Experimental Neutrino Physics
OR
What is νew …

Niki Saoulidou, Fermilab

DISCRETE ‘08, Valencia, Spain

Outline

- Introduction : The fascinating ν (hi)story
- Neutrino Experiments

*(Past , **Present and Future**):*

  - ν mass and ν nature (β, $\beta\beta$, $0\nu\beta\beta$ decays)

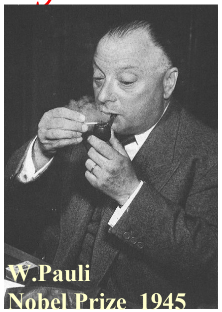
  Covered by J.J.Gomez Gadenas

  - "Solar" νews
  - "Atmospheric" νews
  - "Cross mixing" νews

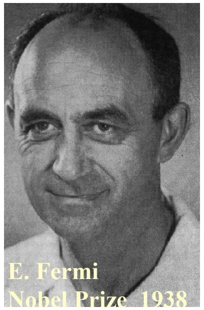
- Summary / Outlook

ν Hi-story : The “smooth” part

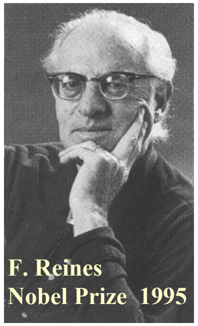
*They **must** exist*



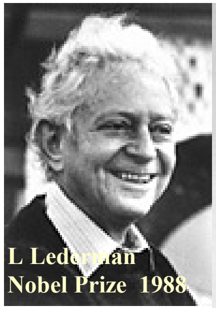
*If they exist they **interact weakly***

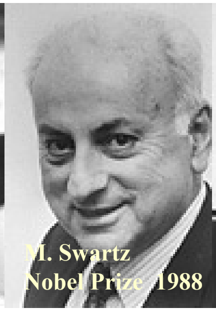


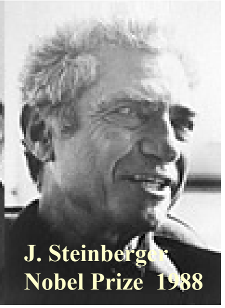
*They **do exist** since we can detect them*

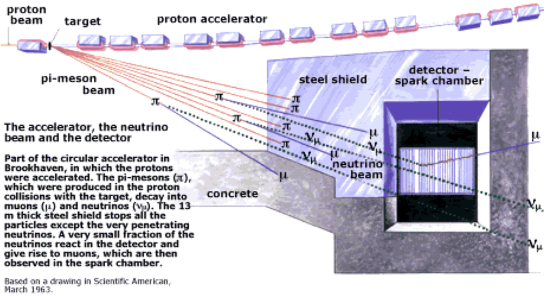


*They are at least **two flavours**, we **can make neutrinos and study them in accelerators***

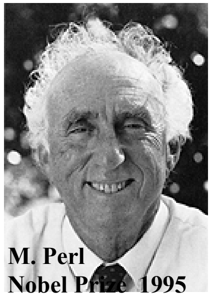


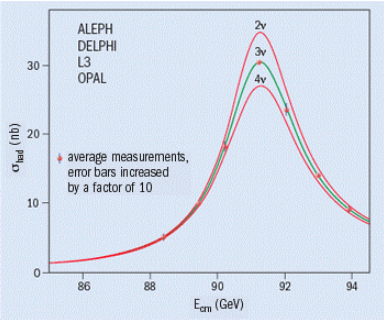




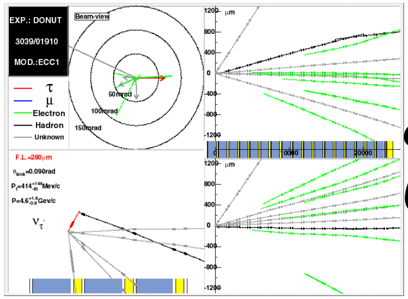


***There are more than two flavours** of leptons (and neutrinos)*



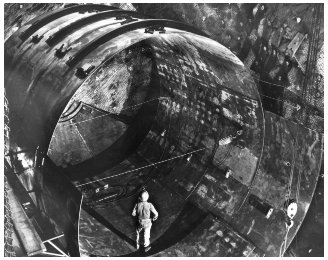


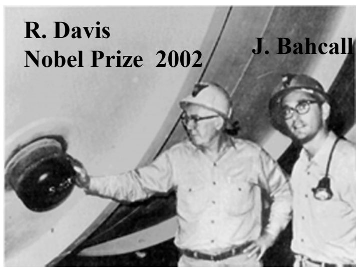
*There are **three active light neutrinos***

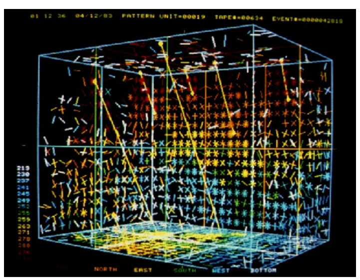


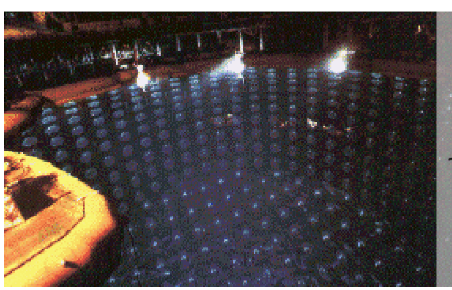
*He have **directly observed the third one** (DONUT Experiment)*

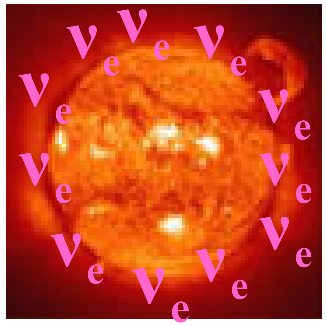
ν Hi-story : The “anomalous” part

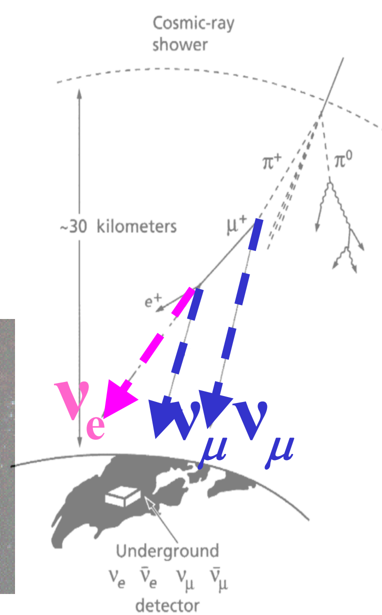












Solar neutrino “anomaly”

R. Davis and J.Bahcall
Homestake experiment

Neutrinos from the Sun less than expected!

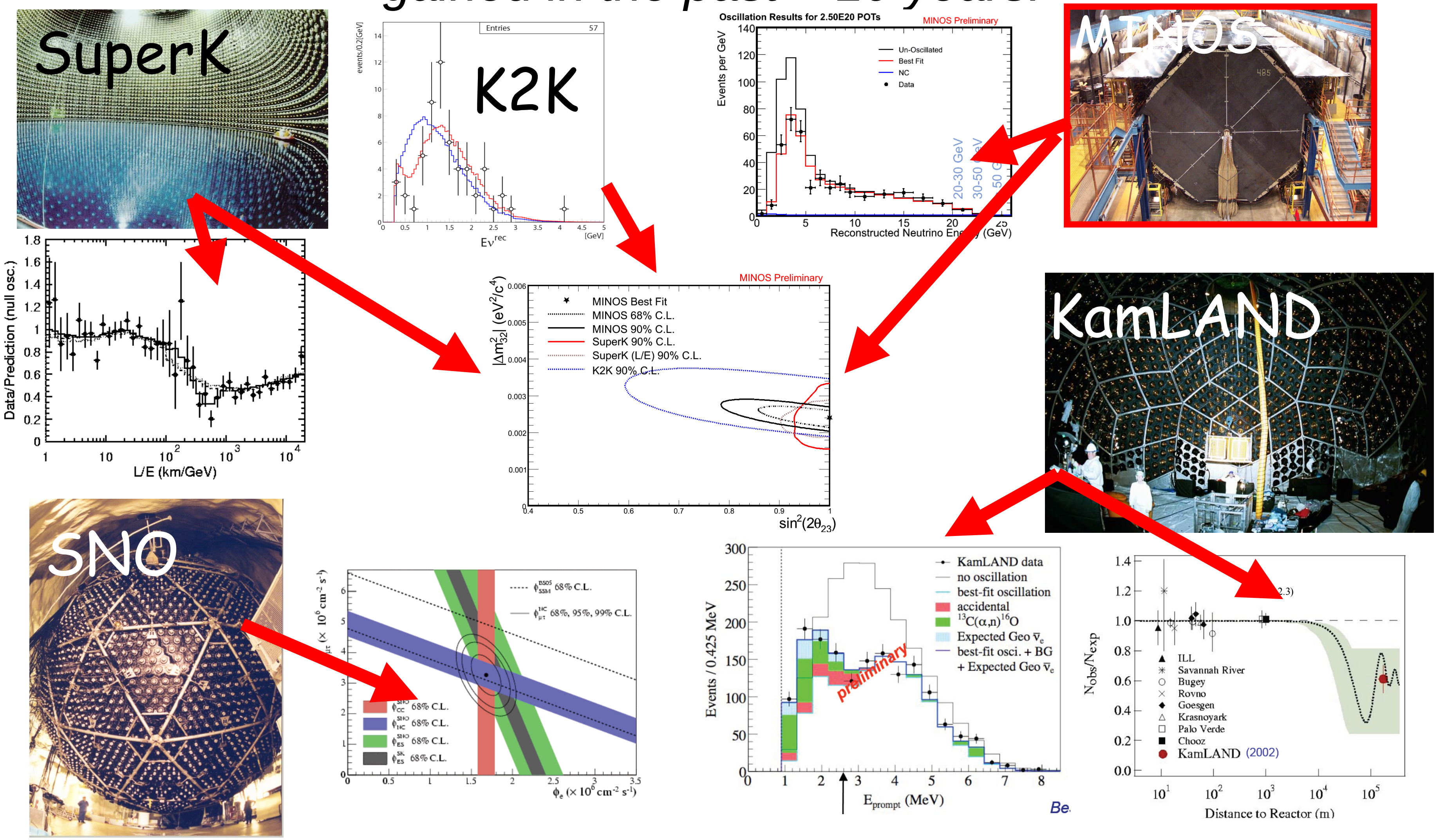
Atmospheric neutrino “anomaly”

Kamiokande and IMB experiments

Neutrinos from the atmosphere less than expected!

What do we know about missing νews

νews are "missing"… because they oscillate, knowledge gained in the past ~ 10 years!



Missing νews still…

EXPERIMENT

Is θ_{23} maximal ?

What is the value of the third mixing angle θ_{13} ?

Do neutrinos violate CP symmetry ?

Which neutrino is the heaviest one?

Are there sterile neutrinos?

What are the neutrino masses ?

Are neutrinos their own anti-particles? (Majorana-Dirac)

THEORY

(How) Do neutrino masses relate to quark masses?

(How) Does neutrino mixing relates to quark mixing?

Origin of Matter – Antimatter Asymmetry in the Universe?

What is happening with Flavour?

3-Flavor ν Oscillation Formalism

If neutrinos oscillate, then the interaction eigenstates (or weak eigenstates, which is what we observe) can be expressed in terms of the mass eigenstates as follows:

$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U^{*}_{e(\mu)(\tau)i}\, \nu_i$$

"Atmospheric" "Cross Mixing" "Solar"

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

2

3 4

"0νββ decays"

Majorana phases

$$\begin{bmatrix} e^{ia_1/2} & 0 & 0 \\ 0 & e^{ia_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

1

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

$$s_{ij} = \sin\theta_{ij}$$

2-Flavor Neutrino Mixing

- In certain experimental situations only one q contributes, in which case one can write the oscillation probability as :

$$P = \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1.267 \cdot \Delta m^2_{23} \cdot L}{E}\right)$$

Physics

Experiment

Different neutrino experiments , depending on what components of the mixing matrix they want to measure involve:

- Different baselines

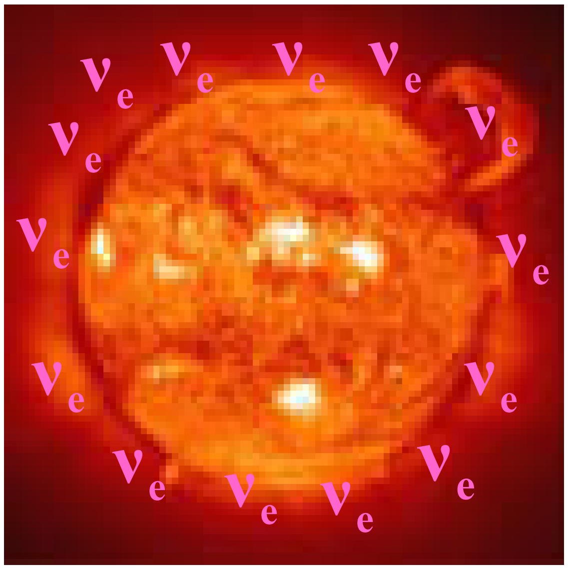
- Different neutrino energies

- Different neutrino flavors

When the region of parameter space (Δm^2, $\sin^2 (2\theta)$) is ~ known then Δm^2 determines the L/E ratio for which the oscillation phenomenon will be maximum and therefore “easier” to observe (in reverse, L/E determines the experiment sensitivity).

The solar ν sub-matrix, were all the “anomalies” started…

$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U^{*}_{e(\mu)(\tau)i}\,\nu_i$$



"Atmospheric" "Cross Mixing" "Solar" "0νββ decays"

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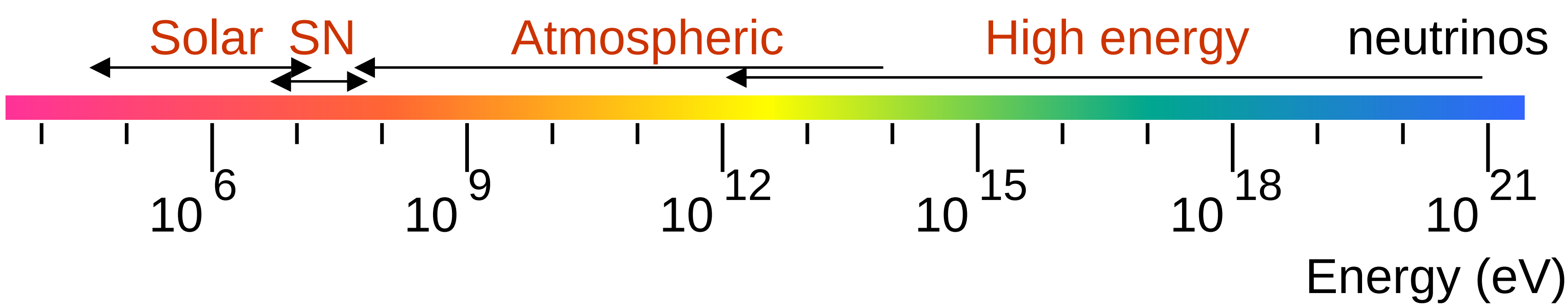


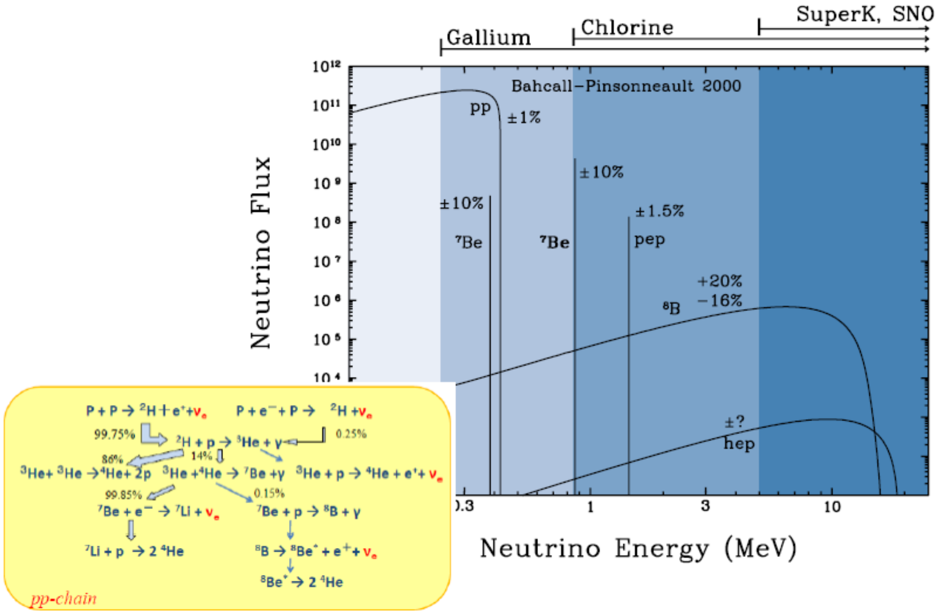
SNO (Canada) : The solar ν "anomaly" is indeed an anomaly…

Confirm the Solar Neutrino "anomaly" 30 years after is was first observed (Davis and Bachall) and made measurements that give confidence that the Solar Model (**J. Bahcall**) is PRECISE!!

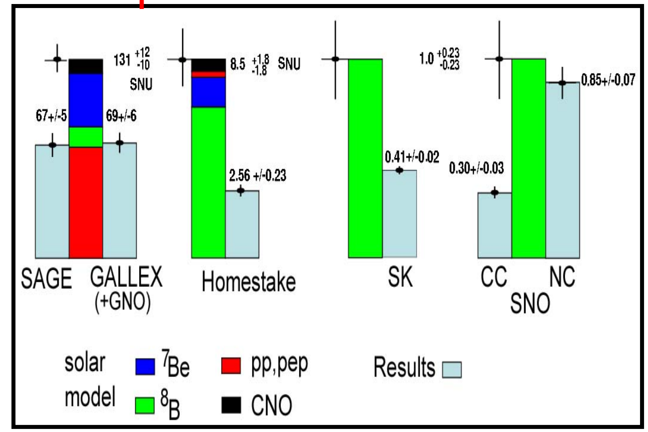
"I feel very much like the way I expect that these prisoners that are sentenced for life do when a D.N.A. test proves they're not guilty, for 33 years, people have called into question my calculations on the Sun."

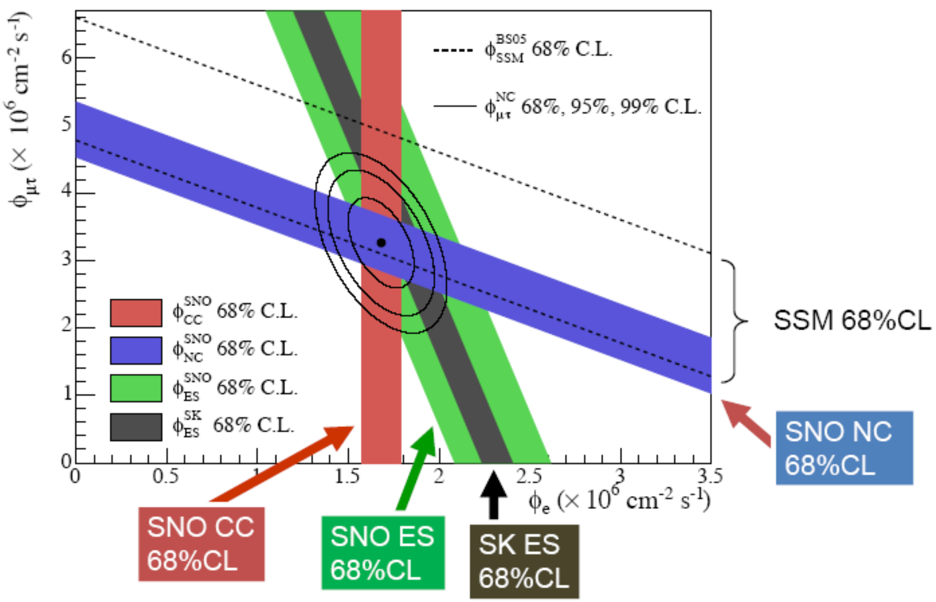
Better Late Than Never

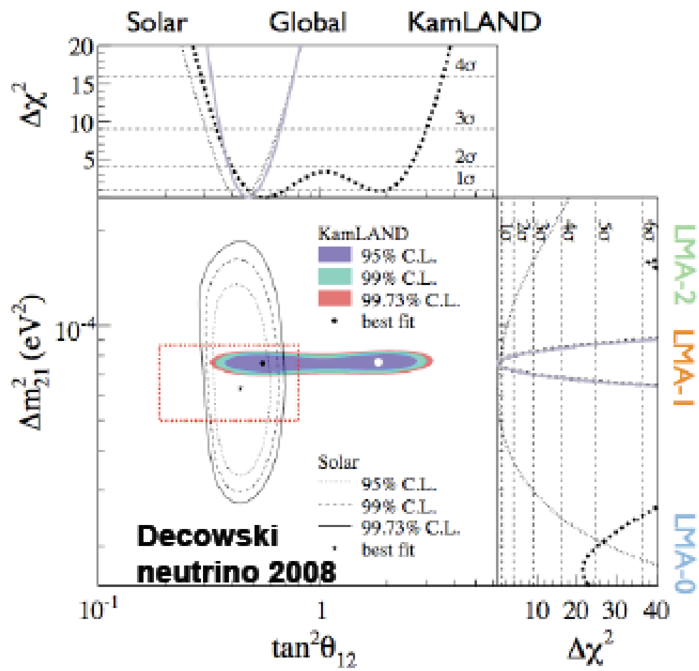
Solar ν Oscillations : What do we know



Deficit of measured fluxes except for SNO NC!!

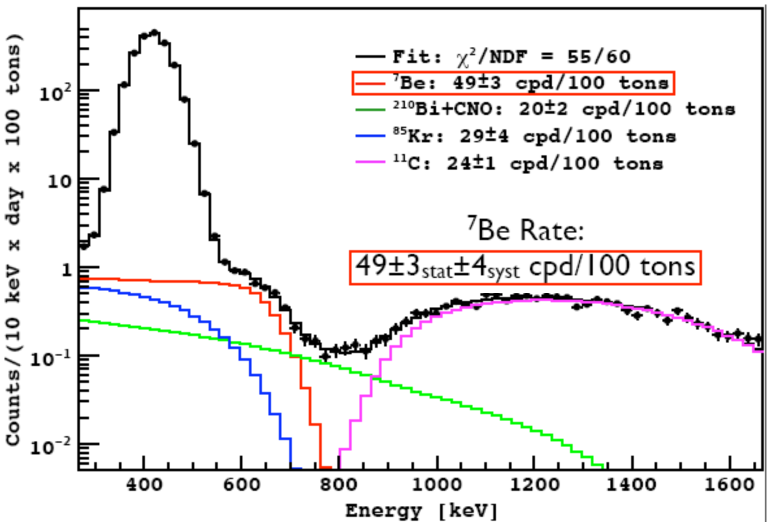


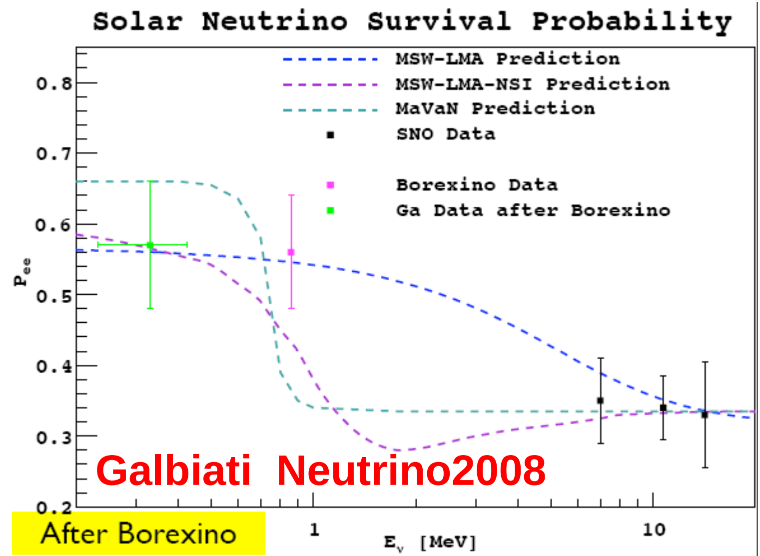




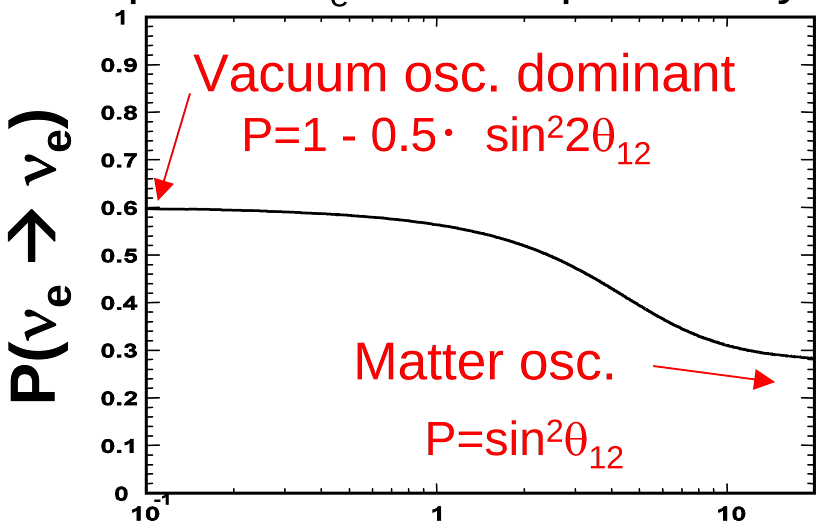
First Results from BOREXINO

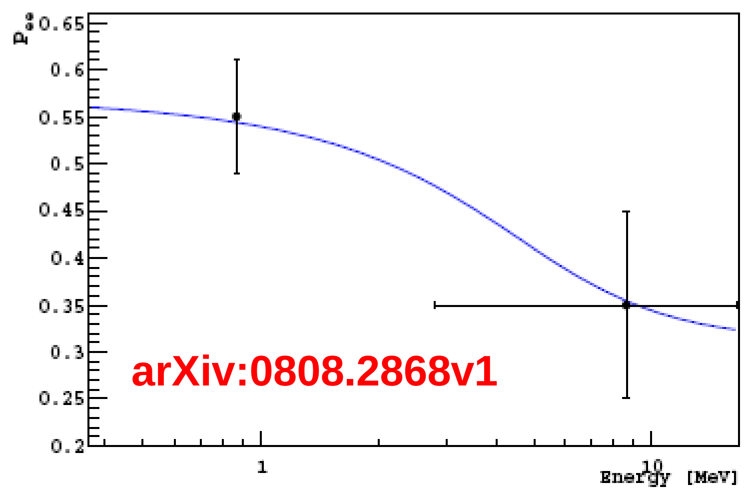
First real time detection of ^{7}Be solar neutrinos by Borexino arXiv:0805.3843





Expected ν_e survival probability





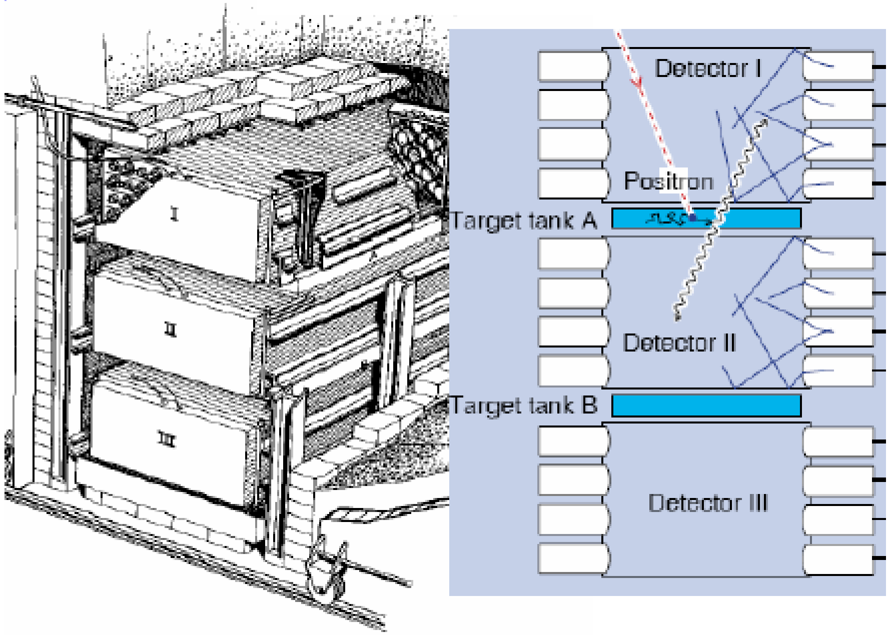
Reactor νews

What are reactor news telling us?

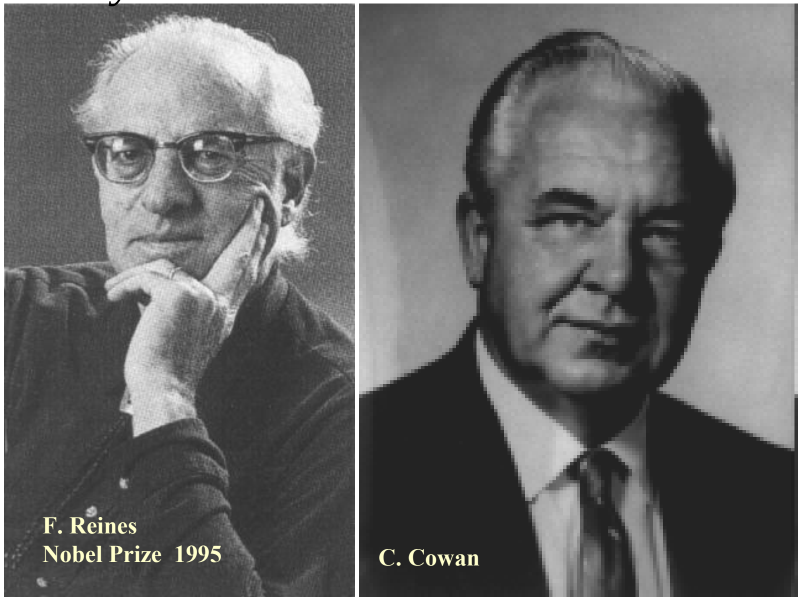
Well…First of all they told us neutrinos

DO EXIST

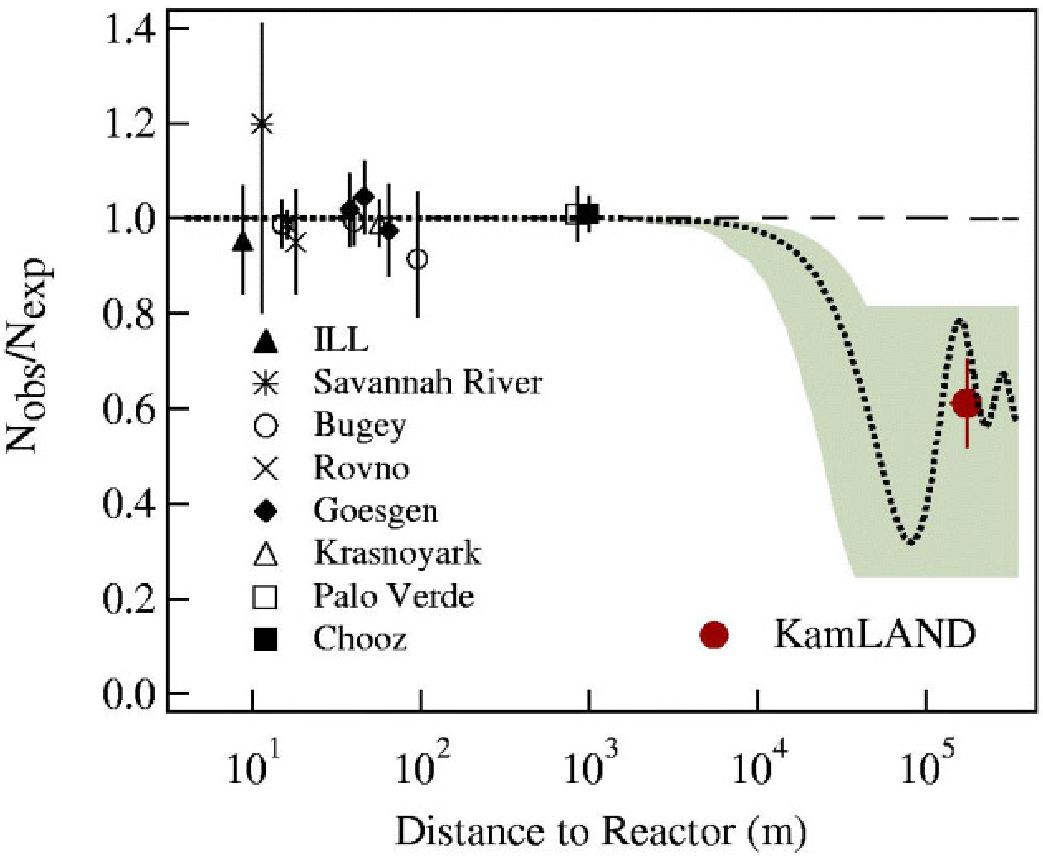
The first successful neutrino detector



They ***do exist*** *since we can detect them*



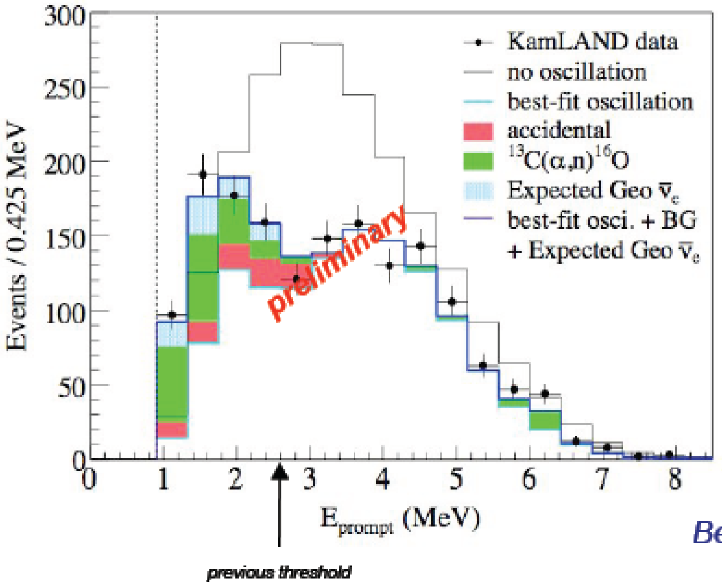
Reactor νews: For long time they were telling us neutrinos do not oscillate (wrong L)… until KamLAND

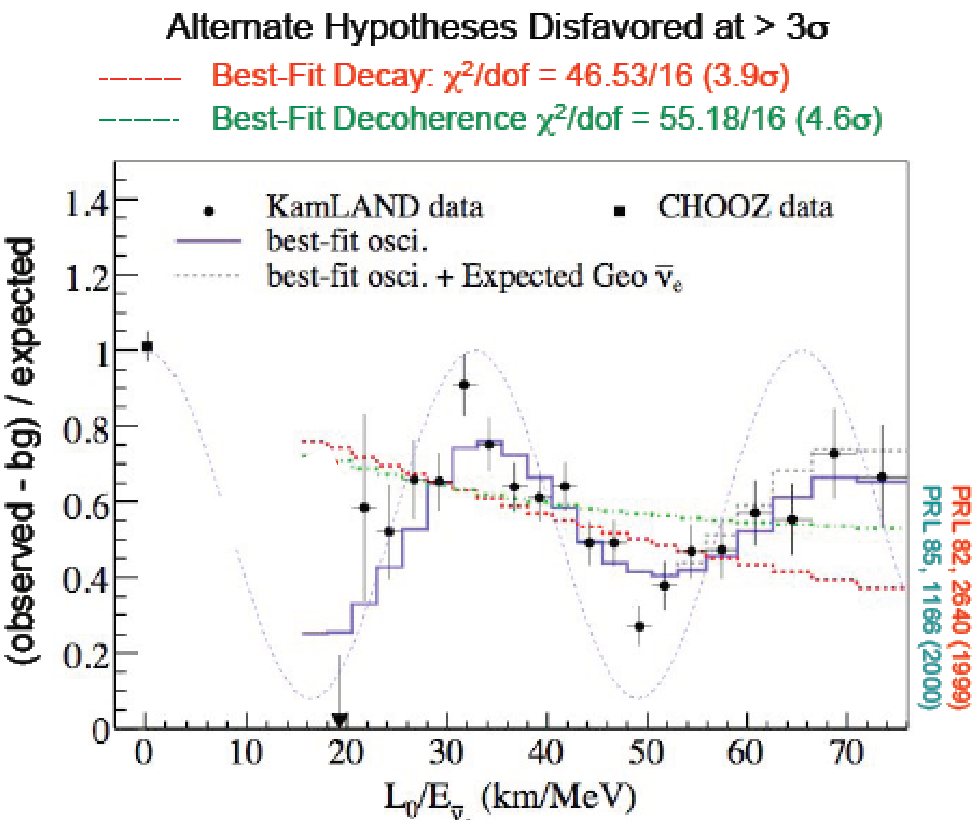


Reactor experiments also determined the upper limit of mixing angle θ_{13} ($\sin^2 2\theta_{13}<0.17$ - Chooz)

More on this later…

KamLAND

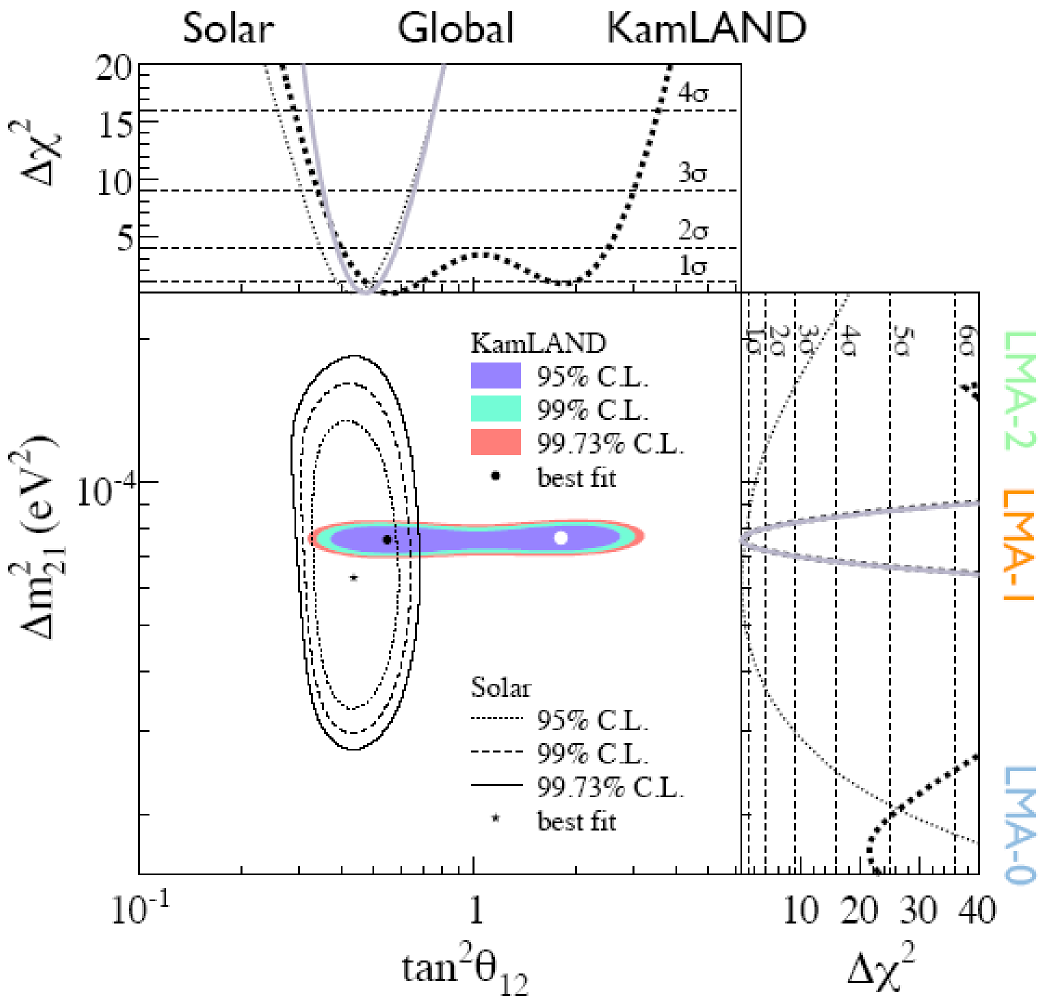




L_0 = 180km flux-weighted average reactor distance

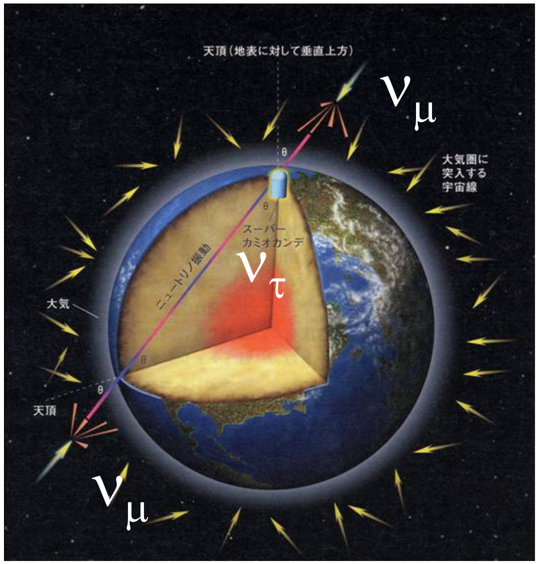
Unambiguous Oscillatory Behavior!

KamLAND



Entering a Precision Measurements Era in the Neutrino Mixing Matrix !!

The atmospheric ν sub-matrix (birth of the “too few numu” anomaly…)

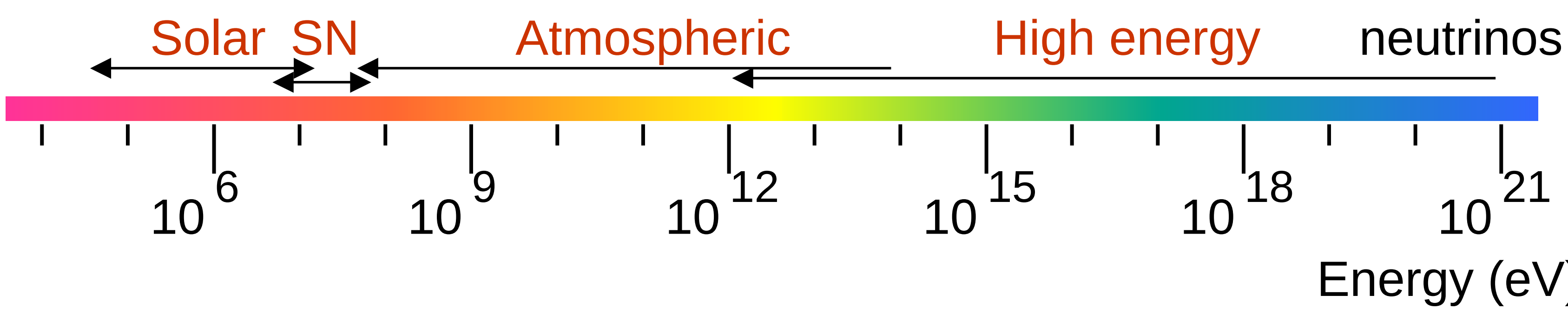


$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U^{*}_{e(\mu)(\tau)i}\,\nu_i$$

“Atmospheric” — **“Cross Mixing”** — **“Solar”** — **“0νββ decays”**

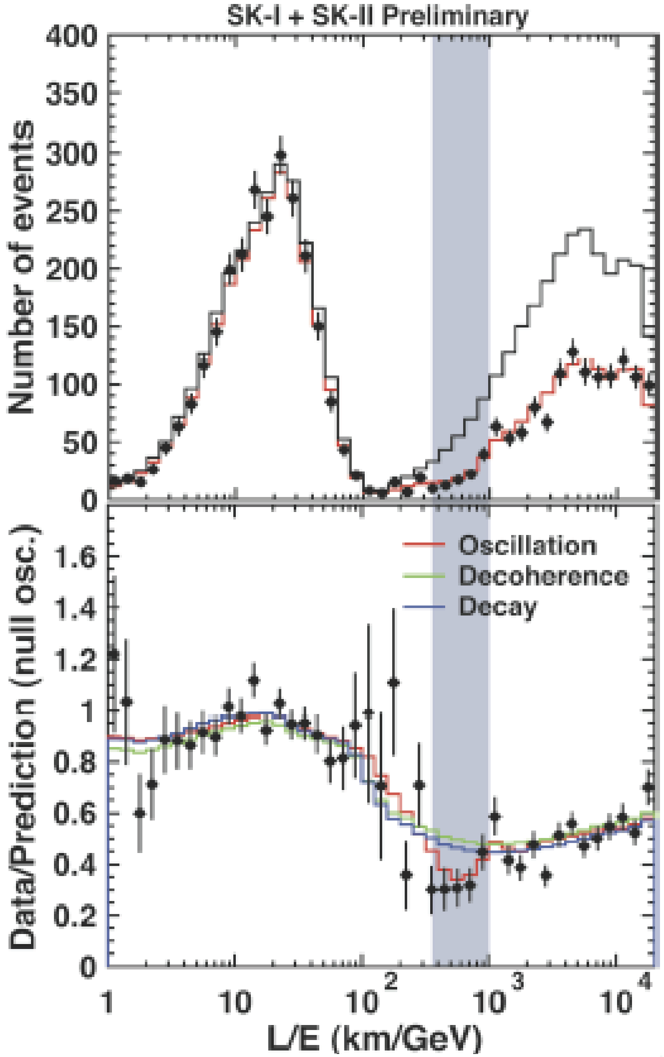
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana phases



Super-Kamiokande
First Strong Evidence of ν Oscillations

J.Raaf Neutrino 2008

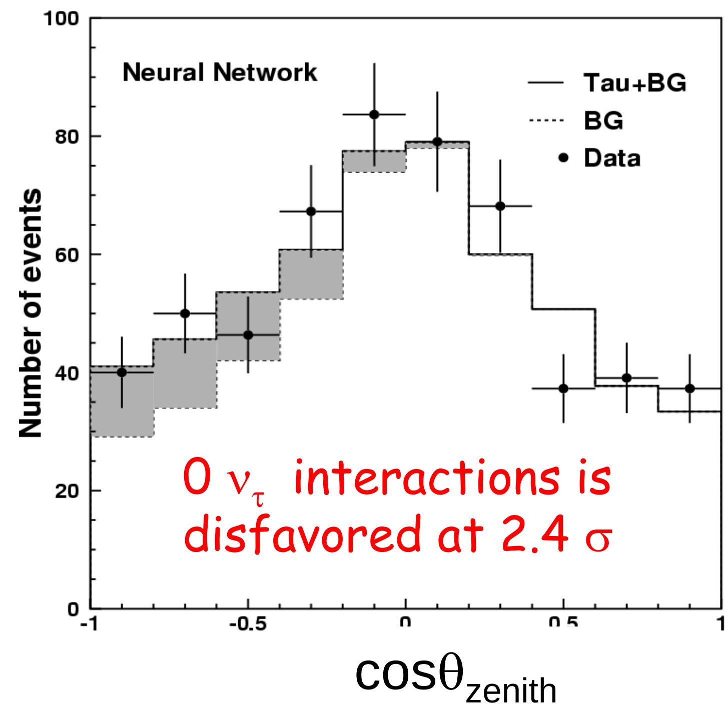


Neutrino decoherence (5.0σ)

Neutrino decay (4.1σ)

SK-collab. Phys.Rev.Lett.97:171801,2006

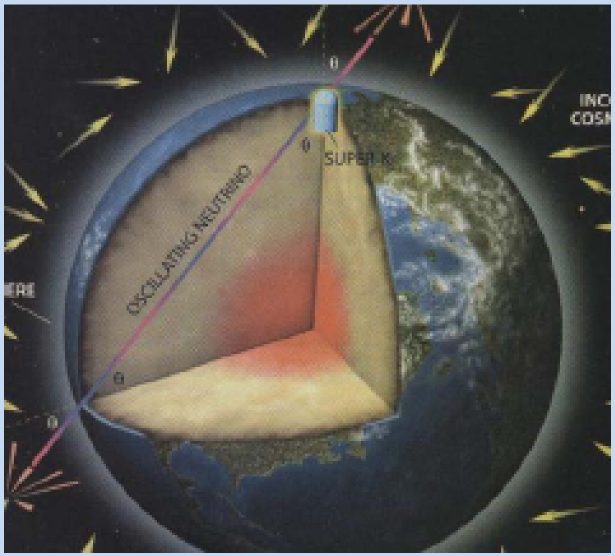
NN analysis



Fitted number of τ events	134 $\pm$ 48(stat) + / -16(syst)
Exp'd number of τ events	78 $\pm$ 27 (syst)

Why use accelerator νews to study ν_μ oscillations??

Atmospheric neutrinos



- ➔ Very wide neutrino flight length
- ➔ Wide neutrino energy
- ➔ Mixture of ν_μ, anti-ν_μ, ν_e and anti-ν_e

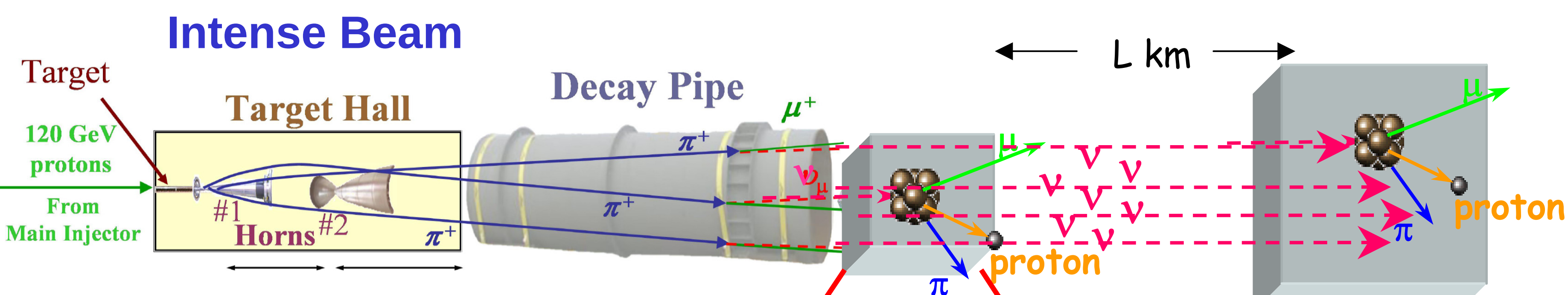
Long baseline Experiments

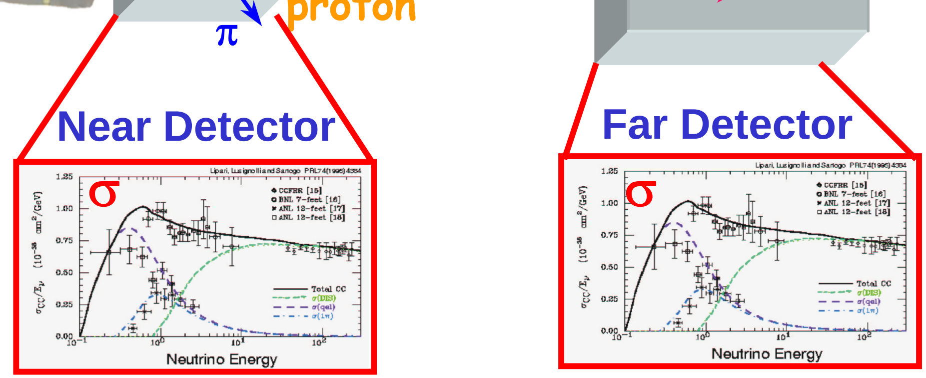
- ➔ Single flight length
- ➔ Controlled neutrino energy
- ➔ almost pure ν_μ (or anti-ν_μ)

Initial discovery ➔ *Precise studies*

Basic Idea of accelerator ν oscillation two-detector experiments

Basic Idea : 2 detectors "identical" in all their important features.



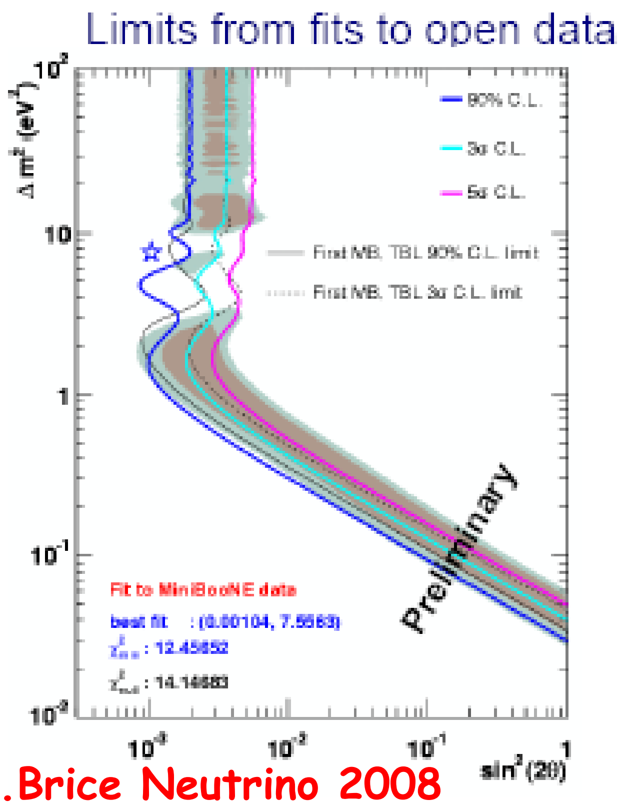


Cross Section (σ) & Beam Modeling (Φ_ν) uncertainties to high accuracy cancel out between the two Detectors

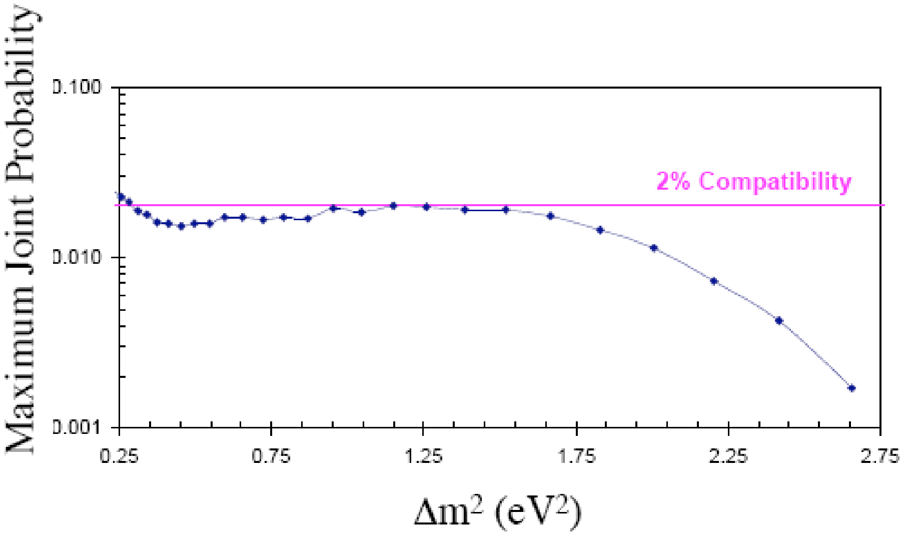
$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$

MiniBooNE : One-detector experiment can do it as well..

Long Standing LNSD "anomaly" solved
(at least as an interpretation of muon neutrino to electron neutrino oscillations)

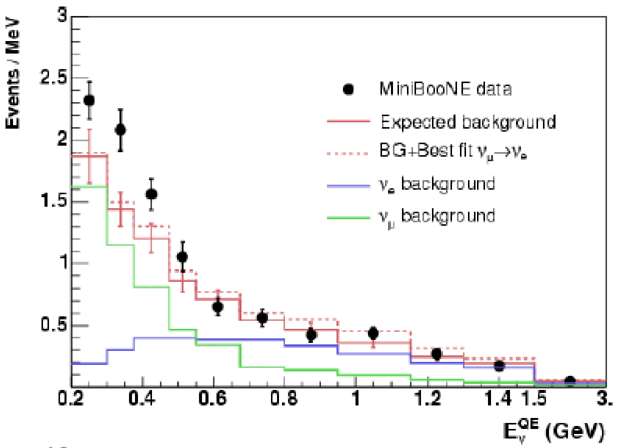


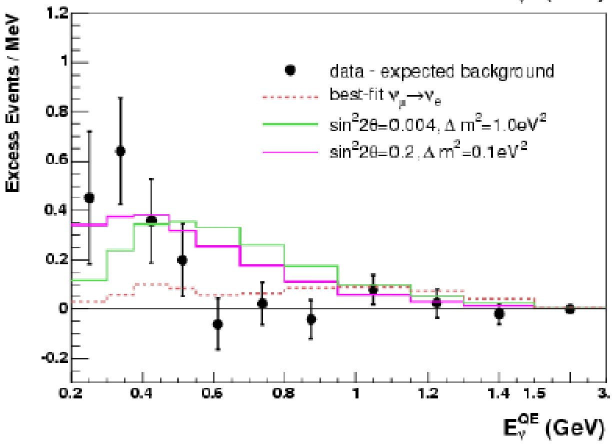
S.Brice Neutrino 2008



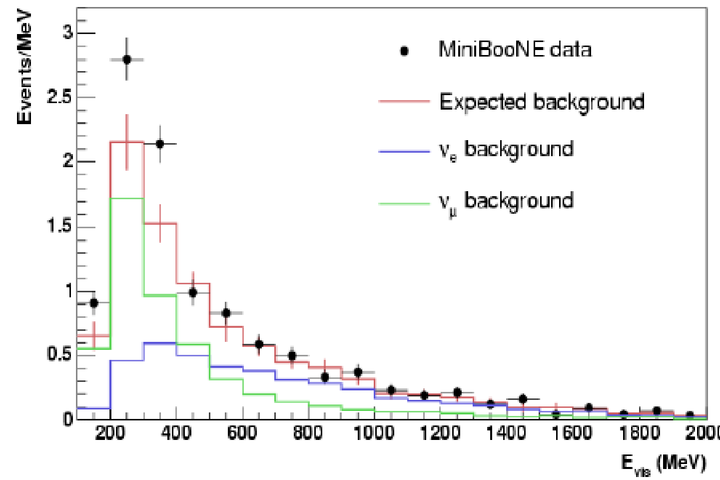
MiniBooNE is incompatible with a $\nu_\mu \to \nu_e$ appearance only interpretation of LSND at 98% CL

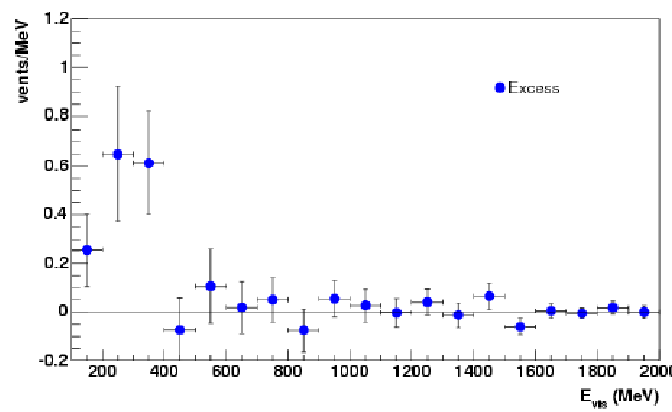
MiniBooNE Prospects





C. Polly, Fermilab W&C August 2008

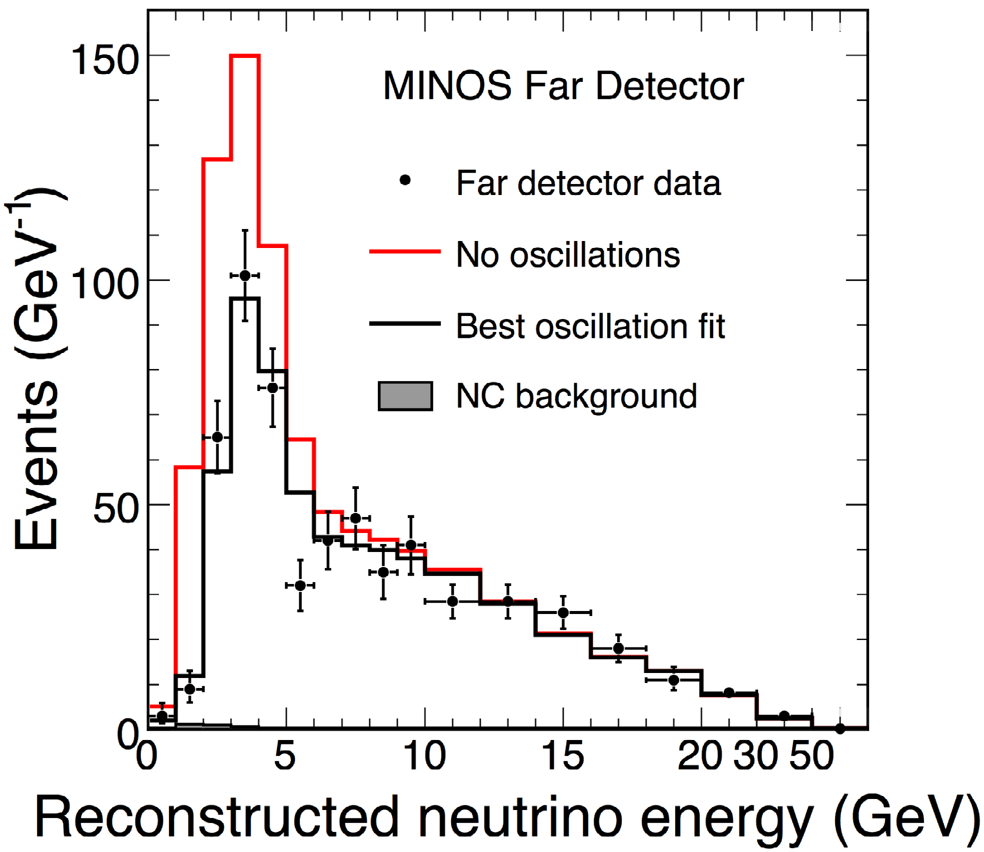


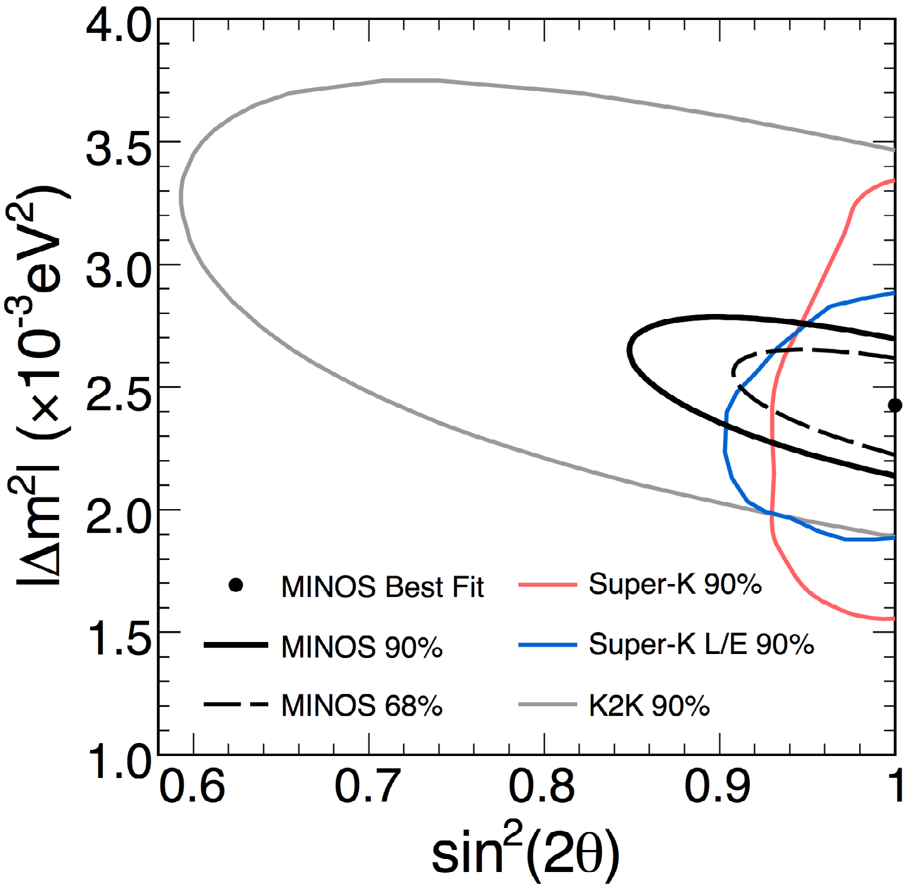


• Further investigation of the “low energy excess”. New LAr experiment, MicroBooNE, to further investigate received Stage I approval.

• Further analysis of neutrino data including exotic models for the LSND effect and anti-neutrino results soon !

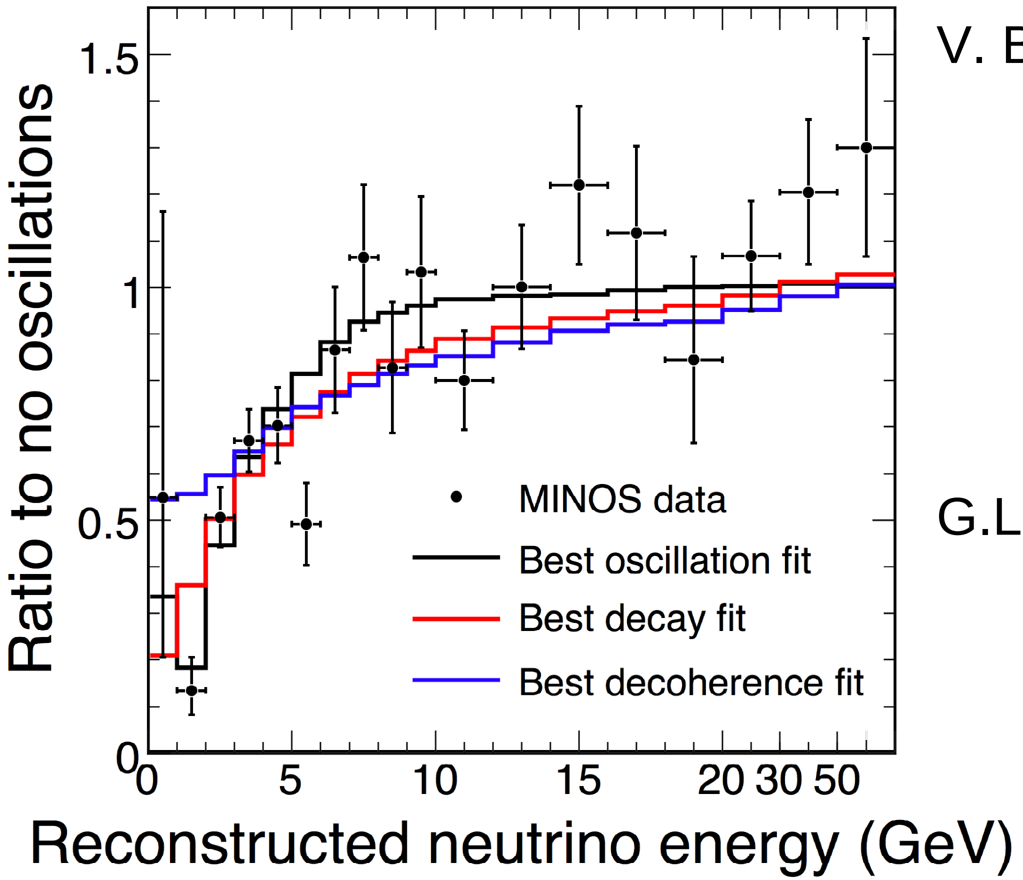
MINOS





Entering a Precision Measurements Era !

MINOS



Decay:

V. Barger *et al.*, PRL82:2640(1999)

$\chi^2/\mathrm{ndof} = 104/97$

$\Delta\chi^2 = 14$

disfavored at 3.7σ

Decoherence:

G.L. Fogli *et al.*, PRD67:093006 (2003)

$\chi^2/\mathrm{ndof} = 123/97$

$\Delta\chi^2 = 33$

disfavored at 5.7σ

Unambiguous Oscillatory Behavior!

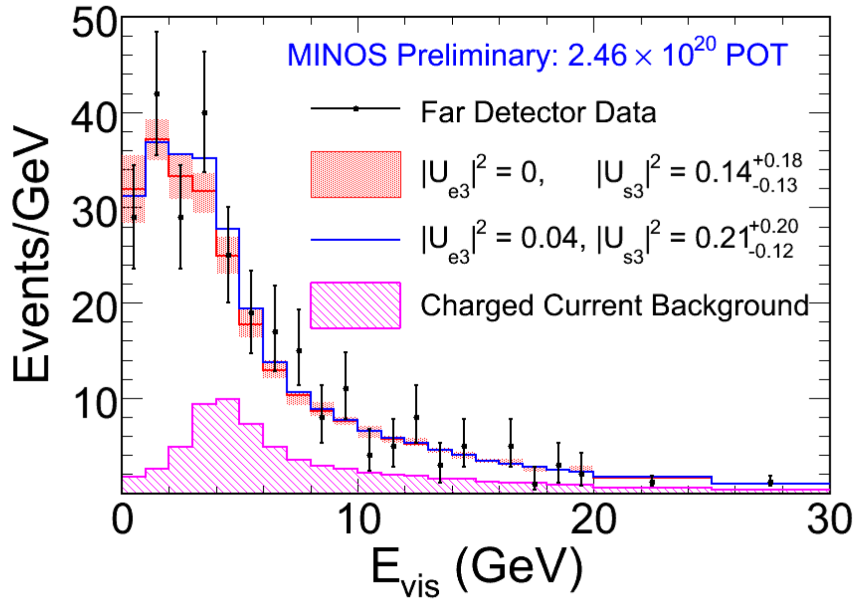
MINOS : Most likely it is not $\nu_\mu \to \nu_s$

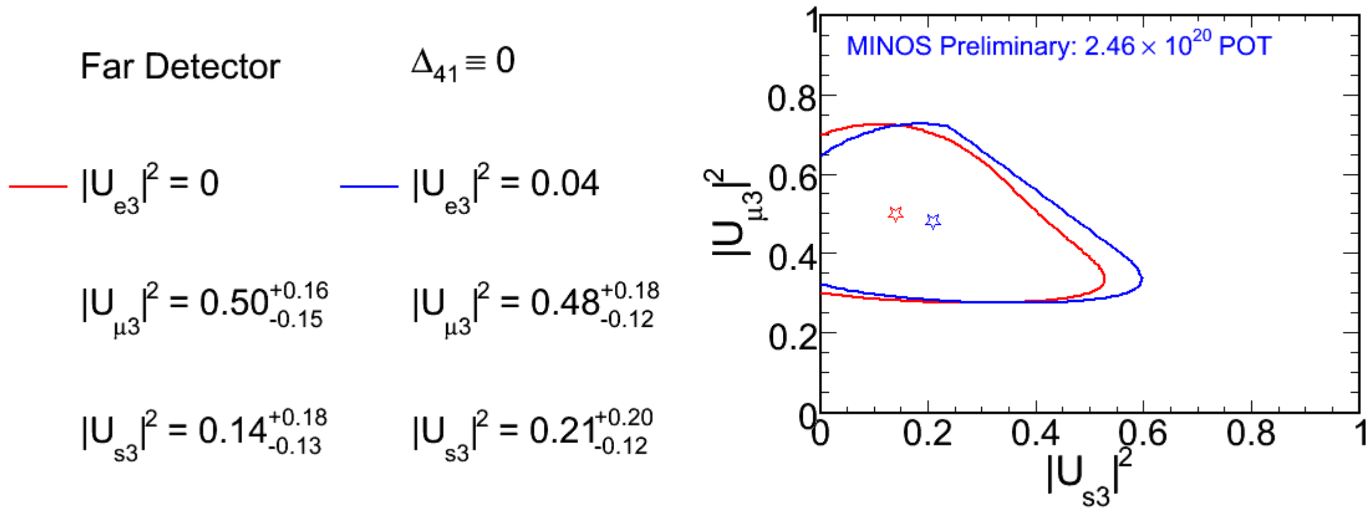
Assume $\Delta m^2_{41} = 0$

– Oscillation at single mass scale

– Oscillation probabilities simplify to:

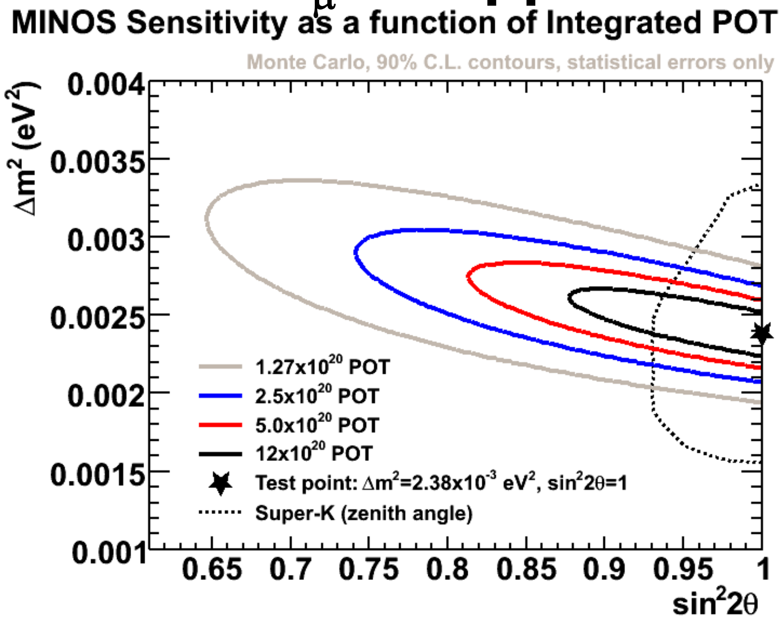
$$P_{\nu_\mu \to \nu_\mu} = 1 - 4\left|U_{\mu 3}\right|^2 \left(1 - \left|U_{\mu 3}\right|^2\right)\Delta^2_{31}$$
$$P_{\nu_\mu \to \nu_e} = 4\left|U_{\mu 3}\right|^2 \left|U_{e 3}\right|^2 \Delta^2_{31}$$
$$P_{\nu_\mu \to \nu_s} = 4\left|U_{\mu 3}\right|^2 \left|U_{s 3}\right|^2 \Delta^2_{31}$$
$$P_{\nu_\mu \to \nu_\tau} = 1 - P_{\nu_\mu \to \nu_\mu} - P_{\nu_\mu \to \nu_e} - P_{\nu_\mu \to \nu_s}$$



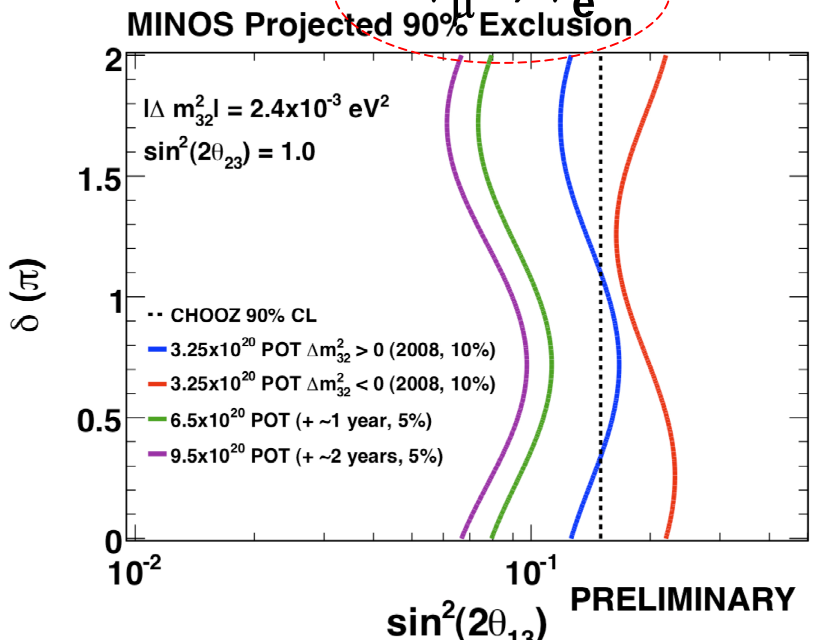


MINOS : Prospects

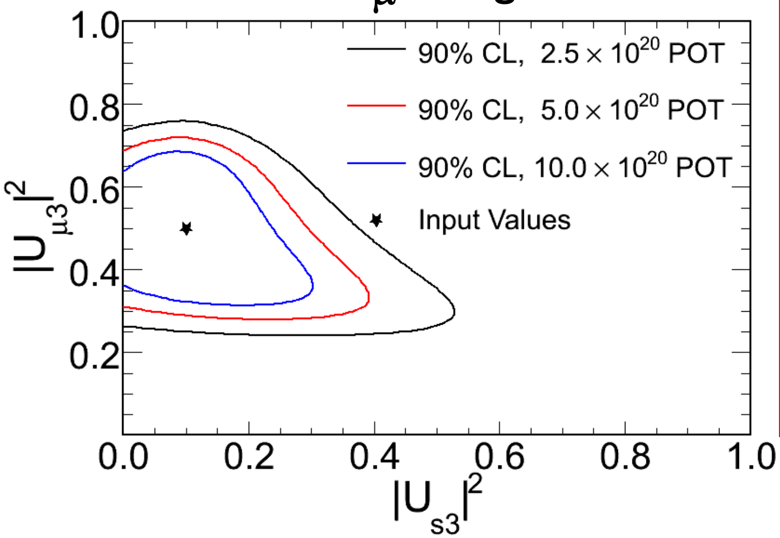
ν_μ disappearance



$\nu_\mu \rightarrow \nu_e$



$\nu_\mu \rightarrow \nu_s$



With increased statistics :

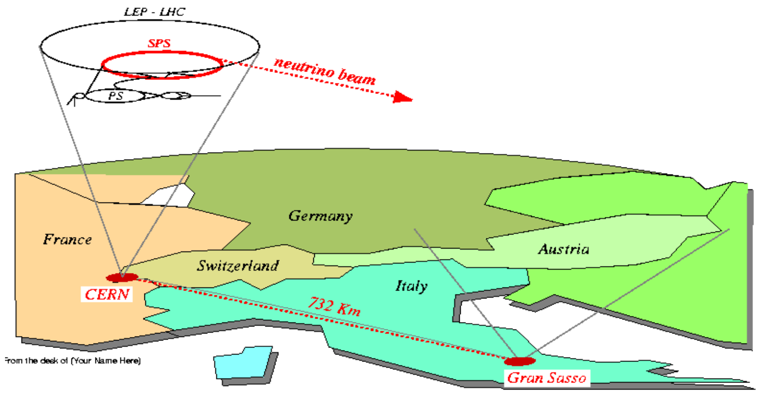
- -Improve precision on Δm^2 and $\sin^2(2\theta)$
- -Set more stringent limits on alternative hypothesis (neutrino decay, sterile neutrinos)
- -Make first measurement on θ_{13} or improve current best limit set by CHOOZ

OPERA : Is it really $\nu_\mu \rightarrow \nu_\tau$?

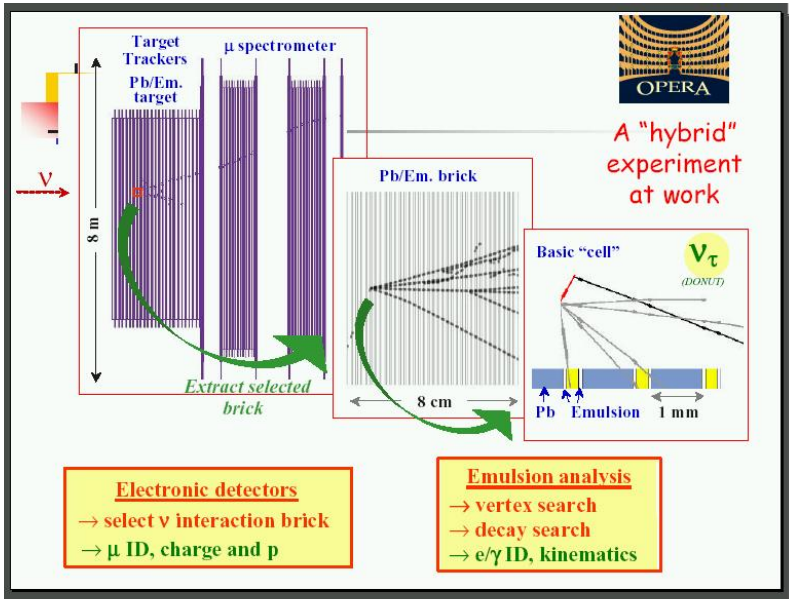
The OPERA Collaboration
(13 Countries, 35 Institutions, ~ 200 members)

Belgium
IIHE(ULB-VUB) Brussels
Bulgaria
Sofia
Croatia
IFB Zagreb
France
LAPP Annecy, IPNL Lyon,
IRES Strasbourg
Germany
Hamburg, Münster, Rostock
Israel
Technion Haifa
Italy
Bari, Bologna, LNF Frascati,
L'Aquila, LNGS, Naples Federico II,
Padova, Rome Sapienza, Salerno
Japan
Aichi, Nagoya, Kobe,
Toho, Utsunomiya
Korea
Gyeongsang Jinju
Russia
INR Moscow, LPI Moscow,
ITEP Moscow, SINPMSU Moscow,
JINR Dubna, Obninsk
Switzerland
Bern, Neuchâtel, ETHZ Zurich
Tunisia
UPHNE Tunis
Turkey
METU Ankara

CERN to Gran Sasso Neutrino Beam



Emulsion Cloud Chamber

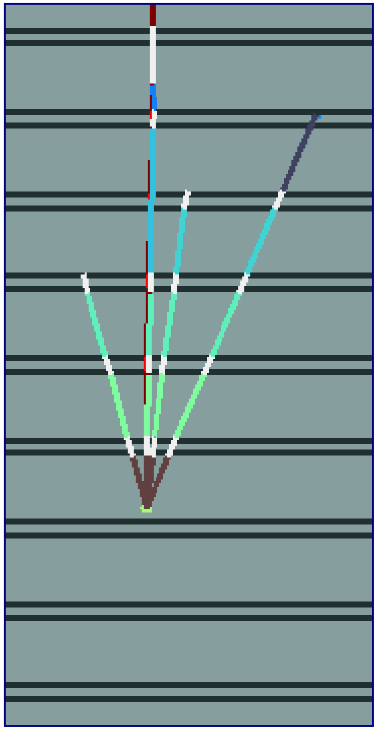


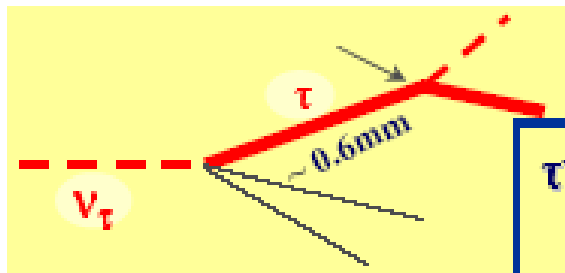
OPERA : Goals

Physics goals:

- Verify oscillation of ν_μ **is to** ν_τ
- **Search for ν_e appearance**

CNGS L/E = 0.04km/MeV (17GeV E_ν)

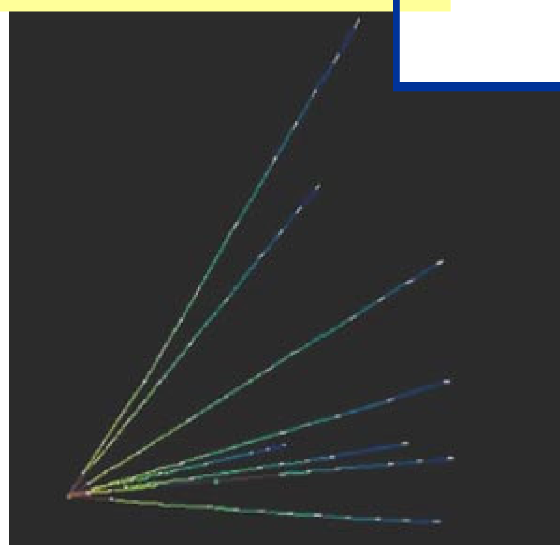




τ^- ↳ :
- $\mu^- \nu_\tau \nu_\mu$ (17.4%)
- $e^- \nu_\tau \nu_e$ (17.8%)
- $h^- \nu_\tau\ n\pi^0$ (49.5%)

} *Kink*

- $\pi^+ \pi^- \pi^- \nu_\tau\ n\pi^0$ (14.5%) *Multiprong*

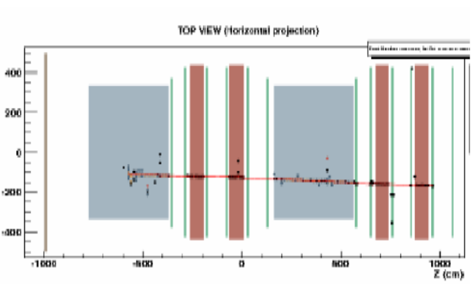


ν_μ interaction vertex from test exposure at NuMI beam (FERMILAB):

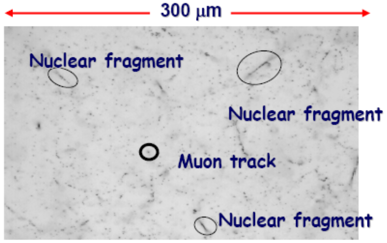
October 2 2007 : First neutrino interaction in the emulsion bricks of the OPERA Experiment! (Many more recorded since then)

OPERA : Emulsion Data

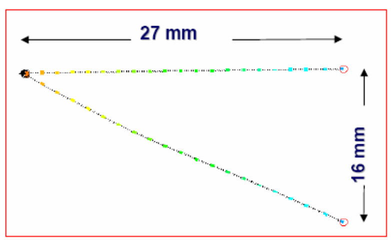
- Now 10100 on-time events and 1700 candidate interactions in emulsion target.
- In located event sample 2 charm candidates with an expectation of ~2



300 μm

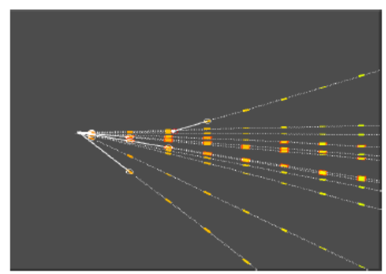


Event 179673325 QE-like topology

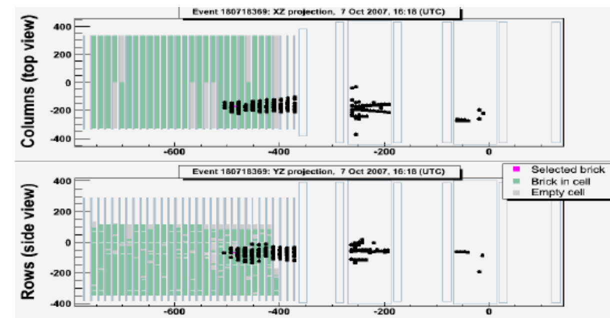


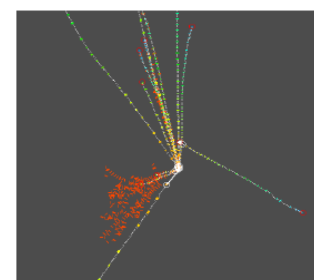
The visual inspection allows the observation of nuclear fragments and the classification of the event as DIS

…a charm candidate!



Flight lenght: 3247.2 μm
θ_{kink}: 0.204 rad
$P_{daughter}$: 3.9 (+1.7 -0.9) GeV
P_T: 796 MeV (> 606 MeV)



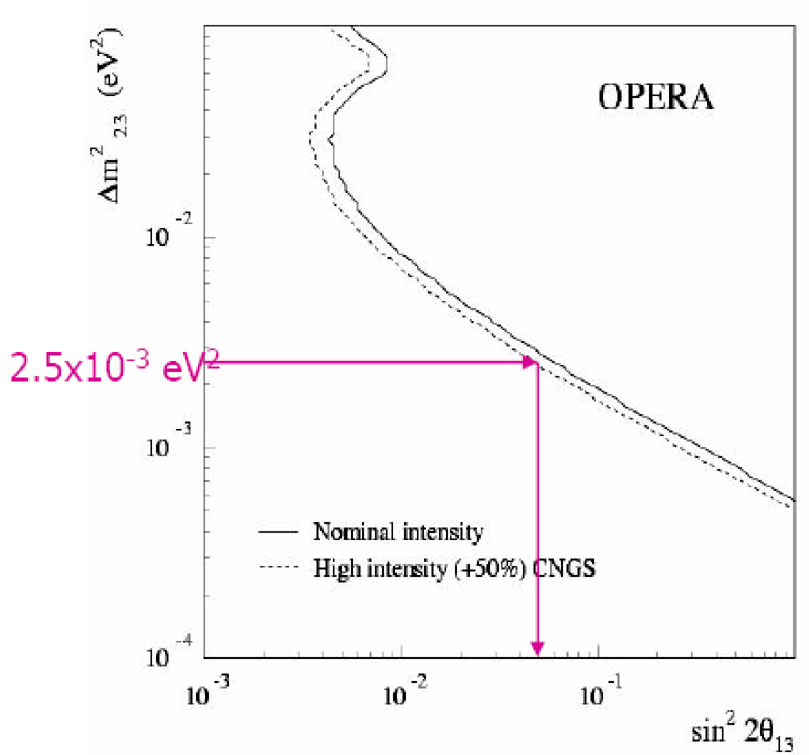


Two e. m. showers pointing to vertex

OPERA : Status + Prospects

10 events expected with 1 bkg. after 5 yrs **(4.5×10^{19} pots/year, 1.35 kton target mass)**

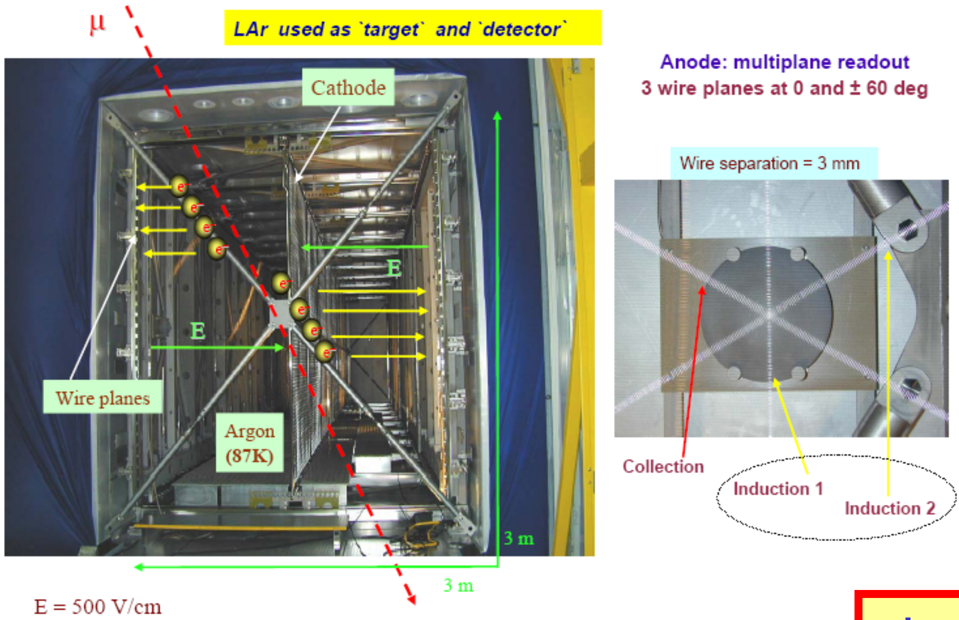
2008 CNGS Run : 2.4-2.6 x 10^{19} pots, 1.2 ν_τ events expected!

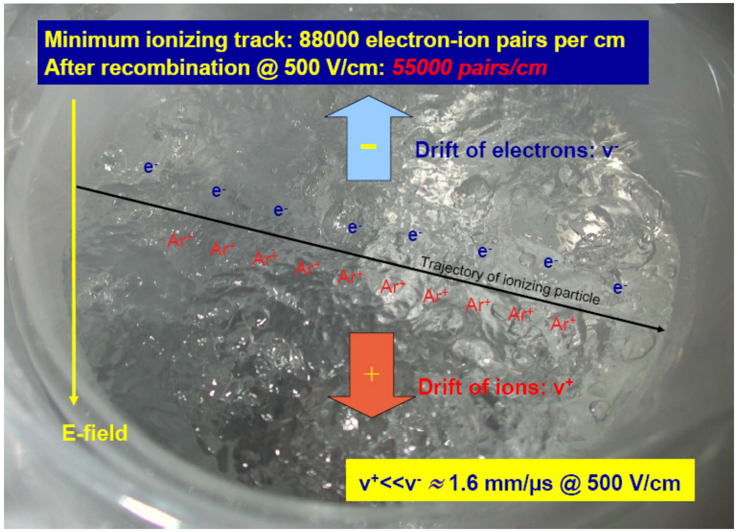


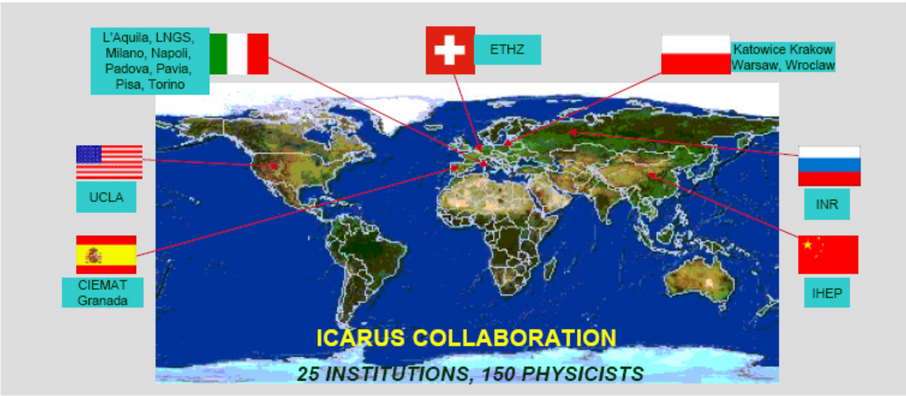
τ Decay Channels	Signal	Background
$\tau \to \mu$	2.9	0.17
$\tau \to e$	3.1	0.17
$\tau \to h$	3.5	0.24
$\tau \to 3h$	0.9	0.17
ALL	10.4	0.76

θ_{13}	Signal	ν_e Beam	$\tau \to e$	ν_μ CC	NC
9^0	9.3	18	4.5	5.2	1.0
7^0	5.8	18	4.5	5.2	1.0
5^0	3.0	18	4.5	5.2	1.0

ICARUS (T600)







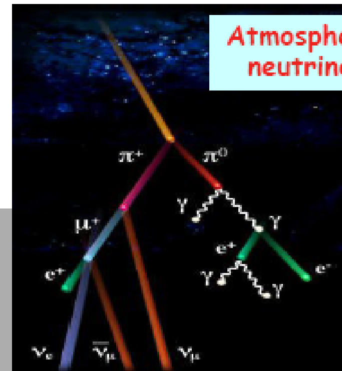
- Ionization electrons drift (msec) over large distances (meters) in a volume of highly purified liquid Argon (0.1 ppb of O_2) under the action of an E field.
- With a set of wire grids (traversed by the electrons in ~ 2-3 μs) one can realize a massive, continuously sensitive electronic “bubble chamber”.

ICARUS (T600) : Goals

1) **Prove a very promising detector technology for next generation neutrino oscillation and proton decay experiments…**

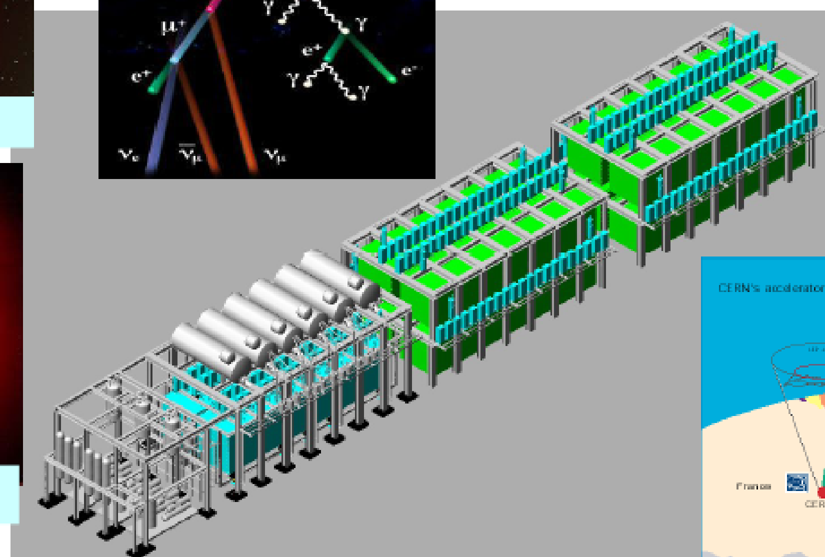
2) **…While doing interesting physics**

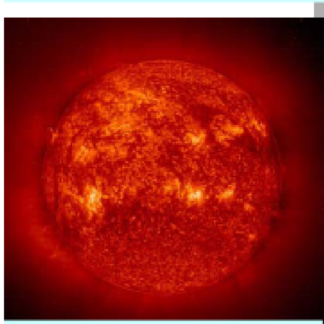
Supernova neutrinos



Atmospheric neutrinos

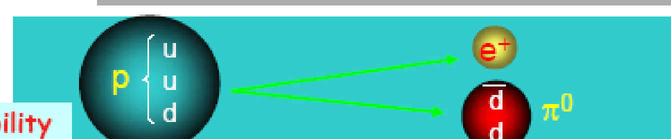
A modular approach :
T600 + T1200 +T1200
to reach the design mass





Solar neutrinos

Long Baseline neutrinos



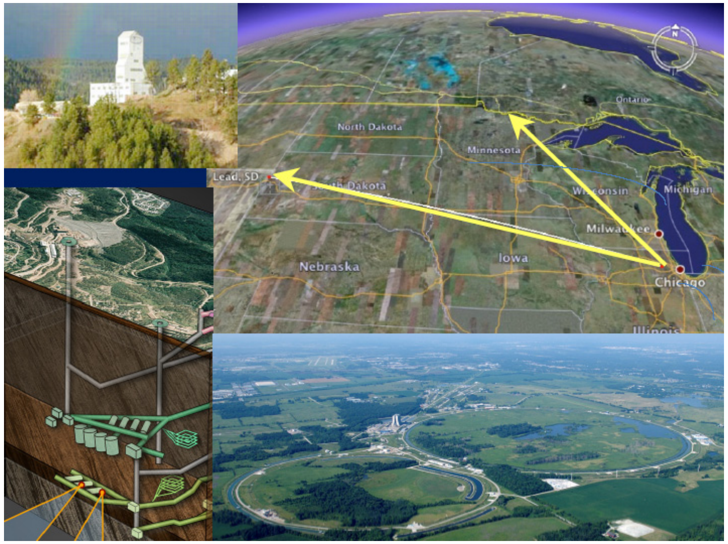
Nucleon stability

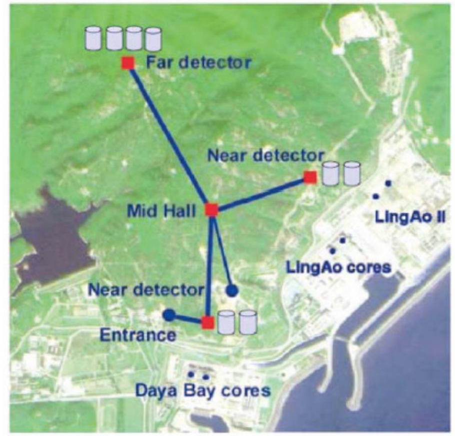
ICARUS T600 : Status and Prospects

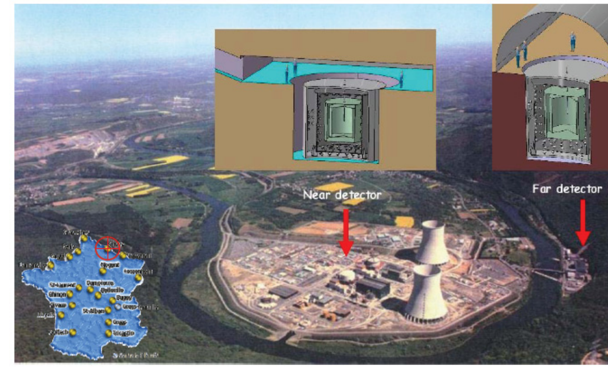
- Straight chimneys mounting
- Extraction of cables/fibers
- Detector inspections (man-holes)
- HV feed-throughs mounting
- Diffusion pipes for LAr (new)

Start taking Data within the coming year!

The "cross–mixing" ν sub-matrix : The big unknown!!







$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U^{*}_{e(\mu)(\tau)i}\,\nu_i$$

"Cross Mixing"

"Atmospheric" "Solar" "0nbb decays"

$$U= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana phases

ν_μ -> ν_e oscillations : Sub-dominant effect and many parameters in play

To a good approximation oscillation probability:

$$P(\nu_\mu -> \nu_e) \cong \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 - \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4$$

$$\alpha = \frac{\Delta m^2{}_{21}}{\Delta m^2{}_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$ **CP Violating**

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$ **CP Conserving**

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

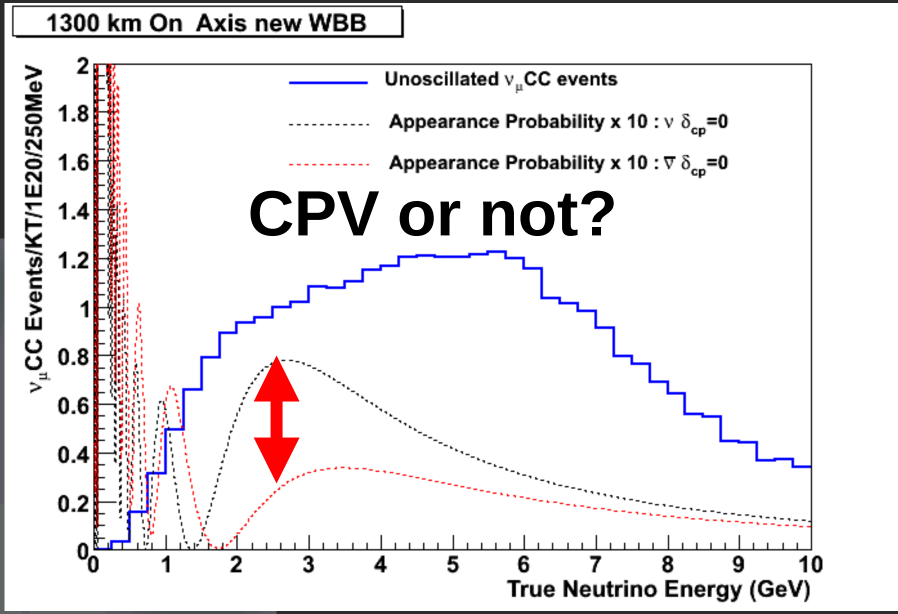
$$\Delta = \frac{\Delta m^2{}_{31} L}{4E_\nu} \qquad x = \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2{}_{31}}$$ **Matter Effects**

Degeneracies (ghost solutions) …

Oscillation Probability **depends on**, at least, 3 parameters

θ_{13} , δ_{cp}, sign(Δm^2_{31})

Multiple Combinations of the 3 parameters can yield the "same" number of events, especially if parameters are "doing" similar things (like CPV and matter effects)



WHAT DO WE NEED :

a) Large Number of neutrinos since we know the effects are small ($\theta_{13} < 11^0$)

b) Multiple measurement of number of events as a function of energy , E , and as a function of distance, L.

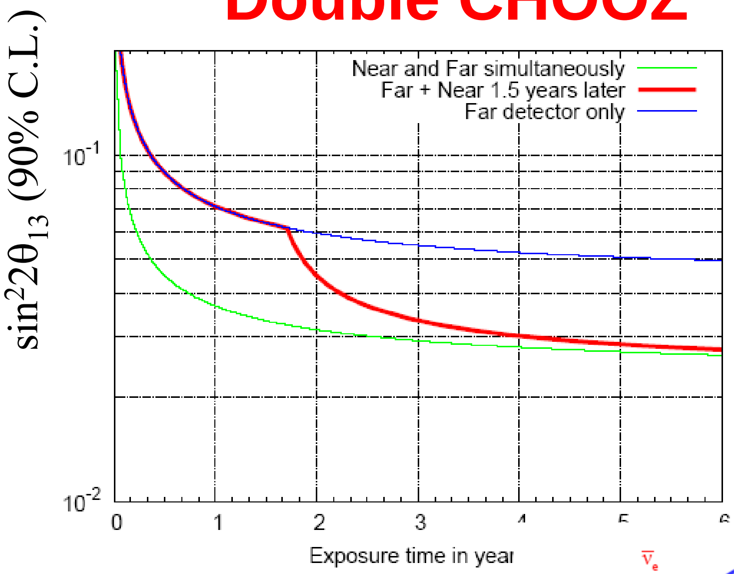
c) Longer Baselines to enhance matter effects

d) Nature to be kind to us !!!

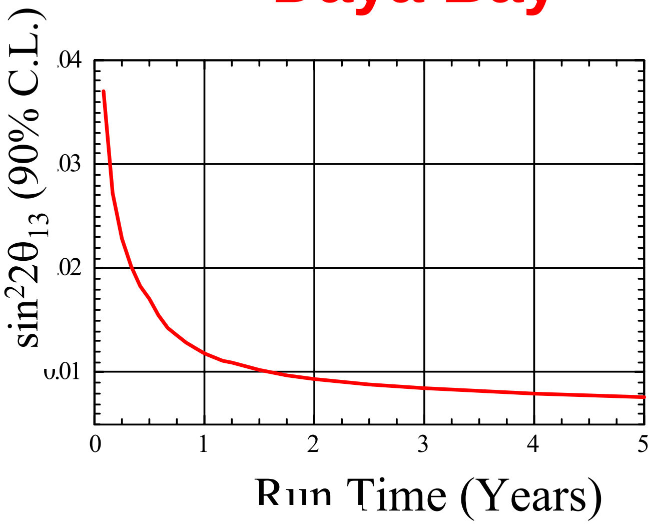
Hunt for a non-zero θ_{13} "cleanly": PhaseI

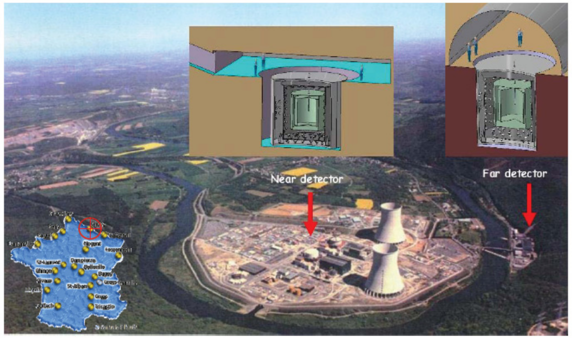
Reactor Experiments

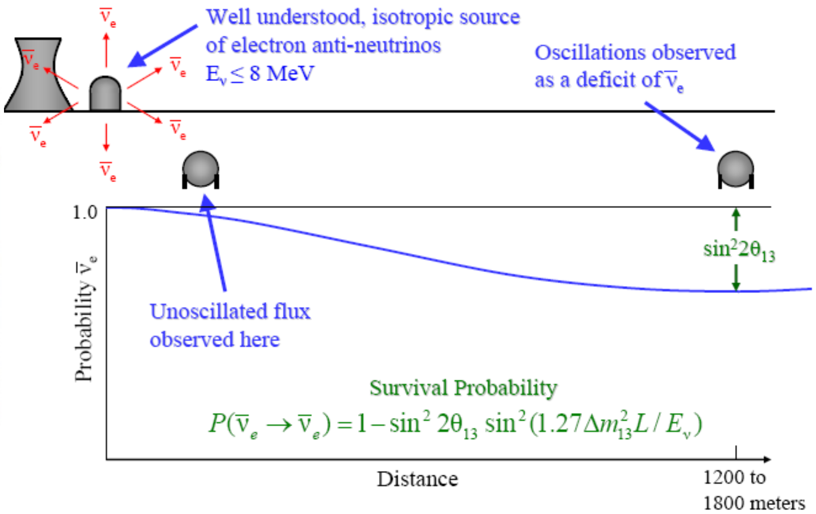
Double CHOOZ

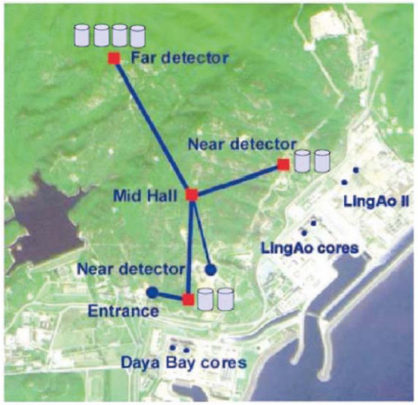


Daya Bay



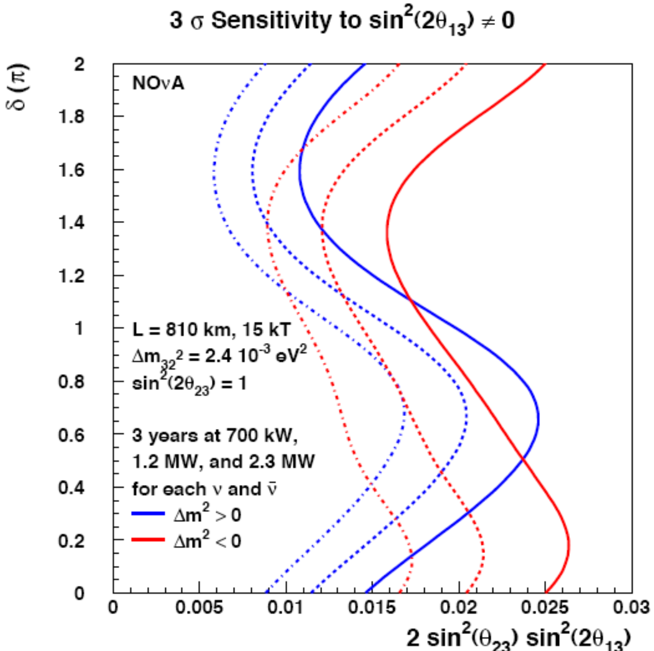




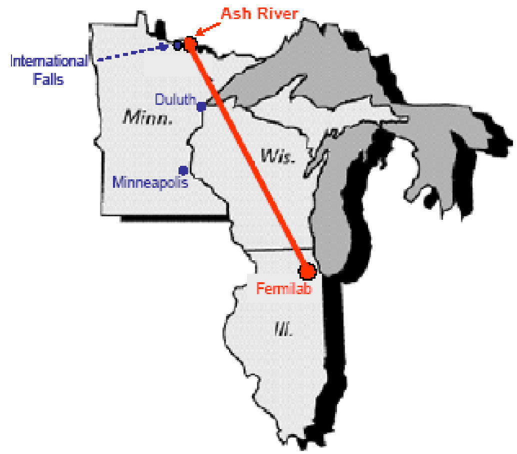


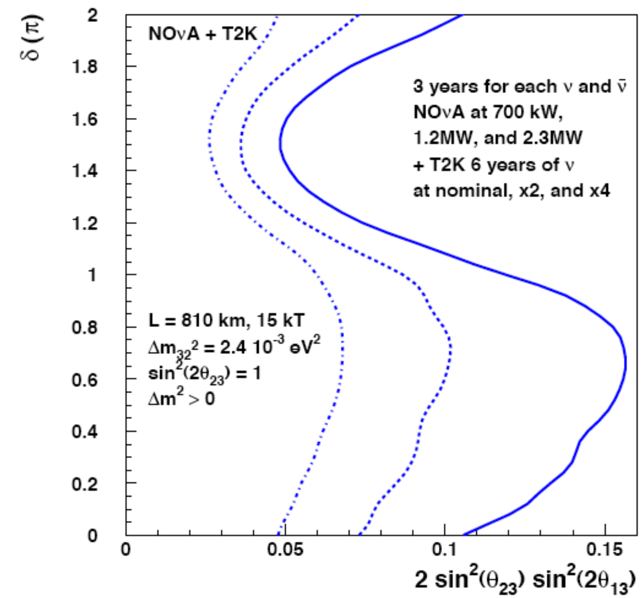
Hunt for a non-zero θ_{13} +more : PhaseI

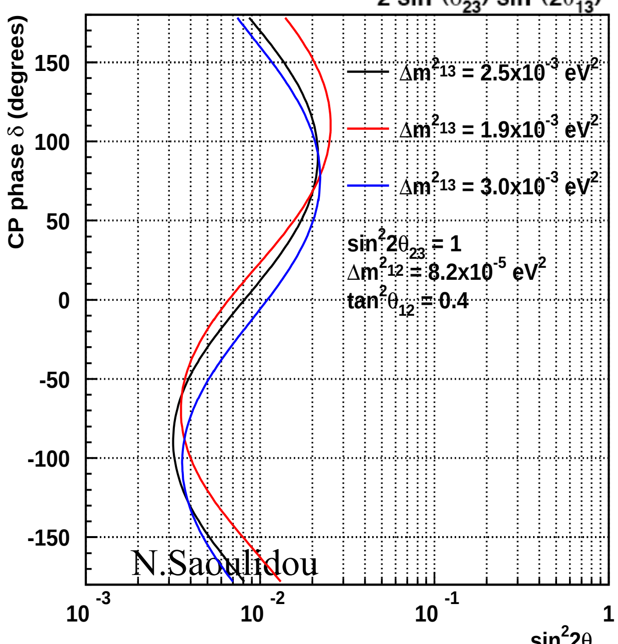
Accelerator Experiments : NOvA & T2K



NOvA







T2K

BONUS from NOvA Experiment : **Depending on the value of the third mixing angle NOvA is the only Phase I experiment that could determine the neutrino mass hierarchy**

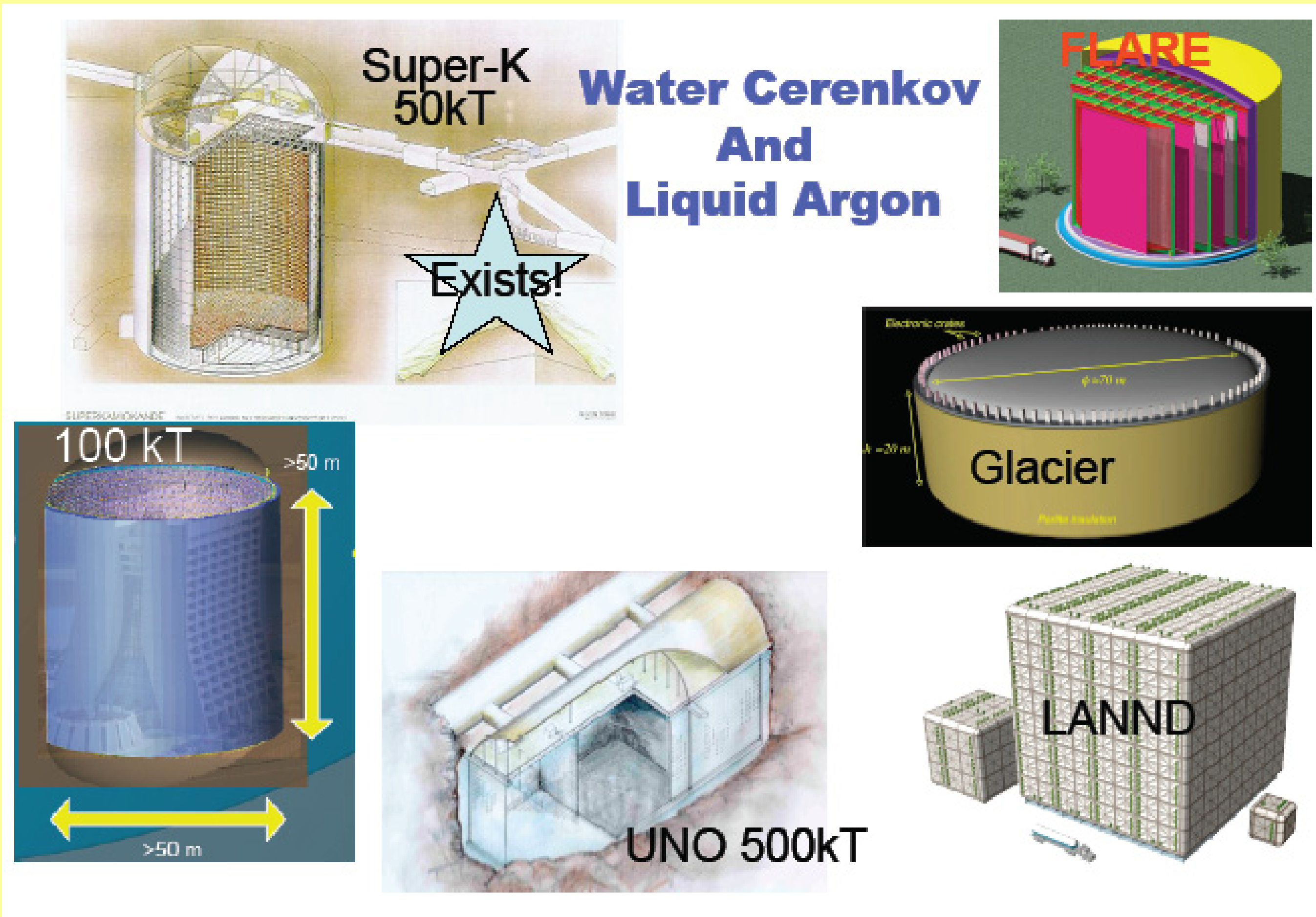
Measure CPV, extend θ_{13} reach, extend ν mass hierarchy reach: Phase II

Numerous studies world-wide over the past several years have studied strategies to achieve the goals of PHASE II and came to the same conclusions. One needs:

- Massive cost effective detectors that are larger than those of Phase I (> 20 KT)
- Intense neutrino beams with intensity possibly higher than that of Phase I (> 700 KW)
- The ability to break inherent degeneracies between genuine CP violation and "Fake CP violation" from matter effects.

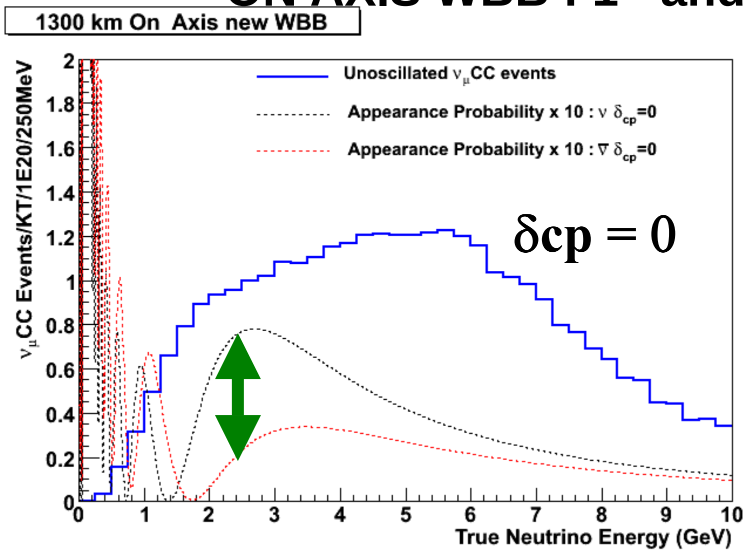
Ingredients for achieving the goals of Phase II : Massive Detectors

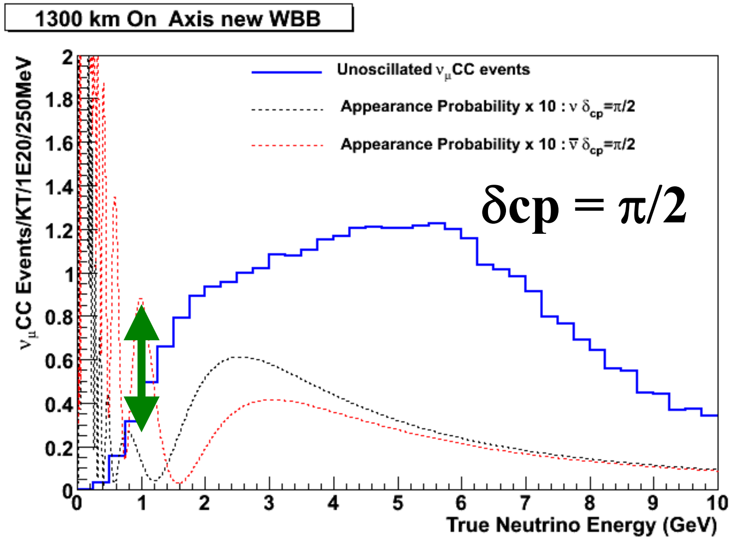
Massive Detectors (Liquid Argon,Water Cherenkov, Liquid Scintillator, etc) that are scalable in the Multi Kt scale



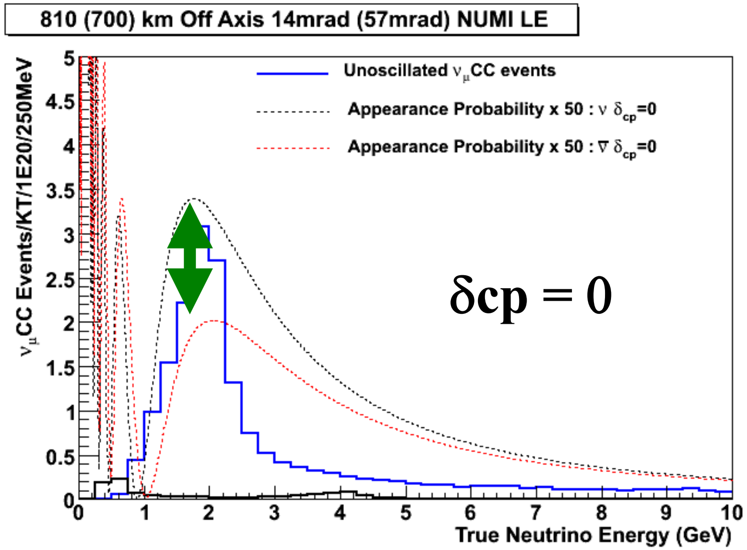
Wide vs Narrow Band Neutrino Beam

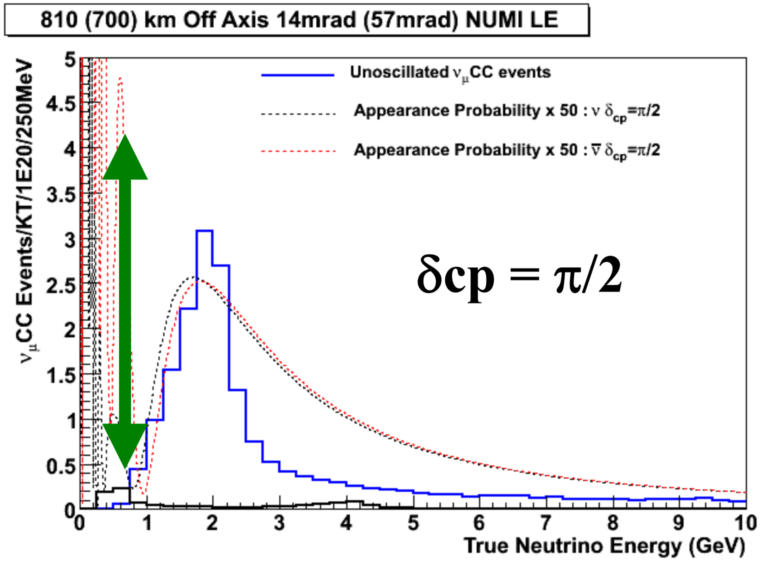
ON AXIS WBB : 1st and 2nd Oscillation Maxima 1 Detector





OFF AXIS NBB : 1st and 2nd Oscillation Maxima 2 Detectors





Ingredients for achieving the goals of Phase II: Powerful Neutrino Beams, JPARC

Plan for Improving Neutrino Beam Intensity by Main-Ring Upgrade

Slide by A.Suzuki, KEK Roadmap Review Committee, March 2008

Assumed in most part of this talk

Linac : 181 MeV to 400 MeV

0.60MW
0.28 Hz → 0.91 MW
0.57 Hz → **1.66MW**
0.52 Hz

- Shorten acceleration time
- More RF system
- Magnet power system

- More beam per pulse
- Operation of 3 GeV RCS in harmonic number =1

Ingredients for achieving the goals of Phase II: Longer Baseline Tokai->Korea

Direction: J-PARC neutrino beam

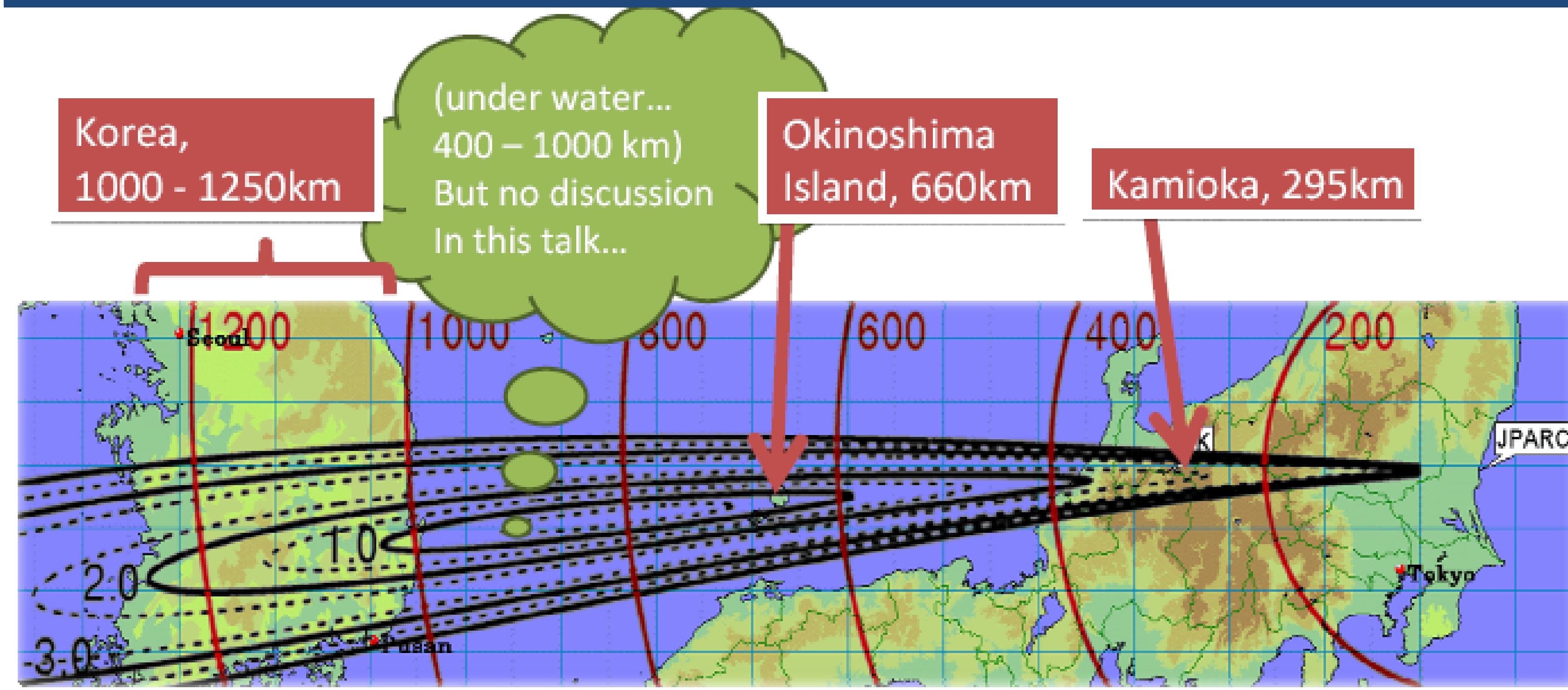
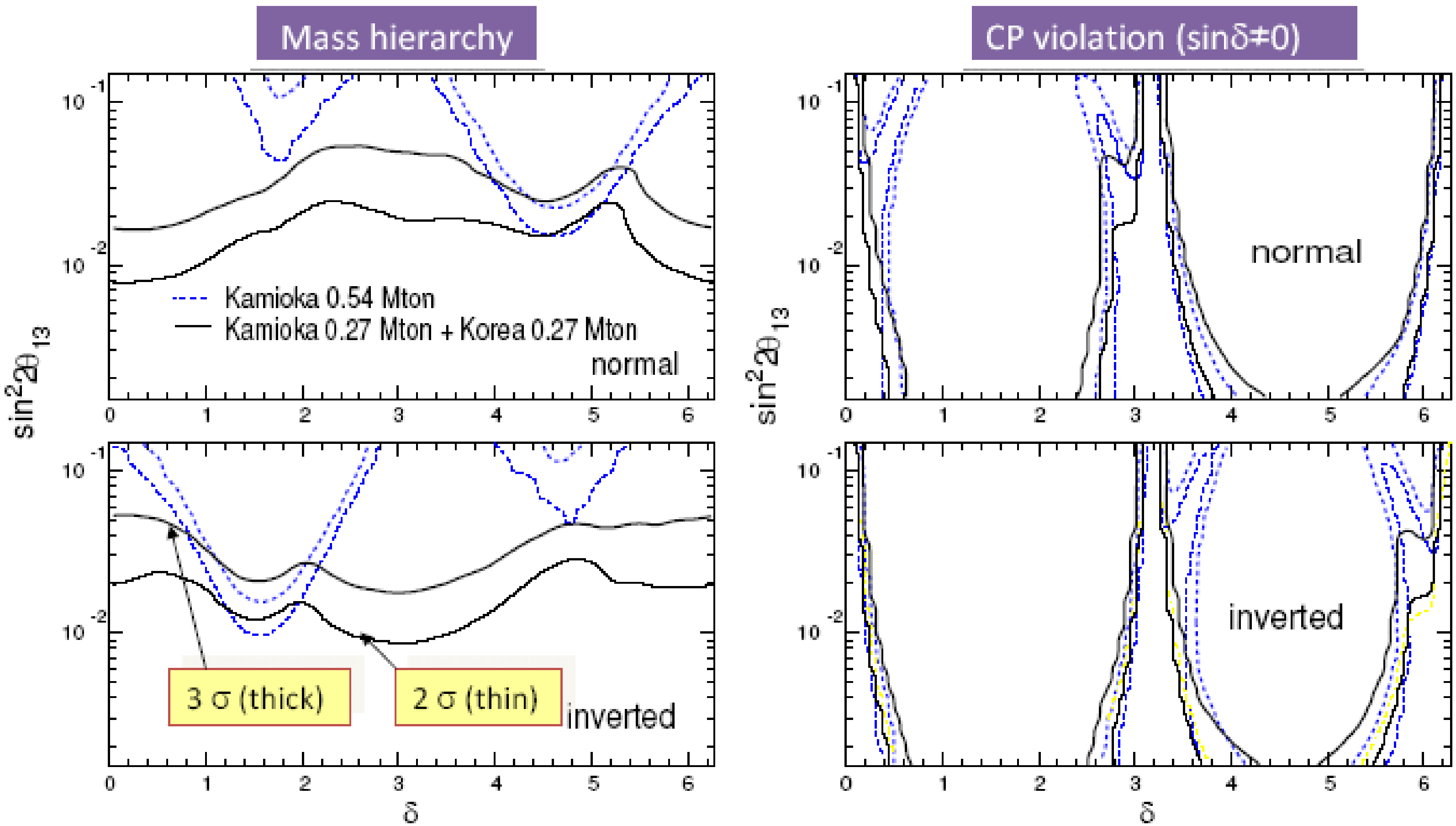


Fig: Senda NP04

Physics Reach : JPARC with two 0.27 Mton WC in Kamioka and Korea

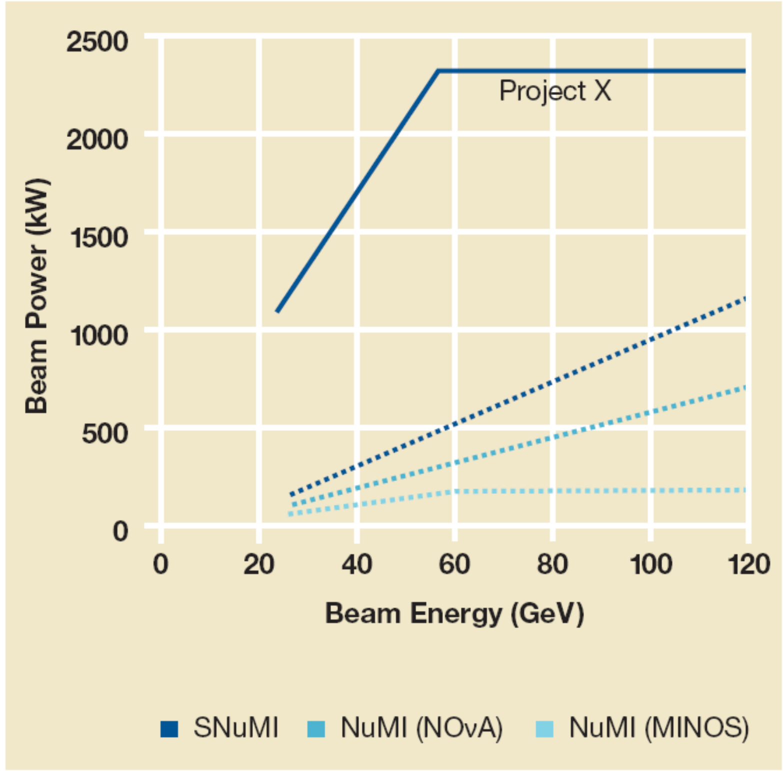
hep-ph/0504026

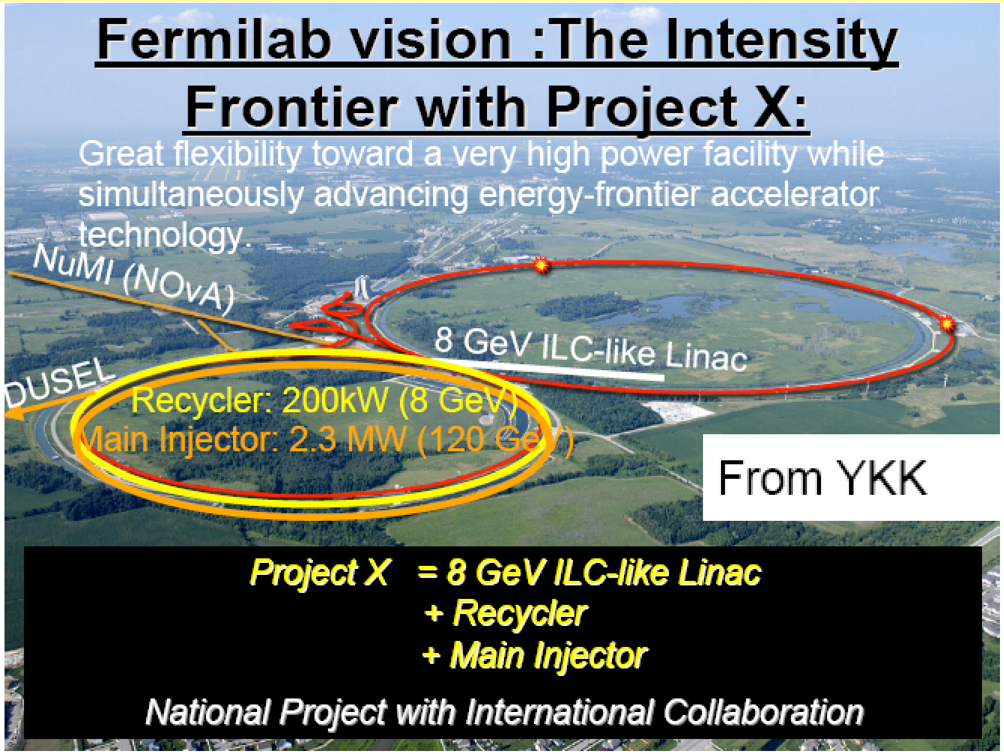
0.27 Mton fid. Mass at Kamioka and Korea (water Ch)
4 years ν beam + 4 years anti-ν beam, 4MW, 2.5 deg Off-axis



Ingredients for achieving the goals of Phase II : Powerful Neutrino Beams, US (FNAL)

Powerful ν beams of very high intensity Project X

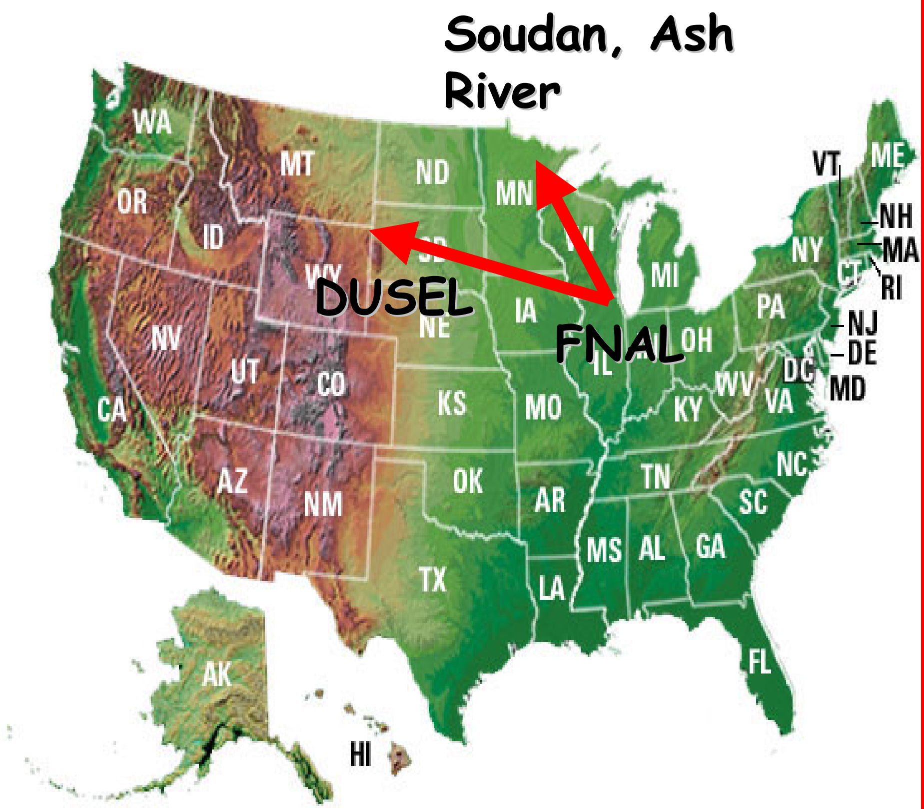




Two options for neutrino beams and experiment baselines exist:

Ingredients for achieving the goals of Phase II :

Longer Baseline FNAL->Ash River, FNAL-> DUSEL



(A) L ~800 Km and NuMI Off Axis Narrow Band Beam.

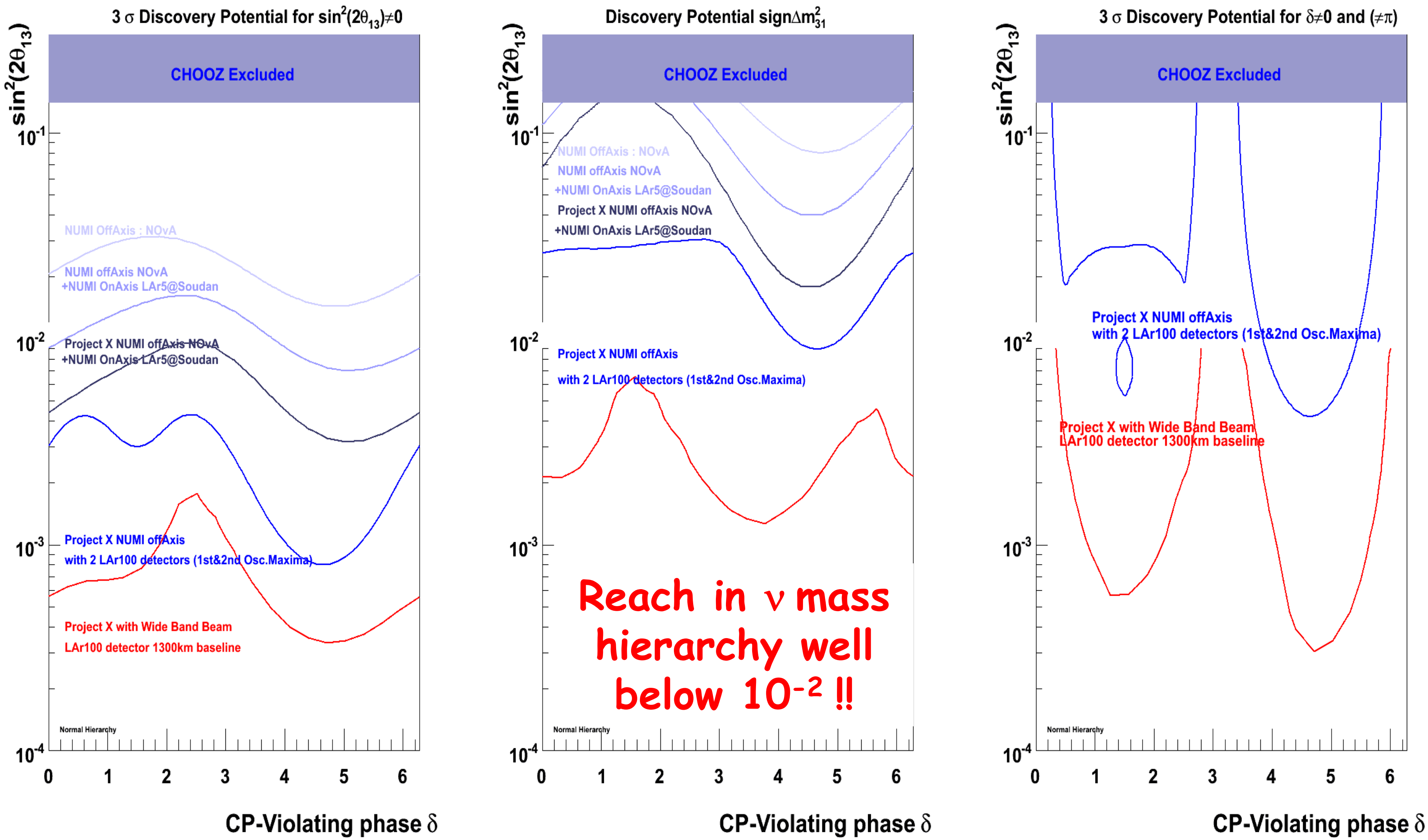
(B) L ~ 1300 Km (FNAL -> *DUSEL*)

New Wide Band Beam (On or off Axis)

Implications on ν beam :

New beam has to be designed and constructed ***(beginning design considerations)***

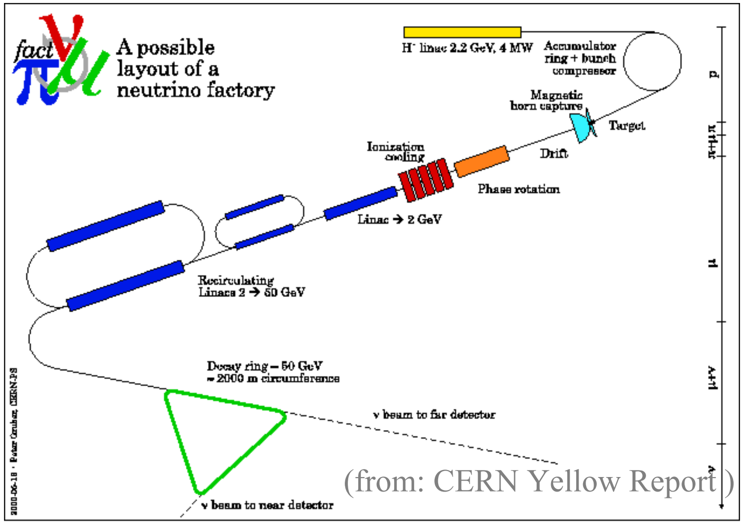
Physics Reach : FNAL to DUSEL with 0.1 Mton LAr



NOvA - NOvA+5ktLAr - NOvA+5ktLAr+PX - NOvA+100kt LAr +PX
100ktLAr (OR 300kt WC) +New WBB+PX at DUSEL

What if θ_{13} too small? We can still dream…

Neutrino Factory



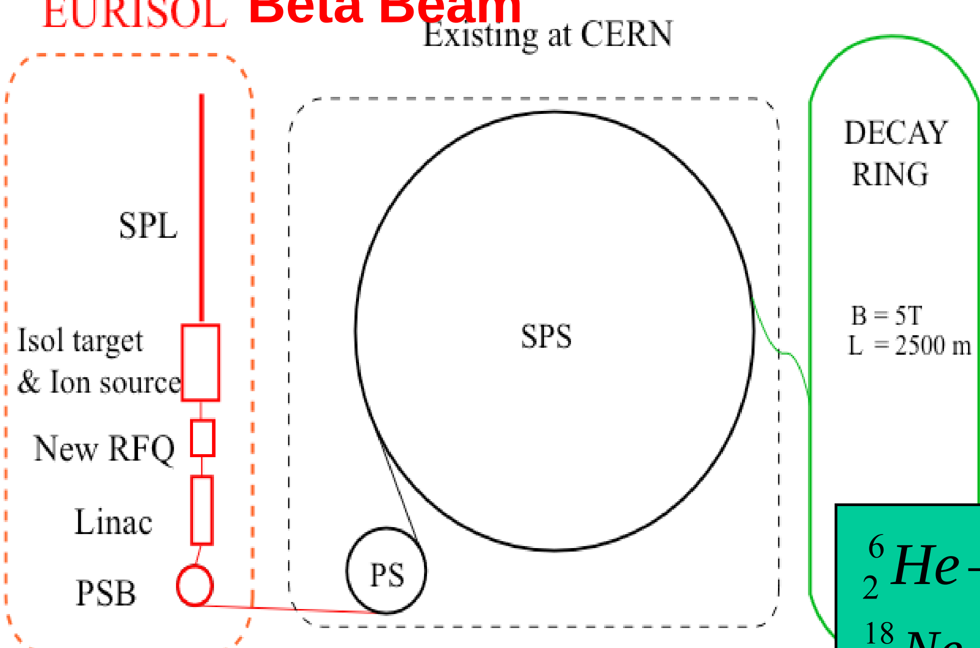
$\mu^- \rightarrow e^- + \bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ "Wrong sign"

$+ \nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$ "Right sign"

$\mu^+ \rightarrow e^+ + \nu_e \rightarrow \nu_\mu \rightarrow \mu^-$ "Wrong sign"

$+ \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ "Right sign"

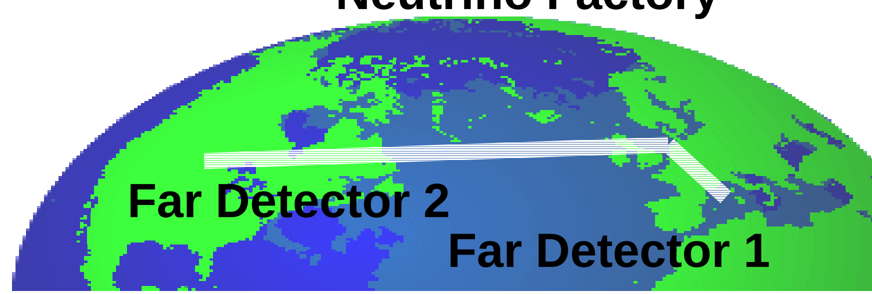
EURISOL Beta Beam



$$ {}^{6}_{2}He \rightarrow {}^{6}_{3}Li\ e^- \bar{\nu} $$

$$ {}^{18}_{10}Ne \rightarrow {}^{18}_{9}Fe\ e^+ \nu $$

Neutrino Factory



W.Pauli
Nobel Prize 1945

But only the one who dare can win

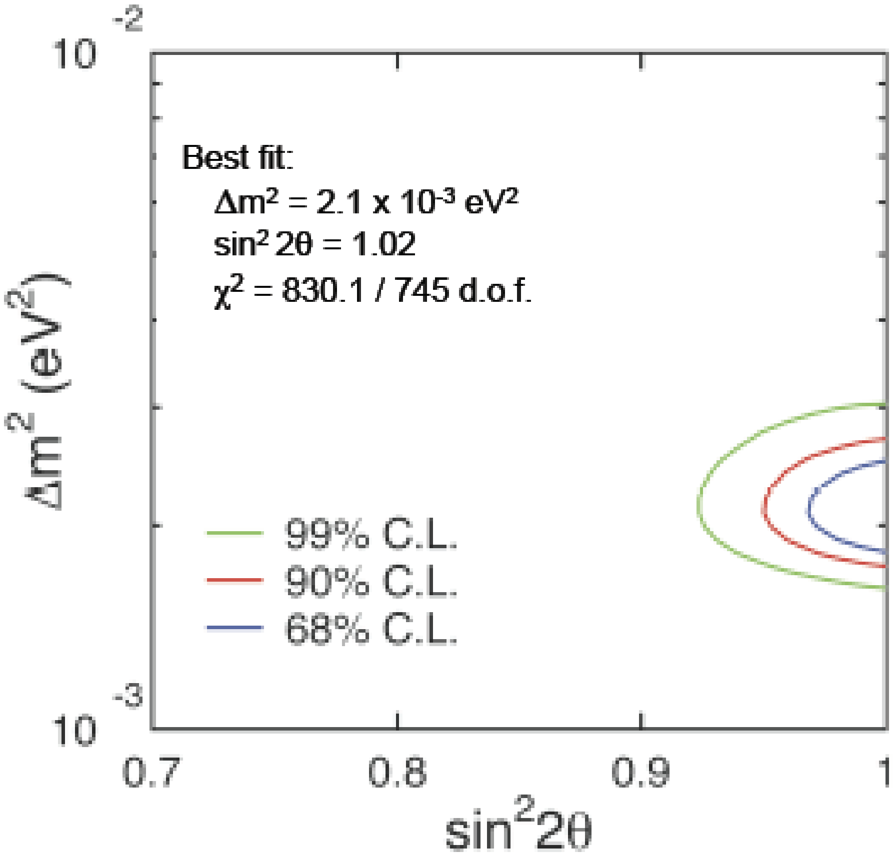
Summary and Conclusions

- So far the behavior of the "little neutral one" has been full of many "big" surprises…
- Some of the questions in neutrino physics have been answered and are answered as we speak, but the remaining ones are more challenging.
- Running and future experiments worldwide aim to address many of these remaining important issues with respect to neutrino physics and neutrino oscillations.
- Stay tuned for the fascinating νews to come..

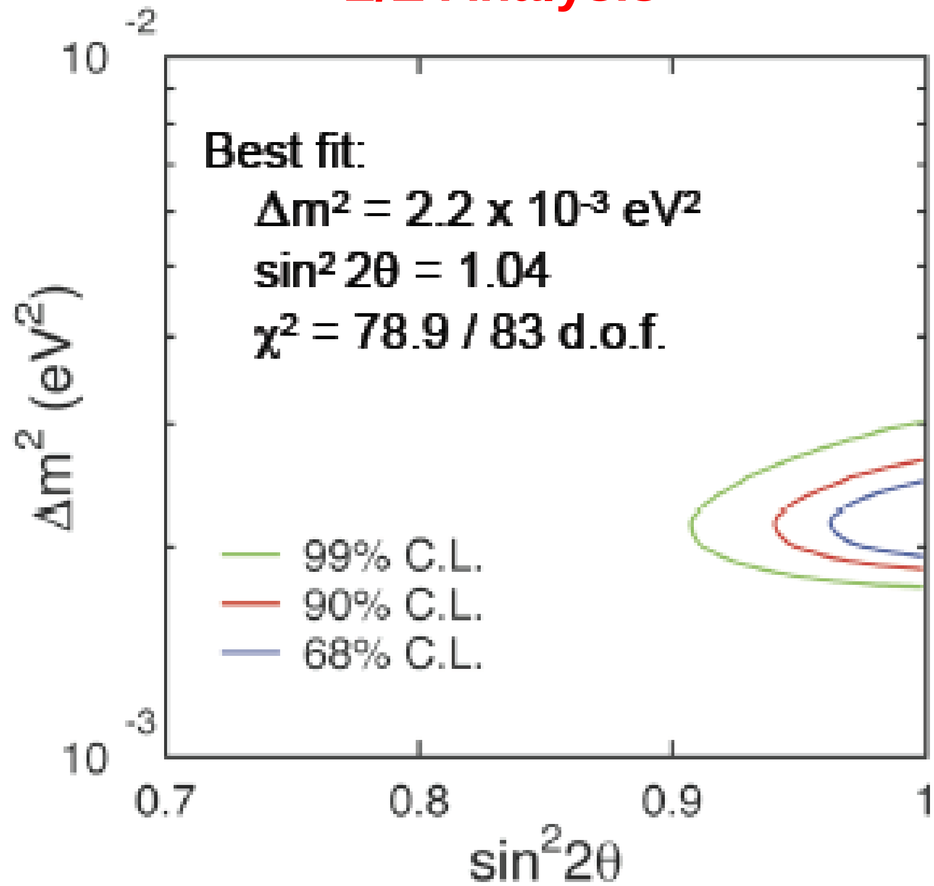
BACKUP SLIDES

Super-Kamiokande : SKI+SKII

Zenith Angle Analysis



L/E Analysis



J.Raaf Neutrino 2008

Open Questions with solar νews

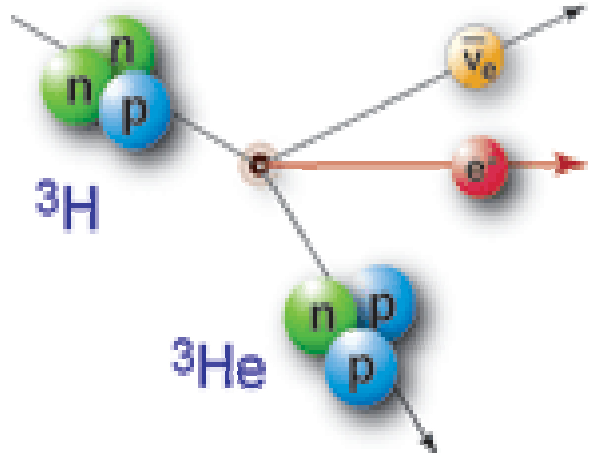
- How large is ^{7}Be neutrino flux?
  - BOREXINO
  - KamLAND
- Is ^{8}B spectrum distorted as expected from LMA solution?
  - SK-III plan to measure with lower energy threshold
  - SNO data analysis with lower threshold
- pp neutrinos by real time experiments?
  - Future experiments (LENS, XMASS, CLEAN …).

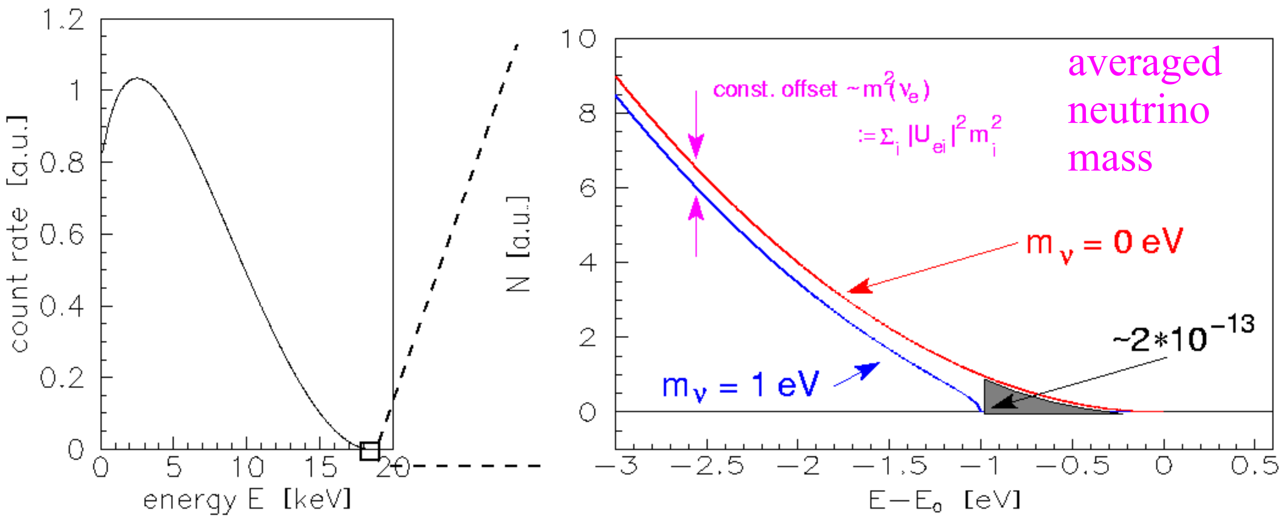
β Decay Experiments, were it all started… Absolute ν mass

$$(A,Z) \rightarrow (A,Z+1) + e^- + \nu_e$$

$$\frac{dN}{dE} \sim \sqrt{\left[(E_o - E_e)^2 - m^2{}_{\nu i}\right]}$$

$$m^2{}_{\nu_e} = \sum_{i=1}^{3} |U_{ei}|^2\, m^2{}_i$$



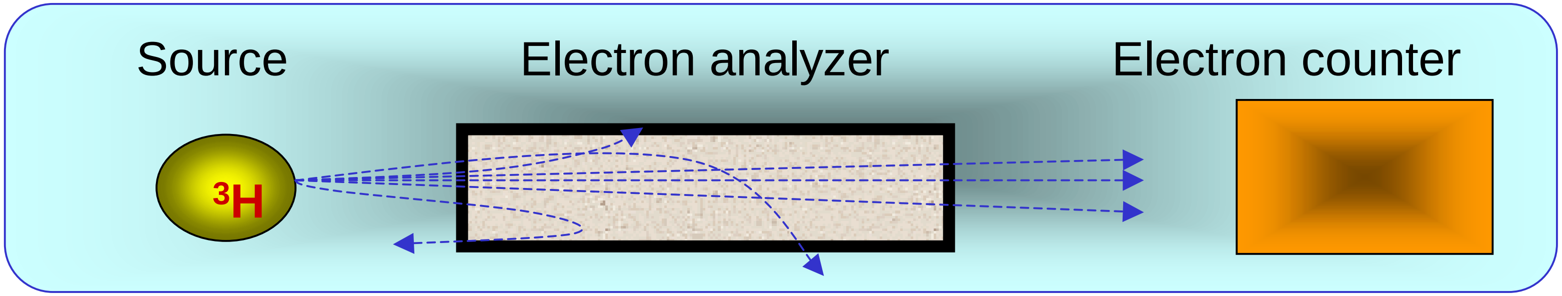


β Decay Experiments : Absolute ν mass

MAINZ: $m^2_\nu = -0.6 \pm 2.2 \pm 2.1\ eV^2$ $m_\nu < 2.3$ eV (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

Troisk: $m^2_\nu = -2.3 \pm 2.5 \pm 2.0\ eV^2$ $m_\nu < 2.05$ eV (95% C.L.)

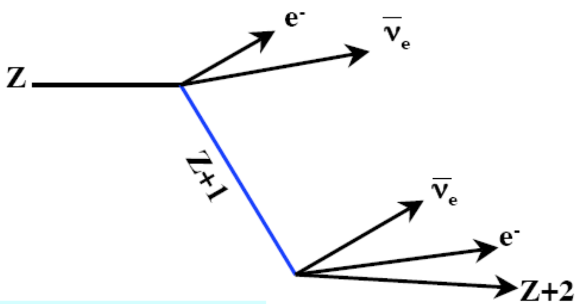


Sensitivity $m_\nu < 0.2$ eV

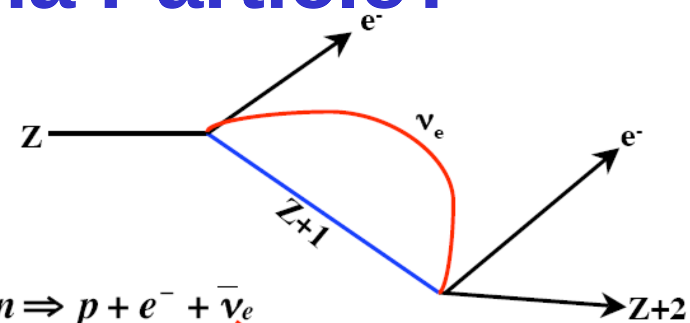
Improvement of ΔE: 0.93 eV
(4.8 eV for Mainz)
Larger acceptance
Statistics 100 days → 1000 days

Commissioning and start : 2010

$\beta\beta(0)\nu$ Decay Experiments: Dirac Or Majorana Particle?



$$2n \Rightarrow 2p + 2e^- + 2\overline{\nu}_e$$

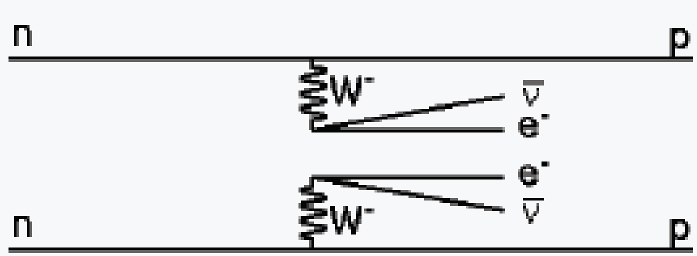


$$n \Rightarrow p + e^- + \overline{\nu}_e$$

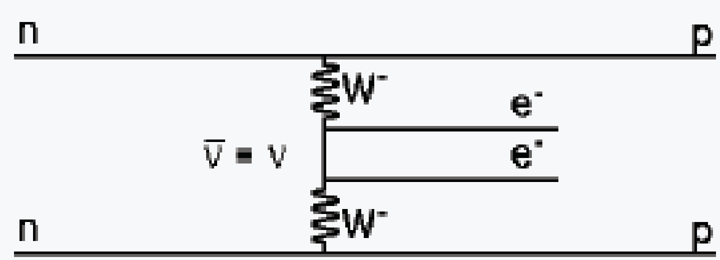
(RH $\overline{\nu}_e$) (LH ν_e)

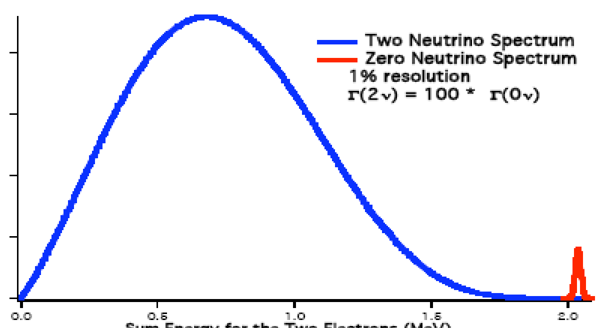
$$\nu_e + n \Rightarrow p + e^-$$

$(Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^- + \overline{\nu}_{e1} + \overline{\nu}_{e2}$



$(Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^-$

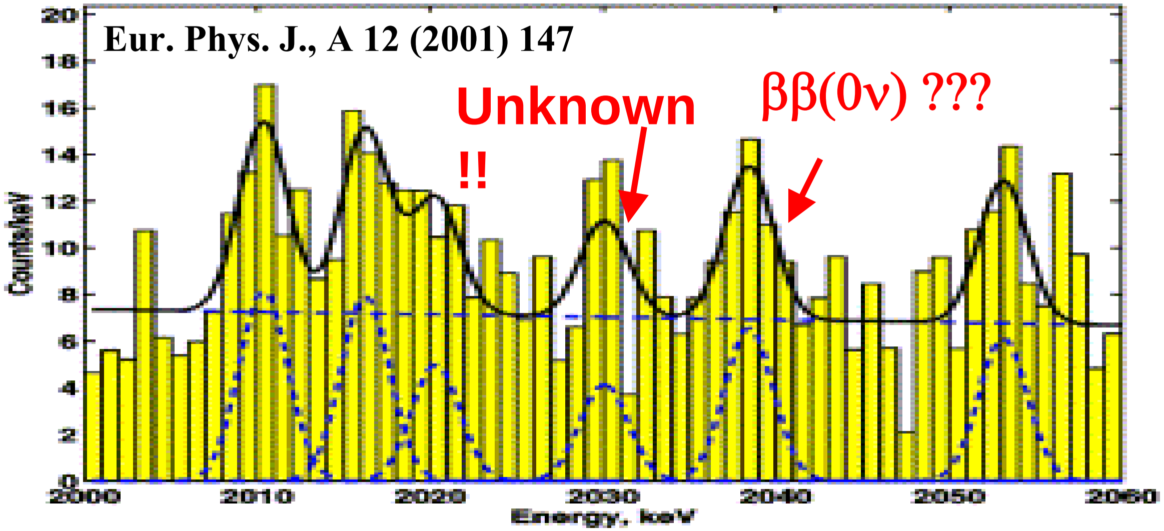




Endpoint Energy

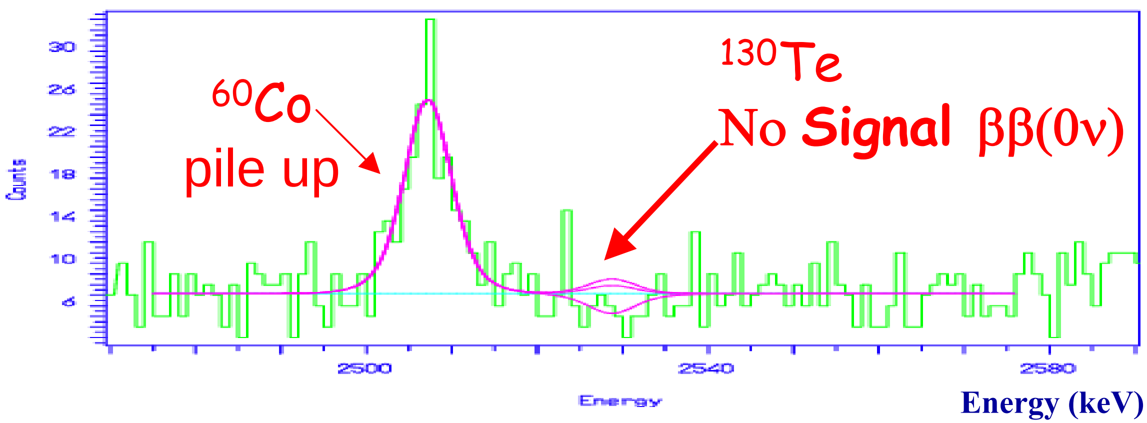
$\beta\beta(0)\,\nu$ Decay Experiments : A positive unconfirmed signal

New Analysis: > 6 σ effect



Heidelberg-Moscow
~11 kg of enriched Ge diodes in ^{76}Ge (86%)

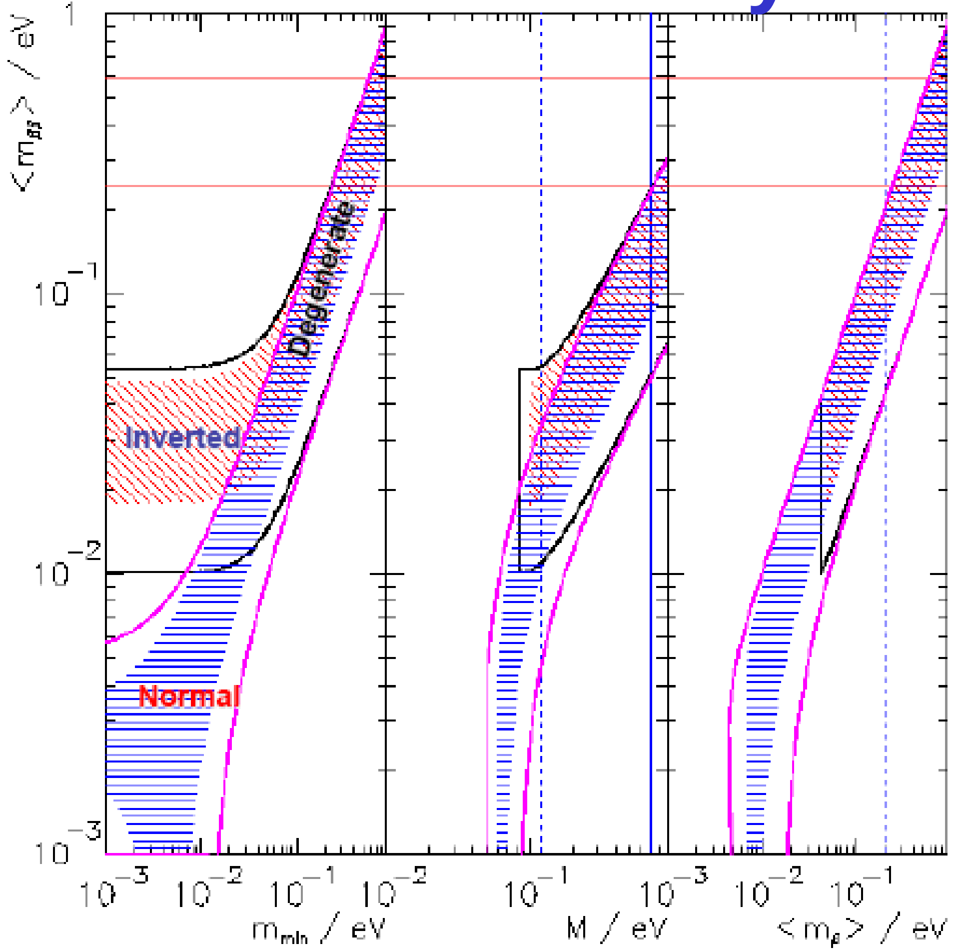
$$\langle m_\nu \rangle = 0.32 \pm 0.03 \text{ eV}$$



Cuoricino (bolometer)
~41 kg of TeO_2

$$\langle m_\nu \rangle < 0.2 - 1 \text{ eV (90\% CL)}$$

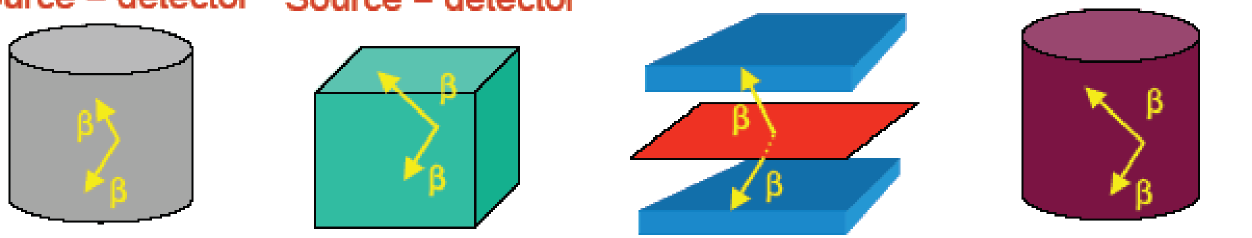
ββ(0) ν Decay Experiments: Depended on hierarchy of ν masses



If neutrino mass hierarchy is normal (need accelerator ν to study this) then measurements become « difficult »…

ββ0ν Decay Experiments: Very active field

Calorimeter	Calorimeter	Tracking + Calorimeter	Xe TPC
Semi-conductors	Loaded Scintillator	Source ≠ detector	Source = detector
Source = detector	Source = detector		



Experiment	Isotope	Enriched isotope mass (kg)	$T_{1/2}$ (yr)	$\langle m_\nu \rangle$ (eV)	Start	Status
CUORE	^{130}Te	203	2.1 10^{26}	0.03 - 0.07*	2011	Funded
GERDA phase I phase II	^{76}Ge	17.9 40	3. 10^{25} 2. 10^{26}	0.2 – 0.5* 0.07 – 0.2*	2009 2011	Funded Funded
Majorana	^{76}Ge	30 - 60	1.10^{26}	0.1 – 0.3*	2011	Funded
EXO-200	^{136}Xe	200	6.4 10^{25}	0.2 - 0.7*	2008	Funded
Super-NEMO	^{82}Se ^{150}Nd	100 100	2. 10^{26} 10^{26}	0.05- 0.09* 0.07	2011	R&D
CANDLES	^{48}Ca	0.5		~0.5	2008	Funded
MOON II	^{100}Mo	120		0.09 – 0.13	?	R&D
DCBA	^{150}Nd	20			?	R&D
SNO++	^{150}Nd	500				R&D
COBRA	^{116}Cd,^{130}Te	420				R&D

* Calculation with NME from Rodim et al., Suhonen et al., Caurier et al. PMN07

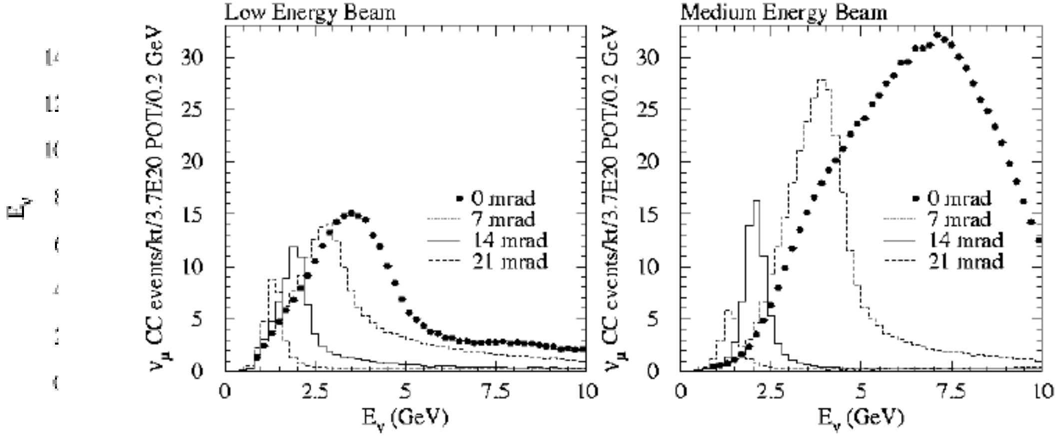
NuMI Neutrino Beam: Capabilities & Advantages

By using a conventional, albeit more intense, neutrino beam:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad < 1\% \nu_e$$

In an Off-Axis detector location

$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$



Advantages

- The Beam Exists and performs well (NUMI Beam took 6 years to be built and cost ~ 110M$)
- There is a well defined upgrade plan
- The off – axis idea of obtaining a NBB is attractive. It reduces the NC background resulting from high energy neutrinos.

ICARUS (T600) Experiment : Detector Capabilities

- **Tracking device**
  - *Precise event topology*
  - *Momentum via multiple scattering*
- **Measurement of local energy deposition dE/dx**
  - *e / γ separation ($2\% X_0$ sampling)*
  - *Particle ID by means of dE/dx vs range measurement*
- **Total energy reconstruction of the events from charge integration**
  - *Full sampling, homogeneous calorimeter with excellent accuracy for contained events*

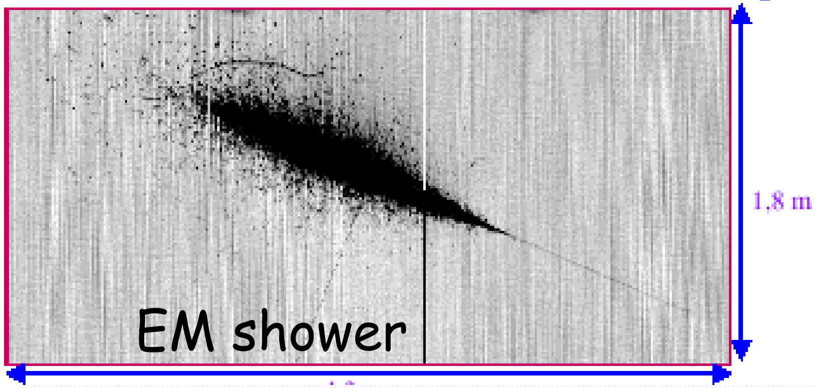
RESOLUTIONS

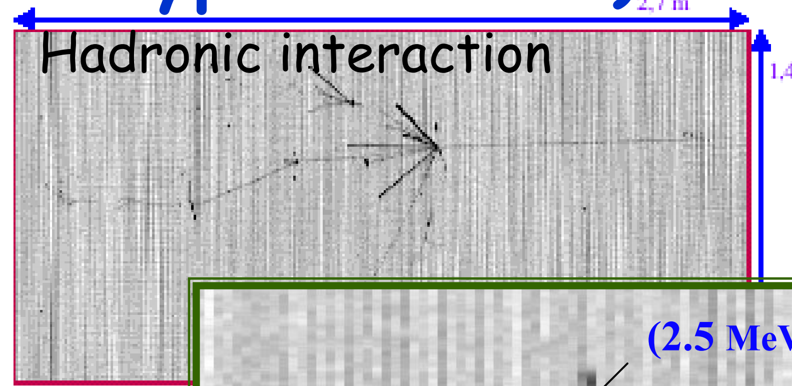
Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$

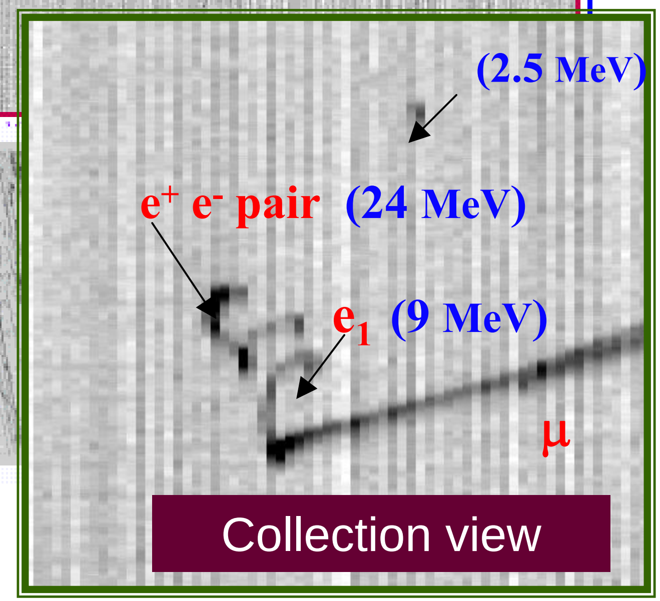
Electromagn. showers: $\sigma(E)/E = 3\% / \sqrt{E(GeV)}$

Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$

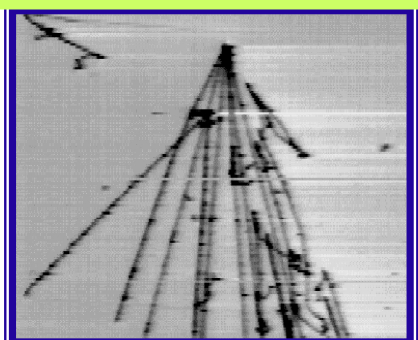
ICARUS T600 : Data (cosmics & neutrino events in a small prototype @ CERN)



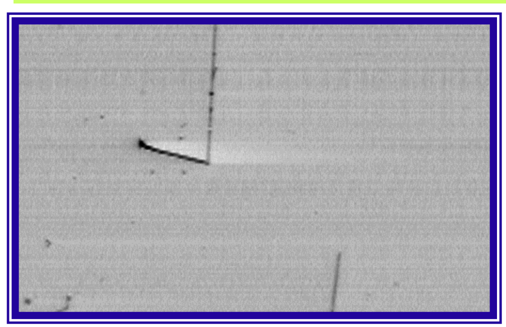




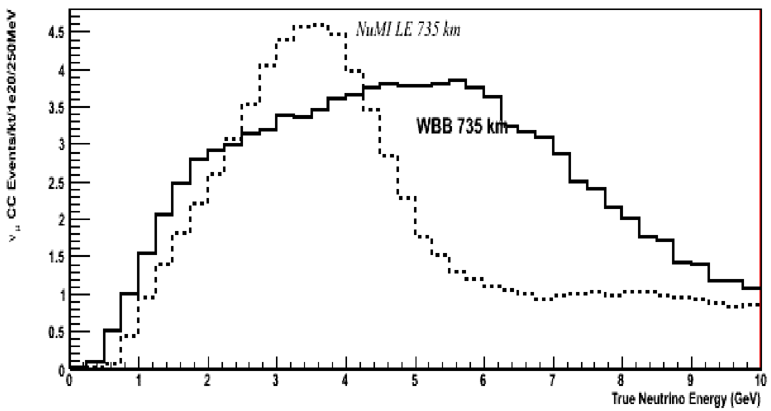
$\nu_\mu + X \rightarrow \mu^- + Shw$.

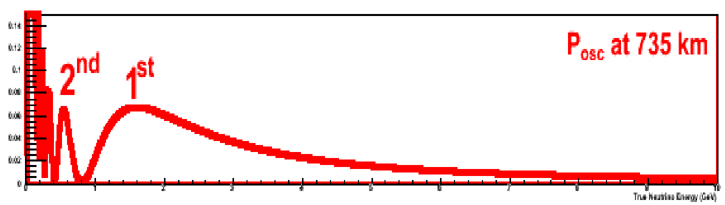


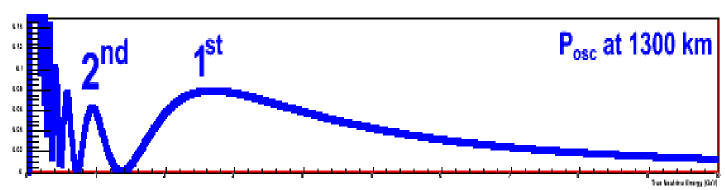
$\nu_\mu + n \rightarrow \mu^- + p$

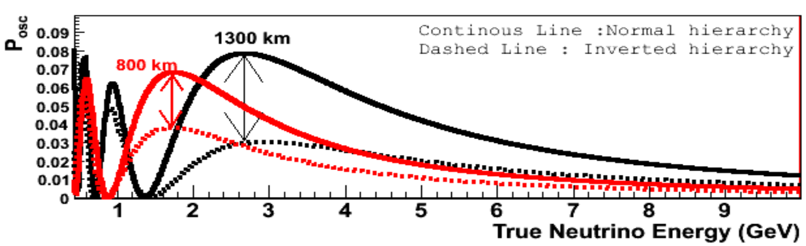


Longer baseline (>>L) AND a new Wide Band Beam









With new Wide Band Beam :

1)Increase "useful" flux (at first and second oscillation maxima)

2)With increasing L oscillation maxima "appear" in more "favourable" positions in the neutrino energy spectra

3)Thus study of first and second oscillation maxima is easier (one detector instead of two, higher rates, etc)

4) With increasing L matter effects increase and hence potential for mass hierarchy determination is increasing