Highlits from Gran Sasso
40th International School of Subnuclear Physics

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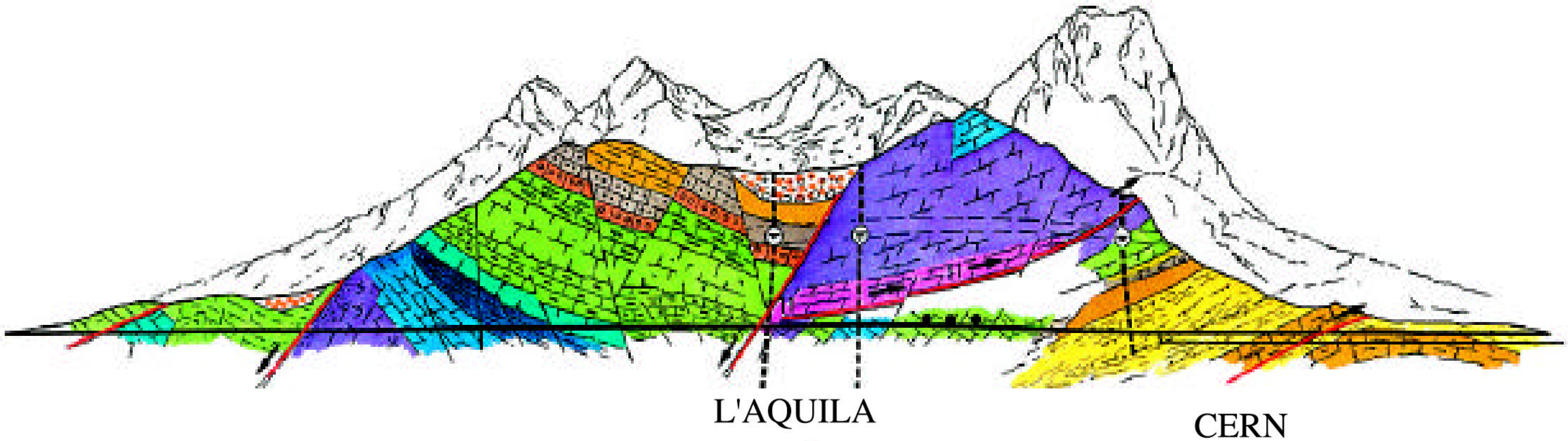
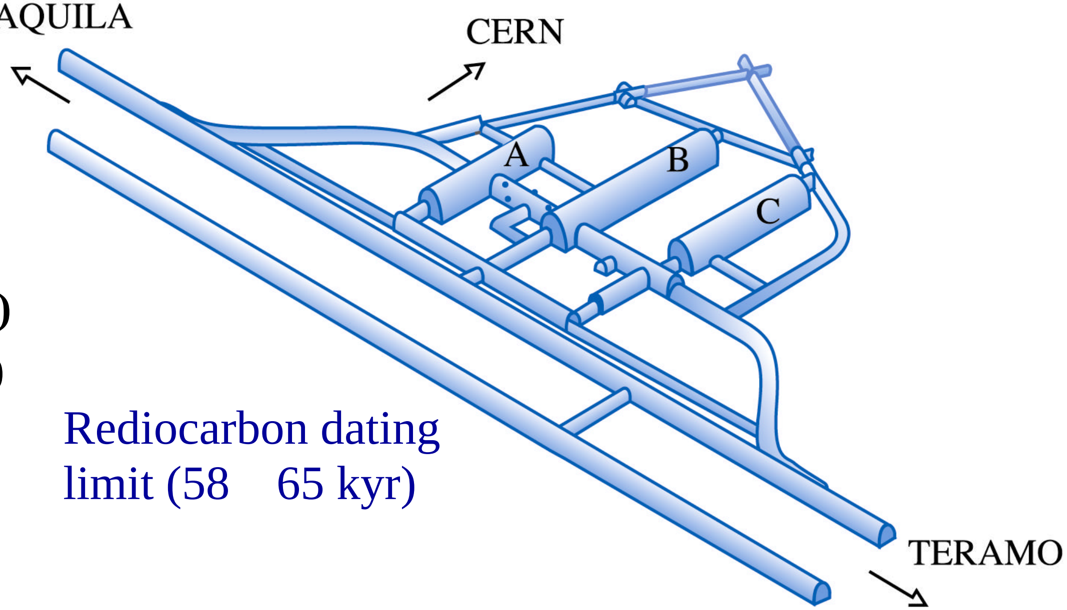


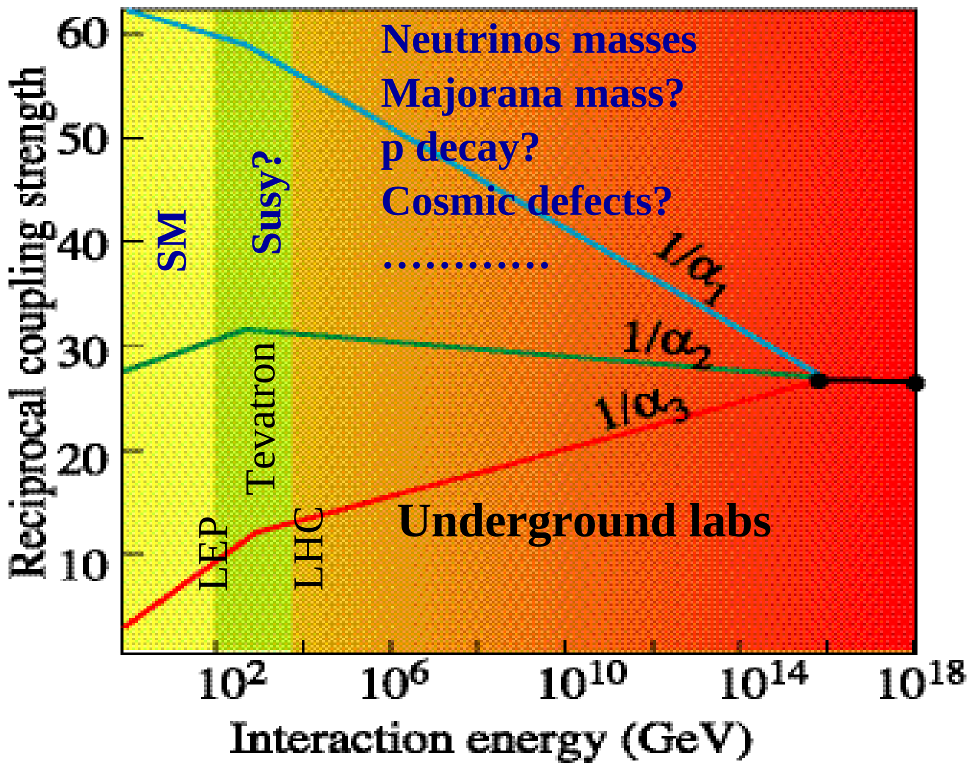


- **1400 m rock overburden**
- **Flat cross-section**
- **Neutron fluence attenuation 10^{-3} ($CaCO_3$)**
- **Cosmic μ flux attenuation = 10^{-6} (1 /m^2 h)**
- **Underground area   18 000 m^2**
- **Support facilities on the surface**
- **Drive-in to the experiments**

Rediocarbon dating limit (58   65 kyr)

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 theory
Look for extremely violent events? (merging n stars, supermassive BH's,….)



Explore the high energy frontier searching for extremely rare signals

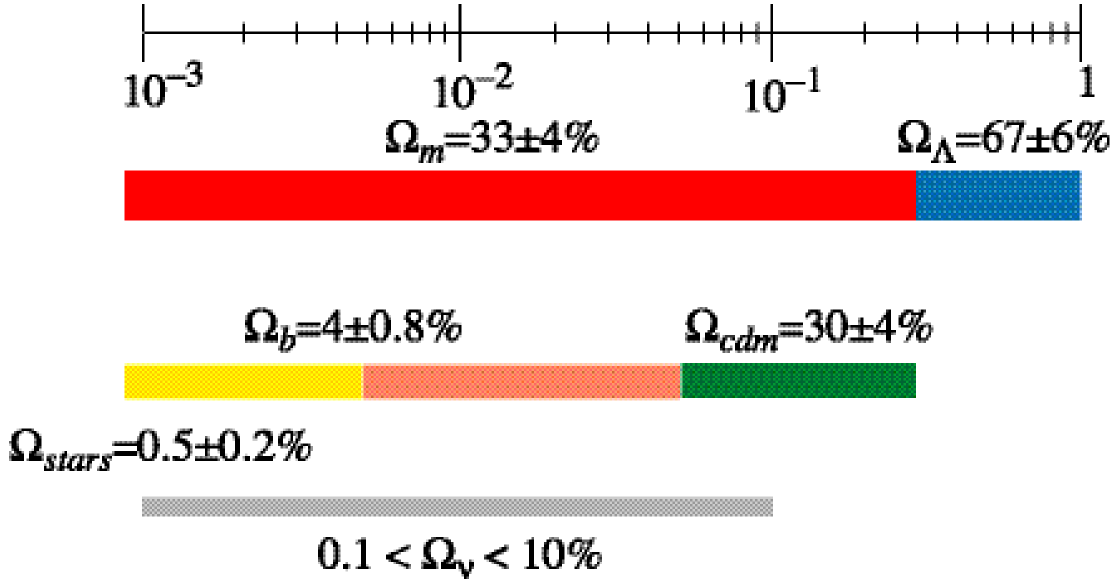
The Standard Model of Cosmology

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



from atmospheric oscillation

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

The standard cosmological model is based on:

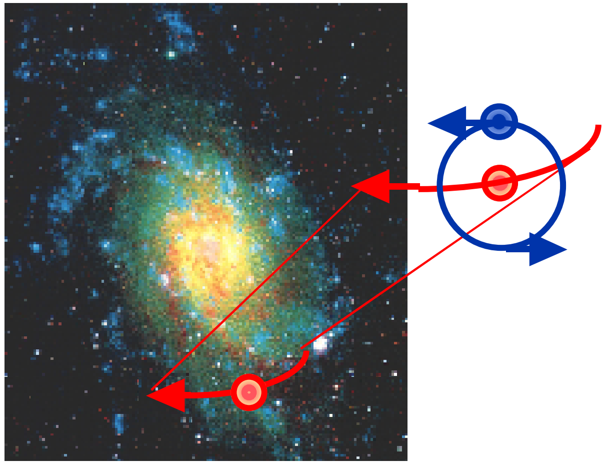
- **A dark matter we don’t see**
- **A dark energy we don’t understand**
- **A fraction of baryons we can’t find**

Cosmologic theories cannot be experimentally checked
Check is consistency not reproducibility

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

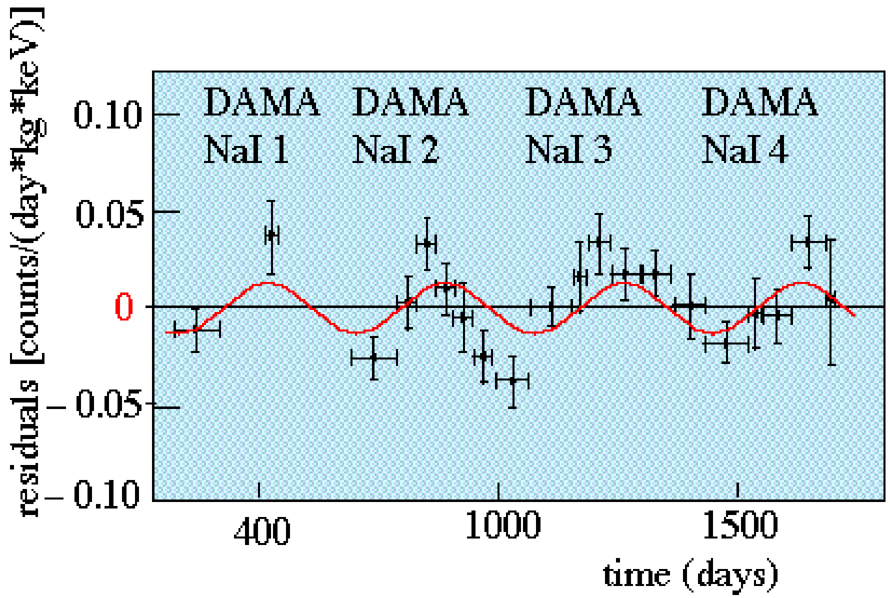
Drak matter search

DAMA looking for annual modulation

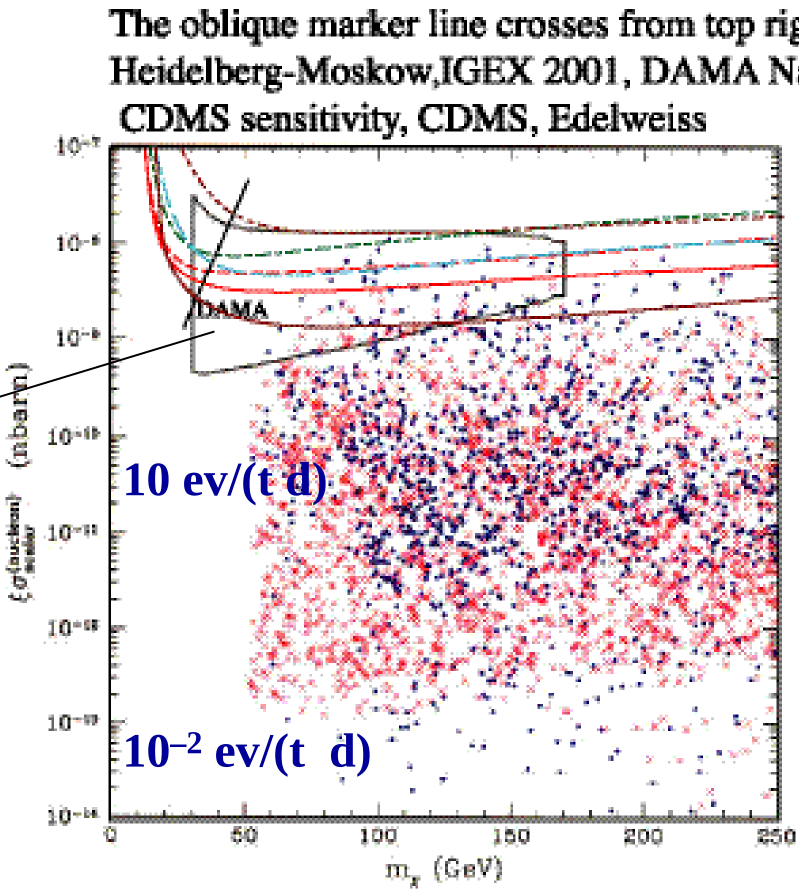


Necessary: multiton detectors and drastic background reduction (now 10^{-1} - 10^{-2} ev./kg d)

Exclusion plots compilation as by A. Morales et al.
N.B. Comparison ot experiments is largely model dependent
Theory by Bottino, Fornengo and Scopel



100 kg NaI. 60 000 kg d exposure

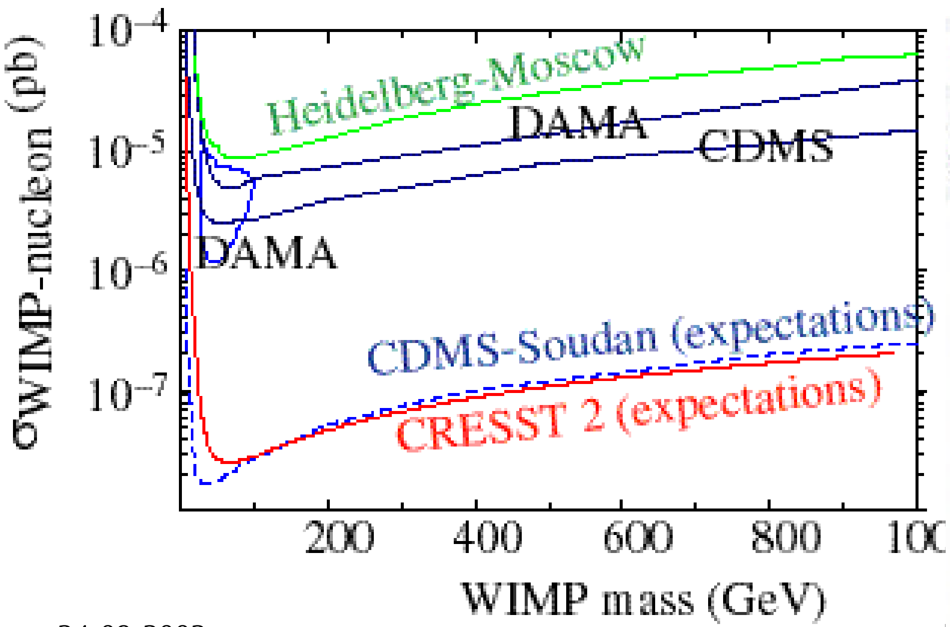


LIBRA, CRESST & GENIUS

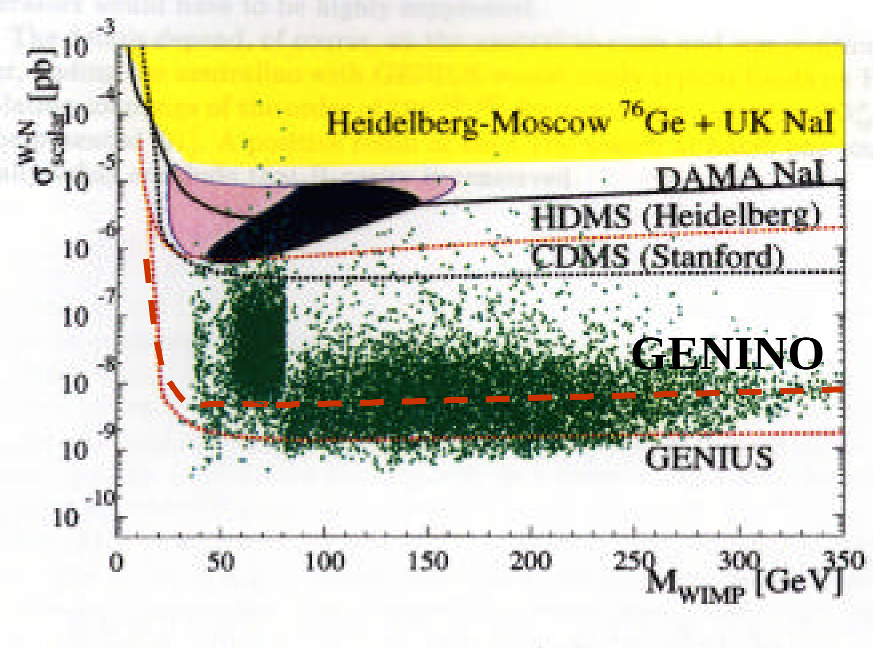
Need a balanced set of different experiments
to check independently the result
to deeper explore the parameters space

DAMAanalysing three more annual cycles increasing detector mass (250 kg) ⇒ LIBRA

CRESST 2
Detect heat and light
Separate signal from γ background
Expect 10^{-2} c/ (kg keV d) @ 15 keV
Expected to run end 2001



GENIUS-TF
if ***b*** **= 10^{-1} ev /(kg keV d)**
GENINO, **100 kg natural Ge**,
if ***b*** **= 3×10^{-3} ev /(kg keV d)**
GENIUS **1000 kg enriched Ge**
if ***b*** **=10^{-4} ev / (kg keV d)**



New neutrino physics

Two independent pieces of evidence for Physics beyond the Standard Model

Both from experiments in <u>underground laboratories</u> on

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

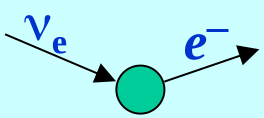
have shown the. oscillation phenomena at different square mass differences

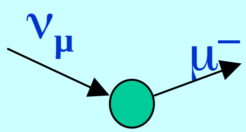
Δm^2 ("atmospheric")

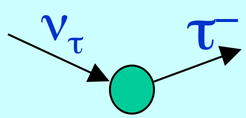
δm^2 ("solar")

Implications

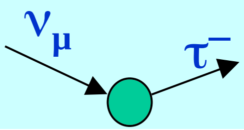
- ν_e, ν_μ and ν_τ are not mass eigenstates (ν_1, ν_2, ν_3) but superpositions of these
  If eigenstates are orthogonal, need to measure
  - three "mixing angeles" θ_{12}, θ_{13}, θ_{23}
  - three phases (one if Dirac)
    - CP violation
- ν_1, ν_2 e ν_3 have m_1, m_2 and m_3 $\neq 0$
- leptionic charges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







  - but also

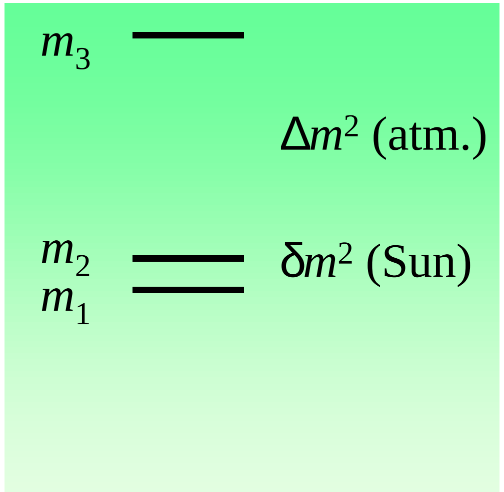


just wait enough

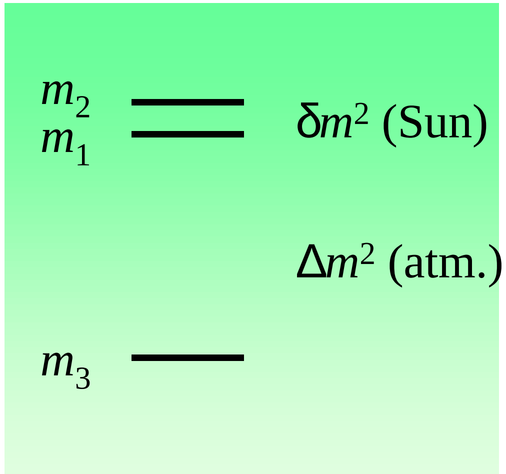
Neutrino masses

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
$\Delta m^2 > 0$



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

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

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

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

Seesaw mechanism

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

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

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" $\theta_{12}, \theta_{13}, \theta_{23}$
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 probabilties 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 – π/2 not 0 – π/4
Talking of "elctron neutrino mass" is misleading
Variables like $\theta_{\mu\tau}$ are misleading (may lead to wrong conclusions)
Beware mistakes of PDG

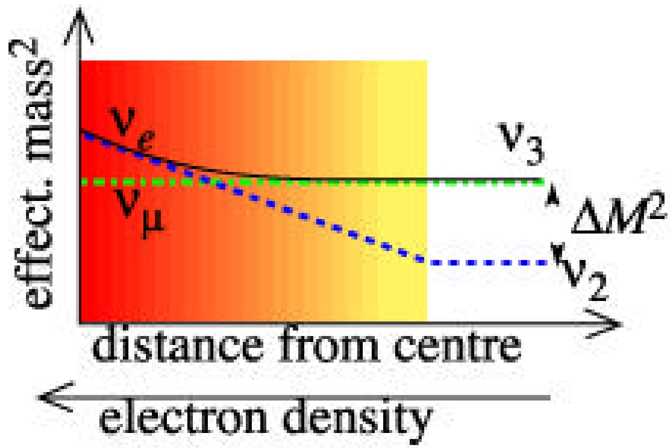
Flavour conversion in matter

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

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 – π/2, even for two neutrino flavours

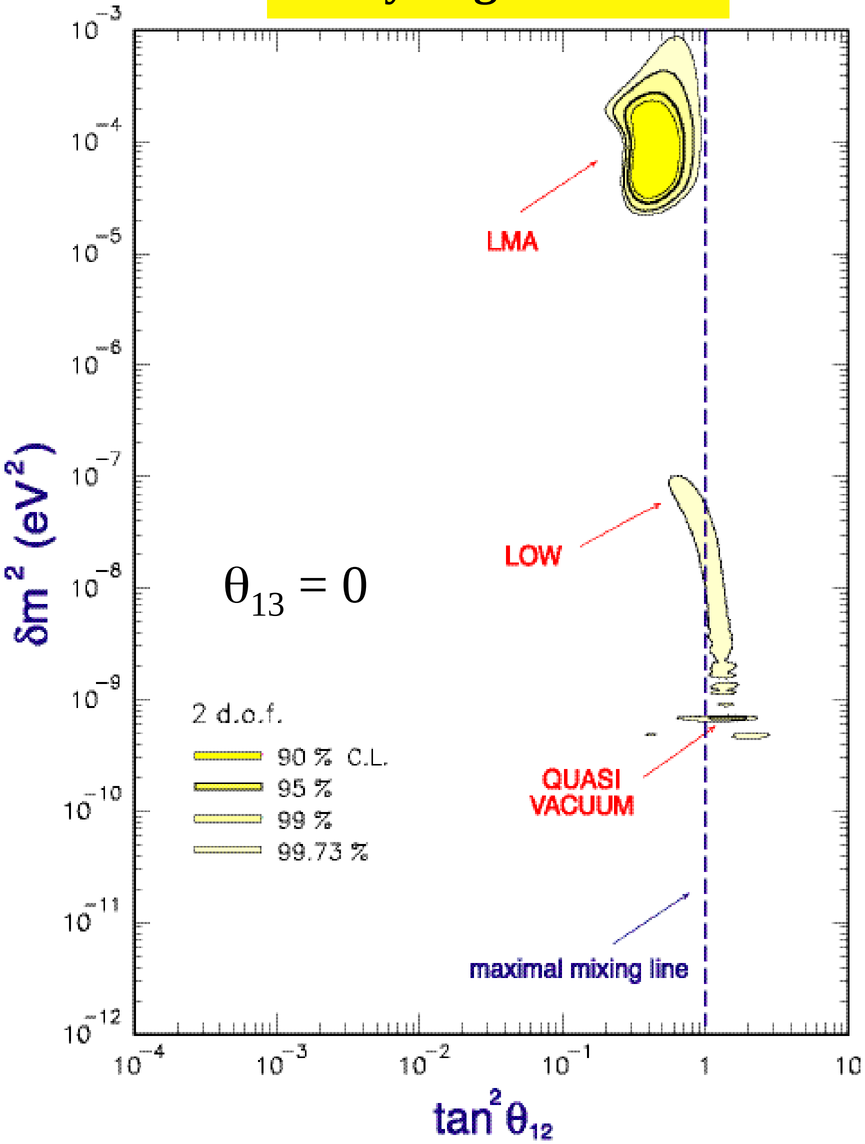
Status of neutrino oscillations

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. 1250 d (77 kt yrs)
Confirmed by MACRO and Soudan2
$1.8 \times 10^{-3} < \Delta m^2 < 4 \times 10^{-3}$ eV^2 (90% c.l.),
$\sin^2 2\theta_{23} > 0.88$

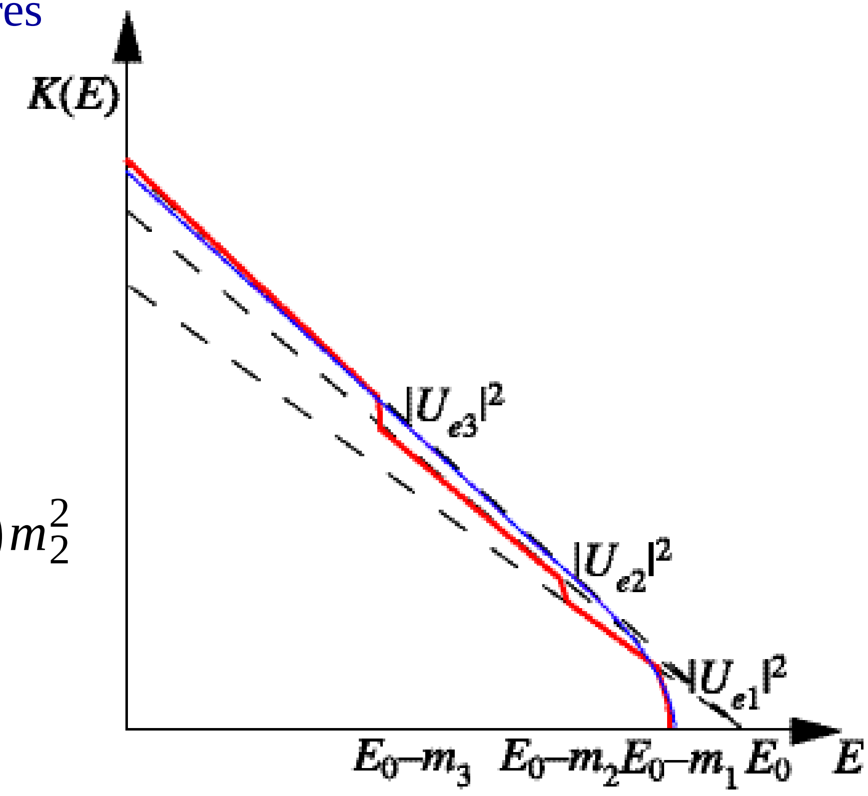
If LMA, KamLAND will see anti-ν_e disappearan
If LOW, BOREXINO will see strong deficit
N.B. Fit assumes all experiments right, all uncertainties correctly evaluated
We need redundancy

Fit by Fogli et al.



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 for reasonable measure time) the different "steps" are not resolved (blu 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**

Cosmology will become sensitive to the 100 meV scale after the next turn of measurements (mainly SDSS)

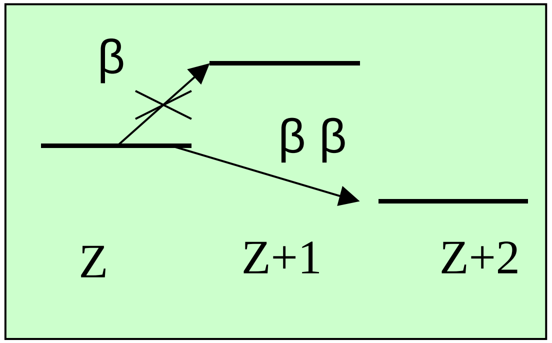
Majorana masses of electron neutrinos

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

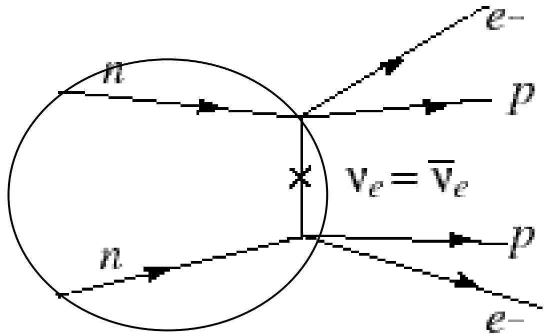
If lepton number is not conserved and if neutrinos are massive (chirality is frame dependent)

$$\nu_e^C = \nu_e$$ Majorana neutrino

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



Measure $0\nu\beta\beta$ lifetimes



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**

Expected M^M_{ee} minimum value depends on the mass spectrum and mixing angles

"Reasonable" values are a few tens mev

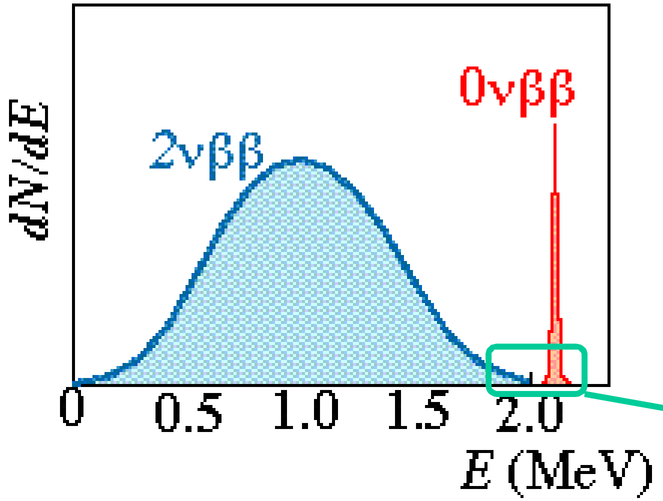
Even an upper limit M^M_{ee} of a few 10 meV can provide info on the type of mass spectrum

Discovery @ 200 meV level combined with KATRIN might establish CP violation in lepton sector

Pascoli and Petkov hep-ph/020522

How to improve limits

Measure total energy
of two electrons



t = Exposure time

M = Detector mass

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

= Half-life

Δ = Energy resolution

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

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

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?

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}<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

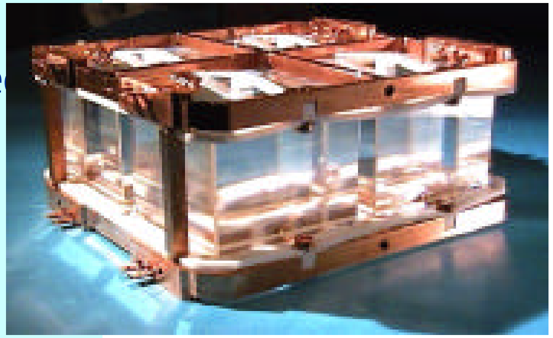
GENIUS
Naked enriched Ge crystals in LN_2
***b* = 3x10^{-4} ev/(kg keV yr))**
Sensitive mass: 1000 kg ^{76}Ge
M_{ee}< 20-30 meV
Status. Experimental tests requested (GENIUS-TF)

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



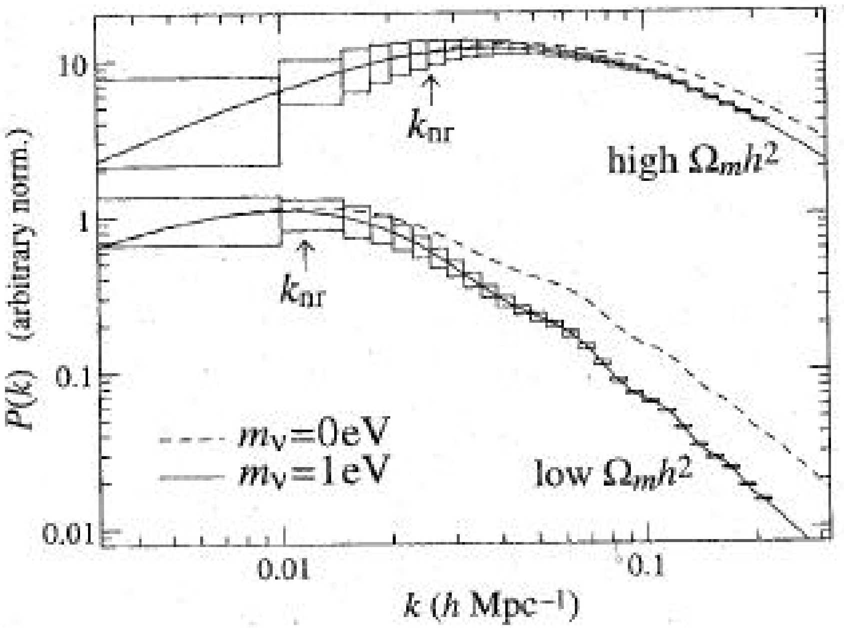
@ sensitivity level of a few 10 meV neutrino effective mass will likely appear
Reminder: 2ν2β decay must be distingushed from 0ν2β decay

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 $\sum m_i < 1.8$ eV $\Rightarrow$ $m_1, m_2, m_3 < 600$ meV

(Ø- Elgaroy et al. astro-ph/0204152 v3, 2002)

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

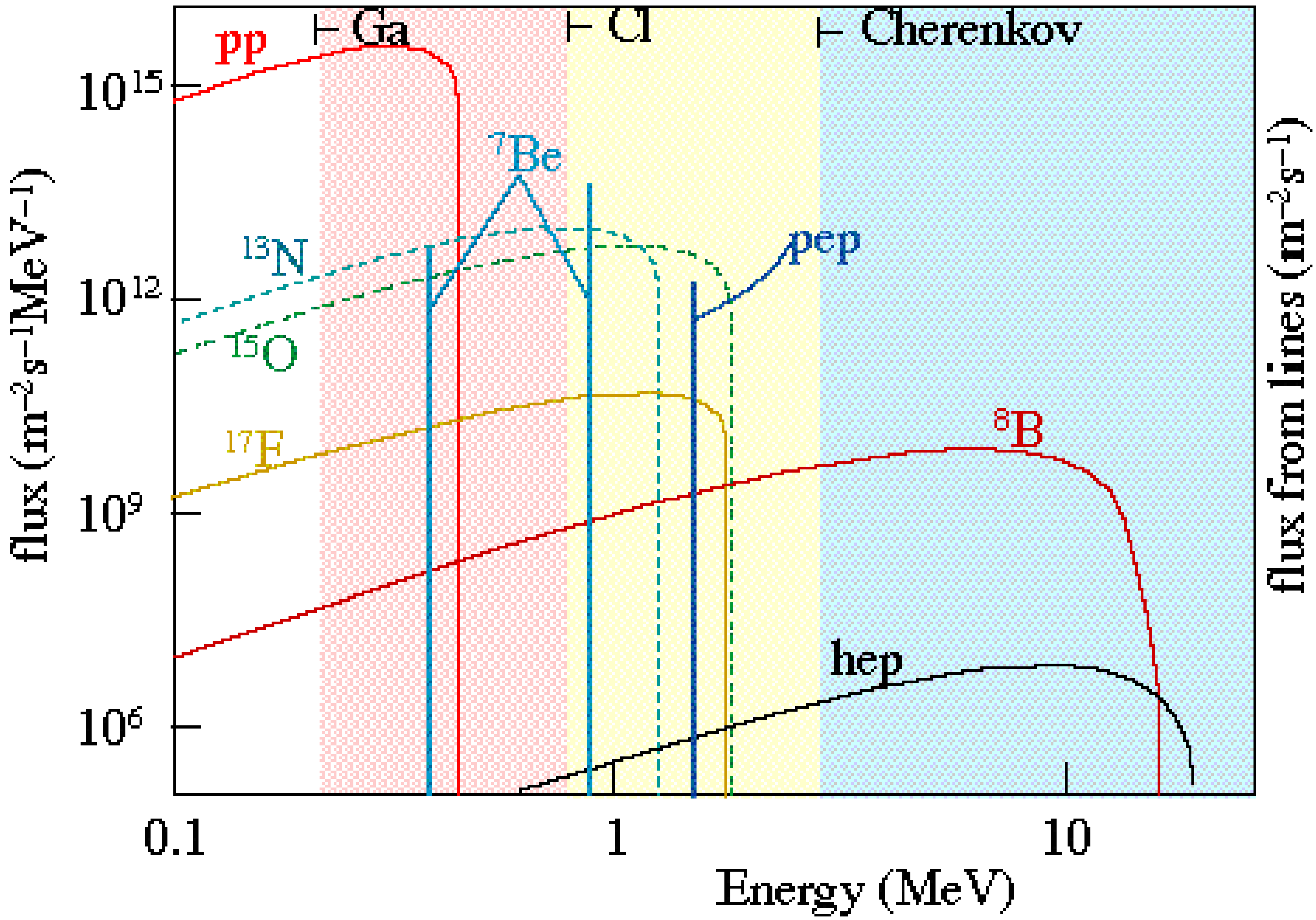
Discovery limit @ 2 σ = $\sum m_i$ = 300 meV

50% uncertainty due to poor knowledge of other parameters

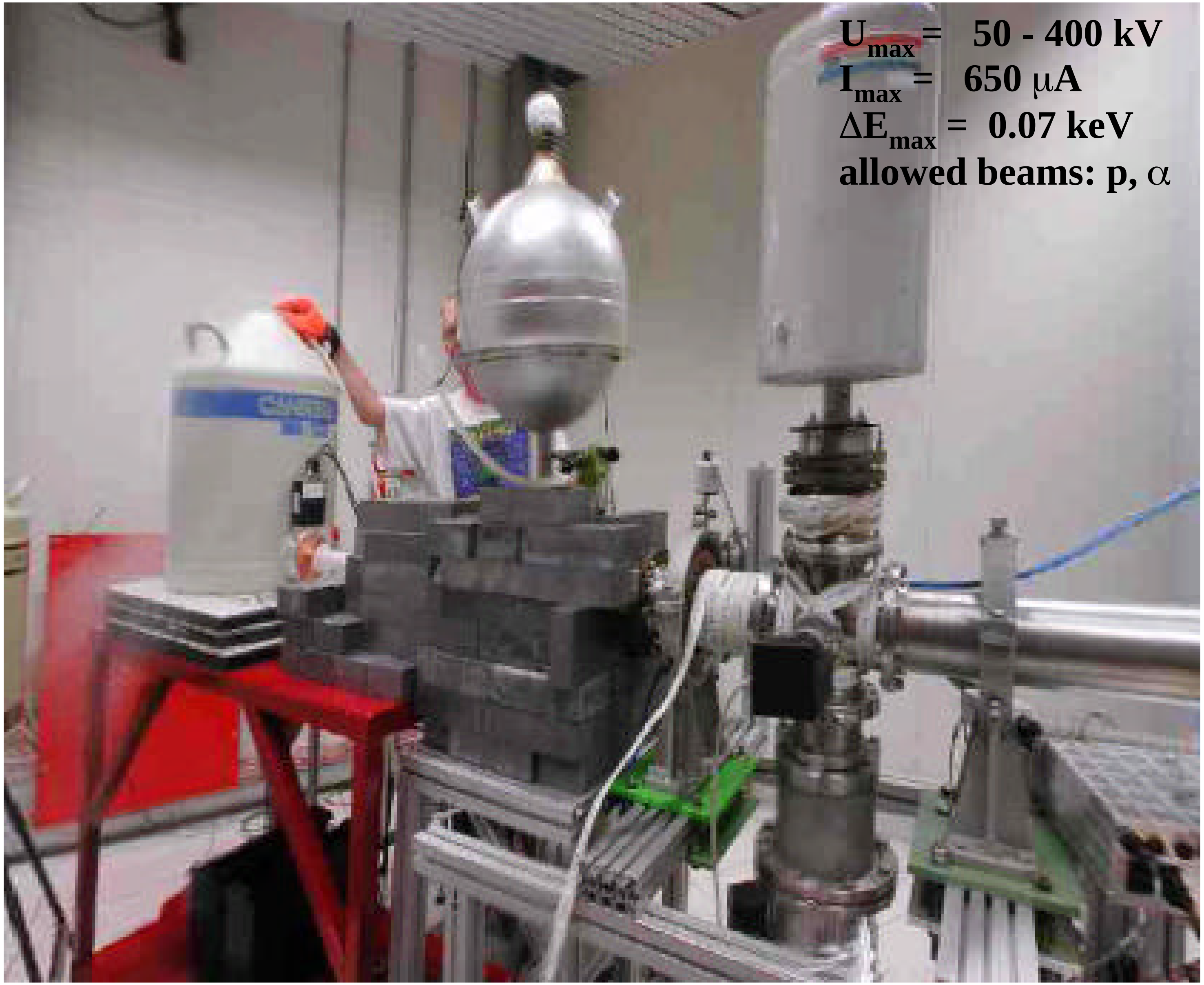
Standard Cosmology may become a sound Theory

Need $\sum m_i$ = 60 meV sensitivity to reach atmospheric oscillation lower bound

Solar electron-neutrino spectrum

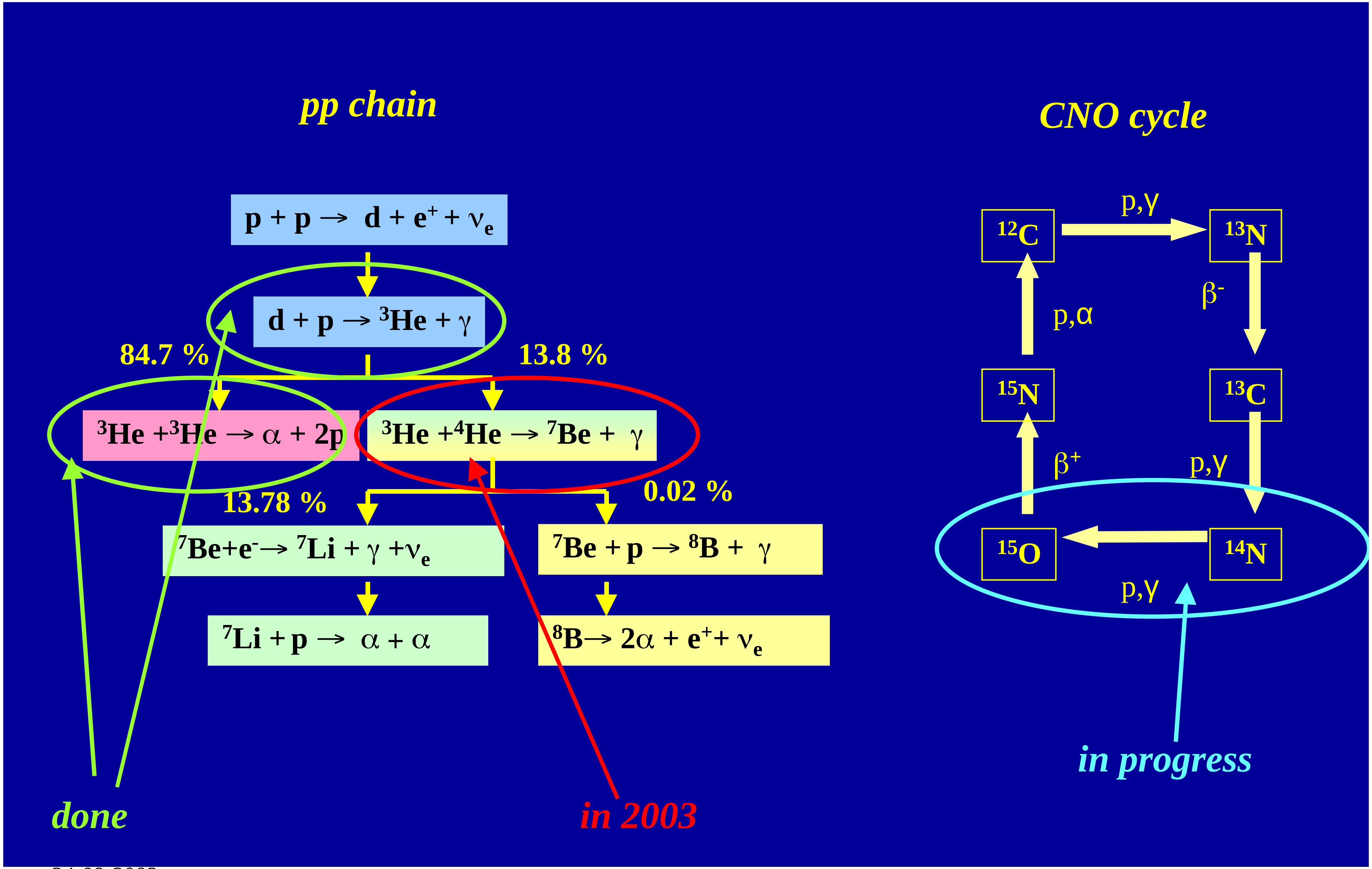


LUNA2

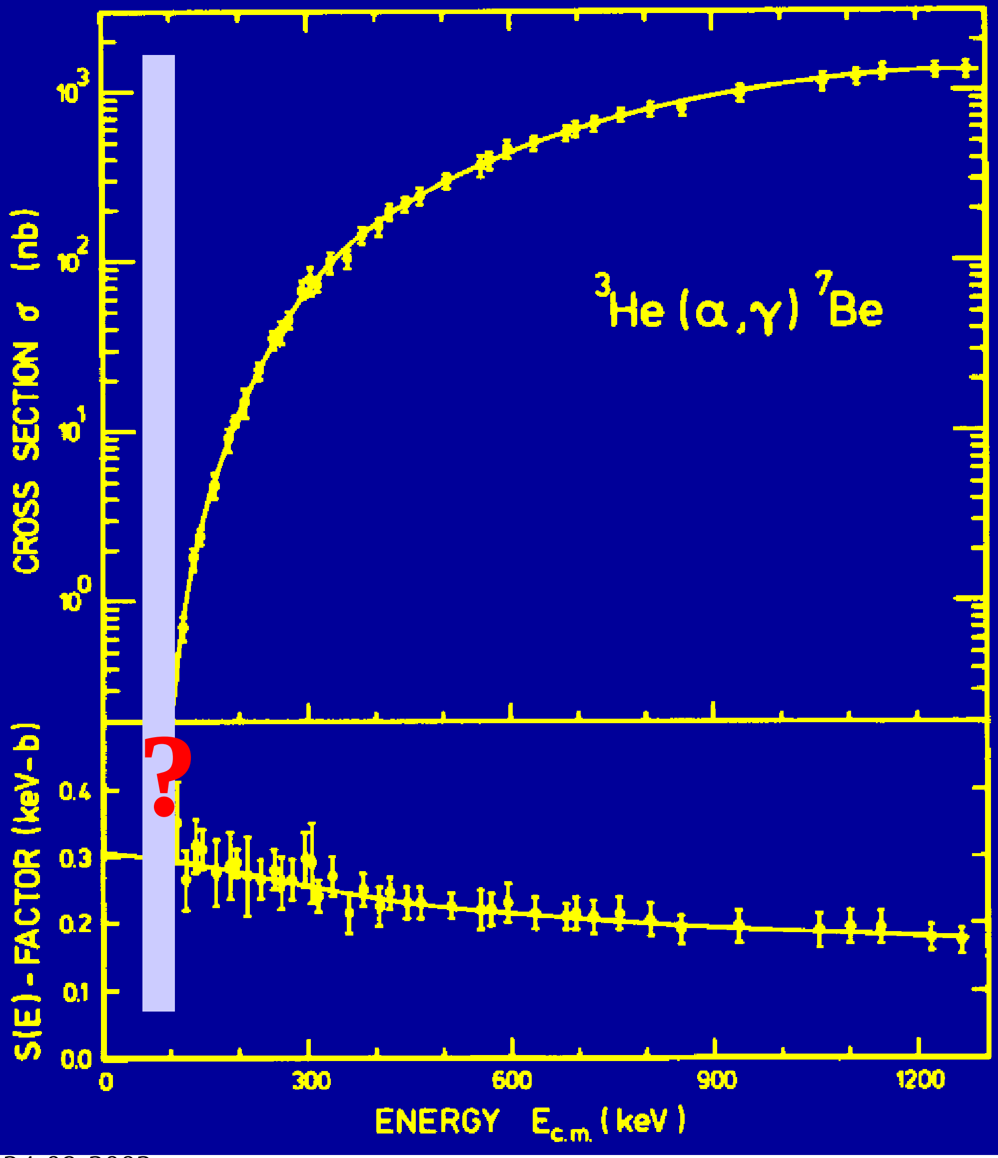


U_{max} = 50 - 400 kV
I_{max} = 650 μA
ΔE_{max} = 0.07 keV
allowed beams: p, α

LUNA scientific program



The astrophysical S-factor



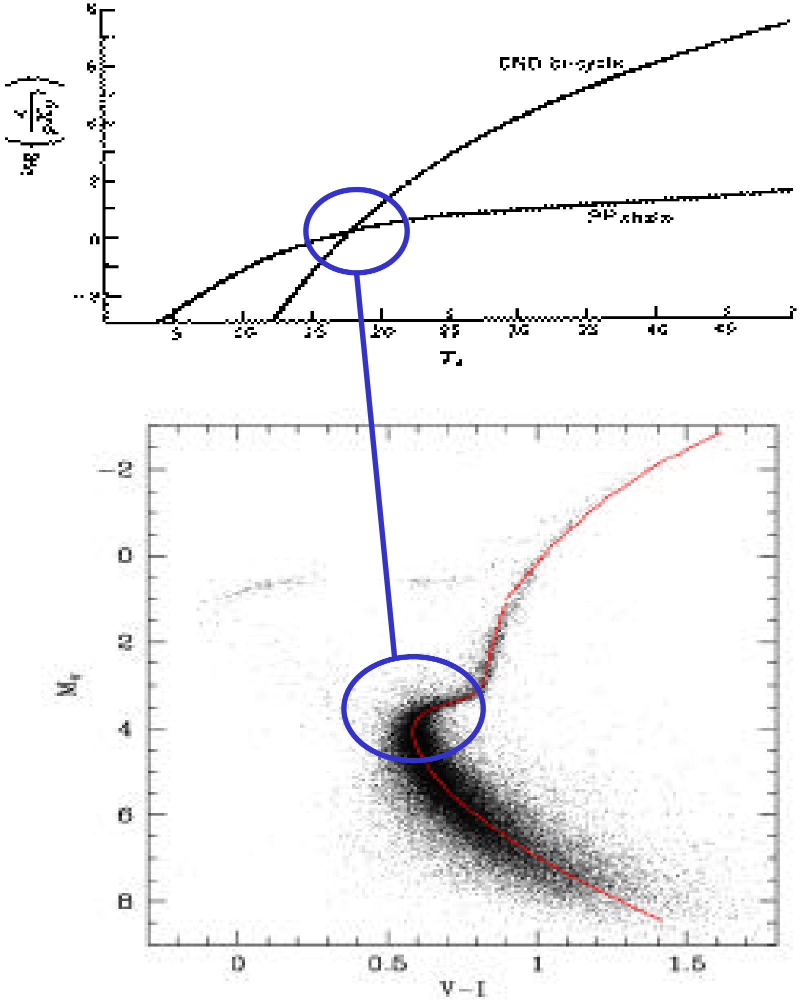
$$\sigma(E) = S(E)\cdot\exp(-2\pi\eta)/E$$

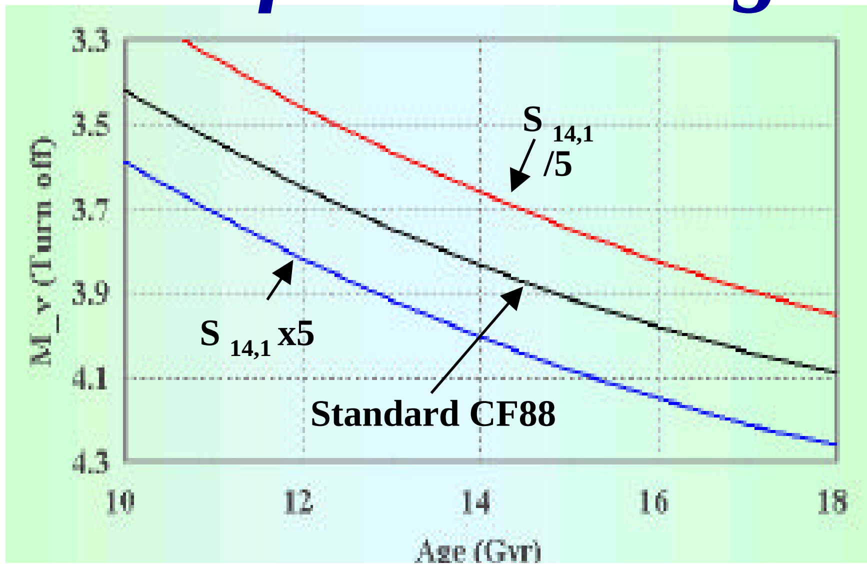
↓

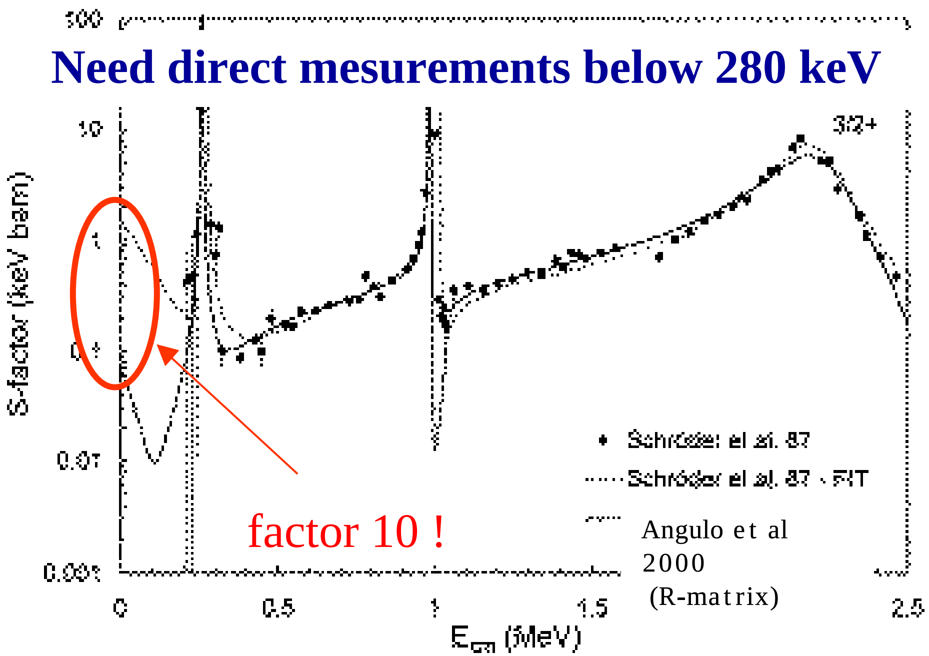
$$S(E) = E\cdot\sigma(E)\cdot\exp(2\pi\eta)$$

$$2\pi\eta = 31.29\ Z_1 Z_2 (\mu/E)^{0.5}$$

•$^{14}N(p,\gamma)^{15}O$, Chronometer of Universe age



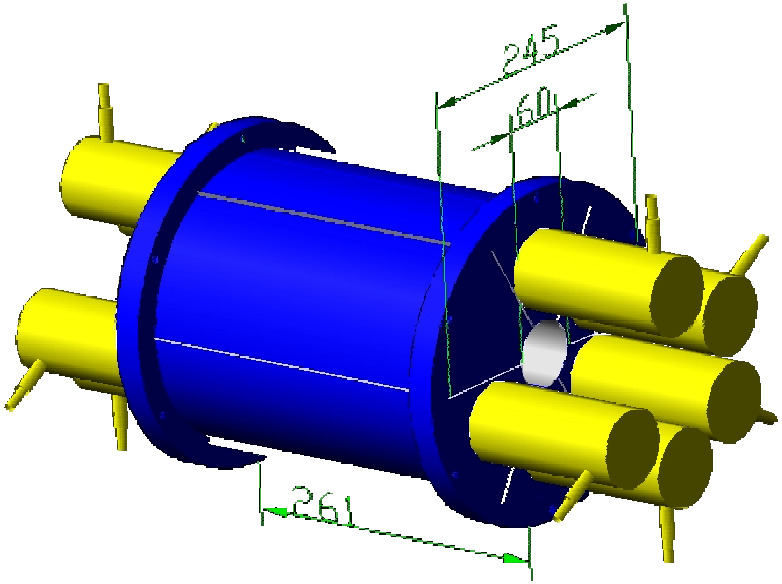


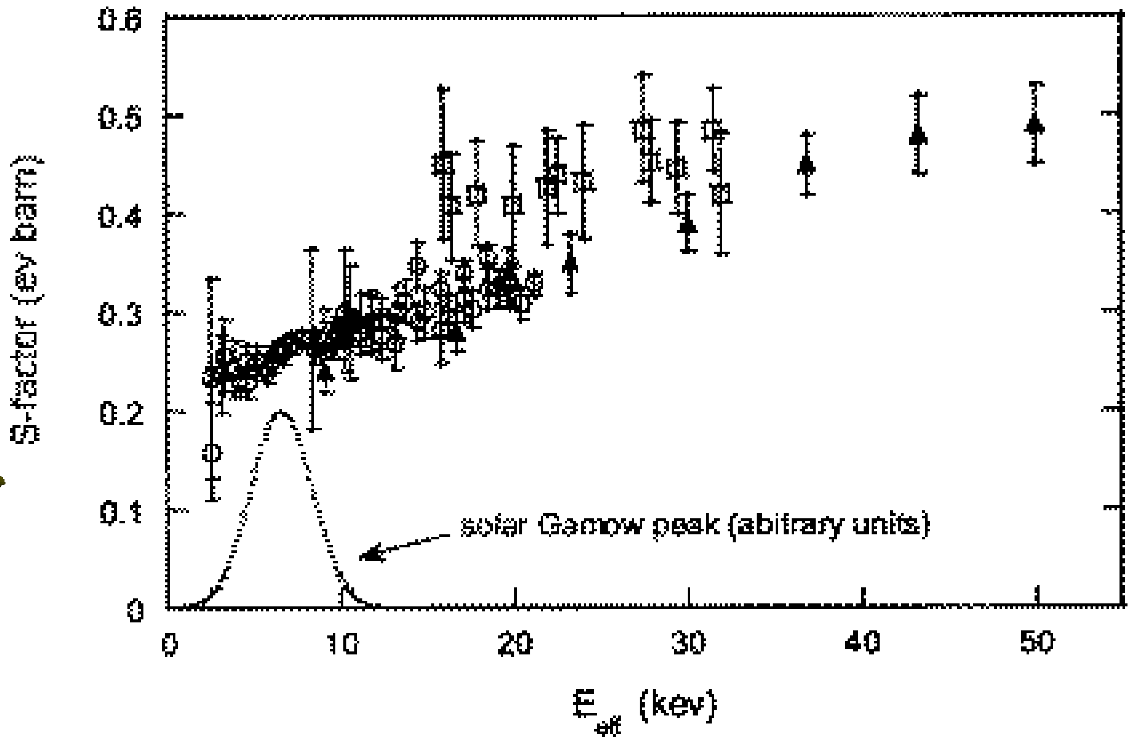


D(p,γ)³He, below the Gamow peak

σ = 0.01 pbarn

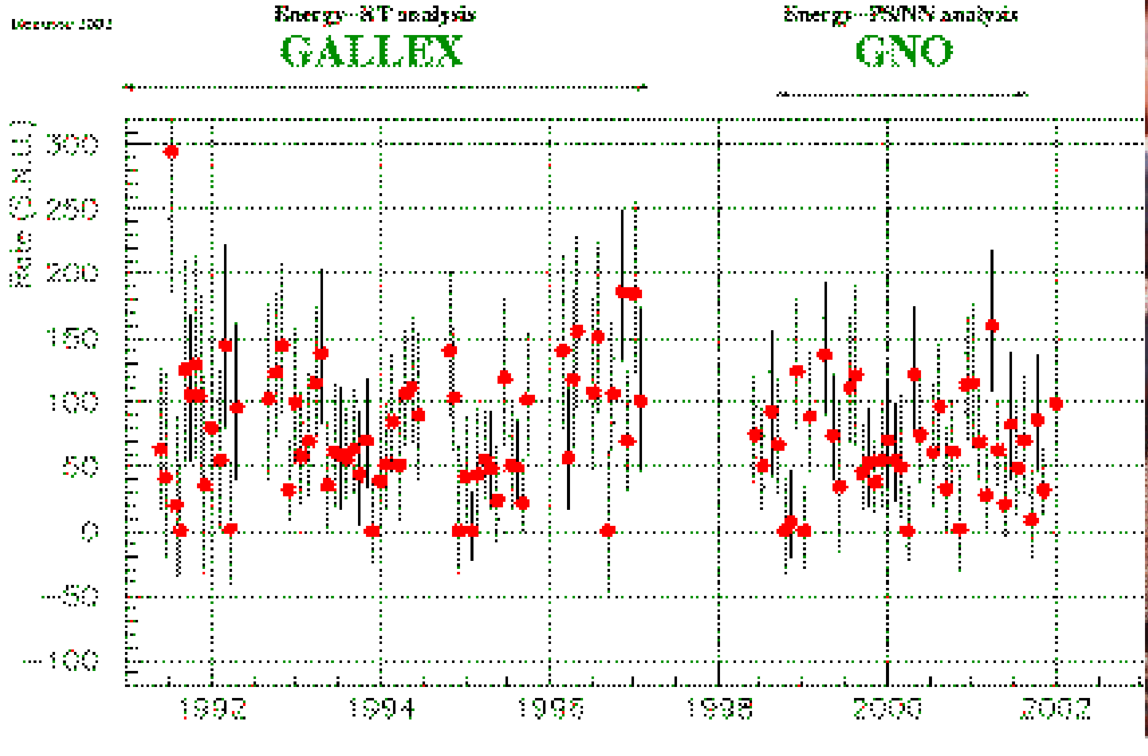
4π BGO





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



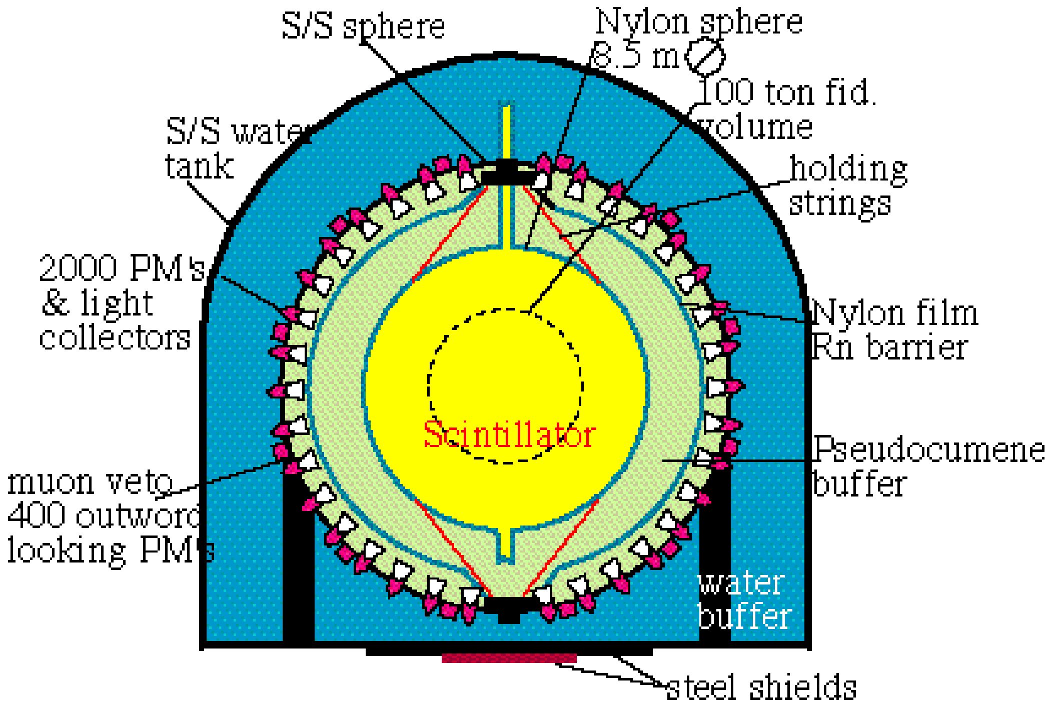
GALLEX	65 SR	77.5 +− 6.2 (stat) +− 4.5 (sys) SNU
GNO	43 SR	65.2 +− 6.4 (stat) +− 3.0 (sys) SNU
GNO+GALLEX	108 SR	70.8 +− 4.5 (stat) +− 3.8 (sys) SNU

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

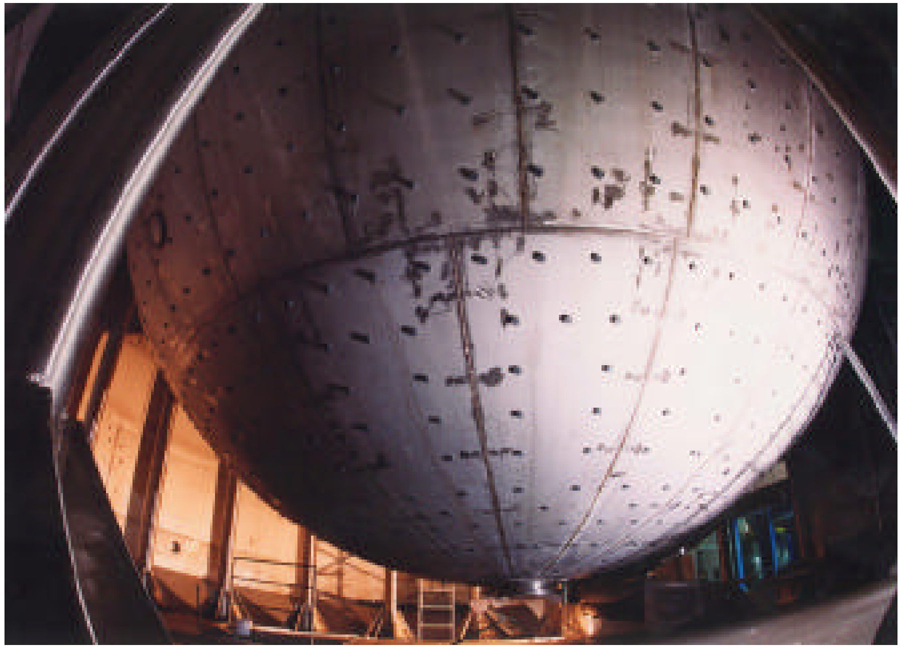


300 t liquid scintillator (PC + PPO) in a nylon bag
Innermost 100 t: fiducial volume
S/S sphere, 13.7 m diam. Supports the PMs & optical concentrators
Space inside the sphere contains purified PC
Second nylon bag (11 m diam.) to block radon
Purified water outside the S/S sphere (18 m diam., 16.9 m height)

The SS Sphere

Scintillator purification
(H_2O extraction and Si-gel column)

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

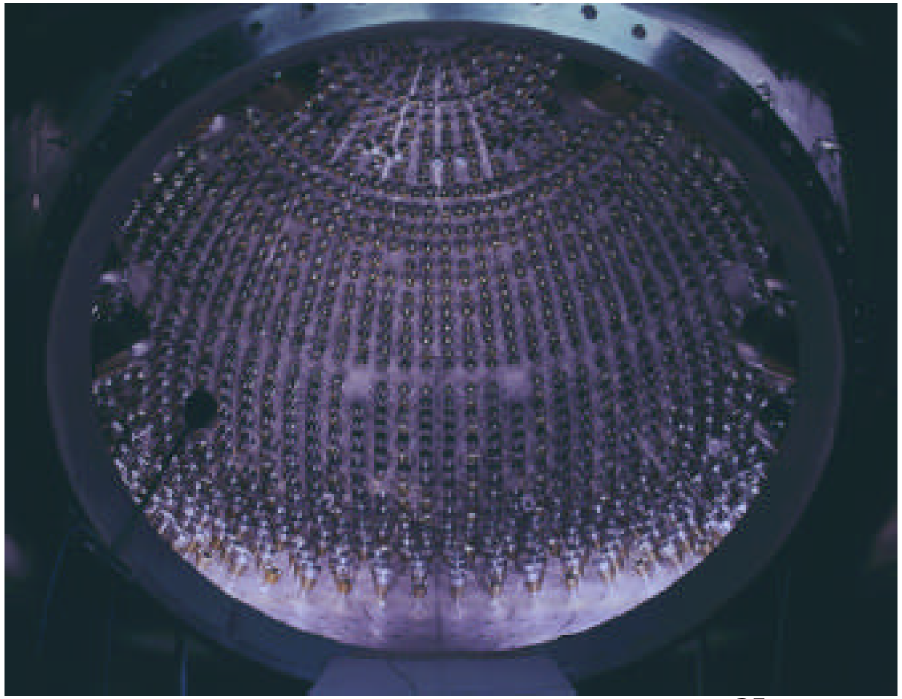


Expected background in 100 t fiducial volume in the ^{7}Be region = 0.4 counts/d.
Signal is 50 counts/day if SSM

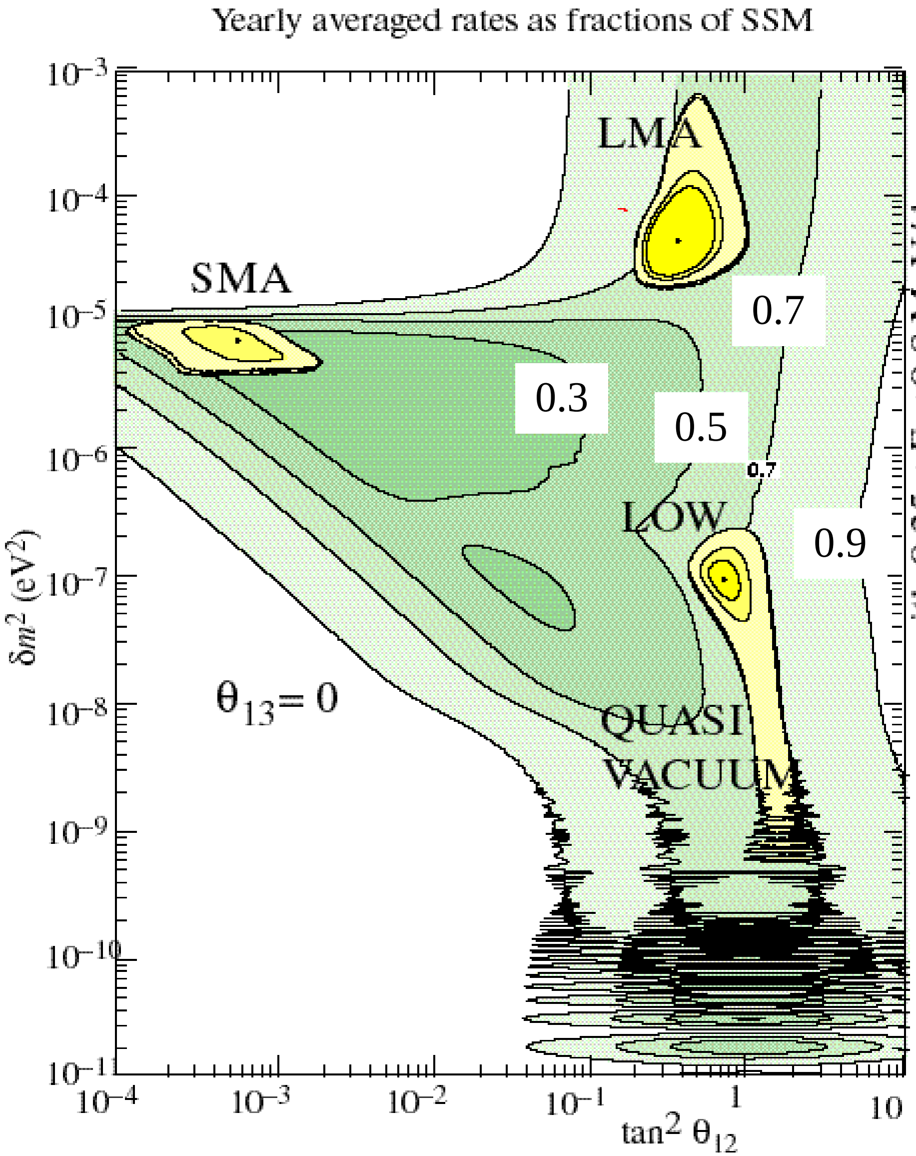
Schedule

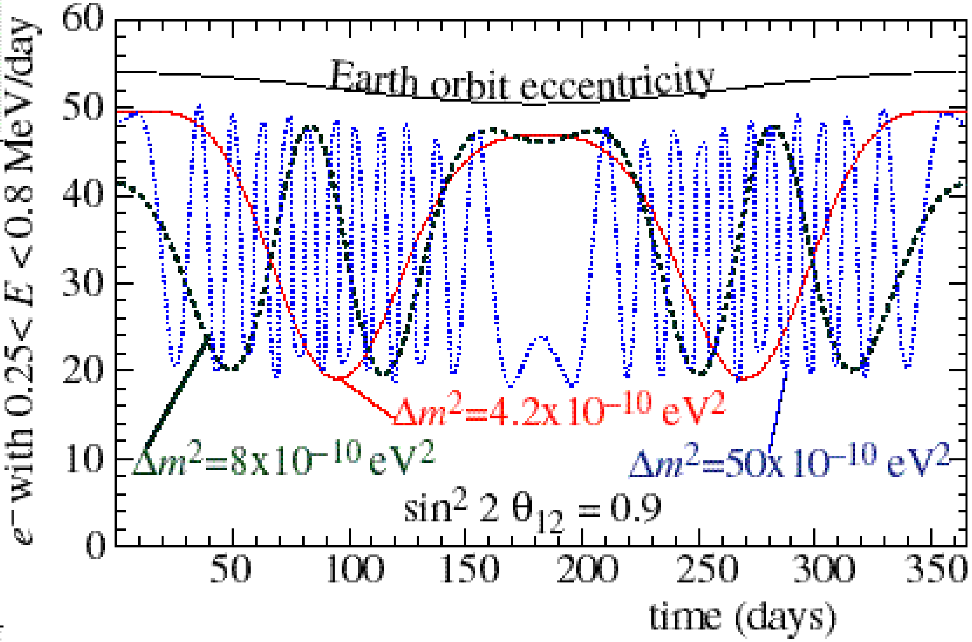
Start of filling	**Autumn 2002**
Start of data taking	**January 2003**

Delayed by wrong manouvres resulted in PC spill in the environment



BOREXINO and Solar solutions





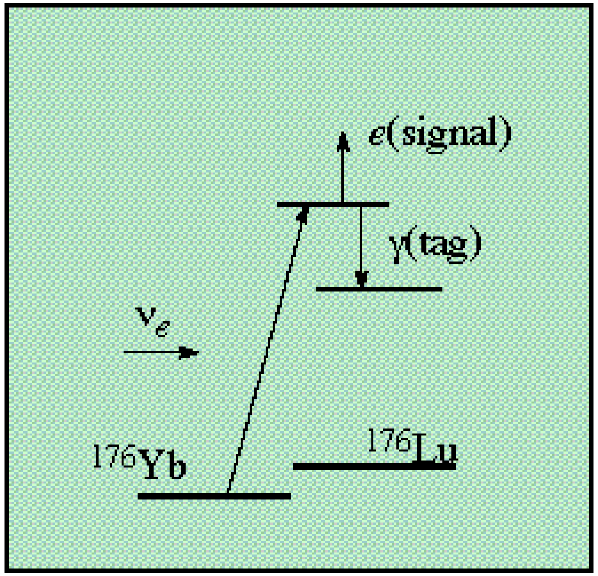
LENS proposal

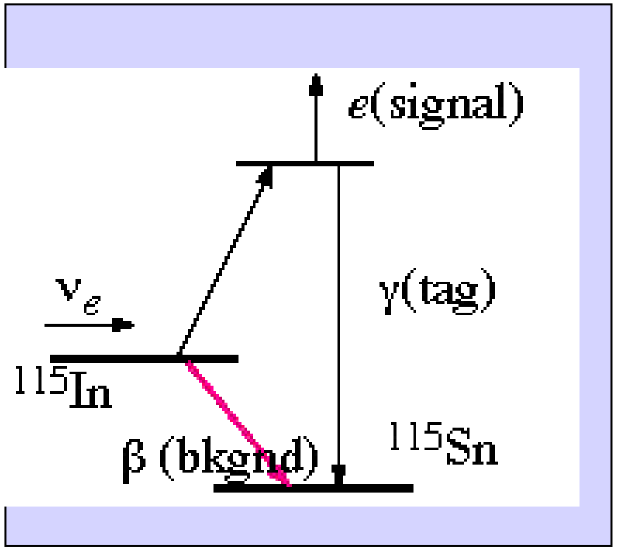
Prove oscillations with a single experiment
Detrmine solution with a single experiment
- sensitivity to the low energy (pp) neutrinos in real time
- flavour sensitivity
- source sensitivity (pp. ^{7}Be,^{8}B)

YbLS technique
Threshold E_ν = 301 keV
pp 200 ev/20 t * y
Be 280 ev/20 t * y

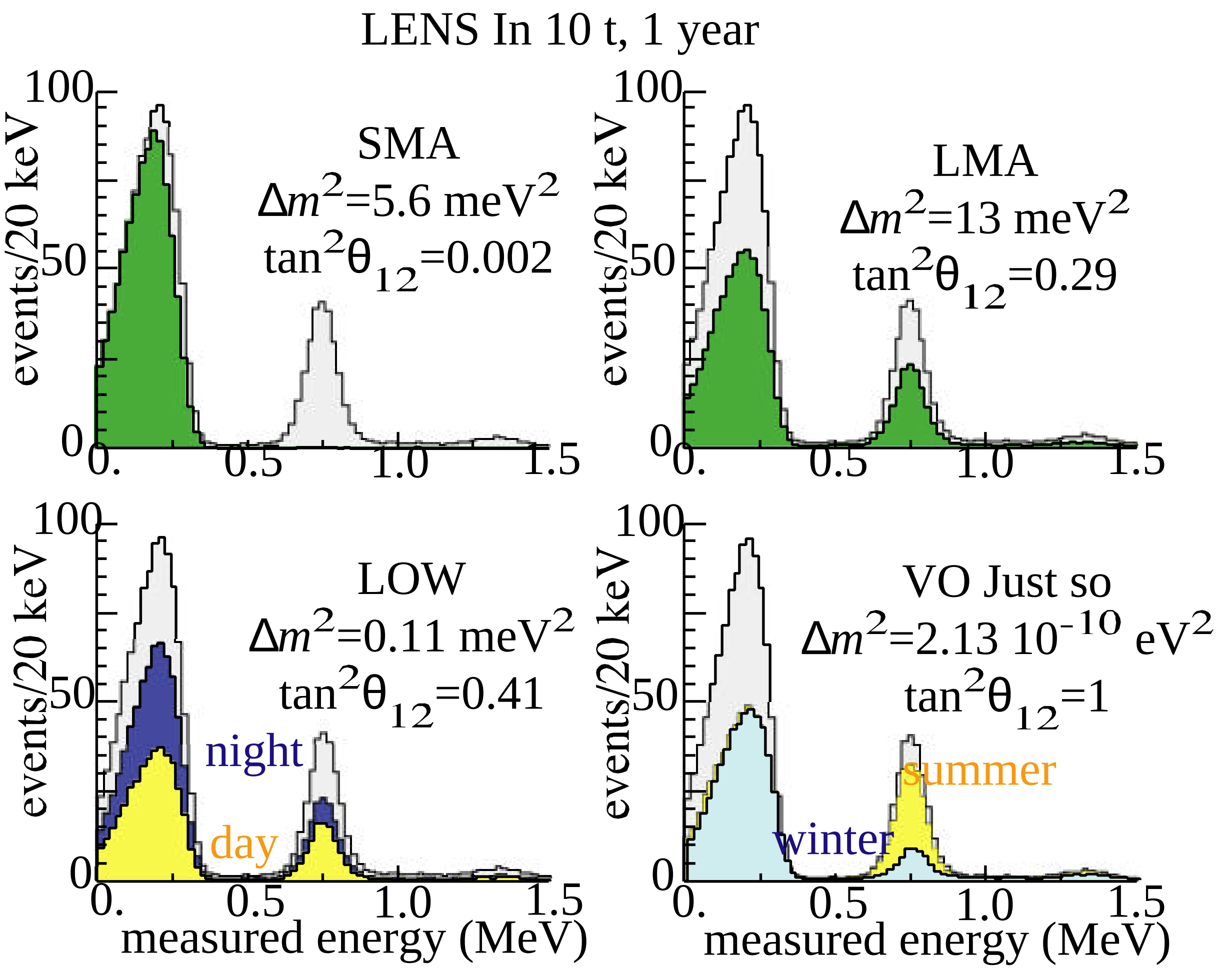
R&D is necessary on
- **liquid scintillator stability**
- **radiopurity**
- **calibration sources**

Return to In as a consequence of the YbLS techniques development





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
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2
Further optimisation (> 1.5) possible
Ready in spring 2006

Beam and experiments optimised for τ appearance

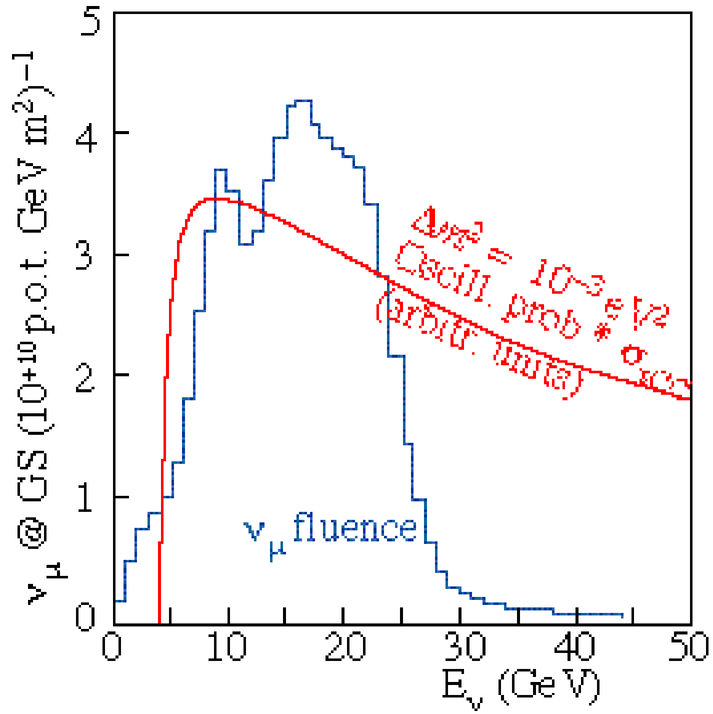
Complementary to K2K and NUMI+MINOS

Produce τ's via CC interactions

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

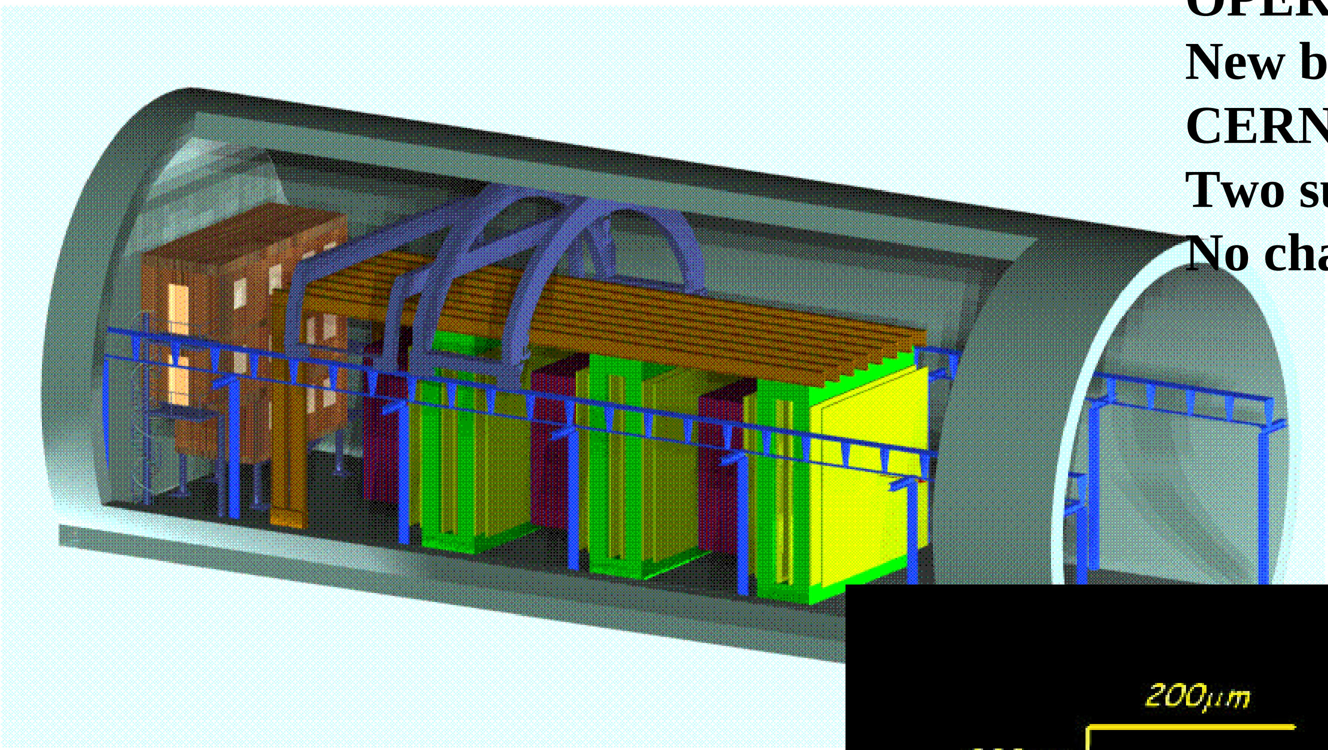
Detect τ^- through its charged decay products

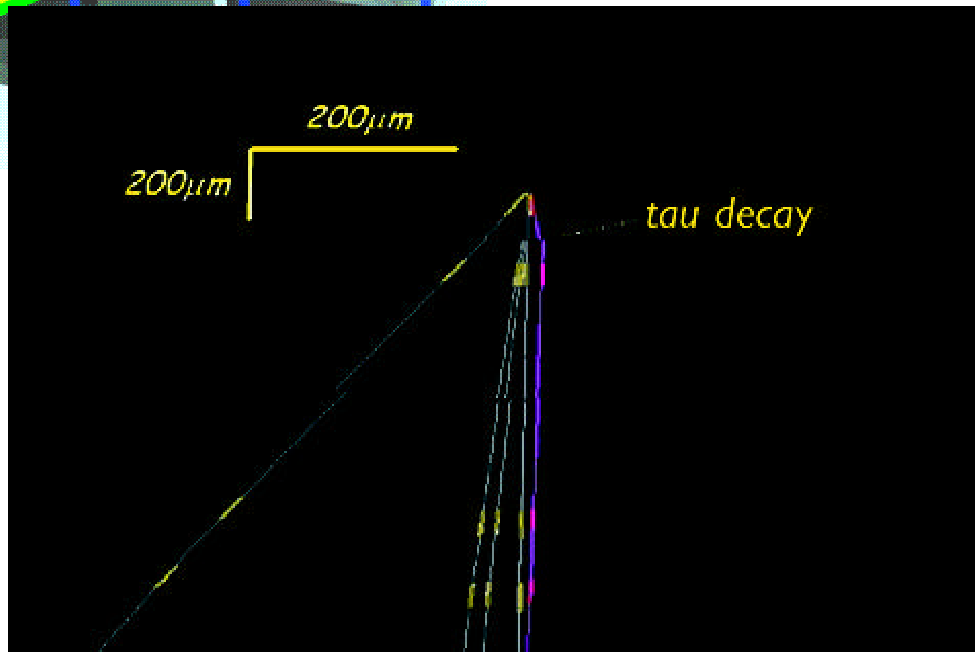
$\mu^- \nu_\tau \nu_\tau$	18%
$h^- \nu_\tau \, n\pi^0$	50%
$e^- \nu_\tau \nu_e$	18%
$\pi^+ \pi^- \pi^+ \, n\pi^0$	14%



OPERA

OPERA (2 000 t)
New baseline presented after CERN withdrawal
Two supermodules
No change in target mass



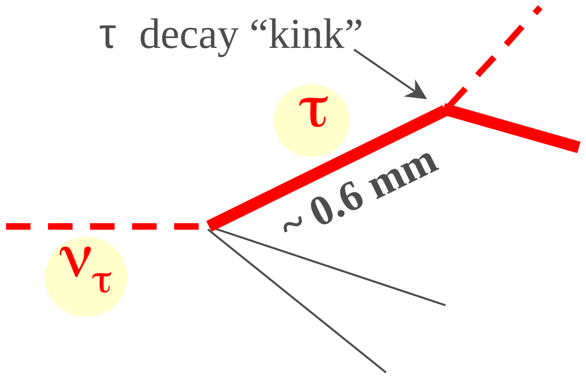


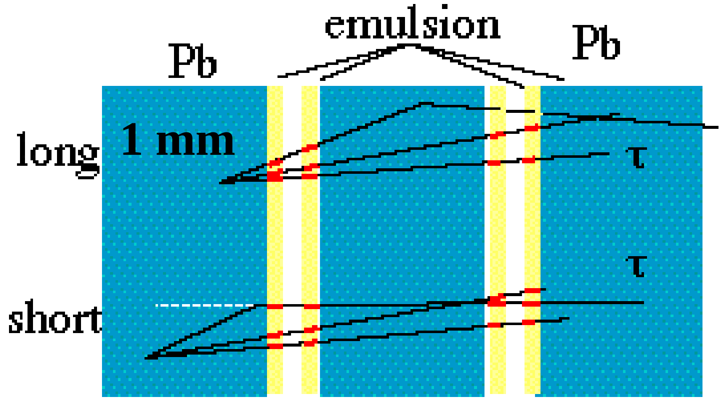
Identify τ (Heavy) Leptons by decay topology

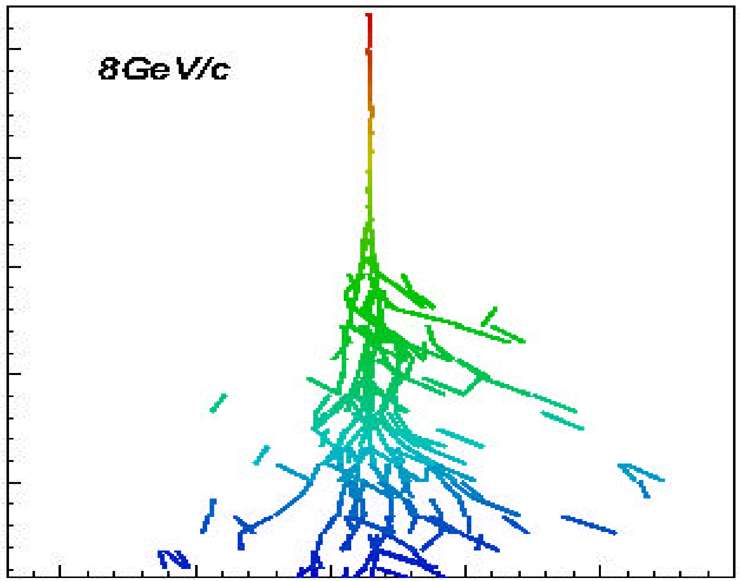
ν oscillation → massive target

ν decay topology → micron resolution

Lead – nuclear emulsion sandwich*"Emulsion Cloud Chamber" (ECC)*







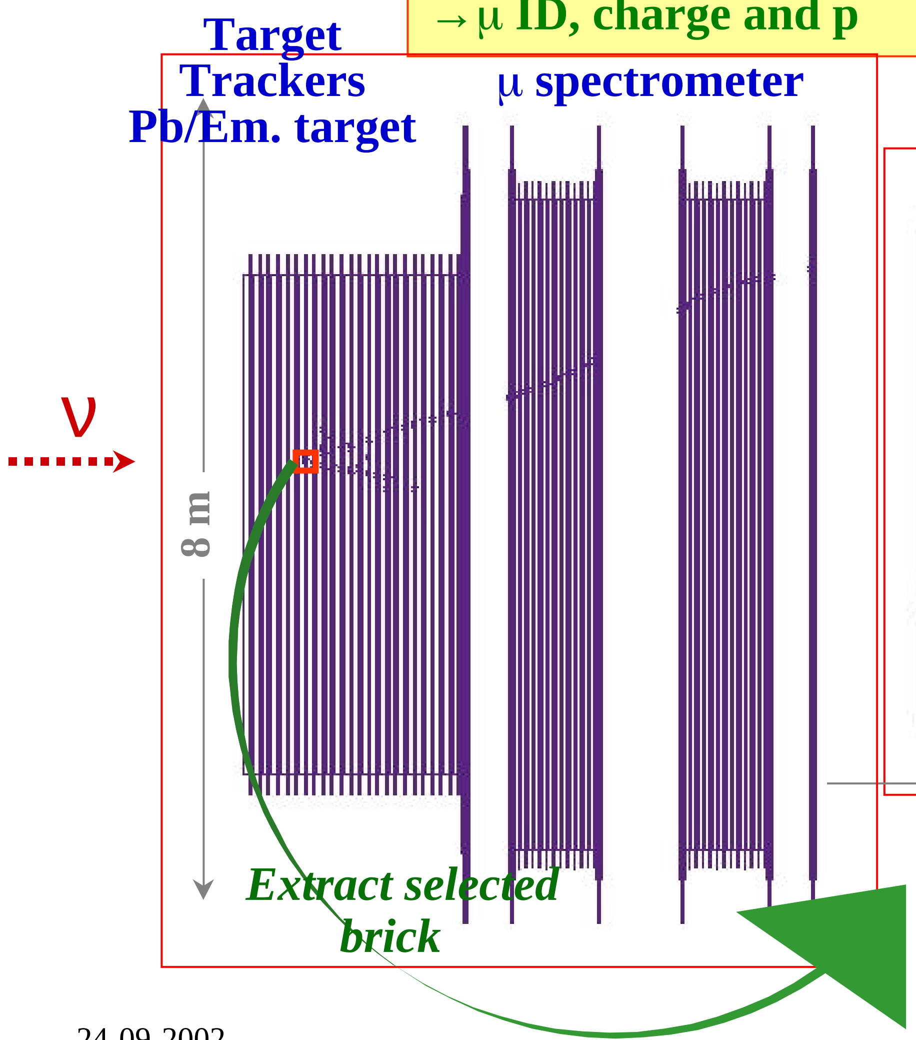
•electron detection for τ →e decays and search for ν_μ-ν_e appearance

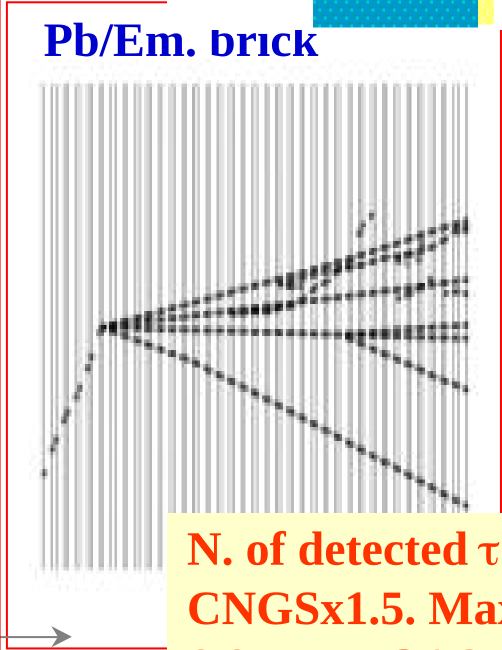
•momentum measurement by multiple scatterin

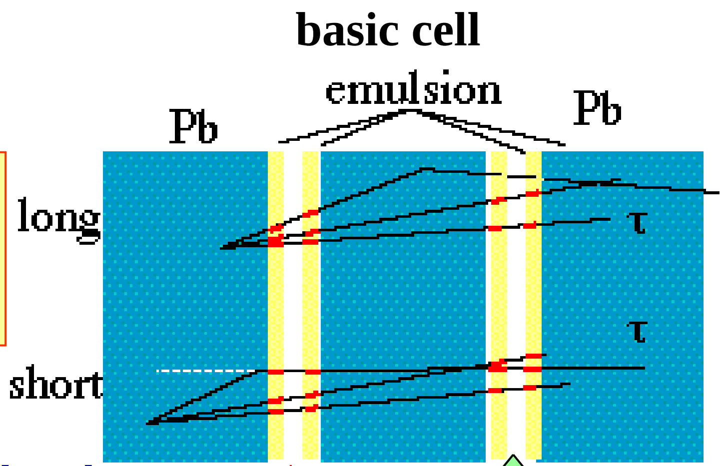
OPERA

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

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



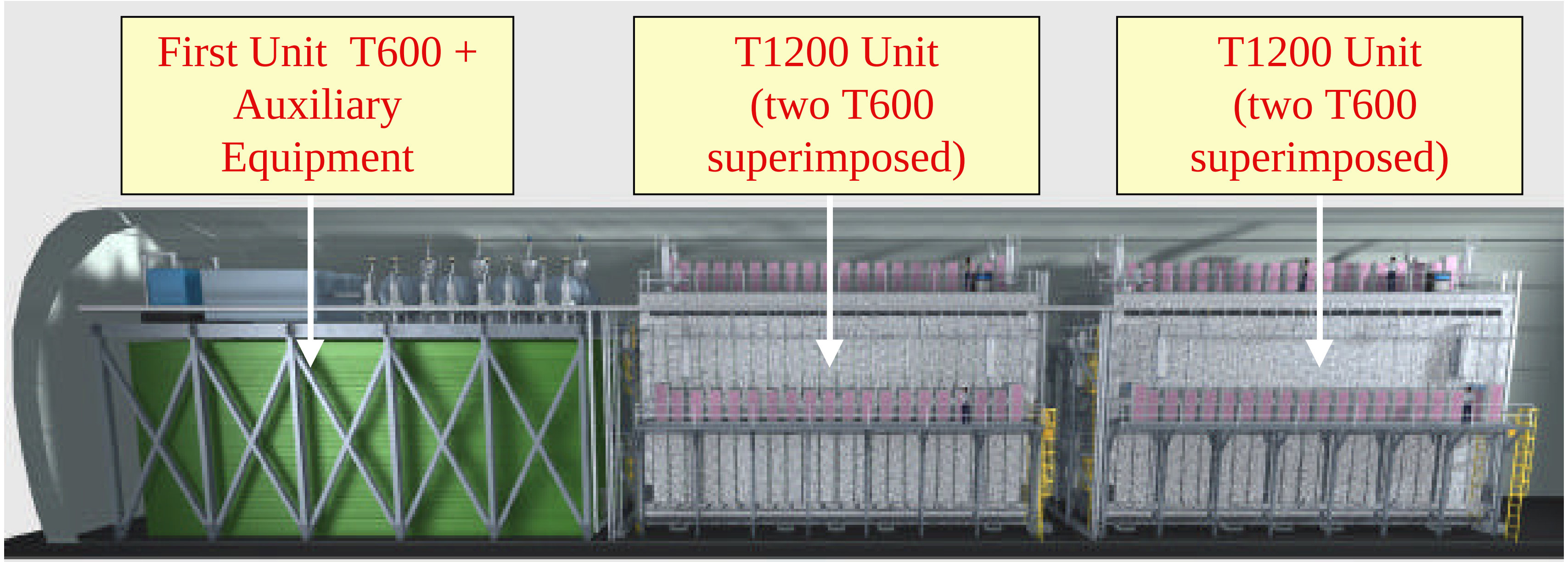




N. of detected τ's per 5 years run.
CNGSx1.5. Maximal mixing

6.6 ev.	**@1.3x10^{-3} eV^2**
15.8 ev.	**@2.5 x10^{-3} eV^2**
40.2 ev.	**@4x10^{-3} eV^2**
backgr	**0.6 ev.**

ICARUS T3000 proposal

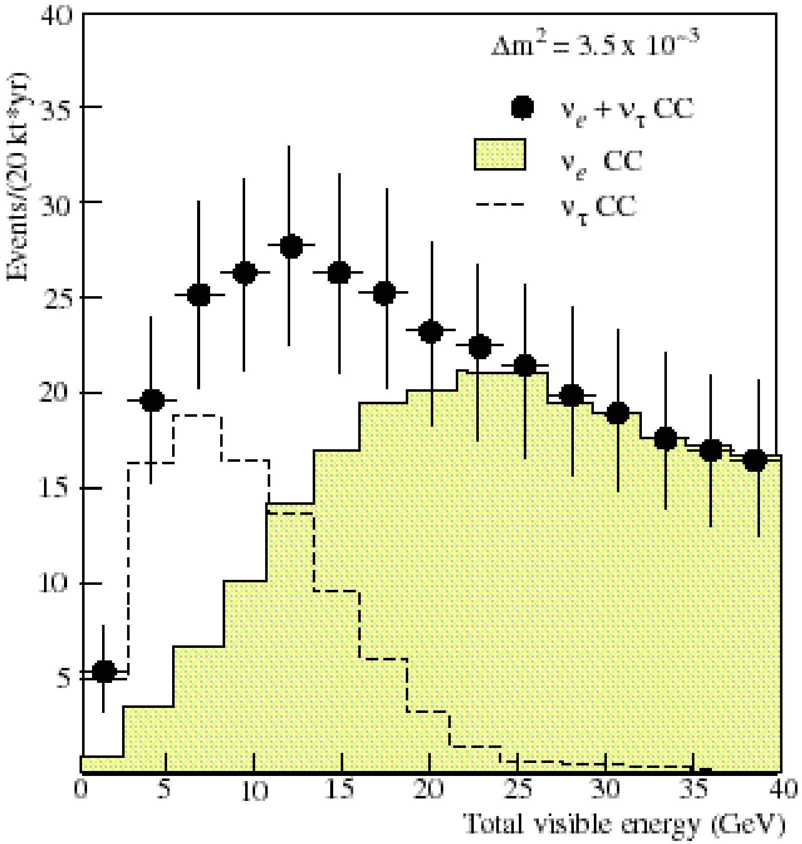


First half of T600 module succesfully operated in Pavia
Power dissipation problems being takled
Risk anlysis under way
Expect to install T600 early 2003
T3000 detector proposed as a series of five T600 modules
Proposed to be operational by summer 2005

- 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 visibile energy

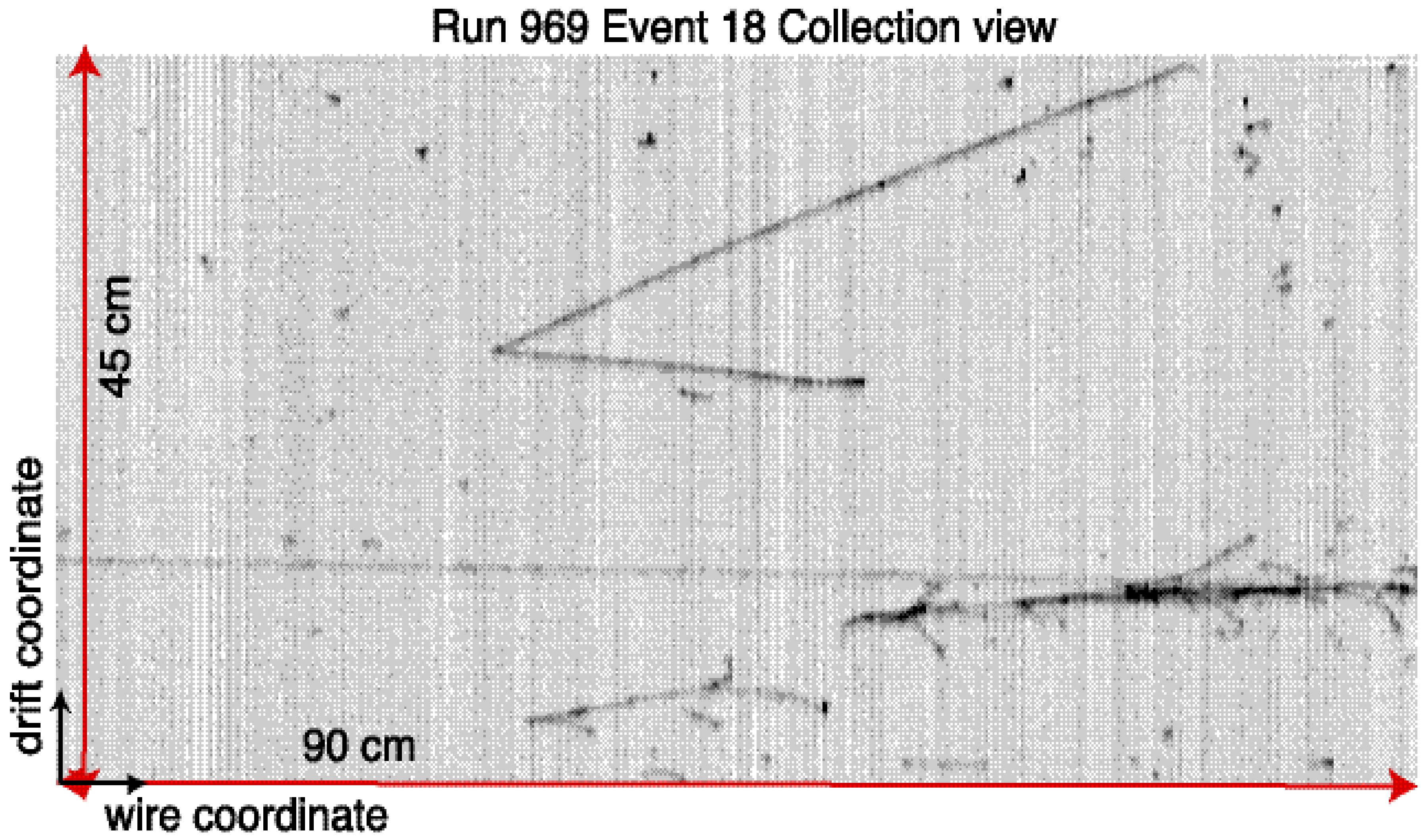


Discriminate signal from background using likelihood function based on kinematical variables
Strong reduction of background

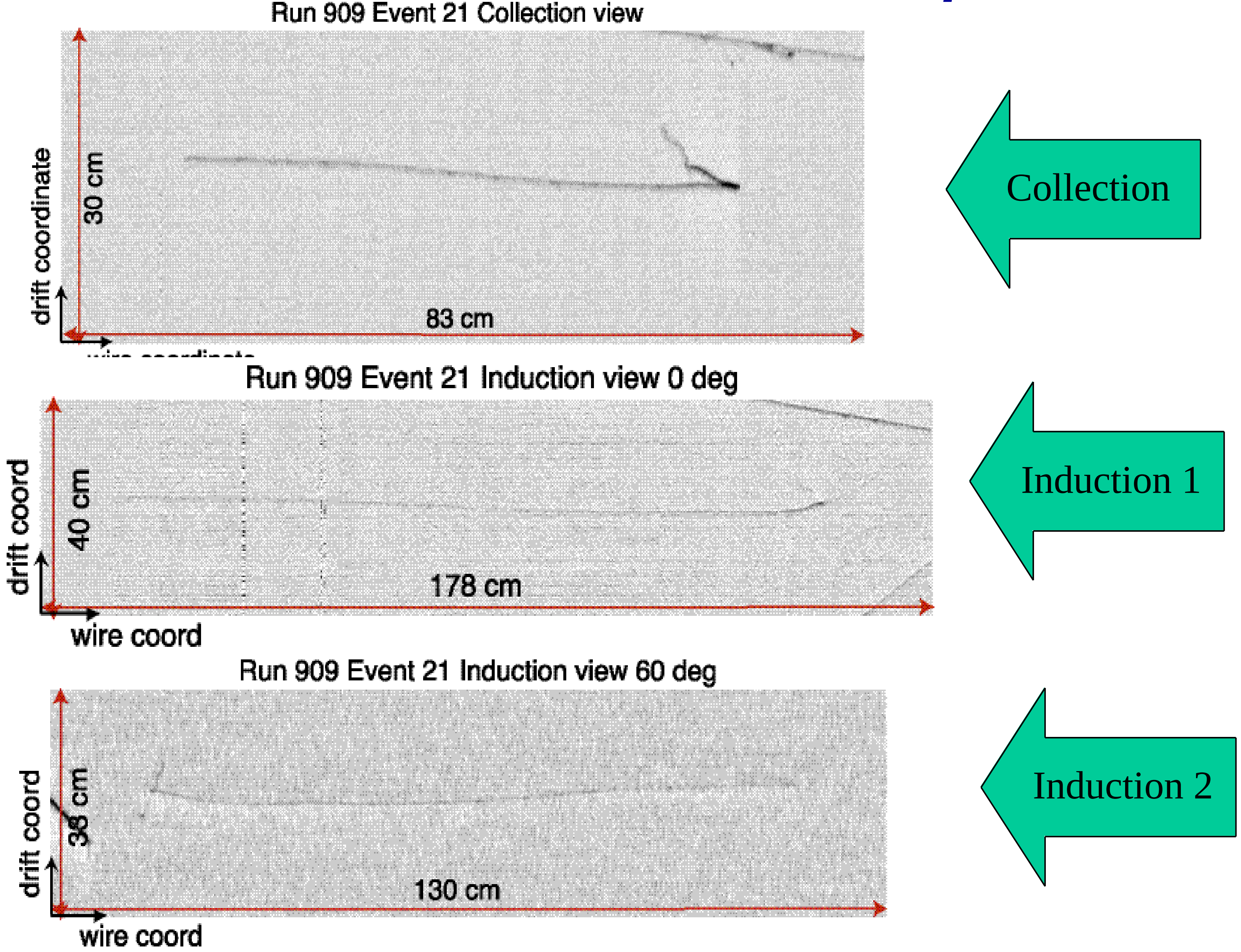
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2
Maximum mixing
Exposure = 15 kt*y
(5 x 600 t modules x 5 years)
After kinematic cuts
$\tau \Rightarrow$ e 9 events
$\tau \Rightarrow$ h 3 events
Backgr 0.7 events

If no signal of ν_e appearance with 20 kt*yr (8 years) exposure push CHOOZ limit on $|U_{e3}^2| \approx$
θ_{13}^2 ________________5

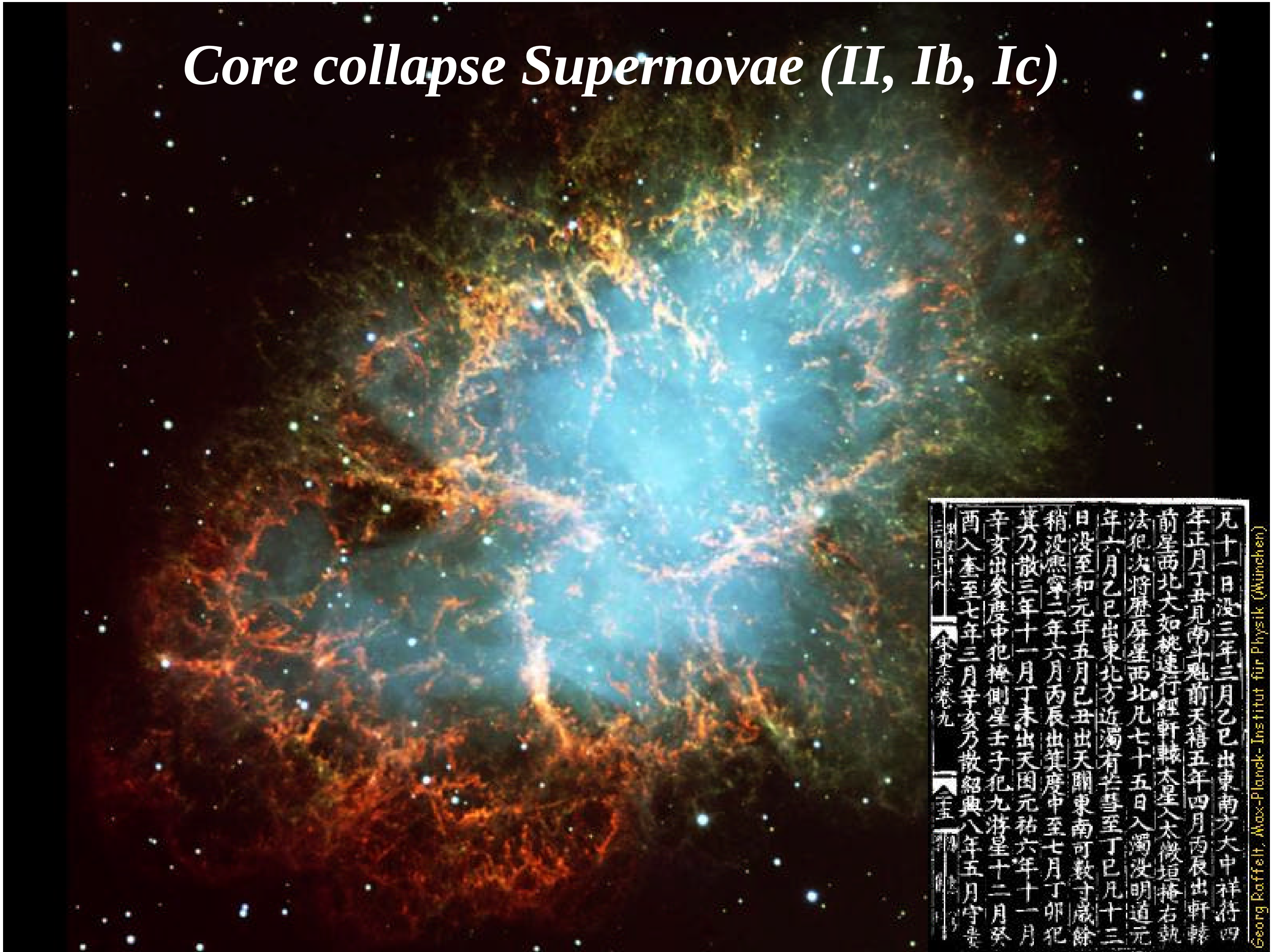
A V^0 candidate from T600



Three coordinate read-out of T600



Core collapse Supernovae (II, Ib, Ic)



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 Magellanian 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 worning of neutrino burst important for astronomical observations with different messangers (light curve, Gravitational Waves)
•**SNEWS = Supernova Early Worning 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 $\overline{\nu}_e$
Expected counts for a collapse in the centre of Galaxy (8.5 kpc)

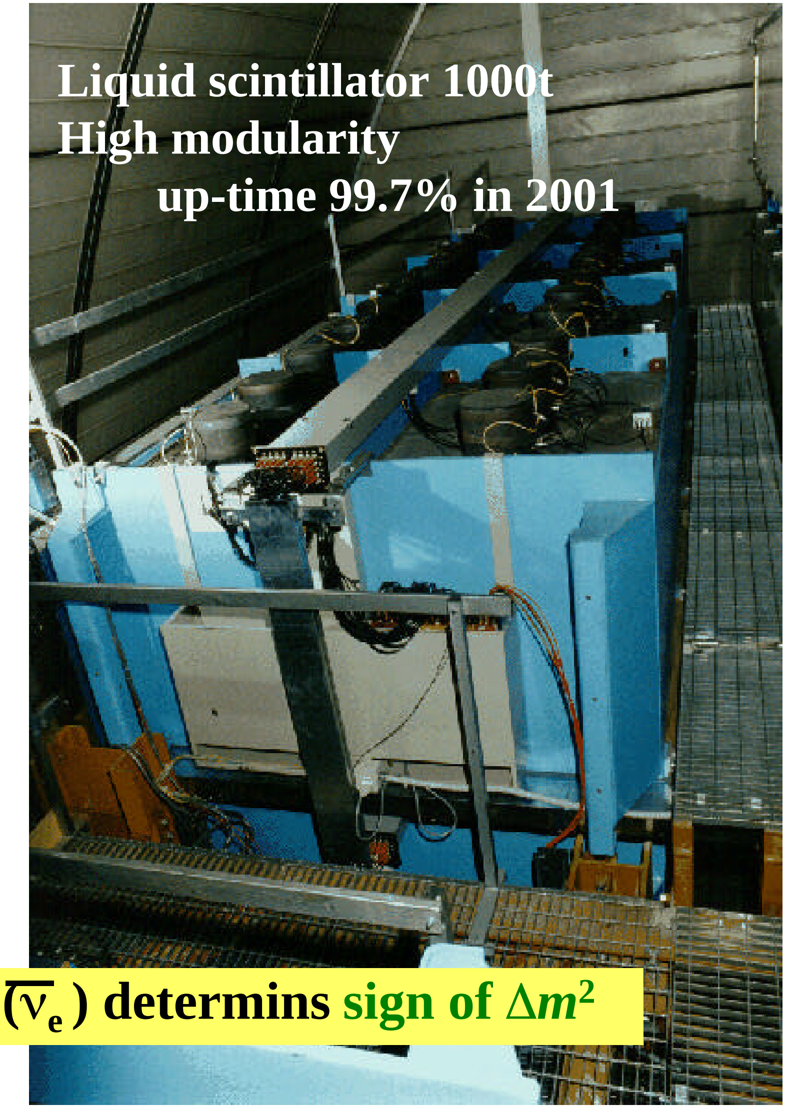
$\overline{\nu}_e + p \rightarrow n + e^+$ 300- 600 evts

Mesurement of electron neutrino and 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 $\overline{\nu}_e$ spectrum depending on **sign of Δm^2**

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

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

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



Indipendent on oscillations

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

Conclusions

- **New 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 mass*
    - *See-saw, p-decay probably close*
  - Fundamental overlap with cosmology and astrophysics
- **New underground experiments**
    - **Measure** the mass-eigenstate mixing in the lepton sector
    - **Measure** neutrino masses
    - **Look** for cold dark matter
- **Experimental ingenuity will give strong rewards**
- **More theoretical effort needed in different sectors**

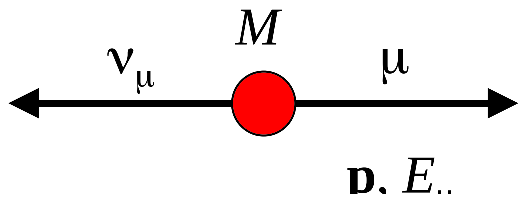
Pion decay spectrum

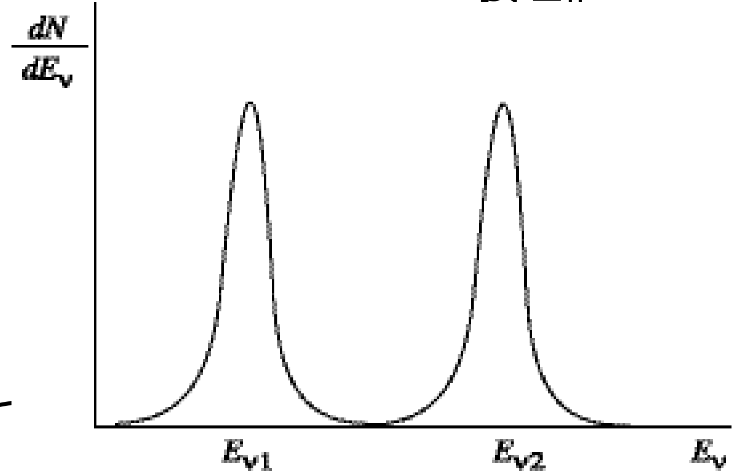
Suppose neutrinos were two, ν_1 and ν_2, with masses m_1 and m_2
Suppose ν_μ and ν_τ were maximum mixings of ν_1 and ν_2

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

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

Consider the decay of a meson of mass M into a μ and a ν_μ
To determine neutrino mass(ess), we measure neutrino energy E_ν





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

We can now tag a sample of ν_1 for example

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

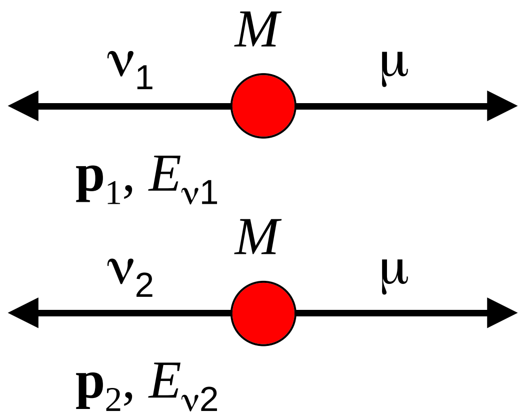
Neutrinos of this sample, hitting a nucleus will produce both μ's and τ's with equal probabilities

Absurd??

How much energy resolution?

$$E_{\nu 1} = \frac{M^2 + m_1^2}{2M} - \frac{m_\mu^2}{2M}$$

$$E_{\nu 2} = \frac{M^2 + m_2^2}{2M} - \frac{m_\mu^2}{2M}$$



We need enough energy resolution to measure

$$E_{\nu 2} - E_{\nu 1} = \frac{m_2^2 - m_1^2}{2M} = \frac{\Delta m^2}{2M}$$

In practice $E_{\nu 2} \approx E_{\nu 1} \approx M/2$

$$E_{\nu 2} - E_{\nu 1} = \frac{\Delta m^2}{4E_\nu}$$

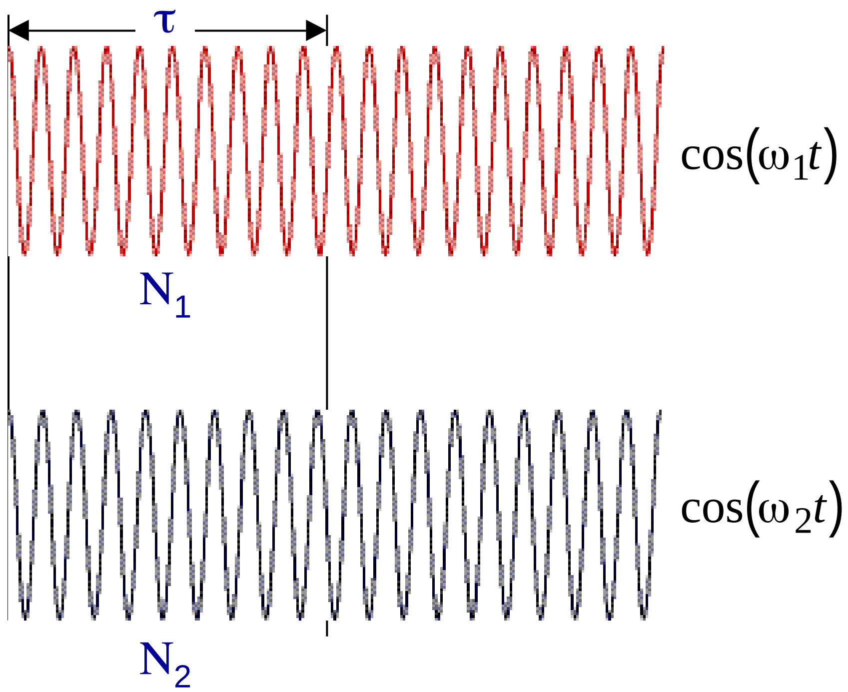
The two ν samples with energy $E_{\nu 1}$ and $E_{\nu 2}$ are monochromatic waves with periods $T_1 = 1/E_{\nu 1}$ and $T_2 = 1/E_{\nu 2}$

Measuring the energies means measuring the two frequencies (4×10^{23} Hz for E = 10 GeV).

Gedanke Experiment: Count the crests in a time interval τ

Accurate energy measurement requires time

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

To resolve the doublet we need a measurement time

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

τ = 20 ms for $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and E = 10 GeV; N_1 and $N_2 \approx 10^{22}$

Need energy resolution of one part in 10^{22}!!

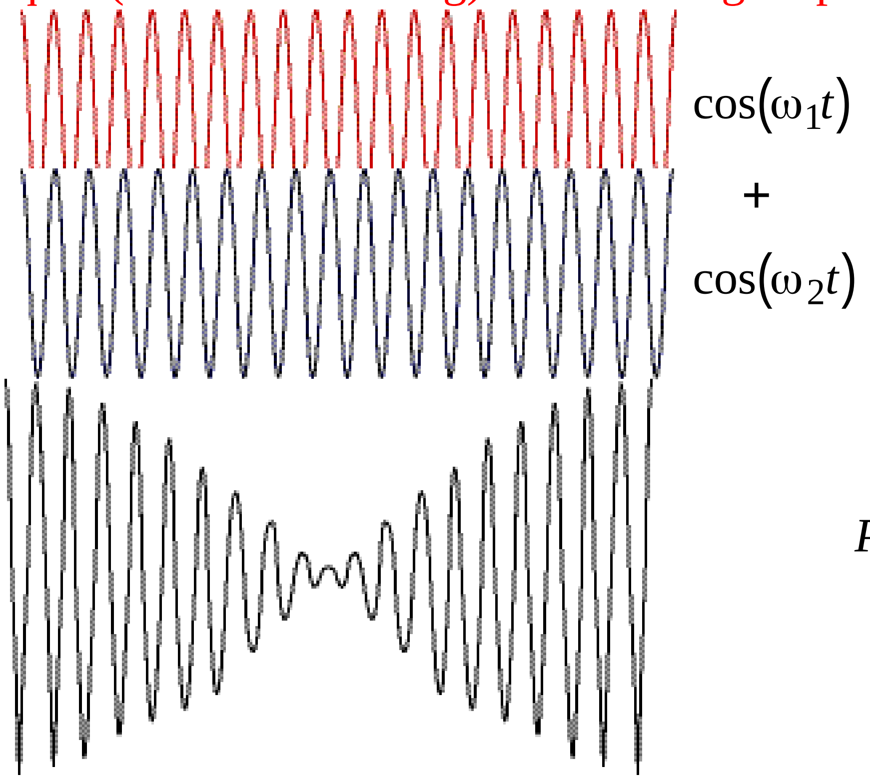
Counting the crests of the wave function

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> $N_2 - N_1$: beat the two waves!

This happens naturally: a pure monoenergetic ν_α beam is a dicromatic wave = a coherent superposition of two monocromatic waves of (angular) frequencies ω_1 and ω_2.

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 theirr 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

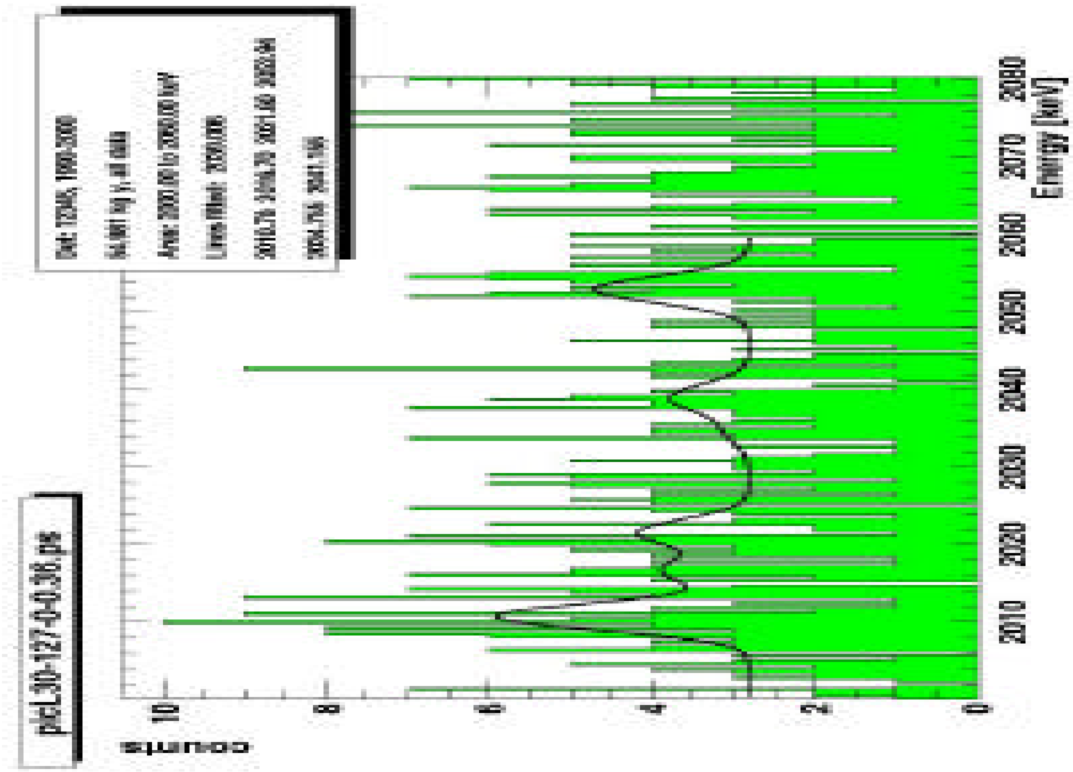
$$P_{\nu\alpha \to \nu\beta} = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 (\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

Evidence for neutrino mass?

Hans Klapor-Kleingrothaus and collaborators have reanalysed with a Bayesian technique the the data of the Heidelberg Moscow experiment at LNGS. A positive evidence is claimed, with

$$M^{M}_{ee} = 390 \pm 110 \text{ eV}$$

Simultaneous fit of the double beta decay spectrum between 2000 and 2060 keV with the four ^{214}Bi lines and signal at 2039 keV



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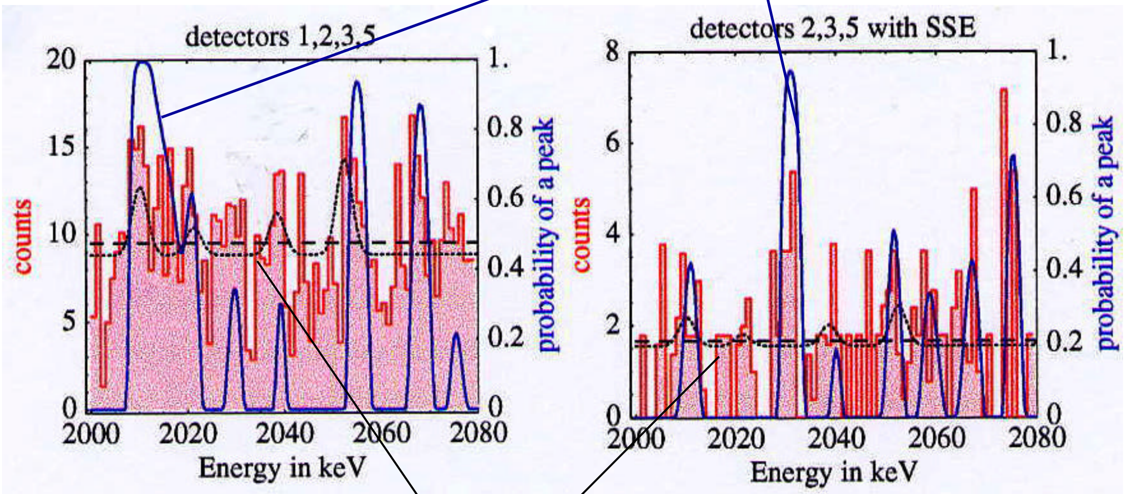
The claim is controversial

Feruglio, Strumia, Vissani discussion

likelihood to have a peak



fit constant background + ^{214}Bi γ lines + 0ν2β at 2039 keV

statistical significance not compelling, two peaks are not explained