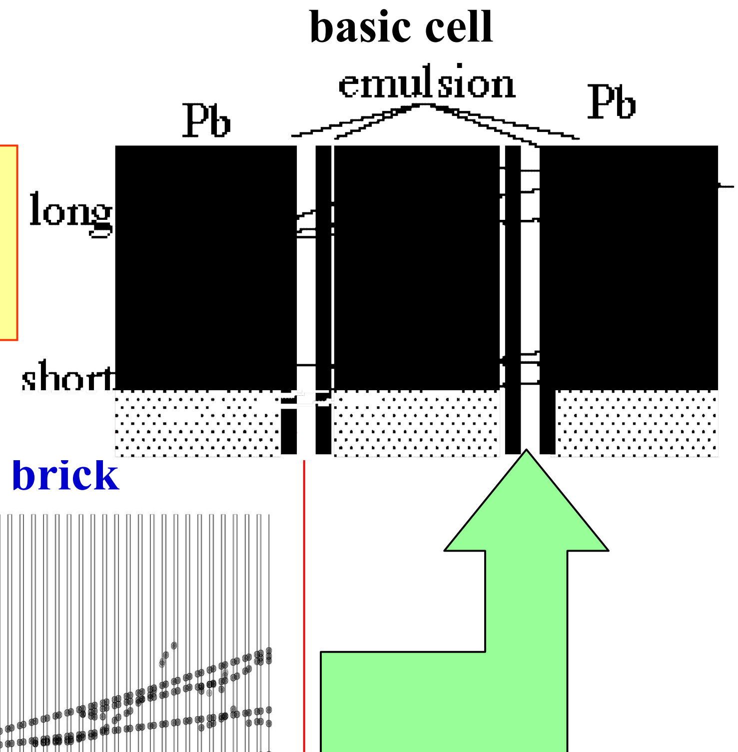
OPERA

3 super-modules
2000 t sensitive mass
μm scale granularity
sub-μm resolution

Electronic detectors
→ select ν interaction brick
→ μ ID, charge and p

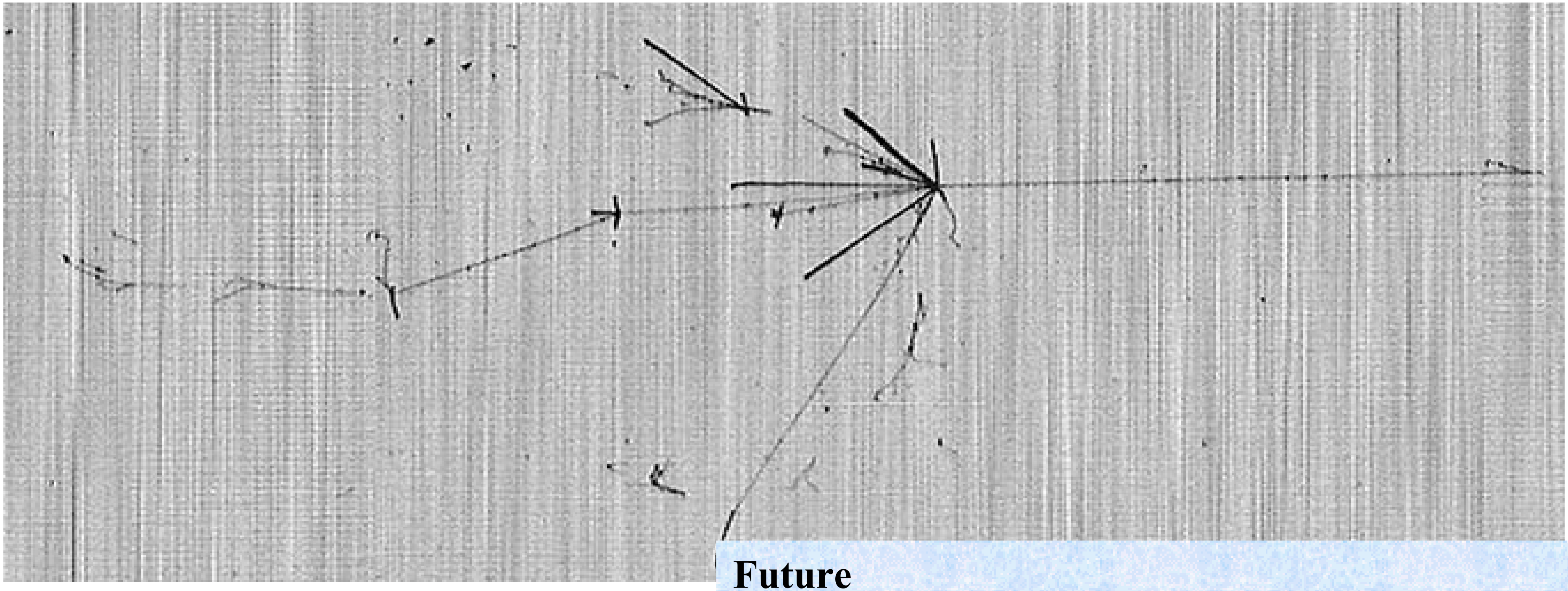






N. of detected τ's per
5 years run. Maximal mixing
4 ev. @1.5×10^{-3} eV^2
11 ev. @2.4×10^{-3} eV^2
44 ev. @5×10^{-3} eV^2
backgr 0.6 ev.
Gain > 1.5 in beam perform. possible

ICARUS. Status



Status

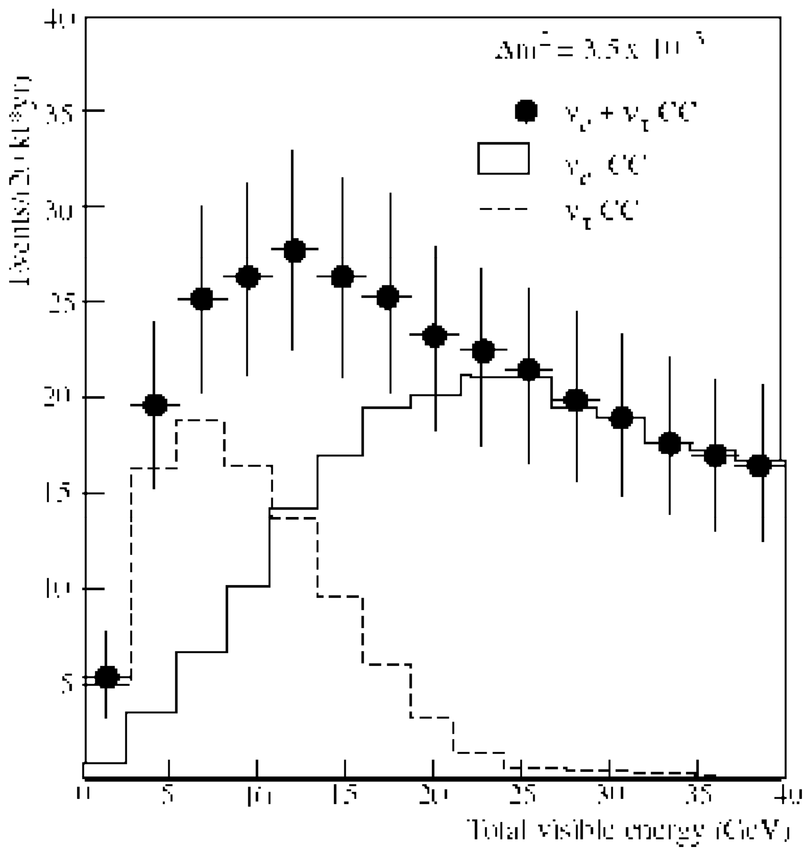
- first 300 t half-module operational
- **long (18 m) tracks images obtained**
- **safety issues (600 t) being studied**

Future

- proposal of a wide physics program with kt's size detector being examined
  - ν_τ and ν_e appearance on CNGS
  - atmospheric neutrinos
  - supernova neutrinos
  - solar neutrinos
  - proton decay
- **Safety issues for large cryogenic volumes underground to be understood**

ICARUS

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



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

$\Delta m^2 = 2.5 \times 10^{-3}$ eV^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

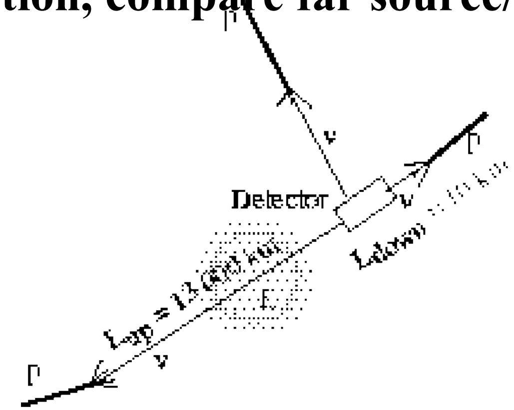
If no signal of ν_e appearance with 20 kt*yr exposure push CHOOZ limit on $|U_{e3}^2| \approx \theta_{13}^2$ □□□□□□□□□□□□□□5

Next on atmospheric neutrinos. MONOLITH

Scopes

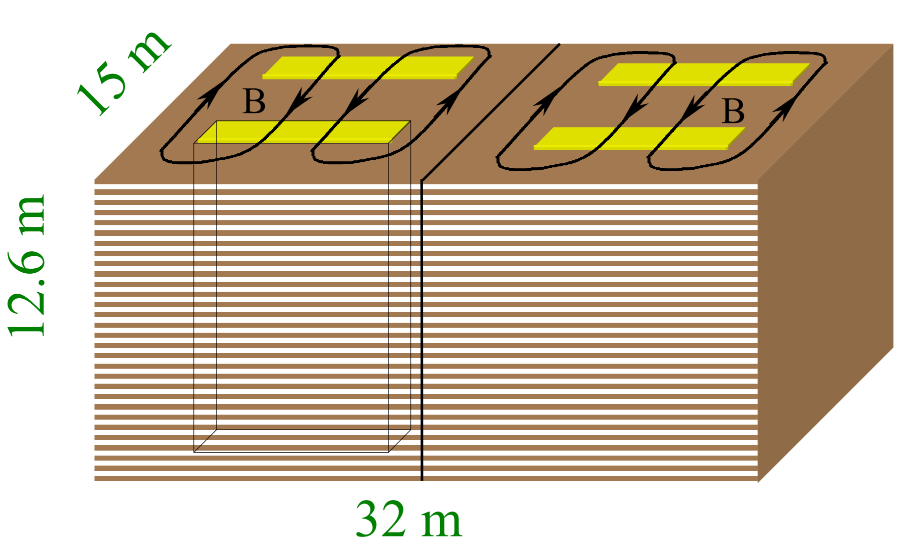
- Detect oscillation pattern
- Good Δm^2 measurement

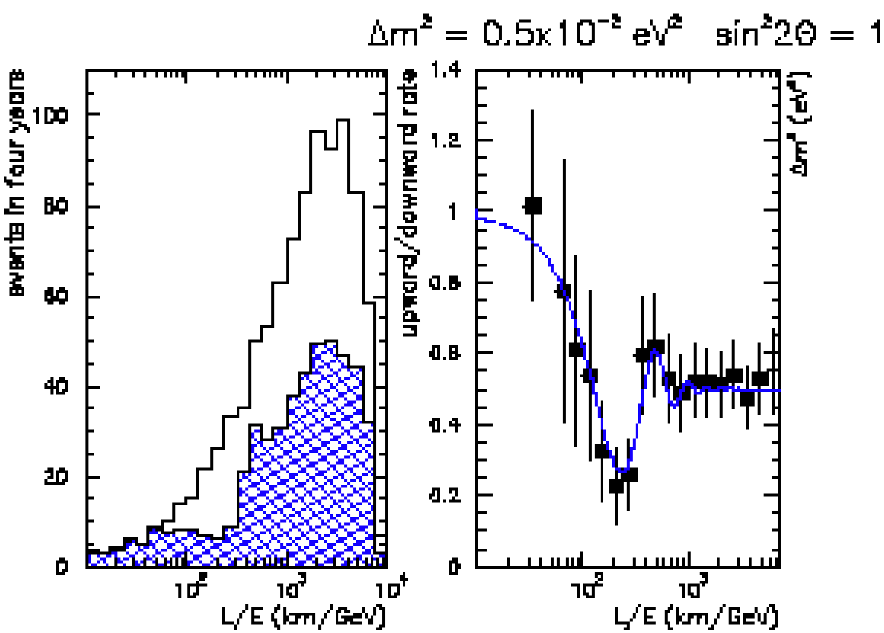
Focus on μ neutrinos (ignore *e* neutrinos)
Profit of up-down symmetry of the source
For each direction, compare far source/near source



Need

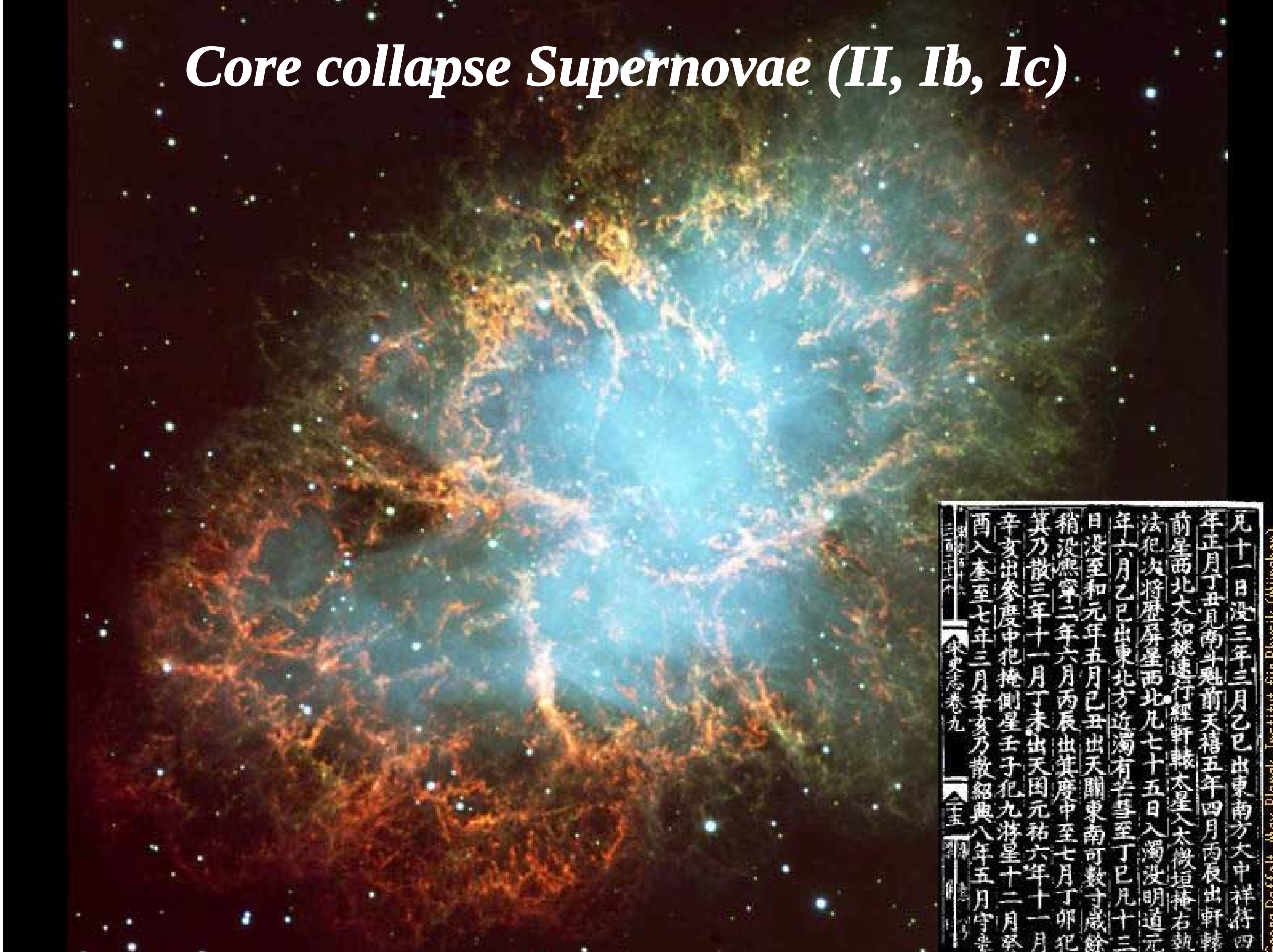
- Good ν_μ direction resolution (*L*)
- Good ν_μ energy resolution (*E*)
  - good *L/E*
- Very large sensitive mass (>30 kt)
- Rough calorimetry





STATUS: not approved by INFN

Core collapse Supernovae (II, Ib, Ic)



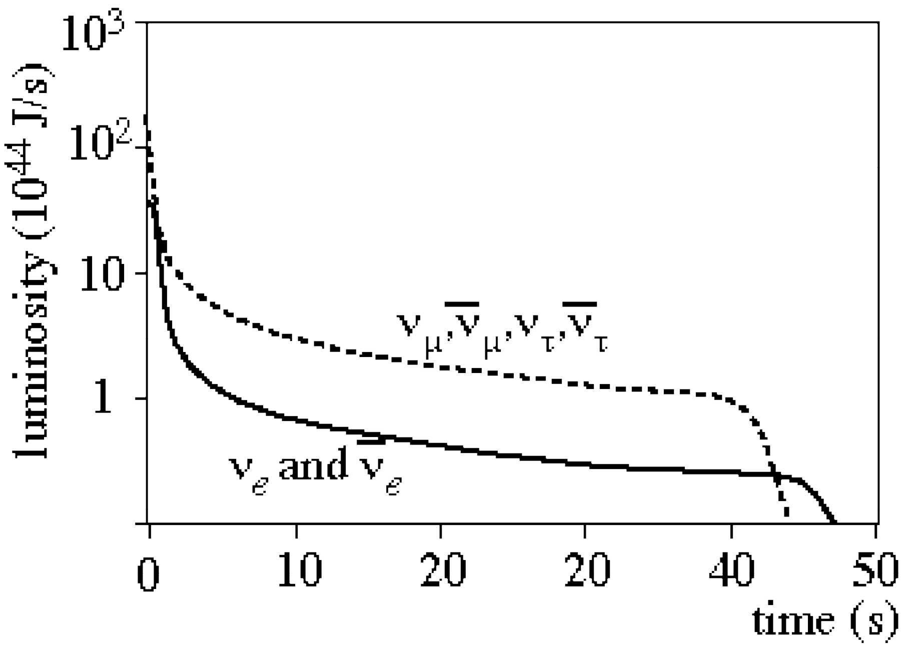
見十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九

Core collapse Supernovae

- Evolution of massive stars, which have lost Hydrogen may lead to the collapse of the core.
  – $E_b = 3 \times 10^{46}$ J
- Neutrino signal detectable only for SN in our Galaxy or Magellanian Clouds
  – **2 - 4 events/century expected in our Galaxy. Plan for multidecennial observations**

- **ν_e <E> = 12 MeV**
- **ν_μ and ν_τ <E> = 20 MeV**
  ν_μ and ν_τ detectable only through NC
- Neutrino oscillations not important for SN physics (matter potential too small)
- Oscillations strongly affect signal time evolution and energy spectrum

Observation of anti-ν_e pulse of SN 1987a
KAMIOKANDE, IMB, BUST
Only a few events
Agreement with expectations, but softer spectrum



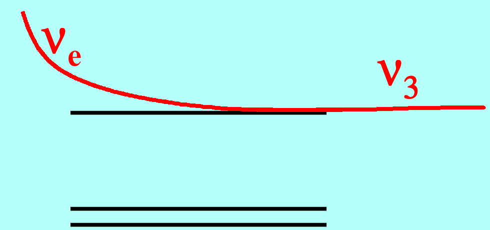
Neutrinos from a Supernova

Neutrinos (all flavours) are produced in the SN core
Change flavour in the mantle (two separate MSW resonances)
Mass eigenstates ν_1, ν_2 and ν_3 (<u>not</u> 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)

Can give important information on neutrino mixing and mass spectrum
An example.
Consider thermal emission ($e^+ e^-$) annihilation.
(Φ_e^{SN}, $\Phi_\mu^{SN} = \Phi_\tau^{SN}$) produced @ SN core ($\Phi_e$,$\Phi_\mu = \Phi_\tau$) detected @ Earth
Average energy: Electron neutrinos ≈ 10 MeV. Muon and tau neutrinos ≈ 20 MeV
Consider case of $|U_{e3}|^2$ not too small (> a few 10^{-4})

$\Delta m^2 > 0$

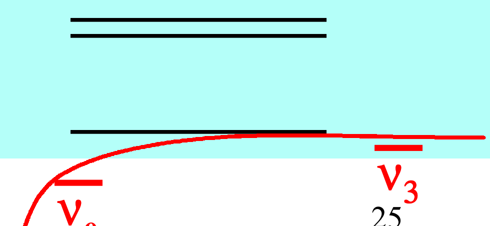
Electron neutrinos $\Phi_e \approx \Phi_\mu^{SN}$
Electron antineutrinos $\Phi_e \approx 0.5\ \Phi_e^{SN} + 0.5\ \Phi_\mu^{SN}$



$\Delta m^2 < 0$

Electron neutrinos $\Phi_e \approx 0.5\ \Phi_e^{SN} + 0.5\ \Phi_\mu^{SN}$
Electron antineutrinos $\Phi_e \approx \Phi_\mu^{SN}$

disfavoured by SN 1987A



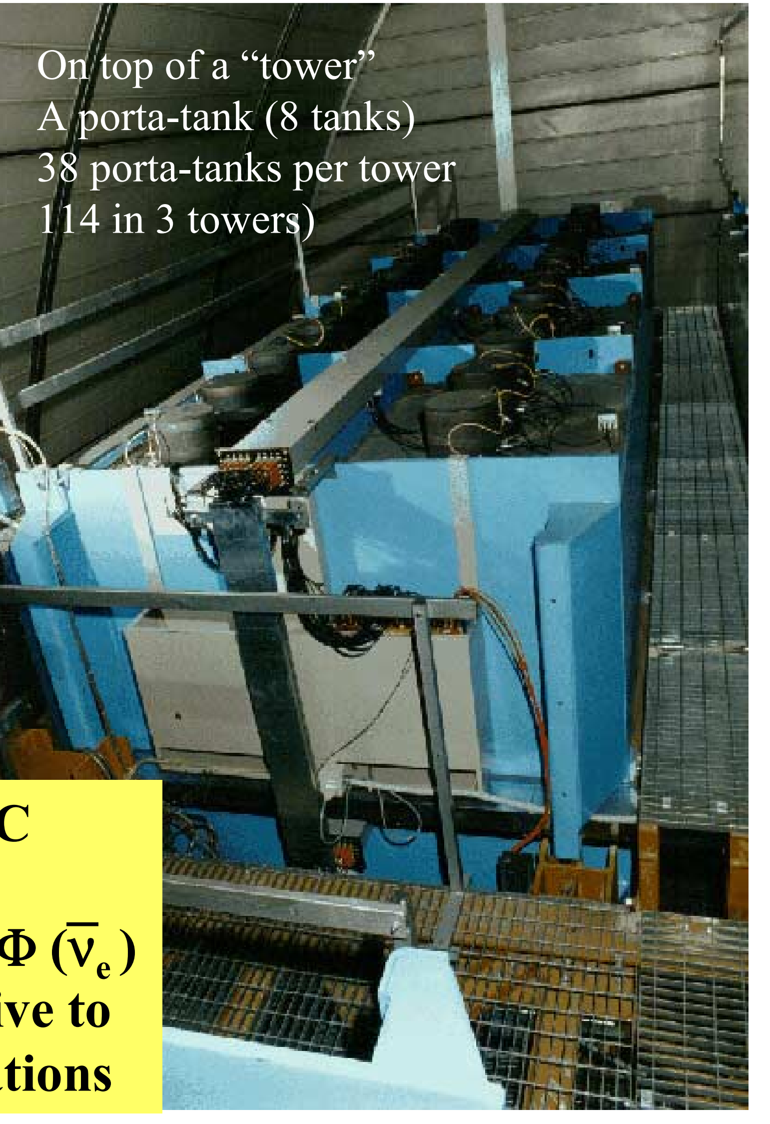
LVD

Detector

Liquid scintillator 1000t

Highly modular

up-time 99.3% in 2000



Expected yield for a collapse in the centre of Galaxy (8.5 kpc) $\overline{\nu}_e + p \rightarrow n + e^+$ 300 - 600 evts

followed (τ =185 μs) by *n* capture (used as a tag)

$$n + p \rightarrow \gamma + d + 2.2 \text{ MeV}$$

detected with 60% efficiency

$\nu_e \Leftrightarrow \nu_{\mu,\tau}$ may render ν_e more energetic

$$\overline{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B \qquad \boldsymbol{E_{thresh}} = \mathbf{14.4\ MeV}$$
$$ {}^{12}B \rightarrow {}^{12}C + e^- + \overline{\nu}_e$$

$$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N \qquad \boldsymbol{E_{thresh}} = \mathbf{17.3\ MeV}$$
$$ {}^{12}N \rightarrow {}^{12}C + e^+ + \nu_e$$

$$\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^* \qquad \boldsymbol{E_{thresh}} = \mathbf{15.1\ MeV}$$
$$ {}^{12}C^* \rightarrow {}^{12}C + \gamma$$

CC/NC and $\Phi(\nu_e)/\Phi(\overline{\nu}_e)$ sensitive to oscillations

NC/Ntot sensitive to $T_{\nu x}/T_{\nu e}$

Sign of Δm^2

Conclusions

- **Come to neutrino physics**
  - Discover **physics beyond the Standard Model**
  - A route towards the *extremely high energy*
    - *Neutrino masses <<< quark masses. Different mechanism?*
    - *Neutrino mixing ≠≠≠ quark mixing. Different mechanism?*
    - *Majorana, see-saw, p-decay*
  - Fundamental overlap with cosmology and astrophysics
- **Come to underground experiments**
    - **Measure** the mass-eigenstate mixing in the lepton sector
    - **Measure** neutrino masses
    - **Look** for cold dark matter
- **Experimental ingenuity will give rewards**
- **Theoretical effort needed in different sectors**