"Neutrinos - experimental status and prospects: 3 flavour oscillations”

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Workshop on the Standard Model and Beyond

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Plan for the lecture…

Experimental view on data on neutrinos oscillations

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

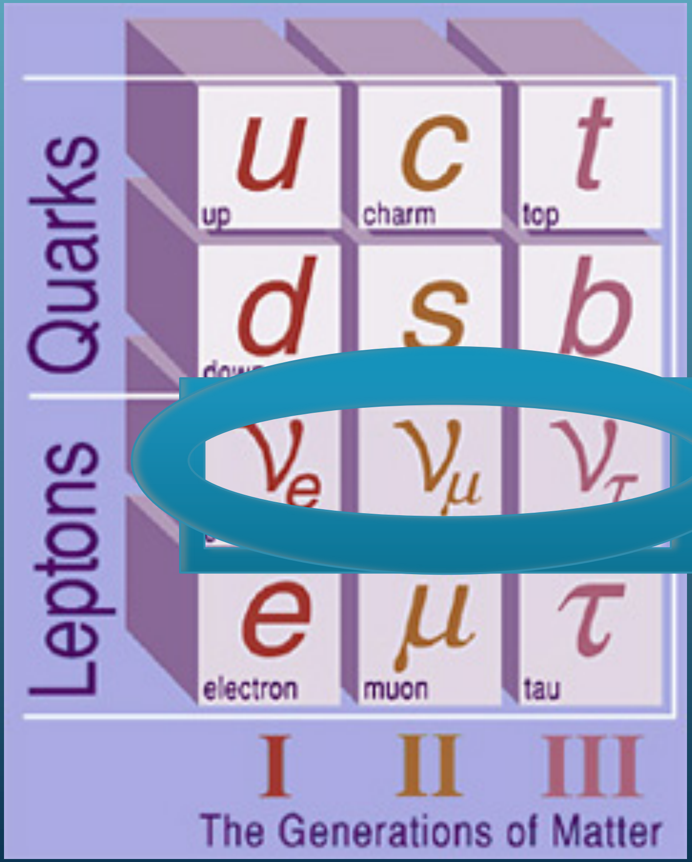
……. I will not talk about sterile neutrino and

doule β decay searches, sorry..

Neutrino?

The most inapprechensible component of matter

F. Reines: *„….the smallest part of reality ever invented by human….”*



- electric charge= 0
- Very hard to observe

→ participates only in weak inter.

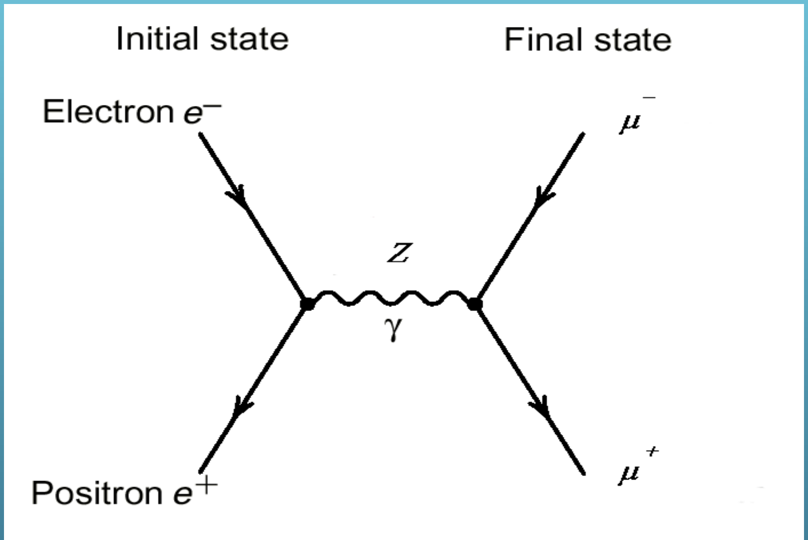
play important role in the Standard Model (SM)

In SM was assumed, that ν mass = 0

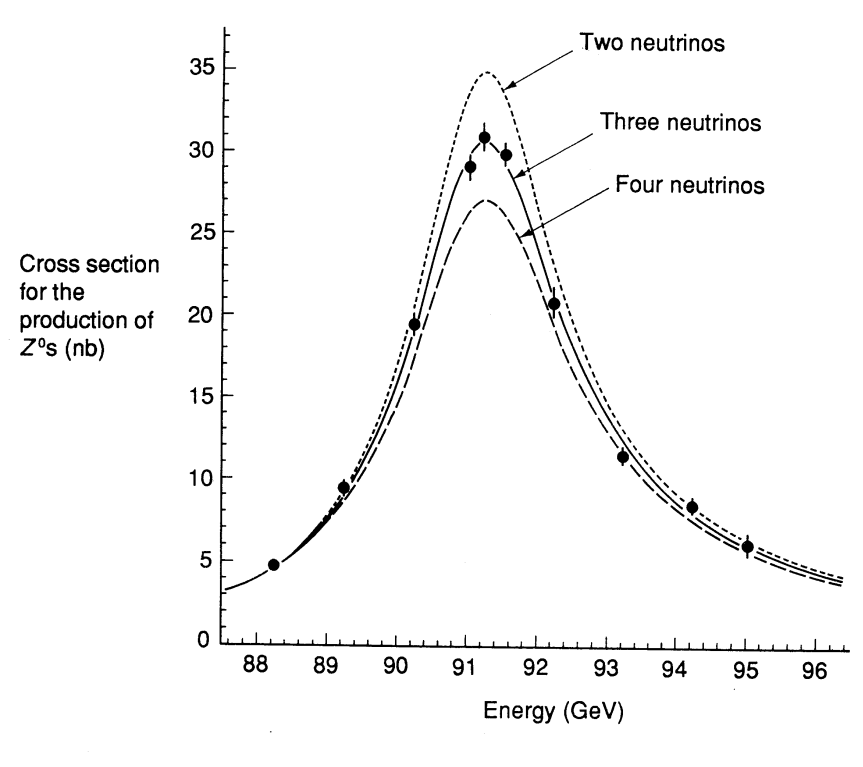
- appear in pairs with charged leptons
- neutrino type (flavour) is defined by leptons participating with it in interaction

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

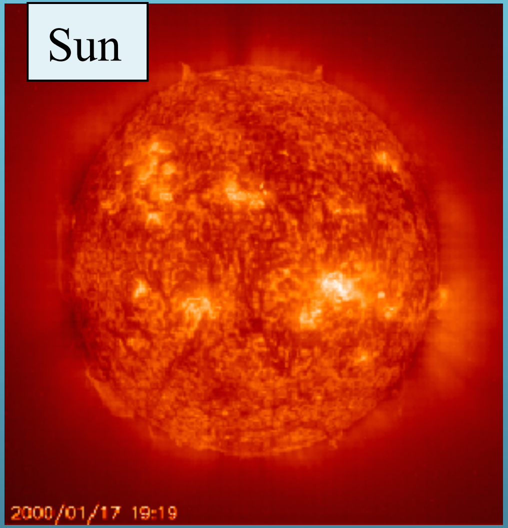
$$\Gamma_Z = \Gamma_{had} + 3\Gamma_l + N_\nu \Gamma_\nu$$

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

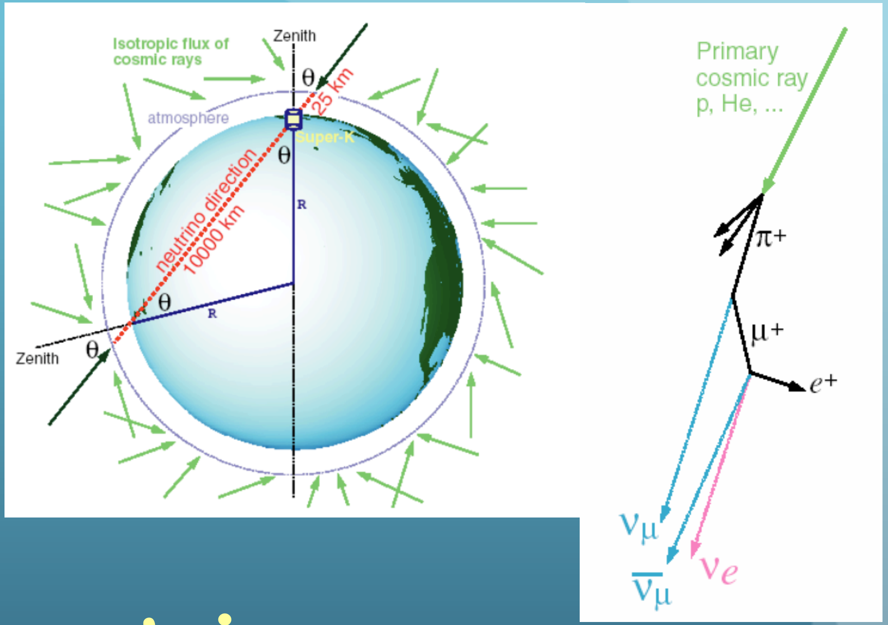
total width ~ decay probability (~1/lifetime)
partial width ~ branching rate (channel i)

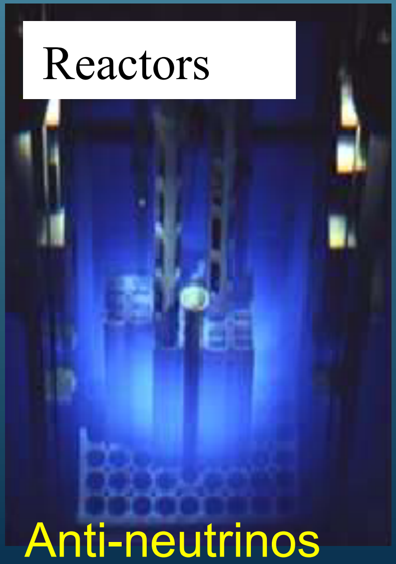
Neutrino sources

Natural

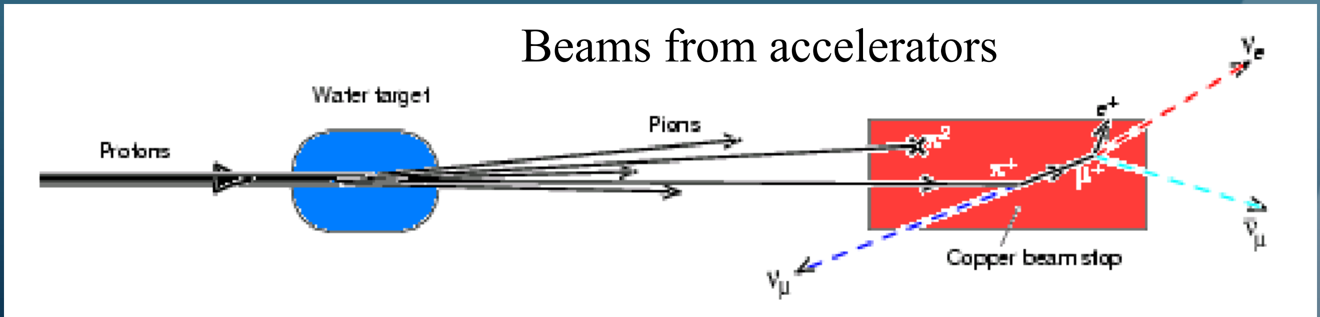


Cosmic rays → atmospheric neutrinos



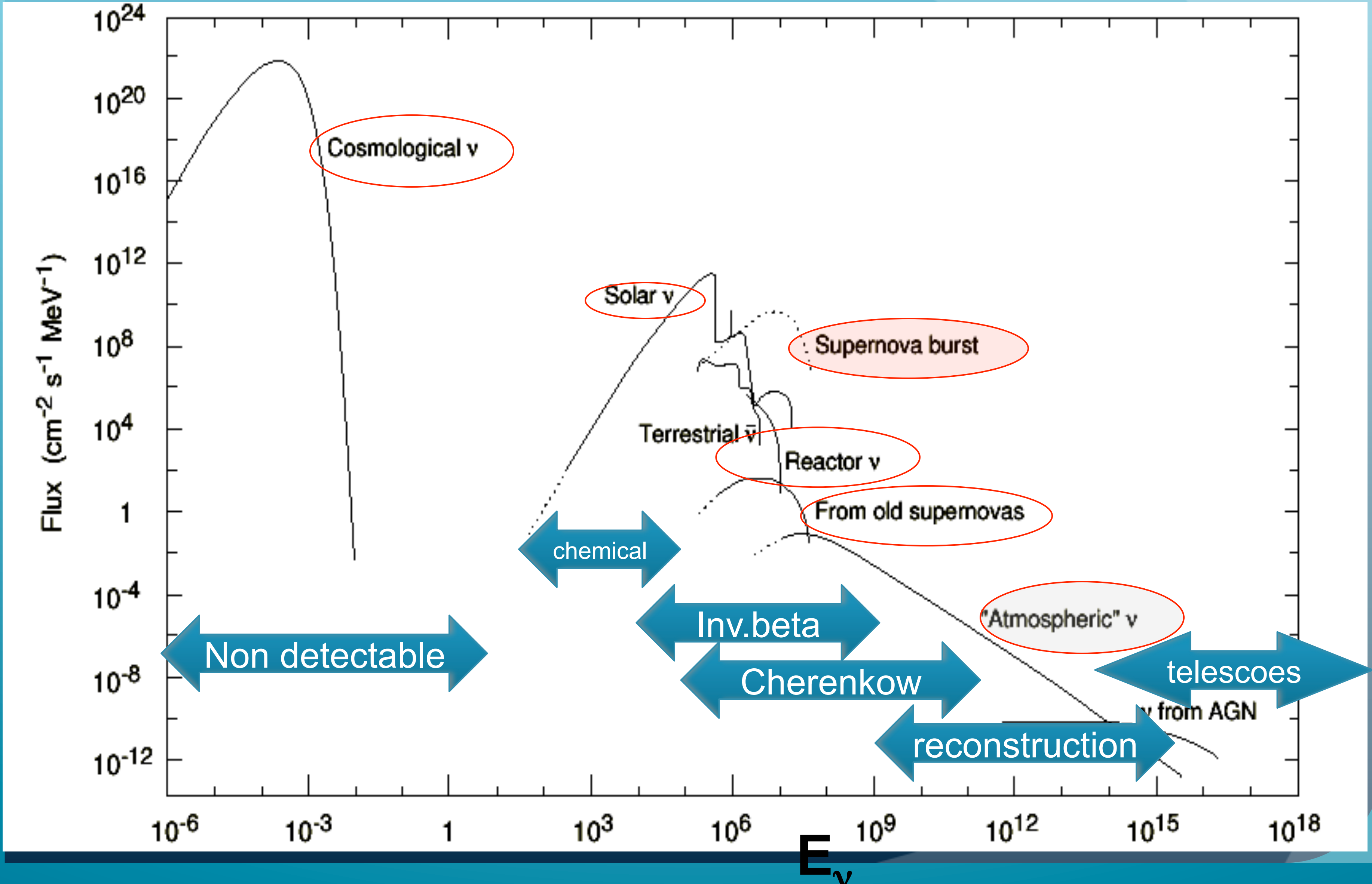


Man made neutrinos



Registration techniques

→ differ depending on neutrino energies



An overview of neutrino oscillations within 3-flavour picture

Phenomenon well understood by now

- Each flavour state is a linear combination of mass states:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \; |\nu_i\rangle$$

Flavour state $\alpha = e, \mu, \tau$

PMNS lepton mixing matrix

Mass state i= $1, 2, 3$

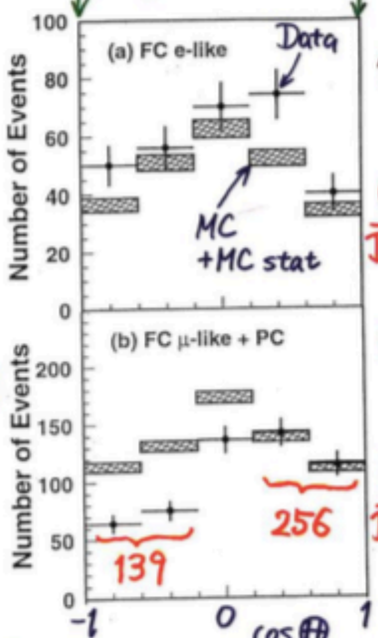
Having long history and involving many experiments NOW

From Y. Hayato talk at Neutrino2018

Atmospheric neutrino ~ First evidence of ν oscillation

Prof. Kajita gave a talk on the "evidence for ν_μ oscillation" at Neutrino 1998. (June 5th, already 20 years ago.)

Zenith angle dependence (Multi-GeV)



e: χ^2(shape) = 2.8/4 dof

$\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

μ: χ^2(shape) = 30/4 dof

$\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$

(6.2σ!!)

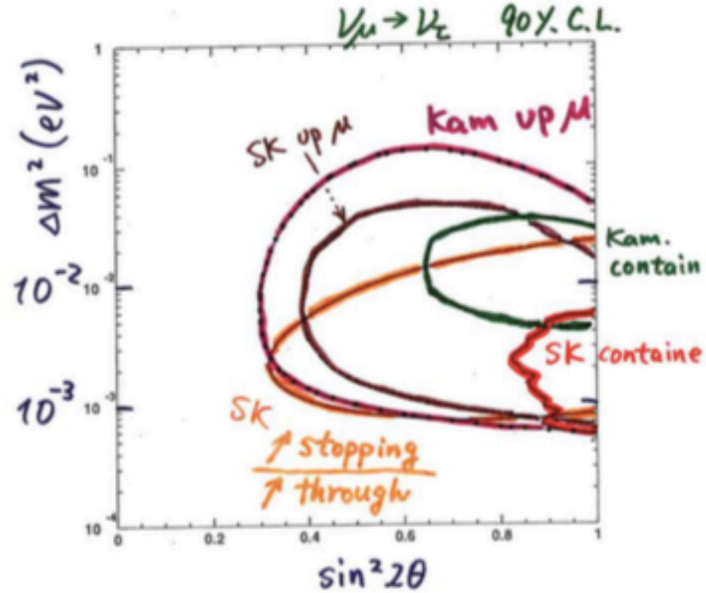
※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background …. < 2%) 2.1%

Summary

Evidence for ν_μ oscillations



• { $\sin^2 2\theta > 0.8$; $\Delta m^2 \sim 10^{-3} \sim 10^{-2}$ }

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

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

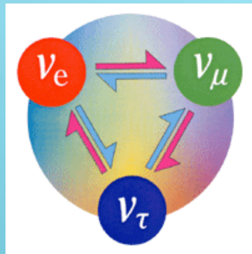
„solar”
SNO, KamLand, SK, Borexino

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

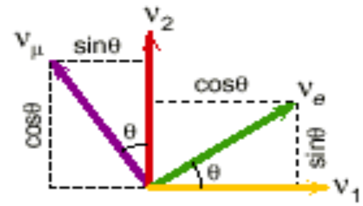
parameter θ_{13} found to be quite large

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



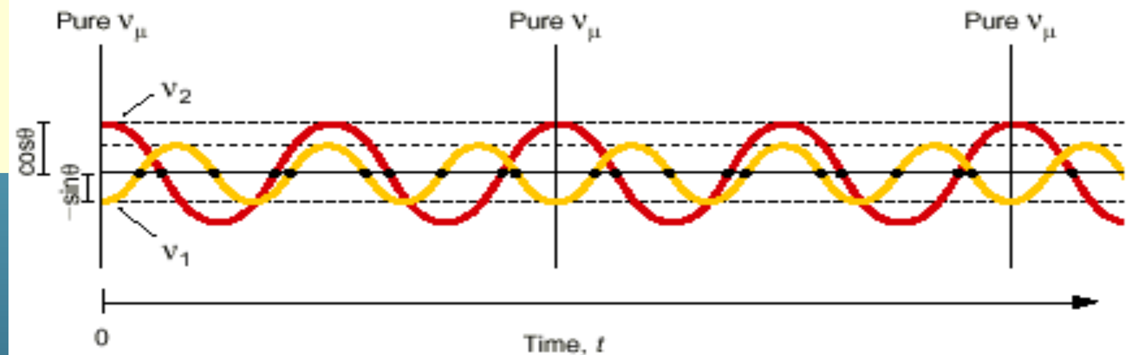
First look at two neutrino case



$$\nu_e = \cos\vartheta \; \nu_1 + \sin\vartheta \; \nu_2$$

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

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

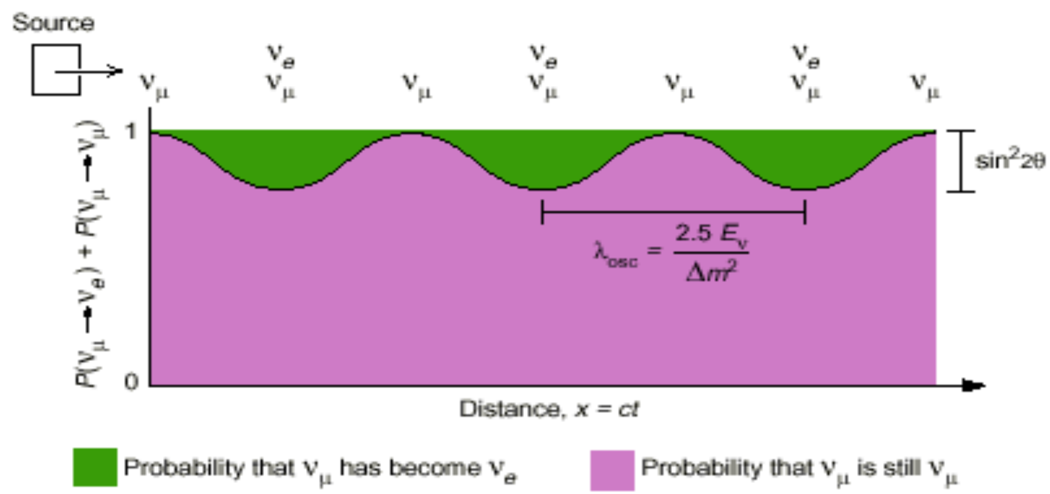


L – dist. to the detector
E - neutrino energy

Maximal effect when

$\sin^2(1.27\Delta m^2 L/E) = 1$

so when we know L and E we can estimate for which mass difference experiment will be sensitive

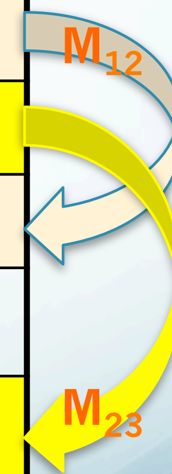


Sensitivity to oscillations

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

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….**

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

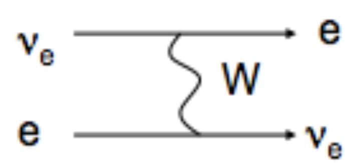
How to get it consistent?

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

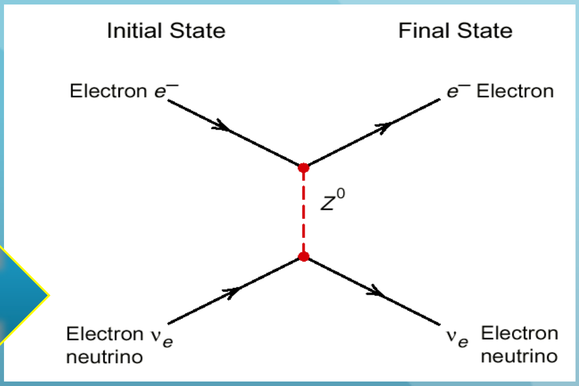
What we need to detect neutrino?

- Produce particle which is visible in the detector
- It happens when:
  1. Neutrinos kicks off electron (or nucleon) from detector material (elastic scattering, energy transfer, neutrino continues – interaction in NC mode)
  2. Neutrino interacts in CC mode and produces charged lepton which is visible in the detector

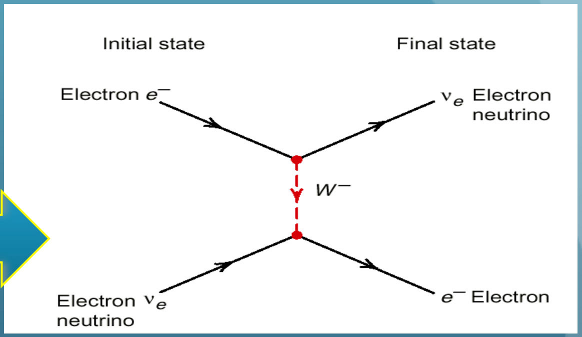
     It can happened on electron or (with Higher probability) on nucleon (if there

     Is enough energy to produce more massive charged lepton and teke nucleon out of nucleus…

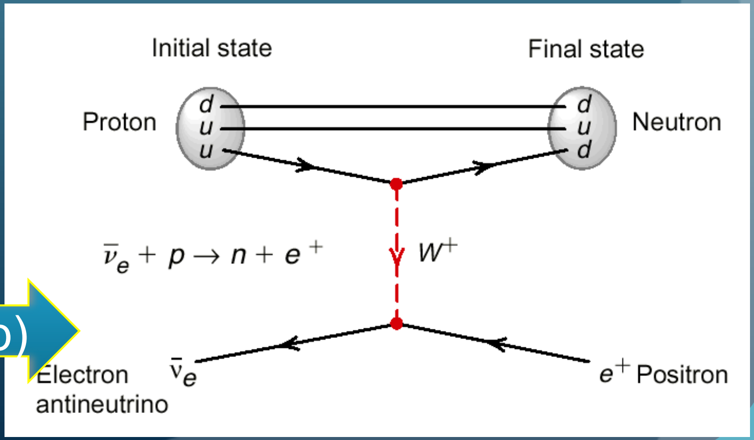
NC



CC (e)



CC(p)



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

Typical detection techniques: →

- Radiochemical n→p or p→n and nucleus changes, count them is counting n inter. (no additional inform.)
- scintillators – record scintillation light of produced charged particle (electron or proton…) – register time and energy
- water (light or heavy) – record Cherenkov light – register direction, time and energy
- liquid argon – record drifting electrons from ionization
- iron slabs as targets and various detectors to record exiting particles, includes emulsion

- Go underground to reduce background
- Make your detector big

→ use large volumes of cheap materials

measurements in sectors
what is measured, where and status

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”

Sector
2-3

Sector

1-3

„solar”

sector
1-2

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

→
Measurements

information needed to understand oscillations:

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 modify 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)

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:
  - observed number of interactions (of given neutrino flavour – defined by produced charged lepton)
  - predicted number of events (from oscillation probability, depends of parameters)

What needs to be done?

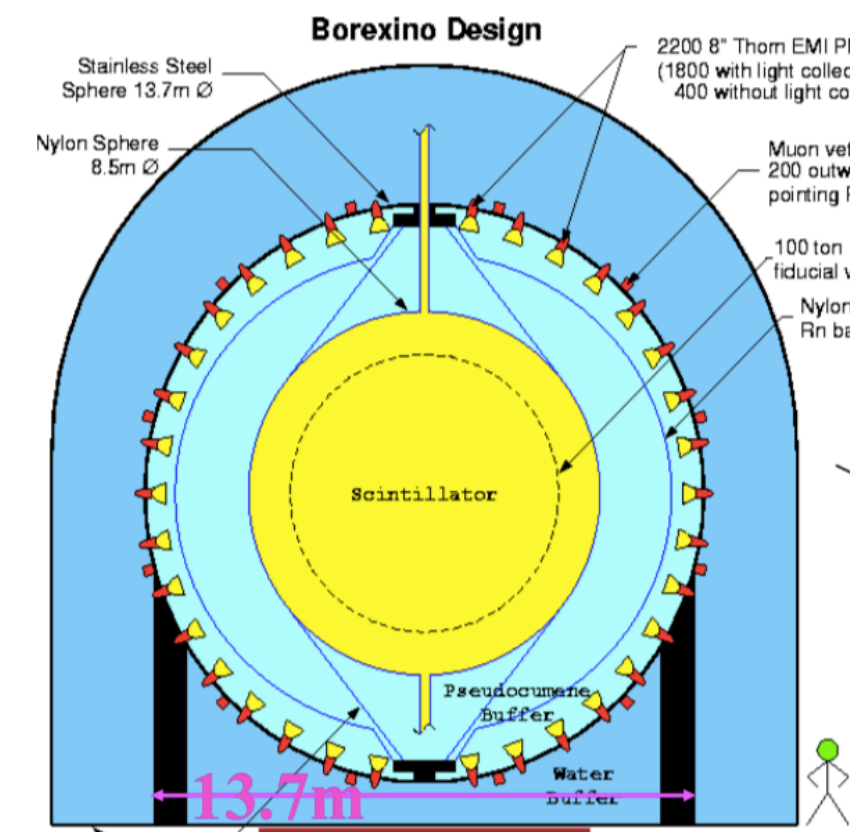
- Improve statistics of interactions observed “after oscillations” → done by larger detectors, long time, better selection
- Improve predictions → understand source (Sun, reactor, beam..) and measure “before oscillation” and extrapolate

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

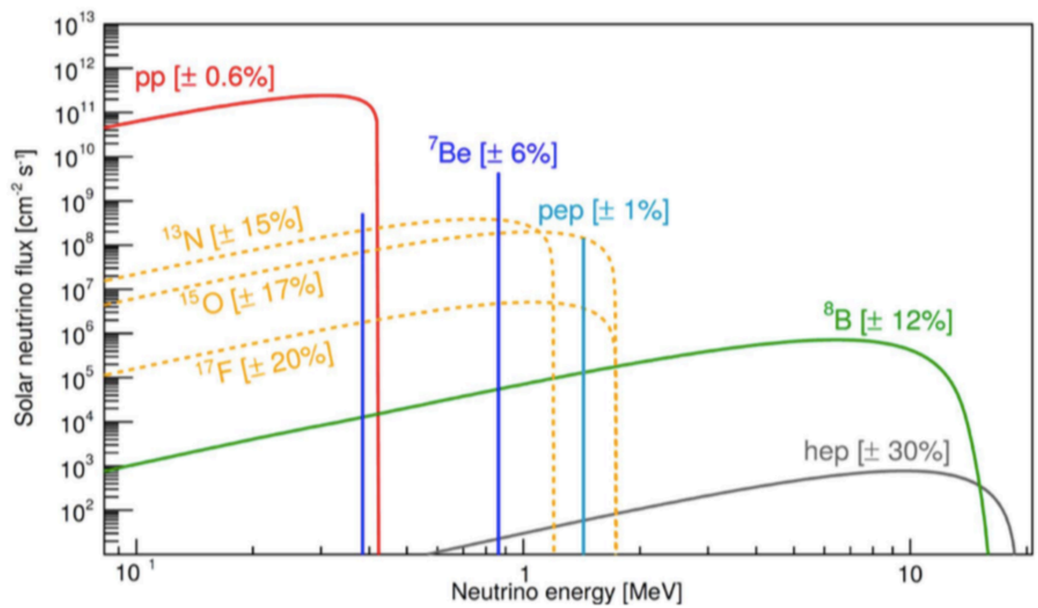
Start with sector 1-2

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

Let start from 1-2 solar neutrinos:



Solar neutrino spectra



Why it is difficult?

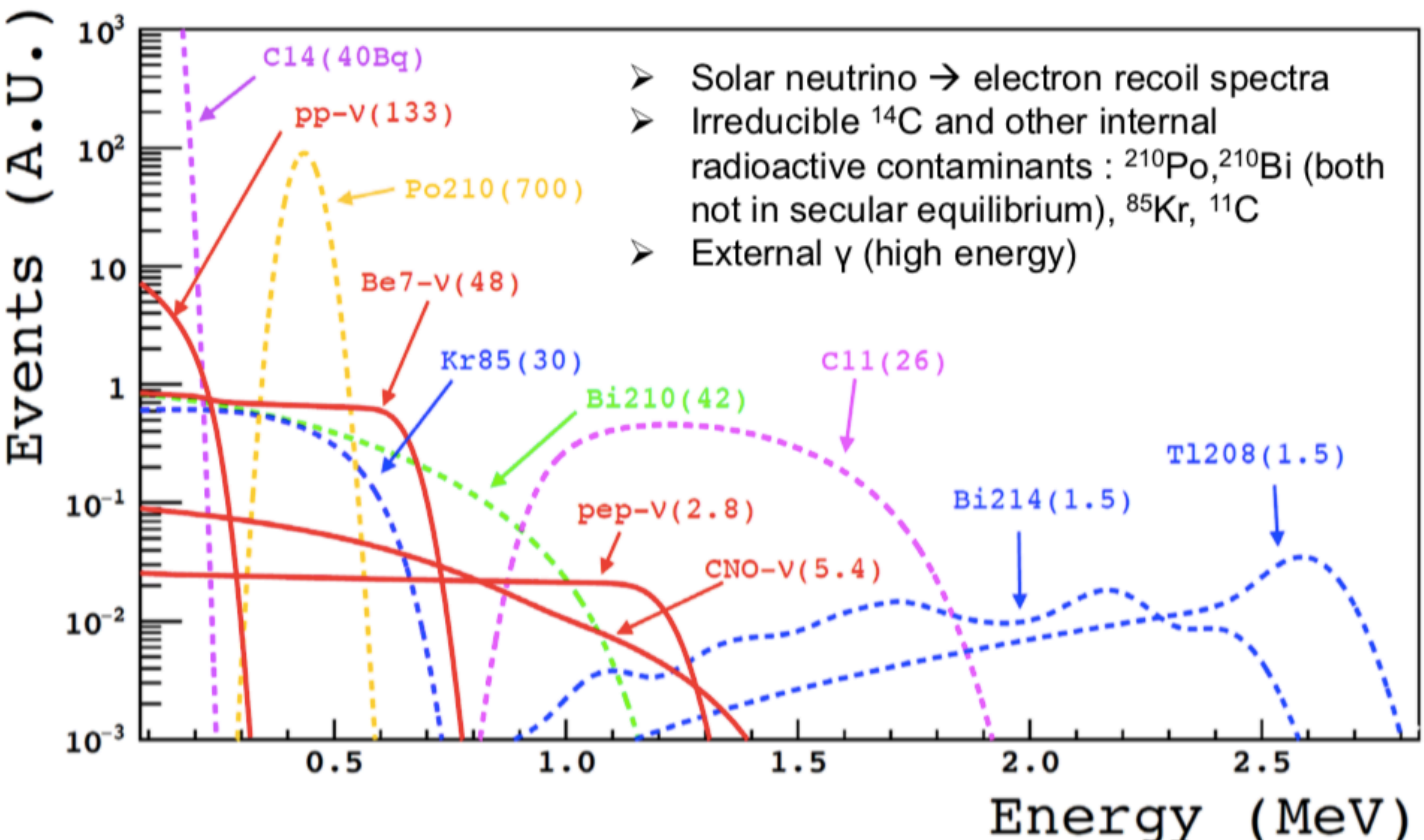
→ Signal is low energy electron (around MeV)

→ and large backgrounds from radioactive decays all around and in the detector

Expected rate in Borexino

50 events/d/100t expected (ν_e and $\nu_{\mu,\tau}$ elastic scattering on e^-) or $5 \cdot 10^{-9}$ Bq/kg (typically: drinking water ~10 Bq/kg; human body in ^{40}K: 5 kBq)

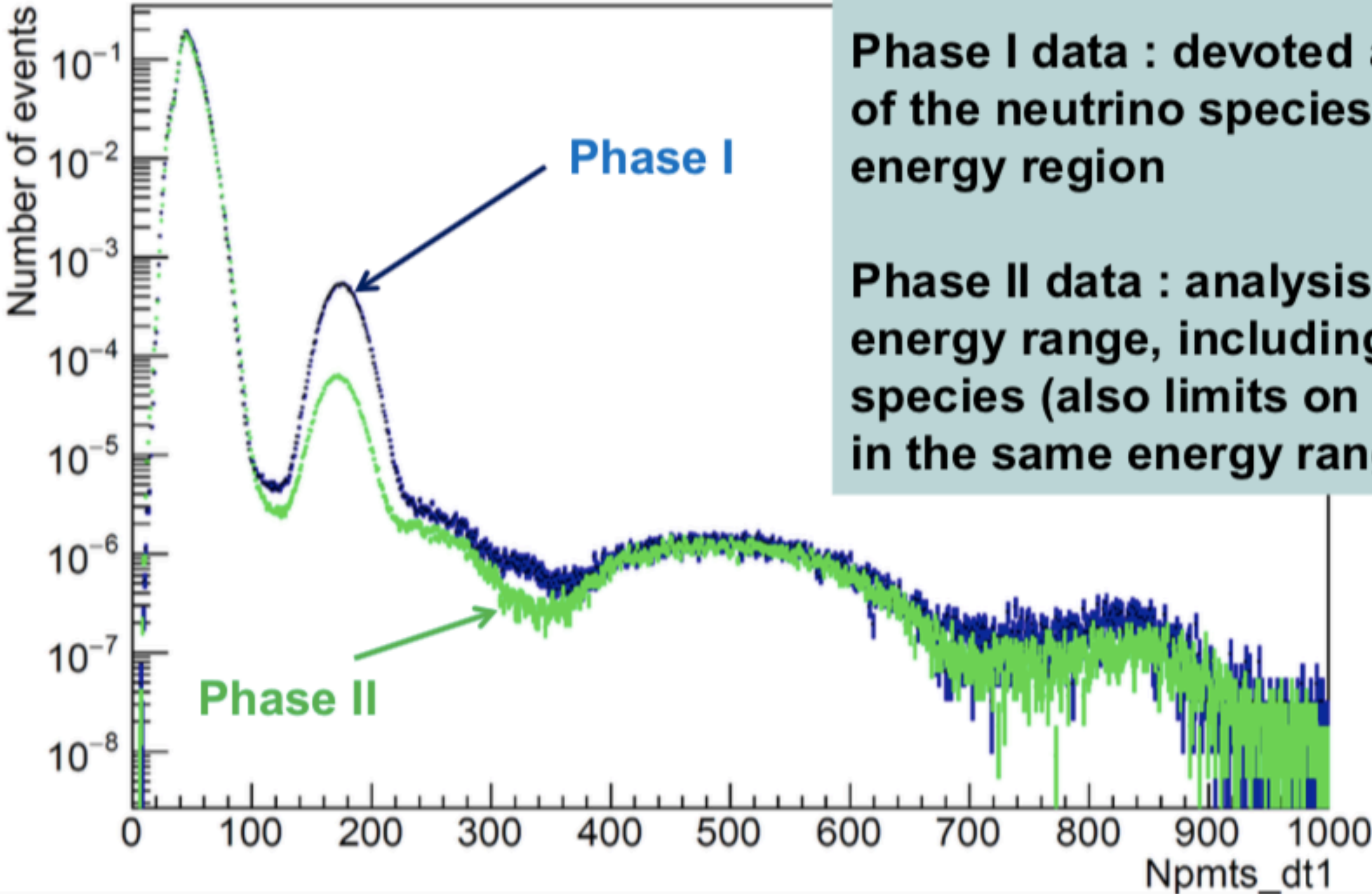
What are the expectations ?



MC input counting rates are quoted in cpd/100 t

and these are the result of measurements

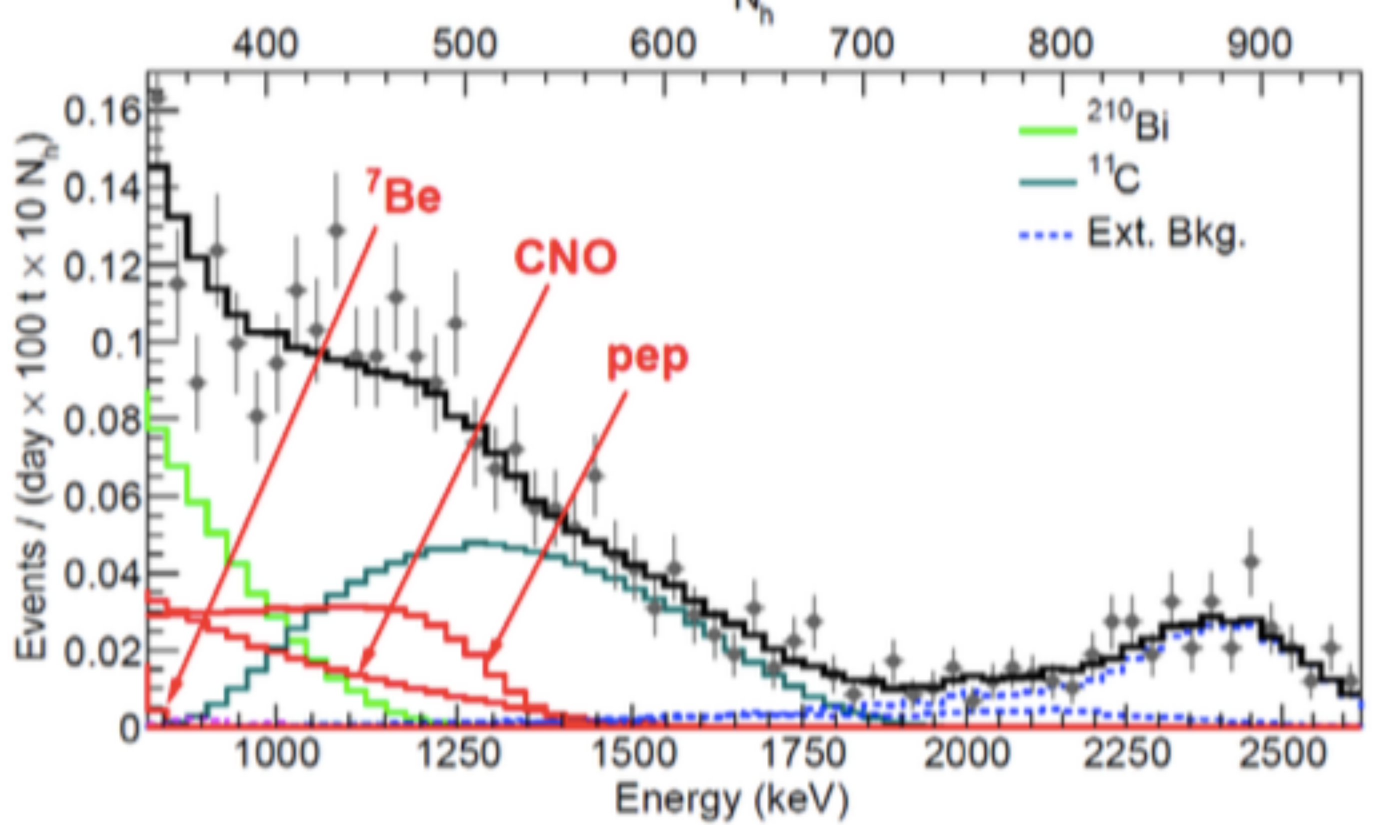
Phase I/Phase II



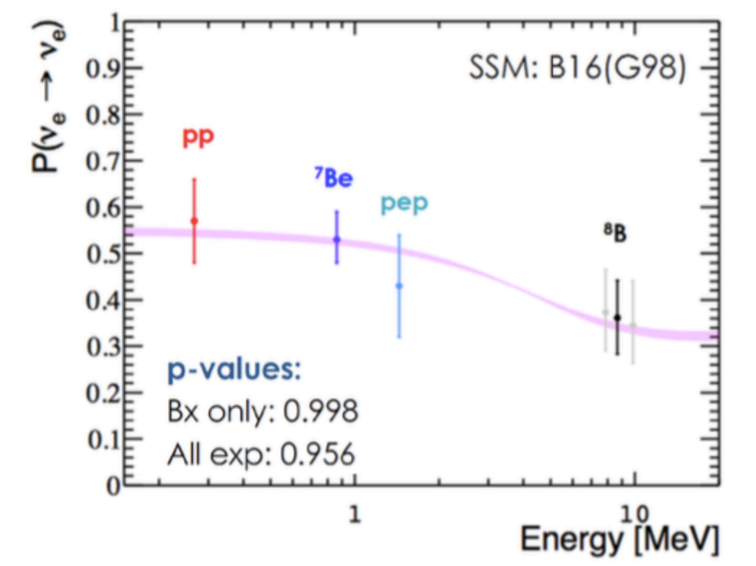
Phase II: lower ^{85}Kr and ^{210}Bi, reduced ^{210}Po

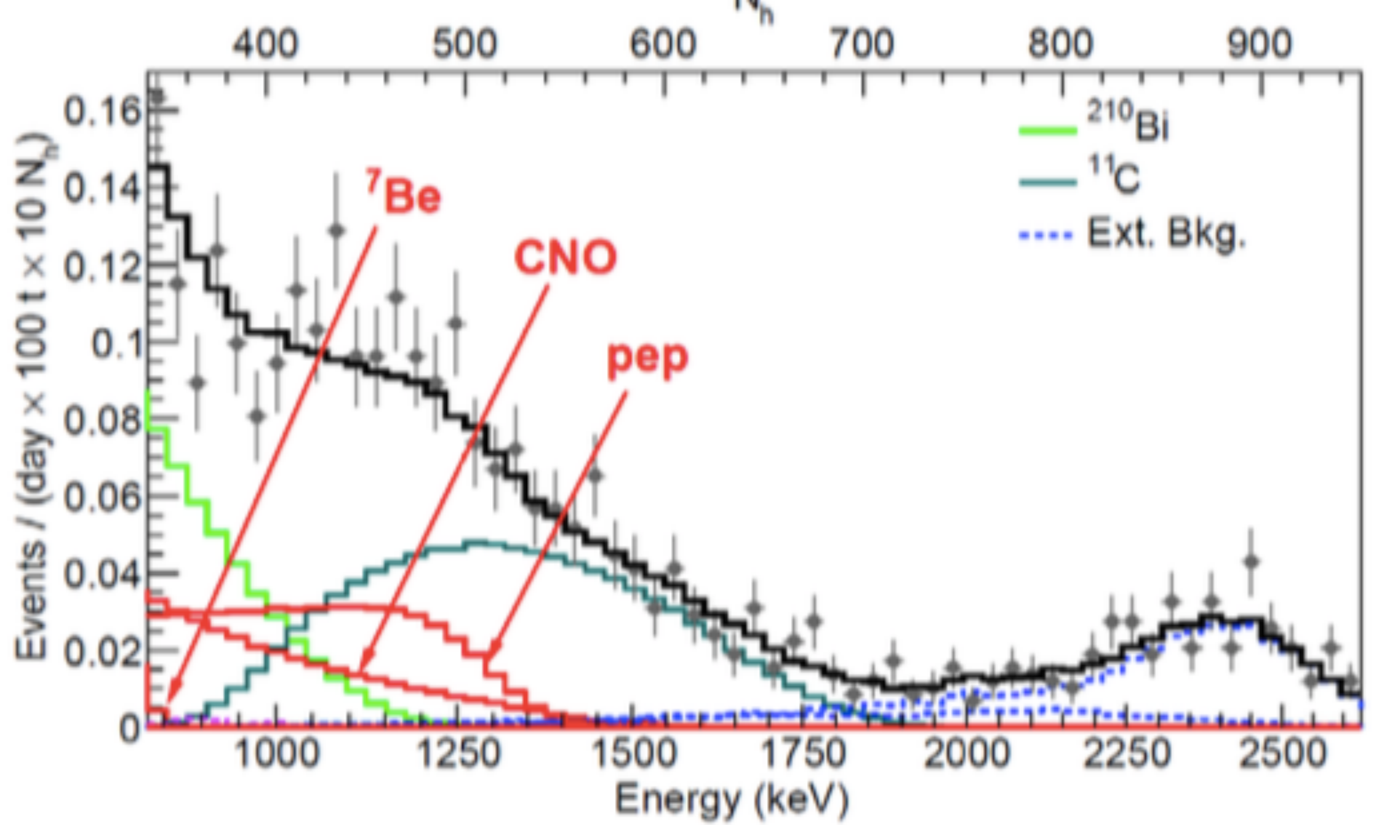
Phase I data : devoted analysis for each of the neutrino species with restricted energy region

Phase II data : analysis in the extended energy range, including pp, ^{7}Be and pep species (also limits on CNO are obtained in the same energy range)



	Earlier result (cpd/100t)	Actual result (cpd/100t)	Precision
pp	144±13±10	$134 \pm 10^{+6}_{-10}$	11%
^{7}Be$^{(*)}$	$46.0 \pm 1.5^{+1.6}_{-1.5}$	$46.3 \pm 1.1^{+0.4}_{-0.7}$	4.7→2.7%
pep	3.1±0.6±0.3	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	22→16%





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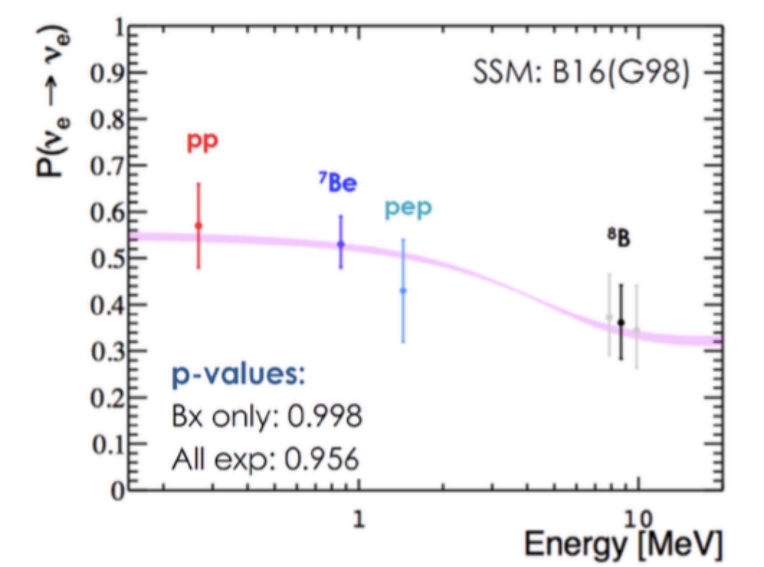
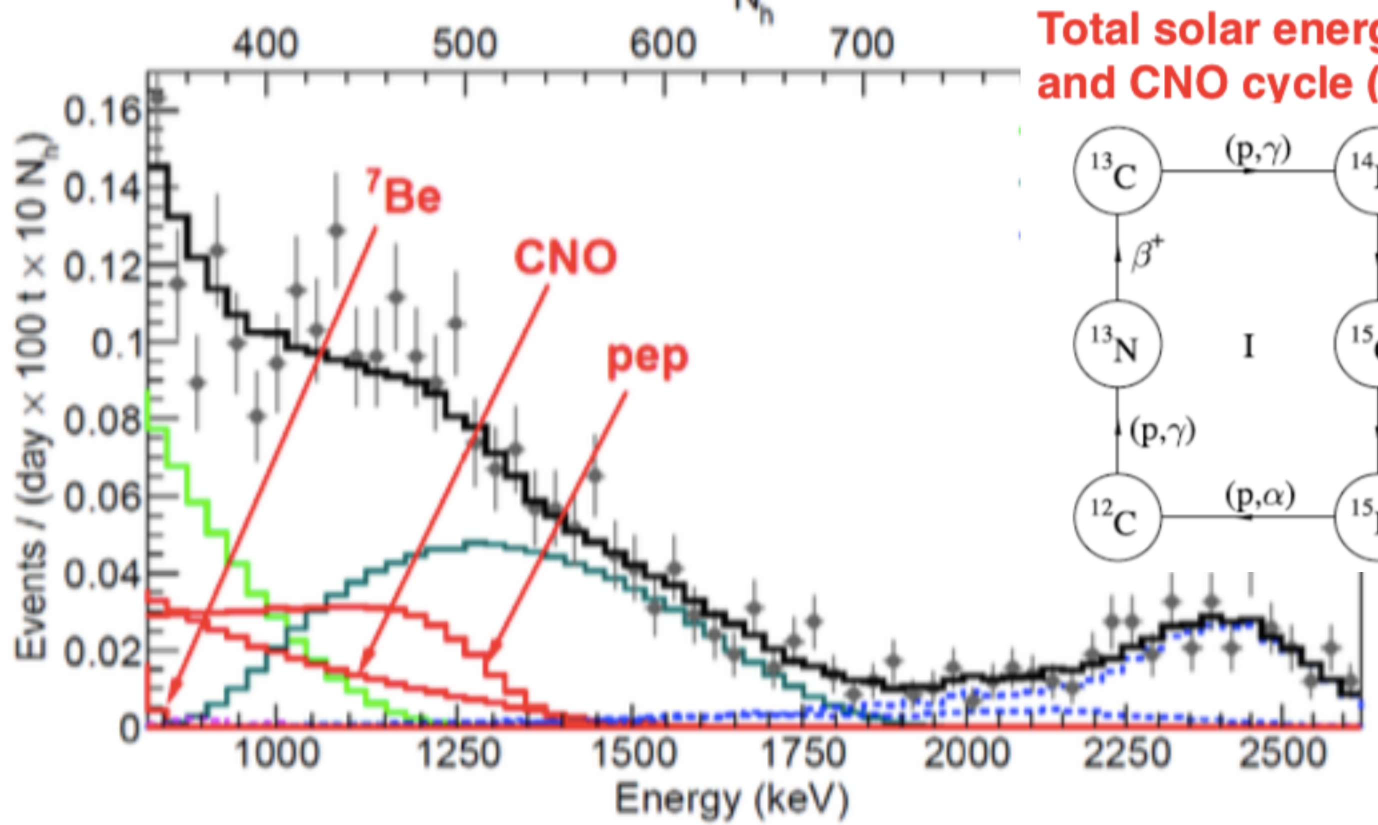
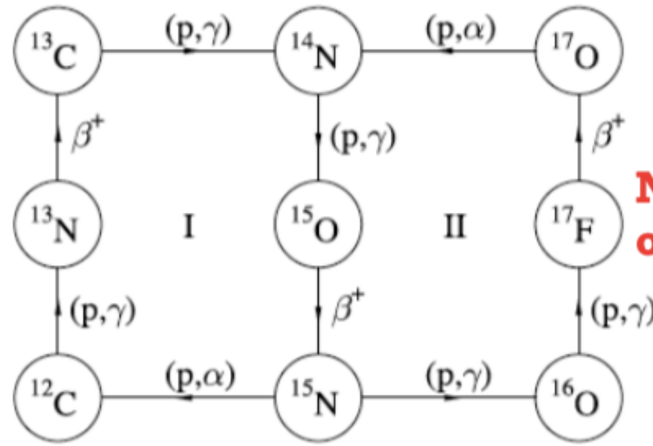




Total solar energy: pp chain (99%) and CNO cycle (1%)



Not yet observed

	Earlier result (cpd/100t)	Actual result (cpd/100t)	P[illegible]on
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^{7}Be$^{(*)}$	$46.0 \pm 1.5^{+1.6}_{-1.5}$	$46.3 \pm 1.1^{+0.4}_{-0.7}$	4.7→2.7%
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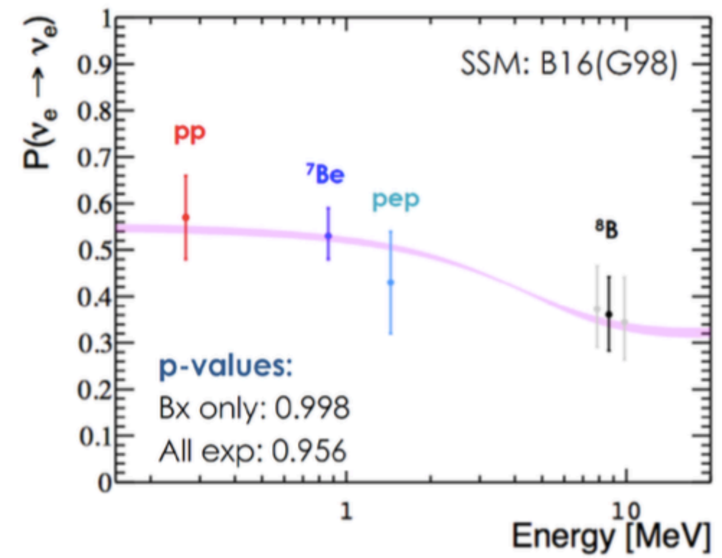
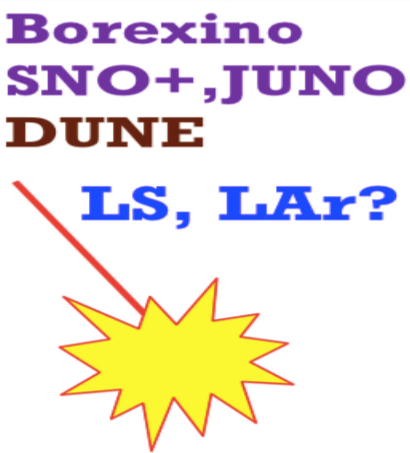
NEW: 5 sigma evidence for pep contribution



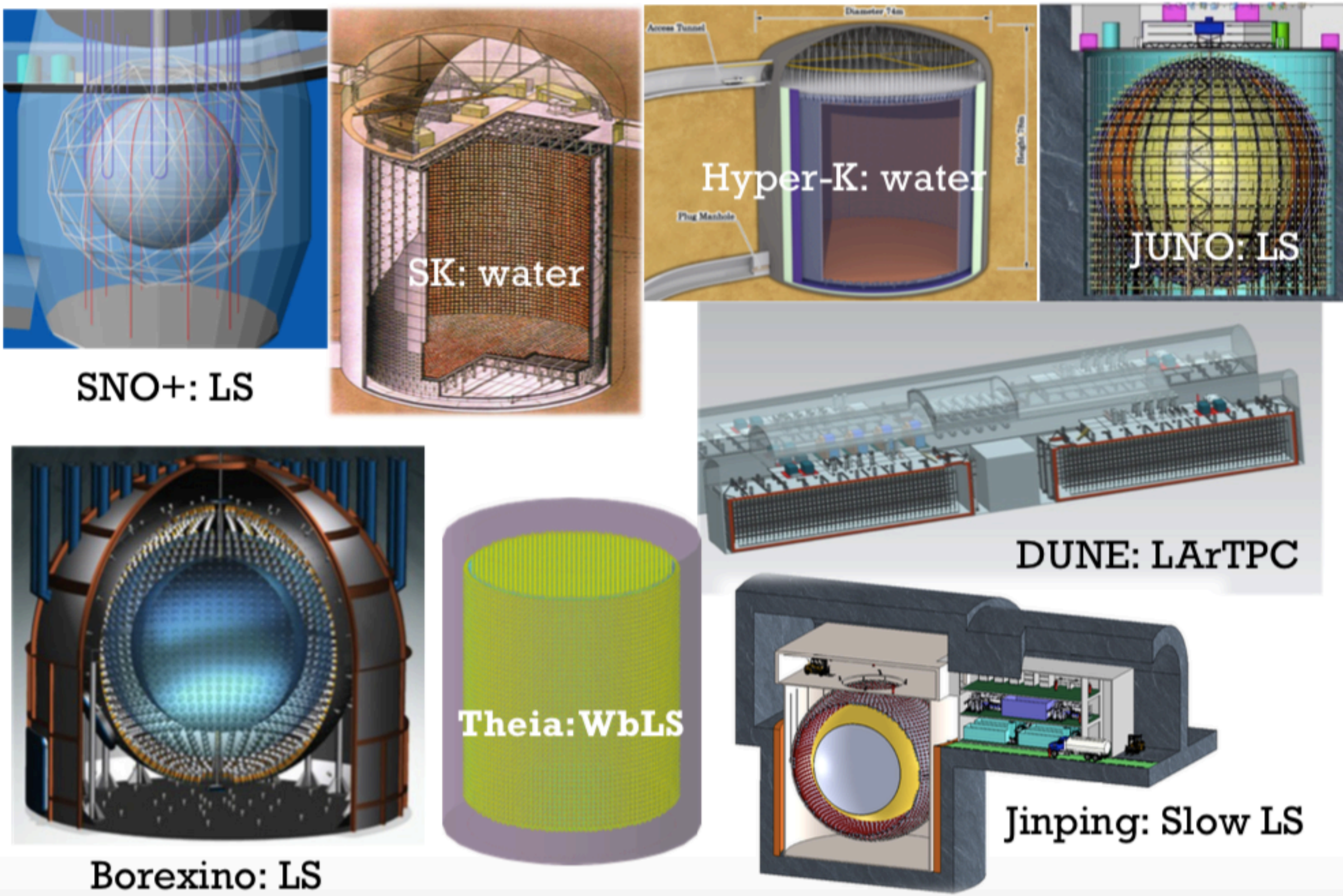
Detectors working for Solar neutrino studies (now and neast future)

From S.Chen talk at Neutrino2018

Detector	Depth (m)	Type	Mass (t)	Live period	Location
Super-K	~1000	Water	22.5k	1996-present	Japan
Borexino	~1400	LS	278	2007-present	Italy
SNO+	~2000	LS	800	July, 2018	Canada
JUNO	~700	LS	20k	Near future	China
Hyper-K	~600	Water	187k	Future	Japan
DUNE	~1500	LAr	34kt	Future	USA
Theia	?	WbLS	25k	Future	USA
Jinping	~2400	Slow LS	2k	Future	China

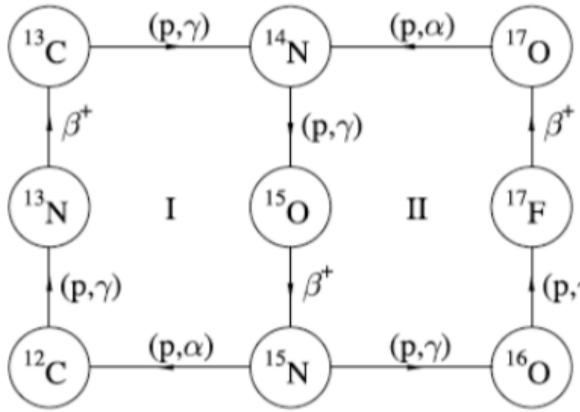


Looking at the detectors....



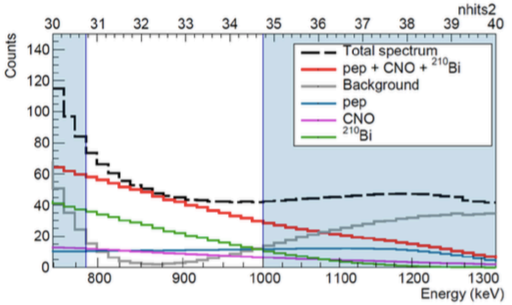
Future:

Total solar energy: pp chain (99%) and CNO cycle (1%)

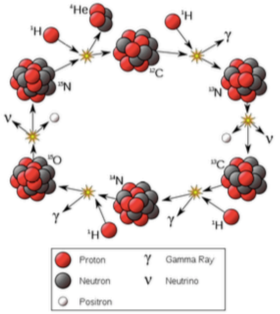


Not yet observed

Key to the Solar metallicity : CNO flux



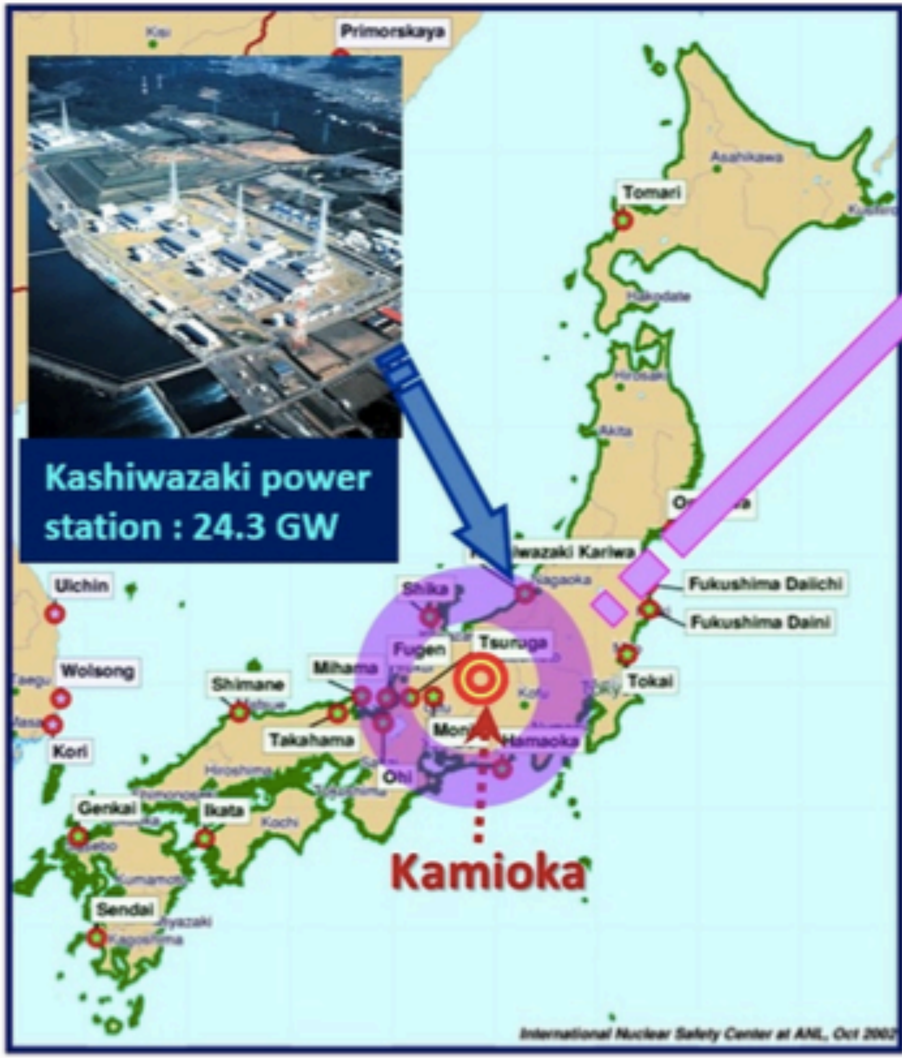
Expected spectrum assuming $\nu(CNO)$ HZ flux and other rates from last solar analysis



Predictions: HZ ~5 cpd/100 t
LZ ~3 cpd/100 t

Search for neutrino/antineutrino in coincidence with 2350 GRB observed during 8 years of the Borexino data taking
Astropart. Phys. 86, p.11 (2017)

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

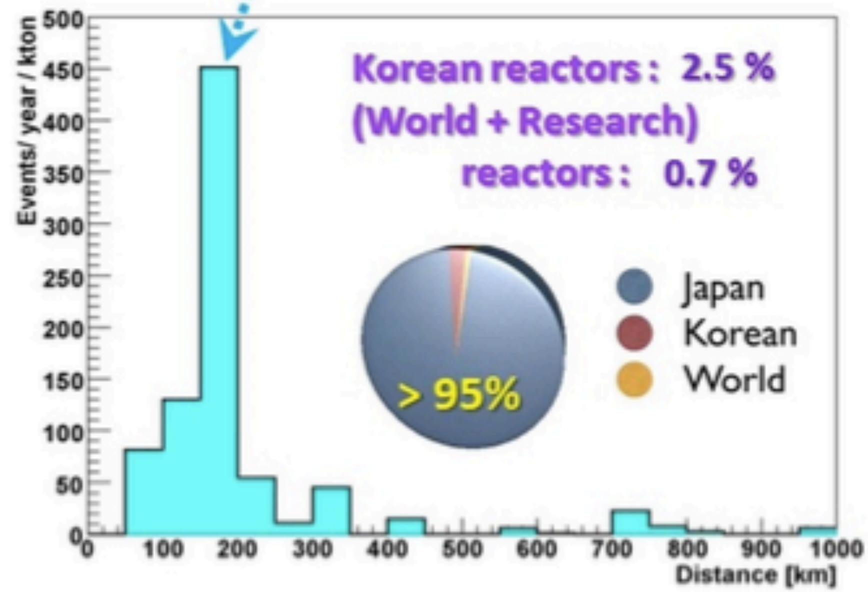


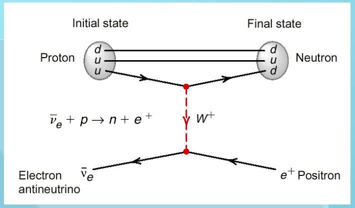
70 GW (~12 % of global nuclear power)

at

L ~ (175 ± 35) km

effective baseline : ~ 180 km

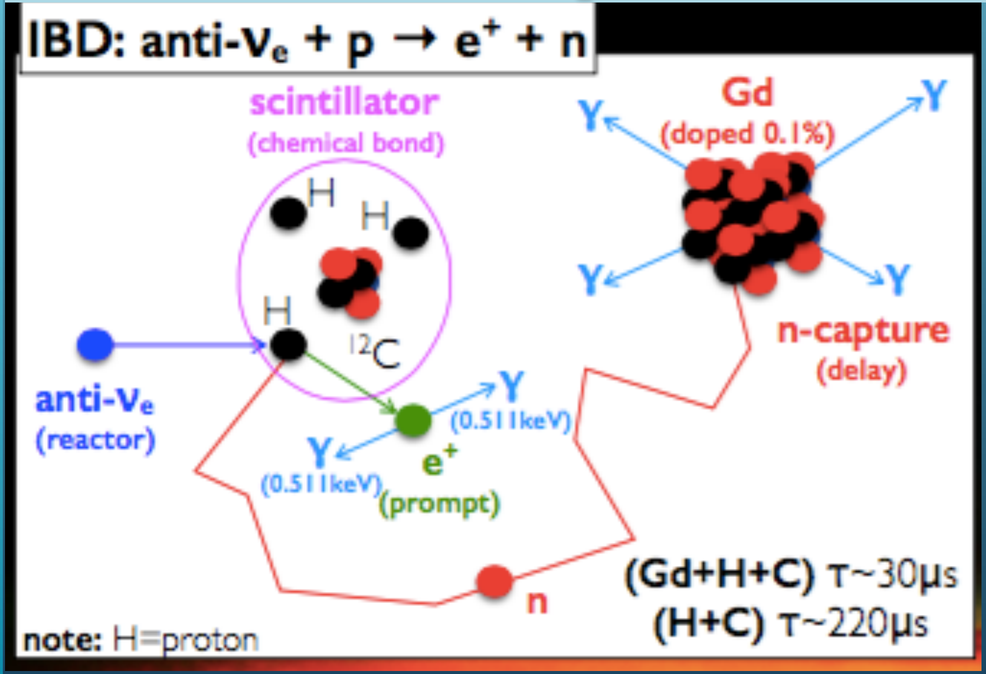


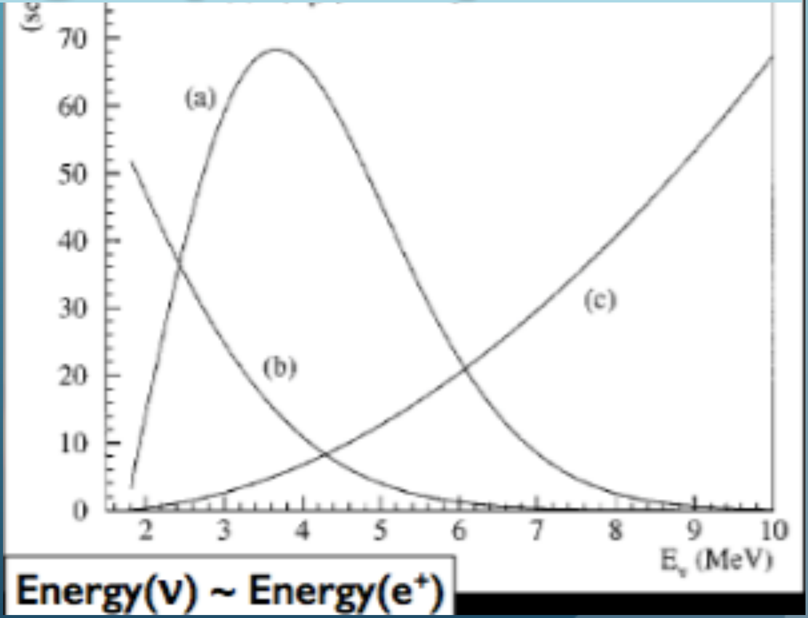


Reactor neutrinos – same energy range, also electron neutrinos

Historicaly – this is where neutrinos were discovered (Reines – Cowan experiment)

Inverse β decay (IBD)





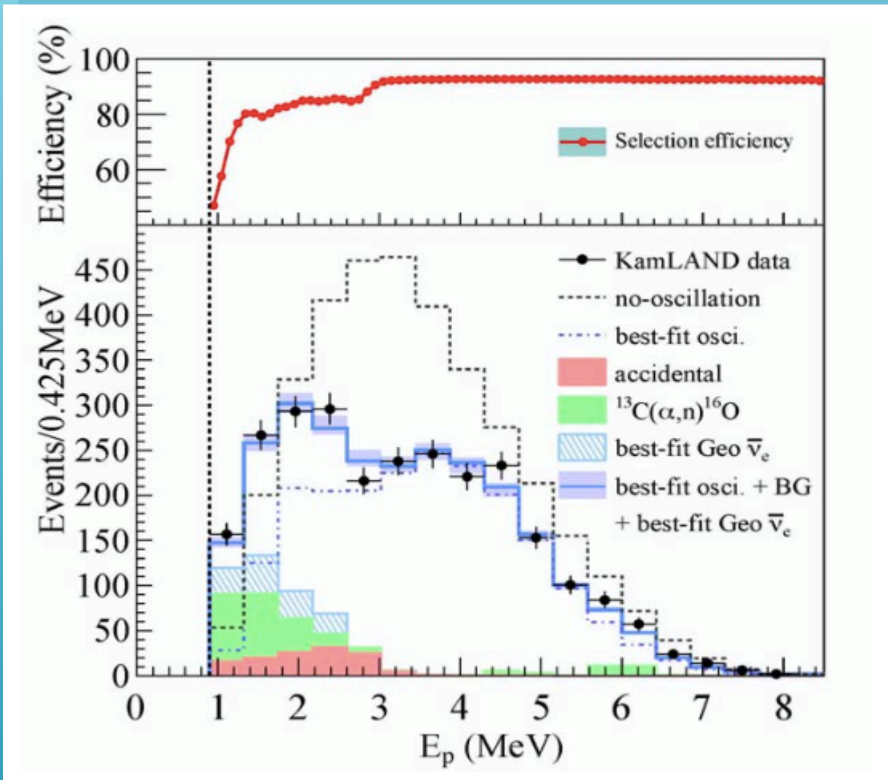
Prompt signal from positron capture
Delayed photons from neutron capture

Observed neutrino energies (reactor) convolution of:

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

Coinncidence is crutial for background reduction

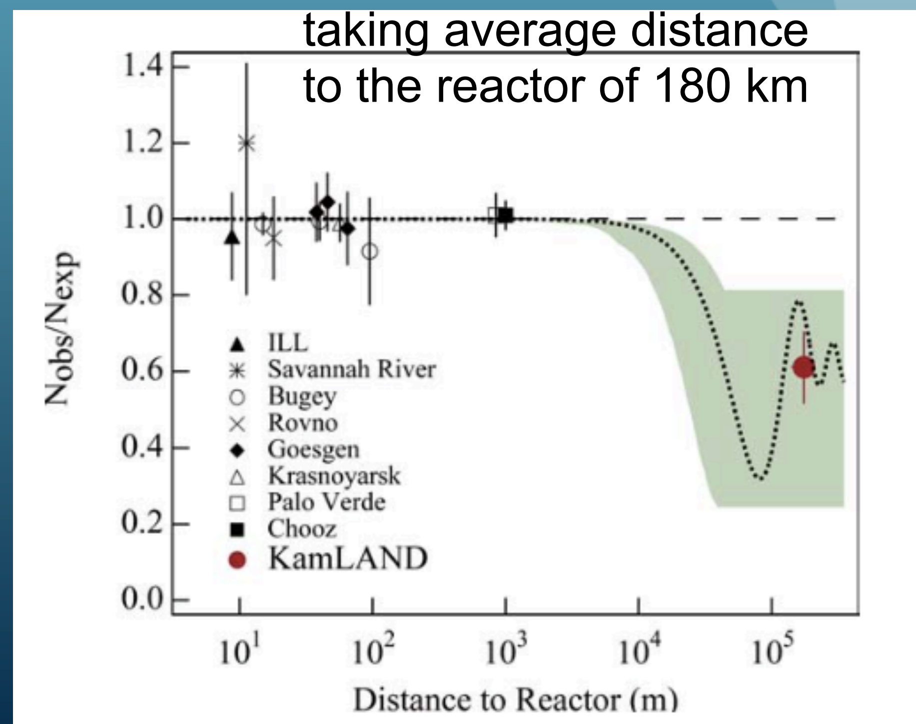
Kamland – exposure of 5780 kton-yr



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

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

Corresponding to
exclusion of non-oscillation at
10.2 σ CL

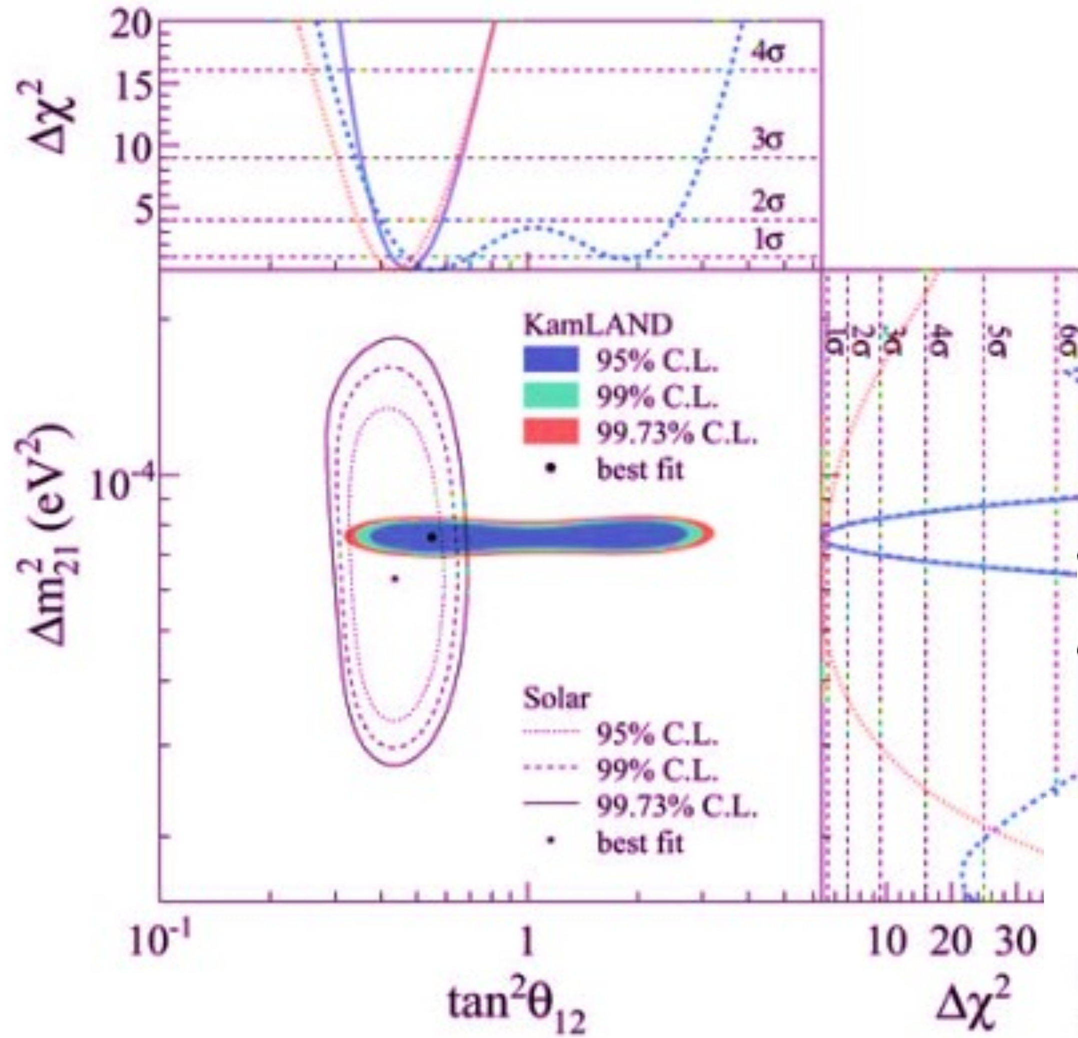


Determination of 1-2 mixing

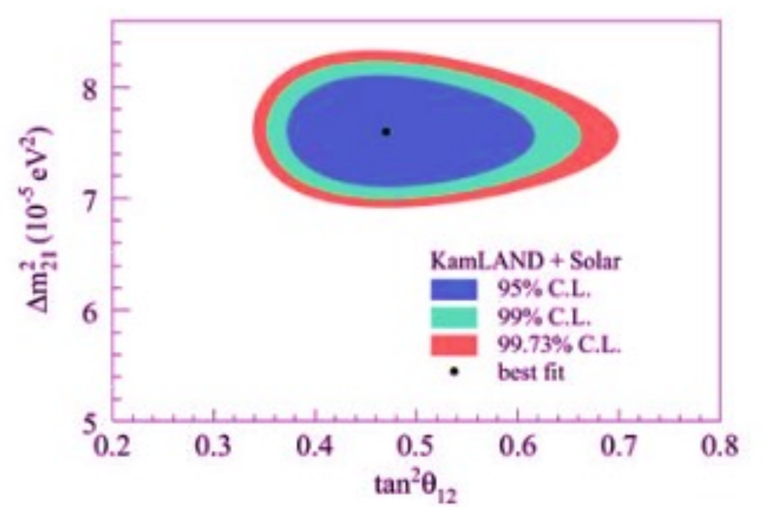
Assuming same values for Neutrinos and anti-neutrinos

We obtain:

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

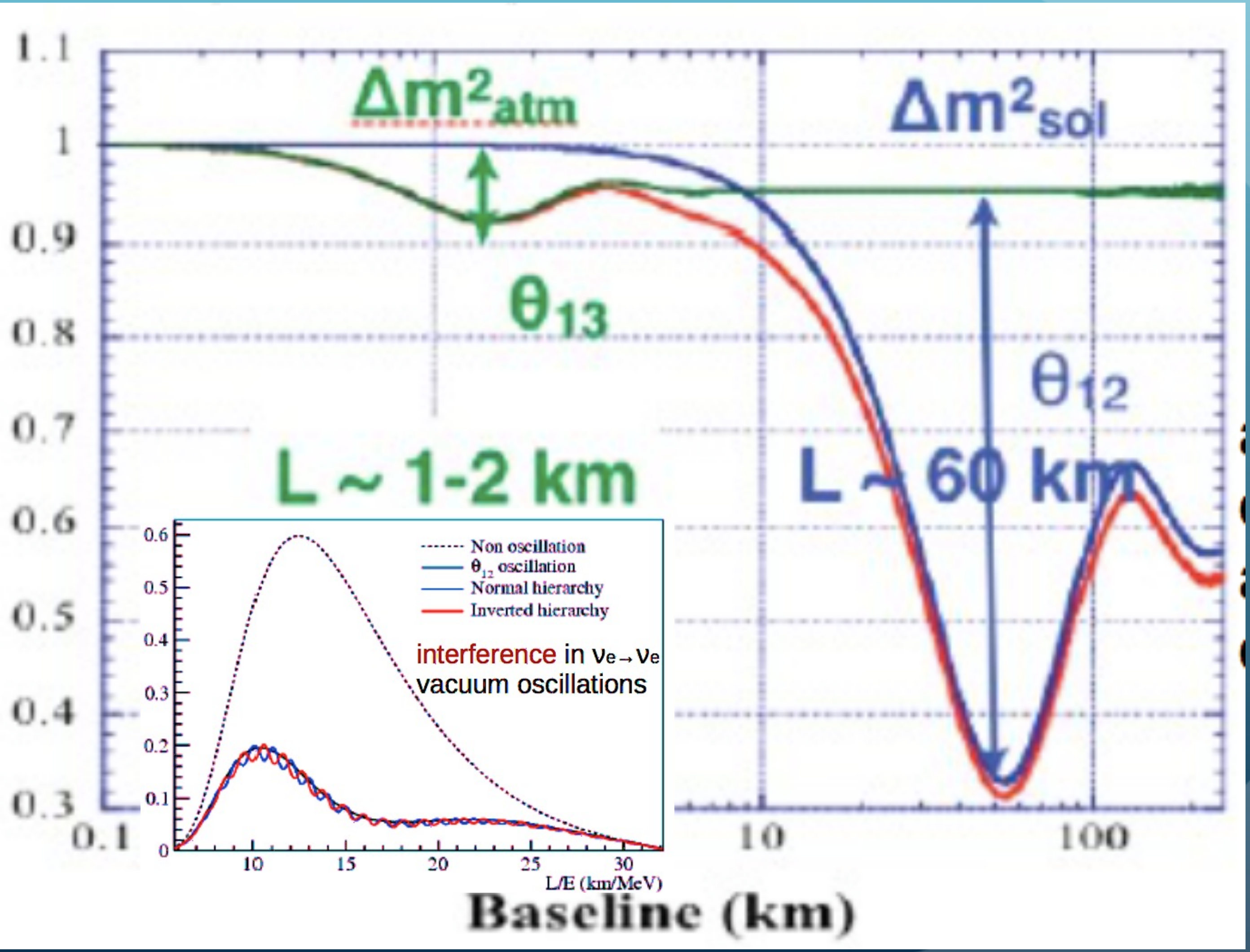


Δm^2_{21} (10^{-5} eV^2)	$\tan^2\theta_{12}$
$7.54^{+0.19}_{-0.18}$	$0.481^{+0.092}_{-0.080}$



- Kamland only ie. for anti-neutrinos

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



Sector 2-3 "atmospheric"

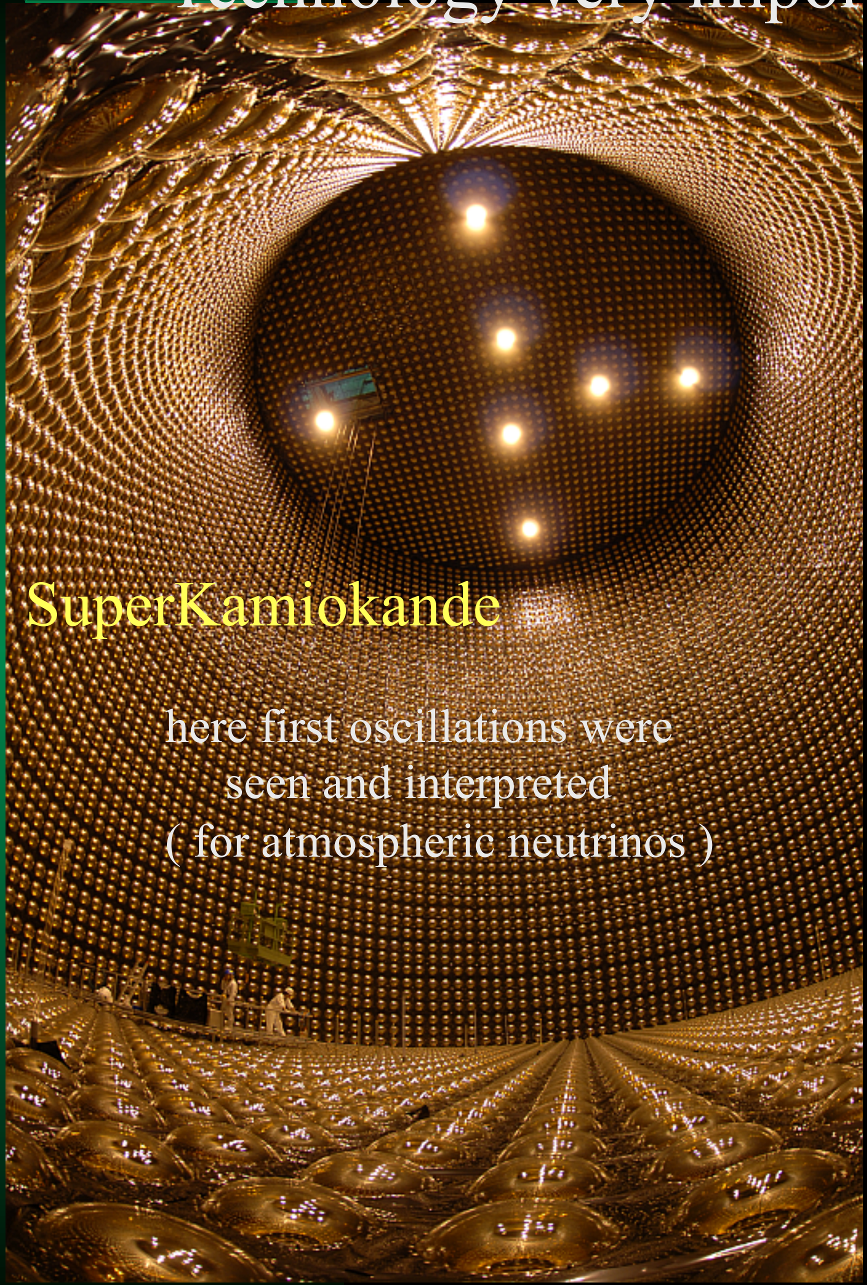
Started with measurements in Super-Kamiokande

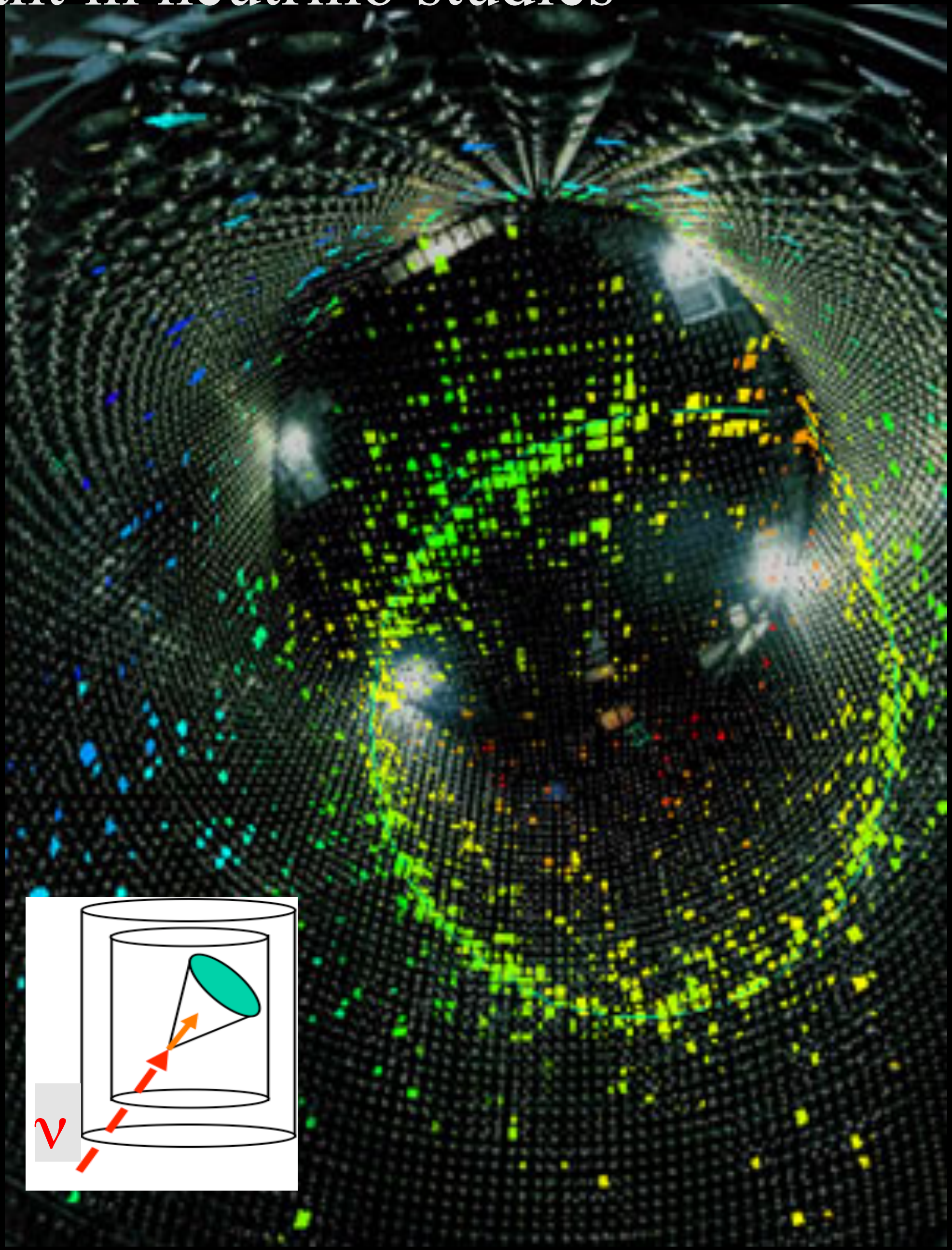
Now includes data from

- Long Base Line experiments
- Atmespheric neutrinos in traditional detectors
- Neutrino telescopes

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

Technology very important in neutrino studies

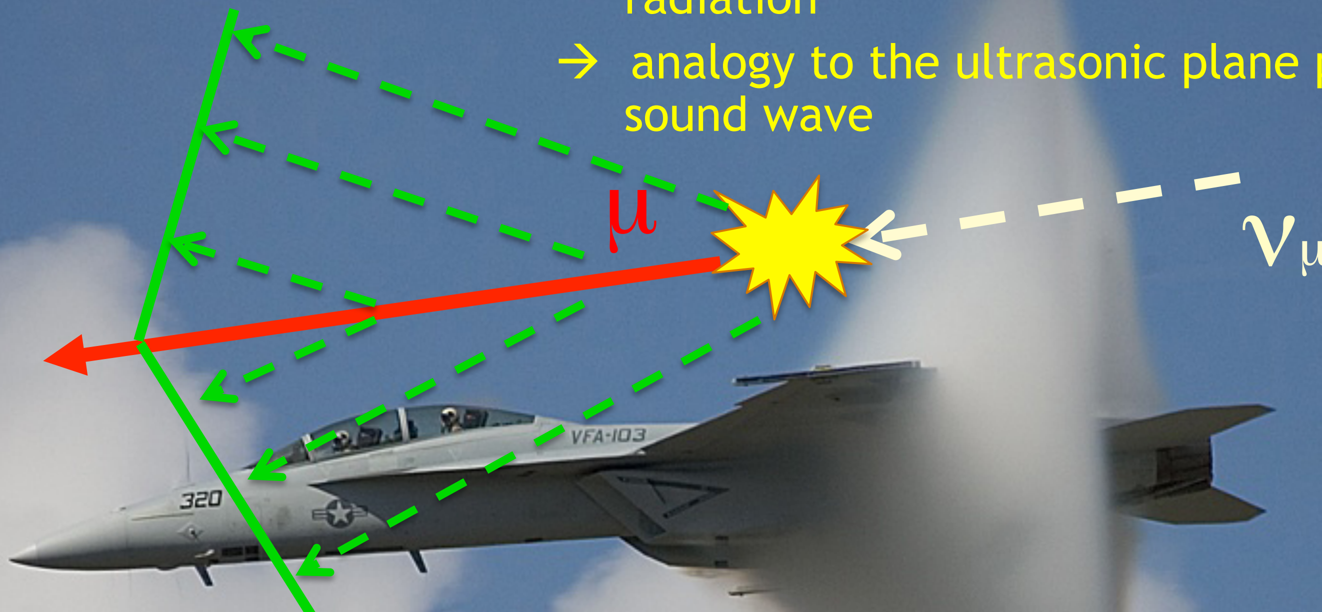




Cherenkov radiation

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

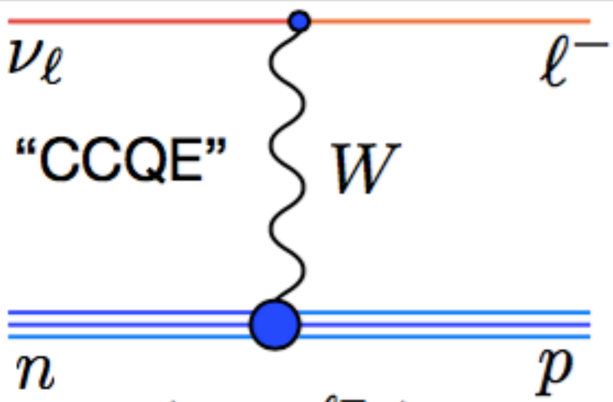
→ analogy to the ultrasonic plane producing sound wave



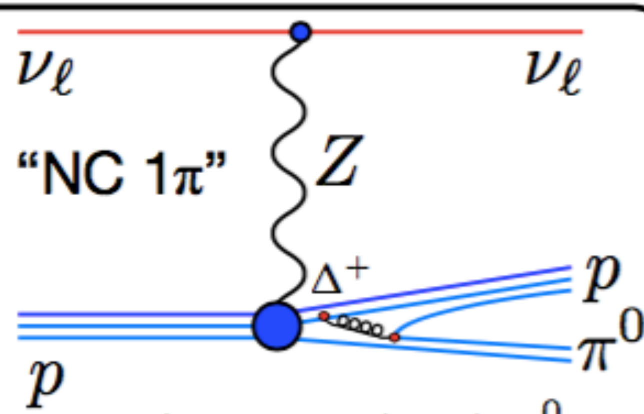
Sensitive to CC
or NC with charge particle production

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

NEUTRINOS AT T2K-SK



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



$$\nu_\ell + p \rightarrow \nu_\ell + p + \pi^0$$

Signal

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

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

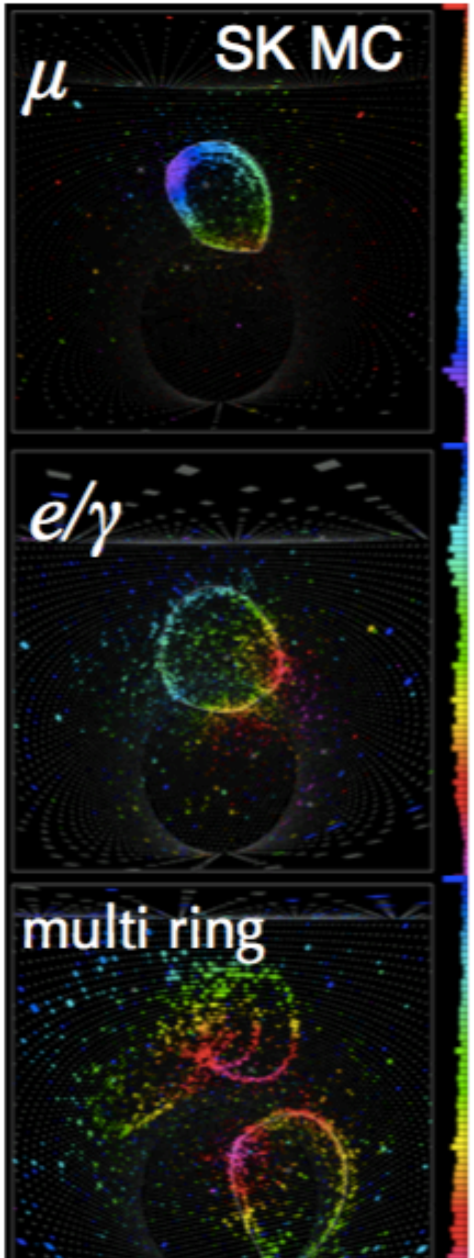
Backgrounds

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

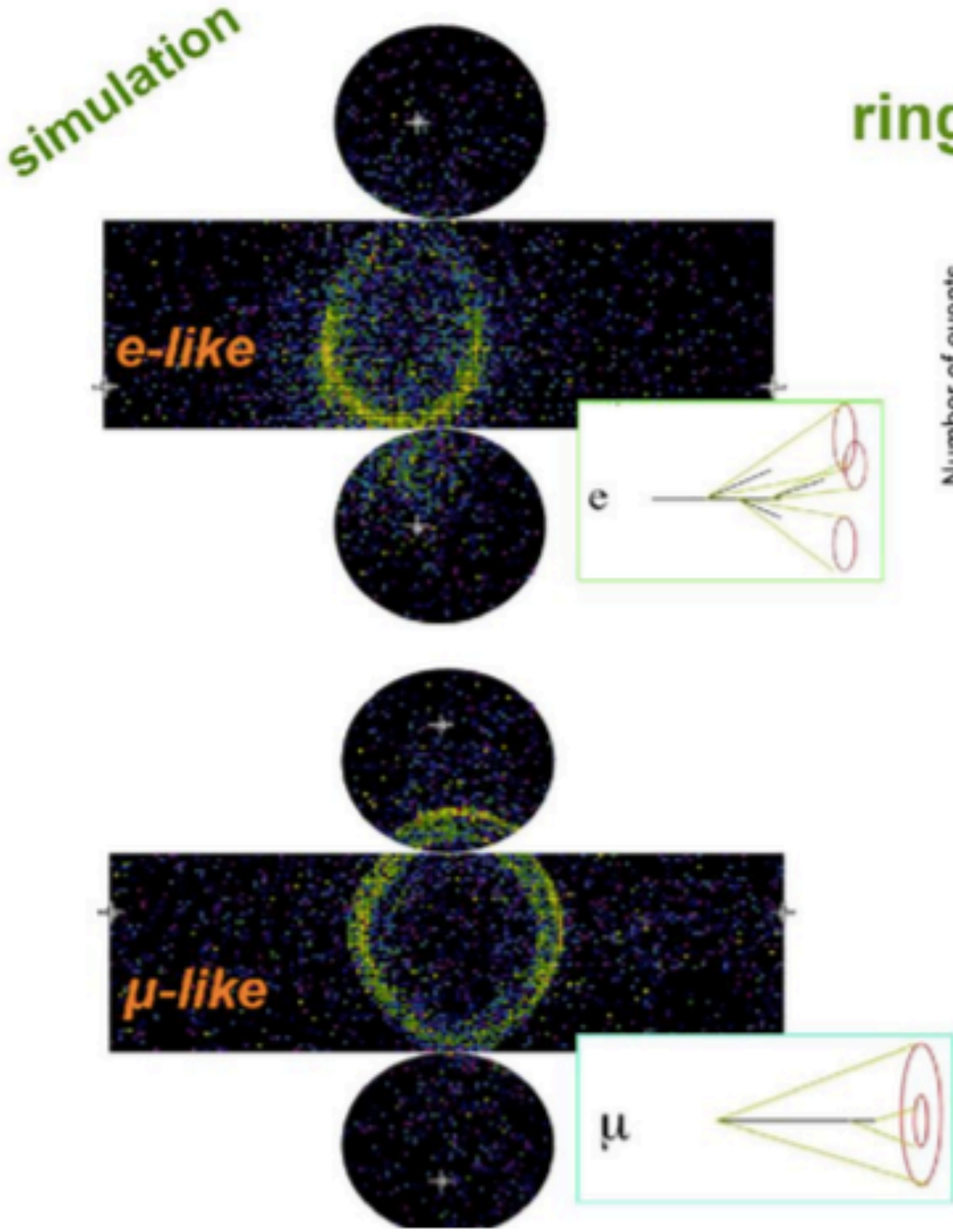
$\nu_\ell + (n/p) \rightarrow \ell^- + (n/p) + \pi$

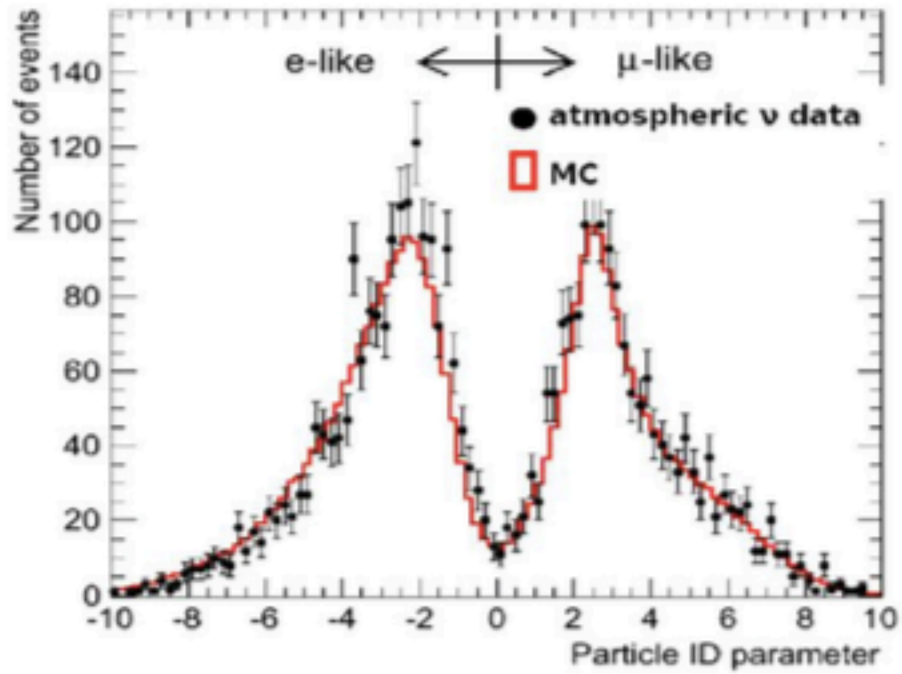
- $\pi^0 \rightarrow \gamma + \gamma$: ring counting, 2-ring reconstruction
  - γ misidentified as e from ν_e CCQE
  - powerful rejection capabilities reduce this by $O(10^2)$
- Ring counting, decay electron cut to reject nCCQE

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



Particle ID using ring shape & opening angle





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

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

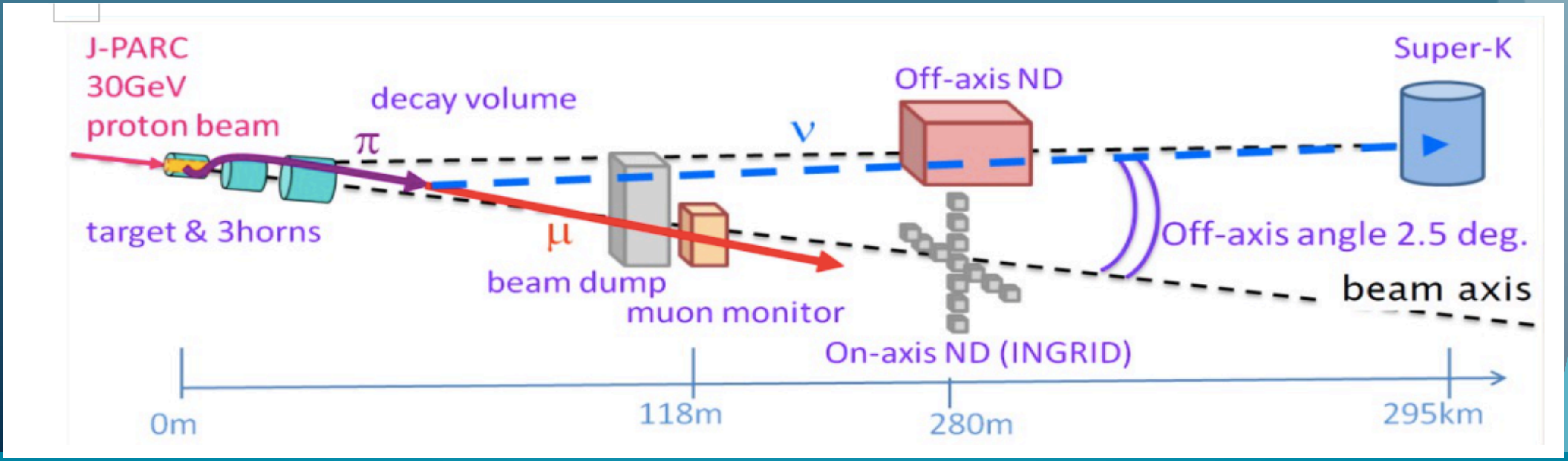
→ NA61 at CERN

Proton beam on target
→ Produces π and K

$$\pi^+ \to \mu^+ + \nu_u$$

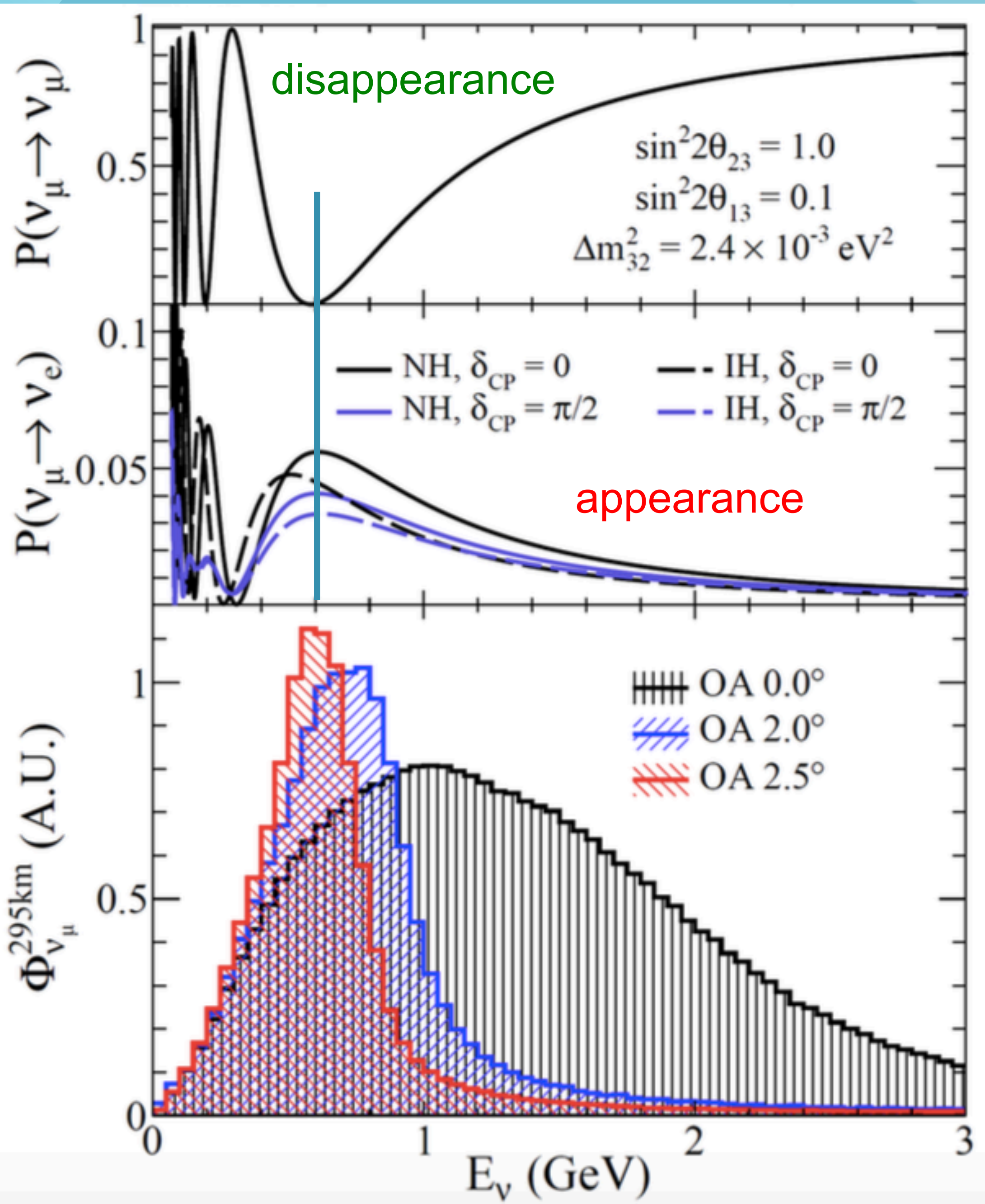
$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

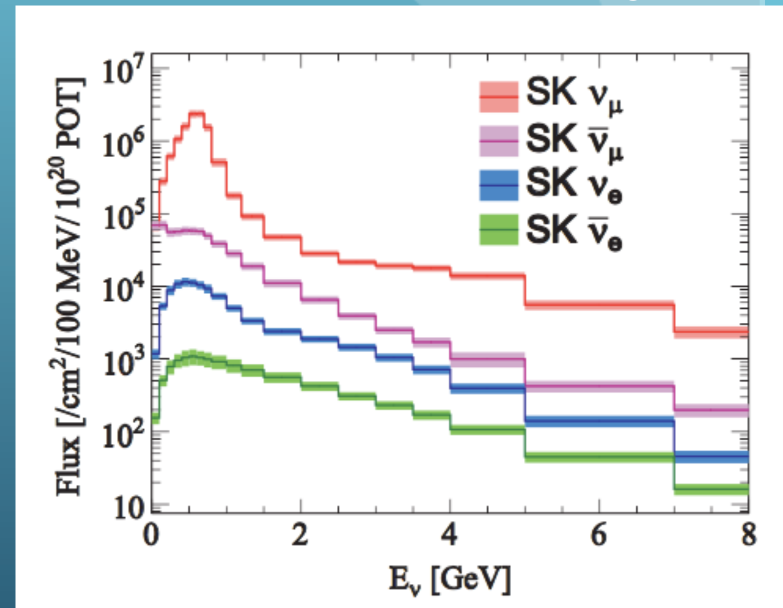
$$K^+ \to \pi^0 e^+ \nu_e$$

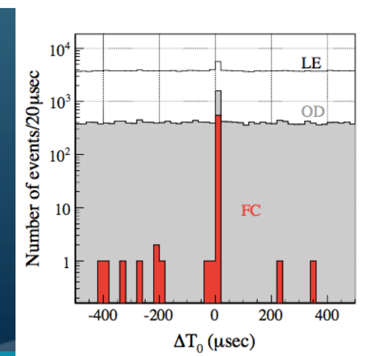


precisely tuned with L and E to oscillation maximum

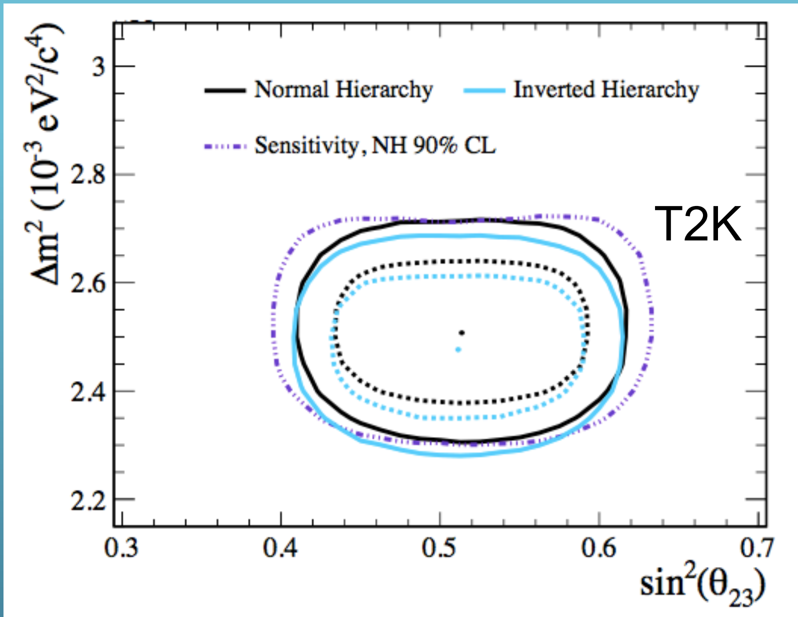
- Maximal effect
- Also lower background (due to smaller number of high energy NC, possibly similar to ν_e CC)

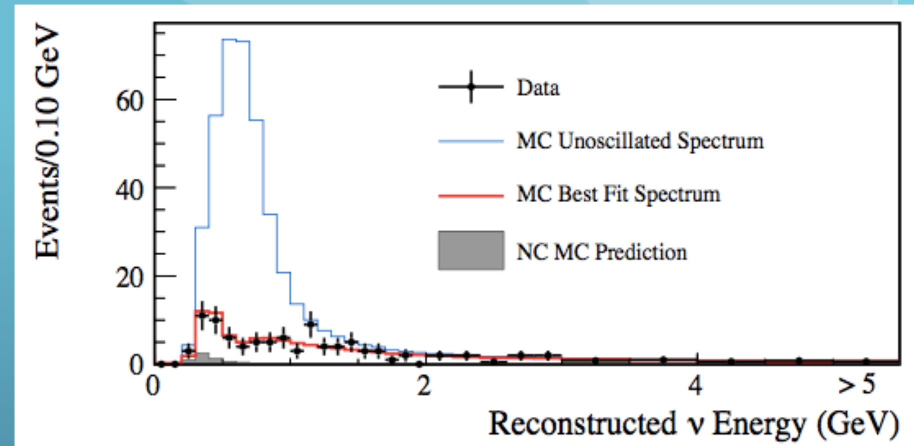


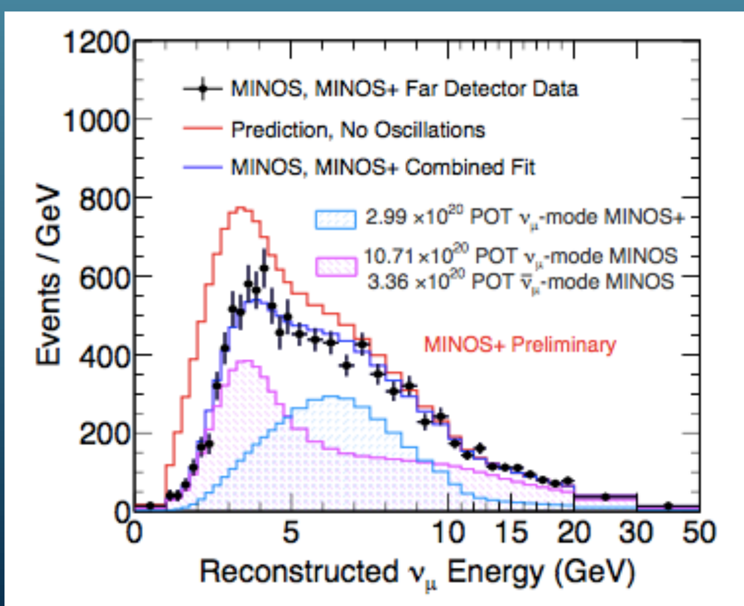


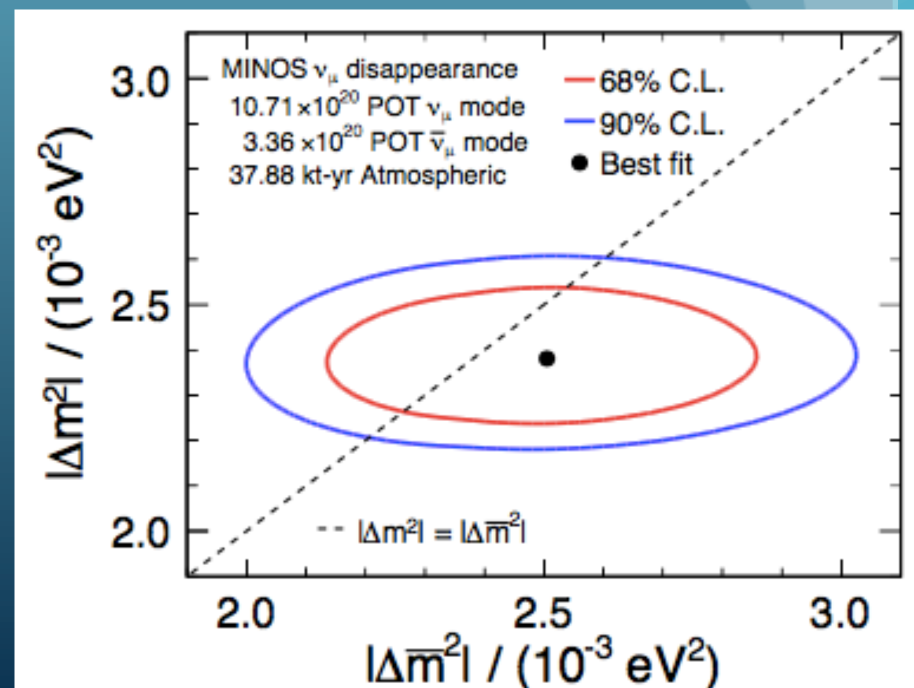


Most precise measurement of Δm_{23}, θ_{23}

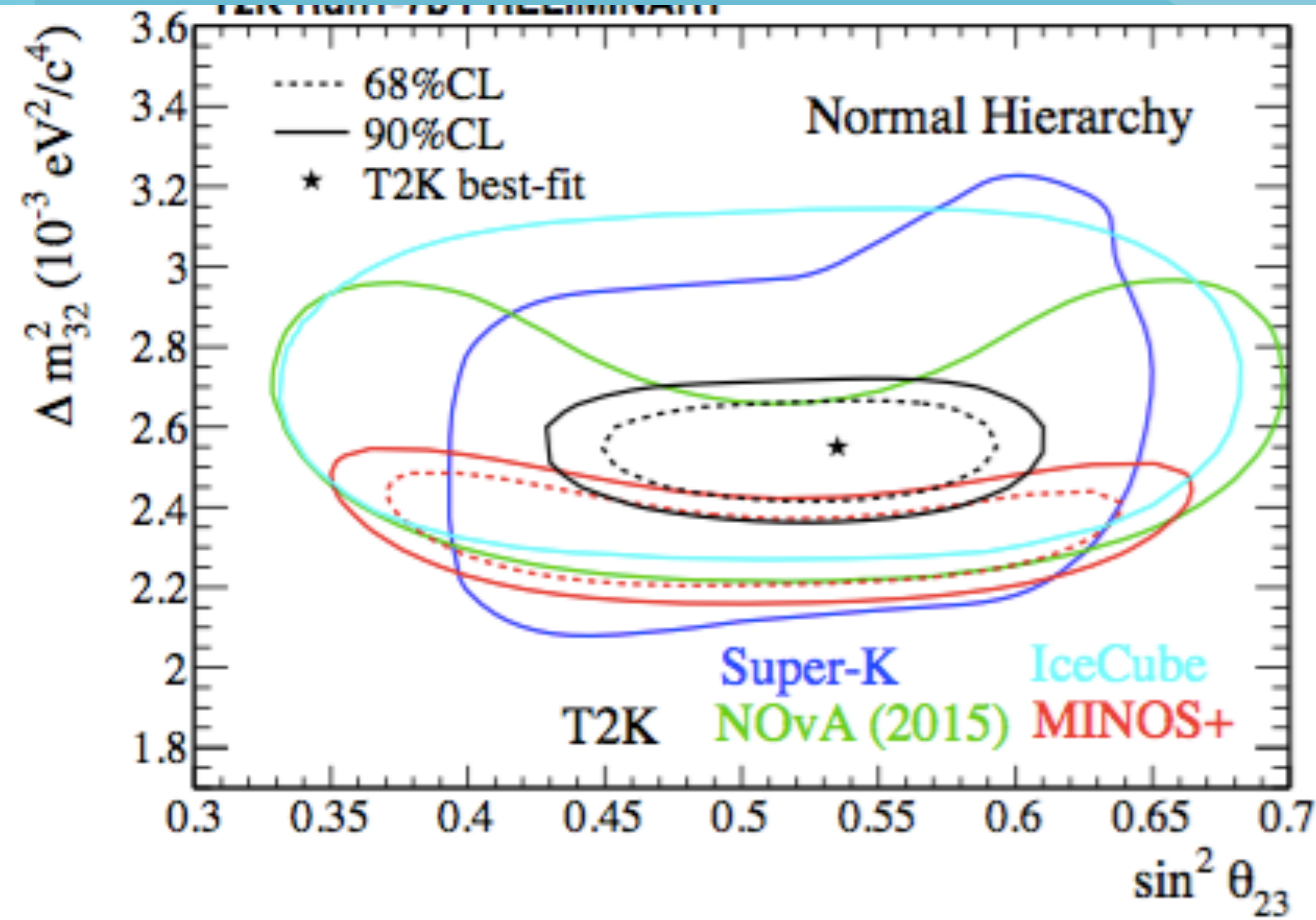








Present status in sector 2-3:



Neutrino 2018

Results differ slightly for NH and IH

No strong preference

Sector 1-3

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

Measurements of $\sin^2 \Theta_{13}$ in ν_e disappearance of reactor ν

and ν_e appearance (in muon neutrino beam)

Tests of CP violation – determination of δ_{CP}

… 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!

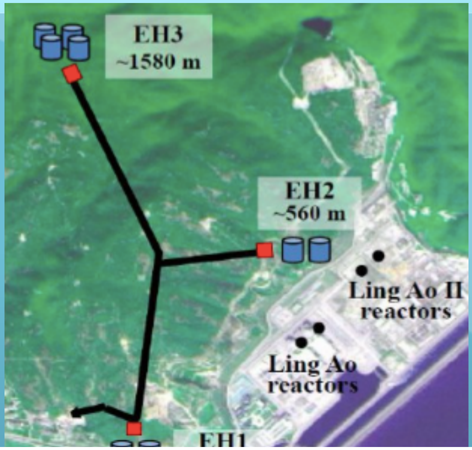
Second order terms depend on δ and mass hierarchy

Energy ~ a few GeV
Distance ~ a few hundred km

Sector 1-3 reactor data

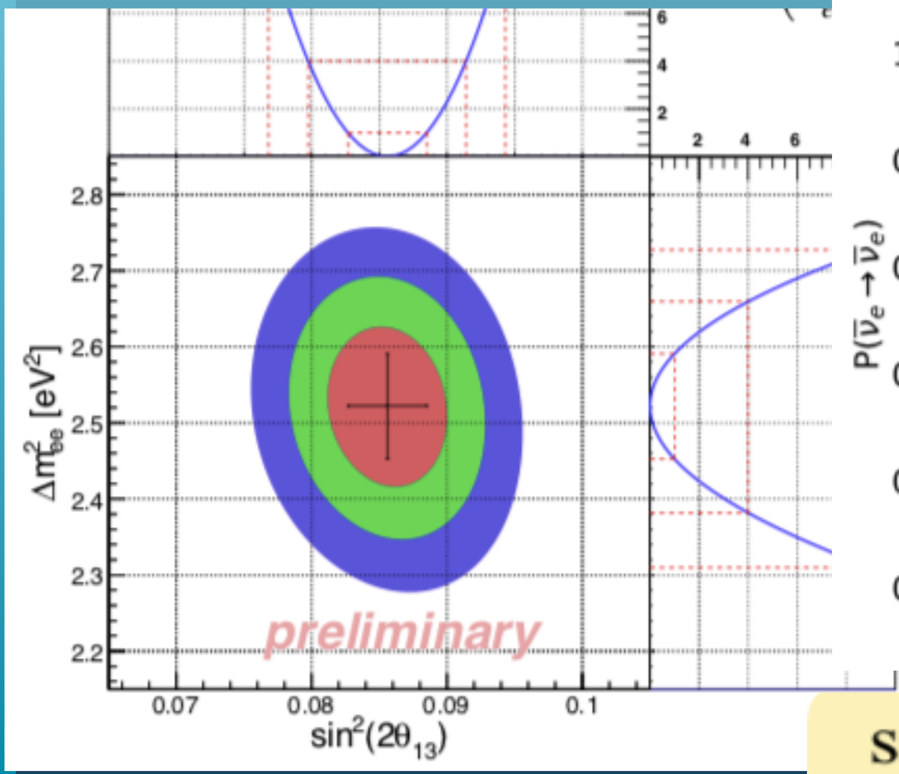
Daya Bay

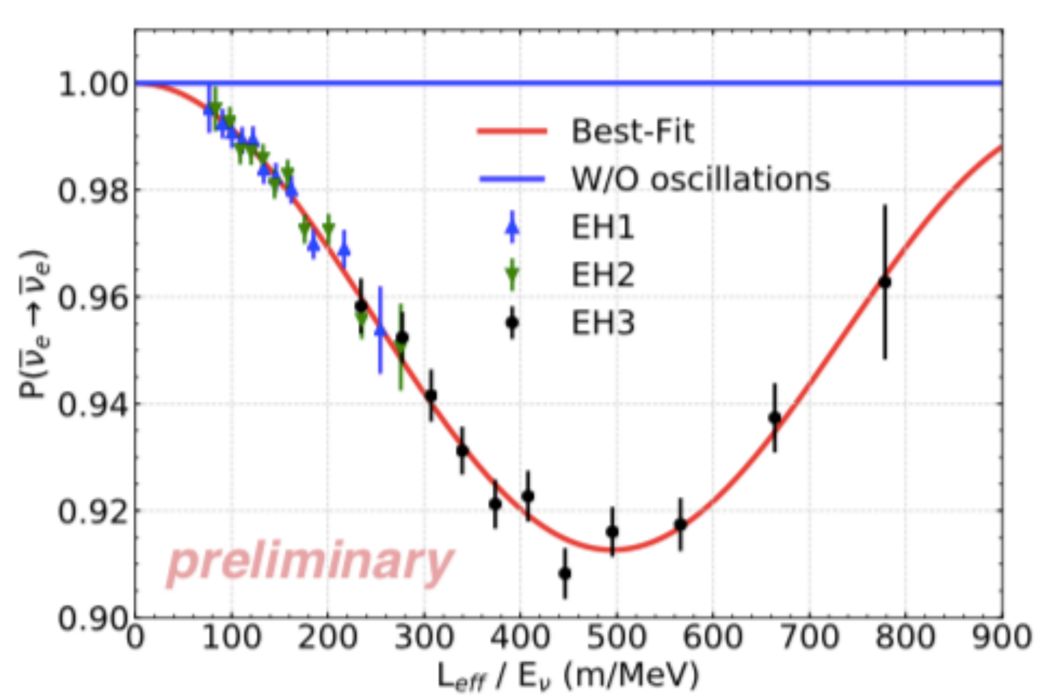
most precise measurements of θ_{13}



far and near detectors

Results with 1958 Days



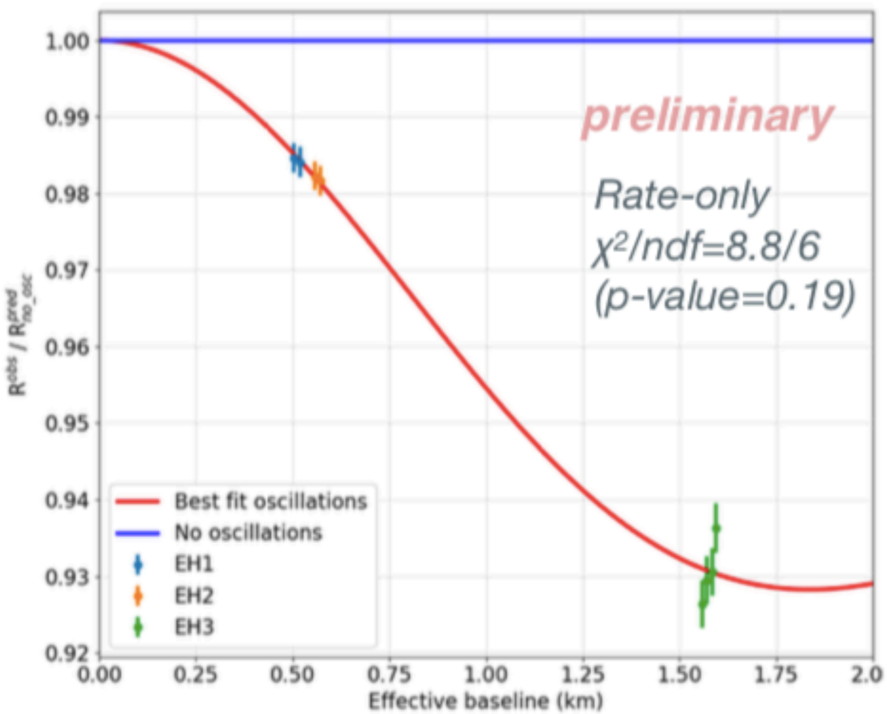


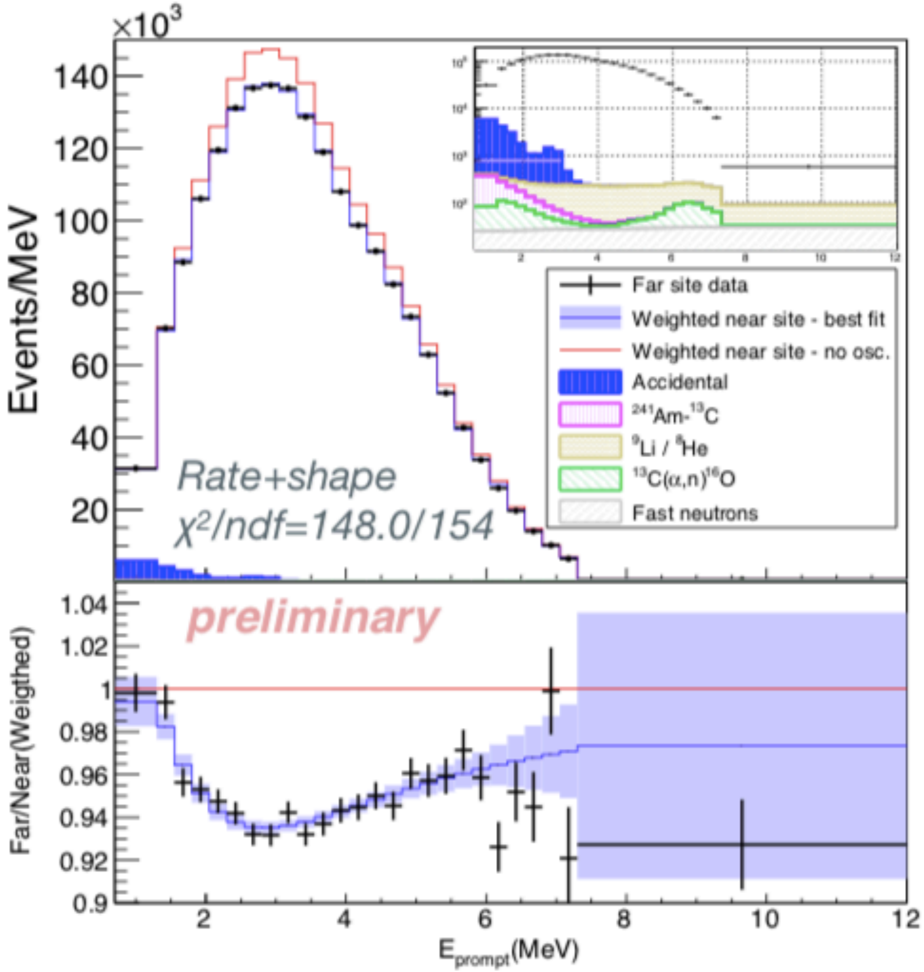
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} \text{ eV}^2$$

Oscillation Results with 1958 Days

- See a clear rate and shape distortion that fits well to the 3-neutrino hypothesis:

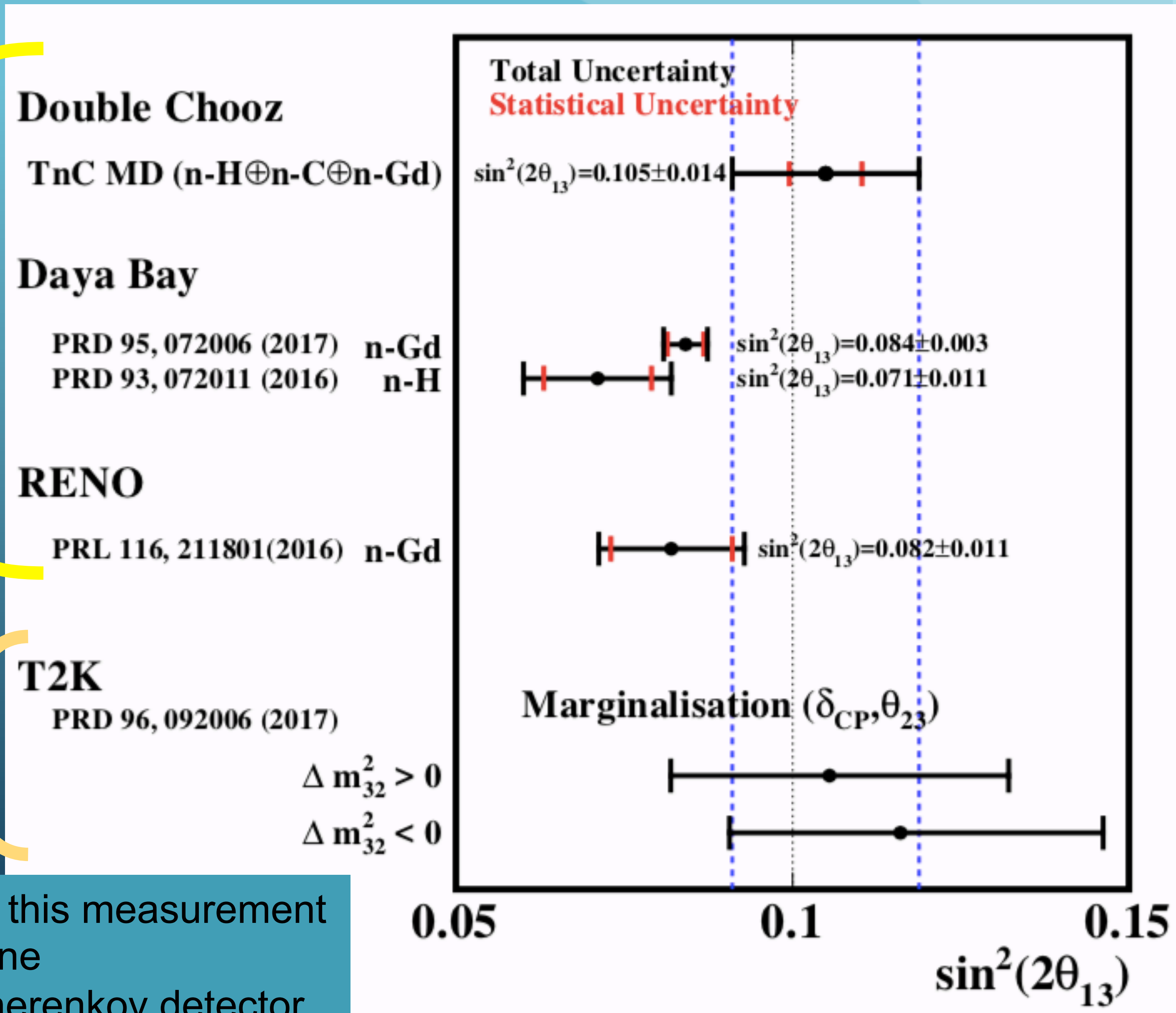




measurements in 1-3 sector

electron anti-neutrino disappearance (reactor)

electron neutrino appearance In ν_μ beam → Sensitive to CP violation



Now move to this measurement
Long Base Line
with water Cherenkov detector

First observation of expected transition

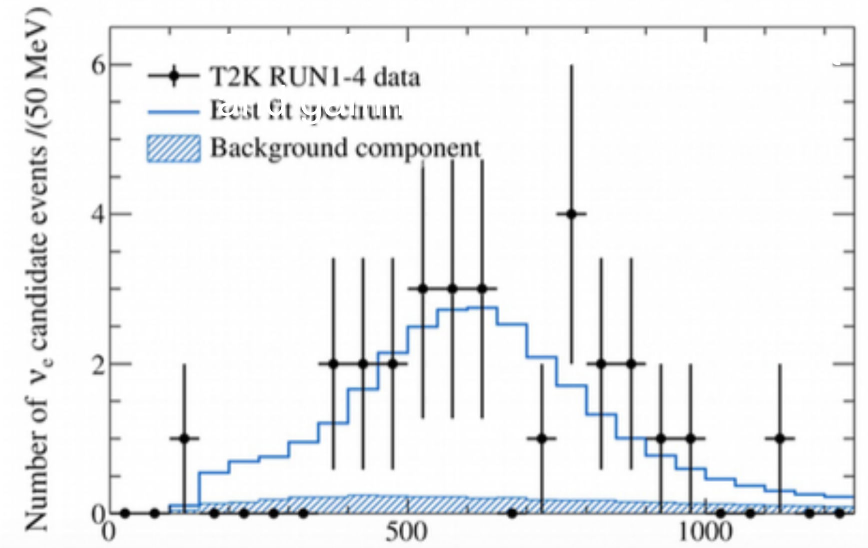
appearance $\nu_\mu \rightarrow \nu_e$ sector 1-3

expected background: 4.64 ± 0.53

observed (2013):

28 events

7.3σ significance for non-zero θ_{13}

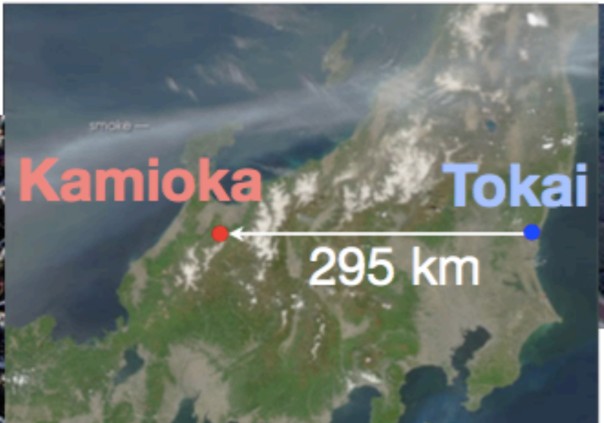


Reconstructed neutrino energy

How this observation was done?

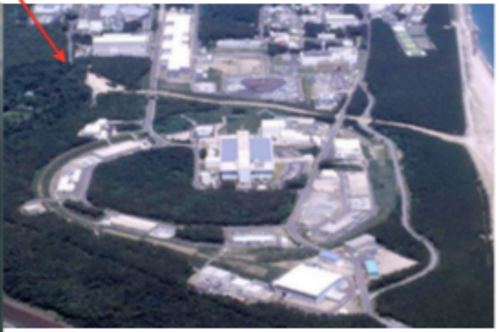
T2K: accelerator experiment
beam from p and K decays

Super-Kamiokande
"far" detector

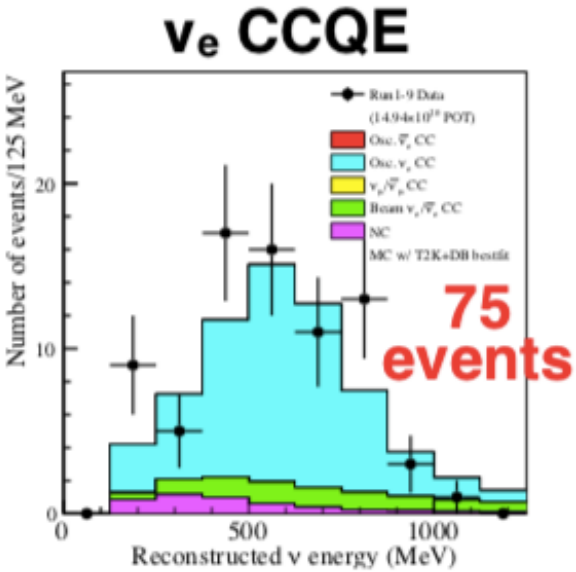


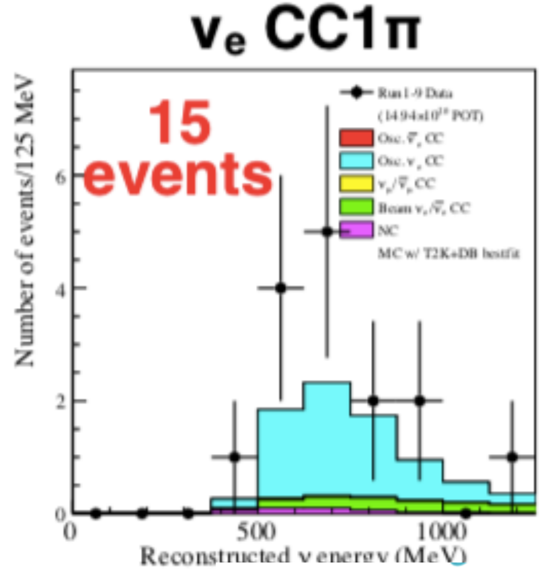
ND280
"near" detectors

accelerator
J-PARC



~400 collaborators
59 institutions

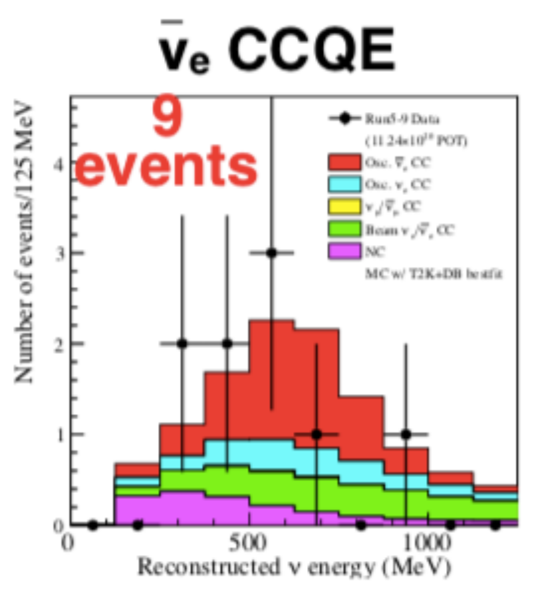


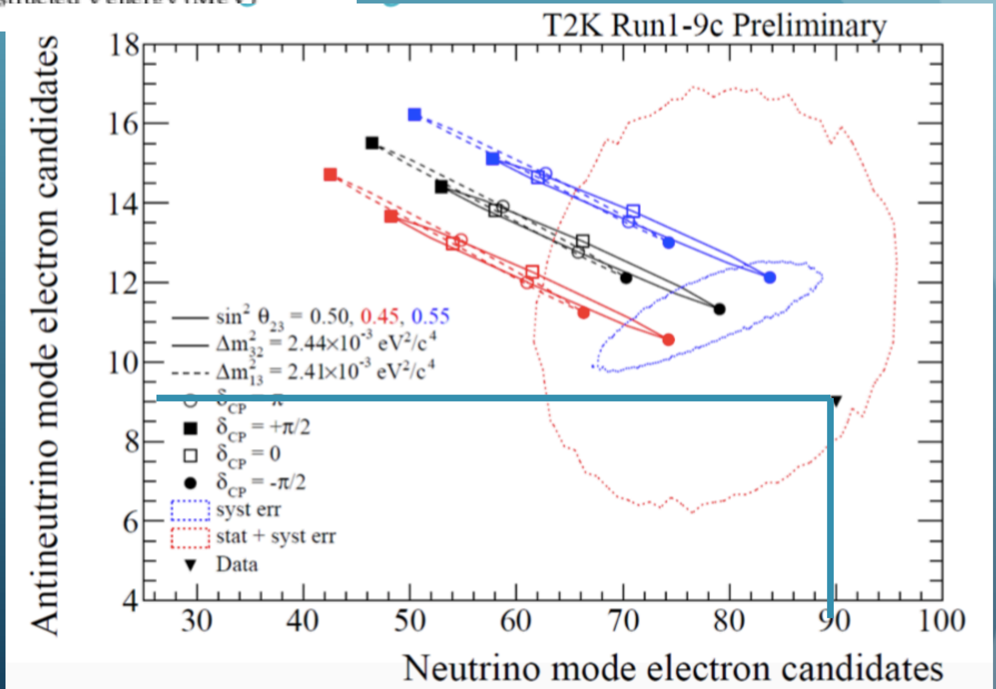


In neutrino beam – observation
Of 75 events with electron (CCQE)
and additional 15 events
with electron and pion (CC1π)

Comparison of ν and $\bar{\nu}$

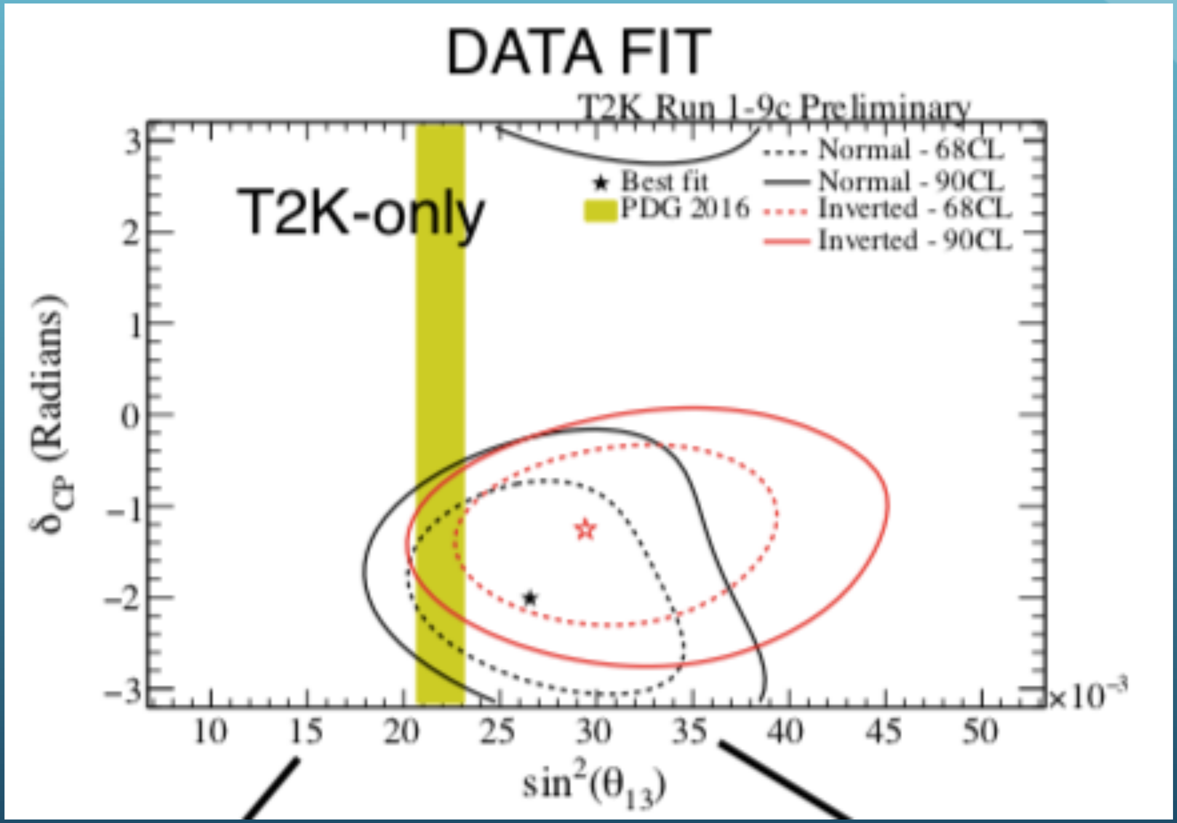
tells us about CP violation





In anti-neutrino beam – observed
by now 9 events, not enough to claim that appearance Is observed, need more data
(expected 6.5 without oscillation)

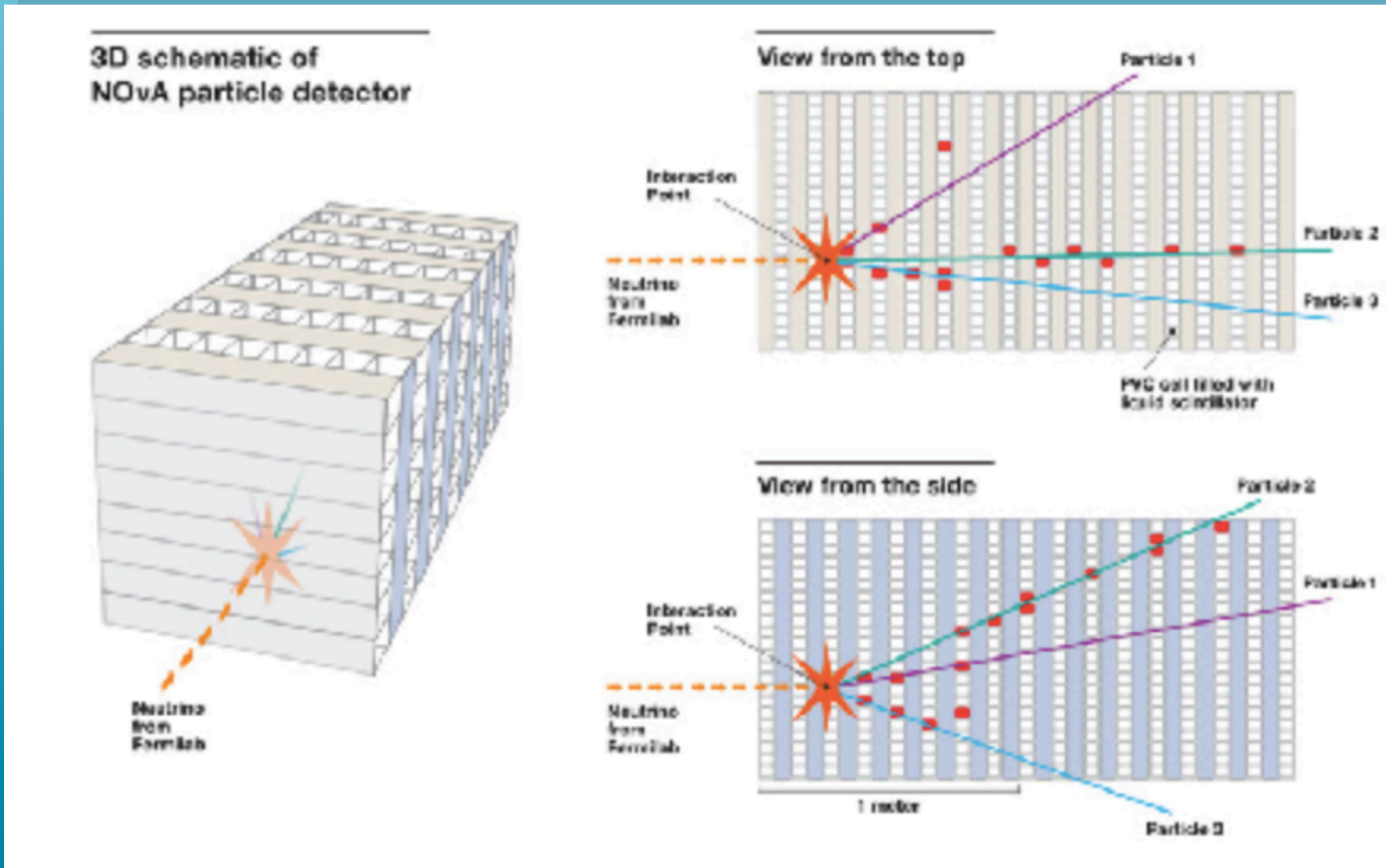
From this data $\sin^2\Theta_{13}$ and also CP violation can be estimated



Oscillation fits

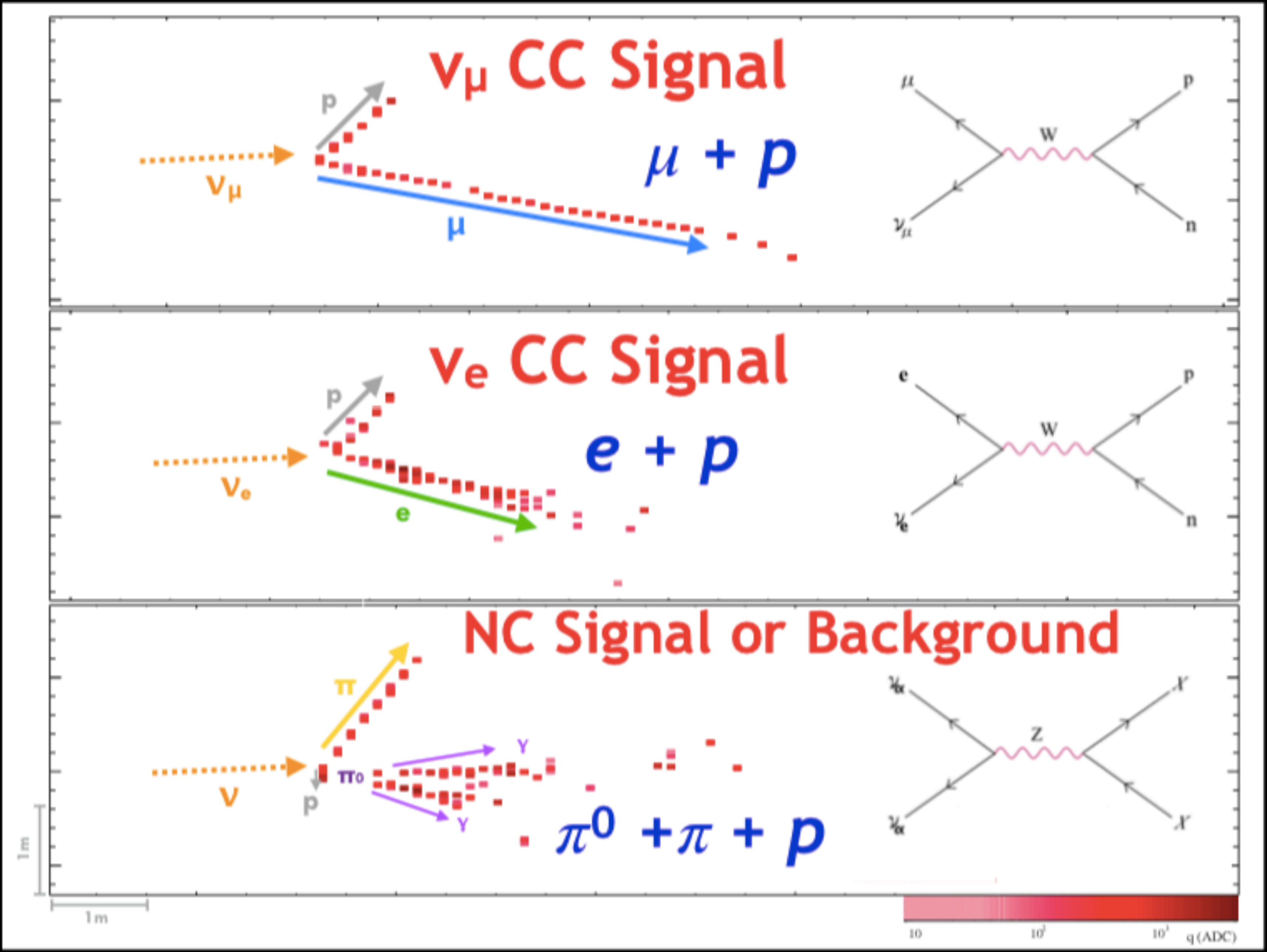
Also data from NOVA – Liquid scintillator segmented detector -

- PVC extrusions + Liquid Scintillator
- Layered planes of orthogonal views with 6-cm cells. Readout via WLS fibers to APDs.
- 0.15 X_0 per layer, excellent for e-identification.



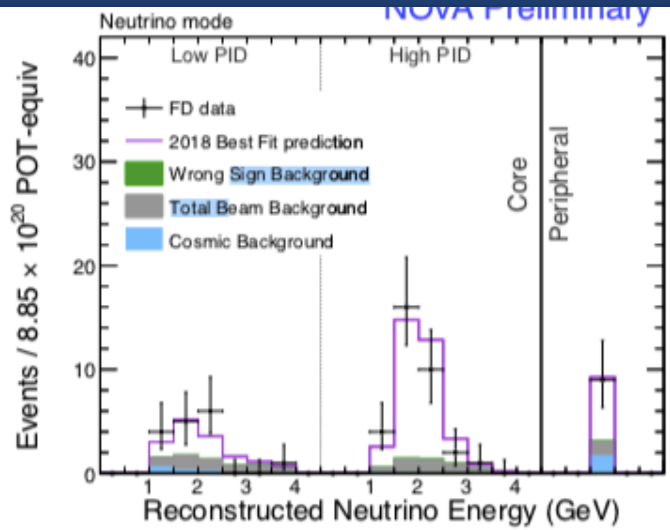
NOVA EVENT TOPOLOGIES

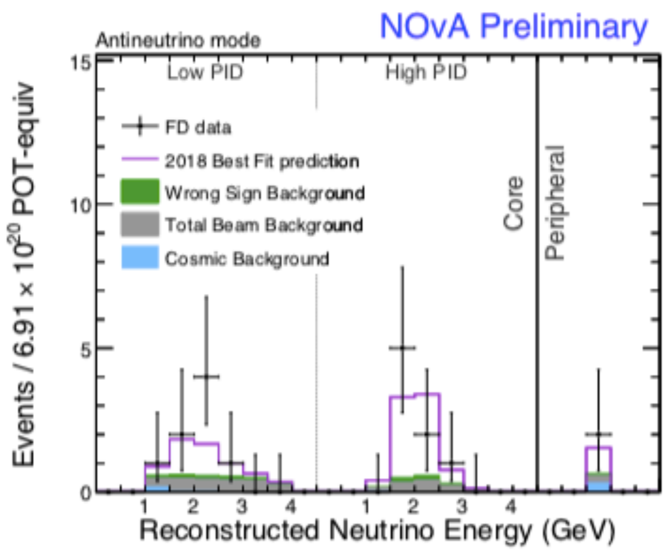
neutrino candidate interactions

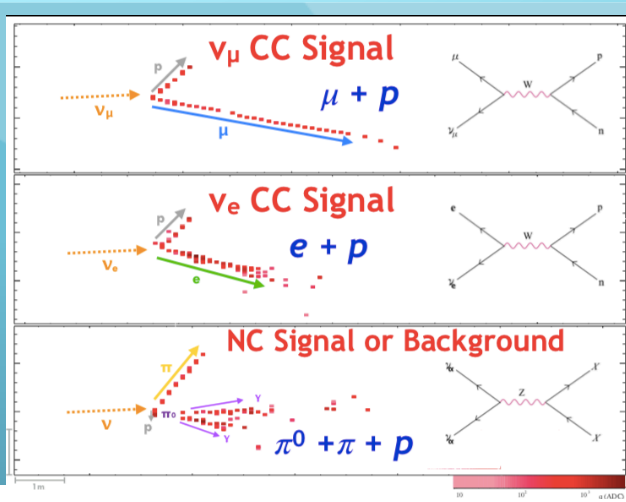


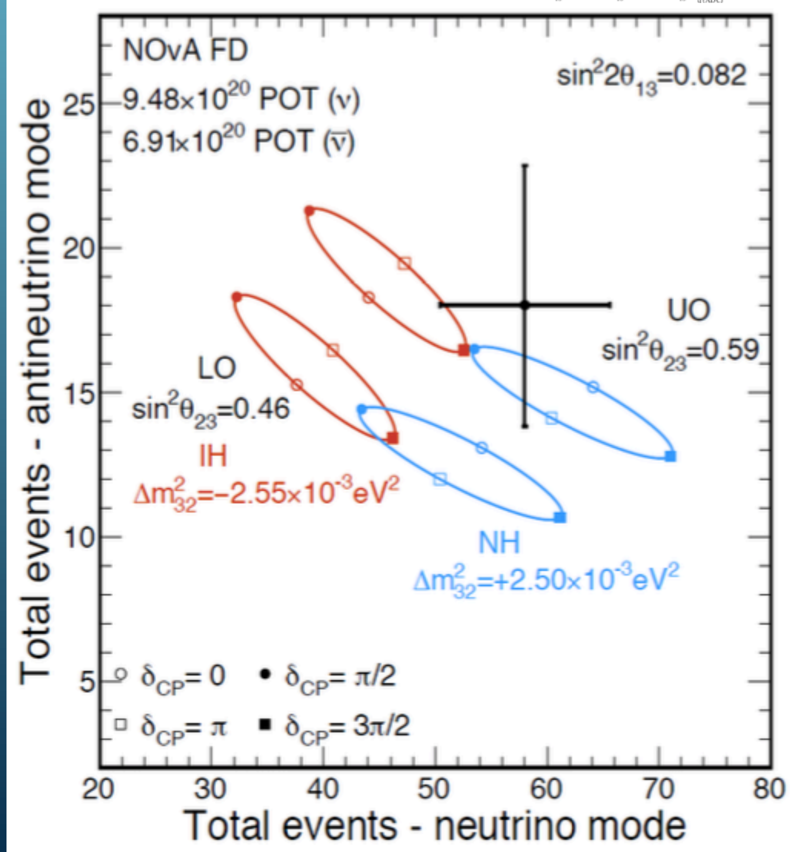
M. Sanchez – Neutrino 2018

> 4σ evidence of electron antineutrino appearance









What's next?

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

Unknown

Differences in neutrino and 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

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

- 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

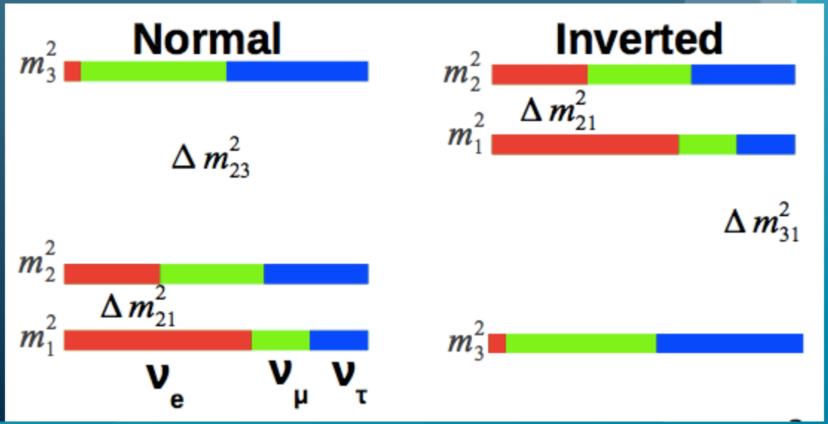
Resonance enhancement appears at specific energies

  (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

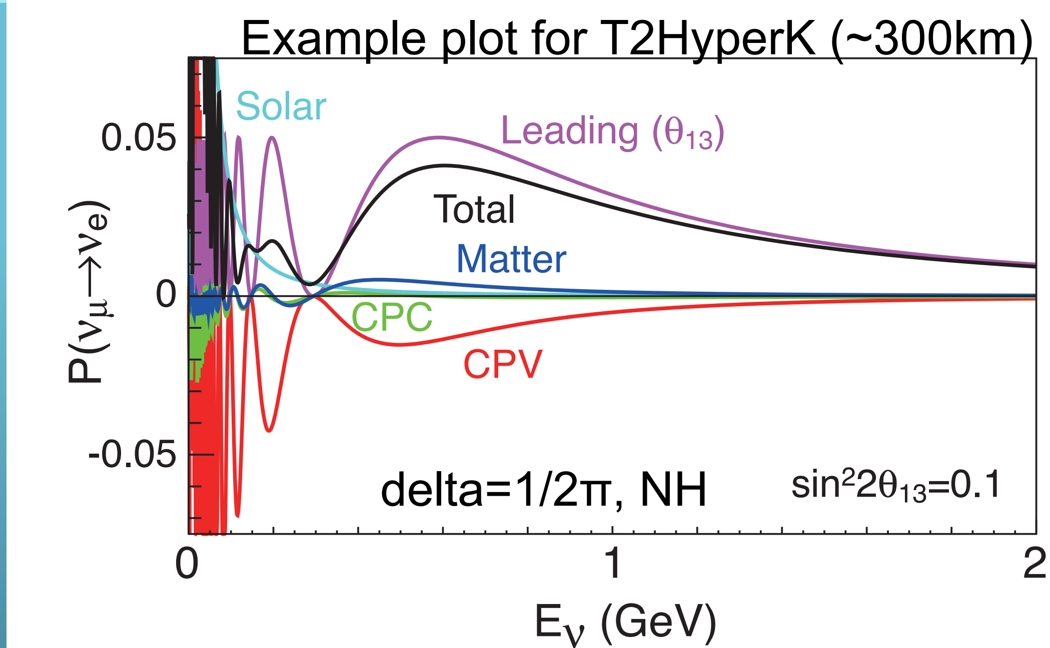
  → open question – two options



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

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

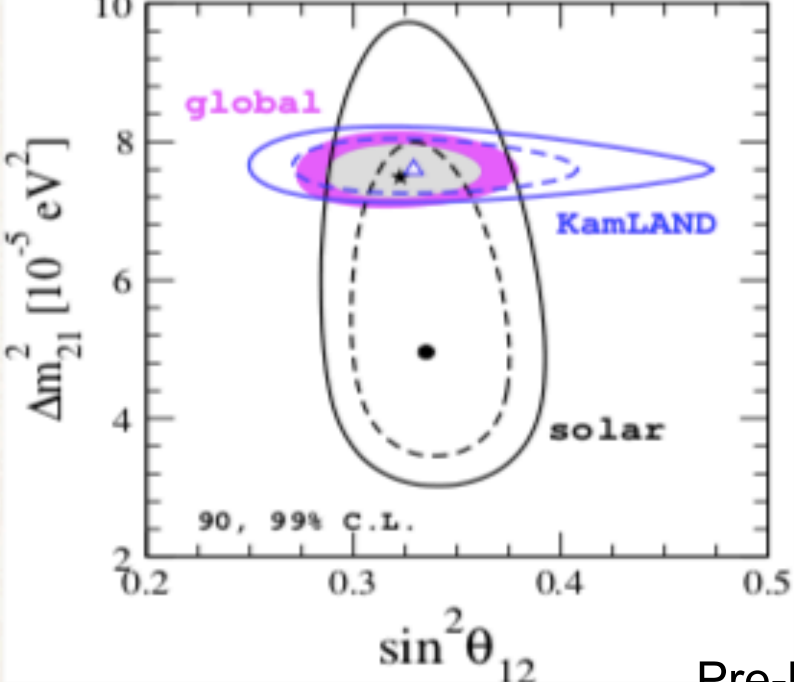
$\cos\theta_{ij},\ \sin\theta_{ij},\ \Delta m_{ij}^2\, L/4E_\nu$

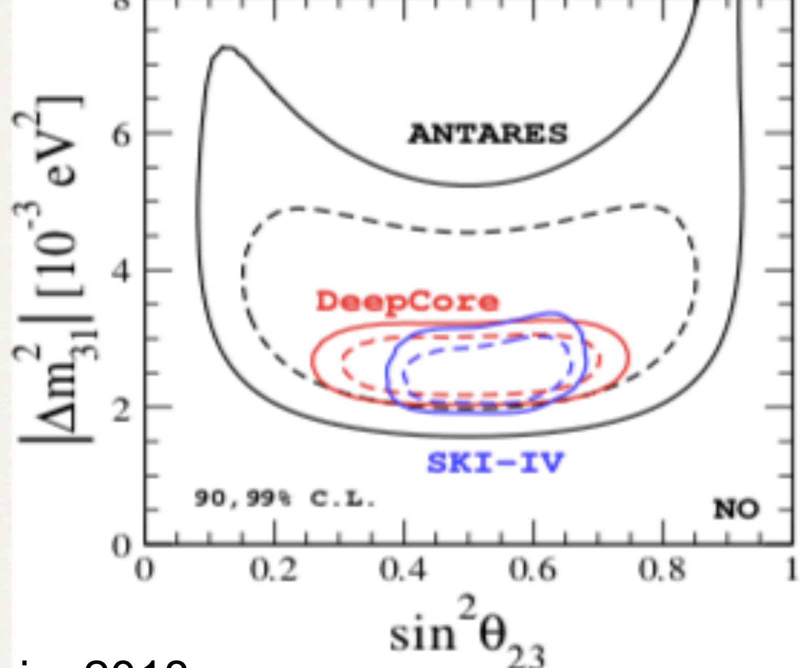
for $\overline{\nu}_\mu \to \overline{\nu}_e$ $\delta \to -\delta$ $a \to -a.$

α~ρ*E_ν

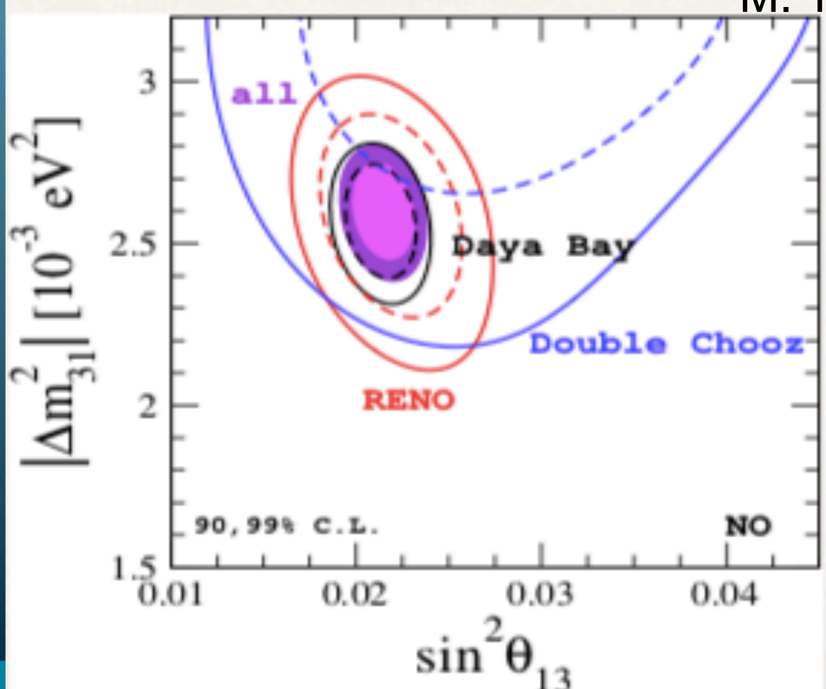
Best information we can get…

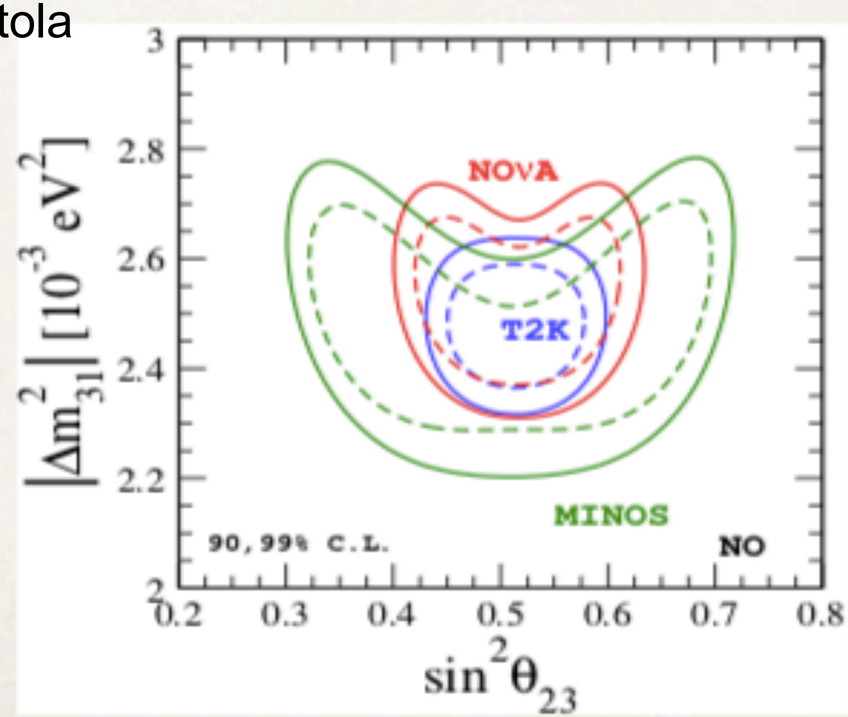
- Combined analysis of long base line, solar, reactor, atmespheric neutrino and neutrino telescope
- oscillations in appearance and
- disappearance channels for
- neutrinos and anti-neutrinos
- gives sensitivity to all parameters
- Including CP violating phase





Pre-Neutrino2018
M. Tortola



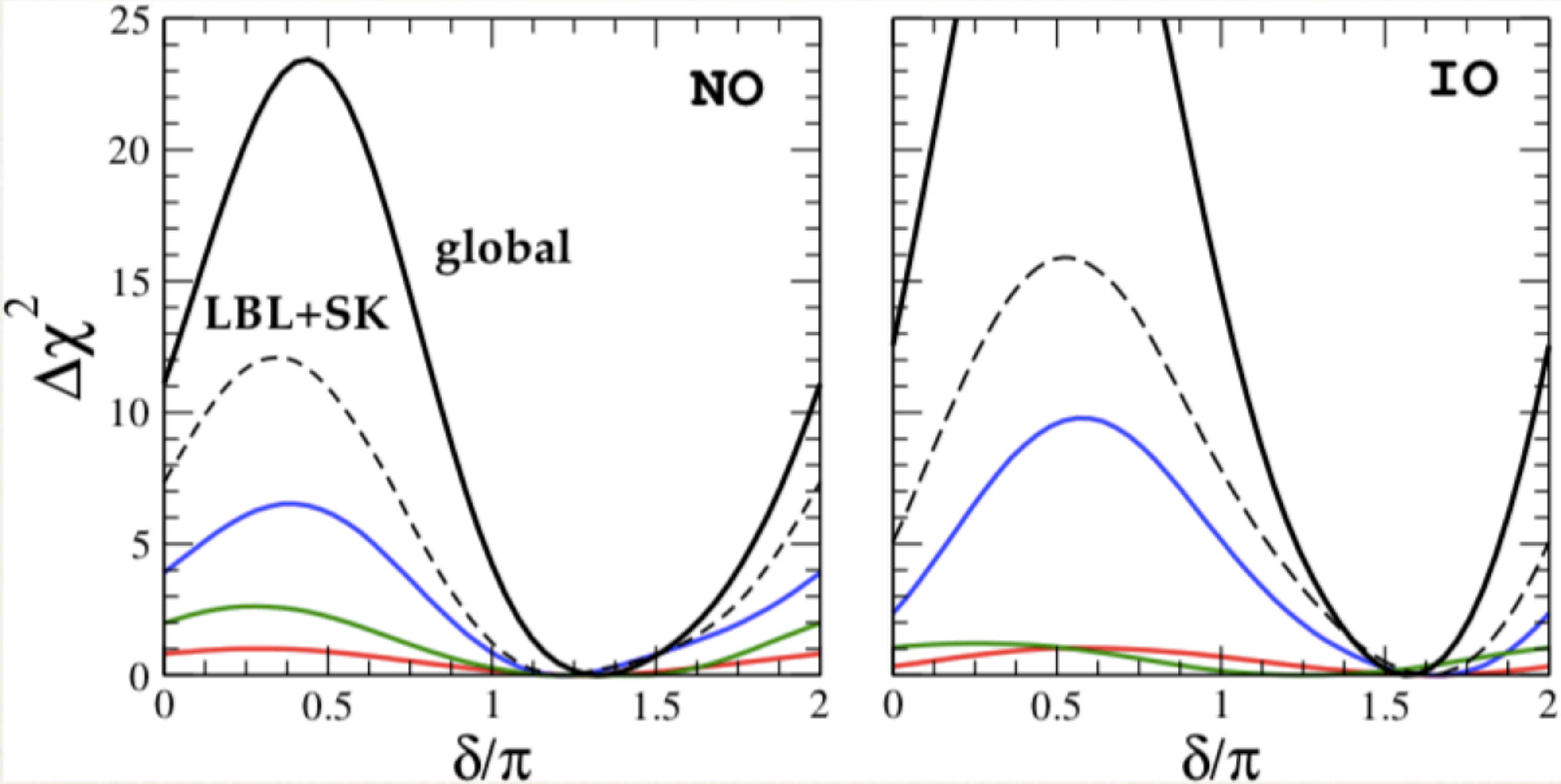


parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncertainty
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

deSalas et al, 1708.01186 (May 2018)

Global fit before Neutrino2018

deSalas et al, 1708.01186



- **T2K**, **NOvA** and **Super-K** prefer $\pi < \delta < 2\pi$ (as well as NO)
- The combination of LBL and Super-K enhances rejection against $\delta = \pi/2$
- From the global analysis, $\delta = \pi/2$ is disfavoured at 4.8σ (6.1σ) for NO (IO)

Role of atmespheric neutrinos in the global fits

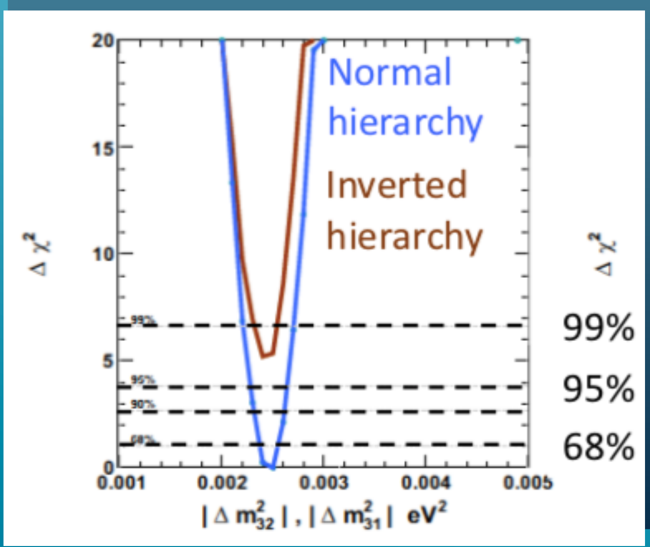
Difference in # of electron events:

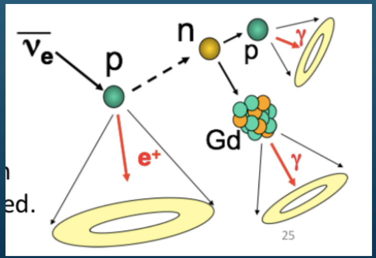
$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \text{Matter effect}$$

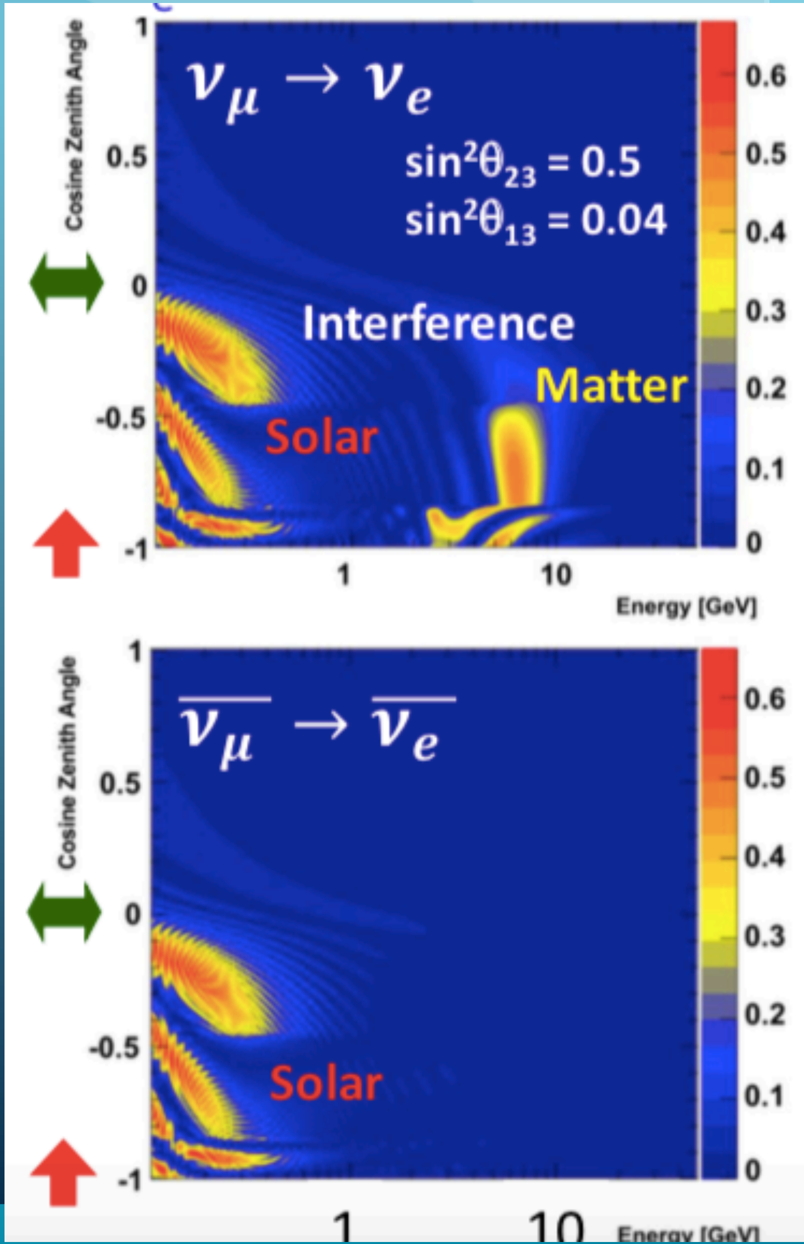
$$+\Delta_2(\Delta m^2_{12}) \quad \text{Solar term}$$

$$+\Delta_3(\theta_{13}, \Delta m^2_{12}, \delta) \quad \text{Interference}$$

- This brings sensitivity to mass hierarchy and CP violation
- this will be improved with better neutron detection (Ga)







Perspectives for Mass Hierarchy

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta m^2_{21}\frac{L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta m^2_{31}\frac{L}{4E} + \sin^2\theta_{12}\sin^2\Delta m^2_{32}\frac{L}{4E}\right)$$

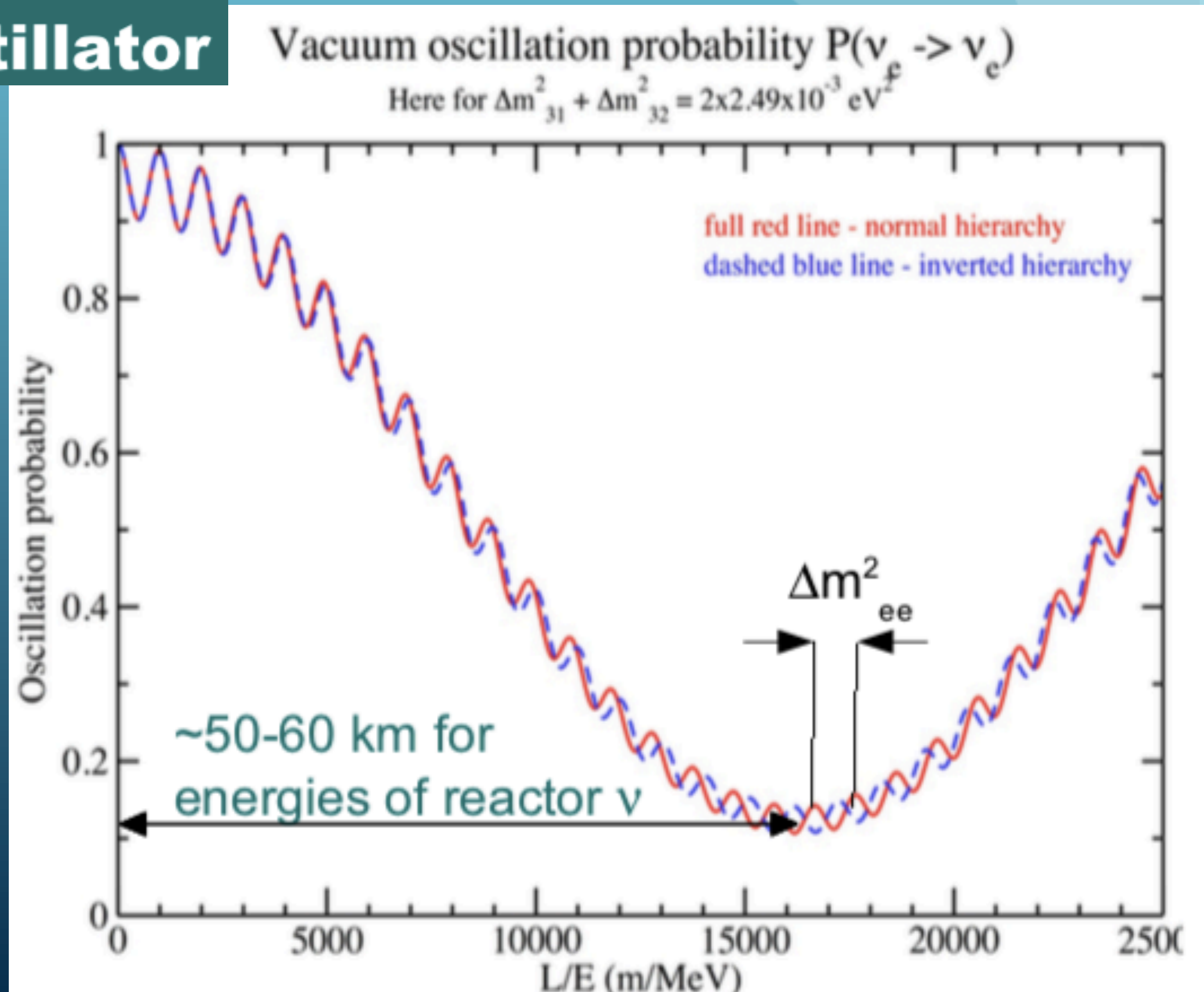
$$\approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta m^2_{21}\frac{L}{4E} - \sin^2 2\theta_{13}\sin^2\Delta m^2_{ee}\frac{L}{4E} \quad ,\text{for} \quad \Delta m^2_{12} \ll \Delta m^2_{32}$$

JUNO Liquid Scintillator

- Energy resolution 3%/sqrt(E)
- Mass 20 kton
- Calibration <1%
- 2021 – detector redy – data taking
- 100 k events

  in 6 years

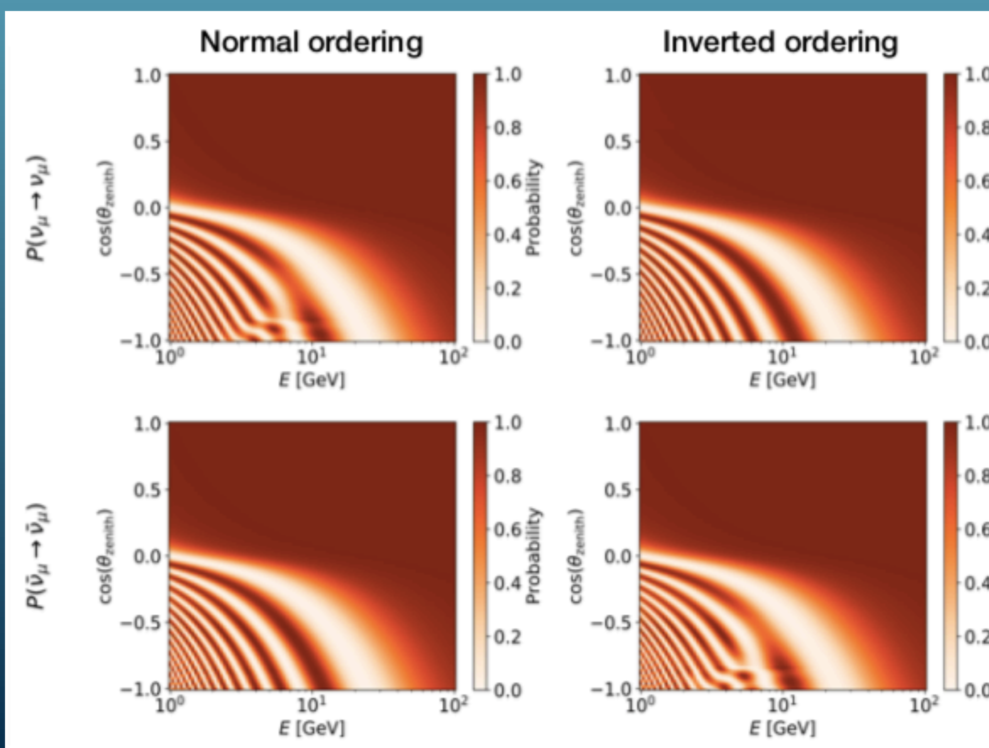
Also very reach program for other measurements



Sensitivity to mass ordering in neutrino telescopes

matter induced transition appear

- For neutrinos in normal mass ordering
- For anti-neutrinos for inverted mess ordering



as fluxes and cross-sections for ν and $\bar{\nu}$ differ expectation for differential distribution on $\cos\Theta - E_\nu$ plane allows determination of mass order

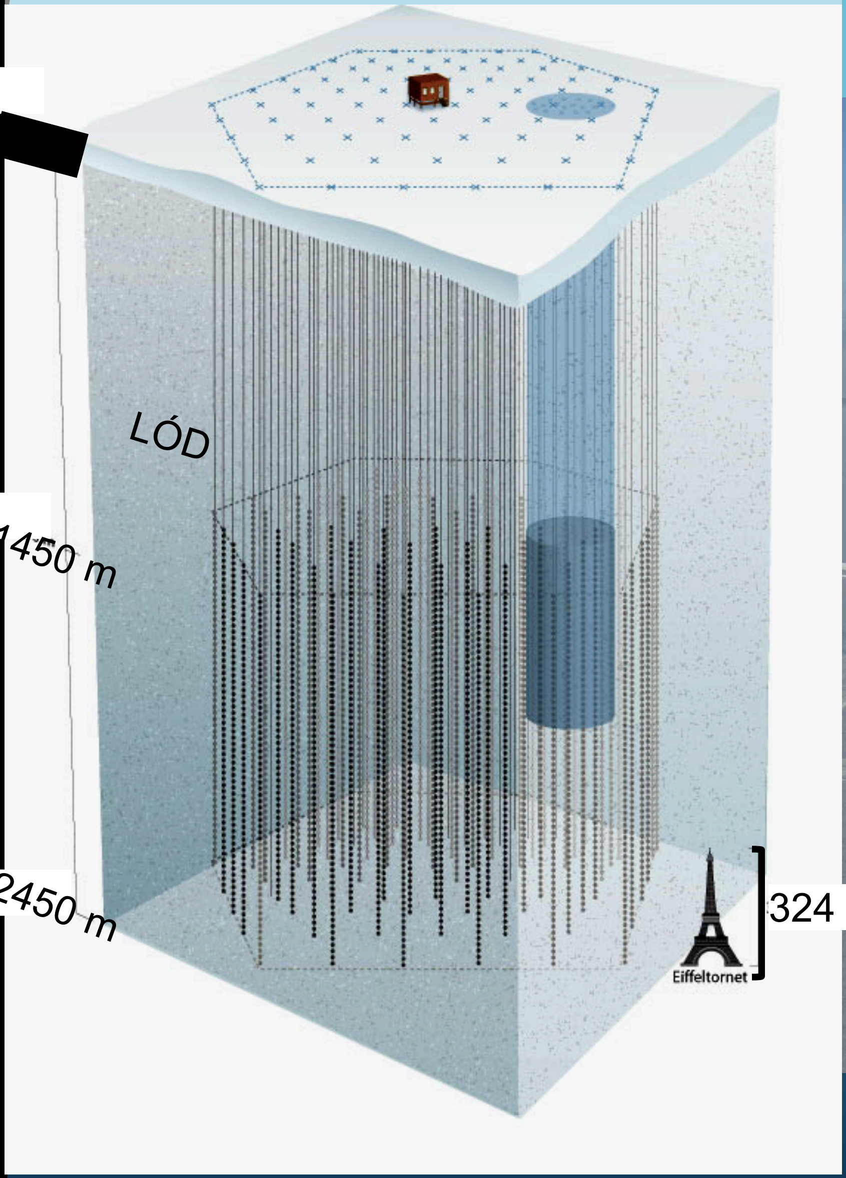
possiiblity to meaureure:

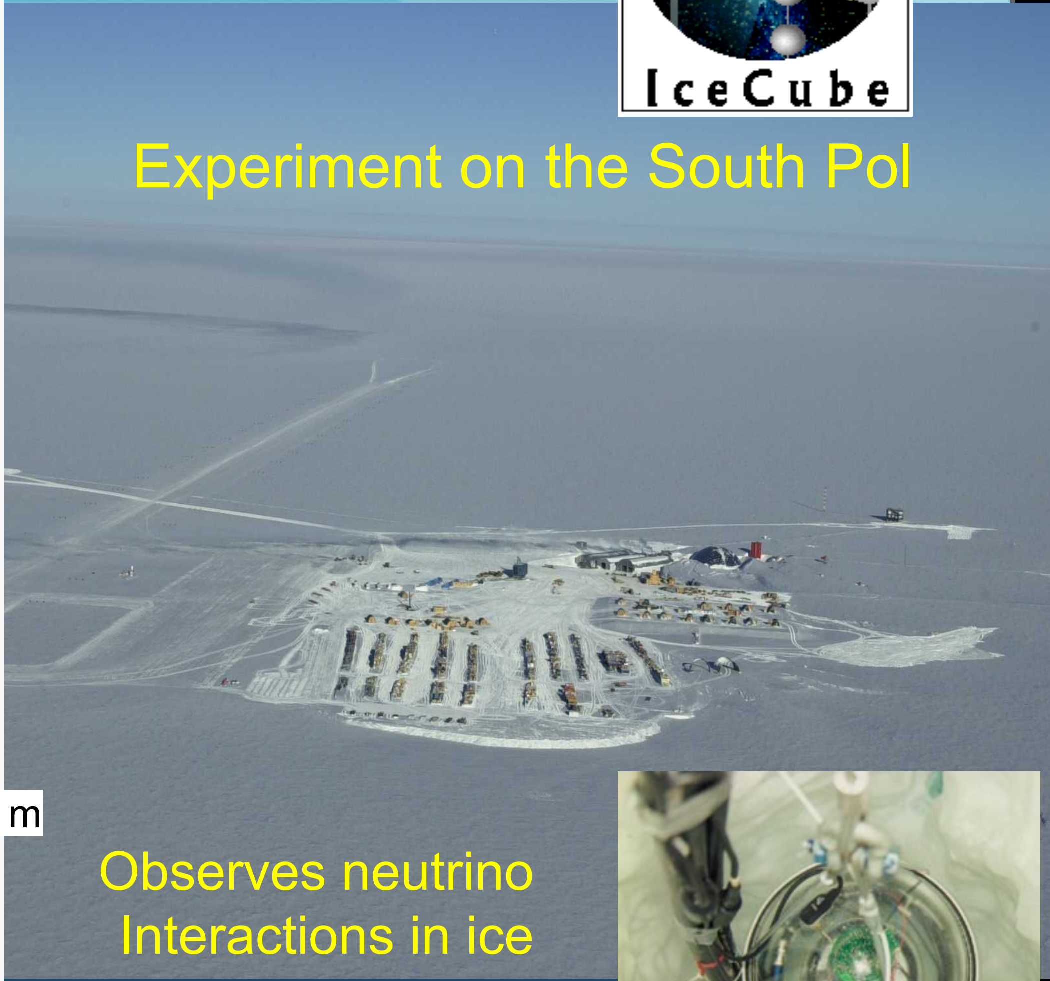
PINGU – within IceCube

ORCA - within KM^3-net

IceCube

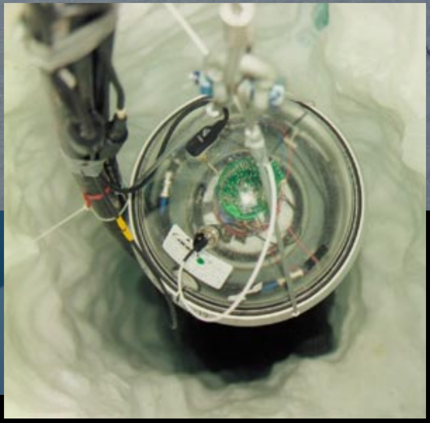
http://icecube.wisc.edu/





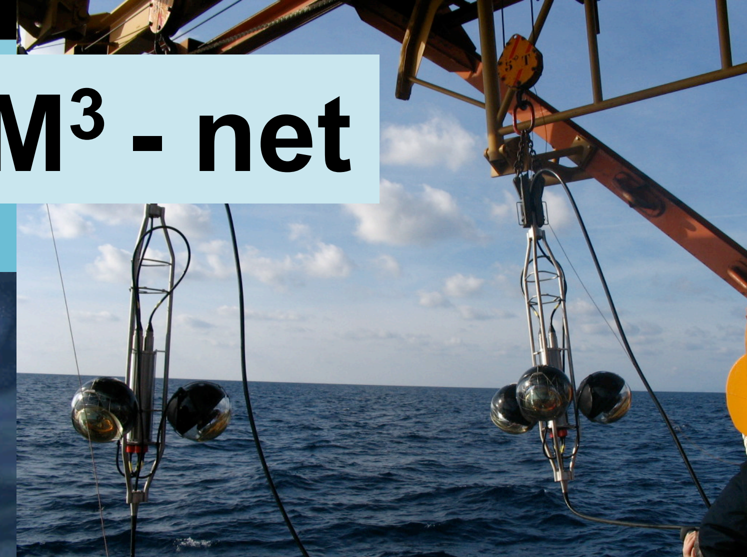
Experiment on the South Pol

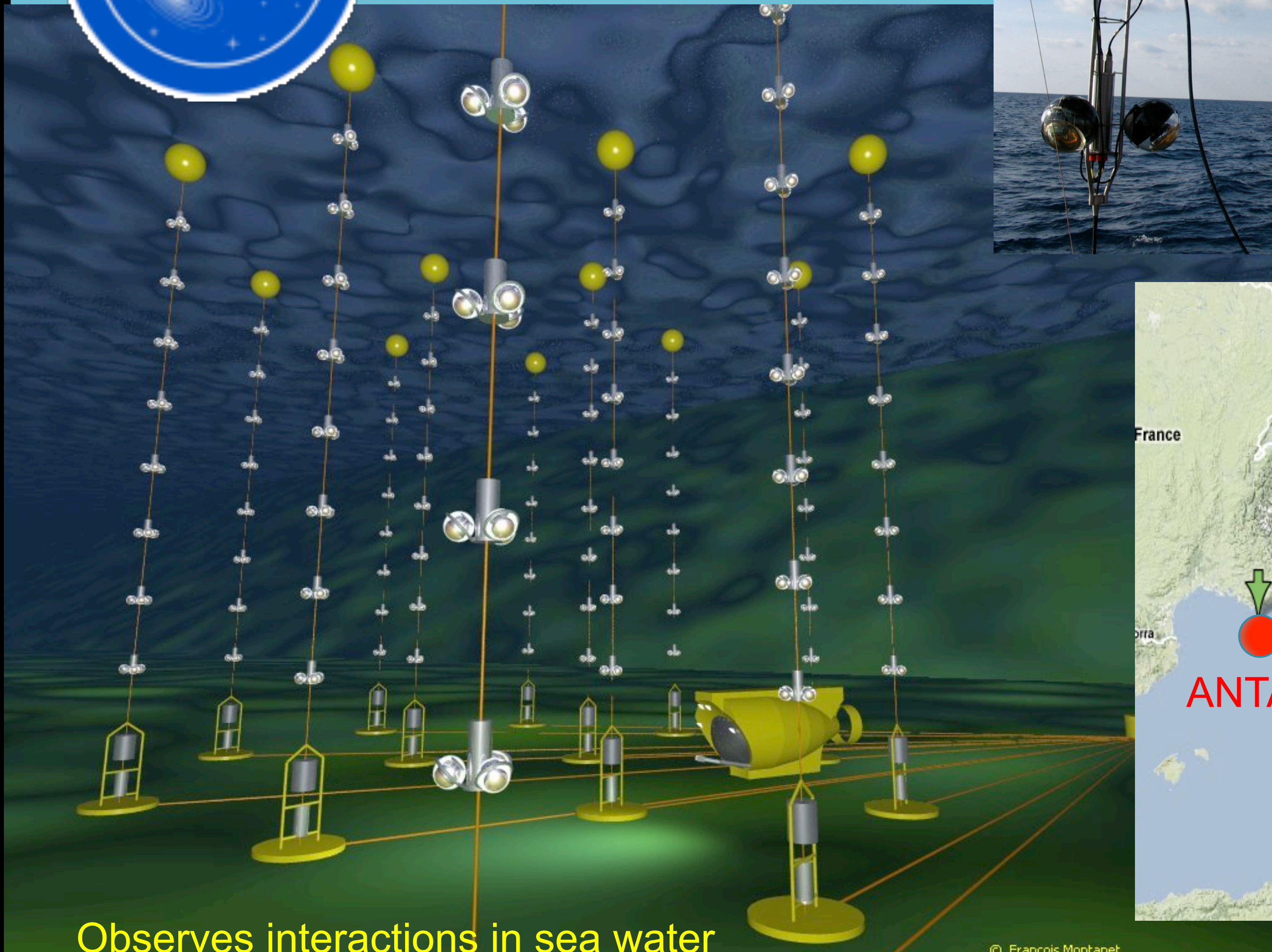
Observes neutrino
Interactions in ice



Antares → KM^3 - net

http://antares.in2p3.fr/



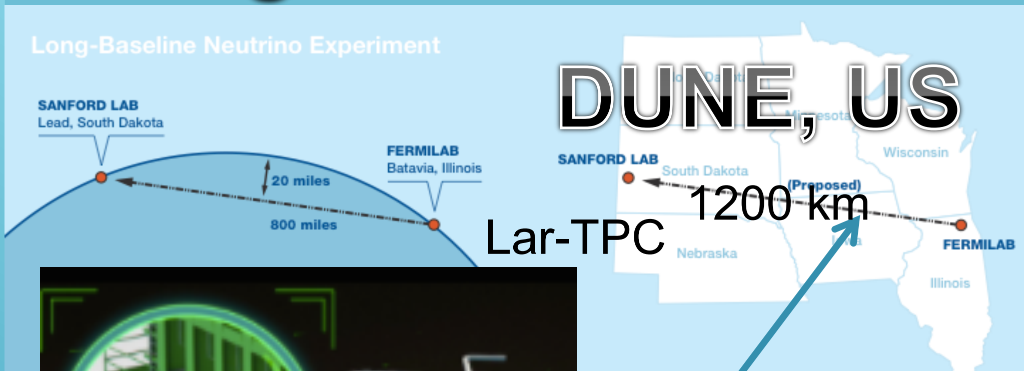


Observes interactions in sea water

Long Baseline Future

Long term
ie. after/around 2025

DUNE, US

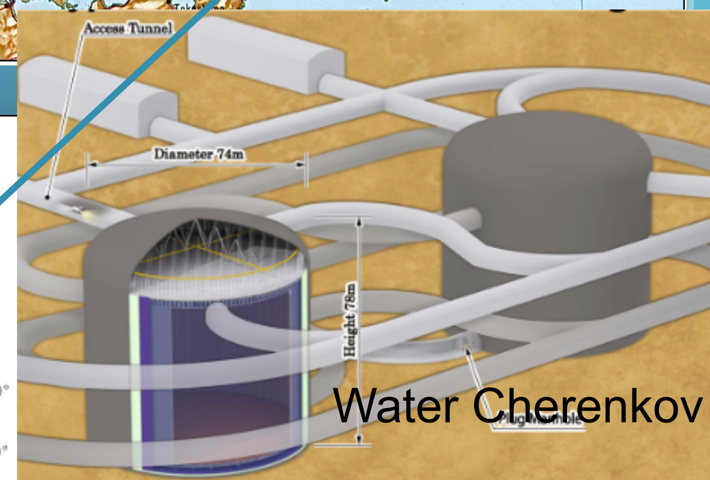


1200 km

Lar-TPC

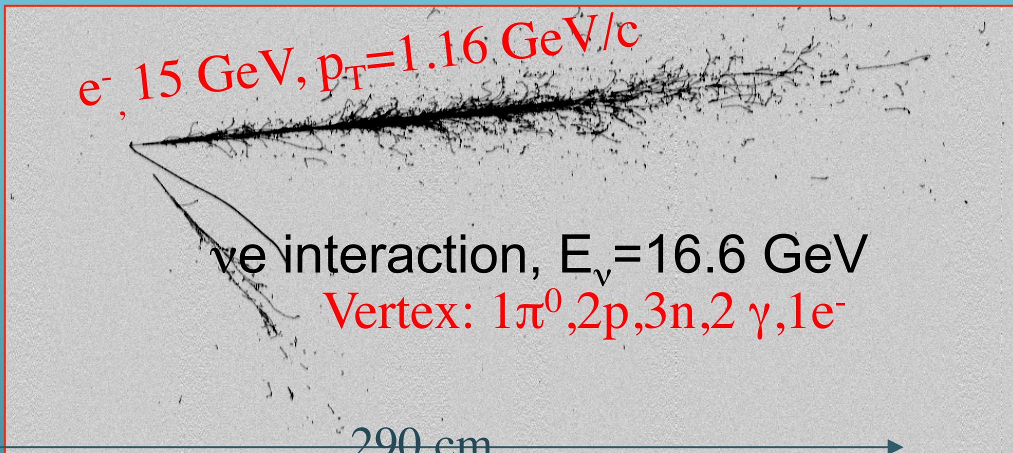
Hyper-Kamiokande, Japan

295 km



Water Cherenkov

liquid argon TPC technique, used first time in ICARUS at CNGS beam from CERN



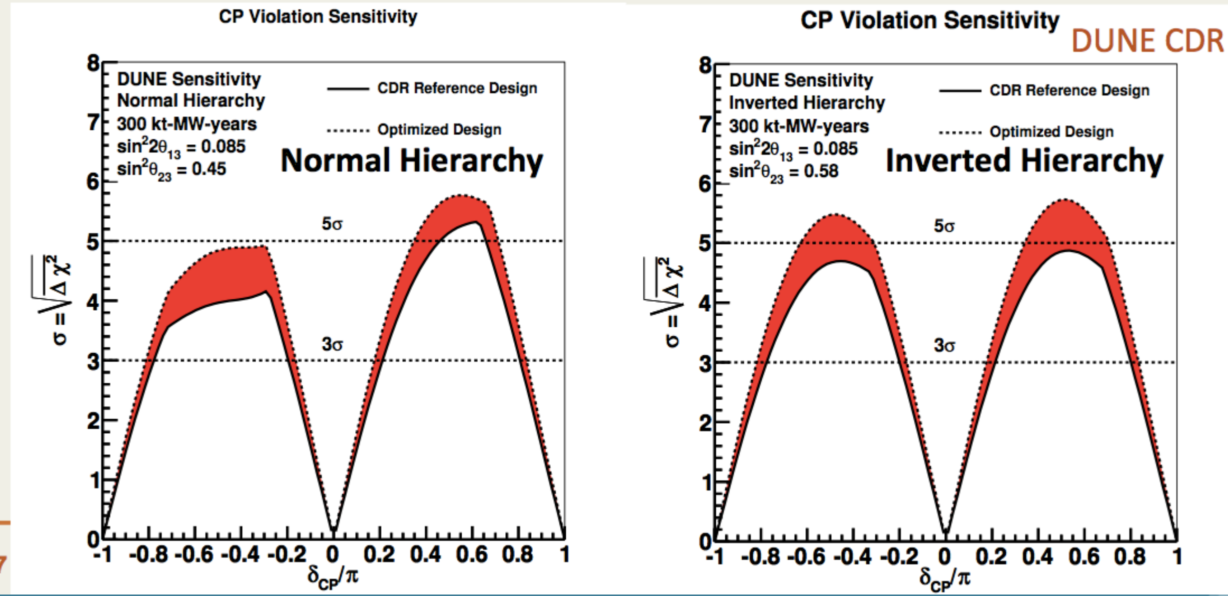
Very good particle ID, energy resolution and “bubble chamber like” picture Of the interaction. Technique developing very fast and promising for large Scale detectors

Prospect for measurements after 2025

Dune with
40 ktons
optimized
beam

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)

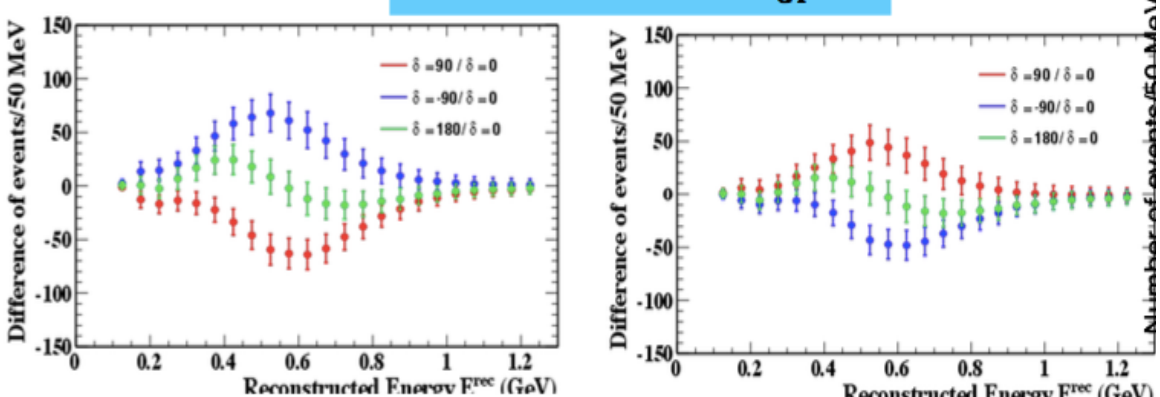


In both experiments more goals than oscillations ….

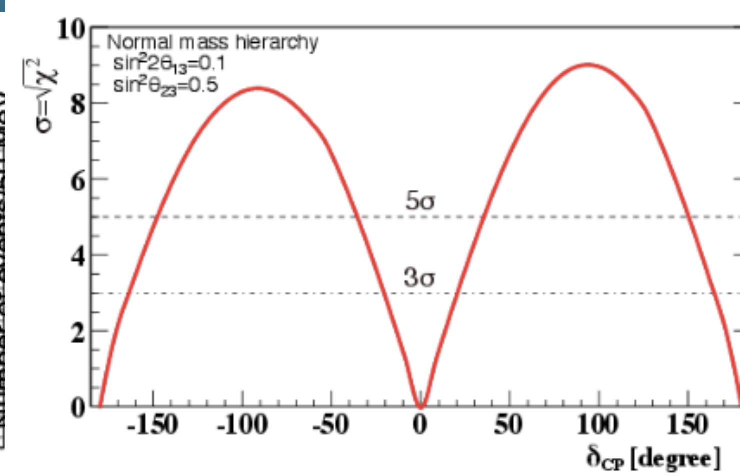
sensitivity for **Hyper-Kamiokande**

10 years data taking

Difference from $\delta_{CP}=0$



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



Summary:

Precision on neutrino mixing parameters is reaching % level,

Some open questions could be sorted out soon

Measurement of CP violation parameter from single experiment may need to wait for next generation experiments

PLEASE CONTINUE TO ENJOY NEUTRINO OSCILLATIONS

^ *precision measurements of*