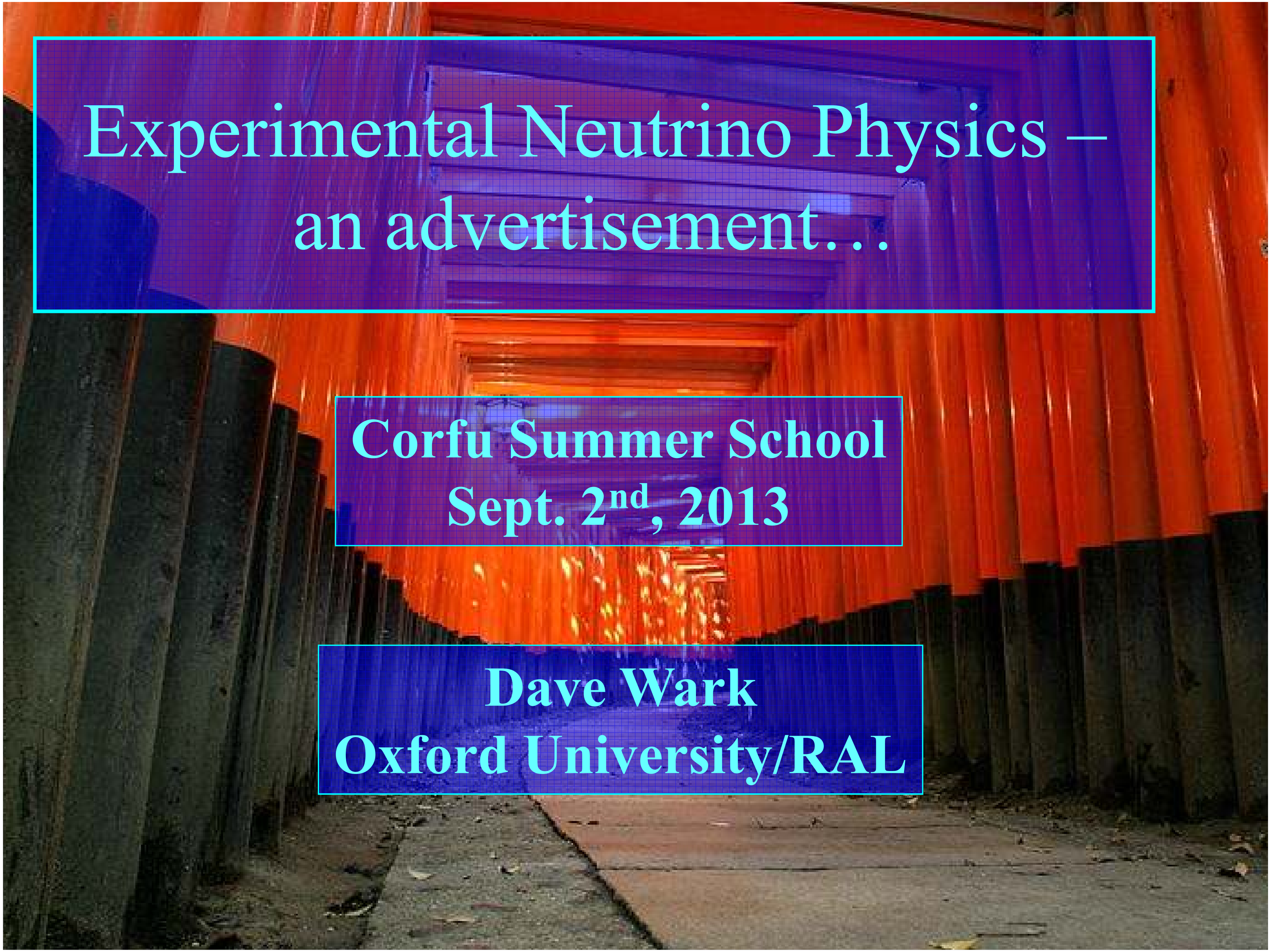
Experimental Neutrino Physics – an advertisement…

Corfu Summer School
Sept. 2nd, 2013

Dave Wark
Oxford University/RAL



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...

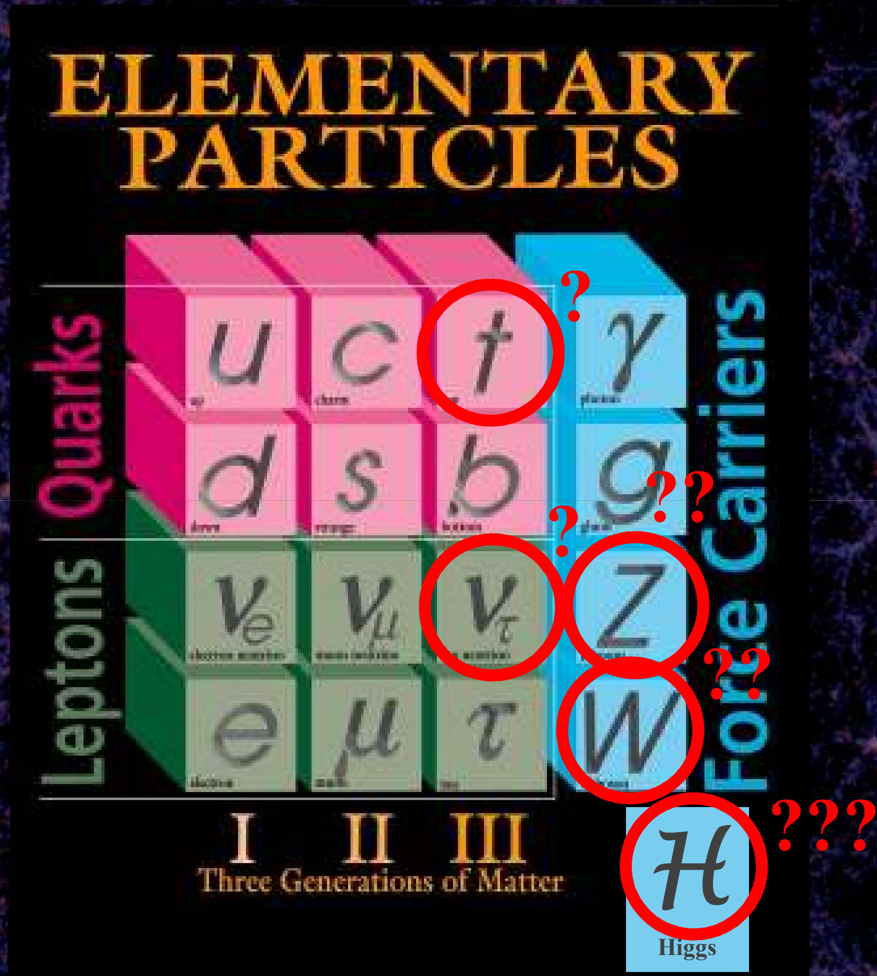
I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye,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

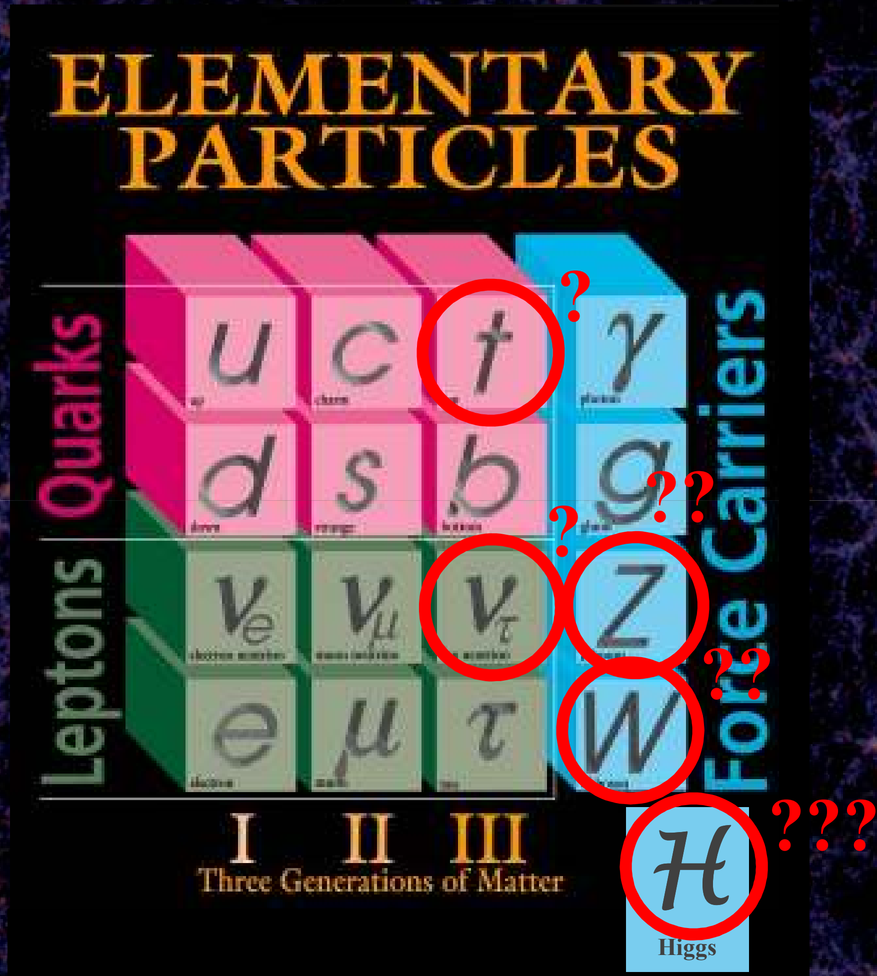
The Standard Model (~1981)

- Neutrinos in the 1981 Standard:
  - Three neutrinos with a conserved lepton flavour number.
  - Massless.
  - Strictly Left-handed.



The Standard Model (~now)

- Neutrinos in the 1981 Stand[illegible]d:
  - T[illegible] t[illegible] h a cons[illegible] flavo[illegible]
  - M[illegible]
  - Stri[illegible]y Left-h[illegible]ded.



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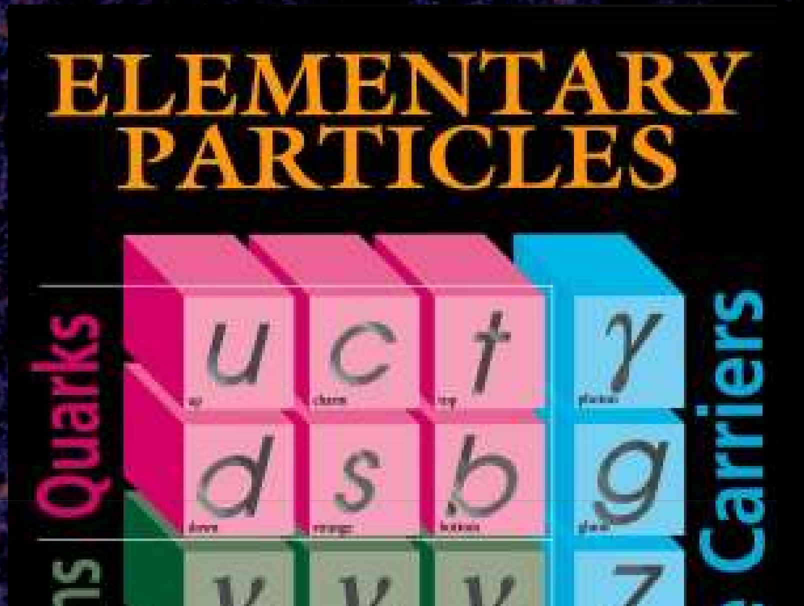


- ➢ During my career, all the really new discoveries have been in neutrino physics and cosmology!
- ➢ We cannot understand particle physics without understanding neutrinos.
- ➢ We will not get this information from any other source, we must build more neutrino experiments.

A Historic Anniversary…

Progress of Theoretical Physics, Vol. 28, No. 5, November 1962

Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya

(Received June 25, 1962)

a) The weak neutrinos must be re-defined by a relation

$$\left.\begin{aligned} \nu_e &= \nu_1 \cos\delta - \nu_2 \sin\delta, \\ \nu_\mu &= \nu_1 \sin\delta + \nu_2 \cos\delta. \end{aligned}\right\} \qquad (2\cdot18)$$

The leptonic weak current (2·9) turns out to be of the same form with (2·1). In the present case, however, weak neutrinos are *not stable* due to the occurrence of a virtual transmutation $\nu_e \rightleftarrows \nu_\mu$ induced by the interaction (2·10). If the mass difference between ν_2 and ν_1, i.e. $|m_{\nu_2} - m_{\nu_1}| = m_{\nu_2}$*) is assumed to be a few Mev, the transmutation time $T(\nu_e \rightleftarrows \nu_\mu)$ becomes $\sim 10^{-18}$ sec for fast neutrinos with a momentum of $\sim$Bev/c. Therefore, a chain of reactions such as[10)]

$$\pi^+ \to \mu^+ + \nu_\mu, \qquad (2\cdot19a)$$

$$\nu_\mu + Z(\text{nucleus}) \to Z' + (\mu^- \text{ and/or } e^-) \qquad (2\cdot19b)$$

is useful to check the two-neutrino hypothesis only when $|m_{\nu_2} - m_{\nu_1}| \lesssim 10^{-6}$ Mev

From Nakaya-san's talk at Nu2012

51 *years ago*

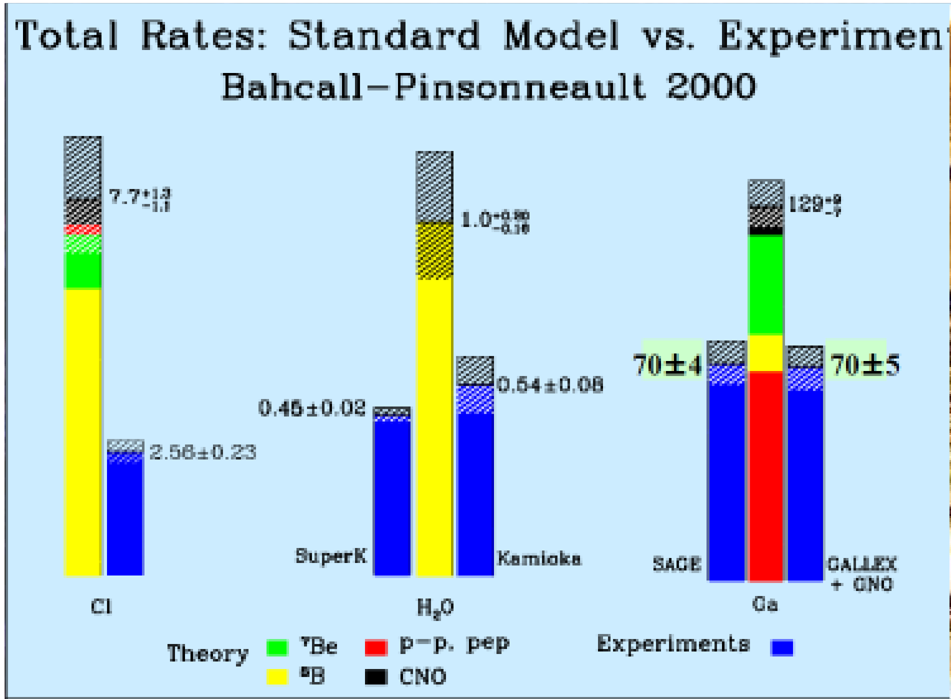
weak neutrinos:

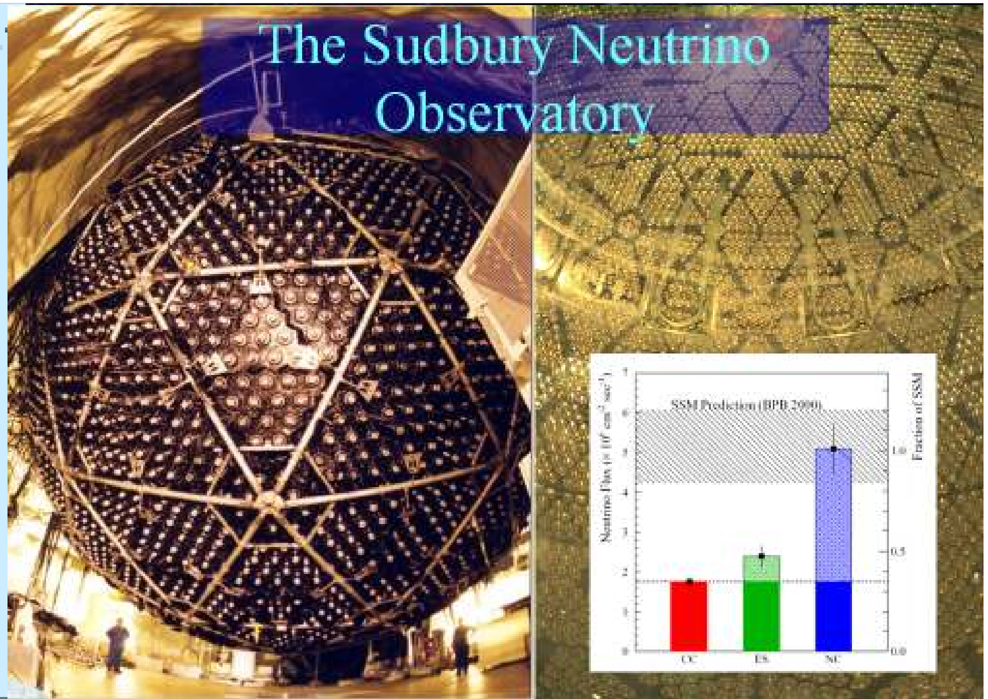
ν_e, ν_μ, ν_τ

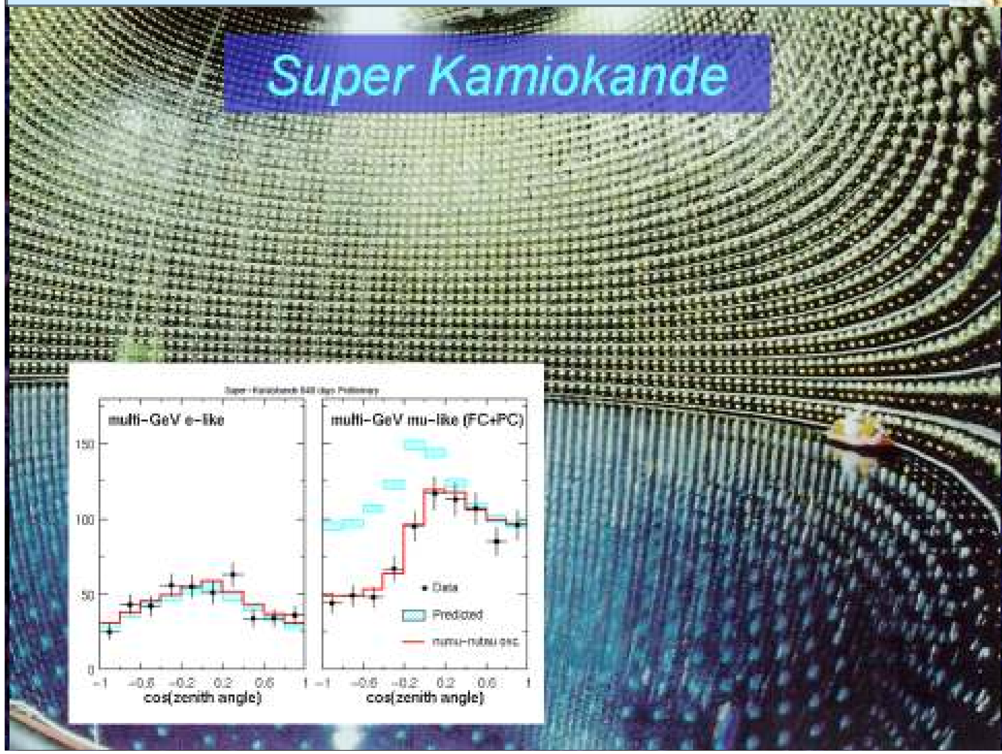
are not stable

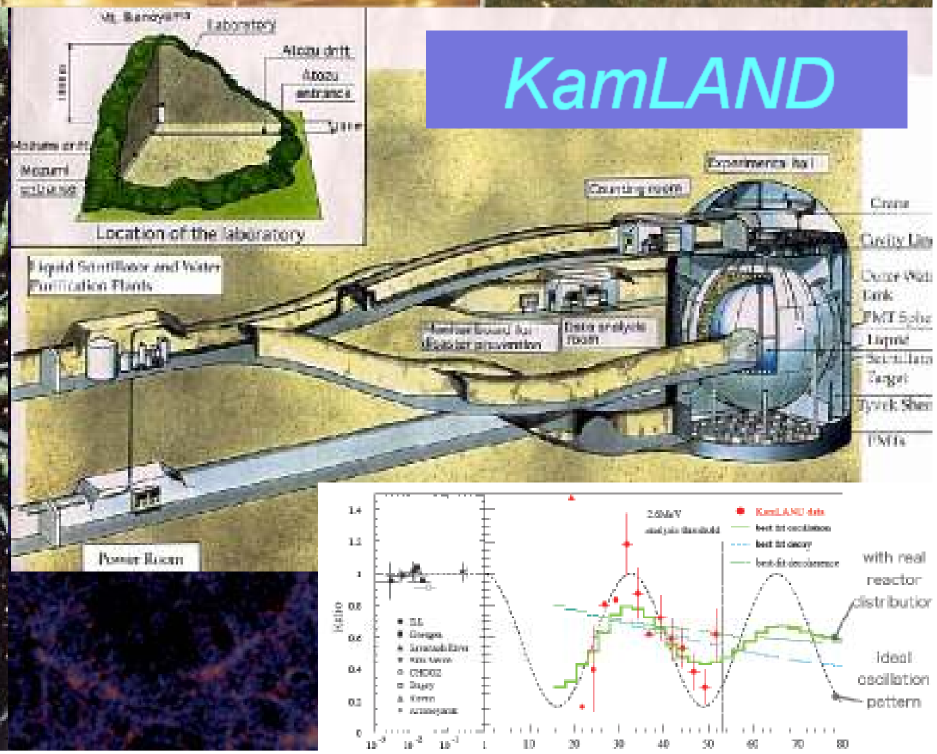
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U_{PMNS}: Pontecorvo–Maki–Nakagawa–Sakata matrix


Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
7.7+1.3 −1.1
2.56±0.23
1.0+0.08 −0.16
0.45±0.02
0.54±0.08
129+8 −7
70±4
70±5
SuperK
Kamioka
SAGE
GALLEX + GNO
Cl
H2O
Ga
Theory
7Be
8B
p-p, pep
CNO
Experiments


The Sudbury Neutrino Observatory
SSM Prediction (BPB 2000)
CC
ES
NC


Super Kamiokande
multi-GeV e-like
multi-GeV mu-like (FC+PC)
Data
Predicted
cos(zenith angle)
cos(zenith angle)


KamLAND
Laboratory
Location of the laboratory
Liquid Scintillator and Water Purification Plants
Experiments hall
Counting room
Data analysis room
Power Room
Crane
PMTs
KamLAND data
with real reactor distribution
ideal oscillation pattern

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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 $c_{ij} = \cos\theta_{ij}$

CP sensitivity mainly because this term flips sign for ν and anti-ν

Complicated equation means covariances and degeneracies!

$$\ldots \frac{\Delta m^2_{31} L}{4E} \times \left(1 + \frac{2a}{\Delta m^2_{31}} (1 - 2S^2_{13})\right)$$

$$+8C^2_{13}S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E}$$

$$-8C^2_{13}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E}$$

$$+4S^2_{12}C^2_{13}\{C^2_{12}C^2_{23} + S^2_{12}S^2_{23}S^2_{13} - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

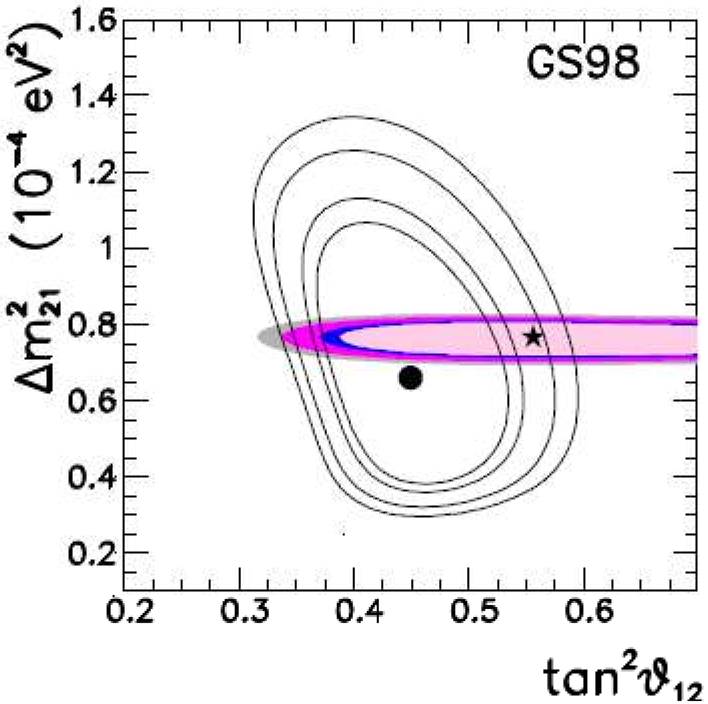
$$-8C^2_{13}S^2_{13}S^2_{23}\cos\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\frac{aL}{4E}(1 - 2S^2_{13})$$

Need Matter effects to get the signs of Δm^2_{ij}

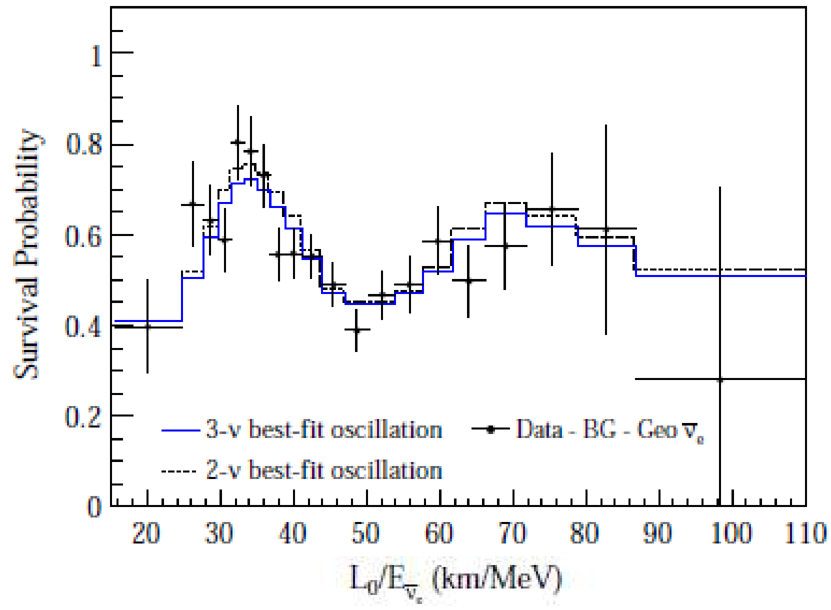
How well do we know θ_{12}?

Gonzalez-Garcia, Maltoni, Salvado, Schwetz

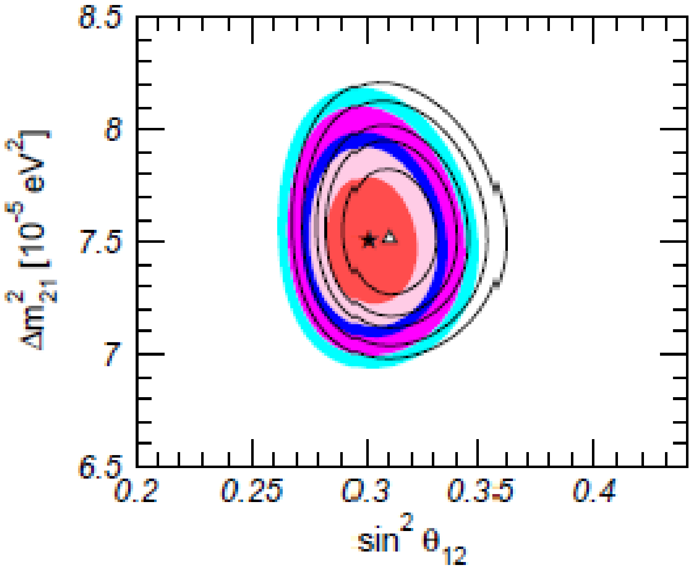
arXiv:1001.4524v4 [hep-ph]



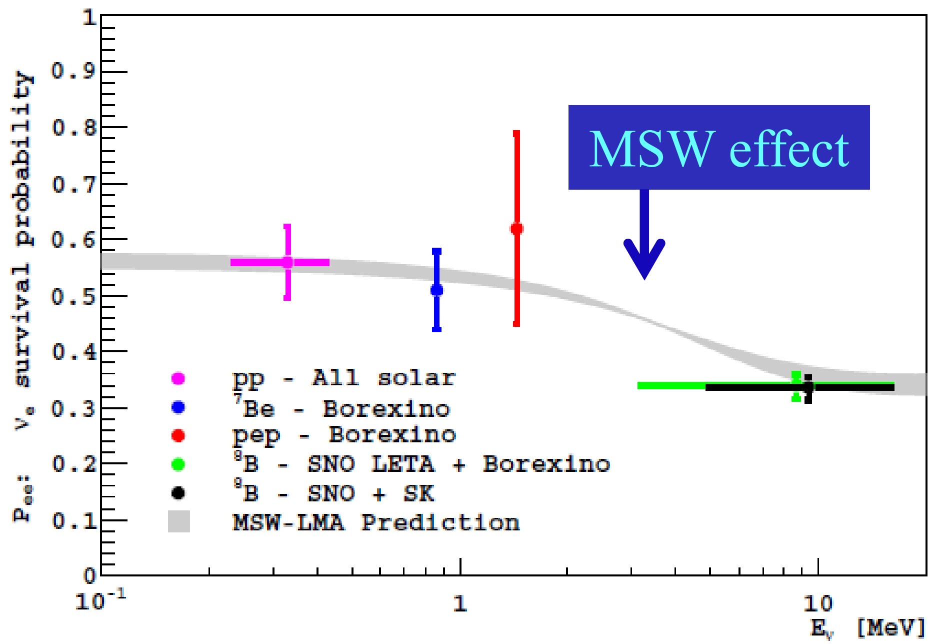
arXiv:1009.4771v3 [hep-ex] 25 Mar 2011



arXiv:1209.3023v2 [hep-ph]



arXiv:1110.3230v1 [hep-ex]



T2K
Just the most recent realization of the
experiment of Steinberger, Schwartz, Lederman et al.
Tsu
Nagoya
Gifu
Gifu
E133°
E137°
Nagano
Japan
Kofu
E139°
Niigata
Sado
Saitama
Tokyo
Honshu
N37°
Mito
J-PARC
N35°
E141°
Downstream ECAL
Solenoid Coil
P0D ECAL
Barrel ECAL
© 2007 ZENRIN
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

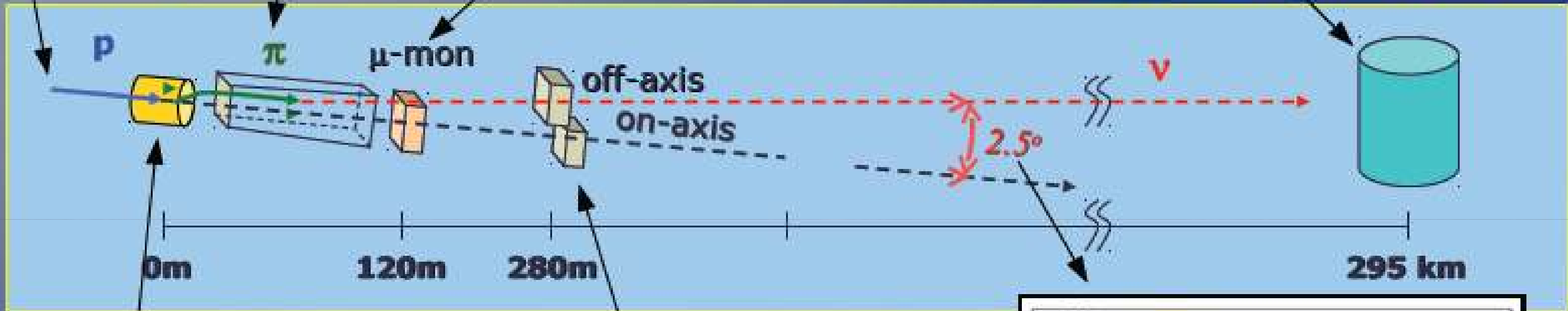
T2K Overview

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



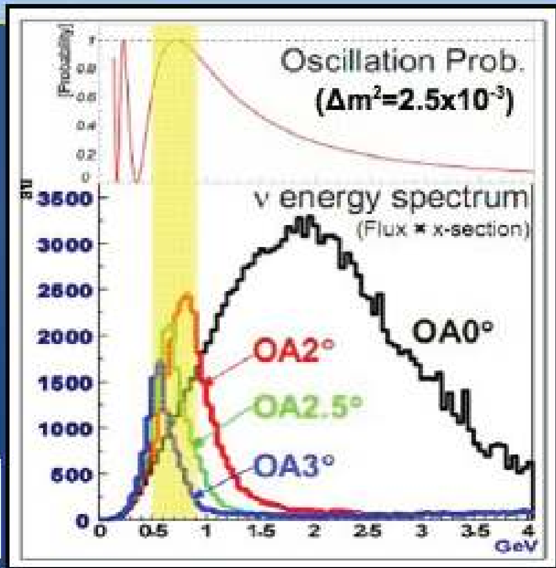
Beam on 90 cm graphite target

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



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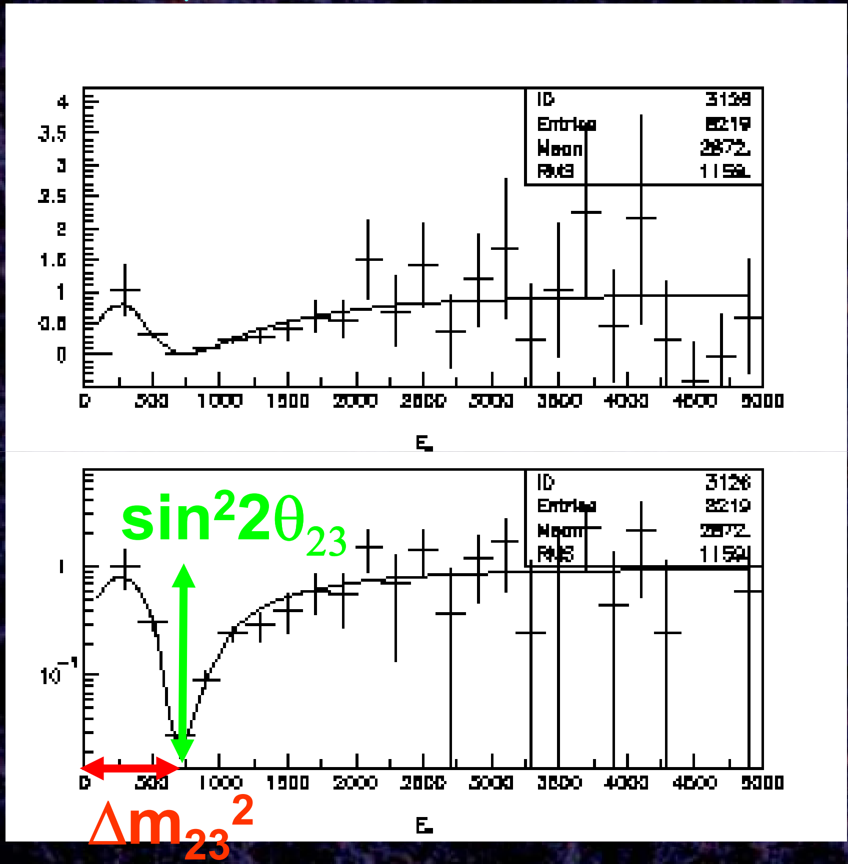
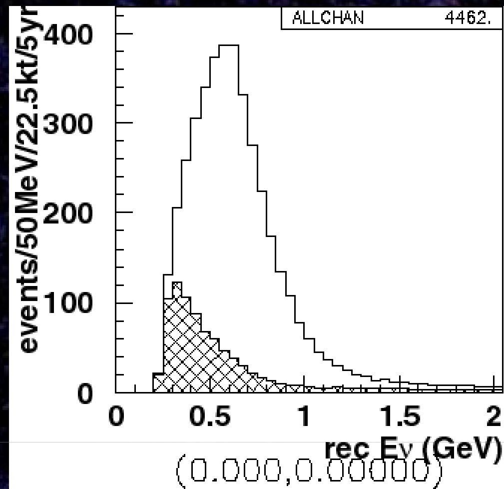
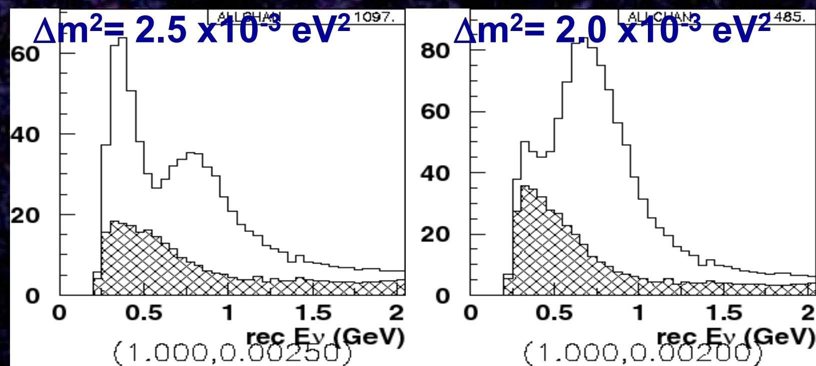
What are we trying to measure?

ν_μ disappearance



No oscillation





Precision measurements

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

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

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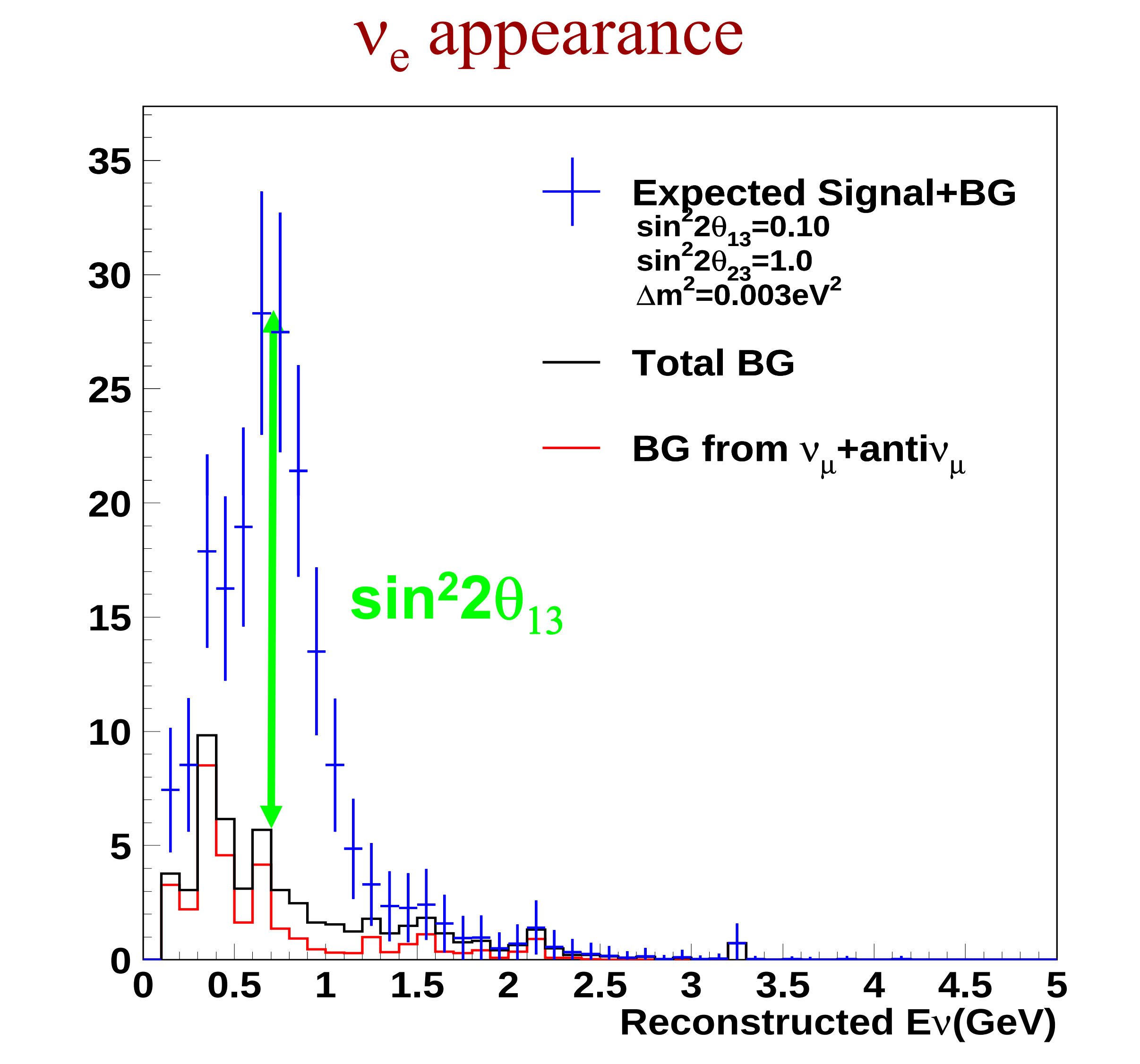
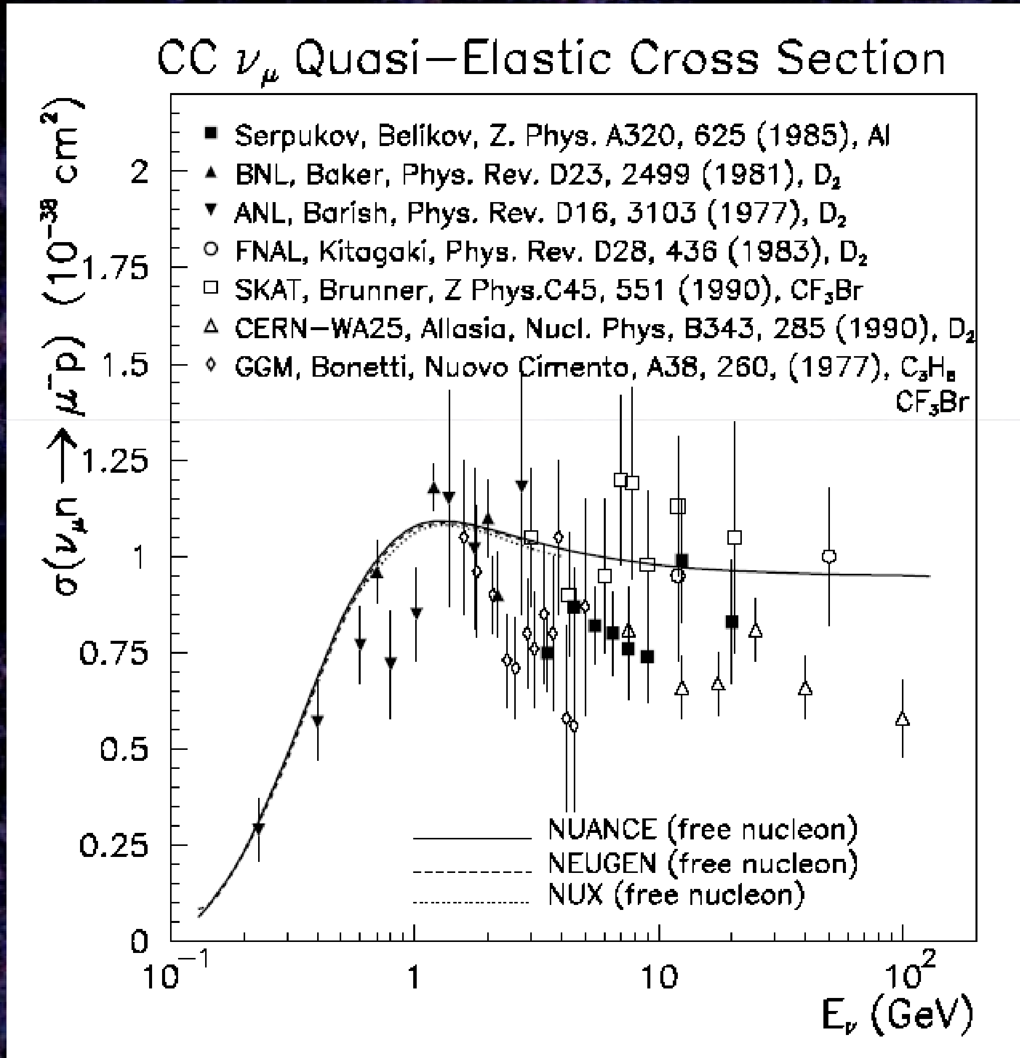
What are we trying to measure?



Cross sections are poorly known in range 0.1-10 GeV

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



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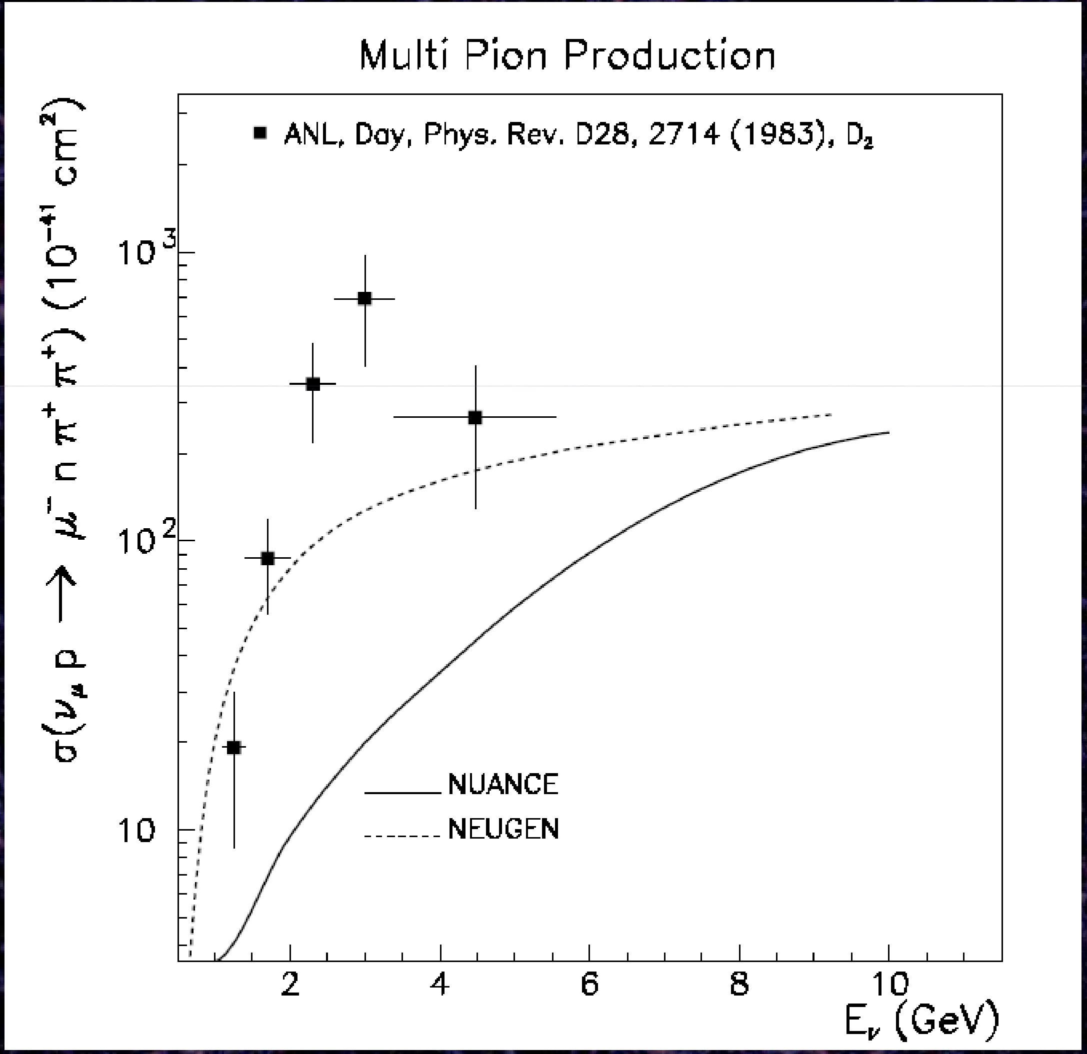
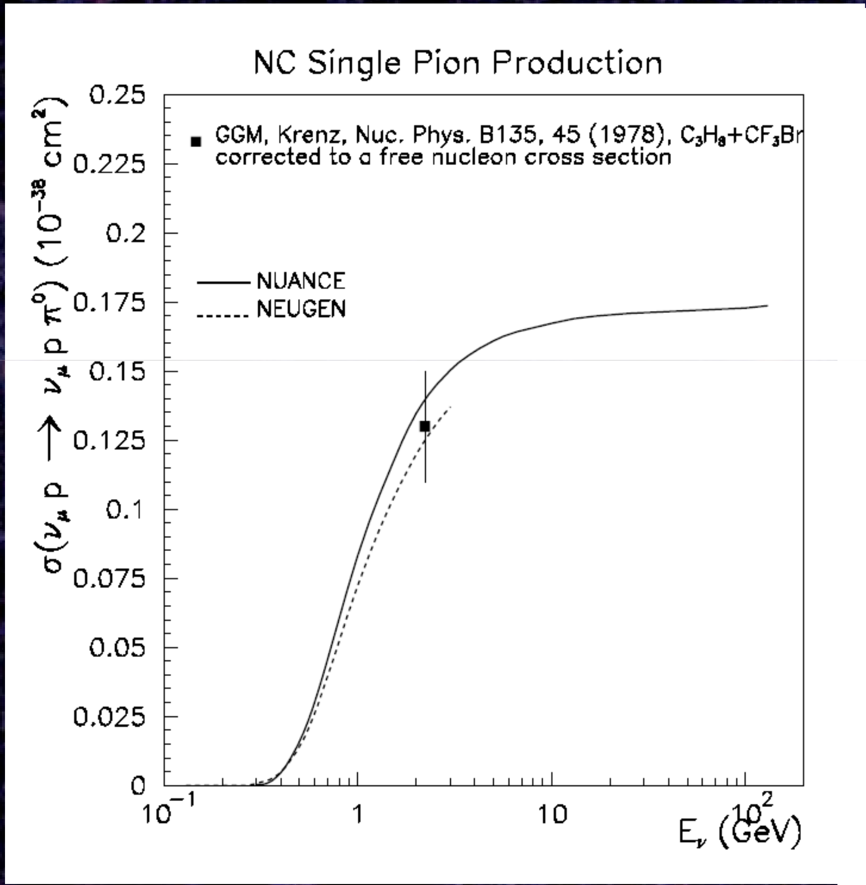
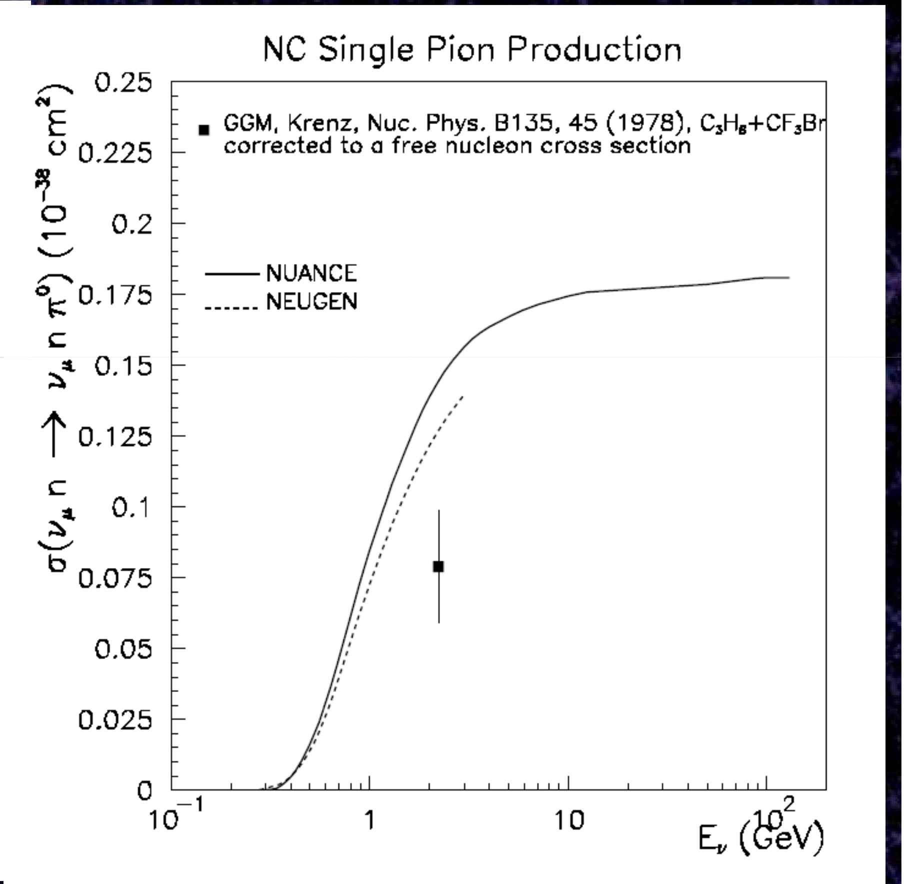


Some are worse than others…

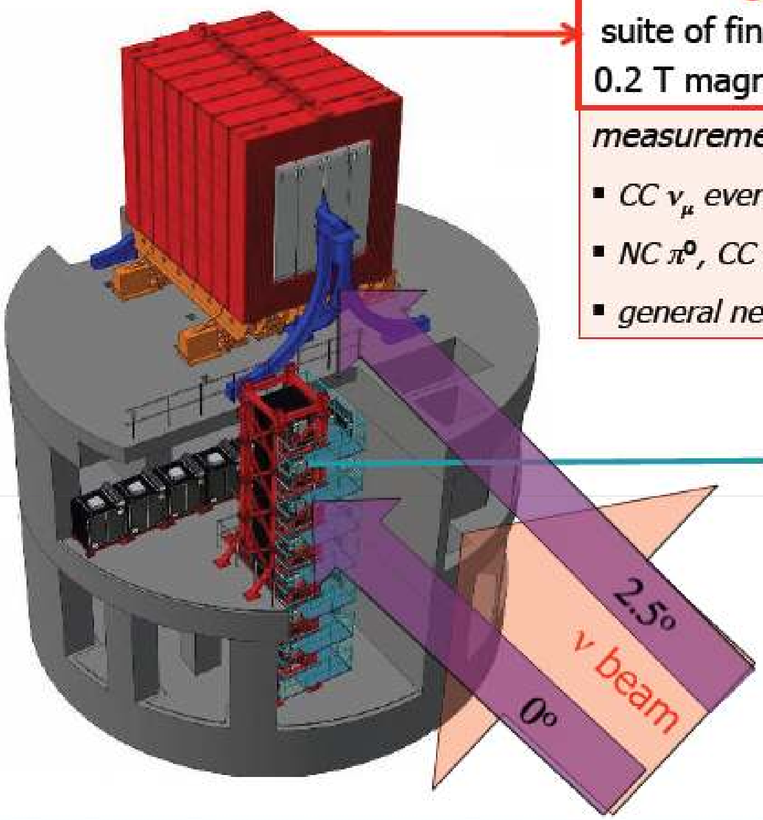
Data compiled by G.Zeller, hep-ex/0312061





ND280 (Near) Detector complex

ND280



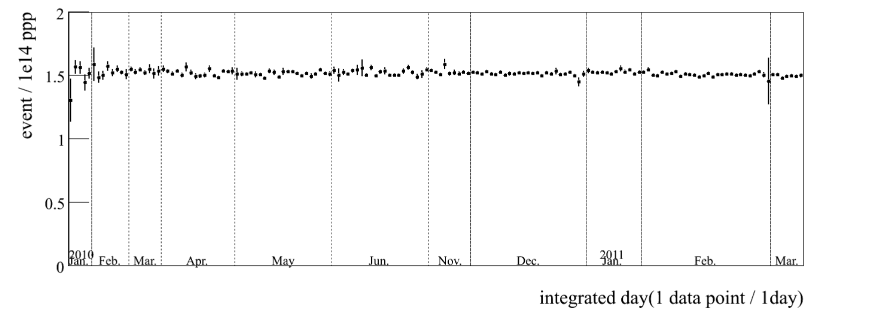
Off-Axis (ND280)
suite of fine grain detectors/tracker in 0.2 T magnetic field (UA1/NOMAD magnet)

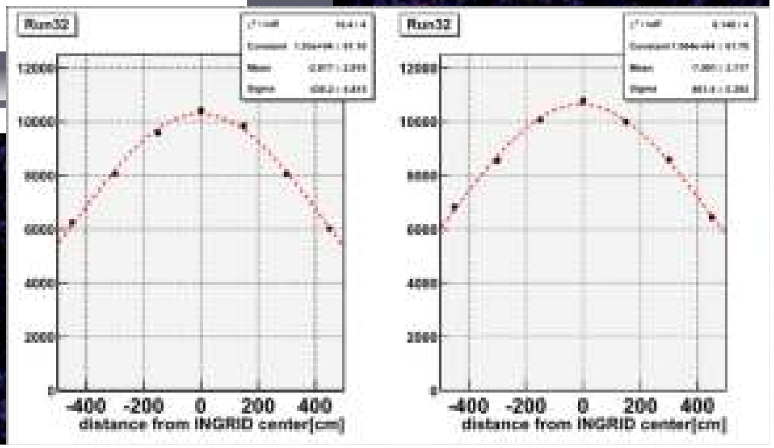
measurements of

- *CC ν_μ events* (normalization, E_ν-spectrum)
- *NC π^0, CC ν_e events* (backgrounds to ν_e appearance)
- *general neutrino interaction properties*

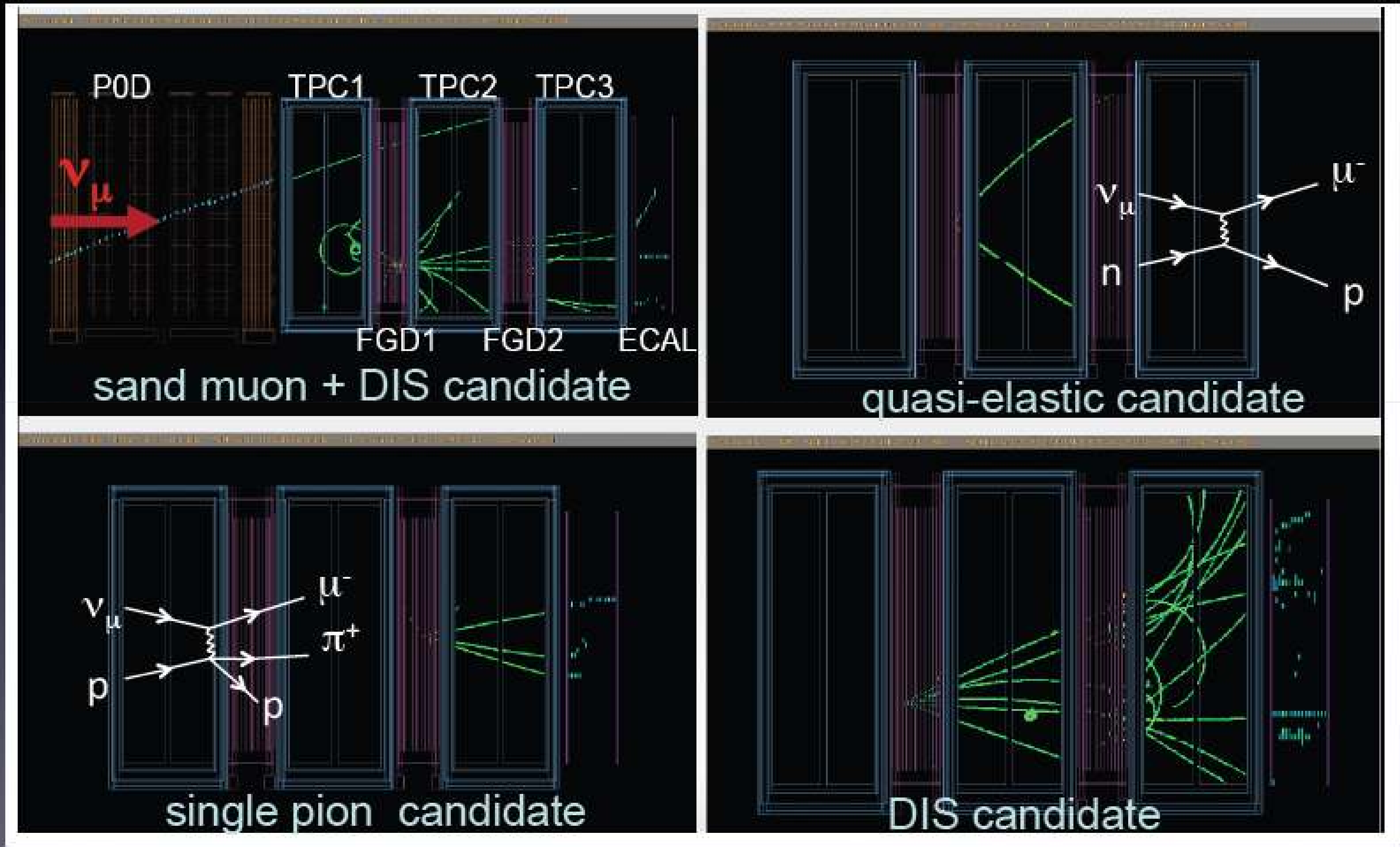
On-axis (INGRID)
scintillator-iron detectors

measurement of beam direction and profile





ND280 off-axis event gallery



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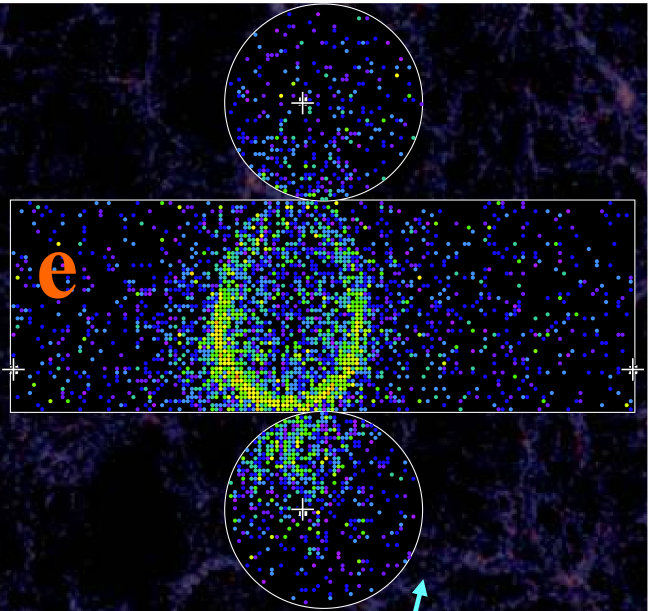
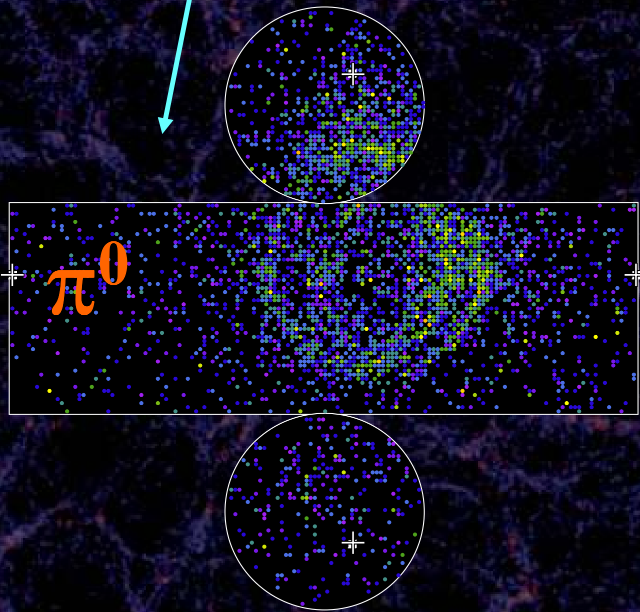
Optimal Far Detector – Super Kamiokande

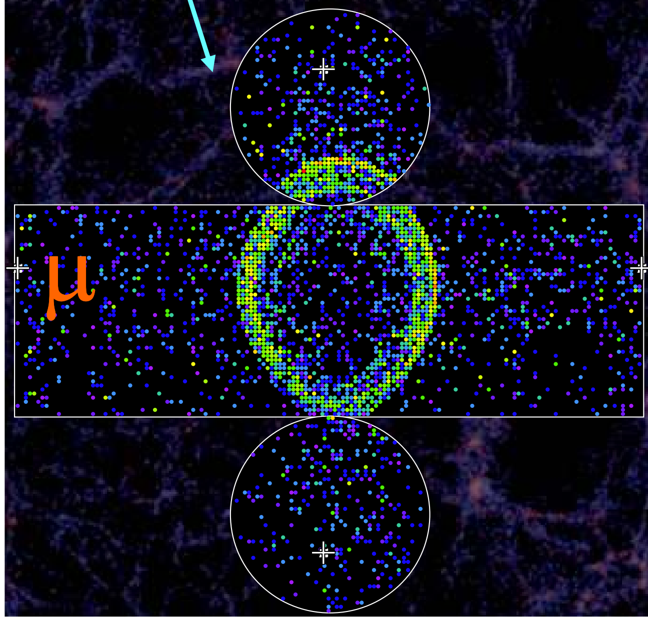
Background from NC interactions



ν_μ disappearance signal



ν_e appearance signal



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

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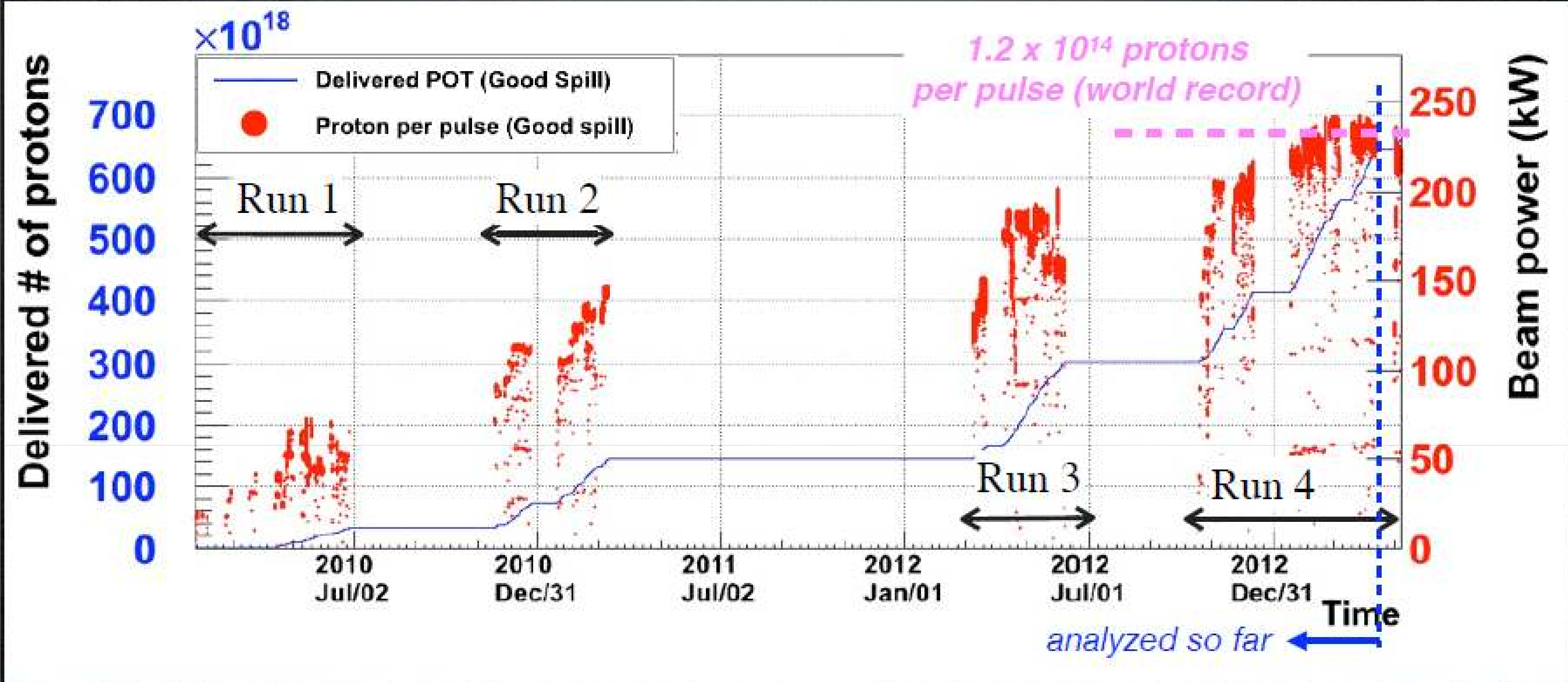
Data Taking (Run 1-4)

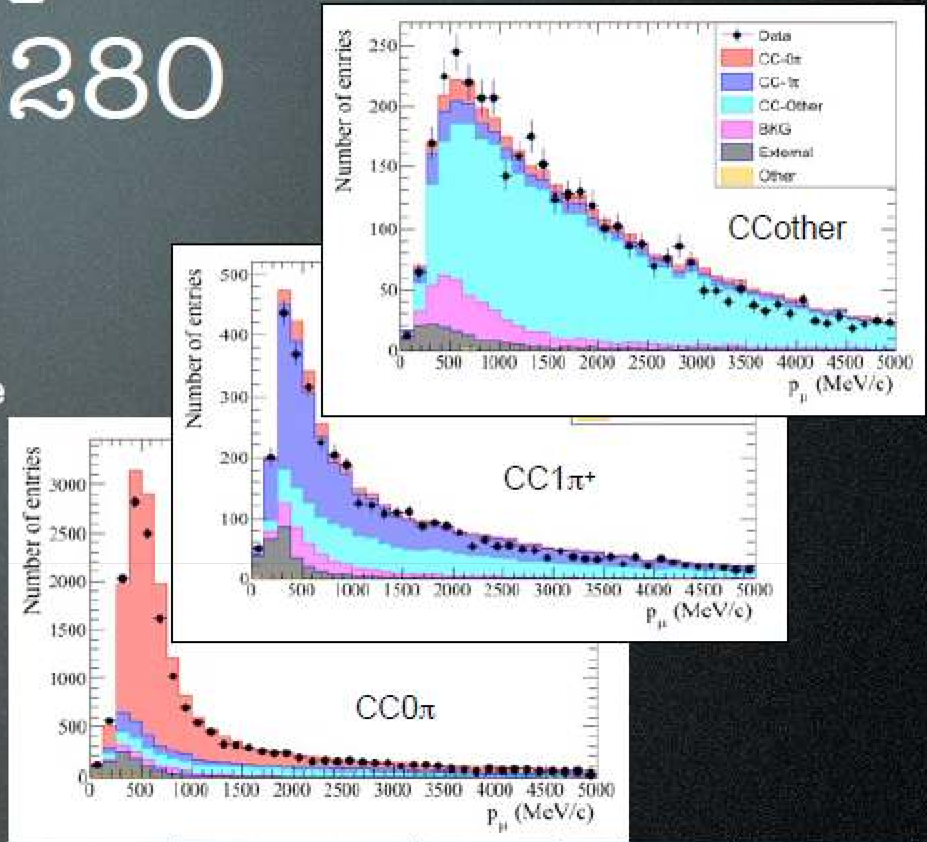


- Today's results are possible due to the efforts of J-PARC accelerator division and other related people.
  - Consistent running at 220 kW for much of Run 4 (**world record protons per pulse**)
- 6.39 * 10^{20} POT analyzed through April 12th (6.63 * 10^{20} through May)
- Previous ν_e appearance result: 3.01 * 10^{20} POT ➜ **Factor of 2.1 increase in statistics**

(relative to 2012 analysis)

Analysis Improvements: ND280

- Separate the CC sample into three subsamples:
  - CC0π: **no pions** in the final state
  - CC1π+: exactly **1 π+** in the final state
  - CCother: **>1 π+** OR **>0 π-** OR **>0 tagged photons**
- Higher purities for all 3 samples, relative to the 2012 analysis
  - Much better samples for constraining CCQE and CCπ+ cross section parameters
- See poster by Raquel Castillo

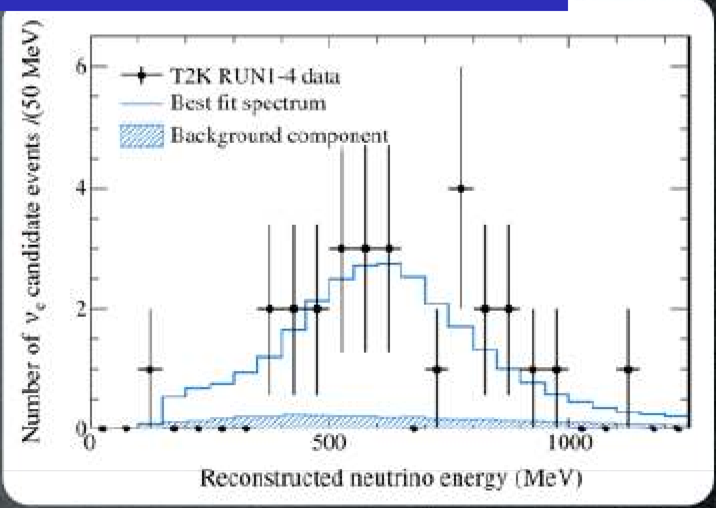


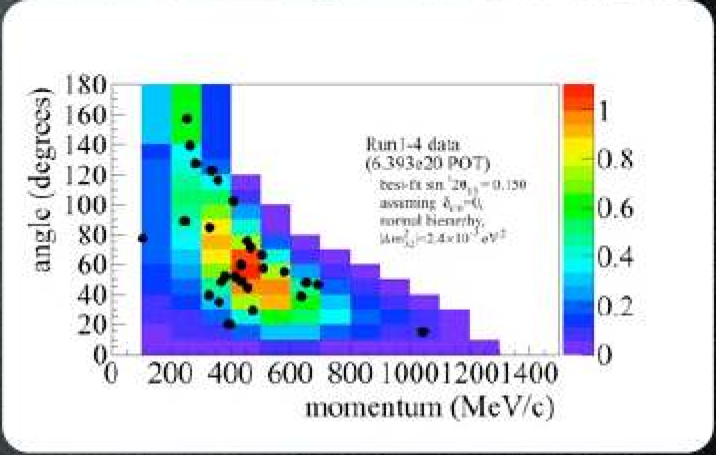
	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-ν)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

ν_e Appearance Analysis

- 4.64 ± 0.53 background events
- 20.4 ± 1.8 events expected
  - For $\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$, and normal mass hierarchy
  - **5.5σ sensitivity to exclude $\theta_{13} = 0$**
- Oscillation parameters were extracted in 2 different ways:
  - using the E_ν distribution
  - using the p-θ distribution

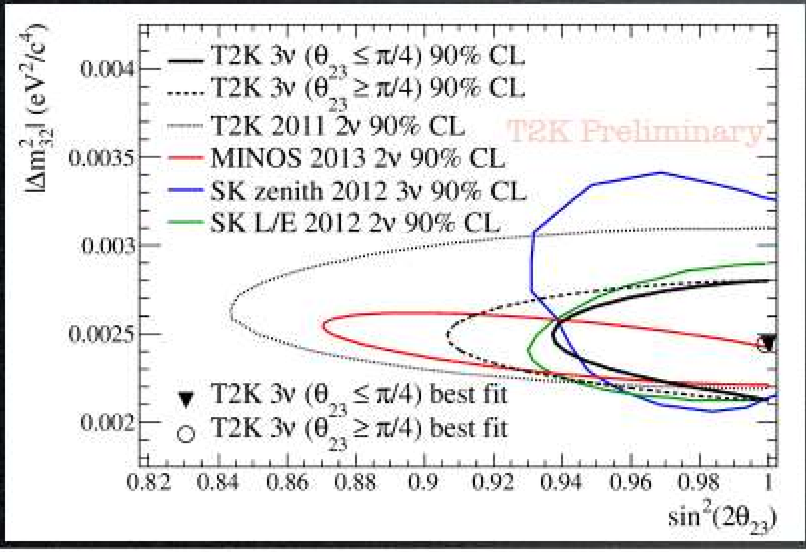
Not in fit NB: 8.8% uncertainty…

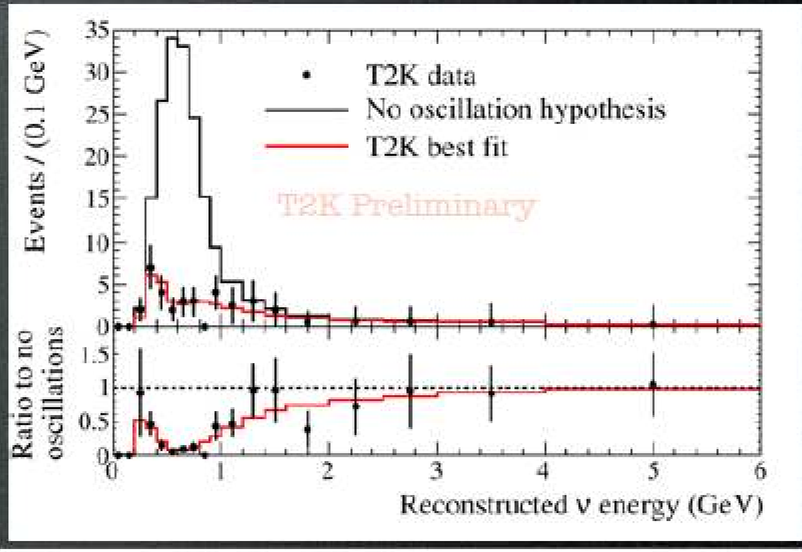




Updated ν_μ Disappearance Results

- Preliminary results using Run 1-3 data ($3.01 * 10^{20}$ POT) were first shown earlier this year
- Previous contours for $\sin^2 2\theta_{23}$ assumed $\theta_{23} < \pi/4$ (first octant)
  - However, octant choice can significantly affect the shape of the 90% C.L. contour
- Contours for both octants are now provided (below)
- In the future, results will be reported in $\sin^2\theta_{23}$ rather than $\sin^2 2\theta_{23}$

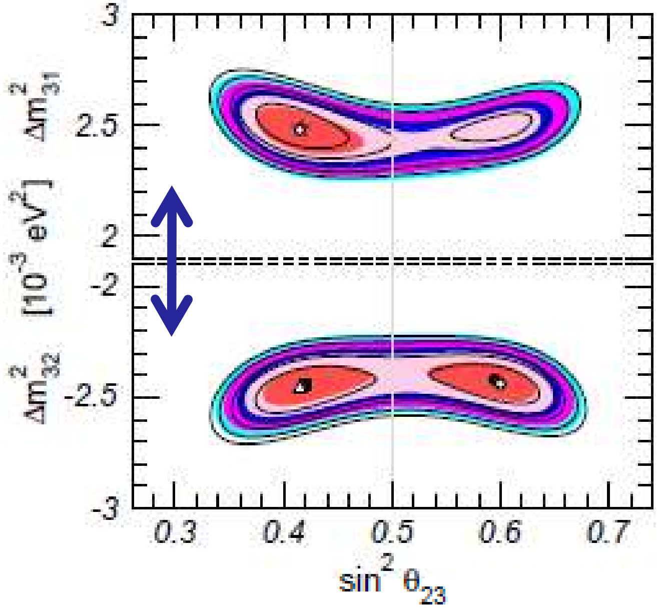


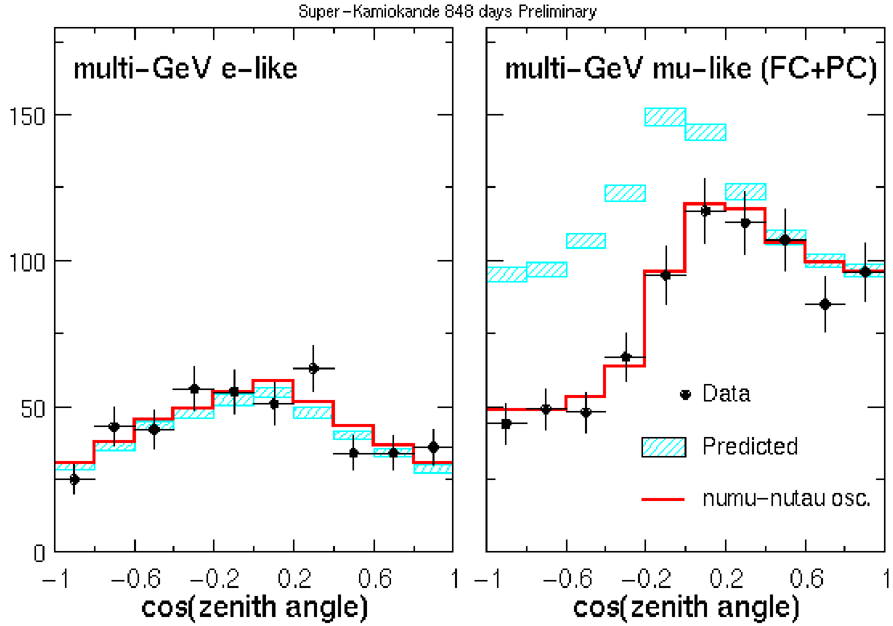


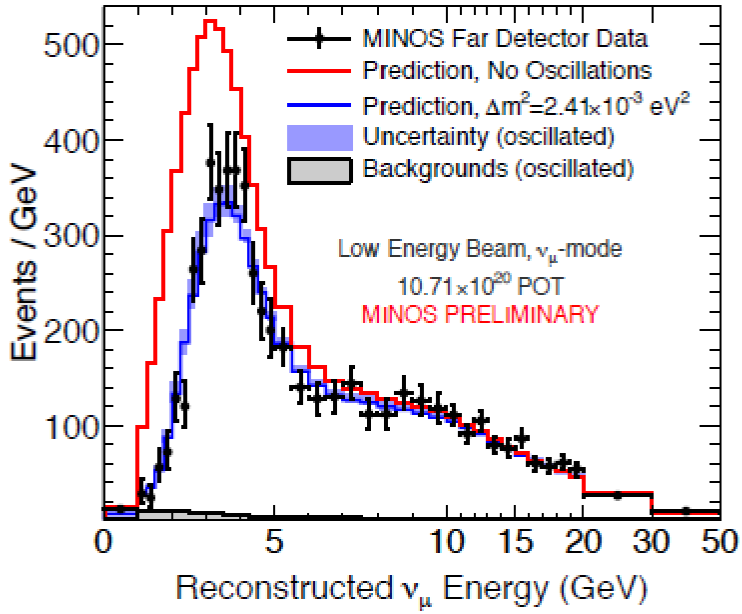
How well do we know θ_{23}?

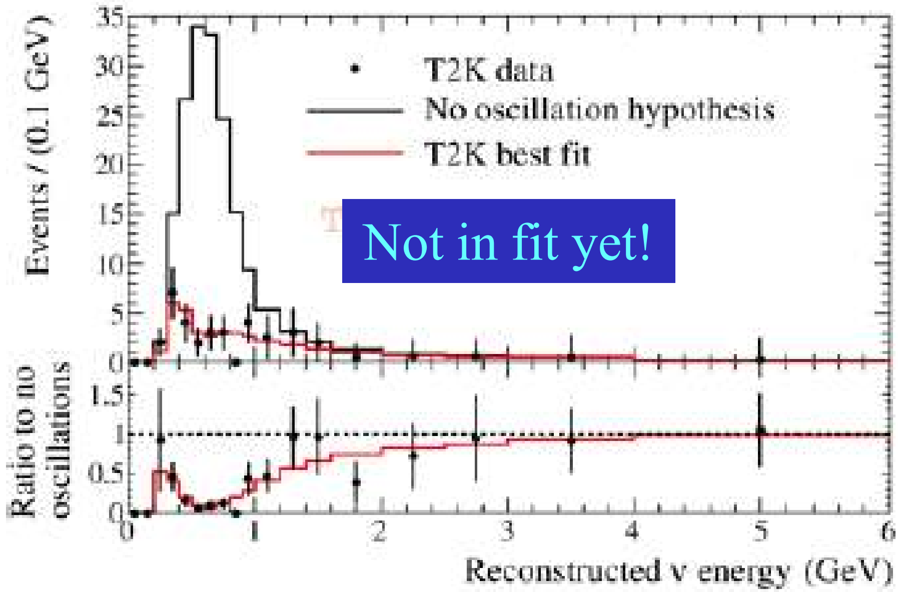
Gonzalez-Garcia, Maltoni, Salvado, Schwetz

arXiv:1209.3023v2 [hep-ph]





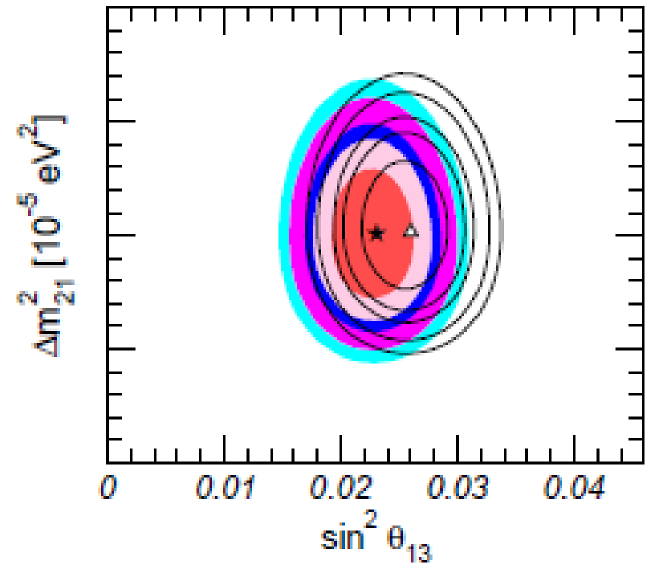


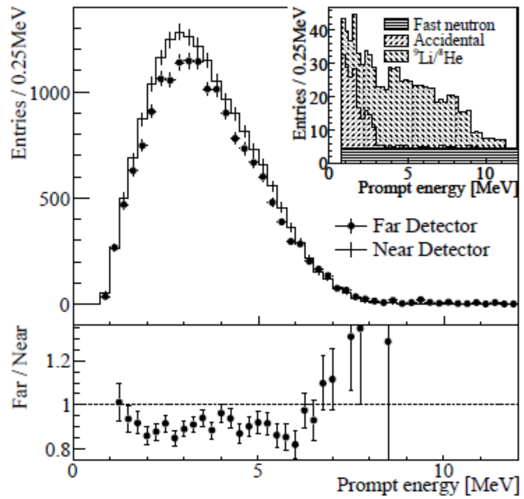


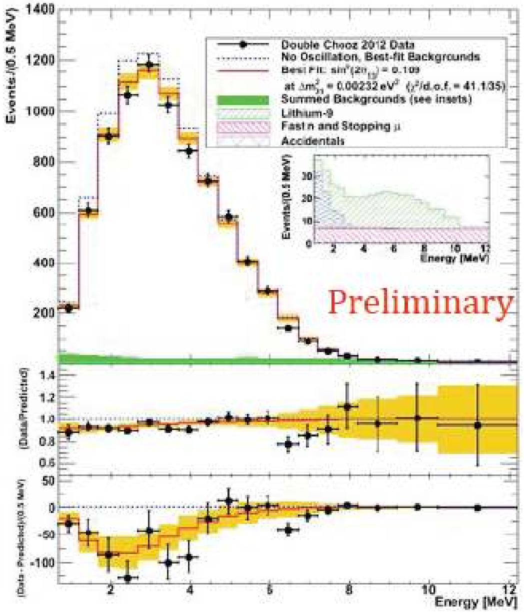
How well do we know θ_{13}?

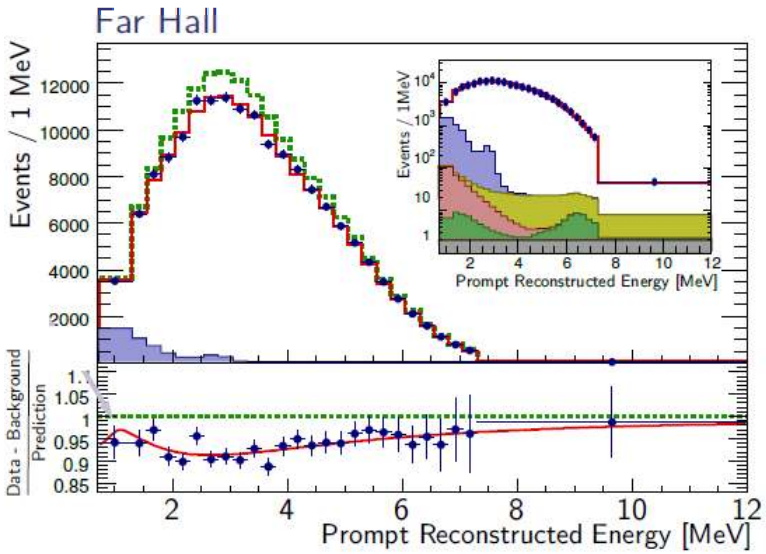
Gonzalez-Garcia, Maltoni, Salvado, Schwetz

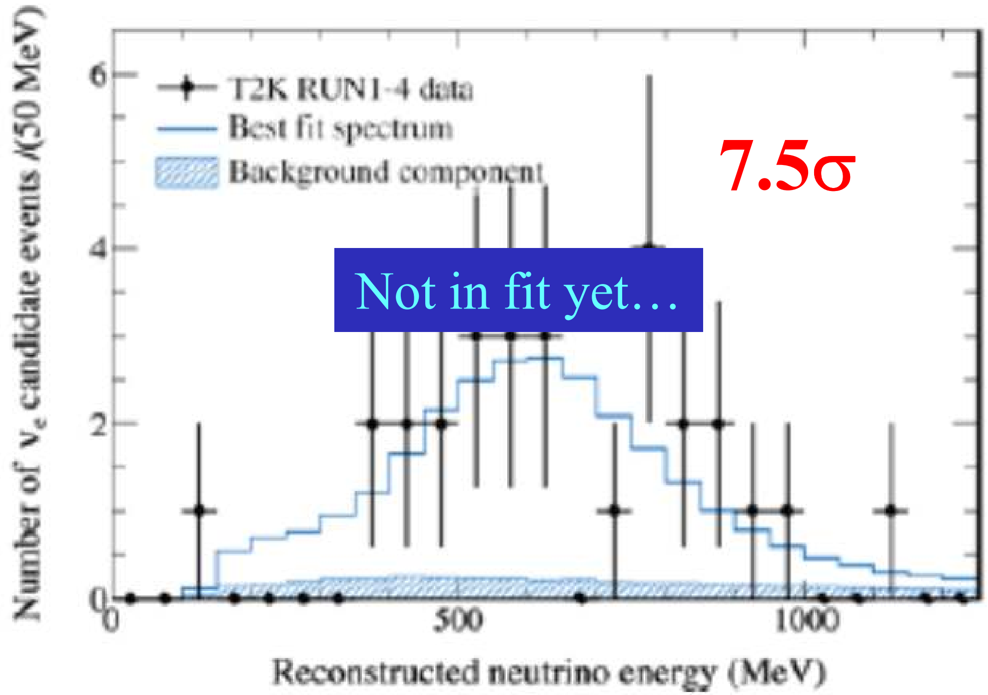
arXiv:1209.3023v2 [hep-ph]











7.5σ

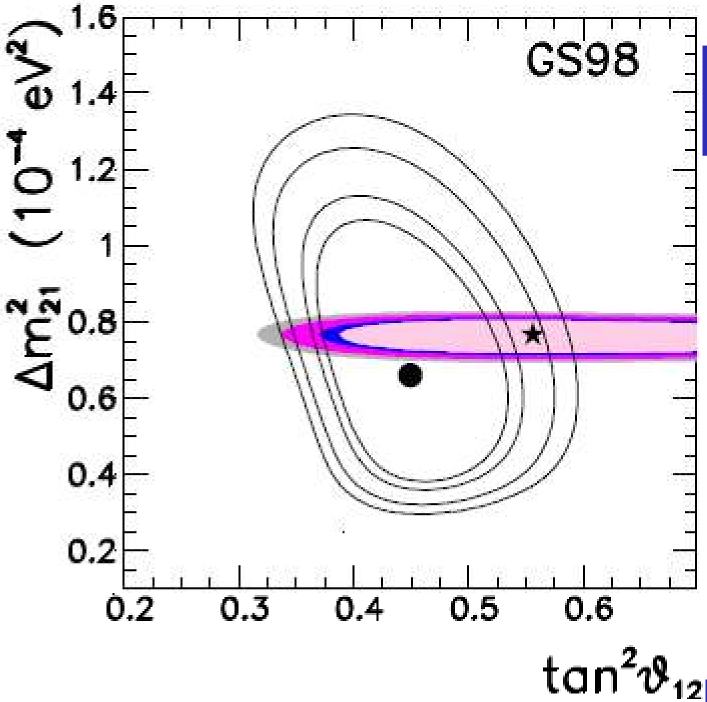
Not in fit yet…

Daya Bay rate plus shape –
New at Nufact13, not in fit yet…

How well do we know θ_{12}?

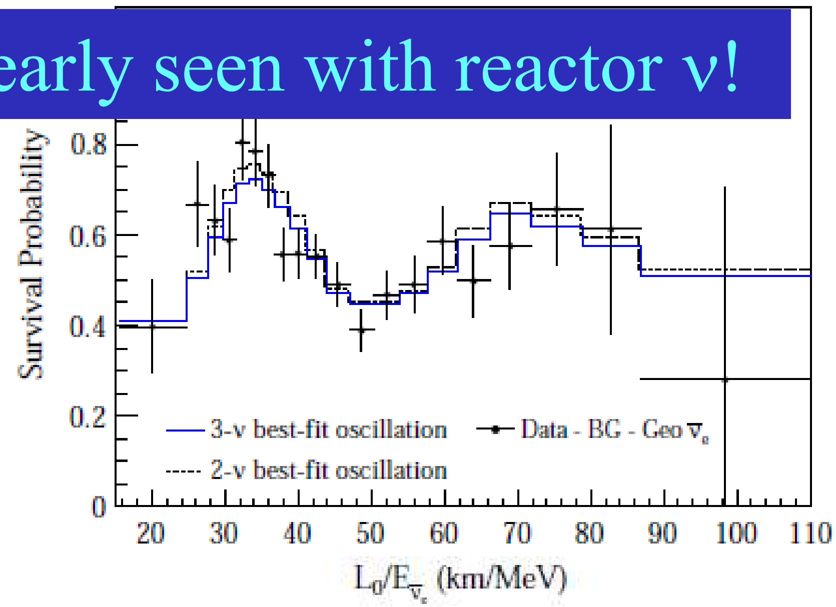
Gonzalez-Garcia, Maltoni, Salvado, Schwetz

arXiv:1001.4524v4 [hep-ph]

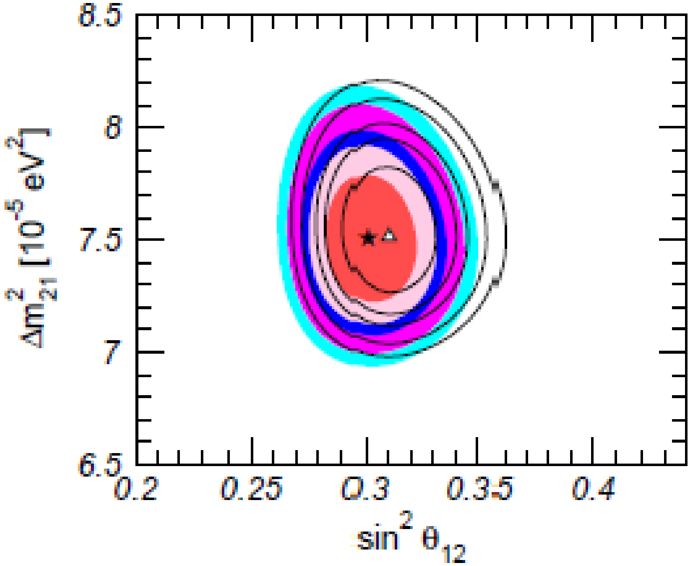


arXiv:1009.4771v3 [hep-ex] 25 Mar 2011

Clearly seen with reactor ν!

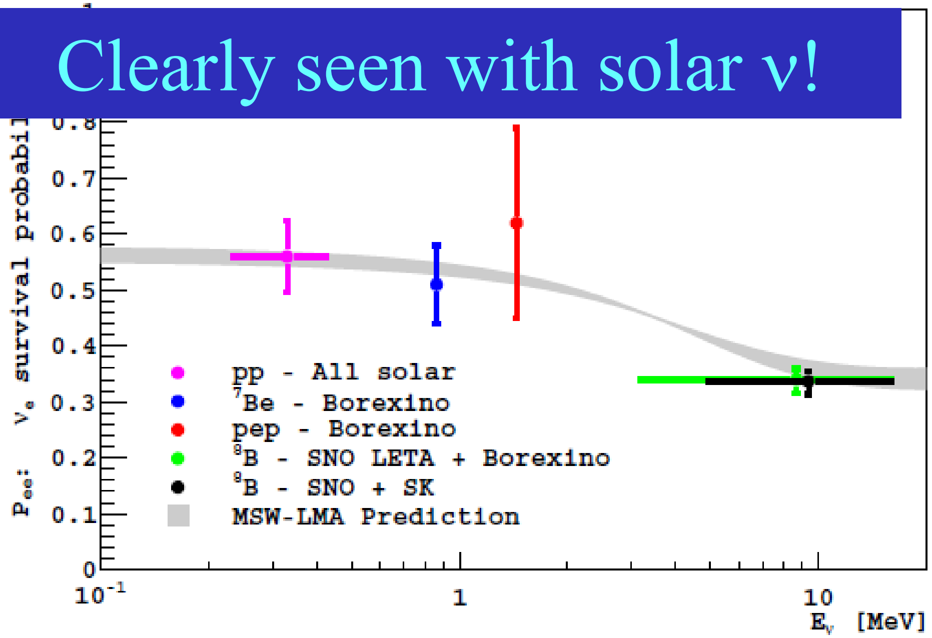


arXiv:1209.3023v2 [hep-ph]



arXiv:1110.3230v1 [hep-ex]

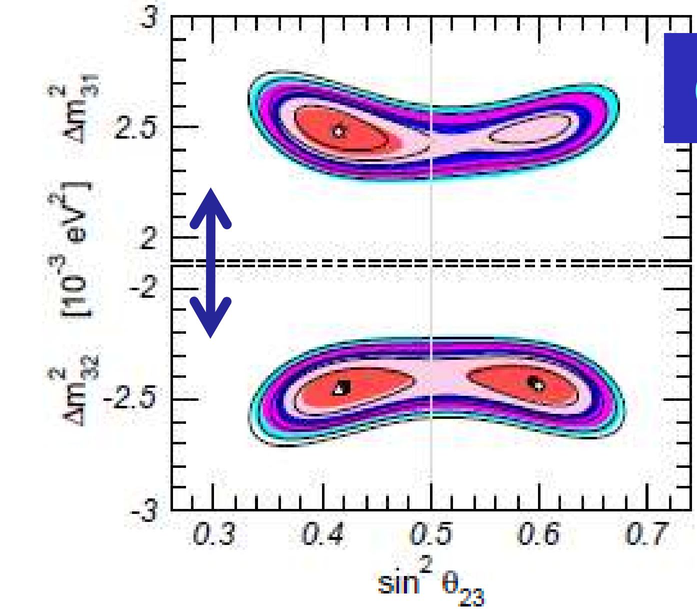
Clearly seen with solar ν!

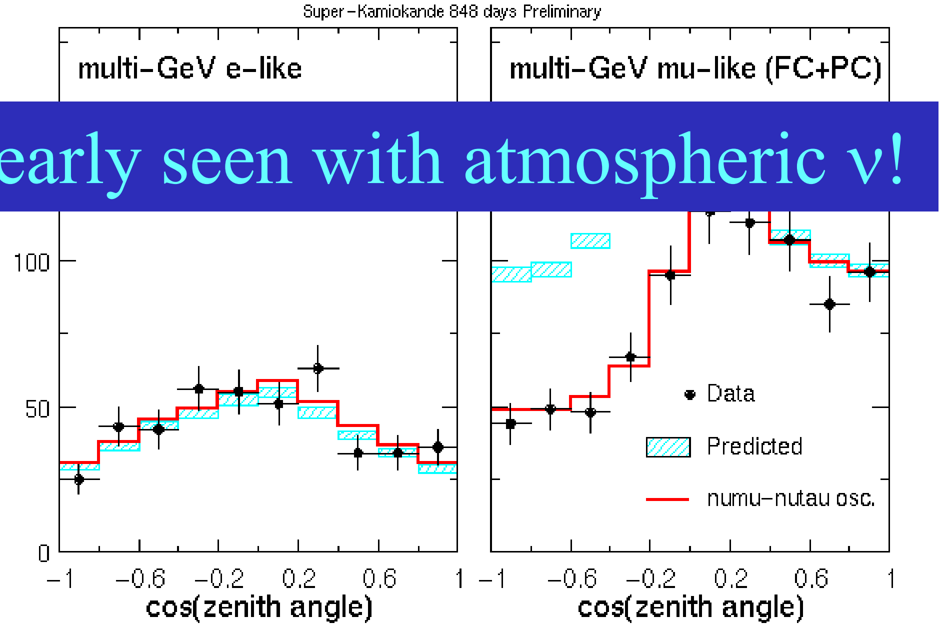


How well do we know θ_{23}?

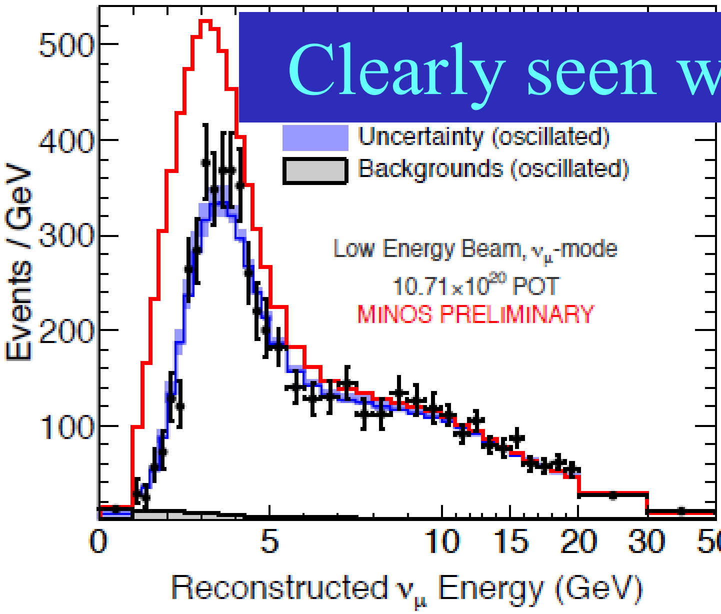
Gonzalez-Garcia, Maltoni, Salvado, Schwetz

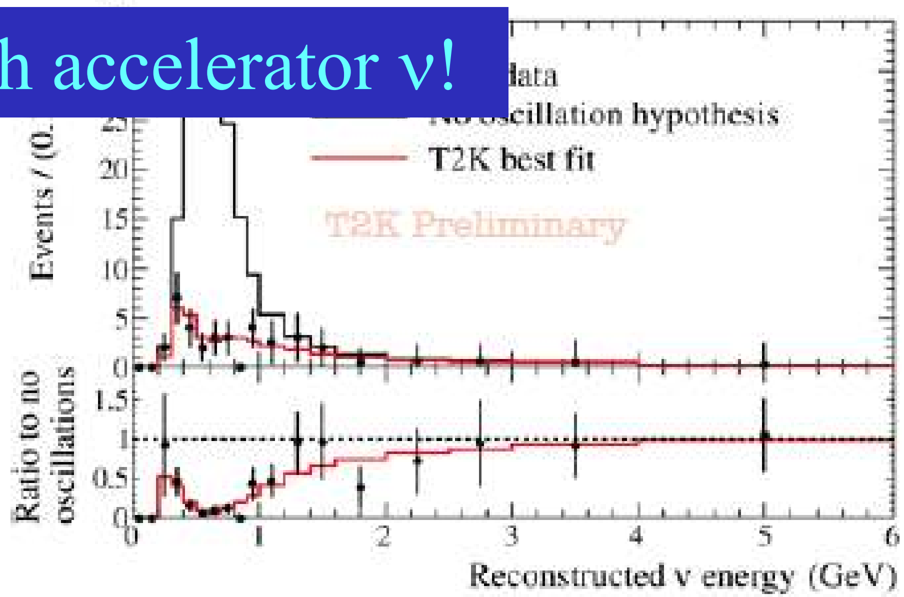
arXiv:1209.3023v2 [hep-ph]





Clearly seen with atmospheric ν!



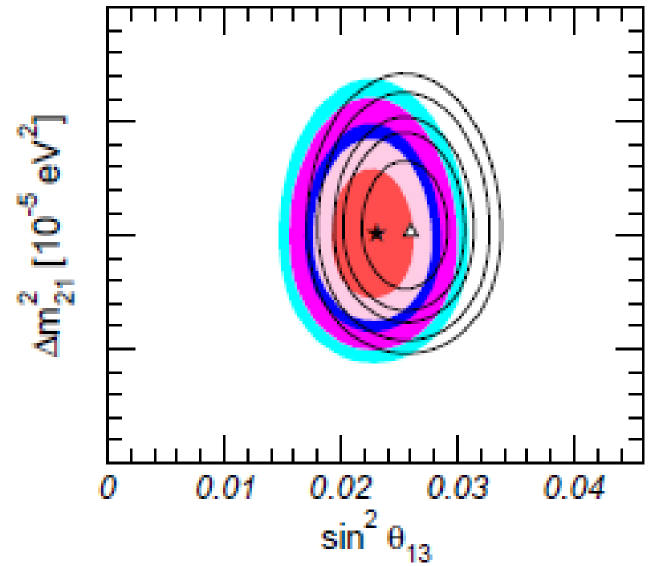


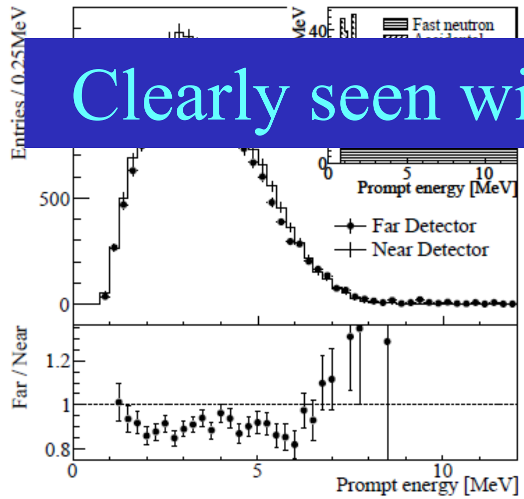
Clearly seen with accelerator ν!

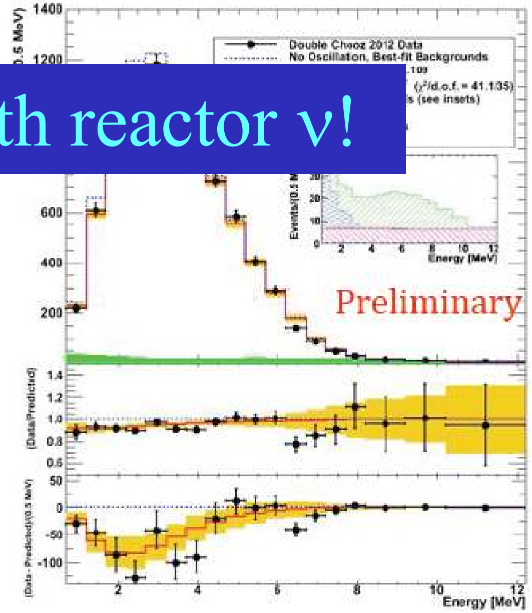
How well do we know θ_{13}?

Gonzalez-Garcia, Maltoni, Salvado, Schwetz

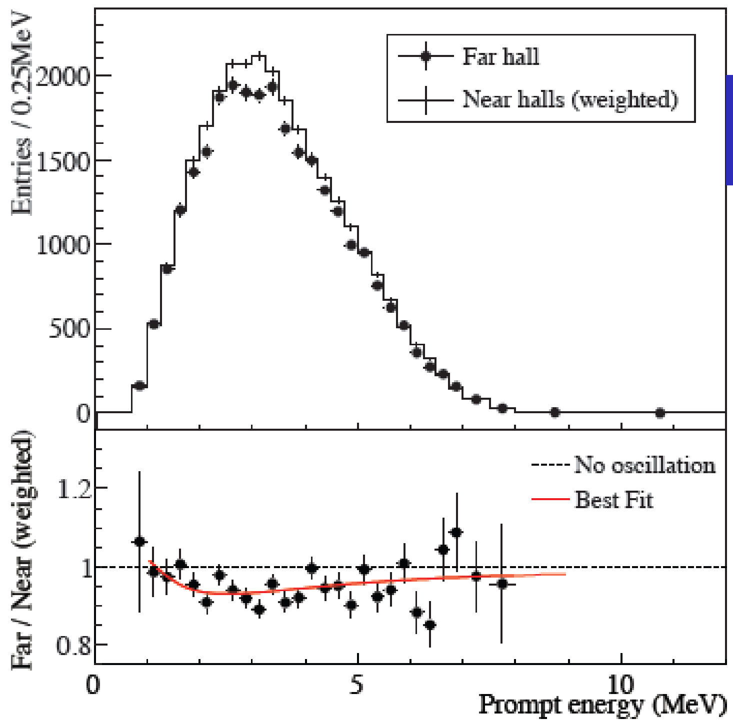
arXiv:1209.3023v2 [hep-ph]

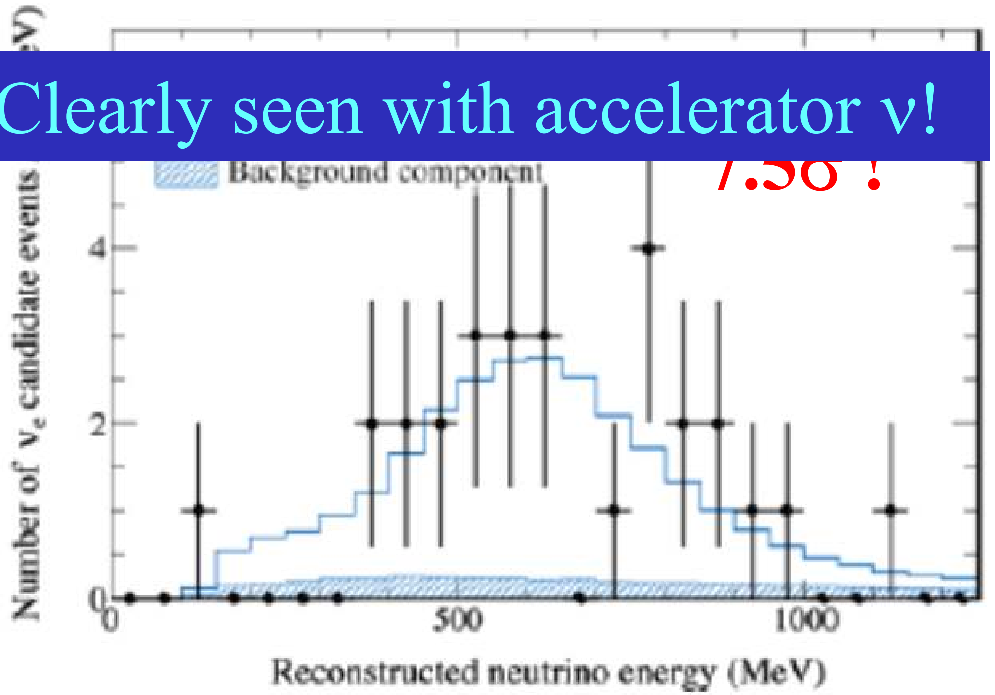






Clearly seen with reactor ν!





Clearly seen with accelerator ν!

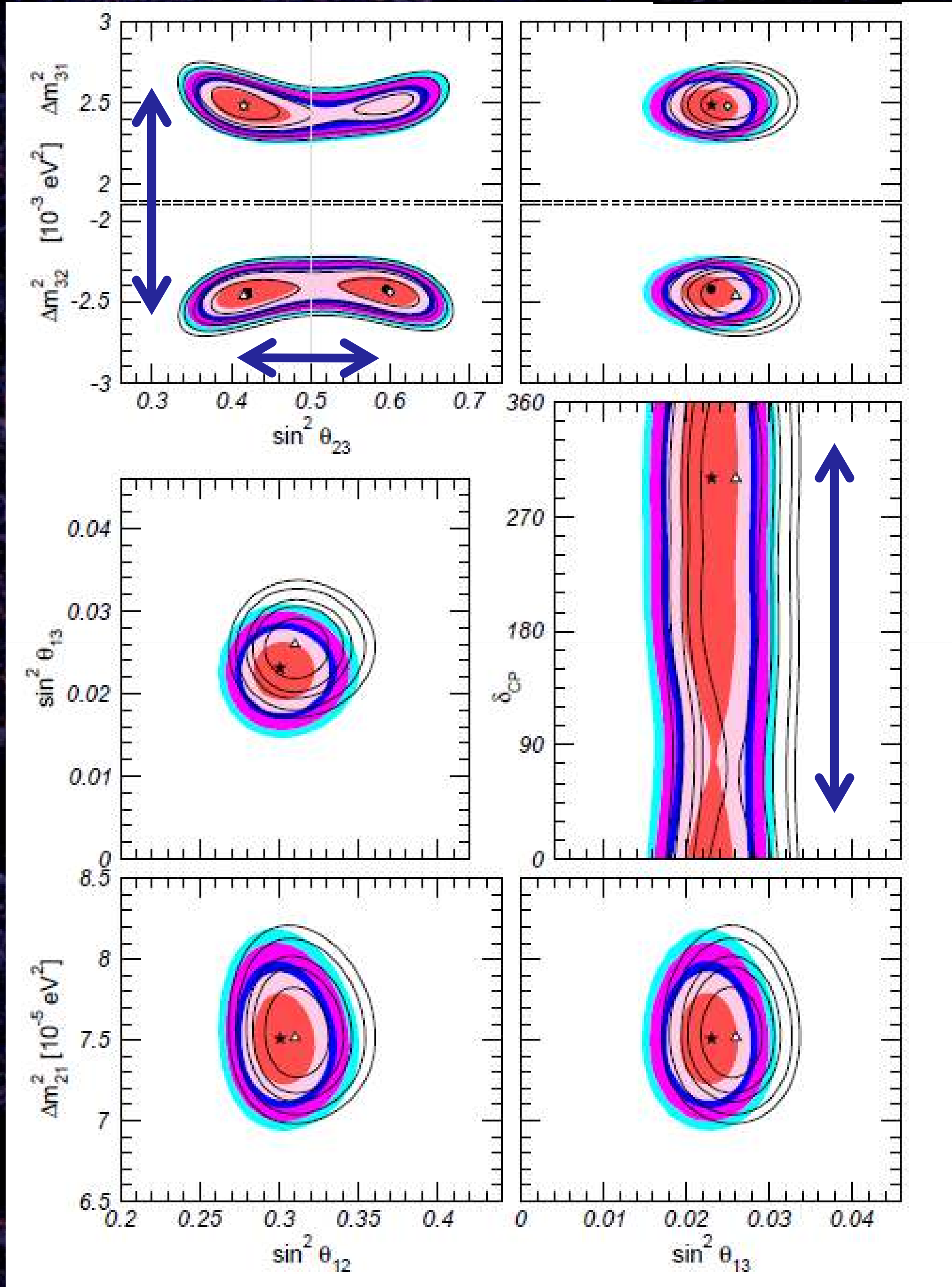
arXiv:1209.3023v2 [hep-ph] 17 Sep 2012

Gonzalez-Garcia,Maltoni,Salvado,Schwetz

What is the MH?

Is θ_{23} maximal?

If $\theta_{23} \neq 45^o$ what is the octant?



What is δ?

How will we learn more? One way:

$$P_{\nu_\mu \to \nu_e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2 \Delta(1-A)}{(1-A)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A^2}$$

$$+ \alpha J \cos(\Delta \pm \delta) \frac{\sin \Delta A}{A} \frac{\sin \Delta(1-A)}{1-A},$$

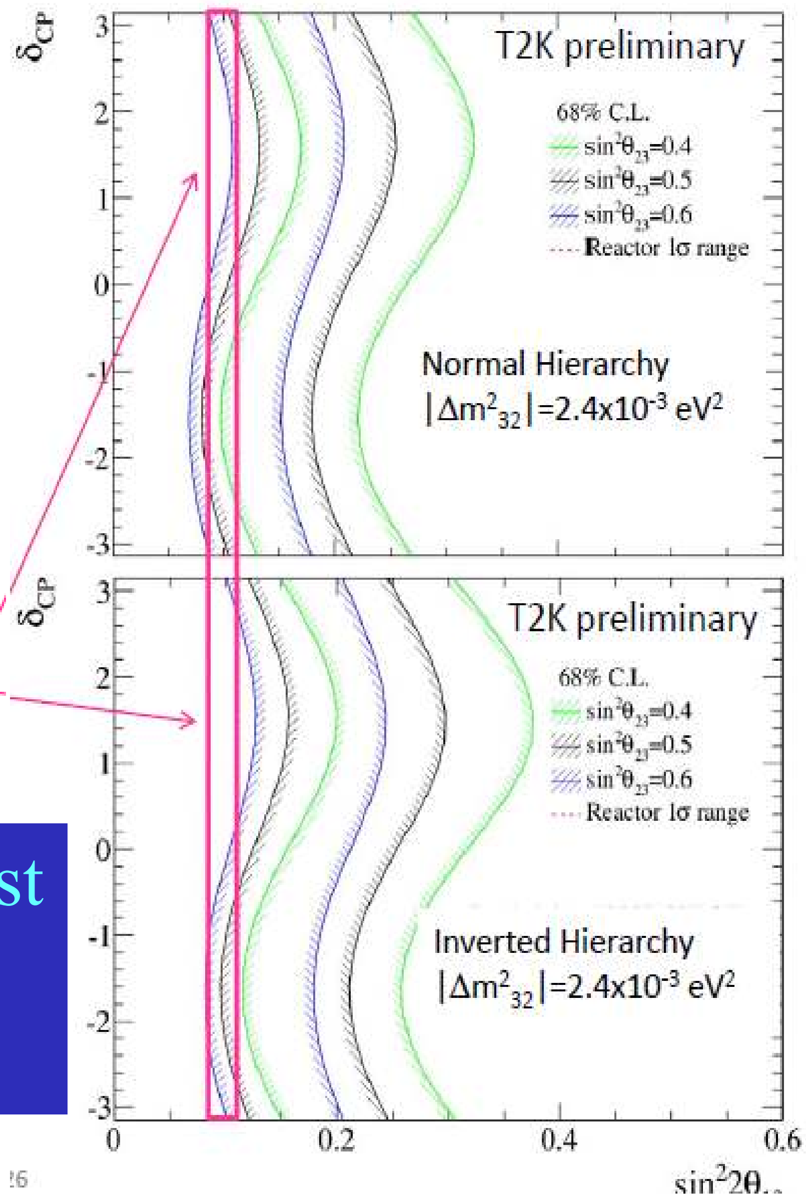
This is data!!!

where: $\Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad A \equiv \frac{2EV}{\Delta m^2_{31}},$

$$J = c_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

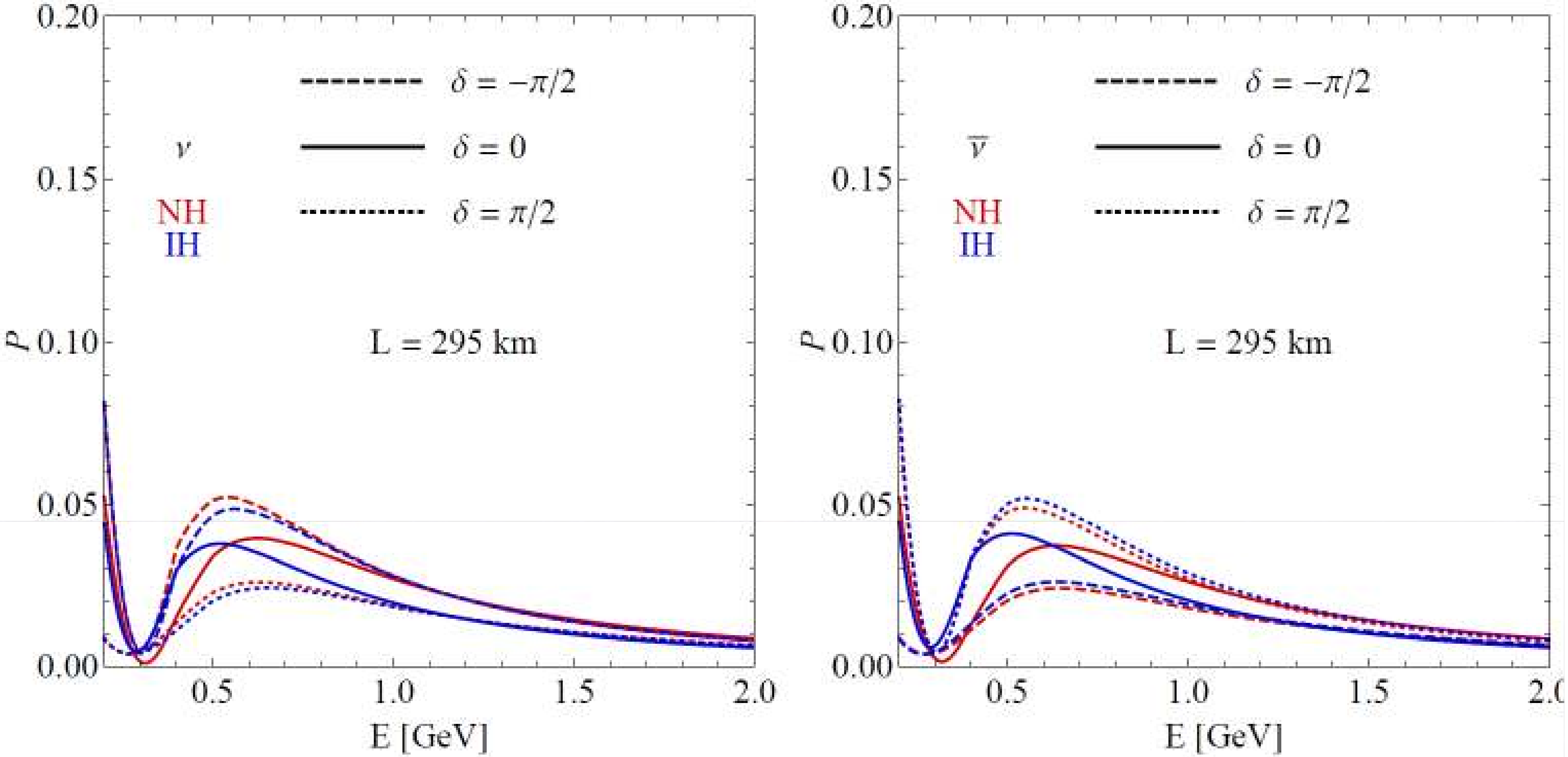
NOTE: PDG'12 3σ region for $\sin^2\theta_{23}$:0.34-0.64

reactor 1σ region (PDG '12)
$\sin^2 2\theta_{13} = 0.098 \pm 0.013$



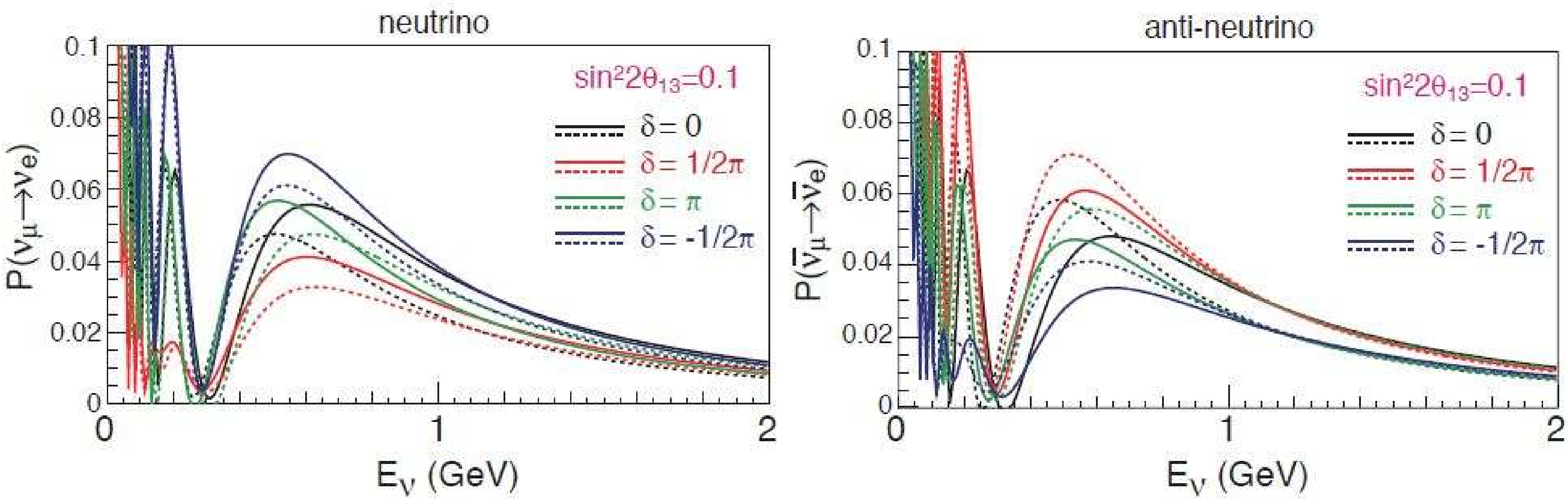
Plot from Ichikawa-san's talk at EPS.

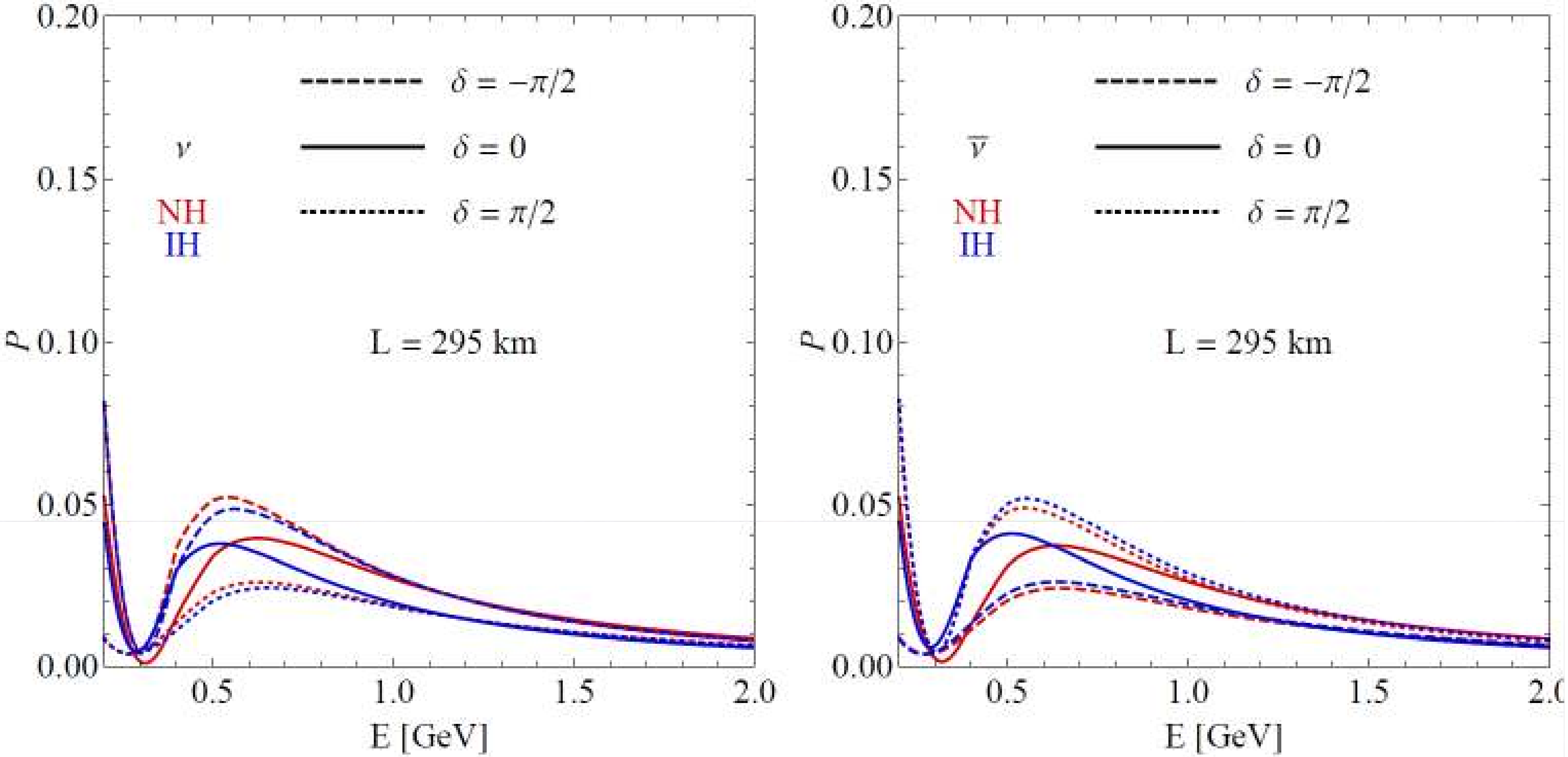
Lesson: What experiment is best depends on what world we Live in…



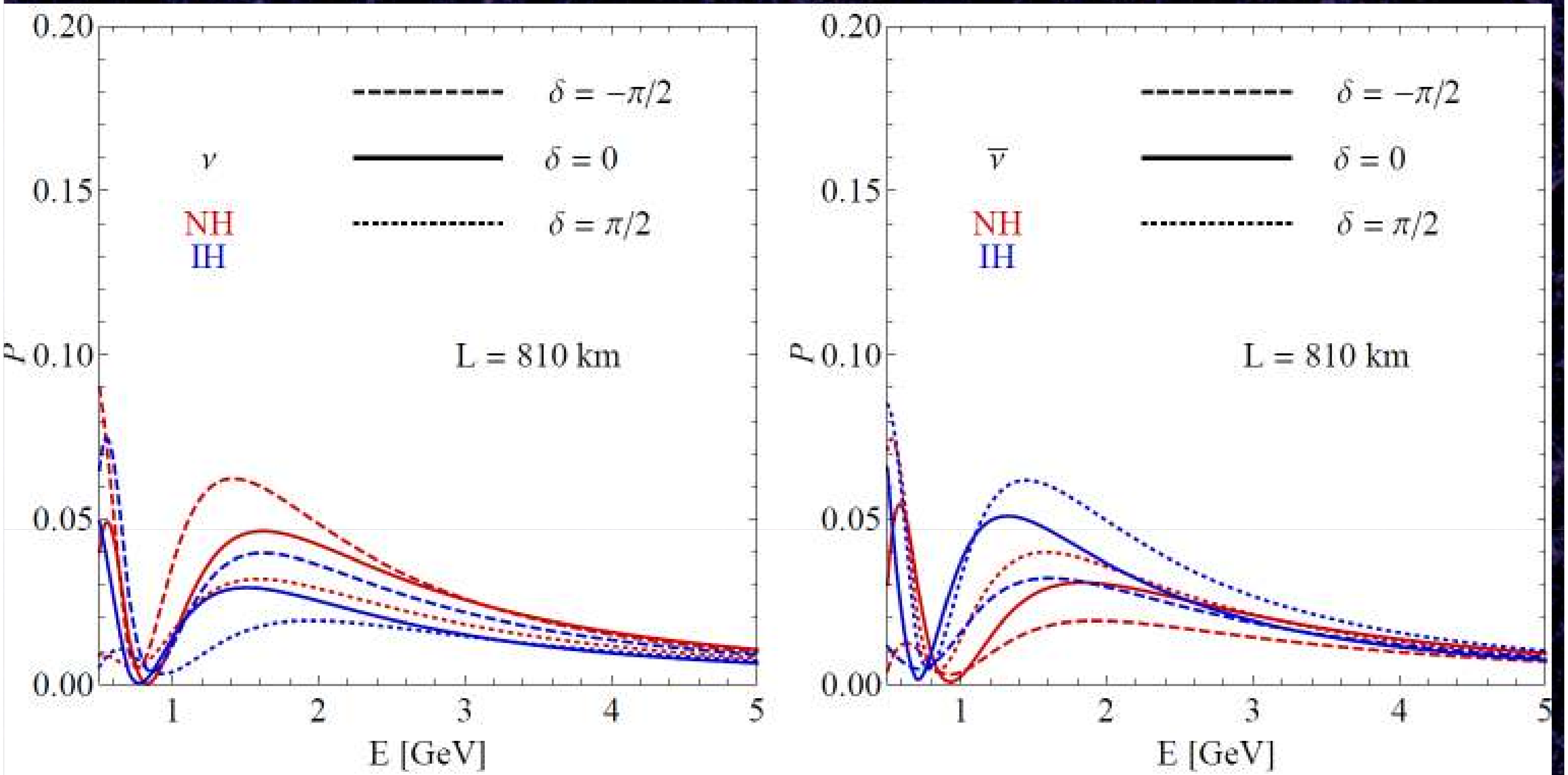
Lots more of these…

Than these…


neutrino
anti-neutrino
$P(\nu_\mu \to \nu_e)$
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$\sin^2 2\theta_{13}=0.1$
$\delta = 0$
$\delta = 1/2\pi$
$\delta = \pi$
$\delta = -1/2\pi$
E_ν (GeV)
0
0.02
0.04
0.06
0.08
0.1
1
2



Dave Wark
Oxford U./RAL



Note that everything is moving to higher energy…

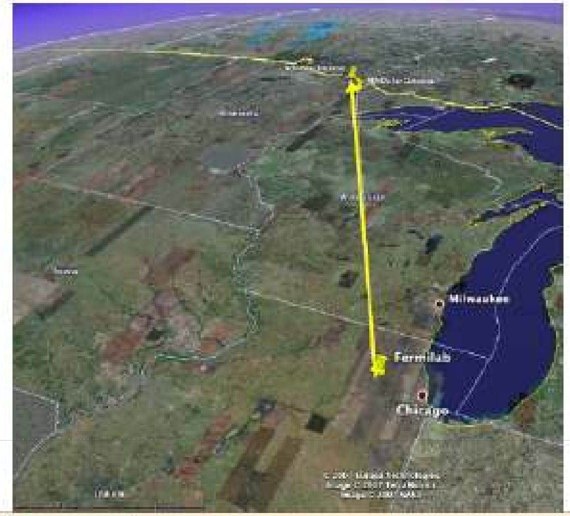
Dave Wark
Oxford U./RAL

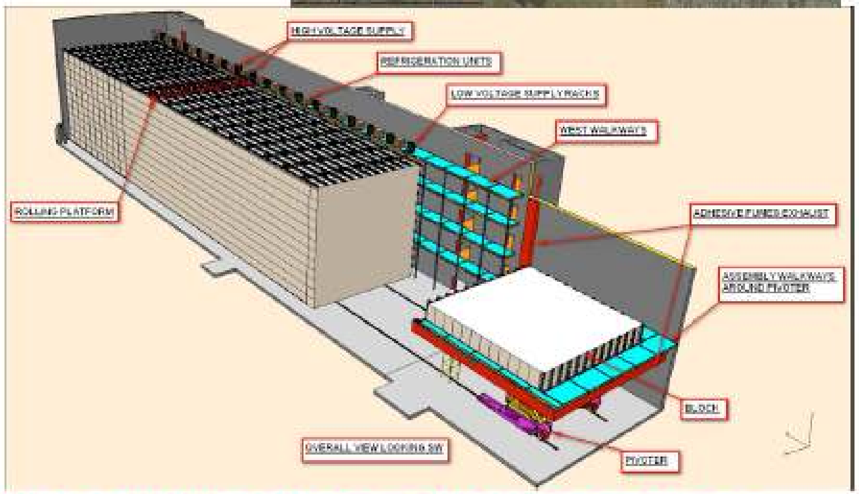
NOVA neutrino appearance

- Fermilab to Ash River (Mn) 810 km,
  – 14 mrad, ~2.2 GeV

14 kt liquid scintillator detector

Under construction

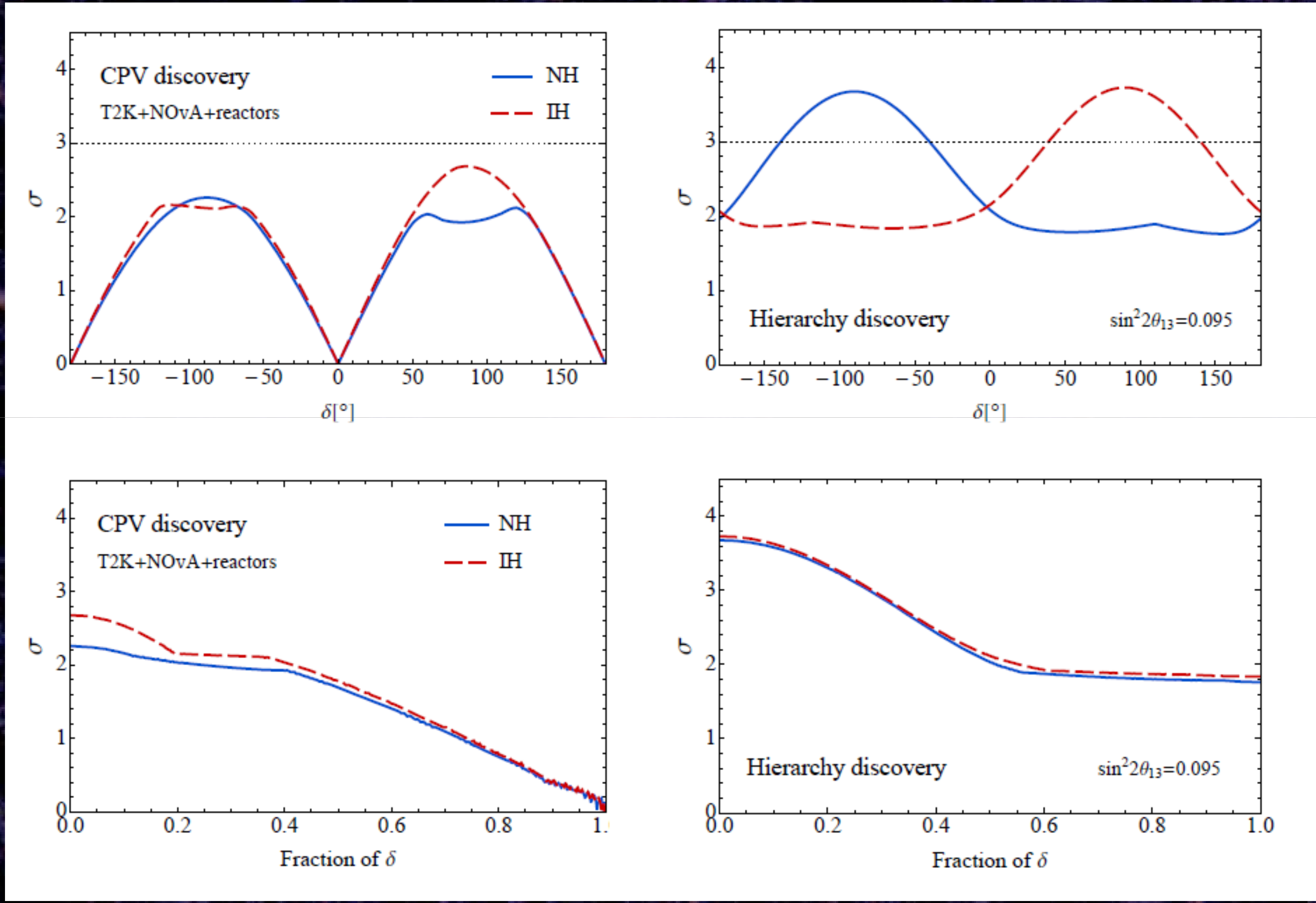




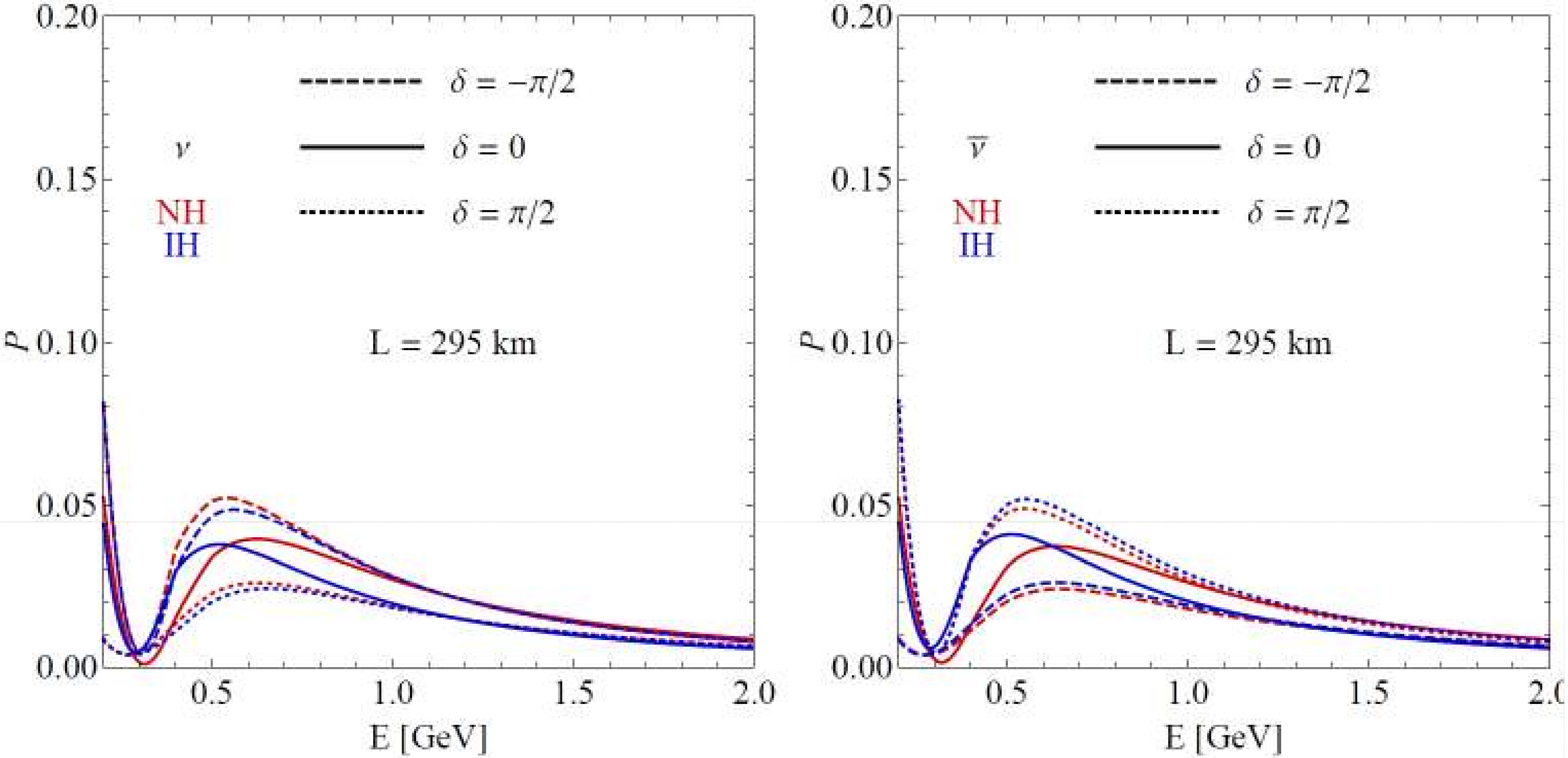
Over 2 kton of NOvA detector instrumented taking cosmics

Page stolen from Paul Soler's 2nd talk at INSS13.

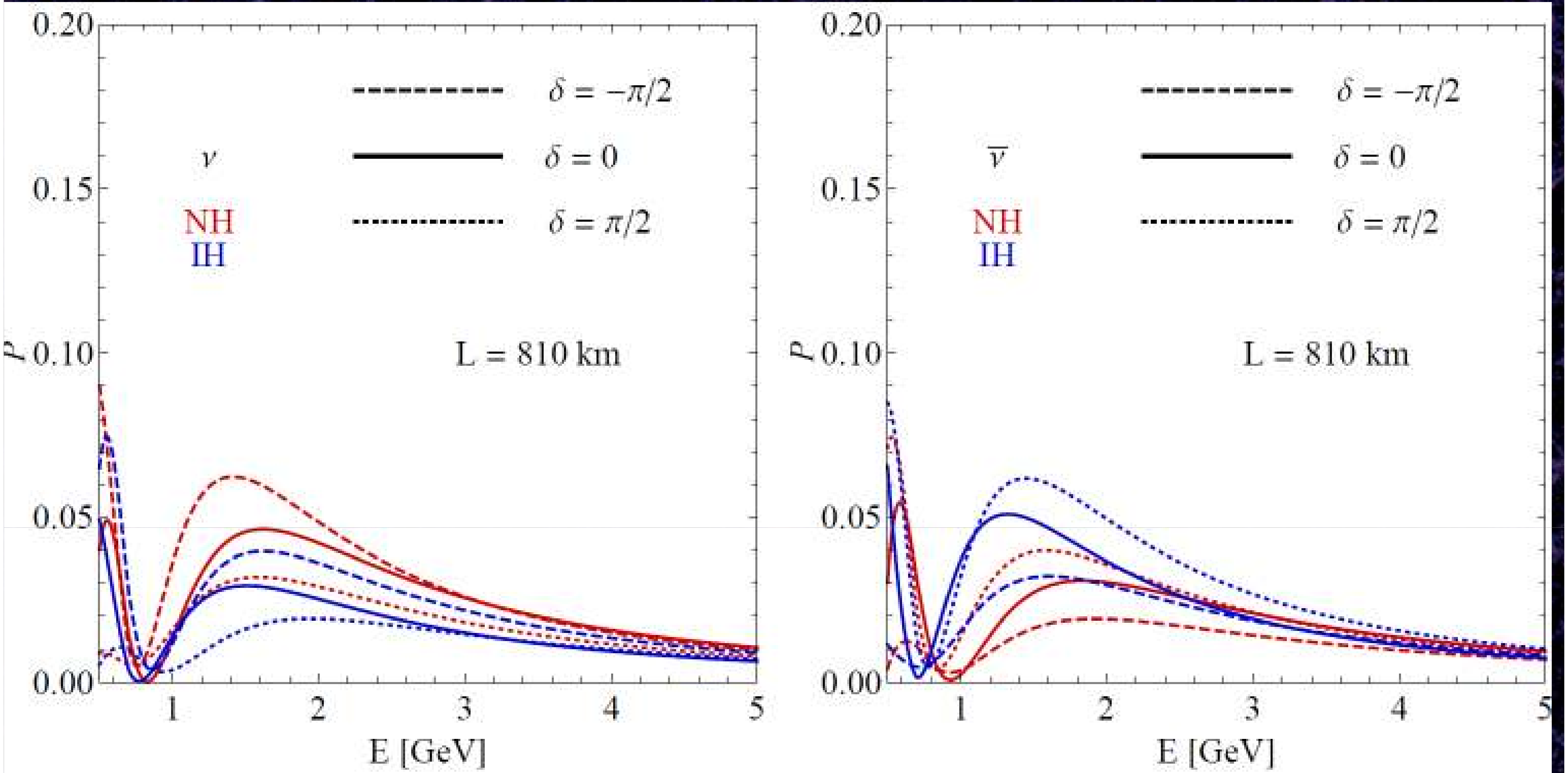
Additional Information from Continuing Long Baseline Experiments - T2K, NOνA (+ reactors)

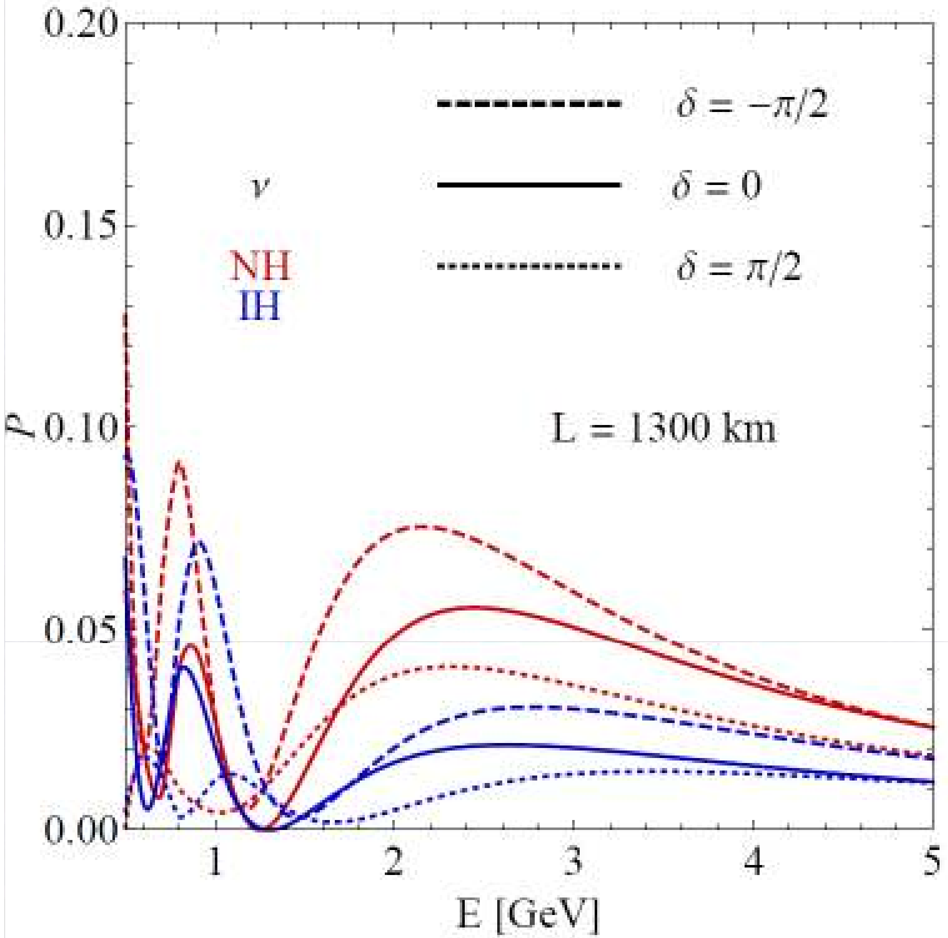


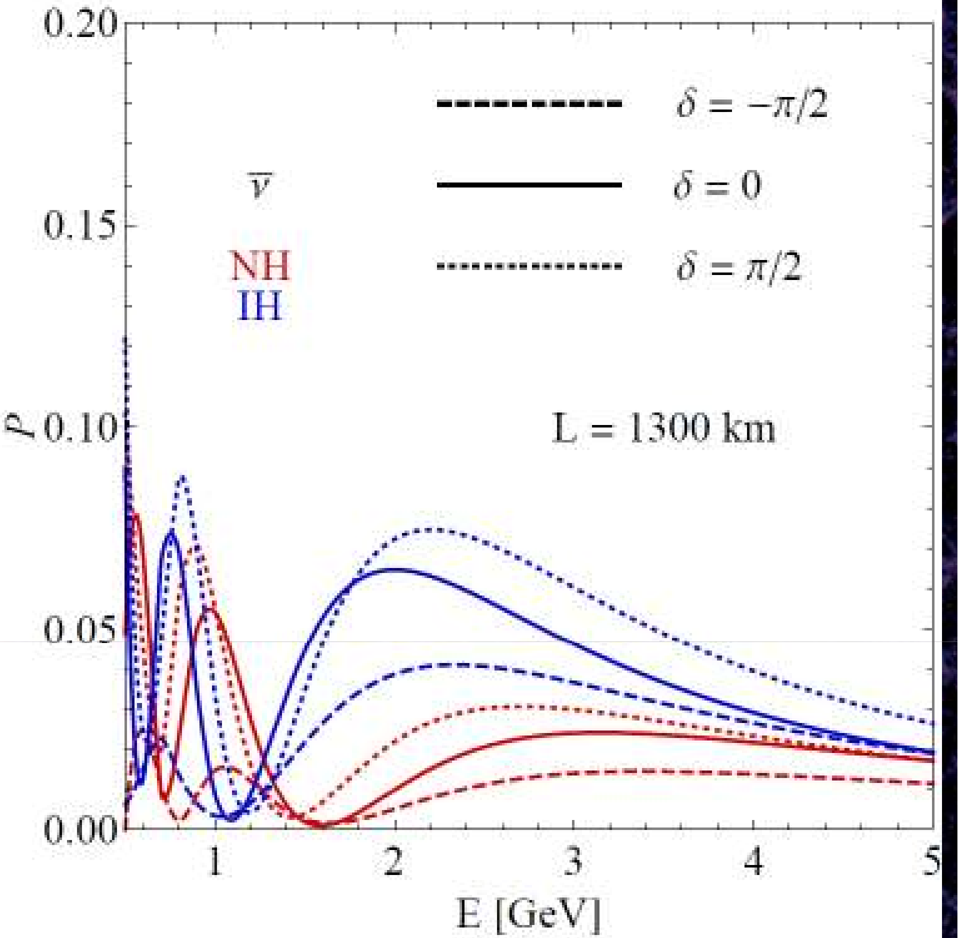
We will probably do a bit better than this; but indications, hints, guidance – Yes! 5σ, sadly, no….

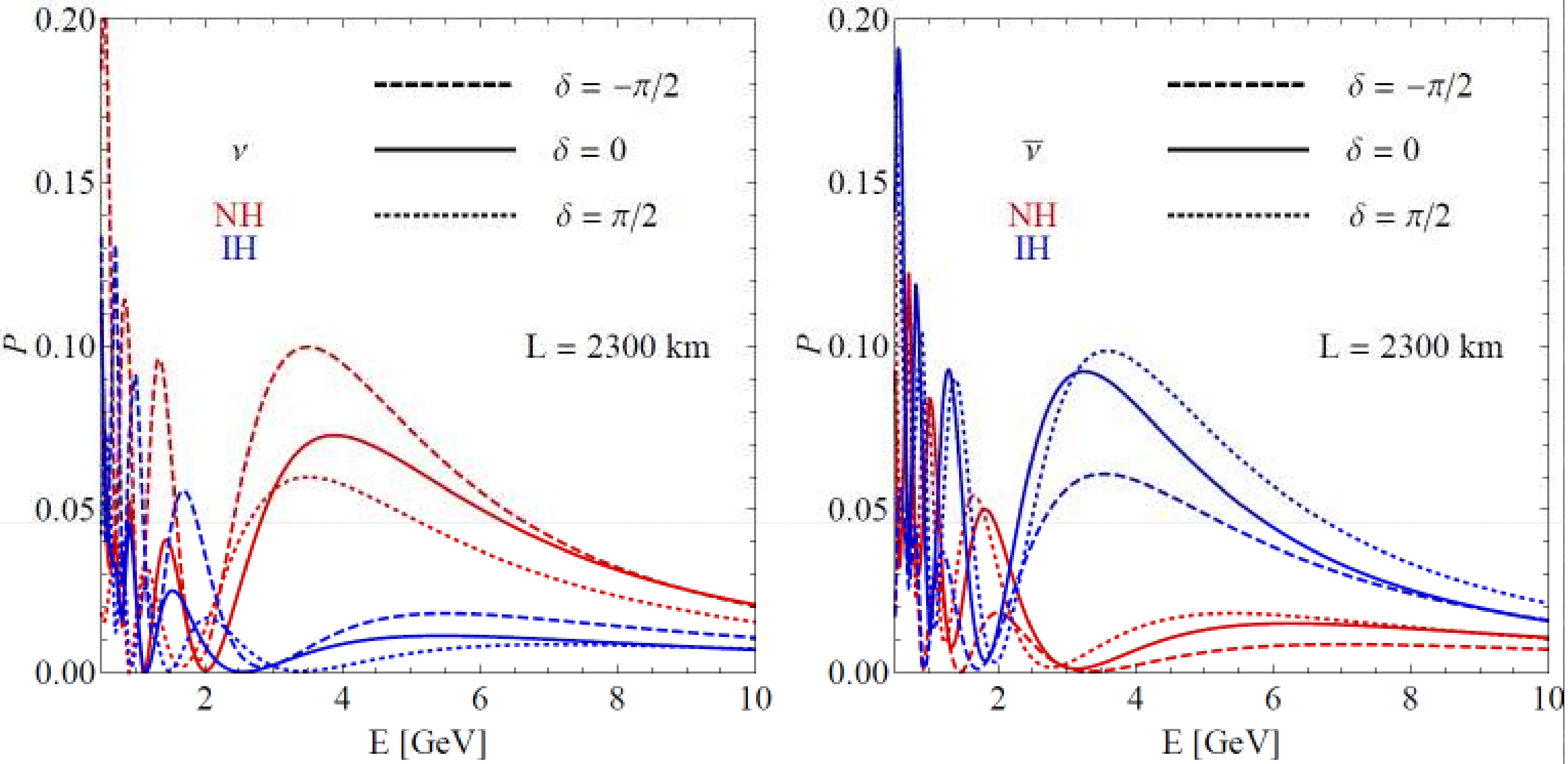


0.20
0.15
0.10
0.05
0.00
P
$\delta = -\pi/2$
$\delta = 0$
$\delta = \pi/2$
ν
NH
IH
L = 295 km
0.5
1.0
1.5
2.0
E [GeV]
$\bar{\nu}$


0.20
0.15
0.10
0.05
0.00
P
$\delta = -\pi/2$
$\delta = 0$
$\delta = \pi/2$
ν
NH
IH
L = 810 km
1
2
3
4
5
E [GeV]
$\bar{\nu}$


0.20
0.15
0.10
0.05
0.00
P
$\delta = -\pi/2$
$\delta = 0$
$\delta = \pi/2$
ν
NH
IH
L = 1300 km
1
2
3
4
5
E [GeV]


0.20
0.15
0.10
0.05
0.00
P
$\delta = -\pi/2$
$\delta = 0$
$\delta = \pi/2$
$\bar{\nu}$
NH
IH
L = 1300 km
1
2
3
4
5
E [GeV]



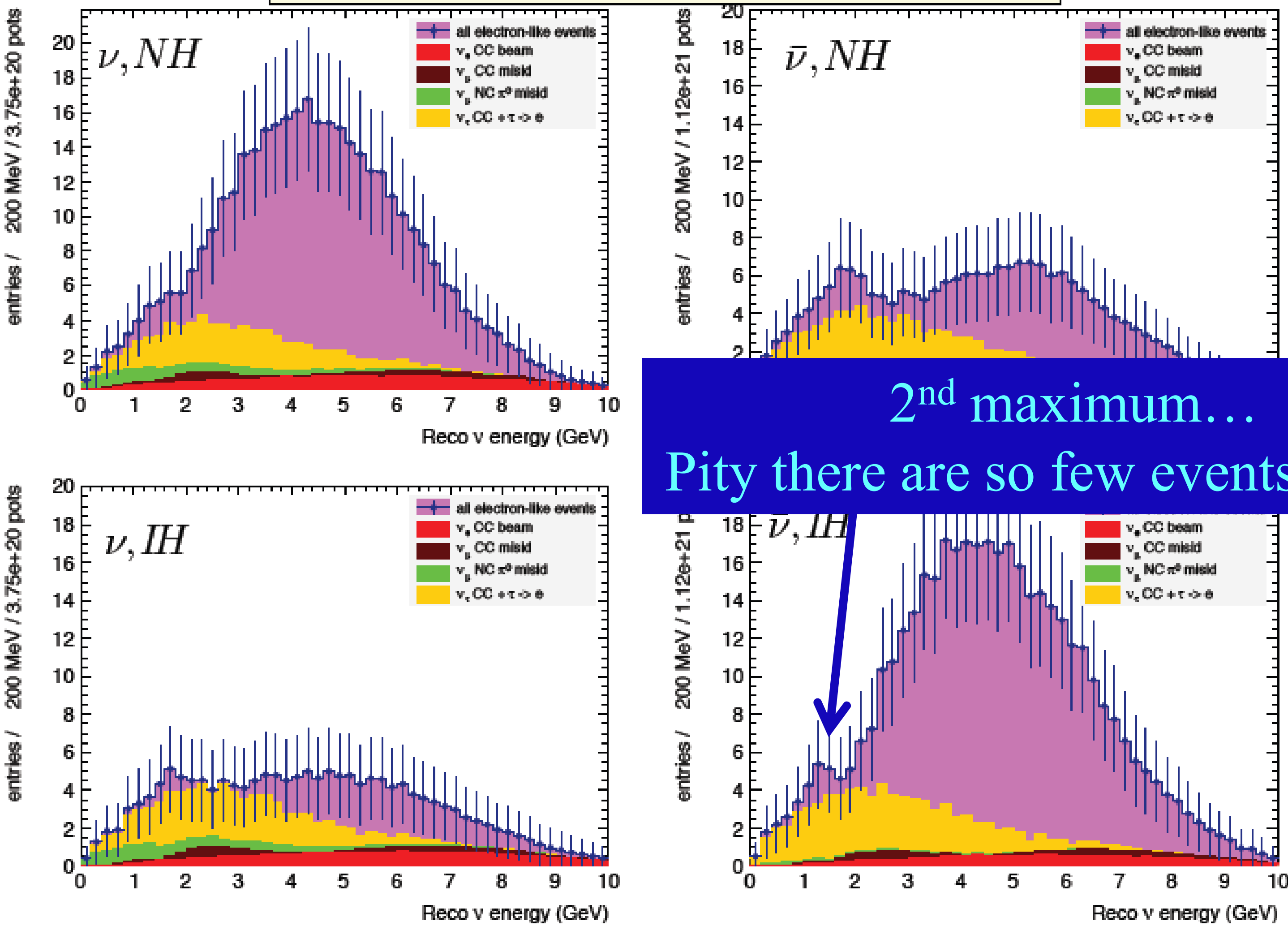
Note size of CP effect in second maximum…

Dave Wark
Oxford U./RAL

Neutrino/antineutrinos and MH

Detector response and resolution included

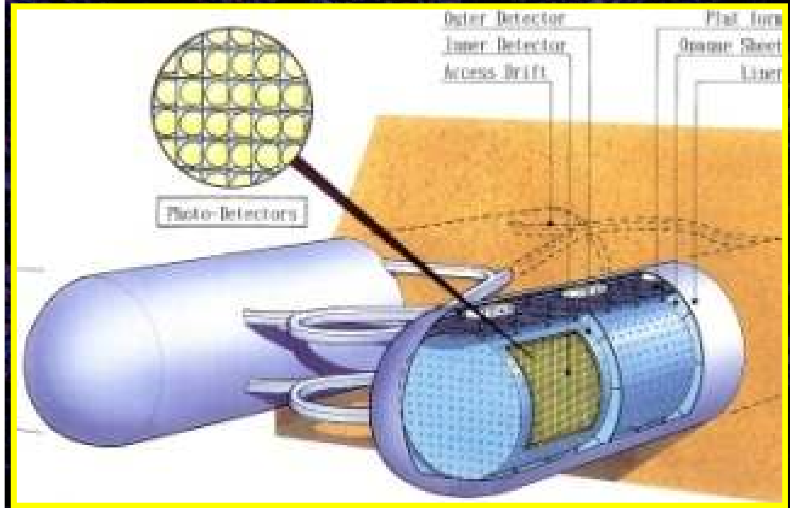
Running mode:
ν/anti-ν:25%/75%



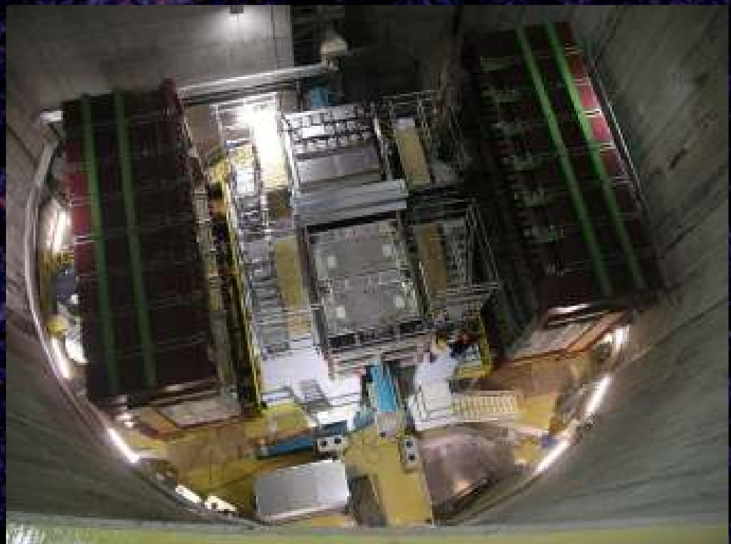
2[nd] maximum…
Pity there are so few events there…

Statistics an issue for all experiments…..

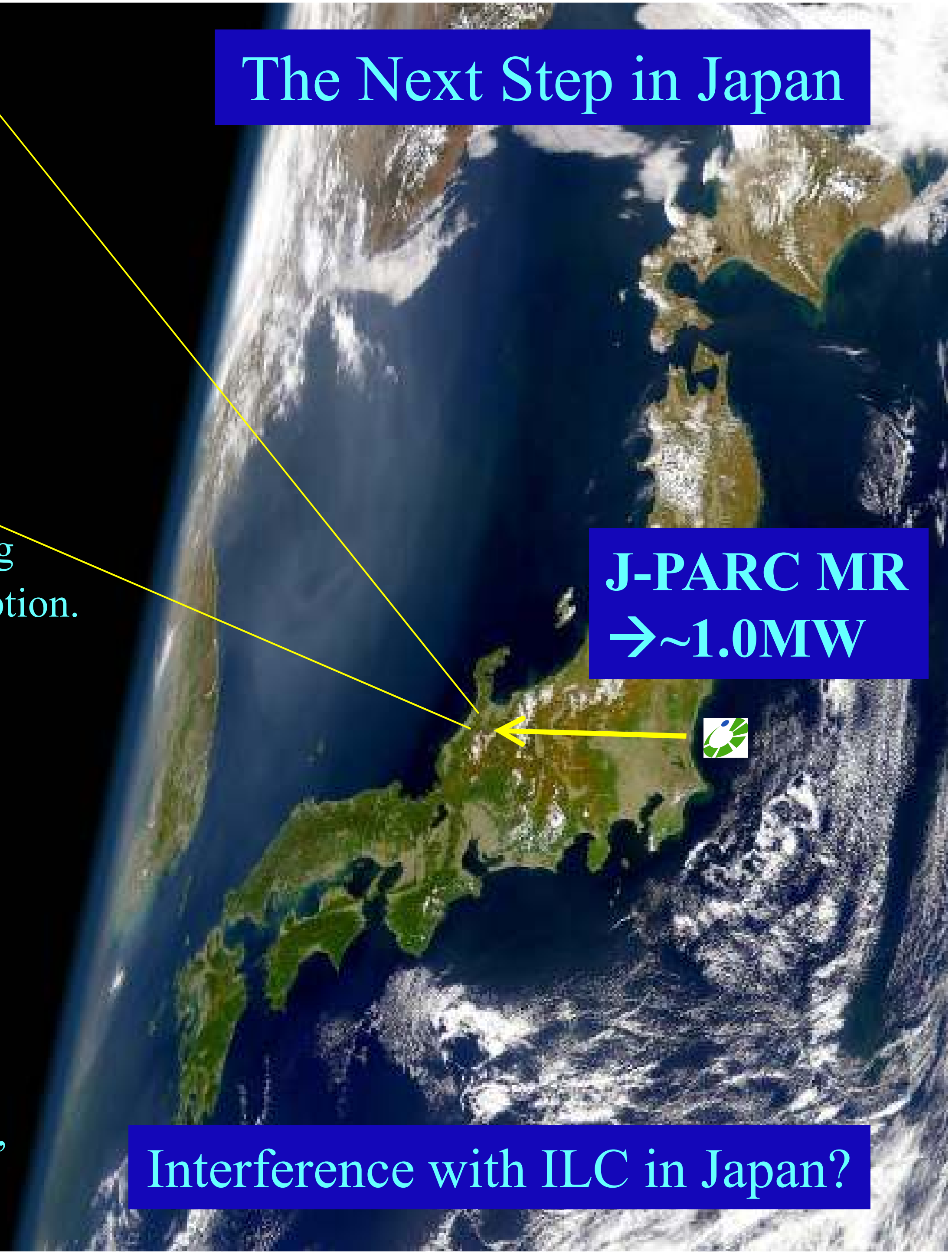
The Next Step in Japan



Hyper Kamiokande L=295km OA=2.5deg
Water Cerenkov selected as the current option.



T2K 280m near detectors, will be re-used, but upgraded (?) and maybe enhanced with new near detector(s) at 2km.

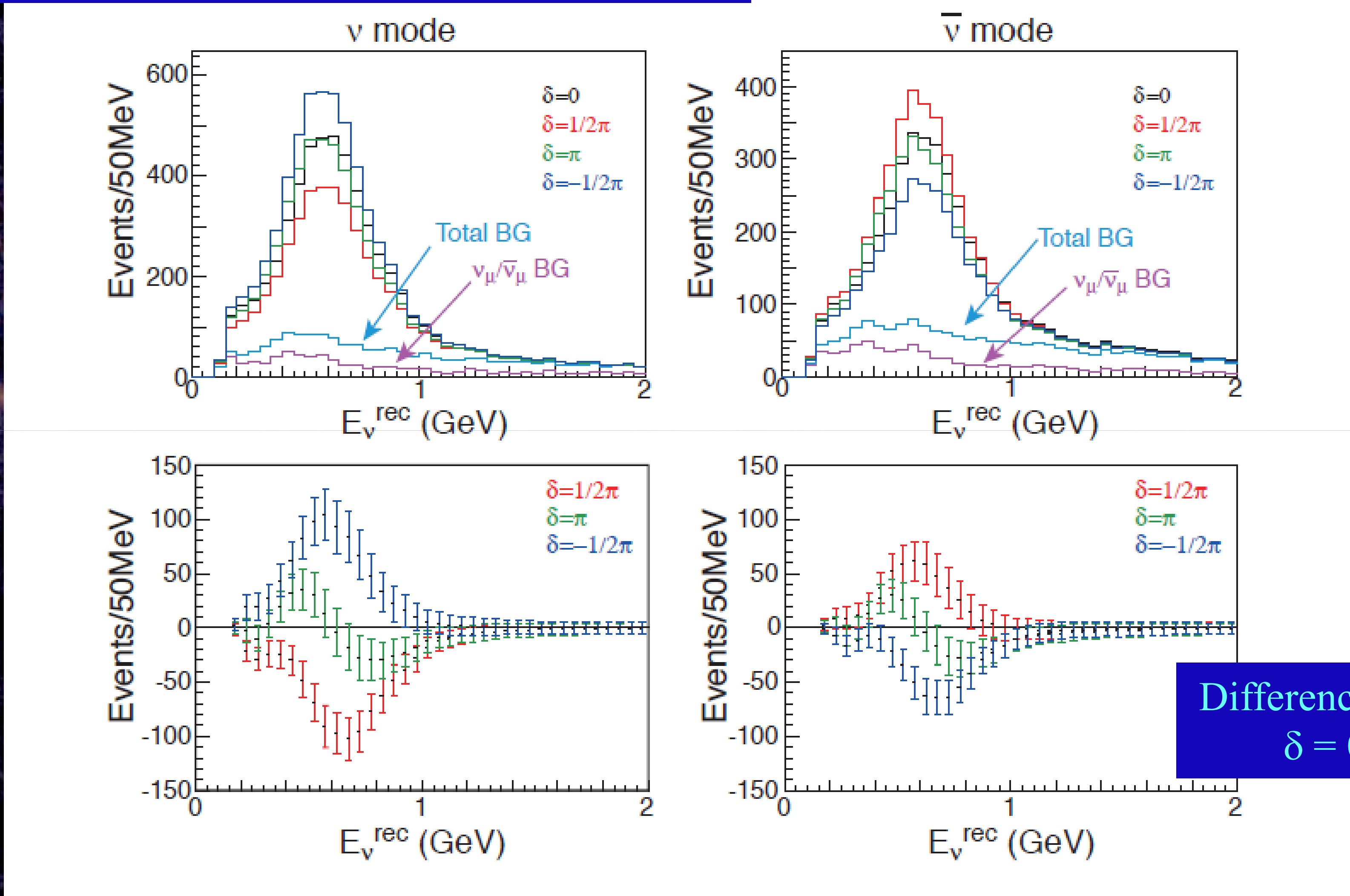


J-PARC MR
→~1.0MW

Interference with ILC in Japan?

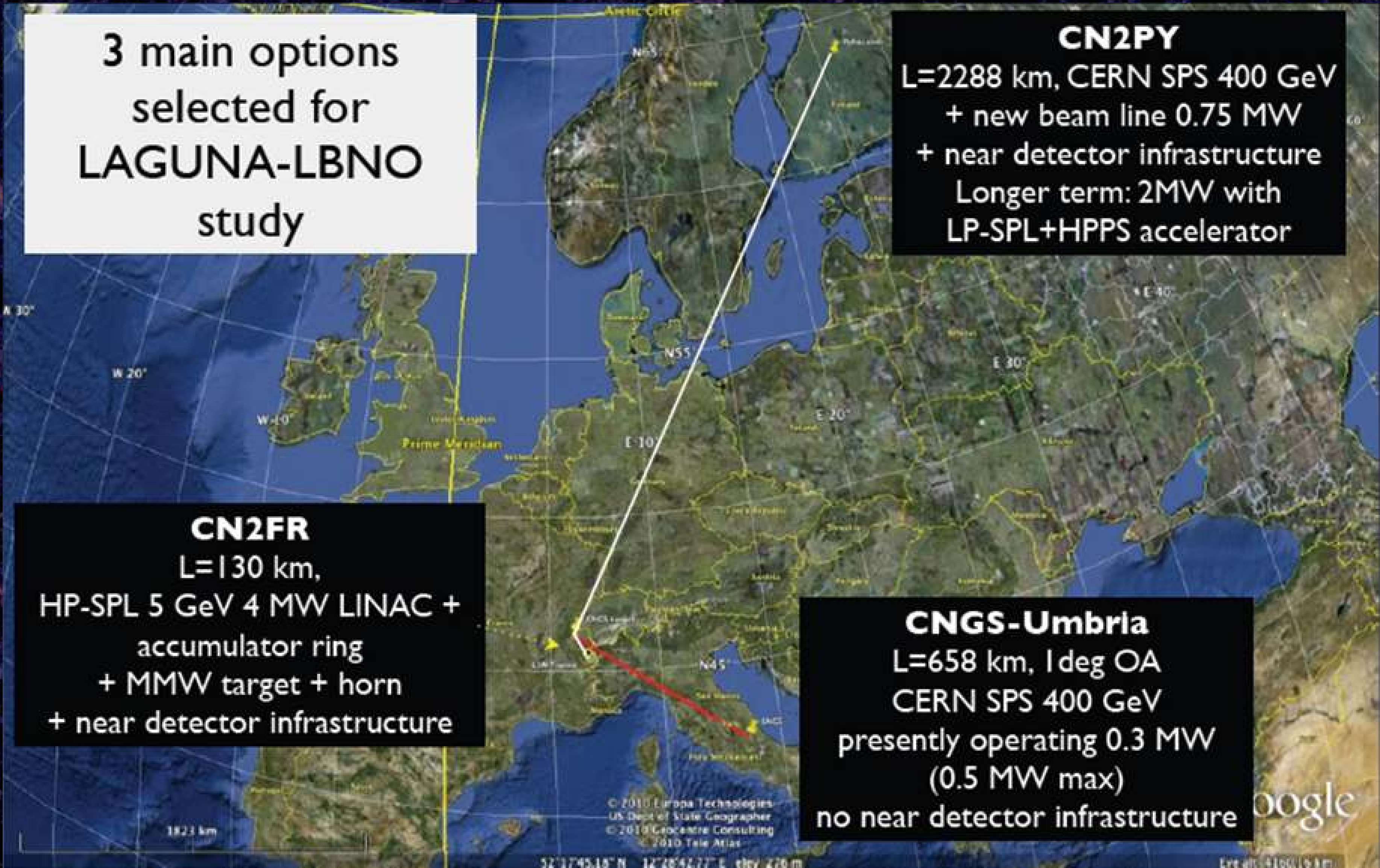
T2HK Appearance Spectra

NB: Normal Hierarchy Assumed!

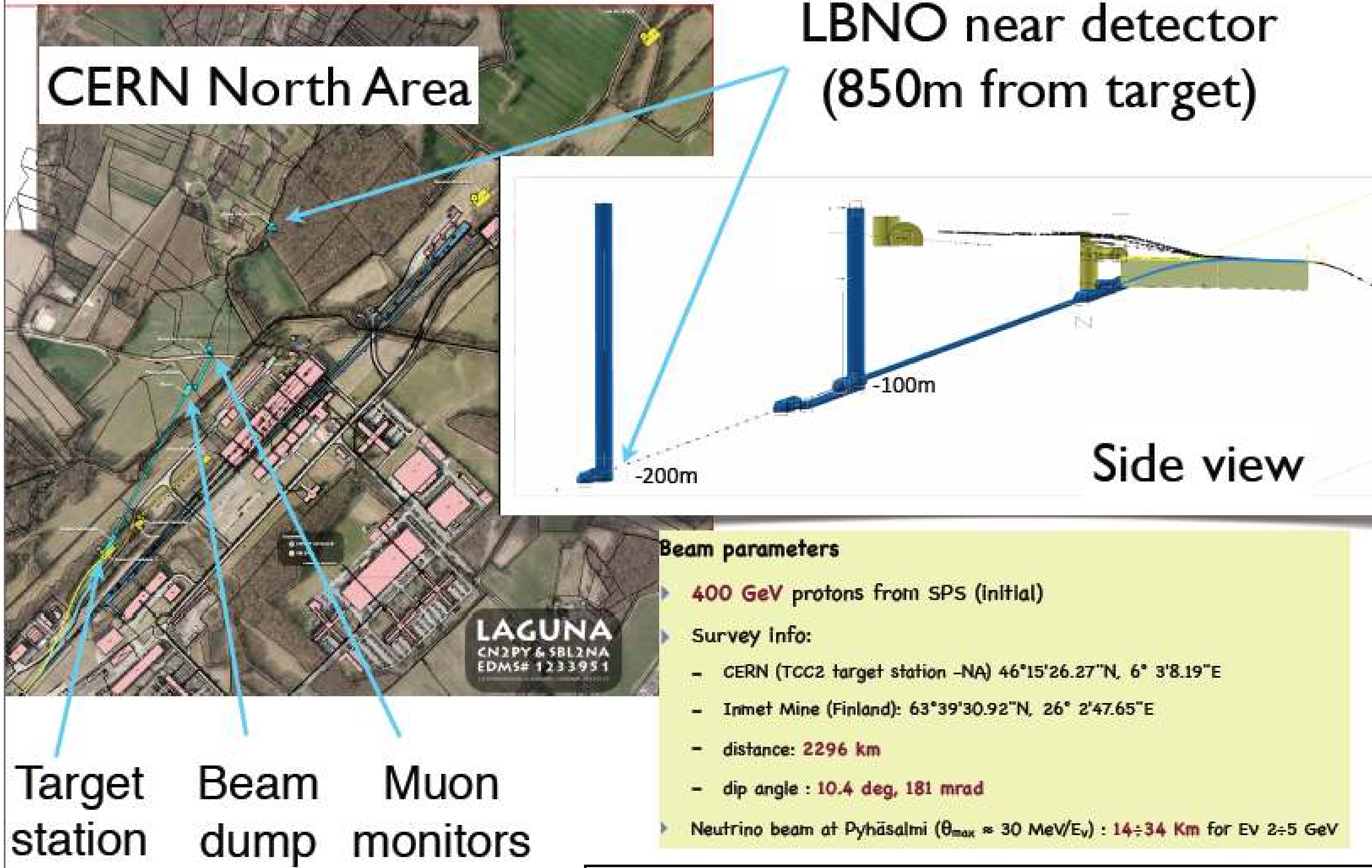


Difference from δ = 0.

Only 5 yrs running (1.5 ν, 3.5 anti-ν) assumed…


3 main options selected for LAGUNA-LBNO study
CN2PY
L=2288 km, CERN SPS 400 GeV
+ new beam line 0.75 MW
+ near detector infrastructure
Longer term: 2MW with
LP-SPL+HPPS accelerator
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

Neutrino beam layout

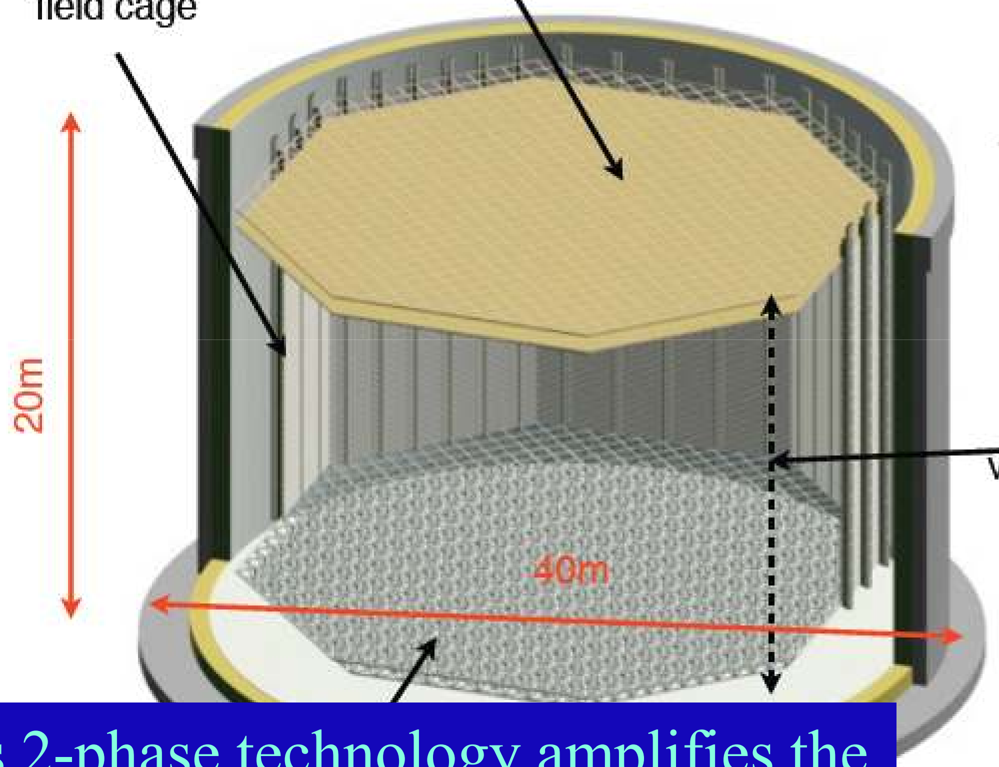


Beam parameters

- 400 GeV protons from SPS (initial)
- Survey info:
  - CERN (TCC2 target station -NA) 46°15'26.27"N, 6° 3'8.19"E
  - Inmet Mine (Finland): 63°39'30.92"N, 26° 2'47.65"E
  - distance: 2296 km
  - dip angle : 10.4 deg, 181 mrad
- Neutrino beam at Pyhäsalmi ($\theta_{max} \approx 30$ MeV/E_ν) : 14÷34 Km for Eν 2÷5 GeV

❖ Primary protons from SPS (7e13 ppp @ 400 GeV with 6 s cycle)
❖ Yearly integrated pot = (0.8–1.3)x 1e20 pot / yr depending on "sharing" with other fixed target programmes (compared to CNGS 4.5x 1e19 pot / yr)
❖ Secondary horn focusing (horn+reflector)

Far liquid Argon detector



- Double phase LAr LEM TPC (GLACIER,2003)
  (hep-ph/0402110, J.Phys.Conf.Ser. 171 (2009) 012020, NIM A 641 (2011) 48-57, JINST 7 (2012) P08026)

Design based on extensive experience with smaller scale devices

This 2-phase technology amplifies the signals, so compensates for loss on drift, which is intended to allow for economical scale-up of the detector.

28

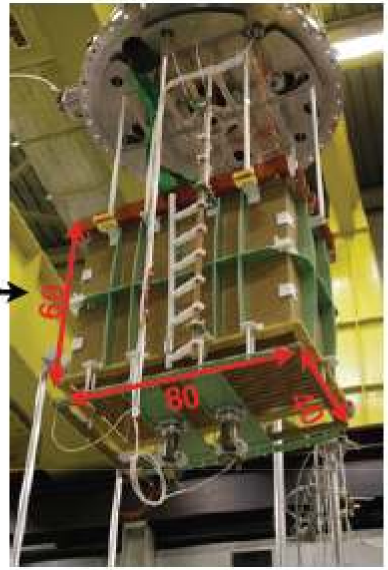
LAr detector prototyping efforts

(1) ArDM-1t @ CERN

J.Phys.Conf.Ser. 39 (2006) 129-132

World's first double phase liquid argon LEM-TPC successfully operated

40x80cm2
JINST 7 (2012) P08026



(2) J-PARC T32

J.Phys.Conf.Ser. 308 (2011) 012008

0.4 ton LAr TPC

World's largest sample of charged particles events ever collected

(3) ArgonTube @ Bern

Nucl.Phys.Proc.Suppl. 139 (2005) 301-310

Aim to demonstrate world's longest electron drift path

(4) 10T @ CERN

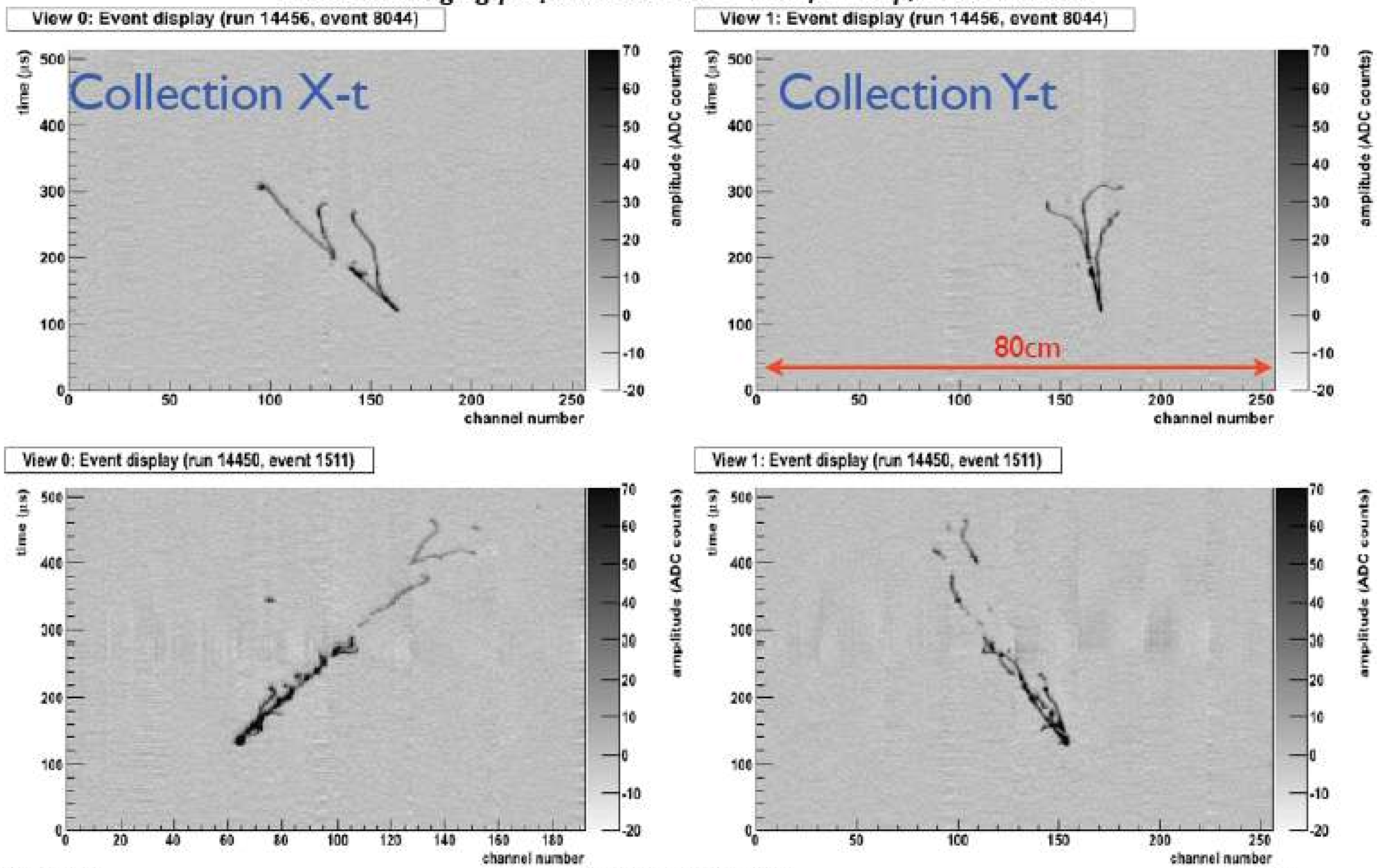
J.Phys.Conf.Ser. 308 (2011) 012024

Purity by flushing w/o evacuation

Real cosmic rays in LAr LEM-TPC

Cosmic track in double phase 80x40cm2 LAr-LEM TPC with adjustable gain

The best imaging performance S/N > 100 for m.i.p, in both views !



LAGUNA LAr prototype @ CERN

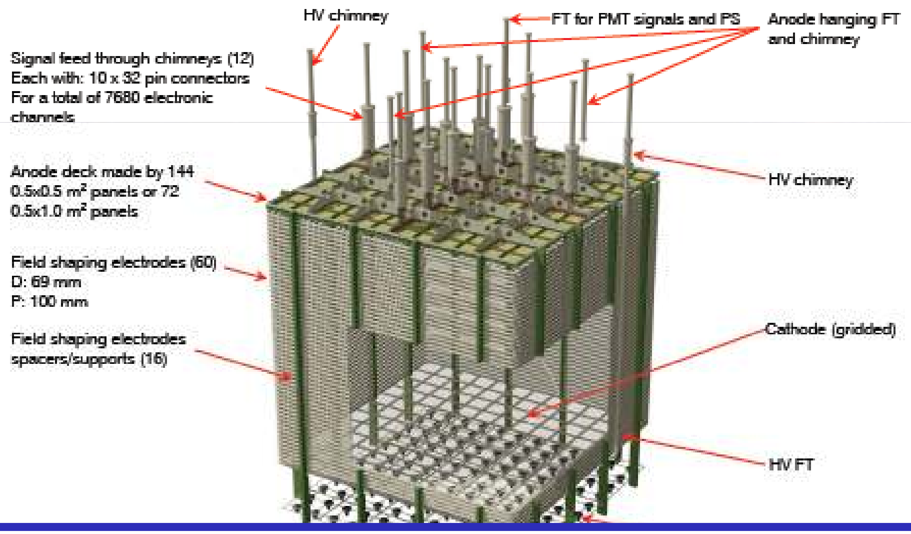
· 6x6x6m^3 prototype to be constructed and operated at CERN, as a prototype of the far detector double-phase TPC

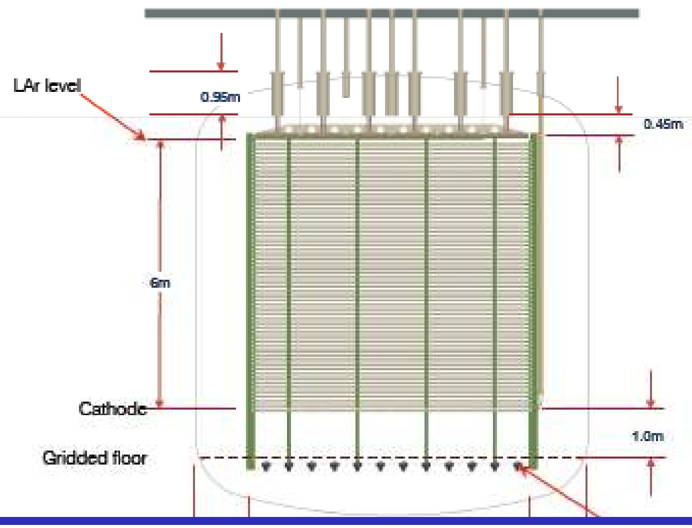
· Charged test beams to collect the large controlled data set allowing electromagnetic and hadronic calorimetry and PID performance to be measured, simulation and reconstruction to be improved and validated

· Detector to be positioned in the North Area in an extension of the EHN1 building

· Timescale: facility for preparation of full LAGUNA-LBNO proposal

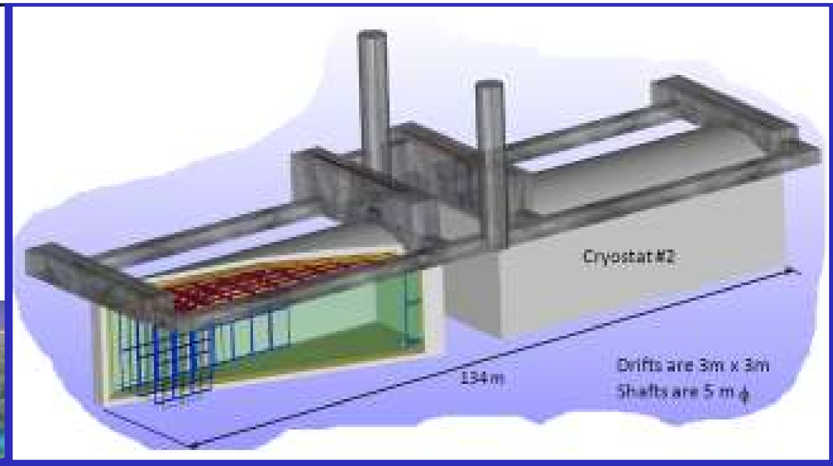
· Also highly relevant to other options wanting to use LAr TPC (LBNE, Okinoshima)



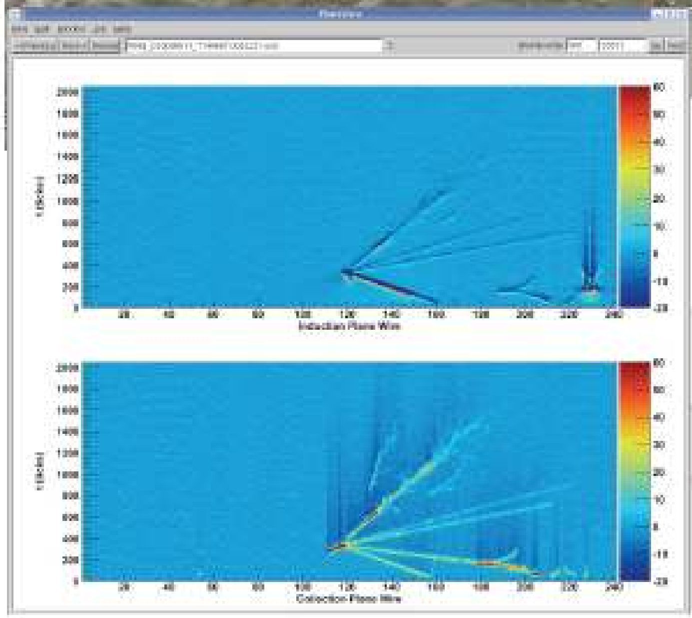


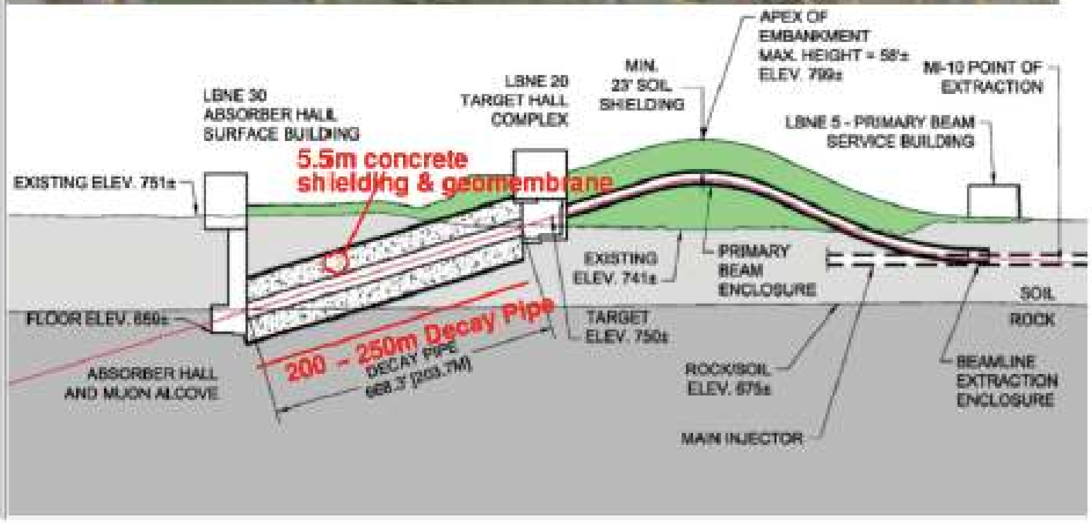
f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading neutrino projects in the US and Japan.*

LBNE experiment



For cost reasons, the project has been phased to a 10 kT detector on the surface and no ND.

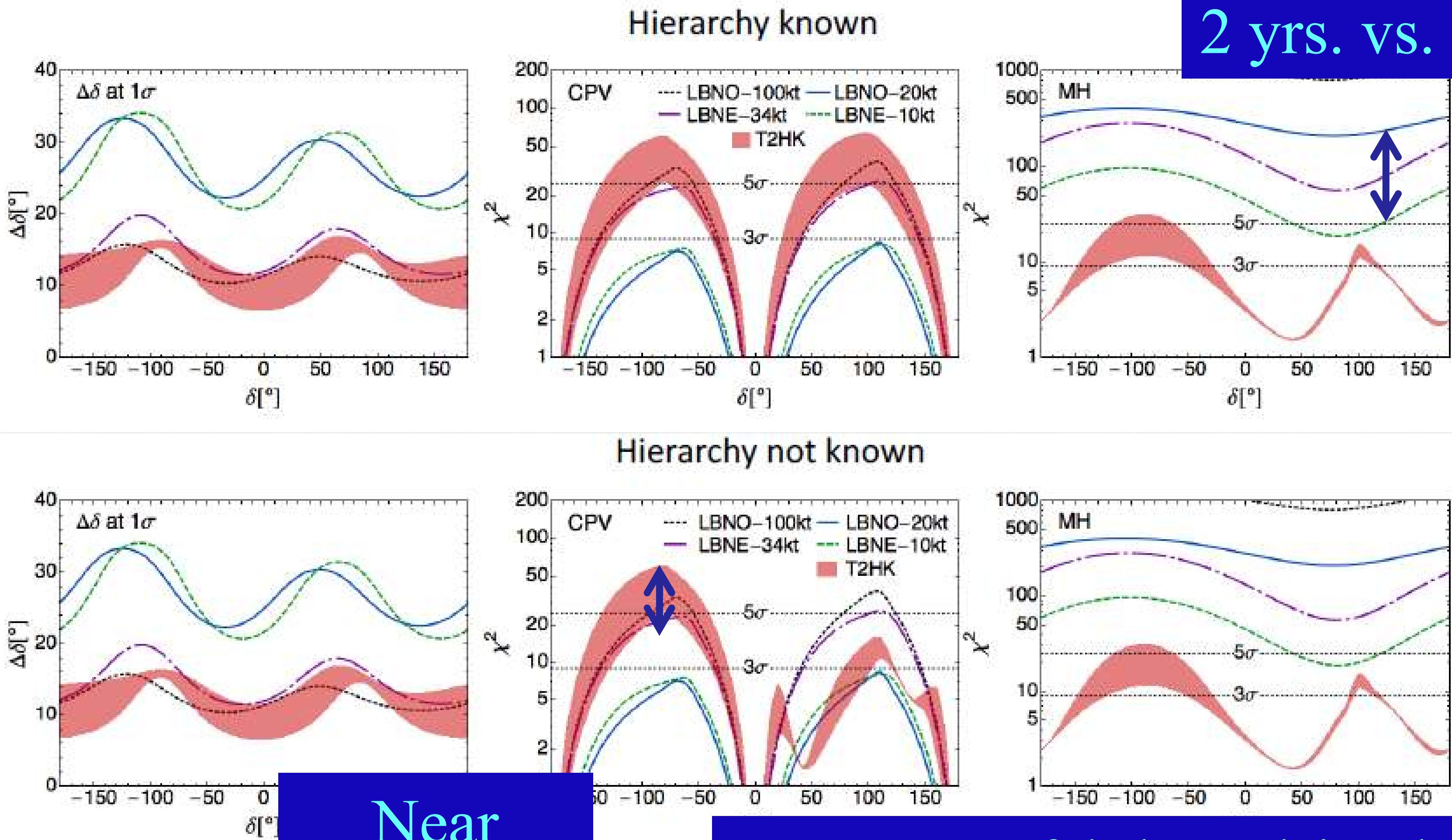




From Pilar Hernandez's talk in Kracow…

In 20 years from now with conventional be

>5σ in
2 yrs. vs. 10



Near Detectors?

Be very careful about claimed systematics…

Recovering scope of LBNE

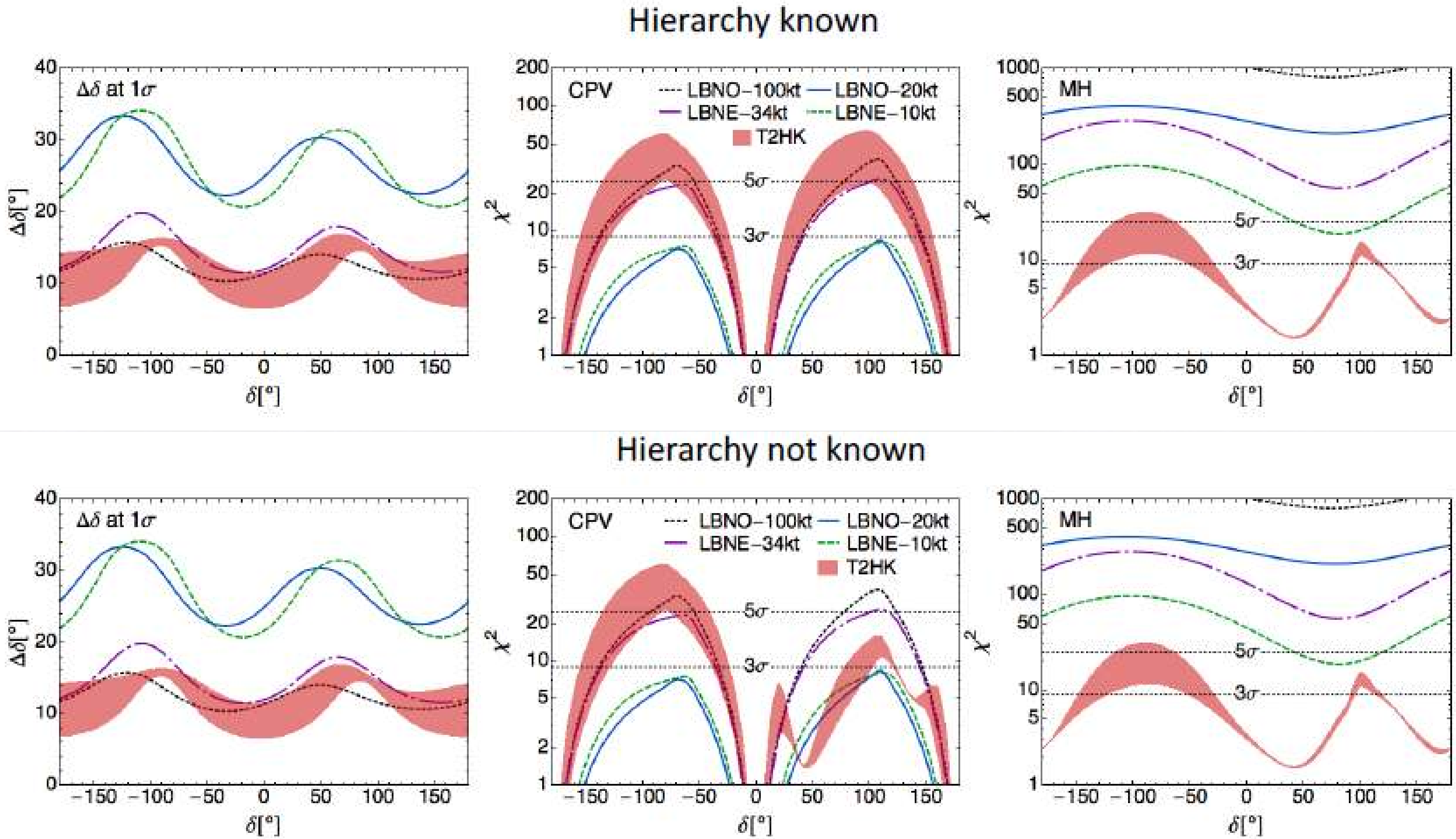
Additional Investment (TPC)	Capability Added	Science Gained	Science Priority
+ $140M *	Underground placement	ATM nus, p-decay, SNB nus	Very High
+ $130-190	Near Detector	Enhanced LB physics, near detector physics	Very High
+ $200-350	Add FD mass (>30 kt)	Precision CP and other 3-flavor paradigm measurements; p-decay	Very High

* Project, with collaboration support, has decided to pursue geo-technical studies of *underground* site and not surface location ac
done should an underground detector not pr

Can Europe supply some of the critical missing elements to restore LBNE to an experiment we would all want to do?

From Pilar Hernandez's talk in Kracow…

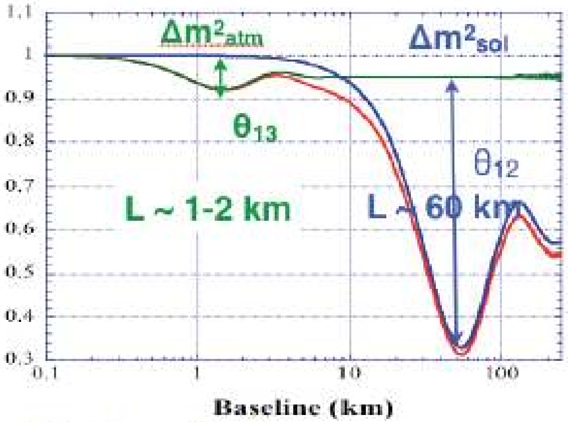
In 20 years from now with conventional beams…



Compiled by P. Coloma
Systematics as in Coloma, Huber, Kopp, Winter to appear

Slide from Nishikawa's summary.

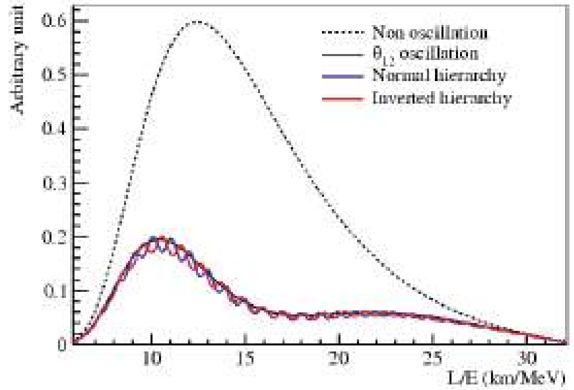
JUNO!



Site Investigation

K. Heeger

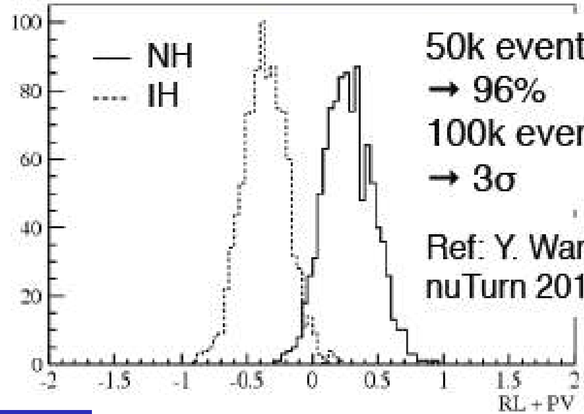
With reactor



$\sin^2\theta_{12}$ to ~2% from dedicated reactor experiment at optimized L~60km

FT of data – Does not create information!

Mass Hierarchy Sensitivity



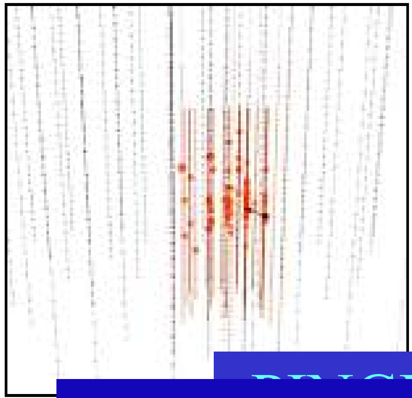
50k events = 20 kton, 3 years
→ 96%
100k events
→ 3σ

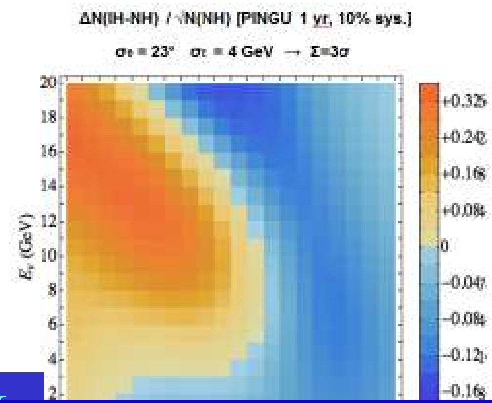
Ref: Y. Wang, J. Cao, et al
nuTurn 2012

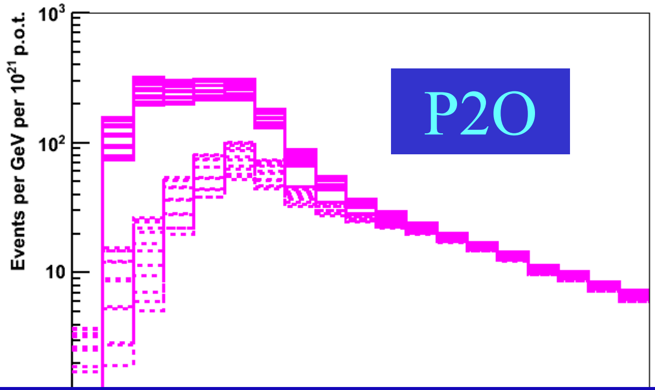
My view- measurement of θ_{12} alone justifies the project.

Assumes 3% energy resolution in a 20 kT organic scintillator!

Many are called to measure the MH…

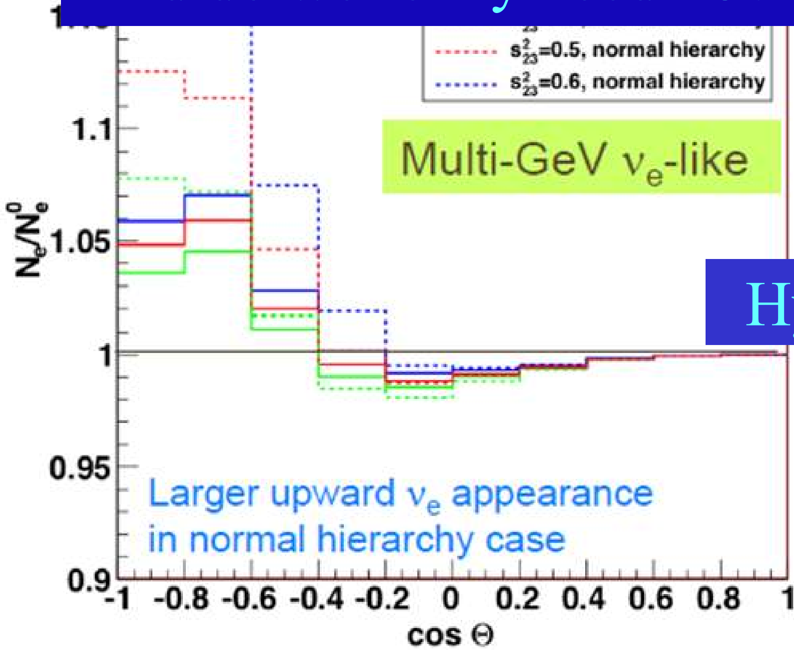


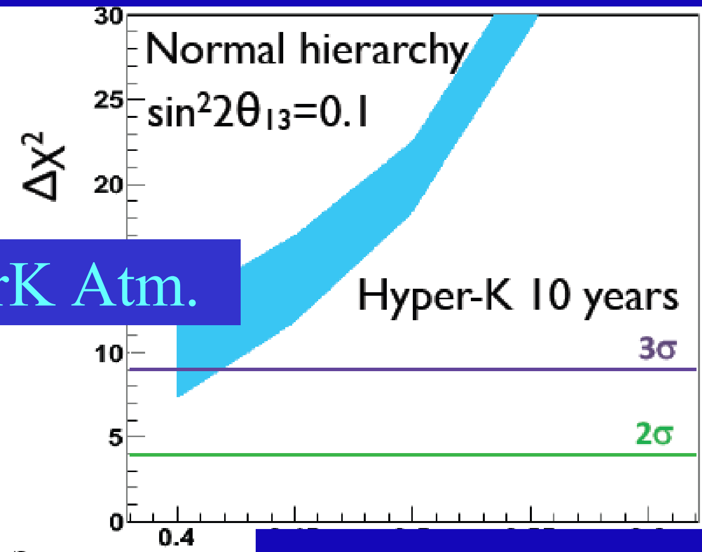




P2O

Many proposals. PINGU looks promising, but in all cases it is hard to get convincing evidence at 5σ. More work is needed. And do we really need 5σ?



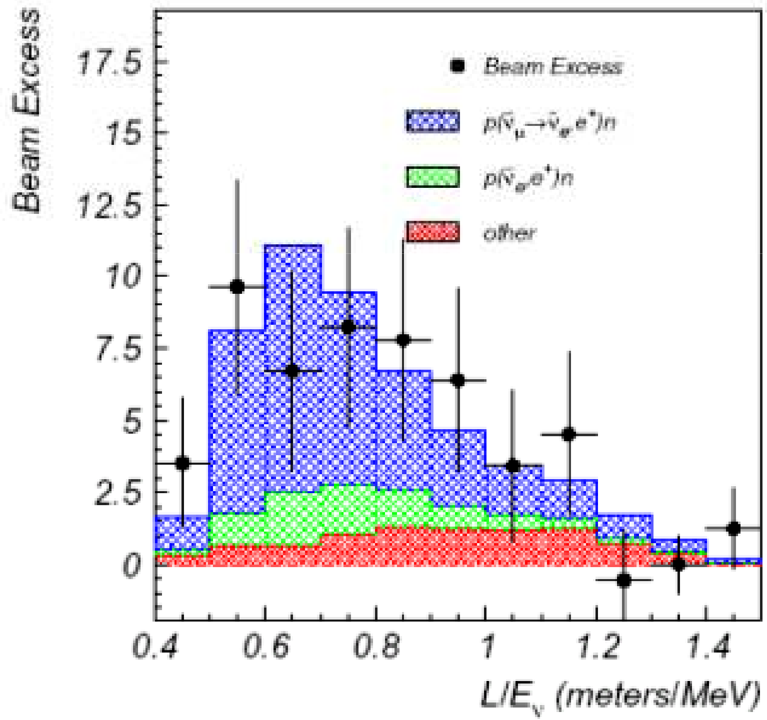


HyperK Atm.

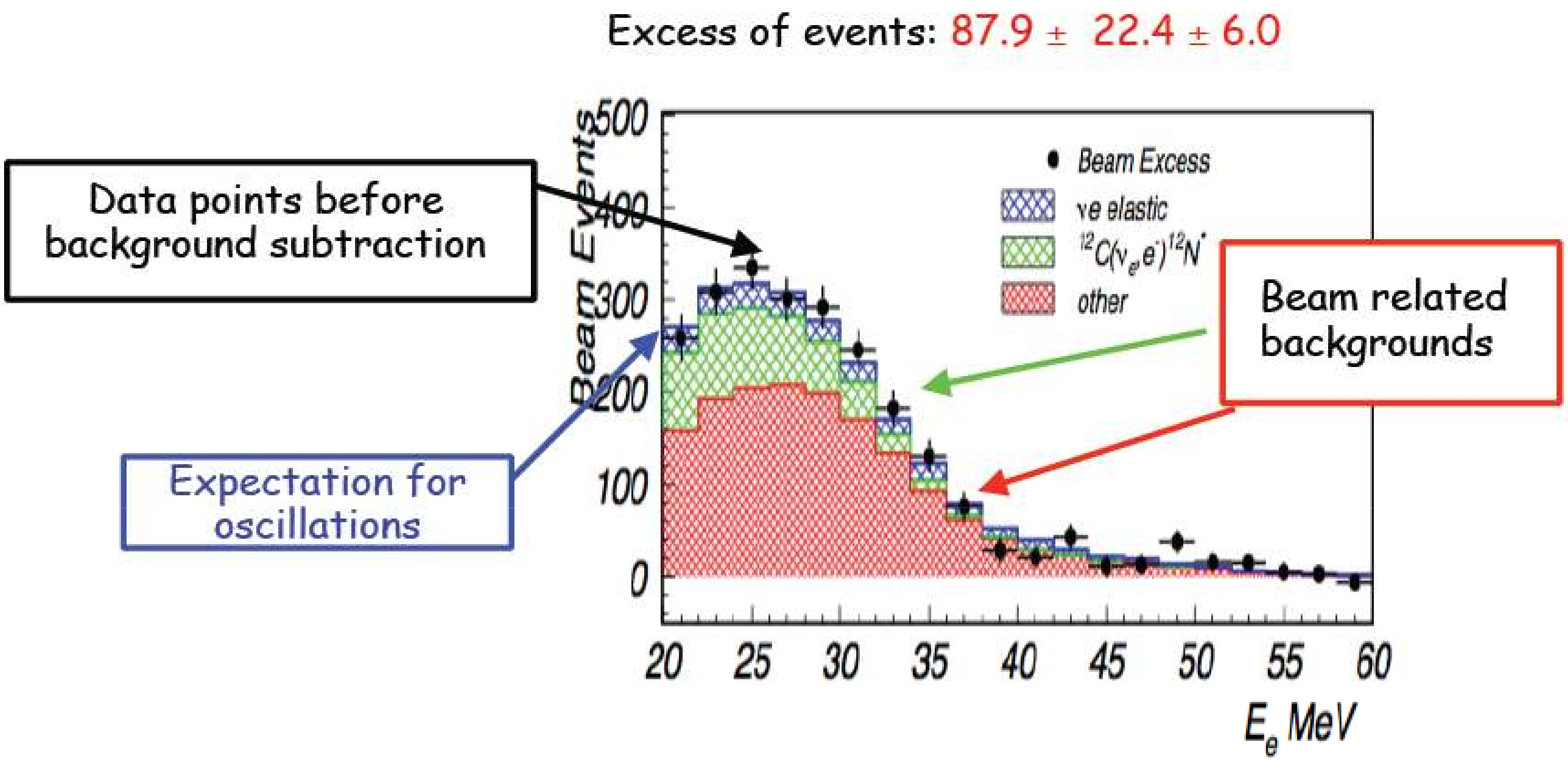
What about steriles?..

LSND Starts it all...

- Backgrounds in green, red
- Fit to oscillation hypothesis in blue



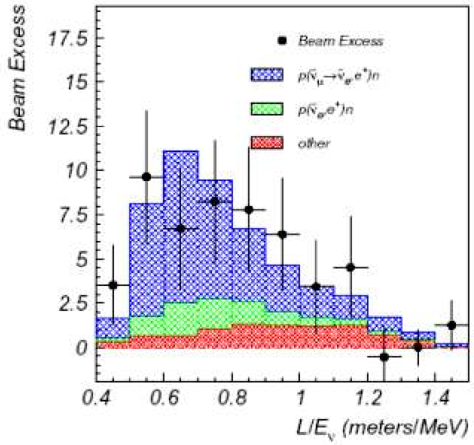
LSND Starts it all...

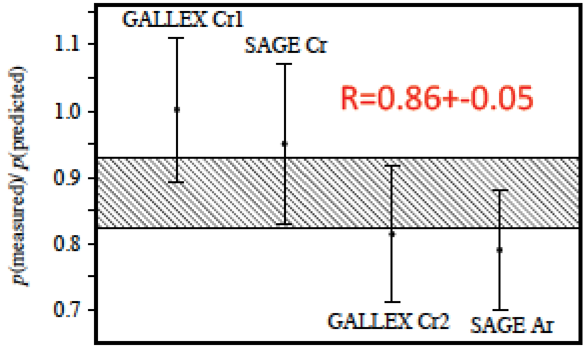


Excess of electron anti-neutrinos in a "beam" from stopped pion decay (not seen by KARMEN experiment with similar sensitivity)..

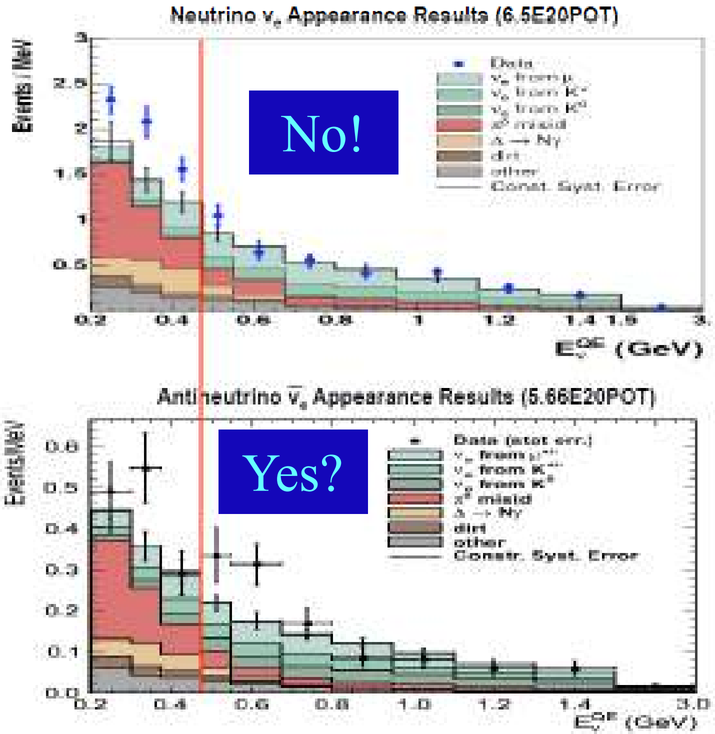
Sterile Indications…

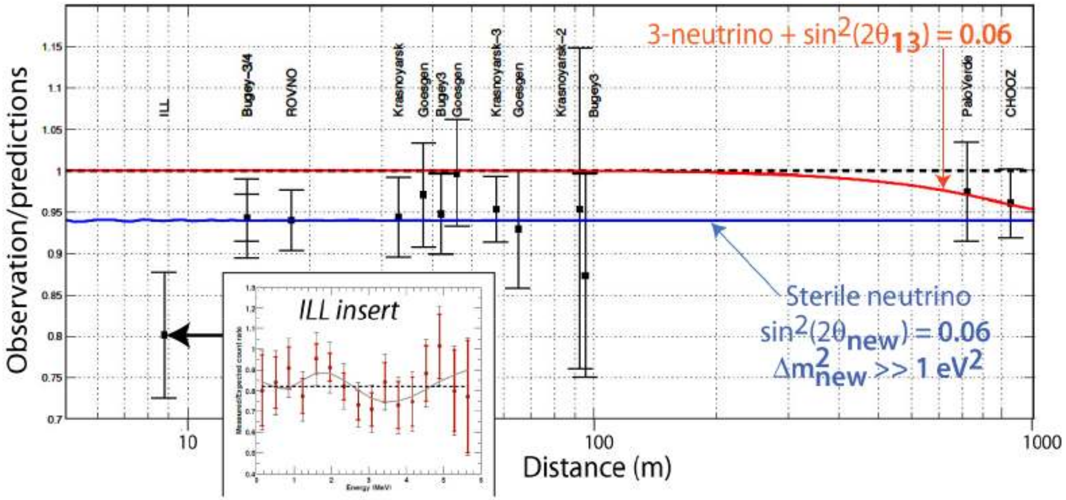
Short baselines (L/E ~ 1) and Sterile ν.



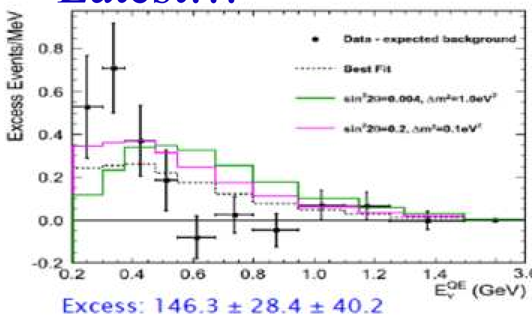


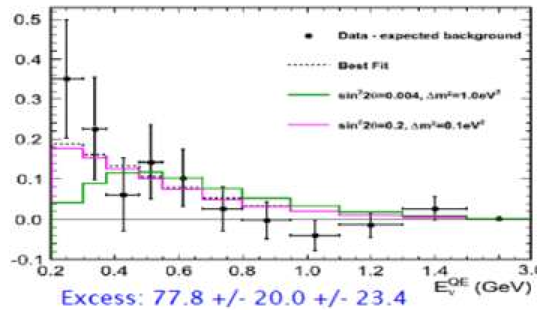
MiniBooNE says....



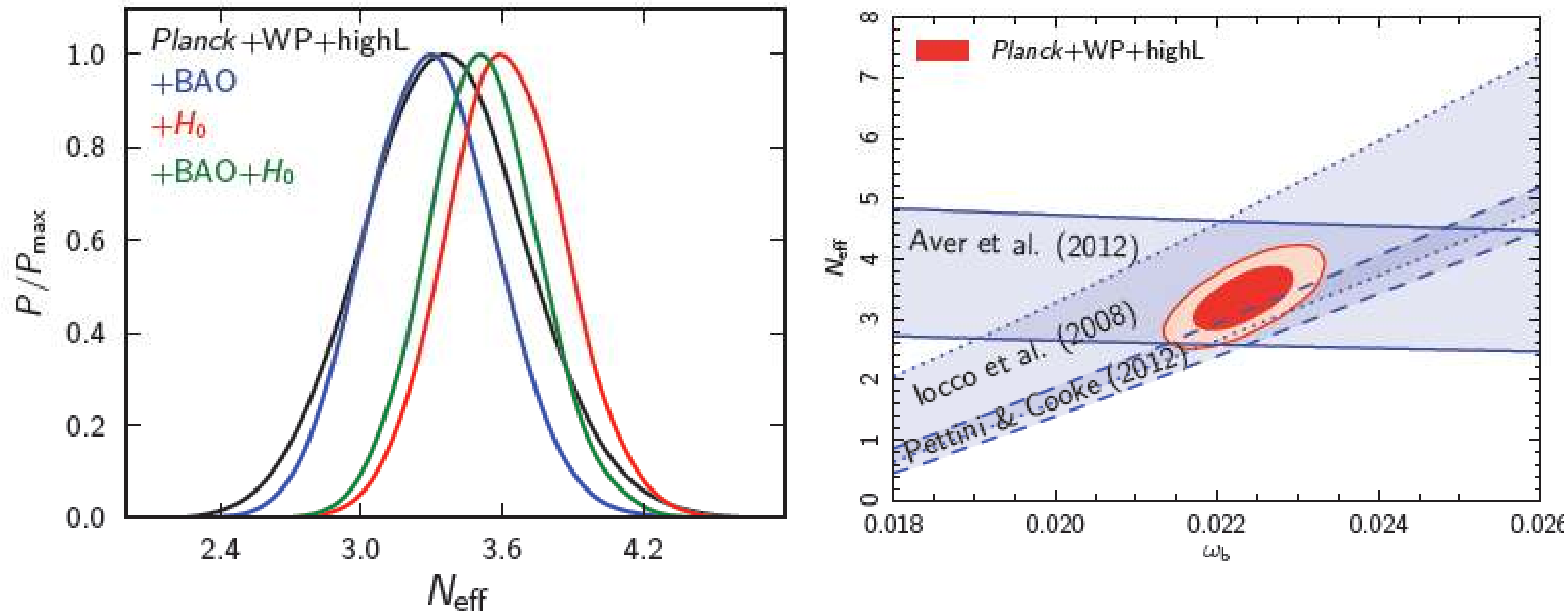


Latest…





Cosmological indications?

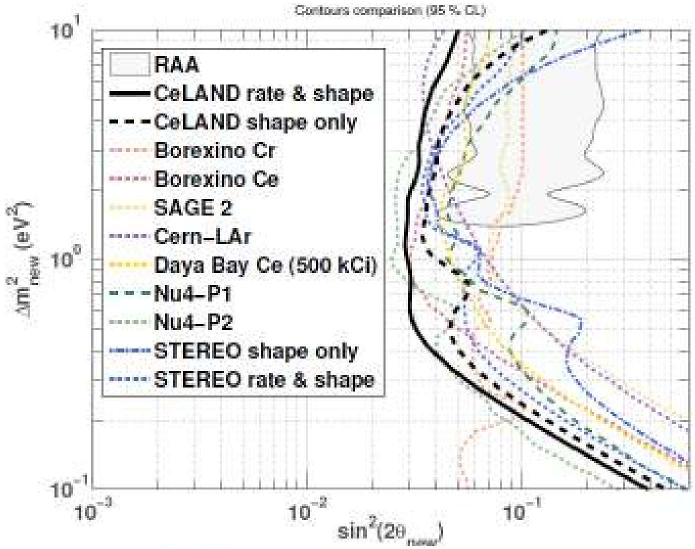


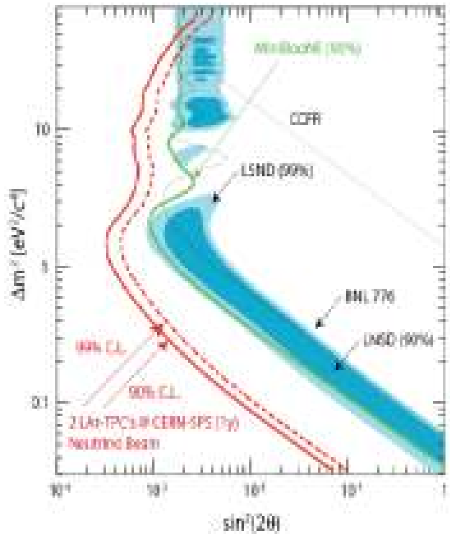
$m(\nu_s) \equiv 0 \quad \rightarrow \quad N_{eff} = 3.52 \pm 0.24$ (all data) $\qquad N_{eff} = 3.36 \pm 0.34$ (CMB)

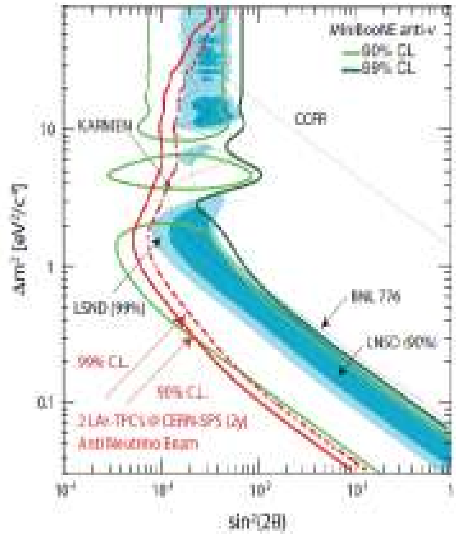
$m(\nu_s)$ free $\rightarrow \quad N_{eff} < 3.80$ (95% CL)

$m(\nu_s) < 0.42$ eV

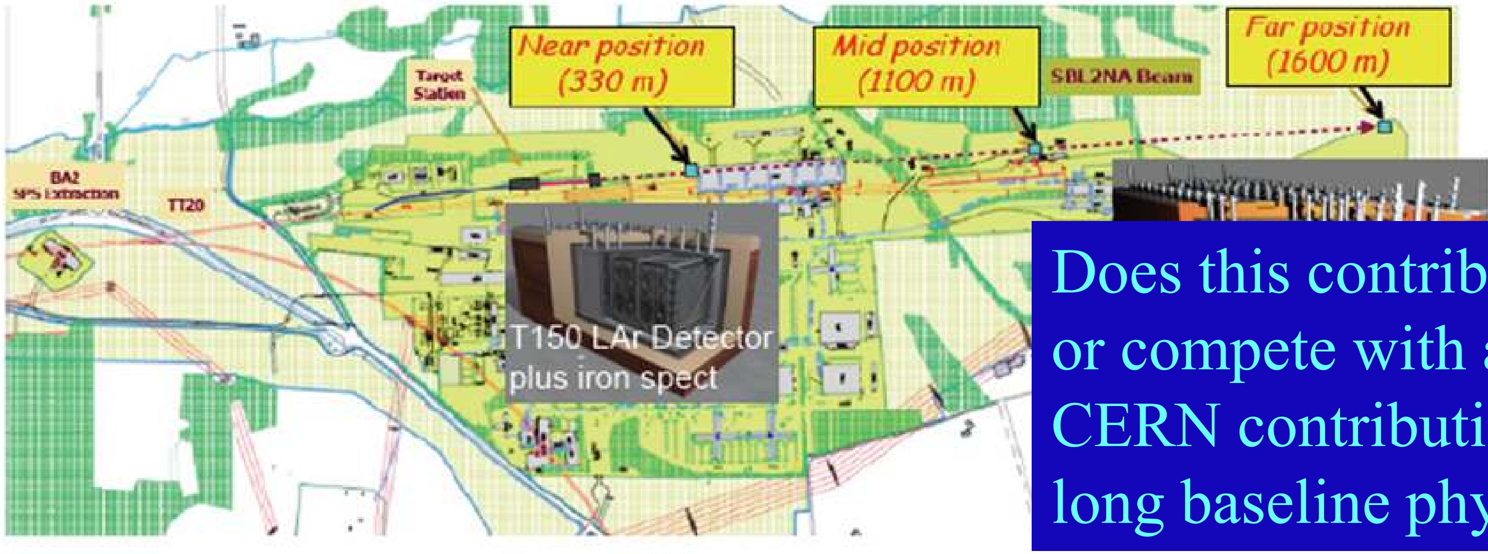
Dozens of proposed experiments to test...







New Neutrino Facility in the CERN North Area

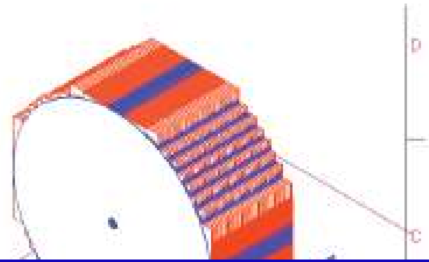


Does this contribute to or compete with a CERN contribution to long baseline physics?

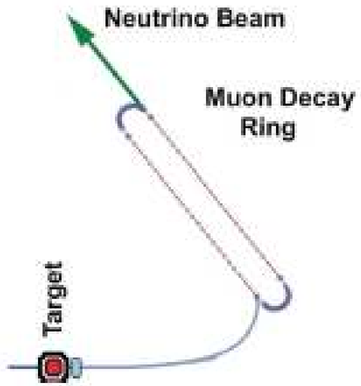
100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe l =100m, ø = 3m; beam dump: 15m of Fe with graphite core, followed by μ stations.

Neutrinos from STORed Muons - νSTORM

- Simplest implementation of the NF concept
  - 60 GeV protons on solid target (100 kW)
  - Horn capture and π transfer
  - Decay ring
- No new technology is required
  - Little R&D is needed
    ≈"Technology" ready

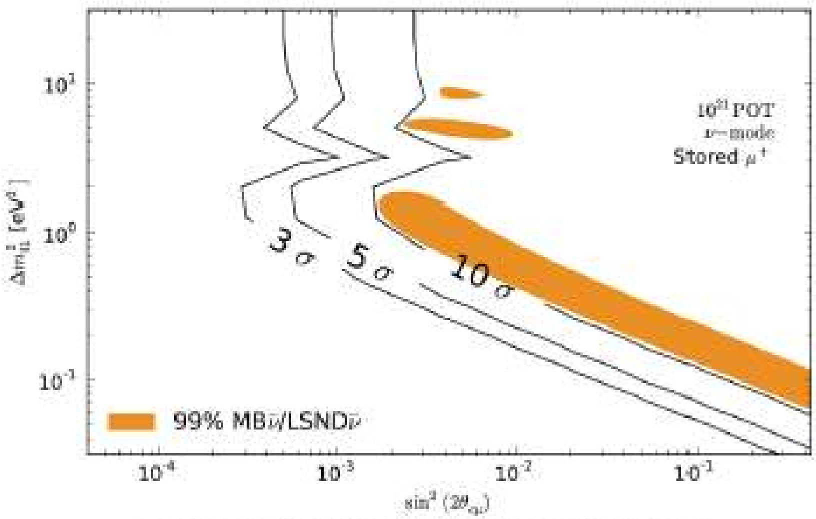


Could measure ν_e cross-sections, critical (?) for <5% systematics?



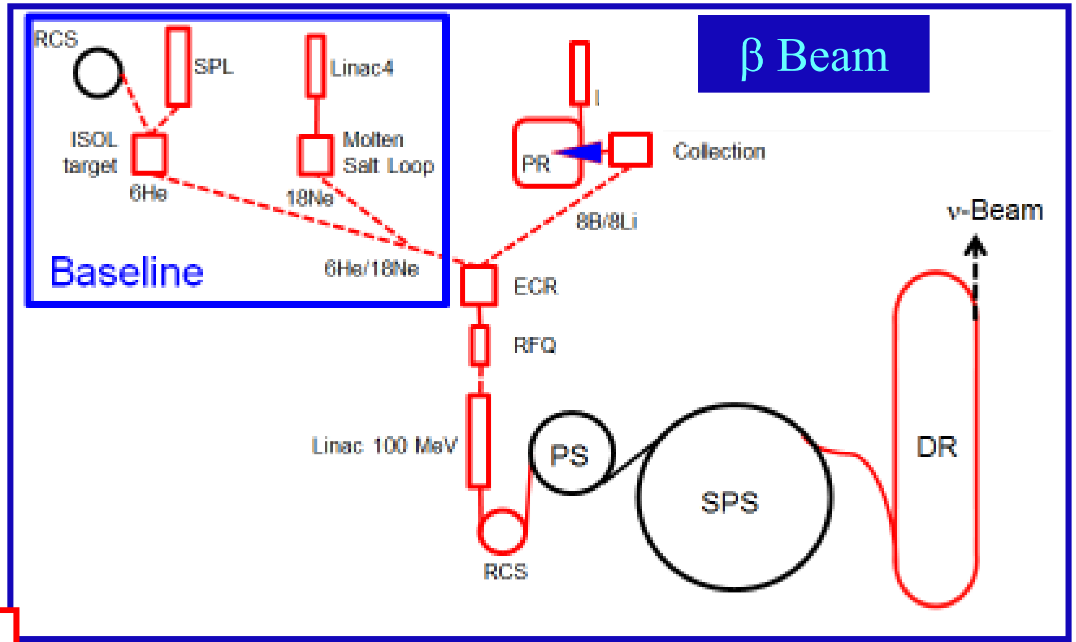
- Performance assumptions:
  - 10^{21} 60 GeV/c POT
- Yields ≃ 2X10^{18} useful ν
- ≃2000 m baseline
- 1.3 kT Minos-like detector: SuperB IND
  - Thinner plates
  - 2T B

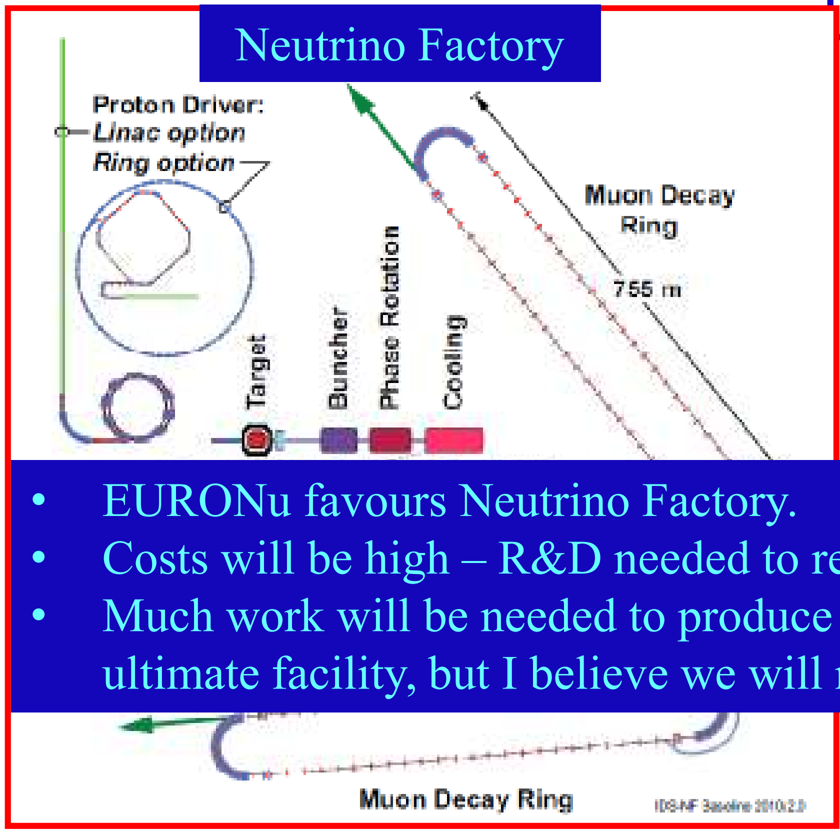
$\nu_e \rightarrow \nu_\mu$: CPT Invariant mode of LSND/MinBooNE



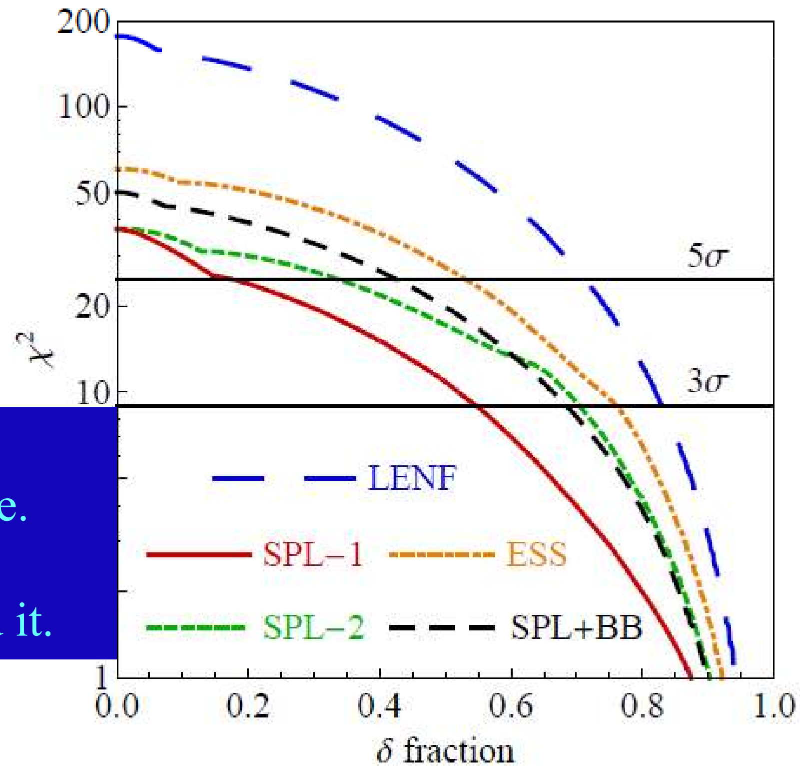
nSTORM/LBNE?

Essential step towards ultimate MNSP sensitivity?





- EURONu favours Neutrino Factory.
- Costs will be high – R&D needed to reduce.
- Much work will be needed to produce this ultimate facility, but I believe we will need it.

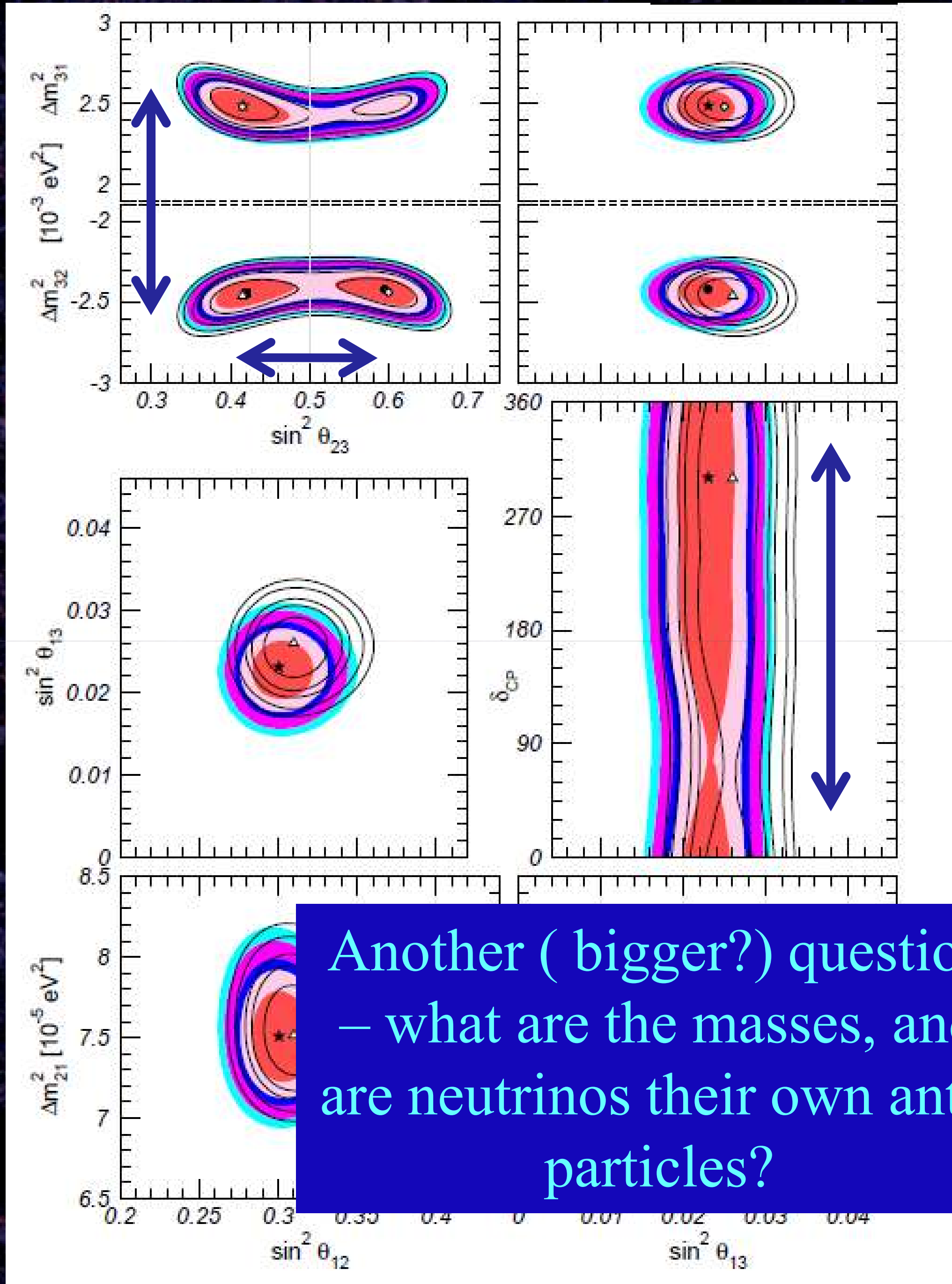


Gonzalez-Garcia,Maltoni,Salvado,Schwetz

What is the MH?

Is θ_{23} maximal?

If $\theta_{23} \neq 45^{o}$ what is the octant?

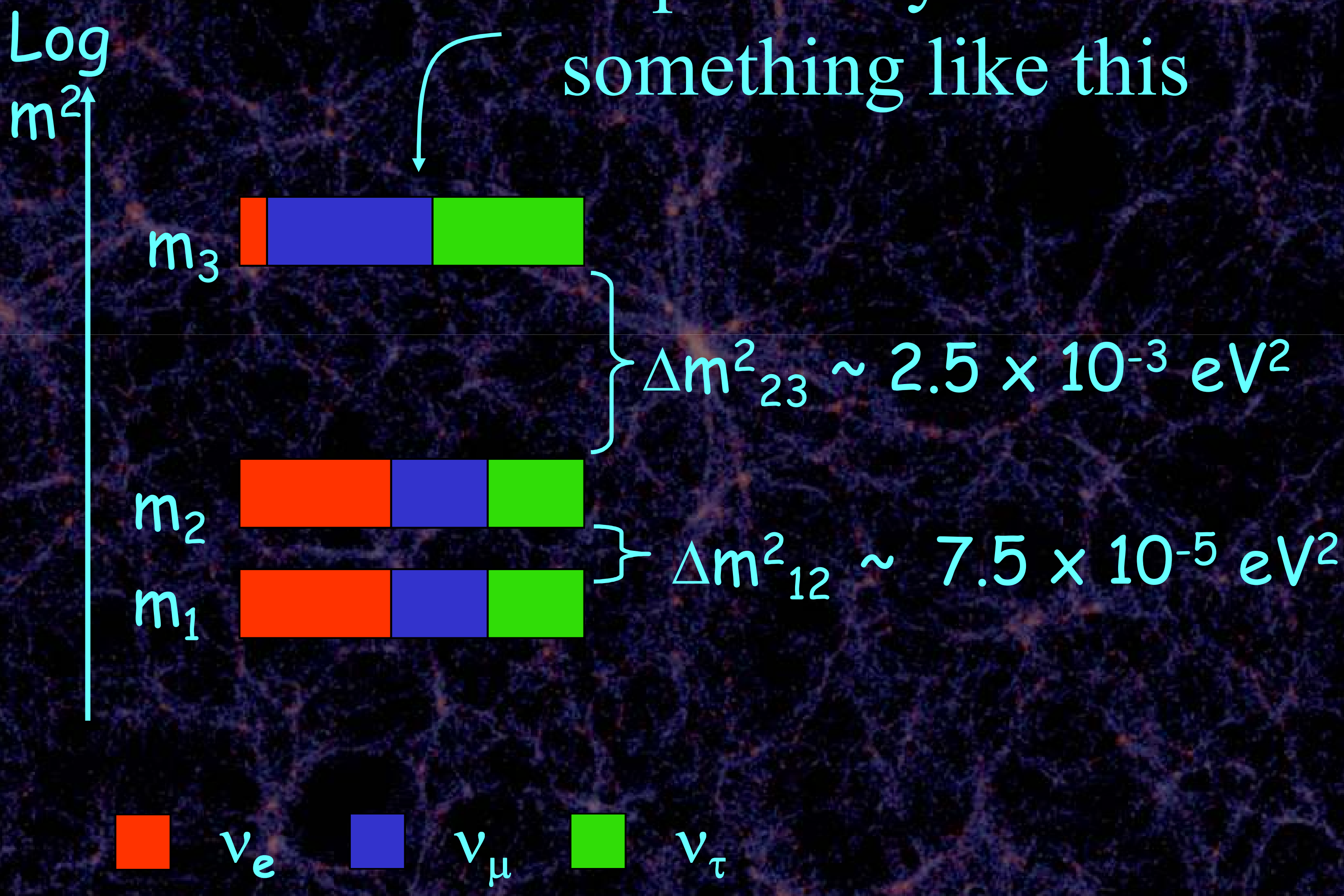


What is δ?

Another (bigger?) question – what are the masses, and are neutrinos their own anti-particles?

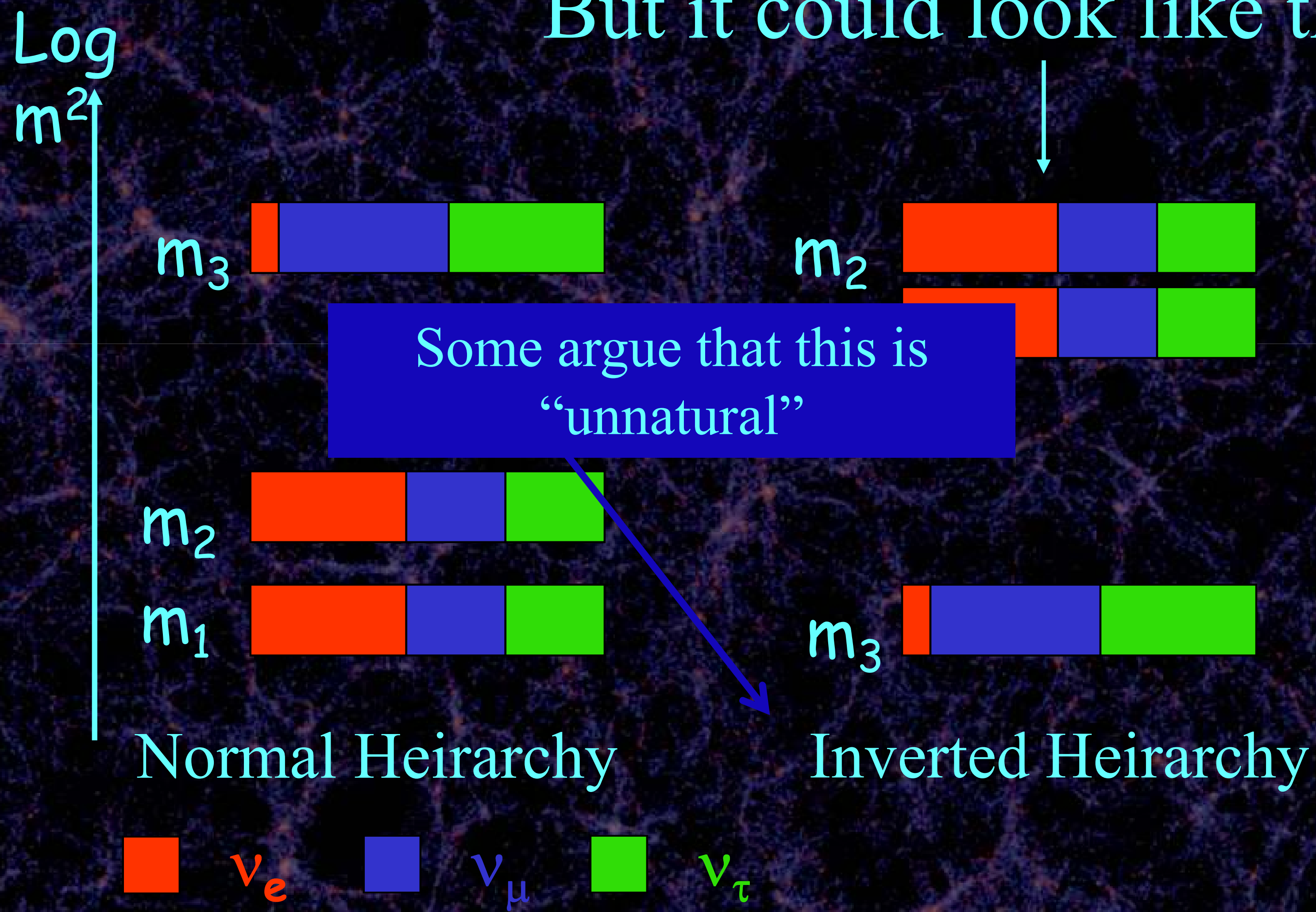
What is the pattern of neutrino masses?

It "probably" looks something like this



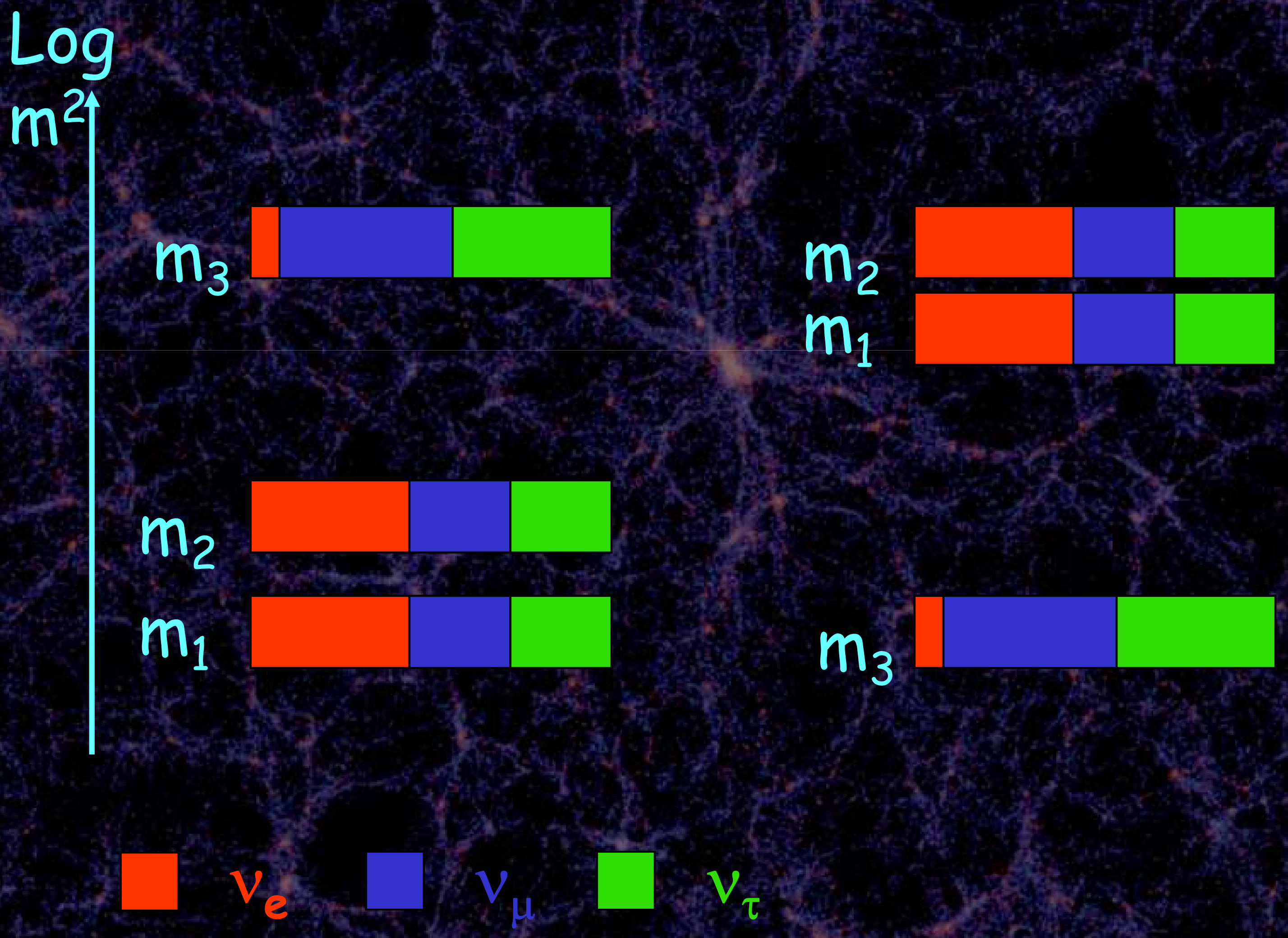
What is the pattern of neutrino masses?

But it could look like this

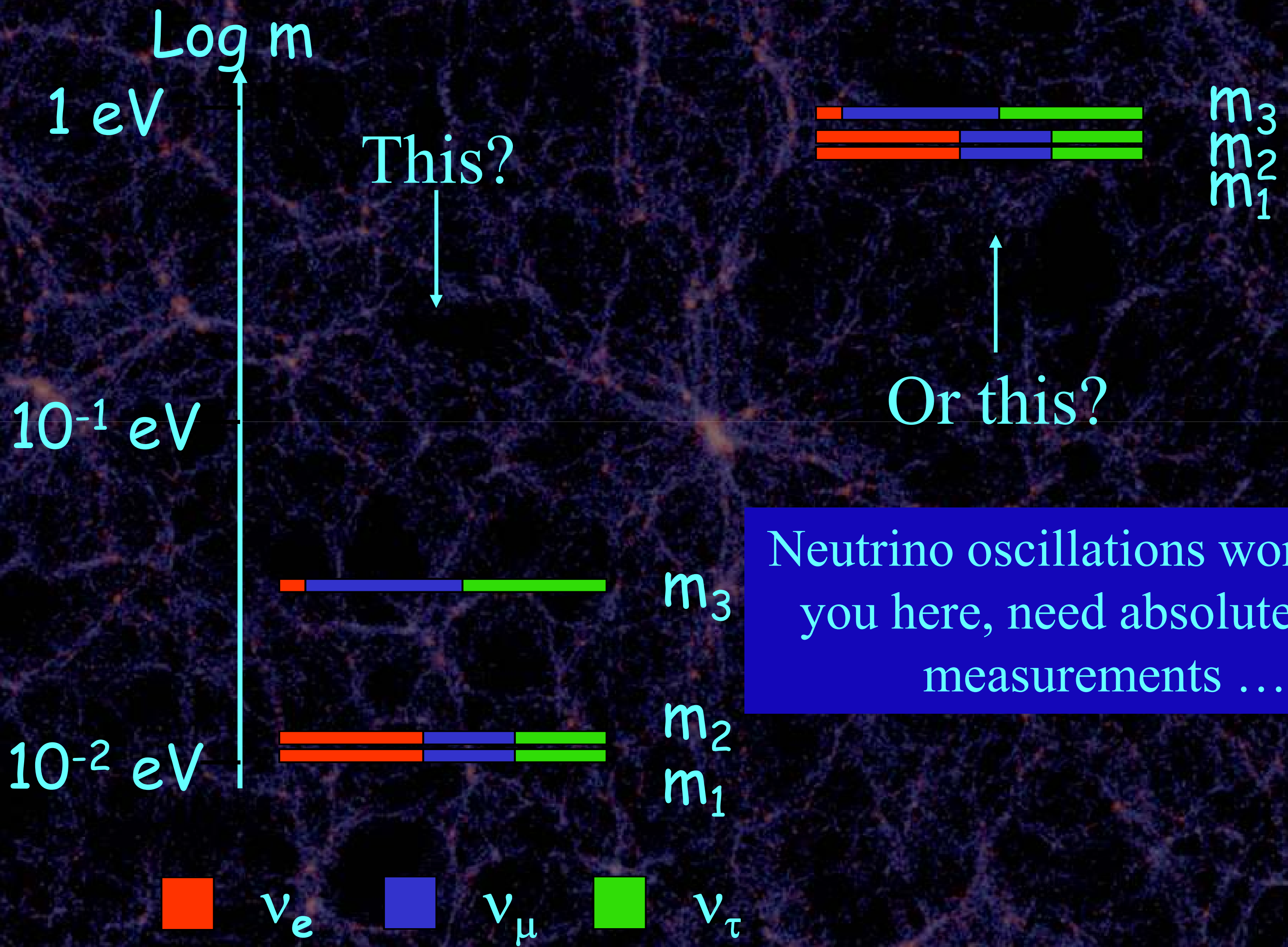


Does this look natural?

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



Even more significant is the absolute scale.



Neutrino oscillations won't help you here, need absolute mass measurements …

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, $\langle m_\nu \rangle < \sim 0.4$ eV.
- Neutrinos are the second most numerous particle in the Universe → even a tiny neutrino mass could have astrophysical implications, $\Sigma m_\nu < 0.25$ eV(?)

Conclusions

- Neutrino oscillations are still the only confirmed BSM particle physics.
- We still have a lot of work to do to completely characterize the MNSP matrix.
- The measurement of "large" θ_{13} has opened up a whole range of new experiments on a realizable scale.
- There is no other way to do this physics than build major projects to measure a few numbers – but we need those numbers.
- A strong case exists for at least two complementary long-baseline projects in the near to mid-term – neutrino physicists should not be shy! If you want this to happen, make your voice heard!
- There is and will (or at least should) be a continuing programme to develop towards a Neutrino Factory.
- The sterile neutrino question also needs an answer. Sigh.
- We will also need more hadron production measurements ala NA61/SHINE, and more neutrino cross section measurements ala MINERvA (nSTORM?) – these will provide good opportunities for the young. Think hard and propose something.
- We have decades of work ahead of us – JOIN US!

A word of caution about Global Fits…

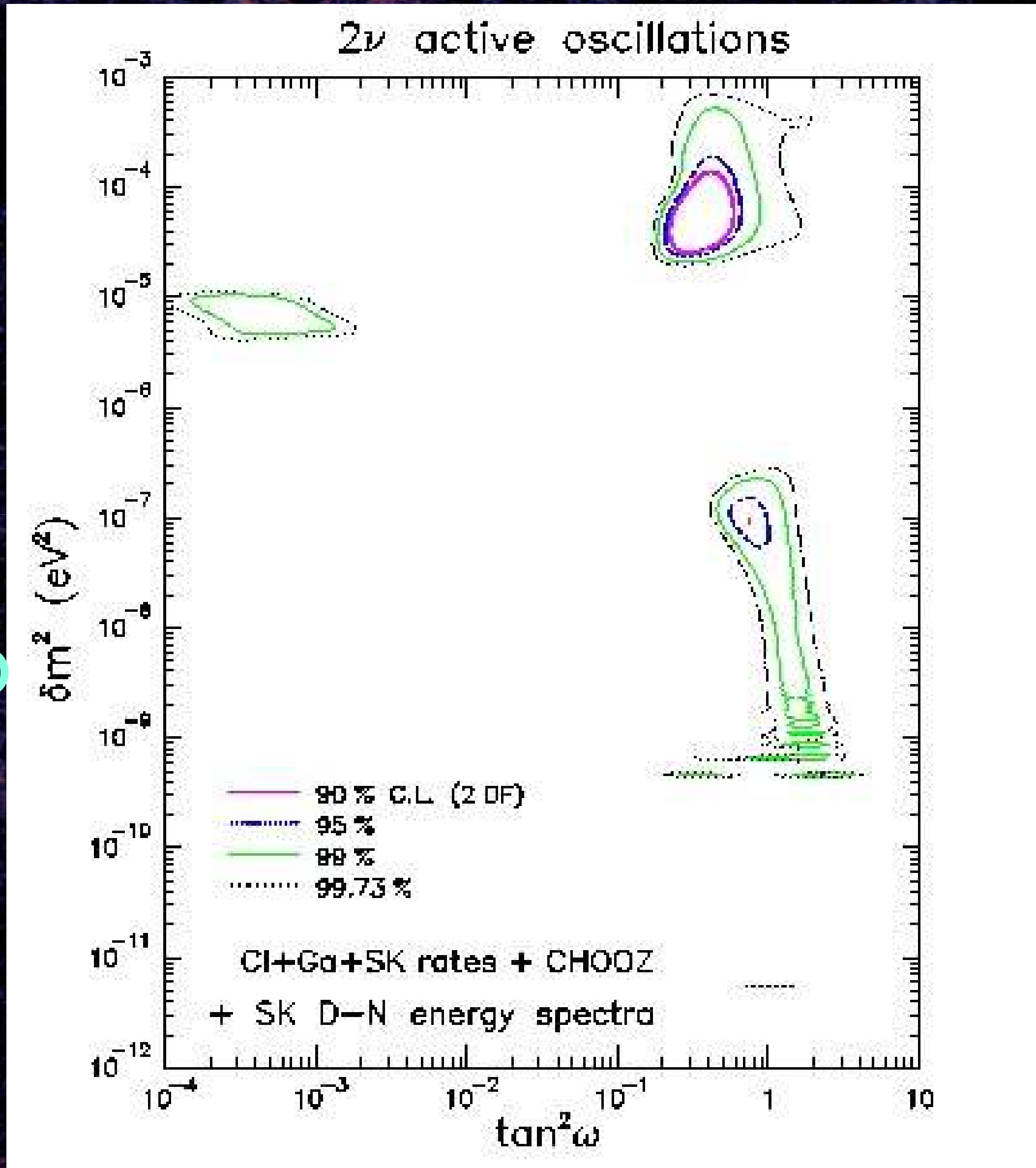
- Why do we need definitive experiments?
- Can't we do global fits of marginal experiments?
- If you need a global fit to "discover" something, then you are combining the edges of allowed ranges.
- If we are successful, our experiments will be limited by systematics.
- Basic problem – systematics don't have distributions, they have values, you just don't know what they are – statistical tests fail.

A word of caution about Global Fits…

- The discoveries shown on the previous slides are true if any of the experiments that found them are right.
- A “discovery” from a global fit is true only if ALL the experiments that go into it get their systematics right, which has not always been true in the history of neutrino physics.
- We cannot escape the need to build definitive experiments, and more than one. Sorry ‘bout that.

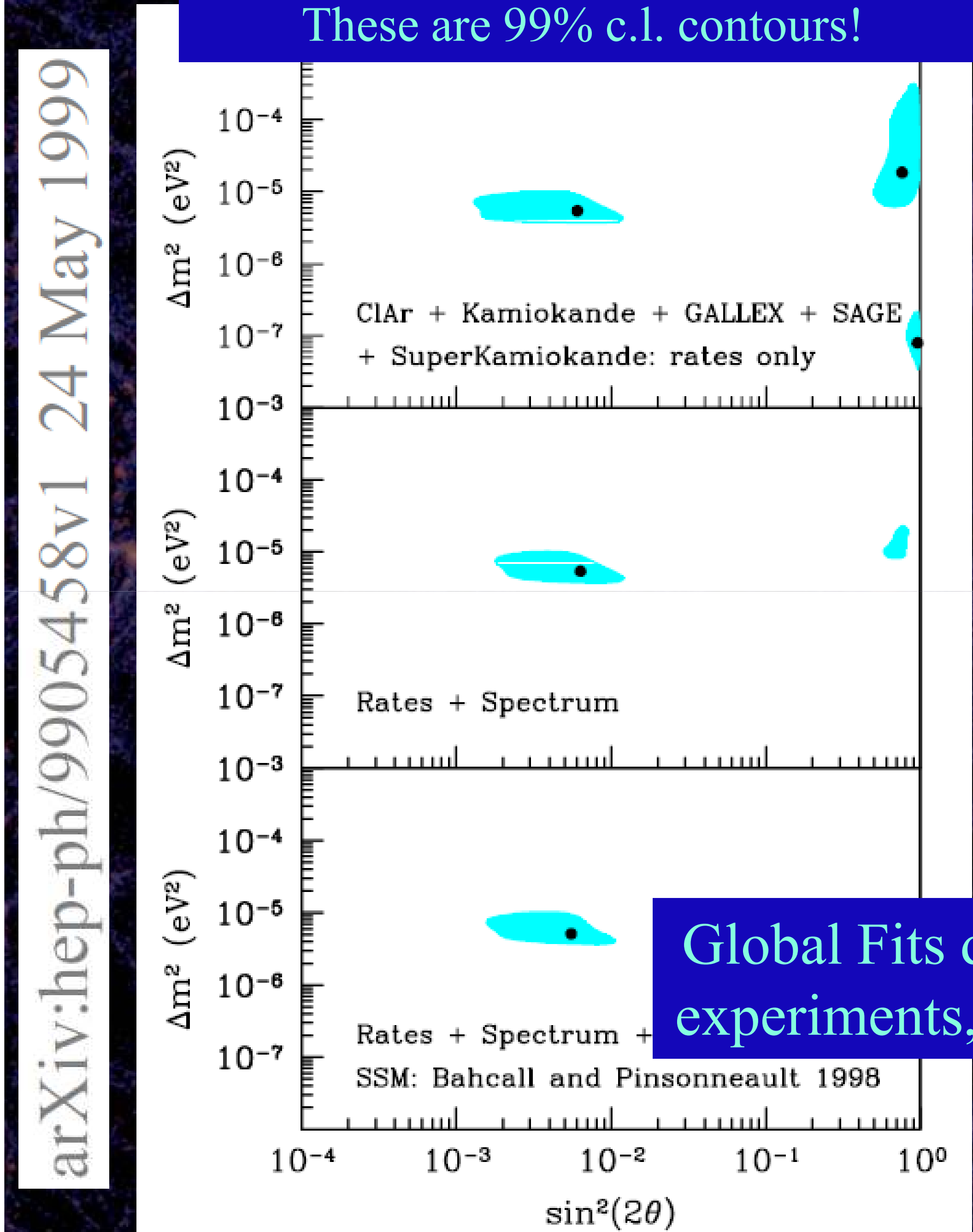
A word of caution about Global Fits…

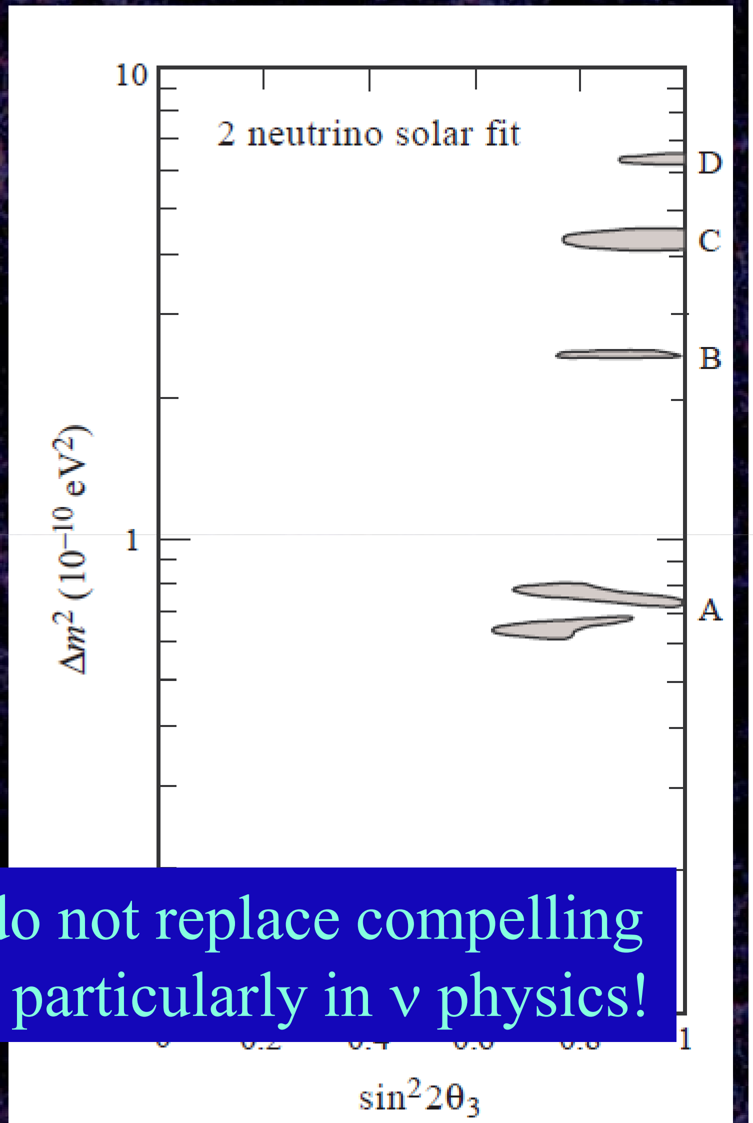
Global Solar ν fit
prior
to SNO/KamLAND



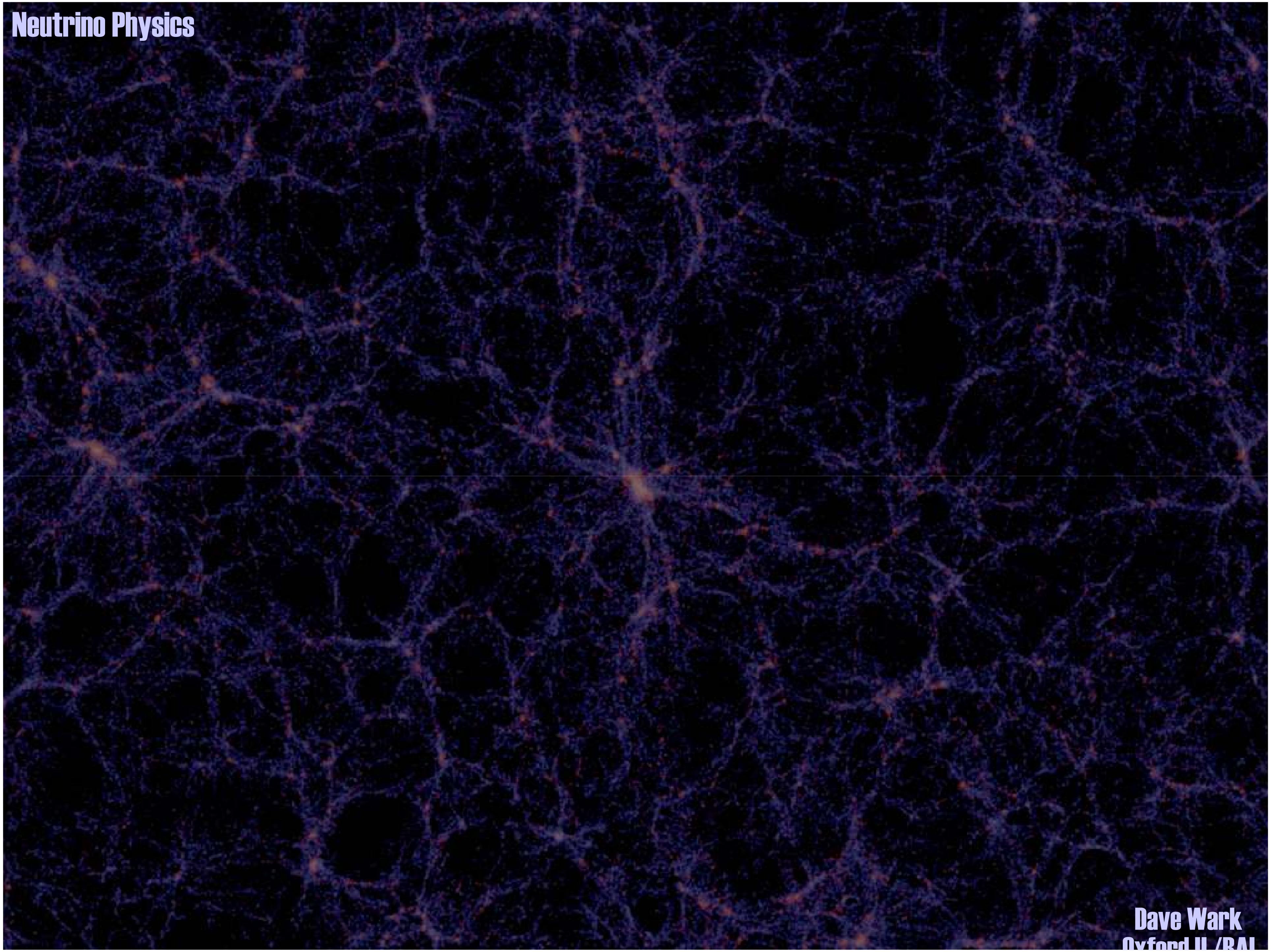
These are 99% c.l. contours!

Using all data as of Neutrinos '98.

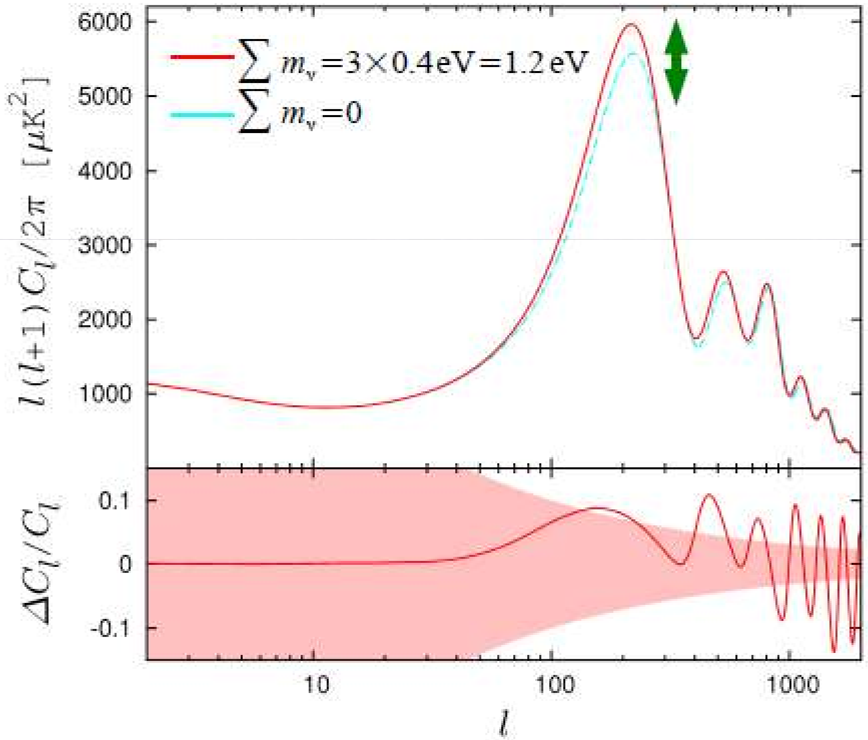


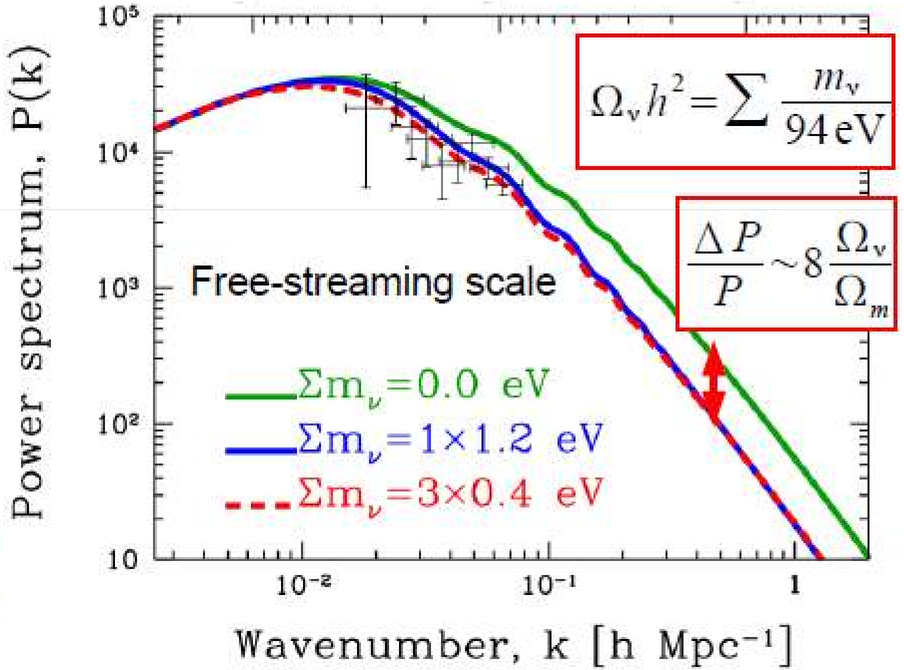


Global Fits do not replace compelling experiments, particularly in ν physics!


Neutrino Physics
Dave Wark
Oxford U./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.

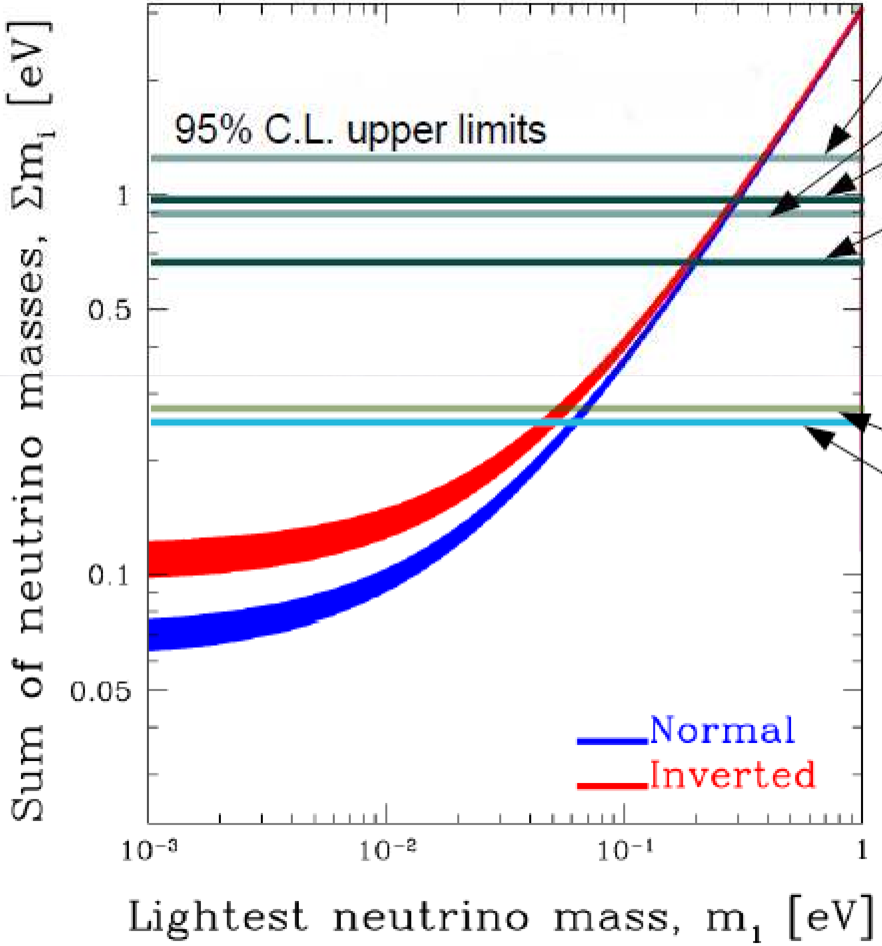




Slide from Yvonne Wong's talk at TAUP '11

Post-Planck...

Ade et al.[Planck] 2013



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\% \text{C.L.})$$

Best CMB-only bound

W7+ matter power spectrum + HST H_0

Planck + WP + (ACT ℓ > 1000 + SPT ℓ > 2000) + baryon acoustic oscillations

$$\sum m_\nu < 0.25 \text{ eV} \quad (95\% \text{C.L.})$$

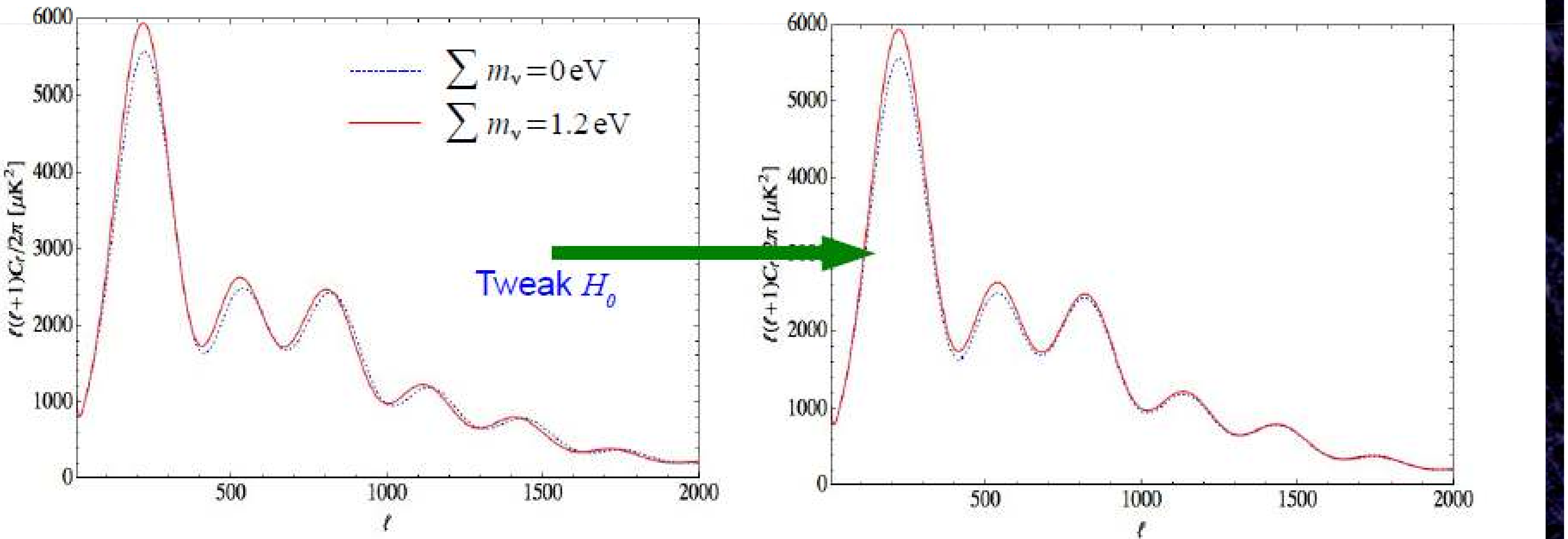
Best minimal bound

Formally similar to the pre-Planck best minimal bound, but arguably less prone to issues of nonlinearities.

Slides from Yvonne Wong's talk at NuFact '13

Model dependence: parameter degeneracies...

- We **do not** measure the neutrino mass *per se*, but rather its indirect effect on the clustering statistics of the CMB/large-scale structure.
  - It is **not impossible** that other cosmological parameters could give rise to similar effects (within measurement errors/cosmic variance).



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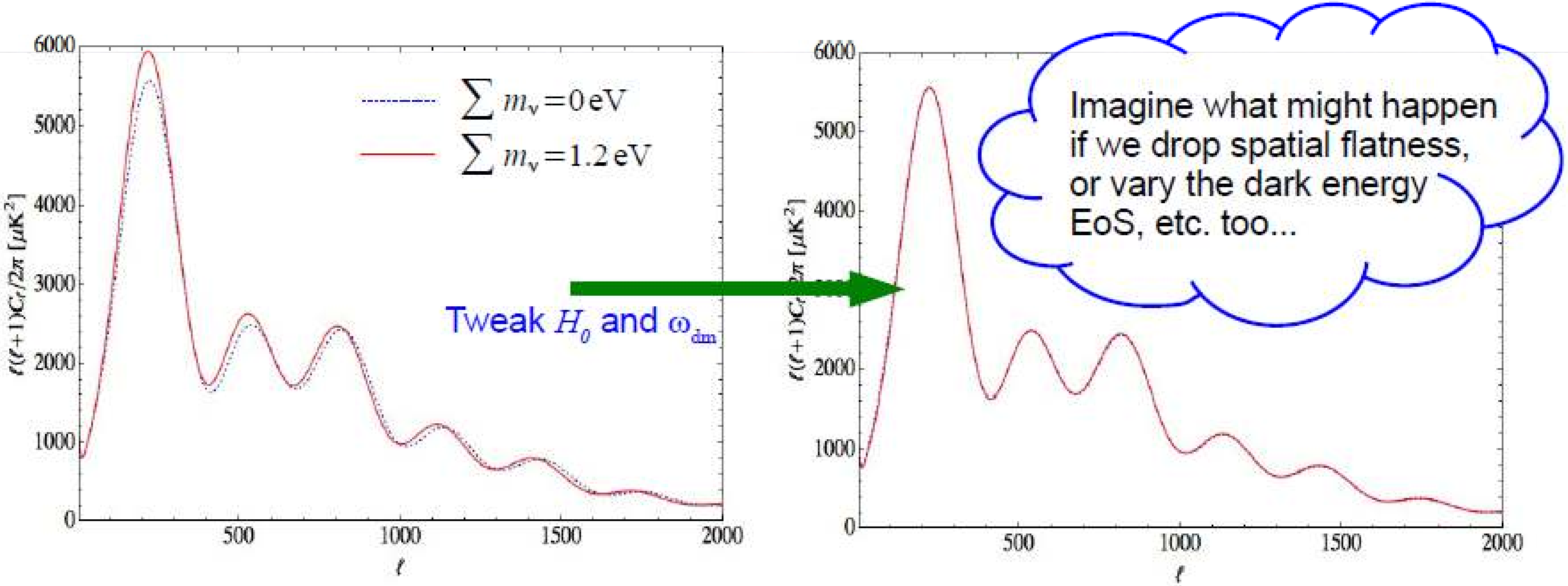
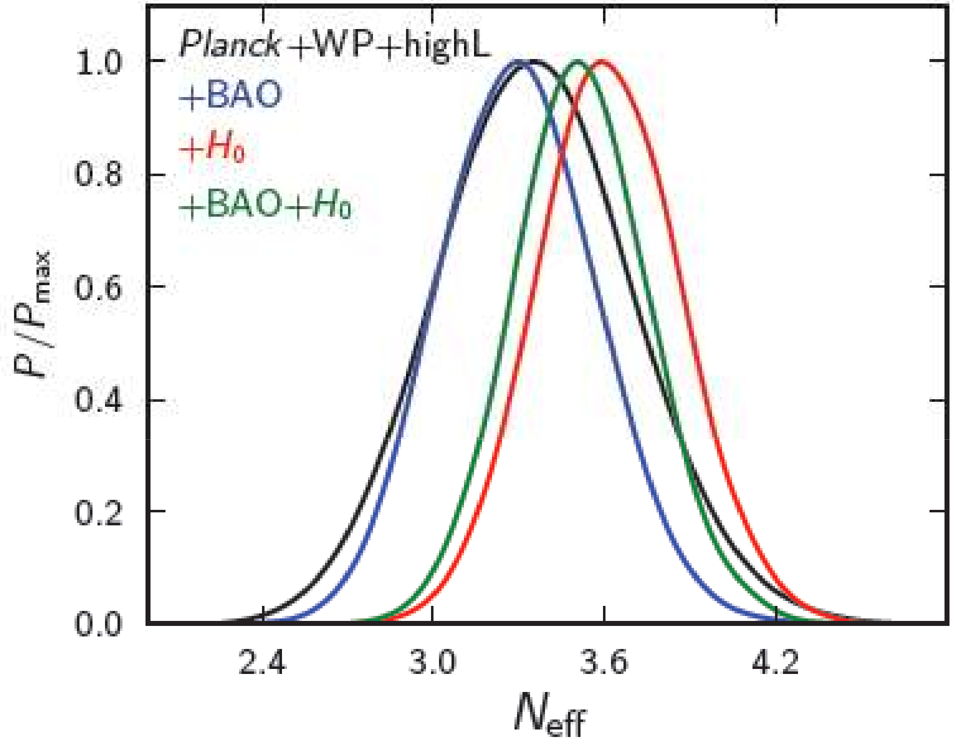
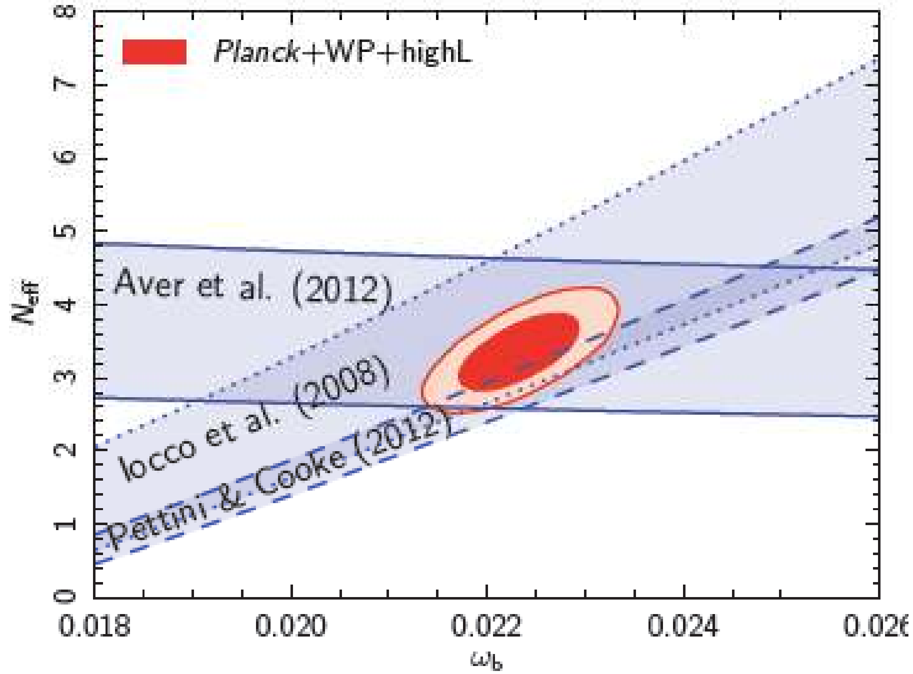


How many are there?





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$m(\nu_s)$ free $\rightarrow$ $N_{\text{eff}} < 3.80$ (95% CL)

$m(\nu_s) < 0.42$ eV

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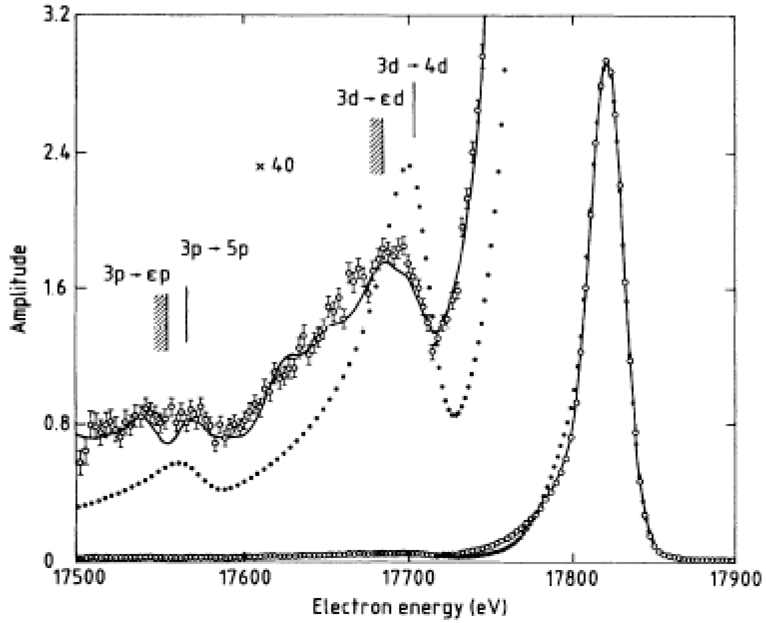
J. Tulkki and T. Åberg
Laboratory of Physics, Helsinki University of Technology, 02150 Espoo, Finland

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

SNO Systematic Flux Uncertainties

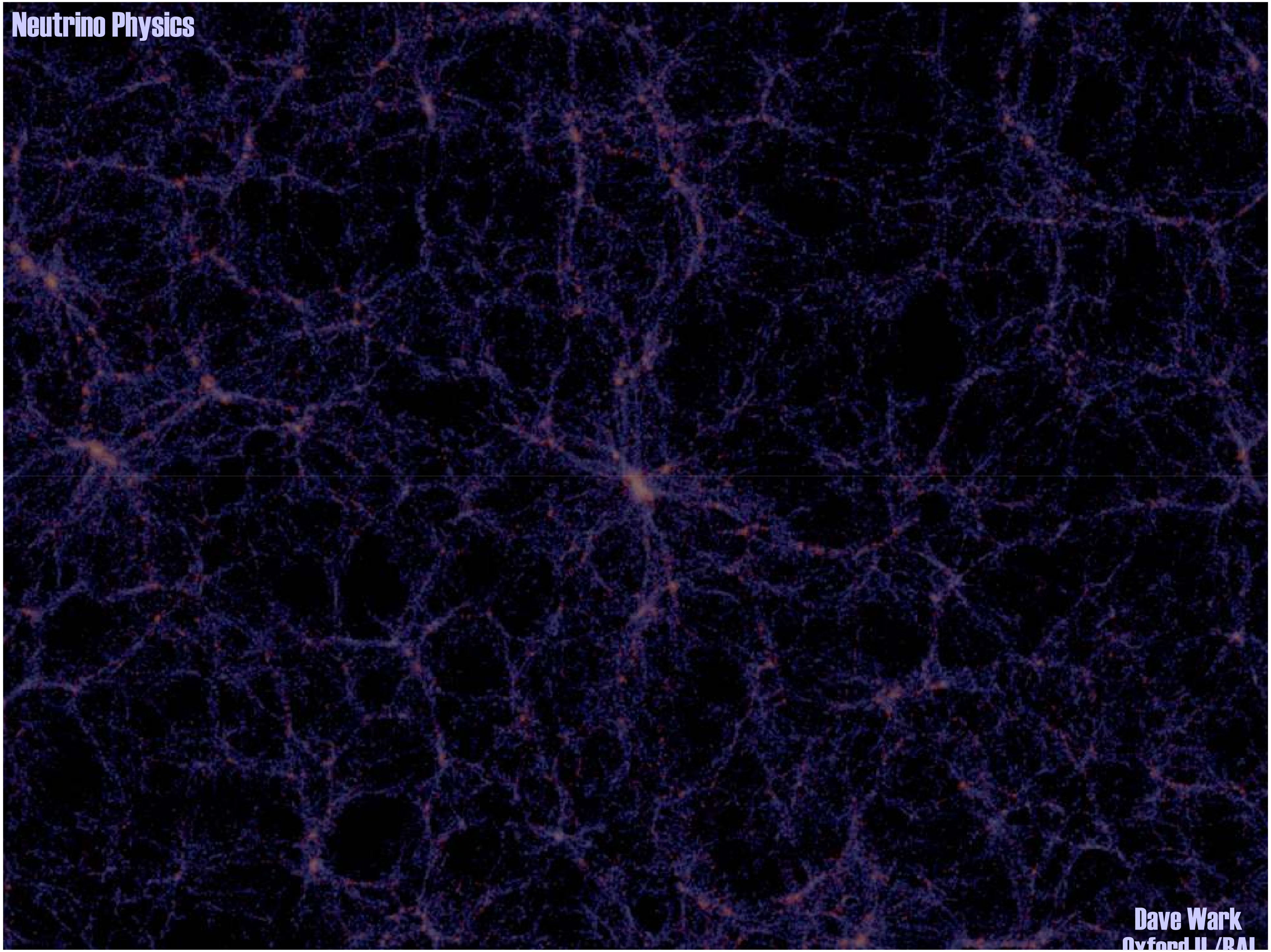
Error Source	CC error (%)	ES error (%)
		−3.5, +5.4
		±0.3
		±0.4
		±3.3
		±0.4
		±2.2
		−1.9, +0.0
Low energy background	−0.2, +0.0	−0.2, +0.0
Instrumental background	−0.8, +0.0	−0.6, +0.0
Trigger efficiency		
Live time		
Cut acceptance		
Earth orbit eccentricity		
^{17}O, ^{18}O		
Experimental uncertainty		
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, even if they reach "sensitivity" to MH.

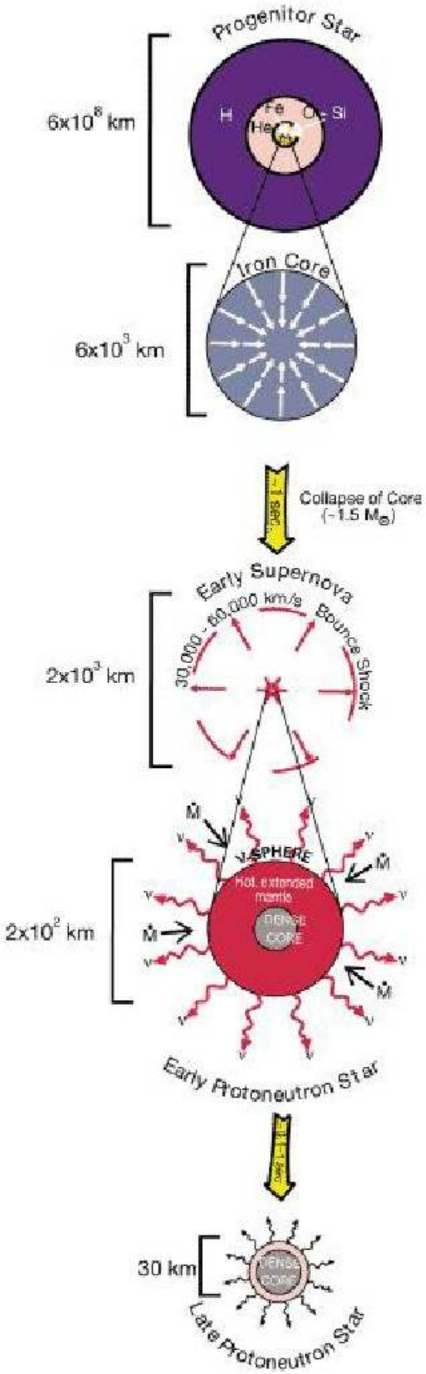
In any case, using precious cosmological data to constrain m_ν would be like using LEP as a tide gauge.

Return ↑

Neutrino Physics



Dave Wark
Oxford U./RAL

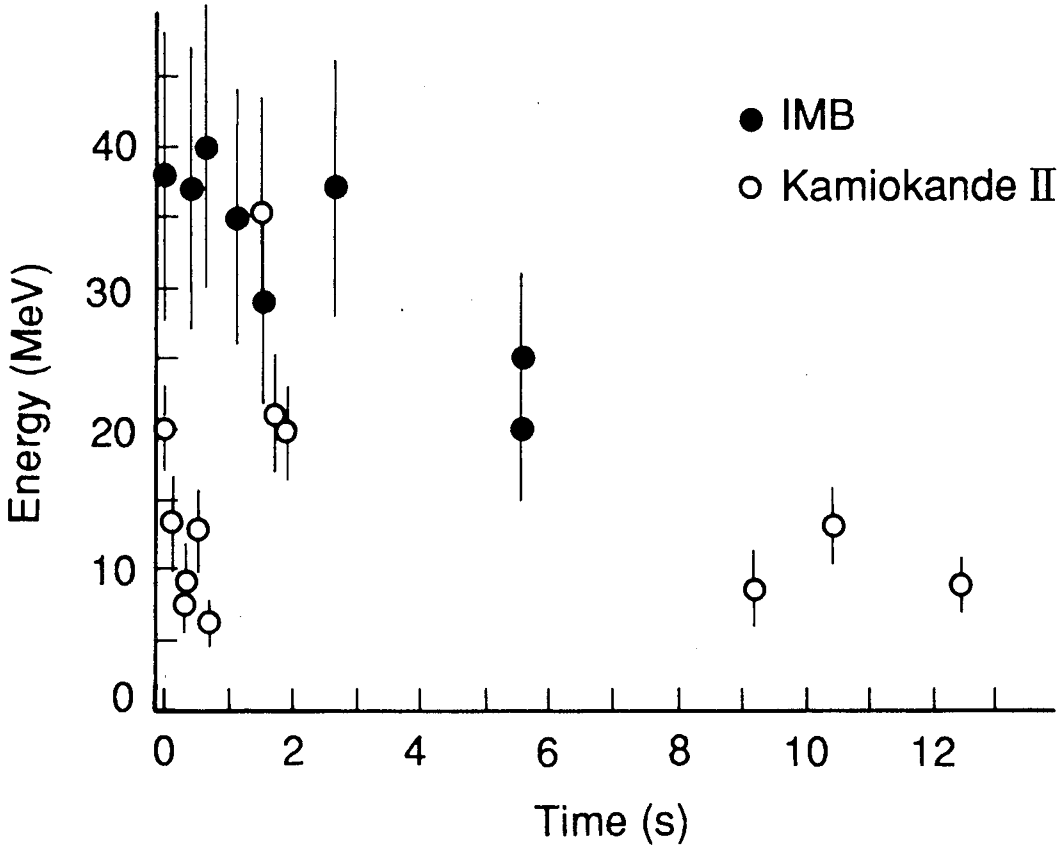


February 1984

March 8,1987

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

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



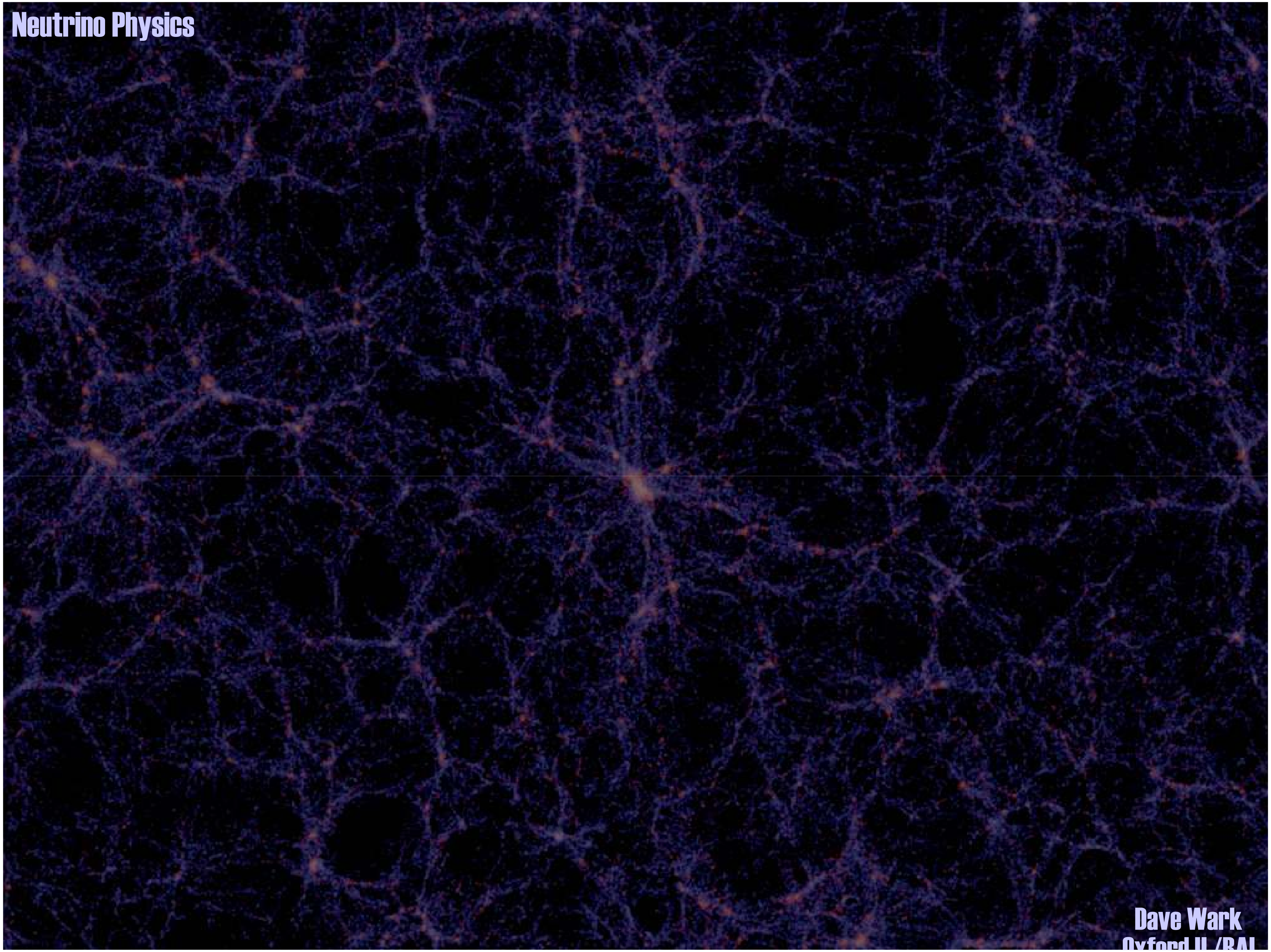
Limit from SN1987a is $m_{\nu_e} > 23$ eV (PDG)

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

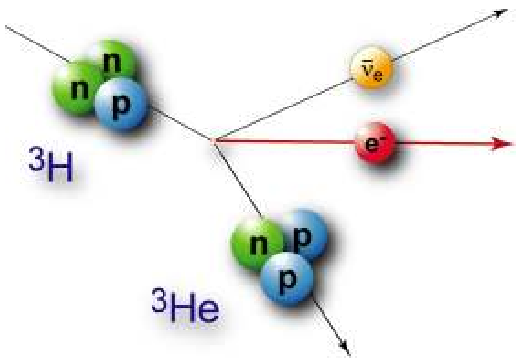
Return ↑

Neutrino Physics



Dave Wark
Oxford U./RAL

Tritium β-decay



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

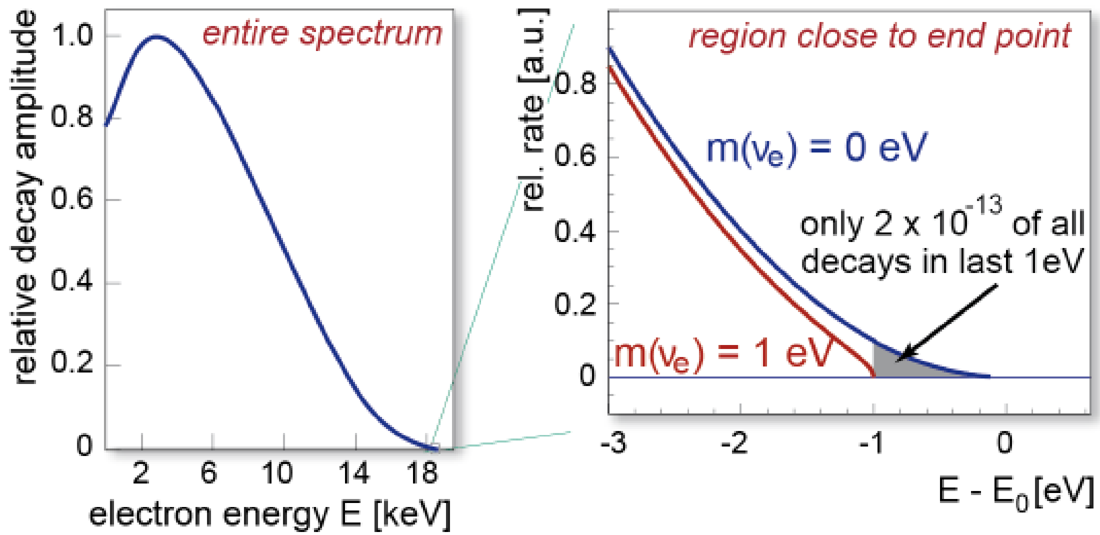
Fermi theory of β-decay:

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

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

tritium as β emitter:

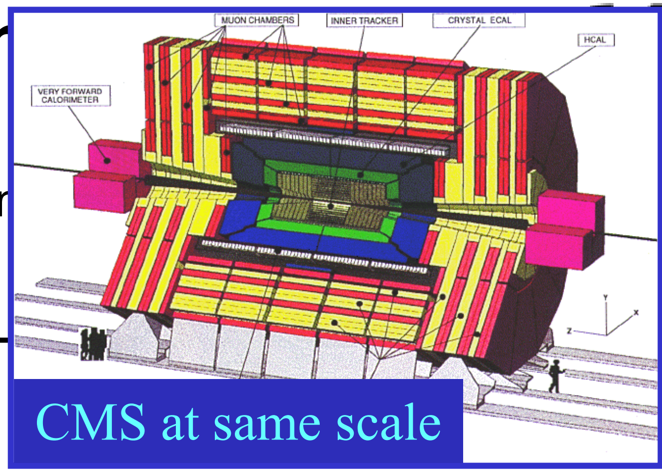
- high specific activity (half-life: 12.3 years)
- low endpoint energy E_0 (18.57 keV)
- super-allowed



KATRIN experi

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

70 m

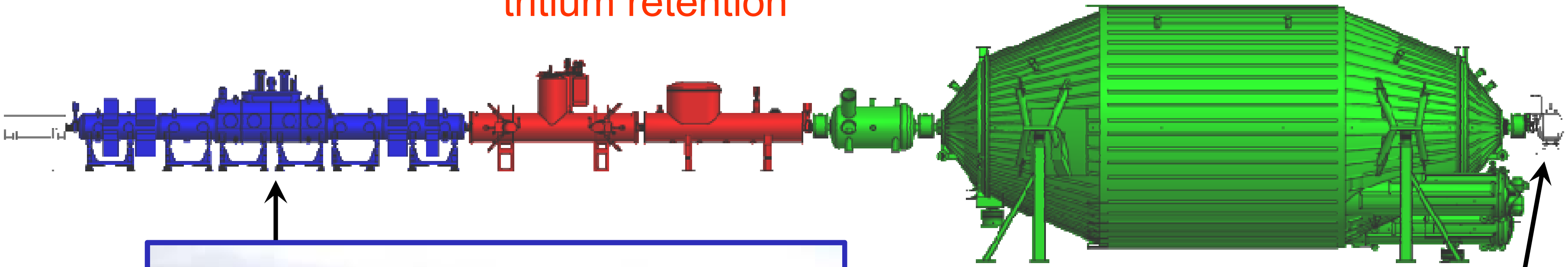


CMS at same scale

tritium decay

electron transport

tritium retention



β-de

T_2 pr

f magnitude

background rate: **10^{-2}** Hz

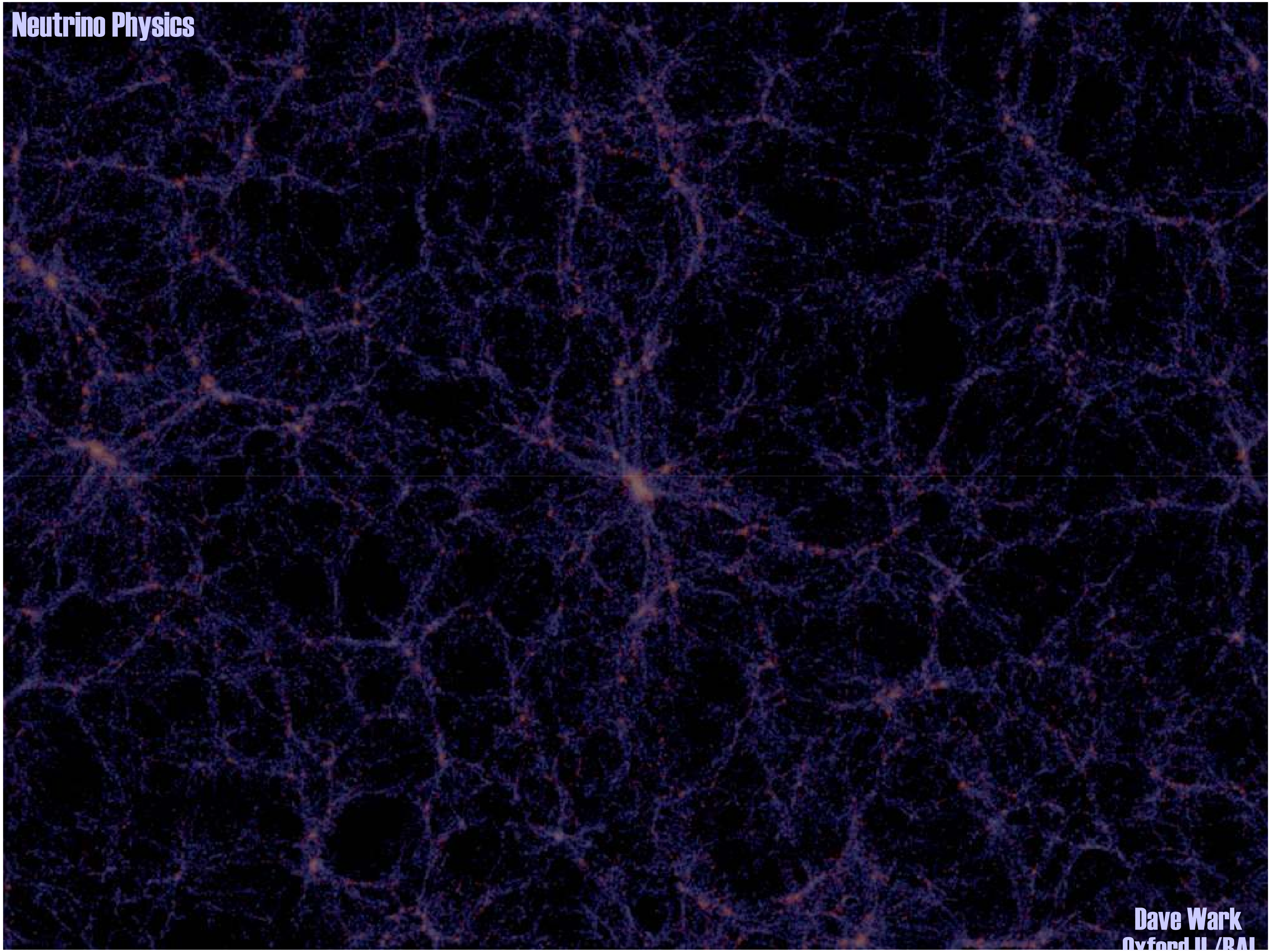
T_2 pressure: **10^{-20}** mbar

n meV level

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

Return ↑

Neutrino Physics



Dave Wark
Oxford U./RAL

Dirac ν vs Majorana ν

C
P
T

$$\begin{bmatrix} \nu_L \\ \nu_R \\ \overline{\nu}_L \\ \overline{\nu}_R \end{bmatrix}$$

Lorentz

Boost,

E, B

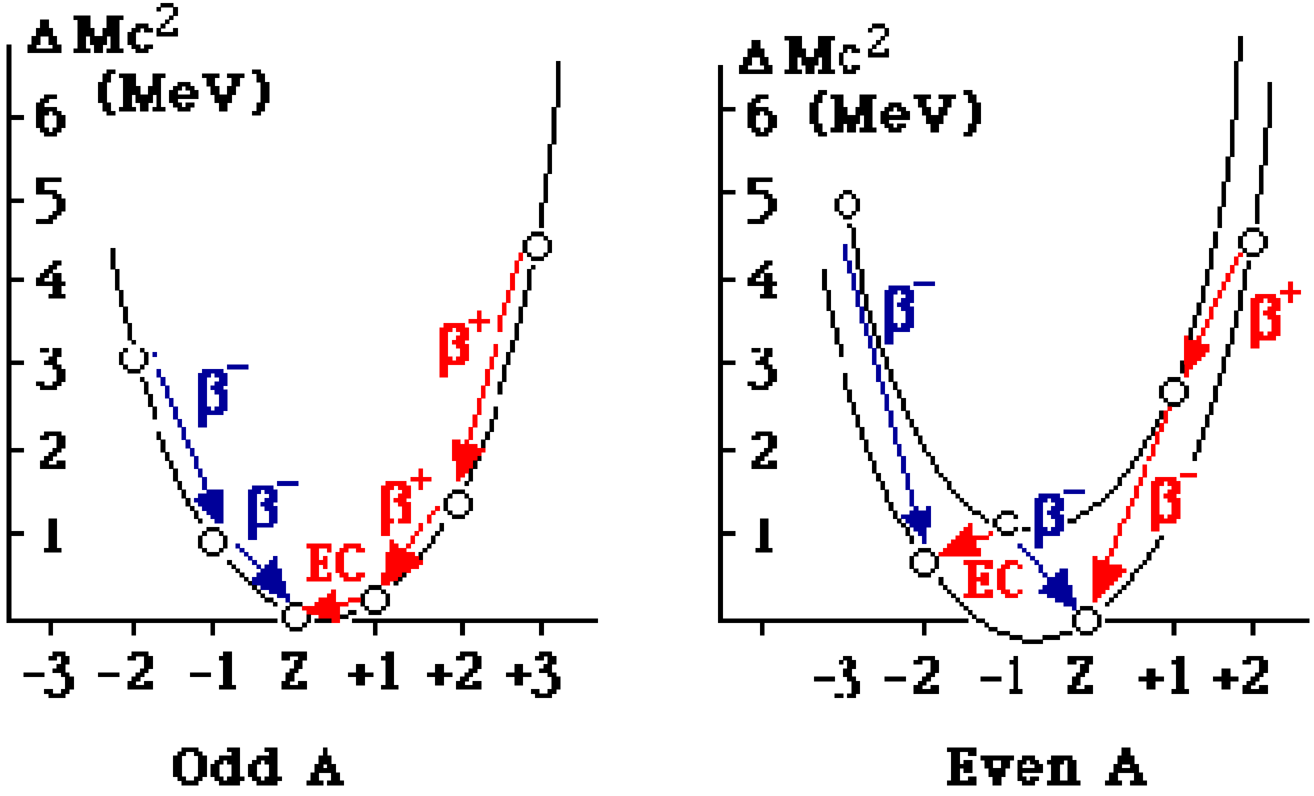
$$\begin{bmatrix} \nu_L \\ \overline{\nu}_R \end{bmatrix}$$

C
P
T

Dirac

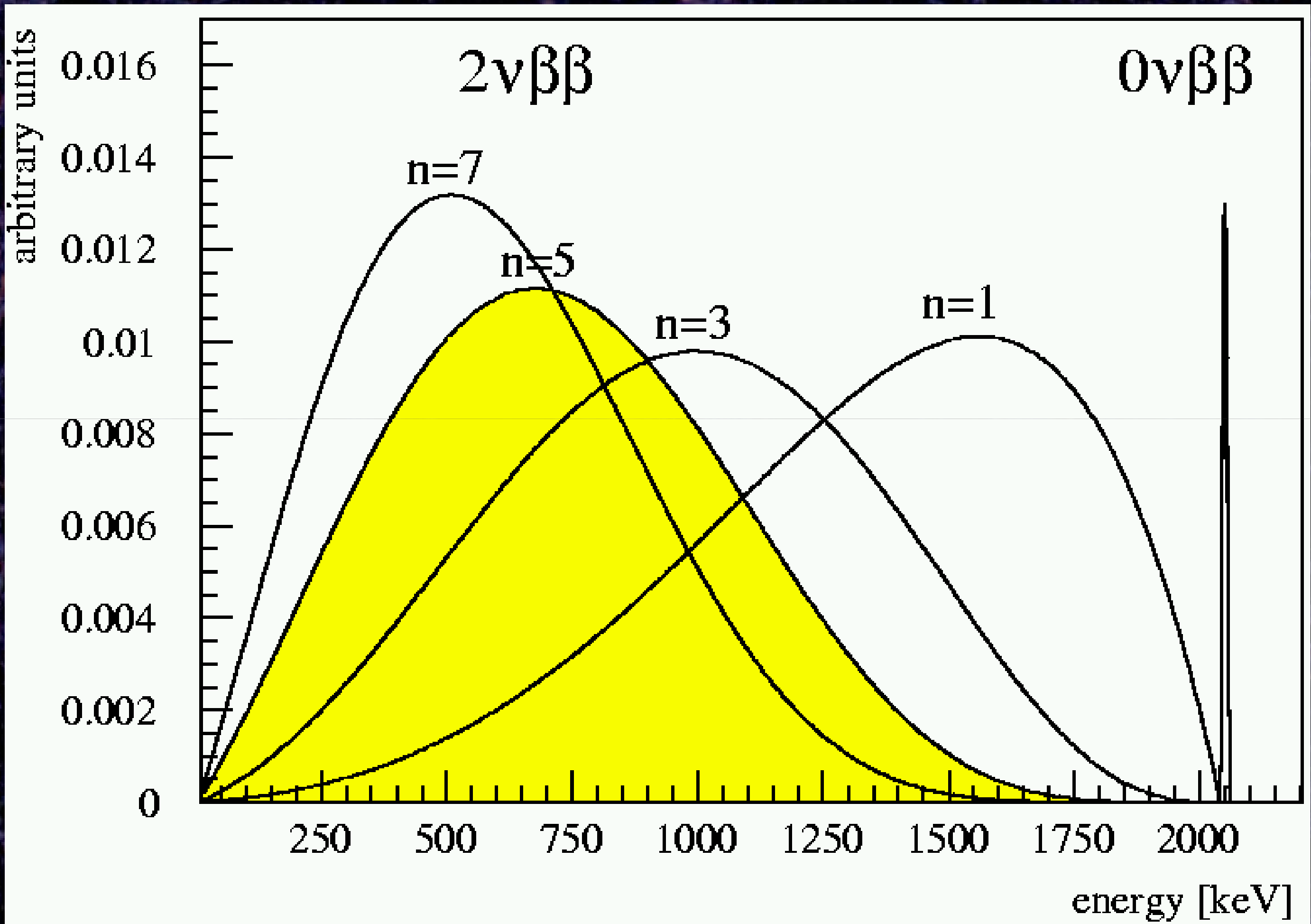
Majorana

ββ decay and neutrino mass



35 isotopes in nature

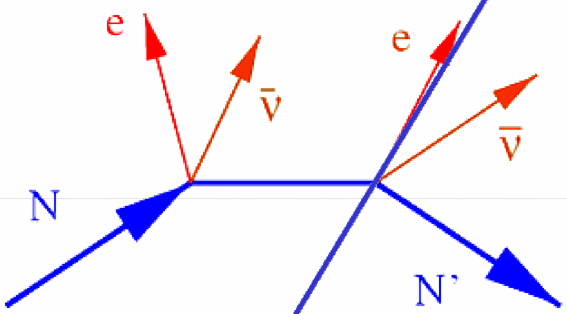
0νββ: Peak at Q-value of nuclear transition



Sum energy spectrum of both electrons

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

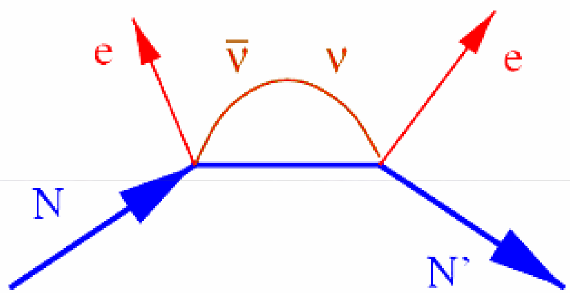
$2\nu\ \beta\beta$ decay: a standard process in nuclear physics



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

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

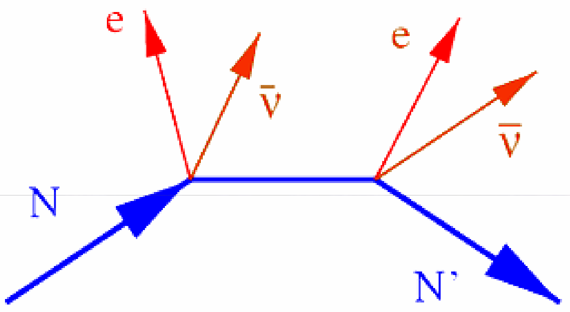
→ $\bar{\nu} = \nu$



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

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

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



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

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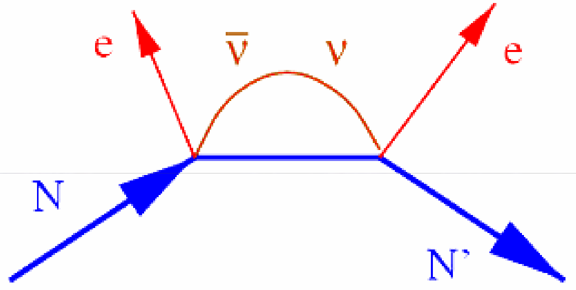
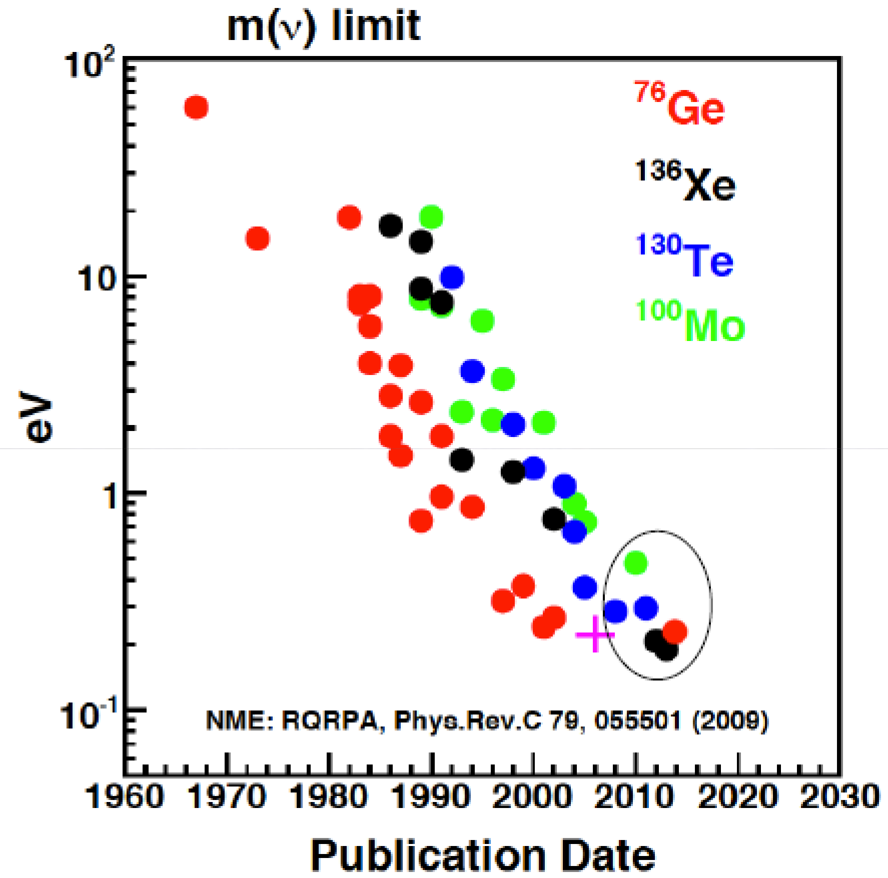


$$\langle m_\nu \rangle = m_{ee} = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k \left| U_{ek} \right|^2 e^{i\alpha_{ek}} m_k \right|$$

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

$0\nu\beta\beta$ Historical Progress



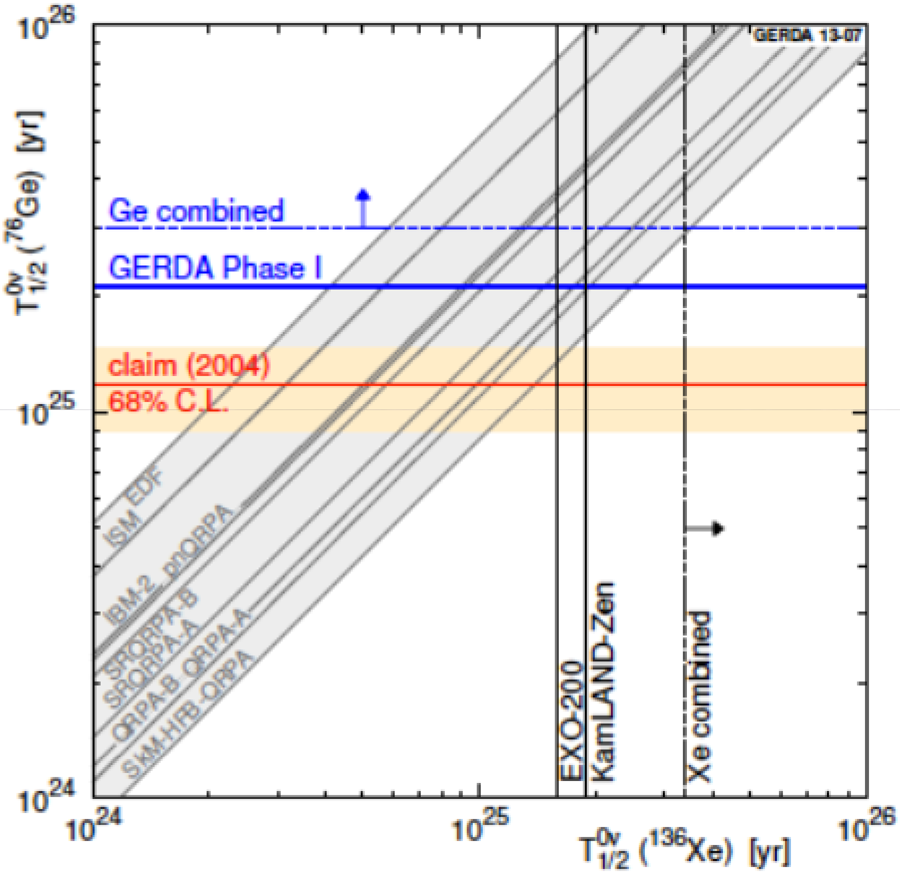
Adapted from C. Hall - Lepton Photon, June 2013

Slide from Yang's talk at NuFact '13

Recent ^{136}Xe and ^{76}Ge Results in Tension with Claimed Discovery

GERDA Phase I

Comparison with Klapdor 2004 claim

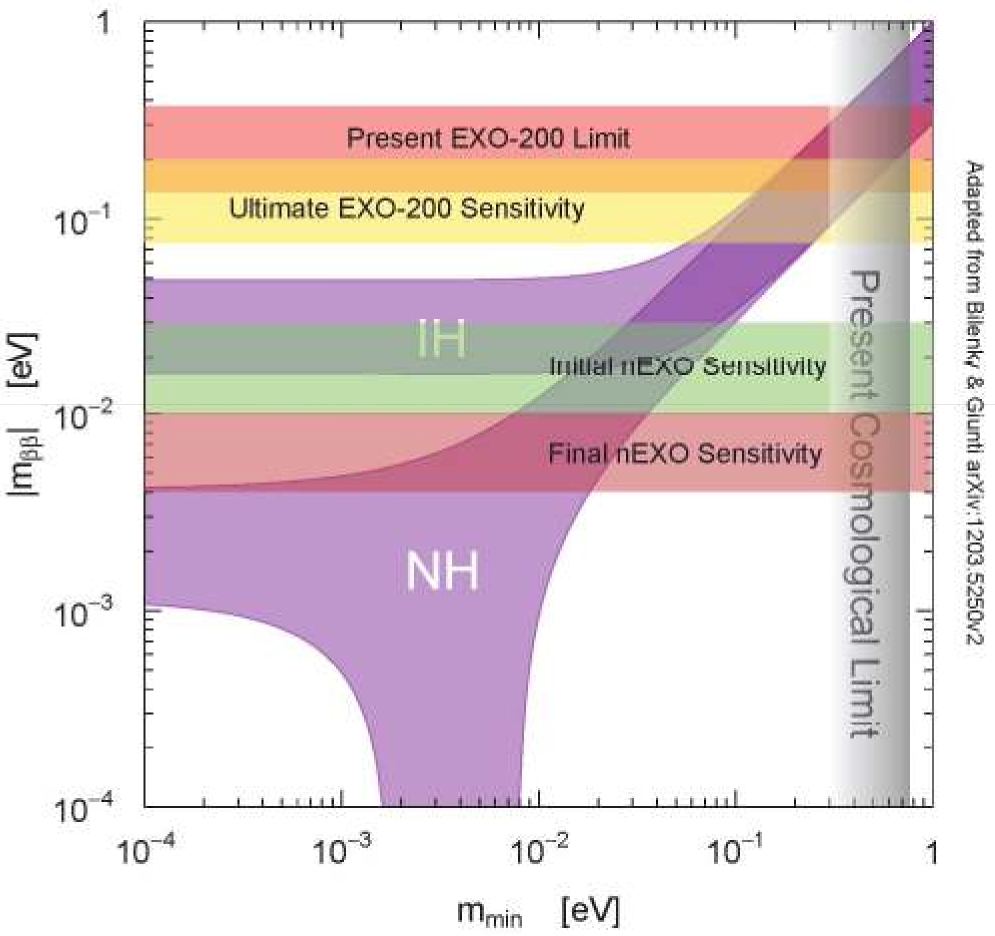


arXiv:1307.4720

KamLAND-Zen & EXO-200

Slide from Yang's talk at NuFact '13

EXO-200 and nEXO projected sensitivity



Blue bands are 68%CL from oscillation experiments for "Inverted" and "Normal" Hierarchy

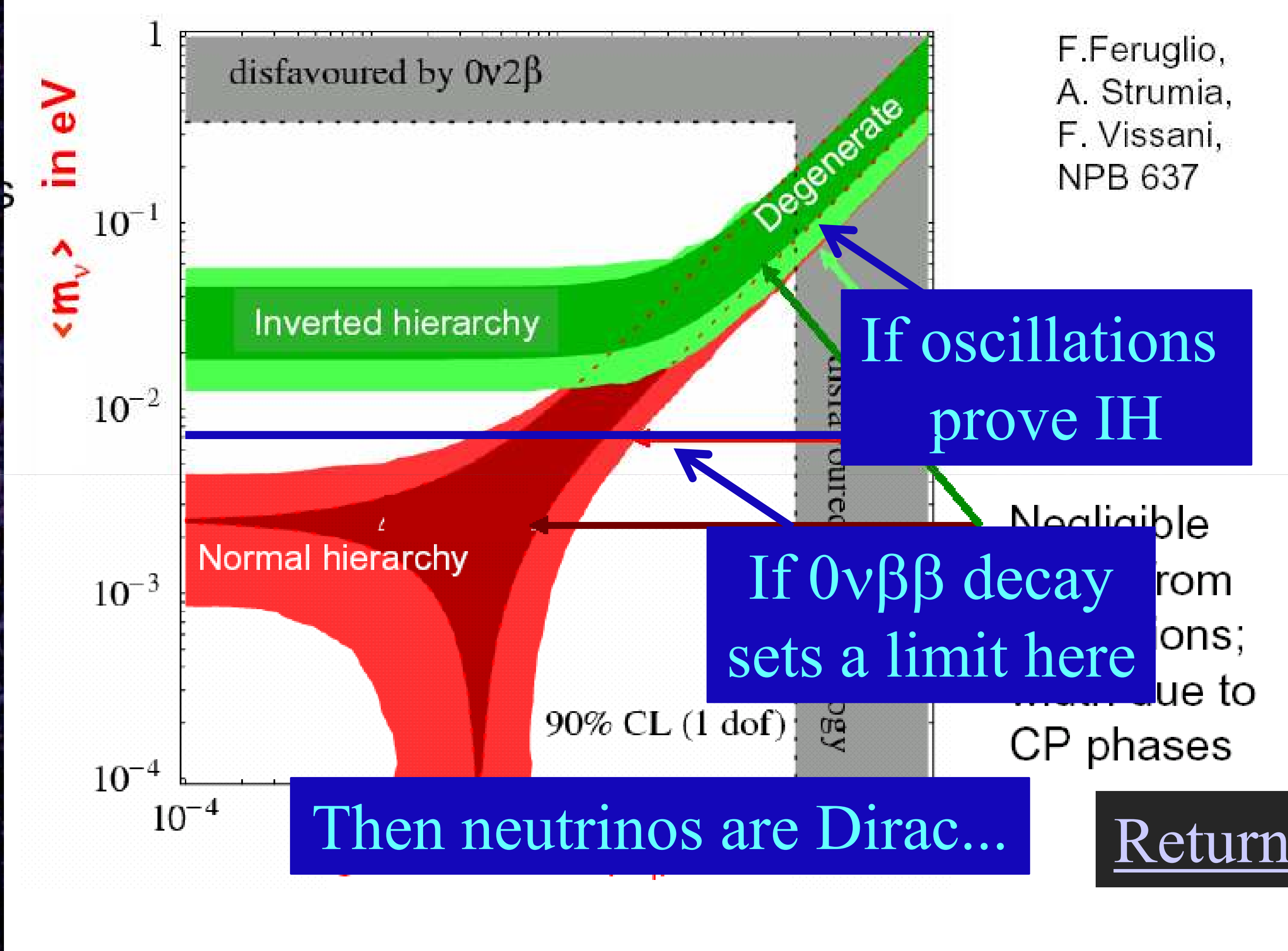
The EXO-200 "Ultimate" sensitivity: 90%CL for no signal in 4 yrs livetime with new analysis & Rn removal

The "Initial nEXO" band refers to a detector directly scaled from EXO-200,

The "Final nEXO" band refers to the same detector and no background other than 2ν

(Different barium tagging techniques under investigation)

Slide from Yang's talk at NuFact '13


1
disfavoured by 0ν2β
$\langle m_\nu \rangle$ in eV
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
Degenerate
Inverted hierarchy
Normal hierarchy
90% CL (1 dof)
F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637
CP phases
If oscillations prove IH
If 0νββ decay sets a limit here
Then neutrinos are Dirac...

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