Theoretical and Experimental aspects on Physics with Megaton-size Detectors

Thomas Patzak, APC

How it started:

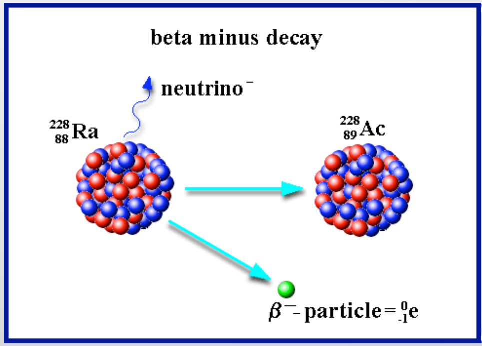
1914: James Chadwick: The energy spectrum is continus! (using an ionisation chamber)

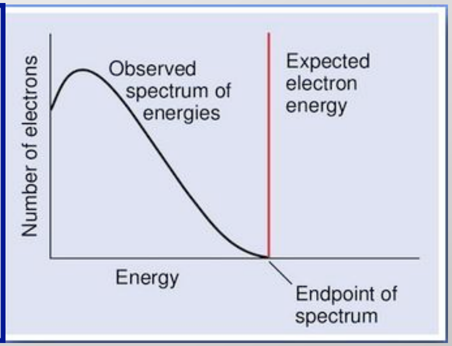
Problem:

At this time the nucleus was made of A protons et A - Z électrons

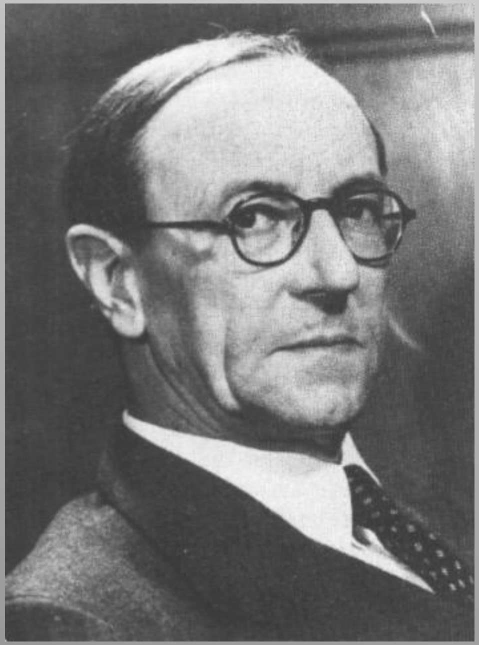
β− Decay: (A, Z) —> (A, Z-1) + e^-

= two-body decay!

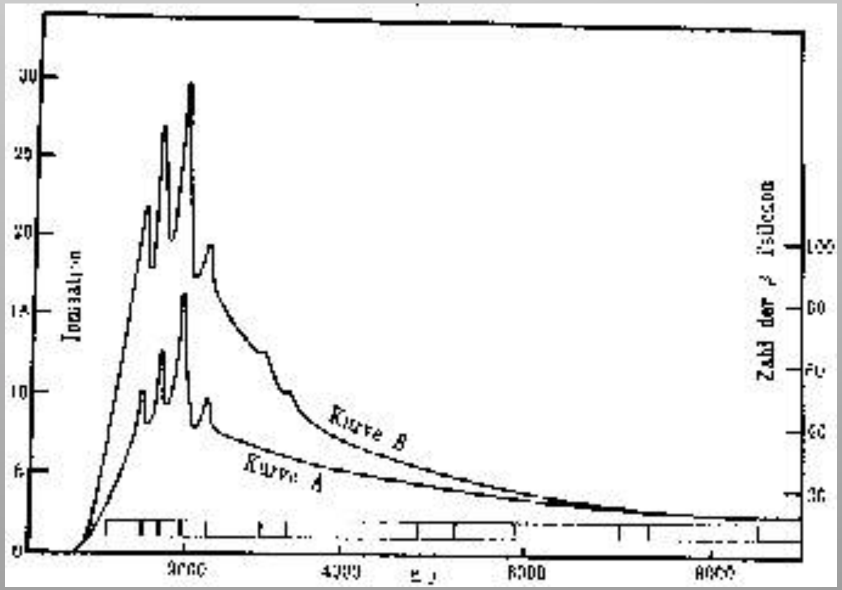




One should get a mono-energetic peak for the e^-



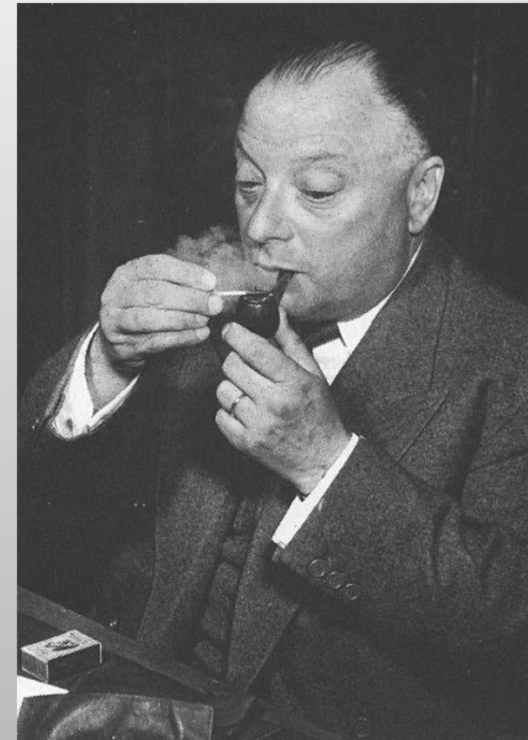
1891 - 1974



How to solve this fondamental problem?

Niel Bohr (1885 - 1962)

Wolfgang Pauli (1900 - 1958)



« Energy is only sticticaly conserved »

Bohr 1930: "At the present stage of atomic theory we have no argument, either empirical or theoretical, for upholding the the energy principle in β-ray disintegrations"

A famous letter…
« emission of an extra particle »

4th 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 Li6 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...**

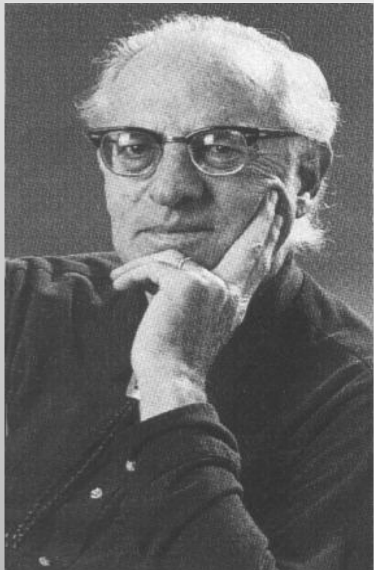
I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honored predecessor, Mr. Debye, 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.

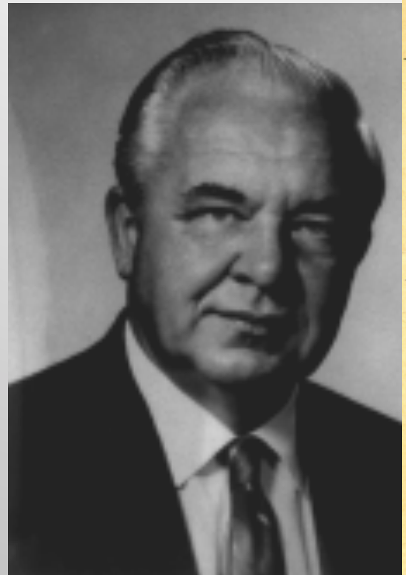
Your humble servant
W. Pauli

(CERN, Pauli archives)

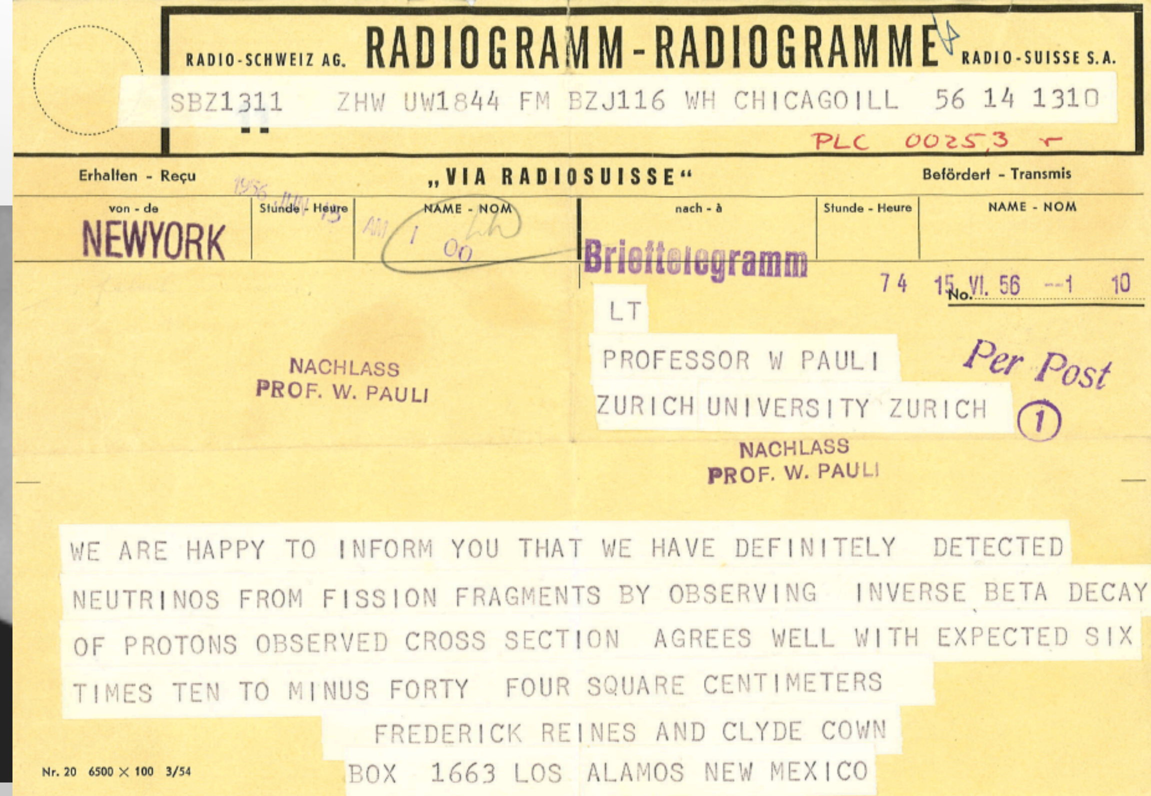
26 years later….



1918-1998



1919-1974



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NEWYORK			Brieftelegramm		

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LT

NACHLASS PROF. W. PAULI

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

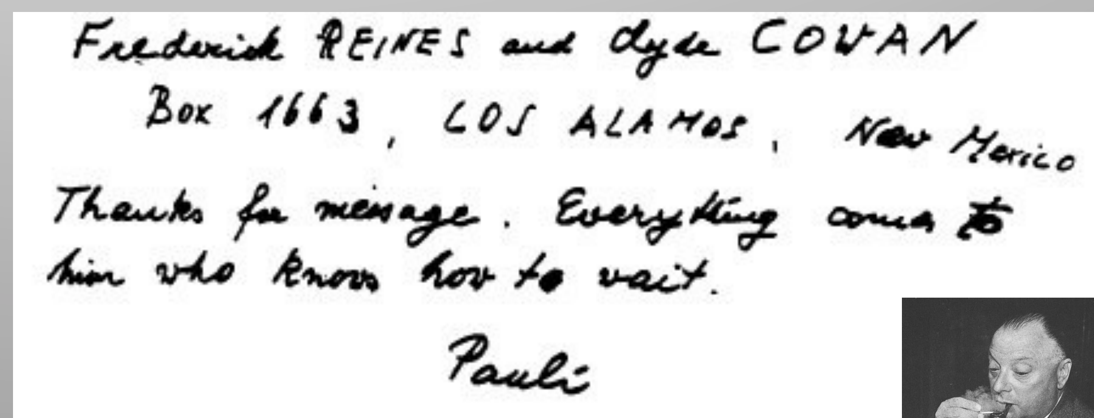
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

Prix Nobel pour Reines en 1995
(Cowan décédé)



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

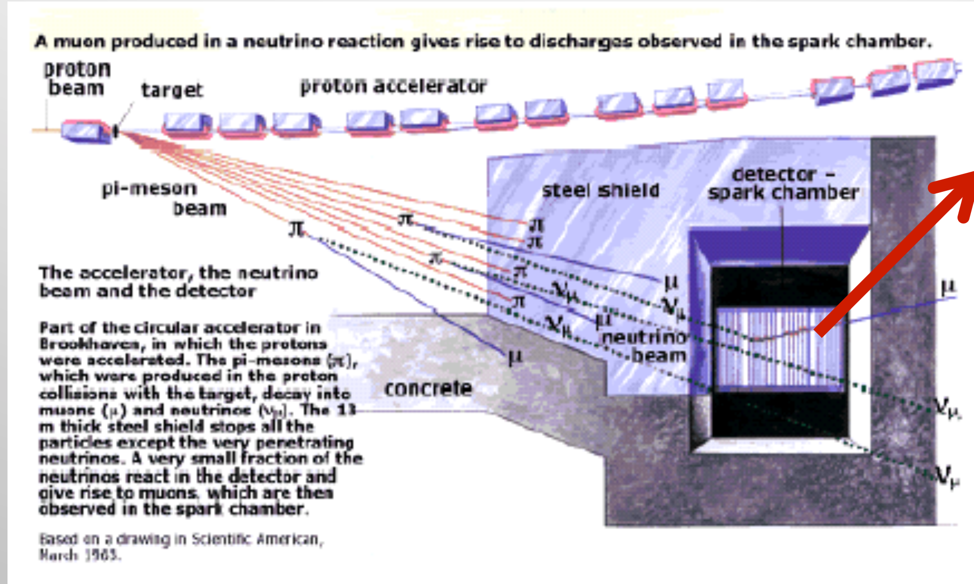
Thanks for message. Everything comes to him who knows how to wait.

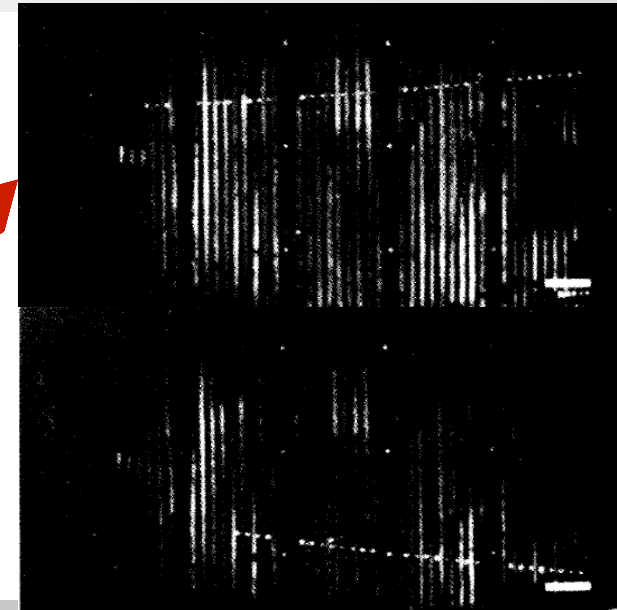
Pauli

1962: Muon Neutrino Discovery:

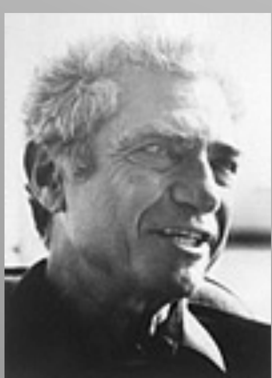
Leon M. Lederman
1922-

Melvin Schwartz
1932-





34 events with a single *μ*
Estimated Background = 5



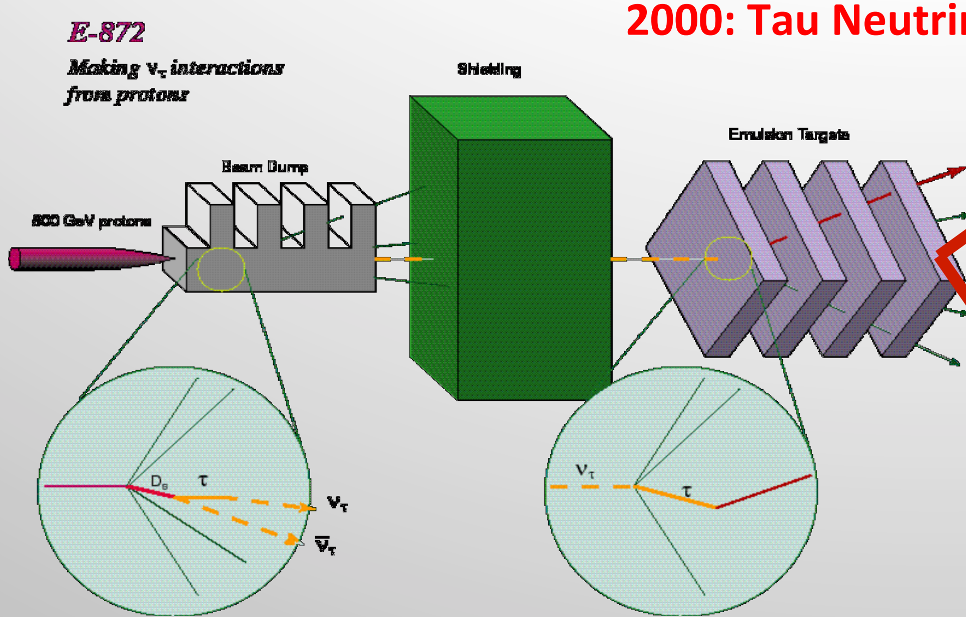
Jack Steinberger
1921-

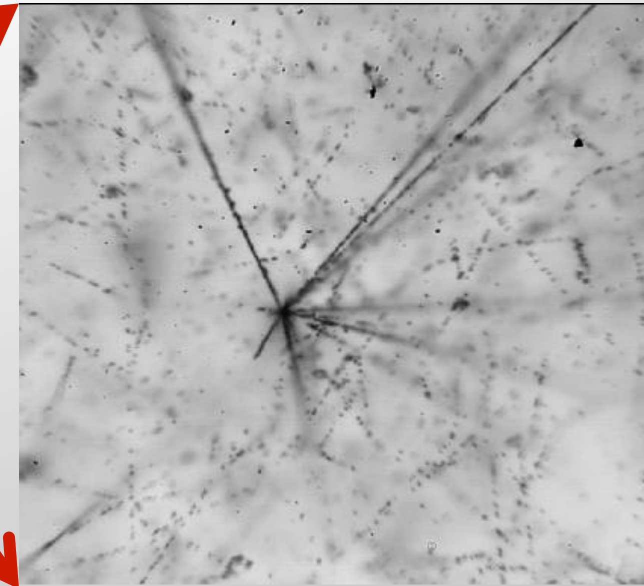
- Passing through 820 cm of Al without interacting!
- if π, λ_π (Al) at 400 MeV = 100 cm
- 8 interactions expected – zero found.

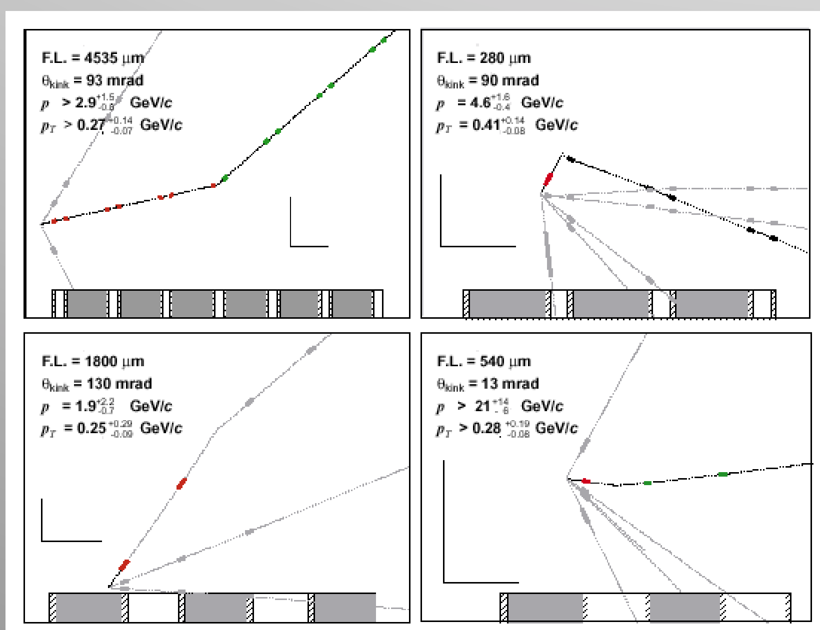
$\nu_\mu \neq \nu_e$

Prix Nobel 1988

2000: Tau Neutrino discovery by DONUT







The New York Times ON THE WEB

So far we have in the standard model:

Doublets d'isospin faible:

I^w	I^w_3	q	$L_e = 1$	$L_\mu = 1$	$L_\tau = 1$
½	- 1/2	-1	e^-_l	μ^-_l	τ^-_l
1/2	+1/2	0	ν_{el}	$\nu_{\mu l}$	$\nu_{\tau l}$

Singlets d'isospin faible : e^-_r μ^-_r τ^-_r

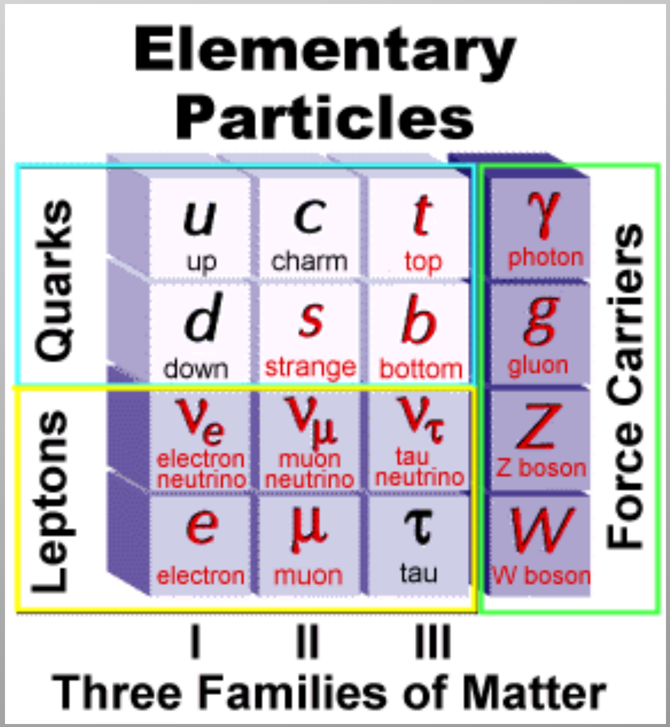
Properties: mass = 0

charge = 0

spin = 1/2

interaction = weak

helicity = ν_l , anti ν_r

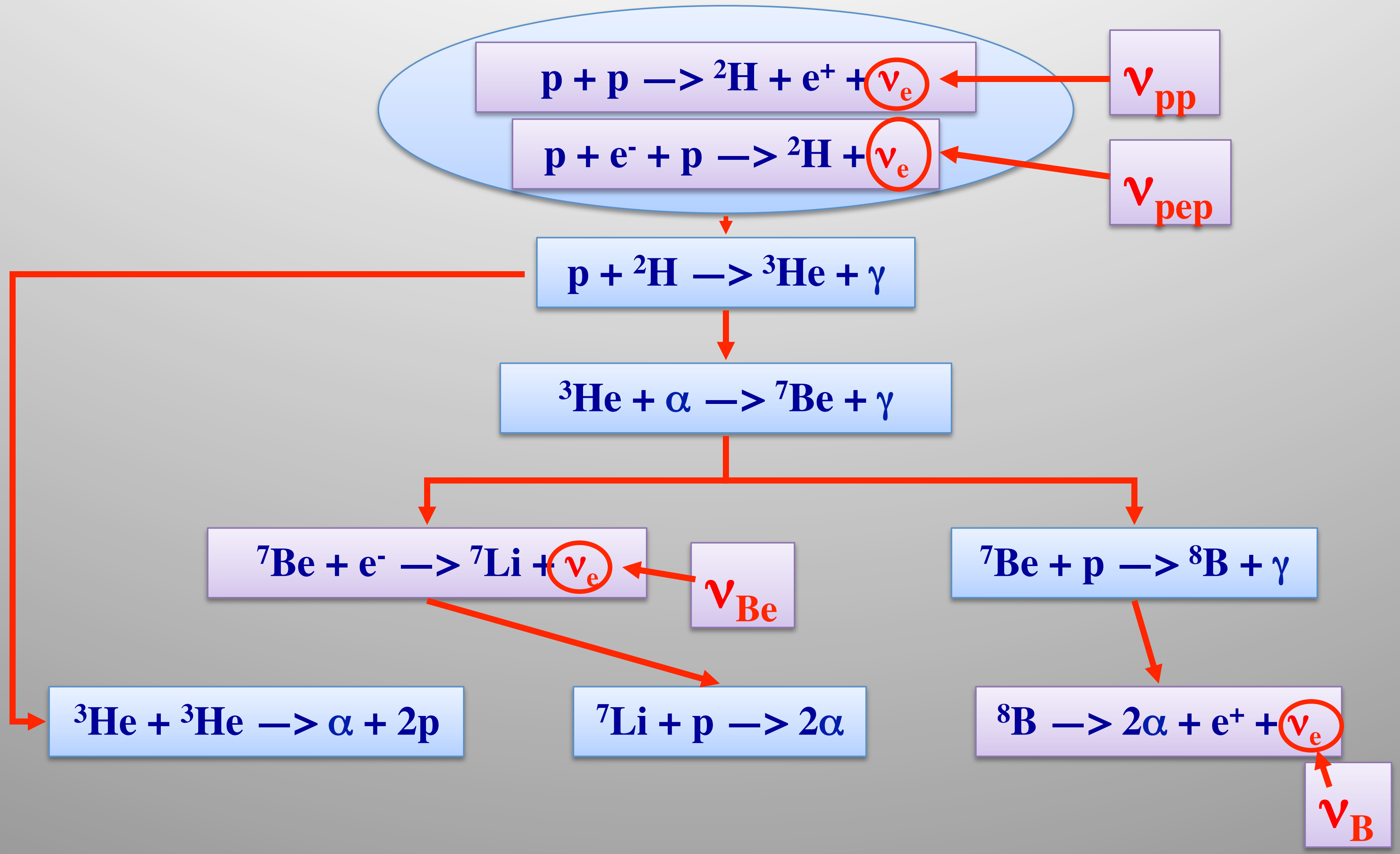


Some surprises:

ν_{atm}

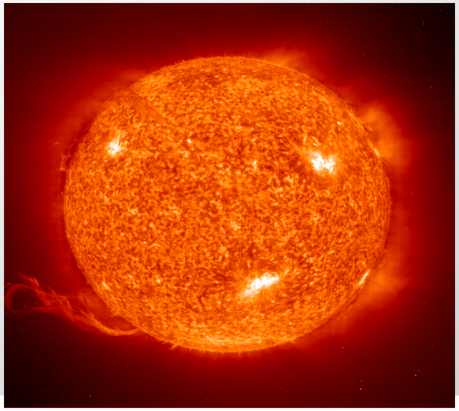
$\nu_{\star}$

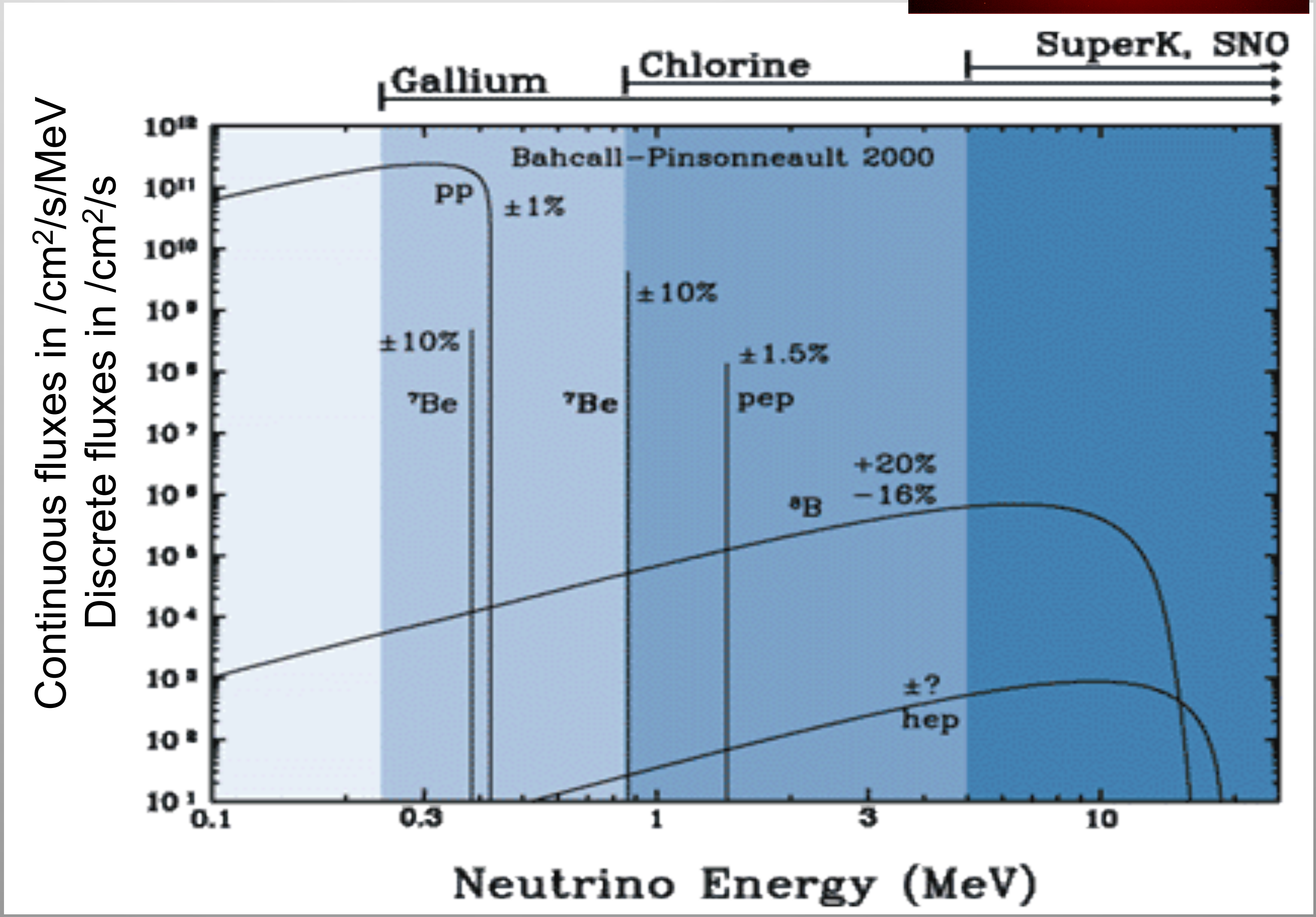
Energy production in the sun:



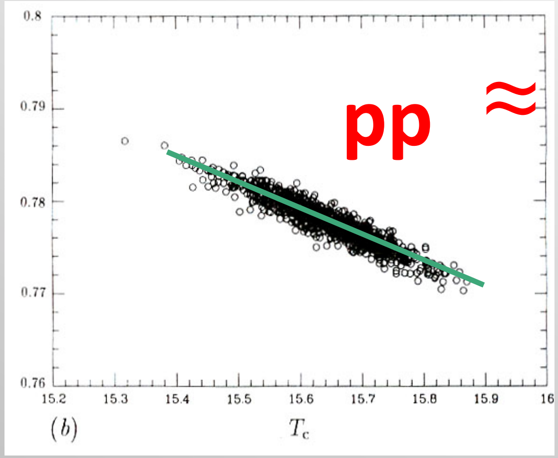
John N. Bahcall

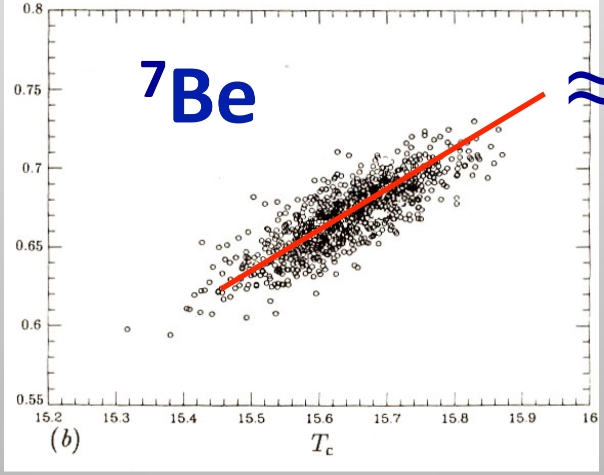
1934 - 2005



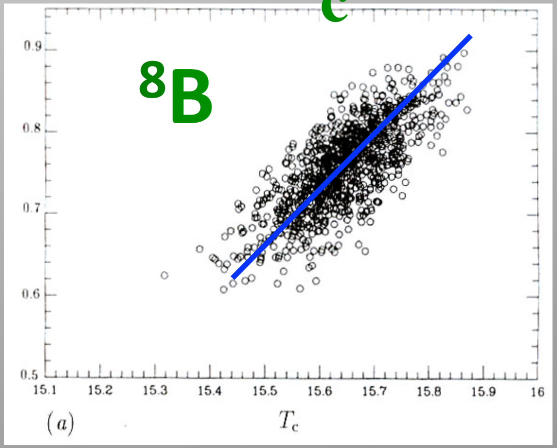


Temperature dependence of the neutrino flux:



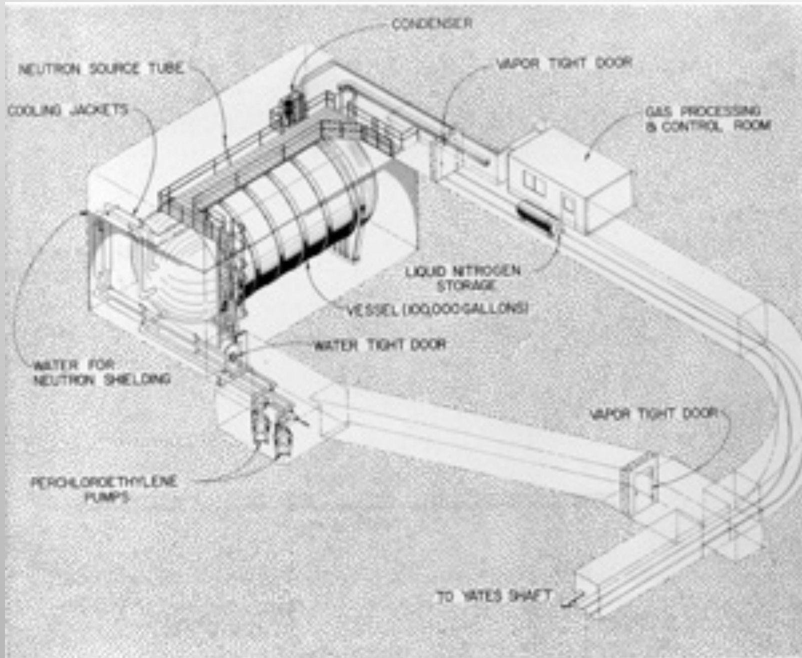


$\approx T_c^{24}$



See also J.N.Bahcall and A.Ulmer, Phys. Rev. D53 (1996) 4202

The « pioneering » chlorine experiment



Homestake mine (South Dakota)

615 tons of C_2Cl_4

$$\nu_e + {}^{37}Cl \longrightarrow {}^{37}Ar + e^-$$

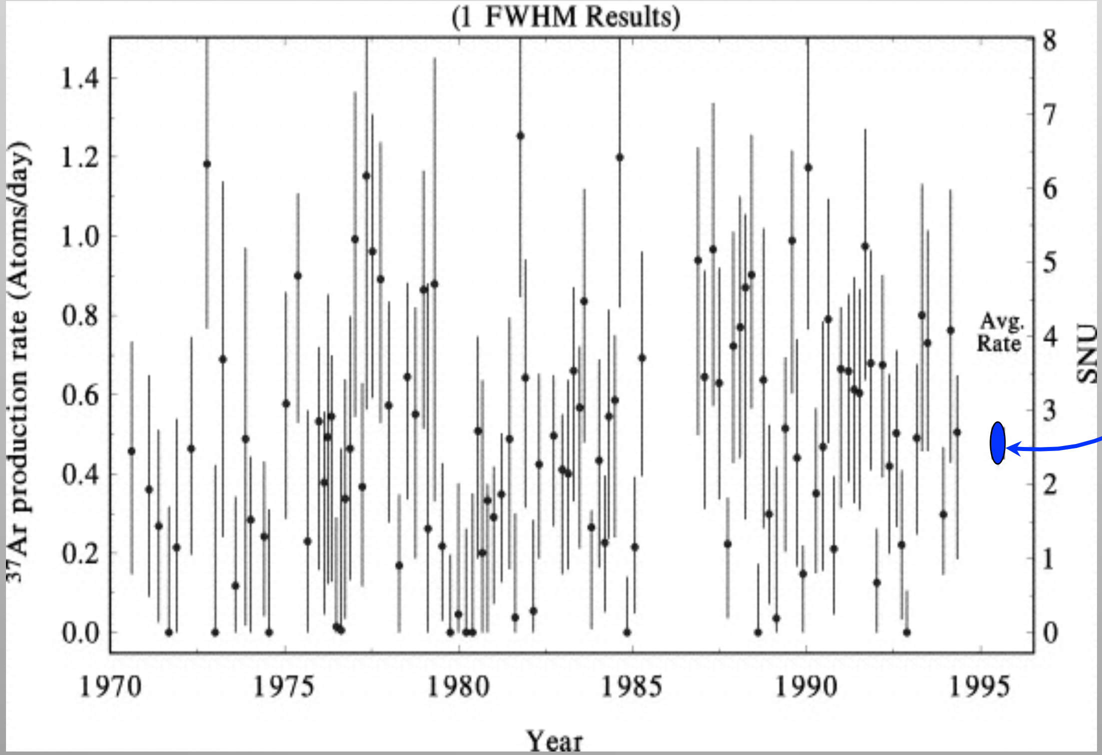
Seuil = 0,8 MeV

$\hookrightarrow$ ^{37}Cl ($T_{1/2}$=35 d)

(R. Davis, Prix Nobel en 2002)

The chlorine experiment

- Radiochemical
- Sensitive to Be and B neutrinos
- 25 years of data (108 runs)

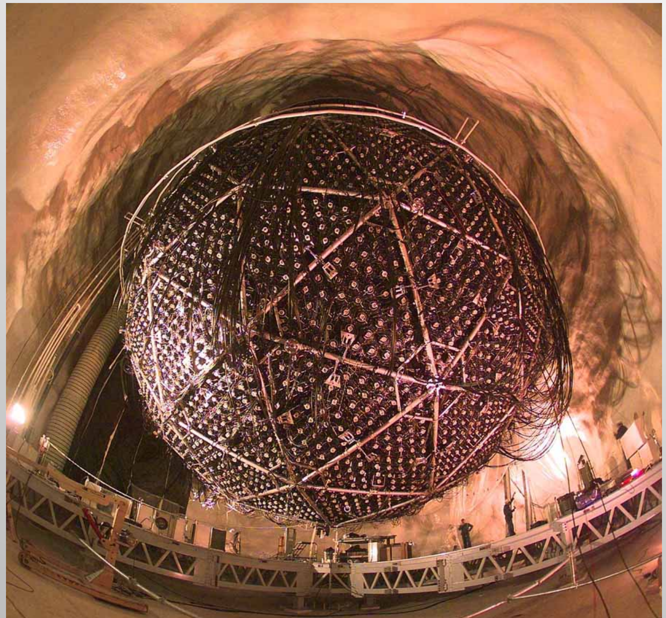


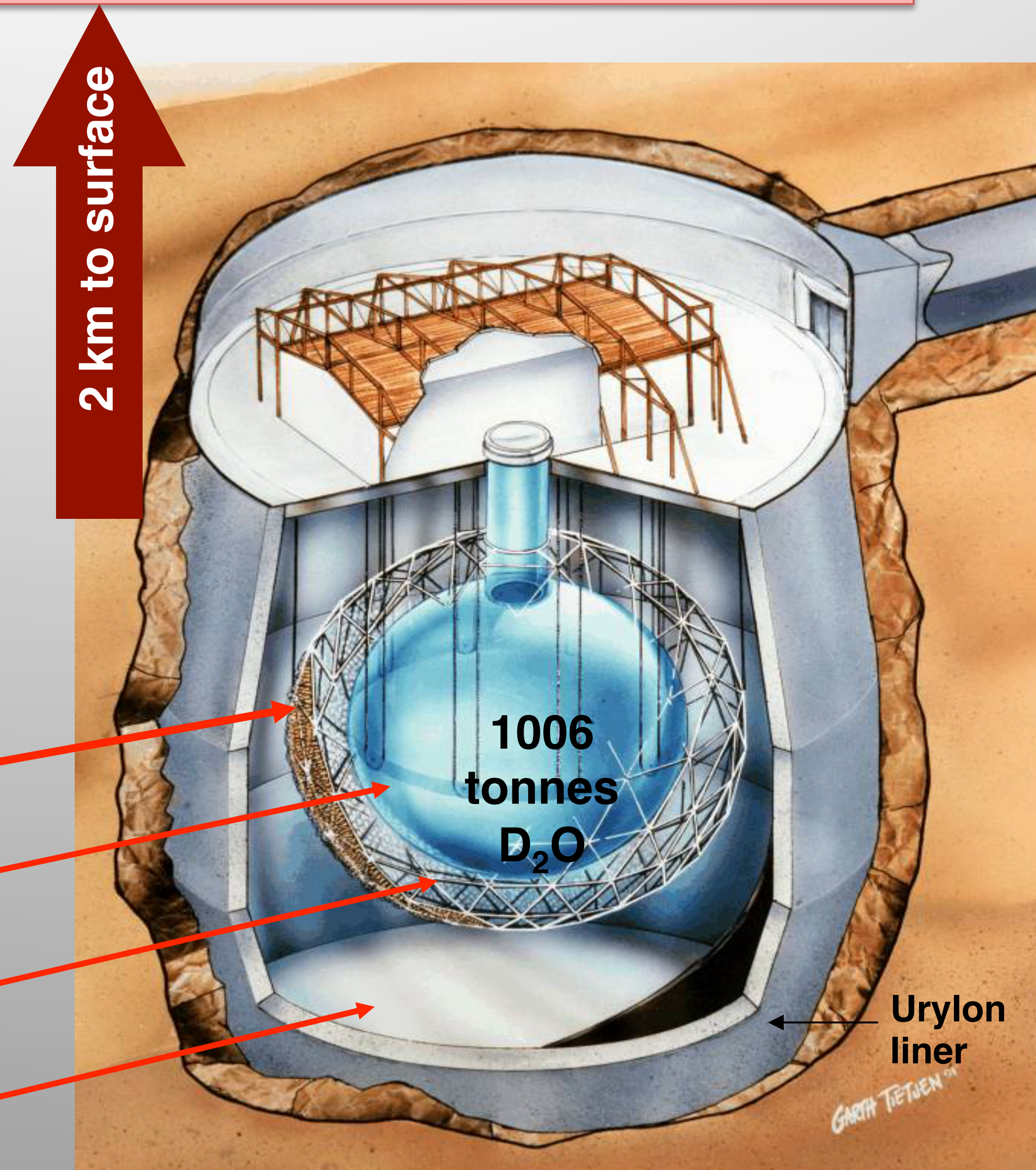
Result :
2.56 ± 0.20 SNU

1/3 of
solar models
(7.6 ± 1.2 SNU)

B.T.Cleveland et al., Ap. J. 496 (1998) 505

L ’expérience SNO (Sudbury Neutrino Observatory) :





17.8m dia. PMT Support Structure
9456 20-cm dia. PMTs
56% coverage

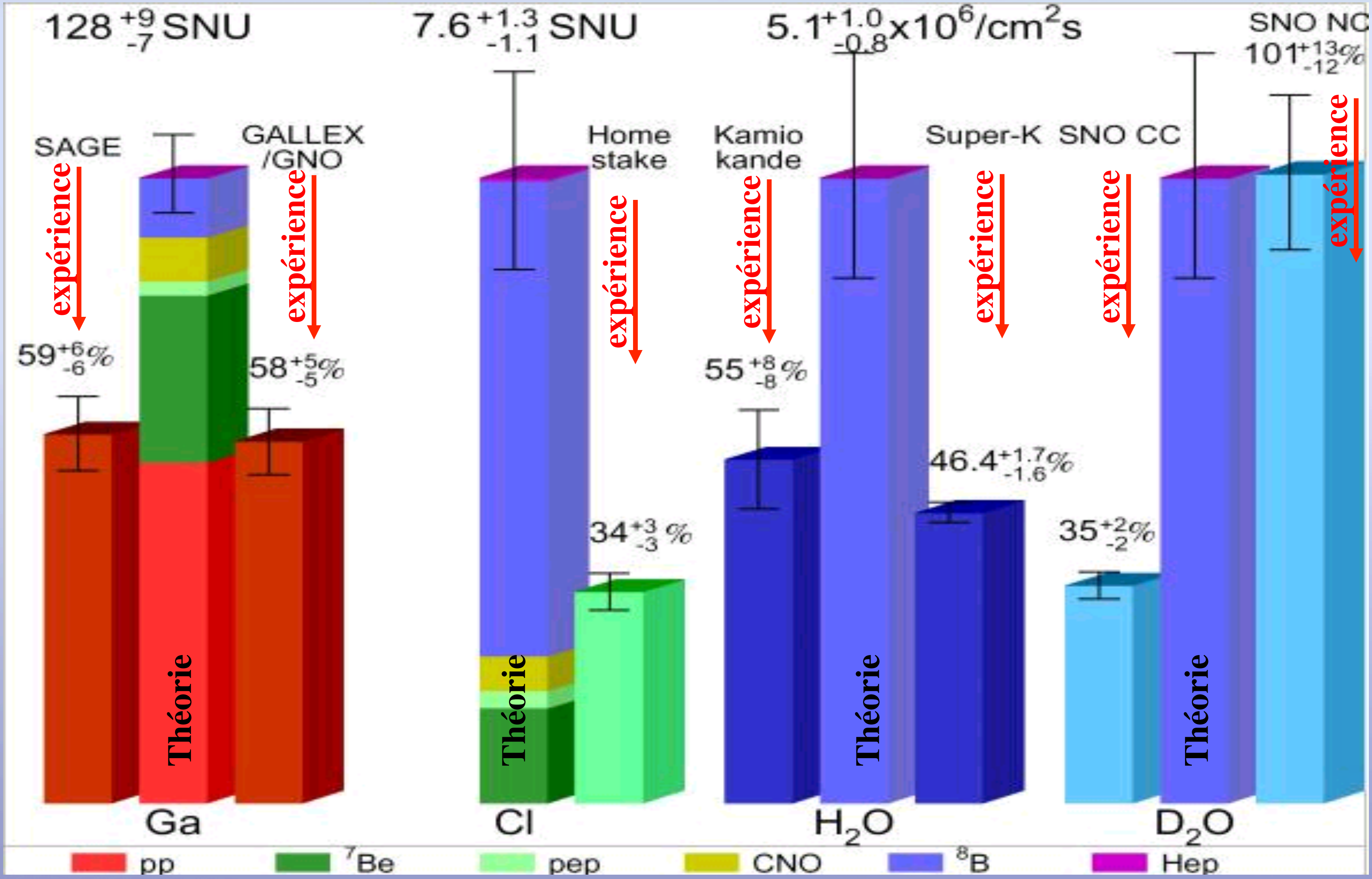
12.01m dia. acrylic vessel

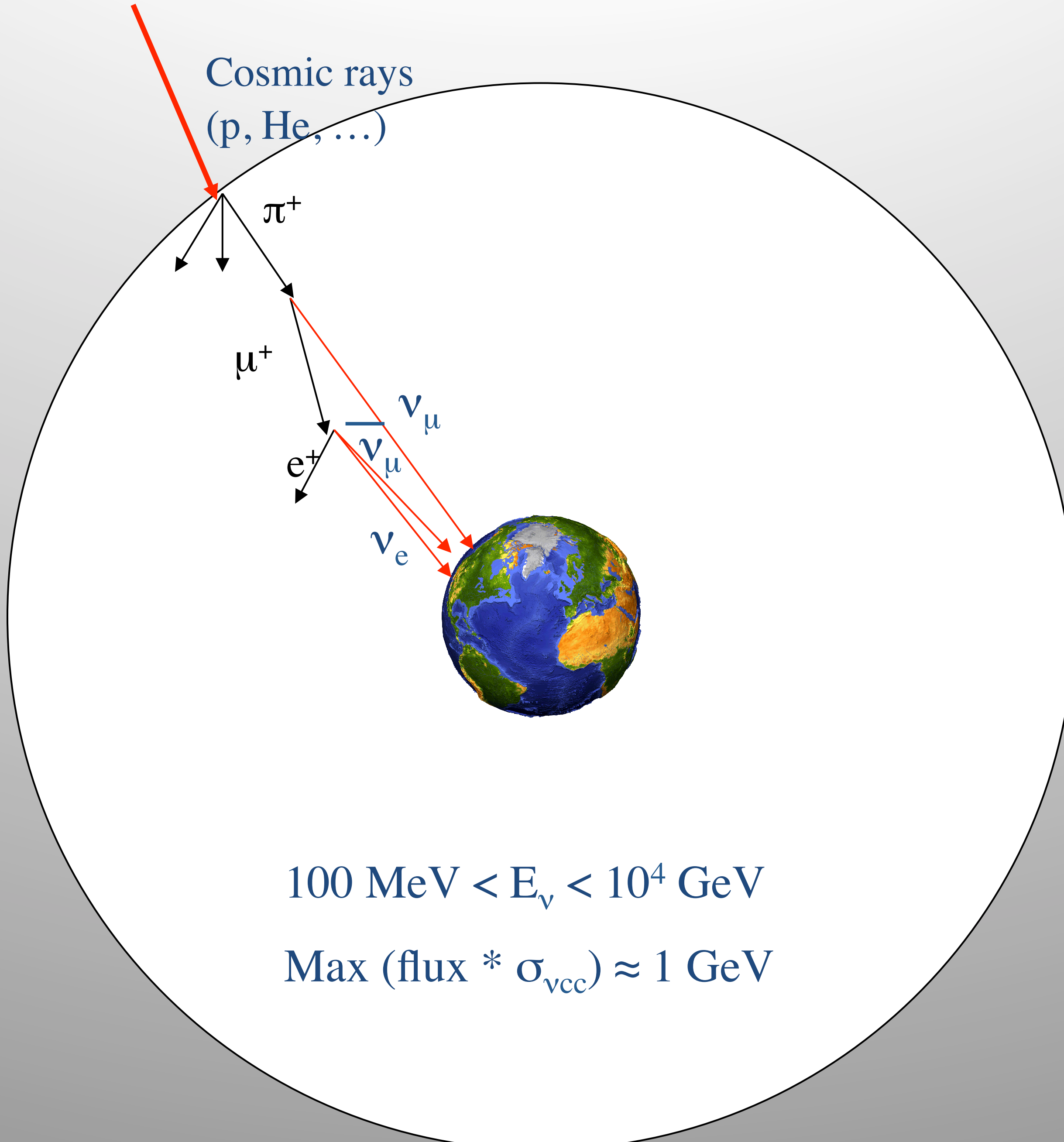
1700 tonnes of inner shielding H_2O

5300 tonnes of outer shielding H_2O

Nucl. Inst. Meth. A449, 127 (2000)

Results from solar neutrino experiments (2002)

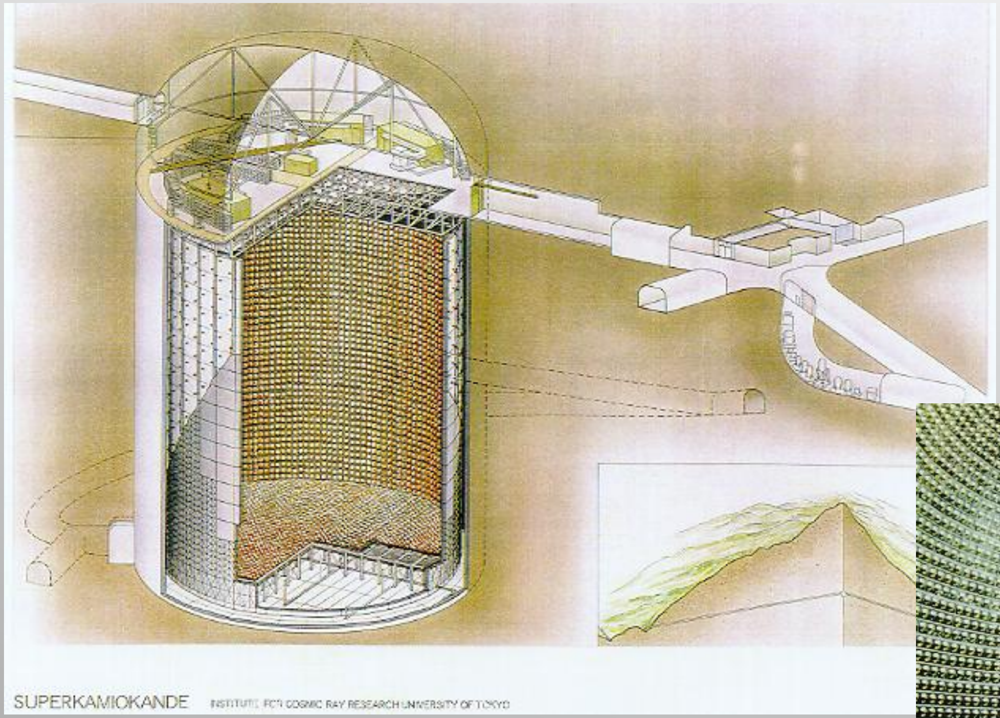




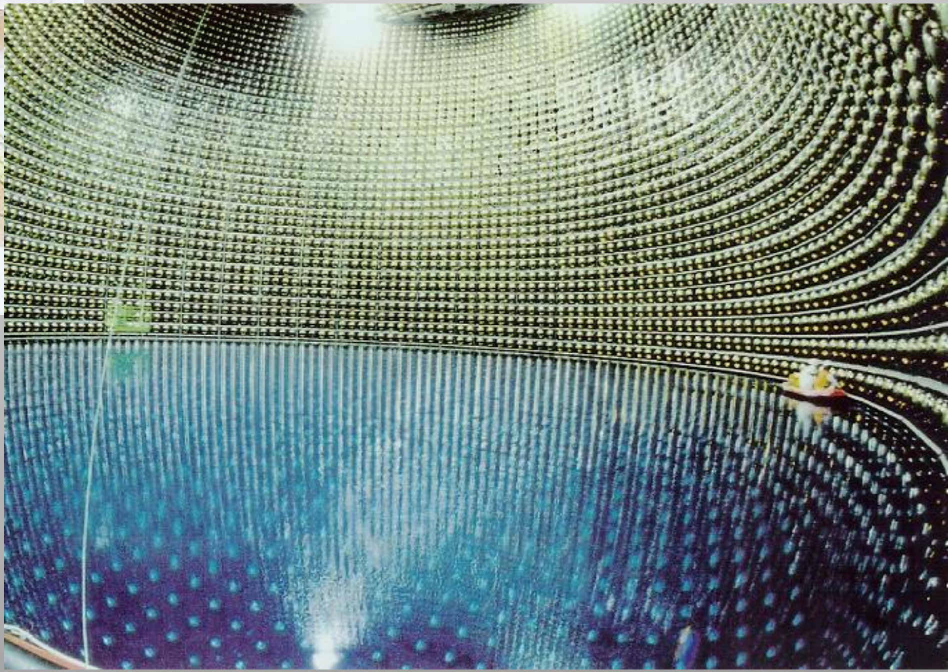
$100\ \text{MeV} < E_\nu < 10^4\ \text{GeV}$

$\text{Max (flux} * \sigma_{\nu cc}) \approx 1\ \text{GeV}$

SuperKamiokande



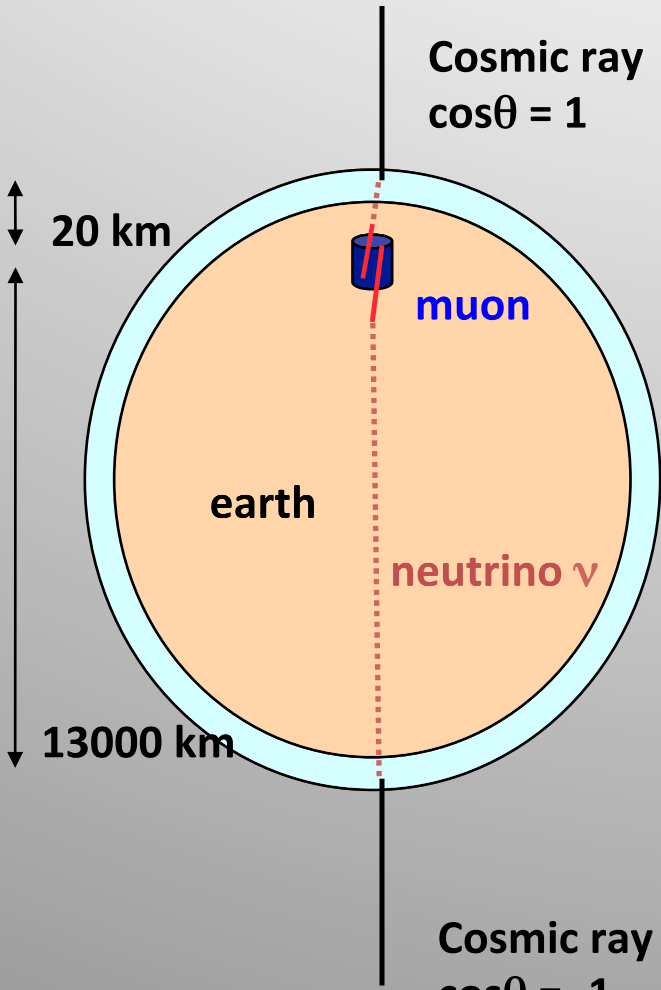
50kt of Water (∅40m 40m high)

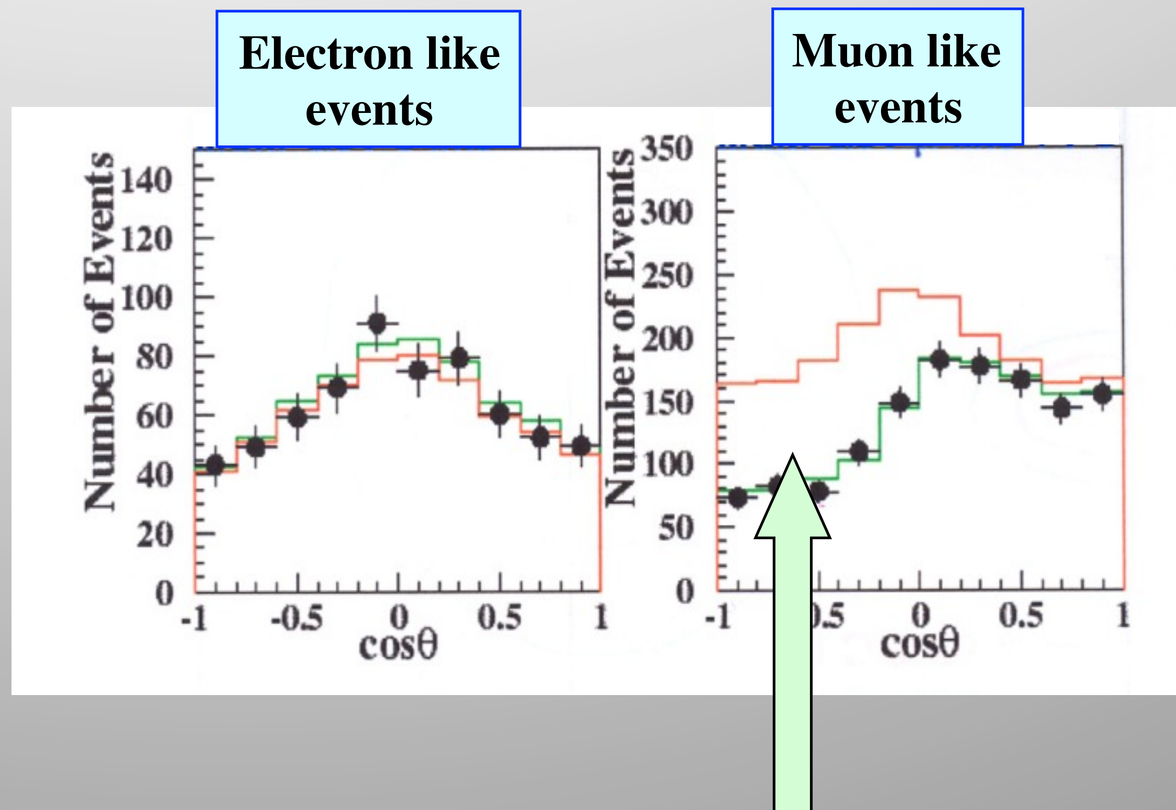


11000 PM (∅50cm)
Surface coverage = 40%

SuperKamiokande

Juin 1998





oscillation $\nu_\mu \longrightarrow \nu_\tau$

Neutrinos in the standard model

$m_\nu = 0$?

$m(\nu_e) < 2.2$ eV/c^2 $\quad$ $^3H \rightarrow {}^3He^+ + e^- + \nu_e$ $\quad$ Troitsk, Mainz

$m(\nu_\mu) < 160$ keV/c^2 $\quad$ $\pi \rightarrow \mu + \nu_\mu$ $\quad$ PSI

$m(\nu_\tau) < 18.2$ MeV/c^2 $\quad$ $\tau \rightarrow 5\pi + \nu_\tau$ $\quad$ Aleph

$\tau \rightarrow 3\pi + \nu_\tau$

\+ Theory: GUT ⟹ $m_\nu > 0$

\+

- atmospheric ν's : Superkamiokande & SoudanII : $\Delta m^2 \approx 10^{-2} - 10^{-3}$ eV^2, $\sin^2 2\theta = 1$
- solar ν's : Homestake, Gallex, Sage, SK & SNO —> ≈ 50% of the SSM predictions
- Cosmologie: ν = candidat for hot dark matter…

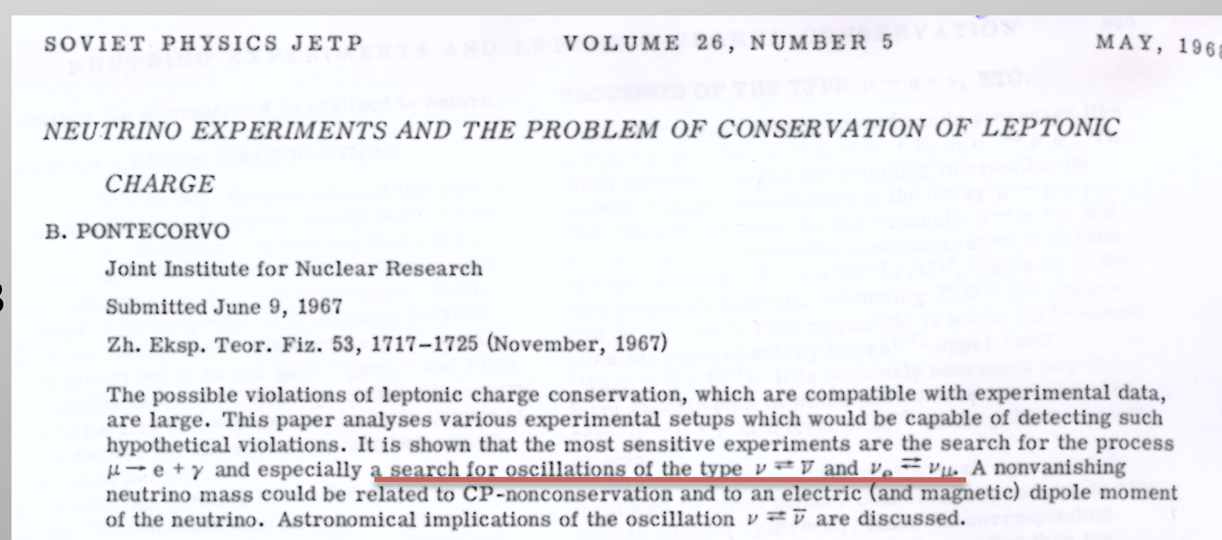
⟹ **Oscillations**

B. Pontecorvo: first proposal for neutrino oscillations!

Bruno Pontecorvo, 1913 - 1993

1957: B. Pontecorvo, « Mesonium and Antimesonium »,
J. Exptl. Theoret. Phys. (USSR) 33, 549-551 (August 1957)

Mai 1968:


SOVIET PHYSICS JETP VOLUME 26, NUMBER 5 MAY, 1968

NEUTRINO EXPERIMENTS AND THE PROBLEM OF CONSERVATION OF LEPTONIC CHARGE

B. PONTECORVO

Joint Institute for Nuclear Research

Submitted June 9, 1967

Zh. Eksp. Teor. Fiz. 53, 1717–1725 (November, 1967)

The possible violations of leptonic charge conservation, which are compatible with experimental data, are large. This paper analyses various experimental setups which would be capable of detecting such hypothetical violations. It is shown that the most sensitive experiments are the search for the process $\mu \to e + \gamma$ and especially a search for oscillations of the type $\nu \rightleftarrows \bar{\nu}$ and $\nu_e \rightleftarrows \nu_\mu$. A nonvanishing neutrino mass could be related to CP-nonconservation and to an electric (and magnetic) dipole moment of the neutrino. Astronomical implications of the oscillation $\nu \rightleftarrows \bar{\nu}$ are discussed.

Too fast...

PHYSICAL REVIEW LETTERS

VOLUME 45 | 20 OCTOBER 1980 | NUMBER 16

Evidence for Neutrino Instability

F. Reines, H. W. Sobel, and E. Pasierb
Department of Physics, University of California at Irvine, Irvine, California 92717
(Received 24 April 1980)

This Letter reports indications of neutrino instability obtained from data taken on the charged- and neutral-current branches of the reaction

$$\bar{\nu}_e + d \begin{cases} n + n + e^+ & \text{(ccd)} \\ n + p + \bar{\nu}_e & \text{(ncd)} \end{cases}$$

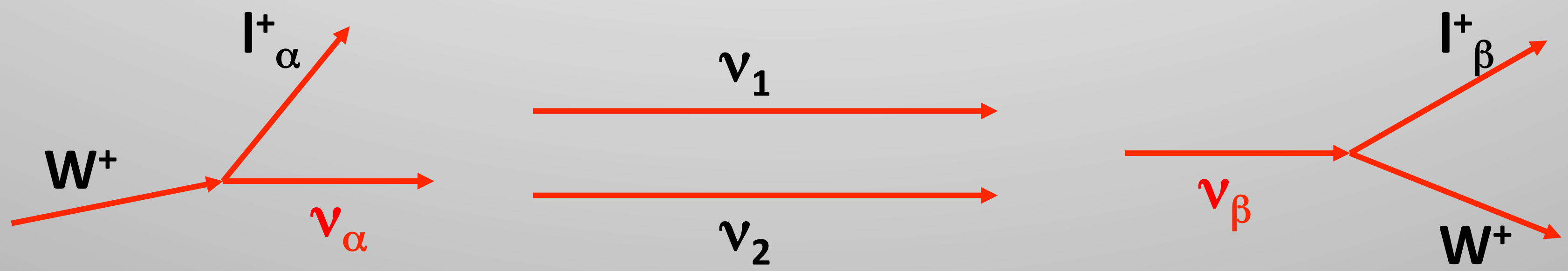
at 11.2 m from a 2000-MW reactor. These results at the (2–3)-standard-deviation level, based on the departure of the measured ratio (ccd/ncd) from the expected value, make clear the importance of further experimentation to measure the $\bar{\nu}_e$ spectrum versus distance.

Neutrino Oscillations

Eigenvalues of propagation: $\nu_1 \neq \nu_2$

The 2 neutrino case:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$P(\nu_\alpha \to \nu_\beta) = \left| \begin{pmatrix} 0 \\ 1 \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \exp^{-i(E_1 t - p_1 x)} & 0 \\ 0 & \exp^{-i(E_2 t - p_2 x)} \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right|^2$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino Oscillations

Si $m_\nu \neq 0$ ⟶ $|\nu_l\rangle = \sum U_{li} \, |\nu_i\rangle$

$l = e, \mu, \tau$ et $i = 1,2,3$

U_{li} = MNSP Matrix (Maki - Nakagawa - Sakata- Pontecorvo)

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{13}s_{23}e^{-i\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{-i\delta} & c_{13}s_{23} \\ s_{12}s_{23}-c_{12}s_{13}c_{23}e^{-i\delta} & -c_{12}s_{23}-s_{12}s_{13}c_{23}e^{-i\delta} & c_{13}s_{23} \end{pmatrix}$$

3 angles

Phase CP

$S_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

$\Delta m_{ij}^2 = \Delta m_i^2 - \Delta m_j^2$

δ = phase CP (Dirac)

(Pontecorvo–Maki–Nakagawa–Sakata)

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

θ_{12} θ_{23} θ_{13}

Atmospheric neutrinos

Reactor Neutrinos

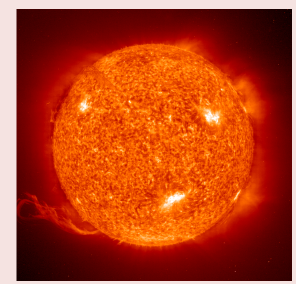
Solar neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\sin^2 2\theta_{23} \geq 0.92$

$\Delta m^2_{23} = (2.35 \pm 0.13) \times 10^{-3} eV^2$

$\sin^2 2\theta_{13} = 0.092 \pm 0.017$

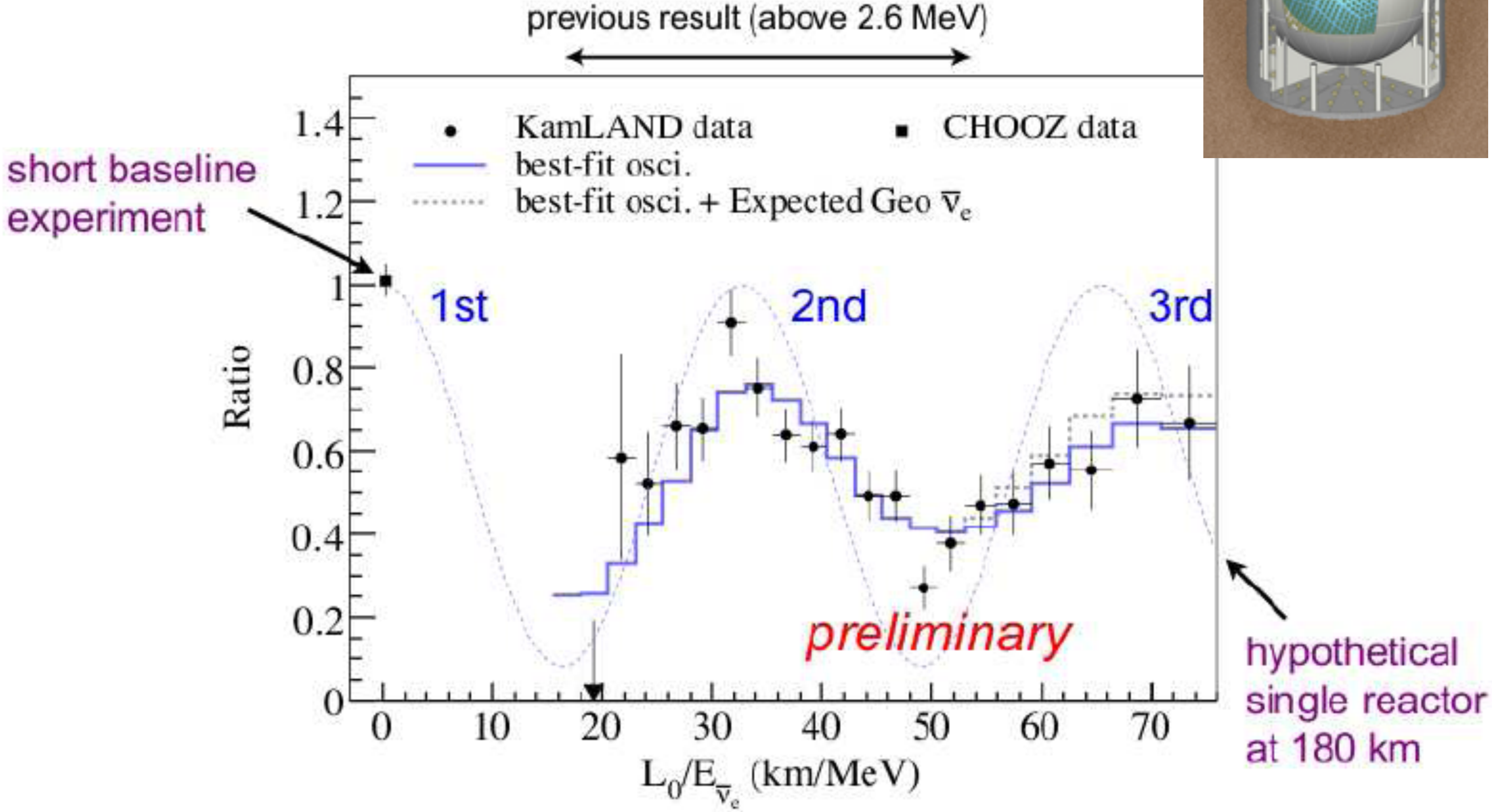


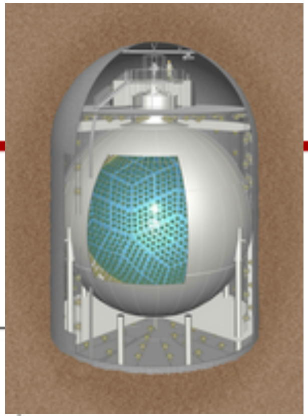
$\sin^2 2\theta_{12} = 0.87 \pm 0.03$

$\Delta m^2_{12} = (7.59 \pm 0.20) \times 10^{-5} eV^2$

$$\left|\Delta m^2_{21}\right| << \left|\Delta m^2_{31}\right| \cong \left|\Delta m^2_{32}\right|$$

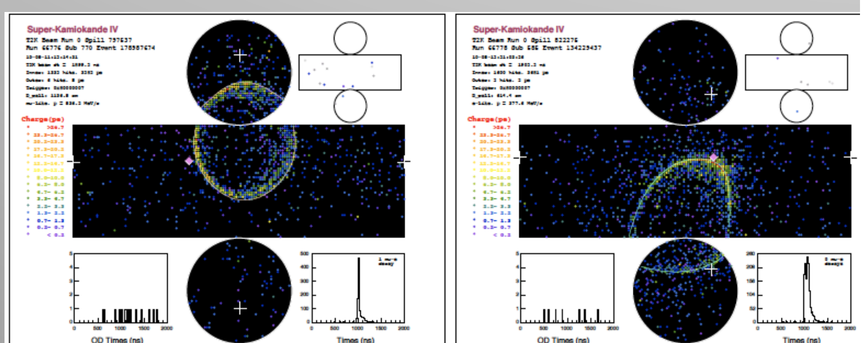
The KamLAND energy spectrum



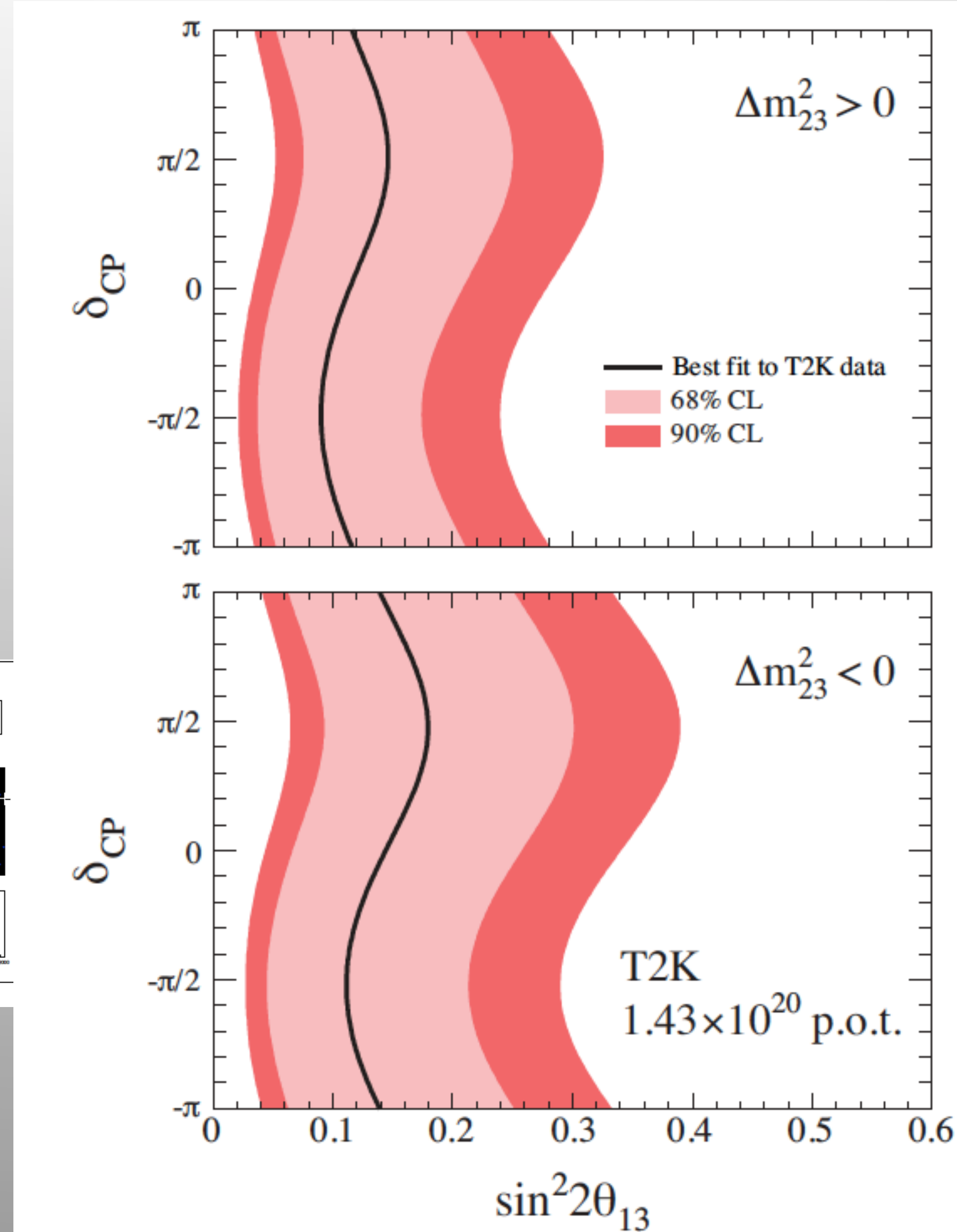


evidence for oscillations in $1/E_\nu$

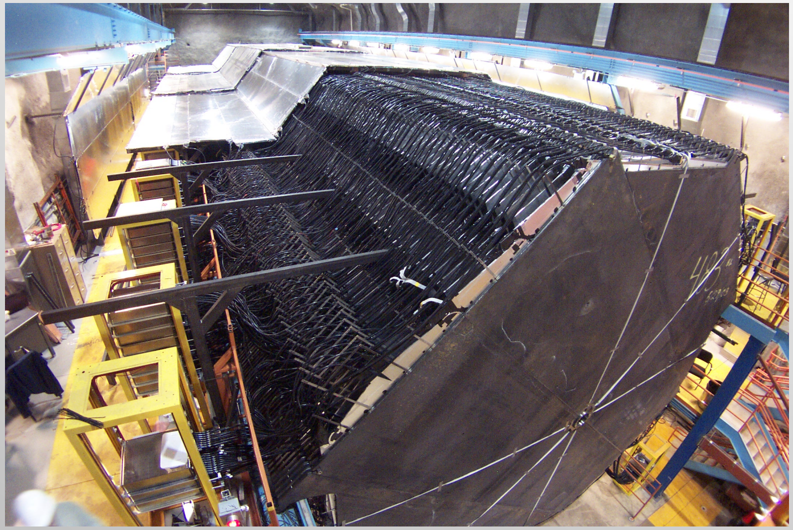
T2K

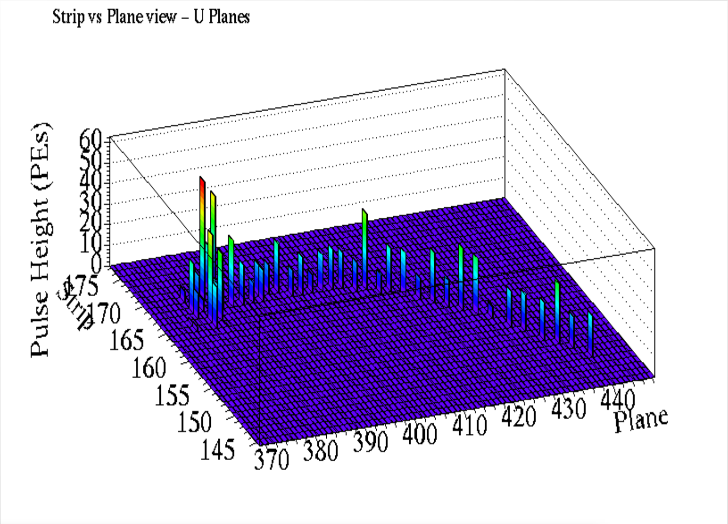


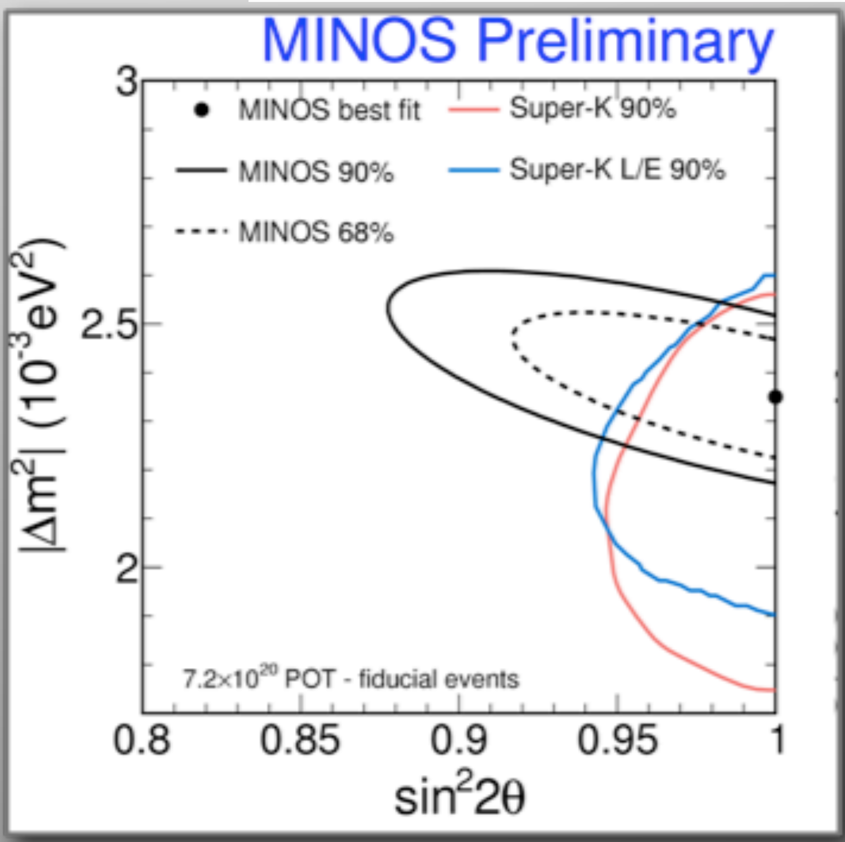
(a) muon-like event (b) electron-like event



MINOS





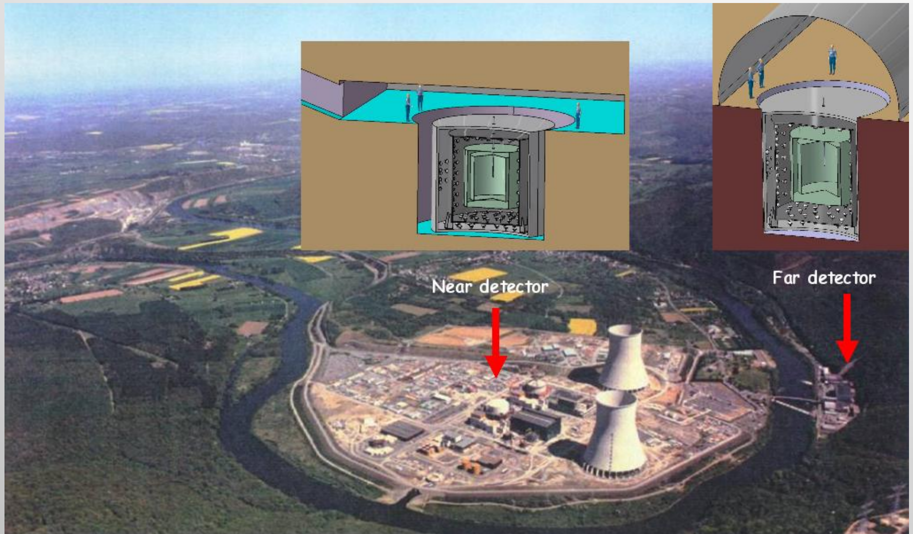


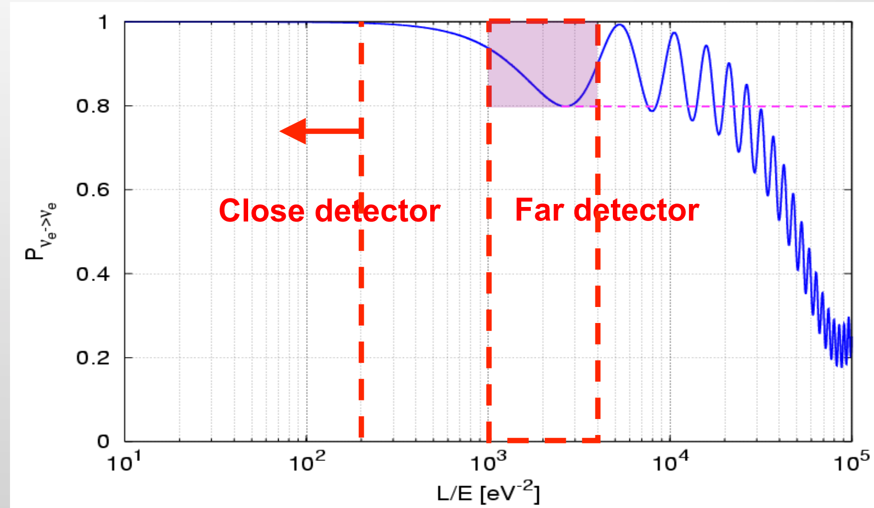
$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2(2\theta) > 0.91 \ (90\% \ \mathrm{C.L.})$$

World's best measurement of Δm^2_{32}!

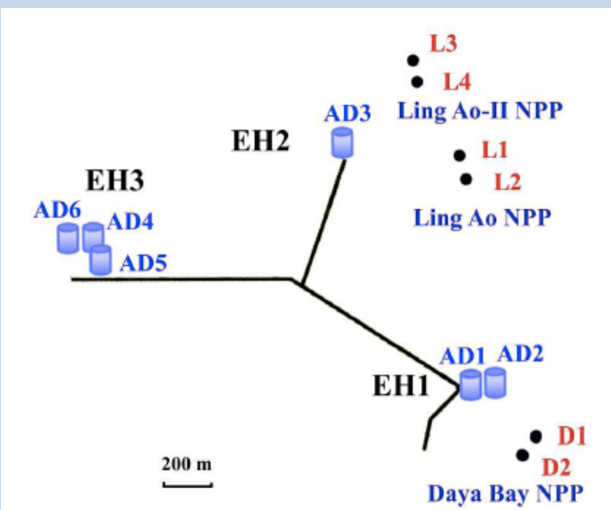
Double CHOOZ; Daya Bay; Reno

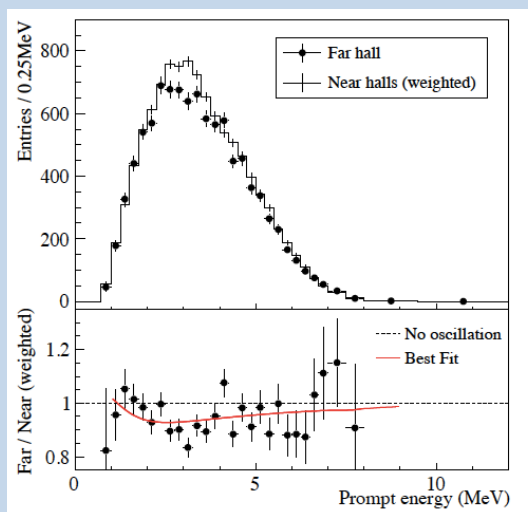
$$P_{sur} = 1 - \sin^2 2\theta_{13} \sin^2(1.267 \times \Delta m^2_{31} \times L/E)$$

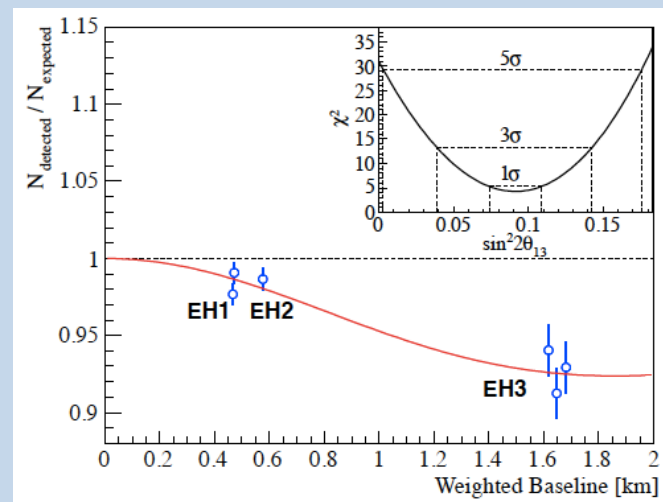




Daya Bay







$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(stat) \pm 0.005(syst)$$

arXiv: 1203.1669v2

The future:

The context:

In 2002 the US NATIONAL ACEDEMY OF SCIENCES stated 11 outstanding questions in the field: (1.) What is dark matter? (2.) What is dark energy? (3.) How did the universe begin? (4.) Was Einstein right about gravity? (5.) How have neutrinos shaped the universe? (6.) What are nature's most energetic particles? (7.) Are protons unstable? (8.) What are the new states of matter? (9.) Are there more space time dimensions? (10.) How were the elements from Fe to U made? (11.) Is a new theory of light and matter needed?

In Europe a roadmap has been established in 2008 and updated in 2011 by ASPERA (ASTroParticle ERA net). In the 2011 update one can read *"The goals of a megaton-scale detector as addressed by the design studies LAGUNA range from low-energy neutrino astrophysics (e.g. supernova, solar, geo and atmospheric neutrinos) to fundamental searches without accelerators (e.g. search for proton decay) and accelerator driven physics (e.g. observation of CP-violation). Due to its high cost, the program can be developed only in a global context; furthermore the timing of its realization depends strongly on whether the indications for the mixing parameter defined as $\vartheta 13$ were to be confirmed within the next one or two years, permitting a series of very exciting measurements for neutrino mass hierarchy and CP violation using CERN beams.* ***LAGUNA is therefore clearly at the interface with the CERN European Strategy Update to be delivered early 2013, where it represents a high-priority astroparticle project."***

Important research topics in neutrino physics and underground science:

Keep in mind that neutrinos give us the only experimental evidence for physics beyond the standard model of particle physics today!

Particle Physics:

- θ_{13} measured with 5.5 σ
- LCPV
- Absolute Mass
- Nature Dirac or Majorana?
- Mass Hierarchy
- ~~SuperLuminal~~
- MNSP (precision)
- Sterile
- Proton decay

Astrophysics:

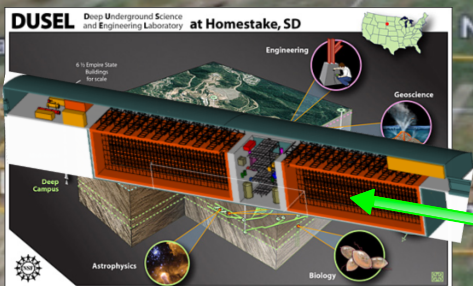
- Galactic SN
- SN diffuse
- HE neutrinos
- GeoNeutrinos
- DM annihilation
- Solar neutrinos
- + Direct dark matter

Projects around the world:

Long Baseline Neutrino Experiment

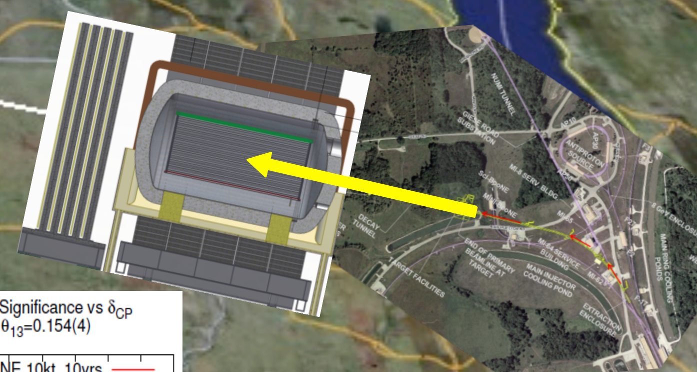
New Neutrino Beam at Fermilab…

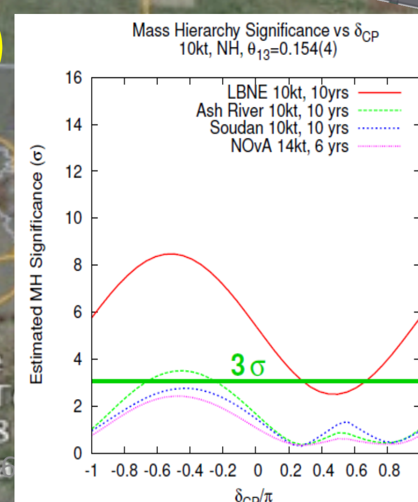
Precision Near Detector on the Fermilab site



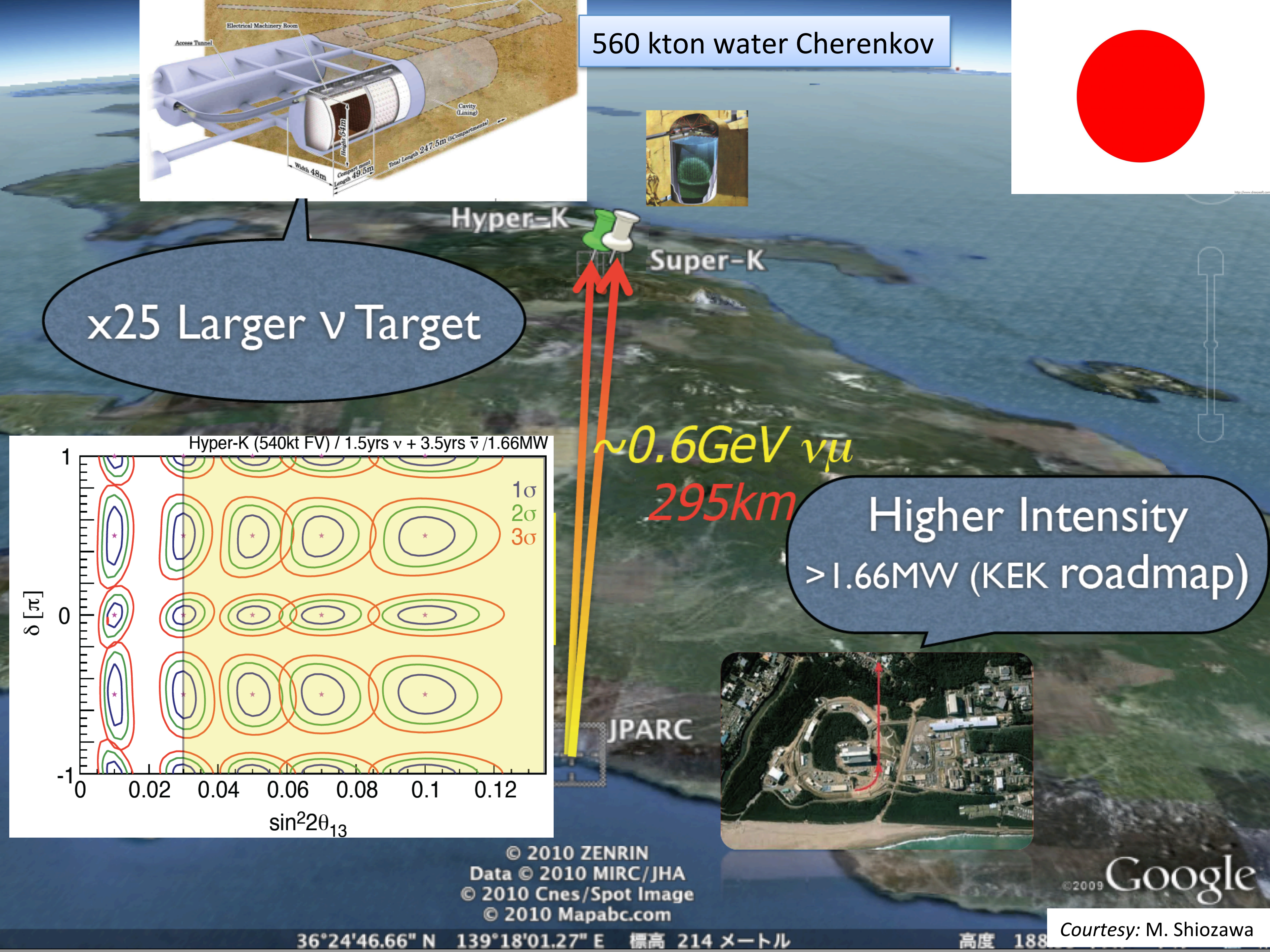
Directed towards a distant detector

33 kton Liquid Argon TPC Far Detector at a depth of 4850 feet (4300 mwe)





Courtesy: Jim Strait

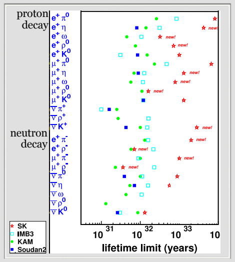


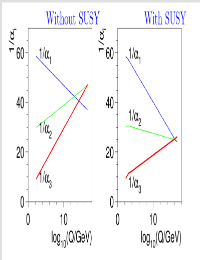
560 kton water Cherenkov
Electrical Machinery Room
Access Tunnel
Cavity (Lining)
Width 48m
Total Length 247.5m
Hyper-K
Super-K
x25 Larger ν Target
~0.6GeV νμ
295km
Higher Intensity
>1.66MW (KEK roadmap)
Hyper-K (540kt FV) / 1.5yrs ν + 3.5yrs ν̄ /1.66MW
1σ
2σ
3σ
δ [π]
1
0
-1
0
0.02
0.04
0.06
0.08
0.1
0.12
sin²2θ13
JPARC
© 2010 ZENRIN
Data © 2010 MIRC/JHA
© 2010 Cnes/Spot Image
© 2010 Mapabc.com
©2009 Google
36°24'46.66" N 139°18'01.27" E 標高 214 メートル
Courtesy: M. Shiozawa

Laguna-LBNO: Large Apparatus for Grand Unification and Neutrino Astrophysics & Long Baseline Neutrino Oscillations

Particle physics without accelerator

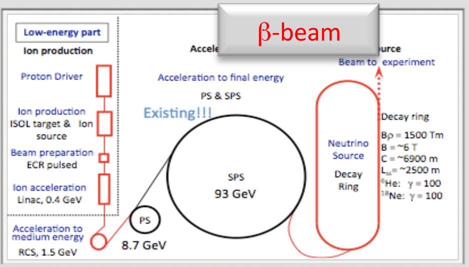
Proton Decay



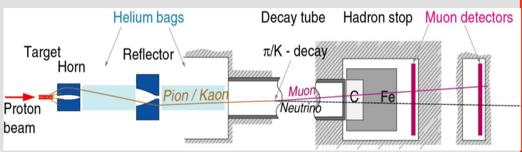


Particle physics with accelerator

β-beam



Superbeam

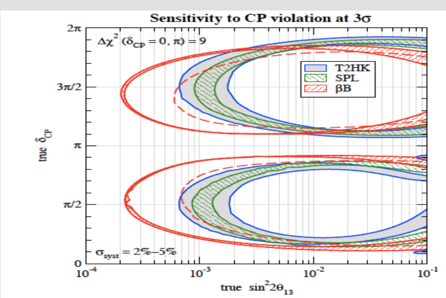


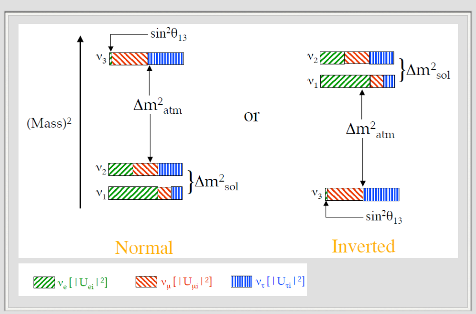
MSNP precision

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

CP-Violation

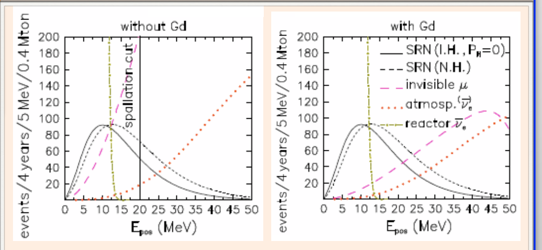
Mass Hierarchy



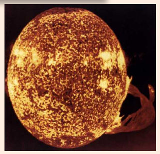


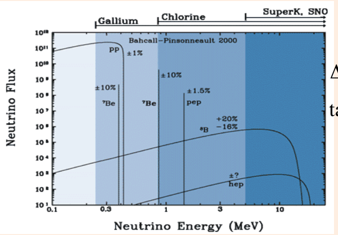
Neutrino astronomy

Supernova neutrinos
Diffuse SN Neutrinos



Solar neutrinos





$$\Delta m^2_{21} = \left(7.41^{+0.21}_{-0.19}\right) \times 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.446^{+0.030}_{-0.029}$$

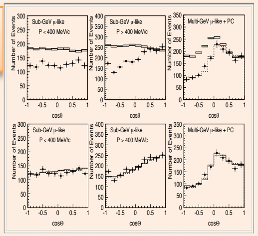
(arXiv:1109.0763)

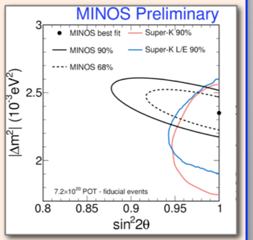
Atmospheric Neutrinos

$$\Delta m^2_{23} = (2.43 \pm 0.13) \times 10^{-5} eV^2$$

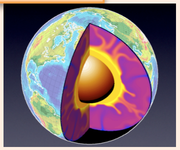
$$\sin^2(2\theta_{23}) > 0.90$$

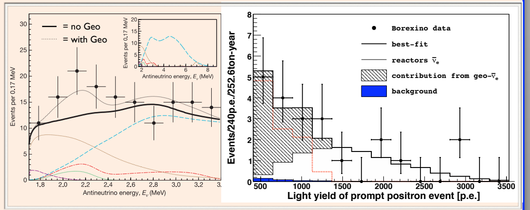
arXiv:1004.2647



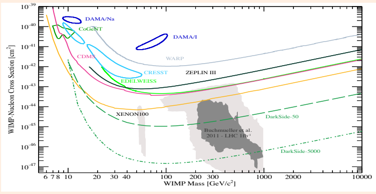


Geo-neutrinos...

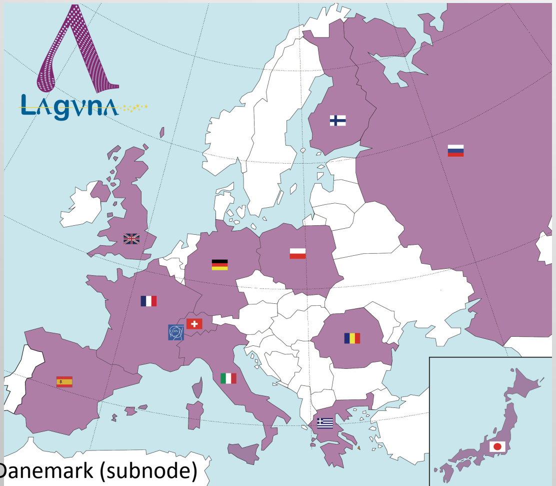




Dark matter annihilation



LAGUNA-LBNO consortium



+Danemark (subnode)

13 countries, 45 institutions, ~300 members

Switzerland

University Bern
University Geneva
ETH Zürich
Lombardi Engineering*

Finland

University Jyväskylä
University Helsinki
University Oulu
Rockplan Oy Ltd*

CERN

France

CEA
CNRS-IN2P3
Sofregaz*

Germany

TU Munich
University Hamburg
Max-Planck-Gesellschaft
Aachen(**)
University Tübingen(**)

Poland

IFJ PAN
IPJ
University Silesia
Wroklaw UT
KGHM CUPRUM*

Greece

Demokritos

Spain

LSC
UA Madrid
CSIC/IFIC
ACCIONA*

United Kingdom

Imperial College London
Durham
Oxford
QMUL
Liverpool
Sheffield
RAL
Warwick
Technodyne Ltd*
Alan Auld Ltd*
Ryhal Engineering*

Romania

IFIN-HH
University Bucharest

Denmark

Aahrus(**)

Italy

AGT*

Russia

INR
PNPI

Japan

KEK

(=industrial partners **=associated)*

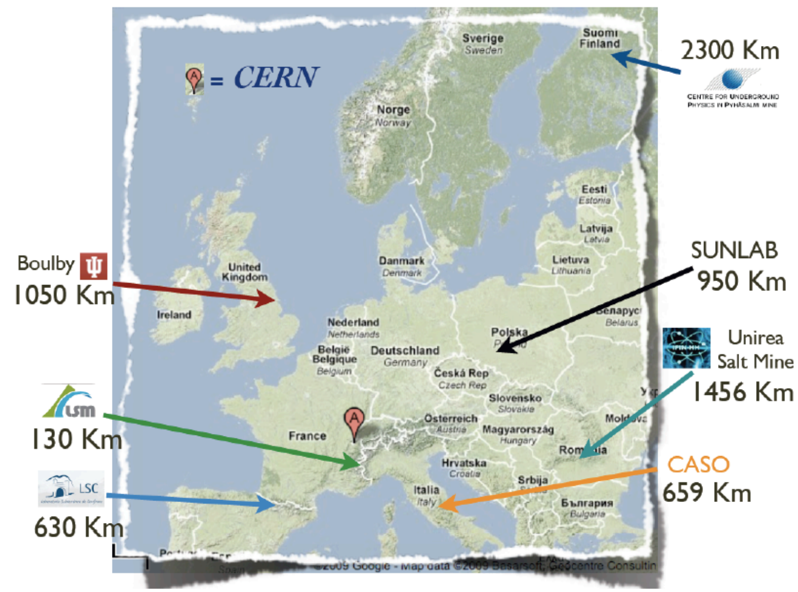
Courtesy: A. Rubbia

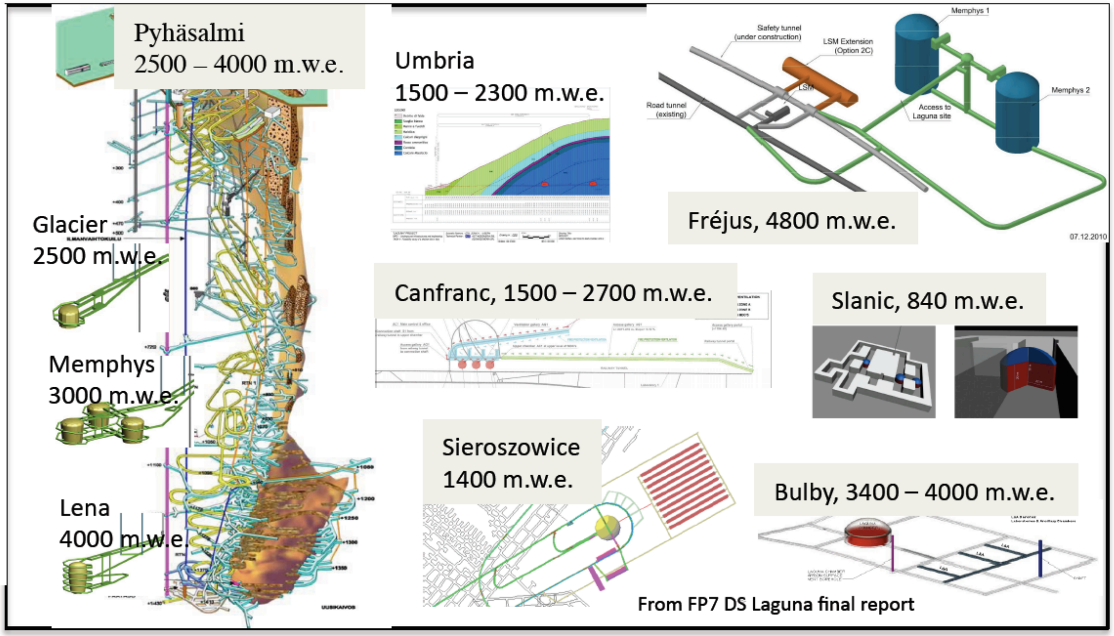
✓Laguna => very comprehensive evaluation of all sites, construction and costs

✓Laguna => baselines from 130 km to 2300 km available in Europe = advantage

✓Laguna => allowed to form a strong community in Europe (> 100 physicists and Ing.)

✓Laguna => showed the need to evaluate constraints and costs for the detector options





New program: Laguna-LBNO (one of the two fully financed by EC, 5M€)
Start September 2011 – End September 2014

LAGUNA-LBNO sites

New conventional beams to be considered based on CNGS experience

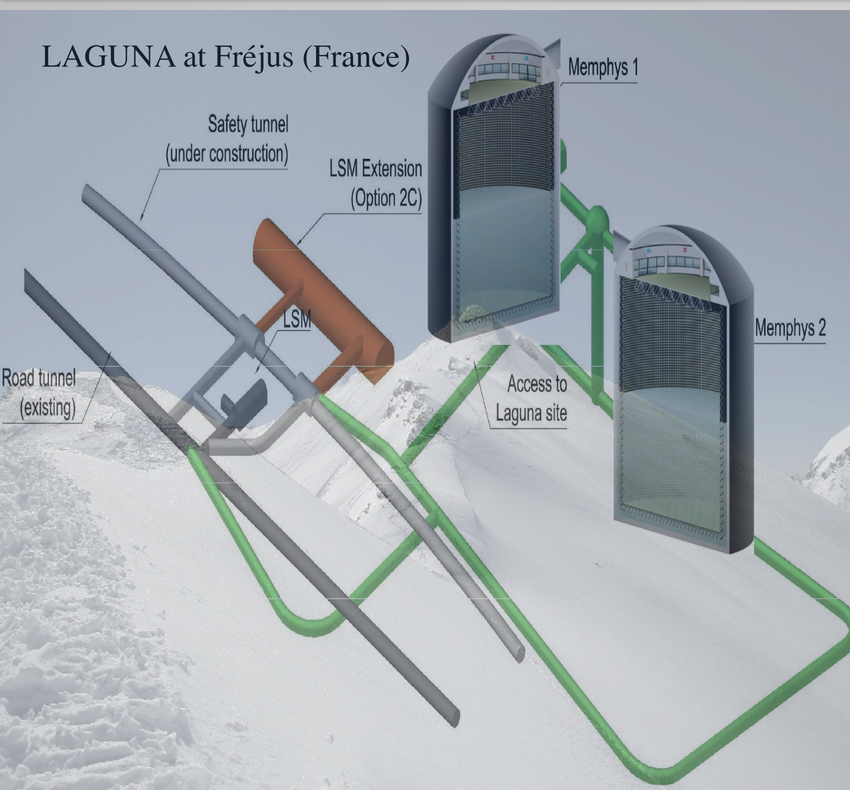
- CERN-Fréjus is a short baseline. It offers good synergy for enhanced physics reach with β-beam at γ=100
- CERN-Pyhäsalmi is the longest baseline. It offers good synergy for enhanced physics reach with a NF
- [CERN-Umbria has an existing beam but is considered at lower priority (missing near detector, limited power upgrade scenarios)]

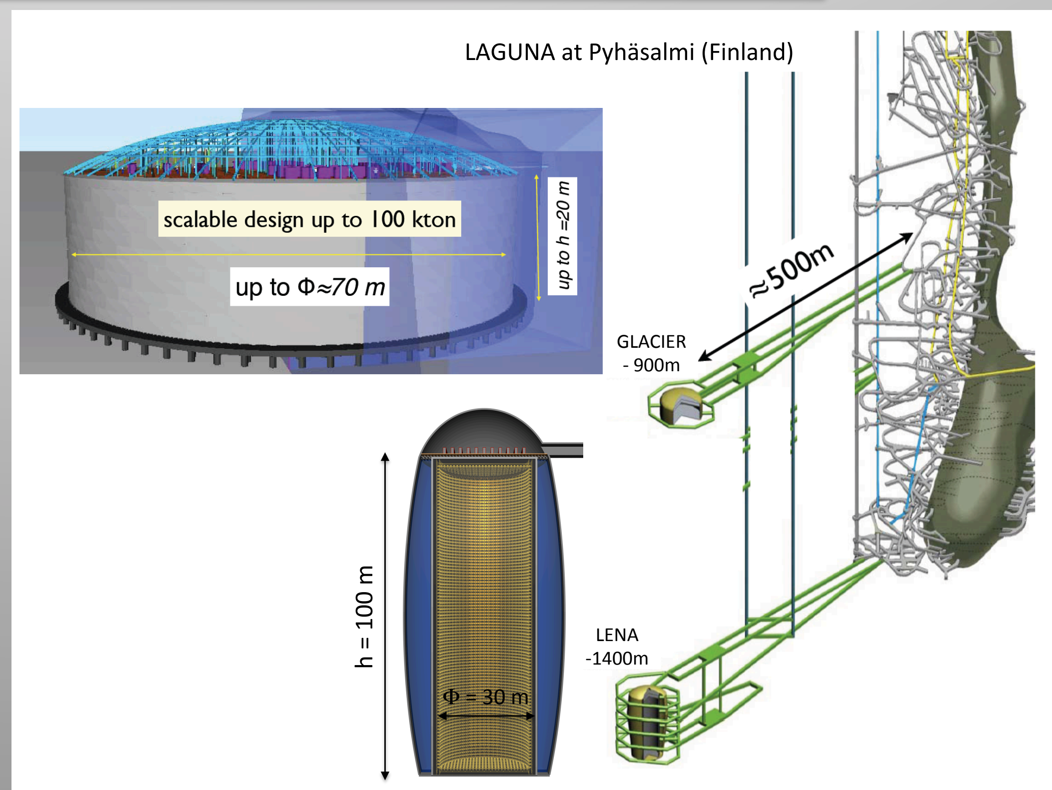
- Laguna-LBNO: evaluate costs for detector construction and long term running (> 30y)
- Laguna-LBNO: investigates complementary beam options from CERN
- Laguna-LBNO: deep study of physics potential for the combination detector/site
- Laguna-LBNO: strengthens the community even more:

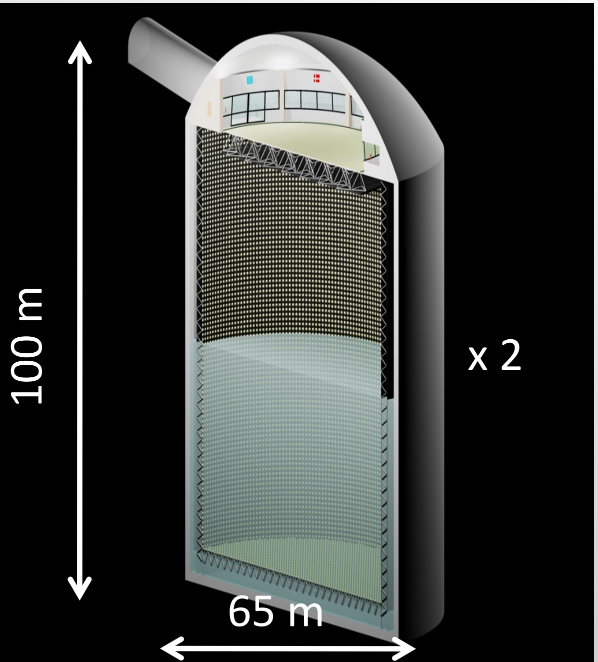
> 300 physicists, 13 countries, 39 beneficiaries

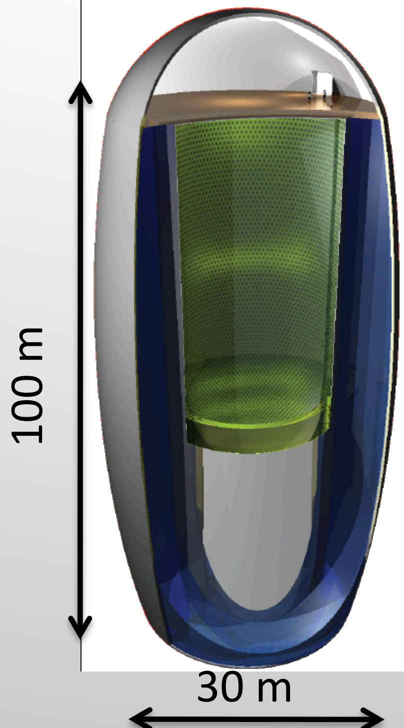
Focus on 2 options:

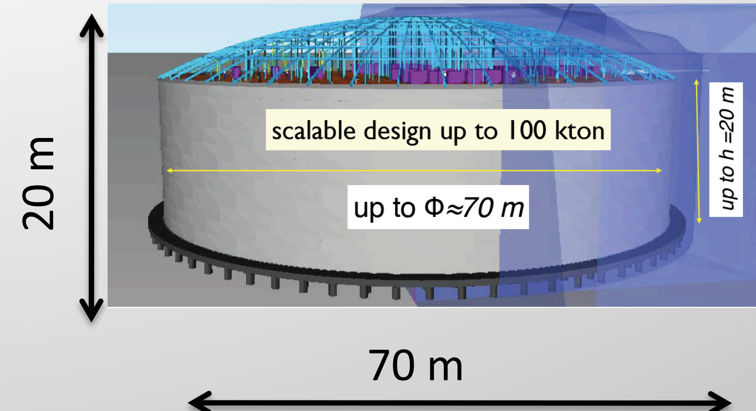
1. Shortest baseline (130 km), CERN -> Fréjus: no matter effects; clean measurement of LCPV
2. Longest baseline (2300 km), CERN -> Pyhäsalmi: matter effect; mass hierarchy, LCPV





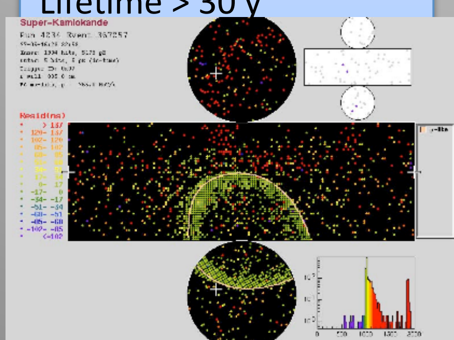






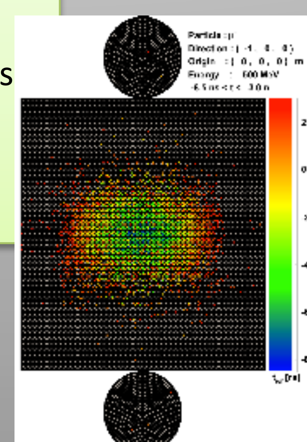
Memphys: 2 x 330 kt
220’000 8” or 10” PMT’s

QE > 25%
DR 1 to 300 p.e.
Time resolution 1 ns
Low after pulsing
Pressure 10 bars
Lifetime > 30 y



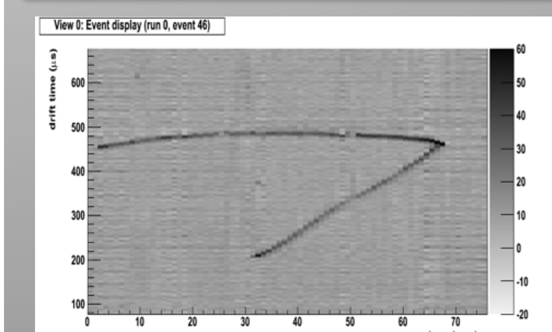
LENA: 50 kt
55’000 8” PMT’s

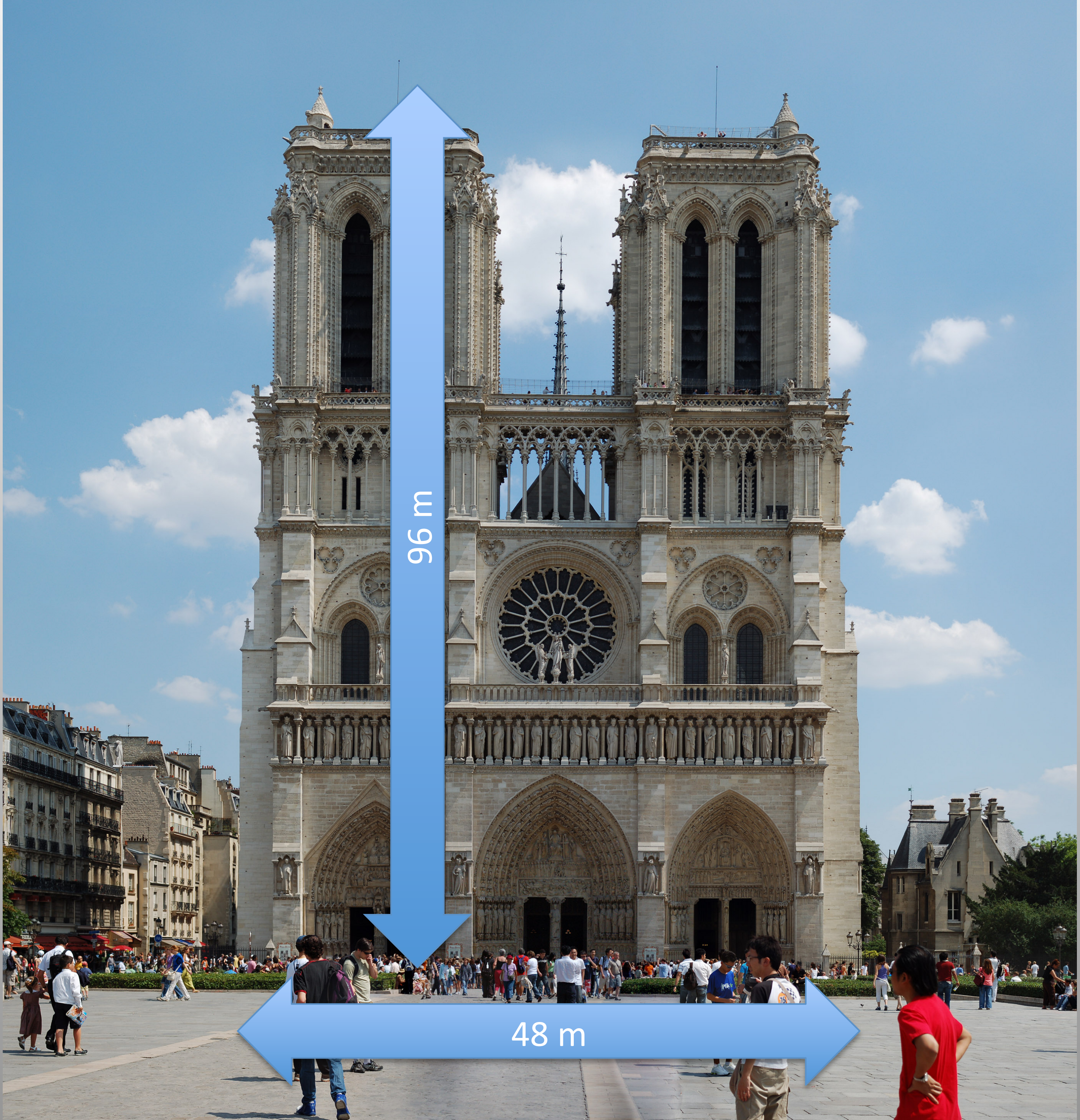
QE > 25%
DR 0.2 MeV to 10 GeV
Time resolution < ns
Low after pulsing
Pressure 15 bars
Lifetime > 30 y

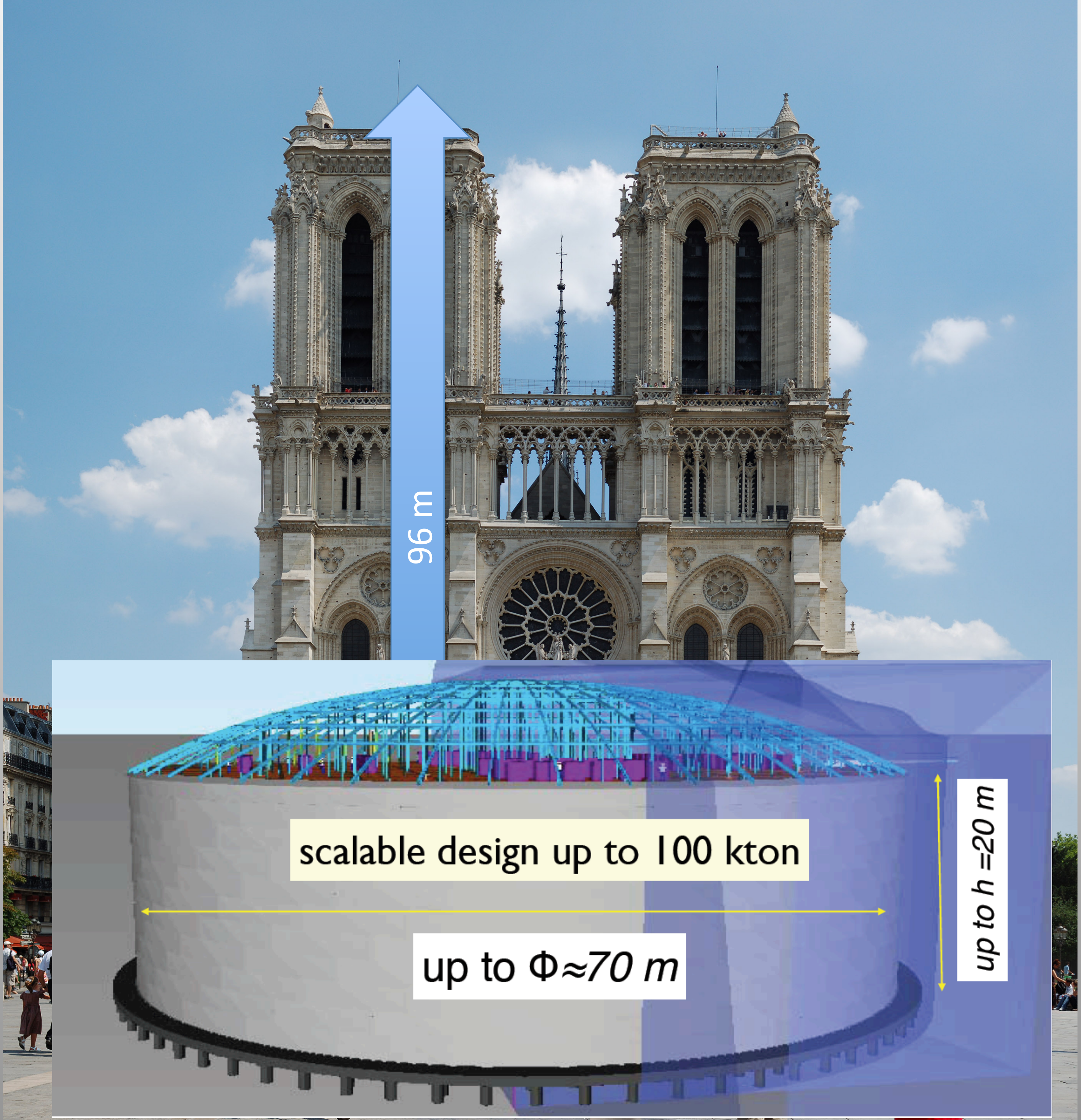


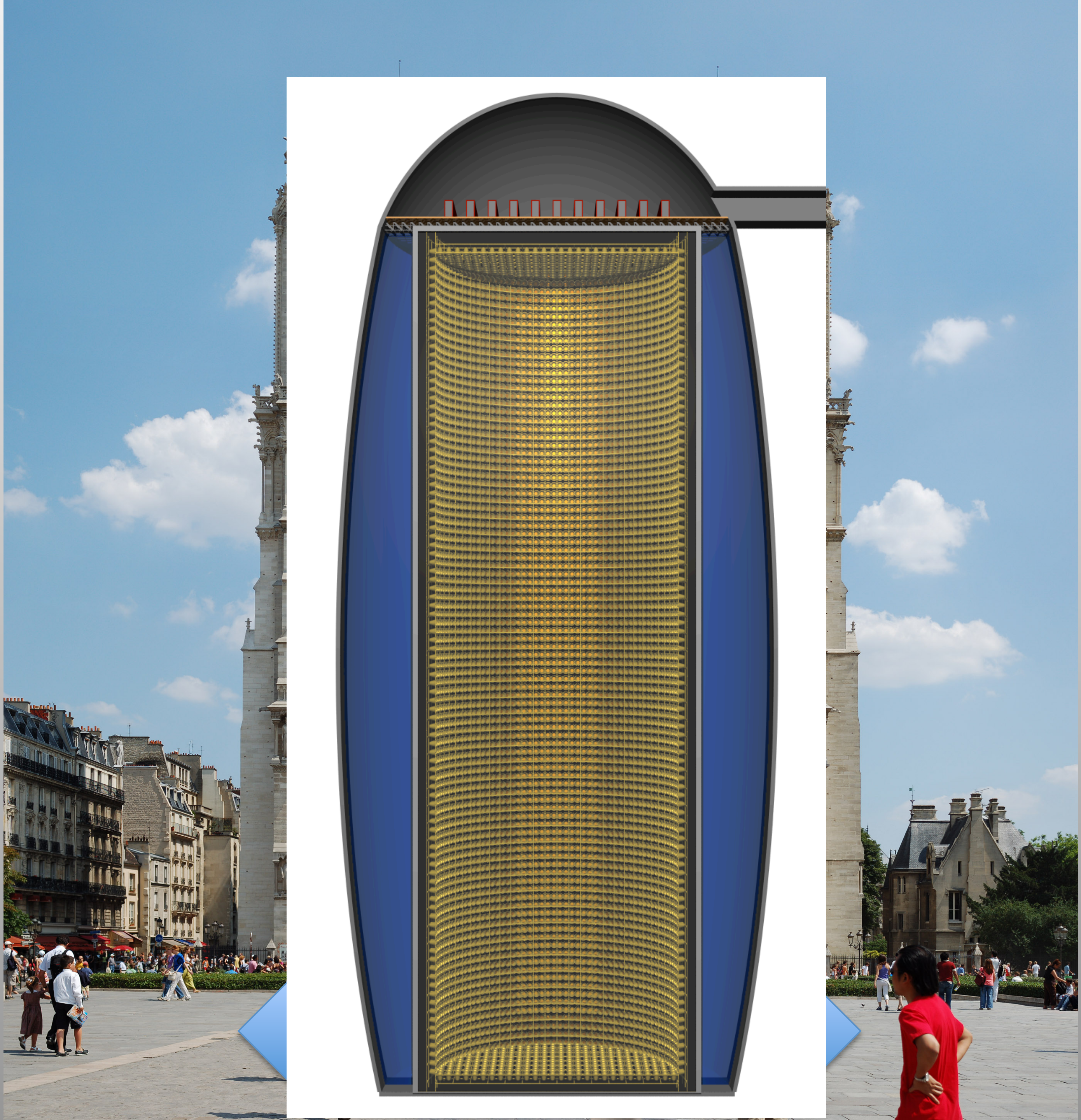
Glacier: 100 kt
1’000 8” WLS-coated cryo PMT’s
27’000 cryogenic PMT’s

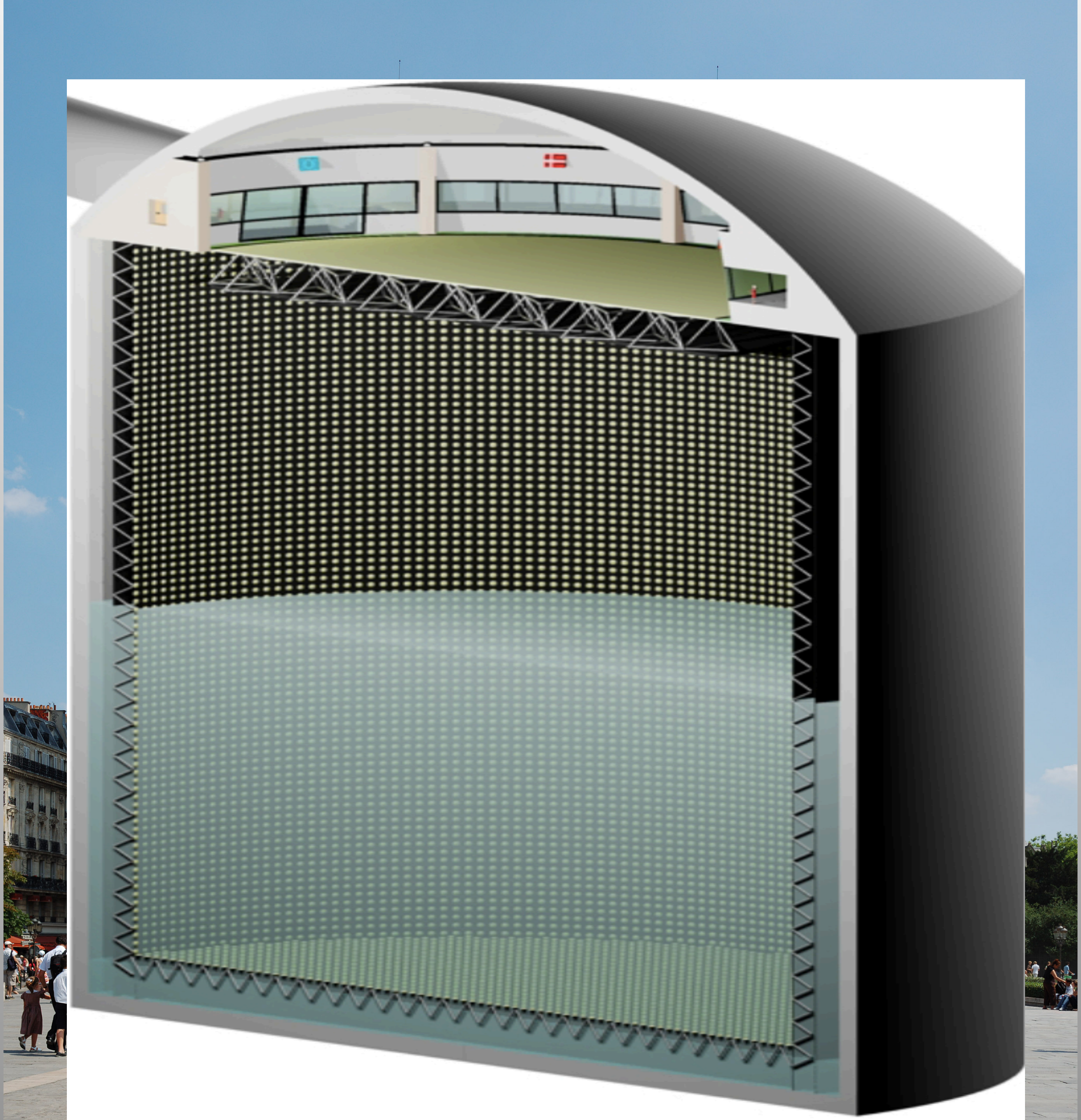
QE > 25%
Time resolution O ns
Lifetime > 30 y cryogenic!




96 m
48 m

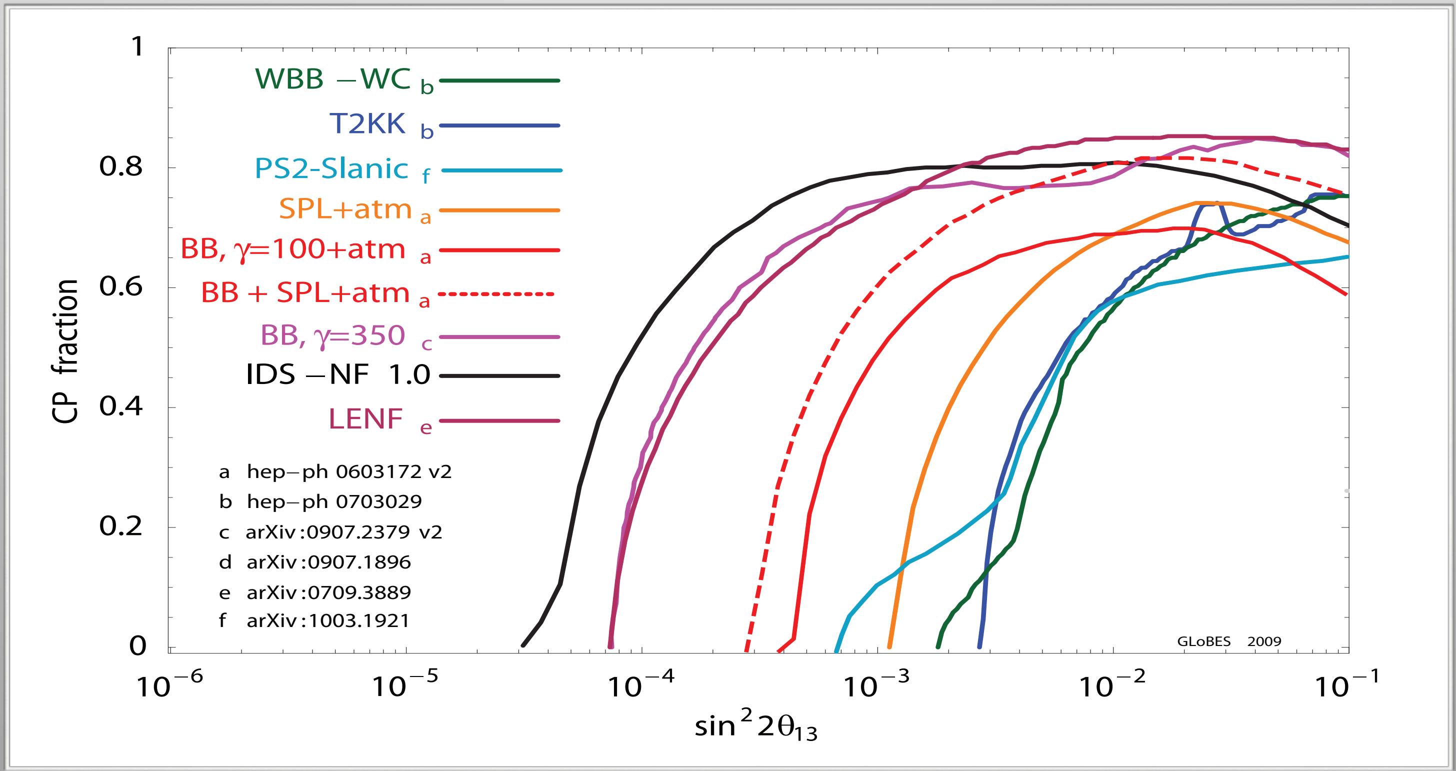

96 m
scalable design up to 100 kton
up to h =20 m
up to Φ≈70 m



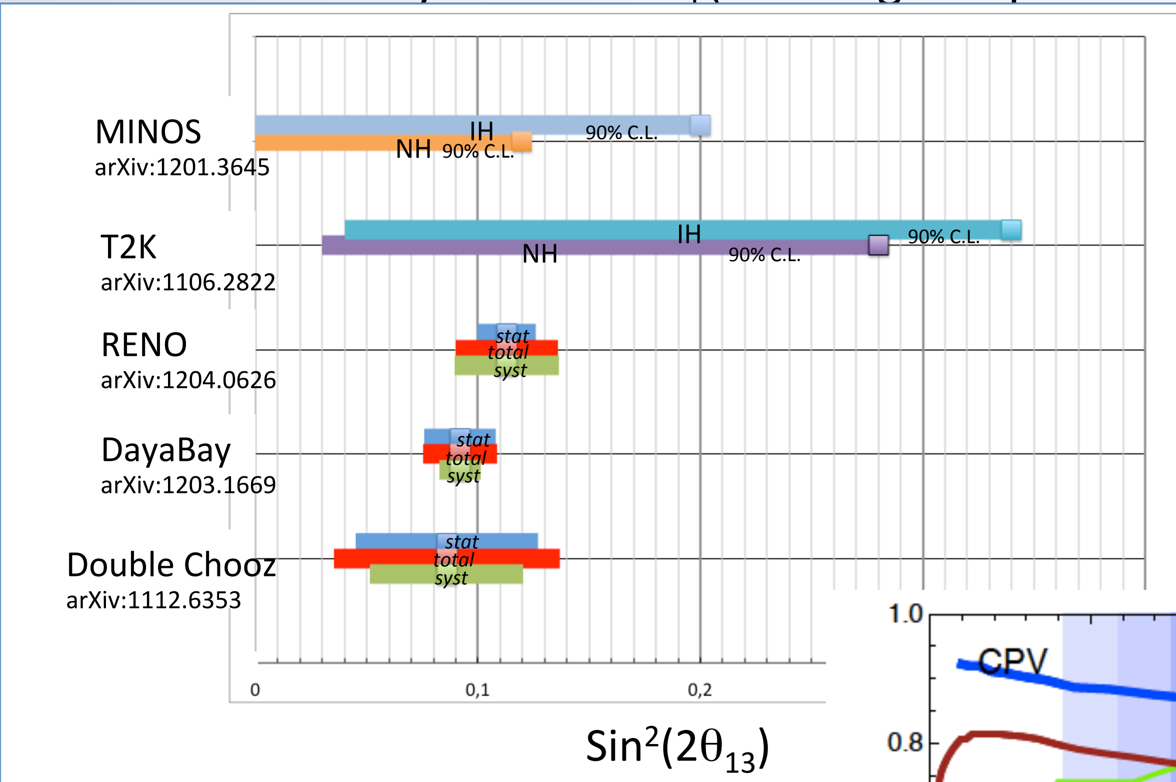


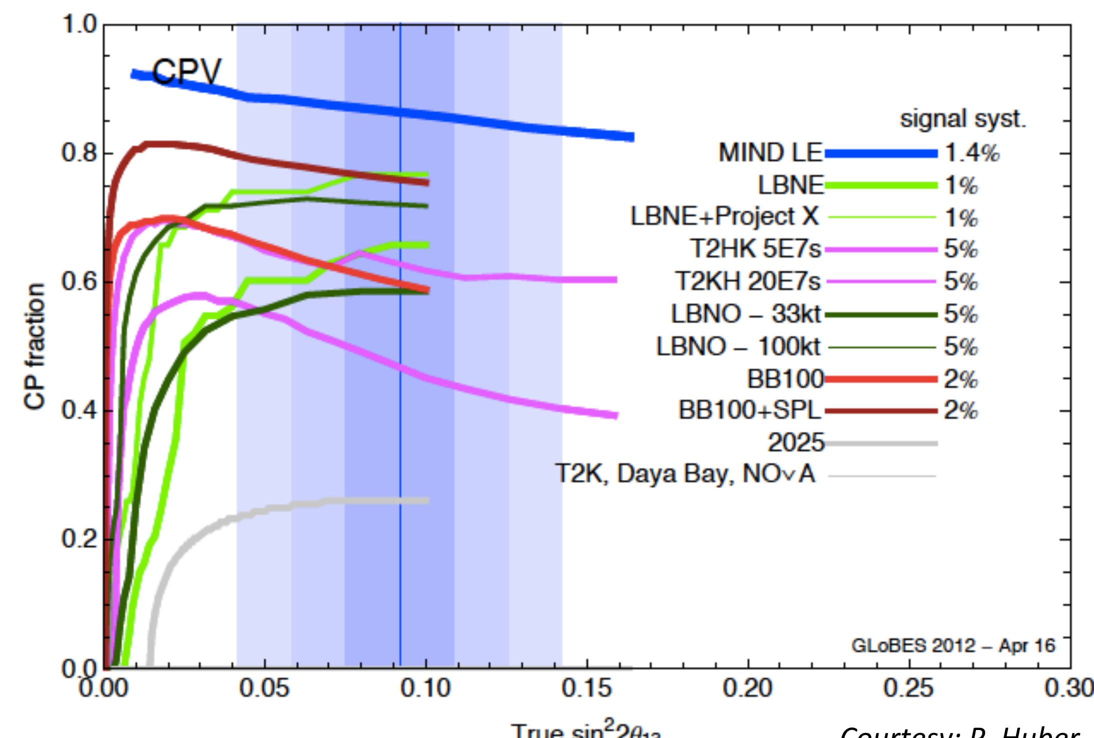
Mass Hierarchy and δ_{cp}

Before T2K, Minos, Dooble Chooz, Daya Bay and Reno the future neutrino facility was evaluated with respect to its sensitivity to θ_{13}



Today we know θ_{13} with highest precision (> 5 σ) and its big!





Courtesy: P. Huber

This implies that we can concentrate on mass hierarchy and LCPV

$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] \quad \theta_{13} \text{ driven}$$

$$+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{CPeven}$$

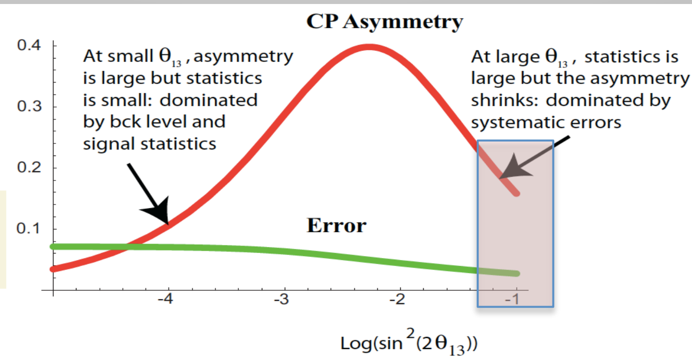
$$\mp 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven}$$

$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1 - 2s_{13}^2) \quad \text{matter effect (CP odd)}$$

With θ_{13} so big, systematic errors are the most important limitation

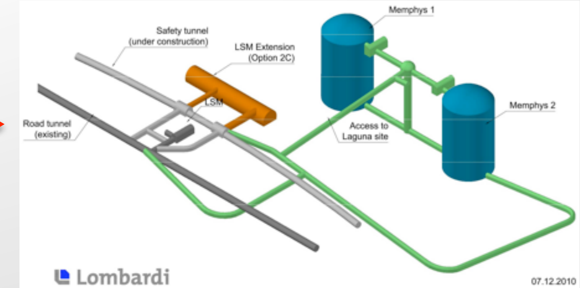
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$



LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

$$A_{CP} = \frac{P_{\nu_\mu \to \nu_e} - P_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_e}} = \frac{2\alpha \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{23} \sin^3 \Delta_{13}}{P_{\nu_\mu \to \nu_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_e}}$$

CERN to Fréjus (CN2FR), 130 km



SUPER-BEAMS BETA-BEAMS

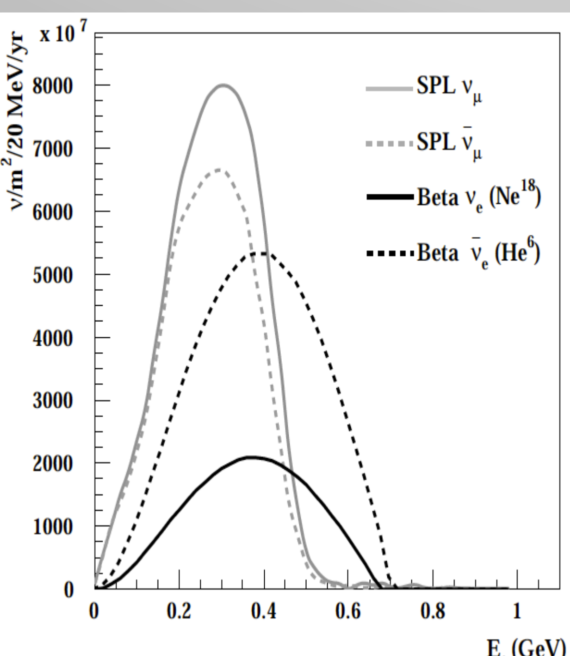
The main goals:

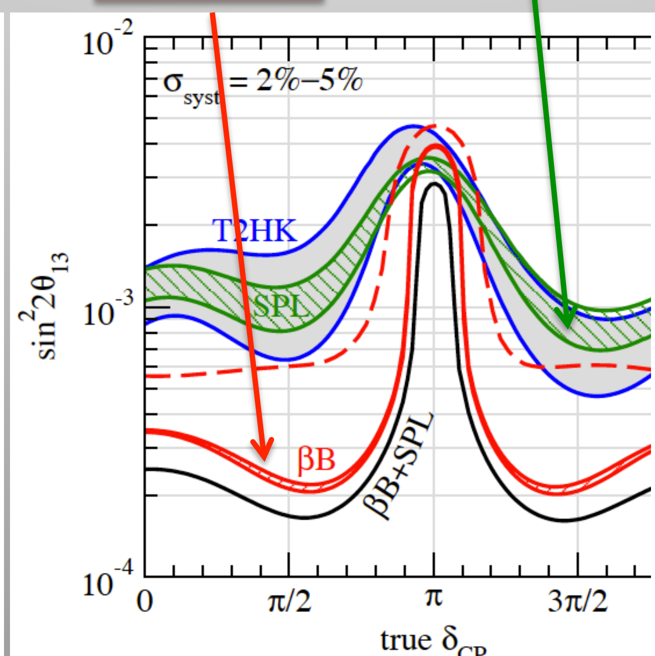
- ✓ search of a non-zero θ_{13} angle or its measurement
- ❑ searching for possible leptonic ***CP violation***
- ❑ determining the **mass hierarchy** and the $\boldsymbol{\theta_{23}}$ ***octant***.

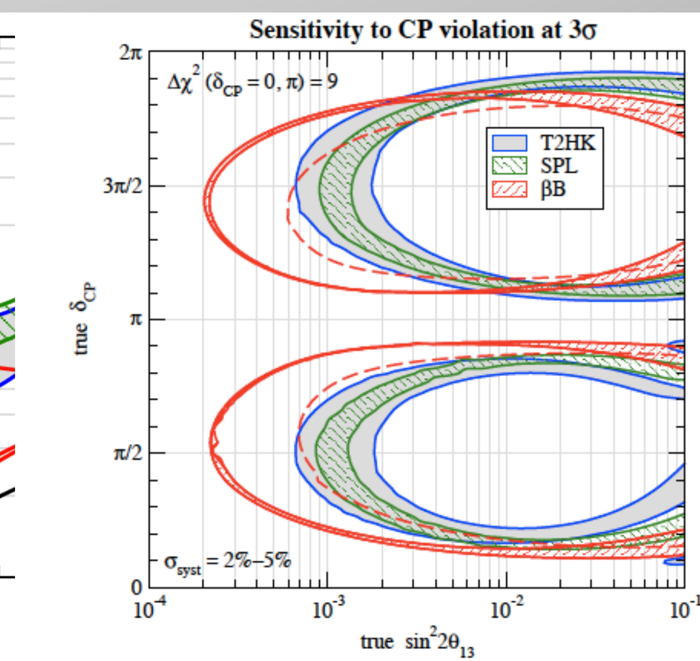
Measuring the asymmetry neutrino / anti-neutrino

5 yr / 5 yr

2 yr / 8 yr

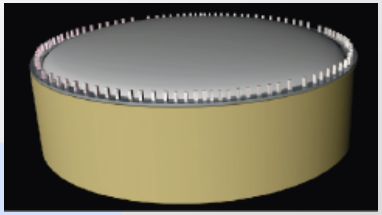






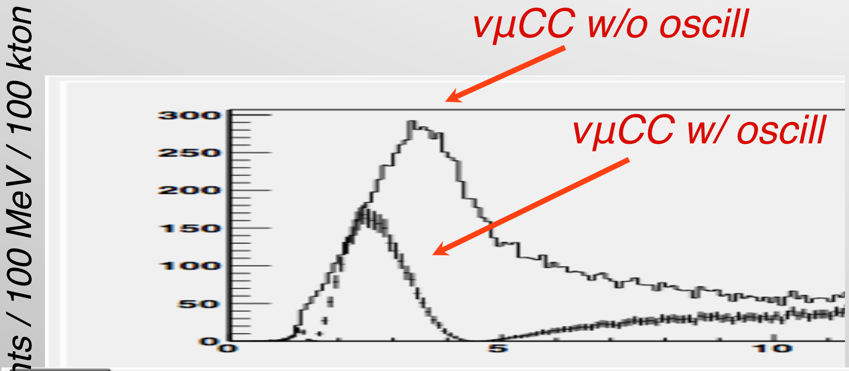
JE Campagne, M. Maltoni, M. Mezzetto, T. Schwetz, arXiv:hep-ph/0603172v3

LAGUNA-LBNO Pyhäsalmi physics prospects and Galcier:



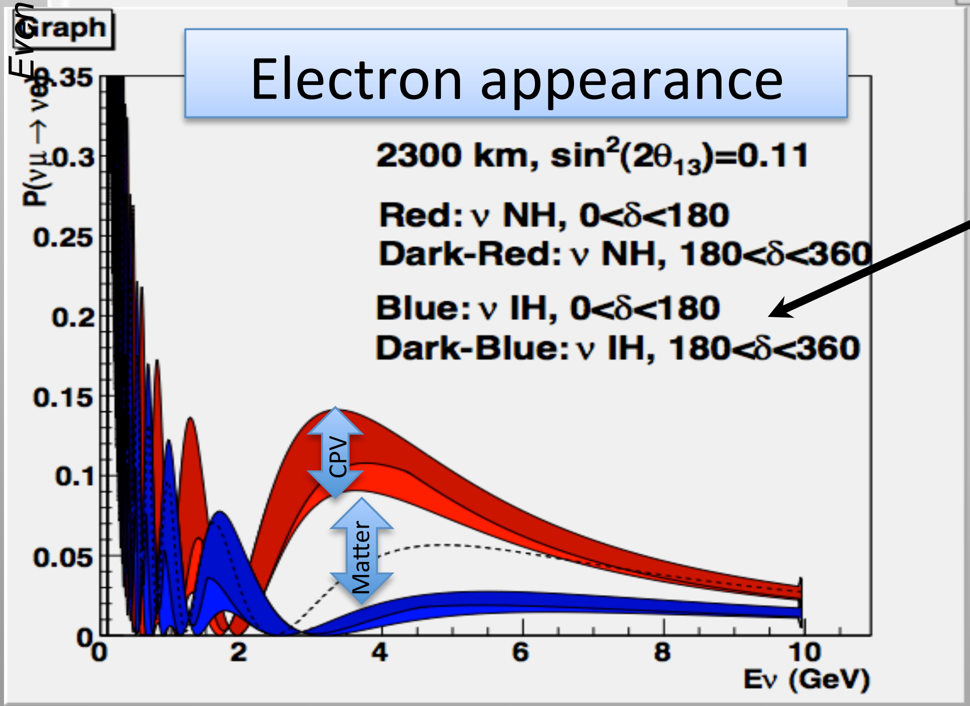
Muon disappearance

Event rates: CERN SPS 400 GeV
5 years @ 9.4×10^{19} pots/year

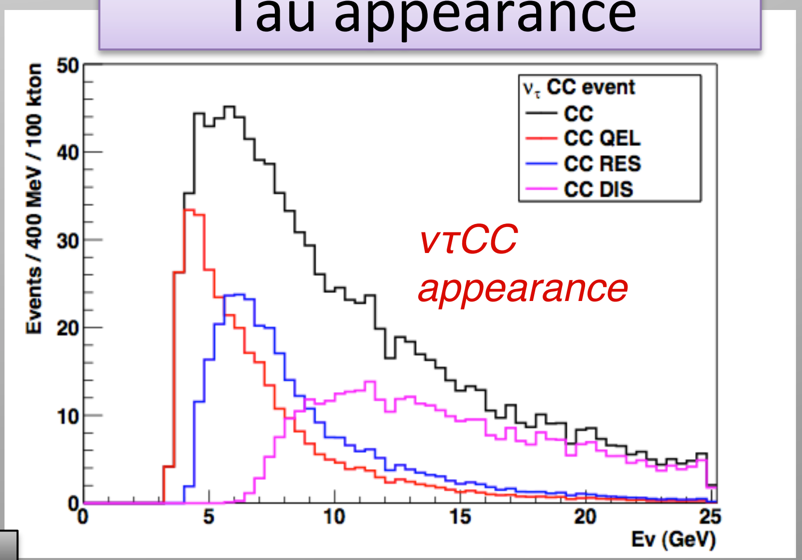


	Neutrino horn polarity $sin^2 2\theta_{23}$=1.0, $sin^2 2\theta_{13}$=0.1			
Distance/OA	ν_μCC	ν_eCC	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\tau$
Pyhäsalmi 2300 km 0.25 deg	17152	250	880	1018

Electron appearance



Tau appearance



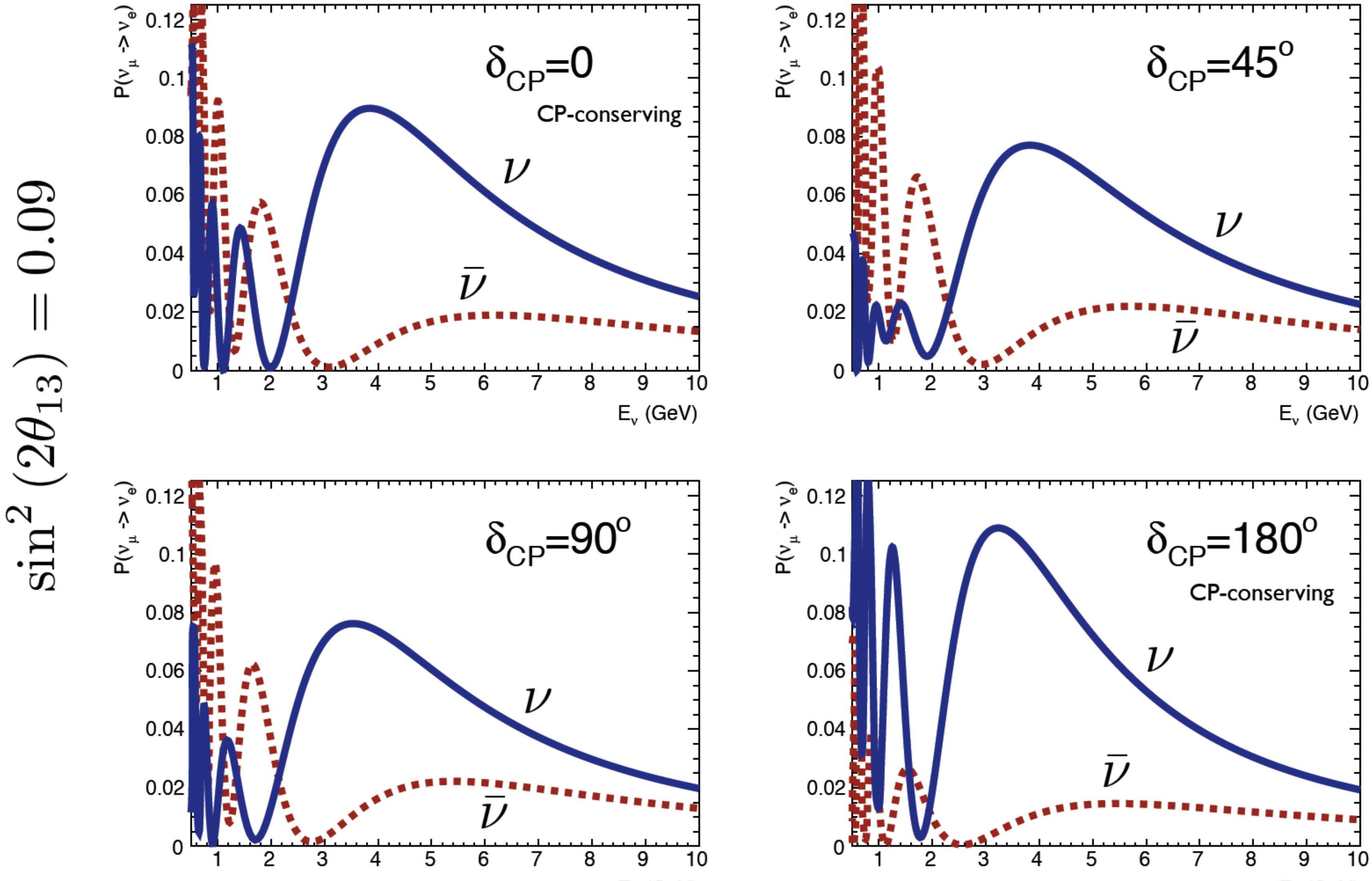
Measuring the peak position and height for 1st and 2nd max and min

Courtesy: A. Rubbia

CERN-Pyhäsalmi: spectral information $\nu_\mu \rightarrow \nu_e$

★ Normal mass hierarchy

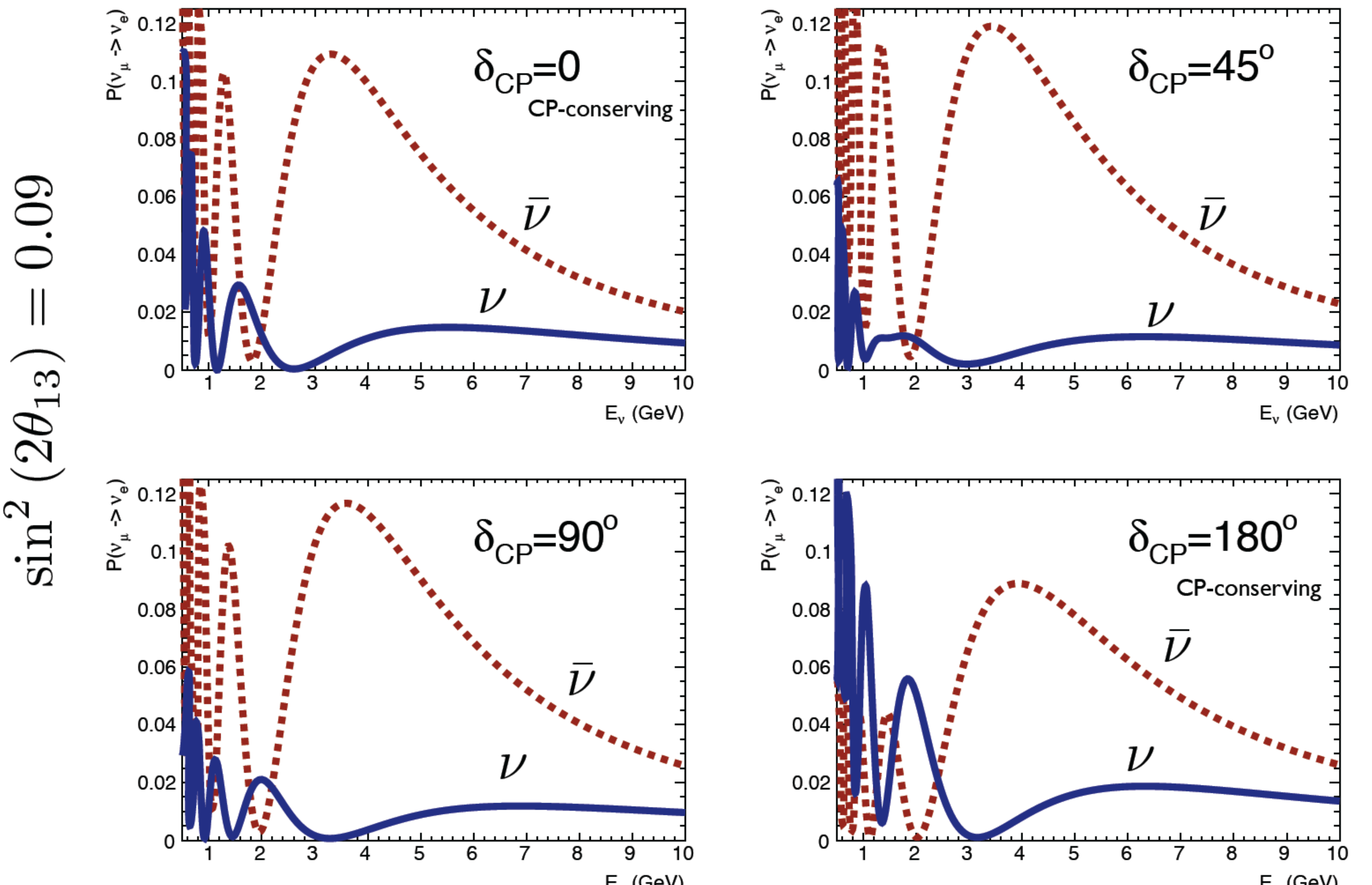
L=2300 km



Courtesy: A. Rubbia

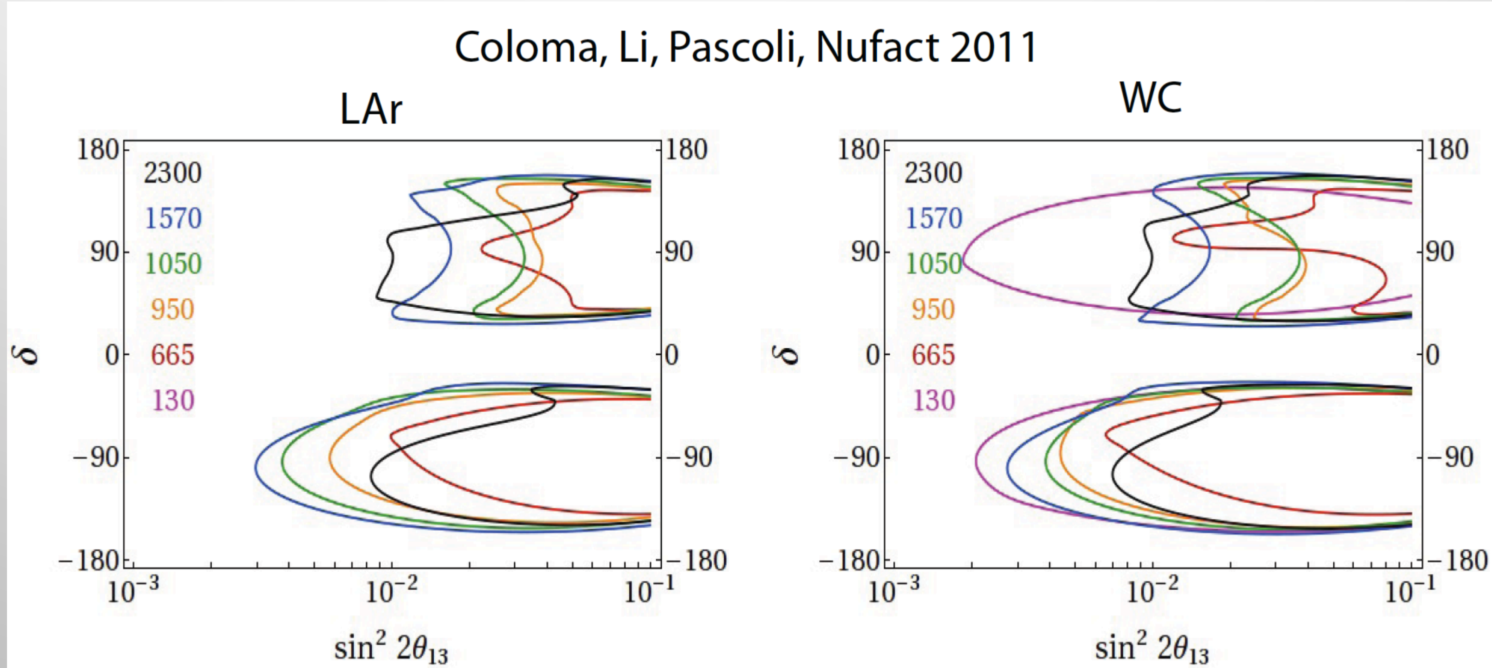
CERN-Pyhäsalmi: spectral information $\nu_\mu \rightarrow \nu_e$

★ Inverted mass hierarchy L=2300 km



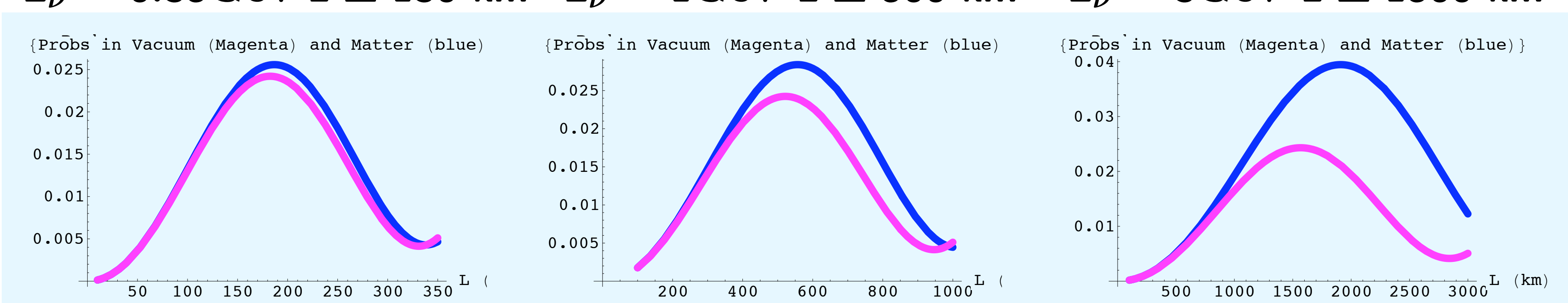
Courtesy: A. Rubbia

For δ_{cp} no difference between the Pyhäsalmi and Fréjus:



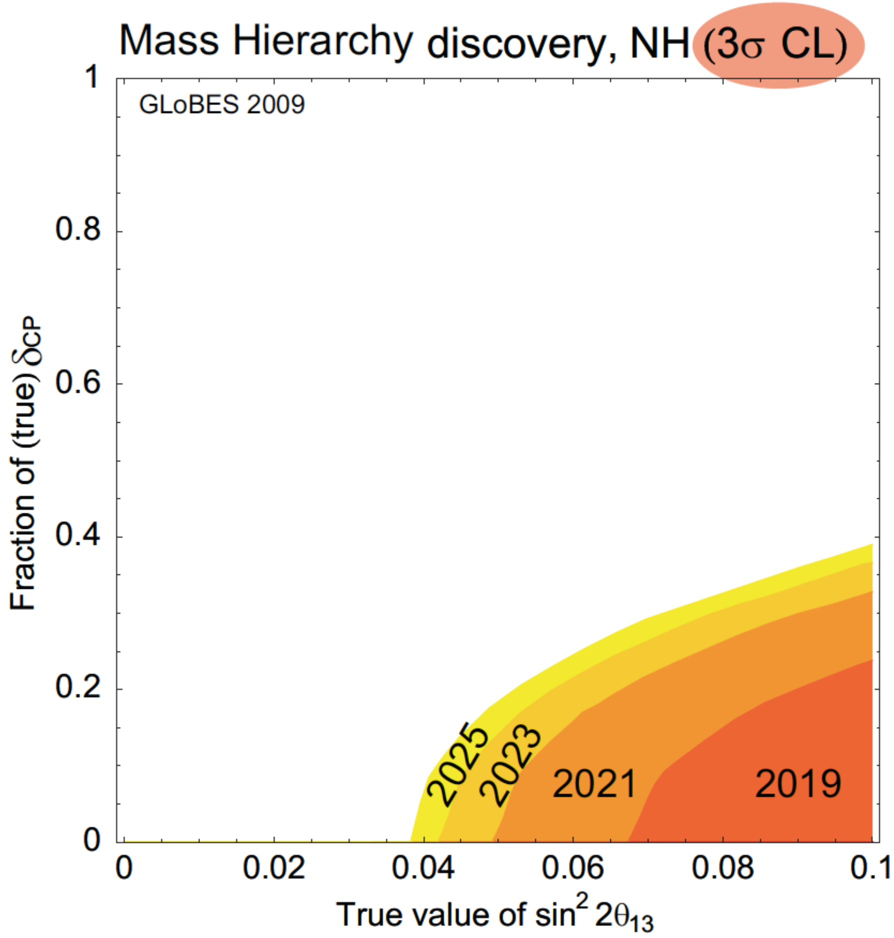
For Mass hierarchy the longer baseline is clearly better:

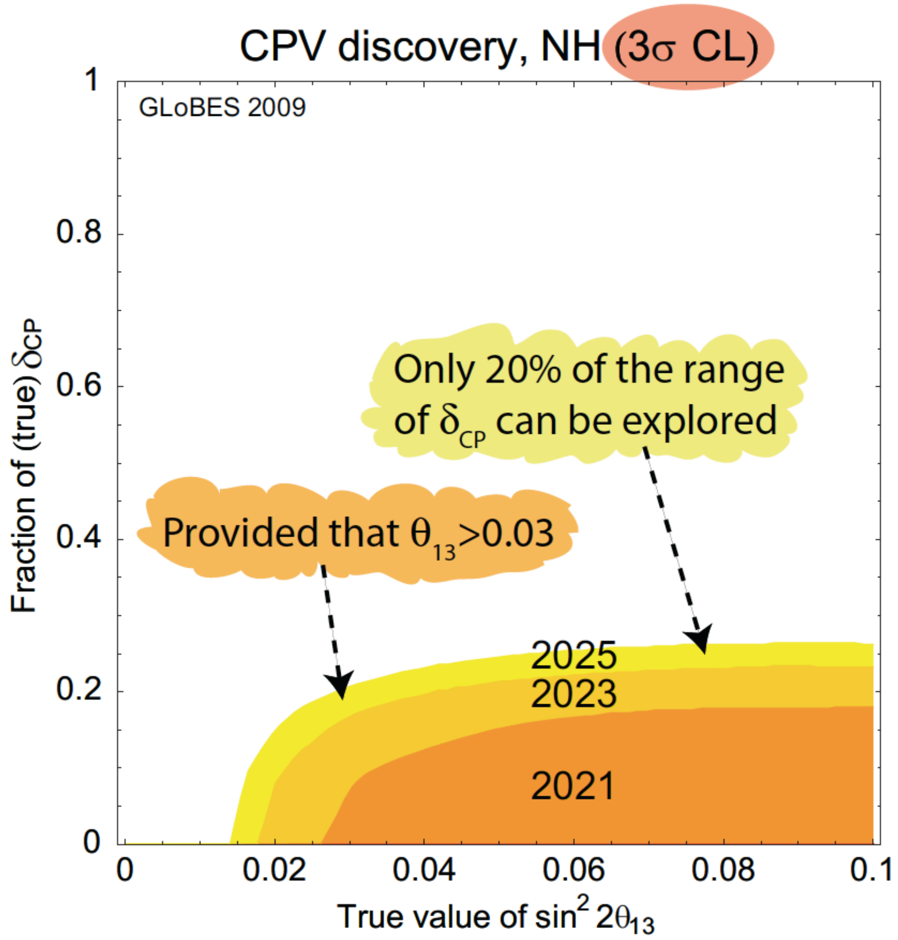
$E_\nu = 0.35\text{GeV}$ $L \simeq 130$ km $E_\nu = 1\text{GeV}$ $L \simeq 500$ km $E_\nu = 3\text{GeV}$ $L \simeq 1500$ km



From P. Huber et al., JHEP 0911:044,2009.

Prediction of sensitivity including a **fully optimized global run** (antineutrinos in T2K and NOνA) and **full upgrade of the accelerators**: 1.6 MW at J-PARC and 2.4 MW at FNAL (Project-X)





Incremental approach by A. Rubbia for Pyhäsalmi (2500 km):

arXiv:1003.1921

Phase 1 = LAr 20kt @ 900m + LSc 25kt @ 1400m + Fe
Phase 2 = Phase 1 + LAr 50kt @ 900m + LSc 25kt @ 1400m + Fe
Phase 3 = replace LAr 20kt by LAr 50kt + Fe

+ increase beam power

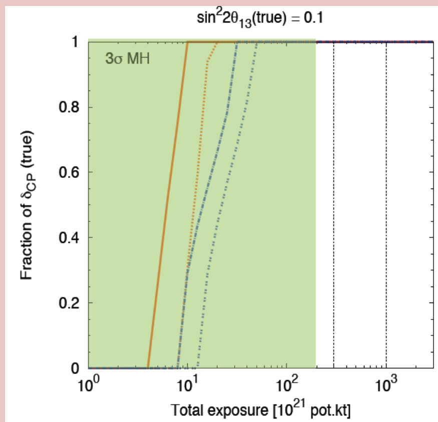
exposure = Npot@50 GeV x mass (kt)

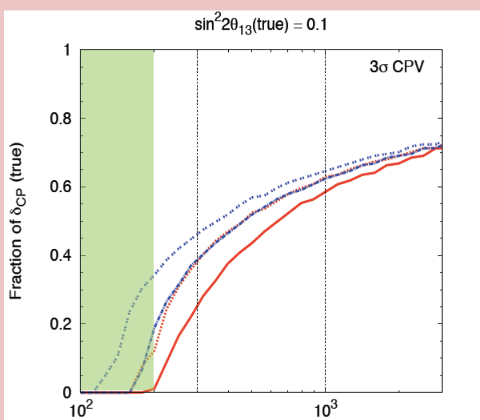
5 + 5 years running for all three phases

3 σ mass hierarchy determination

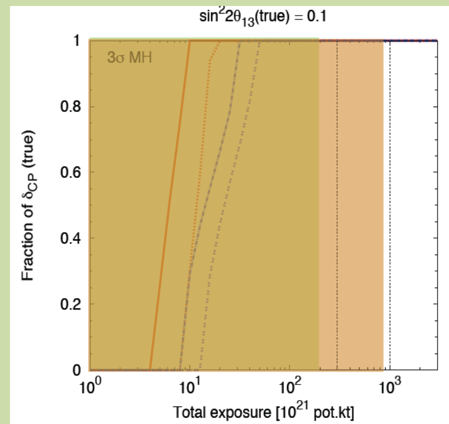
3 σ CPV discovery

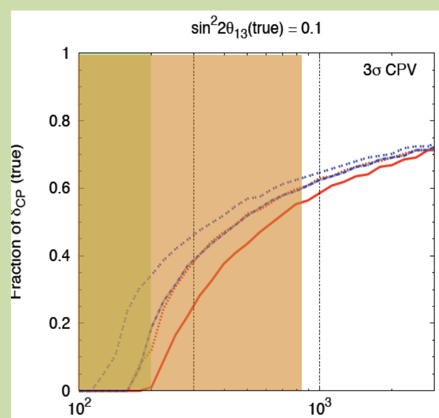
Phase 1



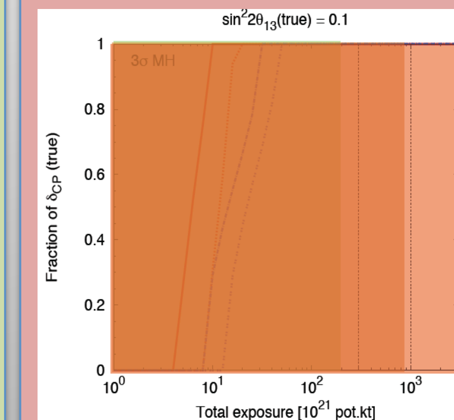


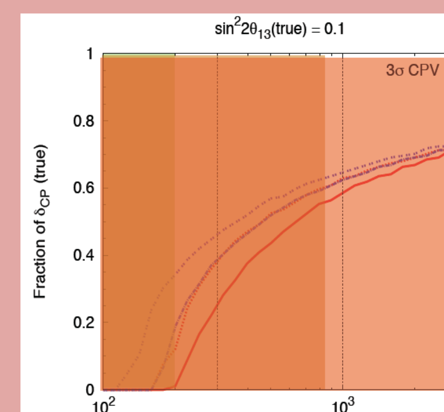
Phase 2





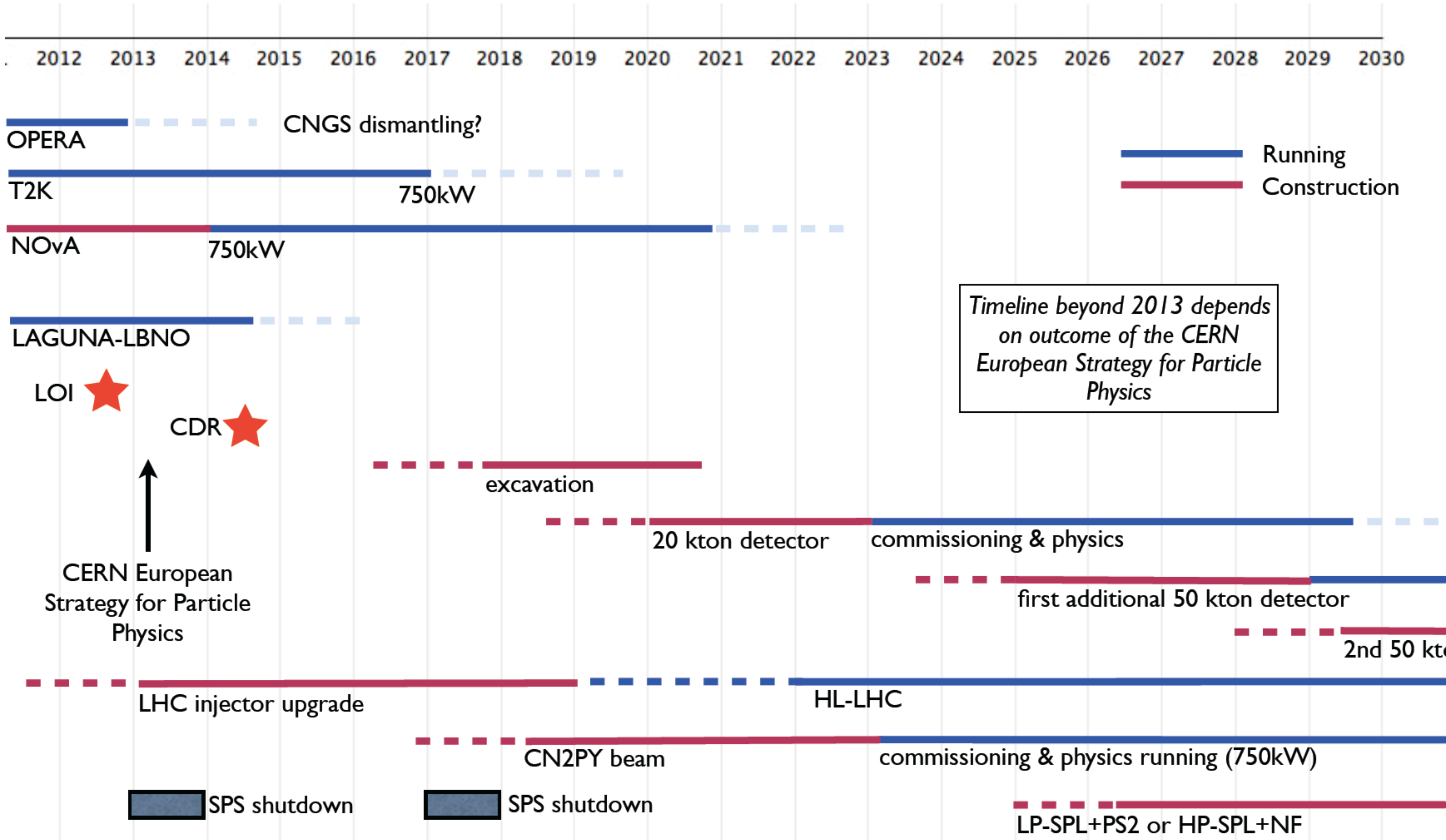
Phase 3





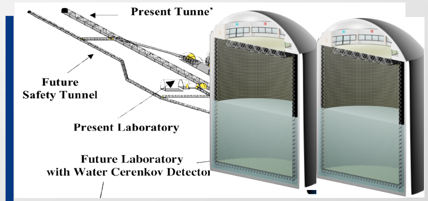
Courtesy: A. Rubbia

LAGUNA-LBNO Timeline



Courtesy: A. Rubbia

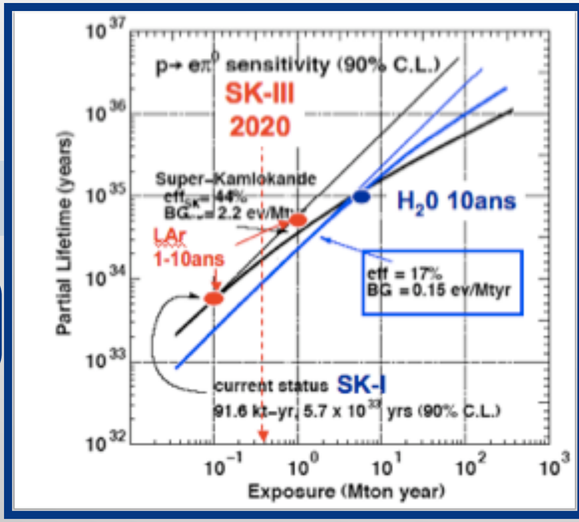
Astroparticle Physics and Proton Decay with MEMPHYS



$$p \to e^+ + \pi^0$$

"Golden channels"

H_2O better then LAr, Scint.

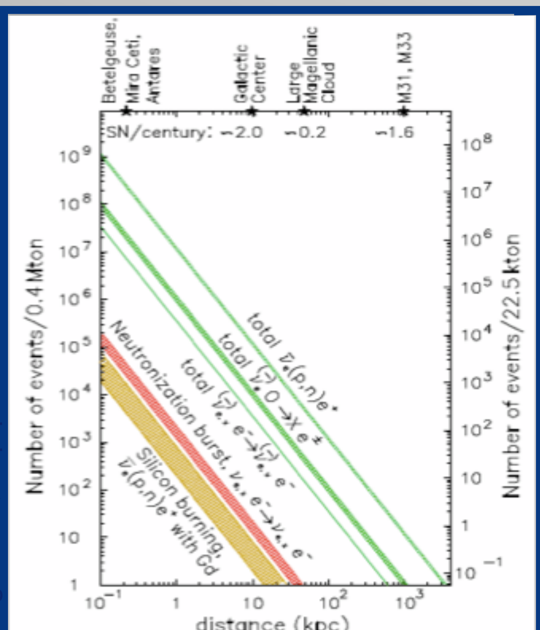


PROTON DECAY

arXiv:hep-ex/0005046v1

SUPERNOVA COLLAPSE NEUTRINOS

Fogli et al., hep-ph/0412046



Evidence up to ~ 1Mpc

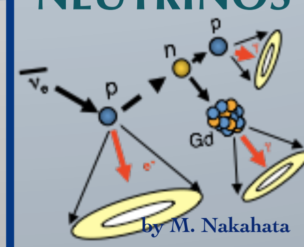
Galactic SN: Huge statistics

- SN explosion mechanism: shock waves, neutronization burst
- Neutrino production parameters:

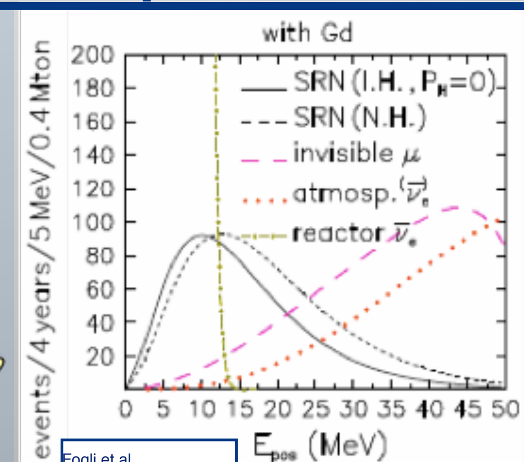
rate, spectra

- Neutrino properties

DIFFUSE SUPERNOVA NEUTRINOS



by M. Nakahata

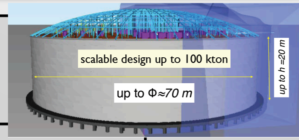


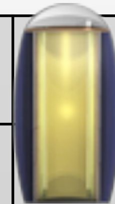
Fogli et al.
JCAP 0504:002,2005

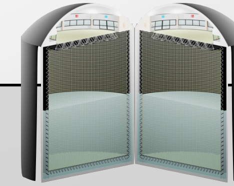
At Frejus one could get O 10 events in a 30 sec time window for an explosion at 1 Mpc

+ ATMOSPHERIC & SOLAR (ES) NEUTRINOS

Summary of the outstanding physics goals







	GLACIER	LENA	MEMPHYS
Total mass	100 Kton	50 kton	500 Kton
p -> eπ^0 in 10 y	0.5 x 10^{35} y ε = 45%, ~1 BG event	?	1.2 x 10^{35} y ε = 17%, ~1 BG event
p -> ν K in 10 y	1.1 x 10^{35} y ε = 97%, ~1 BG event	0.4 x 10^{35} y ε = 65%, <1 BG event	0.15 x 10^{35} y ε = 8.6%, ~30 BG events
SN cool off at 10 Kpc	38·500 (all flavors) (64·000 if NH-L mixing)	20·000 (all flavors)	194·000 (mostly ν_ep->e^+n)
Sn in Andromeda	7 - (12 if NH-L mixing)	4 events	40 events
SN burst at 10 Kpc	380 ν_e CC (flavor sensitive)	~ 30 events	~ 250 ν-e elastic scattering
DSN	50	20-40	250 (2500 with Gd)
Atm. neutirnos	~1·100 events/y	5600/y	56·000 events/y
Solar neutrinos	324·000 events/y	?	91·250·000/y
Geo-neutirnos	0	~ 3·000 events/y	0

Summary

- World-wide interest for next generation long-baseline based on the conventional neutrino beam technology, with longer baselines to address CP-violation and mass hierarchy, as the next step beyond T2K/NOvA.
- Next generation Neutrino Physics will come from new, megaton scale underground detectors
- Europe has a unique advantage of big choice of sites, detector technologies and beam options
- $\beta-$beam is an European invention and provides unreached sensitivity to LCPV and $\theta 13$, intensively studied in Euronu
- Laguna-Pyhäsalmi beam will be studied in Laguna-LBNO by CERN
- A LAGUNA-LBNO staged approach ("pilot project") will likely be proposed. Open to all interested !

http://www.laguna-science.eu/