Neutrino Oscillations (or Physics beyond the Standard Model of elementary particles)

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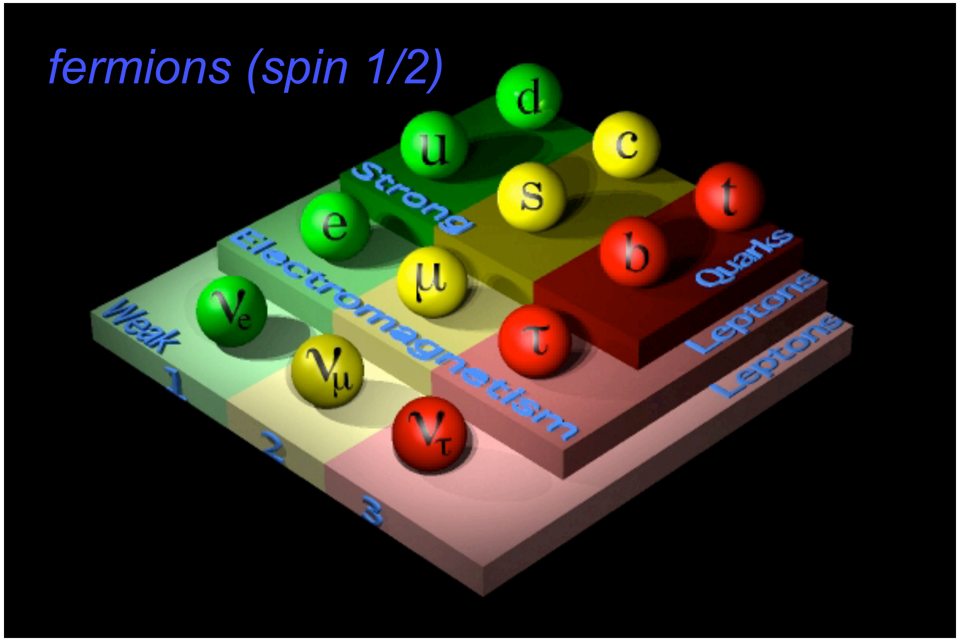
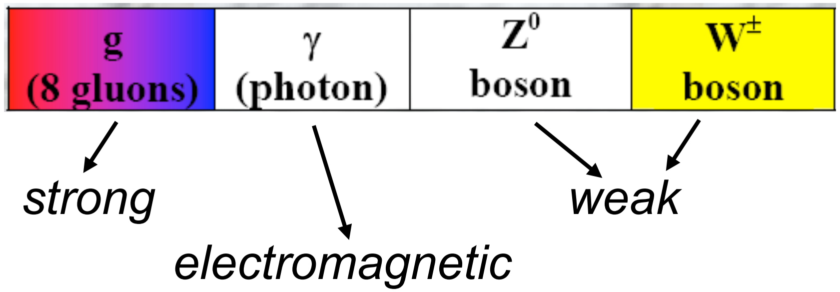
ν

But, what a neutrino is?



+bosons currying the interactions (spin integer)



g (8 gluons)	γ (photon)	Z^0 boson	$W^\pm$ boson

strong

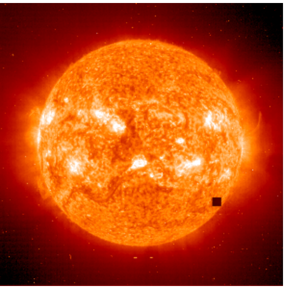
electromagnetic

weak

- elementary particles,
- neutral (electrical charge=0)
- interacting only through weak interaction,
- they have massive and charged partners,
- massless up to recently (this is what was assumed by the Standard Model of elementary particles)?

+ the fermions anti-particles…

Where can we find neutrinos?



- Solar Neutrinos : $2\ 10^{38}\ \nu/s \rightarrow 40$ billions $\nu/s/cm^2$ on the earth $\rightarrow$ 400000 billions ν/s/human (<20 MeV).
- Universe :
  - Big-Bang: 330 ν/cm^3 (0.0004 eV $\rightarrow$ 2000 km/s if $m_\nu = 10\ eV/c^2$).
  - Stars : 0.000006 ν/cm^3.
  - Supernovae : 0.0002 ν/cm^3.
- Earth radioactivity : 50 billions ν/s human.
- Nuclear Plants:10-100 billions ν/s/human (1-10 MeV).
- Human body: 340 millions ν/day (20 mg of ^{40}K, β decay).

Neutrino Oscillations

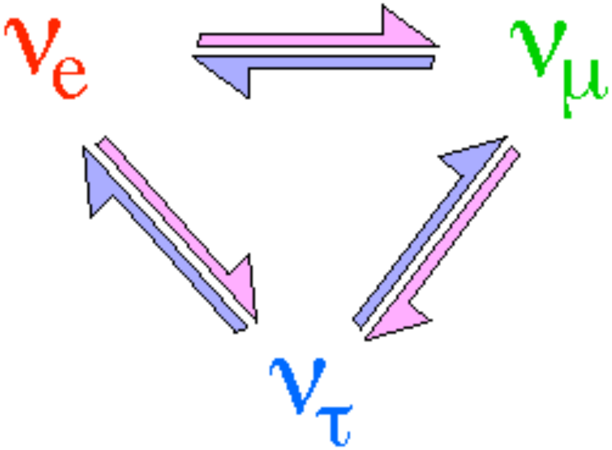
- The Standard Model doesn’t predict any mass for the neutrinos.
- According to Quantum Mechanics, if neutrinos have a non-zero mass they can "oscillate" (change family during traveling).
- Why? Because their mass eigen states could not coincide with their flavour eigen states (or interaction eigen states).

States participating to the weak interaction (flavour eigen states)

$\nu_e \quad \nu_\mu \quad \nu_\tau$

States with masses well defined (mass eigen states)

$\nu_1 \quad \nu_2 \quad \nu_3$



Lepton Mixing and Quantum Mechanics

- The "known" neutrinos are combinations of mass eigen state neutrinos, for example, for electron neutrinos:

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

- For all neutrinos, we can write:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{unitary mixing matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maki-Nakagawa-Sakata matrix

➡

- *change of basis,*
- *U is the transformation operator (matrix, unitarity),*
- *the hypothetical states ν_1, ν_2, ν_3 have unique masses and are neutrino fundamental eigen states.*

Rotations between states

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

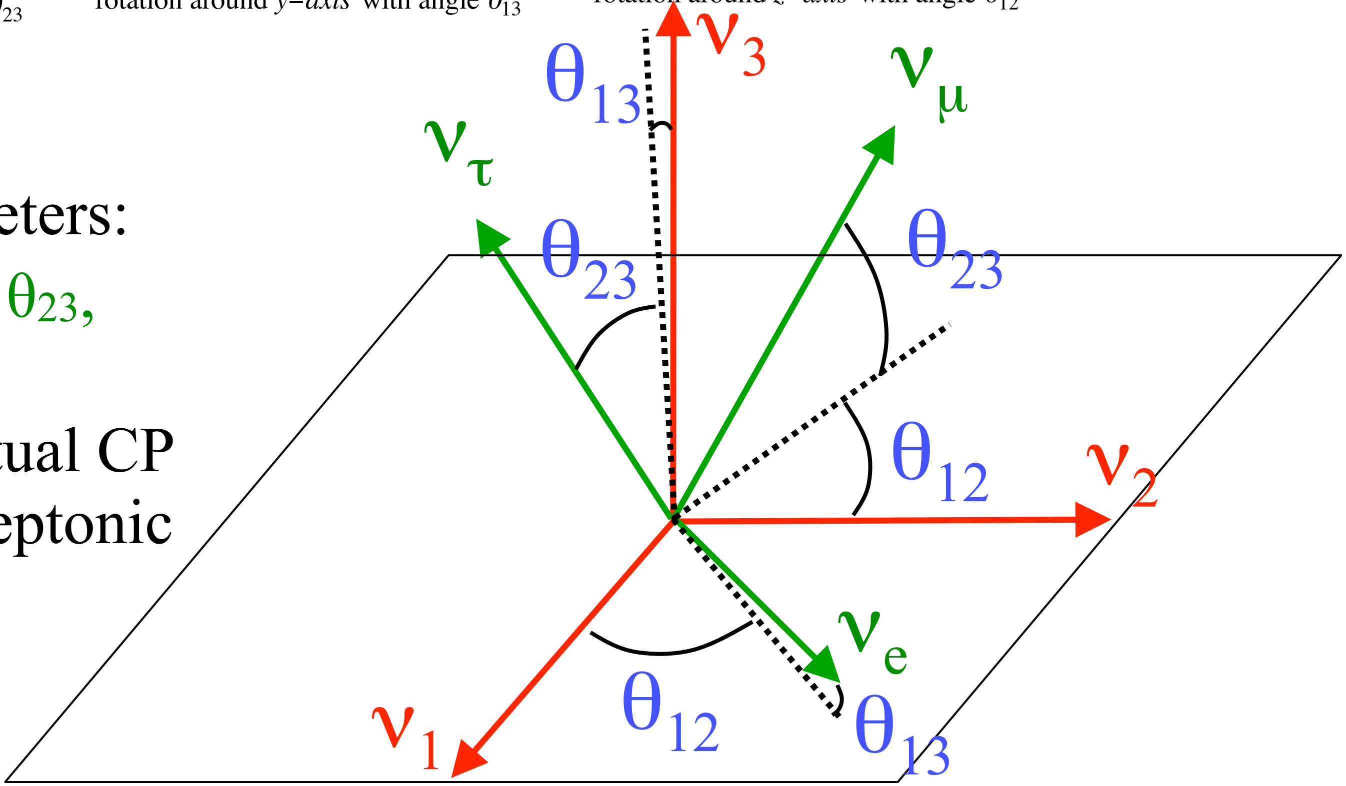
with $c_{ij} = \cos\theta_{ij}$ *and* $s_{ij} = \sin\theta_{ij}$

The most popular representation

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{rotation around } x-axis \text{ with angle } \theta_{23}} \cdot \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{rotation around } y-axis \text{ with angle } \theta_{13}} \cdot \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{rotation around } z-axis \text{ with angle } \theta_{12}}$$

Only 4 free parameters:

- 3 mixing angles: θ_{23}, θ_{12}, θ_{13}
- 1 phase for eventual CP violation in the leptonic sector: δ_{CP}



Transition Probability

$$\left|\nu_j(t)\right\rangle = e^{-iHt/\hbar}\left|\nu_j(0)\right\rangle$$

$$\Rightarrow \quad P_{\nu_\alpha \to \nu_\beta} = \left|\delta_{\alpha\beta} + \sum_{k=2}^{3} U_{\beta k} U^*_{\alpha k}\left[e^{-i\frac{\Delta m^2_{k1} L}{2E}} - 1\right]\right|^2$$

with: $\Delta m^2_{kj} \equiv m^2_k - m^2_j$

(the time has been replaced by the distance)

$\Rightarrow$ the transition probabilities do not depend on the particle masses but on the squared mass differences

Finally, the transition probabilities depend on the mixing matrix elements, the 2 squared mass differences and on the parameter *L/E*.

No transitions if:

$m_\nu = 0$ or

$\Delta m = 0$ or

$\Delta m^2_{k1} L / E \ll 1$

oscillation parameters:

Δm_{13}, Δm_{23}, Δm_{12} (only 2 are free)

θ_{13}, θ_{12}, θ_{23}

Approximations according present measurements

$$\Delta m^2_{32} = 2.45 \pm 0.09 \times 10^{-3}\ \text{eV}^2$$

$$\Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \times 10^{-5}\ \text{eV}^2$$

$$\sin^2\theta_{23} = 0.51 \pm 0.06\ \ (\sim 45°)$$

$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}\ \ (\sim 34°)$$

$$\sin^2\theta_{13} \leq 0.046\ \ (<12.4°)$$

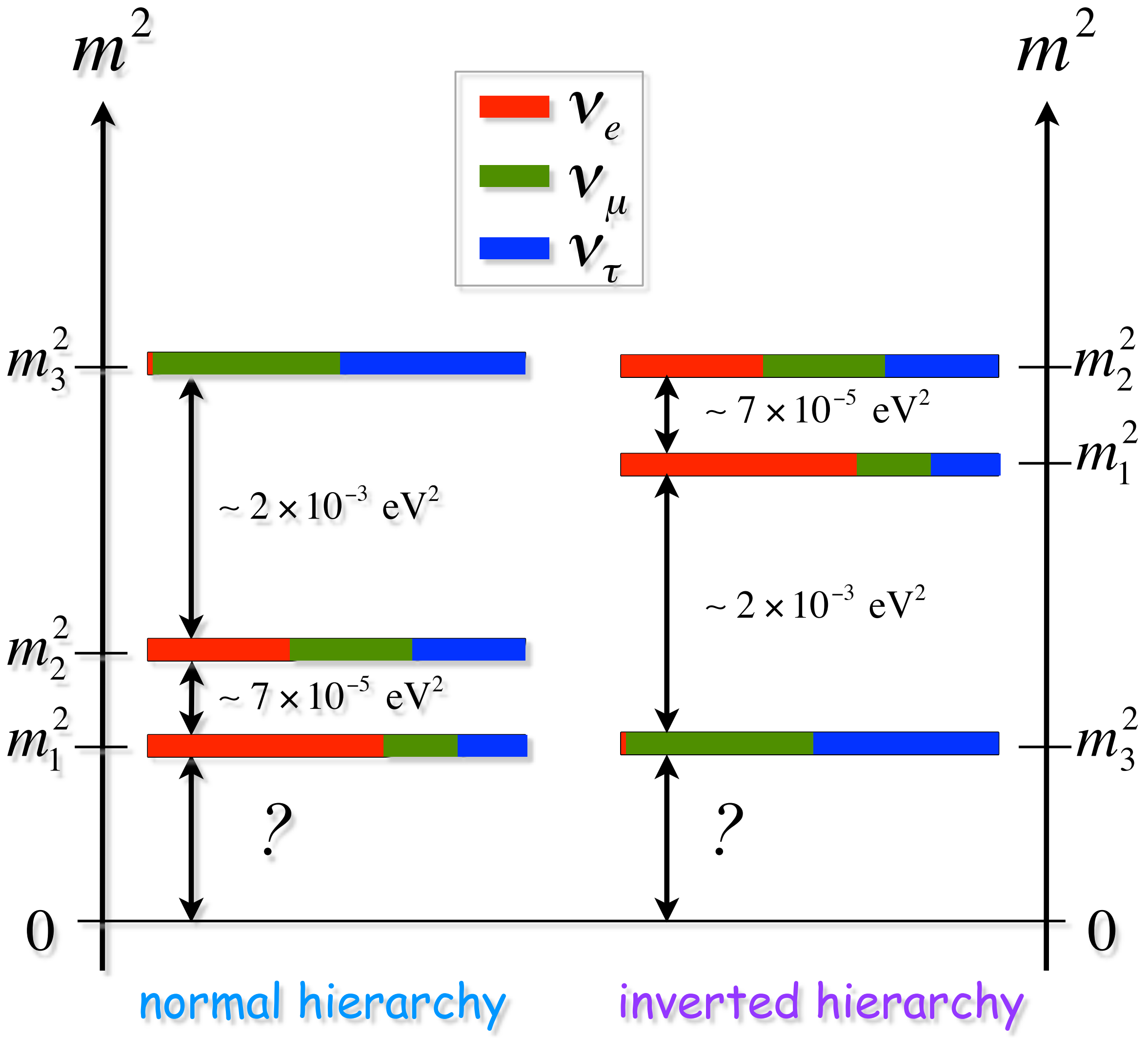
up to recently

We can then write:

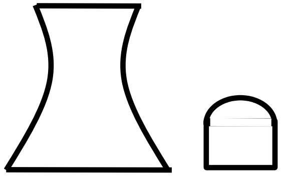
$$\Delta m_{13} \approx \Delta m_{23} \equiv \Delta m$$

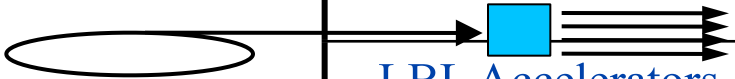
$$\Delta m_{12} \equiv \delta m$$

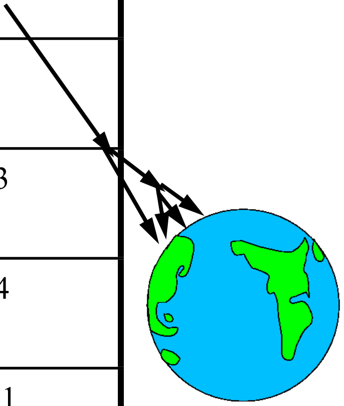
$$\Delta m \gg \delta m$$



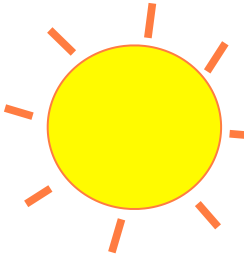
L/E classification of the experiments

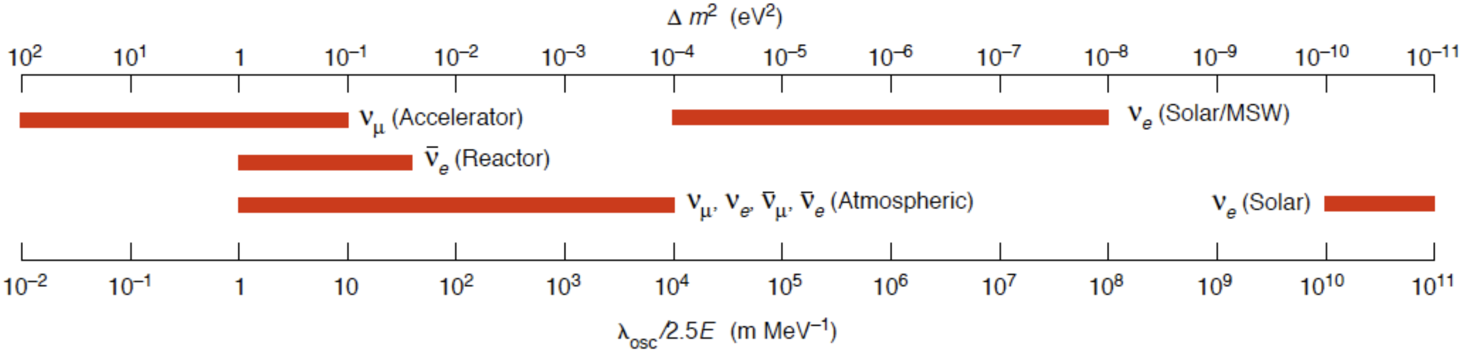






Experiment	L(m)	E (MeV)	L/E	Δm^2 (eV^2) (sensitivity)
SBL Reactors	10^2	1	10^2	10^{-2}
LBL Reactors	10^3	1	10^3	10^{-3}
SBL Accelerators	10^3	10^3	1	1
LBL Accelerators	10^6	10^3	10^3	10^{-3}
Atmospheric	10^7	10^3	10^4	10^{-4}
Solar	10^{11}	1	10^{11}	10^{-11}

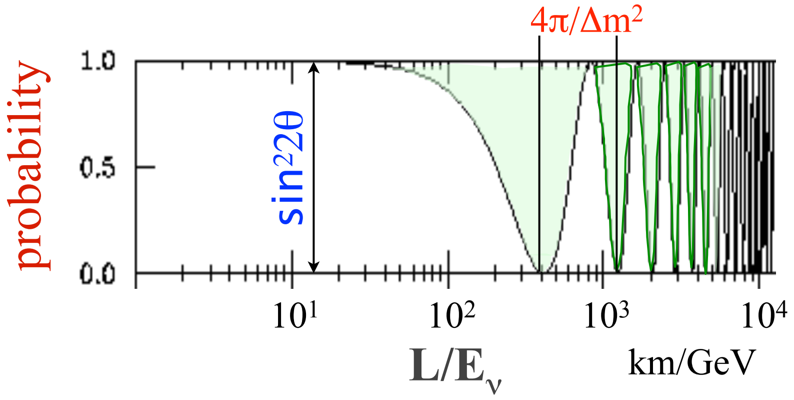




Appearance/disappearance experiments

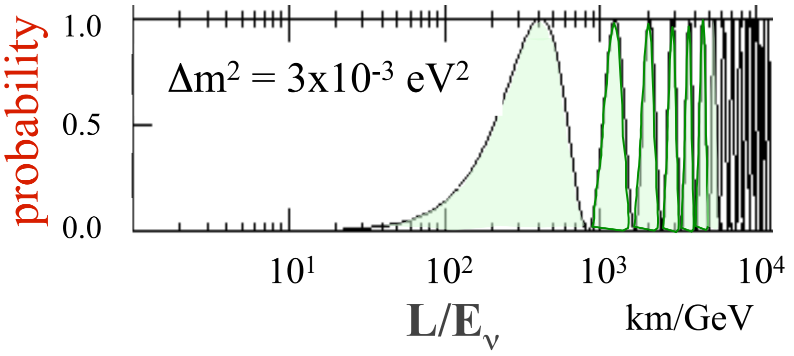
In disappearance experiments we count how many initial neutrinos ν_α survive after traveling over a distance *L (case of 2 flavours)*:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \ \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



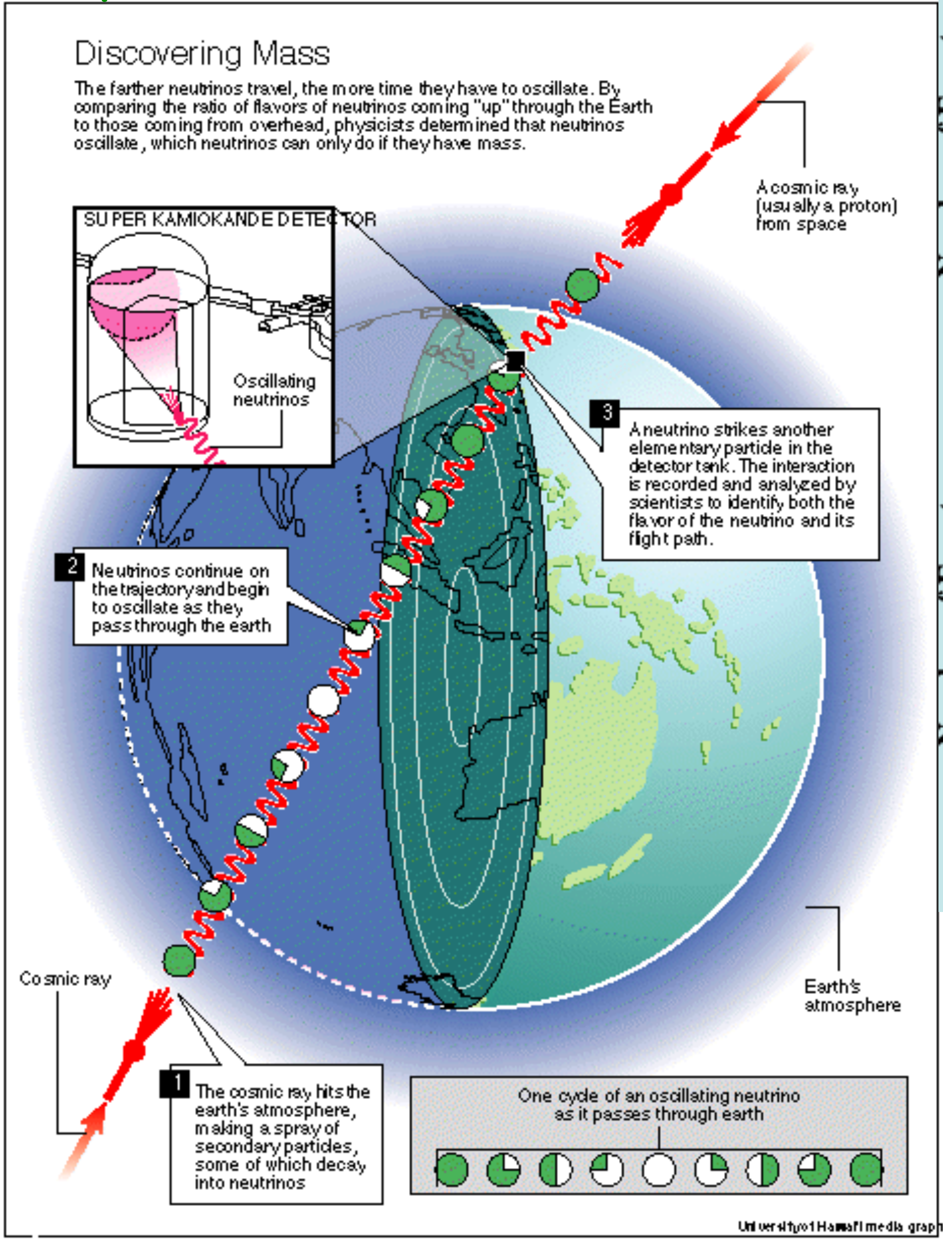
In appearance experiments we look for neutrinos ν_β in a ν_α neutrino beam:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \ \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



Atmospheric Neutrinos and oscillation confirmation

SuperK(first results in 1998)



Discovering Mass

The farther neutrinos travel, the more time they have to oscillate. By comparing the ratio of flavors of neutrinos coming "up" through the Earth to those coming from overhead, physicists determined that neutrinos oscillate, which neutrinos can only do if they have mass.

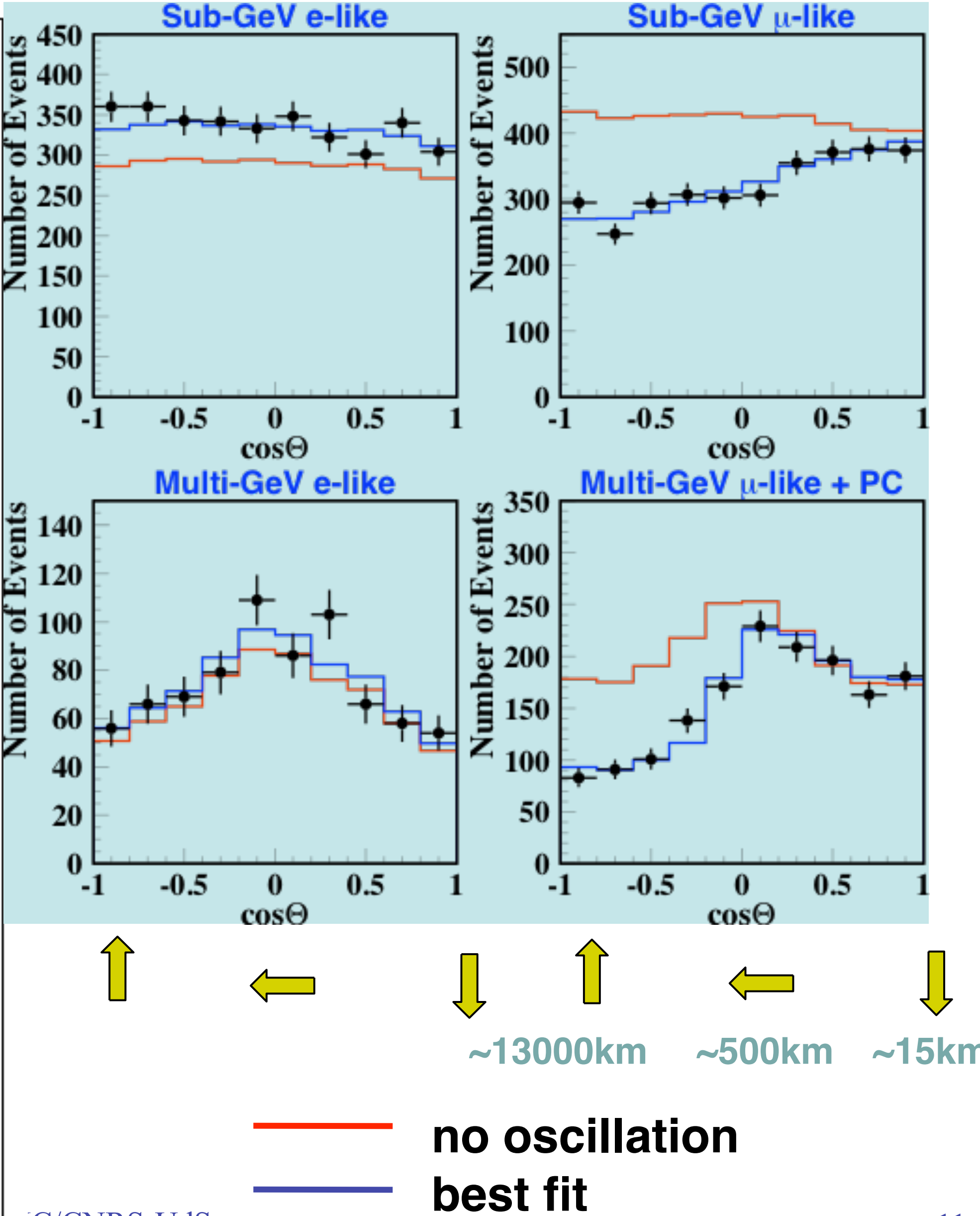
A cosmic ray (usually a proton) from space

1 The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos

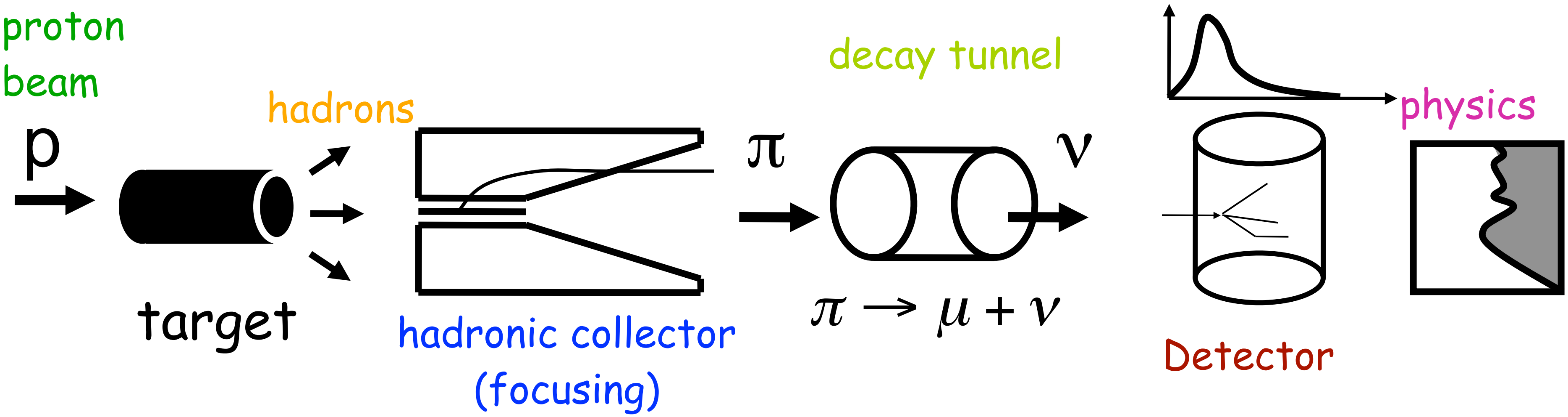
2 Neutrinos continue on the trajectory and begin to oscillate as they pass through the earth

3 A neutrino strikes another elementary particle in the detector tank. The interaction is recorded and analyzed by scientists to identify both the flavor of the neutrino and its flight path.

One cycle of an oscillating neutrino as it passes through earth



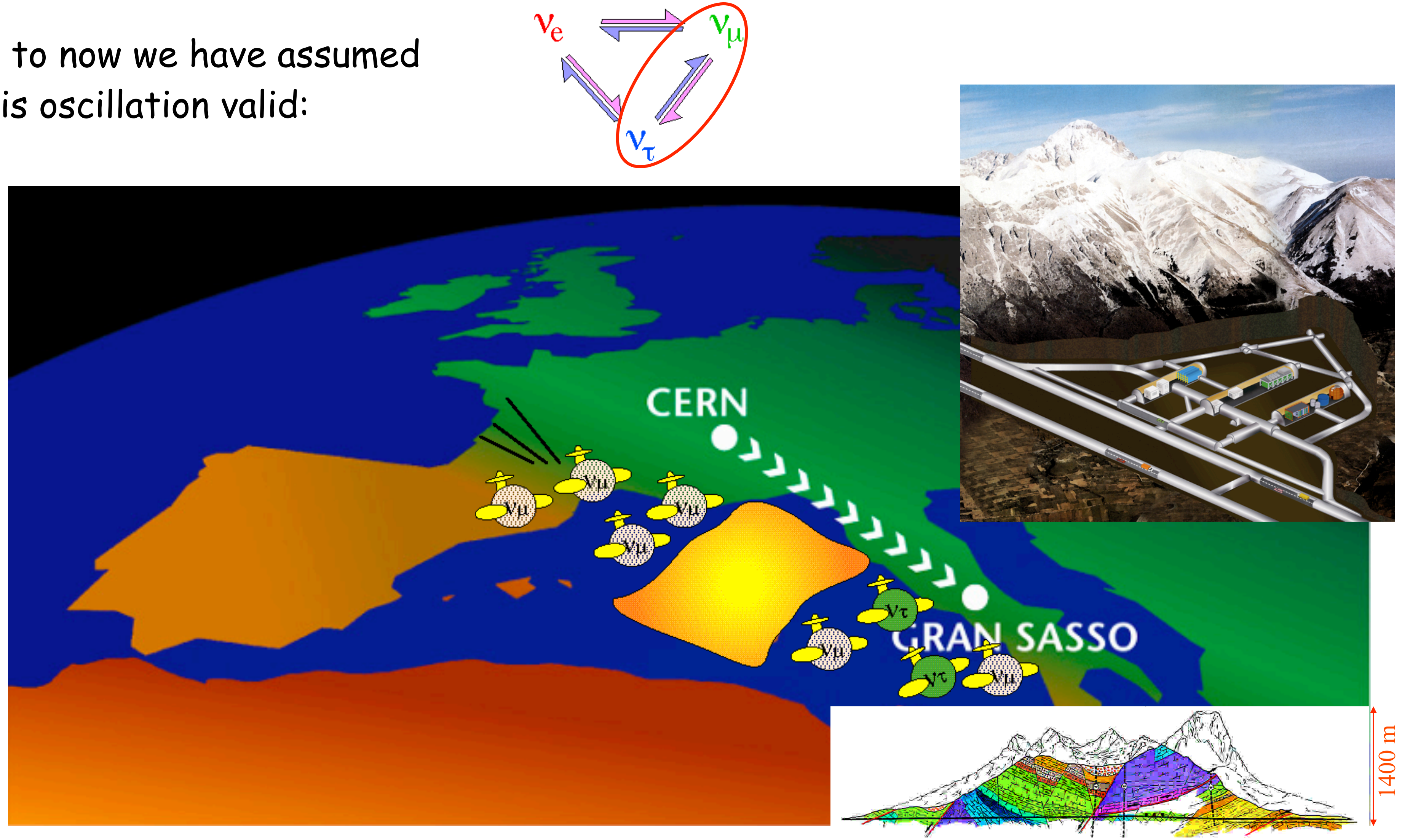
How can we produce a neutrino beam?



- adjustable proton energy,
- adjustable distance between the production point and the detector,
- neutrino type choice,
- but as usually, the neutrino energy is not well defined...

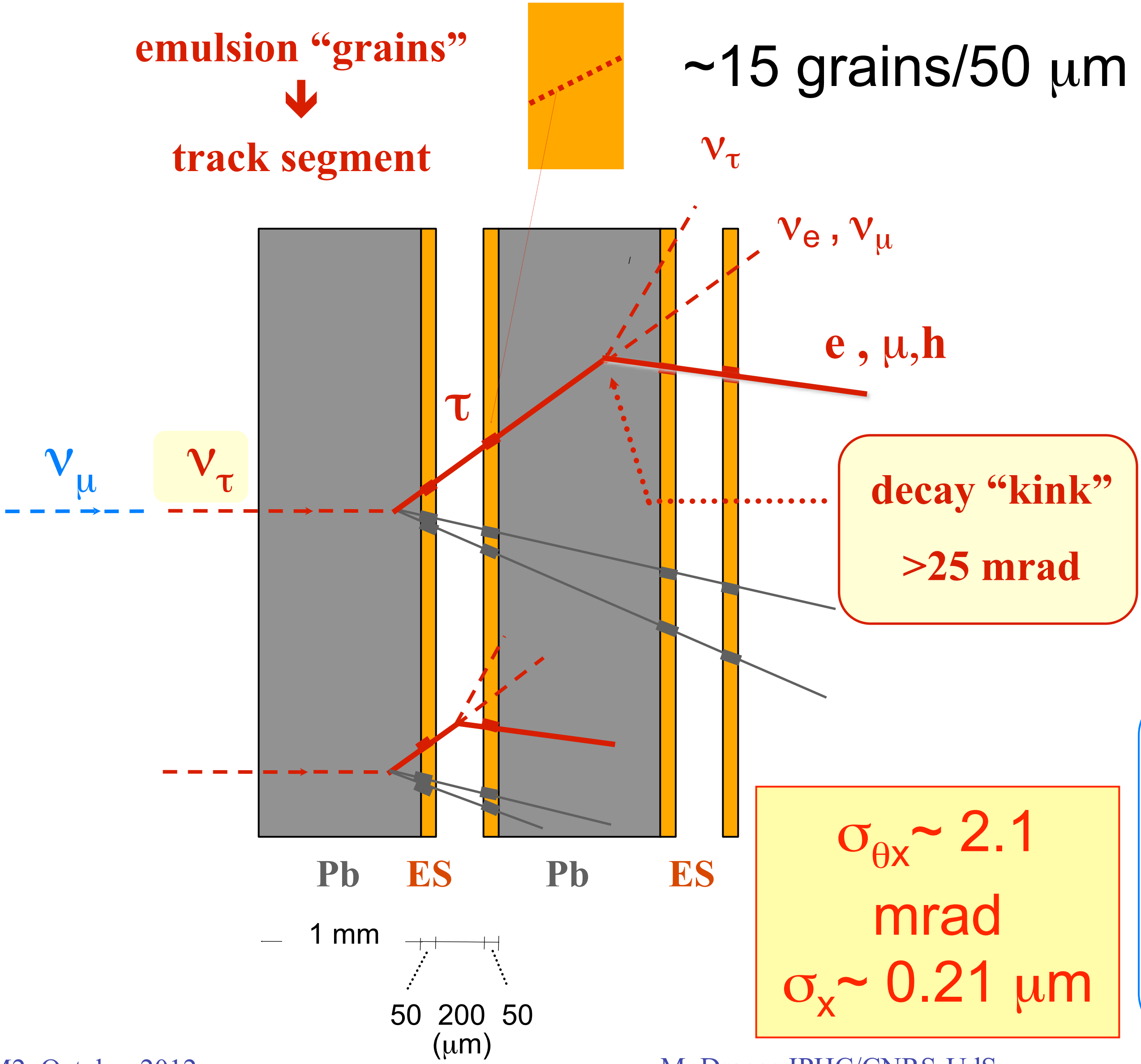
Long Base Line Appearance Experiment

up to now we have assumed
this oscillation valid:



CNGS ν_μ beam CERN-Gran Sasso 732 km (look for ν_τ in a pure ν_μ beam)

ν_τ detection in OPERA

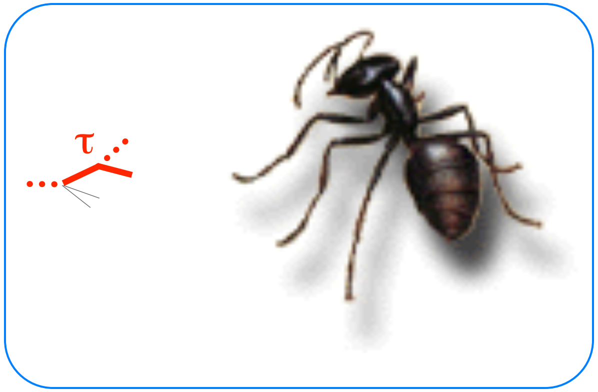


$\sigma_{\theta x}$~ 2.1 mrad

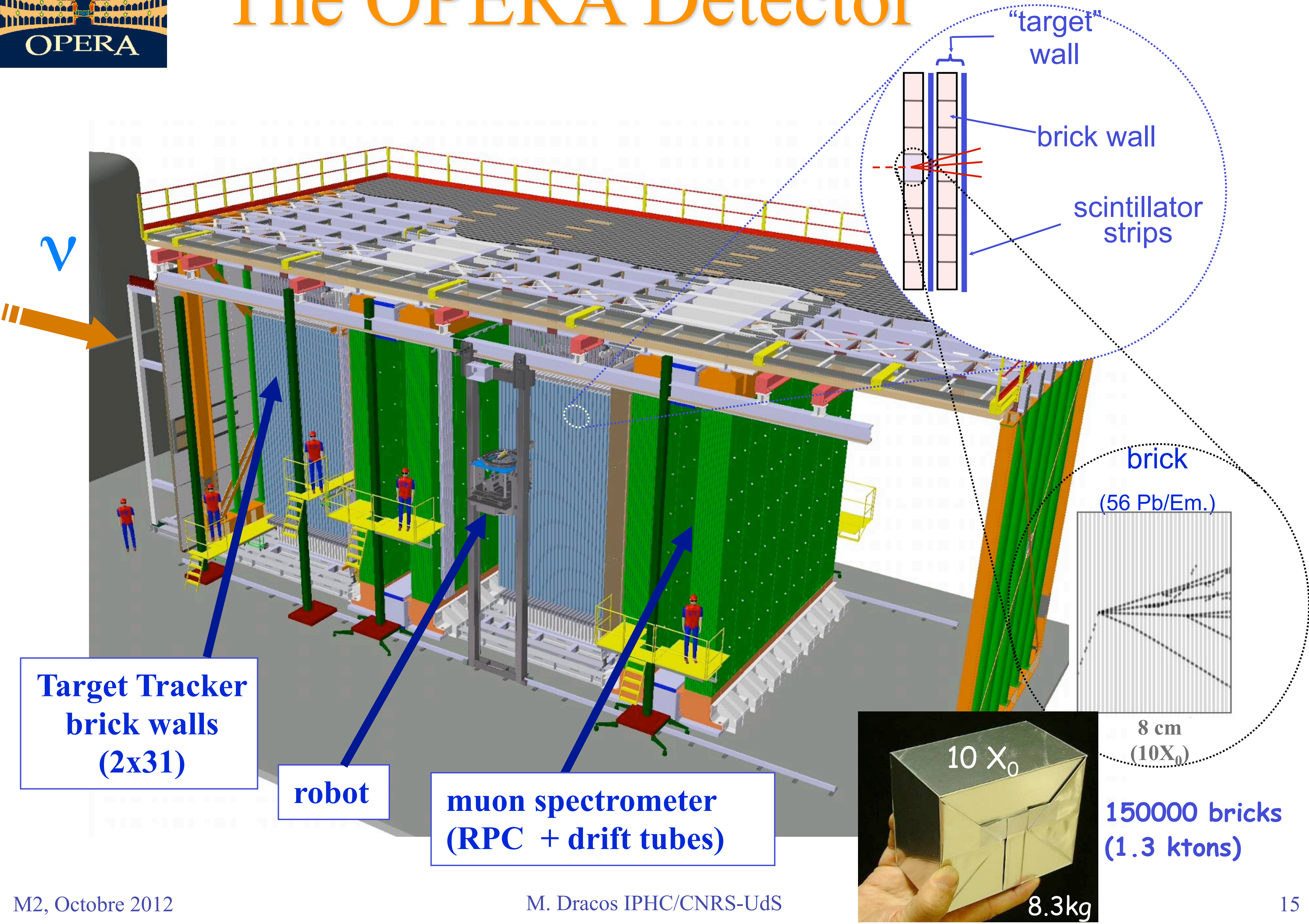
σ_x~ 0.21 μm

A very high spatial resolution is necessary (do not forget that large surfaces have to be covered)

Nuclear Emulsions (photographic)



The OPERA Detector



Target Tracker brick walls (2x31)

robot

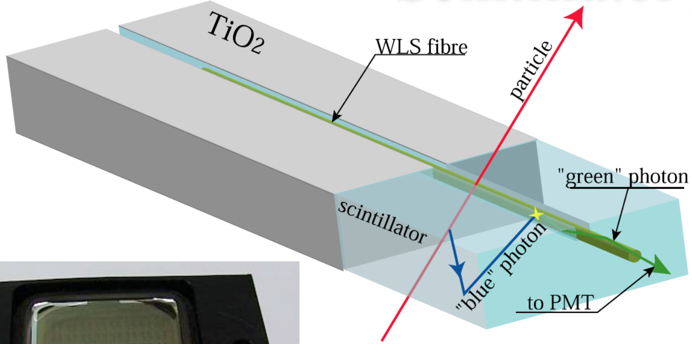
muon spectrometer (RPC + drift tubes)

150000 bricks (1.3 ktons)

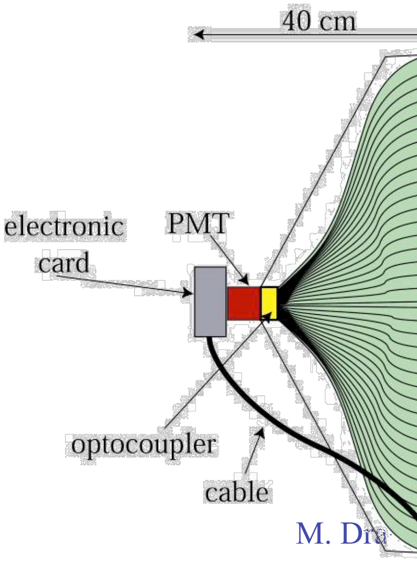
Target Tracker

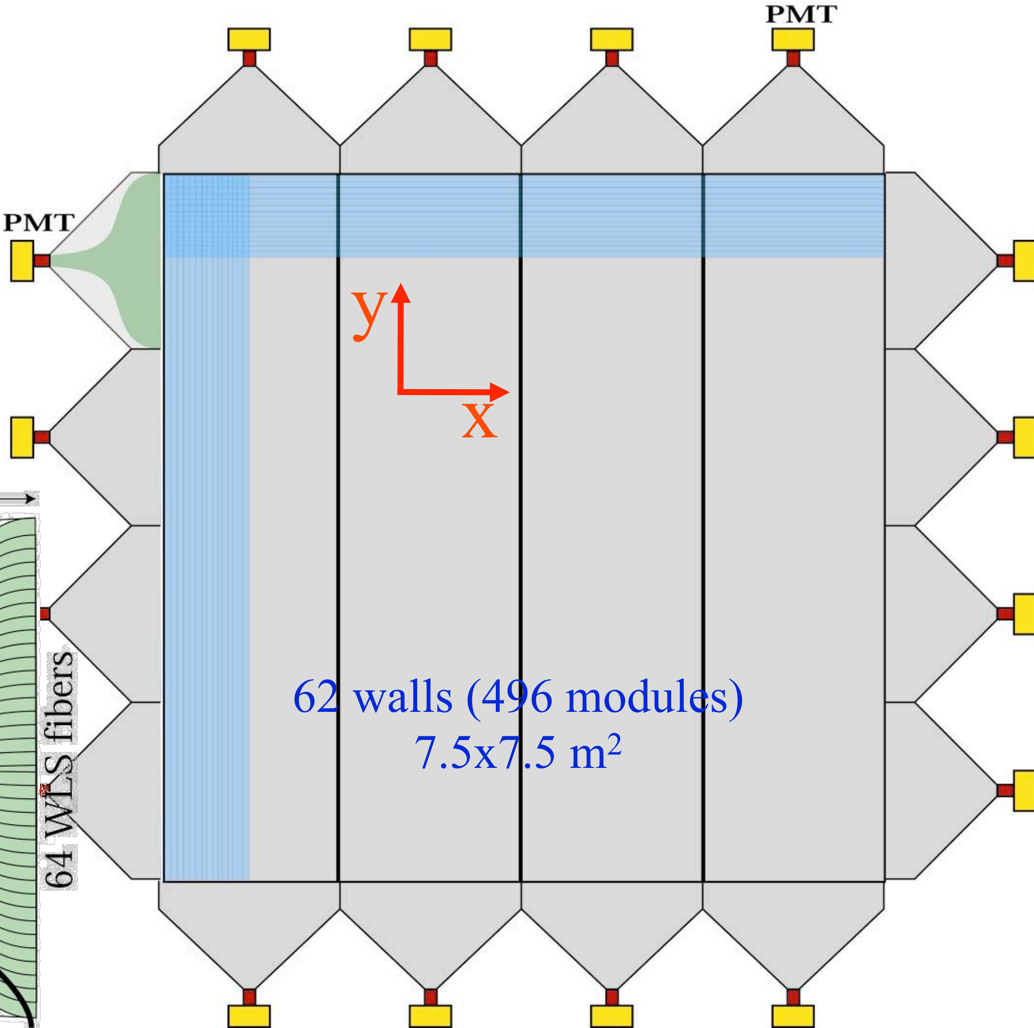
Scintillator polystyrene strips (plastic)

(Bern, Brussels, Dubna, IPHC, LAL, Neuchâtel)



Hamamatsu MA-PMT
(64 channels) 3x3 cm^2





62 walls (496 modules)
7.5x7.5 m^2

The first ν_τ candidate event

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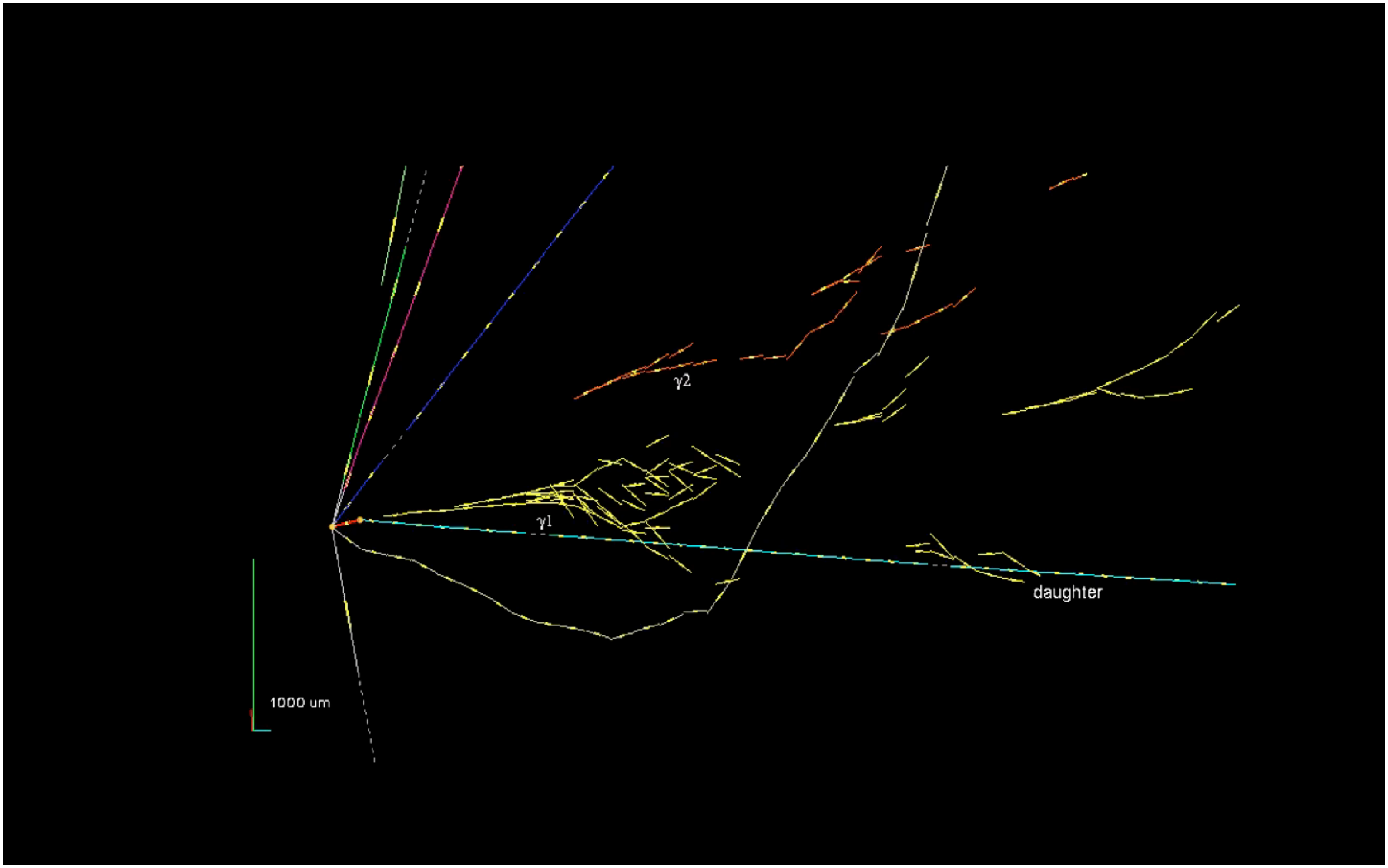
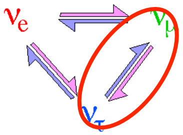
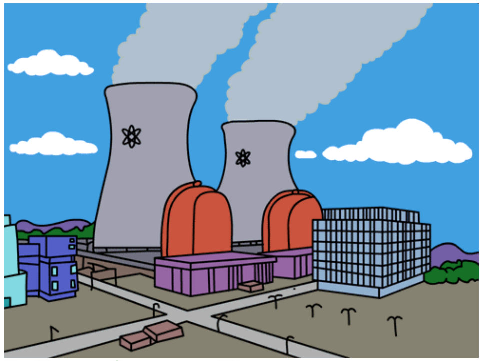


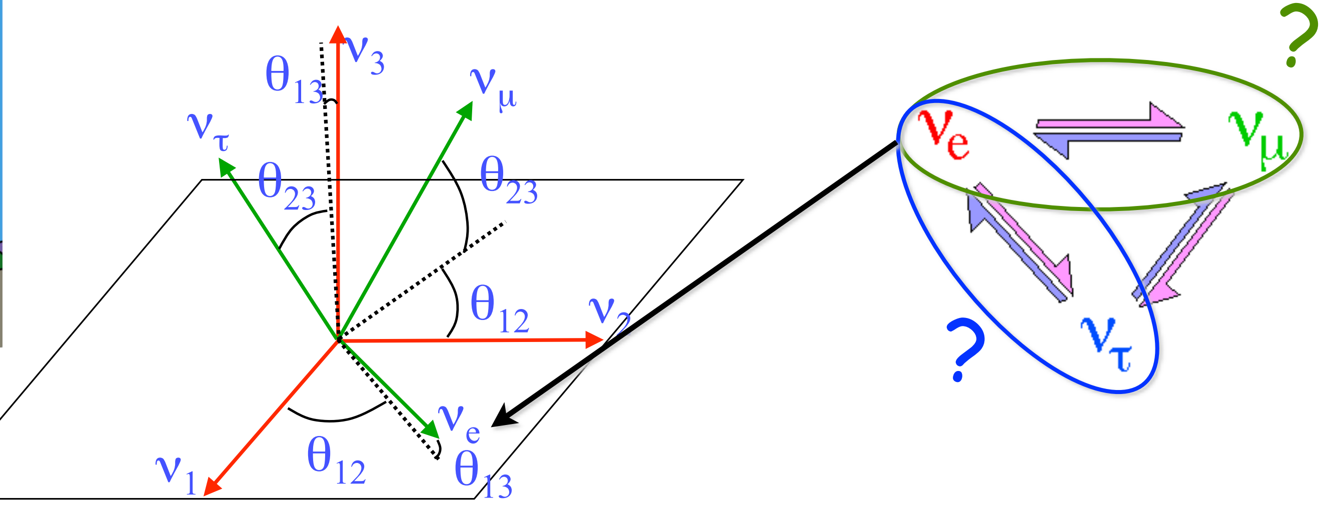
candidate: $\tau \to \underbrace{\pi^- \pi^0}_{\rho^-} \overline{\nu_\tau}$



The θ_{13} hunting



Nuclear Reactors
as neutrino source



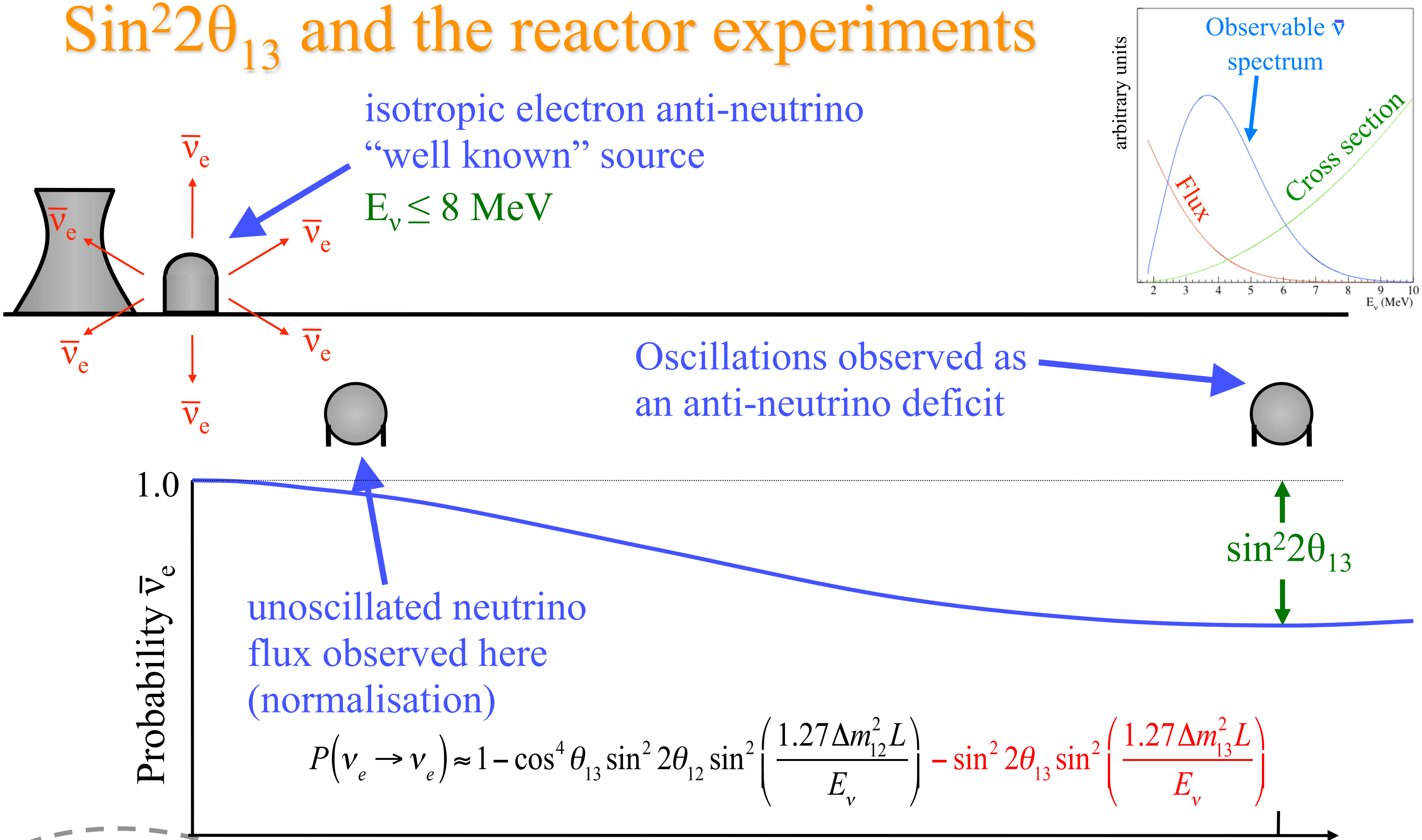
$$U = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{rotation around } x-axis \text{ with angle } \theta_{23}} \cdot \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{\text{rotation around } y-axis \text{ with angle } \theta_{13}} \cdot \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{rotation around } z-axis \text{ with angle } \theta_{12}}$$

atmospheric,
accelerators

if $\theta_{13}=0$ we could not measure
CP violation

solar,
reactors

$\mathrm{Sin}^2 2\theta_{13}$ and the reactor experiments



isotropic electron anti-neutrino
“well known” source

$E_\nu \leq 8$ MeV

Oscillations observed as
an anti-neutrino deficit

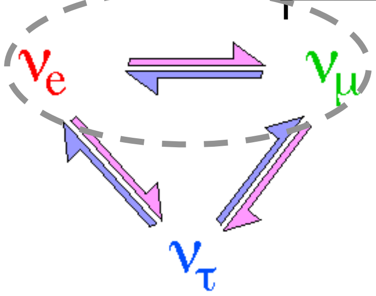
$\sin^2 2\theta_{13}$

unoscillated neutrino
flux observed here
(normalisation)

$$P(\nu_e \to \nu_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E_\nu}\right)$$

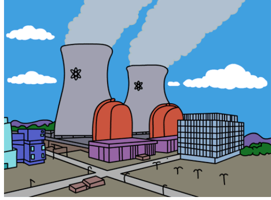
Distance

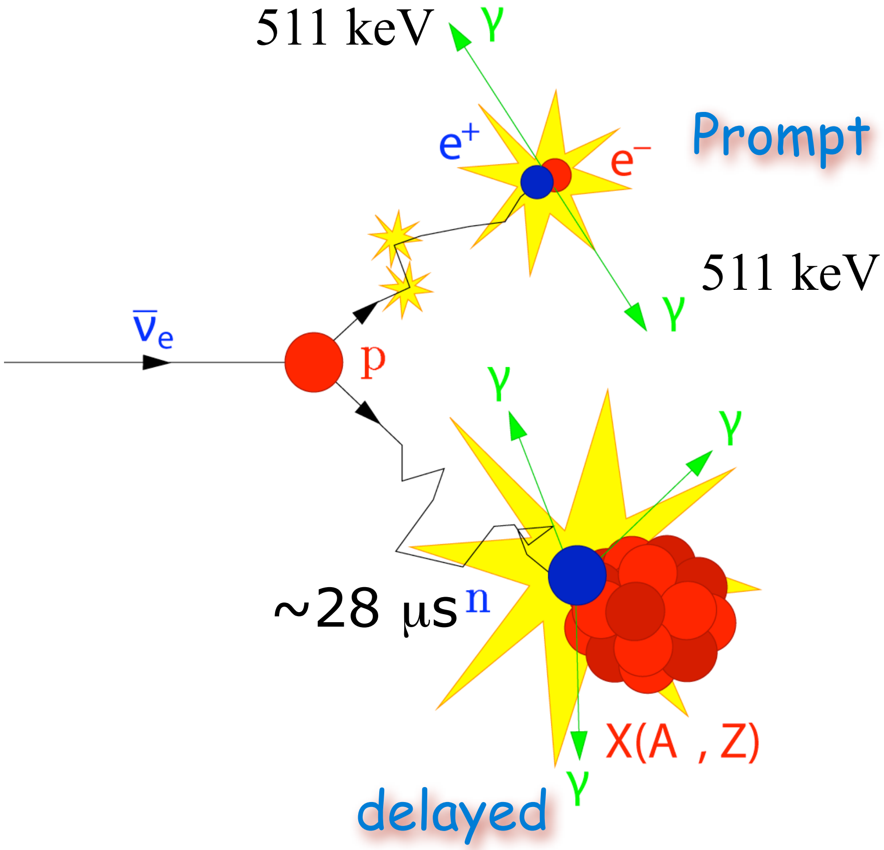
1200 to 1800 meters



$$\boxed{P_{surv.}(E_\nu, d_{far}) = \underbrace{\frac{N_{p,near}}{N_{p,far}}}_{=1!} \times \underbrace{\frac{\varepsilon_{near}}{\varepsilon_{far}}}_{=1!} \times \left(\frac{d_{far}}{d_{near}}\right)^2 \times \frac{N_{far}}{N_{near}}}$$

Inverse β decay and detection mode





In a pure scintillator the neutron will be captured by hydrogen:

$$n\ H \rightarrow D\ \gamma\ \ (2.2\ \text{MeV})$$

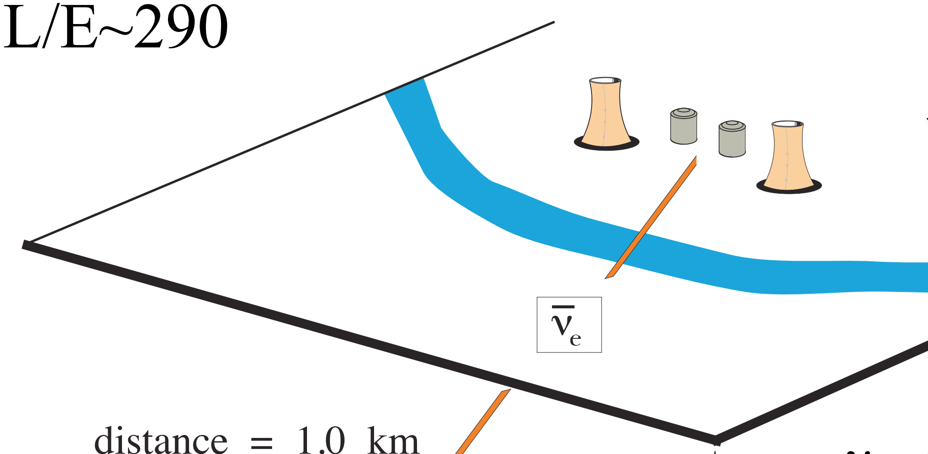
Very often the scintillator is doped with gadolinium that increase the capture probability and liberates more γ's:

$$n\ {}^{m}\text{Gd} \rightarrow {}^{m+1}\text{Gd}\ \gamma\text{'s}\ (8\ \text{MeV})$$

The CHOOZ experiment

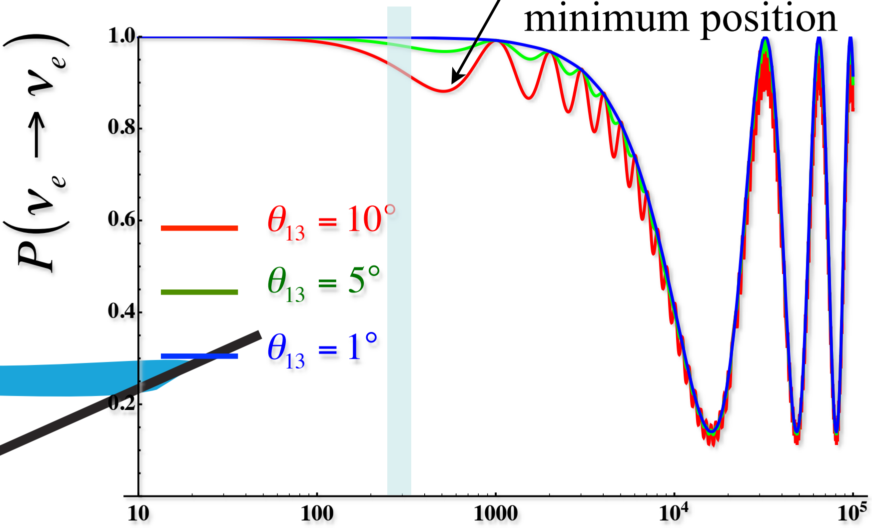
$\Delta m^2_{32} = 2.39^{+0.42}_{-0.33} \times 10^{-3}\ \mathrm{eV}^2$ defines the minimum position

L/E~290



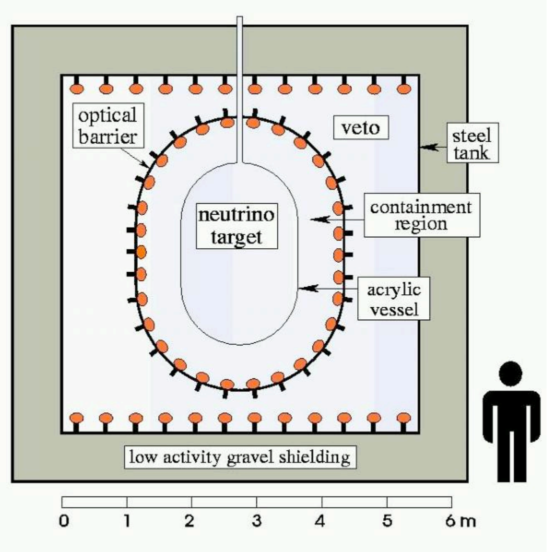
distance = 1.0 km

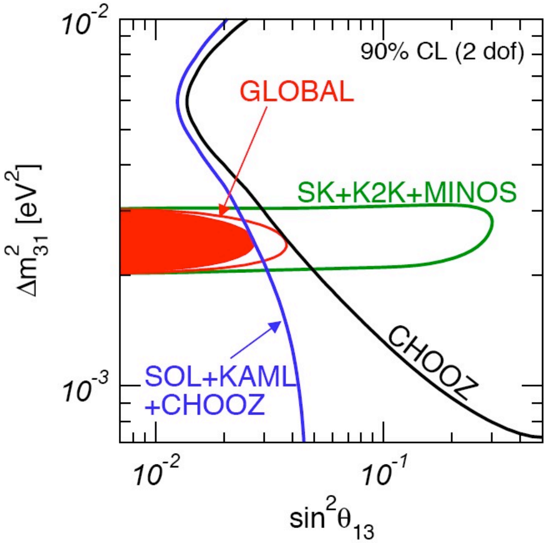
$\nu_e \rightarrow \nu_x$



disappearance experiment

L/E

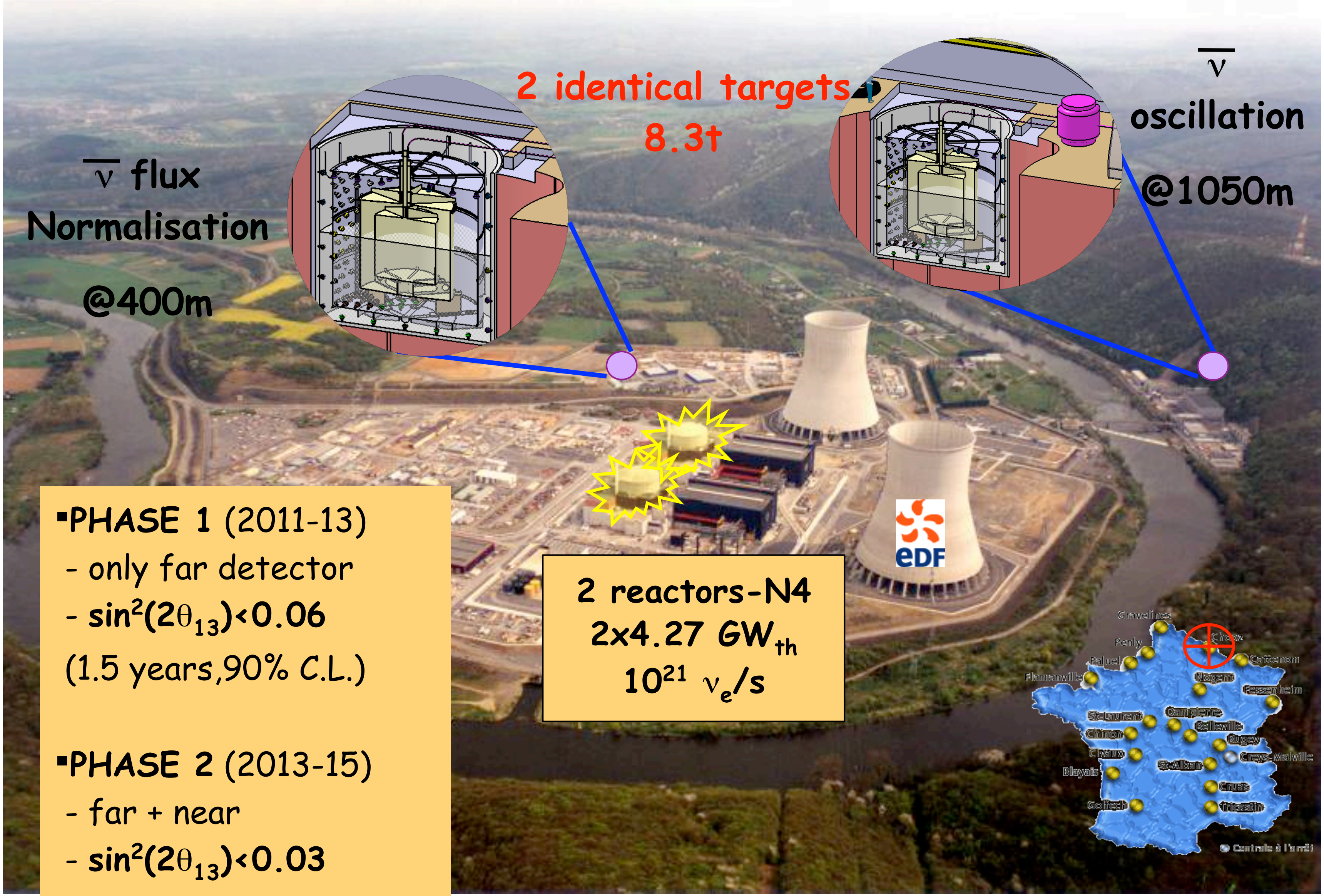




$\sin^2(2\theta_{13}) < 0.12 - 0.2$

(90% C.L)

Double Chooz site



$\bar{\nu}$ flux
Normalisation
@400m

2 identical targets
8.3t

$\bar{\nu}$
oscillation
@1050m

2 reactors-N4
2x4.27 GW_{th}
10^{21} ν_e/s

- **PHASE 1** (2011-13)
  - only far detector
  - **$\sin^2(2\theta_{13})<0.06$**

  (1.5 years,90% C.L.)

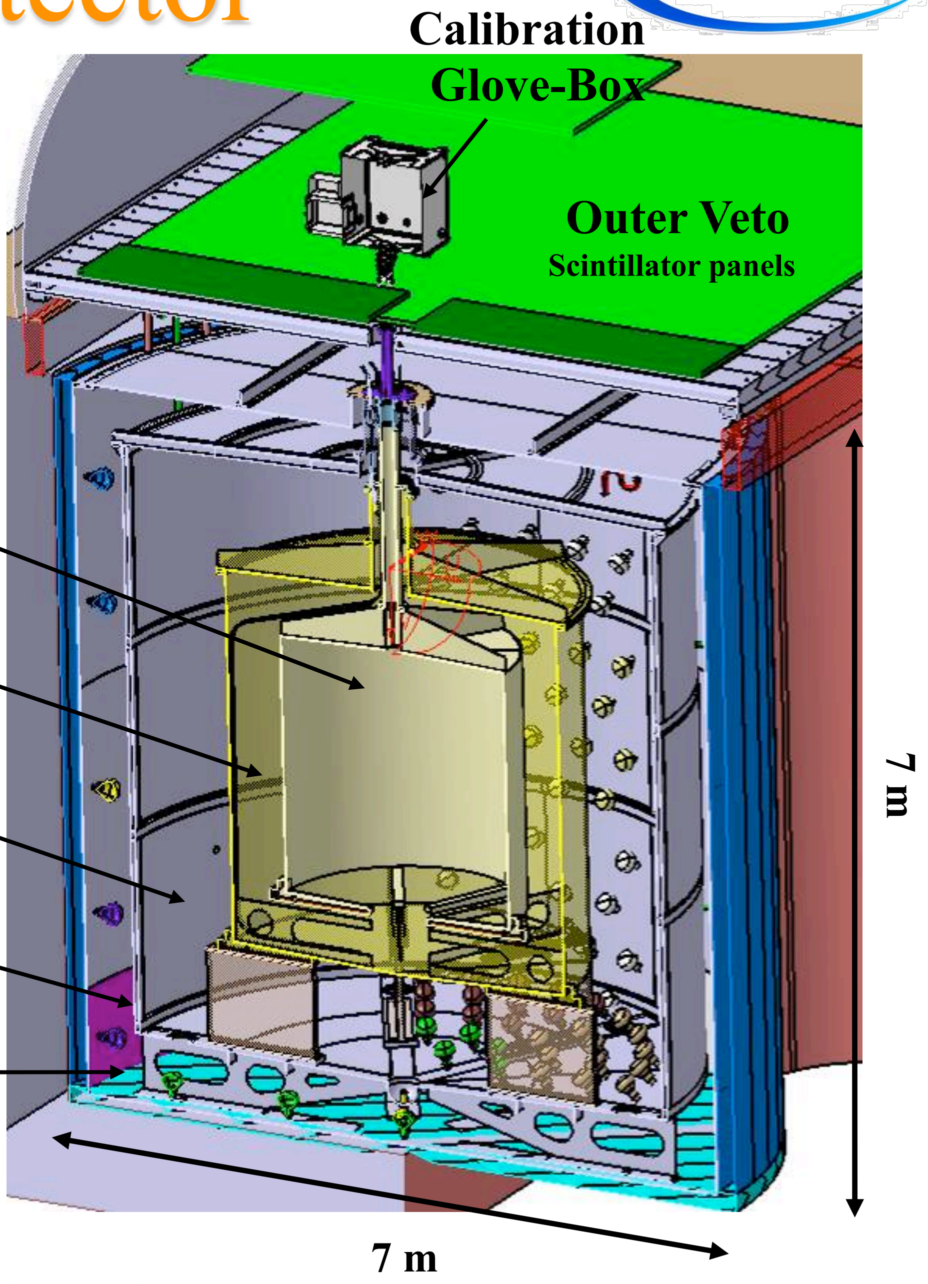
- **PHASE 2** (2013-15)
  - far + near
  - **$\sin^2(2\theta_{13})<0.03$**

  (3.5 years,90% C.L.)

DC detector

$\overline{\nu}_e + p \circledR\ e^+ + n$

$Gd^* \circledR\ Gd + \gamma('s)$



Target ν : 10,3 m³

80% $C_{12}H_{26}$+ 20% PXE + PPO + Bis-MSB +0.1% Gd

γ Catcher : 22,6 m³

80% $C_{12}H_{26}$ + 20% PXE + PPO + Bis-MSB

Non scintillating Buffer : 114 m³

Mineral oil

Buffer vessel & 390 10” PMTs :

Stainless steel 3 mm

Inner Muon Veto : 90 m³

Mineral oil + 78 8” PMTs

Steel Shielding :

15 cm steel, All around

Background (key element)

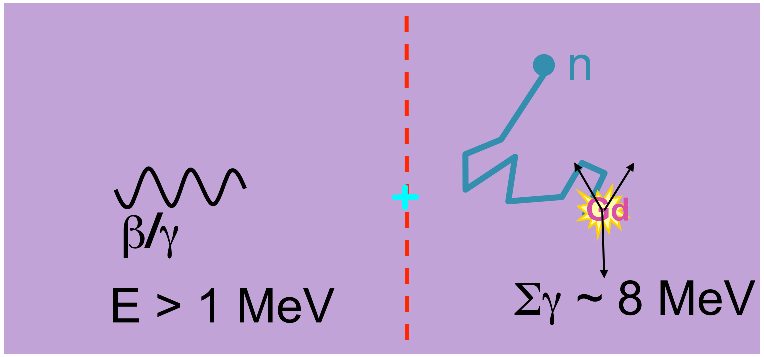
Accidental:

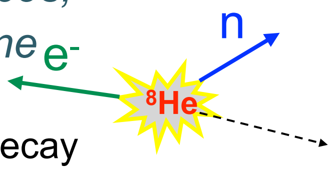
gamma or beta events with E > 1 MeV

+

neutron capture by Gd, E ~ 8 MeV

radiopurity of detector components,
shielding against external radiation sources,
the "single"'s rate can be measured online





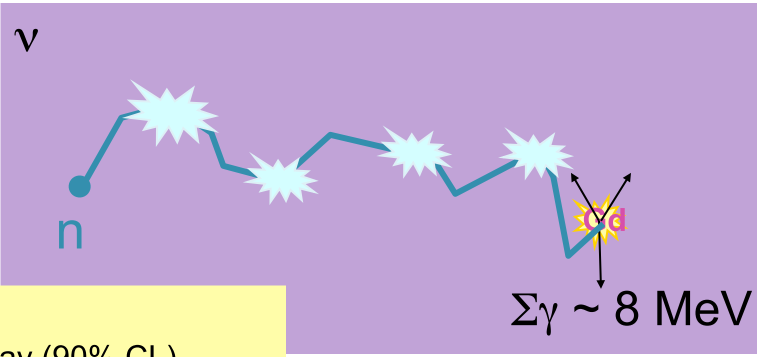
Correlated:

produced by muons and their secondaries

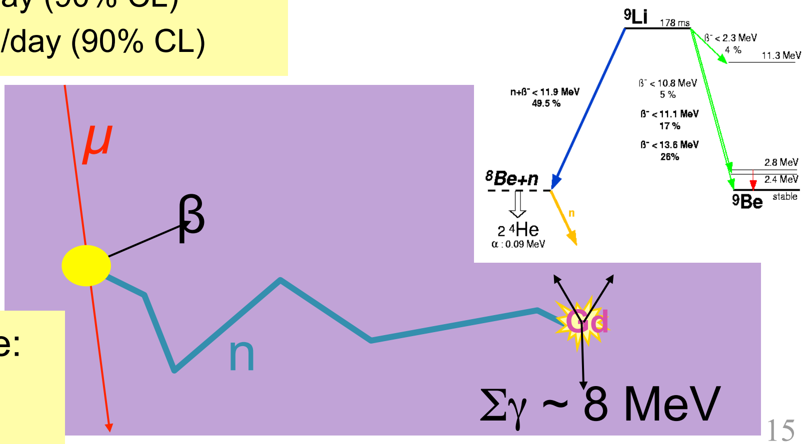
- fast neutrons (produced by μ in the surrounding rock)
- beta-neutron cascades (^{9}Li, ^{8}He): produced by the μ or n interactions with ^{12}C

  mean lifetime ~ (0.1 -1) s

shielding against cosmic rays,
active veto to recognise μ and n,
measurement of the background with the reactors off (if and when possible…).



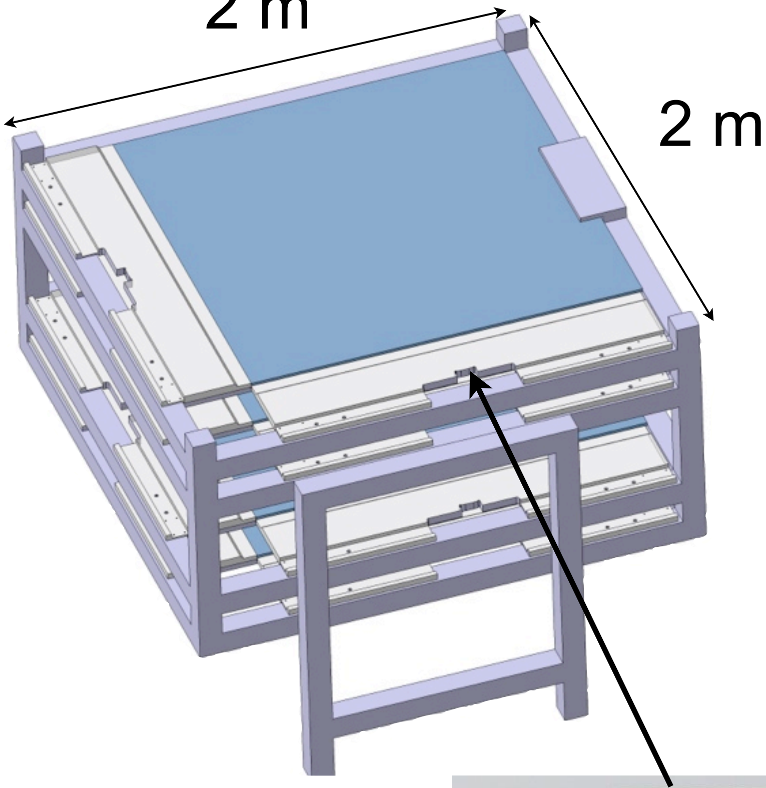
Chooz: ~1/day
- far: $N_b < 0.6$/day (90% CL)
- near: $N_b \sim 3.3$/day (90% CL)

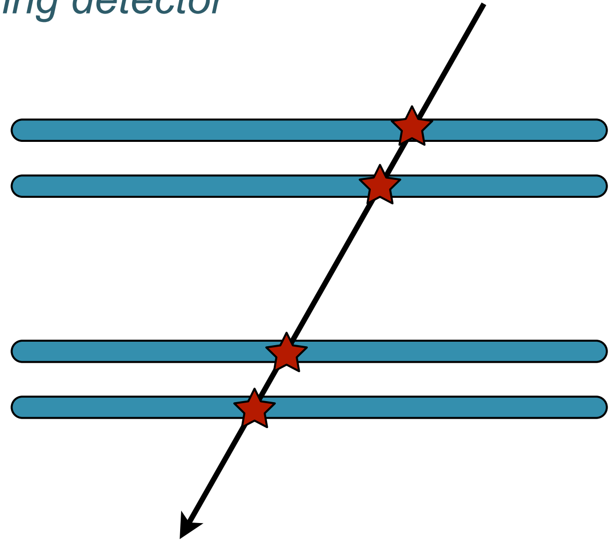


expected rate:
- far: 1.4/day
- near: 9/day

Muon telescope

- *In the near detector the cosmic background will be more important due to the low depth*
- *Better cosmic ray simulation needed*
- *Use a muon telescope to well measure the the muon spacial distribution and introduce it in the simulation*
- *4 layers of plastic scintillators (OPERA)*
- *rotating detector*

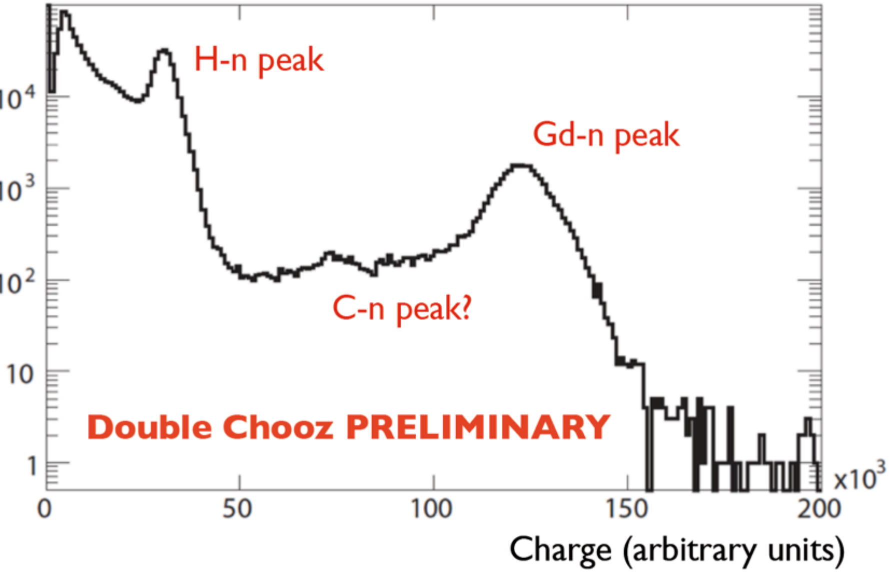


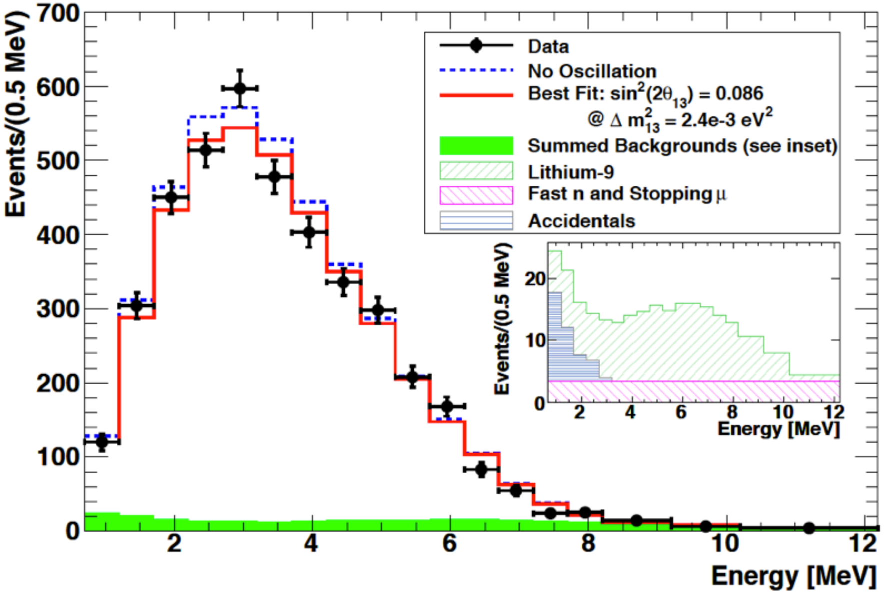


to be constructed during the training

PMT

First DC results
(Nov. 2011)





- Rate + Shape Analysis:
  - ✦$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$
- Rate Only:
  - ✦$\sin^2(2\theta_{13}) = 0.093 \pm 0.029(\text{stat}) \pm 0.073(\text{syst})$

November 2011

Future Projects on Neutrino Oscillations

(essentially to discover CP violation
and measure the mass hierarchy)

Neutrino Related European Projects

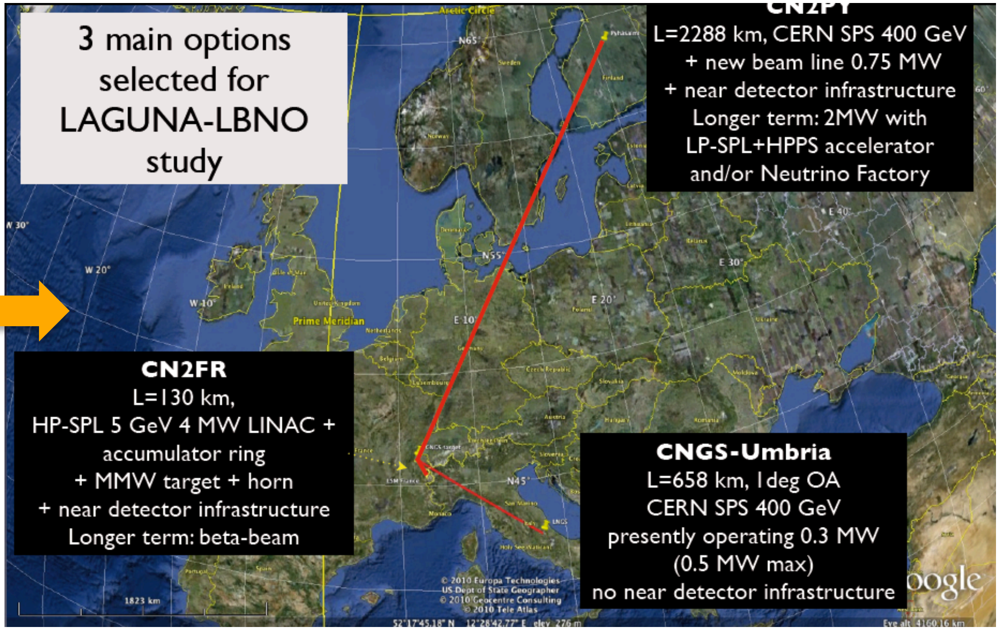
Two FP7 projects:

- **EUROν** (http://www.euronu.org/)
  - Design Study for new neutrino facilities in Europe
  - Project started: 1st September 2008
  - Duration: 4 years – completion August 2012
- **LAGUNA-LBNO** (Large Apparatus for Grand Unification and Neutrino Astrophysics, http://laguna.ethz.ch:8080/Plone)
  - Design Study for large underground laboratories for astroparticle and neutrino studies
  - Project started: 2011
  - Duration: 3 years – completion in 2014

All sites and detection techniques under consideration by LAGUNA and possible neutrino beams from CERN

LAGUNA

LAGUNA-LBNO

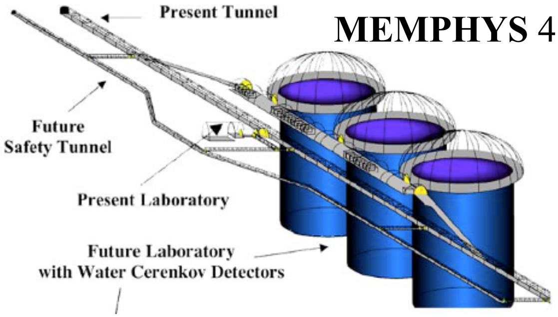


3 main options selected for LAGUNA-LBNO study

CN2PY
L=2288 km, CERN SPS 400 GeV
+ new beam line 0.75 MW
+ near detector infrastructure
Longer term: 2MW with
LP-SPL+HPPS accelerator
and/or Neutrino Factory

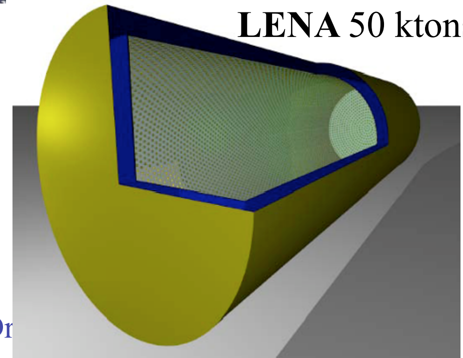
CN2FR
L=130 km,
HP-SPL 5 GeV 4 MW LINAC +
accumulator ring
+ MMW target + horn
+ near detector infrastructure
Longer term: beta-beam

CNGS-Umbria
L=658 km, 1deg OA
CERN SPS 400 GeV
presently operating 0.3 MW
(0.5 MW max)
no near detector infrastructure

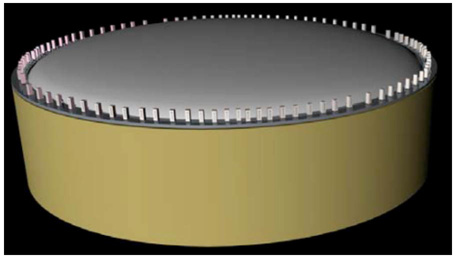


MEMPHYS 450 Ktons

LENA 50 ktons

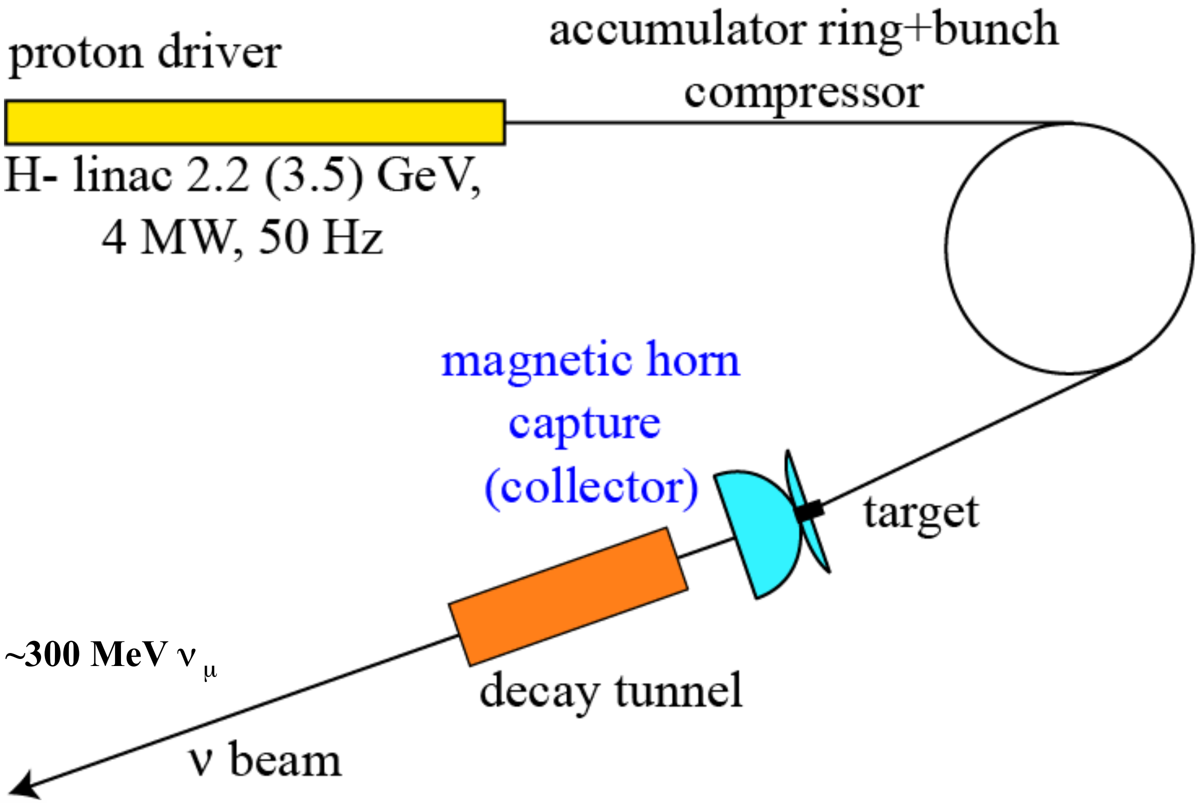


GLACIER 100 ktons



Super-Beams

CERN-SPL



proton driver

H- linac 2.2 (3.5) GeV,
4 MW, 50 Hz

accumulator ring+bunch
compressor

magnetic horn
capture
(collector)

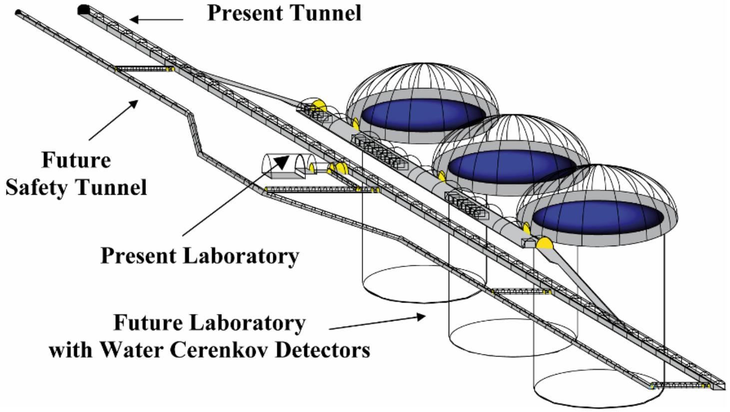
target

decay tunnel

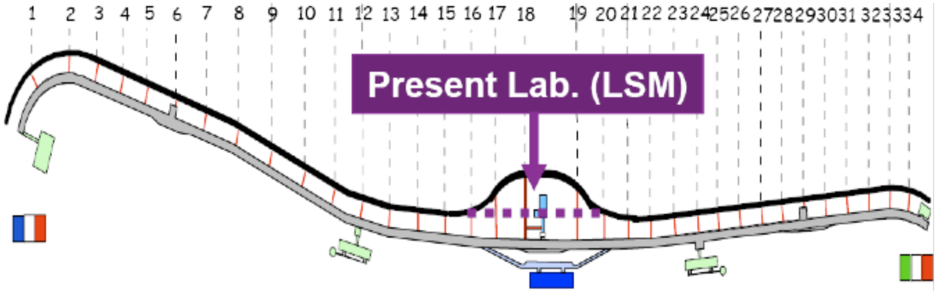
~300 MeV ν_μ

ν beam

MEMPHYS
detector
(Water Cherenkov)

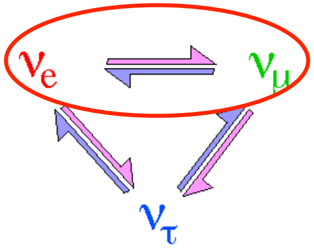


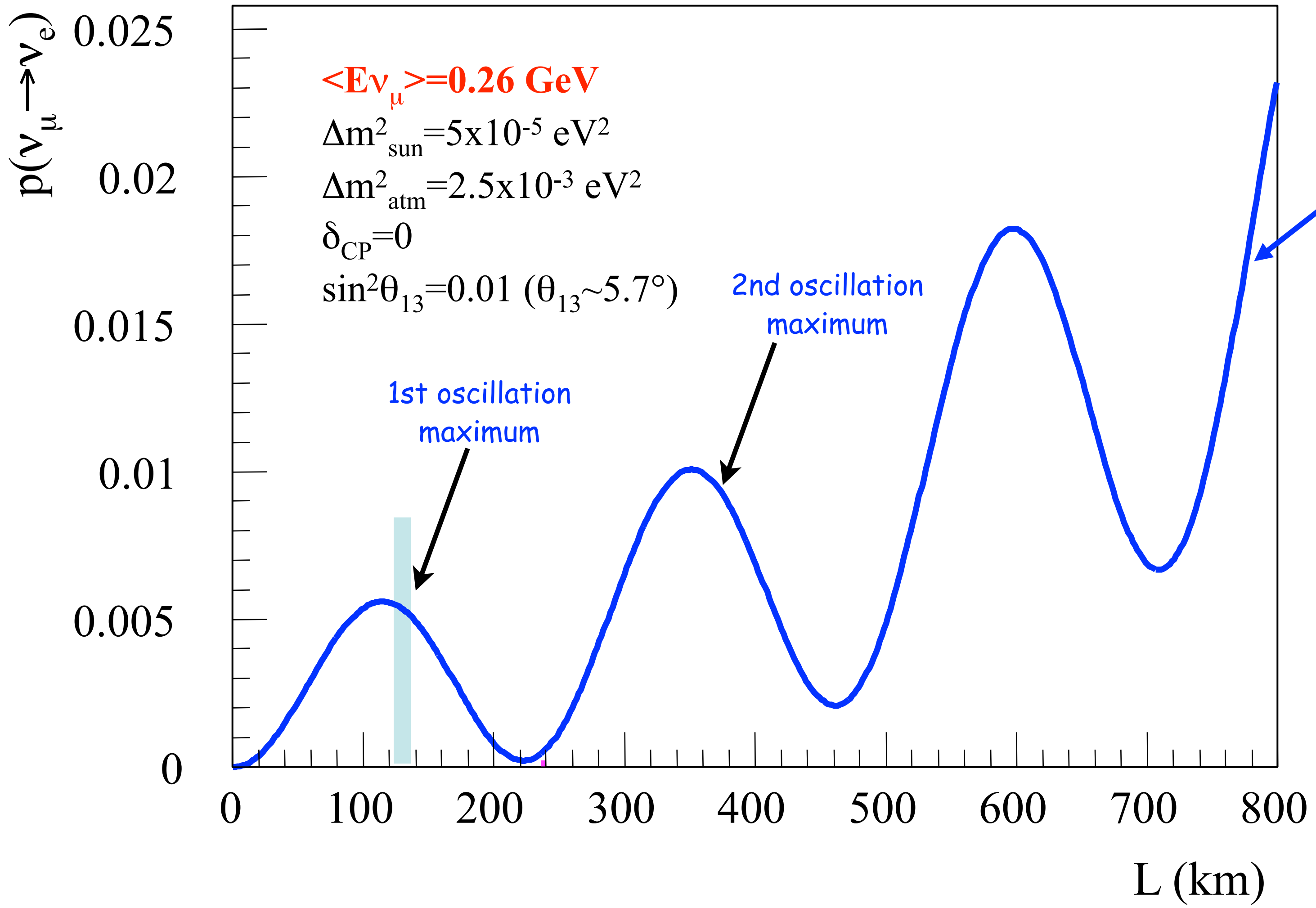
- 3 shafts= 440 kT fid., 1 shaft= 4xSK
- 30% coverage by 81k PMT 12” per shaft



Why this Super-Beam?

ℓ =130 km (distance CERN-Fréjus)





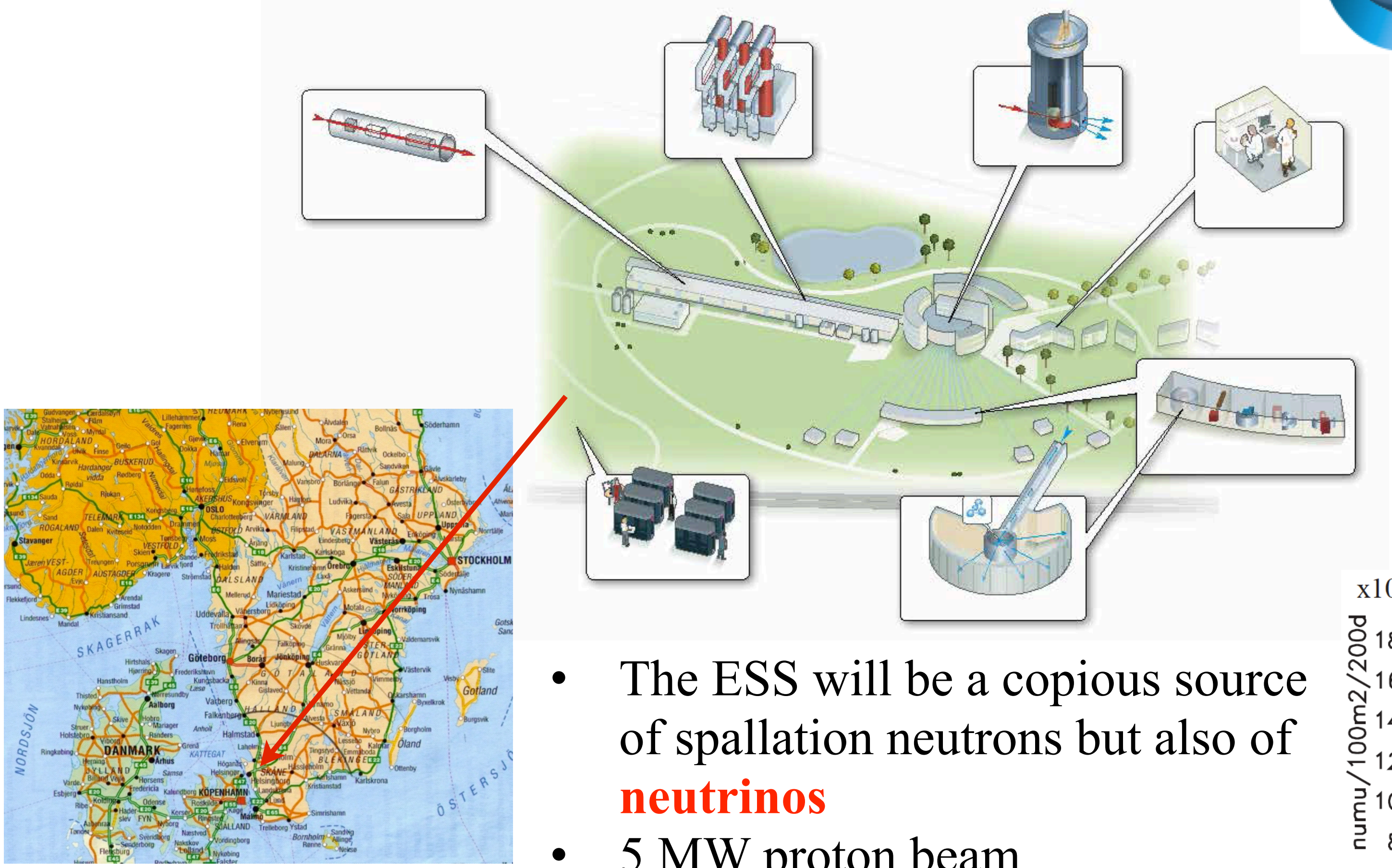
without too many approximations

→ neutrinos of ~300 MeV necessary for this particular projet, C2F (CERN to Fréjus)

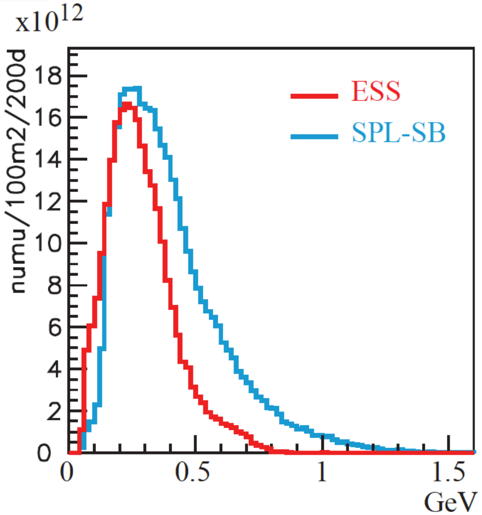
European Spallation Source (Lund)

EUROPEAN
SPALLATION
SOURCE

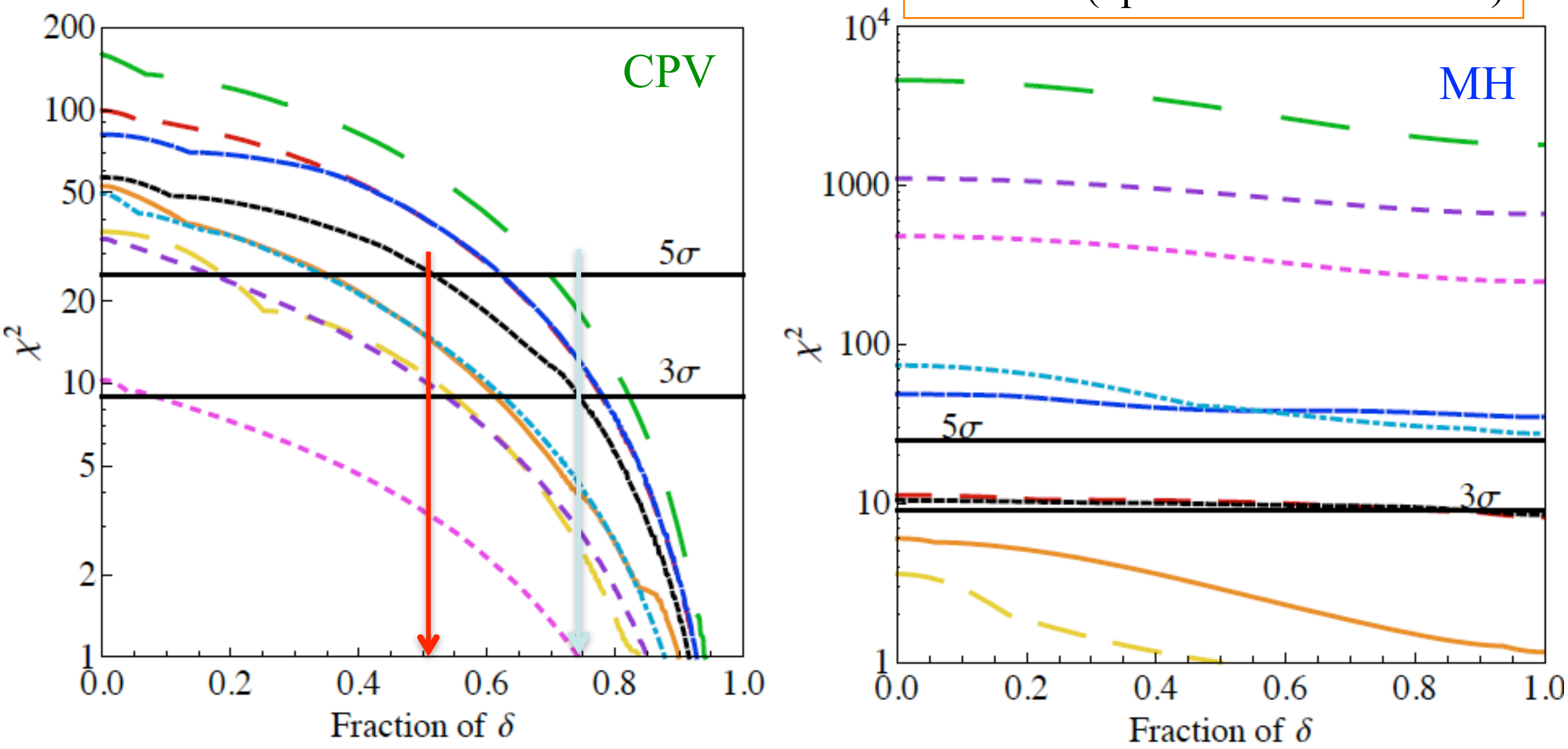
- First beam ~2020



- The ESS will be a copious source of spallation neutrons but also of **neutrinos**
- 5 MW proton beam
- 2.5 GeV protons
- ~300 MeV neutrinos



Physics Performance



without adding yet atmospheric neutrinos (optimization is needed)

EUROν parameters without any particular optimization for ESS

- 1 Mton WC detector (440 kton fiducial), 5% syst.
- 2.5 GeV protons
- 5 MW proton beam

Conclusions

- Deux stages sur Double Chooz
  - Etude du bruit de fond induit par les neutrons rapides.
  - Construction d'un télescope à muons cosmiques pour étudier le bruit de fond du détecteur proche.
- Un sujet de thèse
  - Etude des performances de futurs faisceaux neutrinos.

Dec. 1930: A desperate remedy

Letter of W. Pauli, 4 December 1930

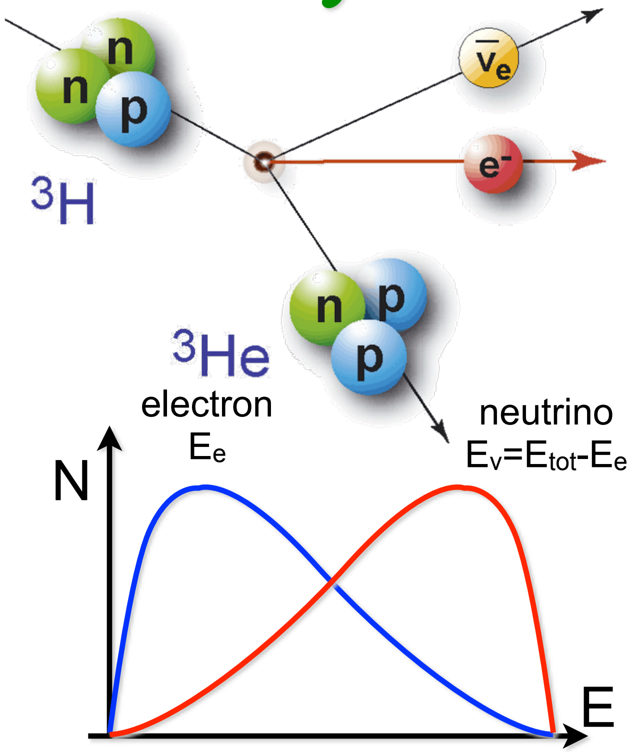
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a ***desperate remedy*** *to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that* ***there could exist in the nuclei electrically neutral particles****, that I wish to call* ***neutrons****, which have* ***spin 1/2*** *and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...*

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

W. Pauli



> “I have done something very bad today by proposing a particle that cannot be detected. It is something no theorist should ever do.”
>
> *W.Pauli*

How neutrinos propagate through the time?

According to Quantum Mechanics:

$$\left|\nu_j(t)\right\rangle = e^{-iHt/\hbar}\left|\nu_j(0)\right\rangle$$

(H: Hamiltonian)

Solutions of Schrödinger equation

For 3 neutrinos with a well defined mass and energy:

Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = H\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

for the mass eigen states

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H_f\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

for the flavour eigen states

with: $H_f = UHU^\dagger$

following the ν history…

1933 : First estimation of the neutrino interaction cross-section (interaction probability) by Hans Bethe and Rudolf Peierls

$\sigma_{\nu N} \approx 10^{-10} \sigma_{eN}$ (N for nucleon), very very weak cross-section!!!

$$\sigma_{\bar{\nu} p} \approx 10^{-43} cm^2$$

$$\lambda = \frac{1}{N_A \rho \sigma}$$

mean free path

$$\lambda(Pb) \approx \frac{1}{6 \times 10^{23} (nucleons / g)(7.9 g / cm^3) \times 10^{-43} cm^2}$$

~ 4 light-years!

mean free path in lead for 3 MeV neutrino

to stop a neutrino a lot of lead is needed or many neutrinos…

The beginning of a long neutrino hunting which lasted 26 years…

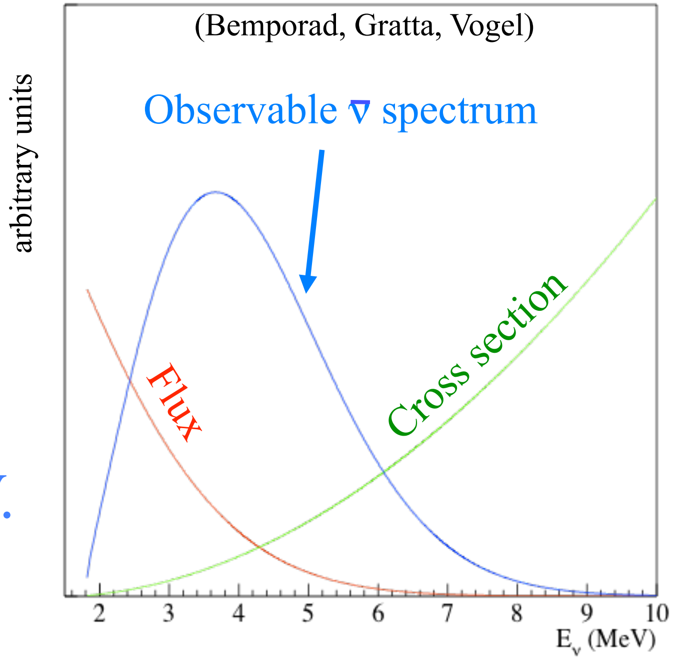
(Pauli: "I *bet a case of champagne that nobody would ever detect the neutrino*")

Nuclear Reactors as neutrino source

- Nuclear reactors are a very intense electron anti-neutrino source (β decay of neutron rich fission fragments).
- Each fission release an energy of ~200 MeV and generates ~6 electron anti-neutrinos. For a typical commercial reactor (3 GW thermal energy):

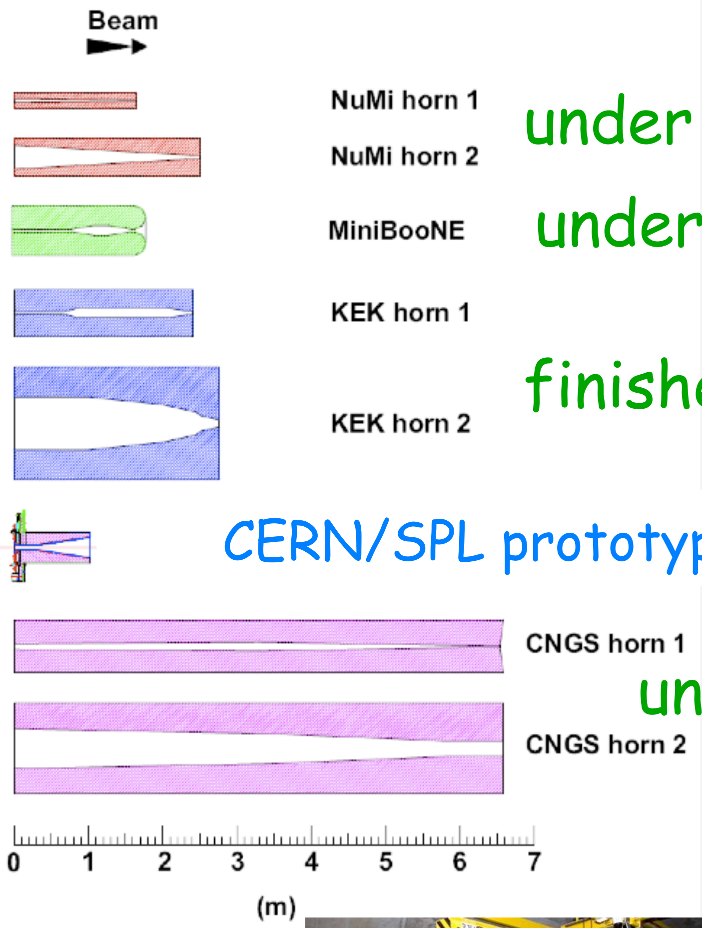
$$3\ \text{GW} \approx 2\times10^{21}\ \text{MeV/s} \rightarrow 6\times10^{20}\ \bar{\nu}_e/\text{s}$$

- Observable neutrino energy spectrum= neutrino flux * cross section.
- The spectrum has a maximum at ~3.7 MeV.



Present Collectors

Experiment	Current	Rep. Rate	Pulses per time period
Numi (120 GeV)	200 kA	0.5 Hz	6 Mpulses 1 year
MiniBoone (8 GeV)	170 kA	5 Hz	11 Mpulses 1 year
K2K (12 GeV)	250 kA	0.5 Hz	11 Mpulses 1 year
Super-Beam (3.5 GeV)	300 kA	50 Hz	200 Mpulses 6 weeks
CNGS (400 GeV)	150 kA	2 pulses/ 6 sec	42 Mpulses 4 year



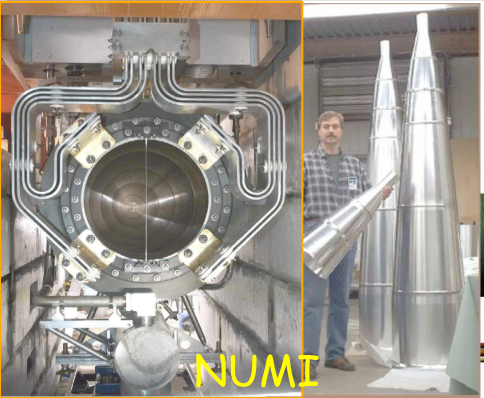
under operation

under operation

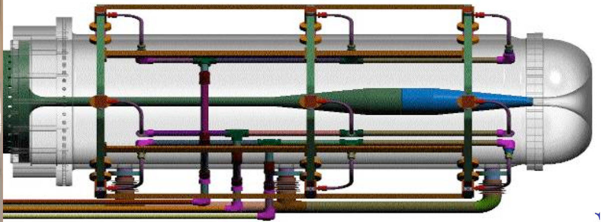
finished

CERN/SPL prototype horn

under operation

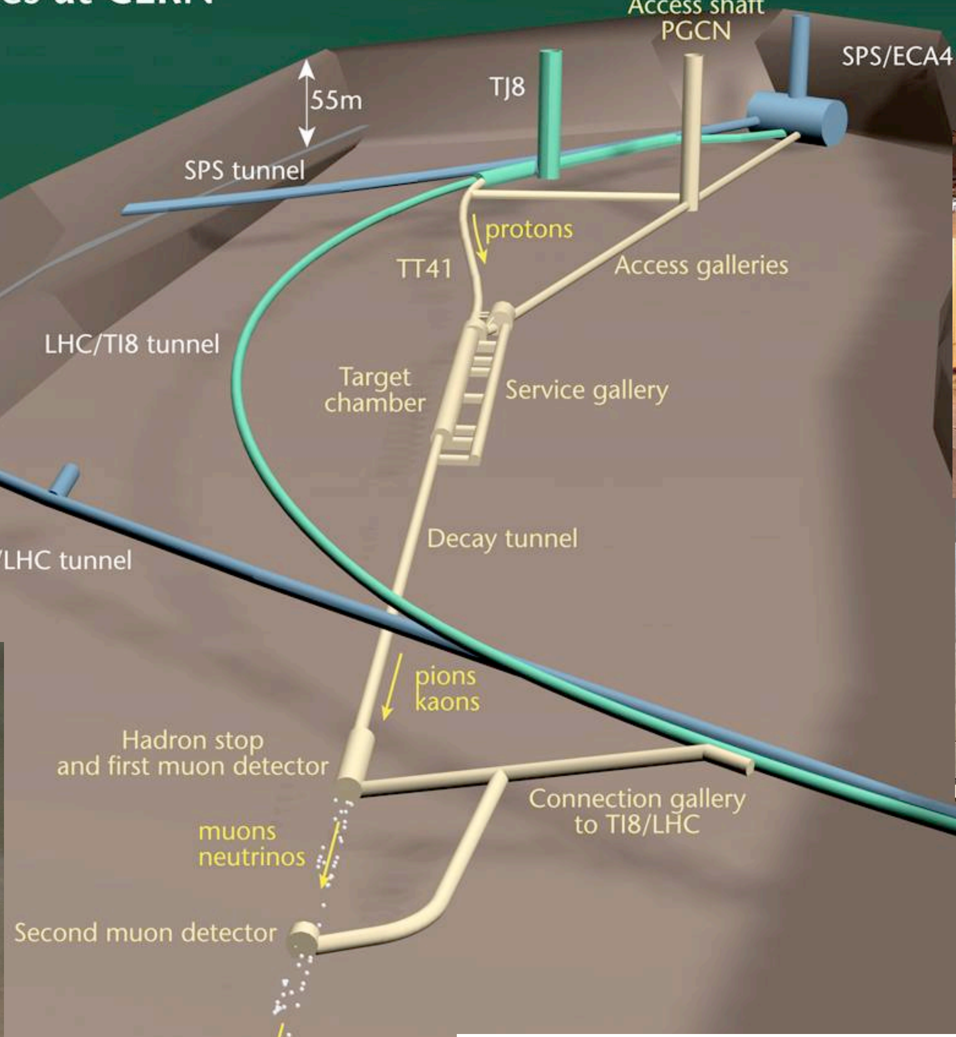


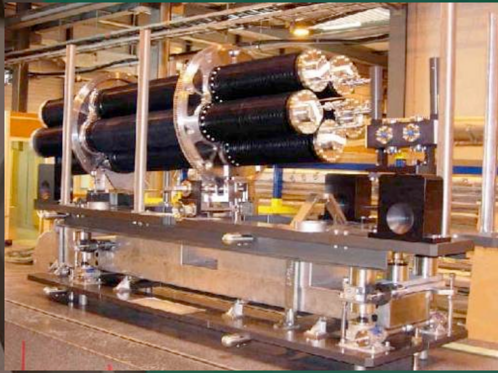
MiniBooNE

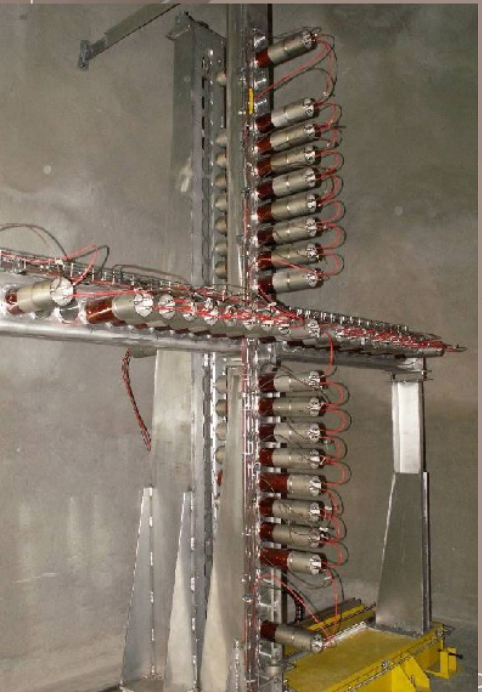


CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

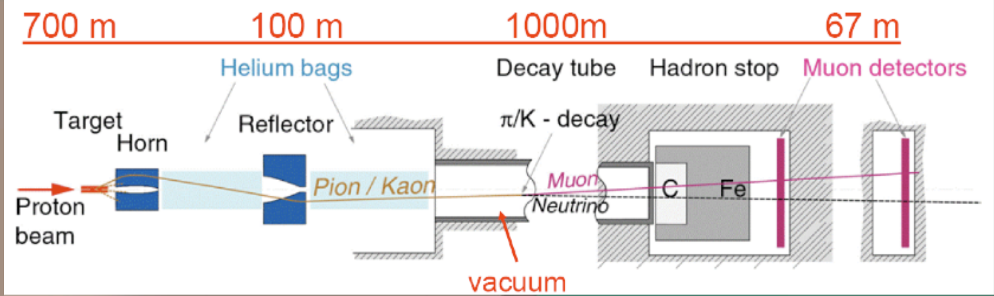
CNGS



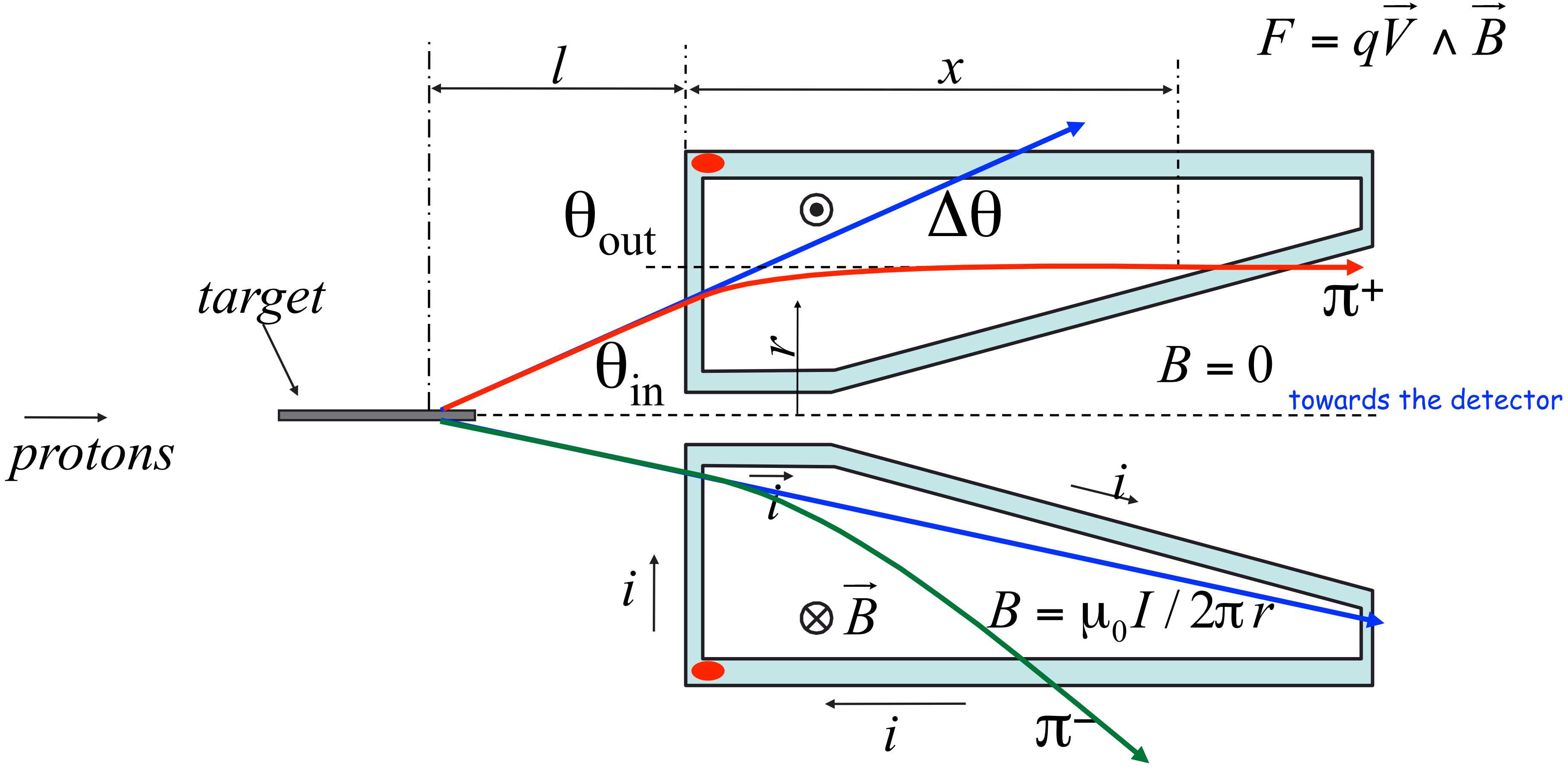




DI/MM

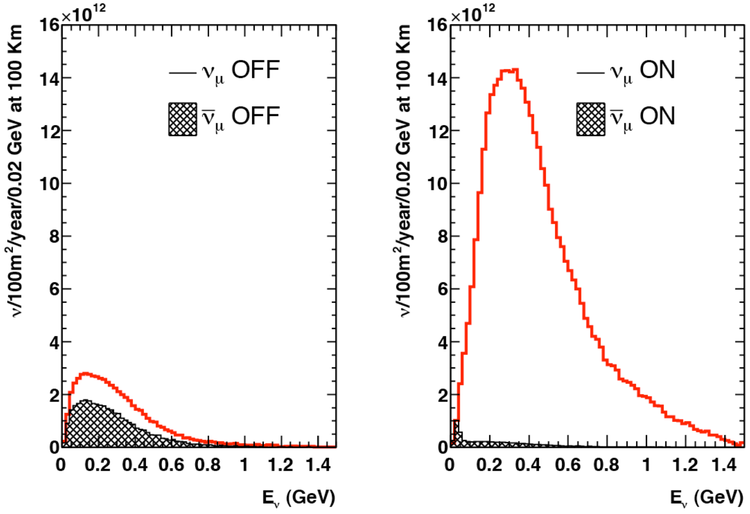


Hadronic Collector

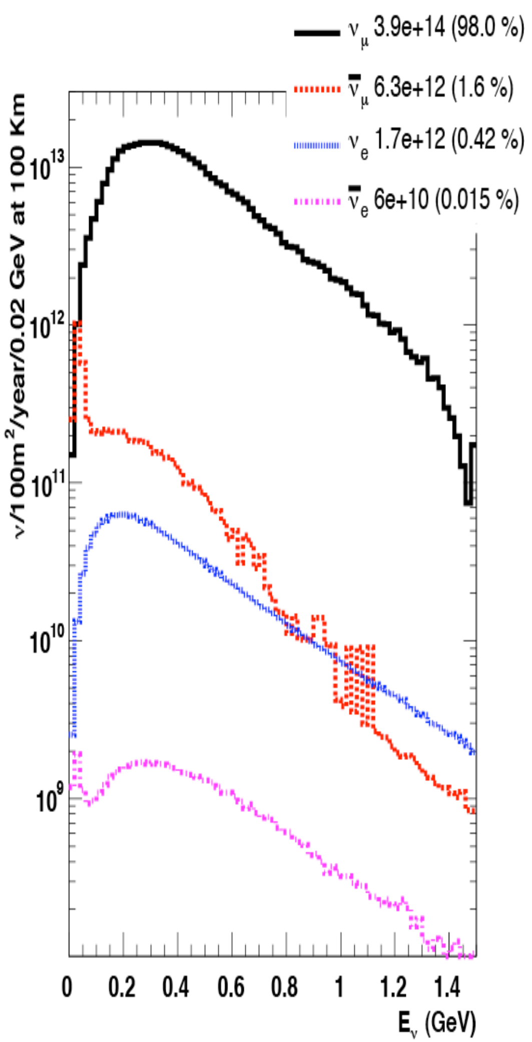


⇒ horn shape (conical)

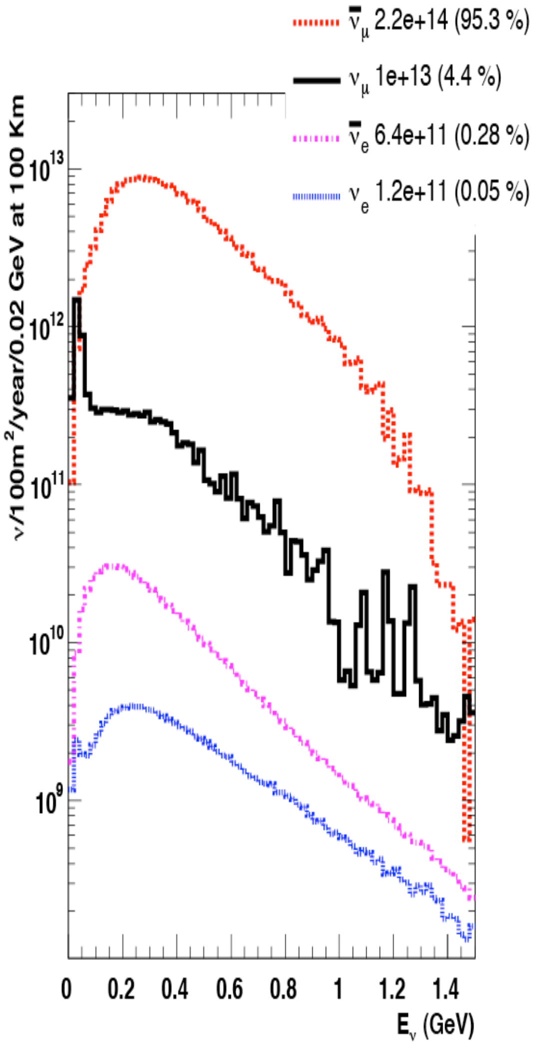
Neutrino Spectra



horn on/off



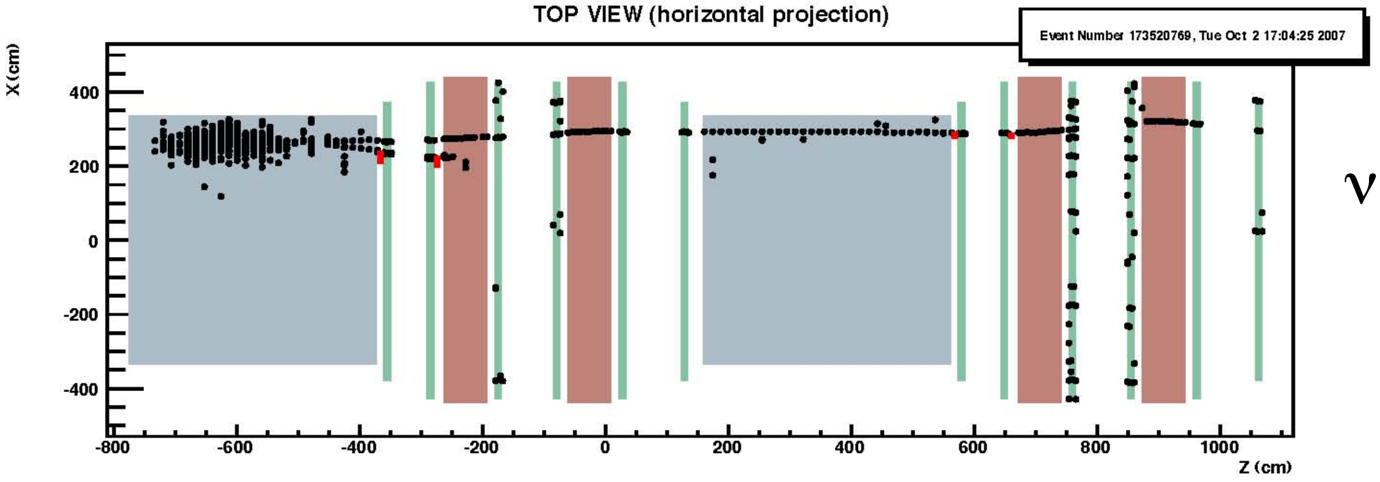
neutrinos

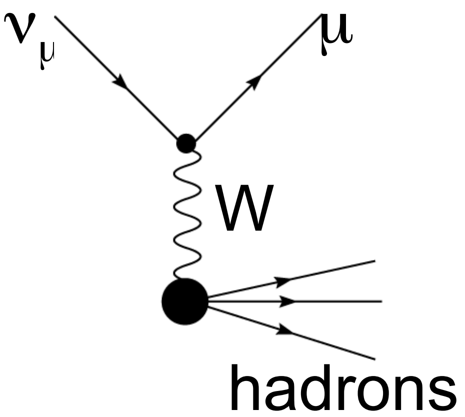


anti-neutrinos

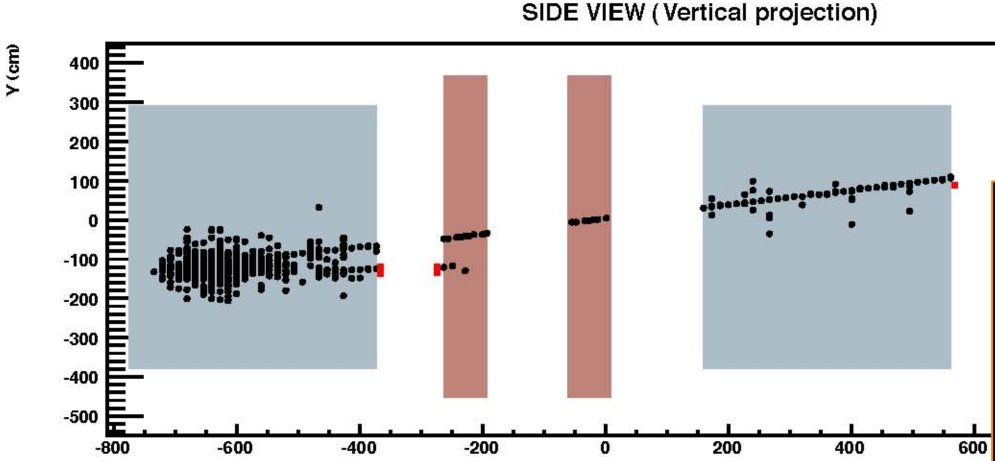
First OPERA events

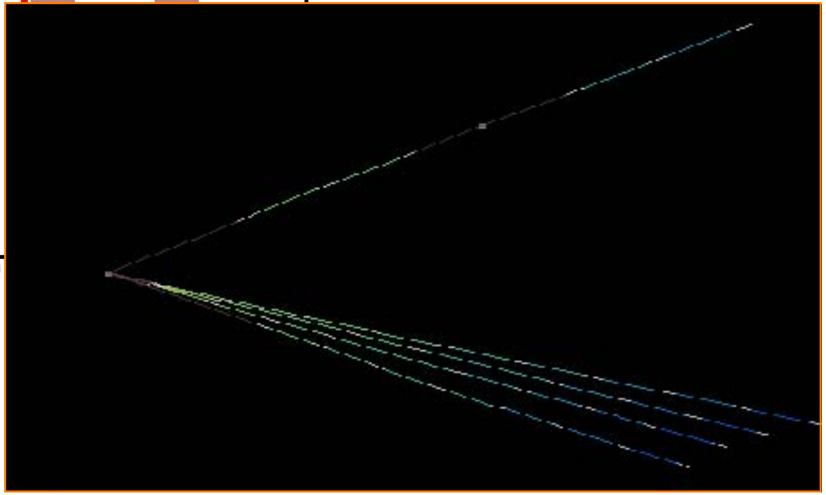
2007





charged current

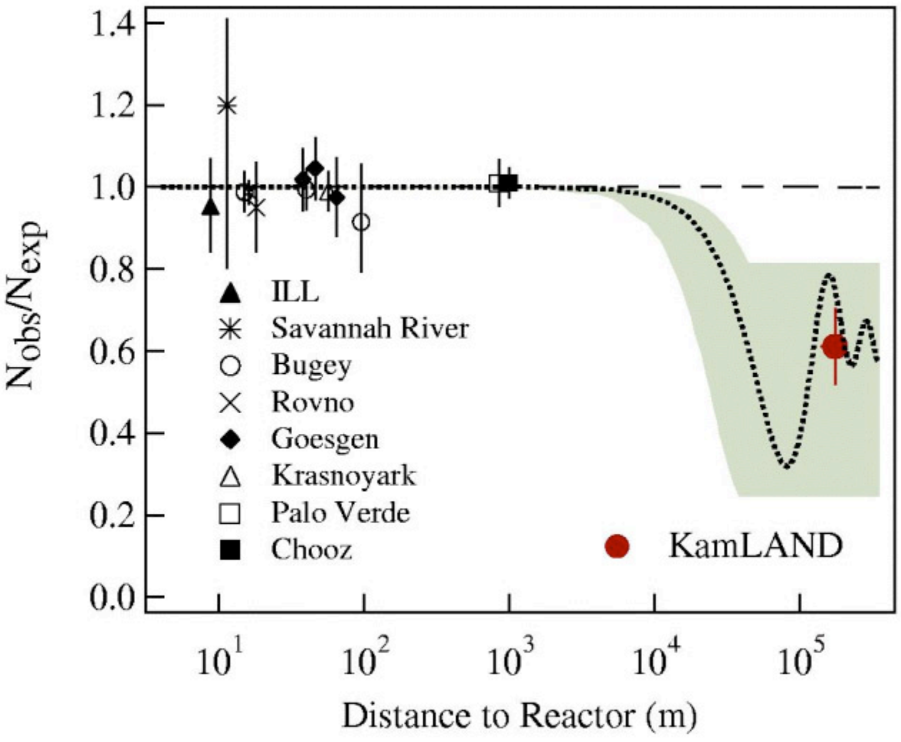


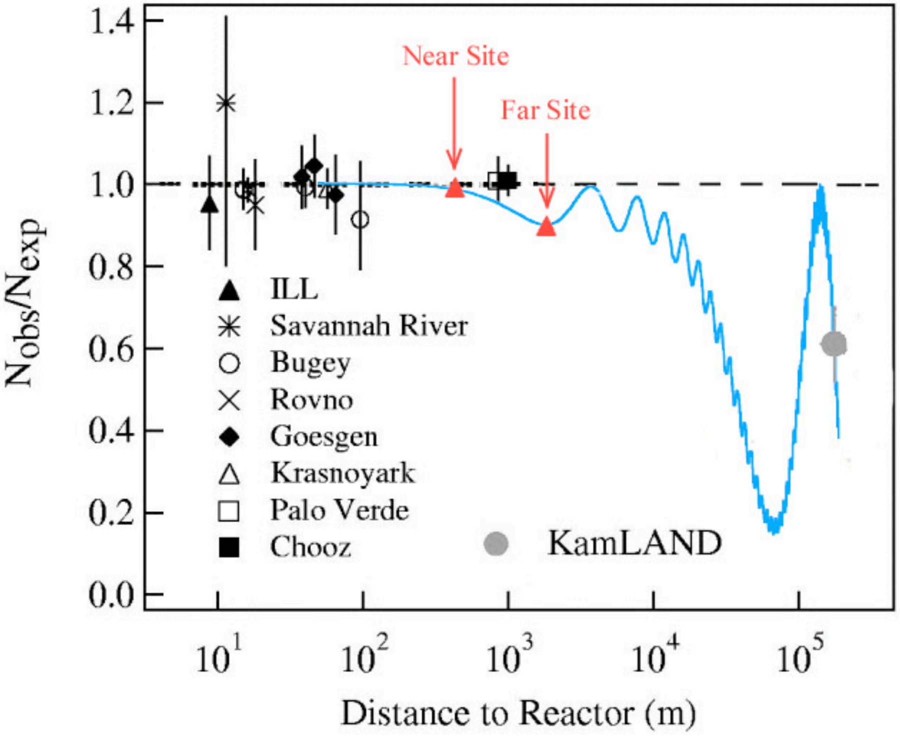


in the emulsions

The θ_{13} hunting

disappearance of electron neutrinos



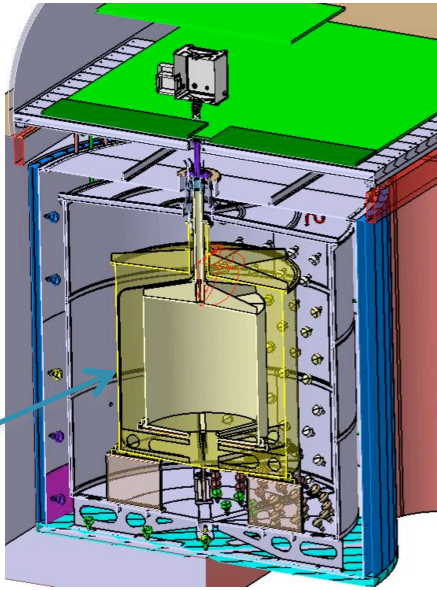


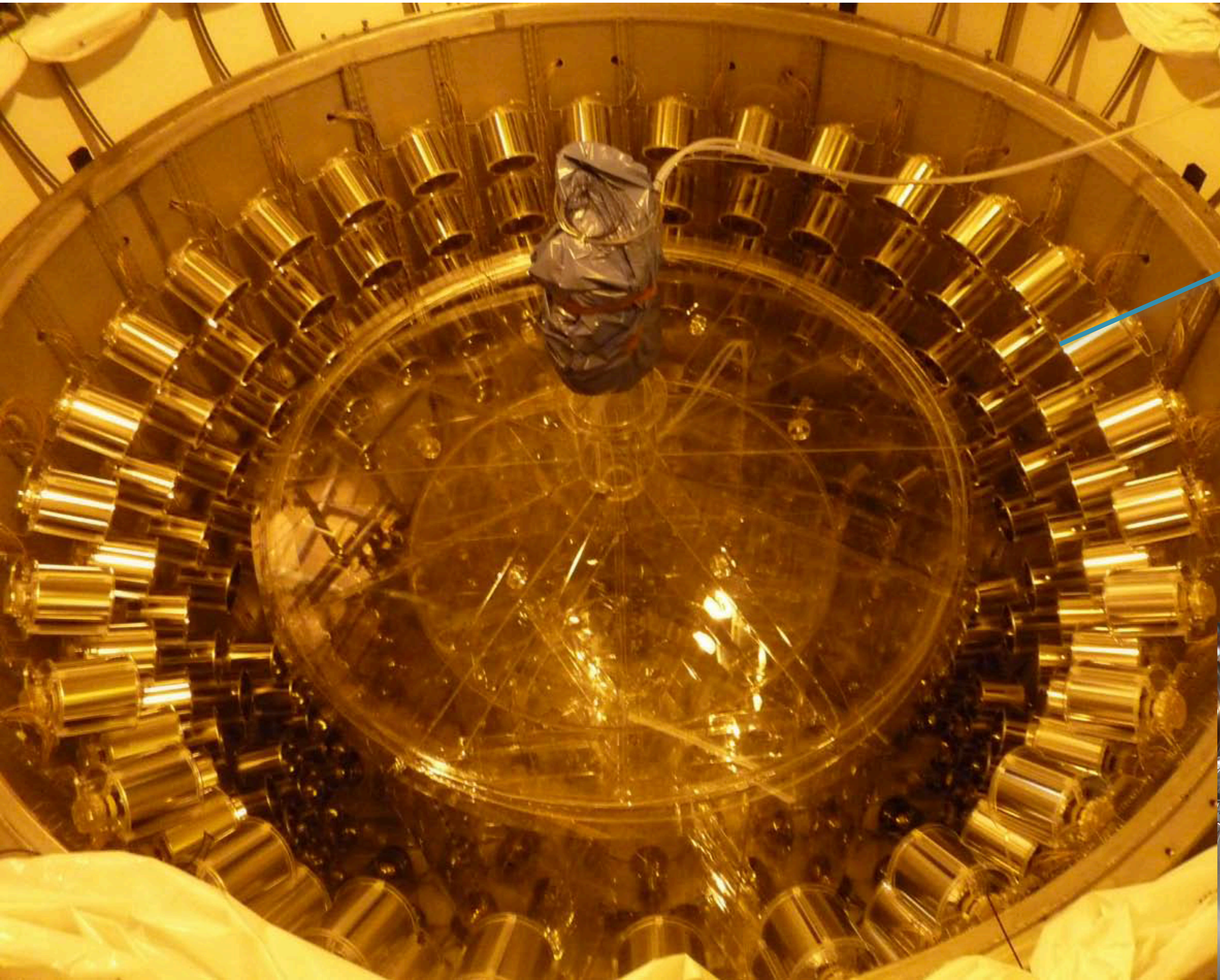
Actually, we have almost neglected θ_{13} on this figure

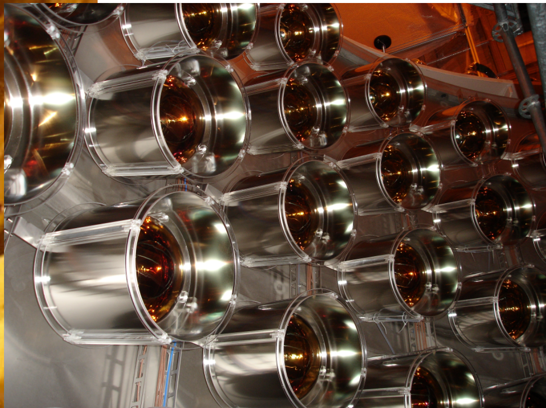
For θ_{13} ~ 10°

Far DC Detector construction

Acrylic Gamma Catcher
installation (May 2010)

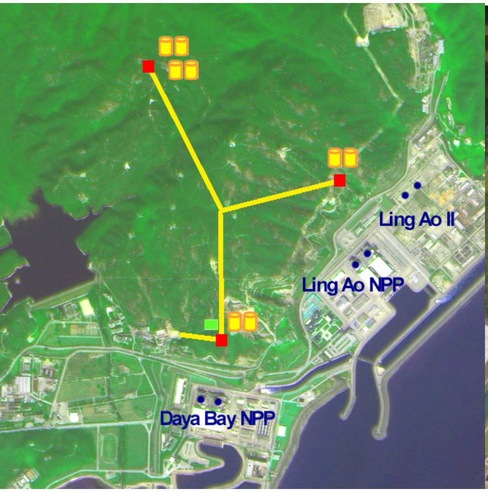






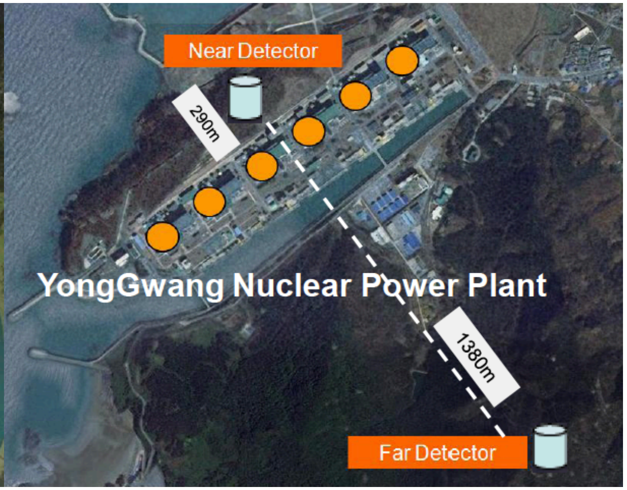
Project Comparison

Daya Bay
(China)



Double Chooz
(France)

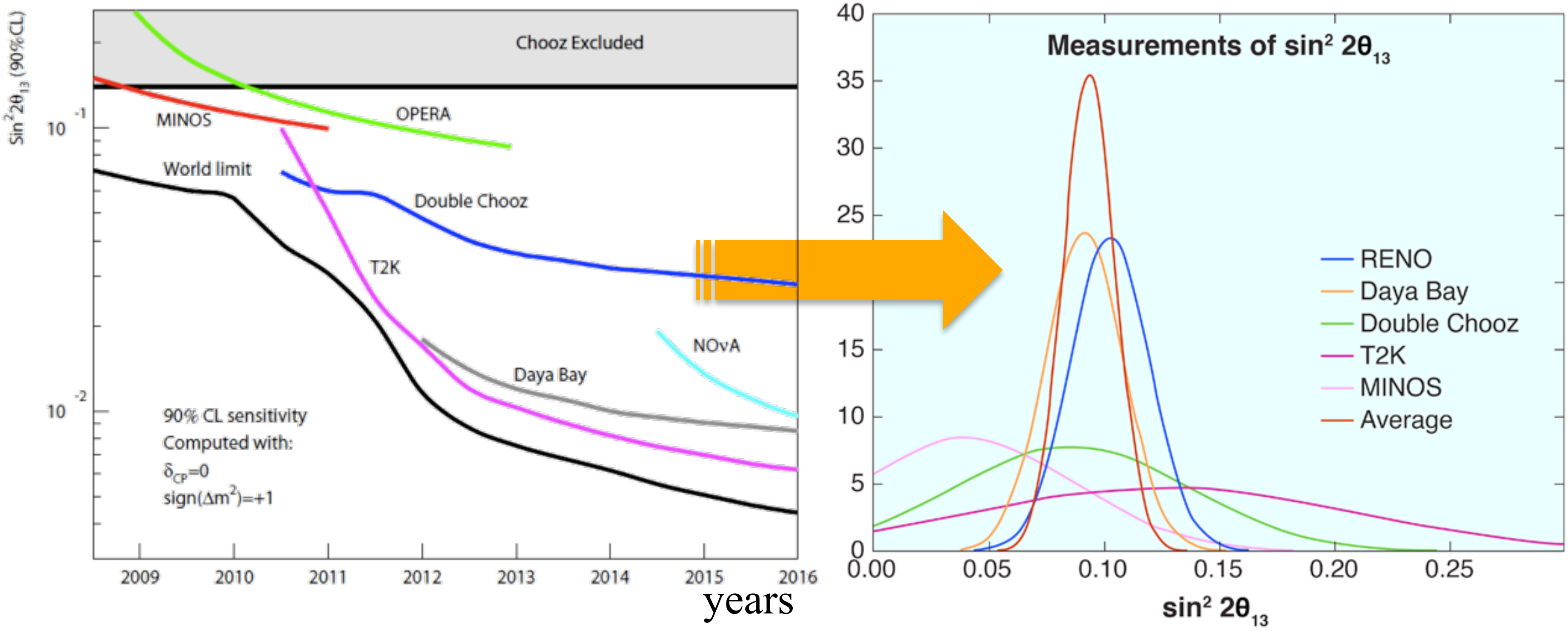
RENO
(South Korea)



	Luminosity in 3 years (ton·GW·y)	Overburden near/far (mwe)	Expected sensitivity	Start of data taking
Daya Bay	4200	270/950	<0.01	August 2011
Double Chooz	210	80/300	0.02~0.03	April 2011
RENO	740	90/440	~0.02	August 2011

Results on θ_{13}

expectations measurements

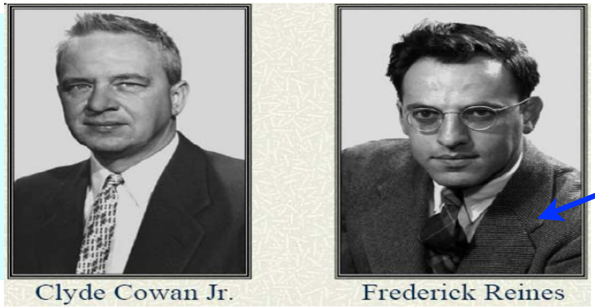


$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$$

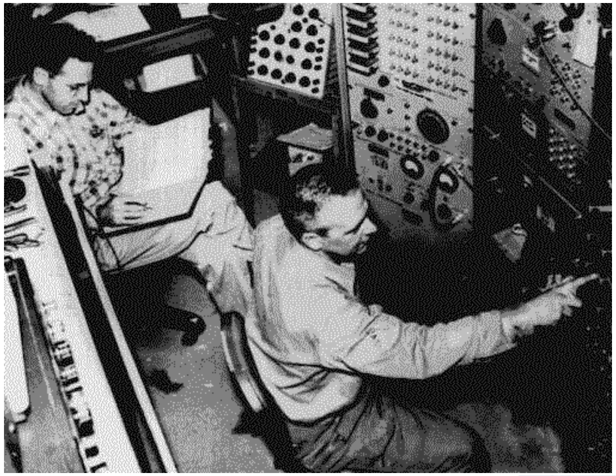
- θ_{13} is large!
- Proposed facilities to be readjusted...

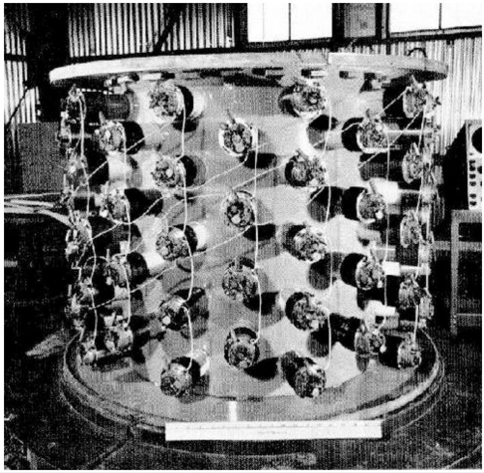
following the ν history…

1956: **Fred Reines and Clyde Cowan** detect the first neutrino interactions near the nuclear reactor of Savannah River at the USA (11 m from the reactor and 12 m underground).

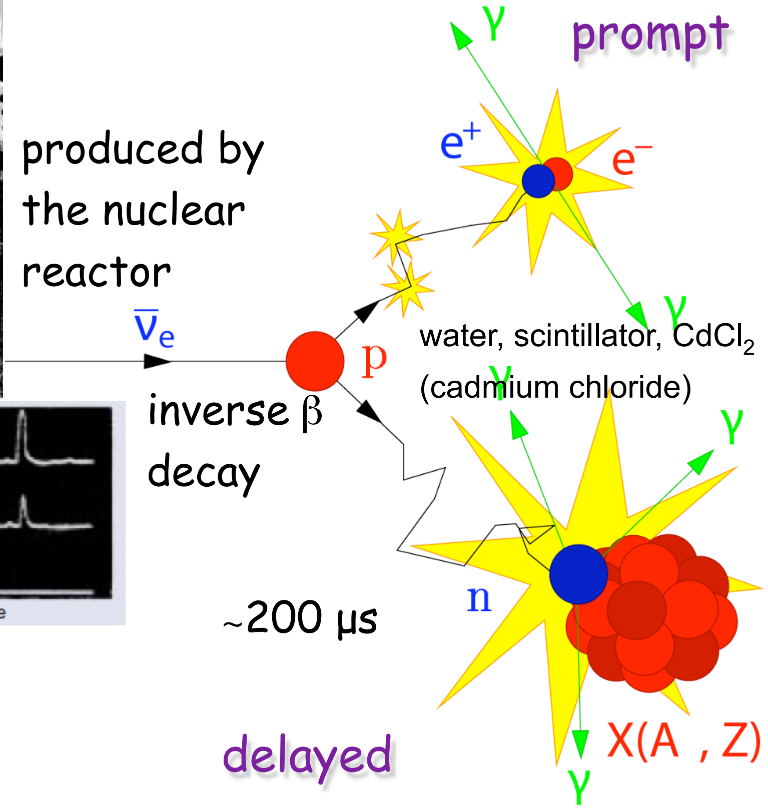


Nobel prize in 1995





about three neutrinos per hour

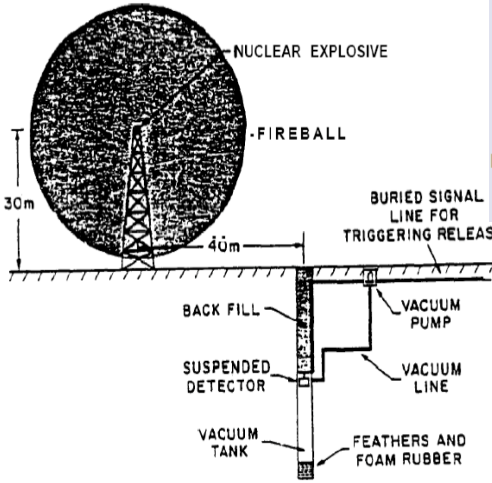


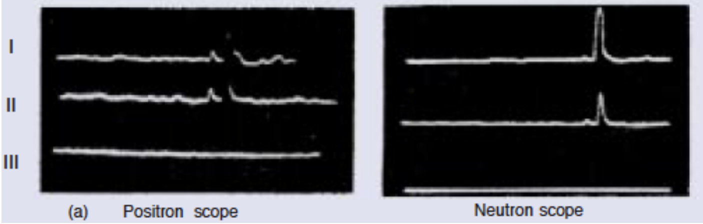
produced by the nuclear reactor

water, scintillator, $CdCl_2$ (cadmium chloride)

inverse β decay

~200 μs



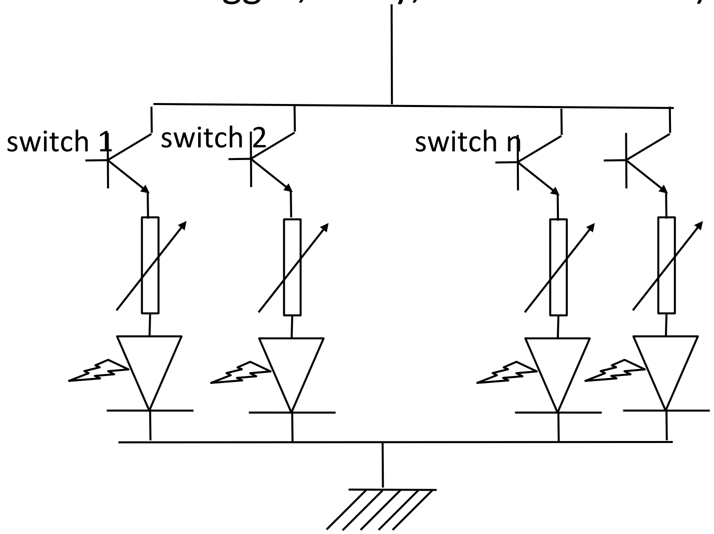


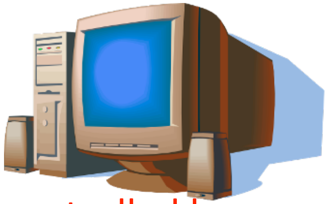
they also envisaged the use of an atomic explosion...

IV Calibration system

Generator (internal or external trigger, delay, remote control)

send to the DAQ a 96 bit word to give the flashed LED pattern

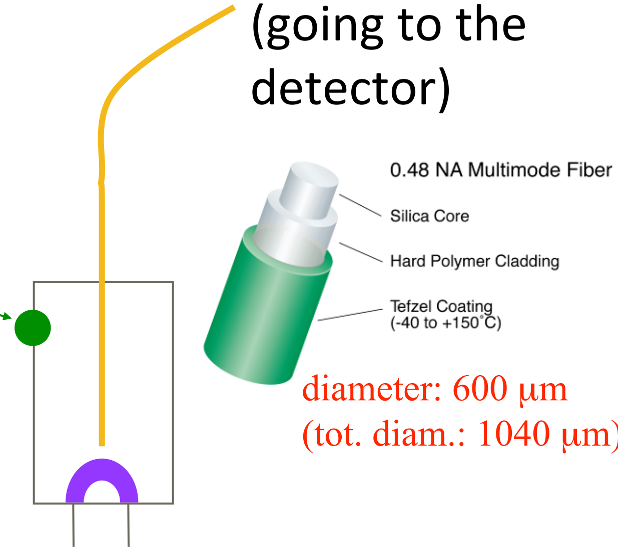




controlled by LabView (GPIB or ethernet)

quartz fibre (going to the detector)

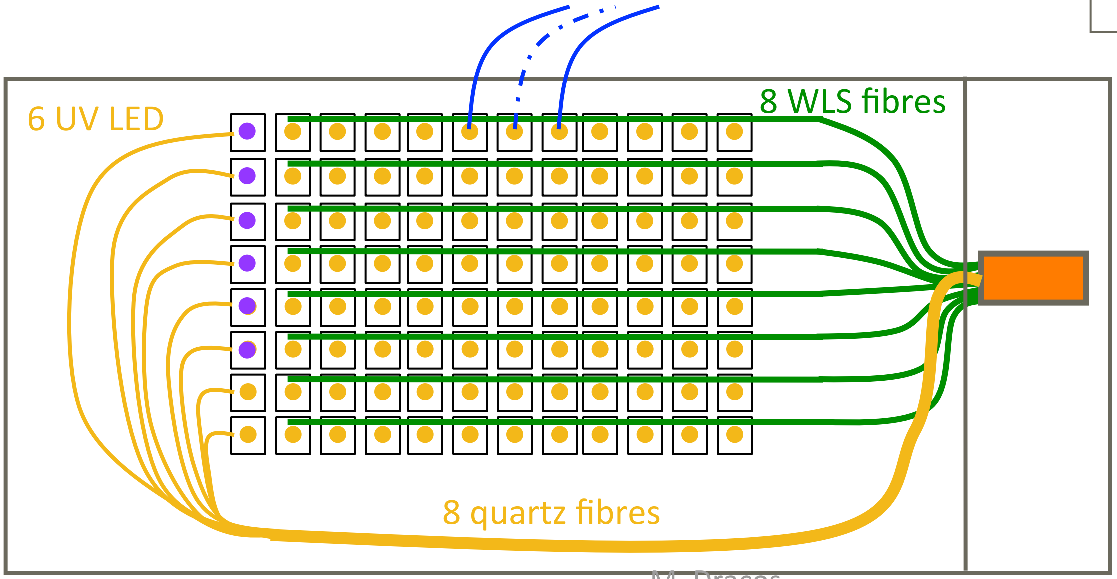
WLS fibre



diameter: 600 µm (tot. diam.: 1040 µm)

LED (475 nm or 365 nm)

to the detector

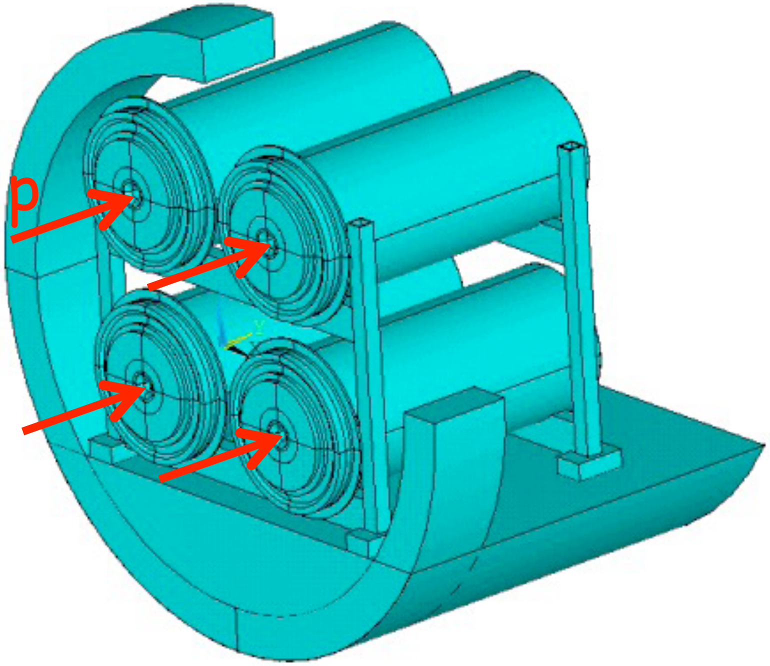


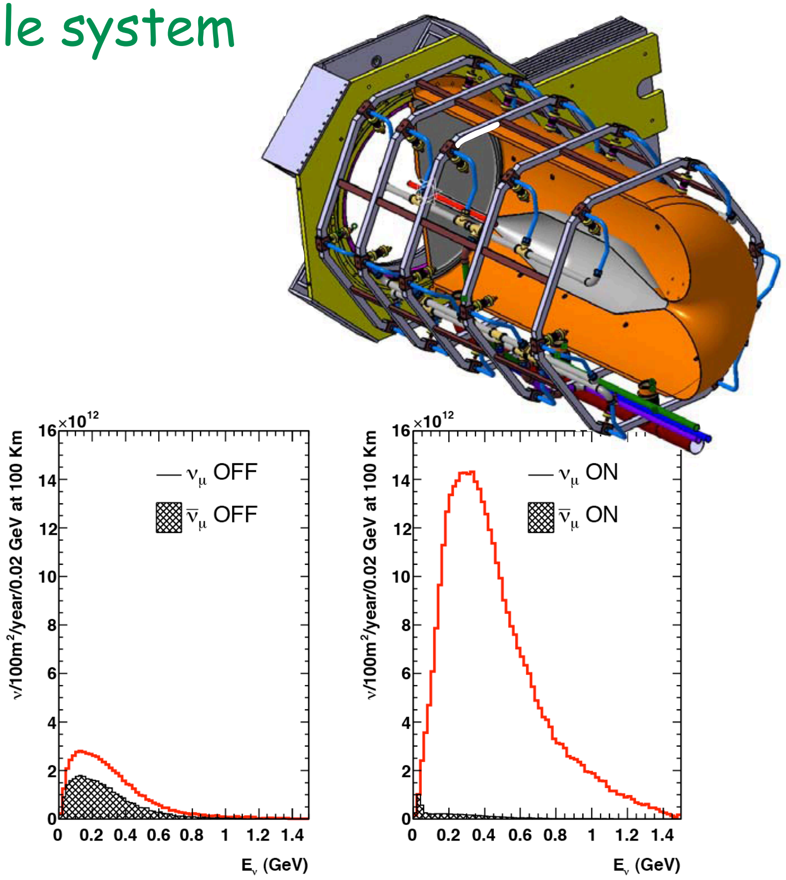
monitoring photodetector (signal to be sent in a “normal channel, FADC, if possible use the same HT than the other IV PMT's)

How to mitigate the power effect

4 target/horn system (4×4 m^2) with single decay tunnel (~30 m) → back to solid targets able to afford up to ~1.5 MW proton beam (get rid of liquid Hg)

more expensive but more reliable system

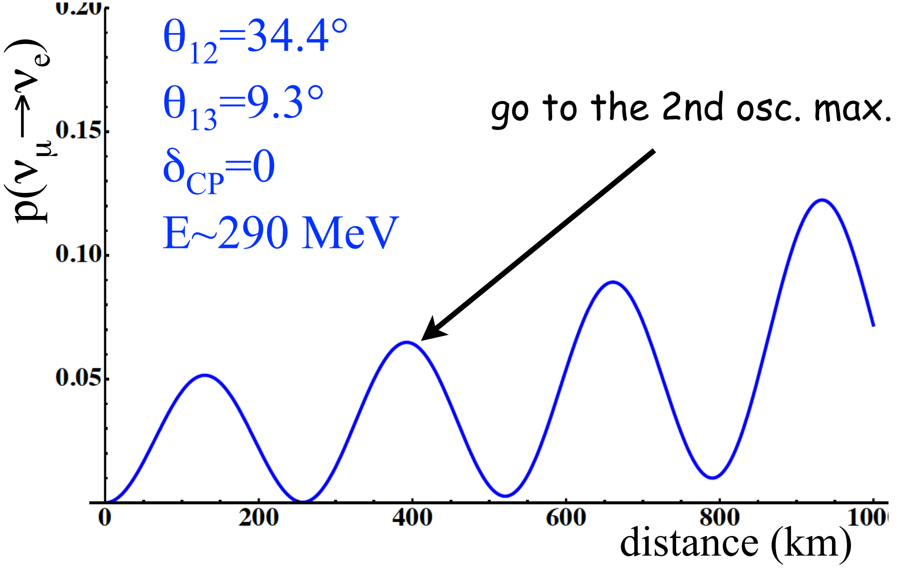




Possible Detector Locations

- Many mines (active or not) are available in Sweden
- What is the optimal position for CPV
- How this project could help for MH?

$\Delta m^2_{sun}=7.6\times10^{-5}$ eV^2
$\Delta m^2_{atm}=2.5\times10^{-3}$ eV^2
$\theta_{23}=44.4°$
$\theta_{12}=34.4°$
$\theta_{13}=9.3°$
$\delta_{CP}=0$
E~290 MeV



go to the 2nd osc. max.