”About Neutrinos and their oscillations”

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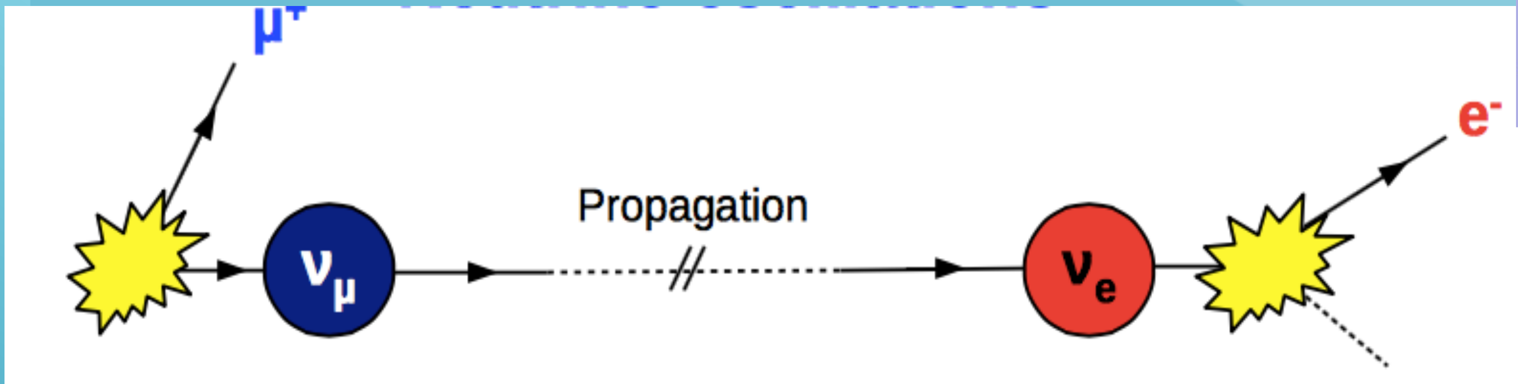
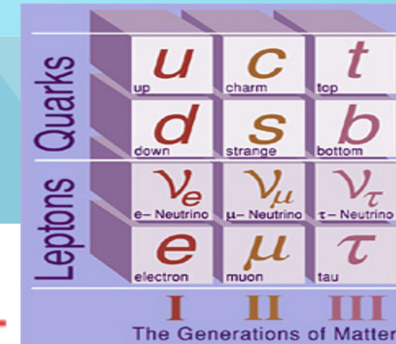
What is “oscillation”??

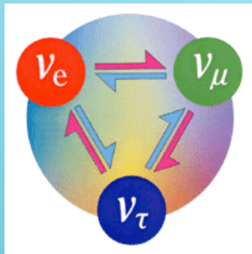




The flavour eigenstate is not the same as the mass eigenstate

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

Mixing matrix (Pontecorvo-Maki-Nakagava-Sakata=PMNS)



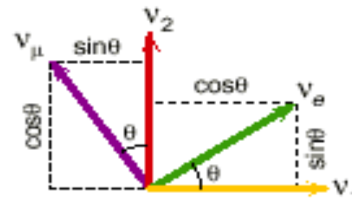
First look at two neutrino case

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

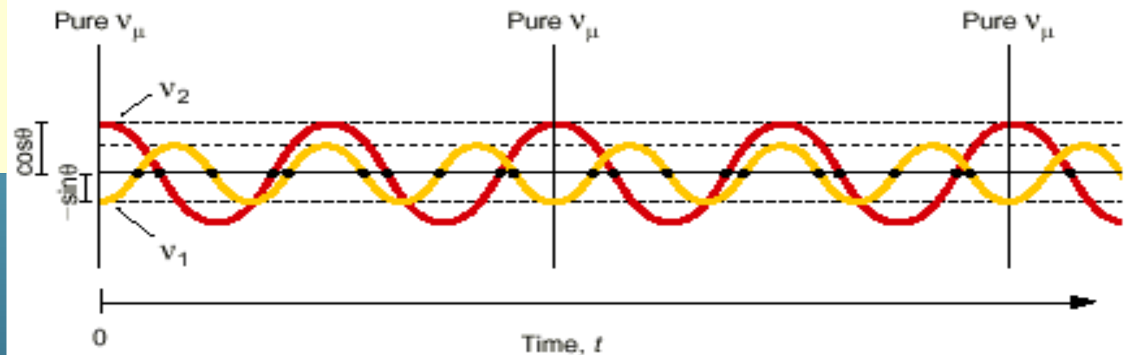
L – dist. to the detector
E - neutrino energy

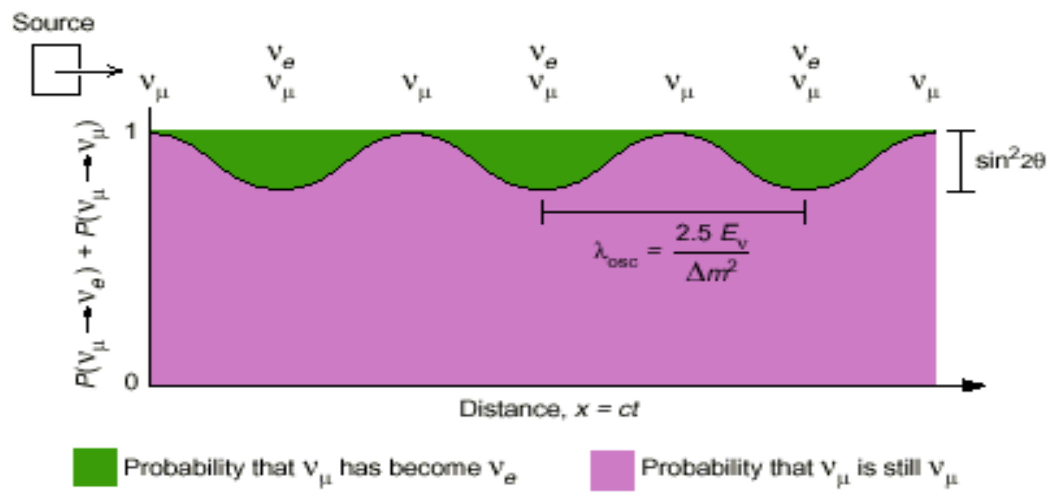
Maximal effect when

$\sin^2\{1.27\Delta m^2 L/E\} = 1$



$$\nu_e = \cos\vartheta\ \nu_1 + \sin\vartheta\ \nu_2$$
$$\nu_\mu = -\sin\vartheta\ \nu_1 + \cos\vartheta\ \nu_2$$





Sensitivity to oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \ \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

ν energy - E and distance L define range of sensitivity

	E_ν (MeV)	L (m)	Range of Δm^2
Supernovae	<100	>10^{19}	10^{-19} - 10^{-20}
Solar	<14	10^{11}	10^{-10} ???
Atmospheric	>100	10^4 -10^7	10^{-3}-10^{-4}
Reactor	<10	<10^6	10^{-5}
Accelerator – SB	>100	10^3	10^{-1}
Accelerator – LB	>100	<10^6	10^{-3}

Two mass differences and three neutrino types oscillatimg

→ **full description in 3x3 oscillation matrix,**

→ **studies in many experiments to get full picture….**

Neutrino oscillations – picture as of today

FLAVOR **PMNS mixing matrix** **MASS**

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

2-3 **Sub-leading 1-3** **1-2**

„atmospheric”
SK, K2K, T2K, MINOS Nova

$$\Delta m^2_{31} = \begin{cases} 2.53^{+0.08}_{-0.10} \\ -(2.40^{+0.10}_{-0.07}) \end{cases} \times 10^{-3}\,\mathrm{eV}^2$$

CHOOZ, DayaBay, Reno, DblChooz, T2K

$\theta_{12} = 34° \pm 1°$

$\theta_{23} = 40° + 5° / - 2°$

$\theta_{13} = 9.1° \pm 0.6°$!

Based on PDG 2012

„solar”
SNO, KamLand, SK, Borexino

$$\Delta m^2_{21} = (7.62 \pm 0.19) \times 10^{-5}\,\mathrm{eV}^2$$

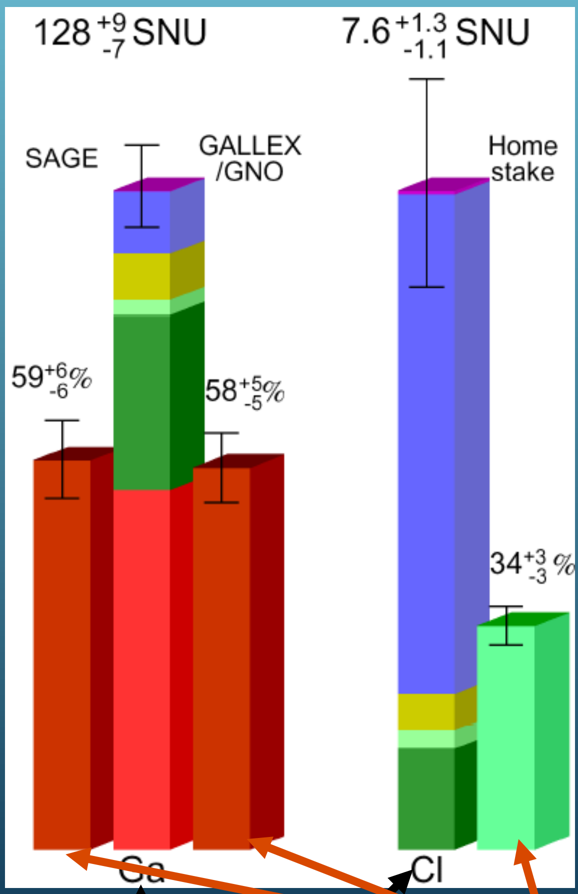
parameter θ_{13} found to be non zero !!!

mixing angles, squared mass differences, CP violation phase - fundamental parameters of nature

* $\Delta m^2_{ji} = m_j^2 - m_i^2$
Two free parameters for the three Δm^2's.
($\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$)

What we know about each sector?

1-2 – solar neutrinos



pp, ^{7}Be, pep, CNO, ^{8}B, Hep

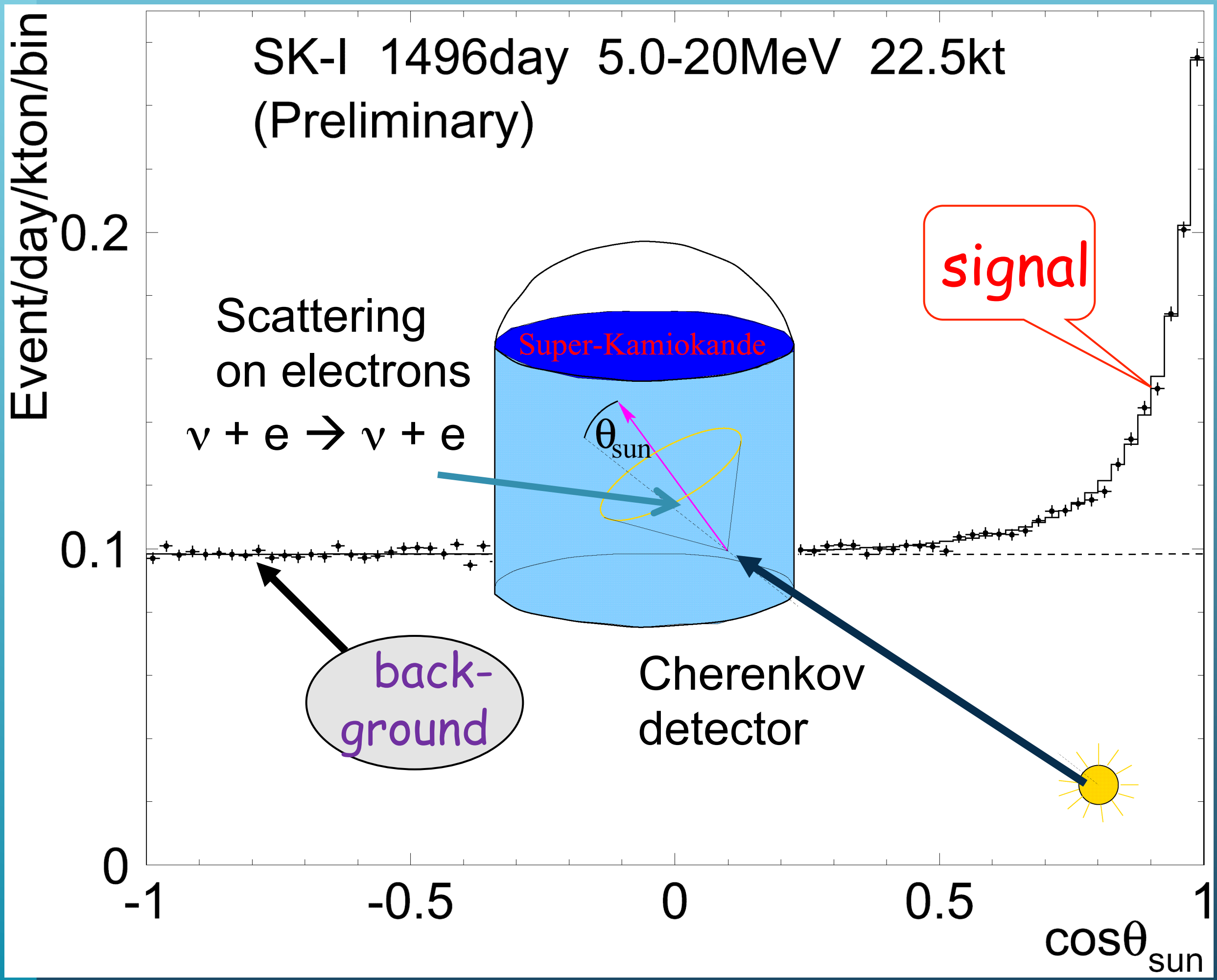
Contribution calculated from „SSM” - Standard Solar Model (SSM):

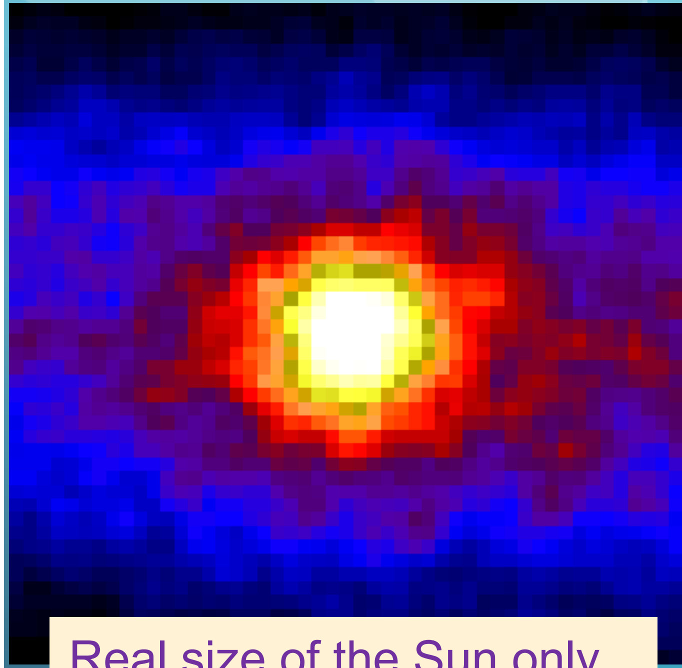
- observations in radio-chemical experiments (counting interactions, no time and direction information
- First data – Davis experiment

Neutrino deficit

measurements

Super-K: neutrino's arriving from the Sun





Real size of the Sun only – ½ pixel. The smearing is due to electon scattering

Here also observed number of neutrinos is too small

Observed about ½ of what was expected

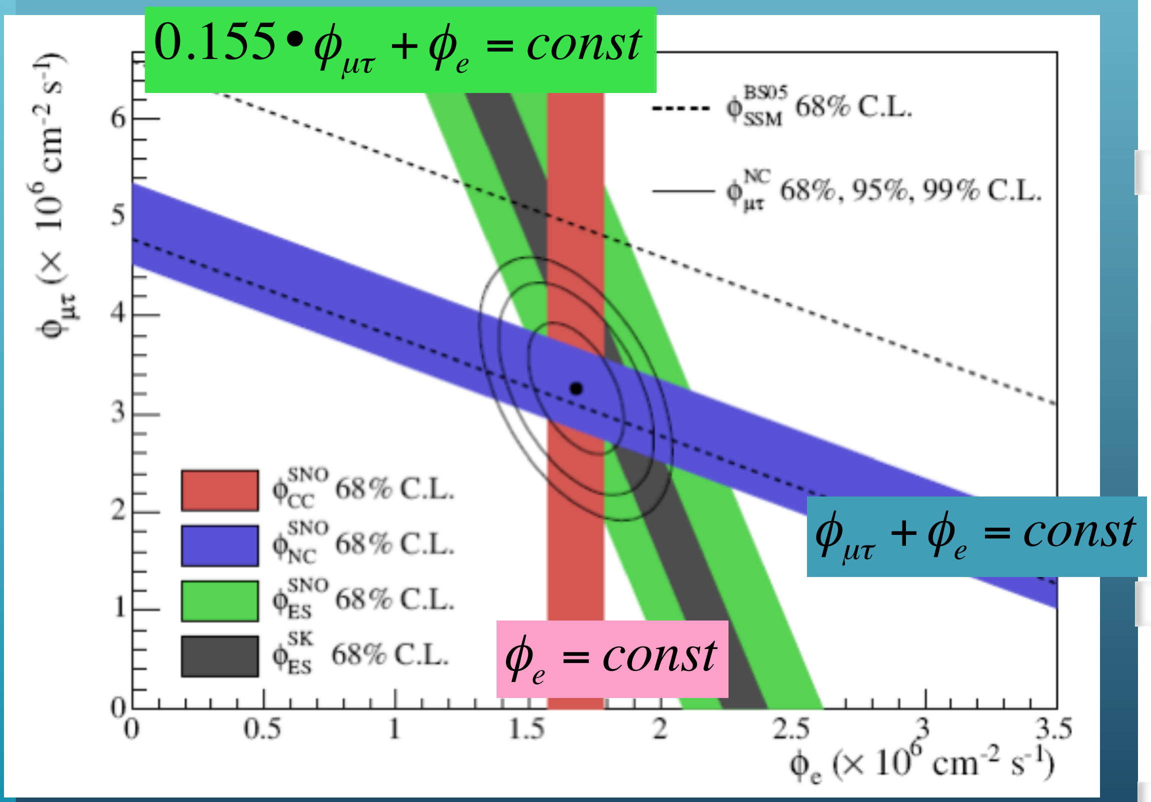
neutrino deficit ….again...

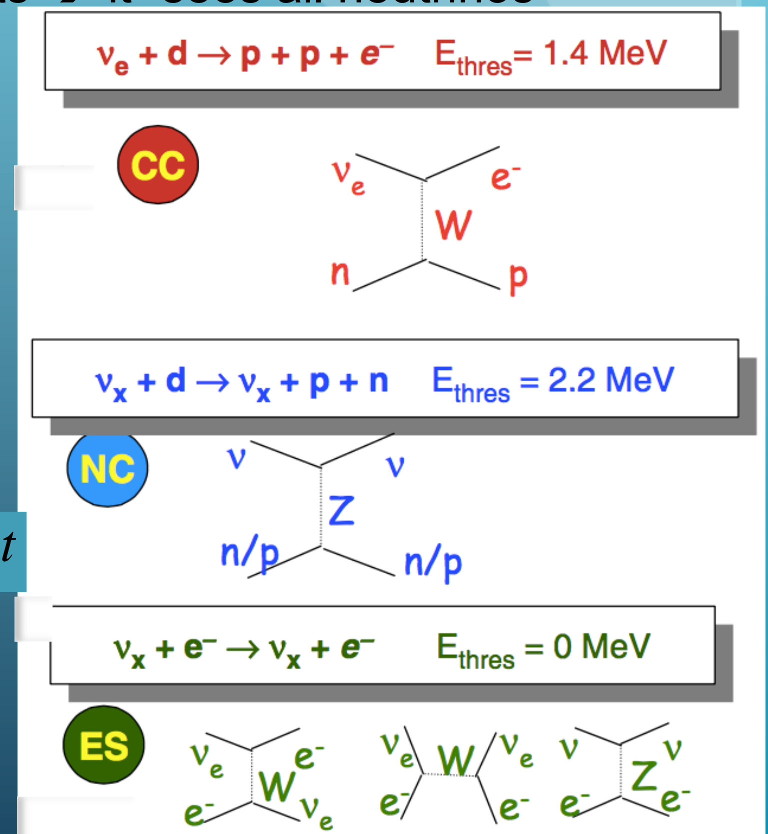
Solution – SNO experiment - heavy water

(½ Nobel Prize 2015)

SNO experiment : measurement sensitive to 3 reactions

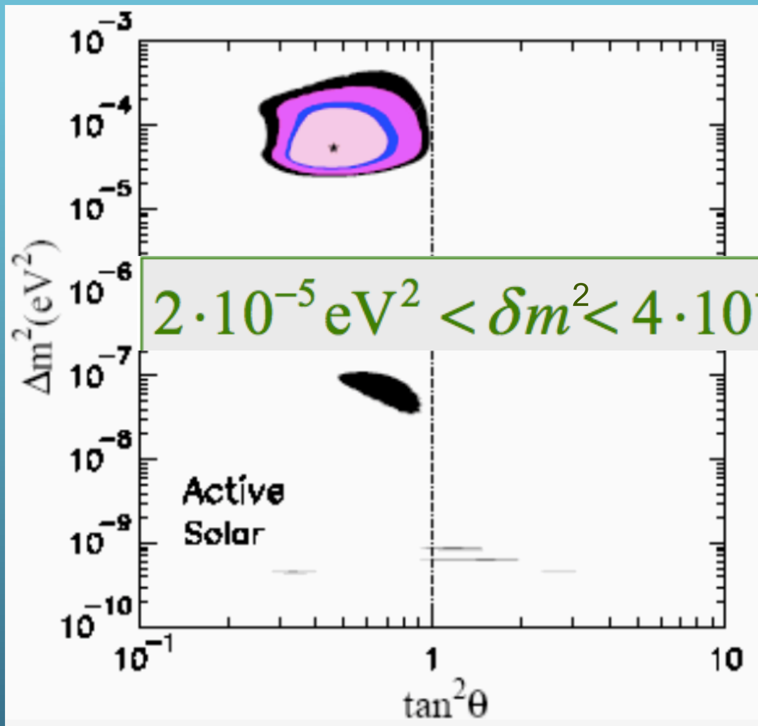
Including sensitivity to Neutral Currents ➔ it “sees all neutrinos”





Here it is seen directly that ν_e flux is smaller than expected from Solar Model, but sum over 3 ν flavours gives expected flux

Parameters for 1-2 sector:



$$2 \cdot 10^{-5}\,eV^2 < \delta m^2 < 4 \cdot 10^{-4}\,eV^2$$

- From sensitivty for Sun-Earth distance – expected 10^{-10}eV
- Why it is different?

we needed to make correction for

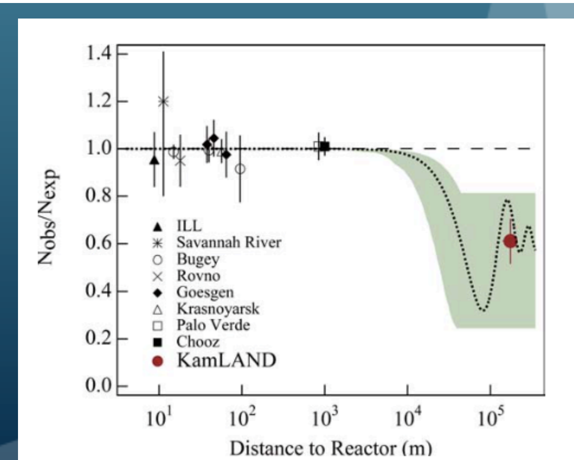
MATTER EFFECTS

→ Moddifivation of potential due to electrons density in matter

$$\Delta m^2{}_{matter} = \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}$$

KAMLAND – sector 1-2 for anti-neutrinos from reactors
Obs/exp = 0.631 +/- 0.014 (stat)
+/- 0.027 (syst)
Corresponding to
exclusion of non-oscillation at
10.2 σ CL

no matter effects !!!

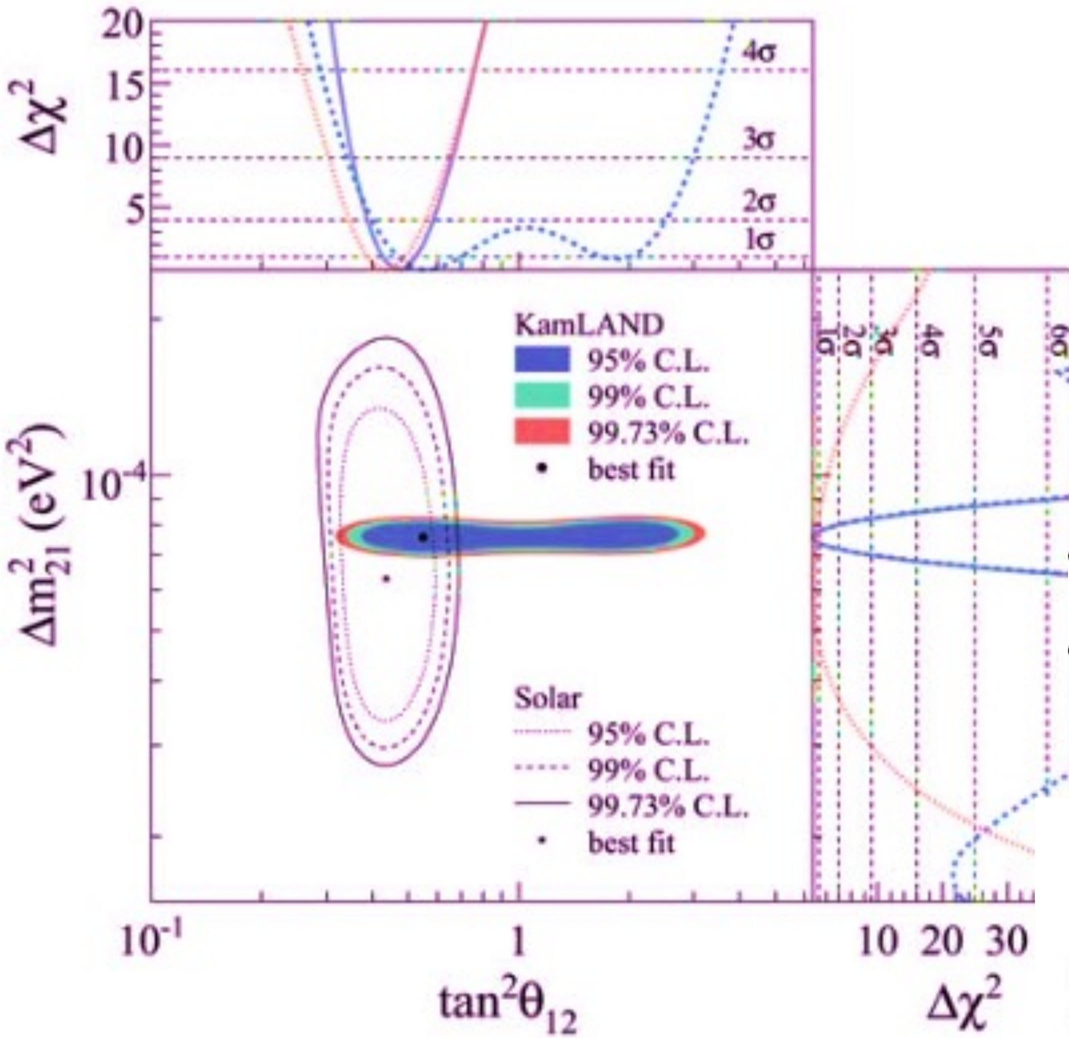


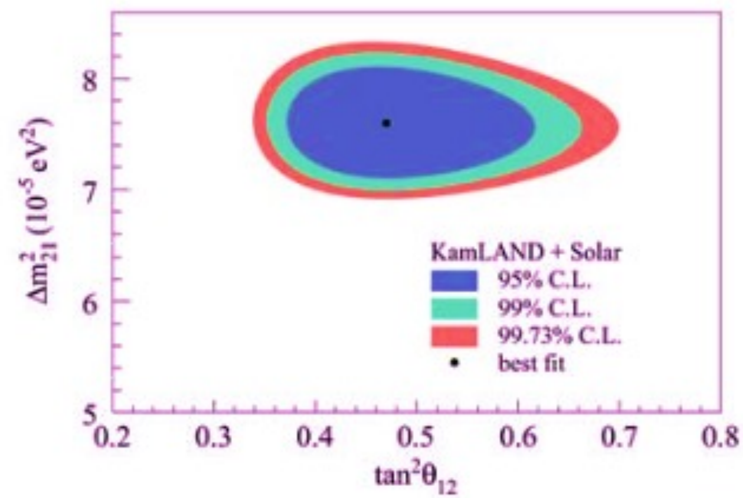
Determination of 1-2 mixing

Assuming same values for Neutrinos and anti-neutrinos

We obtain:

Δm^2_{21} (10^{-5} eV^2)	$\tan^2\theta_{12}$
$7.53\ ^{+0.18}_{-0.18}$	$0.436\ ^{+0.029}_{-0.025}$

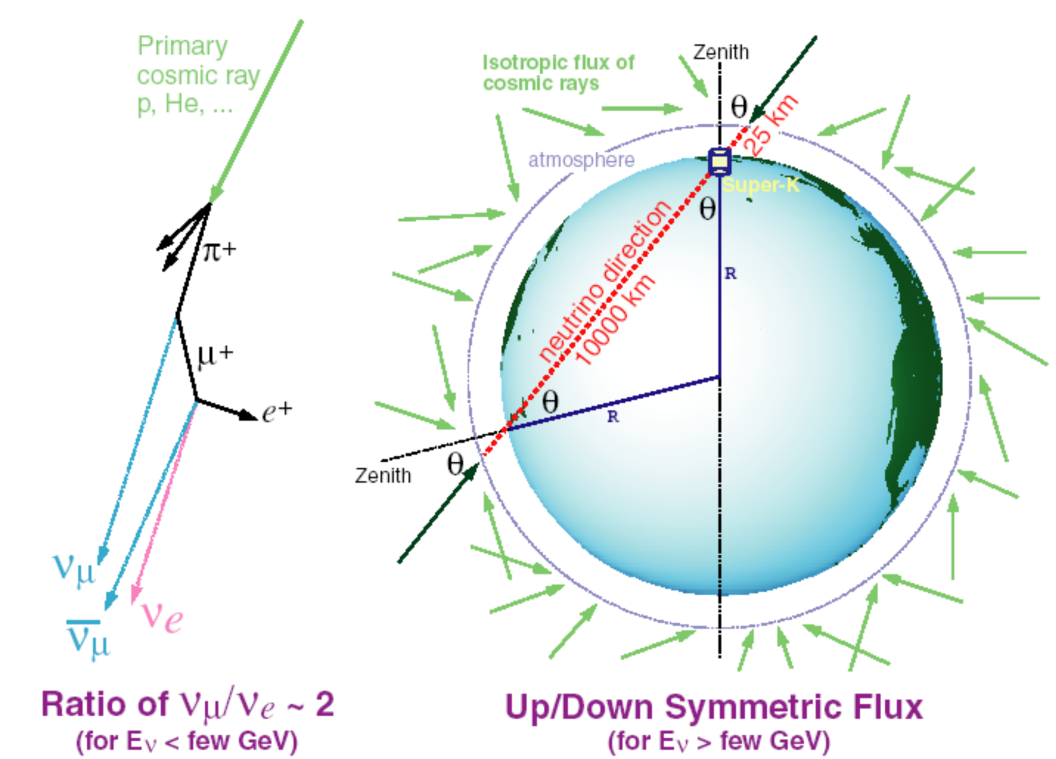




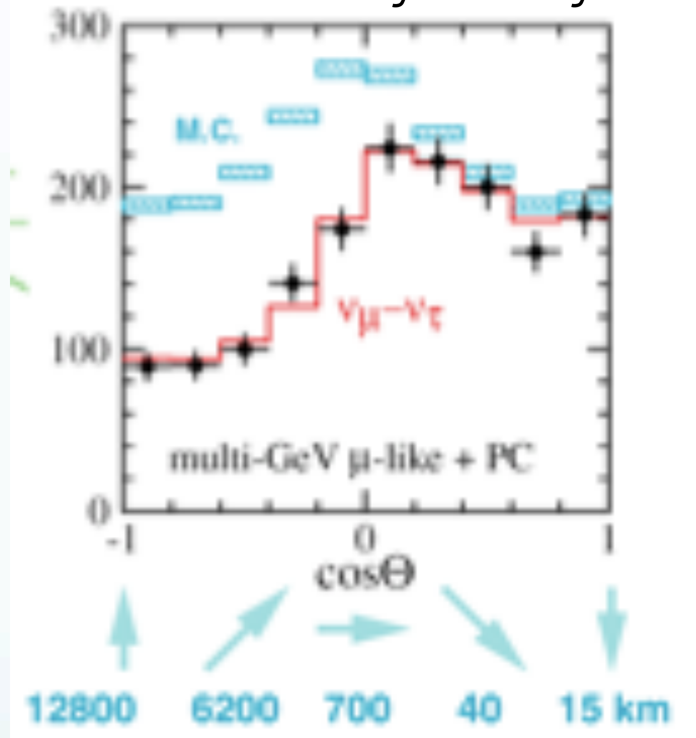
- Kamland - for anti-neutrinos

Sector 2-3 → first signal – atmospheric neutrinos

studies of background for proton decay



Observation of strong UP-DOWN asymmetry



Compare ν_μ to ν_e- take ratios to cancel out errors on absolute neutrino fluxes:

$$R = \frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.638 \pm 0.016 \pm 0.050$$

$$R_{highE} = \frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.658^{+0.030}_{-0.028} \pm 0.078$$

Too few muon neutrinos observed!

Evidence for Oscillation of Atmospheric Neutrinos

interpretation of the deficit of ν_μ after passing the Earth

$$\nu_\mu \rightarrow \nu_x$$

What is x ?
Not e as we do not observe access of ν_e

So we observe $\nu_\mu \rightarrow \nu_\tau$

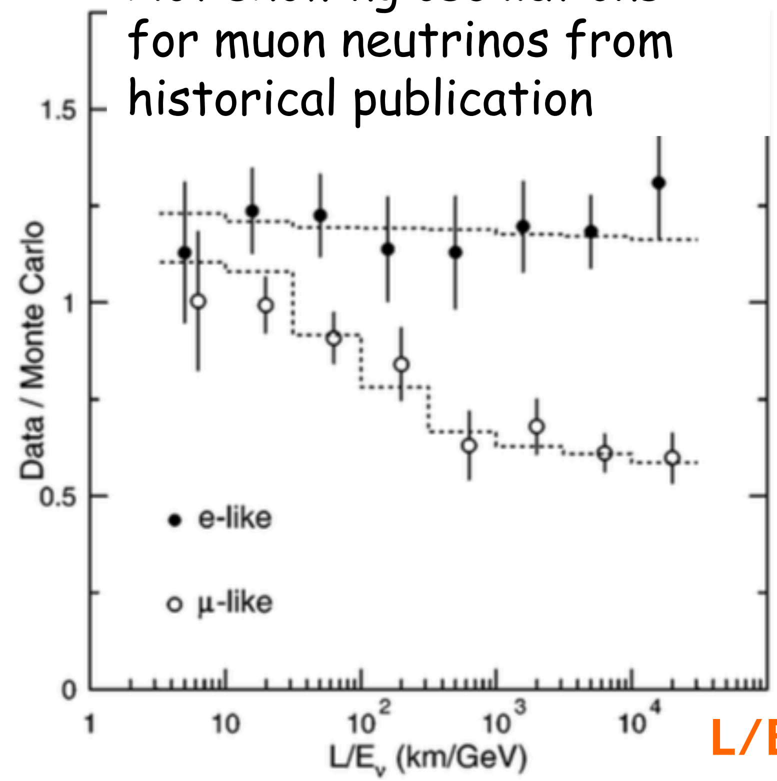
The neutrino interaction in SK is identified by observation of a charged lepton

$$\nu_\mu + N \rightarrow \mu^- + X$$
$$\nu_\tau + N \rightarrow \tau^- + X$$

But $m_\mu << m_\tau$, so if energy is too small to produce τ, ν_τ is not observed

This is why ν_μ are "missing"

Plot showing oscillations for muon neutrinos from historical publication

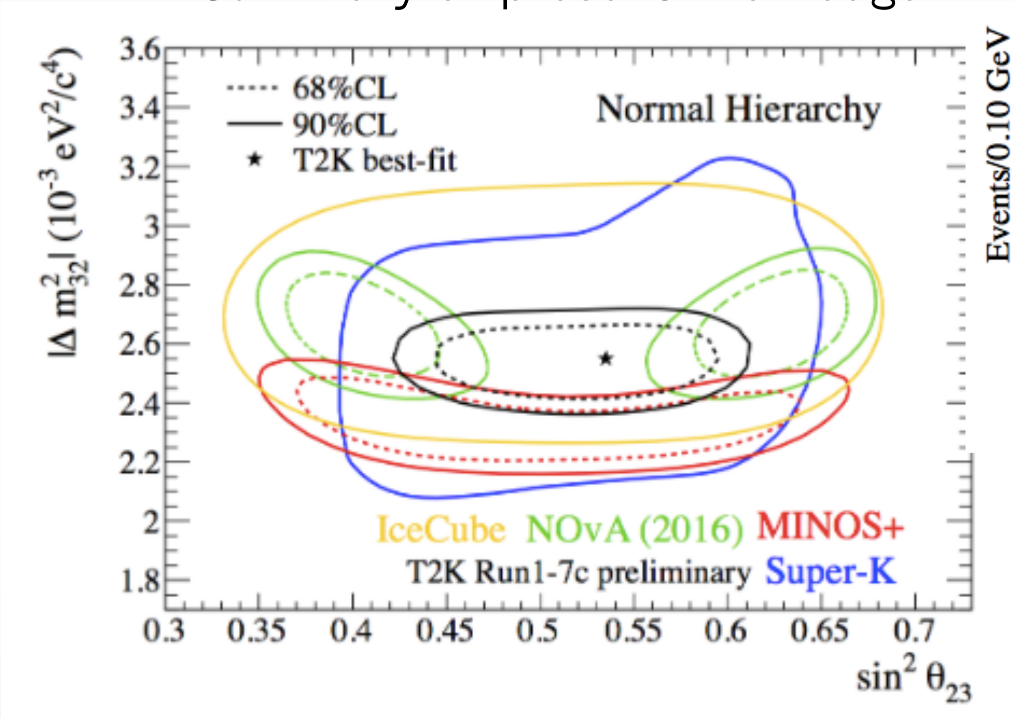


L/E

FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2–7%) of ν_μ CC interactions.

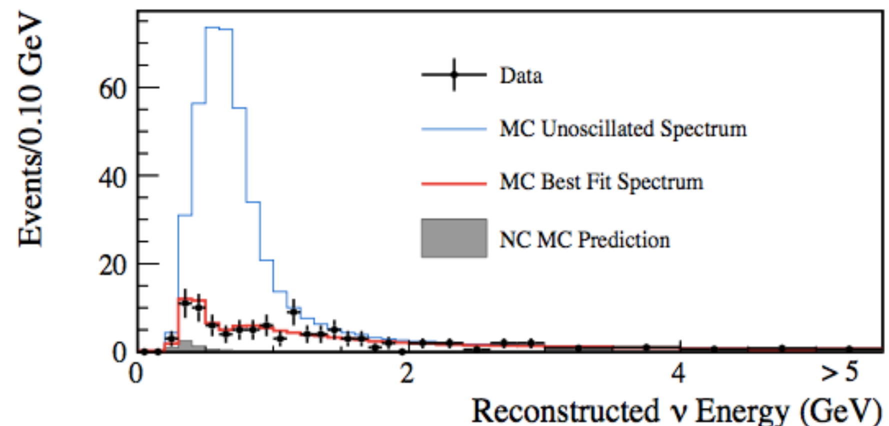
Present knowledge about 2-3 sector parameters:

Summary of present knowledge:

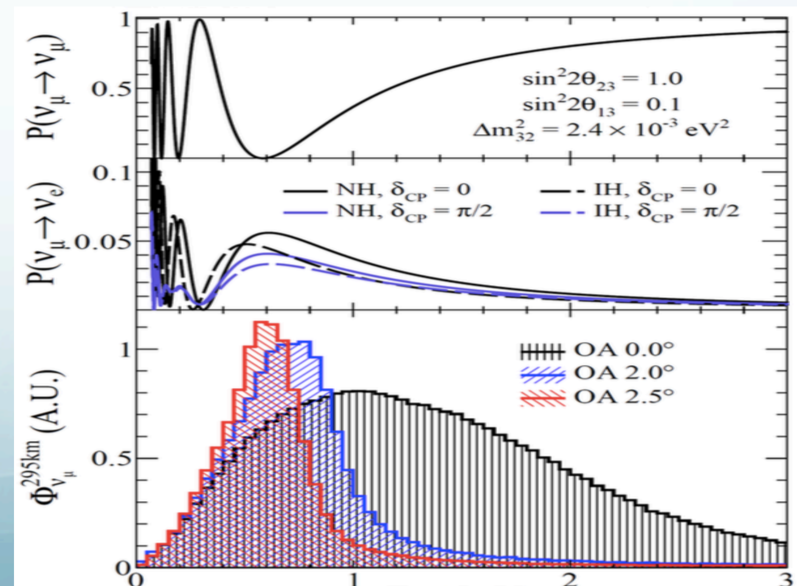


	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.044}_{-0.060}$	$0.534^{+0.041}_{-0.059}$
$\|\Delta m^2_{32}\|$ ($/10^{-3}$eV^2)	$2.545^{+0.084}_{-0.082}$	$2.510^{+0.082}_{-0.083}$

Most precise measurement



Beam energy and distance tuned
To get maximal oscillation effect



1-3 ... and ways of measuring θ_{13}

- disappearance -> **reactor experiments**

$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$

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

Energy ~ a few MeV
Distance ~ a few km

- appearance -> **long-baseline experiments** with ν_μ beam

$$\nu_\mu \rightarrow \nu_e$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(1.27 \Delta m^2_{23} L / E\right)$$

Second order terms depend on δ and mass hierarchy

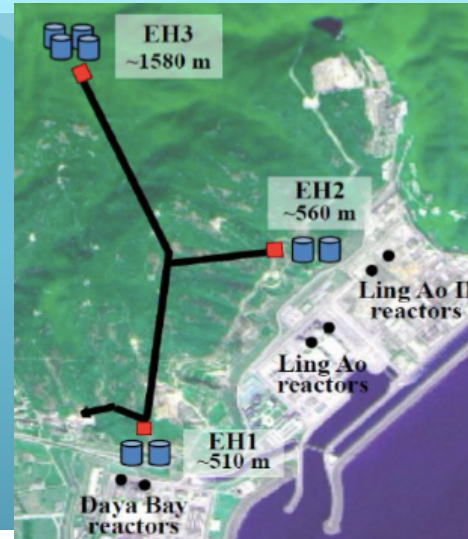
Energy ~ a few GeV
Distance ~ a few hundred km

Leading terms!

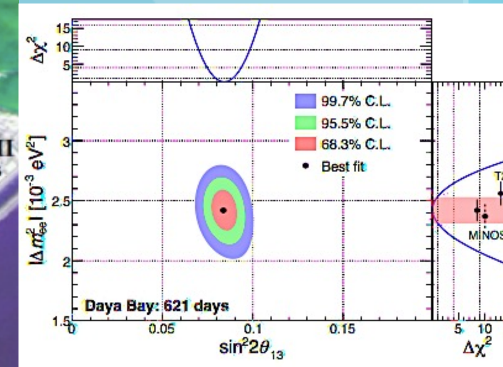
Sector 1-3 reactor data

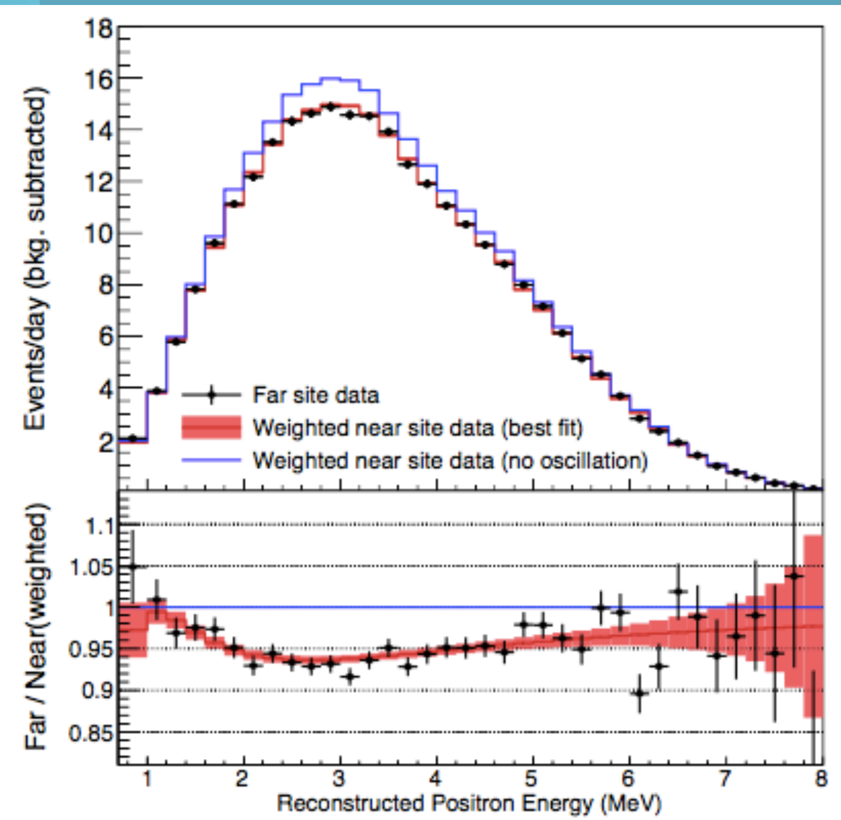
Daya Bay, RENO, Double CHOOZ

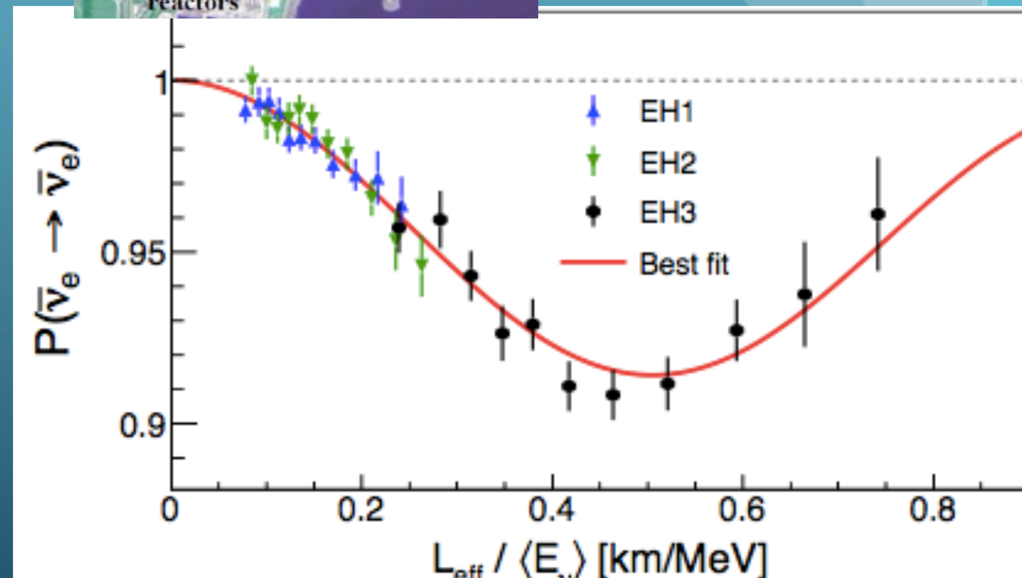
most precise measurements of θ_{13}



far and near detectors







$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \mathrm{eV}^2$$

Observation in muon-neutrino beam

Selecting candidates for electrons | selecting candidates for muons

e-like

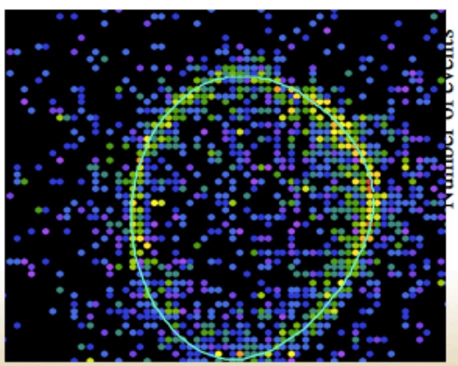
- Electron-like ring
- $E_{vis} > 100$ MeV
- $N_{michels} == 0$
- $E_{\nu,\ rec} < 1250$ MeV
- Not π^0-like

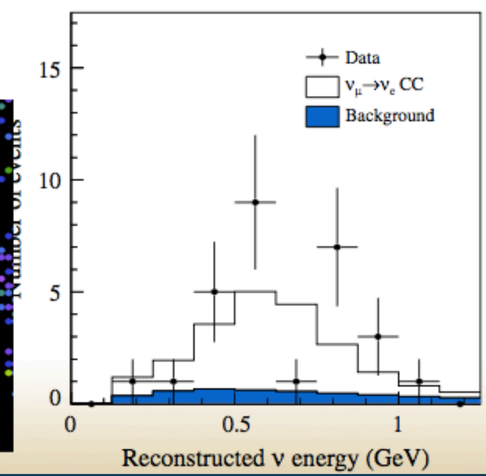
28 ν_e events

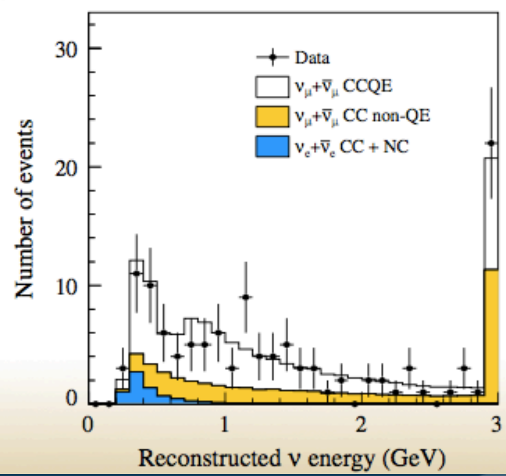
μ-like

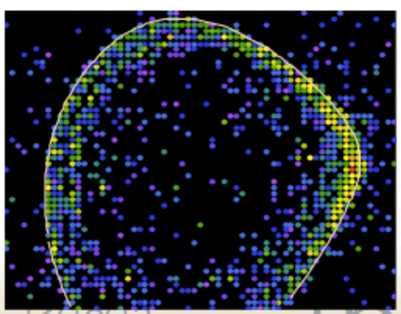
- Muon-like ring
- $P_\mu > 200$ MeV/c
- $N_{Michels} < 2$

120 ν_μ events





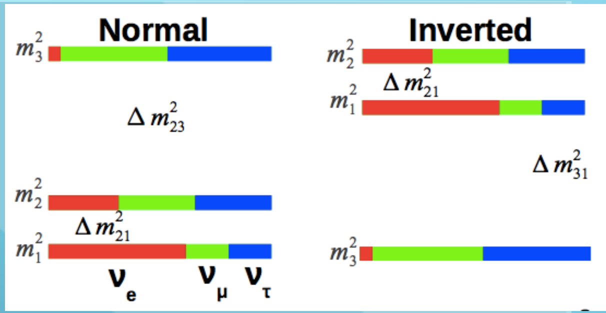




appearance

disappearance

What's next?



CPV $\qquad \delta \neq 0, \pi?$

MH $\qquad m_3 \gtrless m_2?$

$$\theta_{23} \gtreqless 45°?$$

Differences in neutrino vs antineutrino oscillation probabilities

Changes the contribution from matter effects
(important for neutrinos travelling through dense matter e.g through Earth)

Additional source of degeneracies

An unknown hierarchy usually leads to a reduced ability to observe CP violation

Measurement strategies (for LBL):

- Looking for appearance

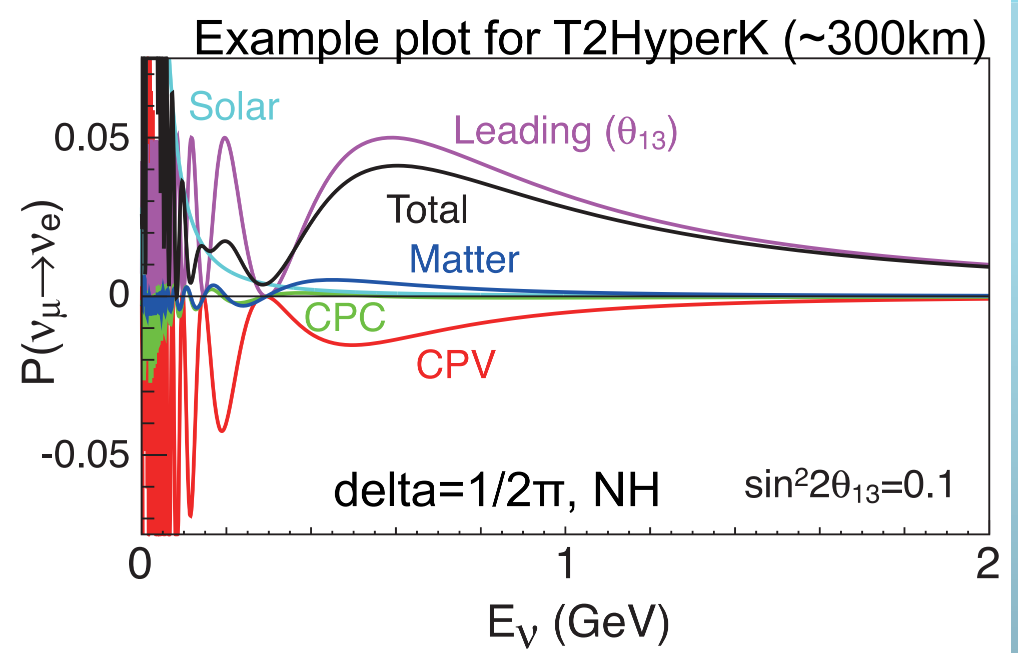
$$P\left(\nu_\mu \to \nu_e\right) \quad vs. \quad P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$$

- The longer the baseline the better (matter effects!)
- Study more than one oscillation maximum to disentangle the effects

CPV and MH

In long baseline neutrino experiments

→ Many contributions, for precisions all need to be considered



$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$ leading term

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$ CP conserving

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$ CP violating

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21}$$ solar term

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},$$ matter effects

for $\overline{\nu}_\mu \to \overline{\nu}_e$ $\delta \to -\delta$ $a \to -a.$

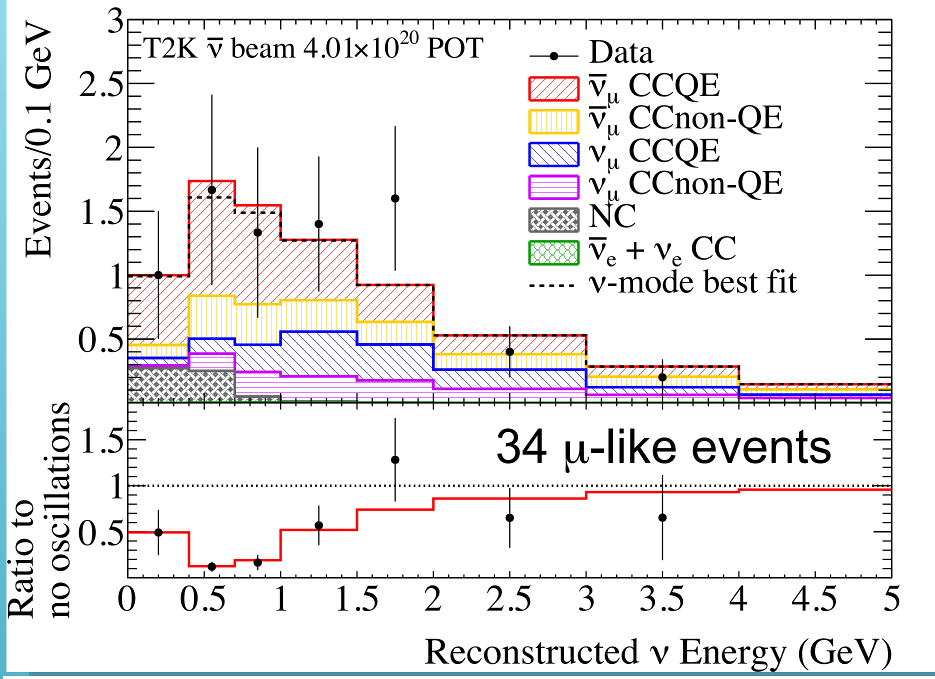
$C_{ij},\ S_{ij},\ \Delta_{ij}$

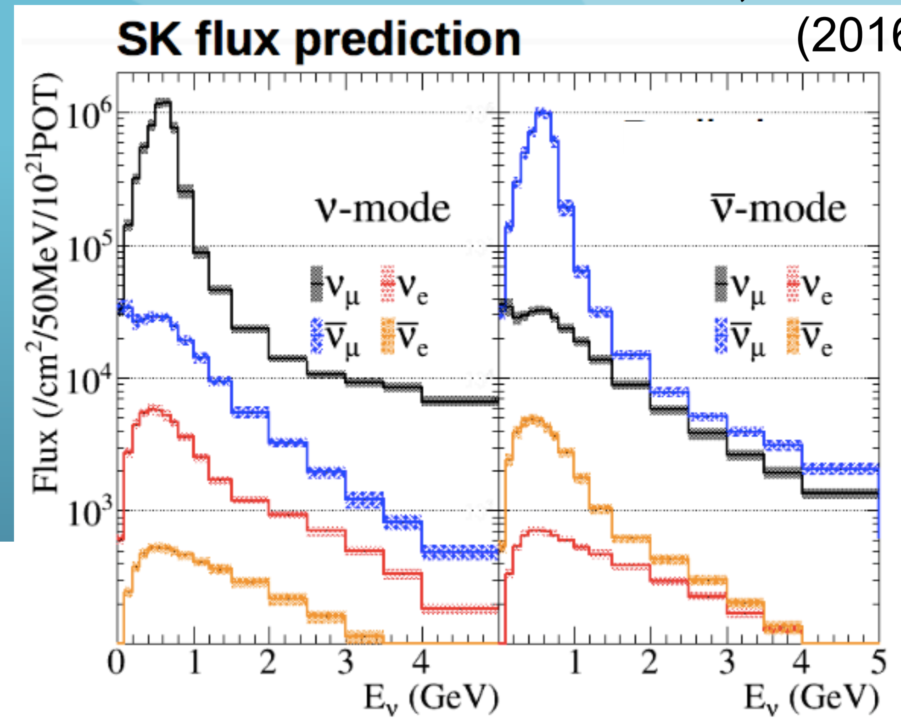
$\cos\theta_{ij},\ \sin\theta_{ij},\ \Delta m_{ij}^2\, L/4E_\nu$

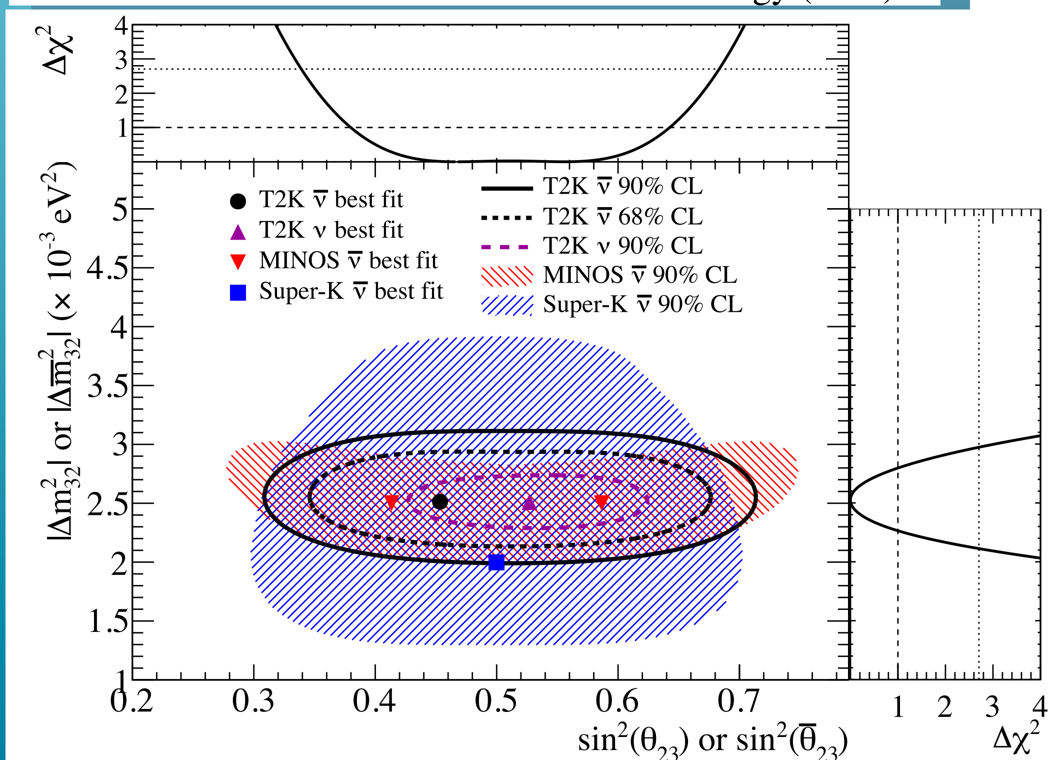
$\alpha \sim \rho * E_\nu$

$\bar{\nu}$ beam – results

PRL 116, 181801 (2016)





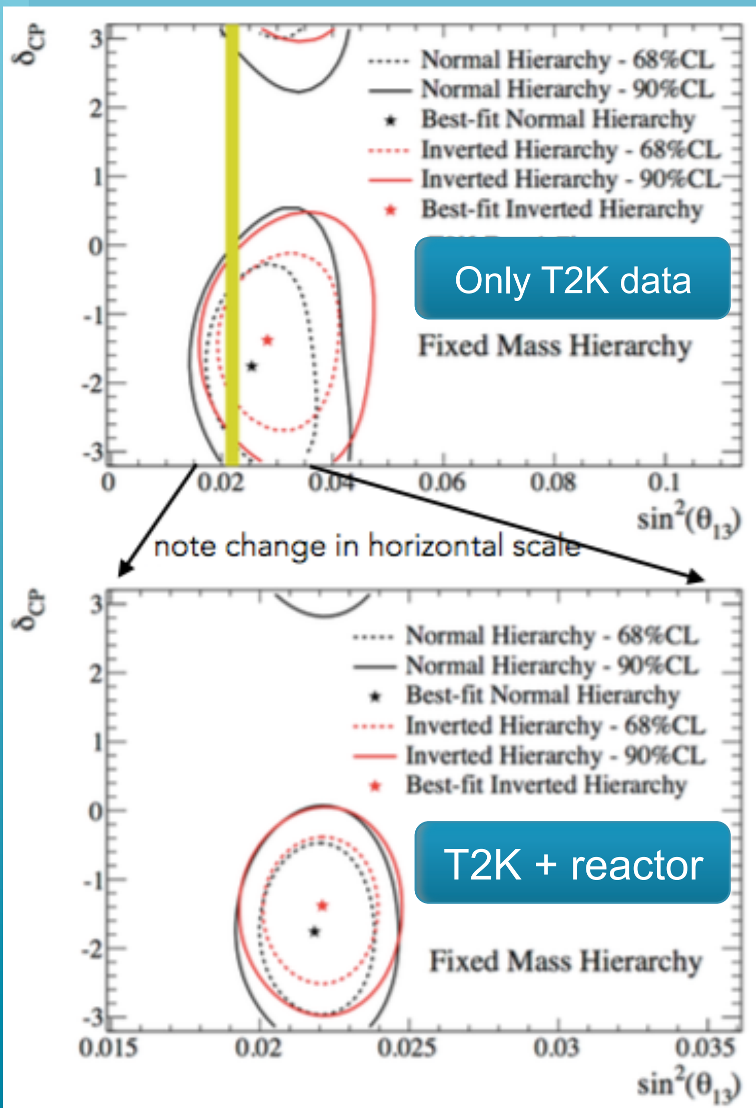


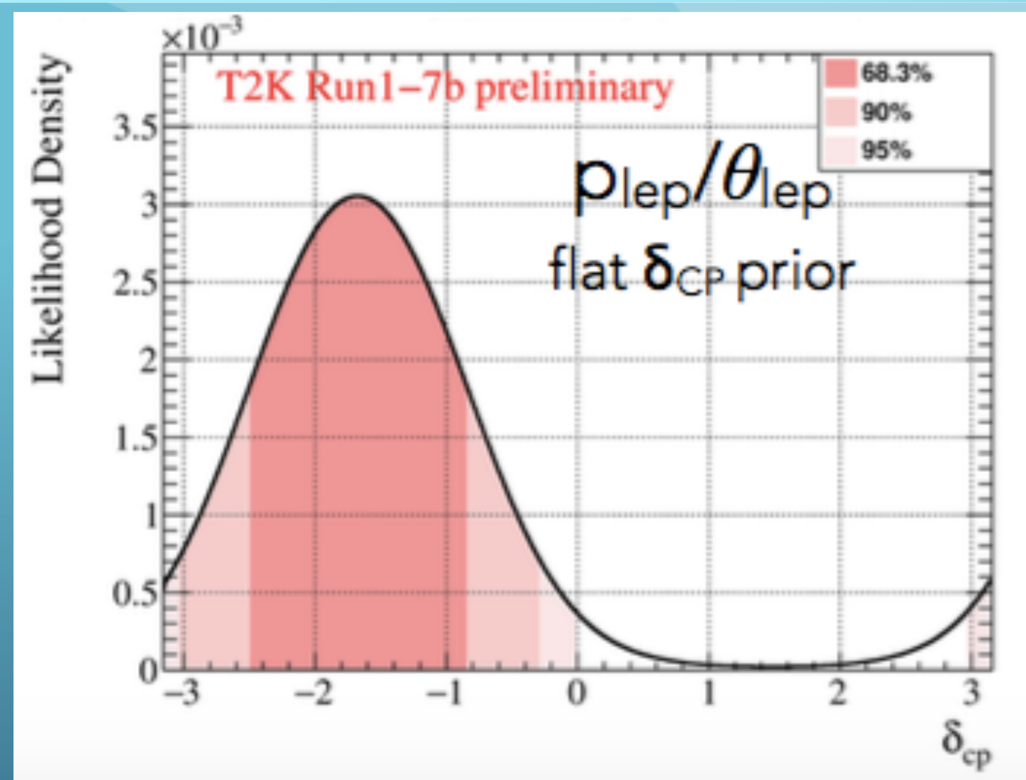
Analysis
with anti-nu beam mode

Disappearance:
parameters consistent with
- maximal mixing
- parameters same as neutrino
- other experiments

Appearance – 3 e-like events seen
more data needed

New analysis
ν and $\overline{\nu}$



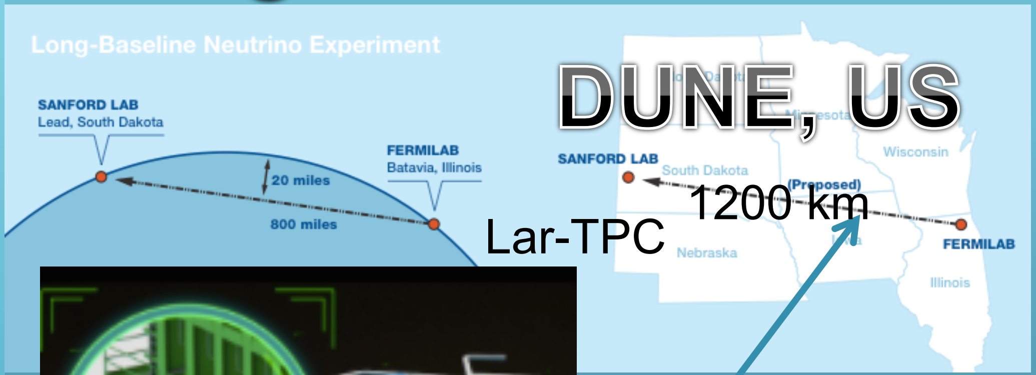


- First time from single experiment 90% CL range for CP violation phase
- Pointing to value corresponding to CP violation (0 and π otside 90% limit)
- More data needed → T2K II
- Combined fits for all experiments will come soon (teoretica groups)

Long Baseline Future

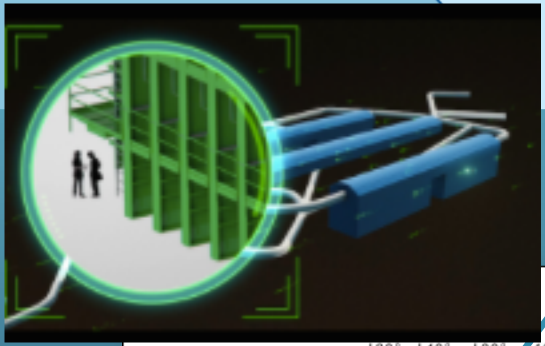
Long term
ie. after/around 2025

DUNE, US



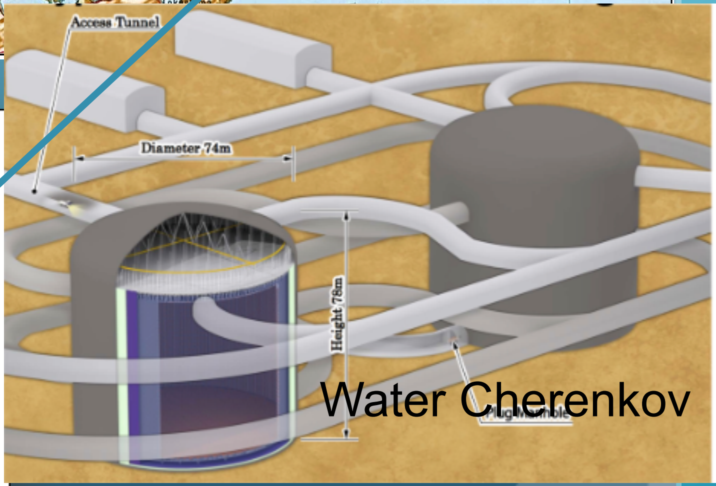
1200 km

Lar-TPC



Hyper-Kamiokande, Japan

295 km



Water Cherenkov

And how about connection of neutrinos with work of Stanisław??

First try….

Small oscillations of a collisionless quark plasma

Paper in Physics Letters B, 188 (1987) 129-132

Abstract:

The oscillations of a collisionless quark plasma are studied on the basis of the gauge covariant kinetic equations. The small oscillation approach provides the dispersion relations which coincide with those predicted by the finite-temperature QCD in one-loop approximation.

→ This connection is weak and not natural (only by playing words)

Next try…. Started with popularization:

"Tachyons: Particles faster than light", Postępy Fizyki **32** (1981) 351

and more in this field…..

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St.Mrøwczyński*

THE PHASE-SPACE OF TACHYONS

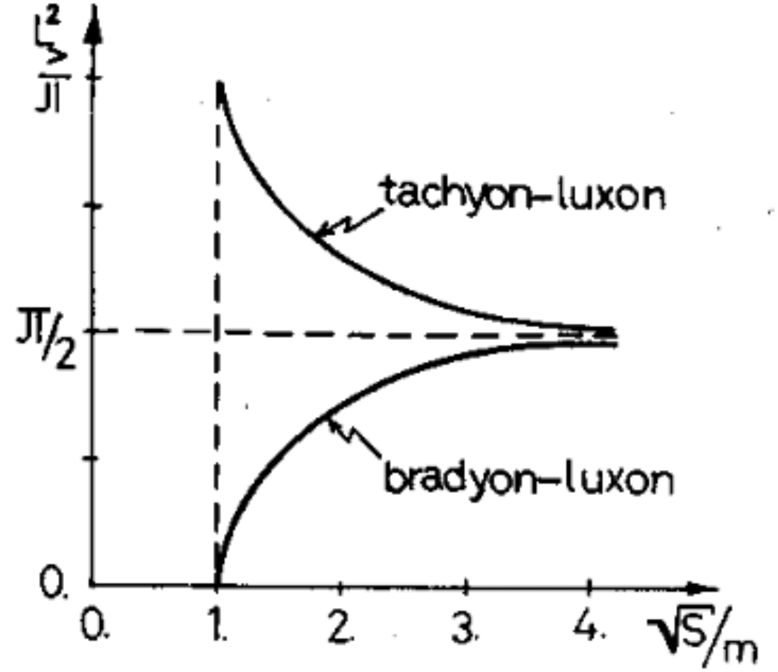


Fig.3. The volume of PS $L^2_>$ in CM for tachyon-luxon and bradyon-luxon systems

We conclude that it is easy to construct PS that is free of difficulties discussed in the previous section, however at the expense of Lorentz invariancy. We accept the view of the authors of /7/ that "the first major problem to be overcome in developing a quantum theory of tachyons is in reconciling the apparent conflict between Lorentz invariancy and need to have only positive energies capable of being observed to the theory".

On the ideal gas of tachyons

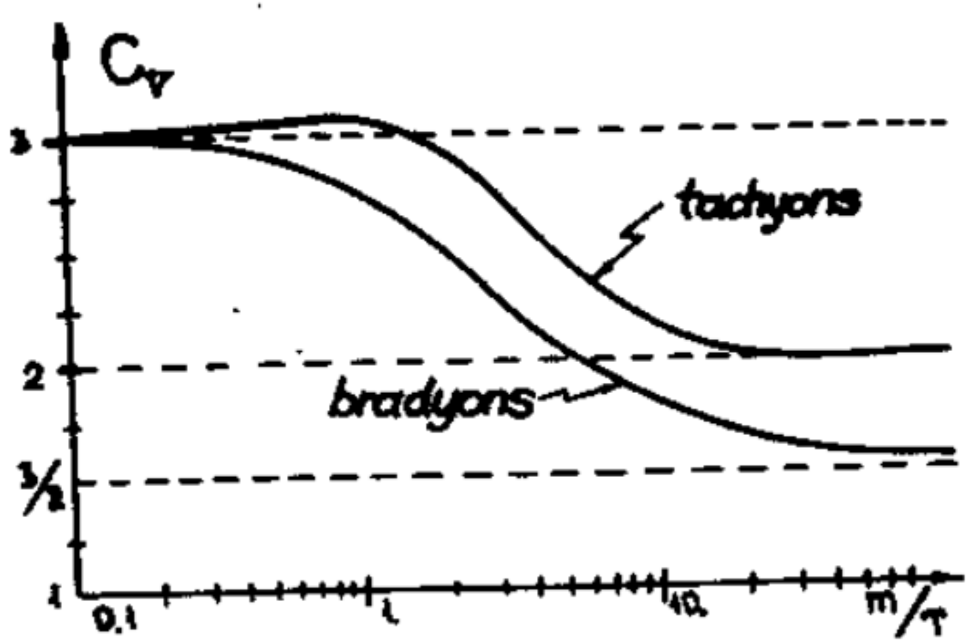
сообщения
объединенного
института
ядерных
исследований
дубна

E2-83-476

St.Mrówczyński*

ON THE IDEAL GAS OF TACHYONS

$$c_V = \begin{cases} = 3 + \mathcal{O}\left(\frac{m^2}{T^2}\,\ell n\,(m/T)\right); & \text{for } T \gg m \\ = 2 + \mathcal{O}(T/m); & \text{for } T \ll m. \end{cases}$$

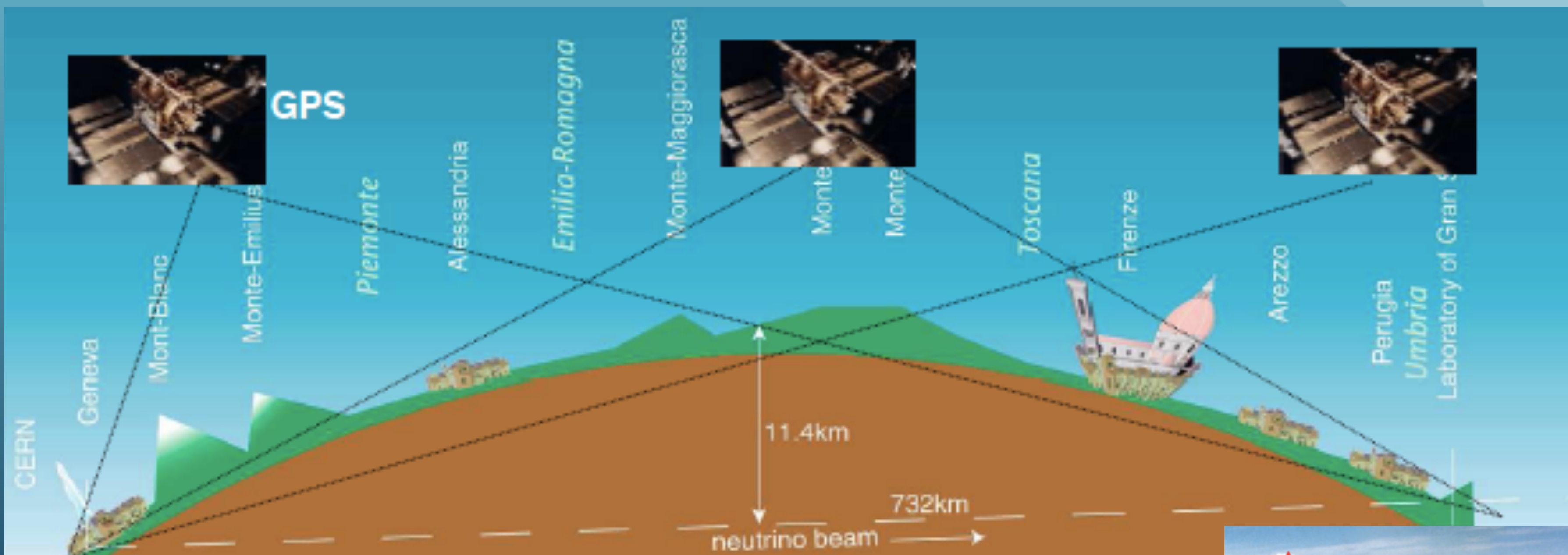


The specific heat of the idea gas of tachyons and the gas of bradyons as a function of m/T•

- **1982 - 1986 - asystent, Joint Institut for Nuclear Research, Dubna, ZSRR**

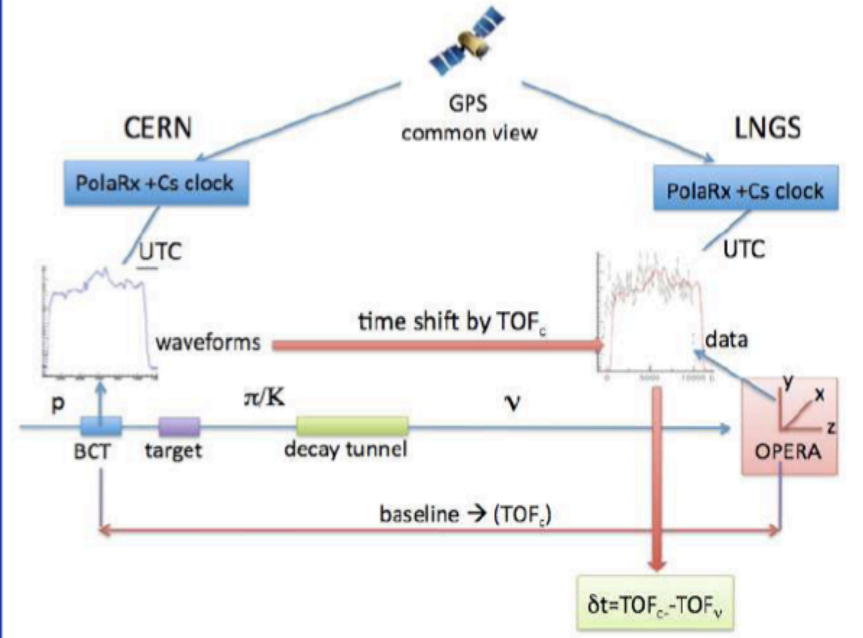
…and here we have connection:

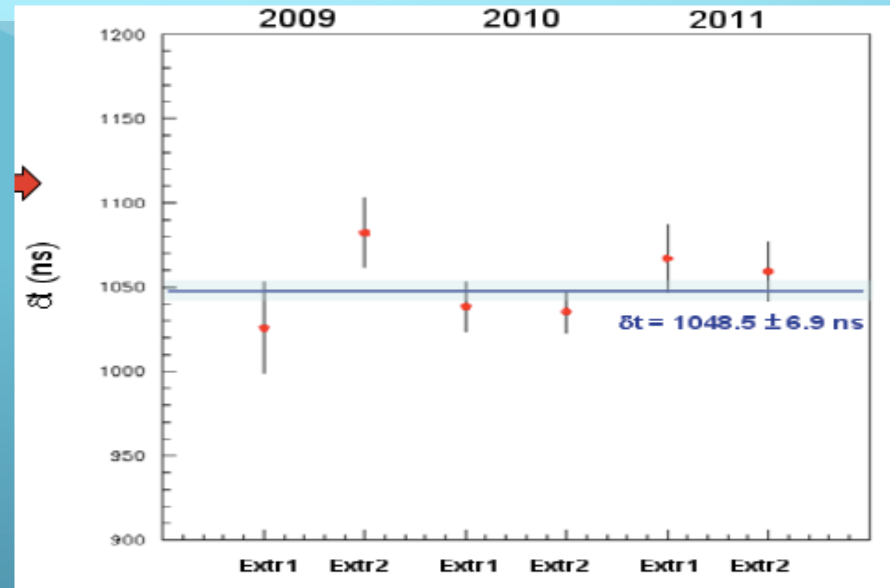
in 2011 for some time ν looked like tachyons



Simple experiment:
known L=732 km
measure time of flight - t

v=L/t → v>c





$$\delta t = TOF_c - TOF_\nu = (1048.5 \pm 6.9(stat.))ns - 987.8ns$$

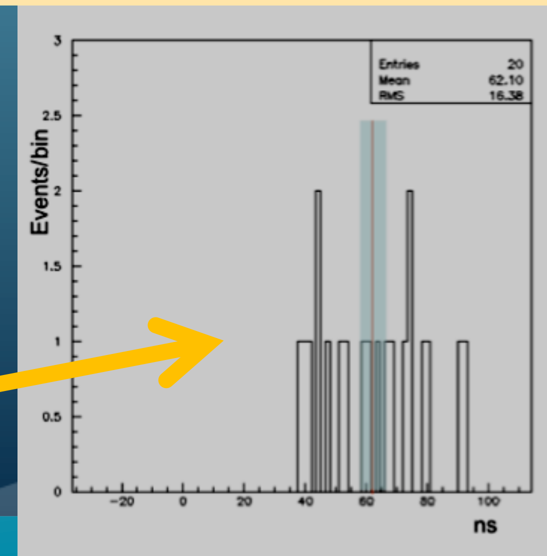
$$= (60.7 \pm 6.9(stat.))ns$$

$$(v - c)/c = \delta t / (TOF_c - \delta t) =$$

$$= (2.49 \pm 0.28(stat.) \pm 0.30(sys.)) \cdot 10^{-5}\, s$$

for test – run with narrow beam banches,

measure δ = **ToF$_\nu$ - ToF$_c$**



Team admits to possible errors in faster-than-light finding.

NATURE, 27 February 2012

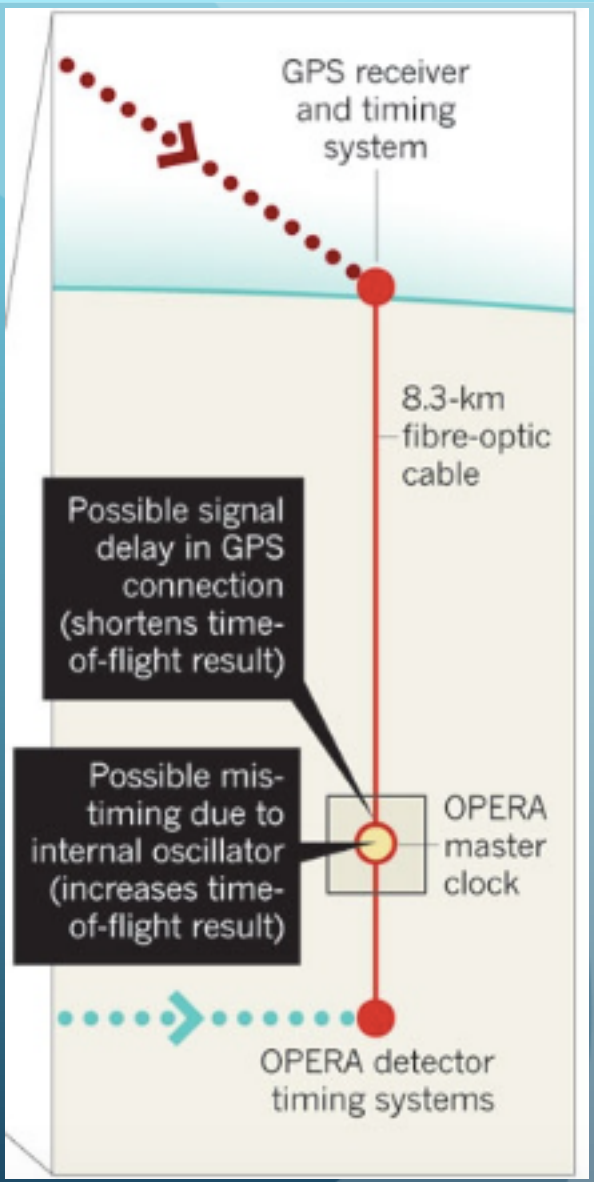
Fault was found in the delay in GPS connection,

after that ν speed < c again

so present status:

no tachyons found experimentaly

(again..)



With best wishes for Stanisław !!!!!!