"Neutrinos - experimental status and prospects”

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Plan for the lecture…

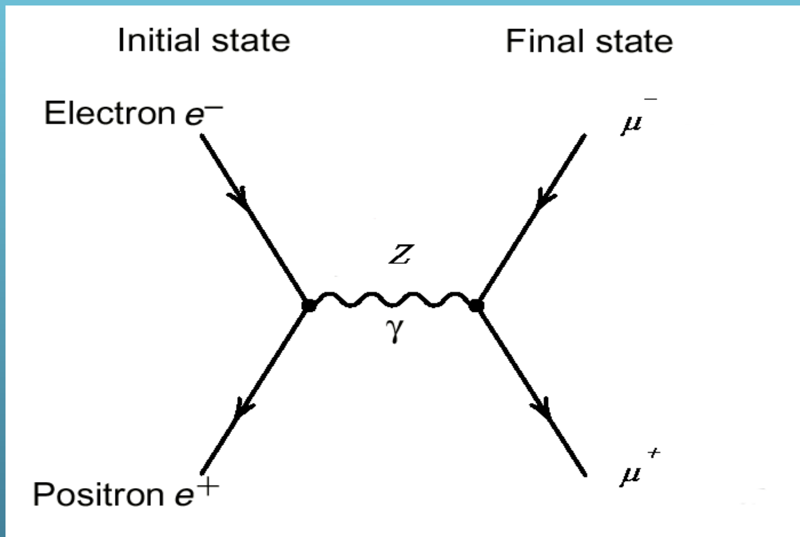
Experimental view on neutrinos

- experimental information on number of neutrinos,
- Neutrino sources and measurement techniques
- How and what we measure to get oscillation parameters
- Summary on neutrino oscillation discovery
- New information from present measurements
- What we know and what is missing
- Prospects for better data

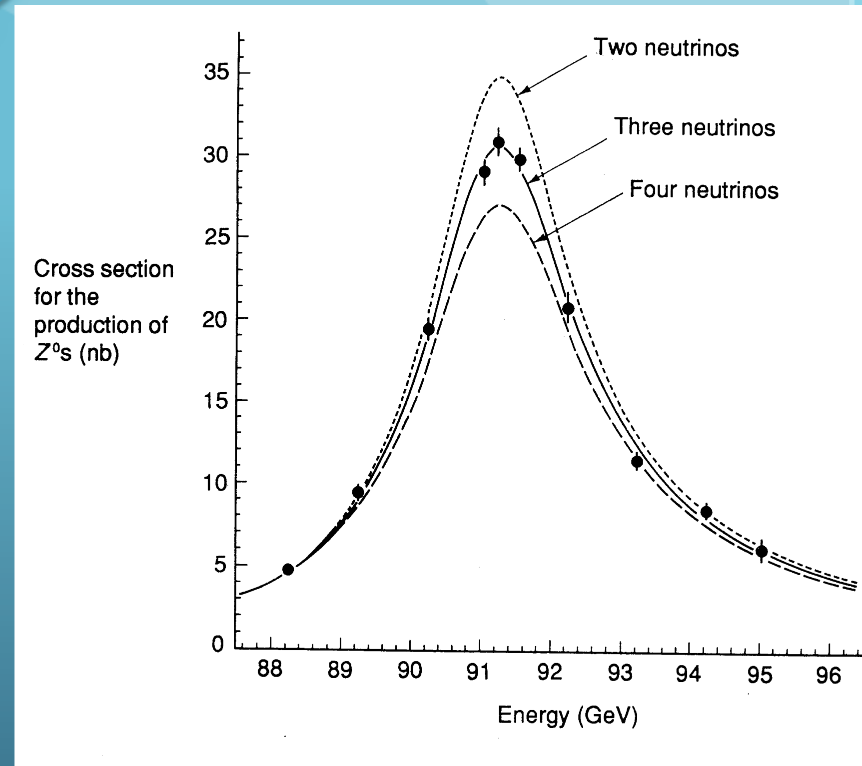
……. I will not talk about doule β decay searches, sorry..

How Many Neutrinos?

Experimental result from LEP



$\nu\bar{\nu}$



$$Z^0 \rightarrow q\bar{q}\,(u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b})$$

$$Z^0 \rightarrow l\bar{l}\,(e^-e^+, \mu^-\mu^+, \tau^-\tau^+)$$

$$Z^0 \rightarrow \nu\bar{\nu}\,(\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau)$$

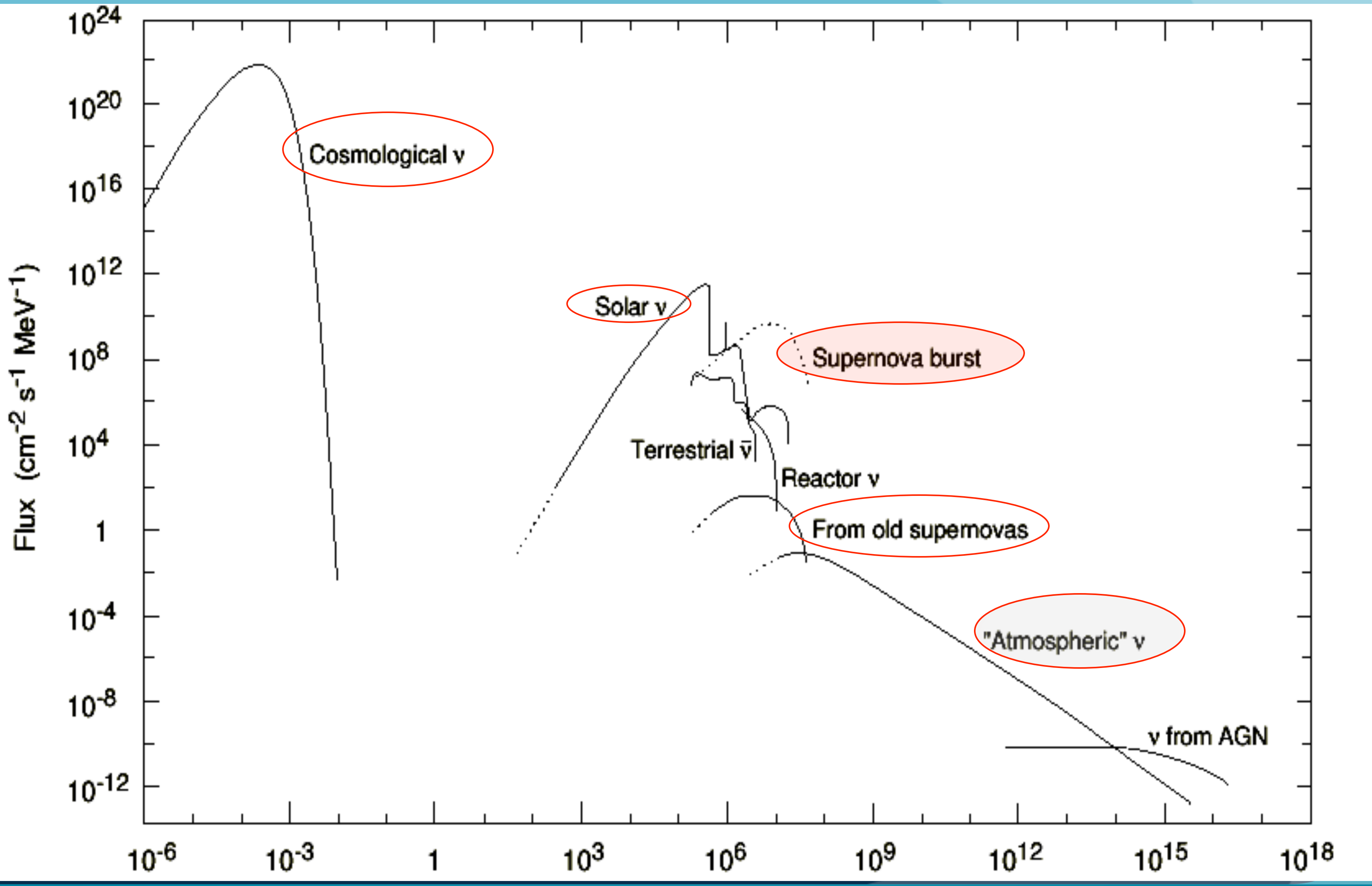
Z^0 width measured
contributions from quarks and leptons calculated

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_l + N_\nu \Gamma_\nu$$

$$N_\nu = 2.99 \pm 0.02$$

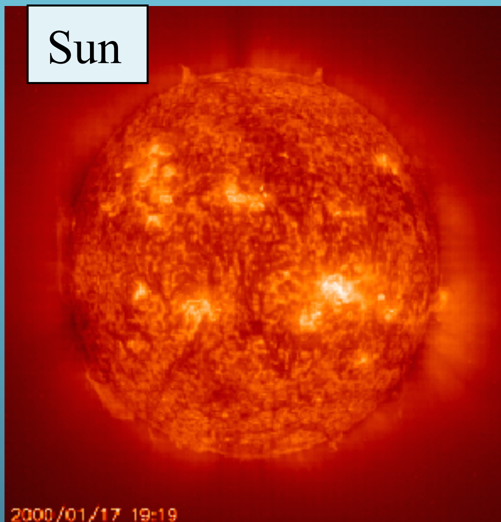
total width ~ decay probability (~1/lifetime)
partial width ~ branching rate (channel i)

Natural sources of neutrinos

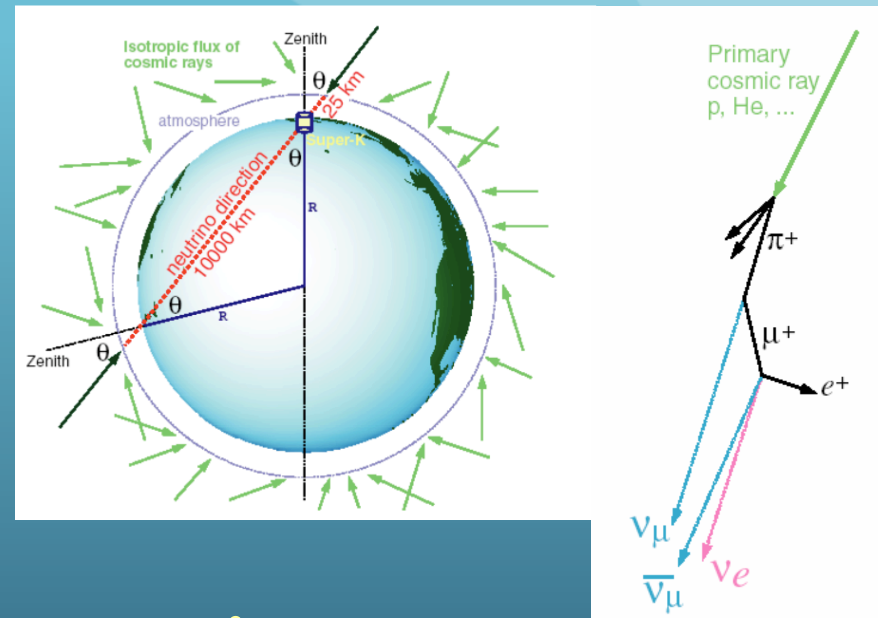


Neutrino sources

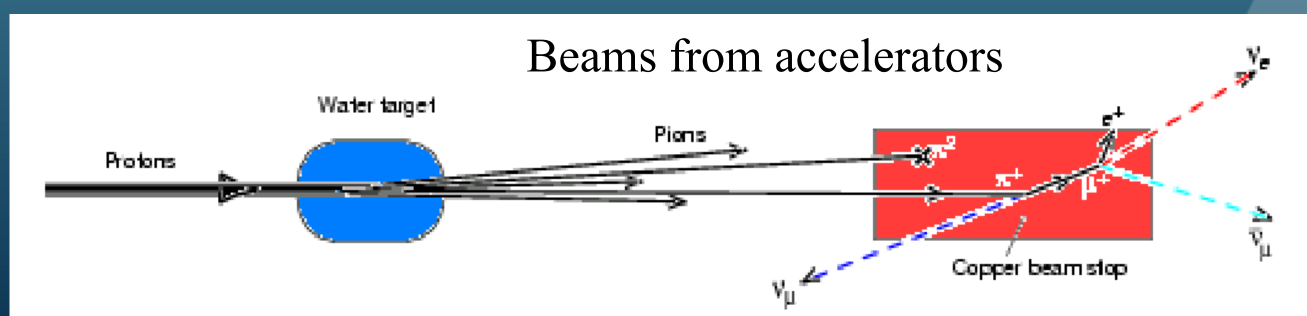
Natural



Cosmic rays → atmospheric neutrinos



Man made neutrinos



How to detect neutrinos – i.e. products of their interactions?

- Go underground to reduce background
- Make your detector big

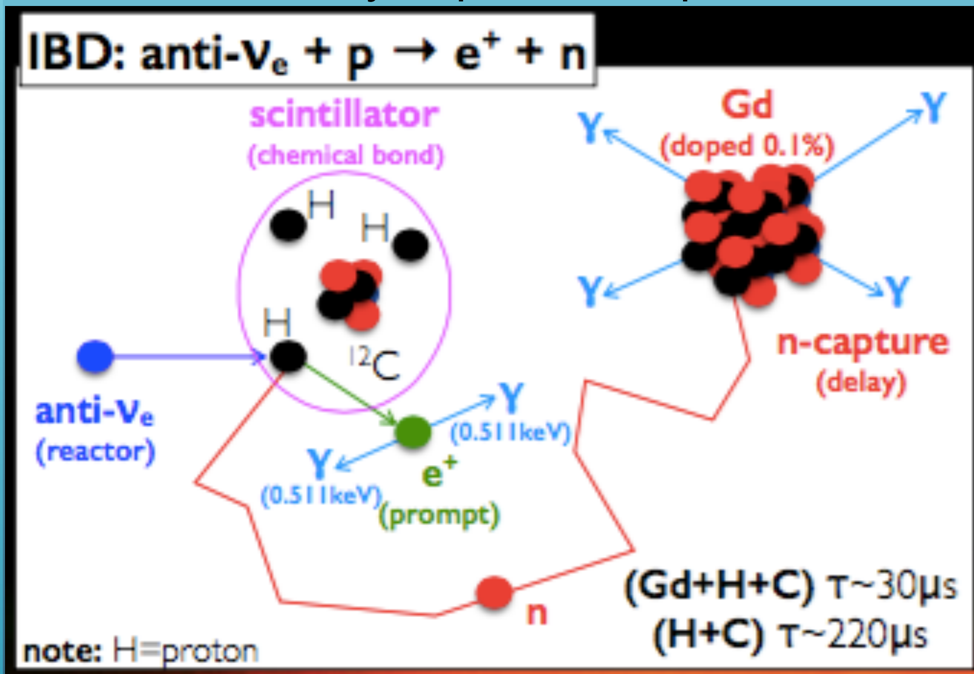
→ use large volumes of cheap materials

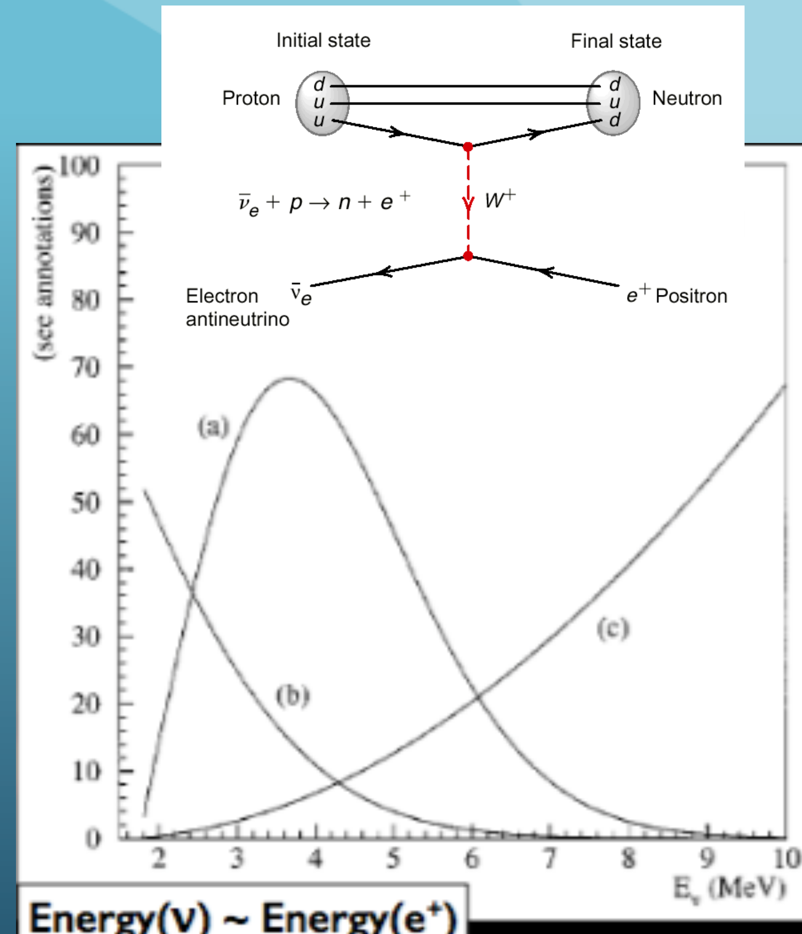
Typical detection techniques:

- **Radiochemical – counting neutrino interactions (no additional inform.)**
- scintillators – record scintillation light
- water (light or heavy) – record Cherenkov light
- liquid argon – record drifting electrons from ionization
- iron slabs as targets and various detectors to record exiting particles, includes emulsion

Inverse β decay (IBD) interaction

Method to observe (anti)neutrinos
from discovery to present experiments





Prompt signal from positron capture
Delayed photons from neutron capture

Method used in Kamland,
Daya Bay, Reno, Double Chooz

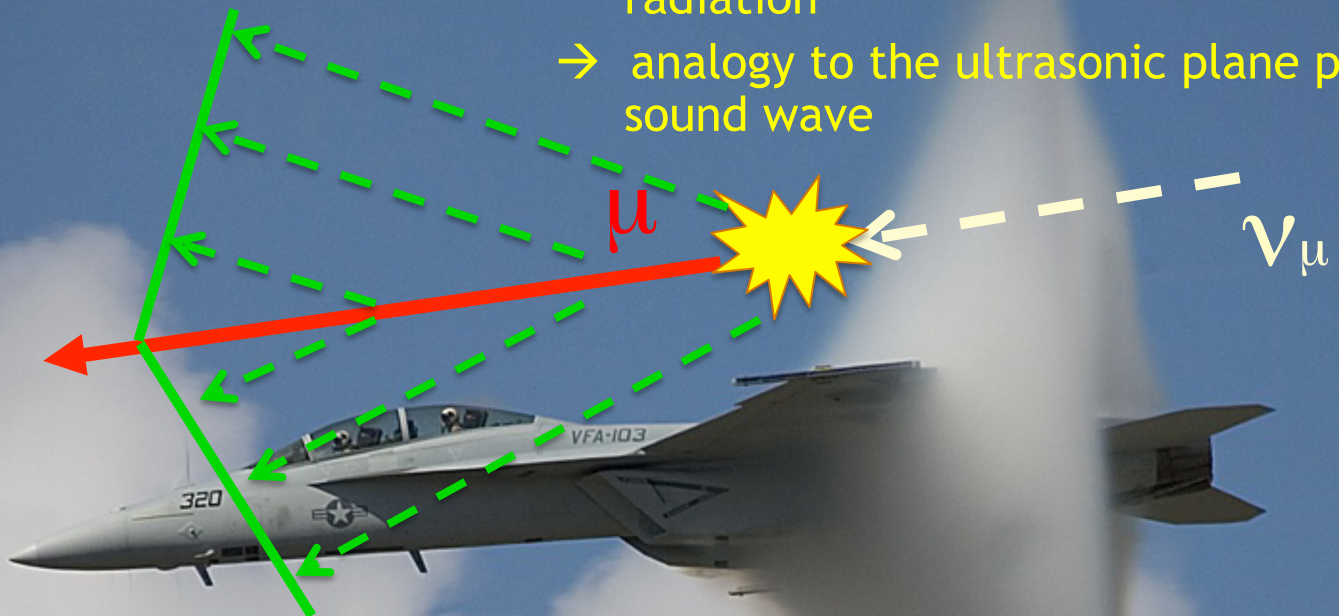
Observed neutrino energies (reactor) convolution of:

- Flux of anti-neutrinos from rector
- Cross section for interaction

Cherenkov radiation

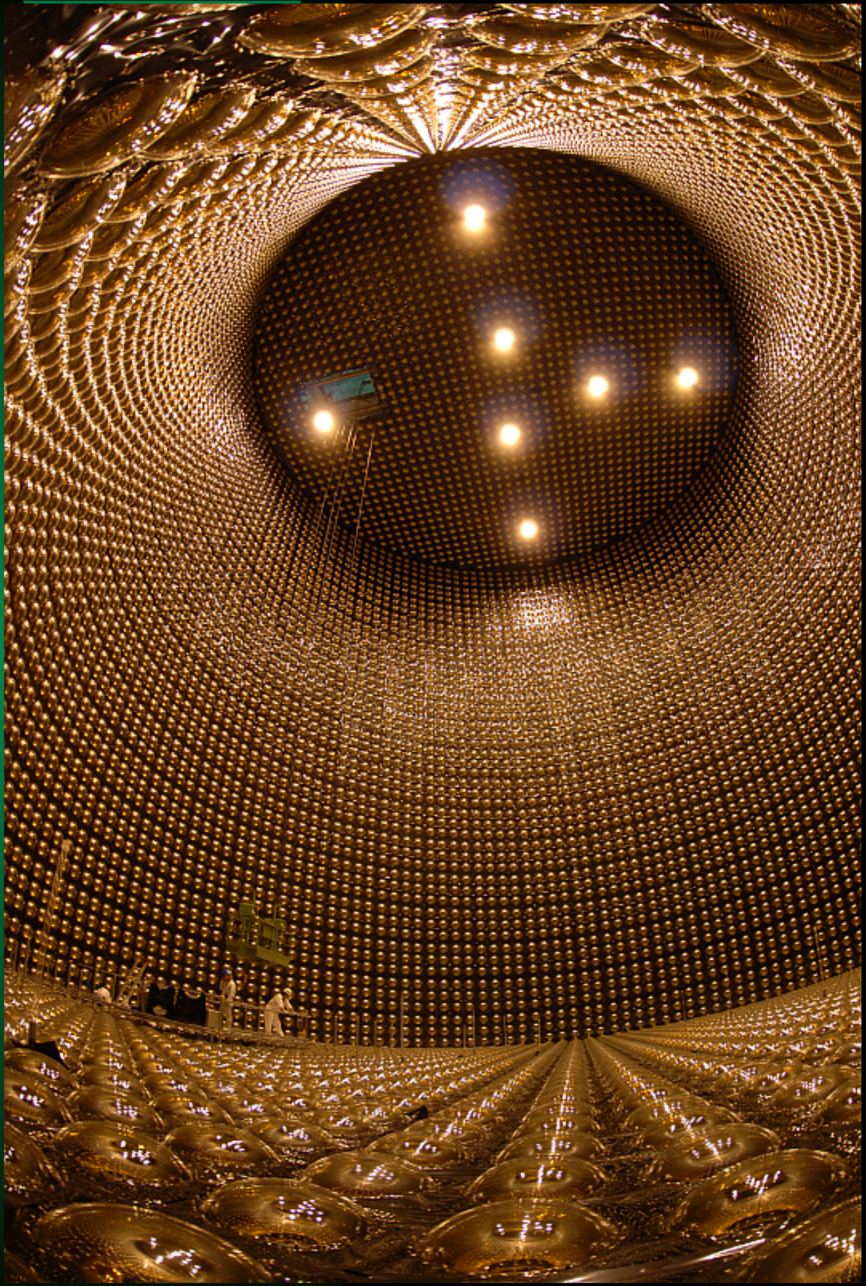
Charge particle moving in the media faster than light in this media emits electromagnetic radiation

→ analogy to the ultrasonic plane producing sound wave



Sensitive to CC
or NC with charge particle production

The light cone is produced
Energy emitted can be summed up from detected light
Direction can be determnied from time signal reaches walls
Position wher the emmision starts (vertex) is the interaction pont where charge particle is produced



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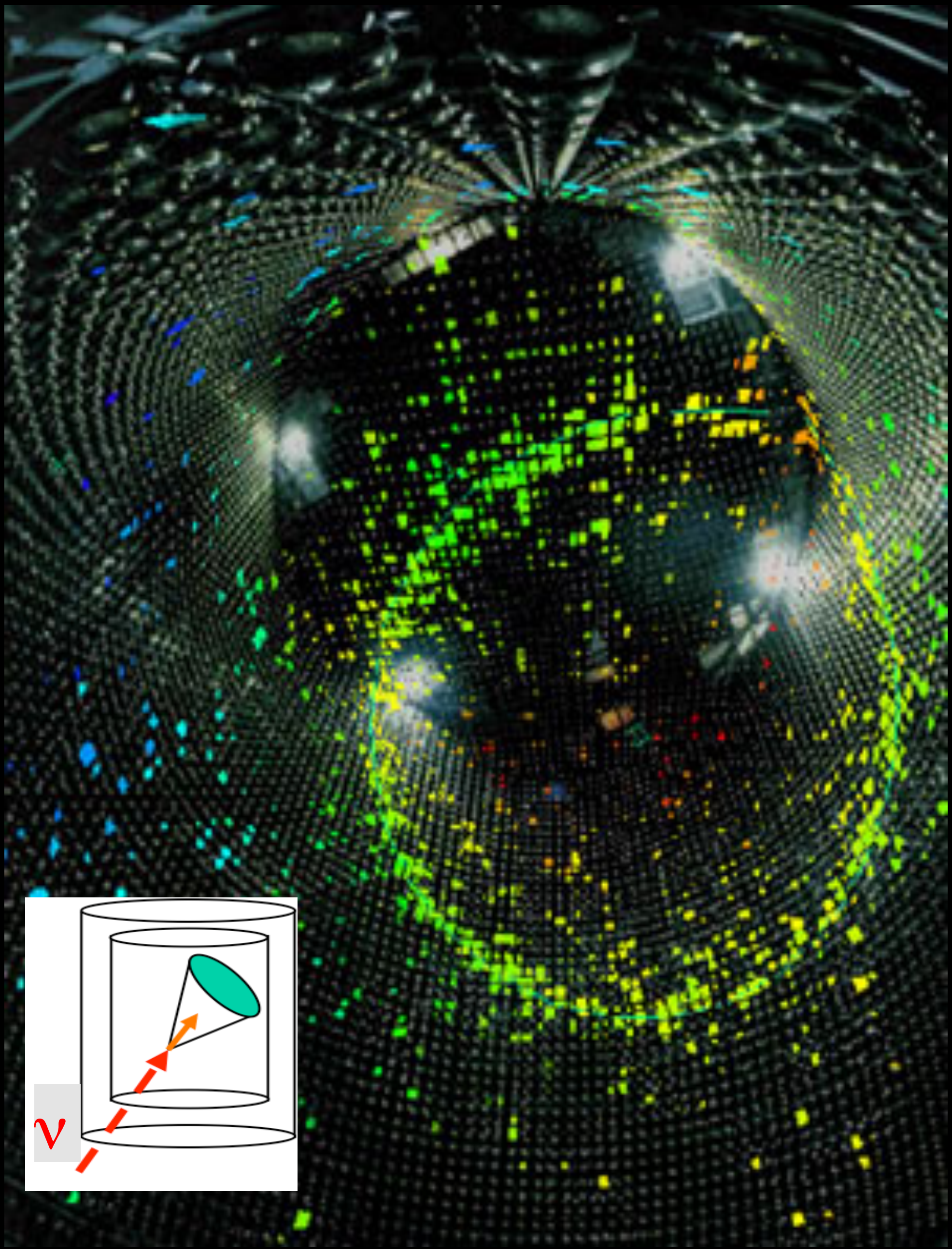

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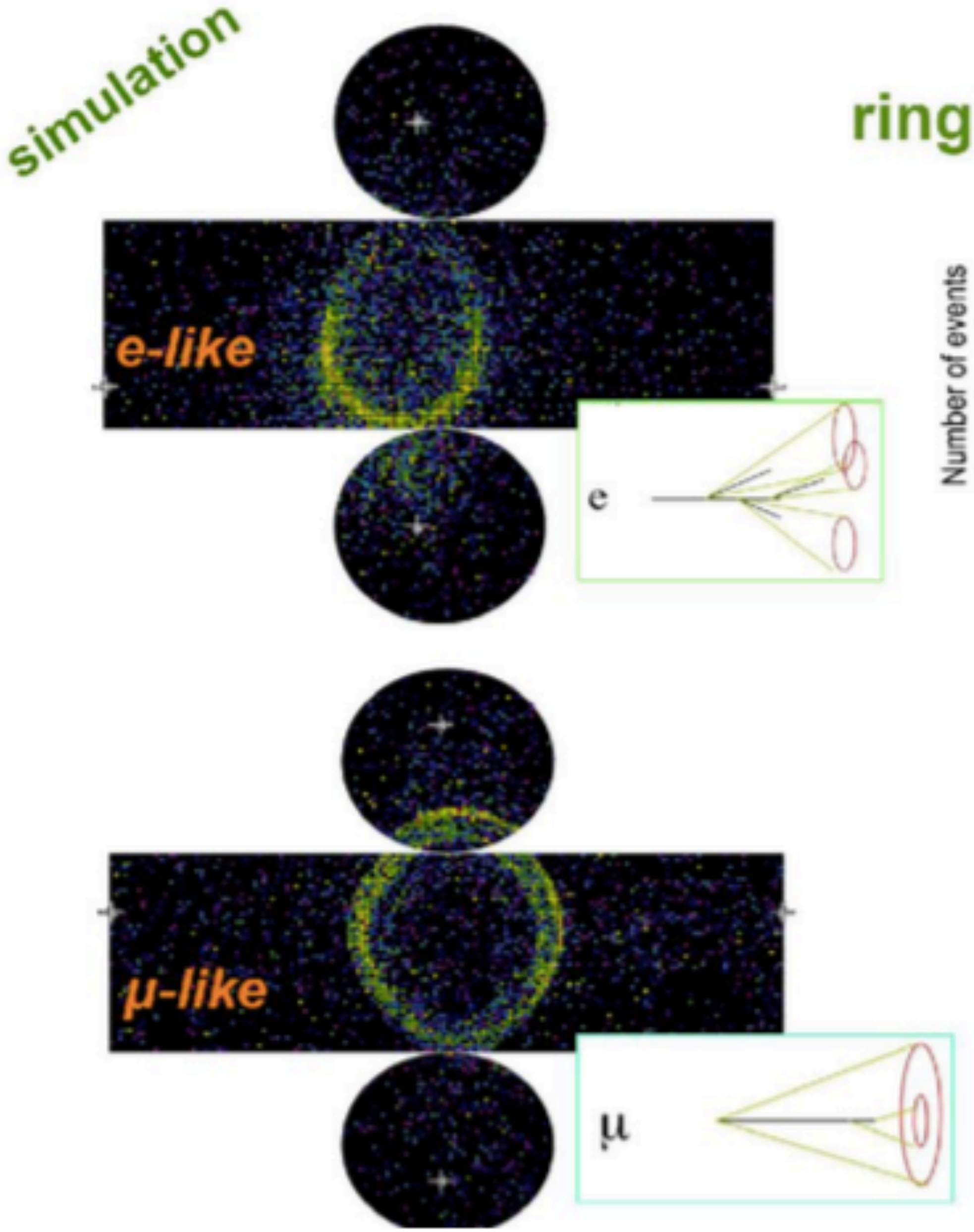
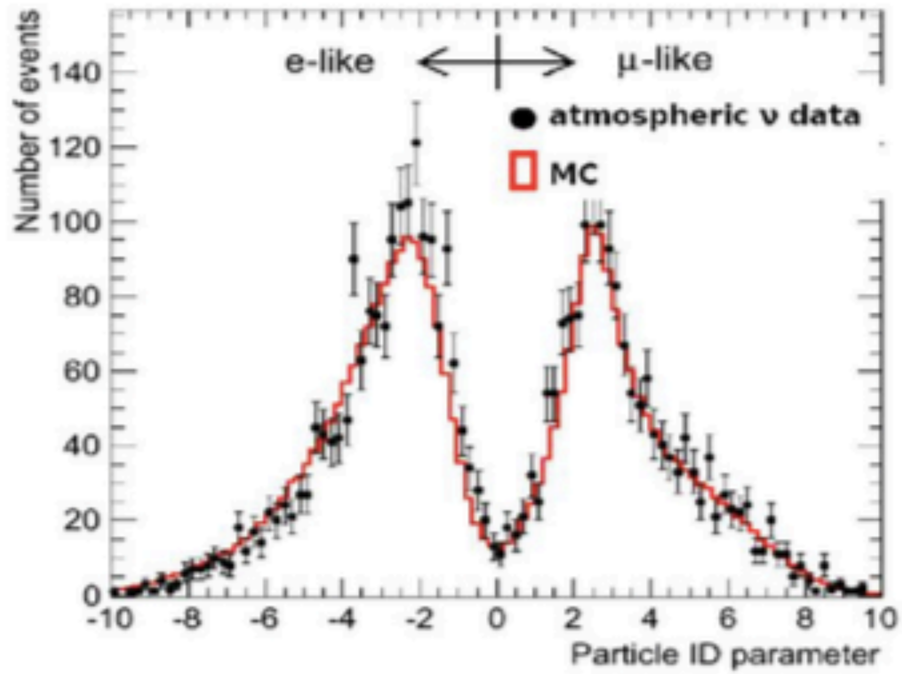


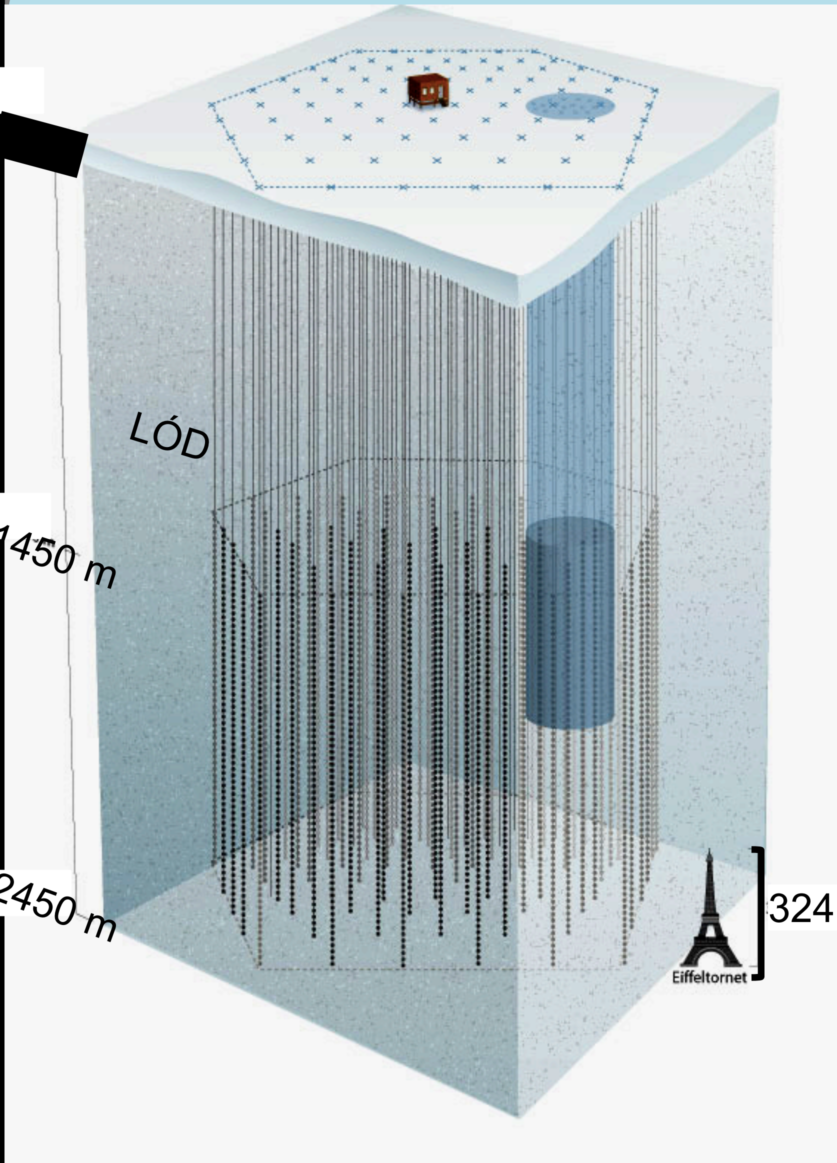
Particle ID using ring shape & opening angle



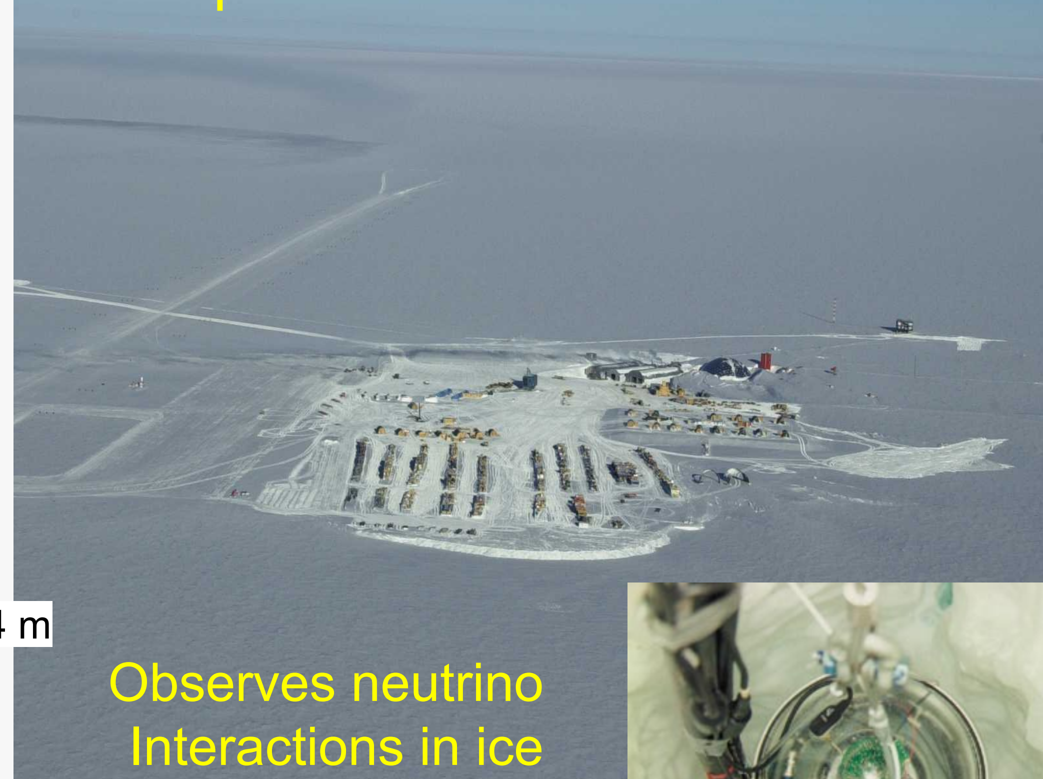
Probability that μ is mis-identified as electron is ~1%

IceCube

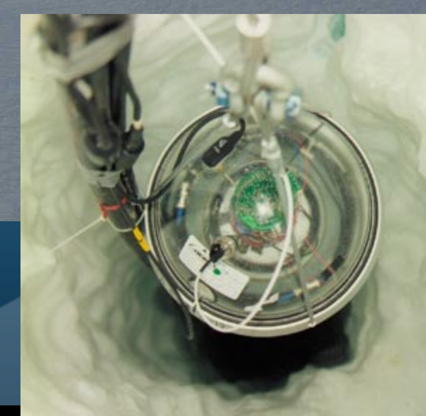
http://icecube.wisc.edu/



Experiment on the South Pol

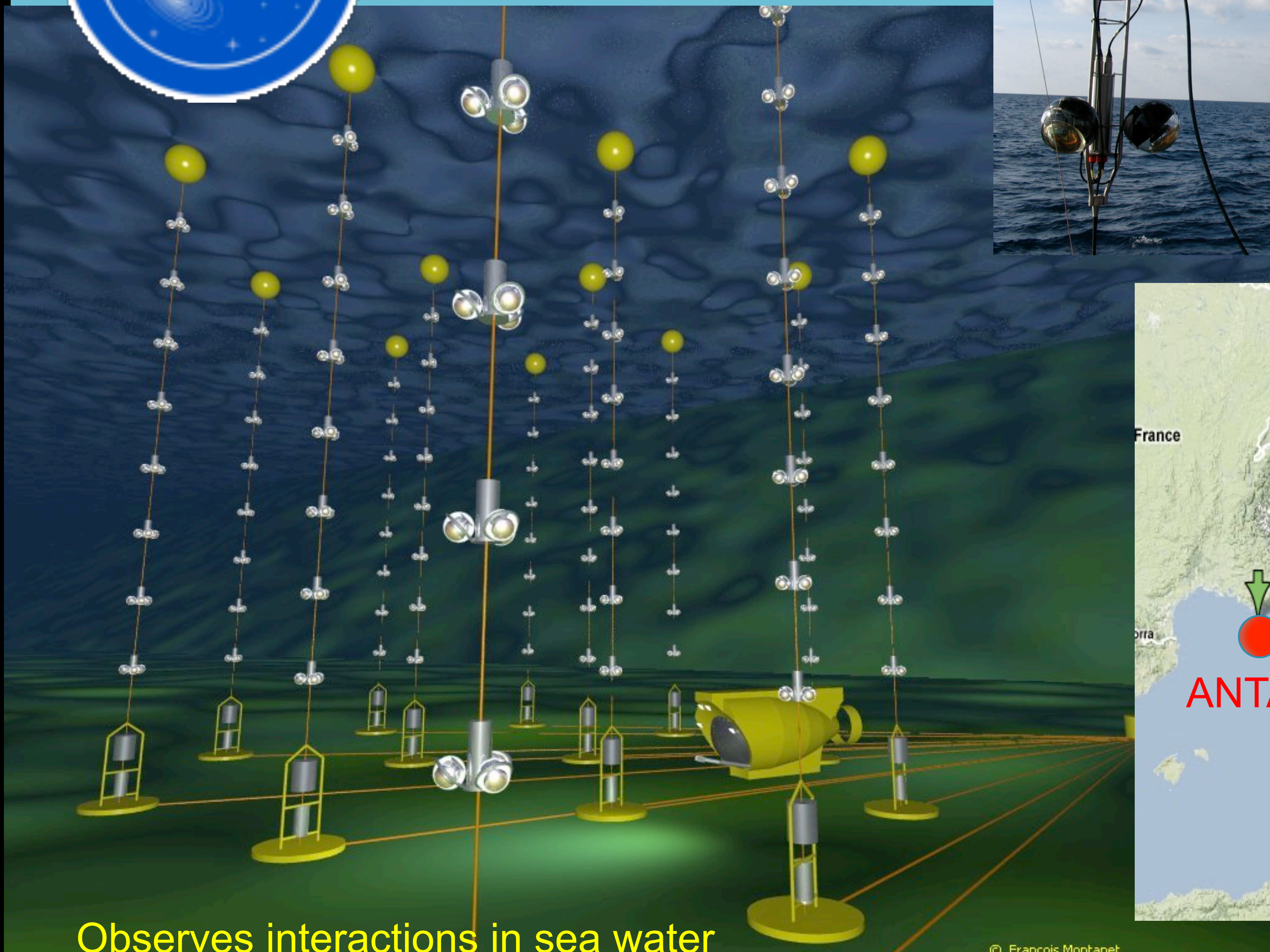


Observes neutrino
Interactions in ice



Antares

http://antares.in2p3.fr/



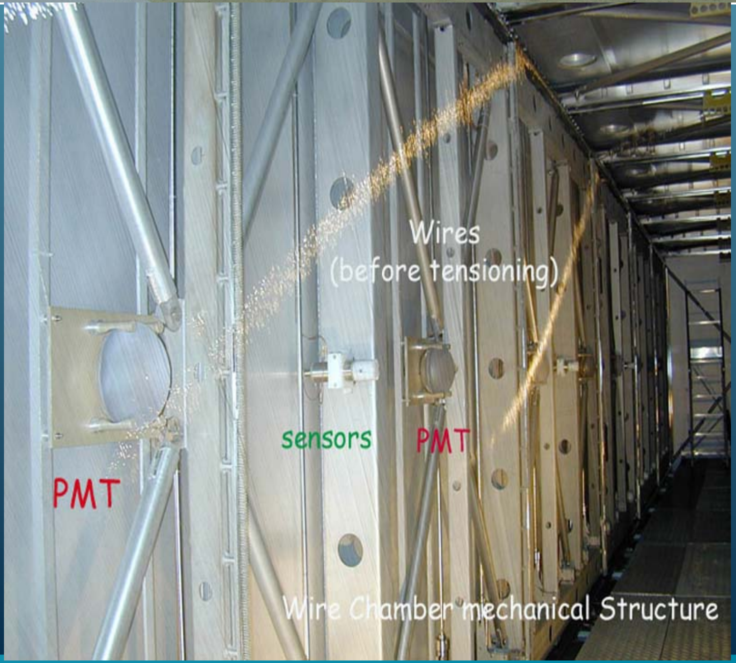
- Liquid argon time projection chamber (**Lar-TPC**)

- Bubble chamber like view o the interaction products
- Particel ID by dE/dx
- Good resolution

- Used in Gran Sasso to serch for

  $\nu_\mu => \nu_\tau$ (CNGS beam)

ICARUS



ICARUS

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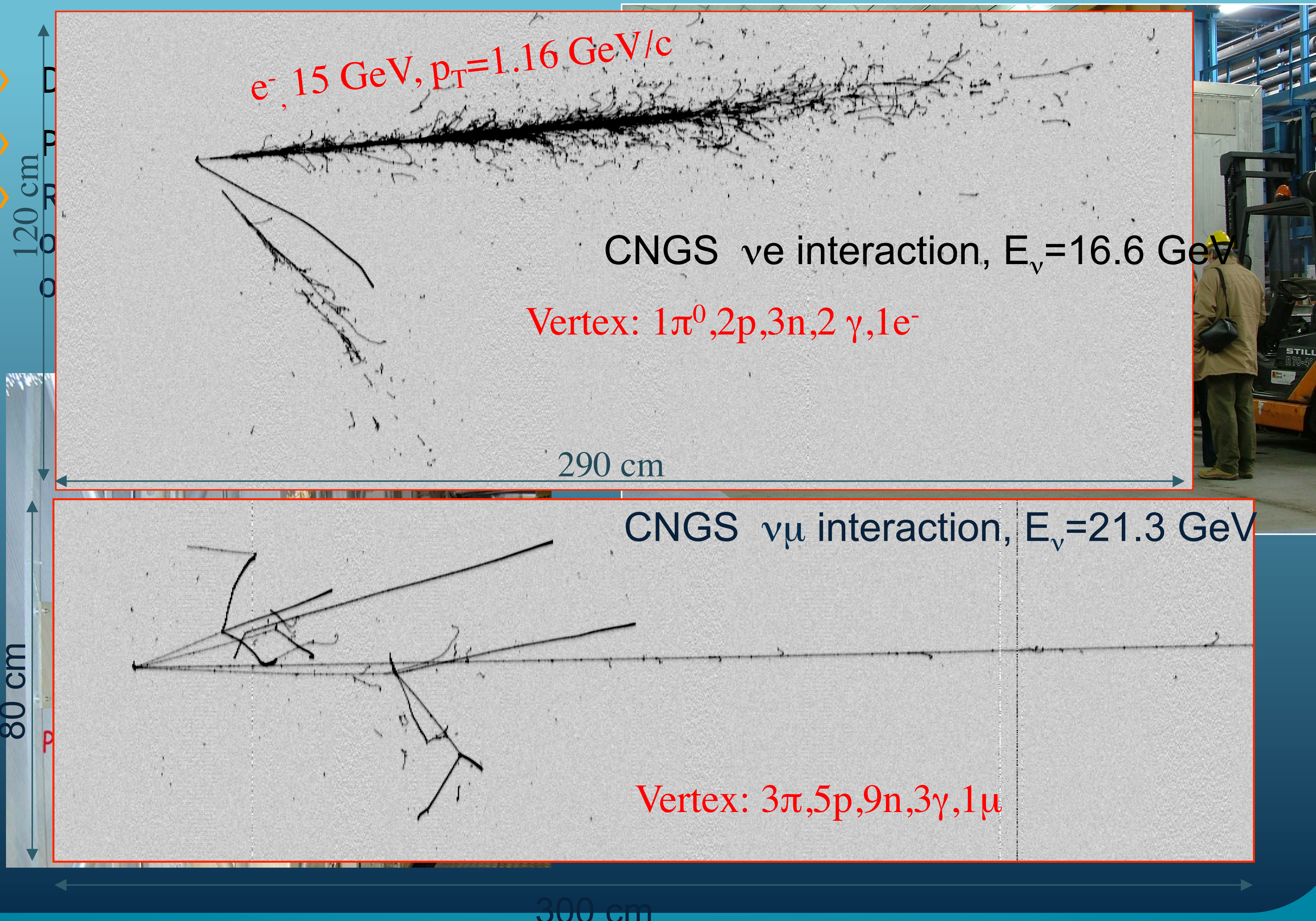
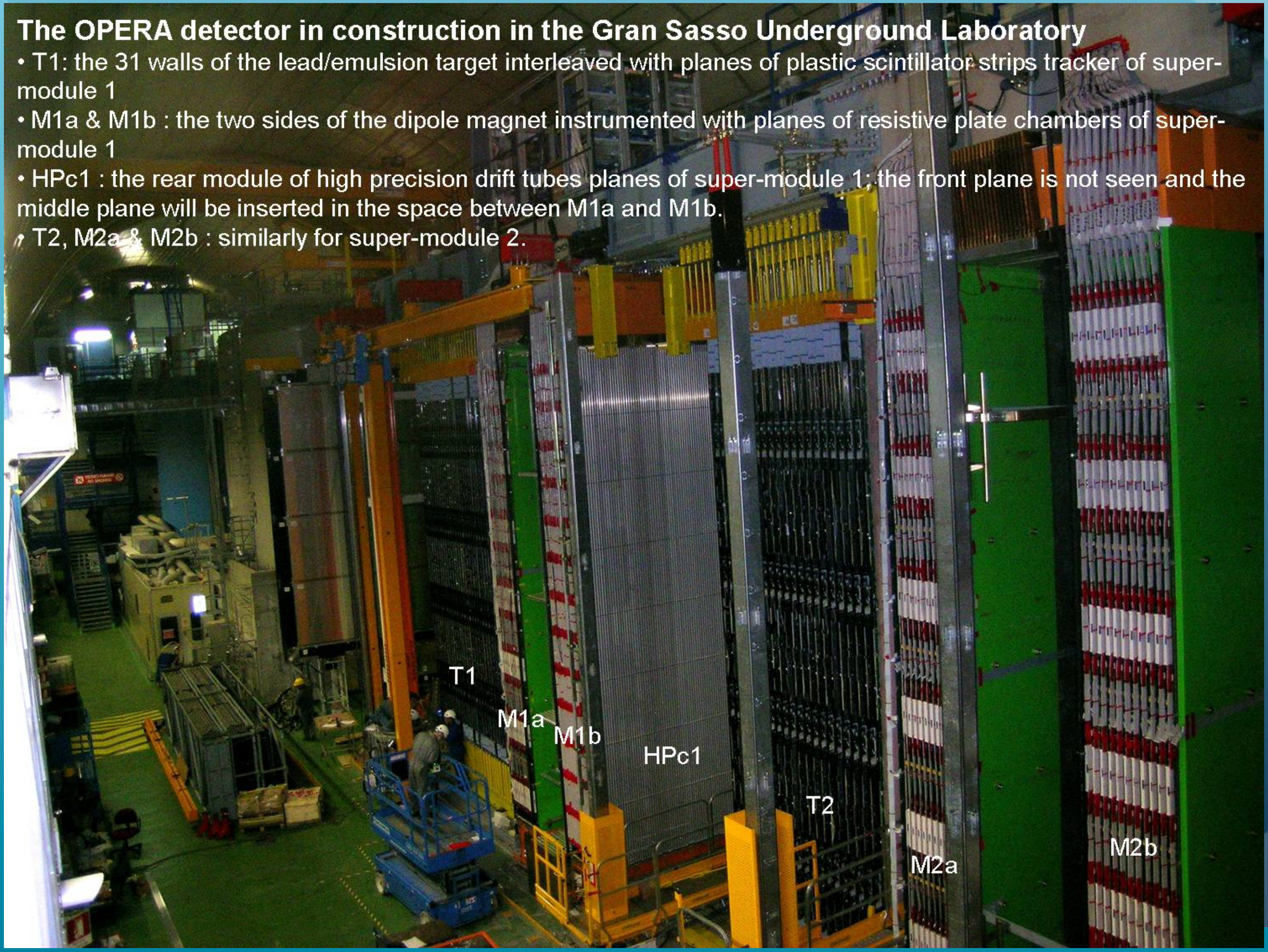


Sandwich like detectors:

interchanging layers of heavy material and sensitive one (scintillator)



large mass
+
tracking
+
energy measurement

possible to magnetize
→ charge measurement

Neutrino oscillations – experimental status and prospects

- From sources to detectors (and in between)

- Neutrino oscillation was a surprise in 90'th,
- now it is well established phenomenon and
  a lot of efforts are made to determine its parameters
- In future it can be a tool for
  - beyond SM effects
  - CP violation mechanism
  - Understanding matter-antimatter asymmetry

Neutrino oscillations – picture as of today

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

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

„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.
($\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$)

Sensitivity to oscillations

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

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….**

information from oscillation data:

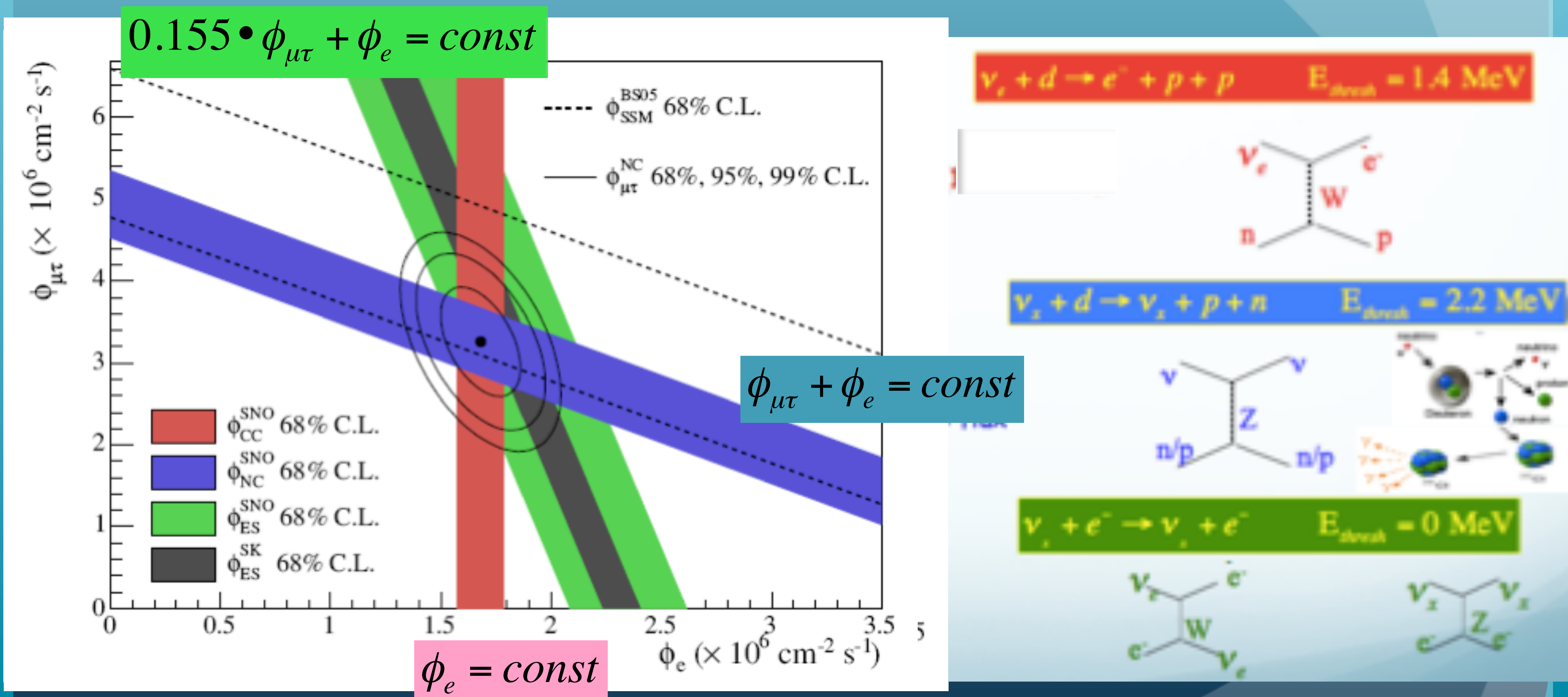
principle of the measurement:
→ Predict how many interactions should be seen in the detector
→ Compare with what is seen
if not consistent – take oscillation formula
and determine parameters

In leading order the analysis can be done for 2X2 cases
(solar and atmospheric), first results
With better precision mixing part (1-3) becomes important
3 flavour analysis is required

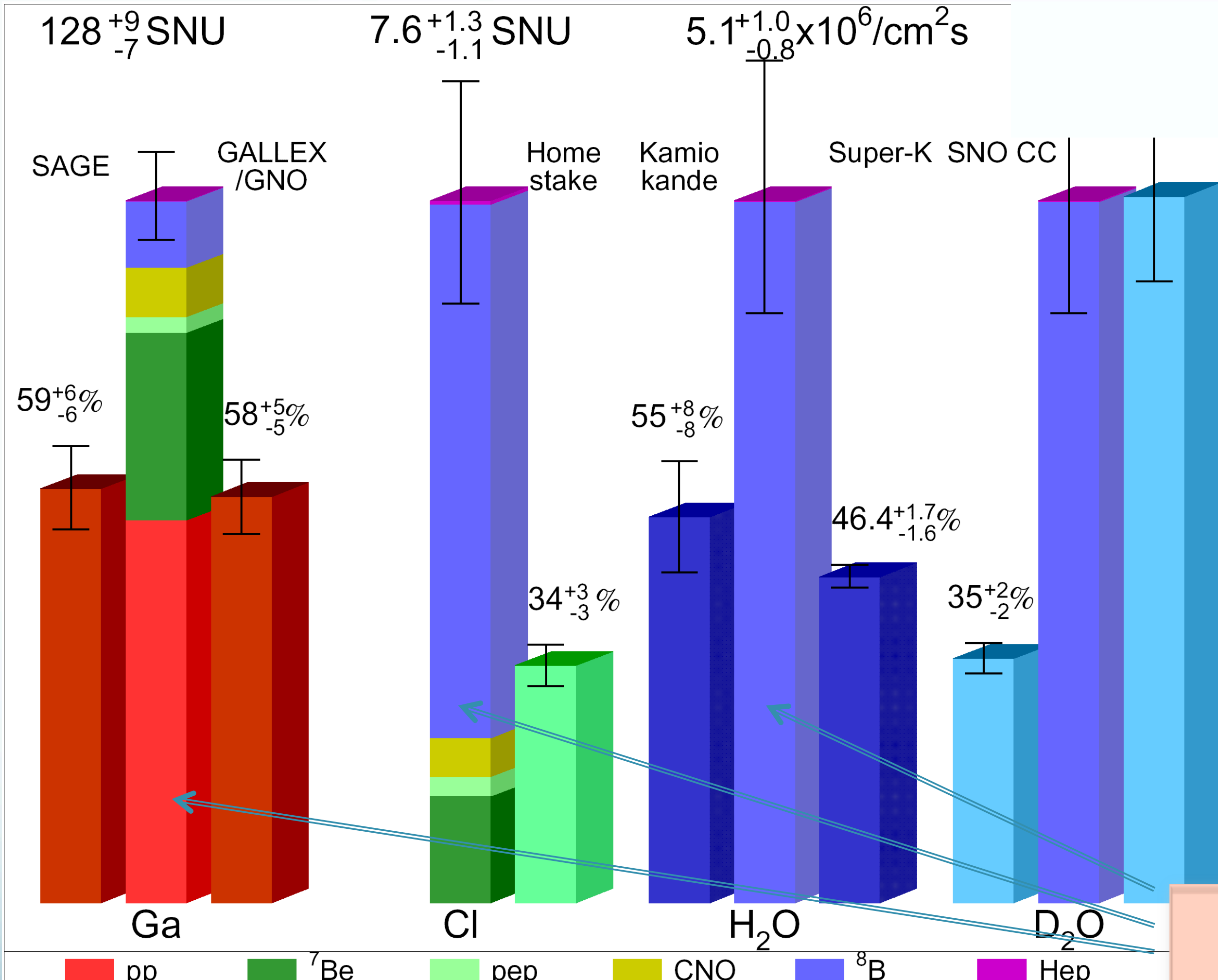
First approach – results leading to dicovery of neutrino oscillations → Nobel Prize 2015 (SK and SNO)

Just a reminder, as it was shown many times after Nobel Prize 2015

SNO experiment : measurement sensitive to 3 reactions
Including sensitivity to Neutral Currents



Solar Neutrino Puzzle - solution



Expectations Solar Model

Experiments

Results of measurements % of expectation

Contributions from processes in the Sun

reason for missing neutrino is their oscillation to other neutrino types, which are not detected in radio-chemical and Cherenkov H_2O experiments

But: $\Delta m^2_{12} \sim 10^{-5}$, not 10^{-10}
and **solar** and **reactor** oscillations are described by the same Δm^2

How to get it consistent?

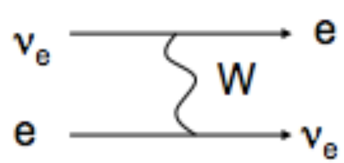
Need to consider matter effects (MSW effects):

propagation in matter neutrinos are not all equal

(as thy are in the vacuum)

Only ν_e has charged current elastic scattering

$\nu_{\mu,\tau}$ have neutral current only



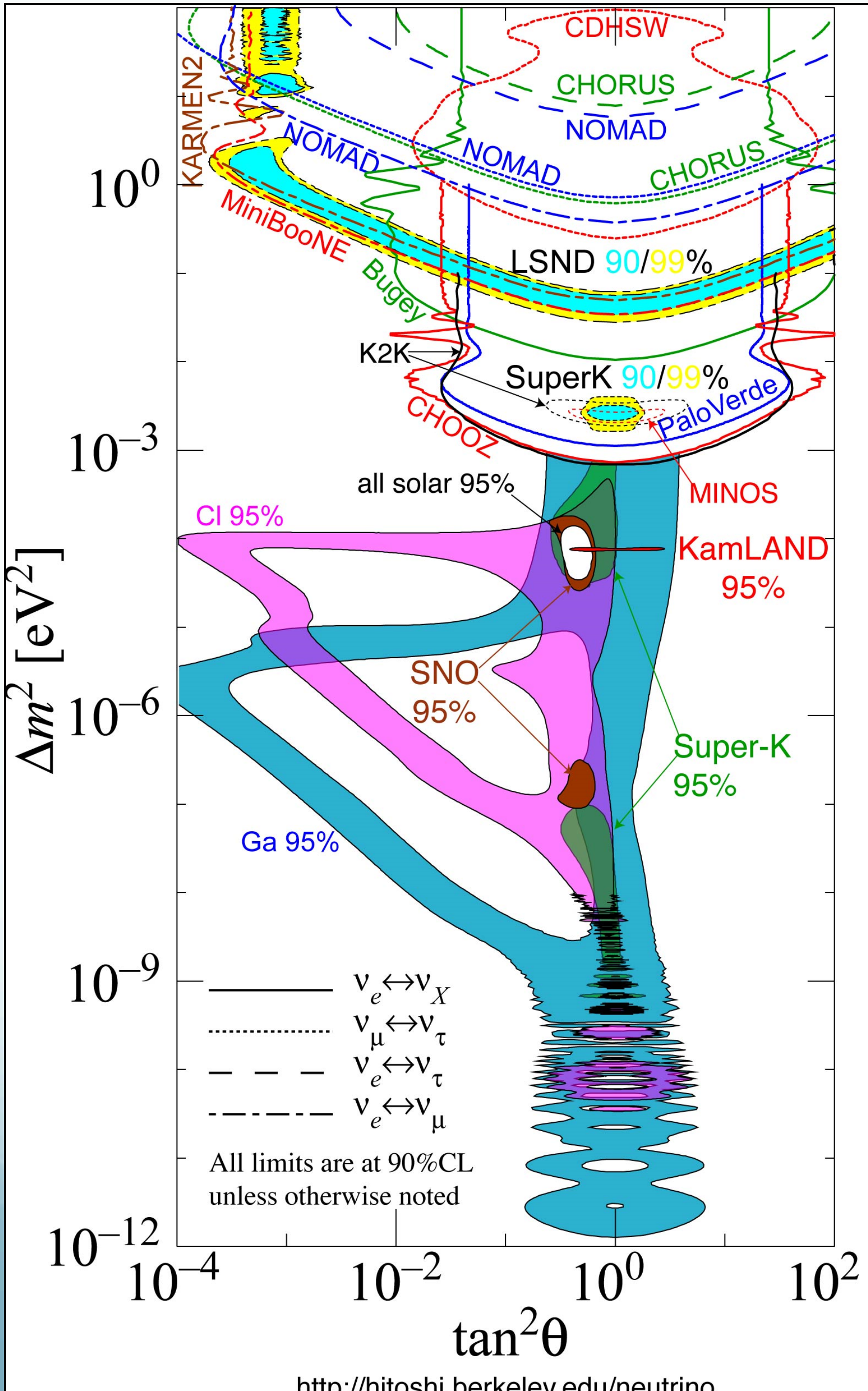
$$\nu_e(CC+NC): V_e = \pm\sqrt{2}G_F(1-\tfrac{1}{2}+2\sin^2\theta_W)\cdot n_e$$

$$\nu_{\mu,\tau}(NC) \quad : V_e = \pm\sqrt{2}G_F(-\tfrac{1}{2}+2\sin^2\theta_W)\cdot n_e$$

Additional term in the potential
modifies oscillation probabiities,
Δm^2 effective is introduce
for maximal effect we have condition:

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

Knowing electron density we can define m_1 , m_2 mass odrering

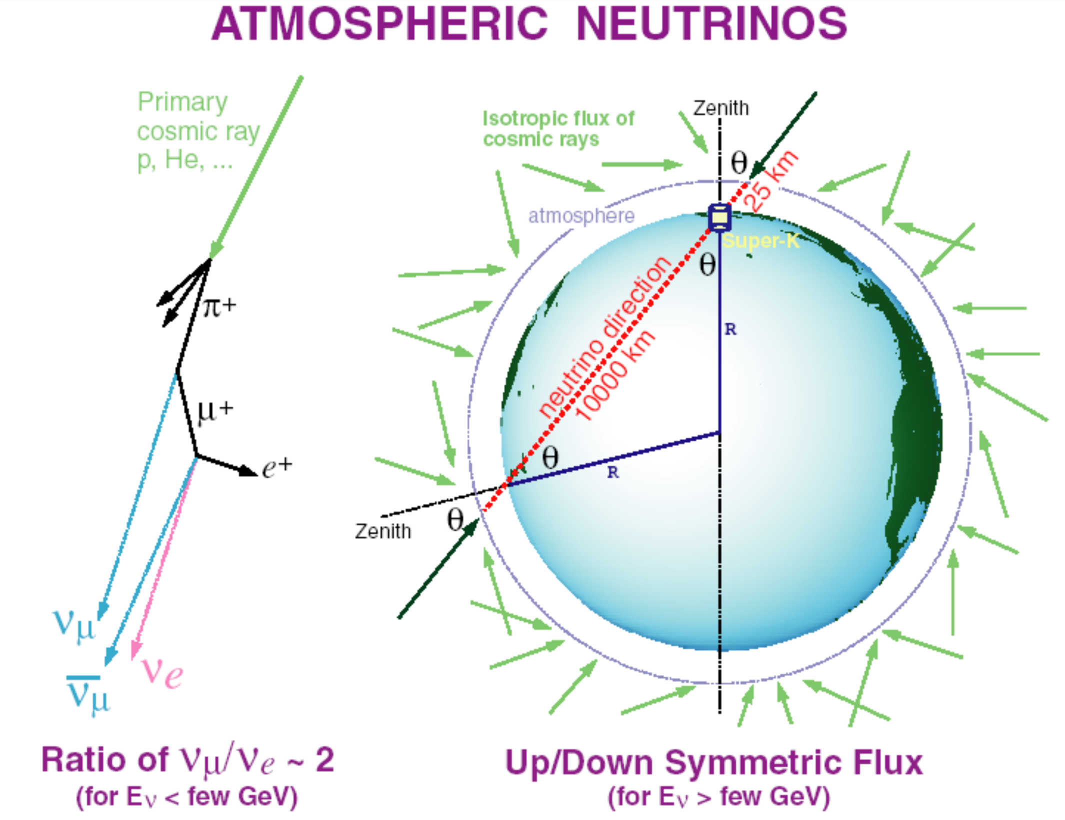


Looking at fits for solar neutrinos solutions for very low masses inconsistent for different energies common solution same as for Kamland (reactor anti-neutrinos)

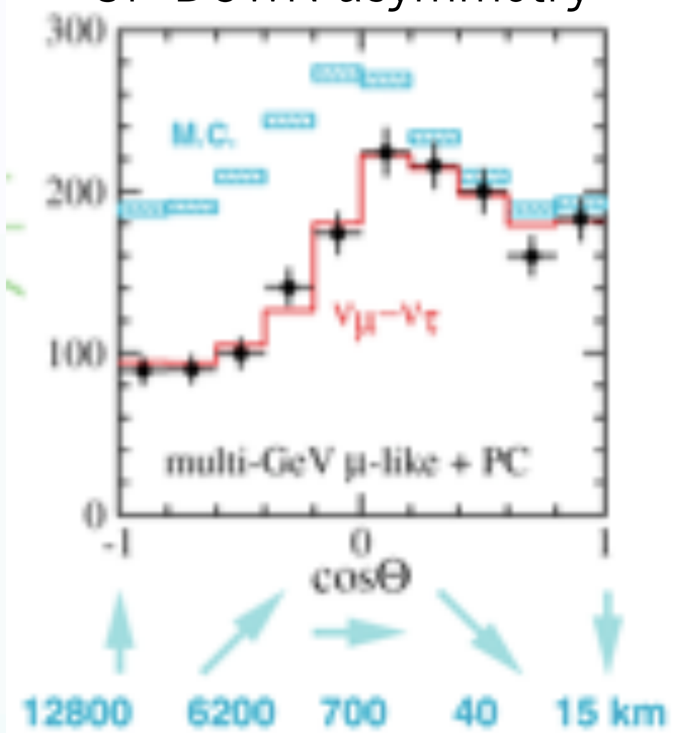
Conclusions for 1-2 sector

- ν_μ appearance shown in SNO through NC observation
- Solar neutrinos need matter effects for consistency
- Reactor anti-neutrino give Δm^2 and mixing consistent with solar neutrinos
- $\Delta m_{12}^2 \sim 10^{-5}$ eV^2
- Mixing not maximal (~30°)

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 $\nu_\mu \rightarrow \nu_\tau$

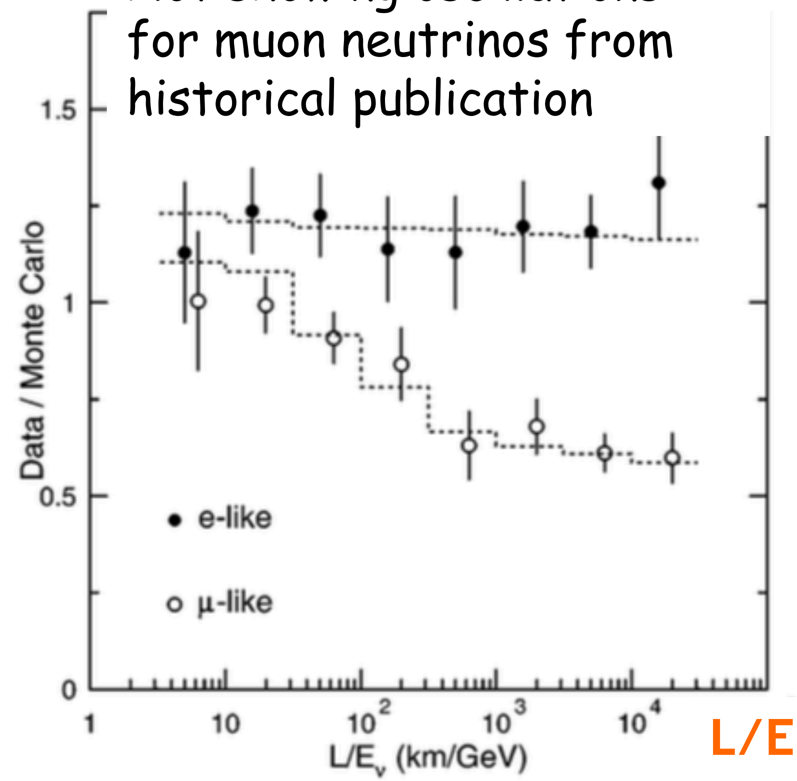
The neutrino interaction in SK is identified by observation of a charged lepton

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

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.

What we know more now from new measurements for solar (1-2), atmospheric (2-3) and sub-leading (1-3) neutrino oscillations?

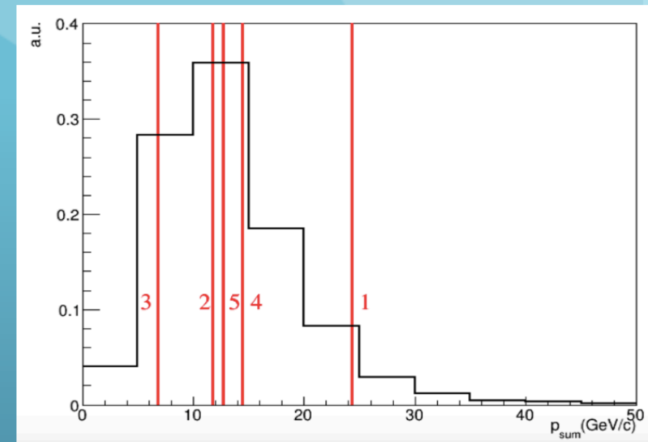
Observation of all expected transitions

appearance $\nu_\mu \rightarrow \nu_\tau$ OPERA

5 ν_τ CC candidates found, with 0.25 events background

exclusion of background-only hypothesis: 5.1 σ

discovery of ν_τ appearance



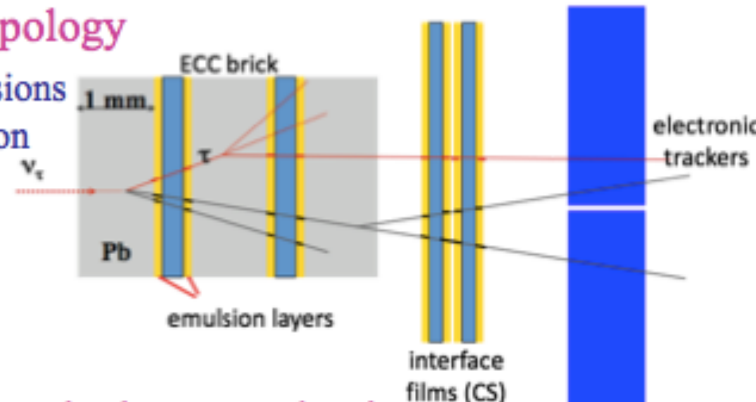
Sum of momenta of charged part and gammas

OPERA principle: hybrid detector with modular structure

direct observation of τ decay topology

→ μm resolution: photographic emulsions

→ large target mass: alternate emulsion films and lead sheets

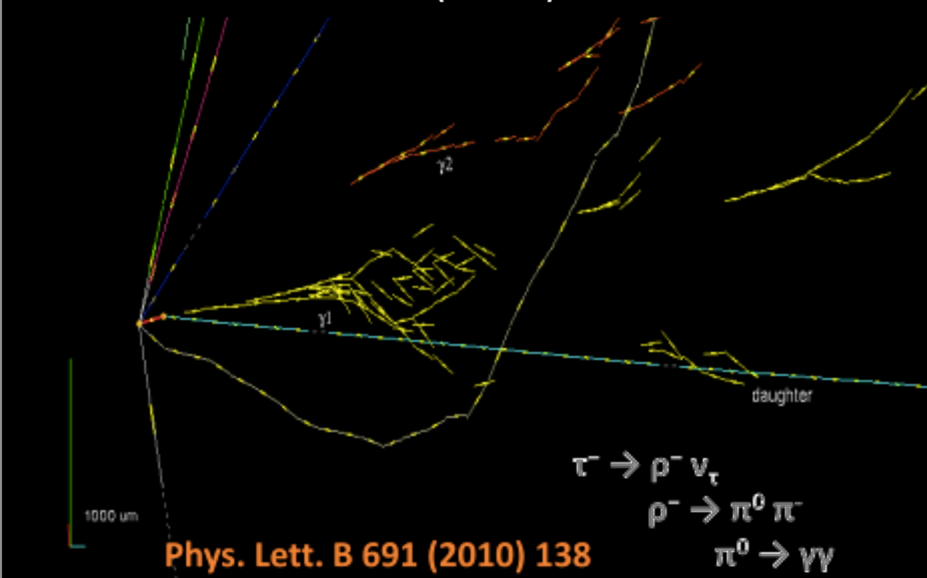


reject main topological background: charm production

→ good muon id and charge reconstruction: use electronic detectors

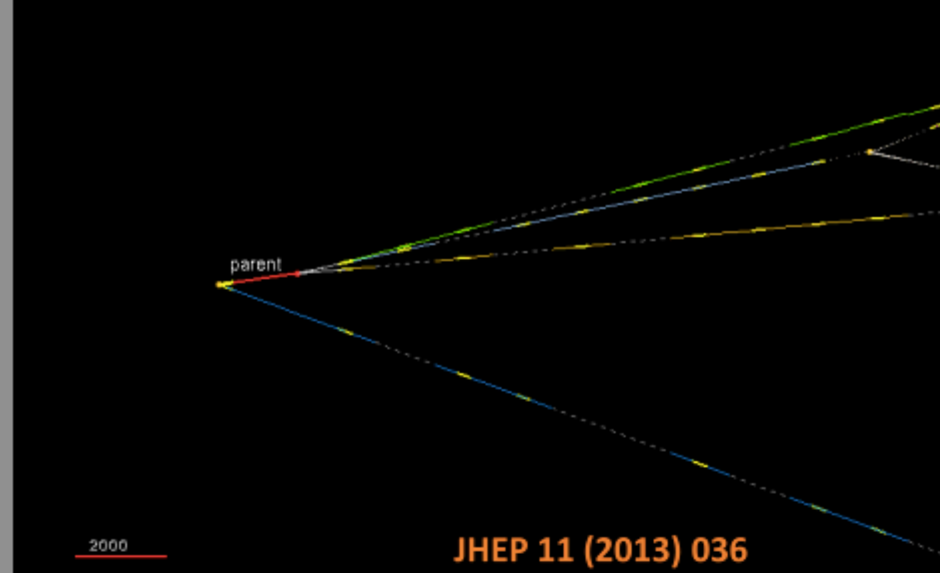
ν_τ events observed in OPERA

1st candidate (2010): $\boldsymbol{\tau \to h}$



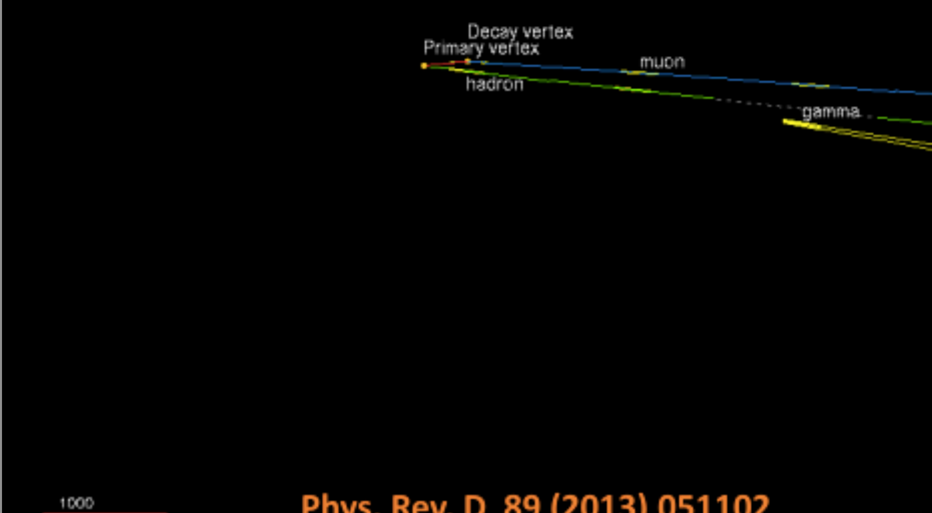
Phys. Lett. B 691 (2010) 138

2nd candidate (2012): $\boldsymbol{\tau} \to 3h$



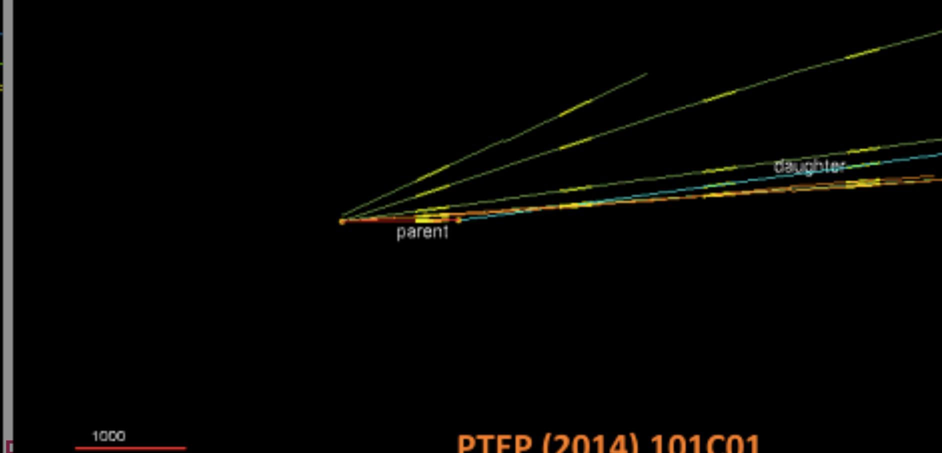
JHEP 11 (2013) 036

3rd candidate (2013): $\boldsymbol{\tau} \to \mu$



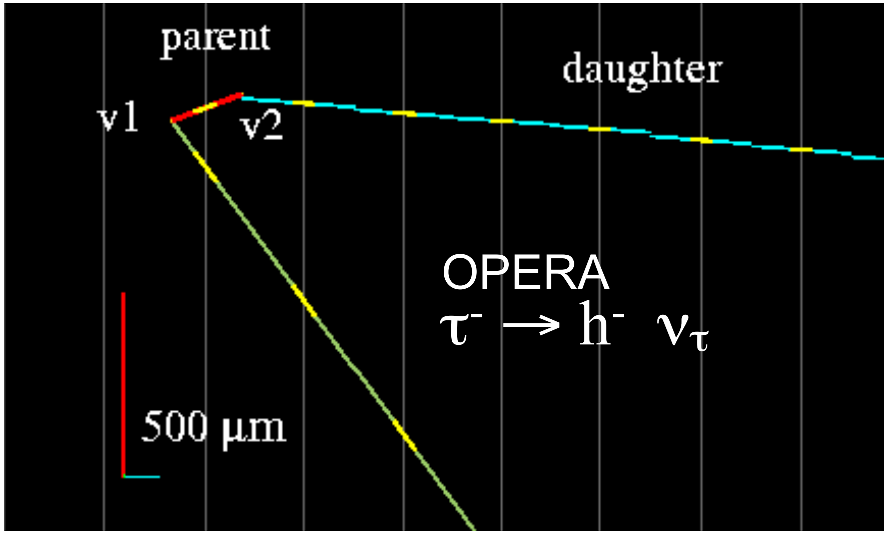
Phys. Rev. D 89 (2013) 051102

4th candidate (2014): $\boldsymbol{\tau} \to h$



PTEP (2014) 101C01

Fifth ν_τ candidate => discovery of ν_τ appearance



Probability to be explained by background fluctuation $p = 1.1 \times 10^{-7}$

No oscillation hypothesis excluded at 5.1 σ

$\Delta m_{23}^2 = 3.3 \times 10^{-3}\ eV^2$ with a 90% confidence interval $[2.0, 5.0] \times 10^{-3}\ eV^2$ (assuming full mixing)

Phys. Rev. Lett. 115 (2015) 121802

Decay channel	Expected background				expected signal events $\Delta m^2 = 2.44\times10^{-3}\ eV^2$	Observed events
	Charm	*Had. Re-interaction*	*Large μ scattering*	*Total*		
$\tau \rightarrow 1h$	0.017±0.003	0.022±0.006	-	0.04±0.01	0.52±0.10	3
$\tau \rightarrow 3h$	0.17±0.03	0.003±0.001	-	0.17±0.03	0.73±0.14	1
$\tau \rightarrow \mu$	0.004±0.001	-	0.0002±0.0001	0.004±0.001	0.61±0.12	1
$\tau \rightarrow e$	0.03±0.01	-	-	0.03±0.01	0.78±0.16	0
Total	0.22±0.04	0.02±0.01	0.0002±0.0001	0.25±0.05	2.64±0.53	5

Observation of last expected transitions

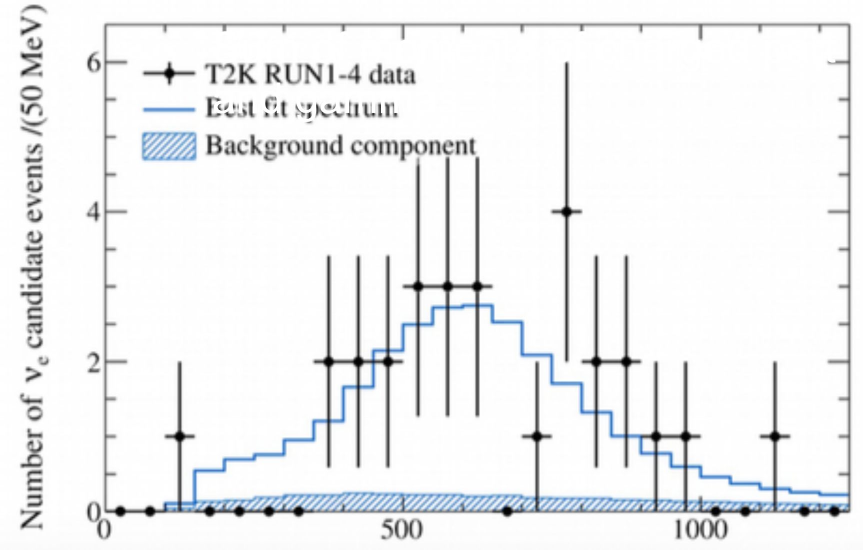
appearance $\nu_\mu \rightarrow \nu_e$ sector 1-3

expected background: 4.64 ± 0.53

observed (2013):

28 events

7.3σ significance for non-zero θ_{13}



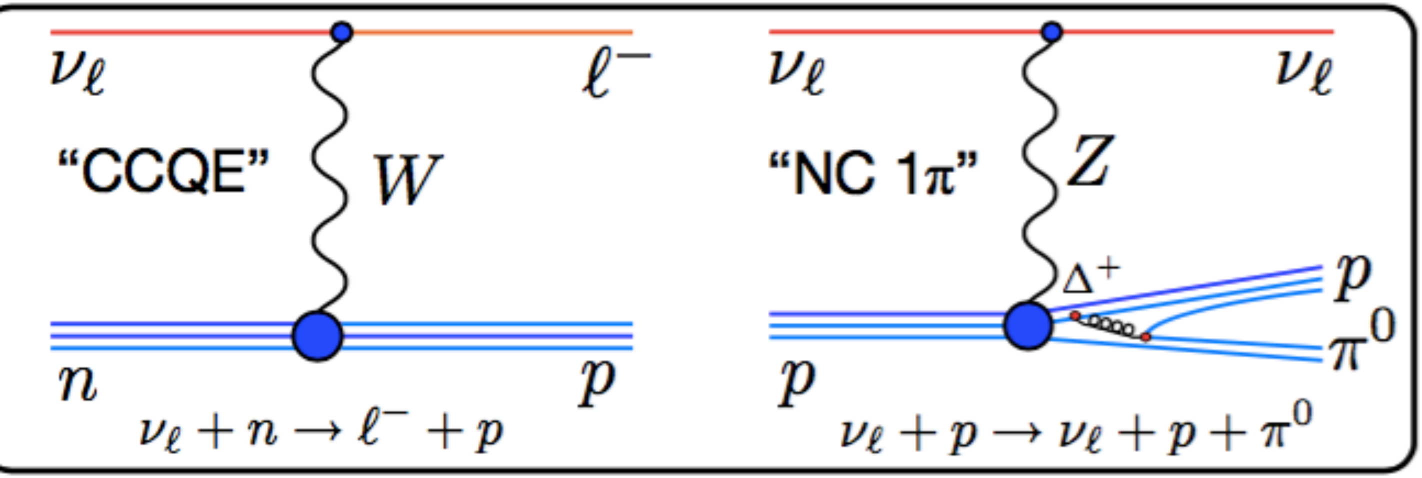
Reconstructed neutrino energy

How this observation was done?

T2K: accelerator experiment
beam from p and K decays

~400 collaborators
59 institutions

NEUTRINOS AT T2K-SK



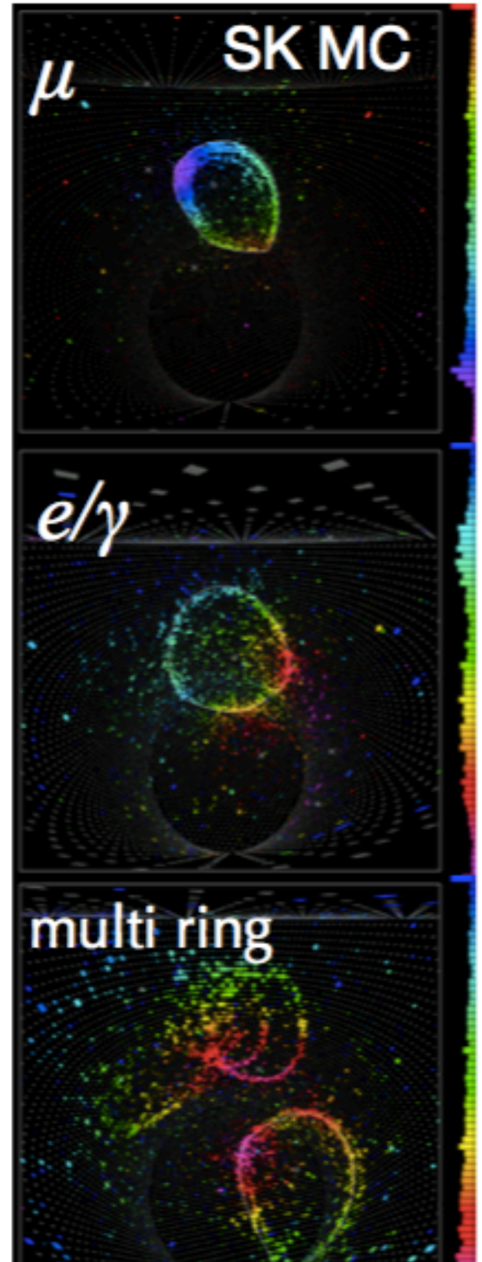
$\nu_\ell + n \rightarrow \ell^- + p \quad \bar{\nu} + p \rightarrow \ell^+ + n$ **Signal**

- Single μ/e-like ring
- E_{rec} by energy/direction of lepton, 2-body kinematics

$\nu_\ell + (n/p) \rightarrow \nu_\ell + (n/p) + \pi^0$ **Backgrounds**

$\nu_\ell + (n/p) \rightarrow \ell^- + (n/p) + \pi$

- $\pi^0 \rightarrow \gamma + \gamma$: ring counting, 2-ring reconstruction
  - γ misidentified as e from ν_e CCQE
  - powerful rejection capabilities reduce this by $O(10^2)$
- Ring counting, decay electron cut to reject nCCQE



- Pure ν_e samples (S/B~10 at peak) obtained with high efficiency

Observation in neutrino beam

Selecting candidates for electrons | selecting candidates for muons

e-like

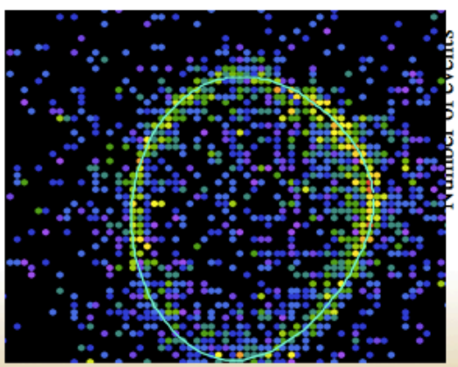
- Electron-like ring
- $E_{vis} > 100$ MeV
- $N_{michels} == 0$
- $E_{\nu,\,rec} < 1250$ MeV
- Not π^0-like

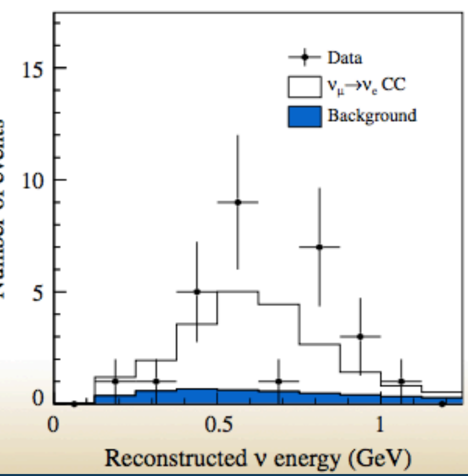
28 ν_e events

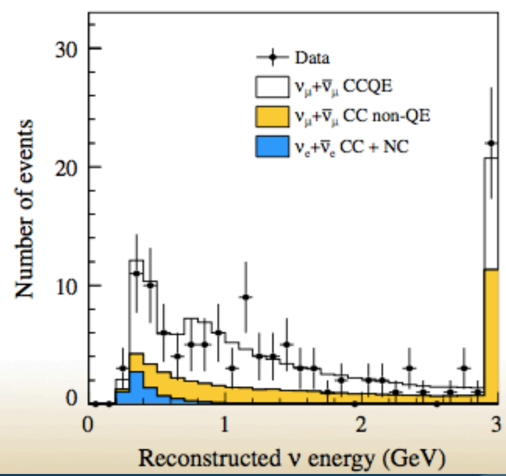
μ-like

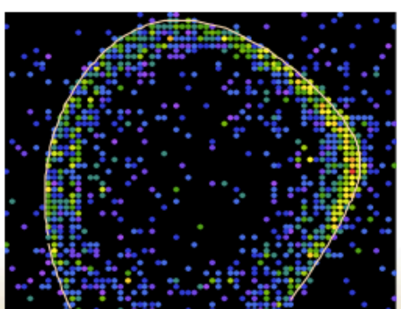
- Muon-like ring
- $P_\mu > 200$ MeV/c
- $N_{Michels} < 2$

120 ν_μ events









appearance

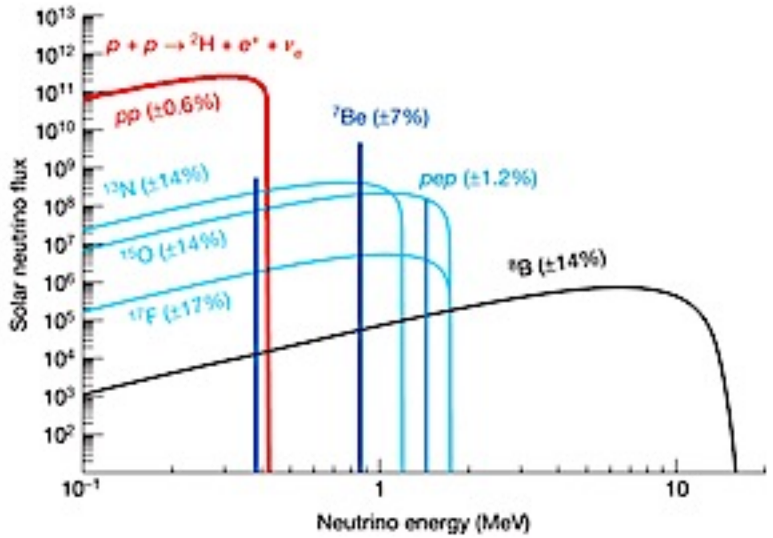
disappearance

Improving oscillation parameters what is a goal, how it is done?

- To get oscillation parameters we need to fit probability of disappearance and/or appearance as a function of L/E
- Input: ratio of observed interactions (of given neutrino flavour – defined by produced charged lepton) to expected number (if no oscillations would be present)
- What needs to be done?
  - Improve statistics of interactions observed "after oscillations" → done by larger detectors, long time, better selection
  - Improve predictions → understand source (Sun, reactor, beam..) and measure "before oscillation" and extrapolate

Borexino precise results

- Detection based on inversed beta-decay
- Present results:
  - Testing SSM (Standard Solar Model)

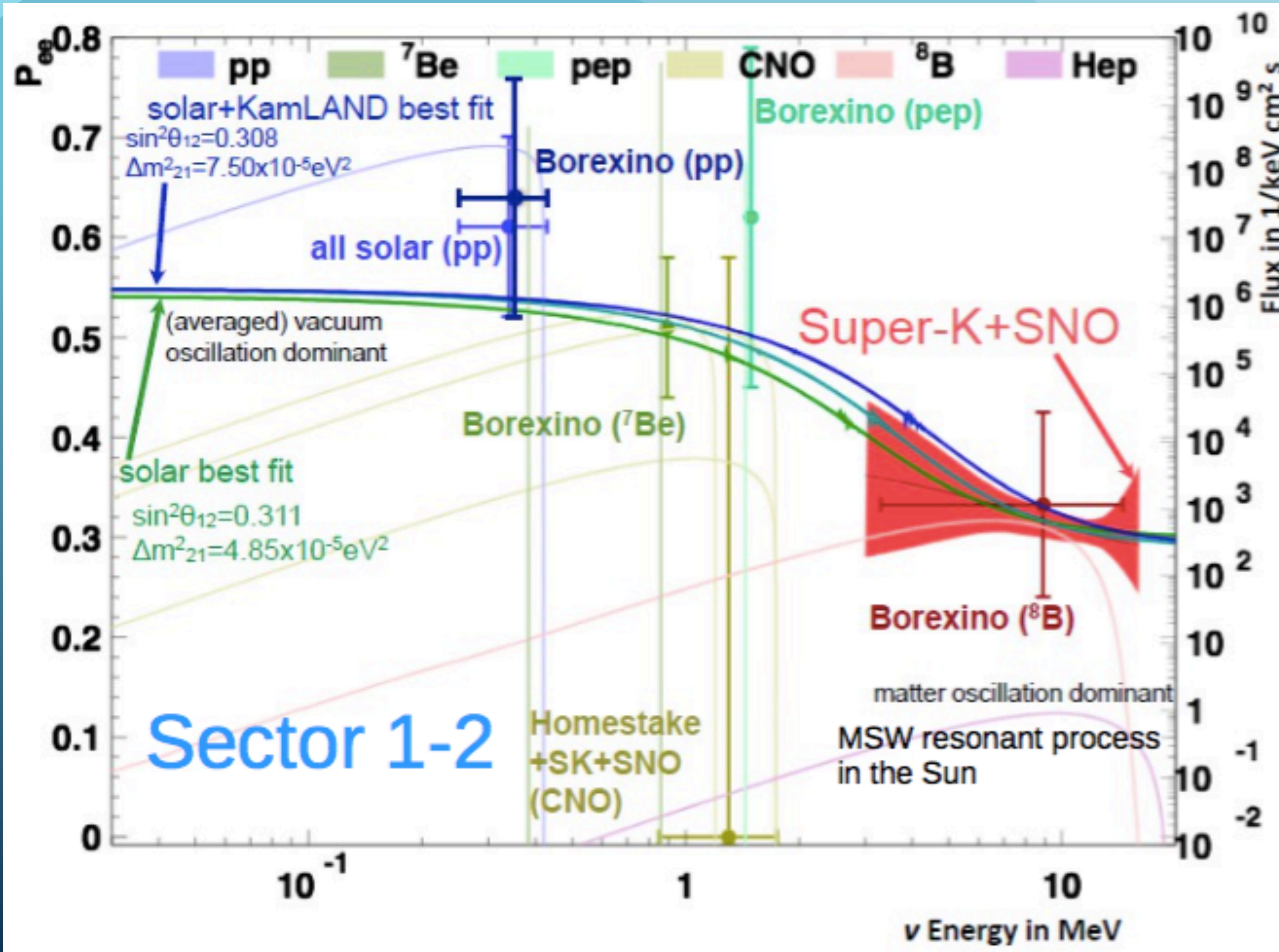


ν flux	GS98	AGS09	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	Experimental result
pep	1.44 ± 0.012	1.47 ± 0.012	$\times 10^8$	1.6±0.3 Borexino
^{7}Be	5.00 ± 0.07	4.56 ± 0.07	$\times 10^9$	4.87 ± 0.24 Borexino
^{8}B	5.58 ± 0.14	4.59 ± 0.14	$\times 10^6$	5.2 ± 0.3 SNO+SK+Borexino+KamLAND $5.25 \pm 0.16^{+0.011}_{-0.013}$ SNO-LETA
^{13}N	2.96 ± 0.14	2.17 ± 0.14	$\times 10^8$	<7.4 Borexino (total CNO)
^{15}O	2.23 ± 0.15	1.56 ± 0.15	$\times 10^8$	
^{17}F	5.52 ± 0.17	3.40 ± 0.16	$\times 10^8$	

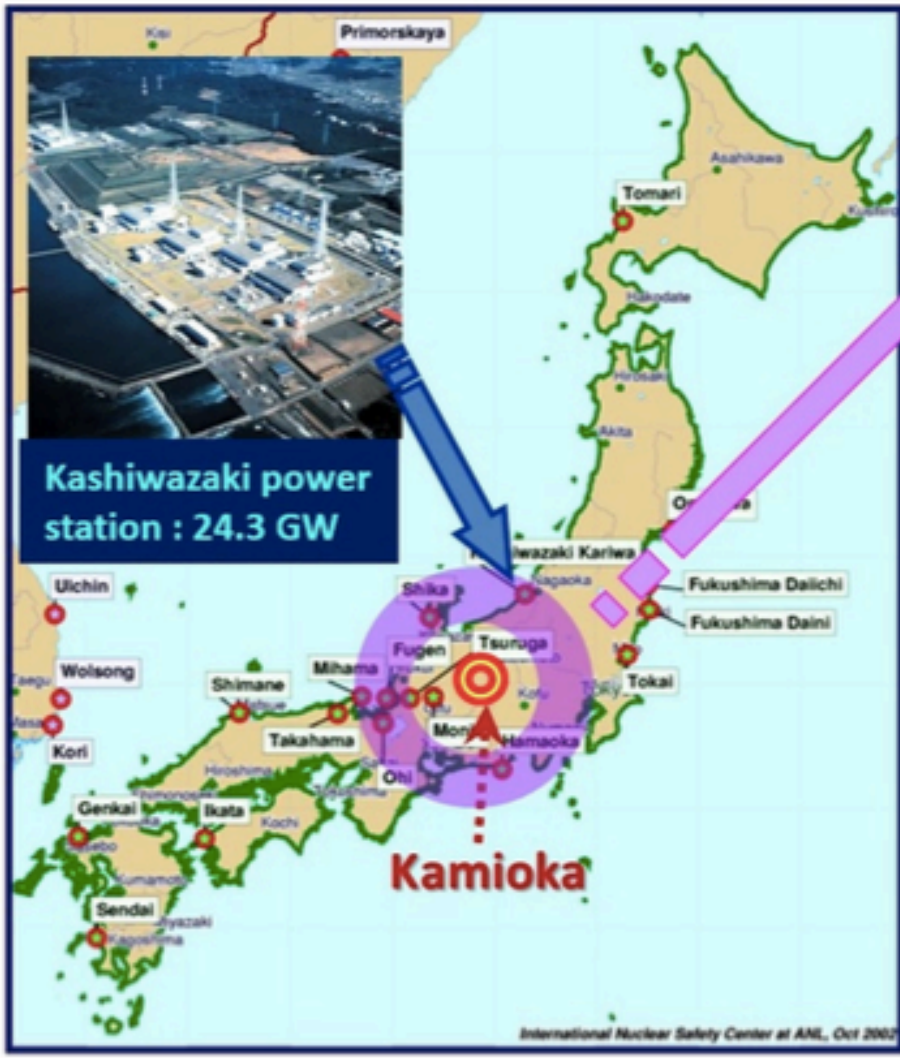
very good agreement with precise measurements

→ We seem to understand our star very well
- Power production from unknown sources <4% !!!!!

This is the way to improve parameters for 1-2 sector


P_{ee}
pp
^{7}Be
pep
CNO
^{8}B
Hep
solar+KamLAND best fit
$\sin^2\theta_{12}$=0.308
Δm^2_{21}=7.50x10^{-5}eV^2
Borexino (pp)
Borexino (pep)
all solar (pp)
(averaged) vacuum
oscillation dominant
Super-K+SNO
Borexino (^{7}Be)
solar best fit
$\sin^2\theta_{12}$=0.311
Δm^2_{21}=4.85x10^{-5}eV^2
Borexino (^{8}B)
matter oscillation dominant
MSW resonant process
in the Sun
Sector 1-2
Homestake
+SK+SNO
(CNO)
ν Energy in MeV
Flux in 1/keV cm^2 s

Same sector (1-2) but for anti-neutrinos Kamland

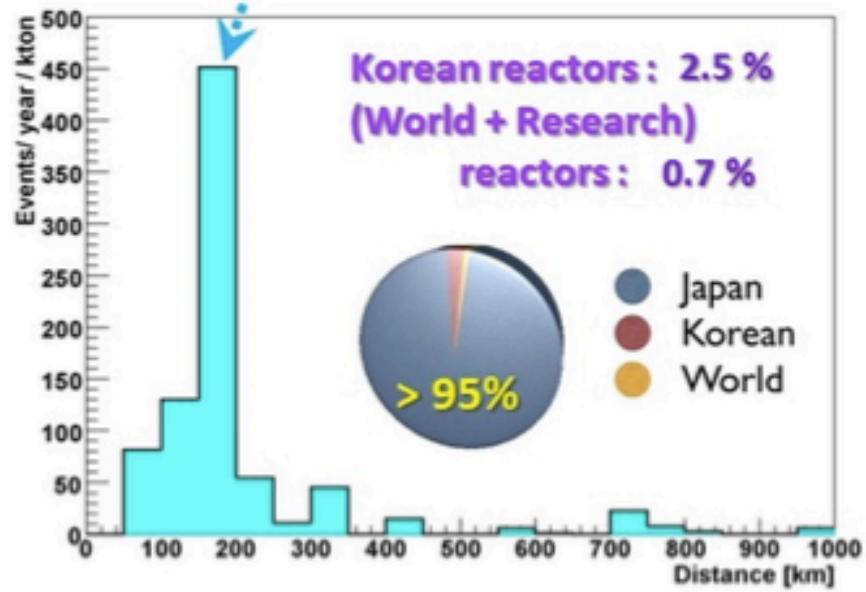


70 GW (~12 % of global nuclear power)

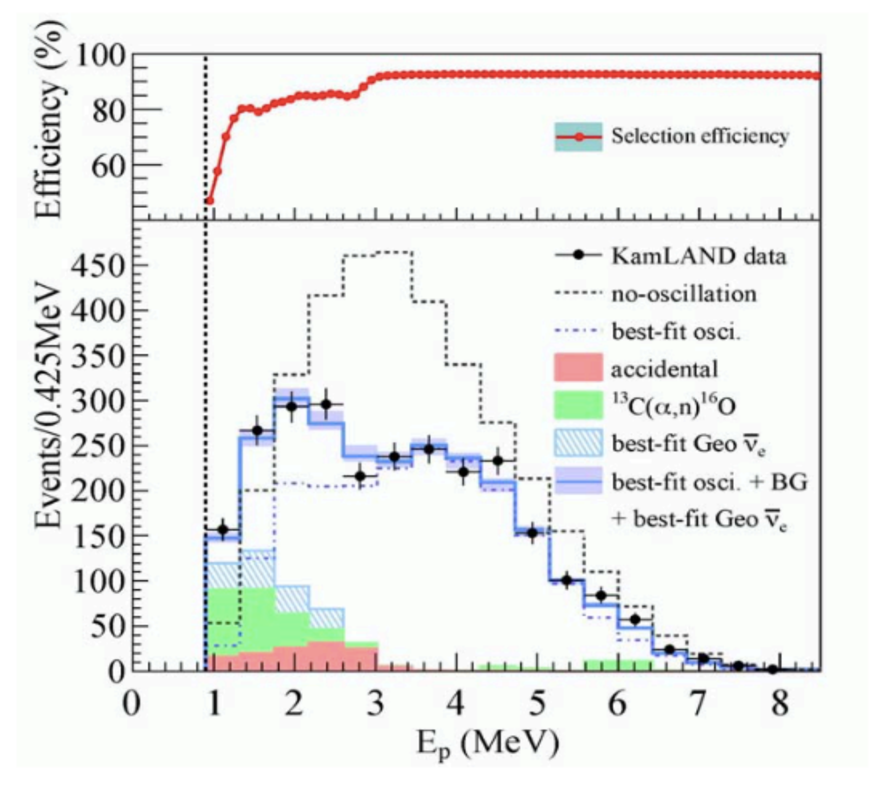
at

L ~ (175 ± 35) km

effective baseline : ~ 180 km

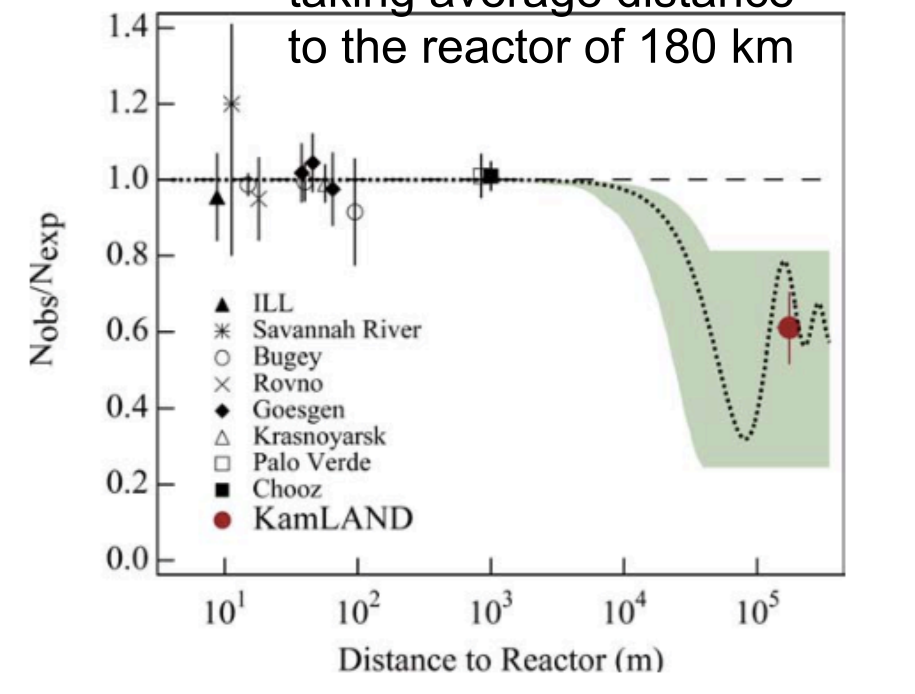


Kamland – exposure of 5780 kton-yr



- Observed events 2611
- Expected events 3564+/- 145
- Bgr 364+/-30 (accidentals 125)

taking average distance
to the reactor of 180 km



Obs/exp = 0.631 +/- 0.014 (stat)
+/- 0.027 (syst)

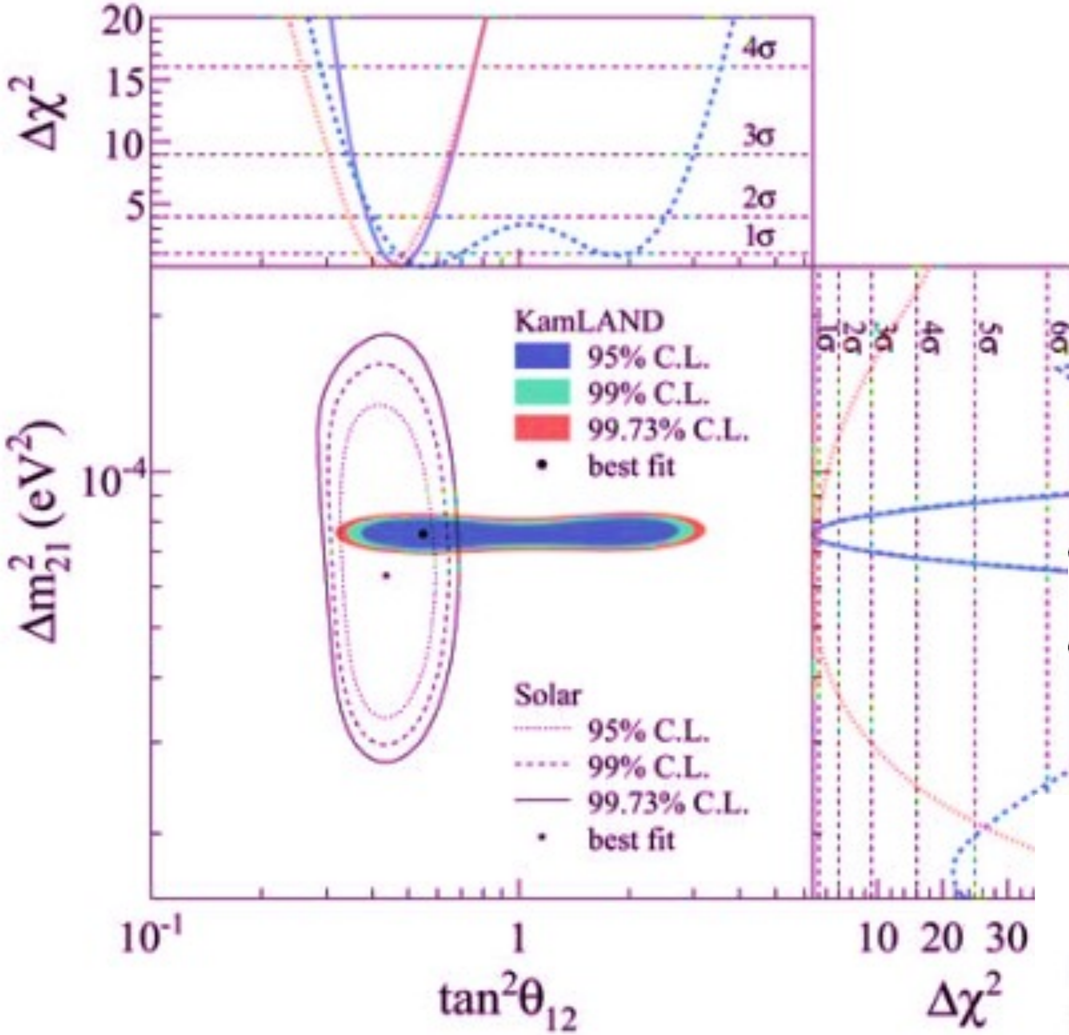
Corresponding to
exclusion of non-oscillation at
10.2 σ CL

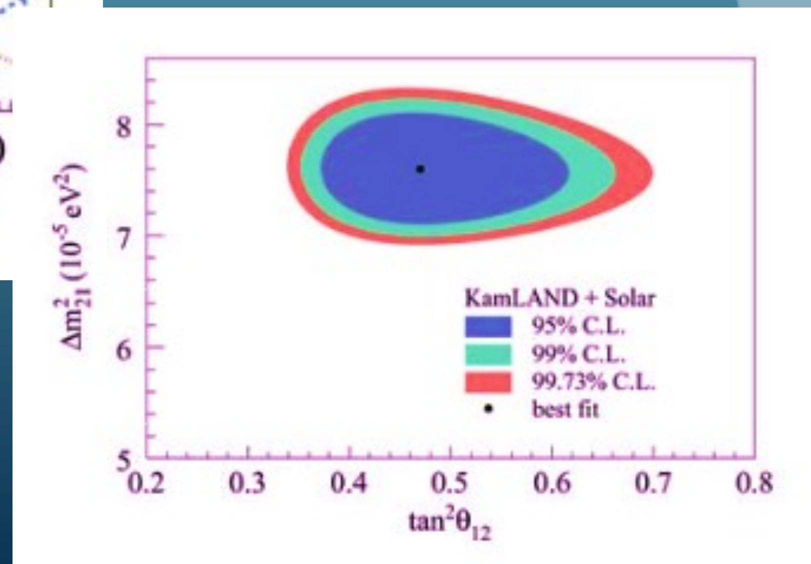
Determination of 1-2 mixing

Assuming same values for Neutrinos and anti-neutrinos

We obtain:

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





Δm^2_{21} (10^{-5} eV^2)	$\tan^2\theta_{12}$
$7.54^{+0.19}_{-0.18}$	$0.481^{+0.092}_{-0.080}$

- Kamland only ie. for anti-neutrinos

... 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

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

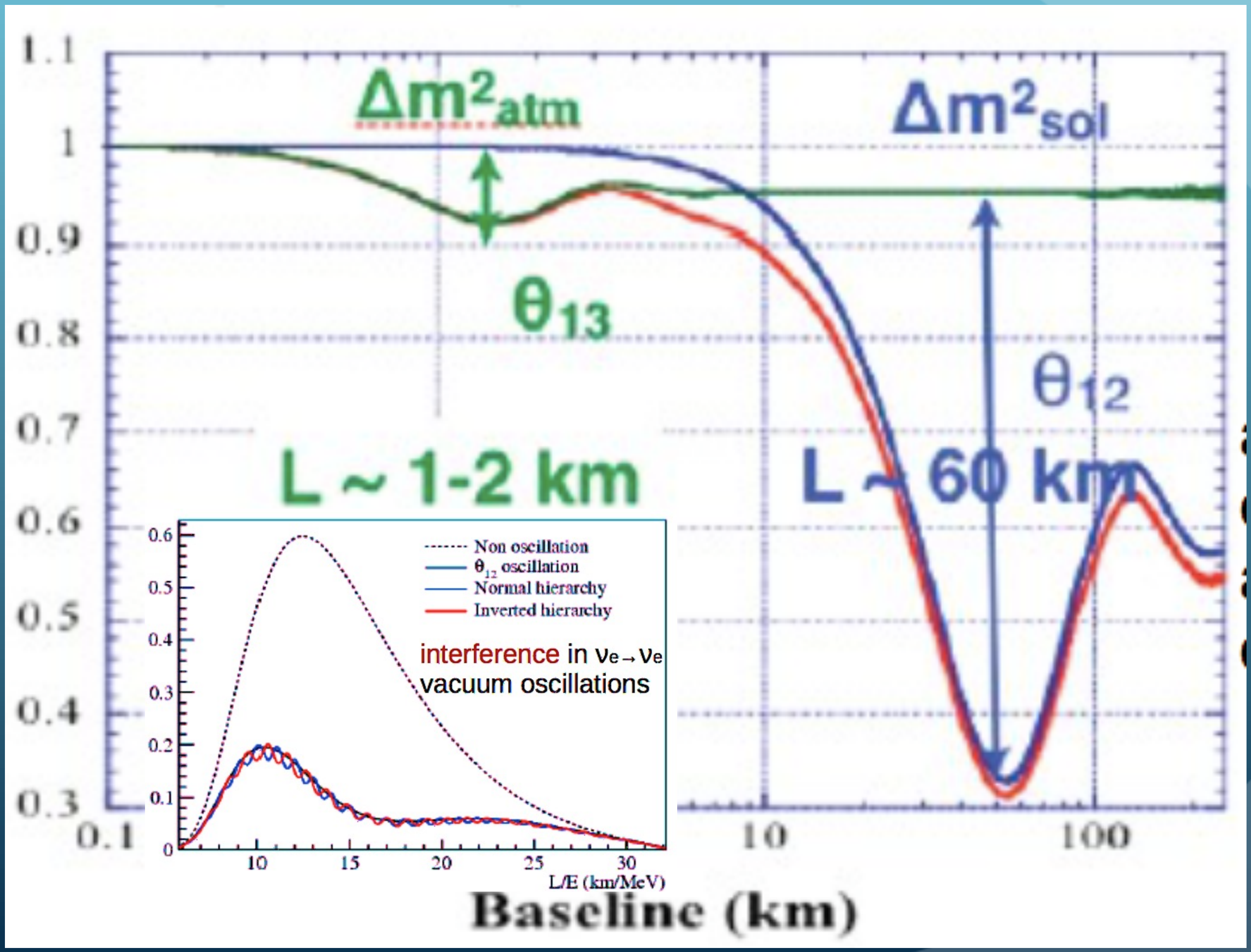
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(1.27 \Delta m^2_{23} L / E\right)$$

Leading terms!

Second order terms depend on δ and mass hierarchy

Energy ~ a few GeV
Distance ~ a few hundred km

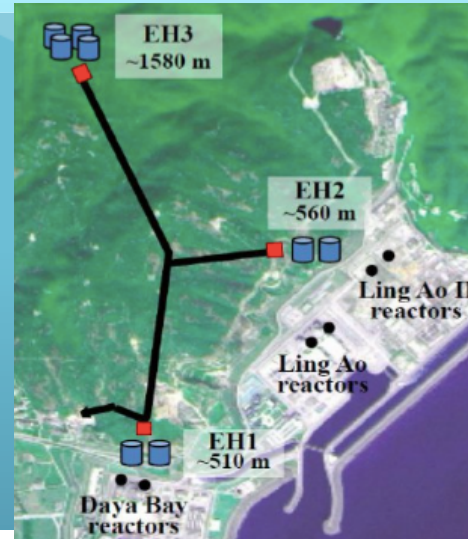
Reactor neutrinos probe sector 1-2 or 1-3 depending on the distance



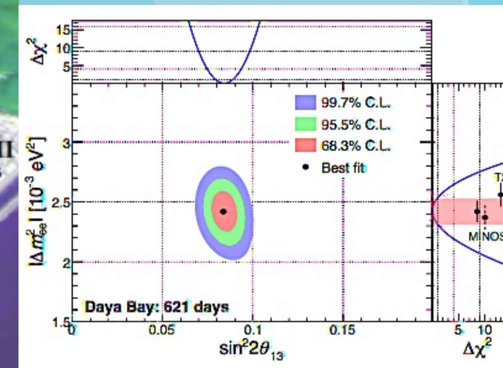
Sector 1-3 reactor data

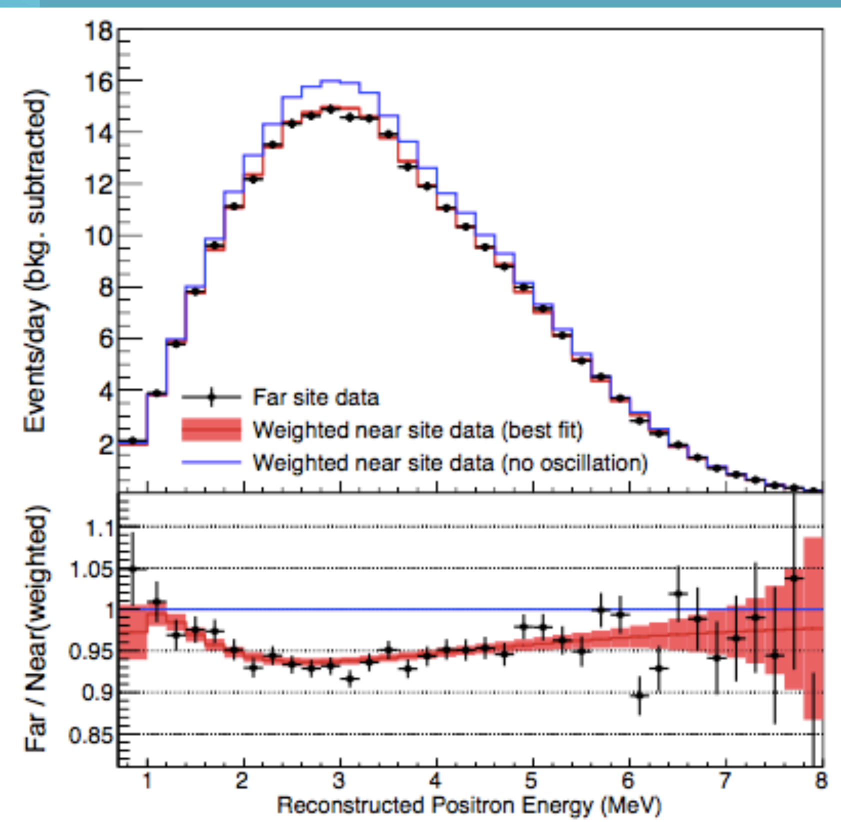
Daya Bay, RENO, Double CHOOZ

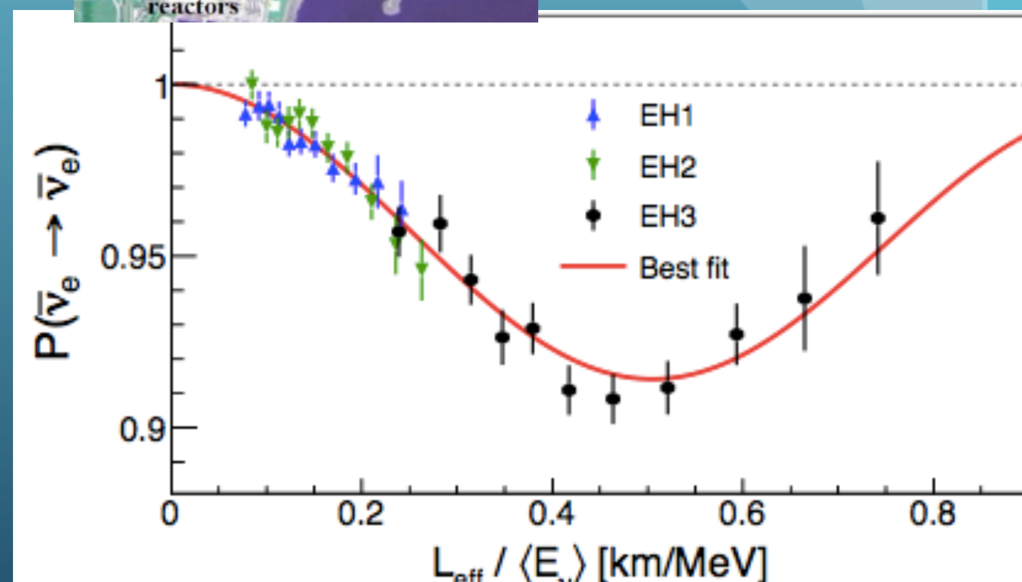
most precise measurements of θ_{13}



far and near detectors







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

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

How neutrino experiments turned to high precision phase?

Example from T2K

→ Artificial dedicated neutrino beams with high intensities

→ Precise information about π and K mesons production is required

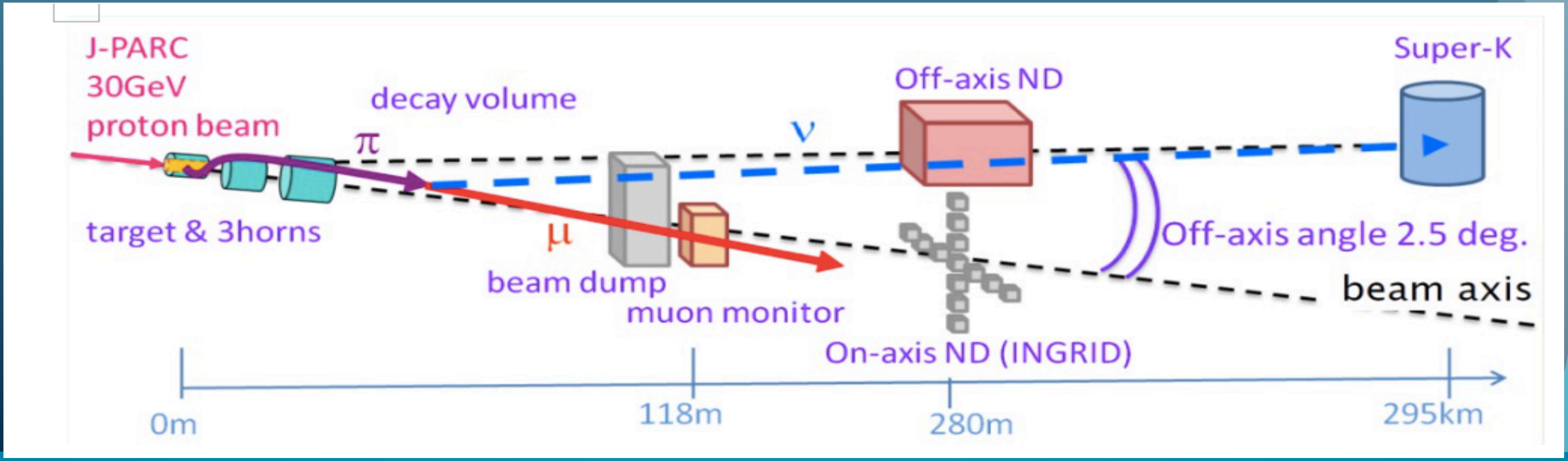
→ NA61 at CERN

Proton beam on target
→ Produces π and K

$$\pi^+ \rightarrow \mu^+ + \nu_u$$

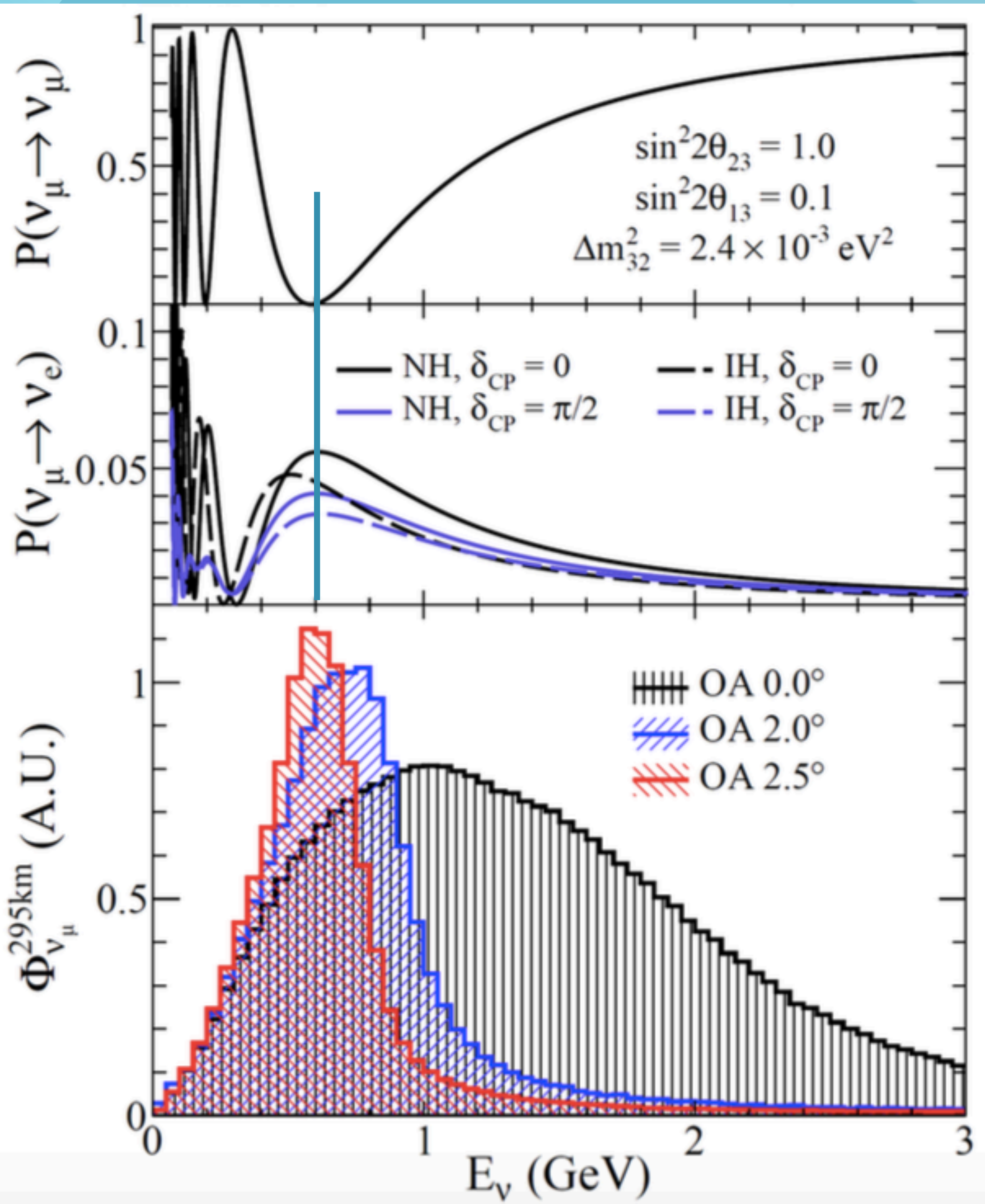
$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

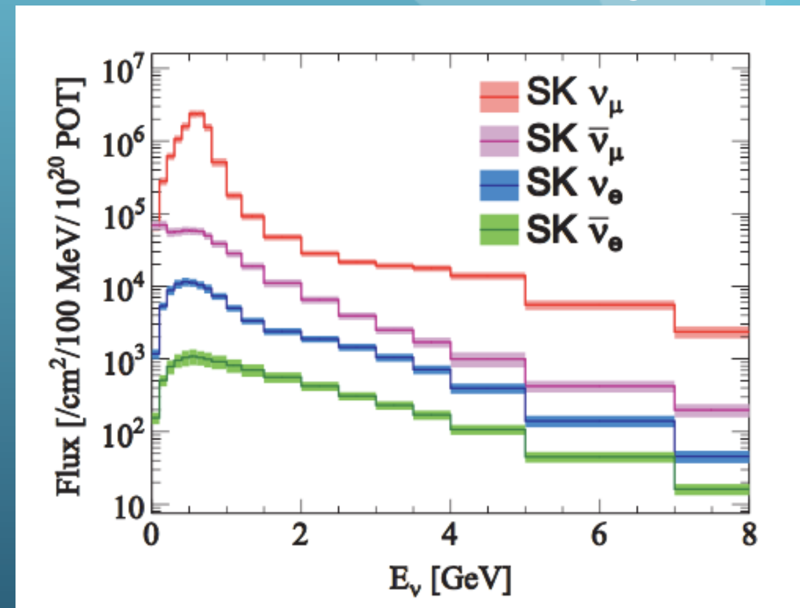
$$K^+ \rightarrow \pi^0 e^+ \nu_e$$

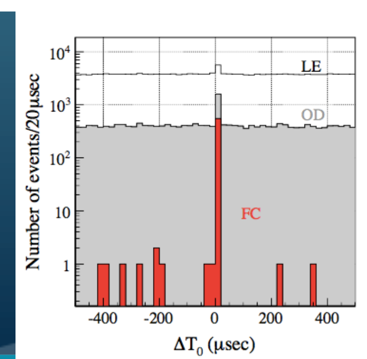


precisely tuned with L and E to oscillation maximum

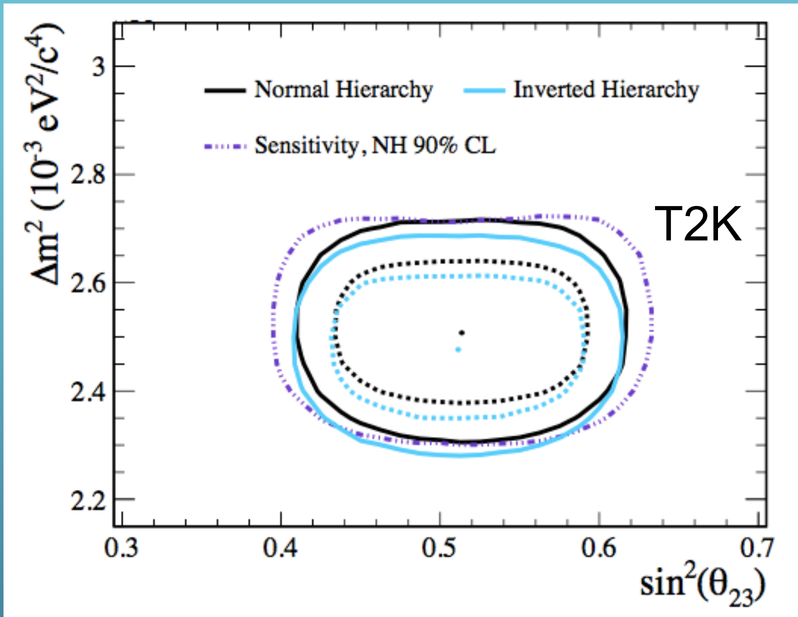
- Maximal effect
- Also lower background (due to smaller number of high energy NC, possibly similar to ν_e CC)

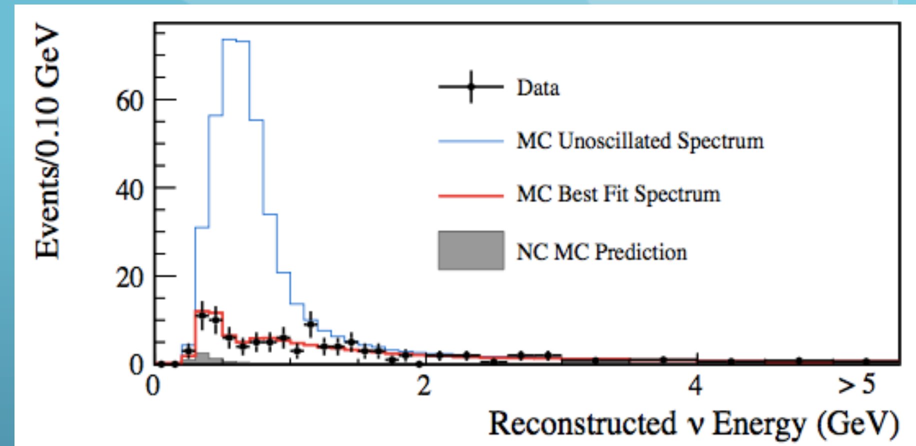


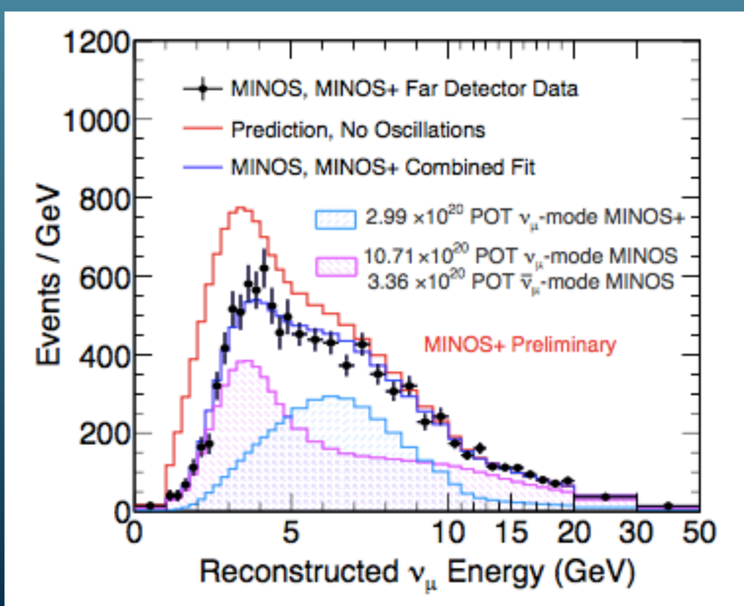


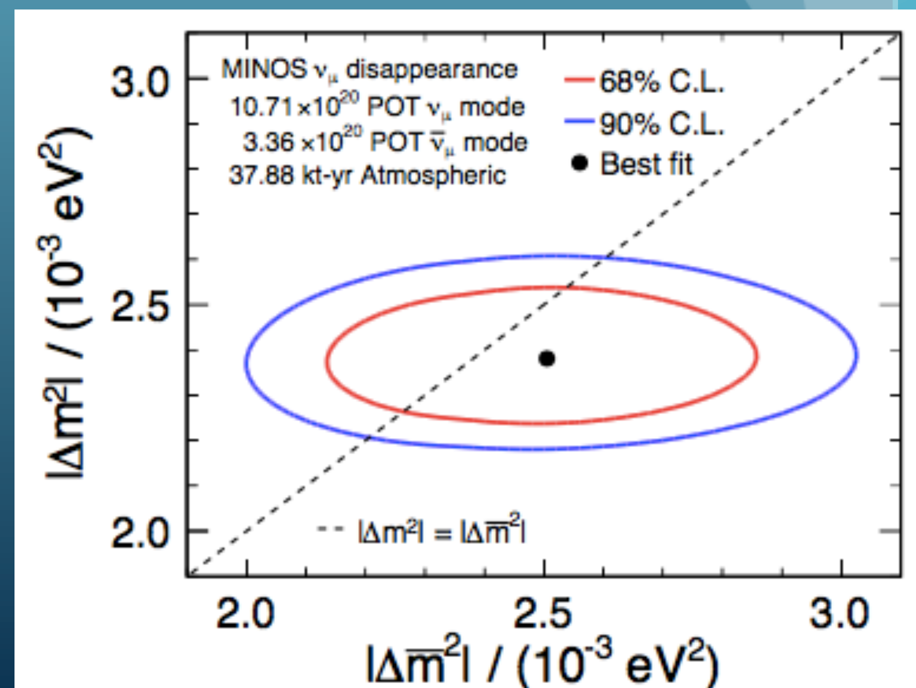


Most precise measurement of Δm_{23}, θ_{23}









What's next?

	Unknown
CPV	$\delta \neq 0, \pi?$
MH	$m_3 \gtrless m_2?$
	$\theta_{23} \gtreqless 45°?$

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

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

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

Mass hierarchy and matter effects

- In the Sun oscillations happen in dense matter

  → MSW effect – matter effect of electron density

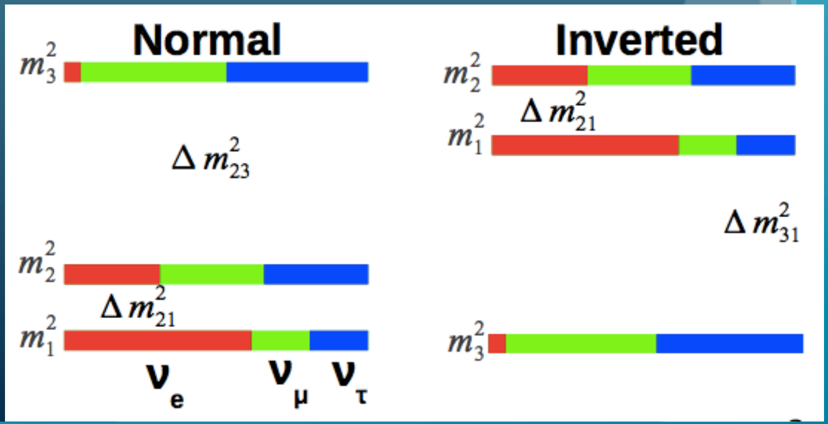
Resonance enhancement appears at specific energies

  (It depends on Δm^2 and electron density)

→ for solar ν we observe resonance around 10MeV

- From that we know that $m_1 < m_2$
- position of m_3 is not known

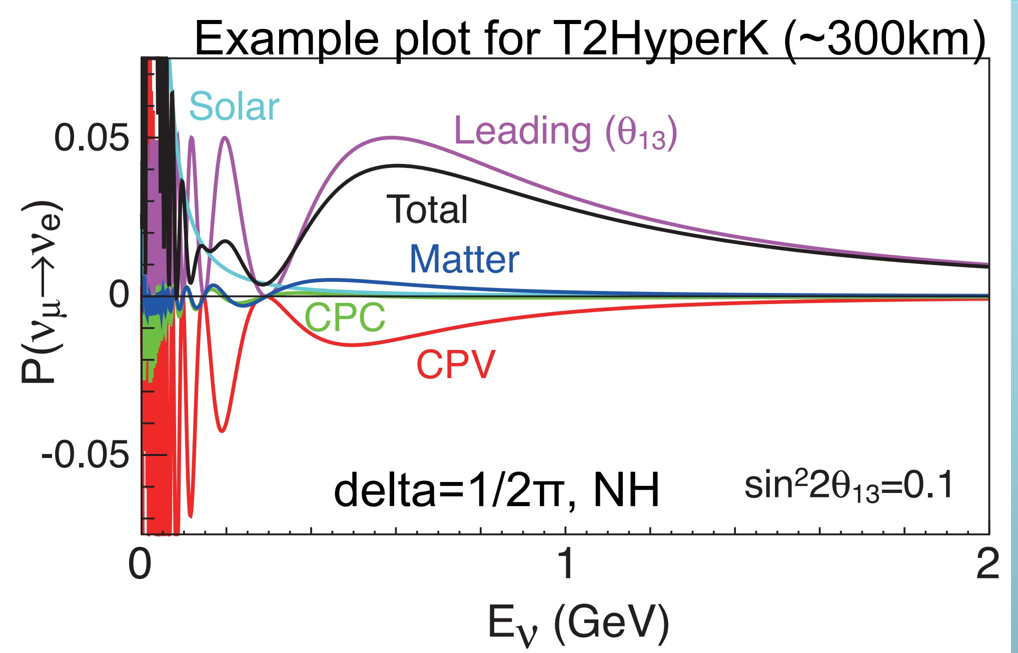
  → open question – two options



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

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

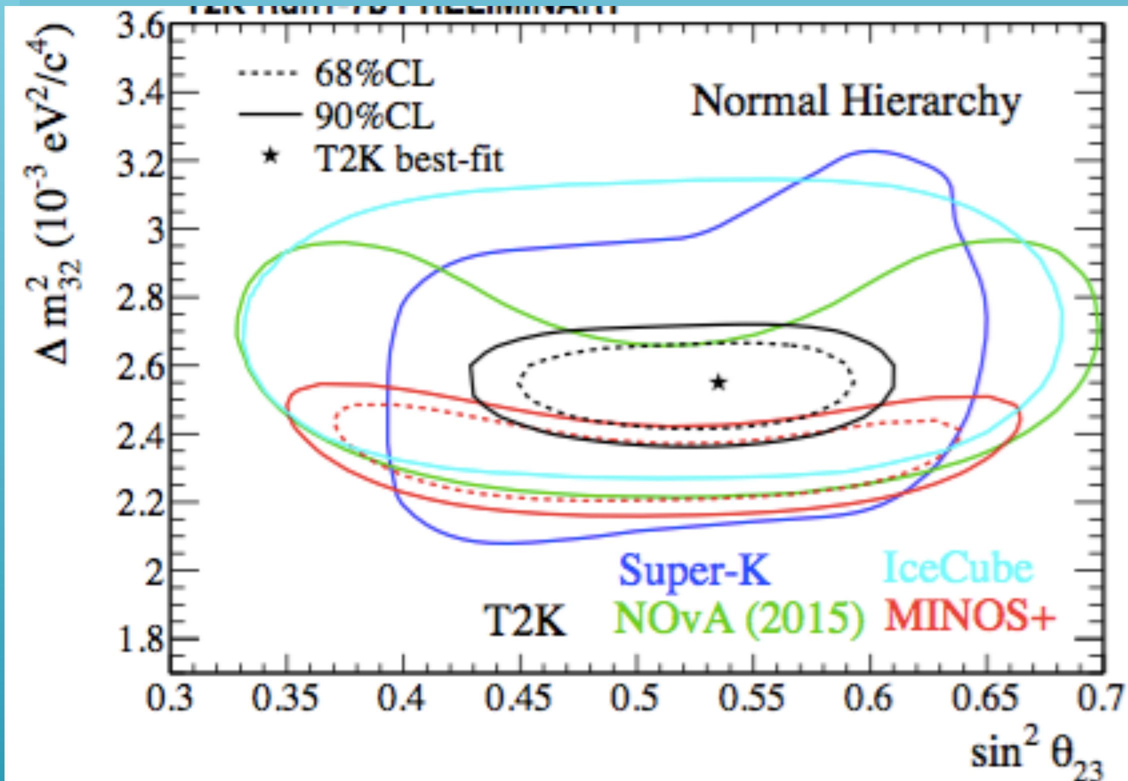
$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2\Delta_{31},$$ matter effects

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

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

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

Present status in sector 2-3:



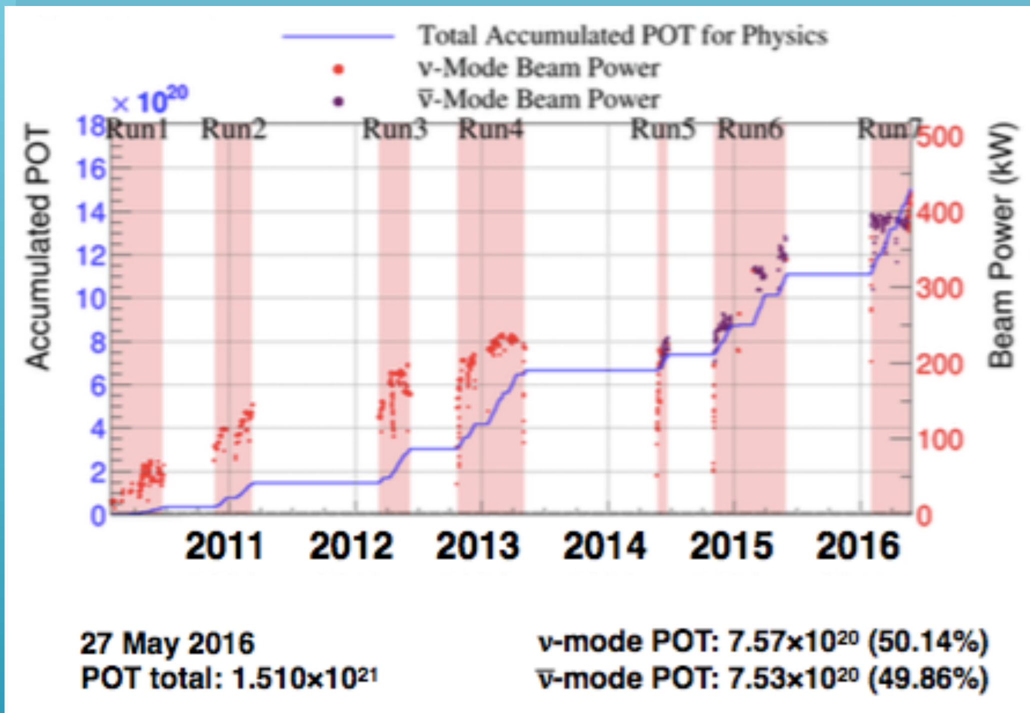
Results differ slightly for NH and IH

No strong preference

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

Parameter not well known δ_{CP}

Combined analysis of long base line
Oscillations in appearance and
disappearance channels for
Neutrinos and anti-neutrinos
Give sensitivity to all parameters
Including CP violating phase



Expected number of events in appearance channel depends on dCP and changes for ν and $\bar{\nu}$

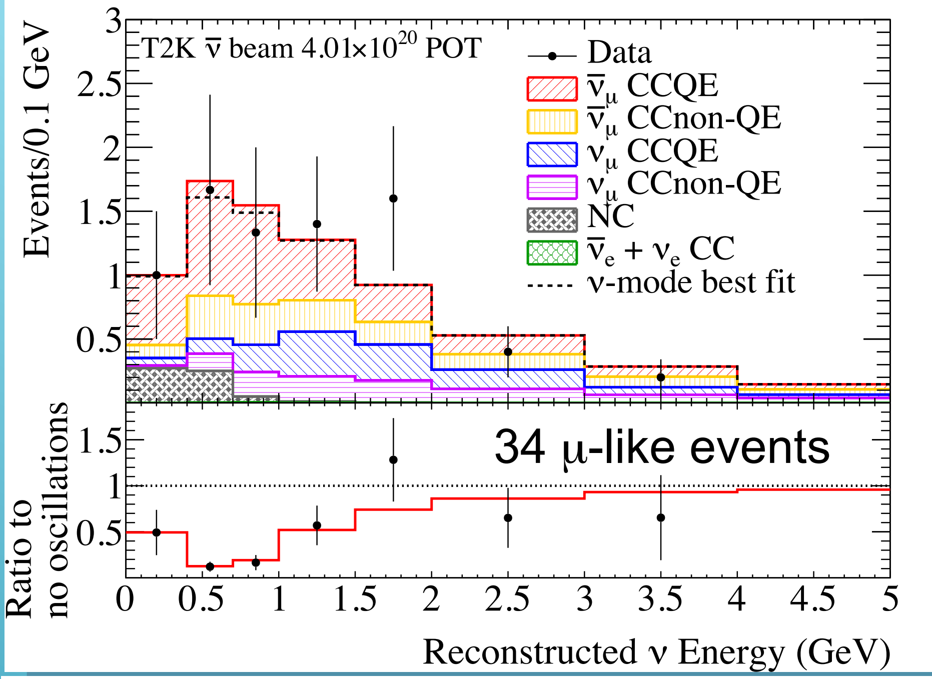
- Comparison of neutrino and anti-neutrino oscillations

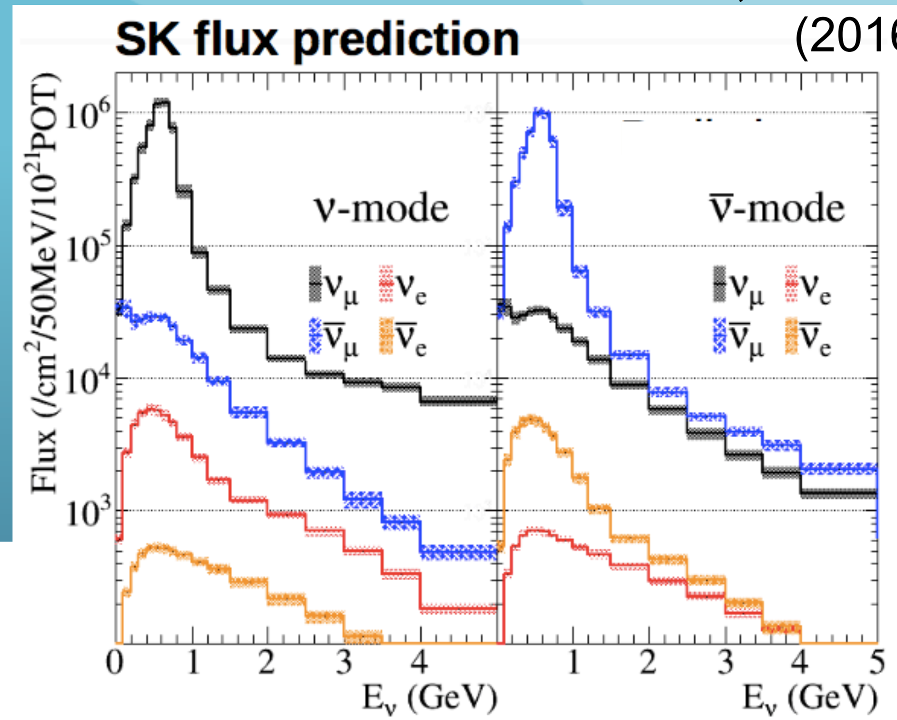
→ direct sensitivity to CP phase

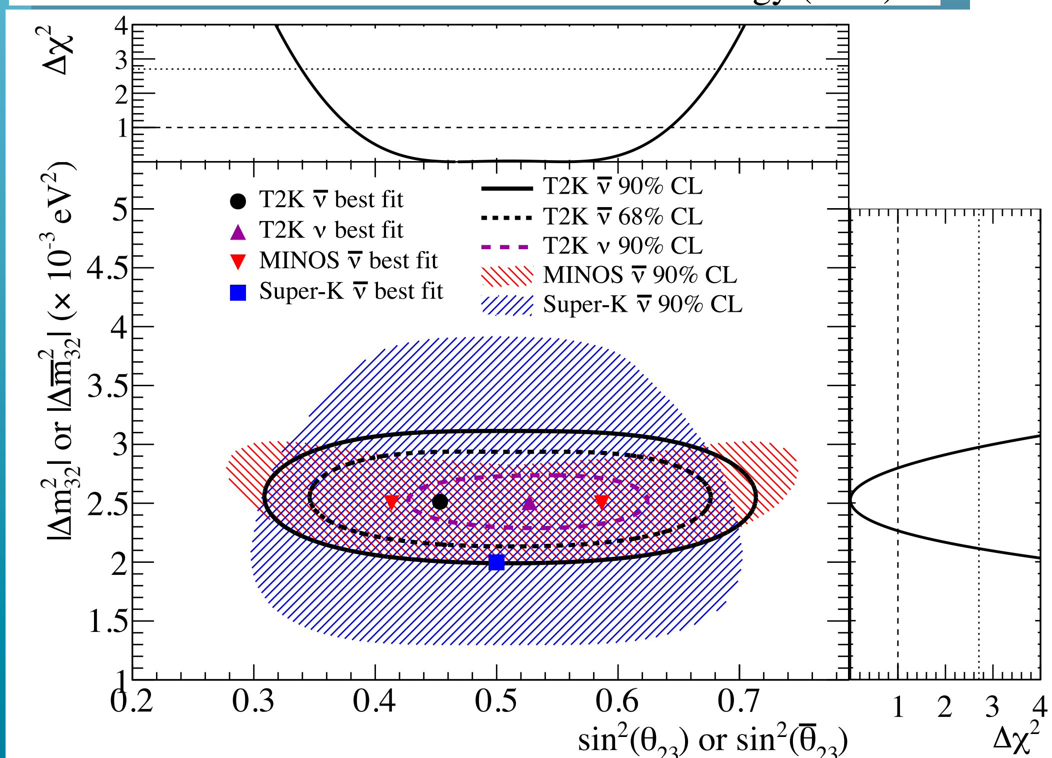
	OBS.	EXP. (NH, $\sin^2\Theta_{23}$=0.528, NH)			
		$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν_μ	125	127.9	127.6	127.8	128.1
ν_e	32	27.0	22.7	18.5	22.7
$\bar{\nu}_\mu$	66	64.4	64.3	64.4	64.6
$\bar{\nu}_e$	4	6.0	6.9	7.7	6.8

$\overline{\nu}$ beam – results

PRL 116, 181801 (2016)







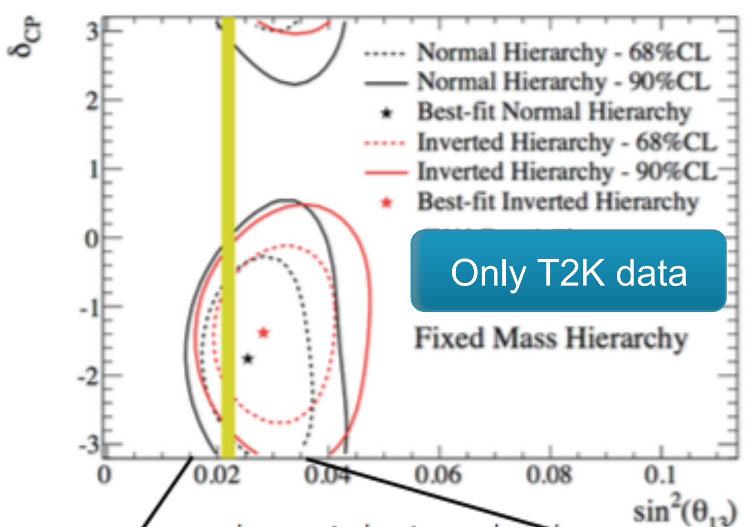
Analysis for 4,01*10^{20} POT with anti-nu beam mode

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

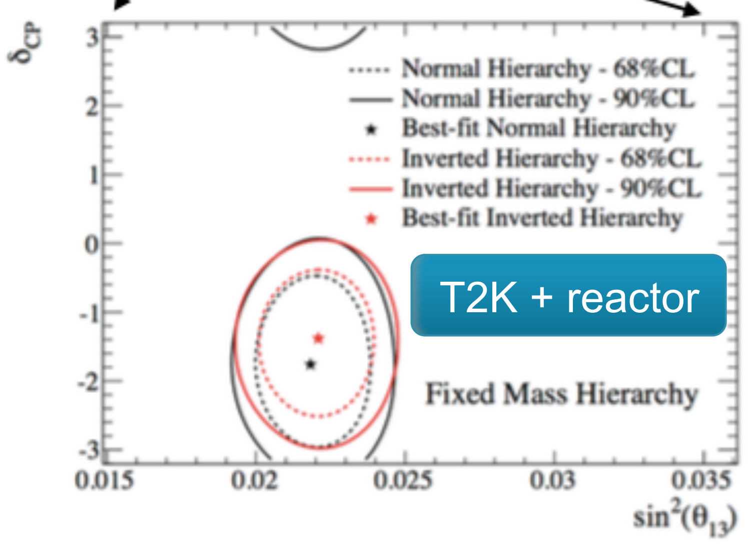
Appearance – 3 e-like events seen

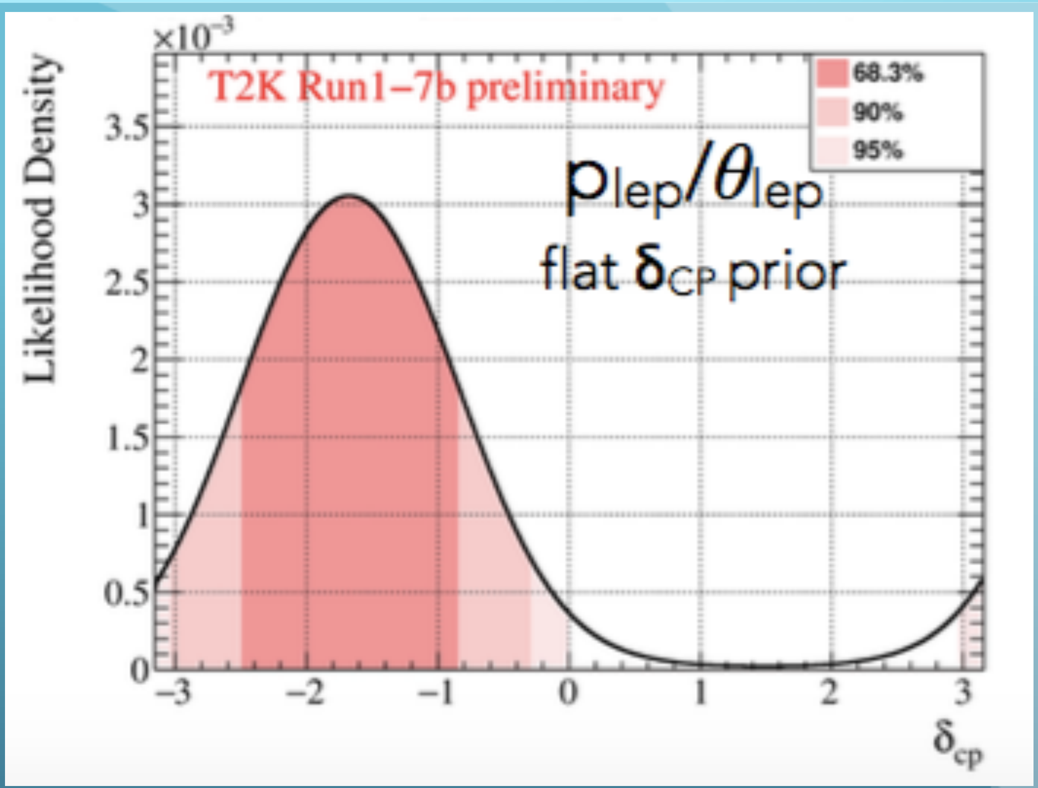
more data needed

New analysis
ν and $\overline{\nu}$



note change in horizontal scale

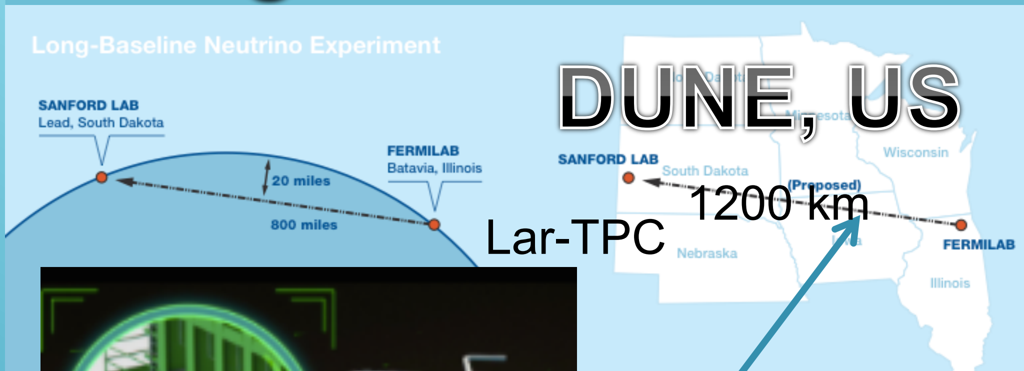




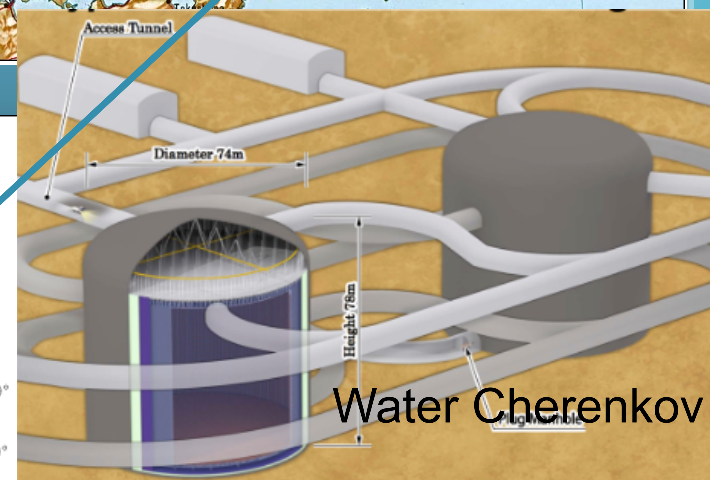
- First time from single experiment 90% CL range for CP violation phase
- Pointing to value corresponding to CP violation (0 and π otside 90% limit)
- More data needed → T2K II
- Combined fits for all experiments will come soon (teoretica groups)

Long Baseline Future

Long term
ie. after/around 2025



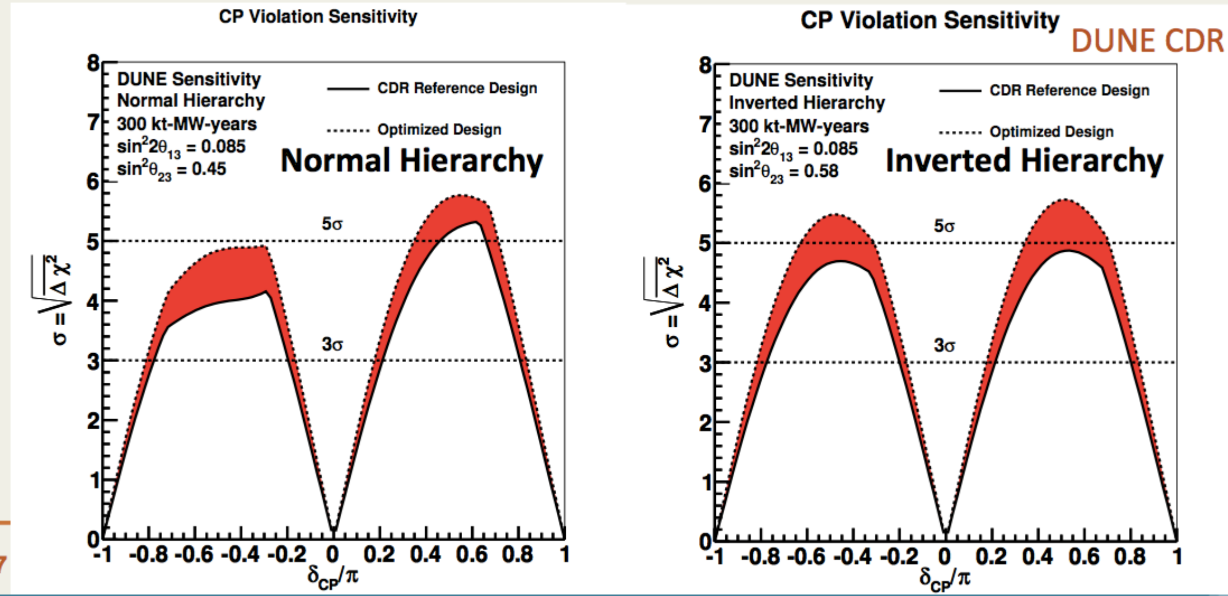
Lar-TPC



Prospect for measurements after 2025

Sensitivity to CP Violation, after 300 kt-MW-yrs (3.5+3.5 yrs x 40kt @ 1.07 MW)

(Bands represent range of beam configurations)



17

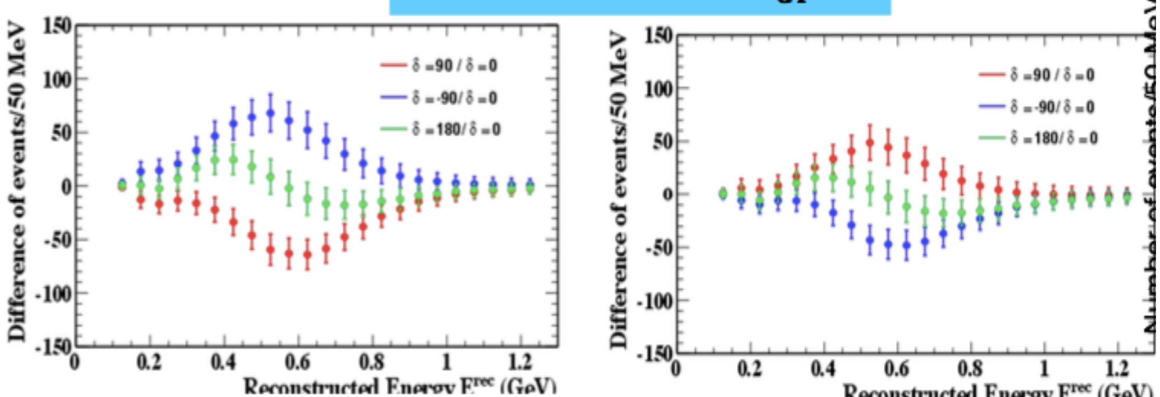
Dune with 40 ktons optimized beam

In both experiments more goals than oscillations ….

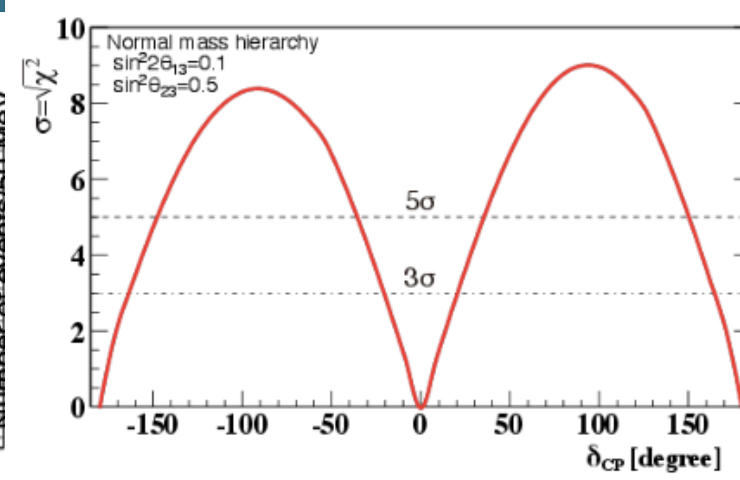
sensitivity for **Hyper-Kamiokande**

10 years data taking

Difference from δ_{CP}=0

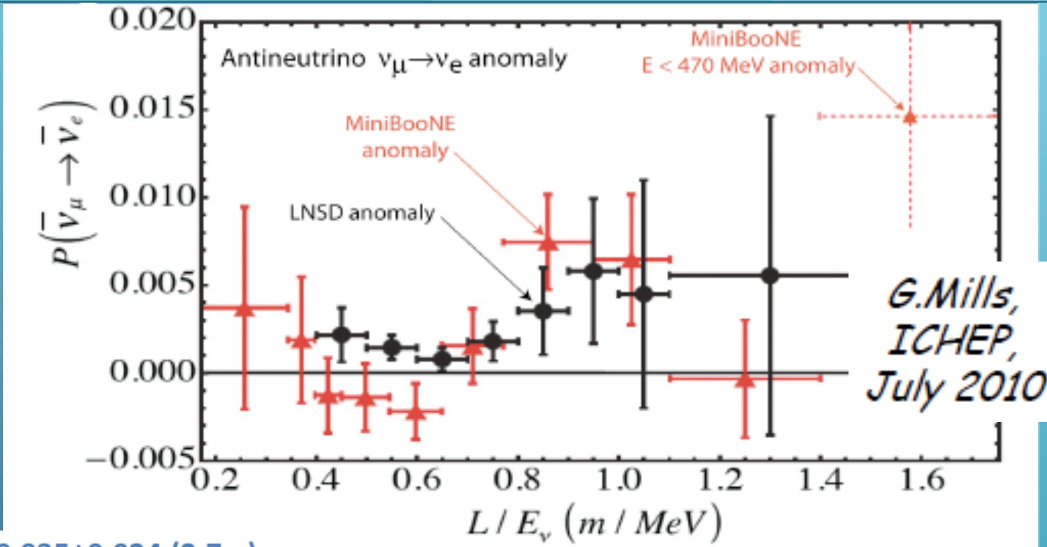


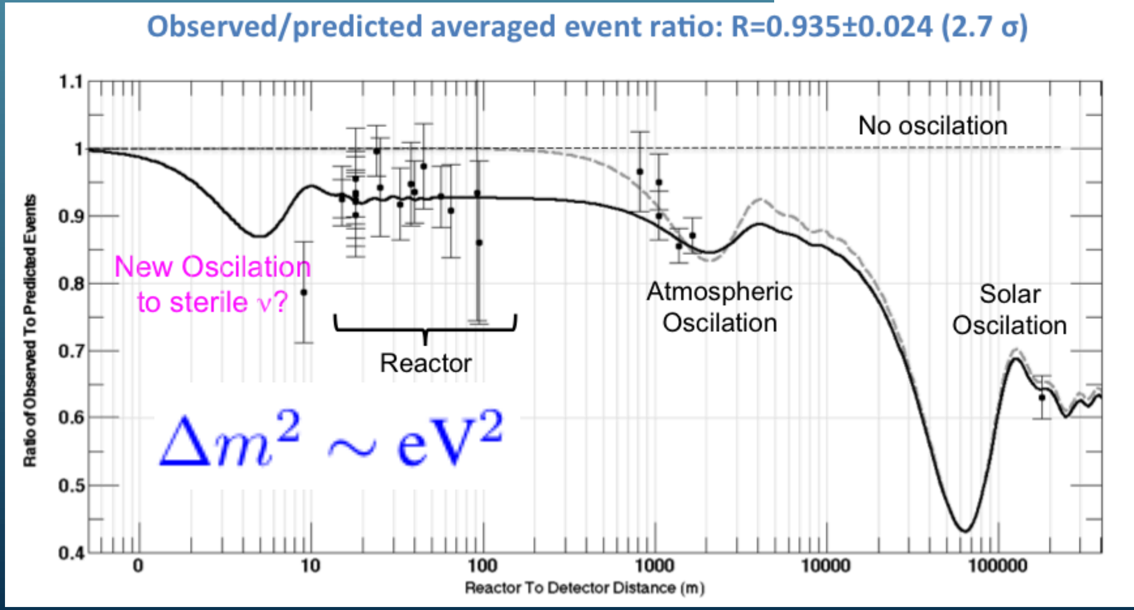
$\sin\delta_{CP}$=0 exclusion



Sterile neutrinos were hypothesized in a paper by Pontecorvo in 1957

- May be we need at least one additional neutrino type to explain some anomalous results from experiments?
  - Short baseline experiments (LSND, MiniBoone)
  - Reactor neutrino anomaly (?)



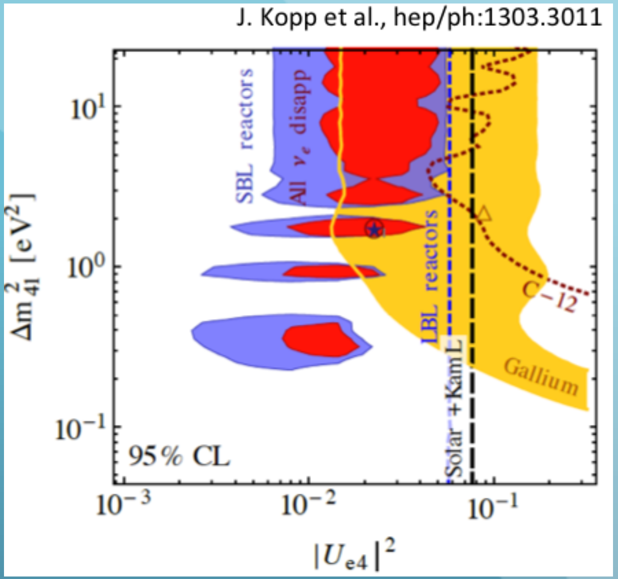


Hints
for more that 3 neutrinos
also from astrophysics

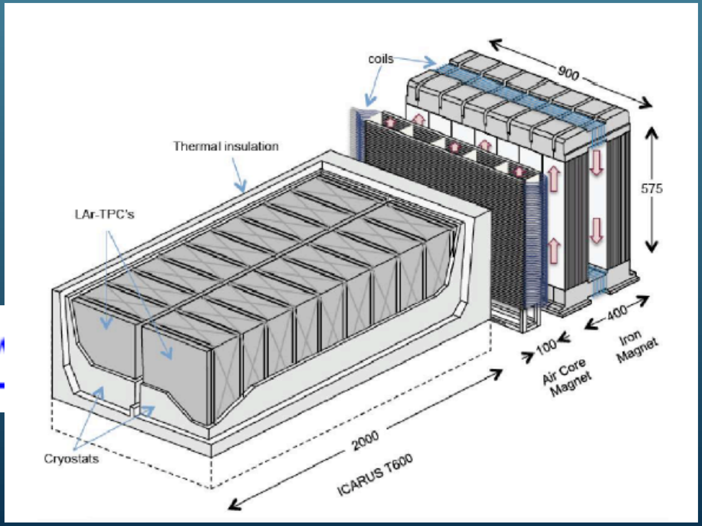
Sterile neutrinos?

Several proposal to search for them

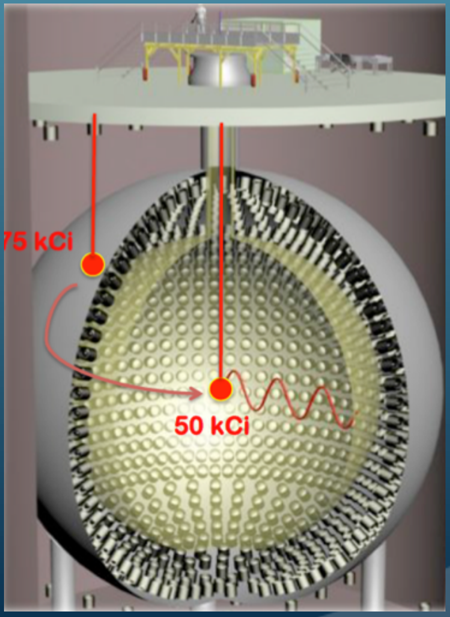
- Short baseline experiment on ~GeV beam with LAr detector
- Very short base line with radioactive sources (even with source inside detector)



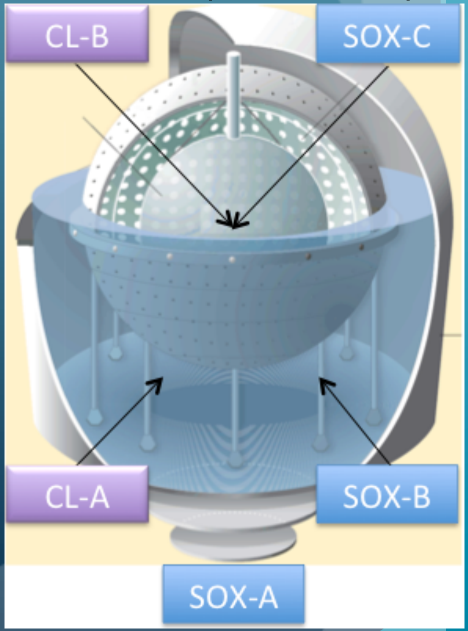
Fermilab SBL on NuMi beam:
LAr1-ND
MicroBoone
ICARAS – far detector



CeLAND (KamLAND)



SOX (Borexino)



Summary:

$\theta_{23} = 45.8 \pm 3.2°$
$\theta_{12} = 33.46 \pm 0.85°$
$\theta_{13} = 8.51 \pm 0.23°$

$\Delta m^2_{21} = (7.53 \pm 0.18)\cdot 10^{-5}\ eV^2$
$|\Delta m^2_{32}| = (2.44 \pm 0.06)\cdot 10^{-3}\ eV^2$
δ_{CP} = some hints

PLEASE CONTINUE TO ENJOY ^ NEUTRINO OSCILLATIONS

precision measurements of