Neutrino Physics

Spaatind 2012
XX11 Nordic Conference on Particle Physics
Jan. 5/6, 2012

Dave Wark
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Science & Technology Facilities Council

Imperial College London

Where did the idea of the neutrino come from?

There were problems in the early days of β decay.

β spectra were continuous

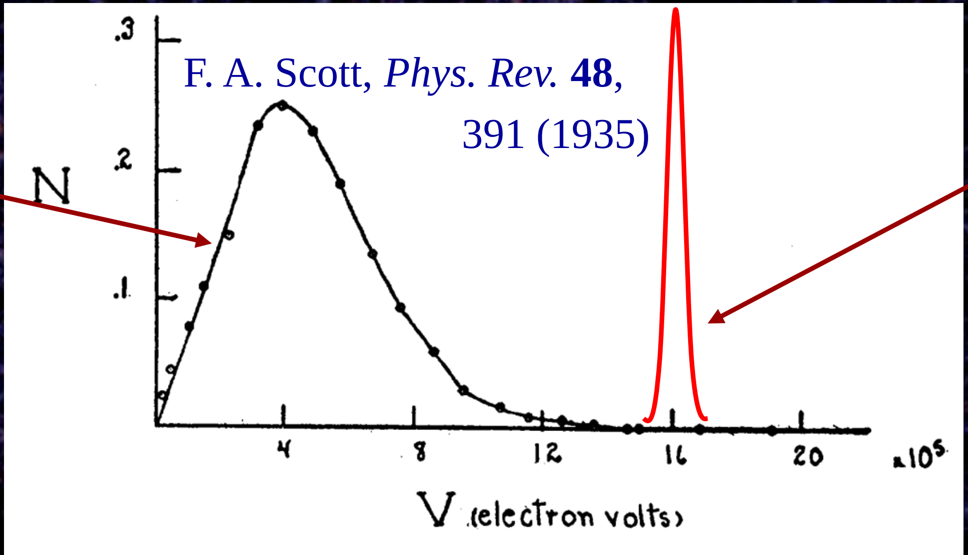

FIG. 5. Energy distribution curve of the beta-rays.

Instead of discrete

And the spins didn't add up… $^{14}C \rightarrow {}^{14}N + e^{-}$

spin 0 spin 1 spin 1/2

Bohr: maybe energy/momentum not conserved in β decay?

Dave Wark
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Pauli's Solution…

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 the 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

How to detect them?

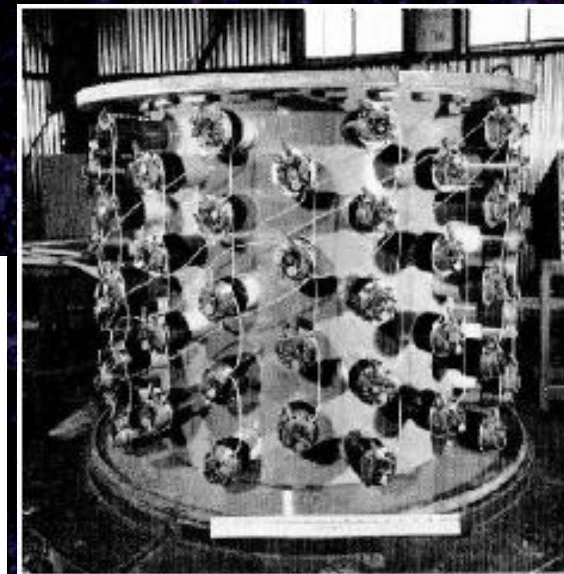
- The detection of neutrinos was an extreme challenge for the experiments of the mid-twentieth century – Pauli, in fact, apologized for hypothesizing a particle that could not be detected.
- In a Chalk River report in 1946, Bruno Pontecorvo pointed out the advantages of a radiochemical experiment based on $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ (and even mentioned solar neutrino detection using this method).
- However the first detection of neutrinos used another method…

Detection of the Free Neutrino*

F. Reines and C. L. Cowan, Jr.
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 9, 1953; revised manuscript received September 14, 1953)

An experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The



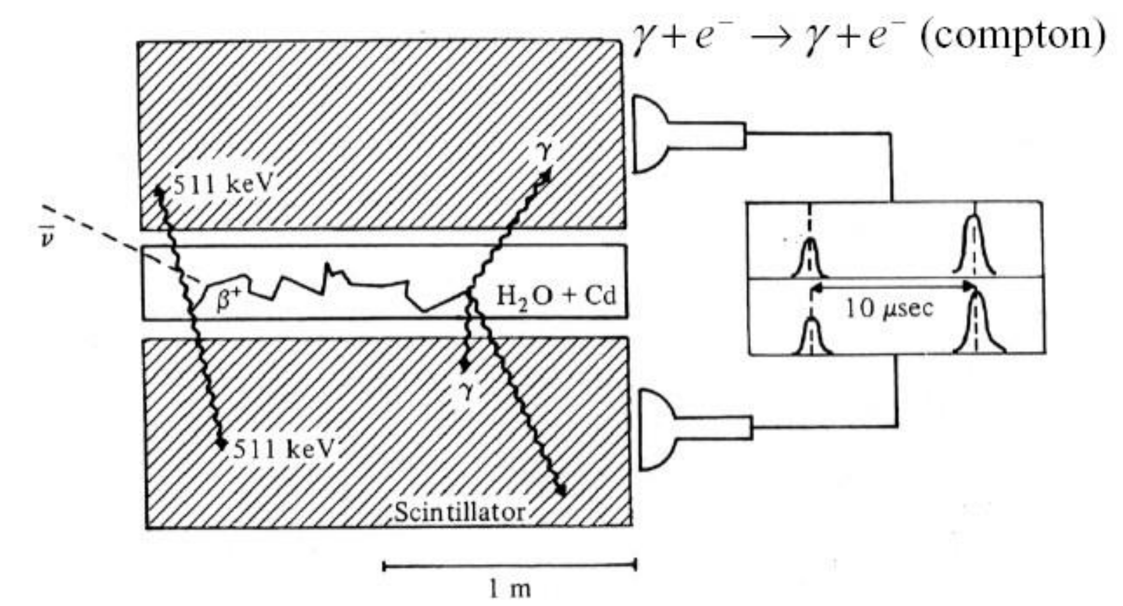
PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

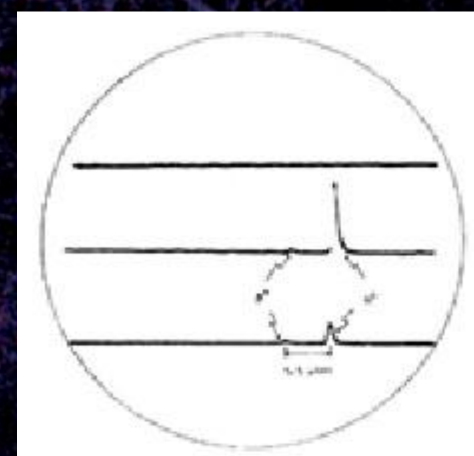
Detection of the Free Antineutrino*

F. Reines,† C. L. Cowan, Jr.,‡ F. B. Harrison, A. D. McGuire, and H. W. Kruse
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 27, 1959)

The antineutrino absorption reaction $p(\bar{\nu},\beta^+)n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal dependended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.





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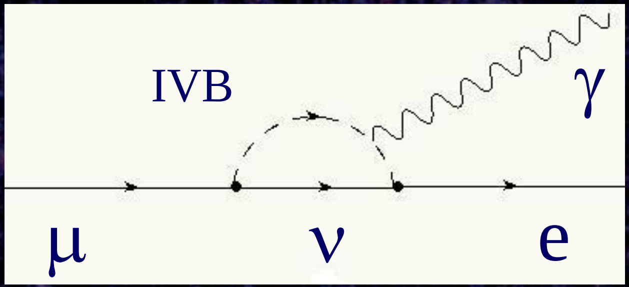
More Ancient History…

- Question in the late 50's: Are the neutrinos in these reactions the same thing?:

$$n \rightarrow p + e + \nu \qquad \pi \rightarrow \mu + \nu \qquad \mu \rightarrow e + \nu + \nu$$

- If so, why no $\mu \rightarrow e + \gamma$ via diagrams like?:



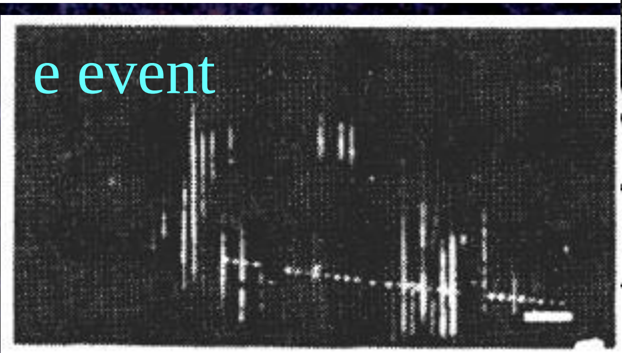
This year is the 50th anniversary!

VOLUME 9, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1962

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)



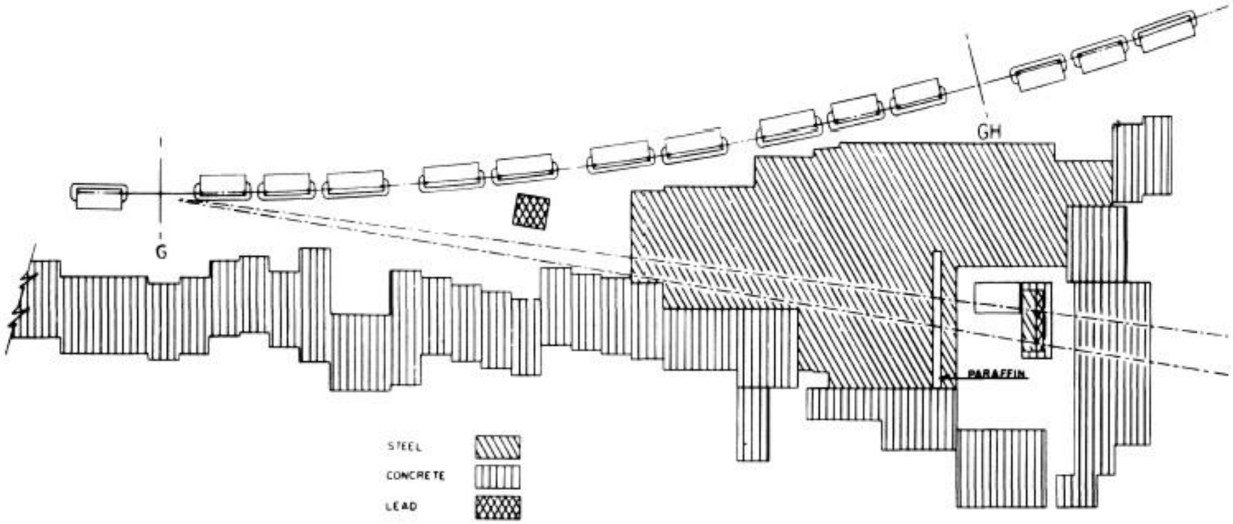


FIG. 1. Plan view of AGS neutrino experiment.

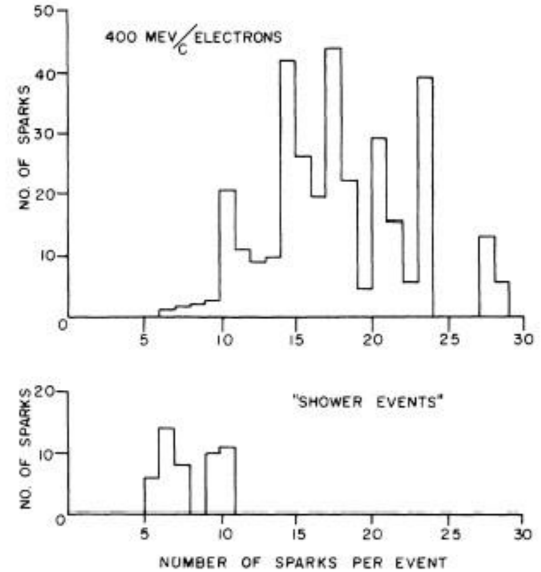
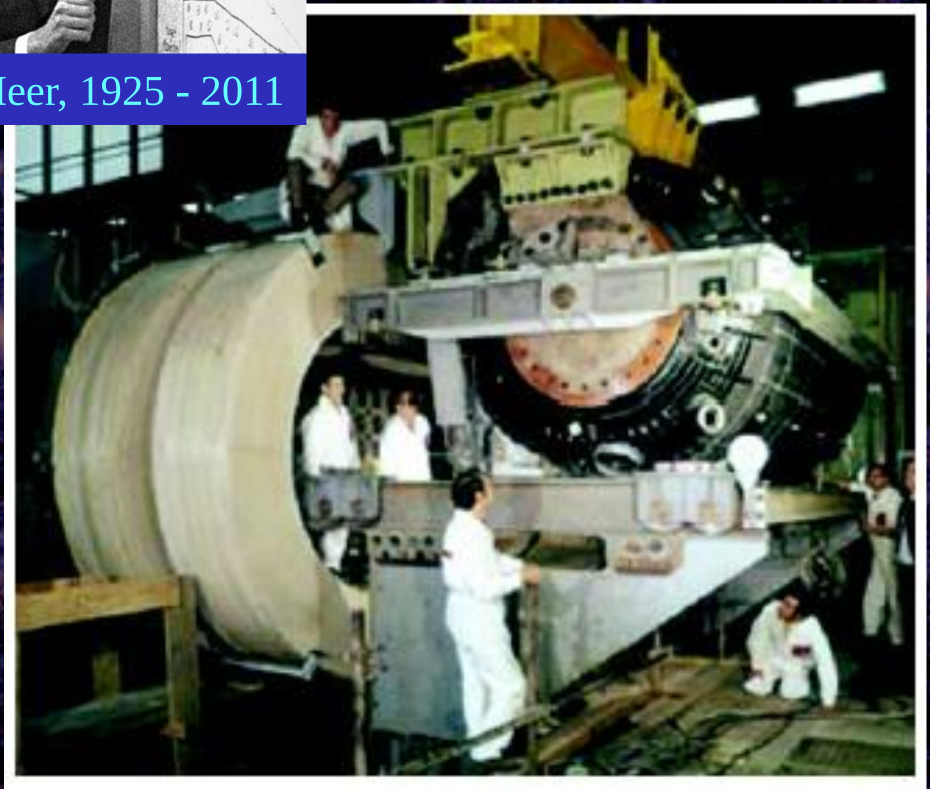


FIG. 9. Spark distribution for 400-MeV/c electrons normalized to expected number of showers. Also shown are the "shower" events.

The Discovery of Neutral Currents

Simon van der Meer, 1925 - 2011

The 1st Neutrino Horn –
Van den Meer, CERN, 1961



The Gargamelle
CF_3Br Bubble Chamber

The Discovery of Neutral Currents

Most of the basic techniques were now in place, and since then we have built them bigger/faster/more sensitive....

Dave Wark
Imperial College/RAL

Why am I spending all this time talking about ancient experiments?

- It's fun…
- I was told that students would be present.
- I would like them to carefully note as I go through all the amazing, expensive, flashy new experiments to come that they are almost all just elaborations of these early ideas.
- This is a beautiful demonstration of the most important single thing my advisor ever taught me:

"Three months in the laboratory will save you three hours in the library".

Neutrino Oscillations

- If neutrinos have mass, then there are two distinct types of neutrino state we must consider – the eigenstates of the weak Hamiltonian $\nu_l = \nu_e, \nu_\mu, \nu_\tau$; and the eigenstates of the free particle Hamiltonian $\nu_i = \nu_1, \nu_2, \nu_3$.
- There is absolutely no reason to believe that these are the same thing.
- In general:

$$|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$$

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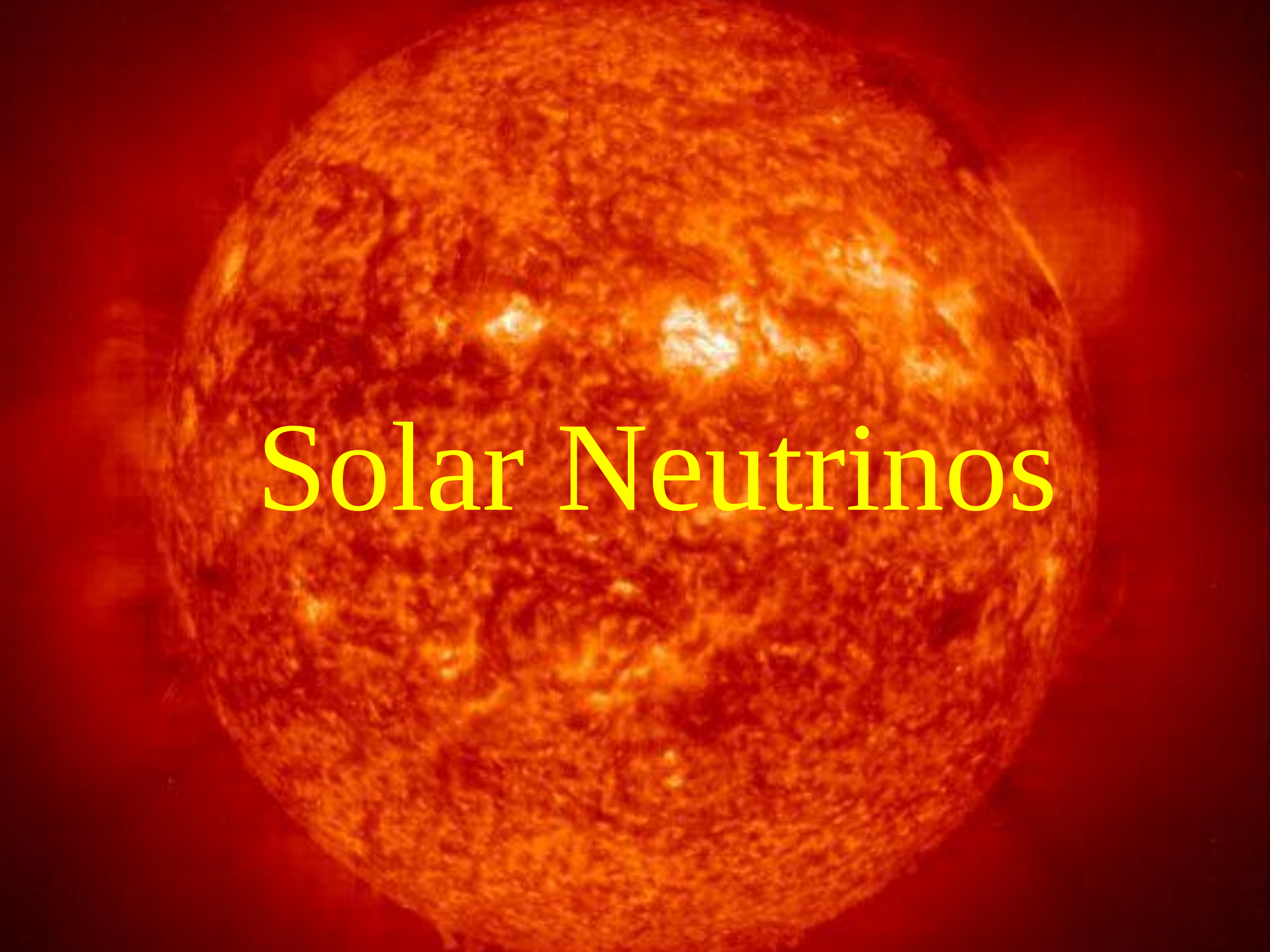
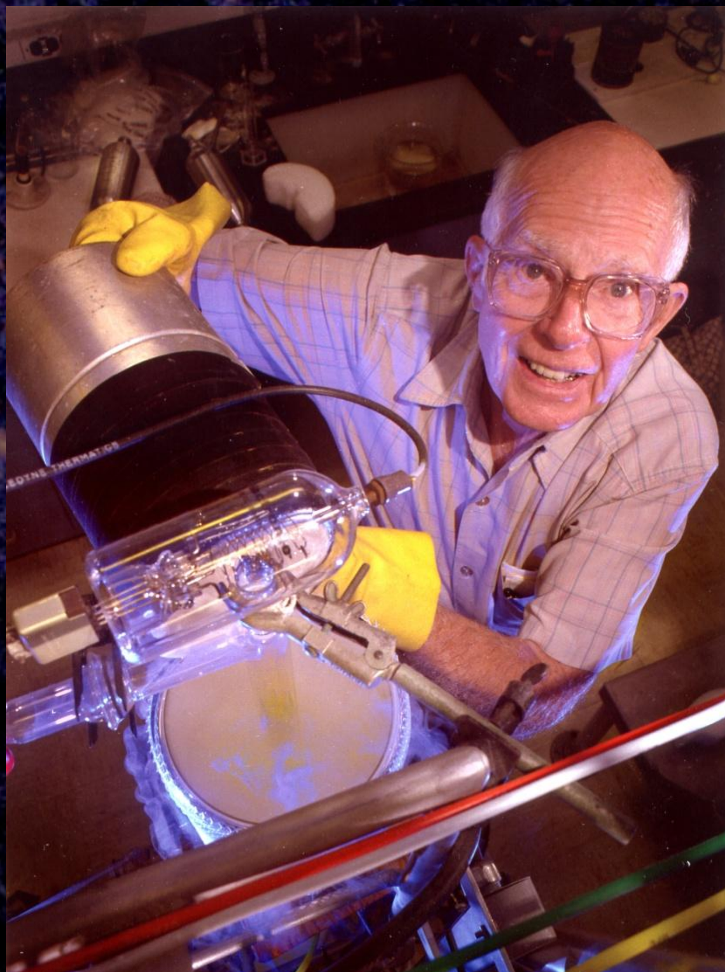
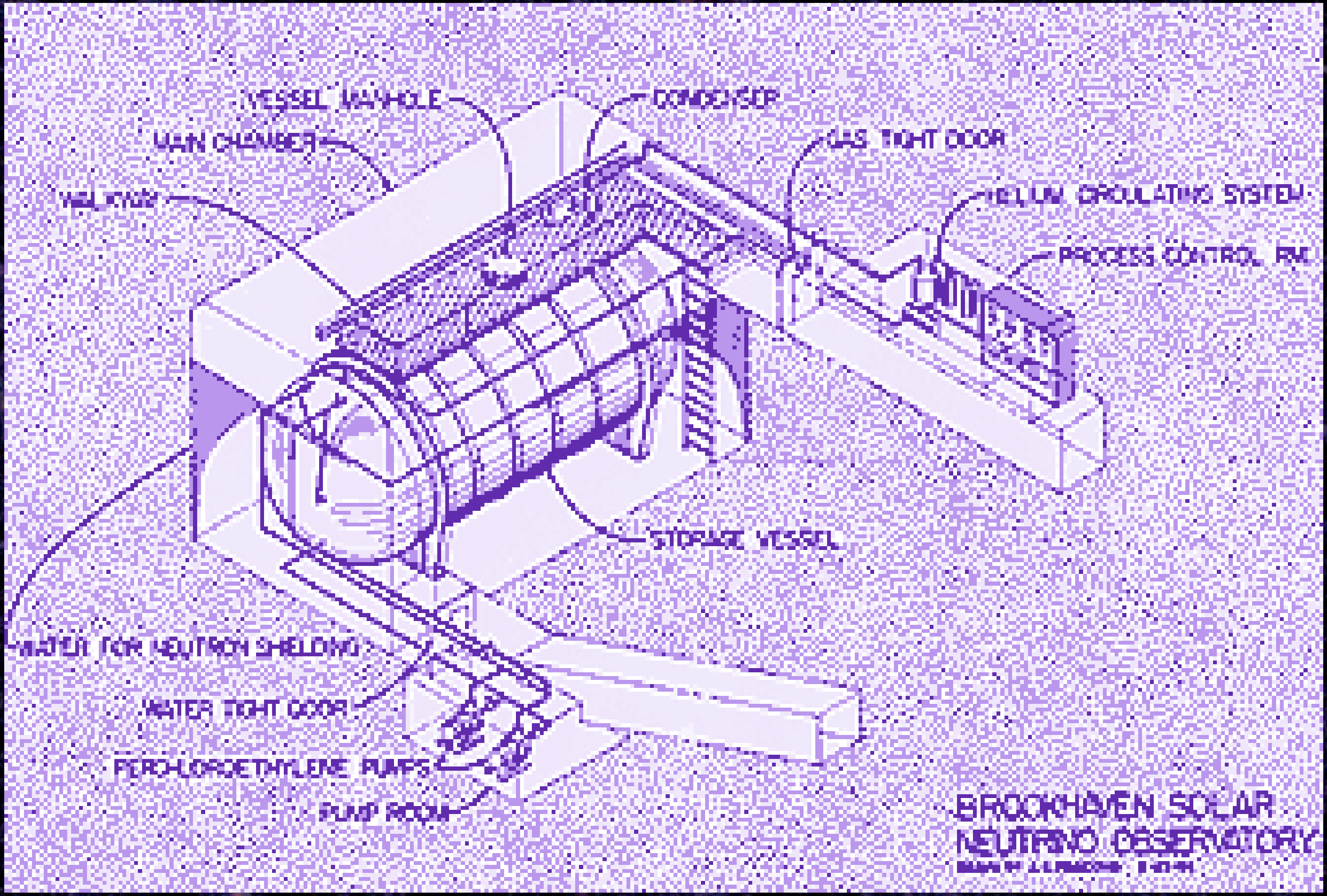

Solar Neutrinos

Ray Davis



John Bahcall

Where it all began – the Davis Experiment



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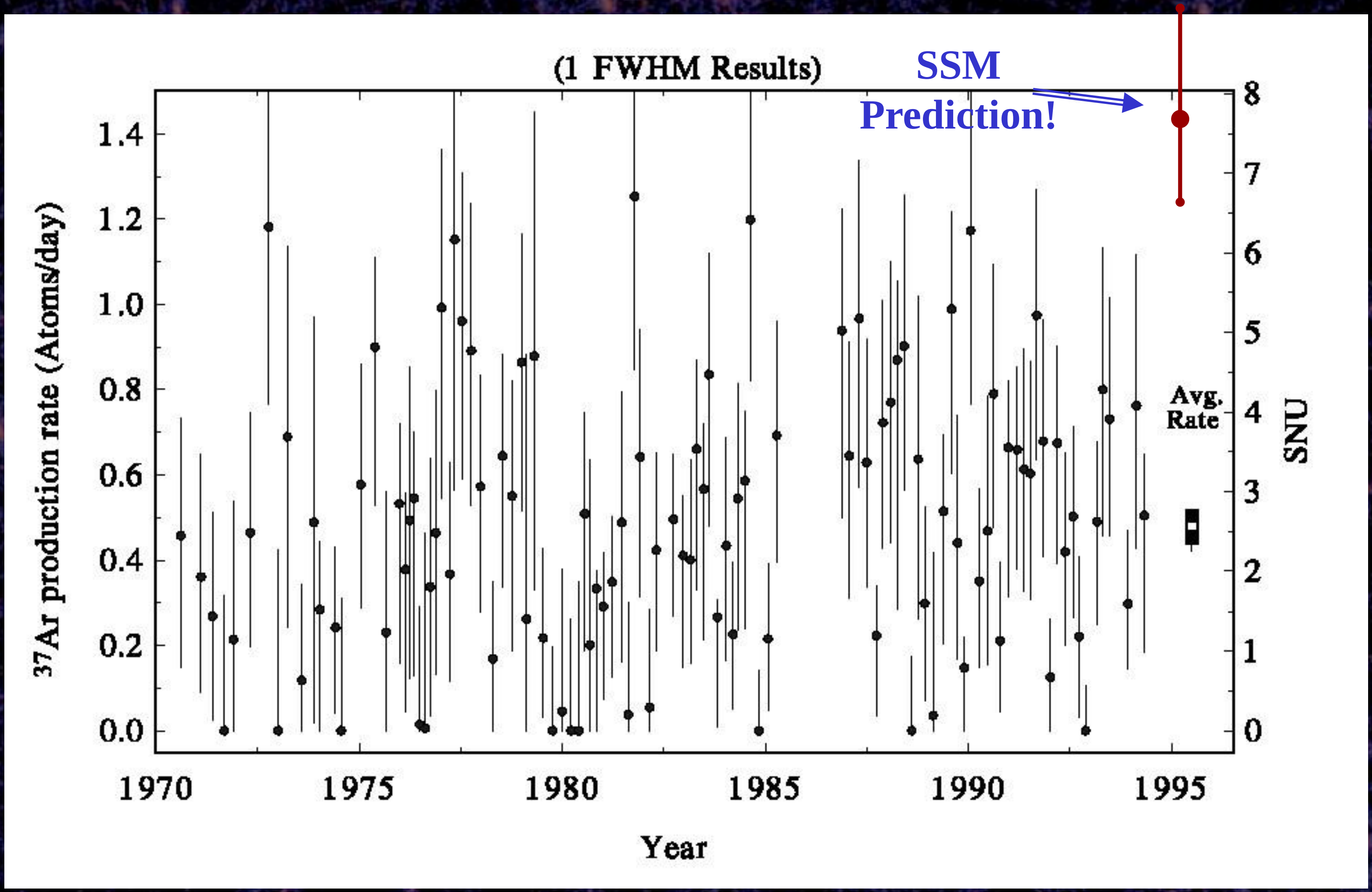
Where it all began – the Davis Experiment



Maybe the experiment is wrong…

Theorists are always thinking….

- 1957 – Bruno Pontecorvo, wondering if there are any other particles which could undergo oscillations analogous to $K^0 \leftrightarrow \overline{K^0}$ oscillations, hit upon the idea of neutrino ↔ anti-neutrino oscillations (more about this later).
- 1962 – Maki, Nakagawa, and Sakata (in the context of what looks today like a very odd model of nucleons) proposed that the weak neutrinos known at the time were superpositions of "true" neutrinos with definite masses, and that this could lead to transitions between the different weak neutrino states.
- 1967 – Pontecorvo then considered the effects of all different types of oscillations in light of what was then known, and pointed out ***before any results from the Davis experiment were known*** that the rate in that experiment could be expected to be reduced by a factor of two!
- 1972 – Pontecorvo is informed by John Bahcall that Davis does indeed see a reduced rate, and responds with a letter….

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79. Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31 April 6/10 19 72

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

looking forward to see you there.

Yours sincerely,

B Pontecorvo

B.Pontecorvo

BMP/nn

2ν Vacuum Oscillations

- For two neutrino flavours in vacuum oscillations lead to the appearance of a new neutrino flavour:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$$

$$\Delta m^2 = m_2{}^2 - m_1{}^2 \text{ in } eV^2, \text{ L in meters, E in MeV}$$

- With the corresponding disappearance of the original neutrino flavour, hence Davis result?
- These oscillations can be significantly modified by the MSW effect when the neutrinos pass through matter…

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Matter Effects – the MSW effect

$$i\frac{d}{dt}\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix}$$

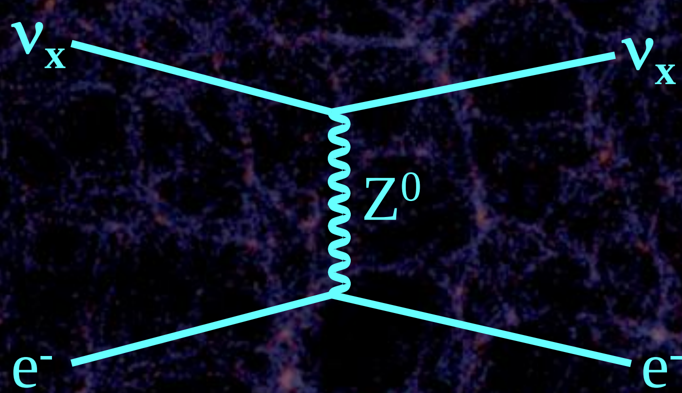
In vacuum:

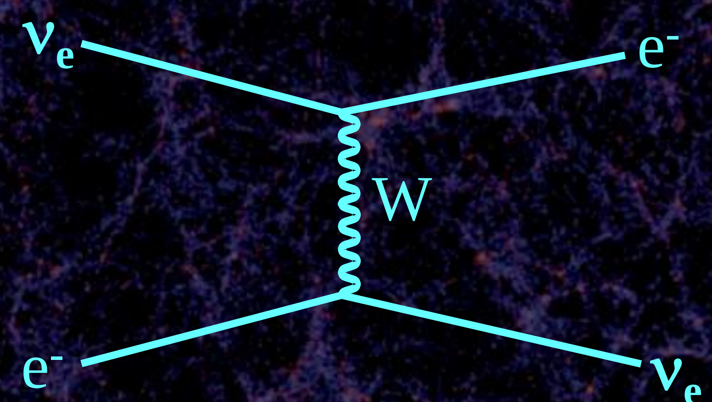
$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

Matter Effects – the MSW effect

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}$$

$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta \quad \text{[redacted]} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$





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Imperial College/RAL

Matter Effects – the MSW effect

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}$$

$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\omega = -2\sqrt{2}G_F N_e E / \Delta m^2$$

Including this effect gives a good (if complicated) fit to all solar ν data....

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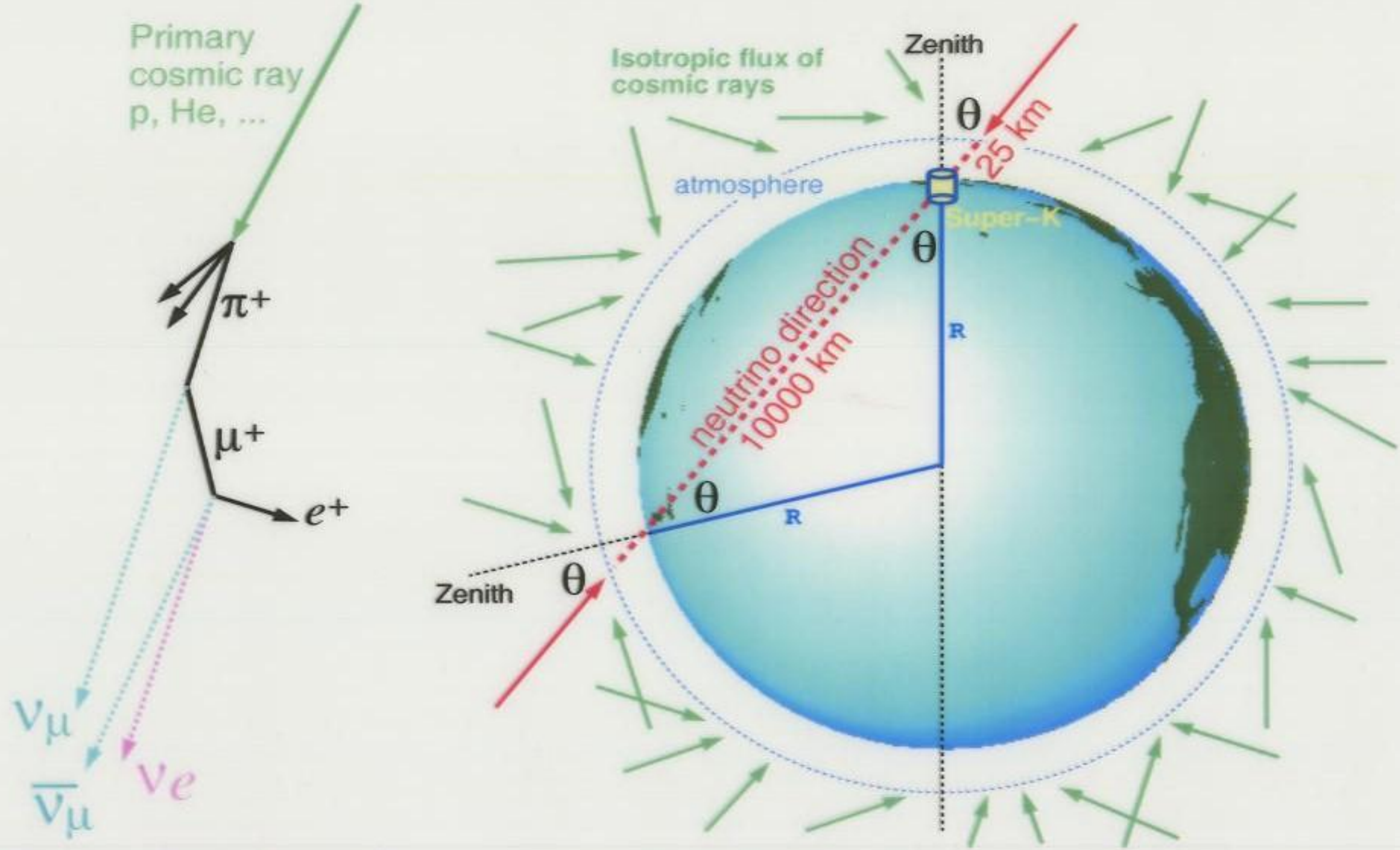
Imperial College/RAL

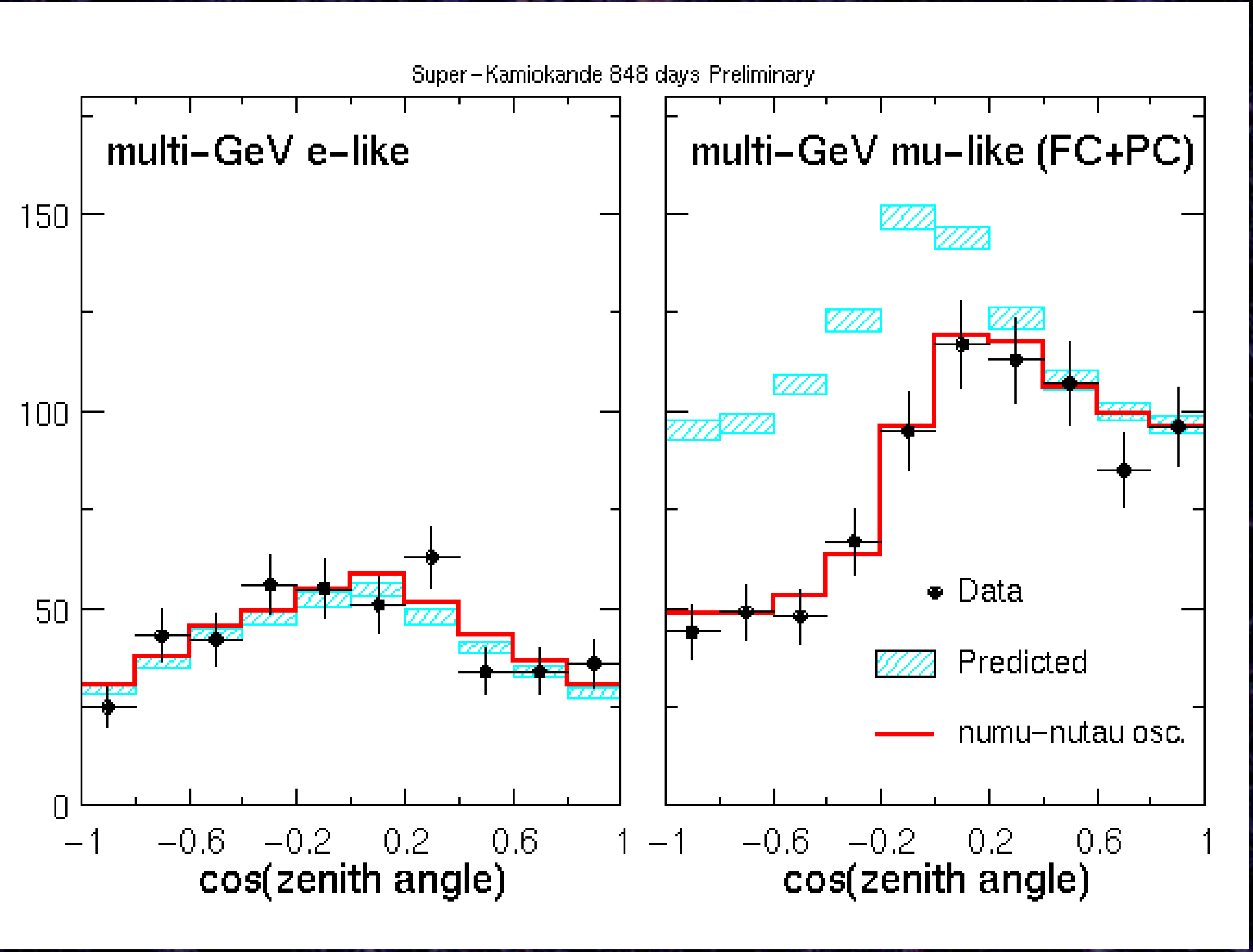
ATMOSPHERIC NEUTRINOS



Ratio of ν_μ/ν_e ~ 2
(for E_ν < few GeV)

Up–Down Symmetric Flux
(for E_ν > few GeV)

SK atmospheric ν data as a function of zenith angle



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Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$$\begin{aligned} P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right) \\ &+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\ &-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\ &+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\ &-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \ (1 - 2S_{13}^2) \end{aligned}$$

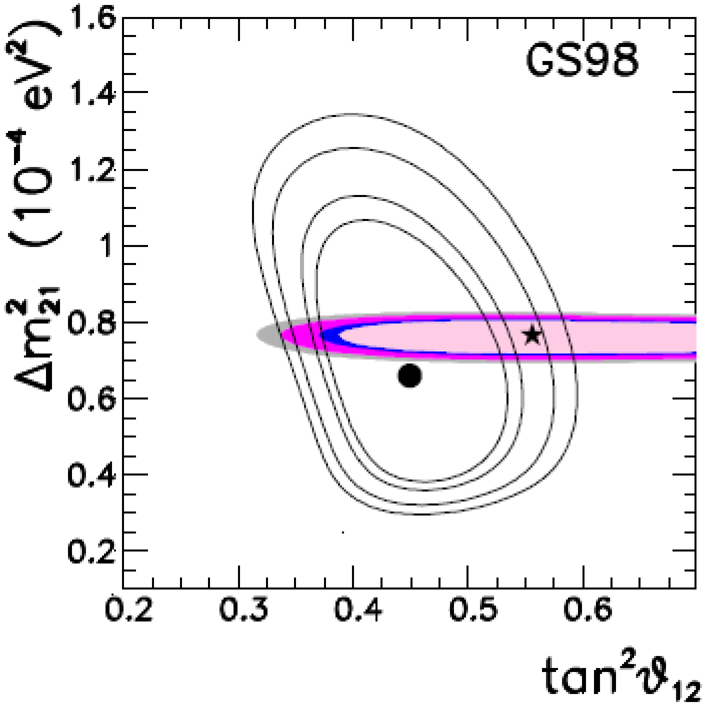
Remember degeneracies
And covariances!

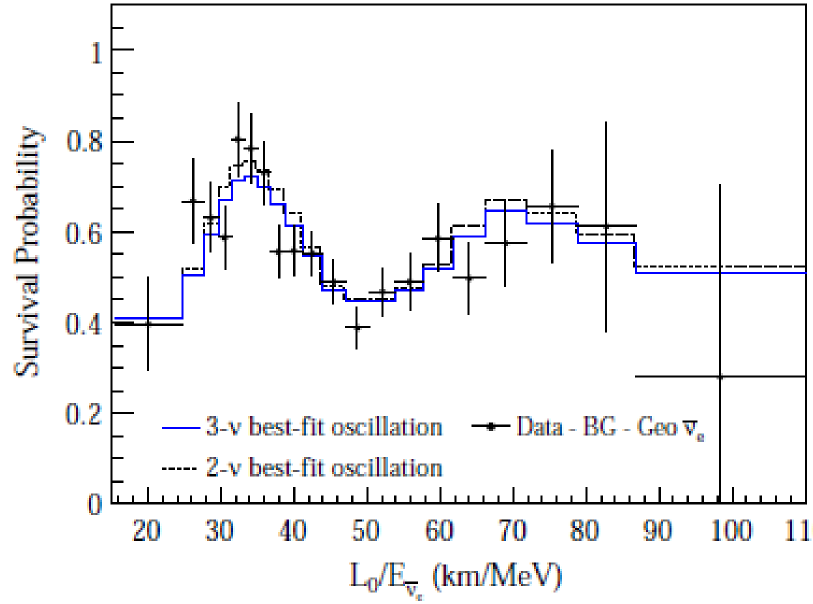
How well do we know θ_{12}?

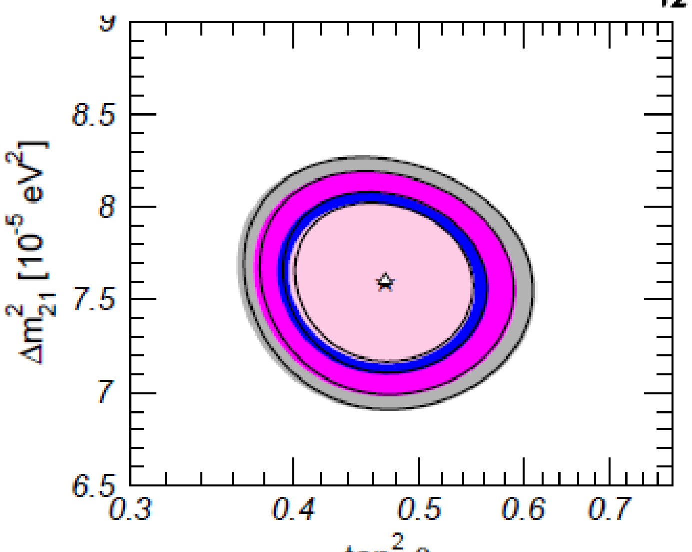
arXiv:1009.4771v3 [hep-ex] 25 Mar 2011

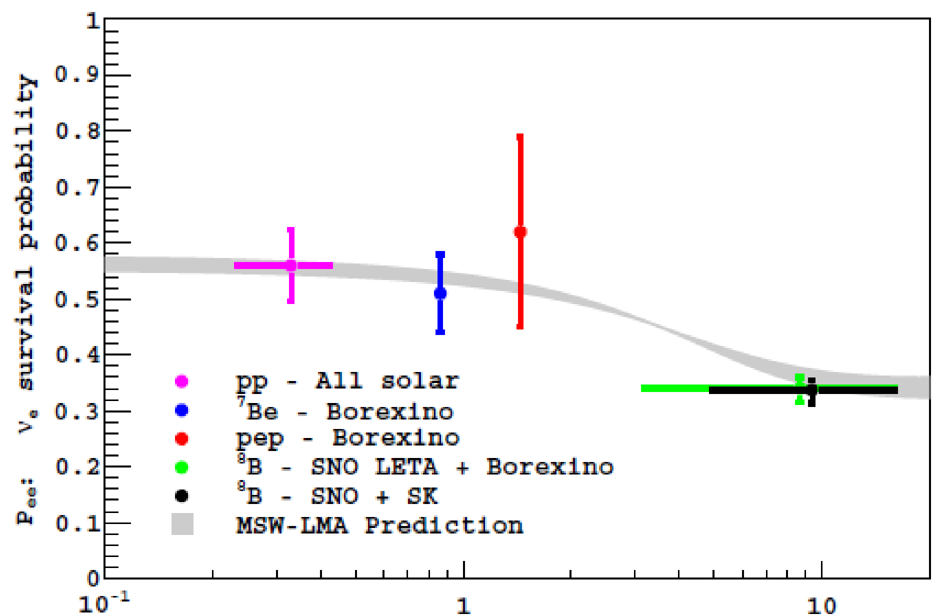
Gonzalez-Garcia, Maltoni, Salvado

arXiv:1001.4524v4 [hep-ph] 16 Jun 2011



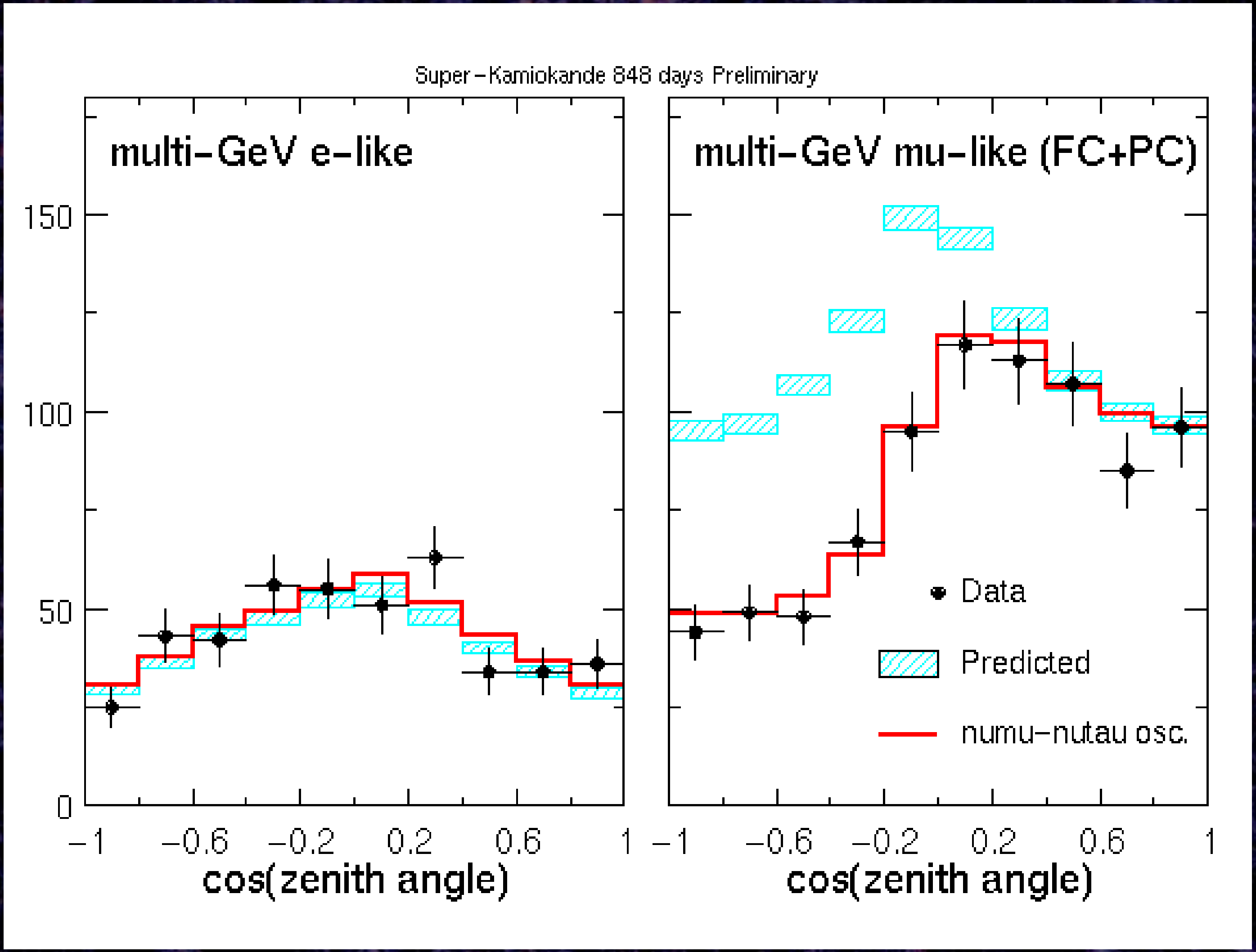






arXiv:1110.3230v1 [hep-ex]

θ_{23}? – Back to SK's atmospheric oscillations



This proves all by itself (well, including SR) that neutrinos have mass...How to check it on earth?

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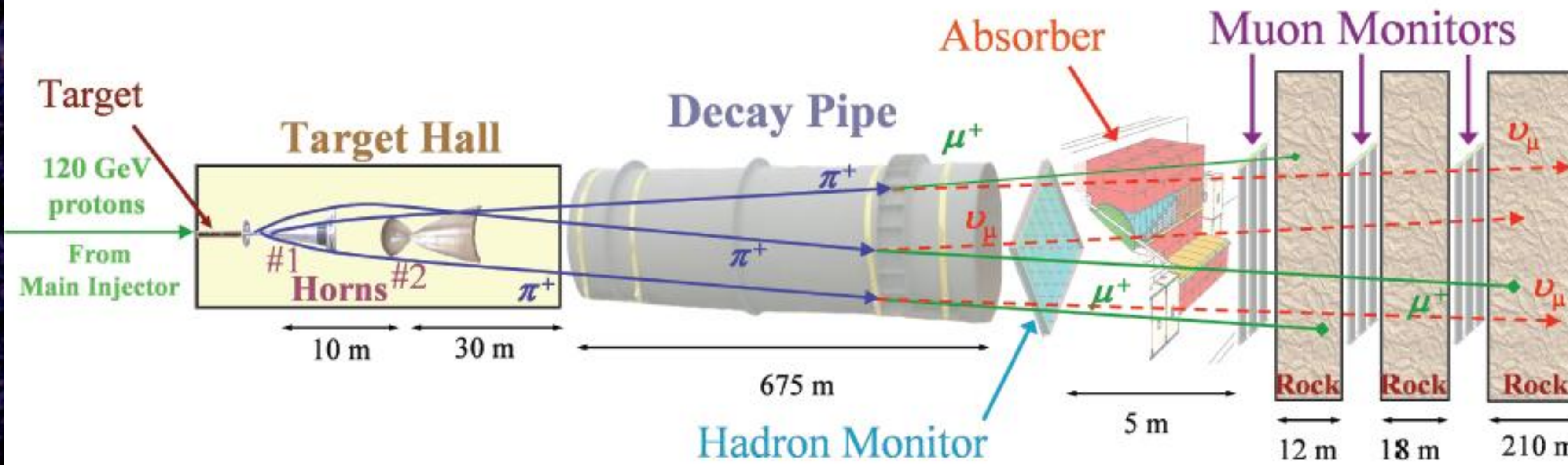
Imperial College/RAL

Making a neutrino beam

10



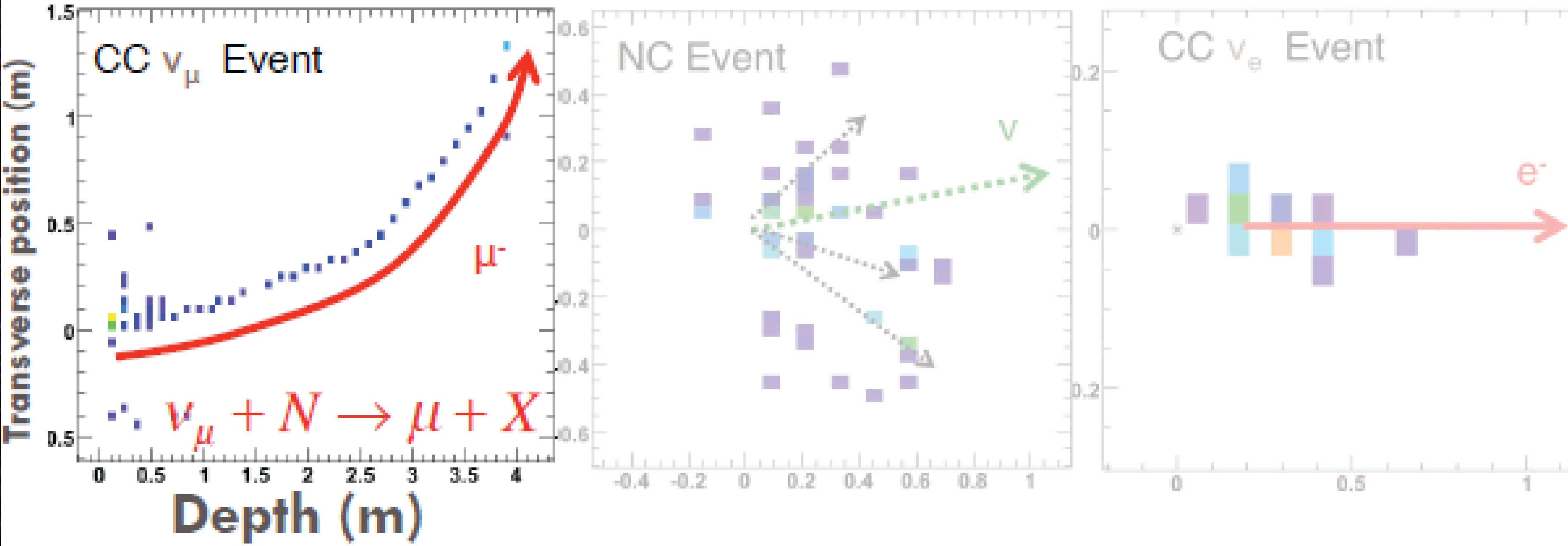
First successful demonstration of ν oscillations with such a beam was by K2K,
but in the interest of time let's skip to MINOS...

From Patricia Vahle's presentation at Neutrinos 2010


ICHEP talk by Justin Evans
Far Detector
735 km from Source
MINOS Far Detector
Wisconsin
735km
Milwaukee
Michigan
Fermilab
Chicago
Near Detector
1 km from Source
MINOS
168 km
© 2007 Europa Technologies
Image © 2007 TerraMetrics
Image © 2007 NASA
Pointer 43°34'32.84" N 89°04'55.60" W elev 271 m
Streaming 100%

Events in MINOS

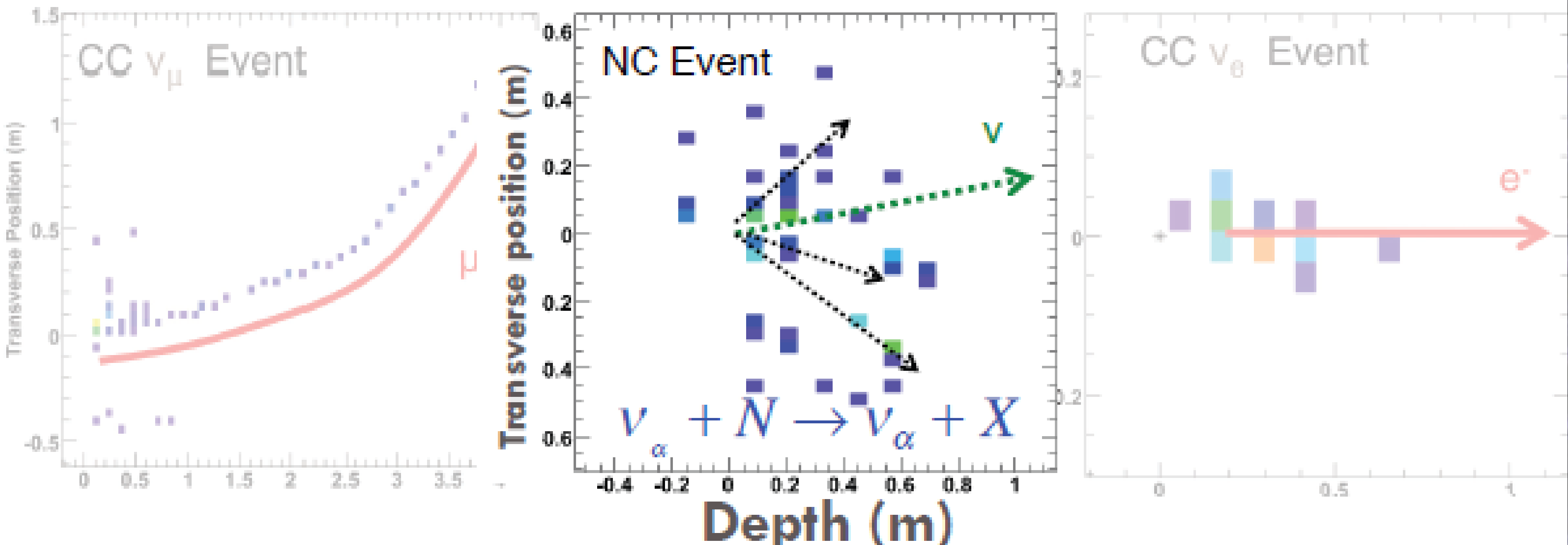
Simulated Events



- ν_μ Charged Current events:
  - long μ track, with hadronic activity at vertex
  - neutrino energy from sum of muon energy (range or curvature) and shower energy

Events in MINOS

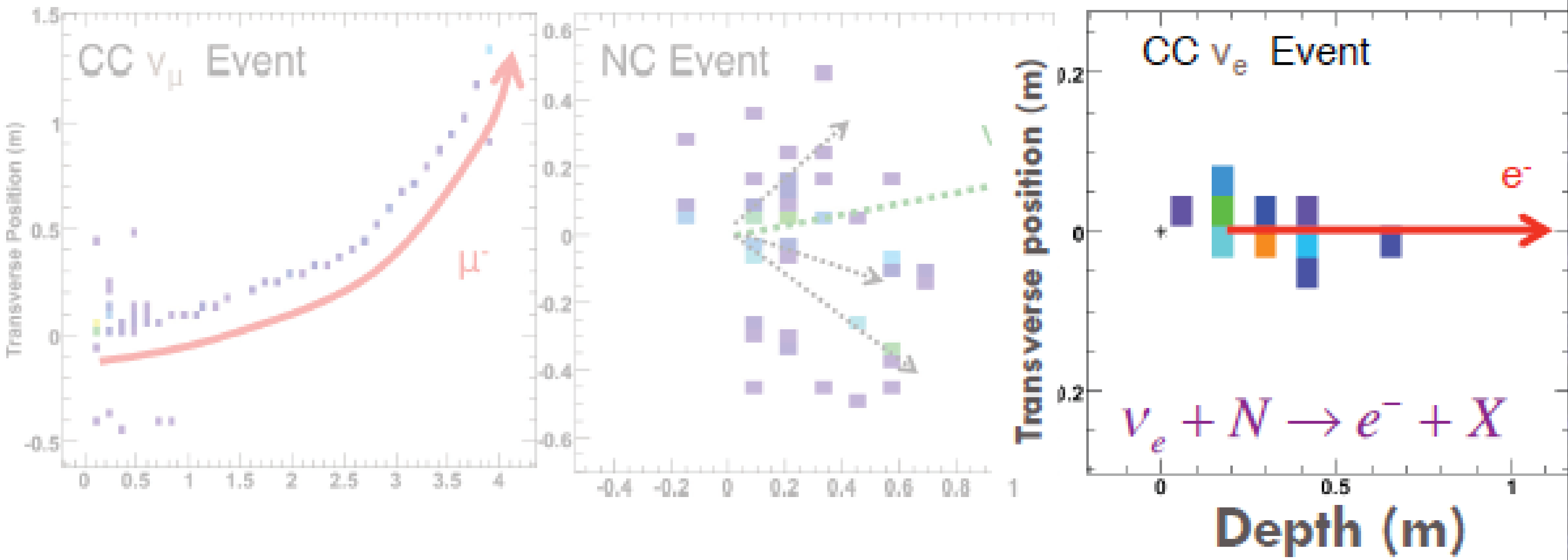
Simulated Events



- Neutral Current events:
  - short, diffuse shower event
  - shower energy from calorimetric response

Events in MINOS

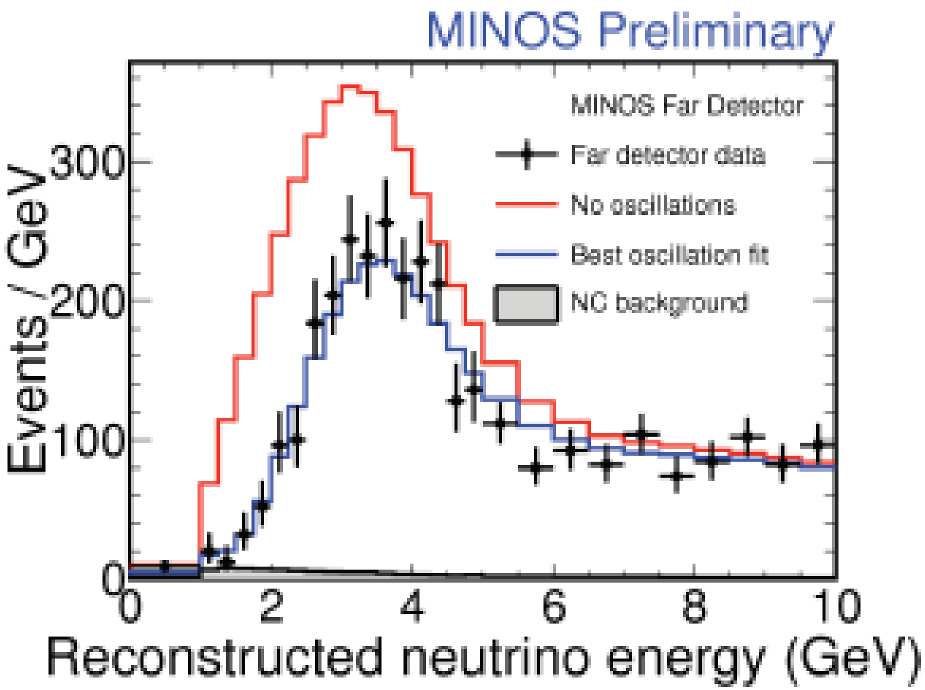
Simulated Events

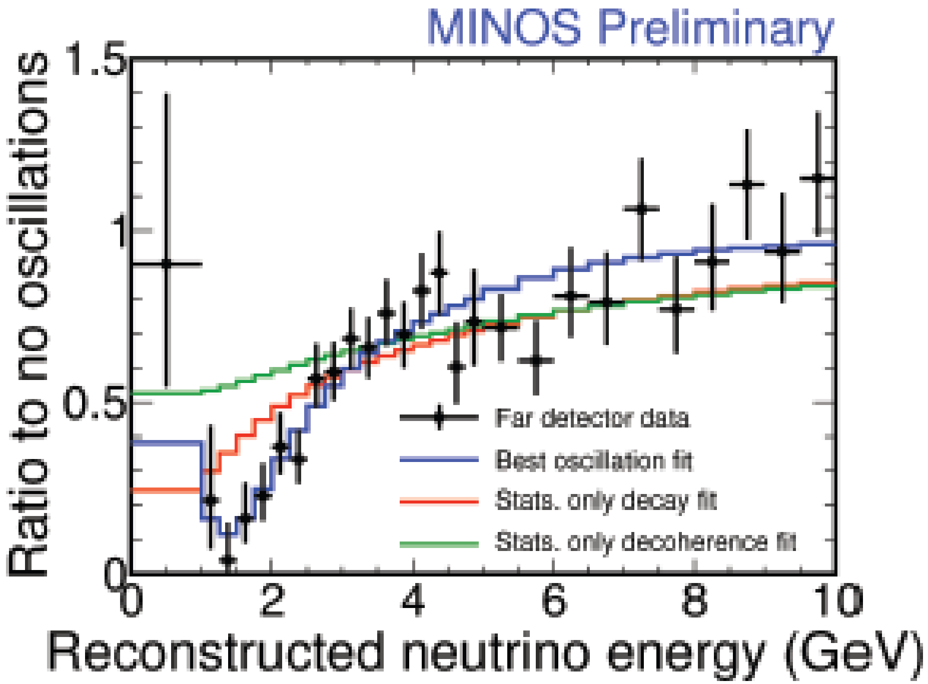


- ν_e Charged Current events:
  - compact shower event with an EM core
  - neutrino energy from calorimetric response

Cross-sections for all processes very poorly known!

Far Detector Energy Spectrum





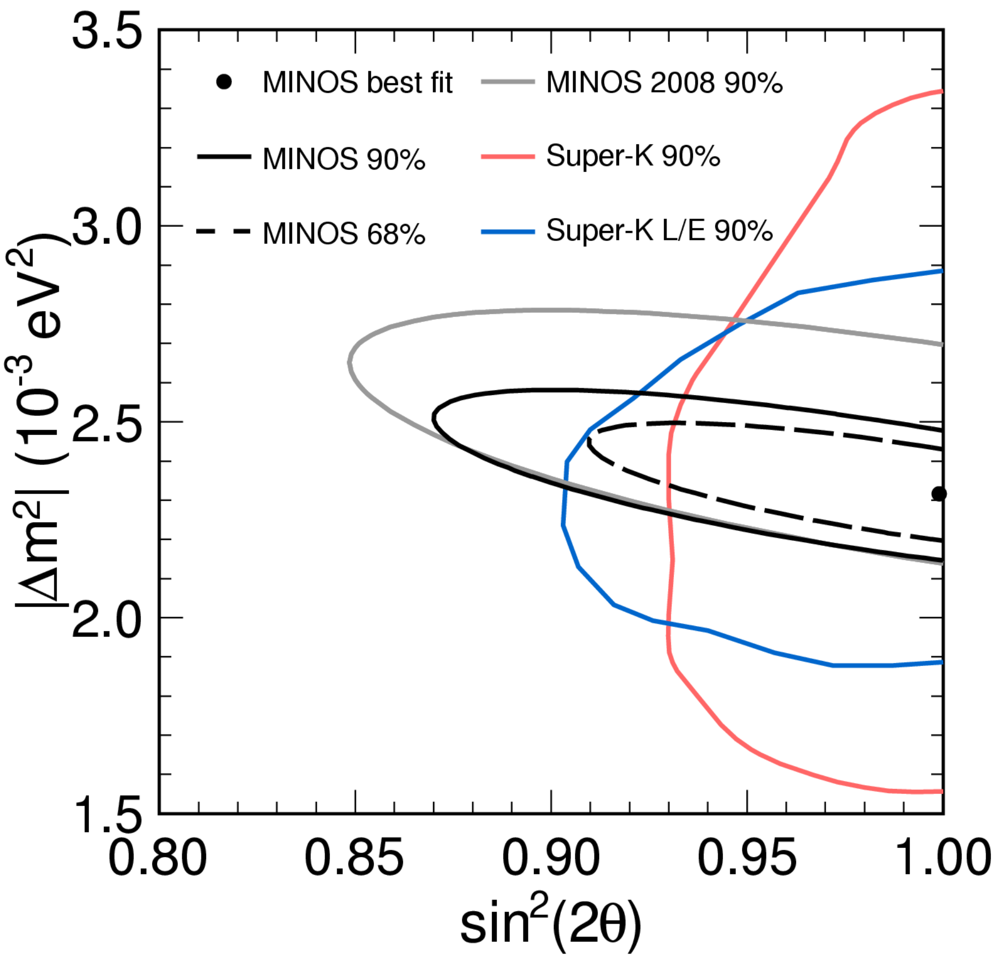
- Oscillations fit the data well, 66% of experiments have worse χ^2
- Pure decoherence† disfavored: > **8σ**
- Pure decay‡ disfavored: > **6σ**

(**7.8σ** if NC events included)

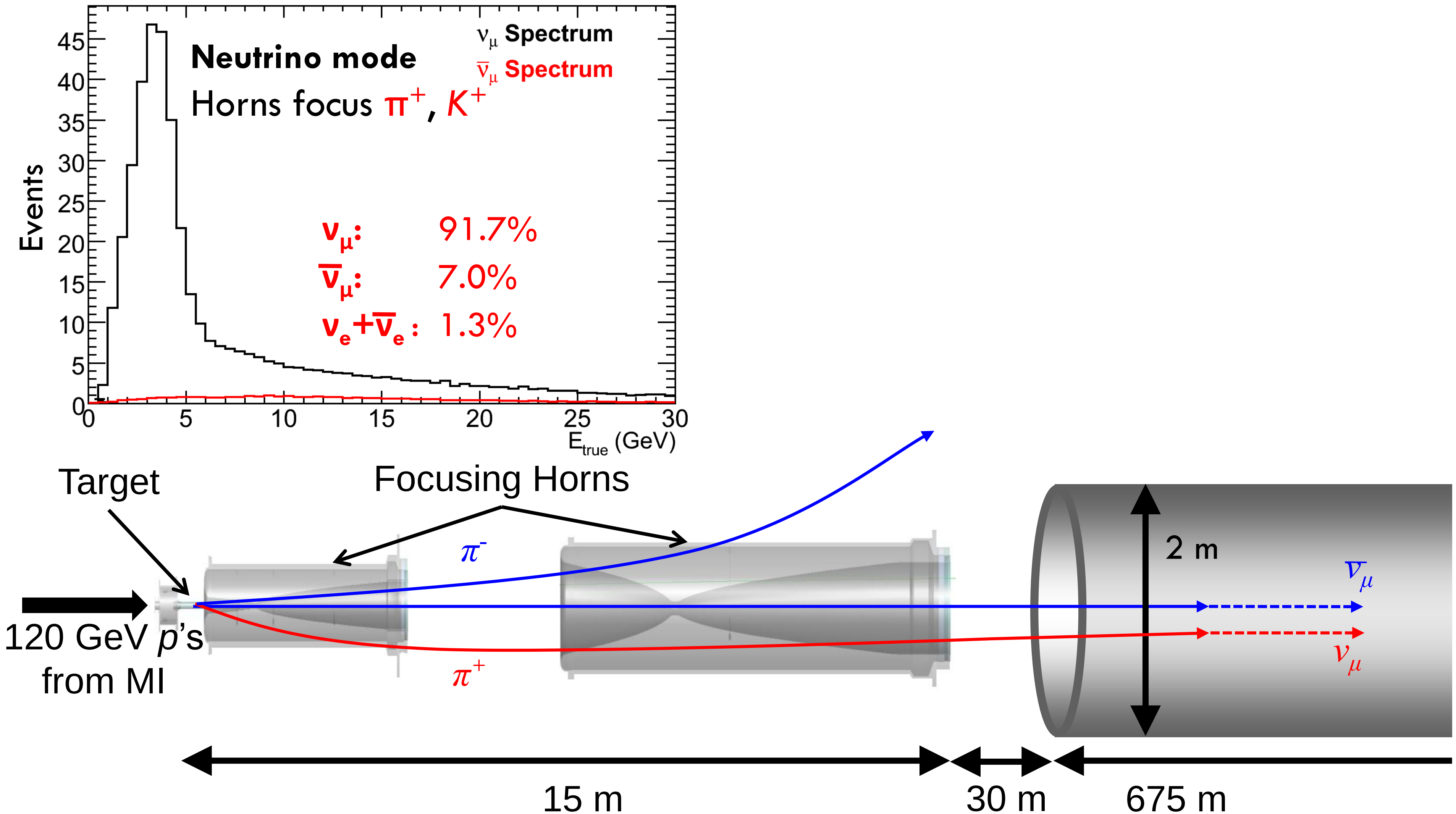
†G.L. Fogli *et al.*, PRD 67:093006 (2003) ‡V. Barger *et al.*, PRL 82:2640 (1999)

Contours

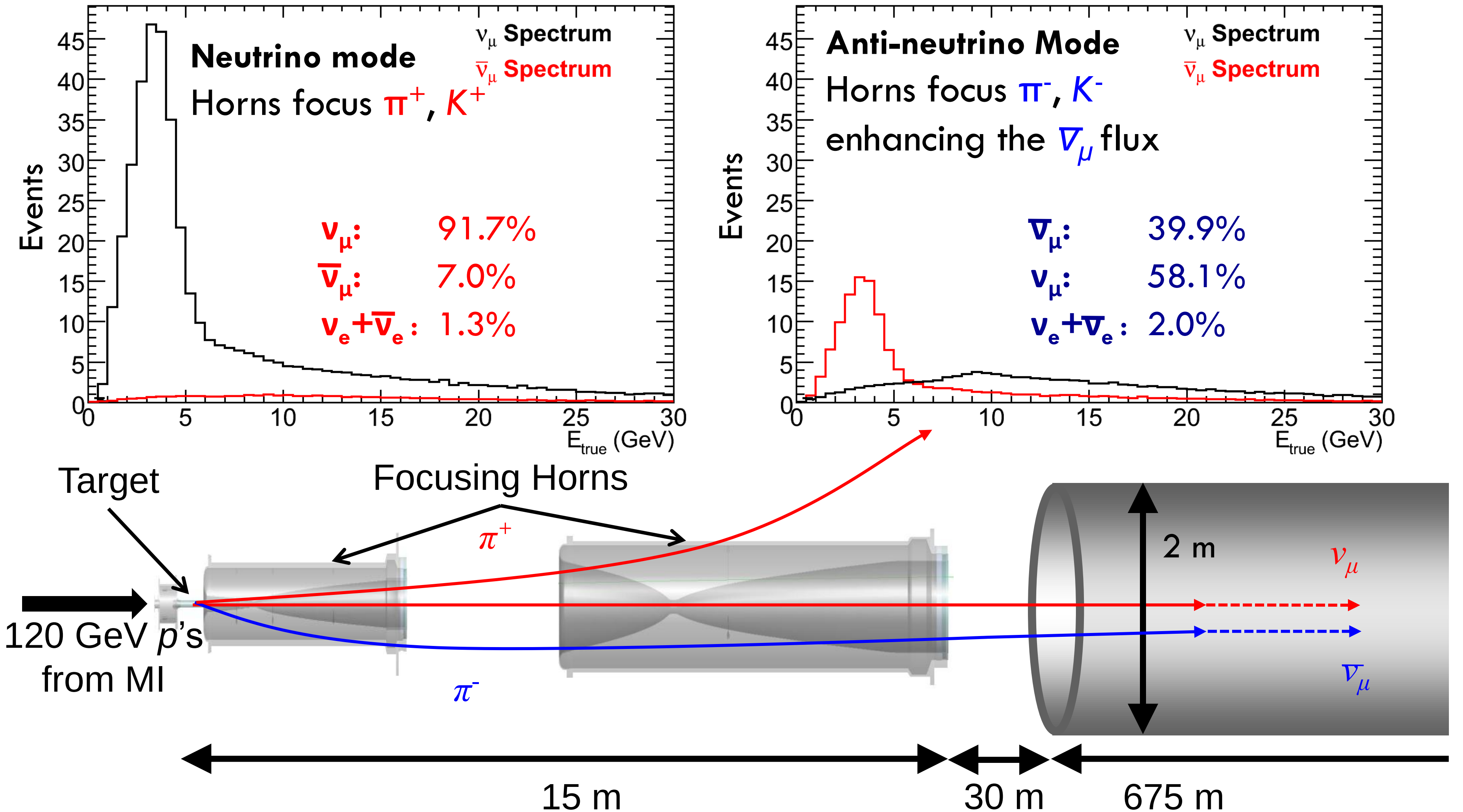
- Contour includes effects of dominant systematic uncertainties
  - normalization
  - NC background
  - shower energy
  - track energy



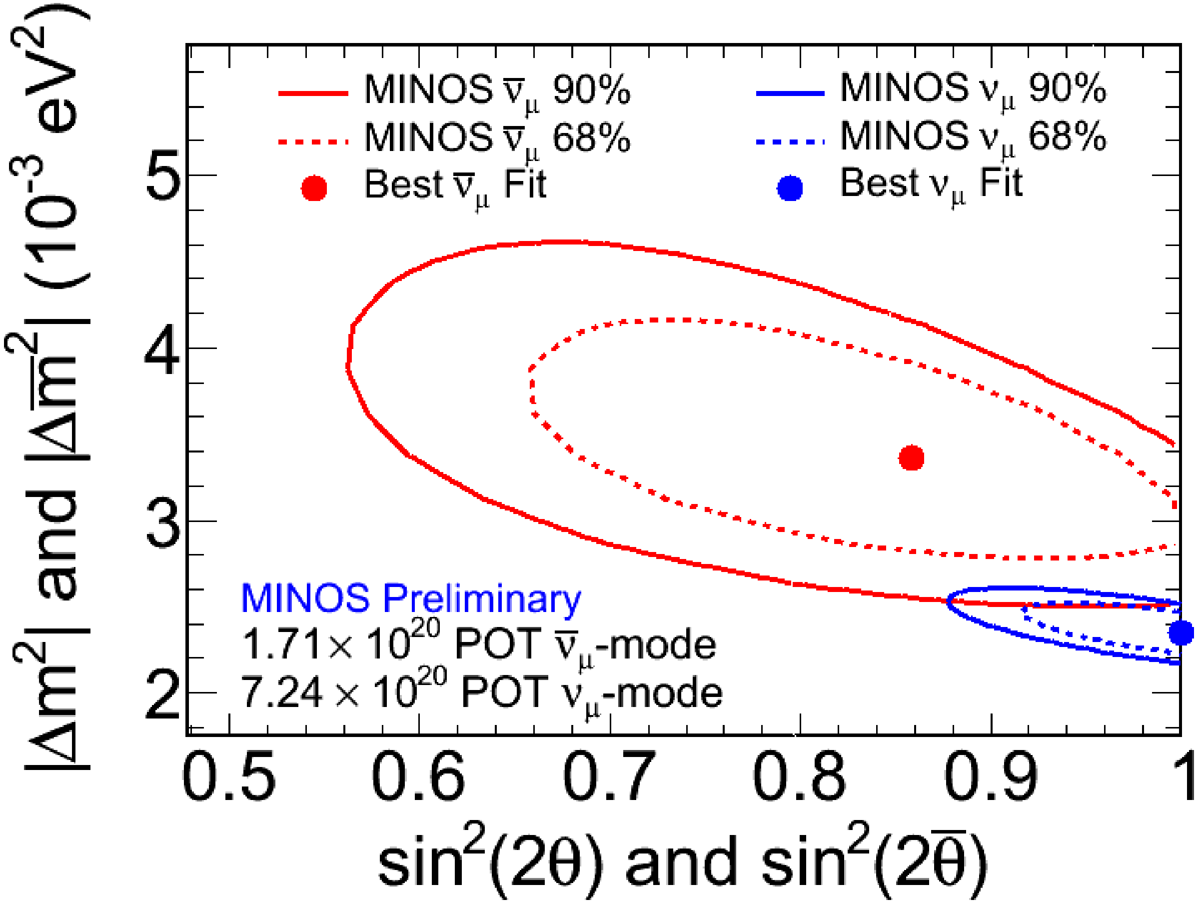
Making an antineutrino beam



Making an antineutrino beam



$\bar{\nu}_\mu$ oscillation parameters

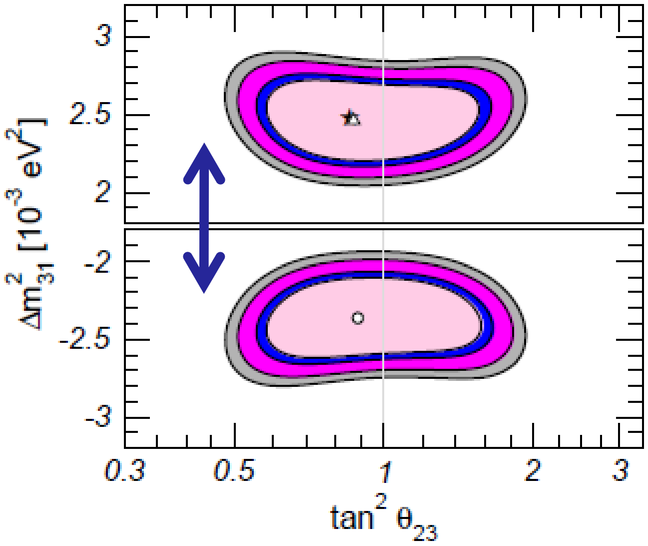


- Contours include the effects of systematic uncertainties

How well do we know θ_{23}?

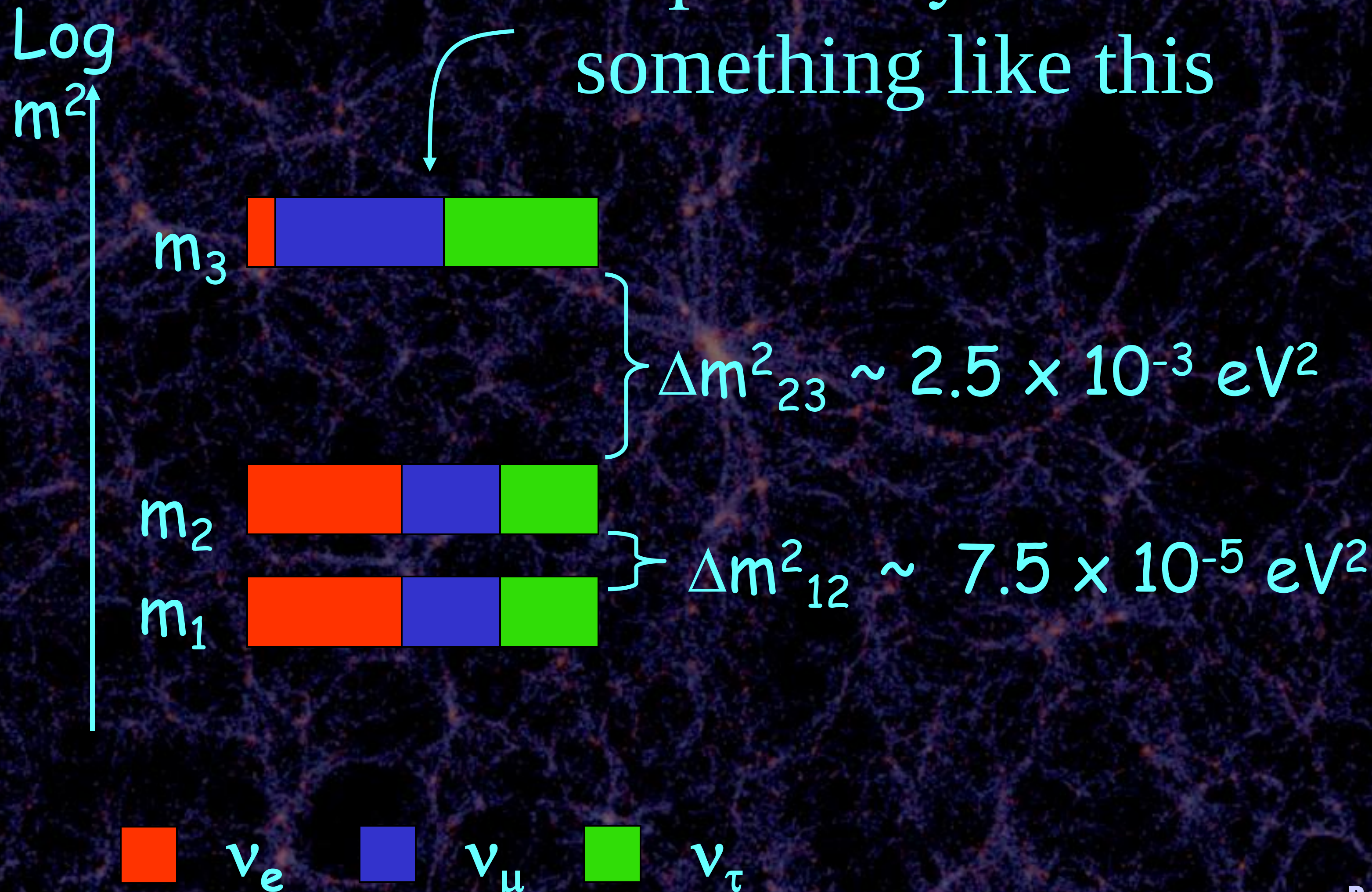
Gonzalez-Garcia, Maltoni, Salvado

arXiv:1001.4524v4 [hep-ph] 16 Jun 2011



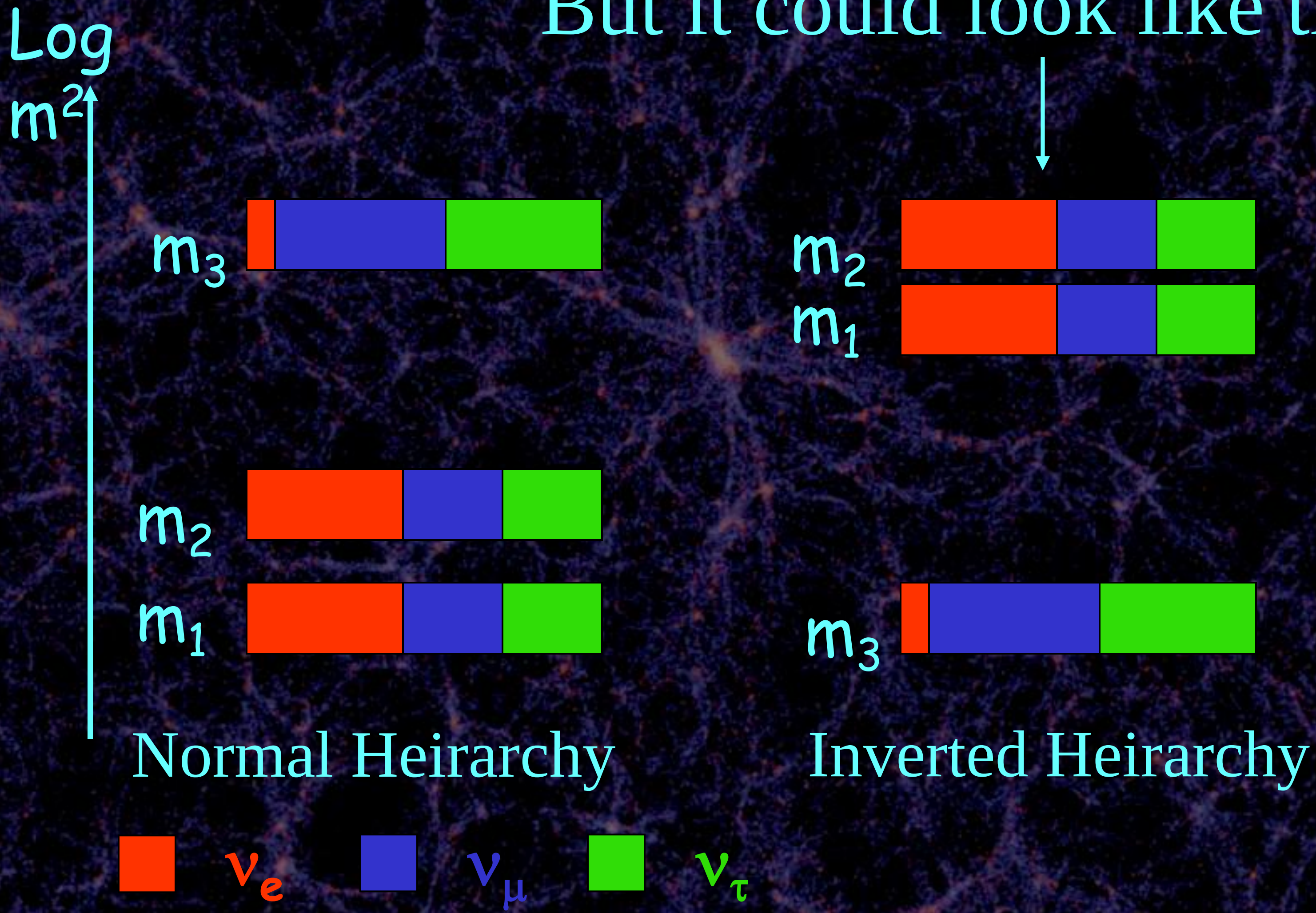
What is the pattern of neutrino masses?

It "probably" looks something like this



What is the pattern of neutrino masses?

But it could look like this



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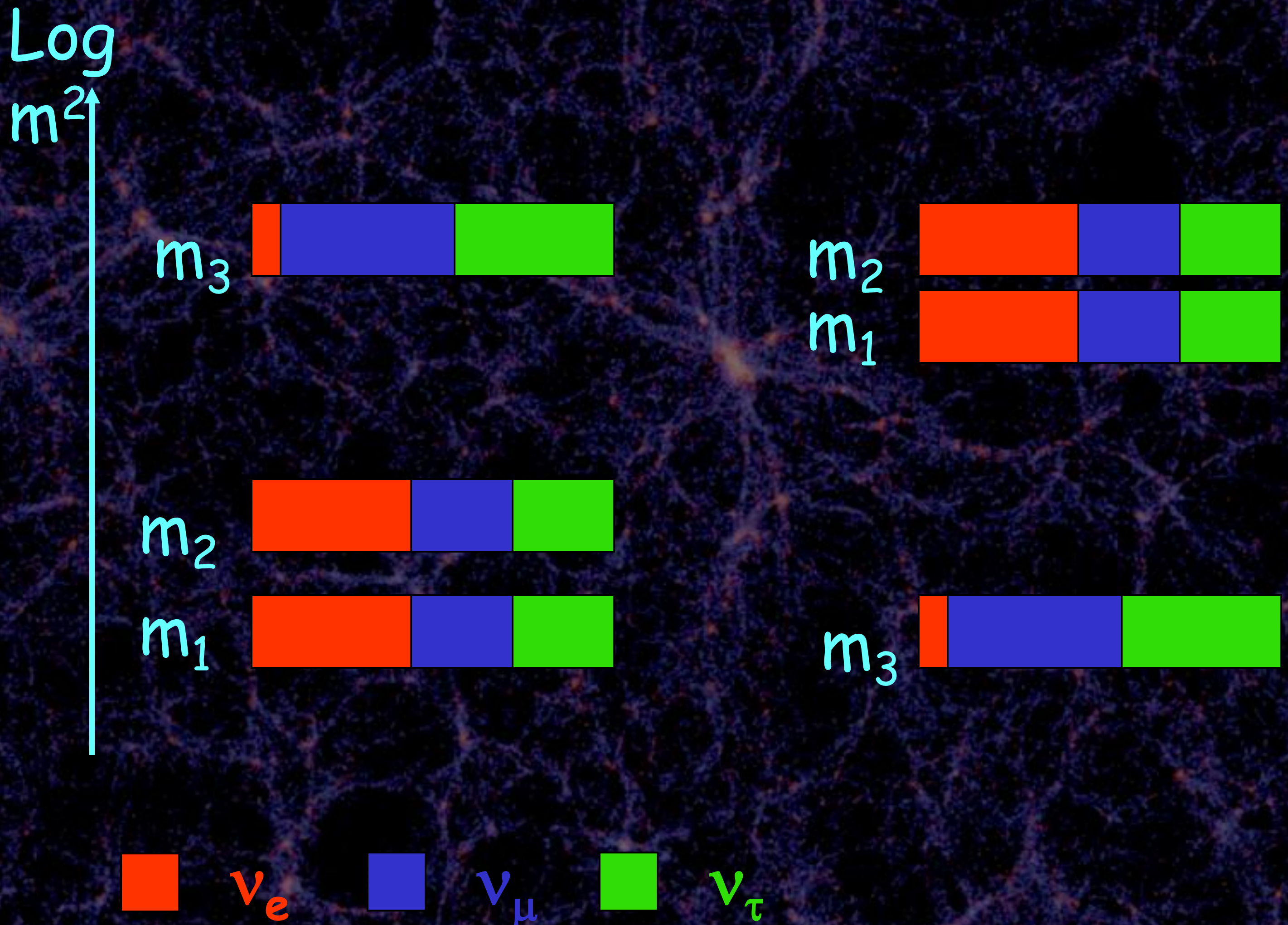
Imperial College/RAL

This makes a factor of two difference in the cosmological contribution, but a factor of two on what?



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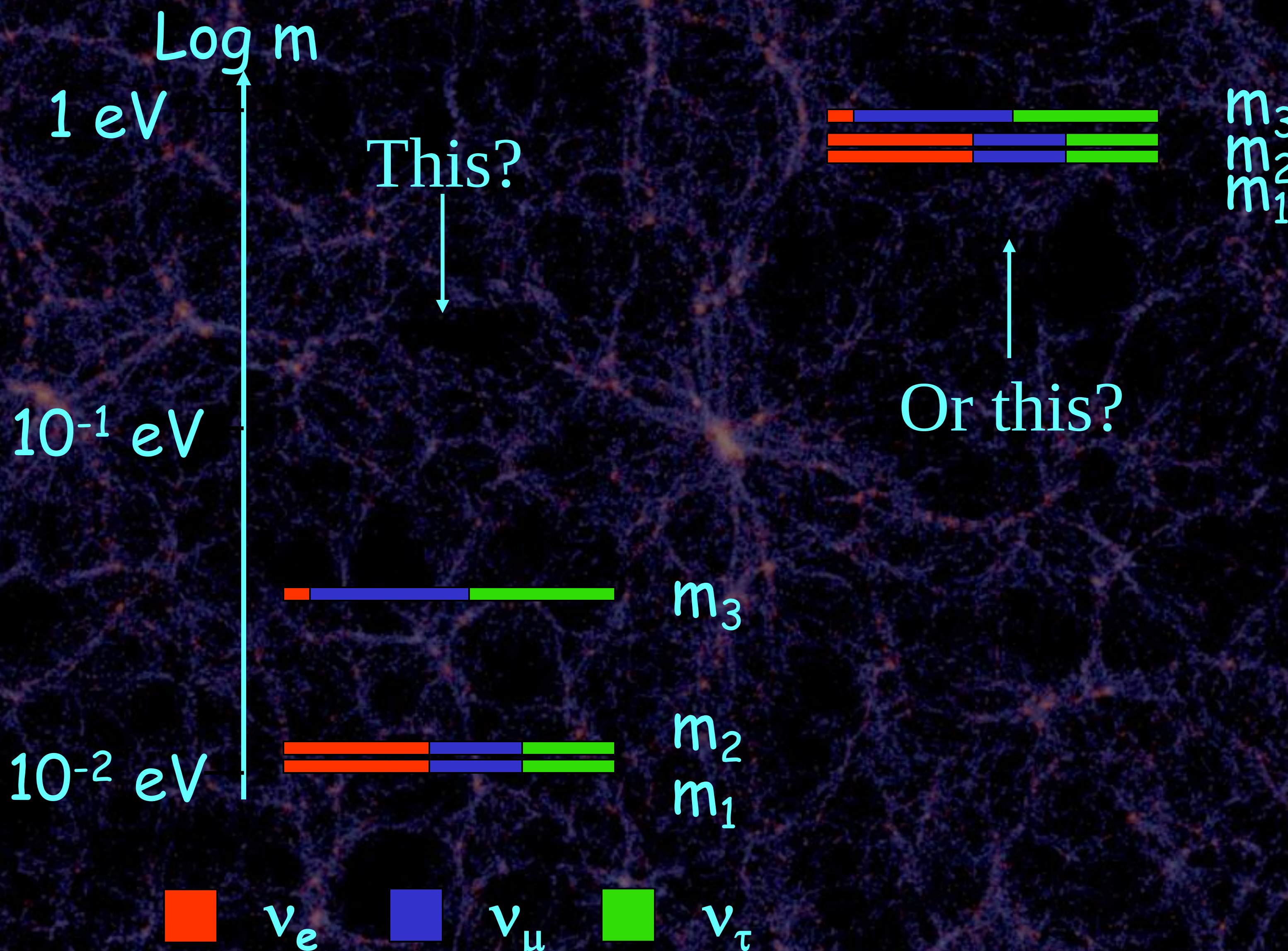
Even more significant is the absolute scale.



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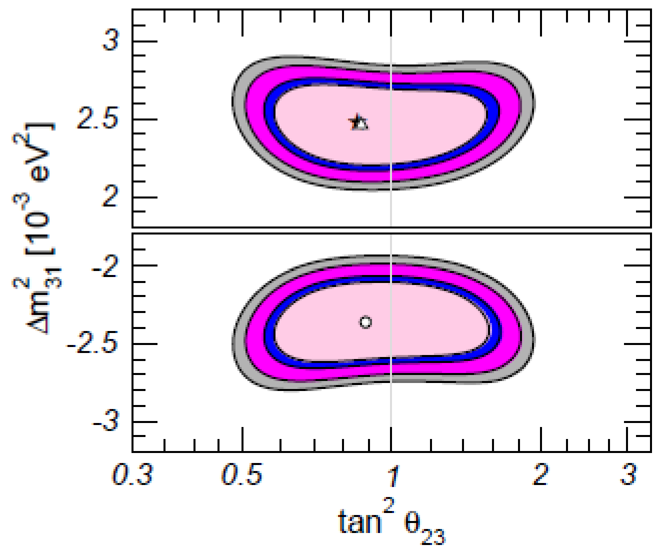
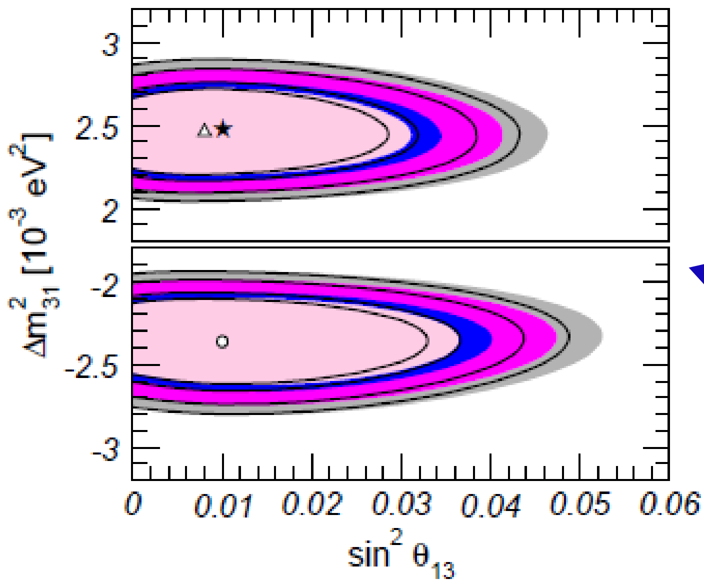
Does this look natural?

How well do we know θ_{23}?

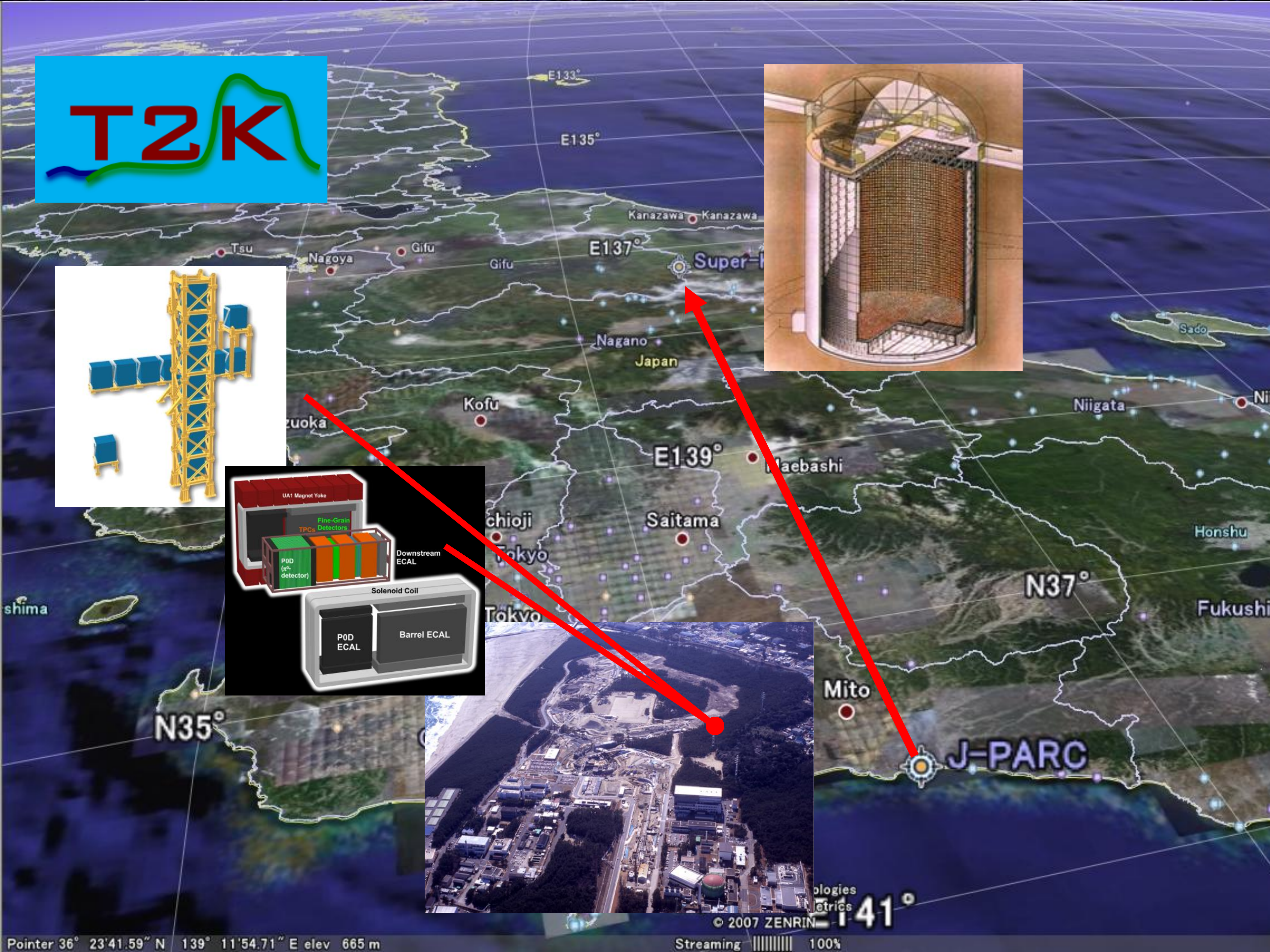
Gonzalez-Garcia, Maltoni, Salvado

arXiv:1001.4524v4 [hep-ph] 16 Jun 2011

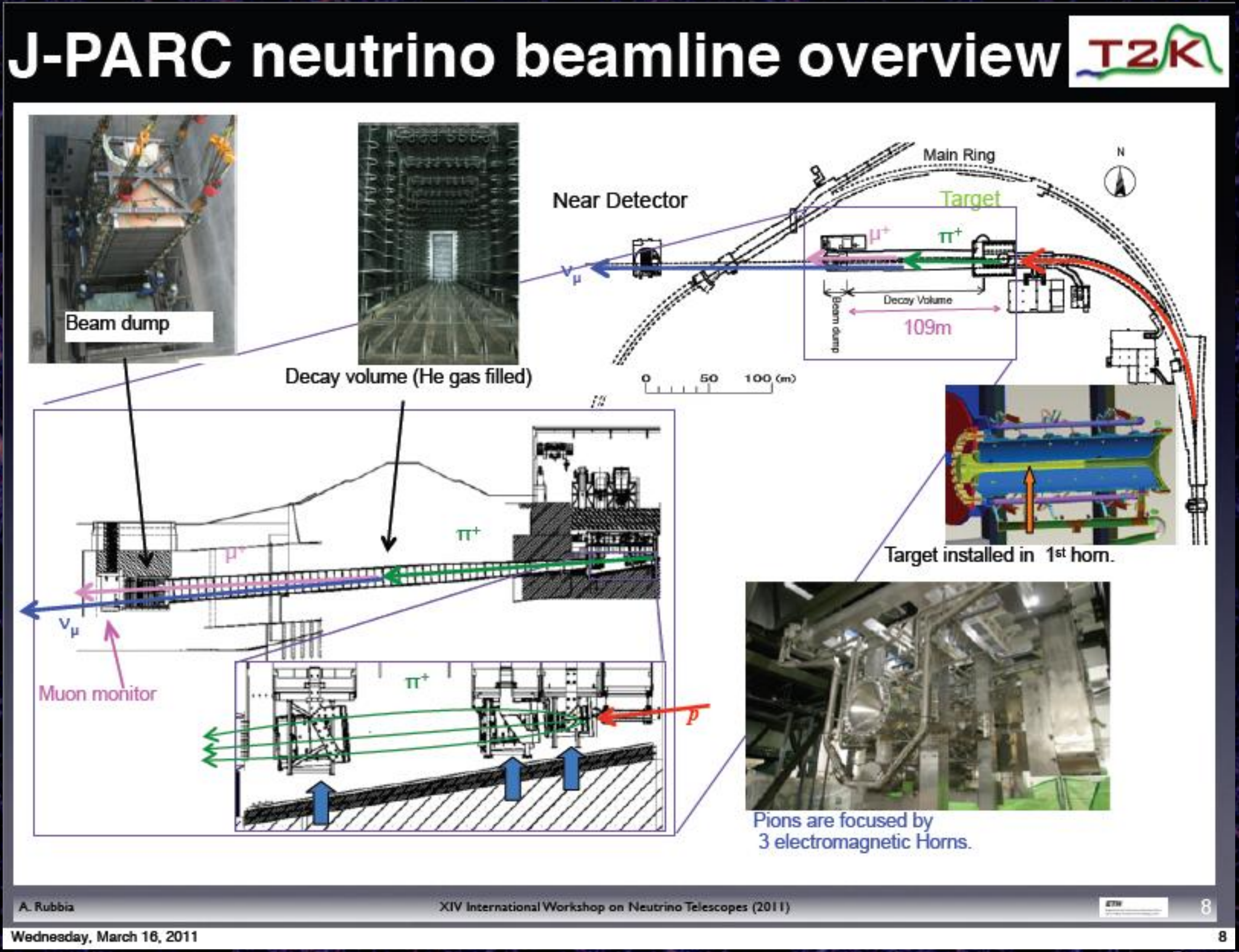




But what about θ_{13}?


T2K
E133°
E135°
Kanazawa
Kanazawa
Tsu
Nagoya
Gifu
Gifu
E137°
Super-
Nagano
Japan
Kofu
Niigata
Sado
E139°
Saitama
Tokyo
Honshu
N37°
Mito
J-PARC
N35°
UA1 Magnet Yoke
TPCs
Fine-Grain Detectors
Downstream ECAL
P0D (π0-detector)
Solenoid Coil
P0D ECAL
Barrel ECAL
© 2007 ZENRIN
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

J-PARC neutrino beamline overview



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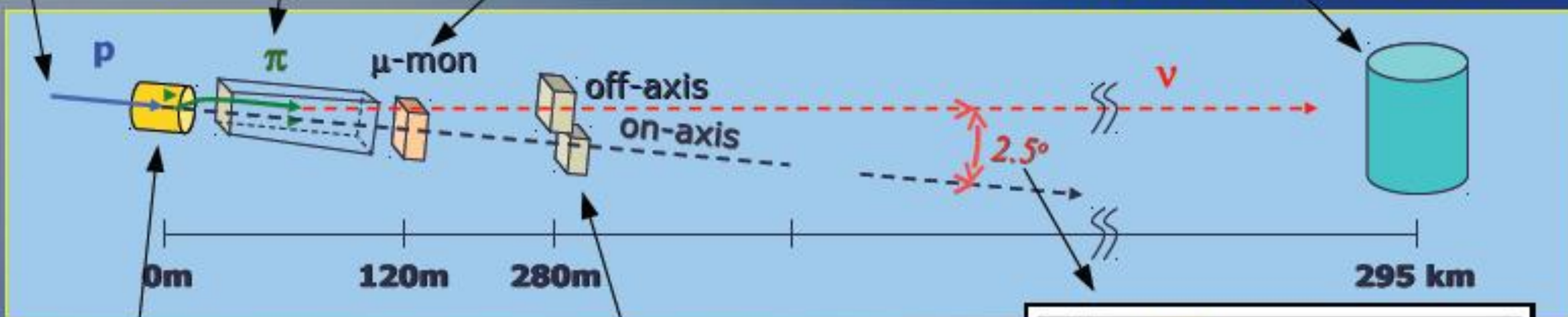
T2K Overview

30 GeV proton beam from J-PARC Main Ring (MR)

Pions decay in ≈100m decay volume

MUMON monitor measures muons from pion decay

Off-axis at 295 km, Super-Kamiokande (SK) water cherenkov detector measures oscillated flux

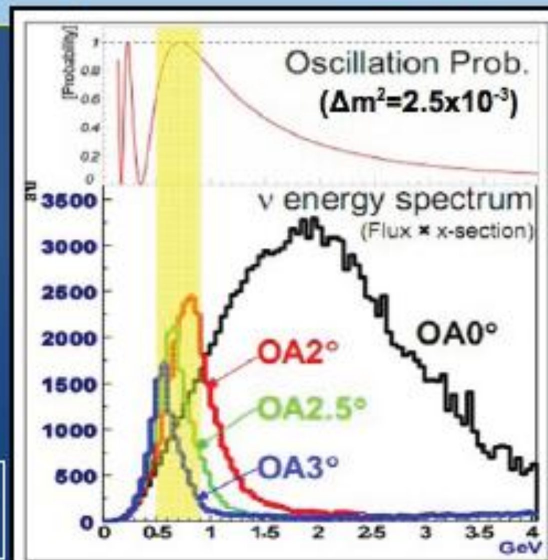


Beam on 90 cm graphite target

3 magnetic horns focus positively charged hadrons

At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

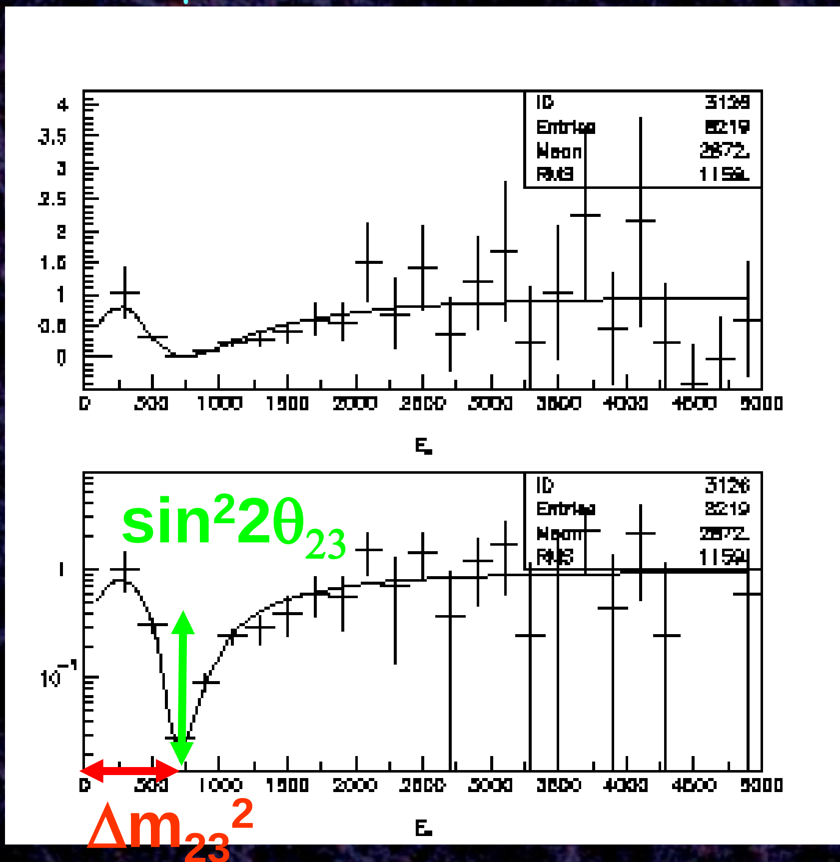
Off-axis ND280 detector measures spectra for various neutrino interactions



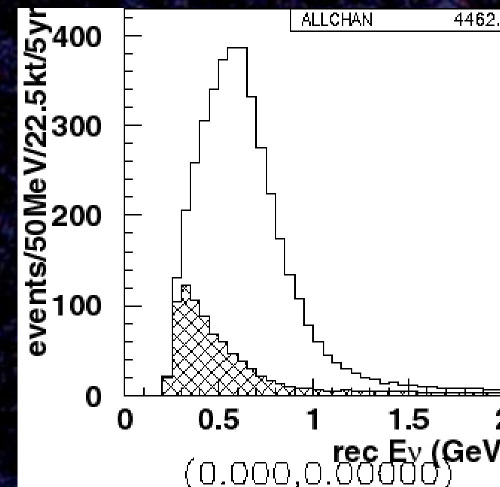
Beam peaked at 1st max E≈600 MeV

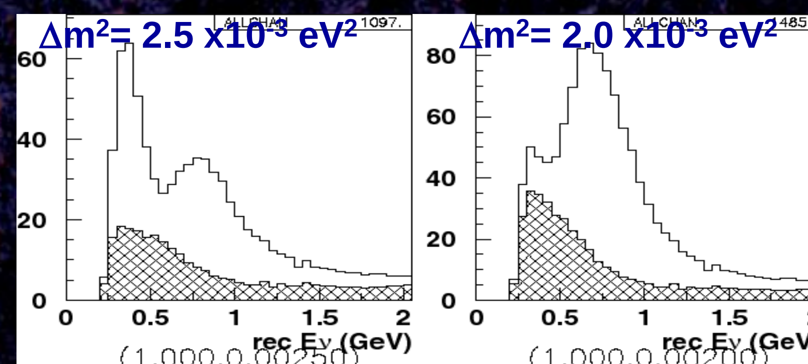
What are we trying to measure?

ν_μ disappearance



No oscillation



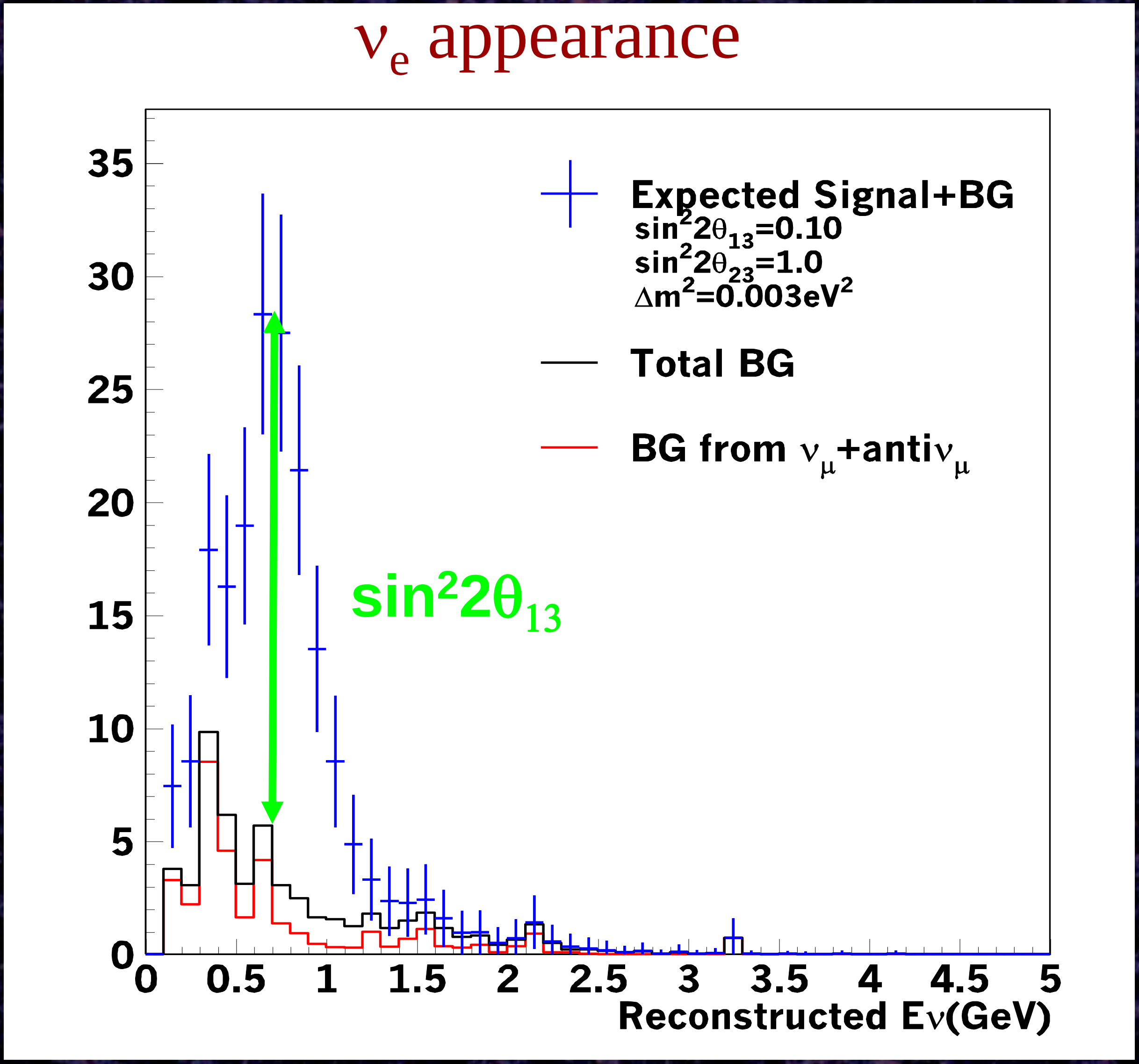


Precision measurements

$\delta(\sin^2 2\theta)$ ~0.01

$\delta(\Delta m^2)$ $<1\times10^{-4}(eV^2)$

What are we trying to measure?



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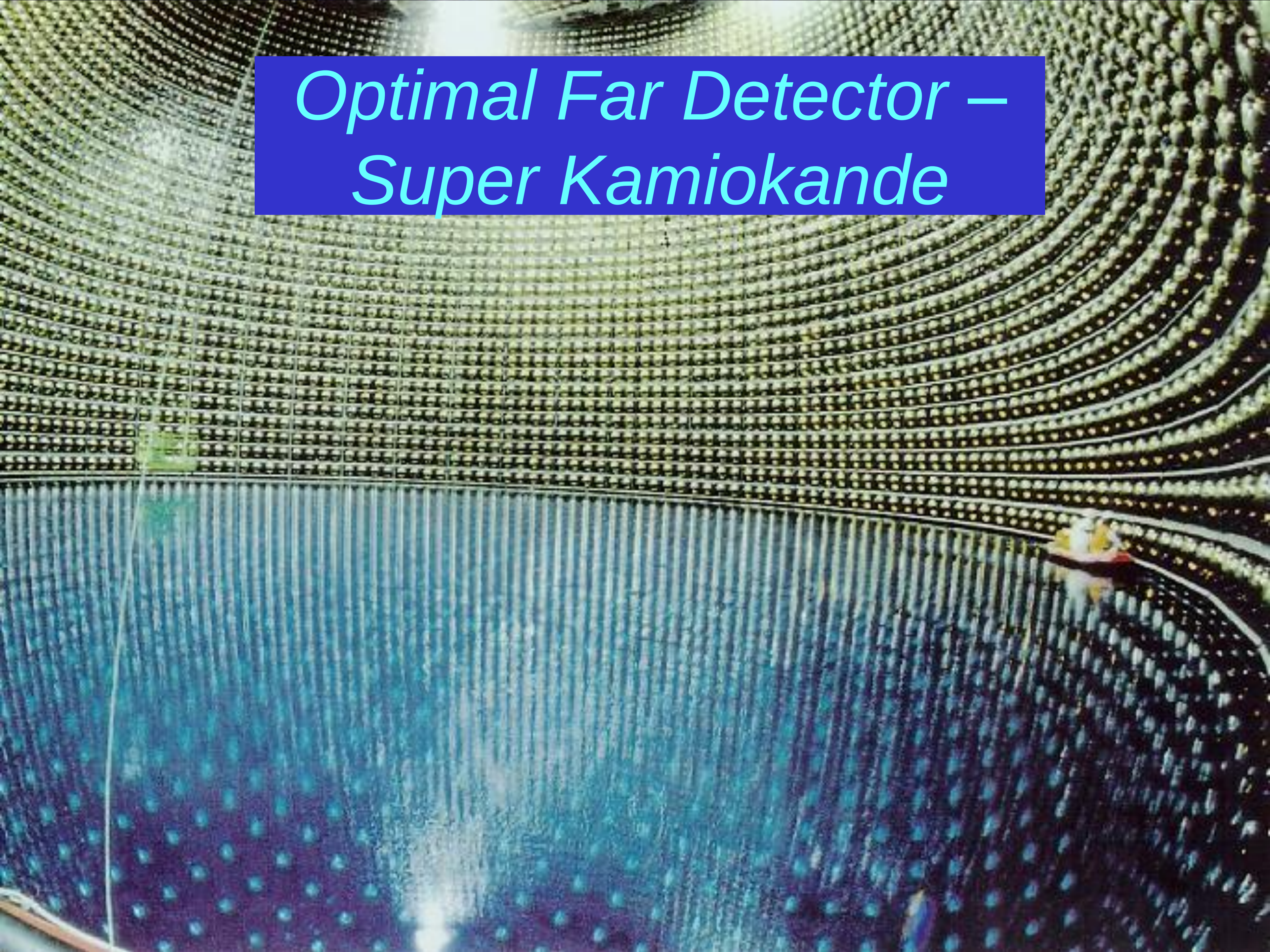
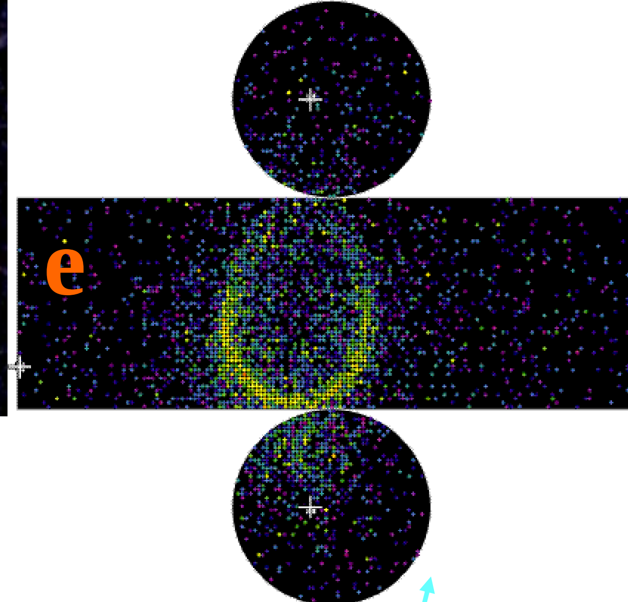
Optimal Far Detector – Super Kamiokande

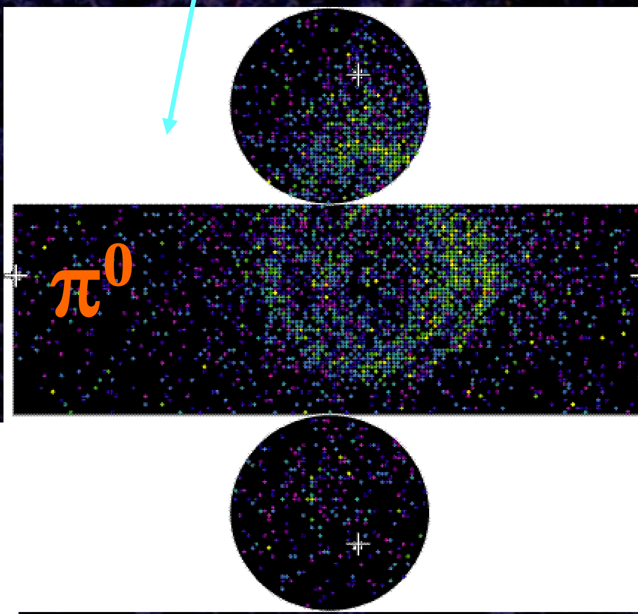


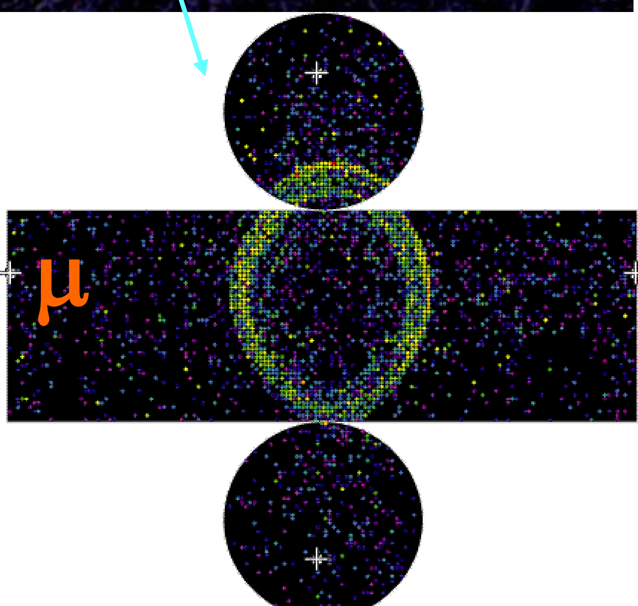
Background from NC interactions



ν_e appearance signal

ν_μ disappearance signal





In this energy range, Super Kamiokande well understood, Excellent for separating electrons, μ, π^0

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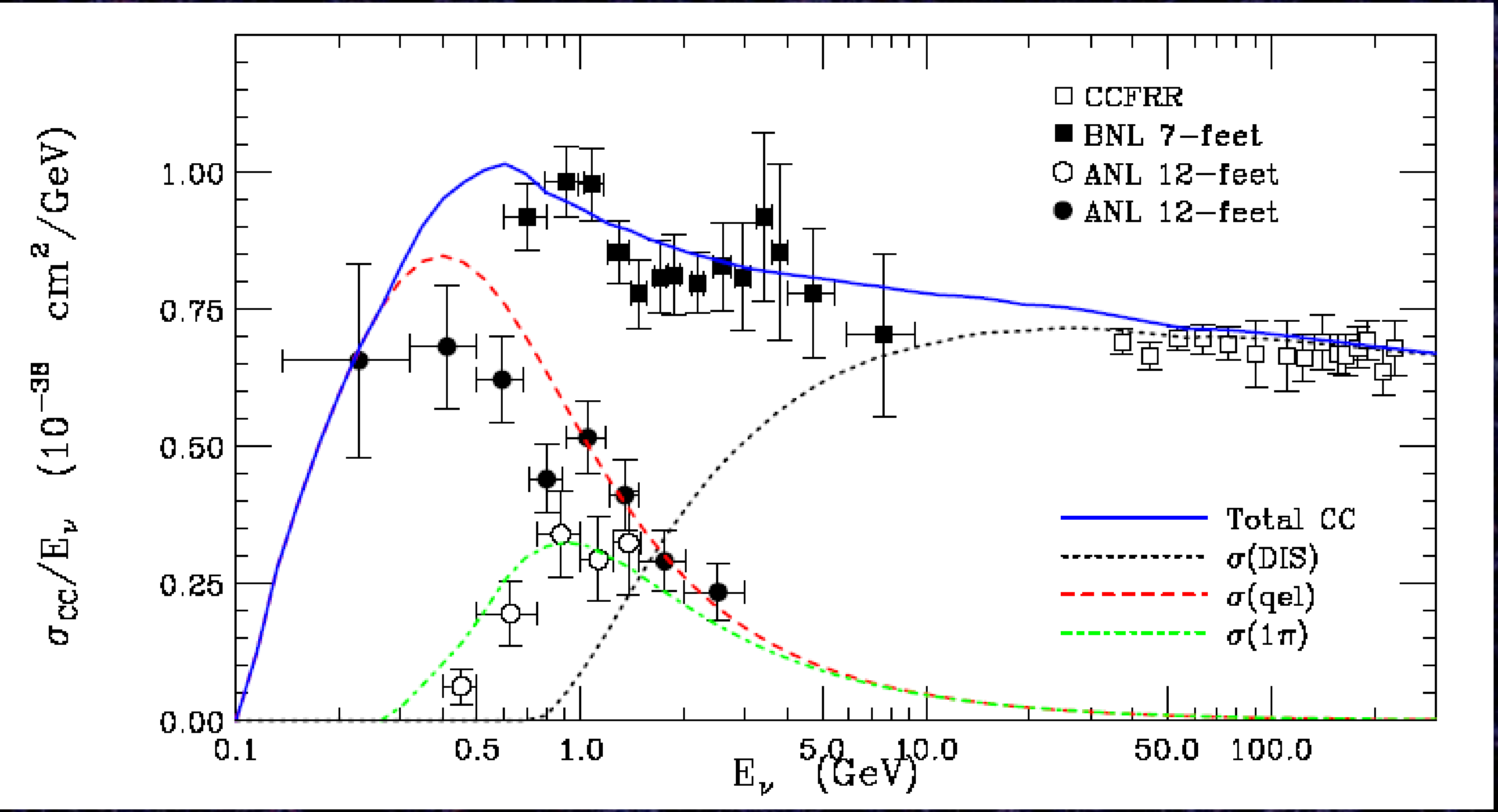
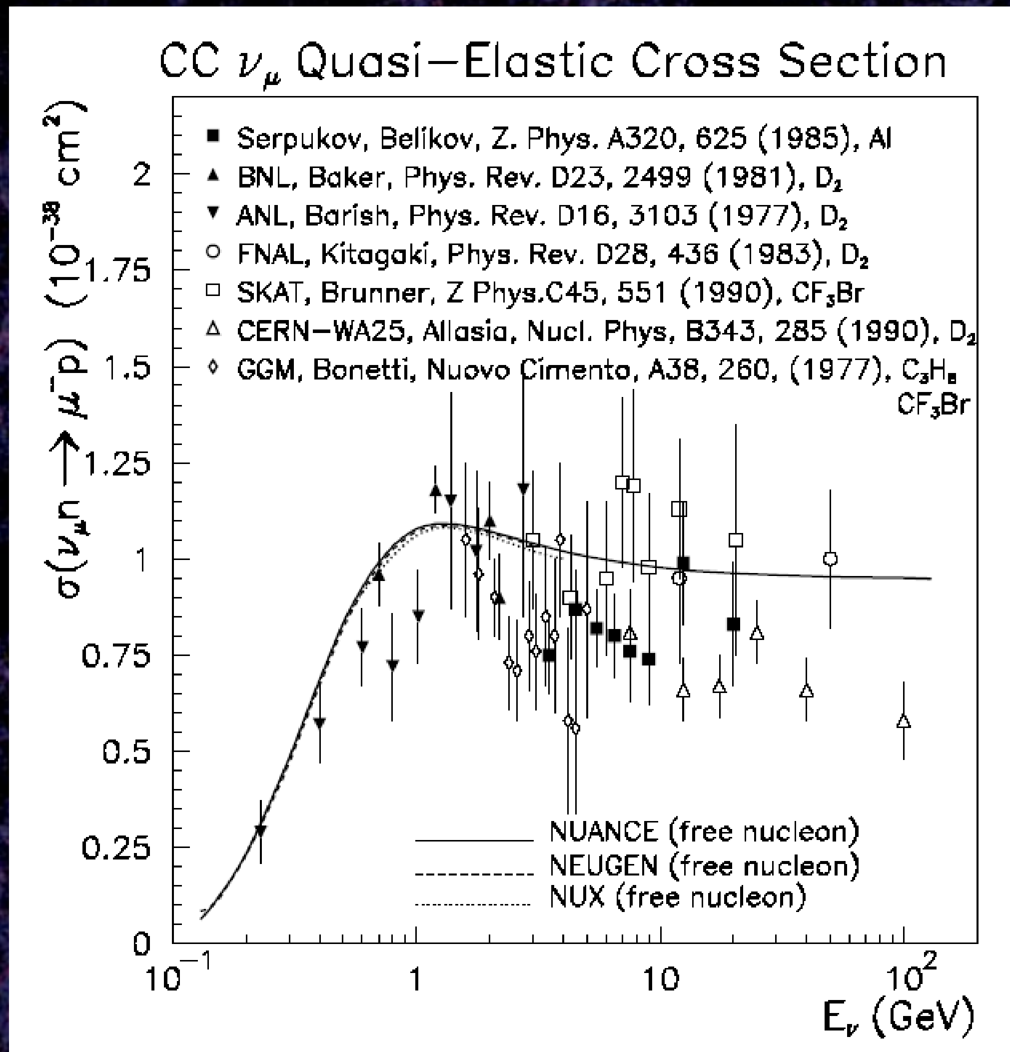
Critical σ's poorly known in range 0.1-10 GeV.

Total ν_μ CC cross section

Data compiled by G.Zeller, hep-ex/0312061

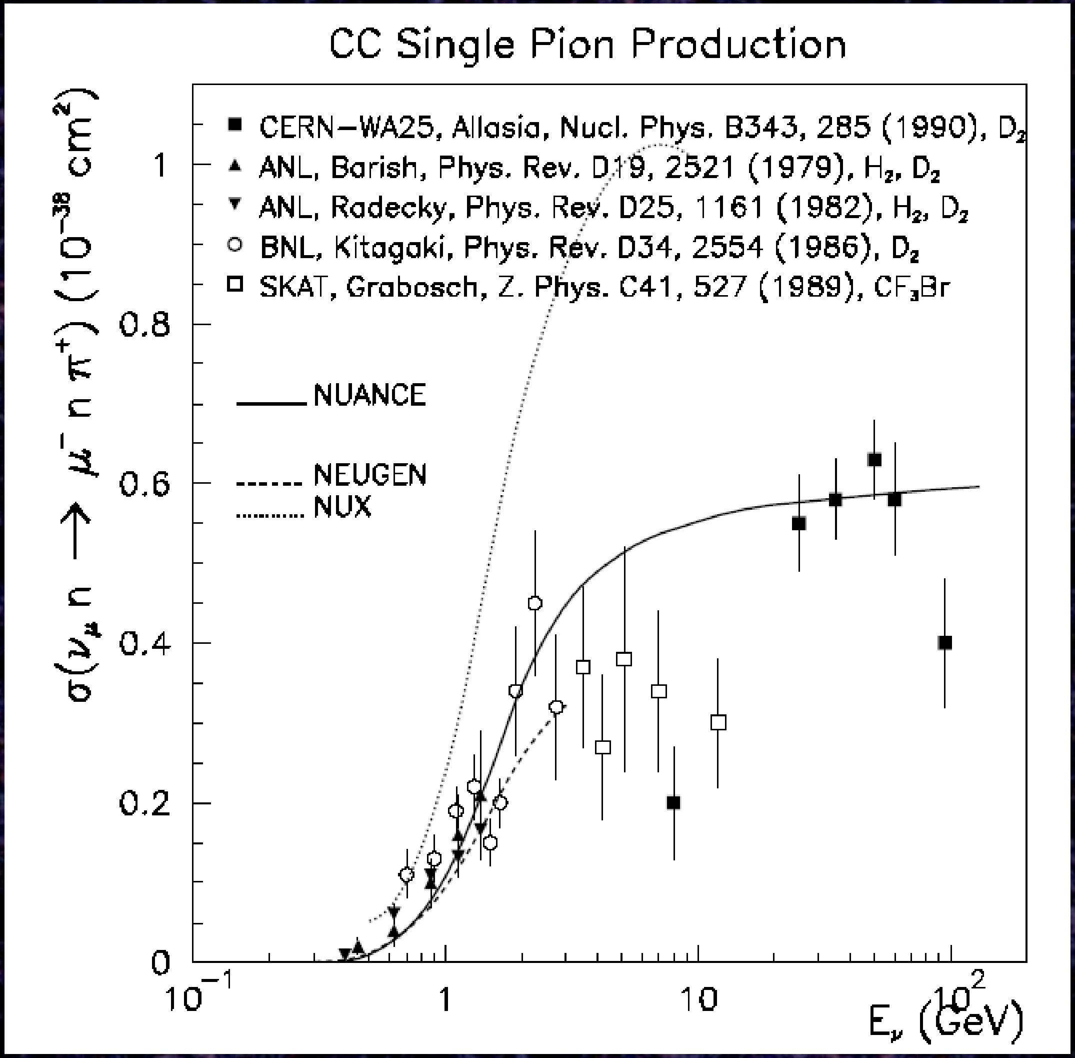


Cross sections are poorly known in range 0.1-10 GeV



Data compiled by G.Zeller, hep-ex/0312061

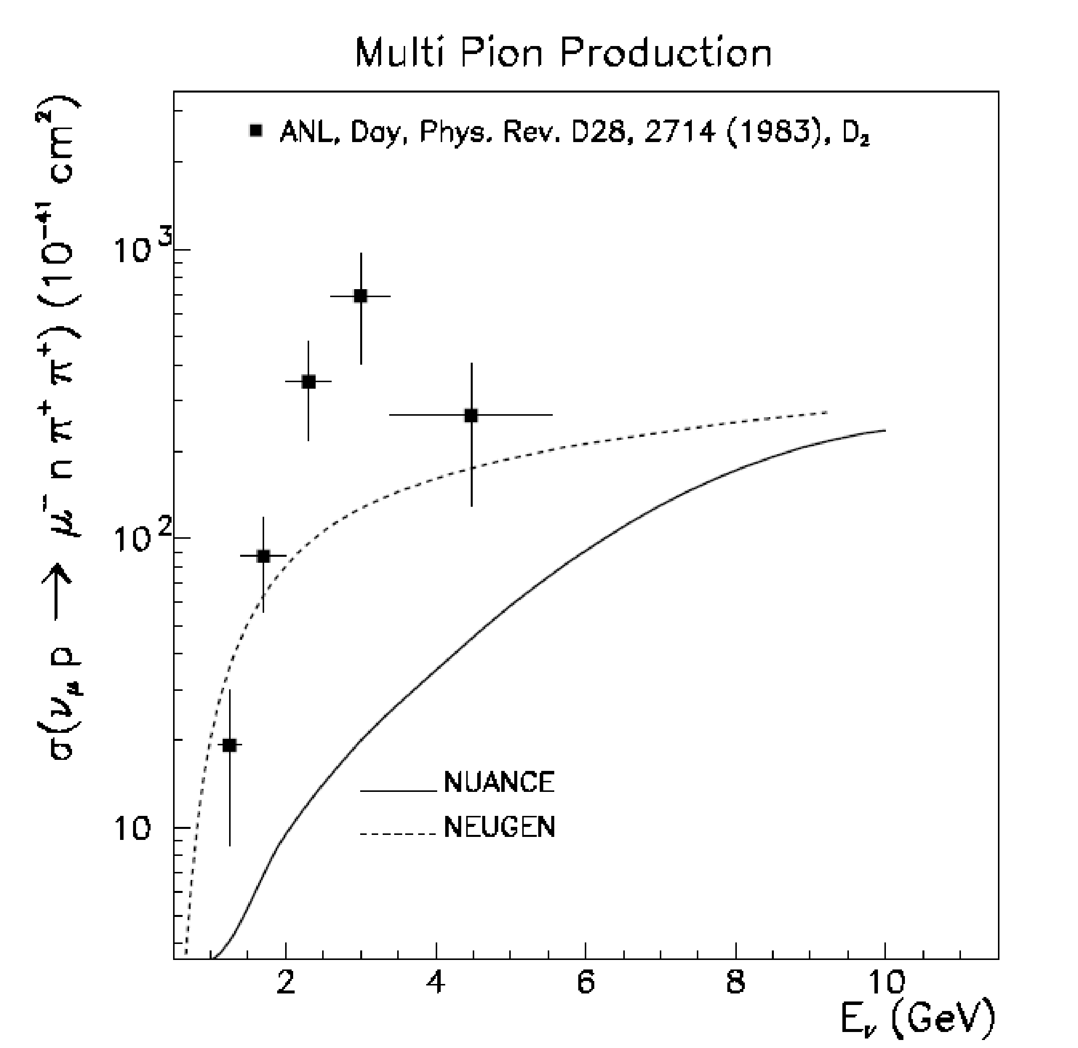
Cross sections are poorly known in range 0.1-10 GeV



Data compiled by G.Zeller, hep-ex/0312061

Cross sections are poorly known in range 0.1-10 GeV

Data compiled by G.Zeller, hep-ex/0312061



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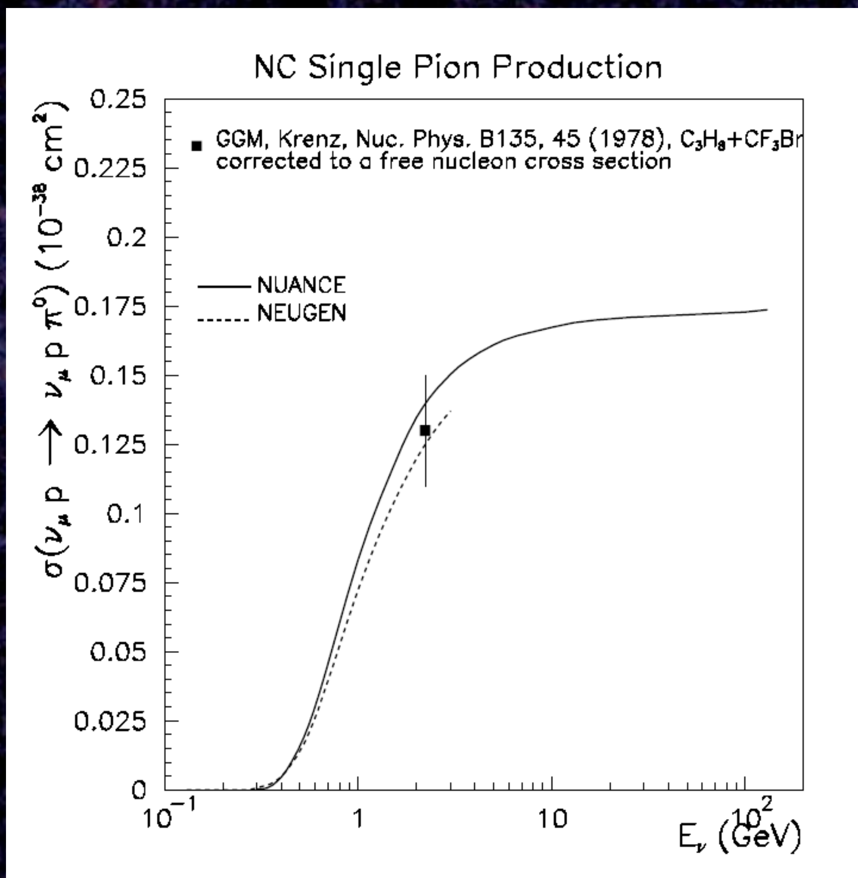
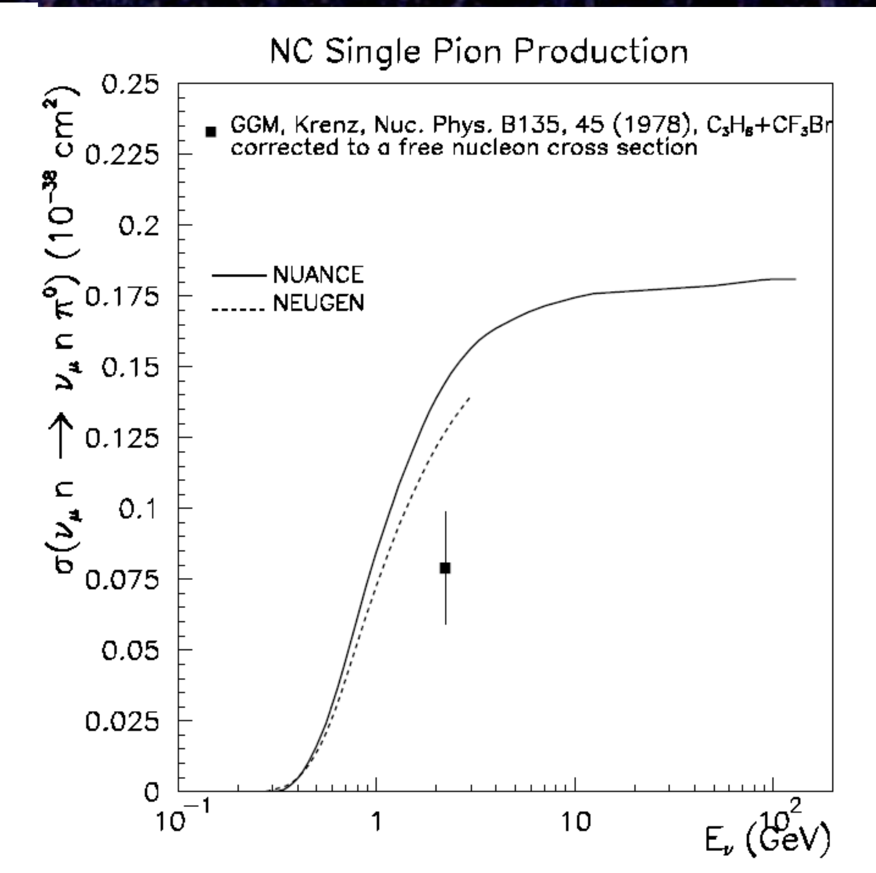
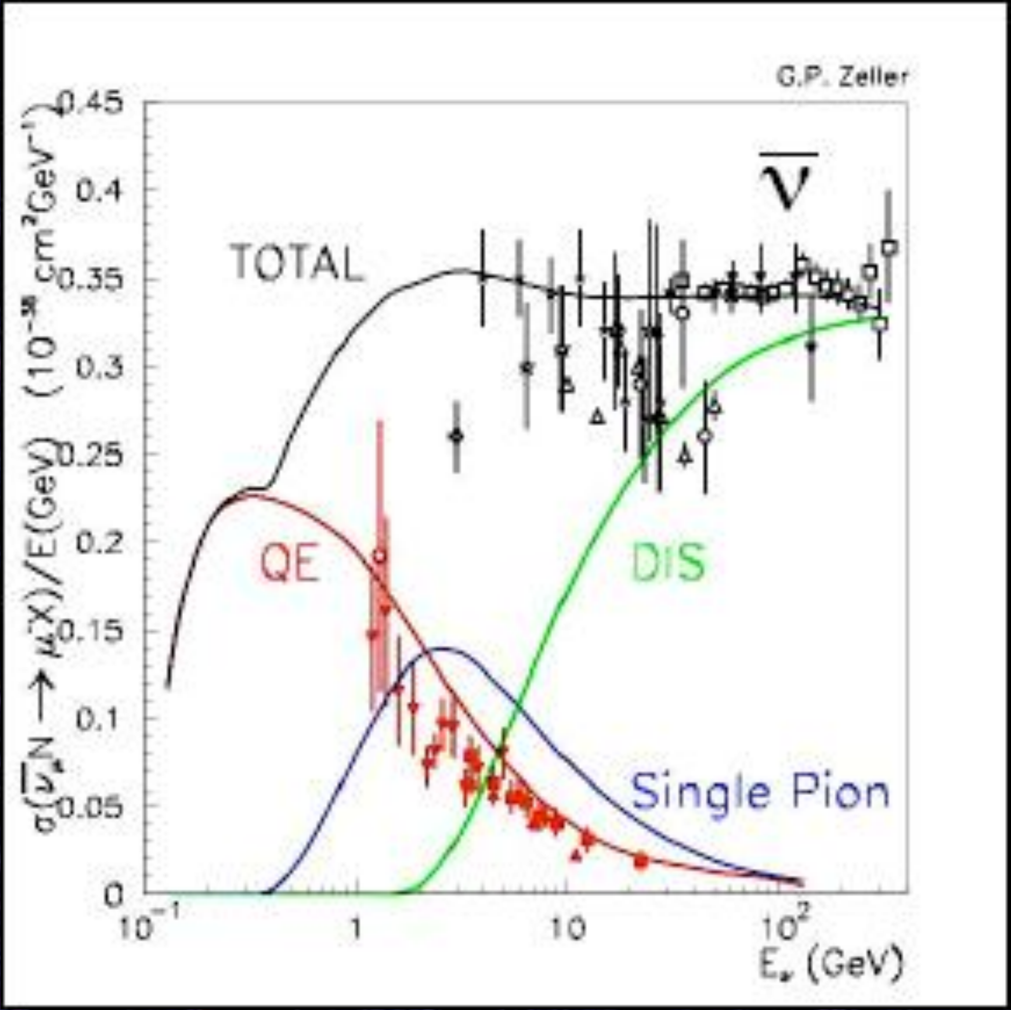
Some are worse than others…

Data compiled by G.Zeller, hep-ex/0312061

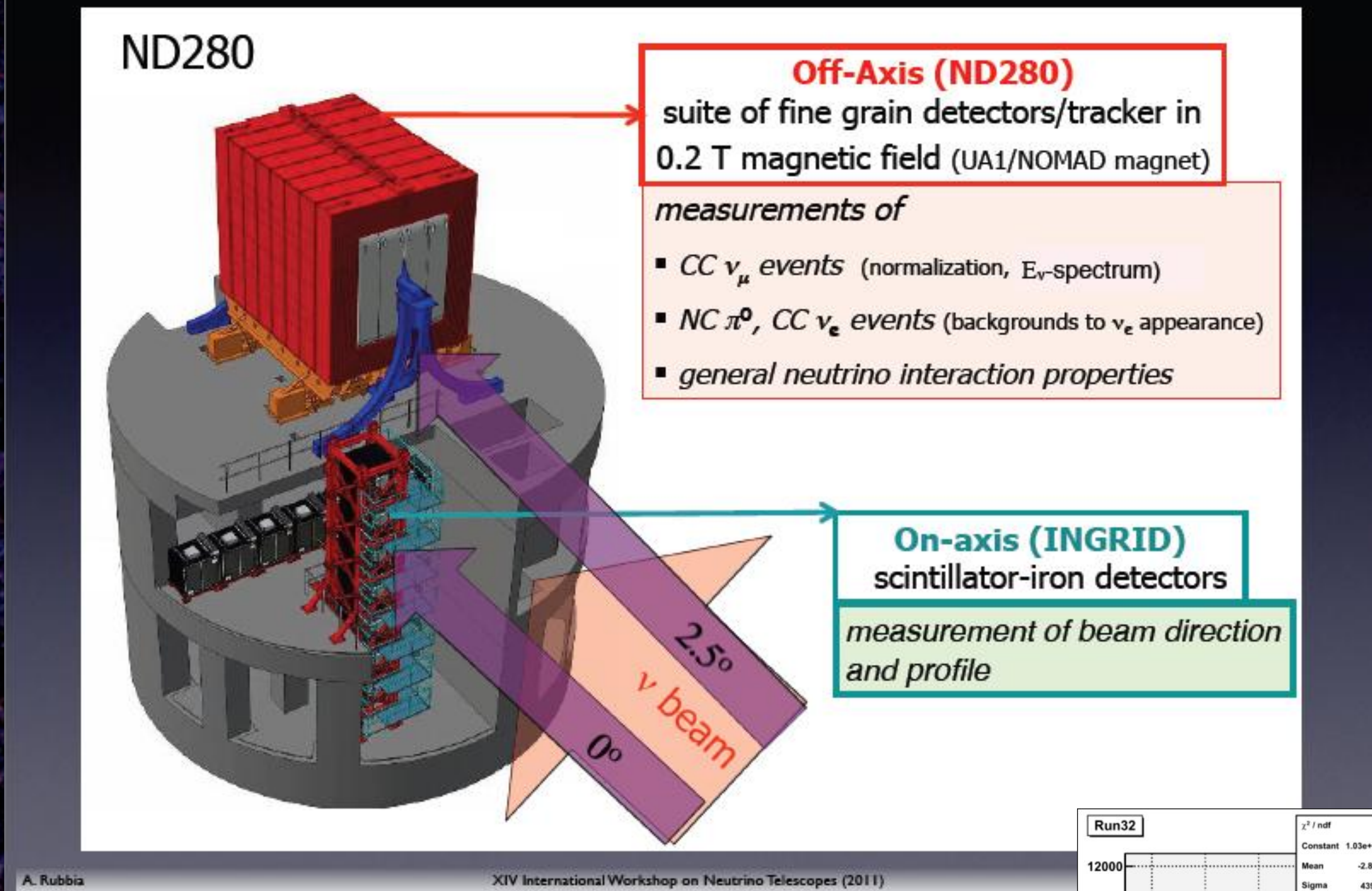


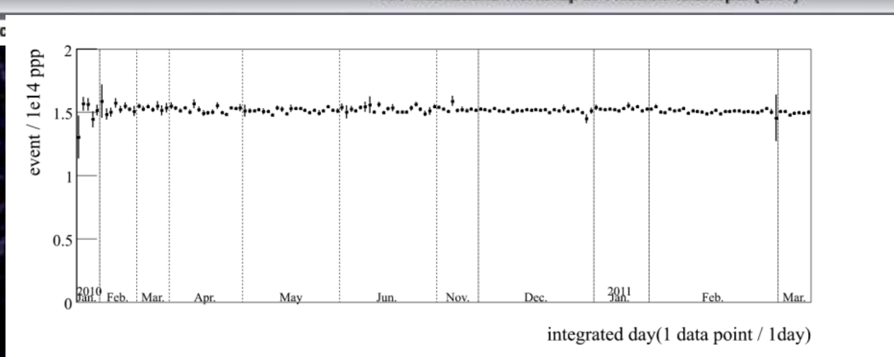


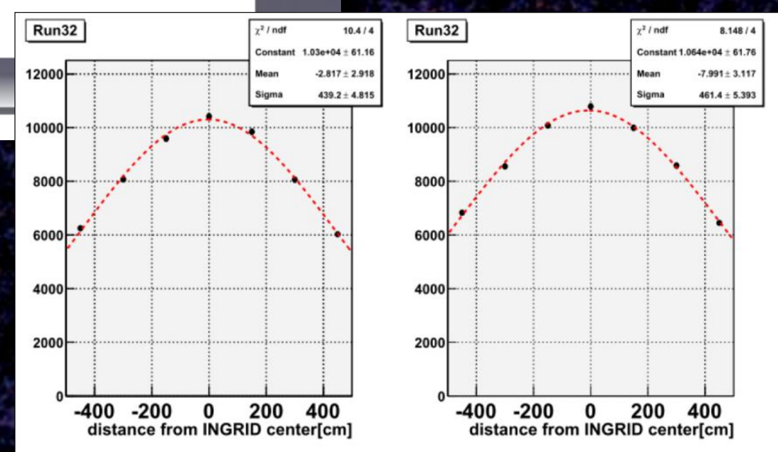
And lets not even talk about $\bar{\nu}$…

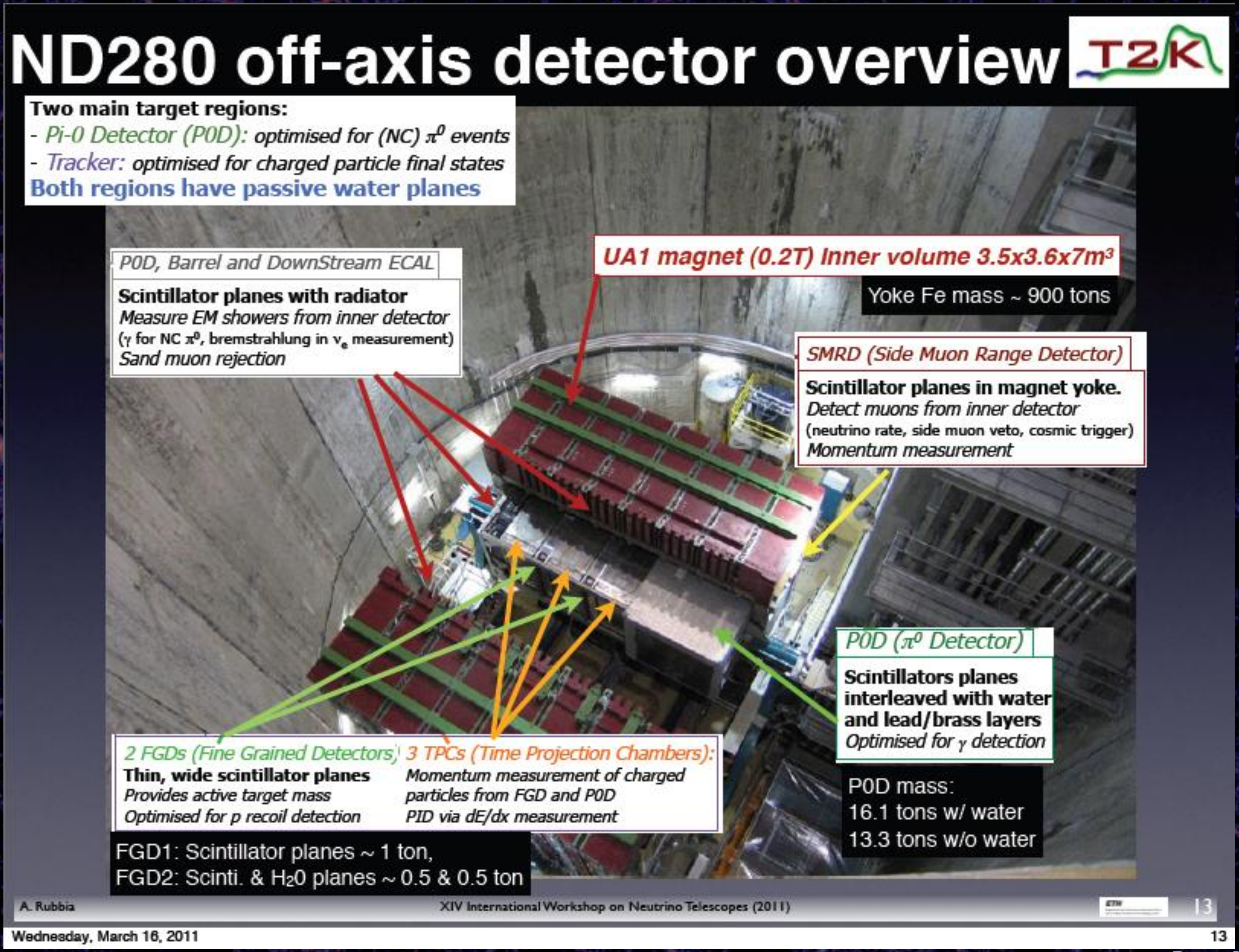


ND280 (Near) Detector complex

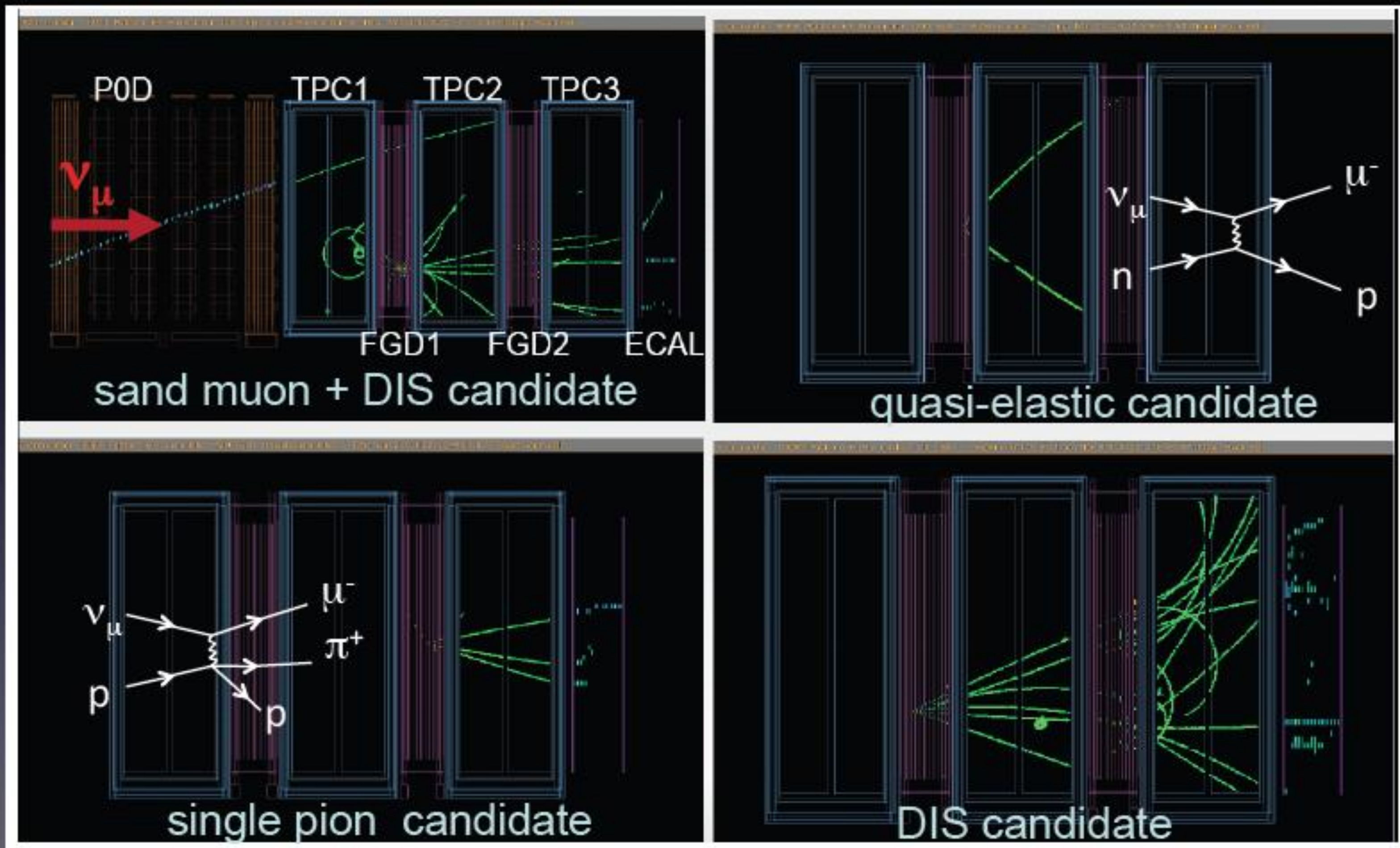







ND280 off-axis detector overview
T2K
Two main target regions:
- Pi-0 Detector (P0D): optimised for (NC) π^0 events
- Tracker: optimised for charged particle final states
Both regions have passive water planes
P0D, Barrel and DownStream ECAL
Scintillator planes with radiator
Measure EM showers from inner detector
(γ for NC π^0, bremstrahlung in ν_e measurement)
Sand muon rejection
UA1 magnet (0.2T) Inner volume 3.5x3.6x7m³
Yoke Fe mass ~ 900 tons
SMRD (Side Muon Range Detector)
Scintillator planes in magnet yoke.
Detect muons from inner detector
(neutrino rate, side muon veto, cosmic trigger)
Momentum measurement
P0D (π^0 Detector)
Scintillators planes interleaved with water and lead/brass layers
Optimised for γ detection
P0D mass:
16.1 tons w/ water
13.3 tons w/o water
2 FGDs (Fine Grained Detectors)
Thin, wide scintillator planes
Provides active target mass
Optimised for p recoil detection
3 TPCs (Time Projection Chambers):
Momentum measurement of charged particles from FGD and P0D
PID via dE/dx measurement
FGD1: Scintillator planes ~ 1 ton,
FGD2: Scinti. & H₂0 planes ~ 0.5 & 0.5 ton
A. Rubbia
XIV International Workshop on Neutrino Telescopes (2011)
13
Wednesday, March 16, 2011
13

ND280 off-axis event gallery



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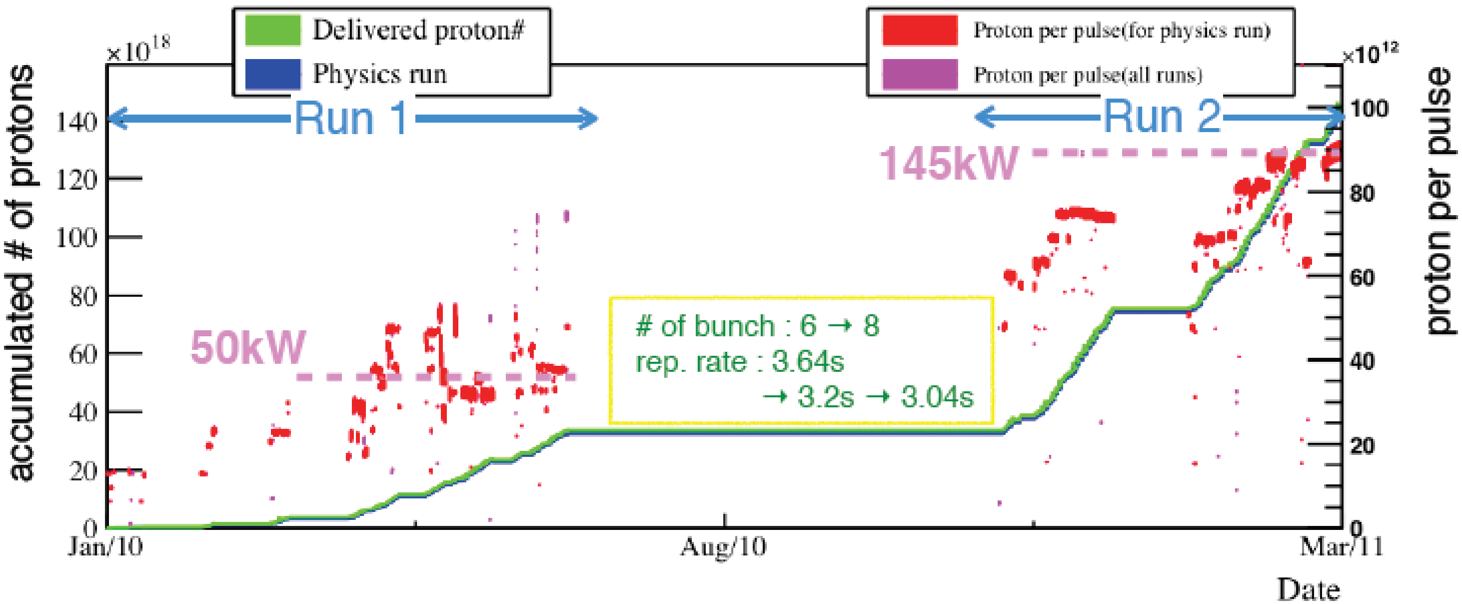
Neut

Total # of protons used for analysis



Run 1 (Jan. '10 - June '10)

- 3.23×10^{19} p.o.t. for analysis
- 50kW stable beam operation

Run 2 (Nov. '10 - Mar. '11)

- 11.08×10^{19} p.o.t. for analysis
- ~145kW beam operation

Total # of protons used for this analysis is 1.43×10^{20} pot

2% of T2K's final goal and ~5 times exposure of the previous report

14

Number of events in on-timing windows (-2 ~ +10 μsec)

Class / Beam run	RUN-1	RUN-2	Total	non-beam background
POT ($\times 10^{19}$)	3.23	11.08	**14.31**	
Fully-Contained (FC)	33	88	**121**	0.023

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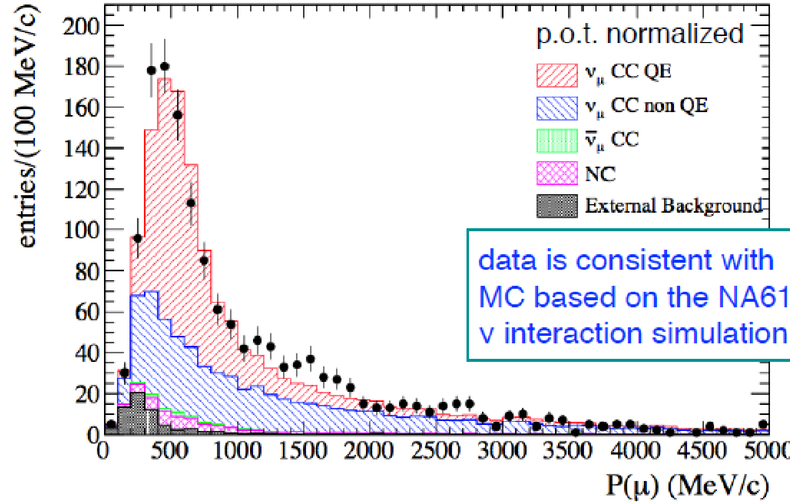
$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

ND ν_μ event rate measurement

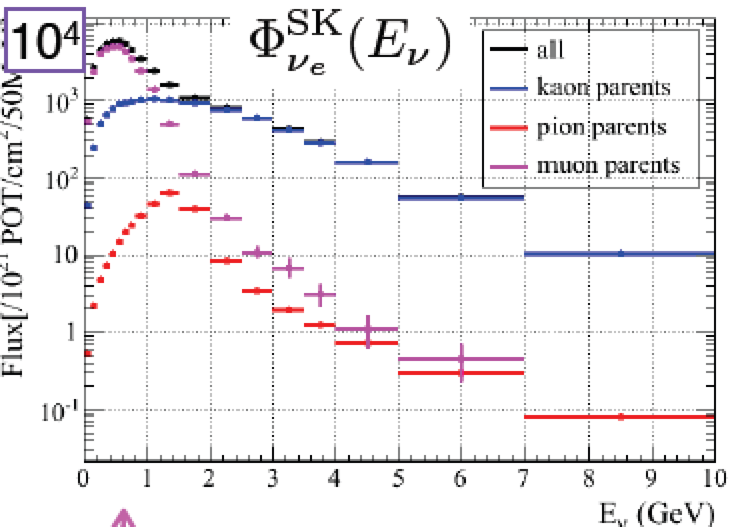
F/N ratio is estimated by using MC which is based on measurements

ND Measurement of muon momentum in inclusive ν_μ CC events ($\nu_\mu + N \rightarrow \mu^+ + X$)



data is consistent with MC based on the NA61 and ν interaction simulation (w/o tuning)

$$\frac{R_{ND}^{\mu,\,Data}}{R_{ND}^{\mu,\,MC}} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$



μ decay is dominated at low energy

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

NA61 pion measurement predicts the beam ν_e from pion origin

- **The number of beam ν_e background events at far detector is predicted using the ν beam simulation based on NA61 measurements (pion) and FLUKA (kaon)**
  - ND measurements (μ momentum and event rate) are consistent with MC based on the ν beam simulation

The expected number of events with 1.43 x 10^{20} p.o.t.

$N^{exp}_{SK\ tot.} = 1.5$ events for $\sin^2 2\theta_{13}=0$

	Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
The expected # of events at SK	0.8	0.6	0.1	1.5

Total Systematic uncertainties

Summary of systematic uncertainties on $N^{exp}_{SK\ total}$ for $\sin^2 2\theta_{13}$=0 and 0.1

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

cf.
$\sin^2 2\theta_{13}$=0:
#sig = 0.1 #bkg = 1.4

$\sin^2 2\theta_{13}$=0.1:
#sig = 4.1 #bkg = 1.3

(due to small Far det. uncertainty for signal)

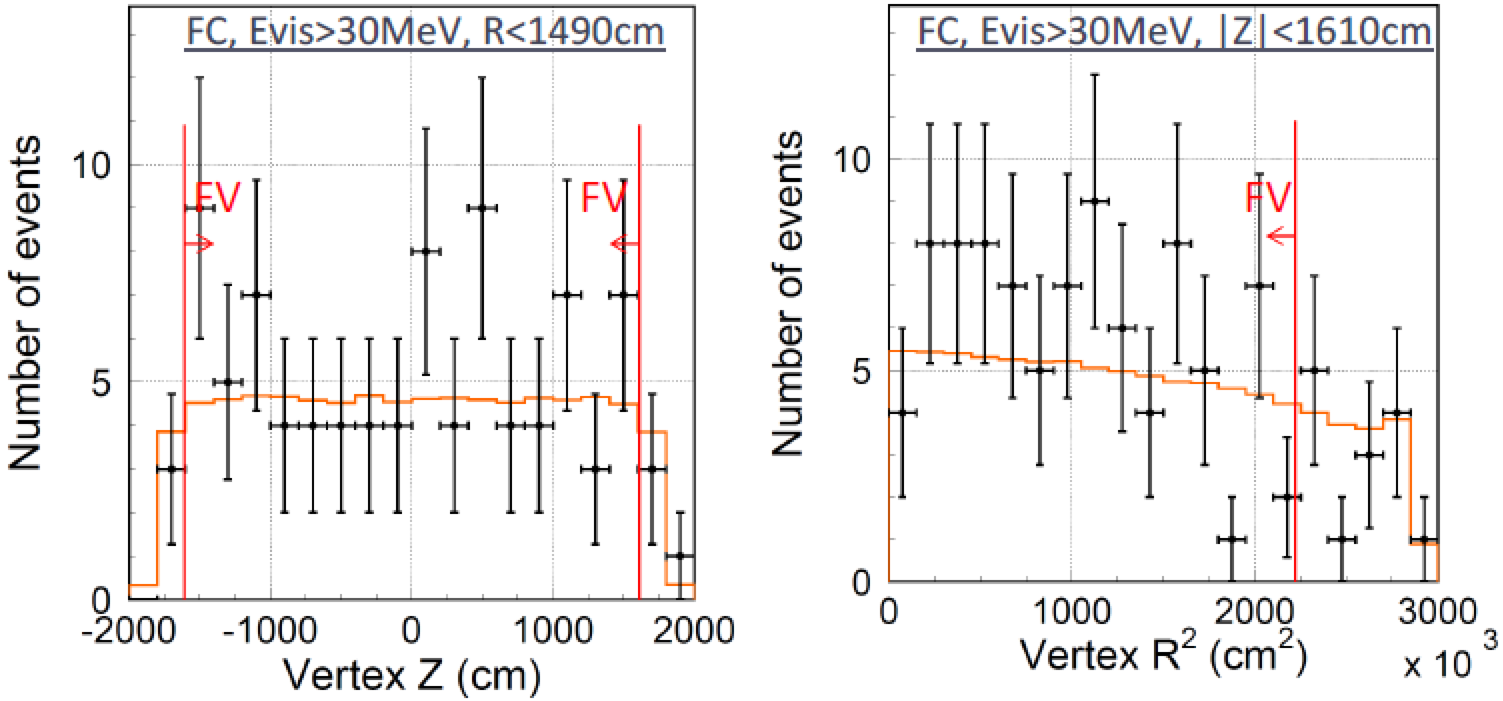
$N^{exp}_{SK\ tot.} = 1.5 \pm 0.3$ events for $\sin^2 2\theta_{13}$=0 (w/ 1.43 x 10^{20} p.o.t.)

Apply ν_e event selection

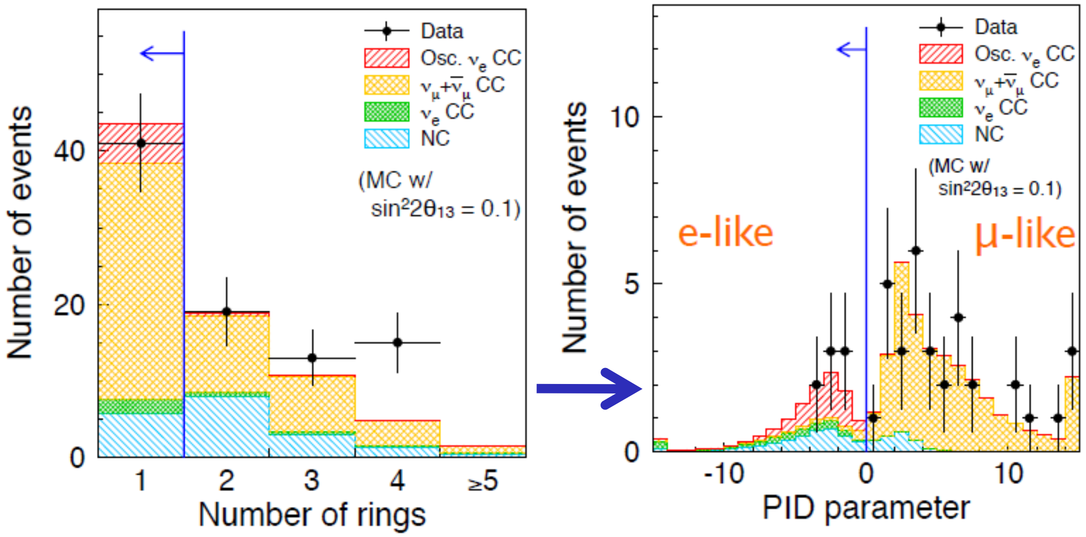
defined before the data collection
6 selection cuts in addition FC cut

Fiducial volume cut

(distance between recon. vertex and wall > 200cm)



T2K ν_e Appearance Data Reduction



SK ν_μ event reduction

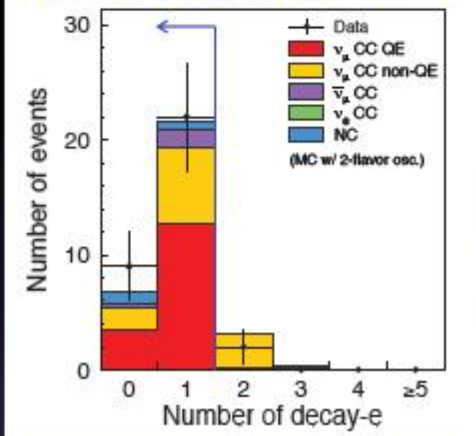
- 1 single ring μ-like → 33 events
- Additional cuts:
  - Less than 2 decay electrons
  - Reconstructed μ momentum larger than 200 MeV
- 31 events pass all the selections

Expected final sample composition with oscillations

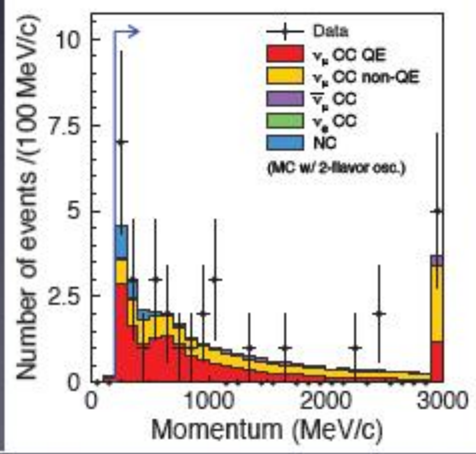
CCQE	CCnonQE	NC	$\overline{\nu}$	νe
57%	30%	6%	6%	<1%

- Systematics on the number of expected events computed using enriched samples of CCQE, CCnonQE and NC in SK atmospheric data
- Dominant systematics on SK efficiency given by the ring counting efficiency

N decay electrons <2→N=31



P(μ)[rec]>200 MeV → N=31



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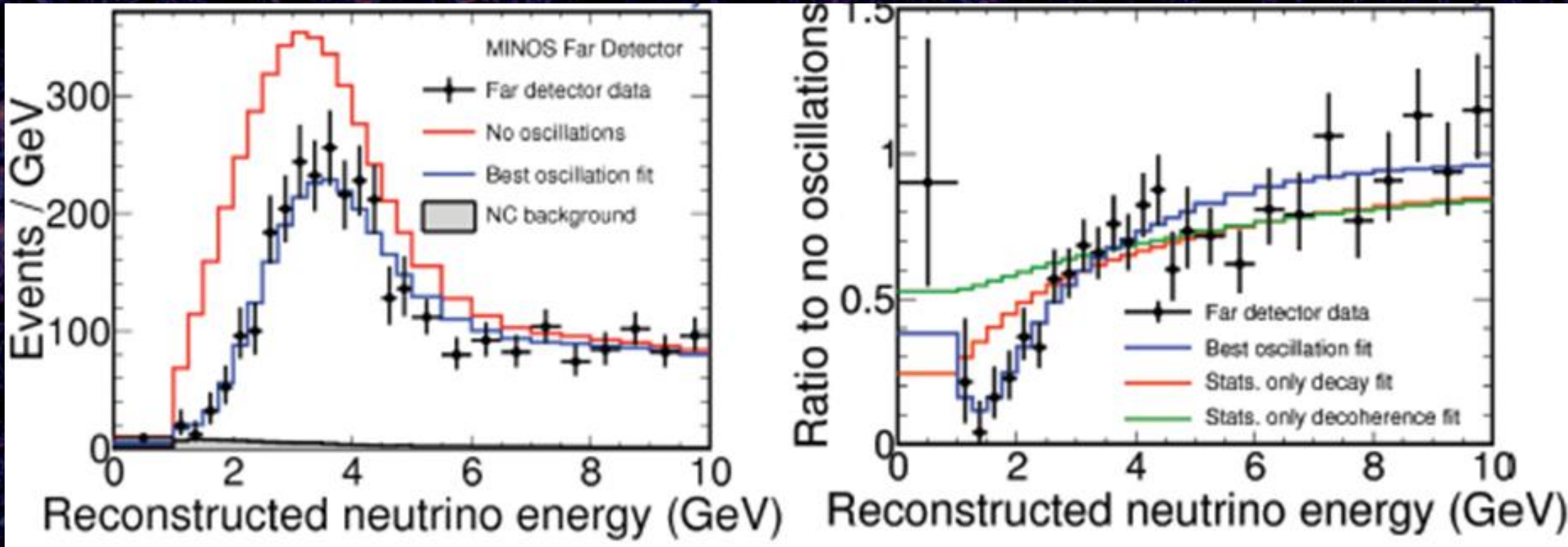
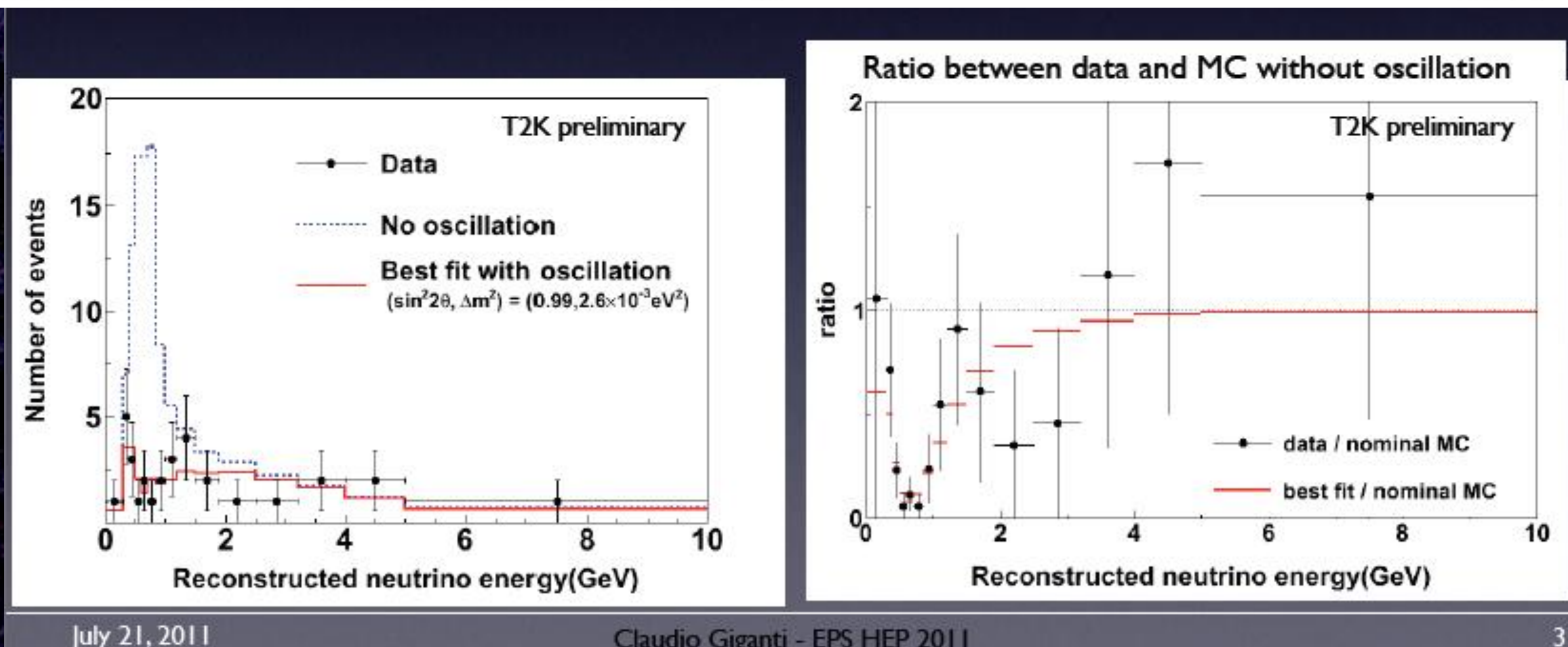
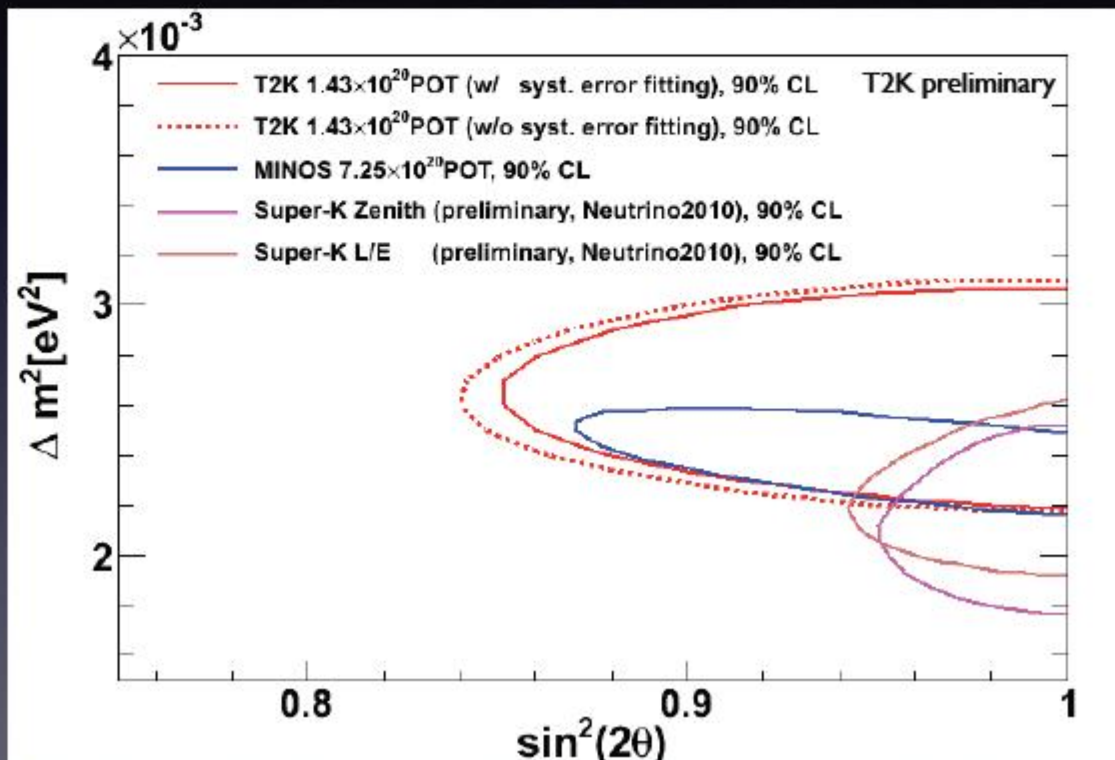
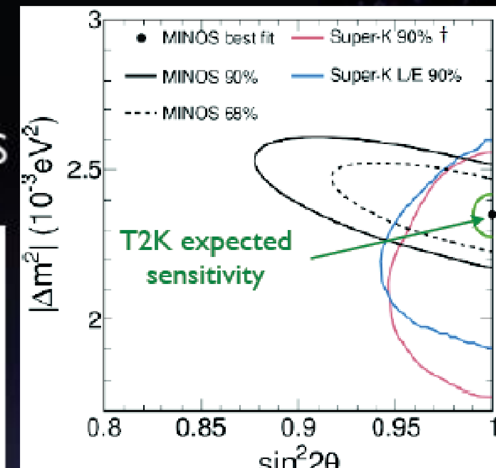

MINOS Far Detector
Far detector data
No oscillations
Best oscillation fit
NC background
Events / GeV
Reconstructed neutrino energy (GeV)
Ratio to no oscillations
Far detector data
Best oscillation fit
Stats. only decay fit
Stats. only decoherence fit
Reconstructed neutrino energy (GeV)


T2K preliminary
Data
No oscillation
Best fit with oscillation
(sin²2θ, Δm²) = (0.99,2.6×10⁻³eV²)
Number of events
Reconstructed neutrino energy(GeV)
Ratio between data and MC without oscillation
T2K preliminary
data / nominal MC
best fit / nominal MC
ratio
Reconstructed neutrino energy(GeV)
July 21, 2011
Claudio Giganti - EPS HEP 2011
31

Comparison with SK and MINOS

- T2K results are in good agreement with results from SK and MINOS





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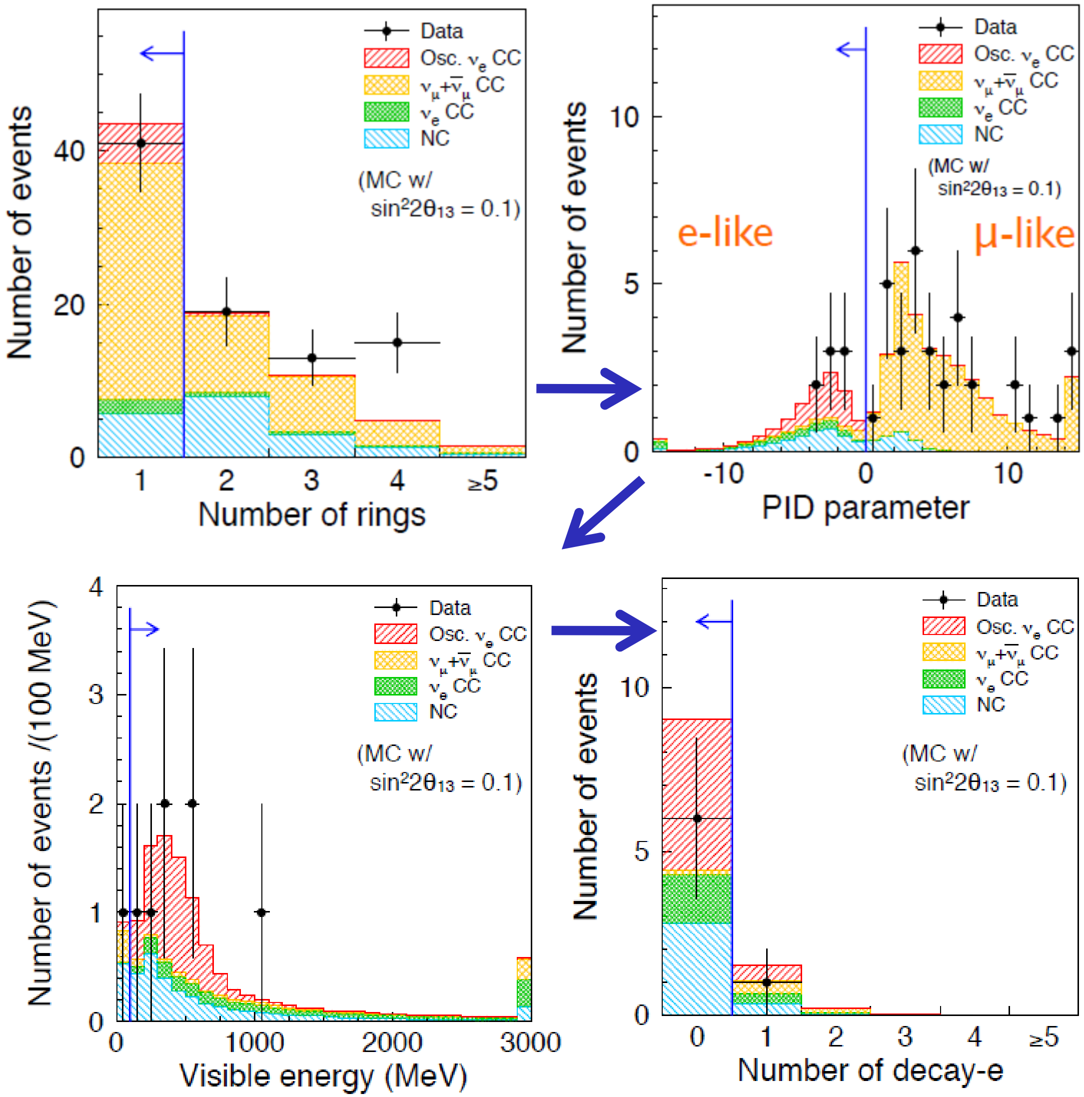
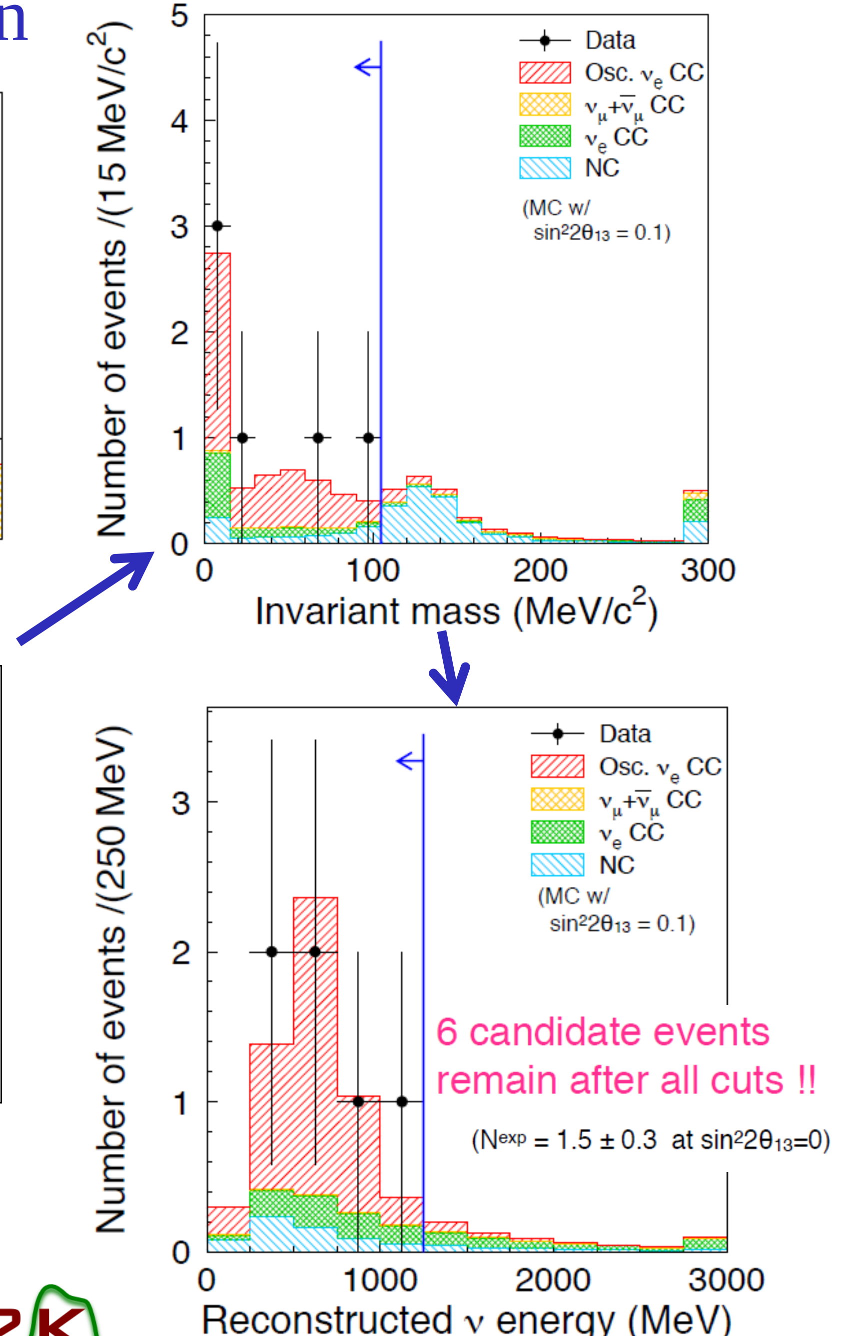
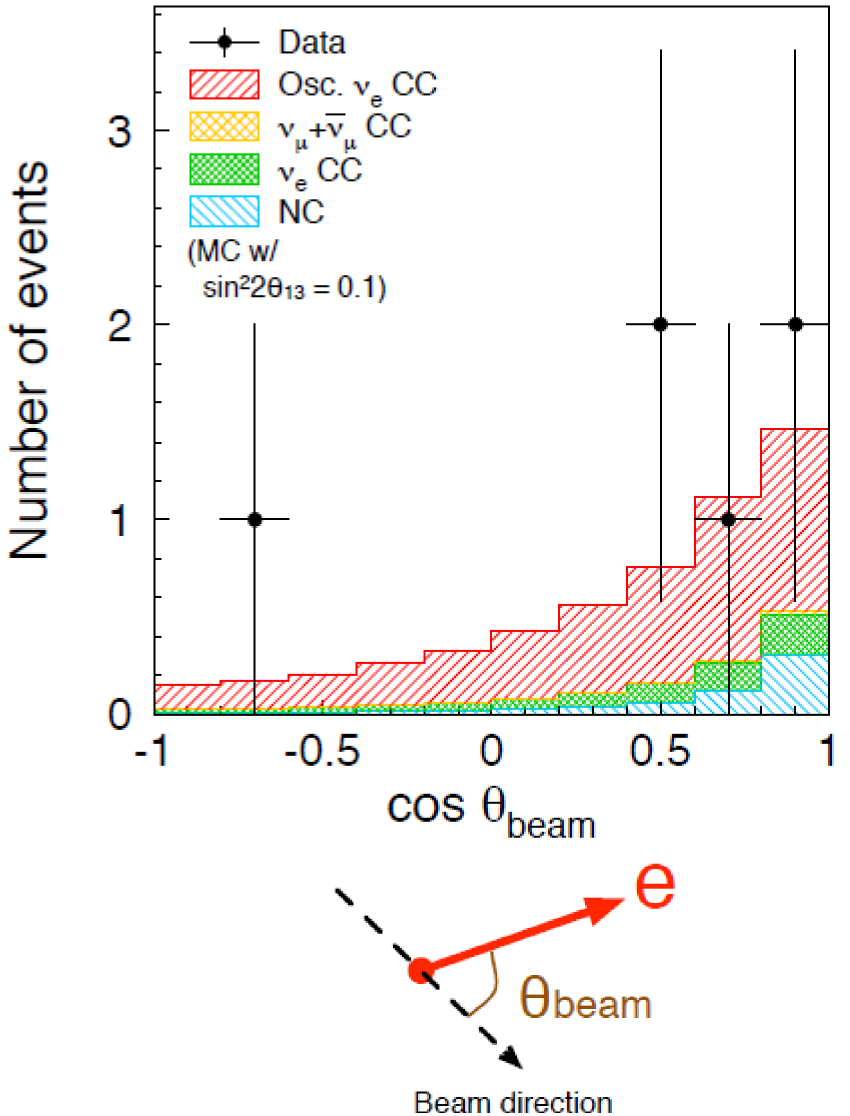
T2K ν_e Appearance Data Reduction

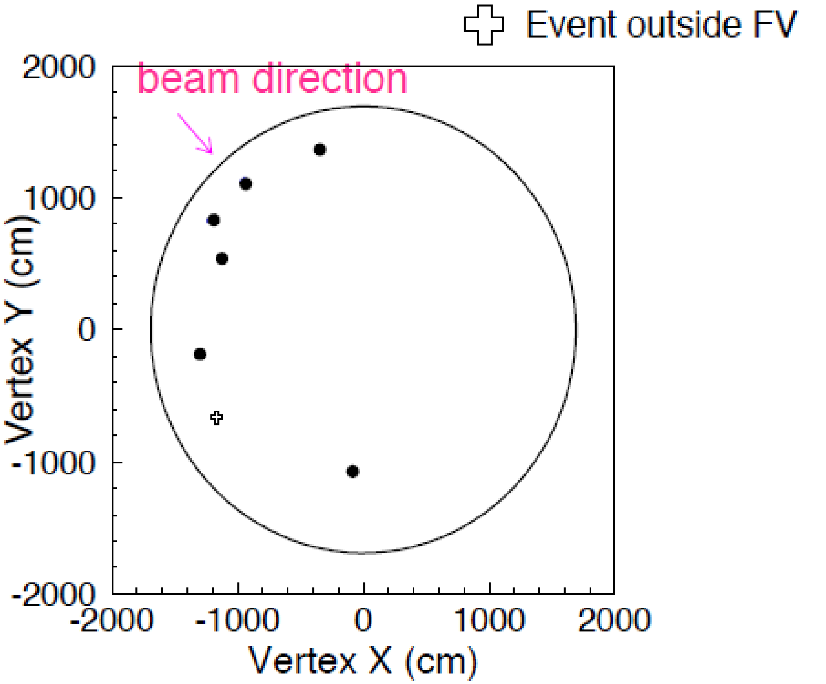




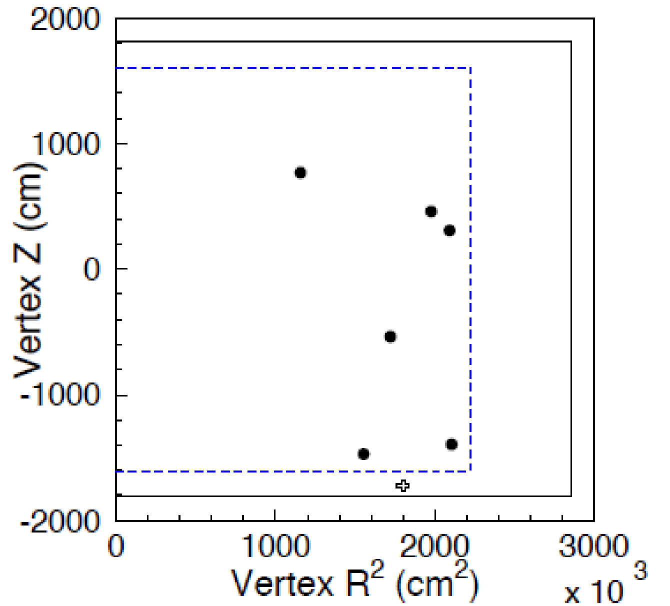
All cuts optimized for low statistics
and fixed before data taken.

Check many distributions….



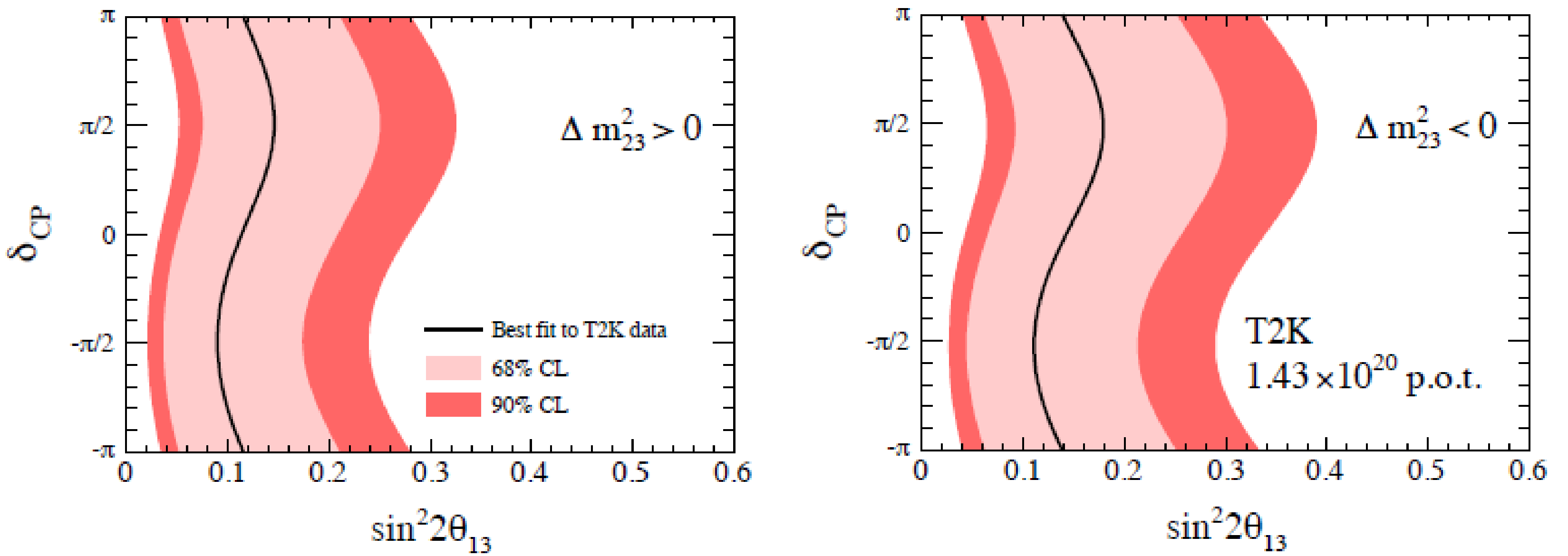


No excess outside FV or in OD, but KS prob. for R^2 is ~3%



Allowed region of $\sin^2 2\theta_{13}$ as a function of δ_{CP}

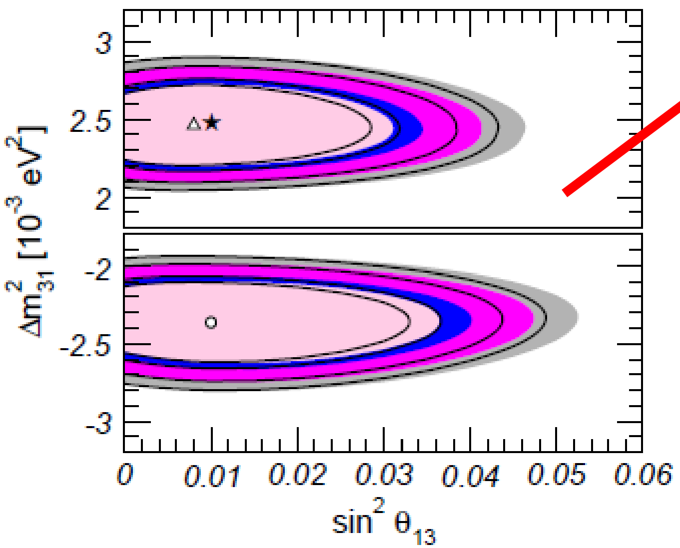
(assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1)

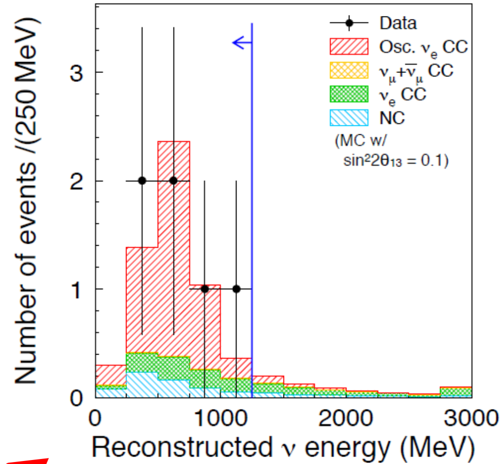


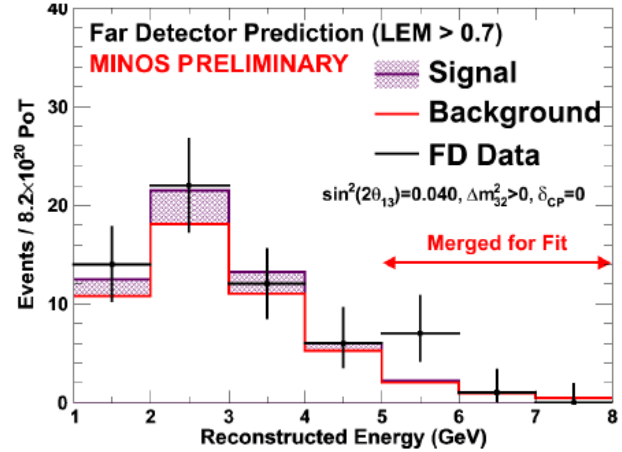
90% C.L. interval & Best fit point (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$	**$0.04 < \sin^2 2\theta_{13} < 0.34$**
$\sin^2 2\theta_{13} = 0.11$	**$\sin^2 2\theta_{13} = 0.14$**

What about θ_{13}?





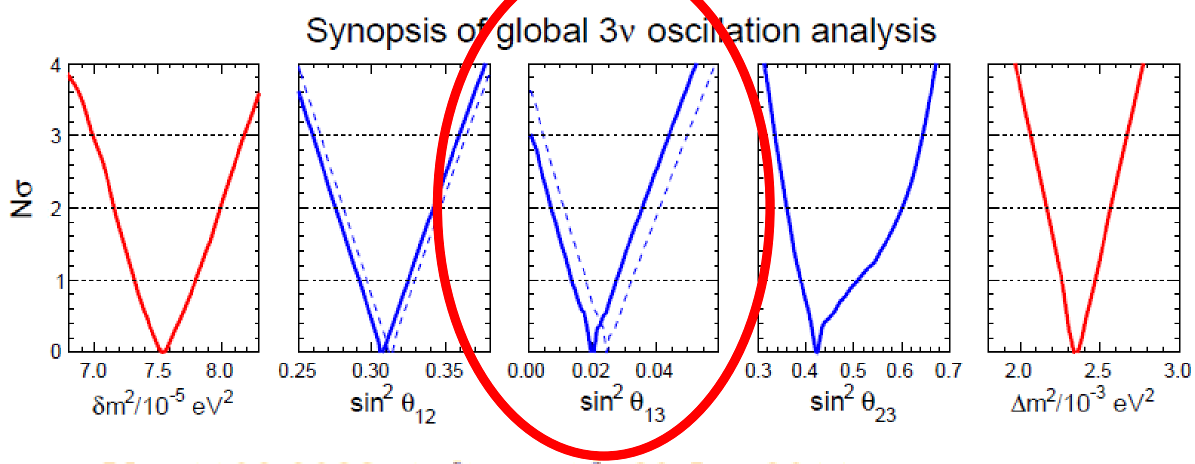


T2K (2.5σ) MINOS (1.7σ)

ν_e appearance, $\theta_{13} > 0$?

Evidence of $\theta_{13} > 0$ from global neutrino data analysis

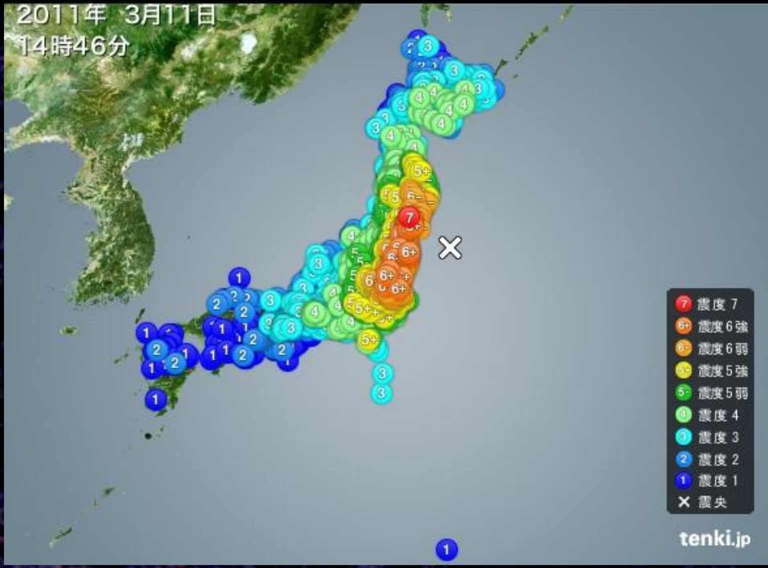
G.L. Fogli,[1,2] E. Lisi,[2] A. Marrone,[1,2] A. Palazzo,[3] and A.M. Rotunno[1]

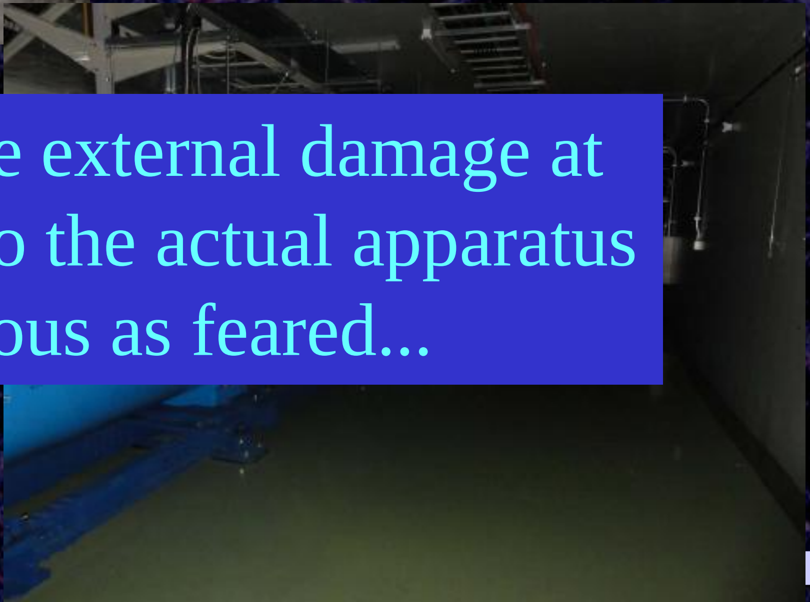


arXiv:1106.6028v1 [hep-ph] 29 Jun 2011

Interesting hints that $\theta_{13} > 0$, but clearly more data needed.

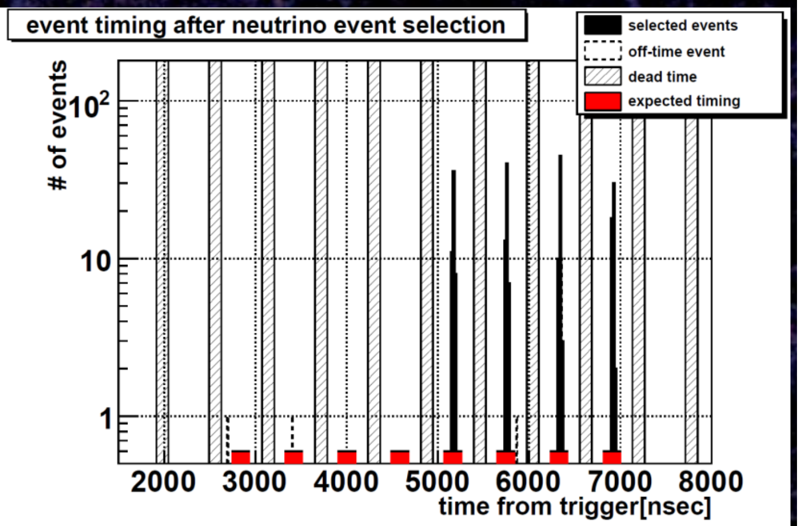
5/11, 14:46, all
Hell broke loose...

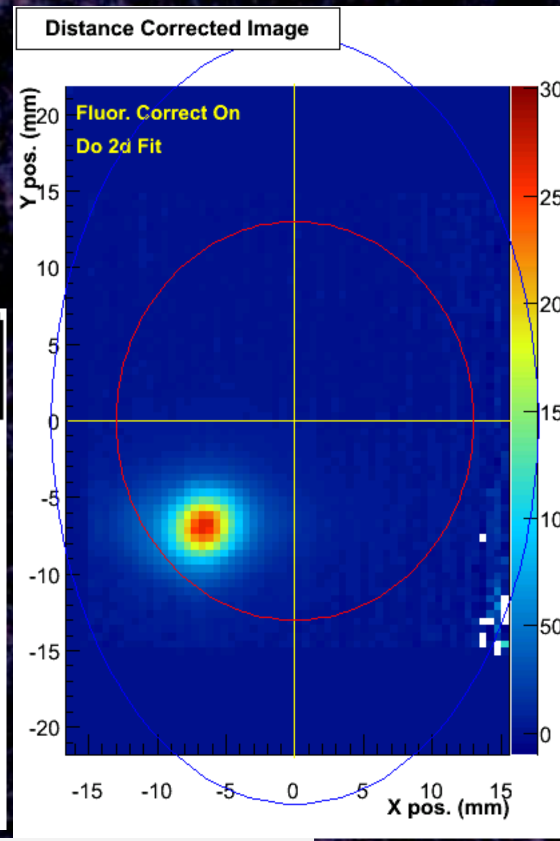


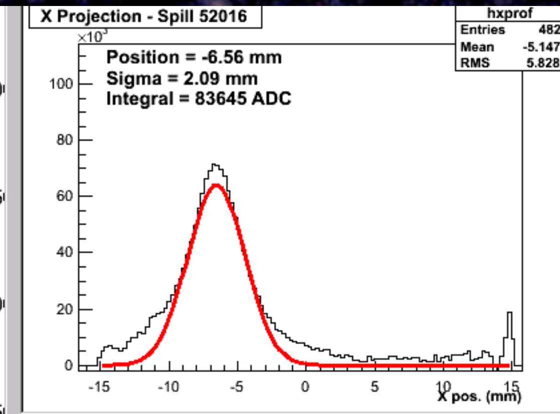


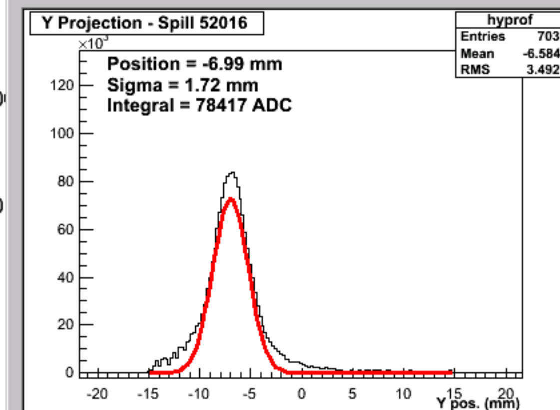
Despite considerable external damage at the facility, damage to the actual apparatus was not as serious as feared...

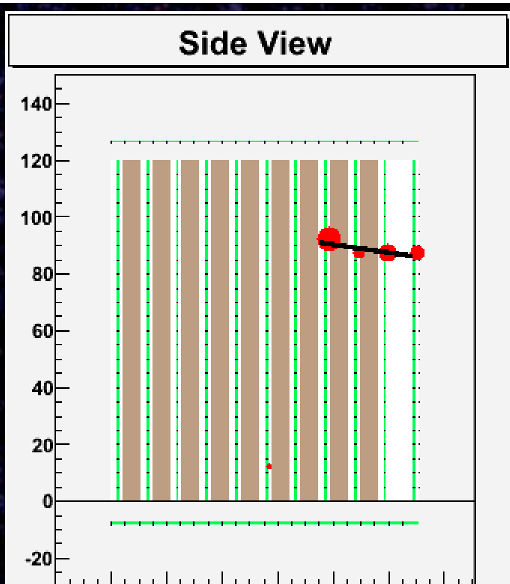
The good news: T2K is running again already!

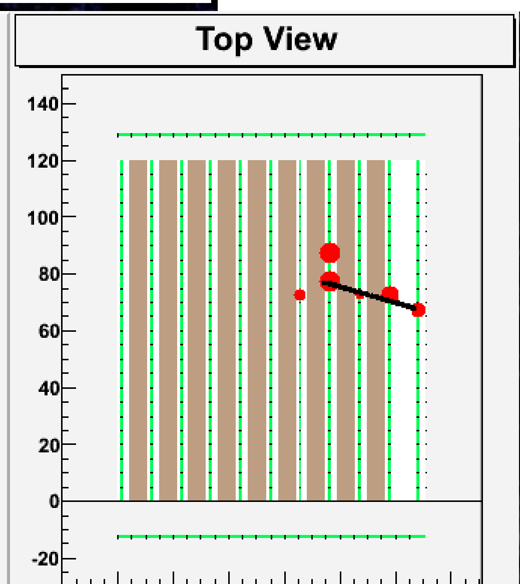










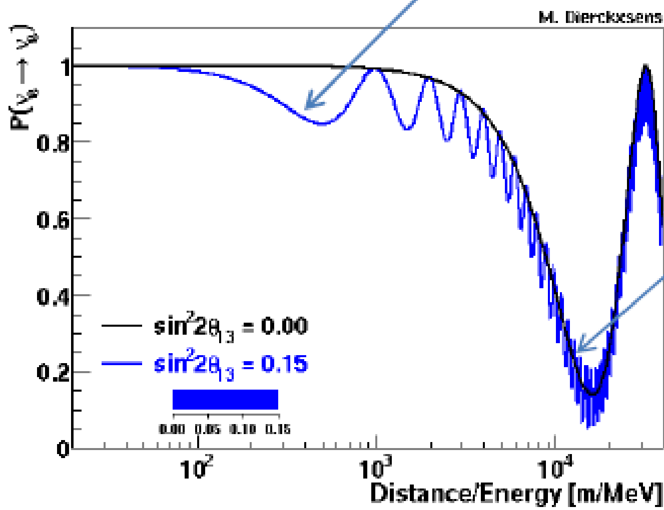


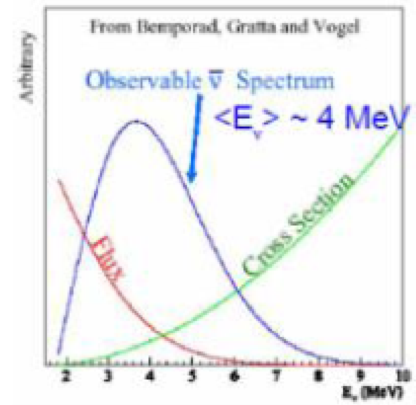
The bad news: The power supply to the horn blew up, so real neutrino data will return in March.

Dave Wark
Imperial College/RAL

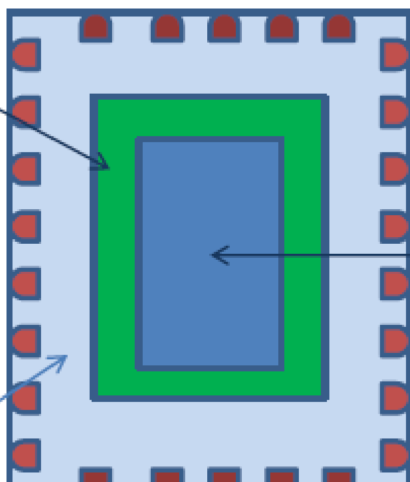
Reactor neutrinos

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\, L\, \Delta m^2_{31}}{E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\, L\, \Delta m^2_{21}}{E}\right)$$





Clean measurement of θ_{13}
Negligeable matter effect
No CP effect



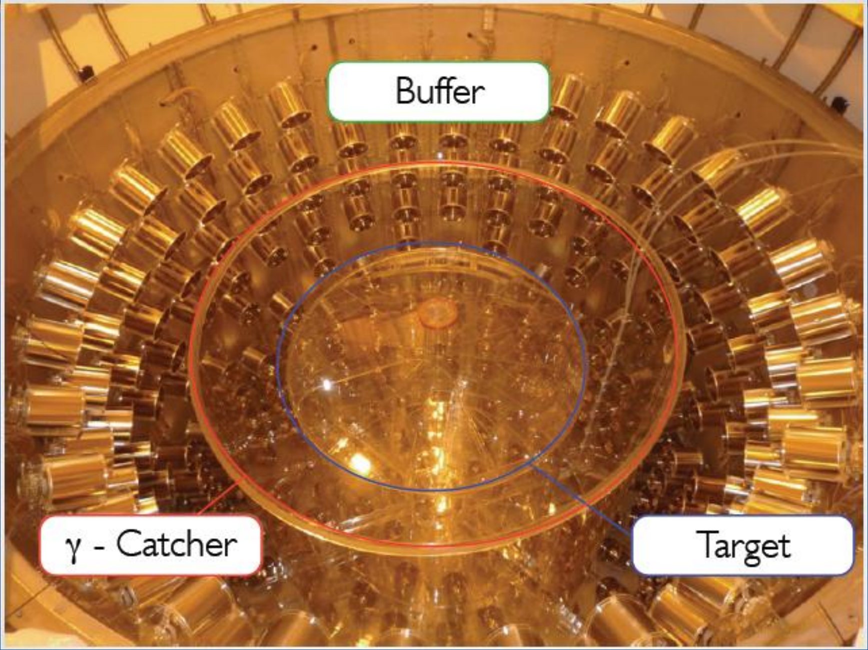
$\bar{\nu} + p \rightarrow e^+ + n$ $\quad E_{th} = 1.8$ MeV

Prompt signal from e^+

Slowing down of the neutron

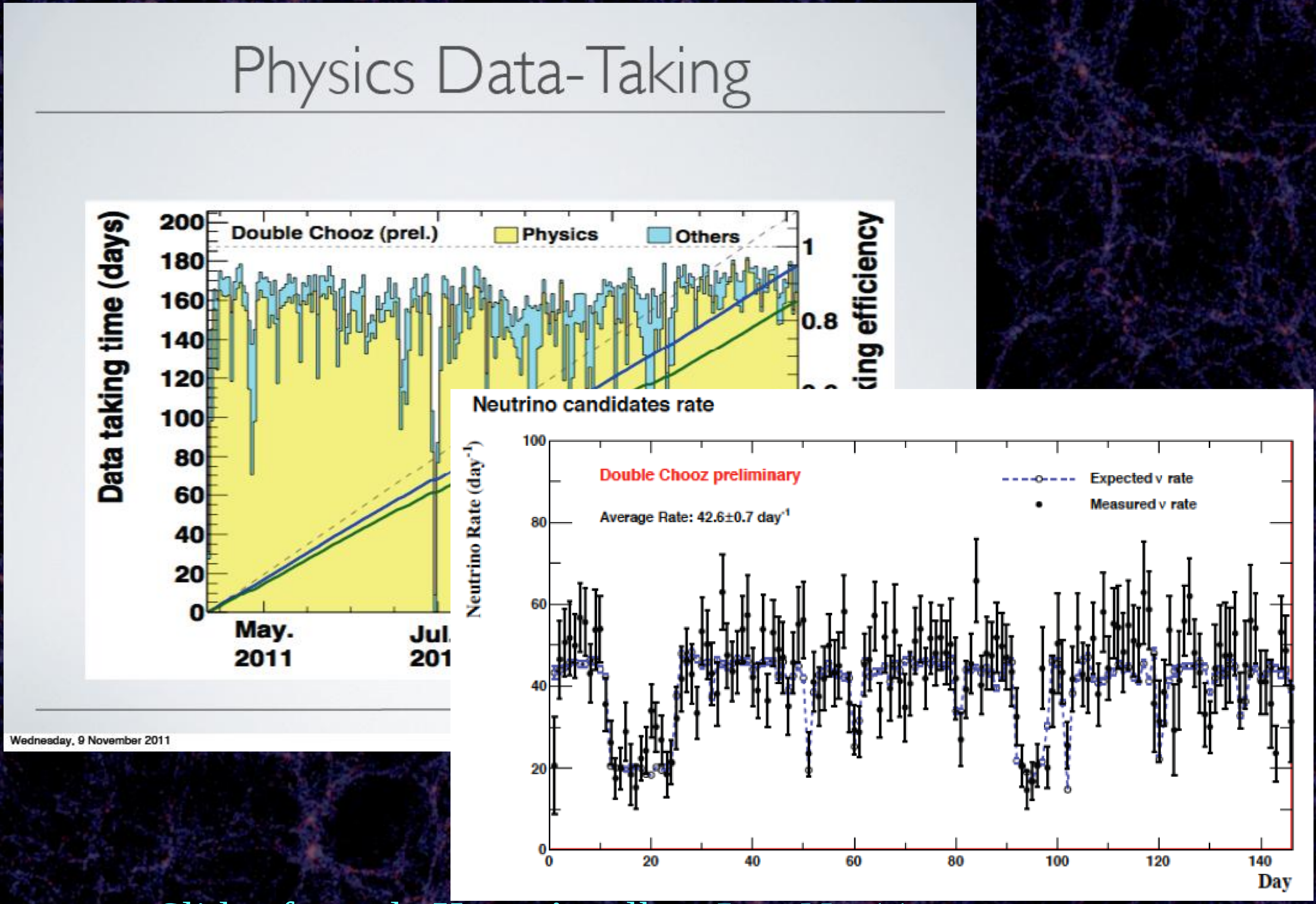
Delayed signal ~100 μs from n capture on H (2.2 MeV γ) or Gd (7 MeV γ)

Reactor neutrinos



	Location	Thermal Power	Distance Near/far	Depth Near/far
Double Chooz	France	8.5	410/1050	120/300
RENO	South Korea	17.3	290/1380	120/450
DAYA BAY	China	17.4	360/1985 500/1613	260/910

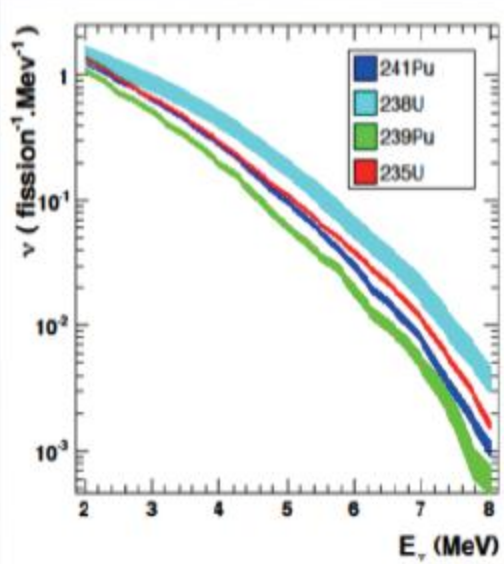
First Double Chooz Results.



Slides from de Kerret's talk at LowNu 11.

Reactor Neutrino Flux

Recent work defining new reference on the neutrino flux prediction



- Recent re-evaluations by
  - Th.A. Mueller et al, Phys.Rev. C83 (2011) 054615.
  - P. Huber, Phys.Rev. C84 (2011) 024617
- Off-equilibrium corrections included

New flux calculation ⟹ +6%

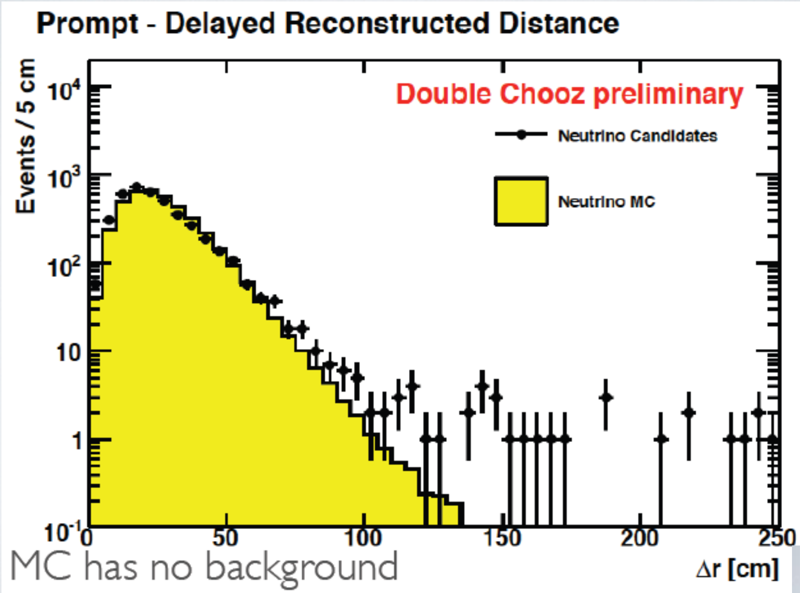
All reactor neutrino experiment are below

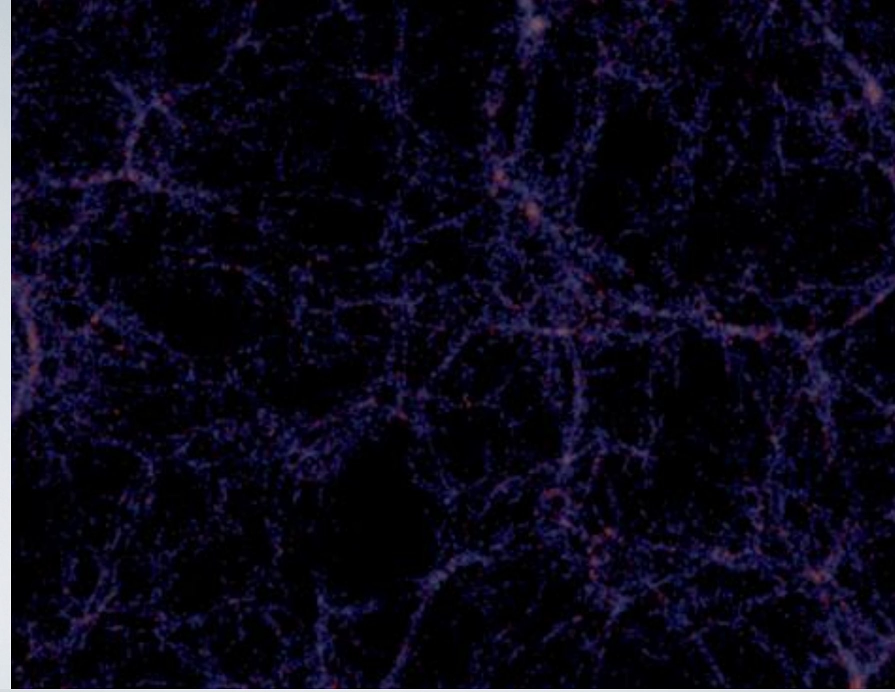
→use Bugey4 anchoring (as CHOOZ) ⟹ Far phase

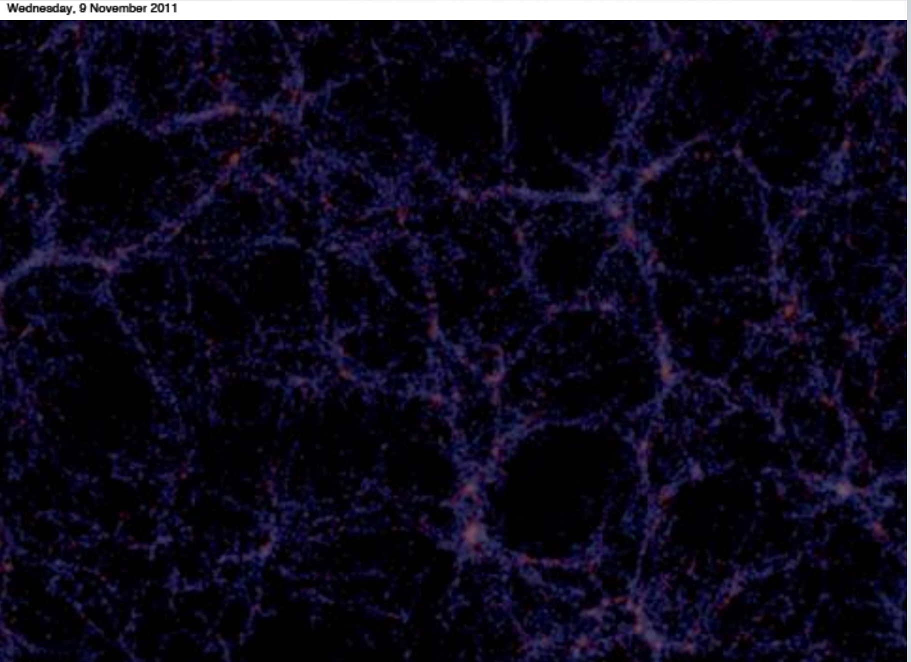
→use 2 detectors ⟹ Near & Far phase

Spatial Correlation

no analysis cut

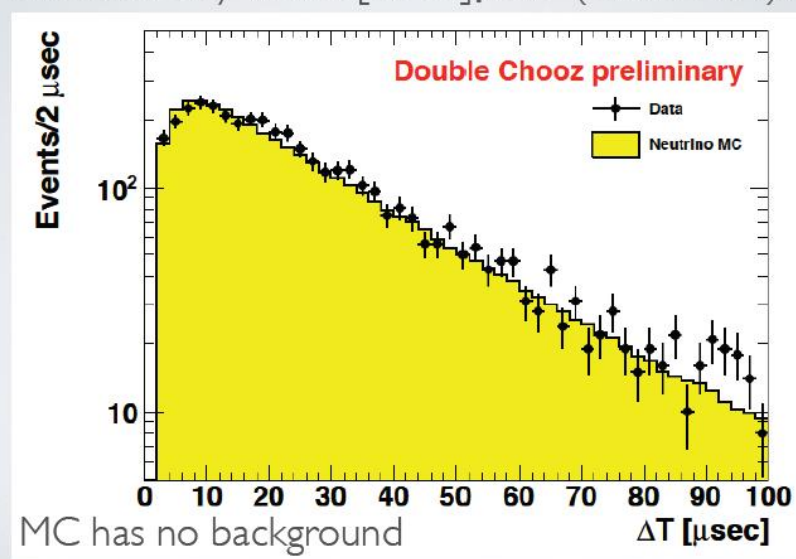


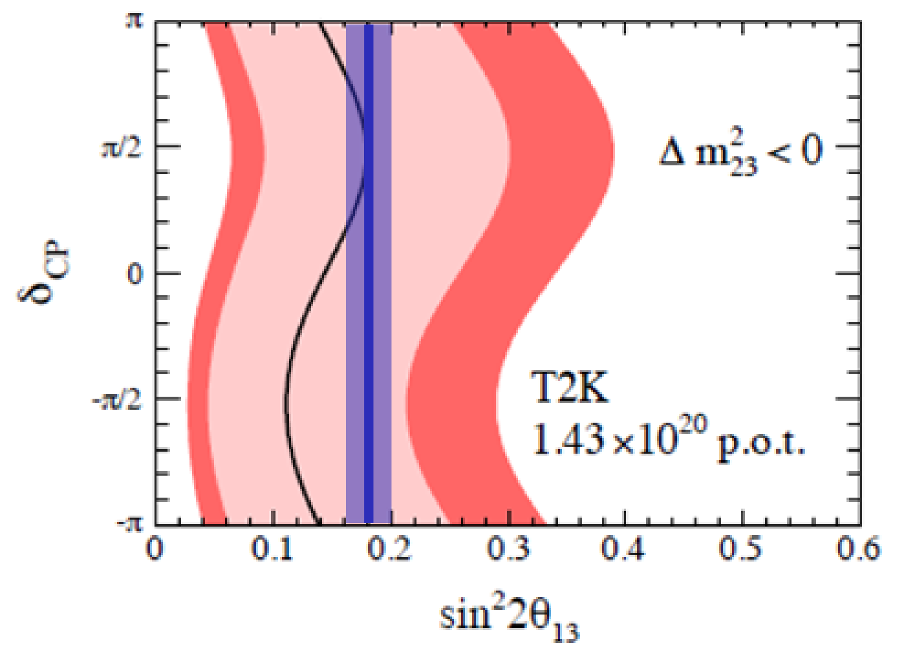




Time Correlation

The efficiency within [2,100]μs is (0.965± 0.4)%





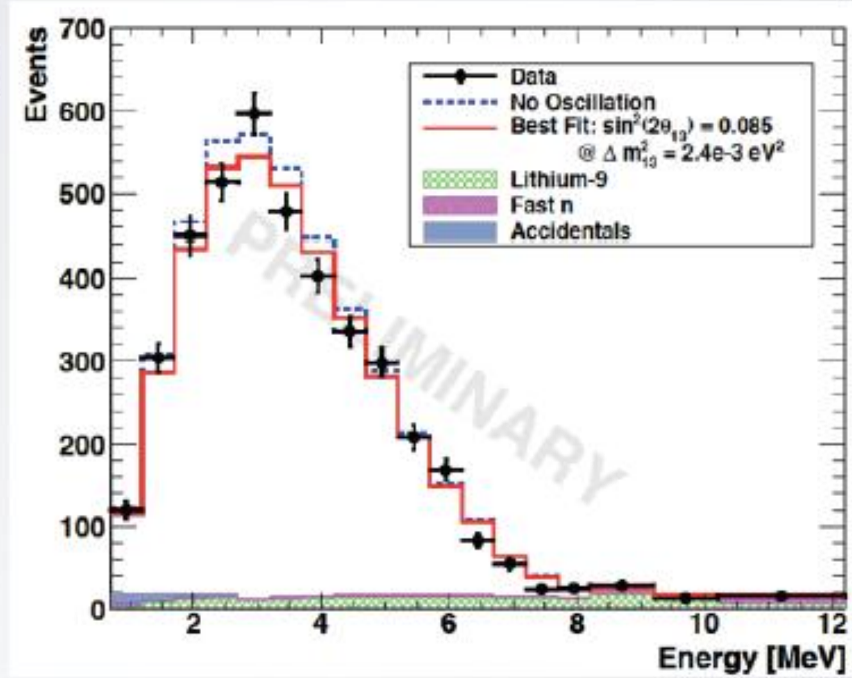
inary Results

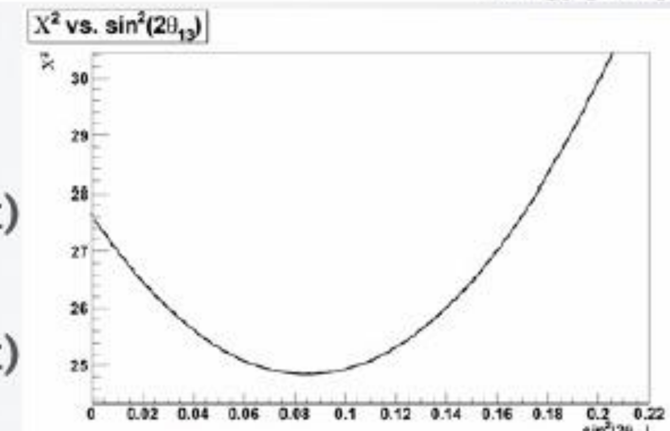
ta

Far detector data only

No-Oscillation:

reactor flux prediction





Rate + Shape Analysis:

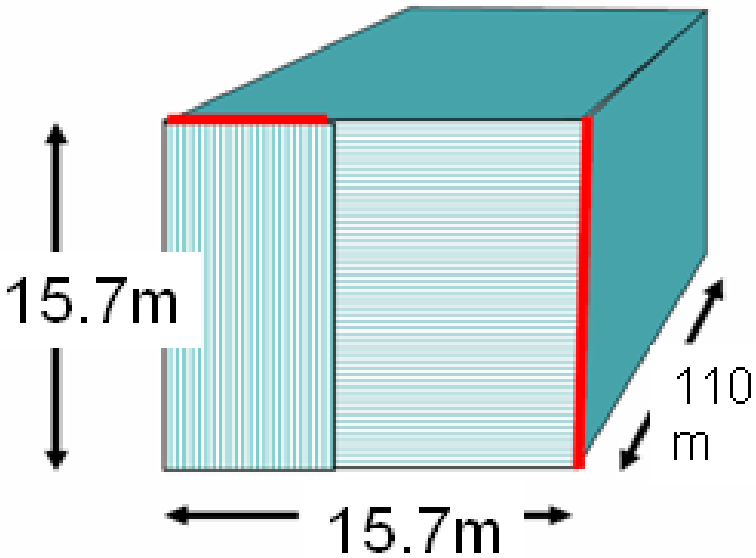
$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(stat) \pm 0.042(syst)$

Rate Only:

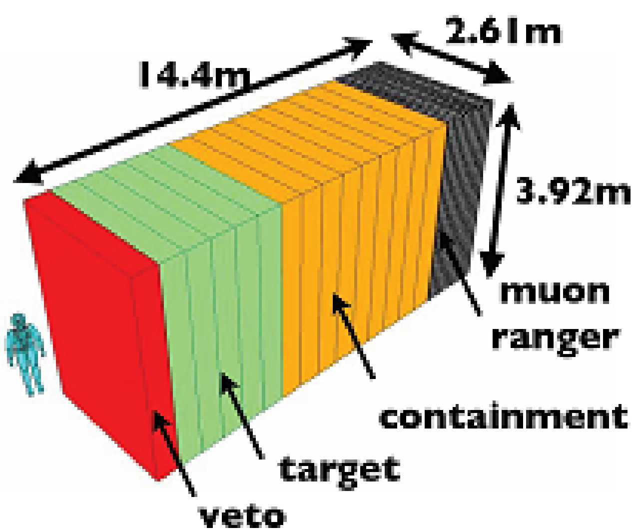
$\sin^2(2\theta_{13}) = 0.093 \pm 0.029(stat) \pm 0.073(syst)$

NOνA
Experiment
Status
Ken Heller
University of Minnesota
Neutrino 2010
NOVA Far Detector
NOvA Far Detector
MINOS Far Detector
Ontario
Minnesota
Minneapolis
Wisconsin
Milwaukee
Fermilab
Chicago

NOvA Detectors

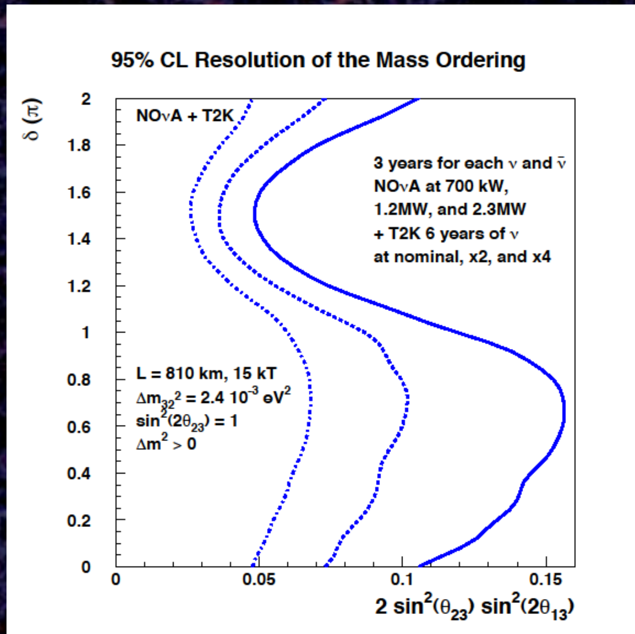


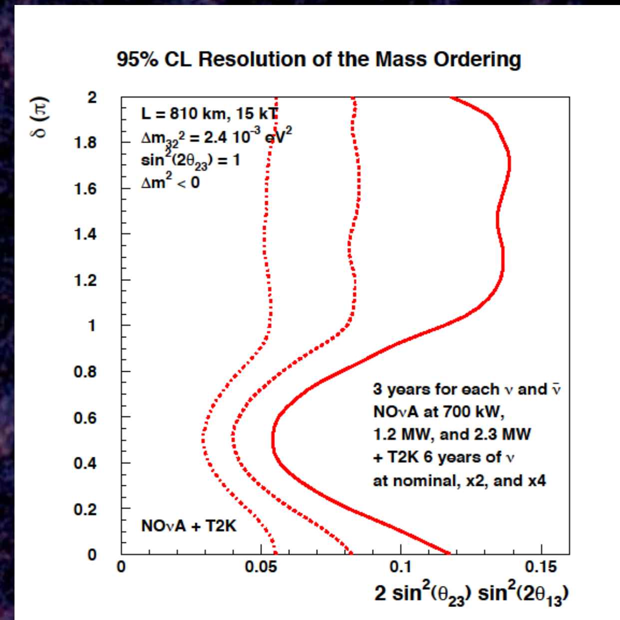
- 25 ktons
- 1984 liquid scintillator planes, no additional absorber (~80% active)
- Scintillator cells
  3.8 x 6.0 x 1570 cm
- Read out from one side per plane with APDs
- Expected minimum signal 20pe



- 126 tons of scintillator, 83 tons of steel
- 23 ton fiducial mass
- 186 liquid scintillator planes in target, 10 in muon ranger, 1m of steel
- Same cell size, same minimum signal
- Read out from one side per plane with APDs plus faster electronics than in far detector

What will existing experiments yield?

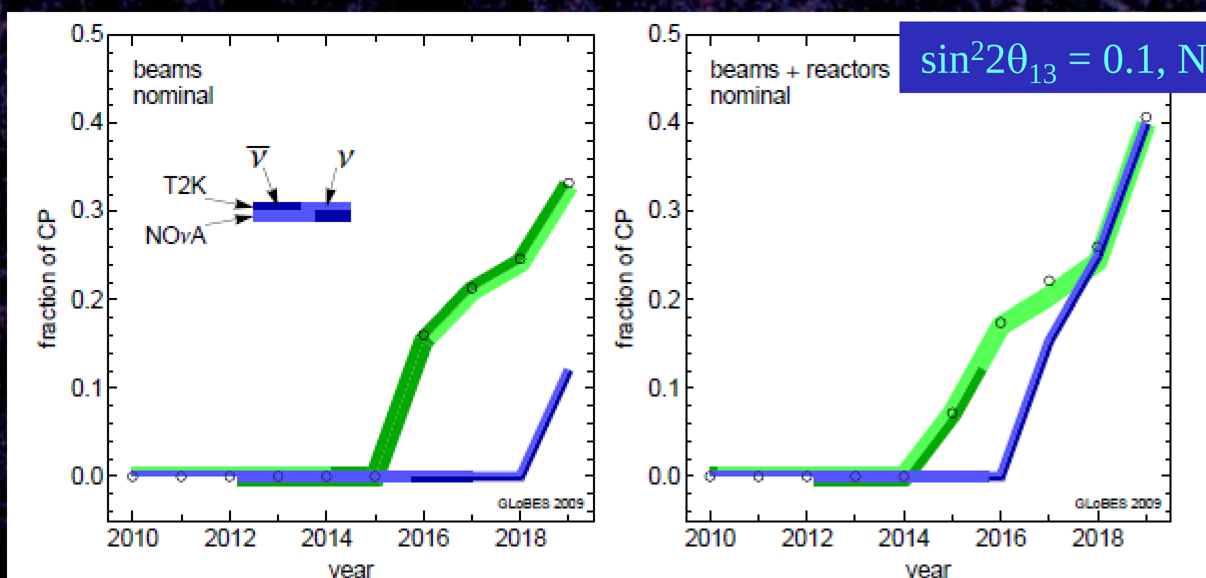




arXiv:0907.1896v1 [hep-ph] 10 Jul 2009

Even some 90% CP violation sensitivity…

$\sin^2 2\theta_{13} = 0.1$, NH



An incremental approach to CP ?

- **Excitement ➡ H. Murayama presented his (anarchical) prediction for mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ which hinted at a large θ_{13}**

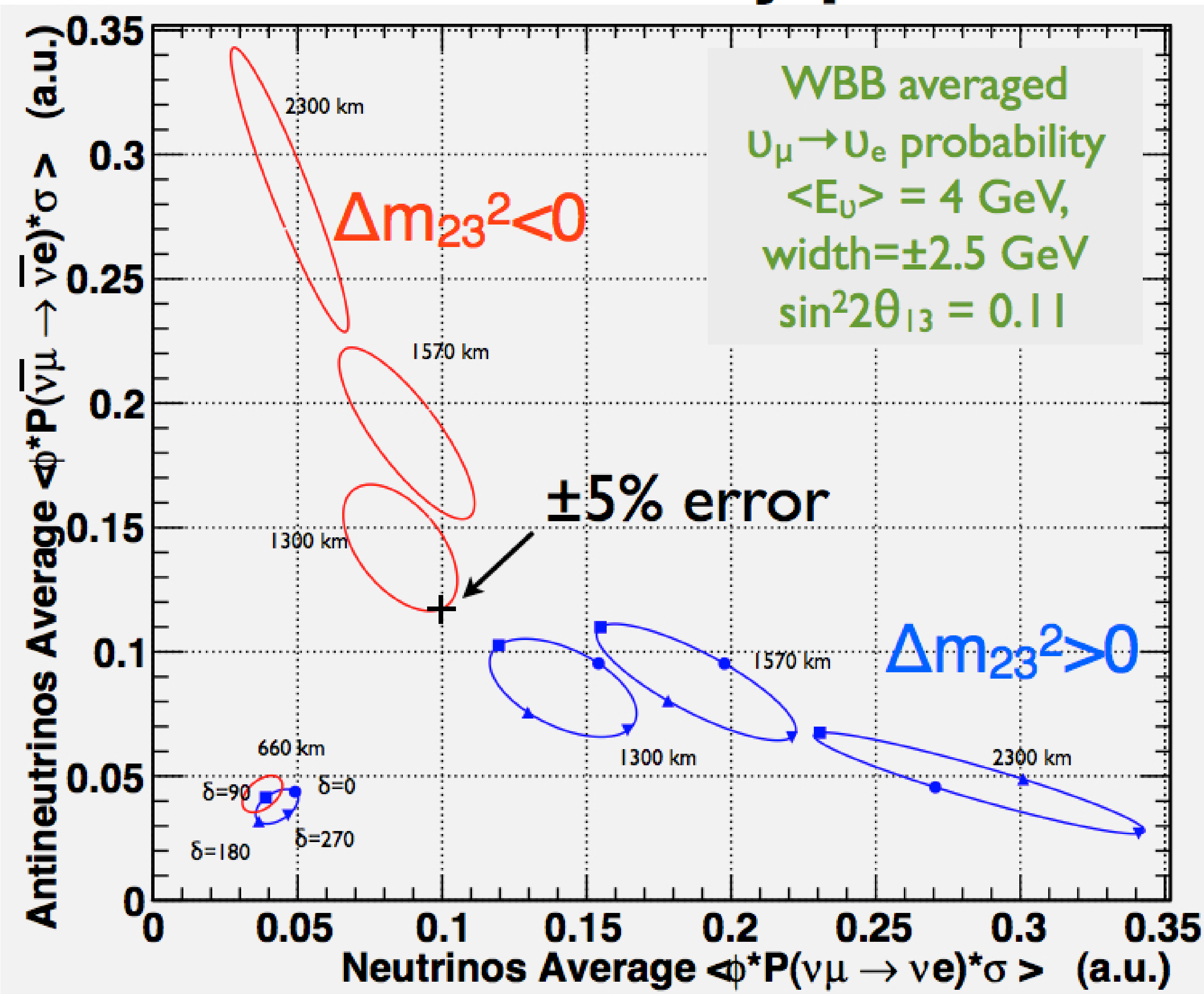
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\frac{\Delta m_{12}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{23}^2 L}{4E}$$

all parameters turned out to be favorable !!!

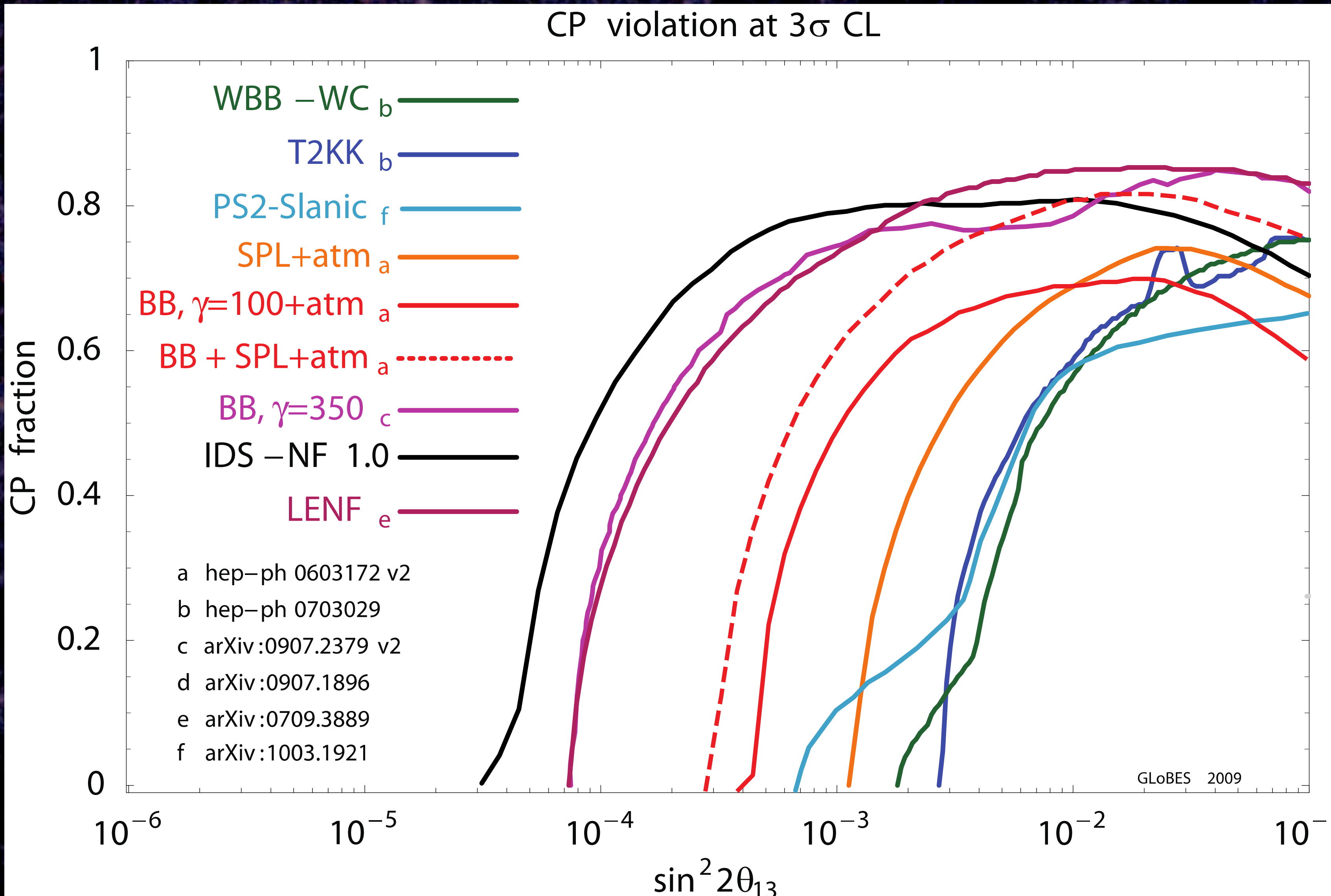
- **What about δ_{CP} ?**
  - ➡ the favorable values δ_{CP}=90, 270º are still allowed. Will Nature be kind again ?
  - ➡ if so, one could find evidence for CP violation in the lepton sector early on
  - ➡ if not, we can upgrade the sensitivity by increasing the far detector mass and/or beam power

Dave Wark
Imperial College/RAL

Simultaneous solution to CP and mass hierarchy problems



Longer baselines are better to determine mass hierarchy


CP violation at 3σ CL
WBB −WC b
T2KK b
PS2-Slanic f
SPL+atm a
BB, γ=100+atm a
BB + SPL+atm a
BB, γ=350 c
IDS −NF 1.0
LENF e
a hep−ph 0603172 v2
b hep−ph 0703029
c arXiv:0907.2379 v2
d arXiv:0907.1896
e arXiv:0709.3889
f arXiv:1003.1921
GLoBES 2009
CP fraction
0
0.2
0.4
0.6
0.8
1
10^−6
10^−5
10^−4
10^−3
10^−2
10^−1
sin^2 2θ13

Three "conventional" beam proposals:

- An upgrade of T2K based on reaching 1.6 MW beam power and a new far detector.
- LBNE – a plan to build a new neutrino beam at Fermilab aimed at Homestake, where either a large water Cerenkov detector or a LAr tracking calorimeter would be built.
- LAGUNA-LBNO – three different options for new long baseline in Europe.

Future Neutrino Oscillation Experiments

- Another round of supererbeams?:
  - Water Cerenkov or Liquid Argon?
  - Upgrade of T2K
  - LBNE
  - LBNO
- The further future?:
  - β beams
  - Neutrino Factory
- Support Experiments...

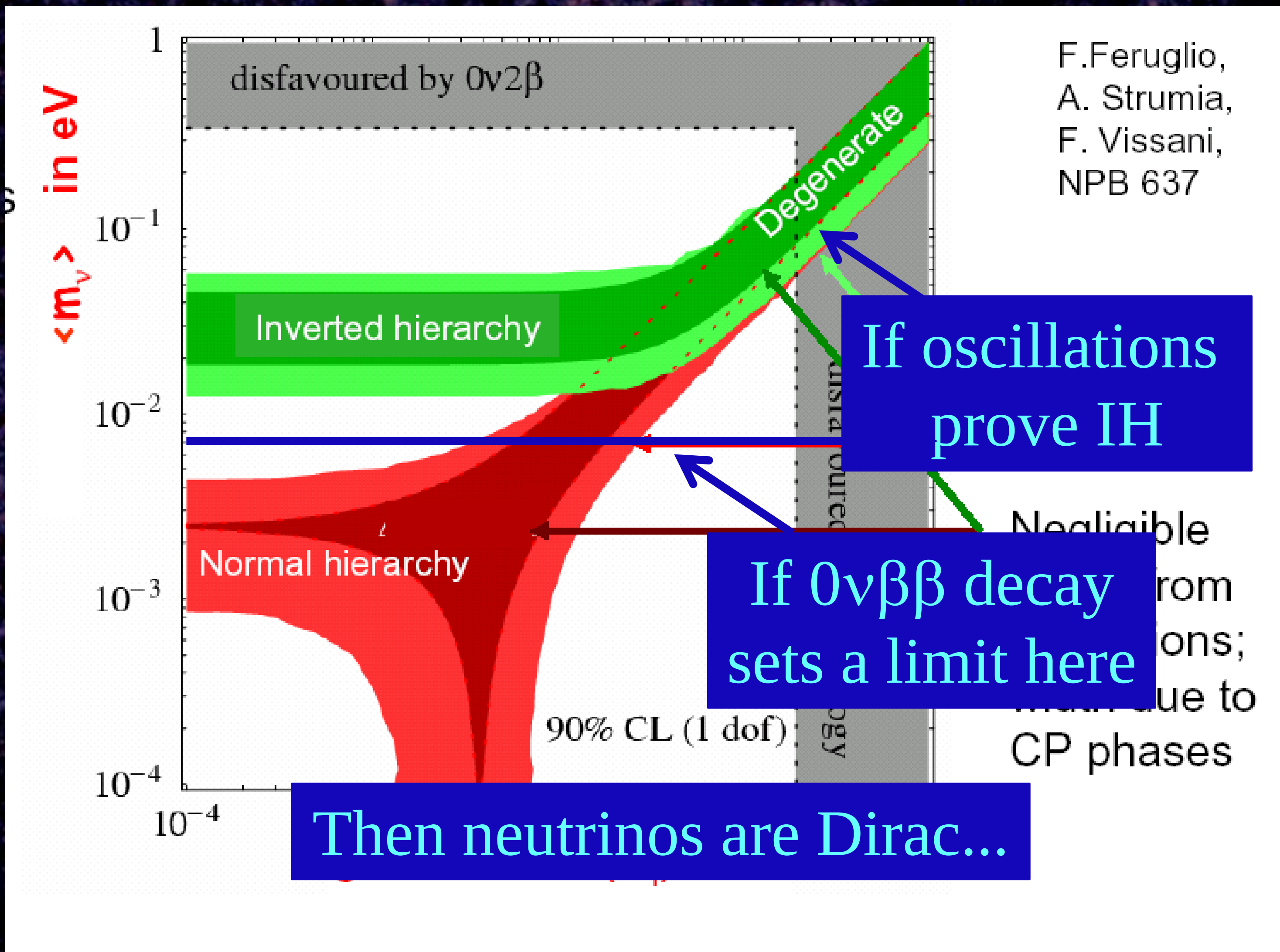
Measuring absolute m_ν

- Supernovae – Prodigious producers of neutrinos, and measuring time shifts can in principle measure neutrino masses, $m_\nu < \sim 30$ eV.
- Kinematic limits: If you believe the oscillation results, all $\Delta m^2 \ll 1$ eV, therefore only ν_e measurements have useful sensitivity → current best is Tritium Beta Decay, $m_\nu < 2.2$ eV.
- If neutrinos have Majorana masses, then zero-neutrino double-beta decay is allowed → observation of $0\nu\beta\beta$ decay would be direct evidence for neutrino mass, $\langle m_\nu \rangle < \sim 1.3$ eV.
- Neutrinos are the second most numerous particle in the Universe → even a tiny neutrino mass could have astrophysical implications, $\Sigma m_\nu < 0.28$ eV(?)

Other Neutrino Physics Topics

- Opera, SN ν, and the Opera Time Anomaly
- Sterile neutrinos
- High-E neutrino astronomy

Dave Wark
Imperial College/RAL



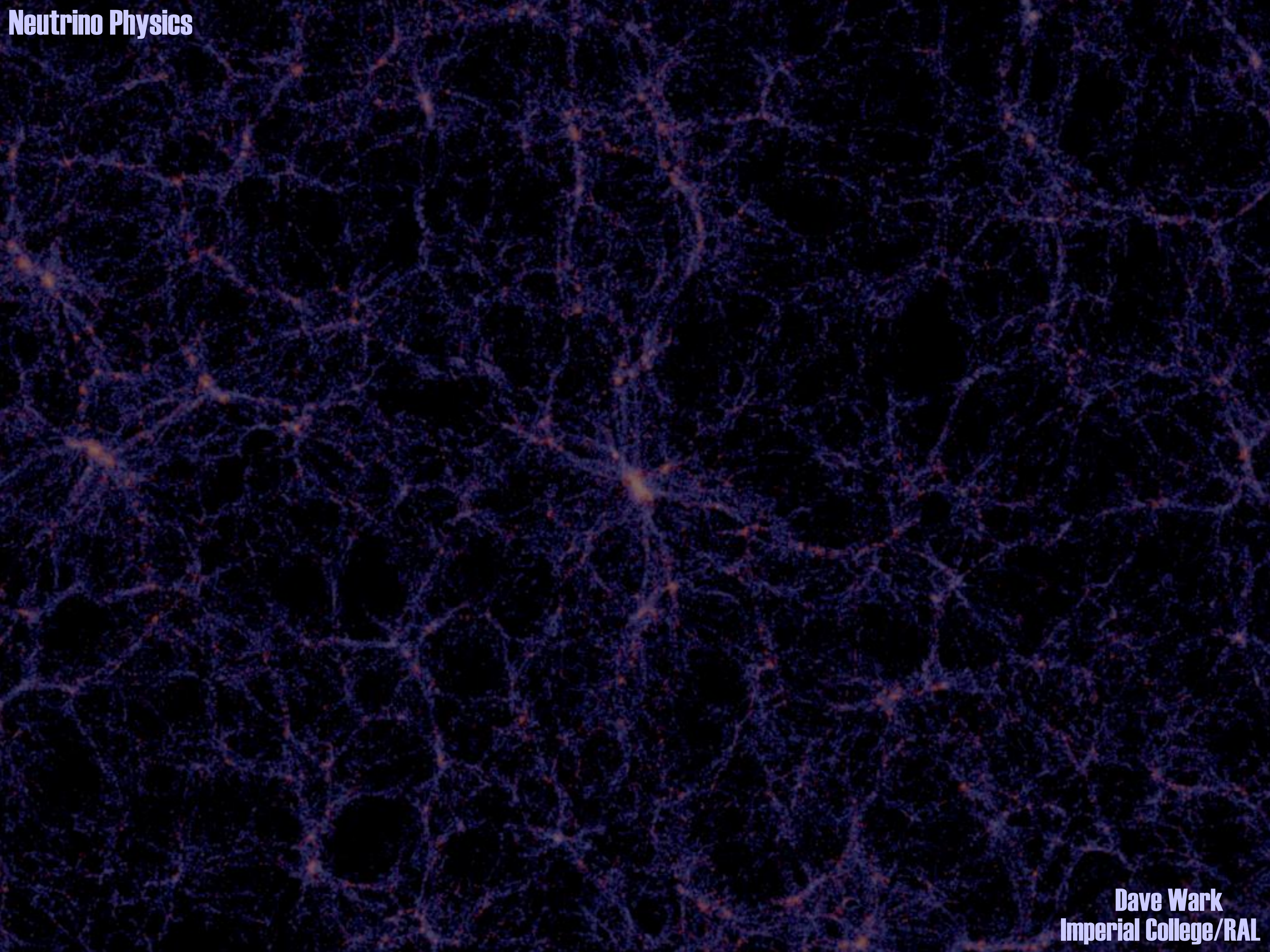
disfavoured by 0ν2β
Degenerate
Inverted hierarchy
Normal hierarchy
90% CL (1 dof)
<mν> in eV
1
10−1
10−2
10−3
10−4
10−4
F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637
If oscillations prove IH
If 0νββ decay sets a limit here
Then neutrinos are Dirac…
CP phases

Conclusions

- ν oscillations are the first confirmed physics beyond the SM (well, other than the mass of the electron)!
- Current indications are that $\sin^2 2\theta_{13} \geq \sim 0.01$, which could give existing experiments the first sensitivity to CP violation in the neutrino sector.
- Do not assume we know everything that is going on – redundancy is essential!
- There are three next-generation superbeam projects, and I think the physics will justify at least two.
- The mine at Pyhäsalmi is potentially an extremely valuable resource for European neutrino physics due to its distance from CERN, but we should move fast if we are going to retain the option of using it in the future. Can we build a 10 kT LAr prototype?
- In my opinion, a large LAr tracking calorimeter will be used in at least one experiment, making LAr development a high priority.
- There will be many other opportunities for smaller-scale involvement in cross-section, hadron production, and perhaps short-baseline projects.

More Conclusions

- There are many other fascinating and important topics in neutrino physics other than in oscillations that will continue to generate significant experiments.
- Neutrino physics has a guaranteed future – JOIN US!
- Each generation of particle physicists has to fight and win the battle to convince governments that our science is important and that our experiments need to be funded and our theorists need support.
- This fight has gotten, and will get, harder as public money is tighter and tighter.
- To win the fight we need new ideas and new initiatives, and the young people are where they should come from.
- The European strategy process that is starting up will have a bigger effect on your future than on mine – give us input and get involved!



Neutrino Physics

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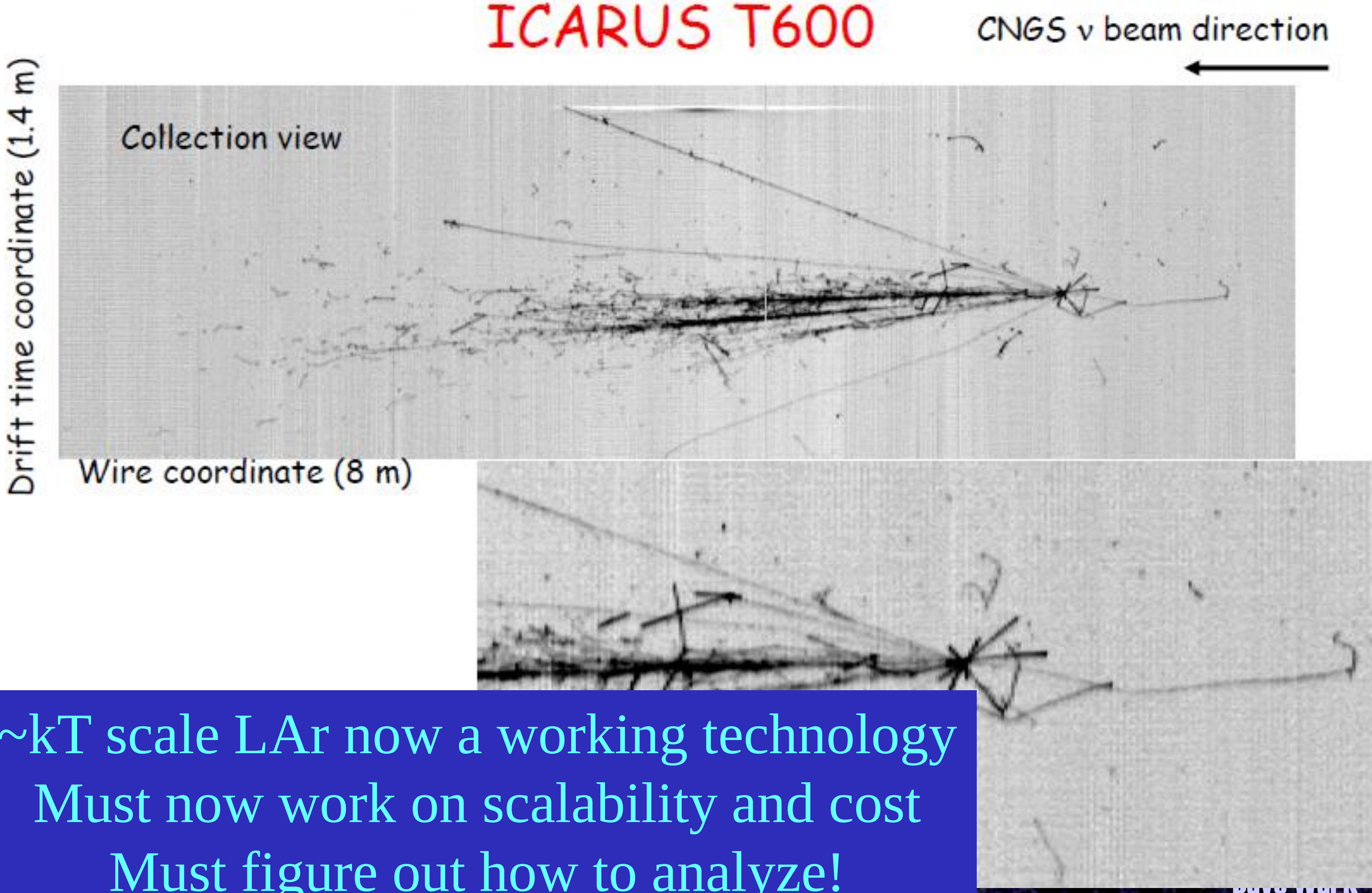
The second CNGS neutrino interaction in ICARUS T600

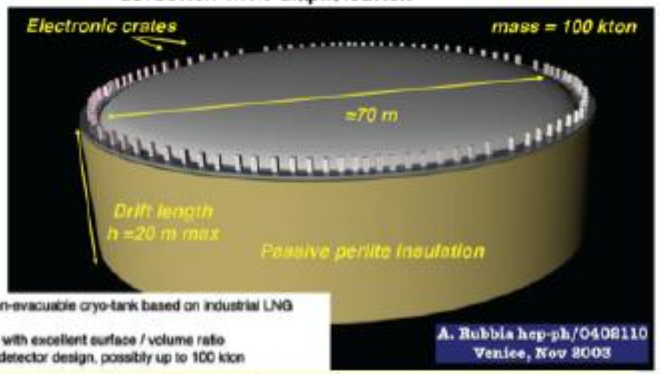


~kT scale LAr now a working technology
Must now work on scalability and cost
Must figure out how to analyze!

Giant Liquid Argon Detector (KEK-ETHZ)

Giant Liquid Argon Charge Imaging ExpeRiment

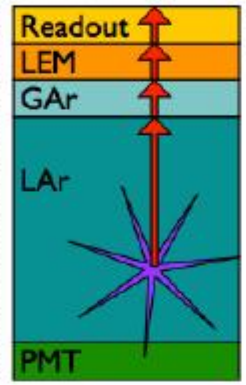
A scalable detector with a non-evacuable dewar and ionization charge detection with amplification

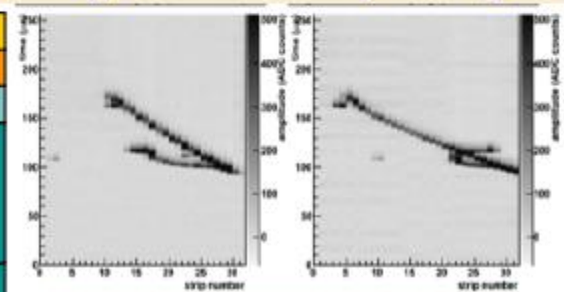


- Single module non-evacuable cryo-tank based on industrial LNG technology
- Cylindrical shape with excellent surface / volume ratio
- Simple, scalable detector design, possibly up to 100 kton

- Extremely high performance
- "Electronic Bubble Chamber"
- 3D tracking of all charged particle from very low energy threshold
- Precise resolution of ~mm
- Fully active homogeneous 4π detector (as WC)
- Good PID w/ dE/dx, π0 rejection
- Double phase w/ Gas amplification
- <10ppt purity needed
- LEM readout (~106ch)
- 600ton detector realized and working

Double phase charge readout w/ adjustable gain

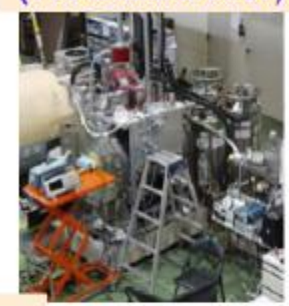




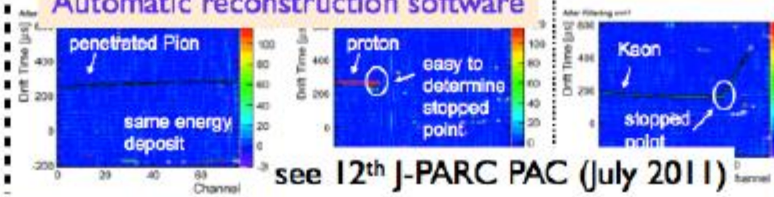
Much improved S/N (>100) compared to single-phase LAr operation (≈15)

ArDM-1ton (CERN RE18 Collab)

Test beam at J-PARC (T32 Collaboration)



Automatic reconstruction software



see 12th J-PARC PAC (July 2011)

Also very significant efforts in the US in LBNE and MicroBooNE

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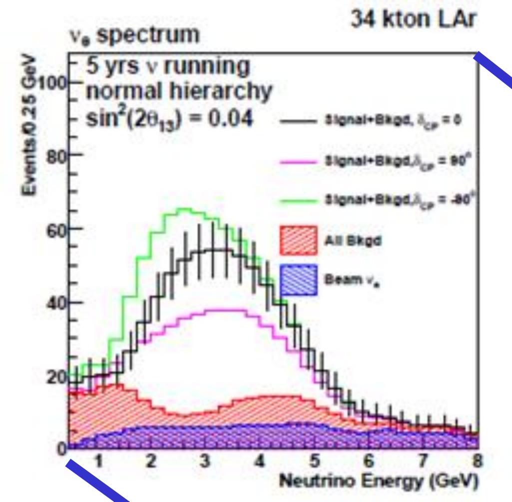
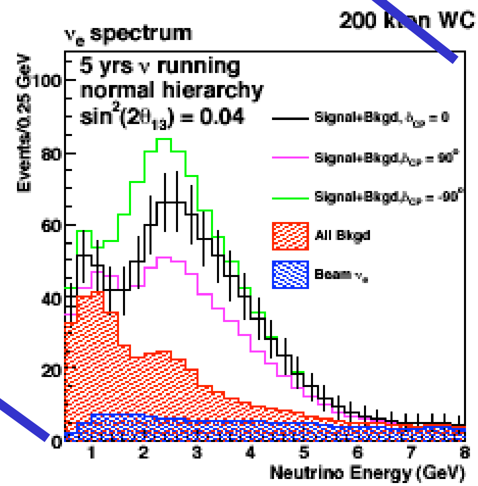
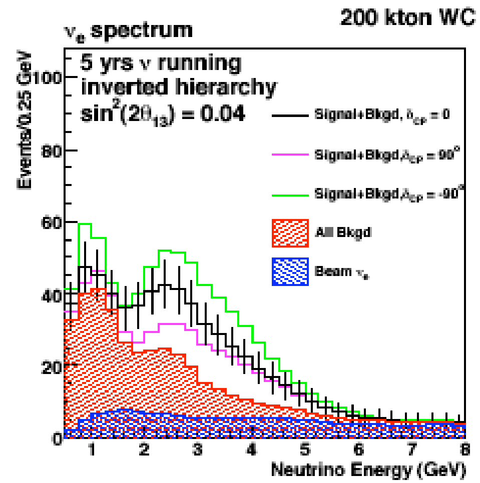


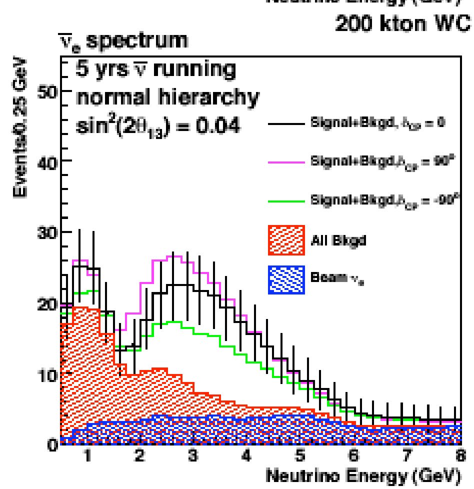
normal | inverted

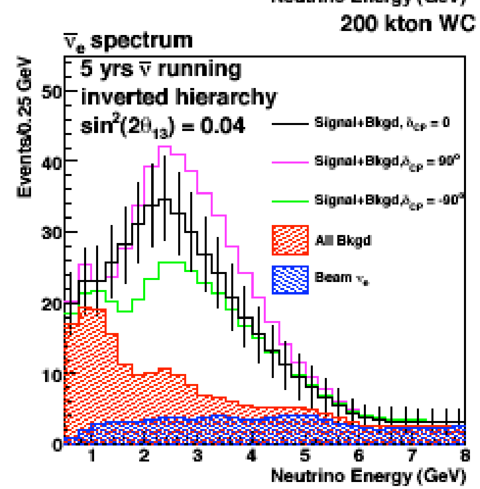
nu





anti-nu

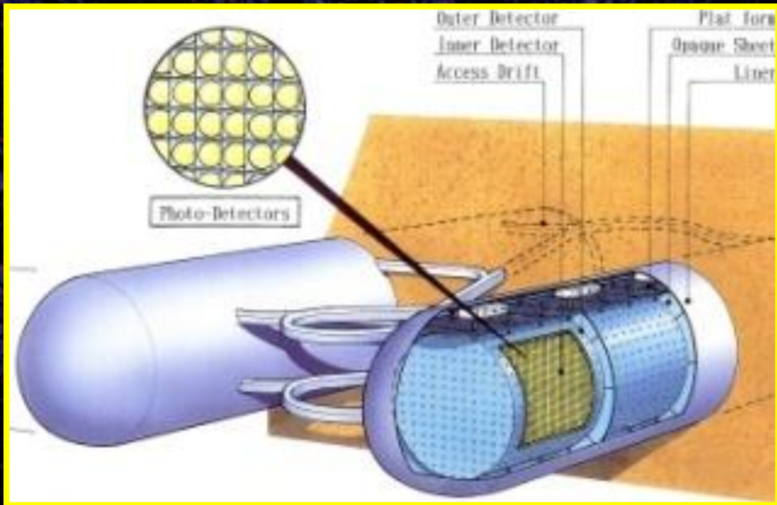




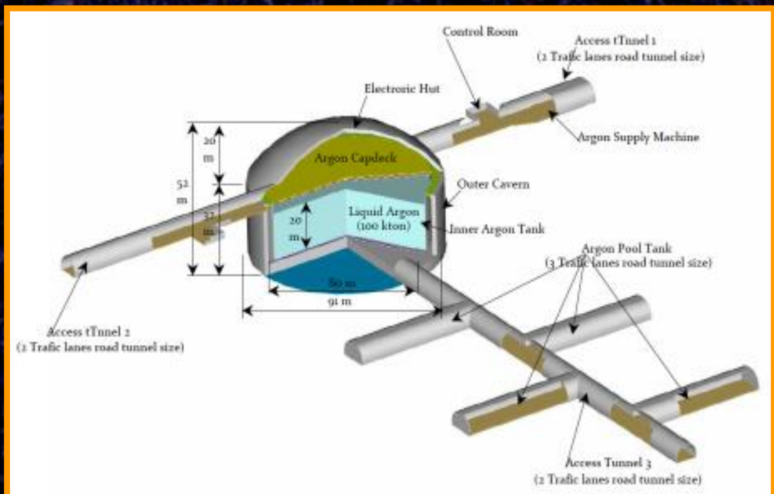
Return ↑

Lisa Whitehead

Scenarios in Japan



Kamioka L=295km OA=2.5deg

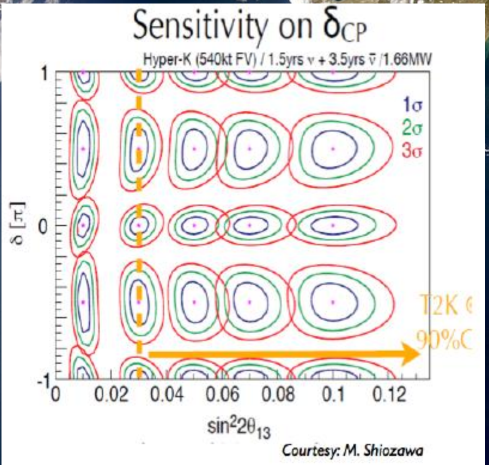


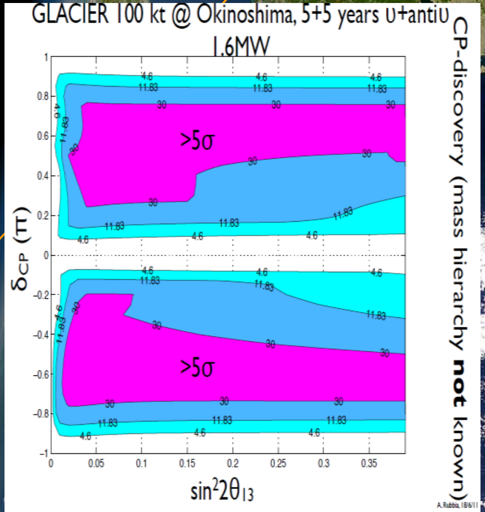
Okinoshima L=658km OA=0.78deg

Almost On-Axis

J-PARC

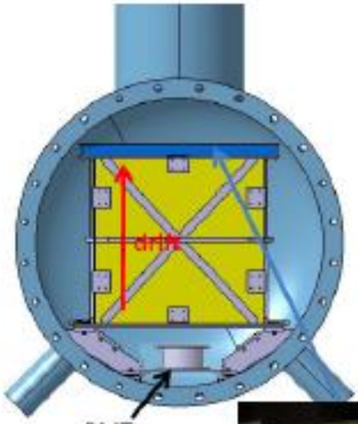
→1.7MW





T32 test beam at J-PARC

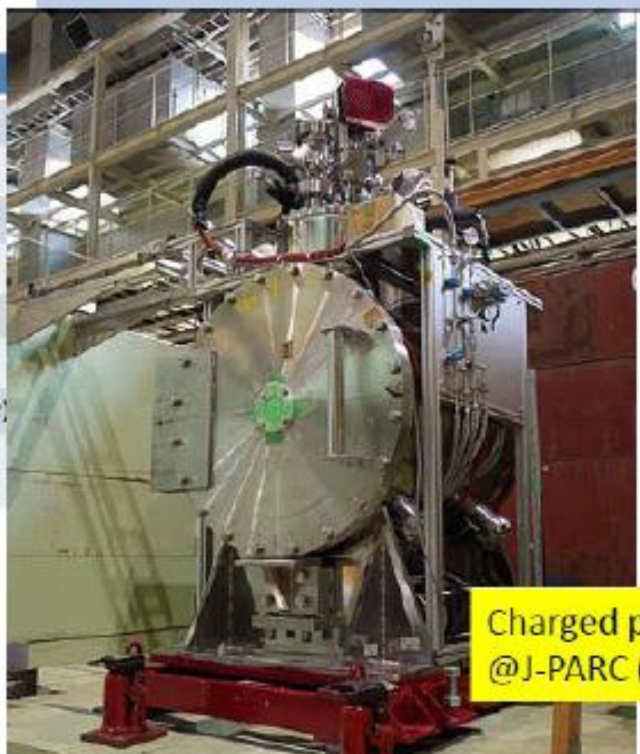
Setup of Oct-2010 test-beam



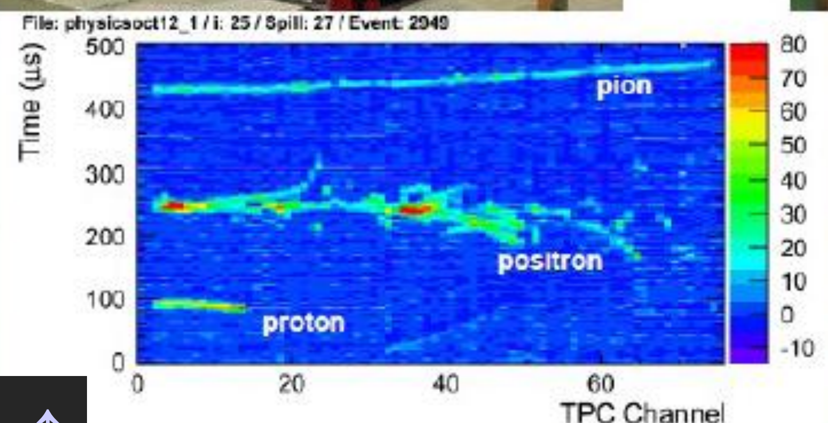
Fiducial mass	170kg
Total LAr mass	~400kg
Field cage dimension	42cm x 42cm x 78cm
Fiducial volume	40cm x 40cm x 76cm
Typical Drift Field	~225V / cm
Maximum drift voltage	12kV
Readout method	single phase (temporary)
Number of readout channels	76 strips (1cm)

76 strips (1cm) anode

- Double phase component is under testing at CERN. (Unfortunately, not in time for the test-beam.)



Charged particle test-beam @J-PARC (Oct/24-31)

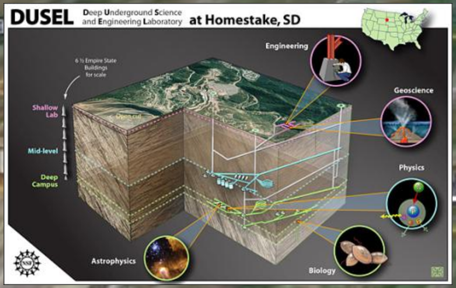


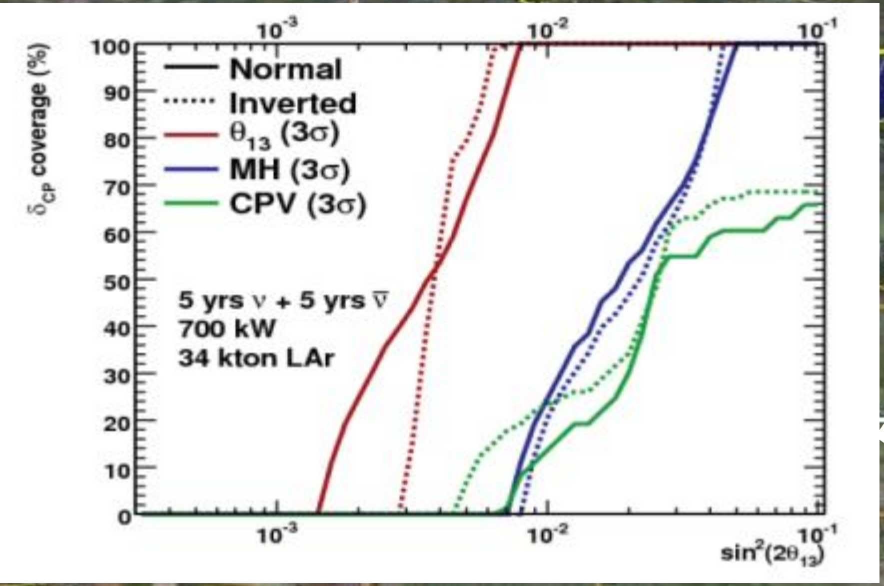
- First beam data taken in Oct/Nov, 2010
- Results will be presented in PAC (Jul.2011)
- Possible beam 2011(?)
- See Maruyama's talk

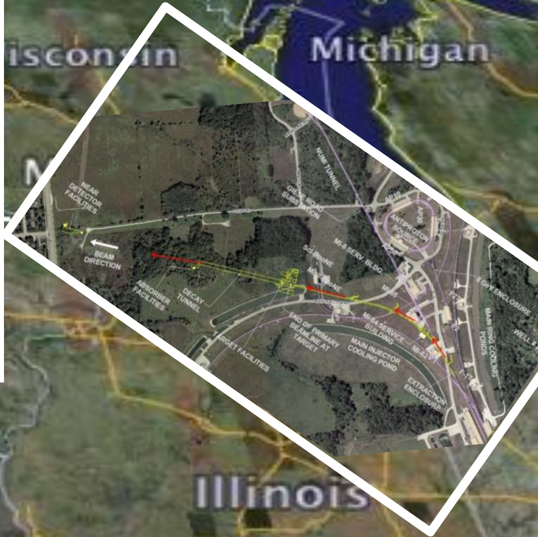
Return ↑

US: Long Baseline Neutrino Experiment

CD 0: January 2010







Collaboration:

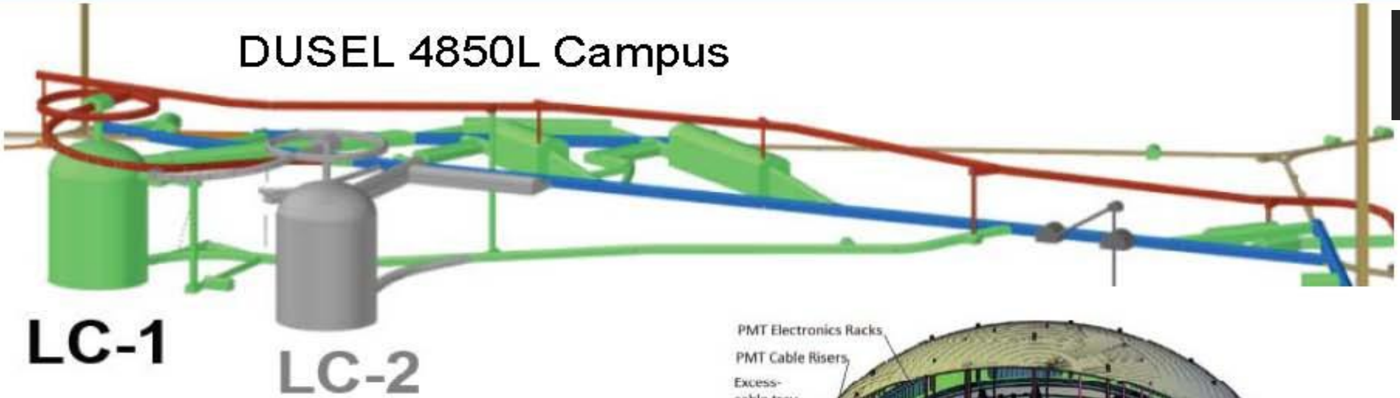
288 members from 54 institutions (India, Italy, Japan, UK, US)

Continue to grow!

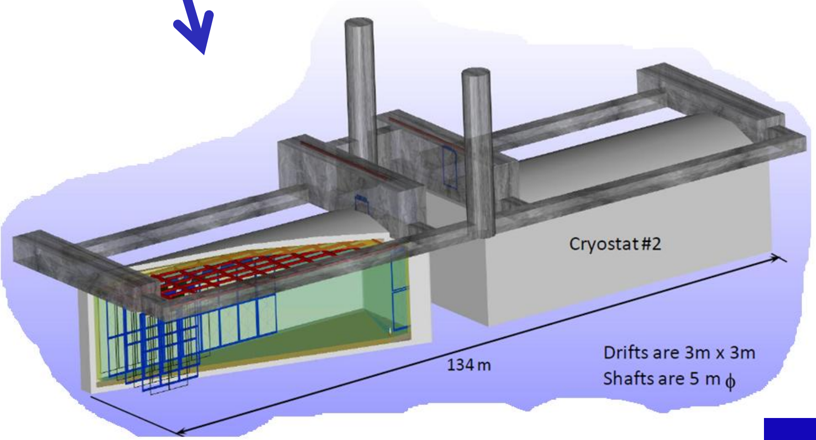
LAr Slight cheaper but riskier – Marx Committee

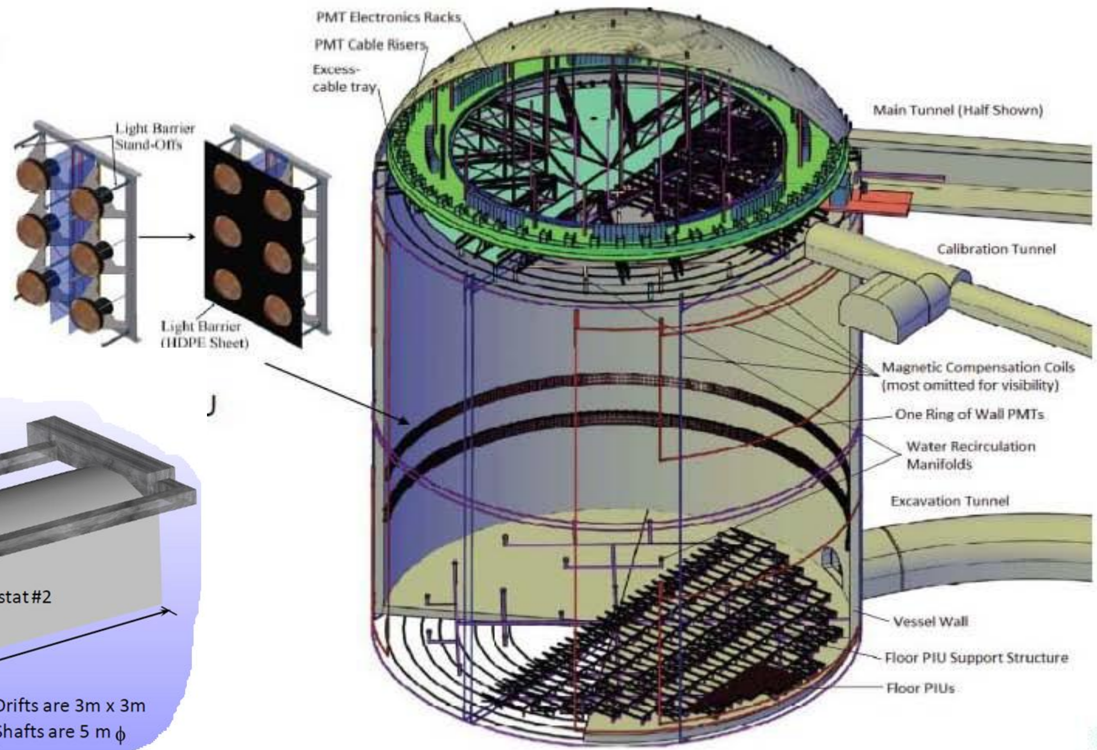
Conceptual Design Overview – Water Cherenkov

Return ↑



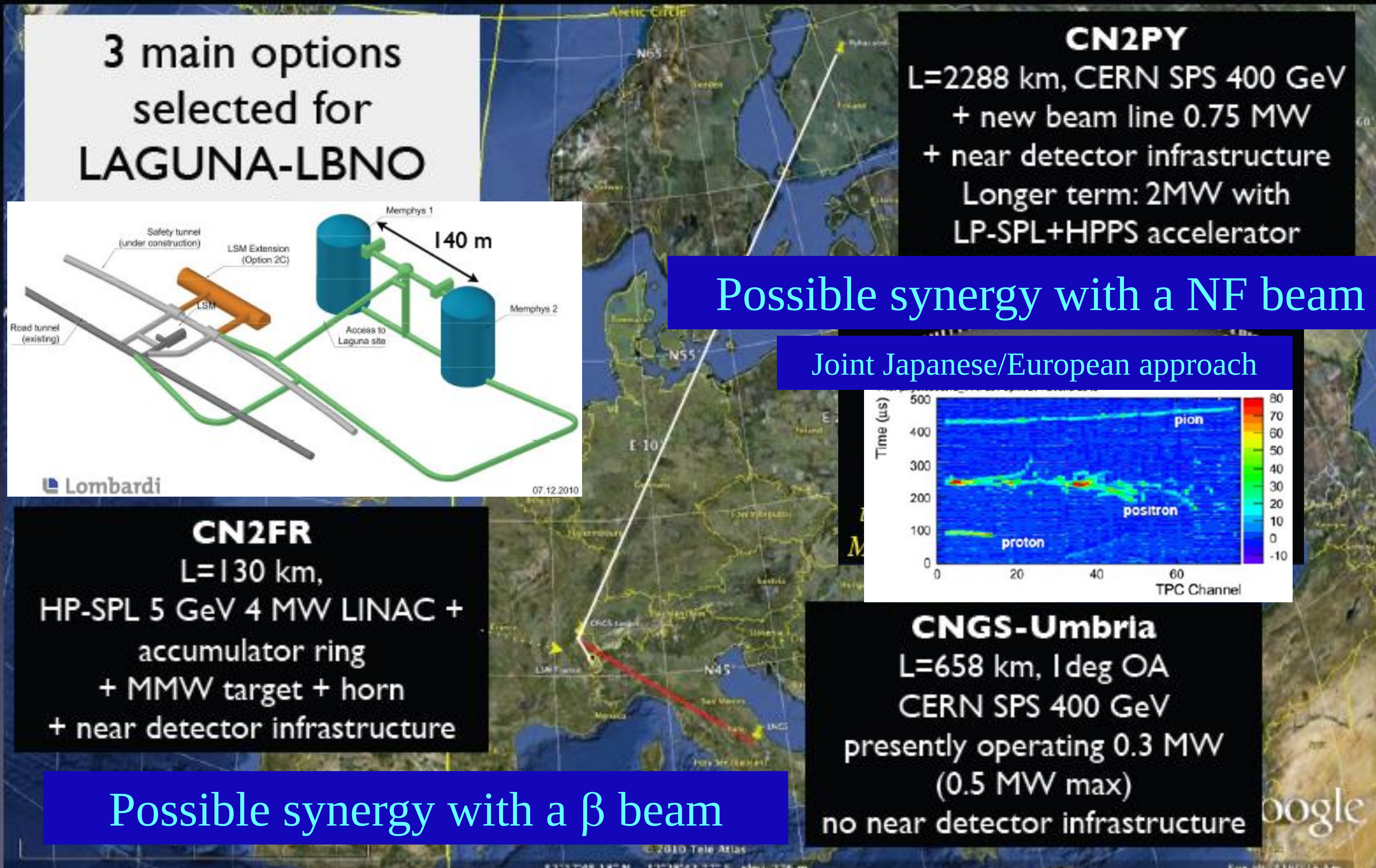
Alternative is 34 kT of LAr





Technology choice underway ....

Three main options



3 main options selected for LAGUNA-LBNO

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

Possible synergy with a NF beam

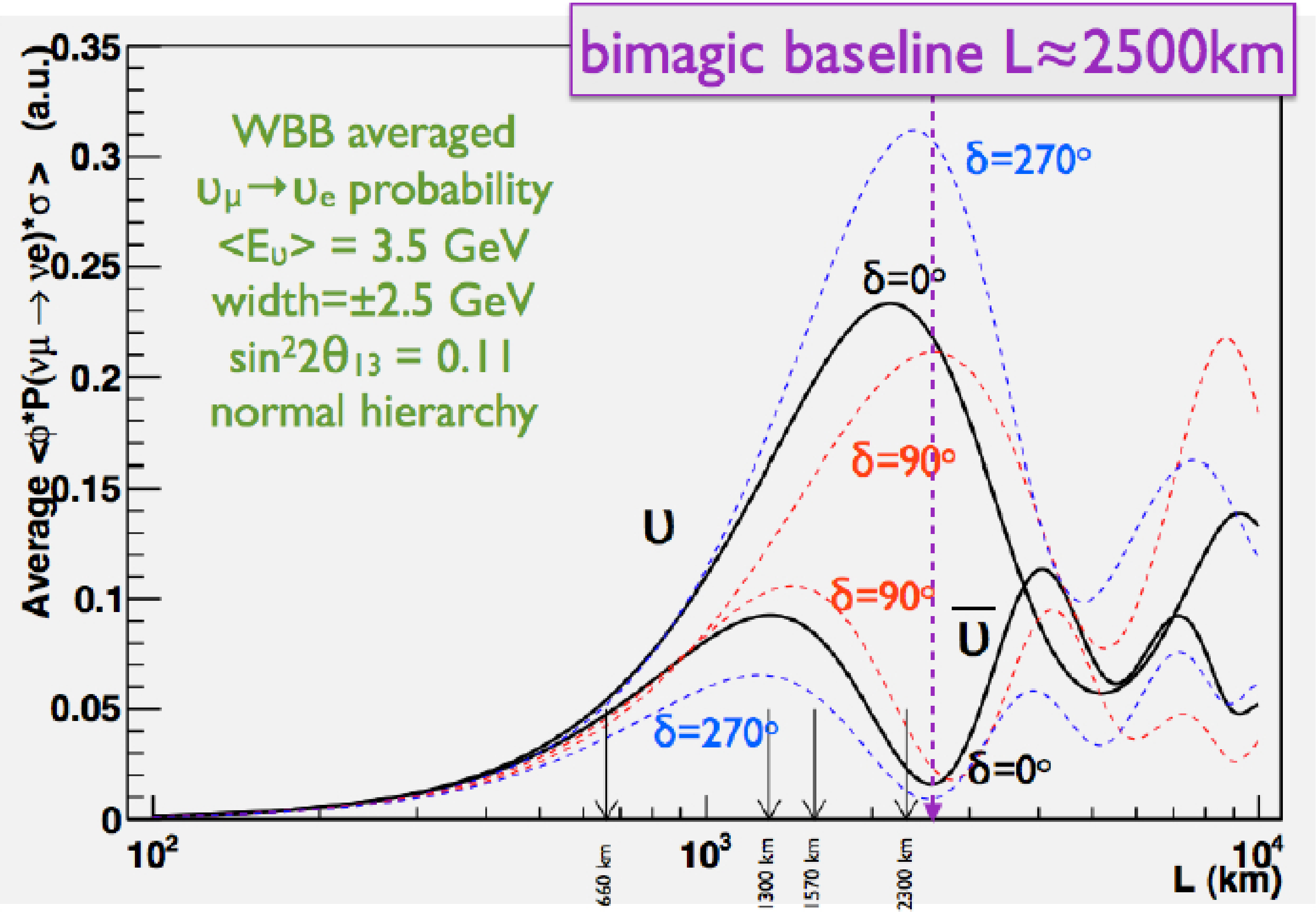
Joint Japanese/European approach

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

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

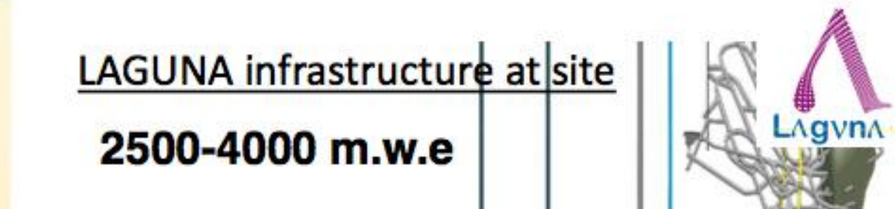
Possible synergy with a β beam

Baseline consideration

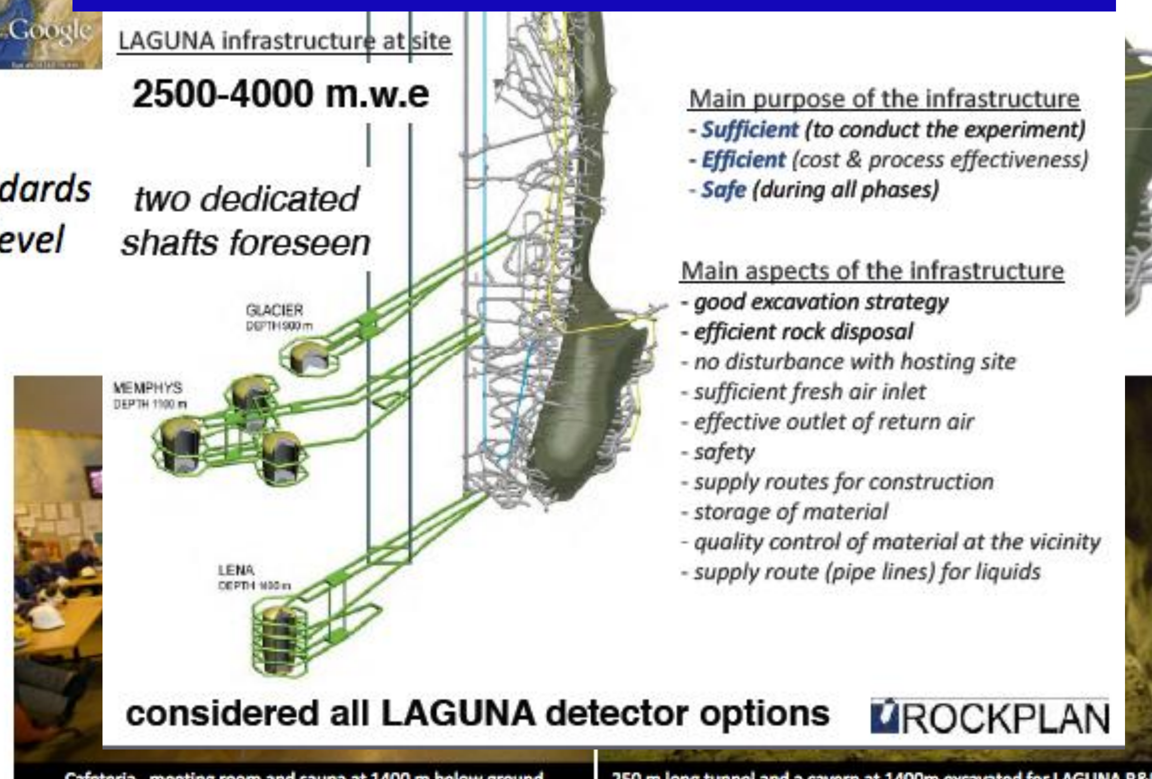


The optimal baselines are in the range 1300-2500 km

LAGUNA Pyhäsalmi w/ GLACIER



LENA + DAEdALUS a complementary way to measure CP violation in neutrino oscillations?



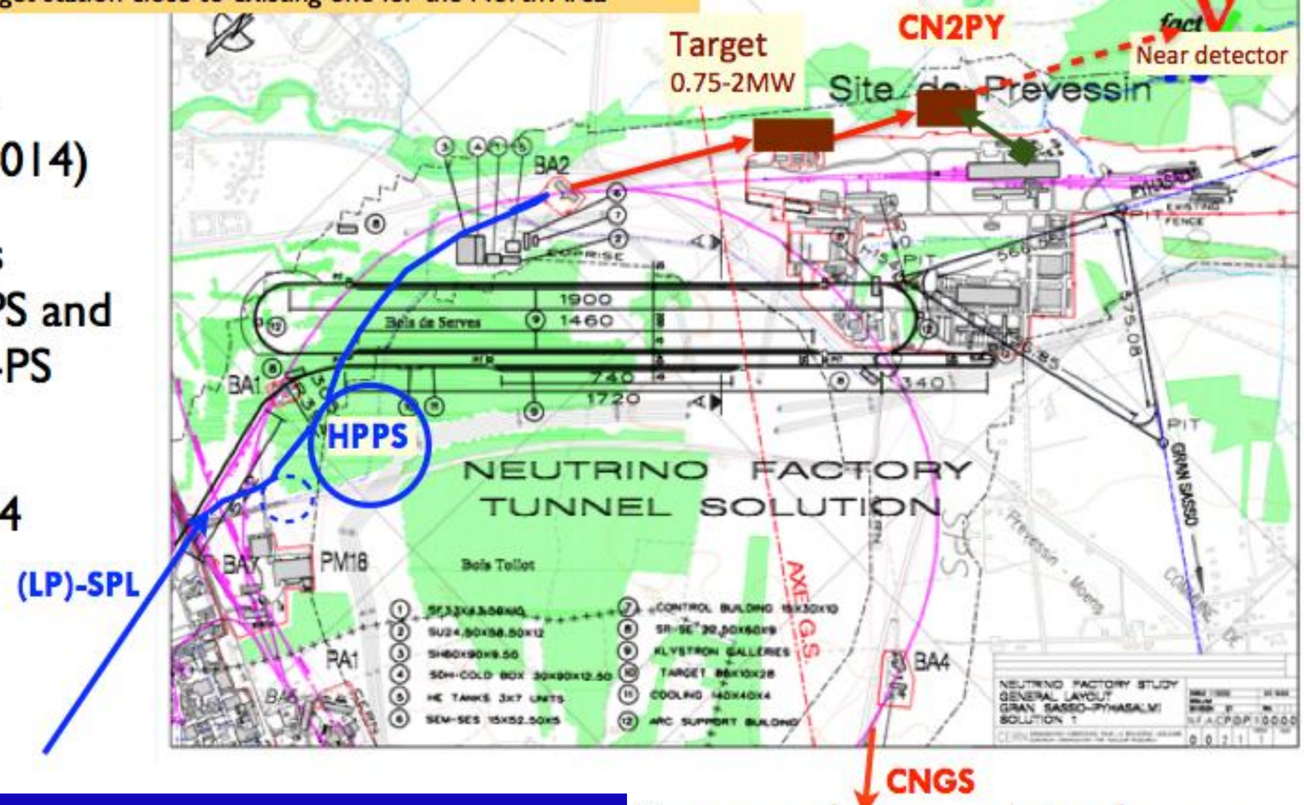
Main aspects of the infrastructure

- *existing working mine with very high standards*
- *existing decline tunnel access to deepest level*
- *excellent excavation strategy*
- *efficient rock disposal*
- *no disturbance with hosting site*
- *sufficient fresh air inlet*
- *effective outlet of return air*
- *safety*
- *supply routes for construction*
- *storage of material*
- *quality control of material at the vicinity*
- *supply route (pipe lines) for liquids*

CERN new conventional beams option

Option B:
Target station close to existing one for the North Area

- Feasibility of new beams approved by CERN study (LAGUNA-LBNO/2011-2014)
- New beam facility accepts protons from 400 GeV SPS and eventual new 50 GeV HP-PS
- Will produce conceptual design reports within 2014

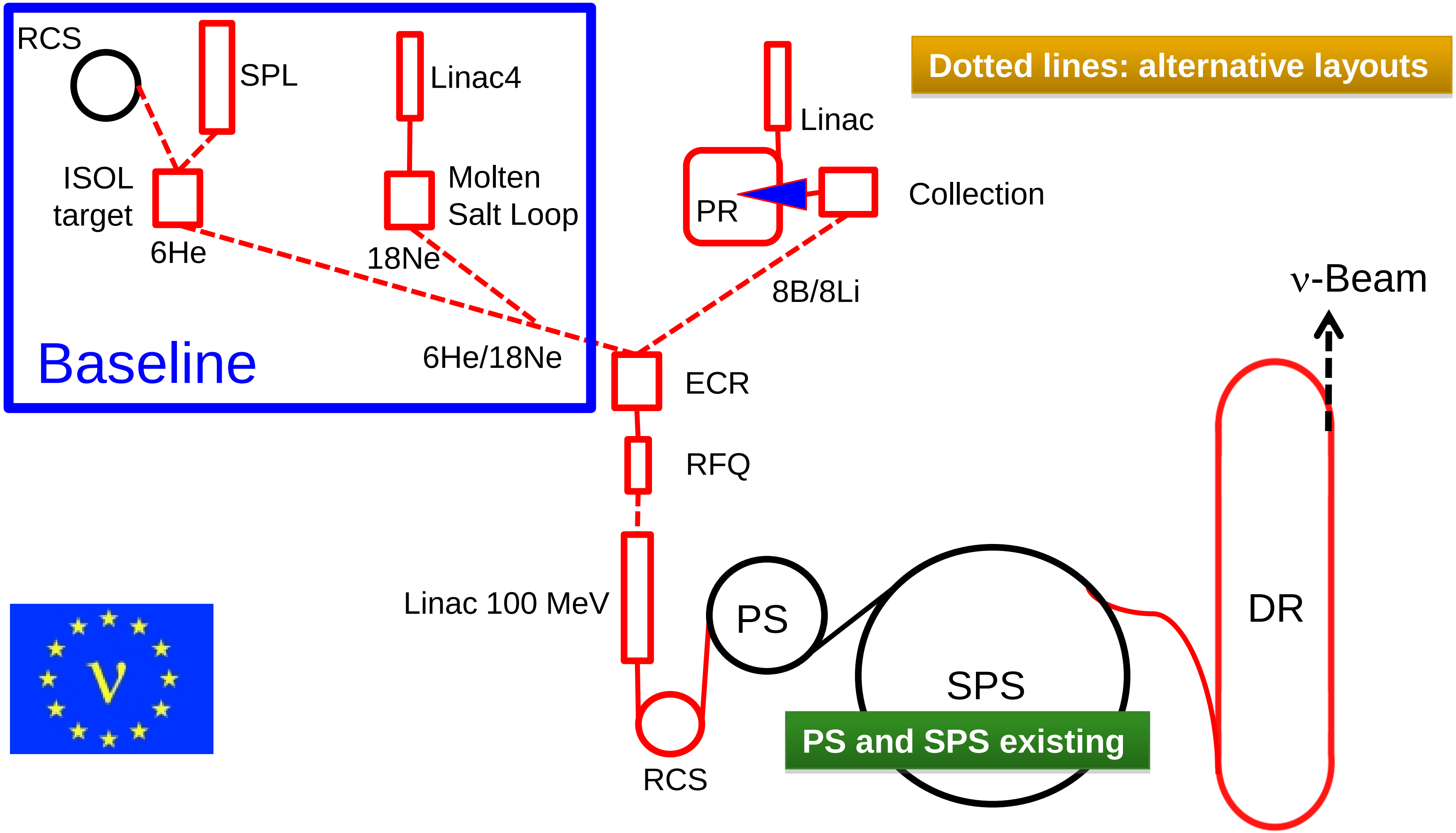


- **Task** … sity upgrade to neutrino beams
- **Task**
- **Task** … m
- **Task**
- **Task** … out at CERN
- **Task** … GUNA detector
- **Task 4.7** Definition of near detector requirements and development of conceptual design

Exploring within LAGUNA-LBNO an LoI for a 10 kT LAr with a muon ranger combined with a new beam in the NA.

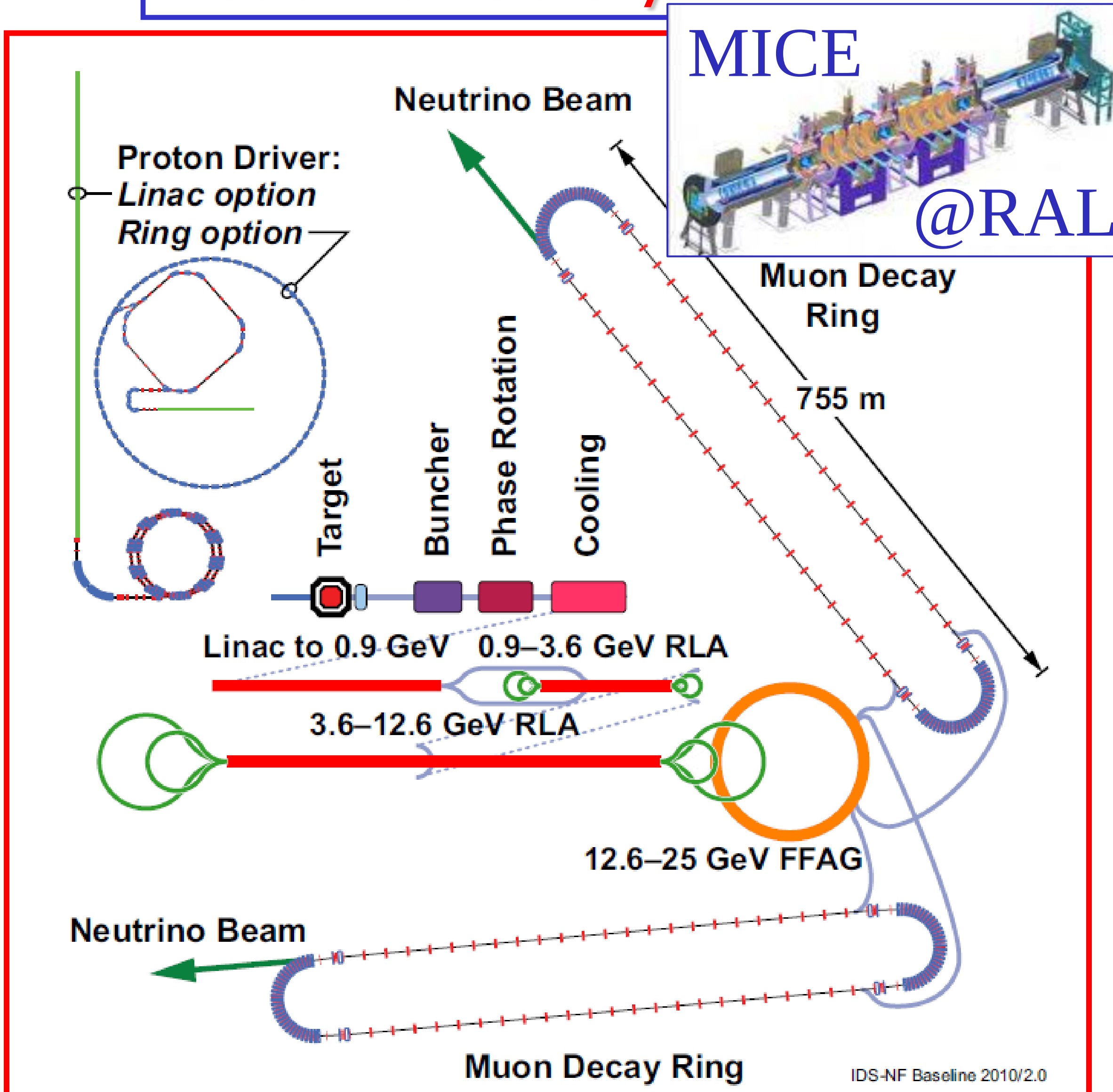
Return ↑

CERN Beta Beams, Synoptic



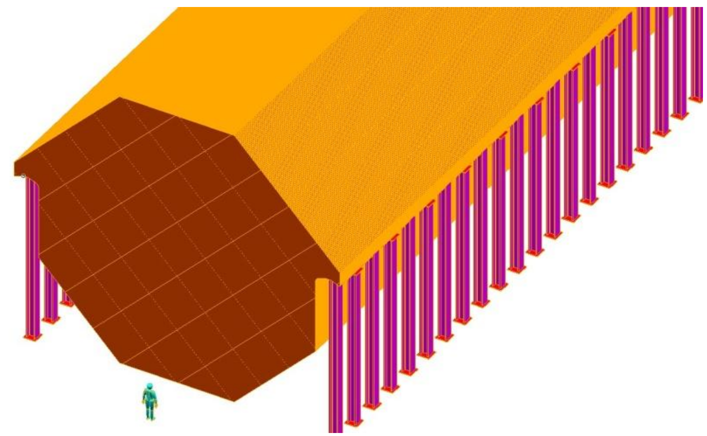
Decay Ring: Bρ ~ 500 Tm, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

Neutrino Factory Baseline

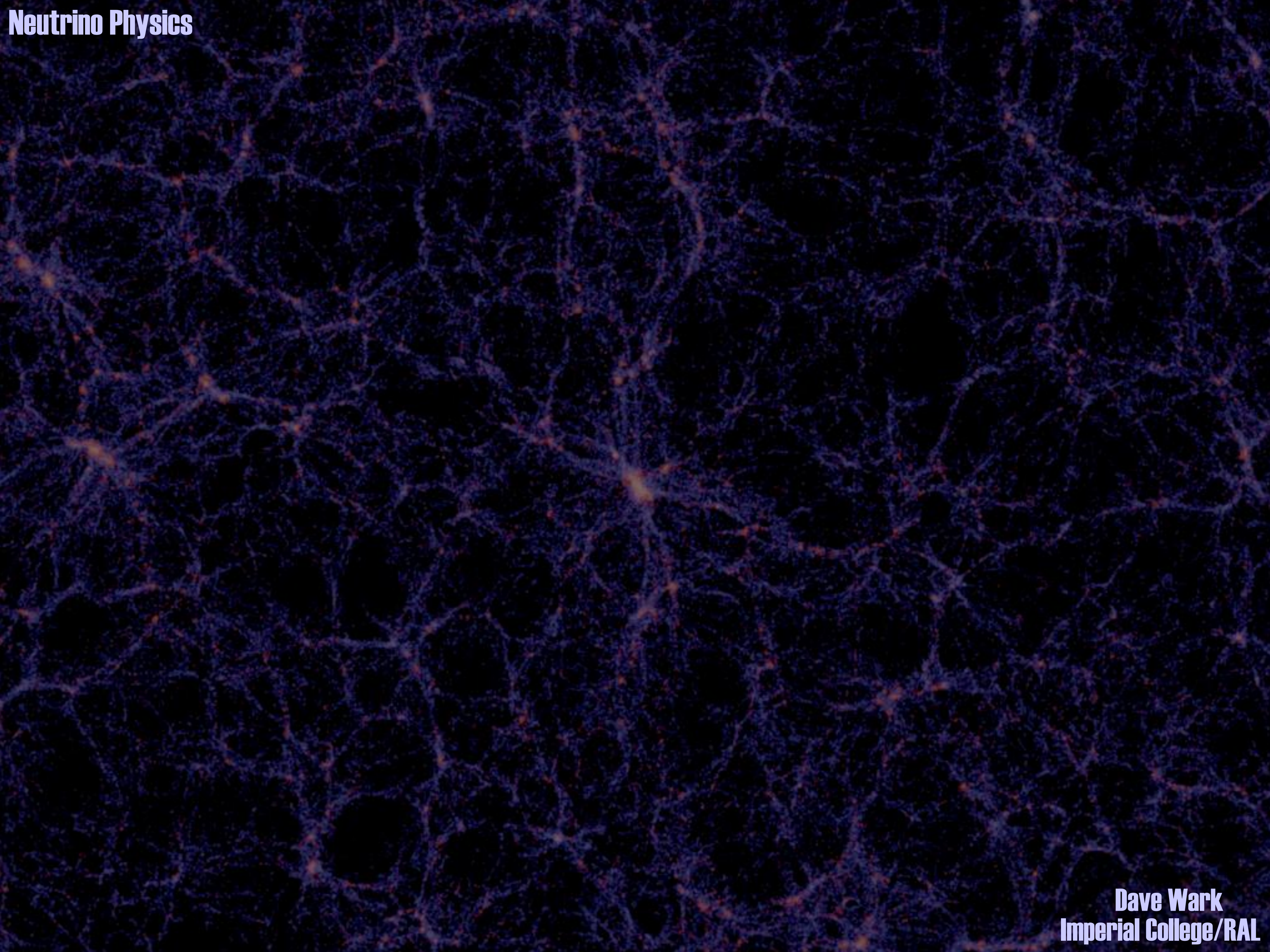


Two Magnetised Iron Neutrino Detectors (MIND):

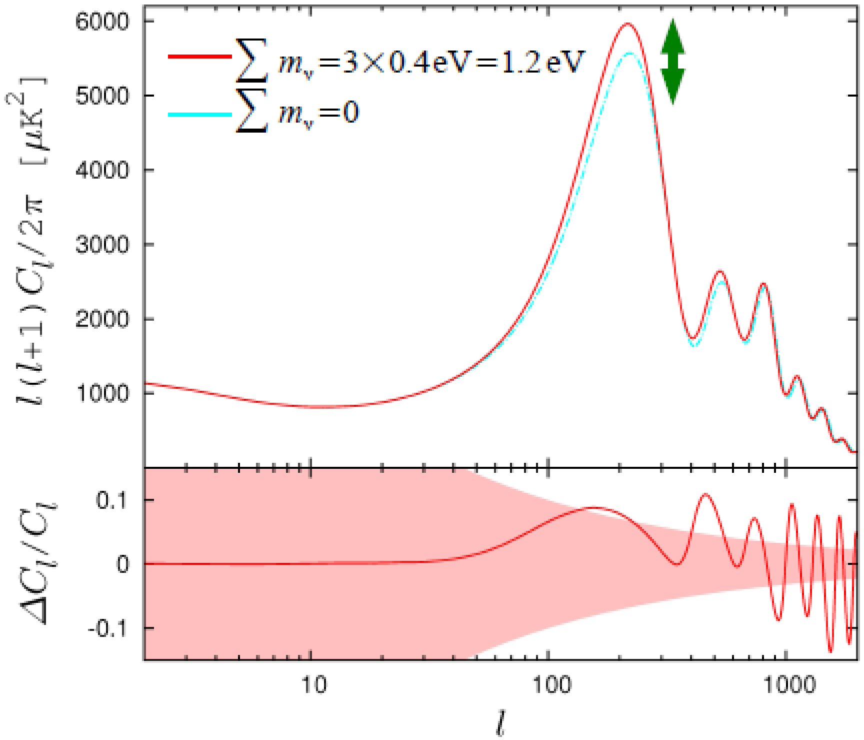
- 100 kton at 2500-5000 km
- 50 kton at 7000-8000 km

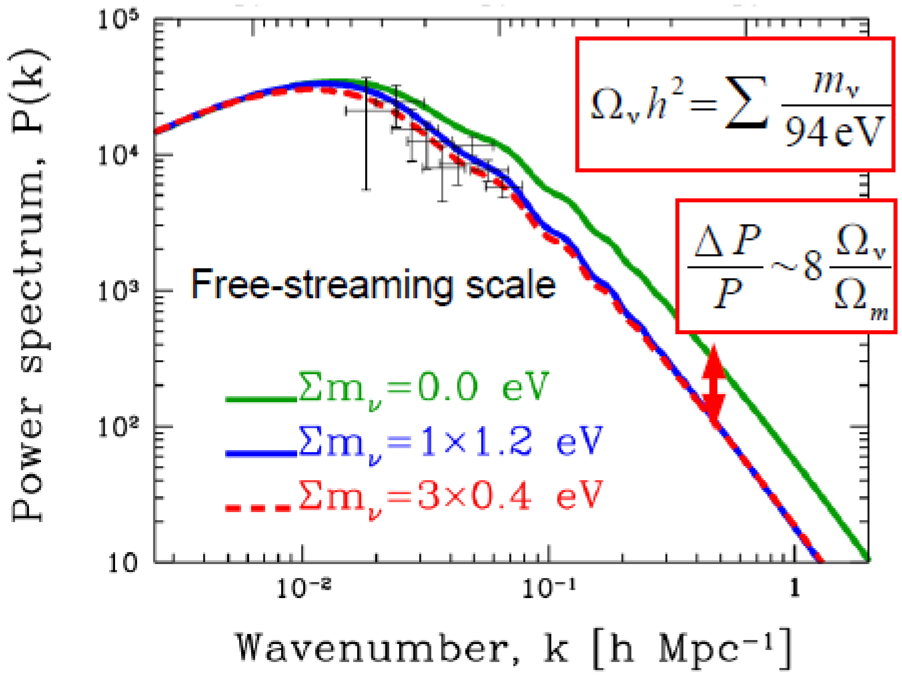


Baseline constantly under review in light of new physics results


Neutrino Physics
Dave Wark
Imperial College/RAL

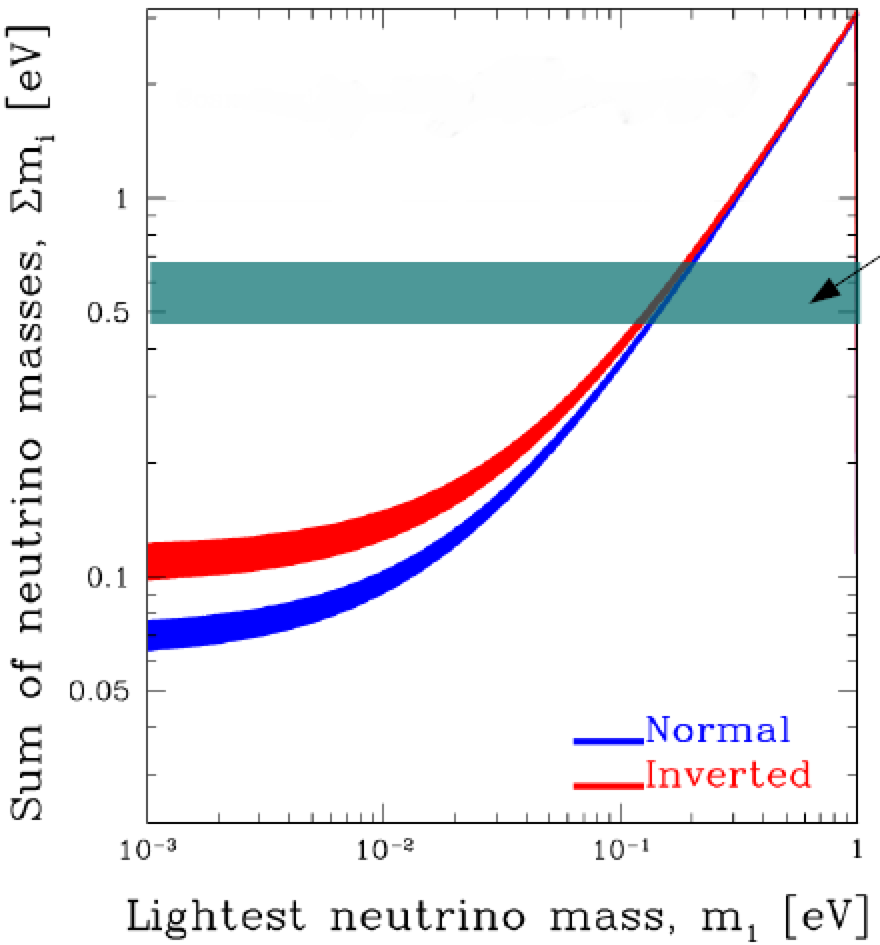
- **CMB** probes the relativistic to non-relativistic transition of neutrinos via the early ISW effect.
- **LSS** measures suppression of power on small scales due to non-clustering neutrinos.





Slide from Yvonne Wong's talk at TAUP '11

Present constraints...



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ HST+SNIa

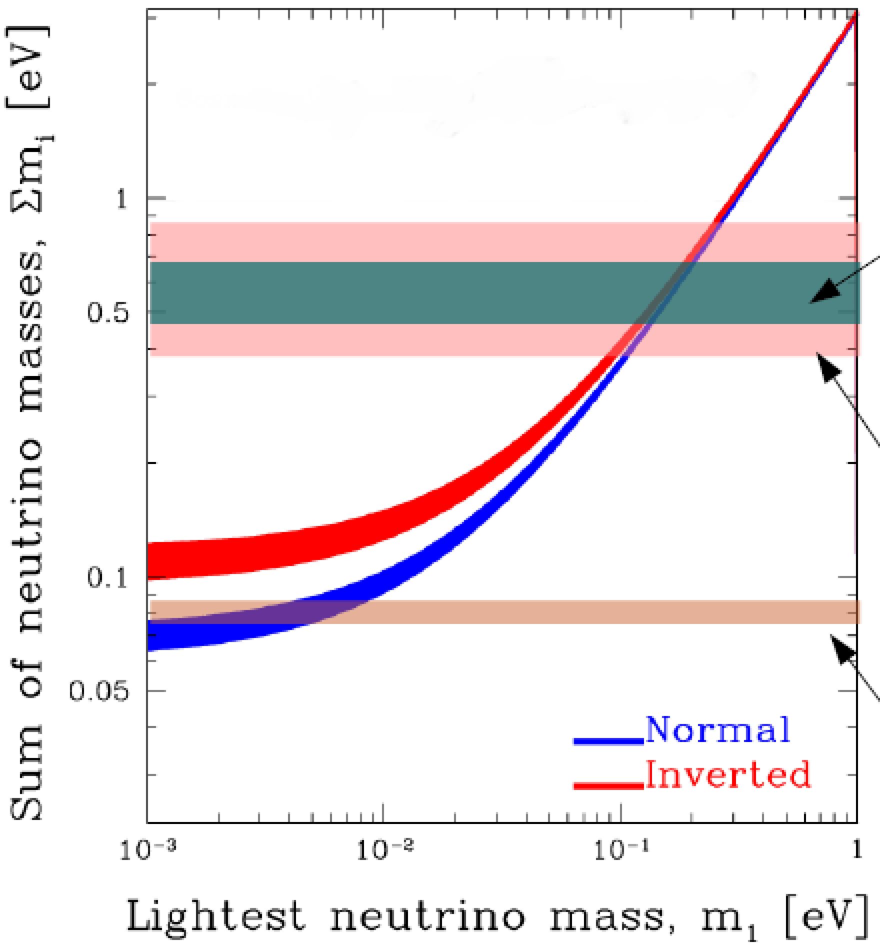
$$\sum m_\nu < 0.44 \rightarrow 0.76\,\text{eV} \quad (95\%\,\text{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y[3]W 2010
Gonzalez-Garcia et al. 2010, etc.

Slide from Yvonne Wong's talk at TAUP '11

Present constraints and future sensitivities...



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ HST+SNIa

$$\sum m_\nu < 0.44 \rightarrow 0.76\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y[3]W 2010
Gonzalez-Garcia et al. 2010, etc.

Planck alone (1 year)

$$\sum m_\nu < 0.38 \rightarrow 0.84\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

Perotto et al. 2006

Planck+Weak lensing (LSST)

$$\sum m_\nu < 0.074 \rightarrow 0.086\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

Hannestad, Tu & Y[3]W 2006

Slide from Yvonne Wong's talk at TAUP '11

If you are measuring a mass, you must

VOLUME 67, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1991

Correspondence of Electron Spectra from Photoionization and Nuclear Internal Conversion

D. L. Wark,[a] R. Bartlett, T. J. Bowles, R. G. H. Robertson, D. S. Sivia, W. Trela, and J. F. Wilkerson
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

G. S. Brown
Stanford Synchrotron Radiation Laboratory, P.O. Box 4349, Bin 69, Stanford, California 94305

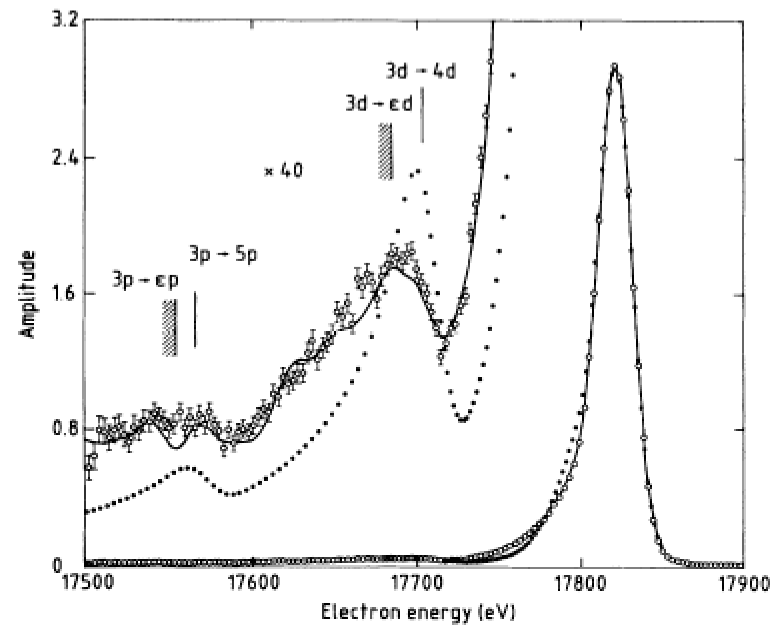
B. Crasemann, S. L. Sorensen,[b] and S. J. Schaphorst
Physics Department, University of Oregon, Eugene, Oregon 97403

D. A. Knapp and J. Henderson
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

J. Tulkki and T. Åberg
Laboratory of Physics, Helsinki University of Technology, 02150 Espoo, Finland

Electron energy spectra have been
mechanisms: (1) photoionization and
It is demonstrated experimentally th
primary 1*s*-electron peak, are identi
given. The spectra agree well with a
tributed to excitation and ionization c

PACS numbers: 32.80.Fb, 23.20.Nx



VOLUME 67, NUMBER

Limit

R. G. H.

TABLE II. Contri
1 standard deviation.

Analysis (thr	
Statistics	
Beta monit	
Energy loss:	
18% in theo	
5% uncertai	
Resolution:	
Variance of response function	5
Tail	15
Final States:	
Differences between theories	8
Limited configuration space	10
Sudden approximation	2
Apparatus efficiency:	
Linear vs quadratic	32
Total	79

Dave Wark
Imperial College/RAL

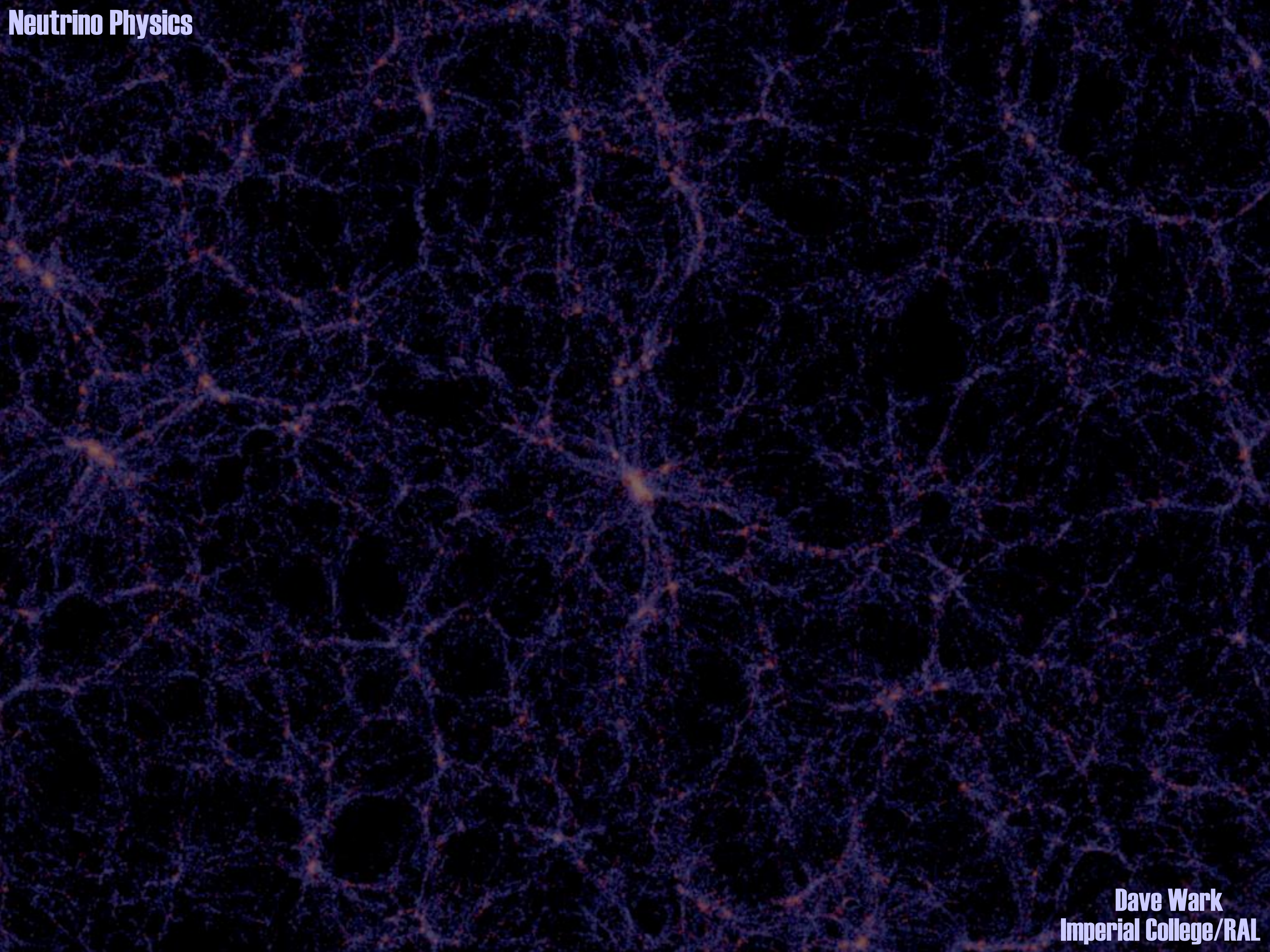
SNO Systematic Flux Uncertainties

Error Source	CC error (%)	ES error (%)
Energy scale	-5.2, +6.1	-3.5, +5.4
		±0.3
		±0.4
		±3.3
		±0.4
		±2.2
		-1.9, +0.0
Low energy background	-0.2, +0.0	-0.2, +0.0
Instrumental background	[illegible]	[illegible]
Trigger efficiency	[illegible]	[illegible]
Live time	[illegible]	[illegible]
Cut acceptance	[illegible]	[illegible]
Earth orbit eccentricity	[illegible]	[illegible]
^{17}O, ^{18}O	[illegible]	[illegible]
Experimental uncertainty	[illegible]	[illegible]
Cross-section	3.0	0.5
Solar Model	-16, +20	-16, +20

Unless a real error analysis is done for astrophysical mass "limits" they cannot really be considered equivalent to laboratory limits.

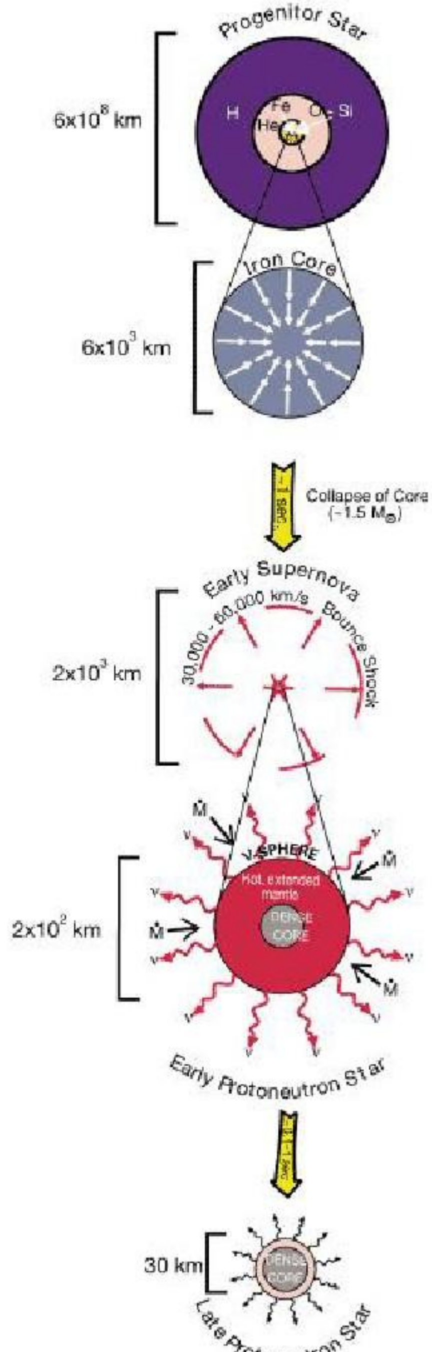
In any case, using precious cosmological data to constrain m_ν would be like using LEP as a tide gauge.

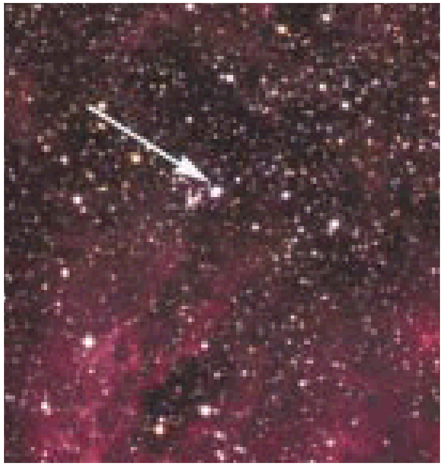
Return ↑



Neutrino Physics

Dave Wark
Imperial College/RAL



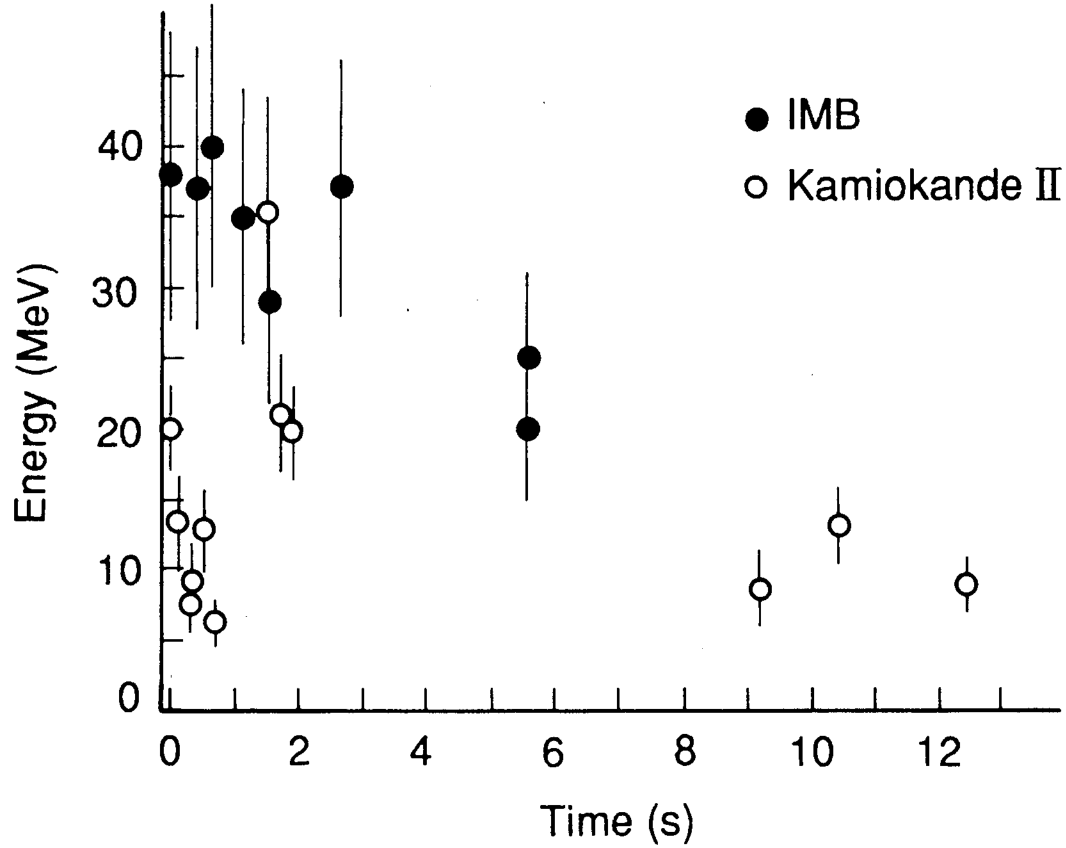


February 1984

March 8,1987

A supernova converts $\sim 1\ M_\odot$ to ν

$$|\Delta t| = \frac{1}{2} L m_\nu^2 \frac{\left|E_1^2 - E_2^2\right|}{E_1^2 E_2^2}$$



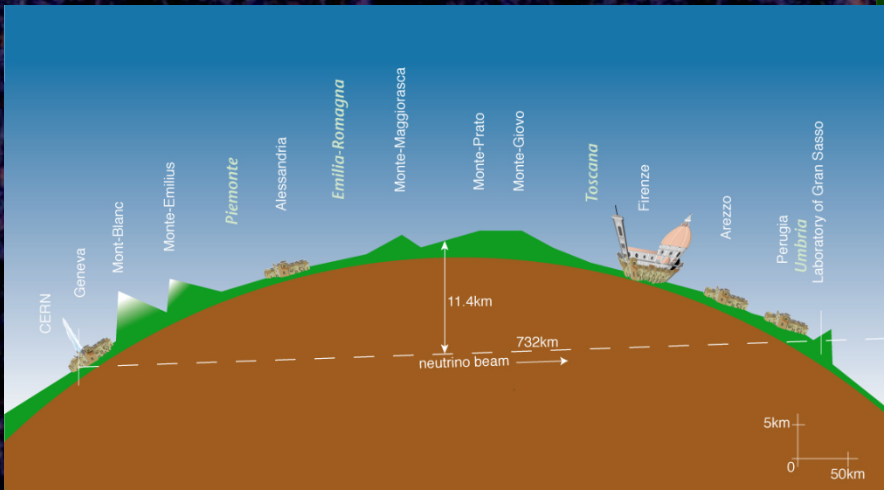
Limit from SN1987a is m_{ν_e} > 23 eV (PDG)

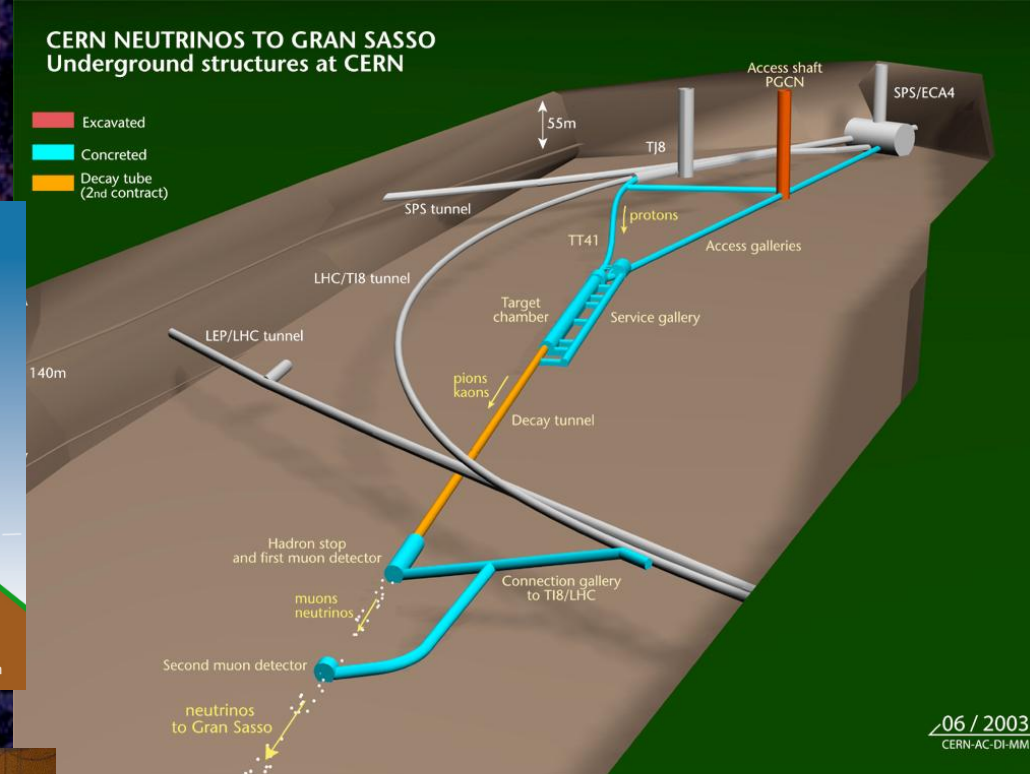
Best you can do is ~5-10 eV, which isn't good enough

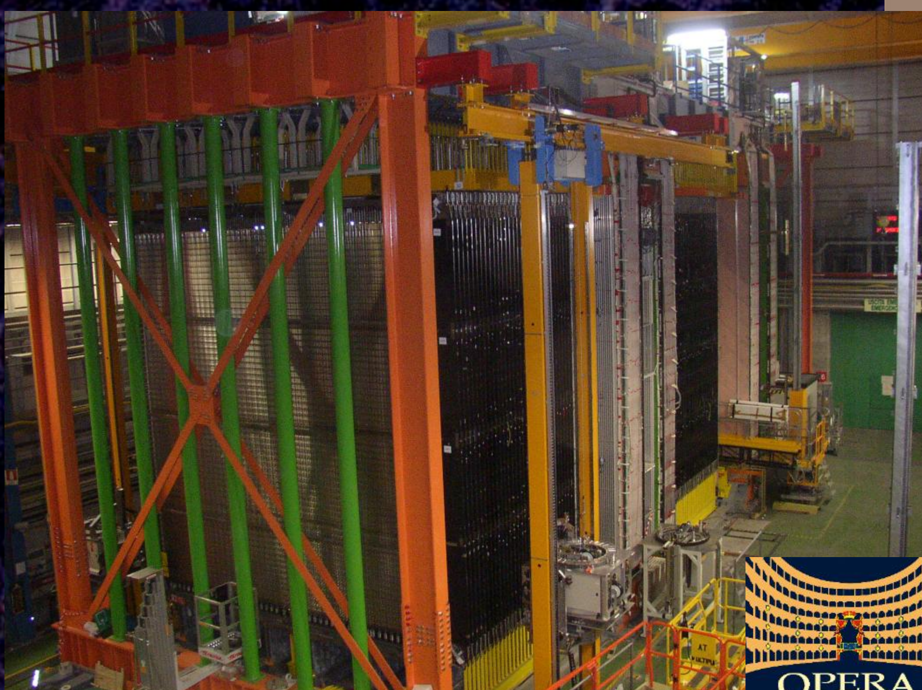
Light and neutrinos got here on the same day after travelling for ~160k yrs, so $|v_\nu - c|/c < 2\times10^{-9}$ at $E_\nu \sim 10$ MeV

Return ↑

Neutrino Physics





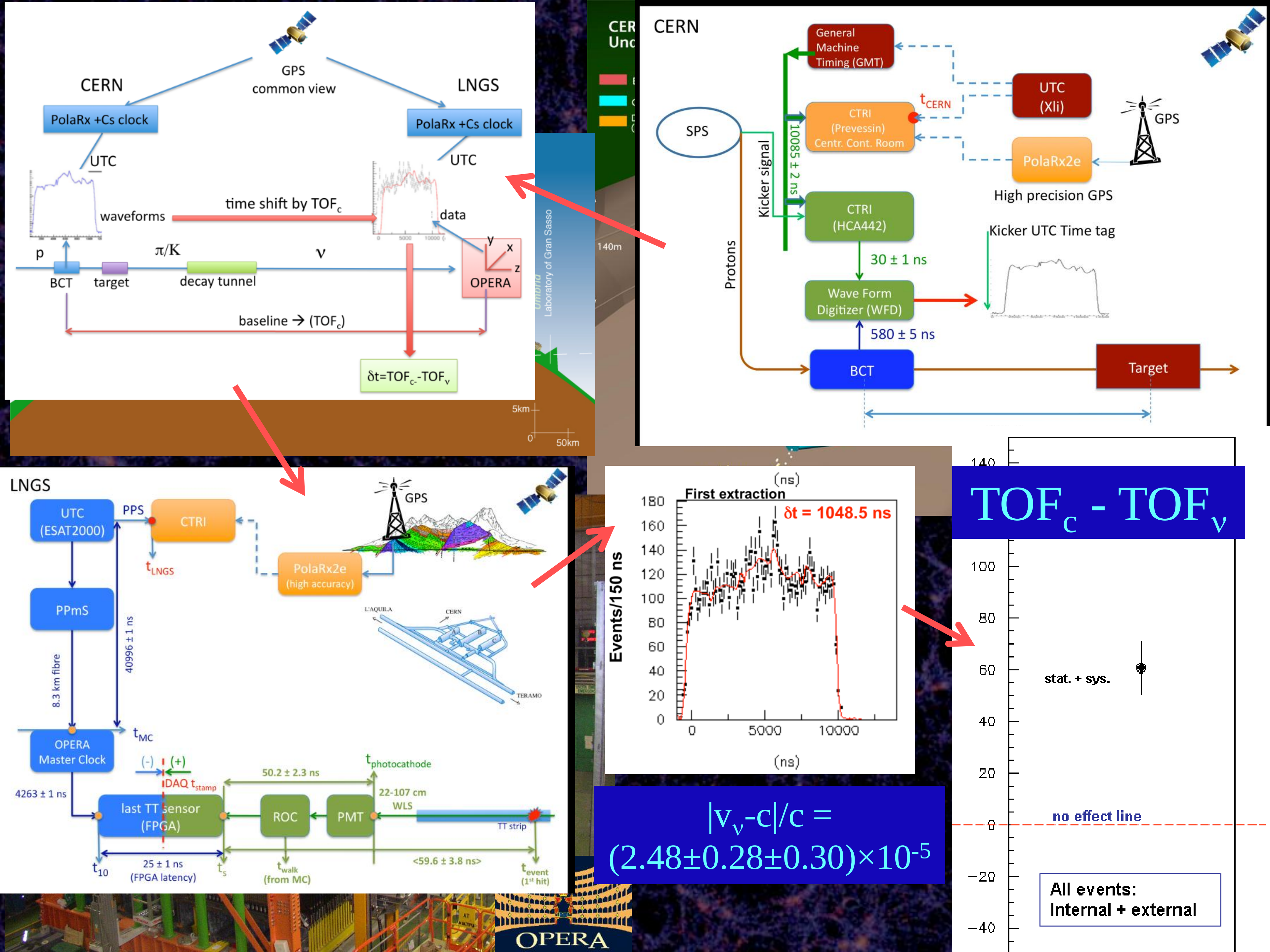


Dusini at EPS

OPERA τ appearance event....

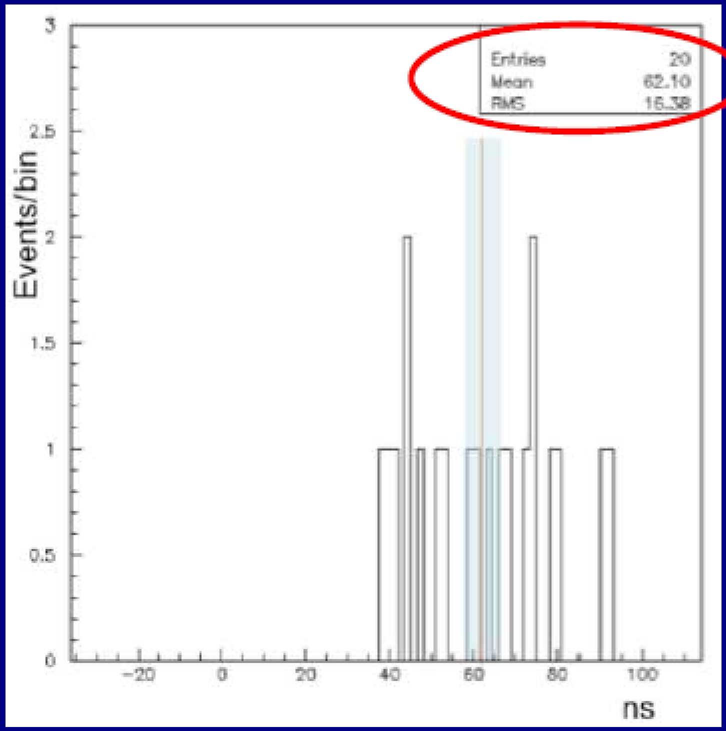
.... has no friends yet. Expect 1.65±0.16

Phys. Lett. B 691 (2010) 138-145



CERN
GPS
common view
LNGS
PolaRx +Cs clock
UTC
waveforms
time shift by TOF_c
data
p
π/K
ν
BCT
target
decay tunnel
OPERA
baseline → (TOF_c)
δt=TOF_c-TOF_ν
General Machine Timing (GMT)
UTC (XLi)
CTRI (Prevessin) Centr. Cont. Room
t_CERN
SPS
Kicker signal
10085 ± 2 ns
PolaRx2e
High precision GPS
CTRI (HCA442)
30 ± 1 ns
Kicker UTC Time tag
Protons
Wave Form Digitizer (WFD)
580 ± 5 ns
BCT
Target
UTC (ESAT2000)
PPS
CTRI
t_LNGS
PolaRx2e (high accuracy)
PPmS
40996 ± 1 ns
8.3 km fibre
t_MC
OPERA Master Clock
(-) (+)
DAQ t_stamp
4263 ± 1 ns
last TT sensor (FPGA)
ROC
PMT
50.2 ± 2.3 ns
t_photocathode
22-107 cm WLS
TT strip
t_10
25 ± 1 ns (FPGA latency)
t_s
t_walk (from MC)
<59.6 ± 3.8 ns>
t_event (1st hit)
L'AQUILA
CERN
TERAMO
First extraction
δt = 1048.5 ns
Events/150 ns
(ns)
TOF_c - TOF_ν
stat. + sys.
no effect line
All events: Internal + external
|v_ν-c|/c = (2.48±0.28±0.30)×10^-5
OPERA

Results with a short-bunch wide-spacing beam



20 events exploitable for TOF measurement

Individual TOF measurement/event

4 bunches/extraction ~3 ns

62.1 ns average TOF, 16.4 ns RMS

RMS dominated by instrumental resolution in relating the DAQ clock 20 MHz to GPS sync signal (+-25 ns jitter)

Thise result excludes overall biases affecting the PDF based analysis

$\delta t = TOF_c - TOF_\nu = (62.1 \pm 3.7\ (\text{stat.}))$ ns

Statistical analysis based on PDF: $\delta t = (57.8 \pm 7.8\ (\text{stat.}))$ ns
Comparable or smaller systematics than statistical measurement

This narrow beam structure will allow Borexino, ICARUS, and LVD to measure δt as well.

Dave Wark
Imperial College/RAL

Improving the MINOS measurement

Current measurement:

$$\delta = -126 \pm 32(\text{stat.}) \pm 64(\text{syst.})\ \text{ns} \quad 68\%\text{C.L.}$$

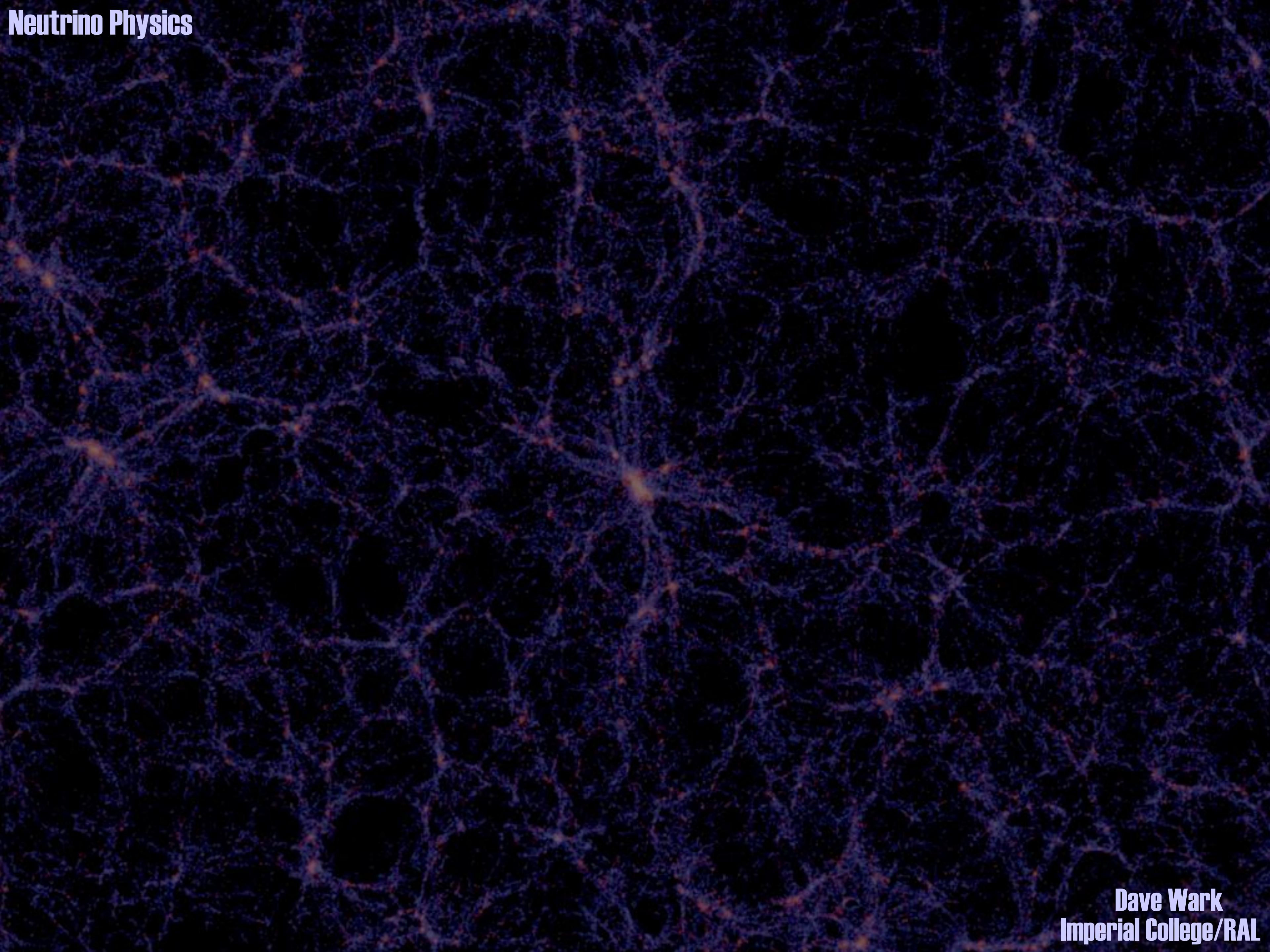
Now have nine times more data

- But the measurement was systematically limited

Three-phase approach to future analysis

Phase 1	Phase 2	Phase 3
6 months	12 months	2013 onwards
Re-analyse existing data, reducing dominant uncertainties	Hardware improvements for 2012 data taking	Further hardware improvements Beam energy and intensity upgrades
18–33 ns sys. uncertainty	11–18 ns sys. uncertainty	2–7 ns sys. uncertainty

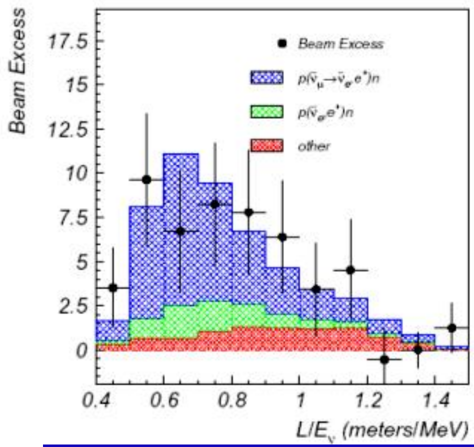
Return ↑



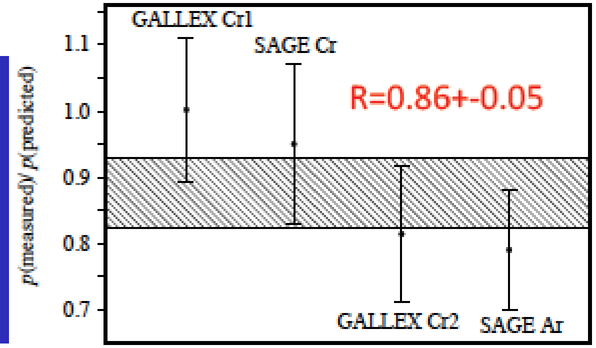
Neutrino Physics

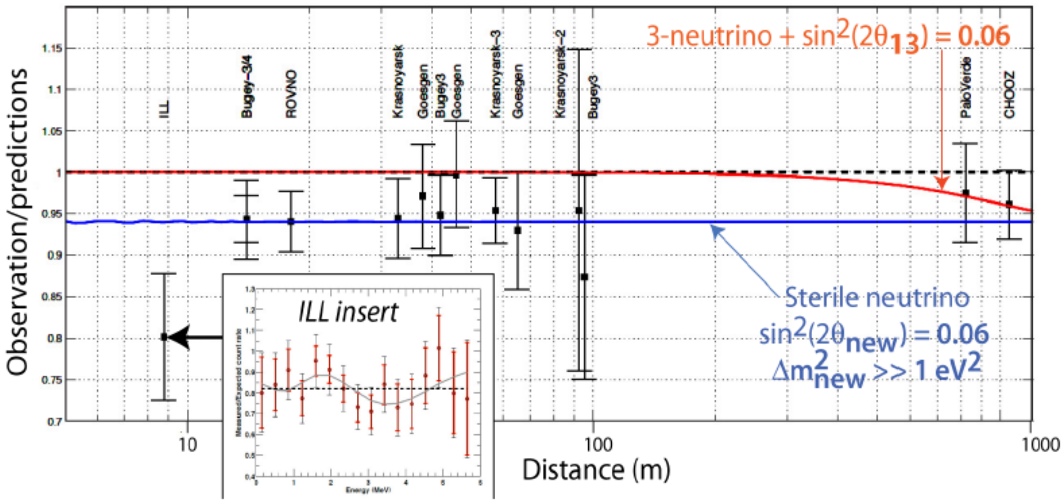
Dave Wark
Imperial College/RAL

LSND Starts it all...

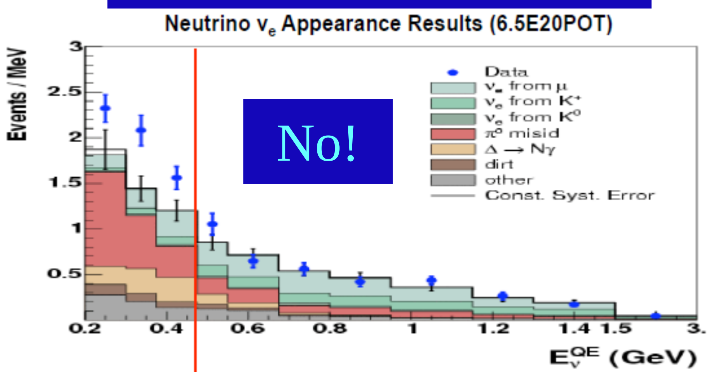


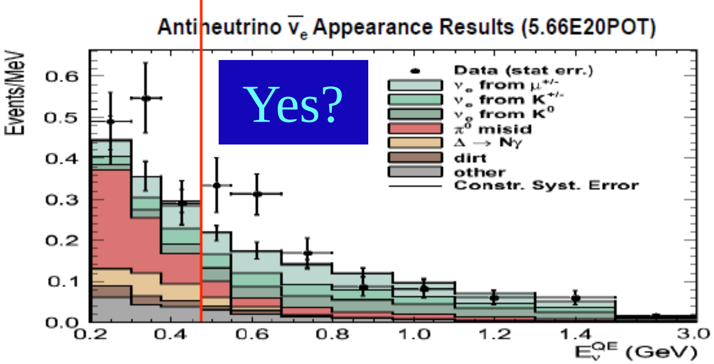
Short baselines (L/E ~ 1) and sterile ν.





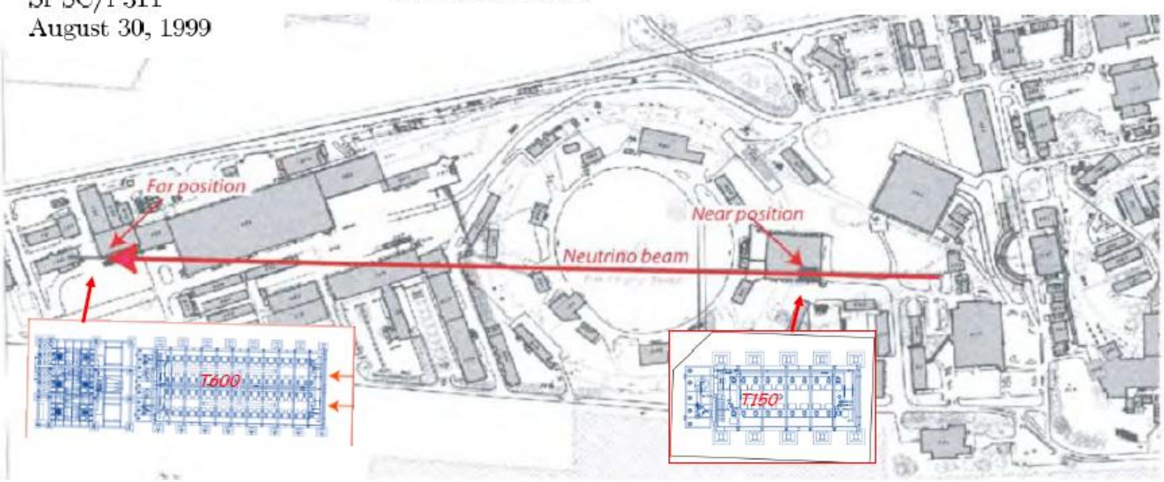
MiniBooNE says....



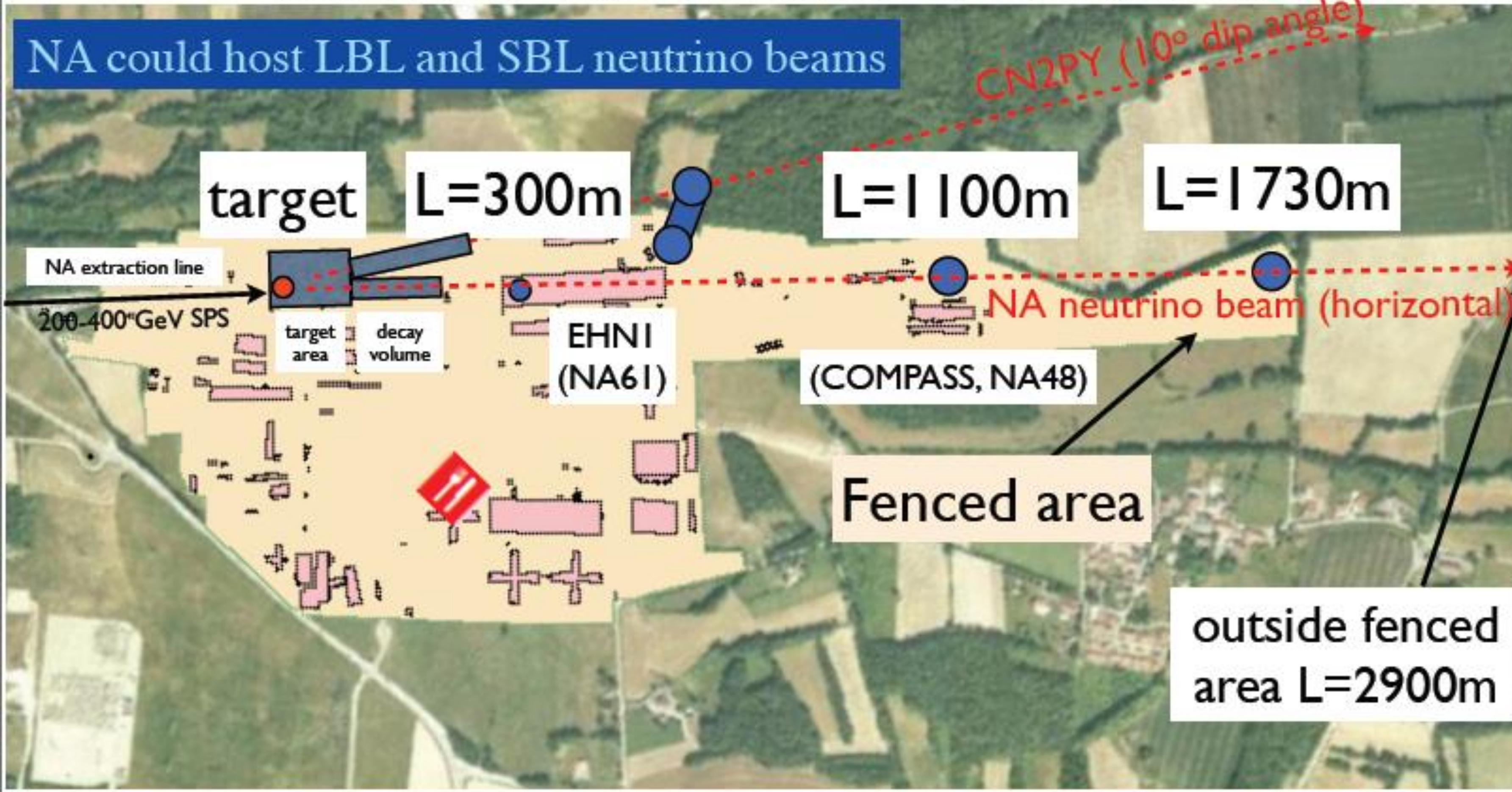


CERN-SPSC/99-26
SPSC/P311
August 30, 1999

SEARCH FOR $\nu_\mu \rightarrow \nu_e$ OSCILLATION AT THE CERN PS



A low/high-energy neutrino (short baseline) beam in the CERN North Area

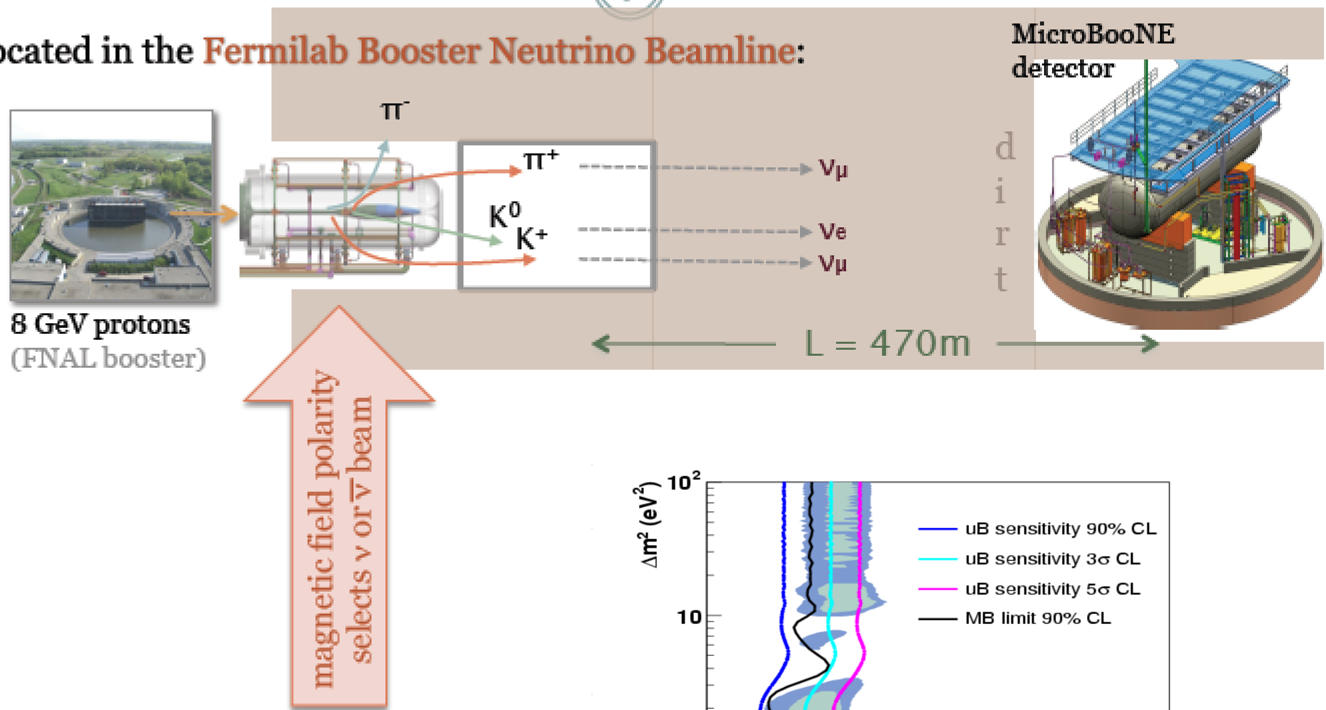


High and low energy beam options possible for detector R&D, cross-section measurements, oscillations @ $L/E \approx 1\ eV^2$, electroweak physics,...

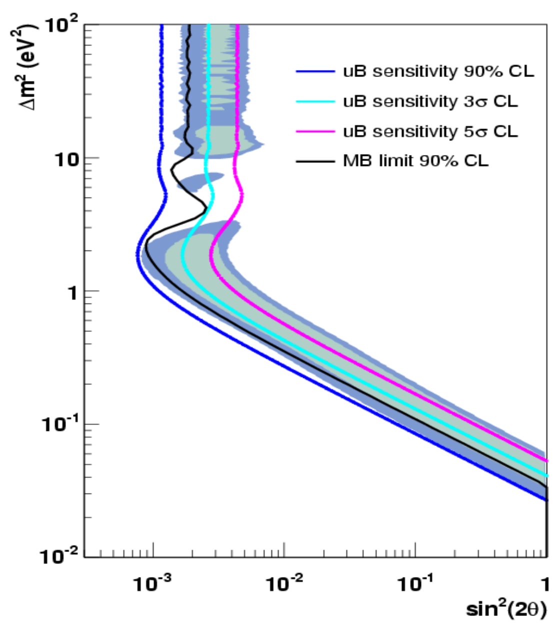
The MicroBooNE Experiment

9

Located in the **Fermilab Booster Neutrino Beamline**:



Present MicroBooNE plan:
Neutrino running, 6.6E20 POT



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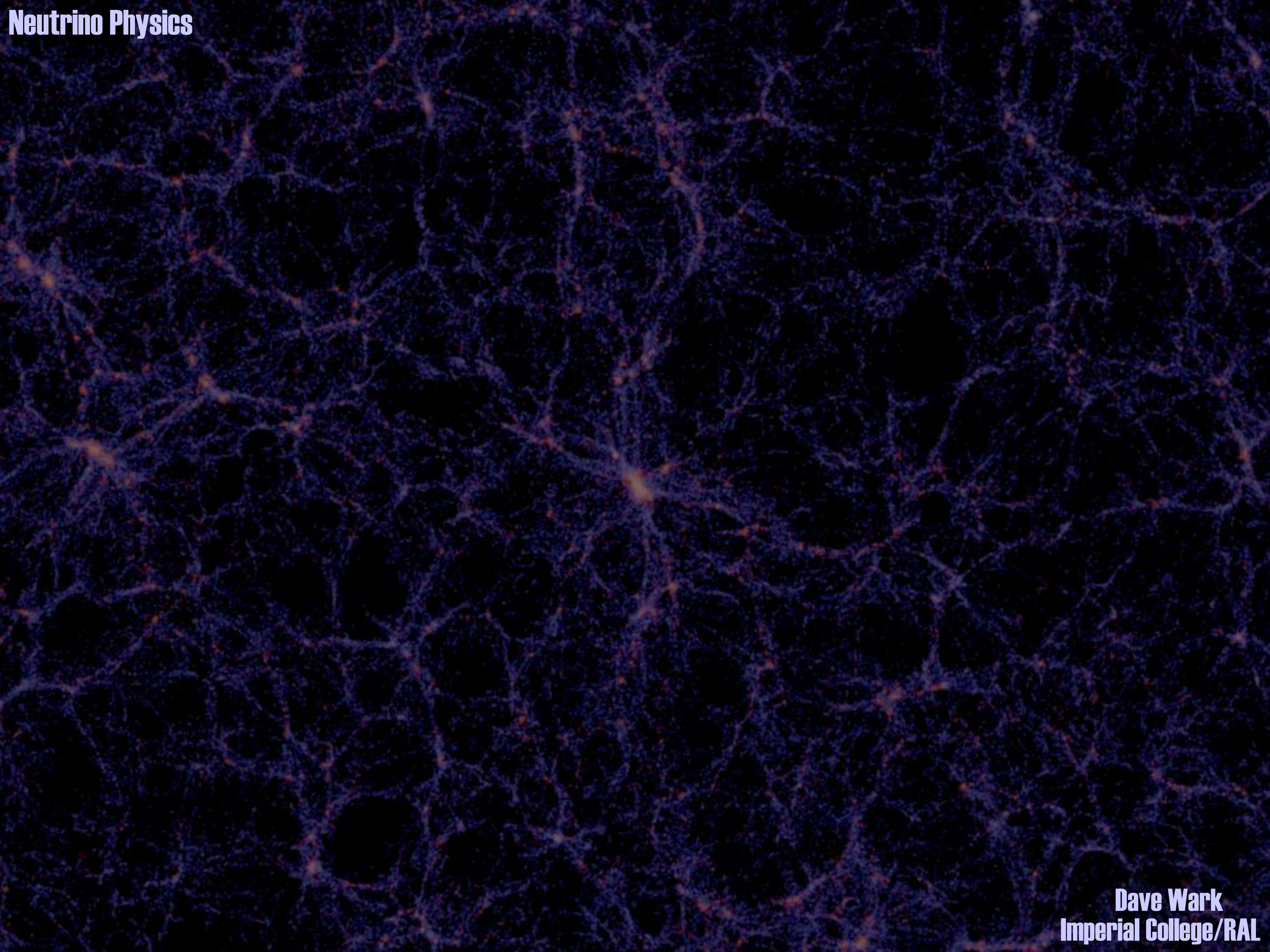
Neutrino Physics

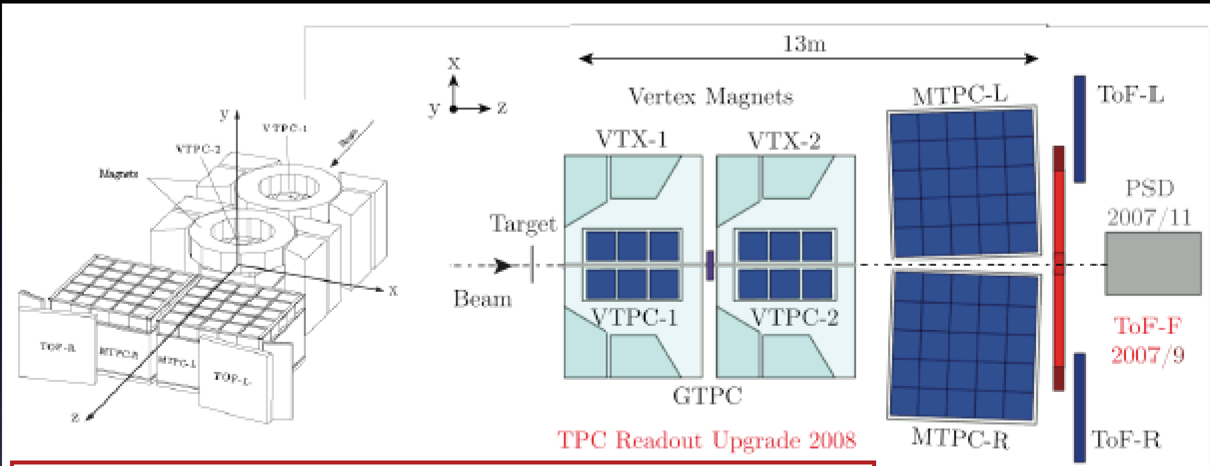


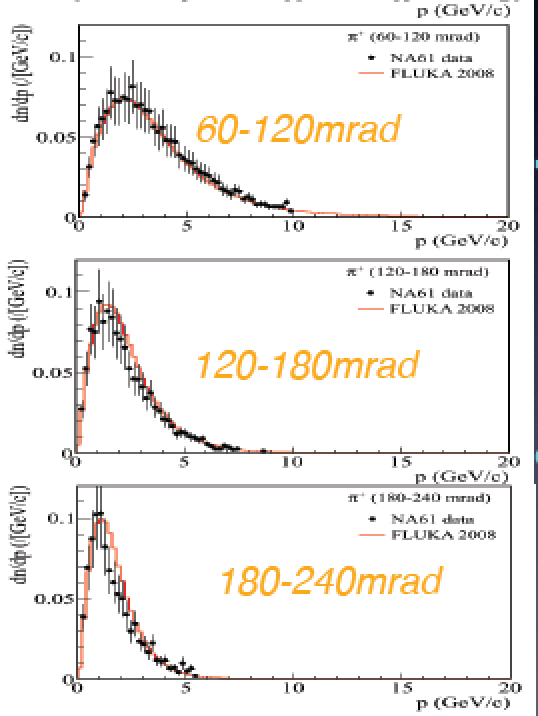
Dave Wark
Imperial College/RAL

In the systematics dominated era support measurements are essential!

CERN NA61 measurements

Evaluation of Particle Yields in 30 GeV p+C Inelastic Interacti and in the T2K replica target





La

σ(p)/

σ(dE/

3 ToFs

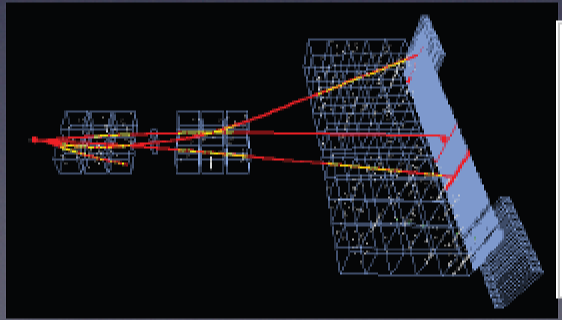
σ(ToF-F) ≈ 120 ps

σ(ToF-L/R) ≈ 60 ps

Full Coverage of T2K phase space

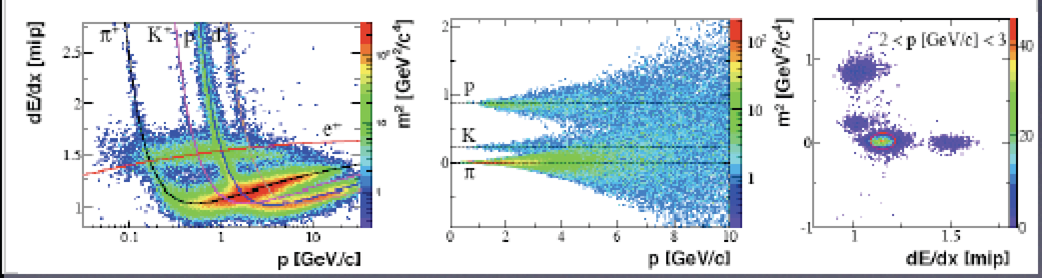
thin target: 2.5x2.5x2 cm³ int. length ~ 0.04 ~600k triggers in 2007

p+C @ 31 GeV/c



Particle ID methods used:

1) dE/dx (p < 1 GeV/c, p > 4 GeV/c)
2) Combined dE/dx + ToF (1 < p [GeV/c] < 4)
3) Negatively charged hadron h- analysis (π- only)



A. Rubbia XIV International Workshop on Neutrino Telescopes (2011) 41

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Imperial College/RAL

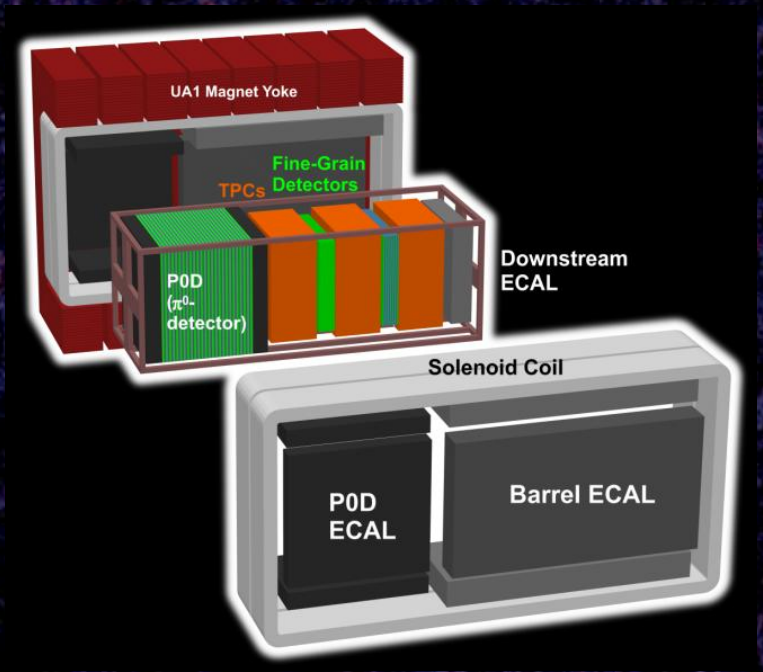
Neutrino interaction properties must also be measured...

SciBooNE

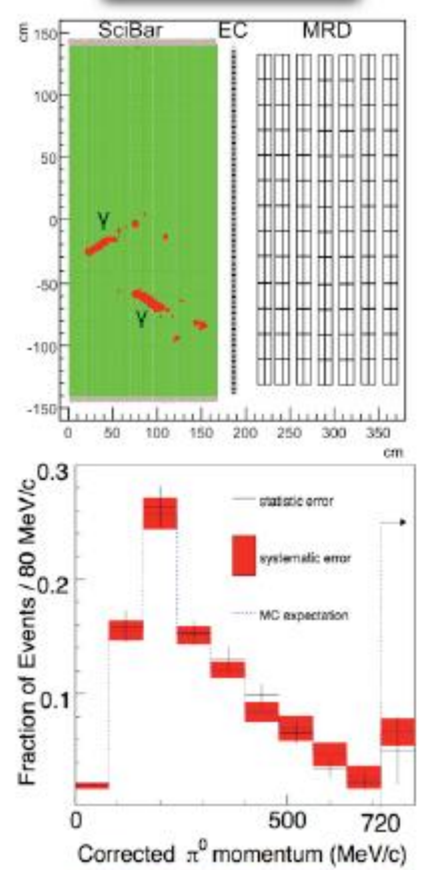
http://www-sciboone.fnal.gov/

But also need....

Near Detectors....



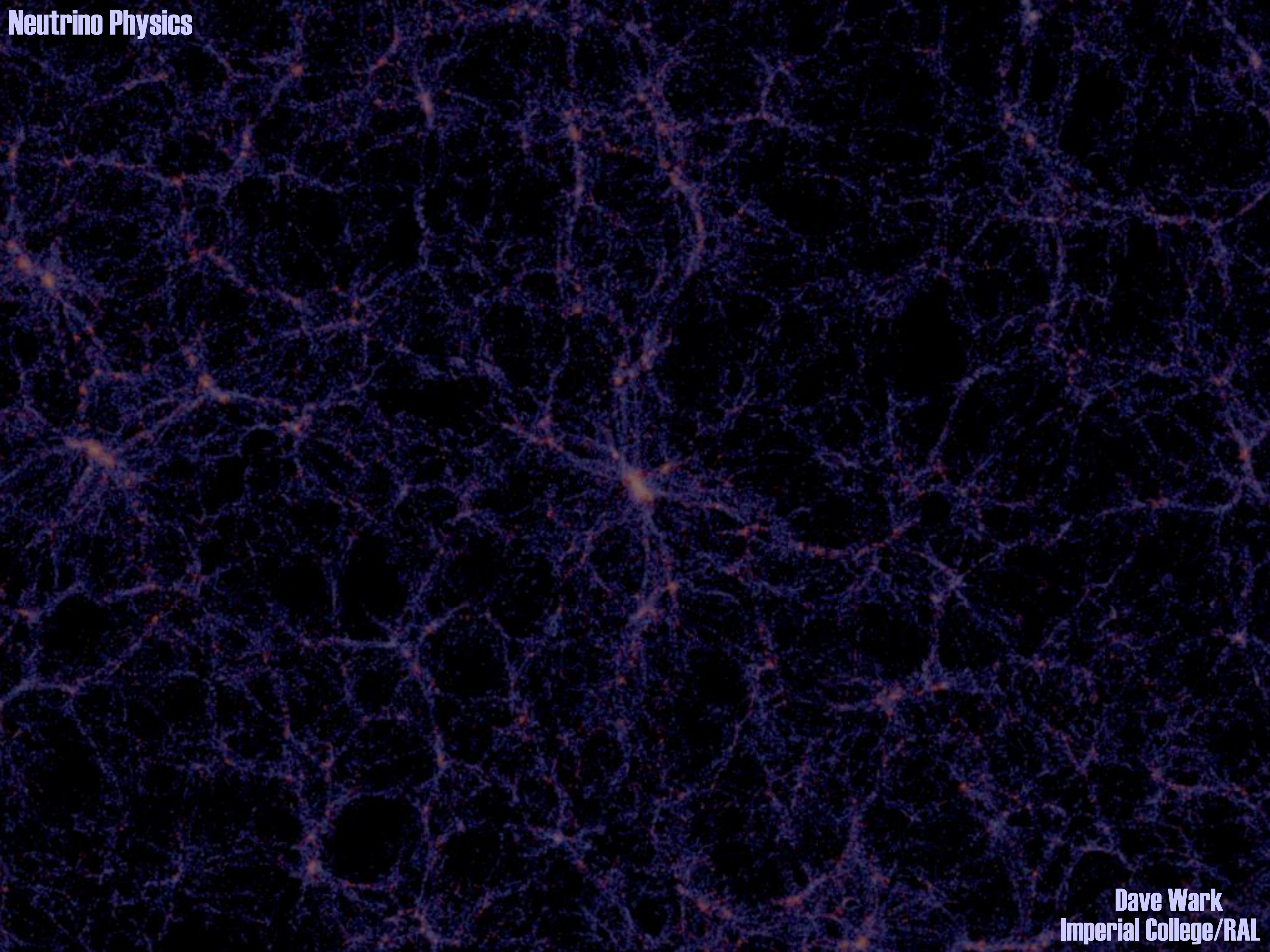
NCπ0 xsecs



Phys. Rev. D 81, 033004 (2009)

Phys. Rev. D 81, 111102(R) (2009)

Return ↑



Neutrino Physics

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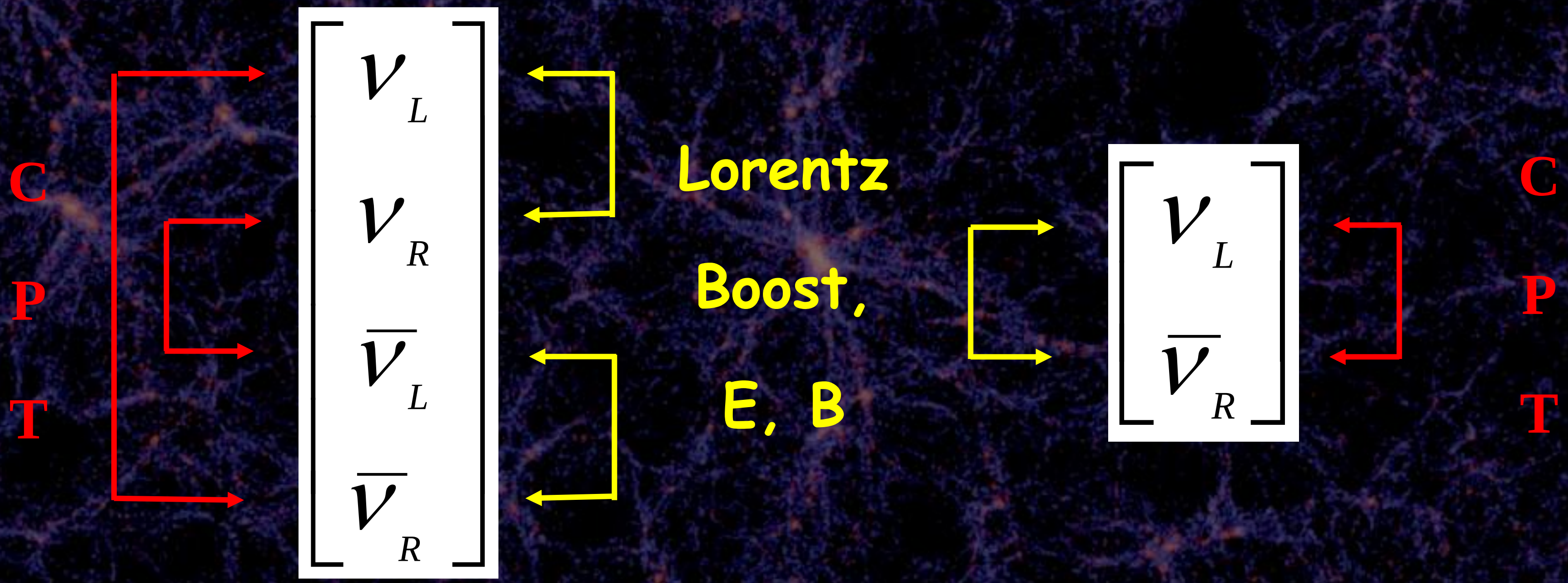
Imperial College/RAL

Dirac ν vs Majorana ν



Dirac **Majorana**

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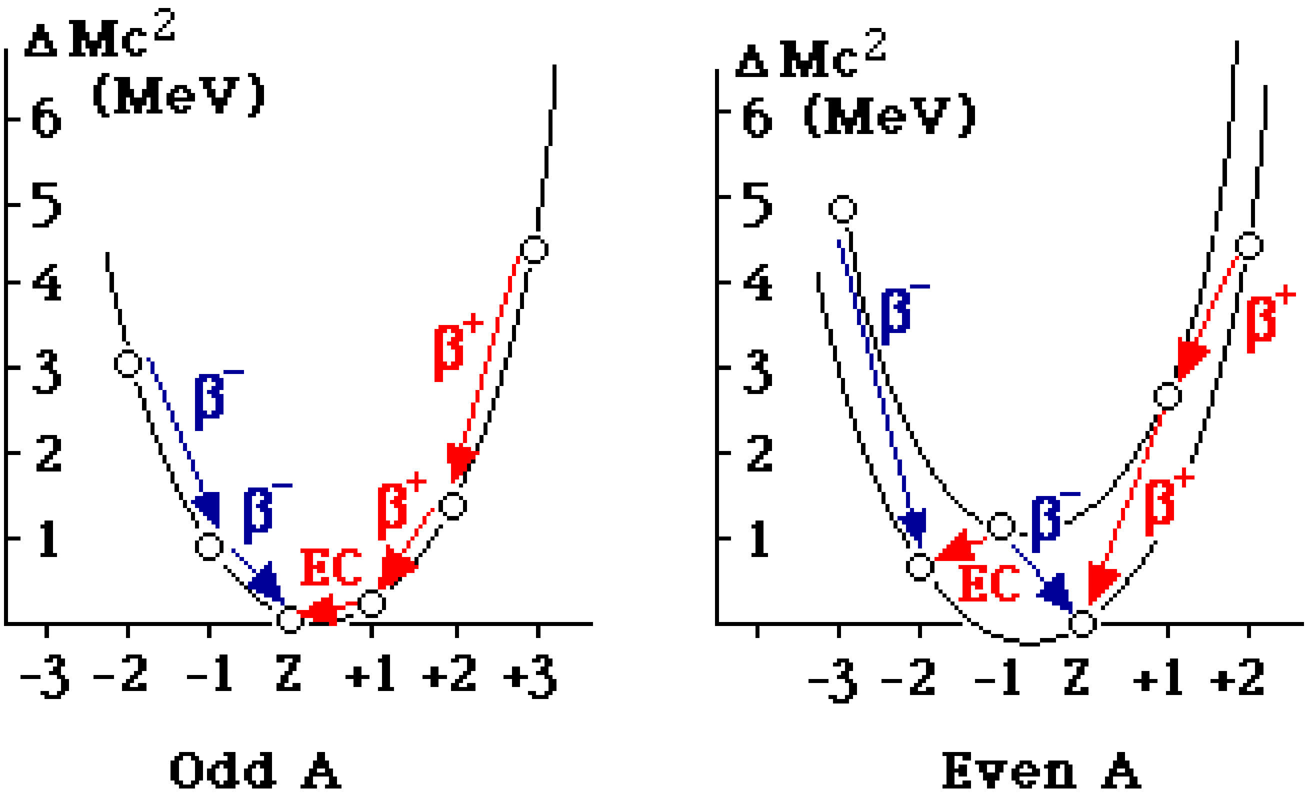
ββ decay and neutrino mass



35 isotopes in nature

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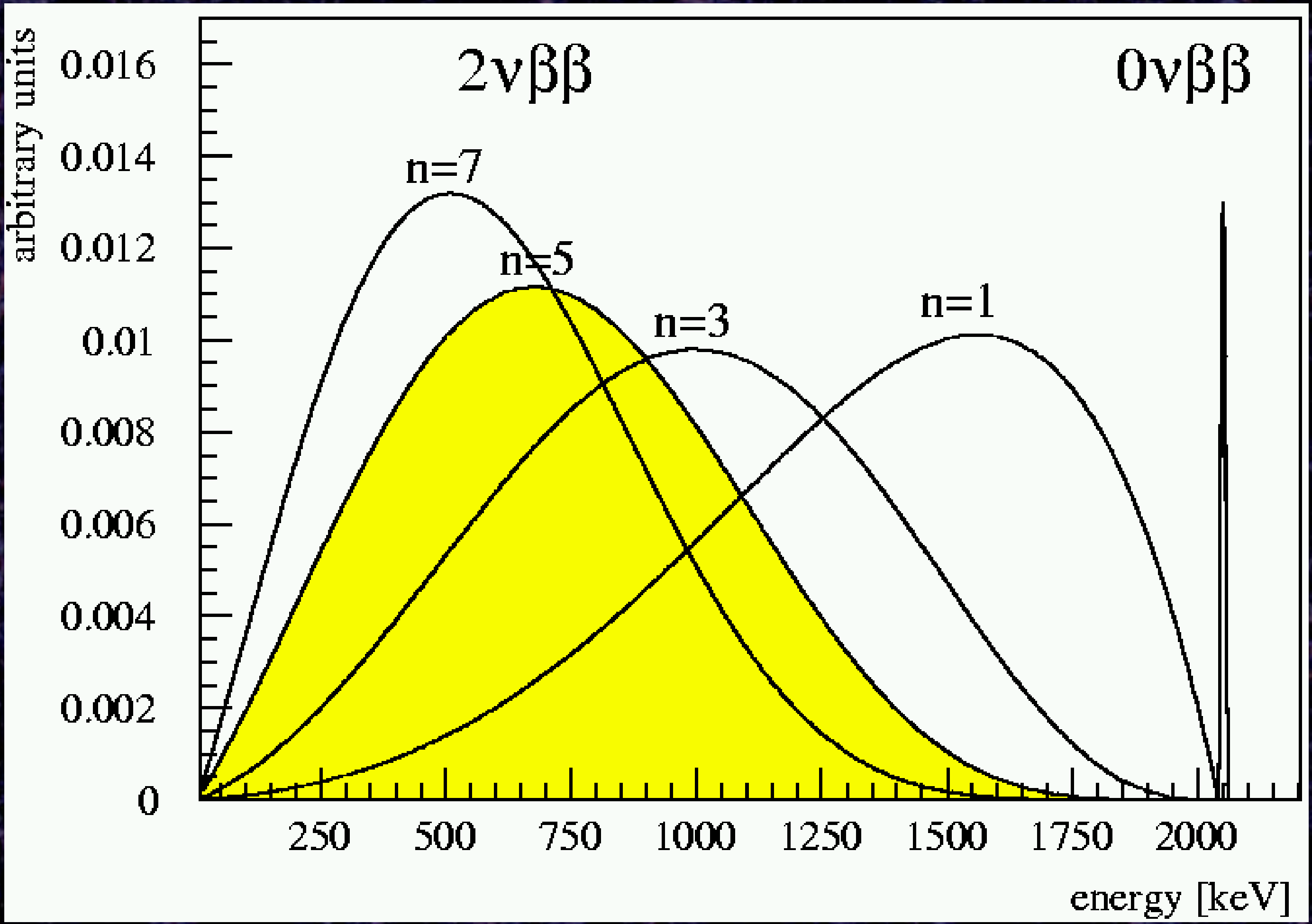
0νββ: Peak at Q-value of nuclear transition



Sum energy spectrum of both electrons

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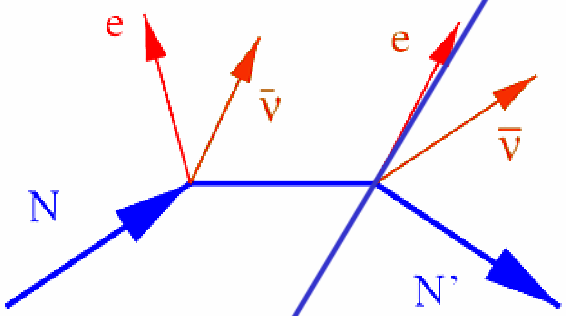
Most sensitive neutrino mass measurements can be obtained from double-beta decay

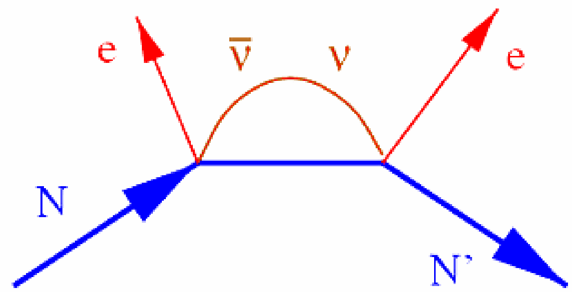
$2\nu\ \beta\beta$ decay: a standard process in nuclear physics



$0\nu\ \beta\beta$ decay: a hypothetical process

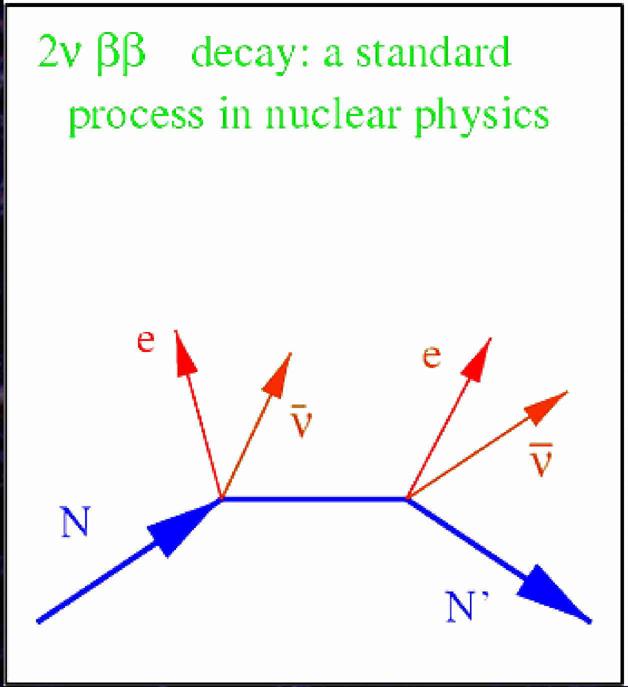
→ $m_\nu \neq 0$ since helicity has to "flip"

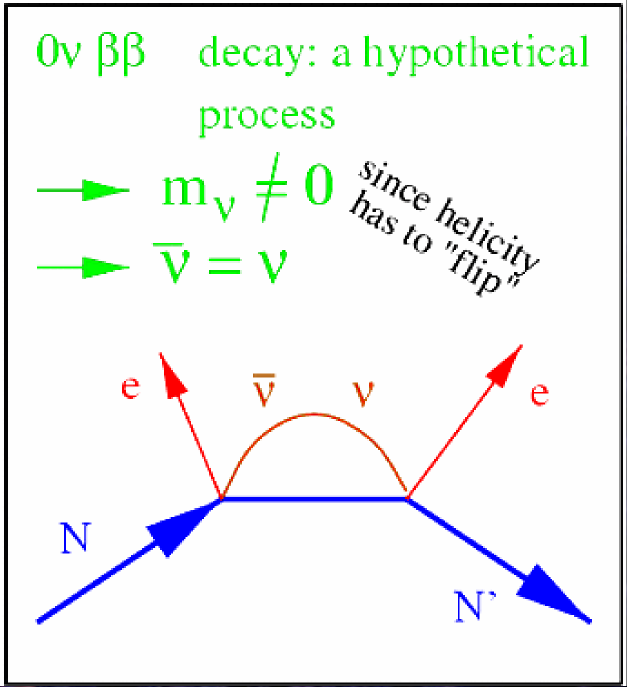
→ $\bar{\nu} = \nu$



$$\frac{1}{t_{1/2}} = (\text{phase space}) \bullet \left(\frac{\langle m_\nu \rangle}{m_e} \right)^2 \bullet \left| \sum M_{if} \right|^2$$

Most sensitive neutrino mass measurements can be obtained from double-beta decay





$$\langle m_\nu \rangle = m_{ee} = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k |U_{ek}|^2 e^{i\alpha_{ek}} m_k \right|$$

Each is ±1 if CP conserved, but there can still be cancellations

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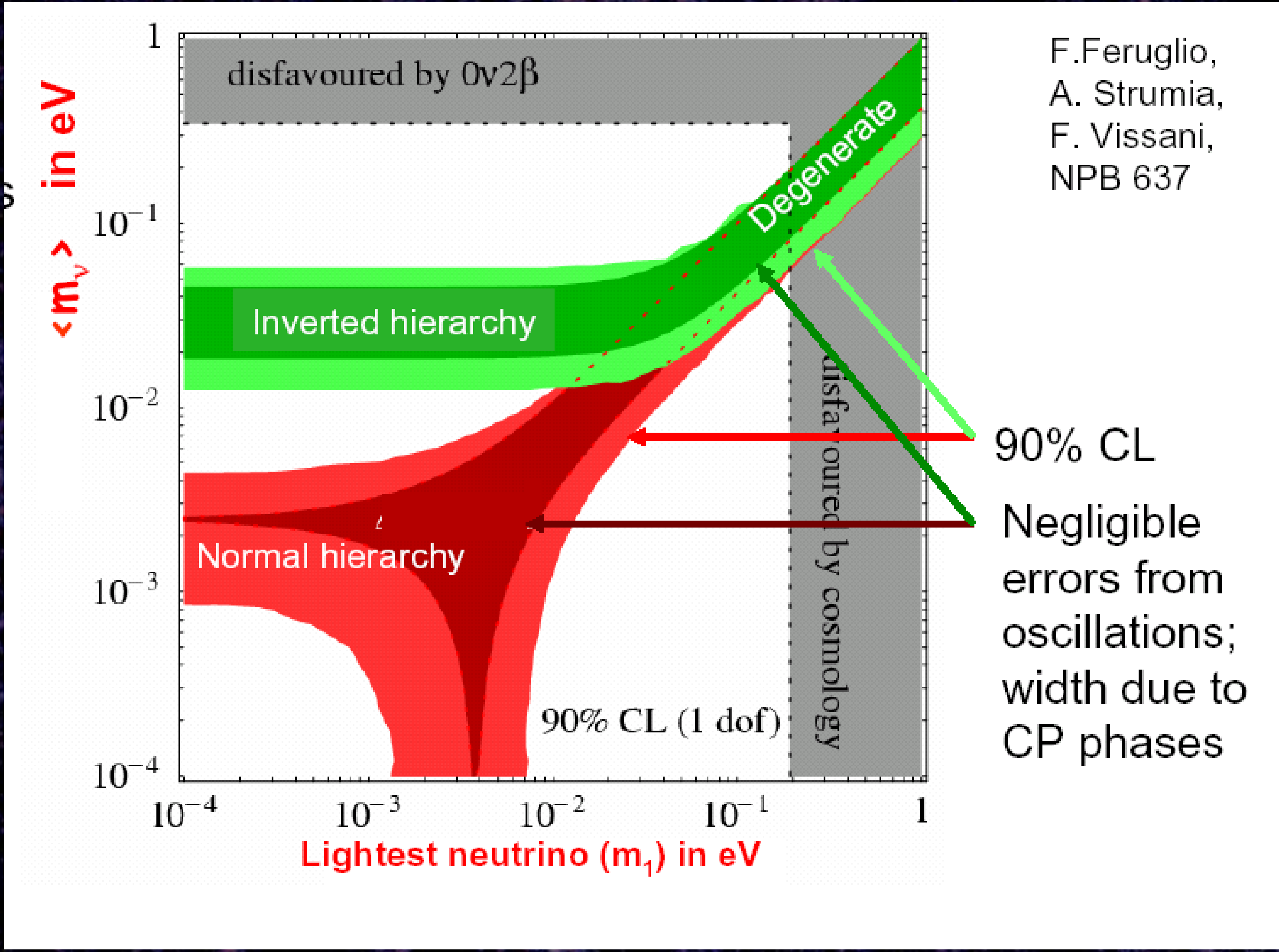
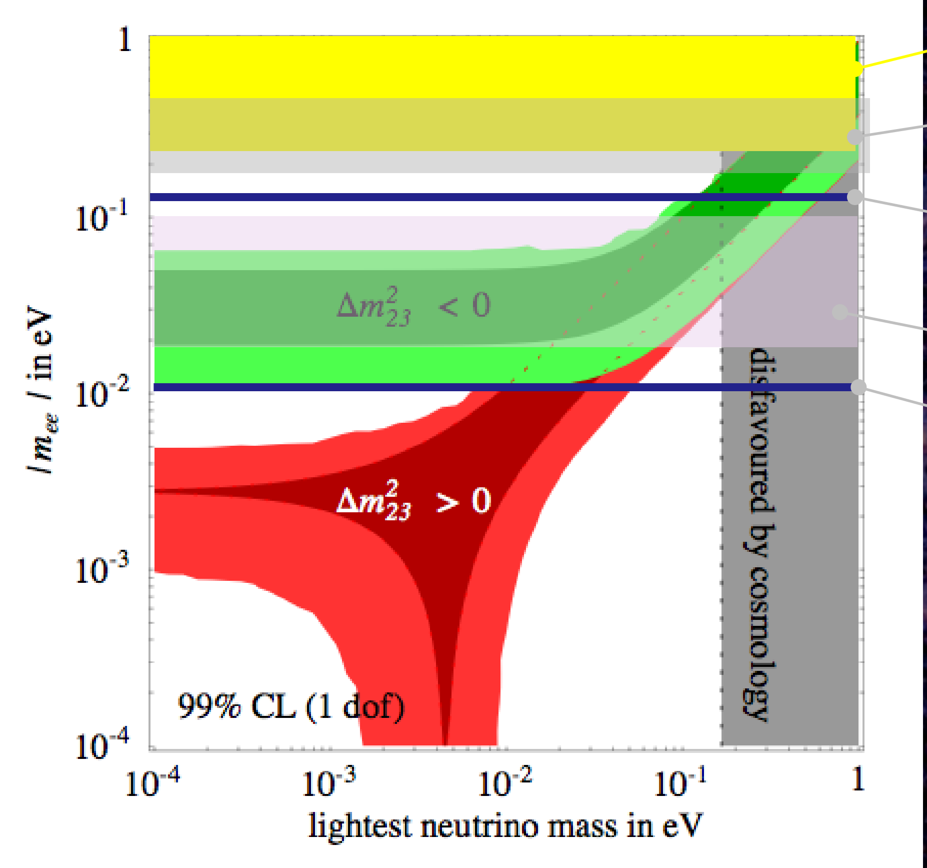

disfavoured by 0ν2β
Degenerate
Inverted hierarchy
Normal hierarchy
90% CL (1 dof)
disfavoured by cosmology
⟨m_ν⟩ in eV
Lightest neutrino (m_1) in eV
1
10^-1
10^-2
10^-3
10^-4
10^-4
10^-3
10^-2
10^-1
1
F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637
90% CL
Negligible
errors from
oscillations;
width due to
CP phases



KKDC Claim
(best fit 0.32 eV)

Present Cuoricino result

GERDA Target

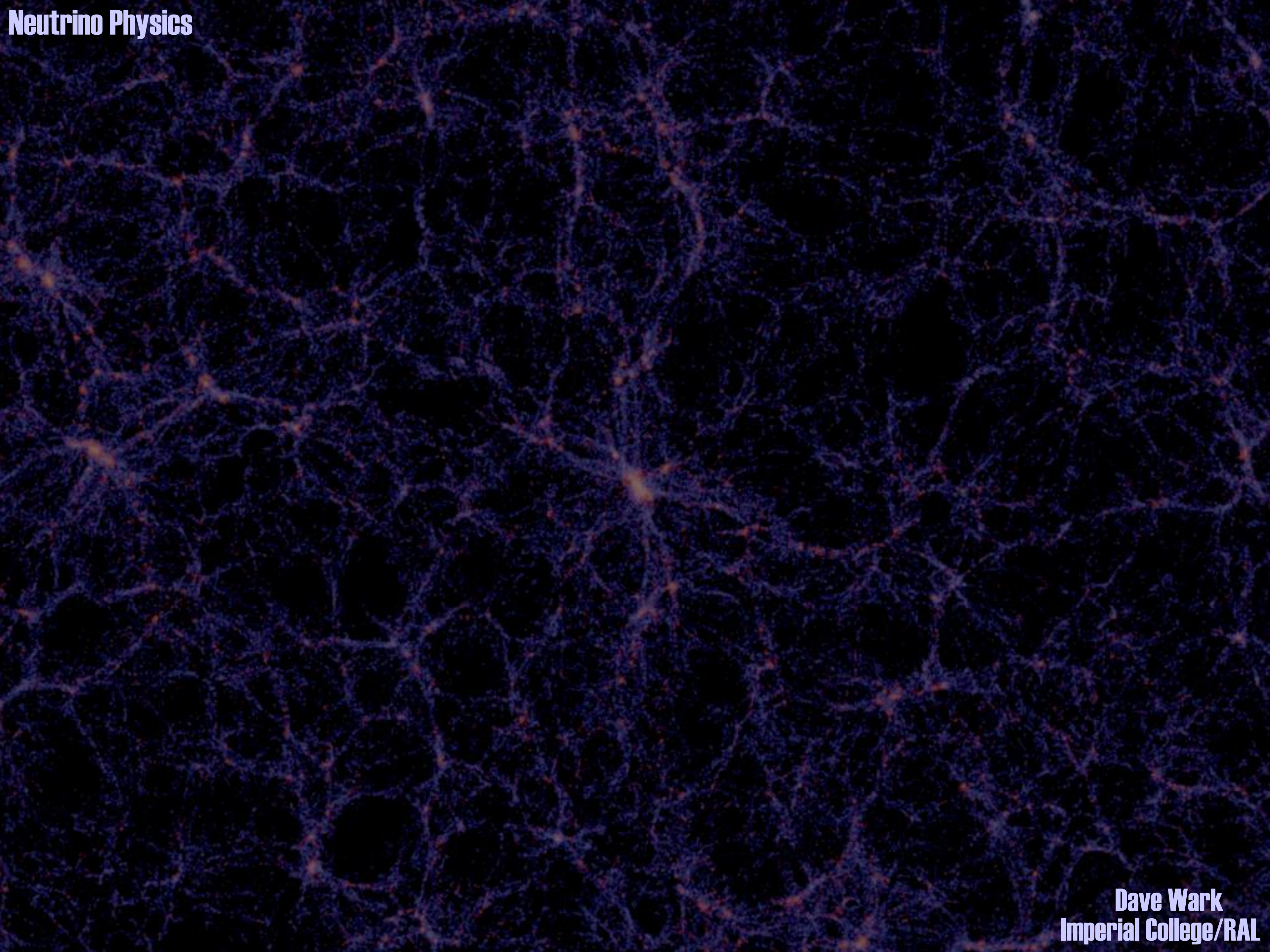
CUORE Target

With SuperNEMO, SNO+, MAJORANA, many others should reach here in ~ 7-10 yrs.

Return ↑

Need new ideas to reach < 10 meV, but kiloton scale low background experiments are not impossible!

Neutrino Physics



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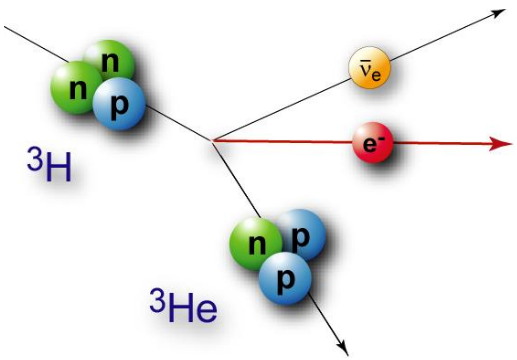
Tritium β-decay



$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

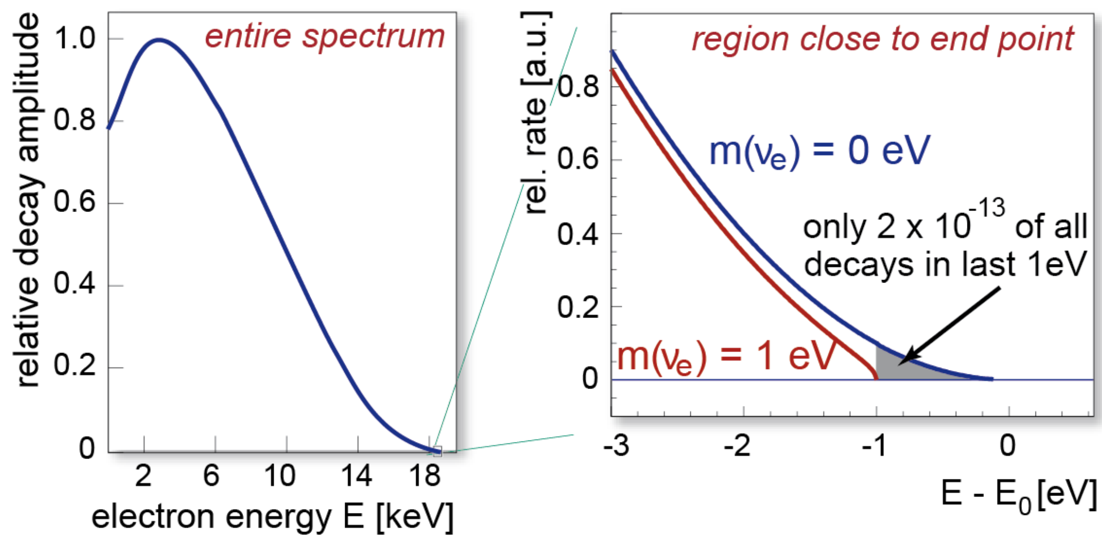
Fermi theory of β-decay:

$$\frac{dN}{dE} = C \cdot F(E,Z) \cdot p(E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

observable: $$m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

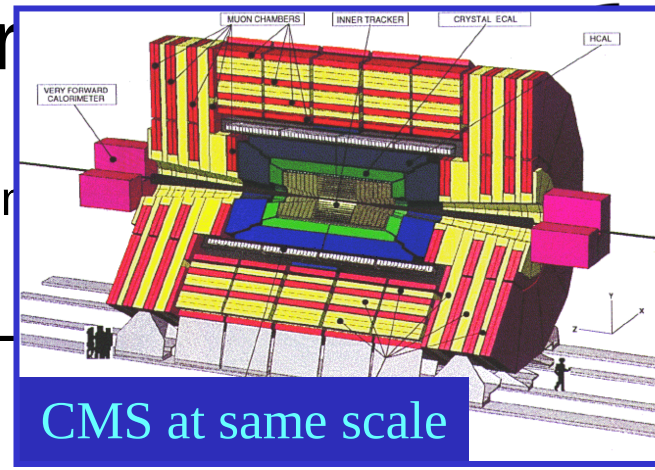
tritium as β emitter:

- high specific activity (half-life: 12.3 years)
- low endpoint energy E_0 (18.57 keV)
- super-allowed



KATRIN experir

(**KA**rlsruhe **TRI**tium **N**eutrino experiment, locatior e)



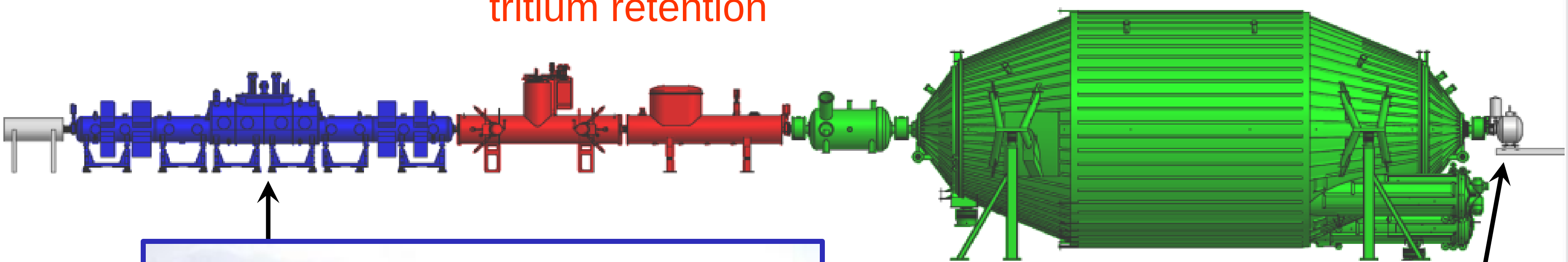
CMS at same scale

70 m

tritium decay

electron transport

tritium retention



β-de

T_2 pr

f magnitude

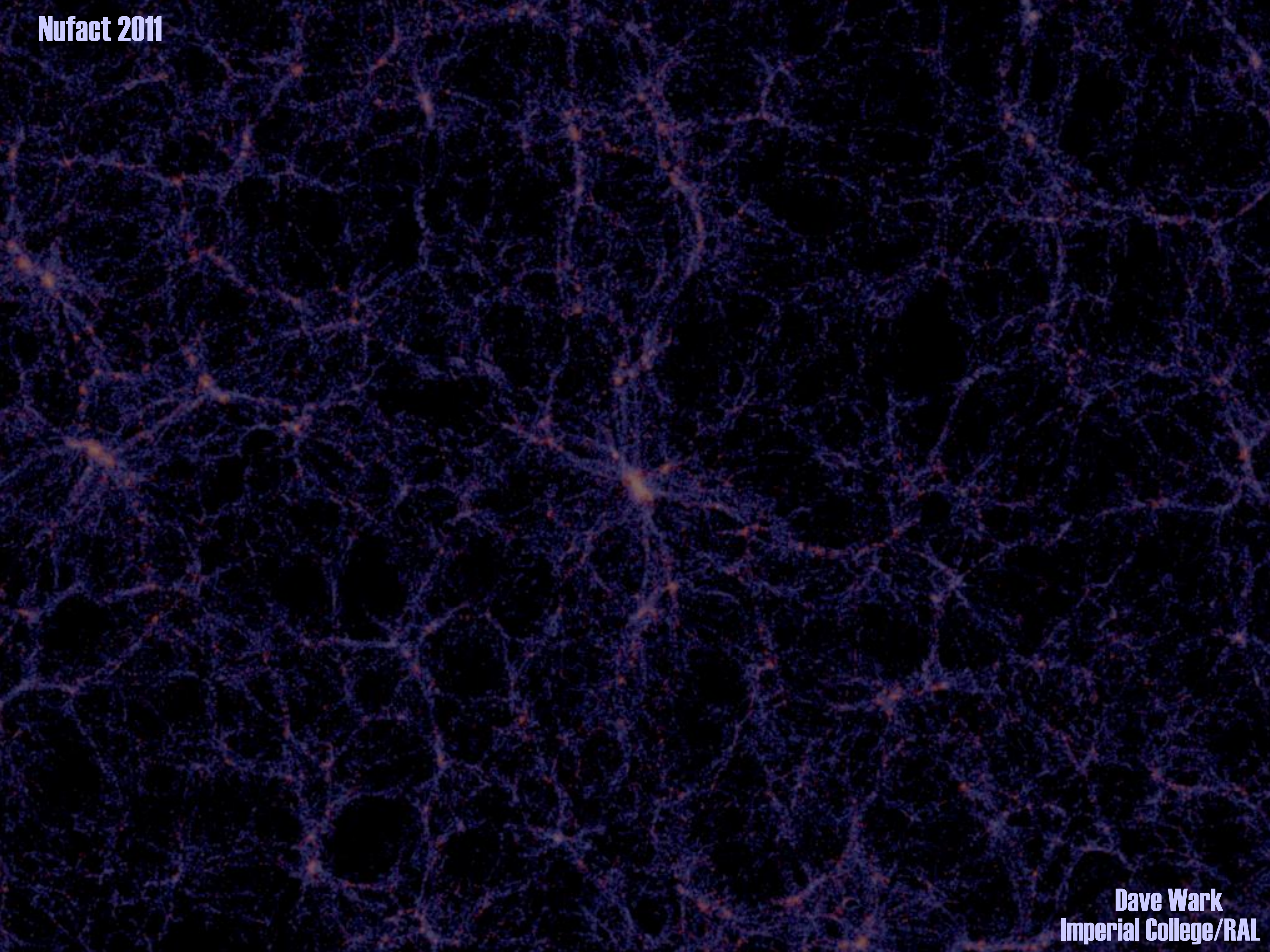
background rate: $\mathbf{10^{-2}}$ Hz

T_2 pressure: $\mathbf{10^{-20}}$ mbar

n meV level

Status:
-commissioning of sub-components ongoing
- Start of physics 2013

Return ↑



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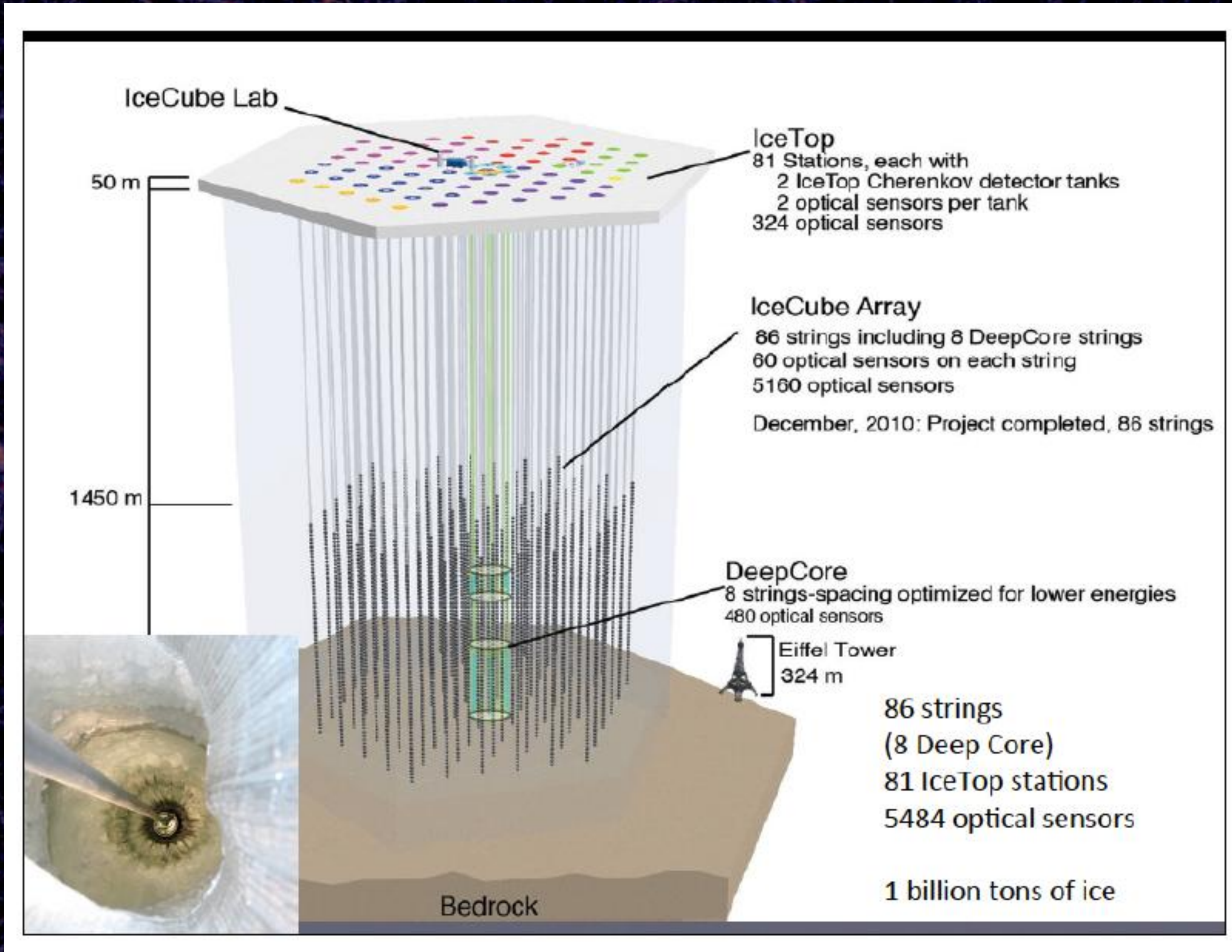
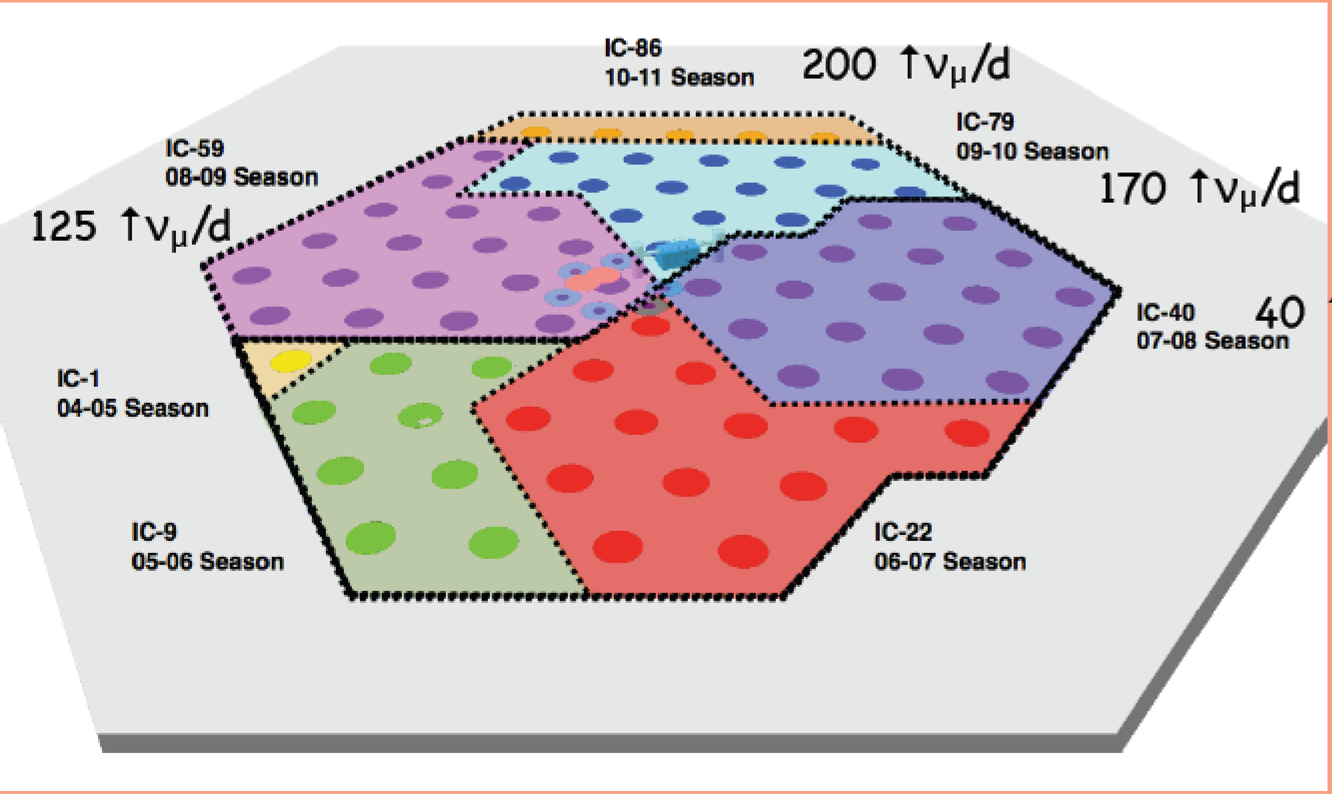

IceCube Lab
50 m
1450 m
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
Bedrock
86 strings
(8 Deep Core)
81 IceTop stations
5484 optical sensors
1 billion tons of ice

IceCube is complete!



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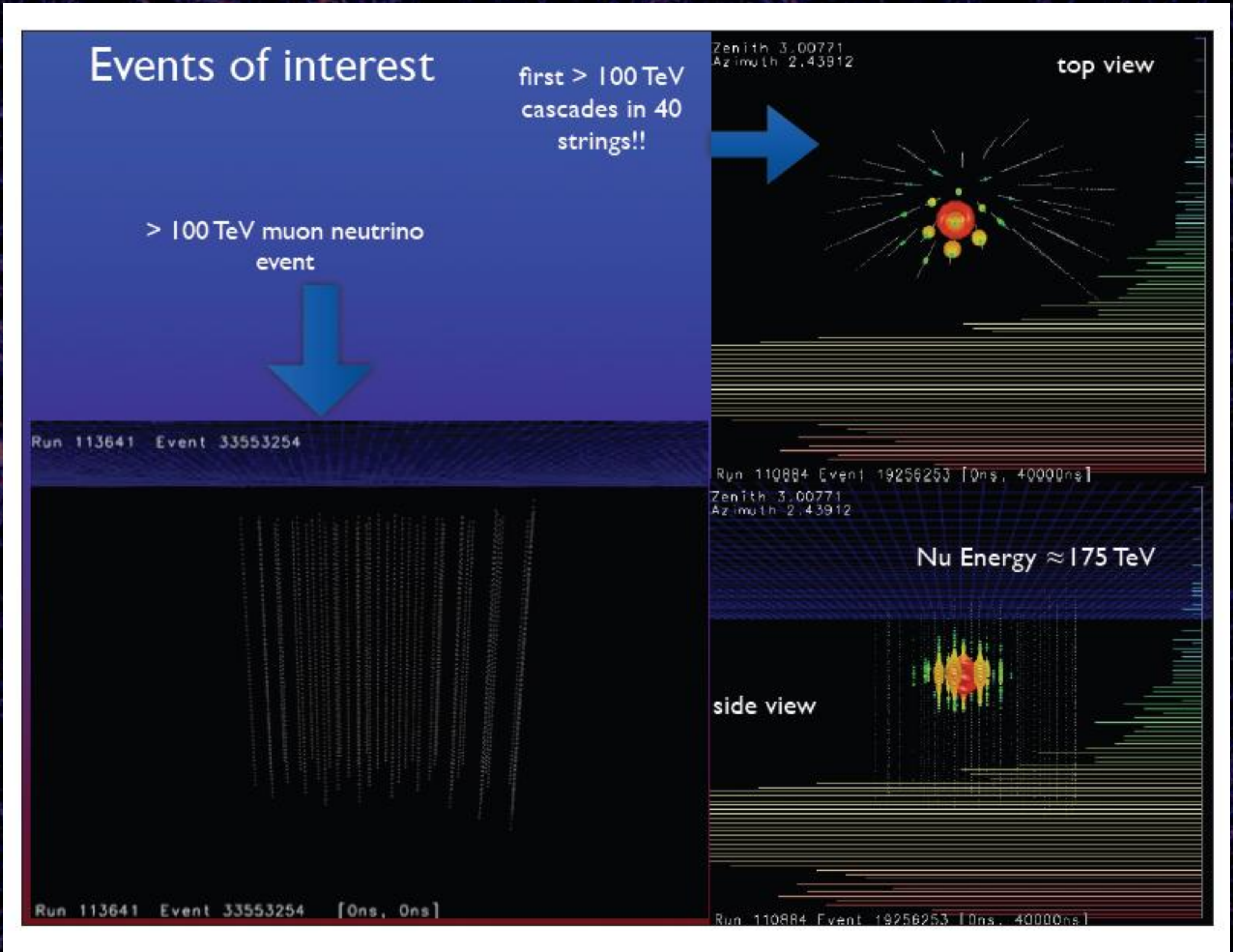

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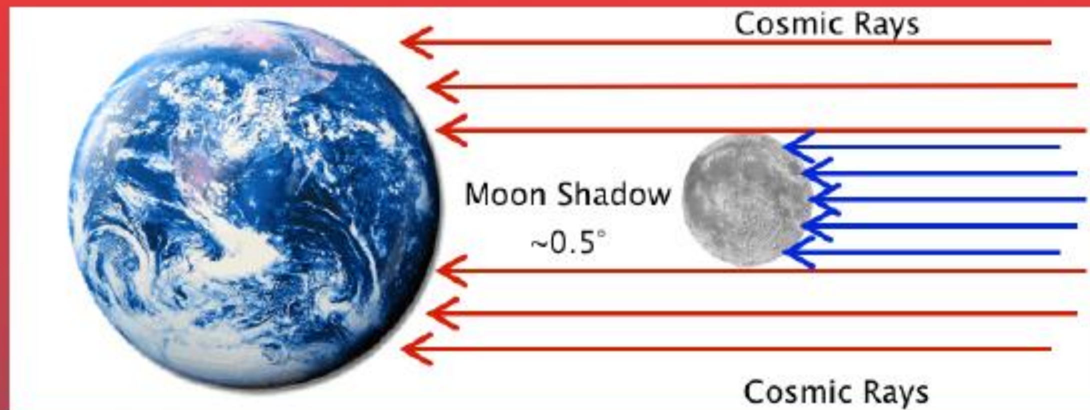
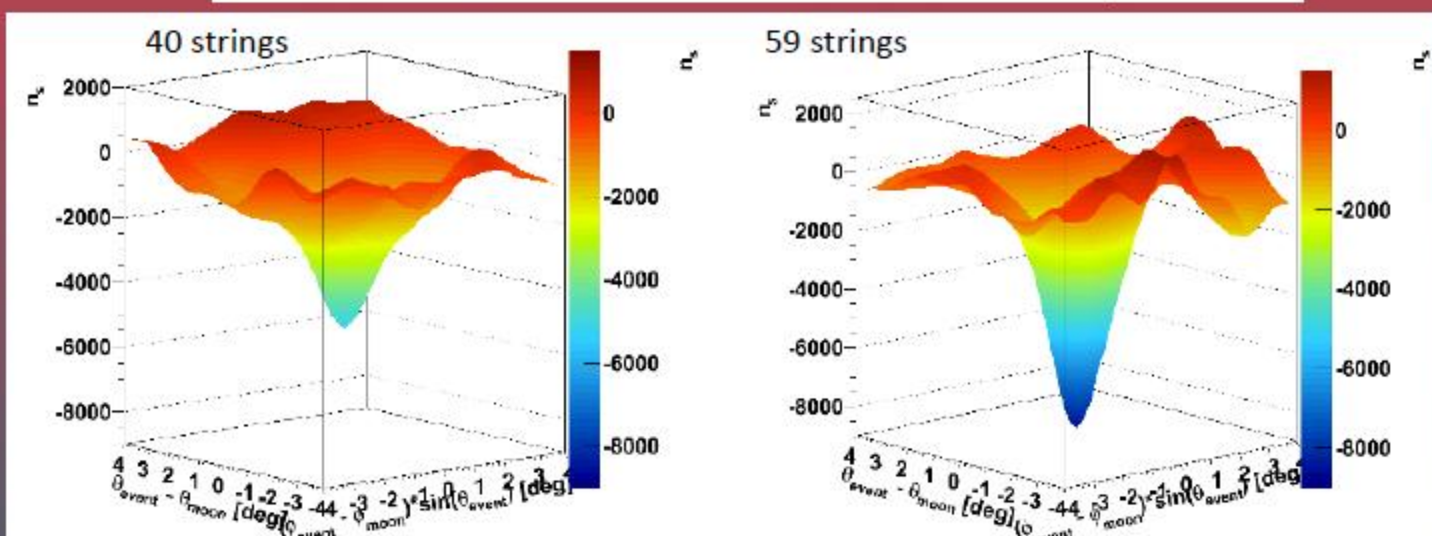
Sub-degree Pointing proved on the Moon

More than 12σ underfluctuation in 59-strings





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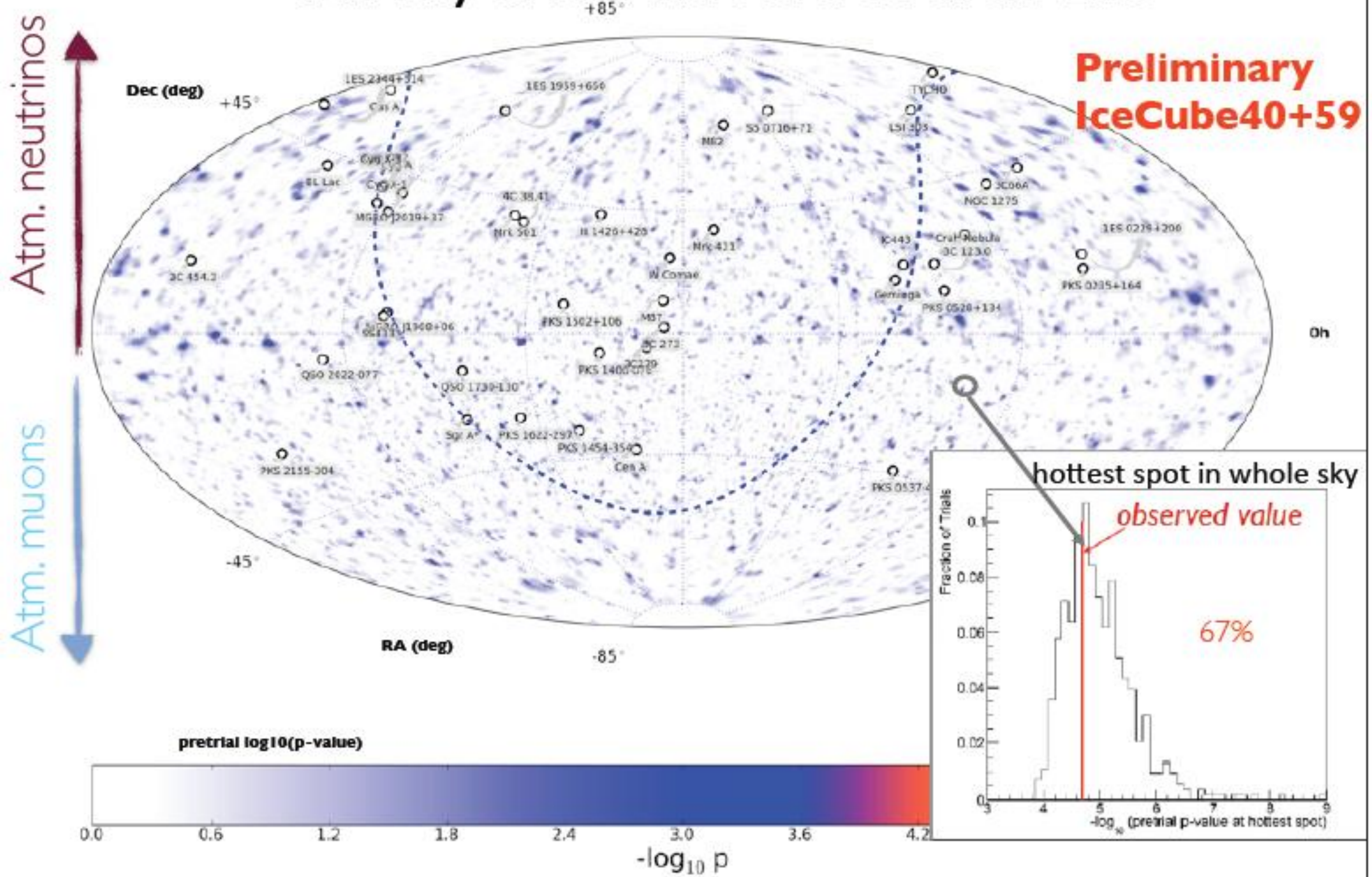
All sky and Selected Source List



No significant fluctuation: best pre-trial p-value = 0.14 pretrial in a list of 43 sources => 95% post-trial for PKS_1454-354

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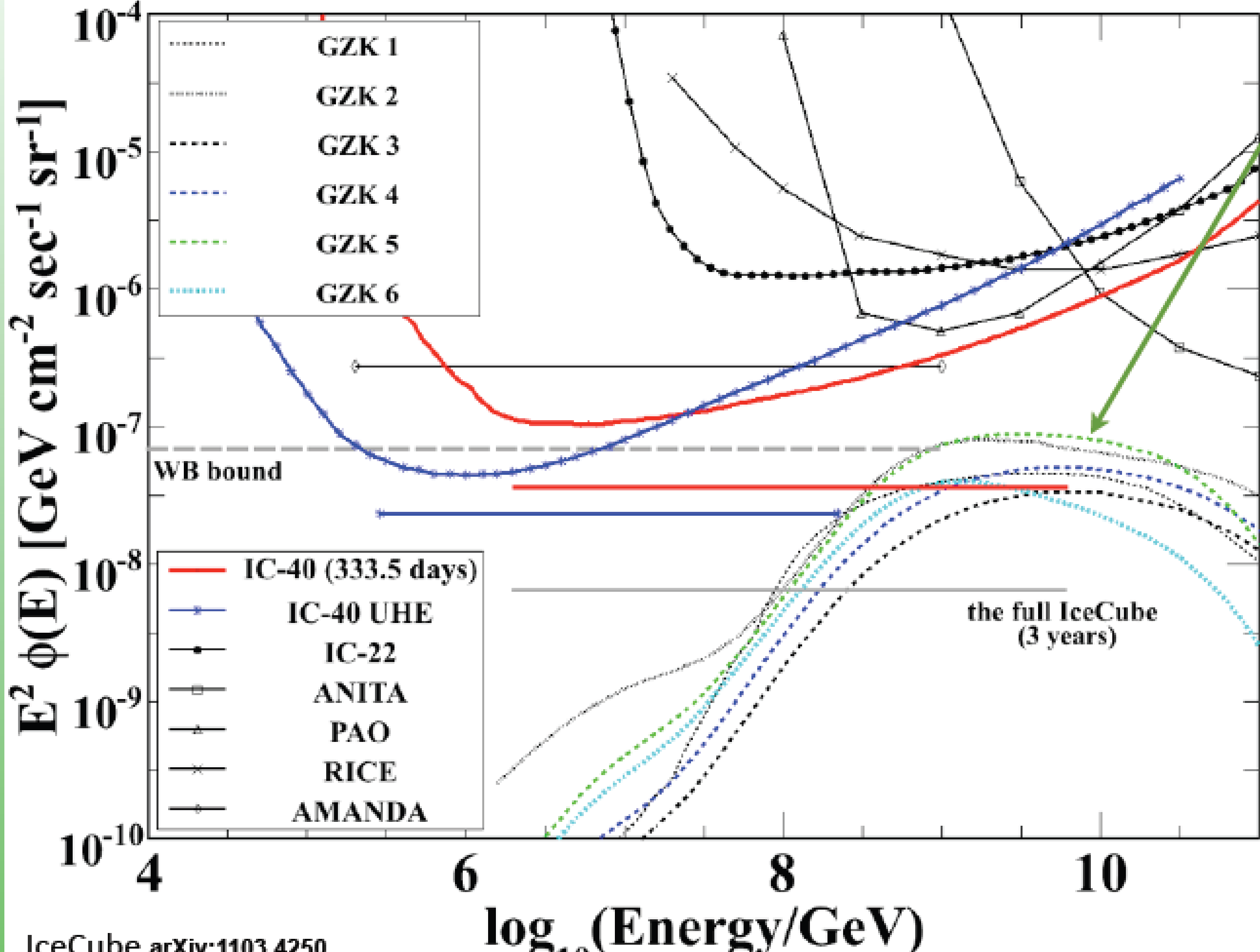
Cosmogenic Neutrinos in IceCube

W&B with cosmological evolution: 24.5 events in IC86/3 yrs (4.5 in IC40)

GZK 5 (M. Ahlers, et al., 2010): 4.8 events in IC86/3 yrs (using constrain from Fermi diffuse gammas)

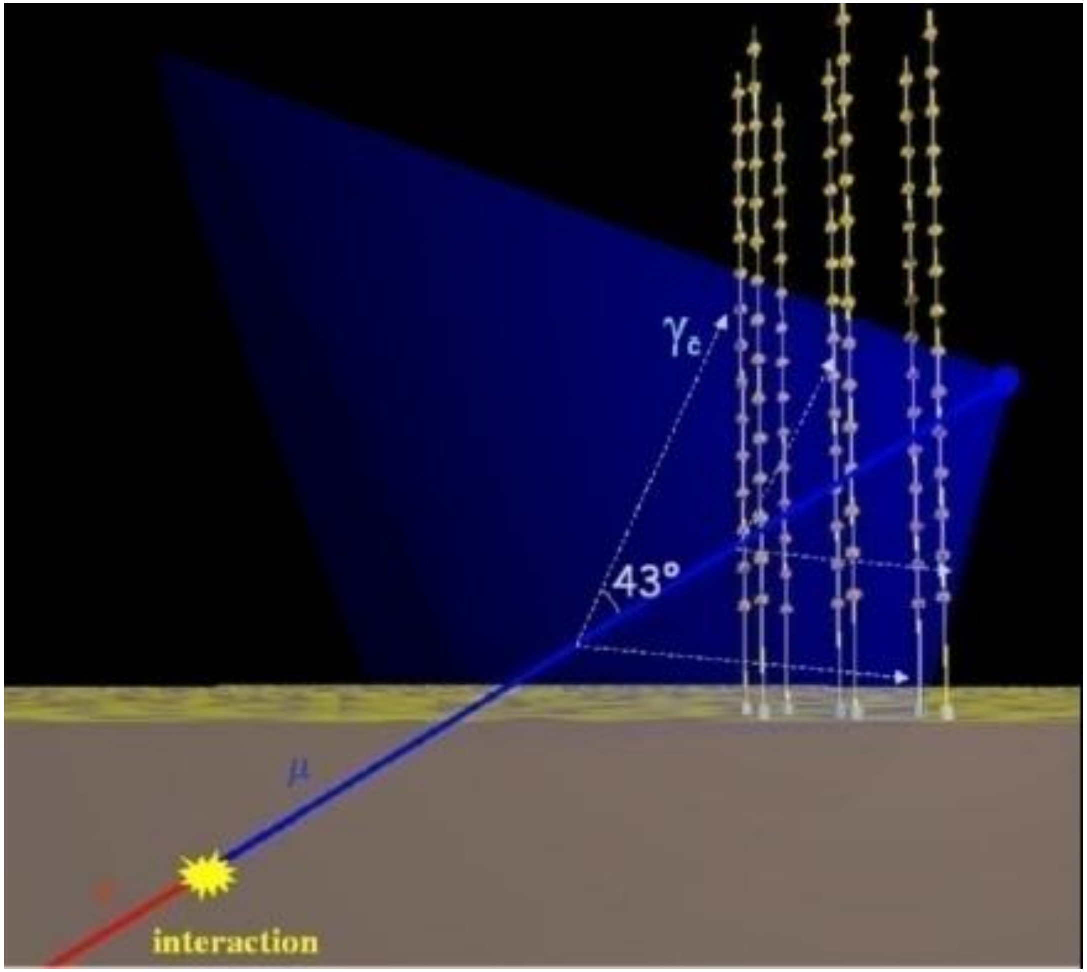


IceCube arXiv:1103.4250

Return ↑

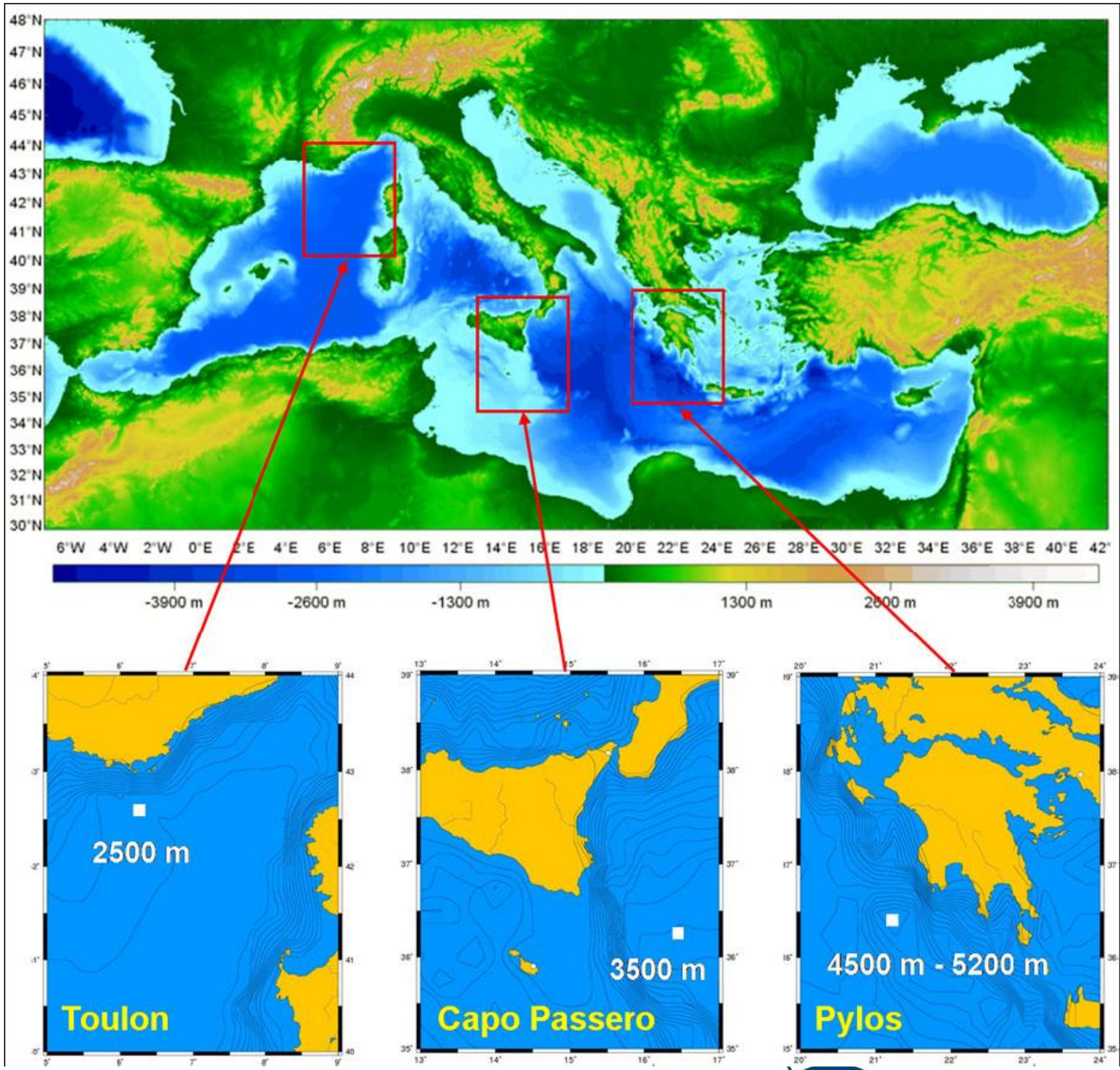
What is KM3NeT ?

- Future cubic-kilometre scale neutrino telescope in the Mediterranean Sea
- Exceeds Northern-hemisphere telescopes by factor ~50 in sensitivity
- Exceeds IceCube sensitivity by substantial factor
- Provides node for earth and marine sciences



Candidate Sites

- Locations of the three pilot projects:
  - ANTARES: Toulon
  - NEMO: Capo Passero
  - NESTOR: Pylos
- Long-term site characterisation measurements performed
- Political and funding constraints
- Possible solution: networked, distributed implementation



ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS