Experimental Status of Neutrino Physics

NuFact 2011
Geneva
August 1st, 2011

Dave Wark
Imperial/RAL

Science & Technology Facilities Council

Imperial College London

Where are we in ν physics?

- Experiments have demonstrated neutrino mass and mixing – or at least do a damned fine imitation of it.
- However very few of the fundamental parameters of the sector are well measured, some aren't measured at all, and almost none are overconstrained as the CKM elements are.
- We do not know the absolute mass scale.
- We don't even know the ordering of the masses.
- We do not know if CP is violated in the ν sector.
- We don't even know if a ν is the same as a $\bar{\nu}$.
- We have a lot of work to do.....

Dave Wark
Imperial College/RAL

What to talk about in 30 minutes?

- Absolute mass scale, measurements and prospects.
- “Known” neutrino oscillations:
  - θ_{12} driven oscillations – solar and reactor.
  - θ_{23} driven oscillations – atmos. and long baseline.
  - θ_{13} driven oscillations – long baseline and the rest.
- Experiments that will determine our sensitivities
  - Hadron production.
  - ν cross sections.
- “Unknown” neutrino oscillations:
  - π decay and short baseline.
- Surprises.....

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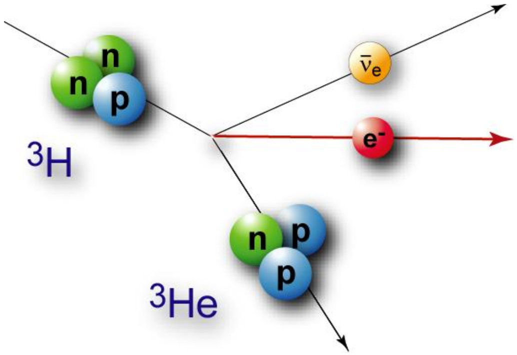
Imperial College/RAL

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 Marjorana 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(?)

Tritium β-decay



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

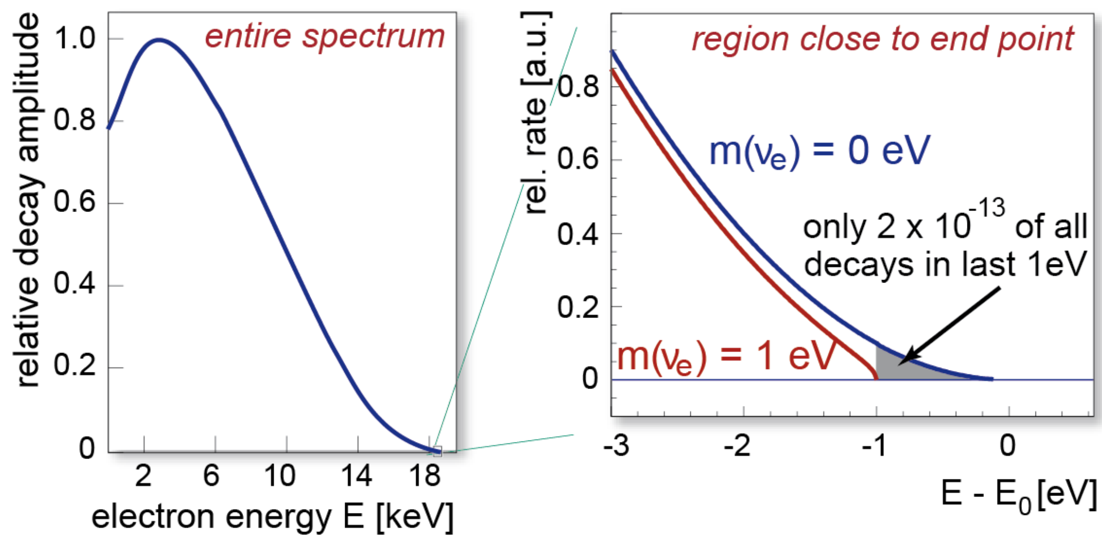
Fermi theory of β-decay:

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

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

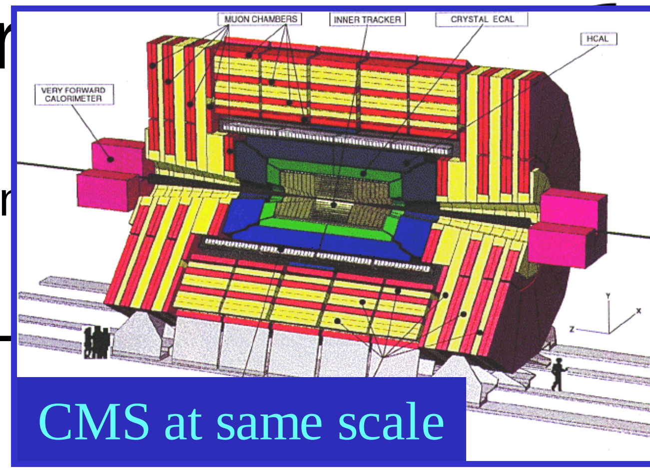


Florian Fränkle
EPS HEP 2009
Krakow

KATRIN experi

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

70 m

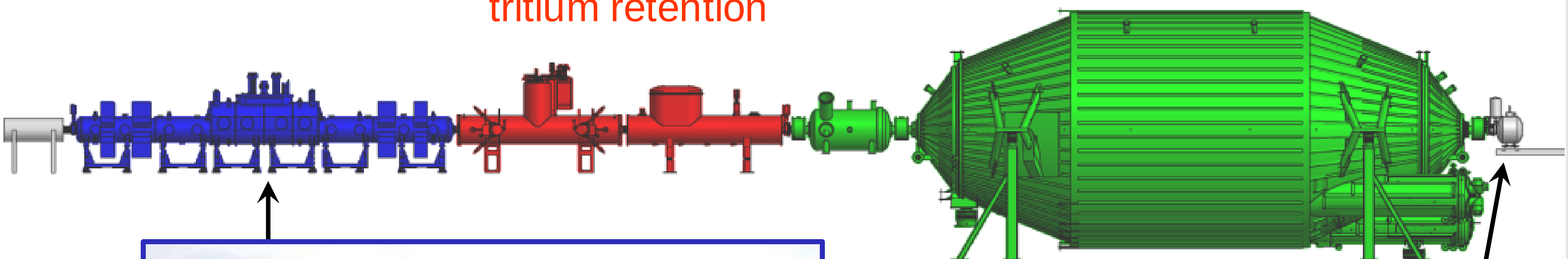


CMS at same scale

tritium decay

electron transport

tritium retention



β-de…

T_2 pr…

…f magnitude

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

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

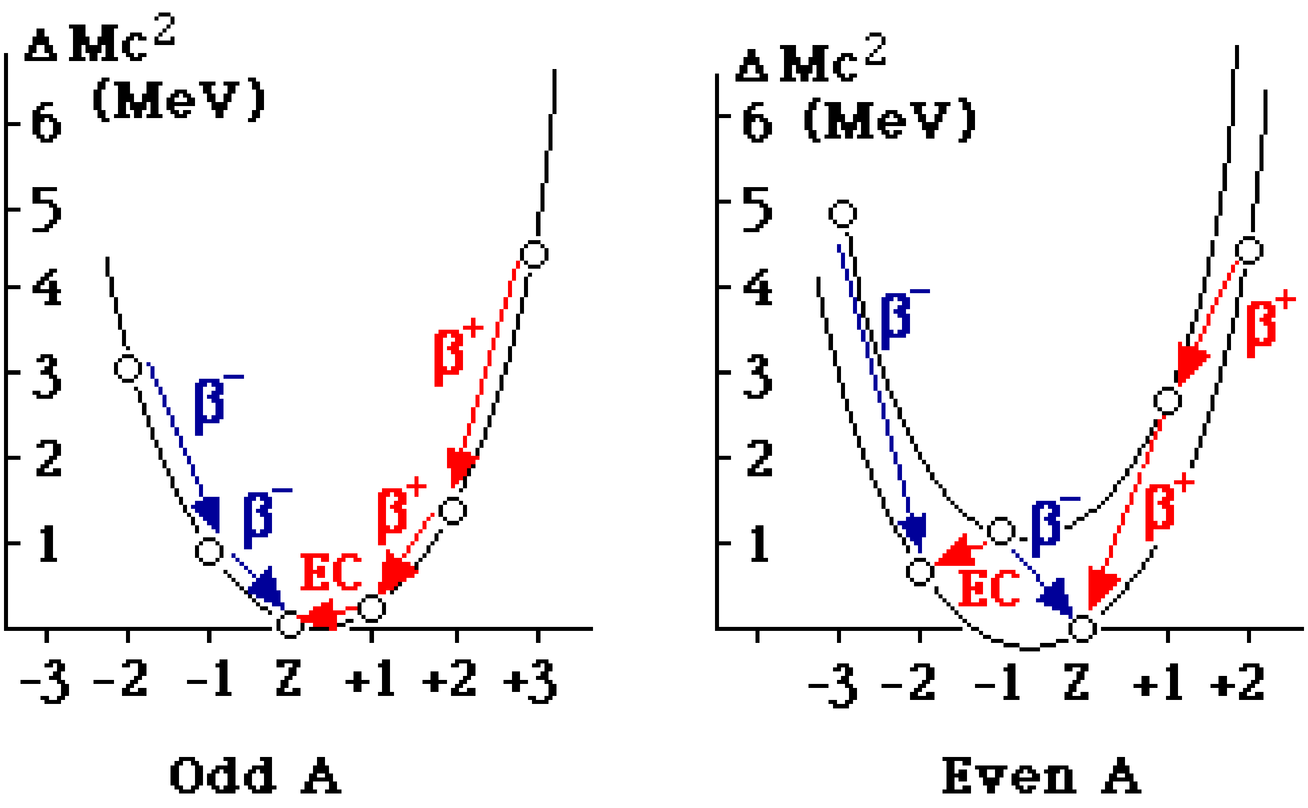
…n meV level

Status:

-commissioning of sub-components ongoing

- Start of physics 2013

ββ decay and neutrino mass



35 isotopes in nature

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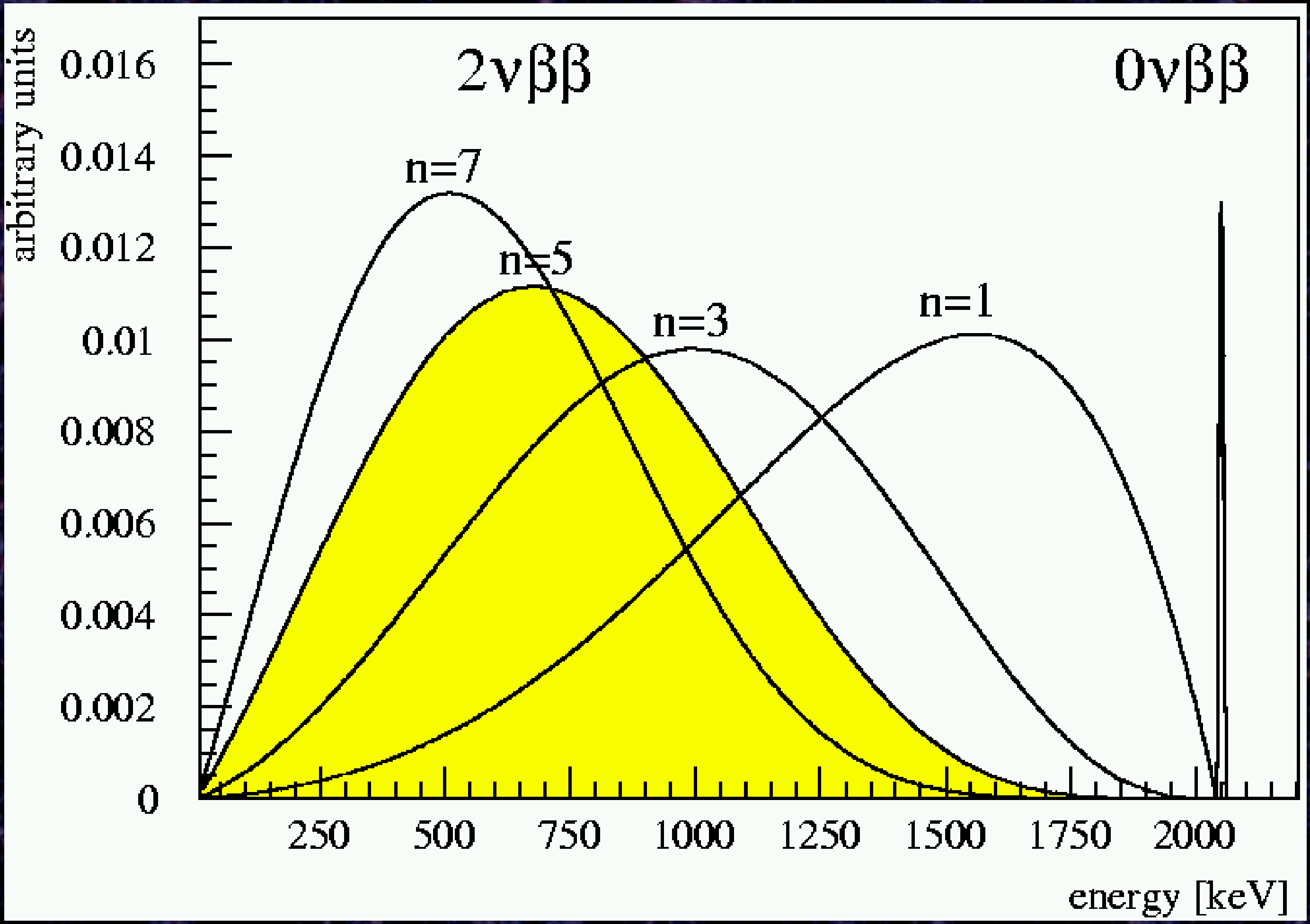
Imperial College/RAL

$0\nu\beta\beta$: Peak at Q-value of nuclear transition



Sum energy spectrum of both electrons

Three neutrino mixing.

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

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

$$\cdot \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

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

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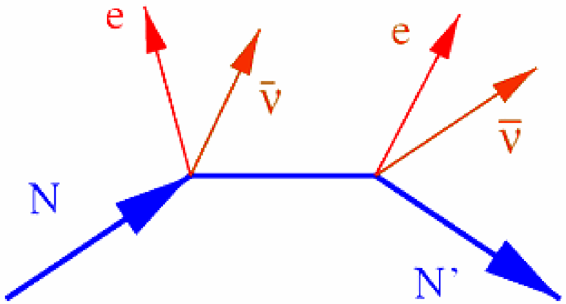
Most sensitive neutrino mass measurements can be obtained from double-beta decay

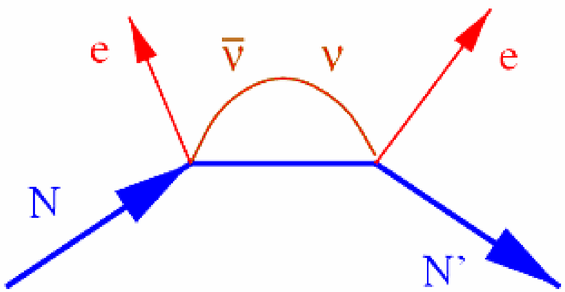
$2\nu\ \beta\beta$ decay: a standard process in nuclear physics



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

→ $m_\nu \neq 0$
→ $\bar{\nu} = \nu$

since helicity has to "flip"



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

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

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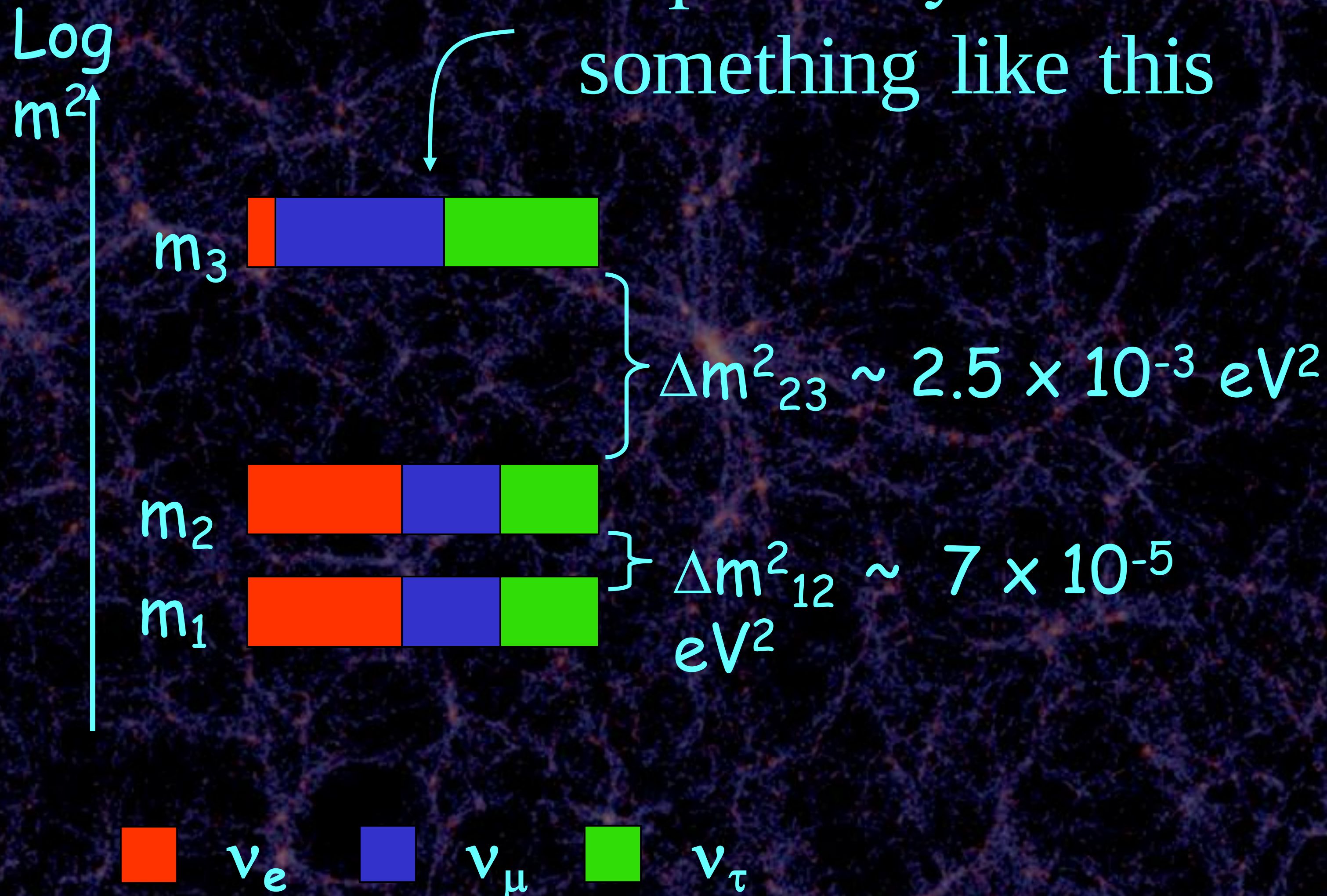
What is the pattern of neutrino masses?

It "probably" looks something like this



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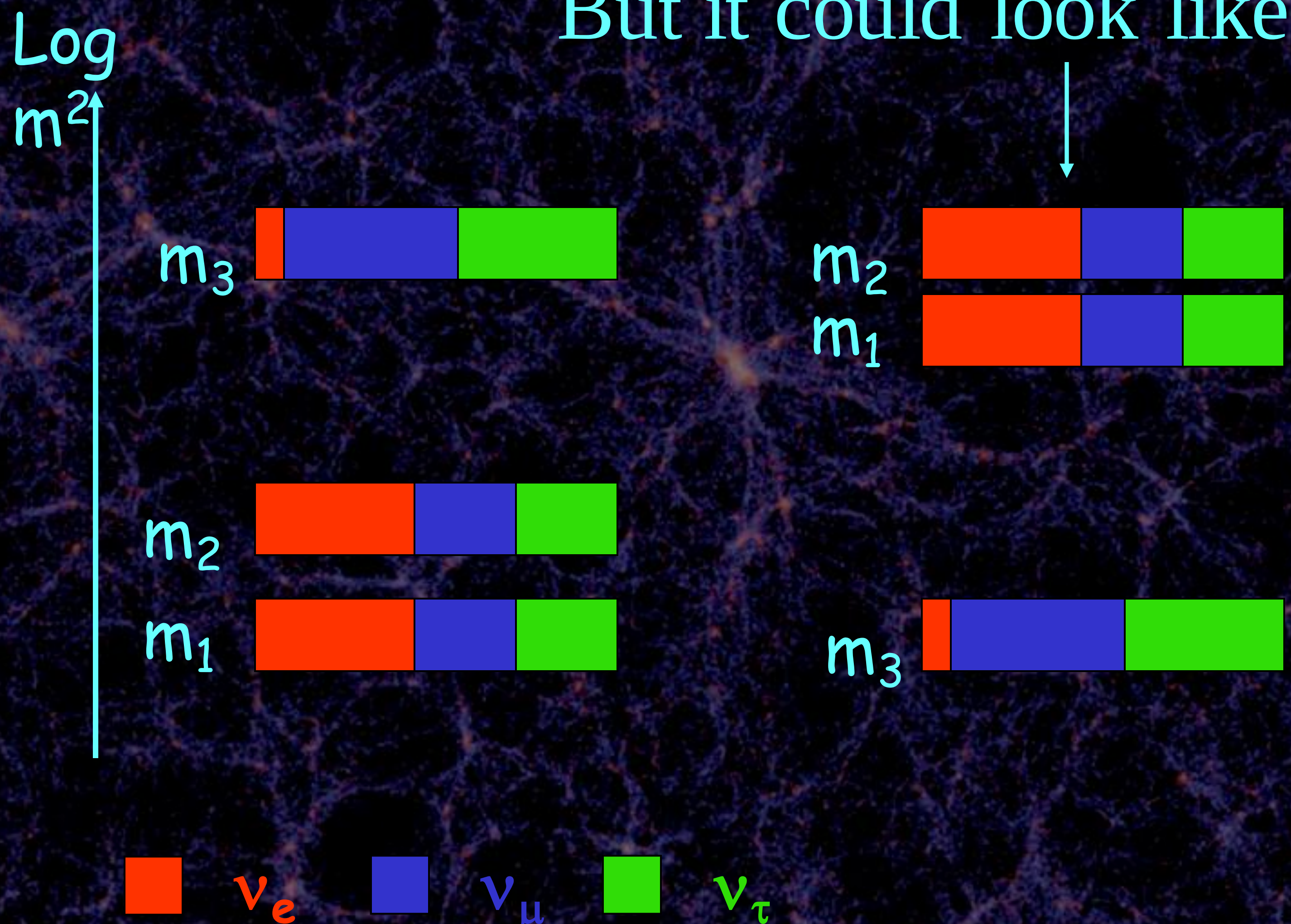
What is the pattern of neutrino masses?

But it could look like this



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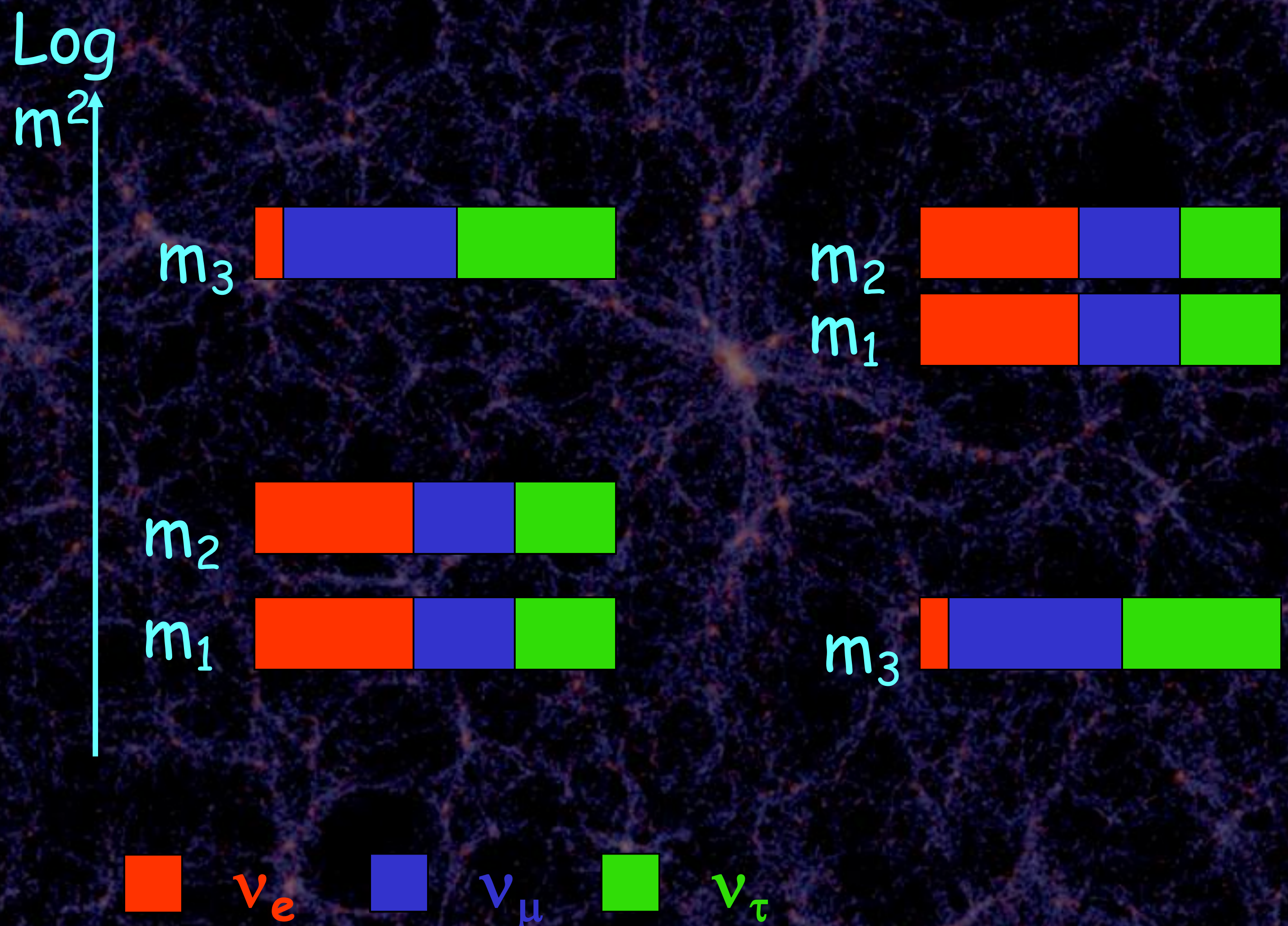
This makes a factor of two difference in the cosmological contribution, but a factor of two on what?



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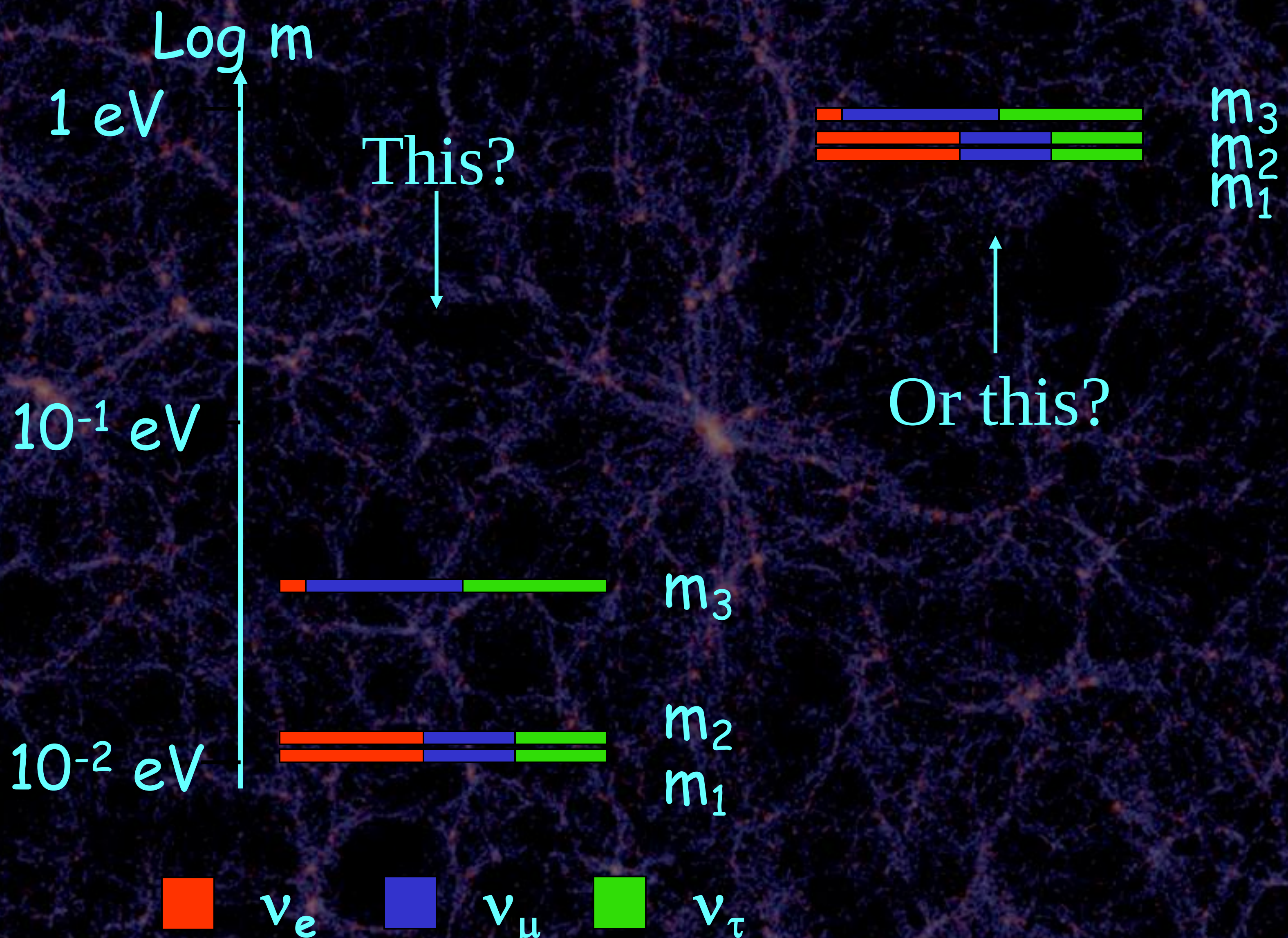
Even more significant is the absolute scale.



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Does this look natural?

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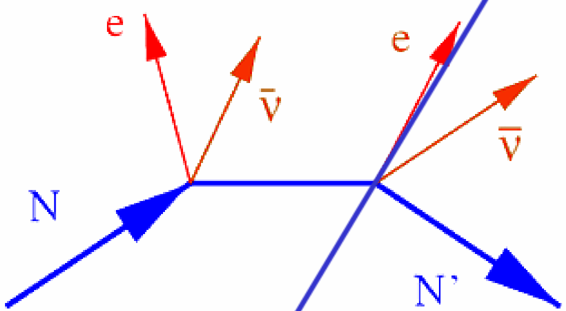
Most sensitive neutrino mass measurements can be obtained from double-beta decay

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



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

→ $m_\nu \neq 0$

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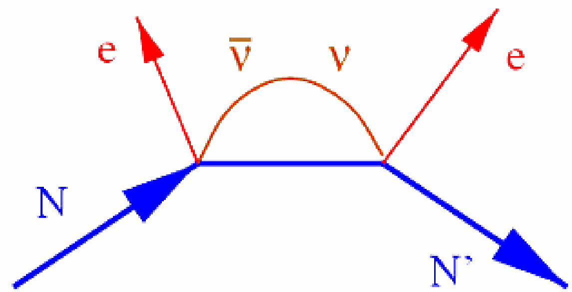
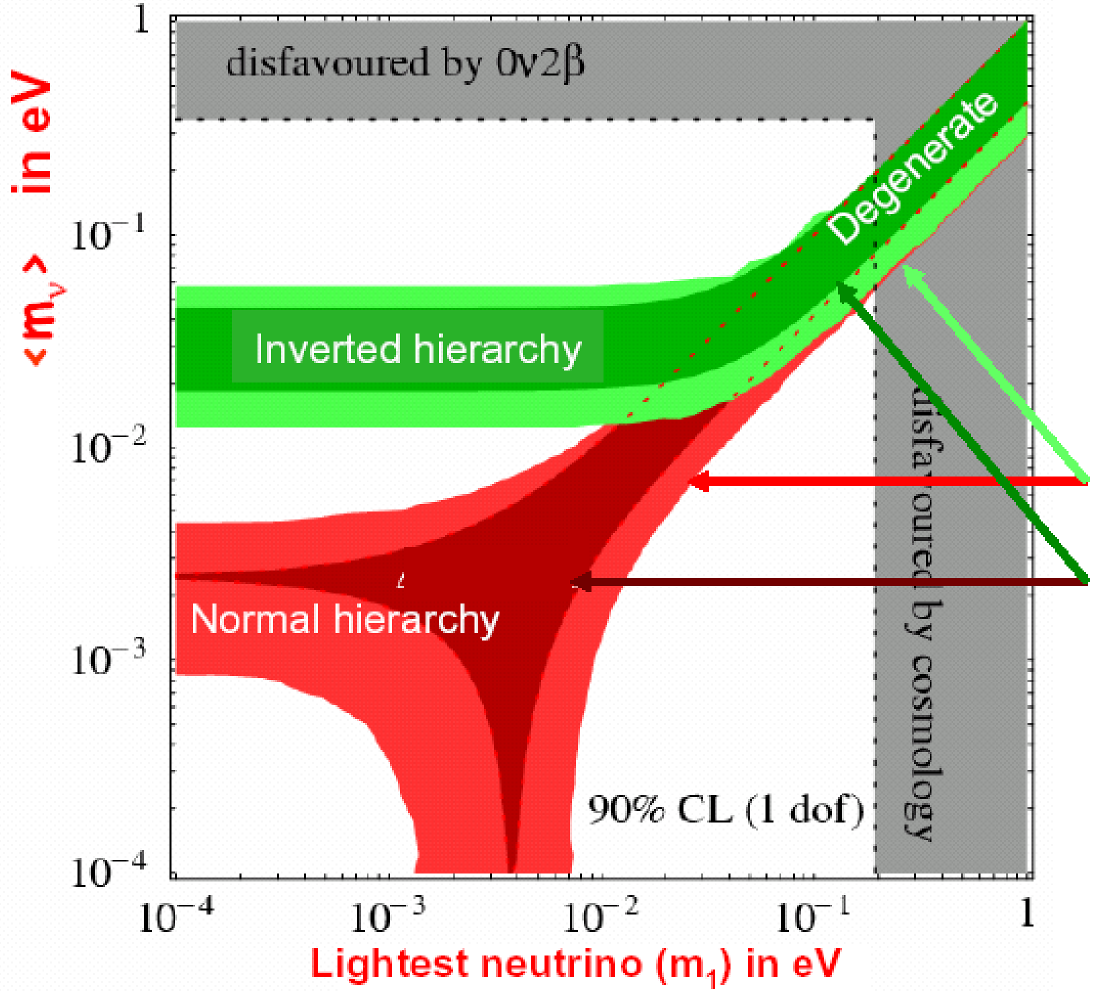


$$1/t_{1/2} = (\text{phase space}) \bullet \left(\frac{\langle m_\nu \rangle}{m_e} \right)^2 \bullet \left| \sum M_{if} \right|^2$$



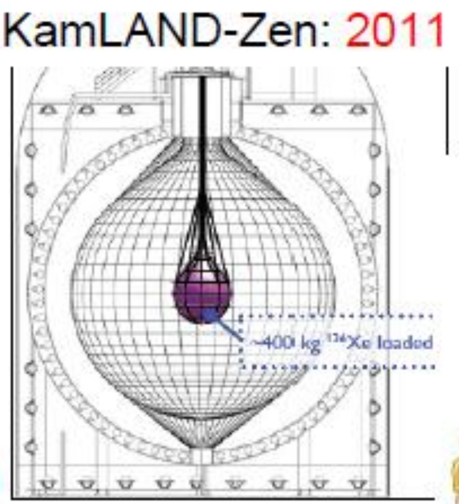
F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637

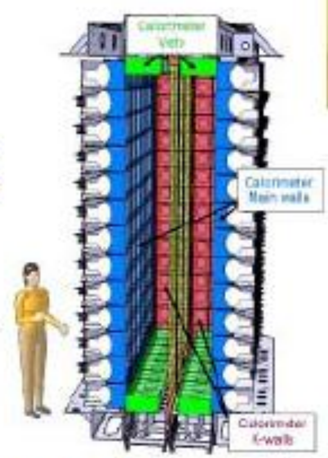
90% CL

Negligible errors from oscillations; width due to CP phases

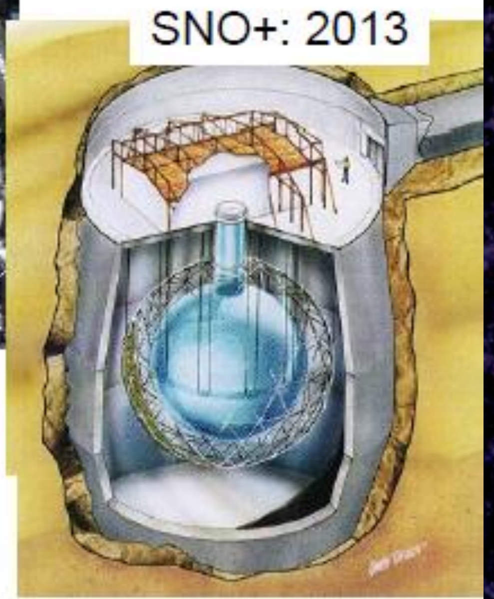
From Stephen Shoenert's talk at EPS

Next generation experiments



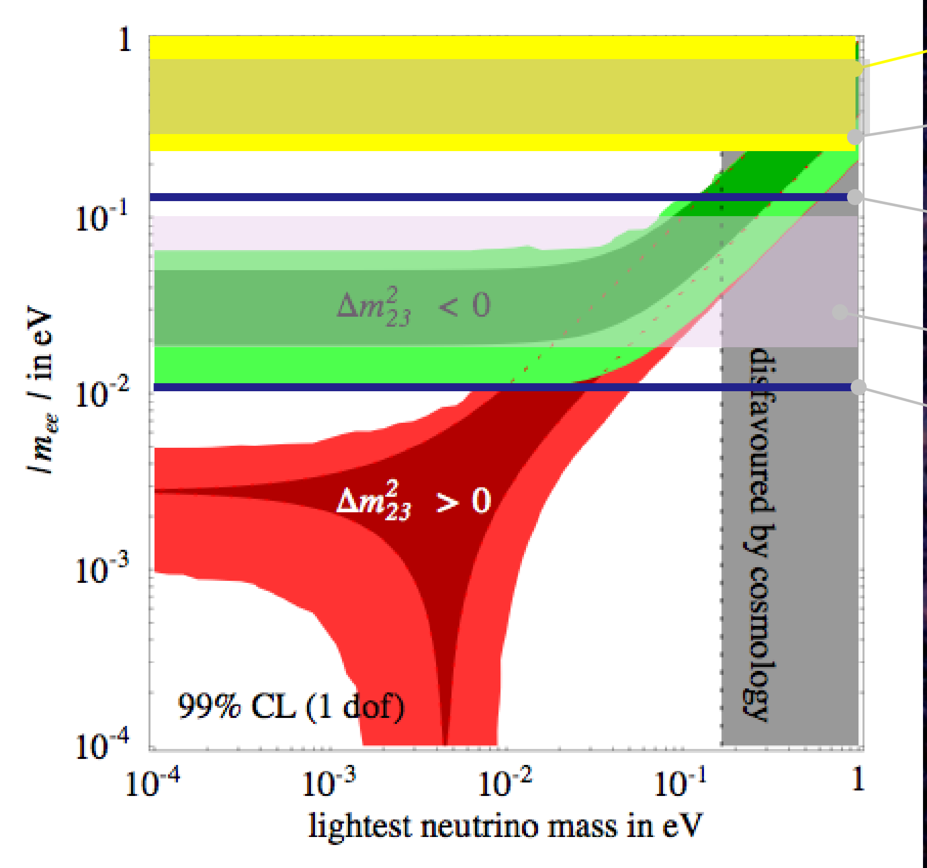


Super-Nemo @ LSM:
Demonstrator2014



Majorana: 2013
NEXT: 2013
Lucifer
EXO-gas
XMASS

KKDC Claim
(best fit 0.32 eV)



Final Cuoricino limit
arXiv:1012.3266v1 [nucl-ex]

GERDA Target

CUORE Target

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

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

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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.
- masses, then zero-
s allowed ⟶
vould be direct
evidence for neutrino mass, $\langle m_\nu \rangle < \sim 1.3$ eV.

Covariances? Systematics? Model too simple? More soon from Planck.

- st numerous particle
y neutrino mass could
ons, $\Sigma m_\nu < 0.28$ eV(?)

In any case, using cosmology to measure m_ν is like using LEP as a tide gauge.

Three neutrino mixing.

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

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$$P_{e\mu} \cong \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta$$
$$\mp \alpha \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta$$
$$- \alpha \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin 2\Delta$$
$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta$$

Remember degeneracies
And covariances!

where $\alpha =$ ~0.03 and $\Delta =$ ~π/4

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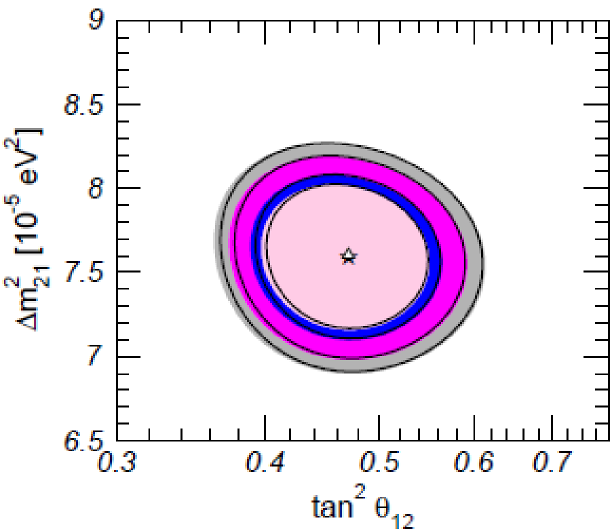
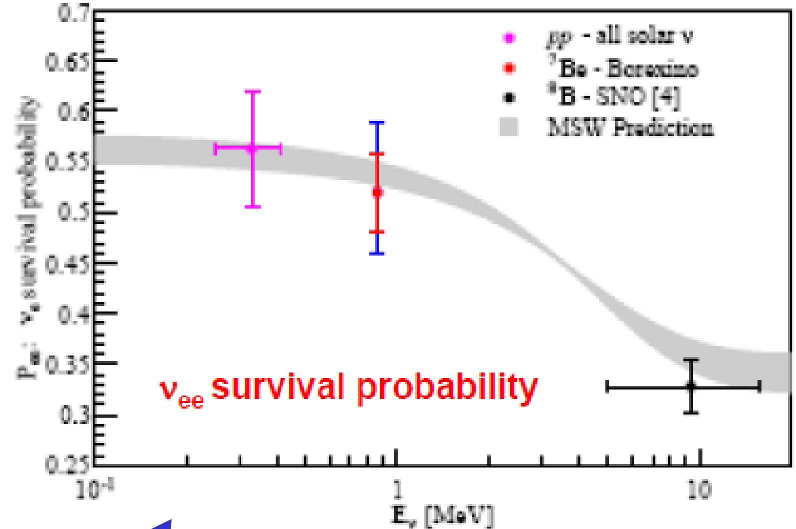
Imperial College/RAL

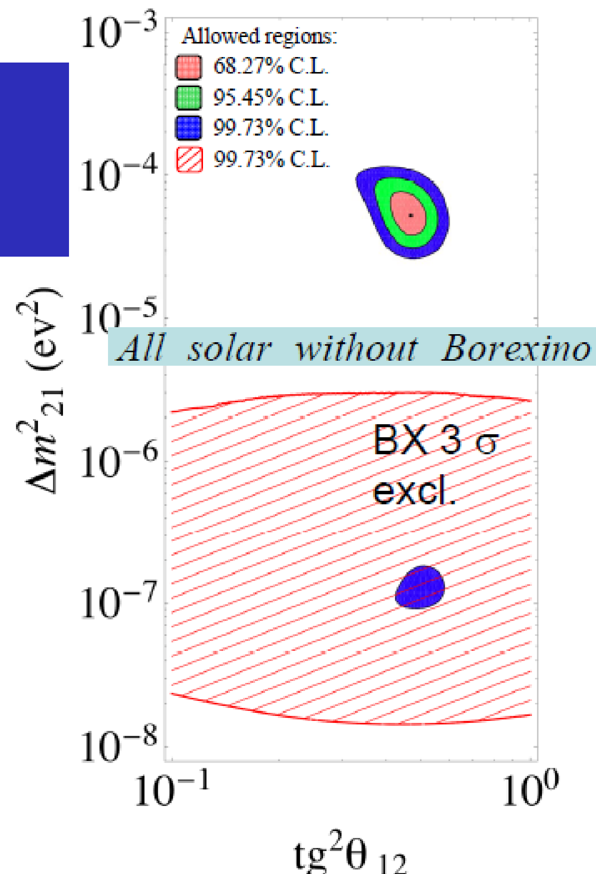
How well do we know θ_{12}?

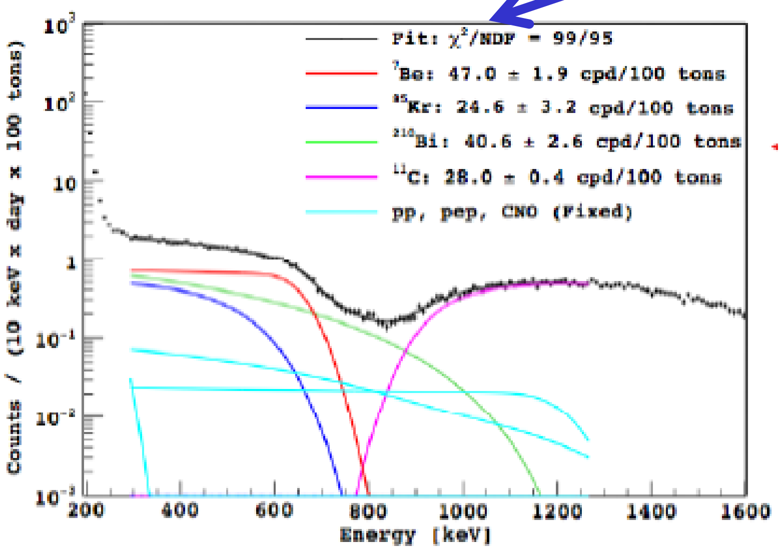
Gonzalez-Garcia, Maltoni, Salvado
arXiv:1001.4524v4 [hep-ph] 16 Jun 2011





From Ranucci's BOREXINO talk at EPS 2011

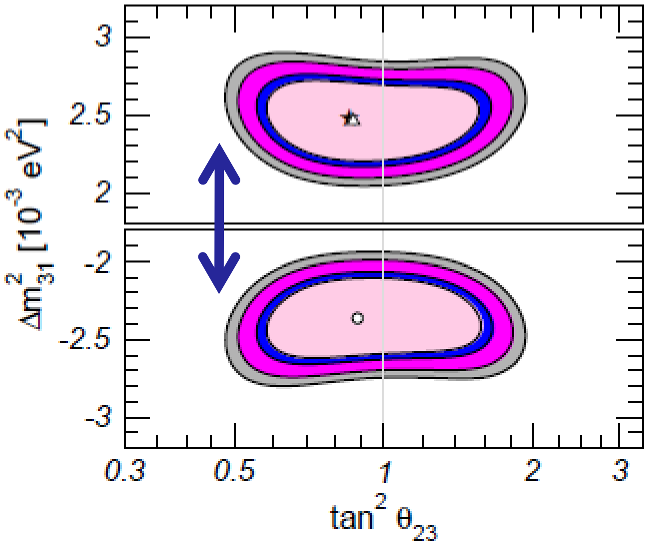




How well do we know θ_{23}?

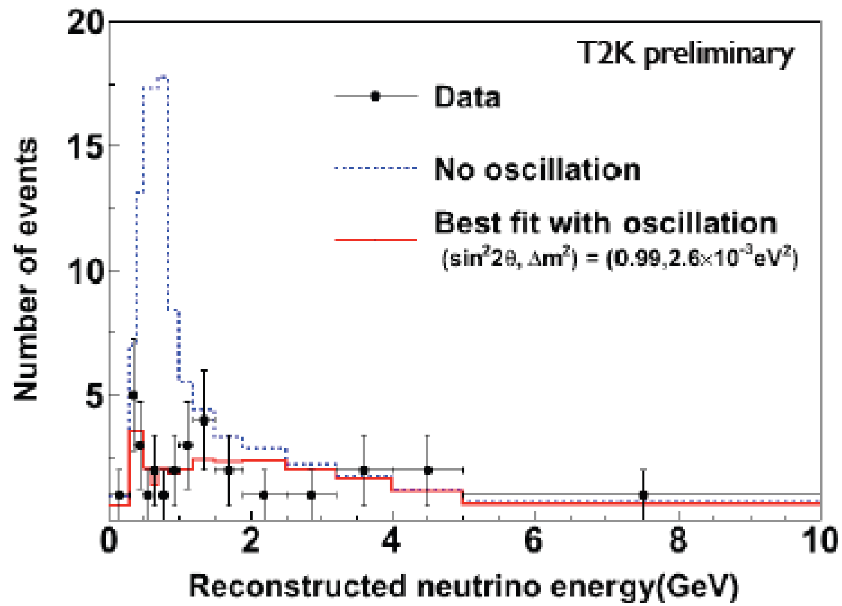
Gonzalez-Garcia, Maltoni, Salvado

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



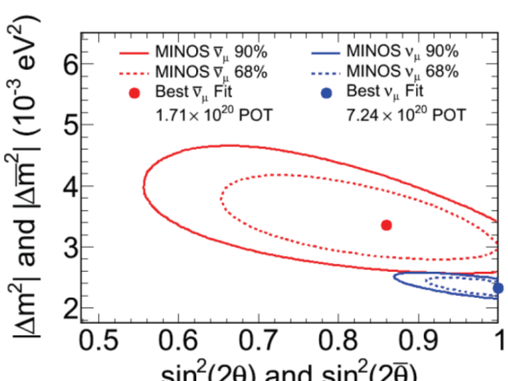
Phys. Lett. B 691 (2010) 138-145

Giganti at EPS



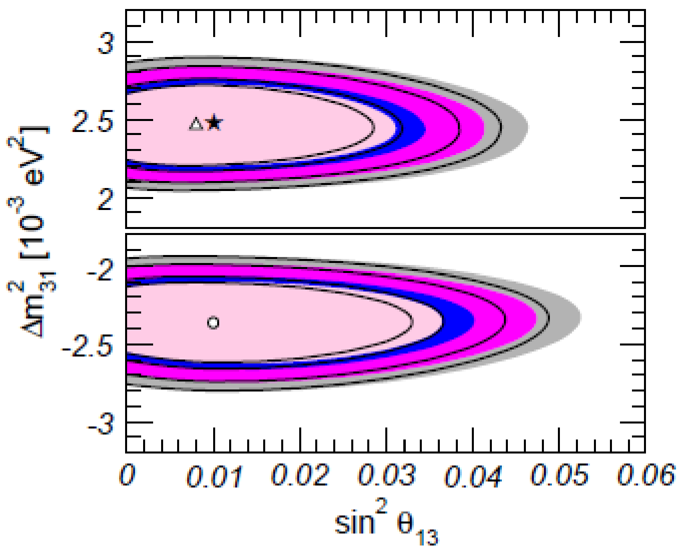
1st T2K ν_μ disappearance

MINOS ν vs $\bar{\nu}$ in mild tension – new result soon.

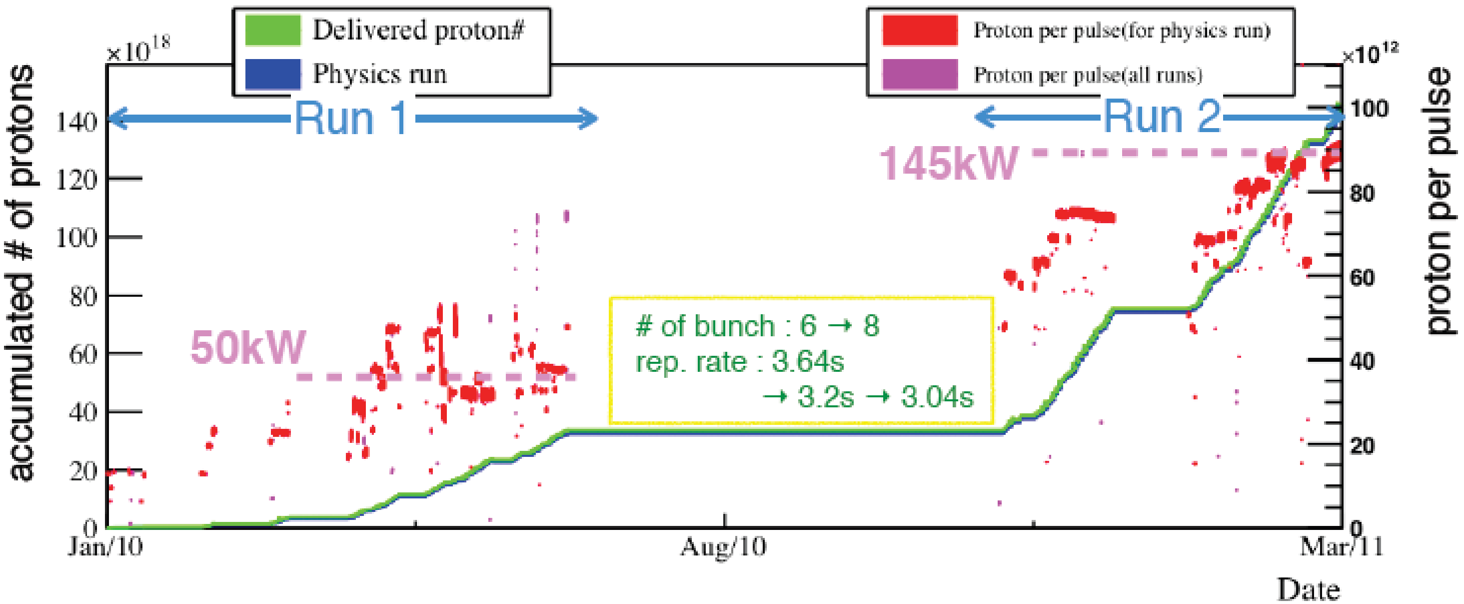


Holin at EPS

What about θ_{13}?



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

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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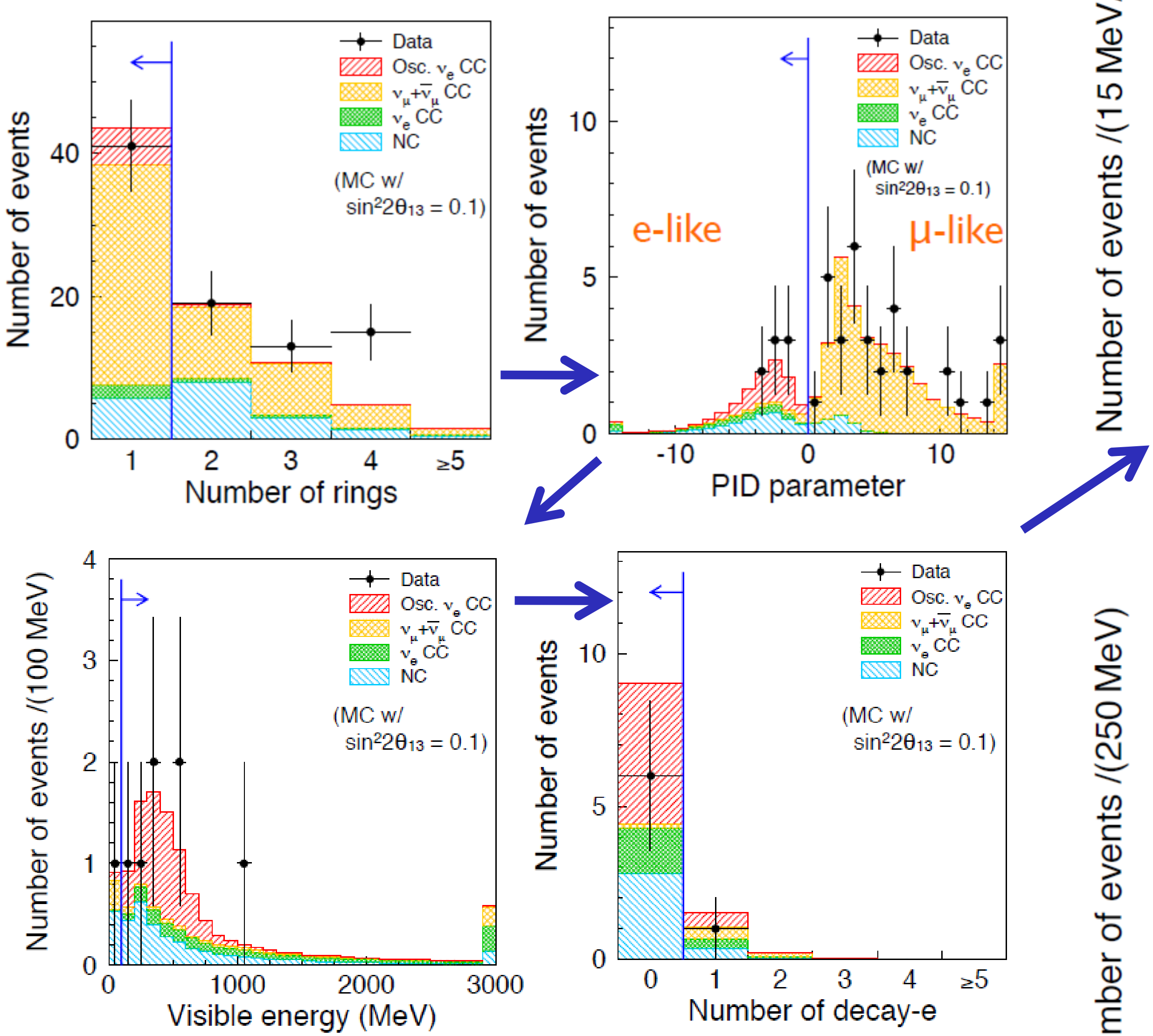
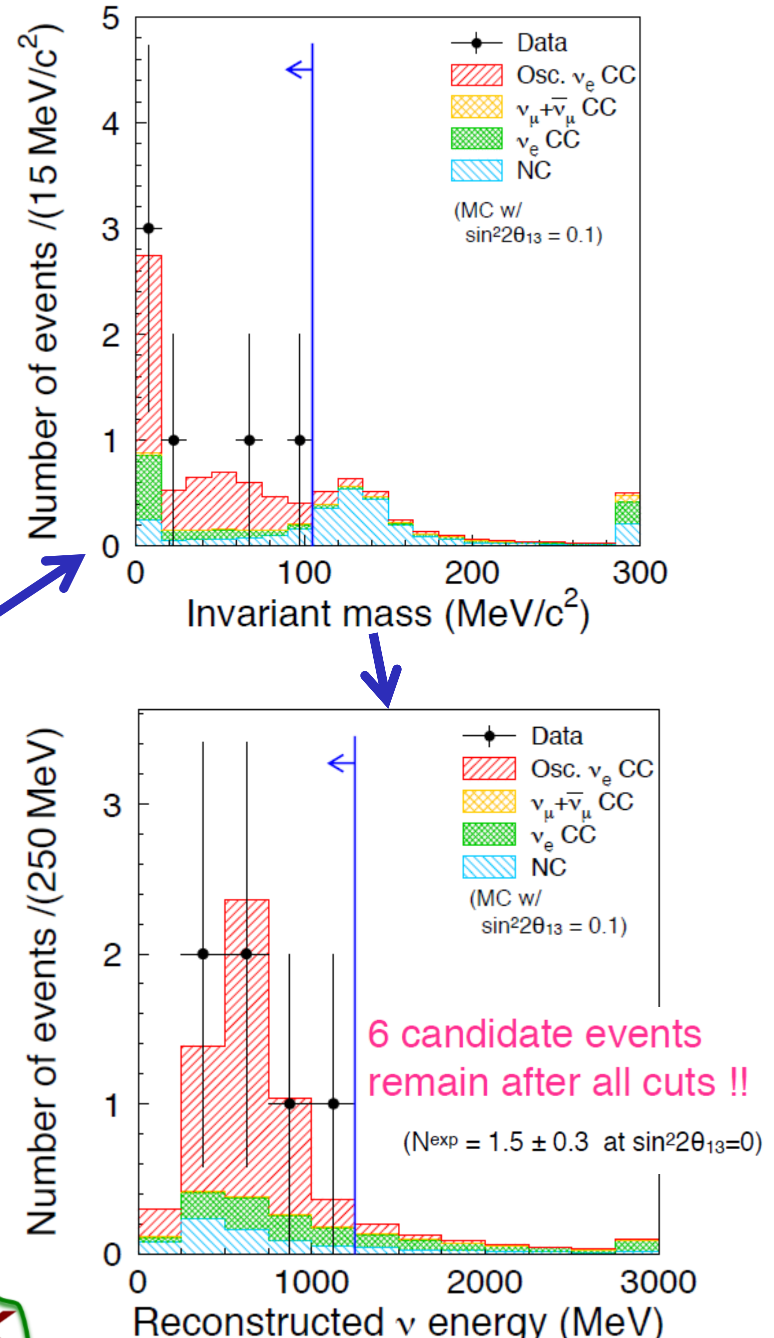
Imperial College/RAL

ν_e Appearance Data Reduction





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

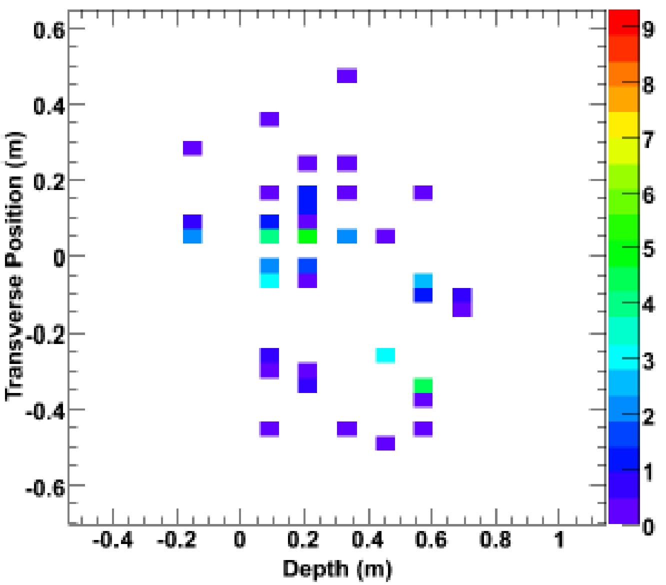
T2K

Selecting ν_e-like events

Preselection cuts to remove events that are obviously not signal:

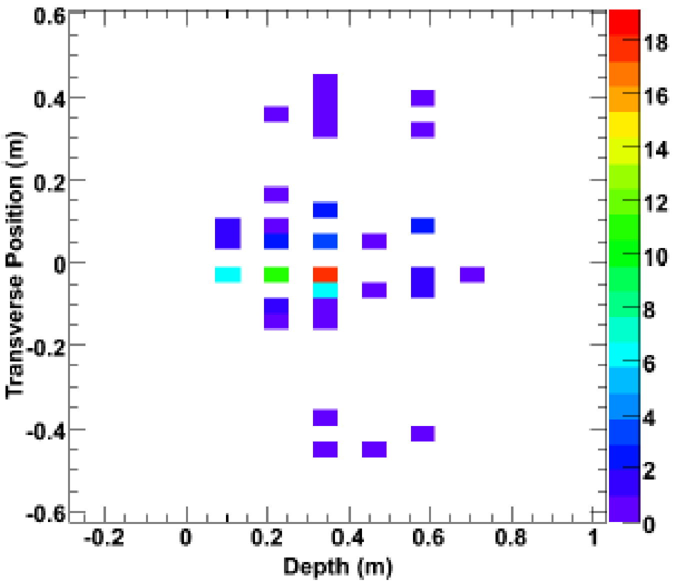
- No long tracks
- At least one well-formed shower
- With visible energy 1-8 GeV

After these cuts, background consists mostly of NC

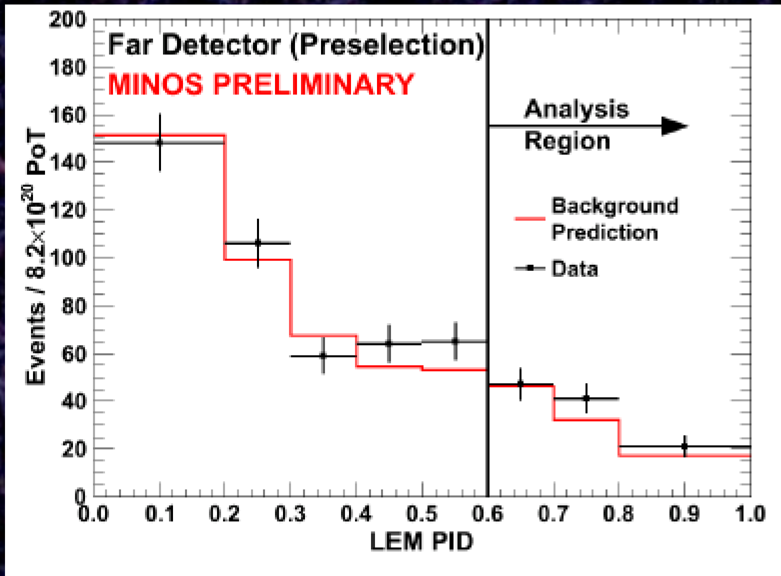


(NC background)

Need to discriminate



(signal)

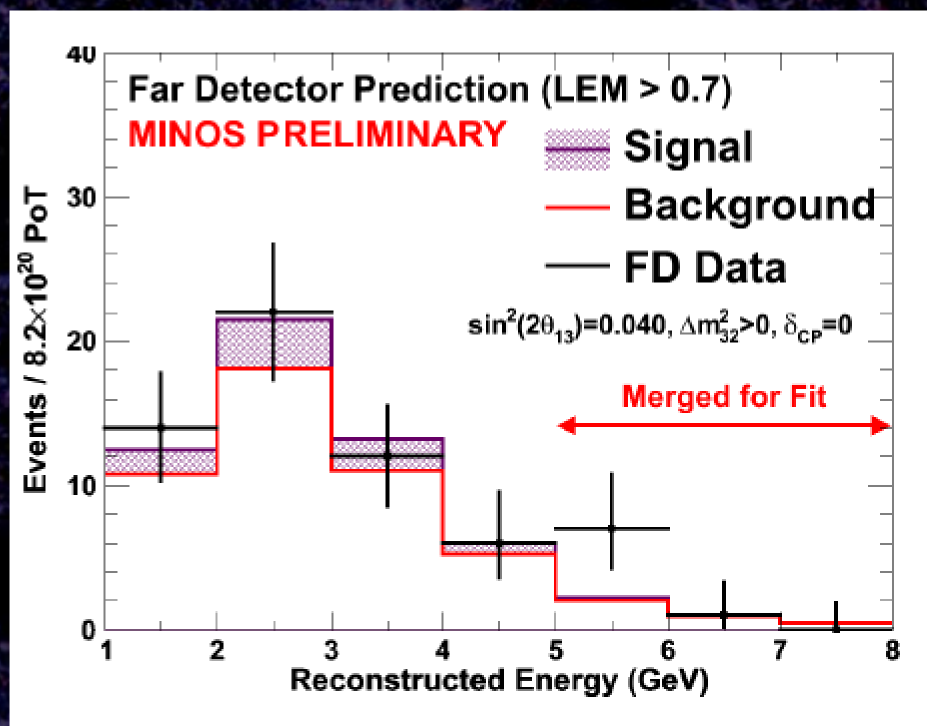


Expected background (θ_{13}=0):

49.5 +- 2.8 (syst) +- 7.0 (stat)

Observed data:

62



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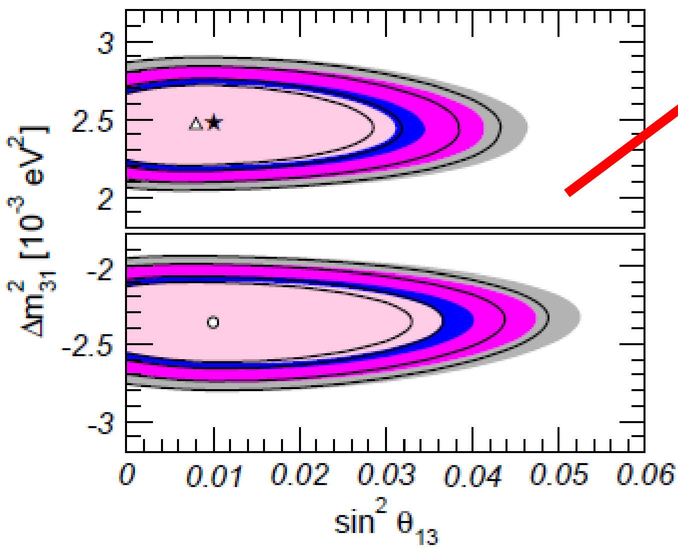
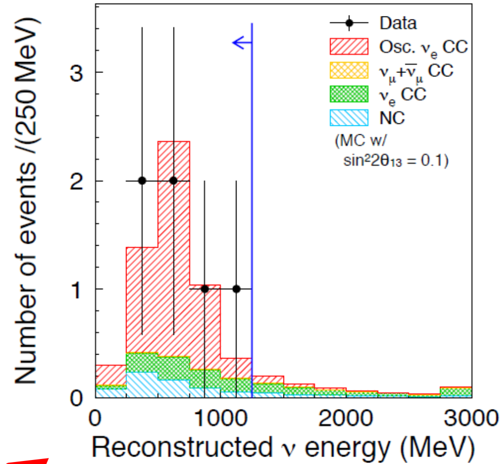
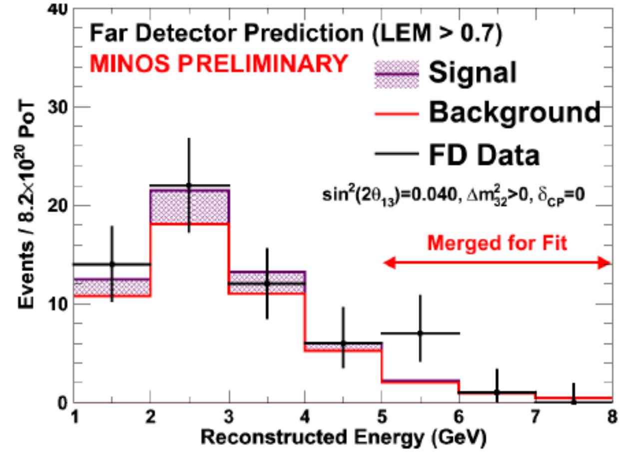
What about θ_{13}?







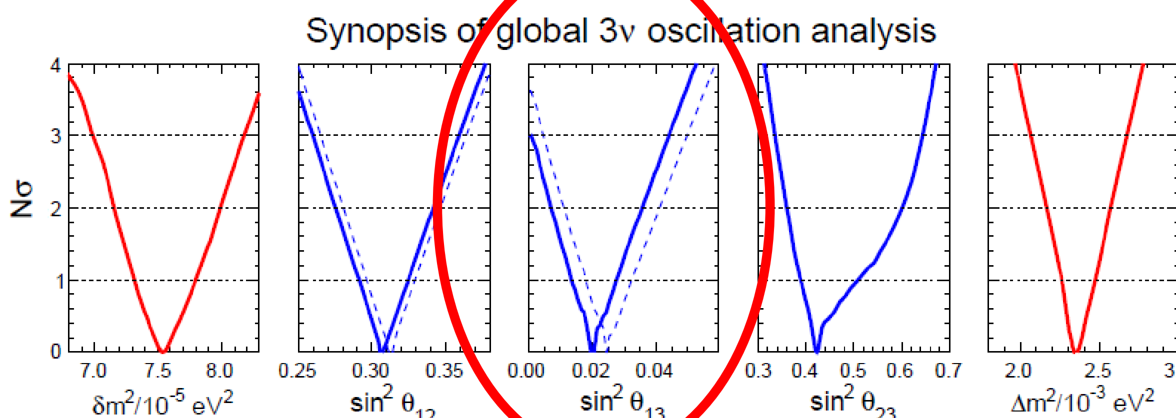
T2K (2.5σ)

MINOS (1.7σ)

ν_e appearance, $\theta_{13} > 0$?

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

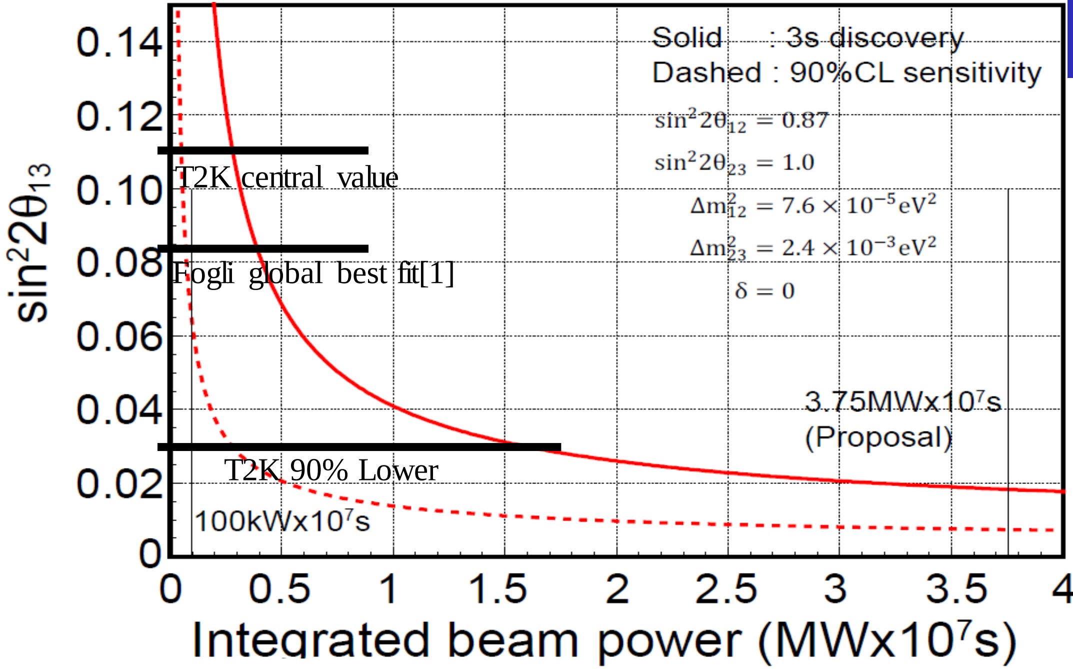
G.L. Fogli,[1,2] E. Lisi,[2] A. Marrone,[1,2] A. Palazzo,[3] and A.M. Rotunno[1]

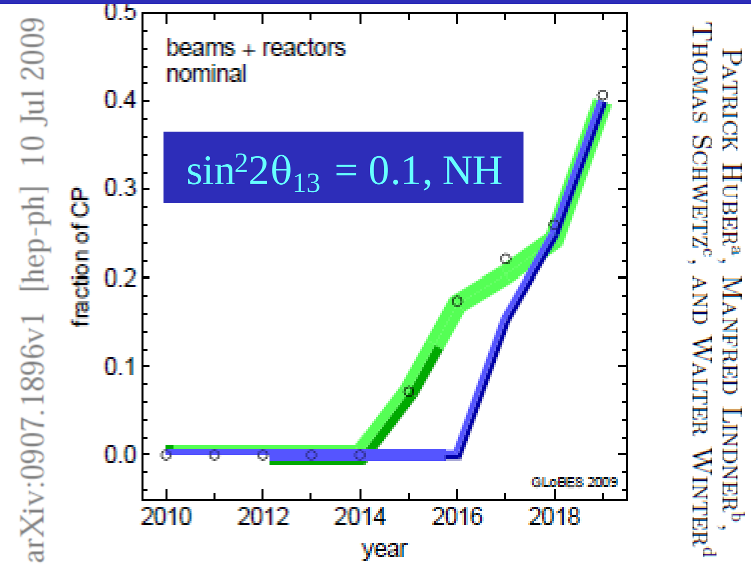


arXiv:1106.6028v1 [hep-ph] 29 Jun 2011

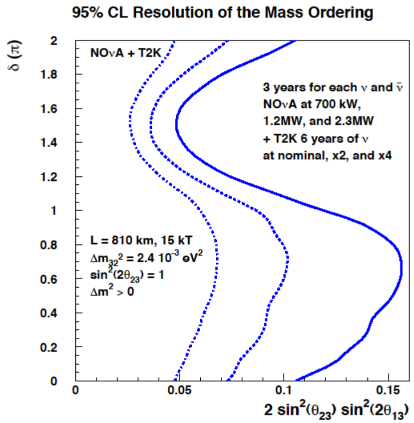
Are we moving into the θ_{13} "large" regime?

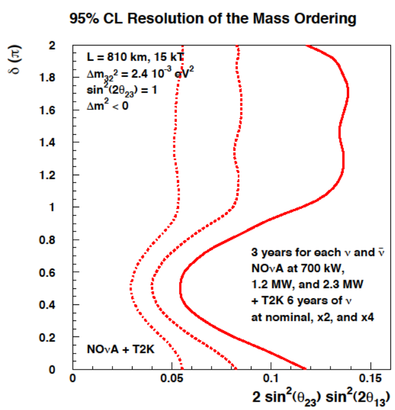
Even some 90% CP violation sensitivity...





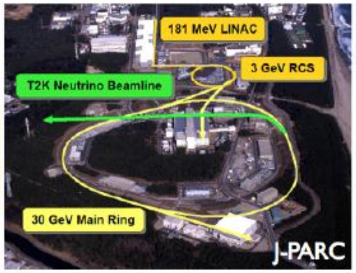
$\sin^2 2\theta_{13} = 0.1$, NH





T2K and NOvA

Kamioka



- Ran from Jan 2010 till March 2011
- Presently stopped; restart foreseen in 2012
- Maximum beam power 145 kW
- Muon disappeara[...] conference
- Electron appeara[...] (90%C.L.):
  - $0.03 < \sin^2 2\theta_{13} < 0.28$ (best fit 0.11) normal
  - $0.04 < \sin^2 2\theta_{13} < 0.34$ (best fit 0.14) inverted

Aim: sensitivity $\sin^2 2\theta_{13} > 0.006$ @ 90%C.L. for $\delta_{CP}=0$

→500 kW (2yr)
→>1 MW (>5yr)

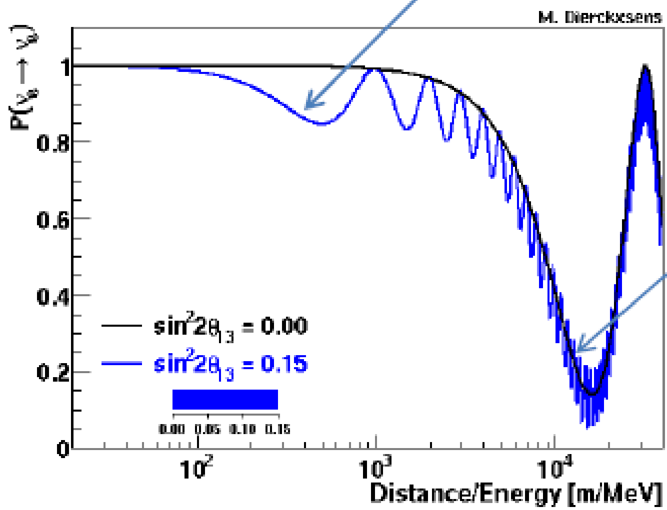
- Far detector under construction
- Start foreseen in fall 2013
- Beam power 750 kW (after upgrade)
- Baseline L=830 km gives some matter effect sensitivity
- Consider neutrino + antineutrino runs

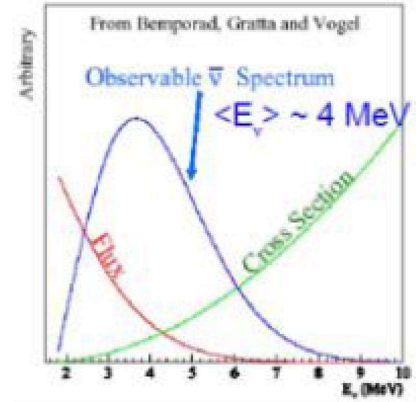
Aim: sensitivity $\sin^2 2\theta_{13} > 0.007$ @ 90%C.L. for $\delta_{CP}=0$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) + higher\ order\ f(\delta_{CP}, \theta_{12})$$

Reactor neutrinos

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



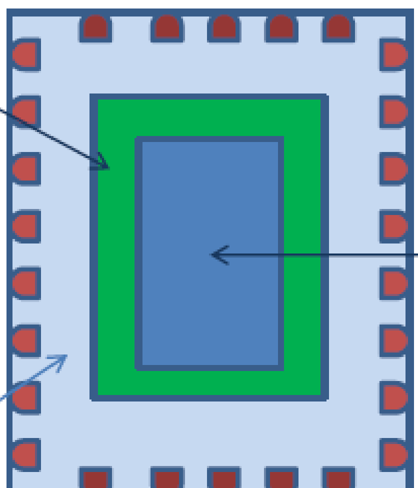


Clean measurement of θ_{13}

Negligeable matter effect

No CP effect

Liquid scintillator for γ tagging



Liquid Scintillator (loaded with Gd)

Transparent buffer with PMT

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

Prompt signal from e^+

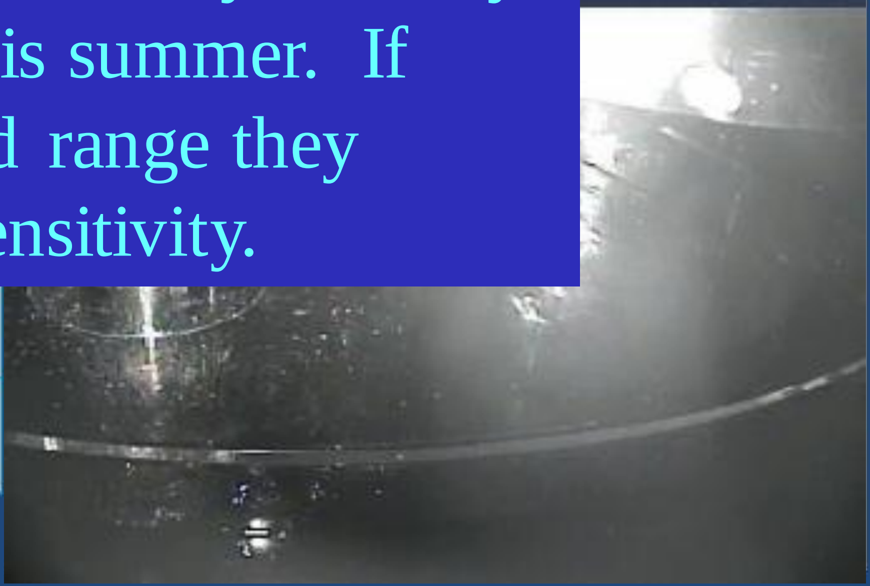
Slowing down of the neutron

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

Reactor neutrinos

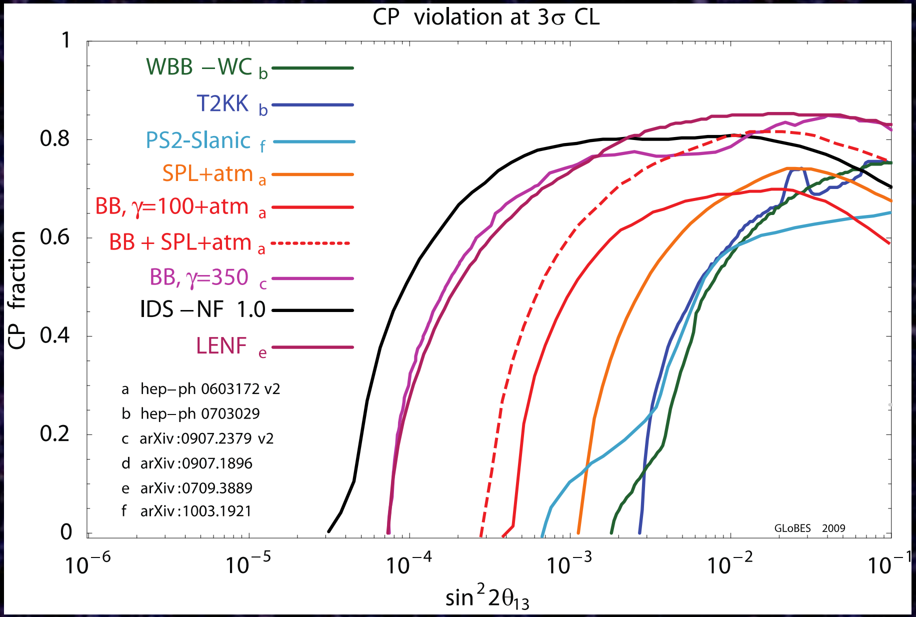
Semi-Double-Chooz now taking data with the far detector, 1st results within the year. Daya Bay and RENO to start this summer. If θ_{13} near top of indicated range they should have early sensitivity.

RENO	South Korea	17.3	290/1380	120/450
DAYA BAY	China	17.4	360/1985 500/1613	260/910



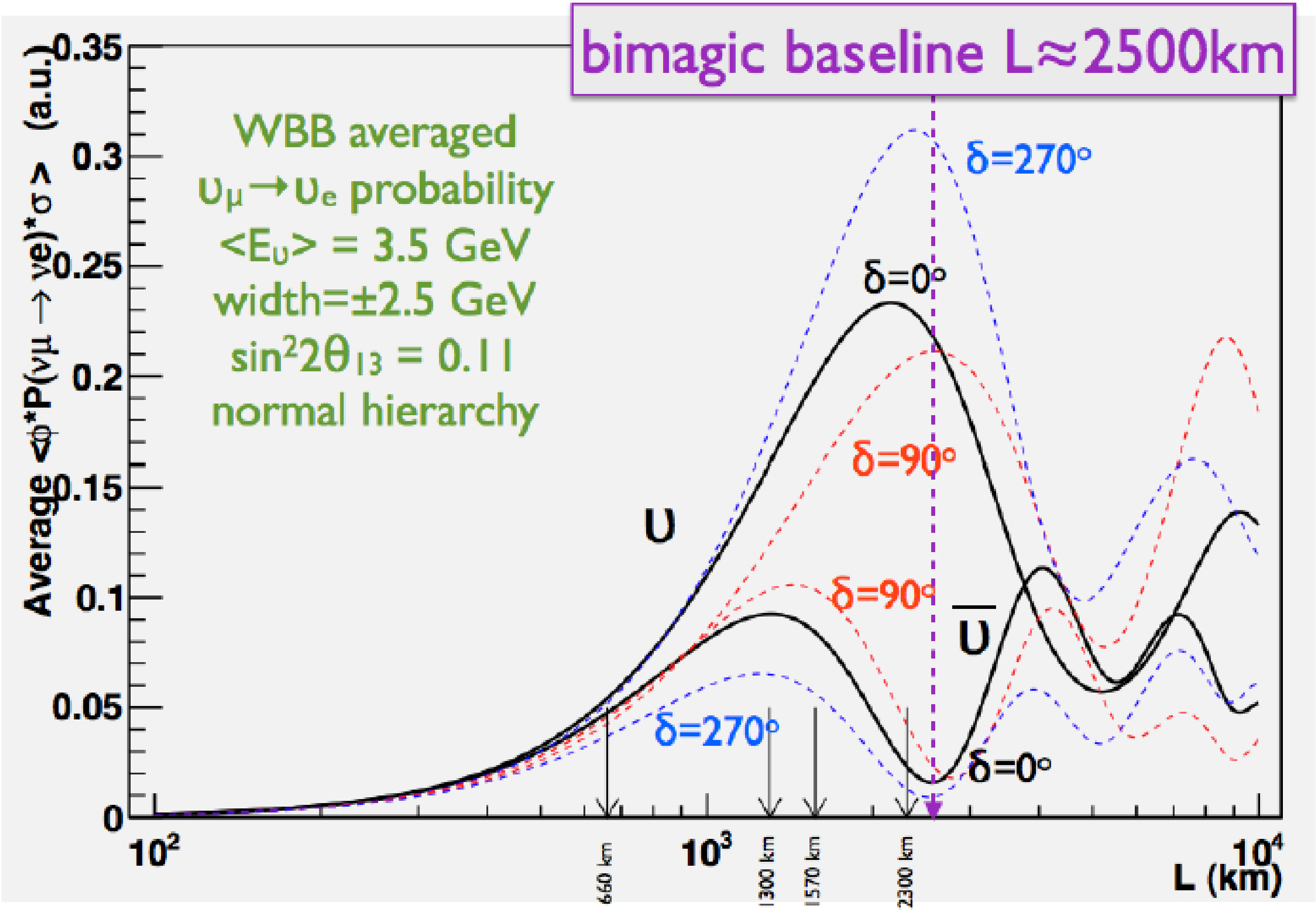
OK, then what?

Simon van der Meer, 1925 - 2011



- 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.

Baseline consideration



The optimal baselines are in the range 1300-2500 km

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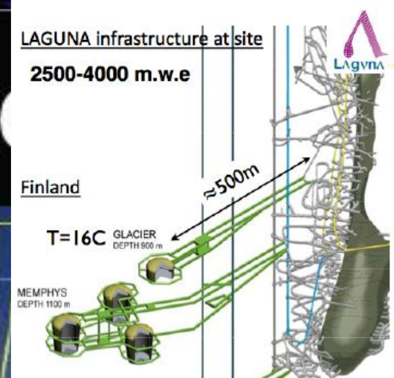
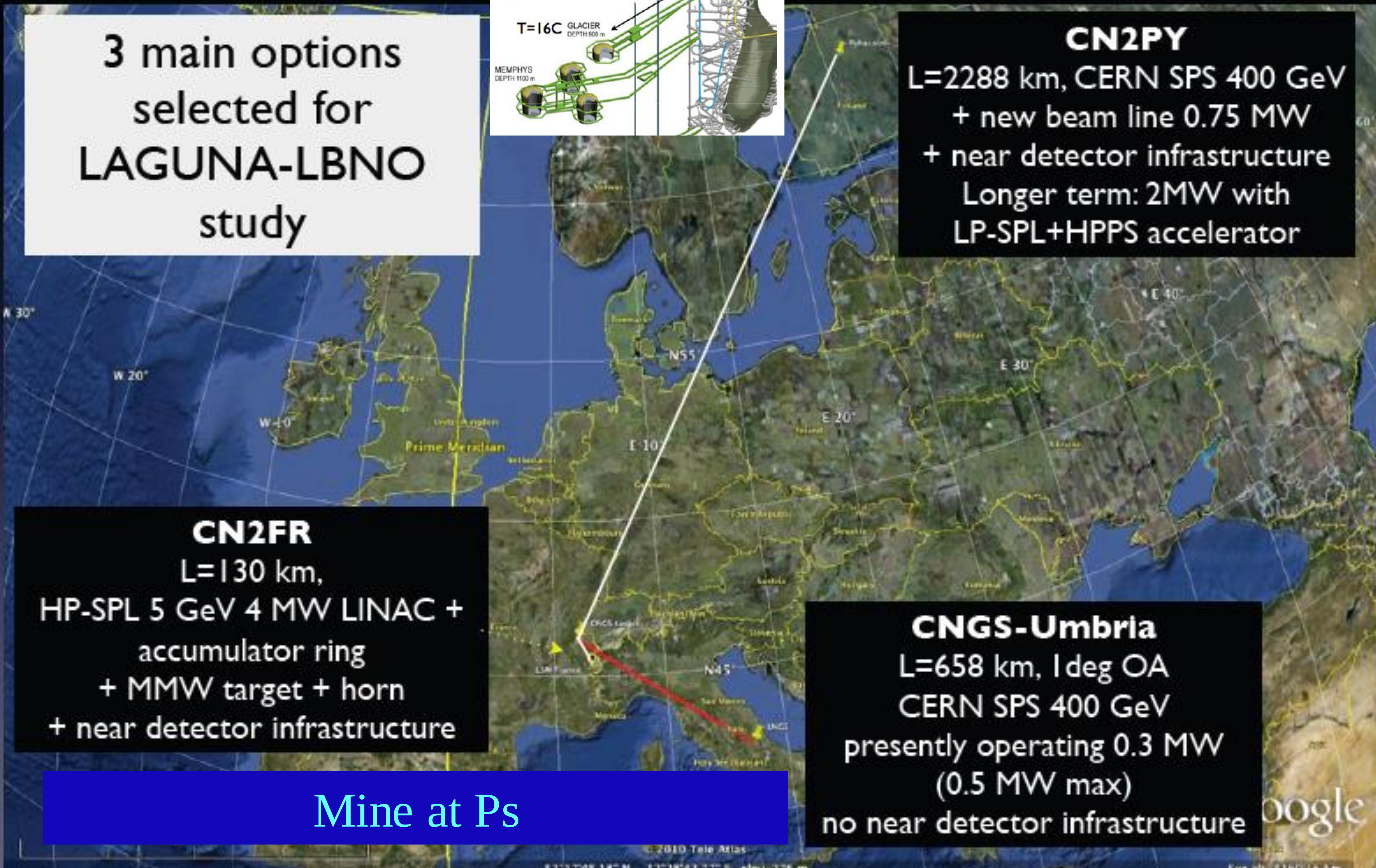
Three options





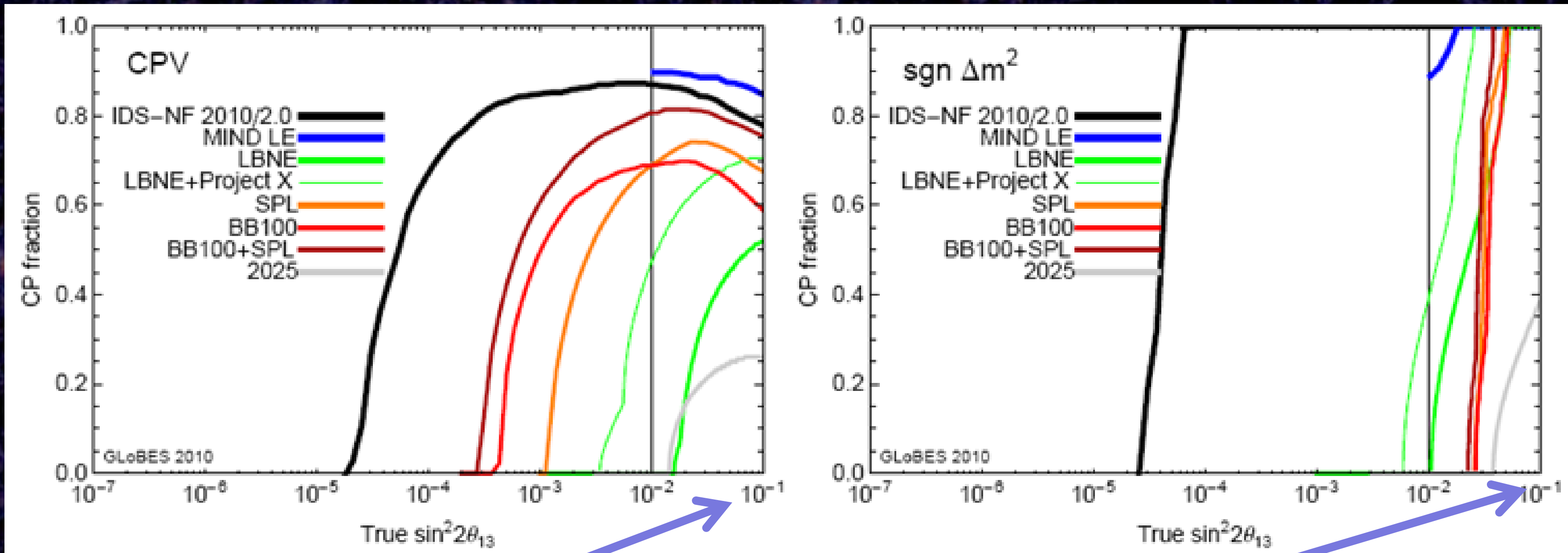
3 main options selected for LAGUNA-LBNO study

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

Mine at Ps



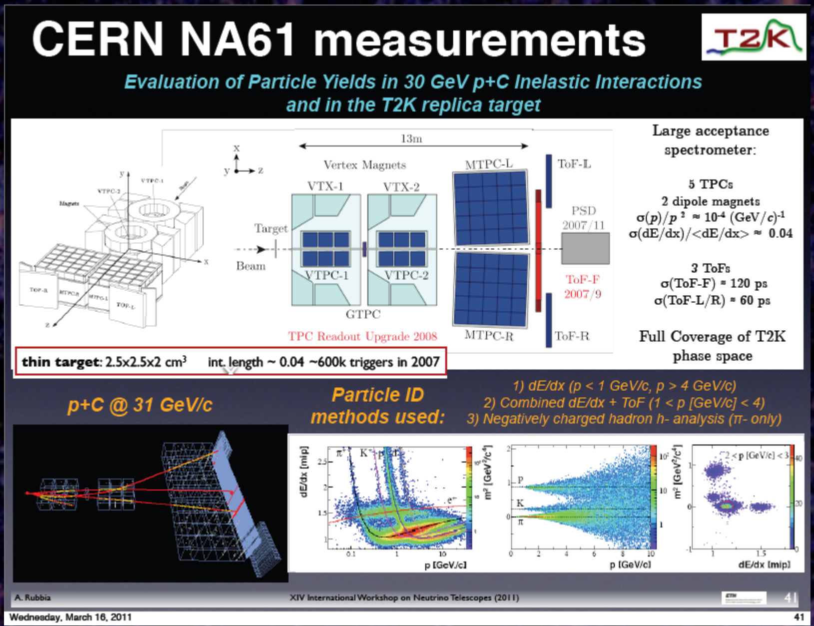
All thinking has to be refined for large θ_{13}.
For large θ_{13} we will quickly be systematics dominated!

Dave Wark
Imperial College/RAL

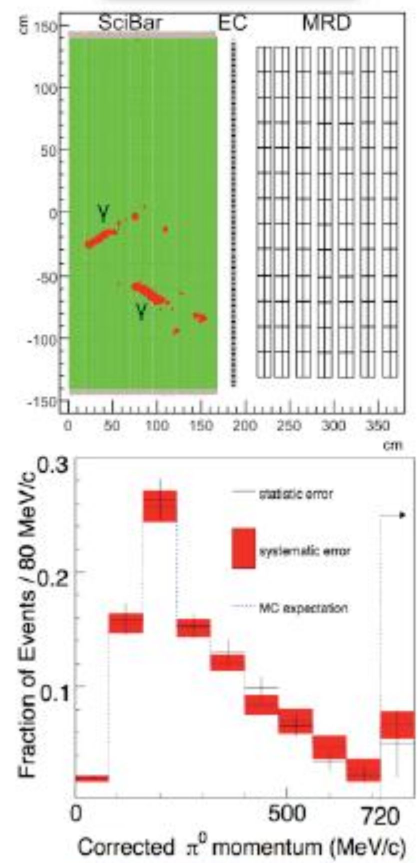
In the systematics dominated era support measurements are even more important

SciBooNE

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

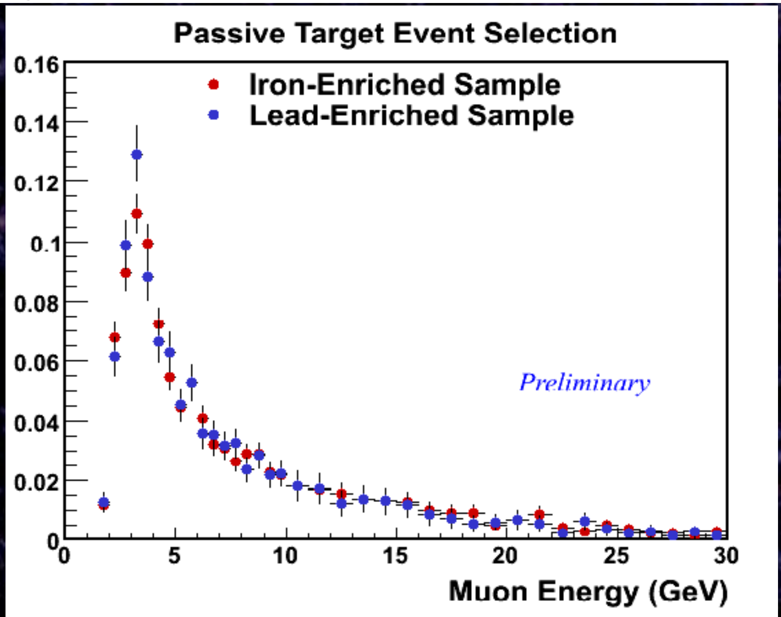


NCπ0 xsecs



Phys. Rev. D 81, 033004 (2009)

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



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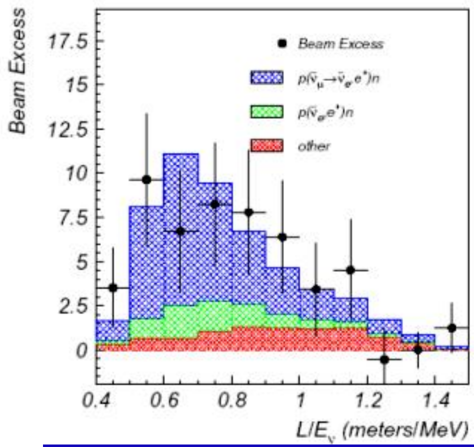
What then for ν oscillations?

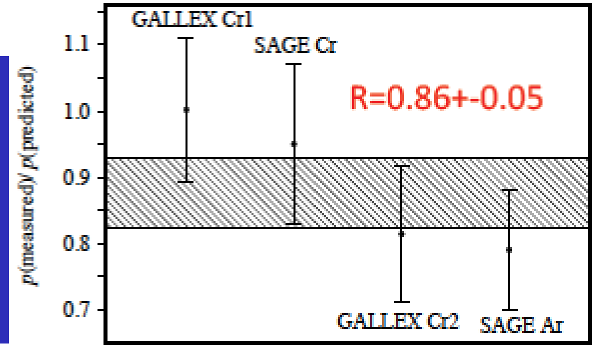
- Prove $\theta_{13} > 0$.
- Measure all parameters with greater precision (because you need it for the rest of the list, but is there any particular necessary accuracy indicated by theory?).
- Make the most sensitive possible test of the deviation of θ_{23} from 45º.
- Determine the mass hierarchy by observing matter effects → higher energy, longer baseline.
- Measure the angle δ!
- Are there any surprises?

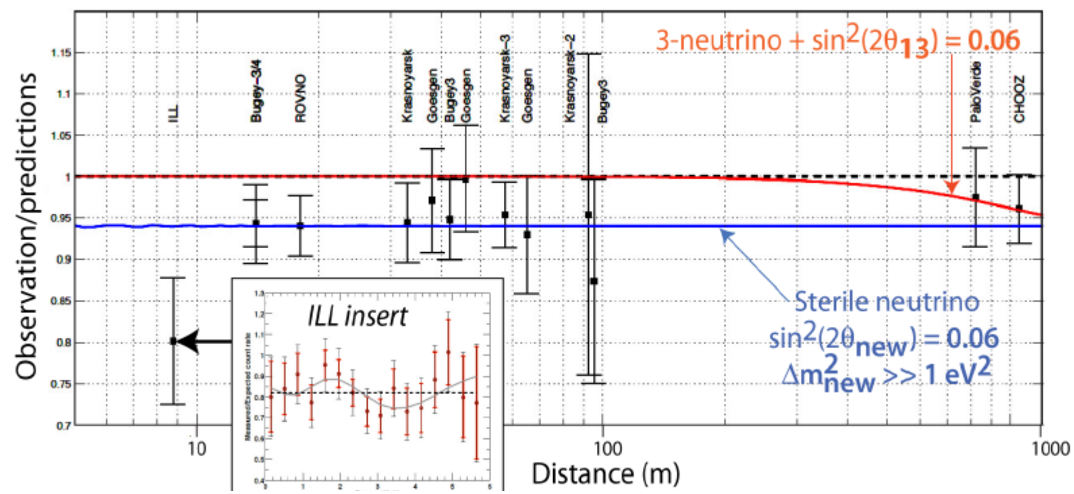
Dave Wark
Imperial College/RAL

LSND Starts it all...

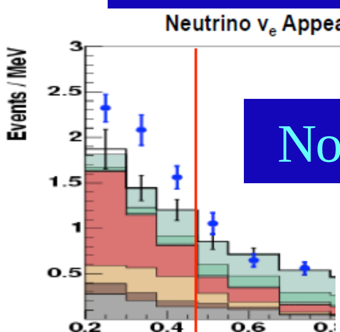


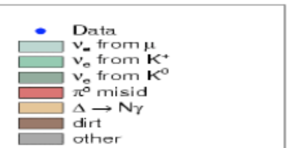
Short baselines (L/E ~ 1) and sterile ν.





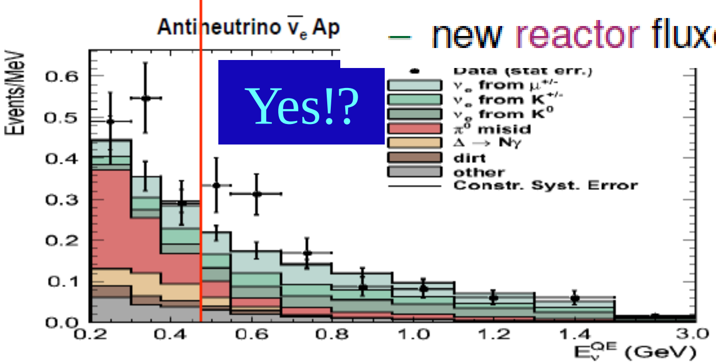
MiniBooNE says....

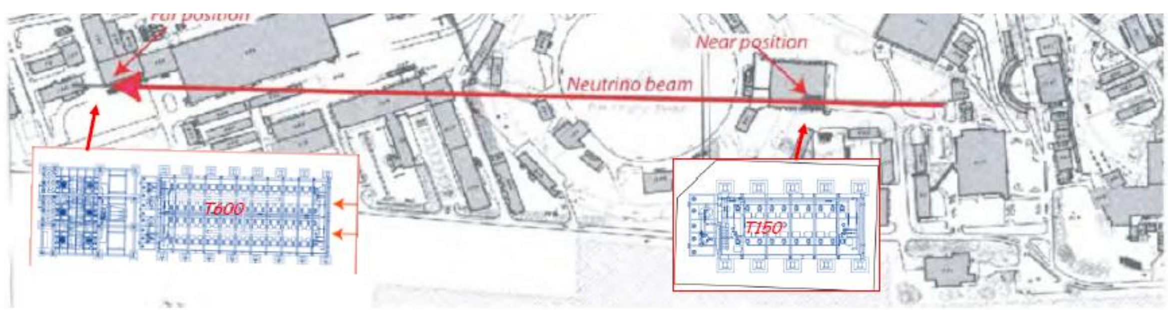




- however, these "hints" for sterile neutrinos are **not** in agreement among them:
  - MiniBooNE asymmetry in $\nu/\bar{\nu}$ requires CP violation, hence at least **two sterile** ν's;
  - (3+2) models reconcile APP data, but DIS ones still show tension;
  - new reactor fluxes reduce tension with DIS data, but **not** for MB low-E excess;

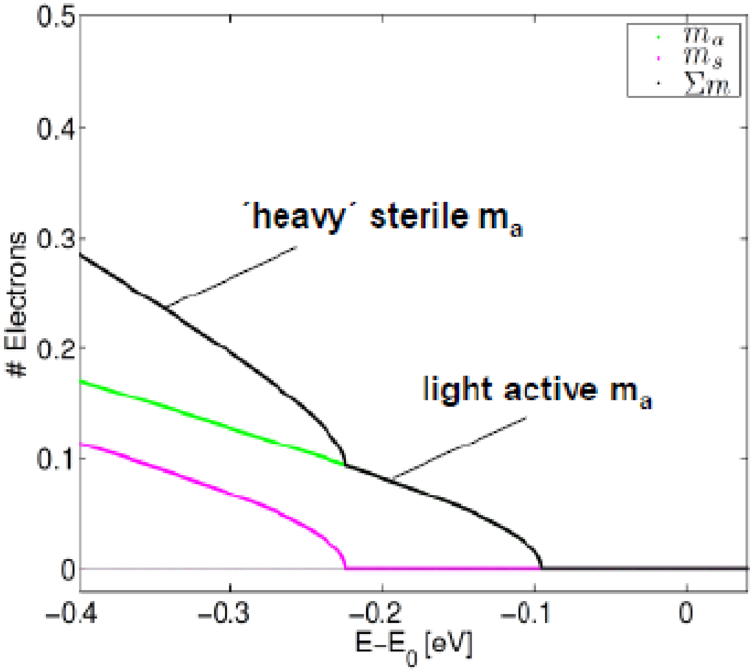
Maltoni



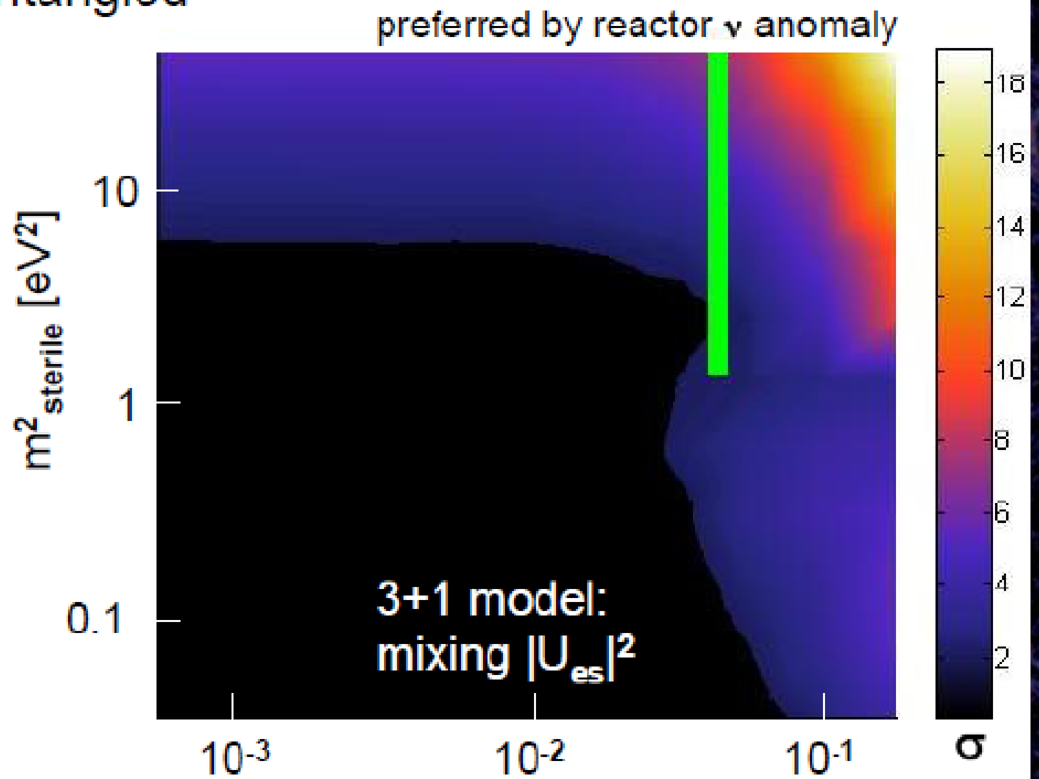


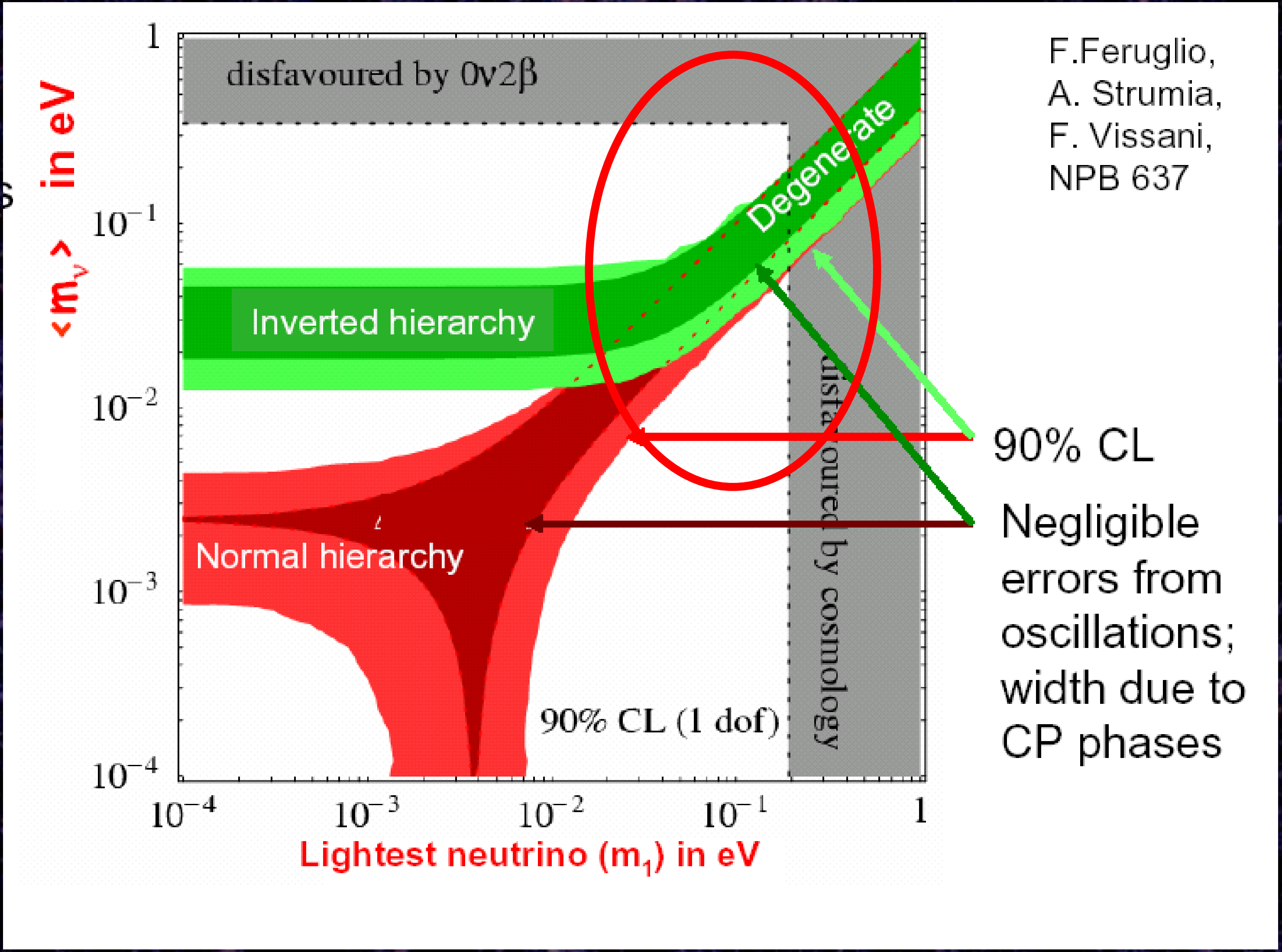
KATRIN sensitivity for sterile neutrinos

- Hannestad et al: initial estimates of KATRIN sensitivity for sterile ν´s assume very light active neutrinos $m_a(\nu) \sim 0$ eV, mixed with sterile $m_s(\nu)$
- 3 σ detection of ´kink´ by $m_{sterile}$ if active-sterile mixing **$|U_{es}|^2 \geq 0.055$** 3+2 scenarios can also be disentangled



A.S. Riis, S. Hannestad,
arXiv: 1008.1495v2, JCAP02(2011)011




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

Conclusions (I)

- Neutrino oscillations are the first confirmed physics beyond the SM, and their continued study is essential to extend our knowledge of fundamental interactions.
- Just or way beyond?
- Current indications are that $\sin^2 2\theta_{13} \geq \sim 0.01$, which would make further long baseline experiments the most attractive option for first searches for CP violation in the neutrino sector.
- Do not assume we know everything that is going on – redundancy is essential!
- Continued operation of "existing" experiments (T2K, MINOS, NOvA, Double Chooz) is the highest priority.
- There are three proposed next-generation projects. We can probably justify two, but not three, so we need to some international coordination.
- 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 5 kT LAr prototype?

Conclusions (II)

- There will be many other opportunities for smaller-scale involvement in cross-section, hadron production, and other critical technological development projects such as the MICE experiment.
- Oscillations depend on L/E, not E or L, so other possibilities should be considered – DAEdALUS?
- Beyond those facilities we will almost certainly wish to have an even more capable facility, either a Beta Beam or a Neutrino Factory – more work is needed to optimize the sensitivity if θ_{13} is large.
- A PS neutrino beam project to look for sterile neutrinos has been suggested for CERN. Here are my very personal views:
  - We don't need another 2-3 sigma effect. Any proposed experiment should have clear 5 sigma sensitivity over the entire indicated range.
  - It could be an interesting part of a broad suite of European neutrino experiments, but I wouldn't want to see it be CERN's only neutrino experiment.
- Neutrino oscillations offers a very wide range of experiments, which must happen, no matter what we do at the energy frontier!